Threshold J/ψ Production

Presented by E.Chudakov, JLAB

J/ψ: 30

announced on Nov, 1974

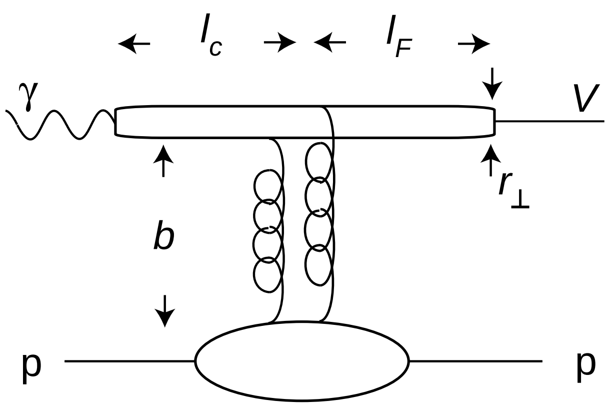
CEBAF at 12 GeV crosses the charm γN threshold:

	reaction	E_γ GeV threshold	useful decay mode	BR	cross section E_γ, GeV	σ 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
⋆	$\gamma p \rightarrow \Lambda_c^+\overline{D}^0$	8.7 GeV	$\overline{D}^0 \rightarrow K^+\pi^-$	4.0%	20.	$\sim 63.\pm30.$
	$\gamma p \rightarrow \chi_{c0}(1P)p$	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/ψ
	$\gamma p \rightarrow \psi(3770)p$	11.0 GeV	$\psi(3770) \rightarrow e^-e^+/\mu^-\mu^+$	0.8%	21.	1.1±0.4
	$\gamma p \rightarrow D\overline{D}p$	11.1 GeV			20.	$\sim 63.\pm30.$

What is special about J/ψ 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:

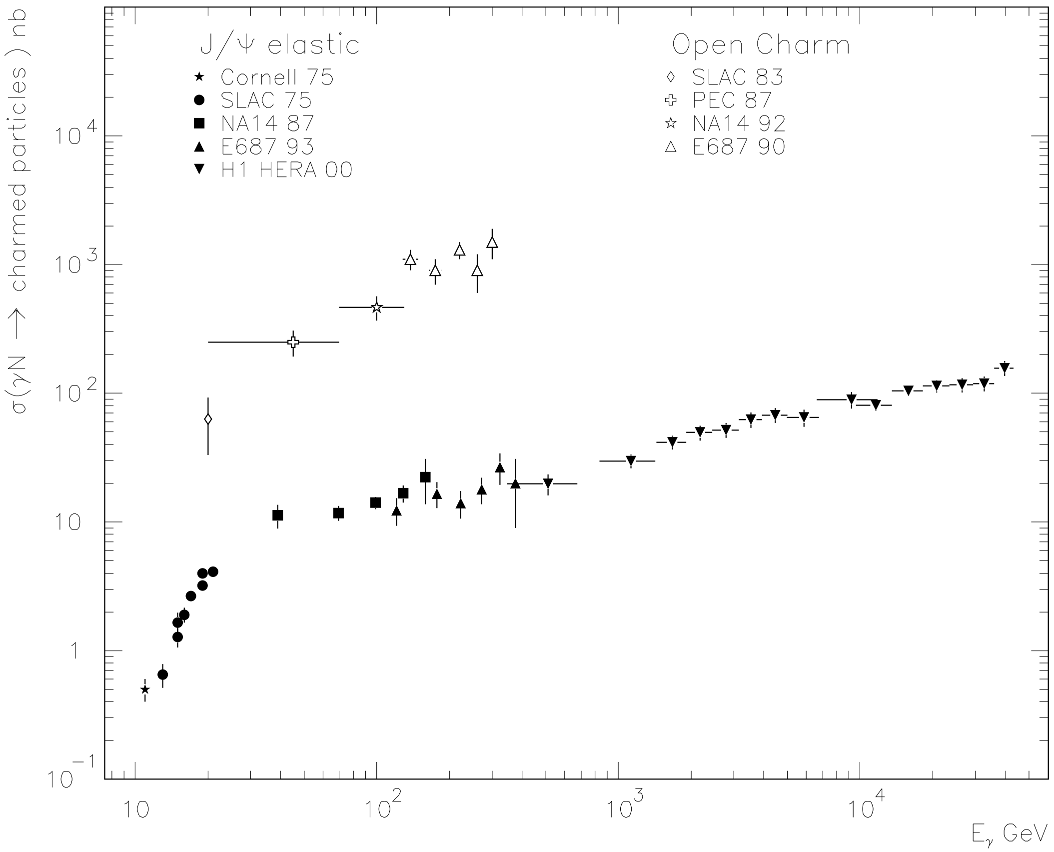
$\ell_{coh} = \frac{2E_\gamma}{4m_c^2+Q^2} \approx 0.4\ fm$

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

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

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

Existing Data on Charm Photoproduction



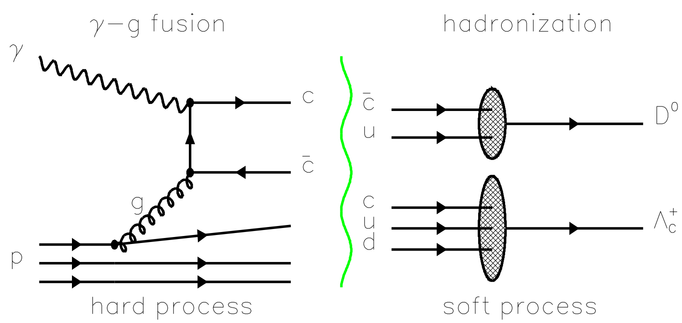
$\gamma p \rightarrow J/\psi(1S)p \quad E_\gamma > 11$ GeV

