BNL-52596

Proceedings of RIKEN BNL Research Center
Joint Sessions of Workshops

Volume 27

Predictions and Uncertainties for RHIC Spin Physics
&
Event Generator for RHIC Spin Physics III

–towards precision spin physics at RHIC–

March 6–31, 2000

Organizers

Jianwei Qiu, Naohito Saito, Andreas Schäfer, and Werner Vogelsang

RIKEN BNL Research Center

Building 510, Brookhaven National Laboratory, Upton, NY 11973, USA

Other RIKEN BNL Research Center Proceedings Volumes:

Volume 26 - Circum-Pan-Pacific RIKEN Symposium on High Energy Spin Physics - BNL-52588

Volume 25 - RHIC Spin - BNL-52581

Volume 24 - Physics Society of Japan Biannual Meeting Symposium on QCD Physics at RIKEN BNL Research Center - BNL-52578

Volume 23 - Coulomb and Pion-Asymmetry Polarimetry and Hadronic Spin Dependence at RHIC Energies - BNL-52589

Volume 22 - OSCAR II: Predictions for RHIC - BNL-52591

Volume 21 - RBRC Scientific Review Committee Meeting - BNL-52568

Volume 20 - Gauge-Invariant Variables in Gauge Theories - BNL-52590

Volume 19 - Numerical Algorithms at Non-Zero Chemical Potential - BNL-52573

Volume 18 - Event Generator for RHIC Spin Physics - BNL-52571

Volume 17 - Hard Parton Physics in High-Energy Nuclear Collisions - BNL-52574

Volume 16 - RIKEN Winter School — Structure of Hadrons —Introduction to QCD Hard Processes— BNL-52569

Volume 15 - QCD Phase Transitions - BNL-52561

Volume 14 - Quantum Fields In and Out of Equilibrium - BNL-52560

Volume 13 - Physics of the 1 Teraflop RIKEN-BNL-Columbia QCD Project First Anniversary Celebration - BNL-66299

Volume 12 - Quarkonium Production in Relativistic Nuclear Collisions - BNL-52559

Volume 11 - Event Generator for RHIC Spin Physics - BNL-66116

Volume 10 - Physics of Polarimetry at RHIC - BNL-65926

Volume 9 - High Density Matter in AGS, SPS and RHIC Collisions - BNL-65762

Volume 8 - Fermion Frontiers in Vector Lattice Gauge Theories - BNL-65634

Volume 7 - RHIC Spin Physics - BNL-65615

Volume 6 - Quarks and Gluons in the Nucleon - BNL-65234

Volume 5 - Color Superconductivity, Instantons and Parity (Non?)-Conservation at High Baryon Density - BNL-65105

Volume 4 - Inauguration Ceremony, September 22 and Non-Equilibrium Many Body Dynamics - BNL- 64912

Volume 3 - Hadron Spin-Flip at RHIC Energies - BNL-64724

Volume 2 - Perturbative QCD as a Probe of Hadron Structure - BNL-64723

Volume 1 - Open Standards for Cascade Models for RHIC - BNL-64722

Preface to the Series

The RIKEN BNL Research Center was established this April at Brookhaven National Laboratory. It is funded by the "Rikagaku Kenkysho" (Institute of Physical and Chemical Research) of Japan. The Center is dedicated to the study of strong interactions, including hard QCD/spin physics, lattice QCD and RHIC physics through nurturing of a new generation of young physicists.

For the first year, the Center will have only a Theory Group, with an Experimental Group to be structured later. The Theory Group will consist of about 12-15 Postdocs and Fellows, and plans to have an active Visiting Scientist program. A 0.6 teraflop parallel processor will be completed at the Center by the end of this year. In addition, the Center organizes workshops centered on specific problems in strong interactions.

Each workshop speaker is encouraged to select a few of the most important transparencies from his or her presentation, accompanied by a page of explanation. This material is collected at the end of the workshop by the organizer to form a proceedings, which can therefore be available within a short time.

Thanks to Brookhaven National Laboratory and to the U.S. Department of Energy for providing the facilities essential for the completion of this work.

T.D. Lee
July 4, 1997

CONTENTS

INTRODUCTION

This volume archives the presentations made at the joint RIKEN BNL Research Center workshops on "Predictions and Uncertainties for RHIC Spin Physics" and "Event Generator for RHIC Spin Physics III - *towards precision spin physics at RHIC*", held in March 2000 at BNL.

The RHIC spin physics program will start in early 2001. RHIC-Spin will be the first polarized-proton collider and will thus represent a new and unique laboratory for studying the spin structure of the proton. There are important further applications of RHIC-Spin, among them the search for physics beyond the Standard Model. The RHIC spin program will mark a completely new era of spin physics and hadron physics because of its high energy, high luminosity, and high polarization, and because of the versatility of the machine.

Given the proximity of the commencement of the RHIC spin physics program, it seemed timely to critically review our ability to make theoretical predictions for spin physics at RHIC, and to identify and study sources of major uncertainties and so far unsolved problems. A solid theoretical framework will be crucial for extracting the quantities of interest from future data! These were the motivations for the workshop on "Predictions and Uncertainties for RHIC Spin Physics".

Making the link between experimental data and theoretical concepts would be impossible without an advanced machinery of Monte Carlo event generators. Only with the help of event generators is it possible to analyze and interpret data, and to compare them to the theoretical predictions. It was already realized several years ago that special attention is required in order to design event generators specifically adapted to spin physics. This led to the origin of a series of workshops on "Event Generator for RHIC Spin Physics", the third of which is also summarized in this volume.

It turned out to be very felicitous to hold both workshops at the same time. This led to an enormous amount of interaction and of exchanges of ideas among the participants and created new collaborations. We are grateful to all participants of the workshops for their valuable presentations and discussions. We believe that it will be very beneficial for the RHIC spin physics program to repeat this combination of workshops in the near future.

The level of support provided by the RIKEN BNL Research Center was magnificent, and we are very grateful to Prof. T.D. Lee and the Center. Larry Trueman has been instrumental in initiating the workshop "Predictions and Uncertainties for RHIC Spin Physics". We also would like to extend our gratitude to Brookhaven National Laboratory and to the U.S. Department of Energy for providing the facilities to hold this workshop. Finally, we would like to express our sincere thanks to the secretaries of the RIKEN BNL Research Center, Tammy Heinz and Fern Simes, for their invaluable help in organizing and running the workshop.

Jianwei Qiu (Iowa State University)
Naohito Saito (RIKEN / RIKEN BNL Research Center)
Andreas Schäfer (Universität Regensburg)
Werner Vogelsang (RIKEN BNL Research Center)

RIKEN BNL Research Center
September, 2000.

Predictions and Uncertainties for RHIC Spin Physics

and

Event Generator for RHIC Spin Physics, III

J. Qiu[a], N. Saito[b], W. Vogelsang[b]

[a] Department of Physics and Astronomy, Iowa State University, Ames, IA-50011
[b] RIKEN-BNL Research Center, Brookhaven National Laboratory, Upton, NY 11973-5000

1 Spin-Dependent Twist-2 Parton Densities and Their Measurement

polarization	quarks	gluons
unpolarized	$q \equiv q_+^+ + q_+^- \equiv q_\uparrow^\uparrow + q_\uparrow^\downarrow$	$g \equiv g_+^+ + g_+^-$
long. polarized	$\Delta q = q_+^+ - q_+^-$	$\Delta g = g_+^+ - g_+^-$
transversity	$\delta q = q_\uparrow^\uparrow - q_\uparrow^\downarrow$	—

Table 1: Compilation of quark and gluon parton densities including spin-dependence. We have suppressed the ubiquitous argument (x, μ^2) of the densities. For brevity we have also omitted a column for antiquarks $\bar{q}$, which would have an identical structure as the quark column. Labels $+, -$ denote helicities, and $\uparrow, \downarrow$ transverse polarizations. Subscripts refer to partons and superscripts to the parent hadron.

1.1 Δq, $\Delta \bar{q}$:

- this is the place where most of our present knowledge resides
- polarized inclusive DIS at fixed target energies gives information only on the sums $\Delta q + \Delta \bar{q}$, and here mainly on up and down flavors
- fits to data now routinely performed at NLO level (see talks by A. Deshpande, M. Stratmann, S. Kumano)
- peculiar situation that number of groups doing fits to polarized DIS data is much larger than in the unpolarized case ! (see talk by M. Stratmann). The main reason for this is that the 'spin crisis' established by the EMC and subsequent experiments has been a particular motivation for performing analyses of polarized DIS. The large number of groups working on fits to polarized DIS reflects the importance, excitement and topicality of the spin physics field. Also, more than in the unpolarized case, the choice of factorization scheme for the NLO parton densities has been an issue, due to a peculiar feature of *polarized* DIS, namely the appearance of the axial anomaly, which people have treated in different ways in their analyses. Finally, from a 'technological' point of view, the large number, and high precision, of data points in the unpolarized case, and the fact that here the information on pdfs comes from very diverse sources, like DIS, hadronic collisions, ..., means that a lot of 'machinery' of codes is needed to be able to fit all data sets simultaneously (see talk by Wu-Ki Tung). In the polarized case, we essentially only have DIS data, which are fairly easy to handle in fits, even at NLO.
- the various analyses in the polarized case extract rather different results concerning some key spin quantities, such as the first moments of $\Delta\Sigma$ and Δg. Partly this is a genuine feature of the data, which simply do not allow more accurate determinations, partly this is related to differing assumptions and approaches made in the fits. Need to have better ways of handling uncertainties, both experimental and theoretical, in the analyses. in order to understand their impact on the extracted distributions and other quantities. First steps in this direction taken in the unpolarized case (see talk by Wu-Ki Tung).
- question is (in view of RHIC starting up): what do we already know, and how well do we *really* know it?
- will set up web page to coordinate efforts in fits of polarized DIS data

- semi-inclusive DIS, as done at SMC and HERMES, is one approach to obtain information on Δq, $\Delta\bar{q}$ separately
- RHIC will extend our knowledge in a totally different way through
  - $W^{\pm}$ production, e.g., $u\bar{d} \to W^{+}$
  - Drell-Yan dilepton production

  (see talk by A. Ogawa)
- work underway aiming at a better theoretical description of these processes: soft-gluon 'k_T' resummations (see talks by P. Nadolsky and C. Balazs)

1.2 Δg:

- Δg key quantity in our understanding of the proton spin
- so far, only little information from ep scattering:
  - scaling violations in polarized DIS: limited amount of information as lever arm in Q^2 is not big
  - reactions that could serve for a more direct determination of Δg, such as the photoproduction process $\vec{\gamma}\vec{p} \to h^+h^-$ studied by E155 and HERMES (where $h^{\pm}$ are charged hadrons at large transverse momenta), presently suffer from the fact that the accessed transverse momenta are in a region where the applicability of perturbative QCD is at least questionable (see talk by D. de Florian)
- at RHIC, various reactions very promising :
  - prompt photon production, $\vec{p}\vec{p} \to \gamma X$
    - supposedly clean signal through electromagnetic probe of QCD hard scattering
    - sensitivity to Δg through QCD Compton subprocess $qg \to \gamma q$ $q\bar{q} \to \gamma g$ competes but, in particular for pp scattering, is subdominant unless polarized gluon distribution is very small
    - however, need to understand better 'fragmentation' (or 'bremsstrahlung') component (dilutes signal; see talk by J. Owens) cannot presently be calculated at NLO in polarized case !
    - photon-isolation cuts will be implemented in experiment (see talk by A. Bazilevsky); several choices possible

    * making progress on Monte-Carlo studies for this reaction (see talks by O. Martin and J.C. Collins)
    * currently biggest problem: in unpolarized case, no satisfactory agreement of theory with most recent and most precise data sets (see talk by J. Owens)
    * situation worst in fixed-target region; at collider energies, agreement better, but not satisfactory
    * QCD soft-gluon effects, in terms of joint threshold and k_T resummations, have the potential of curing the problem. Still further work needed (see talk by G. Sterman)
    * RHIC will add valuable new information – even in the unpolarized case ! Will reach the highest energies ever in pp collisions
- jet production, high-p_T hadron production
    * smaller asymmetries than for prompt photons
    * however, much larger rates and hence better resolution
    * sensitivity to Δg through gg and qg scattering reactions
    * its potential relies on ability to describe jet production in theory
    * NLO calculations done; show, among other features, strong reduction of scale dependence (see talk by D. de Florian)
    * in unpolarized case, NLO calculations work extremely well (see talk by Wu-Ki Tung)
    * STAR's large angular acceptance is advantageous for jet studies
    * as a jet surrogate, one can also consider high-p_T hadron production, $\vec{p}\vec{p} \to \pi X$; better suitable for PHENIX experiment (see talk by Y. Goto)
    * same subprocesses as for jets; however, in addition, have dependence on hadron fragmentation function (known reasonably well from e^+e^- experiments, should anyway be unproblematic for spin *asymmetries*)
    * NLO calculation of hadron production in polarized case still needs to be performed !
- heavy flavor production, e.g., $\vec{p}\vec{p} \to Q\bar{Q}X$ $(Q = c, b)$
    * sensitivity to gluon through $gg \to Q\bar{Q}$ channel
    * $q\bar{q} \to Q\bar{Q}$ competes, but expected small, in particular for pp
    * optimization of future measurements currently under investigation (see talk by H. Sato)

  * full NLO QCD corrections will become available very soon for the polarized case, photoproduction $\vec{\gamma}\vec{p} \to Q\bar{Q}X$ already done; shows that knowledge of the corrections is crucial (see talks by I. Bojak and M. Stratmann)
  * downside also here that situation in the unpolarized case is difficult: while theoretical description of F_2^{charm} in DIS is very successful (see talk by J. Smith), there is no good agreement between data and theory predictions for bottom production at the Tevatron; the situation is (unexpectedly) better for the case of the lighter charm
  * Quarkonia are interesting, too: clear experimental signature
  * however, their production mechanism not understood in theory yet. For instance, we have two very distinct approaches, the color evaporation model and NRQCD. They both have their successes, but recent Fermilab data on J/ψ polarization contradict predictions from both models. Problem for spin asymmetries, or would they help to shed light on the issue?

- Drell-Yan dilepton production at *high* q_T of the pair (see talk by E. Berger)
  * at pair transverse momentum $q_T = 0$: dileptons from annihilation $q\bar{q} \to l^+l^-$. At $q_T \neq 0$: subprocesses same as for prompt photon production, except that the photon is *virtual* and decays into the lepton pair
  * hence sensitive to Δg through $qg \to \gamma^* q$
  * supposedly cleaner: no fragmentation component required
  * a lot of well-established 'theory machinery'
  * downside : event rate much reduced as compared to prompt photons, up to $2-3$ orders of magnitude – hard to afford at RHIC
  * luminosity upgrade would be required

- eventually, need determinations of Δg from different channels, to check mutual consistency !

1.3 Transversity δq, $\delta\bar{q}$:

- the twist-2 parton density about which we do not know anything at all experimentally so far ! (see talk by R.L. Jaffe)

- Lattice calculations being performed (see talk by T. Blum)

- no transversity gluon density at leading twist
- would like to measure δq, $\delta\bar{q}$ in environment where 'parton model' typically provides the right description
- RHIC with transversely polarized beams offers this possibility
- however, many 'standard' reactions (jets, prompt photons, heavy quarks) suffer from large gluonic contributions in the denominator of the asymmetry (hence, transverse-spin asymmetries become small) and from 'selection rule' suppression of hard scattering partonic cross sections
(see talk by R.L. Jaffe)
- most promising possibilities :
  - Drell-Yan dimuon production, $p^\uparrow p^\uparrow \to \mu^+\mu^- X$
    * theoretically clean, would measure $\delta q \times \delta\bar{q}$
    * asymmetry small, if there is little antiquark transversity (which is likely)
    * asymmetry small, even under optimistic assumptions concering size of transversity
    * could be 'just' measurable, taking into account experimental muon acceptances
    * luminosity upgrade is desirable
  - 'interference fragmentation functions' (see talks by R. Jaffe, M. Grosse-Perdekamp, A. Ogawa)
    * look at $s-p$ wave interference of two-pion systems produced with invariant mass around the ρ mass
    * sensitivity to polarization through term $\vec{k}_{\pi^+} \times \vec{k}_{\pi^-} \cdot \vec{s}_T$
    * only one initial polarized beam required
    * better prospects for size of asymmetries
    * much higher event rates – pions are produced copiously
    * downside : do not know involved 'interference fragmentation functions'
    * need reliable theoretical estimate
    * need independent information from experiment, preferrably e^+e^-

2 Spin-Dependent Twist-2 Fragmentation Functions and Their Measurement

Could write down table similar to Table 1 for *fragmentation* functions, instead of distribution functions.

- an ideal candidate for such studies is the Λ hyperon thanks to the polarization dependence of its decay $\Lambda \to \pi p$
- in unpolarized case, have already a lot of information on the Λ fragmentation functions, provided by e^+e^- annihilation
- some first constraints on the spin-dependent (longitudinally polarized) Λ fragmentation functions ΔD_q^Λ have come from Λ production on the Z resonance at LEP.
- RHIC could dramatically improve our knowledge of the spin-dependent fragmentation functions, for both longitudinal and transverse polarization (see talk by J. Soffer)

3 Spin-Dependent Twist-3 Parton Correlation Functions and Their Measurement

3.1 Definitions

Spin-dependent twist-3 parton correlation functions are defined as matrix elements of twist-3 operators between polarized hadron states of momentum p and spin s:

$$T_{\hat{O}}(x,y) = \int \frac{d\lambda}{2\pi}\frac{d\mu}{2\pi}\, e^{i\lambda x}\, e^{i\mu(y-x)}\, \langle p,s|\hat{O}(\lambda,\mu)|p,s\rangle \,.$$

The non-local twist-3 operators $\hat{O}(\lambda,\mu)$ are expressed in terms of quark and gluon field operators, and represent parton correlations between quarks and gluons on the light-cone. They can be divided into *two* general categories: quark-gluon and pure gluon correlations, as shown in Table 2.

3.2 General features

- The spin-dependent twist-3 parton correlation functions are as fundamental as the twist-2 parton distributions, but we do not know much at all.

quark-gluon	$\bar{\psi}_i(0)\,(\Gamma_\alpha)_{ij}\,D_\perp^\alpha(\mu)\,\psi_j(\lambda)$	$\bar{\psi}_i(0)\,(\Gamma_\alpha)_{ij}\,F^{+\alpha}(\mu)\,\psi_j(\lambda)$
pure gluon	$\kappa_{\alpha\beta\gamma}\,F^{+\alpha}(0)\,D_\perp^\beta(\mu)\,F^{+\gamma}(\lambda)$	$\kappa_{\alpha\beta\gamma}\,F^{+\alpha}(0)\,F^{+\beta}(\mu)\,F^{+\gamma}(\lambda)$

Table 2: General operators defining spin-dependent twist-3 parton correlation functions. The $D_\perp^\alpha$ and $F^{+\alpha}$ are operators for transverse components of the covariant derivative and gluon field strength, respectively; the $(\Gamma_\alpha)_{ij}$ and $\kappa_{\alpha\beta\gamma}$ represent possible combinations of spinor contractions with the γ-matrices and contractions of the Lorentz indices, respectively; and the color indices and their contractions are suppressed. For some explicit examples of definitions for the $(\Gamma_\alpha)_{ij}$ and $\kappa_{\alpha\beta\gamma}$, and their symmetry properties, see the talk by X. Ji.

- They provide information on *coherent* parton scattering in QCD.
  $\Longrightarrow$ non-perturbative information beyond the parton distributions
- With different choices of the $(\Gamma_\alpha)_{ij}$ and $\kappa_{\alpha\beta\gamma}$, there are many more spin-dependent twist-3 parton correlation functions than spin-dependent twist-2 parton distributions.
  $\Longrightarrow$ hard to extract these functions
- Because of the coherence requirement, physical observables sensitive to the twist-3 parton correlation functions are suppressed by a factor of $(1/L)/Q \sim \Lambda_{QCD}/Q$, in comparison with the leading-twist observables. Here, L represents the coherence length, which is of the order of the hadron radius, and Q represents a hard scale in the partonic scattering.
  $\Longrightarrow$ smaller rate

3.3 Measurement of spin-dependent twist-3 parton correlation functions

- Ideally, a good observable for extracting spin-dependent twist-3 parton correlation functions should
  - vanish at leading twist;
  - depend only on a very small number of twist-3 correlation functions, at least at low orders of α_s;
  - have sources of enhancements to overcome the generic suppression factor Λ_{QCD}/Q.
- Quark-gluon correlations from measurements of g_2 structure function:

- Extraction of g_2 structure function from DIS data is independent of QCD
- According to QCD, a part of g_2 structure function, known as the Wandzura and Wilczek term g_2^{WW}, is given in terms of the g_1 structure function
- It is the difference between g_2 and g_2^{WW} that is directly proportional to twist-3 quark-gluon correlation functions (if we can neglect contributions of even higher twist)
- Recent measurements of g_2 structure function are consistent with g_2^{WW}, and it is difficult to extract quark-gluon correlation functions from the difference $g_2 - g_2^{WW}$, due to the size of error bars
- A QCD calculation of the one-loop contributions to the coefficient functions of g_2 has recently been completed (see talk by X. Ji)
- Need much more accurate measurements of g_2, in order to extract the functional form of quark-gluon correlation functions

- Single transverse-spin asymmetries are excellent observables for measuring twist-3 correlation functions, and for testing the QCD factorization framework beyond leading-twist formalism.
  - Single transverse-spin asymmetries vanish at leading twist in the framework of QCD factorization
  - Leading contribution to single transverse-spin asymmetries is directly proportional to the twist-3 quark-gluon and/or pure-gluon correlation functions (see talk by Y. Koike)
  - A unique dependence on the derivative of the correlation functions provides an enhancement of the asymmetries in certain kinematic regions

- Theoretical calculations for single transverse-spin asymmetry in direct photon production have been completed for all subprocesses at the leading order in α_s, and are consistent with early Fermilab E704 data.

- The single transverse-spin asymmetry for the Drell-Yan process was studied by two groups.
  - Two different formulas were derived.
  - The debate is on whether or not there should be a term proportional to the derivative of quark-gluon correlation function.

- The controversy is still unresolved.

- Leading contributions to the single transverse-spin asymmetry in prompt pion production :
  - Dominant contributions at large x_F, so-called derivative terms, were calculated, and the asymmetries are most sensitive to only one quark-gluon correlation function.
    The theoretical results are consistent with Fermilab E704 data.
  - Contributions dominating the large negative x_F region were also recently studied (see talk by Y. Koike).
  - A complete calculation for the whole x_F region is needed for possible studies at RHIC.

- Inclusive π production in transversely polarized deep inelastic scattering (see R.L. Jaffe's talk) :
  - Two competing channels: $\delta q(x) \otimes \hat{e}_{q \to \pi}(z)$, and $g_T(x) \otimes D_{q \to \pi}(z)$.
  - Recently, a non-vanishing single transverse-spin asymmetry was observed in the HERMES experiment
  - However, it is not clear which channel dominates because there are too many unknowns: transversity δq, twist-3 chiral-odd pion fragmentation function $\hat{e}_{q \to \pi}(z)$, and twist-3 part of g_2 (also see the discussions on transversity, Sec. 1.3)

- Although single transverse-spin asymmetries are very sensitive to spin-dependent twist-3 parton correlation functions, they only provide information on *T-odd* functions.

- Angular distribution of Drell-Yan lepton pairs produced in collisions of a longitudinal and a transversely polarized hadron :
  - Leading order theoretical calculation exists.
  - Like g_2, this measurement probes the twist-3 chiral-even spin-dependent distributions.
  - No data available, until RHIC spin program turns on.

4 Skewed Parton Distributions

- Normal parton distributions (or forward "scattering" amplitudes) = matrix elements of light-cone bilocal operators between states of equal momenta, e.g.,

$$q(x,\mu^2) = \int \frac{d\lambda}{2\pi} e^{-ix\lambda} \langle P|\bar{\psi}_q(\lambda/2)\frac{\gamma\cdot n}{2P\cdot n}\psi_q(-\lambda/2)|P\rangle$$

with normalization: $\langle P|P\rangle = 2E(2\pi)^3\delta^3(P'-P)$.

- Off-forward "scattering" amplitudes = matrix elements of the same light-cone bilocal operators between states of different momenta, e.g.,

$$F_q(x,\xi,t,\mu^2) = \int \frac{d\lambda}{2\pi} e^{-ix\lambda} \langle P'|\bar{\psi}_q(\lambda/2)\frac{\gamma\cdot n}{2P\cdot n}\psi_q(-\lambda/2)|P\rangle$$

with $\xi = (P'-P)\cdot n/2$ and $t = (P'-P)^2$.

- "Skewed" parton distributions (or off-forward parton distributions) = form factors of the off-forward "scattering" amplitudes, e.g.,

$$\begin{aligned} F_q(x,\xi,t,\mu^2) \equiv\; & H_q(x,\xi,t,\mu^2)\left[\bar{\mathcal{U}}(P')\gamma^\mu\mathcal{U}(P)\right]\frac{n_\mu}{2P\cdot n} \\ & E_q(x,\xi,t,\mu^2)\left[\bar{\mathcal{U}}(P')\frac{i\sigma^{\mu\nu}(P'-P)_\nu}{2M}\mathcal{U}(P)\right]\frac{n_\mu}{2P\cdot n}\,. \end{aligned}$$

Denoted here by $H_q(x,\xi,t,\mu^2)$ and $E_q(x,\xi,t,\mu^2)$.

  - As $\xi\to 0$ and $t\to 0$, skewed parton distributions are reduced to the normal parton distributions, e.g.,

$$H_q(x,0,0,\mu^2) = q(x,\mu^2)$$

  - The first moments of skewed parton distributions are constrained by the form factors of corresponding electromagnetic or axial currents, e.g.,

$$\int_{-1}^{1} dx H_q(x,\xi,t,\mu^2) = F_1^q(t),\; \int_{-1}^{1} dx E_q(x,\xi,t,\mu^2) = F_2^q(t),\ldots$$

  - The second moments of skewed parton distributions are related to form factors of energy-momentum tensors.

- Extrapolation of these form factors to $t = 0$ provides information on total quark and/or gluon contributions to the nucleon spin.

- Deeply-virtual Compton scattering (DVCS) (see talk by A.V. Belitsky)
  - A process to measure the off-forward "scattering" amplitudes.
  - From the amplitudes, one can extract the skewed parton distributions.
  - Large-x_B region for skewed quark distributions.
  - Small-x_B region for skewed gluon distributions.
  - However, experimentally, it is very difficult to measure DVCS because of a large QED background from Bethe-Heitler process.
  - Higher Q^2, smaller background, but, smaller signal as well.
  - Recent ZEUS data indicate a need for contributions from DVCS.

5 Sensitivity to Physics Beyond the Standard Model

Spin asymmetries can be very sensitive to effects of beyond-Standard Model physics, in particular, if the Standard Model predicts that an asymmetry vanishes or is very small.

- For example, the transverse double-spin asymmetry A_{TT} for W production is expected to negligibly small, as follows from a very thorough study of possible contributions to it (see talk by D. Boer). A non-zero value of this asymmetry, if seen at RHIC, would imply new physics

- Another thoroughly studied example is parity-violation in jet production, expressed by a non-zero *single-longitudinal* spin asymmetry $A_L^{\rm jet}$ in $\vec{p}p$ collisions. In the Standard Model, weak interaction is the only source of parity violation. Interferences of QCD and electroweak interaction diagrams give rise to a small non-vanishing $A_L^{\rm jet}$. Deviations from this prediction would immediately imply existence of *new physics*. Conceivable mechanisms are (see talks by J.M. Virey):
  - Compositeness of quark $\Rightarrow$ Contact Interactions at a scale Λ
    * limit from CDF: $\Lambda > 1.8$ TeV; D0 limit: $\Lambda > 2.4$ TeV. Even in Run II of the Tevatron (where $\mathcal{L}$=100 fb^{-1}) the sensitivity will only be $\Lambda > 4.1$ TeV
    * RHIC $\vec{p}\vec{p}$ collisions: $\Lambda > 3.3$ TeV (for $\mathcal{L}$=800 pb^{-1}); if $\mathcal{L}$=3.2 fb^{-1} is reached, sensitivity increases to $\Lambda \sim 4.4$ TeV.

- Leptophobic Z' contribution to jet production
  - Appears naturally from string-derived models
  - UA2 excluded $100 < M_{Z'} < 250$ GeV/c^2, assuming $\kappa \equiv g_{Z'}/g_Z$=1.
  - D0 excluded $365 < M_{Z'} < 615$ GeV/c^2 with $\kappa = 1$.
  - If Z' is found, the study should be extended to $\vec{n}\vec{n}$ collisions for d quark sector studies.
    $\Rightarrow$ acceleration of polarized ^{3}He should be studied.

It needs to be emphasized that a precise knowledge of the Standard Model prediction for $A_L^{\rm jet}$ will be essential. Therefore, studies of uncertainties in the predictions are necessary, and eventually a calculation of the full NLO corrections will be indispensable (see talks by J.M. Virey).

- Yet another area to look for new physics effects is parity violation in lepton-pair production (see talk by J.Murata) :
  - Plug-in Event Generator code for calculating the parity-violating asymmetry in lepton-pair production has been developed. Involved matrix elements have been obtained by crossing those obtained for DIS by J.M. Virey : $e^-q \to e^-q \;\Rightarrow\; \bar{q}q \to e^+e^-$.
  - Cross section asymmetry has been obtained by accumulating events from the event generator, with the weights given by the product of subprocess asymmetry and parton polarization.
  - Preliminary results show $\mathcal{A}_L^{\rm DY} \sim 2\%$ for $\Lambda = 1$ TeV in the lepton pair mass region $40 < M_{l^+l^-} < 100$ GeV/c^2, the region around the Z^0 excluded.

- Effects of new physics should also affect angular distributions. For example, the Standard Model predicts vanishing cross sections at certain angles at subprocess level ('radiation zeros'; see talk by J. Kodaira). New physics processes might change the position of the radiation zeros.

Direct Photon Production
a status report

J.F. Owens
Physics Department
Florida State University
Tallahassee, FL 32306

March 6, 2000

Abstract

Direct photon production has a long history of providing information on the nature of hard scattering in hadronic processes. This talk begins with a brief overview of the theory and then proceeds to a comparison between theory and experiment. Systematic differences are observed and various methods for resolving these differences are reviewed. These include explorations of the scale dependence of the theoretical predictions, examinations of the region of applicability of the theory, and several different types of resummation calculations wherein large higher order corrections are taken into account.

Basic Theory Input

Calculate the hard scattering at the parton level and then convolute with the appropriate parton distribution and fragmentation functions

$$E\frac{d^3\sigma}{dp^3}(AB \to \gamma + X) =$$
$$\sum_{ab} \int dx_a dx_b dz_c G_{a/A}(x_a, \mu_F^2) G_{b/B}(x_b, \mu_F^2) D_{\gamma/C}(z_c, M_F^2)$$
$$E\frac{d^3\widehat{\sigma}}{dp^3}(ab \to \gamma + X)(p_\gamma, x_a, x_b, z_c, \mu_F^2, \mu_R^2, M_F^2)$$

- Parton distribution and fragmentation functions taken from fits to data for various hard scattering processes (Global Fits)
- Three scales to specify: μ_F, μ_R, M_F
- $\widehat{\sigma}$ calculated perturbatively - currently up through $\mathcal{O}(\alpha\alpha_s^2)$

Observe that theory tends to underestimate the data, especially at the lower end of the p_T coverage. What can be done?

1. Examine scale dependence

   - W. Vogelsang and A. Vogt, hep-ph/9505404, Nucl. Phys. B453, 334 (1995).

   - Predictions depend on three scales

   - Examine full flexibility of the theory

2. Examine region of applicability of the theory

   - P. Aurenche *et al.*, hep-ph/9811382, Eur. Phys. J. C9, 107 (1999); hep-ph/9910252

   - Try to estimate where the theory is reliable

   - Avoid data sets where theory uncertainties are not well controlled

3. Look for additional corrections not already included in the NLO predictions

Threshold Resummation

- Corrections are large at the edge of phase space, $x_T \to 1$.

- Threshold resummation can't solve the current dilemma, but the results are interesting nonetheless.

  For more details see:

1. E. Laenen, G. Oderda, and G. Sterman, hep-ph/9806467, Phys. Lett. B438, 173 (1998)

2. S. Catani, M.L. Mangano, and P. Nason, hep-ph/9806484, JHEP 9807 (1998) 024; S. Catani, *et al.*, hep-ph/9903436, JHEP 9903 (1999) 025.

3. N. Kidonakis and J.F. Owens, hep-ph/9912388, Phys. Rev. D (in press)

k_T or Recoil Effects

History

- Well-known since the 70's (ISR experiments)
- High-p_T events show deviations from planar structure expected from $2 \to 2$ hard scattering, e.g., p_{out}, p_T imbalance
- Correlations observed between high-p_T hadrons and opposite side beam fragments
- Early QCD calculations used $2 \to 2$ QCD scattering subprocesses with gaussian k_T smearing (Feynman, Field, and Fox)
- Largely forgotten as new data from colliders at large values of p_T became available
- Effects largest at the low end of the p_T spectrum
- Effects fall off as an inverse power of P_T relative to the leading terms
- "Rediscovered " when precise fixed target data and low-x_T collider data became available

Recent Work

- M.A. Kimber, A.D. Martin, and M.G. Ryskin, hep-ph/9911379: Apply k_T resummation using the D-DT formalism. See some enhancement, but not enough to describe the data.

- E. Laenen, G. Sterman, and W. Vogelsang, hep-ph/0002078: double resummation combining both threshold and k_T methods. Preliminary work that looks promising.

Conclusions

1. Despite many years of study, there is still work needed in the study of direct photons.

2. Can not describe *all* the data with a single NLO QCD calculation.

3. Still room for additional experimental work to resolve possible discrepancies between data sets

4. Recent progress in understanding threshold and k_T resummation corrections

5. Fully understanding direct photon production may force us to revise the methods used to calculate hard scattering processes

6. The times are still interesting...!

Higher Order Corrections to Prompt Photon Production

Eric Laenen[a], George Sterman[b] and Werner Vogelsang[b]

[a]*NIKHEF Theory Group, Kruislaan 409*
1098 SJ Amsterdam, The Netherlands

[b]*C.N. Yang Institute for Theoretical Physics, SUNY Stony Brook*
Stony Brook, New York 11794 - 3840, U.S.A.

The phenomenology of single-particle inclusive production at fixed target energies and transverse momenta (p_T) in the few to few tens of GeV range has long been a challenge to perturbative methods. Despite "large" NLO corrections at moderate P_T, agreement with experiment can often be attained only through the addition of instrinsic transverse momentum. More recently, it has been widely suggested that the observed cross sections for direct photons and hadrons may be dominated by power corrections to the standard collinear factorization formulas. These two proposals are related, but no established theory encompasses either or both.

Recently, we undertook a study of high order corrections to transverse momentum distributions, within the context of collinear factorization. Our aim was to check whether the resummation of high orders in perturbation theory might help explain observed deviations from NLO results, and whether such a resummation might also suggest a nonperturbative component to the physical cross section. Such an approach has been fruitful in describing power corrections to resummed and fixed-order perturbative event shapes in e^+e^- anniihilation.

We began with a study of electroweak annihilation, which we reformulated in terms of a joint threshold- and k_T-resummation. We found an expression for the cross section

$$\frac{d\sigma_{AB\to\gamma^*}}{dQ^2\,d^2\mathbf{Q}_T} = \sum_{ab} \frac{d\hat{\sigma}^{(\mathrm{B})}_{ab\to V}(Q^2)}{dQ^2} \int_C \frac{dN}{2\pi i}\, \tilde{\phi}_{a/A}(N,\mu)\tilde{\phi}_{b/B}(N,\mu)\, \tau^{-N} \times \int \frac{d^2\mathbf{b}}{(2\pi)^2} \mathrm{e}^{-i\mathbf{b}\cdot\mathbf{Q}_T} \exp\left[E_{ab}(N,b,Q,\mu)\right]\,,$$

with $\tau = Q^2/S$, and $\sigma^{(B)}$ the Born cross section, in terms of a resummed exponent $E(N,b,Q,\mu)$, which organizes leading and next-to-leading logarithms in both impact parameter b and moment N, and which suggests a nonperturbative extension of the perturbatively resummed theory. A related cross section for prompt photon production at large p_T may then be derived. Phenomenological tests of the formalism suggest substantial higher-order and nonperturbative effects.

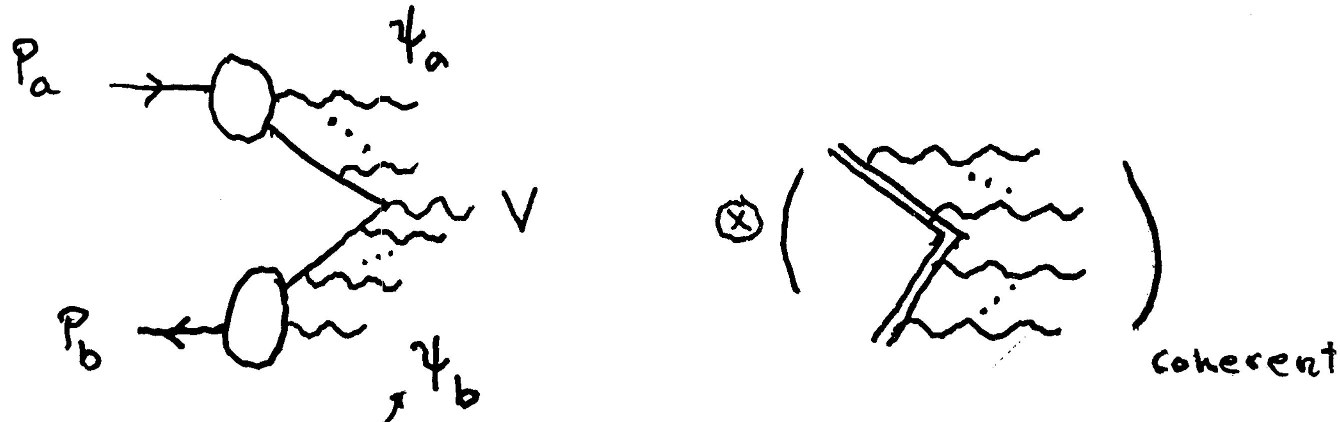
References

[1] L. Apanasevich et al., *Phys. Rev.* D59 (1999) 074007; P. Aurenche *et al.* hep-ph/9910252 .

[2] E. Laenen, G. Sterman and W. Vogelsang, hep-ph/0002078, to appear in *Phys. Rev. Lett.*, and in preparation.

Refactorization for the partonic cross section

$$\frac{d\sigma_{ab\to V}}{dQ^2 d^2\mathbf{Q}_T}$$
$$= \int dx_a d^2\mathbf{k}_a \, \psi_{a/a}(x_a, \mathbf{k}_a, Q) \; \int dx_b d^2\mathbf{k}_b \, \psi_{b/b}(x_b, \mathbf{k}_b, Q)$$
$$\times \int dx_s d^2\mathbf{k}_s \, U_{ab}(w_s, \mathbf{k}_s)$$
$$\times \delta(1 - Q^2/S - (1 - x_a) - (1 - x_b) - w_s)$$
$$\times \delta^2 \left(\mathbf{Q}_T - \mathbf{k}_a - \mathbf{k}_b - \mathbf{k}_s\right)$$
$$\times h'_{ab}(\alpha_s(\mu)) \, \frac{d\sigma^{(B)}_{ab\to V}(Q^2)}{dQ^2} + Y$$
$$+ \mathcal{O}\left(\left(1 - \frac{Q^2}{S}\right)^0, Q_T^0\right)$$



fixed energy and k_T

energy → resum logs of $1 - Q^2/S$ "threshold"

transverse momentum - logs of Q_T " k_T "

well defined set of corrections - $\frac{1}{1-z} \frac{1}{Q_T^2}$

Prompt Photons

Formalism

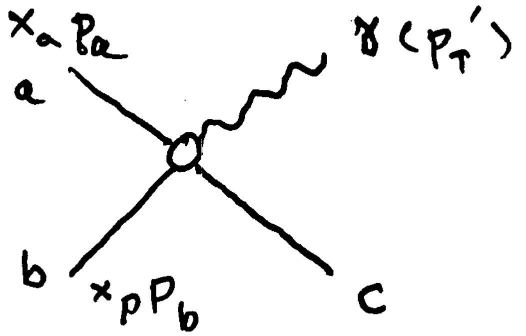
$$p_T^3 \frac{d\sigma_{AB\to\gamma X}(x_T^2)}{dp_T}$$

$$= \sum_{ab} \int dx_a\ \phi_{a/A}(x_a,\mu) \int dx_b\ \phi_{b/B}(x_b,\mu)\ p_T^3 \frac{d\hat{\sigma}_{ab\to\gamma X}\left(\hat{x}_T^2,\mu\right)}{dp_T}$$

$\hat{\sigma}_{ab\to\gamma X}$ by C0-subtraction of:

$$p_T^3 \frac{d\sigma_{ab\to\gamma c}^{(\mathrm{resum})}(\bar{\mu})}{dp_T} \sim \int d^2\mathbf{Q}_T\ p_T^3 \frac{d\sigma_{ab\to\gamma c}^{(\mathrm{resum})}}{d^2\mathbf{Q}_T\, dp_T}\ \Theta\left(\bar{\mu} - Q_T\right)$$

$$\frac{1}{\cosh^2\eta} = \frac{4|\mathbf{p}_T - \mathbf{Q}_T/2|^2}{\tilde{s}} \equiv \frac{4|\mathbf{p}_T'|^2}{\tilde{s}} \equiv \tilde{x}_T^2$$



- treat $Q_T \to 0$ region as in DY
- retain IR finite remainders of real/virtual cancellation resummed into exponentials...

Cross section (as double inverse transform)

$$\frac{p_T^3 d\sigma_{AB\to\gamma X}^{(\text{resum})}}{dp_T} = \sum_{ij} \frac{p_T^4}{8\pi S^2} \int_C \frac{dN}{2\pi i}\, \tilde{\phi}_{i/A}(N,\mu)\tilde{\phi}_{j/B}(N,\mu)$$

$$\times \int_0^1 d\tilde{x}_T^2 \left(\tilde{x}_T^2\right)^N \frac{|M_{ij}(\tilde{x}_T^2)|^2}{\sqrt{1-\tilde{x}_T^2}}$$

$$\times \int \frac{d^2\mathbf{Q}_T}{(2\pi)^2}\, \Theta\left(\bar{\mu} - Q_T\right) \left(\frac{S}{4\mathbf{p}_T'^2}\right)^{N+1} P_{ij}\left(N, \mathbf{Q}_T, \frac{2p_T}{\tilde{x}_T}, \mu\right)$$

with "profile"

$$P_{ij}\left(N, \mathbf{Q}_T, Q, \mu\right) = \int d^2\mathbf{b}\, \mathrm{e}^{-i\mathbf{b}\cdot\mathbf{Q}_T}\, \exp\left[E_{ij\to\gamma k}\left(N, b, Q, \mu\right)\right]$$

E as for electorweak cross section to LL in N and b . . .

The exponent at NLL

initial- and final-state:

$$E_{ij\to\gamma k}(N,b,Q,\mu) = E_{ij}^{\rm IS}(N,b,Q,\mu) + E_{ijk}^{\rm FS}(N,Q,\mu)$$

Initial-state:

$$E_{ij}^{\rm IS}(N,b,Q,\mu) = \int_{Q\chi^{-1}(N,b)}^{\mu} \frac{d\mu'}{\mu'} \left[A_i(\alpha_s(\mu'^2)) + A_j(\alpha_s(\mu'^2)) \right] 2\ln\frac{\bar{N}\mu'}{Q} - b^2 F_{ij}(N,Q)$$

↑ NP: $b^2 \int dk_T^2 \, A(\alpha_s(k_T^2)) \ln Q$

x'z: e^+e^- event shapes and DY

$$\chi(N,b) = \bar{N} + bQ/2e^{-\gamma_E}$$

$$e^{E_{IS}(N,b)} = e^{E_{IS}(N,0)} \; e^{\int_{Q\chi^{-1}(b)}^{Q/\bar{N}} \frac{d\mu'}{\mu'} (A_i + A_j) \ln \frac{\bar{N}\mu'}{Q}}$$

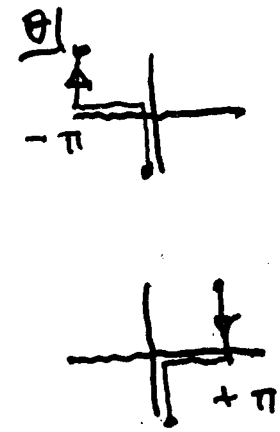
↑ threshold resum

↑ effect of recoil
- = 1 @ b = 0
- redistributes threshold enhancement

The inverse transform – minimal/principle value

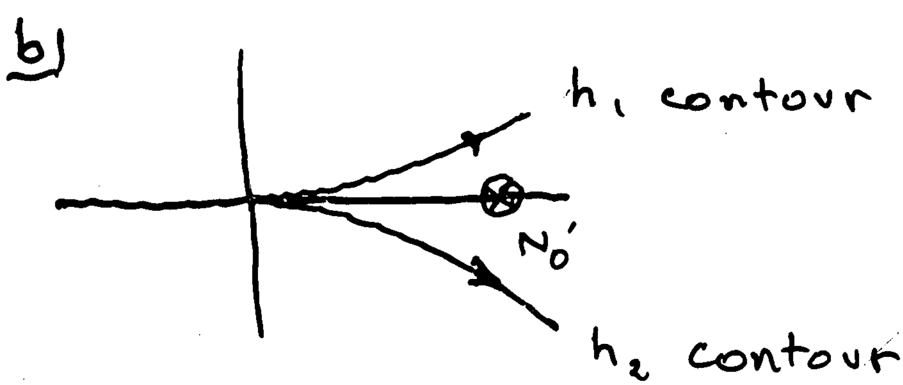
$$P_{ij}\,(N, \mathbf{Q}_T, Q, \mu) \;=\; \pi \int_0^\infty db\, b\, \left[\, h_1(bQ_T, v) + h_2(bQ_T, v) \,\right]\, \mathrm{e}^{E_{ij\to\gamma k}(N,b,Q,\mu)}$$

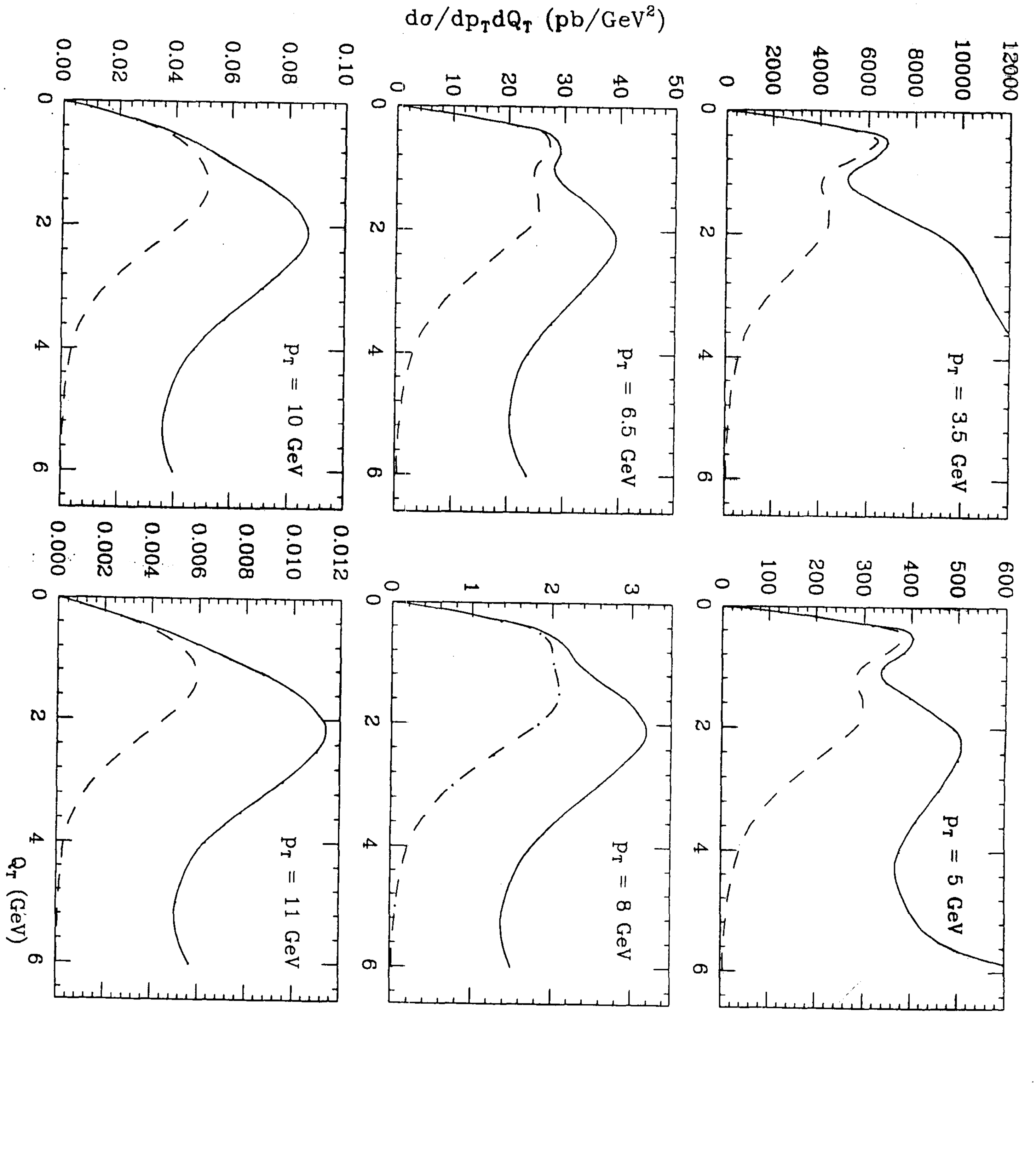
$2J_0 = h_1 + h_2$:



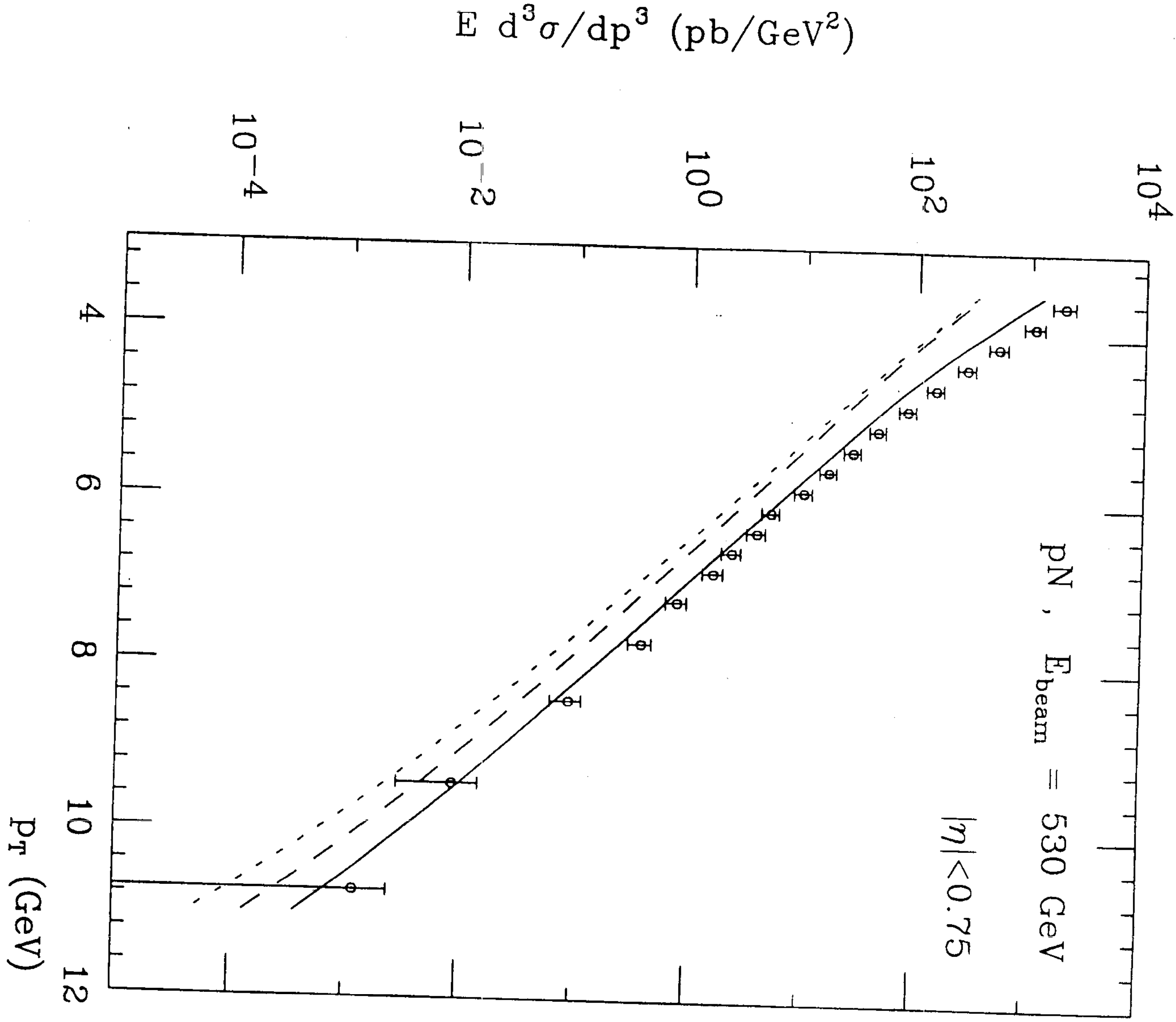
$$h_1(z,v) \;\equiv\; -\frac{1}{\pi} \int_{-iv\pi}^{-\pi+iv\pi} d\theta\, \mathrm{e}^{-iz\,\sin\theta}$$

$$h_2(z,v) \;\equiv\; -\frac{1}{\pi} \int_{\pi+iv\pi}^{-iv\pi} d\theta\, \mathrm{e}^{-iz\,\sin\theta}\,.$$





dσ/dp_T dQ_T (pb/GeV^2)
p_T = 3.5 GeV
p_T = 5 GeV
p_T = 6.5 GeV
p_T = 8 GeV
p_T = 10 GeV
p_T = 11 GeV
Q_T (GeV)



E d³σ/dp³ (pb/GeV²)
10⁴
10²
10⁰
10⁻²
10⁻⁴
pN , E_beam = 530 GeV
|η|<0.75
4
6
8
10
12
p_T (GeV)

- "Demonstration" calculation <u>only</u> so far
- Need
  - redetermination of NP parameters by comparison to DY, W, Z
  - improved matching
- Practical joint resummation will take time, but initial results seem encouraging

Isolation studies for Prompt Photons at PHENIX

Alexander Bazilevsky
RIKEN-BNL Research Center

The polarized *pp* collisions at RHIC provide a unique opportunity to study the spin structure of the nucleon. Prompt photons are a one of the ideal probes to measure the gluon density.

For expected RHIC luminosity of 0.8×10^{32} $cm^{-2}sec^{-1}$ at $\sqrt{s}$=200 GeV we'll be able to perform statistically significant measurements with prompt photons up to p_t = 30 GeV/c.

The main background for prompt photon reconstruction comes from π^0 and η meson decays. Two-photon invariant mass reconstruction considerably suppresses this source of background. Shower profile measurement is extremely important for π^0 rejection with p_t >15 GeV/c. The expected residual background level for prompt photons in PHENIX at $\sqrt{s}$ =200 GeV after two-photon mass reconstruction and shower profile analysis is ~40-50% for p_t > 10 GeV/c. Main contributors are Bremsstrahlung photons (final state parton radiation) and π^0's with merged photons and with one photon lost (out of EMCal acceptance).

The additional background suppression is provided by the Isolation cut. We studied two approaches based on PYTHIA5.7/JETSET7.4 event generator with GRV94LO parton distribution functions. The first one (Fixed Isolation) requires the hadron energy around prompt photon candidate in the cone with radius $R=\sqrt{\Delta\eta^2+\Delta\varphi^2}$ be less than certain fraction ε_F of the prompt photon energy. Another approach (Smooth Isolation) considers the allowed additional energy inside the cone as a function of cone radius *r* (*S.Frixione, Phys.Let.B429 (1998), 369*):

$$E_{add}(r) < \varepsilon_S \cdot E_\gamma \cdot \left(\frac{1-\cos r}{1-\cos R}\right)^n \quad \text{for all r<R .}$$

For 95-98% efficiency for prompt photons both approaches give almost the same efficiencies for π^0's (20-25%) and Bremsstrahlung photons (70-80%). Acceptance cut in PHENIX ($|\eta|<0.35$, $\varphi=180^0$) worsens the efficiency of Isolation cuts only slightly (just shifting cut parameters ε_F and ε_S corresponding to certain isolation efficiency for prompt photons).

After Mass Reconstruction, Shower Profile analysis and Isolation cut the main background to the LO Prompt Photons (Compton and Annihilation) in the range p_t >10 GeV/c are π^0's (7-10%) and Bremsstrahlung photons (10-25%) (*A.Bazilevsky, Proc. of CPP RIKEN Symposium, Nov. 3-6, 1999*).

More detailed study of event generator is needed particularly for Bremsstrahlung photons production and Isolation cut efficiency for them.

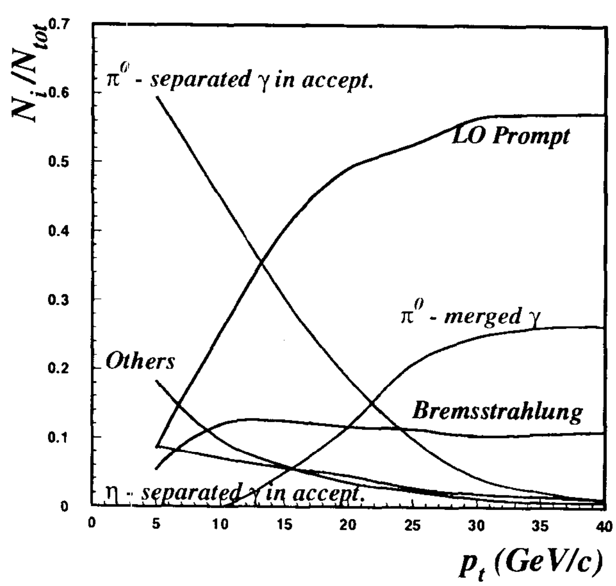
Prompt Photon Yield

- PHENIX acceptance
- $\sqrt{s} = 200\,GeV,\ \int Ldt = 320\ pb^{-1}$

p_t range (GeV/c)	Yield
5-10	1.5×10^6
10-15	1.0×10^5
15-20	1.4×10^4
20-25	2.6×10^3
25-30	570
30-35	140

Photon p_t spectrum contributors

- Without any experimental cut
- PHENIX acceptance

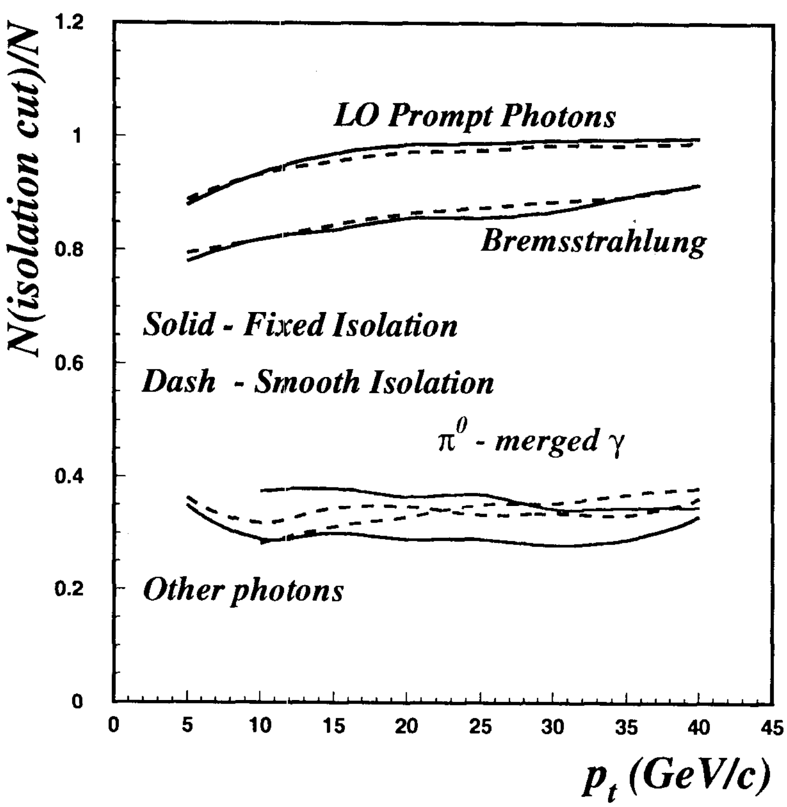


- The main contributors are Prompt Photons, Bremsstrahlung and π^0's

Isolation Cut

Fixed vs Smooth in PHENIX acceptance

Fixed: R_0=0.5, ε_F=0.05
Smooth: R_0=1.0, ε_S=1



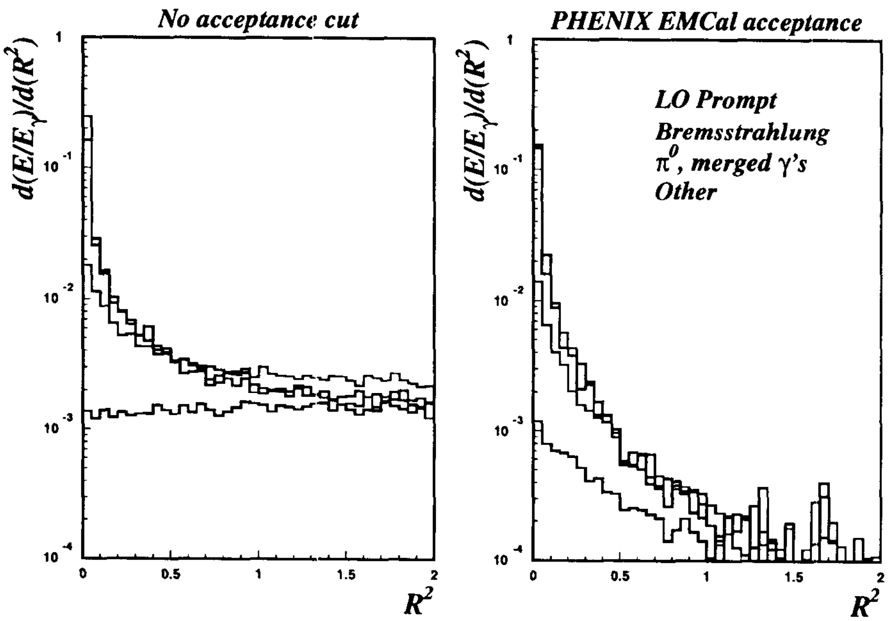
From PYTHIA simulation:

- Fixed and Smooth cuts work with the same efficiency
- Bremsstrahlung is almost not effected by the Isolation Cut

Energy distribution around photon

Photon p_t =25 GeV/c

$$R=\sqrt{\Delta\eta^2+\Delta\varphi^2}$$



Without acceptance cut

- Prompt Photons have almost constant background energy level around (are well isolated)
- Photons from hadron decays are accompanied by essential amount of energy (are not isolated)

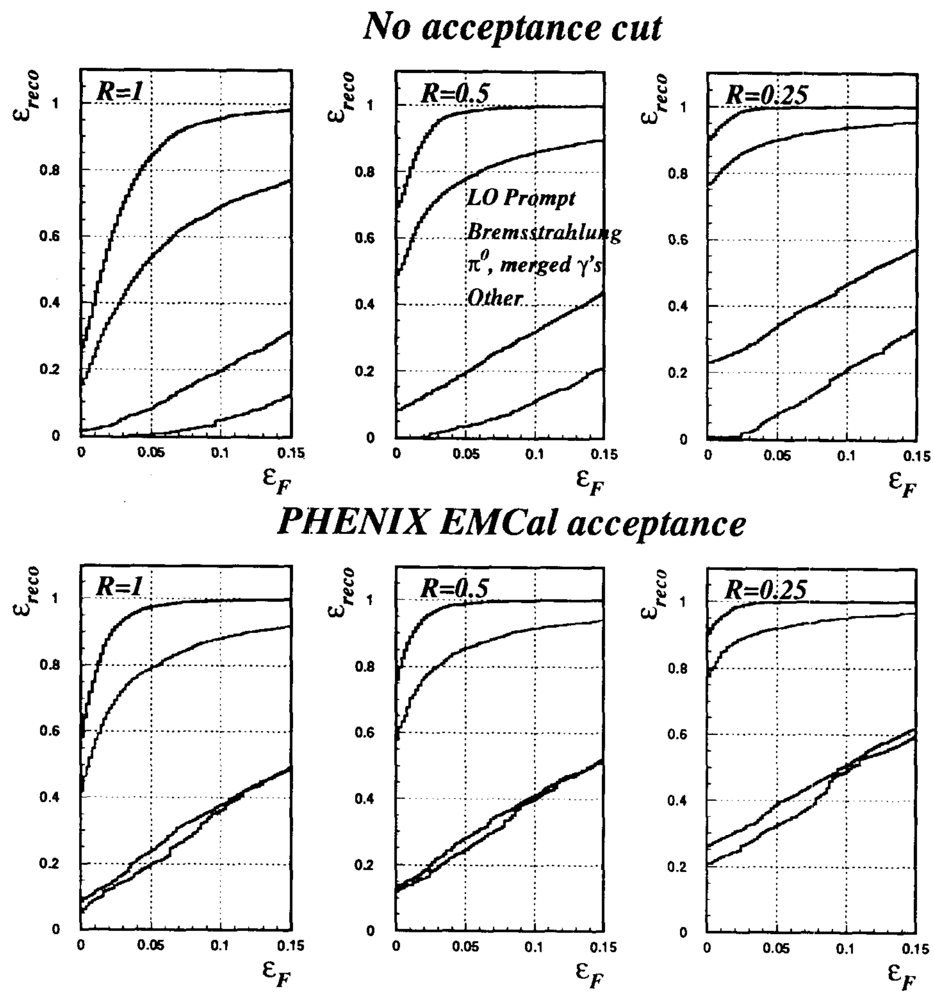
PHENIX acceptance cut

- Distributions change considerably

Fixed Isolation efficiency

$E_{tot} < \varepsilon_F \cdot E_\gamma$ in the Cone with radius R

Photon p_t =25 GeV/c



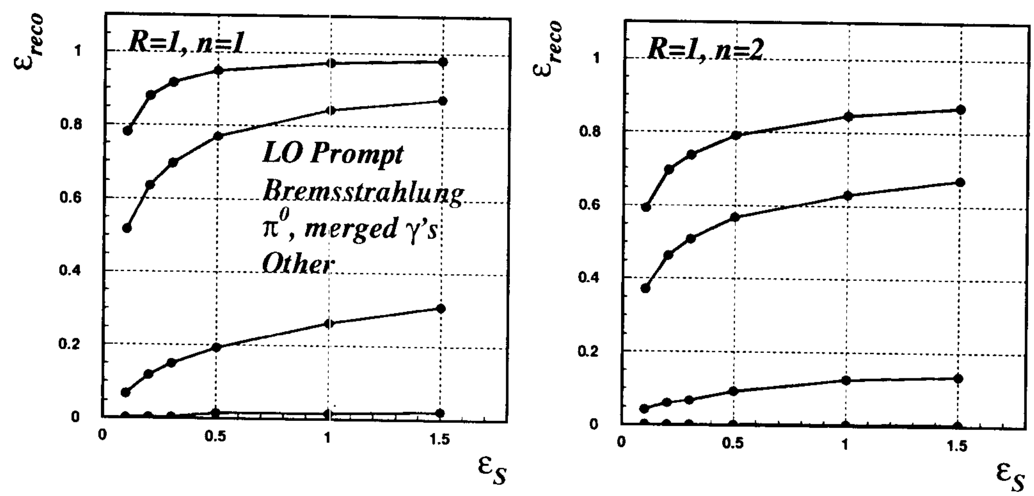
- Keeping the Isolation cut efficiency for Prompt Photons fixed, the efficiencies for Bremsstrahlung and π^0's change only slightly for different isolation cone radius R

Smooth Isolation

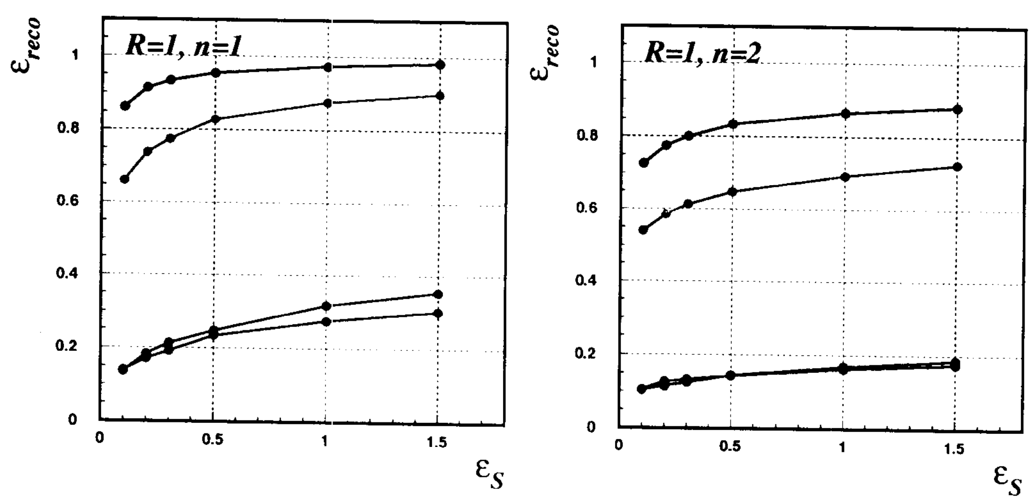
$$E_{tot}(r) < \varepsilon_S \cdot E_\gamma \cdot \left(\frac{1-\cos r}{1-\cos R}\right)^n \text{ for all } r<R$$

Photon p_t =25 GeV/c

No acceptance cut



PHENIX EMCal acceptance

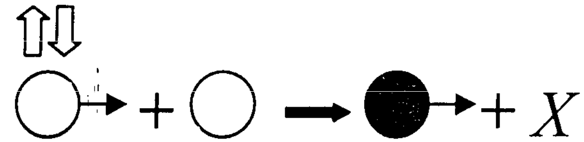


Yuji Koike, Niigata University, Department of Physics, Ikarashi, Niigata 950-2181, Japan

Chiral-odd Contributions to Single Transverse Spin Asymmetry in Hadronic Pion Production

● single transverse spin asymmetry

$$\vec{N}'(T) + N \to \pi + X$$



J. Qiu and G. Sterman, PR, D59,014004(1998)

$$\Delta\sigma_T \sim G_{F,D}(x_1', x_2') \otimes \begin{Bmatrix} f_1(x) \\ G(x) \end{Bmatrix} \otimes \hat{f}_1(z) \otimes \hat{\sigma}_{a+b\to c} \qquad (\underline{x_F \to 1})$$

Qiu and Sterman

$$+ h_1(x') \otimes E_{F,D}(x_1, x_2) \otimes \hat{f}_1(z) \otimes \hat{\sigma}'_{a+b\to c} \qquad (\underline{x_F \to -1})$$

This study

$$+ h_1(x') \otimes f_1(x) \otimes \hat{E}_F(z_1, z_2) \otimes \hat{\sigma}''_{a+b\to c}$$

○ Classification of M_F

- $$\int\frac{d\lambda}{2\pi}\int\frac{d\mu}{2\pi}e^{i\lambda x_1}e^{i\mu(x_2-x_1)}\langle PS|\bar{\psi}(0)\underline{\sigma^{\mu\nu}i\gamma_5}F^{\alpha\beta}(\mu n)n_\beta\psi(\lambda n)|PS\rangle$$

Long. Pol.

$$= iM\underline{(S\cdot n)}\{(g^{\mu\alpha}P^\nu - g^{\nu\alpha}P^\alpha) - P^\alpha(n^\mu P^\nu - n^\nu P^\mu)\}H_F(x_1,x_2)$$

$$+ M(P^\mu\varepsilon^{\nu\alpha\beta\lambda} - P^\nu\varepsilon^{\mu\alpha\beta\lambda})P_\lambda n_\beta E_F(x_1,x_2) + \cdots$$

Unpol.

