Charm at JLab 12 GeV

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[1] JLab

MPS program,
Workshop at Jlab, May 2008

Outline

1. Introduction
   - Experimental opportunities
   - ψN Interaction
2. Program at JLab
   - Experiment in Hall C
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Outline

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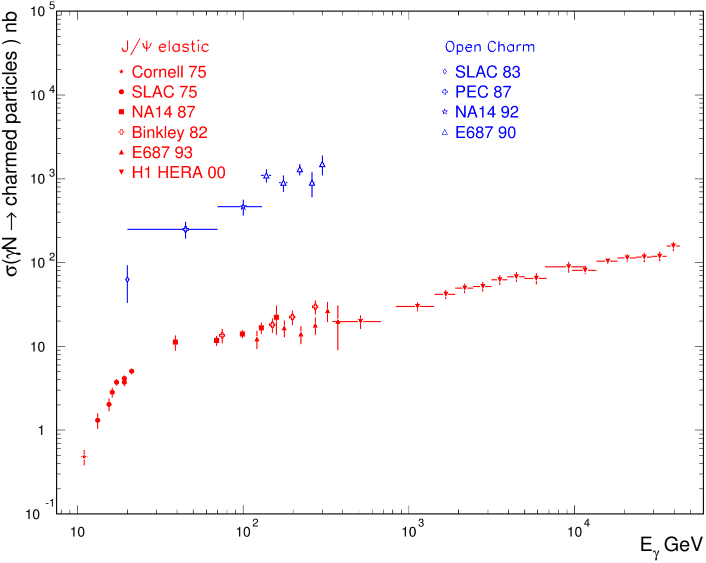
Charm photoproduction at 12 GeV

Charmed particles have been studied extensively since 1974
Can be used as a tool to study the hadronic structure

- Photoproduction cross section $\sigma_{charm} \sim 10^{-5} - 10^{-4}\sigma_{total}$
- Useful decays $BR < 0.06$
- Signal extraction: 2-body decay, small σ_M, leptons, vertex det.

	reaction	E_γ GeV threshold	useful decay mode	BR	cross section E_γ, GeV	σ nb
	$\gamma p \to \eta_c(1S)p$	7.7 GeV	$\eta_c(1S) \to p\bar{p}$	0.12%	-	-
⋆	$\gamma p \to J/\psi(1S)p$	8.2 GeV	$J/\psi(1S) \to e^-e^+/\mu^-\mu^+$	6.0%	11.	0.5±0.2
⋆	$\gamma p \to \Lambda_c^+\overline{D}^0$	8.7 GeV	$\overline{D}^0 \to K^+\pi^-$	4.0%	20.	∼ 63.±30.
	$\gamma p \to \Lambda_c^+ D^*(2010)^0$	9.4 GeV	$D^*(2010)^0 \to \overline{D}^0 X$	100.0%	20.	∼ 63.±30.
	$\gamma p \to \chi_{c0}(1P)p$	9.6 GeV	$\chi_{c1}(1P) \to K^+K^-$	0.71%		
	$\gamma p \to \chi_{c2}(1P)p$	10.3 GeV	$\chi_{c1}(1P) \to J/\psi(1S)\gamma$	13.0%	90.	$<$ 27% J/ψ
	$\gamma p \to \psi(3770)p$	11.0 GeV	$\psi(3770) \to e^-e^+/\mu^-\mu^+$	0.8%	21.	1.1±0.4
	$\gamma p \to D\overline{D}p$	11.1 GeV			20.	∼ 63.±30.

Photoproduction measurements



Jefferson Lab

Potential experimental opportunities at 12 GeV JLab

A vertex detector for $\Lambda_c^+, \overline{D}$ can hardly be used.

