Topics in the physics of Heavy Quarkonium

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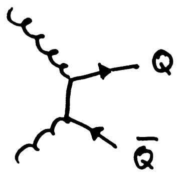
RIKEN-BNL Research Center
and
Physics Dept.,
Brookhaven National Laboratory

1. Why heavy quarkonium is interesting
2. The mechanism of quarkonium production
3. Quarkonium as a probe of
   a) QCD vacuum
   b) light hadrons
   c) nuclear matter
   d) quark–gluon matter
4. Low-energy interactions of quarkonium

⟹ Three reasons to study quarkonium at Jefferson Laboratory

- **Heavy quarks** are heavy: $m_Q \gg \Lambda_{QCD}$,

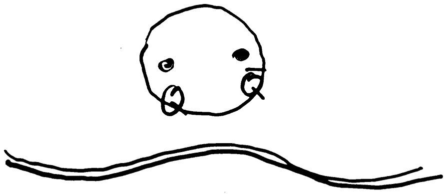
and perturbation theory is meaningful



$$r_{Q\bar{Q}} \sim \frac{1}{2m_Q} \ll \Lambda_{QCD}^{-1}$$

$\Longrightarrow$ a good probe of gluon densities

- **Heavy quarkonia** are small:

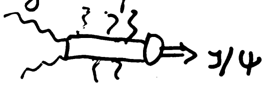


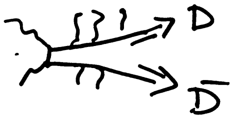
$$r_{(Q\bar{Q})} \sim \frac{1}{m_Q \underset{\uparrow}{v}} < \Lambda_{QCD}^{-1}$$

velocity

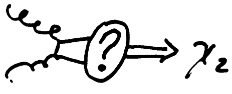
non-perturbative effects can be systematically taken into account using multipole/OPE expansion

$\Longrightarrow$ a good probe of softer gluon fields





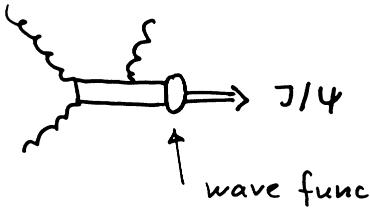
$\Longrightarrow$ a test of hadronization



Mechanisms of quarkonium production

- color singlet model

C.H. Chang,
NPB172(80)425
E.L. Berger, D. Jones,
PRD23(81)1521
R. Baier, R. Rückl,
PLB102(81)364,
Z. Phys. C19(83)251
. . . . .



wave function
at the origin, extracted
from J/ψ → e^+e^-

⇒ everything can be computed

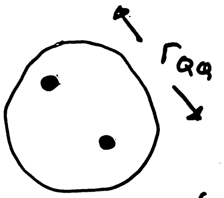
- But: fails in describing the integrated cross sections <u>and</u> high p_T production at the Tevatron (CDF, D0) → figures

- color octet model

G. Bodwin
E. Braaten
G. Lepage
PRD51(95)1125
. . . .

three scales:

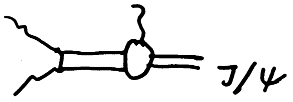
$m_Q \gg$
$\gg m_Q v = r_{Q\bar{Q}}^{-1} \gg$
$\gg m_Q v^2 = \epsilon_{Q\bar{Q}}$



at high p_T

non-perturbative
matrix elements,
to be extracted from
the data

at small p_T



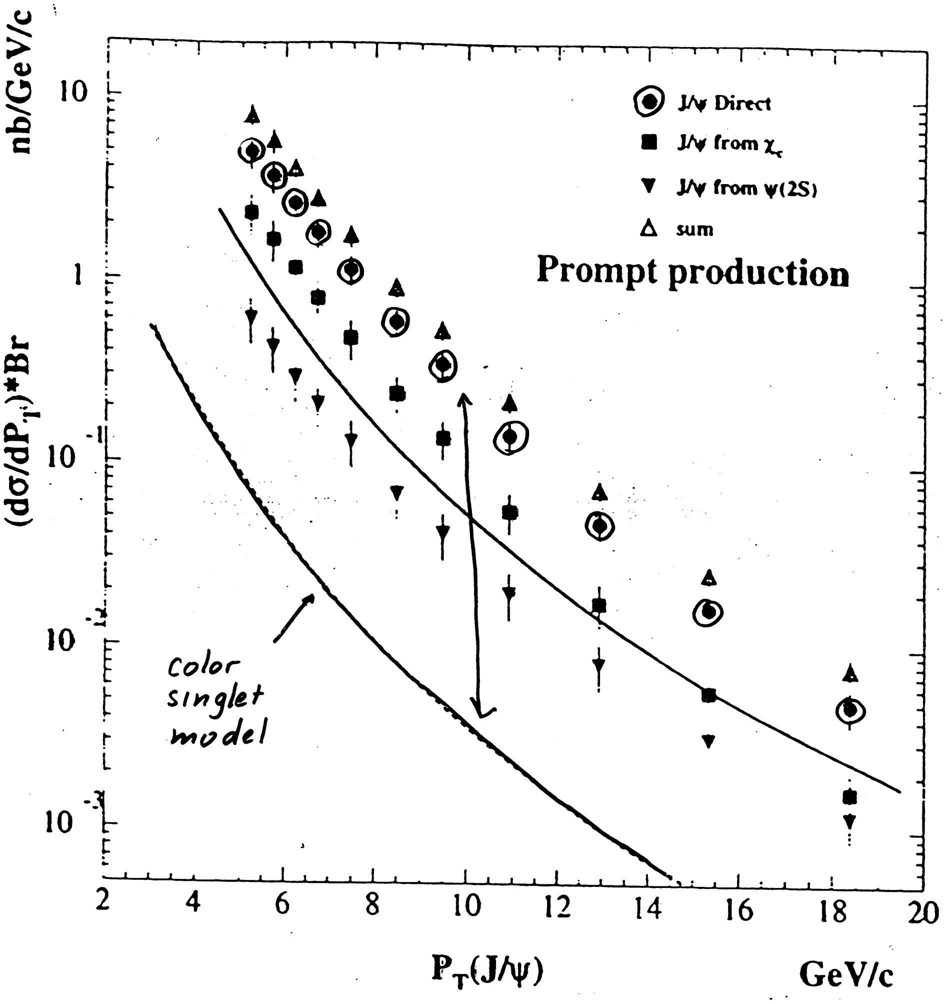


FIG. 3. The differential cross sections of prompt $J/\psi \to \mu^+\mu^-$ as a function of $P_T^{J/\psi}$. The dashed curve is the color singlet calculation for J/ψ production. The solid curve is the calculation of $\chi_c \to J/\psi\gamma$ production and includes both color singlet and color octet contributions. The error bars correspond to the statistical and systematic uncertainties combined and include the uncertainties common to all data points.

From: F. Abe et al (CDF Coll.)
PRL 79 (1997) 578

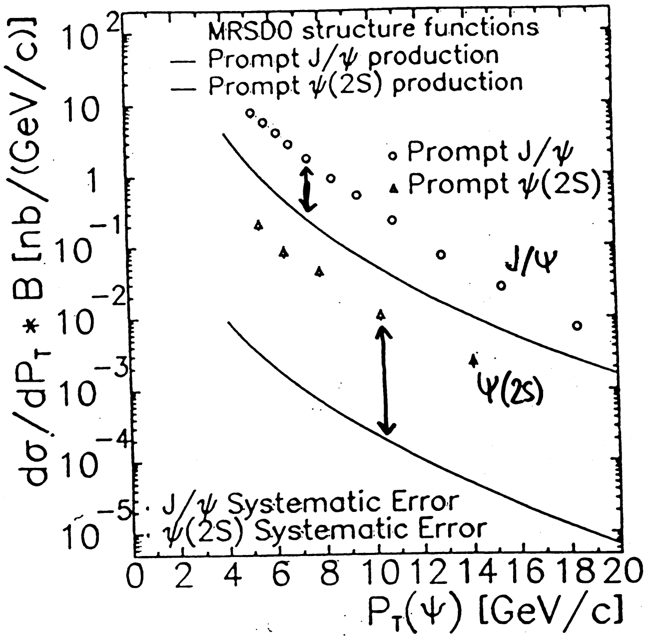


FIG. 3. The differential cross section times branching ratio $\mathcal{B}(\psi \rightarrow \mu^+\mu^-)$ for $|\eta^{\psi}| < 0.6$ for prompt ψ mesons. The vertical error bars are the statistical and the P_T-dependent systematic uncertainties, added in quadrature. Circles: J/ψ; triangles: $\psi(2S)$. The lines are the theoretical expectations based on the color singlet model.

