Surprises and Anomalies in Heavy Quarkonium Production

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BNL Physics Department Colloquium
RBRC workshop on "Heavy Flavor Production and Hot/Dense Quark Matter"
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Outline

- QCD and Strong Interaction
- Heavy Quarkonium
- The November Revolution – the Discovery
- Production Models
- Supprises and Anomalies
- Heavy Quarkonium and RHIC physics
- Summary and Outlook

Quantum Chromodynamics (QCD)

- Known Fundamental Interactions:

  - "Strong" – QCD
  - Weak
  - Electromagnetic - QED
  - …
  - Gravity

  Weak + Electromagnetic: Electro – Weak

  "Strong" + Electro – Weak: Standard Model

- QCD – stands as a very solid building block of the SM:

  - Unbroken SU(3) color gauge symmetry
  - Asymptotic freedom at high energy
  - Success of QCD perturbation theory
  - Nonperturbative results from Lattice calculations
  - …

QCD as a field theory

- **Fields:**

$$\psi_i^f(x)$$

Quark fields, Dirac fermions (like *electron*)
Color triplet: $i = 1,2,3 = N_C$
Flavor: $f = u,d,s,c,b,t$

$$A_{\mu,a}(x)$$

Gluon fields, spin-1 vector field (like *photon*)
Color octet: $a = 1,2,\ldots,8 = N_C^2 - 1$

- **Lagrangian density:**

$$L_{QCD}(\psi, A) = \sum_f \overline{\psi}_i^f \left[\left(i\partial_\mu - gA_{\mu,a} (t_a)_{ij} \right) \gamma^\mu - m_f \right] \psi_i^f$$
$$- \frac{1}{4} \left[\partial_\mu A_{\nu,a} - \partial_\nu A_{\mu,a} - gC_{abc} A_{\mu,b} A_{\nu,c} \right]^2$$

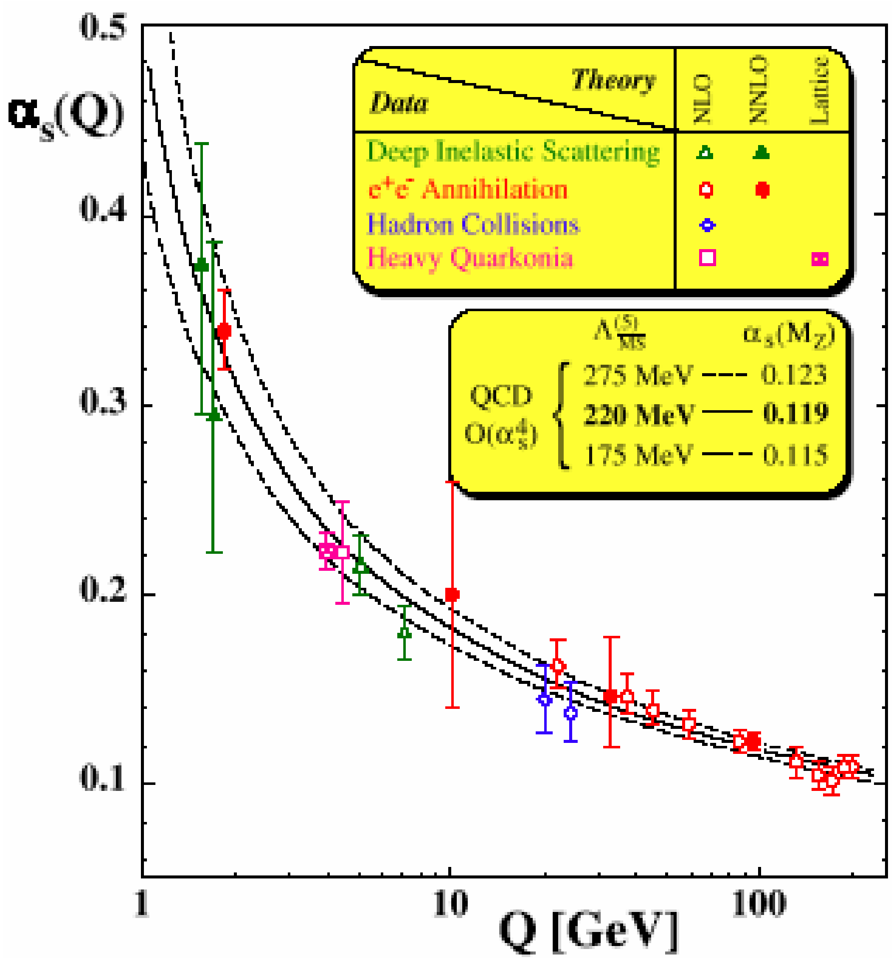
+ gauge fixing + ghost terms

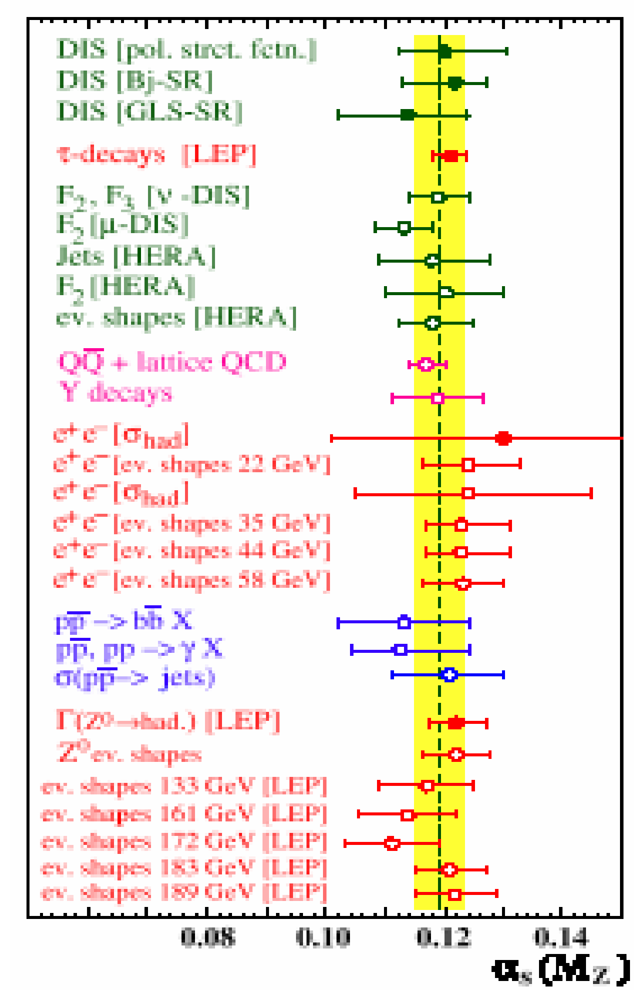
Color matrix: $$[t_a, t_b] = iC_{abc} t_c$$

Asymptotic Freedom

$$\alpha_s(\mu_2) = \frac{\alpha_s(\mu_1)}{1 - \frac{\beta_1}{4\pi}\alpha_s(\mu_1)\ell n\left(\frac{\mu_2^2}{\mu_1^2}\right)} \equiv \frac{4\pi}{-\beta_1 \ell n\left(\frac{\mu_2^2}{\Lambda_{QCD}^2}\right)} \Rightarrow 0 \text{ as } \mu_2 \to \infty$$

CTEQ website





Effective quark mass

❑ Running quark mass:

$$m(\mu_2) = m(\mu_1)\ \exp\left[-\int_{\mu_1}^{\mu_2} \frac{d\lambda}{\lambda}\left[1+\gamma_m(g(\lambda))\right]\right] \Rightarrow\ 0\ \text{ as } \mu_2 \to \infty$$

Perturbation theory becomes a massless theory when $\mu \to \infty$

❖ **for light quarks, *u* and *d*, even *s*,** $m_{u\ \text{and}\ d}(\mu) \ll \Lambda_{\text{QCD}}$

QCD perturbation theory is effectively a massless theory

❑ Infrared safety:

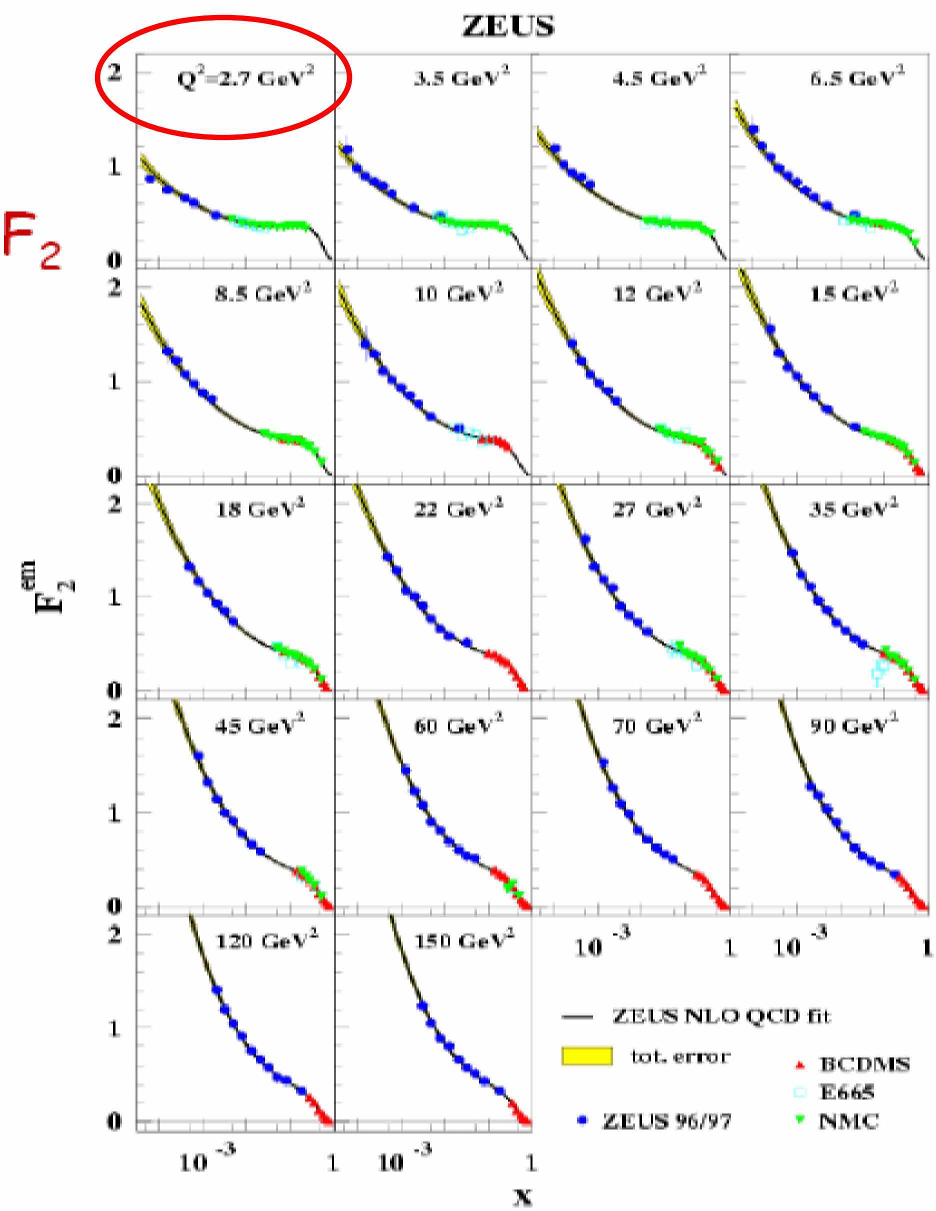
$$\sigma_{\text{phy}}\left(\frac{Q^2}{\mu^2}, \alpha_s(\mu^2), \frac{m^2(\mu^2)}{\mu^2}\right) \Rightarrow \hat{\sigma}\left(\frac{Q^2}{\mu^2}, \alpha_s(\mu^2)\right) + O\left[\left(\frac{m^2(\mu^2)}{\mu^2}\right)^{\kappa}\right]$$