Best chances:

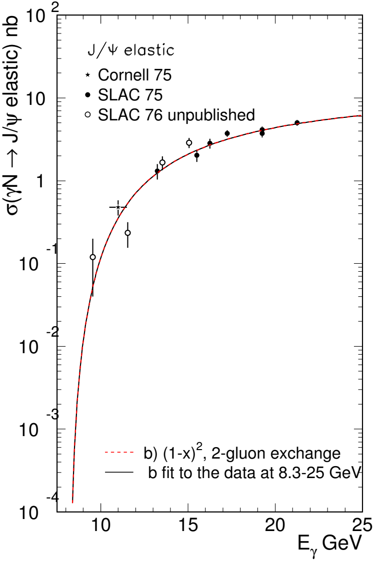
- $\gamma p \rightarrow p\, J/\psi(1S) \rightarrow e^- e^+ / \mu^- \mu^+$, proved at Cornell 11 GeV
- $\gamma p \rightarrow \Lambda_c^+ \overline{D}^0 \rightarrow K^+ \pi^-$ $M_{miss} \sim M_{\Lambda_c^+}$ - seems possible
- $\gamma p \rightarrow p\, \eta_c(1S) \rightarrow p\bar{p} < 0.01$ of $J/\psi(1S)$ - harder

Physics with J/ψ

- Photoproduction of $J/\psi(1S)$ close to threshold (GPD)
- Interaction of $J/\psi(1S)$ - a "long living" particle - with matter
- Double-spin longitudinal $J/\psi(1S)$ (GPD, for CLAS)

Can we use $J/\psi(1S)$ as a probe for the nucleon/nucleus?

J/ψ photoproduction at 10 GeV: Dynamical models

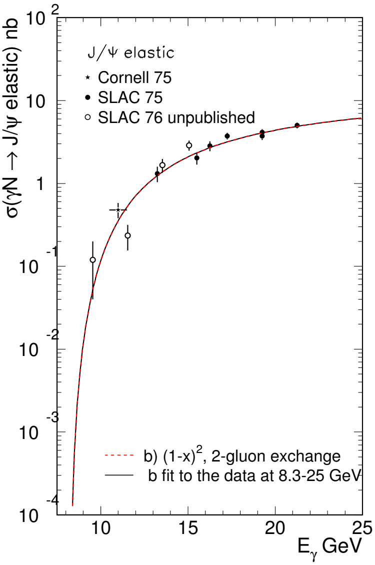


Both models fit the data at 11-25 GeV:

- Frankfurt 2003
- Brodsky 2001: 2-gluon exchange (red curve)

- Brodsky 2001: 3-gluon exchange alone does not fit the data

J/ψ photoproduction at 10 GeV: Dynamical models



Both models fit the data at 11-25 GeV:

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Subthreshold experiment E-03-008

No J/ψ observed
Spectral functions $\otimes$ σ not large

Photoproduction on nucleons

1. Measure $\frac{d\sigma}{dt}(E)$ for $\gamma + \text{p} \rightarrow \text{J}/\psi + \text{p}$
   close to threshold, at $E_\gamma \sim 8.5 - 11$ GeV
   Low energy $\Rightarrow$ sensitive to high-x gluons in the nucleon

ψN Interaction: Physics

- Small size color dipole $r_\perp \sim \frac{1}{\alpha_s \cdot m_c} = 0.3$ fm
  interaction $\propto$ color dipole moment $\propto r_{c\bar{c}}$ (small)
  $\Leftrightarrow$ color transparency,
  $\sigma_{\rm tot}^{\psi N} \ll \sigma_{\rm tot}^{\pi N} \approx 30$ mb

- Low energy: attractive potential (Luke,Manohar,Savage,1992)
  similar to Van der Waals, $E_{binding} \sim 8~MeV$

- Absorption: breakup to $\mathrm{D\overline{D}}$, $\psi + \mathrm{N} \rightarrow \Lambda_c^+ \overline{\mathrm{D}}$

ψN Interaction: Experimental Access

1. Calculated from photoproduction on nucleons using VMD/GVMD

   γN $>$20 GeV $\sigma^{\psi N}_{\rm tot} \sim$ 2.8 - 4.1 mb model dependent

2. Nuclear absorption: from A-dependence, Glauber model

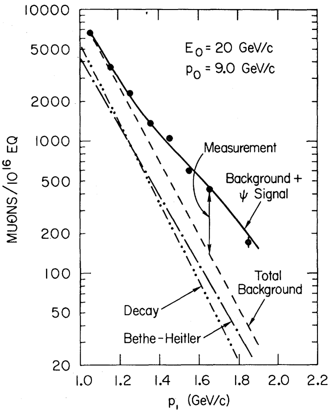
   γA 20 GeV $\sigma^{\psi N}_{\rm abs} = 3.5 \pm 0.9$ mb clean interpretation poor accuracy

   pA $>$100 GeV $\sigma^{\psi N}_{\rm abs} = 4.2 \pm 0.4$ mb not ψN: $\ell_{coh}, \ell_F \gg R_A$ contamination $\chi_c, \psi\prime$

