Photoproduction of charmonium near threshold

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Outline

1. Production of $J/\psi, \psi'$ off a nucleon

   ◇ Data: All energies

   ◇ Theory: High energies - pQCD factorization theorem.

   ◇ Theory: Near threshold - Is skewedness of gluon densities important?

2. Production off the nuclei

   ◇ Coherence length

   ◇ $J/\psi - \psi'$ paradox and Vector Dominance Model

   ◇ Genuine $J/\psi - N$ cross section

   ◇ Heavy ion connection; evidence for large $\sigma(\psi' - N)$.

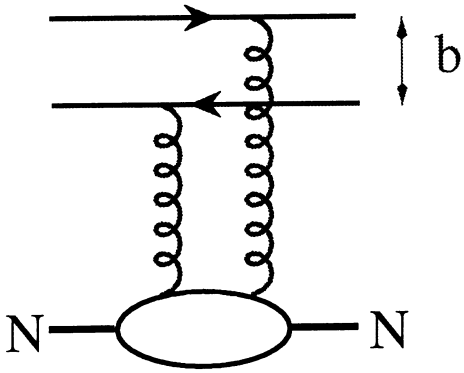
   ◇ Collective effects

   ◇ Experimental options

3. Open charm production

Interaction of small color singlet dipoles with hadrons at high energies

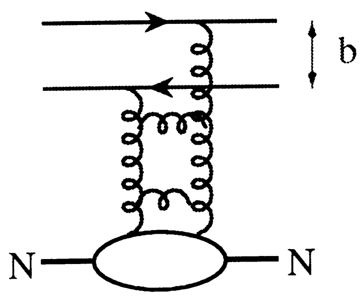
Gauge invariance for a small dipole-hadron interaction $\rightarrow$



Two gluon exchange model

$\sigma = C\, b^2$ (F.Low 75)

C does not depent on E_{inc}



pQCD in the leading log b approximation (Baym, Blattel,FS, 93)

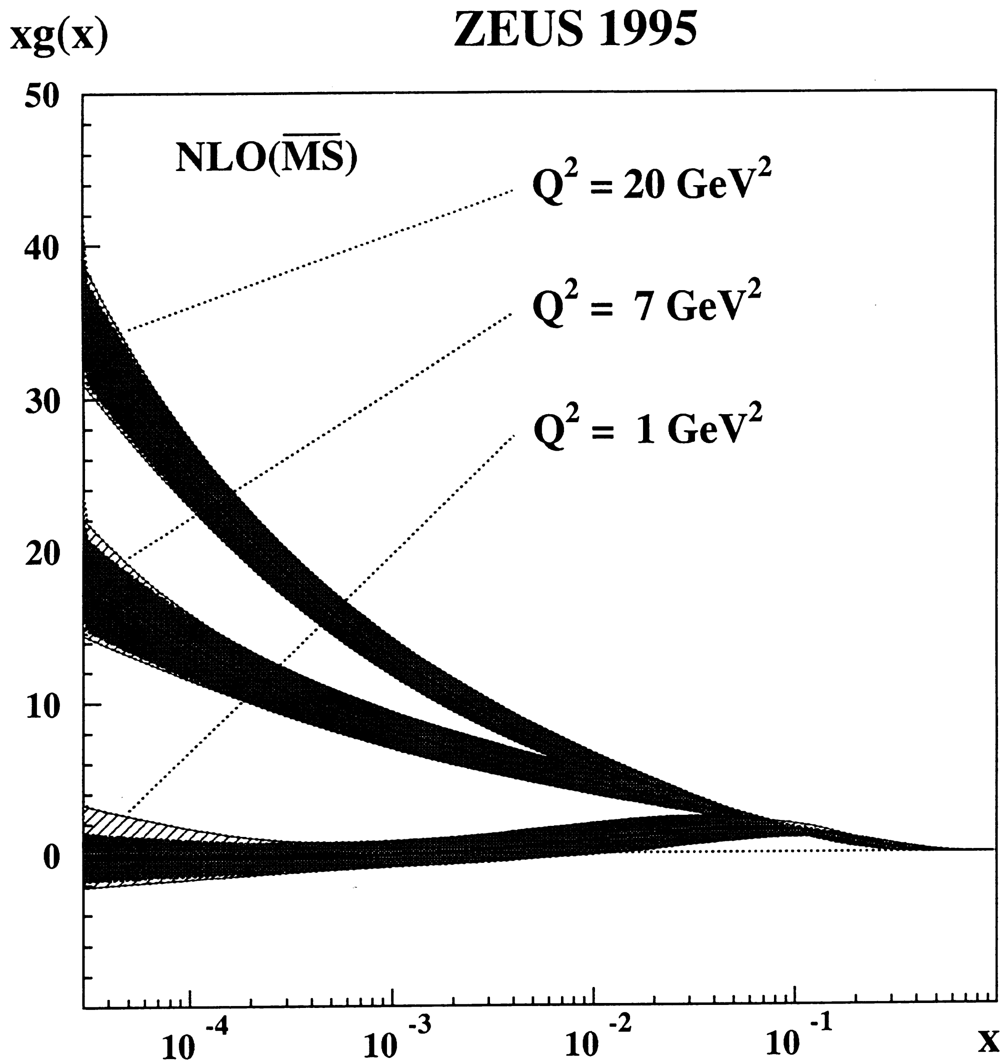
$$\sigma^{inel}(b,E_{inc}) = \frac{\pi^2}{3}\, b^2\, \alpha_S\, x\, G_N(x, \frac{\lambda}{b^2})$$

Qualitative difference from QED: cross section rapidly increases with W - a fingerprint of small size dipole interaction in DGLAP kinematics. ($\lambda(x = 10^{-3}, Q^2 = 10\ GeV^2 \approx 9$)