(Chiral-odd)

- $$\int\frac{d\lambda}{2\pi}\int\frac{d\mu}{2\pi}e^{i\lambda x_1}e^{i\mu(x_2-x_1)}\langle PS|\bar{\psi}(0)\underline{\gamma^\mu}F^{\alpha\beta}(\mu n)n_\beta\psi(\lambda n)|PS\rangle$$

$$= (M) P^\mu\varepsilon^{\alpha\nu\kappa\lambda}P_\nu n_\kappa \underline{S_{\perp\lambda}} G_F(x_1,x_2) + \cdots$$

(chiral-even)

- $$\int\frac{d\lambda}{2\pi}\int\frac{d\mu}{2\pi}e^{i\lambda x_1}e^{i\mu(x_2-x_1)}\langle PS|\bar{\psi}(0)\underline{\gamma^\mu\gamma_5}F^{\alpha\beta}(\mu n)n_\beta\psi(\lambda n)|PS\rangle$$

$$= i(M) P^\mu \underline{S_\perp^\lambda}\widetilde{G}_F(x_1,x_2) + \cdots$$

(Chiral-even)

★ Result

$$E_\pi \frac{d^3\Delta\sigma}{dP_\pi^3} = \frac{\pi\alpha_S^2 M}{S} \sum_{a,b,c} \int_{z_{\min}}^1 \frac{dz}{z^3} \hat{f}_1^{c\to\pi}(z) \int_{x_{\min}}^1 \frac{dx}{x} \frac{1}{xS+T/z}$$

$$\times \int \frac{dx'}{x'} \delta\left(x' + \frac{xU/z}{xS+T/z} \right) \varepsilon_{\mu\nu\lambda\sigma} P_\pi^\mu S_\perp^\nu P^\lambda n^\sigma \left(\frac{1}{-\hat{t}} \right)$$

Chiral-odd

$$\times \left[-x \frac{\partial}{\partial x} E_F^b(x,x) \right] h_1^a(x') \Delta\hat{\sigma}_{ab\to c} \qquad (x_F \to -1)$$

$$+ \frac{\pi\alpha_S^2 M}{S} \sum_{a,c} \int_{z_{\min}}^1 \frac{dz}{z^3} \hat{f}_1^{c\to\pi}(z) \int_{x'_{\min}}^1 \frac{dx'}{x'} \frac{1}{x'S+U/z}$$

Chiral-even

$$\times \int \frac{dx}{x} \delta\left(x + \frac{x'T/z}{x'S+U/z} \right) \varepsilon_{\mu\nu\lambda\sigma} P_\pi^\mu S_\perp^\nu P^\lambda n^\sigma \left(\frac{1}{-\hat{u}} \right)$$

$$\times \left[-x' \frac{\partial}{\partial x'} G_F^a(x',x') \right] \left\{ G(x)\Delta\hat{\sigma}'_{ag\to c} + \sum_b f_1^b(x)\Delta\hat{\sigma}'_{ab\to c} \right\} \qquad (x_F \to 1)$$

- Model for $E_F(x,x)$

$$h_1(x)=\frac{i}{2}\varepsilon_{S_\perp\sigma Pn}\int\frac{d\lambda}{2\pi}e^{i\lambda x}\langle PS|\overline{\psi}(0)\underline{n\cdot\gamma\gamma_\perp^\sigma}\psi(\lambda n)|PS\rangle$$

$$E_F(x,x)=Kh_1(x)$$

$$E_F(x,x)=\frac{-i}{2M}\int\frac{d\lambda}{2\pi}e^{i\lambda x}\langle P|\overline{\psi}(0)\underline{n\cdot\gamma\gamma_{\perp\sigma}}\left\{\int\frac{d\mu}{2\pi}gF^{\sigma\beta}(\mu n)n_\beta\right\}\psi(\lambda n)|P\rangle$$

$$\begin{pmatrix}\varepsilon_{S_\perp\sigma Pn}\equiv\varepsilon_{\rho\sigma\tau\upsilon}S_\perp^\rho P^\tau n^\upsilon \\ \gamma_\perp^\sigma\equiv\gamma^\sigma-n\cdot\gamma p^\sigma-p\cdot\gamma n^\sigma\end{pmatrix}$$

Qiu and Sterman

$$f_1(x)=\frac{1}{2}\int\frac{d\lambda}{2\pi}e^{i\lambda x}\langle P|\overline{\psi}(0)\underline{n\cdot\gamma}\psi(\lambda n)|P\rangle$$

$G_F(x,x)=K'f_1(x)$ ⟶ Explain E704 data.

$$G_F(x,x)=\frac{1}{M}\varepsilon_{S_\perp\sigma Pn}\int\frac{d\lambda}{2\pi}e^{i\lambda x}\langle PS|\overline{\psi}(0)\underline{n\cdot\gamma}\left\{\int\frac{d\mu}{2\pi}gF^{\sigma\beta}(\mu n)n_\beta\right\}\psi(\lambda n)|PS\rangle$$

★ Summary

Chiral-odd contribution for $\vec{N}'(T) + N \to \pi + X$

$$E_\pi d\Delta\sigma / d^3 P_\pi \approx h_1^{\,a}(x') \otimes \frac{\partial}{\partial x} E_F^{\,b}(x) \otimes \hat{f}_1^{\,c}(z) \otimes \Delta\sigma_{ab\to c}$$

at large $x_F \gtrless 0$

● Future problem

- Formula for general $-1 < x_F < 1$.
- Estimate of the asymmetry with some assumption on $E_F(x,x)$ and $h_1(x)$.
- Formula for the twist-3 asymmetry for the polarized baryon production $\vec{N}(T) + N' \to \vec{B}(L) + X$.

Double transverse spin asymmetries in W production

Daniël Boer
RIKEN-BNL Research Center, Brookhaven National Laboratory, Upton, New York 11973

In this talk I will address the following question: the Standard Model (SM) mechanisms seem to produce negligible double transverse spin asymmetries in W production (A_{TT}^W), so if a significant asymmetry is found for instance in the polarized proton-proton collisions at RHIC, can one really conclude something about physics beyond the SM? To give an answer many issues need to be addressed. What precisely are all possible mechanisms within the SM? Which types of A_{TT}^W are there? Can they be measured? What is their magnitude? What do we expect from physics beyond the SM? We will try to address most of these issues.

The reasons the SM mechanisms seem to produce negligible A_{TT}^W are the following: the transversity distribution h_1 does not contribute [1]. At next-to-next-to-leading twist ($\mathcal{O}(M_1 M_2/Q^2)$) the twist-three distribution function g_T (which is a chiral-even distribution) can contribute and its gluon analogue as well (here we simply assume that factorization holds at this order). Furthermore, we argue that one can also neglect contributions which are of higher order in the strong and/or weak coupling constants. So within the SM A_{TT}^W is expected to be of $\mathcal{O}(1/Q^2)$, hence negligible at $Q^2 = M_W^2$.

What about other types of SM A_{TT}^W? For instance, $A_{TT}^W(Q_T)$, where Q_T is the transverse momentum of the produced vector boson. Such an asymmetry can arise if the partons are not completely collinear to the parent hadron momentum. One can study this asymmetry in terms of transverse momentum dependent functions and one then finds a helicity non-flip contribution at leading order in $1/Q$. In the cross section it appears proportional to $\cos(\phi_{S_1}^\ell - \phi_{S_2}^\ell)$, which does not depend on the lepton scattering plane, unlike the transversity $A_{TT}^{\gamma/Z}$ which appears with $\cos(\phi_{S_1}^\ell + \phi_{S_2}^\ell)$. $A_{TT}^W(Q_T)$ might be relevant if the Q_T integration is incomplete, for instance due to imposed cuts, then a left-over asymmetry may result. We have roughly estimated this asymmetry using an expression valid for small and intermediate values of Q_T and conclude that it appears to be negligible at the high Q^2 values, e.g. at $Q^2 = 80^2\,\text{GeV}^2$. But at lower energies this will be a very interesting asymmetry to study, for instance $A_{TT}^{\gamma}(Q_T)$ at $Q^2 = 10^2\,\text{GeV}^2$.

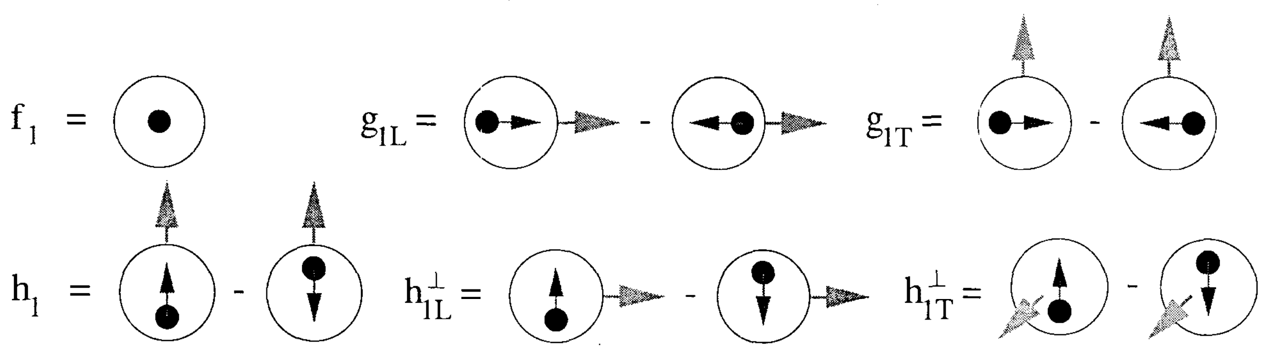
This leaves the option of new physics contributions, e.g. scalar or tensor couplings of the W to quarks. If the scale of new physics is $\Lambda \gg M_W$, say 1 TeV, then one might need to compare effects of order $M_1 M_2/Q^2$ with Q^2/Λ^2, which at RHIC might be $1/80^2$ vs $(80/1000)^2$: the latter is a factor 40 larger. Moreover, the issue of competing higher twist contributions disappears if the new couplings violate symmetries. There might be T-odd asymmetries, for example the one of [2], $A_{TT}^\perp \propto \sin(\phi_{S_1}^\ell + \phi_{S_2}^\ell)$, which can clearly be distinguished from possible initial state interaction effects, which are P-even and only lead to asymmetries independent of the lepton scattering plane. Since $A_{TT}^\perp$ arises from a double transverse spin asymmetry at the parton level ($\hat{a}_{TT}$), it has to be accompanied by $h_1 \overline{h}_1$ and is therefore expected to be small [3]. Moreover, estimates of the contribution to $A_{TT}^\perp$ from the SM CP violation should be made before a definite conclusion about physics beyond the SM can be reached.

[1] C. Bourrely and J. Soffer, Nucl. Phys. B 423 (1994) 329.
[2] V.L. Rykov, hep-ex/9908050.
[3] O. Martin *et al.*, Phys. Rev. D 60 (1999) 117502.

Interpretation

All these functions can be interpreted as momentum densities:

Pictorially:



E.g., $g_{1T}(x, \boldsymbol{p}_T^2)$ is the distribution of longitudinally polarized quarks (with nonzero transverse momemta) inside a transversely polarized hadron

g_{1T} is h^{LT} in Ralston & Soper, NPB 152 (1979) 109

$$\Phi(x, \boldsymbol{p}_T) = \frac{M}{2}\left\{ f_1(x, \boldsymbol{p}_T^2)\,\frac{\not{P}}{M} - \frac{(\boldsymbol{p}_T \cdot \boldsymbol{S}_T)}{M}\, g_{1T}(x, \boldsymbol{p}_T^2)\,\frac{\not{P}\gamma_5}{M} + \ldots \right\}$$

One can show that (m=0)

$$\int d^2\boldsymbol{p}_T\, \frac{\boldsymbol{p}_T^2}{2M^2}\, g_{1T}(x, \boldsymbol{p}_T^2) \overset{WW}{=} x\, g_T(x)$$

Helicity non-flip A_{TT}^{W}

Consider the cross section differential in the transverse momentum of the W (angle and/or magnitude)

In the cross section there is a term proportional to $\cos(\phi_{S_1}^{\ell} - \phi_{S_2}^{\ell})$, which does not depend on the lepton scattering plane

We find at tree level

$$A_{TT}^{V}(Q_T) = \frac{d\sigma(p^\uparrow p^\uparrow \to V\,X) - d\sigma(p^\uparrow p^\downarrow \to V\,X)}{d\sigma(p^\uparrow p^\uparrow \to V\,X) + d\sigma(p^\uparrow p^\downarrow \to V\,X)}$$

$$= -\frac{\sum_{a,\bar{a};b,\bar{b}} K_1^{ab}(y)\, \mathcal{F}\left[\boldsymbol{p}_T \cdot \boldsymbol{k}_T\, g_{1T} \overline{g}_{1T}\right]}{M_1 M_2 \sum_{a,\bar{a};b,\bar{b}} K_1^{ab}(y)\, \mathcal{F}\left[f_1\, \overline{f}_1\right]}$$

$$\mathcal{F}\left[f \overline{f}\,\right] \equiv \int d^2\boldsymbol{p}_T\, d^2\boldsymbol{k}_T\, \delta^2(\boldsymbol{p}_T + \boldsymbol{k}_T - \boldsymbol{q}_T) f^a(x_1, \boldsymbol{p}_T^2) \overline{f}^b(x_2, \boldsymbol{k}_T^2)$$

For W production:

$$K_1^{ab}(y) = 8\chi |V_{ab}|^2 \begin{cases} y^2 & \text{for equal quark and lepton chiralities} \\ (1-y)^2 & \text{for opposite quark and lepton chiralities} \end{cases}$$

$$\chi = \left(\frac{1}{8 \sin^2\theta_W}\right)^2 \frac{Q^4}{(Q^2 - M_W^2)^2 + \Gamma_Z^2 M_W^2}$$

Beyond tree level

Assume Gaussian transverse momentum dependence:

$$g_{1T}(x, \boldsymbol{p}_T^2) = g_{1T}(x)\, \frac{R^2}{\pi}\, \exp\left(-R^2 \boldsymbol{p}_T^2\right)$$

we find

$$\mathcal{F}\left[\boldsymbol{p}_T \cdot \boldsymbol{k}_T\, f\overline{f}\right] = \int \frac{d^2\boldsymbol{b}}{(2\pi)^2}\, e^{i\boldsymbol{b}\cdot\boldsymbol{q}_T}\, (-2b^2)\, e^{-S(b)}\, \tilde{f}(x_1, b_0/b)\, \tilde{\overline{f}}(x_2, b_0/b)$$

Also: $g_{1T}^{WW}(x) = x g_T^{WW}(x)\, 2M^2 R^2 \approx x g_1(x)\, 2M^2 R^2$

$$A_{TT}(Q_T) = \frac{\sum_{a,\bar{a};b,\bar{b}}\; K_1^{ab}(y)\; 8M^2 R^4\, x_1 g_1^a(x_1)\; x_2 \overline{g}_1^b(x_2)}{\sum_{a,\bar{a};b,\bar{b}}\; K_1^{ab}(y)\; f_1^a(x_1)\; \overline{f}_1^b(x_2)}\; \mathcal{A}(Q_T)$$

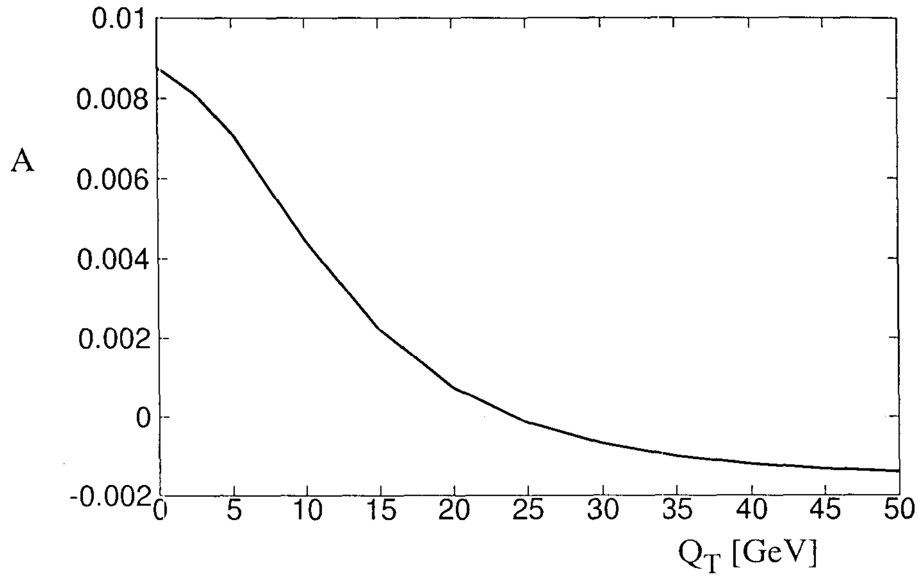
where

$$\mathcal{A}(Q_T) \equiv \frac{\int_0^\infty db\, b^3\, J_0(bQ_T)\, \exp\left(-S(b) - \frac{1}{2}b^2/R^2\right)}{\int_0^\infty db\, b\, J_0(bQ_T)\, \exp\left(-S(b) - \frac{1}{2}b^2/R^2\right)}$$

Estimating the asymmetry

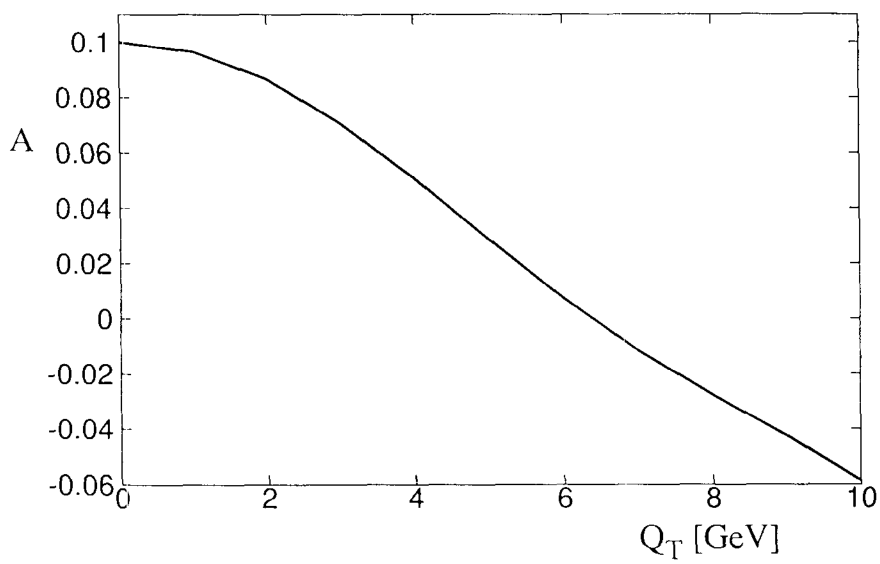
$\mathcal{A}(Q_T)$

$Q^2 = 80^2$ GeV^2



$\mathcal{A}(Q_T)$

$Q^2 = 10^2$ GeV^2



Conclusions

- $A_{TT}^{W} \propto \cos(\phi_{S_1}^{\ell} + \phi_{S_2}^{\ell})$ receives no contributions from quarks or gluons
- $A_{TT}^{W} \propto \cos(\phi_{S_1}^{\ell} - \phi_{S_2}^{\ell})$ receives only $1/Q^2$ contributions
- $A_{TT}^{W}(Q_T) \propto \cos(\phi_{S_1}^{\ell} - \phi_{S_2}^{\ell})$ receives leading contributions, but:

  Difficult to measure

  Sudakov form factors produce a negligible asymmetry at RHIC
- $A_{TT}^{\gamma}(Q_T)$ is still of interest
- Sivers effect would imply $A_{TT}^{V} \propto \cos(\phi_{S_1}^{\ell} - \phi_{S_2}^{\ell})$ and $\propto \sin(\phi_{S_1}^{\ell} - \phi_{S_2}^{\ell})$
- $A_{TT} \propto \sin(\phi_{S_1}^{\ell} + \phi_{S_2}^{\ell})$ requires real CP violation (Rykov)

- Physics beyond the SM versus higher twist effects and possibly initial state interactions

  Testable via Q^2 dependence

  Possible to isolate if BYSM physics breaks symmetries stronger and differently than the electroweak sector

Transverse Spin in Hard QCD Processes

RIKEN/BNL Workshop:
Predictions and Uncertainties
for RHIC Spin Physics

March 2000

R.L. Jaffe

δq | Transverse spin at leading twist $\equiv$ *transversity*

Twist-2, dominant parton distribution, on the same footing as $q(x)$, $\Delta q(x)$

Inaccessible in inclusive DIS

Expected to be roughly the same magnitude as $q(x)$ and $\Delta q(x)$

Attempts to measure δq require more sophisticated QCD analysis of parton processes

Outline

Collaborators/References

Xangdong Ji, Xuemin Jin, Naohito Saito, Jian Tang

- Background
  - RLJ, Spin, Twist and Hadron Structure in Deep Inelastic Processes Lectures in *Erice 1995, The spin structure of the nucleon*
  - B. Lampe & E. Reya, Spin Physics and Polarized Structure Functions, hep-ph/9810270.
- Review
  - RLJ, Can Transversity be Measured? hep-ph/97...
- Helicity Density Matrix Formalism
  - ... Goldstein, RLJ & X. Ji, Nucl. Phys. B445 ... 380
  - RLJ & J. Tang, to be published.
- Measuring Transversity
  - J. Ralston and D. E. Soper, Nucl. Phys. B152, 109 ...
  - ... Artru and M. Mekhfi, Z. Phys. C 45 ...
  - ... X. Ji, Phys. Rev. Lett. 67, 552 ...
  - ... Ralston, Z. Phys. C ...
  - ... Nucl. Phys. B396, 161 ...
  - ... D49 ...
  - ... Heppelmann, and G. A. ...
  - ... hep-ph ...
  - ... D ...
  - ... B3...
- Interference Fragmentation Functions

1 Properties of Transversity

$q(x,Q^2)$	known
$\Delta q(x,Q^2)$	knowing
$\delta q(x,Q^2)$	unknown

Notation:

$q \leftrightarrow f_1$ $\Delta q \leftrightarrow g_1$ $\delta q \leftrightarrow h_1$ process $\longleftrightarrow$ distribution

Q^2 dependence suppressed

Transversity

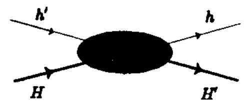
$\star$ $\Delta q = \delta q$?

In non-relativistic quark model boosts and rotations commute so YES

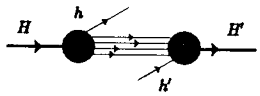
So δq measures relativistic quark motion, already suggested by $G_A/G_V \neq 5/3$ and $\Delta\Sigma \neq 1$

★ Measurement and selection rules

Helicity dependence in quark hadron scattering



(a)



(b)

$$\mathcal{F}^{hh'}_{H'H}(x, Q^2) \qquad H + h' = H' + h$$

Spin average q_a $(\frac{1}{2}\ \frac{1}{2} \to \frac{1}{2}\ \frac{1}{2}) + (\frac{1}{2} - \frac{1}{2} \to \frac{1}{2} - \frac{1}{2})$

Helicity diff. Δq_a $(\frac{1}{2}\ \frac{1}{2} \to \frac{1}{2}\ \frac{1}{2}) - (\frac{1}{2} - \frac{1}{2} \to \frac{1}{2} - \frac{1}{2})$

Helicity flip δq_a $(\frac{1}{2} - \frac{1}{2} \to -\frac{1}{2}\ \frac{1}{2})$

Double density matrix in hadron helicity indices $(H'H)$ and "good" quark helicity indices $(h'h)$.

$$\mathcal{F}(x, Q^2) = \frac{1}{2}\mathbf{I} \otimes \mathbf{I}\ q(x, Q^2) + \frac{1}{2}\sigma_3 \otimes \sigma_3\ \Delta q(x, Q^2) + \frac{1}{2}(\sigma_+ \otimes \sigma_- + \sigma_- \otimes \sigma_+)\ \delta q(x, Q^2)$$

- Helicity Flip ⇔ Transverse Spin Asymmetry

$$|\top\rangle = \frac{1}{\sqrt{2}}(|+\rangle + |-\rangle)$$
$$|\bot\rangle = \frac{1}{\sqrt{2}}(|+\rangle - |-\rangle)$$

where $|\pm\rangle$ are helicity eigenstates. $\sigma_\top - \sigma_\bot$ selects helicity flip.

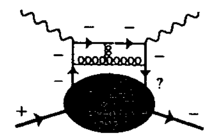
- Helicity ≡ chirality at leading twist, so transversity distribution flips quark chirality

→ δg ↔ "Chiral odd" distribution function

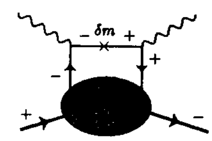
Full helicity structure at leading twist (for spin $\frac{1}{2}$)

$$\begin{pmatrix} q + \Delta q & \delta q \\ \delta q & q - \Delta q \end{pmatrix}$$

Hard processes conserve helicity



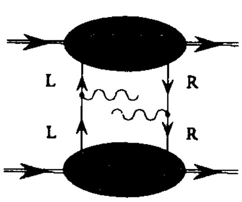
(a)



(b)

Therefore chiral odd distributions must appear in pairs

★ Classic example: ⊥ Drell − ⊥ Yan



★ Properties of Transversity

Soffer's Inequality

$$2\delta q^a \le q^a + \Delta q^a$$

Holds for each flavor of quark and antiquark separately

Care must be taken w.r.t. factorization scale dependence.

Saturation? Replace ≤ → = ? Only at some hadron scale, Q_0^2, after which it reverts to ≠.

Normalization − tensor charges δq_a

[illegible]

Amenable to numerical (lattice) calculation.

Model estimates

Typically based on saturation of Soffer's Inequality at small Q_0^2.

$\delta q \sim \Delta q$

See figures Barone, Caliaro & Drago hep-ph 9702239

Evolution

δq does not mix with gluonic operators (there is no gluon analog of transversity for a spin-$\frac{1}{2}$ target).

All anomalous dimensions for $\int dx x^n \delta q(x, Q^2)$ are positive.

Both imply δq evolves rather quickly to zero with increasing Q^2.

3 Specific Mechanisms

★ Transverse Drell – Tranverse Yan at pp Collider
John Ralston & Dave Soper

$$\vec{p}_\perp \vec{p}_\perp \rightarrow \ell\,\bar{\ell}\,X$$
$$\delta q(x_1) \otimes \delta\bar{q}(x_2)$$

↓ $\delta\bar{q}$ suppressed in nucleon. $\overrightarrow{\text{RHIC}}$

★ Inclusive pion electroproduction from a transversely polarized nucleon
RLJ & Xiangdong Ji

$$e\vec{p}_\perp \rightarrow e'\pi X$$
$$\delta q(x) \otimes \hat{e}(z) \oplus \delta g_T(x) \otimes \hat{q}(z)$$

A practical(?) example for extracting δq at Hermes/HERA. COMPASS & HERMES

Two competing processes:

Chiral-odd ⊗ Chiral-Odd

Twist-two chiral-odd distribution function $\delta q_N(x)$ combines with twist-three chiral-odd fragmentation function $\hat{e}_\pi(z)$

$$\delta q_N(x) \otimes \hat{e}_\pi(z)$$

Chiral-even ⊗ Chiral-even

Twist-three chiral-even distribution function $g_{T,N}(x)$ combines with twist-two chiral-even fragmentation function $\hat{q}_\pi(z)$

$$g_{T,N}(x) \otimes \hat{q}_\pi(z)$$

↓ Twist-3 – $\mathcal{O}(1/Q^2)$

↓ Must subtract chiral even background

↑ Pions should be abundant

↑ g_2 is known to be small, so perhaps even × even term is ignorable.

Is $\hat{e}(z, Q^2)$ large?

★ A_{TT}/A_{TT} in polarized jet production
Xangdong Ji, RLJ & Naohito Saitoh

$$\vec{p}_\perp \vec{p}_\perp \rightarrow j\;j\;X$$

$$\frac{\delta q(x_1) \otimes \delta q(x_2) \oplus \delta q(x_1) \otimes \delta\bar{q}(x_2)}{\Delta G(x_1) \otimes \Delta G(x_2) \oplus \ldots}$$

↓ Suppressed by color exchange factor $1/N_c^2$.

↓ No gluon transversity! $\overrightarrow{\text{RHIC}}$ $\overrightarrow{\text{HERA}}$

★ Inclusive Λ electroproduction from a transversely polarized nucleon
Artru & Mekhfi, RLJ

$$e\vec{p}_\perp \rightarrow e'\Lambda X$$
$$\delta q_N(x) \otimes \delta\hat{q}_\Lambda(z)$$

May be useful if Λ polarization fragmentation function is substantial. COMPASS & HERMES

↓ Λ's may be rare in the current fragmentation region

$\vec{q} \rightarrow \vec{\Lambda}$ fragmentation spin transfer is unknown

Polarised u quarks are *known* to exist at large-x in the nucleon and small x in the Λ. Likewise polarised s quarks are *known* to exist at small-x in the nucleon and large x in the Λ.

★ Azimuthal asymmetry in single particle inclusive DIS
Collins, Heppelmann, Ladinsky

Collins Angle – Let $\hat{n}$ be a normal to the plane defined by current fragmentation. Eg.

$$\hat{n} \propto \vec{p} \times \vec{q}$$

where $\vec{p}$ is a fragment momentum and $\vec{q}$ is the virtual photon momentum. Then

$$\cos\phi \equiv \hat{n} \cdot \vec{s}_\perp$$

$$e\vec{p}_\perp \rightarrow e' h X$$
$$\delta q_N(x) \otimes \delta\hat{q}(z)$$

Abundant: every event has a final state COMPASS & HERMES

Requires final state interaction (FSI) that does not average to zero when summed over X

For example, in $e\vec{p}_\perp \rightarrow e' \ldots X$

violates T-invariance unless ∃ a final state phase in ... But such phases are fragile – one would think they average to zero is performed

★ Azimuthal asymmetry in single particle inclusive DIS with longitudinally polarized target

If target spin and virtual photon spin are both longitudinal, no azimuthal asymmetry is possible.

However at small Q^2 the virtual photon spin is not exactly parallel to the electron's momentum, so the final pion can have an azimuthal distribution relative to the plane defined by the target (longitudinal) spin and the final electron's momentum:

$$\cos\phi \propto \vec{s} \times \vec{k} \cdot \vec{p}_\pi$$

$$\frac{d\Delta\sigma}{dx\,dy\,dz} = \frac{2\alpha^2}{Q^2}\frac{2Mx}{Q}\sqrt{1-y} \times \sum_a e_a^2 \left\{ h_1^a(x) C^a(z) + \frac{2-y}{1-y} h_L^a(x) C^a(z) + \ldots \right\}$$

$C^a(x)$ is "Collins" fragmentation function describing the azimuthal correlation in the fragmentation of a transversely polarized quark into a pion.

. . . denotes some extra terms still under study. [See D. Boer.]

Twist-two sensitivity for h_1. Twist-three sensitivity to $h_L(x)$.

4 Interference Fragmentation Functions

★ Basic Idea

Collins angle for two flavor selected mesons

$$\vec{p}_1 \times \vec{p}_2 \cdot \vec{s}_\perp$$

where $\vec{p}_j$ are momenta of flavor selected mesons.

★ Advantages

Meson pairs with significant FSI are abundant: (π^+, π^-), (K^+, K^-), $(K^\pm, \pi^\mp)$

Meson FSI phase remains fixed as $\sum_X$

Meson pair FSI phase is calculable from meson-meson phase shifts

★ Disadvantages

Cross section must be held differential to avoid averaging phase to zero

Almost certainly averages to zero in m_{12} – meson-meson invariant mass

Asymmetry depends on unknown and possibly zero two meson interference fragmentation function

RHIC, COMPASS & HERMES

★ Frequently Asked Questions

- Doesn't $\langle \vec{\pi}^+ \times \vec{\pi}^- \cdot \vec{s}_\perp \rangle$ vanish by charge conjugation?

Only if $\pi^+\pi^-$ are in a C-conjugation eigenstate. So if $(\pi^+\pi^-)$ form a ρ-meson $(C = -1)$ there is no effect.

Since $C = (-1)^\ell$ for $\pi^+\pi^-$, we must have more than one active partial wave.

- What's this about phases – don't they drop out of

$$\sum_X \langle \pi^+\pi^- X_{out} | \ldots | \pi^+\pi^- X \rangle ?$$

Not if $\pi^+\pi^-$ is a superposition of two or more different partial waves with different relative phases. Eg.

[illegible]

$$\sin\delta_0(m)\ \sin\delta_1(m)\ \sin(\delta_0(m) - \delta_1(m))$$

Figure of merit for $\pi\pi$ scattering data

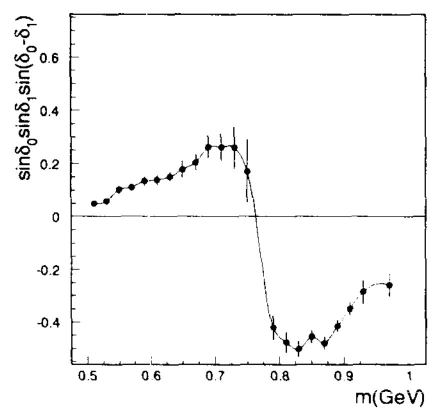
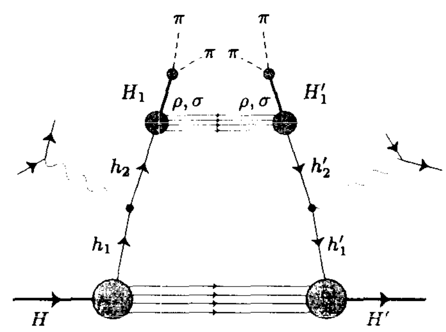


Diagram showing parton distribution and fragmentation functions.



★ Transverse Asymmetry in two pion electroproduction

$$\mathcal{A}_{\perp T} \equiv \frac{d\sigma_\perp - d\sigma_T}{d\sigma_\perp + d\sigma_T} = -\frac{\pi}{4}\frac{\sqrt{6}(1-y)}{1+(1-y)^2}\cos\phi$$
$$\times \; \sin\delta_0 \sin\delta_1 \sin(\delta_0-\delta_1)$$
$$\times \; \frac{\sum_a e_a^2 \delta q_a(x)\delta\hat{q}_I^a(z)}{\sum_a e_a^2 q_a(x)\left[\sin^2\delta_0 \hat{q}_0^a(z) + \sin^2\delta_1 \hat{q}_1^a(z)\right]}$$

★ Note

- "Collin's angle" $\cos\phi$ dependence
- $\sin\delta_0 \sin\delta_1 \sin(\delta_0-\delta_1)$

$\hat{q}_1(z)$ is the $\rho - (\pi\pi)^{\ell=1}$ fragmentation function

$\hat{q}_0(z)$ is the $\sigma - (\pi\pi)^{\ell=0}$ fragmentation function

- $\delta\hat{q}_I^a(z)$ is the $\pi\pi$ $\ell = 0$ & 1 interference fragmentation function

★ Properties of the interference fragmentation function.

- Interference fragmentation function is the first non-trivial generalization of fragmentation toward multiparticle final states.
- Novel objects, three pieces –
  - $q \to \rho, \sigma$ interference fragmentation as a density matrix (UNKNOWN)
  - $\pi\pi$ FSI in partial waves (KNOWN)

$$\frac{d^2\mathcal{M}}{dz\,dm^2} = \Delta_0(m^2)\{\sigma_+ \otimes \eta_- + \sigma_- \otimes \eta_+\}\,\delta\hat{q}_I(z)\Delta_1^*(m^2)$$
$$+ \; \Delta_1(m^2)\{\sigma_- \otimes \eta_+ + \sigma_+ \otimes \eta_-\}\,\delta\hat{q}_I(z)\Delta_0^*(m^2)$$
$$+ \; \text{spin independent terms}$$

$\sigma_\pm$ and $\eta_\pm$ are quark and ρ, σ helicity density matrices. They take care of helicity selection rules.

$\Delta_\ell(m^2)$ are FSI enhanced propagators for $\ell = 0, 1$, $\pi\pi$ final states.

$$\Delta_\ell = -i \sin\delta_\ell e^{i\delta_\ell}$$

which reduces to usual Feynman propogator when there is a narrow resonance in the ℓ^{th} partial wave

- $\pi\pi$ decay density matrix ( )

$$\frac{\delta P}{\delta\cos\Theta\,d\phi} = \frac{\sqrt{6}}{8\pi^2 m}\sin\Theta \ldots (\eta \ldots) + \ldots (\eta \ldots)$$
$$\sqrt{2}\cot\Theta\,(\eta_- + \eta_+)$$

- Flavor simplifications for $\pi\pi$

is an isovector with odd C-conjugation

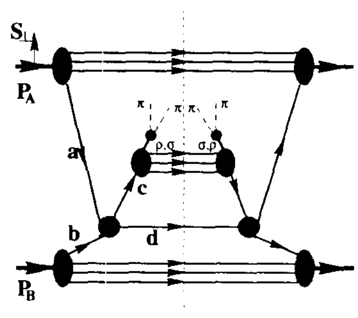
$$\delta\hat{u}_I = -\delta\hat{d}_I \quad \delta\hat{s}_I = 0 \quad \delta\hat{q}_I = -\delta\hat{\bar{q}}_I$$

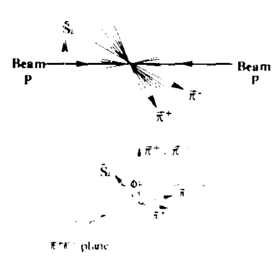
So there is only one independent interference fragmentation function for $\pi\pi$!

★ But the overall magnitude of the interference fragmentation function is unknown

★ Application to $p\vec{p} \to \pi\pi X$ ... hep-ph/9807560

$\overrightarrow{\text{RHIC}}$ $\overrightarrow{\text{HERA}}$





Transversity Measurement with PHENIX

Matthias Grosse Perdekamp, RIKEN BNL Center

Hard lepton-nucleon and hadron-hadron scattering cross sections can be expressed with the help of three independent helicity amplitudes. Measurements of the nucleon structure functions $F_2(x, Q^2)$, helicity average, and $g_1(x, Q^2)$, helicity difference, have explored the helicity conserving part of the cross section with great experimental accuracy. In contrast, no information is presently available on the helicity flip amplitude. The absence of experimental measurements is a consequence of the chiral odd nature of the helicity flip amplitude and the related "transversity quark distributions", $\delta q(x, Q^2)$, which prevents the appearance of helicity flip contributions at leading twist in inclusive DIS experiments.

Transversity distributions were first discussed by Ralston and Soper [1] in doubly transverse polarized Drell-Yan scattering. In Drell-Yan processes the transverse double spin asymmetry, A_{TT}, is proportional to $\delta q \delta \bar{q}$ with even chirality. Unfortunately, a recent analysis [2] estimates $A_{TT} \approx 1 - 2\%$ with statistical errors comparable to the asymmetry itself for a projected measurement at RHIC.

Single spin asymmetries $A^{\perp}$ (eg. unpolarized leptons on transversely polarized nucleon targets) in semi-inclusive DIS and pp scattering may offer an alternative way to observe helicity flip contributions at leading twist. This possibility relies on the presence of fragmentation functions, H, which are sensitive to the quark polarization in the final state and possess the necessary negative chirality. The asymmetries $A^{\perp}$ are proportional to $\sum_q \delta q \times \delta a_i^f \times H$, where a_i^f are the transversity dependent partonic initial-final-state asymmetries a_i^f of the struck quark which can be calculated from pQCD.

For example, Collins suggested that in semi inclusive single pion production the quark spin direction might be reflected in the azimuthal distribution of the final state pion [3]. Collins further demonstrated that the symmetry properties of the process do not require the proposed fragmentation function H_1 to be identical to zero.

The current interest in transversity distributions results from a recent Hermes result [4] which may suggest that Collins's function H_1 in fact is different from 0. Clearly the prospects are exciting to have a tool at hand which provides access to the complete helicity structure of hard scattering processes. At DESY a significant fraction (2 years) of the extended Hermes experimental program has been designated for the measurement of the transversity distributions.

Alternatively, Jaffe, Jin and Tang have proposed to utilize two meson interference fragmentation, both in polarized pp scattering and DIS, [5] in order to access the transversity distributions. In this channel, it is essential to experimentally identify oppositely charged meson pairs coming from the invariant mass region of S/P-wave interference (e.g. the ρ/σ region). It is shown in the talk that the invariant mass resolution of the PHENIX detector is sufficient for this purpose. In addition it is demonstrated that rates are high and that it will be possible to analyze data in a fine binning of invariant mass and other kinematic variables. This will provide good control of systematic errors.

References

[1] J. Ralston, D.E. Soper, Nucl. Phys. B152, 109(1979).

[2] O. Martin et al., Phys. Rev. D60. 117502(1999).

[3] J.C. Collins, Nucl. Phys. B396. 161(1993).

[4] A. Airapetian et al., hep-ph/9910062.

[5] B. Jaffe et al., Phys. Rev. D57. 5920(1998). J. Tang, hep-ph/9807560 and J. Tang. Thesis. MIT (1999).

5 Summary and Conclusions

⋆ Transversity

Twist-two, fundamental, relativistic effect.

Large at small Q_0^2, "quark-model-like".

Evolves to zero with Q^2.

Chiral-odd, hard to measure.

⋆ Most promising ways to measure transversity (my opinion)

$e\vec{p}_\perp \rightarrow e'\pi X$ Azimuthal Asymmetry If Hermes are right and the azimuthal asymmetry is large for a longitudinally polarized target, then the Collins effect is large and the azimuthal asymmetry on a transversely polarized target will measure transversity.

$e\vec{p}_\perp \rightarrow e'\pi X$ Especially because g_2 is small and if $\hat{e}$ is large.

$e\vec{p}_\perp \rightarrow e'\Lambda_\perp X$ Especially if $q \rightarrow \Lambda$ fragmentation functions are large.

$e\vec{p}_\perp \rightarrow e'\pi\pi X$ or $\vec{p}_\perp p \rightarrow \pi\pi X$ Especially if interference fragmentation function is large.

Transversity Measurement with PHENIX

Matthias Grosse Perdekamp, RIKEN BNL Center

Hard lepton-nucleon and hadron-hadron scattering cross sections can be expressed with the help of three independent helicity amplitudes. Measurements of the nucleon structure functions $F_2(x, Q^2)$, helicity average, and $g_1(x, Q^2)$, helicity difference, have explored the helicity conserving part of the cross section with great experimental accuracy. In contrast, no information is presently available on the helicity flip amplitude. The absence of experimental measurements is a consequence of the chiral odd nature of the helicity flip amplitude and the related "transversity quark distributions", $\delta q(x, Q^2)$, which prevents the appearance of helicity flip contributions at leading twist in inclusive DIS experiments.

Transversity distributions were first discussed by Ralston and Soper [1] in doubly transverse polarized Drell-Yan scattering. In Drell-Yan processes the transverse double spin asymmetry, A_{TT}, is proportional to $\delta q \delta \bar{q}$ with even chirality. Unfortunately, a recent analysis [2] estimates $A_{TT} \approx 1 - 2\%$ with statistical errors comparable to the asymmetry itself for a projected measurement at RHIC.

Single spin asymmetries $A^{\perp}$ (eg. unpolarized leptons on transversely polarized nucleon targets) in semi-inclusive DIS and pp scattering may offer an alternative way to observe helicity flip contributions at leading twist. This possibility relies on the presence of fragmentation functions, H, which are sensitive to the quark polarization in the final state and possess the necessary negative chirality. The asymmetries $A^{\perp}$ are proportional to $\sum_q \delta q \times \delta a_i^f \times H$, where a_i^f are the transversity dependent partonic initial-final-state asymmetries a_i^f of the struck quark which can be calculated from pQCD.

For example, Collins suggested that in semi inclusive single pion production the quark spin direction might be reflected in the azimuthal distribution of the final state pion [3]. Collins further demonstrated that the symmetry properties of the process do not require the proposed fragmentation function H_1 to be identical to zero.

The current interest in transversity distributions results from a recent Hermes result [4] which may suggest that Collins's function H_1 in fact is different from 0. Clearly the prospects are exciting to have a tool at hand which provides access to the complete helicity structure of hard scattering processes. At DESY a significant fraction (2 years) of the extended Hermes experimental program has been designated for the measurement of the transversity distributions.

Alternatively, Jaffe, Jin and Tang have proposed to utilize two meson interference fragmentation, both in polarized pp scattering and DIS, [5] in order to access the transversity distributions. In this channel, it is essential to experimentally identify oppositely charged meson pairs coming from the invariant mass region of S/P-wave interference (e.g. the ρ/σ region). It is shown in the talk that the invariant mass resolution of the PHENIX detector is sufficient for this purpose. In addition it is demonstrated that rates are high and that it will be possible to analyze data in a fine binning of invariant mass and other kinematic variables. This will provide good control of systematic errors.

References

[1] J. Ralston, D.E. Soper, Nucl. Phys. B152, 109(1979).

[2] O. Martin et al., Phys. Rev. D60, 117502(1999).

[3] J.C. Collins, Nucl. Phys. B396, 161(1993).

[4] A. Airapetian et al., hep-ph/9910062.

[5] B. Jaffe et al., Phys. Rev. D57, 5920(1998), J. Tang, hep-ph/9807560 and J. Tang, Thesis, MIT (1999).

Transversity Measurement with PHENIX

Matthias Grosse Perdekamp, RIKEN BNL Center

Hard lepton-nucleon and hadron-hadron scattering cross sections can be expressed with the help of three independent helicity amplitudes. Measurements of the nucleon structure functions $F_2(x, Q^2)$, helicity average, and $g_1(x, Q^2)$, helicity difference, have explored the helicity conserving part of the cross section with great experimental accuracy. In contrast, no information is presently available on the helicity flip amplitude. The absence of experimental measurements is a consequence of the chiral odd nature of the helicity flip amplitude and the related "transversity quark distributions", $\delta q(x, Q^2)$, which prevents the appearance of helicity flip contributions at leading twist in inclusive DIS experiments.

Transversity distributions were first discussed by Ralston and Soper [1] in doubly transverse polarized Drell-Yan scattering. In Drell-Yan processes the transverse double spin asymmetry, A_{TT}, is proportional to $\delta q \delta \bar{q}$ with even chirality. Unfortunately, a recent analysis [2] estimates $A_{TT} \approx 1 - 2\%$ with statistical errors comparable to the asymmetry itself for a projected measurement at RHIC.

Single spin asymmetries $A^{\perp}$ (eg. unpolarized leptons on transversely polarized nucleon targets) in semi-inclusive DIS and pp scattering may offer an alternative way to observe helicity flip contributions at leading twist. This possibility relies on the presence of fragmentation functions, H, which are sensitive to the quark polarization in the final state and possess the necessary negative chirality. The asymmetries $A^{\perp}$ are proportional to $\sum_q \delta q \times \delta a_i^f \times H$, where a_i^f are the transversity dependent partonic initial-final-state asymmetries a_i^f of the struck quark which can be calculated from pQCD.

For example, Collins suggested that in semi inclusive single pion production the quark spin direction might be reflected in the azimuthal distribution of the final state pion [3]. Collins further demonstrated that the symmetry properties of the process do not require the proposed fragmentation function H_1 to be identical to zero.

The current interest in transversity distributions results from a recent Hermes result [4] which may suggest that Collins's function H_1 in fact is different from 0. Clearly the prospects are exciting to have a tool at hand which provides access to the complete helicity structure of hard scattering processes. At DESY a significant fraction (2 years) of the extended Hermes experimental program has been designated for the measurement of the transversity distributions.

Alternatively, Jaffe, Jin and Tang have proposed to utilize two meson interference fragmentation, both in polarized pp scattering and DIS, [5] in order to access the transversity distributions. In this channel, it is essential to experimentally identify oppositely charged meson pairs coming from the invariant mass region of S/P-wave interference (e.g. the ρ/σ region). It is shown in the talk that the invariant mass resolution of the PHENIX detector is sufficient for this purpose. In addition it is demonstrated that rates are high and that it will be possible to analyze data in a fine binning of invariant mass and other kinematic variables. This will provide good control of systematic errors.

References

[1] J. Ralston, D.E. Soper, Nucl. Phys. B152, 109(1979).

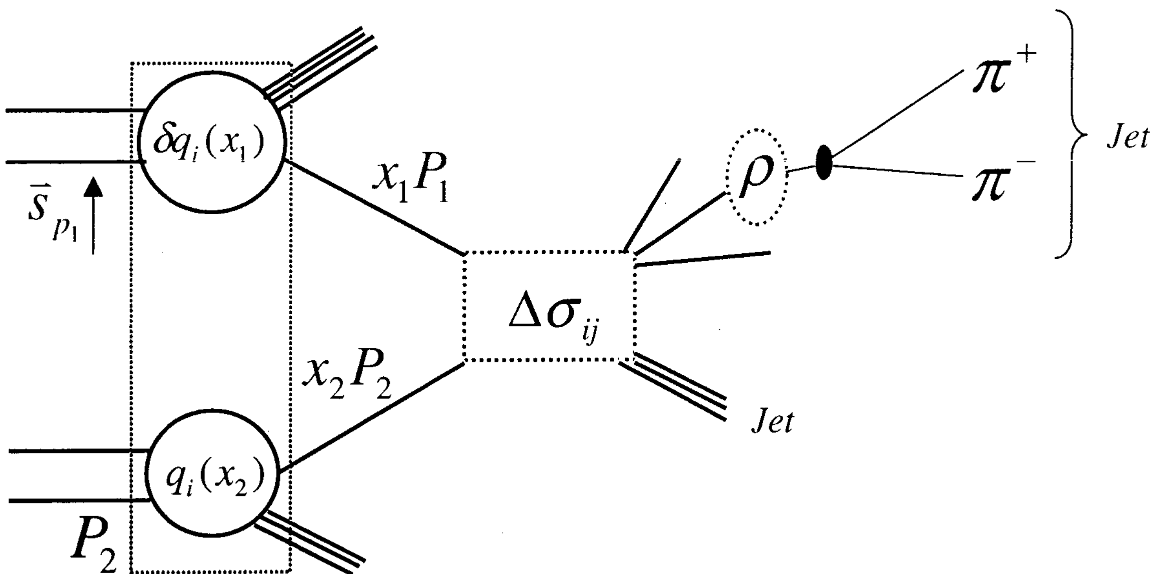
[2] O. Martin et al., Phys. Rev. D60, 117502(1999).

[3] J.C. Collins, Nucl. Phys. B396, 161(1993).

[4] A. Airapetian et al., hep-ph/9910062.

[5] B. Jaffe et al., Phys. Rev. D57, 5920(1998), J. Tang, hep-ph/9807560 and J. Tang, Thesis, MIT (1999).

Nucleon transversity through final state interaction at RHIC

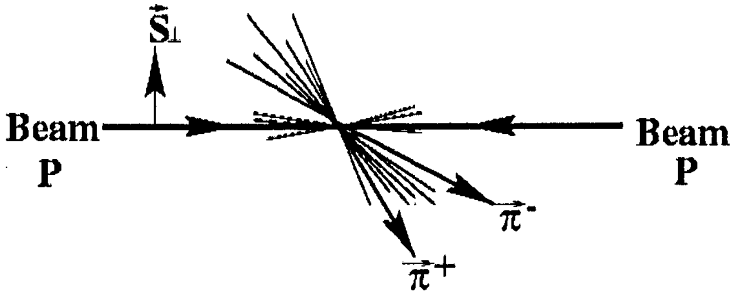


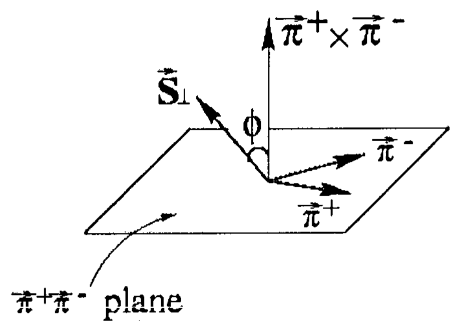
$$\frac{d^7\sigma_H\left(pp^\uparrow \to \pi^+\pi^- X\right)}{dx_1 dx_2 dt dz dm^2 d\cos\theta d\varphi} \propto \underbrace{\delta q(x_1)\cdot q(x_2)}_{\text{Proton Structure}} \cdot \underbrace{\frac{d^3\sigma(q_1 q_2 \to q_3 q_4)}{dx_1 dx_2 dt}}_{\text{Hard Scattering Process}} \cdot \underbrace{\frac{d^2\mathcal{M}}{dz dm^2}}_{\text{Interference Fragmentation}} \cdot \underbrace{\frac{d^2\mathcal{D}}{d\cos\theta d\varphi}}_{\text{Pion Fragmentation}}$$

Jian Tang , Thesis MIT, June 1999
R. Jaffe, X.Jin, J. Tang Phys. Rev. D57 (1999)5920
X. Ji, Phys. Rev. D49 (1994)114
J. Collins, S. Heppelmann, G. Ladinsky, Nucl.Phys. B420 (1994)565

Transverse Single Spin Asymmetry

(Jian Tang, Thesis, MIT)





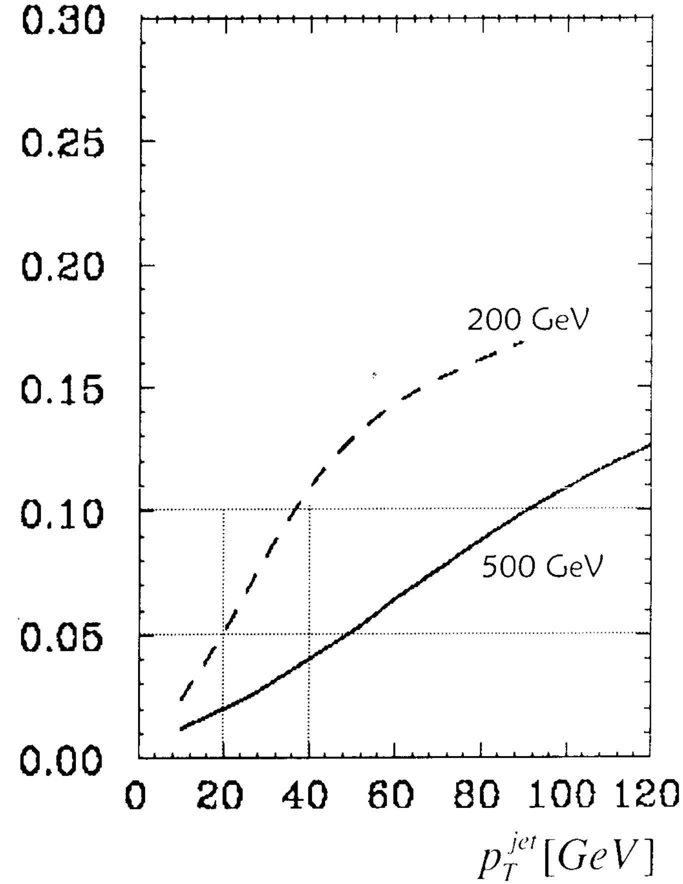
$N^{\rightarrow}$	: Pion Pair Yield
$\sin\delta_l$	: Two Pion Phase Shifts
$\delta q(x)$	: Transversity quark DFs
$\delta\hat{q}(z)$	: Pol. Fragmentation Func.

$$A_{\perp} = \frac{1}{P_{beam}} \frac{N^{\rightarrow} - N^{\leftarrow}}{N^{\rightarrow} + N^{\leftarrow}} = -\frac{\sqrt{6}\pi}{4} \boxed{\sin\delta_0 \sin\delta_1 \sin(\delta_0 - \delta_1)\cdot\cos(\phi)\cdot}$$

$$\frac{[\delta q(x_1)\cdot G(x_2)\cdot \delta\hat{q}_I(z)]\delta\hat{\sigma}^{qg}_{qg} + \ldots}{\{[G(x_1)\cdot G(x_2)]\delta\hat{\sigma}^{q\bar{q}}_{gg} + \ldots\}\cdot[\sin^2\delta_0\hat{q}_0(z) + \sin^2\delta_1\hat{q}_1(z)]}$$

Maximum Asymmetry

$$\eta = 0, m_{\rho,\sigma} = 0.83\ \text{GeV}, \cos\phi = 1$$
$$\delta\hat{q}_I^2 = 4\hat{q}_0\hat{q}_1/3,\ \ 2|\delta q| \le q + \Delta q$$



Interference Fragmentation

$$\frac{d^2\mathcal{M}}{dzdm^2} \propto \sin\delta_0 e^{i\delta_0}\left(\kappa\cdot\hat{q}_I(z)+\lambda\cdot\delta\hat{q}_I(z)\right)\sin\delta_1 e^{-i\delta_1}+\ldots$$

s-wave

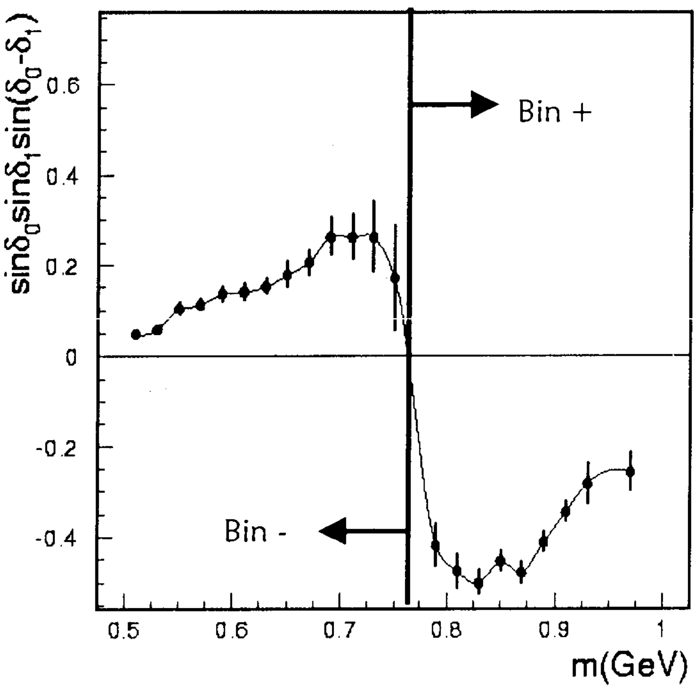
p-wave

Strong interaction π,π phase shifts

Where:

$\kappa = I\otimes\overline{\eta}_0,\ \ \lambda=\sigma_+\otimes\overline{\eta}_- +\sigma_-\otimes\overline{\eta}_+$

$\hat{q}_I(z),\delta\hat{q}_I(z)$: spin average and difference fragmentation functions



P. Estabrooks and A.D. Martin, Nucl. Phys. B79 (1974)301

Non-vanishing "support" only in the ρ mass region!

- Sufficient mass Resolution?
- Great for systematics!

