# Threshold J/$\psi$ Production

Presented by E.Chudakov, JLAB

**J/$\psi$: 30** announced on Nov, 1974

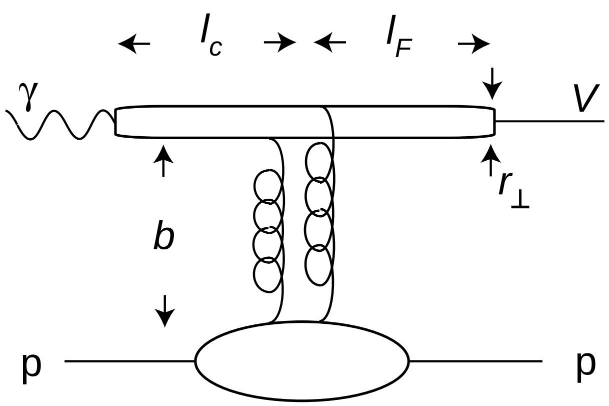
CEBAF at 12 GeV crosses the charm $\gamma$N threshold:

| | reaction | $E_\gamma$ GeV threshold | useful decay mode | BR | cross section $E_\gamma$, GeV | $\sigma$ nb |
|---|---|---|---|---|---|---|
| | $\gamma p \rightarrow \eta_c(1S)p$ | 7.7 GeV | $\eta_c(1S) \rightarrow p\bar{p}$ | 0.12% | - | - |
| ⋆ | $\gamma p \rightarrow J/\psi(1S)p$ | 8.2 GeV | $J/\psi(1S) \rightarrow e^-e^+/\mu^-\mu^+$ | 6.0% | 11. | 0.5±0.2 |
| ⋆ | $\gamma p \rightarrow \Lambda_c^+\bar{D}^0$ | 8.7 GeV | $\bar{D}^0 \rightarrow K^+\pi^-$ | 4.0% | 20. | $\sim$ 63.±30. |
| | $\gamma p \rightarrow \chi_{c0}(1P)p$ | 9.6 GeV | $\chi_{c1}(1P) \rightarrow K^+K^-$ | 0.71% | | |
| | $\gamma p \rightarrow \chi_{c2}(1P)p$ | 10.3 GeV | $\chi_{c1}(1P) \rightarrow J/\psi(1S)\gamma$ | 13.0% | 90. | $< 27\%$ J/$\psi$ |
| | $\gamma p \rightarrow \psi(3770)p$ | 11.0 GeV | $\psi(3770) \rightarrow e^-e^+/\mu^-\mu^+$ | 0.8% | 21. | 1.1±0.4 |
| | $\gamma p \rightarrow D\bar{D}p$ | 11.1 GeV | | | 20. | $\sim$ 63.±30. |

# What is special about J/$\psi$ etc?..

$\Rightarrow$ A "new" probe to study the nucleon/nucleus

- No $c\bar{c}$ in nucleons: $c\bar{c}$ production only via gluons from the target
- Small size
- Important features of charm photoproduction:




$m_c \approx 1.5\ GeV > \Lambda_{QCD}$

$r_\perp \sim \frac{1}{m_c} = 0.13\ fm$

At $E_\gamma \sim 10$ GeV:

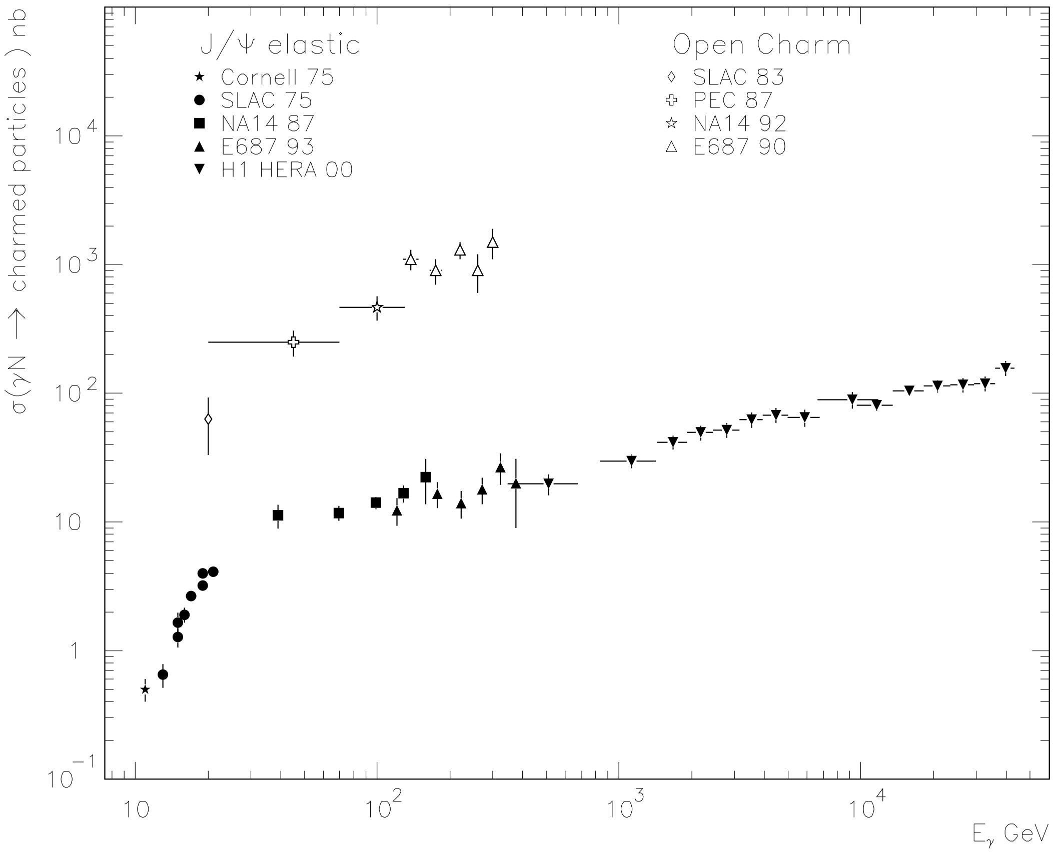
$\ell_{coh} = \frac{2E_\gamma}{4m_c^2+Q^2} \approx 0.4\ fm$

$\ell_F \cong \frac{2}{m_{\psi'}-m_{J/\psi}}\left[\frac{E_{J/\psi}}{2m_c}\right] \sim 1-2\ fm$

$b \sim 1/\sqrt{-t} \sim 0.2\ fm$

- $c\bar{c}$ is a small size probe of the gluon field of the target

# Existing Data on Charm Photoproduction



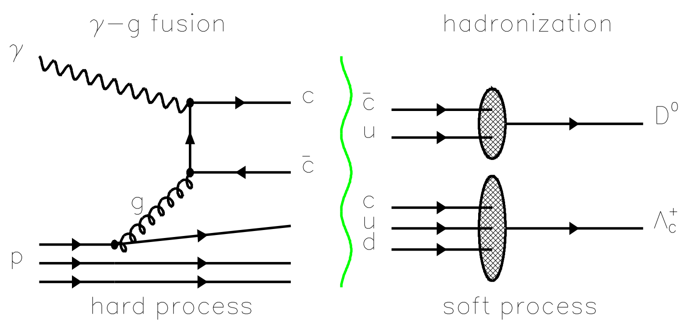

$\gamma$p $\rightarrow$J/$\psi$(1S)p $\quad E_\gamma > 11$ GeV

$\gamma$p $\rightarrow c\bar{c}$+X $\quad E_\gamma > 20$ GeV

*Only a part of the experimental results are presented

# Theory: Open Charm Photoproduction

Factorization




Calculated in LO and NLO

Main parameters:

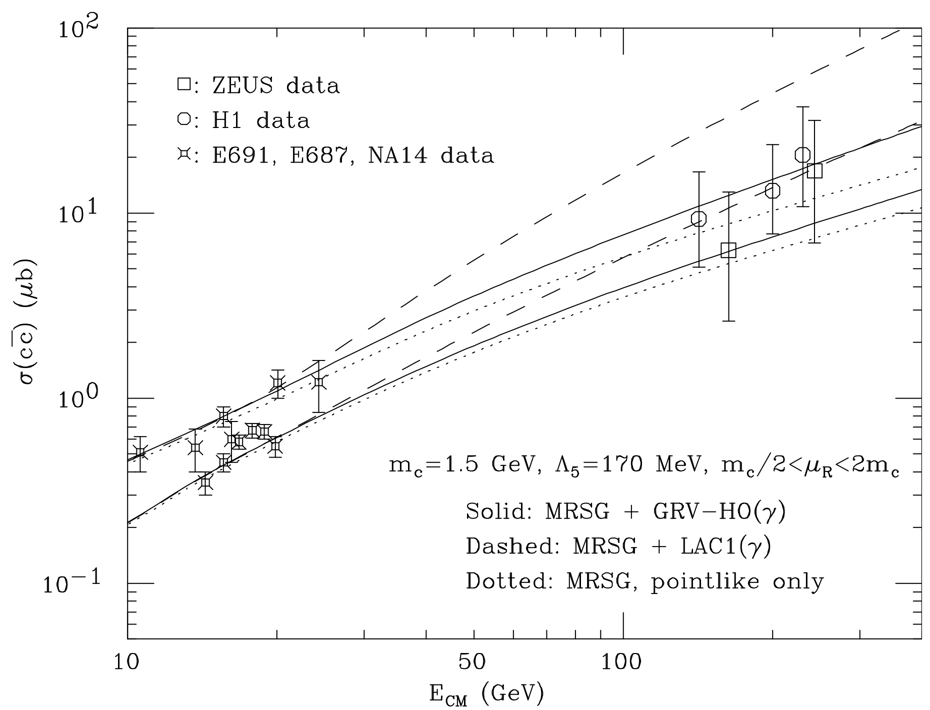
- $m_C$: 1.2-1.8GeV
- renormalization scale
- gluon PDF

Full inclusive charm:

- hadronization ignored

Exclusive production:

- fragmentation from $e^+e^-$
- final state interaction



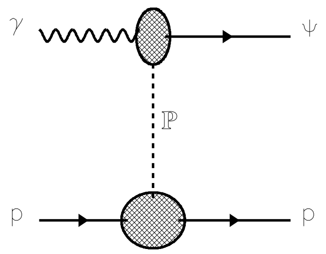

S.Frixione,M.Mangano,P.Nason,G.Ridolfi

CERN-TH/97-16

# Theory: Charmonium Photoproduction

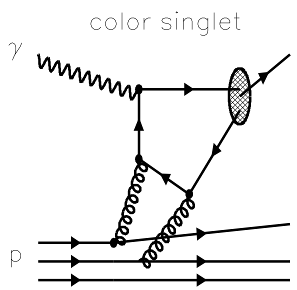
$c\bar{c}$ must combine into a colorless state.

## Pomeron Exchange



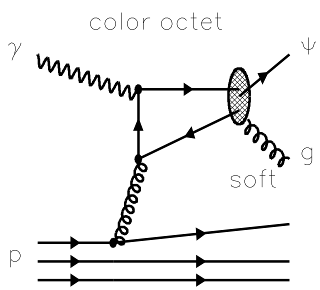

Underestimates
the rise $\sigma(E_\gamma)$
2 pomerons
- "soft" and "hard"

## Color Singlet




All is calculable
Underestimates
Tevatron data
by $\times 50$

## Color Octet




Soft: phenomenology
Tevatron calibration:
$\sigma_{\gamma p \to \psi X} \gg$ exper. z$\sim$1
Polarization problems

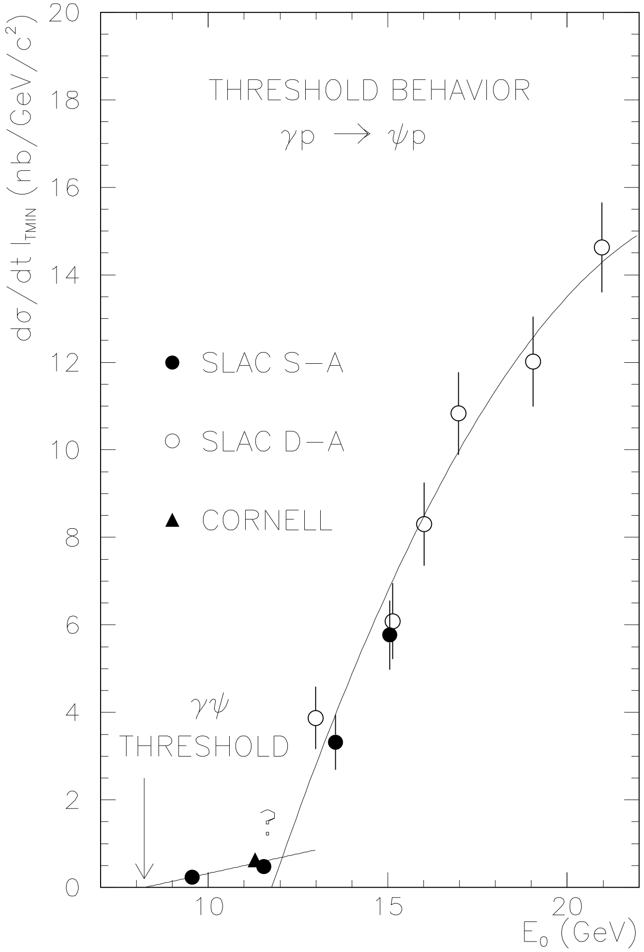
High energy:
probes the gluon PDF at low $x$.

In order to verify the models:

- Cross sections
- Polarization
- Measuring Singlet/Octet ($\Rightarrow \Delta$G ...)

# Experiment: Low Energy Photoproduction

Cornell and SLAC:




SLAC:

Double Arm: published

Single arm: unpublished

large errors <12 GeV

$\sigma$: SLAC≈ Cornell

$$\frac{d\sigma}{dt} = A \cdot \exp Bt$$

| | | |
|---|---|---|
| $E_\gamma$ GeV | 11. | 19 |
| B (GeV)$^{-2}$ | 1.13±0.18 | 2.9±0.3 |

Indication: a slow decrease of cross section towards the threshold

# Production near threshold

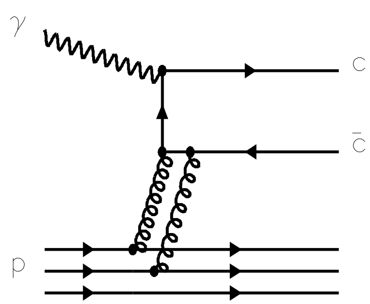
Should probe the particle distributions at high $x$.

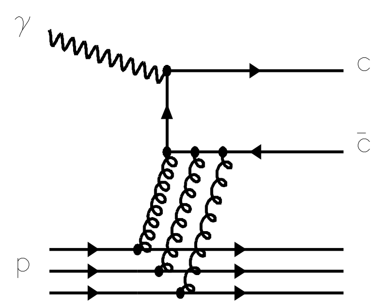
Several constituents from the target should take part.