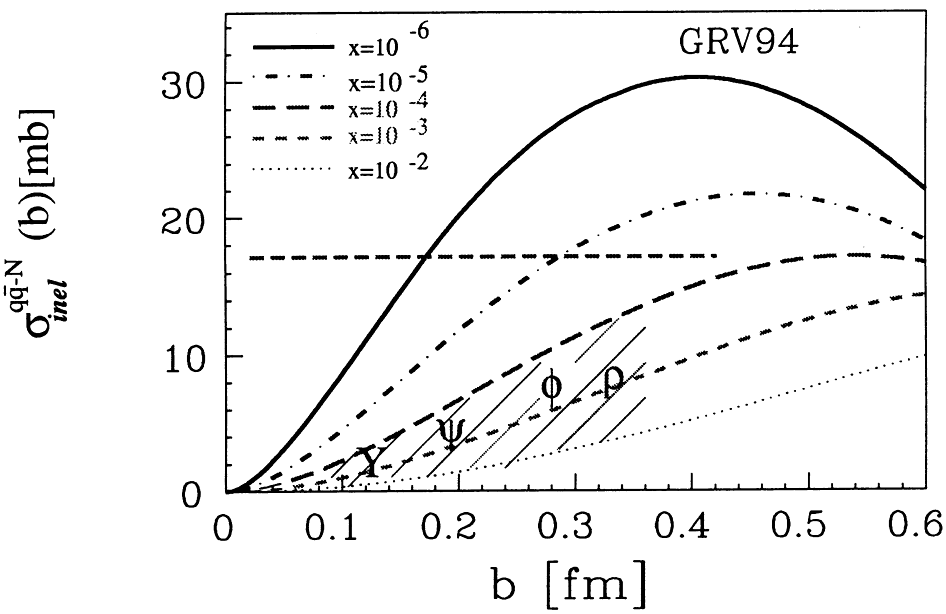
For color octet dipole cross section is $9/4$ times larger.

$$\Longrightarrow \quad \sigma(s, Q^2_{eff} = 4\ GeV^2) \propto \left(\frac{s}{s_0}\right)^{0.2};$$

$$\sigma(s, Q^2_{eff} = 40\ GeV^2) \propto \left(\frac{s}{s_0}\right)^{0.4}$$



xg(x)
ZEUS 1995
NLO($\overline{MS}$)
$Q^2 = 20$ GeV^2
$Q^2 = 7$ GeV^2
$Q^2 = 1$ GeV^2
50
40
30
20
10
0
10^{-4}
10^{-3}
10^{-2}
10^{-1}
x



------------- *Unitarity limit for* $\bar{q}q$*-N scattering*

Exclusive $\rho, \phi, J/\psi, \Upsilon$ vector meson production probes $10^{-4} \leq x \leq 10^{-2}, .1 \leq b \leq .35 fm$

From S-channel unitarity (Froissart) bound - $\sigma_{inel} \geq \sigma_{el}$ the growth should stop - breakdown of DGLAP

$$\sigma^{inel}_{small\ dipole-nucleon} \sim 20mb \text{ (FS \& Koepf 96)}$$

Relevant for HERA where $\sigma^{color\ oct.-N}_{inel}(10^{-4}, 10\ GeV^2) \sim 16$ mb. -Breakdown before the BFKL dynamics could become relevant

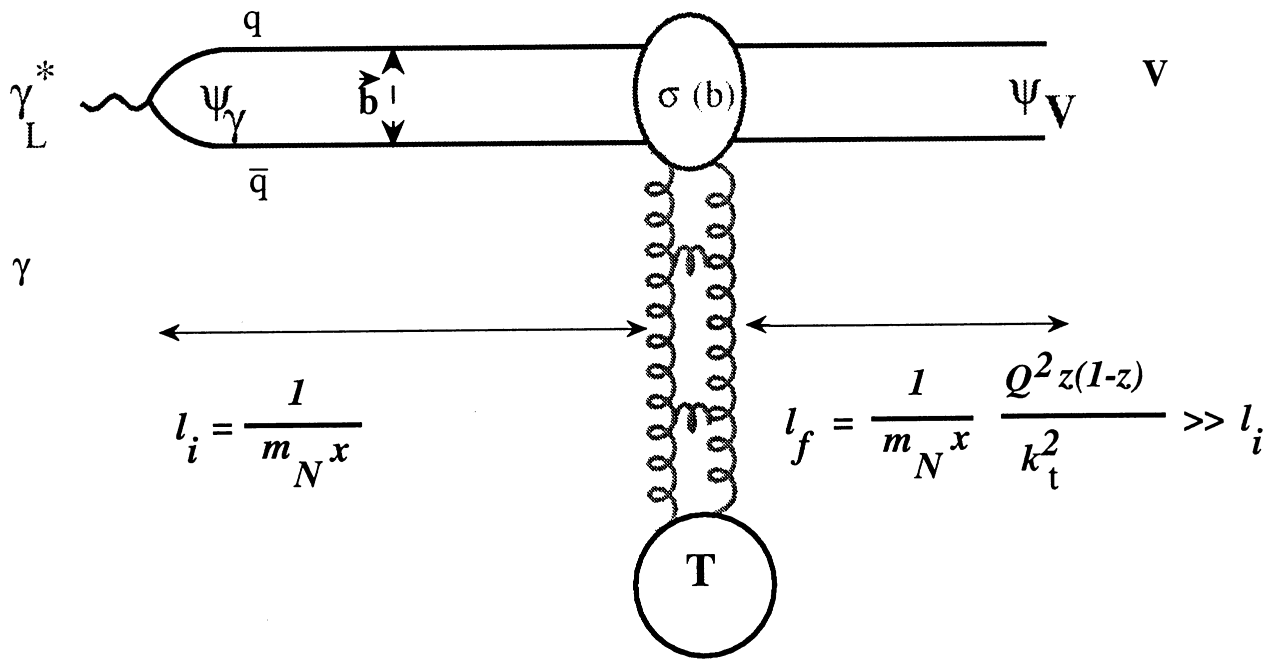
For $A \sim 200$ $\sigma^{color\ oct.-A}_{inel} \leq \pi R_A^2$ implies for A=200: $\sigma^{gg-A}_{inel}/A\sigma^{gg-N}_{inel} \leq 1/3$ for $x = 10^{-4}, Q^2 = 10 GeV^2$