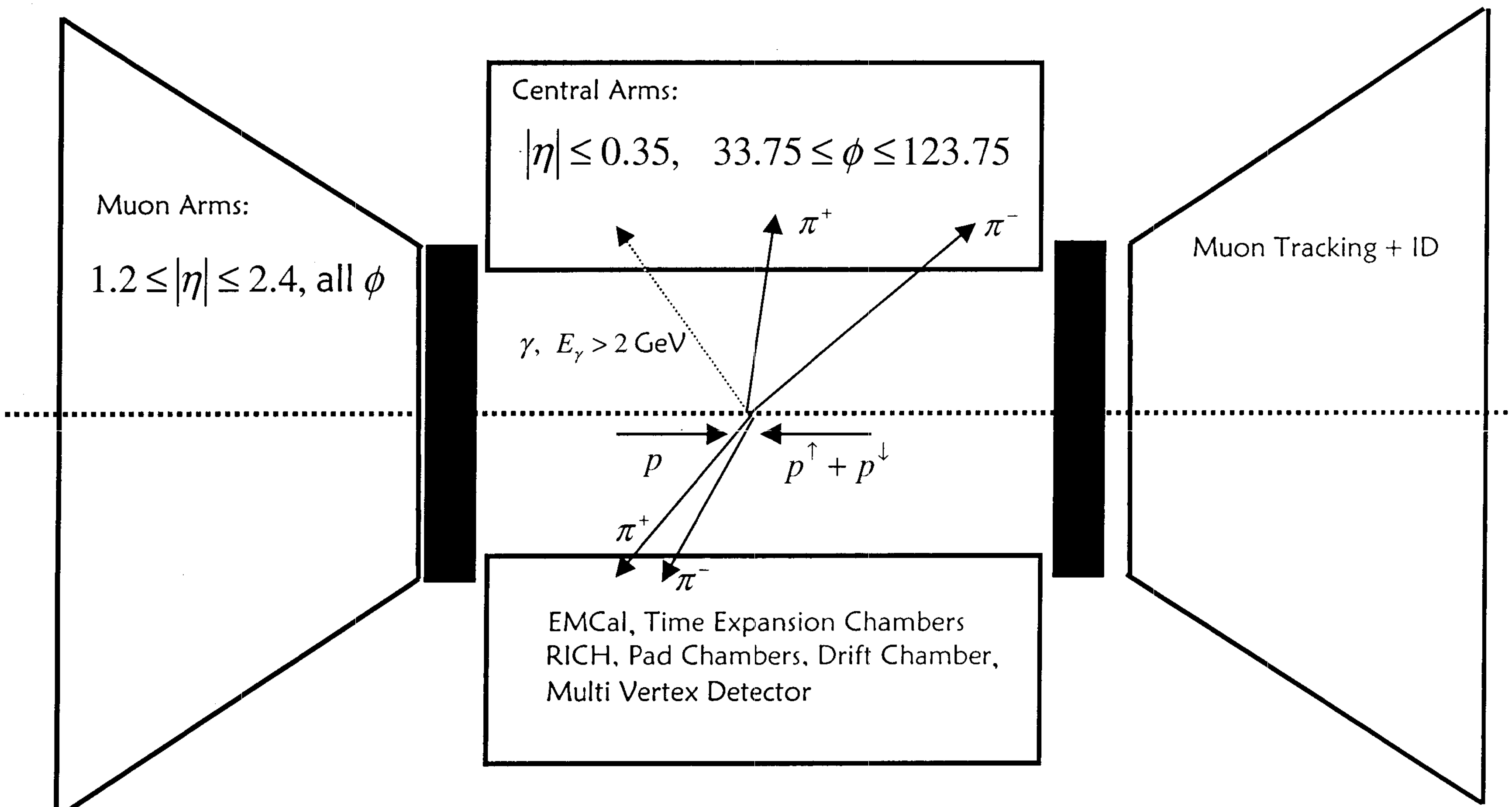
57

PHENIX

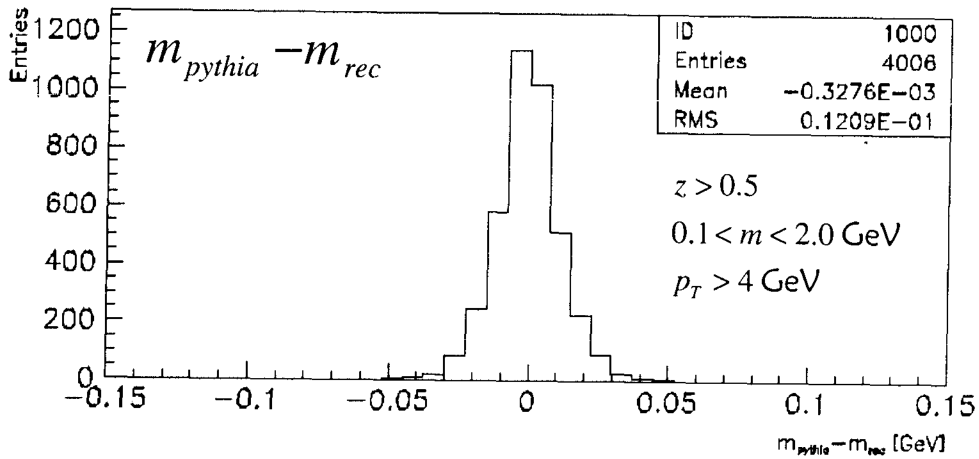
Trigger: Tag $\pi^{+,-}$ in RICH or π^0 EMCal

Reconstruct invariant mass of pion pairs

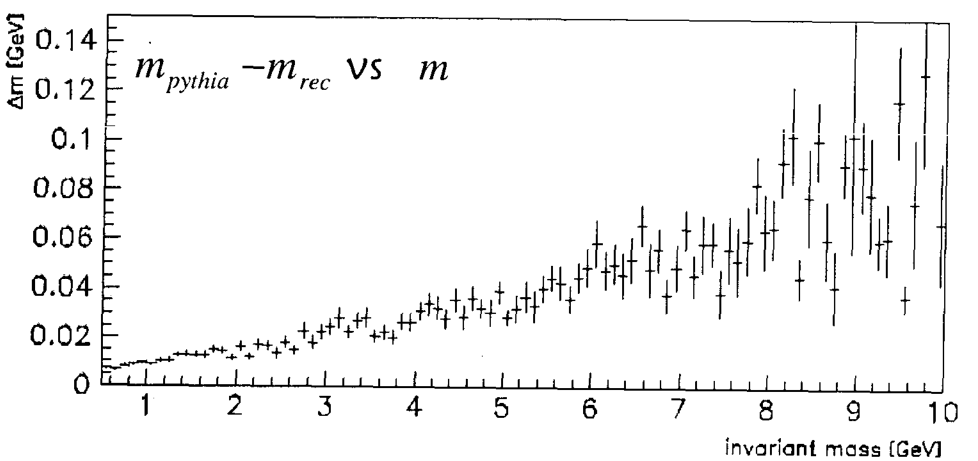
Form single spin asymmetry $A_{exp} = \frac{N^{\uparrow} - N^{\downarrow}}{N^{\uparrow} + N^{\downarrow}}$



Invariant Mass Resolution



RMS=12 MeV



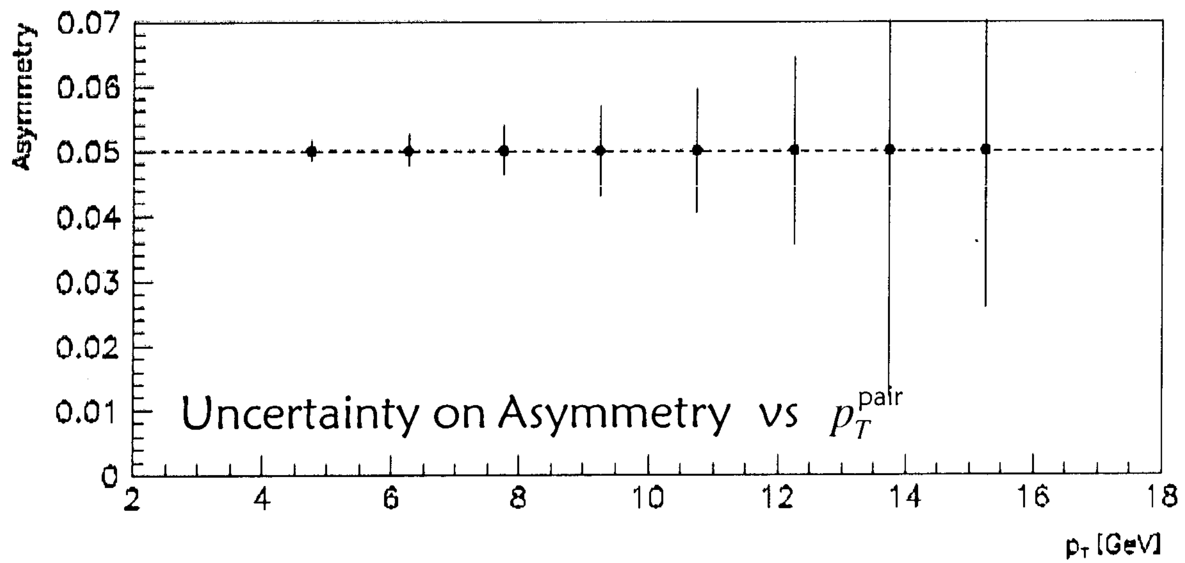
Nice! Need to confirm with full simulation...

Expected Rate

Example:

$$E_{\pi_1,\pi_2} > 4\ \text{GeV}$$
$$\sqrt{p_{1T}^2 + p_{2T}^2} > 4\ \text{GeV}$$
$$800\ \text{MeV} < m < 950\ \text{MeV}$$

5.2 Million events in 32 pb^{-1}
15% with pair after cuts



60

Akio Ogawa, BNL, Upton, NY 11973

STAR detector for Transversity measurement

Wide acceptance :

Jet measurements ~20% Et resolution

check Z dependence

check Pt & Rapidity dependence

Good invariant mass resolution: 2-5 % at 800MeV

But slow:

Need fancy trigger at high luminosity

STAR is a working detector!

Two meson production

$$A = \frac{\sigma^{-\Uparrow+} - \sigma^{+\Uparrow-}}{\sigma + \sigma}$$

$$= -\frac{\sqrt{6}\pi}{4}\sin\delta_0 \sin\delta_1 \sin(\delta_0 - \delta_1)\cos\phi$$

$$\otimes \frac{\sum_{qg\to qg,\bar{q}g\to\bar{q}g\ldots}[\delta q_a(x_a)\otimes q_b(x_b)\otimes \delta\hat{q}_I(z)]\delta\sigma_{ab\to cd}}{\{\sum_{gg\to q\bar{q},qg\to qg\ldots}[q_a(x_a)\otimes q_b(x_b)]\sigma_{ab\to cd}\}\otimes\{\sin^2\delta_0\hat{q}_0(z)+\sin^2\delta_1\hat{q}_1(z)\}}$$

Phase Shift $\sin\delta_0 \sin\delta_1 \sin(\delta_0 - \delta_1)$ is known

ρ, σ Fragmentation function $\hat{q}_0(z), \hat{q}_1(z)$

Interference fragmentation function $\delta\hat{q}_I(z)$

} unknown

In Jian Tang paper, assume { $\delta\hat{q}_I(z) = \frac{3}{4}\hat{q}_0(z)\hat{q}_1(z)$ Schwartz Inquality Limit

No z dependence $\hat{q}_0(z) = \hat{q}_1(z)$

STAR Trigger

Level 0 Trigger

EMC $1.0(\eta)$ x $0.8(\phi)$ trigger patch

- see only 1/3 of total energy at L0 trigger
- bias towards EM rich events

→ Look at the other side of triggered jet

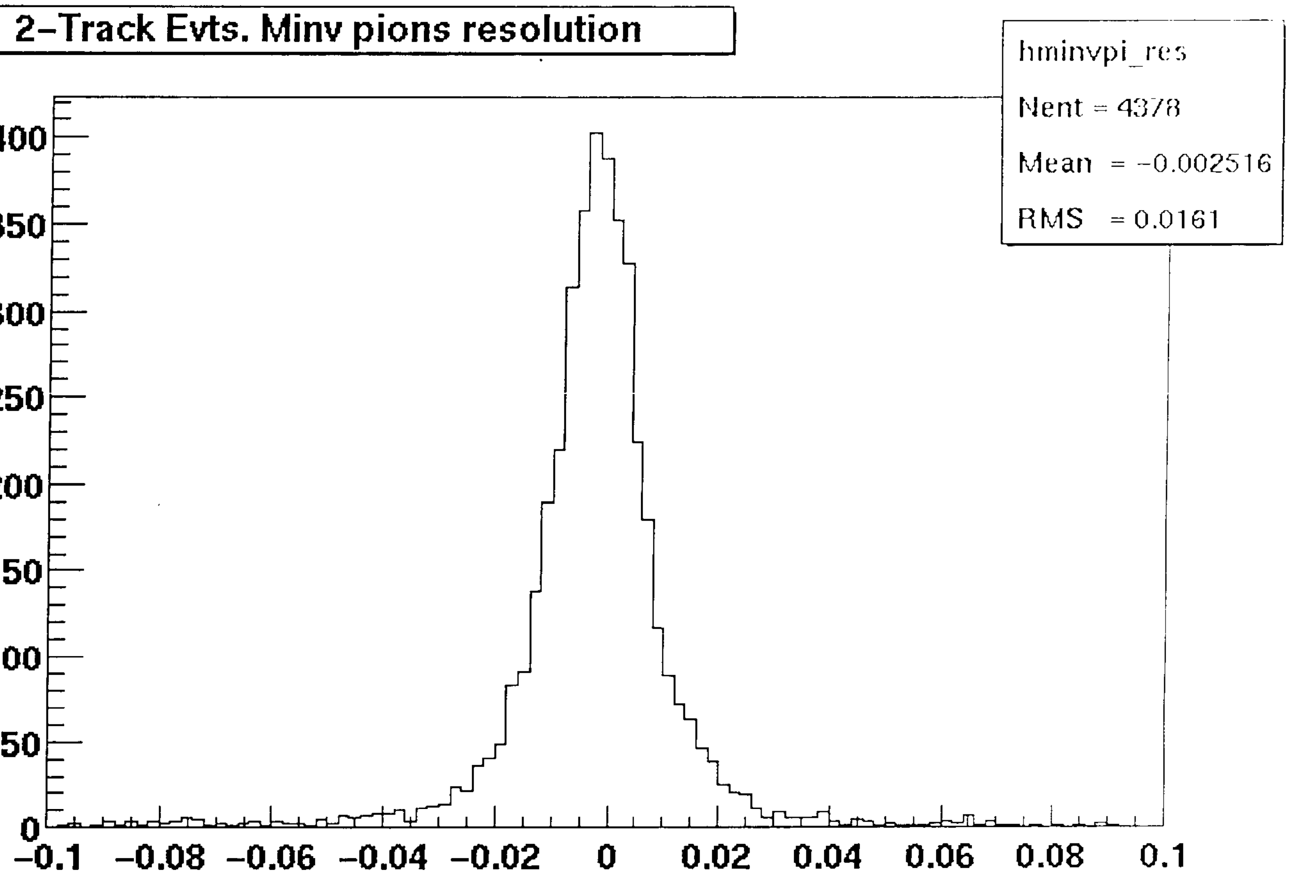
CTB/MWC multiplicity trigger

- works only for low luminosity

Level 3 Trigger

TPC tracking available

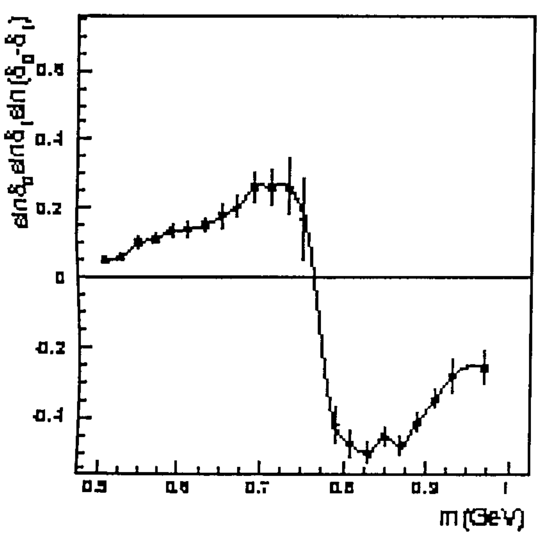
- TPC is slow   1Hz at central AuAu
  - Speed depend on data size
  - → Data size reduction at L3
- Possibly selecting invariant mass / z



A factor

$$\sin\delta_0 \sin\delta_1 \sin(\delta_0 - \delta_1)$$

from Phase Shifts as function of invariant mass



Invariant mass resolution of STAR for Pt = 2-10 GeV pair around mass ~ 0.8 GeV

64

Singal Estimation

Luminosity, triggering, polarization, length of data taking

Cuts : Find jets (EM+charged hadrons) in $-0.3 < \eta < 0.3$ (1.3)

Any 2 opposite charged particle pairs within a jet

Pt > 0.3GeV

$-0.3 < \eta < 0.3$ (1.3)

$0.5 < \text{mass} < 1.0$

Bins : mass , ϕ

z , Pt_jet , η _jet

65

One-loop factorization of the g_2 structure function of the nucleon

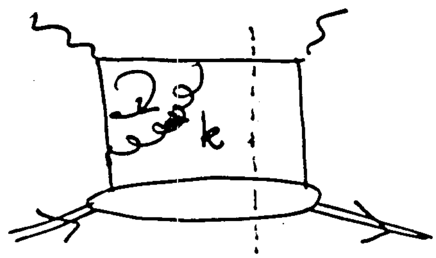
Xiangdong Ji

University of Maryland

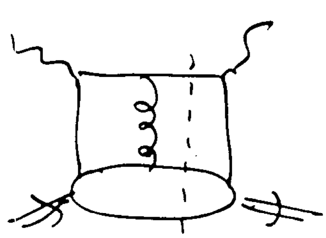
Main points of Talk:

1. Feynman's parton model is useful for incoherent parton scattering. QCD allows also for coherent parton scattering which is the origin of higher-twist physics.
2. Higher-twist in general cannot be separated from leading twist unambiguously. However, this is not the case for twist-three processes. There are many interesting twist-three processes including g_2 structure funtion of the nucleon.
3. No next-to-leading order calculations are available for any twist-three processes.
4. In the large N_c limit, the two-loop evolution equation cannot be simplified as in the one-loop case.
5. We have made the first complete calculation of the one-loop coefficient function for g_2 factorization formula.

A CLEAR Separation of higher twist from leading one is difficult. Consider the following DIS process.



When the loop momentum $k^2 \gg \Lambda_{QCD}^2$, the process is a radiative correction to Feynman's parton model. However, for $k^2 \lesssim \Lambda_{QCD}^2$, the resolution of the initial quark into a quark + a gluon cannot be calculated in pert. theory. Hence the gluon must be considered part of the nucleon structure



Separation of loop momentum into large & small k^2 is scheme dependent, & hence higher twist.

However, there is a class of twist-3 processes in which the leading-twist contribution vanishes.

- $g_2(x, Q^2)$ structure function in polarized DIS.

- π production in transversely polarized DIS   Jaffe & Ji, PRL 71, 1993

- Direct γ single-spin asymmetry in $pp\uparrow$ scattering
  Efremov & Teryaev, 1982
  Qiu & Sterman, PRL 67, 1991
  Ji, 1992

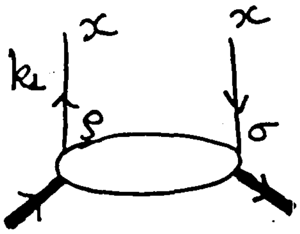
- π single spin asymmetry in $pp\uparrow$ scattering
  Qiu & Sterman, PRD 1999

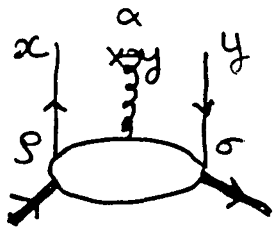
- L-T polarized Drell-Yan process
  Jaffe & Ji, PRL 67, 1991

- .....

Parton Correlations in twist-3 processes

• Quark & Gluon Correlations





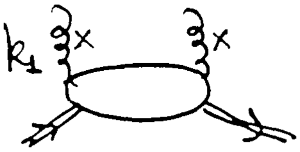
$$M^\alpha_{D\rho\sigma}(x,y) = \int \frac{d\lambda\, d\mu}{(2\pi)^2}\, e^{i\lambda x}\, e^{i\mu(y-x)} \langle ps|\,\bar\psi_\rho(0)\left(i\partial_\perp^\alpha - ig A_\perp^\alpha(\mu n)\right)\psi(\lambda n)\,|ps\rangle$$

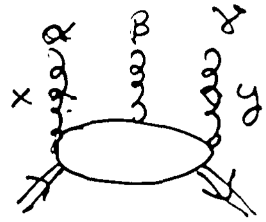
$$= S_\perp^\alpha (\gamma_5 \not p)_{\rho\sigma}\, G_1^D(x,y) + i T_\perp^\alpha \not p_{\rho\sigma}\, G_2^D(x,y) + \ldots$$

$$M^\alpha_{F\rho\sigma}(x,y) = \int \frac{d\lambda\, d\mu}{(2\pi)^2}\, e^{i\lambda x}\, e^{i\mu(y-x)} \langle ps|\,\bar\psi_\rho(0)\, \bar n\, F^{+\alpha}(\mu n)\,\psi(\lambda n)\,|ps\rangle$$

$$= S_\perp^\alpha (\gamma_5 \not p)_{\rho\sigma}\, G_1^F(x,y) + i T_\perp^\alpha \not p_{\rho\sigma}\, G_2^F(x,y) + \ldots$$

• Pure Gluon Correlations

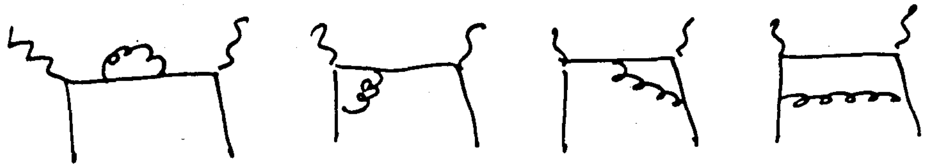




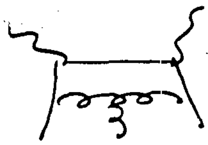
$$\langle ps|\, F^{+\alpha}(0)\, iD^\beta(\mu n)\, F^{+\gamma}(\lambda n)\,|ps\rangle \qquad \langle ps|\, F_a^{+\alpha}(0)\, F_b^{+\beta}(\mu n)\, F_c^{+\gamma}(\lambda n)\,|ps\rangle$$

One-loop coefficient functions for $g_2(x,Q^2)$ were first considered by Kodaira et al in 1979

They calculated



However, there are more diagrams



- What diagrams to include?

  Depend on correlations. For twist-3

  $$\bar{\psi}(i\partial^{\perp} - gA^{\perp})\psi \,, \quad \bar{\psi}F^{+\perp}\psi$$

  two types of diagrams

expand $k_\perp$ once

The second type of diagram corresponds to Compton amplitude

$$\langle q g | T J_\mu J_\nu | q \rangle$$

where q, g are "on-shell", massless quarks and gluons. ["On-shell" is defined from the poles of perturbative quark & gluon propagators]

- On-shell S-matrix amplitude has no UV divergences after coupling constant renormalization.

- On-shell S-matrix amplitude has infrared divergences which can regularized using D.R.

  - The infrared divergent part of the amplitude yields the leading-log evolution of the parton correlations.

  - The finite part gives one-loop coefficient function.

Polarized Parton Distributions SMC's pQCD Analysis of $g_1(x, Q^2)$ at Next-to-Leading order

RIKEN Workshop
Brookhaven National Laboratory
March 13, 2000

Abhay Deshpande
RIKEN-BNL Research Center

SMC's Aim:

- Spin sum rules: Bjorken sum rule & Ellis-Jaffe sum rule
- Perturbative QCD Analysis at NLO using the global data set: Determine polarized parton distributions with complete uncertainty analysis
  $\Longrightarrow$ Stability ond reliability of the analysis with available data
  $\Longrightarrow$ Gluon distribution and its first moment
  $\Longrightarrow$ Scheme dependence

Spin Muon Collaboration, B. Adeva *et al.*, Phys. Rev. D58 (1998) 112002

The pQCD Analysis – The Global fit [1]

- Chose a starting scale $Q^2 = Q_i^2 \Longrightarrow 1\ \text{GeV}^2$
- Parametrize the polarized parton distributions with a functional form:

$$\Delta f(x) = N(\alpha_f, \beta_f, a_f) \cdot \eta_f \cdot x^{\alpha_f} \cdot (1-x)^{\beta_f} \cdot (1 + a_f x)$$

  – $\Delta f(x)$ stands for $\Delta\Sigma(x)$, $\Delta g(x)$, and $\Delta q_{\mathrm{NS}}^{\mathrm{p,n}}$ distributions.

- Each polarized parton distribution is normalized such that:

$$N(\alpha_f, \beta_f, a_f) \int_0^1 \mathrm{d}x \cdot x^{\alpha_f} \cdot (1-x)^{\beta_f} \cdot (1 + a_f x) = 1$$

  $\eta_f \Longrightarrow$ first moments of polarized parton distributions
  η_{S}, η_g free parameters while,

$$\eta_{\mathrm{NS}}^{\mathrm{p,n}} = \pm\frac{3}{4} \cdot \left|\frac{g_{\mathrm{A}}}{g_{\mathrm{V}}}\right| + \frac{1}{4} \cdot a_8$$

  – $a_8 = F/D = 0.575 \pm 0.016$ (Phys. Lett. B **316**, 165 (1993))
  – $g_{\mathrm{A}}/g_{\mathrm{V}}$ free parameter $\Longrightarrow$
  Get fit value and evaluate Bjorken sum

$$\Gamma_1^{\mathrm{p}} - \Gamma_1^{\mathrm{n}} = \frac{1}{6} \cdot \left|\frac{g_{\mathrm{A}}}{g_{\mathrm{V}}}\right| \cdot C_{\mathrm{NS}}(Q^2)$$

  – $g_{\mathrm{A}}/g_{\mathrm{V}} = F + D = 1.2601 \pm 0.0025$ (Phys. Rev. D **54**, 1 (1996))
  $\Longrightarrow$ Bjorken sum rule is built in
  $\Longrightarrow$ [illegible] possible polarized [illegible] distributions and first [illegible]

- Analysis performed in a modified $\overline{\mathrm{MS}}$ scheme called the Adler-Bardeen scheme for historical reasons

$$a_0(Q^2) = \Delta\Sigma_{\overline{\mathrm{MS}}}(Q^2) = \Delta\Sigma_{\mathrm{AB}} - n \cdot \frac{\alpha_s(Q^2)}{2\pi} \cdot \Delta g(Q^2)$$

[1] Based on R. Ball *et al.* Phys. Lett. B **378** 255 (1996)

Reliability of the pQCD Analysis Procedure

- Get out of the analysis that which would normally be input to the analysis, and you know to have been determined well from outside this pQCD analysis.
- It should be a spin-independent quantity
- The Strong coupling constant: $\Longrightarrow \alpha_S(M_Z^2)$
  - Its value itself could be made a fit parameter
  - Since $F_2(x, Q^2)$ from HERA are used in the analysis to get at g_1 we should get back the value of α_S consistent with that determined from HERA experimental data.
- Fit result:

$$\alpha_S(M_Z^2) = 0.120 \pm 0.002(\text{stat}) \pm 0.006(\text{syst and theory})$$

- Consistent with the HERA published values!

FIRST STEP TOWARDS RELIABILITY, BUT A MAJOR ONE

Evaluation of Systematic Errors:

- Experimental sources:
  - Systematic uncertainty on measured $A_1^{\mathrm{p,d,n}}(x, Q^2)$ data points
    For each data set: systematic uncertainties added in quadrature
    Repeat QCD analysis with $A_1 \pm \delta_{\mathrm{syst}} A_1$
  - F_2 and R parameterization:
    Upper and lower limits of the parametrizations (as published)
    Repeat the QCD analysis
  - Maximum deviations from best fit added in quadrature to get total experimental systematic uncertainty

- Theoretical sources: Related to the uncertainties on other inputs in to the pQCD analysis procedure:
  - Functional form of initial parton distribution
    $\Longrightarrow$ Change, repeat fit, see difference w.r.t. best fit
    $\Longrightarrow$ Change initial Q_i^2, repeat fit, see difference...
  - Factorization and Renormalization scales
    $\Longrightarrow$ Change by a factor of 2 (high and low), repeat fit...
  - Value of $\alpha_s(M_Z^2)$, the strong coupling constant
    $\Longrightarrow 0.118 \pm 0.003$
  - Others of smaller consequence:
    * $a_8 = 0.575 \pm 0.016$
    * Quark mass thresholds
    * ...
  - Maximum deviations from best fit added in quadrature to get total theoretical systematic uncertainty

Global Fit Result for Bjorken Sum rule

Table 1: Best parameters at $Q^2 = 1$ GeV^2. The uncertainties shown are statistical only.

Parameter	Value	Parameter	Value
η_S	$0.38^{+0.03}_{-0.02}$	η_g	$0.94^{+1.26}_{-0.29}$
α_S	$1.03^{+0.29}_{-0.27}$	α_g	$-0.71^{+0.22}_{-0.21}$
β_S	$3.64^{+0.63}_{-0.59}$	β_g	(4.0)
$\lvert\frac{g_A}{g_V}\rvert$		$1.15^{+0.03}_{-0.03}$	
η_{NS}^{p}	$\frac{3}{4}\lvert\frac{g_A}{g_V}\rvert + \frac{1}{4}a_8$	η_{NS}^{n}	$-\frac{3}{4}\lvert\frac{g_A}{g_V}\rvert + \frac{1}{4}a_8$
α_{NS}^{p}	$-0.01^{+0.10}_{-0.10}$	α_{NS}^{n}	$0.20^{+0.16}_{-0.14}$
β_{NS}^{p}	$1.86^{+0.30}_{-0.28}$	β_{NS}^{n}	$3.48^{+0.70}_{-0.63}$
χ^2		116.1	
d.f.		133 − 10	

$$\left|\frac{g_A}{g_V}\right| = 1.15^{+0.03}_{-0.03}(\text{stat})^{+0.07}_{-0.06}(\text{exp.syst})^{+0.14}_{-0.04}(\text{theory})$$

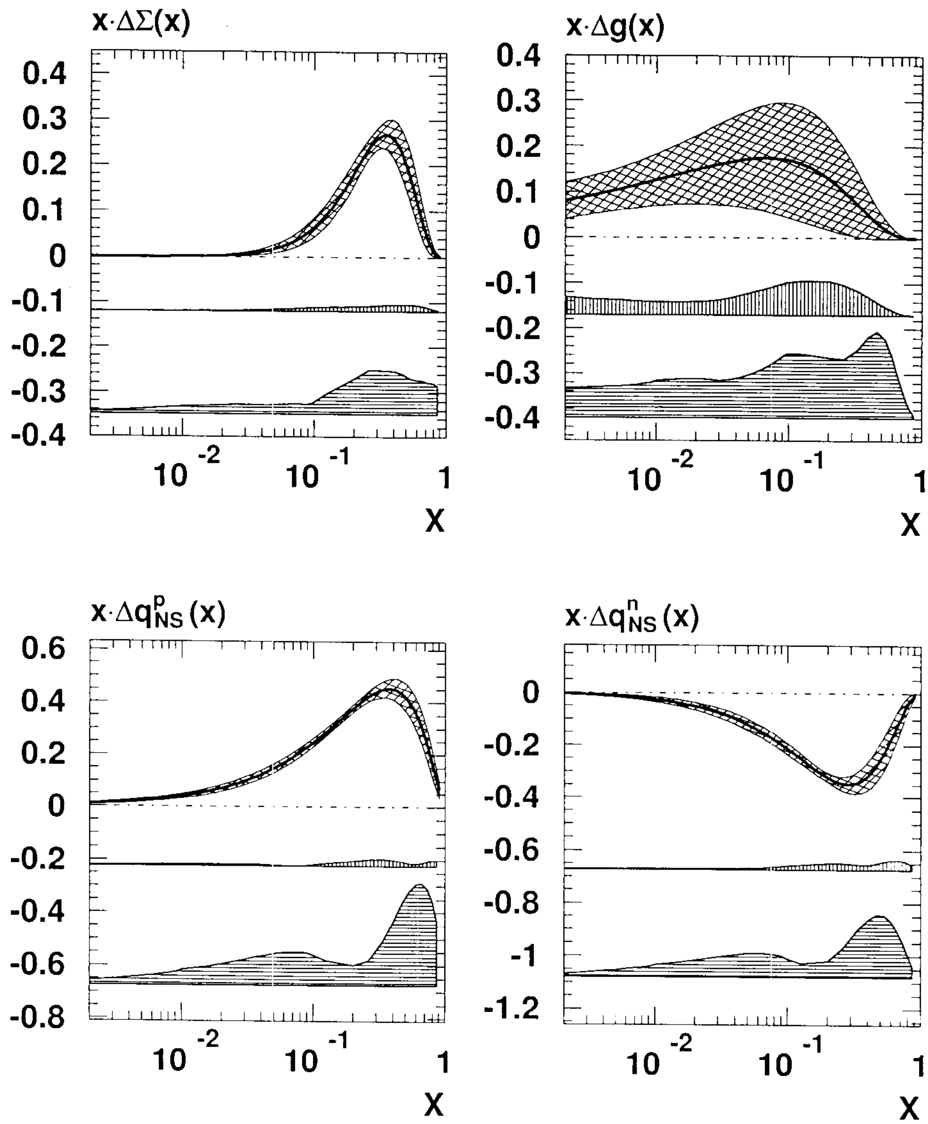
$$[\Gamma_1^p - \Gamma_1^n](Q_0^2) = \frac{1}{6}\cdot\left|\frac{g_A}{g_V}\right|\cdot C_{NS}(Q_0^2) \Longleftarrow \text{Bjorken Sum Rule}$$

$$[\Gamma_1^p - \Gamma_1^n](Q_0^2 = 5\text{GeV}^2) = 0.174 \pm 0.005(\text{stat})^{+0.011}_{-0.009}(\text{exp.syst})^{+0.021}_{-0.006}(\text{theory})$$

$$= 0.174^{+0.024}_{-0.012} \Longleftarrow \text{SMC Result}$$

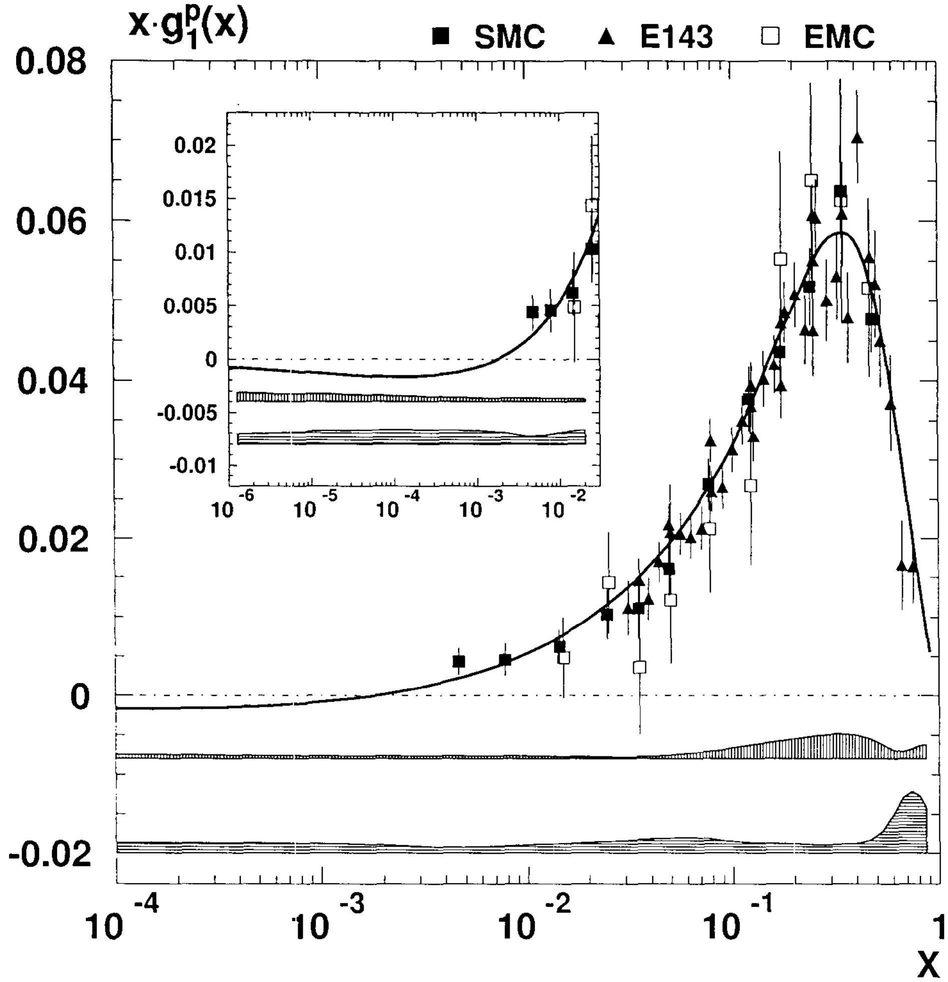
Excellent agreement with theoretical calculation
$\Gamma_1^p - \Gamma_1^n = 0.181 \pm 0.003$ at $Q^2 = 5$ GeV^2

QCD Fit Results: Polarized Parton Distributions



- The singlet and nonsinglet quark distribution functions known reasonably well.
- The polarized gluon distribution function is largely unknown!

The Proton: xg_1^p at $Q^2 = 5$ GeV^2



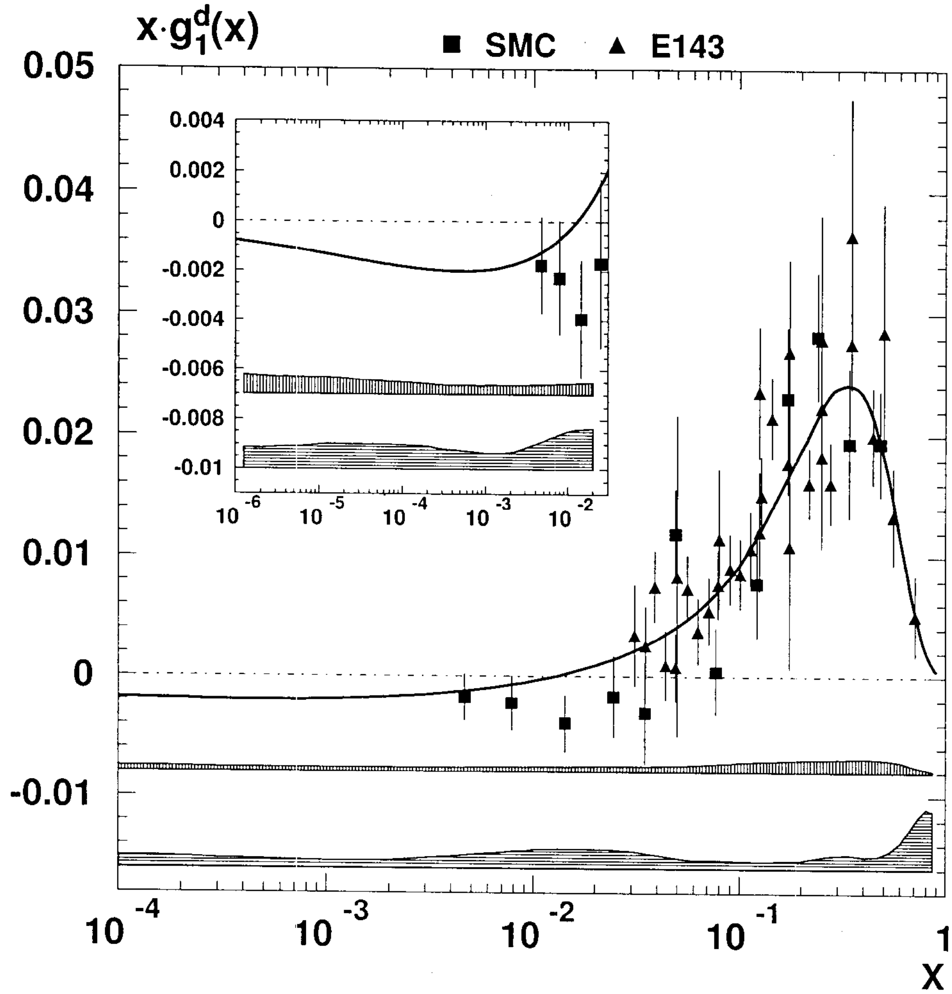
$$\int_0^{0.003} g_1(x)\mathrm{d}x = -0.012^{+0.014}_{-0.025}$$

$$\int_{0.003}^{0.8} g_1(x)\mathrm{d}x = 0.130 \pm 0.003 \pm 0.005 \pm 0.004$$

$$\int_{0.8}^{1} g_1(x)\mathrm{d}x = 0.003^{+0.001}_{-0.001}$$

$$\Gamma_1^p = \int_0^1 g_1(x)\mathrm{d}x = 0.121 \pm 0.003 \pm 0.005 \pm 0.017$$

The Deuteron: xg_1^d at $Q^2 = 5$ GeV^2



$$\int_0^{0.003} g_1(x)\mathrm{d}x = -0.015^{+0.010}_{-0.023}$$

$$\int_{0.003}^{0.8} g_1(x)\mathrm{d}x = 0.036 \pm 0.004 \pm 0.003 \pm 0.002$$

$$\int_{0.8}^{1} g_1(x)\mathrm{d}x = 0.000^{+0.000}_{-0.001}$$

$$\Gamma_1^d = \int_0^1 g_1(x)\mathrm{d}x = 0.021 \pm 0.004 \pm 0.003 \pm 0.016$$

η_g and a_0

- First moment of the polarized gluon distribution at $Q^2 = 1$ GeV^2

$$\eta_g = \int_0^1 \Delta g(x) \mathrm{d}x = 0.99^{+0.99}_{-0.31}(\text{stat})^{+0.42}_{-0.22}(\text{exp.syst})^{+1.43}_{-0.45}(\text{theory})$$

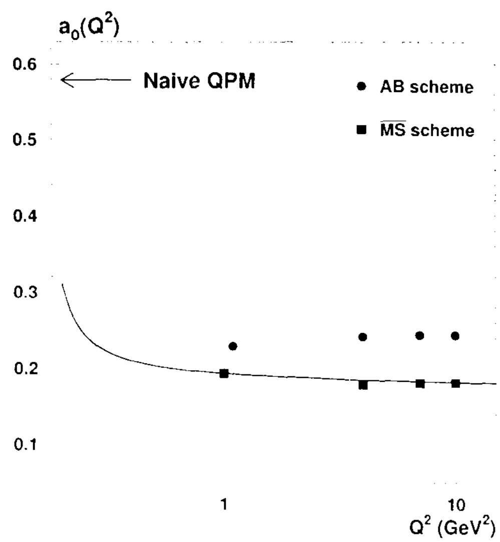
  - η_g is largely unknown
  - Needs measurements over larger kinematic range
    $\Longrightarrow$ Possible future experiments with *Polarized* HERA
  - Measure η_g through photon-gluon fusion (PGF) where gluon enters at leading order
    $\Longrightarrow$ COMPASS at CERN, RHIC-Spin at BNL

- Singlet axial current matrix element a_0

$$a_0(Q^2) = \eta_{\mathrm{S}}^{\overline{\mathrm{MS}}}(Q^2) = \eta_{\mathrm{S}}^{\mathrm{AB}} - n \cdot \frac{\alpha_s(Q^2)}{2\pi} \cdot \eta_g(Q^2)$$

At $Q^2 = 1$ GeV^2:

  - Analysis in $\overline{\mathrm{MS}}$ scheme:
    $\Longrightarrow a_0 = 0.19 \pm 0.05(\text{stat}) \pm 0.04(\text{syst})$
  - Analysis in AB scheme:
    $\Longrightarrow a_0 = 0.23 \pm 0.07(\text{stat}) \pm 0.19(\text{syst})$



Comments on value of a_0
$\Longrightarrow$ QPM expectation too large!
$\Longrightarrow$ Consistent values of a_0 with analysis performed with different Q_i^2

- Summary and Conclusions
  - The Spin Muon Collaboration has presented its final data on g_1
  - SMC has presented a perturbative QCD analysis using its final and all other published data
  - Polarized parton distributions and their uncertainties have been evaluated with special emphasis on the experimental and theoretical uncertainties in the data and theoretical tools available.
  - Singlet quark and non singlet quark distributions functions known reasonably well
  - Bjorken sum rule has been tested and found to be correct within 10% accuracy
  - Ellis-Jaffe sum rule is vioalated with $\sim 3\sigma$ deviation from the predicted values of Γ_1s.
- Open Questions and outlook:
  - Low x behavior of individual structure functions unknown/measur
  - *Large uncertainty in the first moments of* $g_1^{\mathrm{p,d,n}}$
  - Gluon distribution still unknown
    $\Longrightarrow$ Something for the future experiments (COMPASS at CERN, RHIC-Spin at BNL, and Polarized HERA) to measure.

Polarized PDF's at the advent of RHIC

Marco Stratmann

Institute of Theoretical Physics, University of Regensburg, 93040 Regensburg, Germany

Abstract

Some of the theoretical problems which arise in NLO QCD analyses of longitudinally polarized deep-inelastic scattering data are briefly addressed. First of all it is pointed out that DIS data alone can only determine $\Delta q + \Delta\bar{q}$, $q = u, d, s$, whereas the flavor structure of the polarized sea is not accessible. This freedom is reflected by the the fact that a simultaneous transformation $\Delta\bar{u}' = \Delta\bar{u} + f$, $\Delta u' = \Delta u - f$ with an *arbitrary* function f, similarly for $\Delta\bar{d}$, Δd, is still possible without changing g_1, i.e., the χ^2 of the QCD fit. The polarized gluon density Δg, which in principle can be determined from $dg_1/d\ln Q^2$, is only loosely constrained by present fixed target data due to the small lever-arm in Q^2.
It is argued that analyses of A_1 data on the one hand and $g_1(\simeq F_1 A_1)$ data on the other hand *both* suffer from similar problems. Contrary to all unpolarized analyses we cannot afford to impose sufficiently strong enough cuts on Q^2 and W^2 to avoid possible problems with higher twist, etc. contributions. It is well known, however, that in the x, Q^2 region where many of the polarized data reside, perturbative QCD *fails* to describe *un*polarized measurements of F_2 and $R = \sigma_L/\sigma_T$.
An overview of the rather large (and ever growing) number of polarized NLO QCD analyses is presented. It is suggested that a detailed comparison of the different evolution codes - along similar lines as was already done in the unpolarized case - is perhaps a useful task for the future.
Finally, different theoretical models for the SU(2) breaking of the light sea are briefly discussed. First results of a 'toy' analysis of recent semi-inclusive DIS data from HERMES which exploits the above mentioned freedom in the flavor separation seem to indicate that $\Delta\bar{u} - \Delta\bar{d} > 0$, as predicted, e.g., in the chiral quark-soliton model, is preferred.

- <u>What can we learn from DIS data alone?</u>

(see also discussion in Leader et al.)

In NLO QCD we have

$$g_1^{N={}^p_n}(x,Q^2) = \left[\pm\frac{1}{12}\Delta q_3^{\rm NS} + \frac{1}{36}\Delta q_8^{\rm NS} + \frac{1}{9}\Delta\Sigma\right] \otimes \left(1 + \frac{\alpha_s}{2\pi}\Delta C_q\right) + \sum_q e_q^2 \frac{\alpha_s}{2\pi}\Delta g \otimes \Delta C_g$$

$\rightsquigarrow$ from perfect data (+ *assuming* QCD) we would get:

Δq_3	from $g_1^p - g_1^n$
Δq_8, $\Delta\Sigma$, Δg	from $g_1^p + g_1^n$ due to different Q^2-evolution

however, in 'real life' we only get *some* information on

Δq_3, Δq_8, $\Delta\Sigma$ $\leftrightarrow$ $\Delta q + \Delta\bar{q}$ (q=u,d,s)

(no lever-arm in Q^2 to *really* study scaling violations $\leftrightarrow$ Δg)

Note that $\Delta s + \Delta\bar{s} = \frac{1}{3}(\Delta\Sigma - \Delta q_8)$ is fixed by DIS
but we cannot decide if the sea is SU(3) or not!

$\rightsquigarrow$ a transformation with arbitrary functions f and g:

Vogelsang MS

$$\begin{aligned} \Delta\bar{u}' &= \Delta\bar{u} + f \\ \Delta u' &= \Delta u - f \\ \Delta\bar{d}' &= \Delta\bar{d} + g \\ \Delta d' &= \Delta d - g \end{aligned} \quad \rightsquigarrow \quad \Delta\bar{u}' - \Delta\bar{d}' = f - g$$

(assuming $\Delta\bar{u} = \Delta\bar{d}$)

leaves g_1 and -sum invariant!

$\rightsquigarrow$ relevance of semi-incl. and $W^{\pm}$ data

• Should one analyze g_1 or A_1?

In principle it shouldn't matter ...

$$\text{measured: } A_{\|} = \frac{\sigma^{\uparrow\downarrow}-\sigma^{\uparrow\uparrow}}{\sigma^{\uparrow\downarrow}+\sigma^{\uparrow\uparrow}} = D(A_1+\eta A_2)$$

$$\leadsto g_1 = \underbrace{\frac{F_2}{2x(1+R)}}_{=F_1}(A_1+\gamma A_2) \simeq F_1 A_1 \qquad (A_2 \sim g_2 \text{ small})$$

($R = \sigma_L/\sigma_T$ and η, γ only depend on kinematics)

but the measured x, Q^2 range is tricky ...

g_1 analysis:

exp. extraction of g_1 requires knowledge of F_1
(in principle no problem since F_2 and R are measured)

Experience from unpol. fits: CTEQ, GRV, MRST
leading twist description of F_2 fails at low Q^2 and/or high x
$\leadsto$ impose cuts ($Q^2 \gtrsim 4$, $W^2 \gtrsim 10$ GeV^2) to obtain twist-2 PDF's

but we cannot afford *such* 'safe' cuts for g_1 yet
(would loose 'small'-x $\leadsto$ usually only $Q^2 \gtrsim 1$, $W^2 \gtrsim 4$ GeV^2 used)

possible/required improvements for a g_1 analysis:

- include target mass corrections (a la Georgi, Politzer)
  not only a factor $\sim x^2M^2/Q^2 \leadsto$ possible but tedious
  (see, e.g., [illegible] Piccione; [illegible])
- effects a la $g_1 = g_1^{\mathrm{LT}}(1 +$ $)$
- wait for NNLO kernels (*may* eat up some)
- wait for high-energy (collider) data

A_1 analysis:

- higher twists may cancel in ratio
  (*of course*, there is no proof for that ...)
- experimental uncertainties should cancel in ratio
  (not *really* relevant since F_1 comes from *other* exp. anyway)

$\rightsquigarrow$ usually a leading twist ansatz for g_1 is used (∗)

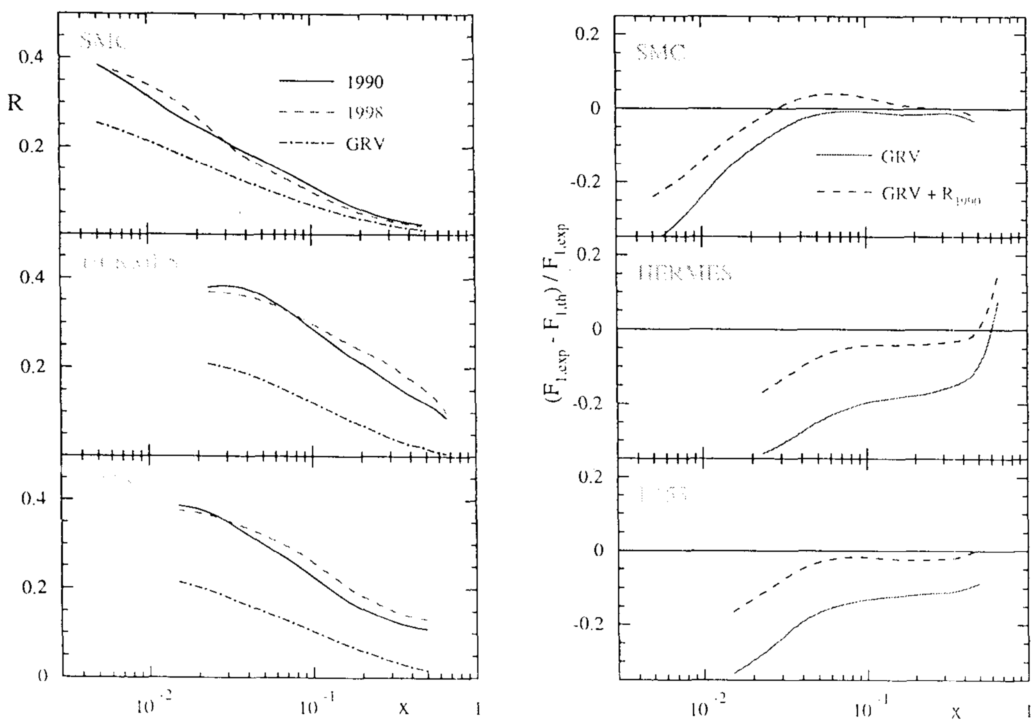
but we need *some* F_1 to extract Δf's – 3 options:

(1) $F_2^{\rm QCD}$ and $R_{\rm QCD}$ (if you *believe* in HT cancellation)

(2) $F_2^{\rm QCD}$ and $R_{\rm exp}$ (since we know that $R_{\rm QCD} \neq R_{\rm exp}$)

(3) $F_2^{\rm exp}$ and $R_{\rm exp}$ (also $F_2^{\rm QCD} \neq F_2^{\rm exp}$ at relevant x, Q^2)

(2)/(3): improved/good F_1 descrip. $\rightsquigarrow$ simul. 'fit' of A_1 and g_1



but: $F_2^{\rm exp}$ and $R_{\rm exp}$ contain $1/Q^2$ ($\leftrightarrow$ HT)

$\rightsquigarrow$ use of inconsistent for as in g_1 analysis!

$\rightsquigarrow$ both methods have *similar* problems

Is there a *fully* consistent procedure ???

- **'Market view': NLO QCD analyses**

unpolarized:

lots and lots of data; 3 groups: CTEQ, GRV, MRST

polarized: sparse data; ever growing number (!) of fits:

GRSV	Glück, Reya, Stratmann, Vogelsang
GS	Gehrmann, Stirling
ABFR	Altarelli, Ball, Forte, Ridolfi
DSS	De Florian, Sampayo, Sassot
SMC	SM Collaboration
E154	E154 Collaboration
E155	E155 Collaboration
LSS	Leader, Sidorov, Stamenov
BBPSS	Bourrely, Buccella, Pisanti, Santorelli, Soffer
GGR	Gordon, Goshtasbpour, Ramsey
TBK	Tatur, Bartelski, Kurzela
GGI	Ghosh, Gupta, Indumathi
AAC	Asymmetry Analysis Collaboration

(highly likely that I still missed some)

Useful/necessary future project:

all groups use *different* methods to solve DGLAP eqs.

⇝ detailed comparison of evolution codes is useful

Unpol.: systematic checks using 'toy inputs' and α_s values

painful, but triggered resolution of small bug in code!

⇝ most codes (except) now agree on 'per mille level'

Anyway, let's have a closer look at all these fits ...

- **NLO QCD analyses: overview & comparison**

	[illegible]	[illegible]	ABFR	DSS	SMC	E154	E155	LSS	BBPSS	GGR	TBK	GGI	AAC
update	8/95	12/95	3/98	11/97	5/98	5/97	prel.	8/98	3/98	3/98	3/99	1/00	1/00
fit to	A_1	g_1	g_1	A_1	g_1	g_1	g_1	A_1	A_1	g_1	A_1	A_1	A_1
R/F_1		-	-	[illegible]	-	-	-	MRST	MRS	-	EXP	CTEQ	SLAC
data	old	old	semi	semi	new	semi	new	new	semi	semi	new	new	new
	✓	✓	×	×	×	×	✓	×	×	×	×	no p	no p
LO	✓	✓	✓	✓	×	×	×	×	×	✓	×	✓	✓
NLO scheme	$\overline{MS}$	$\overline{MS}$	[illegible] $\overline{MS}$	$\overline{MS}$	$\overline{MS}$ AB	$\overline{MS}$ AB	$\overline{MS}$	JET $\overline{MS}$	$\overline{MS}$	$\overline{MS}$ JET	$\overline{MS}$	$\overline{MS}$	$\overline{MS}$
# sets	2	3	4	3	1	1	1	1	7	3	1	1	2
Q_0^2	0.34	4	1	0.5	1	0.34	0.4	1	4	?	1	2.56	1
Λ_4	200	231	fit	200	300	200	246	300	326	?	344	280	246
ansatz	[illegible]	[illegible]	free	free	free	GRV	GRV	MRST	free	SU(6)	free	free	GRV
g_A	✓	✓	fit	fit	fit	fit	fit	✓	✓/fit	✓	fit	✓	✓
$3F-D$	✓/×	✓	✓	fit	✓	fit	fit	✓	✓/fit	?	✓	✓	✓
sea	SU(3) SU(2)	SU(3)	-	SU(2)	-	SU(3)	SU(3)	SU(2)	SU(3) zero	SU(2)	SU(2)	$\bar{u}, \bar{d}$ fit?!	SU(3)
$\lvert\Delta f\rvert \le f$	✓	✓	×	✓	×	(✓)	×	✓	?	✓	✓	×	✓
parametr.	✓	✓	×	✓	×	×	×	×	×	×	×	×	×
comments		LO with GRV	$\mu_{R,F}$ var.	SIDIS in fit	full errors	~like GRSV	pos. badly viol.	jacobi meth.		Q^2 evol. ??		$\bar{u} \neq \bar{d}$ fitted ??	$\Delta\Sigma \leftrightarrow x^{sea}$

• 'Beyond DIS': SU(2) breaking $(\Delta\bar{u} - \Delta\bar{d})$

non-singlet $\rightsquigarrow$ scheme indep. if $\Delta z_{qq} = 0$ ($\overline{\text{MS}}$, AB, JET)

Inclusive DIS (A_1, g_1) fixes only $\Delta q + \Delta\bar{q}$ (q=u,d,s)

$\rightsquigarrow$ relevance of, e.g., semi-inclusive HERMES data !

Theoretical models for $\Delta\bar{u} - \Delta\bar{d}$: (only a selection)

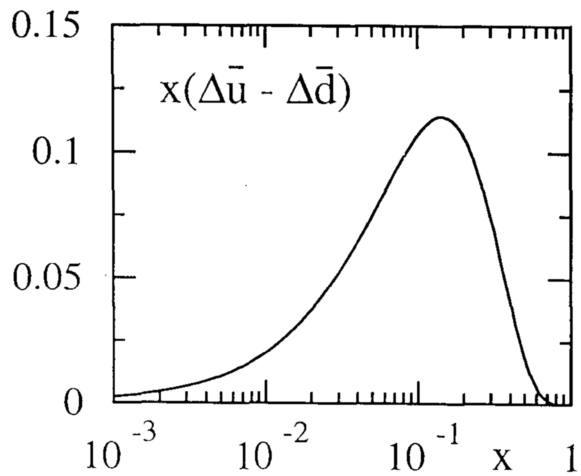
• chiral quark-soliton model Goeke, Polyakov, Weiss et al.

main result:

$\Delta\bar{u} - \Delta\bar{d}$ sizeable

$\Delta\bar{u}$>0 and $\Delta\bar{d}$<0

$\bar{u} - \bar{d}$ agrees with E866



• 'Pauli exclusion principle' Buccella, Soffer; Kumano

$u_v^+ > u_v^- \rightsquigarrow \Delta\bar{u}$<0, $d_v^+ < d_v^- \rightsquigarrow \Delta\bar{d}$>0; sizeable effect

(usually) predicts violation of Bjorken sum rule!

application of 'Pauli principle' not unique (see below)

• meson cloud model Fries, Schäfer

much smaller effect than in chiral soliton model

• phenom. 'guess' (plus 'Pauli blocking')

ansatz at some low scale Q_0:

$$\frac{\Delta\bar{d}(x)}{\Delta\bar{u}(x)} = \frac{\Delta u(x)}{\Delta d(x)} \text{ and ('Pauli') } \Delta q(x)\Delta\bar{q}(x) > 0$$

essentially reproduces results of chiral quark-soliton model!

• Impact of existing HERMES SIDIS data

NO combined NLO anal. of HERMES SIDIS data yet

DSS have analyzed SMC data $\rightsquigarrow$ no impact on fit

Most theoretical models either prefer/predict

$\boxed{\Delta\bar{u}>0 \text{ and } \Delta\bar{d}<0}$ or $\boxed{\Delta\bar{u}<0 \text{ and } \Delta\bar{d}>0}$

and $|\Delta\bar{u} - \Delta\bar{d}|$ rather large

$\rightsquigarrow$ Can HERMES already rule out/disfavor some models/sign combinations ??

[HERMES analysis so far *assumes* same sign: $\frac{\Delta\bar{u}}{\bar{u}} = \frac{\Delta\bar{d}}{\bar{d}} = \frac{\Delta\bar{s}}{\bar{s}}$]

1st 'toy' analysis (using $\Delta\bar{u} - \Delta\bar{d} = f - g$) Vogelsang, MS

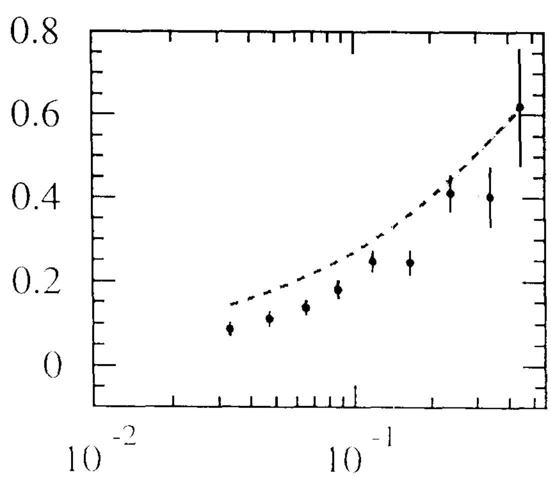
1st step fit to g_1 *assuming* $\Delta\bar{u} = \Delta\bar{d}$

2nd step choose $g = -f \rightsquigarrow \Delta\bar{u} - \Delta\bar{d} = 2f$; $|f| \sim$ soliton model

3rd step calculate SIDIS asymmetries for $f<0$ and $f>0$

solid: $f > 0$
$((\Delta\bar{u} - \Delta\bar{d}) > 0)$

dashed: $f < 0$
$((\Delta\bar{u} - \Delta\bar{d}) < 0)$



$\rightsquigarrow$ $(\Delta\bar{u} - \Delta\bar{d}) > 0$ preferred BUT more work is needed

AAC Polarized Parton Distributions

Shunzo Kumano

Saga University

http://www-hs.phys.saga-u.ac.jp

AAC (Asymmetry Analysis Collaboration)

[a]Y.Goto, [a]N.Hayashi, [b]M.Hirai, [d]H.Horikawa
[b]SK, [b]M.Miyama, [d]T.Morii, [a]N.Saito
[c]T.-S.Shibata, [c]E.Taniguchi, [e]T.Yamanishi

[a]Riken, [b]Saga, [c]TokyoTech, [d]Kobe, [e]FukuiTech

preprint: hep-ph/0001046

March 13, 2000

Riken BNL

Initial parton distributions

$$\Delta f_i (x, Q_0^2) = A_i \, x^{\alpha_i} (1 + \gamma_i x^{\lambda_i}) \, f_i (x, Q_0^2)$$

$(i = u_v, d_v, \bar{q}, g)$ $\quad A_i, \alpha_i, \gamma_i, \lambda_i$: free

positivity $\quad |\Delta f_i (x, Q_0^2)| \leq f_i (x, Q_0^2), \quad |A_1| \leq 1$

flavor-symmetric distributions at initial Q_0^2

$$\Delta \bar{u}(x) = \Delta \bar{d}(x) = \Delta \bar{s}(x)$$

first moments η_{uv}, η_{dv} are fixed

$$F = 0.463 \pm 0.008, \; D = 0.804 \pm 0.008$$

$$\eta_{uv} = 0.986, \; \eta_{dv} = -0.341$$

γ_{uv} and γ_{dv} are determined so as to satisfy these conditions.

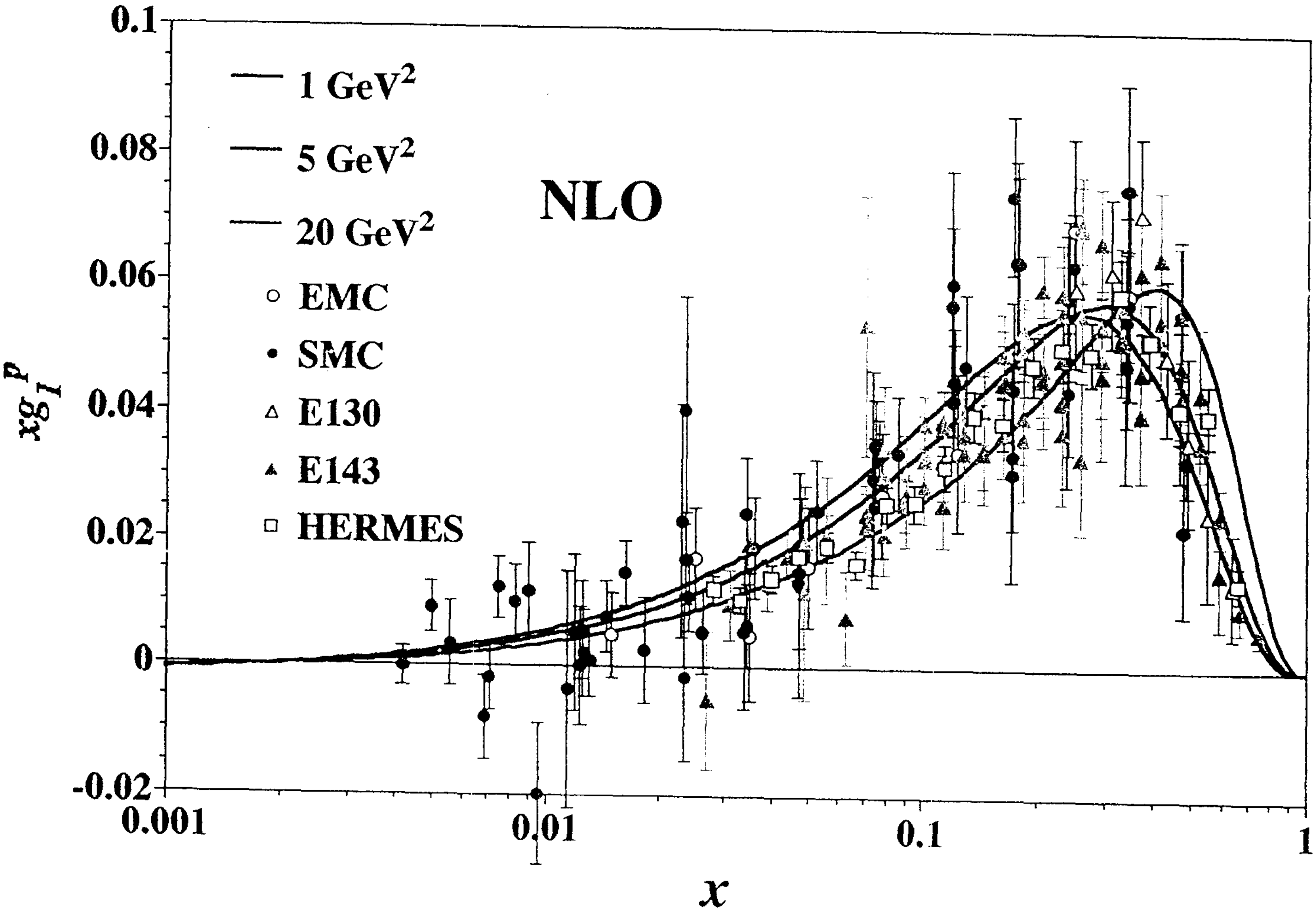
$$\eta_i = \int_{x_{min}}^{1} \Delta f(x, \gamma) \, dx,$$

We determine* 14 *parameters by the χ^2-fitting !

