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Formal Report

Proceedings of RIKEN BNL Research Center Workshop Volume 12

QUARKONIUM PRODUCTION IN RELATIVISTIC NUCLEAR COLLISIONS

September 28–October 2, 1998

Organizer

Dmitri Kharzeev

RIKEN BNL Research Center

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

Other RIKEN BNL Research Center Proceedings Volumes:

Volume 11 - Event Generator for RHIC Spin Physics - BNL-66116
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Volume 4 - Inauguration Ceremony, September 22 and
Non-Equilibrium Many Body Dynamics - BNL- 64912
September 23–25, 1997 - Organizer - Miklos Gyulassy

Volume 3 - Hadron Spin-Flip at RHIC Energies - BNL-64724
July 21 - August 22, 1997 - Organizers: T.L. Trueman and Elliot Leader

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July 14–25, 1997 - Organizers: Robert Jaffe and George Sterman

Volume 1 - Open Standards for Cascade Models for RHIC - BNL-64722
June 23–27, 1997 - Organizer - Miklos Gyulassy

Preface to the Series

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

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

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

T.D. Lee
July 4, 1997

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Introduction

The RIKEN-BNL Workshop on Quarkonium Production in Relativistic Nuclear Collisions was held September 28 – October 2, 1998, at Brookhaven National Laboratory. The Workshop brought together about 50 invited participants from around the world and a number of Brookhaven physicists from both particle and nuclear physics communities.

Brookhaven has been at the origin of heavy quarkonium physics, which was born after the 1974 discovery of the J particle at BNL's AGS and of the Ψ particle at SLAC marked by the 1976 Nobel Prize in Physics. Since that time, the properties of the J/Ψ and other heavy quarkonia have constantly been at the focus of attention – understanding their properties helped to establish QCD as the standard model of strong interactions.

In 1986, T. Matsui (then at MIT) and H. Satz (then at BNL and Bielefeld) proposed that not only production, but also the death of J/Ψ can serve physics – signalling production of quark-gluon matter in relativistic nuclear collisions. Their idea was based on the observation that at sufficiently high temperatures the quark-antiquark potential will be screened, and bound states would cease to exist. This predicted J/Ψ suppression was soon observed in $S-U$ collisions by the NA38 Collaboration at CERN. However the scientific debates which unfolded immediately after the NA38 results were announced have demonstrated that to understand the true origin of the effect one has to further develop the theory of J/Ψ production and accumulate more data.

A very impressive progress in these directions was made during the recent few years, both in theory and experiment, including spectacular effects observed in high p_t J/Ψ production at the Tevatron, quarkonium production in pA collisions at CERN and Fermilab, and most recent exciting observation of "anomalous" J/Ψ suppression in Pb-Pb collisions at CERN. It was timely therefore to summarize the existing knowledge and to discuss critically the current status of quarkonium physics.

Participants extensively discussed the theory of quarkonium hadro-production (Braaten, Matsui, Mueller, Peigne); their attention was drawn also to the recent experimental results from Fermilab fixed target (Leitch) and Tevatron (LeCompte) experiments. The new data and analysis of charmonium and dilepton production in Pb-Pb collisions from the NA50 Collaboration (Gonin, Ramello) stimulated many discussions. The theory and phenomenology of quarkonium production in nuclear interactions were discussed in detail (Capella, Gerland, Gyulassy, Hüfner, Kopeliovich, Mattiello, Qiu), with particular emphasis on the role of coherence effects (Kapusta, Thews). One of the central issues at the Workshop was whether the current data on charmonium suppression require the existence of collective effects (Blaschke, Kourepin, Nardi, Satz, Wong). Knowledge of charmonium dissociation cross sections (Fujii) is very important in this respect, and the proposed direct measurement of $J/\psi - N$ dissociation cross section in low-energy $\bar{p}A$ annihilation at FNAL (Seth) would thus be vital for the high-energy nuclear program.

The future of quarkonium program looks very bright, with two RHIC experiments – PHENIX (Akiba, Rosati, Zajc) and STAR (Hallman, LeCompte, Ullrich) starting operation this year. In a more distant future, the collider quarkonium program will be joined at CERN by ALICE (Morsch). The workshop ended by summary talks on experimental (Lourenço) and theoretical (Mueller and Satz) status of quarkonium physics.

At this stage, when the Relativistic Heavy Ion Collider is approaching its completion, it is particularly important to work out predictions and suggestions for the experiments before RHIC begins its operation in 1999. Confronting pre–, rather than post–dictions with the data will give us much firmer confidence in our understanding of the underlying physics, and can significantly advance the theory. It would be particularly convenient to compare different approaches among themselves if the theorists could work out predictions for the same experimentaly measurable observables. During two dedicated discussion sessions, the participants agreed on the list of observables which would be most useful (the list is included in these Proceedings).

I would like to thank the RIKEN-BNL Research Center for making this Workshop possible. In particular, I am indebted to Pam Esposito, who handled the organization of the Workshop in a very enthusiastic, creative and professional way. Special thanks go out to Fern Simes for her help in publishing these Proceedings.

I thank Brookhaven National Laboratory and the U.S. Department of Energy for providing facilities to hold this Workshop.

Finally, I would like to express my gratitude to the participants of the Workshop for attending, taking part in discussions, and for sharing their ideas and excitement.

Dmitri Kharzeev

Organizer

Talk at Riken-BNL Research Center, 9-28-98

J/ψ suppression: hopes and issues

T. Matsui

Yukawa Institute for Theoretical Physics

1. Hopes :

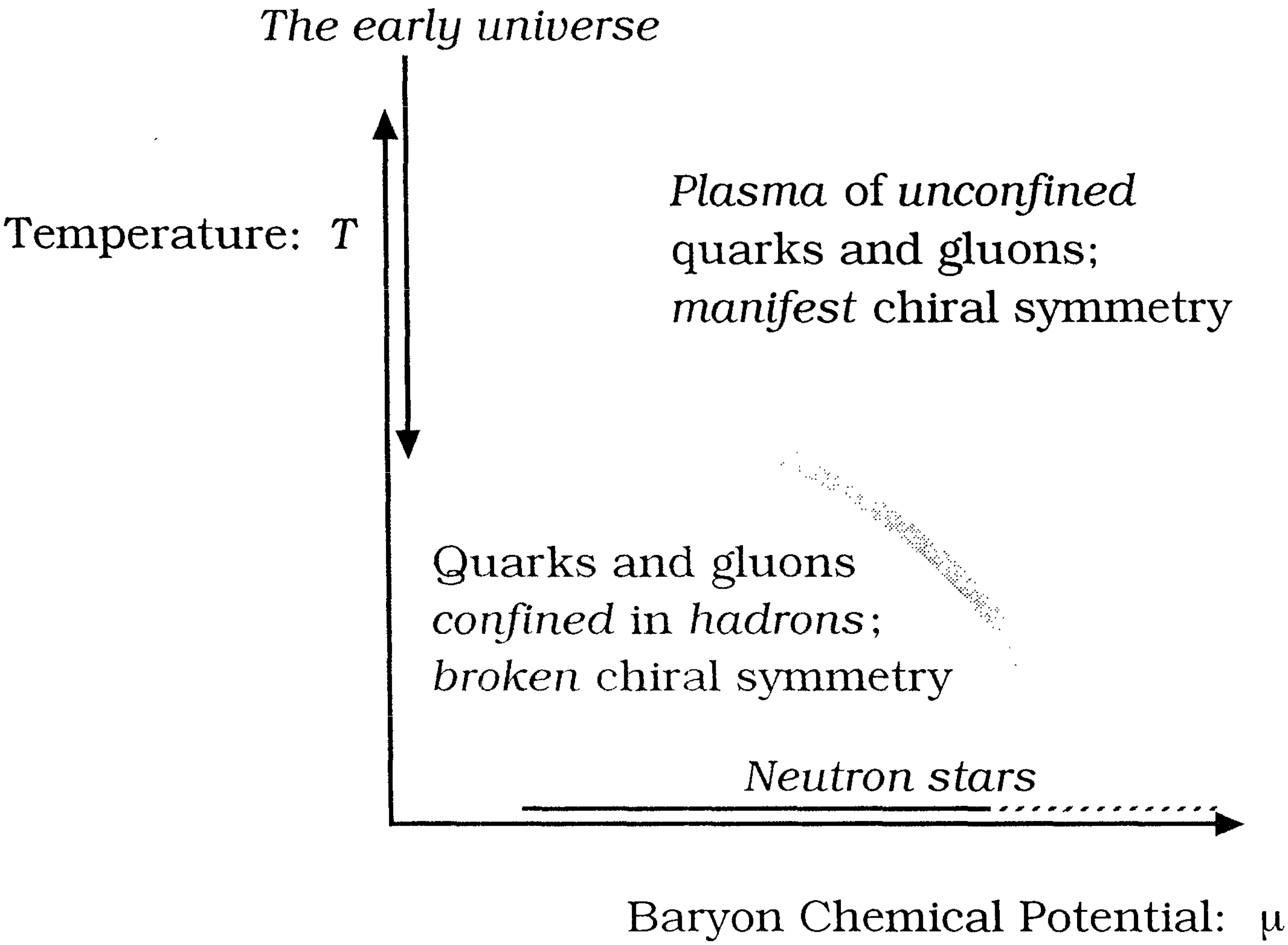
   - goals of ultrarelativistic heavy-ion physics
   - J/ψ suppression: an old idea

2. Issues :

   - production mechanisms
   - suppression mechanisms
   - "anomalous" J/ψ suppression

3. A SPECULATION WITH AN ILLUSTRATIVE MODEL OF J/ψ SUPPRESSION

(Expected) States of matter at extreme conditions:



Monte Carlo simulations of QCD on the lattice at $\mu = 0$ but at finite T indicate that the transition is *abrupt* and may involve *phase transition*.

"confinement-deconfinement transition"
"chiral phase transition"

Three signals:

- anomaly (softning) of the equation of state
- screening of the heavy quark confining potential
- melting of the vacuum condensate

MANIFESTATION OF PLASMA SCREENING

→ J/ψ SUPPRESSION

SATZ & T.M. ('86)

WHY J/ψ?

- WELL UNDERSTOOD IN TERMS OF A SIMPLE POTENTIAL MODEL — "CHARMONIUM"

  IDEAL TO TEST THE ONSET OF DECONFINEMENT & PLASMA SCREENING

  $$r_{Bohr} \sim \frac{1}{\alpha_s m_c} > r_{DEBYE} \sim \frac{1}{gT}$$

  → NO BOUND STATE.

- ONCE DISSOLVED, IT WILL HARDLY BE CREATED AT HADRONIZATION STAGE

  $$M_{J/\psi} = 3.1\ GeV \gg T_c \sim 0.2\ GeV$$

- MAY BE CLEARLY SEEN IN DILEPTON SPECTRUM AS STRONG SUPPRESSION OF J/ψ PEAK RELATIVE TO DRELL-YAN CONTINUUM.

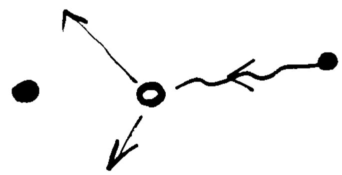
  NO SUPPRESSION TO DRELL-YAN.

  BOTH INVOLVE HARD PROCESS.

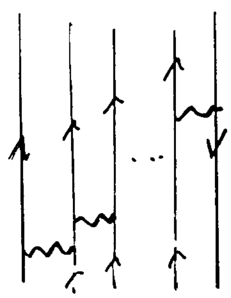
SCREENING V.S. SCATTERING

- SCREENING INVOLVES COHERENT REARRANGE OF PLASMA CONSTITUENTS, WHILE COLLISIONAL DISSOCIATION IS DUE TO THE INCOHERENT SCATTERING WITH INDIVIDUAL PARTICLE.

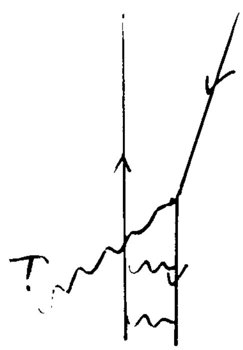
POLARIZATION OF MEDIUM WEAKENS THE $c\bar{c}$ BINDING.



SCATTERING DISRUPTS COHERENCE OF $c\bar{c}$



LONGITUDINAL GLUON (PHOTON) BECOMES "MASSIVE" BY THE FORWARD SCATTERING WITH PLASMA CONSTITUENTS.



TRANSVERSE GLUON (PHOTON) ABSORBED BY THE BOUND $c\bar{c}$.

COLLECTIVE

NON-COLLECTIVE.

A SIMPLE MODEL OF J/ψ SUPPRESSION

WITH SCREENING AND ABSORPTION EFFECTS

CONSIDER TIME-EVOLUTION OF A $c\bar{c}$ WAVE-PACKET FROM A LOCALIZED INITIAL STATE:

$$|\psi(t)\rangle = U(t)|\psi(0)\rangle$$

$$\psi_i(r) = \langle r|\psi(0)\rangle \sim \delta(r)$$

TIME-DEP SCHRÖDINGER EQ.

$$i\frac{\partial}{\partial t}U(t) = H(t)U(t); \quad U(0) = 1$$

$$H(t) \xrightarrow[t\to\infty]{} H_0 = \frac{p^2}{2\mu} + V_0(r)$$

$$H_0|n\rangle = E_n|n\rangle$$

BOUND STATE FORMATION AMPLITUDE:

$$\langle n|\psi(\infty)\rangle = \langle n|U(\infty)|\psi(0)\rangle$$

$$= \int dr\, \varphi_n(r)\langle r|U(\infty)|0\rangle$$

IF $H(t) = H_0$ FOR $t > t_0$

$$\langle n|\psi(\infty)\rangle = e^{-iE_n(t_\infty - t_0)}\int dr\, \varphi_n(r)\langle r|U(t_0)|0\rangle$$

$$\Rightarrow \varphi_n(0) \quad \text{IF } t_0 = 0$$

HARMONIC OSCILLATOR IN 1-DIM.

$$H_0 = \frac{p^2}{2\mu} + \frac{1}{2}\mu\omega_0^2 x^2$$

$$H(t) = \frac{p^2}{2\mu} + \frac{1}{2}\mu\omega^2 x^2 \quad : \quad t < t_0$$

GROUND STATE FORMATION AMPLITUDE:

$$F(t_0) = \int dx\, \varphi_0(x) \langle x | U(t_0) | 0 \rangle$$

$$= \varphi_0(0) \frac{1}{\left[\cos(\omega t_0) + i\frac{\omega_0}{\omega}\sin(\omega t_0)\right]^{1/2}}$$

SUPPRESSION FACTOR:

$$S(t_0) = \left| F(t_0) / F(0) \right|^2$$

$$= \frac{1}{\left|\cos(\omega t_0) + i\frac{\omega_0}{\omega}\sin(\omega t_0)\right|^{\alpha}}$$

$\alpha = 1$ FOR 1-dim.
$\alpha = n$ FOR n-dim.

T. M. Ann. Phys. 196 (1989) 182

NOW WE CONSIDER GENERALIZED HARMONIC "OSCILLATOR" WITH COMPLEX ω

$$\omega = \omega_R + i\omega_I$$

THEN $V(x) = \frac{1}{2}\mu\omega^2 x^2$

$$= \frac{1}{2}\mu(\omega_R^2 - \omega_I^2)x^2 + \mu\omega_R\omega_I x^2 i$$

IF $\omega_R = -\omega_I$, PURE "ABSORPTIVE" POT. WITH COMPLETE "SCREENING".

HOWEVER, OUR FORMULA GIVES

$$S(t_0) = 2\Big\{ \frac{(\omega_R+\omega_0)^2+\omega_I^2}{\omega_R^2+\omega_I^2} e^{-2\omega_I t_0} + \frac{(\omega_R-\omega_0)^2+\omega_I^2}{\omega_R^2+\omega_I^2} e^{2\omega_I t_0} + \left(1-\frac{\omega_0^2}{\omega_R^2+\omega_I^2}\right) 2\cos(2\omega_R t_0) + \frac{4\omega_0\omega_I}{\omega_R^2+\omega_I^2}\sin(2\omega_R t_0)\Big\}^{1/2}$$

OSCILLATORY SUPPRESSION FOR $\omega_R \neq 0$!

~~CAN~~ MAY EXPLAIN OBSERVED OSCILLATION IN E_T?

$E_T \leftrightarrow t_0$

Factorization Approach to Inclusive Charmonium Production

Eric Braaten

The Ohio State University

The factorization approach to inclusive charmonium production unifies and supercedes the color-singlet model and the color-evaporation model. It provides a rigorous basis for the study of charmonium production, so that the standard tools of perturbative QCD, such as factorization and resummation, can be applied to this problem. The basic ingredients of this approach are the folowing:

1. The creation of a $c\bar{c}$ pair occurs at short distances $\lesssim 1/m_c$, but the formation of charmonium involves long distances $\gtrsim 1/(m_c v)$.
2. The sum over final states allows the inclusive cross section to be factored into short-distance parton cross sections for $c\bar{c}$ production and long-distance factors involving the charmonium wavefunction.
3. By expanding the parton cross sections in powers of the relative velocity v ($v^2 \approx 1/3$), the long-distance factors are reduced to numbers (NRQCD matrix elements).
4. A nonperturbative analysis within nonrelativistic QCD (NRQCD) is used to identify the most important matrix elements for a given charmonium state.

The factorization formula for inclusive J/ψ production is

$$d\sigma(J/\psi + X) \;=\; \sum_n d\hat{\sigma}(c\bar{c}_n + X)\langle \mathcal{O}_n \rangle^{J/\psi}.$$

The parton cross sections $d\hat{\sigma}$ can be calculated using perturbative QCD. The nonperturbative matrix elements $\langle \mathcal{O}_n \rangle$ are treated as phenomenological parameters to be determined by experiment. The sum over n includes color-singlet operators $\mathcal{O}_1$ and color-octet operators $\mathcal{O}_8$ with all possible angular momentum quantum numbers $^{2S+1}L_J$. The most important color-singlet operator for J/ψ production is $\mathcal{O}_1(^3S_1)$. The most important color-octet operators depend on the process, but they include $\mathcal{O}_8(^3S_1)$, $\mathcal{O}_8(^1S_0)$, and $\mathcal{O}_8(^3P_J)$.

Inclusive Production (or Annihilation Decay) of Charmonium

- creation (or annihilation) of $c\bar{c}$ pair involves short distances ($\lesssim \frac{1}{m}$)

- Summing over final states allow factorization methods of perturbative QC to be used to separate short distances and long distances.

- Short-distance factors are parton cross sections calculable using perturbative QCD.

- Long-distance factors involving charmonium can be expressed as NRQCD matrix elements that scale with definite powers of v^2.

NRQCD Factorization Formula

for annihilation decay rate

$$\Gamma(J/\psi) = \sum_n \hat{\Gamma}(c\bar{c}[n]) \langle J/\psi | \mathcal{O}[n] | J/\psi \rangle$$

$\sum_n$: sum over color : 1 or 8
angular momentum $^{2S+1}L_J$

Short-distance factors

$\hat{\Gamma}(c\bar{c}[n]) \propto$ annihilation rate of $c\bar{c}$ in state n into hard partons

– calculate using perturbative QCD

Long-distance factors

$$\langle \mathcal{O}[n] \rangle_{J/\psi} \propto \int_{\vec{x}} \int_q q^{2L} \sum_{X_g} \left| \langle c\bar{c}[n, \vec{x}, q] + X_g | J/\psi \rangle \right|^2$$

– matrix element of local operator in NRQCD

– scales like $P_{c\bar{c}[n]} \times v^{2L}$

NRQCD Factorization Formula

for inclusive production of J/ψ

$$d\sigma(J/\psi(P)+X)$$

$$= \sum_n d\hat{\sigma}(c\bar{c}[n](P)+X) \langle \mathcal{O}^{J/\psi}[n] \rangle$$

$\sum_n$: sum over color : $\underline{1}$ or $\underline{8}$

angular momentum $^{2S+1}L_J$

<u>short-distance</u> factor

$d\hat{\sigma} \propto$ parton cross section for creating $c\bar{c}$ pair

calculate using perturbative QCD

<u>long-distance</u> factor

$$\langle \mathcal{O}^{J/\psi}[n] \rangle \propto \int_{\vec{x}} \int_q q^{2L} \sum_{\text{soft gluons}} \left| \langle J/\psi + \text{soft gluons} | c\bar{c}[n, q, \vec{x}] \rangle \right|^2$$

— phenomenological parameter

— scales like $\langle J/\psi | \mathcal{O}[n] | J/\psi \rangle$

Complications in production with 0 hadrons in initial state

In some regions of 4-momentum P of J/ψ, derivation of factorization breaks down because of kinematic constraints.

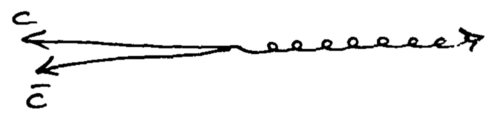
Resonance region $3\ \text{GeV} < \sqrt{s} < 4\ \text{GeV}$

problem: insufficient smearing over light hadron resonances

$$\Longrightarrow \sum_{\text{hadrons}} d\sigma \neq \sum_{\text{partons}} d\sigma$$

solution: smear over CM energy $\sqrt{s}$

Endpoint region: $E_{J/\psi} \longrightarrow \dfrac{\sqrt{s} + M_{J/\psi}^2}{2\sqrt{s}}$

$c\bar{c}$ recoils against hard gluon: 

real soft gluons suppressed by kinematics
virtual " not suppressed
$\Longrightarrow$ cancellations incomplete

solution: resummation (Sterman et al.)

Complications in production

with 1 hadron in the initial state

- factorization is only established for $p_T \gg \Lambda_{QCD}$

- at order $\frac{\Lambda_{QCD}^2}{p_T^2}$ (or higher),

  need correlation functions for

  for 2 (or more) partons in the hadron

- Is there factorization for $d\sigma$ integrated over p_T?

  ① If $p_T < 1$ GeV is negligible, then YES.

  ② If $p_T < 1$ GeV is significant, then MAYBE.

  Factorization in m (rather than p_T)

  is plausible, but not yet established.

  error: $\mathcal{O}\left(\frac{\Lambda_{QCD}^2}{m^2}\right)$? $\mathcal{O}\left(\frac{(mv)^2}{m^2}\right)$?

Complications of production
with <u>2 hadrons</u> in the initial state

- Intrinsic p_T of partons in the colliding hadrons must be taken into account.

- At order $\frac{\Lambda_{QCD}^4}{p_T^4}$,
factorization breaks down completely
(long range correlations between the partons in the 2 hadrons.)

VECTOR MESON PRODUCTION AND NUCLEAR EFFECTS IN FNAL E866

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Fermilab E866/NuSea is a fixed-target experiment which has made a number of measurements of the production of vector mesons by 800 GeV protons. These include the nuclear dependence of J/ψ. ψ' and ϕ production over very broad ranges in x_F and p_T, and the J/ψ decay angular distribution. Preliminary results from these measurements are presented and discussed in the context of models for nuclear effects such as absorption, energy loss and multiple scattering of the partons, and shadowing. Production mechanisms involving color-singlet or color-octet states have implications on the strength of absorption in the nucleus or on comovers and on the decay angular distributions. Over 2.7M J/ψ's and 36k ψ''s with $-0.1 \leq x_F \leq 0.9$ and $p_T \leq 4GeV/c$ on Be, Fe and W targets have been obtained. Preliminary results from these data show that the J/ψ and ψ' have similar suppression for positive x_F, but that the ψ' is more strongly suppressed at negative x_F. This results from formation time effects such that the resonances become physical states in the nucleus at negative x_F, while at positive x_F they remain small $c\bar{c}$ objects. Absorption is the main source of suppression in the integrated cross section but other effects, such at energy loss and shadowing, cause increasing suppression for larger x_F. We also have preliminary angular distributions for J/ψ's produced off our copper beam dump which show some transverse polarization. Early results for dimuons in the 0.5 to 3 GeV dimuon mass region show a much stronger suppression of the ϕ than for the J/ψ. These studies of vector meson production and it's nuclear dependence are critical in furthering our understanding of these processes towards future measurements at RHIC and new results from NA50 at CERN, where J/ψ suppression is predicted to be an important signature of the creation of quark-gluon plasma in heavy-ion collisions.

Vector Meson Production and Nuclear Effects in FNAL E866

M. J. LEITCH (for the E866/NUSEA Collaboration)
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- Preliminary Results for Vector-Meson Production from the E866/NuSea 800 GeV proton-Nucleus Experiment are Reported.

- E866 obtained $\sim 2.7M$ J/ψ and $\sim 36k$ ψ' for $-0.1 \leq x_F \leq 0.9$ and $0 \leq p_T \leq 4$ GeV/c on Be, Fe, and W targets.

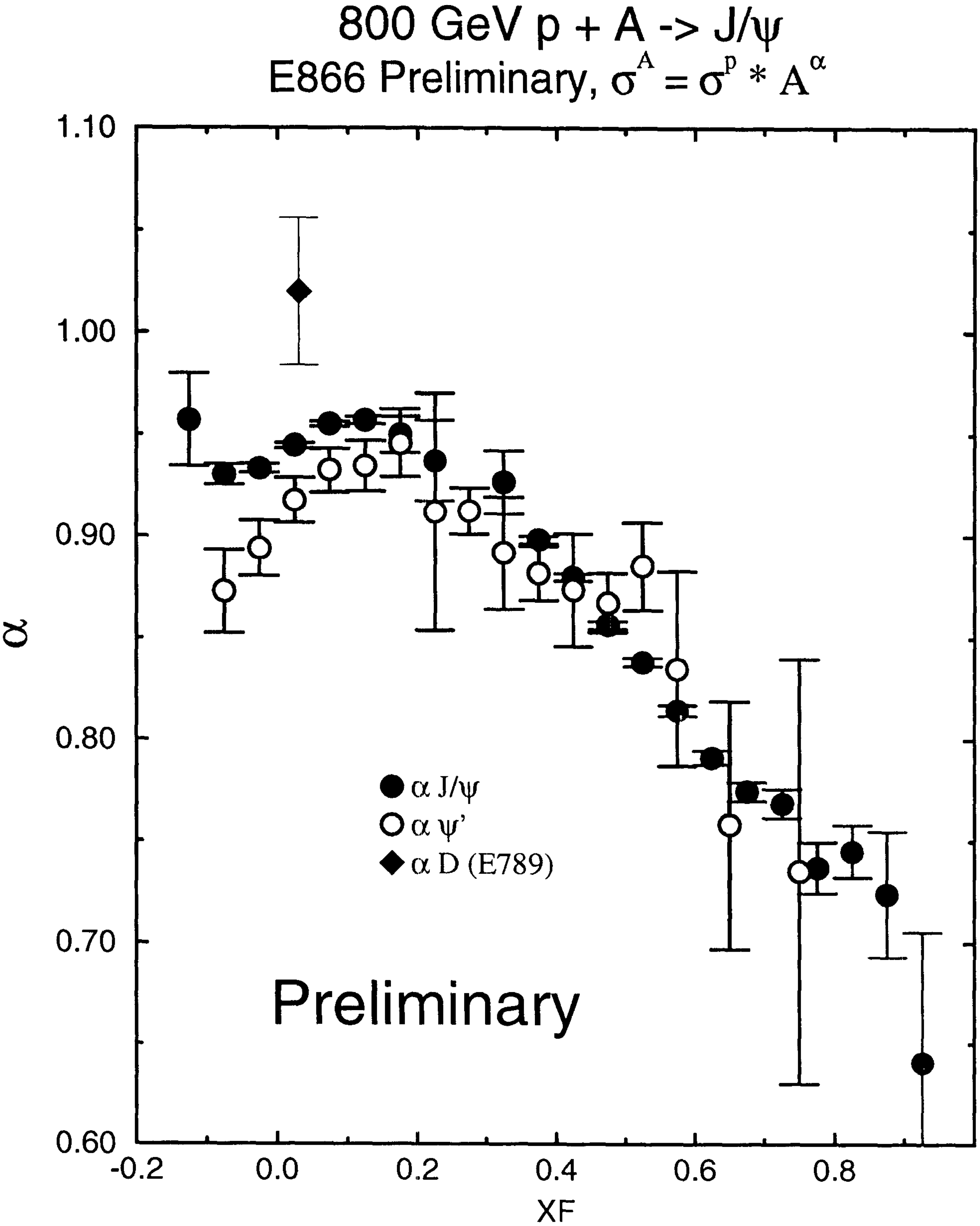
- Preliminary results show that the J/Ψ & ψ' have similar suppression for positive x_F, but the ψ' is more strongly suppressed at negative x_F. This results from formation time effects such that the J/Ψ & ψ' become physical states in the nucleus at negative x_F, while at positive x_F they are small $c\bar{c}$ objects.

- Absorption is the main source of suppression in the integrated cross section but other effects (energy loss & shadowing?) cause increasing suppression at larger x_F.

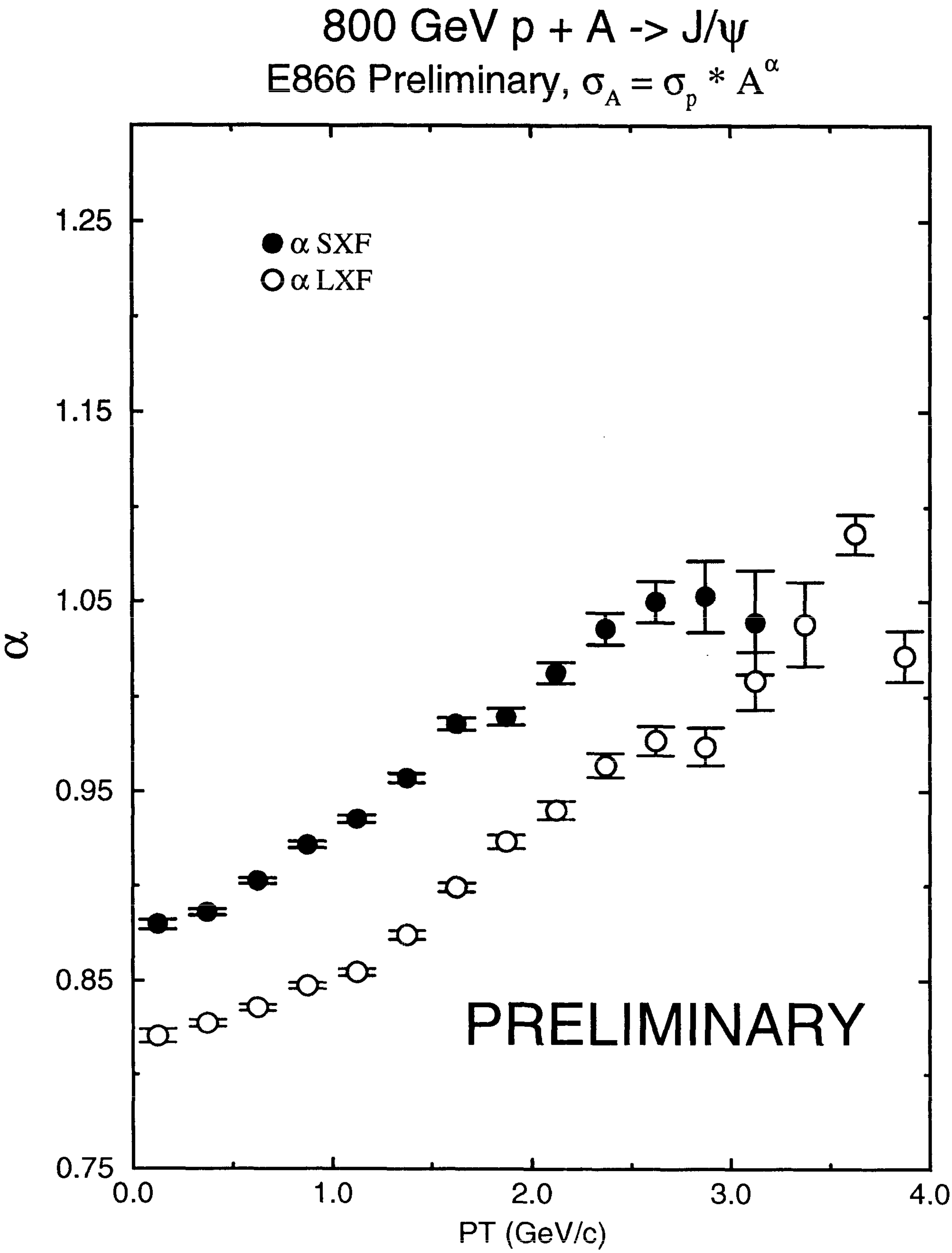
- E866 has preliminary angular distribution data with over 10M J/ψ's which show some transverse polarization.

- Early results from dimuon data in the 0.5 to 3 GeV mass region show much stronger nuclear suppression of the ϕ than for the J/ψ.

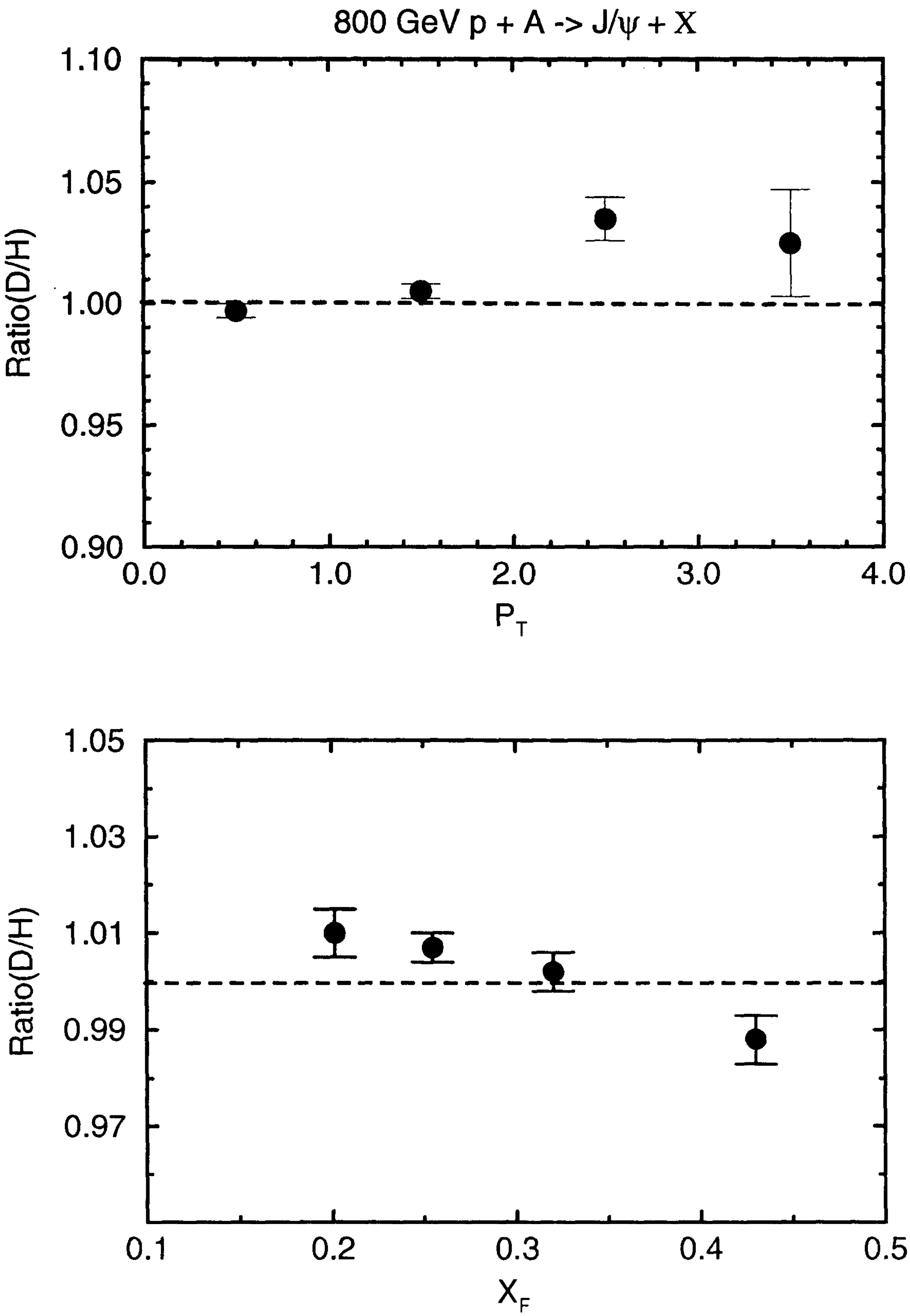
- It is critical to understand J/ψ and ψ' suppression in p-A in order to hope to use them for studying QGP in AA collisons.



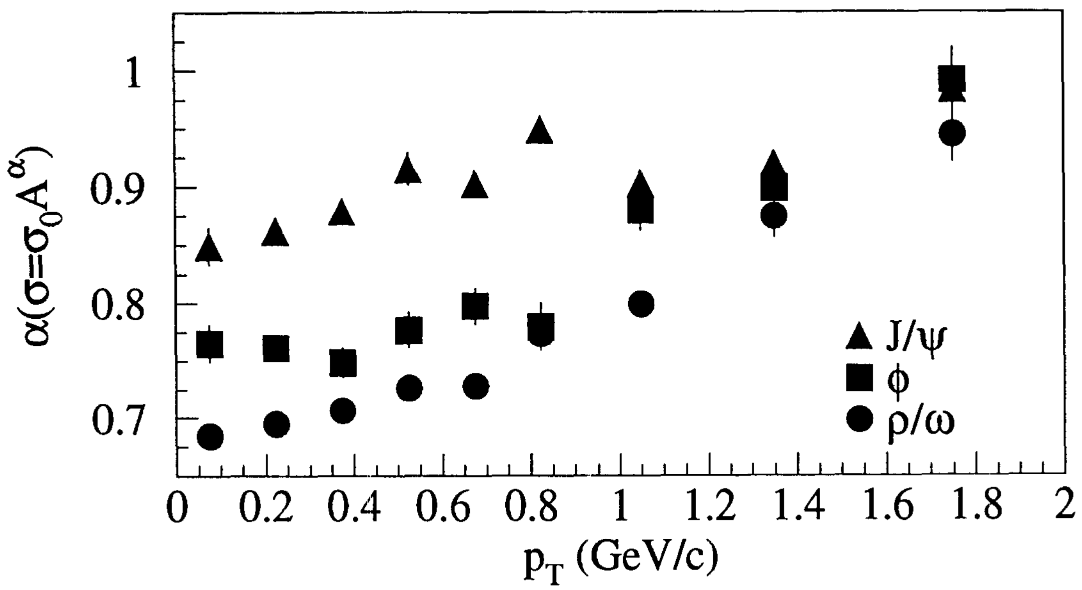
800 GeV p + A -> J/ψ
E866 Preliminary, σ^A = σ^p * A^α
1.10
1.00
0.90
0.80
0.70
0.60
-0.2
0.0
0.2
0.4
0.6
0.8
XF
α
● α J/ψ
○ α ψ'
◆ α D (E789)
Preliminary

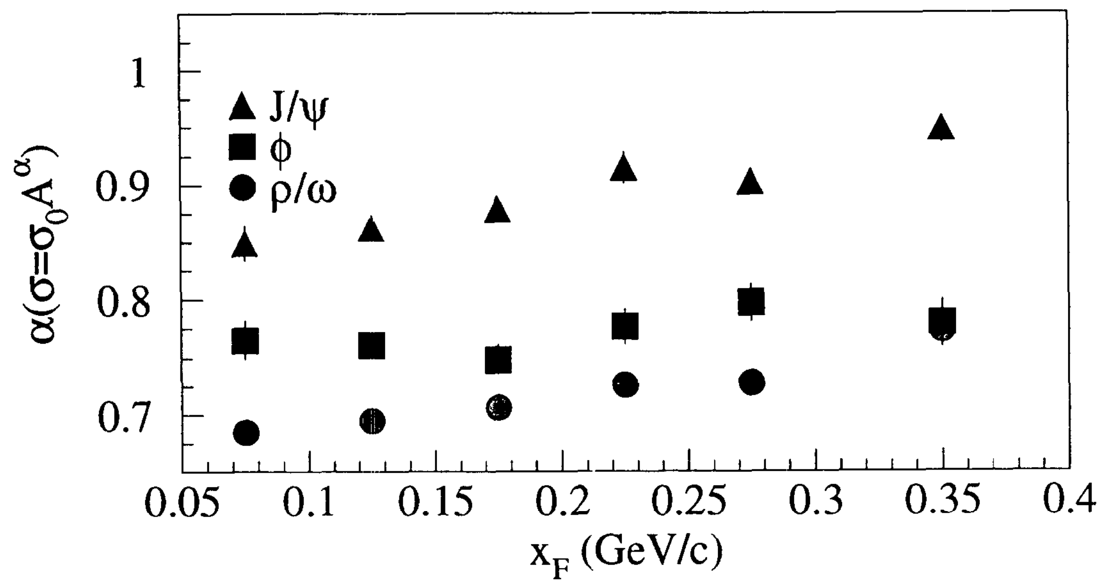

800 GeV p + A -> J/ψ
E866 Preliminary, σ_A = σ_p * A^α
α SXF
α LXF
PRELIMINARY
α
1.25
1.15
1.05
0.95
0.85
0.75
0.0
1.0
2.0
3.0
4.0
PT (GeV/c)

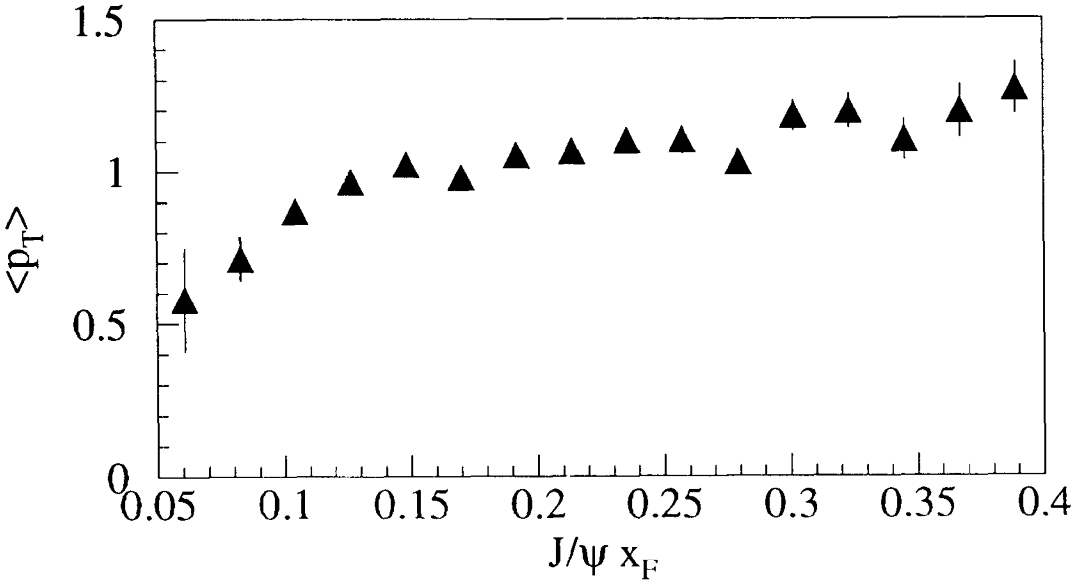
E866 PRELIMINARY



FNAL E866/NuSea - Preliminary







Quarkonium Formation Times from Data in $e^+ - e^-$ Annihilation Reactions

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This talk is based on work in progress, in collaboration with Dima Kharzeev. We show how to use dispersion relations to reconstruct, in a model-independent way, the formation dynamics of heavy quarkonium from the experimental data on $e^+e^- \rightarrow \bar{Q}Q$ annihilation.

The production of a pair of heavy quarks occurs at small distances ($\sim 1/m_Q$) and produces compact $\bar{Q}Q$ states which later transform into physical heavy hadrons. In this work we address the problem of formation time starting from the idea that all the essential information about the space-time picture of hard process is contained in the correlator of the hard scattering operator.

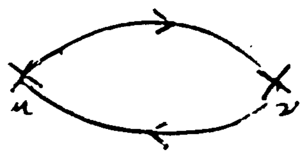
We calculate this correlator via a dispersion relation, which involves experimentally-determined quantities from the cross section for annihilation into quark-antiquark pairs. The expression becomes a sum over narrow resonance contributions, plus a term from the continuum cross section. The physical meaning of such an expression is transparent: it represents the correlator as a superposition of propagators of physical states, with weights proportional to the probability of their production in hard process. The formation time of the ground state can be defined now as the time at which the correlator approaches its asymptotic behavior $\Pi(\tau) \sim exp(-m\tau)$ for Euclidean time.

Operationally, we define the function $F_i(\tau) = \Pi_i(\tau)/\Pi(\tau)$ as the generalization of the $\Theta(\tau - \tau_o)$ shape which would be appropriate if an instantaneous formation were to occur at time τ_o. The distribution of formation times is then the derivative of this curve, $P_i(\tau) = dF_i(\tau)/d\tau$. One can extend this formalism to excited states by omitting all lower states in the dispersion integral. We have extracted numerical formation time distributions for all $\bar{Q}Q$ states in the charm and bottom sectors. They are compared with the simplistic $(M_2 - M_1)^{-1}$ values which result from uncertainty principle arguments. All distributions have support in the expected ranges, but the average values are now determined from all states in the dispersion integral and hence are not equal to the simplistic expectations. In addition, the widths of these distributions are typically comparable to the averages, so that a wide variation of formation time space is indicated.

As an example of the application of this formalism in phenomenology, we calculate expected suppression factors of quarkonium states by collisions with comovers produced in heavy ion collisions. We use comover formation time shapes from among those extracted above, with average values adjusted to those expected for the light hadrons. The resulting average suppression factors depend quite sensitively on these shapes, with one particular shape appearing to provide a quite steep decrease with increasing freezeout time. Several other applications are underway.

Talk presented at RIKEN-BNL Workshop on Quarkonium Production in Relativistic Nuclear Collisions, September 28, 1998.

$$\Pi_{\mu\nu}(x) = \langle 0 | T\{ J_\mu(x)\, J_\nu(0) \} | 0 \rangle$$



$J_\mu = \bar{c}\,\gamma_\mu\, c$ IS E.M. CURRENT OF $c\bar{c}$ PAIR

$$i \int d^4x\, e^{iqx}\, \Pi_{\mu\nu}(x) = \Pi(q^2)\,(q_\mu q_\nu - g_{\mu\nu} q^2)$$

$\Pi(q^2)$ SATISFIES A DISPERSION RELATION

WITH $\quad \operatorname{Im} \Pi(s) = \dfrac{s}{(4\pi\alpha)^2}\, \sigma(e^+e^- \to c\bar{c};\, s)$

WRITE THE DISPERSION RELATION FOR COORDINATE REP:

$$\Pi(x) \equiv \Pi_{\mu\mu}(x) = \frac{1}{4\pi^2} \int_0^\infty s\, R(s)\, D(\sqrt{s}, x^2)$$

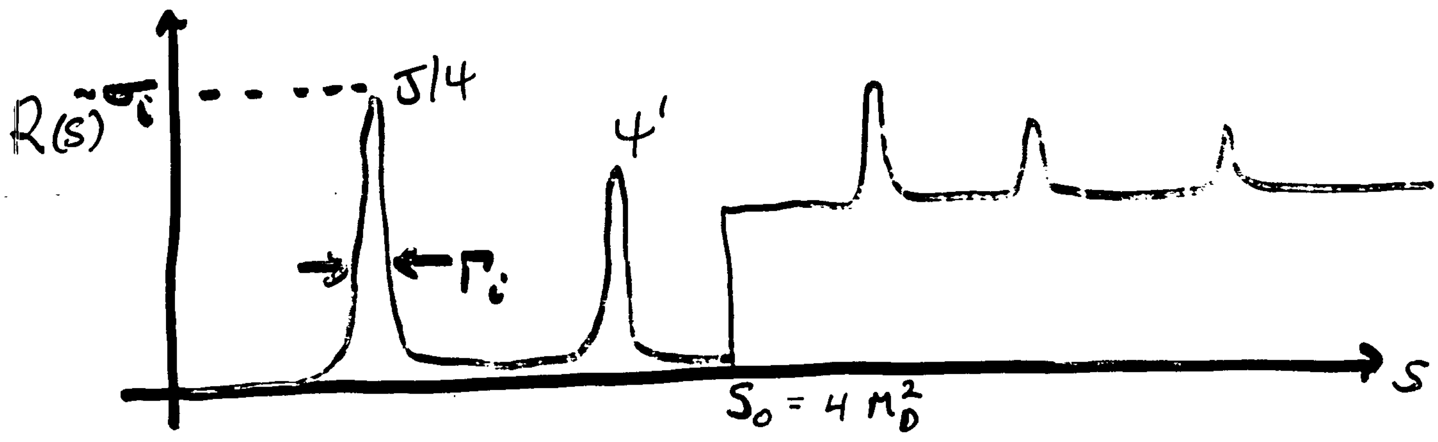
$$R(s) = \frac{\sigma(e^+e^- \to c\bar{c};\, s)}{\sigma(e^+e^- \to \mu^+\mu^-;\, s)}$$

$$D(\sqrt{s}, \tau^2 \equiv -x^2) = \frac{\sqrt{s}}{4\pi^2 \tau}\, K_1(\sqrt{s}\,\tau)$$

(EUCLIDEAN) TIME PROPAGATOR FOR $c\bar{c}$

REF: SHURAK, PHYS LETT B136 (84)

KHARZEEV, NUCL. PHYS A558 (93)



$$\Pi(T) = \sum_i \frac{\sigma_i \Gamma_i M_i^6}{4\pi T} K_1(M_i T)$$

$$+ \frac{S_0 \sigma_{cc}}{2\pi^2 T^6} \int_{\sqrt{S_0}\,T}^{\infty} x^4 \, dx \; K_1(x)$$

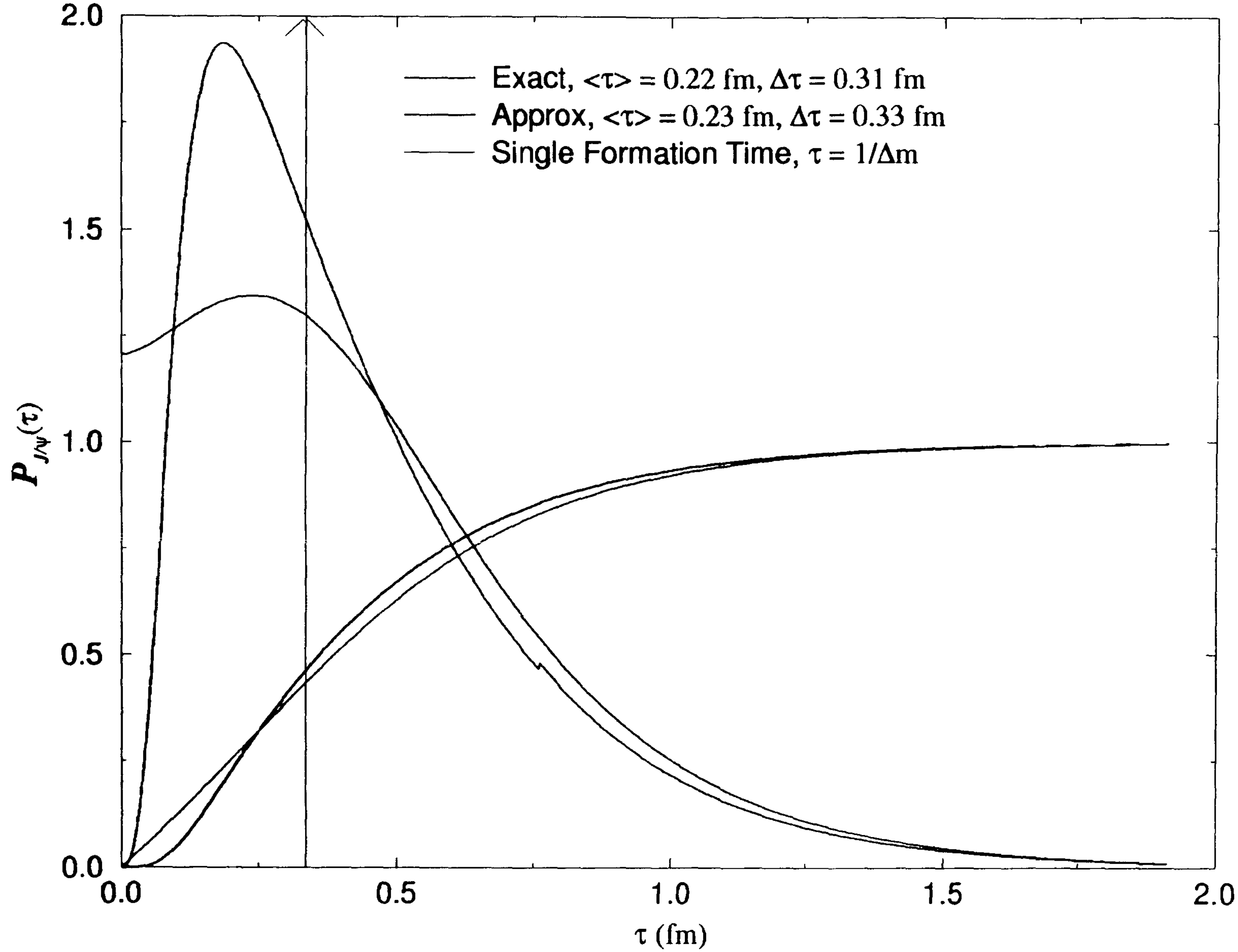
FULL CORRELATOR = SUM OF RESONANCE + CONTINUUM TERMS

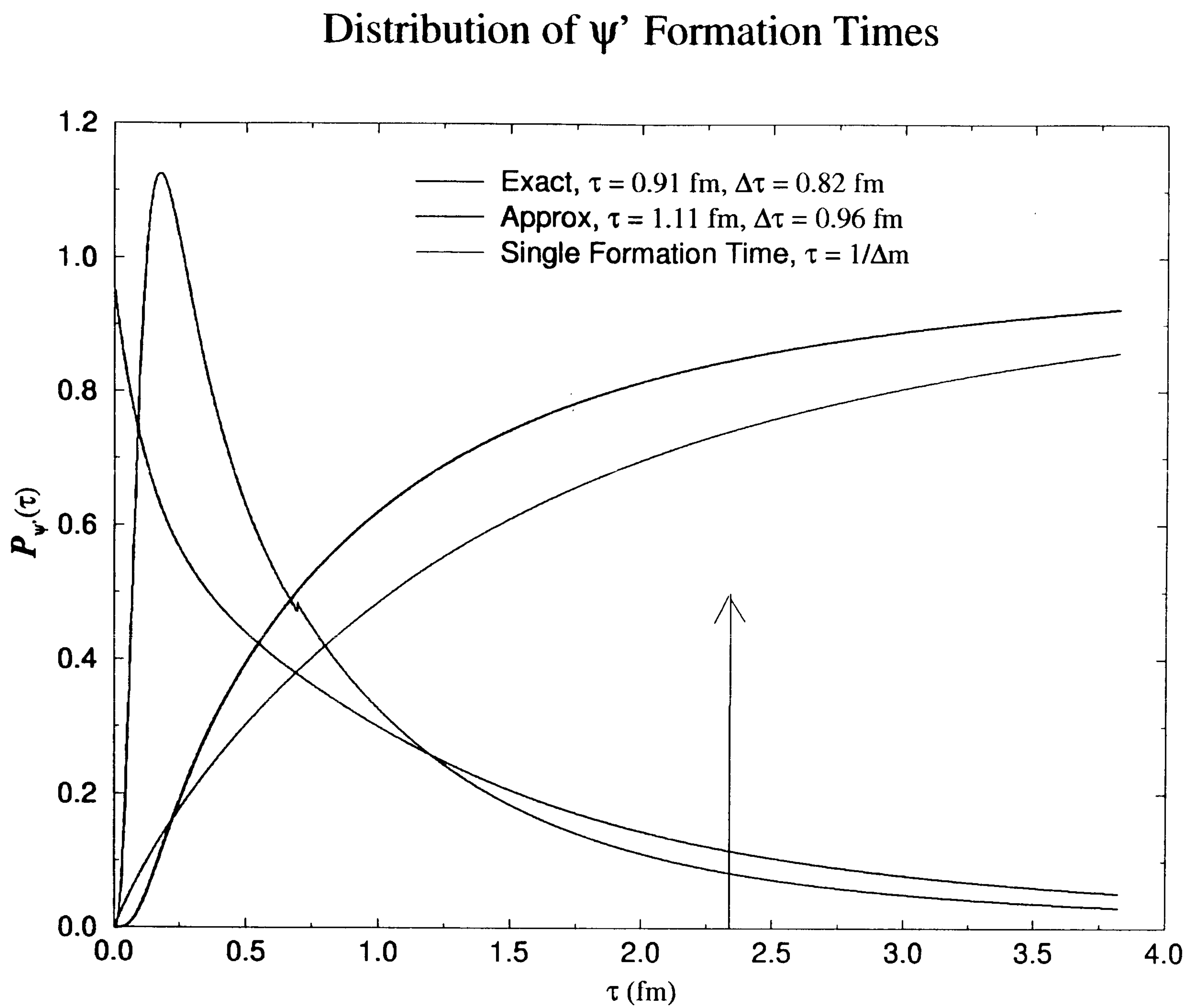
$$\xrightarrow[T \to \infty]{} e^{-M_1 T}$$

INTERPRETATION: FORMATION TIME OF GROUND STATE (M_1) DETERMINED BY TIME AT WHICH CORRELATOR $\Pi(T)$ REACHES ITS ASYMPTOTIC LIMIT

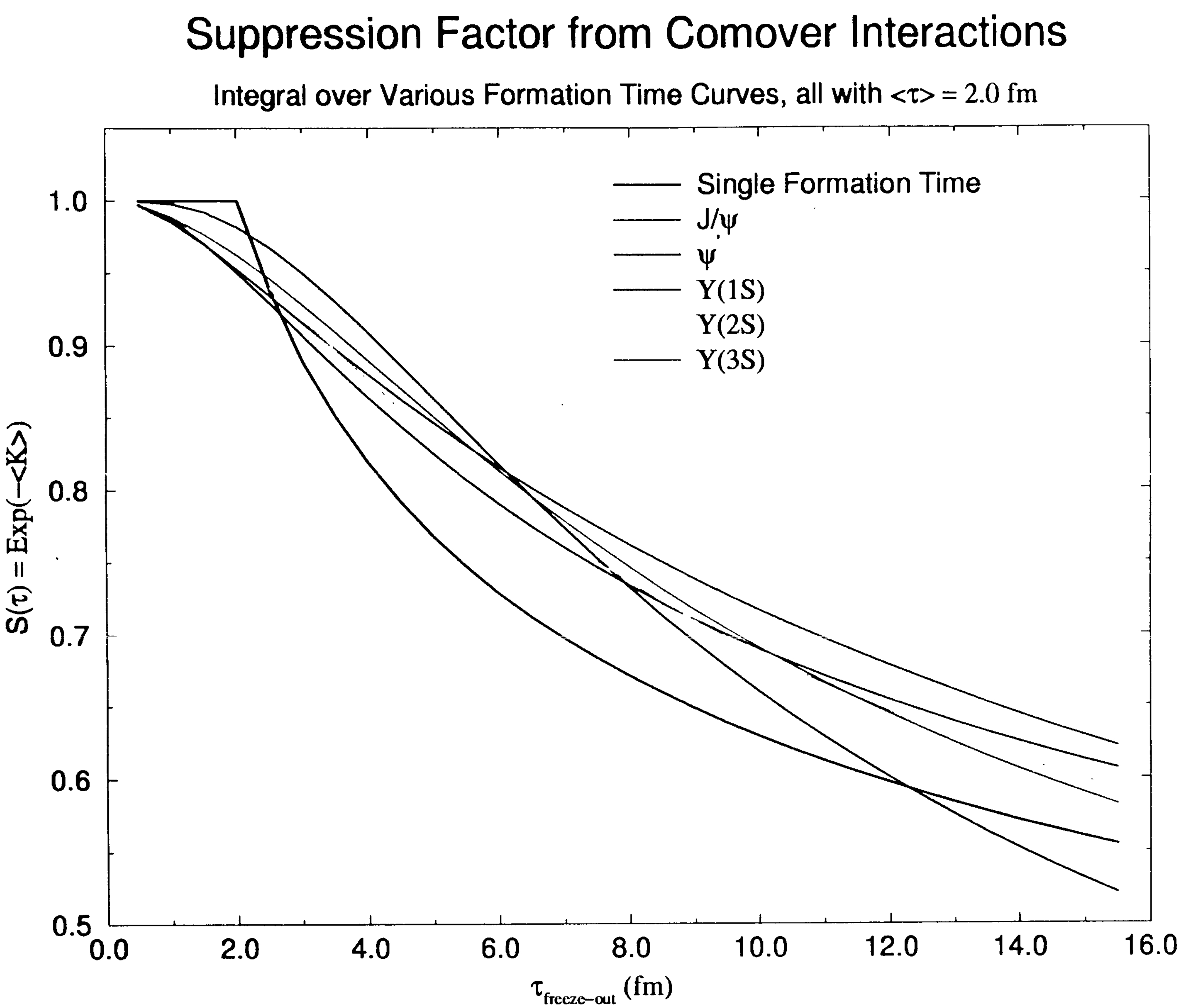
EXAMINE FRACTION $F_1(T) \equiv \dfrac{\Pi_1(T)}{\Pi(T)} \xrightarrow[T \to \infty]{} 1$

Distribution of J/ψ Formation Times

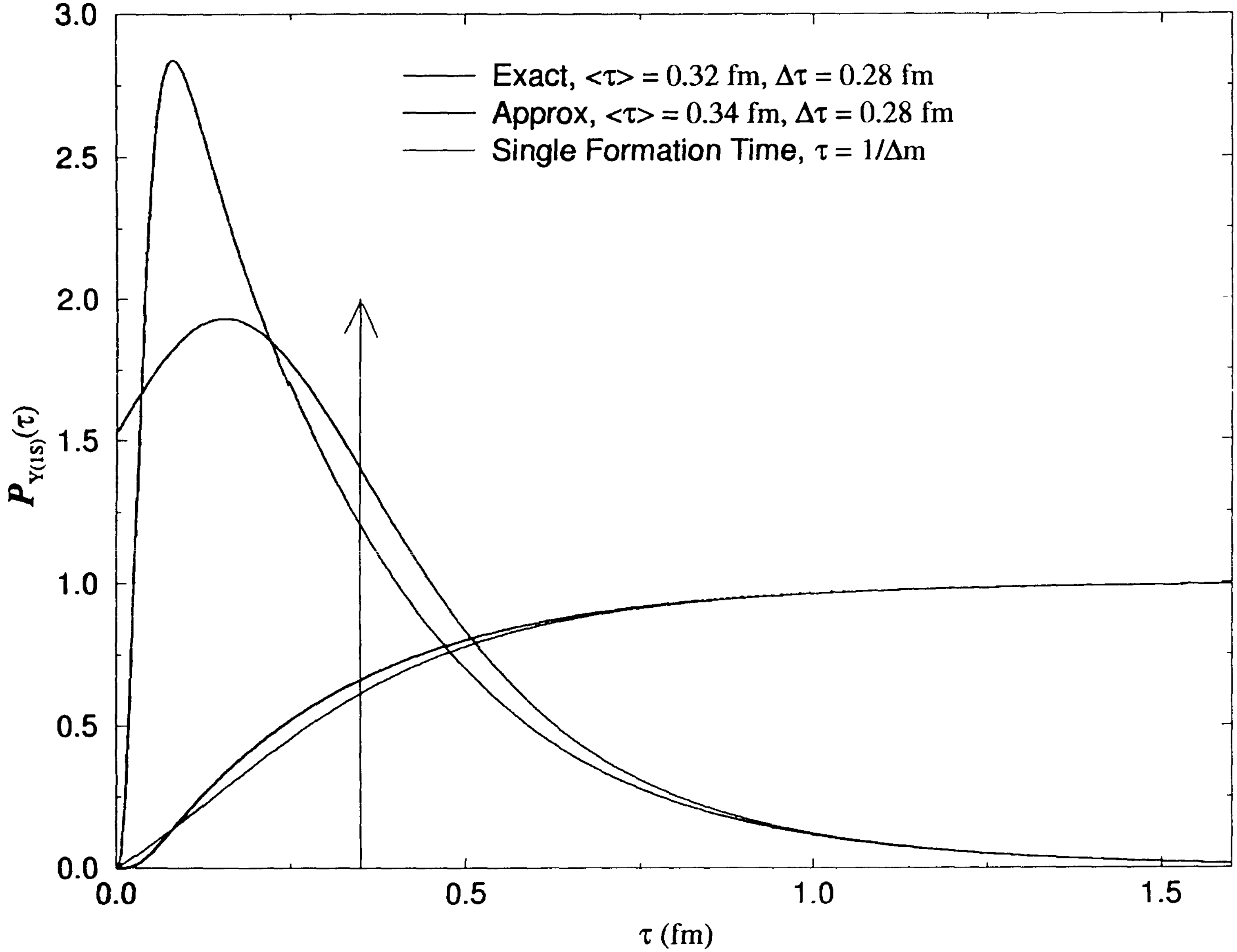




Distribution of ψ' Formation Times
Exact, τ = 0.91 fm, Δτ = 0.82 fm
Approx, τ = 1.11 fm, Δτ = 0.96 fm
Single Formation Time, τ = 1/Δm
P_ψ'(τ)
τ (fm)
0.0
0.2
0.4
0.6
0.8
1.0
1.2
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0


Suppression Factor from Comover Interactions
Integral over Various Formation Time Curves, all with <τ> = 2.0 fm
Single Formation Time
J/ψ
ψ
Υ(1S)
Υ(2S)
Υ(3S)
S(τ) = Exp(−<K>)
1.0
0.9
0.8
0.7
0.6
0.5
0.0
2.0
4.0
6.0
8.0
10.0
12.0
14.0
16.0
τ freeze−out (fm)

Distribution of Υ(1S) Formation Times



Coherence Time in High Energy Proton-Nucleus Collisions

Charles Gale[1], Sangyong Jeon[2], Joseph Kapusta[2*]

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Montreal, Quebec H3A 2T8, Canada

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University of Minnesota
Minneapolis, MN 55455

Precisely measured Drell-Yan cross sections for 800 GeV protons incident on a variety of nuclear targets exhibit a deviation from linear scaling in the atomic number A. We show that this deviation can be accounted for by energy degradation of the proton as it passes through the nucleus if account is taken of the time delay of particle production due to quantum coherence. We infer an average proper coherence time of 0.4 ± 0.1 fm/c, corresponding to a coherence path length of 8 ± 2 fm in the rest frame of the nucleus. We then apply this coherence time to the production of J/ψ in pA collisions. A significnt fraction of the J/ψ suppression in heavy targets appears to be caused by this finite coherence time and consequent energy loss of the beam proton. The J/ψ absorption cross section on nucleons needs to be redetermined, and implications for nucleus-nucleus collisions must be explored.

* Presenter

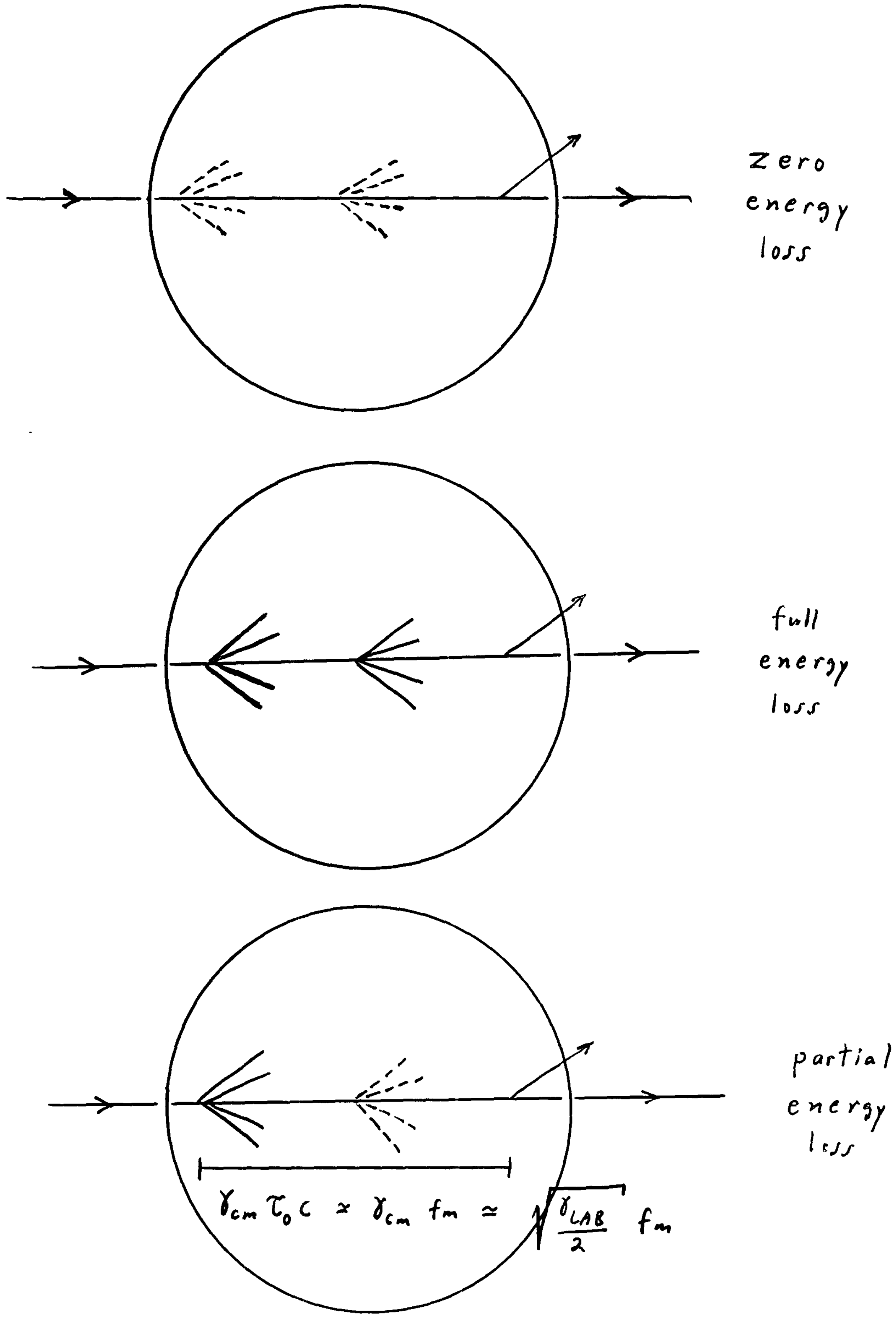
COHERENCE TIME IN HIGH ENERGY PROTON - NUCLEUS COLLISIONS

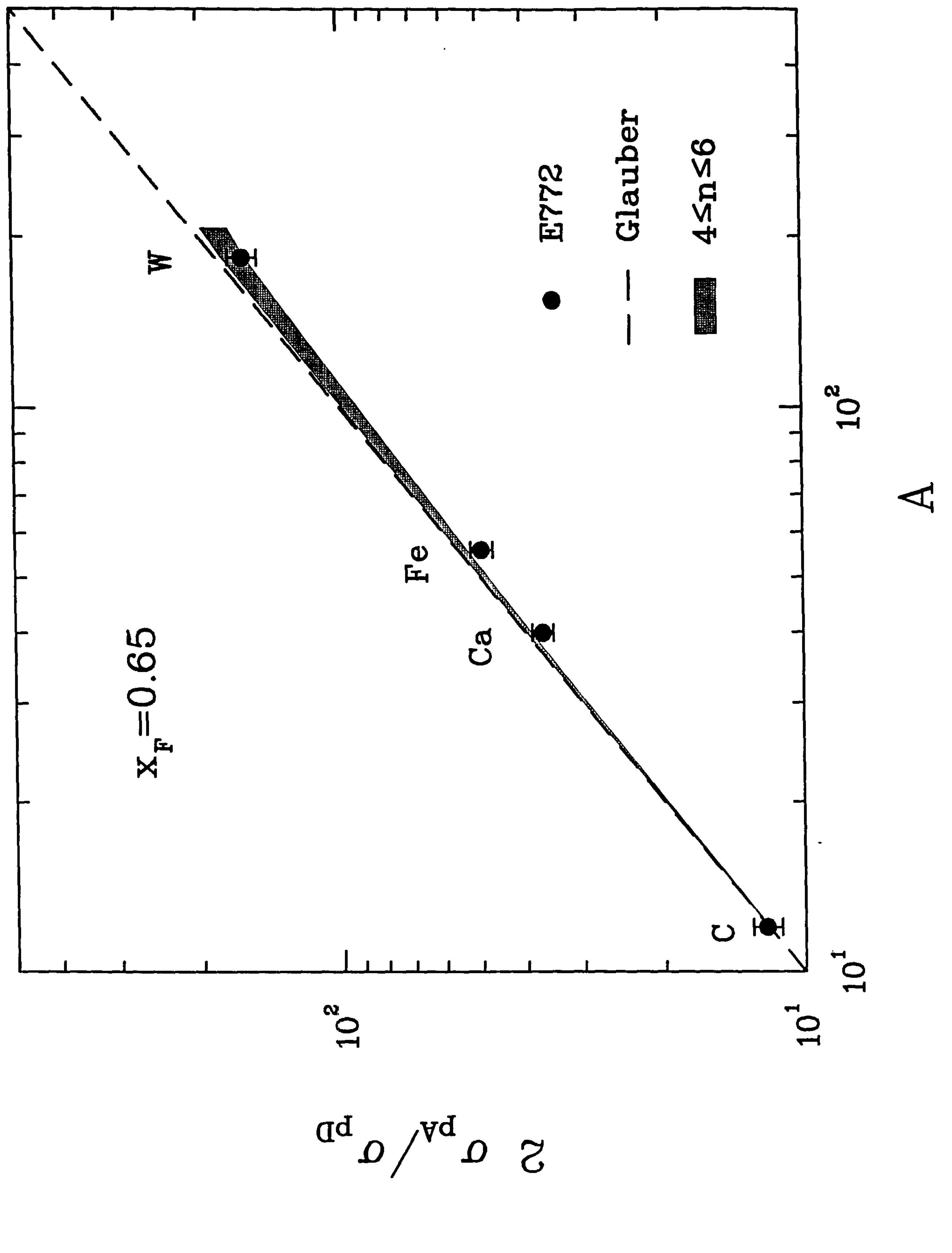
Charles Gale
Sangyong Jeon
Joseph Kapusta

Drell - Yan in pA

⇓

J/Ψ in pA


zero energy loss
full energy loss
partial energy loss
$\gamma_{cm}\tau_0 c \approx \gamma_{cm}$ fm $\approx \sqrt{\frac{\gamma_{LAB}}{2}}$ fm



x_F=0.65
W
Fe
Ca
C
E772
Glauber
4≤n≤6
A
2 σ_pA/σ_pD
10^1
10^2

DY pair is produced with the energy available to the proton after n previous collisions.