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

*Only a part of the experimental results are presented

Theory: Open Charm Photoproduction

Factorization



Calculated in LO and NLO

Main parameters:

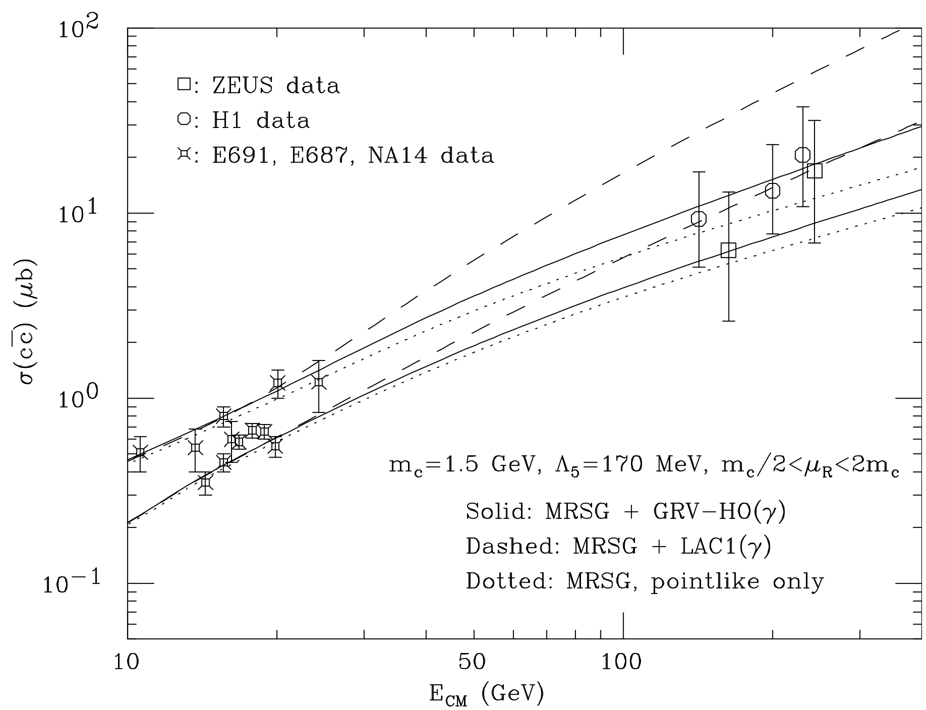
- m_C: 1.2-1.8GeV
- renormalization scale
- gluon PDF

Full inclusive charm:

- hadronization ignored

Exclusive production:

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



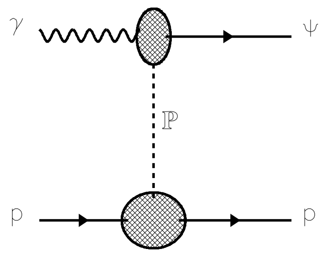
S.Frixione,M.Mangano,P.Nason,G.Ridolfi

CERN-TH/97-16

Theory: Charmonium Photoproduction

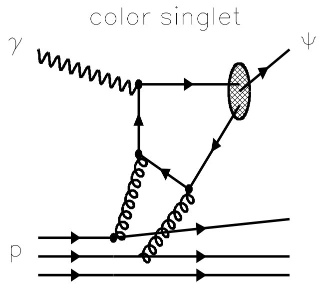
$c\bar{c}$ must combine into a colorless state.

Pomeron Exchange



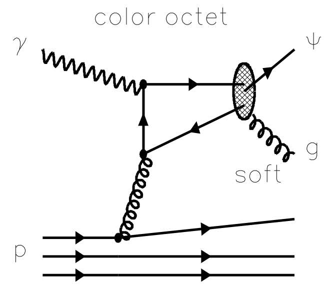
Underestimates
the rise $\sigma(E_\gamma)$
2 pomerons
- "soft" and "hard"

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~1
Polarization problems

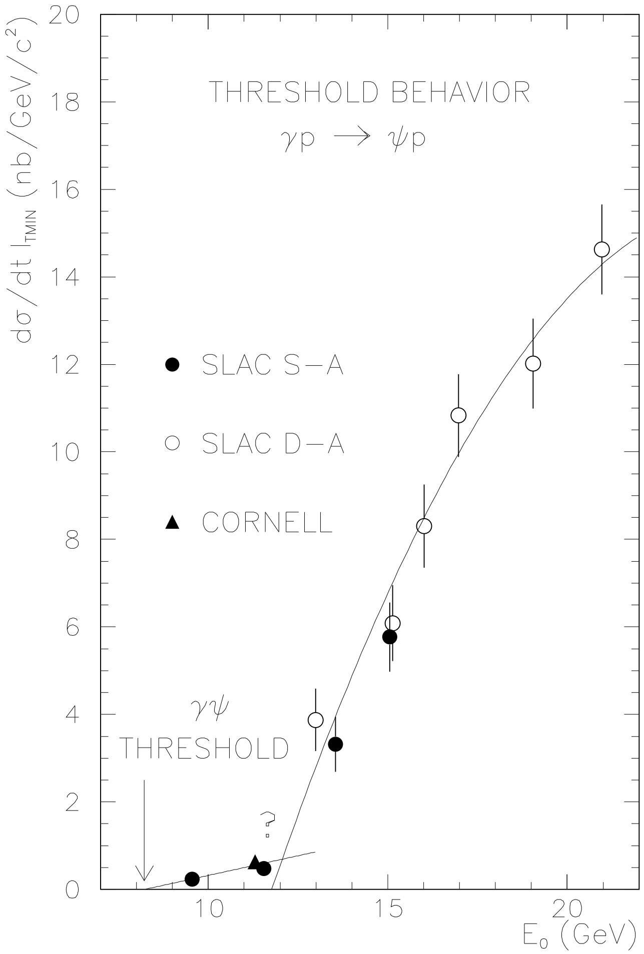
High energy:
probes the gluon PDF at low x.

