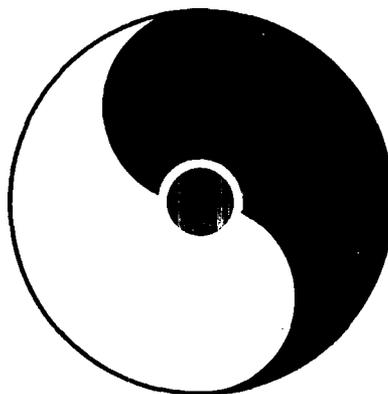


# EVENT GENERATOR FOR RHIC SPIN PHYSICS

March 15–19, 1999



Organizers

Naohito Saito and Andreas Schaefer

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RIKEN BNL Research Center

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

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- 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 Kenkyusho” (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.

T.D. Lee  
July 4, 1997



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## INTRODUCTION

This volume archives the reports from the RIKEN BNL Research Center workshop on "Event Generator for RHIC Spin Physics II" held during the week March 15, 1999 at Brookhaven National Laboratory. It was the second meeting on the subject following a first one in last September.

This workshop has been initiated to establish a firm collaboration between theorists and experimentalists involved in RHIC spin physics with the aim of developing a reliable, high-precision event generator for RHIC spin physics. Needless to say, adequate event generators are indispensable tools for high energy physics programs in general, especially in the process of:

- planning the experimental programs,
- developing algorithms to extract the physics signals of interest,
- estimating the background in the extracted results, and
- connecting the final particle kinematics to the fundamental i.e. partonic level processes.

Since RHIC is the first polarized collider, dedicated efforts are required to obtain a full-fledged event generator which describes spin dependent reactions in great detail.

The RHIC spin project will be in the transition from R&D and construction phase to operation phase in the year 2000. As soon as data will be available, it should be analysed, interpreted and compared with theoretical predictions to extract its physical significance. Without mutual understanding between theorists and experimentalists on the technical details, it is hard to perform detailed comparisons in a consistent framework. The importance of this fact has been recognized especially during the analyses of hadron induced reactions observed at CERN, Fermilab and DESY. Since the use of event generator is indispensable for the analyses, it should be developed in a way that both experimentalists and theorists can agree upon.

During the first meeting we had specified several areas of work to be done. For most of them some actual calculations are well under way and first progress was reported. These areas of work include:

- comparison of polarized event generators with results obtained by using unpolarized event generators and suitable asymmetry weights
- comparison of event generator with next-to-leading order calculations
- implementation of new processes, e.g. parity violating processes
- implementation of new polarized parton distributions and their continued maintenance
- polarization effects in fragmentation processes

We believe that the records of the discussions in these various areas, as combined in these proceedings, will prove to be useful not only for the participants but also for other physicists involved in this field.

Naohito Saito and Andreas Schäfer are grateful to all participants of the workshop for their contributions on the various theoretical and experimental issues to be clarified by our collaboration. We would like to express our sincere thanks to the secretary of RIKEN BNL Research Center, Pam Esposito, for her great help in organizing and running the workshop. Our workshop was celebrated by a big snow storm on the first day. Without the kind and devoted help by Pam and Eva Esposito, we would therefore not have been able to carry out the workshop as planned. We want to extend our gratitude to Brookhaven National Laboratory and to the U.S. Department of Energy for providing the facilities to hold this workshop.

Naohito Saito (RIKEN / RIKEN BNL Research Center)  
Andreas Schäfer (Universität Regensburg)

RIKEN BNL Research Center  
April, 1999

# Needs of Event Generator for RHIC Spin Physics

Naohito Saito

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*RIKEN (The Institute for Physical and Chemical Research)*

*Hirosawa, Wako, Saitama 351-0198, Japan*

and

*RIKEN BNL Research Center*

*Brookhaven National Laboratory*

*Upton, NY11973-5000, USA*

The event generator is a irreducible part of the high energy particle and nuclear physics. This is especially true when one tries to extract partonic level information in QCD events. The efficiency of the experimental cut for the signal and remaining backgrounds are usually estimated with event generators. Since RHIC is a unique machine for both heavy ion and polarized proton beams, special extension of the event generator is necessary.

In this talk, we addressed the needs of more detailed analysis of previous experiments on key reactions, especially prompt photon production, since most of theory calculations underestimate the cross section. To obtain a reasonable agreement, inclusion of intrinsic transverse momentum ( $k_T$ ) is desirable. We also addressed the importance of direct measurement of  $k_T$ . This kind of analysis have to be extended to cover  $W$  production, Drell-Yan production of lepton pairs, open heavy flavor productions, and finally new processes such as compositeness search and so on.

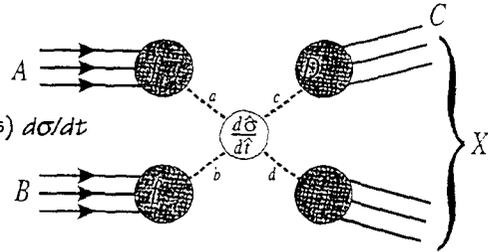
There are many things to do to come to complete understanding of the reactions in hadron collisions. But we should hurry up, since we are going to take real data soon!

# Needs of Event Generator

from experimentalist's viewpoint

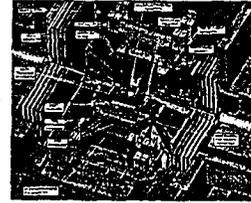
- Experimentalists can touch only Initial and Final state particles

- parton emission  $f_{a/A}(x)$
- initial state radiation
- hard scattering (may include new physics)  $d\sigma/dt$
- final state radiation
- fragmentation  $D_{C/c}(z)$
- decay
- underlying event



- Experimentalists often aim  $f_{a/A}(x)$ ,  $d\sigma/dt$ ,  $D_{C/c}(z)$  to find new physics

- sensitivity for new physics / background studies
- geometrical acceptance for FSPs from physics of interests
- systematic uncertainties in interpretation of results



## Summary of the Last Meeting

- Polarized EvGen vs Unpolarized EvGen+Asymmetry
  - Quick studies showed similarity. What Precision?
- Event Generator vs analytic calculation (NLO, Resummation)
  - Detailed comparison may show some discrepancy
- Library of Pol-PDF in addition to Unpol-PDF
  - interface needed for 1) prediction 2) quick test of obtained PDFs
- Intrinsic Transverse Momentum of Partons
  - could be large at RHIC --> small-x data become "useless" if unknown
- New Processes
  - parity violation in jet production --> parity violation in  $\pi^{0}???$
  - Quarkonium production: popular color octet model with spin dependence
- Polarization Effects in Fragmentation
  - 2 pion correlation in final state
- Comparison of PYTHIA, HERWIG and ISAJET

# Partonic Kinematics - LO vs NLO

prompt photon example

- Simple minded reconstruction of partonic kinematics

$pp$  CMS = parton CMS

- What is  $x$  carried by gluon?

$x = x_T$ ? No!

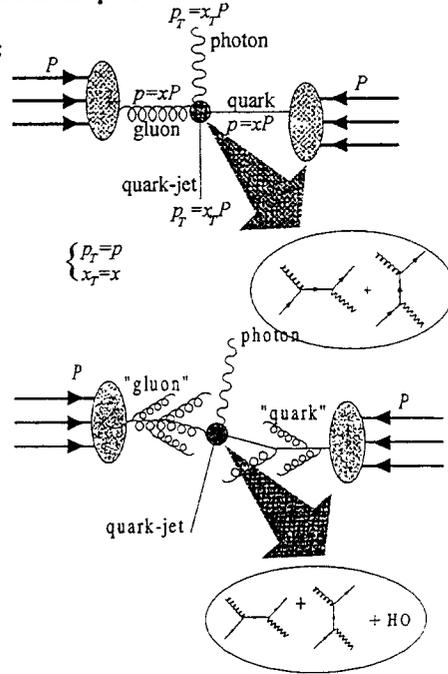
better estimation?

- What is  $Q^2$ ?

•  $Q^2 = p_T^2$ ?

•  $Q^2 = (p_T/2)^2$ ?

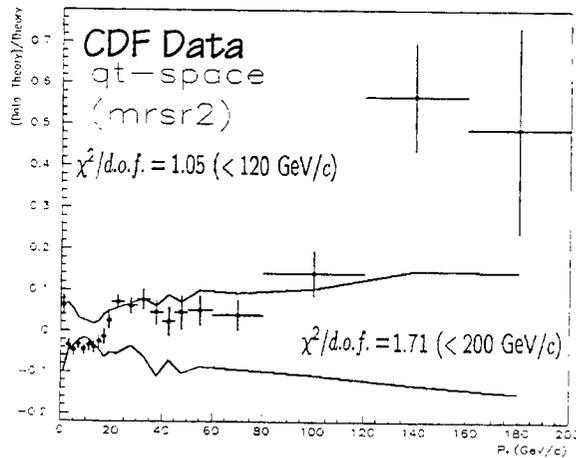
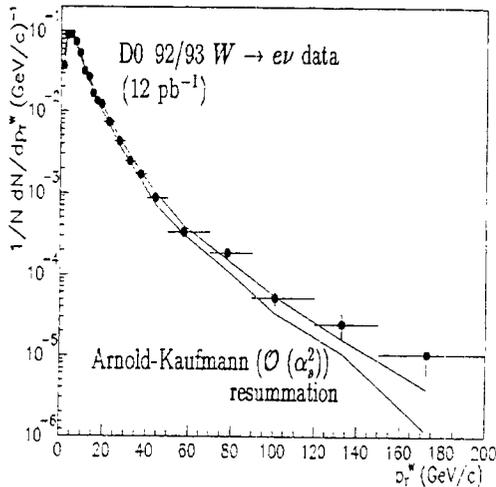
•  $Q^2 = (2 p_T)^2$ ?



## EvGen and Resummed Xsection

$W$  production

- Signal = High- $p_T$  lepton --> affected by  $p_T^W$
- EvGen used: RESBOS, VBP = Full Event Generation?

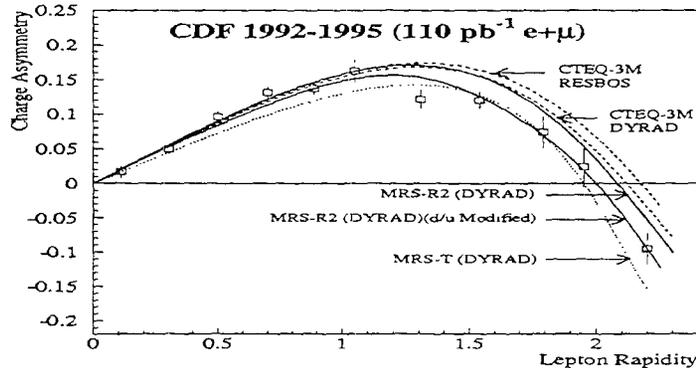
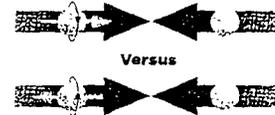


# Unpolarized parton distribution

flavor structure of valence quark

- Spin-flavor structure studies with  $W$  assume knowledge on  $u(x)$  and  $d(x)$

$$A_L^{W^{\pm}} = \frac{\Delta u(x_a, M_W^2) \bar{d}(x_b, M_W^2) - \Delta \bar{d}(x_a, M_W^2) u(x_b, M_W^2)}{u(x_a, M_W^2) \bar{d}(x_b, M_W^2) + \bar{d}(x_a, M_W^2) u(x_b, M_W^2)}$$

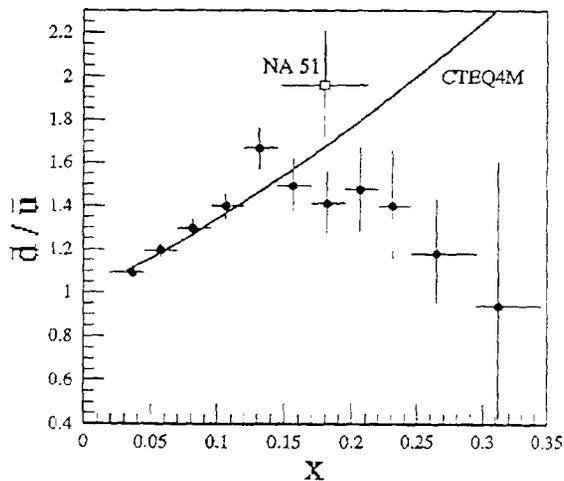


# Unpolarized parton distribution

flavor structure of sea-quark

- Charge Symmetry is a good symmetry to describe hadron properties: ( $u$  in  $p$  and  $d$  in  $n$  are different??): C. Boros, J.T. Londergan, A. Thomas: PRL 81 (1998) 4075
- It is not trivial to assume:  $d/\bar{u} = 1$

FNAL-E866 results  
PRL 80 (1998) 3715

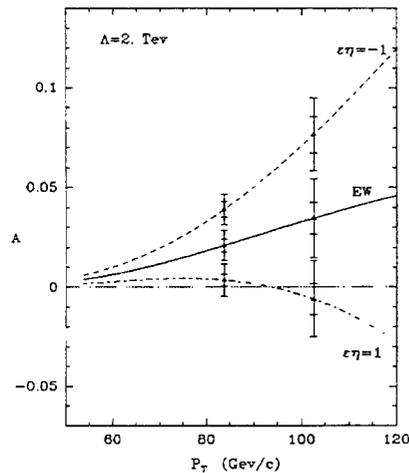
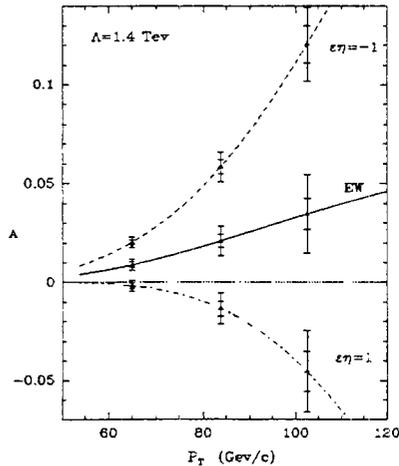


# Parity Violation Beyond SM

P. Taxil, J.M. Virey PLB 364(1995)181-187

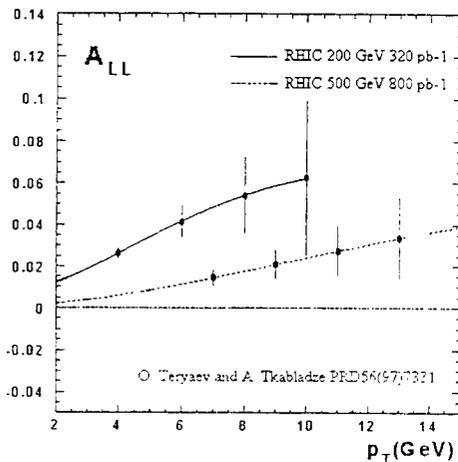
PV in Jet Production due to quark Compositeness (scale: $\Lambda$ )

→ should be reflected to single particle production



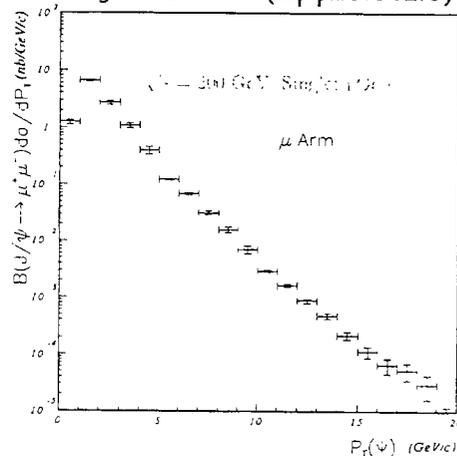
# Charmonium Production

Asymmetry Prediction with Color Octet Model



Yield Estimation with Color Octet Model by Naoki

using COM in PYTHIA (hep-ph/9706270)



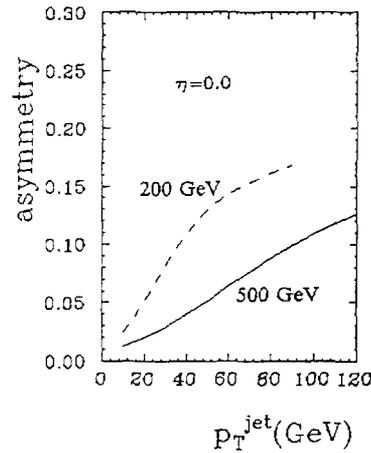
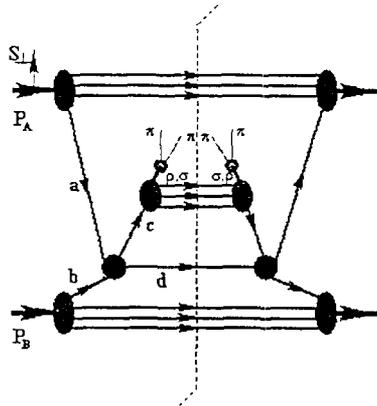
See D. Kharzeev's transparencies at Spin Discussion at <http://rikweb.rhic.bnl.gov/rsc/write-up/Kharzeev/kharzeev1.html>

# Spin Dependent Fragmentation to measure $\Delta_T q(x)$

R.L Jaffe, Xuemin Jin, Jian Tang hep-ph/9807560

- Asymmetry  $A_{\perp\perp} \propto \Delta_T q \otimes a_{TT}^{if} \otimes \Delta_T \hat{q}$

$$p_{\uparrow} p_{\uparrow} \rightarrow \pi^+ \pi^- X$$



Soffer's  
inequality  
assumed to  
be saturated

## Summary

- Many efforts to be ready for RHIC Spin Physics
  - theory, experiment, and accelerator
- Event Generator for polarized pp should be ready for many reasons
- This meeting:
  - progress report
  - further steps to be discussed

# Recent Progress in Theoretical Studies of Spin Physics

Andreas Schäfer (Regensburg)

I review a few results from recent papers which focuss on RHIC spin physics. However, many of the authors participate in the workshop and I avoid overlap with their talks. Instead, I focuss on a few topics which are relevant for RSC but are either not yet well understood or a slightly peripheral to the main interest of RSC.

1.) The lack of a firm theoretical prediction for the small  $x$  asymptotic behaviour of  $g_1(x)$  limits strongly the relevance of DIS data because the most interesting QCD predictions address sum rules. Recently an interesting proposition was made by Kwiecinski et al., the problems and merits of which are shortly outlined.

2.) Higher-twist effects can be studied especially well in spin physics. Furthermore the size of single-spin asymmetries suggest that they are large. I argue that nuclear effects for higher twist effects can be large and cite some work by Guo et al. on this subject. If pQCD at smallish  $Q^2$  would break down this would affect most seriously the whole field of high-energy heavy-ion physics. I argue that it in this context it is interesting to study single spin asymmetries in  $p(\text{pol.})+A$ .

3.) I review the situation of orbital angular momentum distributions for quarks and gluons in the nucleon. I suggest that the production ratios for different  $c\bar{c}$ -Mesons in the collision of polarized protons might provide a way to access the gluon orbital angular momentum distribution directly.

4.) I review recent developments for Off-Forward-Parton-Distributions and pose the question whether they could be investigated at RHIC.

## A collection of topics

- $g_1(x)$  at small  $x$
- higher-twist effects in nuclei  
SSA ; photoproduction data
- $\vec{L}_G(x)$  and  $\vec{L}_g(x)$
- a word on  $g_2(x)$
- OFPDs
- no summary  
→ topics for discussion

The summary will be given by  
Naohito on Friday !

## $g_1(x)$ at small $x$

status: no generally accepted theory prediction for  $g_1(x) \sim x^{-\lambda}$

$\Rightarrow$  no possibility to extract

$\int_0^1 dx g_1^{p,n}(x)$  from data

$\Rightarrow$  no possibility to extract e.g.  $\alpha_s(Q^2)$  from Bj-SR.

new paper: J. Kwiecinski + B. Ziaja, hep-ph/9902440

educated guess for a combination of  $\ln^2 x$  terms, AP-evolution + higher terms

$$\Rightarrow \lambda^{NS} = 0.43 \quad \lambda^S = 0.78$$

# Higher-twist effects for QCD-processes

in nuclei

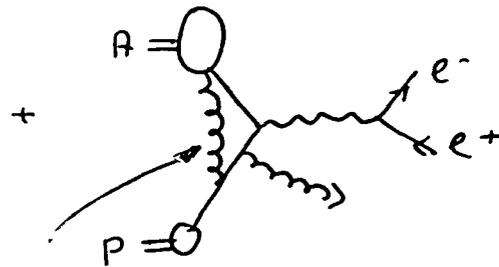
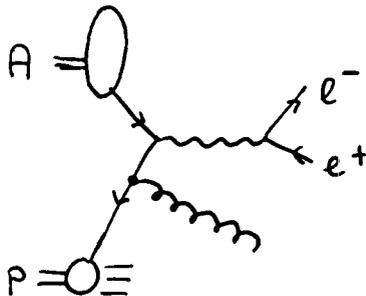
typically  $Q^2 \approx 1-2 \text{ GeV}^2$

Can higher twist contributions acquire an enhancement factor  $\sim A^{1/3}$  ?

X. Guo, Phys. Rev. D 58 036001 (1998)

+ Qiu, Sterman ...