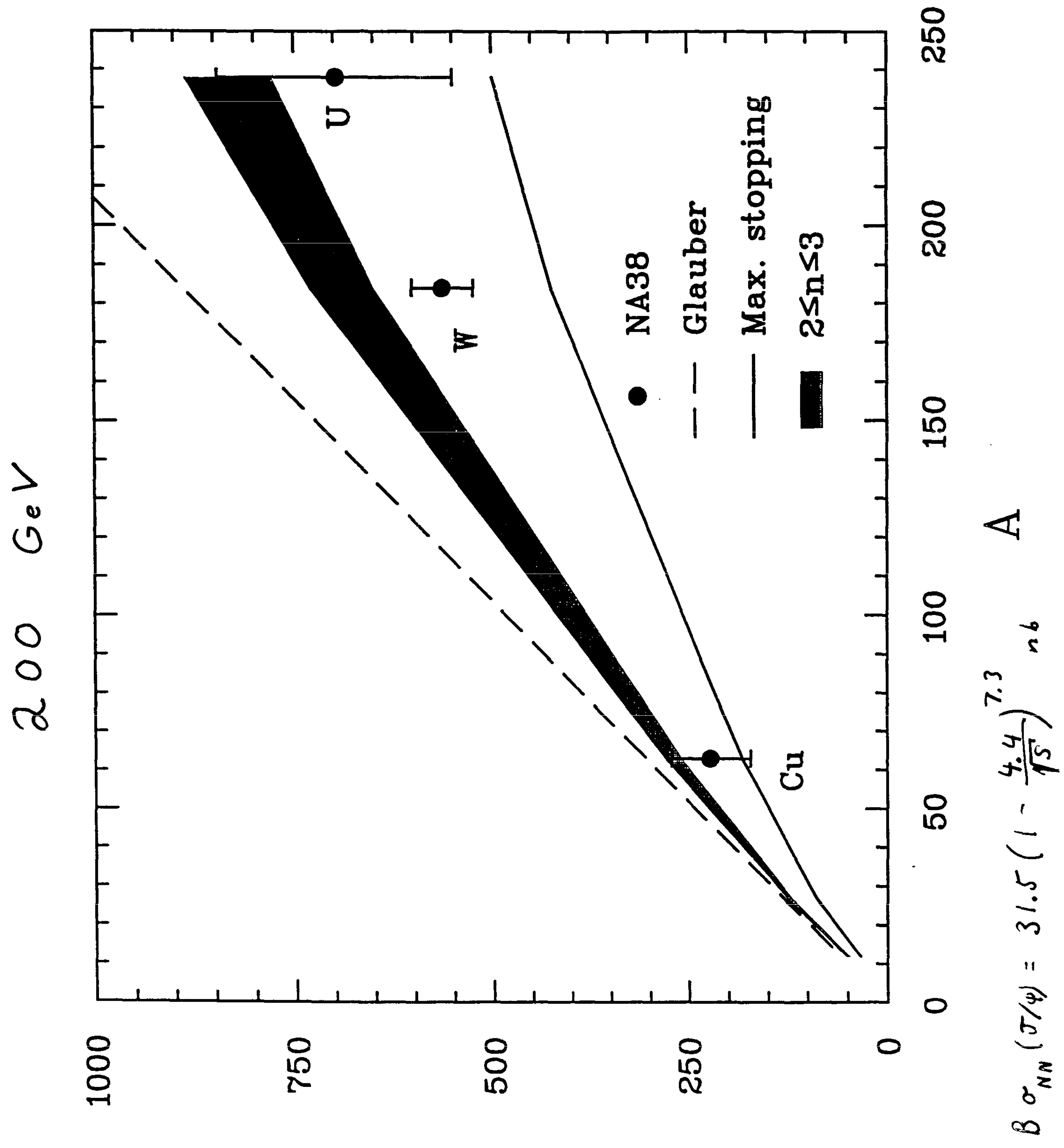
$$n = 5 \pm 1 \qquad \text{at} \qquad 800 \text{ GeV}$$

$$\gamma_{cm}\, c\tau_0 \simeq \sqrt{\frac{\gamma_{lab}}{2}}\, c\tau_0 = n\ell = \frac{n}{\sigma_{tot}^{NN}\rho}$$

$$\sigma_{tot}^{NN} = 40 \text{ mb} \qquad \rho = 0.155 \text{ nucleons/fm}^3$$

$$n\ell = 8 \pm 2 \text{ fm} \quad \text{in target frame at } 800 \text{ GeV}$$

$$\tau_0 = 0.4 \pm 0.1 \text{ fm/c}$$



200 GeV
NA38
Glauber
Max. stopping
2≤n≤3
U
W
Cu
A
0
50
100
150
200
250
1000
750
500
250
0
Bσ^J/ψ (nb)
B σ_NN (J/ψ) = 31.5 (1 − 4.4/√s)^7.3 nb

A New Mechanism for Quarkonium Production*

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The production cross section of a quarkonium state may be viewed as a small fraction of the total heavy quark production rate, where the heavy quarks Q and $\bar{Q}$ are constrained to have a small relative $p_\perp$ (compared to the heavy quark mass m) and to be in a state of given angular momentum. The cross section is thus very sensitive to possible rescatterings between the $Q\bar{Q}$ pair and its colored environment. Some surrounding color field is indeed present in hadroproduction due to DGLAP evolution of the incoming partons, and the strength of this field is suggested by the surprisingly large intrinsic transverse momenta which are needed to reproduce $k_\perp$-distributions or azimuthal correlations in open charm hadroproduction. We thus study the possibility that the 'anomalies' of quarkonium production could be due to a perturbative rescattering between the $Q\bar{Q}$ pair and a comoving color field Γ. We consider S- and P-wave total production cross sections (*ie.*, small x_F and $p_\perp \lesssim m$) in hadron-hadron collisions [1].

The data on quarkonium production displays interesting properties:

(i) In hadroproduction, the ratio $\sigma(\psi')/\sigma_{dir}(J/\psi) \simeq 0.24$ is 'universal' (it is nearly independent of the c.m. energy E_{CM}, x_F, and also of the nature of the beam and target) and compatible with the expectation based on the values of the wave functions at the origin $R(0)$. This seems to indicate that the $Q\bar{Q}$ pair decouples from the environment (*ie.*, turns color singlet) when it is still compact compared to the size of the bound state.

(ii) Quarkonium production (at small x_F) is consistent with a leading-twist mechanism, since all anomalies subsist when E_{CM}, $p_\perp$ or m are increased.

(iii) The Color Singlet Mechanism grossly underestimates the J/ψ rate in hadroproduction, but gives the right normalization (via $R(0)$) in photoproduction. This suggests that something specific occurs with initial parton radiation.

We assume the color field Γ to originate from the radiation fields of the incoming partons. Thus the production mechanism is leading-twist by construction. Since in the radiative evolution process, the gluon virtualities are logarithmically distributed between the factorization scale μ_F and the mass m, we stress the importance of the semi-hard (and perturbative) scale μ, $\mu_F \ll \mu \ll m$, and study the effects of a rescattering between $Q\bar{Q}$ and Γ at this scale μ. The separation between the Q and $\bar{Q}$ at the time of the rescattering must be of order $1/\mu$, larger than the separation $1/m$ at the $Q\bar{Q}$ production time, but still smaller than the size of the bound state. This guarantees $\sigma \propto |R(0)|^2$ for S-wave production. In hadroproduction at high energy, the $Q\bar{Q}$ is dominantly produced by the fusion of two gluons, which carry their respective radiation fields. When these fields cross each other they produce field components at low rapidity in the $Q\bar{Q}$ rest frame, which are 'comoving' with the $Q\bar{Q}$ [2]. It is precisely these field components which we model by the classical color field Γ, isotropically distributed in the $Q\bar{Q}$ rest frame. As photons do not radiate gluons (resolved photon processes are unimportant here), Γ is absent in photoproduction. The proposed mechanism occurs only in hadroproduction.

This picture, combined with the assumption of a *semi-hard* rescattering, leads to very interesting results:

(i) It is possible to understand why in fixed target experiments, the ψ' and (directly produced) J/ψ yields are unpolarized.

(ii) The χ_{c1} and χ_{c2} states are produced at similar rates.

(iii) The anomalous A-dependence of production rates in pA collisions is qualitatively understood.

We encounter one difficulty for the χ_{c2} to J/ψ ratio, which depends on the expansion factor ρ of the $Q\bar{Q}$ pair. The data requires a quite large value $\rho \simeq 3$. The approximation of the bound state wave functions by their values at the origin becomes questionable here.

ACKNOWLEDGMENTS

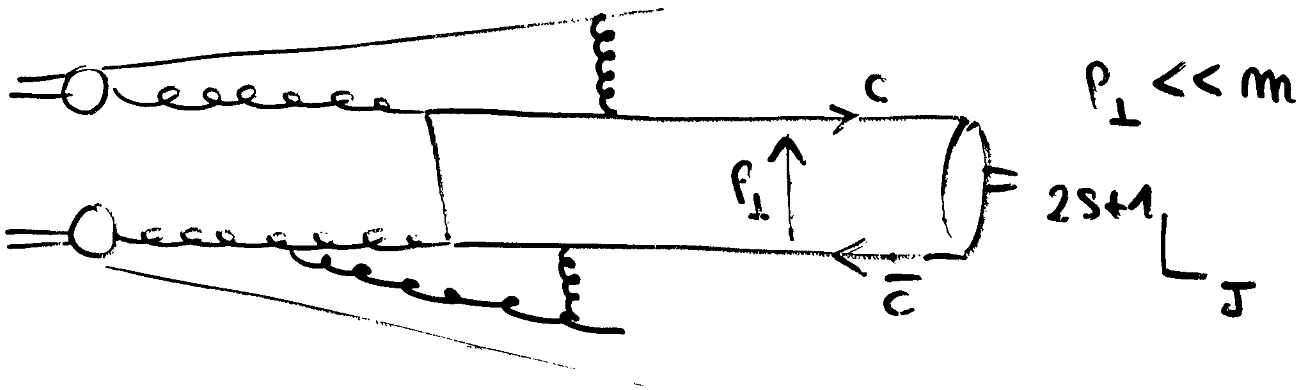
I would like to thank Paul Hoyer, with whom this work has been done.

* Work supported in part by the EU/TMR contract EBR FMRX-CT96-0008.

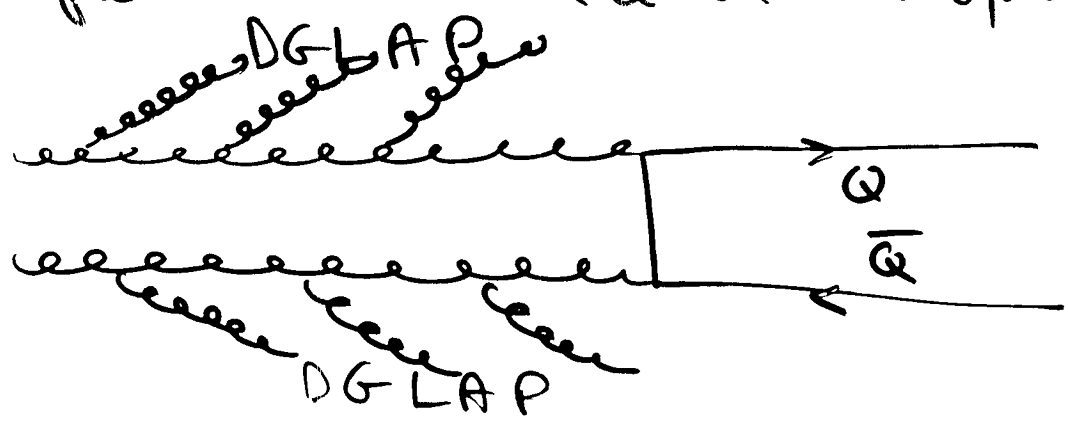
[1] P. Hoyer and S. Peigné, hep-ph/9806424.
[2] P. Hoyer, hep-ph/9809362.

- charmonium

σ = small fraction of σ_{tot} (charm)



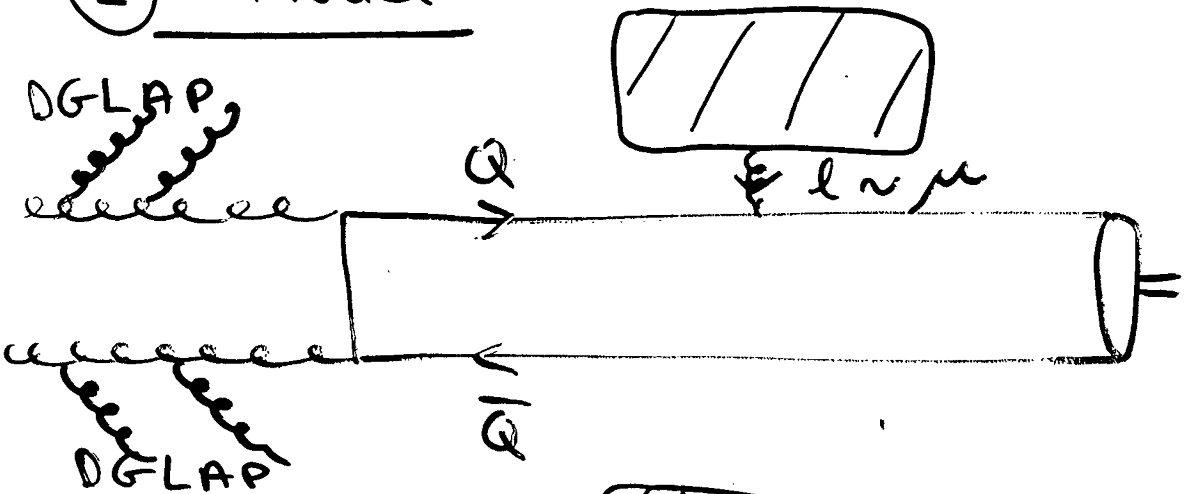
Here rescatterings between $c\bar{c}$ and color field may drastically change σ
(no fact. theorem expected)
Color field around $Q\bar{Q}$ in hadroproduction:

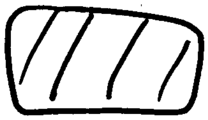


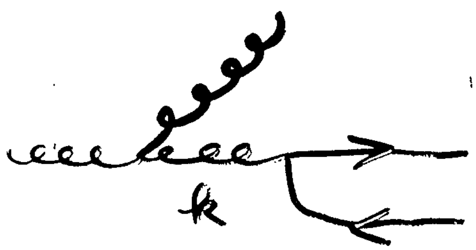
Importance of this field suggested by azimuthal correlations in $\pi^- N \to D\bar{D} + X$
(WA75, WA92)

$\rightarrow$ $\langle k_T^2 \rangle_{intrinsic}$ large $\sim$ 1 GeV^2

② Model



basic assumption :  originates from radiation fields



$$\Longrightarrow \int_{\mu_F^2}^{m^2} \alpha_s(k^2)\,\frac{dk^2}{k^2}$$

$\Rightarrow |k^2|_{eff} \sim \mu^2 \; ; \quad \mu_F \ll \mu \ll m$

$\Rightarrow$ Study the effects of a rescattering at the **semi-hard** scale μ.

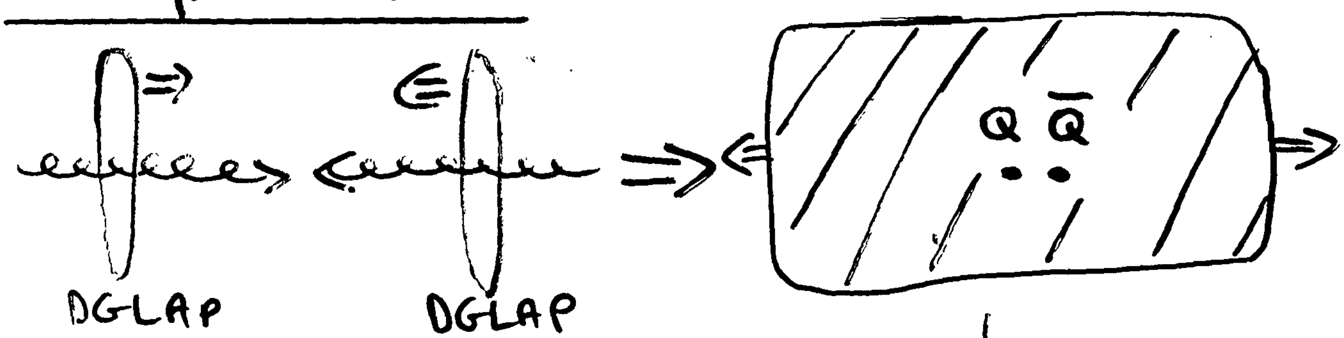
Remark : $\mu \sim$ DGLAP hardness scale

$\Rightarrow$ assume validity of PQCD at this scale

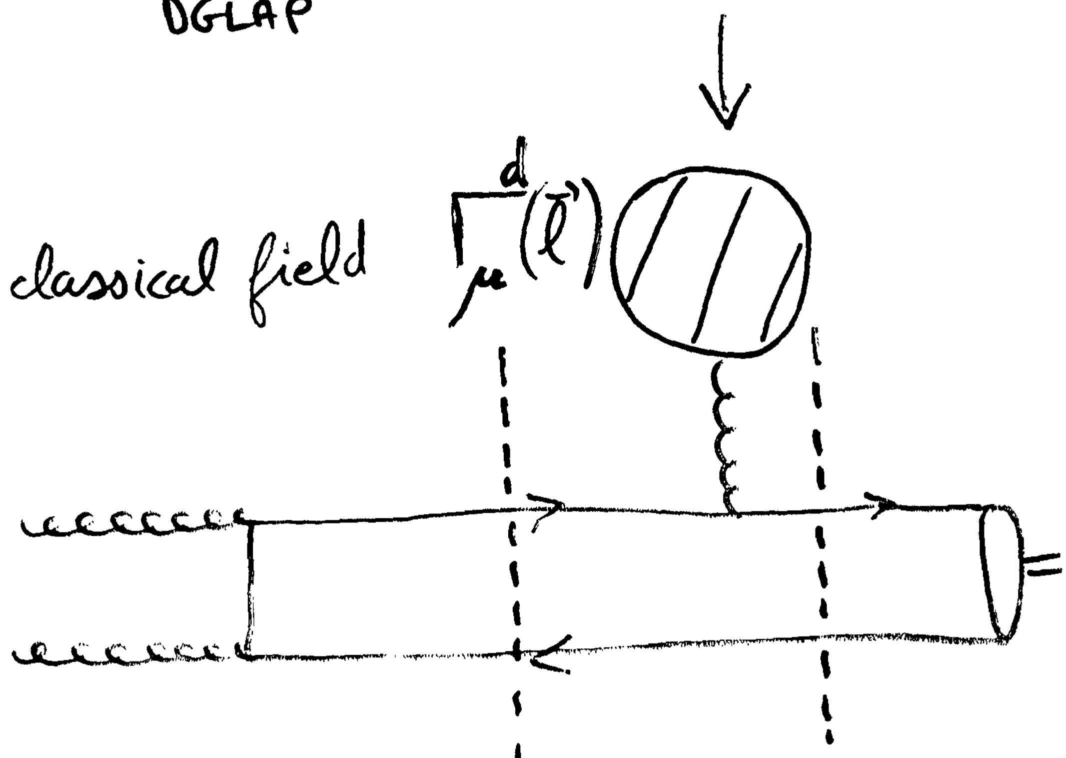
- Picture in photo/hadroproduction

(P. Hoyer, hep-ph/9809362)

Hadroproduction

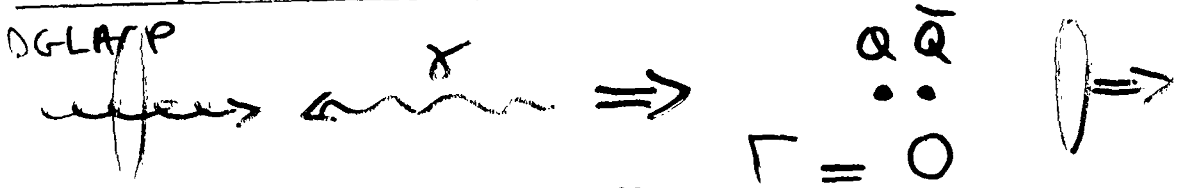


(isotropic) classical field



$$= \sum_{L_z S_z} \langle L L_z ; S S_z | J J_z \rangle \sum_{\lambda\bar\lambda,\sigma\bar\sigma} \int \frac{d^3\vec{p}}{(2\pi)^3} \int \frac{d^3\vec{q}}{(2\pi)^3} \, \Phi^{[8]}_{\lambda\bar\lambda}(\vec{p}) \; \mathcal{R}_{\lambda\bar\lambda,\sigma\bar\sigma}(\vec{p},\vec{q}) \; \Psi^{L_z S_z}_{\sigma\bar\sigma}(\vec{q})^{*}$$

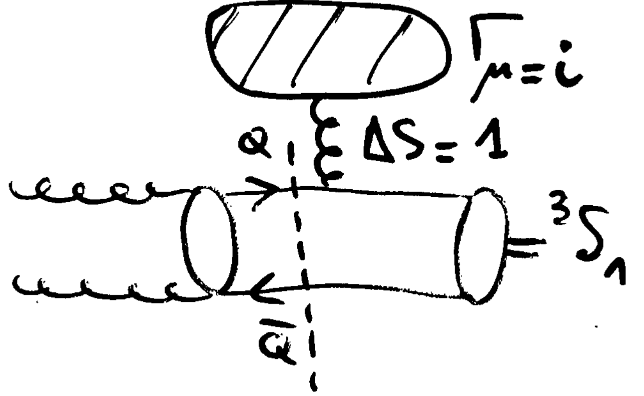
Photoproduction

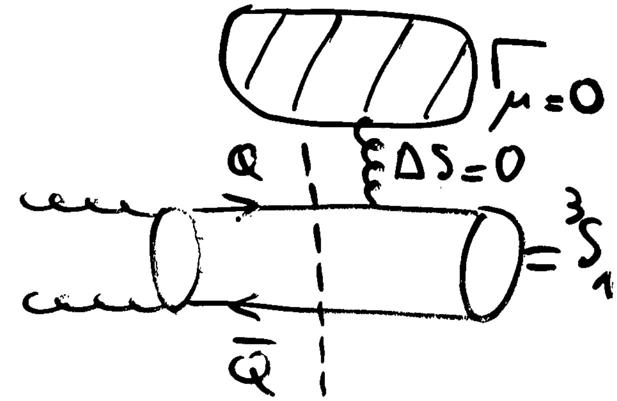


$\Gamma = 0$

Results

1) S-wave production : 2 contributions





$S=L=0$ $\qquad$ $S=L=1$

<u>unpolarized</u> (Γ isotropic) $\qquad$ transversely polarized

to agree with fixed target experiments $\Rightarrow$
we assume Γ contains mostly <u>transverse</u> gluons

another indication for '<u>transverse</u>' :

compare $\dfrac{\sigma(\psi')}{\sigma_{dir}(J/\psi)}$ in photo- and hadroproduction

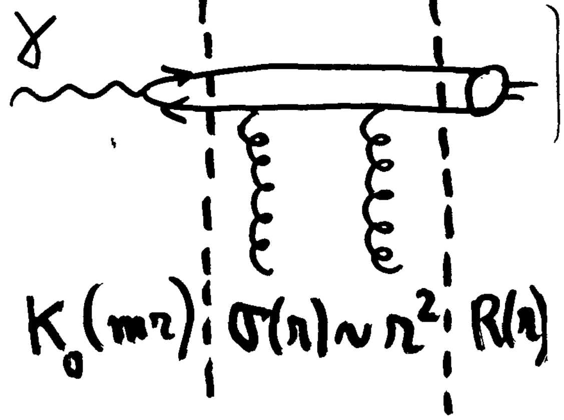
$$\left.\frac{\sigma(\psi')}{\sigma_{dir}(J/\psi)}\right|_{photo} \simeq 0.15$$ (P. Thompson, H1 talk 'DIS'98')

not compatible with $\left|\dfrac{R_{\psi'}(0)}{R_{\psi}(0)}\right|^2$ but

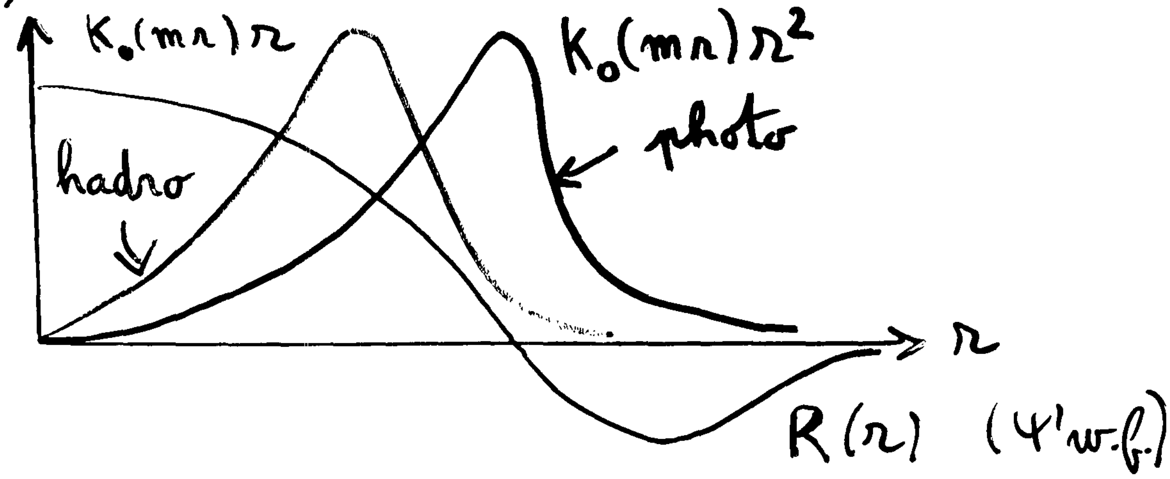
consistent with the value 0.17 calculated by Kopeliovich & Zakharov PRD44(91)3466
Kopeliovich et al PLB309(93)179

Precise form of wave functions is important

$0.17 = \left|\frac{\mathcal{M}_{\psi'}}{\mathcal{M}_{\psi}}\right|^2$ where $\mathcal{M}_{\psi,\psi'} =$



For ψ', overlap =



overlap reduced compared to J/ψ because of the node

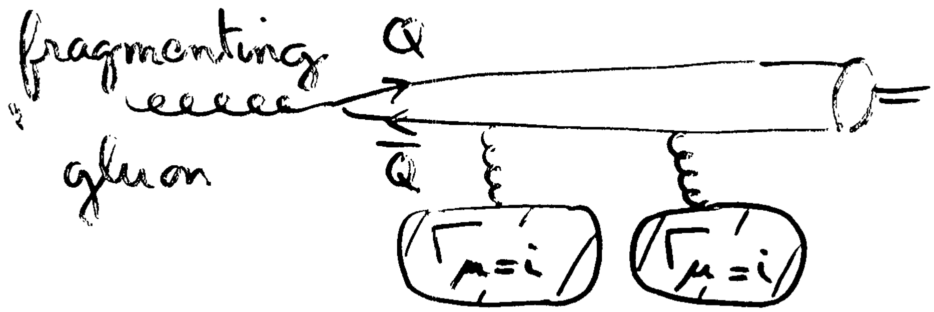
In hadroproduction, if transverse gluon exchange: $\sigma(r) \sim r^2 \rightarrow \sigma(r) \sim r$

$\Rightarrow \psi'/\psi$ is enhanced

data: $\left.\frac{\psi'}{\psi}\right|_{hadro} \simeq 0.24$ more compatible with $\left|\frac{R_{\psi'}(0)}{R_{\psi}(0)}\right|^2$

Summary

- Simple Model based on semi-hard / perturbative rescattering compatible with data at low P_T.
- Using freedom on comoving color field Γ:
  - unpolarized J/ψ, ψ'
  - χ_1 / χ_2
- A-dependence in pA qualitatively understood
- Model applied for high P_T ?



- Model theoretically consistent with COM (we kept only leading order in v) but phenomenologically different: quantitatively important effects = hard rescattering rather than relativistic corrections.

Precursor Phenomena in Particle Production by Relativistic Heavy Ion Collisions

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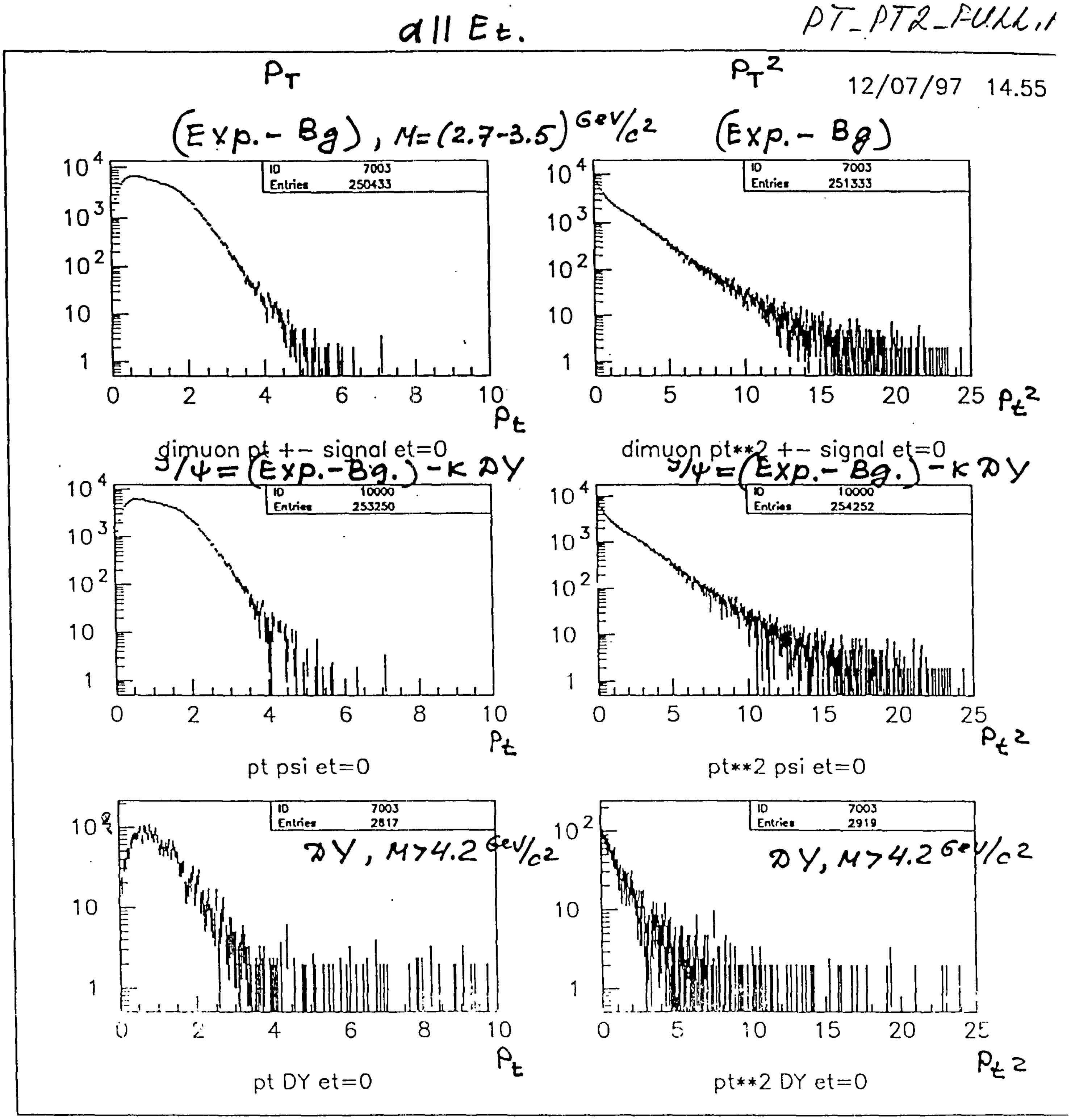
In order to extend a search of Quark Gluon Plasma or precursor phenomena in relativistic heavy ion collisions, it is proposed to transform the experimental momentum distributions of produced particles to dependence on generalized Bjorken parameters of the partons in the projectile and target nuclei.

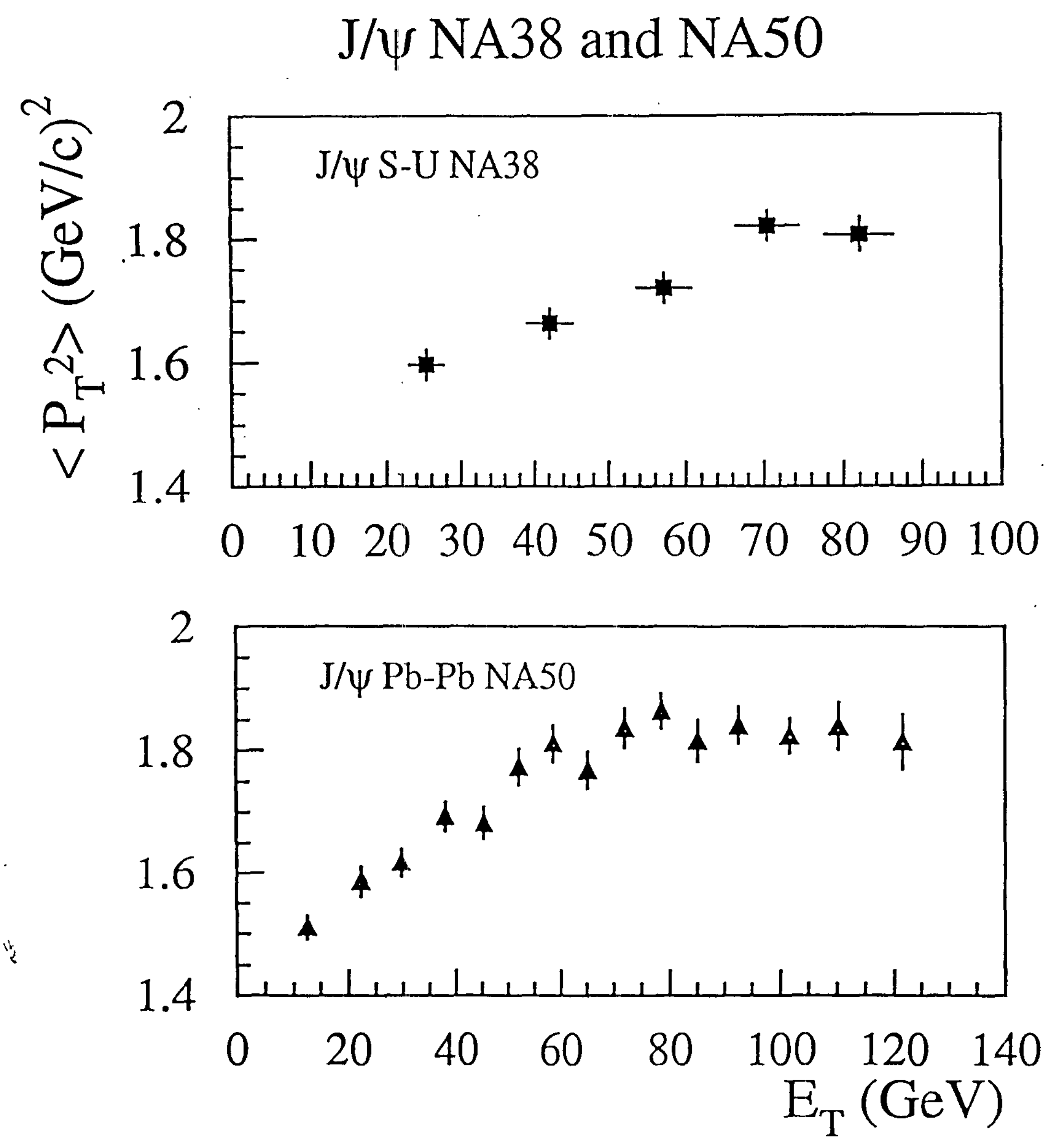
The method was tested for experimental data on pion, kaon and antiproton production at low energy of several GeV/nucleon of colliding nuclei. The observed scaling dependence with heavy partons in projectile and target nuclei could be interpreted as precursor to QGP phenomena due to deconfinement in small space part of the nucleus.

Preliminary analysis of charmonium production in proton-nuclei collisions was made. No indications on the collective parton effects could be seen from existing experimental data. The analysis of nucleus-nucleus collision experiments will be performed.

Simple expressions for parton scaling parameters for colliding beam experiments like PHENIX are presented.



all Et.
PT_PT2_FULL.1
P_T
P_T^2
12/07/97 14.55
(Exp. - Bg), M=(2.7-3.5) GeV/c²
(Exp. - Bg)
ID 7003
Entries 250433
ID 7003
Entries 251333
P_t
P_t^2
dimuon pt +- signal et=0
dimuon pt**2 +- signal et=0
J/ψ = (Exp.-Bg.) - k DY
J/ψ = (Exp.-Bg.) - k DY
ID 10000
Entries 253250
ID 10000
Entries 254252
pt psi et=0
pt**2 psi et=0
ID 7003
Entries 2817
ID 7003
Entries 2919
DY, M>4.2 GeV/c²
DY, M>4.2 GeV/c²
pt DY et=0
pt**2 DY et=0



NA38 E_T: $1.7 \leq \eta_{lab} \leq 4.1$

NA50 E_T: $1.1 \leq \eta_{lab} \leq 2.3$

$$N_1 + N_2 \rightarrow (\pi^{\pm}, K^{\pm}) + X$$

Lowest mass reactions, i.e. highest meson momenta due to exponential $\sigma(z)$ dependence:

$$zN_1 + xN_2 \rightarrow zN_1 + xN_2 + \pi^{\pm}$$

$$zN_1 + xN_2 \rightarrow zN_1 + x\Lambda_2 + K^{+}$$

$$zN_1 + xN_2 \rightarrow zN_1 + xN_2 + K^{+} + K^{-}$$

4 - momentum conservation:

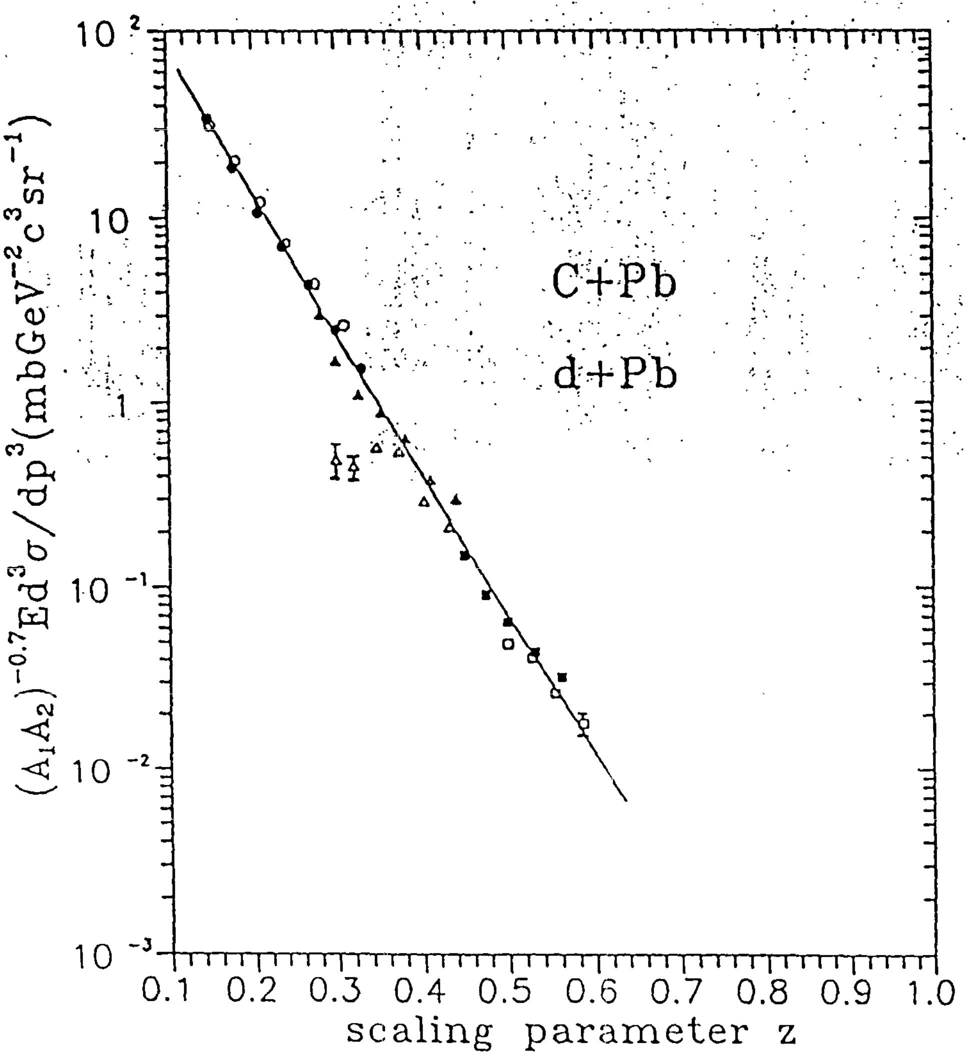
$$(zP_1 + xP_2 - P)^2 = (zP_1' + xP_2' + P_i)^2 \qquad (1)$$

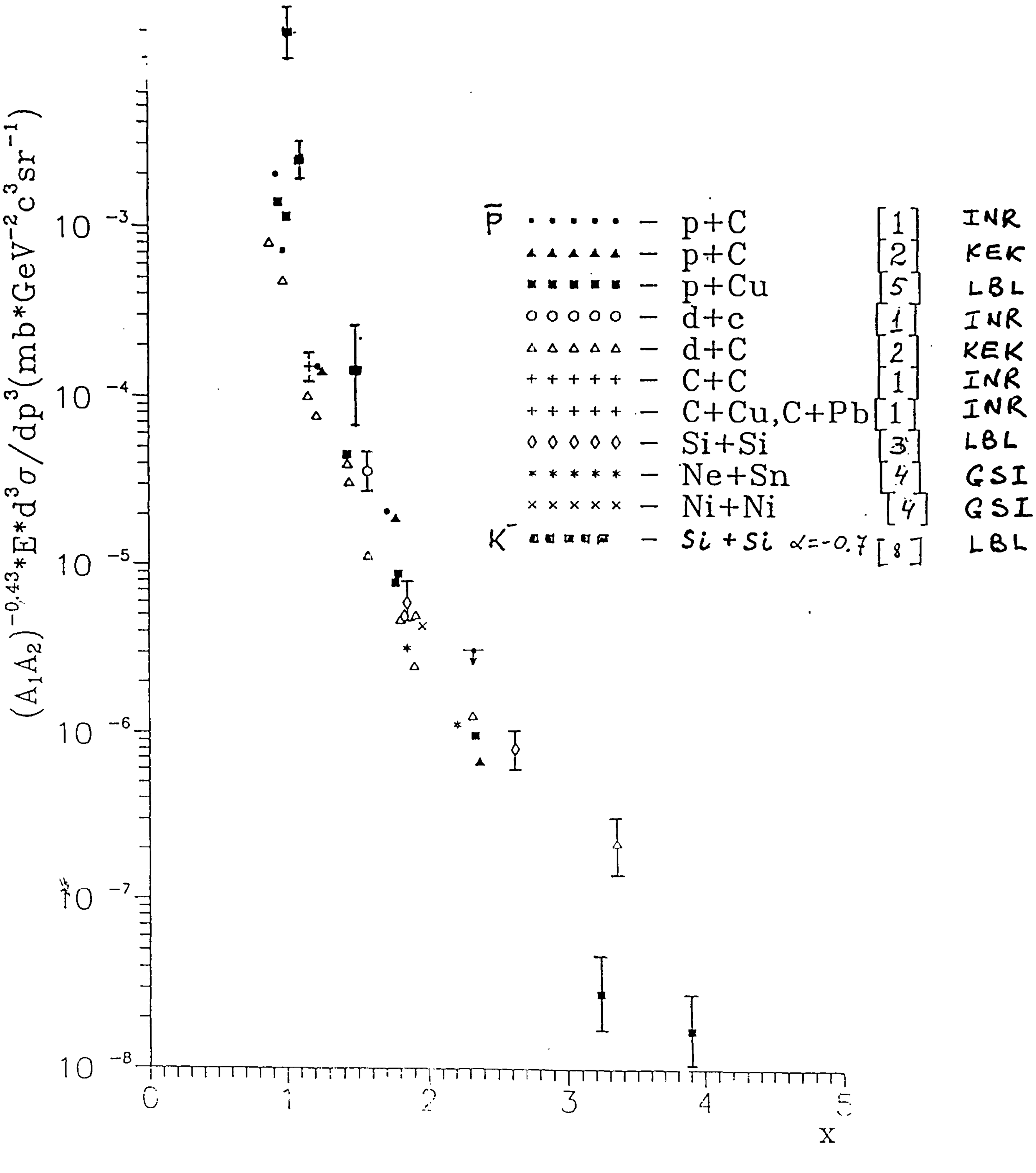
Maximum σ for highest meson momenta or two body reaction:

$$(zP_1 + xP_2 - P)^2 = (zm_N + xm_N + m_i)^2$$

pions	$m_i = 0$
K^+	$m_i = m_\Lambda - m_N$
K^-	$m_i = m_K$

$$Z = \frac{x(P_2P) + xm_Nm_i + 1/2(m_i^2 - m_N^2)}{x(P_1P_2) - (P_1P) - xm_N^2 - m_Nm_i}$$


C+Pb
d+Pb
$(A_1A_2)^{-0.7}Ed^3\sigma/dp^3(mbGeV^{-2}c^3sr^{-1})$
10^2
10
1
10^{-1}
10^{-2}
10^{-3}
0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1.0
scaling parameter z



$z_p = 1$

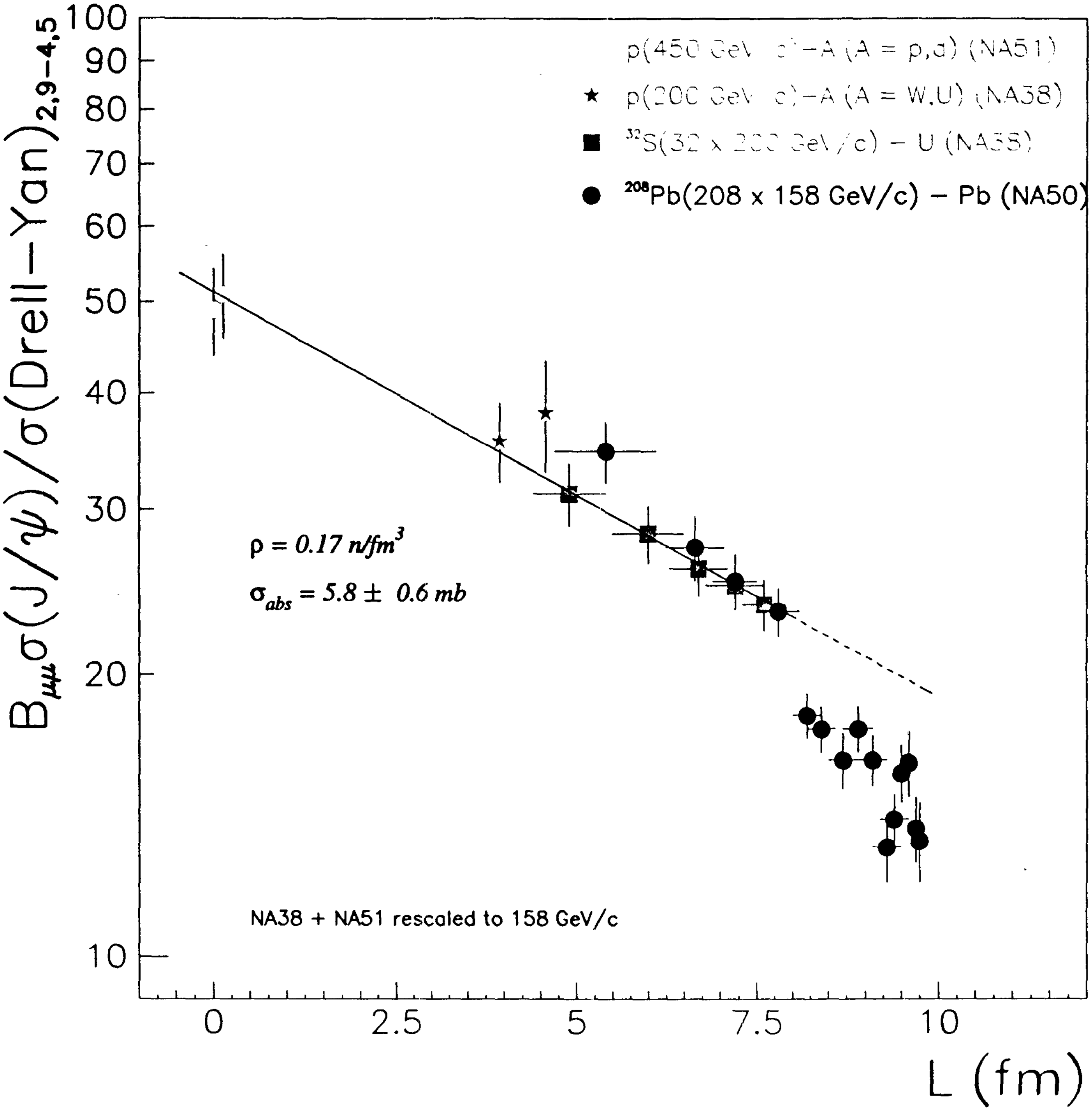
$z_d = 1.3$

$z_c = 2$

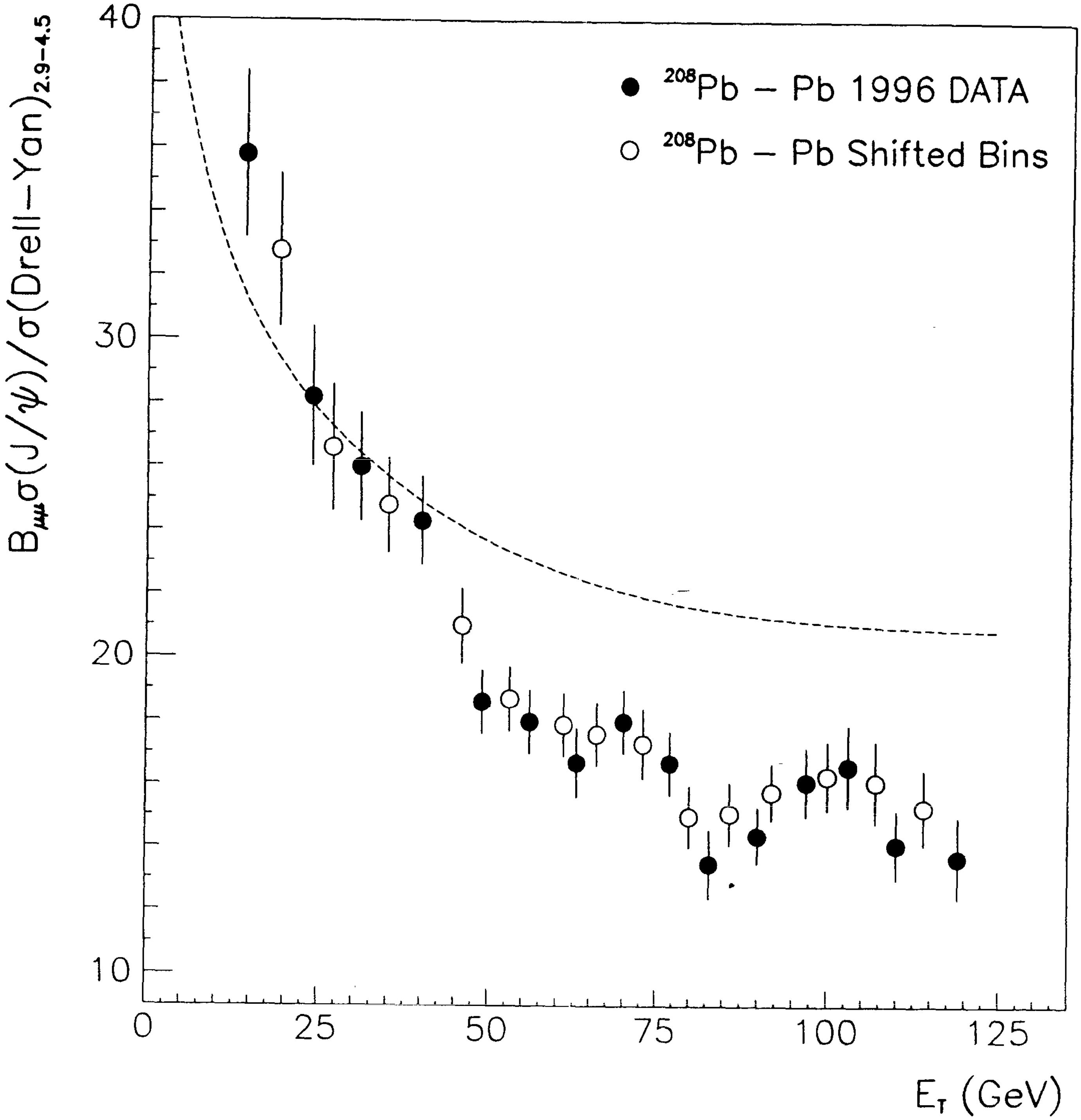
$z_A = 3$

NEW RESULTS ON CHARMONIUM PRODUCTION FROM THE NA50 COLLABORATION

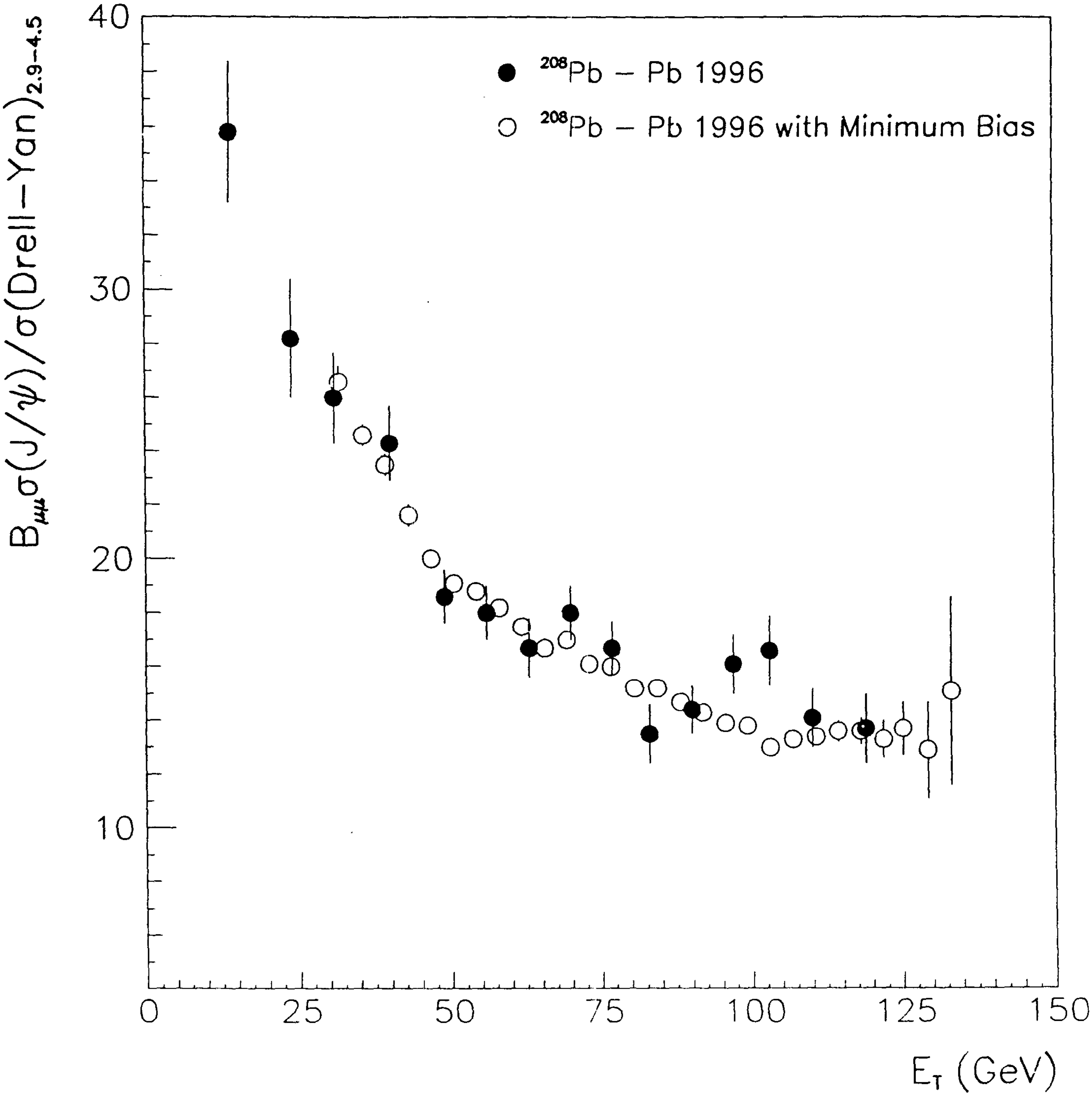
MICHEL GONIN LPNHE - ECOLE POLYTECHNIQUE



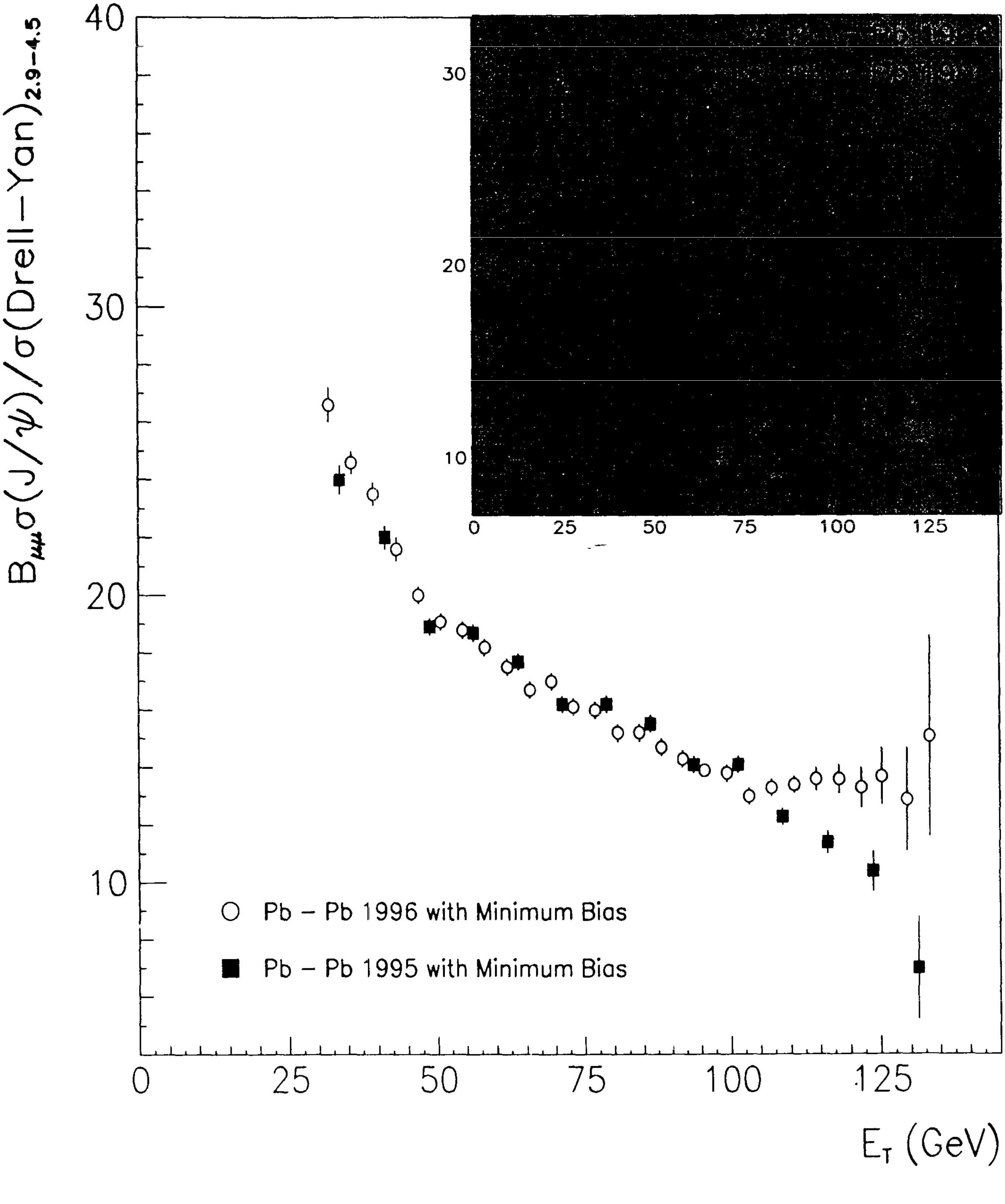
$B_{\mu\mu}\sigma(J/\psi)/\sigma(\text{Drell-Yan})_{2,9-4,5}$
100
90
80
70
60
50
40
30
20
10
p(450 GeV/c)-A (A = p,d) (NA51)
p(200 GeV/c)-A (A = W,U) (NA38)
^{32}S(32 x 200 GeV/c) - U (NA38)
^{208}Pb(208 x 158 GeV/c) - Pb (NA50)
$\rho = 0.17\ n/fm^3$
$\sigma_{abs} = 5.8 \pm 0.6\ mb$
NA38 + NA51 rescaled to 158 GeV/c
0
2.5
5
7.5
10
L (fm)

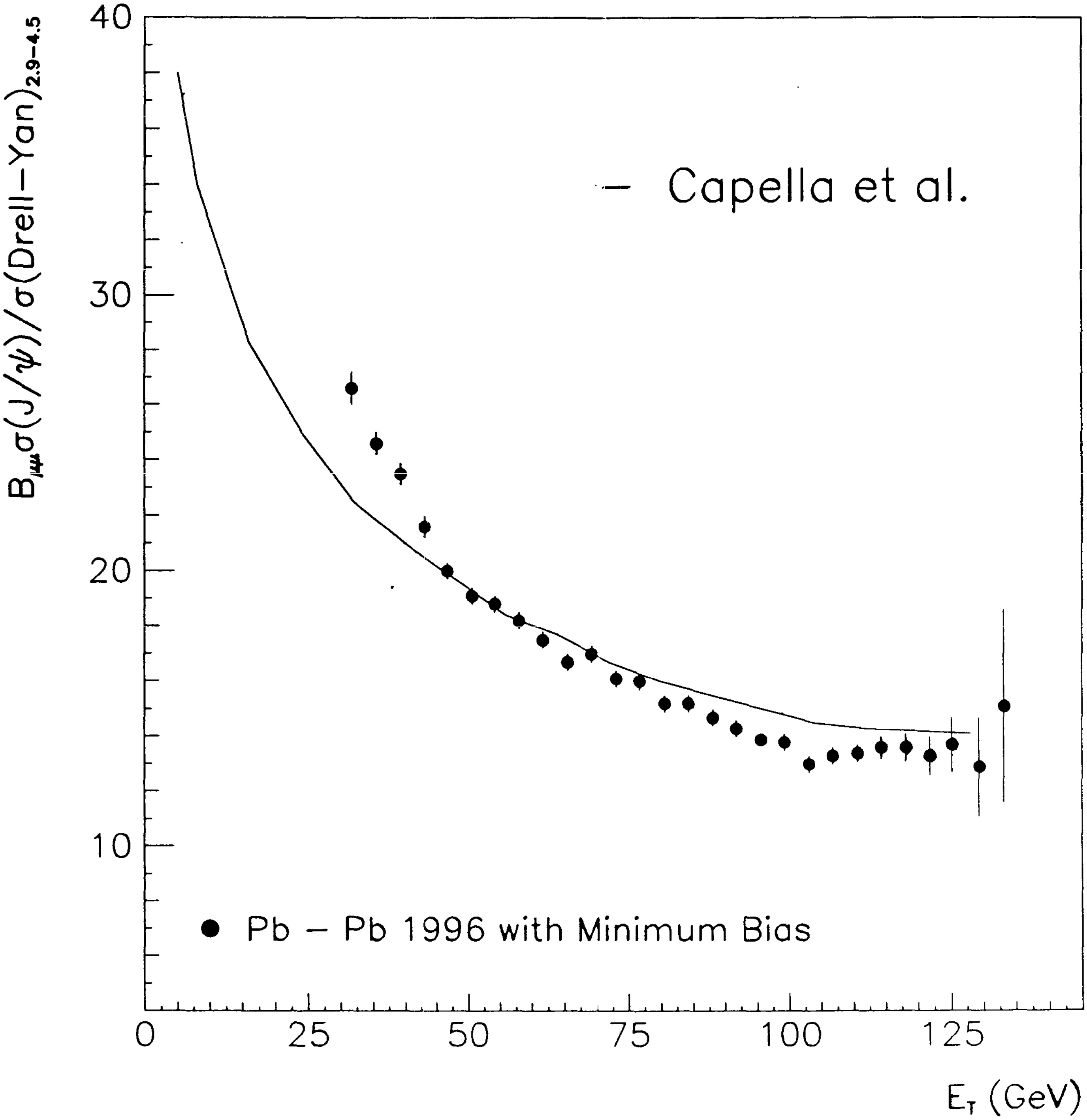


40
30
20
10
0
25
50
75
100
125
$B_{\mu\mu}\sigma(J/\psi)/\sigma(\text{Drell-Yan})_{2.9-4.5}$
^{208}Pb – Pb 1996 DATA
^{208}Pb – Pb Shifted Bins
E_T (GeV)



40
30
20
10
0
25
50
75
100
125
150
$B_{\mu\mu}\sigma(J/\psi)/\sigma(\text{Drell-Yan})_{2.9-4.5}$
E_T (GeV)
^{208}Pb – Pb 1996
^{208}Pb – Pb 1996 with Minimum Bias


$B_{\mu\mu}\sigma(J/\psi)/\sigma(\text{Drell-Yan})_{2.9-4.5}$
40
30
20
10
0
25
50
75
100
125
E_T (GeV)
Pb – Pb 1996 with Minimum Bias
Pb – Pb 1995 with Minimum Bias



$B_{\mu\mu}\sigma(J/\psi)/\sigma(\text{Drell-Yan})_{2.9-4.5}$
40
30
20
10
0
25
50
75
100
125
E_T (GeV)
— Capella et al.
● Pb – Pb 1996 with Minimum Bias

New Results on Intermediate Mass Dileptons

Luciano Ramello for the NA50 Collaboration

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[1] LAPP, CNRS–IN2P3, Annecy–le–Vieux, France; [2] LPC, Université Blaise Pascal and CNRS–IN2P3, Aubière, France; [3] IFA, Bucharest, Romania; [4] Università di Cagliari and INFN, Cagliari, Italy; [5] CERN, Geneva, Switzerland; [6] LIP, Lisbon, Portugal; [7] INR, Moscow, Russia; [8] IPN, Université Paris–Sud and CNRS–IN2P3, Orsay, France; [9] LPNHE, Ecole Polytechnique and CNRS–IN2P3, Palaiseau, France; [10] IReS, Université Louis Pasteur and CNRS–IN2P3, Strasbourg, France; [11] Università di Torino and INFN, Torino, Italy; [12] IPN Lyon, Université Claude Bernard and CNRS–IN2P3, Villeurbanne, France; [13] YerPhI, Yerevan, Armenia.

The NA50 collaboration has measured dimuon production in the mass continuum between the ϕ and the J/ψ, in Pb–Pb interactions at 158 A GeV/c and in p–A interactions at 450 GeV/c at the CERN SPS.

An analysis of these data samples and of the NA38 S–U data (at 200 A GeV/c) has been done in order to establish if the absolute yield and the differential distributions in mass, rapidity and transverse momentum can be explained in terms of known sources, namely Drell–Yan and Open Charm.

The spectral shapes of the sources folded with the apparatus acceptance have been evaluated with PYTHIA. Particular care has been taken for the Combinatorial Background subtraction (muon pairs from π and K decays), based essentially on like sign dimuon data, plus input on charge correlations from the VENUS event generator.

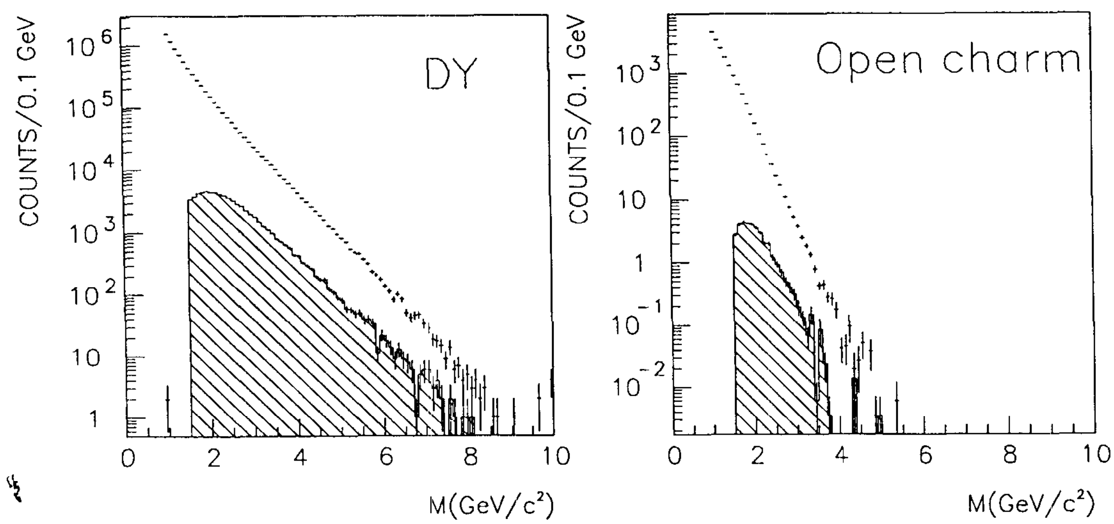
A simultaneous fit to the NA50 p–Al, p–Cu, p–Ag and p–W data samples gives an Open Charm cross-section slightly higher, but compatible with published CERN and FNAL data on proton and pion induced reactions; this cross-section point is used to normalize PYTHIA calculations and therefore to establish the expected source level in A-B collisions.

We find that both Pb–Pb and S–U samples exhibit an excess of dimuons w.r.t. expected sources; this excess is compatible with an enhancement of the open charm component, and increases smoothly with the number of participants in the collision, reaching a factor $\sim$3 for central Pb-Pb collisions. A study of the p_T distributions supports the conclusion that we indeed see a charm-like enhancement in A–B collisions.

Estimation of expected sources ($D\overline{D}$, DY)

- Generate dimuons from DY and $D\overline{D}$ (m_c=1.5 GeV/c^2, $\langle k_T^2 \rangle$ = 0.8 GeV^2) using PYTHIA;
- Track dimuons through the apparatus (for each setup);
- Reconstruct dimuons kinematical variables using the same reconstruction procedure adopted for experimental data.

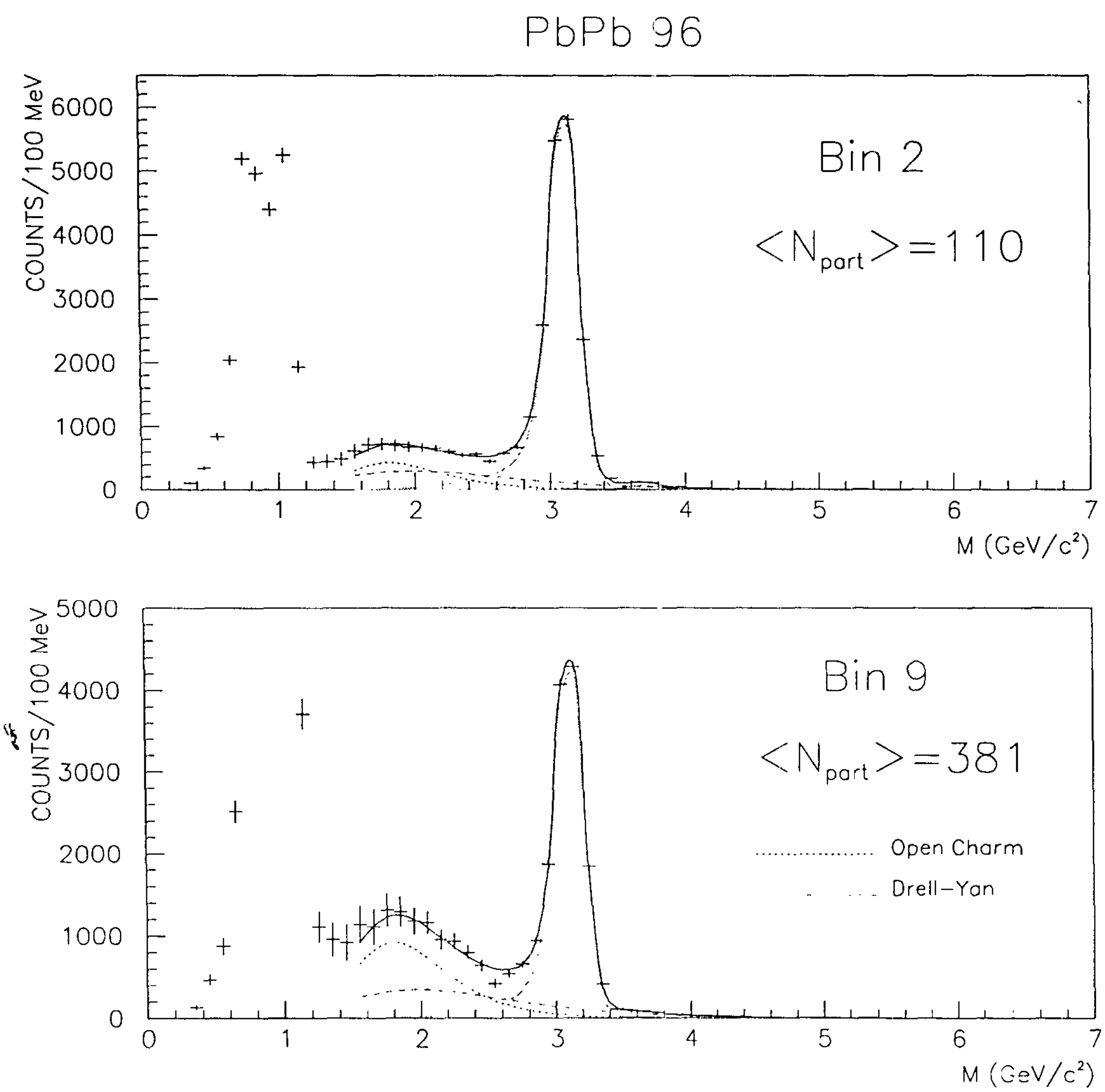
Drell–Yan and open charm mass shapes



- Determine acceptance in kinem. region: -0.5< $\cos\theta_{CS}$ <0.5 and 0< y_{cm} <1 (for p–A: -0.52< y_{cm} <0.48).
- Fit the A–B experimental mass spectra in the region $M > 1.5$ GeV/c^2 with a superposition of the mass shapes of the expected sources, keeping the relative normalizations of the various contributions as free parameters.