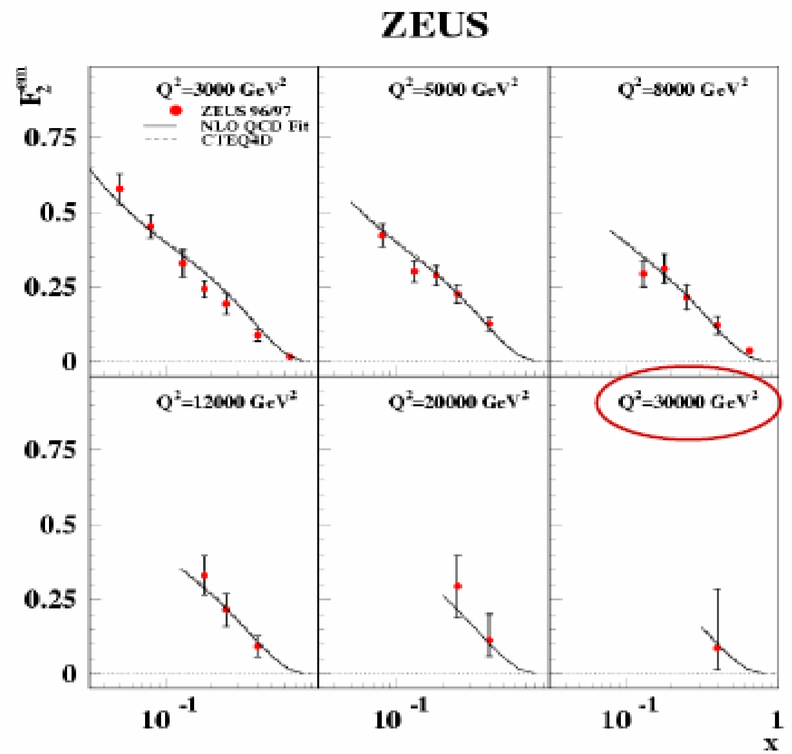
Infrared safe = $\kappa > 0$

Asymptotic freedom is useful for quantities that are infrared safe

Structure function in lepton-hadron DIS

F_2



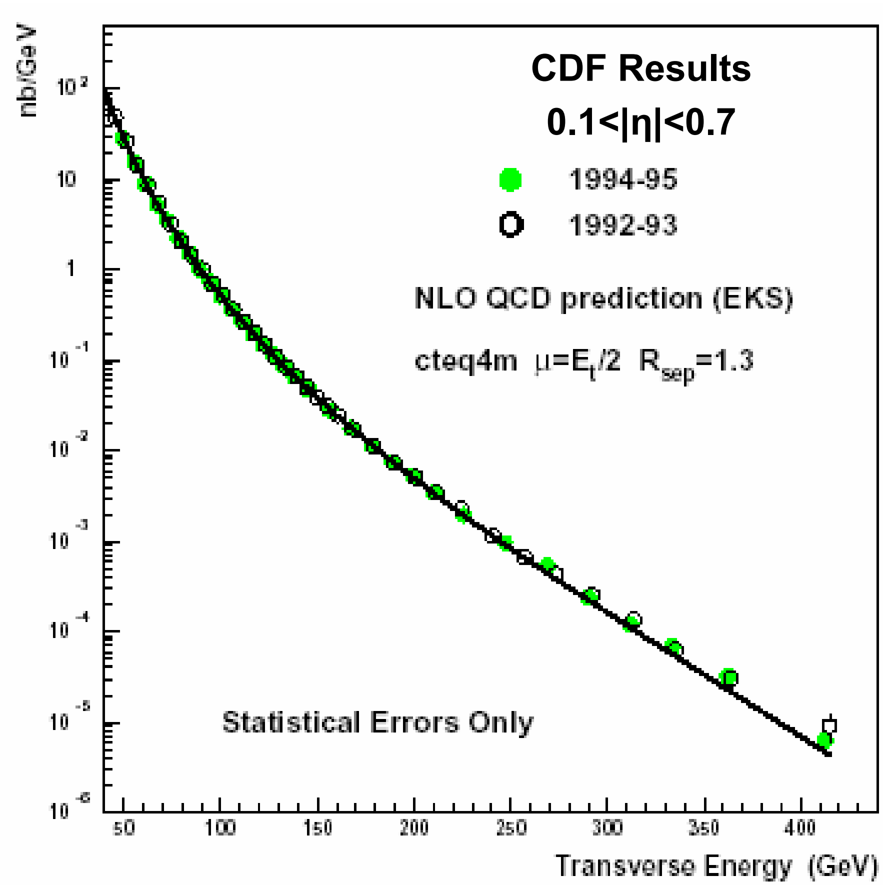


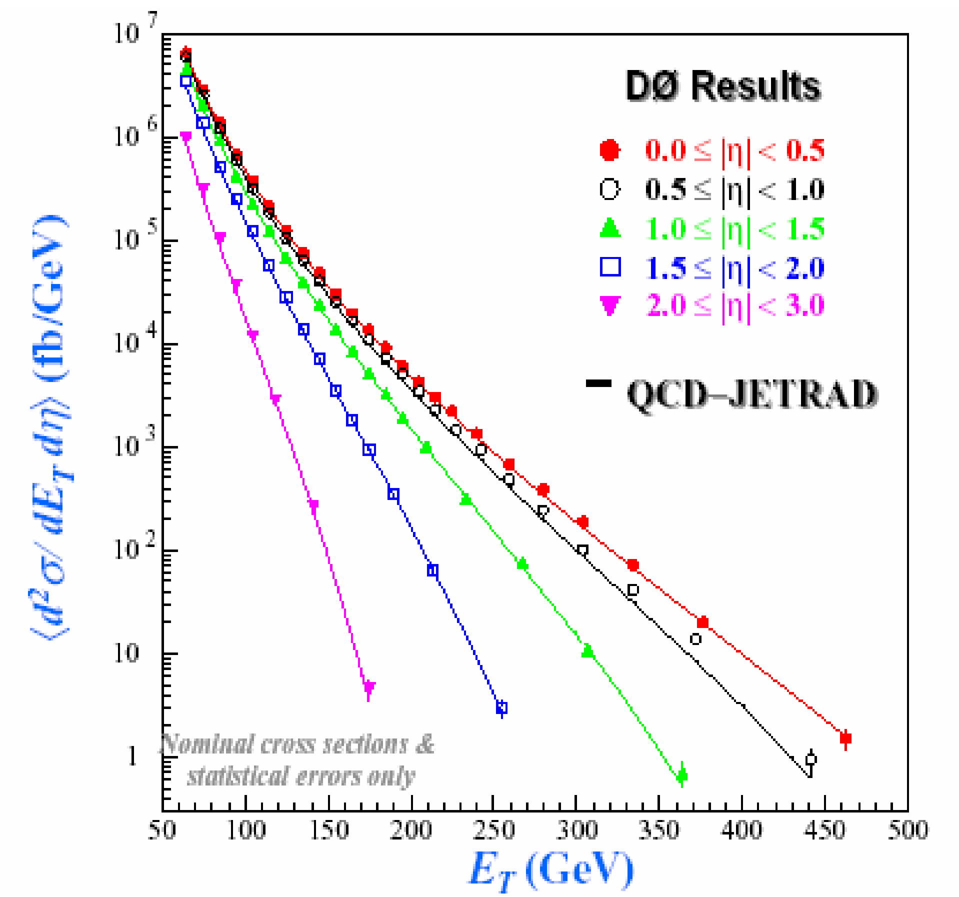
At high-Q^2 still statistics limited… → priority to the measurements at high-Q^2

CTEQ website

Inclusive jet cross section at Tevatron

Run – 1b results





Data and Predictions span 7 orders of magnitude!

CTEQ website

What happens when strong interaction is strong and nonperturbative?

Lattice QCD is doing all it can do and is making steady progress

Heavy quark system could offer some important perspectives to the formation of QCD bound states

Heavy quarks

❑ **Quark masses:**

Flavor	Mass
u	$1.5 - 4.5$ MeV
d	$5.0 - 8.5$ MeV
s	$80 - 155$ MeV
c	$1.0 - 1.4$ GeV
b	$4.0 - 4.5$ GeV
t	174.3 ± 5.1 GeV

Quark masses span a wide kinematical range:

$$\frac{m_t}{m_u} \sim 10^4$$

Light quarks

Λ_{QCD}

Heavy quarks $\qquad \alpha_s\left(m_Q\right) \ll 1$

❑ **Production of heavy quark pairs is likely a perturbative process**

$$\sqrt{\hat{s}} > 2m_Q > 2 \text{ GeV}$$

No free quarks floating around

- QCD color confinement

  ⟹ Mesons and baryons in the detectors

❖ Charmed mesons: $D^+ = c\bar{d},\ D^0 = c\bar{u},\ \bar{D}^0 = \bar{c}u,\ D^- = \bar{c}d,\ \ldots$

❖ Charmed, strange mesons: $D_s^+ = c\bar{s},\ D_s^- = \bar{c}s,\ \ldots$

❖ Bottom mesons: $B^+ = u\bar{b},\ B^0 = d\bar{b},\ \bar{B}^0 = \bar{d}b,\ B^- = \bar{u}b,\ \ldots$

Heavy-light system: heavy quark symmetry ⟹ HQET

❖ Bottom, charmed mesons: $B_c^+ = c\bar{b},\ B_c^- = \bar{c}b,\ \ldots$

❖ $c\bar{c}$ mesons: $J/\psi,\ \chi_c,\ \psi',\ \ldots$

❖ $b\bar{b}$ mesons: $\Upsilon,\ \chi_b,\ \ldots$

Heavy-heavy system: ⟹ NRQCD

Nonperturbative physics is always involved in charm and bottom quark production

Top quark is a better heavy quark

- Charm and bottom quarks decay slowly and leave enough time to form charm and bottom mesons

m_c and $m_b \ll M_W$ Charm and bottom decay via a virtual W into light $q\bar{q}$ or $\ell\bar{\nu}$

⇒ Semi-leptonic decay width: $\Gamma \sim 10^{-10}$ MeV

- Top quark decays very fast, likely before any top meson can be formed

$m_t > M_W + m_b$

$t \rightarrow W^+ + b$

$\quad \hookrightarrow \ell^+ + \nu$ (or $q + \bar{q}$)

$$\Gamma(t \to W^+ b) \approx \frac{G_F m_t^3}{8\pi\sqrt{2}} |V_{tb}|^2$$

$$\approx 1.76 \text{ GeV} \left[\frac{m_t}{175\text{GeV}}\right]^3$$

Top quark should be a better candidate for studying heavy quark production, and heavy quark properties

Hidden heavy flavors - Quarkonia

- **Heavy quark pairs are produced locally:**

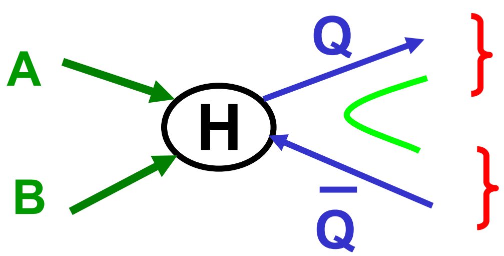
$$\Delta r \sim \frac{1}{2m_Q} \le 0.1\ \text{fm} \quad \text{(for a charm-quark pair)}$$

$$\le 0.025\ \text{fm} \quad \text{(for a b-quark pair)}$$

Heavy quark pairs are produced at a distance scale much less than fm

A heavy quark pair needs to be coherently self-interacted and expanded before a heavy quarkonium can be formed

- **A heavy quark pair is likely to become two open flavor heavy mesons if the invariant mass of the pair is larger than the total mass of the two mesons:**

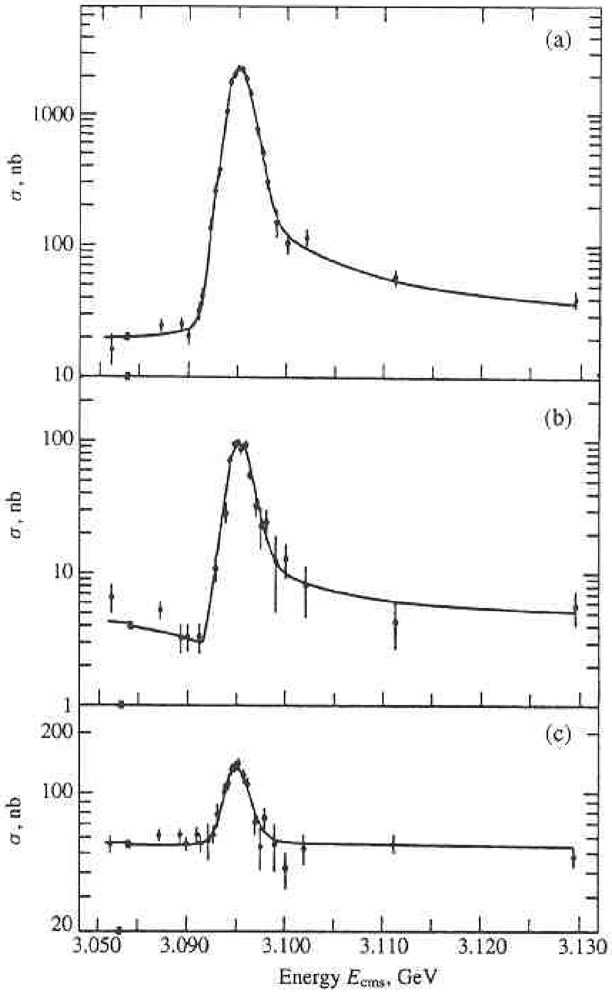


meson

antimeson

Open flavor threshold for the quarkonium production

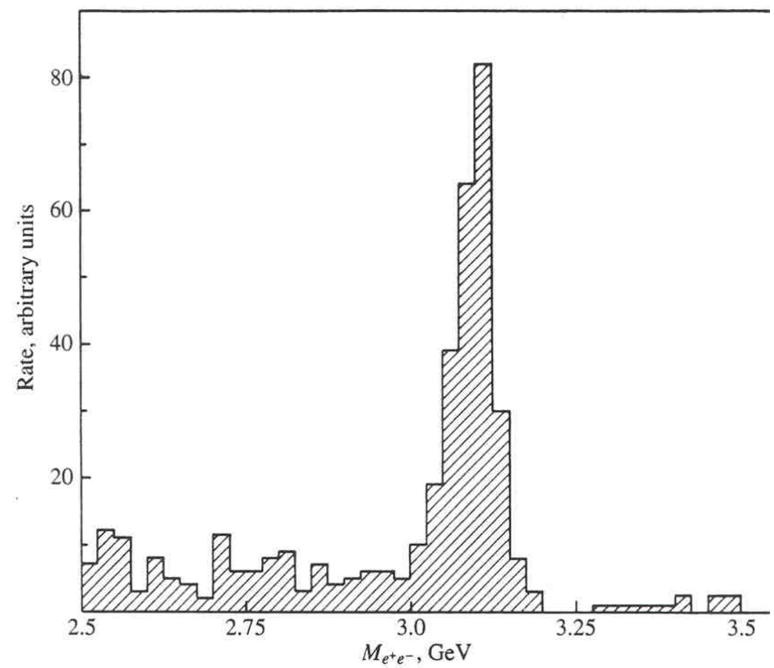
Discovery of the J/ψ



e^+e^- annihilation at SPEAR

- **Near simultaneous discovery**
  - **Ting et al. at BNL AGS**
  - **Richter et al. at SLAC SPEAR**
- **Quarks were no longer mathematical objects, but particles that moved in a potential**

1976 Nobel prize in physics



$p + Be \rightarrow e^+e^- + X$ at AGS

The November Revolution

"… the discoveries of November 1974 were not just additions to our knowledge of Nature. Instead they signaled a change in our understanding of the structure of matter." – F. Gilman (11/84)

"The November revolution just set everything in motion toward the standard model that we have now." – J.D. Bjorken (11/84)

"It may be as surprising as in 1974, when 3 GeV in the center of mass for e+e- was sufficient, and when an unfashionable experiment at <u>an old, antique laboratory like Brookhaven</u> was a big key to opening up the future." – J.D. Bjorken (11/84)

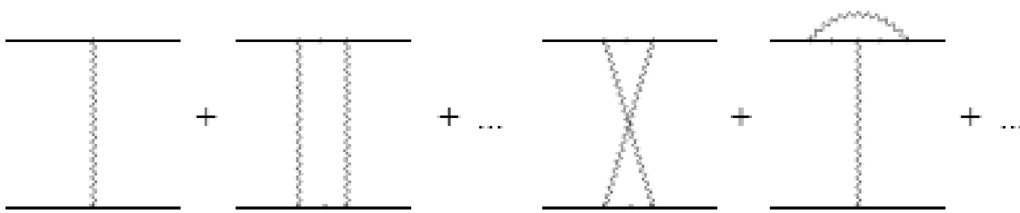
New experiments at <u>this old, antique laboratory like Brookhaven</u> are playing another big key role to opening up the future

Non-relativistic bound states

- **Heavy quarkonium provides a non-relativistic system, potentially very similar to a QED bound state**

Charm: $\frac{v^2}{c^2} \sim \frac{k_Q^2}{m_Q^2} \sim \frac{M^2 - 4m_c^2}{4m_c^2} \sim 0.3$ **Bottom:** $\frac{v^2}{c^2} \sim 0.1$

- **Example: positronium – an e+e- bound state**

V = 

$$\underbrace{\alpha\left(1 + \frac{\alpha}{v} + \ldots\right)}_{\text{Coulomb resummation}}$$

➡ Schrödinger equation $\left(\frac{p^2}{2m} + V\right)\phi = E\phi$

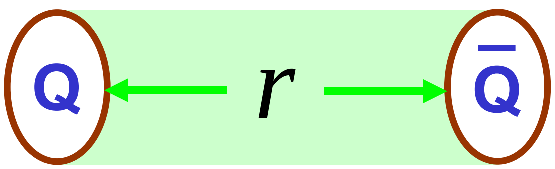
Quarkonium Potential

A OK model of the quark-antiquark potential:

$$V_{Q\bar{Q}}(r) = \frac{A}{r} + Br$$

A spring-like part

A Coulomb-like part



This piece comes from the non-Abelian nature of QCD: the fact that you have 3-gluon and 4-gluon couplings.