From: F. Abe et al (CDF Coll.)
PRL 79(1997)572

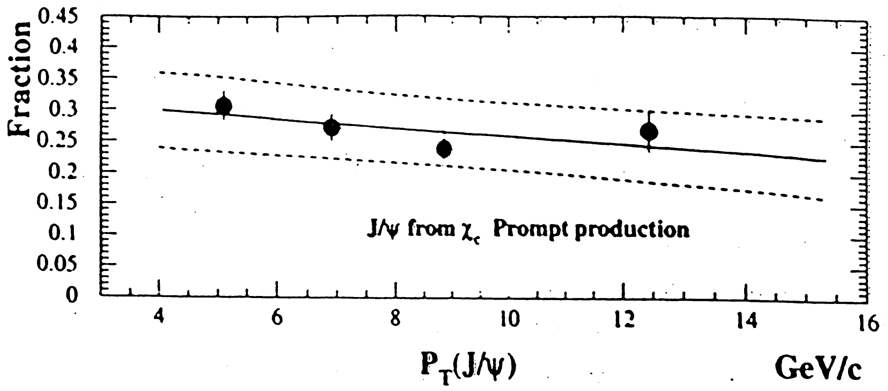
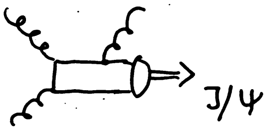
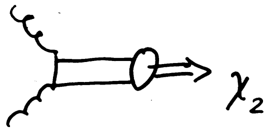


FIG. 2. The fraction of J/ψ mesons from χ_c decays as a function of $P_T^{J/\psi}$ with the contribution from b's removed. The error bars correspond to the statistical uncertainty. The solid line is the parametrization of the fraction. The dashed lines show the upper and lower bounds corresponding to the statistical and systematic uncertainties combined.

From: F. Abe et al (CDF Coll.)
PRL 79(1997)578

J/Ψ's and χ's in the color singlet model are produced differently, with very different p_T distributions:





- But: the fraction of J/Ψ's coming from χ decays (almost) does not depend on p_T!

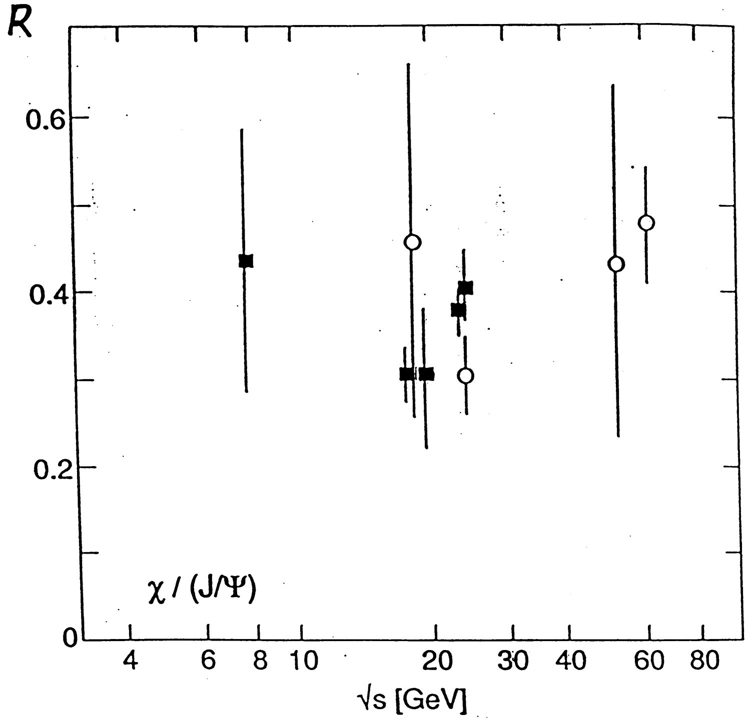


Fig. 2: The ratio of $(\chi_1 + \chi_2) \to J/\psi$ to total J/ψ production, as a function of the center of mass energy, $\sqrt{s}$, by proton (open symbols) and pion beams (solid symbols) [1].

$$R \equiv \frac{(\chi_1 + \chi_2) \to J/\psi\,\gamma}{\text{total } J/\psi}$$

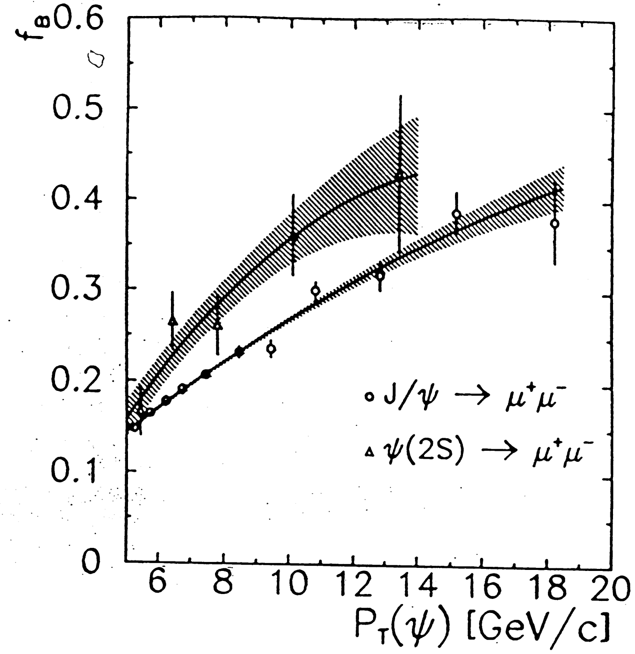


FIG. 1. The fractions of J/ψ (circles) and $\psi(2S)$ (triangles) originating from b-hadron decays. The error bars indicate the combined statistical and systematic uncertainties on the fractions. The solid curve is the fitted function, and the slashed regions indicate the uncertainty in the fit.

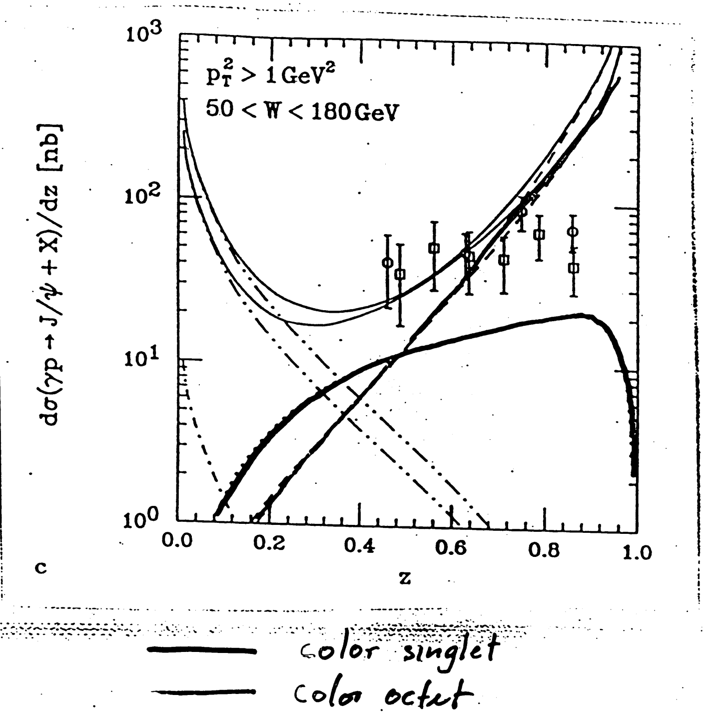
From: F. Abe et al (CDF Coll.)
PRL 79 (1997) 572

- J/ψ's from B decays will be an important "background" to direct J/ψ production at RHIC!