Central vs. peripheral Pb–Pb collisions

- We know that the *DY* exhibits no anomalous behaviour from p–p to Pb–Pb collisions (see Abreu et al., Phys. Lett. B410(1997)337);
- We would then expect: $\sigma_{D\overline{D}}/\sigma_{DY} = const.$ vs E_T;

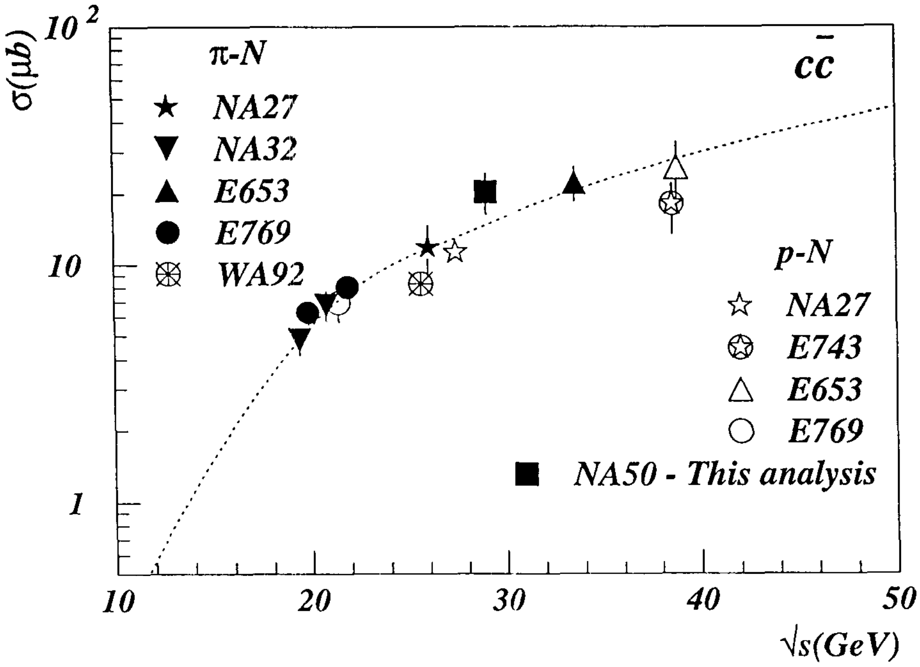


But we see that, in central Pb–Pb collisions, an enhancement of the open charm component, with respect to *DY*, is necessary in order to describe the mass spectrum → **charm–like** enhancement.

BNL 98

Expected open charm contribution

Introducing an overall up–scale factor PYTHIA reproduces the open charm hadro-production $\sqrt{s}$-dependence and the D-meson differential distributions measured at CERN and FNAL energies (see review by Braun–Munzinger et al., Eur. Phys. J. C1(1998)123) :



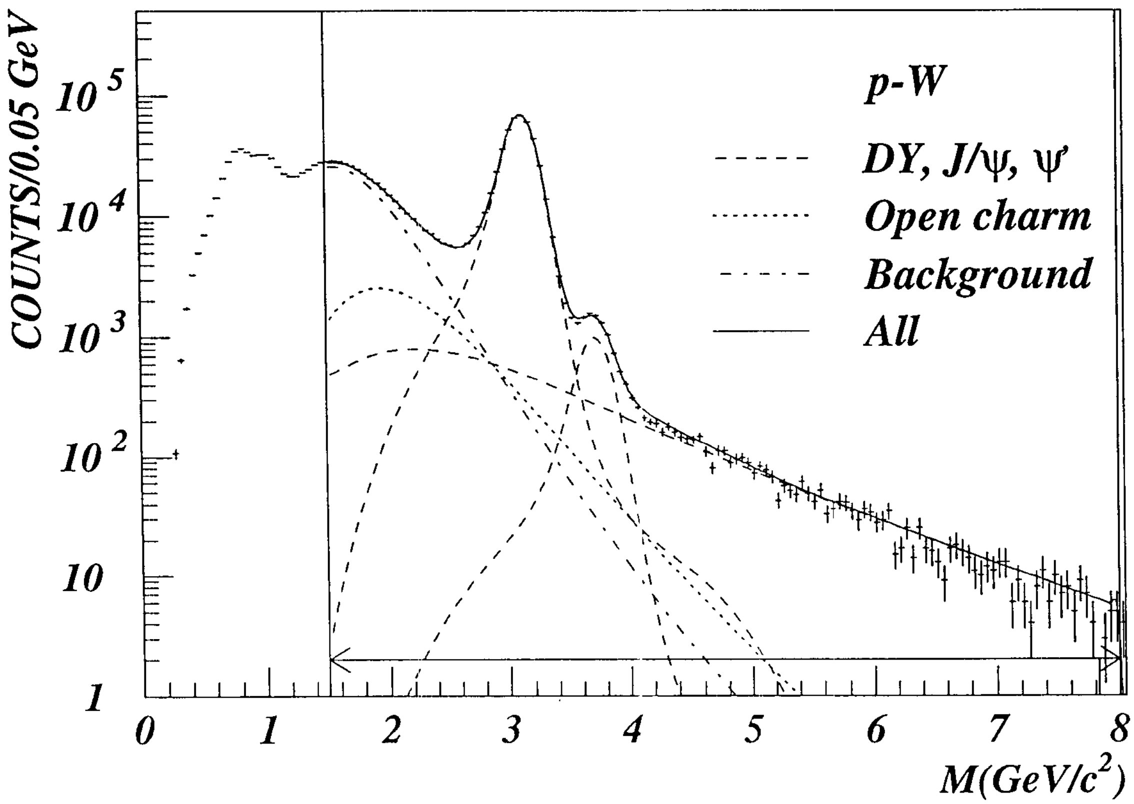
Cross-sections per nucleon in the forward region ($x_f > 0$), averaged between charged and neutral channels, are shown;

PYTHIA multiplied by $K_{neutral}$=4.5 and $K_{charged}$=7

- The NA50 point (obtained from four different p-A systems, see later) is compatible with other data points

- We can use as a reference (expected charm) for A-B collisions either the PYTHIA curve as shown, or the same rescaled to the NA50 point

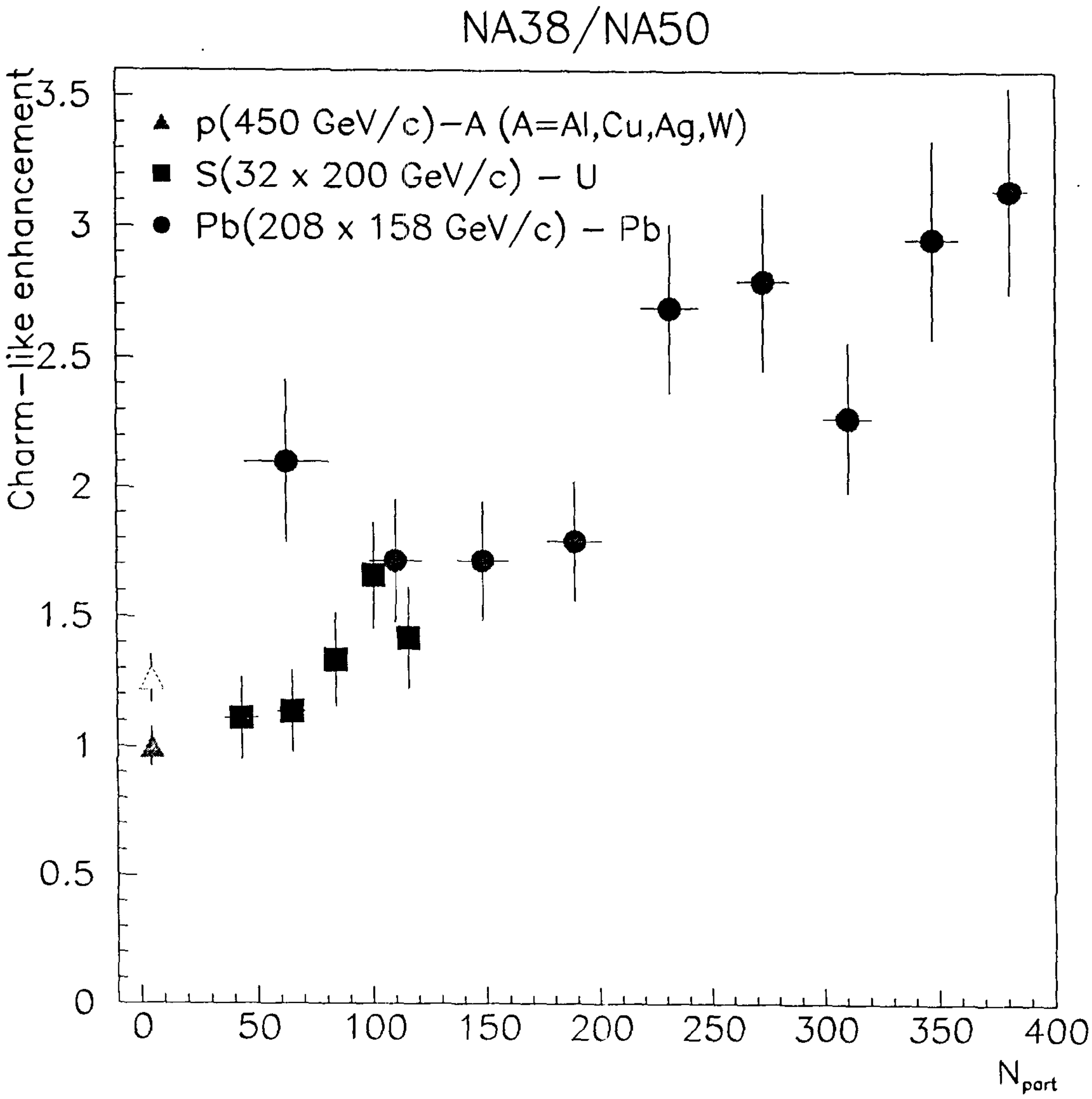
Fit of the p–W mass spectrum



• If the background R–factors are fixed in the fit, a $\sim$ 20% higher value for $\sigma_{D\overline{D}}/\sigma_{DY}$ is obtained (open triangle in the next plots).

BNL-98

Charm–like enhancement vs N_{part}: p–A, S–U, Pb–Pb



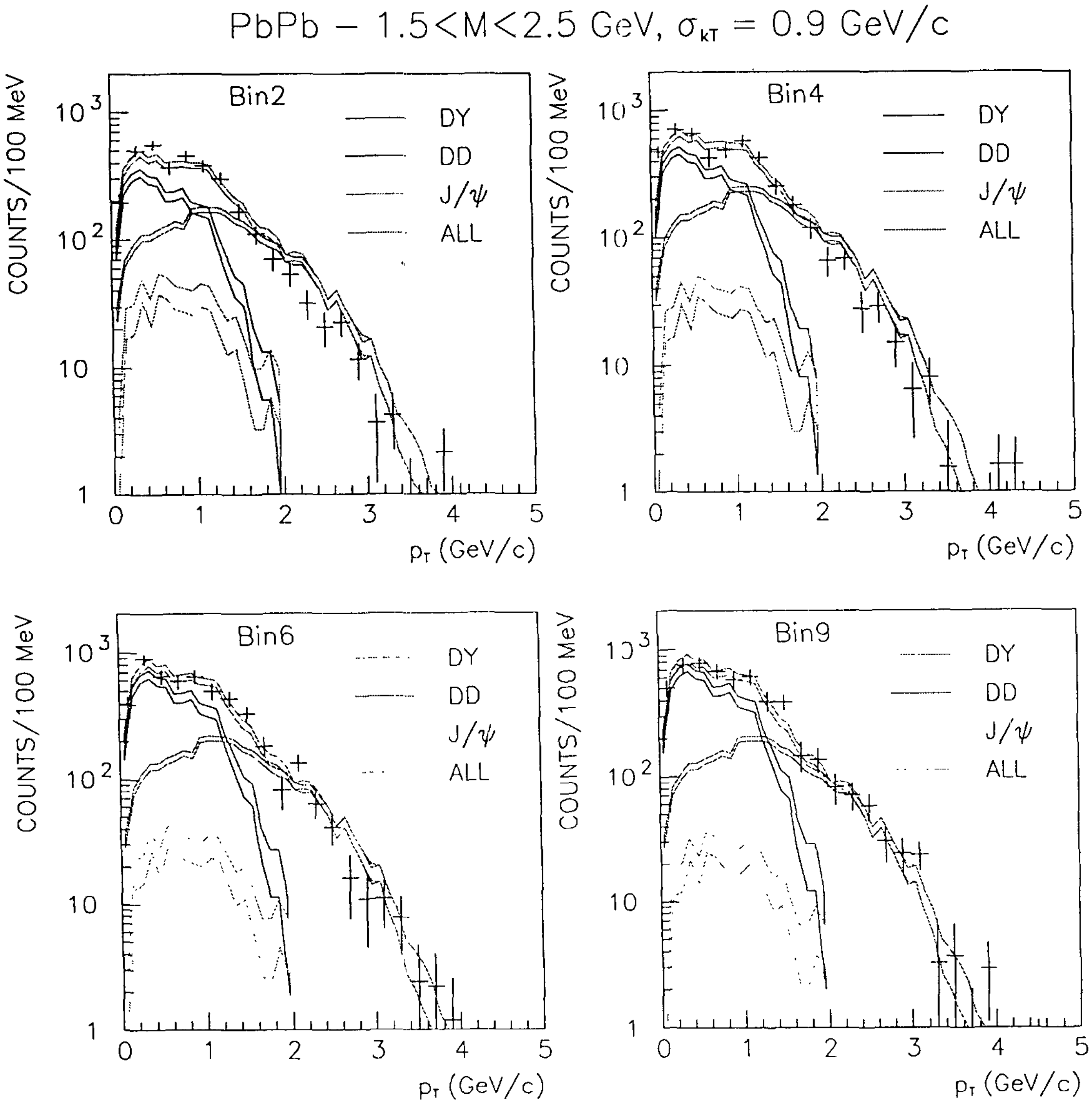
Charm–like enhancement:

a factor 3 in central Pb–Pb with respect to p–A

(Enhancement w.r.t. rescaled PYTHIA)

BNL98

p_T distributions of the Pb–Pb IMR events



- p_T shapes for DY, $D\overline{D}$, J/ψ from PYTHIA (gaussian k_T with $\sigma_{k_T} = 0.9$ GeV/c) + simulation of the detector;
- Absolute normalizations from the fit of the mass spectra;
- Independent evidence that the enhancement is due to a charm like component.

Charmonium Suppression in Lead-Lead Collisions: Is There a Break in the J/ψ Cross-Section?

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Abstract

In the framework of a model based on nuclear absorption plus comover interaction, we compute the E_T distribution of the J/ψ in $PbPb$ collisions at SPS and compare it with available NA50 data. Our analysis suggests that the existence of new physics (deconfinement phase transition) in the region $E_T \lesssim 100$ GeV is unlikely and that signals of new physics should rather be searched in the region $E_T \gtrsim 100$ GeV. The E_T dependence of the J/ψ transverse momentum has been computed. At large E_T it turns out to be much flatter in the comover approach than in a phase transition framework. Estimates of the J/ψ suppression at RHIC and LHC energies are also given.

LPTHE Orsay 98/27

DESY 98-086

hep-ph/9807258

July 1998

REMARKS ON J/ψ SUPPRESSION:

E_T DISTRIBUTIONS OF J/ψ AND DY WITH COMOVERS

Based on: N. Armesto, A.C and E.G. Ferreiro
N. Armesto and A.C. Phys Lett B, 1998 | hep-ph 9807258

- J/ψ SUPPRESSION IS MEASURED THROUGH THE RATIO R = J/ψ / DY. TAKING THIS RATIO ELIMINATES SYSTEMATICS COMMON TO BOTH BUT IS SENSITIVE TO DY.

- RELIABLE DATA ON J/ψ ALONE ARE NEEDED

- IN ORDER TO DECIDE HOW RELIABLE WE NEED DY BOTH THEOR. AND EXPER.

- DY CROSS-SECTION IS WELL KNOWN VERSUS b

$$\sigma_{AB}^{DY}(b) = \frac{\sigma_{pp}^{DY}}{\sigma_{pp}} \, A B \, \sigma_{pp} \, T_{AB}(b)$$

WHERE $T_{AB}(b) = \int d^2s \, T_A(s) \, T_B(b-s)$

CORRELATION $b \leftrightarrow E_T$ MODEL DEPENDENT

DIFFERENT MODELS IN LITERATURE

HOWEVER $b \leftrightarrow E_{ZDC}$ LESS MODEL DEPENDENT

PROPOSAL: PLOT σ_{AB}^{DY} VERSUS E_{ZDC}

$E_{ZDC}(b) = [A - m_A(b)]\, E_{cm}$

- IF DY THEORY AGREES WITH EXPER. STRONG INDICATION THAT SYSTEMATIC ERRORS ARE NOT LARGE

- FOR J/ψ ALSO SMALL SYSTEMATICS (OR ELSE THEY ARE DIFFERENT IN J/ψ AND DY AND TAKING THE RATIO WILL NOT HELP)

- WHAT CAN WE DO IN THE MEAN TIME? WE MUST USE THE EXPERIMENTAL $E_T - E_{ZDC}$ CORRELATION INSTEAD OF A MODEL: THE SHAPE OF THE E_T DISTRIBUTION IS VERY SENSITIVE TO THIS CORRELATION (DRAMATIC ILLUSTATION AT SEATTLE: USING DPM AND WNM GIVES NOT TOO DIFFERENT $E_T - E_{ZDC}$ BUT VERY DIFFERENT E_T DISTRIBUT. OF DY.

DTM BASED PARAMETRIZATION

$$E_T(b) = q\, N_y^{CO} + 0.95 \left[k E_{ZDC}(b)\right]^{1.2} \left[1 - \frac{E_{ZDC}(b)}{E_{ZDC}^{MAX}}\right]^{0.2}$$

$q = 0.78$ GeV, $k = 1/4000$, $E_{ZDC}^{MAX} = A\, E_{in}$.

$N_y^{CO}(b)$ IS TOTAL AVERAGE MULTIPL. IN DTM (LINEAR COMBINATION OF $m_A(b)$, $m_B(b)$ AND $m(b)$)

SECOND TERM MAY BE DUE TO INTRA-NUCLEAR CASCADE (PRESENT IN THE CALORIMETER REGION BUT ABSENT IN THE DI-MUON TRIGGER REGION)

THIS GIVES A VERY GOOD DESCRIPTION OF THE DATA

TO GET $d\sigma^{DY}/dE_T$ WE NEED THE $E_T - b$ CORR

$$P(E_T, b) = \frac{1}{\sqrt{2\pi q a E_T(b)}} \exp\left[-\frac{\left[E_T - E_T(b)\right]^2}{2 q a E_T(b)}\right]$$

WITH $a = 0.73$ DETERMINED EITHER FROM DY OR MB E_T TAIL

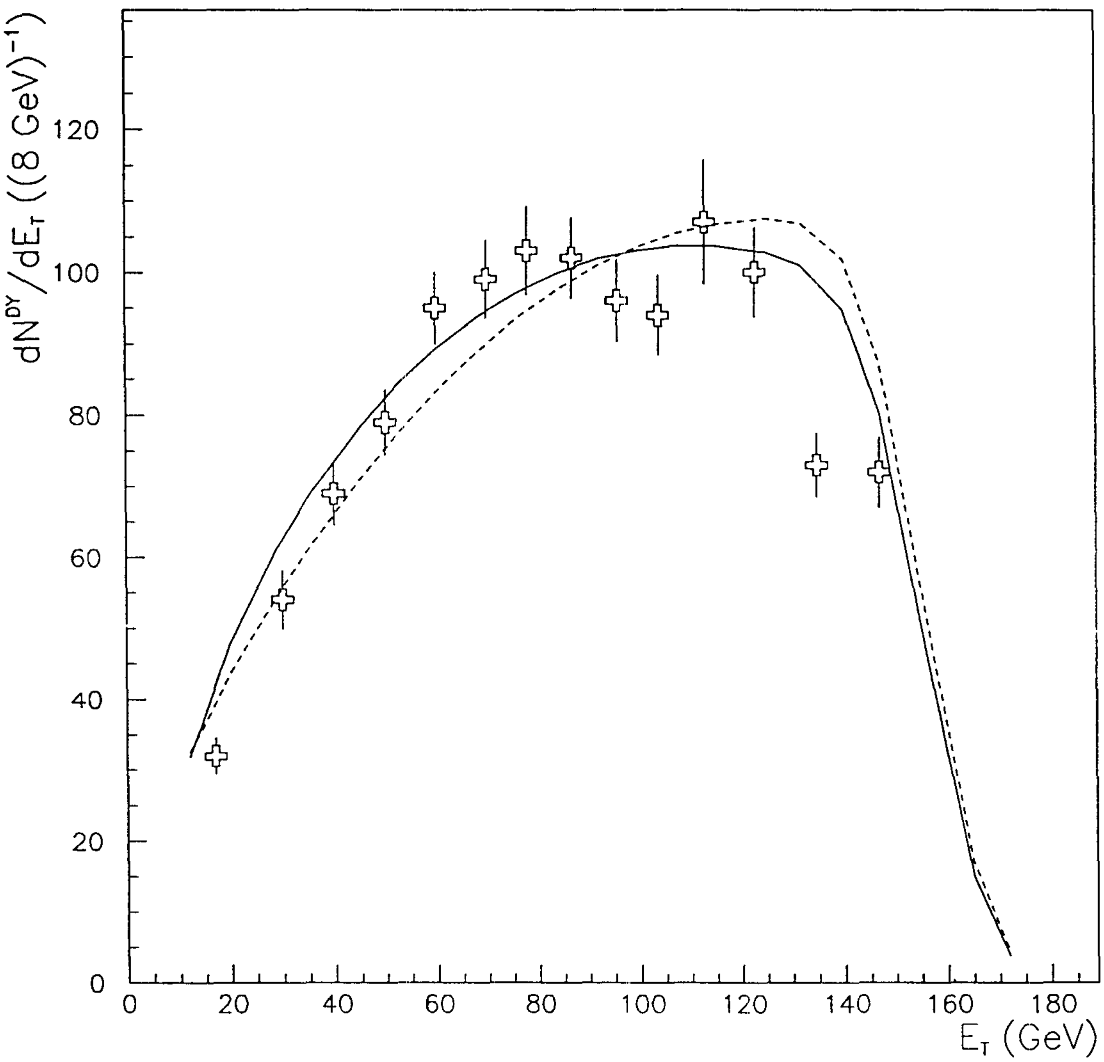
THEN

$$\frac{d\sigma^{DY}}{dE_T} = \int d^2b\, \sigma_{AB}^{DY}(b)\, P(E_T, b)$$

SIMILAR FORMULA FOR J/ψ WITH NUCLEAR ABSORPTION ($\sigma_{abs} = 5.7$ mb) AND COMOVERS DENSITY OF COMOVERS GIVEN BY $N_y^{CO}(b)$ (DTM WITH <u>NO</u> <u>EXTRA</u> <u>TERM</u> IN DI-MUON TRIGGER REGION

RESULTS: FIGS 1 AND 2

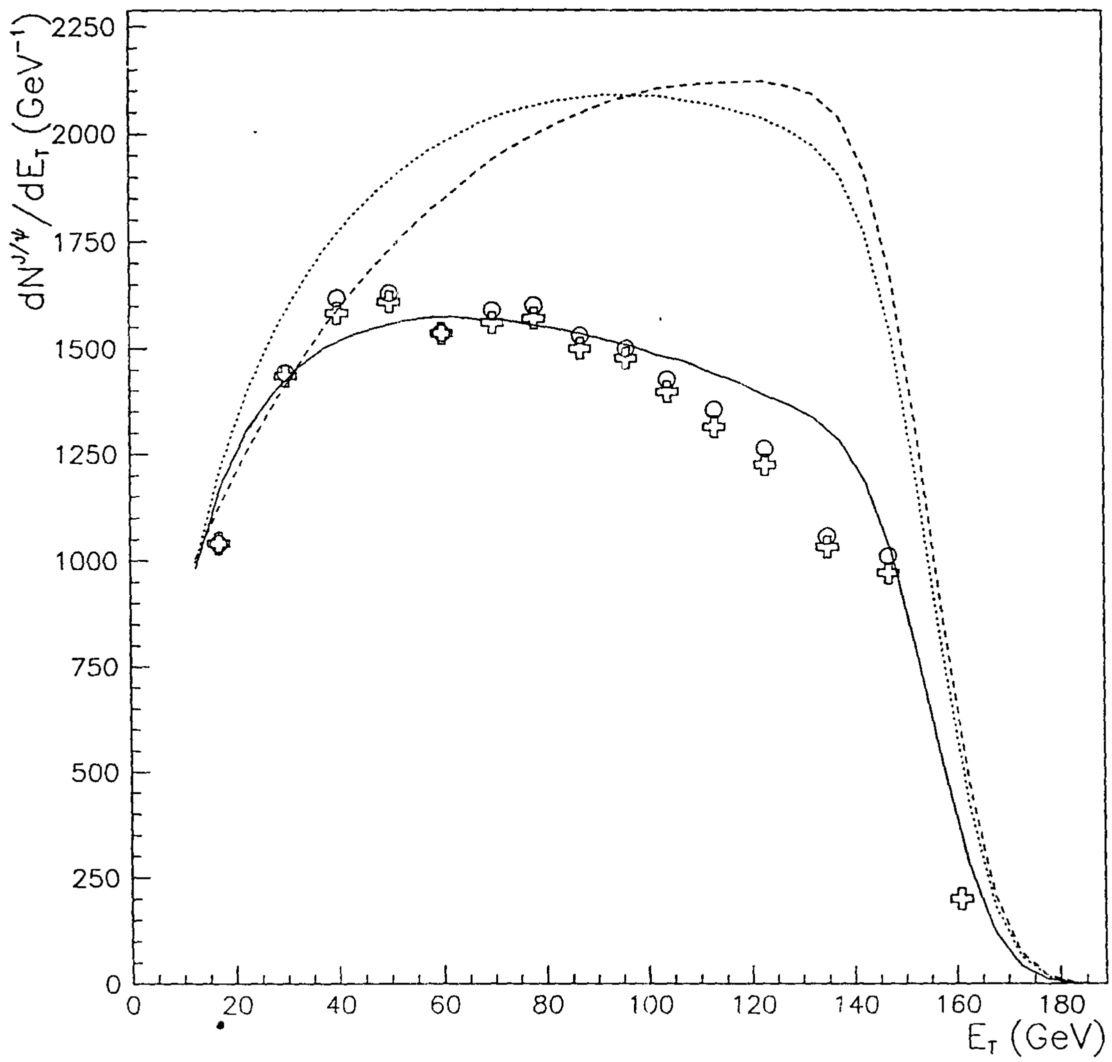
Figure 4



——— DPM

- - - WNM (scaling in n° of participants)

Figure 2



—— DPM + nuclear absorption + comovers

• • • DPM + nuclear absorption

– – – WNM + " "

Marzia Nardi

CHARMONIUM SUPPRESSION AND PERCOLATION IN HEAVY ION COLLISIONS

The aim of high energy nuclear collisions is to create and study the quark–gluon plasma, a new state of matter in which partons (quarks and gluons) are not constrained in hadrons. The momentum distributions of confined partons are measured in deep inelastic–scattering experiments, in particular hard gluons ($x \rightarrow 1$) are known to be suppressed according to $g(x) \sim (1-x)^k$ ($k = 3$ for mesons, $k = 4$ for nucleons). In a medium of deconfined partons these constraints are removed and gluons are, on the average, harder than in normal hadronic matter. A candidate as a deconfinement probe is the J/ψ meson : charmonium and bottomonium resonances are formed only at the earliest stages of a nucleus–nucleus collision, before the possible quark–gluon plasma formation. The J/ψ can distinguish confinement and deconfinement : its "binding energy" of about 0.64 GeV prevents the dissociation by confined gluons (for an hadron gas at the present energies) but it is overcome by free gluons.

In a hard interaction between two nucleons, a colour flux tube (primordial "string") is formed between them and results in a gluon exchange; the radius r of this string is related to the transverse momentum k_T of the gluon : $r \sim 1/k_T$. In a collision between two heavy nuclei, a nucleon undergoes several hard interactions and emits several such strings which overlap in the transverse plane, forming a "cluster". If the time between successive collisions is too short, the nucleons can not recover in a physical, 'normal' hadronic state : the parton momentum distributions are 'disturbed' and the confinement constraints are weakened. Many collisions in a short interval of time imply high density of primordial strings; it is then conceivable that deconfinement is achieved when the nucleon–nucleon collision density approaches a critical value n_c, which we assume to be the mean nucleon–nucleon collision density obtained in a central S–U collision.

The study of clustering of disks, distributed in a two-dimensional region according to a realistic nuclear density, is important to determine the conditions under which this critical density is reached in heavy ion collisions. For a given nucleus–nucleus system, the total number of elementary nucleon–nucleon collisions depends on the impact parameter b; increasing the collision centrality (i.e. decreasing b), the disk density in a cluster increases and, as shown by numerical simulations, the mean cluster size grows very rapidly; in particular, in Pb–Pb collisions, a cluster density of n_c corresponds to a cluster size of $10 - 20$ fm^2. This property has an important consequence : the quark gluon plasma can not appear, in heavy ion collisions, in a region of arbitrarily small size : at the onset of deconfinement, the new phase extends over a finite area in the transverse plane. The discontinuous behaviour of anomalous J/ψ suppression resulting from this argument agrees with the recent NA50 experimental data.

The aim of high energy nuclear collisions is to create and study QGP

CONFINEMENT

- partons are constrained in hadrons
- momentum distributions known from DIS
- in particular :

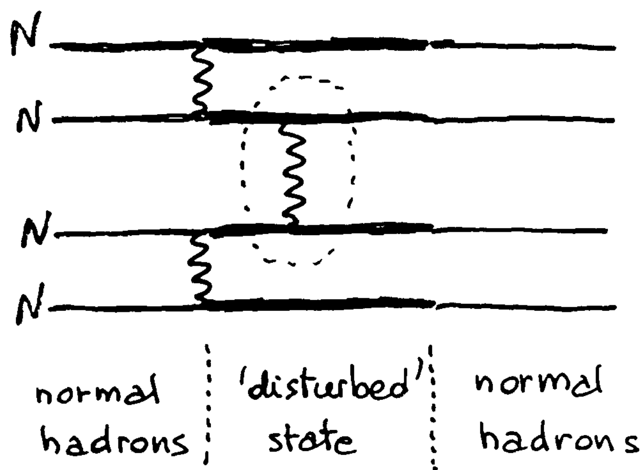
$$g(x) \underset{x \to 1}{\sim} (1-x)^k$$

$\Rightarrow$ hard partons are suppressed

DECONFINEMENT

- no constraints on partons
- mom. distributions different from DIS
- partons become harder

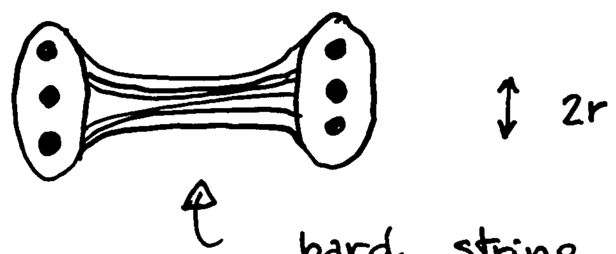
QGP: medium of deconfined partons



smallest subset of QGP

confinement constraints are weakened

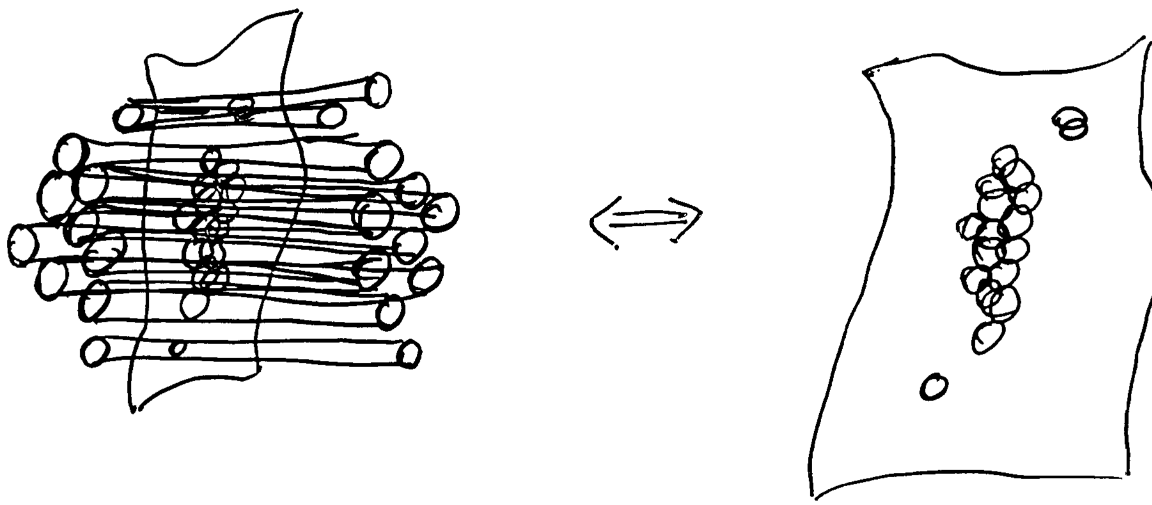
NN collision :



hard string ('primordial' string) = g exchange
transverse size $r \sim 1/k_T$

AB collision :

- nucleons undergo several collisions
- each NN collision establishes a hard string of radius r
- strings overlap in transverse plane ⇒ cluster



Many collisions in a short interval of time

⇕

high density of disks in the transverse plane

Onset of deconfinement ⟺ cluster of disks (area $\pi r^2 \sim \frac{\pi}{k_T^2}$)
with density $\underline{n_c}$ (bubble)

J/ψ SUPPRESSION

<u>confined</u> partons <u>can not</u> dissociate J/ψ — D. Kharzeev, H. Satz

<u>deconfined</u> partons <u>can</u> dissociate J/ψ

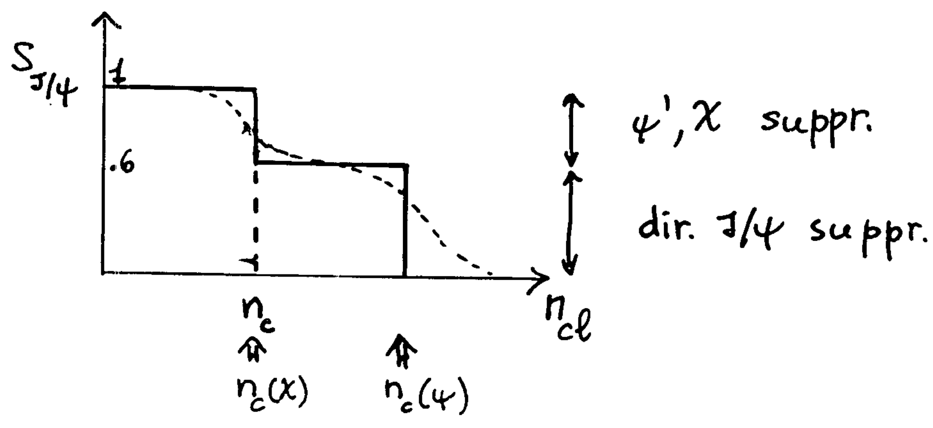
when $n_{cl} \geq n_c$:

J/ψ in bubble is killed

experiment : J/ψ { ~ 60% direct J/ψ; ~ 32% $\chi \to J/\psi + \gamma$; ~ 8% $\psi' \to J/\psi + \ldots$ }

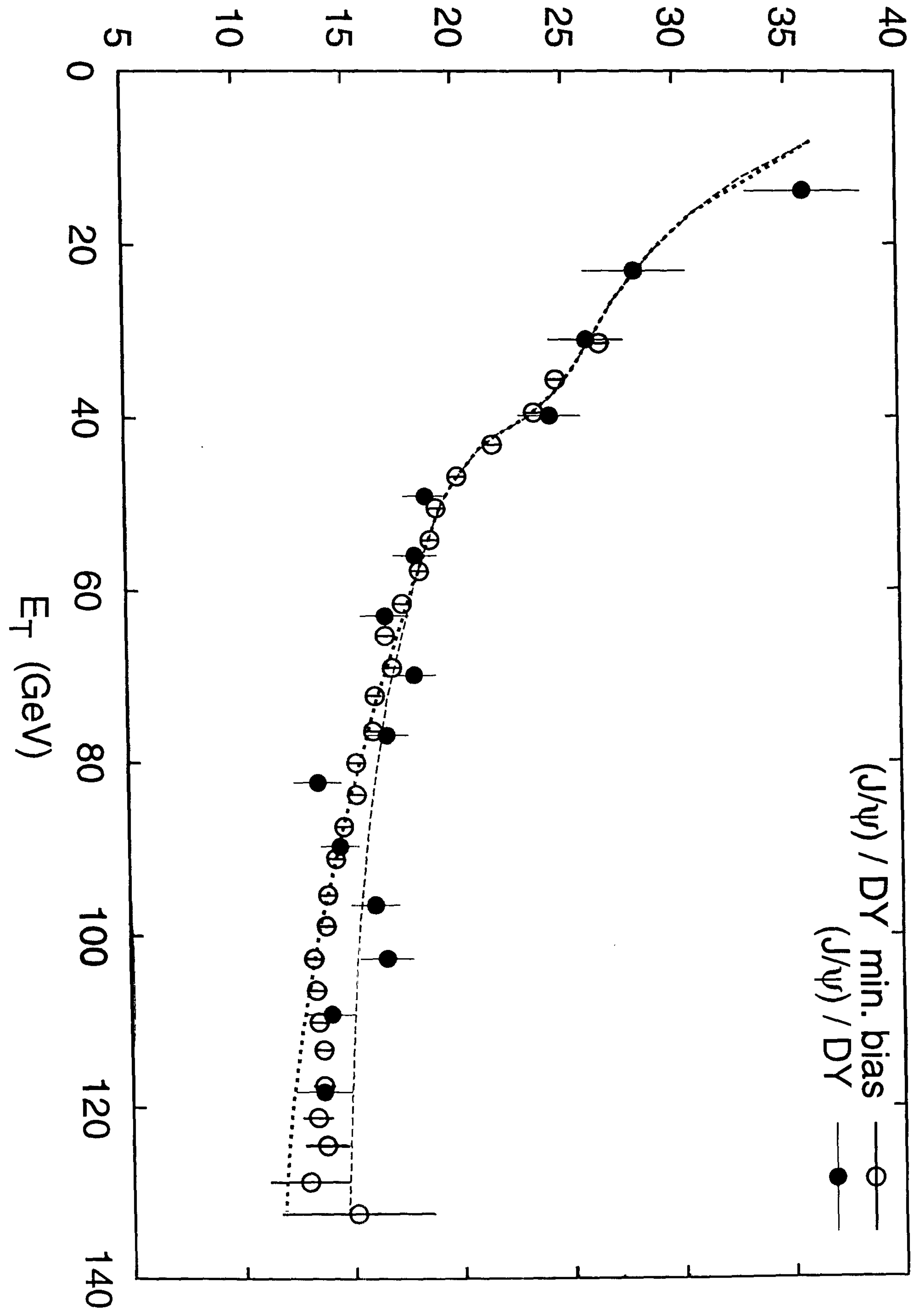
{ χ, ψ' in bubble r_χ is killed (assume $r_{\psi'} = r_\chi$)

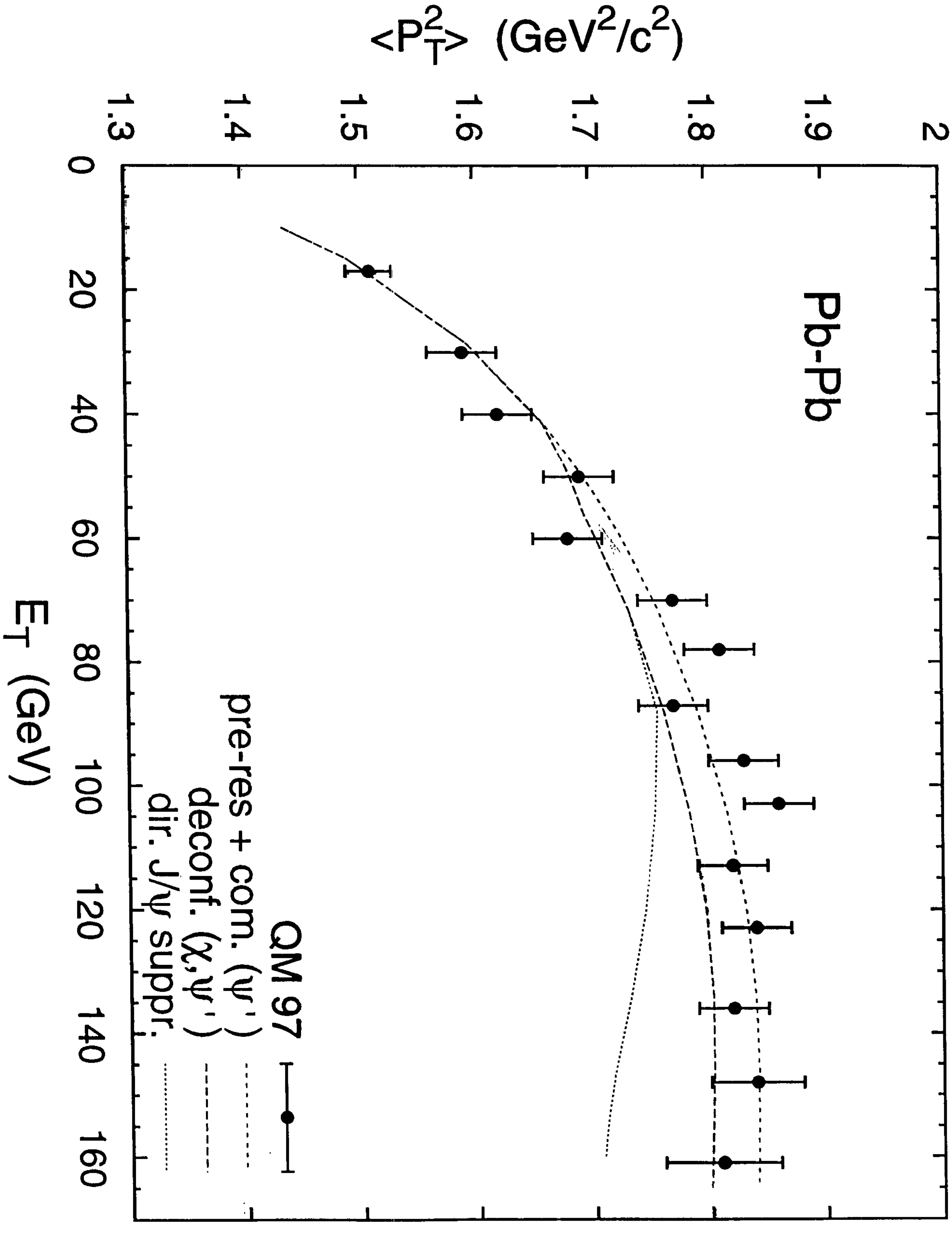
{ J/ψ in bubble $r_{J/\psi}$ is killed



$r_\chi \simeq 0.26$ fm — $n_c(\chi) \simeq 7\ fm^{-2}$

$r_\psi \simeq 0.18 \div 0.20$ fm — $n_c(\psi) \simeq 10\ fm^{-2}$


(J/ψ) / DY min. bias
(J/ψ) / DY
E_T (GeV)
0
20
40
60
80
100
120
140
5
10
15
20
25
30
35
40



Pb-Pb
<P$_T^2$> (GeV^2/c^2)
E$_T$ (GeV)
QM 97
pre-res + com. (ψ')
deconf. (χ,ψ')
dir. J/ψ suppr.

Inelastic Charmonium-Nucleon Cross Sections

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(together with B. Kopeliovich)

Summary

1. J/ψ suppression in pA collisions can be understood in terms of an effective $J\psi N$ absorption cross section of 6-7 mb.

2. Analysis of photo production cross sections $\gamma p \to J/\psi p$ within the vector dominance model leads to $\sigma_{tot}^{J\psi N} = 1$ mb.

3. An analysis of the same data within a multi-channel vector dominance model gives $\sigma_{tot}^{J/\psi N} = 4$ mb in agreement with theoretical predictions based on $\sigma_{tot}^{hN} = C\langle r^2\rangle_h$.(PLB 426 (1998)154)

4. Formation time effects in $hA \to J\psi X$ collisions lead to an effective absorption cross section which is about 30% smaller than the total cross section for a formation time $t_f \to \infty$. (PRL 76 (1996) 192)

5. Another (or an additional) mechanism for suppression even in $pA \to J\psi X$ collisions is called for.

Inelastic Charmonium-Nucleon Cross Sections

with B. Kopeliovich

Outline:

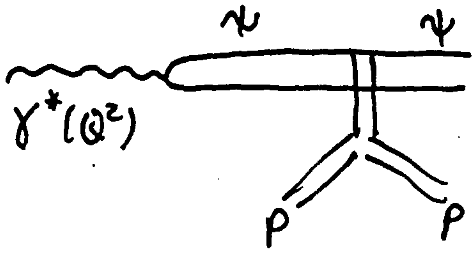
1. some inconsistencies
2. photoproduction and vector dominance model (VDM)
3. multichannel VDM
4. formation time effects

1. some inconsistencies ; $\Psi \equiv J/\psi, \Psi', \Psi'', \ldots \equiv \Psi_0, \Psi_1, \Psi_2 \ldots$

	$J/\psi N$	$\sigma^{\psi' N} / \sigma^{J/\psi N}$	source
$\sigma_{abs}^{\Psi N}$	6-7 mb	$1 \pm .1$	exp: suppression in $pA \to \Psi X$
$\sigma_{tot}^{\psi N}$	$(1.2 \pm .1)$ mb	0.8 ± 0.2	exp: $\gamma p \to \Psi p$ via VDM
$\sigma_{tot}^{\psi N}$	4 mb	3 - 4	theo: 2 g-exchange (Low mod phen: $\sigma_{tot}^{hN} = C \langle r^2 \rangle_h$

2. Analysis of photo-production data via the conventional VDM.

$$\gamma^* p \to \psi p$$



$$f^{forw}(\gamma^* p \to \psi p) = \frac{C^{\gamma\psi}}{M_\psi^2 + Q^2} f^{forw}(\psi p \to \psi p)$$

$$\uparrow \sigma_{tot}^{\psi p}$$

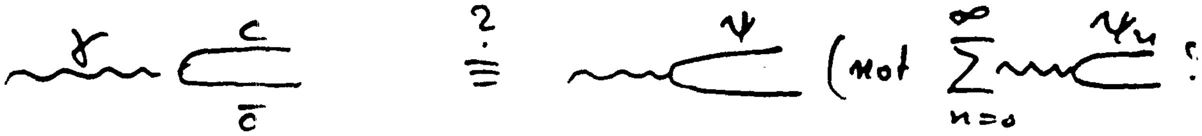
$$\sigma_{tot}^{\psi p} = \left[\frac{16\pi \alpha_{em} M_\psi}{3 \Gamma_{\psi \to e^+e^-} \cdot (1+\beta_{\psi N}^2)} \frac{d\sigma}{dt}(\gamma^* p \to \psi p)\Big|_{t=0} \right]^{1/2}$$

Using the data for $\gamma^* p \to \psi p$

$$\to \quad \sigma_{tot}^{J/\psi N} = (1.24 \pm .13) \left(\frac{\sqrt{s}}{10\,GeV} \right)^{0.4} mb$$

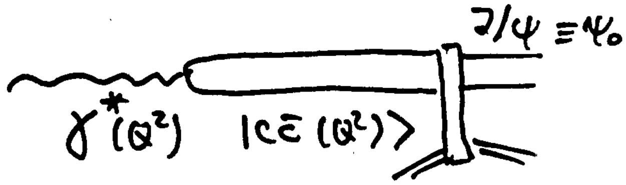
$$\to \quad \frac{\sigma_{tot}^{\psi' N}}{\sigma_{tot}^{J/\psi N}} = 0.8 \pm 0.2$$

Question



$Q^2 = 0$ $\qquad \uparrow \quad \langle r_\perp^2 \rangle_{c\bar{c}} = \frac{2}{3 m_c^2}$ $\qquad \langle r_\perp^2 \rangle_{J/\psi} = \frac{4}{m_c \cdot \Delta M} \gg \langle r_\perp^2 \rangle_{c\bar{c}}$

3. Analysis within multi-channel VDM (P.L.B 426 (1998));



$$|c\bar{c}(Q^2)\rangle = \sum_{n=0}^{\infty} \frac{C^{\gamma\psi_n}}{M^2_{\psi_n}+Q^2}\,|\psi_n\rangle$$

$$f^{forw}(\gamma^* p \to J/\psi p) = \underbrace{\frac{C^{\gamma\psi_0}}{M^2_{\psi_0}+Q^2}\, f(\psi_0 p \to \psi_0 p)}_{\text{conventional VDM}} \cdot N_{\psi_0}(Q^2)$$

$$N_{\psi_0}(Q^2) = 1 + \sum_{n=1}^{\infty} \frac{C^{\gamma\psi_n}}{C^{\gamma\psi_0}}\,\frac{M^2_{\psi_0}+Q^2}{M^2_{\psi_n}+Q^2}\,\frac{f^{forw}(\psi_n p \to \psi_0 p)}{f^{forw}(\psi_0 p \to \psi_0 p)}$$

To evaluate N_{ψ_0} use

(a) $f^{forw}(\psi_n p \to \psi_0 p) \propto \langle \psi_n | r^2 | \psi_0 \rangle$

(b) Use harmonic oscillator functions for $\psi_0, \psi_1 \ldots$

(c) $N_{\psi_0}(Q^2) = O\left(\frac{1}{Q^2}\right)$ for $Q^2 \to \infty$

(a+b) $\langle \psi_n | r^2 | \psi_0 \rangle = 0 \qquad n > 1$

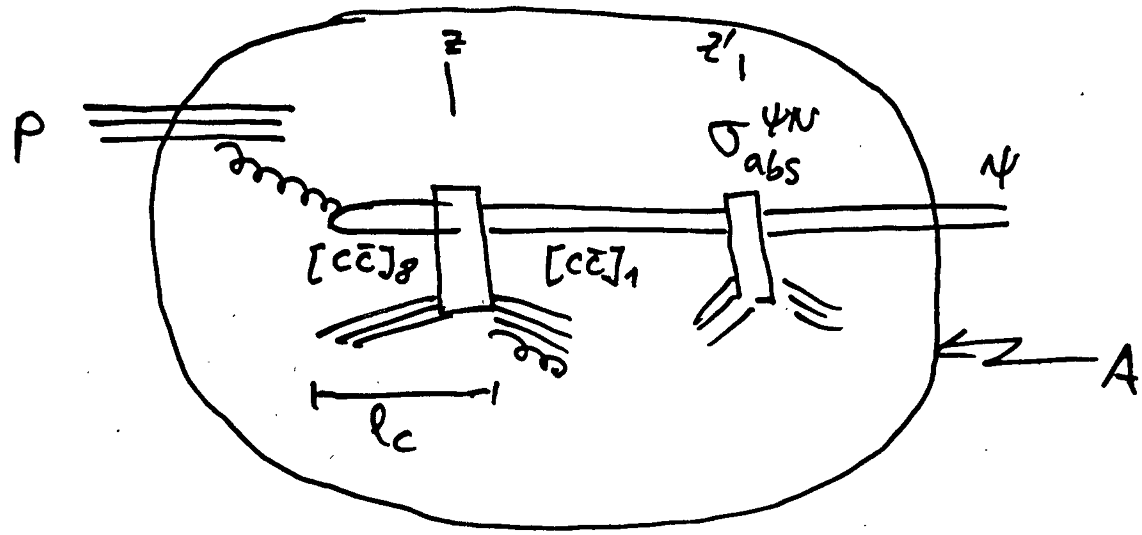
+(c) $N_{\psi_0}(Q^2=0) = \dfrac{M^2_{\psi_1} - M^2_{\psi_0}}{M^2_{\psi_1}} = 0.3 = \dfrac{1}{3.3}$

$$\sigma^{J/\psi N}_{tot} = 3.3\left(\sigma^{J/\psi N}_{tot}\right)_{VDM} = (4 \pm .8)\,\mu b \left(\frac{\sqrt{s}}{10\,GeV}\right)^{0.4}$$

$$\sigma^{\psi' N}_{tot} = (15 \pm ?)\,\sigma^{\psi' N}_{tot}\Big|_{VDM} = (4 \pm ?)\,\sigma^{J/\psi N}_{tot}$$

4. Formation time effects (PRL 76 (1996) 192)

$pp \to \psi X$ and $pA \to \psi X$



$$\ell_c \sim \frac{2E_\psi}{M_\psi^2} \quad \text{coherence length (formation of a } [c\bar c]_1)$$

$$\ell_f = \frac{2E_\psi}{M_{\psi'}^2 - M_{J/\psi}^2} \quad \text{formation length of } J/\psi \text{ or } \psi'$$

$$\sigma_{abs}^{\psi N} = \left\langle \frac{\langle [c\bar c]_1 | C r^2 | \psi\rangle}{\langle [c\bar c]_1 | \psi\rangle} \right\rangle_{z,z'}$$

$$|[c\bar c]_1 (z'-z)\rangle = |J/\psi\rangle + R\, e^{-i(z'-z)/\ell_f} |\psi'\rangle + \cdots$$

$$R^2 = \frac{\sigma(pp \to \psi' X)}{\sigma(pp \to J/\psi X)} = 0.23$$

$$\sigma_{abs}^{J/\psi N} = \sigma_{tot}^{J/\psi N} \cdot \left(1 + R \cdot \epsilon\, F(\ell_f / R_A)\right)$$

$$|\psi(t)\rangle = |\psi_0\rangle + \alpha_1 e^{-i(E_1 - E_0)t} |\psi_1\rangle + \cdots$$

$$\sigma_{abs}^{J/\psi N} = \sigma_{tot}^{J/\psi N} \left(1 + R \epsilon F\right)$$

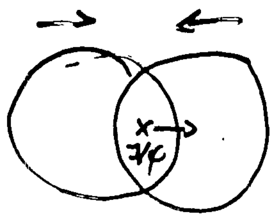
$$\epsilon = \frac{\langle \psi' | r^2 | J/\psi \rangle}{\langle J/\psi | r^2 | J/\psi \rangle} = -\sqrt{\frac{2}{3}}$$

$$F = \frac{2}{A\langle T \rangle} \int_{-\infty}^{+\infty} dz\, \rho_A(b,z) \int_{z}^{\infty} dz'\, \rho_A(b,z')\, e^{i z'/l_f}$$

$$\longrightarrow \begin{cases} 1 & \text{for } l_f/R_A \to \infty \\ 0 & \text{for } l_f/R_A \to 0 \end{cases}$$

$$(1 + R\epsilon F) \longrightarrow \begin{cases} 0.6 & l_f/R_A \to \infty \\ 1 & l_f/R_A \to 0 \end{cases}$$

Pb - Pb
156 GeV



J/ψ $x_F = .15$ in target frame
$x_F = -.15$ in projectile "

	$x_F = .15$, $l_f = 4$ fm	$x_F = -.15$, $l_f = 2$ fm
$\sigma_{abs}^{J/\psi N}$	3.3 mb	3.9 mb
$\sigma_{abs}^{\psi' N}$	4.8 mb	8.6 mb

Charmonium break-up by prompt gluons in heavy ion collisions

Boris Kopeliovich
Max-Planck-Institut für Kernphysik
Heidelberg

Based on J. Hüfner & B.K. hep-ph/9809300

(I) Challenges in charmonium production off nuclei

- J/ψ production in pA collisions treated in naive optical model need

  $\sigma_{abs}(J/\psi N) \approx 6$ mb

  However, VDM analysis of photoproduction data $\gamma p \to J/\psi p$, leads to

  $\sigma_{tot}(J/\psi N) = 1.2$ mb

  This problem was settled using a multi-channel analyses of data which led to

  J. Hüfner & B.K. PLB 426(1998) 154

  $\sigma_{tot}(J/\psi N) \approx 3-4$ mb

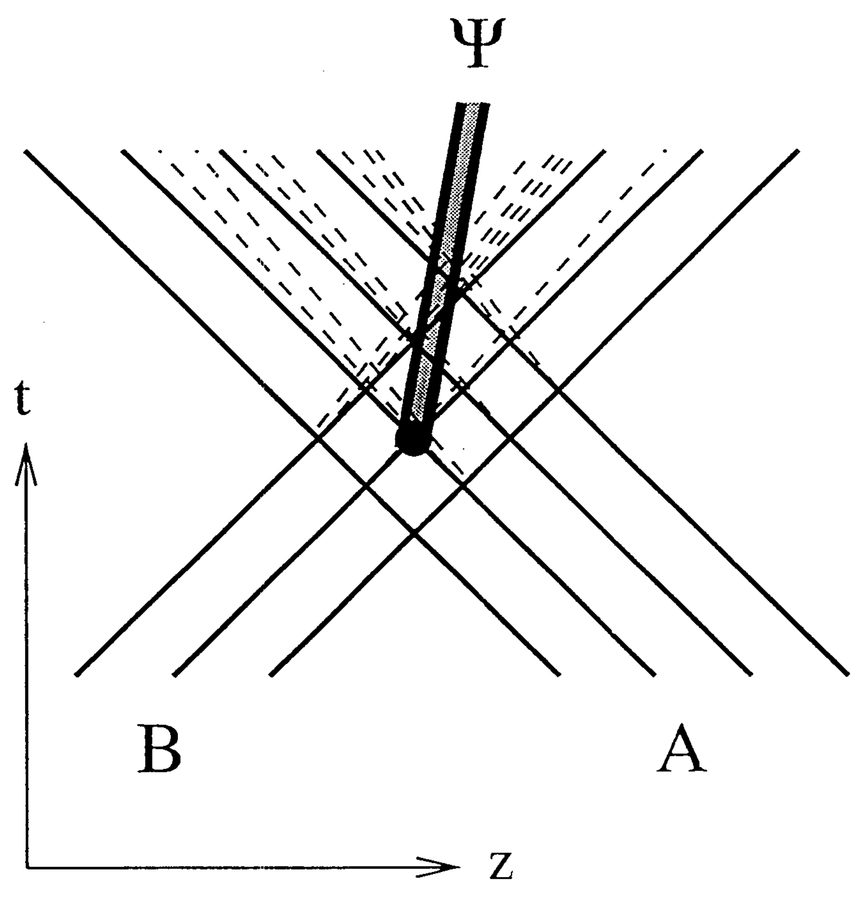
  a couple of mb still needs to be explained.

- $\psi'(2S)$ is expected to have about twice as large radius as J/ψ, correspondingly, a larger absorptive cross section.

- The NA50 found that J/Ψ is suppressed stronger than expected (~ 0.7) extrapolating from data with light projectiles (p, ^{16}O, ^{32}S)

Possible explanations

- Coomoving QGP (!) The late stage
- Coomoving hadrons (?) of Ψ production



★ Interaction with the gluons radiated at the early stage of Ψ production.

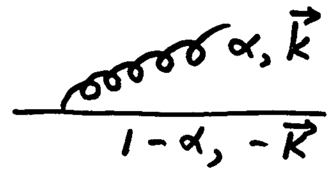
Why does the charmonium interact with the "wounded" nucleons with the same cross section as with the intact ones?

Interaction of Ψ with "wounded" nucleons (N^*) is different

$$\sigma_{tot}(\Psi N^*) \approx \sigma_{tot}(\Psi N) + \sigma_{tot}(\Psi g)\langle n\rangle ,$$

where $\langle n_g\rangle$ is the mean number of gluons radiated by a wounded nuclenon prior crossing the Ψ
The radiation length l_f^g should be shorter than the mean free path of a quark in a nucleus

$$l_f^g = \frac{2E_q\alpha(1-\alpha)}{\alpha^2 m_q^2 + k^2} < \Delta z$$



$\Delta z = \lambda/\gamma$; $\lambda \approx 6\,fm$, $\gamma = 10$ (SPS)

$$\langle n_g\rangle = \frac{3}{\sigma_{in}(NN)} \int_{k^2_{min}}^{\infty} dk^2 \int_{\alpha_{min}}^{1} d\alpha \, \frac{d\sigma(qN \to gX)}{d\alpha\, dk^2}\, \Theta(\Delta z - l_f^q)$$

$$\frac{d\sigma(qN \to gX)}{d\alpha\, dk^2} = \frac{3\alpha_s(k^2)C}{\pi}\, \frac{2m_q^2\alpha^4 k^2 + [1+(1-\alpha)^2](k^4 + m_q^4\alpha^4)}{(k^4 + m_q^2\alpha^2)^4}$$

$$\times \left[\alpha + \frac{9}{4}\frac{1-\alpha}{\alpha}\right],$$

B. K., A. Schäfer & A. Tarasov
hep-ph/9808378

where $C \approx 3$ ($\sigma(\rho) = C\rho^2$)

$k_{min} \approx 0.3 - 0.5$ GeV (θ-function cuts off smaller momenta)

$\omega_{min} = 0.5 - 1$ GeV

$\langle n_g\rangle \simeq 0.25 - 0.69$ (per NN collision)

Charmonium suppression

$$S_\psi^{AB} = \frac{1}{AB}\int d^2b \int d^2s \int_{-\infty}^{\infty} dz_A\, \rho_A(s, z_A) \int_{-\infty}^{\infty} dz_B\, \rho_B(\vec{b}-\vec{s}, z_B)$$

$$\times \exp\left[-\sigma_{eff}^{A}(\psi N)\int_{z_A}^{\infty} dz\, \rho_A(s,z) - \sigma_{eff}^{B}(\psi N)\int_{-\infty}^{z_B} dz\, \rho_B(\vec{b}-\vec{s}, z)\right]$$

$$\times \exp\left[-\sigma_{eff}^{A}(\psi g)\langle n_g\rangle \sigma_{in}(NN)\int_{z_A}^{\infty} dz\, \rho_A(s,z)\int_{-\infty}^{\infty} dz\, \rho_B(\vec{b}-\vec{s}, z)\right]$$

$$\times \exp\left[-\sigma_{eff}^{B}(\psi g)\langle n_g\rangle \sigma_{in}(NN)\int_{-\infty}^{\infty} dz\, \rho_A(s,z)\int_{-\infty}^{z_B} dz\, \rho_B(\vec{b}-\vec{s}, z)\right]$$

$$\times \exp\left[\frac{\langle n_g\rangle}{2}\left(\sigma_{eff}^{A}(\psi g)+\sigma_{eff}^{B}(\psi g)\right)\sigma_{in}(NN)\int_{z_A}^{\infty} dz\, \rho_A(s,z)\int_{-\infty}^{z_B} dz\, \rho_B(\vec{b}-\vec{s}, z)\right]$$

$$S_\psi^{pA} = \frac{1}{A}\int d^2b \int_{-\infty}^{\infty} dz_A\, \rho_A(b, z_A)\exp\left[-\sigma_{eff}^{A}(\psi N)\int_{z_A}^{\infty} dz\, \rho_A(b,z)\right]$$

$$\times \exp\left[-\sigma_{eff}^{A}(\psi g)\langle n_g\rangle \int_{z_A}^{\infty} dz\, \rho_A(b,z)\right]$$

The spatial distribution for the gluons is nearly the same as for the nucleons. Therefore, we use the same form of $\sigma_{eff}^{A,B}(\psi g)$ as for $\sigma_{eff}^{A,B}(\psi N)$.

To get an idea of theoretical uncertainty we try $\langle n_g\rangle = 0.25$ and 0.5

Drell-Yan and J/ψ Production in High-Energy Pb-Pb Collisions

Cheuk-Yin Wong, ORNL

(BNL Workshop, September 28, 1998)

Drell-Yan distribution gives E_T as a function of b

(hep-ph/9809497)

$$d\sigma_{DY}^{AB} = AB\ T_{AB}(\vec{b})\ d\vec{b}\ \sigma_{DY}^{pp},$$

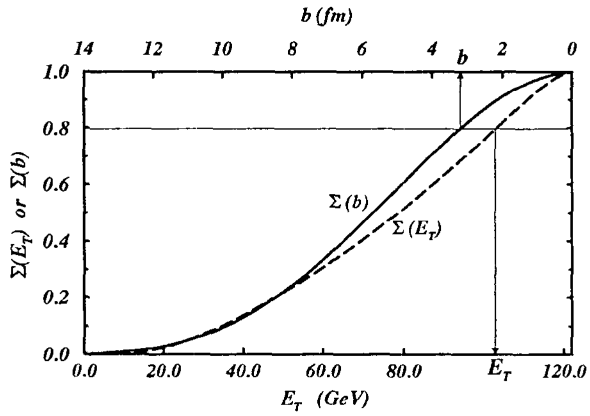
where $T_{AB}(\vec{b})$ is the thickness function. Therefore, we have

$$\frac{d\sigma_{DY}^{AB}}{dE_T} = AB\sigma_{DY}^{pp}\ T_{AB}(b)\ \frac{d\vec{b}}{dE_T},$$

$$\Sigma(E_T) \equiv \frac{1}{\sigma_{DY}^{AB}(total)} \int_0^{E_T} \frac{d\sigma_{DY}^{AB}}{dE_T'} dE_T' = \int_b^{\infty} T_{AB}(\vec{b'}) d\vec{b'} \equiv \Sigma(b),$$

$$\sigma_{DY}^{AB}(total) = \int_0^{\infty} \frac{d\sigma_{DY}^{AB}}{dE_T'} dE_T',$$

$$\Sigma(E_T \to \infty) = \Sigma(b=0) = 1.$$



1. Graphical method: Plot $\Sigma(E_T)$ and $\Sigma(b)$. The line of constant Σ intercepts the curves at b and its corresponding $E_T(b)$.

2. Parametrize $E_T(b)$ as

$$E_T(b) = \frac{E_{T0}}{1 + \exp[(b - b_0)/a]},$$

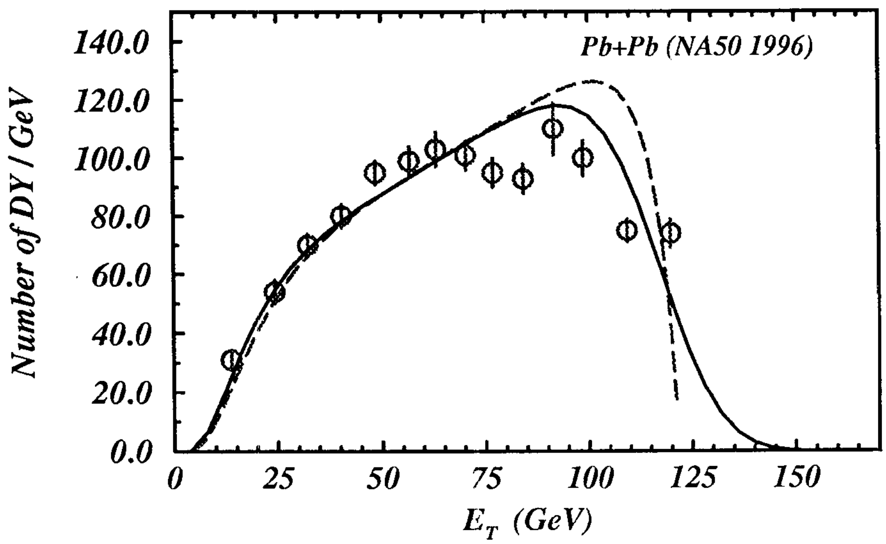
and vary E_{T0}, b_0, and a.

Drell-Yan distribution gives E_T as a function of b

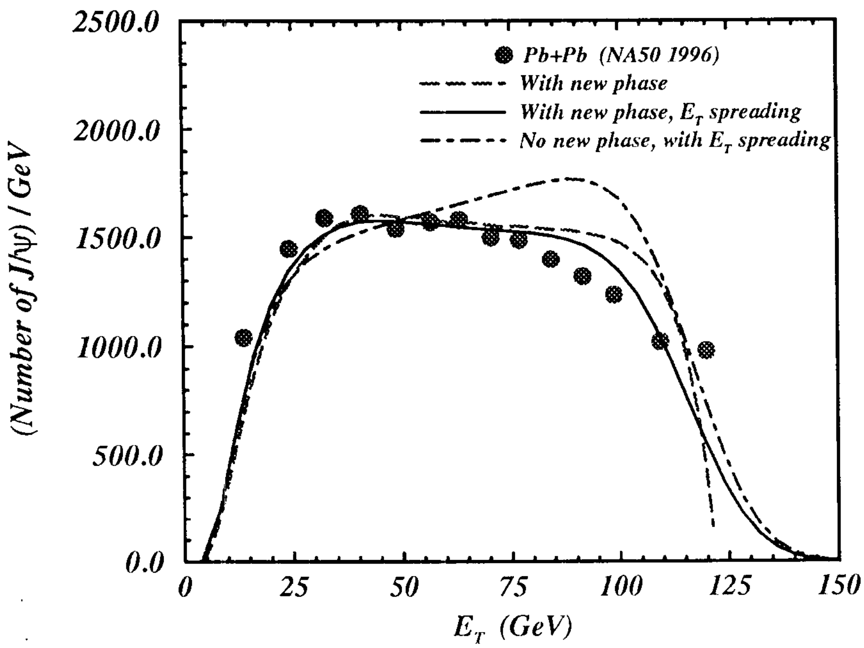
The Drell-Yan distribution dN_{DY}^{AB}/dE_T calculated for

$$E_T(b) = \frac{135 \text{ GeV}}{1 + \exp[(b - 6.7 \text{ fm})/3 \text{ fm}]},$$

is shown as the dashed curve. The Drell-Yan distribution with E_T spreading is shown as the solid curve.



There is good agreement between theory and data when one assumes a new phase of strong J/ψ absorption, with E_T spreading.



A Model of J/ψ Absorption

C.Y. Wong, Phys. Rev. Lett. 76, 196 (1996)
C.Y. Wong, Nucl.Phys. A610, 418c (1996)

The cross section for J/ψ production in AB collision

$$\frac{d\sigma_{J/\psi}^{AB}(\mathbf{b})}{\sigma_{J/\psi}^{NN}\, d\mathbf{b}} = \int \frac{d\mathbf{b}_A}{\sigma_{\rm abs}^2(J/\psi{-}N)} \left\{1 - \left[1 - T_A(\mathbf{b}_A)\sigma_{\rm abs}(J/\psi{-}N)\right]^A\right\}$$
$$\times\left\{1 - \left[1 - T_B(\mathbf{b} - \mathbf{b}_A)\sigma_{\rm abs}(J/\psi{-}N)\right]^B\right\} F(\mathbf{b}_A, \mathbf{b}),$$

$F(\mathbf{b}_A, \mathbf{b})$ is the survival probability due to soft particle collisions,

$$F(\mathbf{b}_A, \mathbf{b}) = \sum_{n=1}^{N_<} \frac{a(n)}{N_> N_<} \sum_{j=1}^{n} \exp\{-\sum_{i=1, i\neq j}^{n} k_{\psi h} t_{ij}^h\},$$

$N_>(\mathbf{b}_A)$ and $N_<(\mathbf{b}_A)$ are the greater and the lesser of the (rounded-off) nucleon numbers $AT_A(\mathbf{b}_A)\sigma_{in}$ and $BT_B(\mathbf{b} - \mathbf{b}_A)\sigma_{in}$, $a(n) = 2$ for $n = 1, 2, ..., N_< - 1$, and $a(N_<) = N_> - N_< + 1$.

$$k_{\psi h} = \rho_h^{NN} v_h \sigma_{\rm abs}(J/\psi{-}h),$$

$$\rho_h^{NN} = \frac{dN_h^{NN}}{dy} \frac{1}{\sigma_{in}(d/\gamma)},$$

$$t_{ij}^h = t_n + t_f - {\rm Max}(t_i + t_h, t_j + t_{c\bar{c}}),$$

$$t_h = \text{ the hadronization time } = 1.2 \text{ fm/c},$$

$$t_{c\bar{c}} = c\bar{c} \text{ production time } = 0.06 \text{ fm/c},$$

$$t_f = t_h + t_h \ln(t_{\rm freezeout}/t_h) = t_h + t_h \ln(\rho_h^{NN}/\rho_{\rm freezeout}^{NN}),\ \rho_{\rm freezeout}^{NN} = 0.5 \text{ hadrons/fm}^3.$$

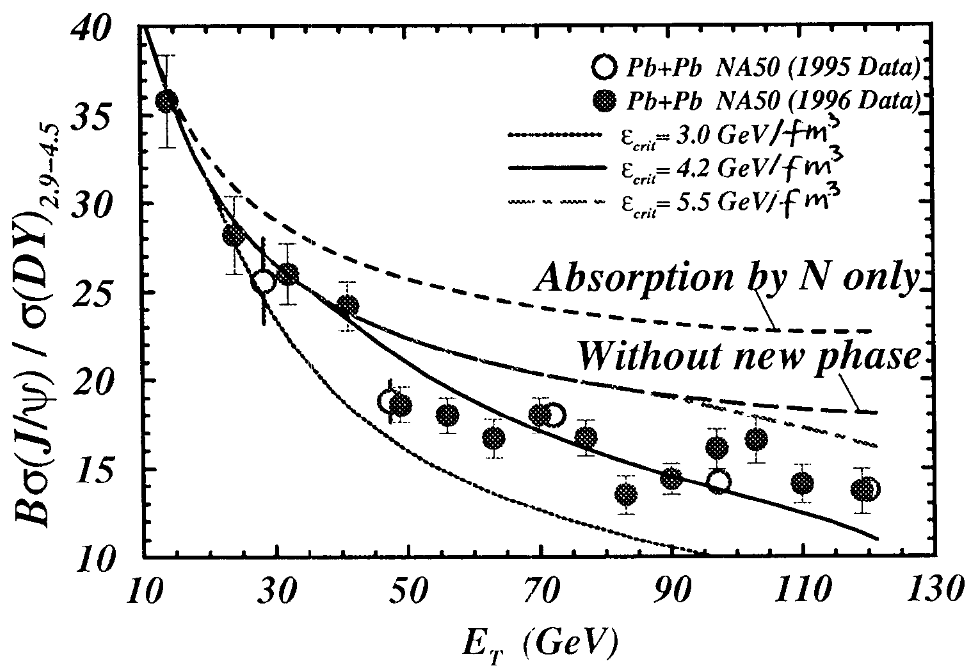
Results from the J/ψ Absorption Model

We found that J/ψ absorption by produced hadrons, as revealed by O-Cu, O-U, and S-U collisions, is small, and the experimental Pb-Pb yield is much smaller than the extrapolated results if one assumes J/ψ absorption by nucleons and produced hadrons only.