In QED, there is no gg coupling, so this term is absent

This is a simple potential model, and there are MUCH better potential models

All models use the quarkonia spectra to fit their parameters, and reasonably successful

Modern Technique: Effective Field Theory - NRQCD

Bodwin's talk tomorrow

Heavy quarkonium production

- Quarkonium has **two** intrinsic scales:

Heavy quark mass:

$$m_Q > \mathrm{GeV} \quad \Rightarrow \quad \alpha_s\left(2m_Q\right) < 0.3$$

A perturbative scale

Heavy quark binding:

$$M_{J/\psi} - 2m_c \sim fm^{-1} \quad \Rightarrow \quad \alpha_s\left(fm^{-1}\right) > 1$$

A non-perturbative scale

Flavor	Mass
u	$1.5 - 4.5$ MeV
d	$5.0 - 8.5$ MeV
s	$80 - 155$ MeV
c	$1.0 - 1.4$ GeV
b	$4.0 - 4.5$ GeV
t	174.3 ± 5.1 GeV

- Non-perturbative physics in "production" is different from "decay"

A heavy quark pair with invariant mass less than the threshold of a pair of open flavor mesons will become a bound quarkonium

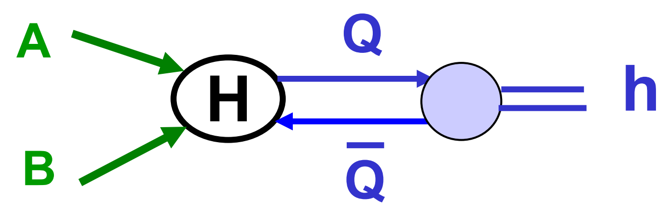
Charm: $$\frac{v^2}{c^2} \sim \frac{k_Q^2}{m_Q^2} \sim \frac{M_D^2 - m_c^2}{m_c^2} \sim 0.8 > 0.3$$

Bottom: $$\frac{v^2}{c^2} \sim 0.4 > 0.1$$

Depend on choice of heavy quark mass

Production of Quarkonia

- Quarkonium production:



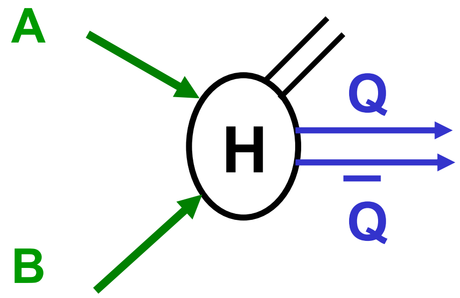
$$\sigma_{AB\to h} = \sum_{states} \int dm_{Q\bar{Q}}^2 \frac{d\sigma_{AB\to states(Q\bar{Q})}}{dm_{Q\bar{Q}}^2} \otimes F_{states(Q\bar{Q})\to h}\left(m_{Q\bar{Q}}^2\right)$$

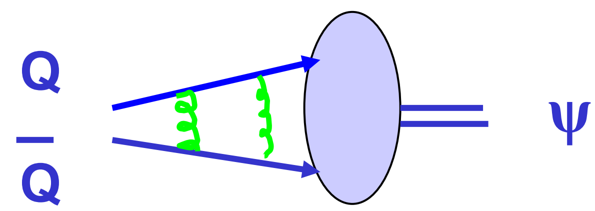
With $m_{Q\bar{Q}}^2$ not too much larger than mass of two heavy flavor mesons

- Production models:

Different assumptions on the non-perturbative transition from the *QQ* pair to a quarkonium lead to different production models

Color singlet model





Einhorn and Ellis (1975), …

- ❖ color singlet pair
- ❖ right quantum numbers for the quarkonium
- ❖ same wave function for production and decay

$$\sigma_{AB\to\psi} \propto \sigma_{AB\to(Q\bar{Q})} \left|R_\psi(0)\right|^2$$

- ❖ absolutely normalized predictions
- ❖ predictions on polarization
- ❖ quantum interference between production and formation suppressed

Works well for J/ψ production in photo-production and others

Inelastic photoproduction of J/ψ and Υ by gluons

Edmond L. Berger and D. Jones
High Energy Physics Division, Argonne National Laboratory, Argonne, Illinois 60439
(Received 17 November 1980)

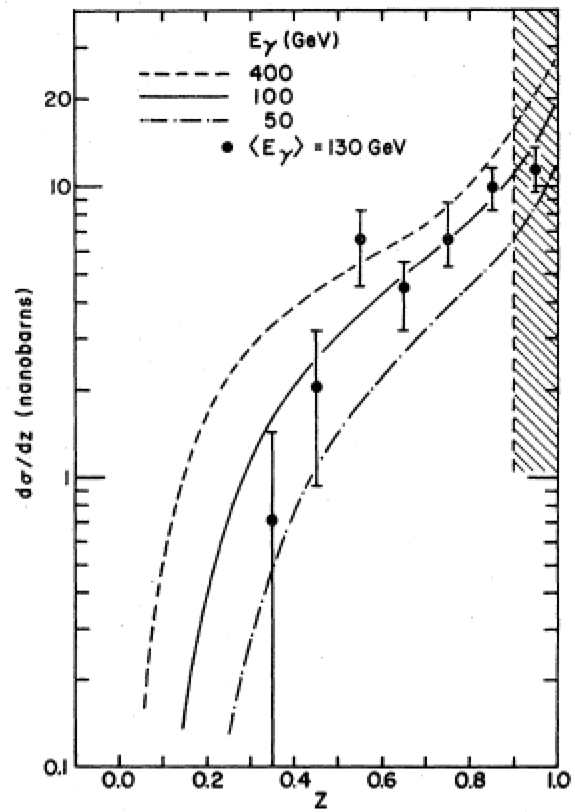


FIG. 5. The distribution $d\sigma/dz$ is predicted for $E_\gamma = 50$, 100, and 400 GeV. The region $z > 0.9$ is excluded from the range of validity of the model. Data points are from the CERN-EMC collaboration (Ref. 10) for the process $\mu N \to \mu'(J/\psi)X$ at $\langle Q^2\rangle \cong 4\ \mathrm{GeV}^2$ and $\langle E_\gamma\rangle \simeq 130$ GeV. The data are plotted with arbitrary normalization relative to our normalized predictions.

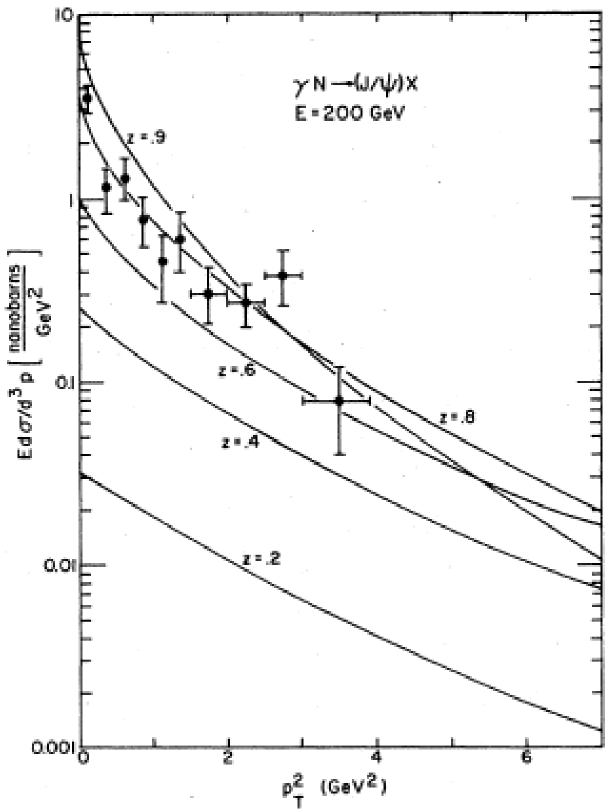
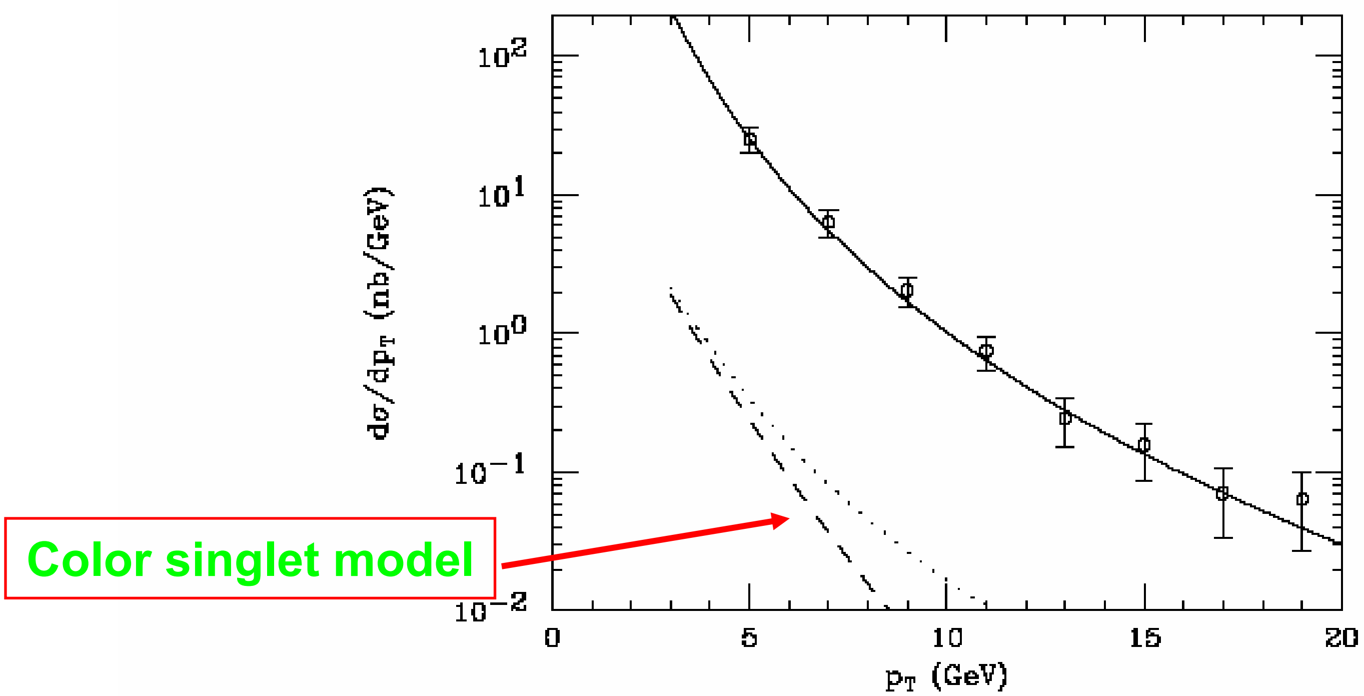


FIG. 7. The inclusive yield $E\,d\sigma/d^3p$ vs $p_T^{\,2}$ at $E_\gamma = 200$ GeV for five values of z. Data from Ref. 10 for inelastic J/ψ production are also shown. Normalization of these data relative to the theory curves is arbitrary. The data cover the range $z > 0.3$ but are concentrated primarily at large z.

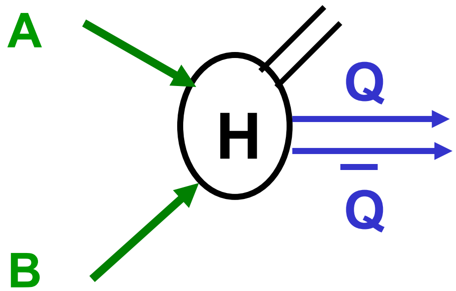
Surprises

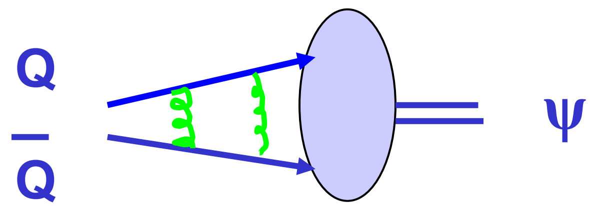
- ❖ **Fails to explain quarkonium total cross section**
- ❖ **Fails to explain the Tevatron pT distribution**
- ❖ **…**

- Prompt ψ' as a function of p_T:



Color Evaporation Model





Fritsch (1978); Halzen; …

- all pairs with invariant mass less than open flavor threshold
- color and spin average

- one constant for non-perturbative formation
- one constant for each quarkonium state

$$\sigma_{AB\to\psi} = f_\psi \int dm^2_{Q\bar{Q}} \frac{d\sigma_{AB\to(Q\bar{Q})}}{dm^2_{Q\bar{Q}}}$$

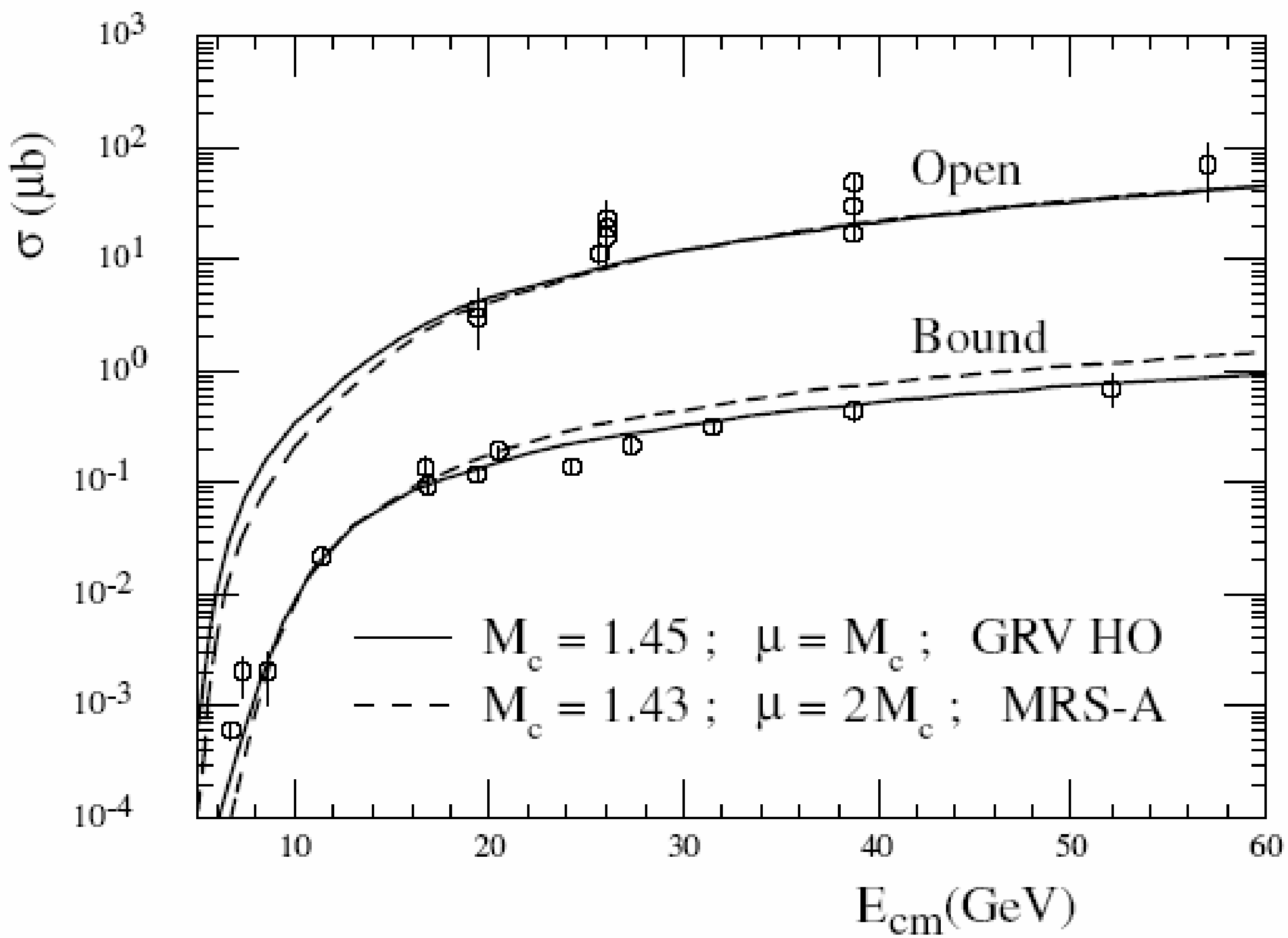
Works well for total cross sections, not perfect for distributions