$\Longrightarrow$ Large nuclear gluon shadowing

Vector meson diffractive production Theory and HERA data

Space-time picture of Vector meson production at small x in the target rest frame

Three stages of the $\gamma_L^* + N \to V + N$ collision:



♣ γ^* breaks up into $\bar{q}q$ ($p_q = (zq_0, k_t)$) with a lifetime

$$\tau_i = l_i/c = \frac{2q_0}{Q^2 + \frac{k_\perp^2 + m_q^2}{z(1-z)}} \approx \frac{1}{m_N x}; \quad l_i \geq 100 \text{ fm at HERA}$$

♣♣ The $\bar{q}q$ pair then scatters off the target proton.

♣♣♣ $q\bar{q}$ then lives a time $\tau_f = l_f/c = \frac{2q_0}{\frac{k_\perp^2 + m^2}{z(1-z)}}$ before the final state vector meson is formed. $\tau_f \geq \tau_i$.

$\Rightarrow$ Similar to the case of $\pi + T \to 2jets + T$ process, $A(\gamma_L^* + p \to V + p)$ can be written as a convolution of the light-cone wave function of the photon $\Psi_{\gamma^* \to |q\bar{q}\rangle}$, the scattering amplitude of the hadron state, $A(q\bar{q}T)$, and the wave function of the vector meson, ψ_V. In the impact parameter space

$$A = \int d^2b \psi_{\gamma*,L}(b) \sigma(b,s) \psi_V(b)$$

The leading twist parameter free answer is

$$\left.\frac{d\sigma^L_{\gamma^* N \to VN}}{dt}\right|_{t=0} =$$

$$\frac{12\pi^3 \Gamma_{V \to e^+e^-} M_V \alpha_s^2(Q) \eta_V^2 \left|\left(1 + i\frac{\pi}{2}\frac{d}{d\ln x}\right) xG_T(x, Q^2)\right|^2}{\alpha_{EM} Q^6 N_c^2}$$

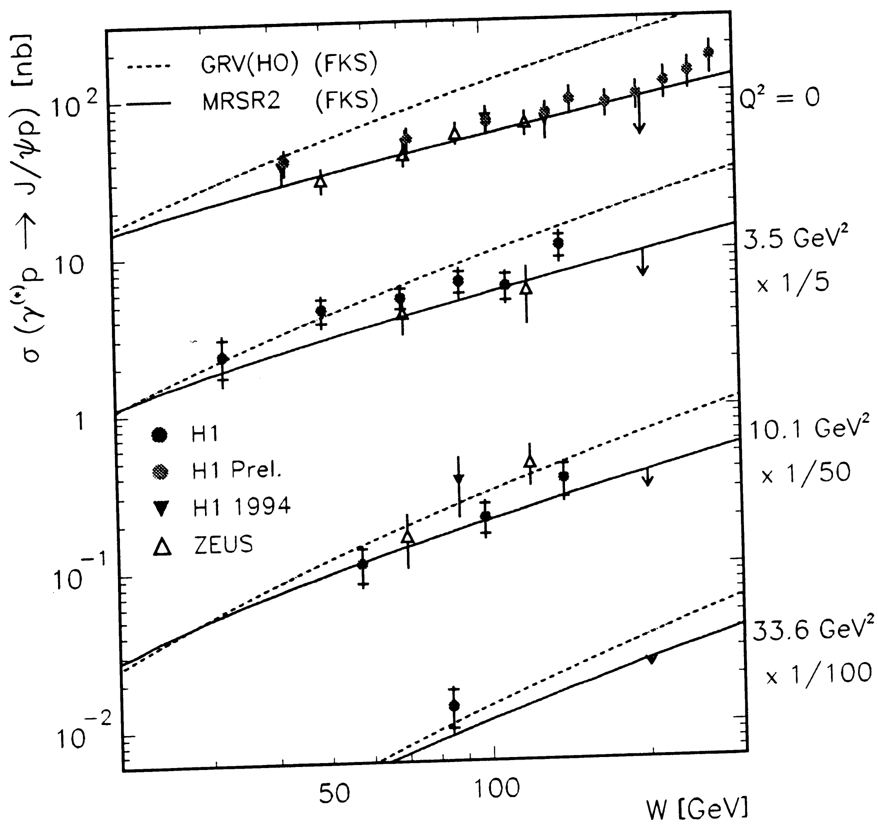
. Here, $\Gamma_{V \to e^+e^-}$ is the decay width of $V \to e^+e^-$;

$$\eta_V \equiv \frac{1}{2} \frac{\int \frac{dz\, d^2k_t}{z(1-z)} \Phi_V(z, k_t)}{\int dz\, d^2k_t\, \Phi_V(z, k_t)} \to 3 \;|_{Q^2 \to \infty}$$

Note: In the leading twist b=0 in $\psi_V(b)$. Finite b effects in the meson wave function is one of the major sources of the higher twist effects.

Extensive data on VM production from HERA support *dominance of the pQCD dynamics.* Numerical calculations including finite b effects in $\psi_V(b)$ explain key elements of high Q^2 data. The most important ones are:

(i) Energy dependence of J/ψ production; absolute cross section of $J/\psi, \Upsilon$ production.