$\Rightarrow$  'Nuclear enhancement' for higher twist contributions in Drell-Yan pair production can be large



soft gluon

# The problem of orbital angular momentum

Ph. Högler + A.S. ; Phys. Lett. B 430 (98) 179  
 O. Martin, Ph. Högler, A.S. ; hep-ph/9810474 v2  
 S.V. Boshinski, R.L. Jaffe ; Nucl. Phys. B 536 (98) 303  
 A. Harindranath + R. Kundu ; hep-ph/9802406 v4  
 X.Ji, J. Tang, + P. Hoodbhoy, PRL 76 (96) 740

$$\Delta \Sigma = \langle P, s | \int d^3x \frac{i}{2} \bar{\Psi} \gamma^T [\gamma^1, \gamma^2] | P, s \rangle$$

$$\Delta G = \langle P, s | \int d^3x (A^1 \delta^+ A^2 - A^2 \delta^+ A^1) | P, s \rangle$$

$$L_q = \langle P, s | \int d^3x i \bar{\Psi} \gamma^T (x^1 \delta^2 - x^2 \delta^1) \Psi | P, s \rangle$$

$$L_G = \langle P, s | \int d^3x \delta^+ A^j (x^1 \delta^2 - x^2 \delta^1) A^j | P, s \rangle$$

$\Rightarrow$

$$\frac{d}{d \ln Q^2} \begin{pmatrix} \Delta \Sigma^n \\ \Delta G^n \\ L_q^n \\ L_G^n \end{pmatrix} = \frac{\alpha}{2\pi} \begin{pmatrix} A_{ss}^n & A_{sL}^n \\ A_{Ls}^n & A_{LL}^n \end{pmatrix} \begin{pmatrix} \Delta \Sigma^n \\ \Delta G^n \\ L_q^n \\ L_G^n \end{pmatrix}$$

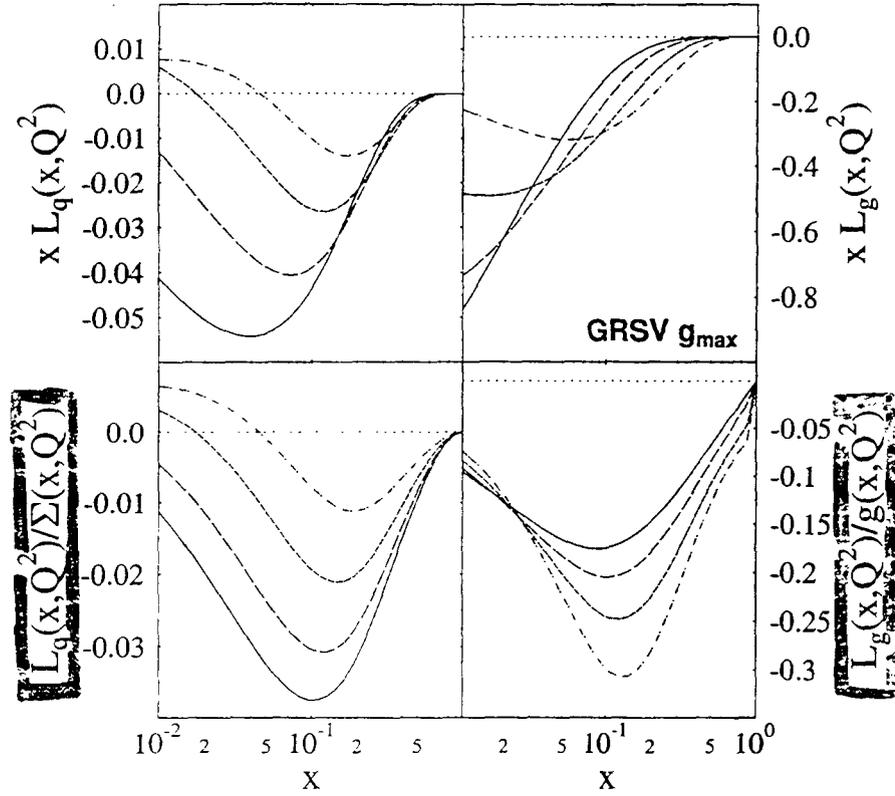


Figure 2: Evolution of orbital angular momentum. The GRSV LO g<sub>max</sub> scenario is used as input for the polarized parton distributions at  $\mu_0^2 = 0.23 \text{ GeV}^2$ . At this scale the missing angular momentum of -0.43 units is evenly distributed among  $L_q(x, \mu_0^2)$  and  $L_g(x, \mu^2)$ , which are assumed to have the same shape as  $u_v(x, \mu_0^2)$  and  $g(x, \mu_0^2)$ , respectively.

# New Processes and Parity Violating Asymmetries

Jean-Marc Virey<sup>1</sup>  
Institut für Physik  
Universität Dortmund  
D-44221 Dortmund, Germany

We have presented the apparent sensitivity of the RHIC Spin experiment to some new physic contributions, from the analysis of the Parity Violating (PV) asymmetry  $A_{LL}^{PV} (\equiv d\sigma^{--} - d\sigma^{++} / d\sigma^{--} + d\sigma^{++})$  defined for jet production ( $d\sigma \equiv d\sigma_{1-jet}$ ). Since the experiment will begin next year, we greatly emphasize the need of detailed simulations at the level of Monte Carlo Event Generators.

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 of the RHIC to these models, 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.

The second part was devoted to an emphasis of the need of simulations from event generators, in order to take into account carefully the experimental conditions and the properties of the detectors. Some opened questions which have to be clarified by such simulations are, for instance : What are the true acceptances and efficiencies for jet reconstruction needed to determine the actual effective integrated luminosity ? Is it possible to use single particle production, on one hand, for an easier treatment within detectors, or on the other hand, to reduce the backgrounds of the gluon's subprocesses ? What are the magnitudes of the systematic errors on  $A_{LL}^{PV}$  ?

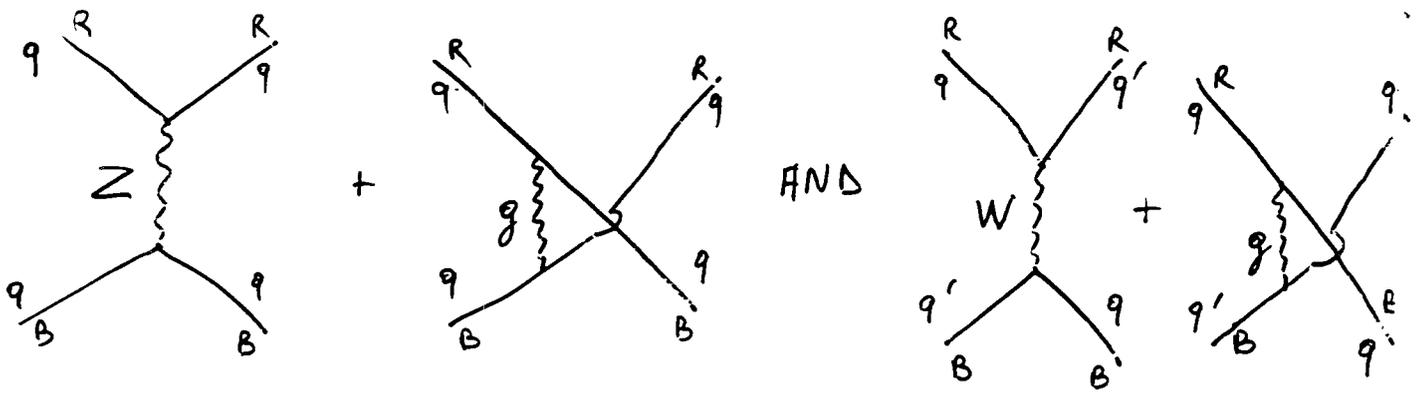
The last section concerned the potentialities for new physics of the RHIC with polarized neutrons, *i.e.* if the option of polarized  $He^3$  is seriously envisaged. In the framework of  $p - n$  collisions, the measurement of  $A_{LL}^{PV}$  could detect the presence of a new charged boson  $W'$  unconstrained by present experimental data. And if some new physics effects are detected in  $p - p$  collisions, it could be very interesting to run in the  $n - n$  mode to constrain the scalar sector of the theory, through the presence or absence of trilinear quark mass terms.

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<sup>1</sup>email: virey@eathert.physik.uni-dortmund.de

• SM effects

$$F_{LL}^{PV} (SM) \neq 0 \quad \{ \text{small} \} \quad \text{due to}$$



$$F_{LL}^{PV} \approx \frac{1}{dV} \sum_{ij} \sum_{\alpha\beta} \int dx_a \left( T_{\alpha\beta}^{(ij)-} - T_{\alpha\beta}^{(ij)+} \right) \left[ q_i(x_a) \Delta q_j(x_b) + \Delta q_i(x_a) q_j(x_b) + (i \leftrightarrow j) \right]$$

$T_{\alpha\beta}^{\lambda_1 \lambda_2 (ij)}$ : matrix element squared for  $\alpha, \beta$  beams exchange between quarks of flavor  $i, j$  and helicities  $\lambda_1, \lambda_2$

$$\left( \frac{dV}{dE}^{\lambda_1 \lambda_2 (ij)} = \sum_{\alpha, \beta} \frac{\pi}{s^2} T_{\alpha\beta}^{\lambda_1 \lambda_2 (ij)} \right)$$

In  $\vec{p} \rightarrow \vec{p}$  we have:  $Z.g \sim 70\%$   $W.g \sim 30\%$

$\Rightarrow$  Dominant terms:

$$a_2 \equiv 4/s_w^2 c_w^2$$

numerator:  $\text{num}(F_{LL}^{PV}) \sim \alpha_s \alpha_2 (C_L^w - C_R^w) [u \Delta u + \Delta u u]$

denominator:  $\text{den}(F_{LL}^{PV}) \sim \alpha_s^2 [qq + qg (+gq) + gq]$   
(ACK)

Main uncertainty: 14 Polarized pdf's (will be reduced with W prod. analysis)

### 3°) Compositeness ( $\rightarrow$ Contact Interactions)

(P. Tarasiewicz JHEP 04 (2015) 181  
PR D 55 (97) 448)

$\rightarrow$  C I effective Lagrangian:

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

$\Lambda \equiv$  compositeness scale  $\left| \begin{array}{l} A_{LL}^{PV} \sim \frac{\varepsilon \cdot g}{\Lambda^2} \\ (\text{q-CI dominant}) \end{array} \right.$

$\rightarrow$  Present situation:

CDF : excess of events in  $V_{jet}^{unpol}$   $\rightarrow \Lambda \sim 1.6$  TeV

$\Delta\phi$  : no excess  $\rightarrow \Lambda_{lim} = 2.0$  TeV

$\rightarrow$  RHIC sensitivity from  $A_{LL}^{PV}$  (p-p coll.)

	$L_1 = 800 \text{ pb}^{-1}$	$L_2 = 3.2 \text{ fb}^{-1}$
$\Lambda$ (TeV)	3.3	4.4

$\sqrt{s} = 500$  GeV  
P = 70%  
GRSV pdf's

$\rightarrow$  TEVATRON sensitivity from  $V_{1-jet}^{unpol}$

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

$\sqrt{s} = 2$  TeV

$\rightarrow$  Conclusions:

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

# 5. Leptophobic Z at RHIC from $H_{LL}$ (jets)

(P. Taxiil & SMV PLB 383 (96) 355; PLB 441 (98) 376)

• Dominant term XXXXXXXXXX

$$A_{LL}^{PV}(\vec{p}\vec{p}) \sim \frac{1}{dV} \int dx \left( C_L^{u^2} - C_R^{u^2} \right) \left[ u(x_2, Q^2) \Delta u(x_1, Q^2) + \Delta u(x_1, Q^2) u(x_2, Q^2) \right]$$

for  $\vec{n} \rightarrow \vec{n}$  collisions :  $u \leftrightarrow d$

• sensitivity

$$\begin{matrix} C_L^d = 0 \\ \rightarrow C_R^u = C_R^d = 1/3 \end{matrix}$$

	$\Pi_{Z'} / \kappa_{GeV}$	$SU(5) \times U(1)$	$\gamma - R$	GG	$\Pi_{\nu\tau - Z'}$
p-p	$L_1 = 800 \text{ pb}^{-1}$	260	170	280	290*
	$L_2 = 3.2 \text{ Pb}^{-1}$	350	290	370	380*
-----					
n-n	$L_1$	/	/	230	300
	$L_2$	/	/	310	400

$\downarrow$   
 $\sqrt{s} = 400 \text{ GeV}$

PC

• conclusions:

→ sensitivity in a domain unconstrained experimentally

→ chiral structure informations from  $A_{LL}^{PV}$

→ if effect detected for  $u$  (from  $A_{LL}^{PV}(\vec{p}\vec{p})$ )

⇒ run in  $\vec{n}\vec{n}$  mode to constrain  $W/Z_\gamma$ :

\* No effect on  $A_{LL}^{PV}(\vec{n}\vec{n})$ : all structures possible

\* effect identical  $u$ -direction:  $\Pi_{\text{minimal}}$  excluded

\* effect opposite  $u$ -direction:  $\Pi_{\text{minimal}} + N \Pi_{\perp}$  excluded

# Need of Simulations from Event Generators

## 1.) Inclusion of Detectors properties:

→ knowledge of actual acceptances/efficiencies for jet reconstruction in order to know the actual effective Luminosity

For Instance:

- STAR (G. Eppley talk BNL April 98)

trigger need  $E_T > 45 \text{ GeV}$  ( $|\eta| < 0.8$ )

with 33% dead time and estimated  $\epsilon = 50$

- PHENIX

problems for jet reconstruction  $\Rightarrow$

look for single particle production  
 $\pi^0$ ?

## 2.) Single particle production

ABCDHW collaboration at CERN ISR (pp  $\sqrt{s}$ :

$\geq \text{Phys. C } 25(84)21$ ,  $\text{PL B } 248(90)220$  (+ ZFC 27 (85)  
33 (87)

$\pi^+$ ,  $K^+$  good triggers for  $u$  initiated jets

$\Rightarrow$  could allow separation of  $q\bar{q}$ ,  $qg$ ,  $q\bar{q}$  <sup>(uu)</sup> subprocess

### 3°) Knowledge of $\delta A$ systematic

In general  $\frac{\delta V}{V}_{\text{sys}} \sim 30-40\%$   $\left\{ \begin{array}{l} \delta Q, c \\ \text{UFI, U} \\ (\text{P}\bar{P}) \end{array} \right.$

For a spin asymmetry it is assumed that systematics largely cancel in the numerator,

$$\rightarrow \frac{\delta A_{\text{sys}}}{A} \sim 10-15\%$$

(Reason why RHIC is competitive with Terrestrial for

To be checked!

### 4°) Inclusion of the degrees of polarization.

see JNV hep-ph/9803439 (Fr)

For  $A_{LL}^{(PC)}$  and  $A_L$  the situation is clear,

we only need to introduce the  $P$ 's in  $\delta A_{\text{stat}}$

$$A_{LL}^{\text{exp/meas}} \stackrel{P \text{ dep.}}{\sim} = P_a P_b \cdot A_{LL} \quad (\text{P indep.})$$

$$\Rightarrow \delta A_{LL} = \frac{1}{P_a P_b} \delta A_{LL}^{\text{exp}} = \frac{1}{P_a P_b} \sqrt{\frac{1 - P_a^2 P_b^2 A_{LL}^2}{N^{++} + N^{--} + N^{+-} + N^{-+}}}$$

Similarly for  $A_L$

For  $A_{PV}$  the situation is quite different

## $k_T$ Issues

M.J.Tannenbaum  
BNL/PHENIX  
March 15, 1999

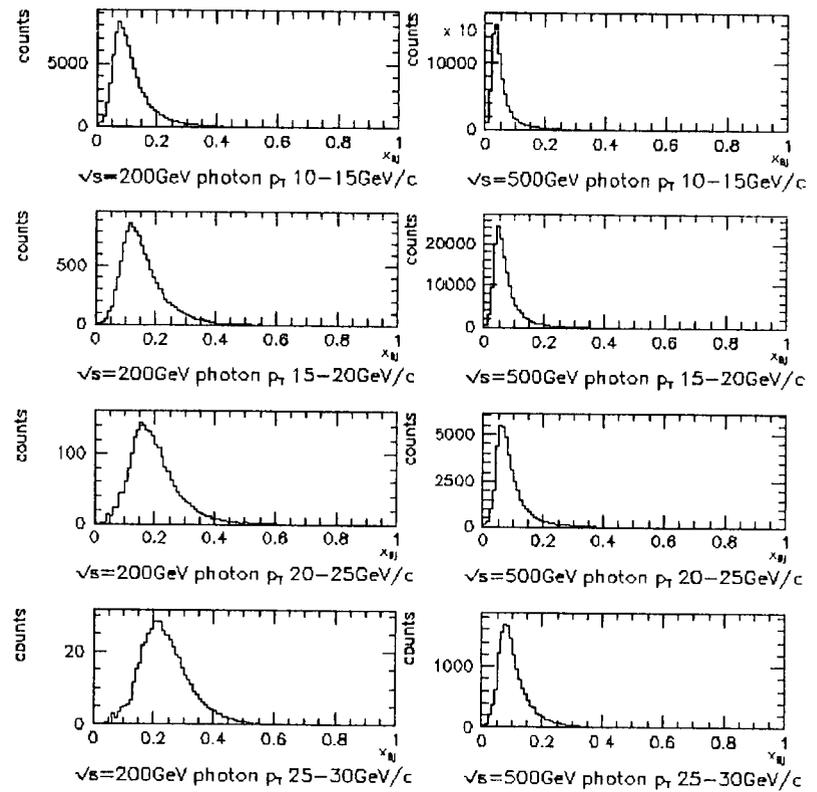
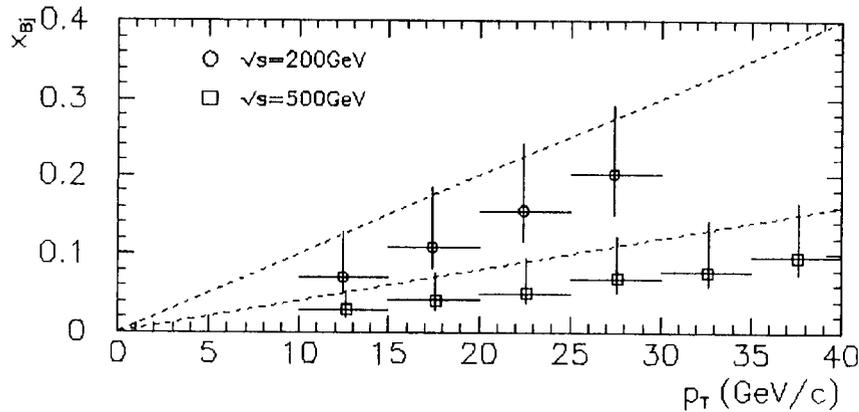
- $k_T$  is related to the net transverse momentum of a hard-scattering jet-pair, or a Drell-Yan pair, or a pair of high  $p_T$  photons, or the  $\gamma$ +Jet pair for direct photon production.
- In leading order QCD or the Quark-Parton model, all the above pairs are coplanar with the incident beam axis:  $k_T = 0$ .
- However, early Drell-Yan and inclusive high  $p_T$  particle studies showed that  $k_T$  was measurable and non-zero. Systematic measurements were made at the ISR and Fermilab.
- Some experimentalists and theorists may view the issue of  $k_T$  differently—Experimentalists: multi-soft gluon, Gaussian; Theorists: Hard-NLO gluons, power-law.
- The definitive work on  $k_T$ , actually on the  $p_T$  distribution of Drell-Yan pairs was made by G. Altarelli, R. K. Ellis and G. Martinelli in Phys. Lett. **151B**, 457 (1985), based on the ISR measurements.  $\Rightarrow$  should be incorporated into event generators.
- The effect of  $k_T$  on the Gluon Spin structure function is mainly that it leads to an uncertainty in the value of Bjorken  $x$  of the inclusive direct photon measurements. This is illustrated and ways to measure  $k_T$  are discussed.

EVENT GENERATOR WORKSHOP MARCH 15, 1999

# Parton kinematics

- Uncertainties in  $x$  estimation
  - PYTHIA prompt photon
  - $p_T$  vs gluon's  $x$ 
    - naïve formula
      - $x_T = 2p_T / \sqrt{s}$
    - evaluation with simulation

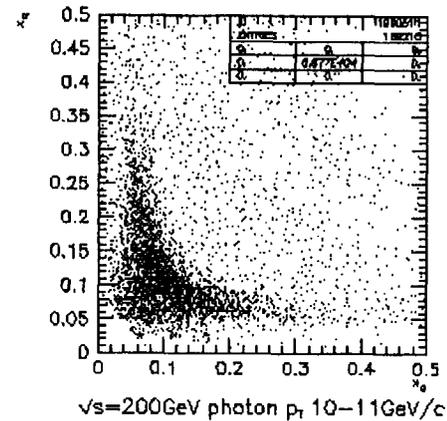
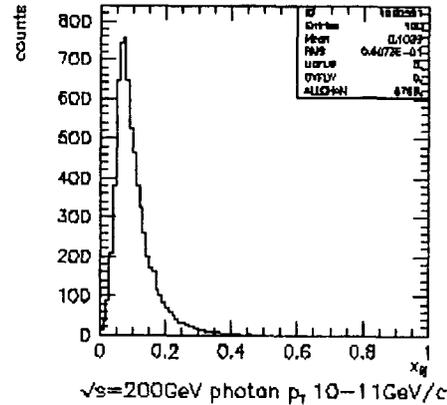
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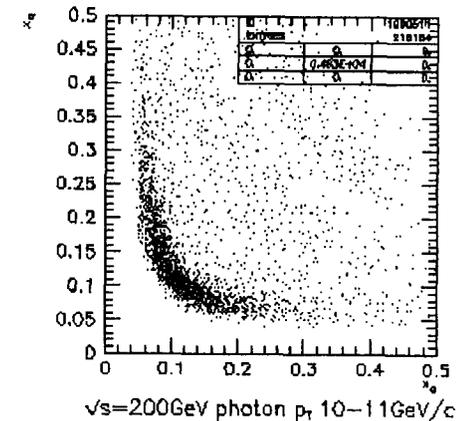
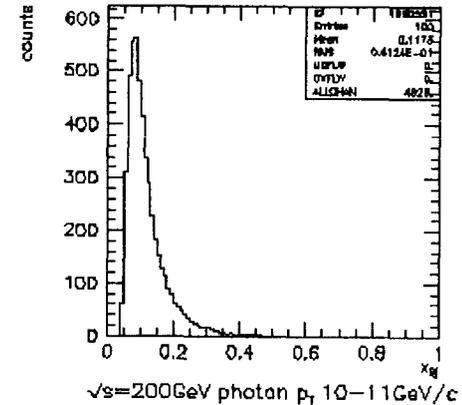
# Parton kinematics

- Uncertainty by  $k_T$  - initial radiation
  - error estimation in the data interpretation
  - what can we learn for QCD reaction itself ?

default setting  
 $k_T^2 = (1-z)Q^2$   
 $z$  - splitting  
 fraction of  
 initial radiation



initial radiation  
 off  
 $k_T^2 = 0$



## LEPTON PAIR PRODUCTION AT ISR ENERGIES AND QCD

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Received 27 November 1984

Motivated by some recent results from the ISR we have considered all available data on the production of Drell-Yan pairs by high energy proton beams. We show that the lepton pair cross sections and  $q_T$  distributions are correctly described by QCD using the known distributions of partons in the proton and acceptable values of the QCD scale  $\Lambda$ . No other free parameter is required. Within the accuracy of the data no appreciable intrinsic transverse momentum is needed.