Predicts zero polarization for quarkonium production

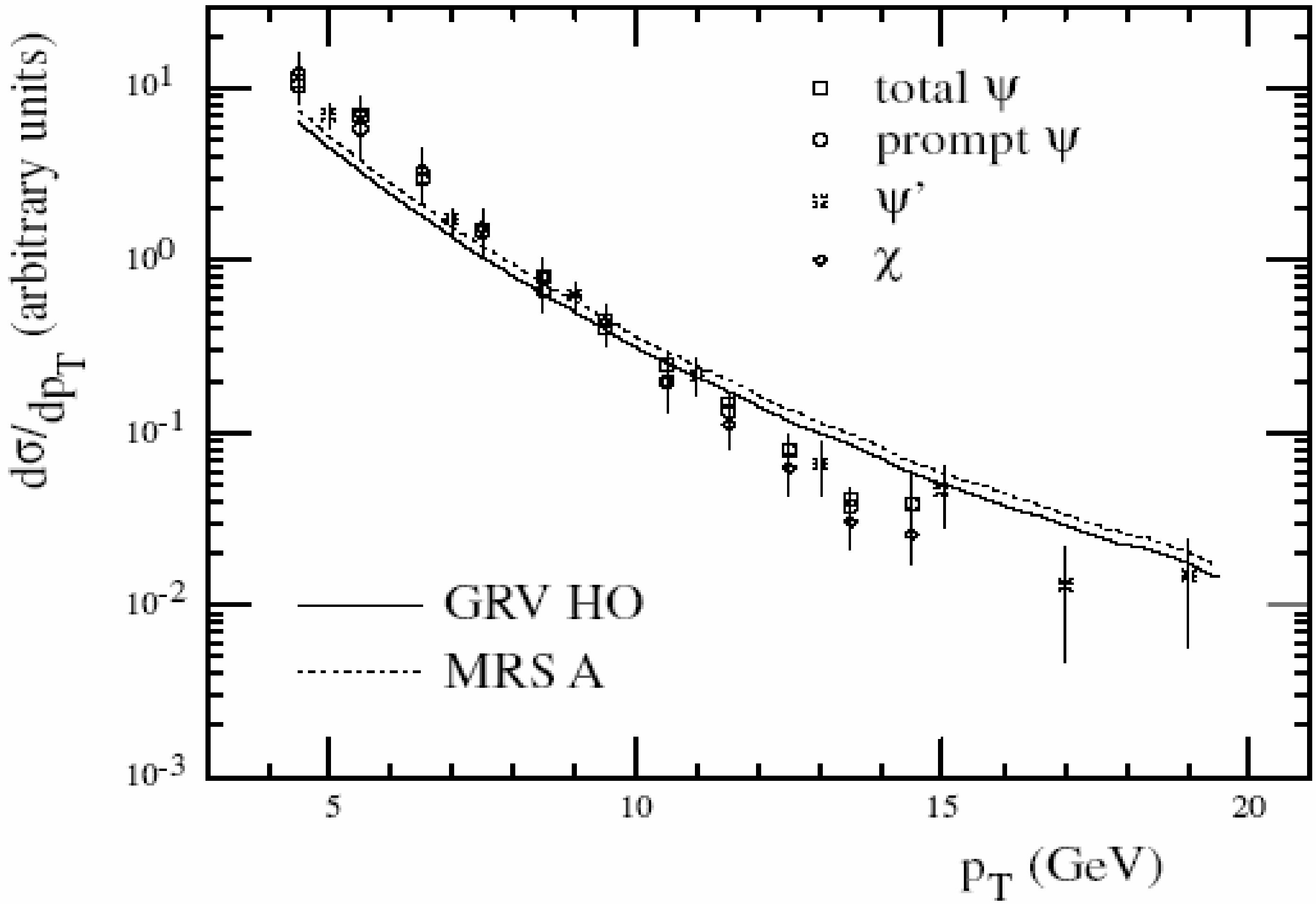
Color evaporation model vs data

- Charm hadroproduction as a function of collision energy

Hard Probe Writeup



- Charmonia production as a function of p_T:



J.F. Amundson et al. Phys. Lett. B390, 323 (1997)

Non-relativistic QCD (NRQCD) model

Bodwin, Braaten, Lapage (1985); …

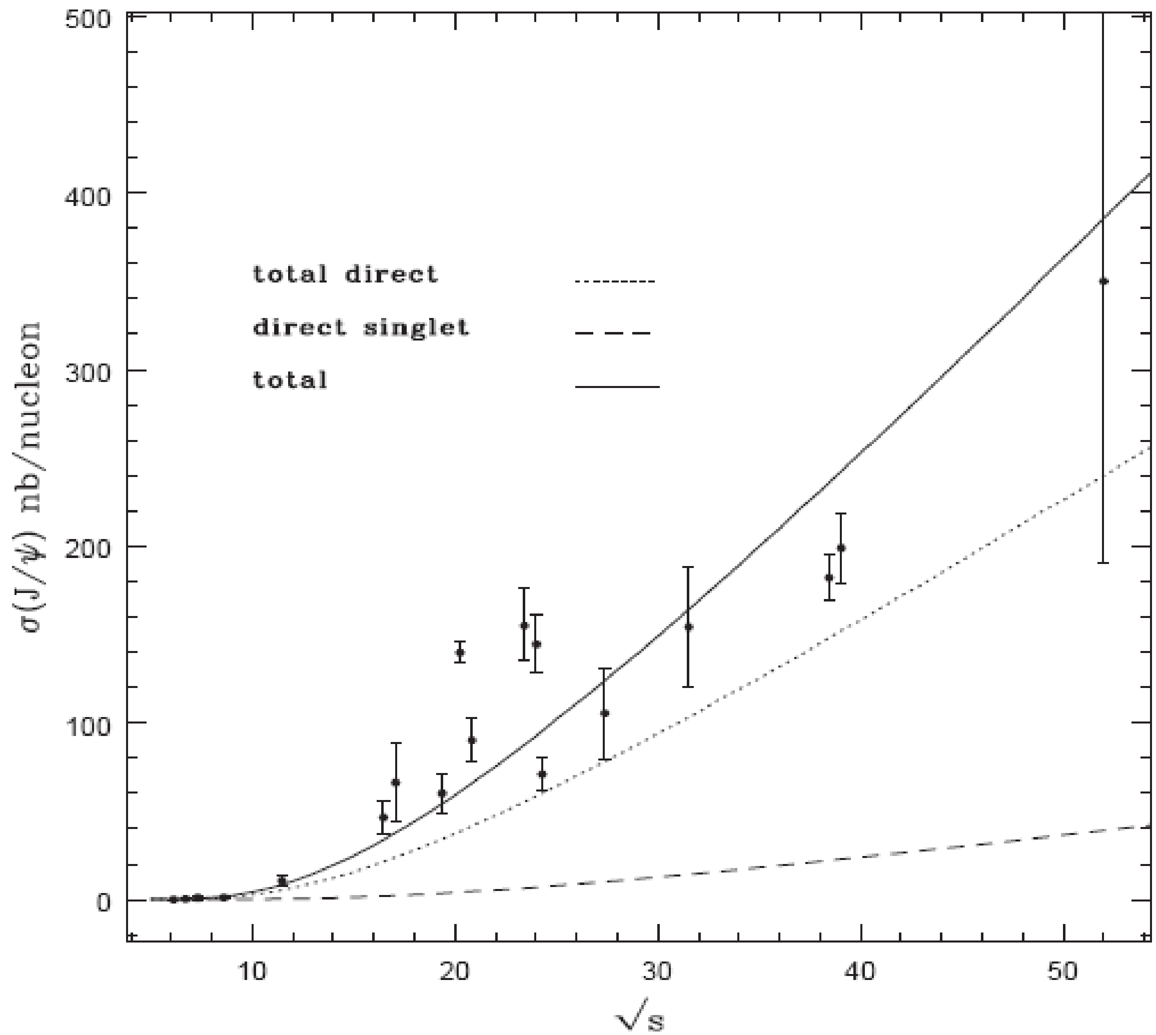
- All colored and uncolored pre-J/ψ partonic states can become color-singlet J/ψ mesons
- Transition probabilities are proportional to non-perturbative local matrix elements
- Factorized cross section:

$$\sigma_{AB\to J/\psi}\left(M_{J/\psi}\right) \approx \sum_{[O]} \sigma_{AB\to[O]}\left(m_{c\bar{c}}^2 = M_{J/\psi}\right)\left\langle O_{J/\psi}(0)\right\rangle$$

- Approximation: $k_i \ll m_{c\bar{c}}$ (velocity expansion)
- **Quantum states [*O*] separated by spin and color**

NRQCD vs total cross section

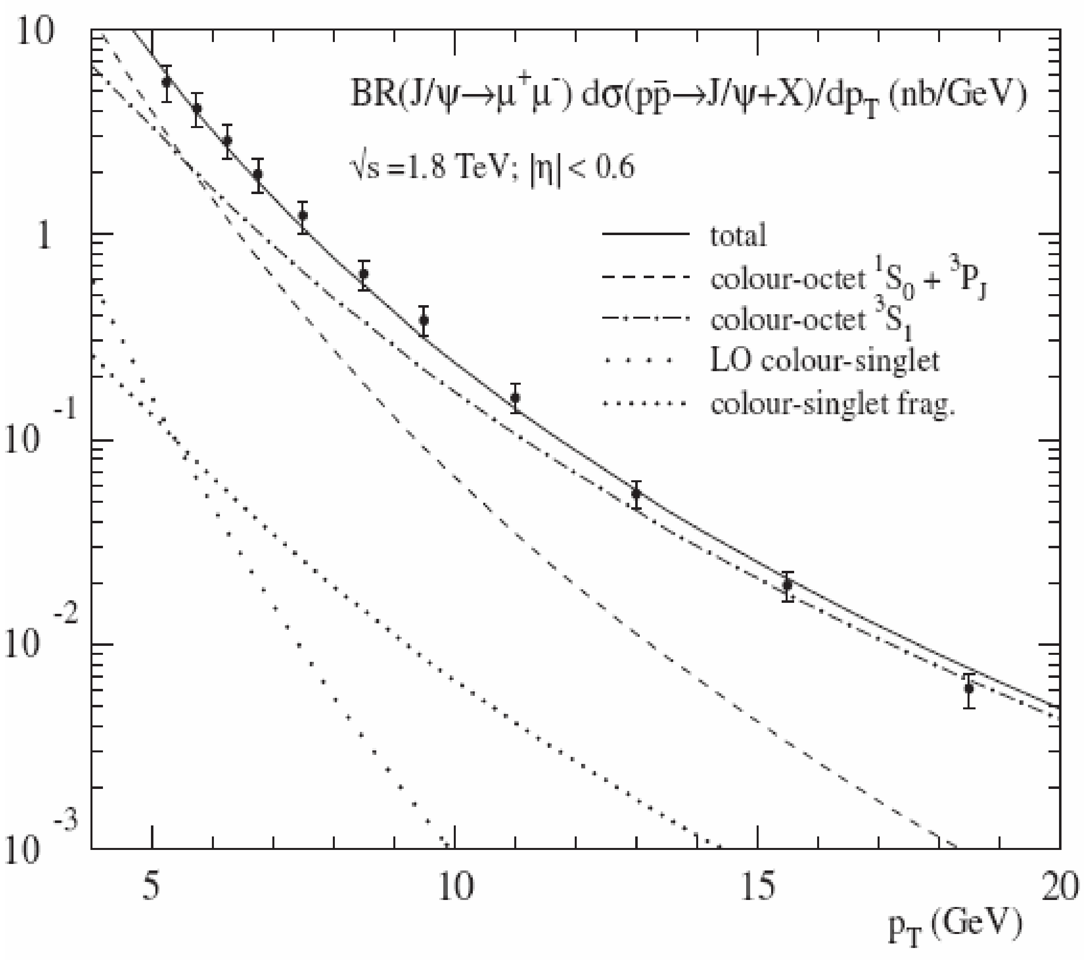
J/ψ production with $x_F > 0$ in pN collisions



Bodwin's talk

NRQCD model vs CDF data

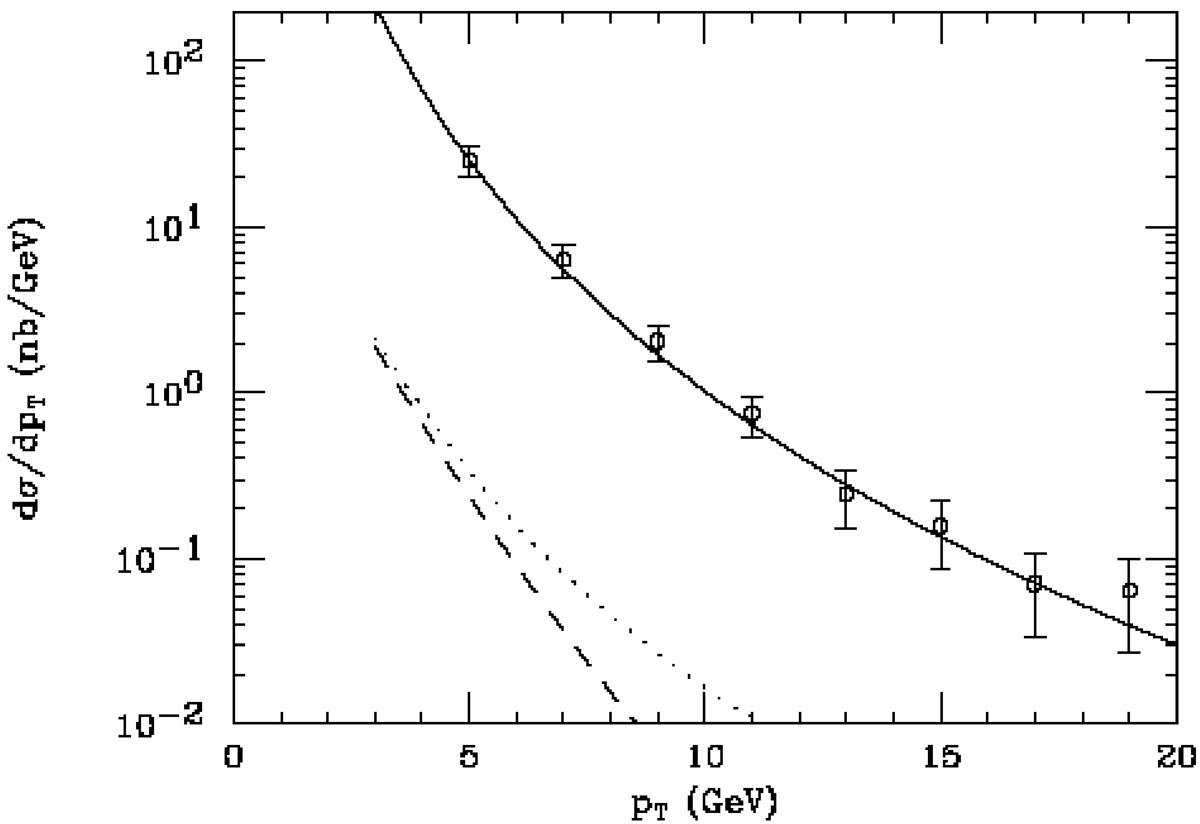
- Tevatron data for J/ψ, ψ', Υ production



- Data are more than an order of magnitude larger than the predictions of the color-singlet model.
- Color-octet matrix elements are determined from fits to the data.
- p_T distributions are consistent with NRQCD, but not with the color-singlet model.