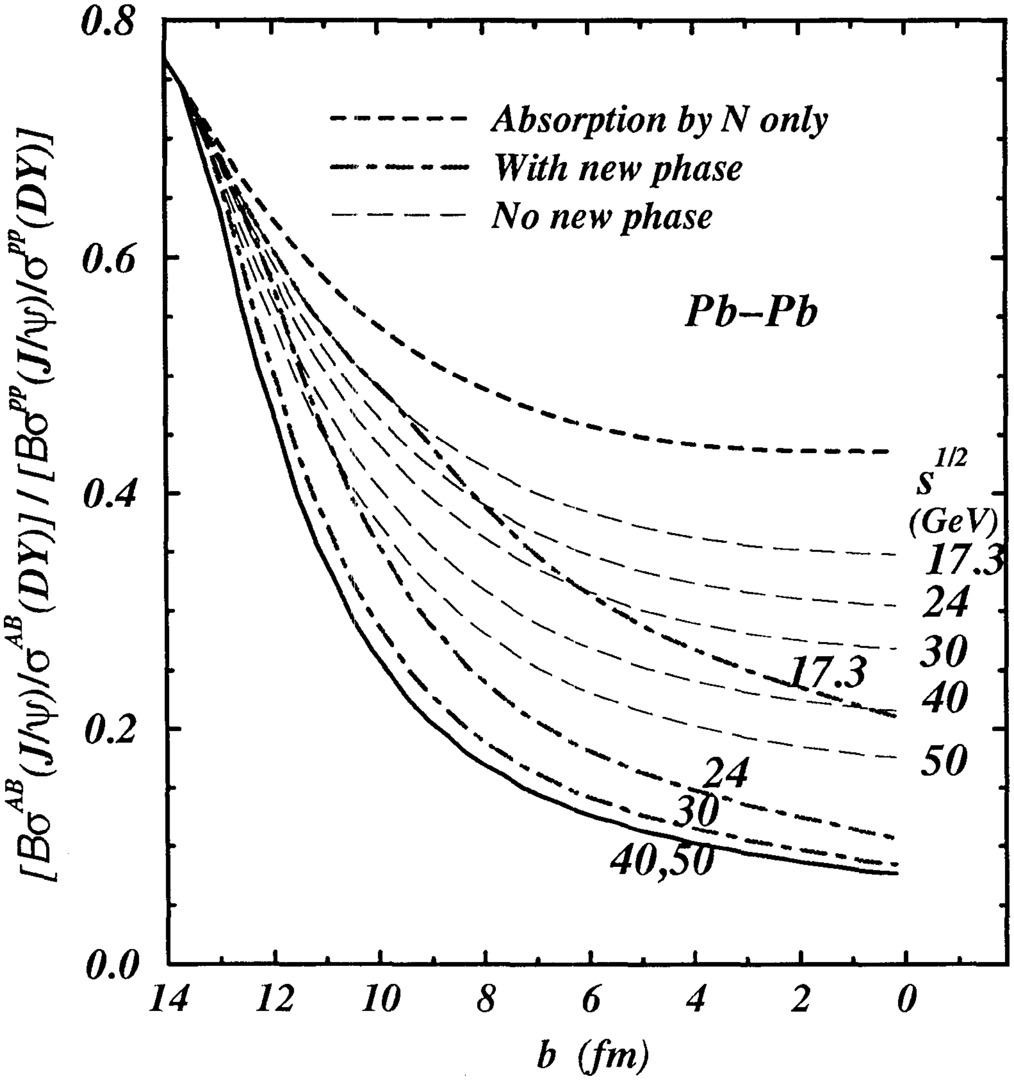
The deviation of the J/ψ data in Pb-Pb collisions from the conventional theoretical extrapolations suggests that there is a transition to a new phase of strong absorption, which sets in when the local energy density ϵ, $\epsilon = \nu \rho_h^{NN} m_t$,

exceeds $\epsilon_{\rm crit}$. Here, ν is the number of prior nucleon-nucleon collisions at that point, and m_t is the transverse mass of a produced hadron.

$\epsilon_{\rm crit} = 4.2$ GeV/fm^3 gives good agreement with data:



Dependence of J/ψ Survival Probability on Collision Energy



If a new phase of strong J/ψ absorption is assumed, the J/ψ survival probability reaches the lowest survival limit (the solid curve) when the nucleon-nucleon center-of-mass energy $\sqrt{s} > 35$ GeV.

CONCLUSIONS:

1. Drell-Yan distribution gives $E_T(b)$.
2. The anomalous suppression of J/ψ in Pb-Pb collisions can be explained by a model in which a new phase of strong absorption sets in when the local energy density exceeds 4.2 GeV/fm^3.
3. The J/ψ survival probability reaches the lowest survival limit when the collision energy $\sqrt{s} > 35$ GeV.

PHENIX Overview

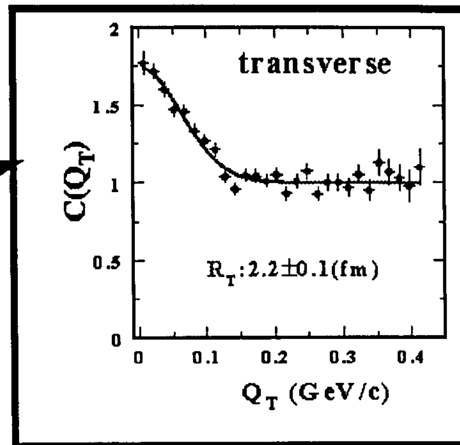
- PHENIX PHilosophy
- PHENIX PHeatures
- PHENIX Physics
- Thanks to:
  - The ~454-1 PHENIX colleagues who have contributed to this talk

Quarkonium Workshop
BNL, Sep-97

Prototypical Heavy Ion Signals

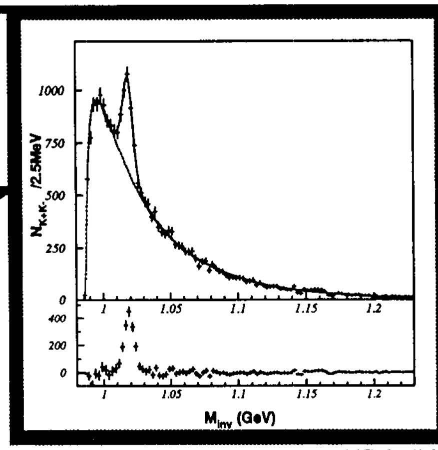
PHENIX

- **Iconography:**
  "The pictorial illustration of a given subject"
  (American Heritage Dictionary)



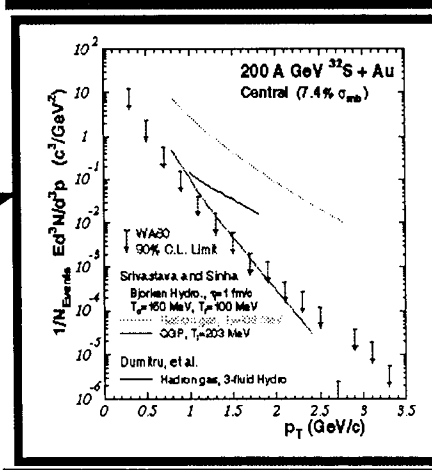
NA44

- **Ratings based on:**
  - Interest generated
  - Relation to primordial state
  - Subjective impression

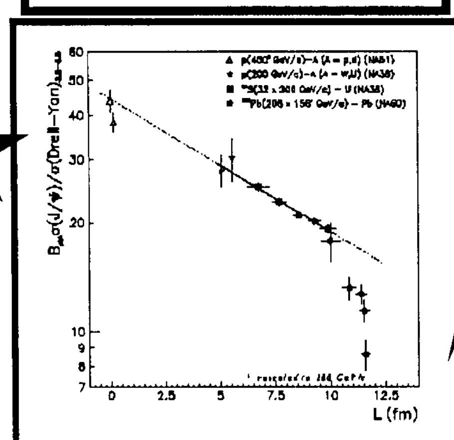


E859

- **PHENIX:**
  - Will measure all of these (and more) in <u>*a single experiment*</u>



WA80



NA50

Nota Bene: These are *not* the ratings of the experiments!

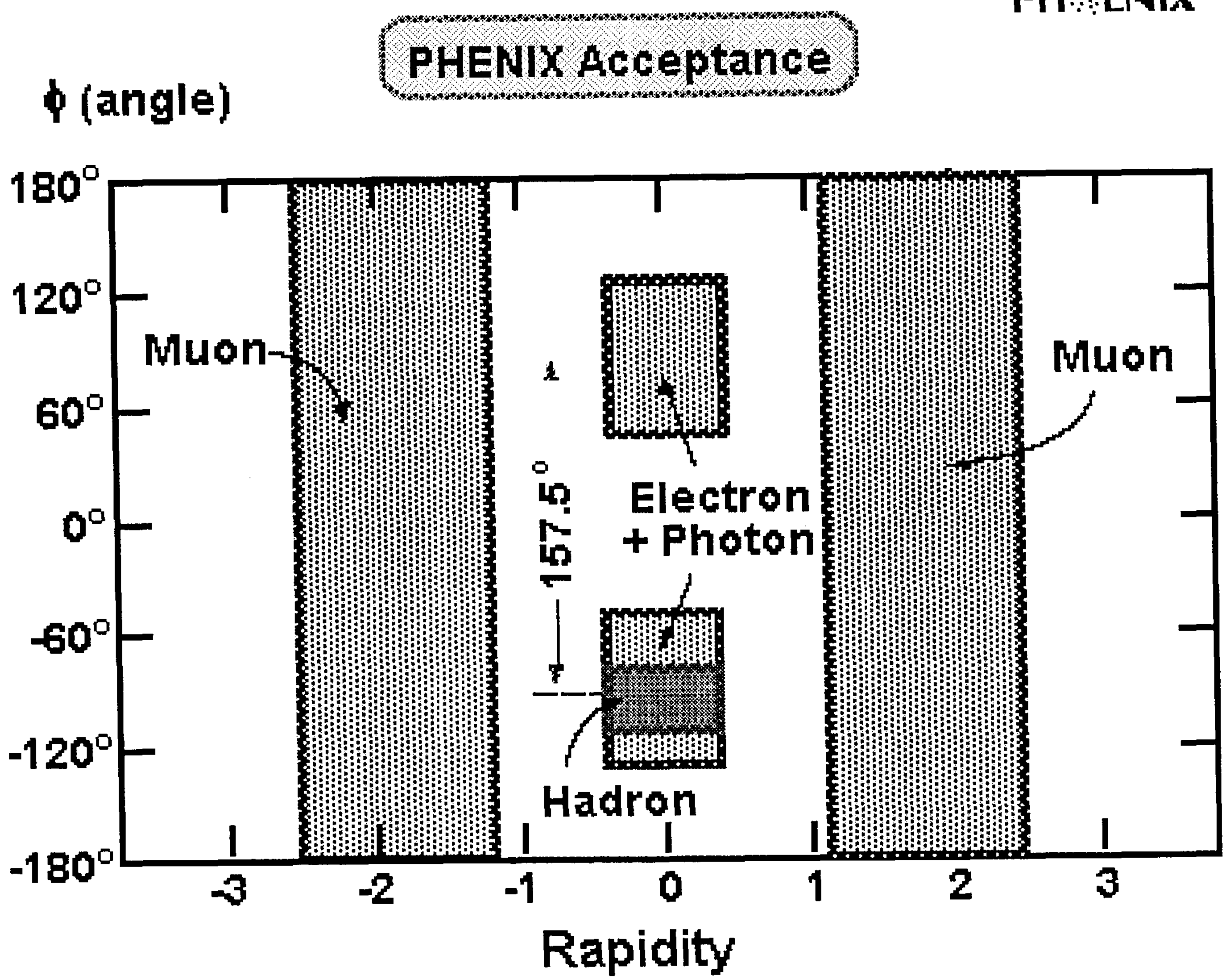
PHENIX Aperture(s)

PHENIX

Philosophy:

- Measure ~ all things well in "small" apertures
- Measure "few" things well in large apertures

PHENIX

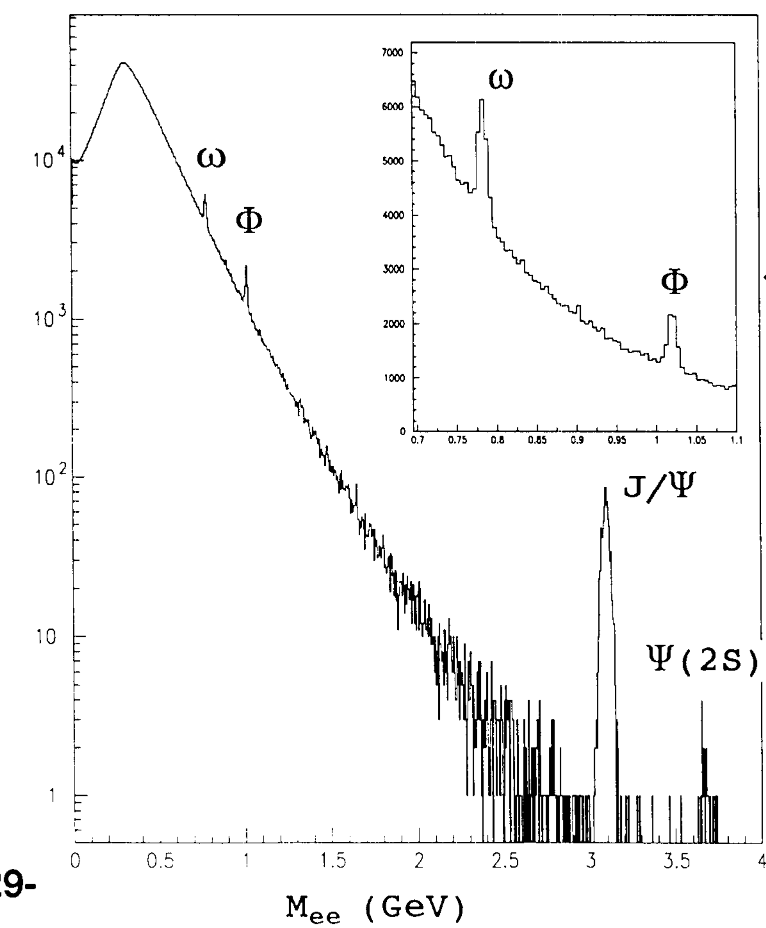


Vector Mesons in PHENIX

PHENIX

- **Rate is not the major problem:**
- **This represents:**
  - ~10 weeks at 1% design luminosity
  - ~1 week at 10% design luminosity
  - ~1 week at 100% design luminosity (without a trigger)
  - ~1 week at 10 x design luminosity (without a trigger)

Vector mesons and background
(π^0 Dalitz, γ conversion, etc)
Rhic Au+Au central collision
32 M events in PHENIX e-arms

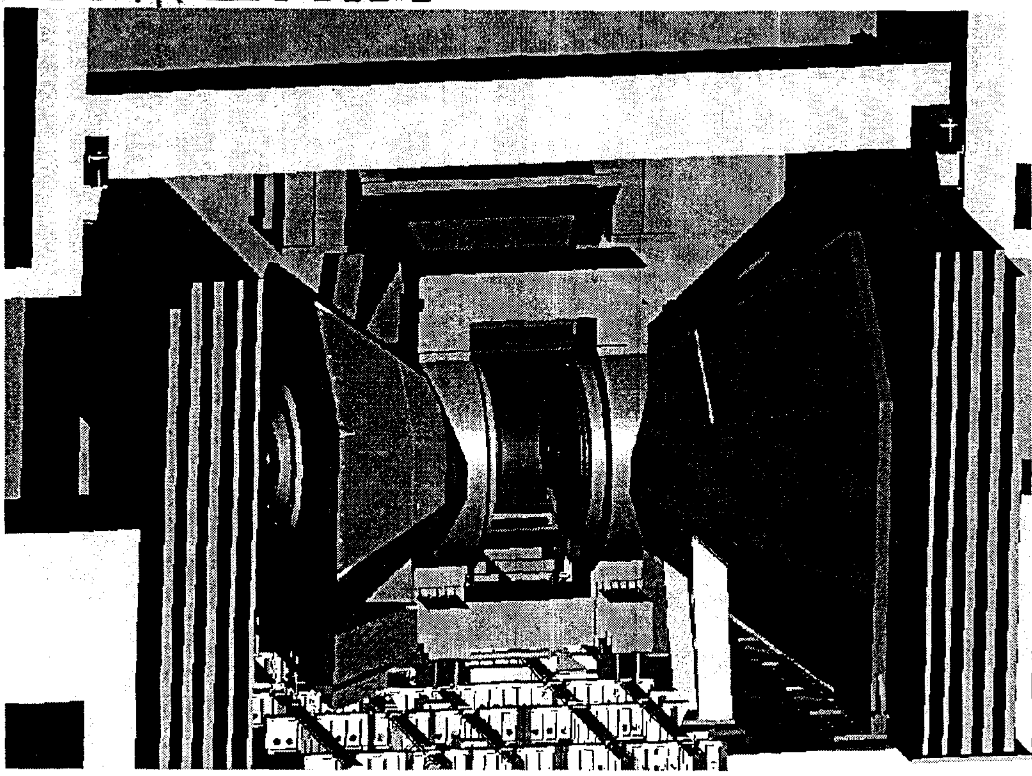


Calculation by Y. Akiba

See talks by M. Rosati (J/Ψ) and Y. Akiba (open charm)

PHENIX Di-Muon Physics

PHENIX



Compilation by M. Leitch

- See talk by M. Rosati for details on J/Ψ rates
- Physics rates compare well to existing fixed-target ``standards":

	PHENIX Central Au + Au	PHENIX Min. bias Au + Au	FNAL E772
$\rho \to \mu^+ + \mu^-$	> 300K	> 1M	-
$\phi \to \mu^+ + \mu^-$	> 139K	> 500K	-
$J/\psi \to \mu^+ + \mu^-$	700K	3M	100K
$\psi' \to \mu^+ + \mu^-$	10K	24K	12K
$\Upsilon \to \mu^+ + \mu^-$	2160	9K	17K
D-Y (4-9 GeV)	~ 24K	~ 100K	450K
$\sqrt{s}$ (GeV)		200	39
x_F		-0.3 to 0.3	0 to 0.6
p_T (GeV)		0-10	0-2.5
x_2		$\sim 10^{-4}$-0.2	~ 0.03-0.27

QGP Discovery

PHENIX

Q. How to categorize various approaches to QGP detection and characterization?

A?. "Factorization":

$$\sigma(QGP) = \sigma(INT) \times \mathcal{P}(formation) \times \mathcal{P}(probe)$$

$\sigma(INT)$ - geometry

$\mathcal{P}(formation)$ - unknown

$\mathcal{P}(probe)$ - below

	Common	Rare
Appearance	Strangeness Charged Pions Neutral Pions HBT Mass shifts Fluctuations in dn/dy	Direct Photons Thermal di-leptons Open Charm
Disappearance	Neutral Pions Charged Pions HBT $\Phi \rightarrow KK$? (jets)	J/Ψ (jets)

Rare probes in disappearance mode will require concerted effort to establish by dependence on

- ✓ centrality
- ✓ E_{CM} (note advantage of collider)
- ✓ A,B
- ✓ p_T

Comments on the Status of STAR Prospects for Detecting Heavy Flavor

T. Hallman

Quarkonium Production in Relativistic Nuclear Collisions

September 28 - October 2, 1998.
A RIKEN BNL Research Center Workshop

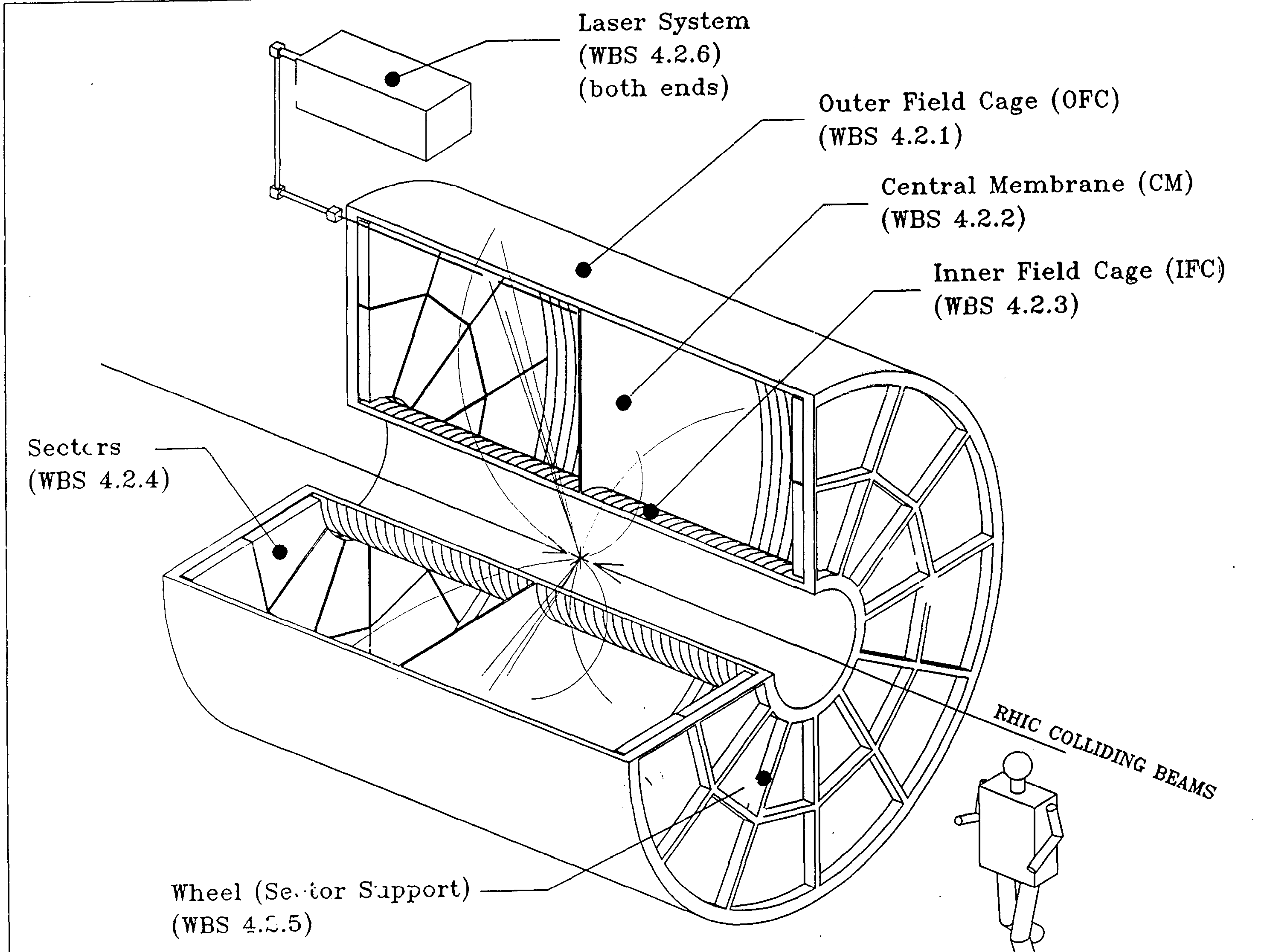
Electron Identification

Backgrounds:

- hadrons incorrectly identified
  (E/p, shower profile)
- gamma conversions
  (vertex pointing, partner, missing track)
- Dalitz electrons
  (partner)
- Pairs of any of the above

Handles On Electron ID:

- Energy-momentum matching (TPC, EMC)
- dE/dx in the tracking chambers (SVT, TPC)
- Shower max size, shape, position (SMD)
- Energy deposited in pre-shower (EMC)
- Identification of conversions (SVT, EMC)



RHIC-STAR TPC (WBS 4.2)

STAR Detector Construction Milestones - 9/11/98 Scheduling Mtg.

	MILESTONE	DATE	DEP
	First 20 CTB trays at BNL	9/15/98	
	DAQ Rm Racks water/power/smoke/intergen system install complete	10/1/98	
	Pull & replace 3 problem sectors complete	10/7/98	
	DAQ Infrastructure installation in DAQ room complete	10/7/98	racks
	Power & tray installation in control room complete	10/15/98	
	Rack water leak detection system install complete	10/15/98	
	Base floor pads/column anchors installation complete	11/1/98	
	Micro DAQ available for TPC FEE/RDO testing	11/1/98	
•	TPC tent & temporary utilities come down	11/3/98	
•	Magnet mapper removal complete	11/7/98	
	First 20 CTB trays installed on TPC	11/10/98	tent rem.
	TCU (1) Board available for system test	11/10/98	
	CTB HV & signal cables, HV supplies & SC installed	11/15/98	
•	TPC Support arm installation complete	11/15/98	Mapper
	Temporary Network installation to Platform complete	11/15/98	
•	Computer & Network installation in Control room complete	11/15/98	power
	FEE Pwr Supply move to South Platform complete	11/15/98	racks/map
	Rack infrastructure (water, power, detection & suppression) ORR	11/15/99	
•	DAQ Final Design Review	11/25/98	
•	First "50%" of FEE & RDO installation &testing w/ Micro DAQ complete	11/26/98	
	Network installation from S to N Platform complete	11/30/98	
•	TPC mechanical installation in MAG complete	12/3/98	
	Clock/Trigger, HDLC & FEE DC Power installation complete	12/15/98	
	DSM (1) Board available for system test	12/18/98	
	Detector ventilation, smoke & flam. mixture detection install complete	1/10/99	
	All CTB trays at BNL	1/11/99	

9/29/98

STAR Detector Construction Milestones - 9/11/98 Scheduling Mtg.

	SVT scaffolding installation complete	1/12/99	
	DAQ production card debug begins	1/15/99	
	Final TPC ORR for operation in MAG	1/15/99	
●	Detector global safety interlock system installation complete	1/20/99	
	Detector interlocks ORR	1/21/99	
●	SVT Cone installation complete	1/25/99	
	TPC ready for operation w/ P-10 in MAG	1/25/99	Cone/ Ventil.
	Festoon installation complete	2/1/99	
	Beampipe support installation complete in WAH	2/15/99	
	Fiber Cabling from Detector to DAQ complete	2/15/99	Festoon
	Permanent Network installation to Platform complete	2/15/99	Festoon
●	DAQ installation in crates begins	2/15/99	
	All CTB trays installed on TPC in MAG	2/15/99	
	SCRAM NET & cable installation complete	2/15/99	Festoon
	All DSM & TCU boards installed & tested	3/1/99	
●	Last "50%" of FEE & RDO installation &testing w/ Micro DAQ complete	3/1/99	
●	Magnet/TPC run and Test	3/1-15/99	FEE inst complete
	Final Detector System ORR	3/16/99	
●	Begin Detector Roll-in (to WAH) process	4/1/99	
	Final ORR walkthrough of detector in WAH	5/15/99	
	Complete baseline TRG system installed & tested	5/31/99	
●	STAR Detector ready for RHIC commissioning run	5/31/99	
	Complete baseline DAQ system installed & tested	7/31/99	

9/29/98

EMC Installation Profile

Year	Modules	Coverage*	
FY 99	12	$1 < \eta < 0$,	$0^\circ < \phi < 72^\circ$
FY00	30	$1 < \eta < 0$,	$-120^\circ < \phi < 120^\circ$
FY01	32	$1 < \eta < 0$,	$-120^\circ < \phi < 120^\circ$
		$0 < \eta < -1$,	$0^\circ < \phi < 192^\circ$
FY02	32	$1 < \eta < 0$,	$-180^\circ < \phi < 180^\circ$
		$0 < \eta < -1$,	$-72^\circ < \phi < 192^\circ$
FY03	14	$1 < \eta < -1$,	$-180^\circ < \phi < 180^\circ$

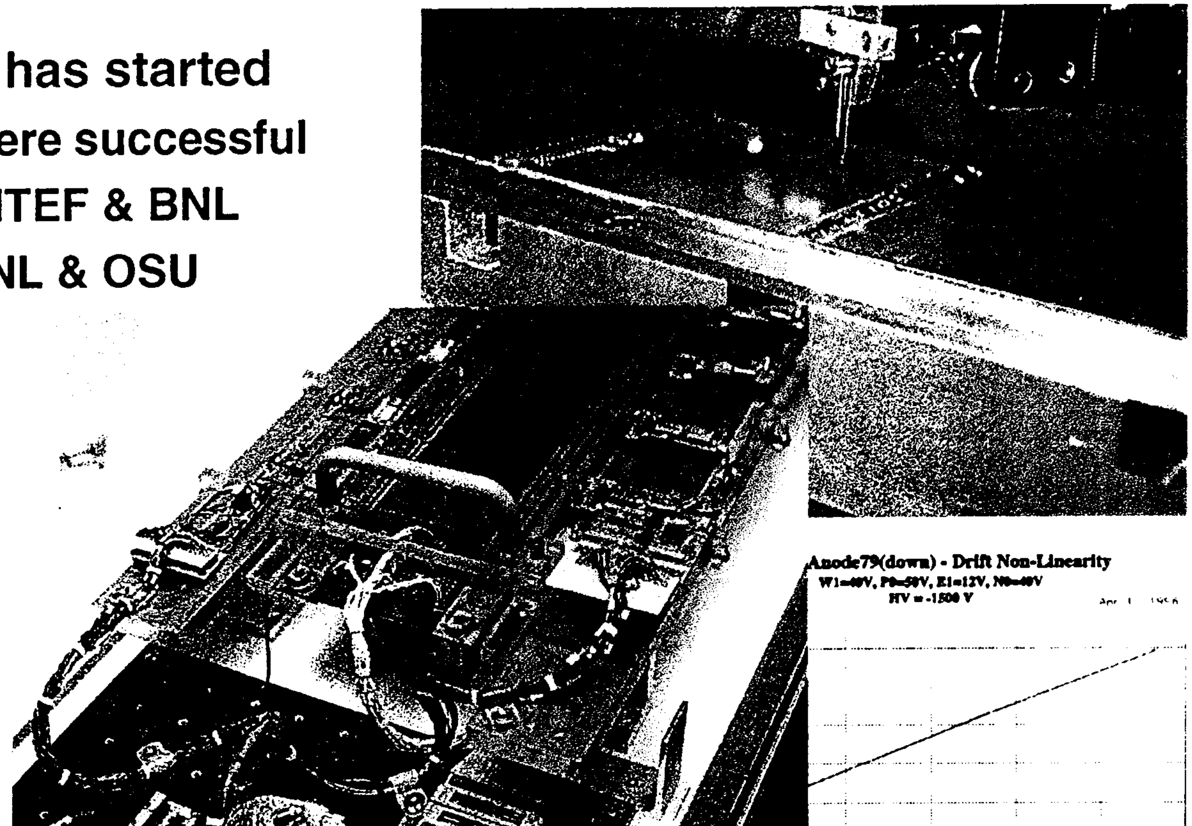
* Assumes $\eta = 1$ is in the west direction, and

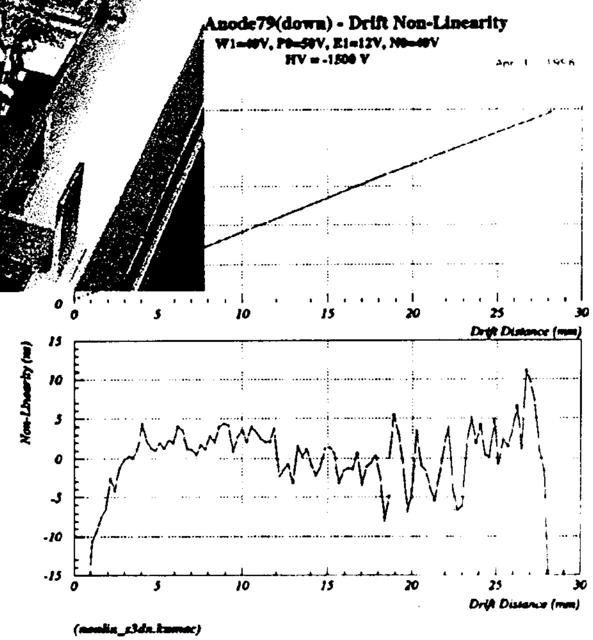
$\phi = 0^\circ$ is at 12:00 0'clock looking west

The SVT - an AEE project

STAR

- Si Wafer production has started
  - Prototype & test were successful
  - Two suppliers: SINTEF & BNL
  - Two Q/A teams: BNL & OSU
- Electronics
  - PASA & SCA in production
  - Hybrids tested & production soon
  - Final design for RDO components
- Mechanical
  - Be ladder prototype was a success
  - French collaborators will build the SVT support cone (This month!)
- Successful Tests
  - E896: Two SDDs test STAR multiplicities
  - Ladder test: 4 wafer test of integration issues





STAR SVT Critical Path Milestones

Apr 1998	**50% completion of die production**
Jun 1998	**Beryllium fabrication start**
Aug 1998	**Flex cable production start**
Sep 1998	**5% hybrids assembled & tested**
Sep 1998	**RDO production model completed**
Nov 1998	**Ladder assembly start**
[illegible] 1999	**Completion of SVT support cone**
[illegible] 1999	**50% hybrids/cables/wafers assembled & tested**
Aug 1999	**100% hybrids/cables/wafers assembled & tested**
Aug 1999	**SVT assembly start**
Nov 1999	**100% ladders completed**
[illegible]	**SVT assembly completed**
	SVT DAQ Installation
[illegible] 2000	**SVT installation completed**

Conclusions

- Preliminary “back of the envelope” calculations indicate that further investigation is warranted
- The full tracking capability required for this physics will come on-line in STAR in the FY 2001 running period
- Given the EMC installation scenario under discussion, the necessary acceptance would begin to be available in the FY 2002 running period, with full acceptance in FY 2003

Open Charm measurement with PHENIX

Y.Akiba (KEK)

September 30, 1998

Quarkonium Production in Relativistic Nucleus Collisions

A Riken BNL Research Center Workshop

Measurement single electron in central arm

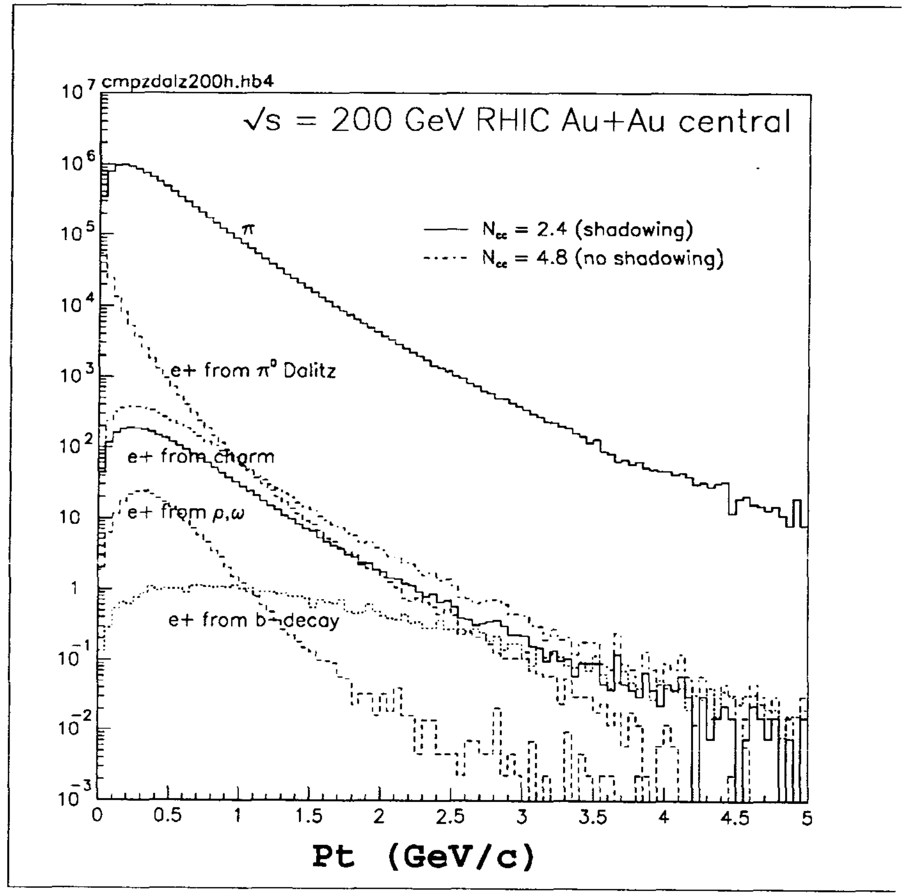
Production of heavy quark (c, b) in central rapidity (y ~ 0) can be detected by single high pt electrons (pt > 1.5 GeV/c) in central arms

Single electron spectrum is dominated by π^0 Dalitz decay electron at low pt (pt < 1-2 GeV/c). In moderately high pt (pt > 1 - 2 GeV/c), charm decay electron contribution becomes comparable to Dalitz decay. At very high pt (pt > 4 GeV/c), b-quark electrons becomes the dominant source.

e/π ratio in high pt region (pt> 1 GeV/c) is about 1/1000, while PHENIX will have pion rejection better than 1000 in this momentum region.

S/B ratio may become even larger if there is a large energy loss of quarks in A+A collisions. (The background pion spectrum becomes softer, while charm electron have a boot from decay)

The yield of single leptons in central arms will be very large. A few million events per year above pt 1 GeV/c is expected with nominal RHIC luminosity.



Electron momentum distribution at y=0 in RHIC Au+Au collisions and their sources. Ncc ~ 2.4 or 4.8 and dN/dy(π^0) ~ 400 is assumed

Measurement of single muon in PHENIX muon arms

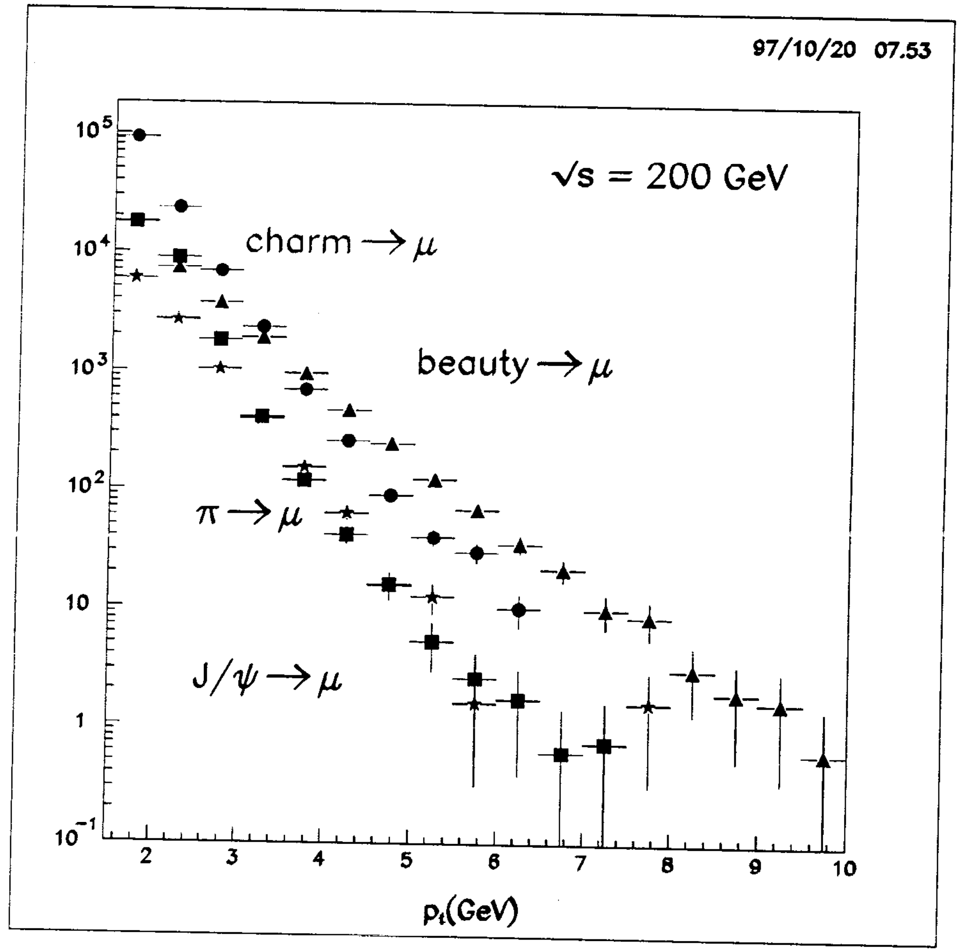
- Heavy quark production in forward and backward rapidity ($1.2 < |y| < 2.4$) can be studied from measurement of single high p_t muons in muon arms.

- Heavy quark production (b, c) is the dominant source of single high p_t muons for $p_t > 2$ GeV/c

- b-quark muons dominates over charm decay muons for pt > 4 GeV/c.

- Pion/kaon decay background can be estimated from the distribution of collision vertex, and then statistically subtracted from the data.

- Yield is very large. More than a million events per year are expected for pt above 2 GeV/c.



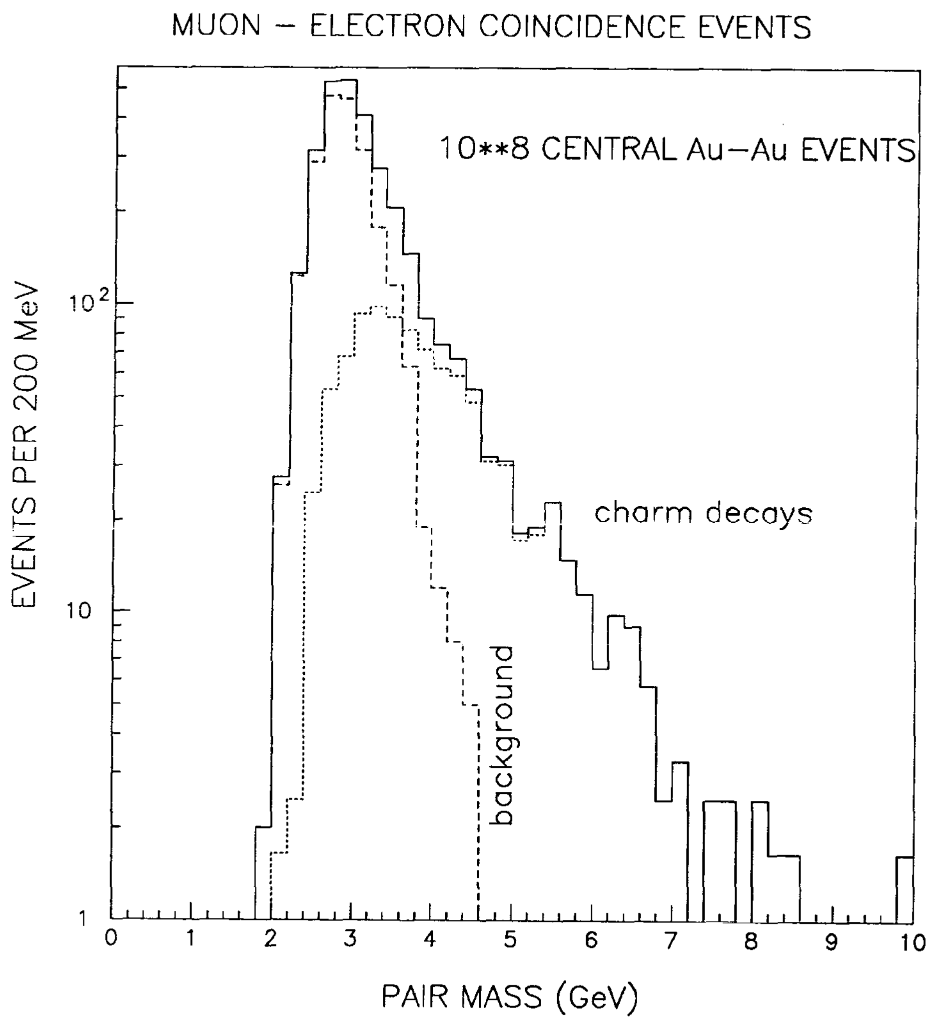
Pt distribution of single muons in PHENIX south muon arm. Studied by M. Brooks and J. Moss

eμ measurement

An unlike-sign high mass em pair is produced from charm pair followed by c → e and c → μ
decays.

Those electrons and muons can be detected by central arms and muons arms.

The charm signal can be observed in eμ pair mass above 4 - 5 GeV.



Mass spectrum of eμ pair from 10^8 Au+Au central events. From PHENIX CDR.

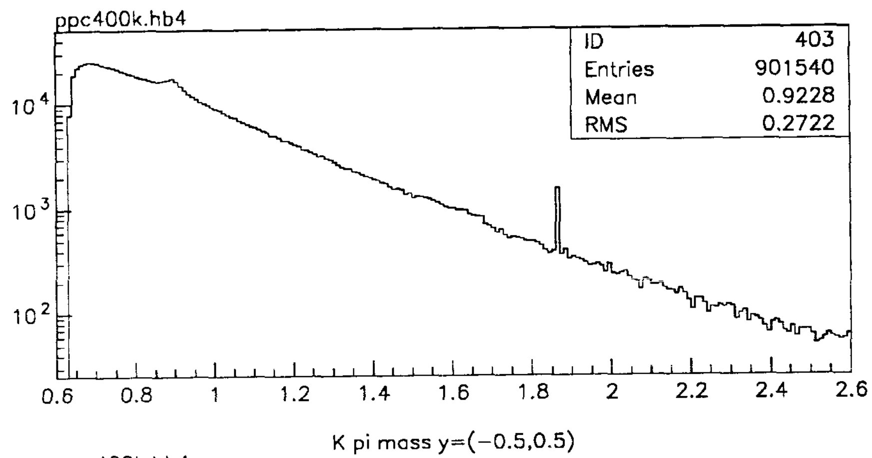
D measurement in p+p and p+A

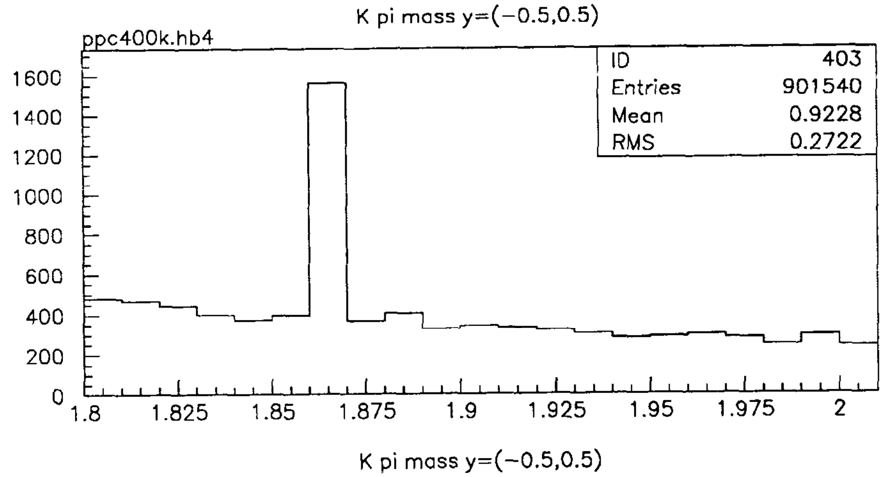
With a help of single lepton tagging in central or muon arms, D^0 mesons from p+p or p+A collision can be reconstructed from its $K\pi$ decay in central arm. (Kaons are identified by high resolution TOF wall or EMCAL TOF). D^0 meson signal with a reasonable S/B ratio will be obtained.

Expected event rate is about 100 reconstructed, electron tagged D^0 per 1 pb^{-1} (1 day of RHIC p+p run at nominal luminosity), and several times more for muon tagged ones. Other charmed meson can also be detected with lepton tag.

This direct measurement will supplement “indirect measurement” using single leptons or lepton pairs in p+p and p+A collisions.

For A+A collisions, this method become much more difficult because of large combinatorial background. It is not feasible except for very light ion collisions or very peripheral collision.





$K\pi$ invariant mass distribution in p+p events with charm pair, calculated with PYTHIA. A peak at 1.8 GeV is a signal of $D^0 \rightarrow K\pi$ decay.

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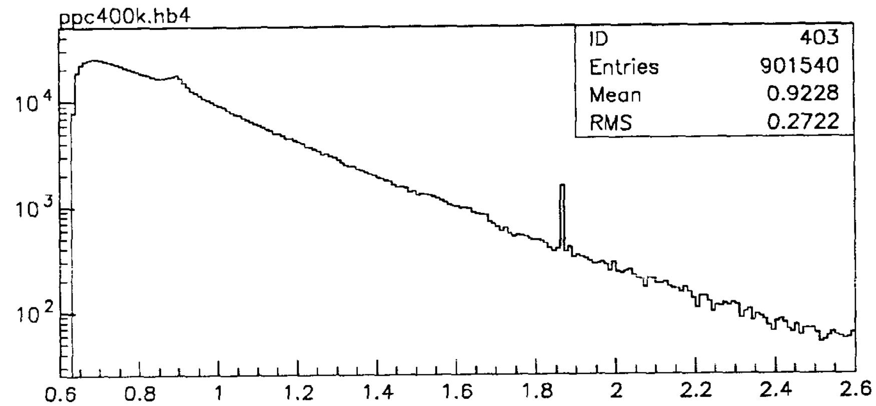
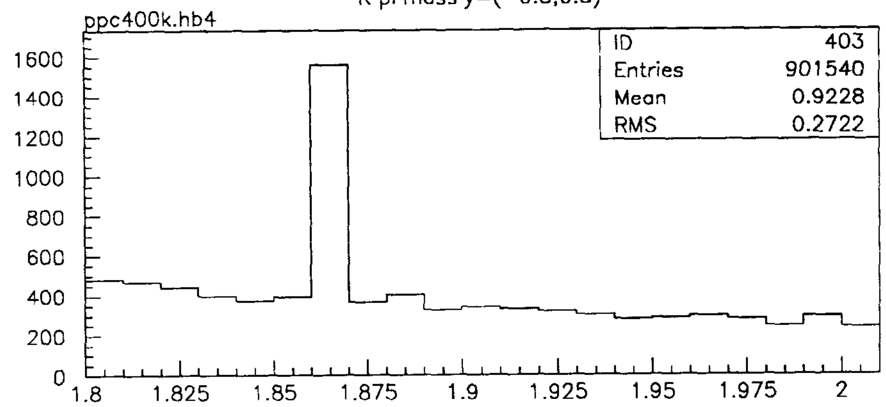




$K\pi$ invariant mass distribution in p+p events with charm pair, calculated with PYTHIA. A peak at 1.8 GeV is a signal of $D^0 \rightarrow K\pi$ decay.

Summary

Large production of charm is expected at RHIC

Charm production can be studied with PHENIX detector through many process with high statistics in wide rapidity coverage ($-2.4 < y < 2.4$).

- high pt single electrons in central arms
- high mass electron pairs in central arm
- high pt single muons in muon arms
- high mass muon pairs in muon arms
- e m coincidence in central and muon arms
- D mesons tagged with high pt leptons (p+p and p+A)

Those variety of measurement can address many physics issues

- Gluon shadowing in p+A and A+A collisions
- Thermal and pre-equilibrium charm production in A+A
- Energy loss of c quarks in hot matter
- Spin dependence of charm production (gluon polarization)

J/ψ Suppression in Nucleus-Nucleus Collisions

Jianwei Qiu[1]
Department of Physics and Astronomy, Iowa State University
Ames, Iowa 50011, USA

We propose a model for the production and suppression of J/ψ mesons in high-energy hadronic collisions. We factorized the process into a production of the $c\bar{c}$ pairs of relative momentum $k = k_c - k_{\bar{c}}$ convoluted with a transition probability from the produced $c\bar{c}$ pairs into the observed J/ψ mesons,

$$\sigma_{A+B\to J/\psi+X}(S) = K_{J/\psi} \sum_{a,b} \int dq^2 \left[\frac{\hat{\sigma}_{ab\to c\bar{c}}(Q^2)}{Q^2}\right] \times \int dx_F\, \phi_{a/A}(x_a,\mu^2)\, \phi_{b/B}(x_b,\mu^2)\, \frac{x_a\, x_b}{x_a + x_b}\, F_{c\bar{c}\to J/\psi}(q^2)\ , \tag{1}$$

where $\sum_{a,b}$ runs over all parton flavors, and $Q^2 = q^2 + 4m_c^2$. Because of the two-parton final-state at the leading order, the incoming parton momentum fractions are fixed by the kinematics, and given by $x_a = (\sqrt{x_F^2 + 4Q^2/S} + x_F)/2$ and $x_b = (\sqrt{x_F^2 + 4Q^2/S} - x_F)/2$, respectively. In Eq. (1), the short-distance hard parts for producing the $c\bar{c}$ pairs, $\hat{\sigma}_{q\bar{q}\to c\bar{c}}(Q^2)$ and $\hat{\sigma}_{gg\to c\bar{c}}(Q^2)$, are calculated in perturbative QCD. In Eq. (1), the integration limits of x_F are chosen to be consistent with the data. The function $F_{c\bar{c}\to J/\psi}(q^2)$ represents a transition probability for a $c\bar{c}$ pair to evolve into a physical J/ψ meson. We propose three alternatives for parameterizing the transition probability,

$$F^{(P)}_{c\bar{c}\to J/\psi}(q^2) = N_{J/\psi}\, \theta(q^2_{\max} - q^2) \left(1 - q^2/q^2_{\max}\right)^{\alpha_F}\ , \tag{2}$$

$$F^{(C)}_{c\bar{c}\to J/\psi}(q^2) = N_{J/\psi}\, \theta(q^2_{\max} - q^2)\ , \tag{3}$$

$$F^{(G)}_{c\bar{c}\to J/\psi}(q^2) = N_{J/\psi}\, \exp\left[-q^2/(2\alpha_F^2)\right]\ , \tag{4}$$

where $q^2_{\max} = 4m'^2 - 4m_c^2$ with m' the mass scale for the open charm threshold. The parameters, $N_{J/\psi}$ and α_F in the $F_{c\bar{c}\to J/\psi}(q^2)$'s, and the K-factor, $K_{J/\psi}$ in Eq. (1) are to be fixed by fitting the existing total production cross section data from hadron-hadron collisions.

As the produced $c\bar{c}$ pairs exit the nuclear matter, the absorption of gluons by the colored c and $\bar{c}$ increases the square of the relative momentum between the c and $\bar{c}$,

$$q^2 = -(k_c - k_{\bar{c}})^2 \longrightarrow \bar{q}^2 = q^2 + \varepsilon^2\, L(A,B)\ . \tag{5}$$

In Eq. (5), $L(A,B)$ is the effective length of nuclear medium for the $c\bar{c}$ pair to pass through in the collisions of two nuclei of A and B. The increase of the relative momentum between the c and $\bar{c}$ reduces the phase space integration dq^2 in Eq. (1), and consequently, J/ψ suppression is expected in nuclear medium. With only one parameter, ε^2, the amount of relative momentum square gained by the produced $c\bar{c}$ pair per unit length in the nuclear medium, our model can fit all observed J/ψ suppression data including recent NA50 data from Pb-Pb collisions.

[1]This talk is based on work done with C. Benesh and J.P. Vary, Phys. Rev. C50, 1015 (1994); and work done with J.P. Vary and X. Zhang, hep-ph/9809442.

1. Model for Hadronic J/ψ Production

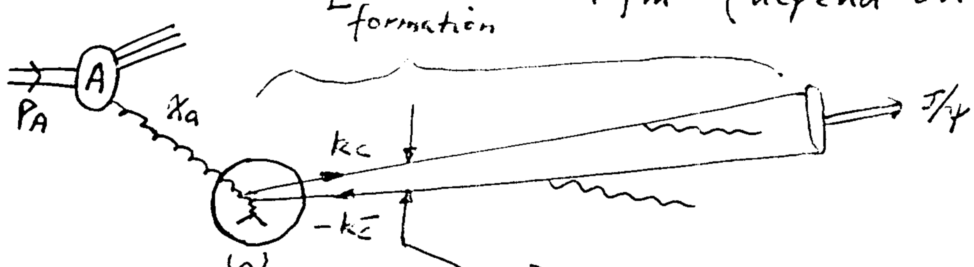
* Process: Nucleon + Nucleon $\longrightarrow J/\psi + X$

* Physics picture of the Production:

$$A(P_A) + B(P_B) \longrightarrow c\bar{c}(Q) + X$$

$$\hookrightarrow J/\psi(P_{J/\psi}) + X'$$

$L_{formation} \sim$ ✲ fm (depend on $P_{J/\psi}$) Brodsky & Mueller '88



$\lesssim \frac{1}{2m_c} < 0.1\,fm$

$$q^2 \equiv -(k_c - k_{\bar{c}})^2 = (\Delta \vec{k}_c)^2$$

↳ in c.m. frame of $c\bar{c}$.

* Factorization:
  - Production of $c\bar{c}$ pairs: short-distance $< 0.1\,fm$
  - Slow formation of J/ψ: ✲ fm, (Slow radiation due to heavy mass)

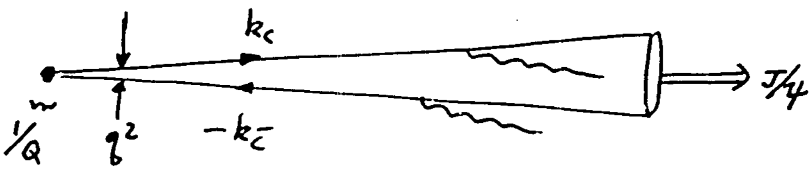
* Model for the <u>total</u> Cross Section:

$$\sigma_{AB\to J/\psi+X}(S) = \int dq^2 \int d^4Q \left(\frac{d\sigma_{AB\to c\bar{c}+X}}{d^4Q}\right)$$

$$* \; \delta(q^2 + (k_c - k_{\bar{c}})^2) * \underbrace{F_{c\bar{c}\to J/\psi}(q^2)}$$

Transition probability.

* Models for the transition Probability : $F_{c\bar{c}\to J/\psi}(q^2)$



- Power-Law probability : (2 parameters)

$$F^{(P)}_{c\bar{c}\to J/\psi}(q^2) = N_{J/\psi}\,\theta(q^2_{max} - q^2)\left(1 - \frac{q^2}{q^2_{max}}\right)^{\alpha_F}$$

$$q^2_{max} \equiv 4m_D^2 - 4m_c^2 \sim 5\,GeV^2$$

[Mimic Color-Octet Model] Note: $v_{c\bar{c}}$ is Not small !! when $q^2 \sim q^2_{max}$.

- Color-Evaporation Model : (1 parameter)

$$F^{(C)}_{c\bar{c}\to J/\psi}(q^2) = N_{J/\psi}\,\theta(q^2_{max} - q^2)$$

$$= F^{(P)}_{c\bar{c}\to J/\psi}(q^2)\Big|_{\alpha_F = 0}$$

Parameters are fixed by "fitting" $\sigma^{(S)}_{NN\to J/\psi}$

- Gaussian Probability : (2 parameters)

$$F^{(G)}_{c\bar{c}\to J/\psi}(q^2) = N_{J/\psi}\,\exp\left[-q^2/(2\alpha_F^2)\right]$$

[Mimic Glauber theory for J/ψ suppression]

- Others : $\left(\frac{k^2}{q^2+m^2}\right)^2$, … — J/ψ wave function, if there is no radiation of gluons.

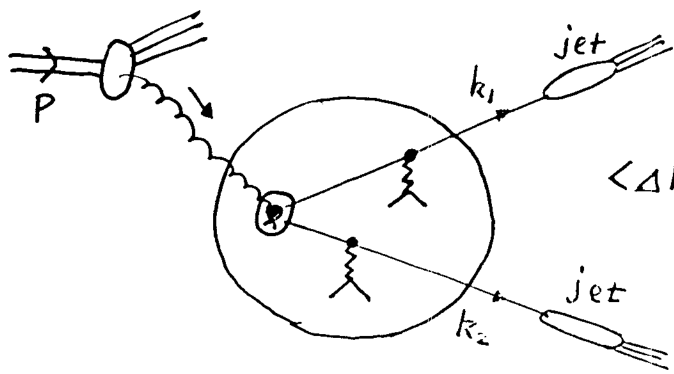
2. Absorption of gluons and J/ψ Suppressions:

* Absorption of gluons (or multiple scattering)

increases relative transverse momentum between 2-jets

(Luo, Qiu, Sterman)

Fermilab E683: $\left.\begin{matrix}\pi(p)\\ \gamma(p)\end{matrix}\right\} + A(P_A) \longrightarrow jet(k_1) + jet(k_2) + X$



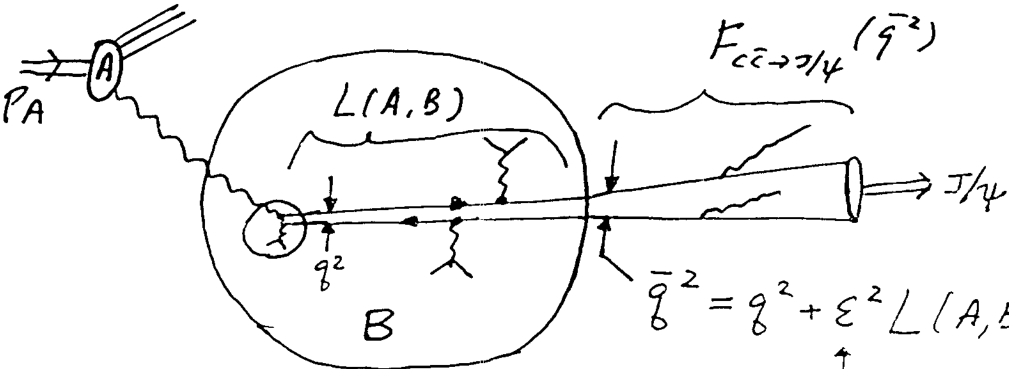
$$\langle \Delta k_T^2 \rangle \approx a + b A^{1/3}$$

b ⟵ $0.2 \sim 0.7$ GeV^2

* Absorption of gluons increases relative momentum of c & $\bar{c}$

Imagine: c & $\bar{c}$ are parent-quark for "2-jets"

[radiation is much weaker due to mass]



$$\bar{q}^2 = q^2 + \varepsilon^2 L(A,B)$$

ε^2 ⟵ $\sim b$ above!

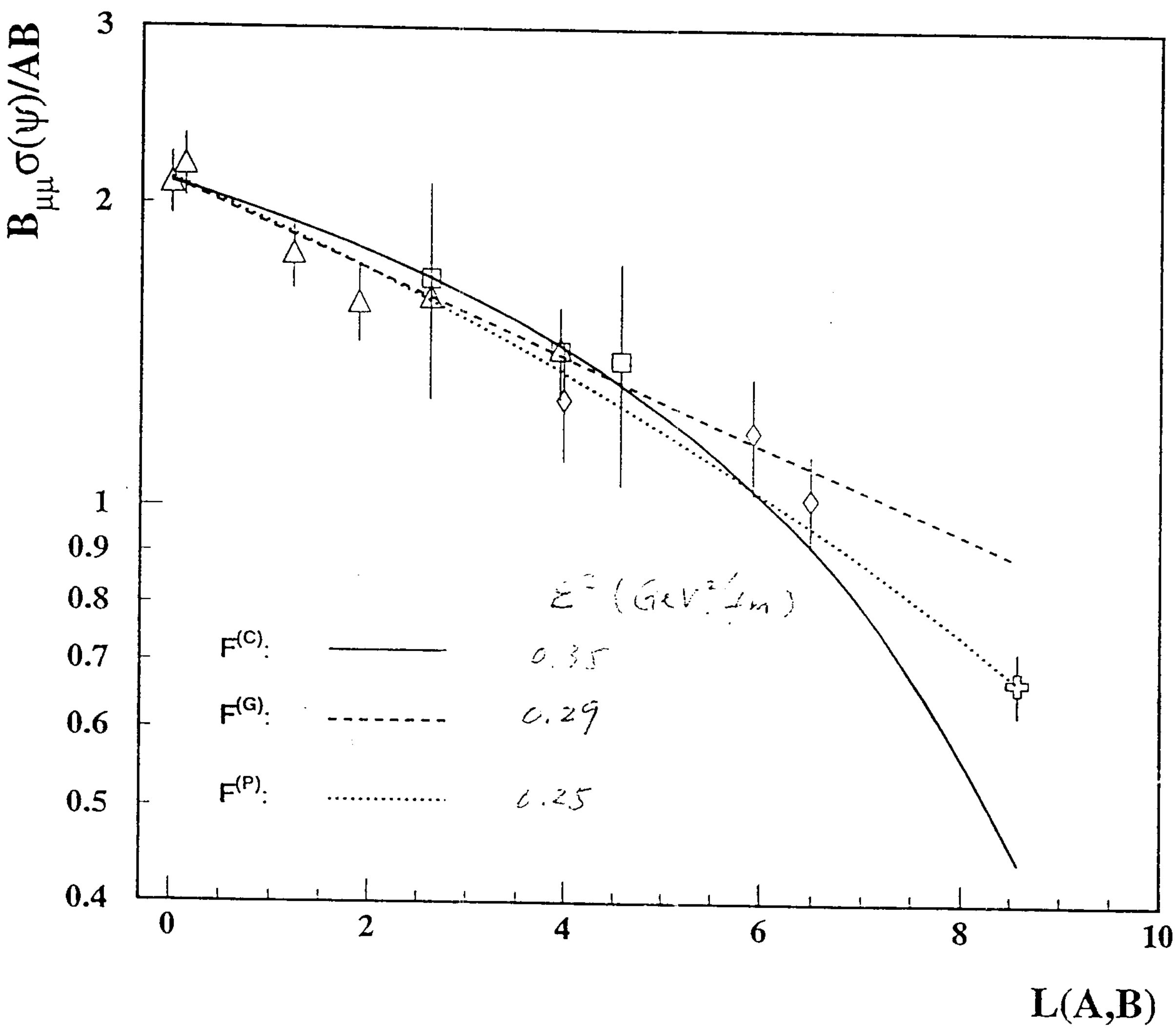
$\bar{q}^2 > q^2 \Rightarrow$ smaller phase space for dq^2 in $\sigma_{AB}(s)$

$\Rightarrow$ Suppression

Only one parameter, ε^2!

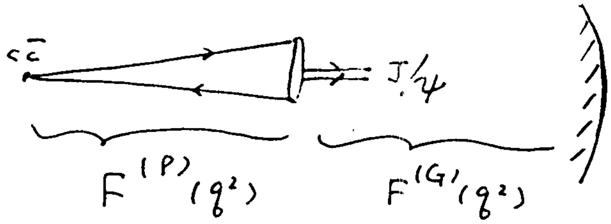
J/ψ Suppression in Nucleus-Nucleus Collisions

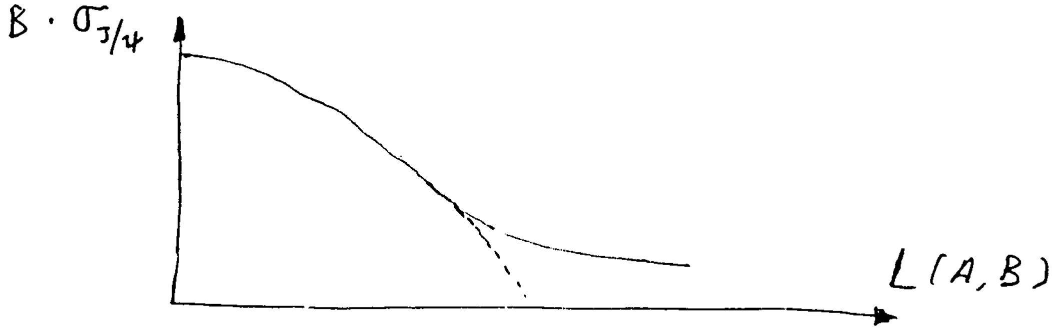
hep-ph/9809442



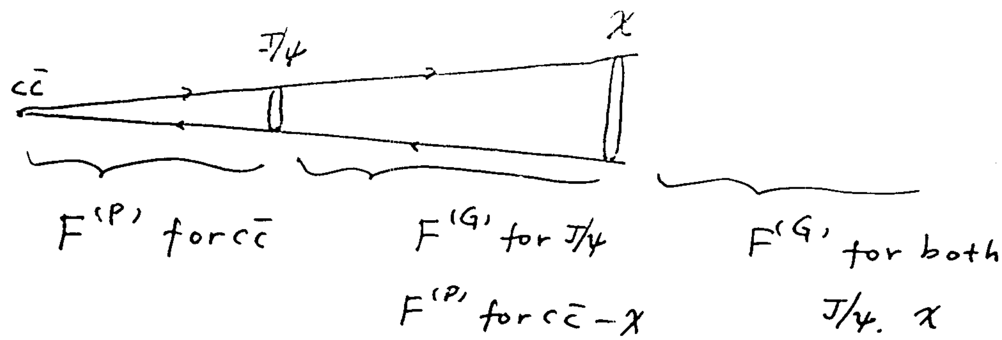
From M.C. Abreu, et al. NA50, Phys. Lett. B410, 337 (1997)

* If Some J/ψ formed inside the nuclear matter,





* Effect of χ states:



Convert "Effective L(A,B)" to E_T. Line shape changes

But, structure at the formation of mesons exists.

Low Energy Theorems for Charmonium Interactions

H. FUJII and D. Kharzeev
RIKEN BNL Research Center, BNL, Upton NY 11973

The quarkonium interactions are studied at low energies based on the combined use of the operator product expansion (OPE) and low energy theorems (LET) in QCD, which gives us model-independent information about them. After a brief review of the OPE formulation for the interaction of massive quarkonium with soft gluons, the use of the LETs in the low energy processes of quarkonium with light hadrons is explained. Especially for pions, it is stressed that the interactions are fully constrained. Two concrete are presented; the onium-onium and the pion-onium interactions.

In the latter example, pion-onium elastic cross section, which may be relevant for the p_T broadening, is found to be tiny due to the "chiral" q^2 suppression as well as the small size of dipole moment. $\Phi \to \Phi'$ transision is also disscussed, even though it involves a formal difficulty in use of the OPE.

INTRODUCTION

- Heavy quarkonium provides a natural cutoff, $r \sim 1/\alpha_s m_Q$
- Separation of soft/hard scales; OPE formulation — systematic (GOTTFRIED'78, PESKIN'79)

> Quarkonium interaction with pions are largely determined by the QCD low energy theorems (LET).

  - No valence quark exchange: Interact with light hadrons through gluonic operators.
- The leading operator is the trace of stress tensor, θ^μ_μ.
  - Matching θ^μ_μ onto low energy expression (χ symm.)
- Applications; extrapolated down to J/ψ or Υ
  - J/ψ–J/ψ interaction (H.F. and D.K. hep-ph/9807383)
  - Quarkonium interactions with pions... relevant for HIC

GENERAL IDEA

- Assuming the separation of the hard and soft scales (OPE), the onium interaction with a soft probe is written as

$$\mathcal{M} = \sum_i c_i \langle O_i \rangle,$$

with local operators, O_i, and their coefficients, c_i.

- The leading twist-two terms can be summed up into the double-dipole form,

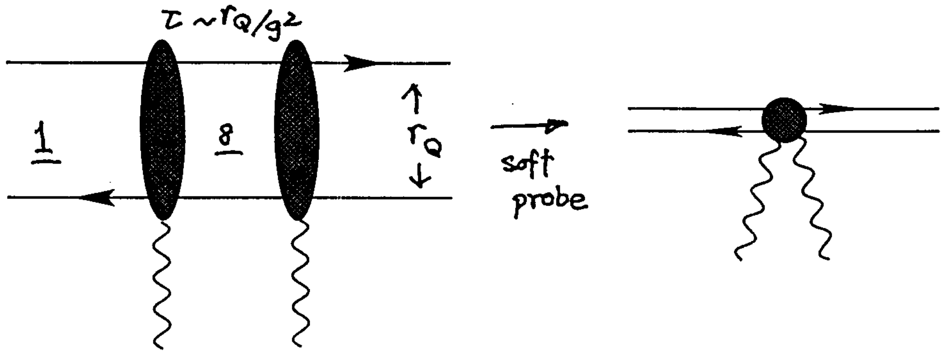
$$\mathcal{M} = \frac{g^2}{N} \langle \phi | \mathrm{tr} \left[\mathbf{r} \cdot \mathbf{E} \frac{1}{H_a + \epsilon + iD^0} \mathbf{r} \cdot \mathbf{E} \right] | \phi \rangle$$

- @ small energies, $E \ll 1/r, 1/r_Q$, we have a quite simple form:

$$\mathcal{M} = \bar{d}_2 \frac{a_0^2}{\epsilon_0} \langle \frac{1}{2} g^2 \mathbf{E}^{a2}(0) \rangle.$$

$B \sim O(\alpha_s) \cdot E$
$r \sim 1/\alpha m$
$E \sim \alpha/r \sim mv^2$
$v^2 \sim \alpha/mr \sim \alpha^2$

- Physically,



- Non-pert. matrix element generally unknown → bypassed by dispersion rel., parton model, etc

Scale Anomaly Relation — *Non-pert. matrix element of gluon op. over hadron state* —

Note that the operator is rewritten as the form

$$\begin{aligned} g^2\mathbf{E}^2 &= -\frac{1}{4}G_{\alpha\beta}G^{\alpha\beta} + g^2(-G_{0\alpha}G_0^\alpha + \frac{1}{4}g_{00}G_{\alpha\beta}G^{\alpha\beta}) \\ &= \frac{8\pi^2}{b}\theta^\mu_\mu + g^2\theta^{(G)}_{00} \end{aligned}$$

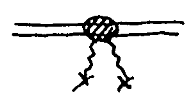
$\theta_{\mu\nu}$: Energy-Mom. tensor (@ chiral limit, u,d,s=0, b=9)

The first term, the scale-anomaly, dominates by a factor, $\alpha_s(1/r_Q)$

E.g.

- In the back ground color field, double Stark effect:

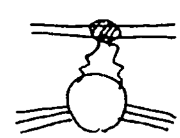
$$\mathcal{M}_\Phi = \frac{a_0^2}{\epsilon_0}\bar{d}_2\frac{1}{2}\langle g^2\mathbf{E}^2\rangle$$



- Elastic scattering with a light hadron @ low energy:

$$\mathcal{M}_{h\Phi} = \frac{a_0^2}{\epsilon_0}\bar{d}_2\left(\frac{4\pi^2}{b}\right)\langle h|\theta^\mu_\mu|h\rangle = \frac{a_0^2}{\epsilon_0}\bar{d}_2\left(\frac{4\pi^2}{b}\right)2M_h^2$$

- In pion case,



$$\langle\pi^k|\theta^\mu_\mu|\pi^l\rangle = 2M_\pi^2\delta^{kl} = 0 \text{ @ chiral limit;}$$

— Decoupling of pions in quarkonium interactions!