No detailed calculation exists so far.

Qualitative arguments on $\sigma(E_\gamma)$

(S.Brodsky, E.Ch., P.Hoyer, J.-M. Laget PL B498, 23 2001):



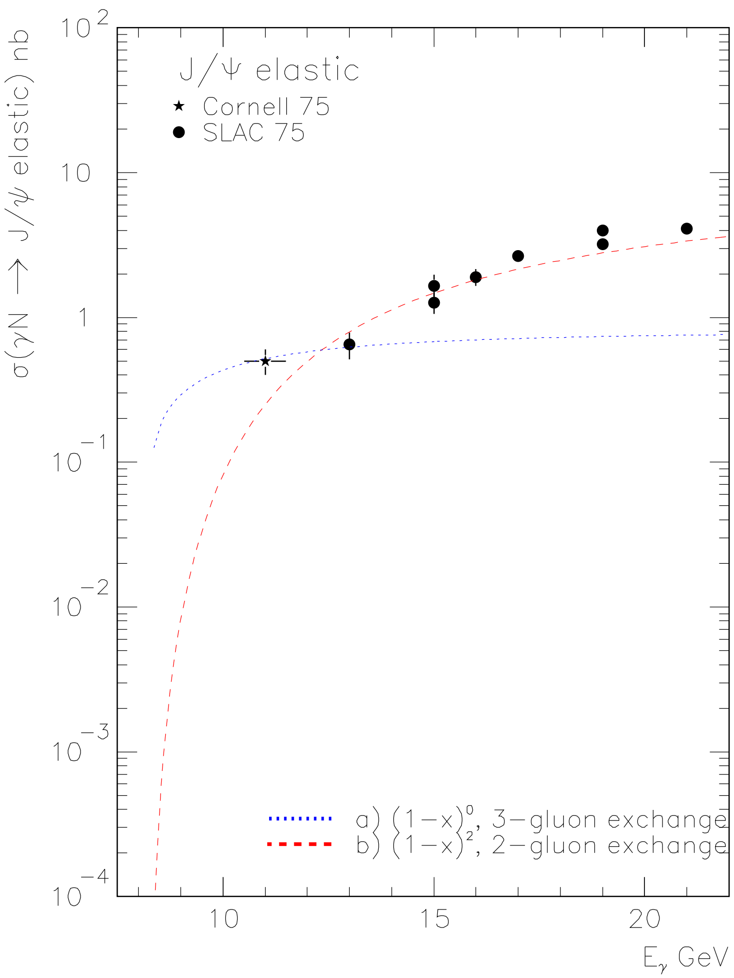

$\frac{d\sigma}{dt} = \mathcal{N}_{2g} v \frac{(1-x)^2}{R^2 \mathcal{M}^2} F_1(\frac{t}{4})(s - m_p^2)^2$

$\frac{d\sigma}{dt} = \mathcal{N}_{3g} v \frac{(1-x)^0}{R^4 \mathcal{M}^4} F_1(\frac{t}{9})(s - m_p^2)^2$

where: $x = \frac{s_{thresh} - m_p^2}{s - m_p^2}$, $\mathcal{M} = 2\ m_c$, $R \approx 1/m_c$

- Applicable at $x \sim 1 \Rightarrow E_\gamma < 12 - 15 GeV$
- The factors $\mathcal{N}$ - fit to the data

# Production near threshold

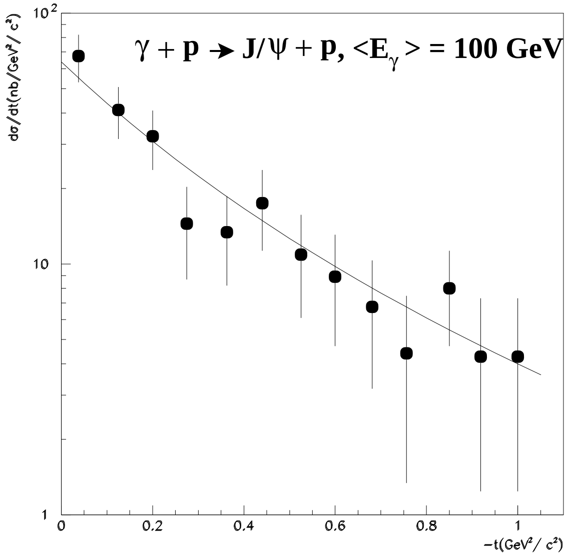


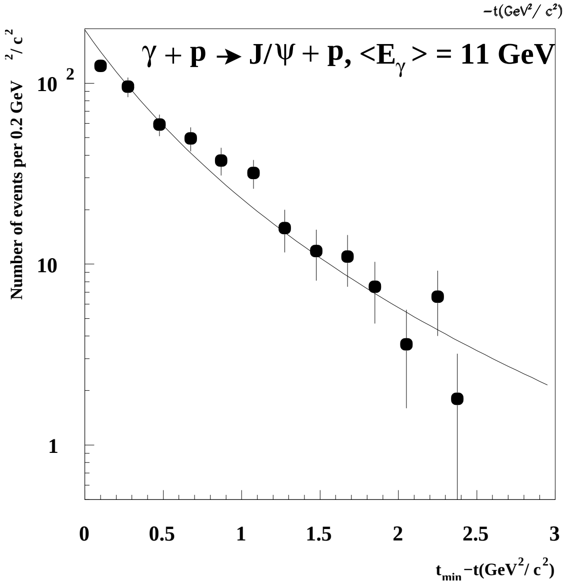

- "2-gluon" fit to high E points
- "3-gluon" fit to 2 low energy points

# Threshold J/$\psi$ Production

## t-Dependence

L.Frankfurt, M.Strikman, Phys.Rev.D66:031502 (2002), M.Str., C.Weiss hep-ph/0408345



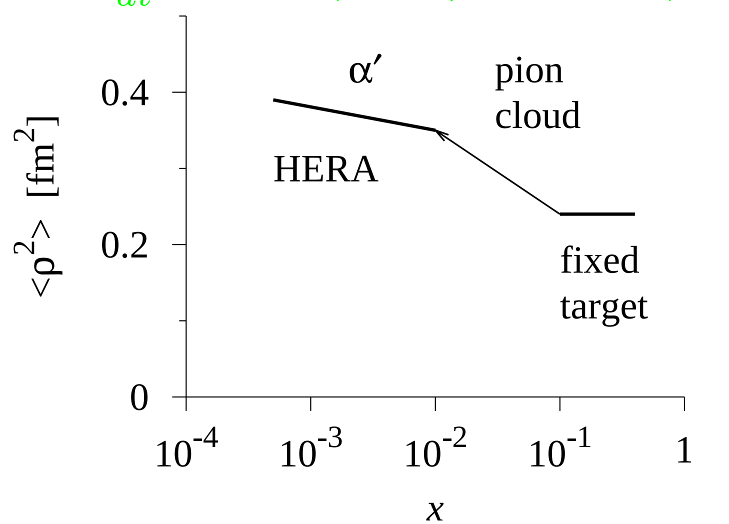




Argued: dipole approximation:

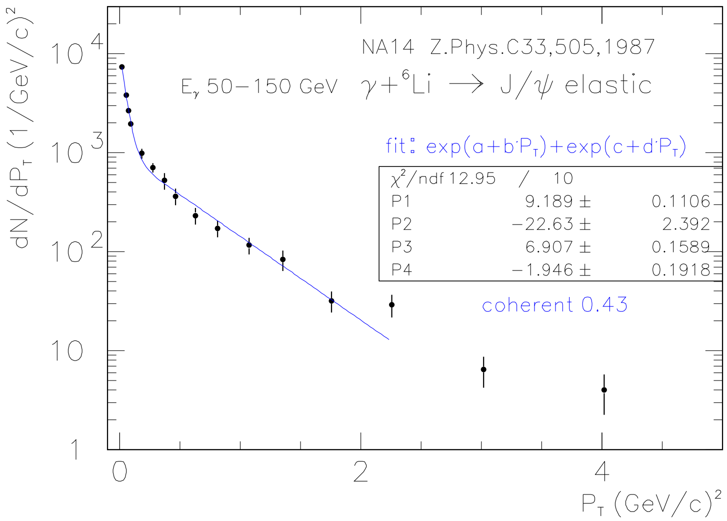
$H_g(x,t) \propto (1 - t/m_g^2)^{-2}$
$m_g^2 \approx 1.1$ GeV/c$^2$ at x$\sim$0.1

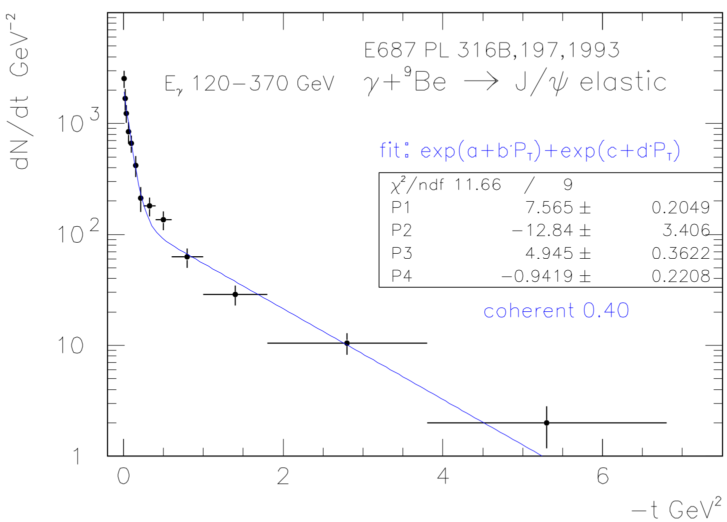
$\langle \rho^2 \rangle = 8/m_g^2 \approx 0.28$ fm$^2$

$\frac{d\sigma_{\gamma P \to J/\psi p}}{dt} \propto (1 - t/1.0GeV^2)^{-4}$



# $J/\psi(1S)$ Photoproduction on Nuclei




Vertex detectors:

- NA14: $^6Li$ 50-150 GeV
- E687: $^9Be$ 120-370 GeV

- A large coherent production: ≈40%
- "Coherent" slopes: NA14 and E687 are inconsistent
- NA14 and E687 - good t resolution, recoil undetected
- full cross-section A-dependence $\approx A^1$
- $L_{coh} > 2$ fm $E_\gamma > 50$ GeV

Generalized VDM

L.Frankfurt,M.Strikman...hep-ph/0304301

# $\psi$N Interactions

$\psi$N interactions: attention from theorists

Practical interest: J/$\psi$ deficit = signature for QGP

Features:

- small color dipole interacting with nuclear matter
- breakup by excitation to $D\overline{D}$ $\Delta E \sim 0.6\ GeV$
- possible loss due to $\psi + N \rightarrow \Lambda_c^+ \overline{D}$ at $P_\psi > 1.8\ GeV/c$

At low energy:

- attractive potential (Van der Waals) (Luke,Manohar,Savage,1992)
  $E_{binding} \sim 8\ MeV$
- $\sigma(\psi N)_{tot} \sim 7$ mb (Bordsky,Miller,1997), falling with energy

How to compare these predictions with experiment?

# $\psi$ in nuclear medium

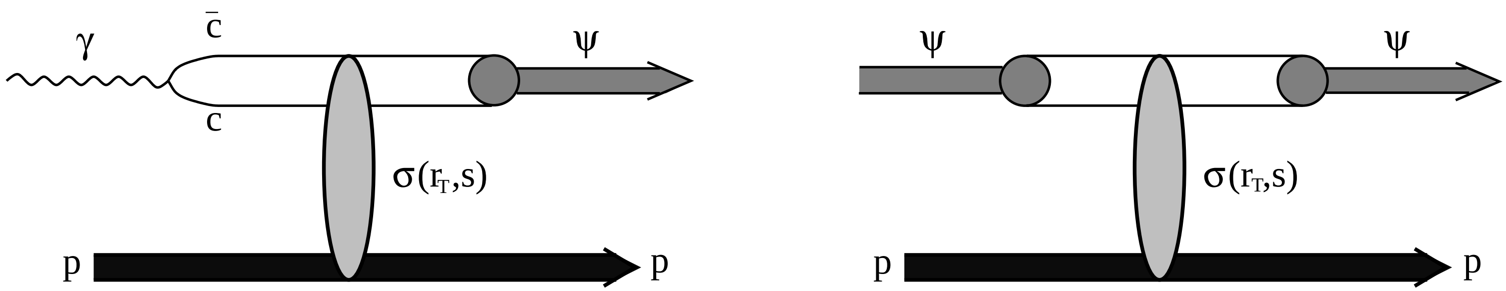
Several calculations

Features:

- $\Delta M$(J/$\psi$)$\sim$ 3 MeV
- $\Delta M(\psi\prime)$ $\sim$ 30 MeV

Not measurable (long lifetime - decay outside of the nucleus)

## Calculation of $\sigma(\psi \mathrm{N})_{tot}$ and $\psi$ Photoproduction




- Similarity between the two processes
- Check the model on photoproduction

## Calculation of $\sigma(\psi N)_{tot}$ and $\psi$ Photoproduction

(From: D.Kharzeev et al Eur.Phys.J. C 9,459 (1999))

Calculation of $\sigma(\psi N)_{tot}$ (rigorous in heavy quark limit):

- short-distance QCD (similar to DIS)
- using gluon PDF of the nucleon

Is $m_c$ large enough?

Test:

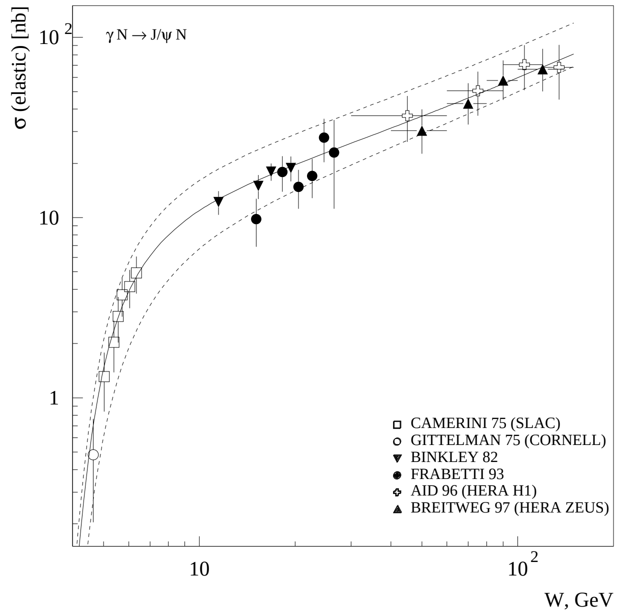
$\psi N \Rightarrow \gamma p \rightarrow \psi p$, using:

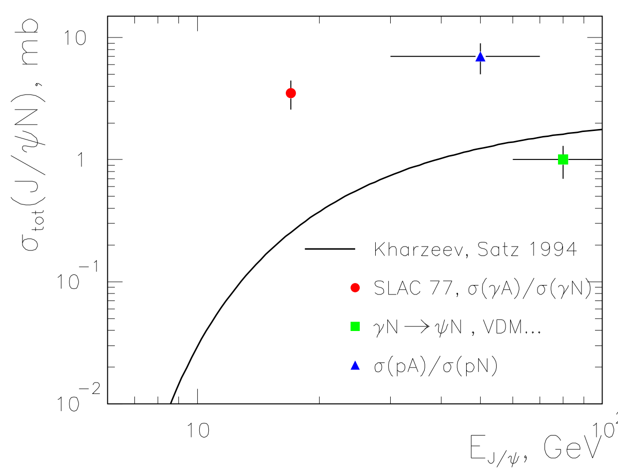
- VDM: $E_\gamma$ >25 GeV
- optical theorem
- dispersion relations

Discrepancy at 17 GeV $\times 10$

Fast drop at E<20 GeV

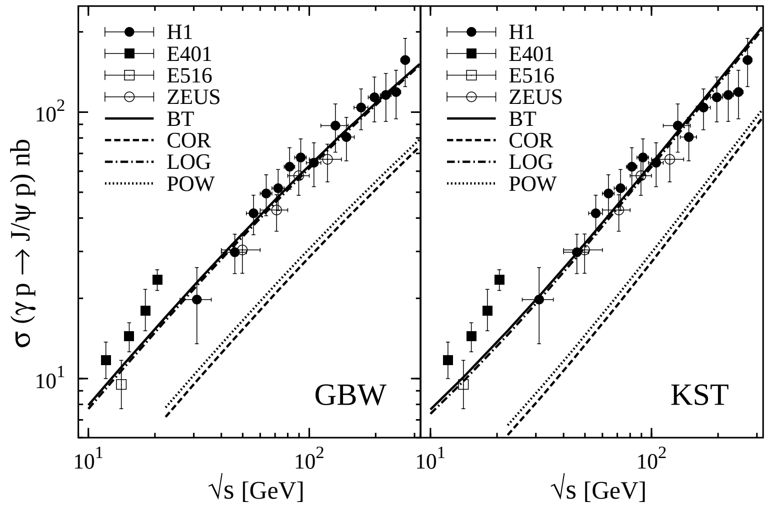
At E∼10 GeV - decisive



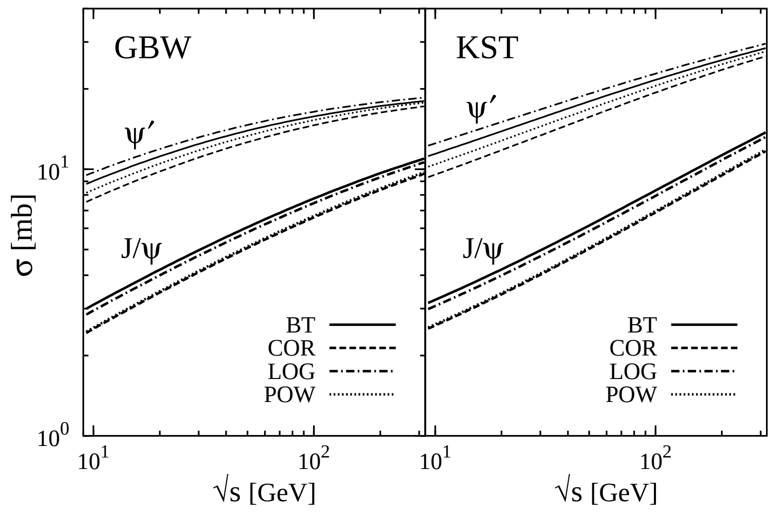



# Calculation of $\sigma(\psi N)_{tot}$ and $\psi$ Photoproduction

B.Kopeliovich, J.Raufeisen LA-UR-03-3079, hep-ph/0305094 Hufner,Kopeliovich




- VDM extended to a multi-channel case (account for J/$\psi$ $\psi\prime$ mixing)
- dipole interaction
- accurate setting of the wave functions etc



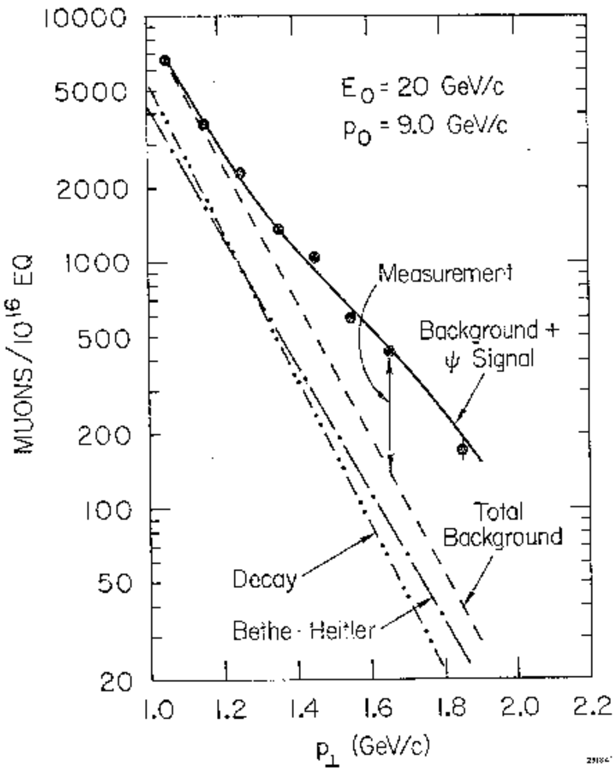
## $\psi$N measurements and interpretations

Experimental situation: was confusing. Now improving. Methods:

- From photoproduction, using VDM, optical theorem and assumptions on Re(A)/Im(A) ($\sim$ 0)
  - 20 GeV: $d\sigma(J/\psi N \rightarrow J/\psi N)/dt \mid_{t=0} \sim 25\ \mu b$
  - 20-200 GeV: $\sigma(J/\psi N)_{tot} \sim 1$ mb $\Rightarrow$ 2.8 - 4.1 mb
- From A-dependence of photo and hadro-production, using Glauber model and considering : color transparency effects at $\ell_{coh}, \ell_F > R_{target}$
  - 20 GeV $\gamma A$: $\sigma(J/\psi N)_{abs} \approx 3.5 \pm 0.8 \pm 0.6$ mb
  - 80-150 GeV $pA$: $\sigma(J/\psi N)_{abs} \approx 7$ mb $\Rightarrow$ 3.6 mb
  - 400-450 GeV $pA$: $\sigma(J/\psi N)_{abs} \approx$ 4.3$\pm$0.3 mb

# SLAC results on $\gamma A \rightarrow \psi + X$

Single spectrometer measurements.




20 GeV $e^-$ on Be and Ta targets

20 GeV spectrometer, $\mu^-$, $\mu$-filter

High statistics on a high background

The background was calculated:

- decays
- Bethe-Heitler

Cross-section per nucleon: $\sigma(Be)/\sigma(Ta) = 1.21 \pm 0.7 \Rightarrow \sigma_{\psi N} = 3.5 \pm 0.8$ mb.