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

σ: SLAC≈ Cornell

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

E_γ GeV	11.	19
B $(\text{GeV})^{-2}$	1.13±0.18	2.9±0.3

Indication: a slow decrease of cross section towards the threshold

Production near threshold

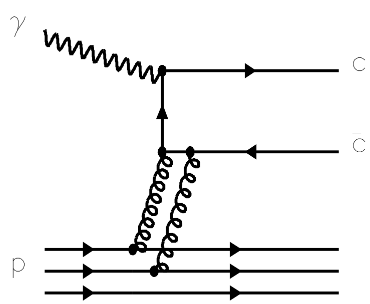
Should probe the particle distributions at high x.

Several constituents from the target should take part.

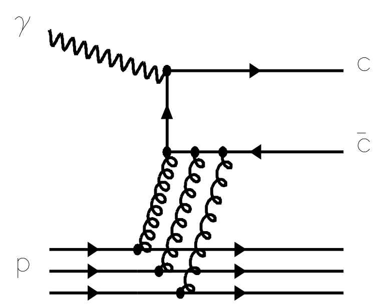
No detailed calculation exists so far.

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

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



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

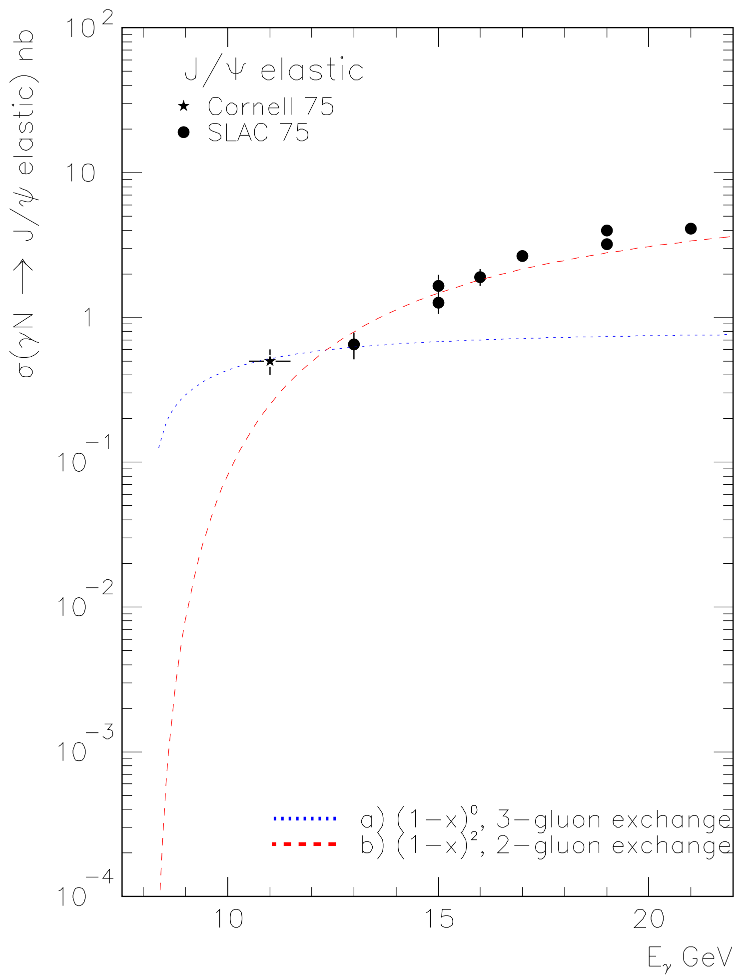


$$\frac{d\sigma}{dt} = \mathcal{N}_{3g} v \frac{(1-x)^0}{R^4 \mathcal{M}^4} F_1(\tfrac{t}{9})(s-m_p^2)^2$$