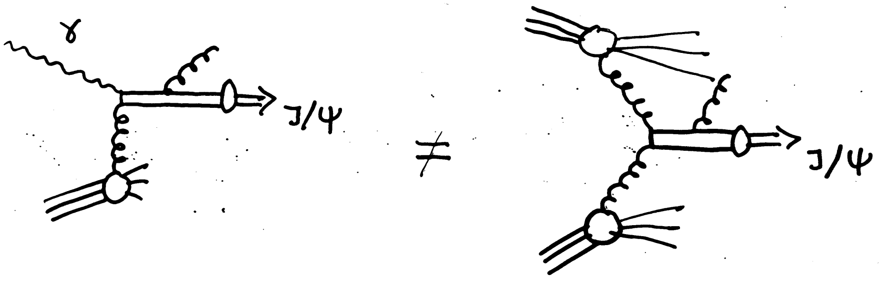
From:

B. Kniehl, G. Kramer,
Eur. Phys. C6(99)493

Data:
J. Breitweg et al
ZPC76(97)599
ZEUS Coll.

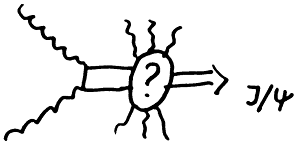


Are color octet matrix elements universal?
If not, factorization (at small p_T)
is violated...



- color evaporation model

M.B. Einhorn, S.D. Ellis
PRD12(75) 2007
H. Fritzsch,
PLB67(77)217
M. Glück, J.F. Owens,
E. Reya, PRD17(78)
2324
J. Babcock, D. Sivers,
S. Wolfram,
PRD18(78)162



$$\tilde{\sigma}_{c\bar{c}}(s) = \int_{4m_c^2}^{4m_D^2} d\hat{s} \int dx_1\, dx_2\, g(x_1)\, g(x_2)\, \sigma(\hat{s})\, \delta(\hat{s} - x_1 x_2 s)$$

assume that

$$\sigma_{pN\to J/\psi}(s) = f^{p}_{J/\psi}\, \tilde{\sigma}_{c\bar{c}}(s)\,,$$ and similarly for other quarkonia

determine parameter from the fit to the data

$$f^{p}_{J/\psi} \simeq 0.025$$

=> Predict energy dependence, x_F (y) distributions

R. Gavai et al.,
HPC, Int. J. Mod. Phys. 10(95)

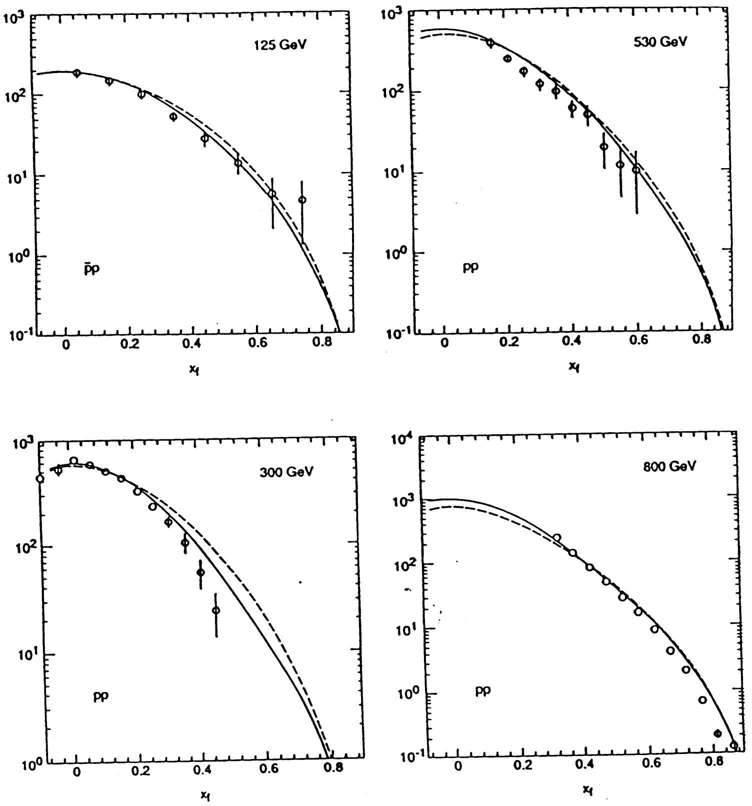


Fig. 10a: The J/ψ longitudinal momentum distributions compared to $\bar{p}N$ and pN data [9], with $x_F = p_L(J/\psi)/p_{max}(J/\psi)$; the MRS results are denoted by a solid, the GRV by a dashed line.

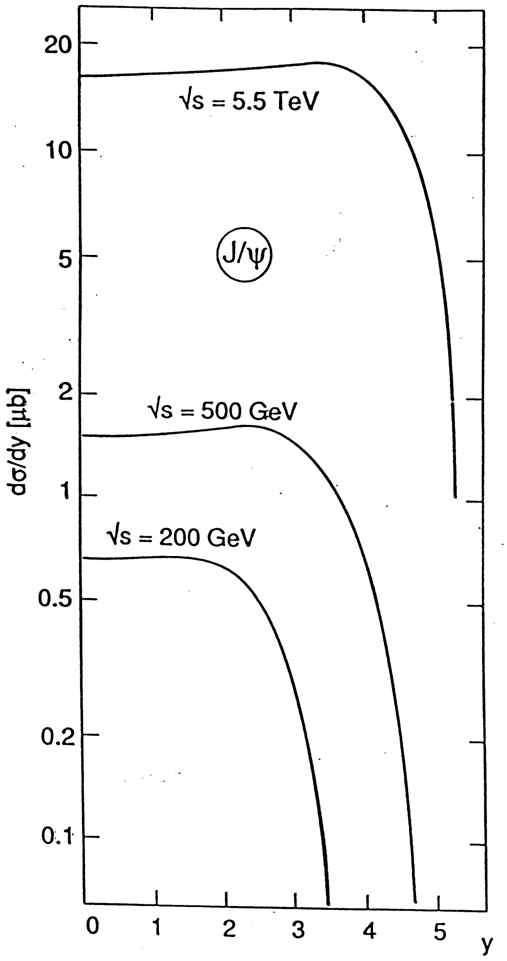


Fig. 12: Rapidity distributions for J/ψ production, calculated with MRS D-' parton distributions at RHIC and LHC energies.