Bodwin's talk

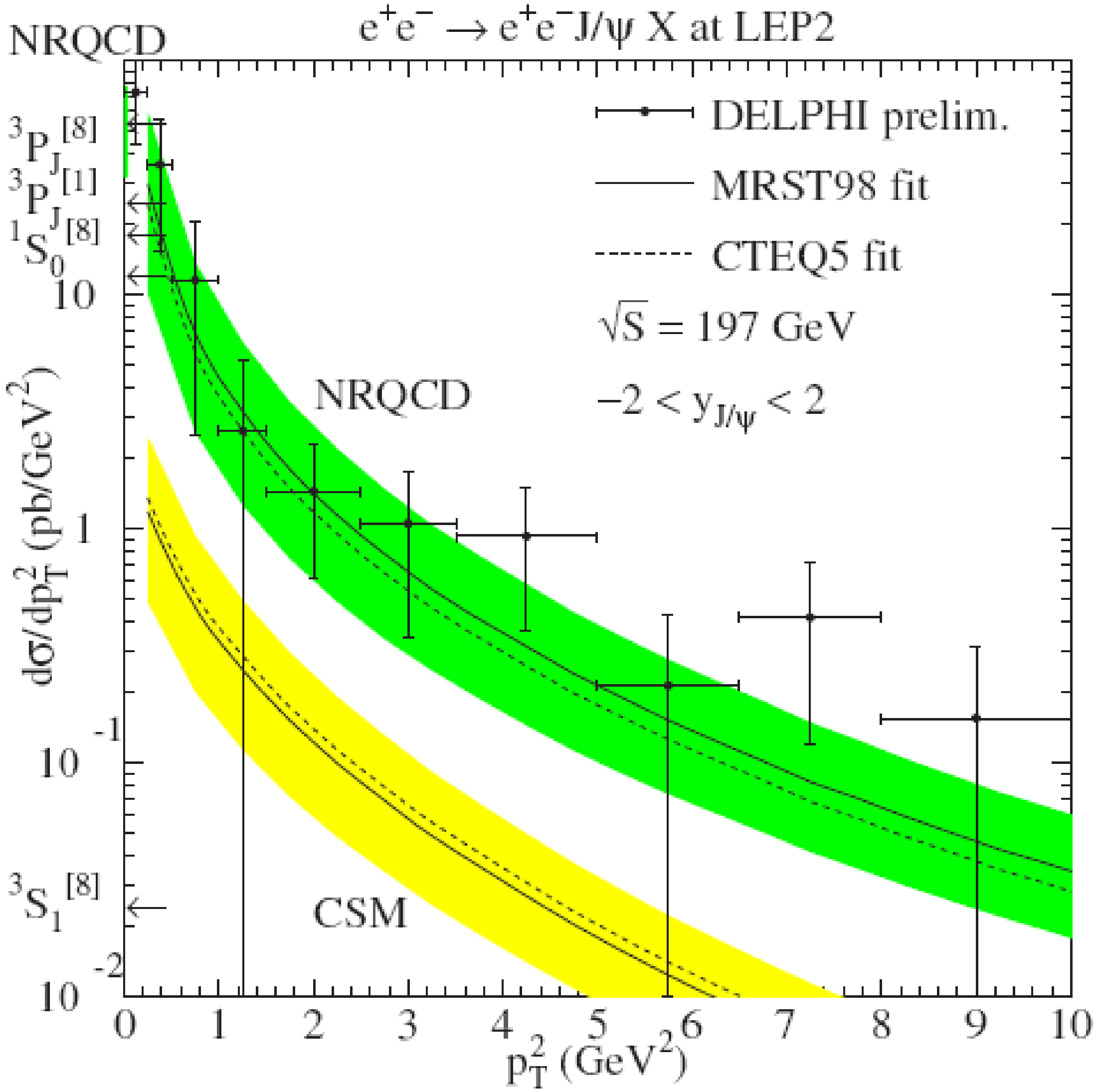
- Prompt ψ' as a function of p_T:



E. Braaten et al. Annu. Rev. Nucl. Part. Sci. 46, 197 (1996)

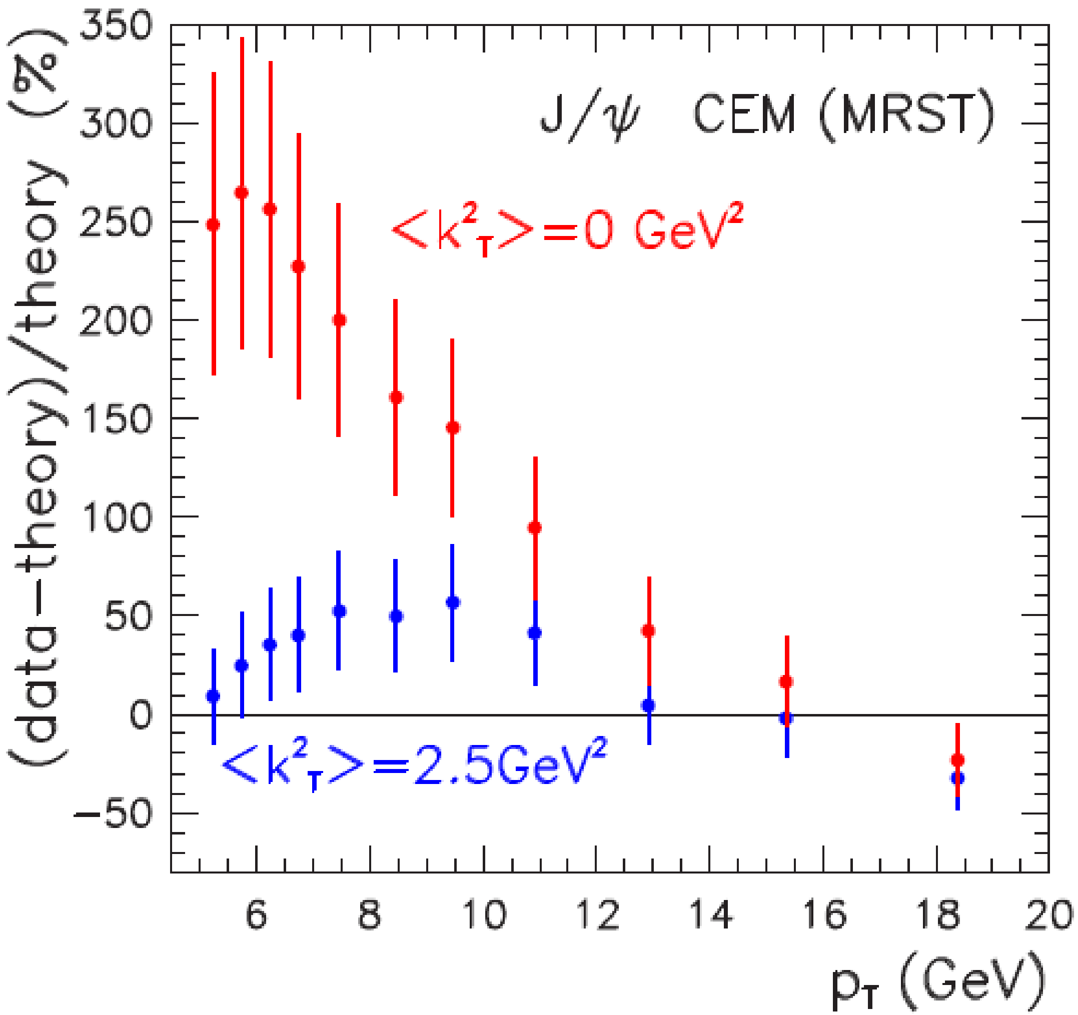
NRQCD model vs LEP data

$\gamma\gamma \to J/\psi + X$ at LEP



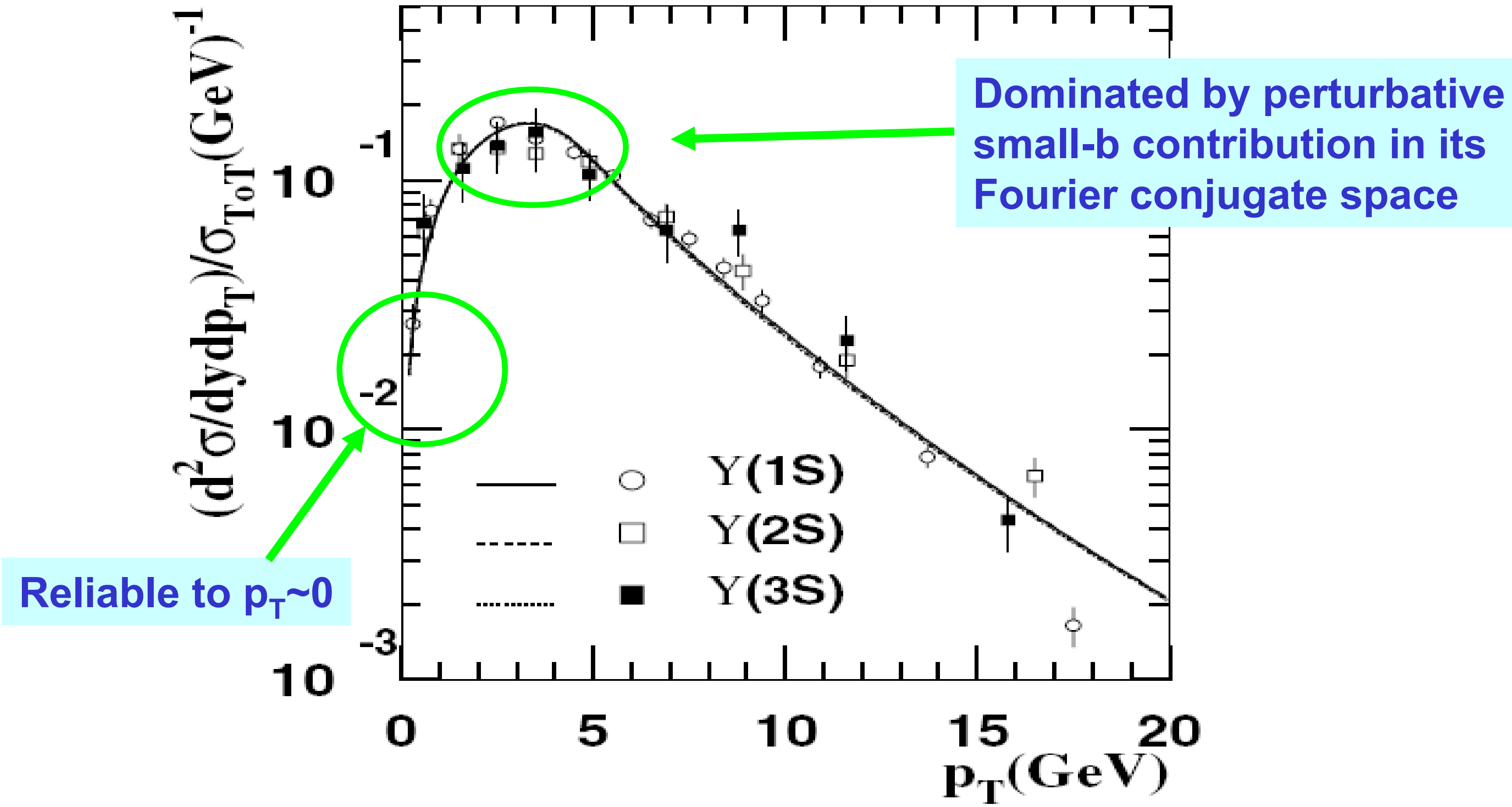
QWG's report

❑ Including k_T smearing, CEM improves its fit to CDF data



R. Vogt; Bodwin et al. PRD 2005

CDF Run – I Upsilon data

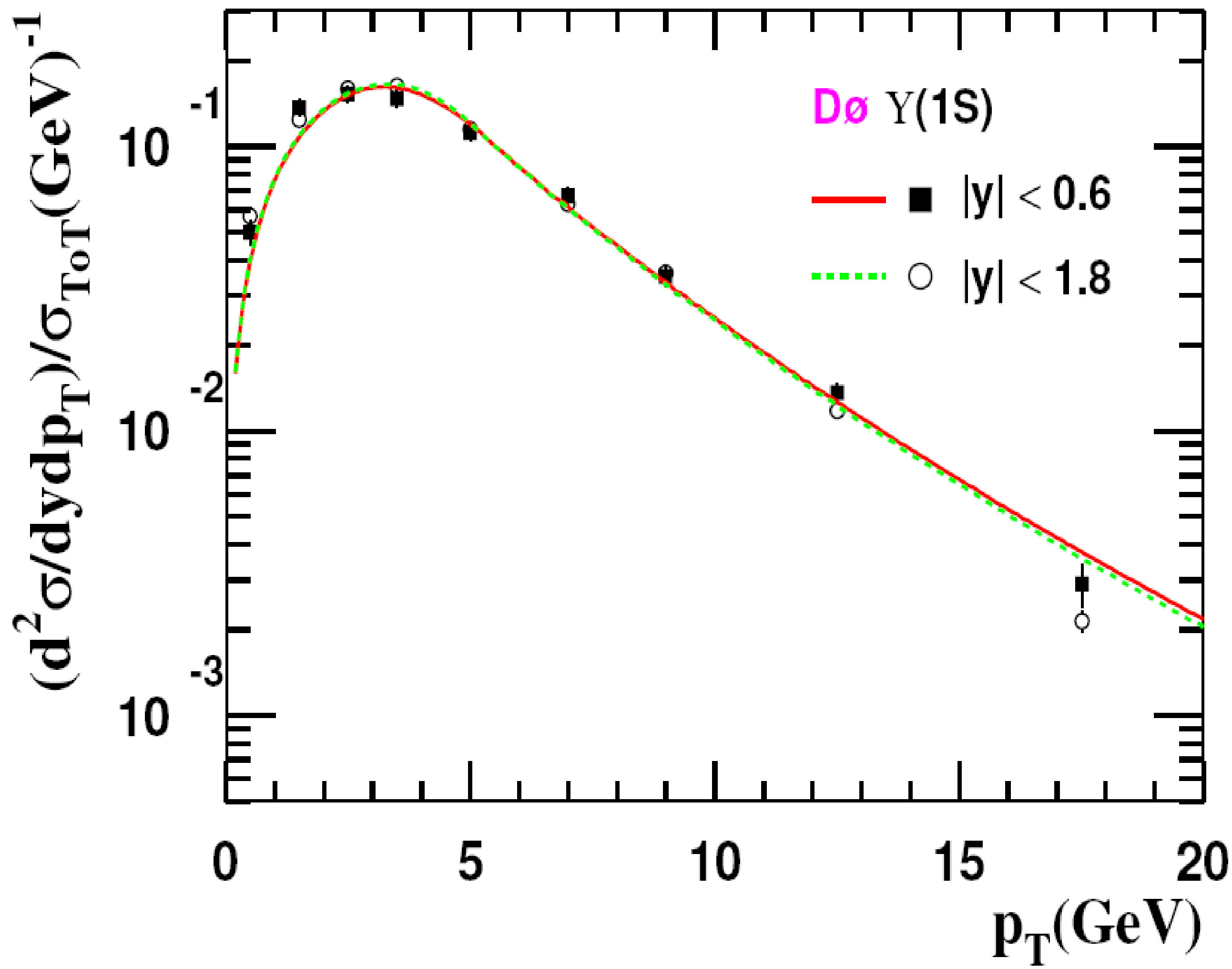


With all order resummation of soft gluon shower

Berger, Qiu, Wang

D0 Run – II Upsilon data

(a prediction)