We have recently made [1] a theoretical reevaluation of the QCD description of lepton pair production in hadron-hadron collisions. A full treatment of the complete transverse momentum ( $q_T$ ) dependence was given including the large amount of theoretical information about this process which has been accumulated over the last few years. The resulting  $q_T$  and  $y$  distribution reproduces the correct perturbative behavior [2] at large  $q_T$  and contains the soft gluon exponentiation at leading [3] and next-to-leading [4,5] double logarithmic accuracy. Upon integration over  $q_T$  it reproduces the known perturbative results [6] for the total cross section and rapidity distribution  $d\sigma/dy$  (including the terms of order  $\alpha_s$  which give rise to the "K-factor"). The phenomenological implications for  $W/Z^0$  production at the CERN collider and for the physics of the future Multi-TeV colliders have been discussed in detail in refs. [1,7]. On the experimental side, new data from the ISR [8] on Drell-Yan

lepton pair production have recently been presented ( $\sqrt{s} \approx 62$  GeV). The investigated range of lepton pair mass  $Q$  was extended up to  $Q \approx 25$  GeV and the  $q_T$  distribution of the pair was measured. This set of data completes a series of excellent experiments on lepton pair production [9-11] performed over the years at the ISR which is now being dismantled.

In view of this theoretical and experimental progress it appears timely to make a complete analysis of all the available data on (continuum) lepton pair production in both  $p-p$  and  $p-\bar{p}$  collisions. We shall concentrate our attention on the data set at large values of the pair mass  $Q$ , i.e. above the  $\Upsilon$  resonances ( $Q \geq 11$  GeV). These data are most appropriate for a comparison with the asymptotic QCD predictions which are only valid if  $Q$  is large enough. For completeness we shall also extrapolate our calculations to values of  $Q$  in the range  $Q \approx 5-9$  GeV between the  $J/\Psi$  and the  $\Upsilon$ . The relevant set of data also includes Drell-Yan  $p-\bar{p}$  processes at  $\sqrt{s} \approx 19-27$  GeV [12] and  $p-p$  processes at ISR with  $\sqrt{s} = 44, 62$  GeV. If we also include the results from the CERN collider on  $W/Z^0$

<sup>1</sup> Work supported in part by the "Ministero della Pubblica Istruzione", Italy.

mental confirmation of this factor in proton-proton scattering at the ISR.

We now consider the  $q_T$  and  $y$  distribution, which is given by [1]

$$\frac{d\sigma}{dQ^2 dq_T^2 dy} = N \left( \int \frac{d^2b}{4\pi} e^{-iq_T b} R(b^2, Q^2, y) e^{S(b^2, Q^2, y)} + Y(q_T^2, Q^2, y) \right). \quad (1)$$

where  $N = 4\pi\alpha^2/9Q^2S$ , the kernel  $R$  and the regular term (at  $q_T = 0$ )  $Y$  are given by eq. (57) and (62) of ref. [1], and

$$S(b^2, Q^2, y) = \int_0^{A_T^2} \frac{dk^2}{k^2} \frac{4\alpha_s(k^2)}{3\pi} [J_0(bk) - 1] \times \{ [1 + D\alpha_s(k^2)] \ln(Q^2/k^2) - \frac{3}{2} \}. \quad (2)$$

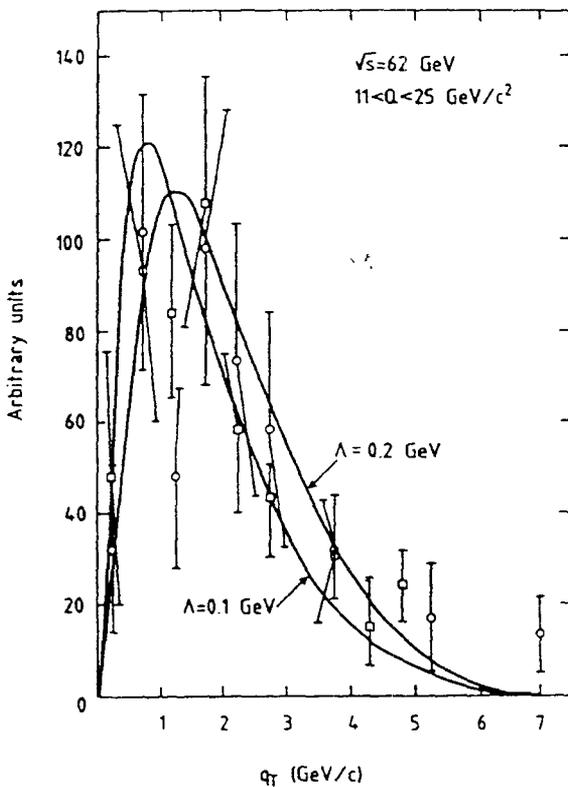


Fig. 2. The data on  $q_T$  distributions at  $\sqrt{s} = 62$  GeV and large pair mass from ref. [8] ( $\circ$ ) and ref. [11] ( $\square$ ) compared with the theoretical predictions for the parton densities of ref. [15] with  $\Lambda = 0.1-0.2$  GeV. The data on the curves are all normalized to the same area. No intrinsic  $q_T$  is included.

Here  $A_T$  is the maximum value of  $q_T$  at fixed  $y$ :

$$A_T/\sqrt{s} = [(1 + \tau)^2/4\text{ch}^2(y) - \tau]^2, \quad (3)$$

and  $D$  is given [4] by

$$2\pi D = \left(\frac{67}{6} - \frac{1}{2}\pi^2 - \frac{5}{9}n_f\right). \quad (4)$$

In fig. 2 the data at  $\sqrt{s} \approx 62$  GeV for the normalized  $q_T$  distribution  $d\sigma/dq_T dy$  at  $y = 0$  and  $Q = 11-25$  GeV are compared with the theoretical curves with  $\Lambda = 0.1-0.2$  GeV. The relatively good precision of the data and the accuracy of the theoretical fit can be better appreciated if one notes that fig. 2 is a linear plot.  $d\sigma/dq_T^2$  is often displayed on a logarithmic scale where only the gross features of the data can be reproduced (see for example fig. 3 which refers to the extrapolated predictions at values of  $Q$  below the  $\Upsilon$ )

In figs. 4, 5 the average transverse momentum ( $\langle q_T \rangle$ ) is plotted as a function of  $\sqrt{\tau}$  at fixed values of  $\sqrt{s}$  ( $\sqrt{s} = 27.4, 44, 62$  GeV) and as a function of  $\sqrt{s}$

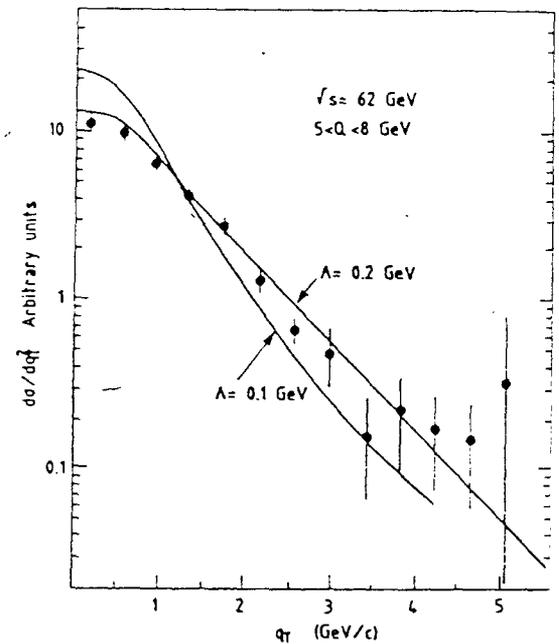


Fig. 3. Data on the  $q_T$  distributions at  $\sqrt{s} = 62$  GeV and relatively small values of the pair mass [11] compared with the theoretical curves obtained with the parton densities of ref. [15] with  $\Lambda = 0.1-0.2$  GeV. No intrinsic  $q_T$  is included.

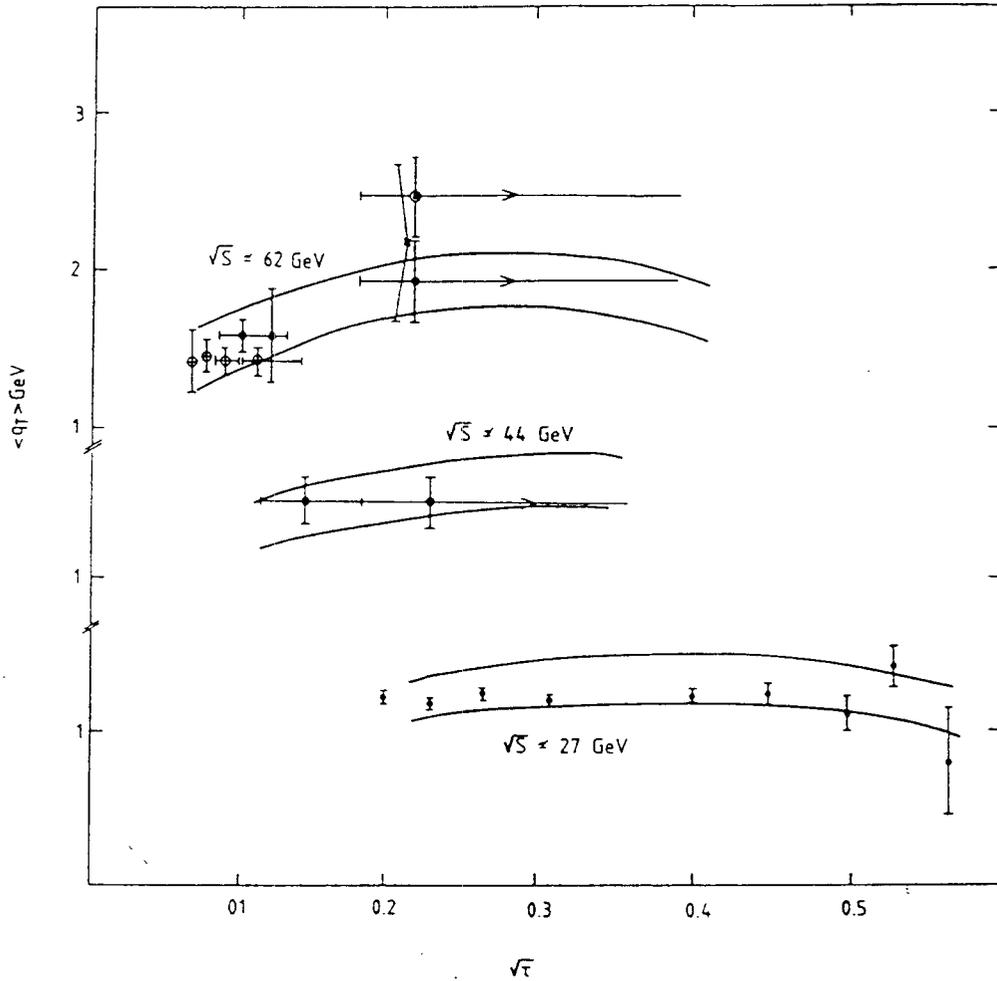


Fig. 4. The average value of  $q_T$ ,  $\langle q_T \rangle$ , as a function of  $\sqrt{\tau}$  at fixed  $\sqrt{S} = 27.4, 44, 62$  GeV. The data at  $\sqrt{S} = 27.4$  GeV are from ref. [12], at  $\sqrt{S} = 44$  GeV from ref. [11], and at  $\sqrt{S} = 62$  GeV from refs. [8-11]. The lower and upper curves given for each value of  $\sqrt{S}$  correspond to the parton densities of ref. [15] and  $\Lambda = 0.1-0.2$  GeV respectively. No intrinsic  $q_T$  is included.

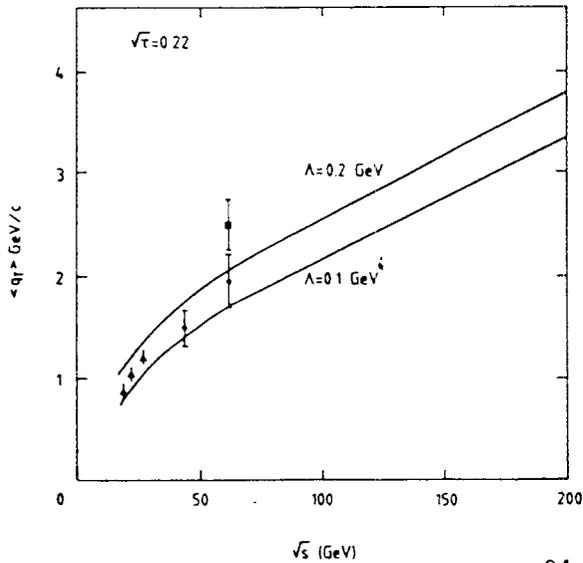


Fig. 5.  $\langle q_T \rangle$  versus  $\sqrt{S}$  at fixed  $\sqrt{\tau} = 0.22$ . The data at  $\sqrt{S} = 19, 27.4$  GeV are from ref. [12], at  $\sqrt{S} = 44$  GeV from ref. [11] and at  $\sqrt{S} = 62$  GeV from refs. [8,11]. The curves are the theoretical predictions obtained by using the parton densities of ref. [15] and  $\Lambda = 0.1-0.2$  GeV. No intrinsic  $q_T$  is included. At large values of  $\sqrt{S}$ ,  $\langle q_T \rangle$  increases linearly with  $\sqrt{S}$ . At smaller values of  $\sqrt{S}$  marked deviations from the linear law are visible, which are due to soft gluon and scaling violation pre-asymptotic effects.

# Quarkonium Productions

T.-A. Shibata

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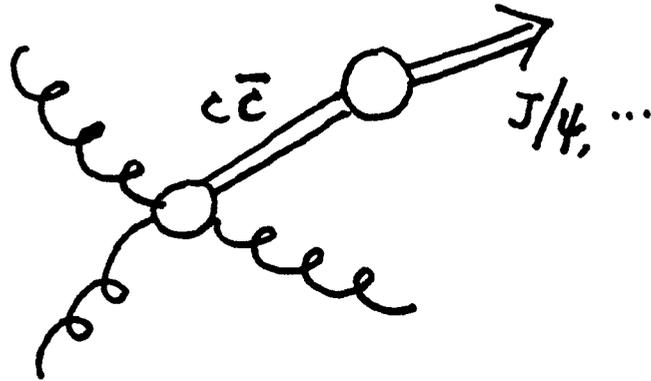
March 16, 1999

## Abstract

Quarkonium productions in the polarized proton-proton collision were discussed. The emphasis is put on the charmonium productions from polarized gluon-gluon collisions. The simulation was done by T. Sakuma of TITech and N. Hayashi of RIKEN. The present work was done in collaboration also with Y. Goto and N. Saito of RIKEN.

It is known that the color singlet model do not reproduce the CDF data satisfactory. In the framework of the color octet model, the model parameters were first determined using the CDF data.

The simulations for PHENIX were done with PYTHIA and the polarized gluon distribution functions. It is shown that the spin asymmetry of charmonium productions is sensitive to the choice of the polarized gluon distribution function. It is essential to further understand the charmonium production mechanism both experimentally and theoretically.



$$A_{LL}(pp \rightarrow J/\psi X) \sim \frac{\Delta G(x_1, Q^2)}{G(x_1, Q^2)} \frac{\Delta G(x_2, Q^2)}{G(x_2, Q^2)} \hat{a}_{LL}(gg \rightarrow J/\psi g)$$

In general ,

$$A_{LL}(pp \rightarrow \psi_Q X) = \frac{d\Delta\sigma}{dp_T}(pp \rightarrow \psi_Q X) / \frac{d\sigma}{dp_T}(pp \rightarrow \psi_Q X)$$

PYTHIA

$$\frac{d\sigma}{dp_T}(pp \rightarrow \psi_Q X) = \int \int dx_1 dx_2 G_1(x_1, Q^2) G_2(x_2, Q^2) \frac{d\hat{\sigma}}{d\hat{t}}(gg \rightarrow \psi_Q g)$$

put a Weight event by event

$$(\text{Weight}) = \frac{\Delta G_1(x_1, Q^2)}{G_1(x_1, Q^2)} \frac{\Delta G_2(x_2, Q^2)}{G_2(x_2, Q^2)} \hat{a}_{LL}(gg \rightarrow \psi_Q g)$$

$$\frac{d\Delta\sigma}{dp_T}(pp \rightarrow \psi_Q X) = \int \int dx_1 dx_2 \Delta G_1(x_1, Q^2) \Delta G_2(x_2, Q^2) \frac{d\Delta\hat{\sigma}}{d\hat{t}}(gg \rightarrow \psi_Q g)$$

## Color Octet Model

$$\hat{\sigma}(\psi_Q) = \sum \hat{\sigma}(c\bar{c}[{}^{2S+1}L_J^{(1,8)}]) \langle 0 | O_{(1,8)}^{\psi_Q} ({}^{2S+1}L_J) | 0 \rangle$$

$\hat{\sigma}(c\bar{c}[{}^{2S+1}L_J^{(1,8)}])$  short-distance coefficient

production cross section of  $c\bar{c}$  pair.

calculated with QCD

$\langle 0 | O_{(1,8)}^{\psi_Q} ({}^{2S+1}L_J) | 0 \rangle$  long-distance Matrix Element

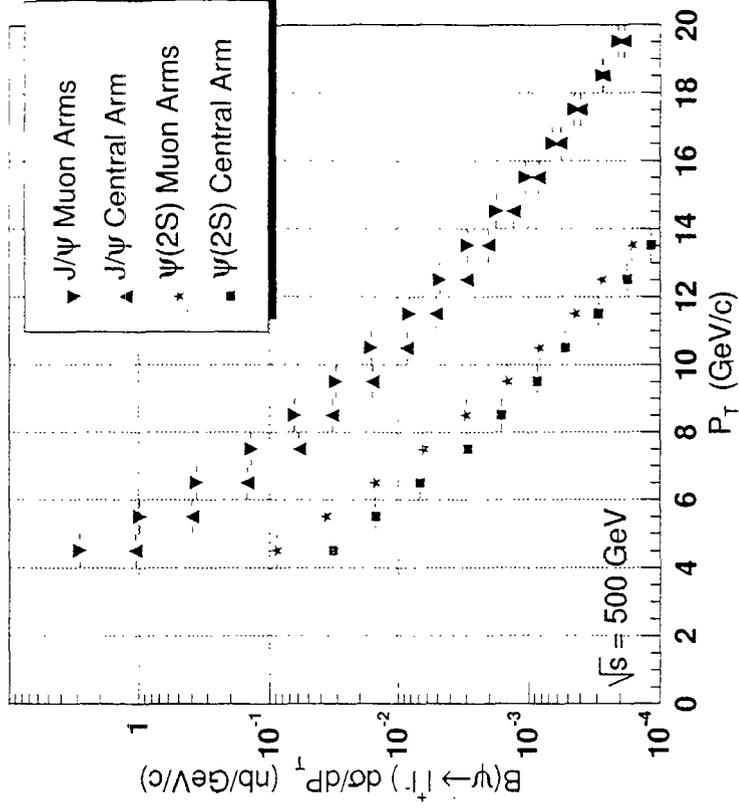
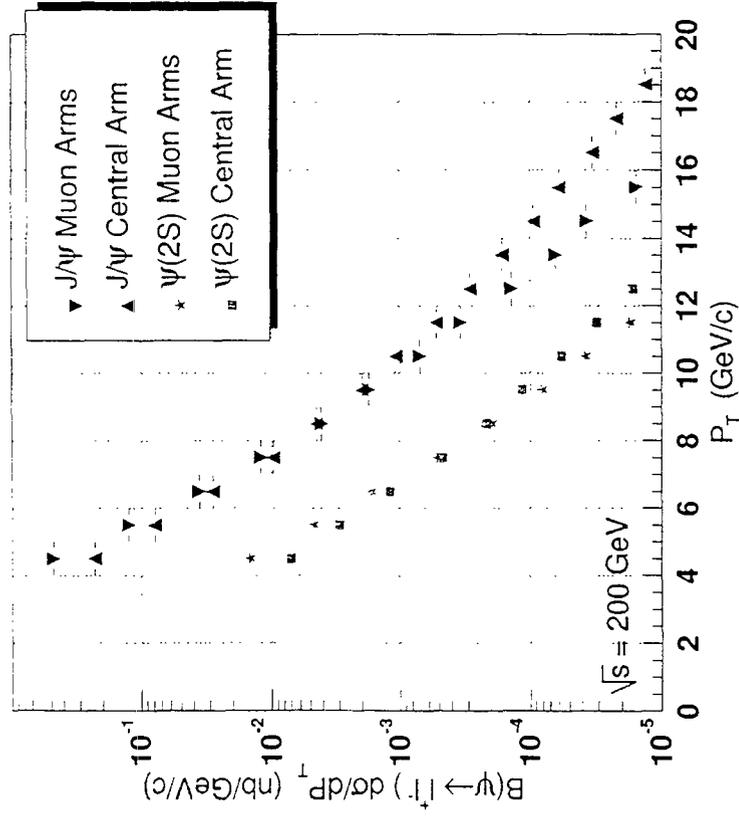
probability for a  $c\bar{c}$  pair to form  
quarkonium  $\psi_Q$

color singlet part  $\leftarrow$  wave function

color octet part  $\leftarrow$  experimental data

# Cross Section for direct $J/\psi$ , $\psi'$ Production in PHENIX

$\sqrt{s} = 200$  and  $500$  GeV



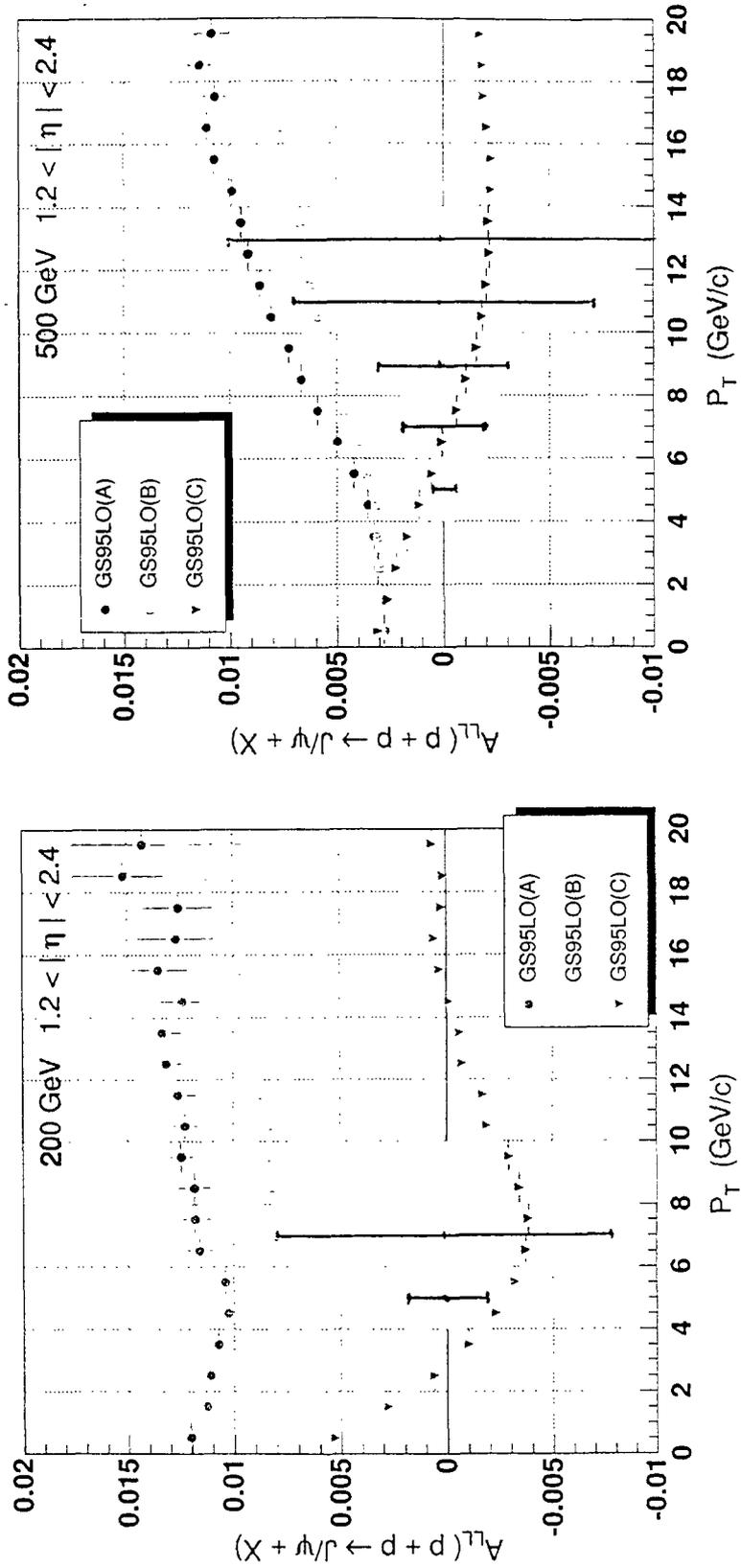
Muon Arms acceptance  $1.2 < |\eta| < 2.4$