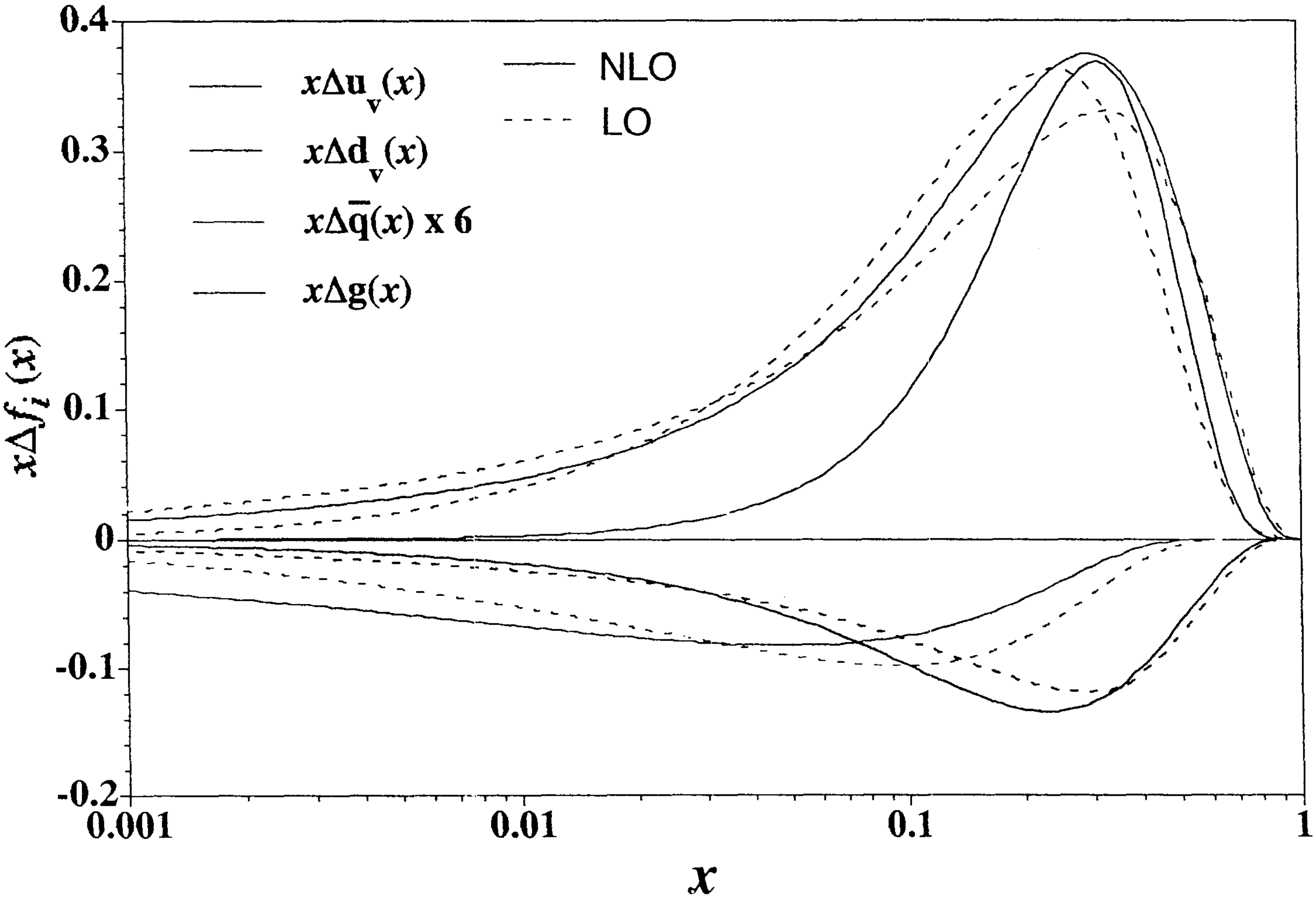
$$A_{uv}, \alpha_{uv}, \lambda_{uv}, A_{dv}, \alpha_{dv}, \lambda_{dv},$$

$$A_{\bar{q}}, \alpha_{\bar{q}}, \gamma_{\bar{q}}, \lambda_{\bar{q}}, A_g, \alpha_g, \gamma_g, \lambda_g$$

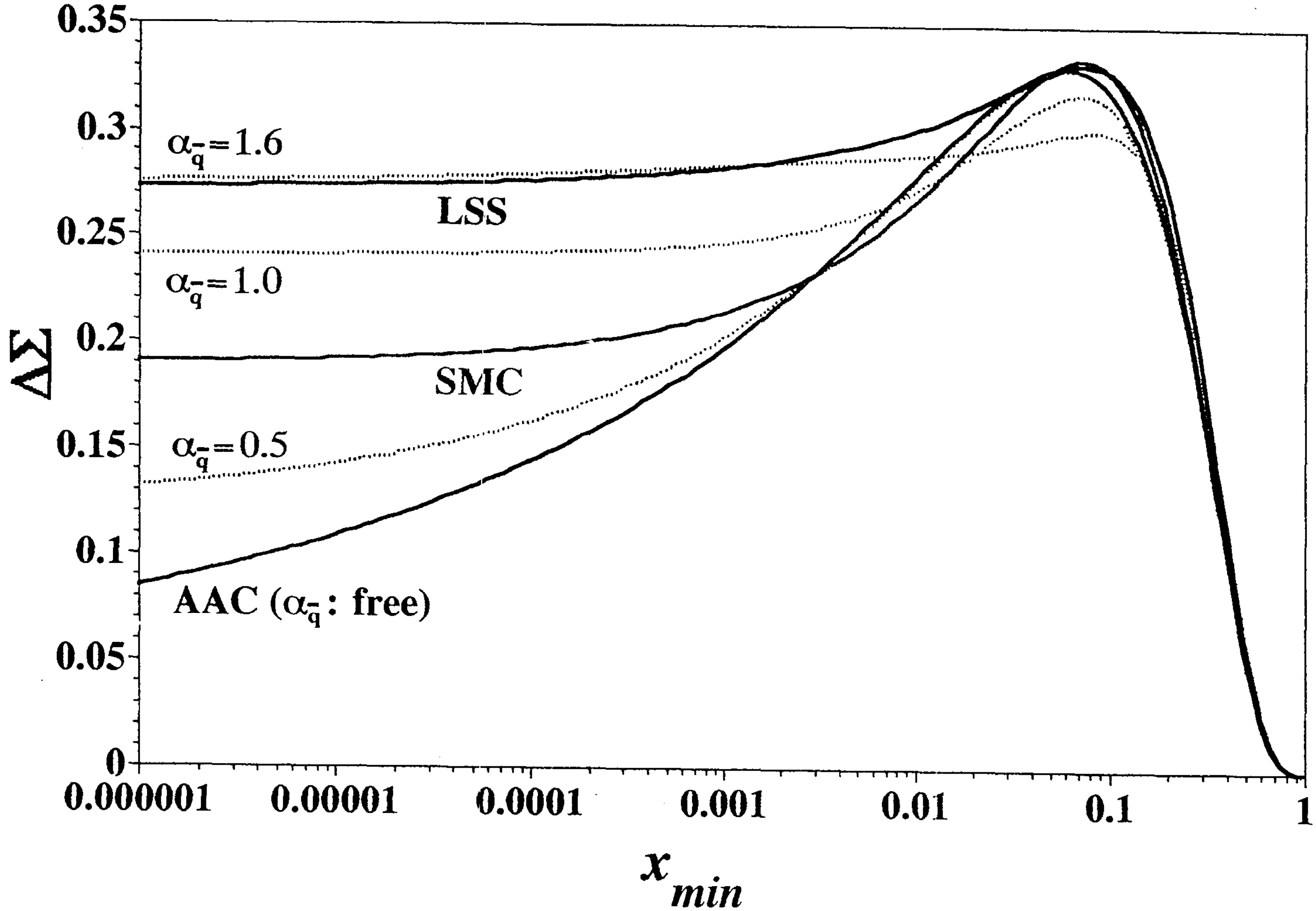
Proton structure function g_1^p



Parton distributions (Q^2=1 GeV^2)



First moment of ΔΣ



$$\Delta\Sigma(x_{\min}) = \int_{x_{\min}}^{1} \Delta\Sigma(x)\, dx$$

- Summary -

- χ^2 analysis of available DIS data
  - NLO χ^2 is significantly smaller than LO χ^2.
    $\rightarrow$ NLO analysis is necessary.
  - $\Delta g(x)$ determination is rather difficult.

- $\Delta\Sigma_{LO}$=20%, $\Delta\Sigma_{NLO}$=5~28%
  - small-x behavior of $\Delta\bar{q}(x)$ is not uniquely determined.

    $\rightarrow$ need small-x measurements

- **propose three AAC distributions:**
  LO, NLO-1 ($\alpha_{\bar{q}}$=free),
  NLO-2 ($\alpha_{\bar{q}}$=1.0 fixed)
  - see hep-ph/0001046 for the details.

Unpolarized Parton Distributions: CTEQ5 and Uncertainties

CTEQ5 Global QCD Analysis of
Unpolarized Parton Distributions

- Brief Summary

Uncertainties of Parton Distributions
and Implications on Physical Predictions
(Example: W-production Cross-section)

- Conventional approach
- Lagrange Multiplier Method
- Error Matrix (Hessian) Method

Conclusions

BNL Polarized Event Generator Workshop
PREDICTIONS AND UNCERTAINTIES
FOR RHIC SPIN PHYSICS

Wu-Ki Tung 2000

Physical processes and experiments *

DIS – Neutral Current (e,μ on p,d)
SLAC, BCDMS, NMC, E665, H1, ZEUS

DIS – Charged Current ($\nu, \bar{\nu}$ on nucleus)
CCFR(F_2, F_3)

Drell-Yan – continuum (lepton-pair)
E605, E866 (d/p ratio)

Drell-Yan – W and Z
CDF (W-lepton-asymmetry)

Direct Photon Production
WA70, UA6, E706, ISR, Ua2, CDF, D0

Inclusive Jet Production
CDF, D0

Lepto-production of Heavy Quark
H1, ZEUS

Hadro-production of Heavy Quark

*Red color indicates "New" for current analysis

Global QCD Fit

* Parametrization of the non-perturbative PDFs: (at $Q_0 = 1$ GeV)

$$f_i(x, Q_0) = a_0^i x^{a_1^i} (1-x)^{a_2^i} (1 + a_3^i x^{a_4^i}).$$

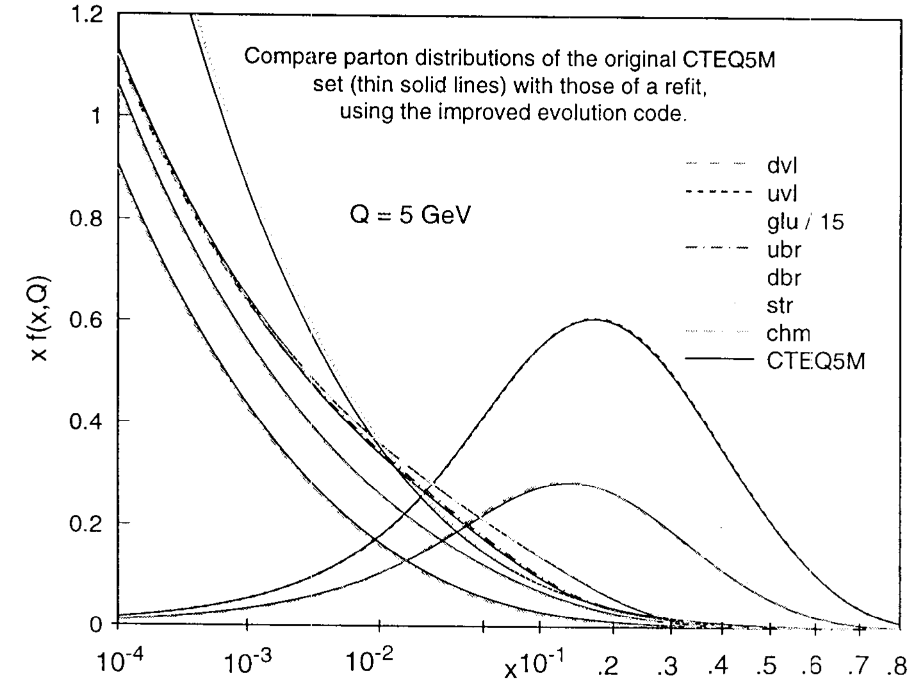
(with exception of $\bar{d}/\bar{u}$)

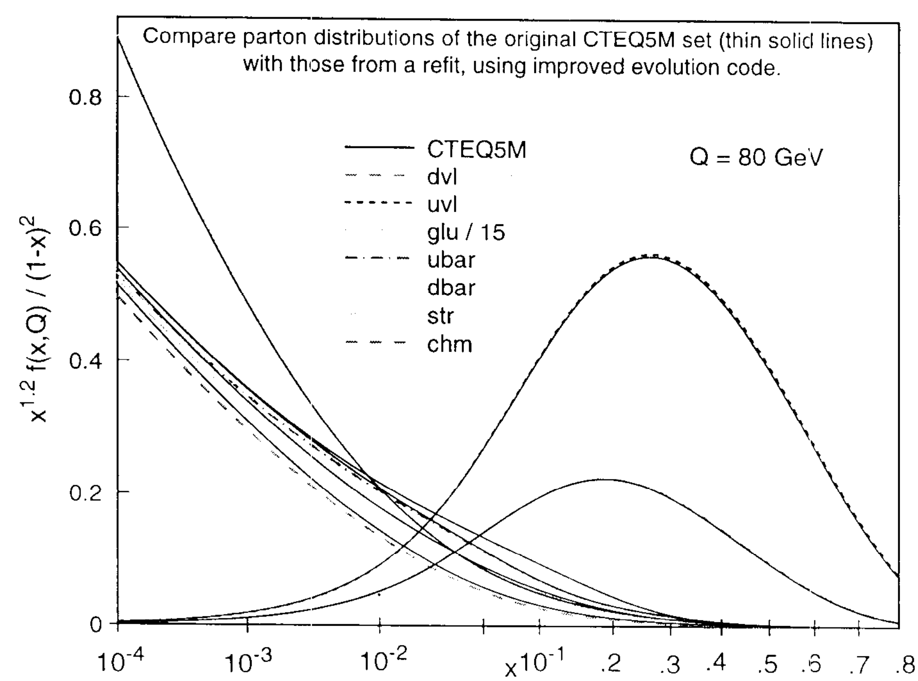
* The fitting is done by minimizing a global "chi-square" function, $\chi^2_{\rm global}$. This function serves as a *figure of merit* of the quality of the global fit; it does not necessarily have the full significance associated with rigorous statistical analysis,

$$\begin{aligned} \chi^2_{\rm global} &= \sum_n \sum_i w_n \left[\left(N_n d_{ni} - t_{ni} \right) / \sigma^d_{ni} \right]^2 \\ &+ \sum_n \left[\left(1 - N_n \right) / \sigma^N_n \right]^2 \end{aligned} \quad (1)$$

d_{ni} : data point
σ^d_{ni}: combined error
t_{ni}: theory value (dependent on $\{a_i\}$)
for the $i^{\rm th}$ data point in the $n^{\rm th}$ experiment.
w_n: a priori weighing factor for certain expts.

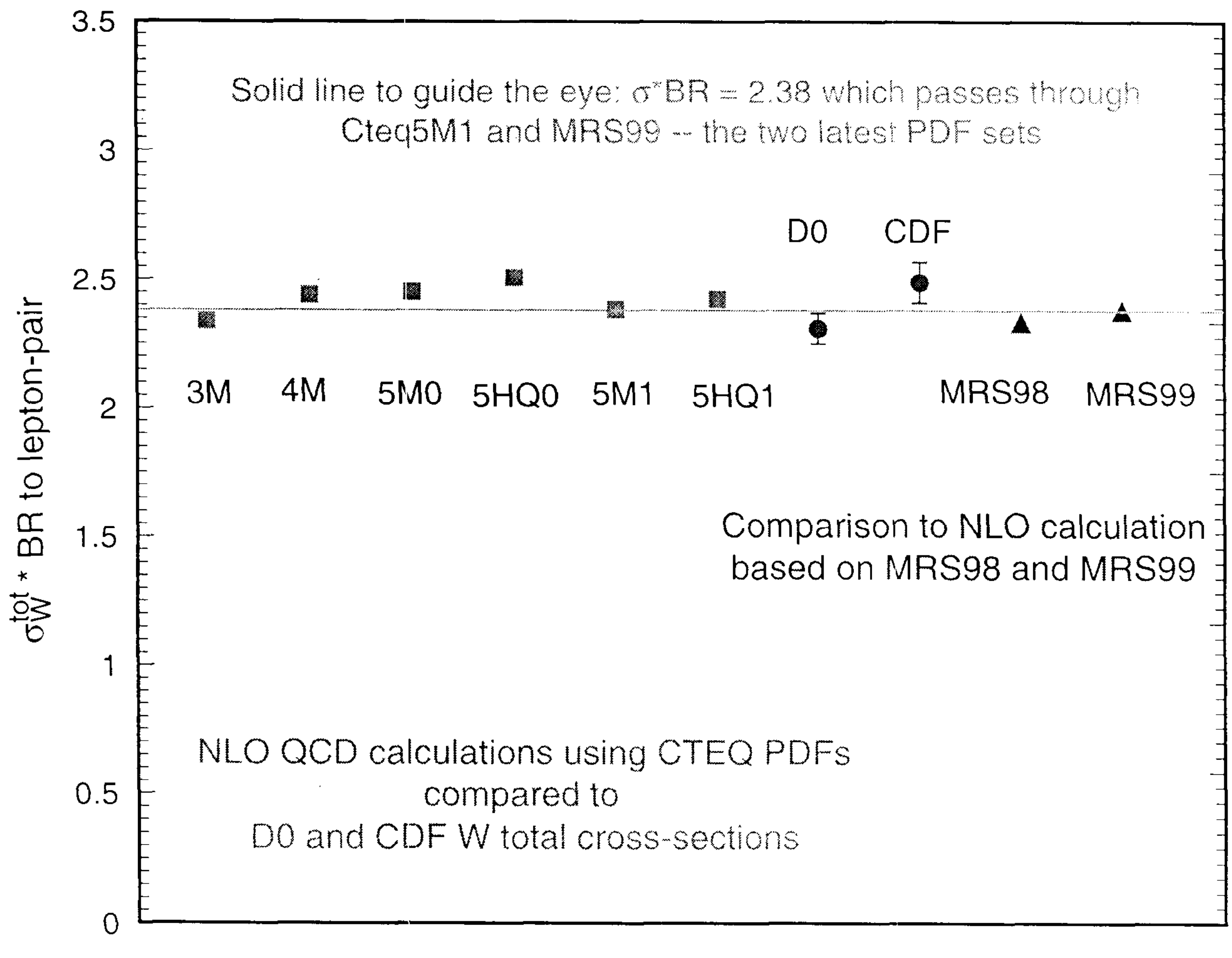
Improvement in QCD Evolution Code



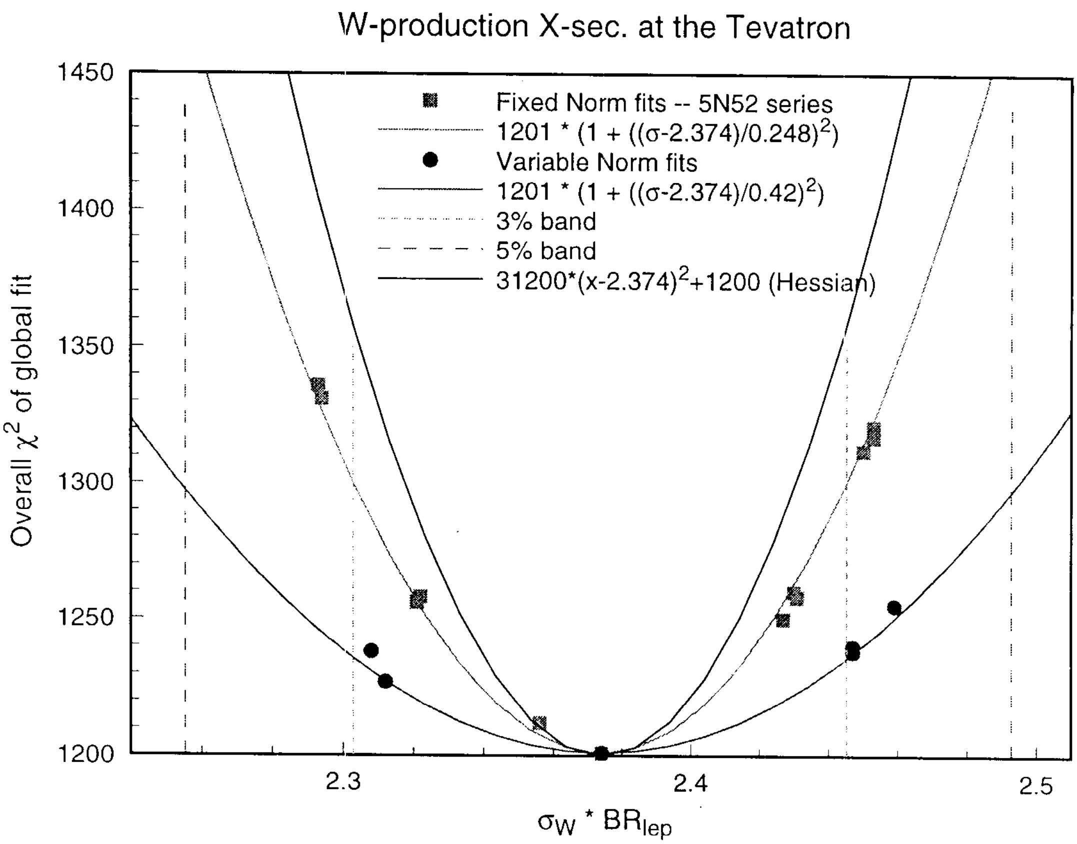


Part II Study of Uncertainties

W-production cross-section with different PDFs



Langrange-multiplier Method of assessing uncertainties



Treatment of Correlated Experimental Errors

Correlated systematic errors a_{jk}
where $k = 1 \ldots n_s$

"True" statistical χ^2:

$$\chi^2 = \sum_j \frac{\left(d_j - t_j\right)^2}{\sigma_j^2} - \sum_{kk'} B_k \left(A^{-1}\right)_{kk'} B_{k'}. \quad (2)$$

The index j labels the data points. The indices k and k' label the source of systematic error and run from 1 to n_s.
B_k is the vector

$$B_k = \sum_j \frac{\left(d_j - t_j\right) a_{jk}}{\sigma_j^2}, \quad (3)$$

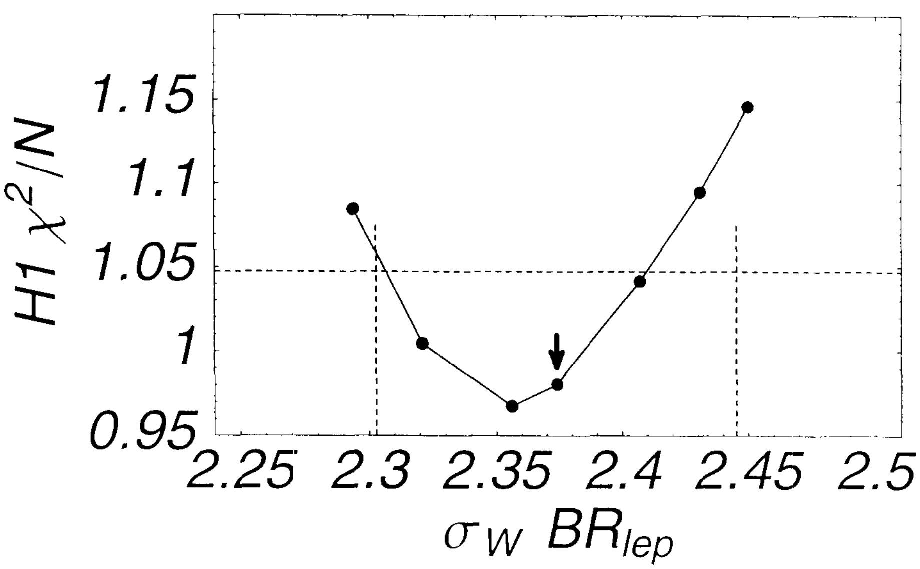
and $A_{kk'}$ is the matrix

$$A_{kk'} = \delta_{kk'} + \sum_j \frac{a_{jk} a_{jk'}}{\sigma_j^2}. \quad (4)$$

Application to the H1 data on F_2

Lagrange multiplier	$\sigma_W \cdot B$ in nb	$\chi^2/172$	probability
3000	2.294	1.0847	0.212
2000	2.321	1.0048	0.468
1000	2.356	0.9676	0.605
0	2.374	0.9805	0.558
-1000	2.407	1.0416	0.339
-2000	2.431	1.0949	0.187
-3000	2.450	1.1463	0.092

χ^2/N of the H1 data, including error correlations, compared to PDFs obtained by the Lagrange multiplier method for constrained values of σ_W



POLARIZED Λ ($\bar{\Lambda}$) FRAGMENTATION FUNCTIONS: PRESENT STATUS AND PROSPECTS AT RHIC

Jacques SOFFER[1]

Centre de Physique Théorique

CNRS Luminy Case 907

13288 Marseille Cedex 09 France

The knowledge of hadron fragmentation functions gives a deeper understanding of the hadron structure and of the *hadronization* mechanism for inclusive production. Here we are concerned about the Λ ($\bar{\Lambda}$) hyperons and we will review the present status of their unpolarized and polarized fragmentation functions.

We first recall the results of a QCD analysis of the data for inclusive ($\Lambda + \bar{\Lambda}$) production in e^+e^- collisions in the energy range $14 \leq \sqrt{s} \leq 91.2\ GeV$, which yields the first simple and reliable parametrization of the unpolarized fragmentation functions $D_f^{\Lambda,\bar{\Lambda}}(z, Q^2)$. The observed longitudinal polarization of the Λ's produced at LEP on the Z-resonance, leads to some inaccurate information on the spin-dependent fragmentation functions $\Delta_L D_f^{\Lambda}(z, Q^2)$. As we will see, several theoretical models have been proposed for these polarized fragmentation functions which are, so far, badly constrained by the existing data. Some predictions can be made for the spin transfer in polarized deep inelastic scattering, but one gets no definite conclusion by comparing them with the present very poor data from HERMES at DESY and E665 at FNAL. We also stress the importance of the Λ ($\bar{\Lambda}$) production in neutrino (antineutrino) deep inelastic scattering, which allows a clean flavor and spin separation. New data will be soon available from NOMAD at CERN.

We will also give the prospects from pp collisions with polarized protons at BNL RHIC, because there are recent interesting suggestions for measuring the helicity (and transversity) transfer asymmetry in the process $p\vec{p} \rightarrow \vec{\Lambda} X$. From its dependence on the rapidity of the Λ, it is possible to discriminate easily between the various theoretical models, thanks to the high luminosity and the small statistical errors.

[1] E-mail: soffer@cpt.univ-mrs.fr

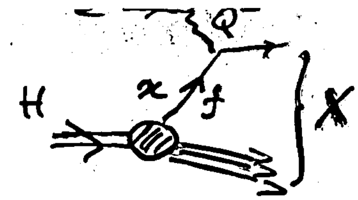
POLARIZED Λ ($\bar{\Lambda}$) FRAGMENTATION FUNCTIONS: PRESENT STATUS AND PROSPECT AT RHIC

(J. SOFFER 14/3/2000)

---

* INTRODUCTION AND DEFINITIONS
* A QCD ANALYSIS (LO AND NLO) FOR D_f^Λ AND ΔD_f^Λ FROM e^+e^- DATA
* POLARIZED (e AND μ) SEMI-INCLUSIVE DIS
  - SEVERAL THEORETICAL MODELS
  - THE PUZZLING E665 DATA
* QUARK FLAVOR SEPARATION IN ν AND $\bar{\nu}$ DIS
* POLARIZED FRAG. FUNCT. IN pp COLLISIONS

A PARTON DISTRIBUTION $f_H(x, Q^2)$

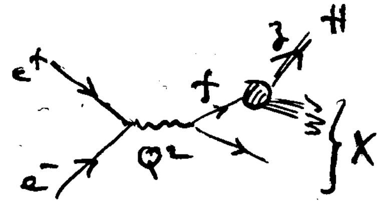


OBTAINED IN DIS FOR $Q^2 < 0$

SPACE-LIKE, HAS A COUNTERPART

FOR $Q^2 > 0$ TIME-LIKE

THE FRAGMENTATION FUNCTION $D_f^H(z, Q^2)$



OBTAINED e.g. IN e^+e^- ANNIHILATION.

PROBABILITY AT MASS SCALE Q TO FIND HADRON H WITH FRACTION z OF PARTON f MOMENTUM

LIKE P.D. FOR THE F.F., QCD PREDICTS THE Q^2 EVOLUTION AND THEY ARE PROCESSES INDEPENDENT i.e. UNIVERSAL

CAN BE MEASURED IN

- $e^+e^- \to (\gamma, Z) \to HX$ (SIA) LEP
- $\ell p \to \ell' HX$ (SIDIS) HERA (HERMES), CERN (COMPASS, NOMAD) FNAL (E665)
- $pp \to HX$ (HC) FNAL, RHIC, HERA-$\vec{N}$

SO FAR BEST KNOWN ARE THOSE OF LIGHT MESONS D_f^π, D_f^K

LET'S SEE WHAT CAN BE SAID ON $D_f^\Lambda(z, Q^2)$

AND SINCE Λ IS A SPIN-1/2 OBJECT

$$\Delta D_f^\Lambda(z, Q^2) \equiv D_{f(+)}^{\Lambda(+)}(z, Q^2) - D_{f(+)}^{\Lambda(-)}(z, Q^2)$$

FOR LONG. POL. Λ AND LONG. POL. PARTON f (D is THE SUM)

AND ALSO FOR TRANS. POL. CASE

$$\Delta_T D_f^\Lambda(z, Q^2)$$

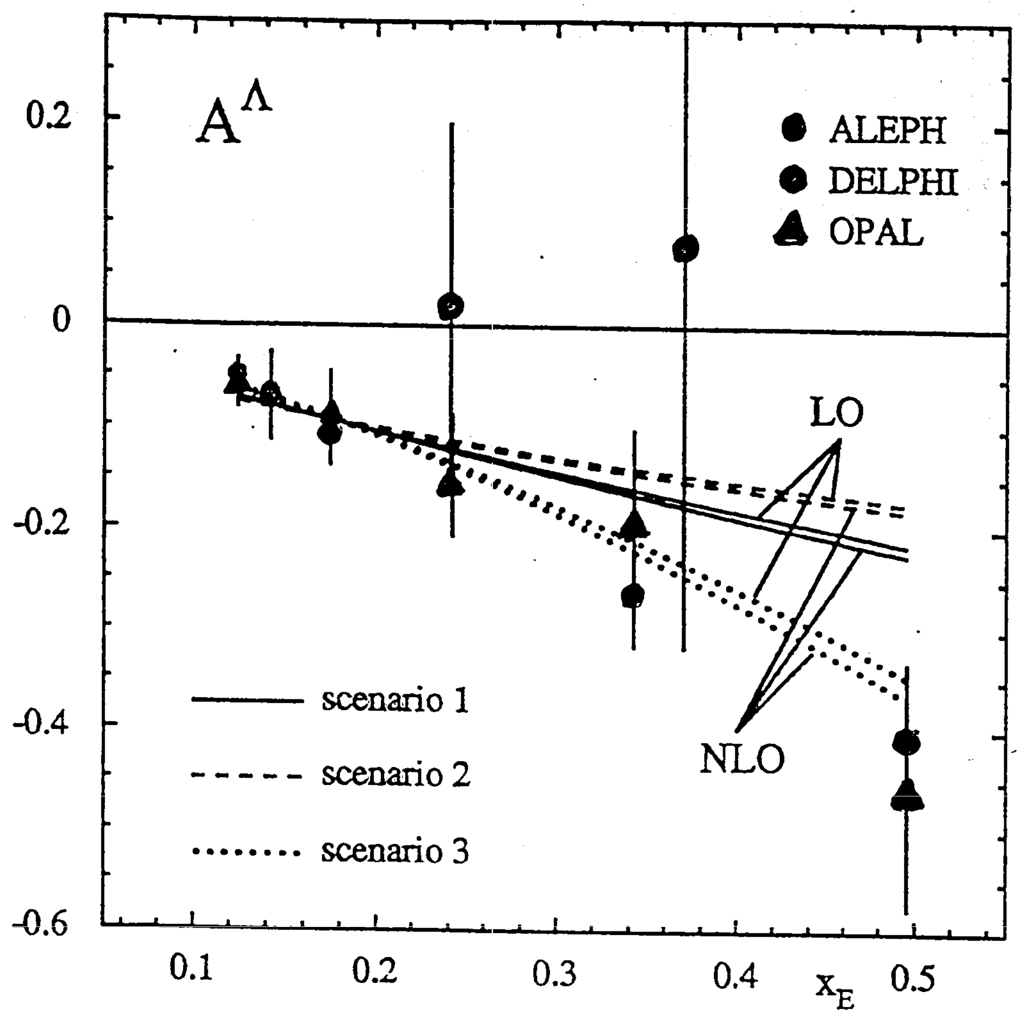


FIG. 4. Comparison of LEP data [10–12] and our LO and NLO results for the asymmetry A^Λ in Eq. (26), using the three different

$x_E = \frac{2p_H \cdot q}{Q^2}$

$= 2E_H / \sqrt{s}$

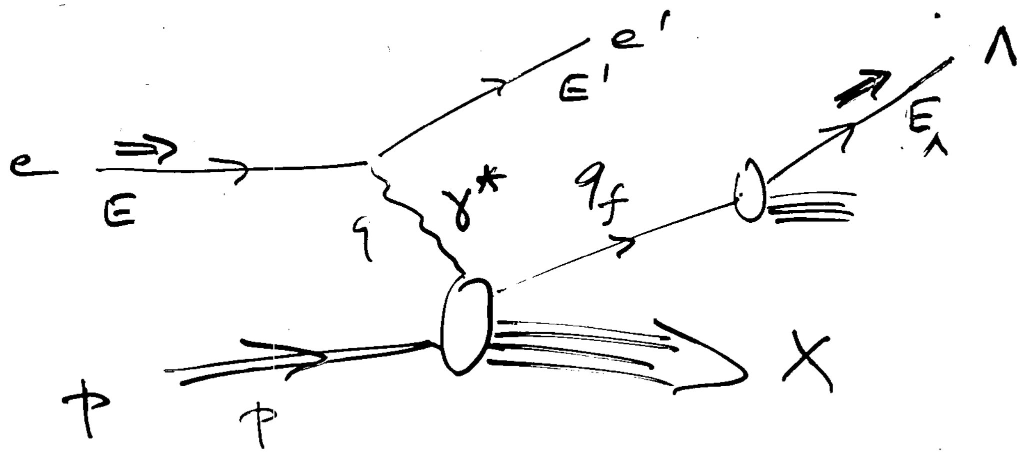
$(q^2 = Q^2 = s)$

– ALEPH AND OPAL PRETTY CONSISTENT AND $A^\Lambda < 0$

– DELPHI $A^\Lambda \sim 0$

POLARIZED (e AND μ) SEMI-INCLUSIVE DIS

$$\vec{e}\, p \to e' \vec{\Lambda} X$$



$Q^2 = -q^2$

$\nu = E - E'$

$x = Q^2/2M\nu \quad , \quad y = \nu/E \quad , \quad z = E_\Lambda/\nu$

Bjorken variable

$$P_\Lambda(x,y,z) = P_B\, D(y)\, D_{LL'}^{\Lambda}(x,z)$$

P_B BEAM POLARIZATION

$$D(y) = \frac{1-(1-y)^2}{1+(1+y)^2} \qquad \gamma^* \text{ DEPOLARIZATION FACTOR}$$

$$D_{LL'}^{\Lambda}(x,z) = \frac{\sum_f e_f^2 \left[q_f^N(x,Q^2)\, \Delta D_{q_f}^{\Lambda}(z,Q^2) + (q \to \bar{q}) \right]}{\sum_f e_f^2 \left[q_f^N(x,Q^2)\, D_{q_f}^{\Lambda}(z,Q^2) + (q \to \bar{q}) \right]}$$

LONG. SPIN TRANSFER

QUARK FLAVOR SEPARATION IN ν AND $\bar{\nu}$ DIS
(BO-QIANG MA , J.S. , PRL 82 (1999) 2250)

ν ($\bar{\nu}$) DIS PROVIDES A SOURCE OF POLARIZED QUARKS WITH SPECIFIC FLAVOR.

From the charged current quark transitions, for neutrino induced reactions

$$\begin{array}{ll} \nu\, d \to \mu^- u; & \nu\, d \to \mu^- c; \\ \nu\, \overline{u} \to \mu^- \overline{d}; & \nu\, \overline{u} \to \mu^- \overline{s}; \\ \nu\, s \to \mu^- c; & \nu\, s \to \mu^- u, \end{array} \tag{2}$$

and for antineutrino induced reactions

$$\begin{array}{ll} \overline{\nu}\, u \to \mu^+ d; & \overline{\nu}\, u \to \mu^+ s; \\ \overline{\nu}\, \overline{d} \to \mu^+ \overline{u}; & \overline{\nu}\, \overline{d} \to \mu^+ \overline{c}; \\ \overline{\nu}\, \overline{s} \to \mu^+ \overline{c}; & \overline{\nu}\, \overline{s} \to \mu^+ \overline{u}, \end{array} \tag{3}$$

the expressions for the Λ and $\overline{\Lambda}$ longitudinal polarizations in the beam direction are, for Λ and $\overline{\Lambda}$ produced in the current fragmentation,

$$P_\nu^\Lambda(x,y,z) = -\frac{d(x)\Delta D_u^\Lambda(z) - (1-y)^2\overline{u}(x)\Delta D_{\overline{d}}^\Lambda(z)}{d(x)D_u^\Lambda(z) + (1-y)^2\overline{u}(x)D_{\overline{d}}^\Lambda(z)} \quad \text{for} \quad \nu N \to \mu^- \overrightarrow{\Lambda} X; \tag{4}$$

$$P_{\overline{\nu}}^\Lambda(x,y,z) = -\frac{(1-y)^2 u(x)\Delta D_d^\Lambda(z) - \overline{d}(x)\Delta D_{\overline{u}}^\Lambda(z)}{(1-y)^2 u(x)D_d^\Lambda(z) + \overline{d}(x)D_{\overline{u}}^\Lambda(z)} \quad \text{for} \quad \overline{\nu} N \to \mu^+ \overrightarrow{\Lambda} X; \tag{5}$$

$$P_\nu^{\overline{\Lambda}}(x,y,z) = -\frac{d(x)\Delta D_u^{\overline{\Lambda}}(z) - (1-y)^2\overline{u}(x)\Delta D_{\overline{d}}^{\overline{\Lambda}}(z)}{d(x)D_u^{\overline{\Lambda}}(z) + (1-y)^2\overline{u}(x)D_{\overline{d}}^{\overline{\Lambda}}(z)} \quad \text{for} \quad \nu N \to \mu^- \overrightarrow{\overline{\Lambda}} X; \tag{6}$$

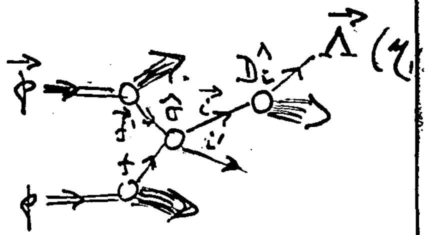
$$P_{\overline{\nu}}^{\overline{\Lambda}}(x,y,z) = -\frac{(1-y)^2 u(x)\Delta D_d^{\overline{\Lambda}}(z) - \overline{d}(x)\Delta D_{\overline{u}}^{\overline{\Lambda}}(z)}{(1-y)^2 u(x)D_d^{\overline{\Lambda}}(z) + \overline{d}(x)D_{\overline{u}}^{\overline{\Lambda}}(z)} \quad \text{for} \quad \overline{\nu} N \to \mu^+ \overrightarrow{\overline{\Lambda}} X. \tag{7}$$

NEGLECT CABIBBO SUPPRESSED PROCESSES
AND SMALL STRANGE QUARK CONTRIBUTION IN P.

POLARIZED F.F. IN pp COLLISIONS

i) HELICITY TRANSFERT IN $\vec{p}p \to \vec{\Lambda}X$

WE CONSIDER THE FOLLOWING SPIN OBSERVABLE



$$D_{LL}^{\Lambda}(\sqrt{s}, \eta, p_T) = \frac{\sigma(++) - \sigma(+-)}{\sigma(++) + \sigma(+-)}$$

($\eta > 0$ ALONG THE DIRECTION OF $\vec{p}$)

$$D_{LL}^{\Lambda} \sim \frac{\sum_f f^{p}(x_1, Q^2)\, \Delta f'^{p}(x_2, Q^2)\, \Delta D_i^{\Lambda}(z, Q^2)\, \Delta\hat{\sigma}(f\vec{f}' \to \vec{i}i')}{\sum_f f^{p}(x_1, Q^2)\, f'^{p}(x_2, Q^2)\, D_i^{\Lambda}(z, Q^2)\, \hat{\sigma}(ff' \to ii')}$$

CAN MAKE PREDICTIONS FOLLOWING THE THREE SCENARIOS

- SIGN AND MAGNITUDE OF D_{LL}^{Λ} FOLLOWS FROM N_u
- LITTLE EFFECTS FROM ΔD_g^{Λ}

ii) TRANSVERSE SPIN ASYMMETRY

CONSIDER D_{NN} SIMILAR TO D_{LL}

NEED TO REPLACE IN NUM $\Delta f'^{p} \to h_1^{f'}$, $\Delta D_i^{\Lambda} \to \Delta_T D_i^{\Lambda}$

AND $\Delta\hat{\sigma} \to \Delta_T\hat{\sigma}$

HOWEVER $\Delta_T D_i^{\Lambda}$ IS <u>NOT</u> KNOWN BUT IN ANALOGY TO THE POSITIVITY BOUND FOR h_1^{f} i.e. $2|h_1^{f}| \leq f + \Delta f$ WE WILL USE $2|\Delta_T D_f^{\Lambda}| \leq D_f^{\Lambda} + \Delta D_f^{\Lambda}$

- WE HAVE CHECKED THAT IT SURVIVES FROM Q^2 EVOLUTION
- WE HAVE OBTAINED BOUNDS FOR D_{NN} FROM THE THREE SCENARIOS

Parity Violating Effects in Jet Production

Jean-Marc Virey[1]

Centre de Physique Théorique, CNRS Luminy Case 907, 13288 Marseille cedex 09, France and Université de Provence, Marseille, France

Within jet production, the Parity Violating (PV) asymmetries $A_L(\equiv d\sigma^- - d\sigma^+/d\sigma^- + d\sigma^+)$ or $A_{LL}^{PV}(\equiv d\sigma^{--} - d\sigma^{++}/d\sigma^{--} + d\sigma^{++})$, that will be measured soon at RHIC, are strongly sensitive to some new interactions belonging to the pure quark sector.

In the first part, after a brief review on the theoretical motivations for the presence of some new quark-quark Contact Interactions (CI) and of a light leptophobic Z' boson, we have presented the sensitivity to these models at RHIC, using conventional experimental parameters for polarized proton-proton collisions. It appears that the RHIC, on one hand, is able to cover some regions in the parameter space of the different models which are unconstrained by present experiments, and also by the expectations of forthcoming's (*e.g.* Tevatron Run II). On the other hand, the RHIC is a unique facility to obtain crucial informations on the chiral structure of the new interaction. It is important to note that the integrated luminosity is a key parameter for this polarized analysis.
If some new physics effects are detected in $p-p$ collisions, it could be very interesting to run in the $n-n$ mode (through polarized He^3) to constrain the scalar sector of the theory, i.e. the presence or absence of trilinear quark mass terms and the number of Higgs doublets.

The second part was devoted to an emphasis of the need of NLO calculations for the SM expectations. At LO the main SM effects come from the interferences between gluons and W, Z exchanges for quark-quark scattering. At NLO we have to consider, on the one hand, the QCD corrections to these QCD.EW interferences, and on the other hand, the EW corrections to the pure QCD amplitudes. Such corrections are rather unconventional and it seems difficult to use existing NLO calculations to get an idea of the behavior of these NLO corrections for the PV asymmetries. For instance, at LO only 2 terms are present but at NLO more than 50 terms are now involved. For example, at order $\alpha.\alpha_s^2$, quark-gluon scattering contribute also to the numerator of the PV asymmetries.
The net conclusion is that we cannot trust the LO SM expectations, which is truly problematic in the view of pinning down any new physics effects.

Given the powerful possibility of the RHIC Spin experiment to discover a new interaction in the quark sector, we strongly recommand NLO experts to carry out these difficult calculations.

[1]email: virey@cpt.univ-mrs.fr

→ Numerator : General considerations

pure QCD contributions $= 0$ to all orders

Dominant contributions at LO

1) Virtual Z, W effects (⇒ on the whole E_T spectrum)

$qq \to qq$ $Z \cdot g$ $\alpha_s \cdot \alpha$ ~70%

$qq' \to qq'$ $W \cdot g$ $\alpha_s \cdot \alpha$ ~30%

(dominant with $\vec{p}\vec{p}$: $uu \to uu$, $ud \to ud$)
$\gtrsim$ 50% / 60%, 30%

2) Real Z, W effects (⇒ Jacobian pic $E_T \sim 45$ GeV)

$q\bar{q} \to Z \to q\bar{q}, q'\bar{q}'$ $Z \cdot Z$ α^2 ~20% (5)

$q\bar{q}' \to W \to q\bar{q}', q''\bar{q}'''$ $W \cdot W$ α^2 ~80% (95)

(W is PV maximal and no partonic suppression for annihilated

Seems difficult to observe in STAR } → G. Eppley, triggers ⇒ $E_T \geq 45$ GeV

PHENIX needs π^0 simulations .... ?

We don't consider real production in the following

3°) Compositeness (→ Contact Interactions)

(P. Taxil & JMV PLB 364 (95) 185
PRD 55 (97) 441)

→ CI effective Lagrangian:

$$\mathcal{L}_{q\text{-}q} = \varepsilon \frac{g^2}{8\Lambda^2} \bar{\Psi} \gamma_\mu (1-\eta\gamma_5) \Psi \cdot \bar{\Psi} \gamma^\mu (1-\eta\gamma_5) \Psi$$

$\Lambda \equiv$ compositeness scale | $A^{PV} \sim \frac{\varepsilon \cdot \eta}{\Lambda^2}$ (g. CI dominant!)

→ Present situation:

CDF : excess of events in σ^{unpol}_{jet} ⟶ $\Lambda \sim 1.6$ TeV ($\lesssim 1.8$ TeV)

DØ : no excess ⟶ $\Lambda_{lim} = 2.0$ TeV ↳ 2.4 TeV

→ RHIC sensitivity from A^{PV}_{LL} (p-p coll.)

max. PV !)

	$L_1 = 800\ pb^{-1}$	$L_2 = 3.2\ fb^{-1}$
Λ (TeV)	3.3	4.4
	3.6	5.1

A_{LL} 7 TeV

$\sqrt{s} = 500$ GeV
P = 70%
GRSV pdf's
(3.6, 5.1) → $\sqrt{s} = 600$ GeV

→ TEVATRON sensitivity from $\sigma^{unpol}_{1\text{-}jet}$

	$L = 1\ fb^{-1}$	$L = 10\ fb^{-1}$	$L = 100\ fb^{-1}$
Λ (TeV)	3.2	3.7	4.1

$\sqrt{s} = 2$ TeV

→ Conclusions: (directly connected to jet studies ⇐)

- RHIC competitive with TEVATRON
- Luminosity is a key factor for A^{PV}
- A^{PV} gives informations on the chiral structure

SU(5) × U(1)

limited by stat. →

"η - k"

limited by syst. →

⇓

No hope for Tevatron to go below !!

Except if they strongly reduced their syst. in run II or III but not their [illegible])

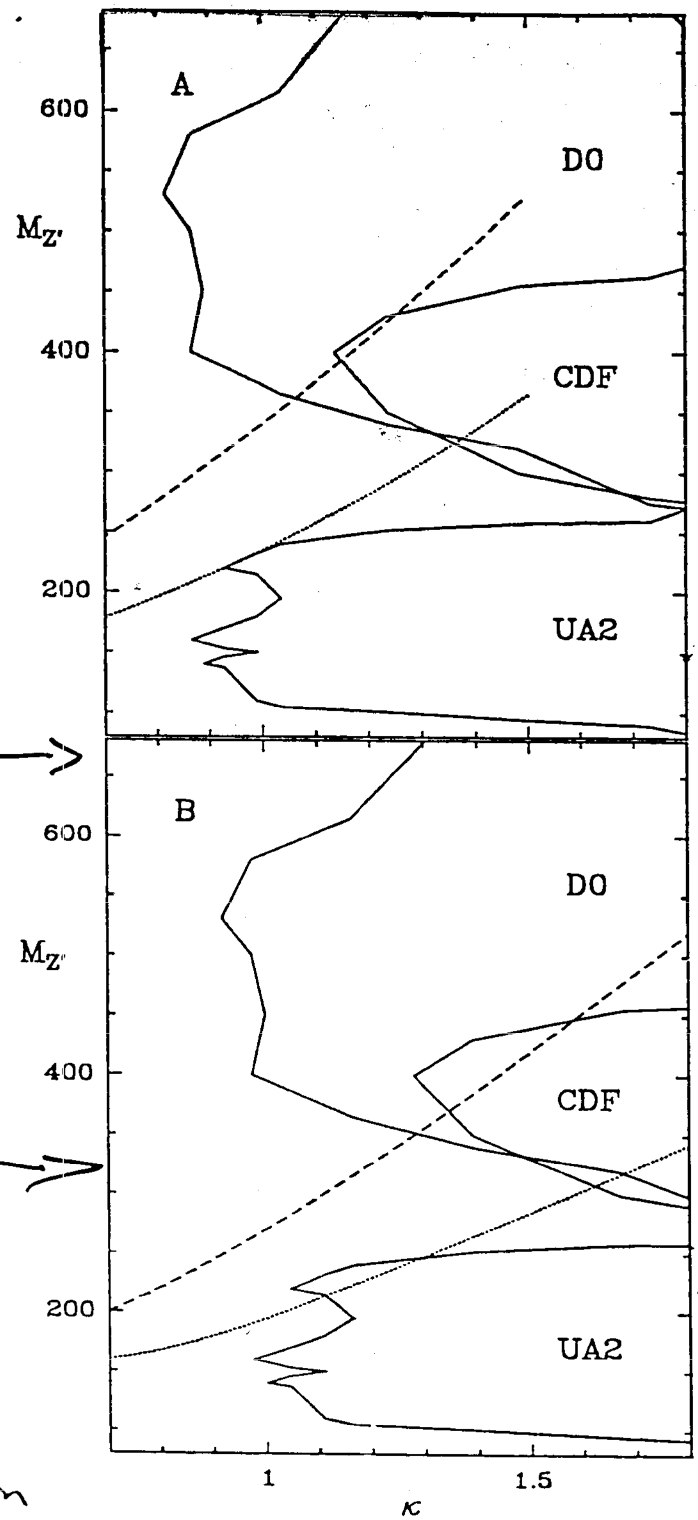


Fig 1

• Remarks on a "degenerate mirror Z" Z' model :

F. Caravaglios and G.G. Ross (PLB 346 (95) 159)

have shown that a degenerate Z' ($M_{Z'} = M_Z \pm 2\Gamma_Z$)

with "mirror" couplings $\left(\frac{C_L^q}{C_R^q} = \frac{C_R'^q}{C_L'^q} \Rightarrow \begin{cases} C_R^{u'} \simeq -2\, C_L^{u'} \\ C_R^{d'} \simeq -5\, C_L^{d'} \end{cases} \right)$

could reconcile LEP and SLAC measurements

on $\boxed{\sin^2\theta_W}$ (which still differ by 2σ)

but the Z' needs to have very small couplings to leptons

(not zero, $\sim 10^{-4}$) : leptophobic !

Idea : SLAC exp. uses polarized collisions

$\Rightarrow$ unexpected polarized effect hard to see in unpolarized exp

Remark: RHIC is a polarized exp., and A_{LL}^{PV} for jet production is sensitive to a Z' through Z'·g interferences i.e. virtual Z' $\Rightarrow$ effects on the broad E_T spectrum ! (↳ like LENC as APV in Cs)

, This Z' could also reconcile other small discrepancies of the S

- R_b at LEP (2.0 σ)
- σ_{jj}^{unpol} on W/Z poles from UA2 (1.5 σ)
- $Q_W(C_s)$ from APV (1.8 σ)

2) pp + nn analysis

deviations from SM ⟶ dominant chirality of qqZ' vertex (i.e. sign of $(C_L^{q2} - C_R^{q2})$)

gauge invariance + leptophobia + symm. breaking pattern

⟹ constraints on $\mathcal{L}_Y$:

First assume all SM fermions have masses from tri-linear mass terms:

$$\mathcal{L}_Y = h_u \bar{Q} H_u u^c + h_d \bar{Q} H_d d^c + h_\ell \bar{L} H_\ell e^c$$

$h_{u,d,\ell}$ ≡ yukawa matrices $H_{u,d,\ell}$ ≡ higgs doublets

- Gauge Invariance under $U(1)'$ ⟹

$$Q'(H_f) + Q'(F) + Q'(f^c) = 0 \Rightarrow \boxed{Q'(H_f) = C_R^{\prime f} - C_L^{\prime f}}$$

fundamental relation ⟷ tri-linear mass terms

Re: mass from non-renormalizable terms ⟹ NO relation among Q''s

Re2: $Q'(H_f) \neq 0$ → $C_L \neq C_R$ → PV exceptional case.

- Leptophobia

↳ $C_L^{\prime e} = 0 = C_R^{\prime e}$ ⟹ $\boxed{Q'(H_\ell) = 0}$

Contact Interaction Studies with Event Generator

Jiro Murata (RIKEN)

A lot of non-standard model scenarios can be examined using PYTHIA. Contact interaction, phenomenologically introduced as a "residual interaction" which have its source in interactions between quark- and lepton-subconstituents, is also included in it. However, as same as for all other sub-processes, PYTHIA includes only helicity averaged cross sections for the contact interaction.

P. Taxil and J.-M. Virey studied the sensitivity of the contact interaction at RHIC and at pol-HERA in some spin asymmetries. The purpose of the present study is, based on their studies, to include the helicity-dependent matrix-elements into PYTHIA and to make an event generator-based study for RHIC-Spin program.

Using helicity-dependent matrix-elements for the polarized e-p collision, corresponding formula for Drell-Yan process can be obtained by crossing. Then we can get partonic-level asymmetries. Final hadronic spin asymmetries were estimated using weighted method. The weight factor consists of partonic-level asymmetries, polarized- and unpolarized-pardon distribution-functions. The event generation was controlled by the unpolarized sub-processes, which were already included in PYTHIA as ISUB=1 for a standard model γ^*/Z production and ISUB=165 for a fermion pair creation via γ^*/Z production by the contact interaction.

The following results were obtained. Parity violating double spin asymmetry, $\bar{A}_{LL}^{PV} = \{\sigma(-+) - \sigma(+-)\}/\{\sigma(-+) + \sigma(+-)\}$, has the largest sensitivity on the contact interaction. However, the resultant beyond standard model asymmetry is rather small ($\sim 1\%$) if the compositeness scale Λ is lager than 3 TeV. Considering the experimental errors, quantitative sensitivity study at dilepton mass of around $M = 10 \sim 20$ GeV and around Z boson is necessary. The other parity violating double spin asymmetry, $A_{LL}^{PV} = \{\sigma(--) - \sigma(++)\}/\{\sigma(--) + \sigma(++)\}$, has very small difference from standard model even at $\Lambda = 1$ TeV. The usual double spin asymmetry A_{LL} has no sensitivity on the contact interaction. It is because all the matrix-elements are zero for the same helicity combination.

As for one jet production, it is considered to have larger sensitivity on contact interaction than Drell-Yan process. Therefore, the next step must be to include the corresponding quark scattering formula into PYTHIA. The procedure has been established. Then, for example, sensitivity on π^0 production can be examined soon.

All the newly obtained formula especially for Drell-Yan process can be found on my web page (http://spin.riken.bnl.gov/~jiro).

Matrix Elements to Asymmetries

Same Helicity Matrix Elements Vanished $|M_{\alpha\beta}^{\lambda\lambda}|^2 = 0$

$$\alpha, \beta = \gamma\gamma, ZZ, \gamma Z, CICI, \gamma CI, ZCI$$

Total Partonic Cross Section $\hat{\sigma}^{\lambda_1\lambda_2} = (\lambda_1\lambda_2) = \sum_{\alpha\beta} |M_{\alpha\beta}^{\lambda_1\lambda_2}|^2$

Total Hadronic Cross Section $\sigma^{\lambda_1\lambda_2} = \sum_{\lambda_1\lambda_2} \hat{\sigma}^{\lambda_1\lambda_2} \otimes q_1^{\lambda_1}\bar{q}_2^{\lambda_2} + \sum_{\lambda_1\lambda_2} \hat{\sigma}^{\lambda_1\lambda_2} \otimes \bar{q}_1^{\lambda_1} q_2^{\lambda_2}$

Proton Spin Asymmetries (to be sum over quark flavors)

$$A_{LL} = \frac{\sigma^{--} + \sigma^{++} - \sigma^{-+} - \sigma^{+-}}{\sigma^{--} + \sigma^{++} + \sigma^{-+} + \sigma^{+-}} = -\frac{\Delta q_1 \Delta\bar{q}_2 + \Delta\bar{q}_1 \Delta q_2}{q_1\bar{q}_2 + \bar{q}_1 q_2}$$

$$A_L = \frac{\sigma^- - \sigma^+}{\sigma^- + \sigma^+} = \frac{\Delta q_1\bar{q}_2 - \Delta\bar{q}_1 q_2}{q_1\bar{q}_2 - \bar{q}_1 q_2}\hat{a}_{LL}^{PV}$$

$$\overline{A}_{LL}^{PV} = \frac{\sigma^{-+} - \sigma^{+-}}{\sigma^{-+} + \sigma^{+-}} = \frac{(q_1^+\bar{q}_2^+ - q_1^-\bar{q}_2^-)(\hat{\sigma}^{-+} - \hat{\sigma}^{+-})}{2\bar{q}_1^- q_2^- \hat{\sigma}^{-+} + 2\bar{q}_1^+ q_2^+ \hat{\sigma}^{+-} + (q_1^+\bar{q}_2^+ + q_1^-\bar{q}_2^-)(\hat{\sigma}^{-+} + \hat{\sigma}^{+-})}$$

$$A_{LL}^{PV} = \frac{\sigma^{--} - \sigma^{++}}{\sigma^{--} + \sigma^{++}} = \frac{(q_1^+\bar{q}_2^- - q_1^-\bar{q}_2^+)(\hat{\sigma}^{-+} - \hat{\sigma}^{+-})}{2\bar{q}_1^+ q_2^- \hat{\sigma}^{-+} + 2\bar{q}_1^- q_2^+ \hat{\sigma}^{+-} + (q_1^+\bar{q}_2^- + q_1^-\bar{q}_2^+)(\hat{\sigma}^{-+} + \hat{\sigma}^{+-})}$$

Including into PYTHIA

Cross Section $\propto$ Generated Event Number
Cross Section Asymmetry -> "Asymmetry" Weight for all events

Weight factor = (PDF & pol-PDF)* partonic asymmetry $(q_1\bar{q}_2+\bar{q}_1 q_2) \Rightarrow q_1 q_2$

$$W(\overline{A}_{LL}^{PV}) = \frac{q_1^+ q_2^+ - q_1^- q_2^-}{q_1^+ q_2^+ + q_1^- q_2^-} \cdot \frac{\hat{\sigma}^{-+} - \hat{\sigma}^{+-}}{\hat{\sigma}^{-+} + \hat{\sigma}^{+-}} = \frac{q_1^+ q_2^+ - q_1^- q_2^-}{q_1^+ q_2^+ + q_1^- q_2^-} \cdot \hat{\bar{a}}_{LL}^{PV}$$

$$W(A_{LL}^{PV}) = \frac{q_1^+ q_2^- - q_1^- q_2^+}{q_1^+ q_2^- + q_1^- q_2^+} \cdot \hat{\bar{a}}_{LL}^{PV} \qquad W(A_{LL}) = \frac{\Delta q_1 \Delta q_2}{q_1 q_2} \cdot (-1) \qquad W(A_L) = \frac{\Delta q_1}{q_1} \cdot \hat{\bar{a}}_{LL}^{PV}$$

SM (ISUB=1) $f_i \bar{f}_i \to \gamma^* / Z^0$

CI (ISUB=165) $f_i \bar{f}_i \to f_k \bar{f}_k (\gamma^* / Z^0)$

Asymmetry $$A = \frac{\sum_{i=SM} W_{SM}^i + \sum_{i=CI} W_{CI}^i}{\sum_{i=SM+CI} 1}$$

SM & CI (ISUB=1 & 165)

For CI (if pure L,R)
$\hat{\bar{a}}_{LL}^{PV} = \mp 1$ L,R

No sensitivity on chirality of lepton coupling

Event Generation Results

$\sqrt{s} = 500$ GeV $\quad \Lambda = 1$TeV

$\varepsilon = 1$ Constructive Interference

$\eta = 1, \eta' = 1$ Left-Left Chirality

CKIN(3)=P_T(min)=10GeV

MSTP(5)=4 all q's are composite

KFPR(165)=13 CI goes muon channel

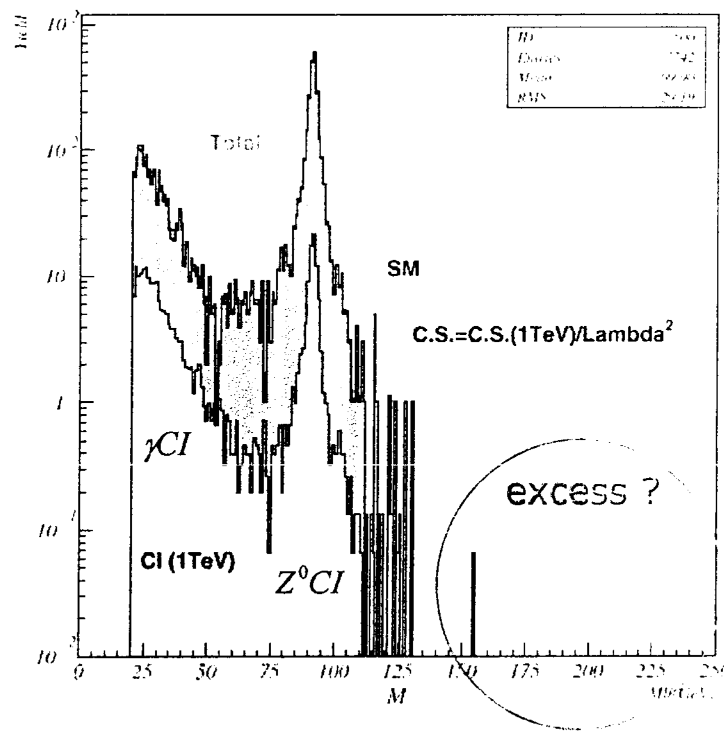
$\sigma_{CI} \propto 1/\Lambda^2$ Interference term (Dominant)

$(\sigma_{CI} \propto 1/\Lambda^4)$ Pure CI term

$$M \le Mz \Rightarrow \frac{\frac{d\sigma_{CI}}{dM}|_M}{\frac{d\sigma_{SM}}{dM}|_M} \cong \frac{\sigma_{CI}}{\sigma_{SM}}$$

7% (1TeV)
3% (2TeV)
0.7% (3TeV)
0.4% (4TeV)
0.3% (5TeV)

Mass Spectra for SM & CI



quark coupling chirality
ISUB(165) E.G. = Left-handed only !

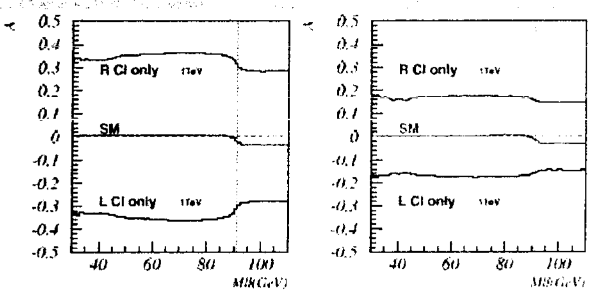
Expected Asymmetries

PRELIMINARY

$$A_{Total}|_M = A_{SM}|_M + \frac{\frac{d\sigma_{CI}}{dM}|_M}{\frac{d\sigma_{SM}}{dM}|_M} A_{CI}|_M$$

$$\rightarrow A_{SM}|_M + \frac{\sigma_{CI}}{\sigma_{SM}} A_{CI}|_M$$

(M-dep, preliminary)

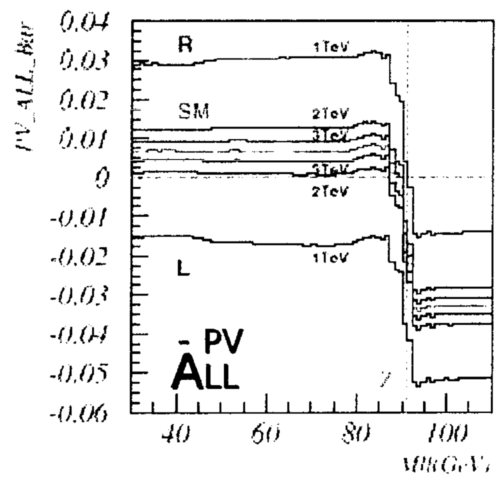


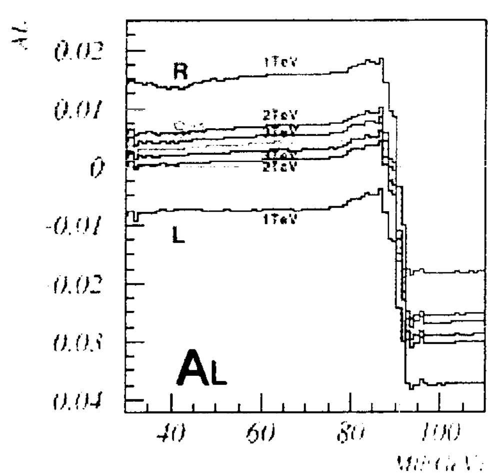
Pure CI

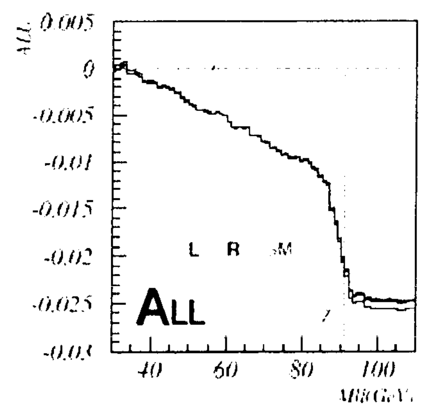
PDF Information

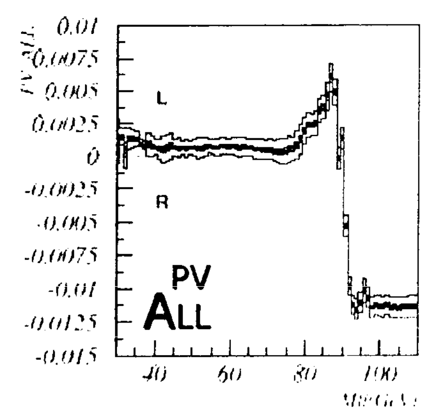
$$A_{LL} = -\frac{\Delta q_1 \Delta\bar{q}_2 + \Delta\bar{q}_1 \Delta q_2}{q_1\bar{q}_2 + \bar{q}_1 q_2}$$

GS95NLO-A









Perspective

HERA, CDF DY -> LARGE Λ (Atomic PV; $\Lambda > 10$TeV)

Prospects gloomy ?