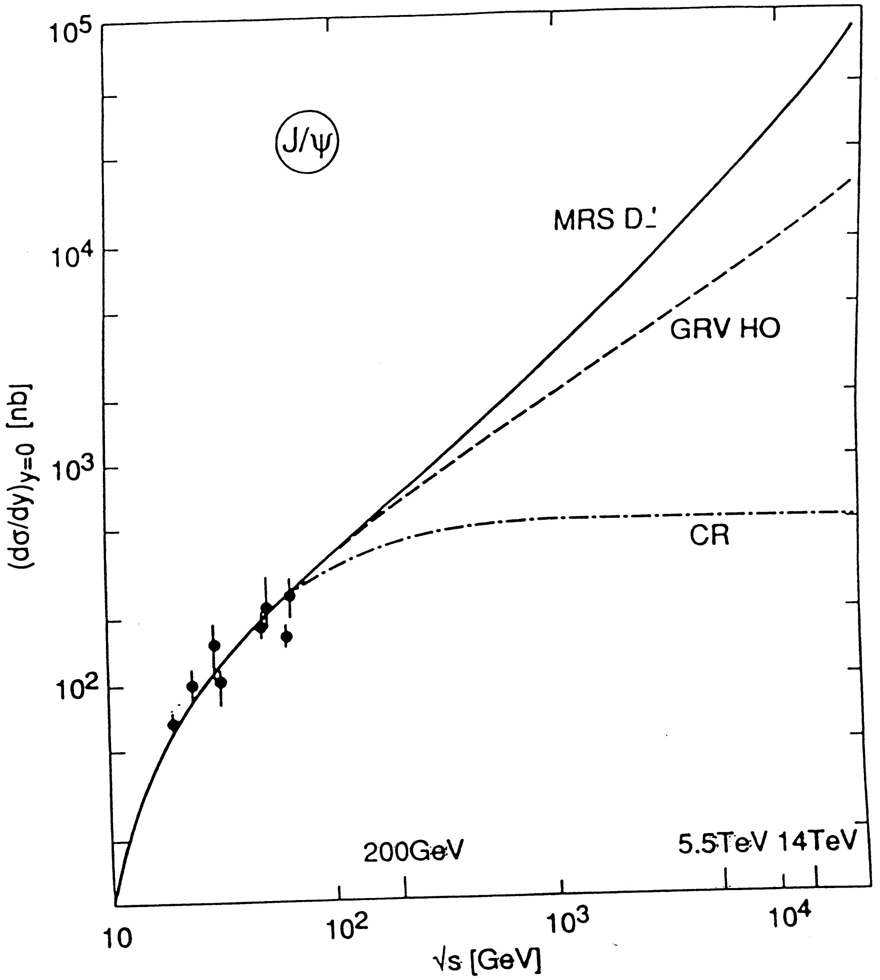


Fig. 2.2: Energy dependence of $(d\sigma^{pN}_{J/\Psi}/dy)_{y=0}$ for J/Ψ production, as obtained with MRS D-' and GRV HO parton distributions.

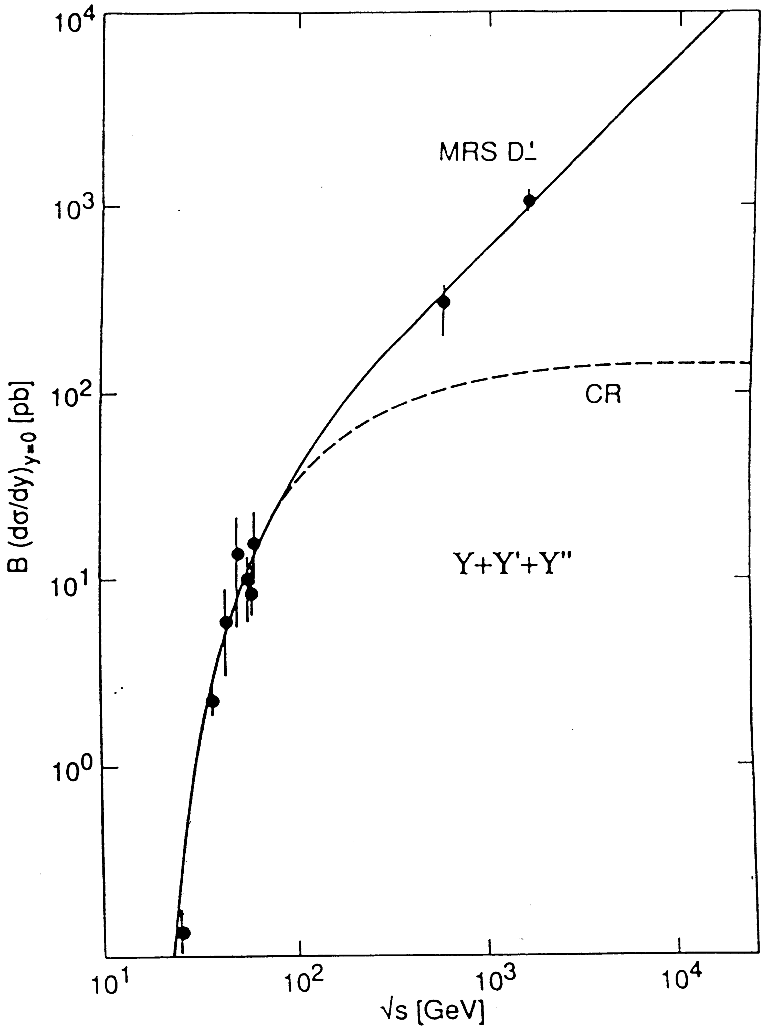


Fig. 2.3: Energy dependence of $(d\sigma_\Upsilon^{pN}/dy)_{y=0}$ for Υ production; the predictions with MRS D-' and GRV HO parton distributions essentially coincide.

R. Gavai, D. K., H. Satz, G. Schuler, K. Sridhar & R. Vogt,
Int. J. Mod. Phys. 10 (95)
3043
"Hard Probe Coll."

What is the true mechanism of quarkonium production? (necessary to understand also pA, AB,...)

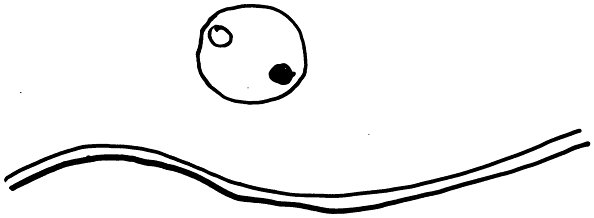
- Can angular distributions/spin asymmetries help?

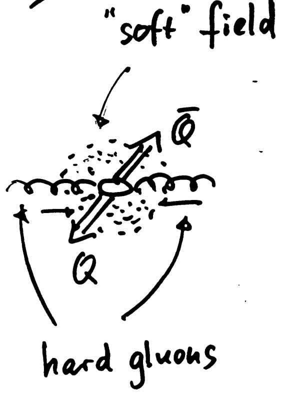
B.L. Ioffe '77
J. Cortes, B. Pire '88

- In non-relativistic QCD approach of Bodwin-Braaten-Lepage, the color octet matrix elements are classified in powers of heavy quark velocity, v

→ • It is also possible to classify matrix elements using QCD multipole expansion; physically as good, but in many situations (angular distributions,...) more practical

R.L. Jaffe, D.K '99



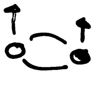


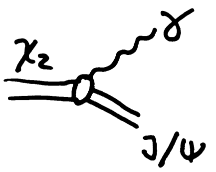
Example:

consider $$pp \rightarrow \chi_2 + X$$
$$\hookrightarrow J/\psi + \gamma$$

- What is the angular distribution of the photon?

χ_2 : $J^{PC} = 2^{++}$ $\quad {}^3P_2$



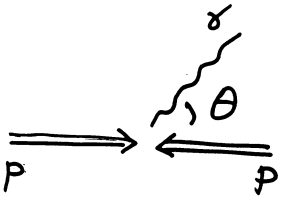


effective coupling

$$\mathcal{L} \sim \psi_\mu^\dagger D_\nu \eta^{\mu\nu} \sim \underset{\uparrow\, J/\psi\text{ field}}{\psi_\mu^\dagger}\ \overset{\text{vector potential}}{\overset{\downarrow}{A_\nu}}\ \eta^{\mu\nu} \nwarrow \chi_2 \text{ field}$$

(QED multipole expansion)

$$\boxed{\begin{aligned} W^{2,\pm 2}(\theta) &= \frac{1}{2} + \frac{1}{2}\cos^2\theta \\ W^{2,\pm 1}(\theta) &= \frac{3}{4} - \frac{1}{4}\cos^2\theta \\ W^{2,0}(\theta) &= \frac{5}{6} - \frac{1}{2}\cos^2\theta \end{aligned}}$$



$\Rightarrow$ angular distribution of the photon can be used to determine the helicity of the χ_2

R.L. Jaffe, D.K.