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

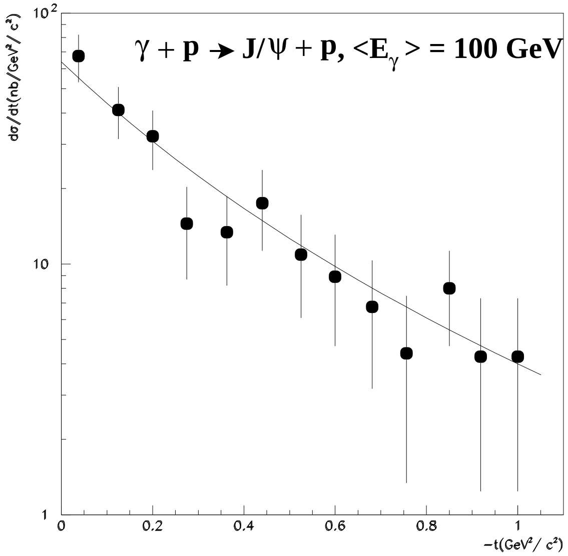
Production near threshold

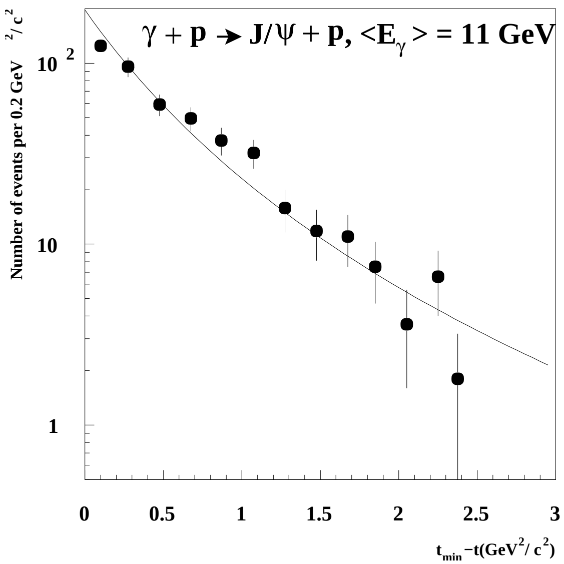


- "2-gluon" fit to high E points
- "3-gluon" fit to 2 low energy points

t-Dependence

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



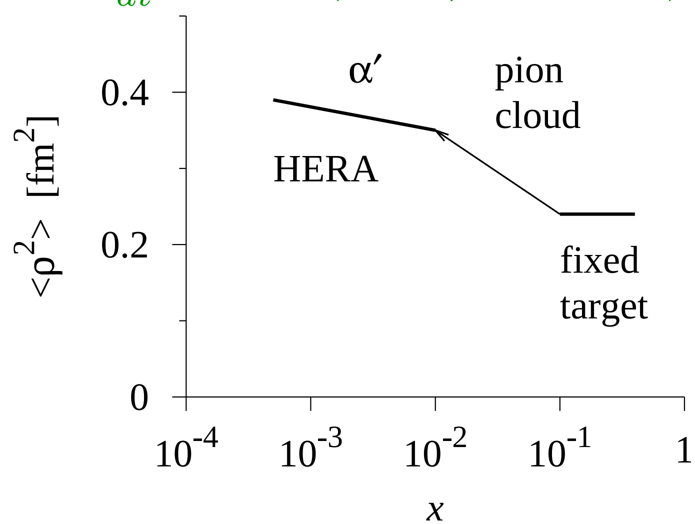


Argued: dipole approximation:

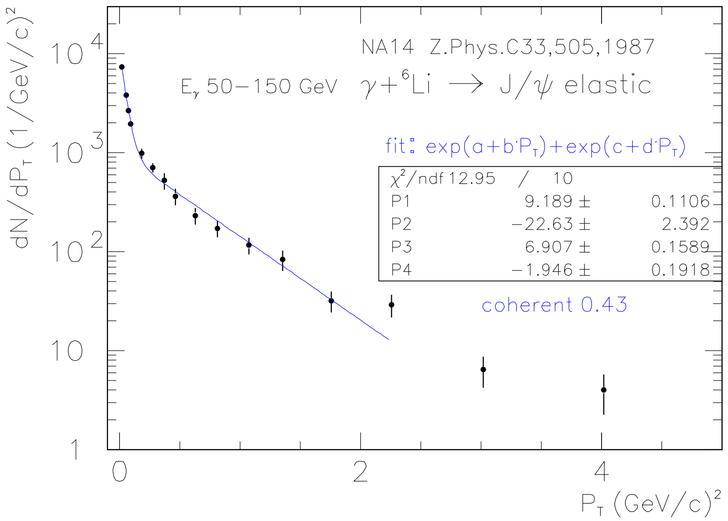
$H_g(x,t) \propto (1 - t/m_g^2)^{-2}$
$m_g^2 \approx$ 1.1 GeV/c^2 at x∼0.1

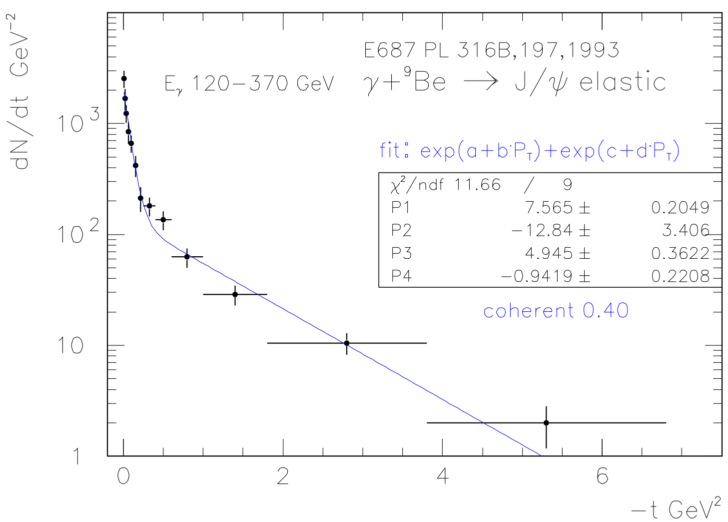
$\langle \rho^2 \rangle = 8/m_g^2 \approx 0.28$ fm^2

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



$J/\psi(1S)$ **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

ψN Interactions

ψN interactions: attention from theorists

Practical interest: J/ψ deficit = signature for QGP

Features:

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

At low energy:

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

How to compare these predictions with experiment?

ψ in nuclear medium

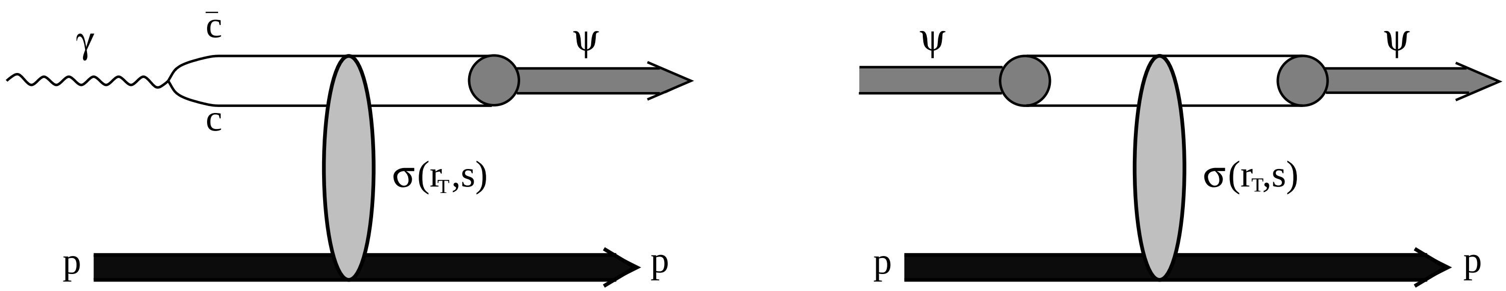
Several calculations

Features:

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

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

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



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

Calculation of $\sigma(\psi N)_{tot}$ and ψ 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:

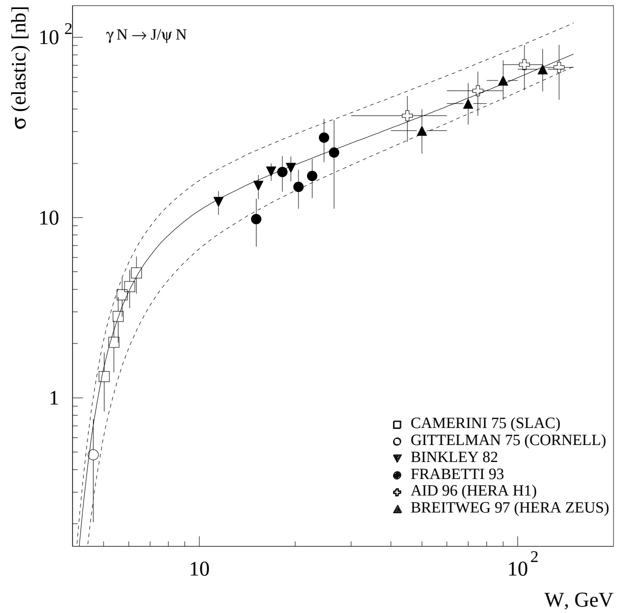
$\psi N \Rightarrow \gamma p \rightarrow \psi p$, using:

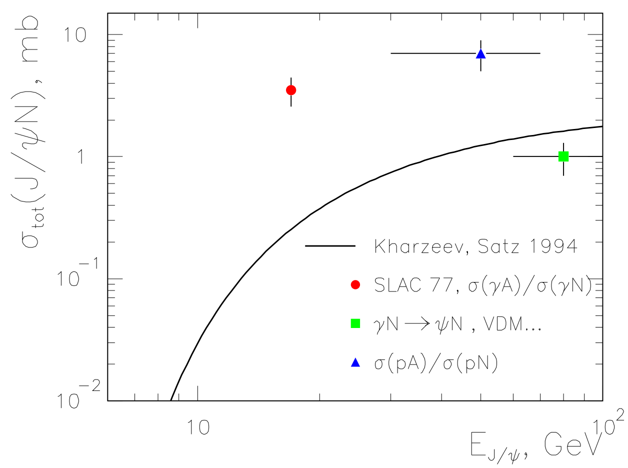
- VDM: $E_\gamma > 25$ GeV
- optical theorem
- dispersion relations