We use arguments from Farrar et al.,1990, Kharzeev et al, 2007

ψN Interaction: Experiment at SLAC 1977

- The cleanest method used so far: $\ell_{coh}, \ell_F < R_A$
- Large experimental uncertainties



- 20 GeV e^- on Be and Ta targets
- Detecting only μ^-, through iron
- The background was calculated (decays, Bethe-Heitler)
- Nuclear coherence not measured

$$\sigma(Be)/\sigma(Ta) = 1.21 \pm 0.7$$

$$\Rightarrow \sigma_{\psi N} = 3.5 \pm 0.8 \pm 0.6 \text{ mb}$$

Authors: syst. errors might be larger

- JLab: we can do a much more accurate experiment!

Photoproduction on Nuclei

1. Measure the A-dependence of $\sigma(\gamma + A \to J/\psi + X)$, extract $\sigma_{abs}^{\psi N}$ at $\sqrt{s} \sim$ 5 GeV
Much improved accuracy and a cleaner interpretation.

Experiment in Hall C

PR12-07-106 for Hall C: conditionally approved.
Objectives:

1. Accurate measurement of J/ψ-nucleon cross-section at $\sqrt{s} = 5$ GeV
   - Test theoretical ideas (color dipole model, Van-der-Waals force)
   - Benchmark for future calculations
   - Interest for heavy ion physics.

2. Measurement of J/ψ photoproduction cross section $\frac{d\sigma}{dt}(E_\gamma)$ at $E_\gamma \sim 8.8 - 11$ GeV
   - Input for (1).
   - Probes large-x gluon GPD / small-size gluon configurations in proton.

Experiment: Setup

- Use decays to $e^+e^-(6\%), \mu^+\mu^-(6\%)$ to identify J/ψ mass

Standard Hall C equipment

- High rate at various targets
- Low background: $< 2\%$, scaled from Cornell, SLAC
- Reconstruction of E_γ, identification of γ+p$\rightarrow$J/ψ+p

Hall C Spectrometers

- HMS: e^-, μ^- at $\theta > 20^\circ$
- SHMS: e^+, μ^+ at $\theta < 20^\circ$
- $e^+, e-$ Gas Cher., Shower
- $\mu^+, \mu-$ Gas Cher.

Beam and target

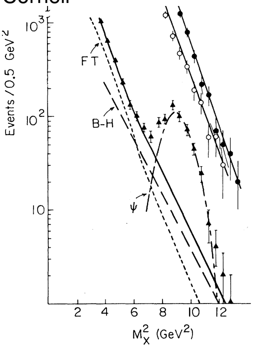
- Bremsstrahlung by 50 μA beam
- 6 targets $A = 9 - 197$, 10% r.l. thick
- Each target: 3 plates $\sim$ 5 cm apart
- 20 cm LH_2 with a 7% radiator
- 20 cm LD_2 with a 7% radiator

Experiment: Counting rates, Backgrounds

Rates

- Single arm: $<$ 250 kHz
- Coinc. (100 ns): $\sim$ 200 Hz

Cornell



$\Delta M =$ 0.5 GeV $BG = 15\%$

Resolutions

- Mass 7.4 MeV/c²

For γ+p$\rightarrow$J/ψ+p:

- Photon energy 0.2%
- t: $\sigma_t \sim 0.015\ (\mathrm{GeV/c})^{-2}$

Backgrounds

- Accidentals $<$ 0.2 per hour

Physics: Bethe-Heitler dominated

- Calculated
- Scaled (Cornell, SLAC) $<$ 2%

Experiment: Rates on Nuclear Targets

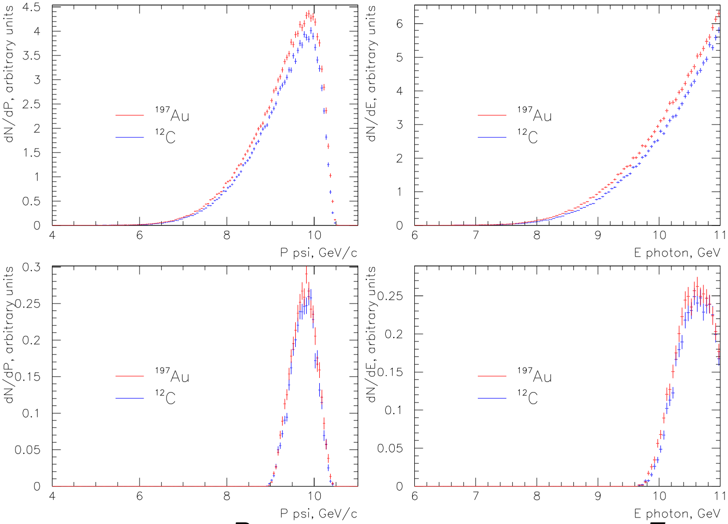
- Acceptance $\epsilon \approx 0.03\%$
- Internal Bremsstrahlung 1.6%
- No nuclear absorption is assumed for the moment

	^1H	^2H	Be	C	Al	Cu	Ag	Au
A	1	2	9	12	27	63.5	108	197
Z	1	1	4	6	13	29	47	79
T/T_{RL}	0.022	0.027	0.10	0.10	0.10	0.10	0.10	0.10
J/ψ per h	170	340	560	370	208	112	78	55
Time*, h	24	12	7	11	19	36	51	72

* – in order to detect 4000 events per target

- 200 hours on nuclear targets

Hall C: acceptance



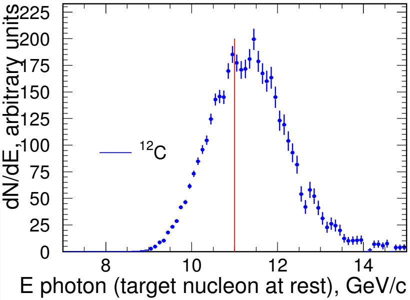
Produced

Detected

P_ψ E_γ

Fermi motion Correction and Hydrogen Measurements

Fermi motion $\otimes\ \sigma_{\gamma N \to \psi X}(E_\gamma)$:
$Au/C \approx 1.10$ sensitive to $\sigma(E_\gamma)$
Need to measure $\sigma(E_\gamma)$



Plan for $\sigma_{\gamma p \to \psi p}(E_\gamma)$ measurement

3 endpoints at 8.8, 10.2, 11.0 GeV
"Elastic" $\gamma p \to \psi p$ dominates
Use reconstructed photon energy $\mathcal{E}_\gamma$
$\mathcal{E}_\gamma > E_{e^-} - 0.3$ GeV: pure "elastic"
Constraints from SLAC $E_\gamma > 15$ GeV
Simulation shows: $\delta(Au/C) < 0.01$

Measurements on LH_2

$< E_\gamma >$ GeV	$\sigma_\psi(E)$ error
8.7	15%
10.0	3%
10.8	3%

Hall C setup evaluation

The Good

- High rate
- High mass resolution
- Low background

The Bad

Small acceptance:

- Many kin. points
- Hard to measure $E, t, \cos\theta$ dependence
- No way to measure the recoil

The Ugly

- Radiation budget

Hall D Potential for Heavy Quark Physics

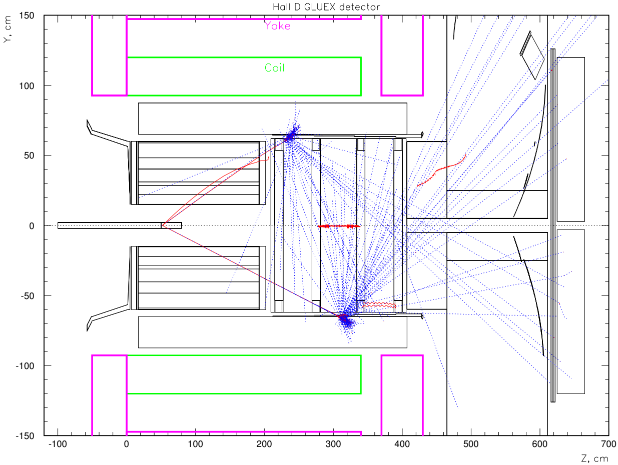
Obvious advantages

1. Large uniform acceptance for all particles, including the recoil: potentially a good measurement of $\frac{d\sigma}{d\Omega}(E, t, \cos\theta)$
2. Separation “elastic”/”inelastic” $\gamma p \to \psi p$ vs $\gamma p \to \psi N\pi$
3. Tagged photon beam of the highest flux usable
4. Possibility to run in parallel with the main program
5. Fast DAQ - no need for a special trigger