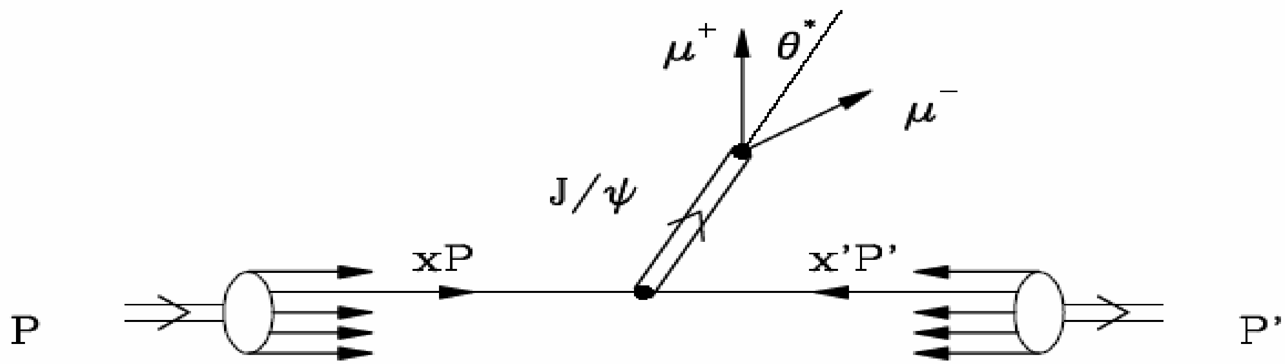


Berger, Qiu, Wang

Polarization of Quarkonium at the Tevatron

Potentially a “smoking gun” for the Color-Octet Mechanism

- Measure angular distribution of $\mu^+\mu^-$ in J/ψ decay

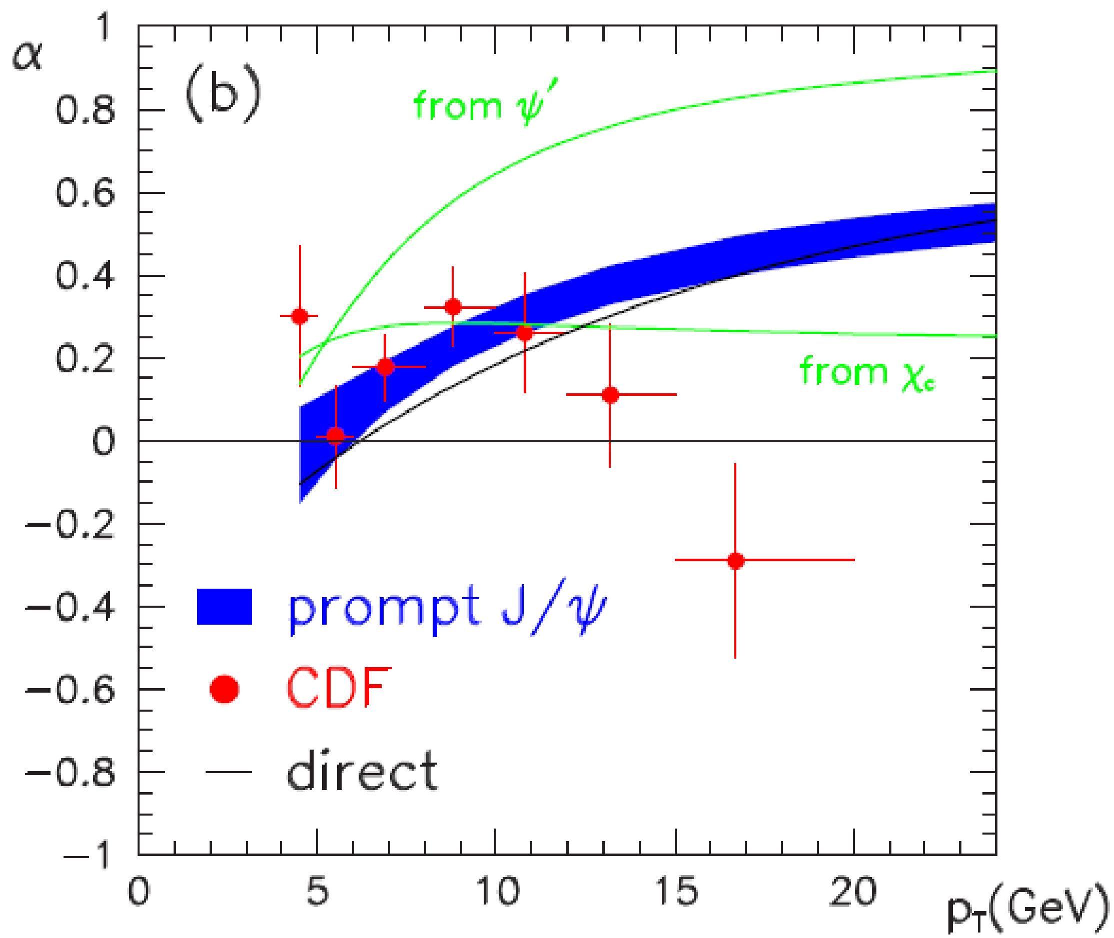


- Normalized distribution:

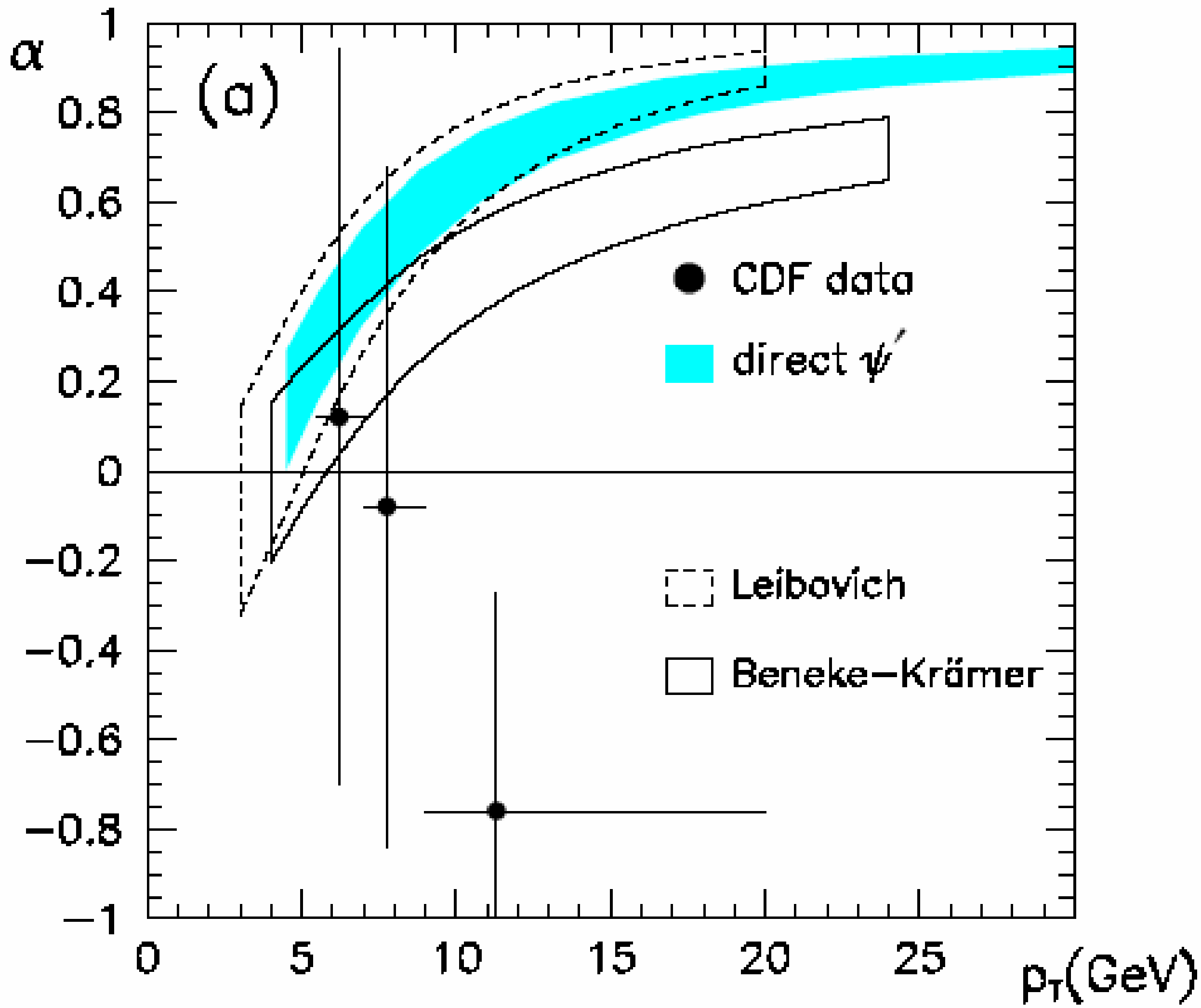
$$I(\cos\theta^*) = \frac{3}{2(\alpha+3)}\,(1+\alpha\cos\theta^*)$$

$$\alpha = \begin{cases} +1 & \text{fully transverse} \\ 0 & \text{unpolarized} \\ -1 & \text{fully longitudinal} \end{cases}$$

Surprises – experimentally

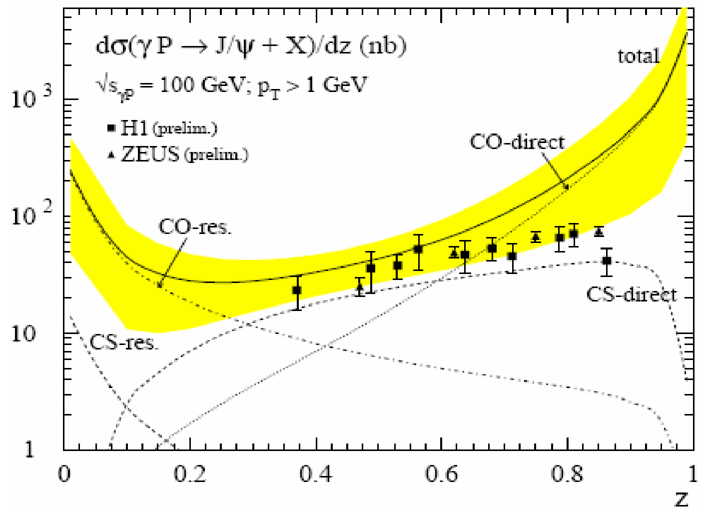


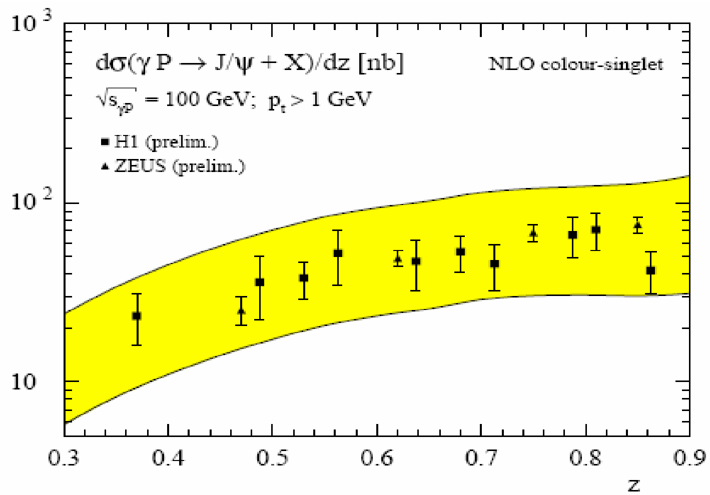
- ψ' polarization as a function of p_T:

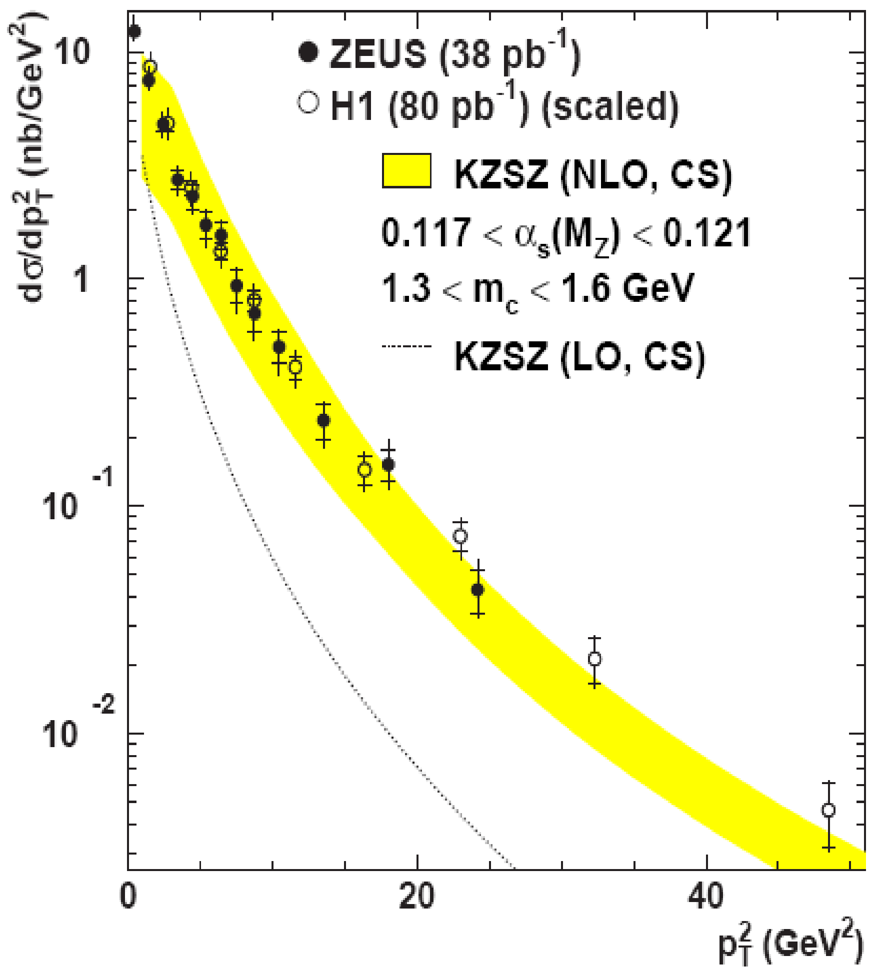


E. Braaten et al. Phys. Rev. D62, 094005 (2000)

Inelastic Quarkonium Photoproduction at HERA







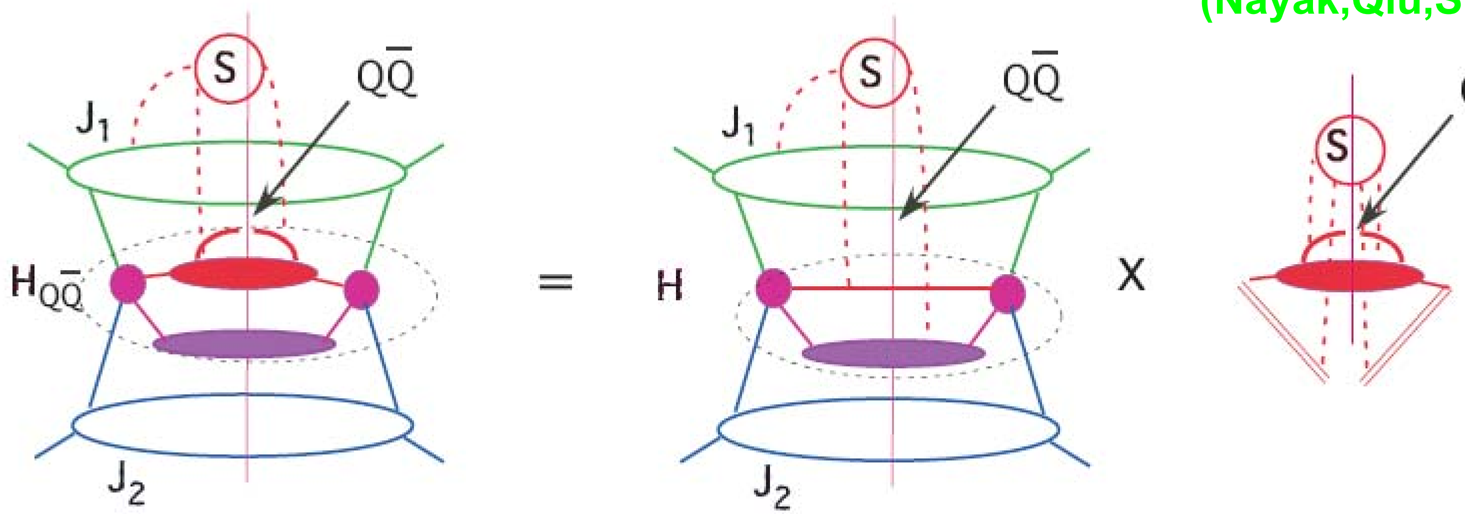
No room for color-octet contribution – universality?

