JLAB,
3 April, 2000

CHARM PRODUCTION NEAR THRESHOLD

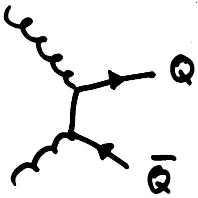
D. KHARZEEV

Physics Dept., BNL
and
RIKEN-BNL Center

1. Why charm?
2. The mechanisms of charmonium production
3. Probing the gluon (and charm) contents of the nucleon
4. Production on nuclei:
    a) Forming slow charmonia inside the nucleus (and testing them!)
    b) Probing the gluon field of the nucleus
    c) Forming, and detecting, charmed "supernuclei"
5. JLab and RHIC: complementary programs on heavy quarkonia?

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

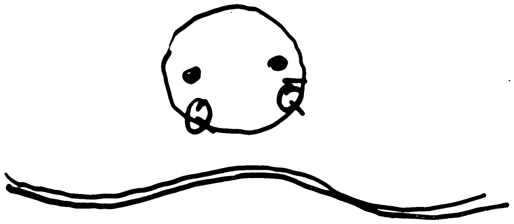
  and perturbation theory is meaningful



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

$\Rightarrow$ a good probe of gluon densities

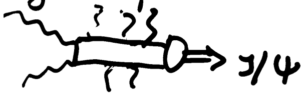
- Heavy quarkonia are small:

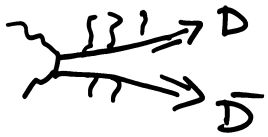


$$r_{(Q\bar{Q})} \sim \underset{\substack{\uparrow \\ \text{velocity}}}{\frac{1}{m_Q v}} < \Lambda^{-1}_{QCD}$$

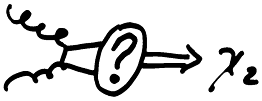
non-perturbative effects can be systematically taken into account using multipole/OPE expansion

$\Rightarrow$ a good probe of softer gluon fields





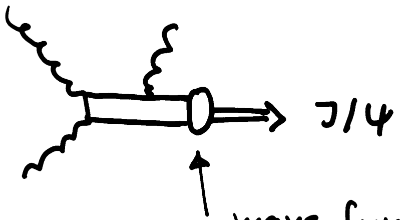
$\Rightarrow$ a test of hadronization



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

$\Rightarrow$ everything can be computed

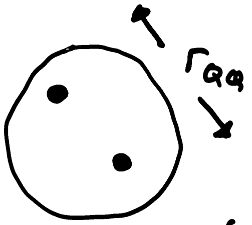
- But: fails in describing the integrated cross sections <u>and</u> high p_T production at the Tevatron (CDF, D0) → figures

- color octet model

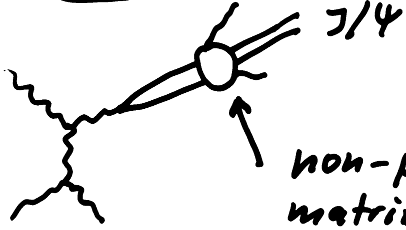
G. Bodwin
E. Braaten
G. Lepage
PRD51(95)1125
. . . .

three scales:

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

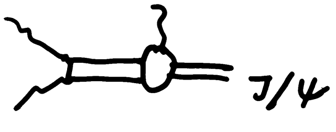


at high p_T



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

at small p_T



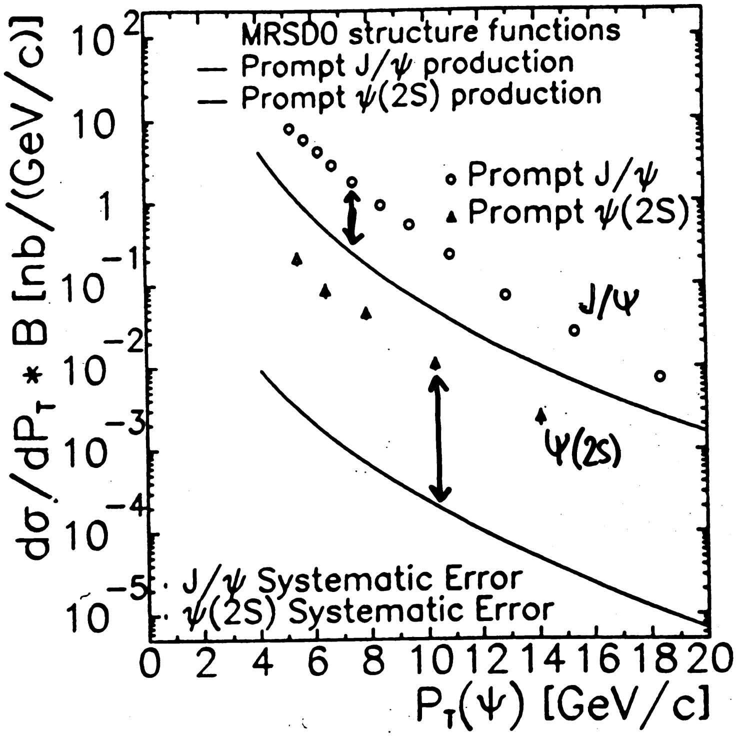
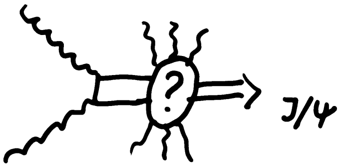