More on onium coupling with pions

— Matching $\theta_{\mu\nu}$ with pionic oparator — (VOLOSHIN&ZAKHAROV'80)

Broken chiral symmetry fixes the low energy realization of $\theta_{\mu\nu}$:

$$\theta^{\mu}_{\mu} = -2\,\frac{f_\pi^2}{4}\,\mathrm{tr}\,\partial_\mu U \partial^\mu U^\dagger \;+\; 4\Lambda\,\mathrm{tr}\left(mU + U^\dagger m^\dagger\right),$$

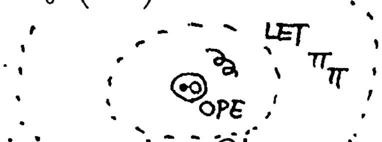
$U = \exp(2i\pi/f_\pi)$, $\pi \equiv \pi^a T^a$, $\mathrm{tr}\, T^a T^b = \frac{1}{2}\delta^{ab}$, m the quark mass matrix, and $\Lambda = -m_\pi^2 f_\pi^2/4\hat{m}$ with $\hat{m}$ being the average light quark mass.

$$\langle \pi^k | \theta^\mu_\mu(0) | \pi^l \rangle = (p' - p)^2 \delta^{kl} + O(m_\pi^2)$$

Thus the LET from the (broken) scale and chiral symmetries of QCD determine the onium coupling with pions as

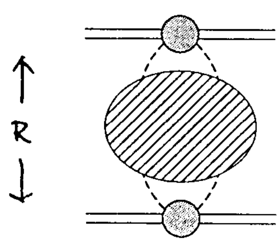
$$\mathcal{M}_{\Phi\pi} = \underbrace{\bar{d}_2 \frac{a_0^2}{\epsilon_0}}_{\text{OPE}} \underbrace{\left(\frac{4\pi^2}{b}\right)(p' - p)^2 \delta^{kl}}_{\text{LET}} \sim \# r^3 q^2$$

up to the small α_s and m_π^2 corrections.



Application; onium-onium interaction @low energy

HF AND D.KHARZEEV HEP-PH/9807383



$$= \mathcal{M}(R) \sim \bar{d}_2^2 \left(\frac{a_0^2}{\epsilon_0}\right)^2 \left(\frac{4\pi^2}{b}\right)^2 \int dt \langle \mathrm{T}\theta^\mu_\mu(x)\theta^\mu_\mu(0)\rangle$$

OPE LET

- At large distances, $R \gg r_B$, inevitably non-perturbative

  Use a dispersive representation:

$$\Pi(q^2) = \mathrm{F.T.}\langle \mathrm{T}\theta^\mu_\mu(x)\theta^\mu_\mu(0)\rangle\rangle = \int ds \frac{\rho_\theta(s)}{s - q^2 - i\epsilon}$$

Non-pert. contrib. required by a QCD theorem:

$$\Pi(0) = -4\langle \theta^\mu_\mu \rangle = -16\epsilon_{\mathrm{vac}} \neq 0$$

lightest hadronic states:

$\rho_\theta(s) \overset{\pi\pi}{\sim} s^2\, |F(s)|^2$ scalar form factor; resonance enhancement

Application; $\pi\Phi$ interactions

— $\pi J/\psi$ Elastic Cross Section —

$$\sigma(s) \;=\; \frac{1}{4\pi s}\frac{M^2}{2\mathrm{p}_{\mathrm{CM}}^2}\left(\bar{d}_2\frac{a_0^2}{\epsilon_0}\right)^2\left(\frac{4\pi^2}{b}\right)^2\int_0^{4\mathrm{p}_{\mathrm{CM}}^2} d(-t)\; t^2$$

$\sim r_Q^6$ $\quad q^4$

- Chiral symmetry: Low momentum suppression, t^2

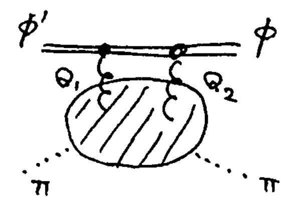
  $\Longrightarrow$ At low energies the $\pi\Phi$ interaction is very weak.

- The cross section is of order, 0.01 mb;

  $\Longrightarrow$ much smaller than the geometrical size of J/ψ.

— $\pi\Phi \rightarrow \pi\Phi'$ Transition —

- Difficulty; The transferred mom.(energy) is of order, $\Delta = M' - M = O(\epsilon_0)$, which invalidates the factorization.



- Fortunately, the double-dipole form is still valid (Peskin),

$$\mathcal{M} = \langle\phi'\pi|\mathrm{tr}\Big[\mathbf{r}\cdot\mathbf{E}\frac{1}{H_a+\epsilon+iD_0}\mathbf{r}\cdot\mathbf{E}\Big]|\phi\pi\rangle$$

$O(\Delta)$

- To get a rough estimate within our formulation, replace $-iD_0$ with the typical value of the gluon momentum, Δ.

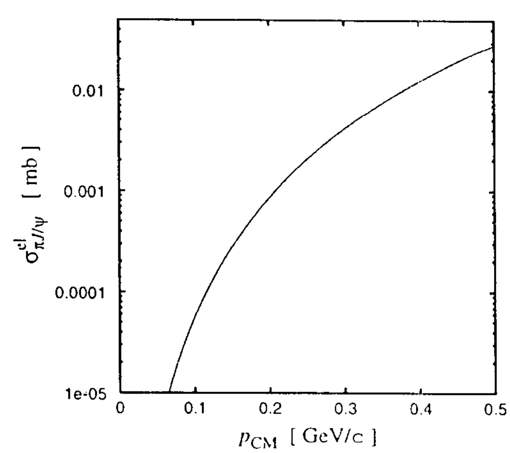
$$\frac{1}{3N}\langle\phi'|r^i\frac{1}{H_a+\epsilon-\Delta}r^i|\phi\rangle\langle\pi|\frac{1}{2}g^2\mathbf{E}^{a2}|\pi\rangle = \bar{d}_2'\frac{a_0^2}{\epsilon_0}\langle\pi|\frac{1}{2}g^2\mathbf{E}^{a2}|\pi\rangle$$

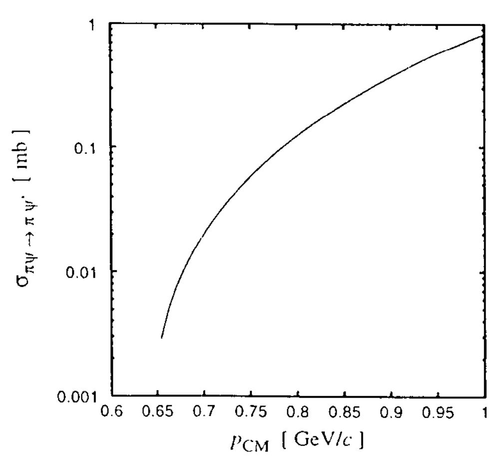
- With this replacement, LET applies:

$$\mathcal{M} = \left(\bar{d}_2'\frac{a_0^2}{\epsilon_0}\right)\left(\frac{4\pi^2}{b}\right)\; t$$

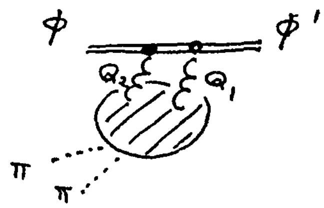
- In Fig., we see $\sigma \sim 0.01 - 0.1$ mb in this mom. region.

  (The 1s and 2s Coulomb wave functions assumed)





☆ — $\Phi' \to \Phi\pi\pi$ Decay —



- $\Phi' \to \Phi$ process always involves the mom. of order, Δ.
- Average over the trans. mom.

$$\mathcal{M}^{kl} \sim \frac{1}{3N}\int_0^{\Delta}\frac{dQ}{\Delta}\langle\Phi|r\frac{1}{H_a+\epsilon'+Q}r|\phi'\rangle\langle\pi^k\pi^l|\frac{1}{2}g^2\mathbf{E}^2|0\rangle$$
$$= \underbrace{\bar{d}_2''\frac{a_0^2}{\epsilon_0}}_{\text{"OPE"}}\underbrace{\langle\pi^k\pi^l|\frac{1}{2}g^2\mathbf{E}^2|0\rangle}_{\text{LET}}$$

- "OPE-like" form: $\mathcal{M} = (\text{number}) \times s \times \left[F(s)\right]$
- Compare the results with the observed decay width to get an idea about the error.

  Γ= 260 keV (70 keV) with (without) the final $\pi\pi$ int. $F(s)$ ⇔ 140 keV (exp).

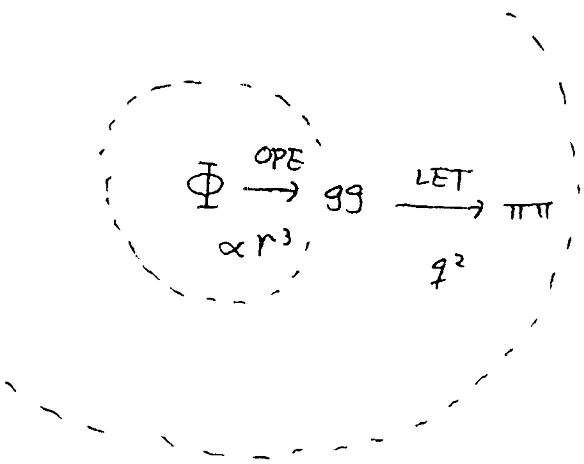
  Error in the absolute value ~ a factor of several at least.

- Experimentally, $M_{\pi\pi}$ dependence of the decay is well described by this form of amplitude (Fig.)

Remarks

- THE COUPLING WITH PIONS IS FULLY FIXED BY THE LET IN QCD
- "ONIUM SURROUNDED BY $\pi\pi$ CLOUD" MAY GIVE A GOOD PICTURE FOR ONIUM INTERACTIONS
- $\pi\Phi$ ELASTIC INTERACTION IS SMALL @LOW ENERGY BY q^2-SUPPRESSION (CHIRAL SYMM) AS WELL AS THE SMALL DIPOLE SIZE OF THE ONIUM. .... P_T broadening (?)
- ESTIMATE FOR $\pi\Phi \to \pi\Phi'$ INTERACTION IS MARGINAL, BUT NOT COMPLETELY WRONG AT LEAST FOR J/ψ ⇐ ESTIMATE FOR THE DECAY PROCESS.

  .... ψ, ψ' ratio



Quarkonium Production in Relativistic Nuclear Collisions (BNL/RIKEN)
Sep. 28–Oct. 2, 1998

J/Psi-Nucleon Cross Section

A Review of the Experimental Situation

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Table 1.

PHOTO & LEPTOPRODUCTION OF J/Ψ

E_γ (GeV)	Detect	Targets	Measured	Model	$\sigma(J/\psi\text{-}N)$ mb	α
Knapp (1975) FNAL						
⟨100⟩	$\mu^\pm$	Be	$\sigma(\to J/\psi + X)$	VDM	≈ 1	
Camirini (1975) SLAC						
13-21	$e^\pm, \mu^\pm$	H_2, D_2	$\frac{d\sigma}{dt}(t=0)$	VDM	$\lesssim 0.8$	
Gittelman (1975) Cornell						
11.8	$e^\pm$	Be	$\frac{d\sigma}{dt}(t=0)$	VDM		
Anderson (1977) SLAC						
20	μ	Be, Ta	$\frac{\sigma(Be)}{\sigma(Ta)}$	Optical	$3.5\pm0.8\pm0.5$	0.96 ± 0.0
Binkley (1982) FNAL						
⟨150⟩	$e^\pm, \mu^\pm$	H_2, D_2	$\frac{d\sigma}{dt}(t=0)$	VDM	1.5 ± 0.2	
Denby (1984) FNAL						
⟨105⟩	$\mu^\pm$	H_2	$\sigma(\to J/\psi\, N)$			
Sokoloff (1986) FNAL						
⟨120⟩	$\mu^\pm$	H_2, Be, Fe, Pb	rel. $\sigma(\to J/\psi + X)$	VDM	1-2	0.94 ± 0.0
Clark (1979) FNAL						
35-150	$\mu^\pm$	Fe	$\frac{d\sigma}{dt}(t=0)$	VDM		
Aubert (1980) CERN						
50-170	$\mu^\pm$	Fe	$\frac{d\sigma}{dt}(t=0)$	VDM	1.26 ± 0.31	
Aubert (1985) CERN						
60-200	$\mu^\pm$	H_2, D_2	$\frac{\sigma(Fe)}{\sigma(H_2, D_2)}$			$1.10+0.1$

Table 2.

HADROPRODUCTION OF J/PSI

Beam Momentum	Hadron	Targets	α	
Antipov (1977) Serpukhov				
43 GeV/c	π^-	Be, Cu, W	0.92(6)	
Anderson				
225 GeV/c	$\pi^\pm, K^+, p^\pm$	C, Cu, W	0.87	
Corden (1982) CERN				
39.5 GeV/c	π^-	H_2, W	0.98(2)	
Badier (1983) CERN				
150, 280	π^-	H_2, Pt	0.96(2)	
200	π^-	"	0.97(2)	
	π^+	"	0.96(2)	
	p	"	0.94(3)	
Katsanevas (1988) FNAL				
125	π^-	Be, Cu, W	0.87(2)	
	$\bar{p}$	"	0.90(3)	
Alde (1991) FNAL - E772				
800	p	D_2, C, Ca, Fe, W	0.914(2)	J/ψ
			0.902(7)	ψ'
			0.998(1)	D-Y
Baglin (1991)/Laurenco (1996) CERN - NA38				
200 /nucleon		p-U, O-U, S-U	0.908(29)	$\bar{c}$ pp
			0.919(21)	
Leitch (1998) FNAL - E866				
800	p	Be, Fe, W	≈ 0.95	$J/\psi, \psi'$

1 The Data

J/ψ suppression in nuclei has been observed almost from the day of the J/ψ its discovery. Photoproduction and hadroproduction of J/ψ with beam energies ranging from 11 GeV to 800 GeV, and nuclei ranging from deuterium to uranium, have been measured. Unfortunately, the data extending over the last 24 years (Tables 1 and 2) are neither of uniform quality, nor have they been analyzed in a uniform manner. The photoproduction experiments have been generally analyzed in terms of the vector dominance model (VDM). It has been shown recently [1] that the J/ψ-nucleon cross section derived from the classical VDM formula and the measured $\frac{d\sigma}{d_t}(\gamma N \to J/\psi N)|_{t=0}$ needs to be increased by a factor of almost 3. Most hadroproduction measurements avoid the problems of absolute cross section measurement by reporting what amounts to ratios of cross sections between different nuclei. They report the variation of the cross sections in terms of α when they are fit as constant $\times A^{\alpha}$ where A is the atomic weight of the nucleus. This parameterization has no theoretical justification and several examples exist which show that it may not have an experimental justification either. But it has become customary. The cross sections can be obtained from α by the approximate relation $A^{\alpha} = A[1 - e^{-n\sigma}] \approx A\left[1 - \frac{9A}{16\pi R^2}\right]$.

When the above considerations are taken into account it is found that all* photoproduction and hadroproduction data are consistent with the following statement:

"At $\sqrt{s} \geq 17$ GeV, $\alpha = 0.92 \pm 0.01$, or $\sigma = 5.5 \pm 0.5$ mb for the heavy nuclei."

*[There is one exception. Preliminary analysis of Fermilab E866 has been reported to yield $\alpha \approx 0.95$, or $\sigma \approx 2.6$ mb. The reasons for this discrepancy are not clear.]

2 What does $\sigma = 5$–6 mb mean?

Not only does $\sigma = 5.5 \pm 0.5$ mb fit all data for J/ψ suppression in p-A collisions, but it fits the data on oxygen-uranium, and sulfur-uranium collisions at 200 GeV/nucleon. This raises the question: what does $\sigma = 5.5 \pm 0.5$ mb mean? Without understanding the answer to this question we cannot understand why it fails to fit the new Pb-Pb data at 158 GeV/nucleon. Without understanding that we cannot call the J/ψ suppression in Pb-Pb collisions truly 'anomalous', or infer that it says something significant about QGP.

Many explanations have been offered about how a cross section of this magnitude can arise. They all add up to a number of questions rather than answers.

- Is this σ largely due to the color-octet $(c\bar{c})_8$ traversing most of the nucleus, and not J/ψ, as the octet-lovers would have us believe.
- Is this σ made up of 0.6 mb of $\sigma(J/\psi\text{-comover})$, and the rest due to $\sigma(J/\psi\text{-nucleon})$, as the comover-lovers would have us believe.
- How many comovers are there, anyway?
- Is this σ a measure of the attenuation of the higher resonances which feed J/ψ in a NN collision at high energies?
- How correct are the present estimates of J/ψ-nucleon cross sections based on QCD inspired models?

The point is that at present there is a total 'unconfinement' of the theorist. He can concoct his favorite mixture of the above ingredients to explain his favorite data. There are no clean-cut experimental constraints.

I wish to propose a set of relatively simple measurements which will provide definitive answers to at least a small part of this potpourri of questions.

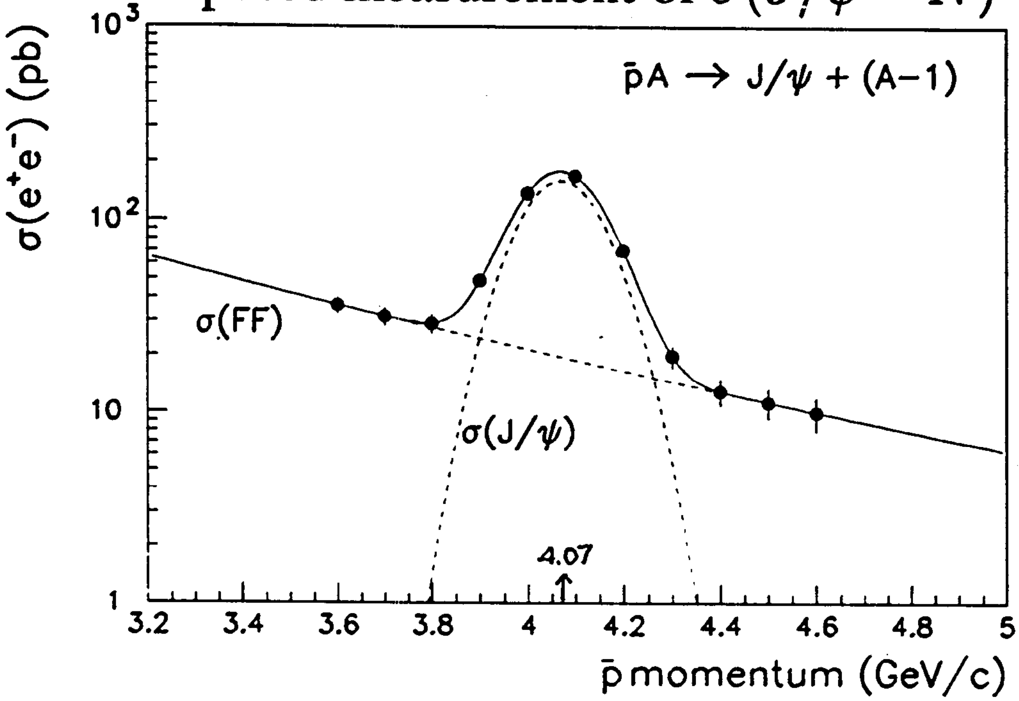
3 A direct measurement of J/ψ-N cross section.

In order to have a cleanly interpretable measurement of J/ψ-N cross section several conditions should be satisfied: (a) J/ψ should be produced exclusively, in order to be free from feed-down and comover contamination, (b) the initial $c\bar{c}$ pair should be produced in a color singlet state, (c) the $c\bar{c}$ pair should be produced with such low momentum that J/ψ is formed before reaching the next nucleon in the nucleus.

The above conditions are uniquely satisfied in J/ψ production in $\bar{p}p$ annihilation with a nuclear proton. The reaction is

$$\bar{p} + A \rightarrow J/\psi + (A-1) \rightarrow e^+e^- + (A-1)$$

Proposed measurement of $\sigma(J/\psi - N)$



- At the Fermilab Antiproton Accumulator, with

  70 mA antiprotons circulating at $\sim$ 0.65 MHz
  10^{12} atoms/cm^3 Xe atoms in the gas jet target
  $\mathcal{L} = 2.5 \times 10^{31}$ cm^{-2} s^{-1}
  σ(peak) = 185 pb = 185 $\times 10^{-36}$ cm^2, $\alpha\epsilon \simeq 0.5$
  Count rate (peak) = 200 / day
  $\therefore$ An 11 point scan across the Fermi-broadened J/ψ (3.60 - 4.60 GeV/c) will require 300 hours, to give $\sigma(J/\psi - N)$ to $\pm5\%$.

- In order to test correctness of assumptions made, and method of data analysis, several targets, from C to Pb need to be measured.

But, there is little hope that this measurement will be done at Fermilab, with HEP priorities.

Annihilation in hydrogen has been studied at Fermilab by E760/E835 for several years now to do precision spectroscopy of charmonium resonances [2]. This is done by detecting photons and electrons following the traversal of a hydrogen gas jet by the stochastically cooled circulating antiproton beam in the antiproton accumulator. Mass resolutions of the order $\Delta m/M \approx 10^{-4}$ are routinely achieved and cross sections down to $\sim$ 1 pb are successfully measured.

It is proposed that the hydrogen gas in the jet-source be replaced by a nuclear gas, Ne, Ar, Xe or CH_3, and the $(J/\psi\text{-}N)$ cross section be measured by detecting the e^+e^- decay of J/ψ. Fermi motion of protons in the target nucleus will cause the J/ψ peak to be smeared over $\sim$ 200 MeV and the peak cross sections will be correspondingly reduced from 360 nb for hydrogen to $\sim$ 180 pb for the nuclear gas, but since the only physics background is due to the timelike formfactor of the proton, $\bar{p}p \to e^+e^-$, and its magnitude is only $\sim$ 20 pb, a very clean measurement can be made by scanning over the 4.07 ± 0.5 GeV/c region of $\bar{p}$ momenta (see Fig. 1). It is estimated that for one target a $\pm 5\%$ measurement of $\sigma(J/\psi - N)$ can be made in $\sim$ 300 hours of running.

It can be shown that a similar scan of ψ' is quite difficult because the peak cross section drops to $\sim$ 7 pb with a form factor 'background' of $\sim$ 2 pb. The measurement is a factor 25 slower than the J/ψ measurement and is intrinsically more difficult to make and analyze.

Fortunately, however, measurement of $\sigma(\chi_2 - N)$ is much more favorable, even though the intermediate step of the radiative decay of $\chi_2 \to \gamma J/\psi$ is involved. The estimated peak cross section is about 38 pb, with the form factor background of $\sim$ 3 pb.

In principle, these measurements can be made tomorrow. However, with the current priorities of Tevatron physics at Fermilab, the likelihood of such measurements being approved at Fermilab is very small, unless, of course, the nuclear physics community puts some of its resources into the effort. Hence, this talk to this group!

This research was supported in part by the U.S. Department of Energy.

[**1**] J. Hufner and B.Z. Kopeliovich, Phys. Lett. **B426** (1998) 154.

[**2**] Kamal K. Seth, Proc. International Conference on Few Body Problems in Physics, Williamsburg, VA, 1994, edited by F. Gross (AIP Proceedings, 1994) p. 248–274.

Thomas J. LeCompte

Quarkonium Production at the TeVatron

Brief Summary

The pre-CDF conventional wisdom of charmonium production was that:

- Few J/ψs and ψ''s are produced directly
- The majority of ψ''s are from bottom quark decay
- The majority of J/ψs are from Chi decay

We should have known this was wrong, because there is still a substantial ψ' cross section at fixed target energies, where there are few bottom quarks produced. Nonetheless, this hadn't really entered the community's consciousness until after CDF measured these processes, and found:

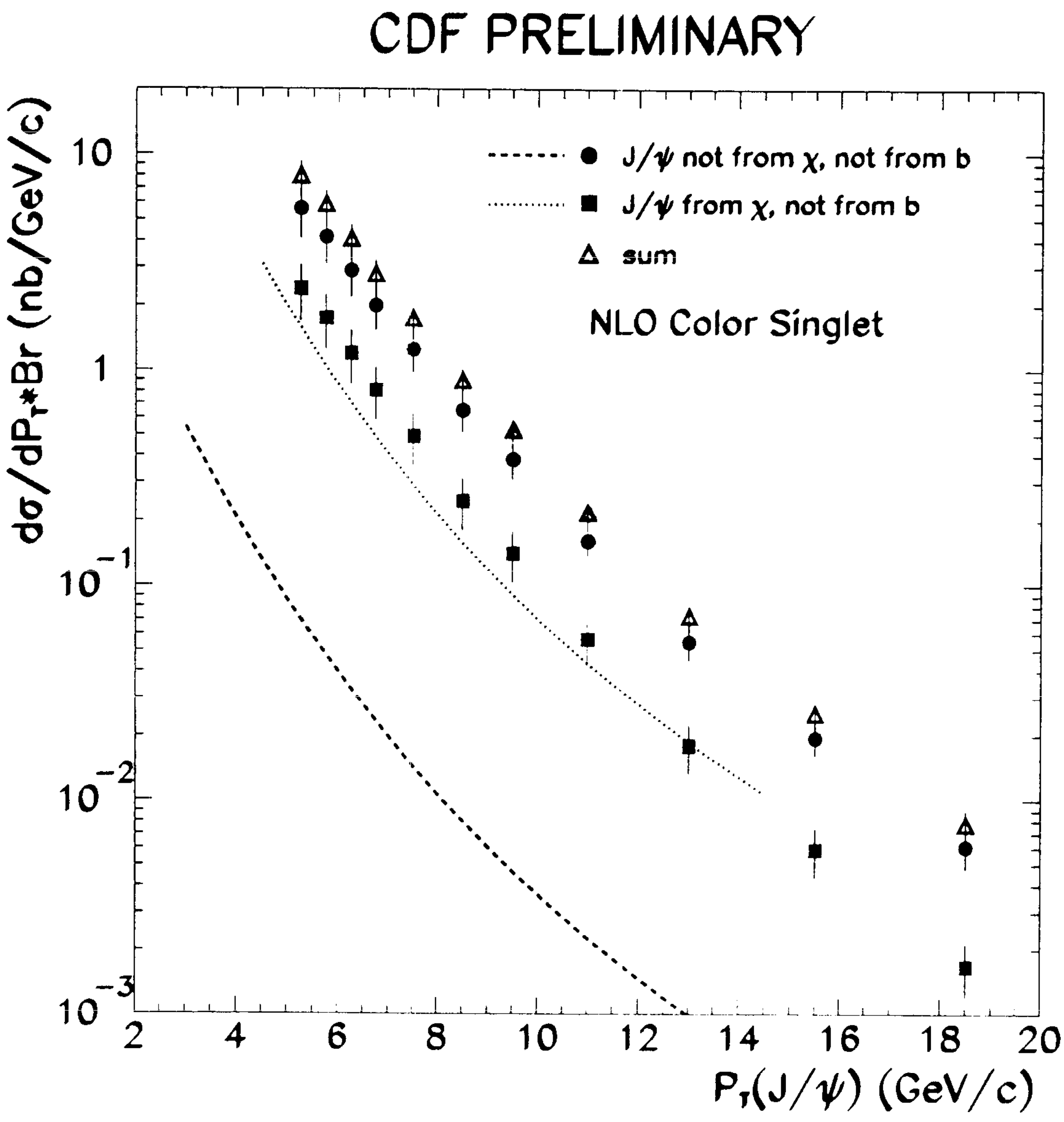
- Most (75%) ψ''s are not from b decay.
- Most (65%) of J/ψs are not from Chi deacy. (and only 15% are from b decay)
- The direct cross sections appear to be 50x larger than theory.

An interpretation of this that fits the data is that the so-called Color Octet Model (not really a model - it's just QCD) is a better description of what's happeneing. While this model contains matrix elements that are hard to be calculated from first principles, the same matrix elements can simultaneously fit the J/ψ and ψ' production.

Similarly, the COM seems to accomodate the upsilon production that we have measured.

While the CDF experiment has the larger dataset and the ability to measure bottom quark contributions from their lifetime, the D0 results are in agreement everywhere.

In the forward region, the J/ψ yields are much smaller, even though the absolute rates are comparable or larger. This is seen by both CDF and D0. The difficulty is that the backgrounds in forward muon detectors are large, and tight roads (and therefore p_T cuts) have to be made, especially at the trigger level. (If these cuts are not or can't be made tight enough, a prescale has to be imposed) These backgrounds generally come from the accelerator rather than the interaction region. Forward muon physics at RHIC needs to have these backgrounds under control.



CDF PRELIMINARY
J/ψ not from χ, not from b
J/ψ from χ, not from b
sum
NLO Color Singlet
dσ/dP_T*Br (nb/GeV/c)
P_T(J/ψ) (GeV/c)
10
1
10^-1
10^-2
10^-3
2
4
6
8
10
12
14
16
18
20

Summary on $\psi(2S)$, J/ψ and χ_c

- Huge excess of direct $\psi(2S)$ production, Data/Theory$_{col.sing.} \sim 50$

- Majority of prompt J/ψ do NOT come from χ_c , $F = 0.307 \pm 0.018 \pm 0.07$ and

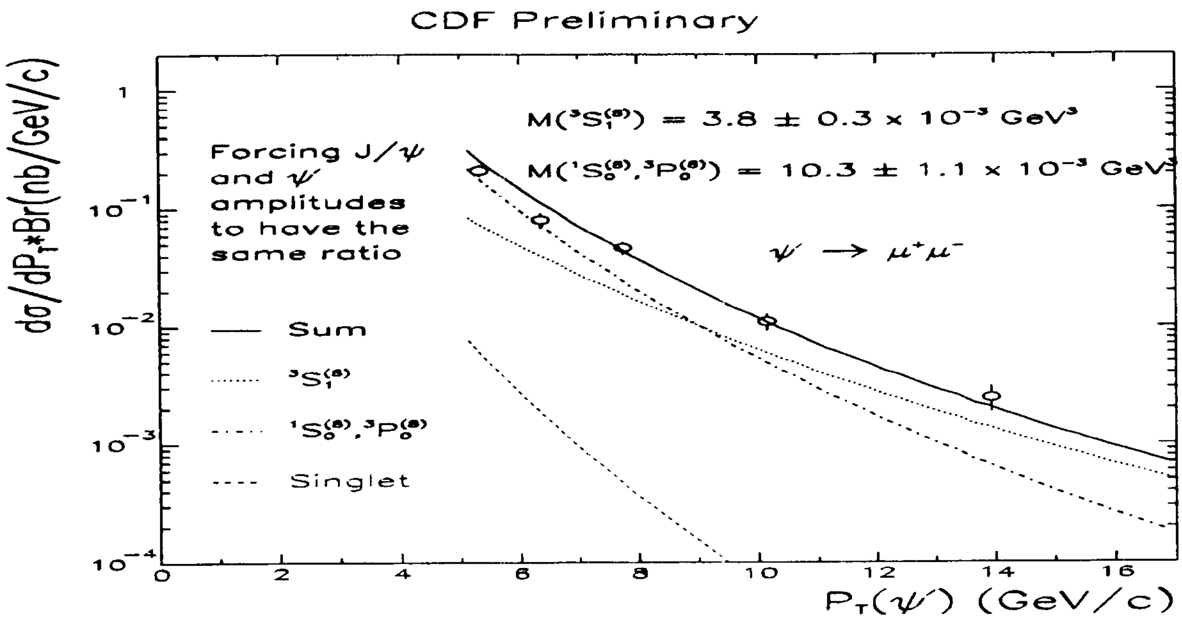
- same excess for direct J/ψ production, Data/Theory$_{col.sing.} \sim 50$

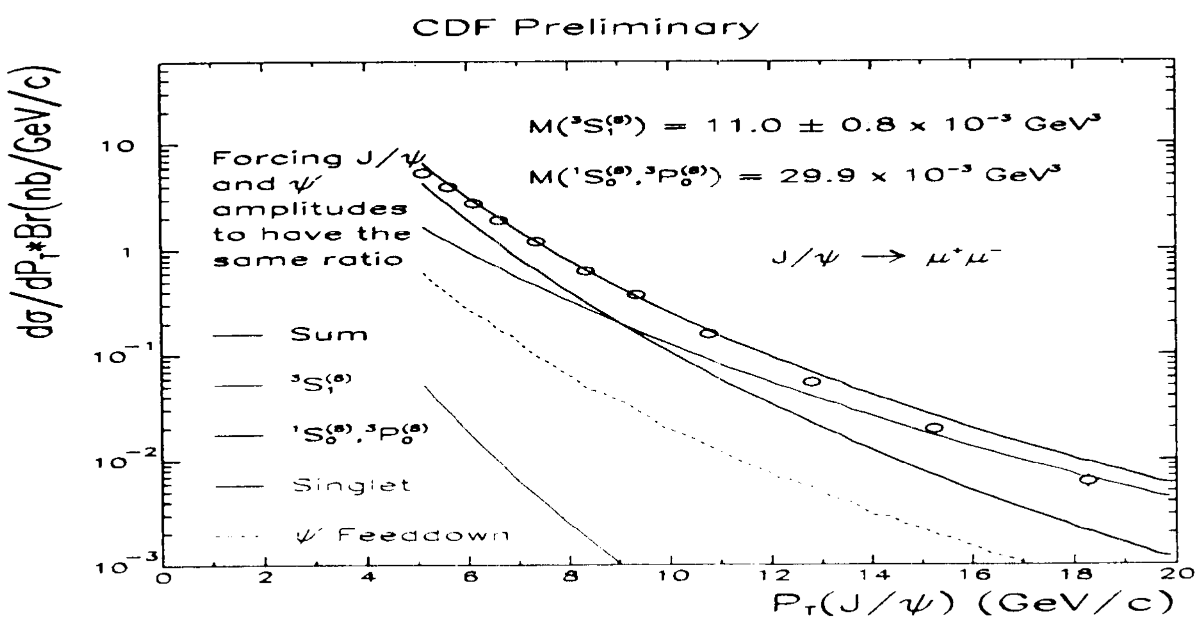
- Excess of direct production can be described with the inclusion of Color Octet contribution.

Open question:

- is the $\psi(2S)$ polarized ?

Combined fit to J/ψ and $\psi(2S)$





Summary

- Quarkonium production is more interesting (or at least harder to understand) than we first thought:

    - $\psi(2S)$ cross section too large by a factor of 50

    - Direct J/ψ cross section too large by similar factor

    ►►► Color Singlet Model appears to be dead.

    - χ cross sections are much closer to expectations.

- Contributions from new states (e.g. 2^3P_1 1^{++}) can't be excluded, but it is an unlikely explanation:

    - We don't see any evidence for them

    - Cross sections and branching fractions have to be both large and conspiratorial to explain both the J/ψ and $\psi(2S)$

- Direct production is the dominant production mechanism of both $^3S_1$ states.

• Color octet contributions can improve the match between prediction and data. (But introduce extra parameters)

• Forward dimuon detection is difficult

• A major upgrade will turn on in 1999, with major detector improvements at both ends of the spectrum:

high p_T (more data)
low p_T (better triggering)

Open Questions

• Testing the Color Octet Model

· Polarization (but is this definitive? Can the RHIC spin program help by measuring the entrance channel?)
· Other experiments (e.g. HERA)

• Can we untangle the upsilons like we have untangled the ψ?

Can STAR Measure Quarkonium Production in AuAu Collisions?

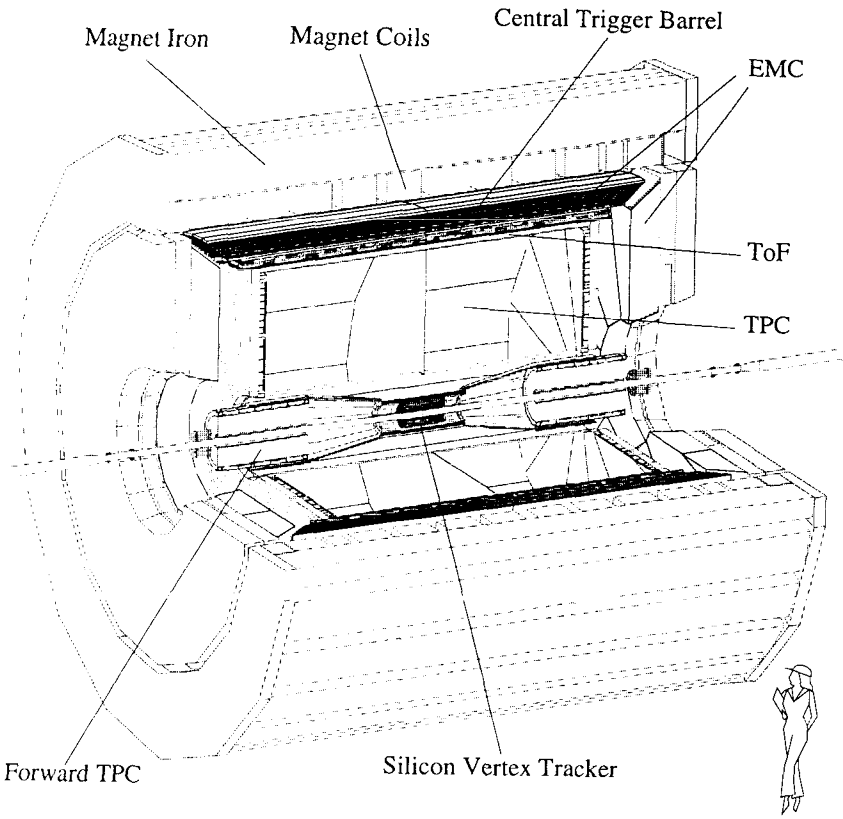
Thomas Ullrich, Yale University

The Solenoidal Tracker At RHIC (STAR) is a large acceptance detector capable of tracking charged particles and measuring their momenta in the expected high multiplicity environment. It is also designed for the measurement and correlations of global observables on an event-by-event basis and the study of hard parton scattering processes.

Although primarily dedicated for the measurement of hadrons and hard photons the detector has enough capabilities to also allow the study of quarkonium production via $J/\Psi \rightarrow e^+e^-$. This decay mode is attractive because it has a large branching ratio (6%) and because the electromagnetic calorimeter (EMC) together with the combined particle identification capabilities of the large Time Projection Chamber (TPC) and the Silicon Vertex Tracker (SVT) allow the identification of electrons with a high efficiency. First studies show that the achievable hadron rejection is sufficiently high to pull the signal out from a large hadronic background. The reduction factors used here are based on preliminary studies, either derived from simulations (TPC/SVT) or prototype tests (EMC). The total J/Ψ yield depends critically on how low in $p_\perp$ one can successfully reconstruct electrons, which in turn depend on what the electron-hadron separation is as a functions of $p_\perp(e)$. Our studies indicate that in one year running (10^7 s) at full luminosity STAR can record 25k J/Ψs at a signal-to-background ratio of 1:5 for a $p_\perp$-cut on the decay electrons of $p_\perp > 1.5$ GeV/c. A stronger cut of $p_\perp > 2.0$ GeV/c results in a much better signal-to-background ratio of 2:1 but with a considerable lower signal of 6000 J/Ψs. One of the key elements for a successful measurement is the sophisticated level-3 trigger which allows us to trigger on electron pairs in a given invariant mass window.

Physics with charmonium looks possible if STAR is able to fully exploit the performances of all components and especially the level-3 trigger. The prediction at this point in time are not entirely stable and the current results represent just a snapshot of work in progress.

The STAR Detector



Important for $J/\Psi \to e^+e^-$ measurement:

· Silicon Vertex Tracker SVT $\to$ tracking, PID
· Time Projection Chamber TPC $\to$ tracking, PID
· Electromagnetic Calorimeter EMC + EEMC $\to$ PID
· solenoidal magnet $\to$ momentum

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Silicon Vertex Tracker

- 3 layers of SDD detectors
- $-1 < \eta < 1$, $\Delta\phi = 2\pi$
- impact parameter resolution $\sigma_b \approx 70\mu$m at 1 GeV/c
- PID via dE/dx, rejection of conversions ($b \neq 0$)

Time Projection Chamber

- 45 padrows
- high tracking efficiency ($\geq 90\%$)
- $-2 < \eta < 2$, $\Delta\phi = 2\pi$
- momentum resolution: $\sigma_p/p \leq 1\%$ for $p < 5$ GeV/c
- PID via dE/dx, particle momentum, tracking

Electromagnetic Calorimeter

- Pb-scintillator sampling em calorimeter
- stack and shower maximum detector
- barrel: $|\eta| < 1.0$, $\Delta\phi = 2\pi$
- endcap: $1.05 < |\eta| < 2.0$, $\Delta\phi = 2\pi$
- 120 modules, each: $|\eta| = 1$, $\Delta\phi = 6°$
- resolution $\sim 16\%/\sqrt{E}$
- E measurement, e/h

The STAR Trigger

RHIC parameters for Au+Au, $\sqrt{s} = 200$ GeV:

- design: $\mathcal{L} = 2 \cdot 10^{26}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1} \rightarrow \sim$100 Hz central collisions
- 1999: $\sim 10\%$ of design value

STAR:

- max. TPC rate $\approx$ 100 Hz
- DAQ limit (tape): 1–2 Hz

Basic Trigger – L0:

- interaction/multiplicity trigger
- combined information CTB+MWC $\otimes$ ZDC $\otimes$ VPD $\otimes$ EMC
- more complex as it sounds ...

Other Trigger – L1, L2: future

High level trigger – L3:

- software trigger
- proposed by Frankfurt University
- currently reviewed
- can be ready for 1999

L3 is one of the key elements for a J/Ψ measurement

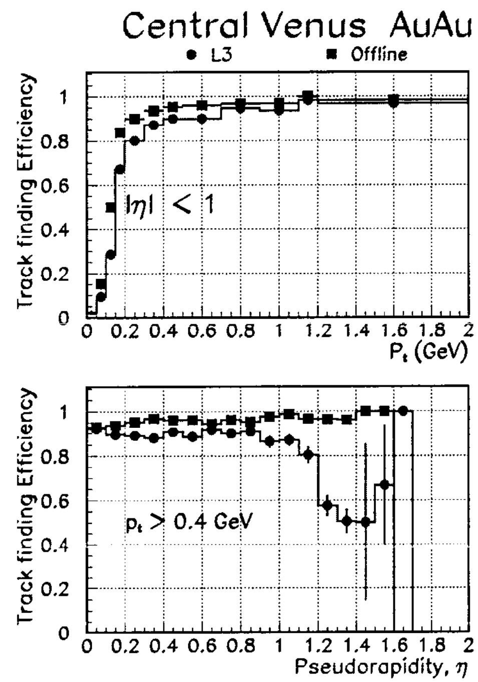
The Level-3 Trigger

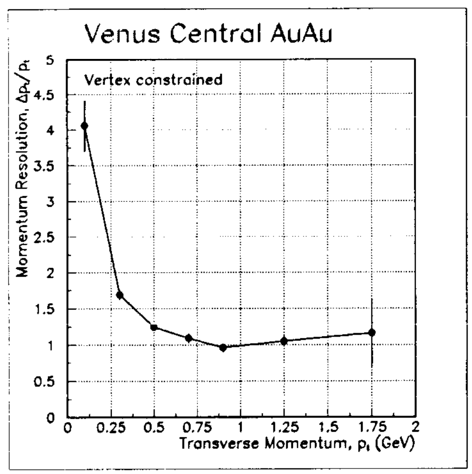
Basic Idea:

- pattern recognition in real time
- TPC tracking + PID (+ EMC)
- select events according to
  - event topology
  - specific signature

Implementation:

- one CPU for each TPC sectors
- reconstruction of full event/sector
- track merging
- hierarchical structure of processors
- $\Rightarrow$ scalable to 100 Hz !!!





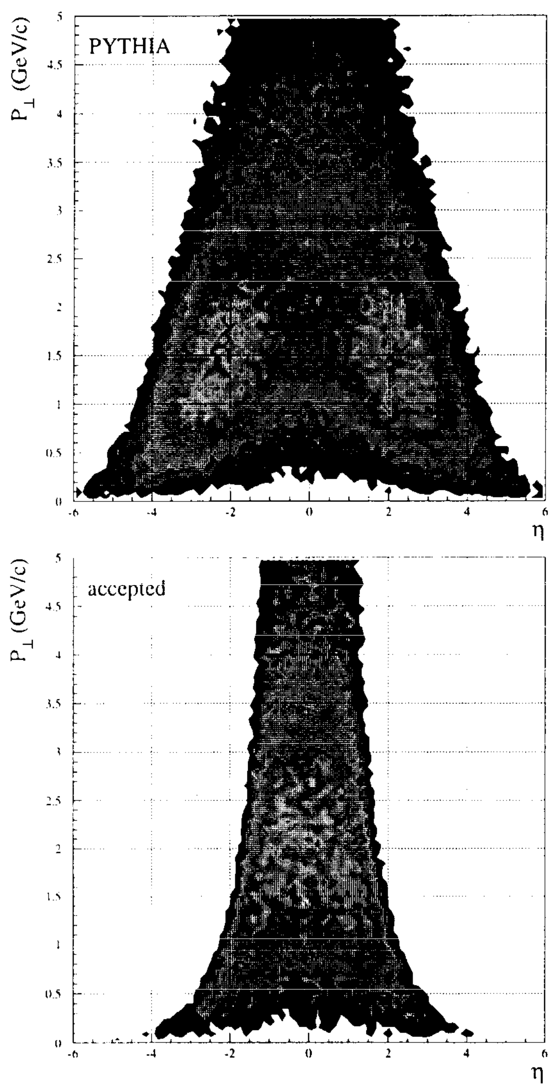
plots: C. Struck, ICHEP '98

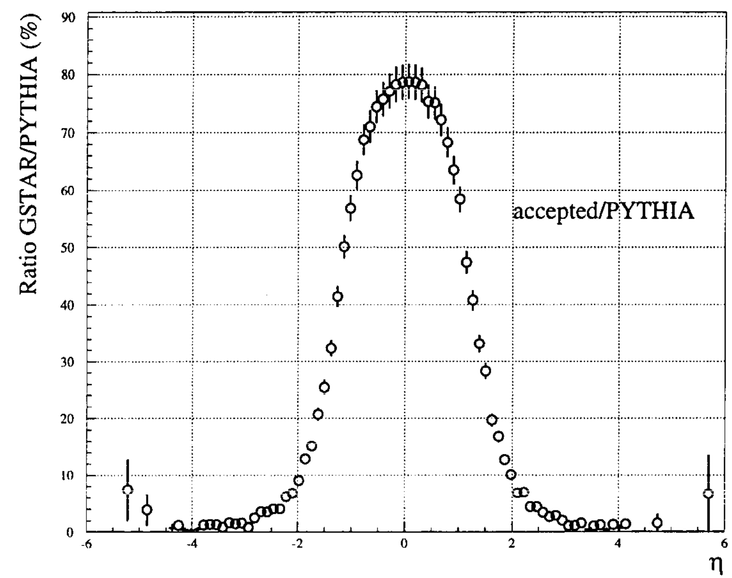
J/Ψ trigger:

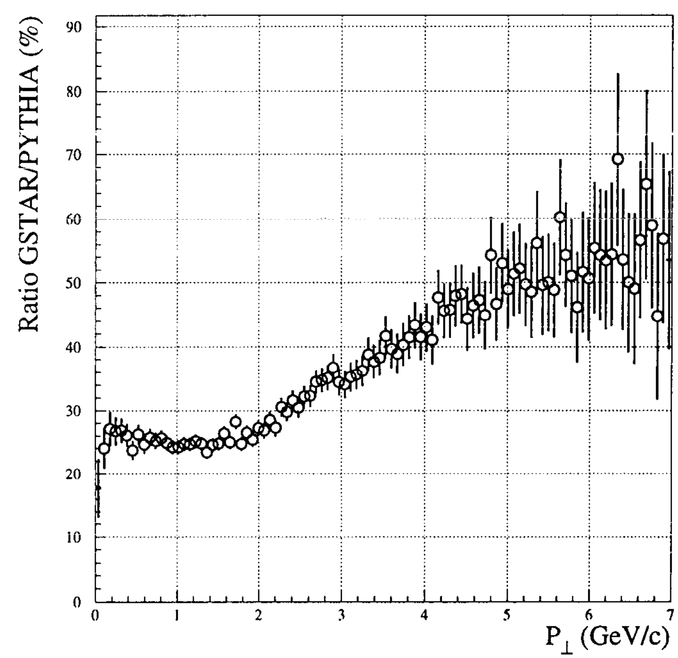
- find electron candidates
- loop over candidates
  - calculate mass with vertex constraint
  - select event if $|m - m_{J/\Psi}| < x \cdot \sigma_{res}$

J/Ψ acceptance in STAR

geometrical acceptance: both electrons in TPC acceptance, each > 20 hits







Signal

- $J/\Psi \rightarrow e^+e^-$ in acceptance : 0.025 Hz
  (each track > 40 hits + 3 SVT hits + EMC)
- both electrons tracked and identified: $(0.9 \times 0.7)^2 = 0.4$
- $p_\perp$-cut:

cut	efficiency
$p_\perp(e) > 1.0$ GeV/c	0.72
$p_\perp(e) > 1.5$ GeV/c	0.23
$p_\perp(e) > 2.0$ GeV/c	0.06
$p_\perp(e) > 2.5$ GeV/c	0.025

big error bars here !

Assume:

- one year RHIC running $\rightarrow 10^7$s
- nominal luminosity $\mathcal{L} = 2 \cdot 10^{26}$ cm^{-2} s^{-1}
- 100% trigger efficiency

$\Rightarrow$ annual STAR yield:

cut	approx. annual yield ($J/\Psi \rightarrow e^+e^-$)
$p_\perp(e) > 1.0$ GeV/c	$72 \cdot 10^4$
$p_\perp(e) > 1.5$ GeV/c	$2.5 \cdot 10^4$
$p_\perp(e) > 2.0$ GeV/c	$0.6 \cdot 10^4$

Background

$\Rightarrow$ HIJING b=0 Au+Au

Fake Electrons:

- use HIJING b=0 Au+Au
- form hadron pairs in: $3.0 < m < 3.2$ GeV/c^2

cut	approx. annual yield ($h^+ h^-$)
$p_\perp(e) > 1.5$ GeV/c	$2360 \cdot 10^6$
$p_\perp(e) > 2.0$ GeV/c	$80 \cdot 10^6$

- hadron suppression: (varies strongly with $p_\perp$)
  - TPC + EMC: $1.5 < p_\perp < 2.5$ GeV/c
  - EMC: $p_\perp > 2.5$ GeV/c

Real Electrons:

- Dalitz and Conversions
- form h-e and e-e pairs

cut	fake $e^\pm h^\mp$ (conversions)	fake $e^\pm h^\mp$ (Dalitz)	$e^\pm e^\mp$ (Conv./Dalitz)
$p_\perp(e) > 1.5$ GeV/c	$0.16 \cdot 10^6$	$0.015 \cdot 10^6$	–
$p_\perp(e) > 2.0$ GeV/c	$0.03 \cdot 10^6$	–	–

- Conversion suppression:
  - impact parameter cut (not from primary vertex)

Results

cut	S	S/B	S_{eff}	Significance (σ)
$p_\perp(e) > 1.5$ GeV/c	$2.5 \cdot 10^4$	1:5	2300	48
$p_\perp(e) > 2.0$ GeV/c	$0.6 \cdot 10^4$	2:1	3000	55

A lot of "best guesses" can be made better

Trigger:

- rate of detectable $J/\Psi \rightarrow e^+e^-$ in detector: 0.025 Hz
- STAR: 1Hz
- assume L3 copes with L0 rate ($\sim$ 100 Hz)

To keep loss of signal (dead-time) small:

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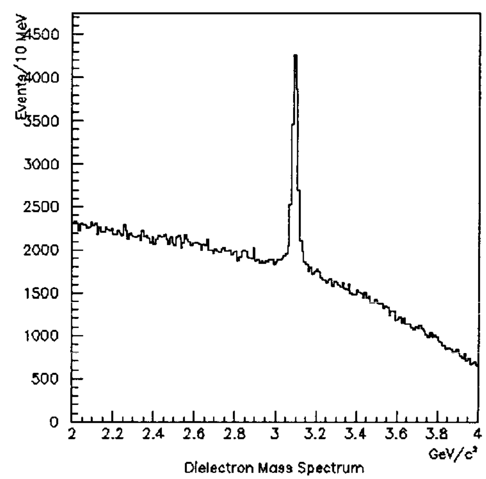
$$\frac{S}{B} > \frac{0.025 \text{ Hz}}{1 \text{ Hz}} = \frac{1}{40}$$

$\Rightarrow$ need L3 trigger studies

- Ups:
  - jet quenching (signal requires 2 high-$p_\perp$tracks)
  - recent improvements in EMC design
  - use cuts on the pair instead at the single electron level
- Downs:
  - trigger losses
  - $\bar{p}$ in EMC (fake electrons)
  - Hijing underestimates background

Summary

- Charmonium physics in STAR looks possible
- There are good reasons to believe that STAR can
  - find J/Ψ's via $J/\Psi \rightarrow e^+e^-$
  - and even find open charm via semileptonic decays
- the requirements are:
  - L3 trigger
  - EMC
  - both are on their way ...
- we are extremely sensitive to the level of background
- predictions not yet entirely stable
- small inprovements in hadron rejection correspond to large improvement in S/B
- current results at this point just a snapshot of work in progess



plot:T. LeCompte

PROOF! I'LL GIVE YOU PROOF!

PHENIX J/ψ Measurements

Marzia Rosati
for the **PHENIX Collaboration**
Department of Physics and Astronomy, Iowa State University, Ames, IA 50011
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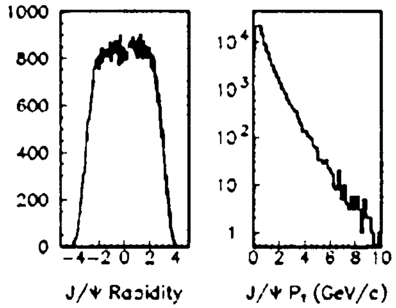
The PHENIX detector at RHIC will allow the measurement of vector mesons through their decay into both dielectrons and dimuons. This is one the of main goals of the PHENIX experiment, which will start taking data in 1999.

Electrons will be reconstructed as charged particles by the Central Arm tracking detectors (Drift Chambers, Pad Chambers and Time Expansion Chamber) and can be identified, in the range of 0.1 GeV/c $\leq$ p $\leq$ 5 GeV/c, by using a combination of detectors: the Ring Imaging Chamber, the Electromagnetic Calorimeter and the Time Expsansion Chamber. All these detectors combined will provide a π rejection factor of better than 10^{-4}.

Muons will be identified by the MUID detectors, made of steel absober interleaved with layers of Iarocci proportional tubes. The low energy muon threshold in this detectors is 2.2 GeV/c and the $\pi/\mu \simeq 10^{-4}$. The muon trajectories will be reconstucted using the Muon Cathode Strip Chambers, which provide a position resolution of 100 μm.

The full tracking and particle identification system has been simulated. The acceptance as a function of p_T and rapidity is calculated. The expected performance of the Central and Muon Arm detectors in measuring J/ψ and ψ' through their $\mu^+\mu^-$ and e^+e^- decay are shown. The expected rate integrated yield in one year of RHIC running at full luminosity is estimated.

Detector Acceptance for J/ψ → dileptons



Using the p-N cross section predictions as calculated at NLO for the transverse momentum and rapidity distribution we calculate the acceptance, that is the percentage of J/ψ which have both leptons going through the detector

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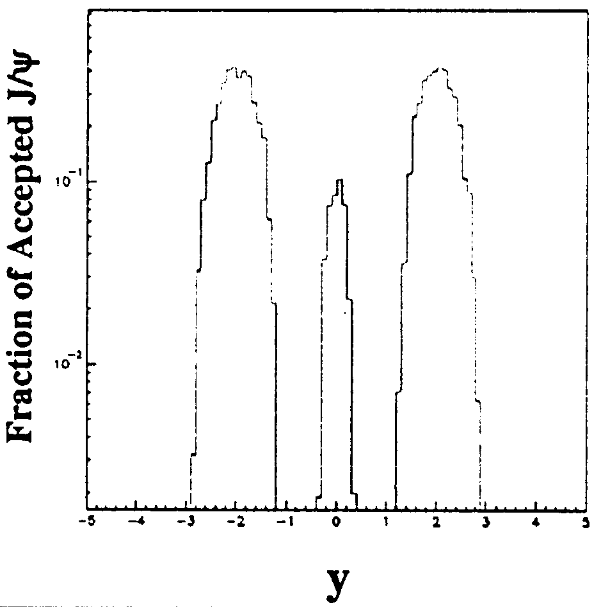


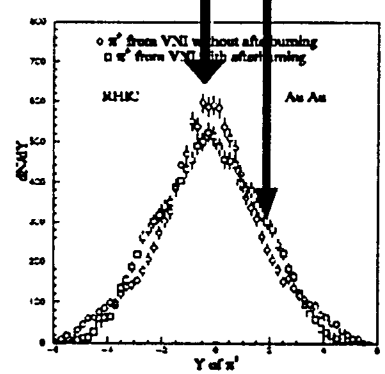
For $J/\psi \to \mu^+\mu^-$

$$\frac{N_{J/\psi}(accepted)}{N_{J/\psi}(total)} = 8.6\%$$

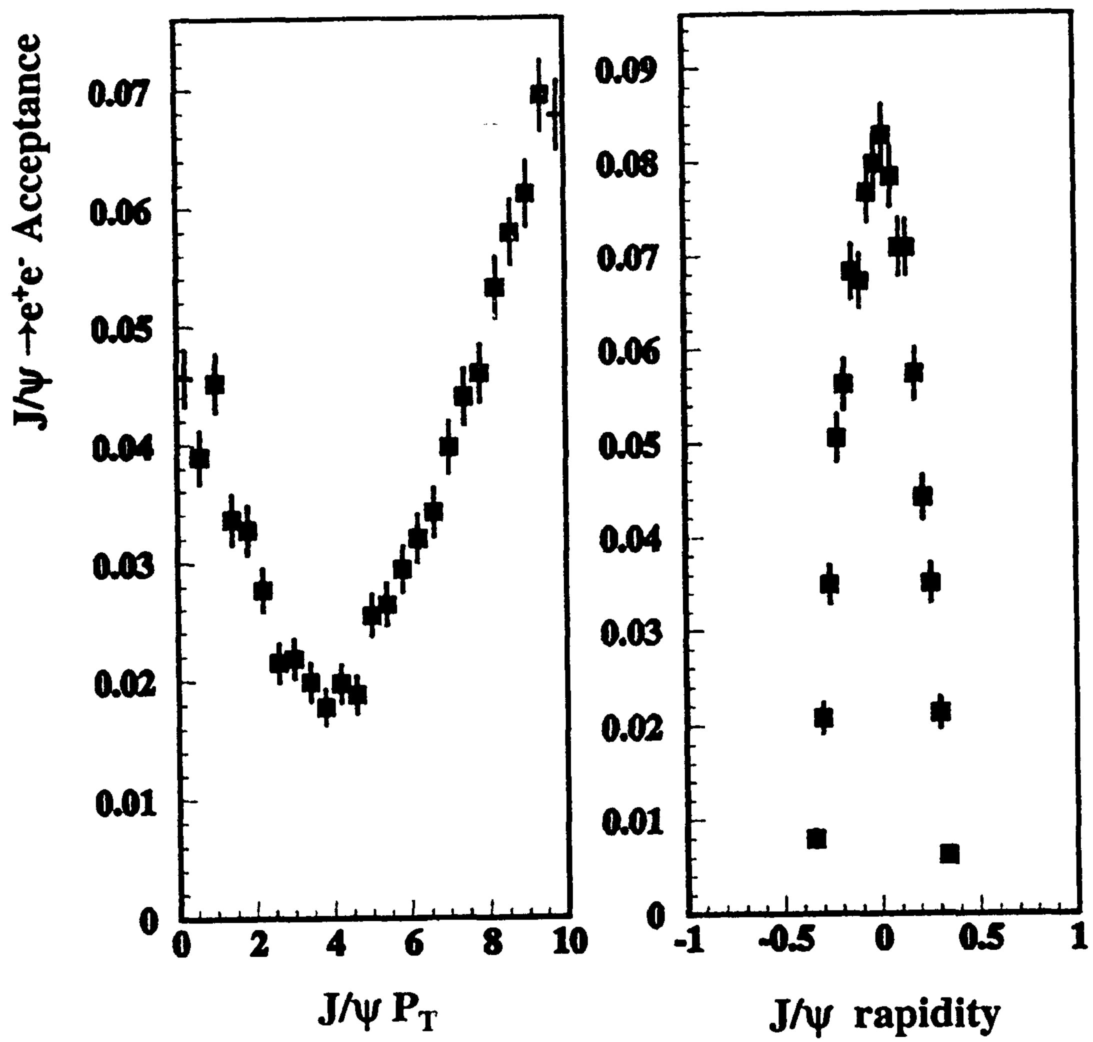
For $J/\psi \to e^+e^-$

$$\frac{N_{J/\psi}(accepted)}{N_{J/\psi}(total)} = 0.75\%$$

VNI Model π+ Rapidity
nucl-th/9705041



$J/\psi \rightarrow e^+e^-$ Acceptance vs P_T and rapidity



Marzia Rosati
Iowa State University

J/ψ →μ⁺μ⁻ Acceptance vs P_T and rapidity

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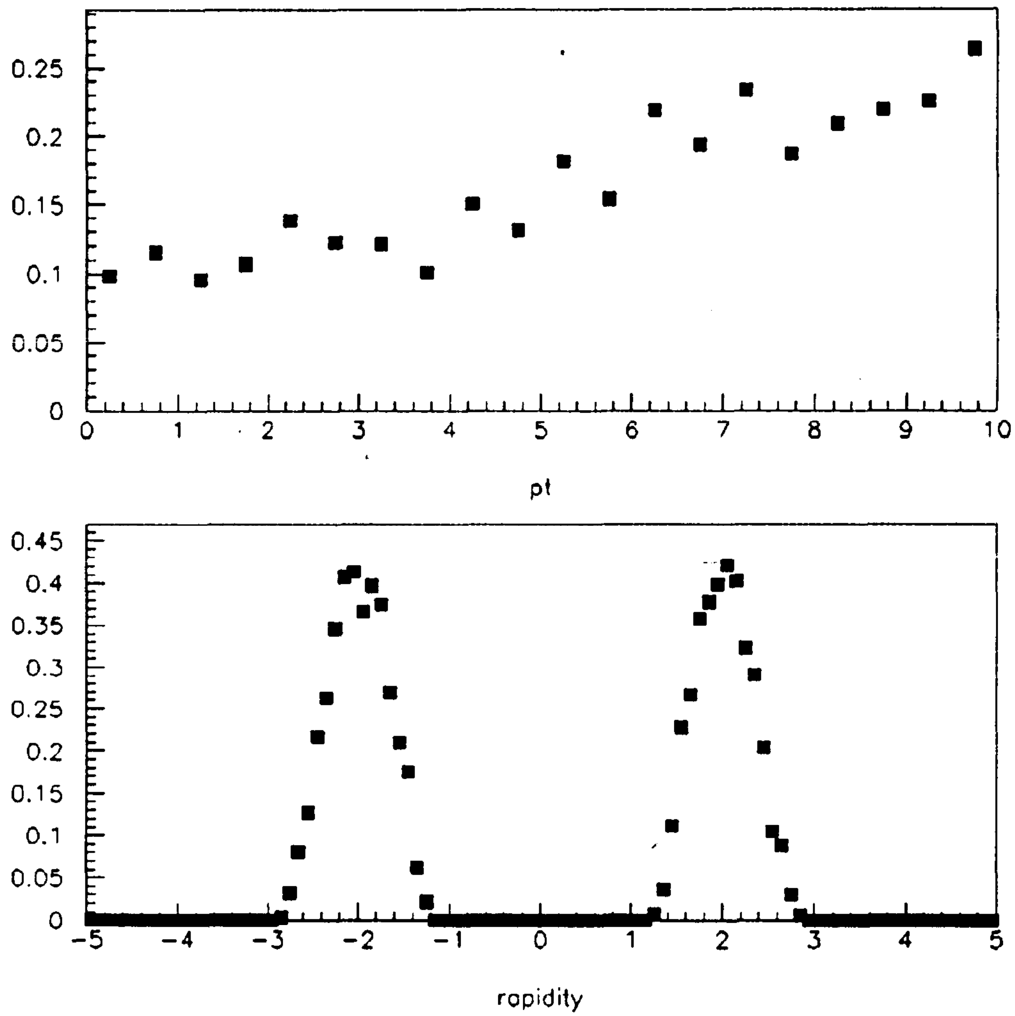

Marzia Rosati
Iowa State University

J/ψ Invariant Mass Resolution and Acceptances

Particle	Mass Resolution (MeV/c^2)	Acceptance (%)
$J/\psi \rightarrow \mu\mu$	105	8.6
$\psi' \rightarrow \mu\mu$	105	8.6
$\Upsilon \rightarrow \mu\mu$	180	8.3
$\psi \rightarrow ee$	20	0.75
$\psi' \rightarrow ee$	20	0.75

Marzia Rosati
Iowa State University

Estimate of J/ψ Integrated Yield in one Year of RHIC

Assuming there is **no anomalous J/ψ suppression** we can calculate an upper limit to the J/ ψ Integrated Yield.

$$\sigma_{AA\to J/\psi}BR = A^{2\alpha}\sigma_{pN\to J/\psi}BR = 3.3mb$$

with $\begin{cases} BR\ \sigma_{pN\to J/\psi} = 185nb \\ \alpha = 0.92 \end{cases}$

We estimate one year of running for 8 months corresponds to 10^7 seconds, to account for detector and accelerator down time(50%). Using the RHIC design luminosity $L= 2x\ 10^{26}\ cm^{-2}\ s^{-1}$.Then the total number of J/ψ produced is:

$$N_{J/\psi}(total) = 6.3\times10^6 events$$

Within the PHENIX acceptance we have:

Particle	Dimuon Decay	Dielectron Decay
J/ψ	530k	53K
ψ'	9k	0.9k
Y	0.8k	

Marzia Rosati
Iowa State University

ALICE Capabilities Concerning Quarkonium Physics

Andreas Morsch
CERN

The LHC (Large Hadron Collider) will allow to perform heavy and light A-A collisions at a centre of mass energy of $Z/A \cdot 14$ TeV/nucleon. The machine will have separate RF systems for both beams allowing also p-A collisions in the same energy range, which will serve as a source of indispensable reference data.

ALICE (A Large Ion Collider Experiment) is the only detector dedicated to heavy ion physics at the LHC. Its central part allows a comprehensive measurement of hadrons, photons and low-mass electron pairs, whereas the forward muon-arm will be used to study the production of the heavy quarkonium states via their dimuon decay channels. As hard, penetrating probes, the quarkonium states provide a tool to study the earliest and hottest stages of heavy ion collisions, probing the strongly interacting matter on short distance scales. The suppression of the heavy quark resonances is the most promising signature for a deconfined state of partonic matter, the Quark Gluon Plasma (QGP).

In order to exclude other more conventional mechanisms of quarkonium suppression the effect has to be measured for the complete family of resonances and as a function of the energy density and the transverse momentum of the resonance. The observed production rates have to be normalized to unsuppressed hard processes that are produced at a similar Q^2 and x of the parton-parton interaction i.e. charm and beauty production.

The measurement of the charmonium transverse momentum spectrum down to $p_T=0$ is only possible in the forward direction owing to the intrinsic momentum cut-off of the absorbers used for muon identification. In order to separate all the members of the Υ family a mass resolution of at least 100 MeV is needed. An absorber has to be placed as close as possible to the interaction point in order to suppress combinatorial background from $\pi,K \rightarrow \mu$ decays, which would otherwise dominate the dimuon continuum and render the measurement of the continuum from heavy quark semileptonic decays impossible.

The acceptance of the forward spectrometer covers the pseudorapidity rang from 2.5 to 4. The tracking system consists of 10 logical planes. One tracking station is placed inside a dipole magnet with a total field integral of B.l=3 Tm and a maximum field of 0.7 T. The momentum of the muons is determined from a combined angle-angle and sagitta measurement. With this set-up, mass resolutions of 55 MeV and 80 MeV are achieved for the J/ψ and the Υ resonance, respectively.

The most demanding running conditions for the muon spectrometer are found for the heaviest system: Pb-Pb collisisions at an initial luminosity of $\sim 10^{27}$ cm^{-2} s^{-1}. In this case, in the J/ψ mass region, the continuum below the resonances is dominated by combinatorial background from π, K and from semileptonic charm decays. In the Υ–mass region, correlated muons from beauty decays dominate and can be used for normalization. The significances of the signals after one month of running are estimated to be 310, 12, 43, 21 and 13 for the J/ψ, ψ, Υ, Υ', Υ''-resonances, respectively.

ALICE Capabilities concerning Quarkonium Physics

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ALICE Dimuon Group

For the ALICE Collaboration

Workshop on
Quarkonium Production in Relativistic Nuclear Collisions
BNL

Physics Goals and Experimental Requirements

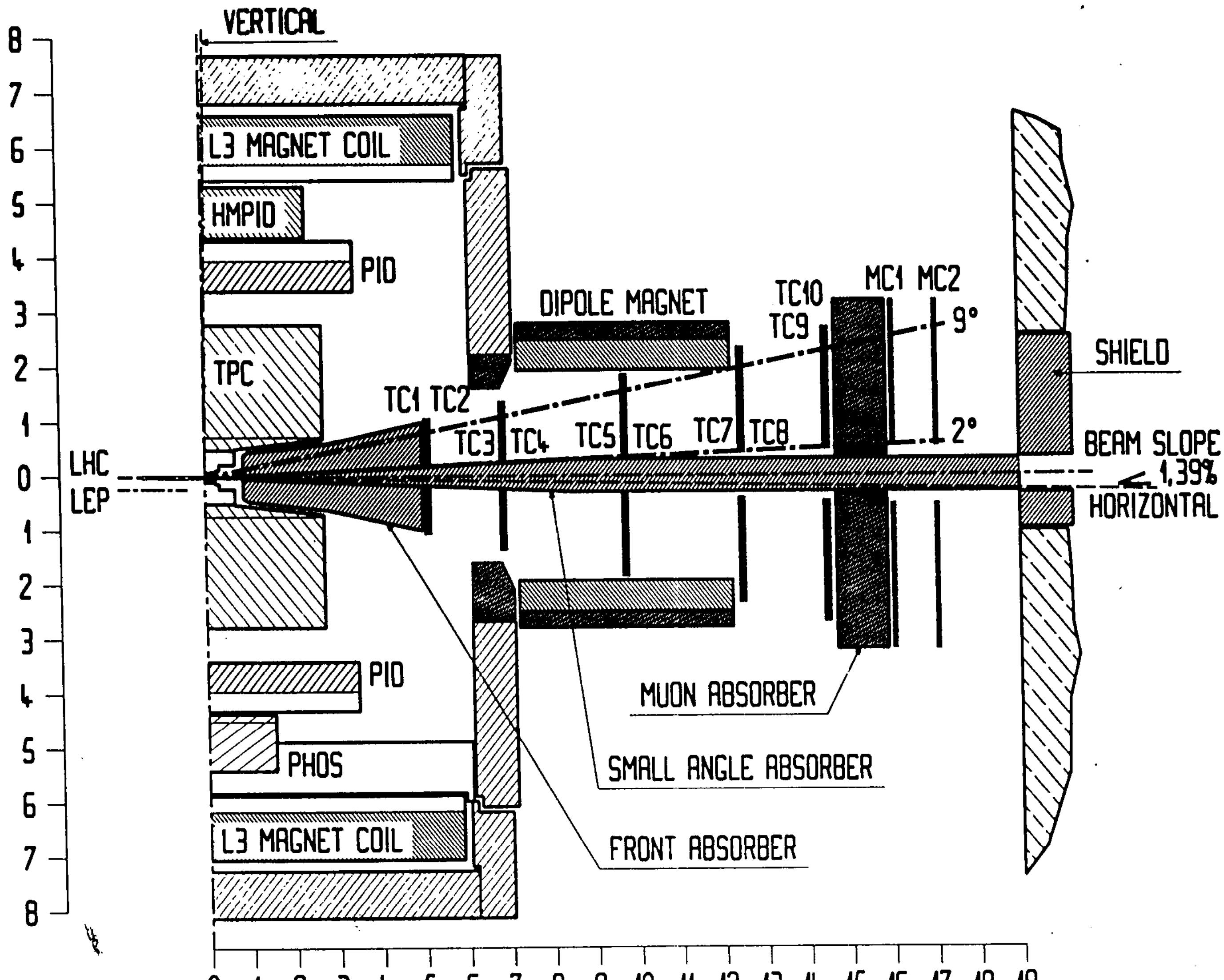
The suppression of the heavy quark resonances J/ψ, ψ', ϒ,ϒ',ϒ'' is the most promising signature for QGP. To exclude other explanations (comovers, hadronic absorption) suppression has to be measured:

- for the complete family of resonances
- as a function of energy density (centrality and *A* of the system)
- as a function of transverse momentum
- by normalising to unsuppressed hard processes, i.e. charm and beauty production.