Within Standard Model

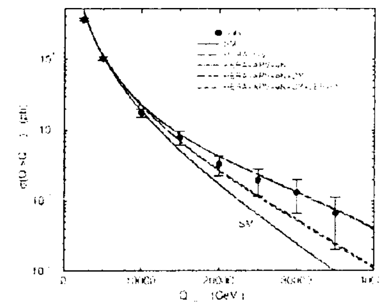
PYTHIA study for polarized DY become possible

PYTHIA study for polarized W may become possible

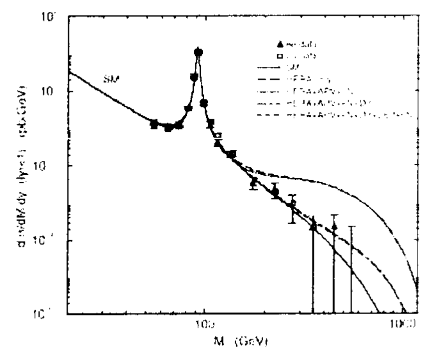
➡ **quark, anti-quark distribution**

Anyway,
Beyond SM Interactions (Z',R-parity Violation, etc.)
can be included into PYTHIA

HERA (H1 & ZEUS)



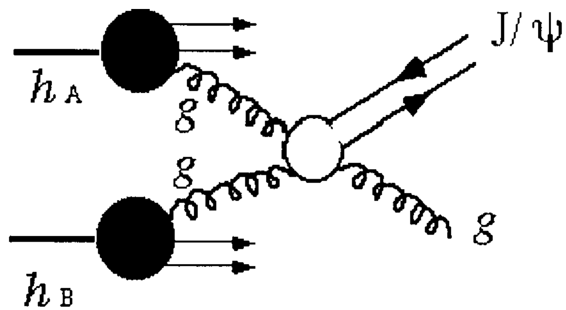
CDF



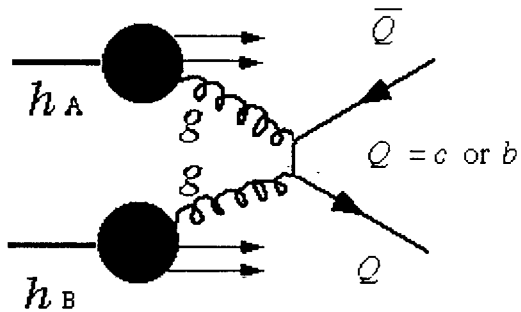
V. Barger et al;
Phys. Rev. D57 (98) 391

Probes for G Measurement

Hiroki Sato



Charmonium Production → e^+e^-, $\mu^+\mu^-$



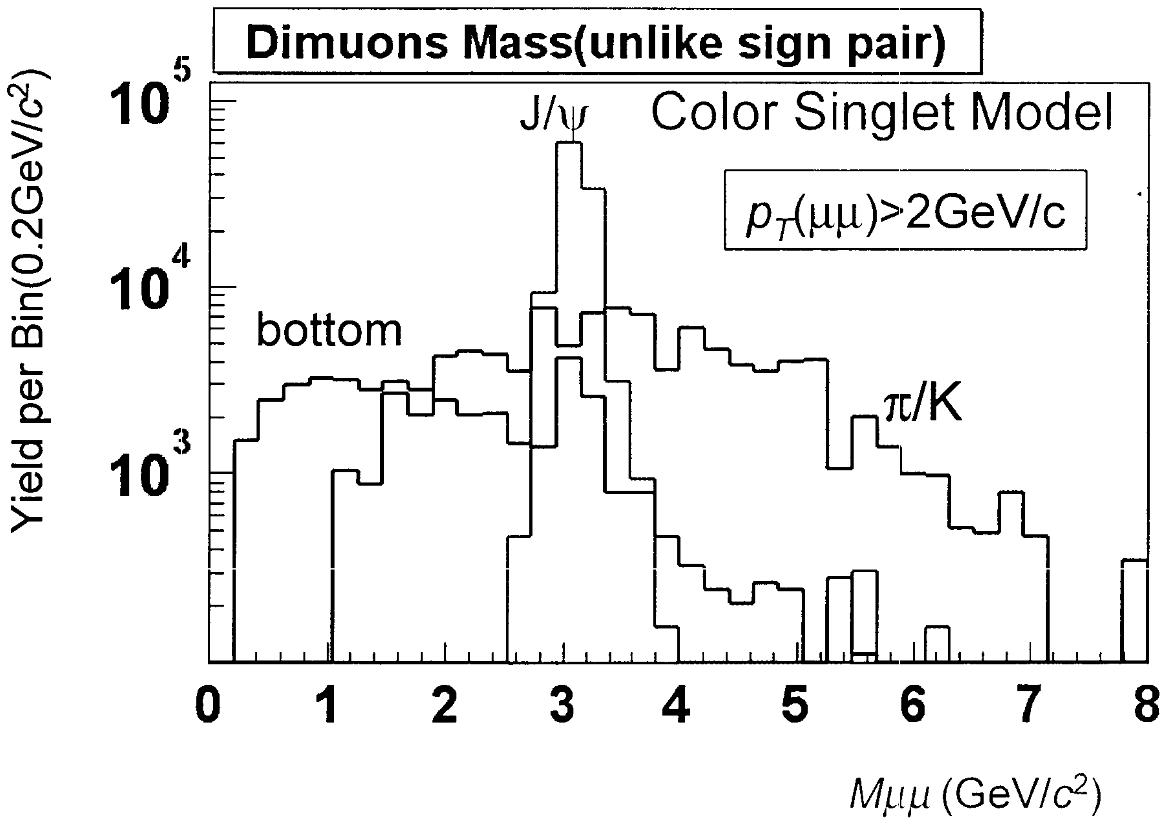
Open Heavy Quark Production → e^+e^-, $\mu^+\mu^-$, e, single e, μ, eD, μD

$$A_{LL}^{pp\to(Q\bar{Q})X}(x_1,x_2) \equiv \frac{\sigma_{++}-\sigma_{+-}}{\sigma_{++}+\sigma_{+-}} = \frac{\Delta G(x_1)}{G(x_1)}\frac{\Delta G(x_2)}{G(x_2)}\, a_{LL}^{gg\to(Q\bar{Q})}$$

Experiment ⇨ A_{LL} ← simulation / → ? $\Delta G(x)$

J/ψ μμ

320pb^{-1} p+p, $\sqrt{s}$=200GeV



$A_{LL}^{J/\psi}$

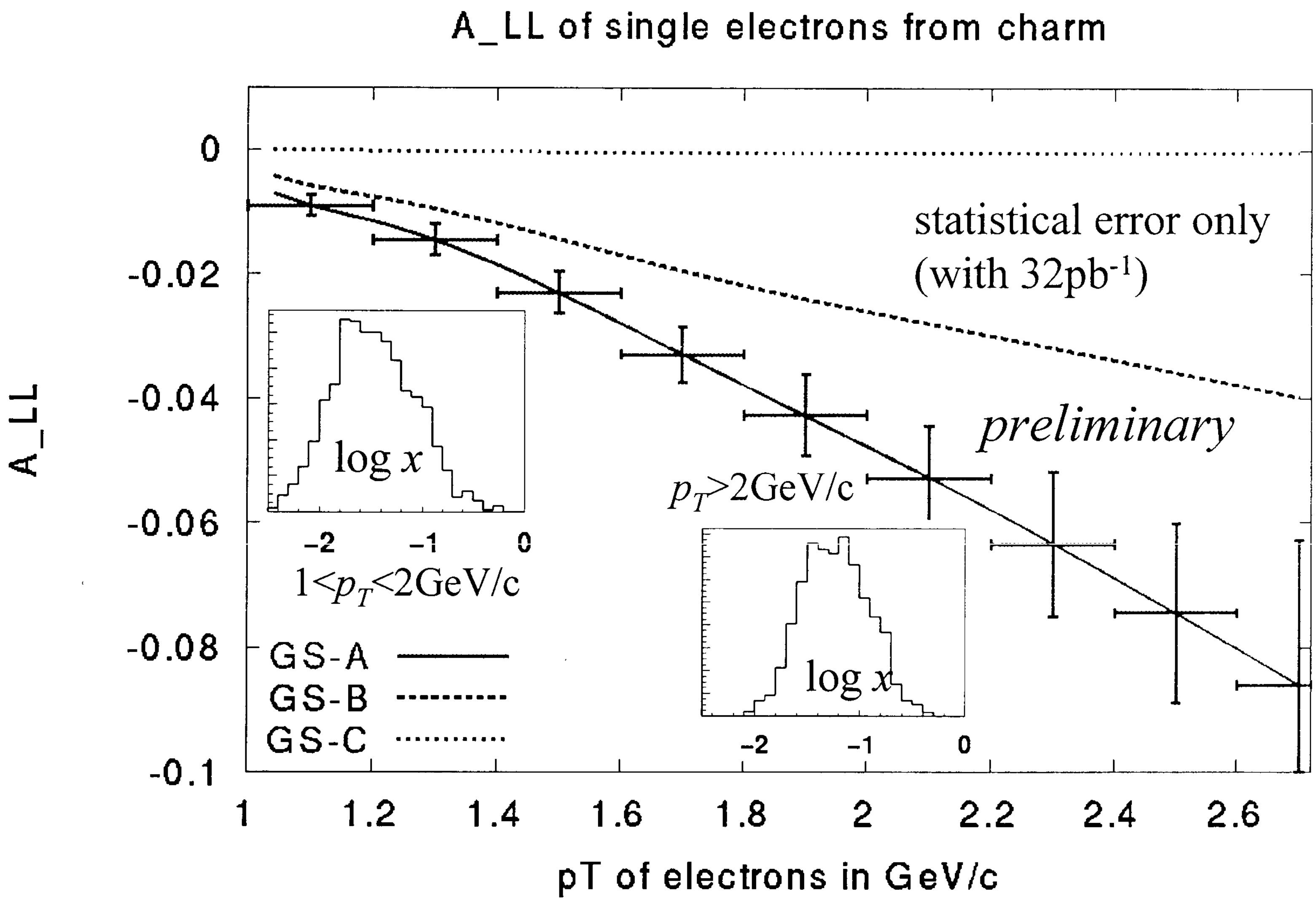
↓ Production Mechanism of J/ψ ?

$\Delta G(x)$

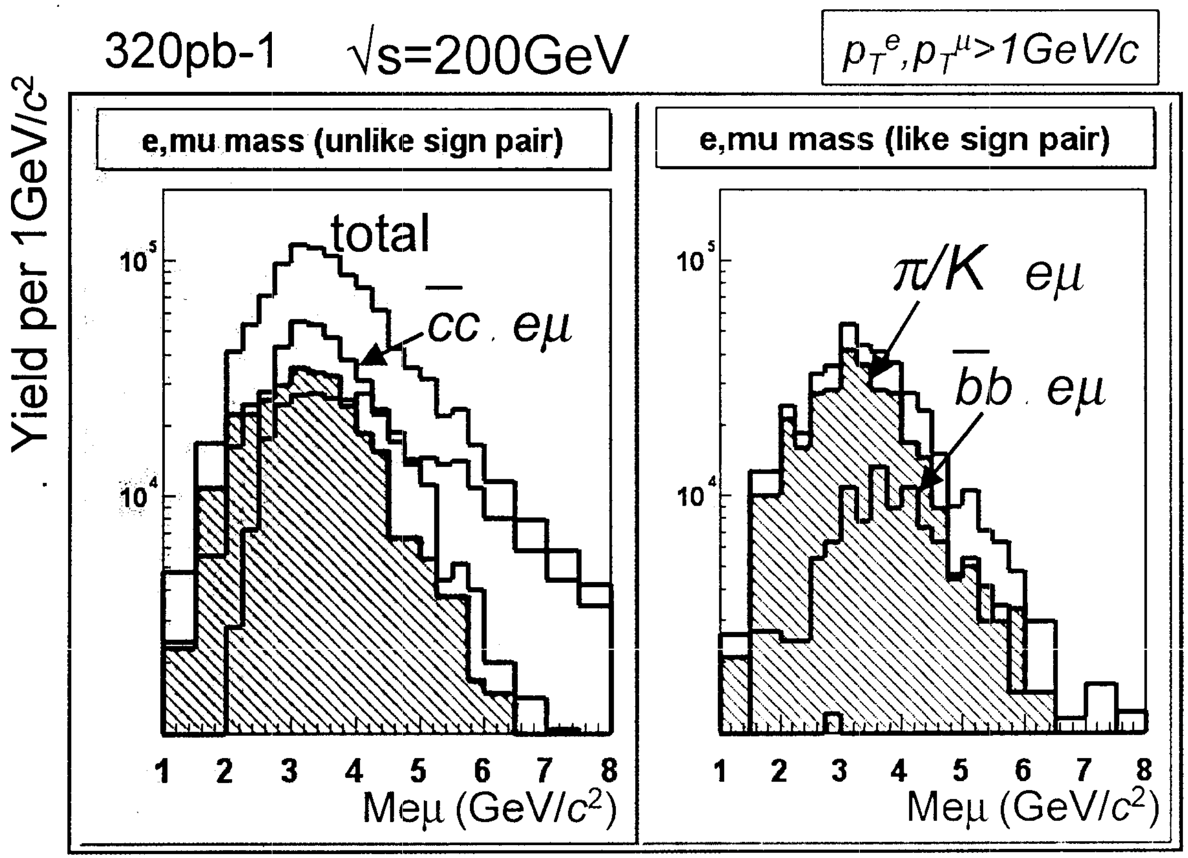
$N_{J/\psi}(p_T$>2GeV) ~120k . $\delta A_{LL}^{J/\psi}$(stat.) ~ 0.006

$N_{\pi/K}/N_{J/\psi}$ ~ 0.15, $\delta A_{LL}^{\pi/K}$ ~ 0.007 . $\delta A_{LL}^{J/\psi}$(syst.) ~ 0.001

$\Delta G(x)$ Sensitivity of Single Electrons



$e\mu$ pairs



$N_{bb.e.}$ ~120k events
$N_{cc.e.}$ ~100k events
$N_{\pi/K.e.}$ ~60k events

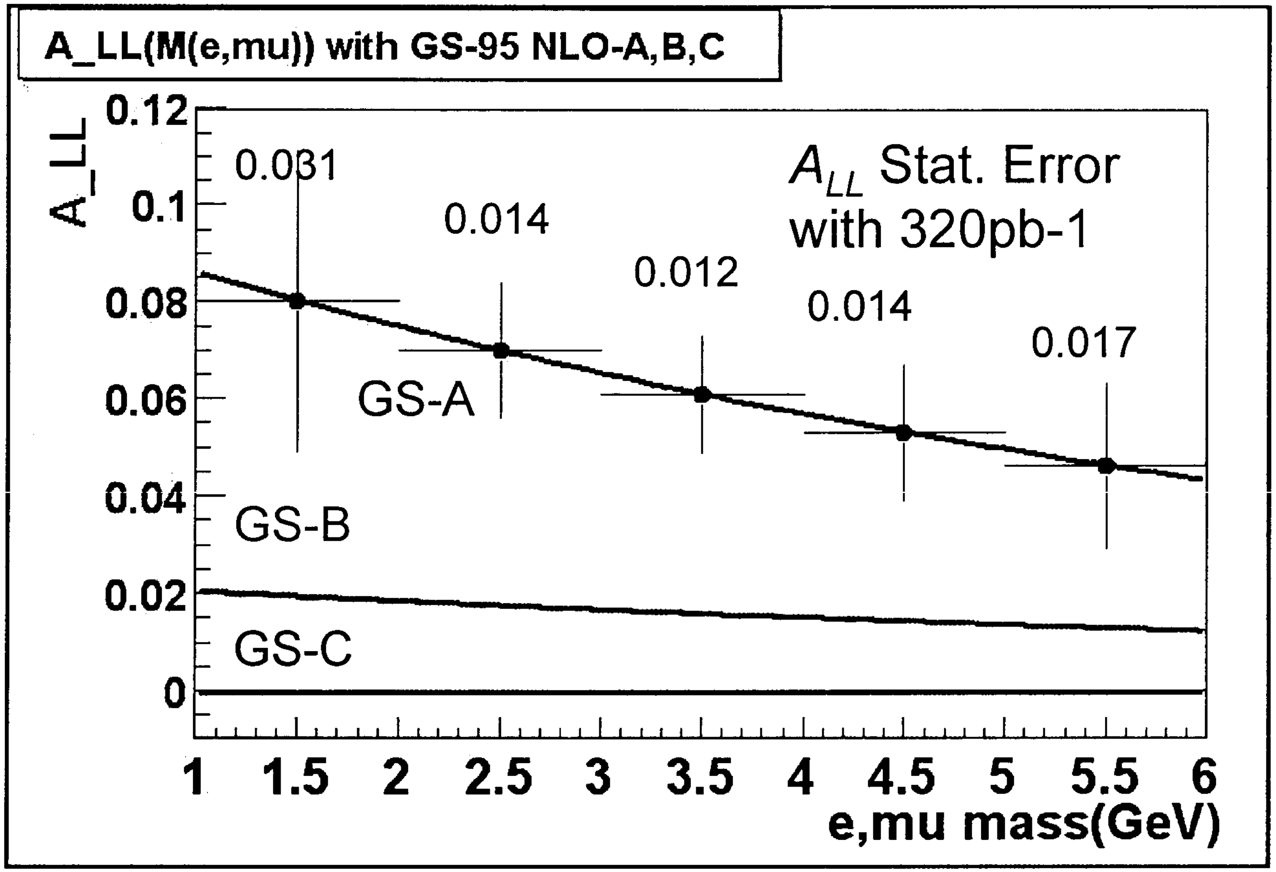
↓

δA_{LL}(stat.)~ 0.006
δA_{LL}(syst.)~0.006

- background of electrons (π^0Dalitz decay and γ conversion) can be reduced
- *b*/*c* separation is under studying . important because A_{LL} is different

$\Delta G(x)$ Sensitivity of $e\mu$ pairs

$\sqrt{s}$=200GeV $b\bar{b} \to e\mu$ (p_T^e, p_T^μ >1GeV/c)



Summary

Double longitudinal spin asymmetries (A_{LL}) for both open and bound-state heavy-flavor production are sensitive to gluon polarization in the proton, since they are dominated by the gluon fusion process at RHIC energy. We have discussed experimental uncertainties and theoretical predictions of A_{LL} for three probes to identify the heavy-flavor production at PHENIX.

We can measure A_{LL} of J/ψs, identified with unlike-sign dimuon pairs, with small experimental uncertainty (~0.006 with 320pb^{-1}). Furthermore, our measurement of the unpolarized cross section and the spin alignment of J/ψ will help to understand its production mechanism.

Systematic error of A_{LL} for the open heavy-flavor production identified with single electron is good enough(~0.001 with 32pb^{-1}) to distinguish three models of polarized gluon distribution($\Delta G(x)$) proposed by Gehrmann and Stirling.

Electron-muon pair is another probe for the open heavy-flavor production complimentary to single electron since it can probe different range of x.

Other channels, such as single muon, dielectron and eD(μD) pair, are possible and under studying.

In conclusion, we have many channels to identify the heavy-flavor production, which complimentary give us information on gluon polarization in the proton.

Some Know-How for Calculating the Polarized Hadroproduction of Heavy Quarks in NLO QCD

Ingo Bojak — T IV, Universität Dortmund

Summary and Description of the Selected Slides

- The importance of determining Δg was reviewed and heavy quark reactions useful for that were introduced ⇝ *Slide 1.*

- Our method of calculation was explained in some detail using photoproduction as example. First projection on helicity states, the HVBM γ_5 scheme, and phase space integration with "hat momenta" were discussed.

- Next virtual loops were treated ⇝ *Slide 2.* The Passarino-Veltman decomposition, basic scalar integral calculation and renormalization were demonstrated. A slide on automatic color-factor calculation followed.

- Real emission (gluon-bremsstrahlung, initial light quarks) was the next topic. Partial fractioning of angular variables, integral "tricks", and phase space slicing were covered. As final step mass factorization was introduced.

- NLO total partonic cross sections for γg and γq were shown, exhibiting large NLO corrections due to new types of Feynman graphs and PGF dominance. Improved NLO stability against $\mu_{r,f}$ variations was examined by plotting relative (hadron level) deviations ⇝ *Slide 3*, but the m_c dependence displayed in similar plots remained strong.

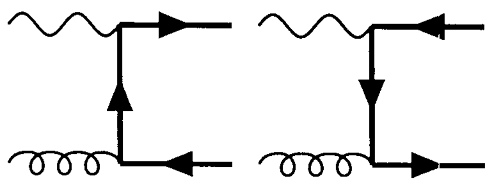
- Spin asymmetries can be enhanced by p_T-cuts, as shown for polarized photoprod. of charm at COMPASS and bottom at HERA ⇝ *Slide 4*. A p_T-cut dependent LO hadroprod. plot showed the promise of RHIC ⇝ *Slide 5.*

- NLO corrections to hadroprod. were displayed next: gq, qq and the real emission part of gg. The helicity conserving $\Delta P_{qq}^{(4)}$ (HVBM) subtraction was explained. The only missing NLO piece, gg virtual loops, is close to completion.

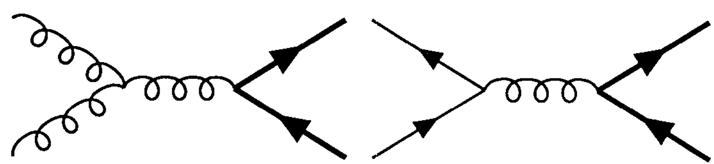
Why is Δg basically undetermined?

- $\nexists$ as in unpol.: $\int_0^1 dx\, x(g+\Sigma) = 1$ & $g \geq 0$
- no small Bjorken-x, polarized HERA-$\vec{e}\vec{p}$?
- no polarized exclusive processes used so far

Attractive heavy quark processes for Δg in LO



Photoproduction @ COMPASS: clean



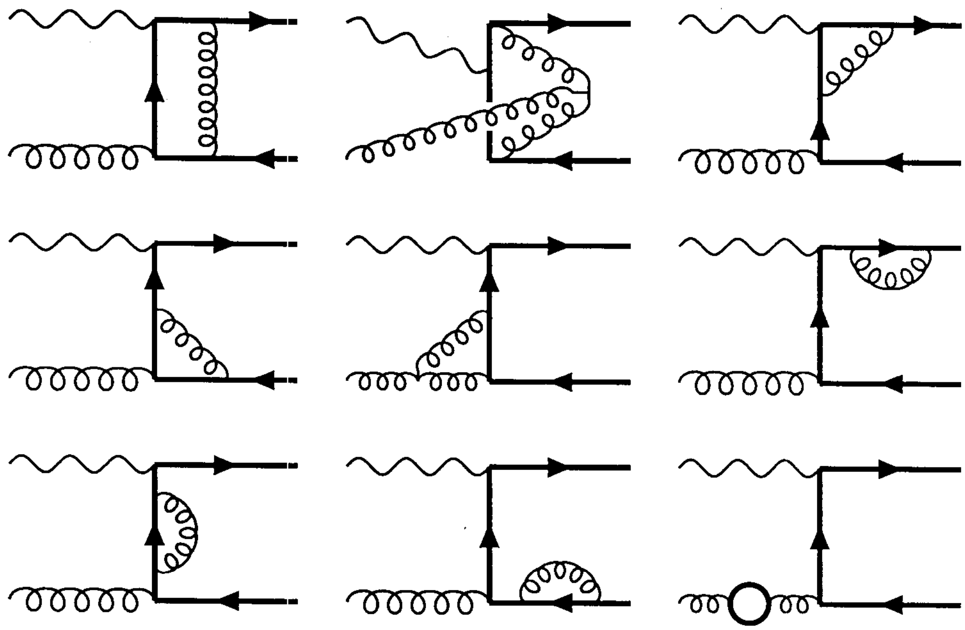
Hadroproduction @ RHIC: high statistics, smaller x

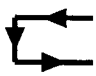
$$\frac{d^2\Delta\hat{\sigma}_{gg}^{(0)}}{dt_1 du_1} = \delta(s+t_1+u_1)\frac{g^4}{16\pi s^2}\frac{1}{2(N_C^2-1)}$$
$$\cdot\left[2C_F - C_A\frac{2t_1u_1}{s^2}\right]\left(\frac{t_1}{u_1}+\frac{u_1}{t_1}\right)\left(\frac{2m^2 s}{t_1u_1}-1\right)$$

LO simple, problems with LO calculations

- strong dependence on μ_r und μ_f in LO
- unpol.: NLO corrections big for $S \to 4m^2$, ...
- new process in NLO: $\vec{g}(\vec{\gamma})\vec{q} \to Q\bar{Q}q$

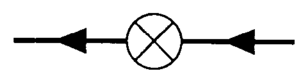
Virtual Loops



additionally  , except for non-planar box.

$\otimes$ both Born amplitudes $\Rightarrow$ matrix elements.

Similar Counterterm-graphs, e.g.,



$i[(Z_2 - 1)\, \not{p} - (Z_2 Z_m - 1) m_r]\delta_{ij}$.

Problem: tensor-loop-integrals, e.g., box:

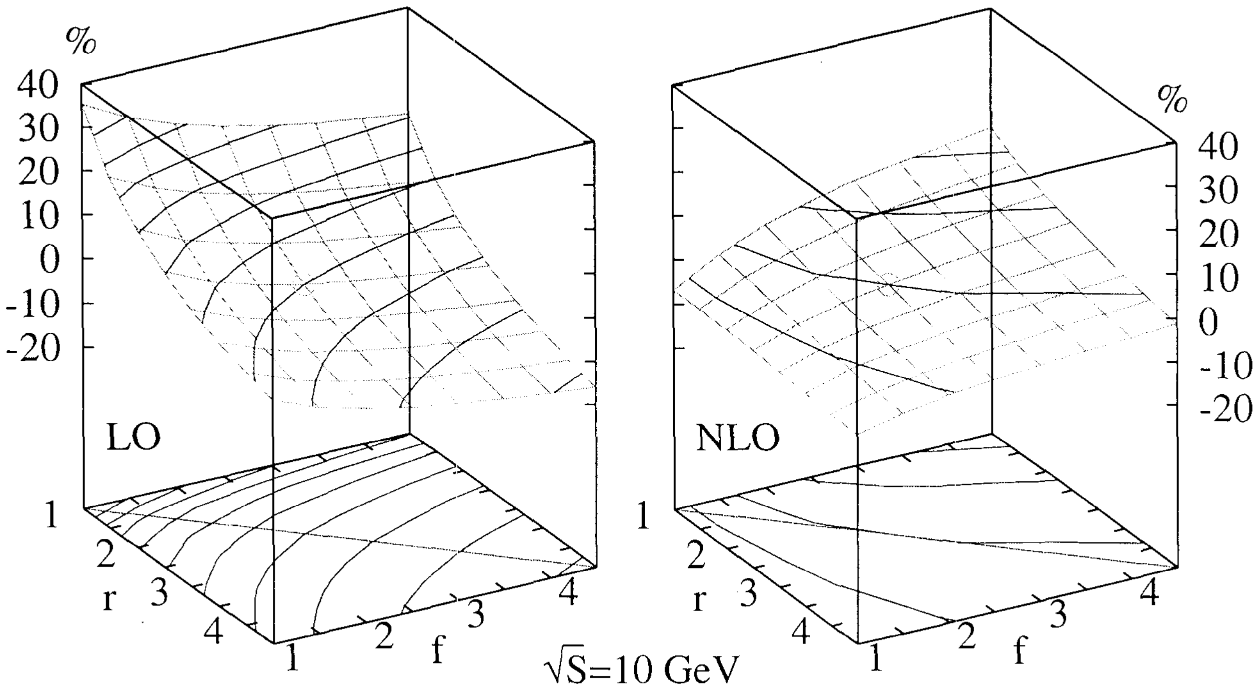
$$D^{\mu\nu\rho} \equiv \mu^{-\varepsilon} \int \frac{d^n q}{(2\pi)^n} \frac{q^\mu q^\nu q^\rho}{L_1 L_2 L_3 L_4}$$

$$L_i = (q + q_1 + \ldots + q_{i-1})^2 - m_i^2$$

Passarino-Veltman-decomposition $\curvearrowright$ scalar n-dim. (Feynman-parameter-)integrals as coefficients:

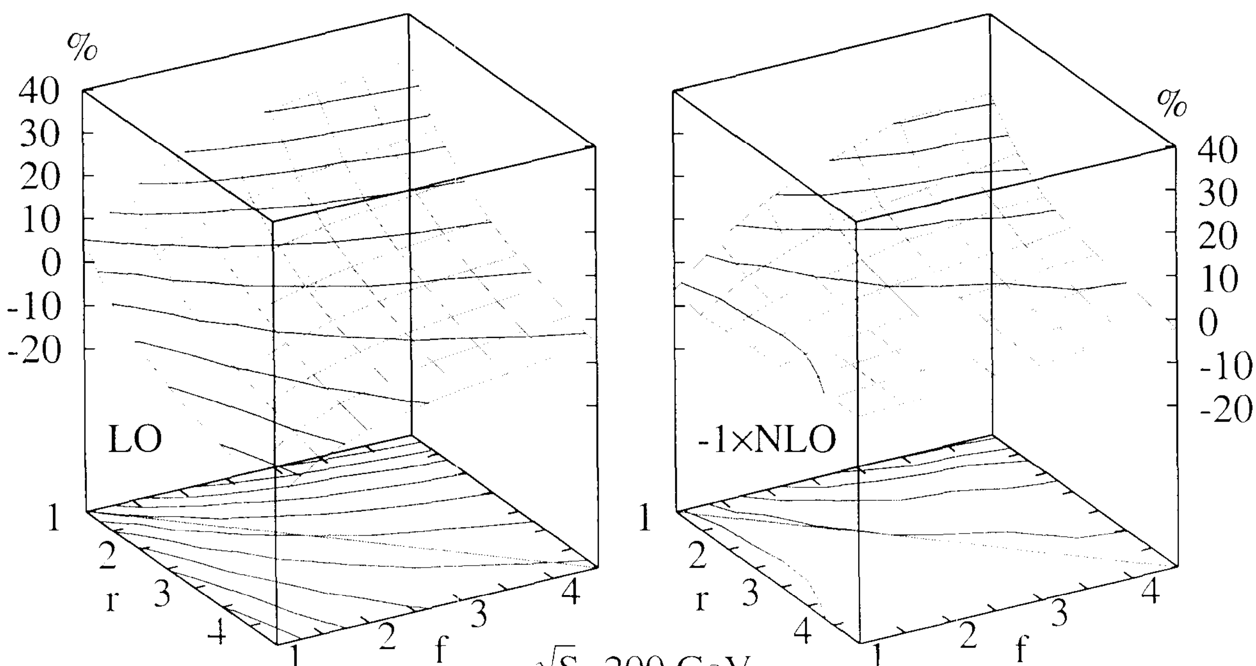
$$D^{\mu\nu\rho} = q_1^\mu q_1^\nu q_1^\rho D_{31} + \ldots + \{q_3 g\}^{\mu\nu\rho} D_{313}$$

Improved stability: μ_r vs. μ_f, $m_c = 1.5$ GeV

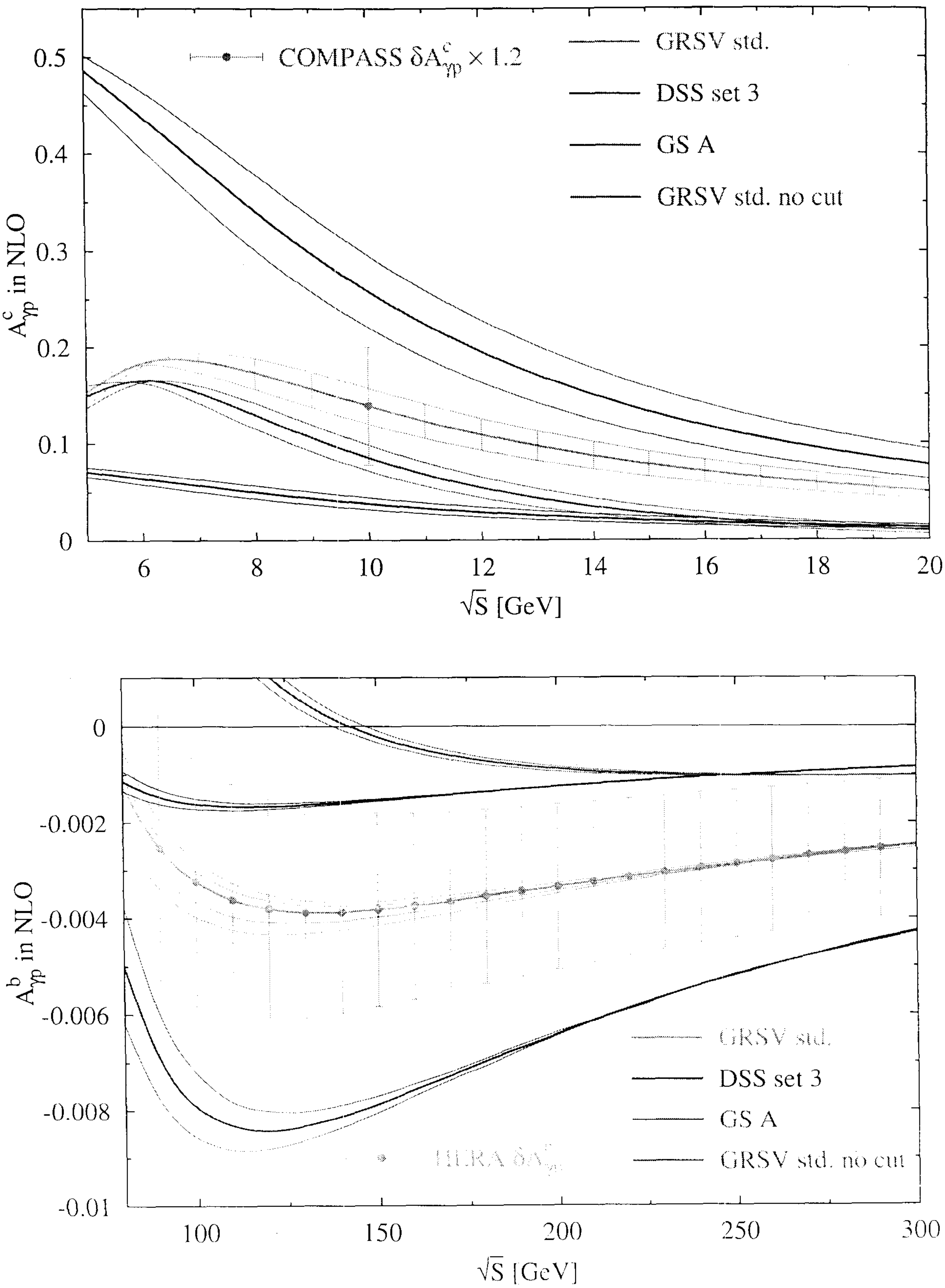


$\sqrt{S}$=10 GeV

$r = \mu_r^2/m_c^2$ and $f = \mu_f^2/m_c^2$, 5% contours

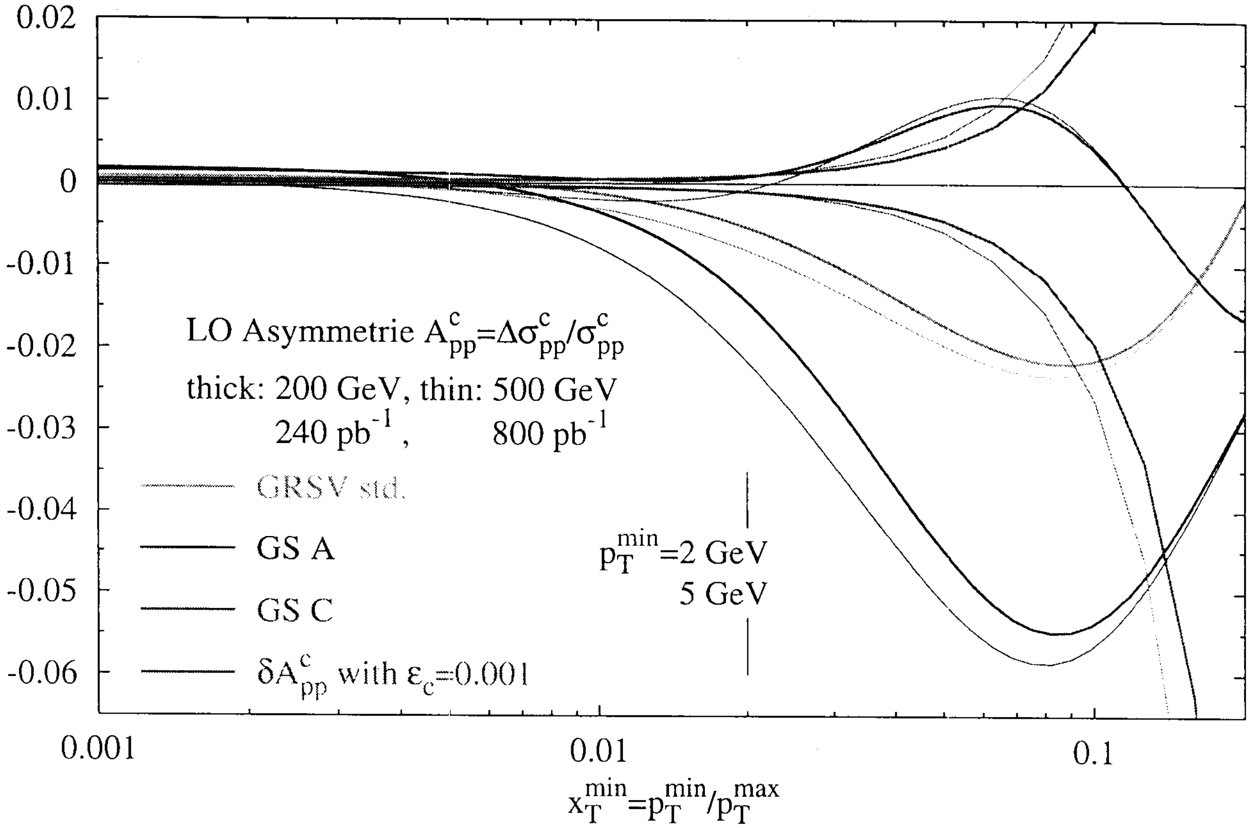


$\sqrt{S}$=200 GeV


COMPASS $\delta A^c_{\gamma p} \times 1.2$
GRSV std.
DSS set 3
GS A
GRSV std. no cut
$A^c_{\gamma p}$ in NLO
0.5
0.4
0.3
0.2
0.1
0
6
8
10
12
14
16
18
20
$\sqrt{S}$ [GeV]
0
-0.002
-0.004
-0.006
-0.008
-0.01
$A^b_{\gamma p}$ in NLO
GRSV std.
DSS set 3
GS A
GRSV std. no cut
100
150
200
250
300
$\sqrt{S}$ [GeV]

First Results for Hadroproduction

Need larger $\sqrt{S}$ for Δg at smaller $x \Rightarrow$ RHIC-$\vec{p}\vec{p}$.



Varying the low $p_T^{\min}$ integration limit.
$p_T^{\max} = \sqrt{S}/2\sqrt{1-4m^2/S}$, define $x_T = p_T/p_T^{\max}$.

p_T-cut can increase asymmetry, because $\Delta\sigma(p_T)$ oscillates. But error $\delta A^c_{pp} = \left[P_p^2\sqrt{\epsilon_c \mathcal{L}\sigma^c_{pp}}\right]^{-1}$ grows, because σ^c_{pp} mainly at small p_T.

LO looks promising. But NLO needed.
Experimental side: charm detection efficiency? Or perhaps rather bottom? Normalization?

Open Heavy Flavor Production: Some Phenomenological Aspects

Marco Stratmann

Institute of Theoretical Physics, University of Regensburg, 93040 Regensburg, Germany

Abstract

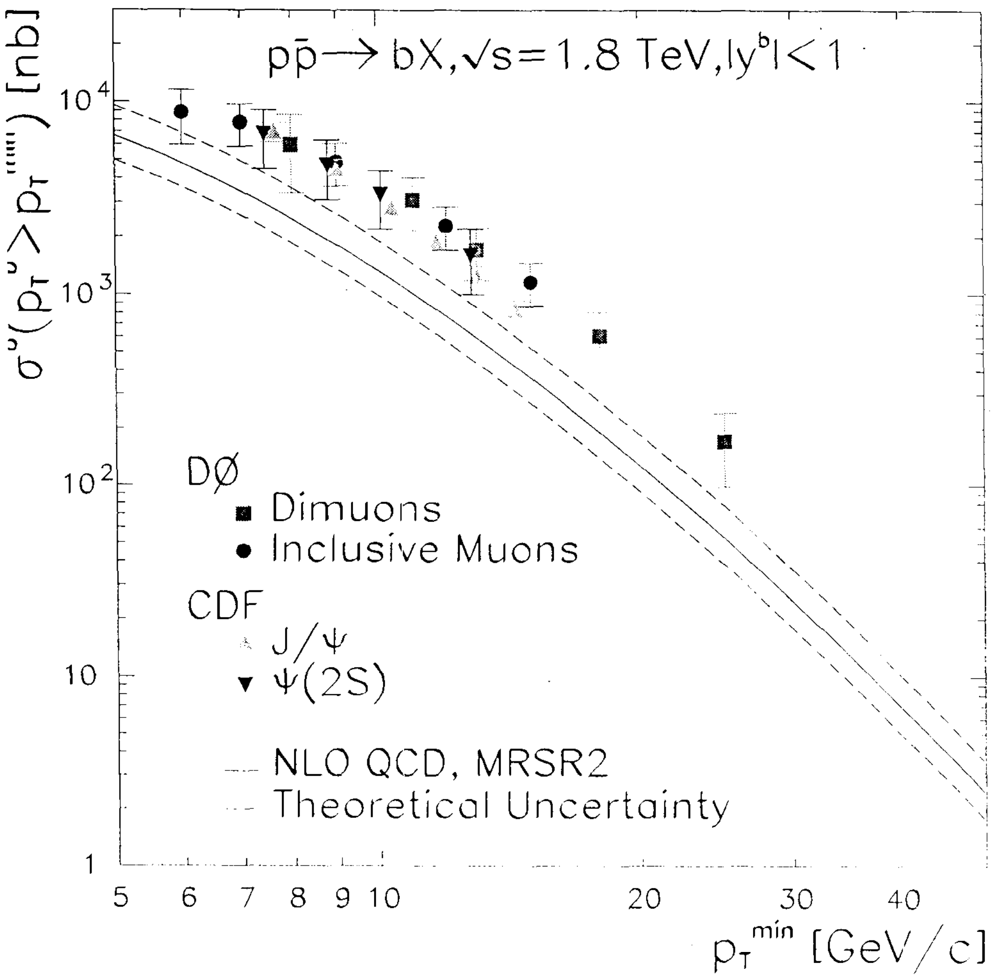
Open heavy flavor production is one of the 'gold-plated' processes to measure the polarized gluon density Δg which is still largely unknown. However, a meaningful extraction of Δg requires first of all a thorough understanding of the corresponding *un*polarized process. We give an overview of the present experimental situation for open b-quark production in unpolarized hadronic collisions. The long-standing problem that the Tevatron data are at least a factor of two above the theoretical predictions for *all* measured values of p_T is still around and not understood at all. Attempts to explain the observed excess by introducing an *ad hoc* k_T smearing for the initial state partons only slightly improves the agreement with data for small values of p_T. Moreover, other observables like heavy quark correlations seem to disfavor large values of $\langle k_T \rangle$. Resummations of $\ln p_T/m$ when $m/p_T \to 0$ also only lead to a slightly better agreement, however, the scale dependence is somewhat reduced in this approach. Uncertainties due to the fragmentation of the b quark or in the shape of the gluon density were also studied without any success. Since b production is expected to be reliably calculable in perturbative QCD, the current situation is extremely puzzling.
In the second part we present expectations for the charm photoproduction and bottom hadroproduction spin asymmetry for COMPASS and RHIC, respectively. Within their statistical accuracy, both exeriments, in particular RHIC, should be able to obtain some constraints on Δg provided a better theoretical understanding of heavy quark production can be achieved. Theoretically *and* experimentally cleaner are heavy quark jets but it is not clear yet if RHIC will be able to measure them. Hopefully upcoming results for b quark/jet production in unpolarized collisons from Tevatron run II and also from RHIC help to improve our understanding of this fundamental QCD process.
In the future we plan to present a NLO parton level generator for heavy quark production in polarized pp collisions which is mandatory for studies of heavy flavor production at RHIC.

- <u>Do we understand *unpolarized* HQ data?</u>

Before one gets too excited about the prospects of determining Δg one *must* check the 'unpol. status':

Let's concentrate on collider (Tevatron) data ...

- Incl. b-quark prod. in central region $(|y^b| < 1,\ p_T^b > p_T^{\rm min})$



$\rightsquigarrow$ long-standing problem:

- different measurements ([illegible]) + methods agree
- theor. predictions below data (data/theory $\approx 2 \div 2.5$) even if one fiddles around with μ_f, μ_r, and α_s however, the shape is OK! ($\approx$ constant shift)

It can be even worse ...

- Inclusive forward b-quark prod. $(2.4 < |\eta^\mu| < 3.2)$ D0

D0 (prel.):

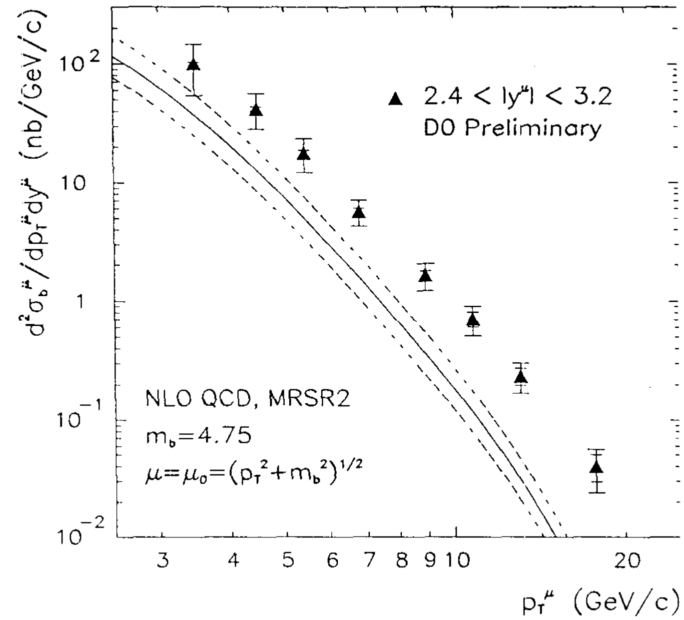
b produced μ's

$(p_T^\mu > 2\,\text{GeV})$

NLO QCD: HVQJET

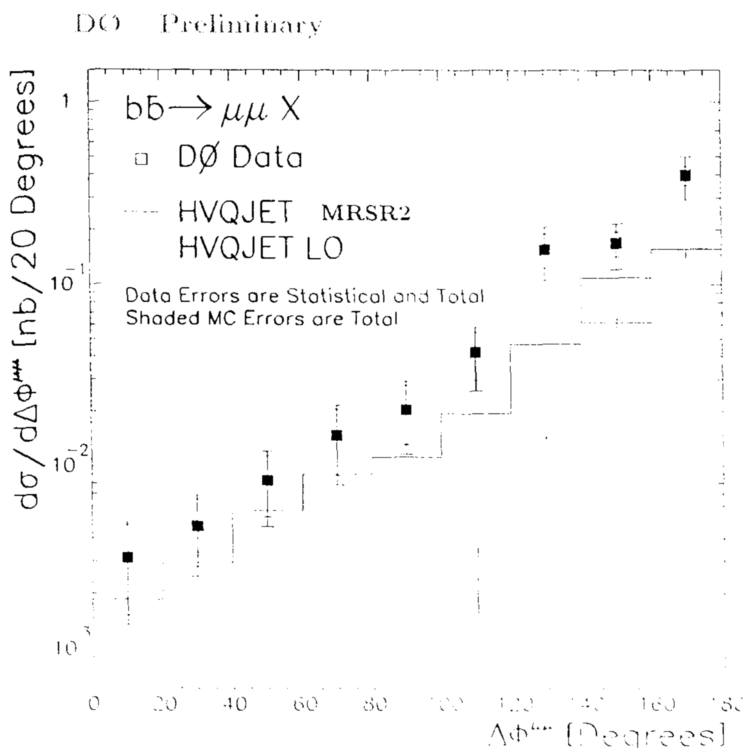
(Baarmand, Paige)

$\rightsquigarrow \frac{\text{data}}{\text{theory}}$ up to ≈ 4 !



- Angular correlations between muons in $b\bar{b} \to \mu\mu$ D0

↘ trivial in LO $\rightsquigarrow$ important test of NLO QCD !



$4 < p_T^\mu < 25\,\text{GeV}$, $|\eta^\mu| < 0.8$

$6 < M_{\mu\mu} < 35\,\text{GeV}$

NLO QCD: HVQJET

(Baarmand, Paige)

MC error band:

dominated by

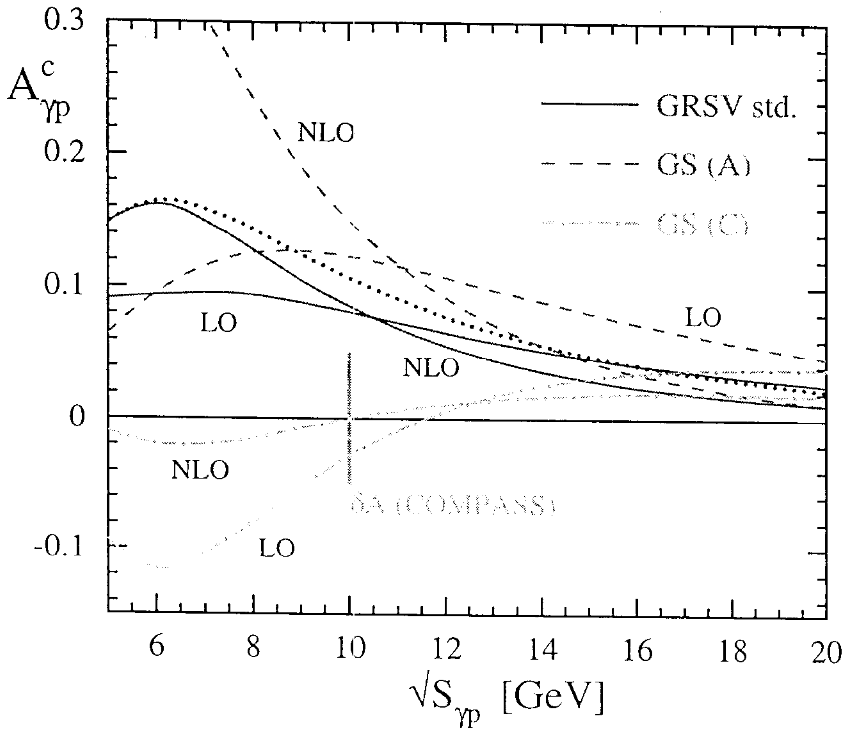
m_b and μ-var.: $^{+67}_{-38}\,\%$

$\frac{\text{data}}{\text{theory}} \simeq 1.8$

(all figs. taken from 's talk @)

• Lepto/photoproduction of HQ's

• photoproduction of charm @ COMPASS



Bojak, MS

– NLO corrections are sizeable

– sizeable dependence on m_{charm}

– can extract Δg only for one $\langle x \rangle \sim \mathcal{O}(0.1)$

+ background from resolved γ's (e.g., $gg \to c\bar{c}$) small

• HQ production @ a polarized

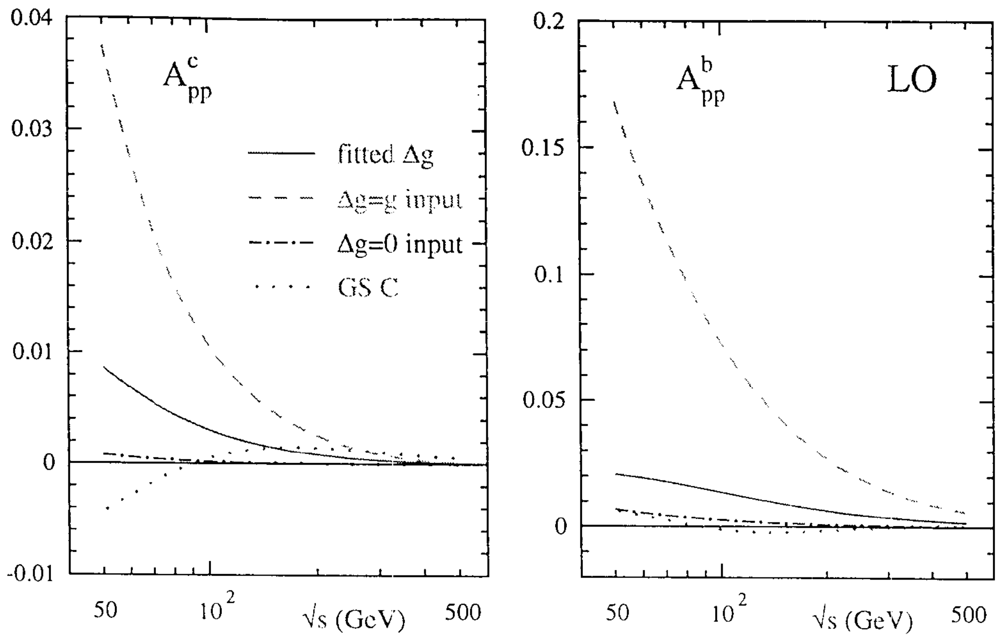
option to polarize p-beam under discussion

first polarized ep *collider*

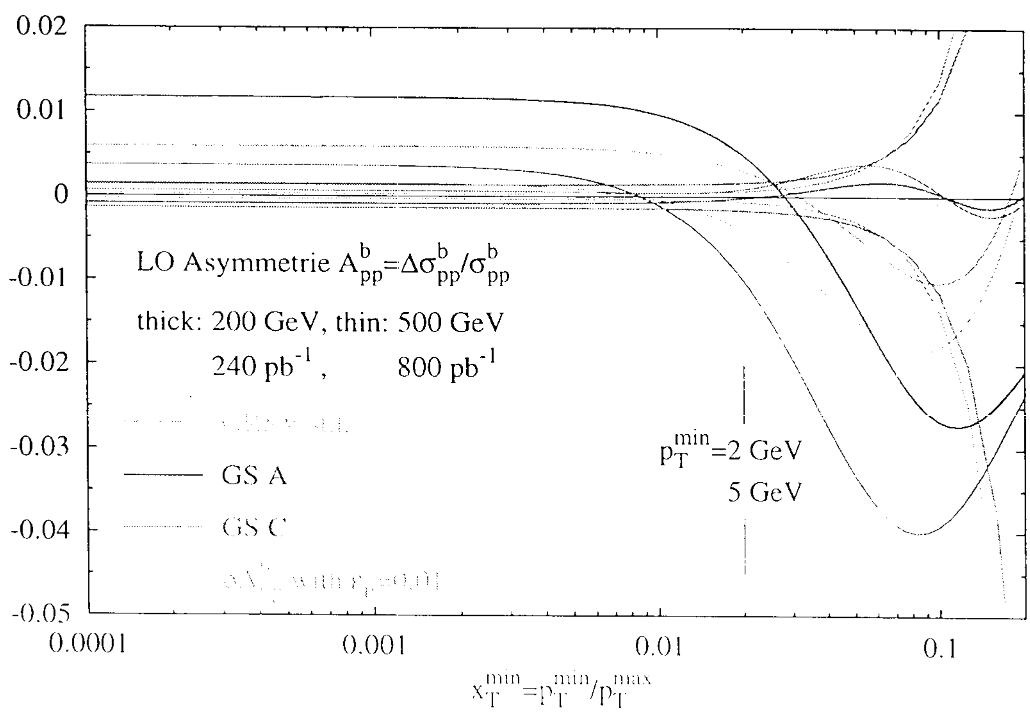
rich physics case: g_1 @ small-x, CC-DIS, photoprod., ...

• Hadroproduction of HQ's @ RHIC

• Total cross section asymmetries A_c and A_b:



• $p_T^{\min}$ dependent b-asymmetry:



⇝ sensitivity to Δg if the b detection is suff. good

[of course, we must understand the unpolarized case first]

• More ‘exotic’ but interesting observables

• HQ jets: (unpol. studies by Frixione, Mangano)

Idea:

study properties of jets (E_T-distr.) containing at least one HQ (regardless of mom. fraction of HQ in the jet)

Advantages:

- $\ln p_T/m$ not present in jet E_T-distributions
- reduced uncertainties (no HQ frag. etc.)
- uncert. due to m not important for high-E_T jets

LO: $\sigma_{\mathrm{HQ-jet}} = \sigma_{\mathrm{open-HQ}}$

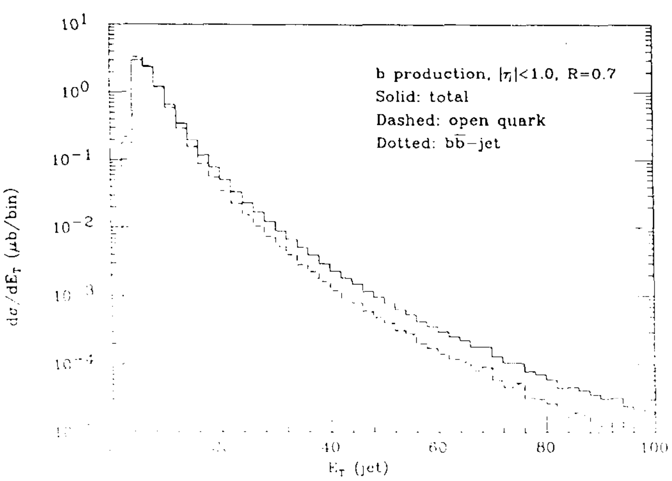
NLO: jet $\in (\mathrm{HQ}, \mathrm{HQ} + \mathrm{light\,parton}, \mathrm{HQ} + \overline{\mathrm{HQ}})$

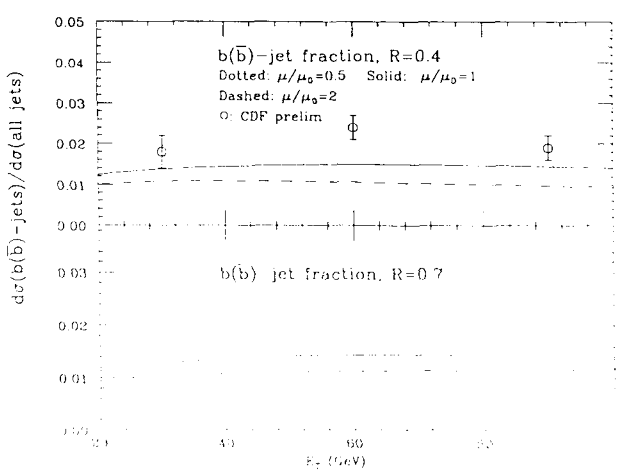
$\rightsquigarrow \sigma_{\mathrm{HQ-jet}} \neq \sigma_{\mathrm{open-HQ}}$

but singularity structures identical (mass = ‘cutoff’)

$\rightsquigarrow$ can write: $d\sigma = d\sigma^{\mathrm{open}} + d\delta\sigma^{\mathrm{jet-like}}$

particularly suited observ.: HQ jet-frac., b-jet/c-jet ratio





Problem: data for c-jet fraction above NLO QCD

F_2 charm at HERA

J. Smith
C.N. Yang Institute for Theoretical Physics,
State University of New York at Stony Brook, New York 11794-3840, USA.

Recently there has been a lot of activity regarding the production of charmed D^* mesons in deep inelastic scattering at HERA. The H1 [1] and ZEUS [2] groups have each collected about one thousand events. The differential distributions for these events are shown in Fig.1 and are in good agreement with the predictions of the computer code HVQDIS [3], which contains the exclusive next-to-leading order (NLO) calculation originally made in [4] and a fragmentation function for the transition from a charmed quark to a charmed meson. The calculation assumes a set of three flavor (masslessx) parton densities and is completely free of collinear divergence problems because the charmed quark is massive. The experimental groups then use HVQDIS to integrate over all the phase space to give predictions for $F_{2,c}(x, Q^2, m^2)$, which we show in Fig.2. To distinguish this theoretical result from the other approaches below we call this NLO prediction $F_{2,c}^{\rm EXACT}(x, Q^2, m_c^2)$. The experimental groups then extract from this data a three-flavor gluon density $g(x)$, which agrees with the one extracted from the slope of the total deep inelastic structure function $F_2(x, Q^2)$.

What more can one do with this data? First of all the experiments are still running and we expect more events over a larger range in Q^2 and p_t. The theorists would like to use the data in several ways. First of all one can treat the charm quark as a massless density, which should be a reasonable assumption at when $Q \gg m_c^2$, but not when $Q^2 \approx m_c^2$. This assumes that the NLO calculation will not be an adequate fit to the data at large Q^2 and the so-called zero mass variable flavor scheme (ZM-VFNS), in which there is a four-flavor set of parton densities (including charm), will be better. This claim is opposed by the Dortmund group [5] who pointed out that the original NLO calculation in [4] is not very sensitive to scale variations and therefore prefer to avoid the introduction of a charm density. Nevertheless the two-loop operator matrix elements which one requires to implement this ZM-VFNS idea in next-to-next-to leading order (NNLO) have been worked out [6]. Recently the NNLO boundary conditions from which the charm density evolves at $Q^2 = m_c^2$ have been implemented into an evolution code [7] and results given for $F_{2,c}(x, Q^2, \Delta)$ in [8]. We note that now there has to be a parameter Δ to distinguish the massless charm quark contribution from the rest of the light quark contributions to $F_2(x, Q^2, \Delta)$. The sum of these parts is independent of Δ. This contribution is called $F_{2,c}^{\rm PDF}(x, Q^2, \Delta)$. Only in the region of intermediate Q^2 should the two descriptions overlap, as $F_{2,c}^{\rm EXACT}$ should be better at small scales and $F_{2,c}^{\rm PDF}$ at large scales.

Finally there are several schemes which interpolate between the above approaches. They are called variable flavor number schemes (VFNS) and contain both three flavor and four flavor parton densities convoluted with appropriate massless or massive coefficient functions. Among them are the ACOT [9], BMSN [6], MRT [10] and CSN [8] schemes. Yet another preprint appeared a few days ago [11]. We show some results from the two NNLO schemes labelled BMSN and CSN in Figs. 3,4. At this order in perturbation theory there is generally very little difference between the schemes. At small scales the ZM-VFNS scheme is a poor appproximation. Since our comparisons are made at very small Q^2 where α_s is large we see for the first time consequences of inadeqate analyses of parton densities. The groups [12], [13], [14] first fit data with convolutions of leading order (LO) densities with leading order coefficient functions to determine the former functions. Then in NLO they should multiply these LO densities with NLO coefficient functions and add them to the convolution of undetermined NLO parton densities with LO coefficient functions. The latter can then be determined from a new fit to the same experimental data. However this is not what is actually done. The parton density groups convolute both the LO and NLO coefficient functions with NLO densities thereby adding in even higher order contributions. Therefore the renormalization group equation, which should express the independence of measured quantities with respect to variations of the mass factorization scale through order α_s^2, is violated by the inclusion of higher order terms. One can see the consequences of this in the plot for $F_{L,c}(x, Q^2)$ in Fig. 4 which is negative and therefore unphysical at very small scales where the α_s is large.

When charm electroproduction data are available at larger values of p_t it will be necessary to work out VFNS schemes for the differential distributions which include the evolution of fragmentation functions for charm.

References

[1] C. Adloff et al. (H1-collaboration), Nucl. Phys. **B545**, 21 (1999).

[2] J. Breitweg et al. (ZEUS Collaboration), Phys. Lett. **B407**, 402 (1997); Eur. Phys. J. C**12**, 35 (2000), hep-ex/9908012.

[3] B.W. Harris and J. Smith, Nucl. Phys. **B452**, 109 (1995).

[4] E. Laenen, S. Riemersma, J. Smith and W.L. van Neerven, Nucl. Phys. **B392**, 162 (1993); ibid. 229 (1993);
S. Riemersma, J. Smith and W.L. van Neerven, Phys. Lett. **B347**, 43 (1995).

[5] M. Glück, E. Reya and M. Stratmann, Nucl. Phys. **B422**, 37 (1994);
A. Vogt in *Deep Inelastic Scattering and Related Phenomena, DIS96*, edited by G.D. 'Agostini and A. Nigro, (World Scientific 1997), p. 254, hep-ph/9601352.

[6] M. Buza, Y. Matiounine, J. Smith, W.L. van Neerven, Eur. Phys. J. **C1**, 301 (1998).

[7] A. Chuvakin, J. Smith, Phys. Rev. D (to be published) hep-ph/9911504.

[8] A. Chuvakin, J. Smith and W.L. van Neerven, Phys. Rev. D. (to be published) hep-ph/9910250; hep-ph/0002011.

[9] M.A.G. Aivazis, J.C. Collins, F.I. Olness and W.-K. Tung, Phys. Rev. D**50**, 3102 (1994);
F.I. Olness and S. Riemersma, Phys. Rev. D**51**, 4746 (1995);
J.C. Collins, Phys. Rev. D**58**, 0940002 (1998).

[10] R.S. Thorne and R.G. Roberts, Phys. Lett. **B421**, 303 (1998); Phys. Rev. D**57**, 6871 (1998).

[11] M. Krämer, F.I. Olness and D.E. Soper, hep-ph/0003035.

[12] M. Glück, E. Reya and A. Vogt, Eur. Phys. J. **C5**, 461 (1998).

[13] H.L. Lai, J. Huston, S. Kuhlmann, J. Morfín, F. Olness, J. Owens, J. Pumplin, W.K. Tung, Eur. Phys. J. C **12**, 375 (2000) hep-ph/9903282.

[14] A.D. Martin, R.G. Roberts, W.J. Stirling and R. Thorne, Eur. Phys. J. **C4**, 463 (1998).

Figure Captions

Fig. 1. Differential distributions from ZEUS.

Fig. 2. $F_{2,c}(x, Q^2)$ from ZEUS.

Fig. 3. The charm quark structure functions $F_{2,c}^{\rm EXACT}(n_f = 3)$ (solid line) $F_{2,c}^{\rm CSN}(n_f = 4)$, (dot-dashed line) $F_{2,c}^{\rm BMSN}(n_f = 4)$, (dashed line) and $F_{2,c}^{\rm PDF}(n_f = 4)$, (dotted line) in NNLO for $x = 0.005$ plotted as functions of Q^2.

Fig. 4. The charm quark structure functions $F_{L,c}^{\rm EXACT}(n_f = 3)$ (solid line) $F_{L,c}^{\rm CSN}(n_f = 4)$, (dot-dashed line) $F_{L,c}^{\rm BMSN}(n_f = 4)$, (dashed line) and $F_{L,c}^{\rm PDF}(n_f = 4)$, (dotted line) in NNLO for $x = 0.005$ plotted as functions of Q^2.