(ii) Absolute cross section of ρ production at $Q^2 \sim 20-30\ GeV^2$ and its energy dependence at $Q^2 \sim 20\ GeV^2$. Explanation of the data at lower Q^2 is more sensitive to the higher twist effects, and uncertainties of the low Q^2 gluon densities.

(iii) Convergence of the t slopes

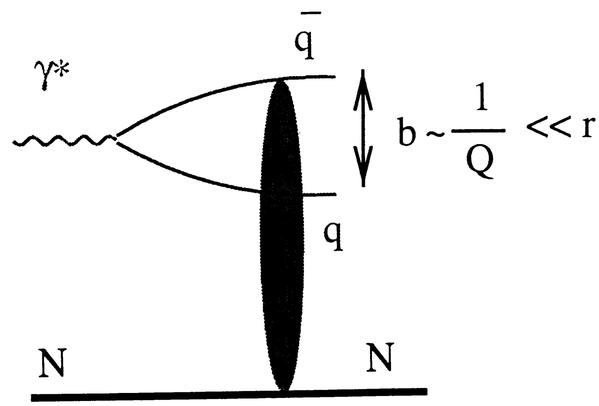
B ($\sigma = A\exp(Bt)$) of

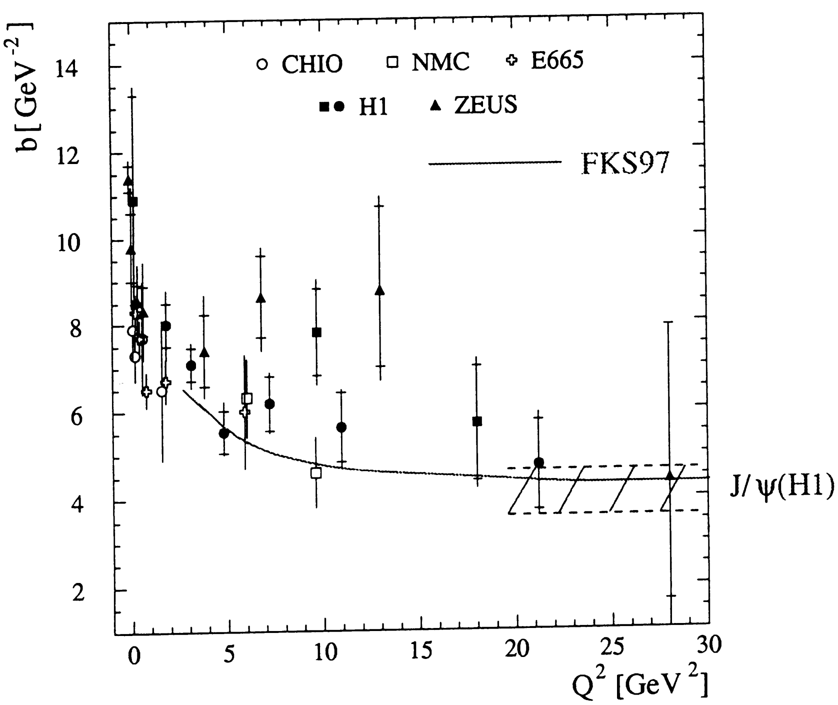
$\rho-$ meson production

at large Q^2 and

J/ψ production

(Brodsky et al 94)





$\Longrightarrow$ Small size $q\bar{q}$ Fock components are present in light mesons.

$\Longrightarrow$ At the transverse separations $b \leq 0.3fm$ pQCD reasonably describes "small $q\bar{q}$ dipole" - nucleon interactions.

$\sqrt{s} \leq 30$ GeV: competing model:

Color evaporation model:

$$\sigma(\gamma N \to J/\psi + X) = f_{J/\psi} \int_{4m_c^2}^{4m_D^2} \frac{dM^2}{s} G\left(\frac{M^2}{s}\right) \cdot \sigma_{\gamma g \to c\bar{c}}(M^2)$$

$$\sigma_{el} \quad \propto \quad x\, G(x)$$

$$x = M^2/s \qquad (*)$$

Note : Near threshold large corrections to (*)

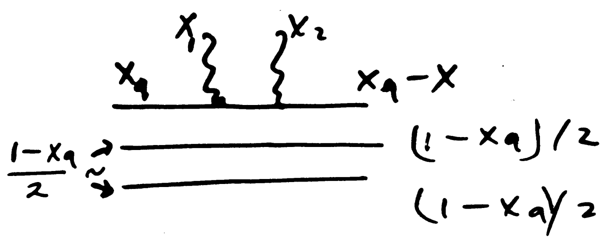
$$x_{thr.} = \frac{m_\psi}{m_\psi + m_N} \quad \text{not} \quad \frac{m_\psi^2}{(m_\psi + m_N)^2}$$

Need for accurate measurement of energy dependence.

What happens for intermediate energies: 1 Gluon or 2 Gluon coupling?

For interpretation difference of $\sigma(x)$ and $\sigma(x_1, x_2)$ may become important if x large.

Consider $x \sim 1$



$x_q - x \sim \frac{(1-x_q)}{2}$

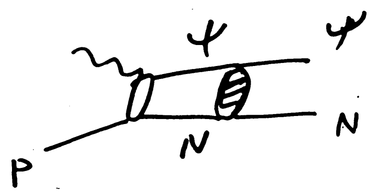
$\Rightarrow$ overlap integral $\sim$ const (x)

$$\Longrightarrow \quad \sigma(x) \sim \sigma^2(x_1, x_2)$$

may mimic 1 Gluon model

Threshold σ

If starting from $E \sim 50$ GeV and use $x\,G(x)$ fit would lead to $\sigma \ll \sigma_{experimental}$.



Enhancement is possible if significant ψN attraction

Brodsky & Miller estimate $\sigma(\psi N) \simeq 6\,mb$

potential attractive [approximation: $v^2/c^2 \ll 1$ not too good]

induced dipole - dipole gluon interaction. (van der Waals forces)

$\Rightarrow$ Accurate measurements of

$\sigma(\gamma + p \to \psi N)$ for $8.2 \le E_\gamma \le 12$ GeV.