Attempts to measure the cross-section down to 9 GeV: unpublished

# Program for JLab at 6 GeV

Hall C E-03-008 - pilot experiment:

- Sub-threshold J/$\psi$ production
- A few hundred events (depending on the cross section at threshold)
- May see an indication of an abnormally high cross section

# Program for JLab at 11 GeV

(1) Measure $\sigma(\mathrm{J}/\psi\mathrm{N})_{abs}$ using
A-dependence of $\sigma(\gamma\mathrm{A}\rightarrow\mathrm{J}/\psi\mathrm{X})$

Advantages (to SLAC):

- lower energy - smaller effects from $\ell_{coh}$,$\ell_F$
- low background for $\mathrm{J}/\psi(1\mathrm{S})$
- reconstructed kinematics of $\mathrm{J}/\psi(1\mathrm{S})$
- separation of coherent and incoherent production
- several targets used

Disadvantages comparing to the SLAC experiment:

- ○ lower energy - stronger effect from Fermi motion

(2) Measure $\frac{d\sigma}{dt}(E)$ for $\gamma\mathrm{p}\rightarrow\mathrm{J}/\psi\mathrm{p}$

Goals:

- Provide Fermi-motion correction for (1)
- Measurement in a new energy range (3-gluon exchange?)

(3) Look for more exotic effects:

- "Hidden color" $\gamma\mathrm{D}\rightarrow\mathrm{J}/\psi\mathrm{pn}$
- Bound state: peak in $\sigma/V$ at x=1 (threshold)

# SLAC results on $\gamma$p$\rightarrow\psi$p at 13-21 GeV

Double spectrometer measurements.

5% RL, 30 cm $^1$H, $^2$H

20, 8 GeV spectrometers

J/$\psi$(1S)$\rightarrow e^+e^-,\mu^+\mu^-$

1200 J/$\psi$(1S) and 13 $\psi$(3770)

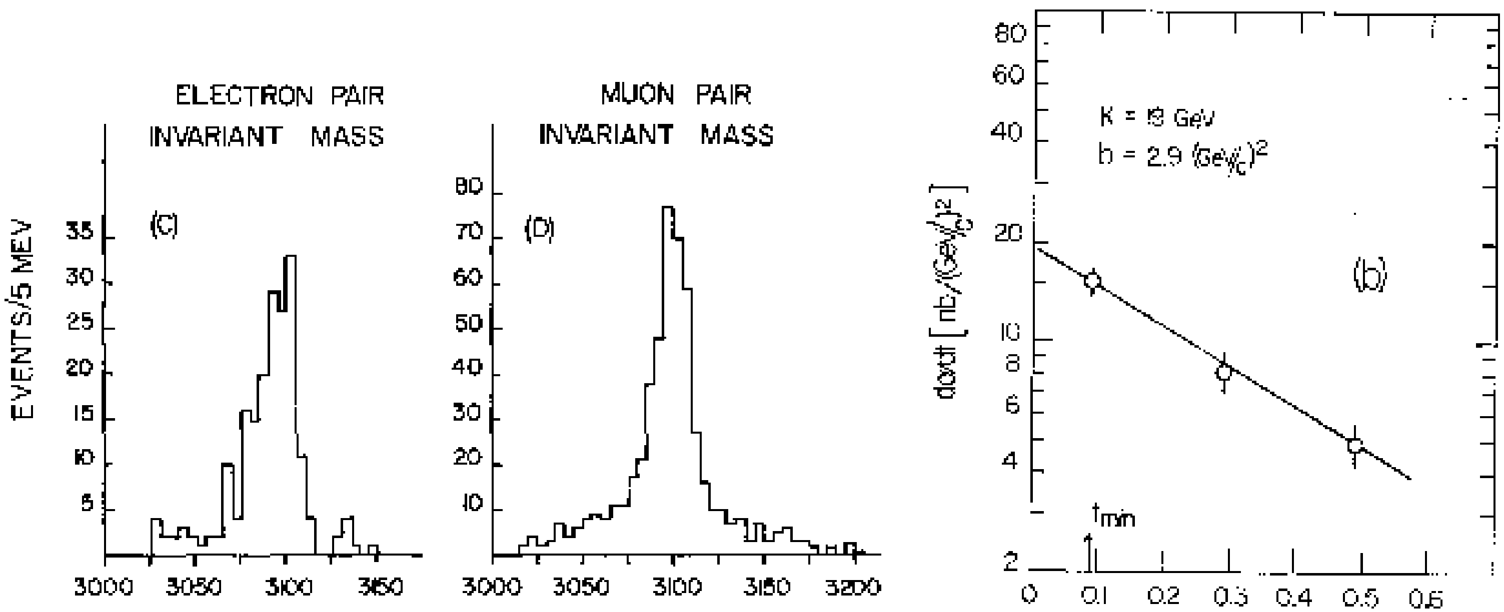
at 13 GeV:

$\frac{d\sigma}{dt}\mid_{tmin} = 3.8 \pm 0.8$ nb/GeV$^2$

at 20 GeV:

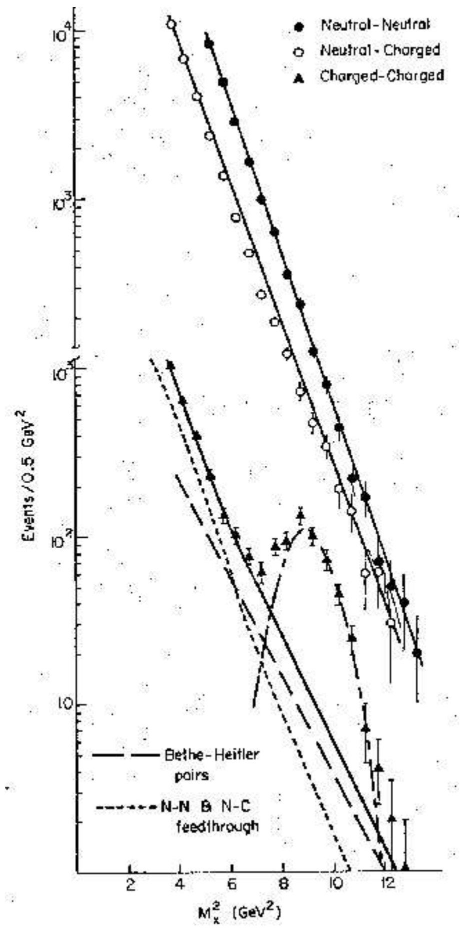
$\sigma$: $\psi(3100)/\psi(3770) \sim 6.8 \pm 2.4$

From VDM: $d\sigma(\psi N \rightarrow \psi N)/dt \mid_{t=0} \approx 25\mu$b

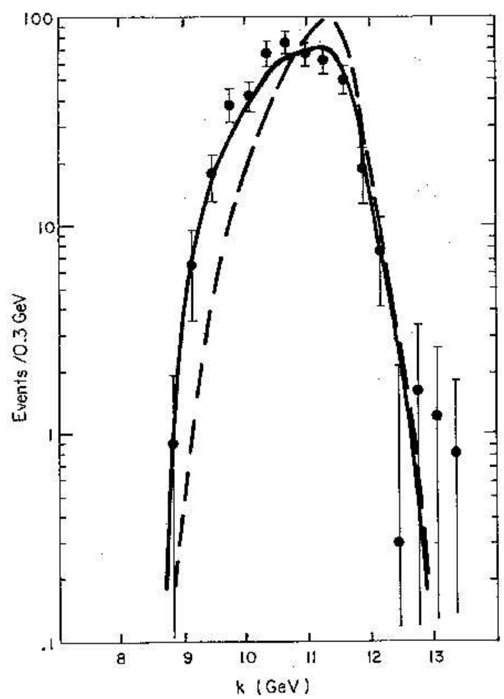


# Cornell Results at 11.8 GeV

- J/$\psi$(1S)$\rightarrow$e$^+$e$^-$ detected with lead-glass calorimeters ($\sigma E/E = 0.16/\sqrt{E}$)
- $\langle$photon flux$\rangle$ $1{\cdot}10^9$/s for 8.5<E$_\gamma$ $< 11.8$ GeV, duty cycle=7%, Be 2.9g/cm$^2$




- Background: neutrals $\times 10$ charged, charged - BH
- Signal/background ∼470/70
- Results: $\frac{d\sigma}{dt} = 0.9 \pm 0.1\ nb/GeV^2 \cdot e^{1.13 \pm 0.18\ GeV^2 \cdot t}$




No dependence of cross-section on E$_\gamma$ observed!