Central Arm acceptance  $|\eta| < 0.35$

Spin Asymmetry of direct  $J/\psi$  Production, Muon Arms  
 $\sqrt{s} = 200$  and  $500$  GeV

PHENIX Muon Arms

Matrix Element  $\langle 0 | O_8^{J/\psi} (3P_0) | 0 \rangle = 0$

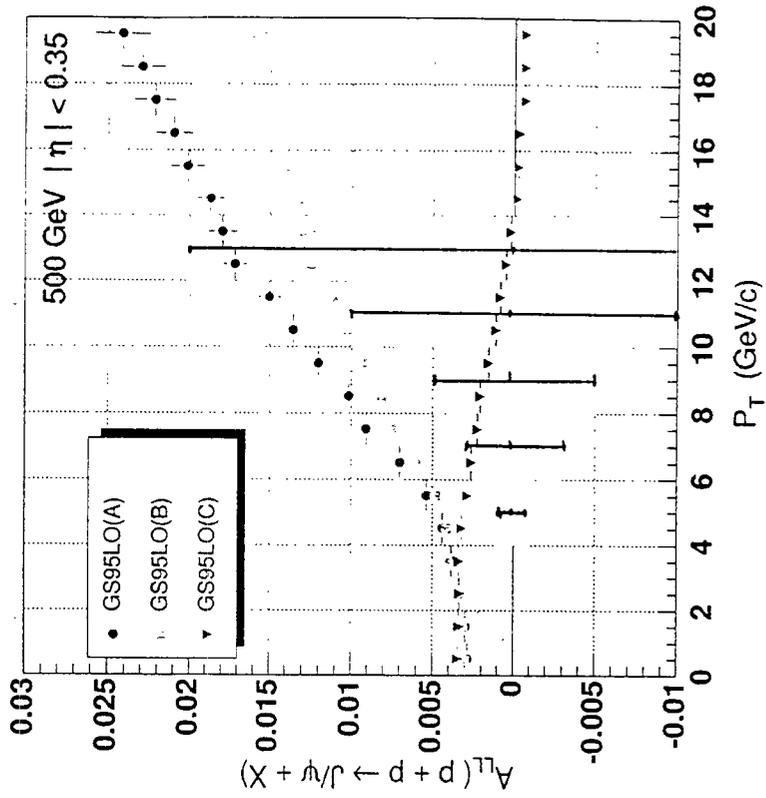
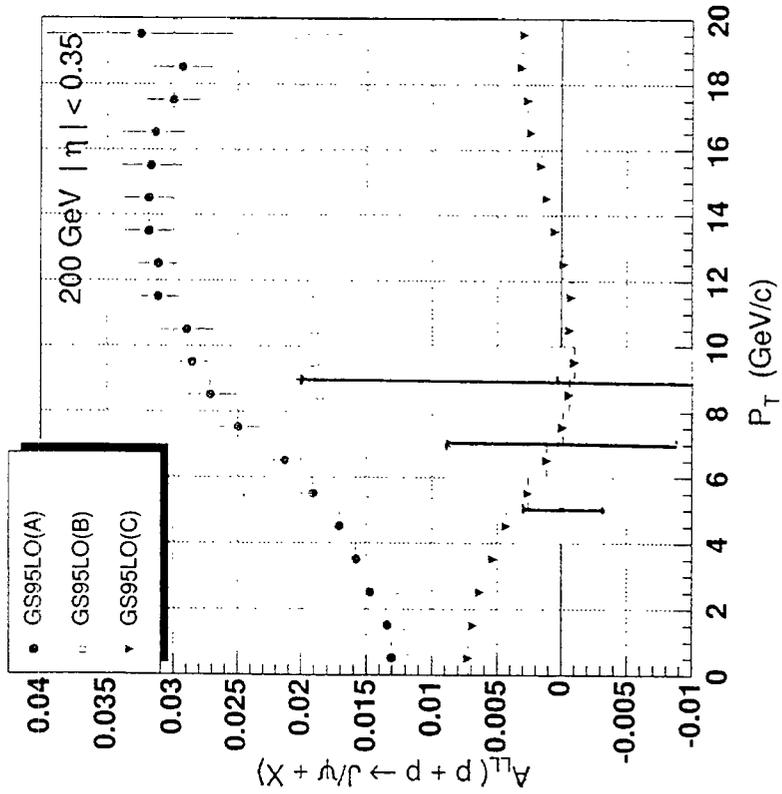


The error bar is for one year run.

Spin Asymmetry of direct  $J/\psi$  Production, Central Arm  
 $\sqrt{s} = 200$  and  $500$  GeV

PHENIX Central Arm

Matrix Element  $\langle 0 | \mathcal{O}_8^{J/\psi} ({}^3P_0) | 0 \rangle = 0$



The error bar is for one year run.

Stefano Frixione

# Event Generators at Fixed Order in QCD: Jets and Isolated Photons

In this talk I will present phenomenological results relevant for isolated-photon and jet production at RHIC.

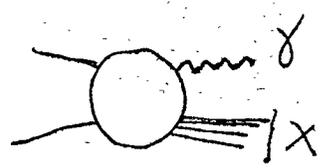
I will briefly describe how to calculate partonic cross sections in perturbative QCD beyond leading order, and the infrared safety of observables will be discussed. I will then concentrate on the problem of defining isolated-photon quantities. After reviewing the standard definitions which can be found in the literature, I will illustrate an alternative definition which has the virtue of being completely independent of the parton-to-photon fragmentation functions, and still it is well-defined order-by-order in perturbation theory. This results in a cleaner estimate of the theoretical uncertainties affecting the predictions for isolated-photon production.

I will then turn to the discussion of a general method, which allows the computation of any infrared-safe quantity in any kind of hard collisions, at NLO accuracy in QCD. The method is based on the subtraction procedure, and therefore does not involve any approximation, neither in the matrix elements nor in the phase space. Furthermore, the method is completely universal, and does not require any algebraic manipulation of the matrix elements. This results in several computer codes, which work in a manner similar to (although they are very different from) ordinary Monte Carlo parton shower codes, and which are available upon request.

Finally, I will present predictions for jet and isolated-photon production at RHIC. It will be shown that RHIC has a great potential for improving the knowledge of the polarized gluon density, if the design luminosity will be achieved.

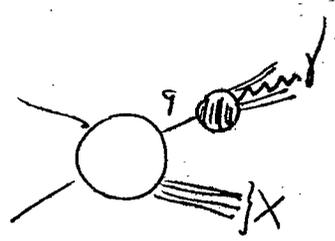
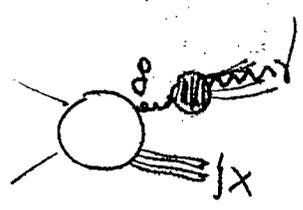
NAIVELY, THIS CORRESPONDS TO TWO VERY DIFFERENT PRODUCTION MECHANISMS

a) DIRECT



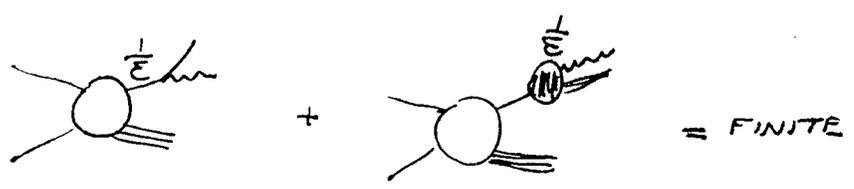
THE PHOTON IS USUALLY WELL SEPARATED FROM THE HADRONS IN THE FINAL STATE

b) FRAGMENTATION

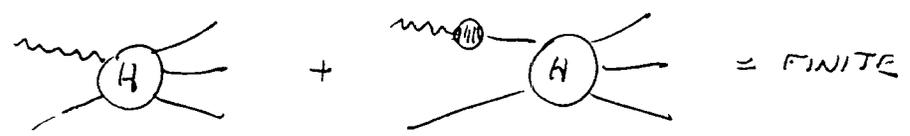


THE PHOTON IS USUALLY INSIDE HADRONIC JETS

BUT: THE TWO CONTRIBUTIONS ARE NOT SEPARATELY MEANINGFUL IN PERTURBATIVE QCD



THE SAME HAPPENS IN THE CROSSED PROCESSES (PHOTOPRODUCTION)



THE FULL ISOLATION SEEMS TO BE IMPOSSIBLE (INCOMPLETE CANCELLATION OF SOFT SINGULARITIES). GLUONS MUST BE ALLOWED EVERYWHERE IN THE PHASE SPACE

HOWEVER: IN QCD, THE FRAGMENTATION MECHANISM IS A PURELY COLLINEAR PHENOMENON

⇒ MODIFY THE CONE APPROACH AS FOLLOWS

$E^{\text{HAD}}(\delta)$  = TOTAL HADRONIC ENERGY INSIDE A CONE OF HALF-ANGLE  $\delta$  AROUND THE PHOTON

IMPOSE  $E^{\text{HAD}}(\delta) \leq \chi(\delta)$  FOR ALL  $\delta \leq \delta_0$

WITH  $\lim_{\delta \rightarrow 0} \chi(\delta) = 0$ ,  $\chi(\delta) \neq 0$  FOR ALL  $\delta \neq 0$

IN THIS WAY

- A GLUON WHOSE ENERGY IS SMALL ENOUGH CAN BE EMITTED ANYWHERE IN THE PHASE SPACE, EXCEPT FOR THE ZERO-MEASURE SET  $\delta = 0$
- A PARTON WHICH IS COLLINEAR TO THE PHOTON IS ALSO SOFT  $\Rightarrow$  THE QUARK VANISHING ENERGY DAMPS THE QUARK-PHOTON COLLINEAR SINGULARITY

MORE PRECISELY...

GIVEN AN EVENT WITH A PHOTON AND A SET OF HADRONS  $i=1, \dots, N$ , THEN THE ISOLATION CUTS ARE AS FOLLOWS

- ① EVALUATE  $R_{i\gamma}$ , THE ANGULAR DISTANCE BETWEEN THE PHOTON AND THE HADRON  $i$ . IT IS DEFINED BY

$$R_{i\gamma} = \delta_{i\gamma} \quad (e^+e^-) \quad R_{i\gamma} = \sqrt{(\eta_i - \eta_\gamma)^2 + (\varphi_i - \varphi_\gamma)^2} \quad (MH, \gamma H)$$

- ② THE EVENT IS REJECTED UNLESS

$$\sum_{i=1}^N E_i \Theta(\delta - R_{i\gamma}) \leq \chi(\delta) \quad \text{FOR ALL } \delta \leq \delta_0$$

- ③ APPLY A JET-FINDING ALGORITHM TO THE HADRONS OF THE EVENT  $\rightarrow m$  ( $m'$ ) BUNCHES OF COLLIMATED HADRONS OUTSIDE (INSIDE) THE CONE (CANDIDATE JETS)

- ④ APPLY ADDITIONAL CUTS TO THE PHOTON AND THE CANDIDATE JETS OUTSIDE OF THE CONE  $\rightarrow$  PHOTON +  $m$ -JET EVENT

A SUITABLE CHOICE IS

$$\chi(\delta) = E_\gamma E_\gamma \left( \frac{1 - \cos \delta}{1 - \cos \delta_0} \right)^m$$

$$E_\gamma = 1, \quad m = 1$$

IS ① - ④ INFRARED SAFE?

# AT RHIC

JETS

PHOTONS

SCALE  
DEPENDENCE

GREAT!!

IMPROVING FROM  
LO TO NLO

CROSS  
SECTIONS

$$\Delta\sigma(p_T > 10 \text{ GeV}, |y| < 1) = 3.4 \cdot 10^{-1} \mu\text{b}$$

$$\Delta\sigma(p_T > 10 \text{ GeV}, -1 < \eta < 2) = 2.9 \cdot 10^{-4} \mu\text{b}$$

$$\Delta\sigma(p_{T1} > 10 \text{ GeV}, p_{T2} > 15 \text{ GeV}, |y| < 1) = 4.7 \cdot 10^{-2} \mu\text{b}$$

$$\Delta\sigma(p_{T1} > 10 \text{ GeV}, p_{T2} > 10 \text{ GeV}, -1 < \eta < 2) = 1.9 \cdot 10^{-4} \mu\text{b}$$

$E_{\text{cm}} = 500 \text{ GeV}$ , GR2V STD  
CONE WITH  $R=1$ ,  $E_T=M=1$ ,  $d_0=0.7$

ASYMMETRIES

$$5 \cdot 10^{-4} < \frac{\Delta\sigma}{\sigma} < 3 \cdot 10^{-2}$$

$$10^{-3} < \frac{\Delta\sigma}{\sigma} < 2 \cdot 10^{-2}$$

$$\left(\frac{\Delta\sigma}{\sigma}\right)_{\text{MIN}} = 6 \cdot 10^{-4}$$

$$\left(\frac{\Delta\sigma}{\sigma}\right)_{\text{MIN}} = 2 \cdot 10^{-3}$$

$E_{\text{cm}} = 500 \text{ GeV}$ , GS-C < ... < GR2V MAX

# CONCLUSIONS

- A SET OF ISOLATION CUTS FOR FINAL STATE PHOTONS HAS BEEN PRESENTED, WHICH DOES NOT DEPEND UPON THE FRAGMENTATION MECHANISM AND IS WELL DEFINED TO ALL ORDERS IN PERTURBATIVE QCD
- MONTE CARLO INTEGRATORS ARE AVAILABLE WHICH EVALUATE JET AND PHOTON OBSERVABLES AT NLO IN QCD. ANY IR-SAFE QUANTITY CAN BE DEFINED BY THE USER AS IN ORDINARY MC PARTON SHOWER CODES
- AT RHIC ENERGIES, BOTH JET AND PHOTON QUANTITIES APPEARS TO BE UNDER GOOD PERTURBATIVE CONTROL
- THE SENSITIVITY TO THE CHOICE OF POLARIZED PARTON DENSITIES IS EXTREMELY LARGE. EXPECTED LUMINOSITIES WILL ALLOW A GREAT IMPROVEMENT IN THE DETERMINATION OF THE POLARIZED GLUON DENSITY

**Comparisons between Sphinx, Pythia+Asymmetries and LO/NLO QCD.** Oliver Martin, University of Regensburg, Germany

The extraction of polarized parton distributions is only possible with a correct simulation of the physical processes involved. There are several theoretical approaches to calculate spin dependent observables respecting the experimental cuts. A LO/NLO QCD calculation is based on the analytical polarized and unpolarized cross sections which are integrated using the Monte Carlo method. The NLO (and higher order) corrections can also be modelled using a LO cross section supplemented with parton showers, as it is done by PYTHIA and its polarized version SPHINX. Even though PYTHIA is an unpolarized code it can be used to calculate asymmetries by calculating and binning the asymmetry event by event. Since the comparisons between the methods have by far not been completed yet, this is only supposed to be a status report.

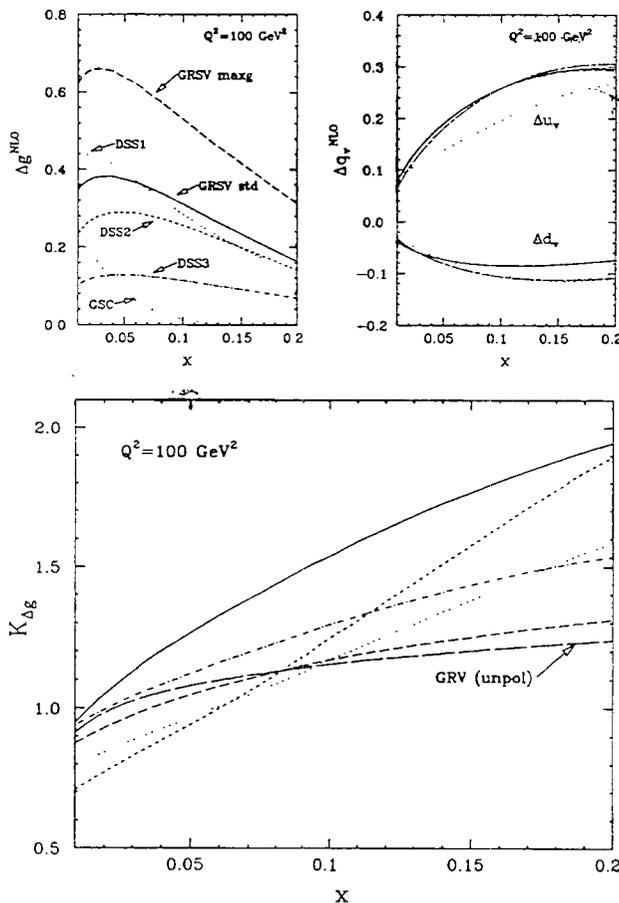
All three methods obviously have to agree on the LO QCD result, which can be obtained in the event generators by switching off everything but the hard subprocess. Indeed the SPHINX and PYTHIA results for the unpolarized cross sections for the production of inclusive jets, prompt photons and prompt photons plus jet agree on the 1 percent level, whereas agreement within the (5 percent) statistical error was shown for the polarized case. Switching on initial and final state radiation leads to deviations for large transverse jet energies. The origins still must be studied. The results of PYTHIA and the LO jet and prompt photon codes by Stefano Frixione and Lionel Gordon differ by about 5 percent and are therefore not satisfactory. More work remains to be done here also.

The parton showers are based on the collinear singularity and therefore underestimate hard radiation off an initial or final state parton. They compensate for it by allowing multiple radiations to occur and effectively sum part of the perturbation series to all orders. It is therefore interesting to see in how far NLO calculations agree with the results of an event generator. With the standard shower parameters of PYTHIA 5.6 the inclusive one-jet rates show large differences of up to 40 percent and the asymmetries also differ by as much as 20 percent. However, tuning the parton showers leads to an improved agreement so that the rates and asymmetries differ by about 10 percent only.

# PRELIMINARIES

- Processes:
- jet production (one-jet inclusive)
  - inclusive  $\gamma$ -production
  - $\gamma$ +jet production

## Polarized Parton Distributions:



Differences in valence distributions can be traced back to different data samples.

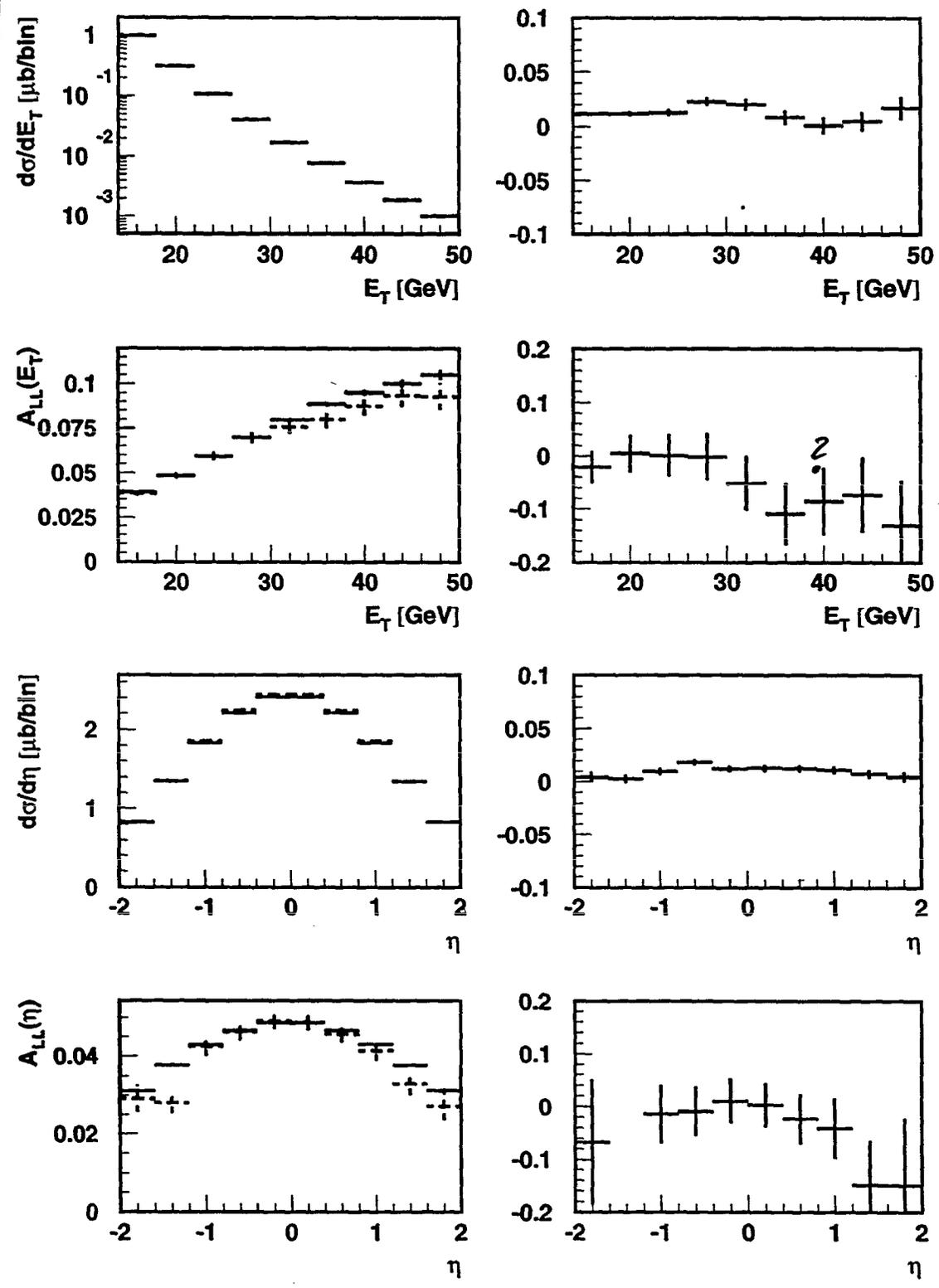
Event Generator must also use NLO pdf so that comparison to NLO QCD makes sense.