- χ_2 wave function

composite tensor field $\eta^{\mu\nu}$

irreducible: symmetric $\eta^{\mu\nu} = \eta^{\nu\mu}$

traceless $\eta^{\mu}_{\mu} = 0$

transverse $\partial_\mu \eta^{\mu\nu} = 0$

the w.f.: helicity

$$\langle P, \lambda | \eta^{\mu\nu} | 0 \rangle = H^{\mu\nu}(P, \lambda)$$

momentum

- Interaction with external gauge fields

effective Lagrangian

$$\mathcal{L}_{int} = \psi^+_\mu D_\nu \eta^{\mu\nu} \sim \psi^+_\mu A_\nu \eta^{\mu\nu}$$

massive vector field

- apply first to angular distributions in $\chi_2 \to J/\psi + \gamma$ decay

amplitude $A \sim \epsilon^+_k(\lambda_\psi) \epsilon^+_\ell(\lambda_\gamma) H^{k\ell}(\Lambda)$ ← helicity state of χ_2

$$\sum_{\lambda_\psi} \epsilon^m(\lambda_\psi) \epsilon^{k+}(\lambda_\psi) = \delta^{km} \qquad \sum_{\lambda_\gamma} \epsilon^n(\lambda_\gamma) \epsilon^{\ell+}(\lambda_\gamma) = $$

$$= \delta^{n\ell} - \hat{k}^n \hat{k}^\ell$$

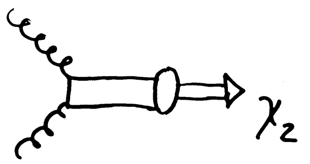
cross section

$$\sigma \sim \sum_{\lambda_\psi, \lambda_\gamma} A^+ A \sim H^{+k\ell}(\Lambda)(\delta^{\ell n} - \hat{k}^\ell \hat{k}^n) H^{kn}(\Lambda)$$

$$H^{jk}(\Lambda) = \sum_{\mu\mu'} (1\mu\, 1\mu' | 2\Lambda)\, v^j(\mu)\, v^k(\mu')$$

$$V(\pm 1) = \mp \frac{1}{\sqrt{2}} (V_1 \pm V_2); \quad V(0) = V_3$$

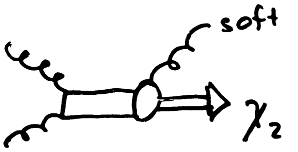
- Color singlet model:



helicities $\Lambda = 0, \pm 2$
are in general allowed,
but:
the $\Lambda = 0$ amplitude
vanishes in lowest order
perturbation theory!

$\Longrightarrow$ <u>only $\Lambda = \pm 2$</u> contributes

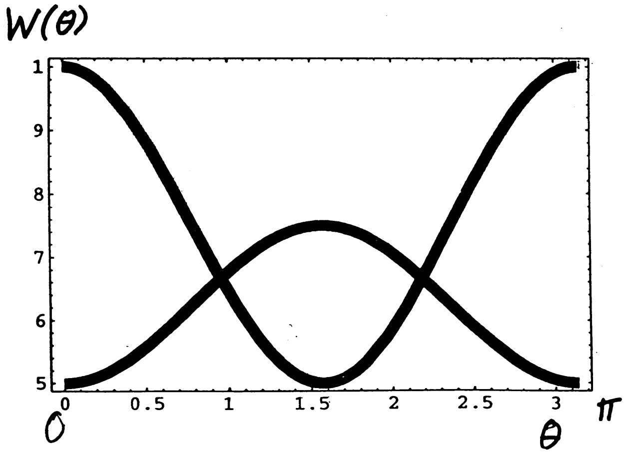
- Color octet model:

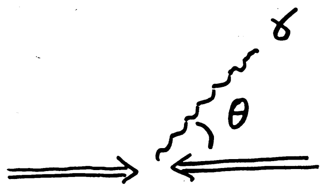


note: in QED, ${}^3P_2 \not\to \gamma\gamma\gamma$
in QCD, this is
possible: $f_{abc} \sim \mathrm{Tr}(abc) - \mathrm{Tr}(acb)$

$$\mathcal{L} = g\, \mathrm{Tr}\{\vec{\Psi}^{\dagger}_{\mu} \vec{D}_{\nu}\}\eta^{\mu\nu} \sim \mathrm{Tr}\{\vec{\Psi}^{\dagger}_{\mu} \vec{A}_{\nu}\}\eta^{\mu\nu}$$

chromoelectric dipole $\Rightarrow$ 1^{--} color octet; only $\Lambda = 0$ allowed $\Rightarrow$
<u>only $\Lambda = \pm 1$</u> are produced





▬ color singlet

▬ color octet

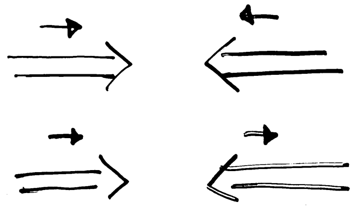
<u>VERY</u> different distributions!

$$\Downarrow$$

The angular distribution in the decay $\chi_2 \to J/\psi + \gamma$ determines the ratio of octet/singlet amplitudes:

$$\frac{d\sigma}{d\Omega} \sim g(x_1, M_\chi^2)\, g(x_2, M_\chi^2) \left\{ \left(\frac{1}{2} + \frac{1}{2}\cos^2\theta\right) \underline{A}^1 + \left(\frac{3}{4} - \frac{1}{4}\cos^2\theta\right) \underline{A}^8 \right\}$$

- Once A^8/A^1 is measured, in polarized $\vec{p}\,\vec{p}$ one can measure ΔG!

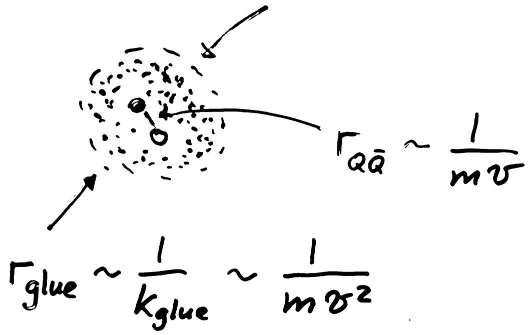


$$\frac{d\sigma^{\uparrow\uparrow} - d\sigma^{\uparrow\downarrow}}{d\sigma^{\uparrow\uparrow} + d\sigma^{\uparrow\downarrow}} = - \frac{\Delta g(x_1, M_\chi^2)}{g(x_1, M_\chi^2)} \frac{\Delta g(x_2, M_\chi^2)}{g(x_2, M_\chi^2)} \times$$

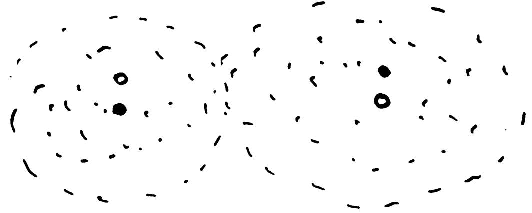
$$\times \frac{\frac{1}{2} + \frac{1}{2}\cos^2\theta - \frac{A^8}{A^1}\left(\frac{3}{4} - \frac{1}{4}\cos^2\theta\right)}{\frac{1}{2} + \frac{1}{2}\cos^2\theta + \frac{A^8}{A^1}\left(\frac{3}{4} - \frac{1}{4}\cos^2\theta\right)}$$

Quarkonium as a probe

- QCD vacuum



Let us measure the gluon field around onium (by another onium)



M. Peskin '79

H. Fujii, D.K. '99

At low energy, OPE expression for the scattering amplitude:

$$V(R) = -i\int dt \, \langle 0| T\{(\sum_i c_i O_i)(\sum_j c_j O_j)\}|0\rangle$$

the leading twist-two operators:

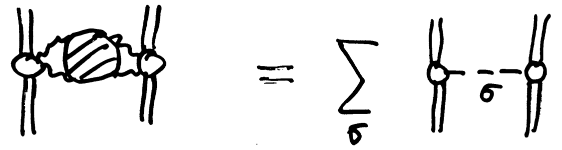
$$V(R) = -i\,\underset{\substack{\uparrow\\ \text{Wilson}\\ \text{coefficient}}}{(W.c.)^2}\int dt \, \langle 0|T\{\tfrac{1}{2}g^2\vec{E}^2(0), \tfrac{1}{2}g^2\vec{E}^2(t,R)\}|0\rangle$$

$$g^2\vec{E}^2 = \frac{8\pi^2}{b}\,\theta_\mu^{\ \mu} + g^2\,\theta_{00}^{(G)}$$

$$b = \tfrac{1}{3}(11N_c - 2N_f) = 9; \qquad \theta_\mu^{\ \mu} = \frac{\beta(g)}{2g}\,G_a^{\alpha\beta}G^a_{\alpha\beta} = -\frac{b g^2}{32\pi^2}\,G^2$$