FIG. 3. The differential cross section times branching ratio $\mathcal{B}(\psi \rightarrow \mu^+\mu^-)$ for $|\eta^{\psi}| < 0.6$ for prompt ψ mesons. The vertical error bars are the statistical and the P_T-dependent systematic uncertainties, added in quadrature. Circles: J/ψ; triangles: $\psi(2S)$.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

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

- 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



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

$$\sigma_{\gamma\to c\bar{c}}(s) = \int_{4m_c^2}^{4m_D^2} d\hat{s} \int dx\, g(x)\, \sigma(\hat{s})\, \delta(\hat{s} - x s)$$

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

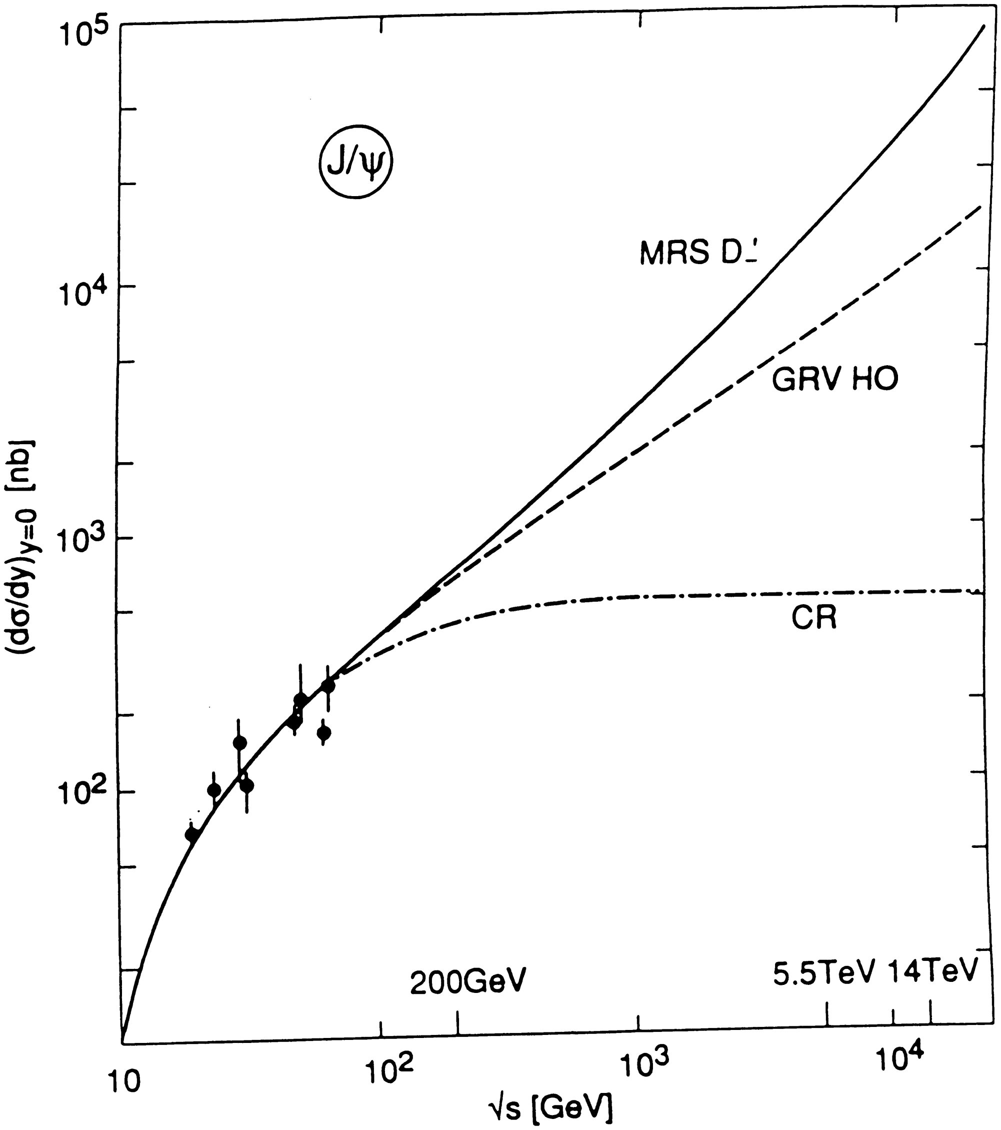


Fig. 2.2: Energy dependence of $(d\sigma^{pN}_{J/\Psi}/dy)_{y=0}$ for J/Ψ production, as obtained with MRS D-' and GRV HO parton distributions.