& $\sigma(\gamma + p \to \psi' N)$ for $11 \le E_\gamma \le 13$ GeV.

Measurements close to threshold

$E_\gamma = 8.2$ GeV for $\gamma + p \to \psi + p$

11 GeV for $\gamma + p \to \psi' + p$

(a) SLAC 1975

(b) Cornell 1975

$\left.\frac{d\sigma}{dt}\right|_{t=0}$ seems to be $\simeq$ const near threshold (but $|t_{min}|$ increases!!)

$\Rightarrow$ To match SLAC data - steep increase between $E_\gamma = 12$ GeV and 13 GeV ??

$\Rightarrow$ Perhaps data of SLAC & Cornell are not consistent

Cornell

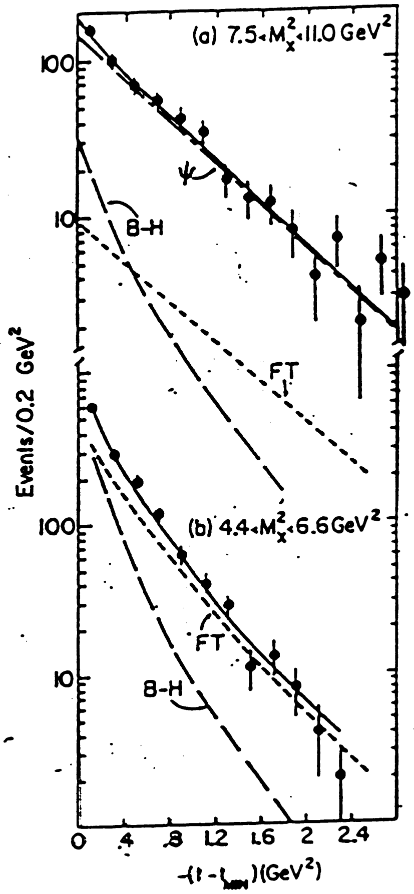


FIG. 2. $t - t_{min}$ distributions for c–c events in two mass regions. The solid curves represent the sum of the contributions from Bethe-Heitler pairs (B-H), n-n and n-c feedthrough (FT), and for (a) the fit to the ψ cross section described in the text.

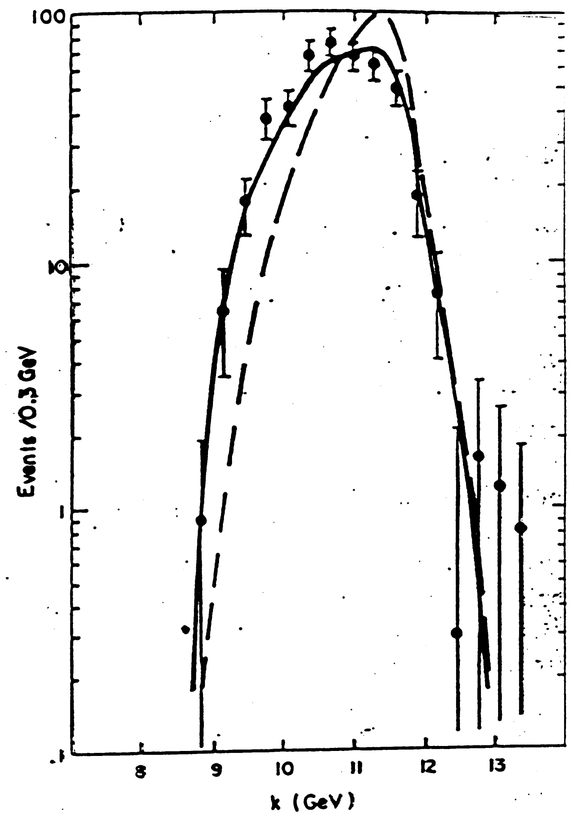


FIG. 3. The reconstructed photon energy distribu[tion] for the ψ events with Bethe-Heitler pairs and feed-throughs subtracted. The solid line is the expected [dis]tribution for a cross section $d\sigma/dt = 0.9\exp(1.2t)$. T[he] dashed line is for $d\sigma/dt = 0.144(k-8.2)^2\exp(1.2t)$ nb/GeV^2.

$\left.\frac{d\sigma}{dt}\right|_{t=0}$

$\left.\frac{d\sigma}{dt}\right\|_{t=0}$	$9.3 \le E_\gamma \le 10.4$	0.94 ± 0.20	$\frac{nb}{GeV^2}$
	$10.4 \le E_\gamma \le 11.1$	1.10 ± 0.17	
	$11.1 \le E_\gamma \le 11.8$	0.60 ± 0.12	

Threshold enhancement ?

$\gamma p \to \psi p$ attraction in ψN-channel ?