$\uparrow$ trace of the energy-momentum tensor

Write down the spectral representation:



$$V(R) = -(w.c.)^2\left(\frac{4\pi^2}{b}\right)^2\int d\sigma^2\,\rho(\sigma^2)\,\frac{1}{4\pi R}\,e^{-\sigma R}$$

In perturbation theory, $\rho(\sigma^2) = \left(\frac{b g^2}{32\pi^2}\right)^2 \frac{N_c^2-1}{4\pi^2}\,\sigma^4$

$$\Rightarrow \quad V(R) \sim -g^4\,\frac{1}{R^7}$$ ← Casimir-Polder result!

atomic physics: $\frac{1}{R^6}$ at "short" distances,

$\frac{1}{R^7}$ at long distances – <u>retardation</u> effects

- OPE/multipole expansion $\neq$ potential model

At small σ^2, perturbation theory cannot be trusted...

but $\rho(\sigma^2)$ can still be computed!

M. Voloshin
V. Zakharov

match anomalous θ^μ_μ onto effective chiral Lagrangian:

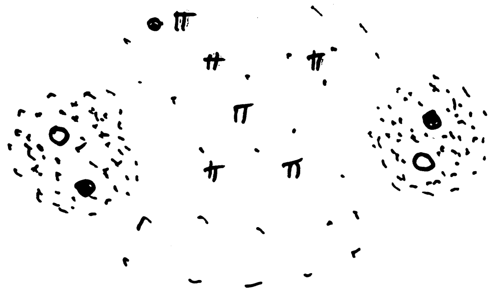
$$\theta^\mu_\mu = \frac{\beta(g)}{2g} G^2 \Longleftrightarrow \theta^{\mu\,(\text{chiral})}_\mu = -\partial_\mu \pi \partial^\mu \pi + 2m_\pi^2 \pi^a \pi^a + \ldots$$

$$\Downarrow$$

$$\langle 0 | \theta^\mu_\mu | \pi^+ \pi^- \rangle = \sigma^2$$

$$\rho(\sigma^2) \sim (N_f^2 - 1)\sigma^4$$

Pions dominate at long distances



$$V(R) \sim R^{-5/2} e^{-2\mu R}$$

H. Fujii
D. K. '99

Note: Gluon shadowing $\Leftrightarrow$ pion excess...

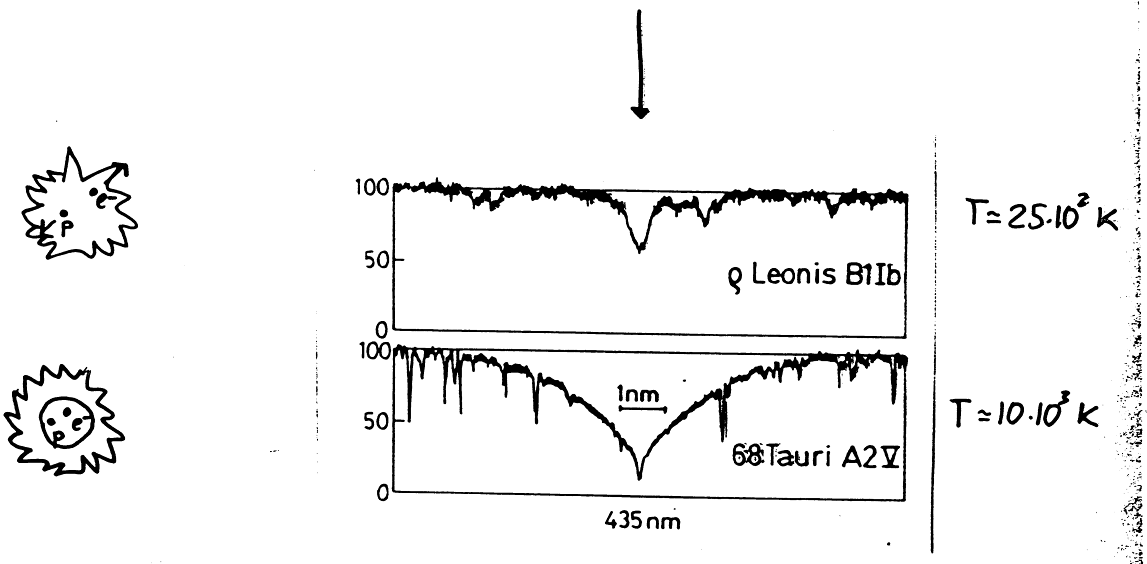
$\langle \pi | G^2 | \pi \rangle \to 0$ Decoupling of pions from J/ψ's in cool hadronic matter!