(Figs. taken from D. de Florian et al. hep-ph/9808262)

## Strong Coupling:

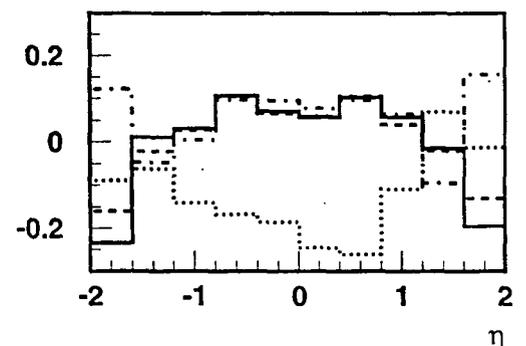
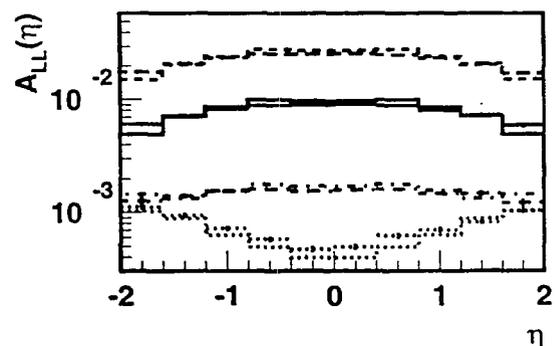
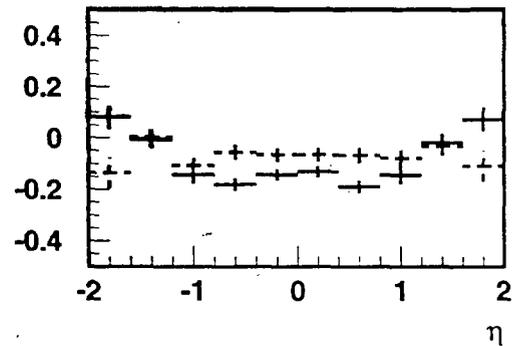
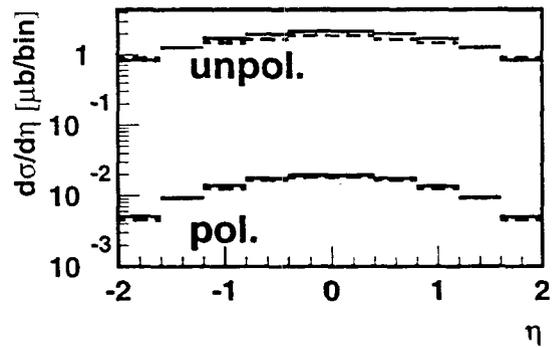
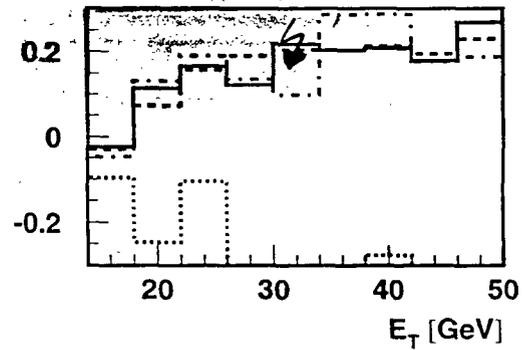
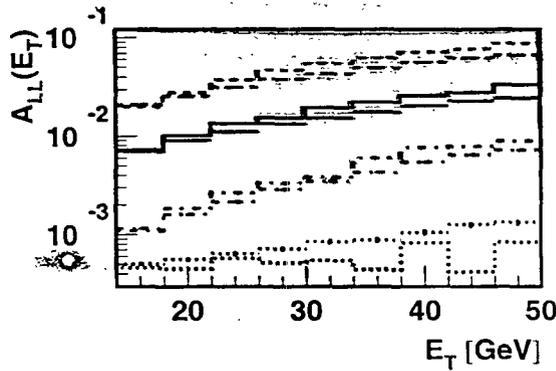
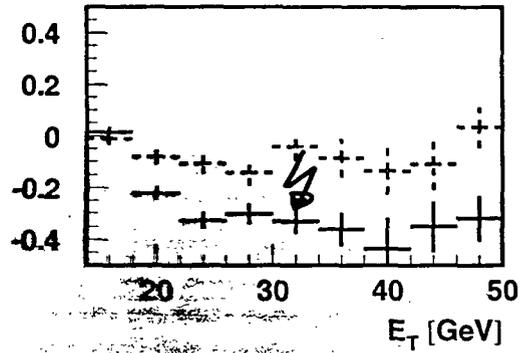
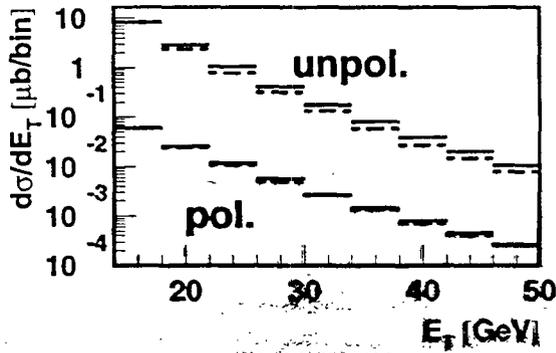
NLO  $\alpha_s$  used, fixed at  $n_f = 5$  for all observables.

# SPHINX vs. PYTHIA - HI+Shower



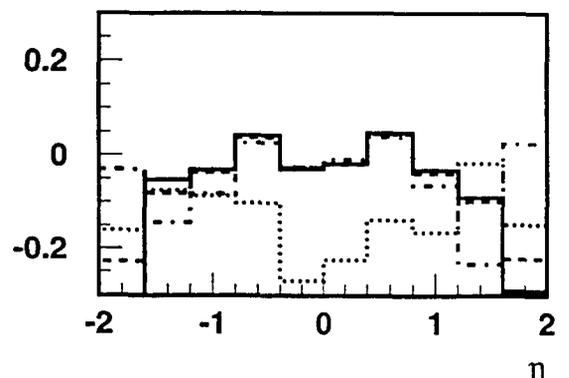
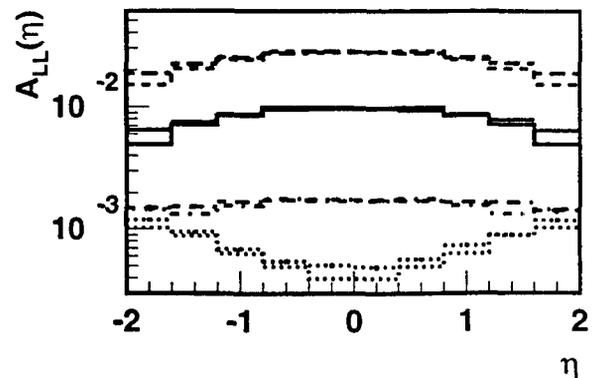
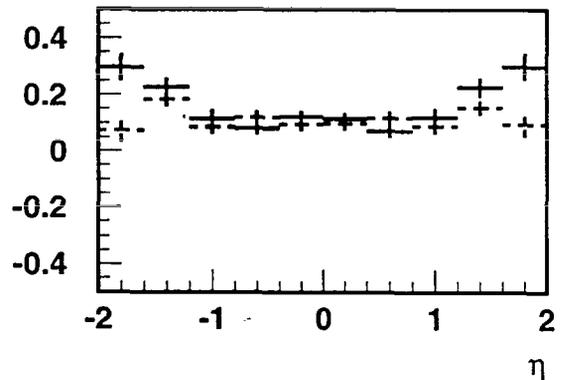
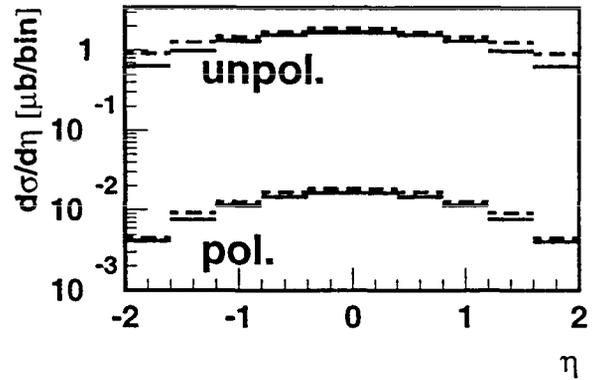
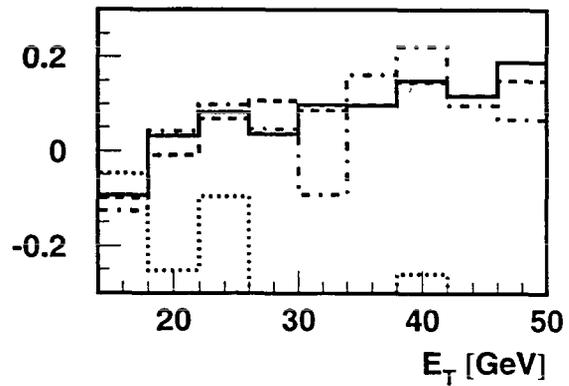
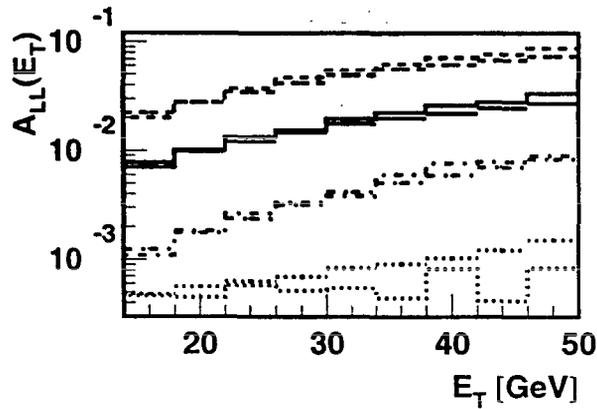
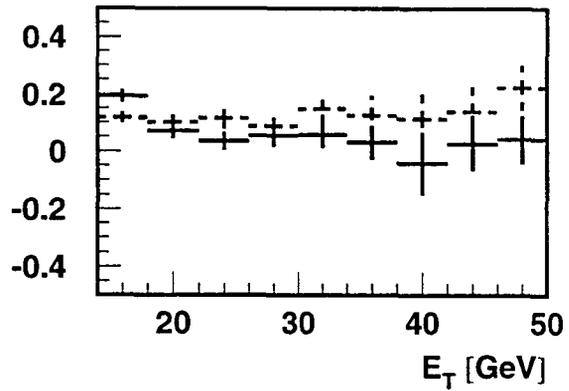
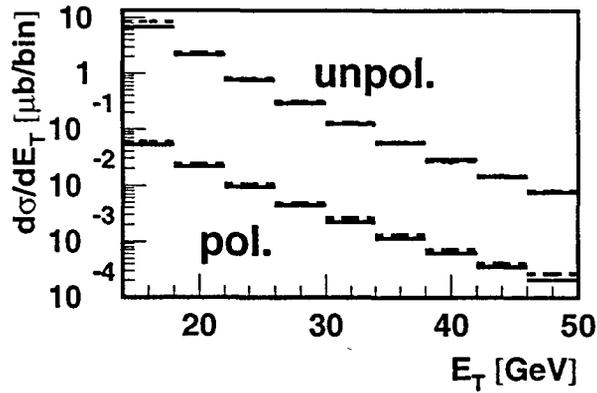
(Pythia-Sphinx) / Pythia

# NLO QCD vs. PYTHIA (HI+Shower)



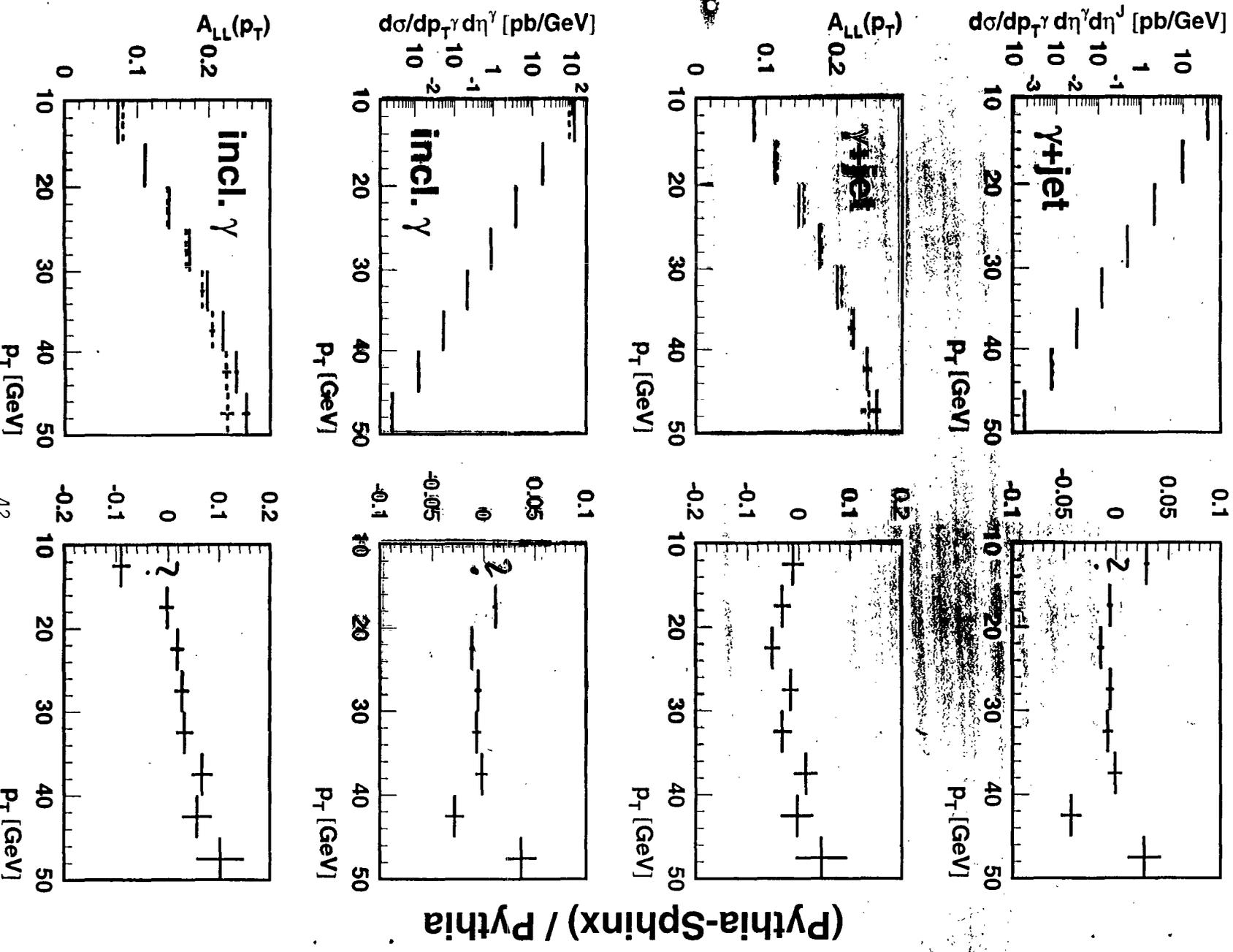
(NLO QCD - PYTHIA) / NLO QCD

# NLO QCD vs. PYTHIA (HI+Shower, tuned)

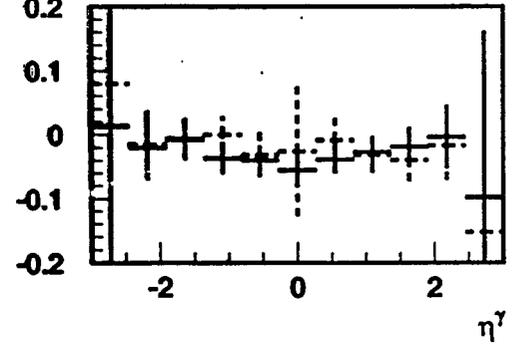
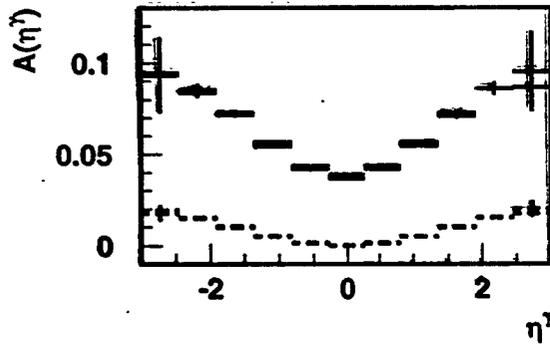
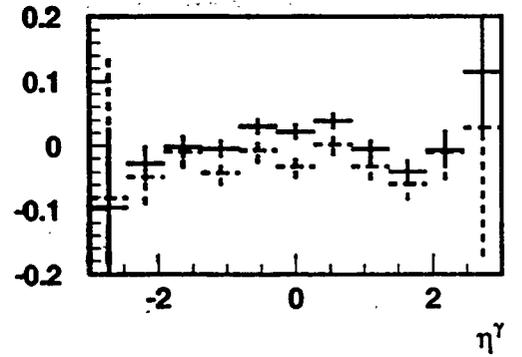
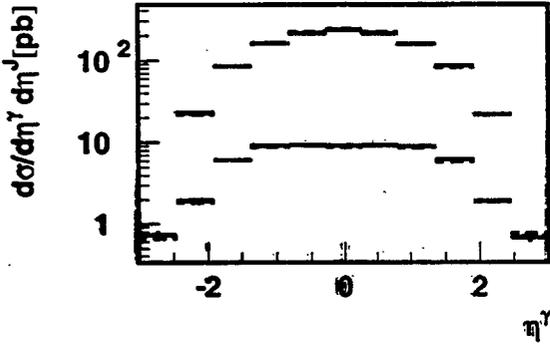
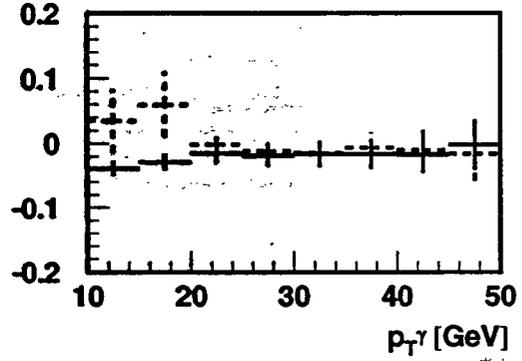
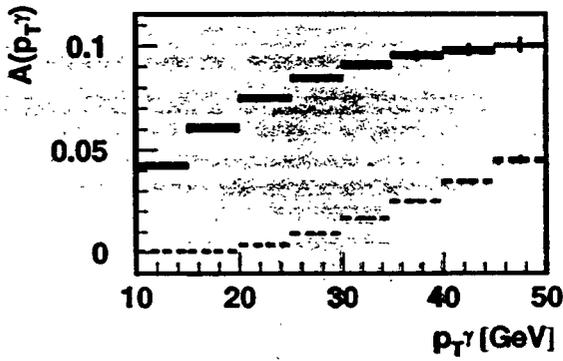
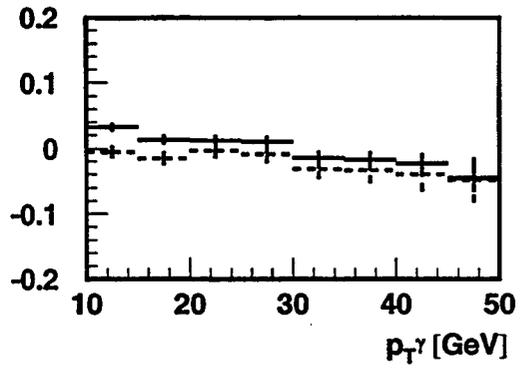
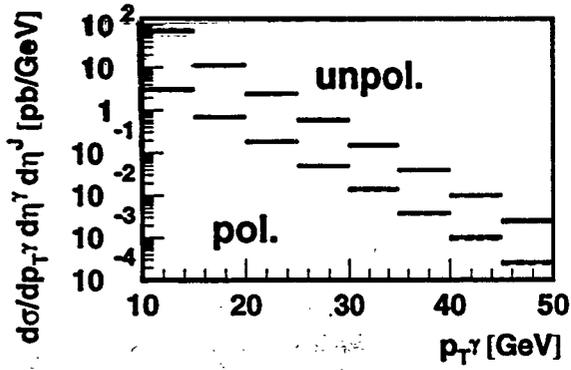


(NLO QCD - PYTHIA) / NLO QCD

# SPHINX vs. PYTHIA - HI + Shower



# LO QCD vs. Pythia (HI)



$(\text{LO QCD-PYTHIA}) / \text{LO QCD}$

## Problems with and Alternatives to Prompt Photon Production

L.E. Gordon

### Summary:

Despite years of effort by theorists and experimentalists, prompt photon production has still not yet lived up to its potential to tightly constrain the gluon distributions in hadrons. Useful information on gluon distributions have certainly been obtained, but many unresolved theoretical and some experimental issues are still hampering us from exploiting the full potential of this process. All this has important consequences for the RHIC spin program, where direct photon production is expected to be one of the main processes measured in order to constrain the spin dependent gluon distribution of the nucleon,  $\Delta G$ .