U. Camerini et al PRL 35, 48

$eD \to \psi +$

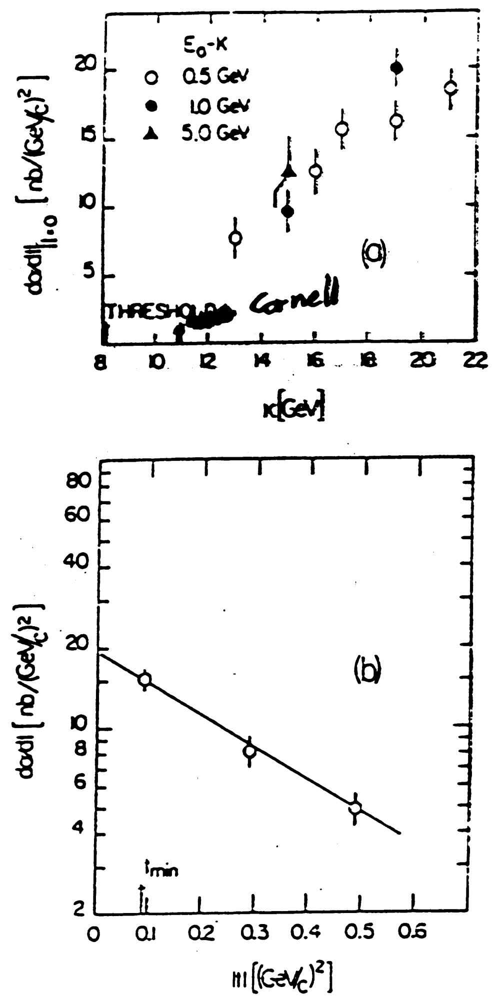


FIG. 2. (a) Cross section extrapolated to $t=0$ for $\psi(3100)$ as function of energy. Thresholds for $\psi(3100)$ and $\psi(3700)$ are indicated. (b) Differential cross section for $\psi(3100)$ for $k = 19$ GeV and $E_0 = 20$ GeV as a function of t. $b = 2.9$ (GeV/c)$^{-2}$.

$$\sigma_{tot}(\gamma p \to \psi p)\Big|_{20\,GeV} \simeq 7\,nb$$

$$\sigma_{tot}(\gamma p \to charm) \simeq 62 \pm 8\ (+15, -10)\ nb$$

$$\sigma(\gamma p \to D\,D\,bar) = 17^{+8}_{-6}$$

$$\Rightarrow \sigma(\gamma p \to \bar{D}\Lambda_c) \gg \sigma(\gamma p \to D\bar{D} + X)$$

J/Ψ photoproduction at $E_\gamma \lesssim 20$ GeV

- Average longitudinal distance in $\gamma \to c\bar{c}$ transition small

$$z \lesssim \frac{2E_\gamma}{4m_c^2} \lesssim 1\,fm$$

$\therefore$

$$l_{coh} = \frac{2P_\psi}{m_{\psi'}^2 - m_\psi^2} = \underbrace{\frac{P_\psi}{m_\psi}}_{\gamma\text{-factor}} \cdot \frac{1}{m_{\psi'} - m_\psi}$$

$$\simeq \gamma/3 \cdot fm.$$

$\Longrightarrow$ For $P_{J/\psi} \lesssim 20$ GeV genuine ψN interaction can be studied in γA scattering

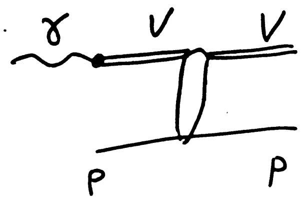
[F.S & Farrar 90.

$\sigma_{\psi N}$ is Needed for interpretation of J/Ψ data from AA collisions at CERN

Charmonium – Nucleon cross section

$\sigma_{\psi N} \sim 1$ mb often used.

Origin – vector dominance model



$\Rightarrow \sigma^{tot}_{\psi N} \simeq 0.8$ mb $\Big|_{E \simeq 20\,\mathrm{GeV}}$

Paradox (FS 85) Apply VDM to ψ'

production $\Rightarrow$

$$\sigma^{tot}_{\psi' N} / \sigma^{tot}_{\psi N} \simeq 0.7$$

violates geometry of strong interactions

$$r_{\psi'}/r_{\psi} \simeq 2 \Longrightarrow \sigma_{\psi' N}/\sigma_{\psi N} = \left(\frac{r_{\psi'}}{r_{\psi}}\right)^2 = 4\,!$$

Explanation ψ' & J/ψ produced in small configurations $r \sim 1/m_V$

$$\sigma_{\psi' N}(eff) / \sigma_{\psi N}(eff) \simeq \left(\frac{m_\psi}{m_{\psi'}}\right)^2 \simeq 0.7$$

$$\Rightarrow \quad \sigma_{eff}(\psi N) \ll \sigma_{\psi N}$$

FS 85

Experiment : SLAC 77 [bremstr. beam $E_0 = 20\,\text{GeV}$]

$$\left.\frac{\sigma(\gamma + Be \to \psi + A')}{\sigma(\gamma + Ta \to \psi + A')}\right|_{\text{incoh.}} = 1.21 \pm 0.07$$

$\Rightarrow \quad \sigma_{\psi N} = 3.5 \pm 0.8\ \text{mb}$ — expansion effec small) and woul increase $\sigma_{\psi N}$

Compare $\sigma_{\psi N}(\text{VDM}) < 1\ \text{mb}$

Comfirms explanation of ψ/ψ' paradox

What is dynamics of $\sigma_{\psi N}$?