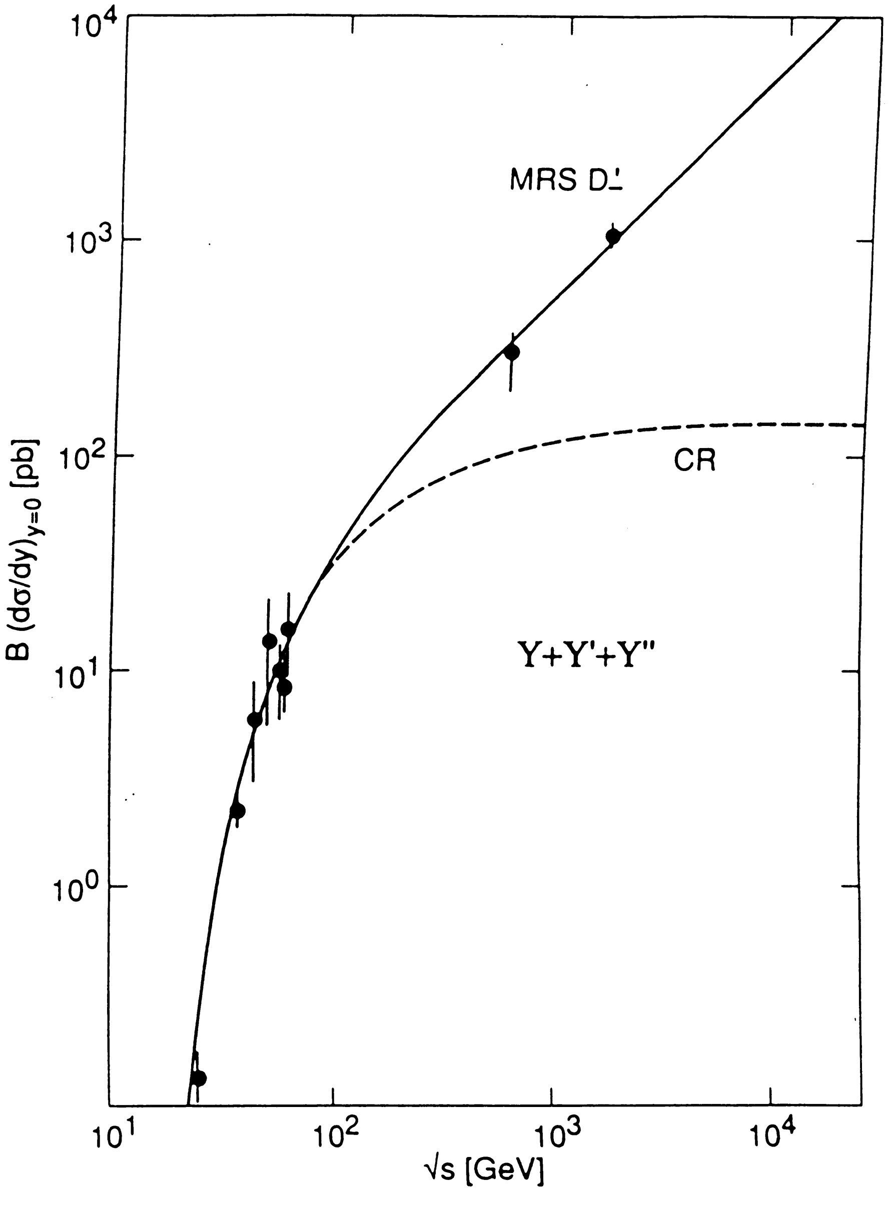


Fig. 2.3: Energy dependence of $(d\sigma_{\Upsilon}^{pN}/dy)_{y=0}$ for Υ production; the predictions with MRS D-' and GRV HO parton distributions essentially coincide.

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

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

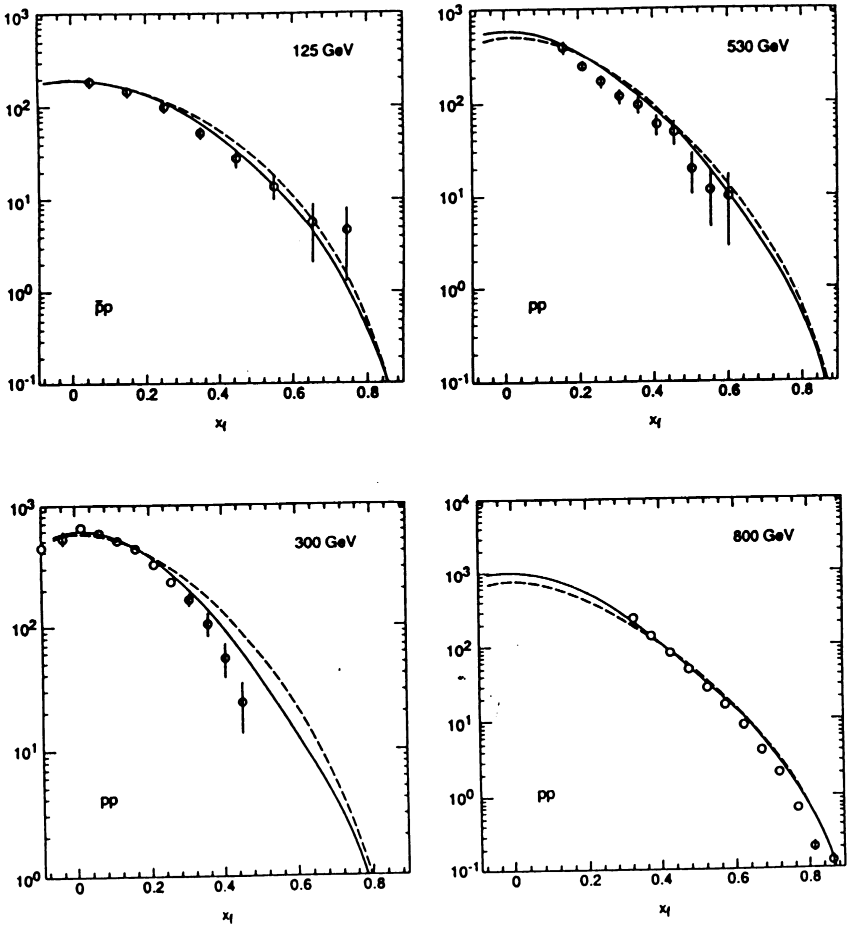


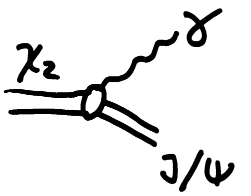
Fig. 10a: The J/ψ longitudinal momentum distributions compared to $\bar{p}N$ and pN data [9], with $x_F = p_L(J/\psi)/p_{max}(J/\psi)$; the MRS results are denoted by a solid, the GRV by a dashed line.