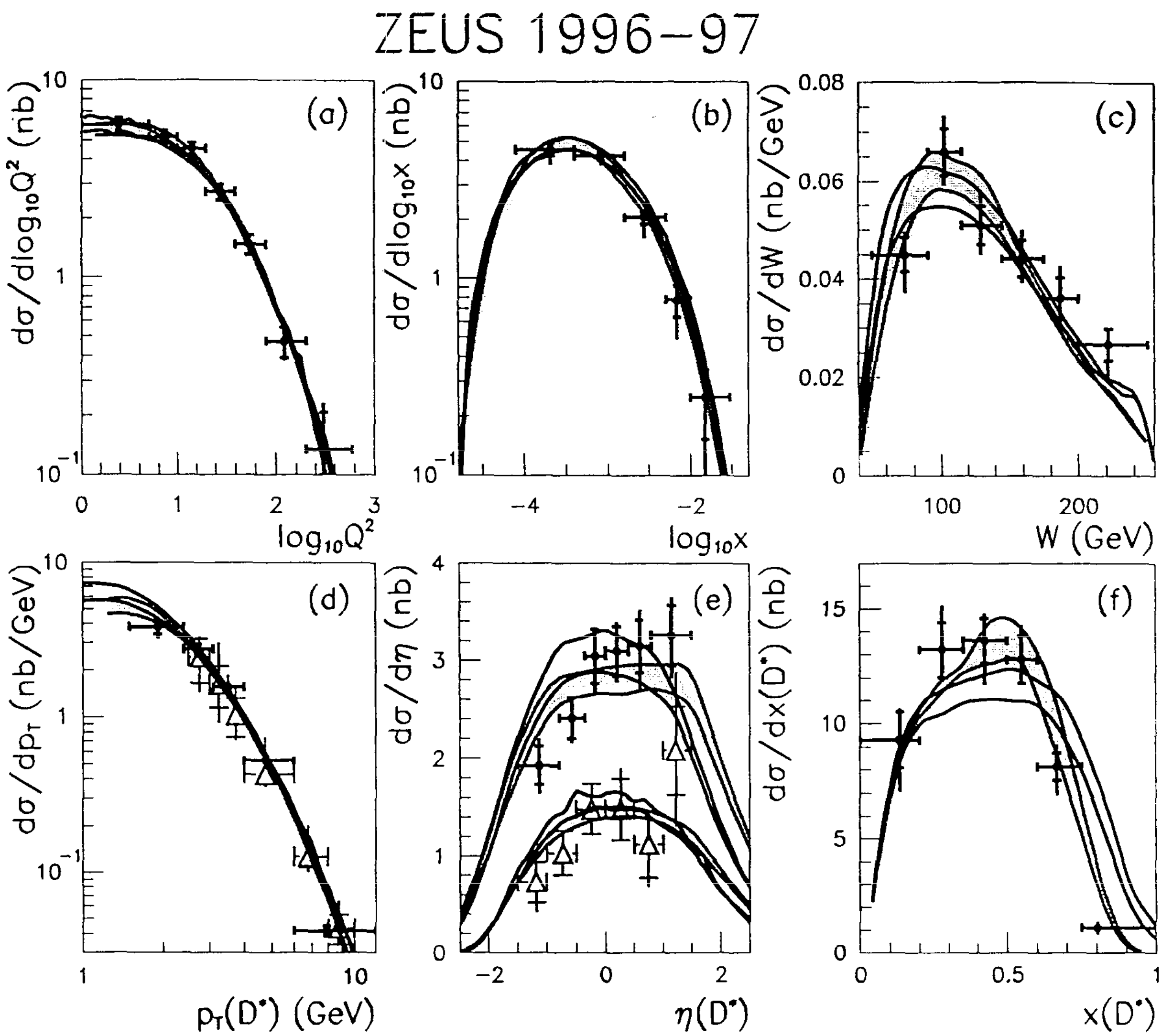


Figure 1: *Differential cross sections for $D^{*\pm}$ production from the $K2\pi$ final state (solid dots) in the Q^2, y, $p_T(D^*)$ and $\eta(D^*)$ kinematic region as functions of (a) $\log_{10} Q^2$, (b) $\log_{10} x$, (c) W, (d) $p_T(D^*)$, (e) $\eta(D^*)$ and (f) $x(D^*)$. The inner error bars show the statistical uncertainties while the outer ones show the statistical and systematic uncertainties summed in quadrature. The results from the $K4\pi$ channel (open triangles) are also shown in the $p_T(D^*)$(d) and $\eta(D^*)$ (e) plots. The data are compared with the NLO QCD calculation as implemented in HVQDIS using the ZEUS NLO pdf's. The open band corresponds to the standard Peterson fragmentation function with the parameter ϵ = 0.035. For the shaded band, the Peterson fragmentation was replaced by that extracted from RAPGAP (see the text for details). The boundaries of the bands correspond to charm mass variations between 1.3 (upper curve) and 1.5* GeV*(lower curve). In (a) and (b), the open band is indistinguishable from the shaded band.*

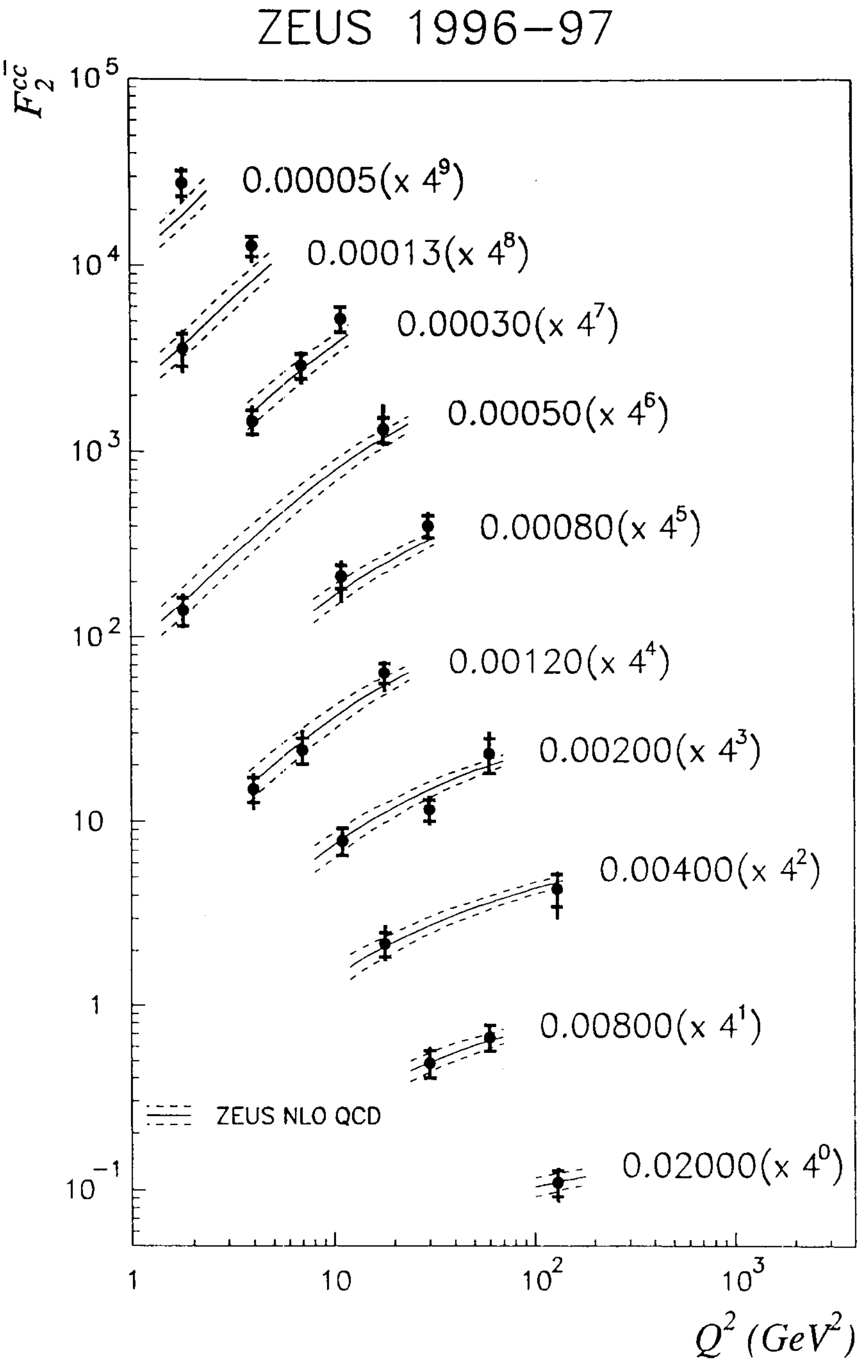


Figure 2: *The measured $F_2^{c\bar{c}}$ at x values between 0.00005 and 0.02 as a function of Q^2. The various values of x are indicated to the right of the data points. For clarity of presentation, the $F_2^{c\bar{c}}$ values have been scaled by the number shown in parentheses next to the x value. The inner error bars show the statistical uncertainty and the outer ones show the statistical and systematic uncertainties summed in quadrature. The curves correspond to the NLO QCD calculation [7, 46] using the result of the ZEUS NLO QCD fit to F_2 [41]. The solid curves correspond to the central values and the dashed curves give the uncertainty due to the parton distributions from the ZEUS NLO fit. Details of this calculation are given in the text. The overall normalization uncertainties arising from the luminosity measurement ($\pm$1.65%), the $D^{*\pm}$ and D^0 decay branching ratios, the charm hadronization fraction to D^{*+} ($\pm$9%) and the extrapolation uncertainties (see text) are not included.*

Fig 3

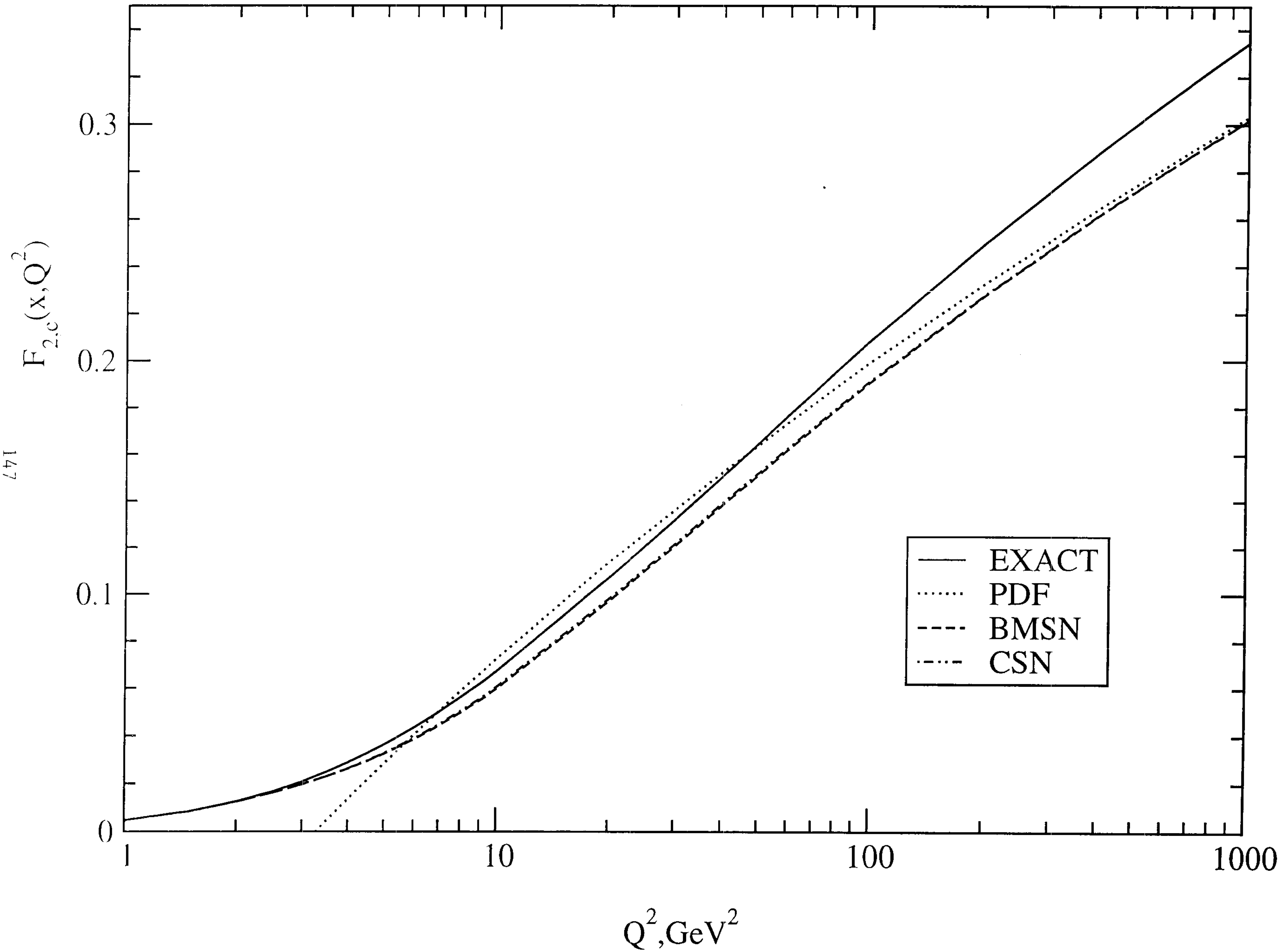
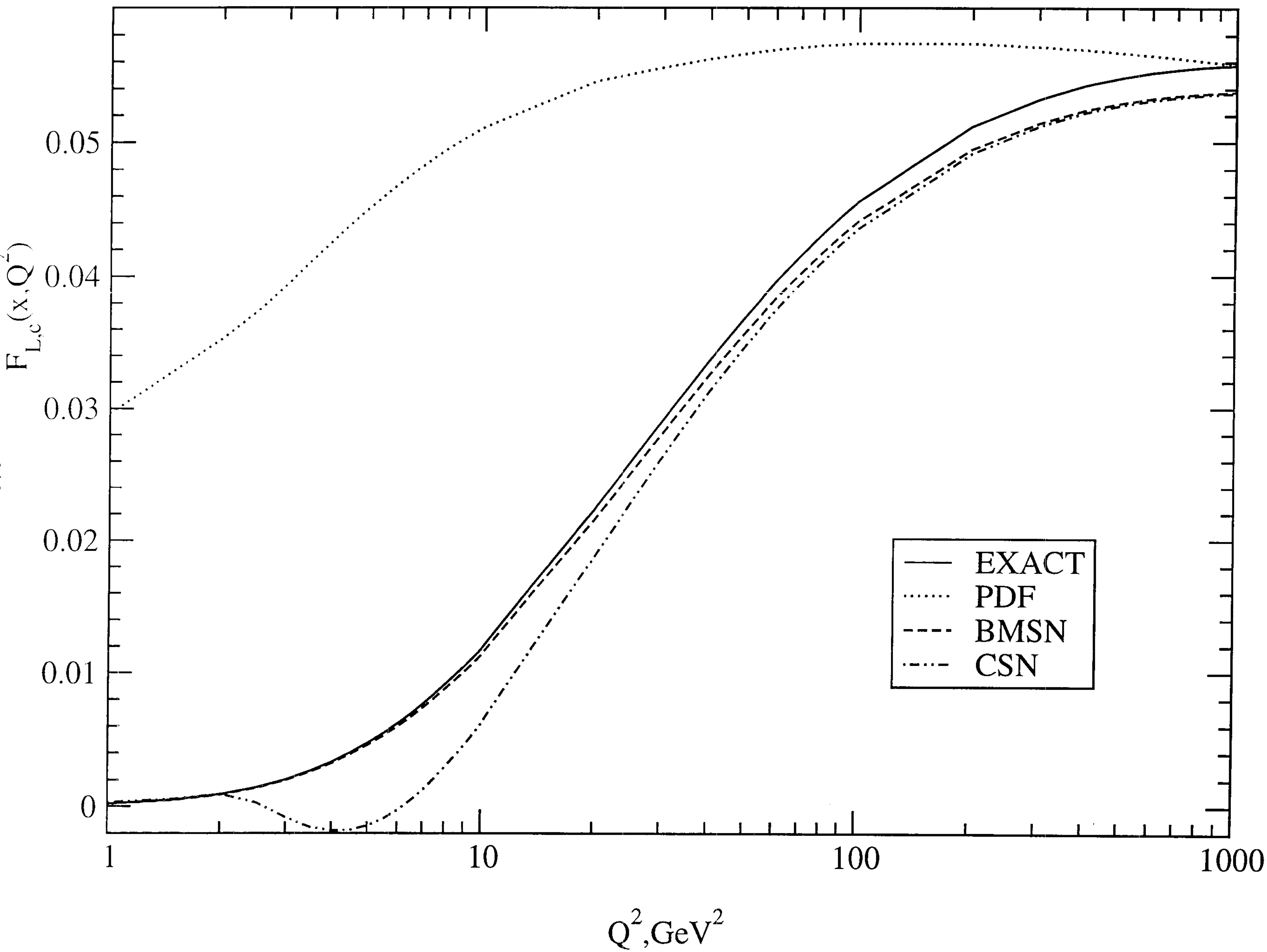


Fig 4



$F_{L,c}(x,Q^2)$
0.05
0.04
0.03
0.02
0.01
0
1
10
100
1000
Q^2,GeV^2
EXACT
PDF
BMSN
CSN

LONGITUDINAL SPIN DEPENDENCE OF LEPTON PAIR PRODUCTION IN HADRON COLLISIONS

RIKEN BNL Workshop on

Predictions and Uncertainties for RHIC Spin Physics

March 6 – 31, 2000

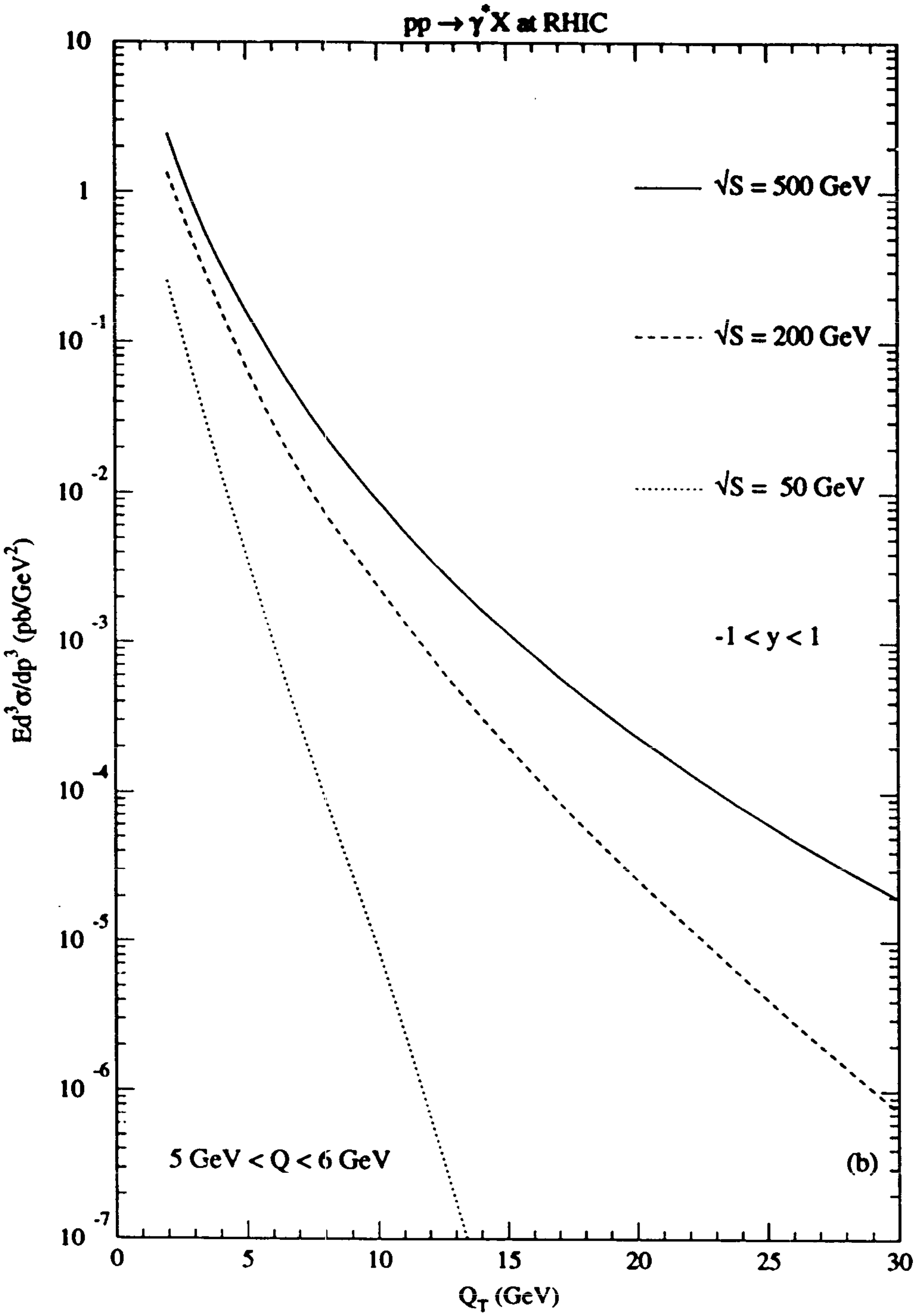
Edmond L. Berger

with Lionel Gordon and Michael Klasen, hep-ph/9909446, hep-ph/0001190, and Phys.Rev. D58, 074012 (1998)

Outline:

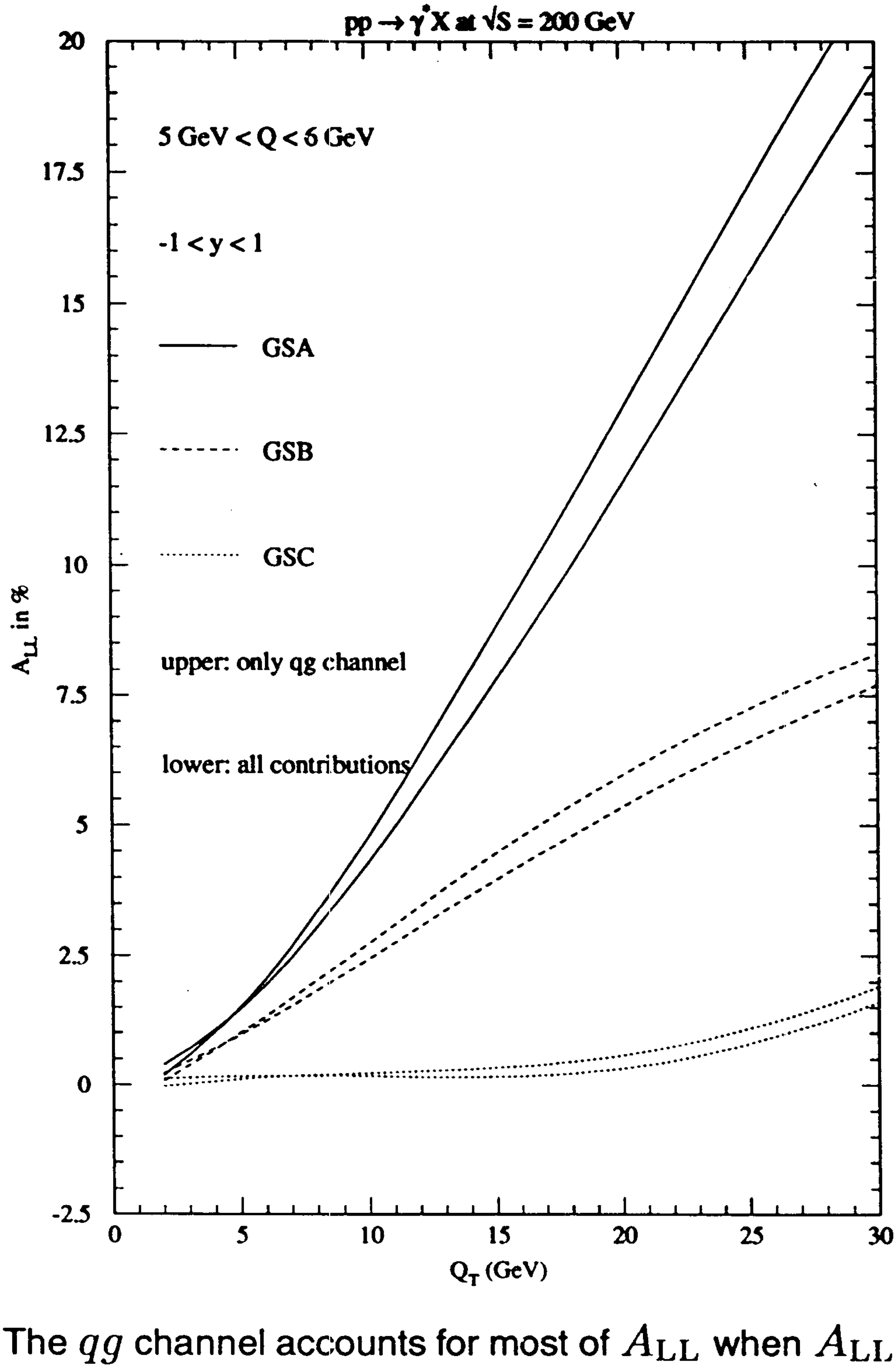
- Introduction
- Next-to-Leading Order QCD Formalism
- Transverse Momentum Distributions
- Predictions for A_{LL} at RHIC Energies
- Discussion/Summary

http://gate.hep.anl.gov/berger/seminars/BNL-RIKEN.ps



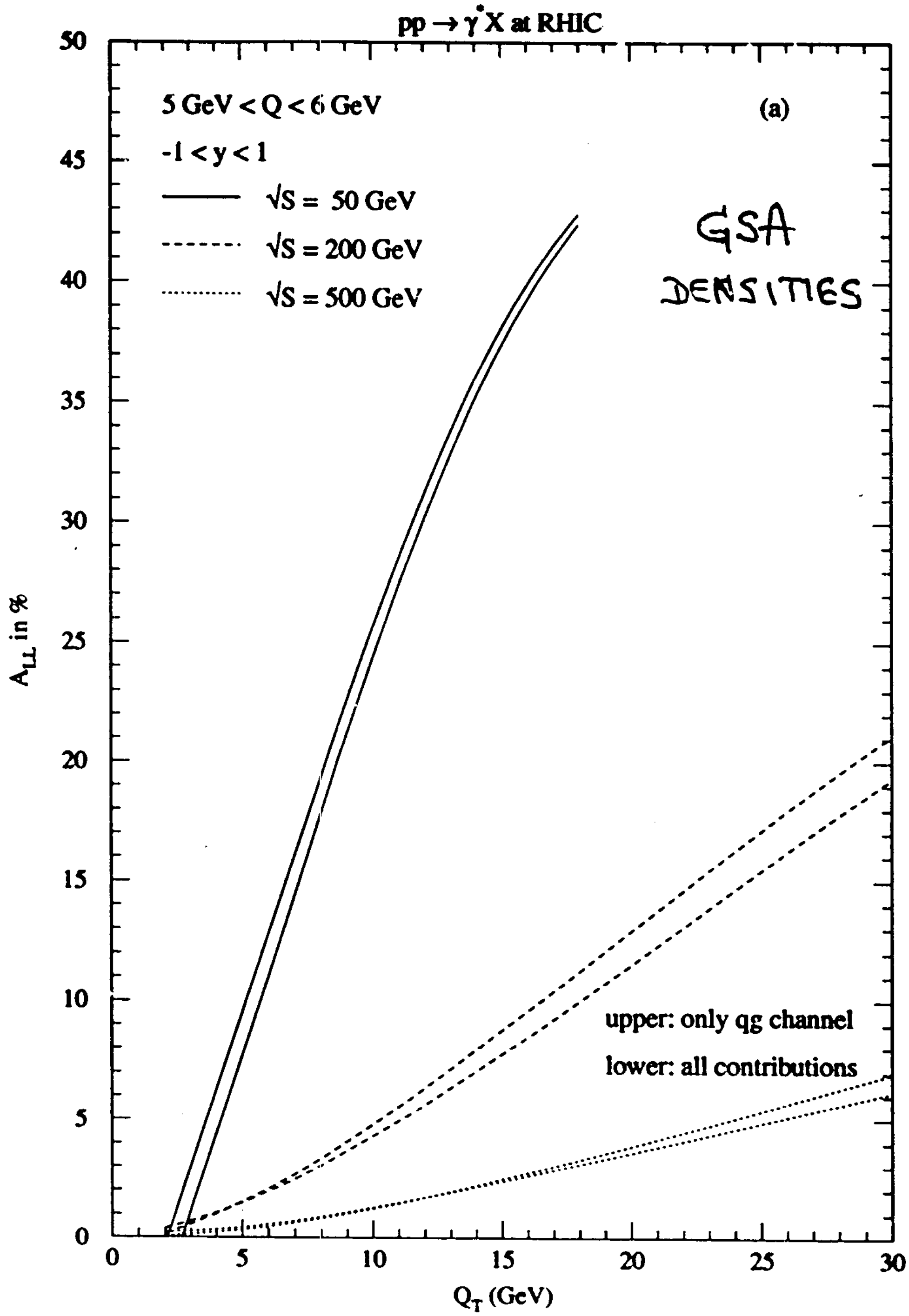
- *Drell-Yan* results for the RHIC collider at three energies; intermediate value of mass; central rapidity region

PREDICTIONS FOR $A_{\rm LL}$ - THREE CHOICES OF $\Delta G(x)$



- The qg channel accounts for most of $A_{\rm LL}$ when $A_{\rm LL}$ is large

- The $q\bar{q}$ subprocess, with $\hat{a}_{\rm LL} = -1$ dilutes the effect



- *Drell-Yan* results for the RHIC collider at three energies; intermediate value of mass

REMARKS ON THE SPIN-DEPENDENT CASE

- A_{LL} is nearly independent of Q as long as Q_T is not too small; this feature should be helpful for the accumulation of statistics

- Many subprocesses can contribute small and conflicting asymmetries in all hard scattering reactions

- General Rule: Asymmetries are readily interpretable only in situations where the basic dynamics is dominated by one major subprocess and the overall asymmetry is sufficiently large

- For the Drell-Yan (and real prompt photon) case, if A_{LL} itself is small, the contribution from the qg subprocess cannot be said to dominate the answer

- If a large asymmetry is measured, calculations show that the answer is dominated by the qg contribution, and data will serve to constrain $\Delta G(x, \mu_f)$

- If $\Delta G(x, \mu_f)$ is small, e.g., the GSC parton set, or at small Q_T for all parton sets, no information could be adduced about $\Delta G(x, \mu_f)$, except that it is small

- For Q_T not too small, A_{LL} is well described by a scaling function $A_{LL}(\sqrt{S}, Q_T) \simeq h_{\gamma^*}(x_T)$

SENSITIVITY TO QUARK DENSITIES?

- qg Compton subprocess is dominant, but will uncertainties in the quark density compromise the possibility to determine the gluon density?
- Recall (Berger and Qiu): when the Compton subprocess is dominant
- spin-averaged cross section:

$$\frac{Ed^3\sigma^{l\bar{l}}_{h_1h_2}}{dp^3} \approx \int dx_1 dx_2 \left(\frac{F_2(x_1)}{x_1} G(x_2) \frac{Ed^3\hat{\sigma}^{l\bar{l}}_{qg}}{dp^3} + (x_1 \leftrightarrow x_2) \right.$$

- spin-dependent cross section:

$$\frac{Ed^3\Delta\sigma^{l\bar{l}}_{h_1h_2}}{dp^3} \approx \int dx_1 dx_2 \left(2g_1(x_1)\Delta G(x_2) \frac{Ed^3\Delta\hat{\sigma}^{l\bar{l}}_{qg}}{dp^3} + (x_1 \right.$$

- $F_2(x,\mu_f^2)$ and $g_1(x,\mu_f^2)$ are *measured* in spin-averaged and spin-dependent deep-inelastic lepton-proton scattering.
- Massive lepton-pairs at large enough Q_T will determine the gluon density provided the proton structure functions are measured well in deep-inelastic lepton-proton scattering.

- Spin-dependence in hard-scattering processes is a complex topic; understanding is at an early stage of development.
- Several defensible approaches for extracting polarized parton densities must be pursued with the expectation that consistent results must emerge.
- Several processes for extracting $\Delta G(x, Q_T)$, each with strengths and limitations
  - inclusive/isolated prompt photon production at large p_T (with or without a tagged recoil jet)
    * *inclusive* case is theoretically clean except for the non-perturbative long-range fragmentation
    * experimenters measure *isolated* photons; contact with theory somewhat murky
  - hadronic jet production at large p_T
    * large rate
    * large number of subprocesses; complications of jet definition
  - heavy flavor production, c and b: $g + g \to c + \bar{c} + X$.
    * c is too light for reliable perturbation theory at colliders
    * b is heavy enough, but why does the measured cross section at the Tevatron exceed NLO QCD by x2 or x3?
  - the Drell-Yan process at large Q_T
    * theoretically clean
    * rate is low

Measurement of ΔG : theoretical uncertainties

D. de Florian

Institute for Theoretical Physics, ETH Zürich, CH-8093 Zürich, Switzerland

In order to measure the polarized gluon distribution it is necessary to study less inclusive processes than DIS but, unfortunately, only a few of them can be measured. Most of these processes are not used to study the unpolarized gluon distribution since they are affected by large theoretical uncertainties. In the polarized case one can not afford not using them and, therefore, it is important to know to which extent the available theoretical calculations can be trusted.

In this talk I summarize the uncertainties of theoretical calculations for jet and prompt photon production in *pp* collisions and 2 hadron production in *ep* collisions by looking at the scales dependence of the theoretical results and comparing them with available data in the unpolarized case.

In the case of jet production, it is found that the NLO corrections reduce drastically the scale dependence to less than 10% showing an excellent perturbative stability and a very good agreement with the unpolarized data in a wide kinematical range. From such a measurement it would be possible to pin down the polarized gluon distribution in the range of $0.05 > x > 0.2$ by analysing the data in a similar way as done by the CTEQ collaboration in the unpolarized case.

For prompt photons, the scale dependence is still large, but the most serious problem comes from the necesity of introducing an artificially large value of 'intrinsic' transverse momentum for the partons in order to understand unpolarized data. There were many theroretical improvements in the last two years in the subject and it is possible that a full solution will appear by the time RHIC begins the analysis of the data. In any case it is possible to study first unpolarized RHIC data to obtain from there the needed k_T and use it for the analysis of the asymmetries in a rather safe way.

For 2 hadron production in *ep* collisions, I mainly concentrate on recent data published by HERMES. I show that one can not apply (parton model) perturbative QCD in the kinematical range corresponding to HERMES data and that, therefore, no information about Δg can be obtained from it, on contrary with claims from the HERMES collaboration.

Motivations

- Objective of this talk: How well do we know $d\sigma^{TH}$?

- Important reasons:
  - Can we trust studies on sensitivity?
  - TH uncertainties will be reflected in $\delta(\Delta G)$
  - In the worst scenario, if TH not under control, when data come we will have to unknowns: ΔG and the procedure to extract it from the data!

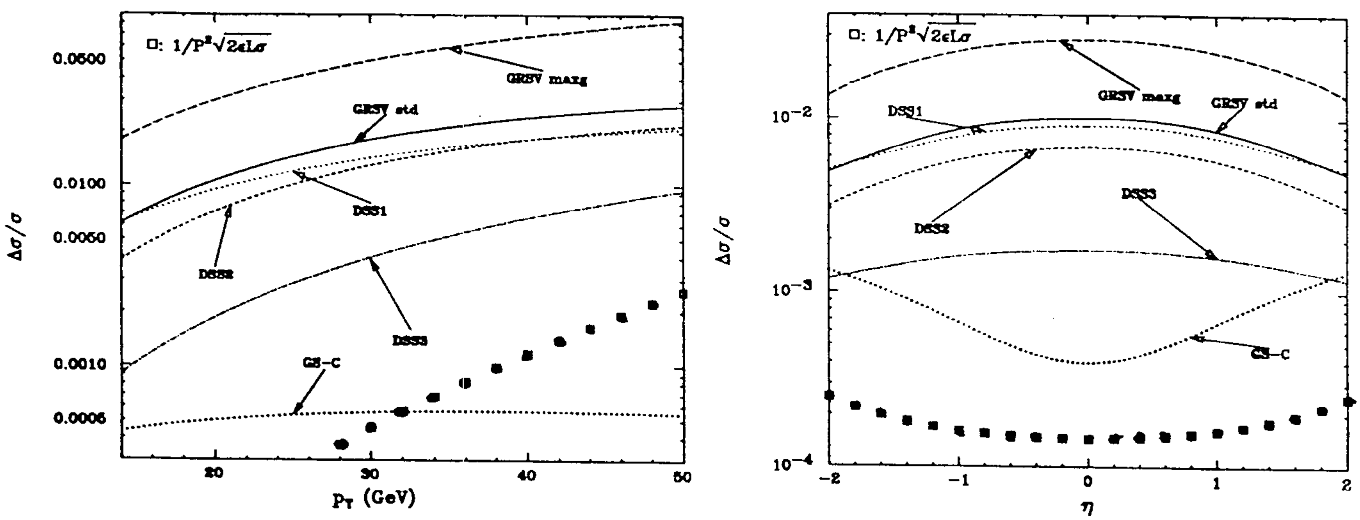
- Advantage for polarized physics: check how it works for unpolarized cross-sections and learn from it $d\sigma^{TH}$ vs DATA

- To avoid problems like the following example: Photoproduction of $\pi^{\pm}$ at SLAC(E155) $ep \to \pi^{\pm}(p_T) \quad (Q^2 \simeq 0)$

D.deF, S.Frixione, A. Signer, W.Vogelsang (1998) NLO

Jet production in pp: Sensitivity to ΔG

- Asymmetries at RHIC: $\epsilon = 1$, $P = 0.7$ and $\mathcal{L}$=100 pb^{-1}
  - p_T distribution $|\eta| < 1$, ES D=1 (p_T bin size 2 GeV)
  - η distribution $p_T > 15$ GeV (η bin size 0.2)

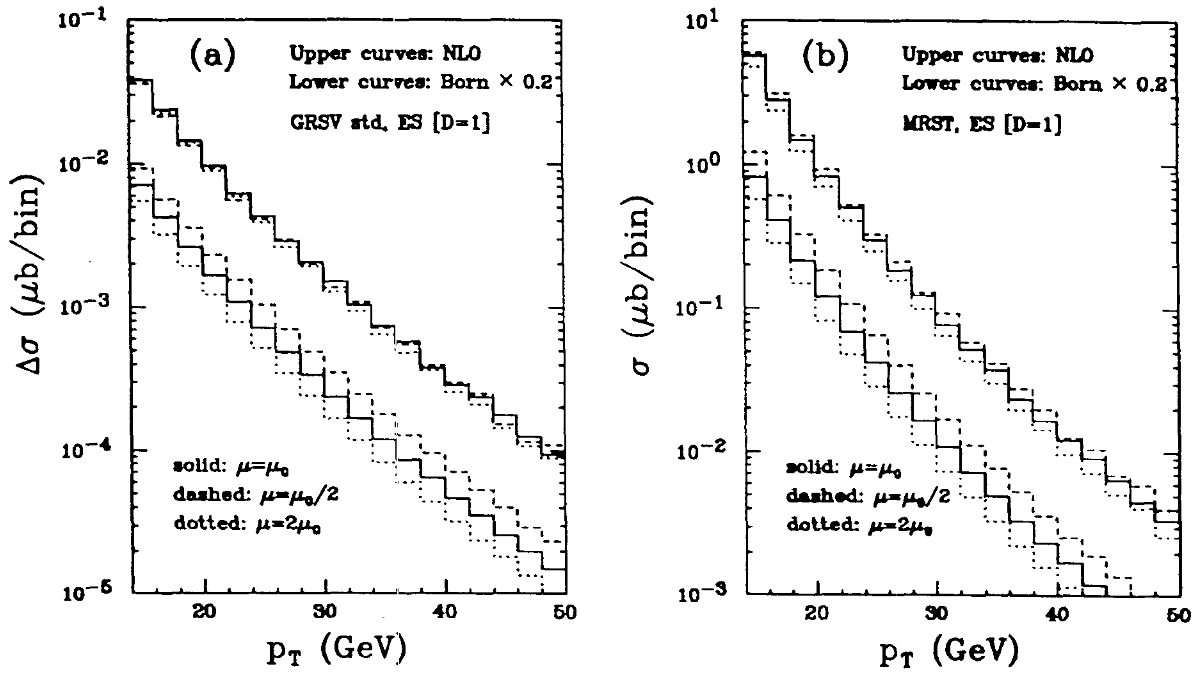


- Large sensitivity to Δg due to dominance of gg and qg initial states: not spoiled by NLO corrections ⇑
- p_T distribution more sensitive to 'size' of Δg $x \sim 0.05 \to 0.2$
- η distribution also sensitive to 'shape' of Δg
- Similar situation for different cuts, less inclusive observables and other jet definitions (see next slides)
- Excellent prospects to obtain Δg from RHIC data

Jet production in pp: Perturbative stability

D.de F., S. Frixione, A. Signer, W. Vogelsang (98)

- Single-jet production (ES D=1) at RHIC $\sqrt{s} = 500$ GeV, $|\eta| < 1$ and $\mu_R = \mu_F = \mu_0 = \frac{1}{2}\sum_i k_{iT}$



- Scale dependence substantially reduced from LO to NLO: less than 10% ! TH well under control ⇑

- NLO corrections moderate (to Born): affect the asymmetry ~ 20% (at the default scale!)

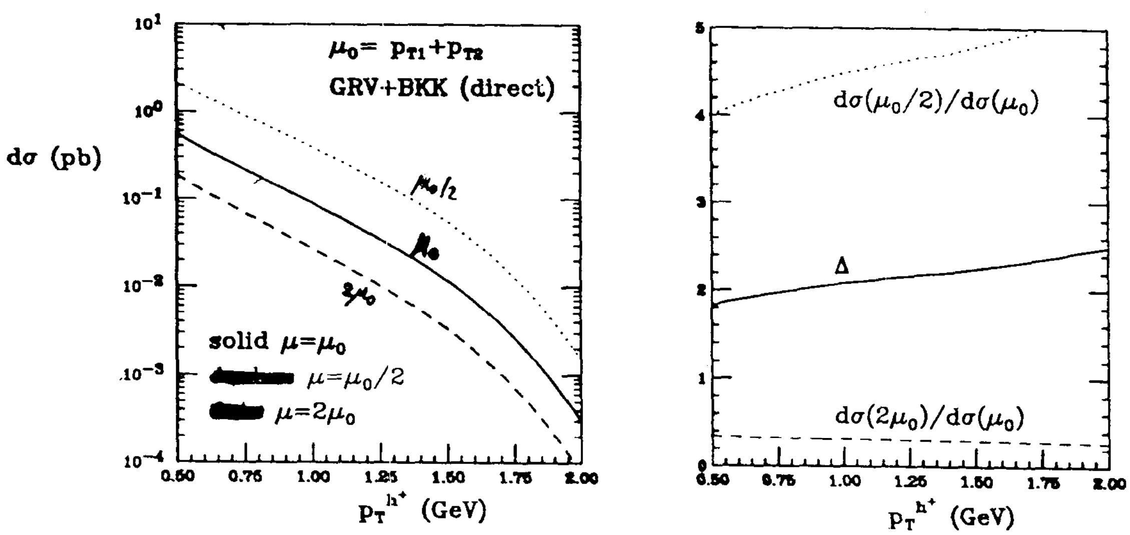
- The same happens for other pdfs and rapidity distribution

- Comparison to unpolarized data: very good agreement ⇑

- Excellent prospects to obtain Δg from RHIC data with a NLO analysis (like CTEQ does for the un-

Photoproduction of two hadrons

- Correlations between h^+ and h^- increase the sensitivity on ΔG
  A. Bravar, D. von Harrach, A. Kotzinian (1997)
- For Compass, $x \sim 0.1$
- Hermes measured $p_T^{h_1}$ distribution ($0.6 < p_T^{h_1} < 2$ GeV) requiring $p_T^{h_2} > 1.5$ GeV
- One can expect problems (soft contributions): kinematically similar to SLAC
- Look at the scale dependence of the unpolarized cross-section (direct contribution): only LO available
  D. de F., M. Stratmann, W. Vogelsang (~~1999~~ 2000)



- Scale dependence very large due to small scales and kinematics close to end of phase space. pQCD valid?
- Theoretical uncertainty so large that no conclusion about ΔG can be drawn from the measured asym-

Conclusions

- I have summarized which are the main TH uncertainties for processes that will be relevant for the extraction of ΔG

- Summarizing:
  - Jet production: Rather small TH uncertainties and large sensitivity to gluons **(NLO)**
  - Prompt photons: Large TH uncertainties due to scale dependence and large k_T effects: need to measure unpolarized cross-section to 'fix' k_T (μ) to use it in the polarized case. TH improvements in last years, solution close? **(NLO)**
  - Charm photoproduction: Large TH uncertainties due to scale dependence and m_c: need to measure unpolarized cross-section to 'fix' m_c (μ) to use it in the polarized case **(NLO)**
  - Two hadrons: Only known to **LO** accuracy yet. Non-perturbative effects expected to be important at Hermes kinematics. For Compass NLO can help, but TH uncertainties will be probably still large: compare to unpolarized cross-section

- Since the analysis of most of these processes still implies large TH uncertainties (effective procedures), a global fit will be needed as a check of consistency of all the extractions of Δg

- All these processes can give information about Δg at medium and large $x \rightarrow$ another reason to measure unpolarized cross-section: still large uncertainties on g

Measurement of Asymmetry for Pion Production in PHENIX

Yuji Goto

RIKEN BNL Research Center

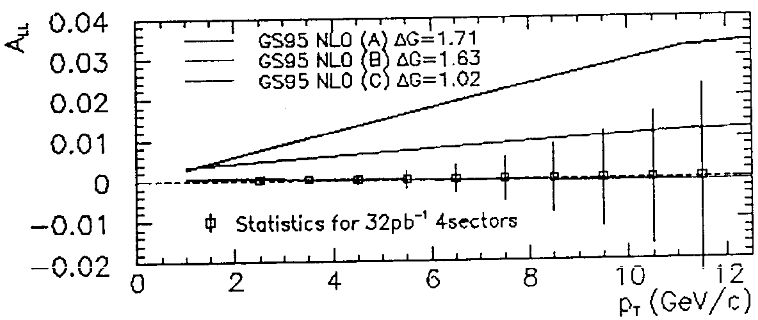
We plan to measure the gluon polarization in the PHENIX experiment. Many channels of physics signals can be detected to do it by using both the Central Arms and the Muon Arms. We have presented asymmetry measurements of the prompt photon and π^0 with EM calorimeters in the Central Arms. The measurement of π^0 serves as an alternative to the jet measurement in the limited acceptance. We will have high enough statistics of this measurement in the first year of the RHIC polarization proton run, although we need to wait full luminosity in the second year for the prompt photon measurement to obtain much enough data. As a natural extension of the π^0 measurement, we can measure asymmetry of charged pions in the Central Arms to extract the gluon polarization.

Because of different fragmentation functions from specific partons to charged and neutral pions, the asymmetry of the charged and neutral pions should be different. By utilizing this property, charged hadron measurements of the polarized DIS experiments like HERMES or SMC achieve flavor decomposition of the quark polarization. In the polarized proton collision, measurements of the charged and neutral pions needs to be interpreted by considering contributions of quark–quark, quark–gluon and gluon–gluon reactions.

There are many more uncertainties to be considered, fragmentation functions, parton densities, scale dependence, etc. It is more difficult to extract flavor decomposition information of the quark polarization than the case of the polarized DIS experiments. One clear gain of the charged pion measurements adding to the neutral pion measurement is to obtain 3 times more data for the gluon polarization measurement. In order to take the charged pion data experimentally, we need discussion about trigger for high p_T charged particles.

π^0 production

- ΔG information
  - alternative to jet measurement in the small acceptance
  - high statistics
  - clear particle identification
- Asymmetry measurement
  - PYTHIA simulation with GRV94LO
  - $\sqrt{s} = 200$ GeV
  - 10% luminosity 1year (32pb^{-1})



π^0 Asymmetry

- Background information for prompt photon measurement

Extension to charged pions

- Fragmentation function

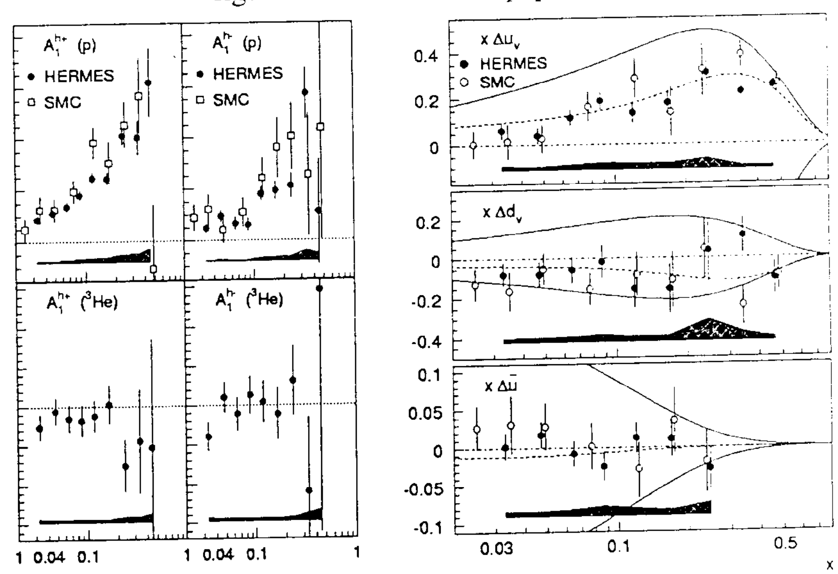
$$D^{\pi^0}_{u,d} \neq D^{\pi^+}_{u,d} \neq D^{\pi^-}_{u,d}$$

➔ Asymmetry

$$A^{\pi^0}_{LL} \neq A^{\pi^+}_{LL} \neq A^{\pi^-}_{LL}$$

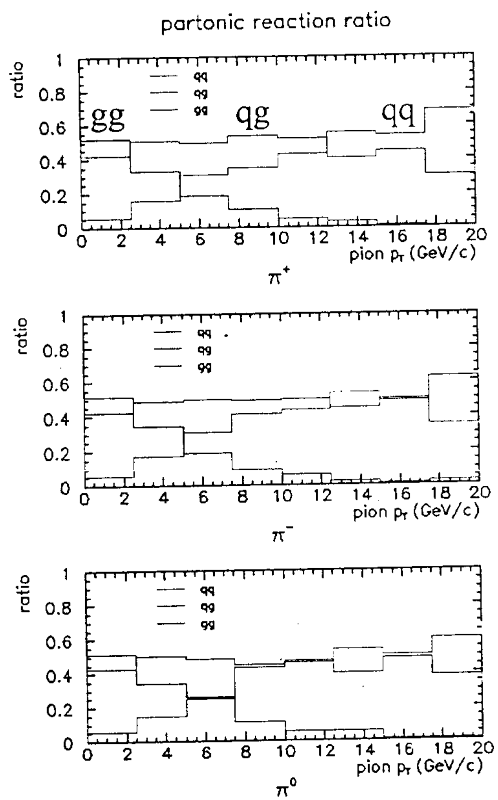
- *cf.* DIS semi-inclusive h^+/h^- measurement
  - HERMES [PLB 464 (99) 123.]
  - SMC [PLB 420 (98) 180.]
  - flavor decomposition of the quark polarization

figures from HERMES paper



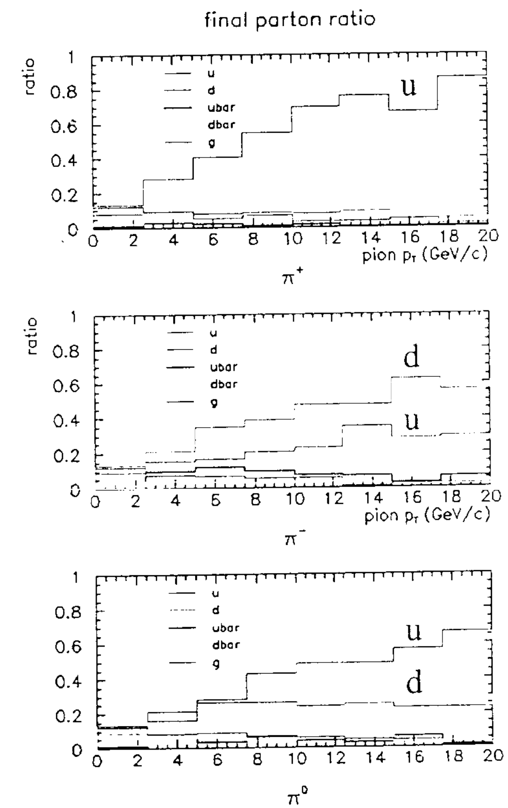
Simulation study

- PYTHIA6 simulation
  - string fragmentation – Lund model
  - with GRV94LO PDF
  - signal only, perfect particle-ID
  - $\sqrt{s} = 200$ GeV
- Parton reaction ratio



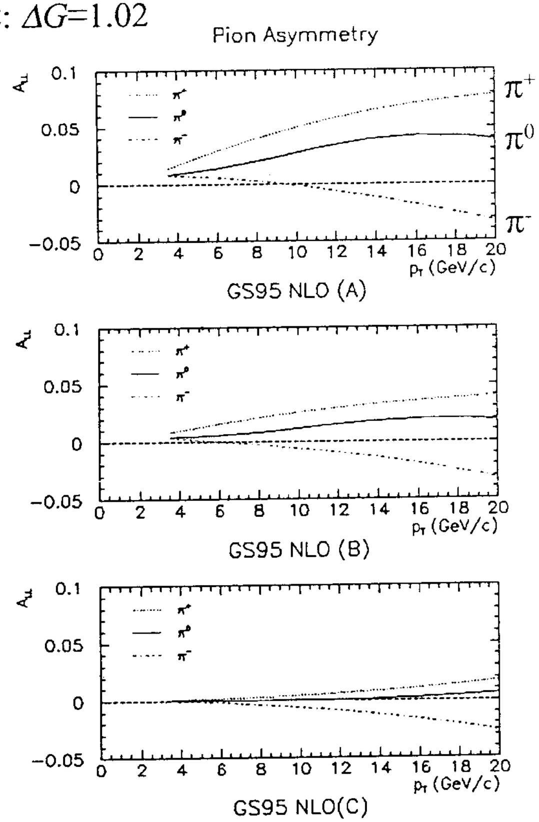
Final parton ratio

- Fragmentaion process
  - difference between charged and neutral pions
  - π^+ - u-quark dominant
  - π^- - d-quark dominant
  - π^0 - u and d



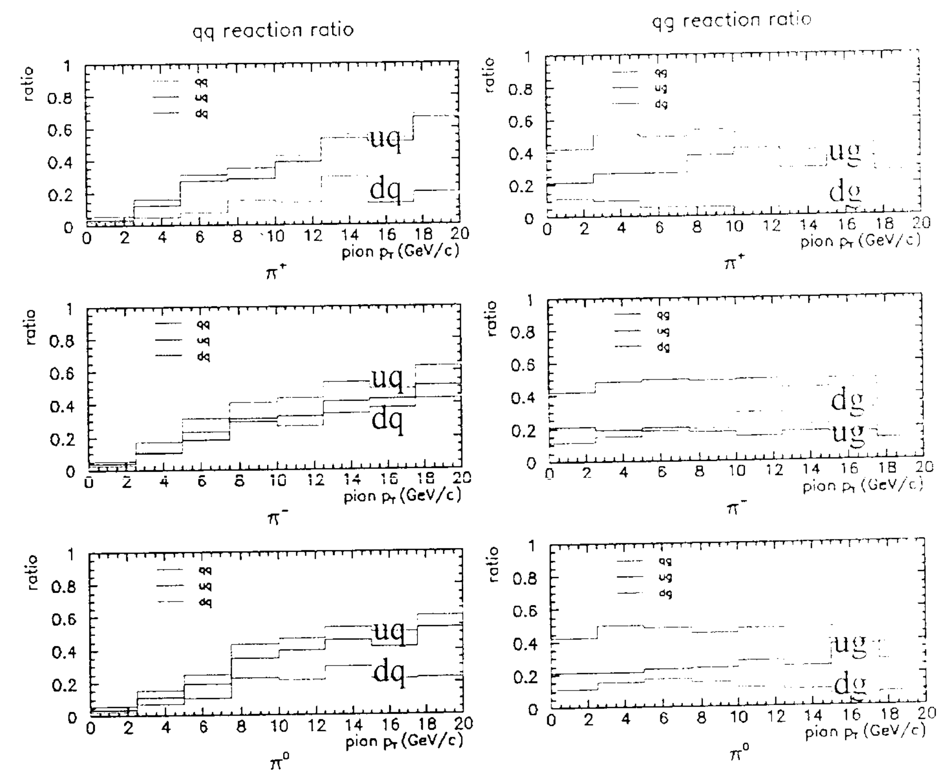
Pion asymmetries

- Different asymmetry between charged and neutral pions
- Comparison of 3 Gehrmann-Stirling models
  - A: ΔG=1.71
  - B: ΔG=1.63
  - C: ΔG=1.02



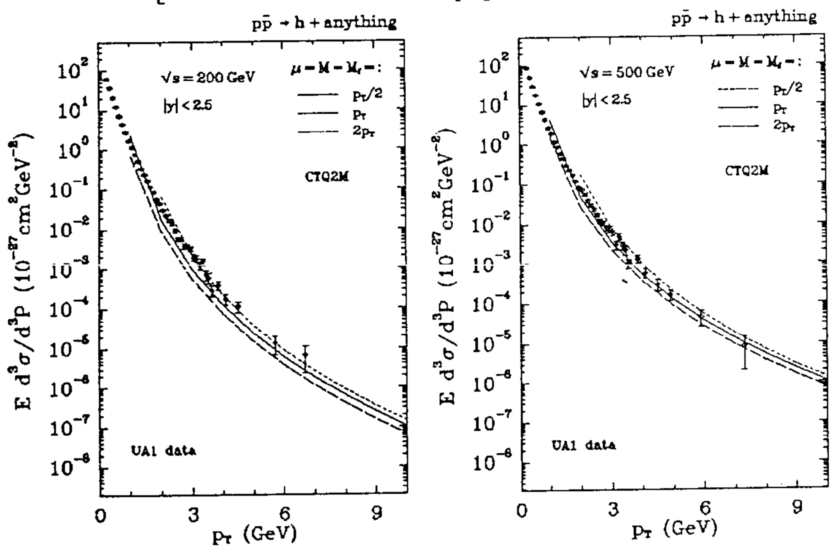
Initial parton ratio

- To probe the quark polarization …
  - but, not so significant …



Uncertainties

- Fragmentaion functions
- Fragmentaion mechanism
  - factorization theorem ←→ event generator
  - Can we really evaluate pion asymmetries by using event generator ?
- PDF
  - qq + qg + gg contributions
  - especially at low p_T (< 5 GeV/c)
- Scale dependence
  - not significant for $\sqrt{s}$ > 60 GeV
    [P. Aurenche et al. hep-ph/9910252]



[F.M. Borzumati, G. Kramer, hep-ph/9502280]

Fragmentation function

- BKK fragmentation function
  [J.Binnewies, B.A.Kniel, and G.Kramer, PRD 52 (95) 4947.]
  - LEP (ALEPH + OPAL) + PEP (TPC) data
  - fragmentation to $\pi^+ + \pi^-$
  - large uncertainties at high-z
    - PHENIX: z = 0.6 – 0.7
  - large uncertainties in the gluon fragmentaion

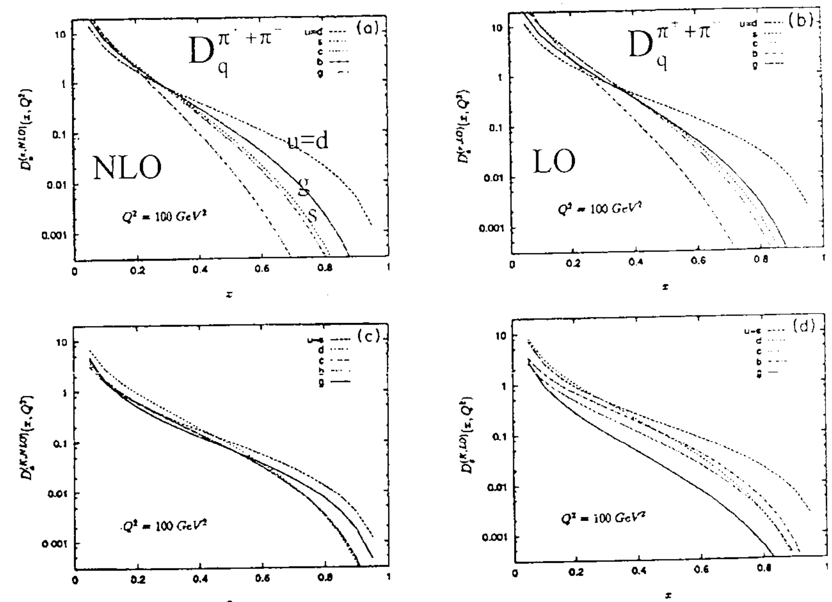


FIG. 1. x dependence of the FF's at $Q^2 = 100$ GeV^2 for (a) charged pions at NLO, (b) charged pions at LO, (c) charged kaons at NLO, and (d) charged kaons at LO.

Fragmentation function

- EMC data
  [NPB 321 (89) 541.]
  - u-quark fragmentation to π^+ and π^-
  - charge conjugation for d-quark fragmentation

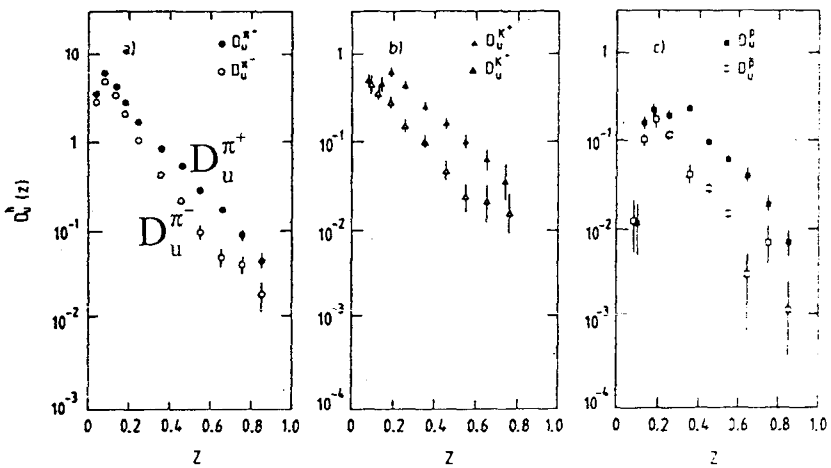


Fig. 5. Fragmentation functions of the u quark into pions (a), kaons (b) and protons (c) vs. the energy fraction z. The errors shown are the statistical errors.

Questions (as a summary)

- By taking charged pion asymmetry data …
  - flavor decomposition data of the quark polarization ?
  - for the gluon polarization measurement, we obtain 3 times more data (using existing quark polarization data)
- To take charged pion asymmetry data …
  - trigger for high p_T charged particles
    - $p_T > 5$ GeV/c only ?

Non-leading corrections for Monte-Carlo event generators

John Collins
Physics Department, Penn State University,
University Park PA 16802, U.S.A.

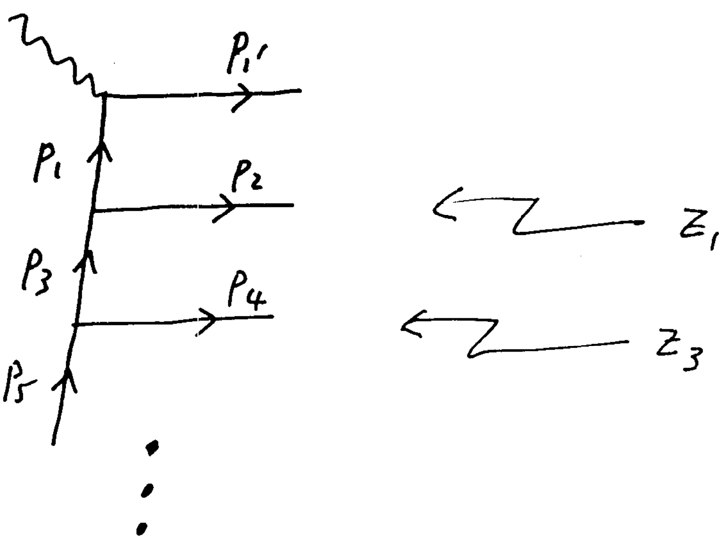
This talk summarized results from my preprint hep-ph/0001040.

Monte-Carlo event generators are a very useful tool for analyzing data on hard scattering, because they provide predictions for the whole final state. However, at present they are limited to a somewhat improved leading logarithm accuracy. "Analytic" calculations, in contrast, provide systematically improvable predictions (in powers of $\alpha_s(Q)$), but do not make detailed predictions about the final state. Improvement is urgently needed for the event generators. This is particularly the case when the LO subprocesses are induced by a small parton density and some NLO subprocesses involve large parton densities. A particular example is deep-inelastic scattering in the small-x and diffractive regions.

I explained a new subtractive method to incorporate NLO corrections, with its application to the photon-gluon fusion process. Two classes of events are generated: LO events, as at present, and NLO events. The partonic hard scattering cross section for the NLO events is the basic NLO parton-level cross section, but with a subtraction of the approximation to it that is in the LO Monte-Carlo. The result is a hard cross section that is collinear finite. Particular attention must be paid to a consistent definition of the kinematics and a modification to the standard Bengtsson-Sjöstrand algorithm is proposed. Adjustments to the algorithm can be made to reduce the number of negative weighted events.

Generalizations to other processes can be made, including those of interest at RHIC and in polarized scattering. Technical difficulties will involve the treatment of real and virtual soft gluons. The generalizations can also include NLO corrections to the showering, i.e., to the DGLAP evolution. When this program is completed, Monte-Carlo event generators could be at least as precise in their predictions as analytic calculations.

Tricky problem — definition of kinematics



$$\frac{p_1\cdot(p_1+q)}{p\cdot q} = x_1 \qquad\qquad = x$$

$$\frac{p_3\cdot(p_3+q)}{p\cdot q} = x_3 = \frac{x_1}{z_1} \qquad\qquad = \frac{x}{z_1}$$

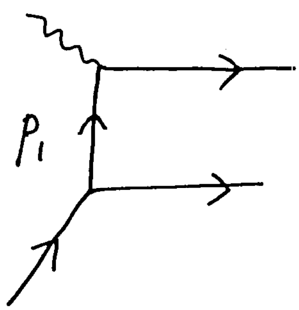
$$\frac{p_5\cdot(p_5+q)}{p\cdot q} = x_5 = \frac{x_3}{z_3} = \frac{x_1}{z_1 z_3} \qquad\qquad = \frac{x}{z_1 z_3}$$

$\vdots$

w' virtualities & azimuths give p_1^μ &c (Bengtsson-Sjöstrand) — scalars from MC

Inconsistency.

One equation too many.



Given: p_1^2, $x_1 = x$, $x_3 = x/z_1$, ϕ.] 4

Need x_3, ϑ, ϕ.] 3

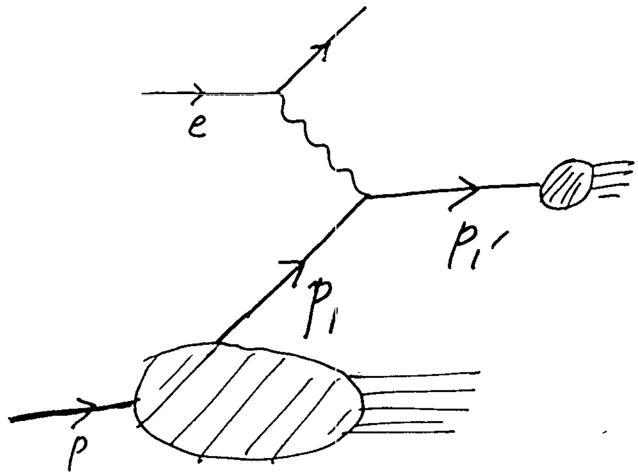
(+ external virtualities)

Solutions

1. Modify equations (Bengtsson-Sjöstrand); used in PYTHIA
2. Drop an equation (JCC).

General approach to NLO

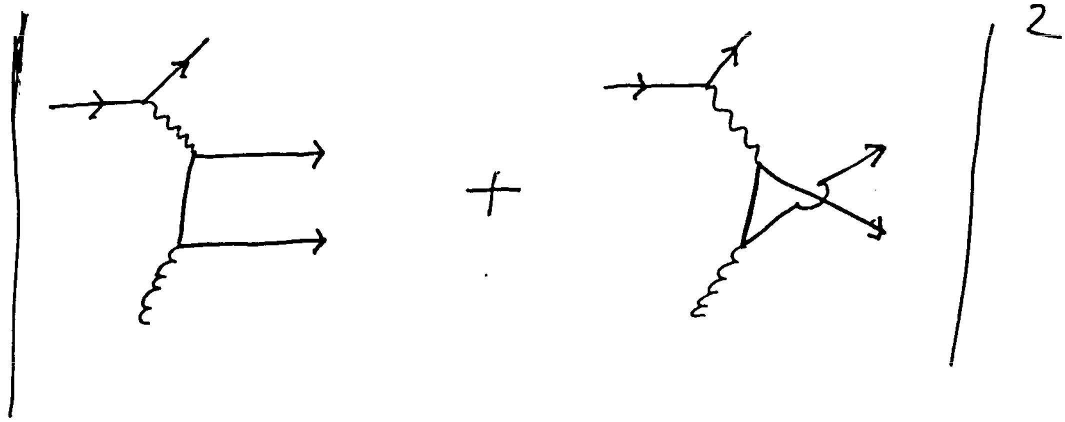
1. Start from smallest hard scattering:

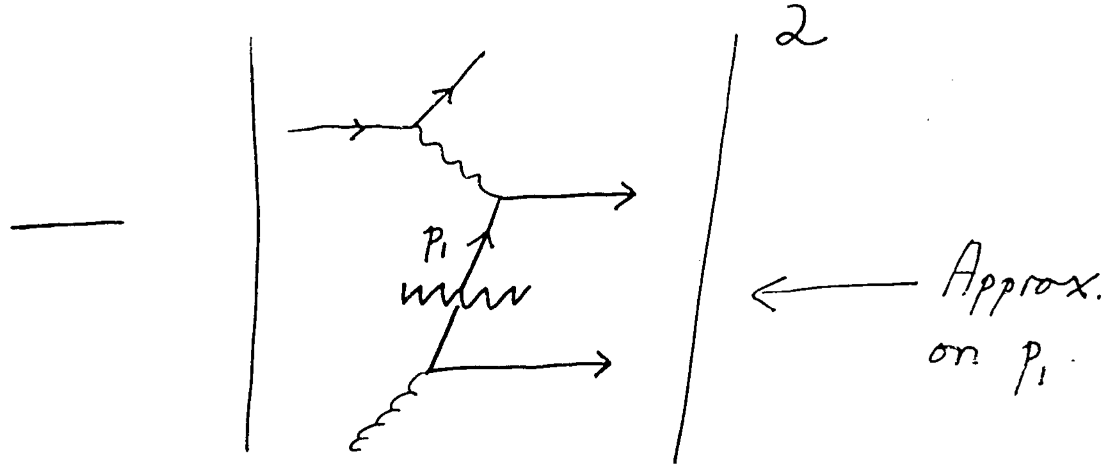


Approximation for $|p_1^2|, p_1'^2 \ll Q^2$, extrapolated to $p_1^2, p_1'^2 \sim Q^2$.