pQCD for $\sigma(c\bar{c}\,N)$ for

$E_\gamma \sim 20\ \text{GeV}$ leads to

$$\sigma^{tot}_{hard}(J/\psi - N) \simeq 0.2\ \text{mb}$$

New NA-48 AA data

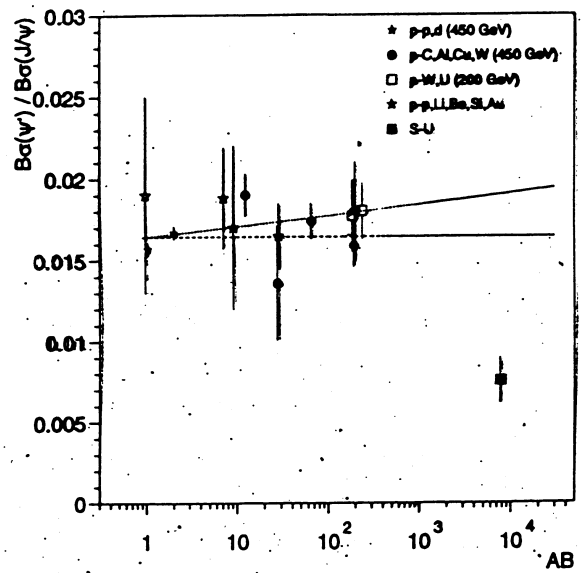
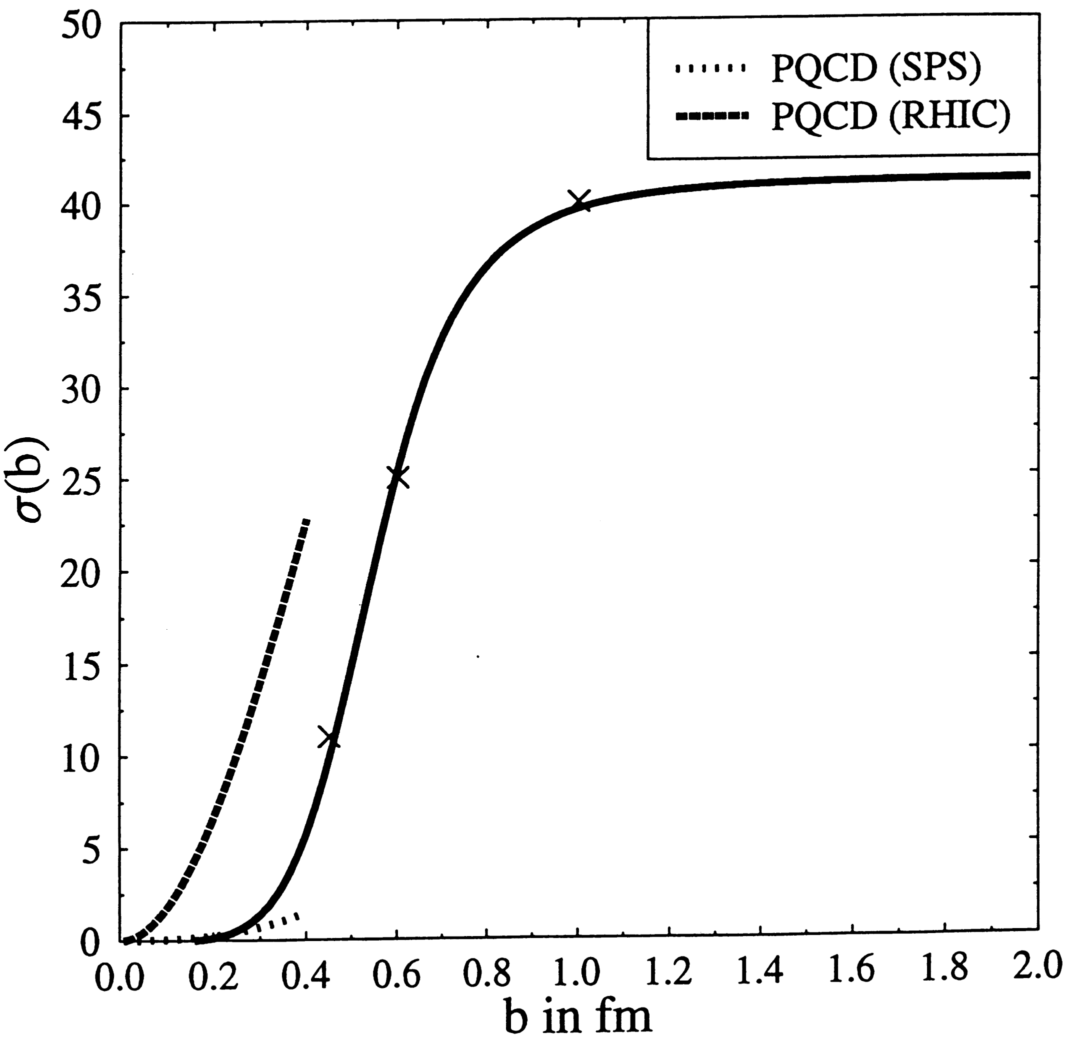


Figure 4: Ratio between ψ' and J/ψ production cross-sections, $B'_{\mu\mu}\sigma^{\psi'} / B_{\mu\mu}\sigma^{\psi}$, as a function of A×B. See the text for the meaning of the lines.

$$\Longrightarrow \quad \sigma(\psi' N) = 20\,mb$$

agrees well with our predictions.



PQCD (SPS)
PQCD (RHIC)
σ(b)
b in fm
0
5
10
15
20
25
30
35
40
45
50
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0

for $E_\gamma \sim 20$ GeV leads to $\sigma_{hard} \lesssim 0.2\,mb$

Recent analysis L. Gerland, F, S, Stöcker, Greine

dominant contribution from large transverse $c\bar{c}$ separations. Matching pQCD for small b, and soft QCD for $b \gtrsim 0.3\,fm$

$\sigma_{\psi N} = 3.6\ mb$, $\sigma_{\psi' N} = 20\,mb$

$\sigma_{\chi_{c10} N} = 6.8\ mb$ ($m=0$) $\sigma_{\chi_{c11}} = 15.8\ mb$ ($m=1$)

Allows to explain J/ψ A-dependence in pA, BA scattering at CERN

prediction ⟹ Strong absorption in $\gamma A \to \psi' A'$

$\frac{A_{eff}}{A}$	0.76	0.551	0.38
A	9	50	200

$\Rightarrow$ J/ψ interaction at intermediate energies is small but not govern[ed] by perturbative QCD.

(soft interactions of $c\bar{c}$ in rare large configurations in J/ψ)

Need much better J/ψ data, and ψ' photoproduction data.

How to look

$\psi N \to \psi N$ $\Rightarrow$ p_t broadening

$\psi N \to \psi N^*$ energy loss

$\psi N \to \bar{D}_c \Lambda_c$ $e\mu$ events ?