Recent phenomenological studies of collider and fixed target data using NLO QCD calculations have lead to differing conclusions concerning both the compatibility of the various data sets, and whether it is necessary, useful or even consistent to supplement fixed order NLO QCD calculations with  $k_T$  smearing effects in order to better fit the data.

One recent study concluded that since no single set of scales and structure functions can be made to fit all the various prompt photon data sets, then it is possible that the sets are simply incompatible, while another concluded that parton  $k_T$  broadening from soft gluon radiation can be *consistently* used to bring theory into agreement with experiment.

Everyone admits that there are still serious outstanding issues such as poorly known photon fragmentation functions, possible infrared sensitivity of the NLO calculation when isolation is implemented and large renormalization and factorization scale sensitivity of even the NLO calculation in some important kinematic regions. This has lead to the suggestion that large  $q_T$  ( $q_T > Q/2$ ) lepton pair production may be used as a surrogate for direct photon production since it completely avoids the problems with isolation and fragmentation.

Despite its problems, recent measurements of direct photon (and photon + jet) production cross sections at HERA are showing promise in shedding some light on the gluon distribution in the real photon. And the case of the gluon in the photon before HERA has many parallels with the case of  $\Delta G$  before RHIC, thus developments at HERA should be at interest to us here.

Given current problems with prompt- $\gamma$  Production in the Unpol. case, how much can RHIC realistically tell us about AG?

## Problems:

(1) Discrepancy between NLO theory & experiments.

- NLO theory does not describe all existing collider & fixed target data very well.

why? Two recent studies concluded:

(a) Data sets may simply be incompatible  
(Aurenche et. al.)

(b) NLO theory may simply be insufficient & need extra physics to supplement it.

(Openshaw et. al.)

(2) Outstanding issues in NLO calculations:

(a) scale dependence

(b) inadequate knowledge of frag. functions

(c) difficulties in implementing isolation

## Can $K_T$ -broadening cure the problem?

Apanasovich et. al.

Traditional 'intrinsic'  $K_T$  due to <sup>finite</sup> proton size  
 $\sim 0.3 - 0.4 \text{ GeV}$

but measured average  $P_T$  of dimuon, dijet + diphoton  
pairs  $\Rightarrow \langle P_T \rangle_{\text{pair}} \sim 1-5 \text{ GeV}$  (depending on  $\sqrt{s}$ ).

$\Rightarrow K_T$  (per parton)  
 $\sim 1 \text{ GeV}$  at fixed target  
+  $\sim 3-4 \text{ GeV}$  at colliders

This  $K_T$  due to soft gluon radiation off hard  
scattering partons.

Soft gluons provide  $K_T$ -broadening  $\Rightarrow$   
modification of observed  $P_T$ -spectrum.

$\langle k_T \rangle$  needed to fit data in line with  $\langle p_T \rangle_{\text{point}} / \sqrt{2}$  at CDF + DØ.

$k_T$  needed & present for  $p_T < 30 \text{ GeV}$

Frag. is LO only.

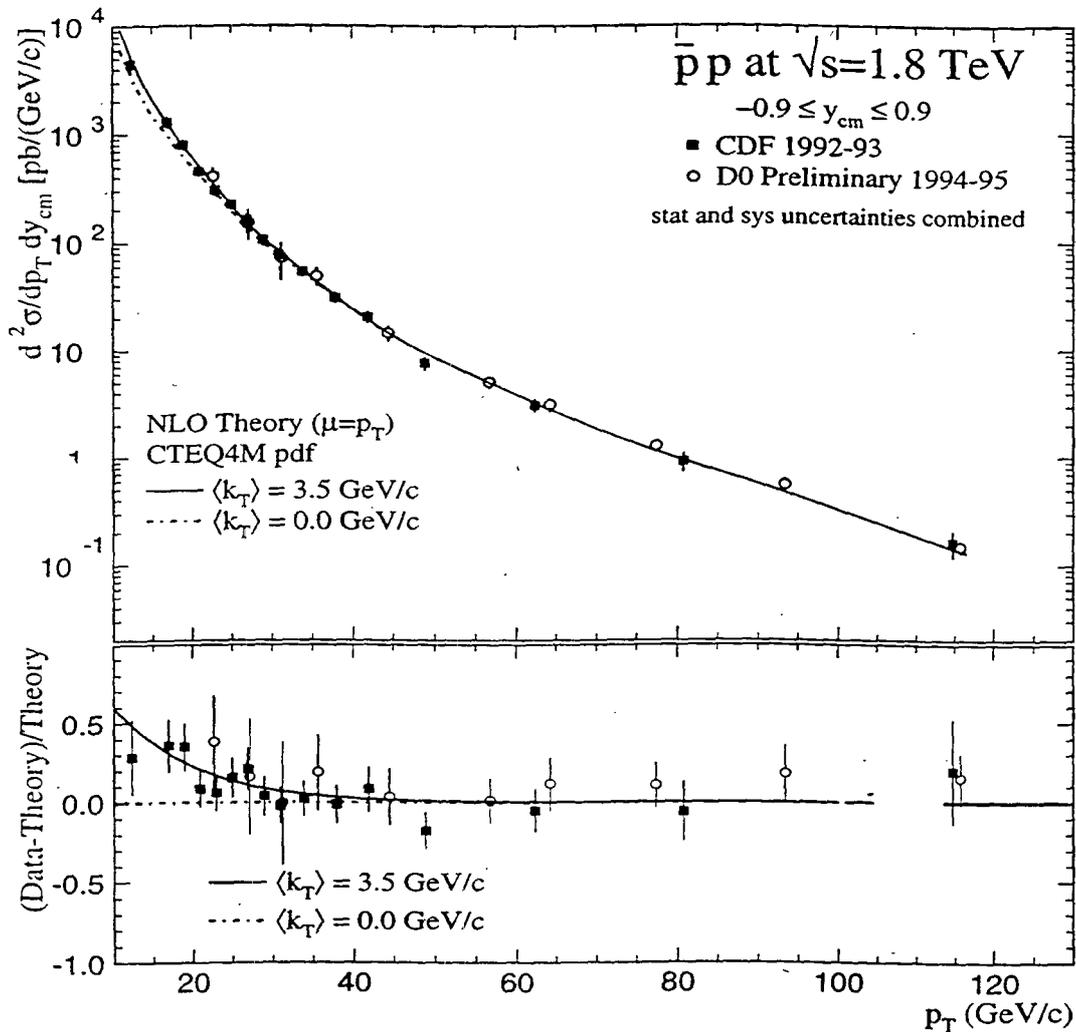


FIG. 2. Top: The CDF and DØ isolated direct-photon cross sections, compared to NLO theory without  $k_T$  (dashed) and with  $k_T$  enhancement for  $\langle k_T \rangle = 3.5 \text{ GeV}/c$  (solid), as a function of  $p_T$ . Bottom: The quantity  $(\text{Data-Theory})/\text{Theory}$  (for theory without  $k_T$  adjustment), overlaid with

## Conclusion:

- (1) This approach suggests that supplementing fixed order QCD with  $K_T$  broadening effects may improve agreement between theory & experiment.
- (2) It does not refute Aurenche et. al's. Argument that the UA6 & WA70 data may be incompatible.
- (3) The method is still very unsophisticated & it is therefore hard to see how it will lead to improvement in the extraction of gluon distribution from prompt- $\gamma$  data.

---

when all the uncertainties are considered, how well will direct- $\gamma$  production at RHIC constrain  $\Delta G$ ?

(Answer: probably not as well as some hope, but consider the case of the gluon in the photon  $g^{\gamma}(x, Q^2)$  for HERA.

## Conclusions of Aurenche et. al.

(1) It is not possible to find one set of ~~parameters~~ structure functions that will fit all the data sets satisfactorily.

- changing any parameter to fit a particular set increases disagreement with other sets

∴ data sets are probably incompatible.

(2) Including  $R_T$  effects in ad hoc manner has no justification, only hides the problem.

⇒ look for reasons why data sets may be incompatible.

# Unpolarized Parton Distributions: Current Status and Open Issues

Global QCD Analysis of Parton Distributions

Scope of Experimental Input

Theoretical Considerations/Uncertainties

Issues for new (1998/9) global analyses

Recent Results and Comparisons

Open Issues and Challenges

Comments on Uncertainties of Parton  
Distributions

BNL Polarized Event Generator Workshop

Wu-Ki Tung

1999

# What goes into Global QCD Analysis of Parton Distributions?

## In principle

- ⇒ Experimental data on all available hard scattering processes
- ⇒ NLO QCD Hard-cross-sections (or beyond) for these processes
- ⇒ Parametrized functions for the non-perturbative initial parton distributions  
+ NLO QCD-evolution of these functions

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- Global fitting of theoretical calculation (based on *factorization theorems* of PQCD) to the experimental data, to determine the fundamental QCD constants ( $\Lambda_{QCD}, m_i; i = \text{quark flavors}$ ) and the non-perturbative PDF parameters.

## In Practice

Many subtleties and complications ... most due to imperfect theory and/or experiment.

- ⇒ This Workshop and This Subgroup ⇐

## Physical processes and experiments \*

- DIS – Neutral Current ( $e, \mu$  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, BAB, E706, TOR, BAZ, CDF, D0
- Inclusive Jet Production  
CDF, D0
- Lepto-production of Heavy Quark  
H1, ZEUS
- Hadro-production of Heavy Quark  
CDF, D0

\* \_\_\_\_\_  
Red color indicates “New” for current analysis  
Green color for “often not used” in global analysis  
750

## Issues on Theoretical Input

	Sensi- tive to	NLO size	Stability : ScaDep	NLO-Exp discrep.	Comment
DIS	q,G	S	S	S	OK
DY	q,G	L	S	S	OK
Dir. Ph.	G,q	L	L	0 - 300%	Soft-gluon Res.?
Incl. Jet	G,q	S-M	S	S	OK?
L-H->C	G,C	M	M	M	refine HQ QCD
H-H->C,B	G,C	L	L	50-100%	refine HQ QCD

### Obvious observations:

- Magenta: reliable processes to perform quantitative global analysis
- Red : need better theory to make full use of existing/future data
- To determine the Gluon distribution at present, need DIS + DY + Jet

## Major/Typical Issues Confronting Current Global Analyses

- Heavy Quark Schemes: new th. feature
- Zero-mass-HQ-parton: "conventional" sch.
- No HQ parton at all : 3(4)-flavor sch.
- On-mass-shell HQ partons : — generalized MS sch. CWZ(77), ACOT(87-98) ; TR(97)
- Direct photons: pin the gluons?
- Are current expts consistent?
- Is current theory sufficient for the task?
- Apanasevich, etal, 9808467; Aurenche, etal, 9811
- Quark flavor – d/u large (small)  $x$
- Interplay of charge asymmetry data: E866, Wasym, NMC
- Deuteron target effect and Target mass correction? Bodek&Yang, 9809480; Kuhlmann talk & CTEQ paper in prep.
- The strong coupling constant  $\alpha(m_s)$
- Determined by global fit, or set to best current value?
- NLO QCD or Beyond?

# Comparison of MRS and CTEQ Global Analyses

Previous versions of general MRS and CTEQ analyses yielded very similar results – due to similar choices of th./exp. input.

⇒ Differences between these do not measure true *uncertainties* of PDFs.  
(Specific diff., eg. CDF high  $p_T$  jet, due to clearly identified difference in choices of parametrization.)

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New MRST and CTEQ5 Analyses  
(Both fit input DIS and DY data well)

	MRST	CTEQ5
HQ sch.	on-shell (TR)	conventional, on-shell (ACOT), & fixed-flavor
Dir.Ph.	WA70 + $k_T$ 's ( $\sqrt{E706}$ )	— ( $\sqrt{WA70, E706}$ )
Incl.Jet	—	CDF + D0
Deut.Corr.	—	—
$\alpha_s(m_Z)$	fixed: 0.1175	fixed: 0.118

⇒ Greater differences in gluon, charm differences than before.

⇒ Beware of scheme difference (especially for HQ processes).

## Open Issues and Challenges

### The Gluon Distribution

#### SM & New Physics searches

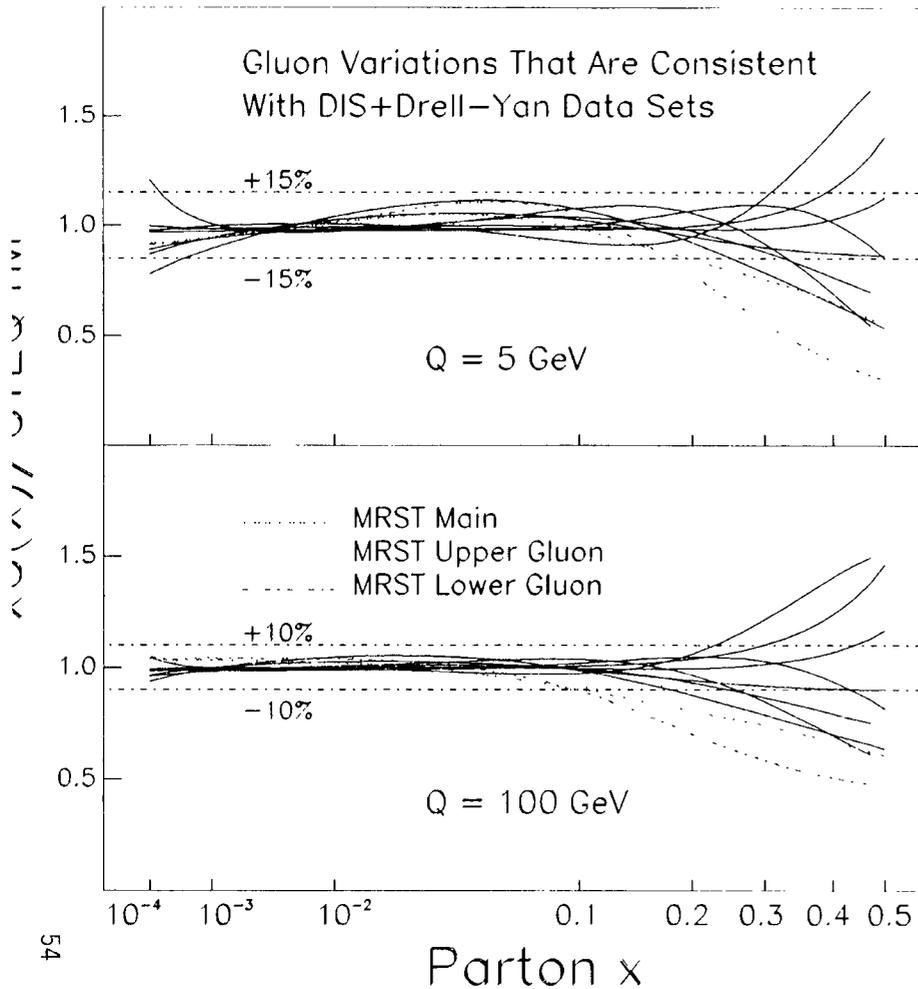
- Can the theory of Dir.Ph. at fixed-target energies and B-prod. at colliders be improved, to render these processes indep. sources of information on the gluon?
- Can double and triple diff.  $\sigma$ 's of jet production give more detailed information on the gluon?
- Better measurement of direct photons production at collider energies?

### $u d$ Quark Differentiation

#### Precision W-, Z- physics:

- Systematic study of the uncertainties most relevant for precision  $M_W$  measurement at RunII
- Better understanding/control of deuteron, heavy target ("EMC") and deuteron (large x) corrections
- Power-law (higher-twist) corrections

An earlier study of the range of  $G(x, Q)$



Note the new MRST gluons relative to the range.  
Clearly more definitive work is needed.

Strange and Heavy Quarks:

**QCD Physics**

- Resolution of the discrepancy of NC-CC single  $\mu$  and di-muon determination of strange (violation of the DIS “charge ratio” (5/18) rule)
- NC and CC production of charm, bottom; non-perturbative (intrinsic) charm?

Theory and phenomenology of QCD beyond NLO:  
How do 2- (or more) scale problems affect PDF analysis?

- $W$ -,  $Z$ - (+ jets)  $X$ -sec. -  $P_T$  distributions : Sudakov resummations
- Small- $x$  (BFKL) resummation
- Large  $x$  (threshold) resummation
- Power-law corrections

# Parametrization of polarized parton distributions in the nucleon

Y. Goto<sup>1</sup>, N. Hayashi<sup>1</sup>, M. Hirai<sup>2</sup>, H. Horikawa<sup>3</sup>, S. Kumano<sup>2</sup>, M. Miyama<sup>2</sup>,  
T. Morii<sup>3</sup>, N. Saito<sup>1</sup>, T.-A. Shibata<sup>4</sup>, E. Taniguchi<sup>4</sup>, and T. Yamanishi<sup>5</sup>

<sup>1</sup>Radiation Laboratory, RIKEN, Saitama 351-01, Japan

<sup>2</sup>Department of Physics, Saga University, Saga 840-8502, Japan

<sup>3</sup>Faculty of Human Development, Kobe University, Kobe 657-8501, Japan

<sup>4</sup>Department of Physics, Tokyo Institute of Technology, Tokyo 152-8551, Japan

<sup>5</sup>Department of Management Science, Fukui University of Technology,  
Gakuen, Fukui 910-0028, Japan

Experimental data on the polarized structure functions have been accumulated for the last several years. The structure function  $g_1$  is measured with the proton, deuteron, and  $^3\text{He}$  targets. We study the parametrizations of the polarized parton distributions in the leading order (LO) of  $\alpha_s$ , and in the next-to-leading order (NLO) [1]. The polarized distributions are provided with a number of parameters at  $Q_0^2=1 \text{ GeV}^2$ . Considering the positivity condition and helicity retention property, we propose the following distribution:

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

where  $f_i(x, Q_0^2)$  is an unpolarized distribution. The parameters  $\alpha_i$ ,  $\gamma_i$ , and  $\lambda_i$  are determined by fitting the available experimental data on the spin asymmetry.  $A_1 \cong g_1(x, Q^2)/F_1(x, Q^2) = g_1(x, Q^2) 2x(1 + R(x, Q^2))/F_2(x, Q^2)$ . Here, the first moments of  $\Delta u_v$  and  $\Delta d_v$  are fixed by the semileptonic decay data by assuming the SU(3) symmetry. We can reduce the number of free parameter from 12 to 10 by using those fixed first moments. The subscript  $i$  denotes the type of the parton distribution:  $\Delta f_i = \Delta u_v, \Delta d_v, \Delta \bar{q},$  or  $\Delta g$ . We compare the theoretical asymmetries  $A_1$  with the experimental data and minimize  $\chi^2 = \sum (A_1^{data} - A_1^{calc})^2 / (\sigma_{A_1^{data}})^2$  by using the CERN subroutine MINUIT. We got minimized  $\chi^2$  which is the  $\chi^2/\text{d.o.f}=368.84/339$  for the LO, and  $\chi^2/\text{d.o.f}=304.25/339$  for the NLO. The total  $\chi^2$  for the NLO is smaller than the one for the LO. We found that the analysis including the NLO effect is very important, and it is necessary to extract information on  $\Delta g$ . Our research activities are listed at <http://www.rarf.riken.go.jp/rarf/rhic/theory/pol-pdf.html>.

## References

1. Y. Goto, N. Hayashi, M. Hirai, H. Horikawa, S. Kumano, M. Miyama, T. Morii, N. Saito, T.-A. Shibata, E. Taniguchi, and T. Yamanishi, in preparation.

- Structure Function  $g_1$

$$g_1(x, Q^2) = \frac{1}{2} \sum_{i=1}^{nf} e_i^2 \left\{ \Delta q_i(x, Q^2) + \Delta \bar{q}_i(x, Q^2) + \frac{\alpha_s}{2\pi} \left[ \Delta C_q \otimes (\Delta q_i(x, Q^2) + \Delta \bar{q}_i(x, Q^2)) + \Delta C_g \otimes \Delta g(x, Q^2) \right] \right\}$$

$\Delta q = q_{\uparrow} - q_{\downarrow}$ ,  $\Delta C_i$  : coefficient functions

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- $Q^2$  evolution equation (DGLAP equation)

$$\frac{d}{d \ln Q^2} \begin{pmatrix} \Delta \Sigma(x, Q^2) \\ \Delta g(x, Q^2) \end{pmatrix} = \begin{pmatrix} \Delta P_{qq}(x, \alpha_s) & \Delta P_{qg}(x, \alpha_s) \\ \Delta P_{gq}(x, \alpha_s) & \Delta P_{gg}(x, \alpha_s) \end{pmatrix} \otimes \begin{pmatrix} \Delta \Sigma(x, Q^2) \\ \Delta g(x, Q^2) \end{pmatrix}$$

## ● Initial distributions

$$\Delta f_i(x, Q_0^2) = \frac{1}{1 + \gamma_i} x^{\alpha_i} (1 + \gamma_i x^{\lambda_i}) f_i(x, Q_0^2), \quad (i = u_v, d_v, \bar{q}, g)$$

## ● Constraints

1) Positivity condition

$$\left| \Delta f_i(x, Q_0^2) \right| < f_i(x, Q_0^2)$$

2) Counting rule for the helicity dependent parton distributions

$$f_{\uparrow} \sim (1-x)^{2n-1}, \quad f_{\downarrow} \sim (1-x)^{2n-1+2}$$

$$f_{\uparrow} \gg f_{\downarrow} \quad (x \rightarrow 1),$$

$$\frac{\Delta f_i(x, Q_0^2)}{f_i(x, Q_0^2)} = 1 \quad \text{for } x \rightarrow 1.$$

**So, we obtain the following conditions for the 12 parameters,**

$$\alpha_i \geq 0, \quad \gamma_i \neq -1, \quad \lambda_i > -\alpha_i.$$

We assume the **SU(3)** flavor symmetry for  $\bar{q}(x)$  at initial  $\mathbf{Q}_0^2$ ,

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

and, the first moments  $\eta_{uv}$ ,  $\eta_{dv}$  are fixed,

$$\begin{cases} \eta_{u_v} - \eta_{d_v} = F + D \\ \eta_{u_v} + \eta_{d_v} = 3F - D \end{cases}$$

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

$$\eta_{u_v} = 0.926, \quad \eta_{d_v} = -0.341$$

We determine  $\lambda$  to satisfy the requirement

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

*We must determine 10 parameters by the  $\chi^2$ -fitting!*

$$\alpha_{uv}, \gamma_{uv}, \alpha_{dv}, \gamma_{dv},$$

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

$\chi^2$ -fitting to the data (Proton, Neutron, and Deuteron)

$$\chi^2 = \sum_i \frac{\left( A_{1,i}^{data} - A_{1,i}^{cal} \right)^2}{\sigma_i^{data\ 2}}, \left( \sigma_i^{data} = \sqrt{err_{sys}^2 + err_{sta}^2} \right)$$

Which is minimized by the CERN subroutine MINUIT.