2. Consider successively larger hard scatterings. Apply subtractions for approximate calculation in lower order hard scattering

Essentially — expansion in $\alpha_s(Q^2)$.



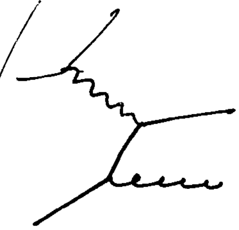


- All times gluon density
- Care needed — approximation must be EXACTLY the same as in MC.
- Jacobians of changes of variables
- "4-momentum conservation".
  (Analytic calcs. replace actual momenta by nearby unphysical momenta.)

Summary

- Need for NLO corrections in MCs.
- $\gamma^* g \rightarrow \bar{q} q$ is most urgent.
- Have constructed NLO term with subtraction term — 2nd class of event.
- Previous attempts — reweighted LO + showers to reproduce analytic calc.
  - — can't easily generalize
  - — complicates algorithm
- Positivity issue
  - — negative weight events
  - — or modify LO xsect. & use generalized RG.

Future

1. $\gamma^* q \to q g$ term ( &c.)

Need to treat:

final-state collinear emission

→ soft emission ←

virtual graphs w/ collinear & soft regions.

Cf. overlapping UV divergences

2. Generalize to other processes.

3. Generalize to the showering (NLO evolution)

If all this is achieved, then MC event generators will be as precise as analytic calculations.

Small Q_T factorization and resummation

Csaba Balázs
Department of Physics and Astronomy, University of Hawaii,
Honolulu, HI 96822, U.S.A.

March 16, 2000

The standard factorization formula for weak boson production fails when the transverse momentum (Q_T) of the weak boson is much smaller than its invariant mass (Q). A symptom of this is the two very different scales in the hard scattering function producing large logarithms of the form $\ln(Q_T/Q)$. The failure of the standard factorization occurs because it neglects the transverse motion of the incoming partons in the hard scattering.

As proved by Collins, Soper, and Sterman (CSS), small Q_T factorization gives the cross section as a convolution of transverse momentum distributions. This treatment formalizes the intuitive notion that partons have transverse momentum and that this transverse momentum gives rise to the transverse momentum of the weak boson. A consequence of the properties of soft-gluon emission, proved by CSS, is a particular form of the evolution equations for the k_T-dependent parton densities. These equations are the generalizations of the DGLAP equations. Just as in the DGLAP case, although their evolution is predicted by perturbative QCD, the non-perturbative component of the k_T dependent parton distributions have to be extracted from experiments.

Because the CSS formalism is designed to treat correctly the $Q_T \ll Q$ region, it also provides an appropriate resummation of the large logarithms, $\ln(Q/Q_T)$ in the standard factorization formula. The formalism also matches the low Q_T (resummed) to the high Q_T region, where the traditional factorization theorem is reliable, thus predicting a distribution which is valid for all values of Q_T.

This extended factorization formalism is applied to calculate the transverse momentum (and other distributions) of vector bosons, inclusively produced in hadronic collisions. The perturbative uncertainties of the CSS formalism are examined by varying the new renormalization scales which arise in the course of the resummation.

The understanding of weak boson signals at hadron colliders depends upon the understanding of the effects of the soft-gluon emission from the initial state partons. Since Monte Carlo event generators are heavily utilized to simulate these effects, it is crucial to establish the reliability of their predictions. After a short comparison of the main features of resummation and the parton shower formalism, predictions of transverse momentum distributions for various weak boson production processes are compared at various center of mass energies and hadronic initial states. This comparison is useful in understanding the strengths and the weaknesses of the different theoretical approaches, and in testing their reliability.

Comparison of the resummed predictions to existing Tevatron data is also performed for various processes. The resummed prediction are in very good agreement with the inclusive $W^{\pm}$ and Z^0 production data, which latter are precise enough to constrain the perturbative and non-perturbative uncertainties of the low Q_T factorization formalism. The resummed predictions for diphoton production are also consistent both with the collider and fixed target data.

Low Q_T factorization

"Cogito ergo resum!" Modified Descartes

Collins, Soper, PRL48 ('82) 655,

NPB193 ('81) 381, 197 ('82) 446

Collins, Soper, Sterman, NPB250 ('85) 199

— Modified factorization theorem:

$$\frac{d\sigma}{dQ_T} = W(Q_T, Q) + Y(Q_T, Q)$$

$$W(Q_T, Q) =$$

$$\int d^2 k_T \, C(\vec{k}_T, Q) \, H(Q, Q_T) \, C(\vec{Q}_T - \vec{k}_T, Q)$$

- $C(\vec{k}_T, Q)$ are k_T dependent "parton densities"
- No need for "intrinsic k_T"
- W is simpler in transverse position (b) space

$$W(Q_T, Q) = \int d^2 b \, e^{i \vec{Q}_T \vec{b}} \tilde{W}(b, Q)$$

$$\tilde{W}(b, Q) = \tilde{C}_{a/h_1}(b, Q) \, \tilde{H}(b, Q) \, \tilde{C}_{b/h_2}(b, Q)$$

— Why b-space?

Parisi, Petronzio, NPB154 ('79) 427

- multi-gluon phase-space factorizes
- cross section factorizes $\Leftarrow F(f \otimes g) = F(f)\, F(g)$
- transverse momentum conservation is explicit
- RG invariance is preserved

Matching

Plan A.

— QCD corrections to the Q_T dist'n contain log's:

$$\frac{d\sigma}{dQ_T^2} \xrightarrow[Q_T \to 0]{} \frac{1}{Q_T^2} \alpha_s^n c_{n,m} L^m + O\left(\frac{1}{Q_T}, \delta(Q_T^2)\right)$$

$$FXO = \text{Singular } (Asy) + \text{Regular } (Y)$$

$$Y \equiv FXO - Asy$$

— After exponentiation of the singular pieces:

$$Res = W + Y$$

$$= W + FXO - Asy$$

$$W \equiv \text{"}1 - e^{-Asy}\text{"}$$

- At low Q_T: $Asy \gg Y \Rightarrow FXO \approx Asy \Rightarrow Res \approx W$

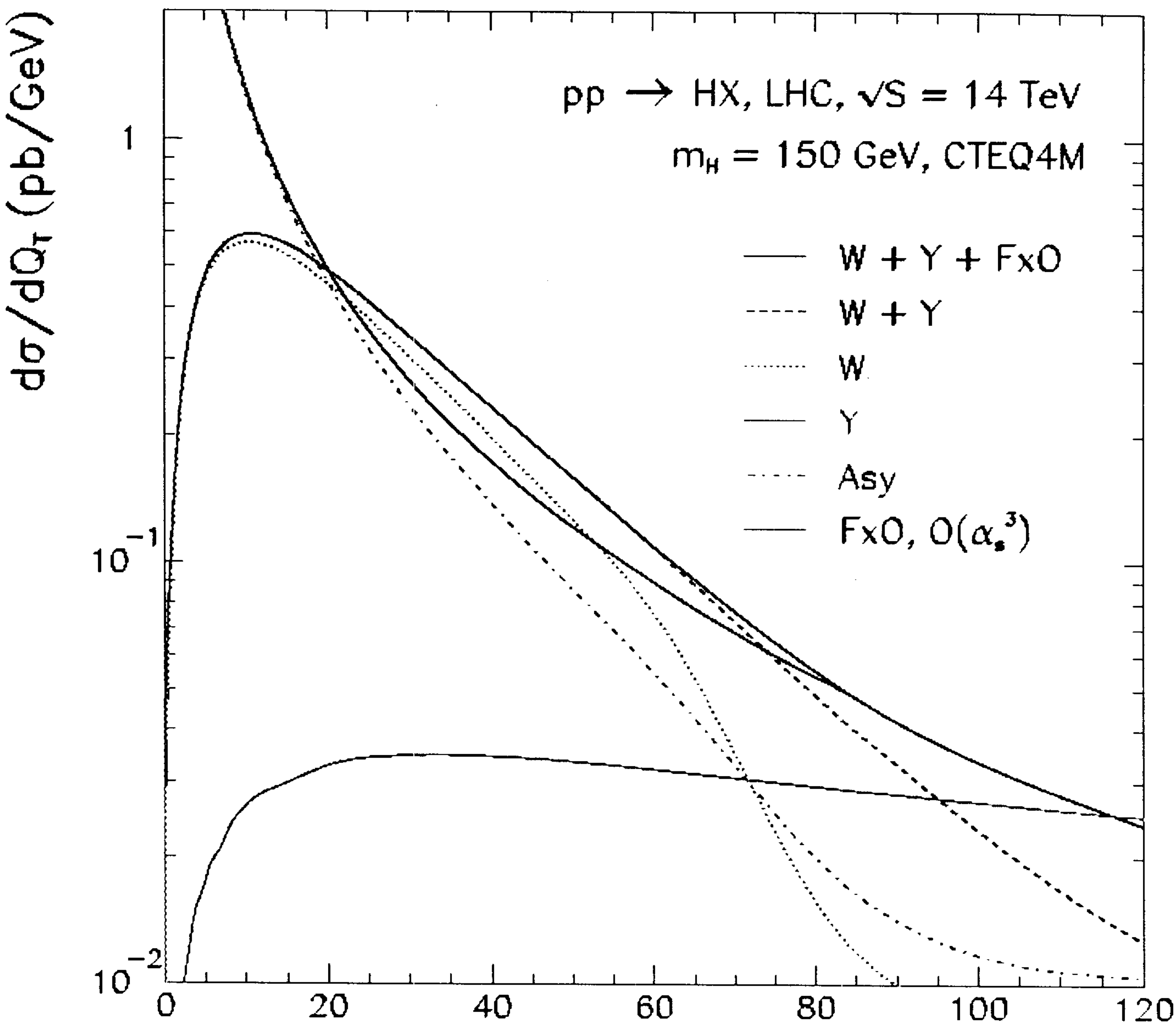
— Here's how matching works:

- At high Q_T: logs small $\Rightarrow W \approx Asy \Rightarrow Res \approx FXO$

  The correct high Q_T behavior is built in

Low Q_T factorization in one picture

— The full story of the reΣummation of $\log(Q_T/Q)$



Low Q_T factorization vs. parton shower

Balazs, Huston, Puljak, hep-ph/0002032

— Parton showers include soft gluon effects resumming logs generated by real emission of on-shell partons ⇒

• Parton showering is process independent → it's Sudakov can only include terms equivalent to $A^{(i)}$ (by default)

• Kinematic corrections → effectively include part of $B^{(1)}$

• Virtual corrections are not included → the total rate is the lowest order

• Modification of the PDF's is not included → no equivalent of $C^{(i)}$ (but cf. S.Mrenna)

• Gaussian non-perturbative smearing is included → non-perturbative treatment is different

• High Q_T matrix elements and matching are not included (but cf. ME corrs.)

— The above lead to potential differences in rate and shape between ResBos and PYTHIA/HERWIG/ISAJET/etc.

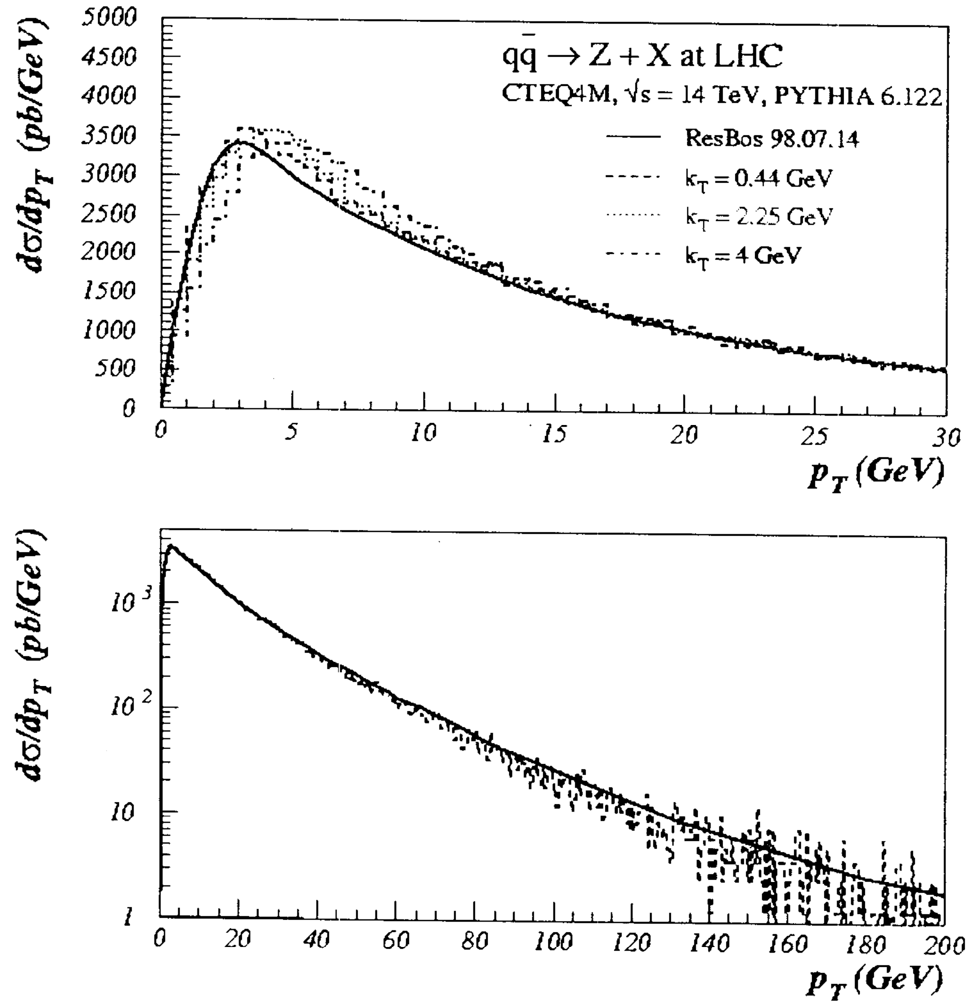
• To understand the differences we can vary the theoretical input (e.g. which $A^{(i)}$, $B^{(i)}$, $C^{(i)}$ to include, etc.) and compare numerical results

Comparison of ResBos and PYTHIA

"Why not Just run PYTHIA?" The unknown experimentalist

Balazs, Huston, Puljak, hep-ph/0002032

— The reliability of parton showers can be tested by comparing them to analytic calculations



Balazs, Huston, Puljak, hep-ph/0002032

- Dialing the non-perturbative k_T in PYTHIA, it can be tuned to agree with ResBos at low Q_T
- ME corrections in PYTHIA work well at high Q_T for Z^0 production

Comparisons of Polarized Event Generators
Oliver Martin (University of Regensburg, Germany)

Experimentalists of the RHIC Spin Program make extensive use of polarized event generators to determine asymmetries of the signal and the background, to study the reliability of the reconstruction of the kinematics of the hard partonic scattering, to estimate the unpolarized and polarized acceptance of the detector system, etc. The latter point is especially important for all measurements conducted with the PHENIX detector since its geometrical coverage is far from being perfect. Currently, two different kind of polarized event generators are in use which are both based on the unpolarized event generator PYTHIA:

- SPHINX features a correct treatment of the polarization of the partons participating in the initial state shower (ISS) and the hard partonic scattering. Therefore, it allows for a direct calculation of rates for different configurations of the helicities of the colliding protons.
- The method of weighted asymmetries (MWA) only generates unpolarized events but provides an asymmetry weight for each event which is based on a LO formula. Due to the direct calculation of the hadronic double spin asymmetry it is much faster than SPHINX but does not describe any effect of polarization in the ISS correctly.

In this presentation I try to answer two questions:

- Has the correct treatment of particle helicity in the initial state shower any observable effect?
- How well do the results of the polarized event generators agree with those of NLO QCD calculations that are performed with the help of parton generators which allow for a crude implementation of experimental cuts?

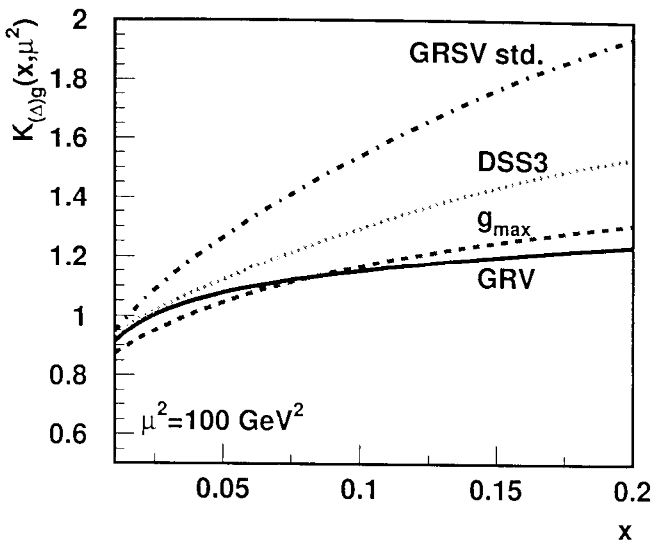
To answer both questions we study the production of γ, γJ as well as 1-jet and 2-jet inclusive observables. Of course the ultimate question to answer would be in how far the polarized event generators describe nature but, since no polarized pp data are available yet, this question has to remain unanswered at the moment.

My study yielded the following results:

- In all cases I was able to identify at least one observable which shows significant deviations between asymmetries calculated with both polarized event generator methods. I found relative differences of up to 20%. Interestingly, they nearly vanished by switching off polarization in the ISS of SPHINX. Therefore, they are a direct effect of the correct treatment of partonic helicity in the ISS, i.e. for precision studies the usage of SPHINX is recommended.
- Lacking the neccessary computer power I was only able to compare the MWA with NLO QCD for several sets of polarized parton distributions which mainly differed in the parametrization of $\Delta g(x, \mu^2)$. Aside from the fact that the absolute rates didn't agree well, which is not surprising due to the large scale dependence of the event generator results, I found a reasonable agreement of the predictions for the asymmetries. In the case of jet production, relative differences of up to 20% could be reduced to 10% by fine tuning the parton showers. For prompt photon production the relative difference of the asymmetries was below 10% for most bins. In general, predictions for very small $\Delta g(x, \mu^2)$ tend to be worse since a delicate cancellation of polarized cross sections of the various partonic subprocesses occurs here. A systematic reduction of the deviations probably requires an event generator which is based on NLO QCD instead of LO formulae.

Preliminaries

NLO α_s and NLO pdf used throughout:
GRV95, GRSV std. and $g_{\max}$, DSS3.



$$K_{(\Delta)g}(x,\mu^2) = \frac{(\Delta)g^{NLO}(x,\mu^2)}{(\Delta)g^{LO}(x,\mu^2)}$$

Start from pure Born xsec and regard NLO / parton shower effects as 'small' corrections.
ES jet algorithm with $R = 1$.

1- and 2-Jet Observables

(inspired by D. de Florian et al., Nucl. Phys. B539, 455-476 (1999).)

$$\frac{d(\Delta)\sigma}{dE_T}, \quad 14 \text{ GeV} < E_T < 50 \text{ GeV}, \quad |\eta| < 1$$

$$\frac{d(\Delta)\sigma}{d\eta}, \quad 0 < \eta < 2, \quad E_T > 15 \text{ GeV}$$

Requirements for 2-jet events:

$$E_{T,J_1} > 15 \text{ GeV}, \quad E_{T,J_2} > 10 \text{ GeV}, \quad |\eta_{J_1}| < 1, \quad |\eta_{J_2}| < 1.$$

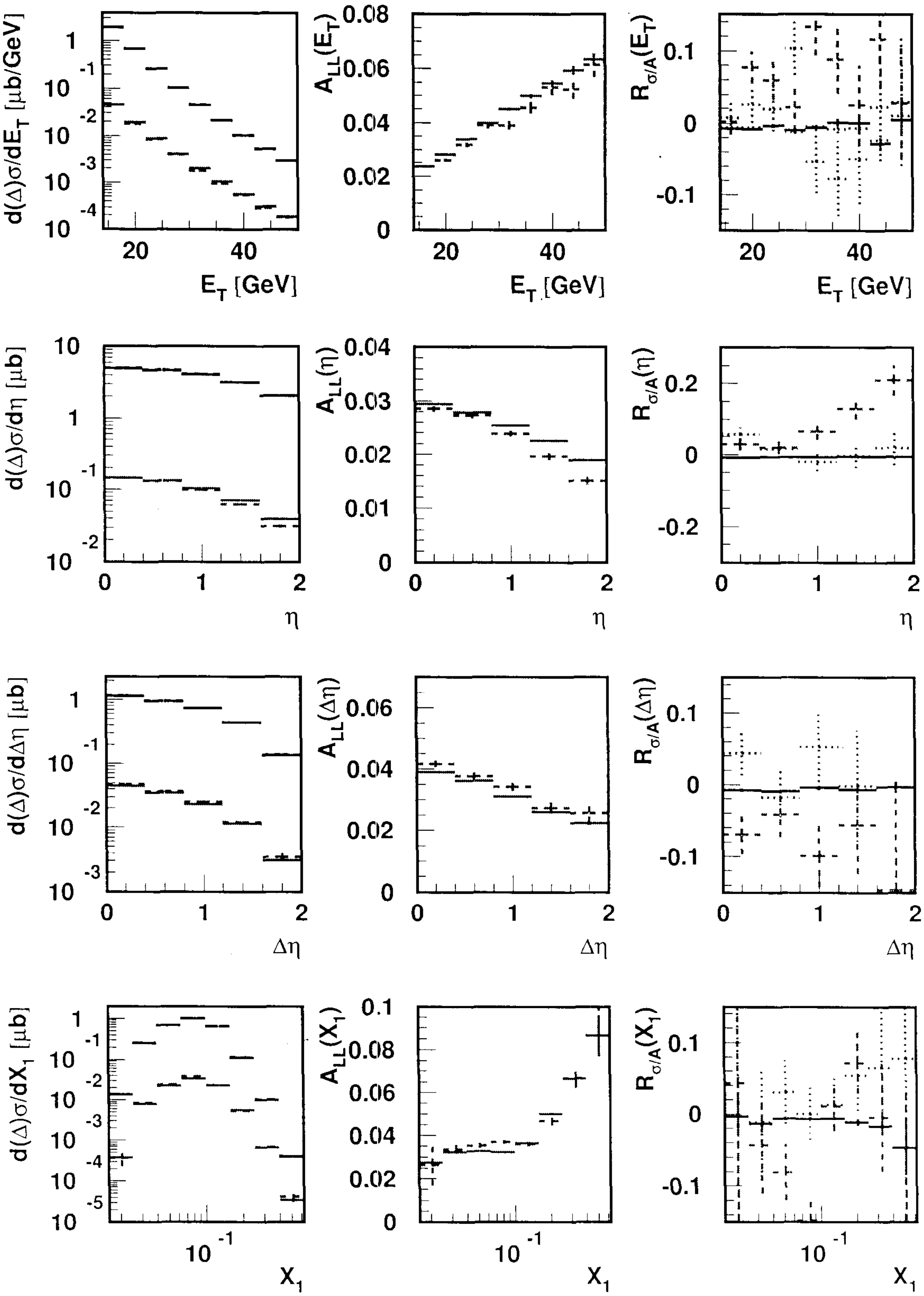
$$\frac{d(\Delta)\sigma}{d\Delta\eta}, \quad 0 < \Delta\eta < 2, \quad \Delta\eta \equiv \eta_{J_1} - \eta_{J_2}$$

$$\frac{d(\Delta)\sigma}{dX_1}, \quad X_1 \equiv \frac{E_{T,J_1}e^{\eta_{J_1}} + E_{T,J_2}e^{\eta_{J_2}}}{\sqrt{S}}$$

$$\frac{d(\Delta)\sigma}{dM_{JJ}}, \quad M_{JJ} < 100 \text{ GeV}, \quad M_{JJ}^2 \equiv (p_{J_1} + p_{J_2})^2$$

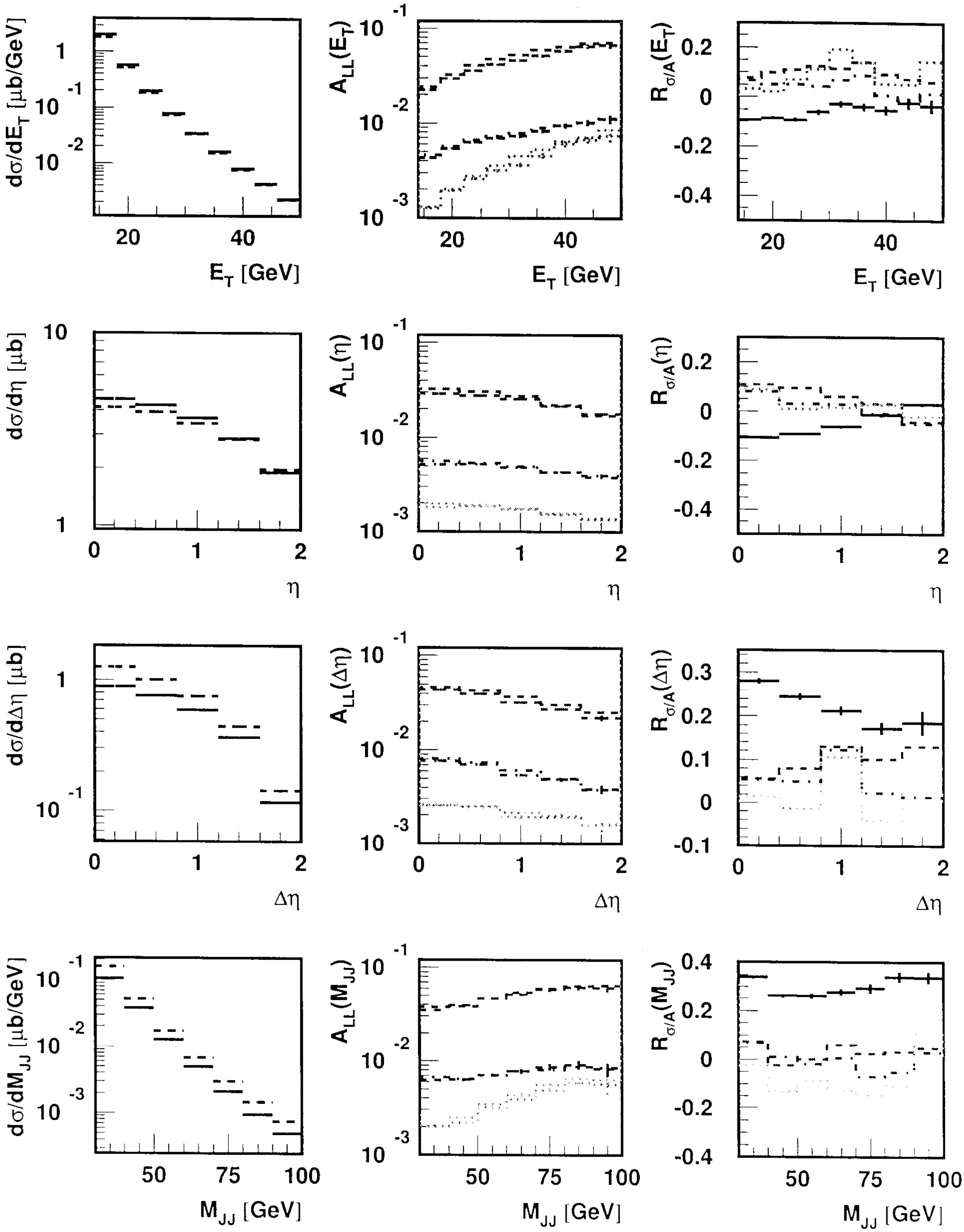
$$\frac{d(\Delta)\sigma}{d\Delta\phi}, \quad 1.6 < \Delta\phi \leq \pi, \quad \Delta\phi \equiv \phi_{J_1} - \phi_{J_2},$$

Jets - SPHINX vs. MWA



$$R_\sigma \equiv \frac{\mathrm{d}\sigma_{\mathrm{MWA}} - \mathrm{d}\sigma_{\mathrm{SPHINX}}}{\mathrm{d}\sigma_{\mathrm{MWA}}}, \qquad R_A \equiv \frac{A_{LL,\mathrm{MWA}} - A_{LL,\mathrm{SPHINX}}}{A_{LL,\mathrm{MWA}}}$$

Jets - NLO QCD vs. MWA (tuned)



$$R_\sigma \equiv \frac{d\sigma_{\text{NLO QCD}} - d\sigma_{\text{MWA}}}{d\sigma_{\text{NLO QCD}}}, \qquad R_A \equiv \frac{A_{LL\,\text{NLO QCD}} - A_{LL\,\text{MWA}}}{A_{LL\,\text{NLO QCD}}}$$

γ- and γJ-Observables

(inspired by S. Frixione, W. Vogelsang, hep-ph/9908387)

- Photon isolation according to S. Frixione, Phys. Lett. B429, 369-374 (1998) with $\delta_0 = 0.7$ $\Rightarrow$ no fragmentation contribution.
- $\sqrt{S} = 200$ GeV yields larger asymmetries.

$$\frac{\mathrm{d}(\Delta)\sigma}{\mathrm{d}p_{T,\gamma}}, \quad 10\text{ GeV} < p_{T,\gamma} < 50\text{ GeV}, \quad |\eta_\gamma| < 0.5$$

$$\frac{\mathrm{d}(\Delta)\sigma}{\mathrm{d}\eta_\gamma}, \quad 0 < \eta_\gamma < 2, \quad p_{T,\gamma} > 10\text{ GeV}$$

Requirements for γJ-events:

$$E_{T,J} > 11\text{ GeV}, \quad -1 < \eta_{J,\gamma} < 2, \quad |\Delta\phi| \equiv |\phi_J - \phi_\gamma| > \frac{\pi}{2}$$

$$\frac{\mathrm{d}(\Delta)\sigma}{\mathrm{d}\Delta\eta}, \quad 0 < \Delta\eta < 2.4, \quad \Delta\eta \equiv \eta_J - \eta_\gamma$$

$$\frac{\mathrm{d}(\Delta)\sigma}{\mathrm{d}M_{\gamma J}}, \quad M_{\gamma J} < 100\text{ GeV}, \quad M_{\gamma J}^2 \equiv (p_\gamma + p_J)^2$$

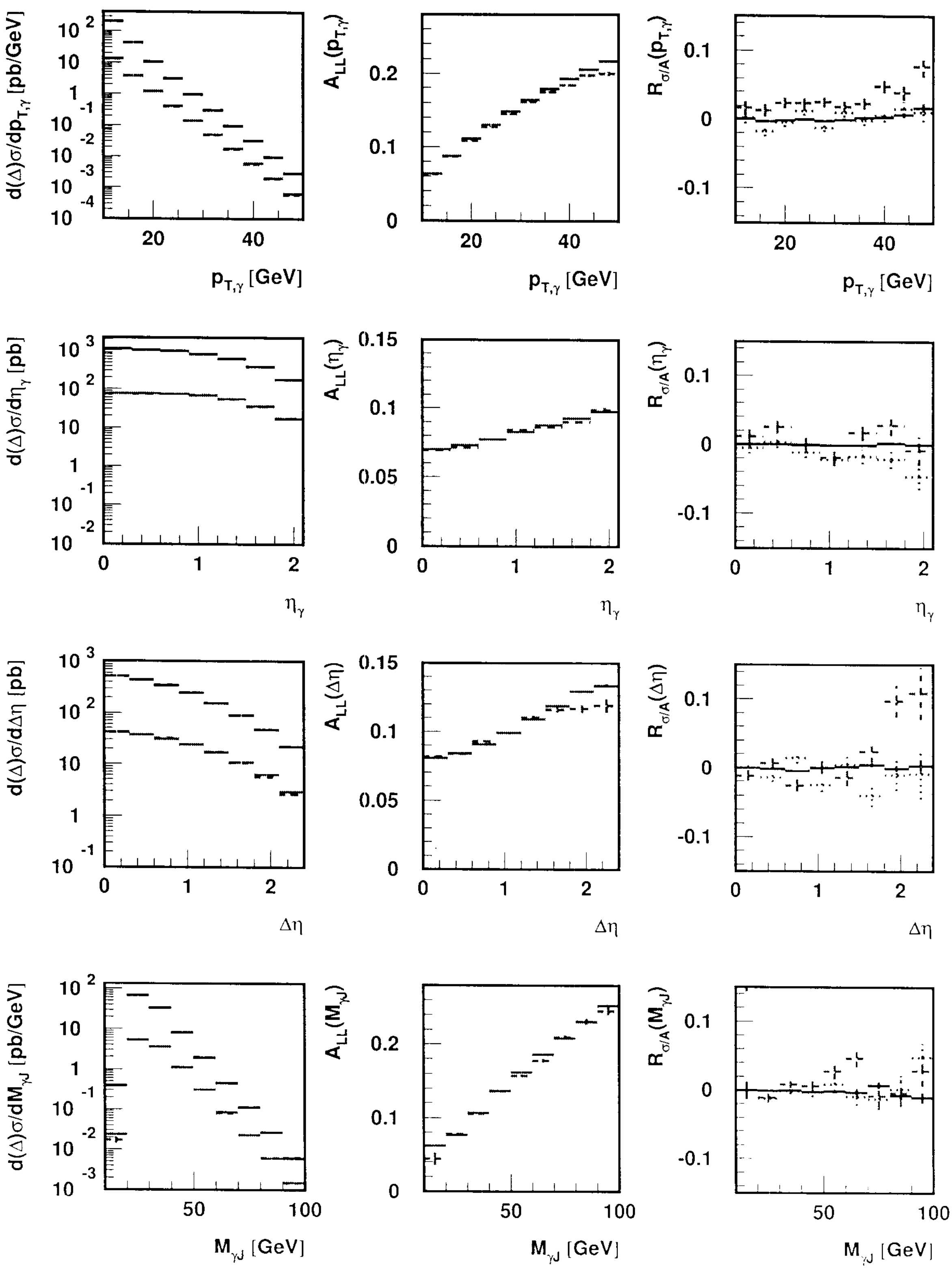
$$\frac{\mathrm{d}(\Delta)\sigma}{\mathrm{d}X_{\text{min}}}, \frac{\mathrm{d}(\Delta)\sigma}{\mathrm{d}X_{\text{max}}}, \quad 0.01 < X_{\text{min}}, X_{\text{max}} < 1,$$

$$X_{\text{min/max}} \equiv \text{min / max}\left(\frac{p_{T,\gamma}e^{\eta_\gamma} + E_{T,J}e^{\eta_J}}{\sqrt{S}}, \frac{p_{T,\gamma}e^{-\eta_\gamma} + E_{T,J}e^{-\eta_J}}{\sqrt{S}}\right)$$

$$\frac{\mathrm{d}(\Delta)\sigma}{\mathrm{d}R_{\gamma J}}, \quad R_{\gamma J} \equiv \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$$

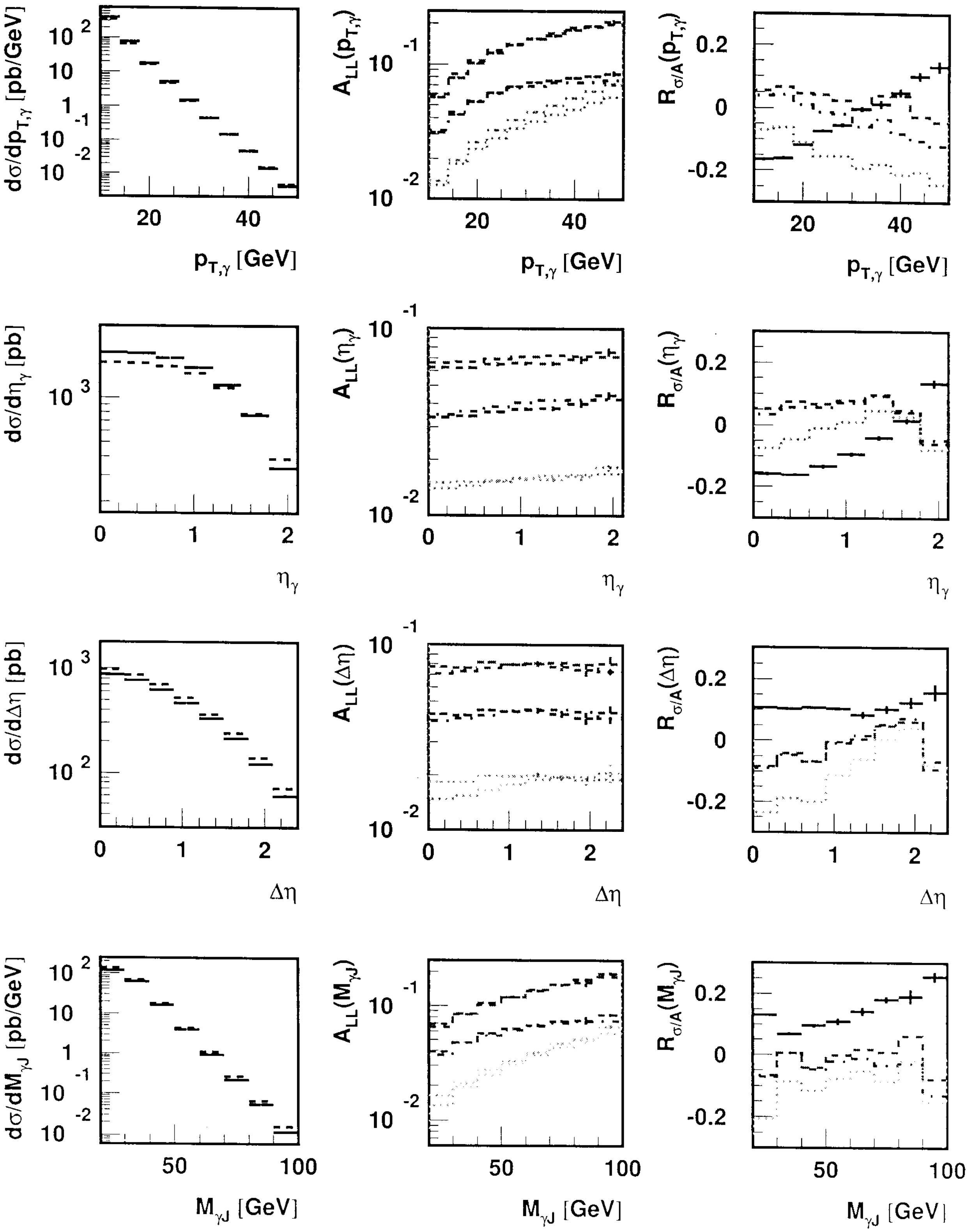
$$\frac{\mathrm{d}(\Delta)\sigma}{\mathrm{d}\Delta\phi}, \quad \frac{\pi}{2} < \Delta\phi < \pi$$

Photons - SPHINX vs. MWA (no Bremsstrahlung-γ)



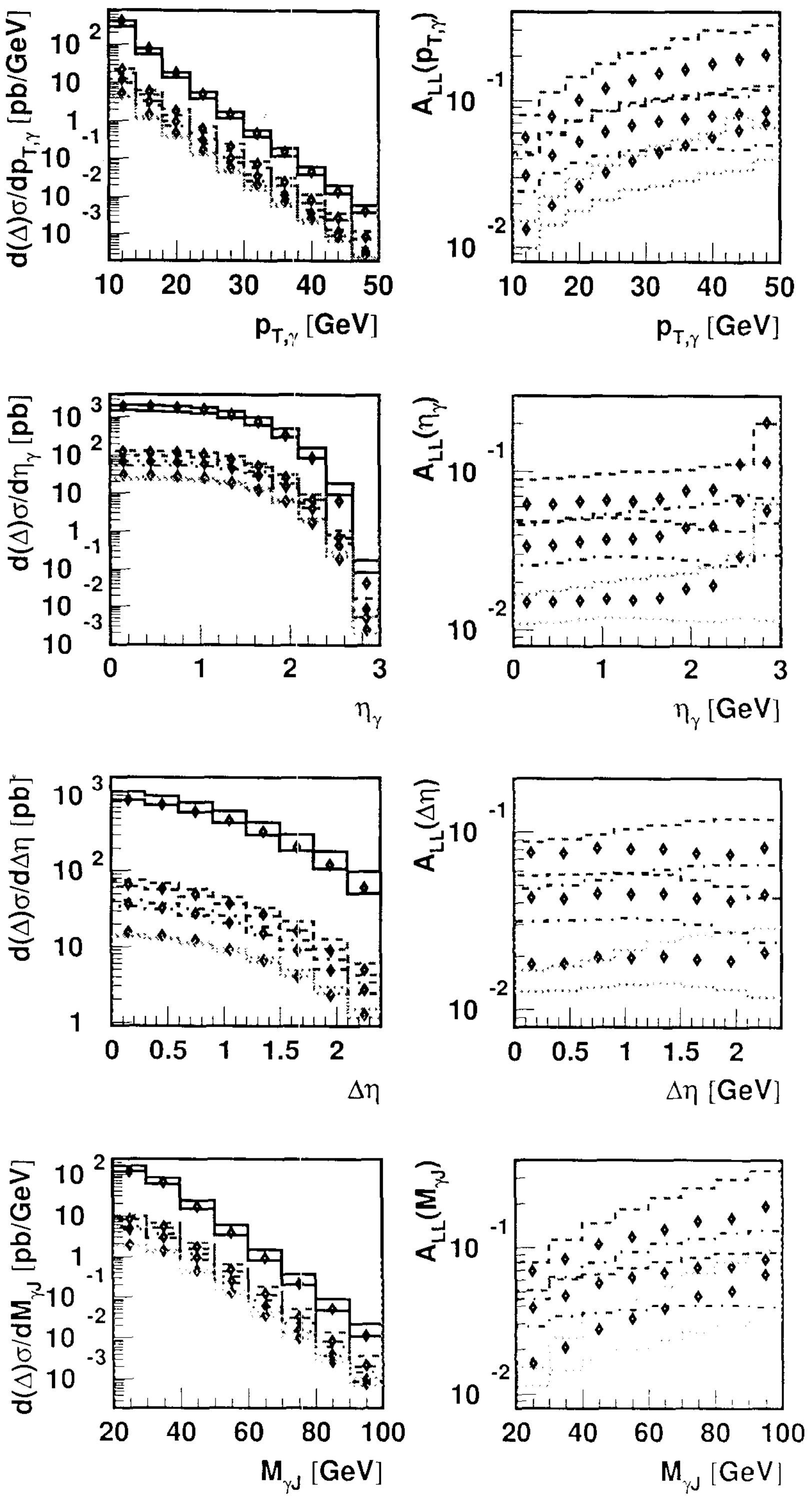
$$R_\sigma \equiv \frac{d\sigma_{\mathrm{MWA}} - d\sigma_{\mathrm{SPHINX}}}{d\sigma_{\mathrm{MWA}}}, \qquad R_A \equiv \frac{A_{LL,\mathrm{MWA}} - A_{LL,\mathrm{SPHINX}}}{A_{LL,\mathrm{MWA}}}$$

Photons - NLO QCD vs. MWA



$$R_\sigma \equiv \frac{d\sigma_{\mathrm{NLO\,QCD}} - d\sigma_{\mathrm{MWA}}}{d\sigma_{\mathrm{NLO\,QCD}}}, \qquad R_A \equiv \frac{A_{LL,\mathrm{NLO\,QCD}} - A_{LL,\mathrm{MWA}}}{A_{LL,\mathrm{NLO\,QCD}}}$$

Photons - scale dep. of NLO QCD vs. MWA



$$R_\sigma \equiv \frac{d\sigma_{\mathrm{NLO\,QCD}} - d\sigma_{\mathrm{MWA}}}{d\sigma_{\mathrm{NLO\,QCD}}}, \qquad R_A \equiv \frac{A_{LL,\mathrm{NLO\,QCD}} - A_{LL,\mathrm{MWA}}}{A_{LL,\mathrm{NLO\,QCD}}}$$

Vector boson production with small transverse momenta: spin-dependent case

Pavel Nadolsky, Michigan State University

The production of vector bosons (γ^*, $W^{\pm}, Z^0$) with the virtuality $Q \gg \Lambda_{QCD}$ will be intensively studied at RHIC with the goal to obtain information on the polarized parton densities. It is well known that the polarized PDFs can be most easily extracted from the rapidity distributions, which were calculated up to the next-to-leading order of the perturbative QCD.

It is also well-known that the perturbative expansion breaks down in the region of small transverse momenta, making the fixed-order results for the integrated rate generally unreliable. The theoretical predictions can be improved by the summation of the most singular contributions (leading and next-to-leading logarithmic terms) through all orders of the perturbative expansion. The resummed cross-section obtained this way collects the most singular pieces arising due to the collinear and soft radiation in the perturbative region. It also contains a non-perturbative Sudakov function S_{np} which is not calculable with the present means, and which must be found from the data.

For a high-precision measurement of the parton densities, good understanding of the non-perturbative Sudakov factor is needed. A suitable phenomenological parameterization of S_{np} in the polarized collisions can be found by fitting it in one process (for instance, the Drell-Yan process at low Q) and verifying its consistency with the transverse momentum distributions in another processes (for instance, the Z^0 production). This is important especially for the $W^{\pm}$ production, where the modified small q_T behavior of the polarized cross-section may add to the uncertainties in the reconstruction of the vector boson rapidity.

Resummation in the polarized vector boson production

The pioneering works were done by *(A. Weber, 1992-1993)*

What is included in his published results

- Discussion of the resummation for on-shell vector bosons
- The complete resummation formula for the single-polarized W production in a slightly unconventional factorization scheme
- The most part of the resummation formula for the double-polarized Drell-Yan process
- The demonstration that the perturbative Sudakov factor does not depend on the polarization of the beams

What is not included in his calculation

- Complete result for the double-polarized process (finished C-functions, dependence on the scales in the resummation formula, modular structure of the resummed piece)
- Leptonic decay of the final state
- "Standard" factorization prescription for the gluonic states
- New parameterizations of the PDFs
- Knowledge about the specifics of the VB detection at RHIC

Outline of our calculation *(P. Nadolsky, C.-P. Yuan, in preparation)*

1. Calculate the hadronic part of the perturbative cross-section using standard methods *(described by Ingo Bojak at this Workshop)*

2. For the on-shell vector boson, convolute with $g_{\mu\nu}$; for the decaying vector bosons, convolute with

$$L^{\mu\nu} = (f_L^2 + f_R^2)\left(-g^{\mu\nu}Q^2 + q^\mu q^\nu + l_{12}^\mu l_{12}^\nu\right) \\ +(f_L^2 - f_R^2) i\epsilon^{\mu\nu\alpha\beta} q_\alpha l_{12\beta}$$

$$q^\mu = l_1^\mu + l_2^\mu; \qquad l_{12}^\mu = l_1^\mu - l_2^\mu$$

   We have taken $\mu, \nu = 0, ..3$ in $H_{\mu\nu}L^{\mu\nu}$

3. Extract the part that diverges as $\mathcal{O}(q_T^{-2})$ when $q_T \to 0$.

4. Fourier transform the perturbative cross-section to the b-space

5. Cancel the soft singularities between the real and virtual diagrams; factorize the collinear singularities into the PDFs

6. In the HVBM scheme, additional terms

$$\frac{\hat{q} \cdot \hat{q}}{q_T^4} \to -\epsilon \frac{1}{q_T^2}$$

   will contribute finite pieces to the Fourier transformed result Take care of them in order to restore the conservation of quark helicity

7. Find the $\mathcal{O}(\alpha_s)$ coefficients in the perturbative part of $W(b, Q)$ by comparing the NLO b-space result with the perturbative expansion of $W(b, Q)$

The polarized resummation formula at the NLO

$$W_{AB}(b, x_a, x_b, Q) = \sum_{a,b,j} e^{-S_p - S_{np}}[\mathcal{C}_{bj}^{out} \circ f_{b/B}](x_b, \mu)[\mathcal{C}_{ja}^{in} \circ f_{a/A}](x_a, \mu)$$

The NLO perturbative Sudakov factor is the same for any polarization of the beams

$$A_1 = C_F; \qquad B_1 = 2C_F \log \frac{e^{-3/4+\gamma} C_1}{2C_2}$$

The collinear contributions of the exponential piece depend only on the properties of the beam along which the collinear parton is radiated

The quark $\mathcal{C}$-functions

$$\begin{aligned} \mathcal{C}_{jk}^{(1)}(x, \mu b) &= \Delta \mathcal{C}_{jk}^{(1)}(x, \mu b) = \\ &= \frac{C_F}{2}(1 - x) - P_{qq}(x) \log(\frac{\mu b}{b_0}) \\ &- C_F \delta(1 - x)\Big(\frac{23}{16} + \frac{\pi^2}{4} + \log^2(\frac{e^{-3/4} C_1}{b_0 C_2})\Big) \end{aligned} \quad (1)$$

$\mathcal{C}_{jk}^{(1)}(x, \mu b) = \Delta \mathcal{C}_{jk}^{(1)}(x, \mu b)$ because of the helicity conservation for the massless quarks

Here the overall negative sign is included into the overall normalization of the cross-section

Gluon $\mathcal{C}$-functions

$$\mathcal{C}^{(1)}_{jg}(x,\mu b) = \frac{1}{2}x(1-x) - P_{qg}(x)\log(\frac{\mu b}{b_0})$$
$$\Delta C^{(1)}_{jg}(x,\mu,b) = \frac{1}{2}(1-x) - \log(\frac{\mu b}{b_0})\Delta P_{qg}(x)$$

To be compared with the C_{jg}-functions of Weber for the single-spin cross-section

$$\mathcal{C}^{(1)Weber}_{jg}(x,\mu b) = \frac{1}{2} - P_{qg}(x)\log(\frac{\mu b}{b_0})$$

$\mathcal{C}^{(1)}_{jg}(x,\mu b)$ is different because the unpolarized cross-section for $gq \to VX$ is normalized by the spin factor $1/2$, not $1/2(1-\epsilon)$

$$\Delta C^{(1)Weber}_{qg}(x,\mu,b) = -\log(\frac{\mu b}{b_0})\Delta P_{qg}(x).$$

$\Delta C^{(1)Weber}_{qg}(x,\mu,b)$ is different from our result because of the unconventional prescription in his paper,

$$\Delta g(x,\mu) = \delta(1-x) - \frac{\alpha_s}{2\pi\epsilon}\Delta P_{qg}(x) - (1-x)$$

"Canonical" choice $\mu = b_0/b$:

$$\Delta C^{(1)Weber}_{qg}(x,\mu,b) = 0$$

Decay into the lepton pair

The cross-section can be decomposed into the sum over angular functions in the Collins-Soper frame (a special rest frame of the vector boson)

$$\frac{d\sigma^{NLO}}{dydQ^2dq_T^2d\phi d\cos\theta} = \sum_i \frac{df_i(y,Q,q_T)}{dydQ^2dq_T^2} A_i(\theta,\phi)$$

Only the angular functions $A_{-1} = 1+\cos^2\theta$ and $A_3 = 2\cos\theta$ pick up contributions from the resummation of the $\mathcal{O}(q_T^{-2})$ pieces

Then, the complete result is

$$\frac{d\sigma}{dydQ^2dq_T^2d\phi d\cos\theta} =$$

$$(g_L^2+g_R^2)(f_L^2+f_R^2)A_{-1}(\theta,\phi)\Big(\frac{d\sigma^{exp}}{dydQ^2dq_T^2} - \frac{df_{-1}^{asymp}}{dydQ^2dq_T^2}\Big)+$$

$$(g_L^2-g_R^2)(f_L^2-f_R^2)A_3(\theta,\phi)\Big(\frac{d\sigma^{exp}}{dydQ^2dq_T^2} - \frac{df_3^{asymp}}{dydQ^2dq_T^2}\Big)+$$

$$\sum_i \frac{df_i(y,Q,q_T)}{dydQ^2dq_T^2} A_i(\theta,\phi)$$

This formula is expected to be valid up to $q_T \sim Q$. At $q_T > Q$, it is more reliable to use the perturbative piece

Polarization Studies with W's in STAR

OGAWA, Akio for the STAR Collaboration
Pennsylvania State University / Brookhaven National Laboratory
Upton, NY, 11973-5000, U.S.A

The question of how the spin degrees of freedom in the nucleon are organized has still not been fully answered even after recent polarized deep inelastic scattering experiments.

The Relativistic Heavy Ion Collider(RHIC) will accelerate polarized proton beams. The STAR detector, although originally designed for heavy ion physics, has excellent capability for spin physics as well.

STAR will be able to measure the parity violating single spin asymmetry A_L in $\vec{p}p \rightarrow W^{\pm} + X \rightarrow e^{\pm} + \nu + X$ processes which are sensitive to quark/anti-quark polarization in the nucleon. A big advantage of using $W^{\pm}$ production process is that qurak flavor can be separated. Especially at high η region, where we planning to install Endcap EMC, we will have very clean measurement of d and $\overline{u}$ quark polarizations in the case of W^-. A monte Carlo studies using PYTHIA and SPHINX has been done. It shows we will have about 80k and 20k W^+ and W^- at $\sqrt{s}$ = 500GeV, 800/pb. The asymmetries which is calculated using models of polarized parton distributions functions are large(5 to 50%). Our measurement will give much more accurate information about sea quark polarization compare to the one from polarized DIS experiment. Backgrounds from high p_T hadrons, Z^0 and heavy quark decay had been studied and found to be very small. x_{bj} ranges of quarks we will measure are from 0.05 to 0.6. The measured energy of election has a good correlation with x_{bj} of quarks, especially at Endcap EMC region($1 < \eta < 2$) and we will be able to measure x_{bj} dependence of quark polarizations.

$W^{\pm}$ at Proton-Proton

- W selects spin as well as flavor
- $W^{+/-}$ emmmits positron/electrion to backword/forwards
- Balence quark have high x, seq quark has low x

$e^- \Leftarrow\Leftarrow \;\; \Rightarrow \nu$	$\nu \Leftarrow \;\; \Rightarrow\Rightarrow e^-$
$W^- \Leftarrow$	$\Rightarrow W^-$
$\overline{u} \Rightarrow \;\; \Leftarrow\Leftarrow d$	$d \Rightarrow\Rightarrow \;\; \Leftarrow \overline{u}$

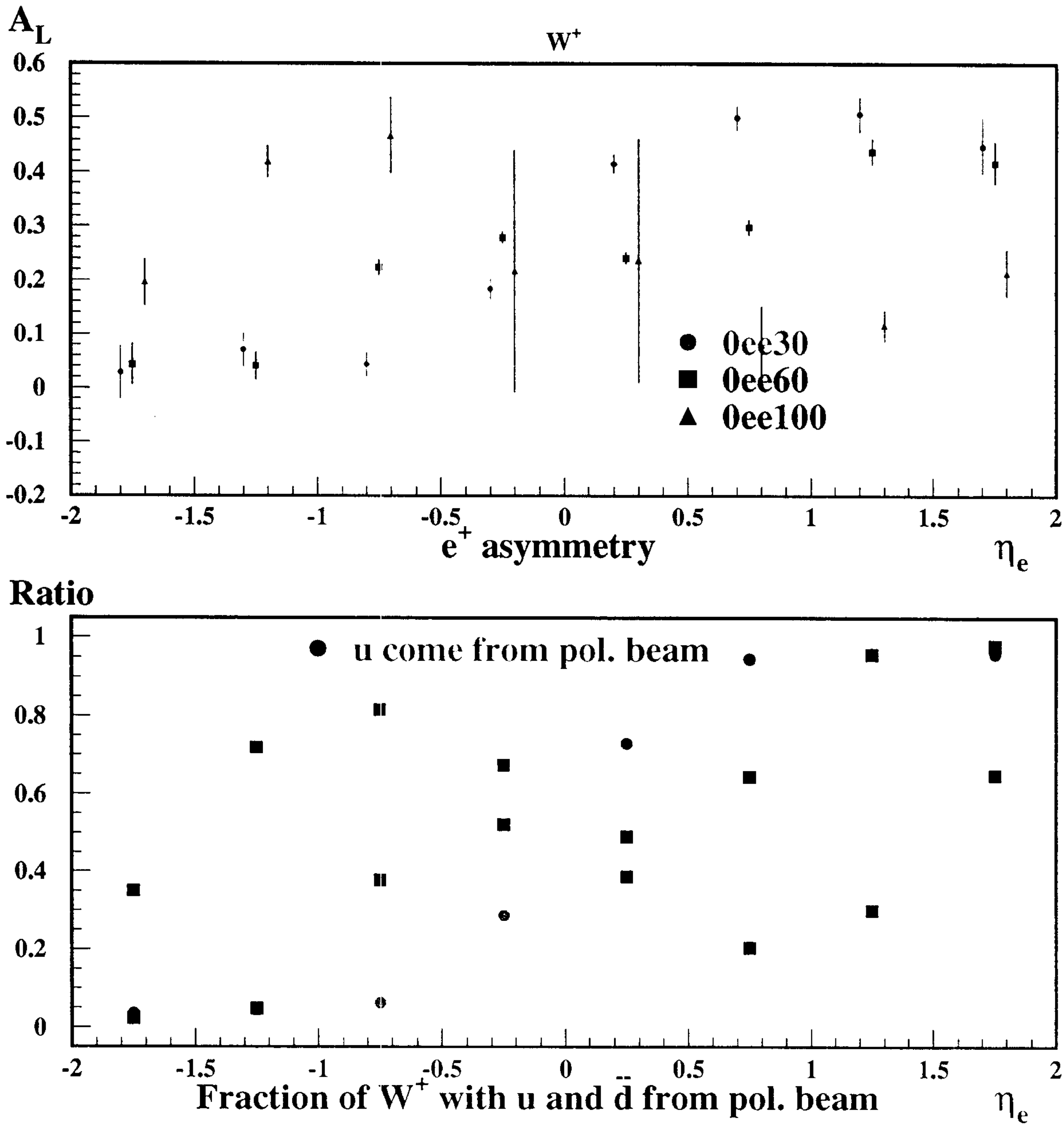
Unpol. Proton $\quad \Rightarrow\Rightarrow\Rightarrow \;\; \Leftarrow\Leftarrow\Leftarrow \quad$ Pol. Proton

$u \Rightarrow\Rightarrow \;\; \Leftarrow \overline{d}$	$\overline{d} \Rightarrow \;\; \Leftarrow\Leftarrow u$
$\Rightarrow W^+$	$W^+ \Leftarrow$
$e^+ \Leftarrow \;\; \Rightarrow\Rightarrow \nu$	$\nu \Leftarrow\Leftarrow \;\; \Rightarrow e^+$

Positron Asymmetry for W^+ depend on E_e

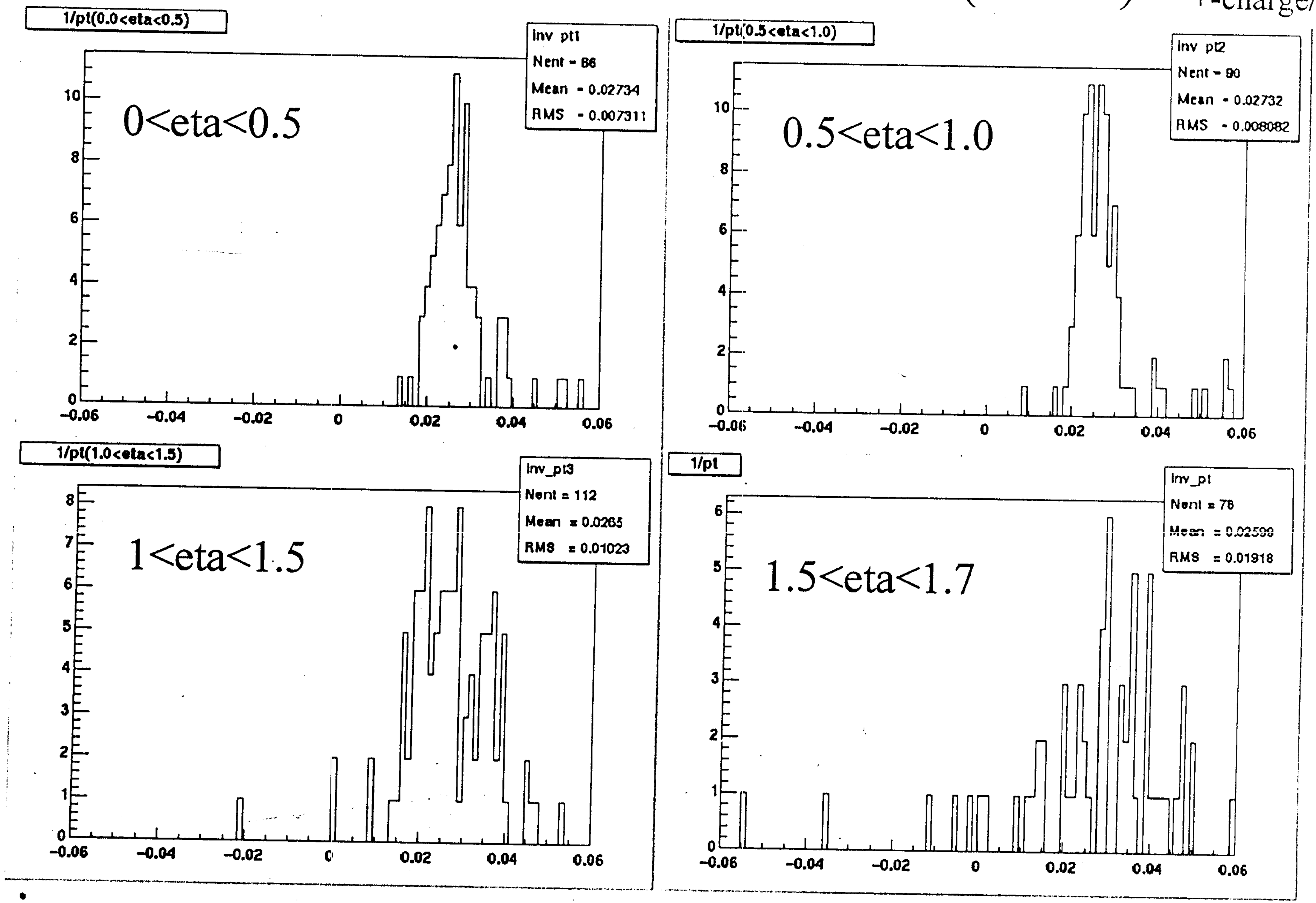
$\sqrt{s} = 500 GeV$ 800/pb P_b=0.7

Unpol. beam → ← Polarized beam



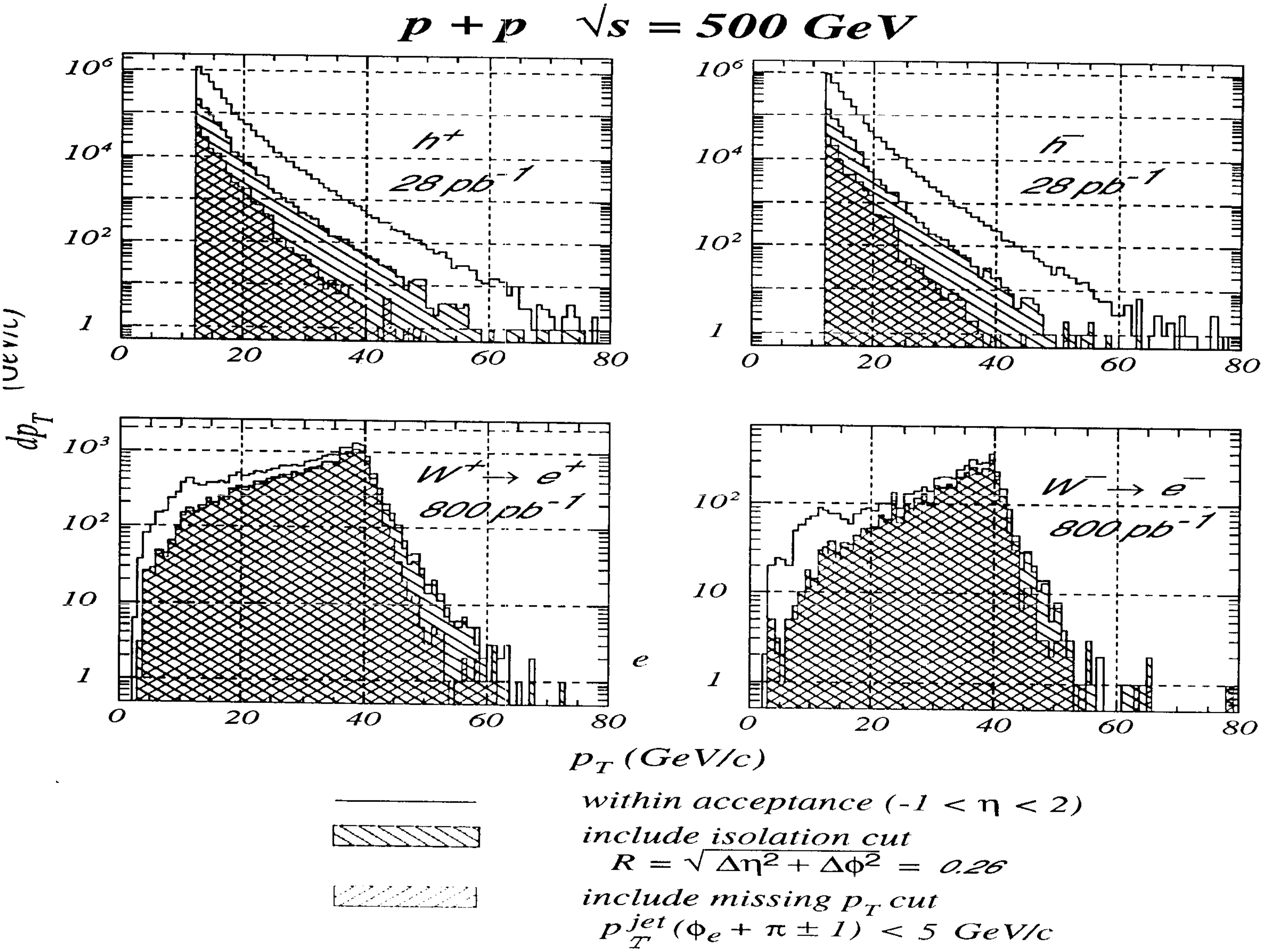
Positron with pt=40GeV TPC+Vertex (+SMD)

+-charge/pt

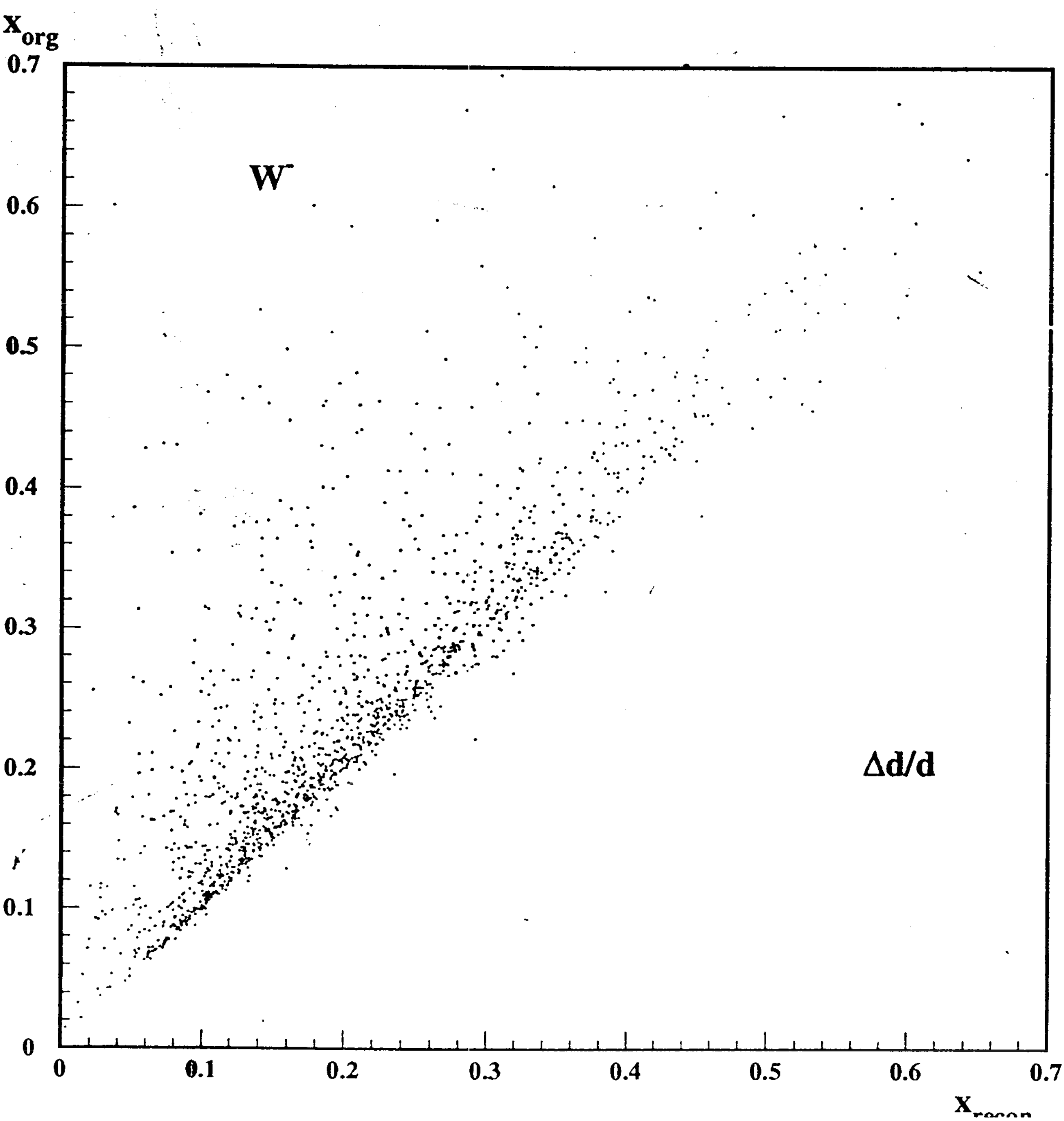


Background

- High P_T jets



- Z^0 one missing electron
- electron from heavy quark decay



x_{org}
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
W^-
Δd/d
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
x_{recon}

POLARIZED STRUCTURE FUNCTIONS from the LATTICE

Tom Blum

RIKEN BNL Res. Cent.