# JLab spectrometers

| hall | beam | setup | $\Delta\Omega$ | $P_{max}$ | $\frac{\Delta P}{P}$ | $\frac{\sigma P}{P}$ | $\sigma\theta_{in}$ | $\sigma\theta_{out}$ |
|---|---|---|---|---|---|---|---|---|
| | $\mu A$ | | ster | GeV | % | % | mrad | mrad |
| Hall A | 100 | HRS | 0.006 | 4.0 | 4.5 | 0.01 | 0.6 | 2.0 |
| | | HRS | 0.006 | 3.2 | 4.5 | 0.01 | 0.6 | 2.0 |
| | | MAD | 0.030 | 8.0 | 15 | 0.3 | 1.0 | 2.0 |
| | | | 0.006 | 8.0 | 15 | 0.3 | 1.0 | 2.0 |
| Hall C | 100 | HMS | 0.006 | 7.5 | 10 | 0.1 | 0.8 | 0.8 |
| | | SOS | 0.009 | 1.8 | 40 | 0.1 | 1.0 | 1.0 |
| | | SHMS | 0.004 | 12. | 15 | 0.1 | 1.0 | 1.0 |
| Hall B | 0.01 | CLAS | $\sim 2\pi$ | - | - | 0.5 | | |
| Hall D | $\gamma$ | | $\sim 4\pi$ | - | - | $<$1. | | |

# Specialized Setup

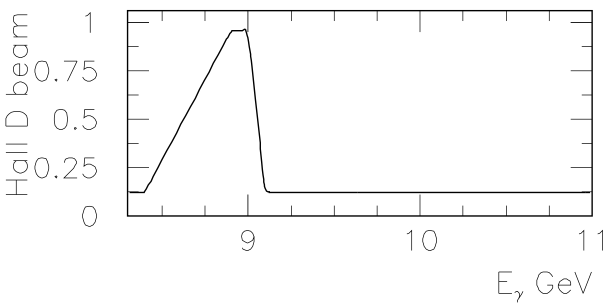
Specialized setup "ECAL":

- Solenoidal magnet R$\sim$0.6 m, L$\sim$1.5 m
- Calorimeter $\sim$2000 channels
- Hodoscope
- GEM(?)

# Luminosity and Acceptance

Possible photon flux:

- Halls A,C: 50$\mu A$ at 6% RL radiator: $6 \cdot 10^{12}\gamma$/s/GeV 8.5-11 GeV on 15 cm LH
- A,C ECAL: 2$\mu A$ at 6% RL radiator: $2 \cdot 10^{11}\gamma$/s/GeV 8.5-11 GeV on 15 cm LH
- Halls B: no tagging forseen
- Halls B: $\mathcal{L} < 10^{35}$ cm$^{-2}$s$^{-1}$: $8 \cdot 10^{8}\gamma$/s/GeV 8.5-11 GeV on 15 cm LH
- Halls D, tagged:
  $\sim 2 \cdot 10^7/s$ in $8.4 < E_\gamma < 9.1$GeV coherent
  $\sim 2 \cdot 10^7/s$ in $8.4 < E_\gamma < 11.$GeV incoherent




- "Standard" 12 GeV equipment: acceptance A/B/C/D/ECAL
  $0.6 \cdot 10^{-3}$ / $0.2$ / $0.4 \cdot 10^{-3}$ / $0.4$ / $0.4$

# Measuring the photon energy

Measuring $\frac{d\sigma}{dt}(E_\gamma)$: $\sim 6$ bins of $\sim 0.4$GeV in $E_\gamma$.
$E_\gamma$ should be measured to about 1%.

- Hall D tagger: $\sigma E_\gamma / E_\gamma < 0.1\%$
- Hall A,C - no tagging:
  - 2-body decay of $\mathrm{J}/\psi(1\mathrm{S})$ or $\overline{\mathrm{D}}^0$, (assuming the 2-body "elastic" reaction!) $\sigma E_\gamma / E_\gamma \approx 0.2\%$
  - Since the recoil particle is not detected, one can not be sure that the reaction is indeed defined, apart from a narrow energy band - just above the threshold.
  - Subtraction method: measuring several ($\sim 6$) end-points.
    - Time/measurement selected to equalize the errors at different energies
    - Direct (no subtraction) measurement at low energy, example: $\gamma$p $\rightarrow \overline{\mathrm{D}}^0$ X in a range 8.7-9.4 GeV, is limited to the $\Lambda_c^+ \overline{\mathrm{D}}^0$ final state.

## Threshold $J/\psi$ Production

Resolution, obtained using the $J/\psi(1S)$ mass in the fit or the tagger:

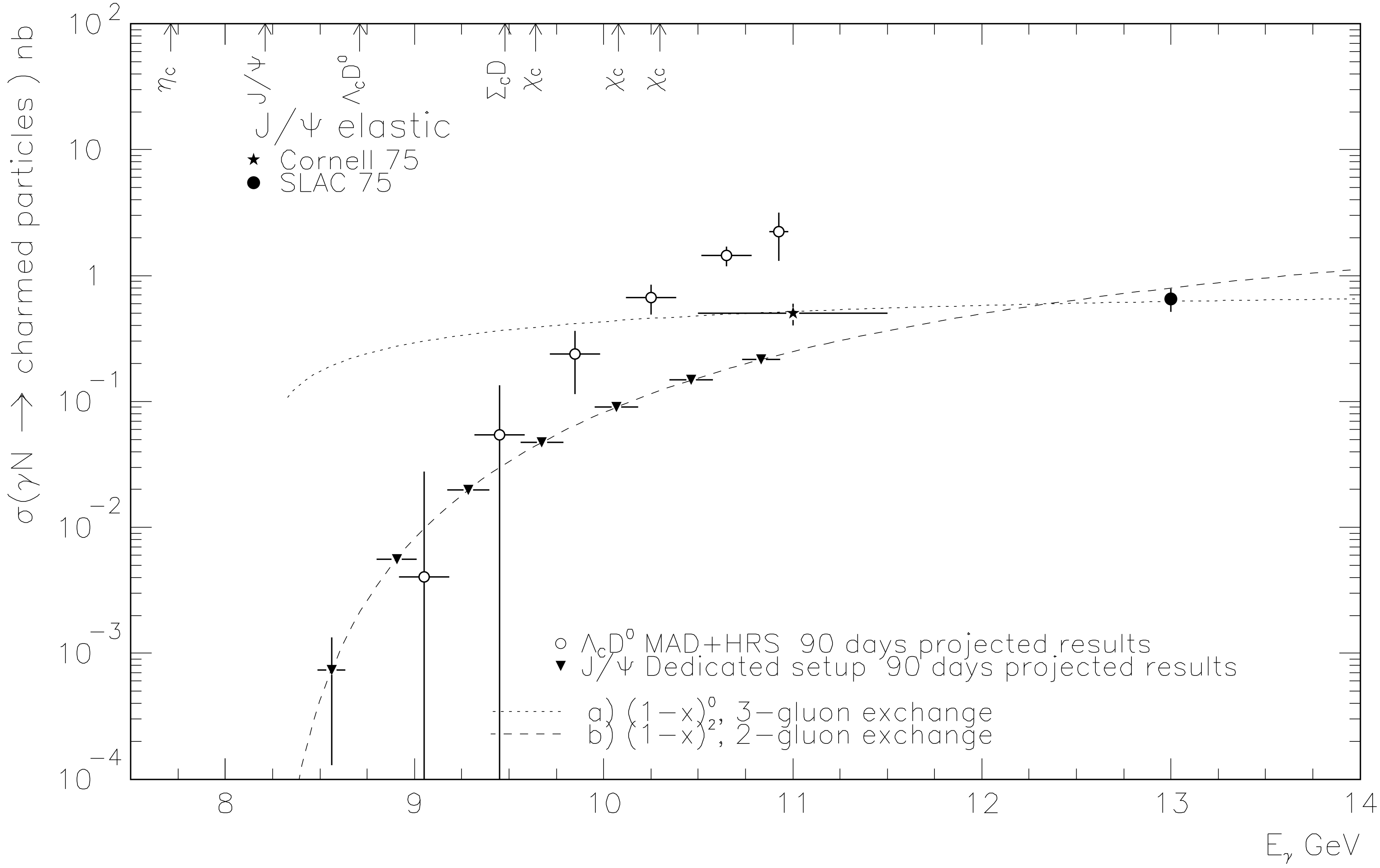
| setup | $\sigma M/M$ | $\sigma E_\Psi/E_\Psi$ | $\sigma E_\gamma/E_\gamma$ | $\sigma t (GeV/c)^2$ |
|---|---|---|---|---|
| ECAL | 0.035 | 0.007 | 0.01 | 0.11 |
| HRS+MAD | 0.002 | 0.001 | 0.002 | 0.014 |
| Hall B,D no tag | 0.010 | 0.004 | 0.001 | 0.03 |