Discrepancy at 17 GeV $\times 10$

Fast drop at E<20 GeV

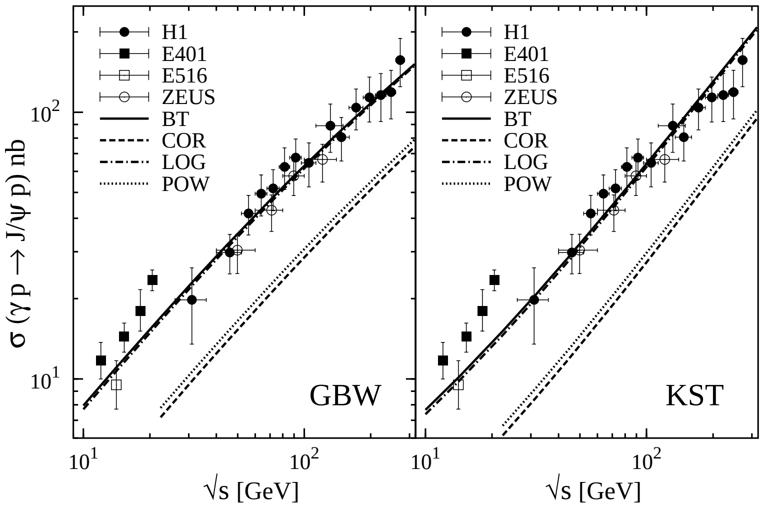
At E$\sim$10 GeV - decisive



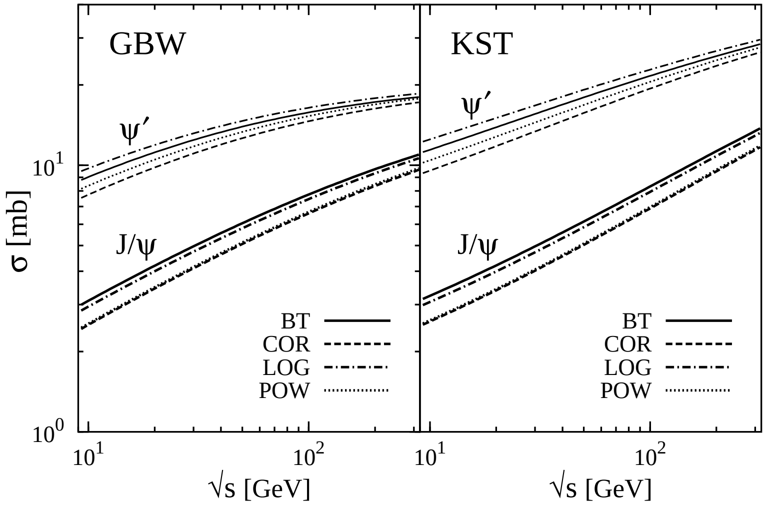


Calculation of $\sigma(\psi N)_{tot}$ and ψ Photoproduction

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



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



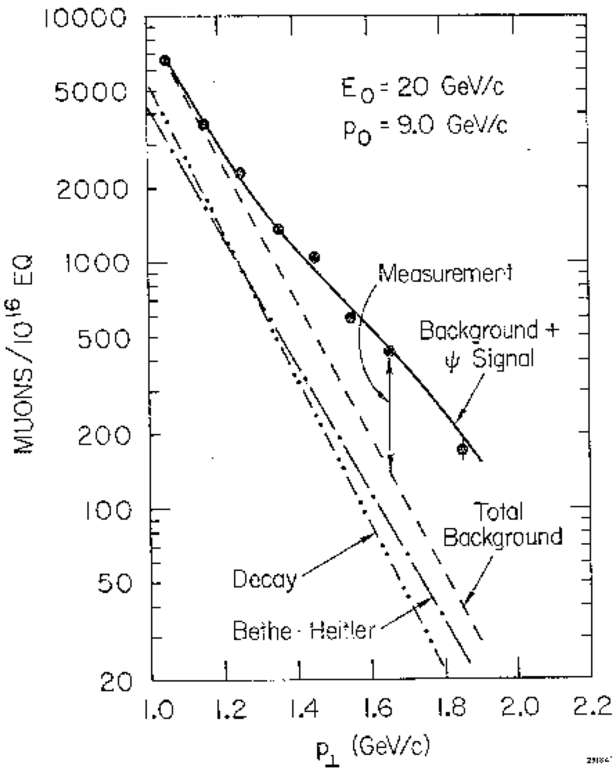
ψN measurements and interpretations

Experimental situation: was confusing. Now improving. Methods:

- From photoproduction, using VDM, optical theorem and assumptions on Re(A)/Im(A) ($\sim$ 0)
  - 20 GeV: $d\sigma(J/\psi\mathrm{N}\rightarrow J/\psi\mathrm{N})/dt\mid_{t=0}\ \sim\ 25\ \mu\mathrm{b}$
  - 20-200 GeV: $\sigma(\mathrm{J}/\psi\mathrm{N})_{tot}\sim 1$ 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 γA: $\sigma(\mathrm{J}/\psi\mathrm{N})_{abs}\approx 3.5\pm 0.8\pm 0.6$ mb
  - 80-150 GeV pA: $\sigma(\mathrm{J}/\psi\mathrm{N})_{abs}\approx 7$ mb $\Rightarrow$ 3.6 mb
  - 400-450 GeV pA: $\sigma(\mathrm{J}/\psi\mathrm{N})_{abs}\approx$ 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, μ^-, μ-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/ψ 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 ℓ_{coh},ℓ_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 σ/V at x=1 (threshold)

Threshold J/ψ Production

SLAC results on γp$\rightarrow$ ψp at 13-21 GeV

Double spectrometer measurements.

5% RL, 30 cm ^{1}H, ^{2}H

20, 8 GeV spectrometers

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

1200 J/ψ(1S) and 13 ψ(3770)

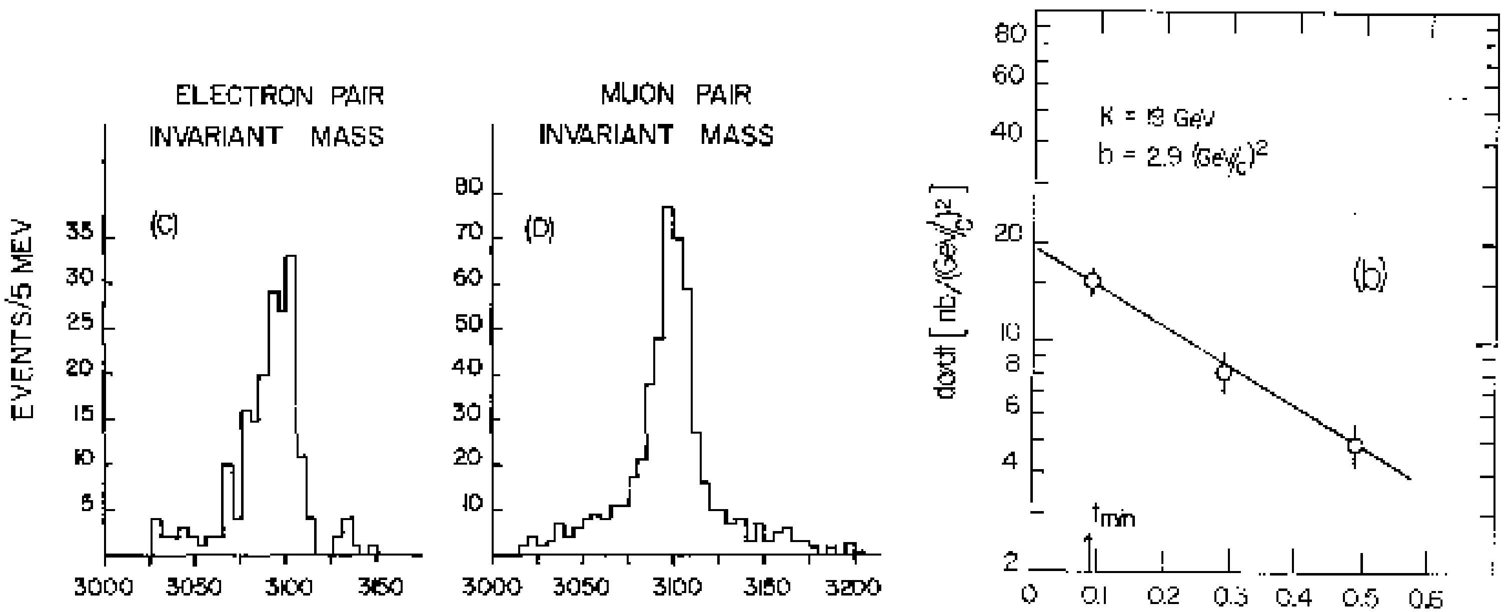
at 13 GeV:

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

at 20 GeV:

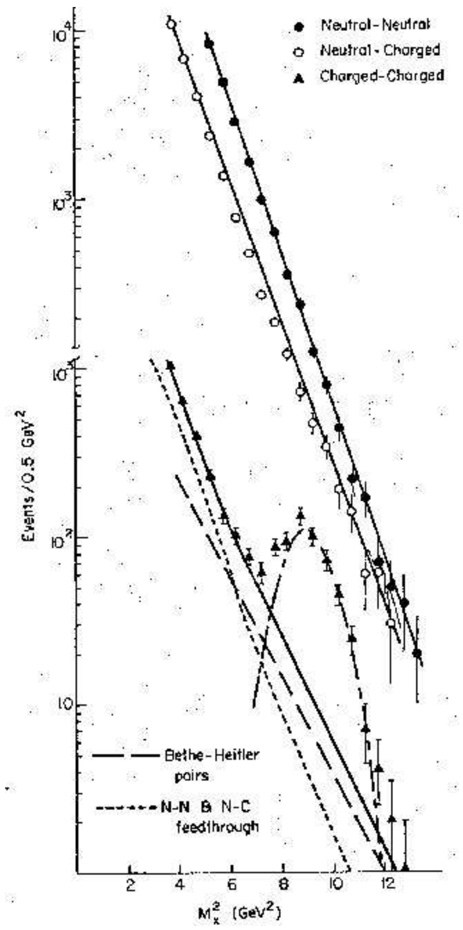
σ: $\psi(3100)/\psi(3770) \sim 6.8 \pm 2.4$

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

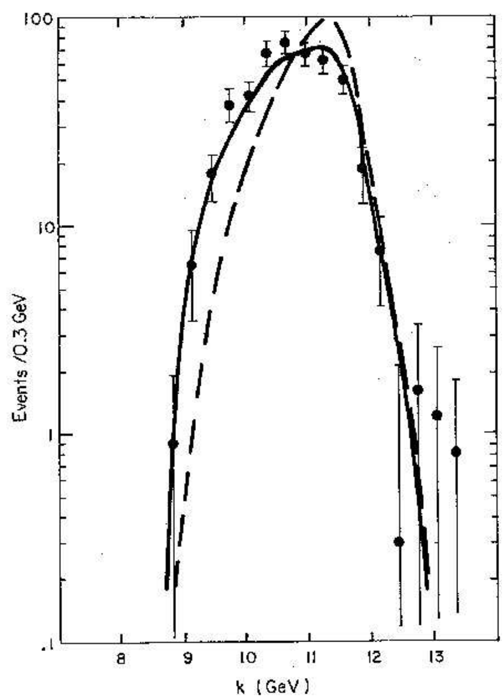


Cornell Results at 11.8 GeV

- J/ψ(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 $\sim$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	$\Delta\Omega$	θ_{min}	P_{max}	$\frac{\Delta P}{P}$	$\frac{\sigma P}{P}$	$\sigma\theta_{in}$	$\sigma\theta_{out}$
	μA		ster	deg	GeV	%	%	mrad	mrad
Hall A	100	HRS	0.006	12.5	4.0	4.5	0.01	0.6	2.0
		HRS	0.006	12.5	3.2	4.5	0.01	0.6	2.0
		MAD	0.030	12.0	8.0	15	0.3	1.0	2.0
			0.006	12.0	8.0	15	0.3	1.0	2.0
Hall C	100	HMS	0.008	10.5	7.5	10.0	0.1	0.8	0.8
		SOS	0.009	-	1.8	40.0	0.1	1.0	1.0
		SHMS	0.004	10.0	11.0	0.1	1.0	1.0	1.0
Hall B	0.01	CLAS	$\sim 2\pi$	-	-	0.5			
Hall D	γ		$\sim 4\pi$	-	-	$<1.$			

Specialized Setup

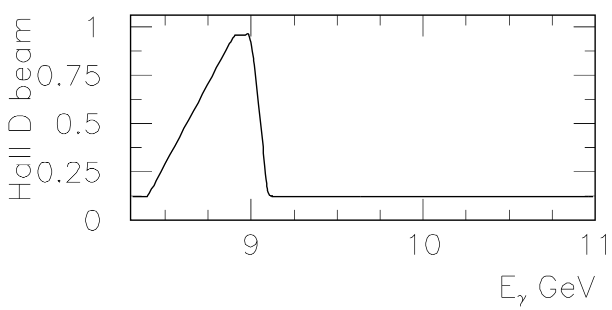
Specialized setup "ECAL":

- 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: 50μA at 6% RL radiator: $6 \cdot 10^{12}\gamma$/s/GeV 8.5-11 GeV on 15 cm LH
- A,C ECAL: 2μA 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 $\frac{d\sigma}{dt}(E_\gamma)$: ~ 6 bins of ~ 0.4GeV in E_γ.
E_γ 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 (~ 6) end-points.
    - Time/measurement selected to equalize the errors at different energies
    - Direct (no subtraction) measurement at low energy, example: γp $\rightarrow \overline{\mathrm{D}}^0$ X in a range 8.7-9.4 GeV, is limited to the $\Lambda_c^+ \overline{\mathrm{D}}^0$ final state.