DWF advantage:

Because DWF maintain Chiral symmetry to a high degree, $Z_A/Z_V = 1$ (see NPR results)

so,

$$g_A = \frac{Z_A \langle p,s | A_\mu^{Latt} | p,s \rangle}{Z_V \langle p,s | V_\mu^{Latt} | p,s \rangle}$$

$$= \frac{\langle p,s | A_\mu^{Latt} | p,s \rangle}{\langle p,s | V_\mu^{latt} | p,s \rangle} \longleftrightarrow \frac{G_A(t)}{G_V(t)}$$

i.e., very "clean" calculation of g_A

similarly for tensor charge, etc...

Recent results, g_A, $\Delta\Sigma$

Table 1: Summary of renormalized results for g_A. Results are for Wilson fermions. In cases where point-split(PS) currents were used, the renormalization was calculated using *local* currents. While the second entry is consistent with the measured value of $g_A = 1.26$, the configuration ensemble is quite small. Subscript "con" refers to the connected contribution to the matrix element.

type of simulation	group	type of current	lattice size	β	conf.	value
Quench	KEK[2]	Local	$16^3 \times 20$	5.7	260	g_A=0.985(25) Δu_{con} = 0.763(35) Δd_{con} =-0.226(17) $\Delta\Sigma$ = 0.18(10)
Quench	Liu et al.[3]	Local PS	$16^3 \times 24$ $16^3 \times 24$	6.0 6.0	24 24	g_A=1.18(11) g_A=1.20(10) Δu_{con}= 0.91(12) Δd_{con}=-0.30(12) $\Delta\Sigma$= 0.25(12)
Quench	DESY[4]	PS	$16^3 \times 32$	6.0	400-1000	g_A=1.07(9) Δu_{con} = 0.830(70) Δd_{con} =-0.244(22)
Full ($n_f = 2$)	SESAM[1]	Local	$16^3 \times 32$	5.6	200	g_A=0.907(20) Δu_{con} = 0.695(18) Δd_{con} =-0.212(8) $\Delta\Sigma$ = 0.20(12)

References

[1] S. Güsken *et al.*, Phys. Rev. D 59, 1999, 114502.

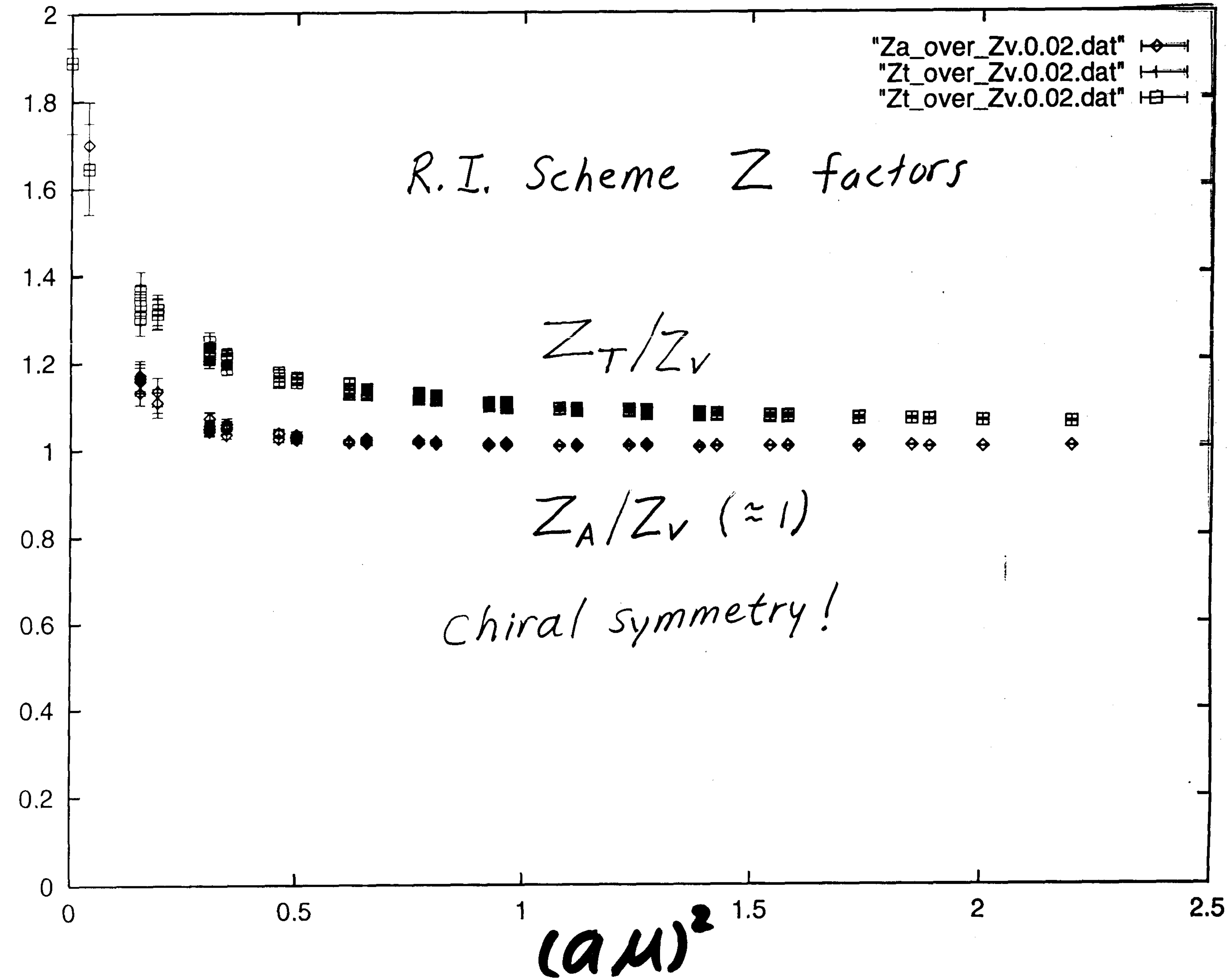
[2] M. Fukugita, Y. Kuramashi, M. Okawa and A. Ukawa, Phys. Rev. Lett. 75, 1995, 2092.

[3] S.J. Dong, J.-F. Lagaë and K.F. Liu, Phys. Rev. Lett. 75, 1995, 2096; K.F. Liu, S.J. Dong, T. Draper and J.M. Wu, Phys. Rev D 49, 1994, 4755.

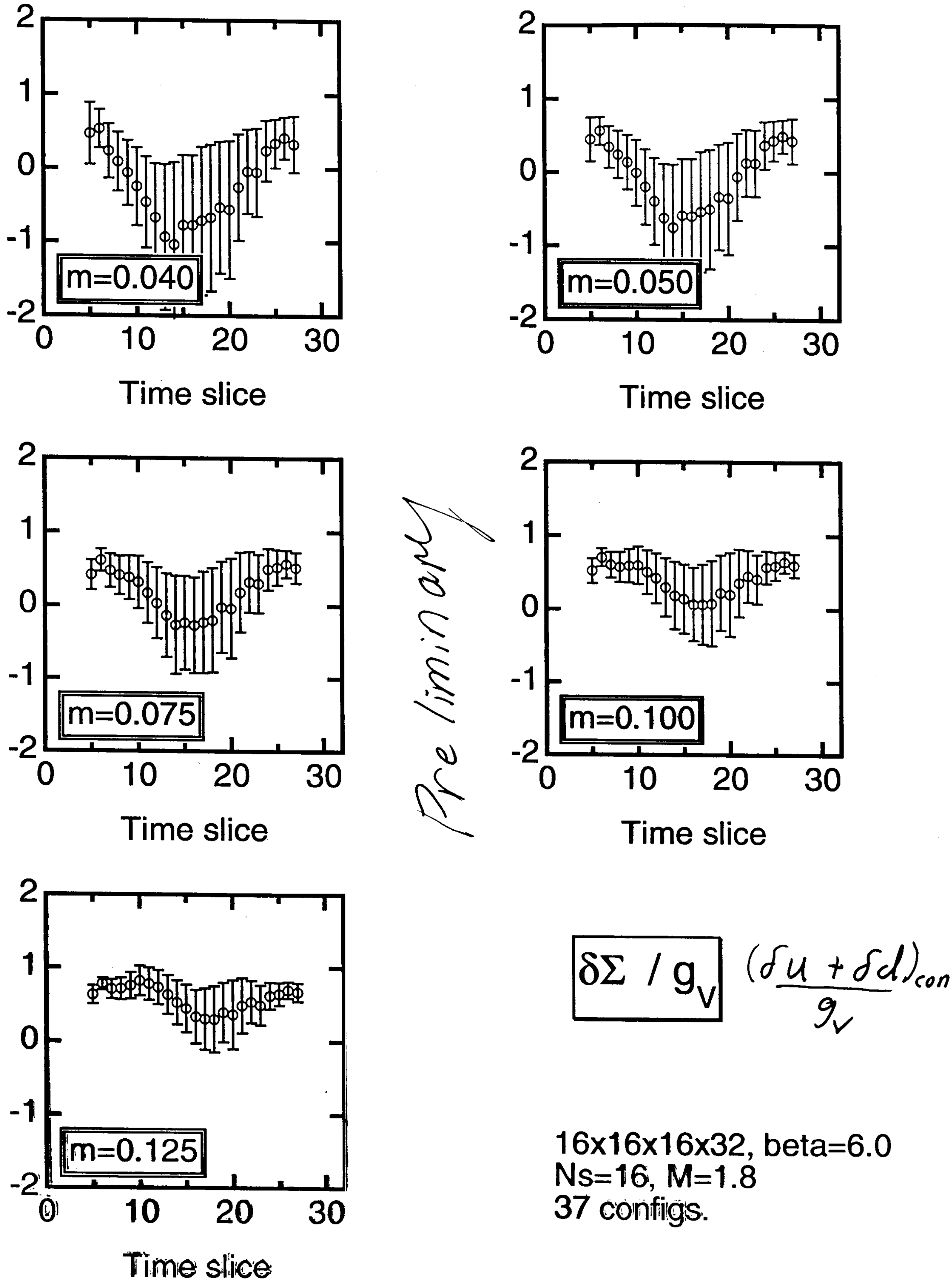
[4] M. Göckeler *et al.*, Phys. Rev. D 53, 1996, 2317.

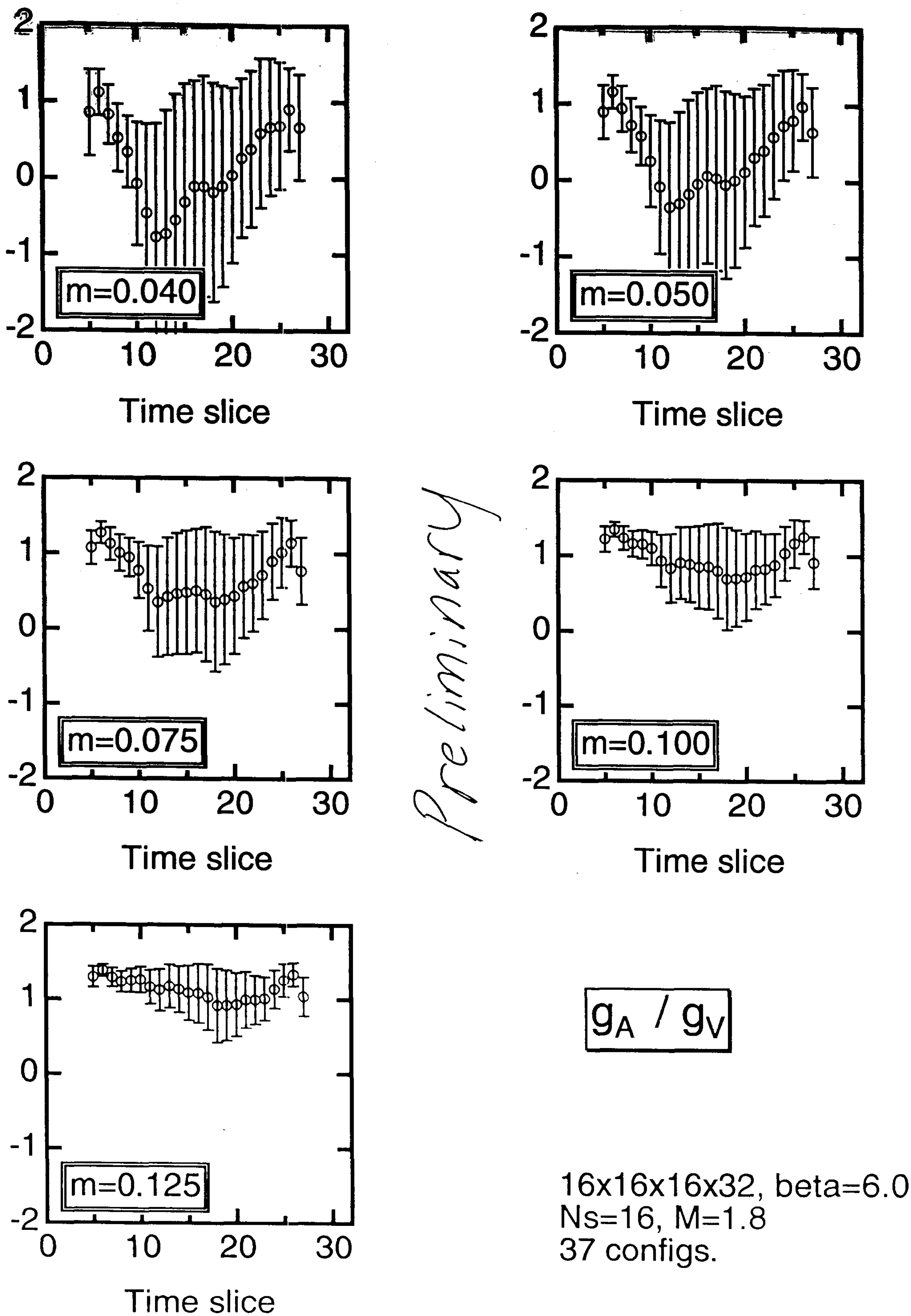
g_A under-predicted

(quenching, renormalization)



"Za_over_Zv.0.02.dat"
"Zt_over_Zv.0.02.dat"
"Zt_over_Zv.0.02.dat"
R.I. Scheme Z factors
Z_T/Z_V
Z_A/Z_V (≈1)
Chiral symmetry!
(aμ)²
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0.5
1
1.5
2
2.5


m=0.040
m=0.050
m=0.075
m=0.100
m=0.125
Time slice
Preliminary
δΣ / g_V
(δu + δd)_con / g_V
16x16x16x32, beta=6.0
Ns=16, M=1.8
37 configs.



m=0.040
m=0.050
m=0.075
m=0.100
m=0.125
Time slice
Preliminary
g_A / g_V
16x16x16x32, beta=6.0
Ns=16, M=1.8
37 configs.

Asymmetries in DVCS and skewed parton distributions.

A.V. Belitsky[a], D. Müller[a,b], L. Niedermeier[b], A. Schäfer[b]

[a] *C.N. Yang Institute for Theoretical Physics*
State University of New York at Stony Brook
NY 11794-3840, Stony Brook, USA
[b] *Institut für Theoretische Physik, Universität Regensburg*
D-93040 Regensburg, Germany

The scattering of electroweak probes off hadrons serves as a clean tool, free of complications of hadron-hadron reactions on theoretical as well as experimental sides, for extraction of reliable information on the substructure of strongly interacting particles.

Recently the deeply virtual Compton scattering has attracted much attention [1] in light of conceivable opportunity to learn more on the spin structure of nucleon by measuring the so-called skewed parton distributions. The former are of interest in their own right being hybrids of parton densities/distribution amplitudes and form factors. In electroproduction processes of a real photon there is a strong contamination to the DVCS (Fig. 1 (a)) from the Bethe-Heitler (Fig. 1 (b)) process. In view of extreme interest to extract, or at least to constrain, SPDs it is timely to address the question of the best observables which allow to get rid of unwanted background. In the present contribution we consider a number of spin, azimuthal and charge asymmetries which share these properties and give predictions for kinematics of HERA and HERMES experiments. Spin asymmetries make it possible to extract the imaginary part of the DVCS amplitude and thus, due to the reality of SPDs, which holds owing to the spatial and time reversal invariance of strong interactions, give directly the measurement of the shape (at leading order in α_s in complete analogy to DIS) of SPDs on the diagonal $t = \xi$.

The calculation of the four-fold cross section in the rest frame (Fig. 2) of the target leads to the asymmetries given in Eq. (1) valid in approximation $|\Delta^2| \gg M^2x^2/(1-x)$. For numerical estimates presented in Fig. 3 they are not, however, enough and we refer the reader to Ref. [2].

References

[1] D. Müller et al., Fortschr. Phys. 42 (1994) 101; X. Ji, Phys. Rev. D 55 (1997) 7114; A.V. Radyushkin, Phys. Rev. D 56 (1997) 5524.

[2] A.V. Belitsky, D. Müller, L. Niedermeier, A. Schäfer, in preparation.

The diagrams contributing to the electroproductions of the reals photon

$$e(\boldsymbol{k})N(M) \to e(\boldsymbol{k}')N(\boldsymbol{P}_2)\gamma(\boldsymbol{q}_2).$$

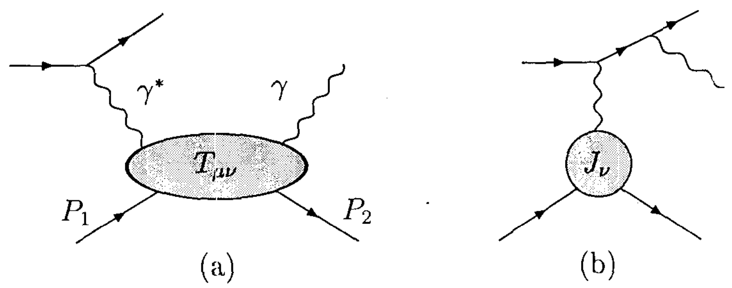


Figure 1:

The kinematics of the reaction in the laboratry frame, i.e. the rest frame of the target.

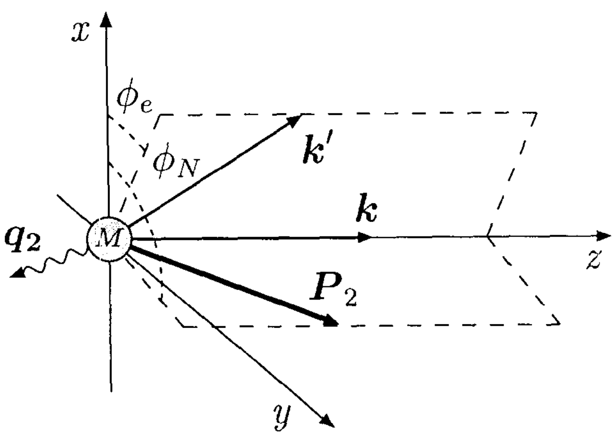


Figure 2:

The cross section of the reaction depends on the kinematical variables

$$Q^2 \equiv -q_1^2, \qquad x \equiv -q_1^2/(2P_1q_1), \qquad \Delta^2 = (P_2 - P_1)^2,$$
$$y = P_1.q_1/P_1.k = \frac{Q^2}{x \cdot s}, \qquad \phi_r = \phi_N - \phi_e,$$

which are conventional momentum transfer squared from lepton to hadron, Bjorken variable. t-channel momentum transfer, enerfy loss of lepton and the azimuthal angle.

Asymmetries (for $\Delta^2_{\rm min}/\Delta^2 \ll 1$):

1. Polarized lepton beam and unpolarized target:

$$\Delta_{\rm SL} d\sigma \equiv d\sigma^{\uparrow} - d\sigma^{\downarrow} \tag{1}$$
$$= -\frac{16(2-y)\sqrt{1-x}}{\sqrt{1-y}x\sqrt{-\Delta^2 Q^2}} \sin(\phi_r) {\rm Im}\left\{ F_1 \mathcal{H}_1 + \frac{x}{2-x}(F_1+F_2)\widetilde{\mathcal{H}}_1 - \frac{\Delta^2}{4M^2} F_2 \mathcal{E}_1 \right\} d\mathcal{M}.$$

2. Unpolarized lepton beam and longitudinally polarized target:

$$\Delta_{\rm SLN} d\sigma \equiv d\sigma_{\uparrow} - d\sigma_{\downarrow} = \frac{16(2-2y+y^2)\sqrt{1-x}}{\sqrt{1-y}yx\sqrt{-\Delta^2 Q^2}} \sin(\phi_r)$$
$$\times {\rm Im}\left\{ \frac{x}{2-x}(F_1+F_2)\mathcal{H}_1 + F_1 \widetilde{\mathcal{H}}_1 + \frac{x}{2-x}\left(\frac{x}{2}F_1 + \frac{\Delta^2}{4M^2}F_2\right)\widetilde{\mathcal{E}}_1 \right\} d\mathcal{M}.$$

3. Unpolarized lepton beam and transversally polarized target: ($\Phi = \{0, \pi\}$):

$$\Delta_{\rm STN} d\sigma \equiv d\sigma_{\rightarrow} - d\sigma_{\leftarrow} = \frac{16(2-2y+y^2)}{\sqrt{1-y}yx(2-x)\sqrt{Q^2 M^2}}$$
$$\times \left[\frac{\cos(3\phi_r/2)}{2\pi}(1-x){\rm Im}\left\{2F_2(\mathcal{H}_1 + \widetilde{\mathcal{H}}_1) - [(2-x)F_1 - xF_2]\mathcal{E}_1 - xF_1\widetilde{\mathcal{E}}_1\right\}\right.$$
$$+ \frac{\cos(\phi_r/2)}{2\pi}{\rm Im}\Big\{2(1-x)F_2\left(\mathcal{H}_1 - \widetilde{\mathcal{H}}_1\right) - [(2-x)F_1 + xF_2]\mathcal{E}_1$$
$$\left. + x(F_1 + xF_2)\widetilde{\mathcal{E}}_1\Big\}\right] d\mathcal{M}.$$

4. Charge asymmetry in unpolarized experiment:

$$\Delta_{\rm C}^{\rm unp} d\sigma \equiv d^{+}\sigma^{\rm unp} - d^{-}\sigma^{\rm unp} = -\frac{16(2-2y+y^2)\sqrt{1-x}}{\sqrt{1-y}yx\sqrt{-\Delta^2 Q^2}} \cos(\phi_r)$$
$$\times {\rm Re}\left\{ F_1 \mathcal{H}_1 + \frac{x}{2-x}(F_1+F_2)\widetilde{\mathcal{H}}_1 - \frac{\Delta^2}{4M^2} F_2 \mathcal{E}_1 \right\} d\mathcal{M}.$$

where $d\mathcal{M} = \frac{\alpha^3 xy}{8\pi Q^2}\left(1 + \frac{4M^2 x}{Q^2}\right)^{-1/2} dx dQ^2 d|\Delta^2| d\phi_r$.

Here

$$\mathcal{O}(\xi, Q^2, \Delta^2) = \left\{ \frac{Q_i^2}{1 - t/\xi - i\epsilon} \mp (t \to -t) \right\} \otimes O_i(t, \xi, \Delta^2, \mu^2),$$

with O_i being a given quark (of charge Q_i) skewed parton distribution.

For numerical estimate we choose an oversimplified factorized form of Δ^2 and (t, ξ) dependence for all skewed parton distribution:

$$O^i(t, \xi, \Delta^2, Q^2) = F^i(\Delta^2) q^i(t, \xi, Q^2).$$

Here $F^i(\Delta^2)$ is an elastic parton form factor. $q(t, \xi, Q^2)$ is the non-forward function

$$q(t, \xi, Q^2) = \int_{-1}^{1} dx \int_{-1+|x|}^{1-|x|} dy \delta(x + \xi y - t) \frac{3}{4} \frac{[1-|x|]^2 - y^2}{[1-|x|]^3} q(x),$$

with forward parton density $q(x)$.

Now let us turn to the predictions for HERMES experiment with $E = 27.5$ GeV positron beam scattered on hydrogen target and give result for the charge, single (lepton) spin, single longitudinal and transverse proton spin asymmetries which can be accesed there. We use the following azimuthal averaging

$$A_{\rm C} = \left(\int_{-\pi/2}^{\pi/2} d\phi_r \frac{\Delta_C^{\rm unp} d\sigma}{d\phi_r} - \int_{\pi/2}^{3\pi/2} d\phi_r \frac{\Delta_C^{\rm unp} d\sigma}{d\phi_r} \right) / \left(\int_0^{2\pi} d\phi_r \frac{d^- \sigma^{\rm unp} + d^+ \sigma^{\rm unp}}{d\phi_r} \right),$$

$$A_{\rm SL} = \left(\int_0^{\pi} d\phi_r \frac{\Delta_{\rm SL} d\sigma}{d\phi_r} - \int_{\pi}^{2\pi} d\phi_r \frac{\Delta_{\rm SL} d\sigma}{d\phi_r} \right) / \left(\int_0^{2\pi} d\phi_r \frac{d\sigma^{\uparrow} + d\sigma^{\downarrow}}{d\phi_r} \right),$$

$$A_{\rm SLN} = \left(\int_0^{\pi} d\phi_r \frac{\Delta_{\rm SLN} d\sigma}{d\phi_r} - \int_{\pi}^{2\pi} d\phi_r \frac{\Delta_{\rm SLN} d\sigma}{d\phi_r} \right) / \left(\int_0^{2\pi} d\phi_r \frac{d\sigma_{\uparrow} + d\sigma_{\downarrow}}{d\phi_r} \right),$$

$$A_{\rm STN} = \left(\int_{\pi/3}^{2\pi/3} d\phi_r \frac{\Delta_{\rm STN} d\sigma}{d\phi_r} - \int_{2\pi/3}^{5\pi/3} d\phi_r \frac{\Delta_{\rm STN} d\sigma}{d\phi_r} \right) / \left(\int_0^{2\pi} d\phi_r \frac{d\sigma_{\rightarrow} + d\sigma_{\leftarrow}}{d\phi_r} \right).$$

As a starting point we choose $Q^2 = 6$ GeV^2 and the range of $x = 0.1 - 0.4$ and t-channel momentum transfer $-\Delta^2 = 0.1 - 0.5$ GeV^2.

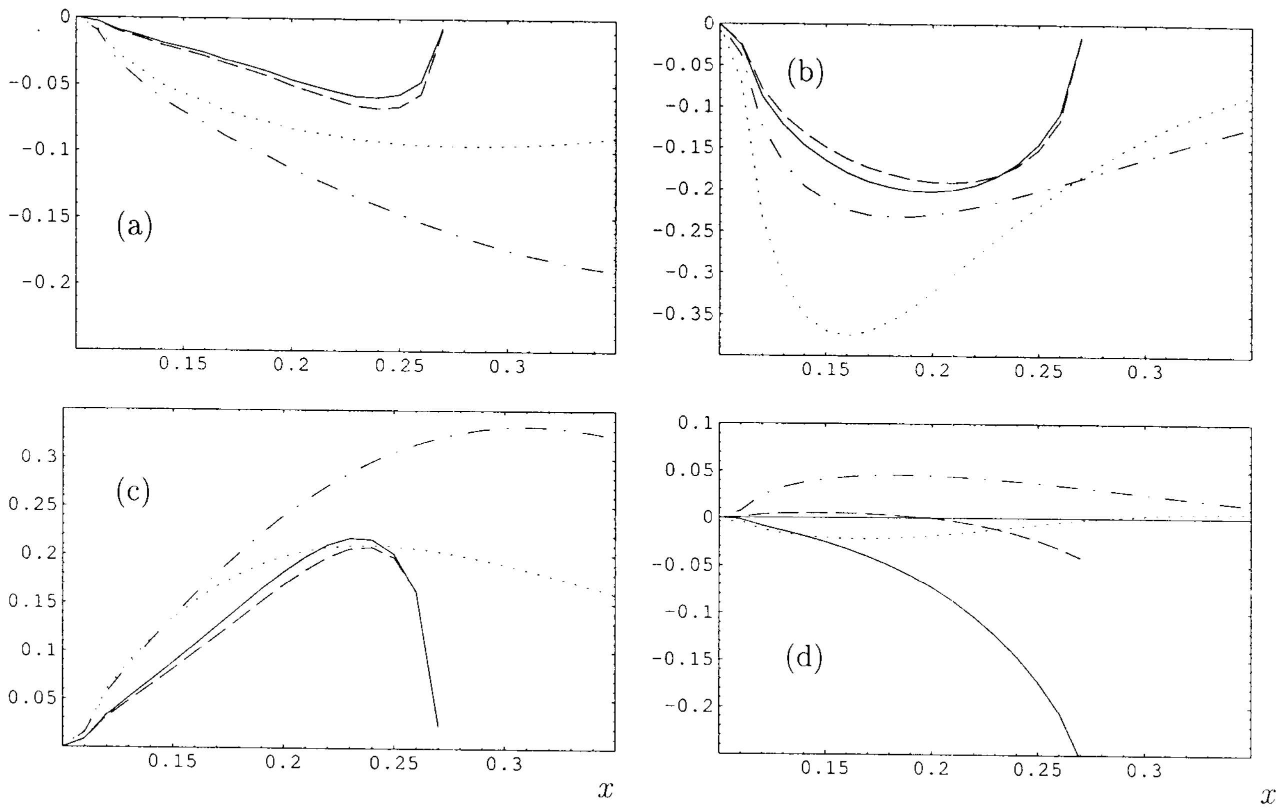


Figure 3: Perturbative leading order results for the charge asymmetry for an unpolarized beam (a), single spin asymmetries for a polarized positron beam (b) and an unpolarized target; as well as for an unpolarized lepton beam and a longitudinally (c) (transversally (d)) polarized proton target versus x, for $Q^2 = 6$ GeV^2. The predictions for the model specified in the text are shown as solid (dotted) curves for $\Delta^2 = -0.1(0.5)$ GeV^2, respectively. The same model however with neglected spin-flip contributions are presented as dashed (dash-dotted) line for the same values of Δ^2.

Radiation Zeros in Polarized $p(\bar{p}) - p$ Processes

Jiro Kodaira
Department of Physics, Hiroshima University
Higashi-Hiroshima, 739-8526, Japan

The RHIC Spin Experiments are expected to provide us with many important information on the structure of Nature. The spin dependent quantity is, in general, very sensitive to the structure of interactions among various particles. Therefore, we will be able to study the detailed structure of hadrons based on QCD. However, the purpose of RHIC Experiments should not be limited to only the check of QCD. We also hope that we can find some clue to New Physics beyond the Standard Model.

From this point of view, I will discuss the interesting phenomena called Radiation Zeros (RAZ). The RAZ has long history and many theoretical and phenomenological analyses have been done. However the many works so far assumed unpolarized and high energy colliders like Tevatron and LHC. In this report, I try to reanalyze this phenomena at the realistic RHIC polarized collider. I will point out that the polarization of the colliding protons will emphasize the RAZ phenomena in the cross section and the "moderate energy"machine is better than the extremely high energy machines to find this phenomena.

RAZ might be smeared by the radiative corrections and we must also take into account the realistic experimental situations. These detailed analyses are now in progress.

Radiation Zeros in Polarized $p\,(\bar{p}) - p$ Processes

J.Kodaira (Hiroshima)

March 17, 2000
at RIKEN - BNL, BNL

"What Should be Revealed by RHIC Spin Experiments ? "

- Hadron Structure with QCD Dynamics

  But ONLY This ?

- Dynamics of the Standard Model

  Off course

- Physics beyond the Standard Model

  Good Chance with Spin Degrees of Freedom !!

- ⋯

in collaboration with

H. Kawamura, Y. Kiyo

♣ History and What We Want to Know

History

Radiation Zeros (Theory of Nothing) was Found in 1979
by
Brown, Mikaelian, Shadev and Samuel

- Radiation Zeros

  Cross Section (Amplitude) for Some Process

  Develops Zero in Some Point of PS

  Famous Example

  $$f_1 f_2 \to W^- \gamma \quad \text{at} \quad \cos\theta = (Q_1 + Q_2)/(Q_1 - Q_2)$$

- Sensitive to Model (Structure of Interaction)

  Test of Model and /or New Physics

- Many Analyses

  Radiative Corrections to Radiation Zeros
  Realistic Phenomenology
  See. e.g. de Florian and Signer hep-ph/0002138

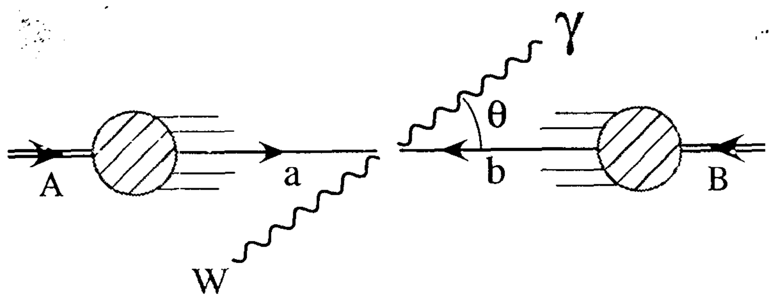
Simple Interest

How Radiation Zeros Look Like in Polarized Processes
Should be Emphasized

Actually already Works *e.g.* Wiest, Stump, Carlson and Yuan

But, Realistic Case with More Details

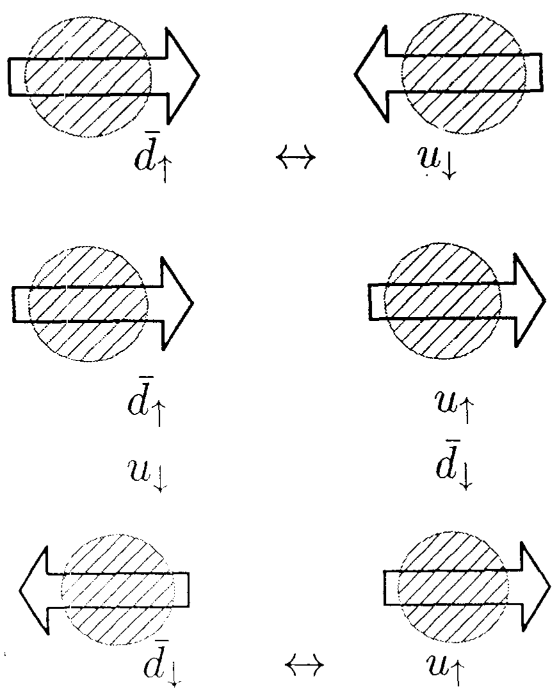
♣ Preliminary Result

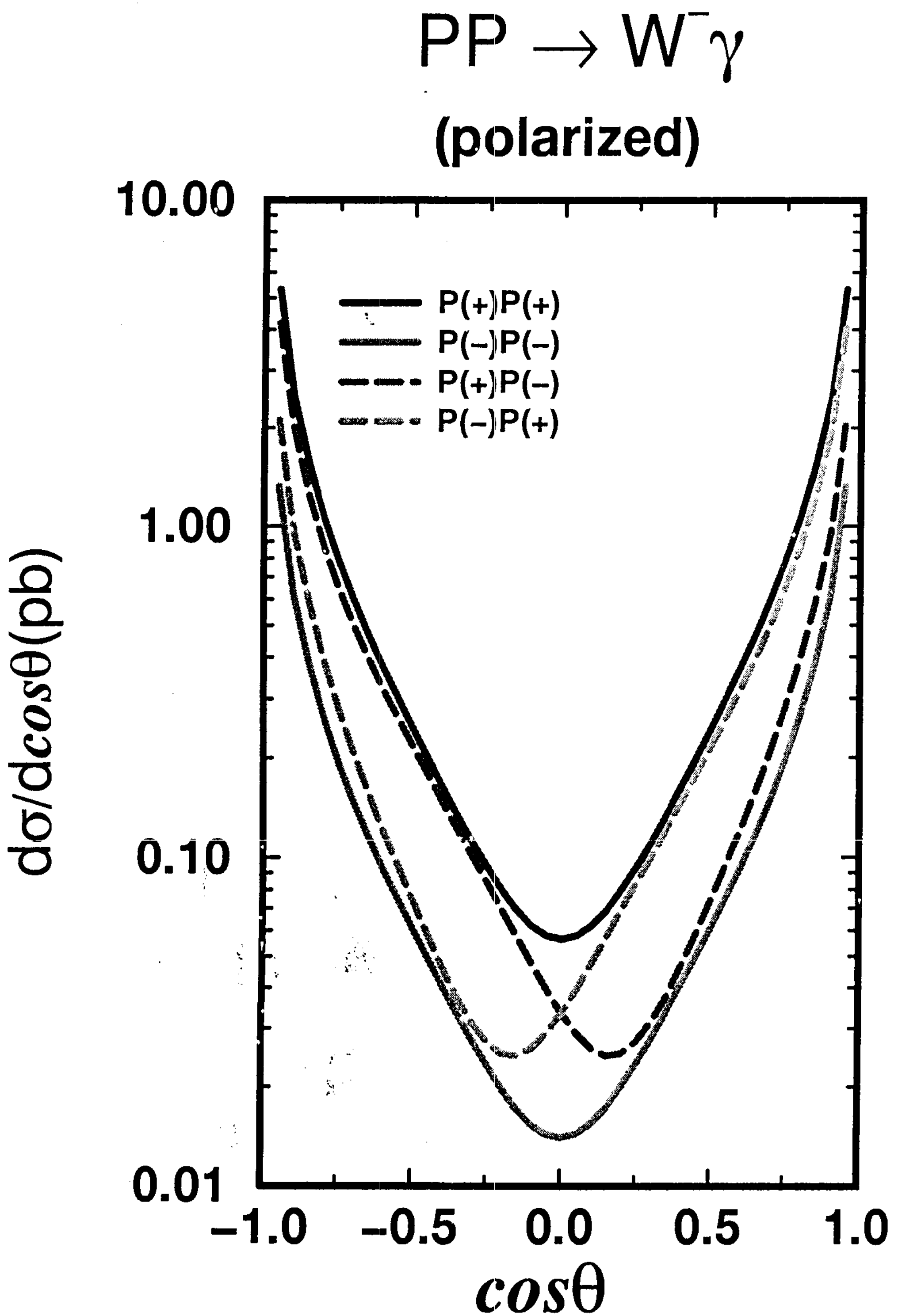


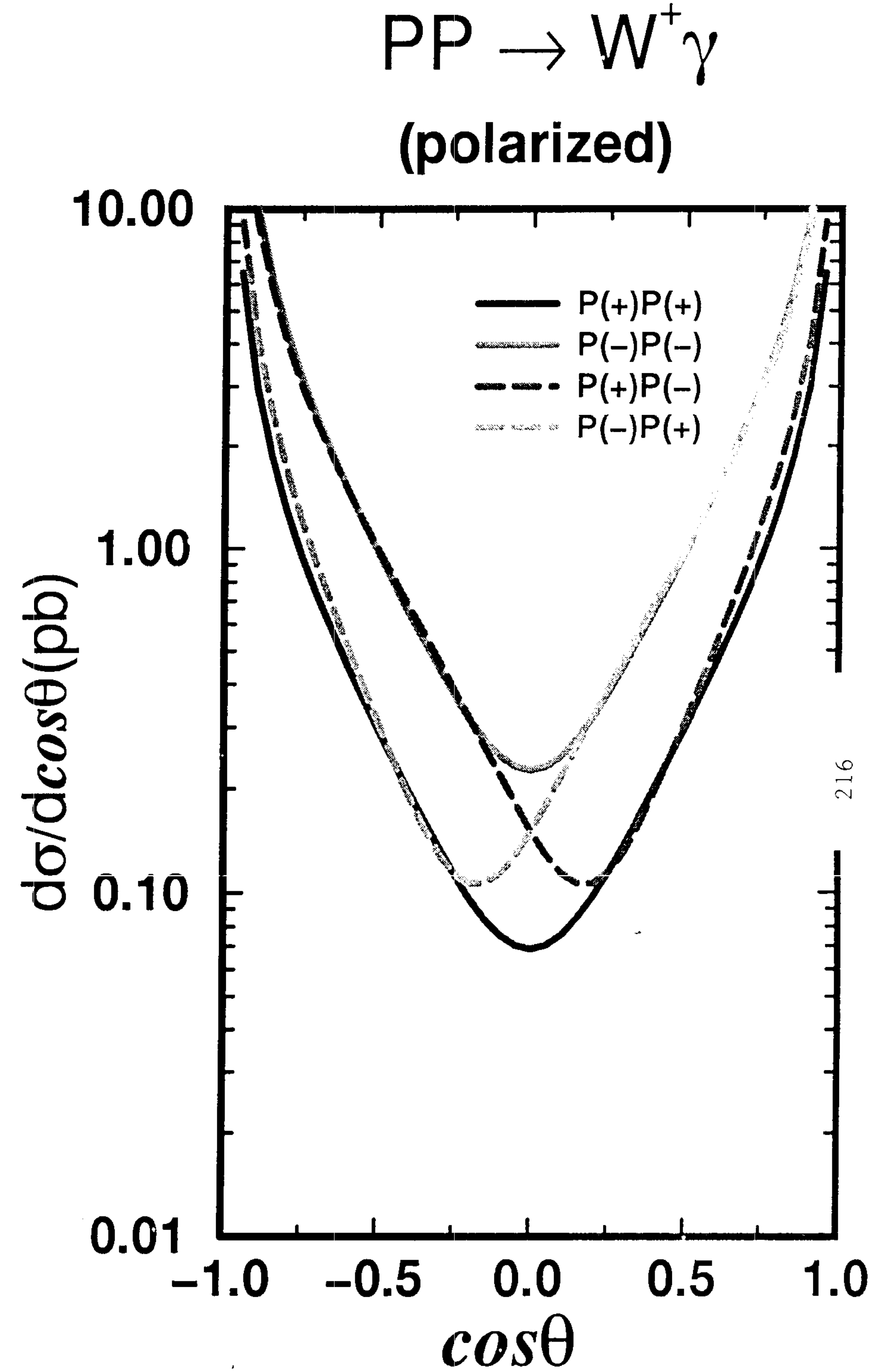
1. Parton Level Cross Section $\bar{d}\,u \to W^+\,\gamma$
2. PDF in Up Spin Proton

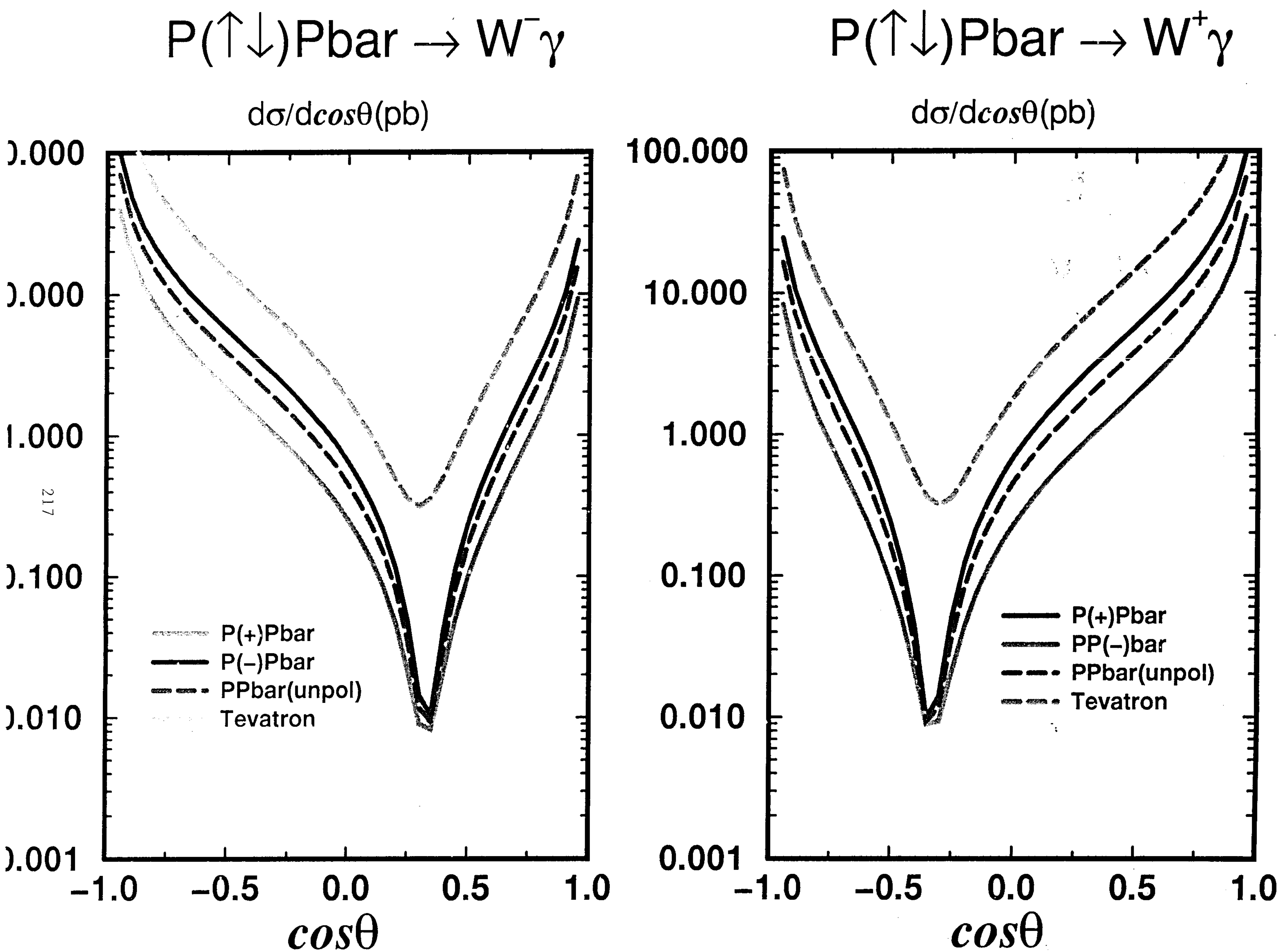
$$u_\uparrow \gg d_\downarrow \sim u_\downarrow \gg d_\uparrow \gg \bar{u}_{\uparrow,\downarrow} \sim \bar{d}_{\uparrow,\downarrow}$$

3. Convolution (Note: Interaction is $V - A$)




PP → W⁻γ
(polarized)
P(+)P(+)
P(−)P(−)
P(+)P(−)
P(−)P(+)
10.00
1.00
0.10
0.01
dσ/dcosθ(pb)
−1.0
−0.5
0.0
0.5
1.0
cosθ


PP → W⁺γ
(polarized)
P(+)P(+)
P(−)P(−)
P(+)P(−)
P(−)P(+)
10.00
1.00
0.10
0.01
dσ/dcosθ(pb)
−1.0
−0.5
0.0
0.5
1.0
cosθ


P(↑↓)Pbar → W⁻γ
dσ/dcosθ(pb)
).000
).000
1.000
).100
).010
).001
−1.0
−0.5
0.0
0.5
1.0
cosθ
P(+)Pbar
P(−)Pbar
PPbar(unpol)
Tevatron
P(↑↓)Pbar → W⁺γ
dσ/dcosθ(pb)
100.000
10.000
1.000
0.100
0.010
0.001
−1.0
−0.5
0.0
0.5
1.0
cosθ
P(+)Pbar
PP(−)bar
PPbar(unpol)
Tevatron

Program for Joint Sessions of Workshops

Predictions and Uncertainties for RHIC Spin Physics

&

Event Generator for RHIC Spin Physics III

-towards precision spin physics at RHIC-

March 6th – March 31st, 2000

A RIKEN BNL Research Center Workshop

LIST OF REGISTERED PARTICIPANTS

NAME	AFFILIATION AND ADDRESS	E-MAIL ADDRESS
Csaba Balazs	University of Hawaii Department of Physics 2505 Correa Rd. WAT 435 Honolulu, HI 96822	balazs@phys.hawaii.edu
Alexander Bazilevsky	RIKEN Research Center Brookhaven National Laboratory Physics Dept. – Bldg. 510A Upton, New York 11973-5000	shura@bnl.gov
Andrei Belitsky	SUNY Stony Brook YITP Stony Brook, N.Y. 11794-3840	belitsky@insti.physics.sunysb.edu
Edmond L. Berger	Argonne National Laboratory High Energy Physics Division Argonne, IL 60439	berger@anl.gov
Les Bland	Indiana University Cyclotron Facility 2401 Milo B. Sampson Lane Bloomington, IN 47408	bland@iucf.indiana.edu
Tom Blum	RIKEN Research Center Brookhaven National Laboratory Physics Dept. – Bldg. 510A Upton, New York 11973-5000	tblum@bnl.gov
Daniel Boer	RIKEN Research Center Brookhaven National Laboratory Physics Dept. – Bldg. 510A Upton, New York 11973-5000	dboer@bnl.gov
Ingo Bojak	TIV, Institut für Physik Universität Dortmund D-44221 Dortmund Germany	bojak@dilbert.physik.uni-dortmund.de
Gerry Bunce	RIKEN Research Center Brookhaven National Laboratory Physics Dept. – Bldg. 510A Upton, New York 11973-5000	bunce@bnl.gov
John Collins	Penn State University Physics Department 104 Davey Lab University Park, PA 16802	collins@phys.psu.edu
Sally Dawson	Brookhaven National Laboratory High Energy Theory Group Physics Department – Bldg. 510 Upton, New York 11973-5000	dawson@bnl.gov
Abhay Deshpande	RIKEN Research Center Brookhaven National Laboratory Physics Dept. – Bldg. 510A Upton, New York 11973-5000	abhay@bnl.gov
Daniel de Florian	Theoretische Physik ETH Zurich CH-8093 Zurich Switzerland	dflorian@itp.phys.ethz.ch

Program for Joint Sessions of Workshops

Predictions and Uncertainties for RHIC Spin Physics
&
Event Generator for RHIC Spin Physics III

-towards precision spin physics at RHIC-

March 6th – March 31st, 2000

A RIKEN BNL Research Center Workshop

LIST OF REGISTERED PARTICIPANTS

NAME	AFFILIATION AND ADDRESS	E-MAIL ADDRESS
Geary Eppley	Rice University MS 315 6100 Main Street Houston, TX 77005	eppley@physics.rice.edu
Yuji Goto	RIKEN Research Center Brookhaven National Laboratory Physics Dept. – Bldg. 510A Upton, New York 11973-5000	goto@bnl.gov
Matthias Grosse Perdekamp	RIKEN Research Center Brookhaven National Laboratory Physics Dept. – Bldg. 510A Upton, New York 11973-5000	matthias@bnl.gov
Andrew Hoover	Brookhaven National Laboratory Building 902C Upton, New York 11973-5000	andhoove@nmsu.edu
Robert Jaffe	MIT Department of Physics Room 6-311 Cambridge, MA 02139	jaffe@mit.edu
Xiangdong Ji	University of Maryland Department of Physics College Park, MD 20742	xji@physics.umd.edu
Jiro Kodaira	Department of Physics Hiroshima University Higashi-Hiroshima 739-8526 Japan	kodaira@theo.phys.sci.hiroshima-u.ac.jp
Yuji Koike	Niigata University Department of Physics Ikarashi, Niigata 950-2181 Japan	koike@nt.sc.niigata-u.ac.jp
Shunzo Kumano	Saga University Department of Physics Saga 840-8502 Japan	Kumanos@cc.saga-u.ac.jp
Kazu Kurita	RIKEN Research Center Brookhaven National Laboratory Physics Dept. – Bldg. 510A Upton, New York 11973-5000	kurita@bnl.gov
Oliver Martin	Institut fuer Theoretische Physik Universitaet Regensburg D-93040 Regensburg Germany	Oliver.Martin@physik.uni-regensburg.de
T. S. McShane	Creighton University Physics Department 2500 California Street Omaha, NE 68178	tmcshane@creighton.edu
Jiro Murata	Brookhaven National Laboratory Physics Department – Bldg. 510C Upton, New York 11973-5000	jiro@bnl.gov

Program for Joint Sessions of Workshops

Predictions and Uncertainties for RHIC Spin Physics

&

Event Generator for RHIC Spin Physics III

-towards precision spin physics at RHIC-

March 6th – March 31st, 2000

A RIKEN BNL Research Center Workshop

LIST OF REGISTERED PARTICIPANTS

NAME	AFFILIATION AND ADDRESS	E-MAIL ADDRESS
Michael Murray	Cyclotron Texas A&M College Station, TX 77843-3366	murray@comp.tamu.edu
Pavel M. Nadolsky	Michigan State University Department of Physics & Astronomy E. Lansing, MI 48824	nadolsky@pa.msu.edu
Akio Ogawa	Brookhaven National Laboratory Upton, New York 11973-5000	akio@bnl.gov
Joseph (Jeff) Owens	Florida State University Physics Department Tallahassee, FL 32306-4350	owens@hep.fsu.edu
Frank Paige	Brookhaven National Laboratory High Energy Theory Group Physics Department – Bldg. 510 Upton, New York 11973-5000	paige@bnl.gov
Jianwei Qiu	Iowa State University Department of Physics Ames, IA 50011	jwq@iastate.edu
Naohito Saito	RIKEN Research Center Brookhaven National Laboratory Physics Dept. – Bldg. 510A Upton, New York 11973-5000	saito@bnl.gov
Jack Smith	SUNY Stony Brook YITP Stony Brook, N.Y. 11794-3840	smith@nuclear.physics.sunysb.edu
Jacques Soffer	Centre de Physique Theorique CNRS Luminy Case 907 13288 Marseille Cedex 09, France	soffer@cpt.univ-mrs.fr
George Sterman	SUNY Stony Brook YITP Stony Brook, N.Y. 11794-3840	sterman@inst.physics.sunysb.edu
Marco Stratmann	Institut fuer Theoretische Physik Universitaet Regensburg D-93040 Regensburg Germany	marco.stratmann@physik.uni-regensburg.de
Stefan Streit	Creighton University Physics Department 2500 California Street Omaha, NE 68178	elisar-rnl@juno.com
Atsushi Taketani	Brookhaven National Laboratory Building 510C Upton, New York 11973-5000	taketani@bnl.gov
Jaw-Luen Tang	Brookhaven National Laboratory P.O. Box 942 Upton, New York 11973-5000	jawluen@bnl.gov
Michael Tokarev	Laboratory of High Energy Joint Institute for Nuclear Research 141980 DUBNA Moscow Region – Russia	tokarev@sunhe.jinr.ru

Program for Joint Sessions of Workshops

Predictions and Uncertainties for RHIC Spin Physics

&

Event Generator for RHIC Spin Physics III

-towards precision spin physics at RHIC-

March 6th – March 31st, 2000

A RIKEN BNL Research Center Workshop

LIST OF REGISTERED PARTICIPANTS

NAME	AFFILIATION AND ADDRESS	E-MAIL ADDRESS
Hisayuki Torii	Brookhaven National Laboratory Physics Department – Building 510A Upton, New York 11973-5000	htorii@bnl.gov
Larry Trueman	Brookhaven National Laboratory Physics Department – Building 510A Upton, New York 11973-5000	trueman@bnl.gov
Wu-ki Tung	Michigan State University Department of Physics & Astronomy E. Lansing, MI 48824	tung@pa.msu.edu
W. Van Neerven	Institut Lorentz Niels Bohrweg 2 2333 CA Leiden The Netherlands	neerven@lorentz.leidenuniv.ivl
Christos Velissaris	Brookhaven National Laboratory Building 902C Cornell Avenue Upton, New York 11973-5000	christos@rcf.rhic.bnl.gov
Jean-Marc Virey	Centre de Physique Theorique CNRS Luminy Case 907 13288 Marseille Cedex 9 France	virey@cpt.univ-mrs.fr
Werner Vogelsang	RIKEN Research Center Brookhaven National Laboratory Physics Dept. – Bldg. 510A Upton, New York 11973-5000	vogelsan@insti.physics.sunysb.edu
Tammy Heinz (Workshop Secretary)	RIKEN Research Center Brookhaven National Laboratory Physics Dept. – Bldg. 510A Upton, New York 11973-5000	theinz@bnl.gov

Program for Joint Sessions of Workshops

Predictions and Uncertainties for RHIC Spin Physics
&
Event Generator for RHIC Spin Physics III

-towards precision spin physics at RHIC-

March 6th – March 31st, 2000
A RIKEN BNL Research Center Workshop

All talks will be in the Small Seminar Room, except for Thursday 03/09 (see Note)

AGENDA

Monday 6 March

Morning *Opening Session (Chair: Larry Trueman)*

8:30 – 9:00		*Registration*
9:00 – 9:15	Gerry Bunce	*Welcome*
9:15 – 9:35	Werner Vogelsang	*Predictions & Uncertainties for RHIC Spin Physics – Introductory Remarks*
9:35 – 9:55	Naohito Saito	*Event Generators for RHIC Spin Physics (Towards Precision Spin Physics at RHIC) – Introductory Remarks*
10:00 – 10:30		COFFEE BREAK
Prompt Photon Production		
10:30 – 11:30	Jeff Owens	*Direct Photon Production – A Status Report*
11:30 – 12:10	George Sterman	*Higher Order Corrections to Prompt Photon Production*
12:10 – 12:30		*Discussion on Prompt Photon Production (Theory)*
12:30 –		LUNCH

Afternoon *Afternoon Session (Chair: Naohito Saito)*

15:00 – 15:30	Alexander Bazilevsky	*Isolation Studies for Prompt Photons at PHENIX*
15:30 – 16:30		*Discussion on Prompt Photon Production (RHIC Experiments)*

Tuesday 7 March

Wednesday 8 March

Afternoon

Transverse Spin Effects (I) *(Chair: Werner Vogelsang)*

15:00 – 15:45	Yuji Koike	*Chiral-odd Contributions to Single Transverse Spin Asymmetry in Hadronic Pion Production*
15:45 – 16:30	Daniel Boer	*Double Transverse Spin Asymmetries in W Production*

Thursday 9 March * NOTE: Large Seminar Room*****

Afternoon **(Note: This is a joint meeting with PHENIX Spin Physics Working Group.)**

Transverse Spin Effects (II) *(Chair: Naohito Saito)*

15:50 – 16:35	Bob Jaffe	*Transversity*
16:35 – 17:00	Matthias Grosse-Perdekamp	*How we measure Transversity at RHIC*
17:00 – 17:25	Akio Ogawa	*Transversity at STAR*

Friday 10 March

Monday 13 March

Morning *(Chair: Naohito Saito)*

9:00 – 9:45	Xiangdong Ji	*One-loop Factorization of the Nucleon's g2 Structure Function*
Parton Densities		
9:45 – 10:15	Abhay Deshpande	*SMC Analysis*
10:15 – 10:45		COFFEE BREAK
10:45 – 11:30	Marco Stratmann	*Polarized PDFs at the advent of RHIC*
11:30 – 12:00	Shunzo Kumano	*AAC Analysis*
12:00		LUNCH

Monday 13 March		
Afternoon	*(Chair: Gerry Bunce)*	
13:30 – 14:15	Wu-ki Tung	*CTEQ5 Parton Densities*
14:15 – 15:15		*Discussion on (Un)Polarized PDFs and their Determinations*
16:00 – 18:00		***TOUR OF RHIC***
Tuesday 14 March		
Morning	*(Chair: Jianwei Qiu)*	
9:30 – 10:15	Jacques Soffer	*Polarized Lambda Fragmentation Functions: Present Status and Prospects at RHIC*
Afternoon	*(Chair: Werner Vogelsang)*	
13:30 – 14:15	Jean-Marc Virey	*Parity Violating Effects in Jet Production (I)*
14:15 – 14:45		REFRESHMENTS
14:45 – 15:30	Jean-Marc Virey	*Parity Violating Effects in Jet Production (II)*
15:30 – 16:00	Jiro Murata	*Contact Interaction Studies with Event Generator*
Wednesday 15 March		
Morning		
Heavy Flavors, Delta G Measurements (I)	*(Chair: Werner Vogelsang)*	
9:00 – 9:30	Hiroki Sato	*Delta G Measurements with Heavy Flavor Production at PHENIX*
9:30 – 10:30	Ingo Bojak	*Some Know-How for Calculating the Polarized Hadroproduction of Heavy Quarks in NLO QCD*
10:30 – 11:00		COFFEE BREAK
11:00 – 11:45	Marco Stratmann	*Open Heavy Flavor Production: Some Phenomenological Aspects*
11:45 – 12:30	Jack Smith	*Open Heavy Flavor Production: Lessons from F2(Charm) at HERA*
12:30 –		LUNCH

Wednesday 15 March

Afternoon

Delta G Measurements (II) (Chair: Jianwei Qiu)

15:00 – 15:45	Edmond Berger	*Constraints on the Gluon Density from Lepton Pair Production (TBC)*
15:45 – 16:30	Daniel de Florian	*Measurement of Delta G: Theoretical Uncertainties*
16:30 – 17:00	Yuji Goto	*Measurement of Asymmetry for Pion Production in PHENIX*
17:00 – 17:30		*Discussion on Measurements of Delta G at RHIC*
18:00 - ????		WORKSHOP BUFFET

Thursday 16 March

Morning

Event Generators, Weak Bosons (I) (Chair: Naohito Sato)

9:00 – 10:00	John Collins	*NLO and Event Generators*
10:00 – 10:45	Csaba Balazs	*Weak Boson Production (ResBos vs PYTHIA, HERWIG)*

Afternoon

Event Generators, Weak Bosons (II) (Chair: Werner Vogelsang)

15:00 – 15:45	Oliver Martin	*Comparison of Event Generators*
15:45 – 16:30	Pavel Nadolsky	*Soft Parton Effects in Vector Boson Production at RHIC*
16:30 – 17:00	Akio Ogawa	*W Production*
17:00 -		*Discussion on Event Generator and NLO, Resummation*

Friday 17 March

Morning	*(Chair: Jianwei Qiu)*	
9:30 – 10:00	Tom Blum	*Spin on Lattice*
10:00 – 10:45	Andrei Belitsky	*Asymmetries in DVCS and Skewed Parton Distributions*
10:45 – 11:25	Jiro Kodaira	*Radiation Zeros in Polarized* $p\ (\bar{p}) - p$ *Processes*

Forthcoming RIKEN BNL Center Workshops

Title:	**Future Transversity Measurements**
Organizers:	Daniel Boer and Matthias Gross Perdekamp
Dates:	September 18–20, 2000

For information please contact:

Ms. Pamela Esposito / Ms. Tammy Heinz
RIKEN BNL Research Center
Building 510A, Brookhaven National Laboratory
Upton, NY 11973, USA
Phone: (516)344-3097 Fax: (516)344-4067
E-Mail: rikenbnl@bnl.gov
Homepage: http://penguin.phy.bnl.gov/www/riken.html

RIKEN BNL RESEARCH CENTER

PREDICTIONS AND UNCERTAINTIES FOR RHIC SPIN PHYSICS & EVENT GENERATOR FOR RHIC SPIN PHYSICS III

–TOWARDS PRECISION SPIN PHYSICS AT RHIC–

MARCH 6–31, 2000

Li Keran

Nuclei as heavy as bulls
Through collision
Generate new states of matter.
T. D. Lee

Speakers:

C. Balazs	A. Bazilevsky	A. Belitsky	E. Berger	T. Blum
D. Boer	I. Bojak	D. deFlorian	J. Collins	A. Deshpande
Y. Goto	M. Gross-Perdekamp	R. Jaffe	X. Ji	J. Kodaira
Y. Koike	S. Kumano	O. Martin	J. Murata	P. Nadolsky
A. Ogawa	J. Owens	N. Saito	H. Sato	J. Smith
J. Soffer	G. Sterman	M. Stratmann	W.-K. Tung	J.-M. Virey
W. Vogelsang				

Organizers: Jianwei Qiu, Naohito Saito, Andreas Schäfer, and Werner Vogelsang