Bodwin's talk

Surprises – theoretically

- No proof for NRQCD factorization for production for $p_T \leq m_Q$
- When $p_T >> m_Q$, single hadron inclusive cross section factorizes

(Nayak,Qiu,Sterman)



- Further factorization: $D_{H/g}(z, m_c, \mu) = \sum_n d_{g\to c\bar{c}[n]}(z, \mu, m_c) \, \langle \mathcal{O}_n^H \rangle$

  succeeds up to two-loop level, after a redefinition of NRQCD matrix elements – No all order proof for the production!

Anomalies

Double $c\bar{c}$ Production at Belle and BaBar

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

- Belle: $\sigma(e^+e^- \to J/\psi + \eta_c) \times B_{>2} = 25.6 \pm 2.8 \pm 3.4$ fb.
- BaBar: $\sigma(e^+e^- \to J/\psi + \eta_c) \times B_{>2} = 17.6 \pm 2.8 \pm 2.1$ fb
- NRQCD: $\sigma(e^+e^- \to J/\psi + \eta_c) = 2.31 \pm 1.09$ fb

Comparison to Belle & Theory

$J/\psi\ c\bar{c}$	η_c	χ_{c0}	$\eta_c(2S)$
Nevt, BaBar (124.4 fb^{-1}) Nevt, Belle (155 fb^{-1}) (*)	127 ± 20 235 ± 26	81 ± 16 89 ± 24	121 ± 20 164 ± 30
(+) $\sigma_{Born} \times \mathcal{B}_{>2}$, BaBar $\sigma_{Born} \times \mathcal{B}_{>2}$, Belle (*)	$17.6 \pm 2.8 \pm 2.1$ $25.6 \pm 2.8 \pm 3.4$	$10.3 \pm 2.5 \pm 1.8$ $6.4 \pm 1.7 \pm 1.0$	$16.4 \pm 3.7 \pm 3.0$ $16.5 \pm 3.0 \pm 2.4$
(+) NRQCD by Braaten and Lee [1]	2.31 ± 1.09	2.28 ± 1.03	0.96 ± 0.45
(+) NRQCD by Liu, He and Chao [2]	5.5	6.9	3.7

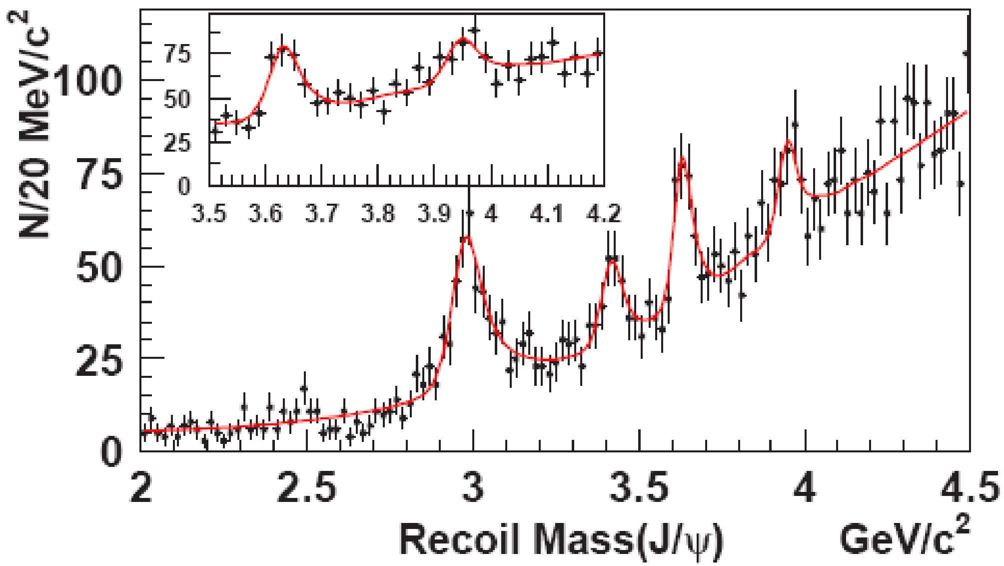
See Bodwin's talk for updated numbers

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

NRQCD prediction (Bodwin et al):

$$\sigma(e^+e^- \to J/\psi + J/\psi) = 8.70 \pm 2.94 \text{ fb}$$

- New Belle result for spectrum recoiling against J/ψ:



- η_c, χ_{c0}, $\eta_c(2S)$, $X(3940)$ seen.
- No evidence for J/ψ, χ_{c1}, $\psi(2S)$

BaBar also finds no evidence for J/ψ, χ_{c1}, $\psi(2S)$.

Belle bound on $J/\psi + J/\psi$ cross section: $\sigma(e^+e^- \to J/\psi + J/\psi) \times B_{>2} < 9.1$ fb

The Belle angular distributions of $J/\psi + \eta_c$ and $J/\psi + \eta_c(2S)$ events disfavor NRQCD

Bodwin's talk

RHIC physics – another revolution?

"… it is clear that the matter that is created at RHIC differs from anything that has been seen before. Its precise description must await our deeper understanding of this matter."

RHIC White Paper

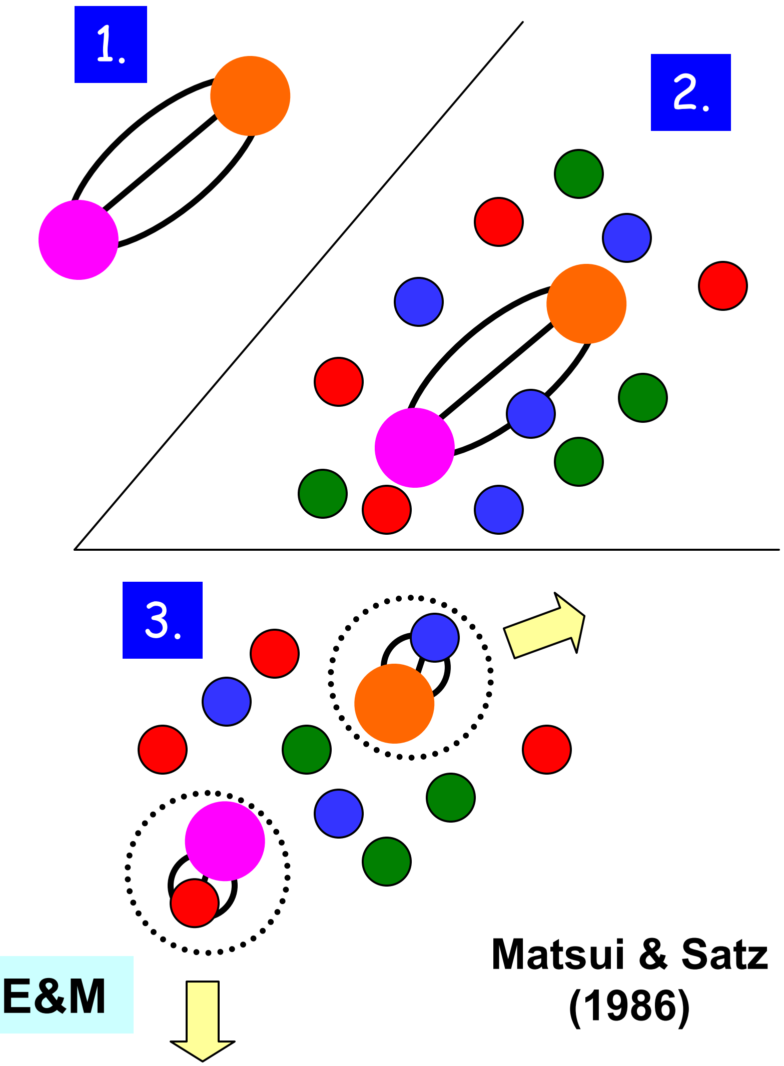
To diagnose this new matter, a good probe needs to be:

- **sensitive to the typical momentum scale/temperature of this matter – a few hundred MeV – a nonperturbative scale**

- **produced at a time scale much short than the typical scale of the matter – a large momentum exchange – a perturbative scale**

Charmonium Suppression and QGP

- **Start with a J/ψ**
  - **This works with other charmonium states as well**
  - **The J/ψ is easiest to observe**
- **Put it in a sea of color charges**
- **The color lines attach themselves to other quarks**
  - **This forms a pair of charmed mesons**
- **These charmed mesons "wander off" from each other**
- **When the system cools, the charmed particles are too far apart to recombine**
  - **Essentially, the J/ψ has melted**



Matsui & Satz (1986)

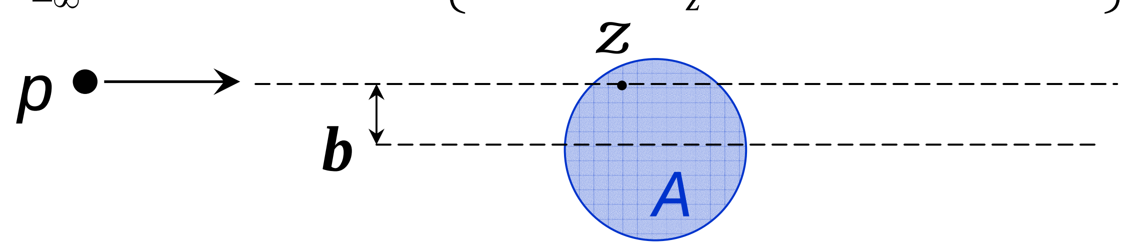
Often called Debye screening, in analogy with E&M

Quarkonium production in medium

Normal suppression: $$S_{AB} = \sigma_{AB} / (AB\sigma_{pN})$$

J/ψ suppression in p-A collisions is well described by a probabilistic formula

$$S_{pA} = \int d^2b \int_{-\infty}^{\infty} dz \rho_A(b,z) \exp\left\{ -(A-1) \int_z^{\infty} dz' \rho_A(b,z') \sigma_{abs} \right\}$$



- From a fit of experimental p-A data (NA38,NA50):

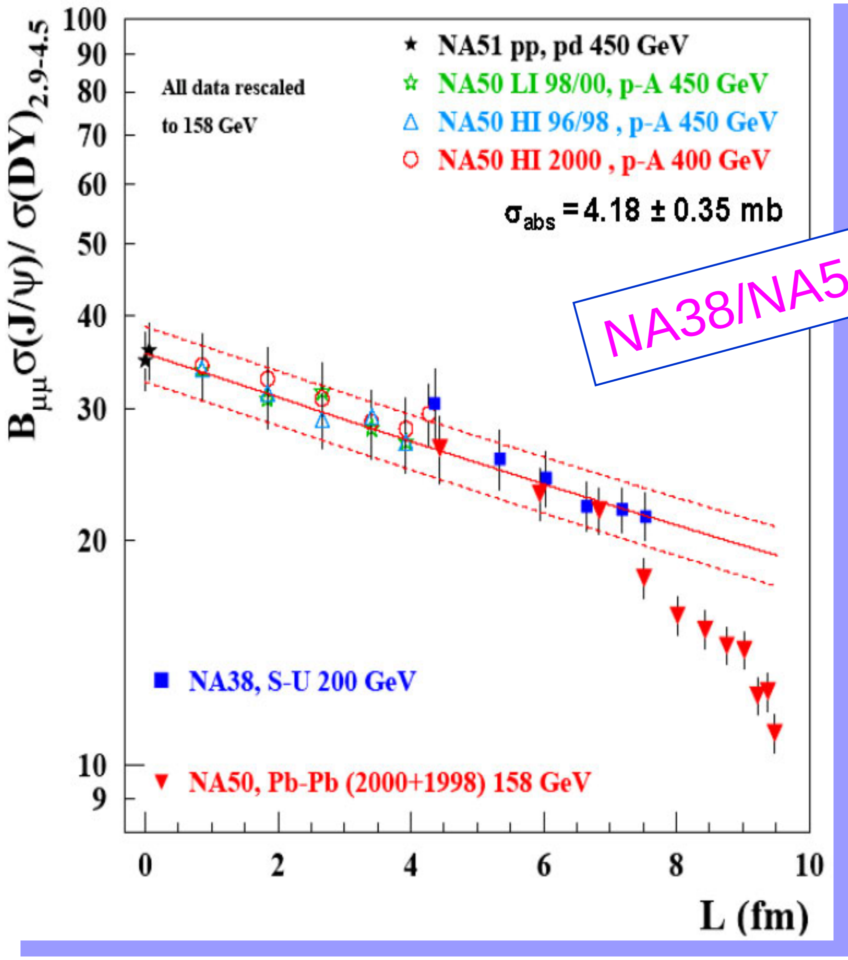
  σ_{abs}=4.18 +- 0.35 mb (hep-ex/0412036)

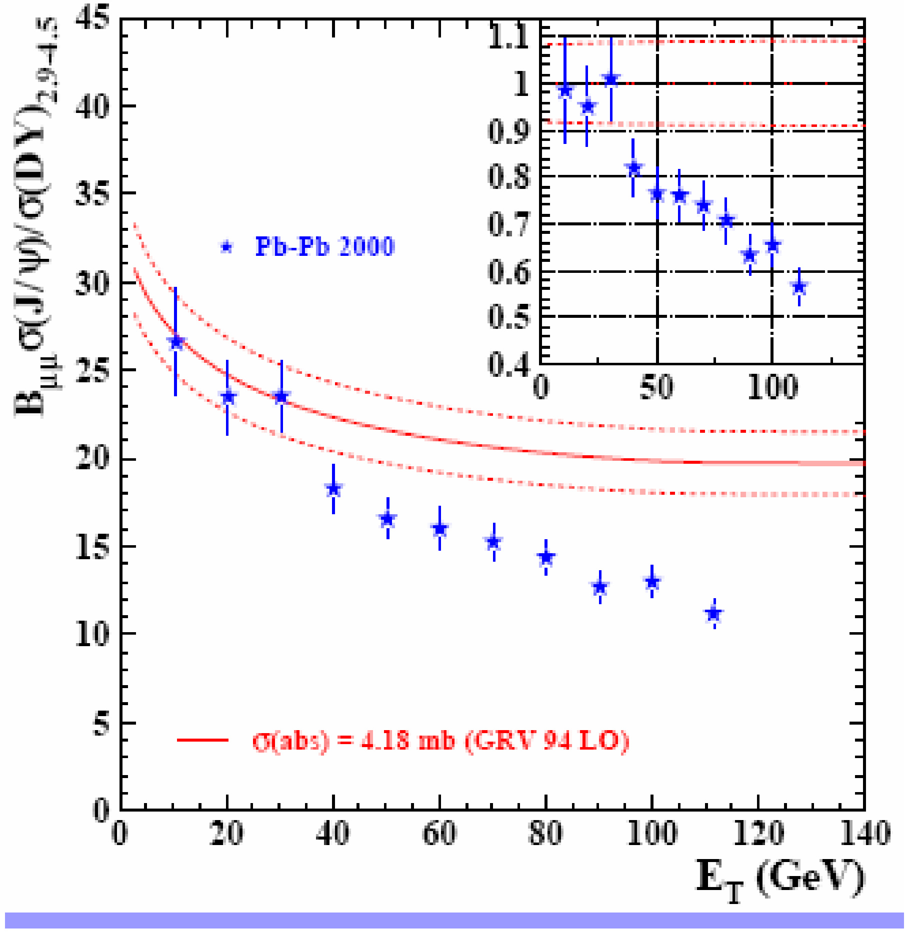
- RHIC dA data suggests a smaller value ~ 1 – 3 mb ?