$\psi N \to \psi' N$ different ψ' energy than in $\gamma p \to \psi' p$

[γ beam much better than electron beam]

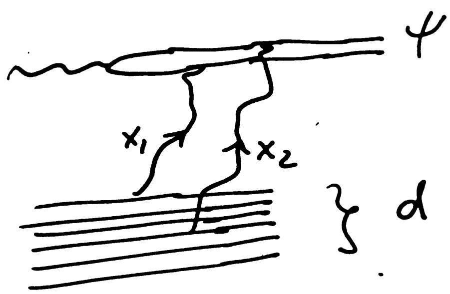
$\psi N \to \chi N$ (?feasible? since $\frac{\sigma(\gamma p \to \chi p)}{\sigma(\gamma p \to \psi p)} << 1$)

Note $\psi N \to \bar{D}_c \Lambda_c$ leads to rather low velocity Λ_c $\to$ $\frac{p_{\Lambda_c}}{m_{\Lambda_c}} \sim 0.4$

good chances to form charm hypernuclei

Close to threshold $E_\gamma \lesssim 12$ GeV

nuclear short-range correlation effects ?!



??

x is smaller in this case

Example $E_\gamma = 8.2$ GeV

$x\,(\gamma p) = 0.77$ $\quad p_\psi = 6.2$ GeV

$x\,(\gamma d) = 0.6$ $\quad p_\psi = 7.4$ GeV

Thereshold $E_\gamma = m_\psi + m_\psi^2 / 2\, m_{eff\ target}$.

$E_\gamma^{(1)} = 8.22$ GeV

$E_\gamma^{(2)} = 5.66$ GeV

$E_\gamma^{(3)} = 4.8$ GeV

$E_\gamma^{(\infty)} = 3.1$ GeV

beam dump with 6 GeV Beam. ?!

Note Effect of nuclear enhancement should be local [small volume of γ interaction with $c\bar{c}$ production]

$\Rightarrow$ Exotics using lightest nuclei

^4He, ^6Li, ...

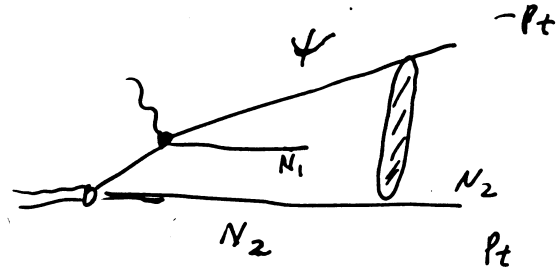
& final state interactions using $A \geq 40$ nuclei

Since probability of exotics per nucleon in ^{12}C and $A \sim 200$ rather close.

Use of recoil to study J/ψ + N

elastic scattering via

$\gamma + d \to \psi + p + n$

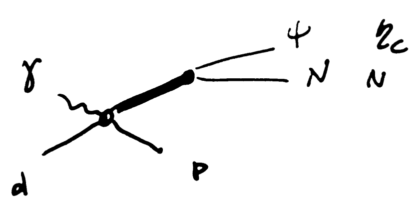


Expect $d\sigma(\psi N \to \psi N)/dp_t^2 \propto e^{-4p_t^2}$

– tails to rather large p_t.

$\theta_{lab} \simeq 80° - 70°$

& Look for bound states (Brodsky et al)



Missing mass with $\ell^+\ell^-$

trigger.

Note: Structure of recoil.

For threshold ($E_\gamma = 8.2$) $\gamma + p \to \psi + p$

$p_N \simeq 2$ GeV

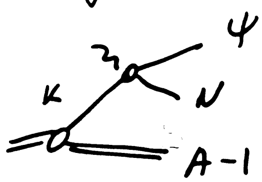
For the same E_γ : $\gamma + d \to \psi + d$: $p_d = 0.76$

For $E_\gamma = 11$ GeV

$p_N \cdot min = 0.76$ GeV/c

$p_{N\perp} \; max = 1.0$ GeV/c

Fermi motion model for productio[n] of J/ψ



$k_{min}(E_\gamma)$?

E_γ (GeV)	A=2 (pair correlations)	A=4
5.5		0.57
5.8	0.74	0.50
6	0.53	0.39
6.5	0.32	0.27
7	0.19	0.17
7.5	0.1	0.08

$\Longrightarrow$ For $E_\gamma \simeq 7$ GeV $\sigma_{\gamma A\to\psi X}/A \simeq$
$\sim (10^{-2} - 10^{-1})$ nb

⟹ A-dependence in the impulse approximation model may be strongly E_γ-dependent.

for $E_\gamma \leq 5.5$ GeV — short range correlations dominate

$E_\gamma \gtrsim 7$ GeV — mean field

Caviats : ⊙ collective initial interactions:

- 2 gluons from two different nucleons

⊙⊙ Attraction in the final state

Bound states??

Comment on open charm production.

Threshold for $\gamma + p \to \overline{D}^0 + \Lambda_c \Leftarrow E_\gamma = 8.7\,GeV$

corresponds to $p_{D^0}, p_{\Lambda_c} \sim 4-5\,GeV/c$.

Data: SLAC $E_\gamma \sim 20\,GeV$

$\overline{D}\Lambda > D\overline{D}$

- How large is σ for $E_\gamma \sim 10\,GeV$??
- For $\vec{\gamma}$ - would Λ_c be polarized.

small partial branchings $\Rightarrow$ trigger ?

semileptonic decays ?

Nuclei $\Rightarrow$ A-dependence of D, Λ_c

Expect l_{coh} small $\Rightarrow$ measure

$\sigma_{DN}, \sigma_{\Lambda_c N}$

Naive expectation: $\sigma_{DN} \to$ 12-15 mb, $\sigma_{\Lambda_c N} \to$ 25-30 mb

Strong A-dependence, change of the momentum distribution.

$\Sigma\Sigma$ Study of charmonium photoproduction

- Unique source of information about "charmonium - nucleon" interaction

  - heavy quark QCD

- Connection to heavy ion physics.