59

We analyzed with the following conditions;

The unpol PD            GRV94    (by PDF-Lib)

Initial  $Q_0^2$              $Q_0^2 = 1 \text{ GeV}^2$

Number of flavor         $N_f = 3$

$\Lambda_{\text{QCD}}$                  $\Lambda_{\text{LO}} = 232 \text{ MeV},$

$\Lambda_{\text{NLO}} = 248 \text{ MeV}$

## Semi-exclusive reactions in pp collisions

M. Maul, Nordic Institute for Theoretical Physics (NORDITA)  
Blegdamsvej 17, 2100 Copenhagen, Denmark

Recently in [1] the idea was proposed to study semi-exclusive events in electron proton collisions at HERA. The simplest reaction in such a case would be  $e + p \rightarrow \text{jet} + \pi^+ + X$ . Kinematically this process is analogous to the corresponding elastic reaction in exclusive meson production, and the factorization theorems which apply for the exclusive case are also valid in the semi-exclusive case.

The basic idea is to look for events, where a large rapidity gap between the produced hadron and the produced jet exists. In this case soft interactions in the production process of the final meson are excluded and consequently the production process can be described by a hard scattering amplitude times the wave function of the produced meson. This is a much more direct access than the tracking of leading particles in the end-particle spectrum, where the production mechanism can only be described in terms of fragmentation functions, which are unknown objects of their own, and where the underlying physics is from its nature of a soft type and is not really understood so far.

It would be of great interest to compare the semi exclusive pion production to the corresponding process in pp collisions. In this case, to account for the color neutrality, two jets, a quark jet and a gluon jet, have to be produced, i.e.  $p + p \rightarrow \pi^+ + \text{jet}_1 + \text{jet}_2 + X$ . We then have to require two rapidity gaps, one between the gluon jet and the produced meson and a second one between the quark jet and the produced meson. If the two jet momenta and the momentum of the produced meson can be measured with good accuracy, then we are from a kinematical point of view in the same situation as in Drell Yan and can get hold of the two momentum fractions  $x_1$  and  $x_2$  of the scattered quark and the scattered gluon, so that all theorems that apply for Drell Yan can be also applied to this process.

The very interesting point for such a reaction to be compared with the corresponding ep reaction is that we might be able in this way to get hold of 'in medium effects' in the pp reactions. Such effects have been studied so far for  $J/\Psi$  production: While in the ep case the color singlet model is successful, a consistent description seems not to be feasible up to now in pp, however it was indicated in [2] that the existence of a cloud of gluonic comovers could account for most of the signatures in pp charmonium production. It would be of great interest, whether such an effect could be observed analogously in semi-exclusive  $\pi^+$  production including all the possibilities of polarization.

[1] S. J. Brodsky, M. Diehl, P. Hoyer, S. Peigne. hep-ph/9812277.

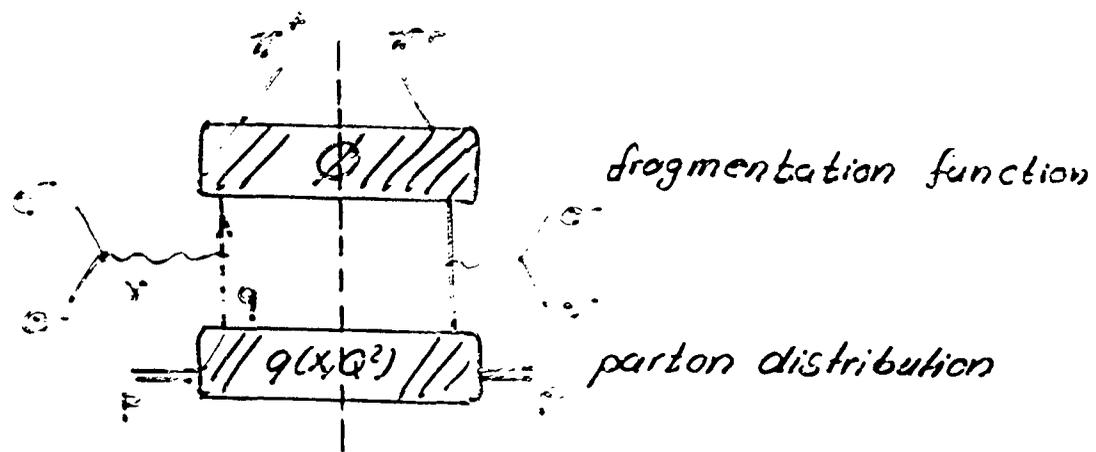
[2] P. Hoyer, S. Peigne (Nordita), Phys. Rev. D59:034011,1999.

1. The general concept: Semi-exclusive

$\pi^+$  production in ep collisions

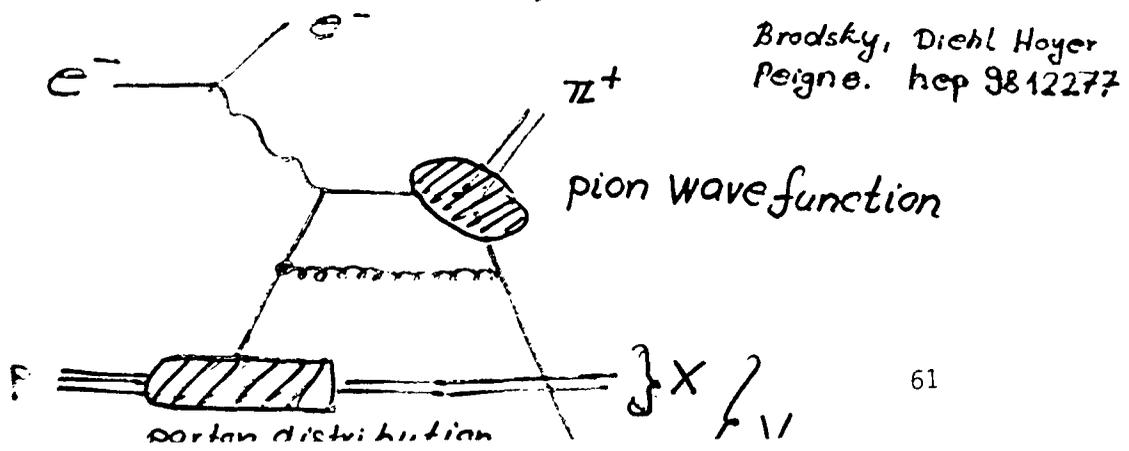
- Describe the production of hadrons by means of hadronic wavefunctions and pure perturbative QCD

→ semi inclusive  $\pi^+$  production:



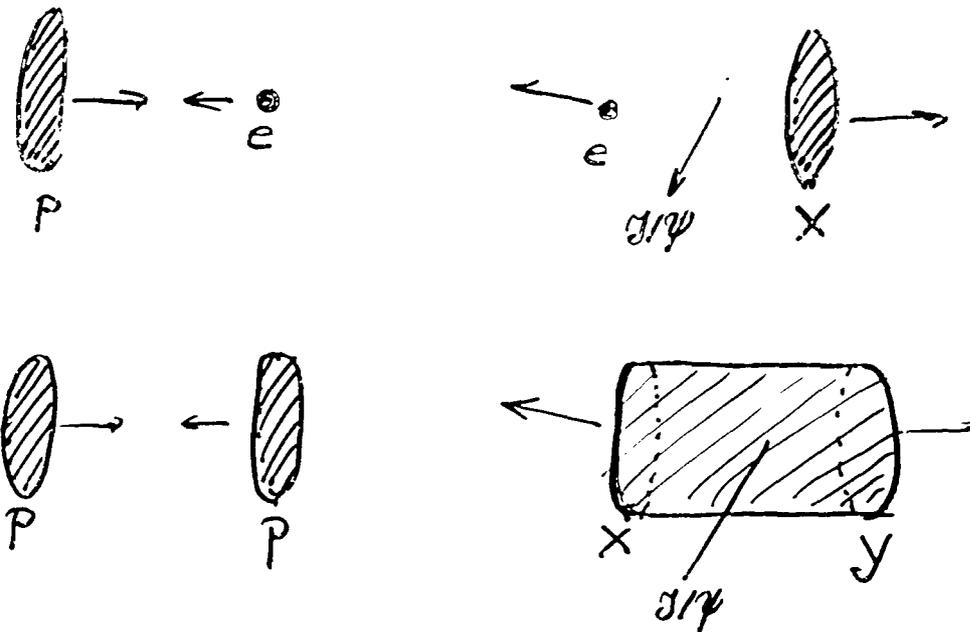
- inserts a noncalculable object in form of the fragmentation function

→ semi exclusive  $\pi^+$  production



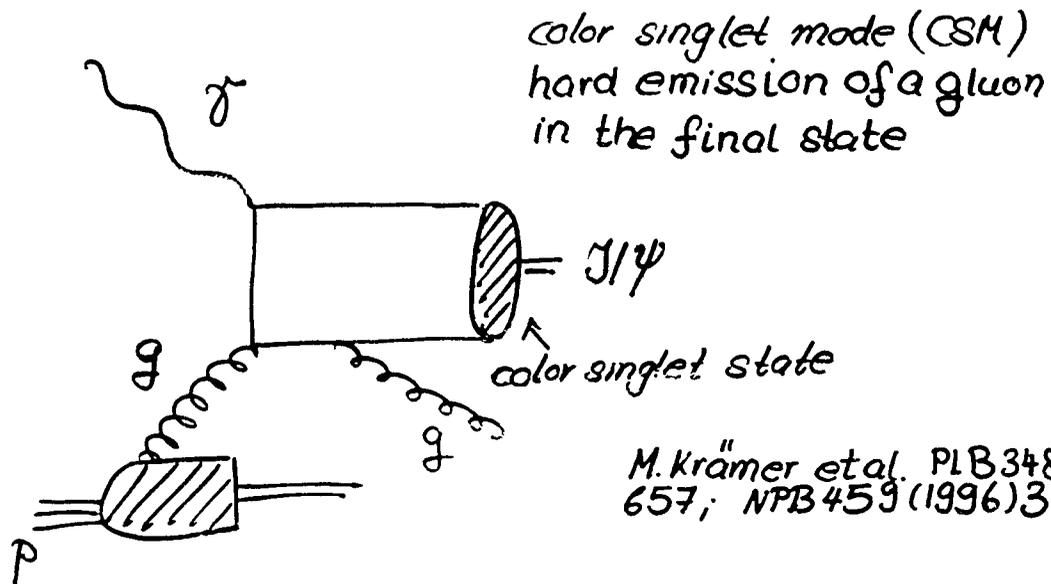
5. The general interest in a comparison between similar ep and pp collisions

- Unlike in ep reactions, which are basically QED processes, the self interacting gluons generate a kind of gluonic medium

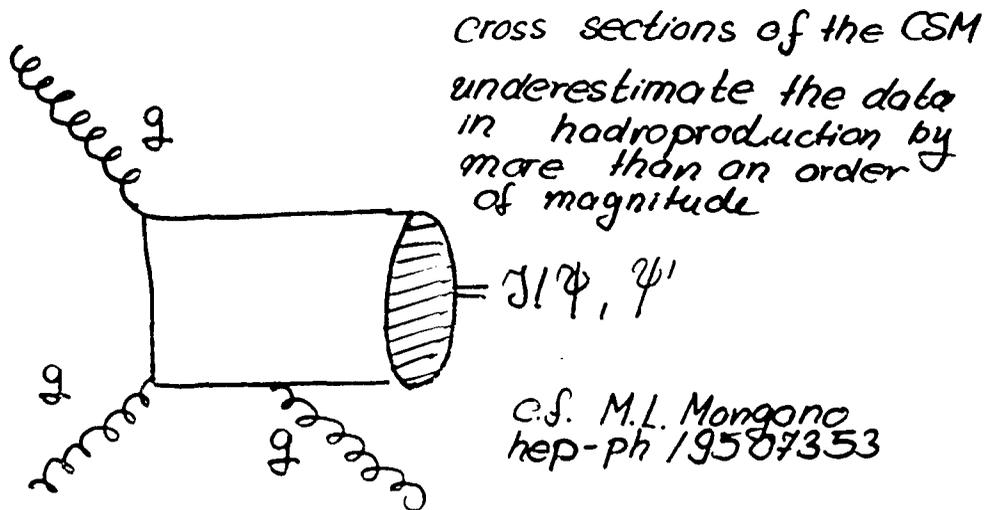


- similar processes rely on a completely different physical background in ep and pp reactions → example  $J/\psi$  production

6. Example:  $J/\psi$  ( $\psi'$ ) production

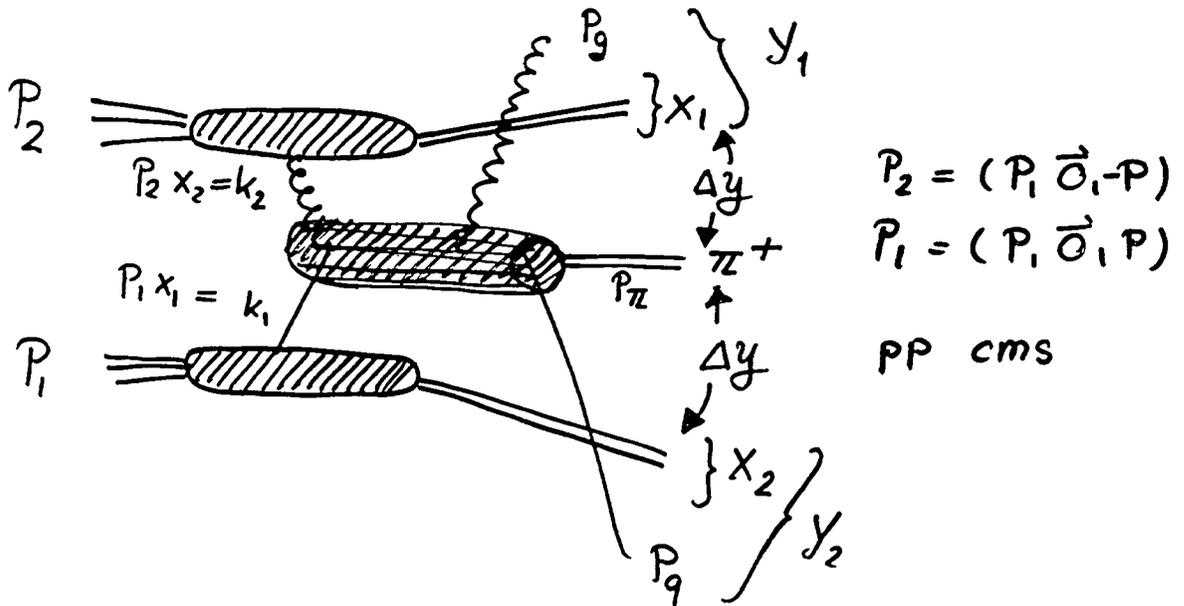


- The color singlet model describes photo production well, but fails in hadroproduction!



## 8. Semi exclusive $\pi^+$ production

in pp collisions



$$P_1 P \rightarrow \pi^+ + 2 \text{jet} + X$$

- between the  $\pi^+$  and the other particles a large rapidity gap should be visible.
- The invariant mass  $s_{ij} = (p_i + p_j)^2$  should be large to ensure the hardness of the propagators.

## 9. Kinematic preliminaries

- If the two jet momenta can be measured sufficiently well, then  $x_1$  and  $x_2$  are known:

$$q := P_g + P_q + P_\pi = x_1 P_1 + x_2 P_2$$

$$q^+ = q_0 + q_z = x_1 P_1^+$$

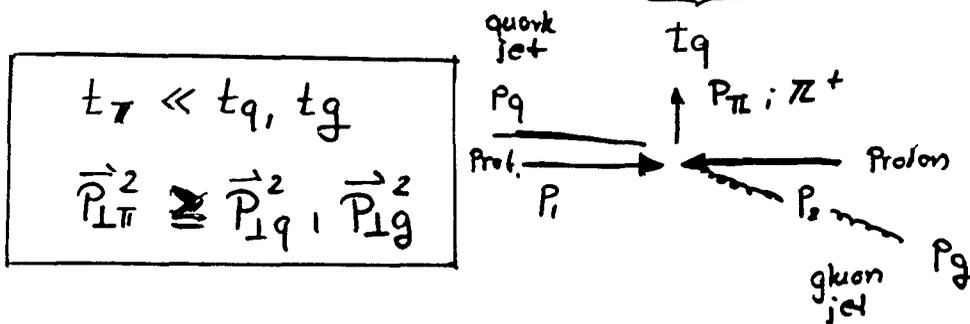
$$q^- = q_0 - q_z = x_2 P_2^-$$

- conditions for the rapidity gaps

$$|\Delta y_{\pi q}| = \frac{1}{2} \left| \ln \frac{P_q^+ P_\pi^-}{P_q^- P_\pi^+} \right|; \text{ use } P_q = \left( \frac{\vec{P}_{q\perp}^2}{P_{q-}}, P_{q-}, \vec{P}_{q\perp} \right)$$

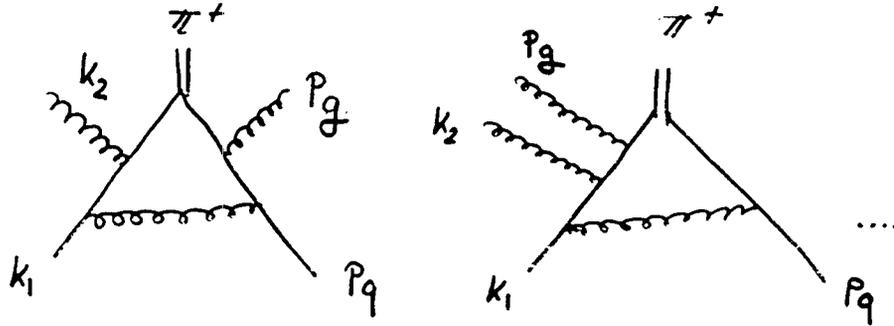
$$= \frac{1}{2} \left| \ln \frac{\vec{P}_{q\perp}^2}{P_{q-}^2} \times \frac{P_\pi^-^2}{P_{\pi\perp}^2} \right| \gg 0$$

$$\rightarrow \frac{1}{2} \left| \ln \left( \frac{\vec{P}_{q\perp}^2}{P_{\pi\perp}^2} \times \frac{(P_\pi - k_1)^4}{(P_q - k_1)^4} \right) \right| \gg 0$$

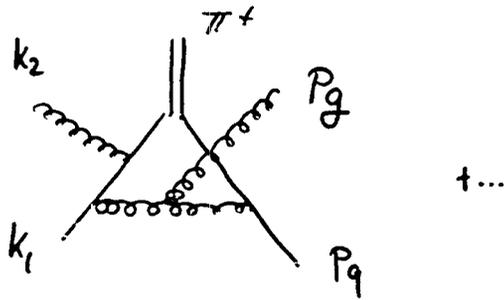


# 10. Typical diagrams

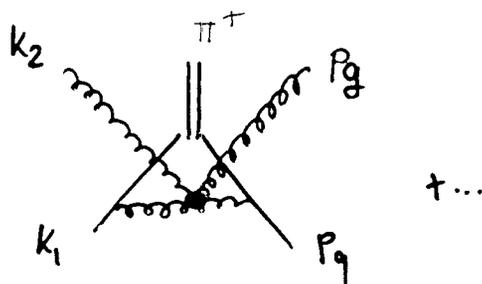
- Leading order contribution  $\alpha_s^4$



- Sensitiv to a three gluon vertex in LO



- and to a four gluon contribution



## Higher-Order Contributions to Prompt Photon Production

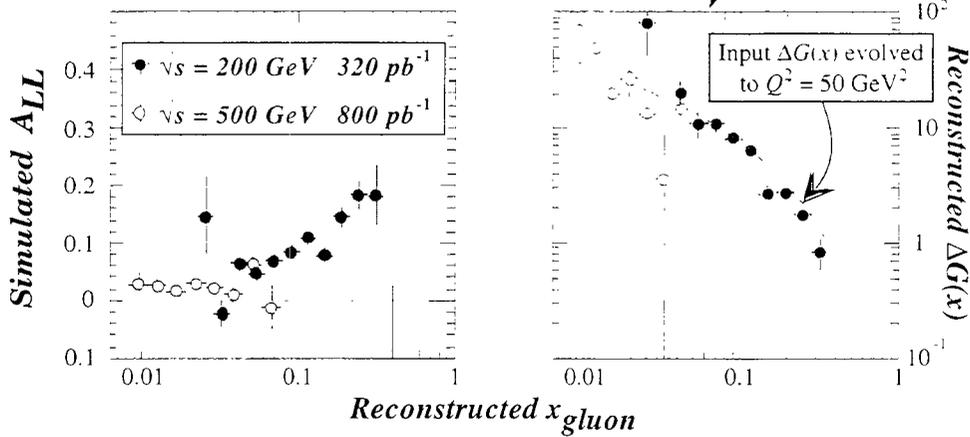
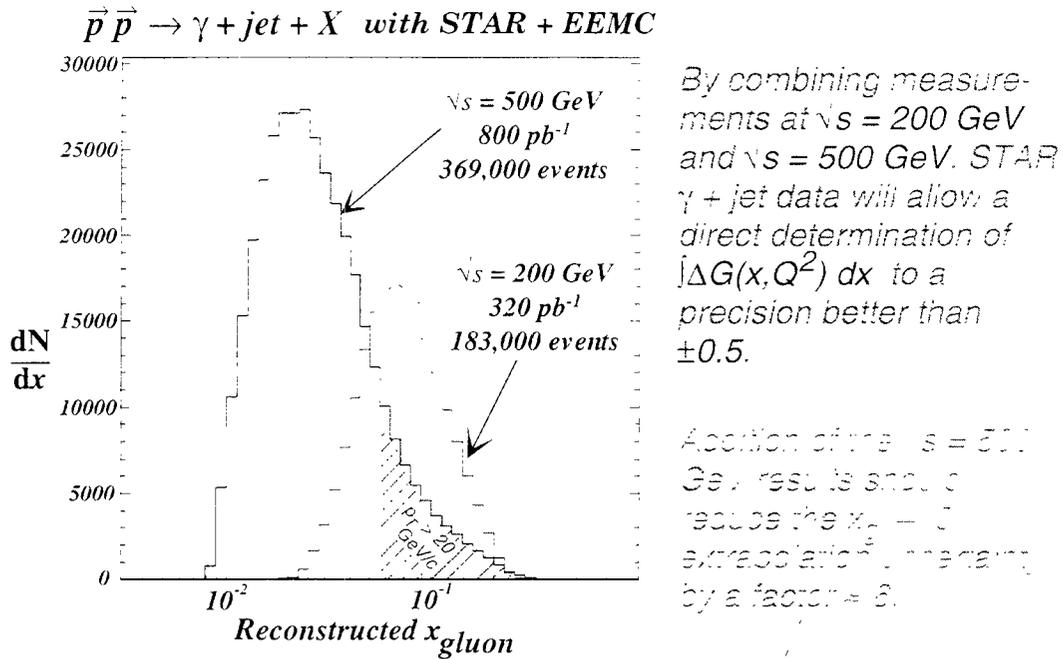
L.C. Bland, *Indiana University*

One of the primary goals of the RHIC spin program is to determine the contribution gluons make to the proton's spin. The dependence of photon production on the helicities of colliding protons promises to be one of the most sensitive probes of the polarized gluon distribution. The STAR spin program will focus on observing photons in coincidence with 'away-side' jets, thereby enabling an event-by-event reconstruction of the initial-state partonic kinematics. This method enables the possibility of directly extracting  $\Delta G(x)$  from the measured longitudinal spin asymmetry  $A_{LL}$  (Fig. 1).