Comparison with SPS data

Anomalous suppression:

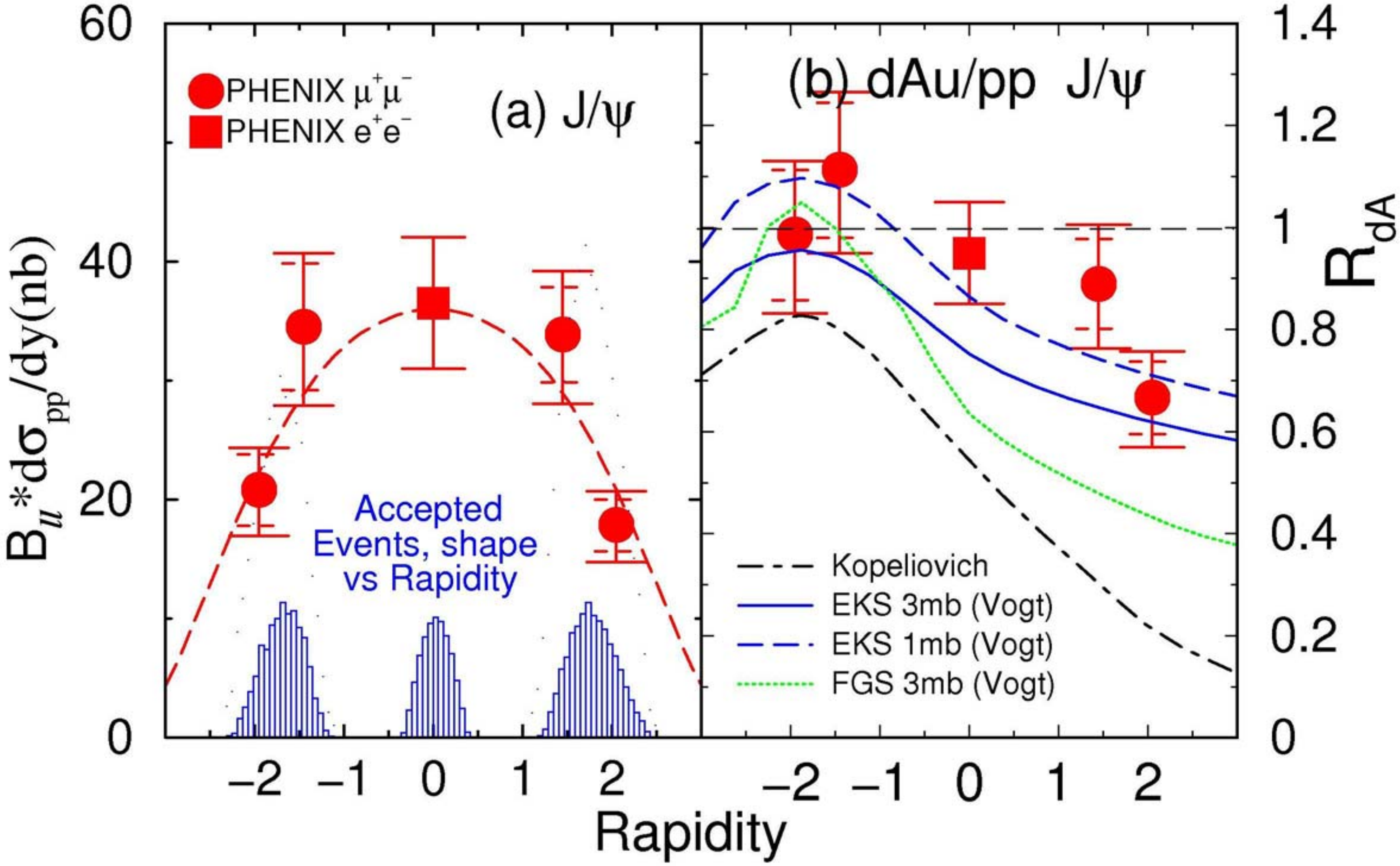
– Not a straight line on the semi-log plots – additional suppression!





Comparison with PHENIX dA data

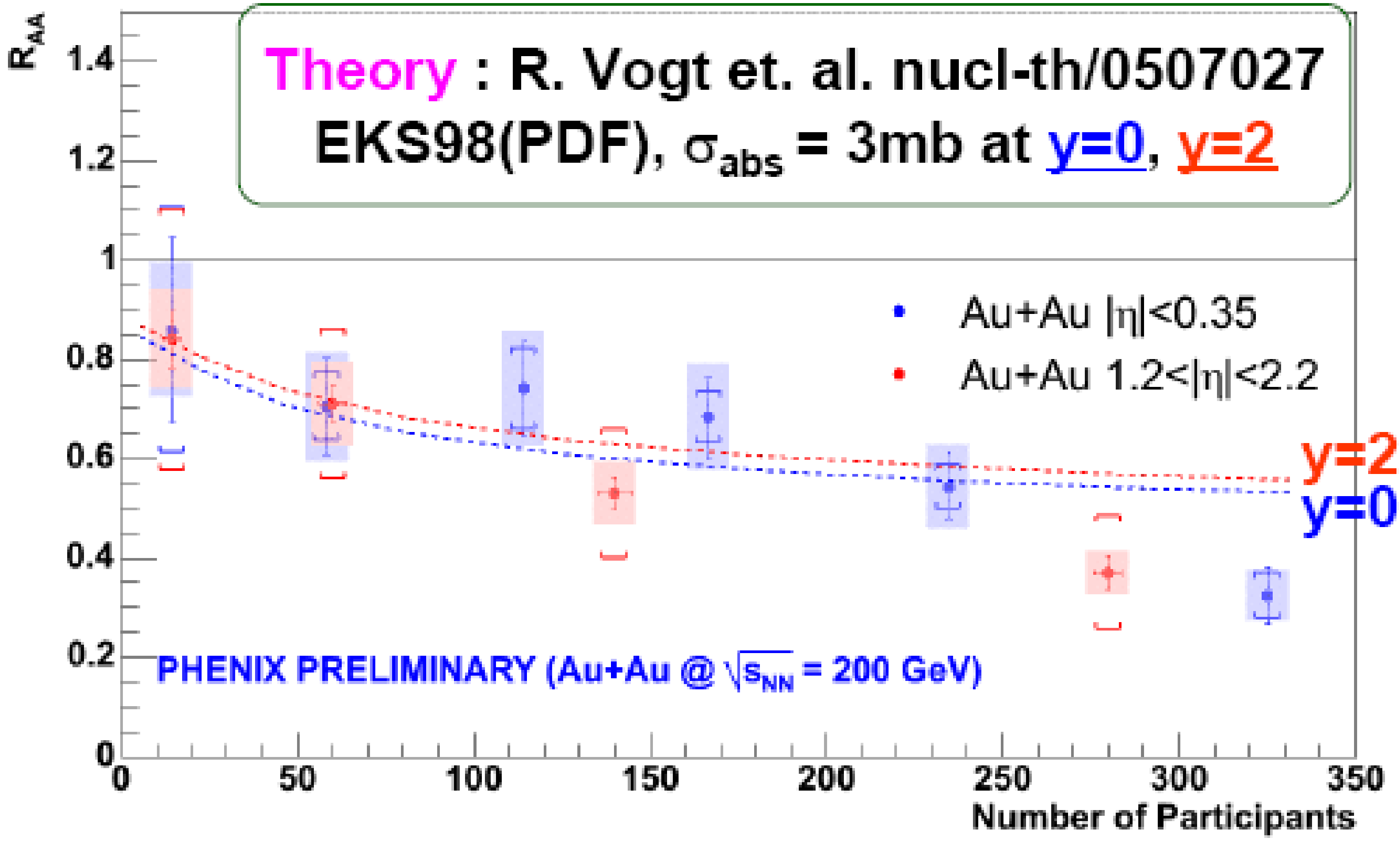
- Nuclear absorption and gluon shadowing – cold matter:



$\sigma_{abs} \sim$ 1-3mb

PHENIX website

Comparison with RHIC AA data

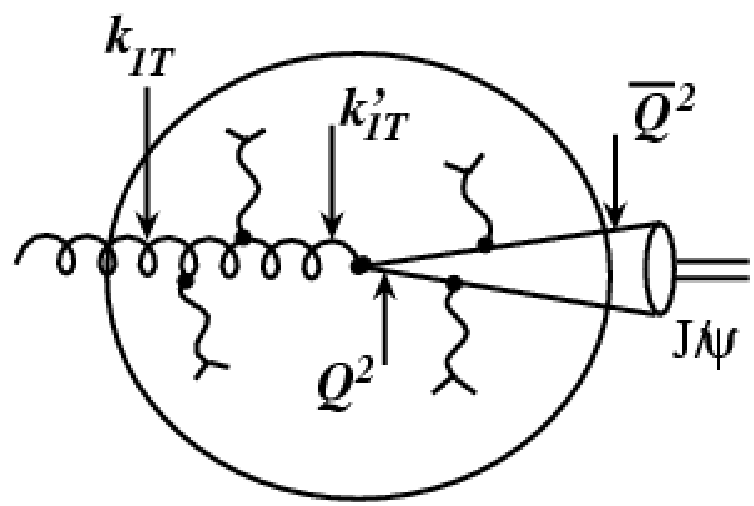


- ❑ Too strong suppression from Models fit SPS A-A data
- ❑ Charm quark recombination, …

Gunji's talk

Multiple parton rescattering model

- J/ψ is unlikely to produce at the production point



- Final-state:

  Increases the relative momentum of the pair

  $\overline{Q}^2 > Q^2$

  leads to suppression of J/ψ

- Threshold effect leads to different effective σ_{abs}

- Leads to curved line for the suppression factor.

- Initial-state:

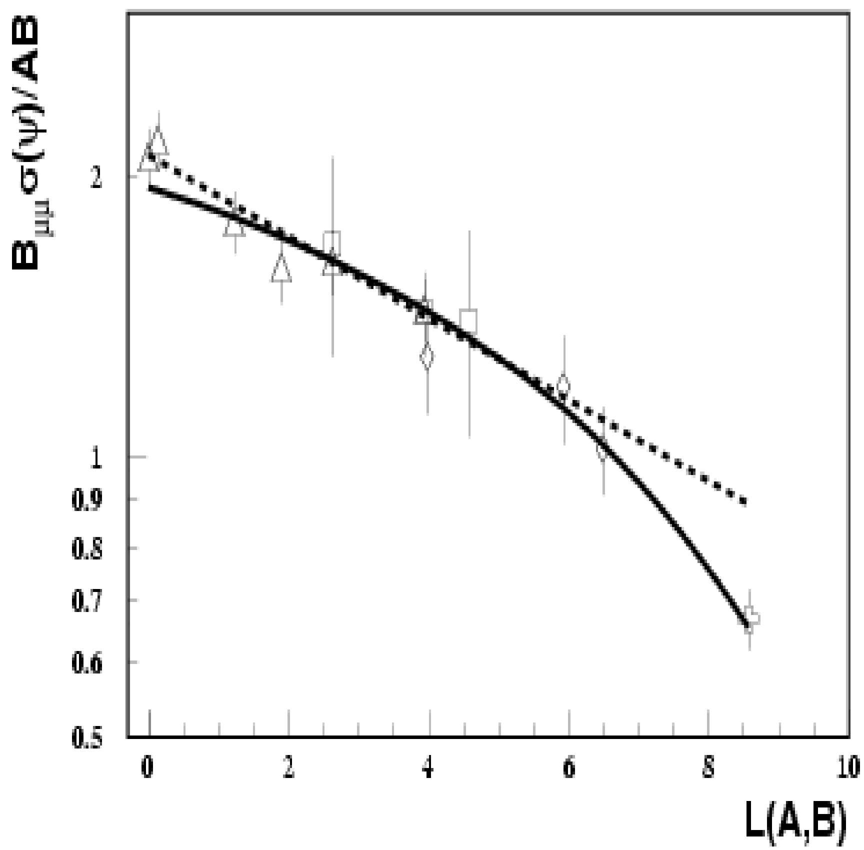
  Broadening in k_T

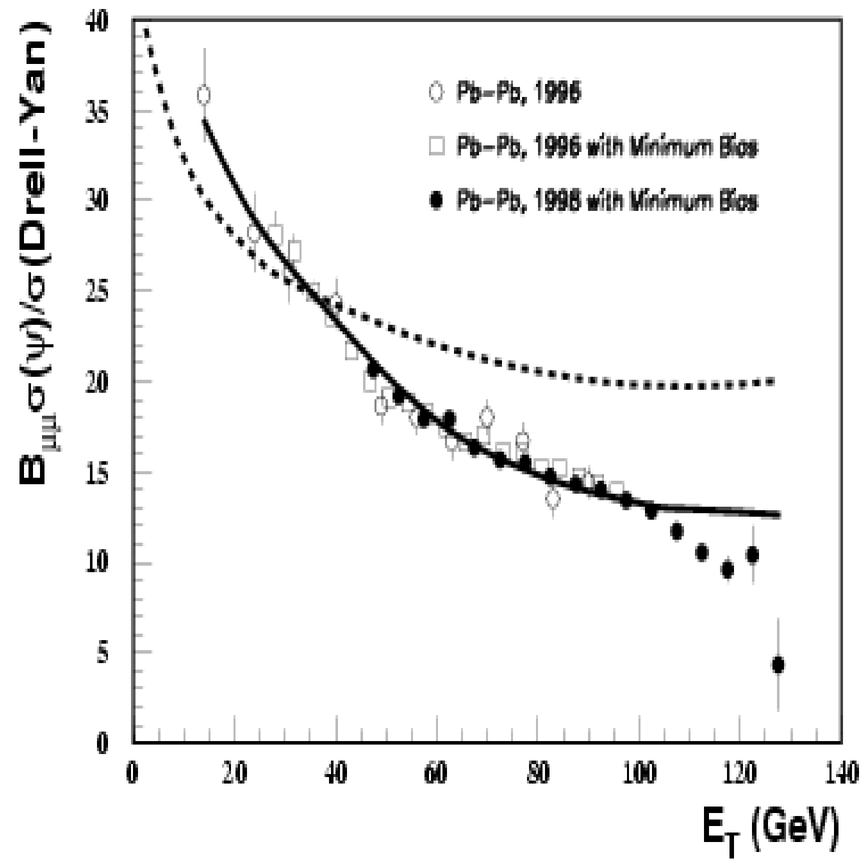
  $k_T' > k_T$

  leads to x_F-dependence of the suppression in pA

Comparison with SPS data

Qiu, Vary, Zhang, PRL 2002





Calculation for RHIC kinematics is underway

Accardi and Qiu

Summary and outlook

- **QCD is a very successful theory for strong interaction physics. We have only learned a very little of it.**

- **Heavy quarkonium provides a non-relativistic system, and could offer some important perspectives to the formation of QCD bound states**

- **After 30 years, since the discovery of J/psi, theorists still have not been able to fully understand the production mechanism of heavy quarkonia**

- **RHIC is offering an excellent opportunity to learn and exam the formation of QCD bound states – nuclear matter could be an effective filter.**

Backup slices