Threshold J/ψ Production

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

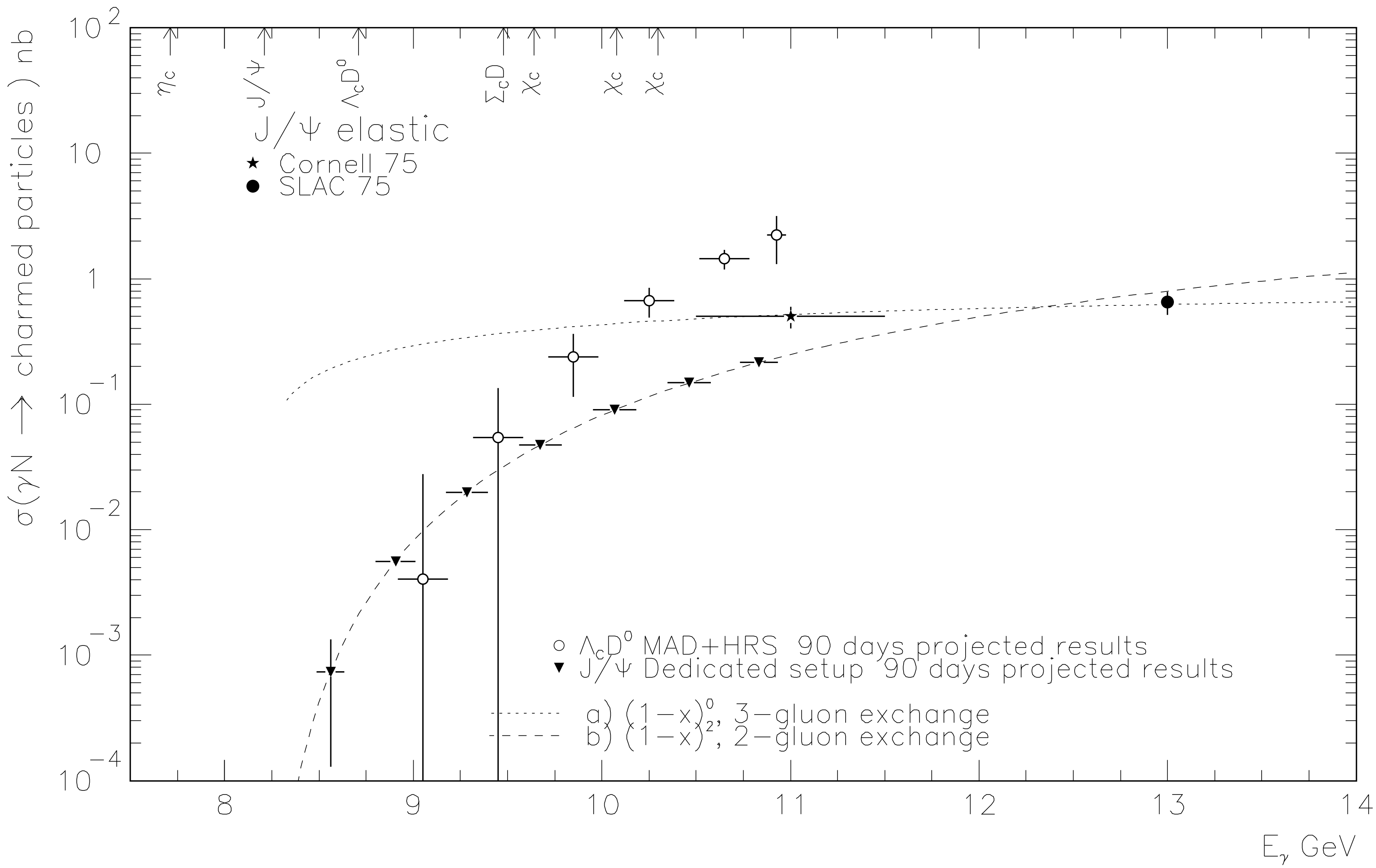
setup	$\sigma M/M$	$\sigma E_\Psi/E_\Psi$	$\sigma E_\gamma/E_\gamma$	$\sigma t (GeV/c)^2$
ECAL	0.035	0.007	0.01	0.11
HRS+MAD	0.002	0.001	0.002	0.014
Hall B,D no tag	0.010	0.004	0.001	0.03

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**
γp $\to J/\psi(1S)$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
γp $\to \Lambda_c^+ \overline{D}^0$						
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

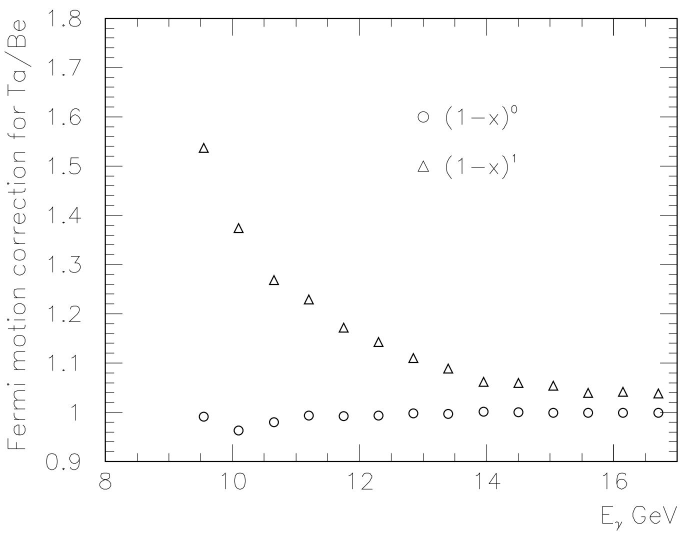
Extraction of $\sigma_{\psi N}$

- 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 ψ-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 ...)