The assessment of the expected value for  $A_{LL}$  is based on the PYTHIA 5.7 event generator, extended to account for polarization observables. PYTHIA is widely used to predict the expected experimental backgrounds to photon production associated with high- $p_T$   $\pi^0(\eta^0)$  production and is extensively used for designing experimental triggers. A reasonable question to ask is *how well does PYTHIA describe existing data?* For high- $p_T$  hadron production, it is straightforward to compare PYTHIA predictions to measurements made by the UA1 detector at CERN (Fig. 2). Over the range of the measurements, PYTHIA, operated in its default mode, gives a reasonable description of the data. The comparison for photon production is less straightforward to make because of the complex conditions employed in most experiments to extract the prompt photon yield from the prolific neutral meson production background. Employing only the UA1 isolation condition, but not the other conditions used to analyze the data, the PYTHIA 'direct photon' processes (including the gluon Compton process and  $q\bar{q}$  annihilation) significantly underpredicts the UA1 inclusive photon data (Fig. 3a). The other more complex cuts used by the UA1 group, if applied to the PYTHIA predictions, would result in even smaller values for the photon production cross section.

The question now is whether there are other mechanisms within PYTHIA that can produce high- $p_T$  photons, and whether these mechanisms are constrained by experiment. The answer to both questions is yes. The CDF group has recently compared their  $p\bar{p} \rightarrow \gamma + 2jet$  data sample at  $\sqrt{s} = 1.8$  TeV to 'bremsstrahlung' photons arising within the initial and final-state parton shower model in PYTHIA. The event generator adequately explains most of the CDF data. We can now compare this yield to the UA1 data (Fig. 3b). With only the isolation cut, this 'fragmentation' photon yield overpredicts the UA1 data. Once again, the other, more complex, cuts used by the UA1 group would result in smaller yields, suggesting that PYTHIA might be able to fully explain the inclusive photon cross sections at  $\sqrt{s} = 546$  and 630 GeV.

With these two mechanisms for producing photons, we can predict the photon yield expected at RHIC at  $\sqrt{s} = 200$  GeV (Fig. 4). From the PYTHIA simulation, the 'direct photon' processes are seen to dominate at this low energy. It is expected that the 'fragmentation photon' yield increases more rapidly with energy than does the 'direct photon' yield. Turning to the polarization observables, in contrast to the 'direct photon' processes, processes resulting in 'fragmentation photons' are found to have  $A_{LL} \approx 0$  (Fig. 5). By combining the polarization observables from all the subprocesses contributing to *both* the 'direct' and 'fragmentation' photon yields, the proton longitudinal spin asymmetry,  $A_{LL}$ , is found to be only slightly *reduced* relative to the 'direct photon' subprocesses alone (Fig. 5). This suggests that prompt photon production can still serve as a quantitative measure of the gluon polarization within the proton.



- Fit uncorrected  $\Delta G(x)$  reconstructed from 200 + 500 GeV simulations with Gehrman-Stirling functional form  $\Rightarrow$

$$\int_0^1 \Delta G_{\text{recon}}(x) dx = 1.62 \pm 0.23 \quad \text{vs.} \quad \int_0^1 \Delta G_{\text{input}}(x) dx = 1.71$$

$\Rightarrow \approx 0.4$  when other syst. errors included

Fig. 1

$p \bar{p} \rightarrow \text{charged particle}$

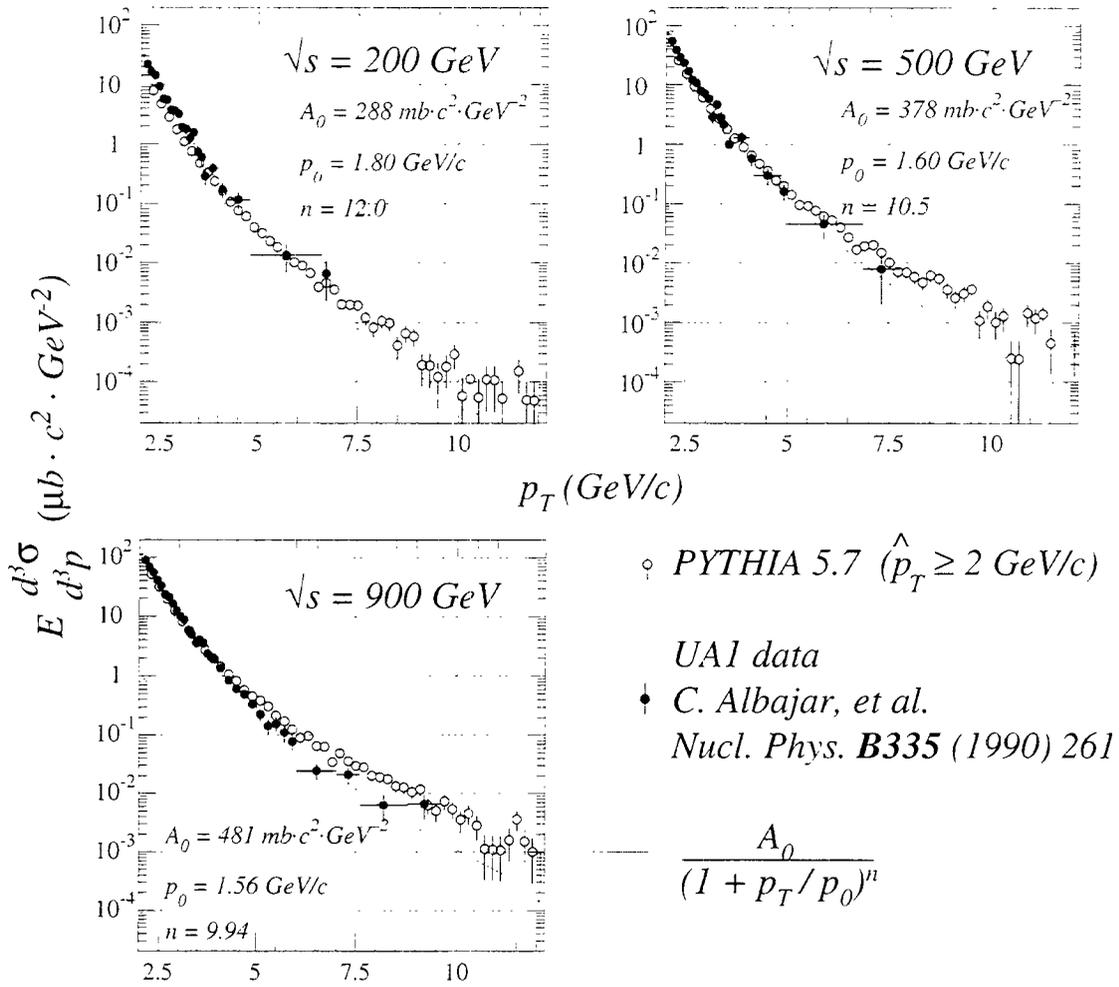
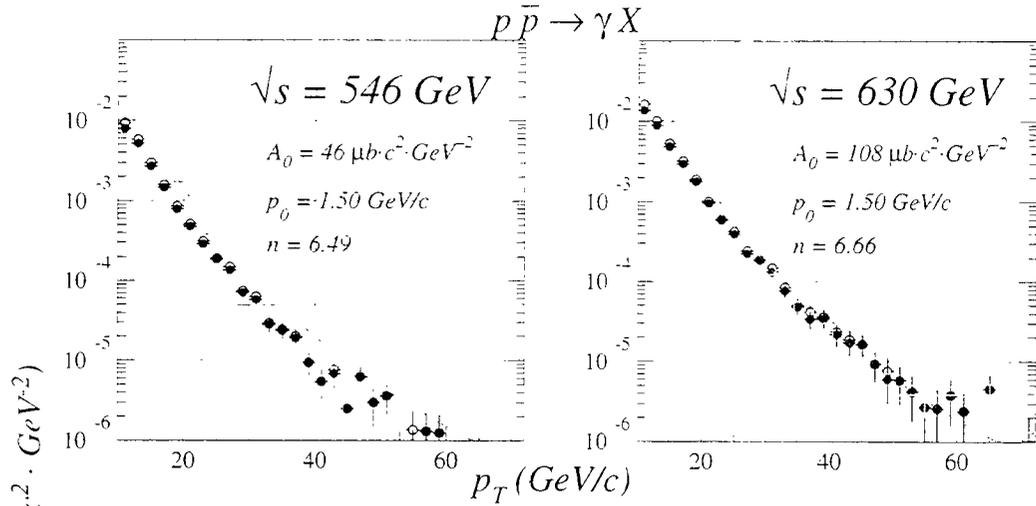


Fig. 2

NOTE: Only UA1 isolation cut is applied. *Missing*  $E_T$  cut and deconvolution of *summed*  $E_T$  distribution within isolation cone **are not performed**.

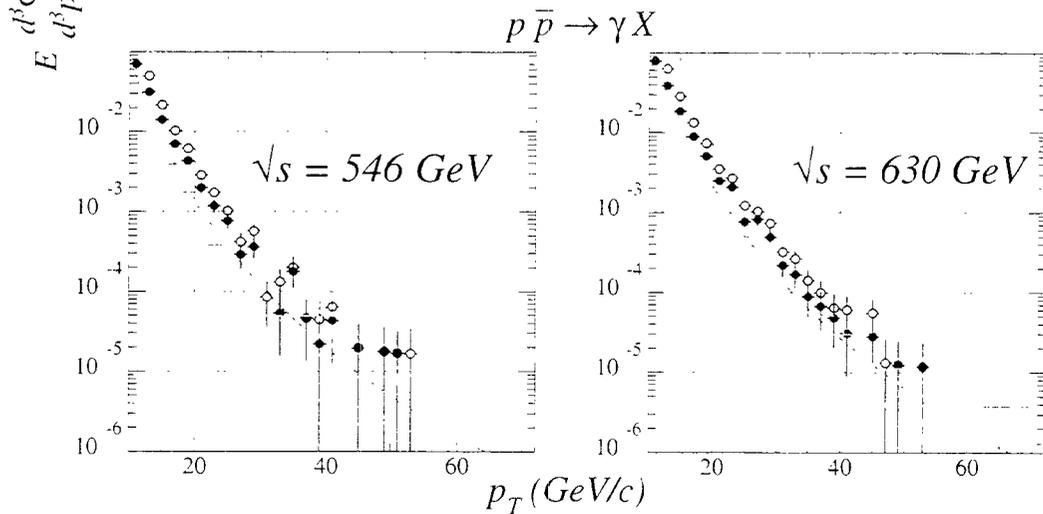
Comparison of 'Direct Photon'  
Prediction (PYTHIA) to UA1 Data

Fig. 3a



Comparison of 'Fragmentation Photon'  
Prediction (PYTHIA) to UA1 Data

Fig. 3b



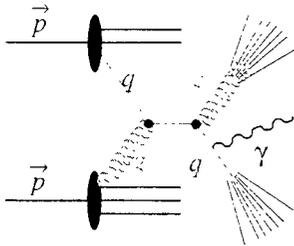
◇ PYTHIA 5.7 no isolation cut

● PYTHIA 5.7 UA1 isolation cut *only*

UA1 data – C. Albajar, et al. *Phys. Lett.* **B209** (1988) 385

—  $A_0 \cdot (1 + p_T/p_0)^{-n}$

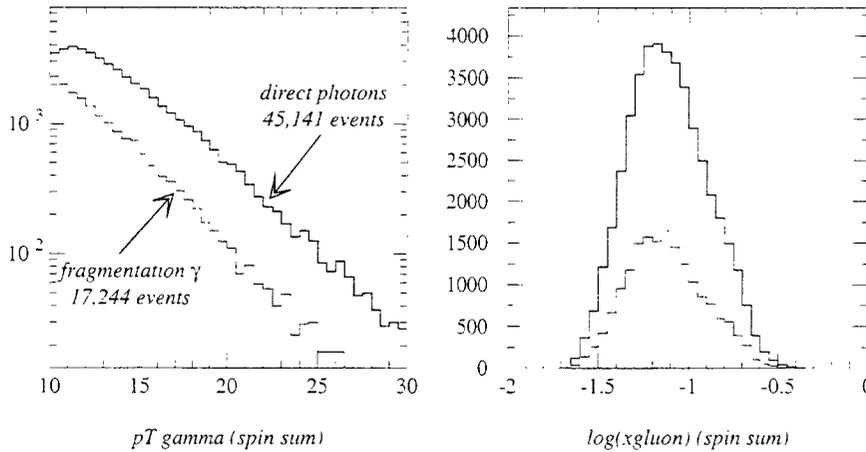
What are the contributions from higher-order processes?



From calculations (Gordon & Vogelsang), we should expect important contributions to the photon yield from higher-order processes.

PYTHIA includes only LO pQCD processes. Higher-order effects are modeled via 'parton showers'. The above process is contained within PYTHIA via so-called 'fragmentation photons'. Comparison between  $p + \bar{p} \rightarrow \gamma + 2 \text{ jet}$  data and the PYTHIA 'fragmentation' photon yield has been made by the CDF group at  $\sqrt{s} = 1.8 \text{ TeV}$  (PRD 57, 67). Good agreement is found.

$p + p \rightarrow \gamma + \text{jet} + X$   $\sqrt{s} = 200 \text{ GeV}$   $75 \text{ pb}^{-1}$  (PYTHIA 5.7)  
(includes UA2 isolation condition)



$\Rightarrow$  a larger radius isolation cone is **essential** to reduce the yield from 'fragmentation photons'

Fig. 4

*What is the influence of  
'fragmentation photons' on  
polarization observables?*

Cuts applied to simulation:

$$10 < p_{T,\gamma} < 20 \text{ GeV}/c$$

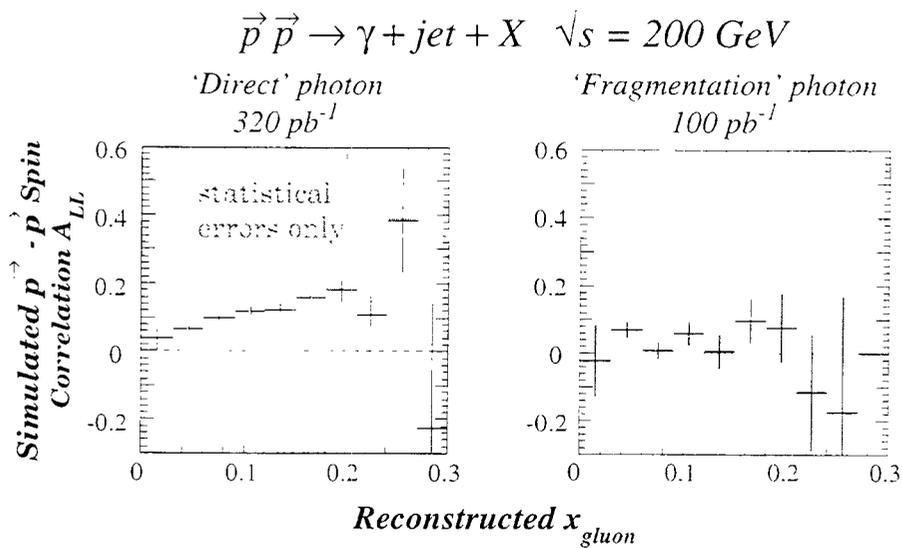
UA2 isolation condition

$$-0.3 < \eta_{\text{jet}} < 1.3 \text{ (for leading jet)}$$

$\max[x_+, x_-] > 0.2$ , where

$$-1 < \eta_\gamma < 2 \text{ (barrel + endcap EMC)}$$

$$x_\pm = \frac{2p_T}{\sqrt{s}} (e^{\pm\eta_\gamma} + e^{\pm\eta_{\text{jet}}})$$



$\Rightarrow$  expect a small dilution of  $A_{LL}$  from fragmentation photons

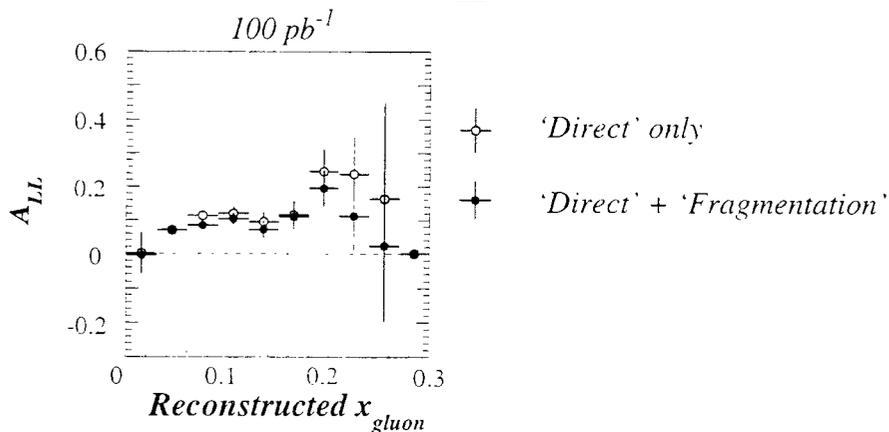


Fig. 5

**WORKSHOP ON EVENT GENERATOR FOR RHIC SPIN PHYSICS**  
**MARCH 15-19, 1999**  
**ORGANIZERS: NAOHITO SAITO AND ANDREAS SCHÄFER**

**ACTUAL PARTICIPANTS**

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# RIKEN BNL Research Center

Workshop on Event Generator for RHIC Spin Physics  
Physics Department  
March 15–19, 1999

## AGENDA

### Monday, March 15 (Room 2-160):

09:30–10:30 Introduction [Naohito Saito]  
10:30–11:00 *Coffee*  
11:00–12:00 Recent Progress in Theoretical Studies of Spin Physics [Andreas Schaefer]  
13:30–14:30 New Processes and Parity Violating Spin Asymmetries [Jean-Marc Virey]  
14:30–15:00 *Coffee*  
15:00–16:00  $k_T$  Issues (TBC) [Mike Tannenbaum]

### Tuesday, March 16 (Room 2-160):

09:15–09:45 Quarkonium Production [Toshi-Aki Shibata]  
09:45–10:00 *Coffee*  
10:00–11:00 Special Spin Discussion: Transversity and Interference Fragmentation Functions  
[Robert Jaffe] (no proceedings package)  
11:00–11:15 *Coffee*  
11:15–12:15 Event Generators at Fixed Order in QCD: Jets and Isolated Photons [Stefano Frixione]

### Wednesday, March 17 (Room 2-160):

09:30–10:30 Comparisons Between Sphinx, Pythia+Asymmetries and NLO QCD [Oliver Martin]  
10:30–11:00 *Coffee*  
11:00–12:00 Potential Problems with, and Alternatives to, Prompt Photon Production at Colliders  
[Lionel Gordon]

### Thursday, March 18 (Room 2-160):

09:00–10:00 CTEQ Parton Distribution Functions [Wu-Ki Tung]  
10:00–11:00 Special Spin Discussion: Spin Measurements with HERMES [Naomi Makins]  
(no proceedings package)  
11:00–11:30 *Coffee*  
11:30–12:30 Parametrization of Polarized Parton Distributions in the Nucleon [Masanori Hirai]

### Friday, March 19 (Room 2-160):

09:30–10:30 Semi Exclusive  $pp$  Reactions [Martin Maul]  
10:30–11:00 *Coffee*  
11:00–12:00 Higher-Order Contribution to Direct Photon Yields [Les Bland]





## Forthcoming RIKEN BNL Center Workshops

Title: **Numerical Algorithms at Non-Zero Chemical Potential**  
Organizers: T. Blum/M. Creutz  
Dates: Apr. 27–May 1, 1999

Title: **Gauge Invariant Observables in Gauge Theories**  
Organizers: P. Orland/P. van Baal  
Dates: May 25–29, 1999

Title: **OSCAR II: Predictions for RHIC**  
Organizers: Y. Pang/M. Gyulassy  
Dates: July 8–16, 1999

Title: **Coulomb and Pion-Asymmetry Polarimetry and Hadronic Spin Dependence at RHIC Energies**  
Organizer: E. Leader  
Date: August 18, 1999

For information please contact:

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RIKEN BNL RESEARCH CENTER

# EVENT GENERATOR FOR RHIC SPIN PHYSICS

MARCH 15-19, 1999



Li Keran

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*Nuclei as heavy as bulls  
Through collision  
Generate new states of matter.  
T. D. Lee*

Speakers:

L. Bland  
M. Hirai  
O. Martin  
T.-A. Shibata  
J.-M. Virey

S. Frixione  
R. Jaffe  
M. Maul  
M. Tannenbaum

L. Gordon  
N. Makins  
A. Schaefer  
W.-K. Tung

Organizers: Naohito Saito and Andreas Schaefer