➡

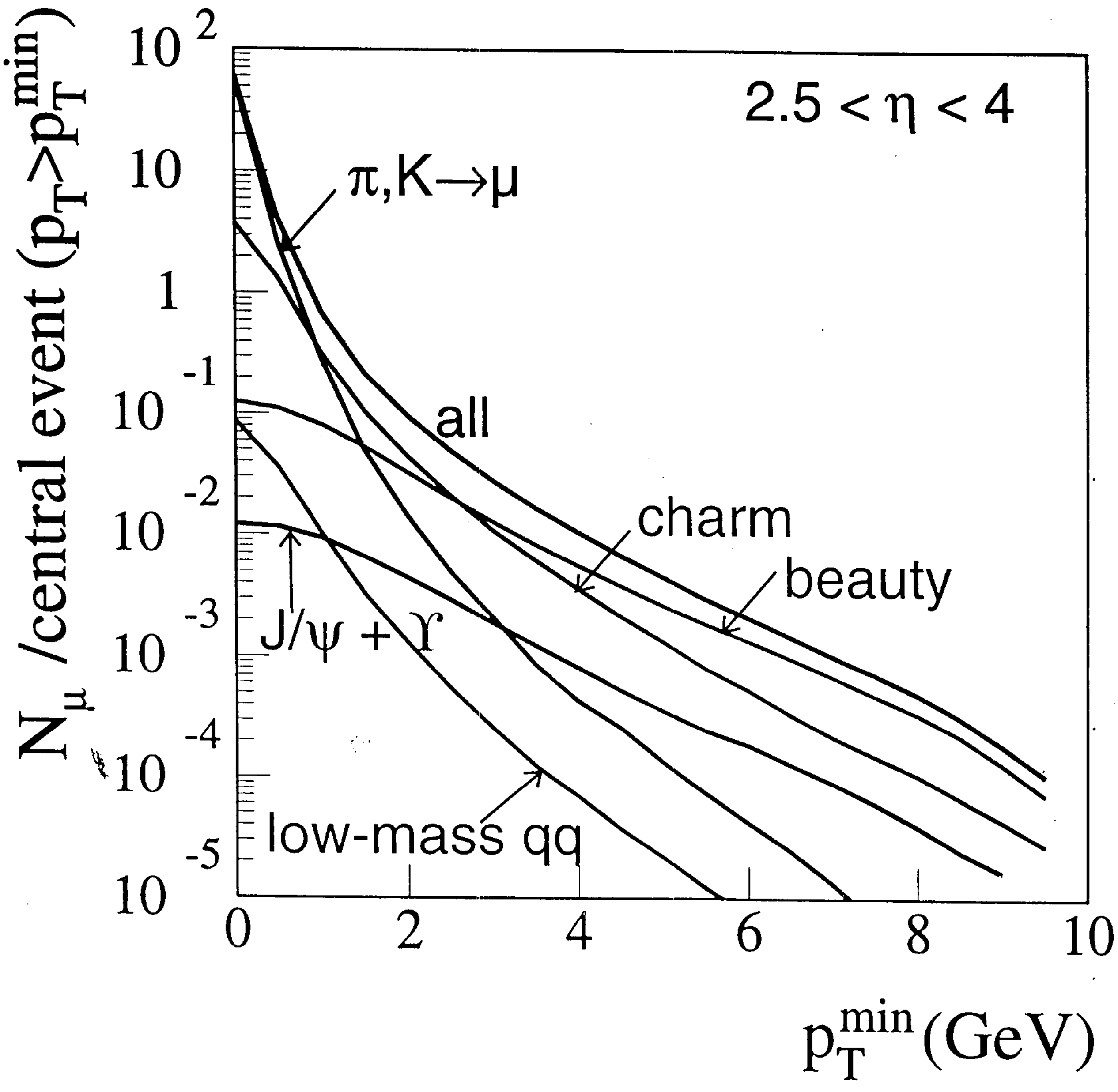
- Mass resolution at least 100 MeV in order to separate ϒ',ϒ''
- Measurement of J/ψ down to p_T=0 GeV only possible in the forward direction, owing to the intrinsic momentum cut-off of absorbers/calorimeters (~ 4 GeV).
- Use absorber close to IP to suppress dominating π,K decay background. Forward direction more favourable because of boost.

Layout of the Muon Arm

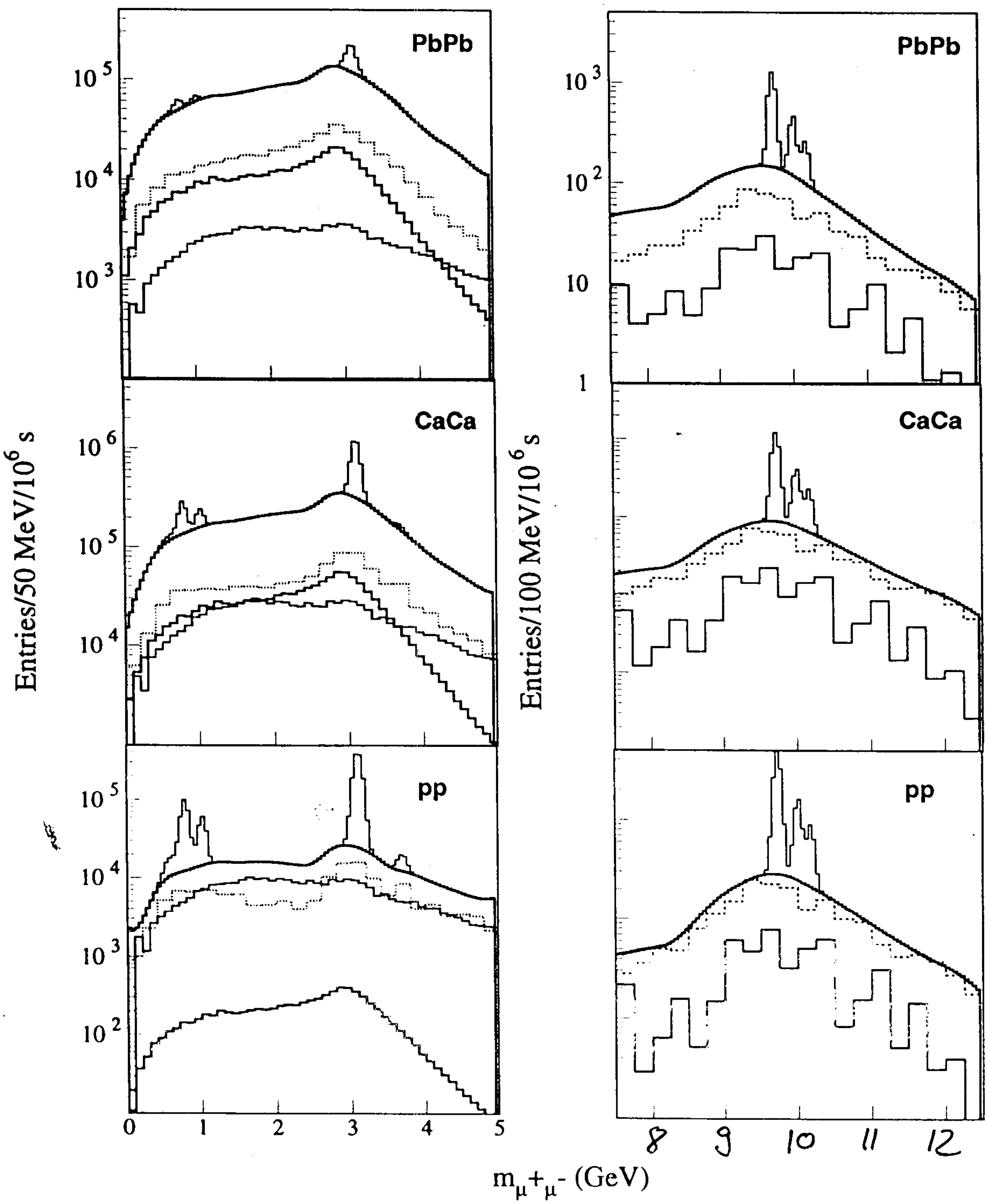


- **acceptance:** θ = 2° - 9 η = 2.5- 4
- **front absorber** ≈11λ C +Concrete heavy metal shield (W or Pb)
- **beam shield** θ < 2°, r_i = 4cm, r_o < 29 cm heavy metal (mainly W)
- **dipole magnet** B=1T, Bl = 3 Tm r = 1.9 m
- **tracking chambers** 10 logical planes, high resolution & granularity
- **hadron absorber** ≈11λ Fe
- **trigger chambers** 2 logical planes, low resolution & granularity

Number of Muons per Central PbPb Collision

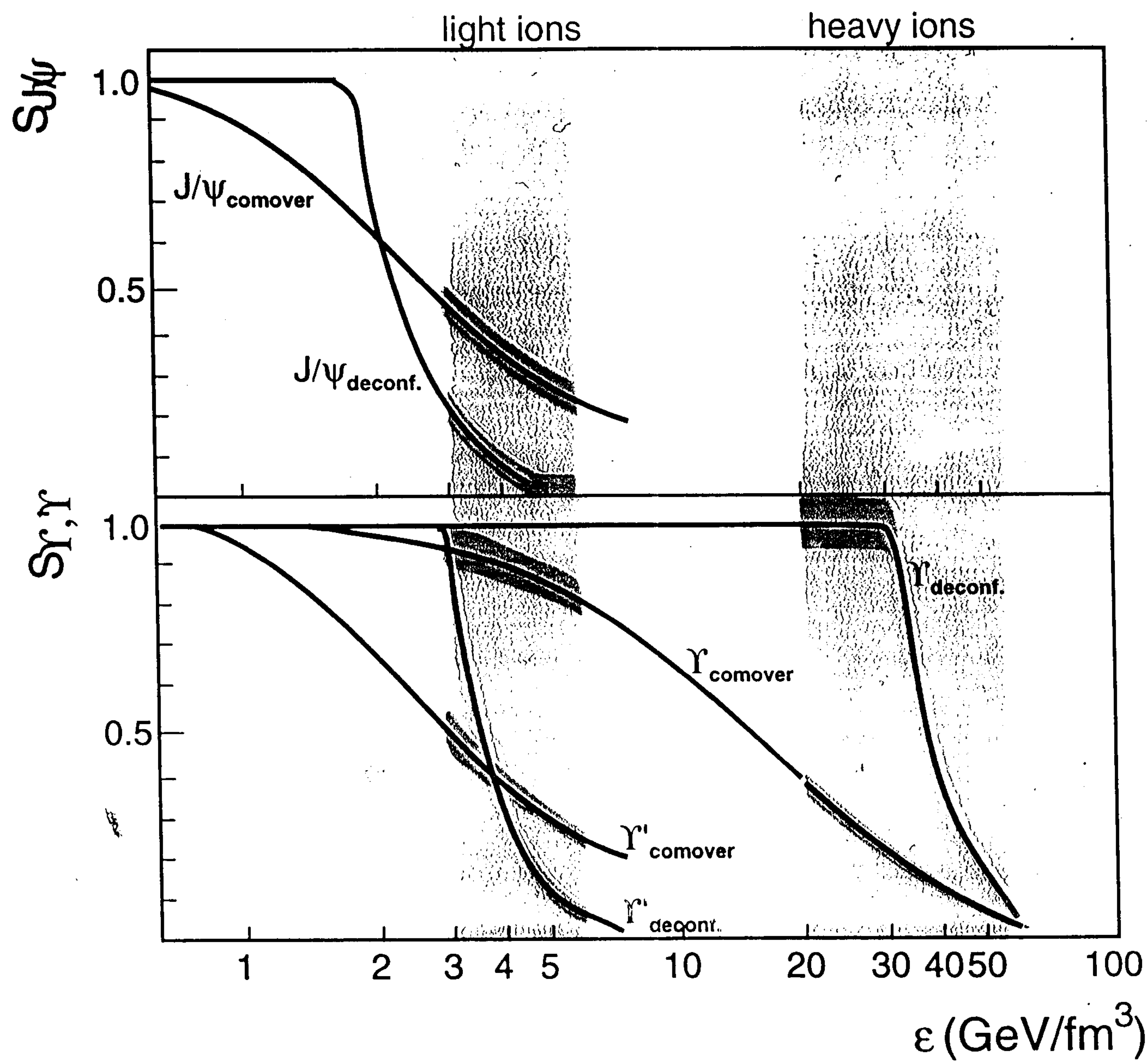


Dimuon Mass Spectra in central PbPb



π,K → μ charm beauty

Suppression Measurements



What Produces the x_F Dependence of ψ Production in pA Interactions?*

R. Vogt

The nuclear target, A, dependence of particle production is conventionally parameterized by a power law as $\sigma_{pA} = \sigma_{pN} A^{\alpha}$. If production were independent of nuclear matter, $\alpha = 1$. Experiments have measured $\alpha < 1$ and a decrease in α as a function of x_F. There are a number of effects which could contribute to the x_F dependence. The nuclear parton densities are different than those in a free proton. The incoming parton or the final-state $c\bar{c}$ pair could lose energy in nuclear matter. Absorption of the produced ψ or $c\bar{c}$ state by nucleons and/or produced particles can cause ψ suppression. Another effect is a possible intrinsic $c\bar{c}$ component of the projectile.

We compare $\alpha(x_F)$ with the preliminary E866 ψ and ψ' data [1]. Since the E866 targets are tungsten and beryllium,

$$\alpha(x_F) = 1 + \frac{\ln[(A_{\rm Be} d\sigma_{p{\rm W}})/(A_{\rm W} d\sigma_{p{\rm Be}})]}{\ln(A_{\rm W}/A_{\rm Be})} \, .$$

We calculate quarkonium hadroproduction in two ways. The color evaporation model, CEM, treats all charmonium production identically to $c\bar{c}$ production. The more recent non-relativistic QCD approach, NRQCD, involves an expansion of quarkonium production in powers of the relative $q - \bar{q}$ velocity.

We consider three different models of nuclear absorption: either all states are produced as color octets or color singlets or in an octet/singlet combination. Comoving secondaries also scatter with the $c\bar{c}$ pair or the ψ.

We have assumed that the nuclear parton distributions can be written as $f_i^A(x, Q^2, A) = S^i(A, x, Q^2) f_i^p(x, Q^2)$. The first parameterization, $S_1(A, x)$, does not differentiate between q, $\bar{q}$ and g or include Q^2 evolution. The second, $S_2^i(A, x, Q^2)$, modifies the valence quark, sea quark and gluon distributions separately and includes Q^2 evolution from 2 to 10 GeV. The most recent, $S_3^i(A, x, Q^2)$, evolves all q, $\bar{q}$ and g distributions separately above 1.5 GeV. The gluon distribution has a larger antishadowing peak than S_2 while the sea quarks are shadowed.

We use two different models of energy loss. The first, GM, from Gavin and Milana, depletes the projectile parton momentum fraction, x_1. The second model is from Kharzeev and Satz, KS. A color octet $c\bar{c}$ propagates some distance before emitting a soft gluon because the QCD Landau-Pomeronchuk effect causes a delay. Each successive interaction degrades the $c\bar{c}$ pair momentum.

To compare with the preliminary data, we calculate $\alpha(x_F)$ in the following way. For pure octet absorption, we use both GM and KS energy loss. Only GM loss is used with pure singlet absorption and the combination of singlet and octet production. The CEM is used to calculate charmonium production for pure octet and pure singlet absorption while NRQCD is used for octet/singlet combination absorption. All three shadowing parameterizations are used in each case. The absorption cross sections are chosen so each S^i grees with $\alpha(x_F)$ at $x_F > 0$.

A single mechanism cannot describe the shape of $\alpha(x_F)$, thus a combination of effects is necessary. The forward x_F data is understandable as a combination of shadowing, initial-state parton energy loss, final-state absorption by nucleons and comovers and intrinsic charm. The preliminary central and negative x_F data is more difficult to describe without invoking a much stronger than expected absorption mechanism.

[1] M.J. Leitch, in proceedings of "Quarkonium Production in Relativistic Nuclear Collisions", Institute for Nuclear Theory, Seattle, WA, May 1998.

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*LBNL-42294; to be submitted.

What Influences the x_F Dependence of J/ψ Production in pA Interactions?

R. Vogt

LBNL and UC Davis

We Study:

J/ψ and ψ' Production: Color Evaporation (CEM) (Gavai…
NRQCD (Beneke + Rothstein)

Drell-Yan: An Important Test

A Combination of Effects Considered:

Nuclear Absorption

Pure Octet (x_F-independent)

Pure Singlet (color transparency - no effect if ψ produced outside target)

Mix of Octet and Singlet Absorption (NRQCD)

Comoving Secondaries

Shadowing $f_i^A(x,Q^2) = S^i(A,x,Q^2) f_i^p(x,Q^2)$

S_1 $S_{q_v} = S_{\bar q} = S_g$, no evolution (Eskola, Qiu, Czyżewski…

S_2 $q_v, \bar q, g$ identified + evolved separately (Eskola…

S_3 all partons evolved separately (Eskola, Kolhinen, Ruuskanen, Salga…

Energy loss

initial state loss by projectile parton, GM (Gavin + Milana)

octet $c\bar c$ loss in final state, $x_F \geq 0$, KS (Kharzeev + Satz)

Intrinsic Charm

	octet $\sigma_{\psi N}$ (mb)	singlet $\sigma_{\psi N}$ (mb)	combination octet (mb)	combination singlet (mb)
S_1	2	8	3	2
S_2	1	5	1	1
S_3	3	10	3	5

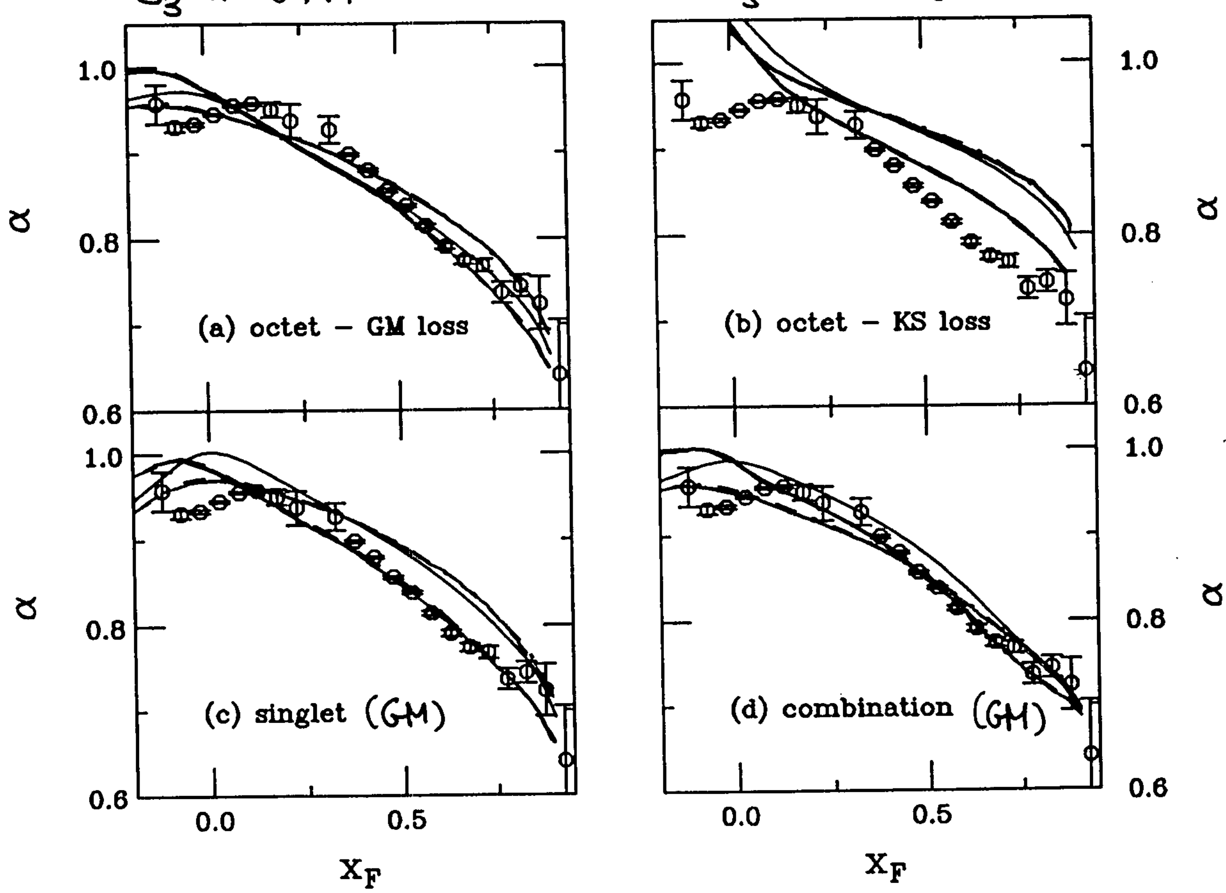
Comparison with preliminary E866 ψ data

integrated α given in range $-0.2 < x_F < 0.8$

- CEM with GRV 94 LO PDFs for all but combination model (NRQCD with CTEQ 3L)

S_1 $\alpha = 0.938$
S_2 $\alpha = 0.954$
S_3 $\alpha = 0.946$

S_1 $\alpha = 0.987$
S_2 $\alpha = 0.975$
S_3 $\alpha = 1.006$



S_1 $\alpha = 0.957$
S_2 $\alpha = 0.962$
S_3 $\alpha = 0.977$

S_1 $\alpha = 0.943$
S_2 $\alpha = 0.972$
S_3 $\alpha = 0.973$

- octet model with GM loss and combination model give best general agreement for all shadowing parameterizations
- antishadowing peak prevents turnover at low x_F

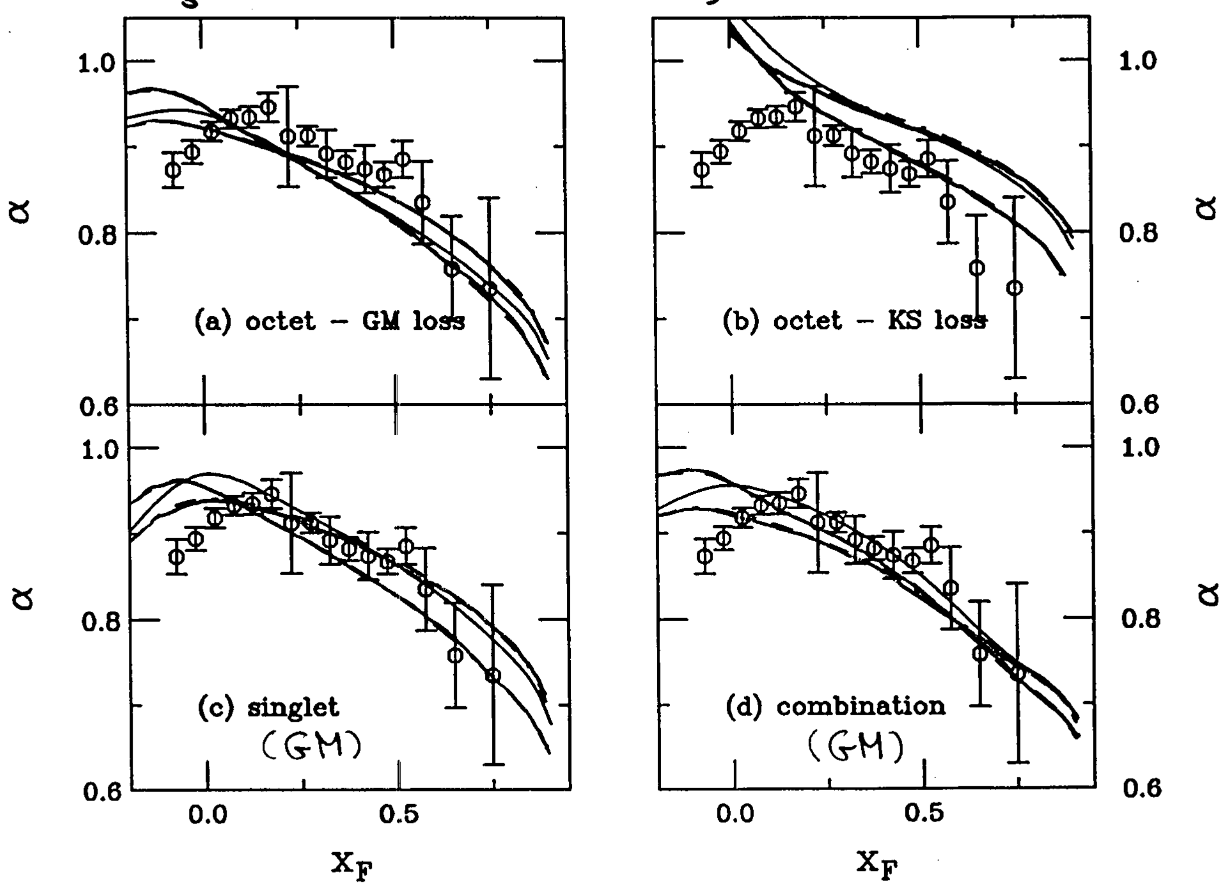
Comparison with preliminary E866 ψ' data

integrated α given for $-0.2 < x_F < 0.8$

- CEM with GRV 94 LO PDFs for all but combination model (NRQCD with CTEQ 3L)

S_1 α = 0.911
S_2 α = 0.927
S_3 α = 0.919

S_1 α = 0.986
S_2 α = 0.973
S_3 α = 1.005



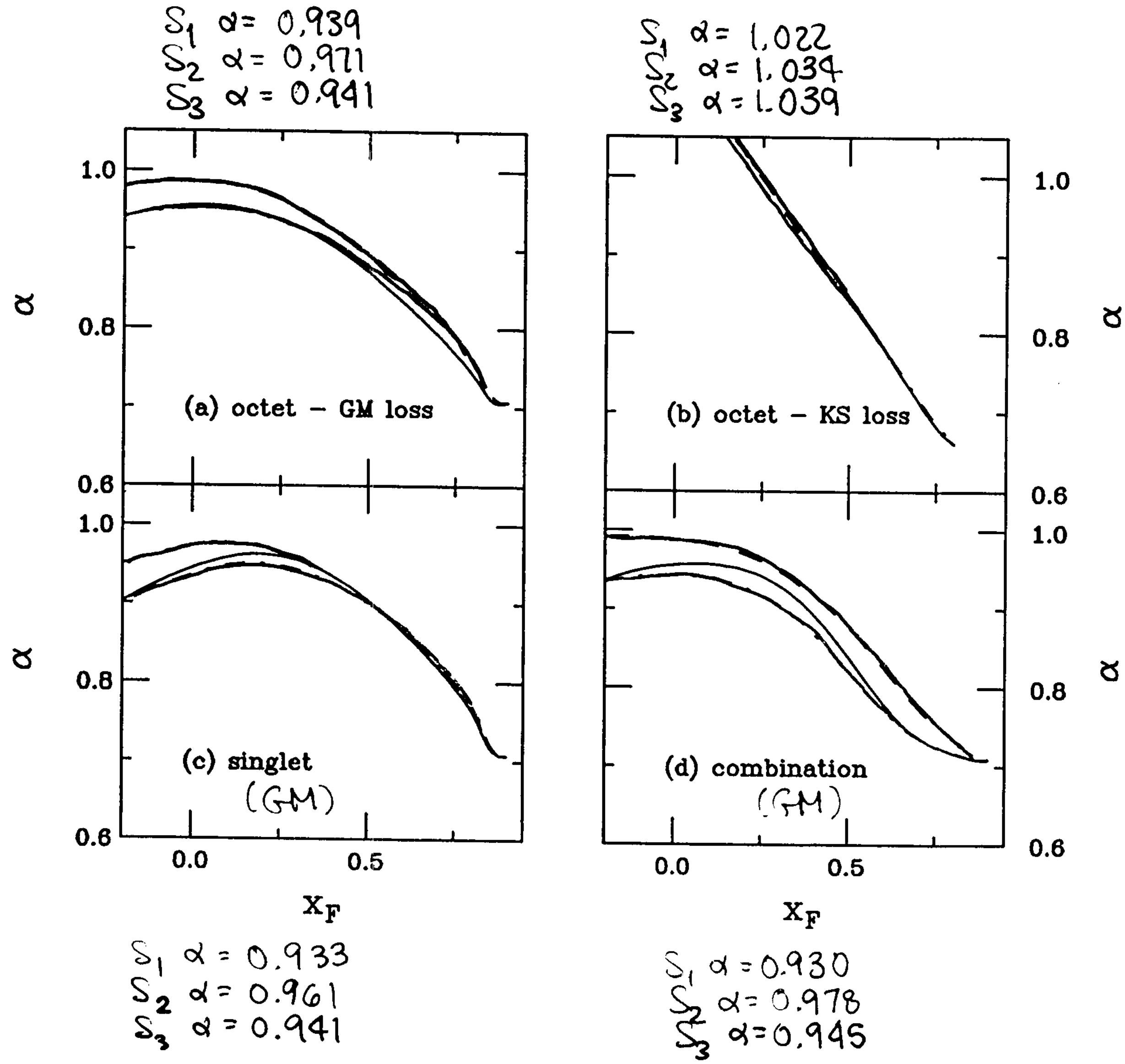
S_1 α = 0.926
S_2 α = 0.931
S_3 α = 0.945

S_1 α = 0.916
S_2 α = 0.944
S_3 α = 0.943

- relative agreement for most models (except KS loss)
- differences in integrated α a few percent except pure singlet absorption somewhat larger
- in these cases, the difference is from comover contribution
- no agreement at negative x_F

Predictions of ψ A dependence at 120 GeV
for Be + W targets, integrated α in same x_F range
$-0.2 < x_F < 0.8$

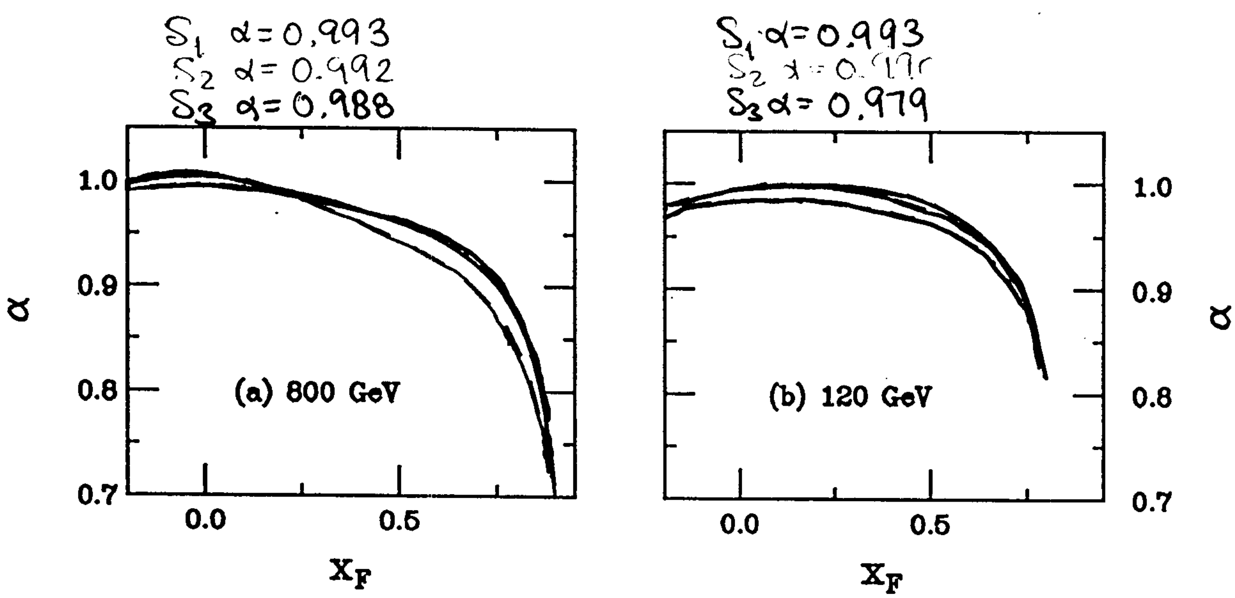
- CEM with GRV 94 LO PDFs for all but combination model (NRQCD with CTEQ 3L)



- energy dependence of α is typically not large

Predictions of Drell-Yan A dependence at 800 GeV and 120 GeV

- GRV 94 LO PDFs, GM energy loss, $-0.2 < x_F < 0.8$ range of integrated α
- integrated α very close to unity in all cases except S_3 due to sea quark shadowing



Charmonium Dissociation and Anomalous J/ψ Suppression

D. Blaschke, G. Burau, K. Martins (Rostock)

Outline

1. Mott dissociation of $c\bar{c}$ pairs in matter
2. Anomalous E_T dependence
3. Saturation of $\langle p_T^2 \rangle$ broadening
4. Transverse momentum $R_{E_T}(p_T)$

RIKEN-BNL Workshop "Quarkonium Production ...", Brookhaven, Sept 28- Oct 2, 1998

Mott dissociation of preresonance charmonium

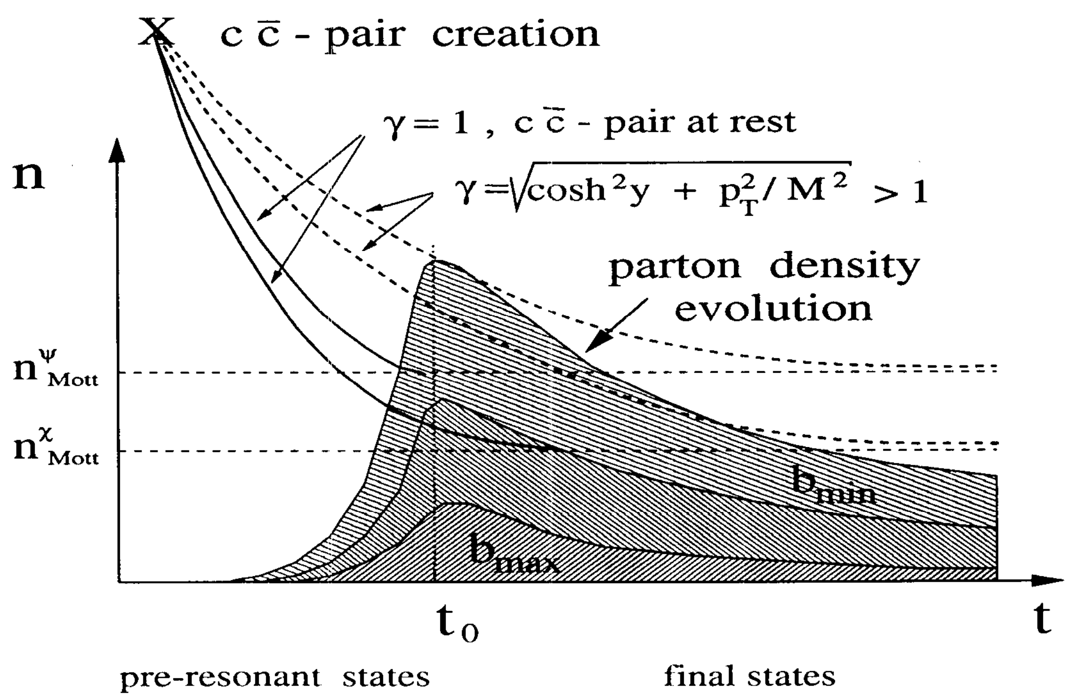
Mott effect: Bound state dissolution in dense matter
Here: "String-Flip" of interaction to "nearest neighbor" partons.
Critical density $n_{\text{Mott}}(J/\psi) > n_c^{QGP} \approx n_{\text{Mott}}(\psi')$

Simplify description of critical behavior:

- criterion of "nearest neighbor"
- $\langle r^2_{c\bar{c}} \rangle \leq \langle r^2_{c\bar{q}} \rangle \Rightarrow$ no absorption;
  $\langle r^2_{c\bar{c}} \rangle > \langle r^2_{c\bar{q}} \rangle \Rightarrow$ complete absorption
- time dependent $\langle r^2 \rangle$ in different rest frames
  $\Longrightarrow$ role of Lorentz boost γ of charmonium with respect to the collision c.o.m. system

Criterion for the onset of Mott dissociation of J/ψ and χ_c in S-U and Pb-Pb collisions K.M., D. Blaschke nucl-th/9702044

$\Longrightarrow$ charmonium suppression in central region of Pb-Pb collisions

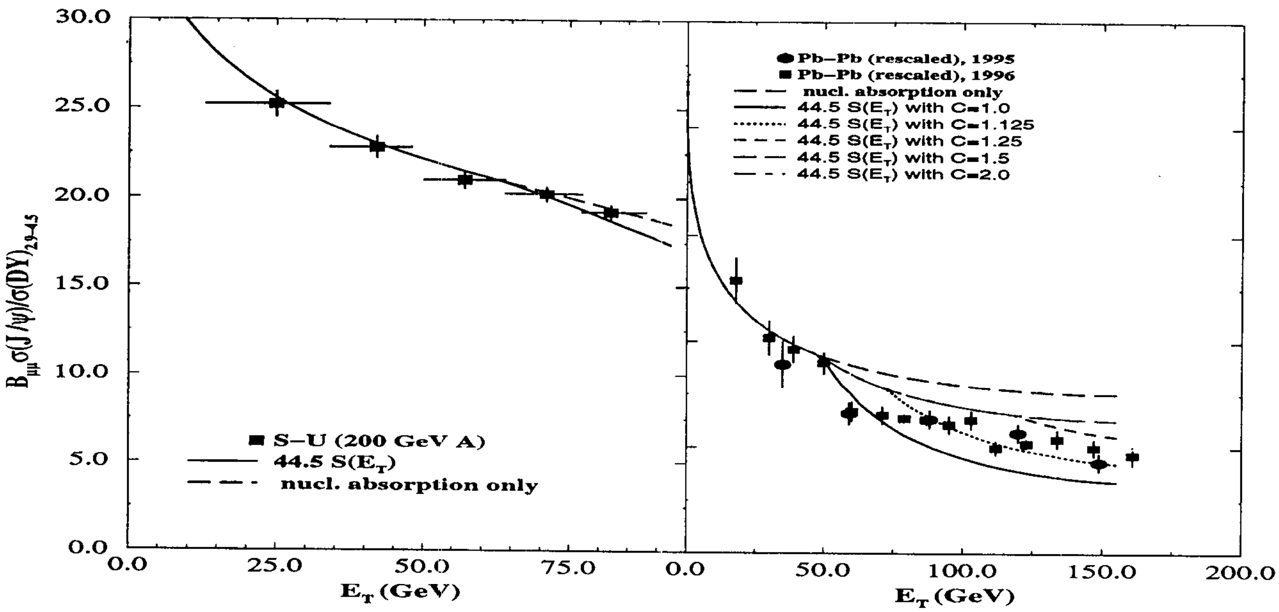


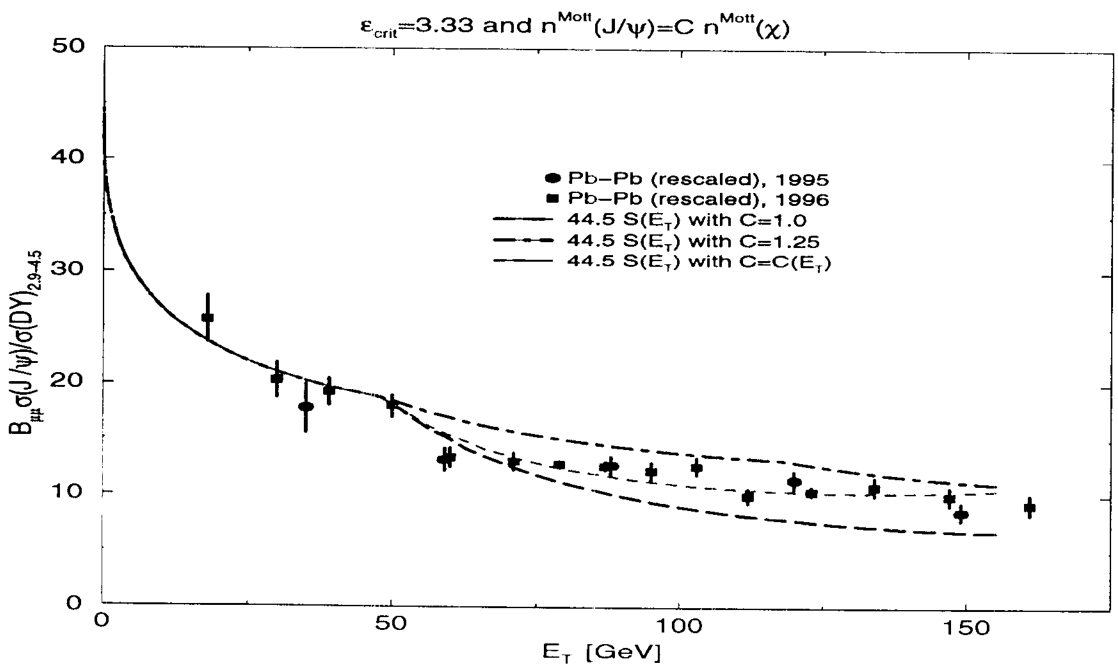
Seen J/ψ come from about 30% χ_c + 8 % ψ' + 60 % direct J/ψ

"Anomalous" E_T dependence

$$S(b) = \left[\frac{d\sigma_{prod}}{db}\right]^{-1} \int_0^\infty d^2\mathbf{b}_A \frac{d^2\sigma_{prod}}{db\,d\mathbf{b}_A} P^{abs}_{nuc,A}(\mathbf{b}_A) P^{abs}_{nuc,B}(\mathbf{b}-\mathbf{b}_A) P^{abs}_{\mathrm{MOTT}}(\mathbf{b},\mathbf{b}_A)$$

$$P^{abs}_{\mathrm{MOTT}}(\mathbf{b},\mathbf{b}_A) = 0.3\,\Theta[\gamma^2 n^{\chi}_{\mathrm{MOTT}} - n(\mathbf{b},\mathbf{b}_A)] + 0.7\,\Theta[\gamma^2 n^{\psi}_{\mathrm{MOTT}} - n(\mathbf{b},\mathbf{b}_A)]$$





Saturation of $\langle p_T^2 \rangle$ broadening

Initial state scattering

$$\mathcal{F}(p_T) = \frac{1}{\pi \langle p_T^2 \rangle} e^{-p_T^2/\langle p_T^2 \rangle}$$

$$\langle p_T^2 \rangle = \langle p_T^2 \rangle_{pp} + \rho_0 \sigma_{gN} \langle p_T^2 \rangle_{gN} L(\vec{b}, \vec{b}_A)$$

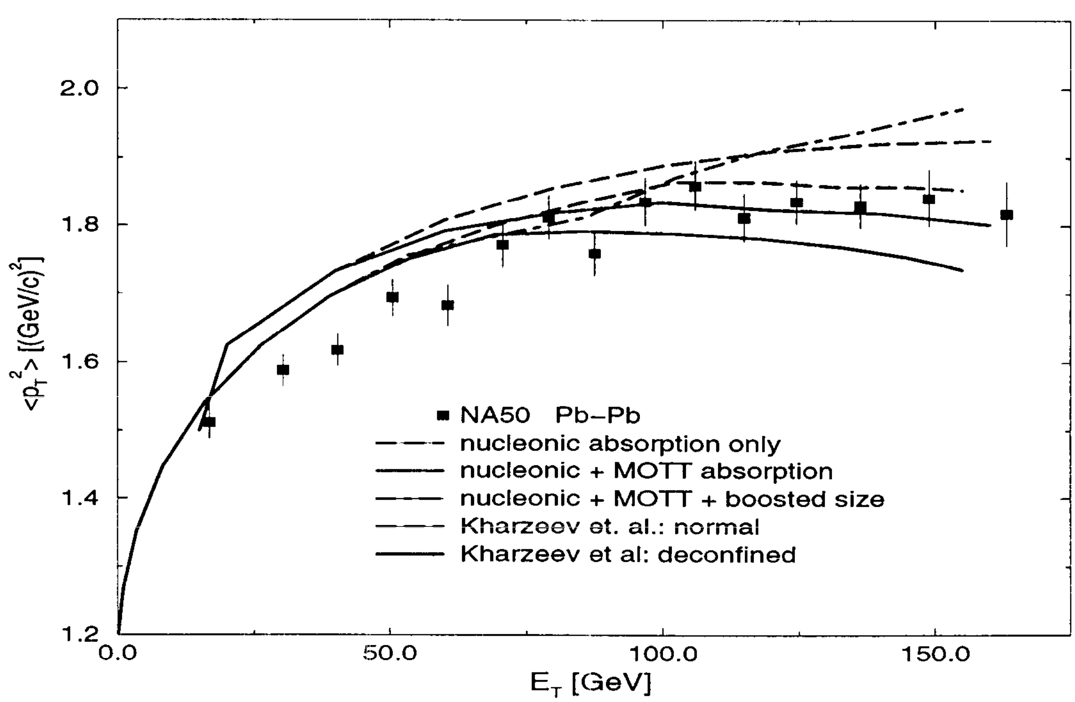
	$\langle p_T^2 \rangle_{pp}$ (GeV/c)^2	$\rho_0 \sigma_{gN} \langle p_T^2 \rangle_{gN}$ (GeV/c)^2 fm^{-1}
S - U	1.21 ± 0.04	0.080 ± 0.007
Pb-Pb	1.12 ± 0.04	0.077 ± 0.005

Boost of the $c\bar{c}$ size

Mott criterion p_T- dependent via gamma factor

$\gamma^2(p_T) = \sqrt{(\Delta y)^2 + p_T^2/M_{c\bar{c}}^2}$

Large p_T $c\bar{c}$ pairs not efficiently blocked out $\Rightarrow$ $\langle p_T^2 \rangle$ rises with E_T

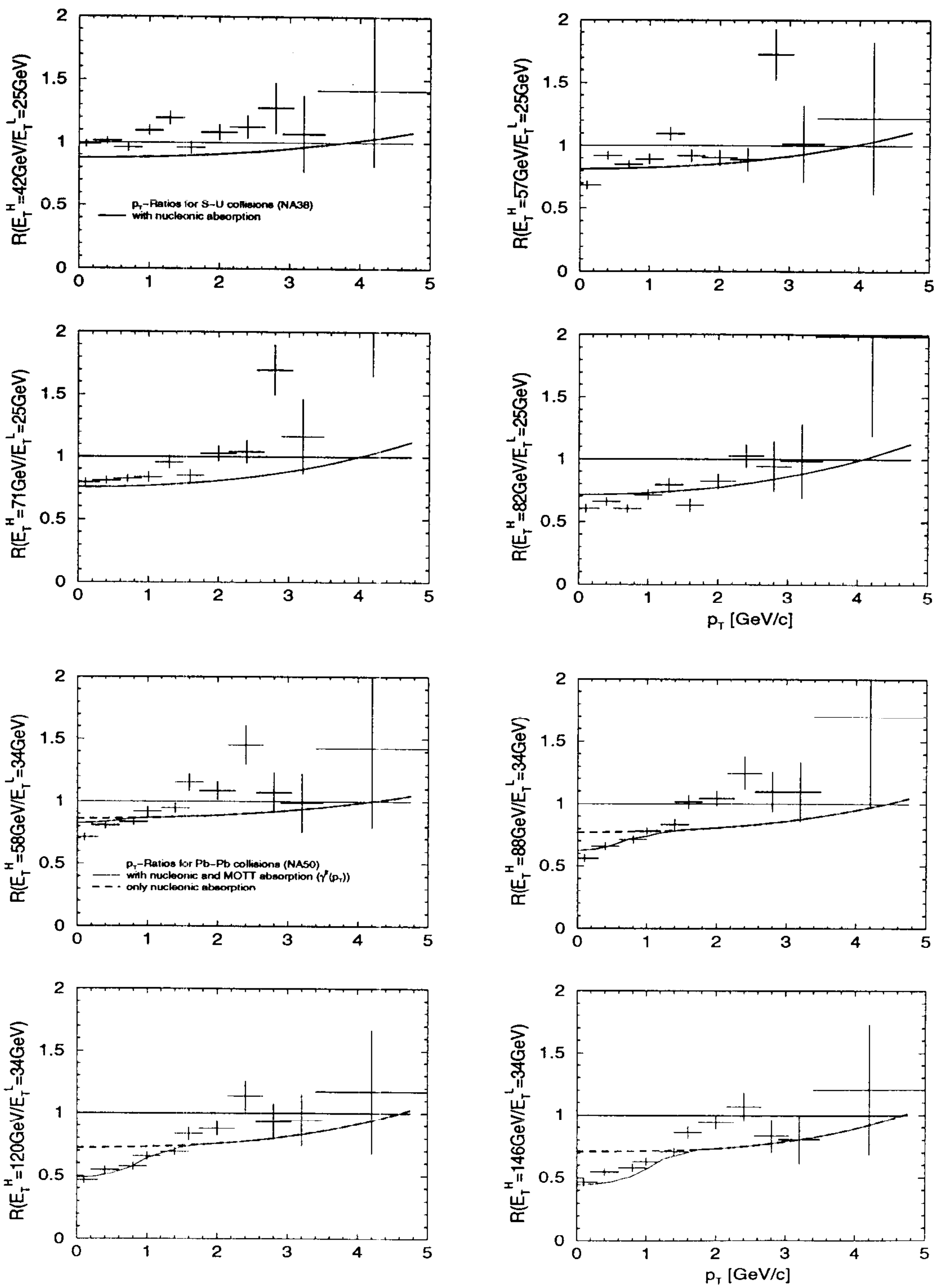


Transverse momentum dependence $R_{E_T}(P_T)$

$$R(E_T^H/E_T^L) = \frac{n_\psi(E_T^H)/n_{DY}(E_T^H)}{n_\psi(E_T^L)/n_{DY}(E_T^L)}$$

S-U

Pb-Pb



Summary (D. Blaschke, G. Burau, K. Martins)

- The cross section for $c\bar{c}$ dissociation in correlated quark matter ($q\bar{q}$ pairs) has been calculated in NRQCD. It is energy dependent and characterized by a threshold and a slope.

- The medium dependence of the mean dissociation cross section $\langle\sigma_{\mathrm{DISS}}\vec{v}\rangle$ has been estimated by changing rms radii and masses of quark-antiquark pairs. A dependence on $\langle r^2_{c\bar{c}}\rangle$ (similar to the Povh- Hüfner law) and an increase from 0.5 mb in the vacuum to 10 mb at the dissociation threshold is found.

- Application to J/ψ suppression in ultrarelativistic AB collisions (NA 50) is performed within a modified Glauber model, with simplifying assumptions:
  - nearest neighbor criterion for sudden breakup (Mott densities) in the transverse plane
  - preresonance evolution of the transverse size

- Results for Pb-Pb collision experiment (NA50)
  - "anomalous" threshold(s) in the E_T dependence: one threshold if $n^{\chi}_{\mathrm{MOTT}} \approx n^{\psi}_{\mathrm{MOTT}}$, otherwise a second threshold is expected.
  - saturation of $\langle p_T^2\rangle$ broadening not necessarily a plasma signal, also further rise possible.
  - slope of $R(p_T)$ dependence modified due to p_T dependence of the additional suppresion mechanism.

- Further studies will be devoted to
  - ψ'/ψ ratio
  - beyond the instantaneous breakup
  - inverse kinematic A-p and A-B experiments (Pb-S)
  - calculation of the dissociation cross section within the Schwinger- Dyson Approach at finite temperature

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Color Fluctuation Phenomena in J/Ψ Production in pA and AB Collisions

L. Gerland[a], L. Frankfurt[a,b], M. Strikman[c], H. Stöcker[a], W. Greiner[a]
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b Tel Aviv University, 69978 Ramat Aviv, Tel Aviv, Israel
c Pennsylvania State University, University Park, PA 16802, USA

The QCD factorization theorem is used to evaluate the PQCD cross sections of heavy quarkonium interactions with ordinary hadrons. However, the charmonium states (here denoted X) are not sufficiently small to ignore nonperturbative QCD physics. Thus, we evaluate the nonperturbative QCD contribution to the cross sections of charmonium-nucleon interaction by using an interpolation between known cross sections [1]. The J/Ψ-N cross section evaluated in this paper is in reasonable agreement with SLAC data [2].

The A-dependence of the J/Ψ production studied at SLAC at $E_{inc} \sim 20$ GeV exhibits a significant absorption effect [2] leading to $\sigma_{abs}(J/\Psi\text{-}N) = 3.5\pm0.8$ mb. It was demonstrated [4] that, in the kinematic region at SLAC, the color coherence effects are still small on the internucleon scale for the formation of J/Ψ's. So, in contrast to the findings at higher energies, at intermediate energies this process measures the *genuine* J/Ψ-N interaction cross section at energies of $\sim$ 15-20 GeV [4].

To evaluate the nonperturbative QCD contribution we use an interpolation formula [1] for the dependence of the cross section on the transverse size b of a quark-gluon configuration Three reference points are used to fix our parametrization of the cross sections (cf. Tab. 1). The X-N cross sections is calculated via: $\sigma = \int \sigma(b) \cdot |\Psi(x,y,z)|^2 dx\,dy\,dz$, where $\Psi(x,y,z)$ is the charmonium wave function. In our calculations we use the wave functions from a non-relativistic charmonium model (see [5]).

We follow the analysis of [6] to evaluate the fraction of J/Ψ's (in pp collisions) that come from the decays of the χ and Ψ'. So, the suppression factor S of J/Ψ's produced in the nuclear medium is calculated as:
$S = 0.6 \cdot (0.92 \cdot S^{J/\Psi} + 0.08 \cdot S^{\Psi'}) + 0.4 \cdot S^{X}$. Here S^X are the respective suppression factors of the different pure charmonium states X in nuclear matter. The S^X are for minimum bias pA collisions within the semiclassical approximation (cf. [7]). We assume that the charmonium states are produced in a hard process, uniformly at any point in the nucleus, the weight is given by the local nuclear density $\rho(x,y,z)$

The charmonium states are produced as small configurations, then they evolve to their full size. Therefore, if the formation length of the charmonium states, l_f, becomes larger than the average internucleon distance, one has to take into account the evolution of the cross sections with the distance from the production point [4].

The formation length of the J/Ψ is given by $l_f \approx \frac{2p}{m^2_{\Psi'} - m^2_{J/\Psi}}$, where p is the momentum of the J/Ψ in the rest frame of the target. For a J/Ψ produced at midrapidity at SPS energies, this yields $l_f \approx 3$ fm. Due to the lack of better knowledge, we use the same $l_f \approx 3$ fm for the χ. For the Ψ' we use $l_f \approx 6$ fm, because it is not a small object, but has the size of a normal hadron, i.e. the pion. For $E_{lab} = 800$ AGeV we get a factor of two for the formation lengths due to the larger Lorentz factor.

However, this has a large impact on the Ψ' to J/Ψ-ratio depicted in Fig. 1, which shows the ratio $0.019 \cdot S_{\Psi'}/S_{J/\Psi}$ calculated with (squares (200 GeV) and triangles (800 GeV)) and without (crosses) expansion. The factor 0.019 is the measured value in pp collisions, because the experiments do not measure the calculated value $S_{\Psi'}/S_{J/\Psi}$ but $\frac{B_{\mu\mu}\sigma(\Psi')}{B_{\mu\mu}\sigma(J/\Psi)}$. $B_{\mu\mu}$ are the

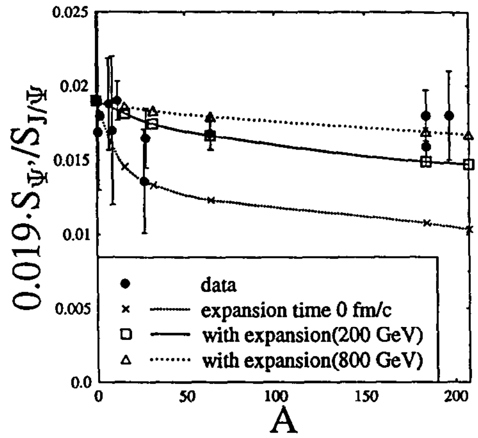

Figure 1: The ratio $0.019 \cdot S_{\Psi'}/S_{J/\Psi}$ is shown in pA (crosses) in comparison to the data (circles). The squares and the triangles shows the ratio calculated with the expansion of small wave packages (see text).

branching ratios for J/Ψ, $\Psi' \to \mu\mu$. The calculations which take into account the expansion of small wave packages show better agreement with the data (circles) (taken from [3]) than the calculation without expansion time, i.e. with immediate J/Ψ formation, $l_f = 0$. We calculated this effect both at $E_{lab} = 200$ AGeV and 800 AGeV. The data have been measured at different energies ($E_{lab} = 200$, 300, 400, 450, 800 GeV and $\sqrt{s} = 63$ GeV). One can see that this ratio is nearly constant in the kinematical region of the data, but it decreases at smaller momentum (e.g. $E_{lab} = 200$ AGeV and $y < 0$) due to the larger cross section of the Ψ'.

However, the P-states yield two vastly different cross sections (see Tab. 1) for χ_{10} and χ_{11}, respectively. This leads to a higher absorption rate of the χ_{11} as compared to the χ_{10}. This new form of color filtering is predicted also for the corresponding states of other hadrons; e.g. for the bottomium states which are proposed as contrast signals to the J/Ψ's at RHIC and LHC!

$c\bar{c}$-state	J/Ψ	Ψ'	χ_{c10}	χ_{c11}
σ (mb)	3.62	20.0	6.82	15.9

Table 1: The total quarkonium-nucleon cross sections σ. For the χ two values arise, due to the spin dependent wave functions ($lm = 10, 11$).

References

[1] L. Gerland, L. Frankfurt, M. Strikman, H. Stöcker, W. Greiner: *Phys. Rev. Lett.* **81**, 762 (1998)
[2] R. L. Anderson et al.: *Phys. Rev. Lett.* **38**, 263 (1977)
[3] C. Lourenco: *Nucl. Phys.* **A610**, 553c (1996)
[4] G. Farrar, L. Frankfurt, M. Strikman, H. Li: *Phys. Rev. Lett.* **64**, 2996 (1990)
[5] L. Frankfurt, W. Koepf, M. Strikman: *Phys. Rev.* D **54**, 3194 (1996)
[6] D. Kharzeev, C. Lourenco, M. Nardi, H. Satz: *Z. Phys.* C **74**, 307 (1997)
[7] C. Gerschel, J. Hüfner: *Phys. Lett.* B **207**, 253 (1988)

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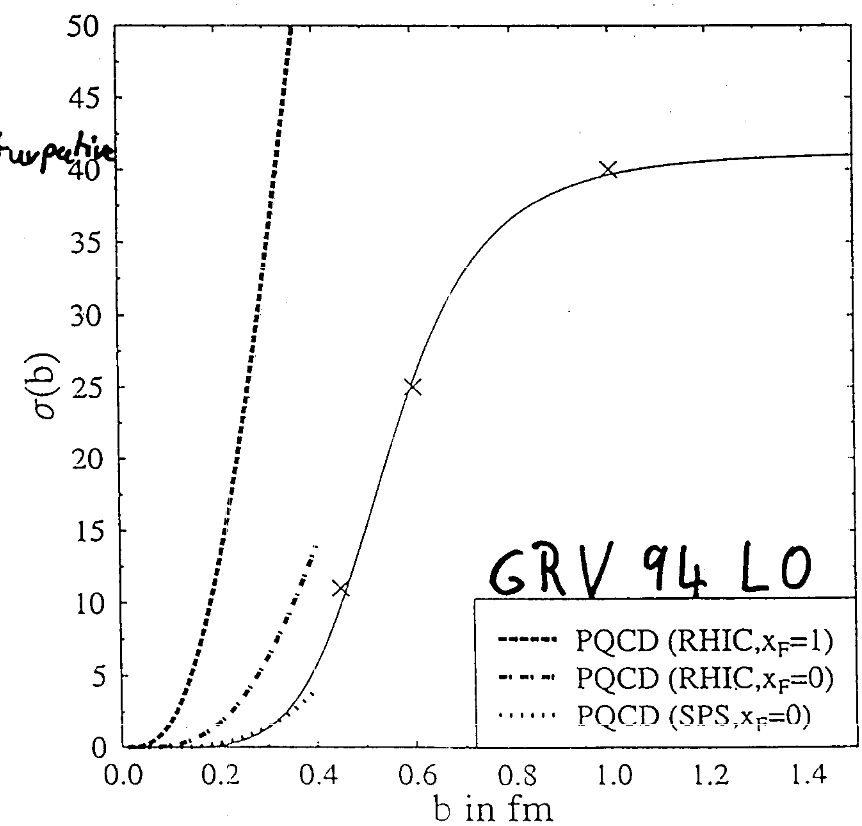
University
University Park, PA 16802, USA

Parametrization of non-perturbative $\sigma(b)$

- PQCD-behaviour at small b (b is the transverse distance of the $c\bar{c}$-quarks)
- ϕ-N cross section: $\sigma(b \approx 0.4\text{ fm}) = 10 - 12$ mb
- π-N cross section: $\sigma(b \approx 0.6\text{ fm}) = 25$ mb
- $2 \cdot D$-N cross section: $\sigma(1\text{ fm}) = 40$ mb (string fragmentation at large b)

Interpolation to model the nonperturbative contribution to the cross sections



Photoproduction at SLAC: $\sigma(J/\psi - N) = 3.5 \pm 0.8$ mb

$\Longrightarrow \sigma(\mathrm{J}/\Psi - N) = 3.6$ mb, $\sigma(\Psi' - N) = 20$ mb, $\sigma(\chi_{10} - N) = 6.8$ mb and $\sigma(\chi_{11} - N) = 15.9$ mb.

Two different cross sections for the χ due to a L_z [redacted]-dependent transverse size

J/Ψ-suppression in pA

L. Gerland

⊗ $S = 0.6 \cdot (0.92 \cdot S^{J/\Psi} + 0.08 \cdot S^{\Psi'}) + 0.4 \cdot S^{\chi}$

The charmonium states may are produced as point-like-configurations and expand to their full size

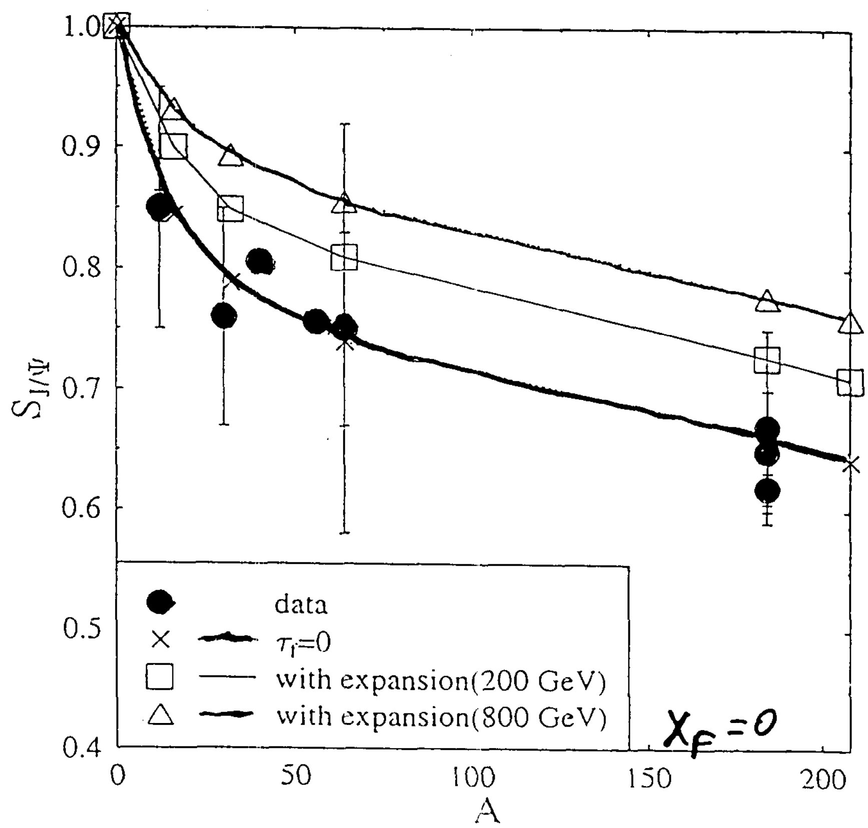
× : no formation time $\tau_f = 0$

□ : with expansion (200 GeV) during τ_f

△ : with expansion (800 GeV) during τ_f

● : pA-data C. Lourenco, Nucl. Phys. A610 (1996) 553c

⊗ D. Kharzeev, C. Lourenco, M. Nardi, H. Satz, Z. Phys. C74 (1997), 307



In ⊗ : 1 cross section (7.3 ± 0.6 mb) for all charmonium states ("preresonance")

⟹ Too large errorbars preclude to conclude whether this CT-effect is important

The Ψ' : J/Ψ-ratio in pA

L. Gerland

$0.019 \cdot S(\Psi')/S(J/\Psi)$, 0.019 is the pp-data point

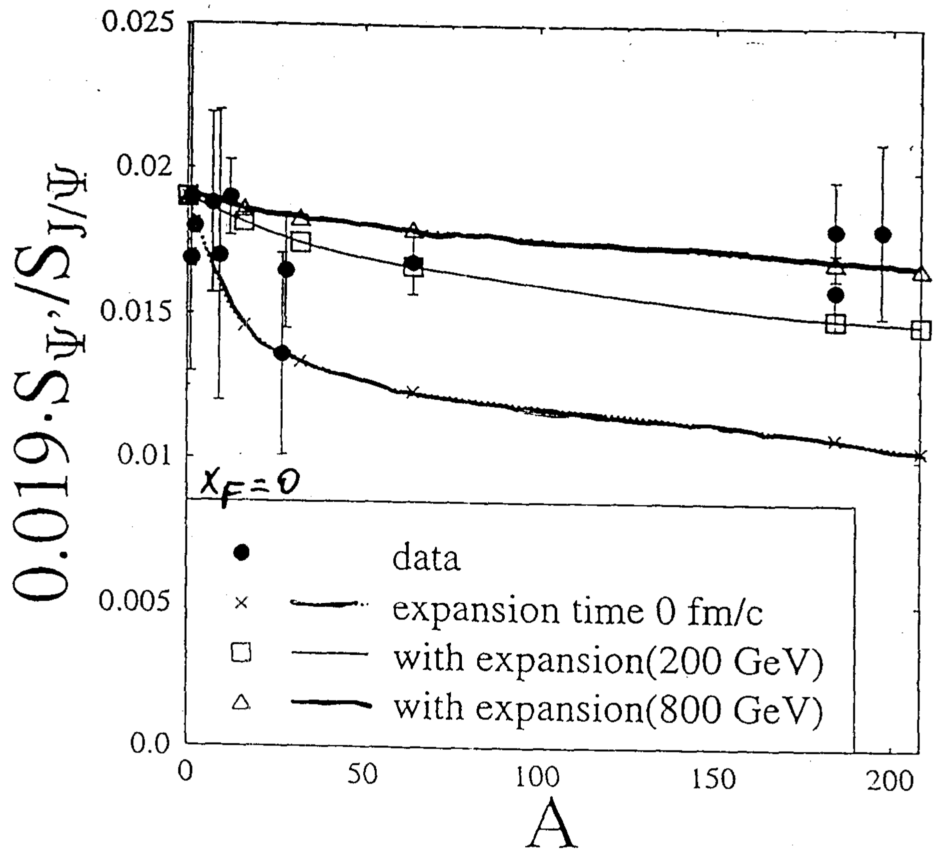
× : no formation time $\tau_f = 0$

□ : with expansion (200 Gev) during τ_f

△ : with expansion (800 Gev) during τ_f

● : pA-data $(B_{\mu\mu}\sigma(\Psi' - N)/B_{\mu\mu}\sigma(J/\Psi - N))$

C. Lourenco, Nucl. Phys. A610 (1996), 553c (QM'96 procs.)

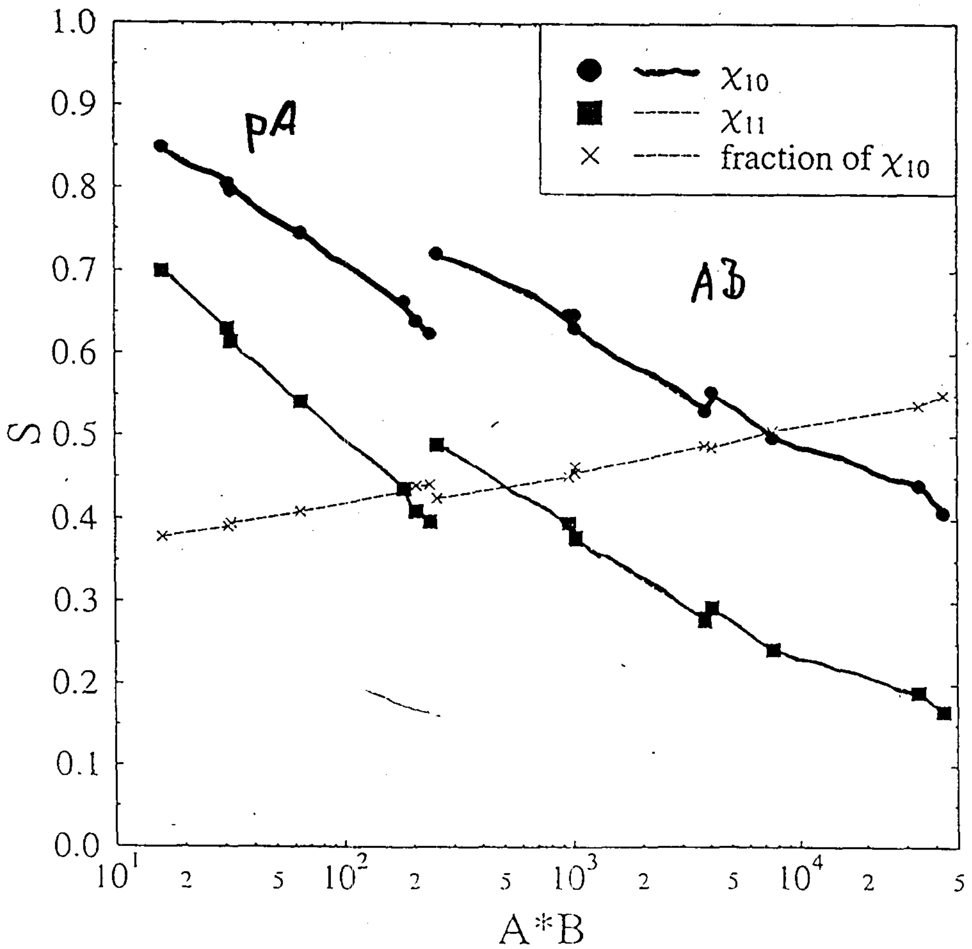


$\Longrightarrow$ Also too large errorbars to decide whether this CT-effect is important

χ-polarization

Polarization, due to a spin-dependent cross section

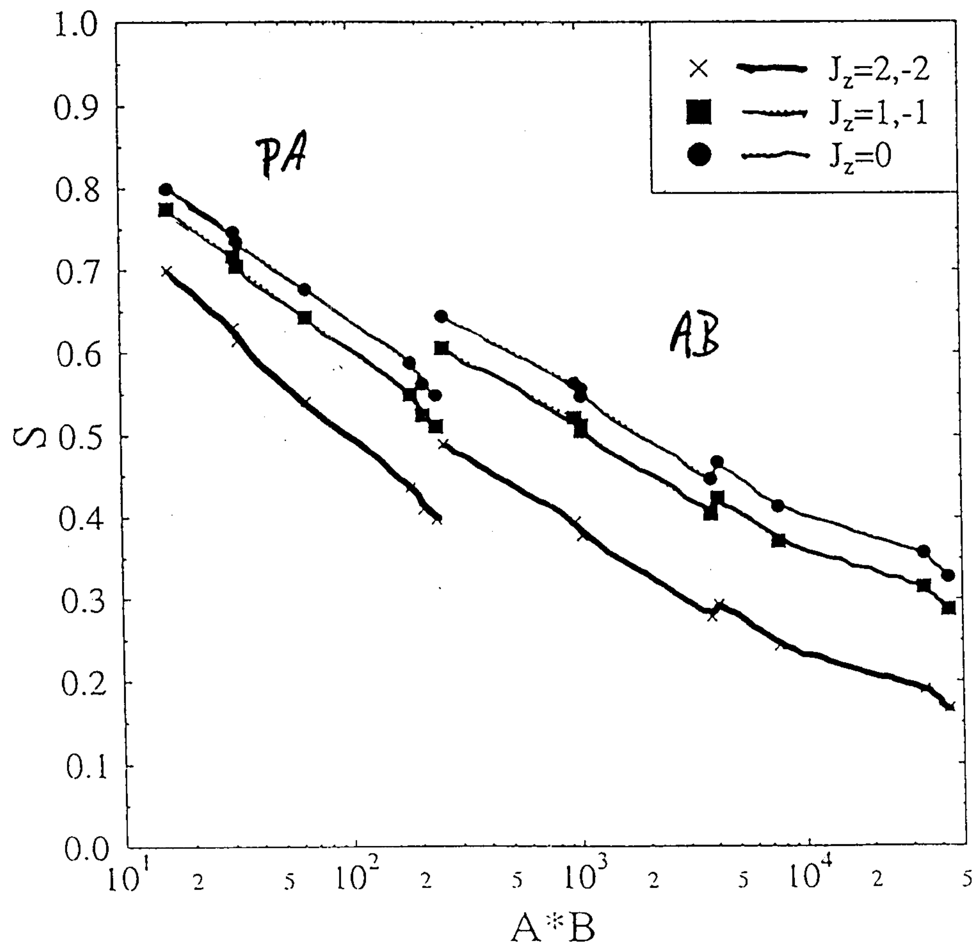
$$\text{fraction of } \chi_{10} = \frac{\#\text{ of } \chi_{10}}{\#\text{ of } \chi_{10} + \#\text{ of } \chi_{11} + \#\text{ of } \chi_{1-1}}$$



Difficult to measure ?!

χ(J=2)-polarization

$J_z = 0, 1(-1), 2(-2)$ states are mixture of
χ_{10} and $\chi_{11(-1)}$:
$\chi(J, J_z) = a_1 \cdot \chi_{10} + a_2 \cdot \chi_{11} + a_3 \cdot \chi_{1-1}$.
The a's are given by the Clebsch-Gordan coefficients
(i.e. $a_1 = a_3 = 0$ and $a_2 = 1$ for J=2 and J_z=2).



Reality Constraints on Charming scenarios involving mini-jet bursts

or

What do Horses, Elephants, and Camels have in common ??

1) Do Mini jets percolate at SPS ?