Example:

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

- What is the angular distribution of the photon?

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



effective coupling

vector potential

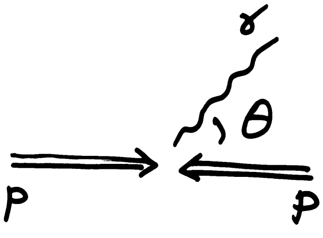
$$\mathcal{L} \sim \psi_\mu^\dagger D_\nu \eta^{\mu\nu} \sim \psi_\mu^\dagger A_\nu \eta^{\mu\nu}$$

J/ψ field

χ_2 field

(QED multipole expansion)

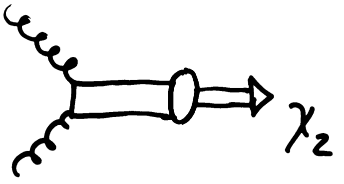
$$\boxed{\begin{aligned} W^{2,\pm 2}(\theta) &= \frac{1}{2} + \frac{1}{2}\cos^2\theta \\ W^{2,\pm 1}(\theta) &= \frac{3}{4} - \frac{1}{4}\cos^2\theta \\ W^{2,0}(\theta) &= \frac{5}{6} - \frac{1}{2}\cos^2\theta \end{aligned}}$$



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

R.L. Jaffe, D.K.
Phys. Lett. B '99

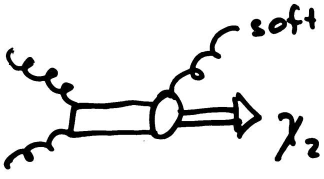
- Color singlet model:



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

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

- Color octet model:

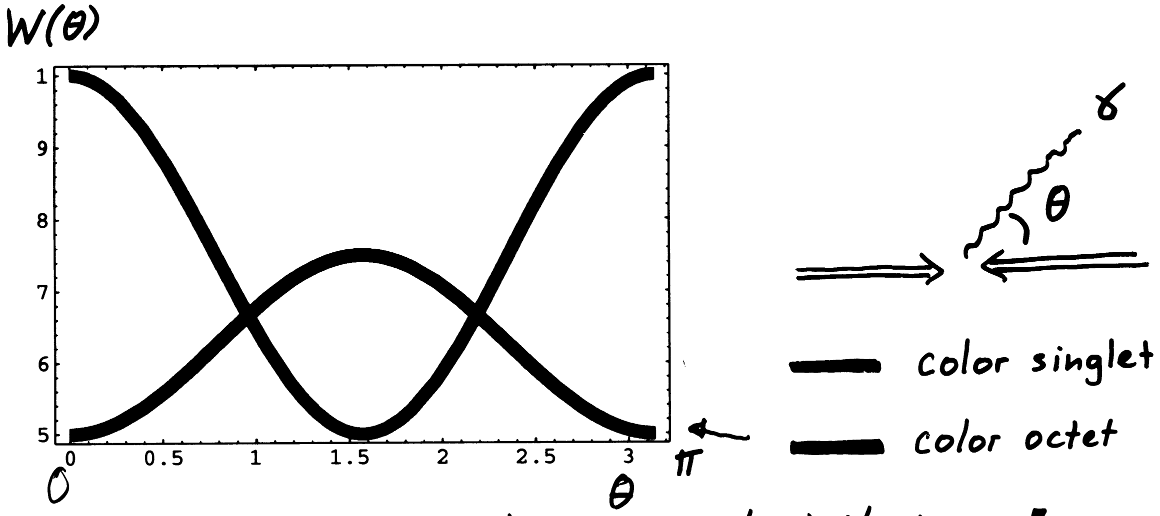


note: in QED, $^3P_2 \not\to \gamma\gamma\gamma$

in QCD, this is possible: $f_{abc} \sim \mathrm{Tr}(abc) - \mathrm{Tr}(acb)$

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

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



<u>VERY</u> different distributions!

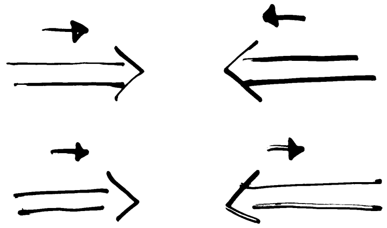
R.L. Jaffe, D.K.
hep-ph/9903280

$\Downarrow$

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

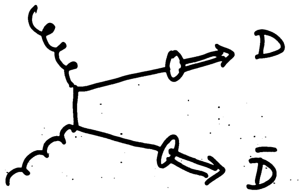
$$\frac{d\sigma}{d\Omega} \sim g(x_1, M_\chi^2)\, g(x_2, M_\chi^2) \left\{ \left(\frac{1}{2} + \frac{1}{2}\cos^2\theta\right) \underline{A}^1 + \left(\frac{3}{4} - \frac{1}{4}\cos^2\theta\right) \underline{A}^8 \right\}$$