Stellar connection

K. Kajantie,
QM'88

stellar spectra = thermal + absorption lines

hydrogen H_γ line



Plasma suppresses the absorption (emission) lines, atoms are ionised

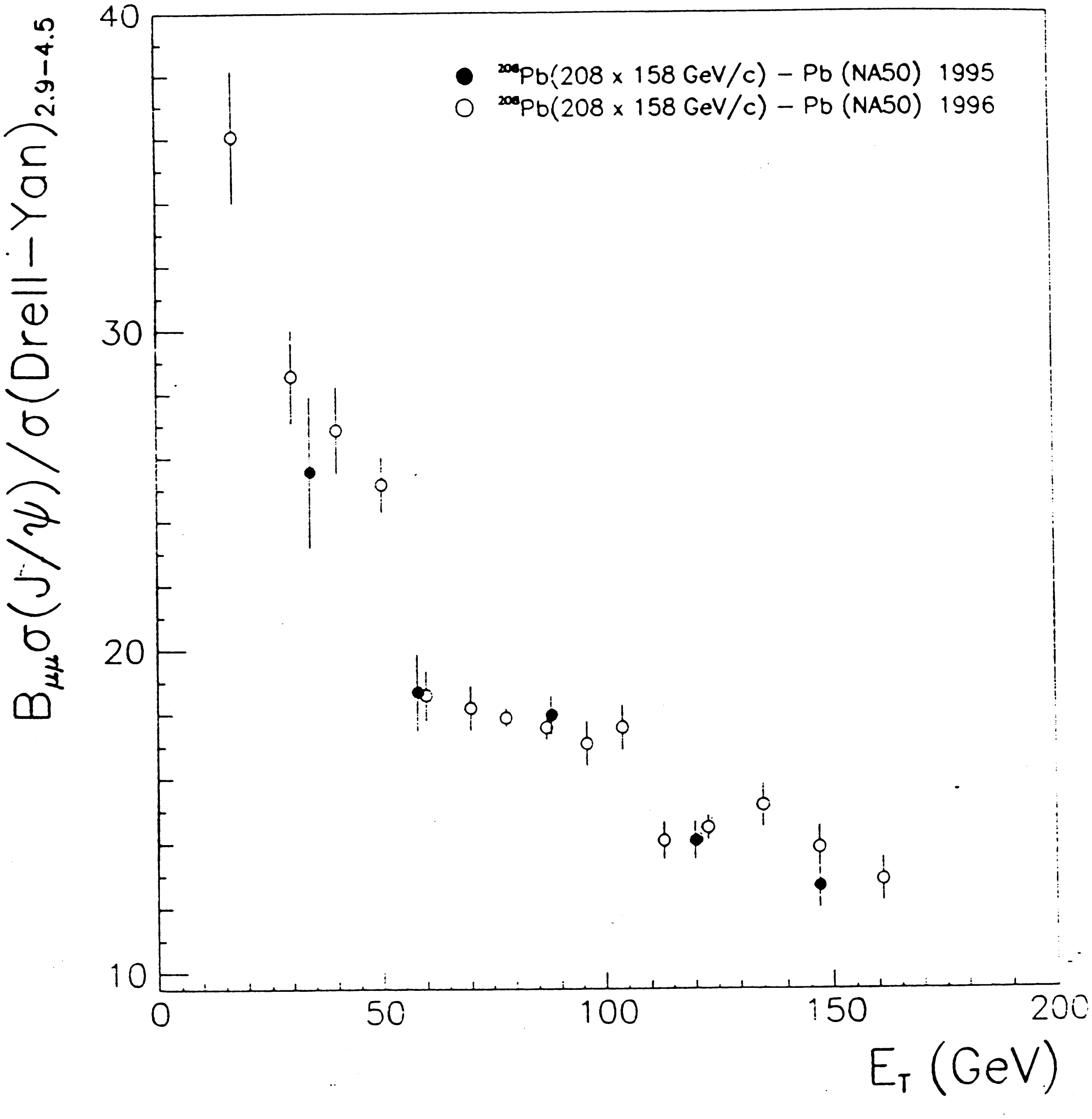
T. Matsui,
H. Satz '86

Similar things must happen in QCD!

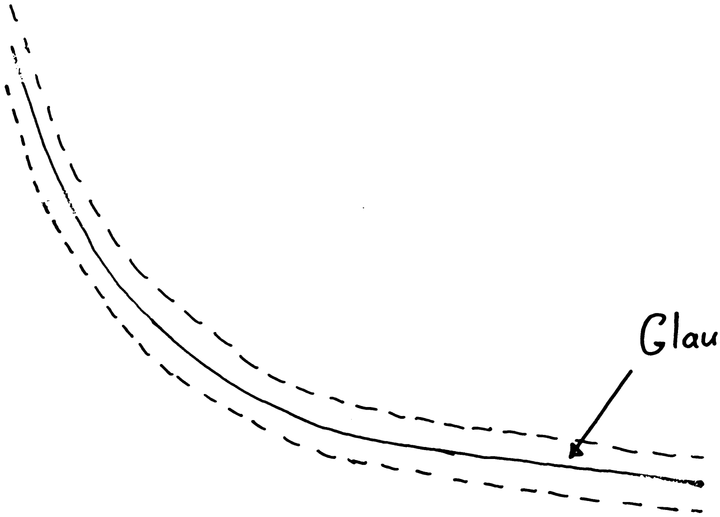
QED atoms ↔ heavy quarkonia

L. Ramello, QM'97

M. Gonin, NA50

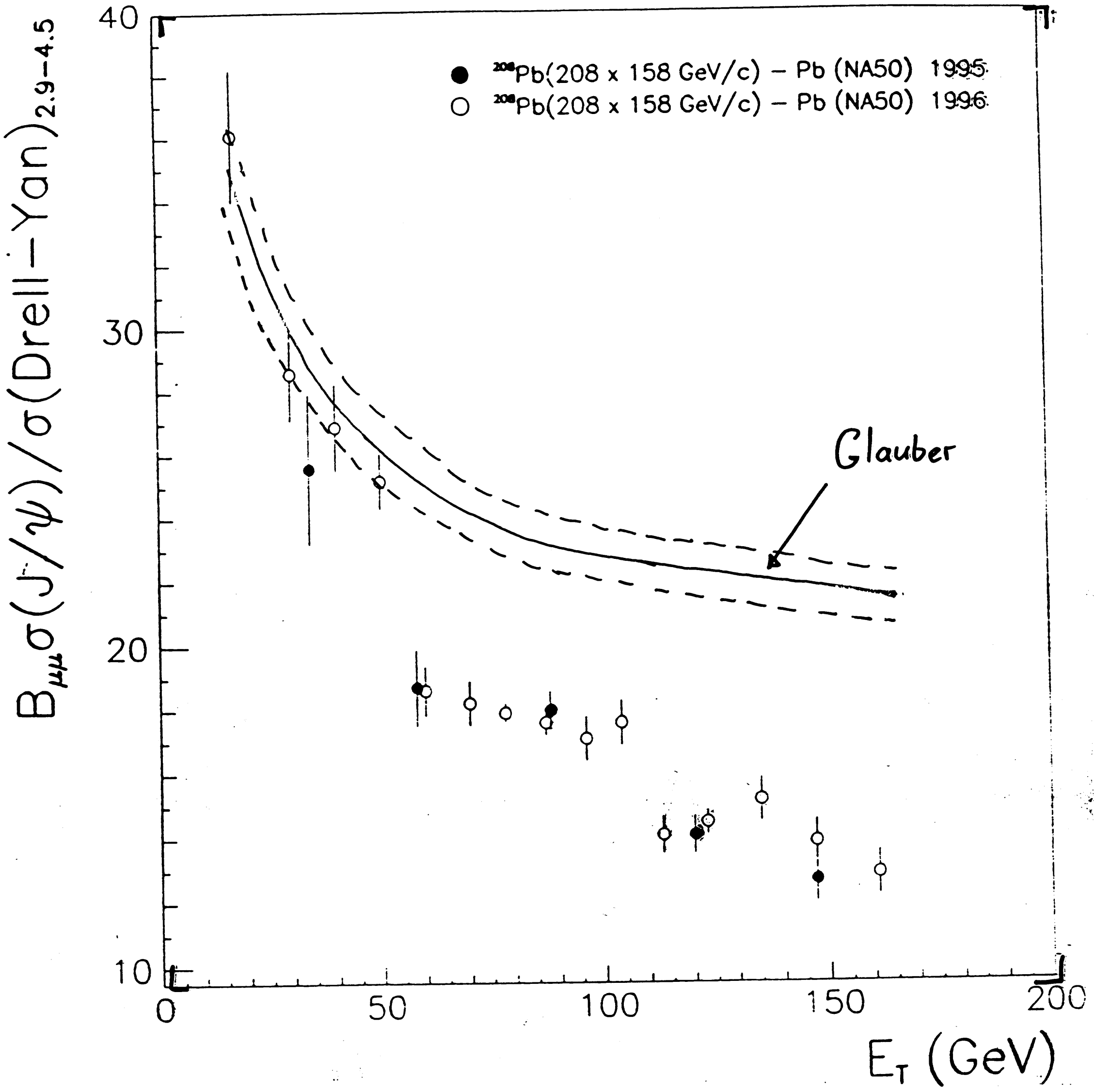


- Is this "anomalous"?