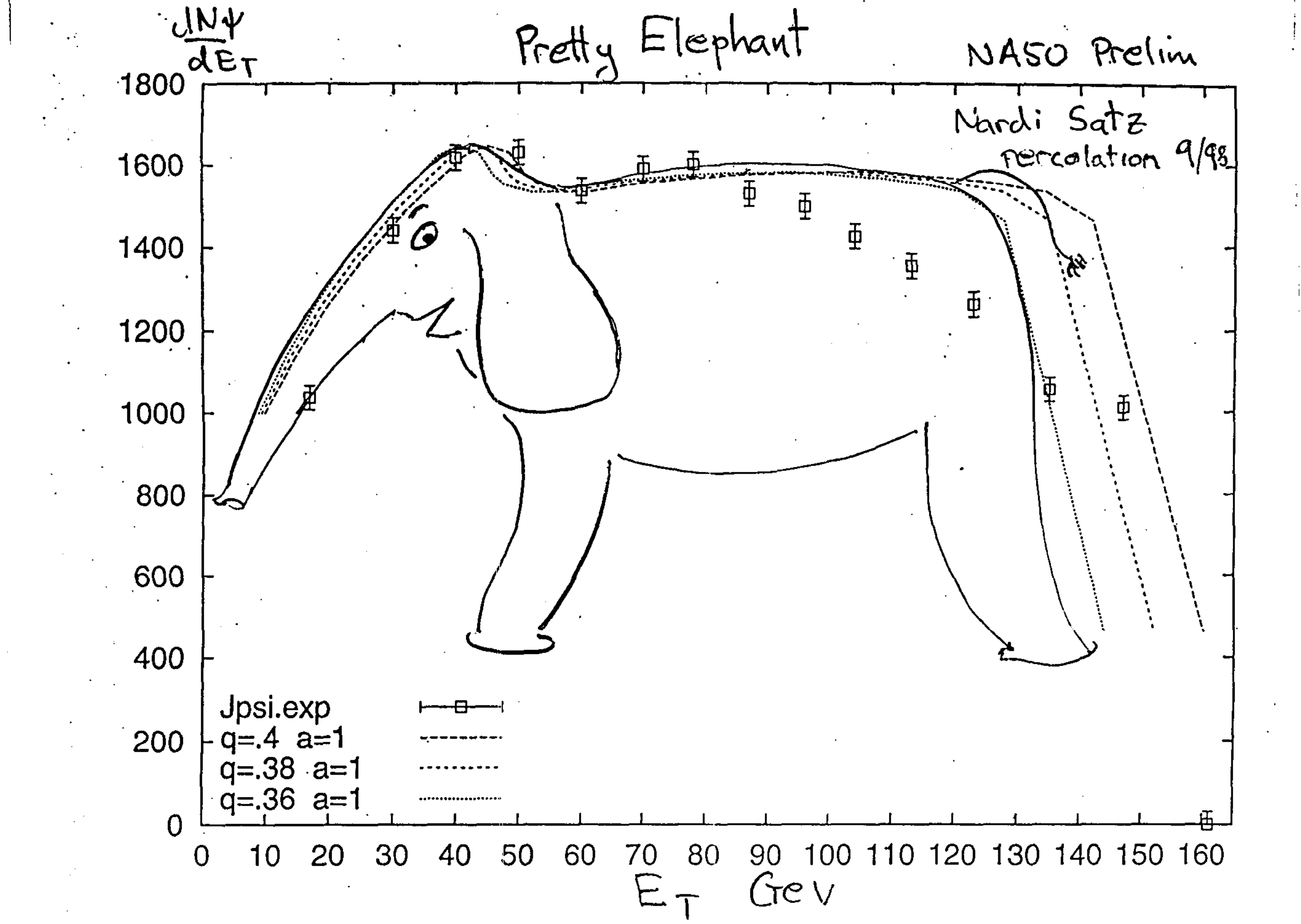
Yes: Geiger Muller VNI; Kopeliovics Hüfner

Maybe: HIJING $p_0 = 1$ GeV

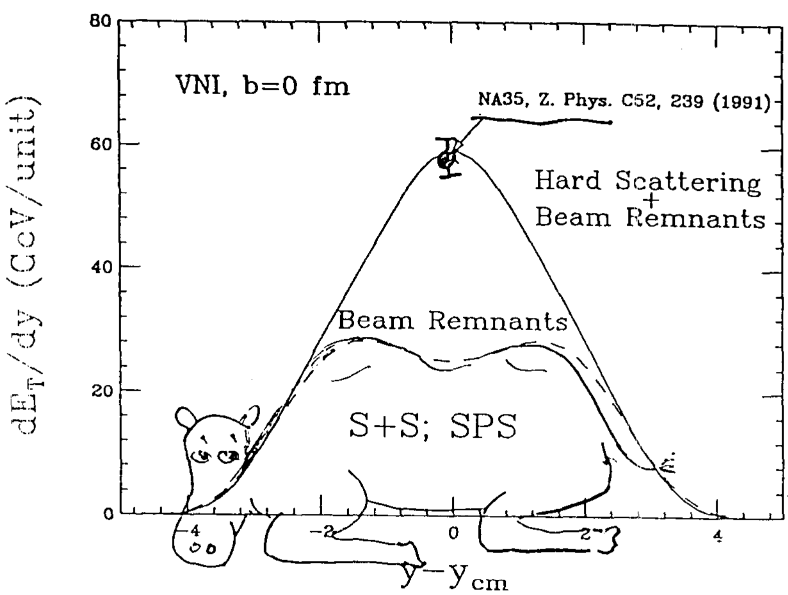
No : HIJING $p_0 = 2$ GeV

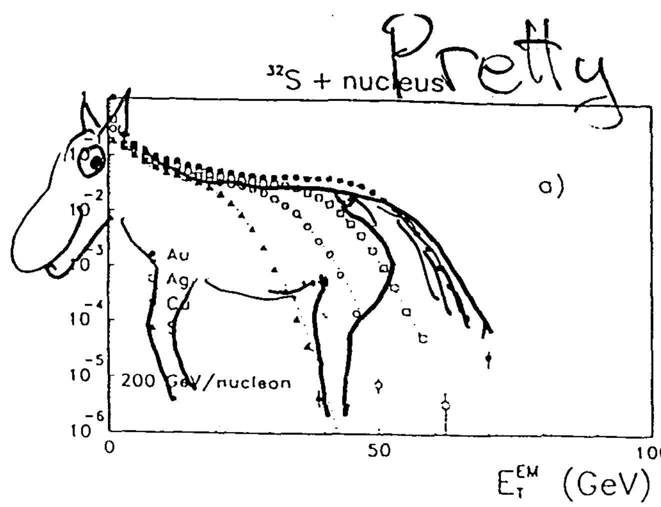
2) $\frac{dN}{dy}$, $\frac{dE_\perp}{dy}$, $\frac{dN}{dp_\perp}$ constraints NO on No

M. Gyulassy
RIKEN/BNL
10/1/98



Pretty CAMEL





Assuming anomalous χ suppression threshold around $E_T \sim 40$ GeV:

1) What is special about $b \approx 8$ fm?

2) What is really percolating?

Possible answer: Simply ~1 GeV/c minijets

Non-linear $A^{4/3}$ of pQCD (Geiger Müller)

But is rate high enough?

answer: no with $p_0 = 2$ GeV HIJING

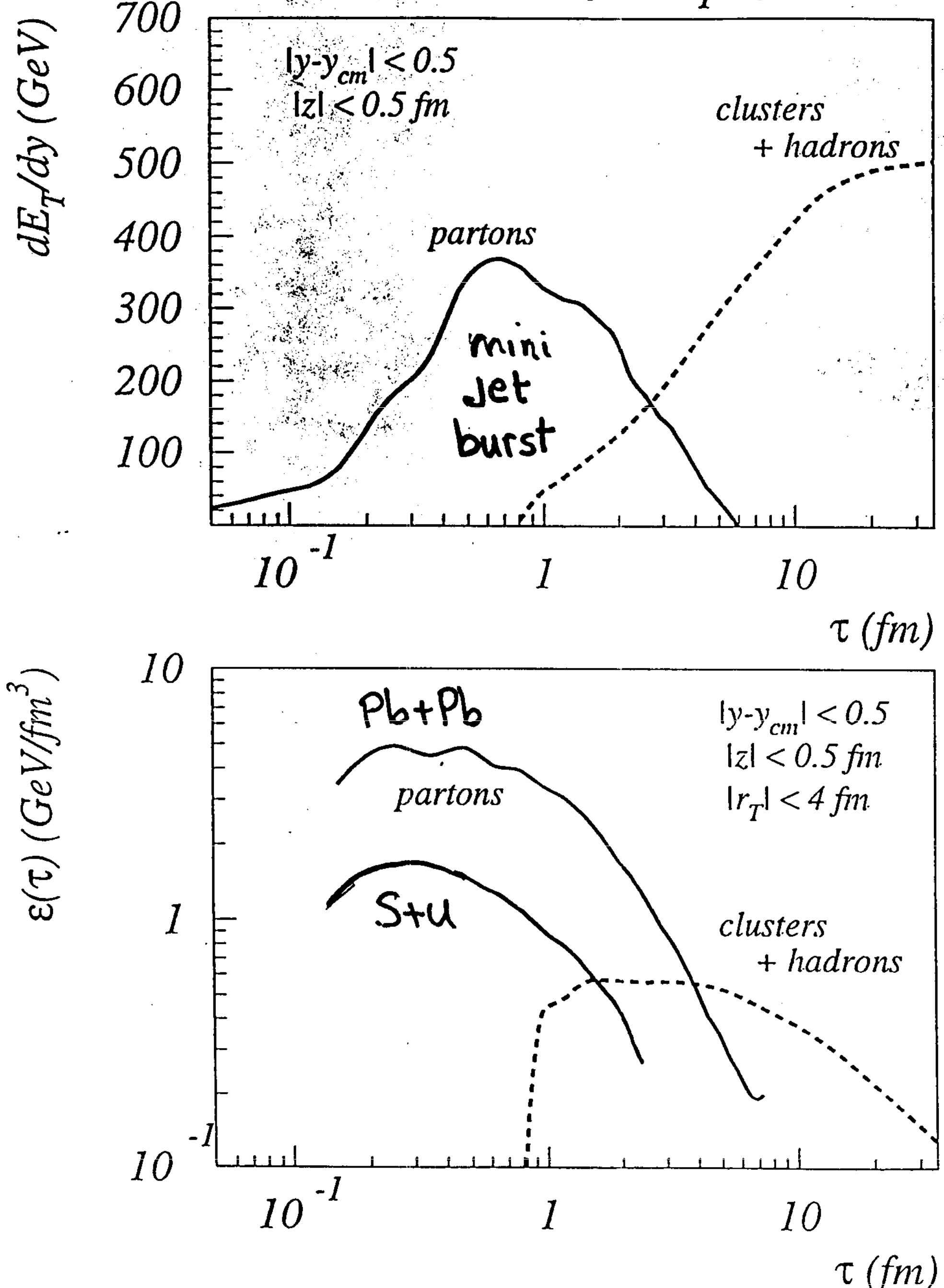
maybe ~~yes~~ " $p_0 = 1$ GeV "

YES $p_0 = 1$ GeV VNI

Evidence may hinge critically on absolute dE/dy and its scaling with A, $\sqrt{s}$

Geiger Müller
VNI 97

Pb+Pb at E_{cm} = 17 A GeV
Time evolution of dE_T/dy and ε



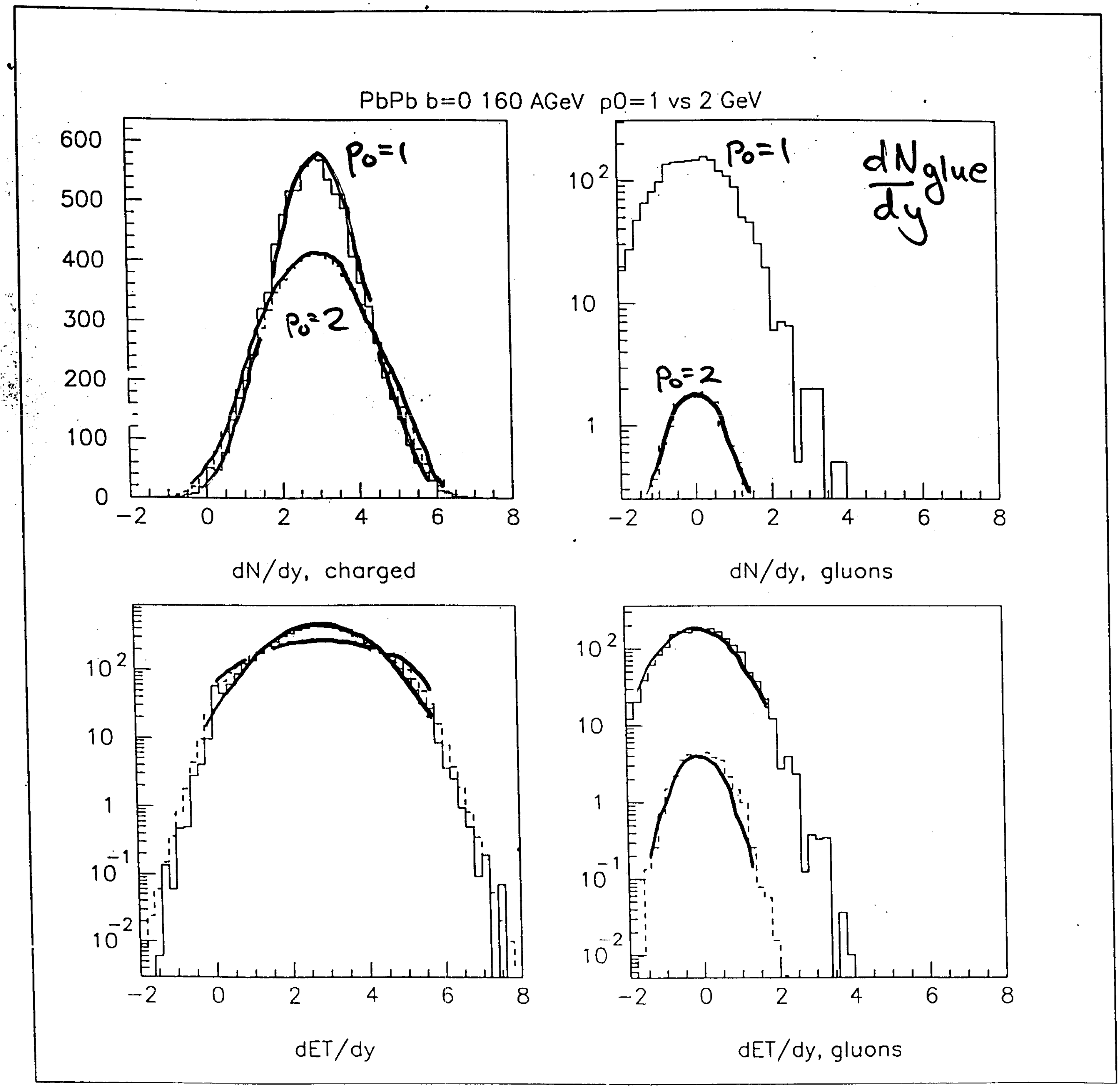
$\frac{dE_\perp^{parton}}{dy} \sim 400$ Ge

$p_\perp \sim 1$ GeV

$A_\perp^{parton} \sim 400 \frac{\pi}{p_\perp^2} \sim 40\, fm^2$

$Area_{Pb} \sim 150\, fm^2$

HIJING

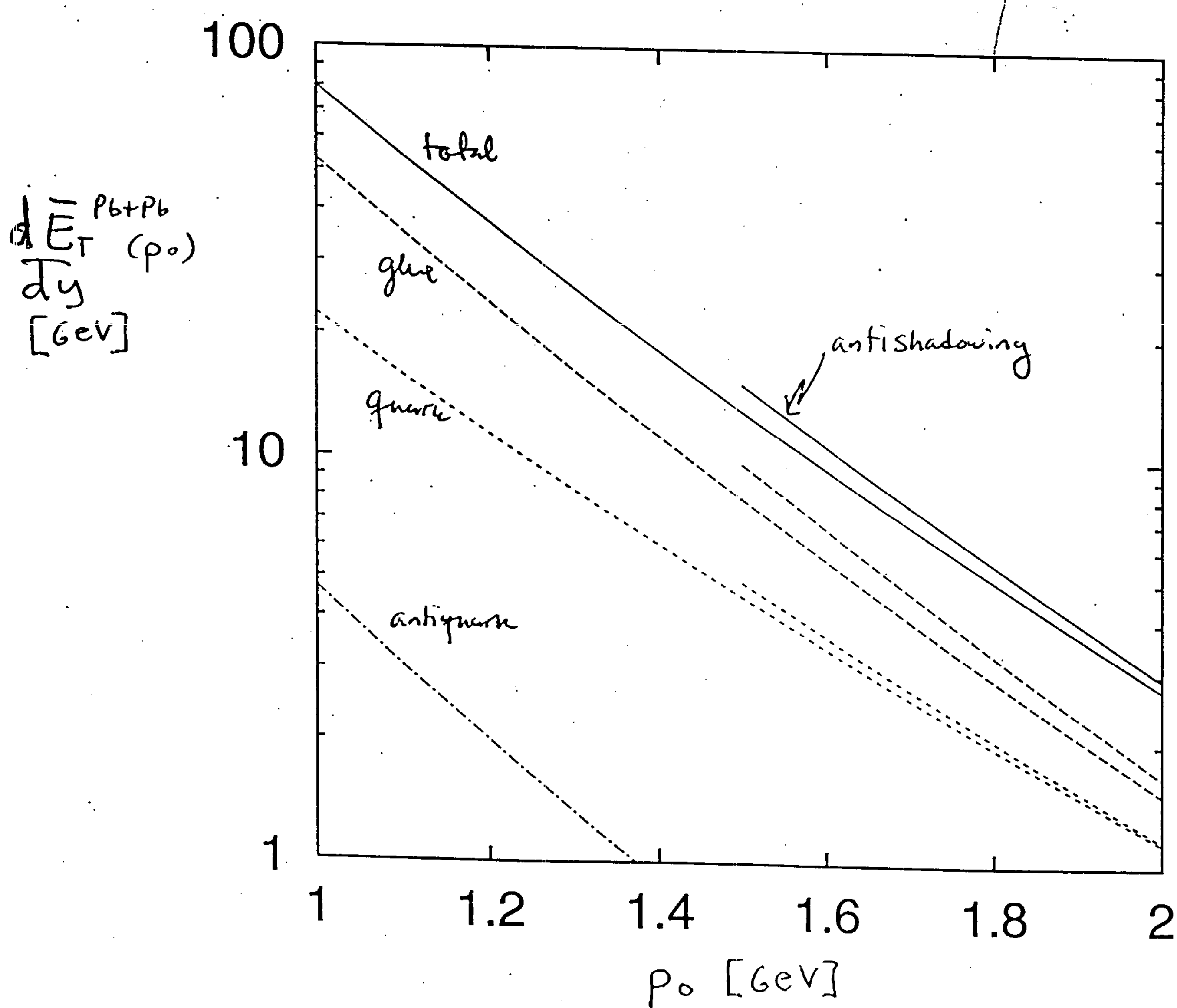


PbPb b=0 160 AGeV p0=1 vs 2 GeV
p0=1
p0=2
dN/dy, charged
p0=1
dN/dy glue
p0=2
dN/dy, gluons
dET/dy
dET/dy, gluons

$$\frac{dE_\perp}{dy} = T_{AB}(b) \int_{p_0}^{\infty} p_\perp \frac{d\sigma^{pQCD}}{dy\,dp_\perp} dp_\perp$$

$$\lesssim 100\,\text{GeV} \quad \ll \frac{dE_\perp}{dy}^{VNI} \sim 400$$

$\sqrt{s} = 17.2$ GeV ; Pb + Pb ; $\underline{b} = 0$; $\Delta y = 1$; GRV-LO

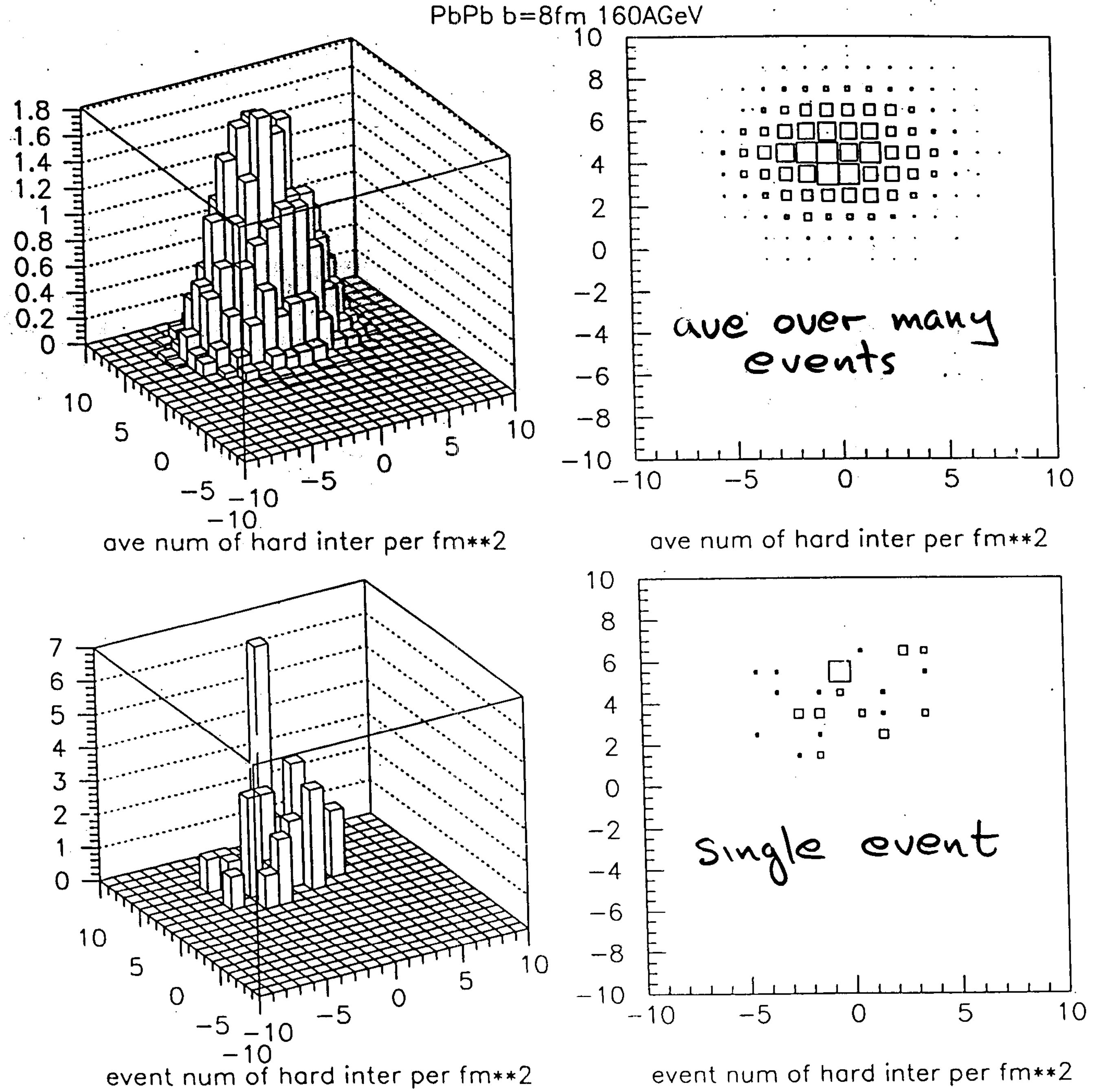


percolating mini jets

or hot spot in turbulent glue scenario

$p_0 \simeq 1$

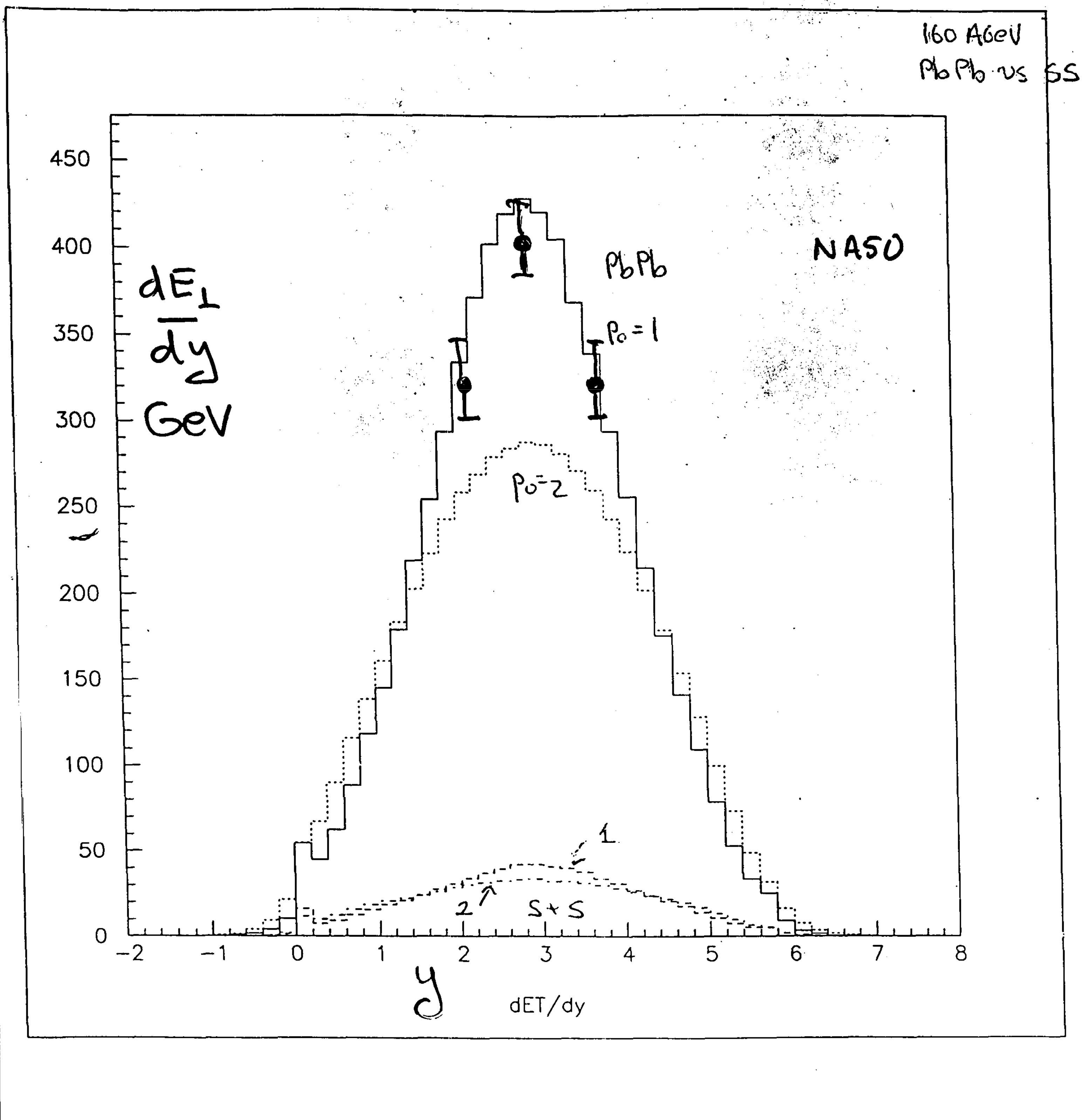
MG, Rischke, Zhang



area hot spot $\frac{\pi}{p_0^2} \simeq 0.1\, fm^2$ $\quad p_\perp \gtrsim 1 GeV$

packing fraction $= \frac{\# \text{hard}}{\text{area}} \times$ area hot spot $= \frac{2}{fm^2} \times 0.1\, fm^2 \approx 0.2 < 1$

too dilute?



160 AGeV
PbPb vs SS
NA50
PbPb
Po=1
Po=2
dE⊥/dy GeV
1
2
S+S
y
dET/dy

Conclusions:

1) Mini Jets percolate beyond S+U only if Camels live in zoo!

Camel = suppression of soft (string) dynamics as hard pQCD turns on

2) In dynamical models (HIJING, Fritiof, ..) with Soft + Hard ($p_\perp > p_0$)

dE_T/dy needs $p_0 \sim 1$ GeV at SPS Pb^2 but may not be enough to percolate (recall Eskola plot too)

Horses ($dE_\perp/dy$) can coexist with (pink) Elephants ($d\sigma^{\psi}/dE_T$) only if Camels (soft beam jet suppression) live harmoniously together

J/ψ Suppression in a Cascade Transport Approach

R. Mattiello, J.P. Bondorf
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October 9, 1998

Abstract We present J/ψ suppression rates in p+A and A+A reactions based on a microscopic transport approach that combines flux-tube fragmentation with the cascade of const. quarks and hadrons. Since hard processes are strongly suppressed at SPS energies we treat the formation of $c\bar{c}$ pairs by gluon fusion as a 'virtual' excitation superimposed to the soft dynamics of the system. The coherence in the leading particle wave function of the ingoing nucleons is simulated by the resummation of the energy and momentum in the (leading) particle spectrum to be produced later on.

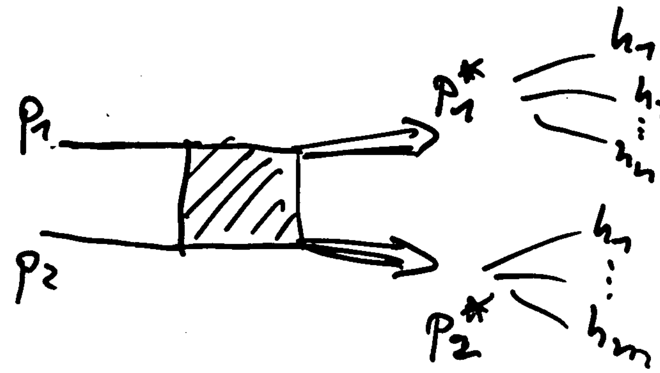
For J/ψ, ψ' and χ states we employ individual formation times τ_{spread} and dissociation cross sections. As for usual hadrons the interaction of Quarkonium states is suppressed before formation. For their reinteraction we use a straight line geometry starting from the formation vertex. Dissociation on mesons includes an energy dependence similar to the one introduced by Kharzeev and Satz which essentially dies out for small pion (meson) momenta. The size of dissociation cross sections is still subject of debate (see the contribution by Blaschke et al.). An enhanced absorption in the final state could add significantly to the suppression in reactions with large numbers of produced secondaries, i.e. large transverse energy production. The major part of the dissociation is expected to take place in the early (and dense) stage of the reaction. Thus it is crucial to employ interactions with the constituent quarks of the excited nucleon wave functions which are parametrized by resonances and classical strings. We assume here a scaling according to the additive quark model (AQM) which is consistent with the general treatment of non-pertubative interactions.

One could interprete our picture as an interpolation between calculations from Huefner and Kopeliovich and the comover picture introduced by Gavin et al. (see the contribution by Capella et al.). The essential link is the space-time kinematics of the fragmentation process which is borrowed from the factorized description via excitation and subsequent fragmentation of gluons into hadrons by classical strings. For simplicity, initial constituent quarks in string-type objects carry no formation time and follow the trajectories of those hadrons which finally pick up the original valence quarks. As a consequence of delayed hadron formation and gradual energy loss the ingoing constituents traverse the first 1-2 fm/c almost completely without loosing energy. This picture bears some uncertainties which have been minimized by comparing to different sets of observables sensitive to hard and soft processes, i.e. the simultaneous description of hadron production, baryon stopping and Drell-Yan pair production in p+A and A+A reactions. Information on the somewhat larger absorption cross sections for ψ' states at small x_F can be gained from recent E866 results (see the contributions by Leitch et al. and Gerland et al.). The strong suppression at large values of x_F might not be related to break up processes (see the contribution of Peigne at al.) and have been disregarded. A 'faster' energy loss in the gluonic degrees of freedom as compared to valence quarks could, however, simulate a stronger suppression also for large x_F.

The results show that the break up of Quarkonium states happens on very early time scales and basically within the geometrical overlap of the two nuclei. The relatively strong change of the survival rates at small transverse energies reflects a transition from surface- to volume- type reactions. The strong absorption in massive central events can be traced back to energy loss and additional 'pile-up' of energy and particle densities within the first 3-5 fm/c where non-equilibrium processes dominate. Such compressional effects have long been proposed and find confirmation in the recent observation of characteristic flow observables. The rather good agreement with the J/ψ suppression rate is another indicator for the quality of the particle production scheme used. The contribution of a somewhat enhanced suppression of χ and ψ'-states gives some hope that even structures in the transverse energy excitation function might be explained by different 'formation times' for different bound states. Such processes are already indicated by the strong decrease of the relative suppresion $S(\psi')/S(J/\psi)$ as function of transverse energy. In this case the onset of the suppression depends more strongly on the geometry and time scales of the interaction and one should expect different suppression patterns as function of beam energy. We would like to finally comment on the sharp structures observed in the the E_t dependence of the J/ψ excitation function in Pb+Pb reactions. The transport calculations show a different E_t dependence of the suppression as function of the impact parameter (or 'geometry'). Selecting different impact parameter ranges we demonstrate that a certain 'granularity' in centrality related triggers could possibly lead to structures in the suppression rate. Therefore, we suggest a systematic study using transport calculations which take into account appropriately trigger conditions and acceptance effects.

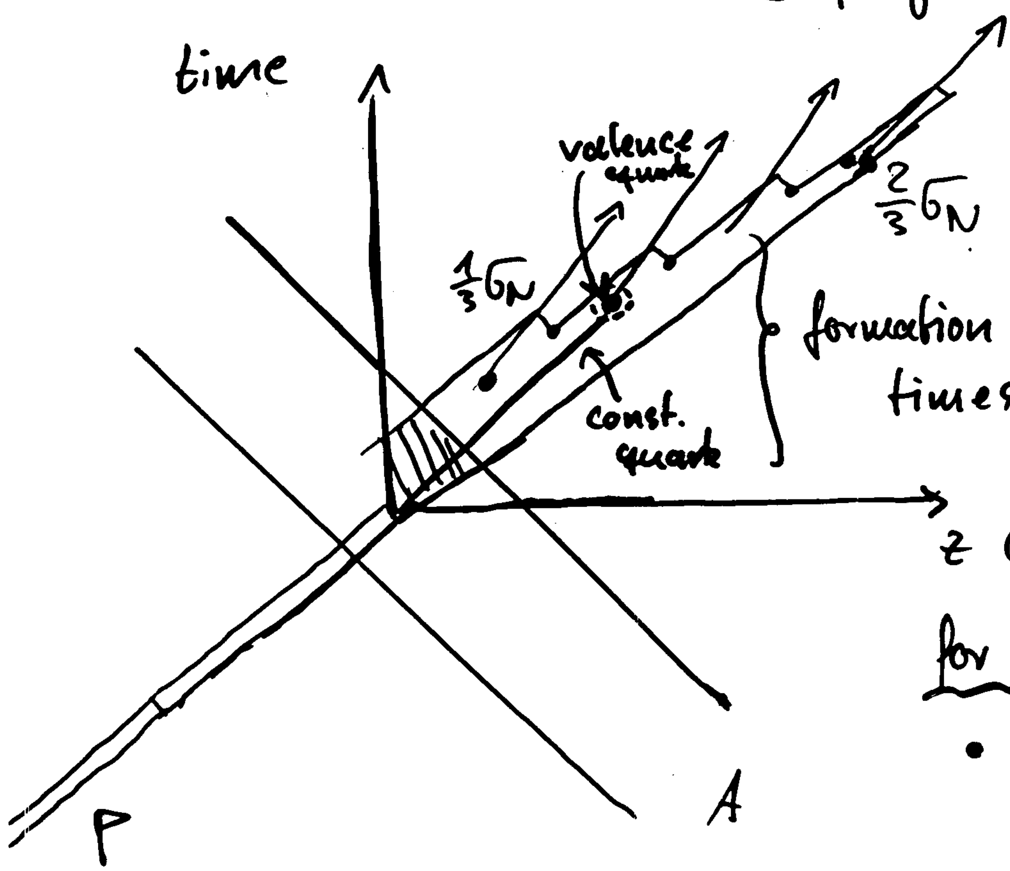
Soft kinematics & coherence

- usual picture



factorization into [excitation $M \to M^*$]

$\otimes$ [fragmentation]



Lund - Interpretation
classical strings

formation times <=> "coherence effect"

for early stage:

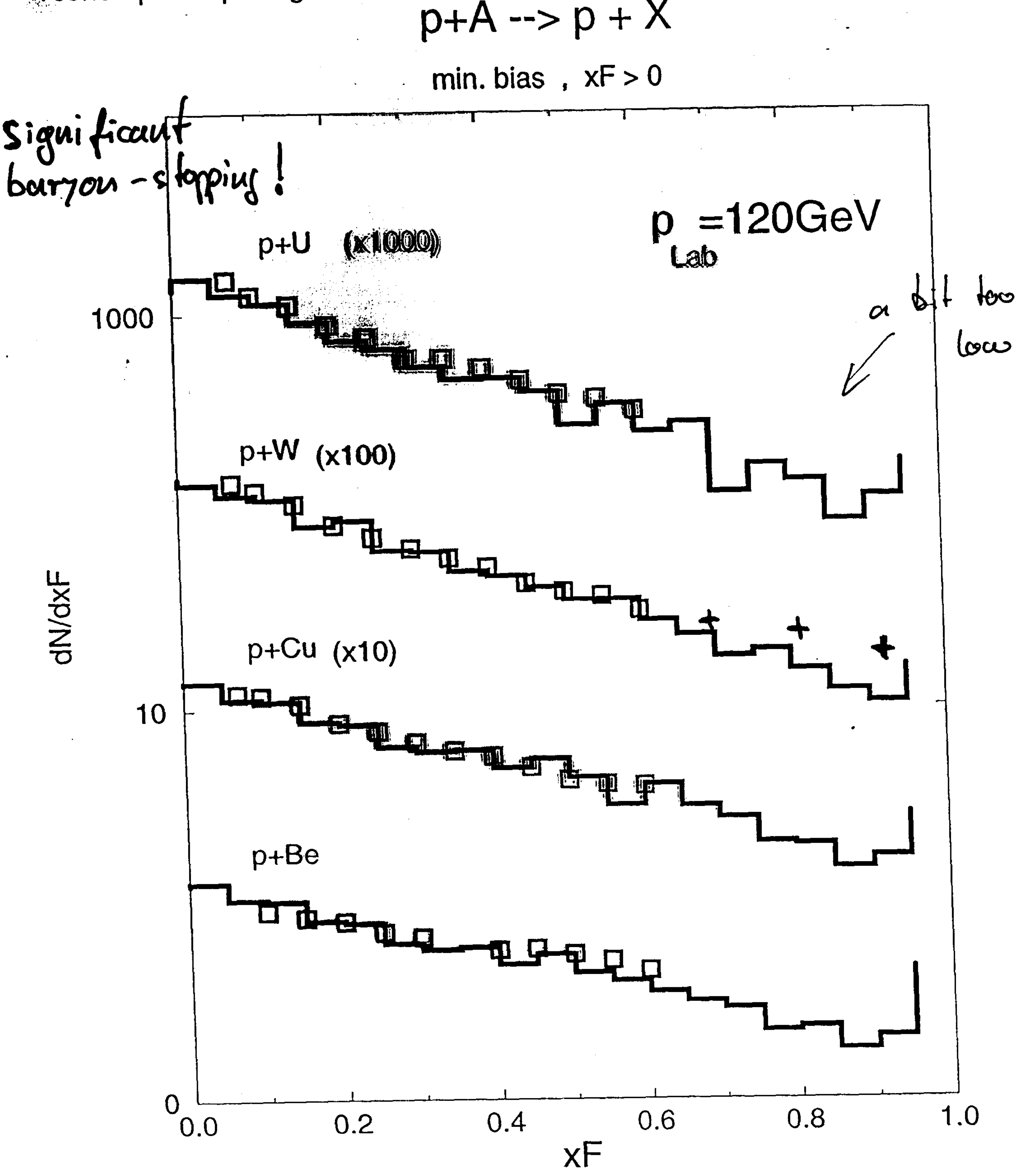
- resum energy in forward leading particle
- take into account "energy loss" by $G^M \to q\bar{q}$ within target

! ENERGY - DEPENDENCE

data: R. Bailey et al. ZPC 29 (8?)
D.S. Barton et al. PRD 27 (8?)

Rel. cascade
+const.quark splitting

"cross check"



DY & $c\bar{c}$ production (hard modes in a soft lake)

- $\sigma^{NN}_{c\bar{c}, DY} \sim \left(1 - \frac{M}{\sqrt{s}}\right)^{12}$

  note $\sigma_{DY} = \sigma_{c\bar{c}}$ is assumed

  works fine, use it!

  => J. Kapusta

  σ^{MB} similar, see data R. Gavai et al. Int J. Mod. Phys 9

- x_F distributions

$$\frac{dN}{dp^3} \sim (1 - x_F)^q \quad e^{-b p_t^2}$$

$$q_{BB} = q_{NN} = 2.9 \qquad q_{MB} = 1.7$$

$$b = 0.9 \ \mathrm{GeV}^{-2}$$

- extrapolation for "constituent quarks"

$$\sigma_{hh} = \sum_{i,j} \sigma_{q_i q_j}$$

just as AQM ...

! extremely good as far as $\sum_q p^\mu_q = p^\mu_h$ ∞

$c\bar{c}$ - "dynamics"

Parameters

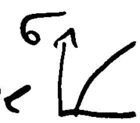
- straight line geometry
- t_f^{hadrons} $\begin{pmatrix}\Delta t \\ \Delta x\end{pmatrix} \simeq \frac{m_h}{\kappa} \begin{pmatrix}\sinh y \\ \cosh y\end{pmatrix}$

string tension $\kappa = 1\,\text{GeV/fm}$

- J/ψ , ψ' , χ $\quad 0.54 : 0.06 : 0.4$

see L. Gerland et al.

$\sigma_{J/\psi + B} = 3.6\,\text{mb}$

$\sigma_{J/\psi + M} = \frac{2}{3}\,\sigma_{J/\psi + B}$ * energy dependence 

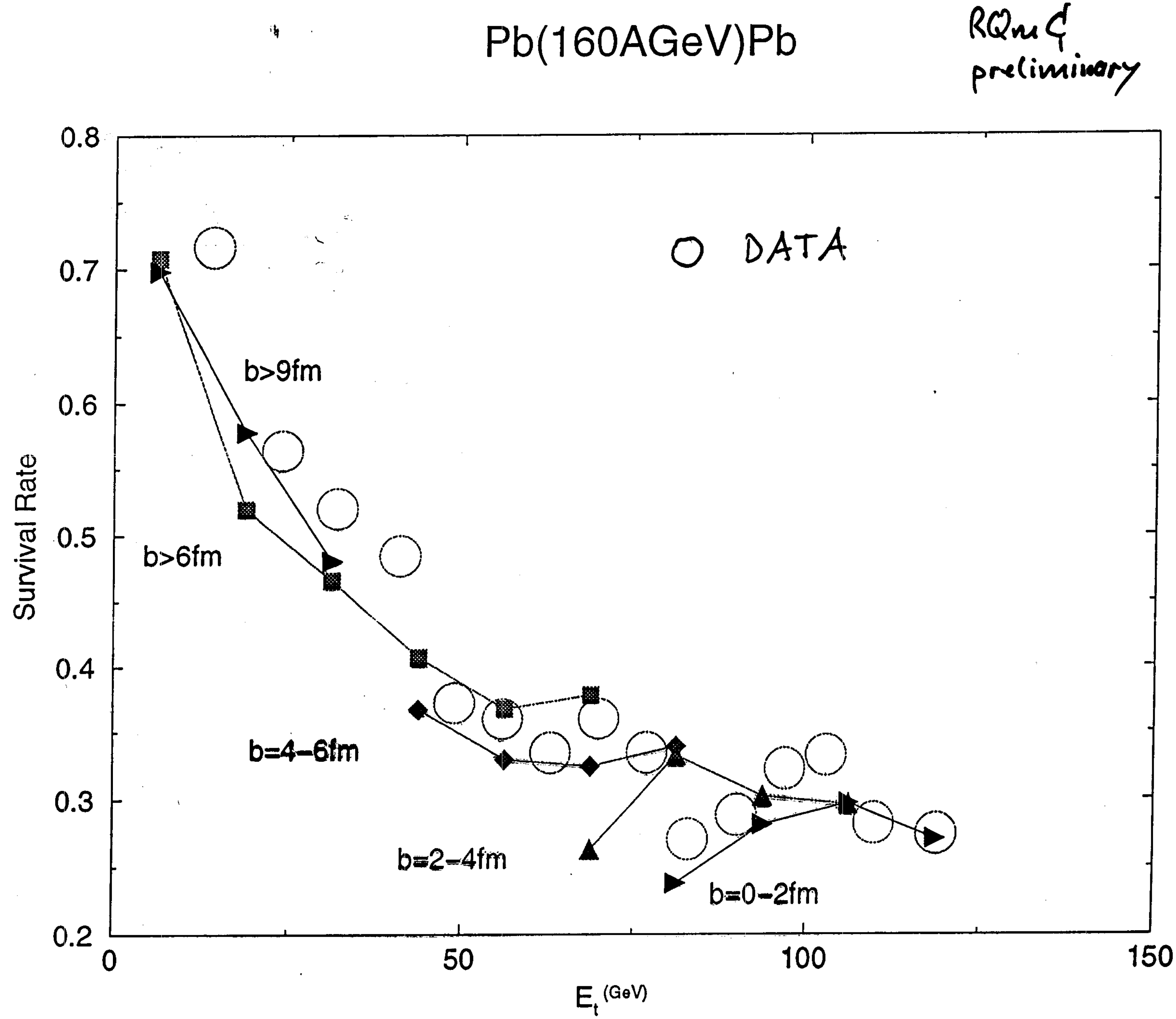
20 mb $\quad \sigma_{\psi'} = 6 * \sigma_{J/\psi} \qquad \sigma_{\chi} = 2 * \sigma_{J/\psi} \approx 7m$

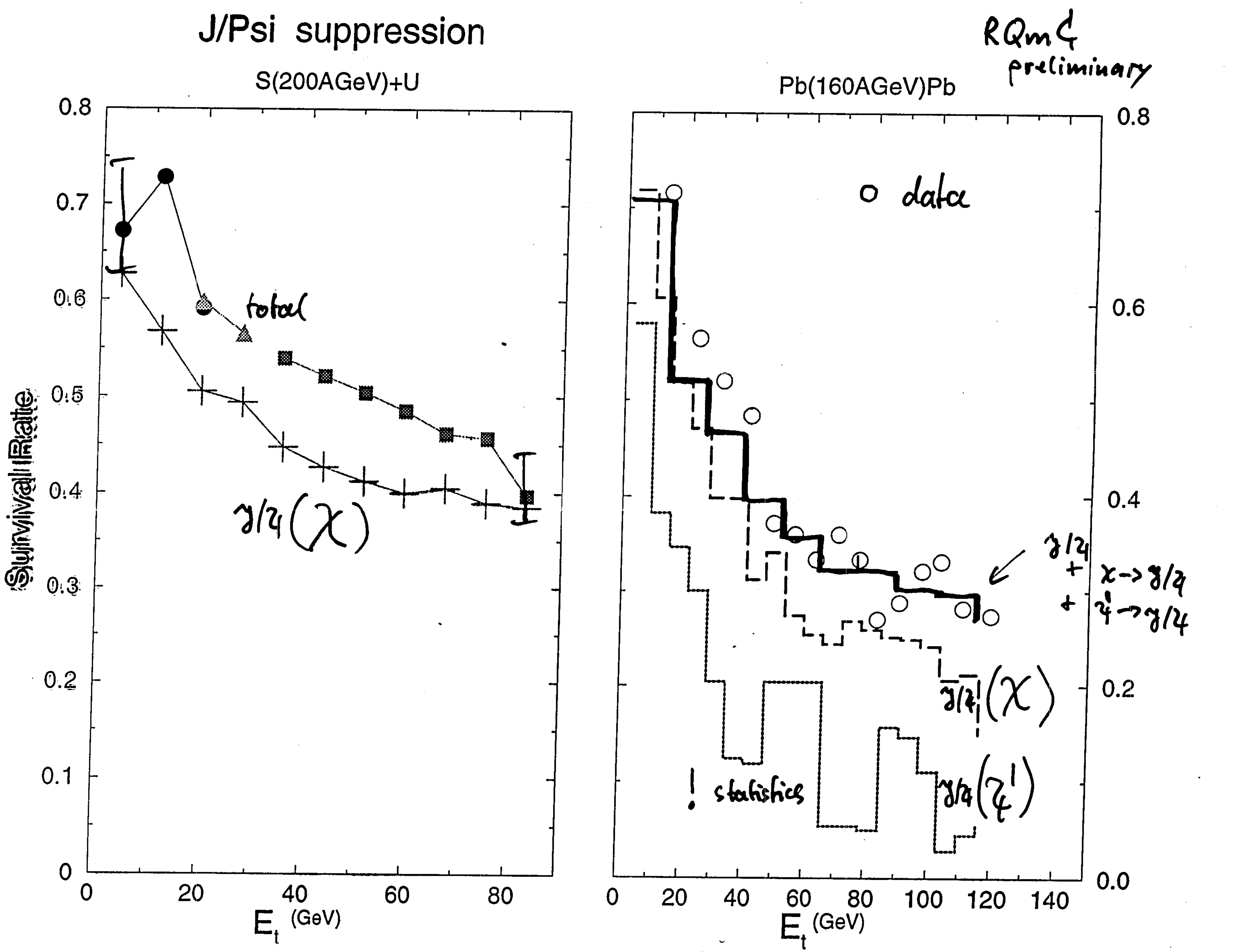
- $t_{\text{spread}} = 0.1 \;,\; 0.2 \;,\; 0.3$

$\qquad\qquad J/\psi \quad \chi \quad \psi'$

- extrapolation for scattering with const. quarks : Additive Quark Model γ/4

RQMD preliminary





J/Psi suppression
S(200AGeV)+U
Pb(160AGeV)Pb
RQMD
preliminary
Survival Rate
total
o data
! statistics
E_t (GeV)

CONCLUSIONS

- suppression in Pb + Pb

  by fast transition from

  "surface" to "volume"

  $\xrightarrow[E_t]{}$ + Baryon Stopping

  + Life time

- ψ', χ are relevant

- ! comovers ! (soft components in leading particle wavefunction)

- some energy-loss (10%) at SPS

- absorption is an early process

  ~ $c\bar{c}$ is still very relevant for extracting high density correlations

- $x_F > 0.2$, problem

  not clear where it comes from!

RQMD

Degrees of freedom:

Hadrons + Resonances	Strings	Partons
n, p, N^*, Δ^* $\Lambda, \Lambda^*, \Sigma, \Sigma^*, \Xi, \Omega$ $\pi, \sigma, \rho, \omega, \eta, \eta'$ $K, \bar{K}, K^*, \bar{K}^*, \phi$	Const. Quarks + coherent glue?!	virtual ... (?)
Mass Dispersion	Fragmentation Function	-

Quasi particles move on-shell

- $p_i^2 + m_i^{*2} = E_i^2 =: H_i$
- $H := \sum_i H_i$
- $\dot{f} = \{H, f\} \qquad f = q, p$

classical path ...
(CASCADE)

$\Longrightarrow$ Interaction based on 'soft' phenomenology

J/ψ suppression: an experimental overview

Carlos Lourenço

The relativistic heavy ion programme at the SPS has recently seen a number of very important developments. Some of the new results, based on the analysis of data taken during the 1996 heavy ion beam time, have the quality of experimental breakthroughs. The new data provide additional support to the expectation that matter with a structure radically different from nuclear or hadronic matter is created in Pb-Pb collisions at the SPS. Although the results stop short of furnishing unambiguous evidence for a transition to quark matter, there is growing confidence that this evidence may be within reach.

The most notable achievement over the past year concerns the suppression of J/ψ production. The earlier evidence for an anomalous mechanism of J/ψ suppression in Pb-Pb collisions has been confirmed by a new analysis of the data taken by the NA50 collaboration. The new analysis compares the J/ψ cross section as a function of transverse energy, E_T, with the minimum bias distribution, known with much smaller statistical errors than the corresponding Drell-Yan spectrum.

The data clearly reveal that the E_T-dependence of J/ψ suppression strongly differs from that observed in lighter systems. Once the analysis is extended to smaller and larger values of E_T, the observation of a threshold behaviour in a single collision system will be clarified. Such a behaviour is expected if the QCD deconfinement transition occurs within the covered E_T-range. In fact, two consecutive thresholds are predicted, since the dissolution of the χ_c and J/ψ states is expected to occur at different energy densities.

J/ψ Suppression :

an Experimentalist Overview

1986 – 1998 :

⟹ lots of measurements

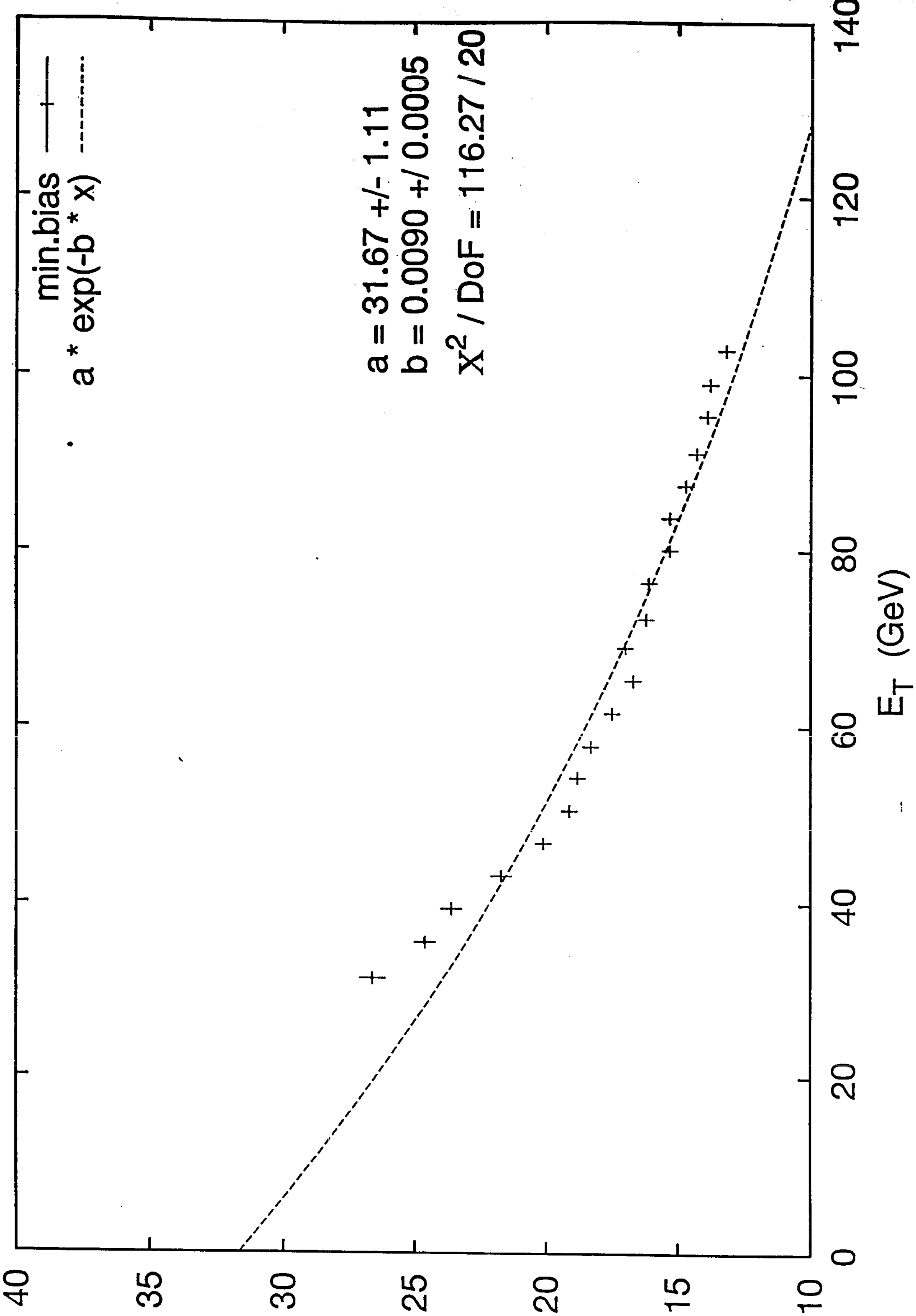
but not enough ...

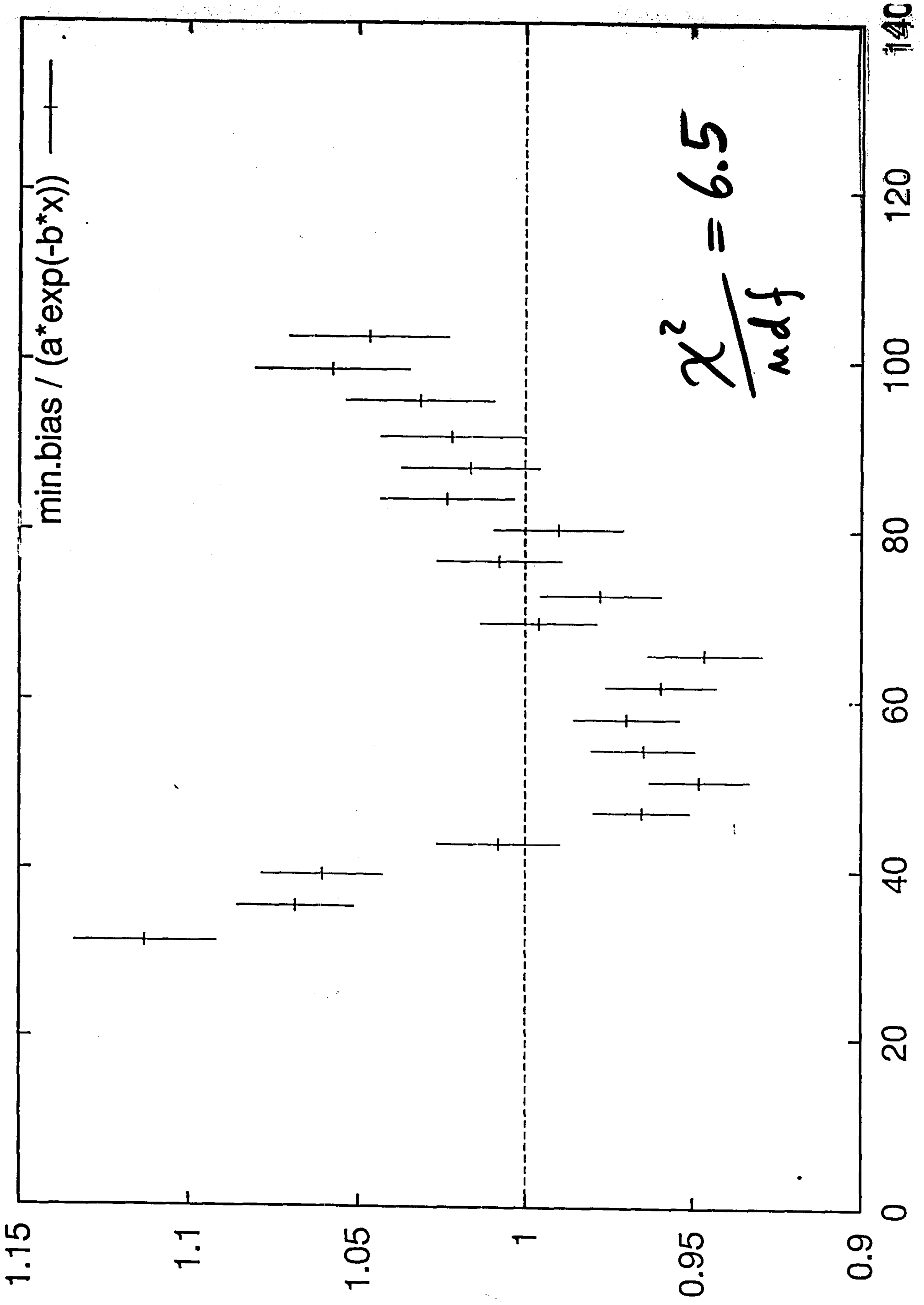
⟹ lots of models

far too many !

1. J/ψ in a broader context
2. SPS ⟶ RHIC : open issues

Carlos Lourenço / CERN
BNL, Oct. '98


min.bias
a * exp(-b * x)
a = 31.67 +/- 1.11
b = 0.0090 +/ 0.0005
X2 / DoF = 116.27 / 20
E_T (GeV)
0
20
40
60
80
100
120
140
10
15
20
25
30
35
40


min.bias / (a*exp(-b*x))
$\frac{\chi^2}{ndf} = 6.5$
0
20
40
60
80
100
120
140
0.9
0.95
1
1.05
1.1
1.15

From SPS to RHIC: Points to be clarified

- ⊛ J/ψ, ψ' : A-dep vs. $\sqrt{s}$
- ⊛ Drell Yan : PDFs ; NNLO ; shadowing
- ⊛ Open charm enhancement in IMR $\mu\mu$
  - ⇒ Background ?
  - p_T broadening ?
  - secondary DY ?
- ⊛ Influence of beauty : $B \rightarrow J/\psi$

The STRANGE influence of BEAUTY in the UPs and DOWNs of CHARMonium production

① pp @ $\sqrt{s} = 200$ GeV ; all p_T

$$\sigma(pp \to B + X) \simeq 3\,\mu b * 4 = 12\,\mu b$$

$$\sigma(pp \to J/\psi + X) \simeq 3.6\,\mu b$$

$$\Longrightarrow \frac{\sigma(pp \to B) * Br(B \to \psi)}{\sigma(pp \to \psi)} \simeq \frac{12 \times 1.14\%}{3.6} \simeq 4\%$$

② From pp to AuAu

$$\Longrightarrow * \frac{197 \times 197}{(197 \times 197)^{0.91}} \simeq 2.6$$

{ Beauty A-dep: $\alpha = 1$
J/ψ Adep: $\alpha \simeq 0.91$

If 'anomalous' suppression of ~50% as in central Pb-Pb collisions at the SPS

$$\longrightarrow \frac{\sigma(B) * Br(B \to \psi)}{\sigma(\psi)} \sim \frac{4\% * 2.6}{50\%} \simeq \underline{20\%}$$

③ For $p_T(\psi) > 4-5$ GeV/c

⟹ Beauty contribution DOMINATES !?

Overview of missing experimental data

√ – $\frac{dN^{ch}}{d\eta}\Big|_{\eta\sim 0}$ vs. E_{ZDC} ⇒ WNM vs. DPM (min. bias Trigger)

√ – ψ'/ψ vs. A in pA at the % in $\alpha^{\psi'} - \alpha^{\psi}$.

'98 – ψ/M.B. in PbPb : extend high and low E_T data

'99 – ψ/M.B. and ψ/DY in $(AB) \sim 100^2$

'00 – Open Charm : { IMR yield in PbPb ; D-meson kinematics

– A-dependence of high p_T single lepton

'01 – A-dep. of χ_c production, in p-A

Big physics potencial for a Dimuon measurement with identified vertex

⟹ SPS proposal end '98

Heavy Quarkonium Production: An Outsider's View

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New York, New York 10027

Abstract

Heavy quarkonium production in nucleon-nucleon, nucleon-nucleus and nucleus-nucleus collisions has become an important probe for understanding possible phase changes in QCD matter. However, there are quite different, and seemingly contradictory, pictures of J/ψ production in nucleonic and nuclear collisions. In this talk the main pictures of J/ψ production in nucleonic and nuclear collisions are reviewed with an attempt to point out the strengths and weaknesses of the various proposals and to compare them where possible.

Heavy Quarkonium Production: An Outsider's View

Many interesting pictures of J/ψ production mechanism in nucleon-nucleon collisions and of absorption in nucleon-nucleus and in nucleus-nucleus collisions.

Try to look at strong and weak points of the various proposals

Key Facts:

A. Non nuclear collisions

Color singlet model fails badly in J/ψ production in nucleon-nucleon collisions but seems to be ok for photon-nucleon interactions

B. Nucleon-nucleus collisions

Gerschel-Hüfner picture of J/ψ absorption works well with $\sigma^{in}_{J/\psi,N} \approx 6\text{-}7$ mb.

J/ψ and ψ' have same absorption rate $\Rightarrow$ absorption should happen pre formation of $J/\psi, \psi'$

Υ absorption according to $\sigma^{in}_{\Upsilon N} \sim 1.5\text{-}2$ mb

C. Nucleus-Nucleus collisions

$J/\psi, \psi'$ absorption differ in S-U and Pb-Pb reactions
Longer time interactions important

In Pb-Pb collisions more J/ψ absorption than expected using $\sigma^{in}_{J/\psi N} \approx 6\text{-}7$ mb

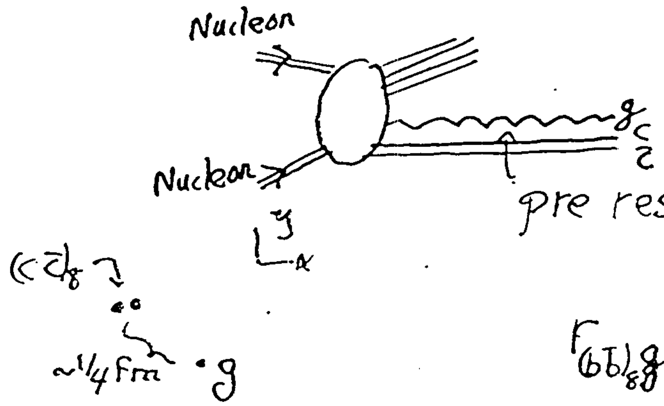
Big Uncertainty: Convincing picture of J/ψ production not yet at hand.

Big Mystery: Why is $\sigma^{in}_{J/\psi, N}$ so big?

Different pictures attempt to explain some or all of the main features of $J/\psi, \psi', \Upsilon$ production in nucleon-nucleon and nucleon-nucleus collisions.

Kharzeev-Satz picture: An all-encompassing picture

Early stage of production



pre resonance $(c\bar{c})_8 g$ system

$$r_{(b\bar{b})_8 g} \approx \sqrt{\frac{m_c}{m_b}}\, r_{(c\bar{c})_8 g}$$

$\sigma_{\psi N} \approx$ 6-7 mb comes from $r_{(c\bar{c})_8 g} \sim 1/4$ fm and octet dipole cross section

In nucleon-nucleus collisions the gluon is stripped away with a cross section $\approx$ 6-7 mb and acts like an effective $\sigma^{in}_{J/\psi, N}$.

In nucleus-nucleus collisions the ψ' begins to be broken up by comovers while the J/ψ is too robust to be broken up by gluons coming from hadron gas. At sufficiently high density the QGP, with energetic gluons, can destroy the J/ψ.

Overall a plausible picture except (for me) one unnatural feature, the pre resonance $(Q\bar{Q})_8 g$ system. $(Q\bar{Q})_8$ and g do not have time to talk to each other before formation of onium. $r = 1/4$ "anticipates" J/ψ wavefunction. Will not be same r for ψ'. Also no way for m_Q to get into problem.

Bodwin, Braaten, Lepage Formalism: A formalism for J/ψ production.

$$d\sigma(\psi + X) = \sum_n d\sigma((c\bar{c})_n + X') \langle O_n^\psi \rangle$$

$\langle O_n^\psi \rangle$: nonperturbative transition of $(c\bar{c})_n$ to $J/\psi + X'$

$d\sigma((c\bar{c})_n + X')$: hard (perturbative) production of $c\bar{c}$ in state n

$d\sigma((c\bar{c})_n + X')$ ordered in $\alpha(m_c^2)$

$\langle O_n^\psi \rangle$ ordered in v^P

Singlet model: $(c\bar{c})$ in singlet color state (wins in v^2)

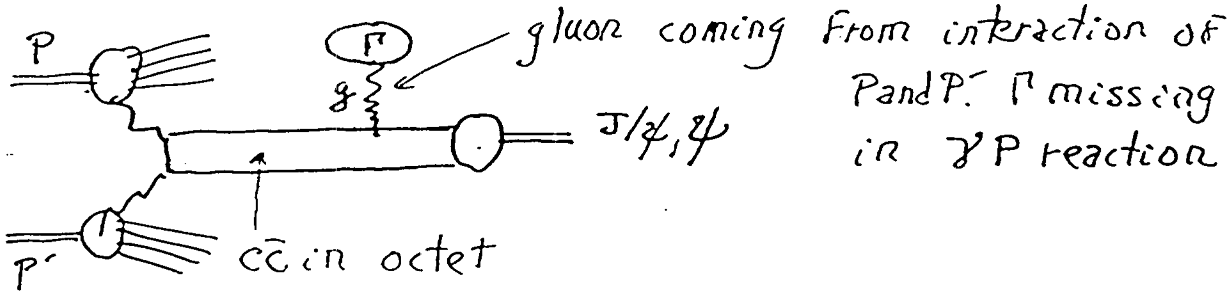
Octet model: $(c\bar{c})$ in octet (wins in $\alpha(m_c^2)$) Braaten, Fleming

Nice general formalism but need much more insight in order to use in nuclei.

Kharzeev-Satz is (partial) model for $\langle O_8^\psi \rangle$

Hoyer-Peigné picture: Focuses on production mechanism.

Formally similar to BBL, but more explicit.



Does not factorize hard and "soft" parts so completely as BBL.

Interaction with g is "moderately" hard.

Similar to Kharzeev-Satz. Size of $c\bar{c}$ state when g interacts is comparable to $r_{J/\psi}$.

Little understanding of what $r_{c\bar{c}}$ should be when g is absorbed. Not clear why $\sigma^{in}_{J\psi,N}$, $\sigma^{in}_{\psi',N}$ should be the same.

Bridges ... and

Armesto - Capella (Comovers)

Focuses on nuclear number dependence of J/ψ and ψ' production in nucleon-nucleus and nucleus-nucleus collisions.

Essential elements

I $\quad \sigma^{in}_{J/\psi,N}, \sigma^{in}_{\psi',N} = 7.3\ mb$ $\quad$ no comovers

$\quad \sigma^{\psi}_{co} = \sigma^{\psi'}_{co} = 0$

II $\quad \sigma^{in}_{J/\psi,N} = \sigma^{in}_{\psi',N} = 6.7\ mb$ $\quad$ comovers

$\quad \sigma^{\psi'}_{co} = 6\ mb \quad \sigma^{\psi}_{co} = 0.6\ mb$

Dual Parton Model (DPM) used to get comovers. Good fit to π production in A·B collisions.

Without Pb-Pb data I and II both work. With Pb-Pb data an ok? fit

Biggest worry is whether the large π-density at $t \sim 1\ fm$, $\rho_\pi \approx 4\text{-}5\ fm^{-3}$, is reasonable. May be compatible with short quark-gluon "phase"?

Hüfner–Kopeliovich picture. All-encompassing model. Brave but not unreasonable.

Essential idea: In nucleon-nucleus and nucleus-nucleus collisions enough semihard gluons are produced to partial destroy $J/\psi, \psi'$ production.

(i) gluons, in CM frame, have $k_L, k_\perp \lesssim 1$ GeV with $\frac{2k_L}{k_\perp^2} \lesssim \frac{\lambda_g}{\gamma} \sim \frac{1}{2}$ Fm (Several longitudinal layers of gluons.)

(ii) Number of gluons estimated in perturbative QCD. For Pb-Pb about 2 Fm^{-2}, or about ½ gluon per nucleon-nucleon collision.

(iii) $\sigma^{in}_{J/\psi,N} \Rightarrow \underbrace{\sigma^{in}_{J/\psi,N}}_{4mb} + \underbrace{\sigma_{J/\psi,g}}_{3mb} \langle n_g \rangle$

(iv) Number of gluons/area grows like $(AB)^{1/3}$ leading to increased suppression for larger nuclei. Hard gluons but not a plasma.

Good Feature

$\sigma^{in}_{J/\psi,N} \sim 4mb$ is big improvement

gluons are effective at "early" times

Worries

Do gluons live long enough before decaying into π's?

Can ψ' suppression work without comovers?

Observables in J/ψ production

D. Kharzeev

RIKEN-BNL Research Center,
Brookhaven National Laboratory,
Upton NY 11973, USA

During the RIKEN-BNL Workshop on Quarkonium Production in Relativistic Nuclear Collisions (held September 28 – October 2, 1998, at Brookhaven National Laboratory), participants agreed on the list of observables which are most useful in terms of comparison of theoretical approaches with the experimental data and among themselves.

It would be most beneficial for further progress in the field if the interested theorists make predictions for all or some of these observables (both for RHIC and LHC energies) before the data become available.

Here is the list:

- Differential minimum bias cross sections, as a function of charged multiplicity N_{ch} and forward (Zero Degree Calorimeter) energy:

$$\frac{d\sigma_{AB}}{dN_{ch}}; \quad \frac{d\sigma_{AB}}{dE_{ZDC}} \tag{1}$$

(All of the calculations should include $A = B = 197$ at $\sqrt{s} = 200$ GeV and $A = B = 208$ at $\sqrt{s} = 5500$ GeV; N_{ch} should refer to the rapidity interval $-0.5 \leq y^*_{ch} \leq 0.5$).

- Differential cross sections of J/ψ and χ production in pp collisions as a function of rapidity and transverse momentum:

$$\frac{d^2\sigma_{pp\to J/\psi}}{dy\ dp_\perp^2}; \tag{2}$$

at energies $\sqrt{s} = 50 \div 500$ GeV (including $\sqrt{s} = 200$ GeV) and $\sqrt{s} = 5500$ GeV.

- Differential cross sections of J/ψ production in AB collisions as a function of rapidity and transverse momentum:

$$\frac{d^2\sigma_{AB\to J/\psi}}{dy\ dp_\perp^2}; \tag{3}$$

at energies $\sqrt{s} = 200$ GeV and $\sqrt{s} = 5500$ GeV.

- Triple–differential cross sections of J/ψ production in AB collisions as a function of rapidity, transverse momentum, and charged multiplicity:

$$\frac{d^3\sigma_{AB\to J/\psi}}{dy\, dp_\perp^2\, dN_{ch}}; \tag{4}$$

at energies $\sqrt{s} = 200$ GeV and $\sqrt{s} = 5500$ GeV.

- Triple–differential cross sections of J/ψ production in AB collisions as a function of rapidity, transverse momentum, and forward energy:

$$\frac{d^3\sigma_{AB\to J/\psi}}{dy\, dp_\perp^2\, dE_{ZDC}}; \tag{5}$$

at energies $\sqrt{s} = 200$ GeV and $\sqrt{s} = 5500$ GeV.

It was also realized that understanding the production of open charm and beauty would be important, both for providing the reference point for quarkonium suppression and filtering the background from B meson decays. Therefore the following quantitites are also of interest:

- Differential cross sections of D and B meson production in pp collisions as a function of rapidity, transverse momentum, and charged multiplicity:

$$\frac{d^5\sigma_{pp\to D}}{dy_{D,\bar{D}}\, dp_{\perp D,\bar{D}}^2\, dN_{ch}}; \tag{6}$$

at energies $\sqrt{s} = 200$ GeV and $\sqrt{s} = 5500$ GeV.

- Differential cross sections of D and B meson production in AB collisions as a function of rapidity, transverse momentum, and charged multiplicity:

$$\frac{d^5\sigma_{AB\to D}}{dy_{D,\bar{D}}\, dp_{\perp D,\bar{D}}^2\, dN_{ch}}; \tag{7}$$

at energies $\sqrt{s} = 200$ GeV and $\sqrt{s} = 5500$ GeV.