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



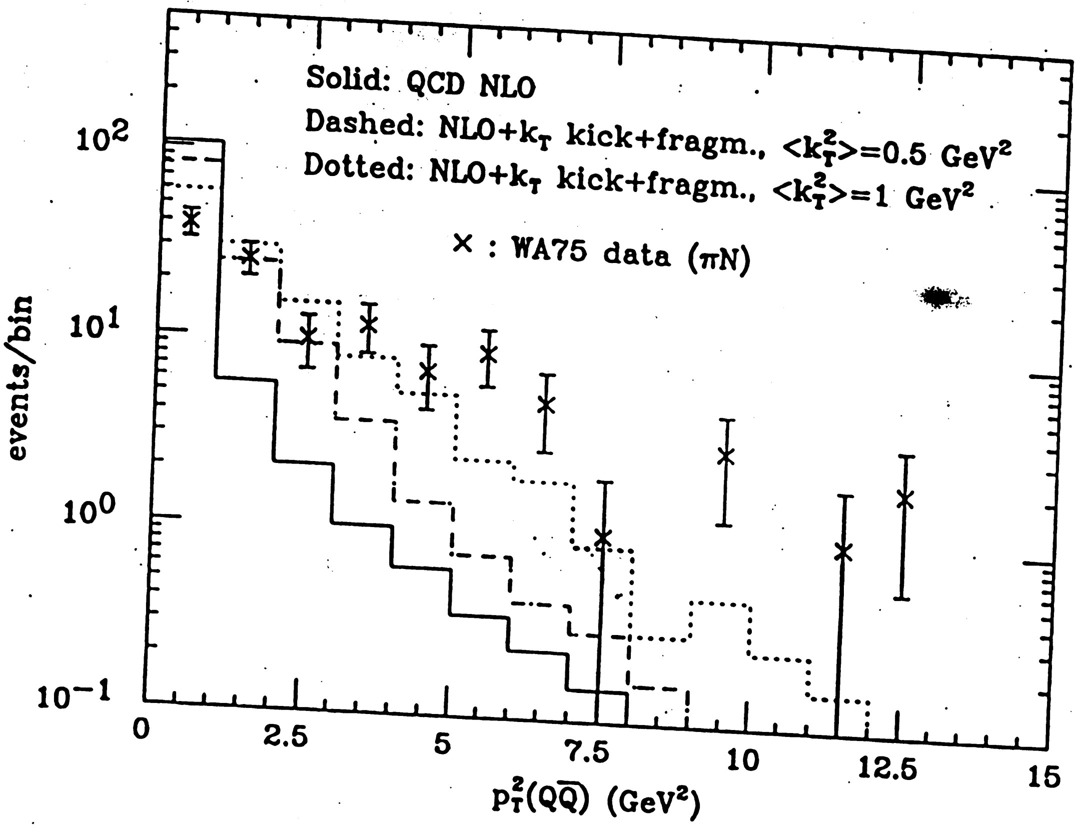
$$\frac{d\sigma^{\uparrow\uparrow} - d\sigma^{\uparrow\downarrow}}{d\sigma^{\uparrow\uparrow} + d\sigma^{\uparrow\downarrow}} = - \frac{\Delta g(x_1, M_\chi^2)}{g(x_1, M_\chi^2)} \frac{\Delta g(x_2, M_\chi^2)}{g(x_2, M_\chi^2)} \times$$

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



$$p_T(Q\bar{Q}) = |\bar{p}_D + \bar{p}_{\bar{D}}|$$

(In lowest order perturbation theory, $p_T(Q\bar{Q}) = 0$ without "intrinsic" k_T)



From S. Frixione et al., hep-ph/9702287

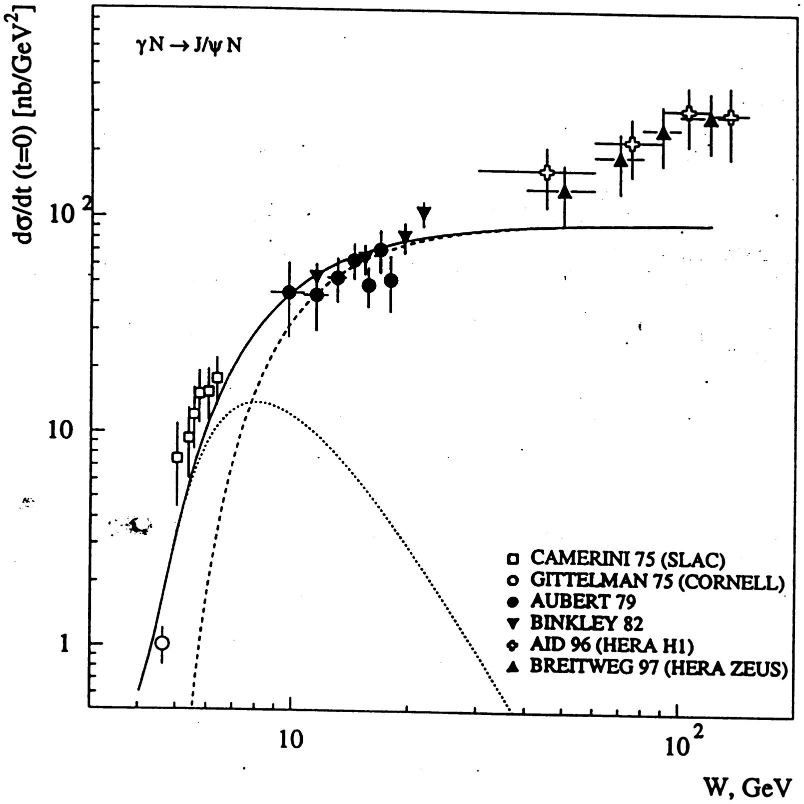
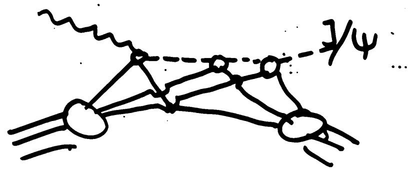


Figure 1: Forward J/ψ photoproduction data compared to our results with (solid line) and without (dashed line) the real part of the amplitude. The curves were obtained using a scaling PDF [4]



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

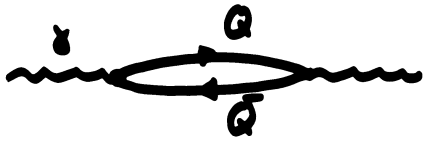
large real part is a consequence of LET's of QCD

⇒ interesting coherence effects!
(Glauber formalism applicable)

What is charmonium formation time?