Glauber

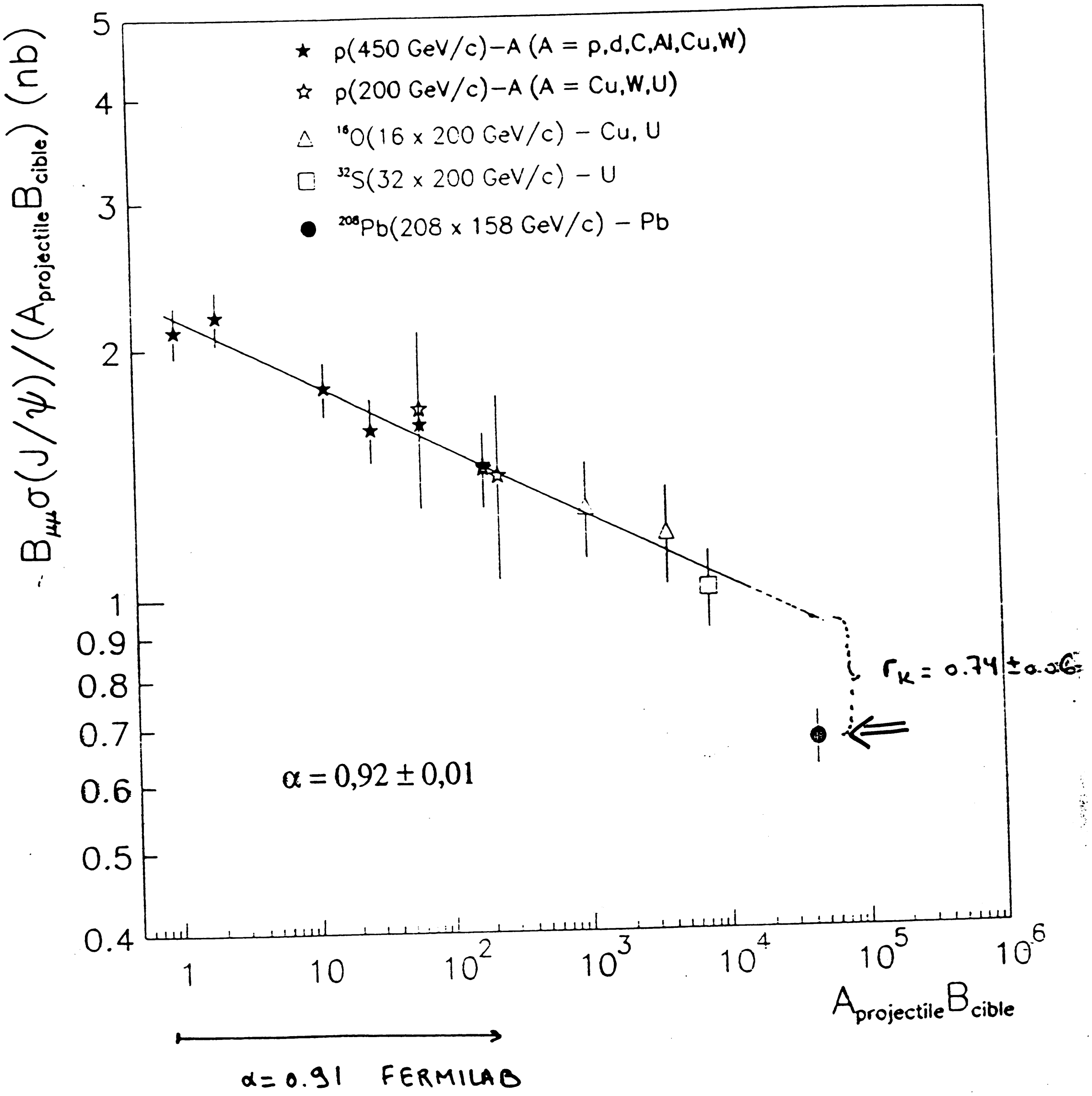
L. Ramello, QM'97

M. Gonin, NA50



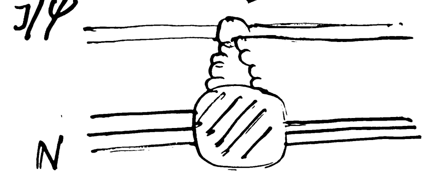
- Is this "anomalous"?

M. Gonin, NA50



★ p(450 GeV/c)–A (A = p,d,C,Al,Cu,W)
☆ p(200 GeV/c)–A (A = Cu,W,U)
△ ^{16}O(16 x 200 GeV/c) – Cu, U
□ ^{32}S(32 x 200 GeV/c) – U
● ^{208}Pb(208 x 158 GeV/c) – Pb
$B_{\mu\mu}\sigma(J/\psi)/(A_{projectile}B_{cible})$ (nb)
5
4
3
2
1
0.9
0.8
0.7
0.6
0.5
0.4
α = 0,92 ± 0,01
r_K = 0.74 ± 0.06
1
10
10^2
10^3
10^4
10^5
10^6
$A_{projectile}B_{cible}$
α = 0.91 FERMILAB

Wilson coefficients; computable in perturbation theory



non-perturbative local matrix elements

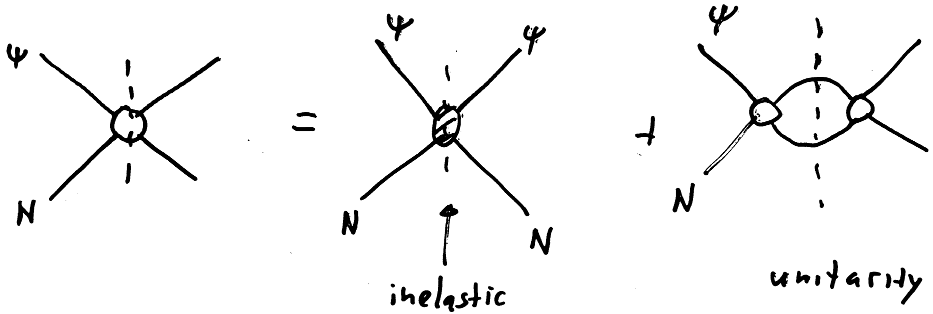
$$\mathcal{M} = \sum_i C_i O_i$$

Peskin;
Kaidalov, Volkovitsky;
Luke, Manohar, Savage;
Fujii
D.K.

at very low energy, the leading operator

$$O = \alpha_s \vec{E}^2 \leftarrow \text{couples to scale anomaly and to the nucleon mass}$$

$$\theta^\mu_\mu \sim \alpha_s G_{\mu\nu} G^{\mu\nu} + \sum m\bar{q}q$$



inelastic final states

unitarity correction

$$\sigma\left(\frac{\lambda_0}{x}\right) \sim x g(x)$$

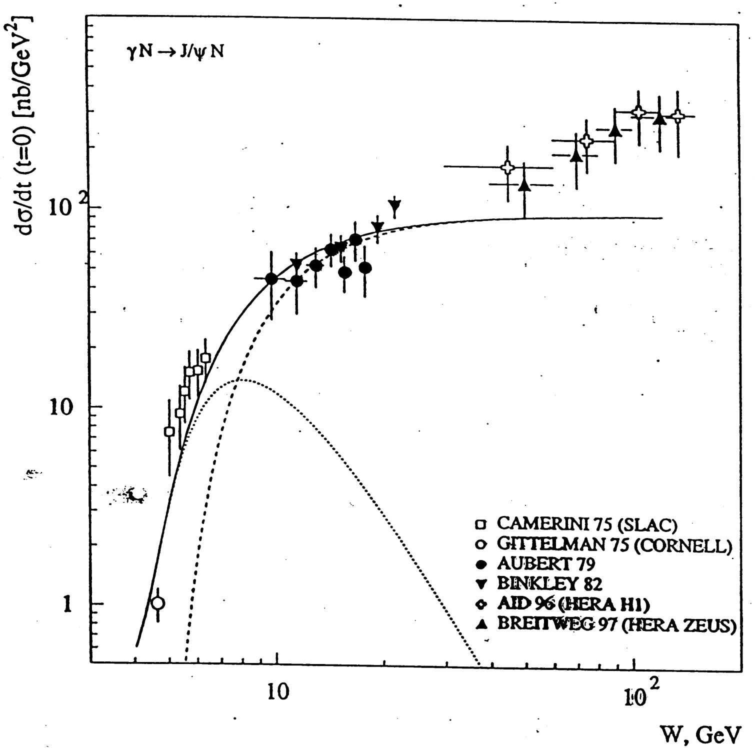
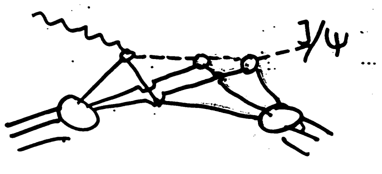


Figure 1: Forward J/ψ photoproduction data compared to our results with (solid line) and without (dashed line) the real part of the amplitude. The curves were obtained using a scaling PDF [4]



D.K.,
H. Satz
A. Syamtomov
G. Zinovjev '99

large real part is a consequence of LET's of QCD

⇒ interesting coherence effects!

(Glauber formalism applicable)

Reasons to study J/Ψ production at Jefferson Laboratory:

1) Establish mechanism of J/Ψ production (+ polarization measurements?)

2) Test QCD predictions for J/Ψ-N amplitude in production on nuclei

3) Extract low-energy absorption cross section: of great importance for the interpretation of AB data (SPS CERN, RHIC)