Riken/BNL, Oct. 1998

H. Satz

J/Ψ Suppression: A Summary

Aim: use quarkonium states to probe the nature (confinement/deconfinement) of dense media produced in early stages of nuclear collisions

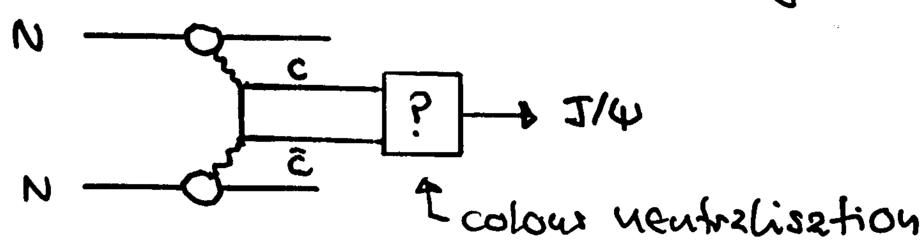
1. Making the Probe: p-p
2. Gauging the Probe: p-A
3. Using the Probe: A-B
4. Interpretation: Th-Th

1. Making the Probe $pp \to J/\psi + \ldots$

a. 60% direct 1S 'ψ'
32% 1P $\chi_c \to \psi + \ldots$
8% 2S $\psi' \to \psi + \ldots$

– independent of $\sqrt{s}$, p_T

b. parton interactions $\to c\bar{c}$ "gluon fusion"



$$\sigma(NN \to J/\psi + \ldots) = f_{J/\psi}\ \sigma(NN \to c\bar{c})\Big|_{M_{c\bar{c}} < M_{D\bar{D}}}$$

$f_{J/\psi}$: constant, ~ 0.025

'colour evaporation model' = admitted ignorance

$\sqrt{s}$, x_F, p_T dependence : quite good

colour neutralisation:

– colour singlet ~ perturbative
CDF & DØ → out! T. LeCompte

– colour octet ~ $[(c\bar{c})_8 + g]_1 \to c\bar{c})_1$
rates OK, polarisation? E. Braaten

Conclusion: probe predictable up to RHIC & LHC

2. Gauging the Probe $pA \to J/\Psi + \dots$

two basic questions:

- how is it made in A ? *initial state effects*:
  nuclear shadowing, coherence, parton energy loss, p_T broadening
- how does 'it' behave in nuclear matter ?
  final state effects:
  pre-resonance absorption, formation times, multi-channel fluctuations

M. Leitch

R.L. Thews, J. Kapusta, S. Peigné, J. Hüfner

a. Composition:

$\Psi'/(J/\Psi) \neq f(A)$; $\chi/(J/\Psi)$?

b. suppression:

$\exists$ A-dependent reduction of J/Ψ & Ψ' production.

initial state effect? for $x_F \simeq 0.15$: *NO!*

Drell-Yan, W/D $\to$ 0.994 ± 0.018

D-production $\to$ 1.06 ± 0.18

M. Leitch

nuclear absorption

for $x_F \geq 0$, same suppression of J/ψ & ψ'

∴ pre-resonance absorption

x_F dependence ?

NA 38/51 : $\sigma_{pre} \simeq 6 \pm 1$ mb

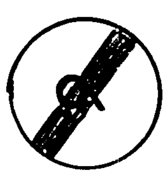
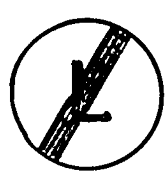
$\sigma_{pre}(s)$? E 776 → 7 ± 1 mb

E 866 ? need corrected ratios, not α ! K. Seth

∴ define normal J/ψ suppression :

pre-resonance suppression with $\sigma_{pre} = 6 \pm 1$ mb (at SPS energy);

calculate actual suppression using 'glauber' formalism;

3. Using the Probe $AB \to J/\psi + \dots$

a. the light ion era : O-Cu, O-U, S-U

define J/ψ (ψ') survival probability

$$S = [(J/\psi)/D\text{-}Y]_{AB} \,/\, [\div]_{pp}$$

isospin corrections for D-Y

compare to normal J/ψ suppression

conclusion: nothing new (or very little...) - fig. -

ψ': $\exists$ additional suppression - fig -

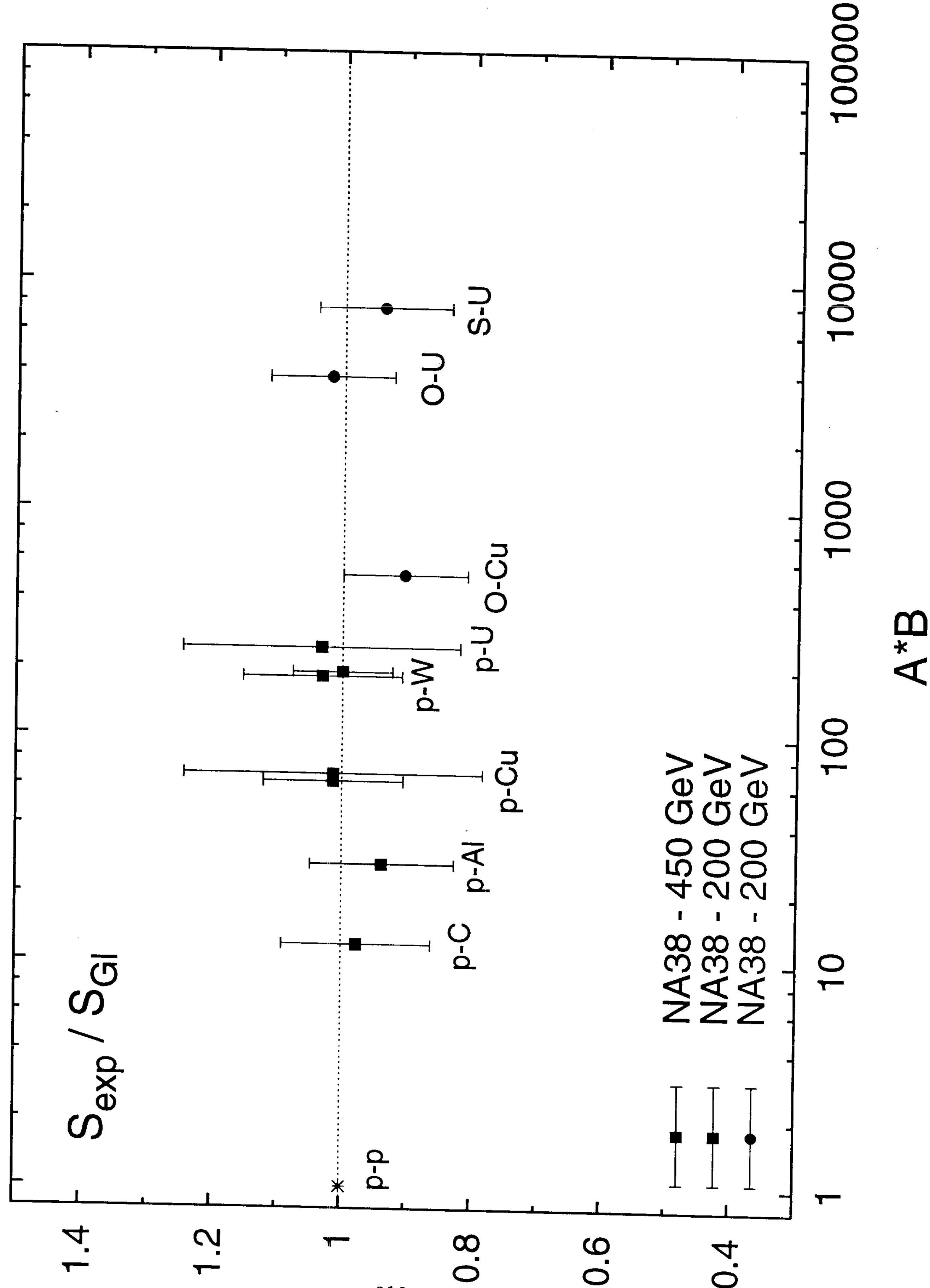
NB: medium first 'sees' ψ';
- smallest binding energy (65 MeV)
- latest formation time ($t_{\psi'} \gtrsim 2\text{-}3\, t_\psi$)

role of medium vs. probe ...

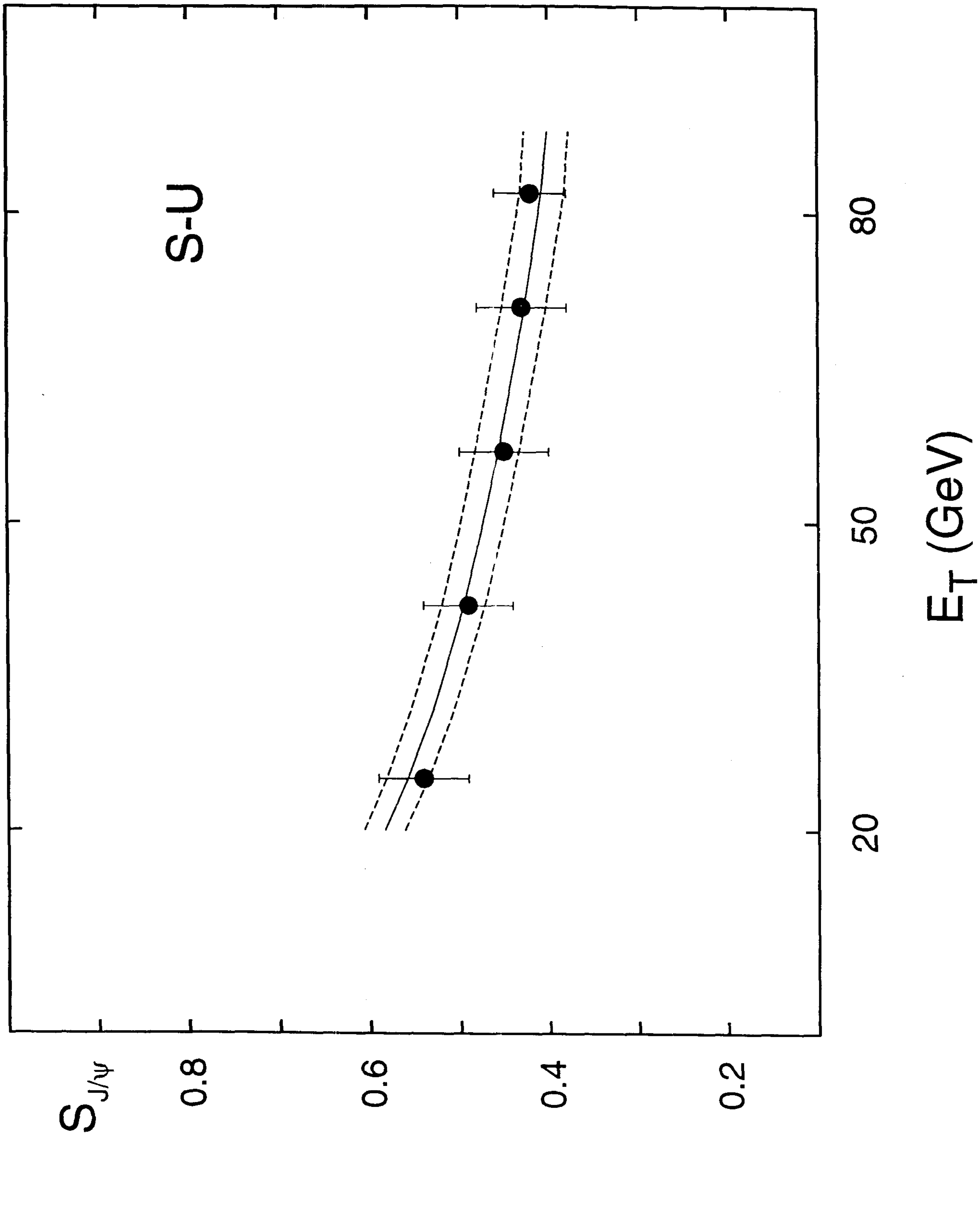
b. the Pb era : Pb-Pb

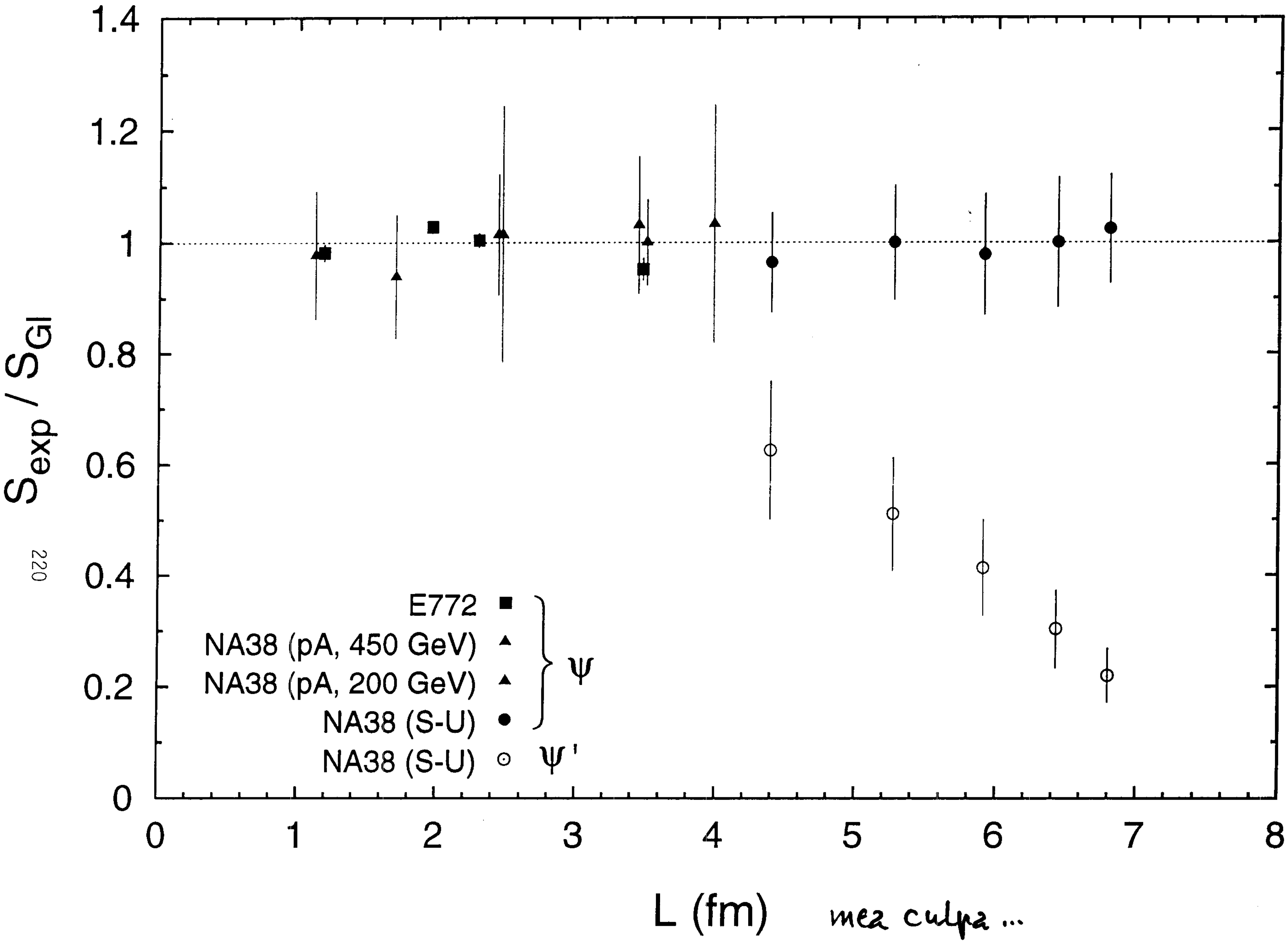
$\exists$ anomalous suppression M. Gonin

- centrality integrated - fig. -
- as f(centrality) ~ f(E_T) fig. -
- onset around $b \sim 8$ fm



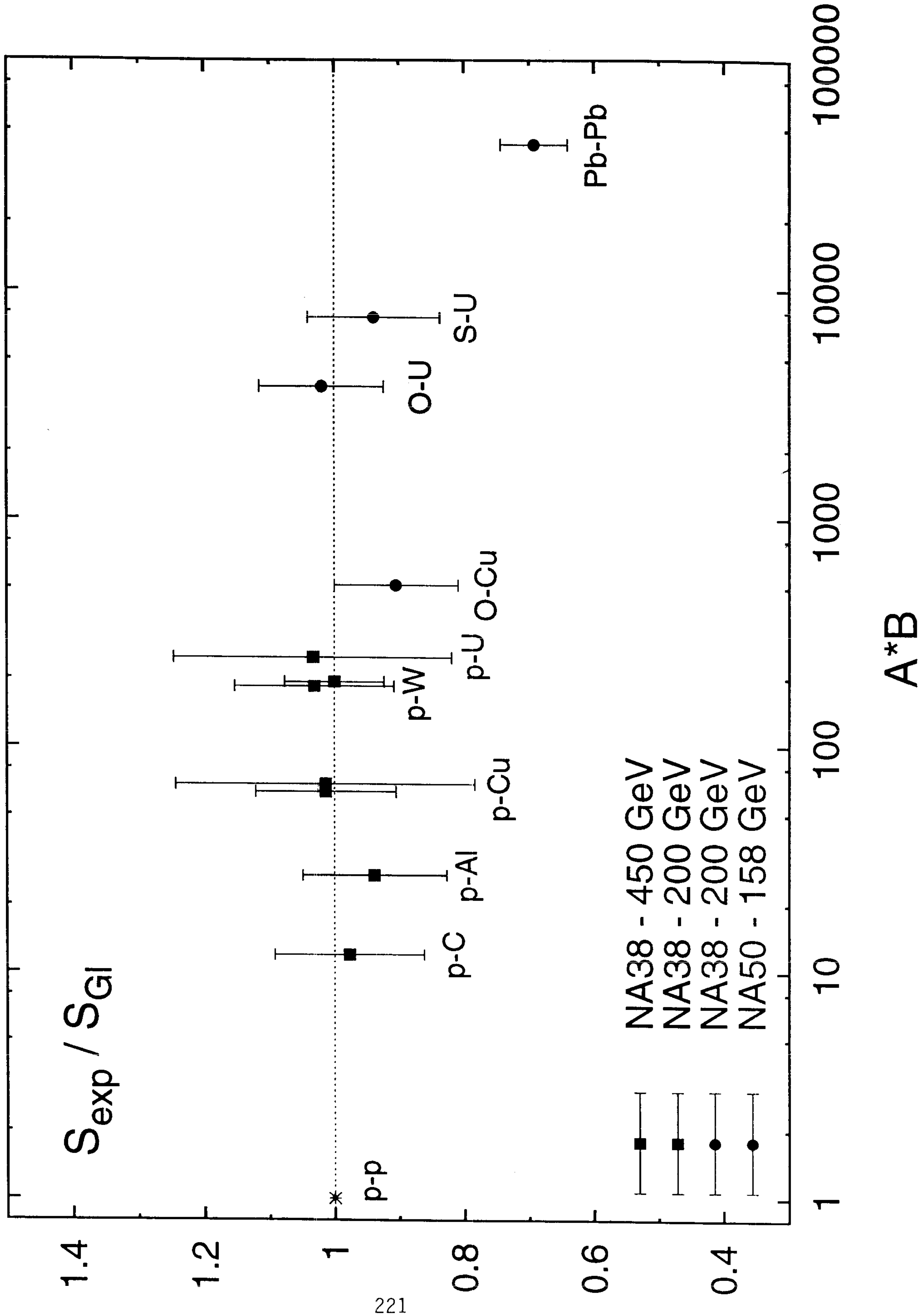
S_{exp} / S_{Gl}
A*B
1
10
100
1000
10000
100000
0.4
0.6
0.8
1
1.2
1.4
p-p
p-C
p-Al
p-Cu
p-W
p-U
O-Cu
O-U
S-U
NA38 - 450 GeV
NA38 - 200 GeV
NA38 - 200 GeV

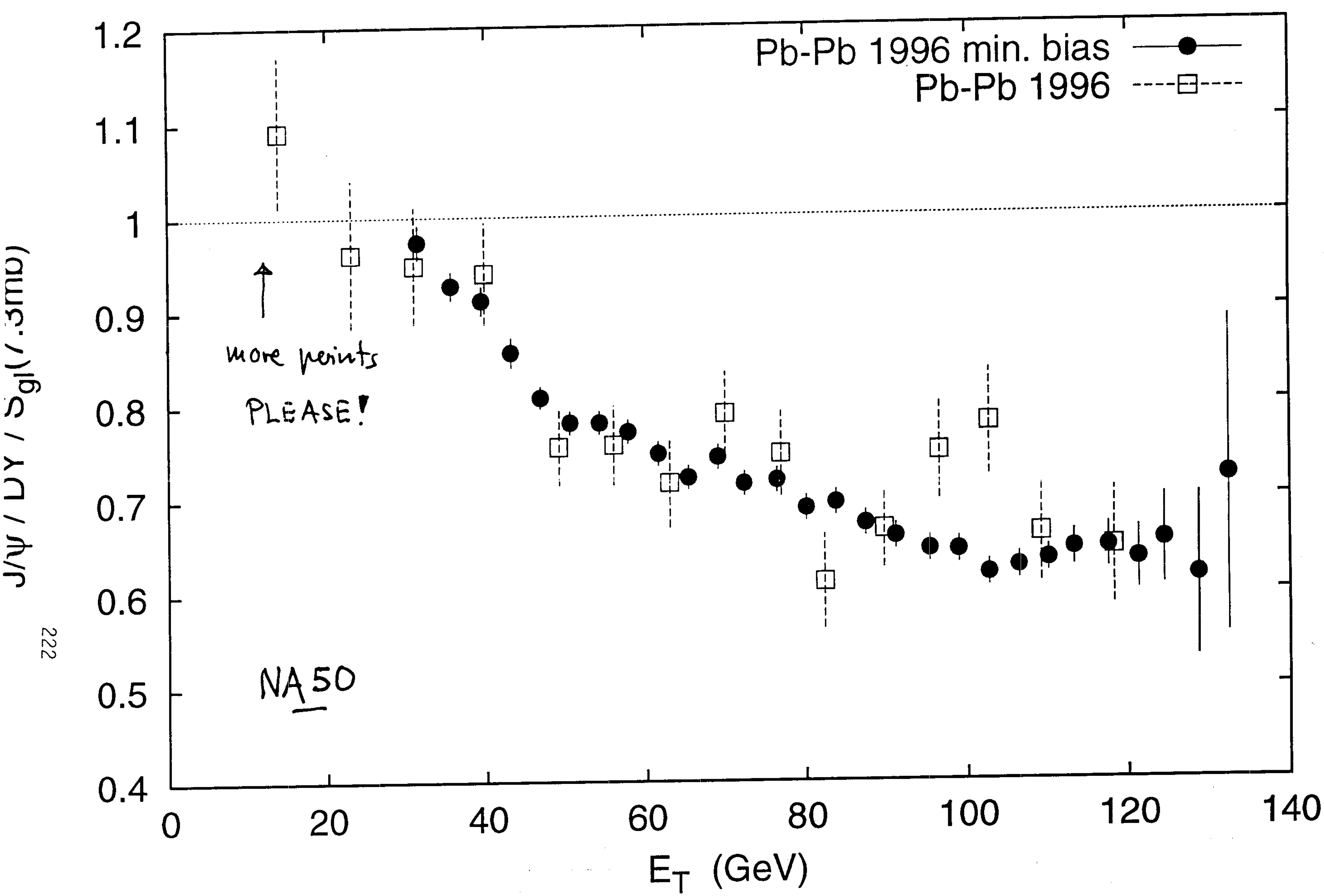

S-U
$S_{J/\psi}$
0.8
0.6
0.4
0.2
20
50
80
E_T (GeV)



1.4
1.2
1
0.8
0.6
0.4
0.2
0
0
1
2
3
4
5
6
7
8
S exp / S Gl
L (fm)
E772
NA38 (pA, 450 GeV)
NA38 (pA, 200 GeV)
NA38 (S-U)
NA38 (S-U)
ψ
ψ '
mea culpa ...

220


S_{exp} / S_{Gl}
A*B
1.4
1.2
1
0.8
0.6
0.4
1
10
100
1000
10000
100000
p-p
p-C
p-Al
p-Cu
p-W
p-U
O-Cu
O-U
S-U
Pb-Pb
NA38 - 450 GeV
NA38 - 200 GeV
NA38 - 200 GeV
NA50 - 158 GeV



Pb-Pb 1996 min. bias
Pb-Pb 1996
J/ψ / DY / S_{gl}(7.3mb)
E_T (GeV)
more points
PLEASE!
NA50

4. Interpretation

Basic question: colour deconfinement or absorption by hadronic comovers ?

- colour deconfinement

  - charmonium dissociation by colour screening (Matsui & HS)

  - charmonium dissociation by interaction with deconfined gluons (Kharzeev & HS)

relation? global medium vs 2-body
T. Matsui

combination? percolation of hard gluon strings or minijets created in N-N collisions
M. Nardi, M. Gyulassy

how much medium = new phase?

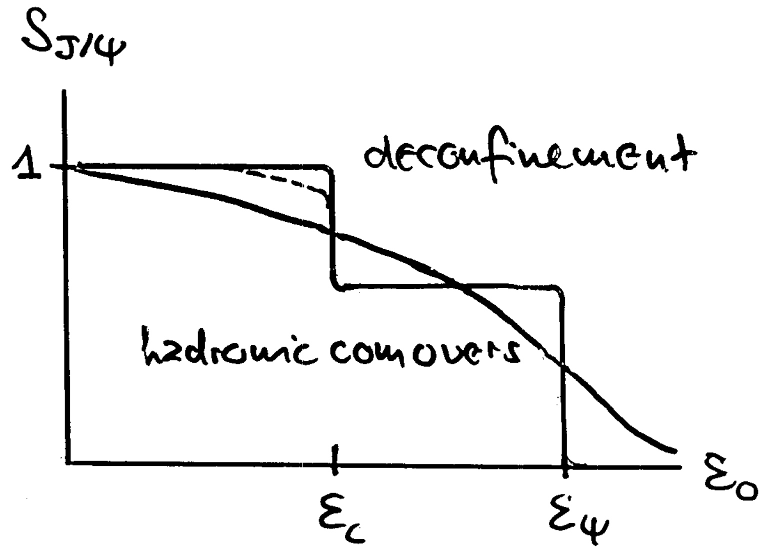
- hadronic comovers

  - dissociation by interaction with hadronic secondaries (Brodsky/Mueller, Capella, Gavin/Vogt, ...)

$\sigma_{in}(h\text{-}J/\psi)$? heavy quark QCD $\lesssim 0.1$ mb
comover models 0.5 - 1 mb
A. Capella
string flip 10 - 15 mb
D. Blaschke

exp'tl answer: - inverse kinematics Pb + N
- $\bar{p}A$ interactions
K. Seth

- Basic suppression patterns (uniform medium)



deconfinement: well defined onsets for χ & ψ suppression;

∴ structure in suppression pattern.

hadronic comovers: always present, no threshold;

∴ no structure in suppression pattern.

- <u>nuclear collisions</u> (finite, non-uniform medium)

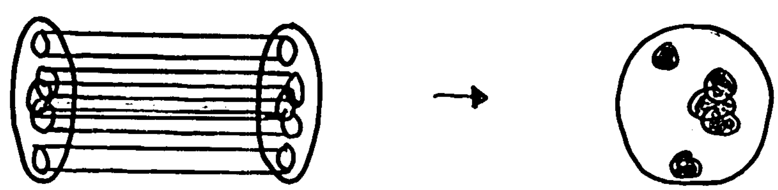
∃ smearing from

- nuclear profile (hot & cold regions); known from Woods-Saxon.
- exp't'l $E_T - b$ uncertainties; know from $E_T - E_{ZDC}$.
- possible smooth onset of critical conditions. C-Y. Wong vs. M. Nardi

how much structure can survive?

- <u>Percolation model</u> as illustration M. Nardi / HS

deconfinement when enough hard enough N-N collision overlap: cluster in transverse plane



interacting nucleons → strings of radius ~ k_T of gluons

relevant string radius ~ k_T of gluon required to dissociate J/ψ (or χ):

$r_\chi \sim 1/k_T^\chi$, $r_\psi \sim 1/k_T^\psi$.

- Analysis in terms of percolation deconfinement
  M. Nardi & HS, hep-ph/9805247, PL B in press.

  Parameters: $r_\chi \sim 1/k_T^\chi$ "χ gluons"

  $r_\psi \sim 1/k_T^\psi$ "ψ gluons"

  → { critical collision densities for deconfinement (χ, ψ' suppression) & for direct ψ suppression

  "fine tuning"; in ∞-volume limit
  $n_c = 1.175/\pi r^2$

  ψ' suppression by comovers determined from S-U data.

- Results:

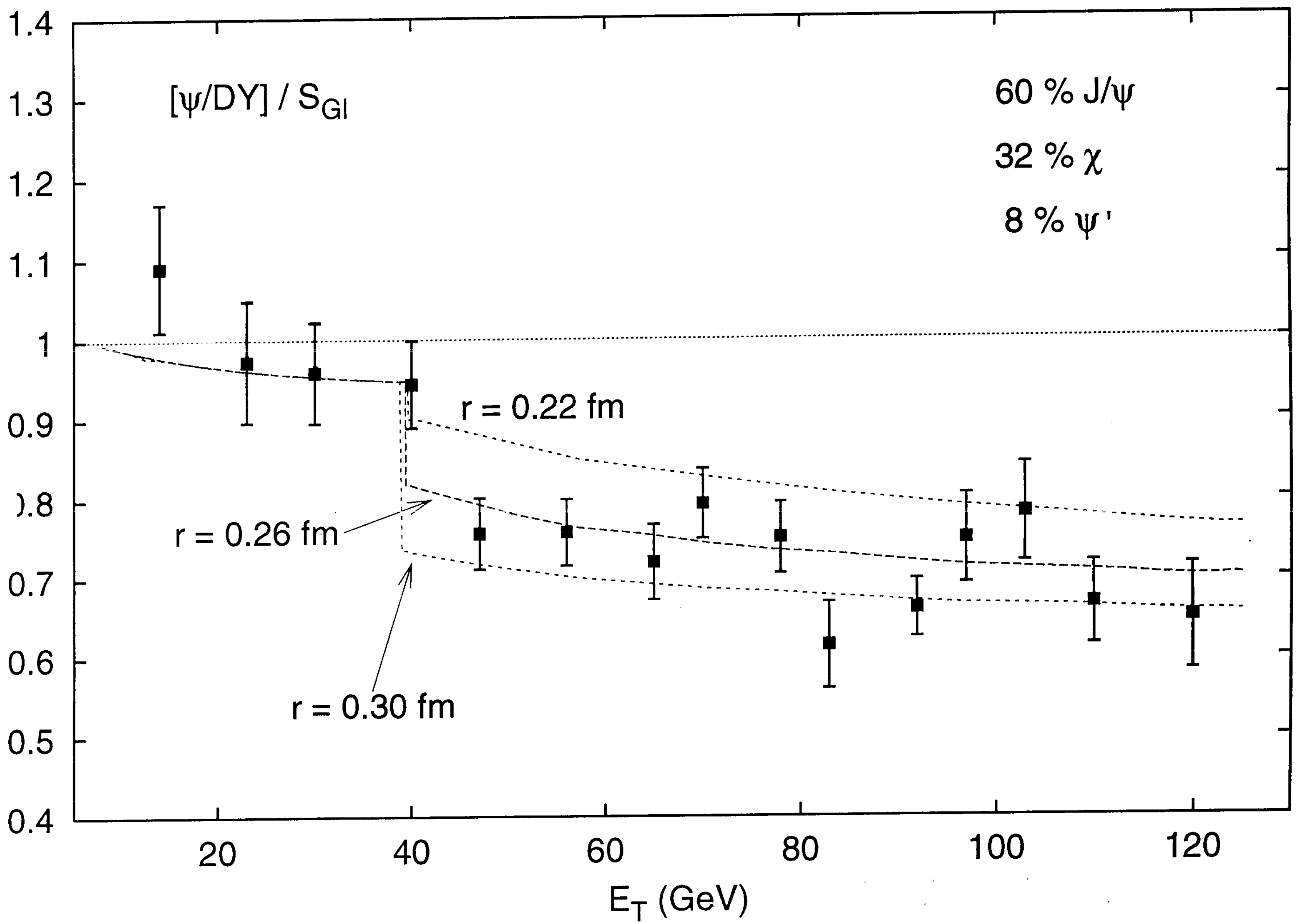
  1) χ & ψ' suppression only
  $r_\chi = 0.26\ fm^{-2}$, $n_c = 6.5\ fm^{-2}$
  ($n_\infty = 5.5\ fm^{-2}$)

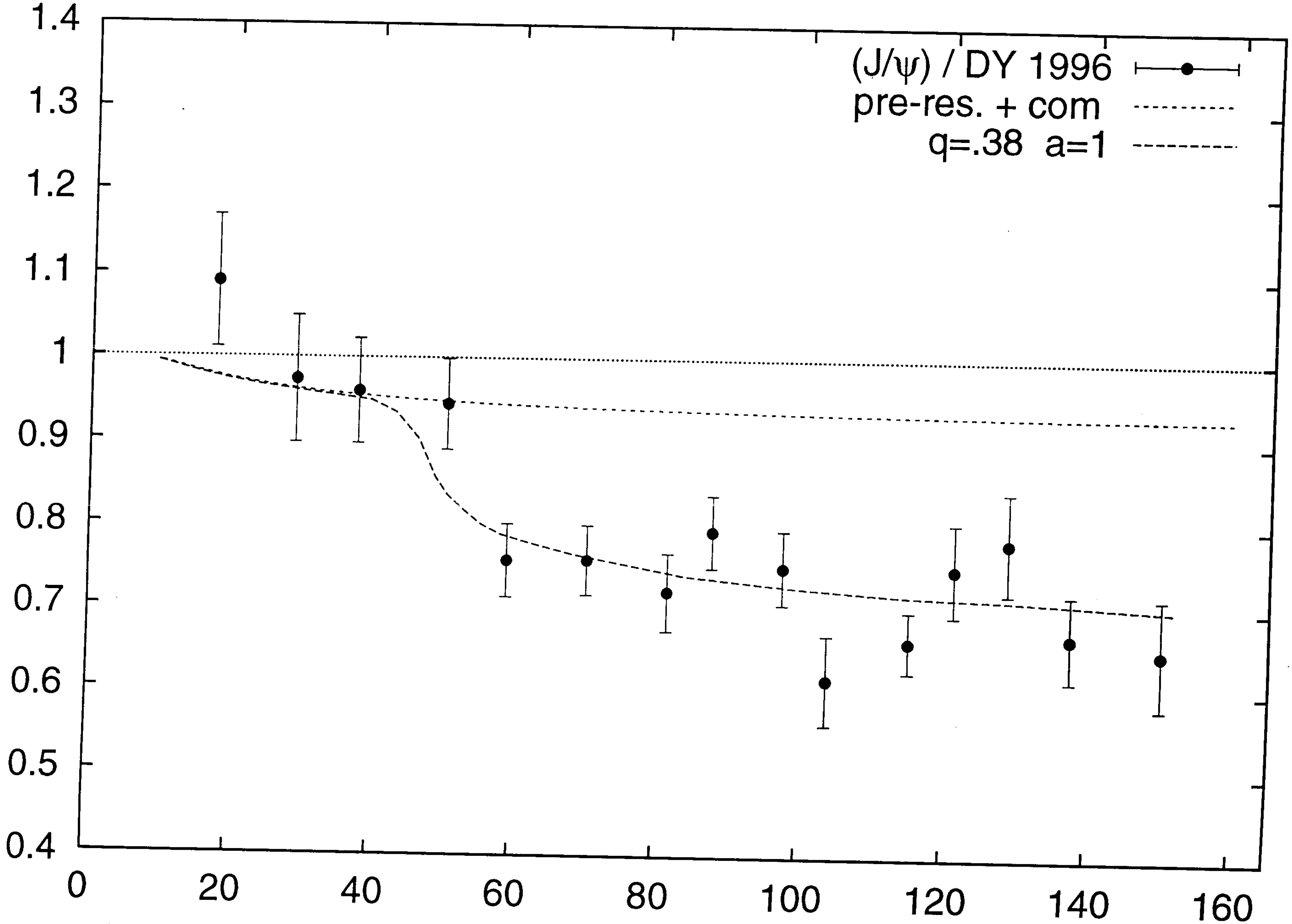
  - Fig's

  Conclude: need direct J/ψ suppression

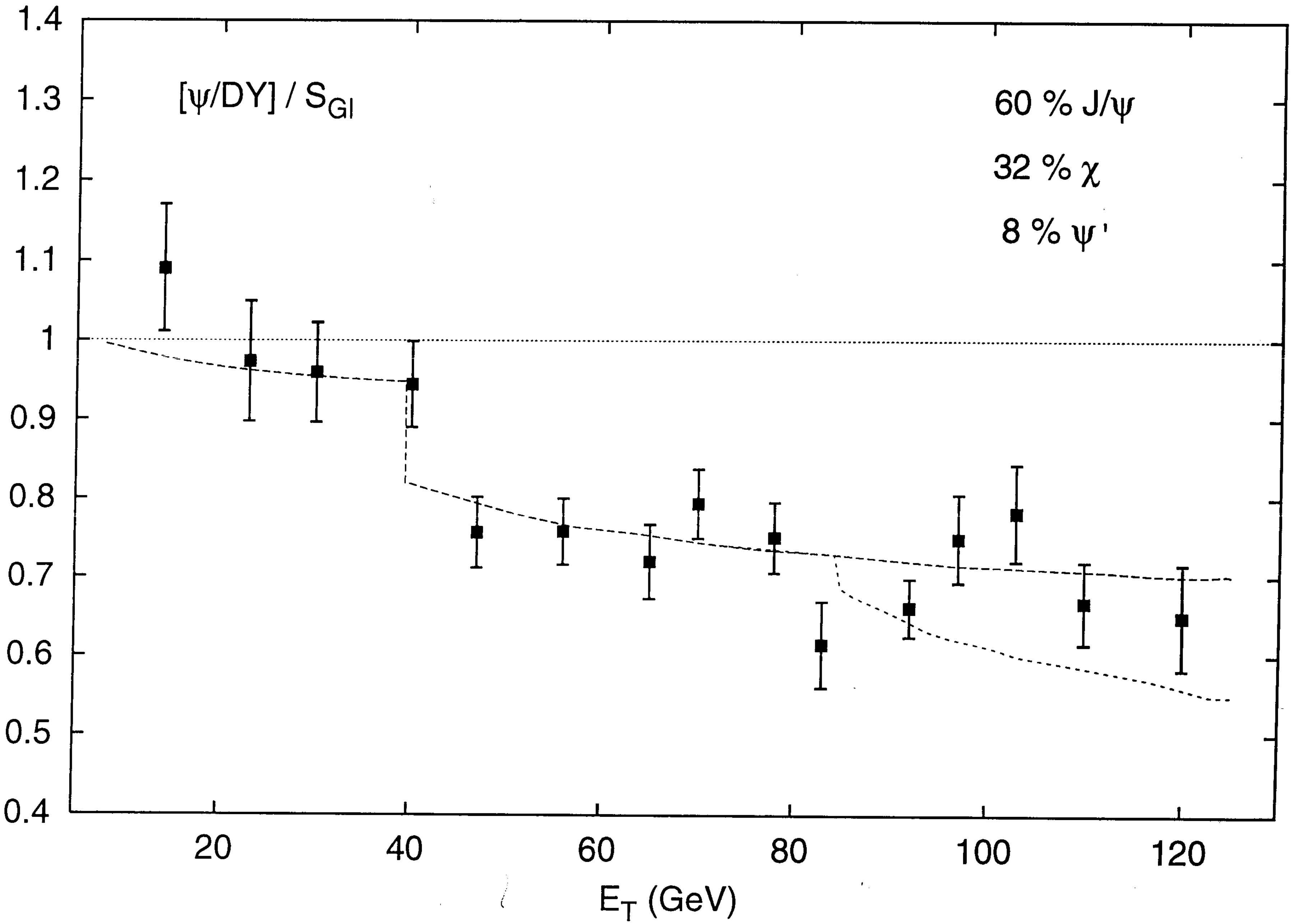
  2) χ & ψ' as before, + direct ψ:
  $r_\psi = 0.18\ fm^{-2}$, $n_c = 10.3\ fm^{-2}$
  ($n_\infty = 11.1\ fm^{-2}$)

  - Fig's


[ψ/DY] / S_GI
60 % J/ψ
32 % χ
8 % ψ'
r = 0.22 fm
r = 0.26 fm
r = 0.30 fm
1.4
1.3
1.2
1.1
1
0.9
).8
0.7
0.6
0.5
0.4
20
40
60
80
100
120
E_T (GeV)


(J/ψ) / DY 1996
pre-res. + com
q=.38 a=1
1.4
1.3
1.2
1.1
1
0.9
0.8
0.7
0.6
0.5
0.4
0
20
40
60
80
100
120
140
160

-6a



[ψ/DY] / S_Gl
60 % J/ψ
32 % χ
8 % ψ'
1.4
1.3
1.2
1.1
1
0.9
0.8
0.7
0.6
0.5
0.4
20
40
60
80
100
120
E_T (GeV)

3) compare to new NA 50 analysis

- Fig's

Conclude:
- need both χ & direct ψ suppression
- data at high E_T (> 110 GeV) are too high; rescattering? '95 min bias?

Freedom on direct ψ parameters?

- Fig. $\quad r_\psi = 0.20\ \mathrm{fm}^{-2} \quad n_c = 11.0\ \mathrm{fm}^{-2}$ $\quad (n_\infty = 9.5\ \mathrm{fm}^{-2})$

4) S-U : no anomalous suppression

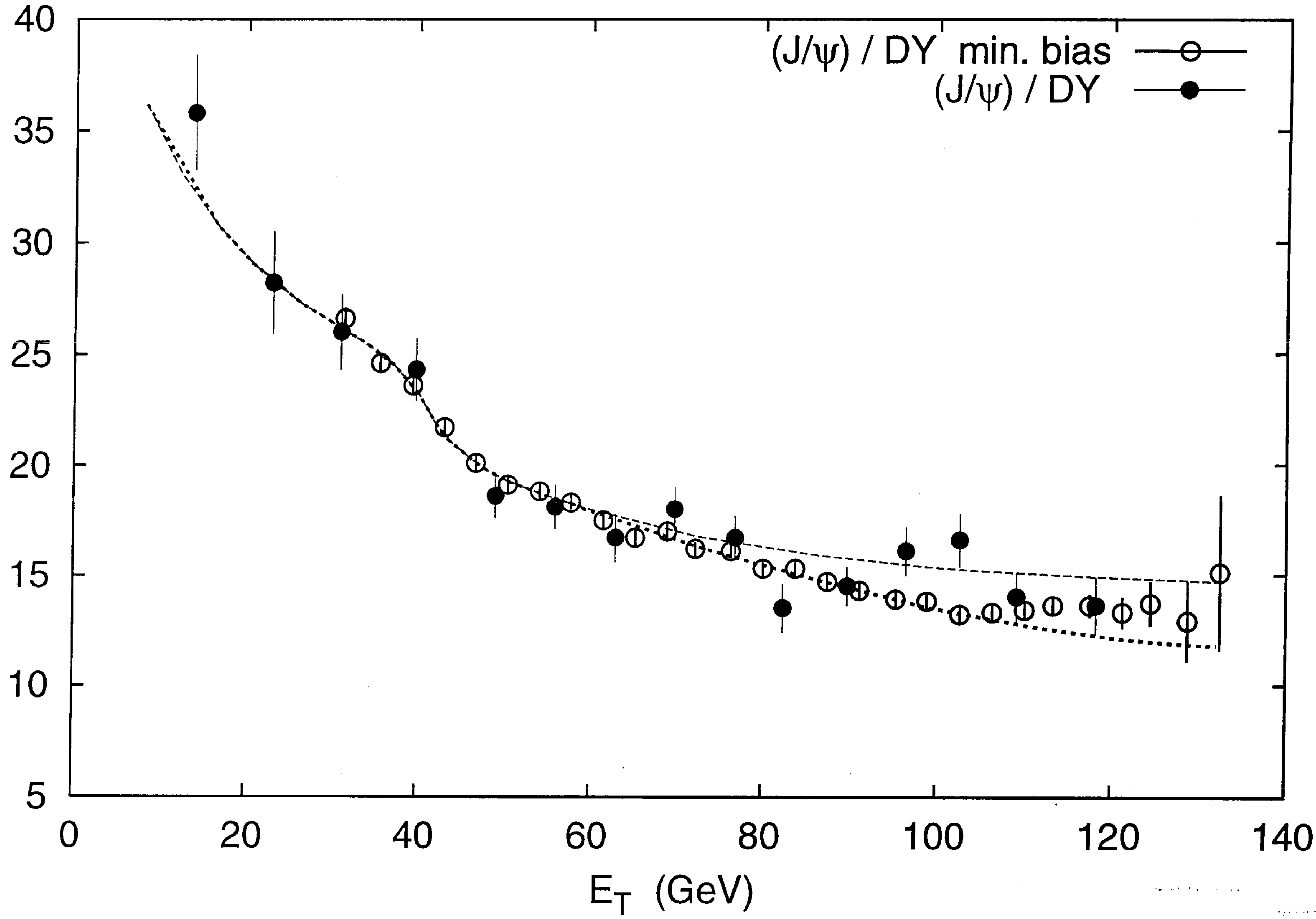
∴ use S-U $\langle P_T^2 \rangle$ data to determine δ^2 in initial state parton scattering; Pb-Pb $\langle P_T^2 \rangle$ then predicted

5) Pb-Pb $\langle P_T^2 \rangle$:

- Fig.

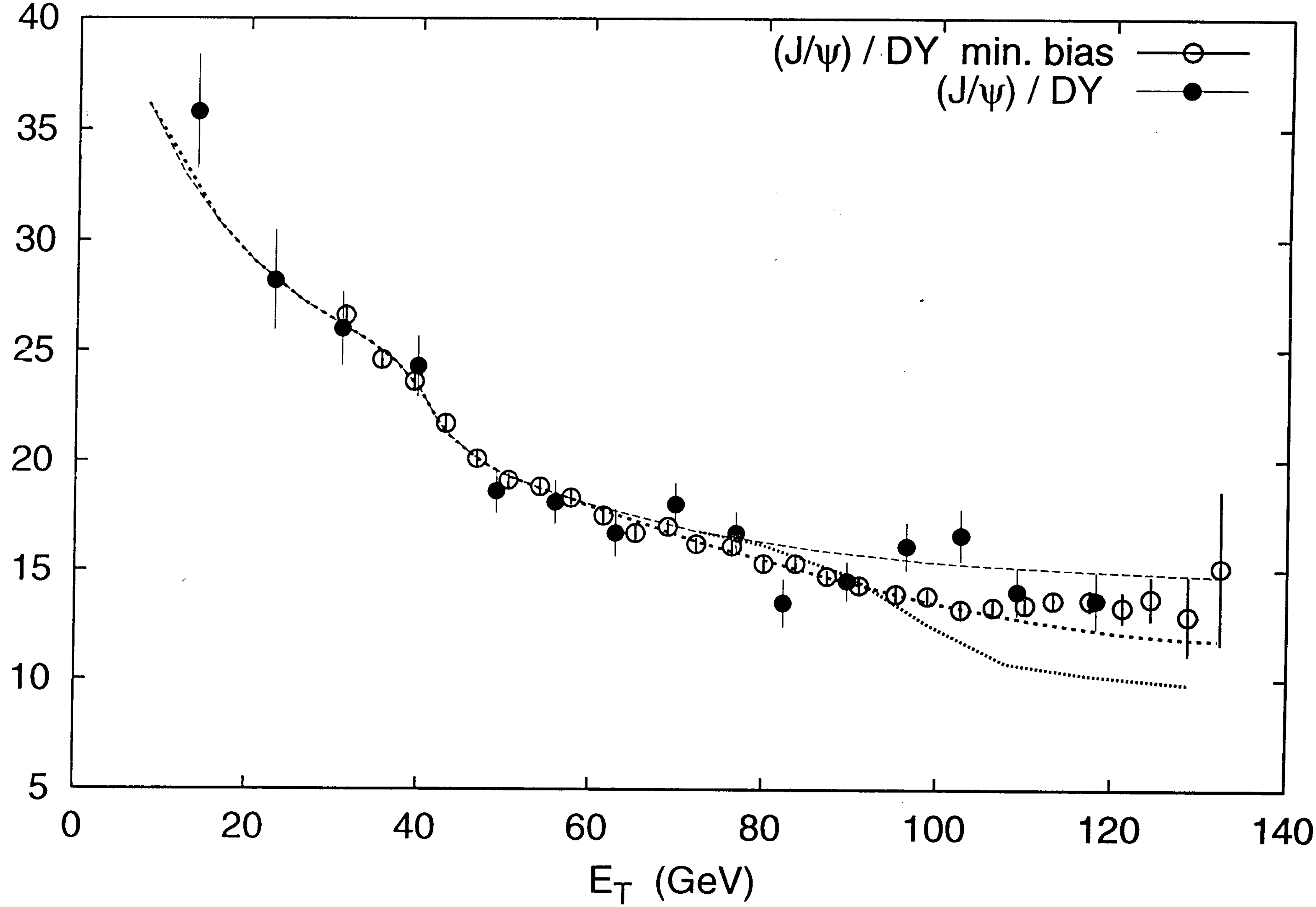
Conclude:
- $\langle P_T^2 \rangle$ data at high E_T are too high; rescattering? '95 min bias?

8

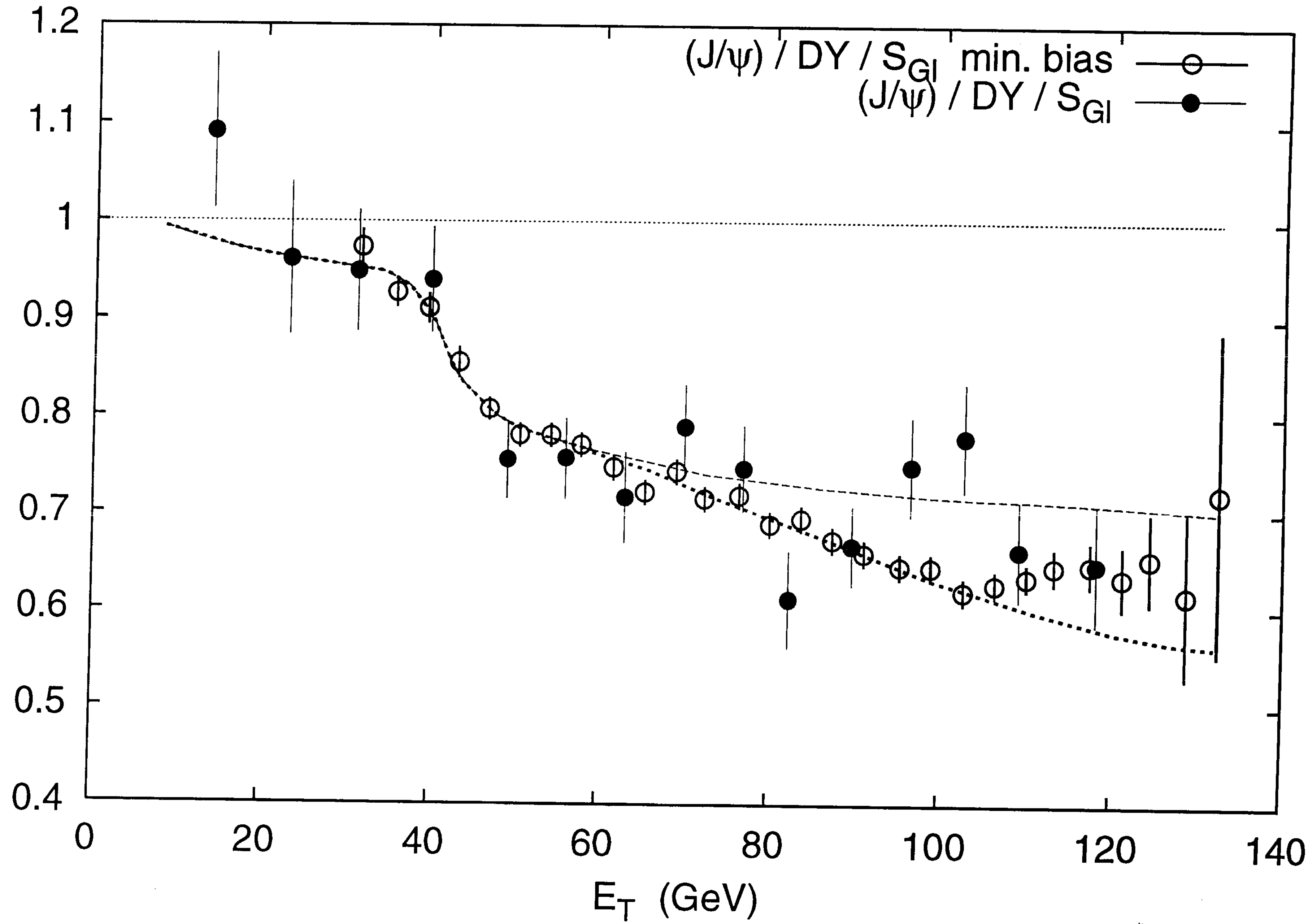


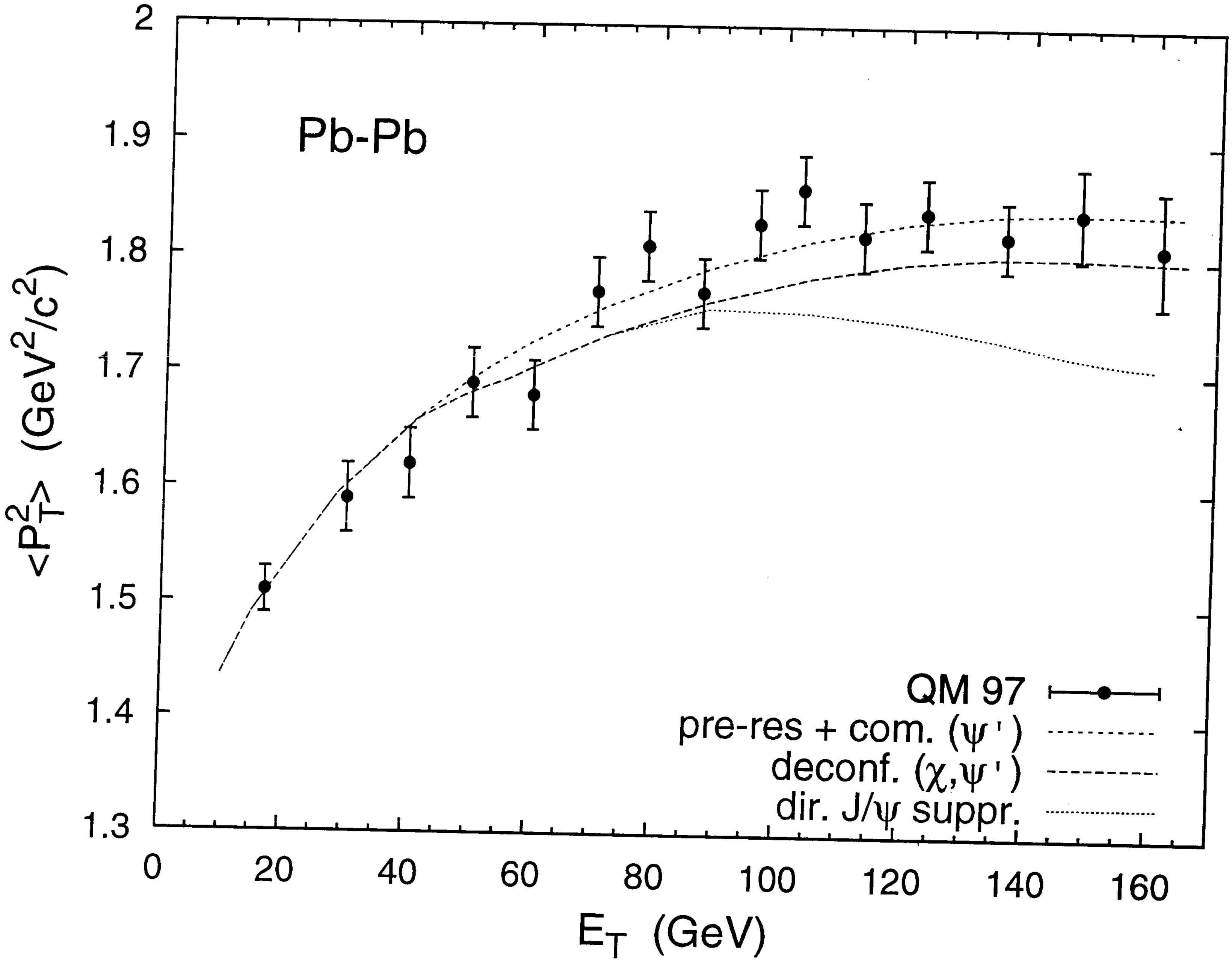
(J/ψ) / DY min. bias
(J/ψ) / DY
40
35
30
25
20
15
10
5
0
20
40
60
80
100
120
140
E_T (GeV)

1c



(J/ψ) / DY min. bias
(J/ψ) / DY
40
35
30
25
20
15
10
5
0
20
40
60
80
100
120
140
E_T (GeV)


(J/ψ) / DY / SGl min. bias
(J/ψ) / DY / SGl
1.2
1.1
1
0.9
0.8
0.7
0.6
0.5
0.4
0
20
40
60
80
100
120
140
ET (GeV)


Pb-Pb
$<P_T^2>$ (GeV^2/c^2)
2
1.9
1.8
1.7
1.6
1.5
1.4
1.3
0
20
40
60
80
100
120
140
160
E_T (GeV)
QM 97
pre-res + com. (ψ')
deconf. (χ,ψ')
dir. J/ψ suppr.

6) Hadronic comovers?

examples: Kahana[2], Capella, URQMD

- Fig's

A. Capella, B. Kopeliovich
L. Gerland, R. Mattiello

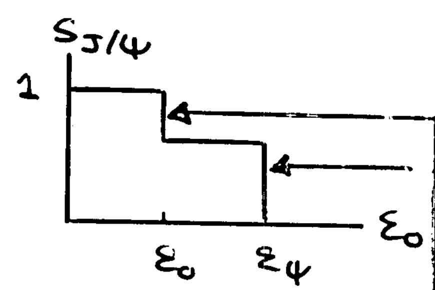
Conclude: ◉ incompatible with new NA50 analysis

More general: no conventional model has ever provided 'structure'

(caveat: → J.-W. Qiu)

Moreover: high E_T 'hopes' contrary to deconfinement predictions.

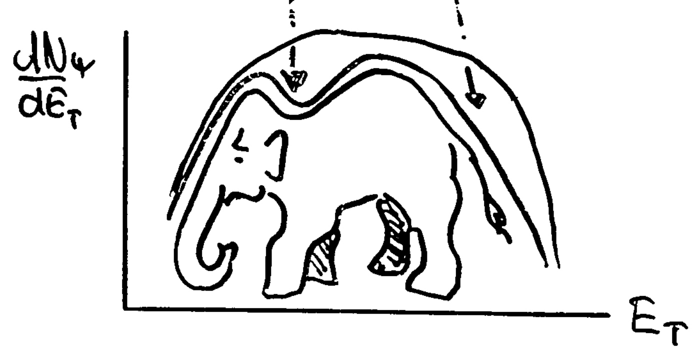
7) Re structure:

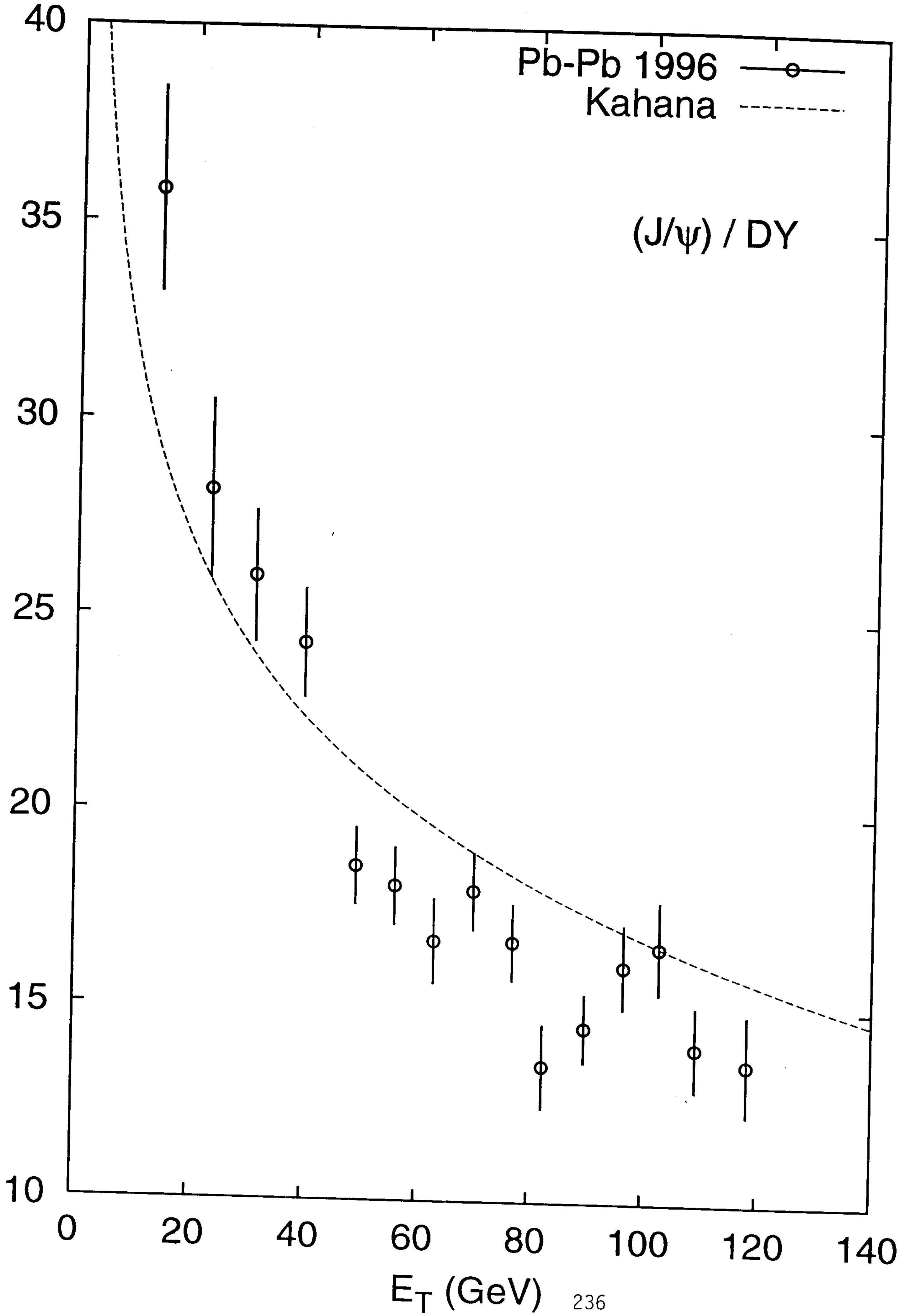


+ finite bubble size at deconfinement (e.g. percolation, ...)

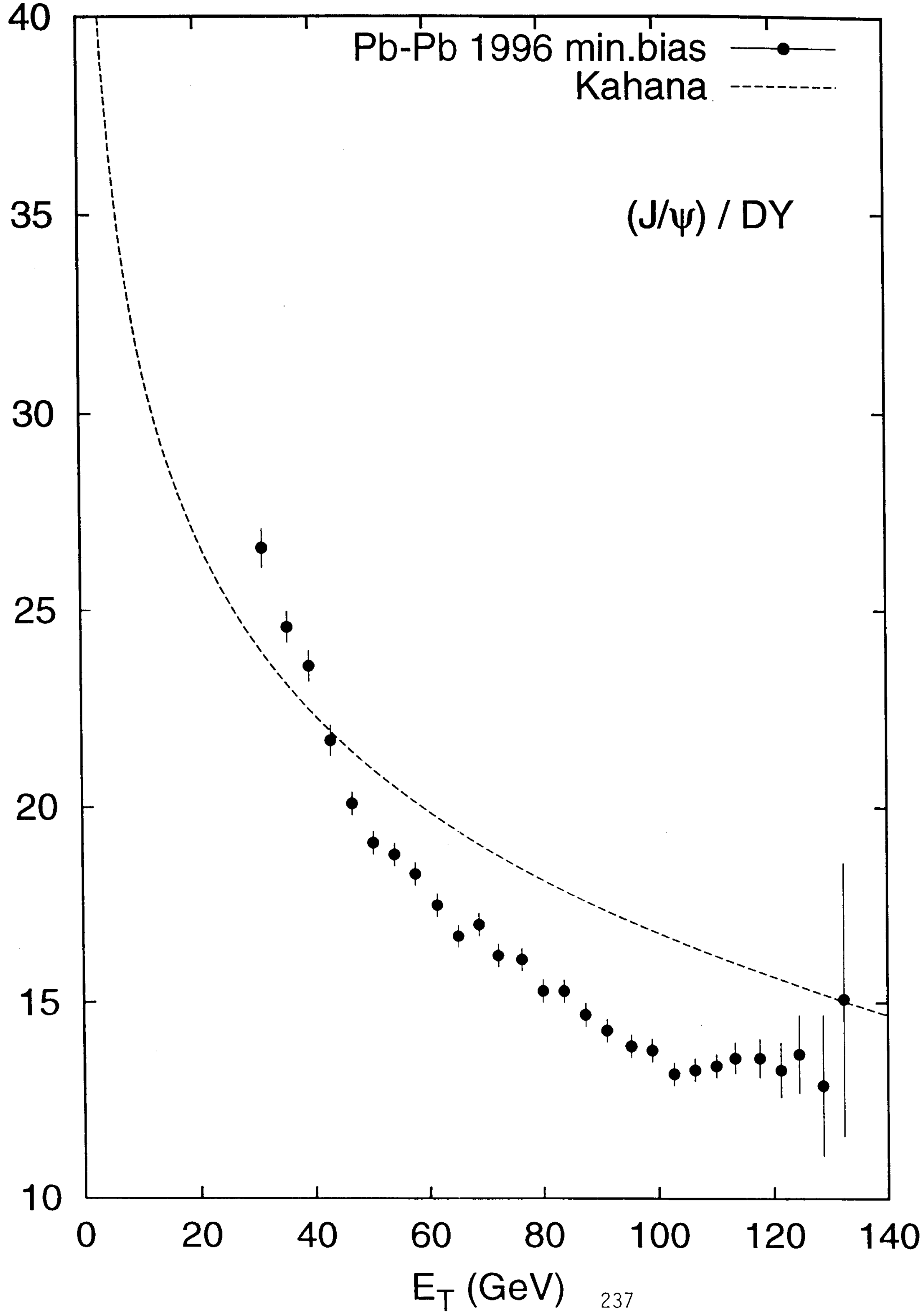
+ nuclear profile + E_T-b smearing

⟹





Pb-Pb 1996
Kahana
(J/ψ) / DY
40
35
30
25
20
15
10
0
20
40
60
80
100
120
140
E_T (GeV)


Pb-Pb 1996 min.bias
Kahana
(J/ψ) / DY
40
35
30
25
20
15
10
0
20
40
60
80
100
120
140
E_T (GeV)

– Some further questions:

- structure from

  <u>medium</u> $\varepsilon_{\psi'} < \varepsilon_{\chi} < \varepsilon_{\psi}$

  $\sim$ $\Delta E_{\psi'} < \Delta E_{\chi} < \Delta E_{\psi}$

  or

  <u>probe</u> $\tau_{\psi} < \tau_{\chi} < \tau_{\psi'}$? J.-W. Qiu

  needs further study; but:

  – exp't'l ψ' suppression first, in S-U ?

  – change at $E_T \simeq 40$ GeV re ψ,
    high E_T re χ ?

- high E_T & direct ψ suppression ?

  hot/cold regions ~ constant for $E_T \gtrsim 80$ GeV

  ∴ little variation

RHIC: ideal to check direct J/ψ suppression,
sharp onset?

- other observables:

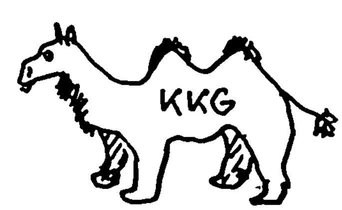
  $J/\psi \rightarrow$ minijet density

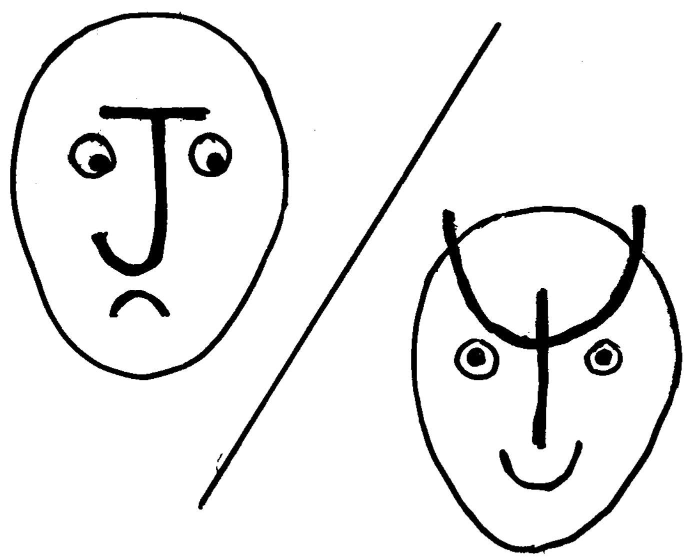
  soft hadrons: ↳ consistency check

M. Gyulassy

modified soft physics ?

camels?





WORKSHOP ON QUARKONIUM PRODUCTION IN RELATIVISTIC NUCLEAR COLLISIONS
SEPTEMBER 28 - OCTOBER 2, 1998
ORGANIZER: DMITRI KHARZEEV

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WORKSHOP ON QUARKONIUM PRODUCTION IN RELATIVISTIC NUCLEAR COLLISIONS
SEPTEMBER 28 - OCTOBER 2, 1998
ORGANIZER: DMITRI KHARZEEV

LIST OF REGISTERED PARTICIPANTS

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Quarkonium Production in Relativistic Nuclear Collisions

September 28 - October 2, 1998.

A RIKEN BNL Research Center Workshop

Scientific Program

Monday 28 September

8:30	- Registration	
9:30	N. Samios	*Welcome from the RIKEN-BNL Center*
	T. Kirk	*Welcome from BNL*
	T. Matsui	*Opening Talk* (50'+10')
10:50		Coffee break
11:00	E. Braaten	*Inclusive Quarkonium Production in High Energy Collisions* (50'+10')
12:00		Lunch
13:30	M. Leitch	*Vector Meson Production and Nuclear Effects in Fermilab E866* (45'+15')
	R.L. Thews	*Formation Time for Quarkonium from e+ e- Annihilation* (30'+10')
15:10		Coffee break
15:40	J. Kapusta	*Coherence Time in High Energy Proton-Nucleus Collisions* (30'+10')
	S. Peigne	*A New Mechanism for Quarkonium Production* (30'+10')
	K. Kourepin	*Precursor Phenomena in Particle Production by Relativistic Heavy Ion Collisions* (30'+10')
18:00		Welcome reception

Tuesday 29 September

9:30	M.Gonin	*New Results on Charmonium Production from NA50* (45'+25')
10:40		Coffee break
10:50	L. Ramello	*New Results on Intermediate Mass Dileptons from NA50* (30'+10')
	W. Zajc	*PHENIX Overview*(30'+10')
12:10		Lunch
13:30	A. Capella	*J/Psi and Drell-Yan E_t Distributions with Comovers* (30'+10')
	M. Nardi	*Charmonium Suppression and Percolation in Heavy Ion Collisions* (30'+10')
14:50		Coffee break
15:00	J. Huefner	*J/Psi-proton Cross Section from Photoproduction and ccbar-nucleon Cross Section in Nuclear Collisions*(30'+10')
	B. Kopeliovich	*Charmonium Break-up by Prompt Gluons in Heavy Ion Collisions* (30'+10')
16:20		Coffee break
16:30	C.-Y. Wong	*J/psi and Psi' Suppression in High Energy Pb-Pb Collisions* (30'+10')
	D. Blaschke	*Charmonium Dissociation and Anomalous J/Psi Suppression* (30'+10')

Wednesday 30 September

9:30	T. Hallman	*Comments on the Status of STAR Prospects for Detecting Heavy Flavor* (30'+10')

	Y. Akiba	*PHENIX Open Charm Measurements* (30'+10')
10:50		Coffee break
11:00	J. Qiu	*J/Psi Suppression in Nucleus-Nucleus Collisions* (30'+10')
	H. Fujii	*Low Energy Theorems for Charmonium Interactions* (30'+10')
12:20		Lunch
13:40	K. Seth	*J/Psi-Nucleon Cross Section - A review of the Experimental Situation* (45'+15')
16:30		Workshop party

Thursday 1 October

9:30	T. LeCompte	*Quarkonium Production at CDF* (30'+10')
	T. Ullrich	*Can STAR measure Quarkonium Production in Au Au Collisions?* (30'+10')
10:50		Coffee break
11:00	M. Rosati	*PHENIX J/Psi Measurements* (30'+10')
	A. Morsch	*ALICE Capabilities concerning Quarkonium Physics* (30'+10')
12:20		Lunch
13:40	R. Vogt	(to be confirmed) (30'+10')
	L. Gerland	*Color Fluctuation Phenomena in J/Psi Production in pA and AB Collisions* (30'+10')
15:00		Coffee break
15:10	M. Gyulassy	*Survival of Charmonium in Mini-Jet Bursts and Turbulent Glue* (30'+10')
	R. Mattiello	*Quarkonium Production in a Microscopic Transport Approach* (30'+10')
16:30		Coffee break
16:40	Contributed talks	

Friday 2 October

9:30	C. Lourenco	*J/Psi Suppression: an Experimental Overview* (50'+25')
10:45		Coffee break
11:00	A. Mueller	*QCD and Quarkonium* (50'+15')
12:05		Lunch
13:30	Discussion -	*"The Future of Quarkonium Physics"* (50')
14:20	H. Satz	*Summary* (50')

RIKEN BNL Center Workshops

Title: **Workshop on Physics of the 1 Teraflop**
Organizer: Robert Mawhinney
Dates: October 16, 1998

Title: **Quantum Fields In & Out of Equilibrium**
Organizers: D. Boyanovsky/H. deVega/R.D. Pisarski
Dates: Oct. 26–30, 1998

Title: **QCD Phase Transitions**
Organizers: T. Schaefer/E. Shuryak
Dates: Nov. 4–7, 1998

Title: **RIKEN Winter School: Structure of Hadrons**
Organizers: N. Saito/T.-A. Shibata/K. Yazaki
Dates: Dec. 9–12, 1998

Title: **Hard Parton Physics in High-Energy Nuclear Collisions**
Organizers: J. Carroll/R. Venugopalan/C. Gale/M. Tannenbaum
Dates: Mar. 1–5, 1999

Title: **Event Generator for RHIC Spin Physics**
Organizers: N. Saito/A. Schaefer
Dates: Mar. 1-31, 1999 (tentative)

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

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