| setup | recoil | BG/sig* | $d\sigma/dt \propto (1-x)^2$ | | $d\sigma/dt \propto (1-x)^0$ | |
|---|---|---|---|---|---|---|
| | | | events/ 90 days | days needed** | events/ 90 days | days needed** |
| $\gamma$p $\rightarrow J/\psi(1S)$p | | | | | | |
| ECAL | yes | 0.10 | $0.6\cdot10^5$ | 10 | $3.0\cdot10^5$ | 0.2 |
| HRS+MAD | no | <0.02 | $2.4\cdot10^3$ | 190 | $2.8\cdot10^4$ | 45 |
| HMS+SHMS | no | <0.02 | $1.5\cdot10^3$ | 300 | $1.6\cdot10^4$ | 70 |
| D tag | yes | 0.07 | $2.6\cdot10^2$ | 640 | $2.1\cdot10^3$ | 100 |
| $\gamma$p $\rightarrow \Lambda_c^+ \overline{D}^0$ | | | | | | |
| HRS+MAD | no | 0.05 | $2.9\cdot10^3$ | - | $2.9\cdot10^4$ | - |
| D tag | yes | 0.25 | $5.4\cdot10^2$ | - | $3.4\cdot10^3$ | - |

$*$ – at about 11 GeV

$**$ – to reach at least 10% accuracy in the energy range $> thresh + 0.4$GeV

# Expected Results



## J/$\psi$(1S) on nuclear targets

- Hall D does not plan to use nuclear targets for the first stage.
- Hall A,C (say, MAD+HRS) can use nuclear targets for A-dependence measurements. No need to detect the recoil.

$\sigma_{\Psi N}$ can be derived from the A-dependence of the cross-section
Assume for MAD+HRS:

- LH,LD 15 cm, with a 6%RL radiator
- Heavy targets of 7.7%RL ($\approx$ 6% radiator + LH target)
- For J/$\psi$(1S) production $\sigma_A \approx A \cdot \sigma_N$
- End point of 11 GeV

| target | | $^1$H | $^2$H | Be | C | Al | Cu | Pb |
|---|---|---|---|---|---|---|---|---|
| J/$\psi$(1S) | $(1-x)^2$ | 160 | 320 | 550 | 360 | 210 | 110 | 60 |
| /day | $(1-x)^0$ | ×5.4 | | | | | | |

1000 events per target: $\sim$ 50 days run

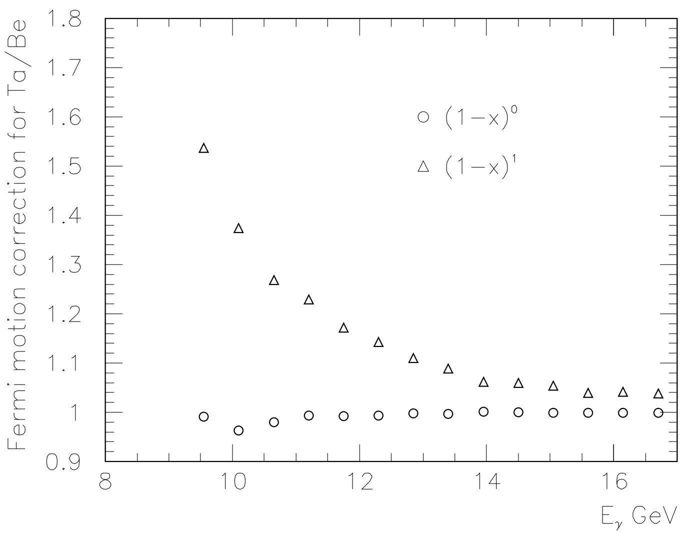
# Extraction of $\sigma_{\psi N}$

- Nuclear transparency: $T = \sigma_{\gamma A}/(A \cdot \sigma_{\gamma N})$

SLAC model: semi-classical eikonal approximation of nuclear rescattering

Assumed: statistical error for each target 3%

| $\sigma_{\psi N}$ mb | | A: 9 | 12 | 27 | 63 | 108 | 207 | $\sigma(\sigma_{\psi N})$ mb |
|---|---|---|---|---|---|---|---|---|
| T | 1.0 | 0.982 | 0.980 | 0.974 | 0.963 | 0.952 | 0.929 | 0.28 |
| | 3.5 | 0.938 | 0.931 | 0.908 | 0.870 | 0.833 | 0.751 | 0.24 |
| | 7.0 | 0.876 | 0.863 | 0.816 | 0.740 | 0.665 | 0.502 | 0.17 |




- Fermi-motion correction.

# Conclusion

At 12 GeV JLab is capable of using $c\bar{c}$ as a probe of nuclear matter:

(1) Measurements of $\psi$-Nucleon cross-section. The expected errors are about 10% statistical and 15% systematic. This measurements are aiming to test if there is a considerable gluonic potential between colorless states. This cross-section has also been of a considerable interest for heavy ion physics.

(2) Measurements of $\frac{d\sigma}{dt}(E_\gamma)$ of $\mathrm{J}/\psi(1\mathrm{S})$ is needed in order to fulfill (1). It is also of independent interest, probing compact, coherent states of valence quarks.

Experimental possibilities:

- The part (1) MAD+HRS / SHMS+HMS in 2 months
- The part (2) MAD+HRS / SHMS+HMS in 3 months
- The part (2) on $\mathrm{J}/\psi(1\mathrm{S})$ - Hall D in 2 years.
- Dedicated setup (ECAL) + search for more rare phenomena ("hidden color", bound states ...)