It can be evaluated in a model-independent way:

- consider



$J_\mu \sim \bar{Q}\gamma_\mu Q$

$$\Pi(x) = \langle 0|T\{J(x)J(0)\}|0\rangle$$

•• write down dispersion relation in coordinate space:

$$\Pi(x) = \frac{1}{\pi}\int \mathrm{Im}\,\Pi(s)\, D(\sqrt{s}, x^2)\, ds,$$

where

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

$$\mathrm{Im}\,\Pi(s) = \frac{s}{(4\pi\alpha)^2}\underbrace{\sigma(e^+e^- \to \bar{Q}Q; s)}_{\text{measured experimentally}}$$

∴ Define

$$F_\psi(\tau) \equiv \frac{\Pi_\psi(\tau)}{\Pi(\tau)}, \quad \Pi(\tau) \xrightarrow[\tau\to\infty]{} \frac{1}{\tau^{3/2}} e^{-m_\psi \tau}$$

the fraction of J/ψ in $Q\bar{Q}$ wave packet

Euclid → Minkowski

$$\boxed{\tau_\psi \sim 0.45 \text{ fm}}$$

(when $F_\psi \geq 1/2$)

D. K.,
R. L. Thews
PRC '99

Formation length inside the nucleus

$$l_{form} = \gamma\tau \, ; \quad \gamma \approx \frac{P_\psi}{(M_\psi + M_{\psi'})/2} \simeq \frac{P_\psi}{M_\psi}$$

$$\gamma \cdot 0{,}45\,\text{fm} \leq R_A$$

is very short in threshold production

$\gamma \sim 2 \div 3$

<u>Other processes</u>:

- $\bar{p}A \to J/\psi(A-1)$

S. J. Brodsky,
A. H. Mueller '88

problem(?) – Fermi motion
$S \sim 10^{-4}$ D. K. '89

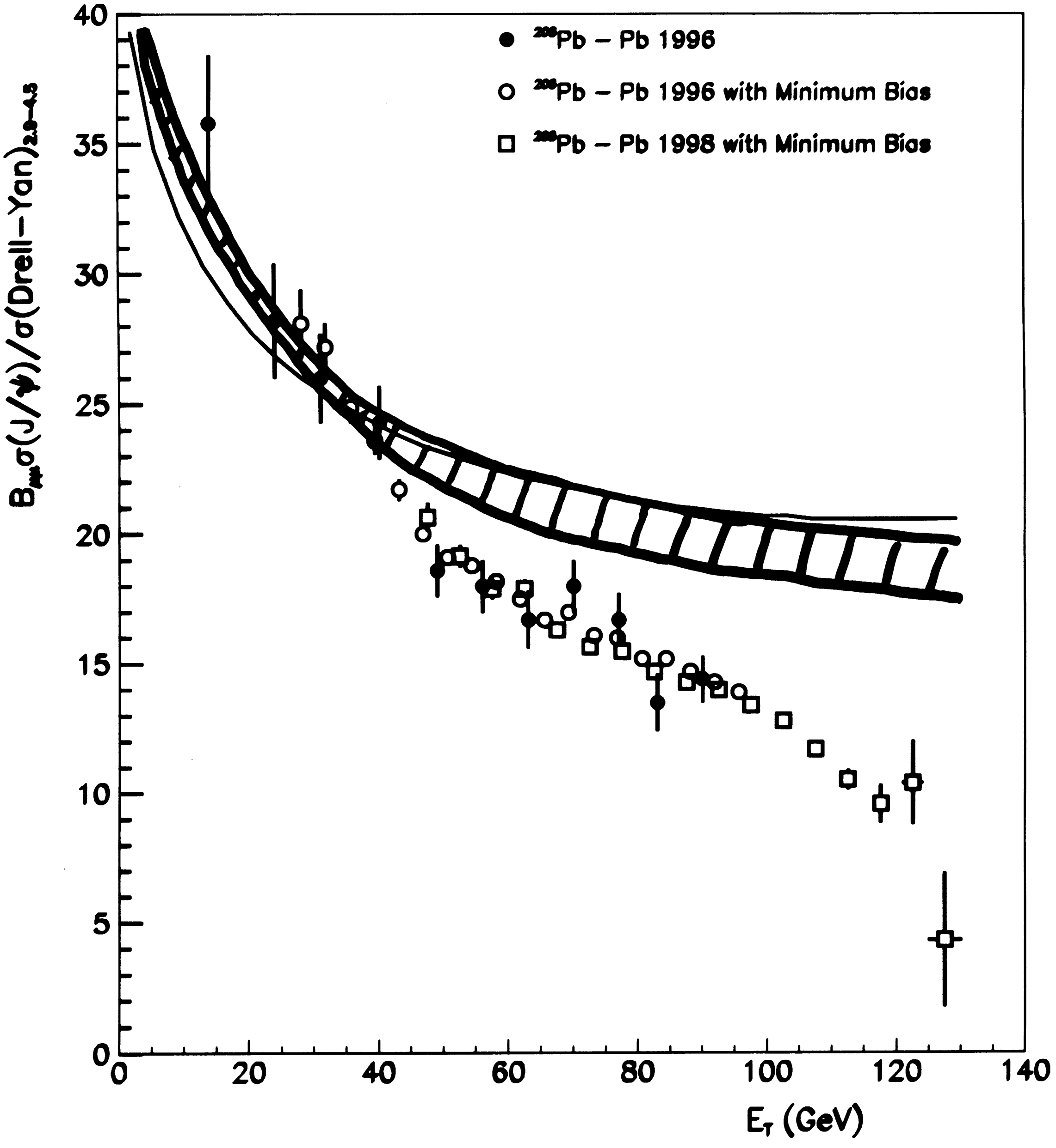
- $Ap \to \psi X$

"inverse kinematics"

$\Downarrow$

Can extract low-energy ψN amplitude

- Attractive? (VdW forces, ...) S. Brodsky et al ......
- (Almost) real?
- $\sigma_{\psi N \to X}$? – heavy ion implications...


^{208}Pb – Pb 1996
^{208}Pb – Pb 1996 with Minimum Bias
^{208}Pb – Pb 1998 with Minimum Bias
$B_{\mu\mu}\sigma(J/\psi)/\sigma(\text{Drell-Yan})_{2.9-4.5}$
E_T (GeV)
0
5
10
15
20
25
30
35
40
0
20
40
60
80
100
120
140

- Testing in-medium modifications of ψ', ψ'' ?

Several models predict the D-meson mass decrease in nuclear matter,
e.g. A. Hayashigaki, nucl-th/0001051

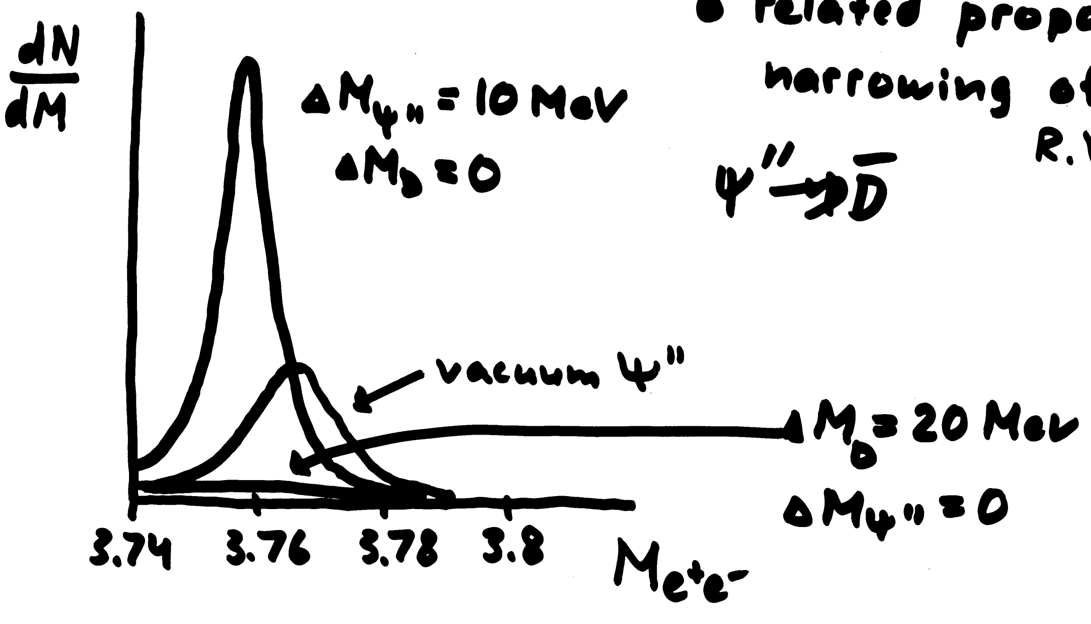
$$\Delta M_D \simeq 50 \text{ MeV}$$

If $\Delta M_{\psi'} \ll \Delta M_D$, it can decay into $\psi' \to D\bar{D}$, acquiring the width (from $\Gamma \sim 300$ keV)
$\Gamma_{\psi'} \sim 20$ MeV ~ 10 fm $\Rightarrow \ell_d \simeq \gamma \Gamma_{\psi'}$
$\Rightarrow$ significant overall broadening of ψ'? Measure $\gamma A \to \psi' A^{*}$, $\hookrightarrow e^+e^-$

- related proposal: narrowing of ψ''

$\psi'' \nrightarrow D\bar{D}$

R. Vogt, A. Jackson
D.K.



Forming, and detecting, charmed "supernuclei"?

- $\gamma N \to (\bar{Q}Q) N$

$$(\bar{Q}Q) N \to \Lambda_c + \bar{D}$$

1-2 GeV/c

very unique for γA and $\bar{p}A$

D.K.,
N. Starkov
"Physics at SuperLEAR"
'91

$$\sigma_{SN} = \sigma(\gamma A \to (\bar{Q}Q)) \langle W_{int} \cdot W_c \rangle$$

reinteraction probability $\simeq 0.1$ for Pb

Λ_c capture probability $\simeq 10^{-6}$ @ $p_{c\bar{c}} \sim 4\,\mathrm{GeV}/c$

$$\sigma_{SN} \simeq 200\,\mathrm{nb} \cdot 10^{-7} \sim \underline{10^{-5}\,\mathrm{nb}}$$

- Signature: nonmesonic decay

$$\Lambda_c + N \to \Lambda_s + p$$

$p_{cm} \simeq 1{,}25\,\mathrm{GeV}/c$

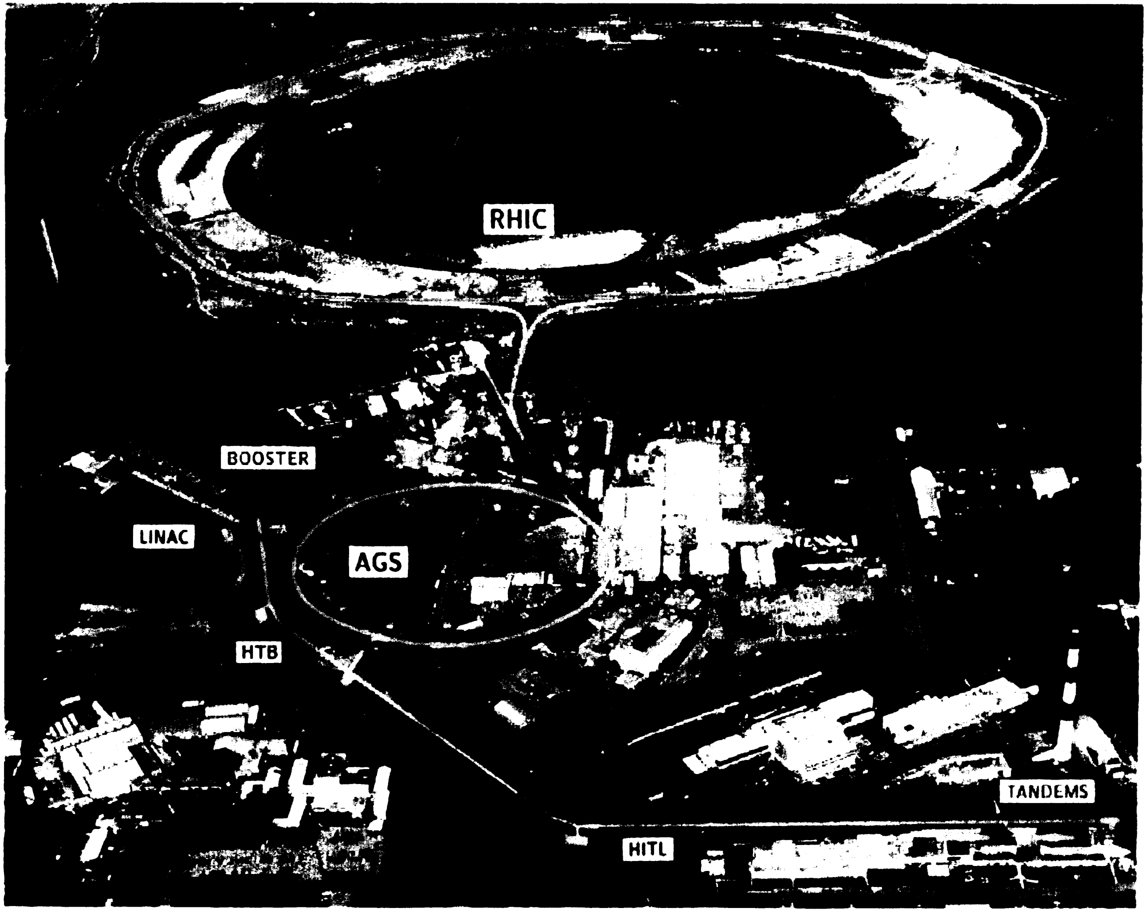
probability $\sim \cos^4\theta_c$ — Cabbibo angle

compared to $\sim \cos^2\theta_c \sin^2\theta_c$

for $\Lambda + N \to N + N$

but less Pauli blocking

RELATIVISTIC HEAVY ION COLLIDER (RHIC)
BROOKHAVEN NATIONAL LABORATORY



Configuration:	**Two Concentric Superconducting Magnet Rings (3.8 km Circumference); Six Interaction Regions**	
Injection:	**Van de Graaff —> Booster —> AGS**	
Ion Species:	**Ranges from A~200 (Au) to proton; also p + A**	
Performance:	**Au + Au**	**p + p**
E_{beam} (Max)	**100 GeV/u**	**250 GeV**
Luminosity	**2×10^{26} cm^{-2}s^{-1}**	**1.4×10^{31} cm^{-2}s^{-1}**
Completion:	**Expected in June 1999**	

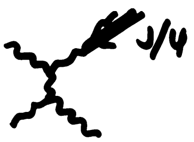
- physics run in summer 2000!

The Future of Quarkonium at RHIC

1. Elementary production mechanism

- X sections in wide $\sqrt{s}$, p_T range
- Polarization as a function of p_T:

  $\psi' \to \mu^+\mu^-$, (e^+e^-), $\psi' \to J/\psi + \pi^+\pi^-$
- Spin asymmetries
- J/ψ + jet



. . .

- Diffractive production
- Problem: B decays

  (a way to measure B ??)

2. Quarkonium as a probe

- Impact parameter dependence
- p_T dependence
- Polarization ?
- J/ψ + jet ?
- Diffractive production

} at different A,B

- Problem: benchmark process ?

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)