Questions

1. Is the production rate sufficient?
2. What are the mass/energy resolutions?
3. What is the expected background?
4. Is linear polarization useful?

Hall D: detecting γ+p$\rightarrow$p+J/$\psi$$\rightarrow$e$^+e^-$



Acceptance:

e$^\pm$ 75/25 BCAL/FCAL
p 88/12 BCAL/TOF
Accept.: $\varepsilon \sim$70%
Losses: $\varepsilon \sim$70%

Identification:

e$^+$e$^-$ - calorimeter
$\mu^+\mu^-$ - ?
p 70%, TOF π^+ $\times$0.01
p kin. fit π^+ $\times$0.01

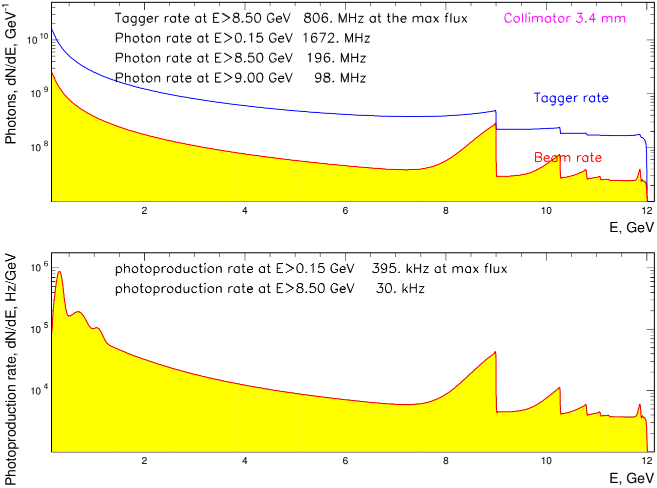
Hall D: detecting J/ψ, resolutions

- Track momentum, angular resolutions - from reconstruction
- Track fit assumes the beam $\sigma_X = \sigma_Y = 1$ mm
- Tagger energy resolution 60 MeV / $\sqrt{12}$ = 17 MeV

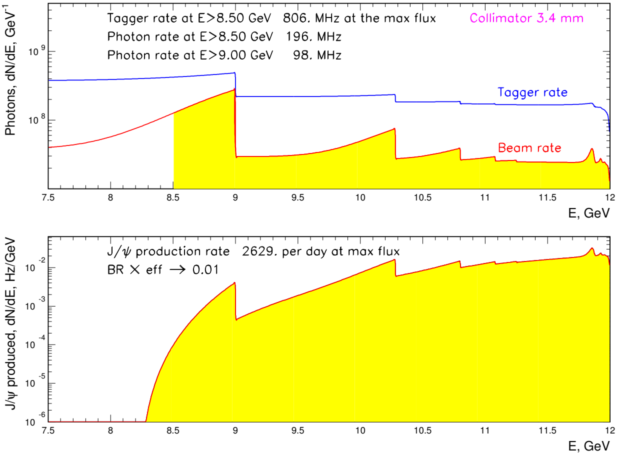
Event fit	Variable		
	M_ψ GeV/c^2 e^+,e^-	E_{beam} GeV e^+,e^-,p	M_{recoil} GeV/c^2 e^+,e^-,tagger
none	0.045	0.190	0.100
Using E_{tagger}	0.022	-	-
Using M_ψ	-	0.080	0.032

- M_ψ window (no fit) $5\sigma \sim 0.230$ GeV/c^2: BG$\sim$7%
- Tagger window $5\sigma \sim 1$ GeV (no fit), 0.4 GeV (M_ψ fit)

Hall D high intensity beam, standard collimation



Hall D J/ψ rate, standard collimation



Low beam: 800 events is 1 year, for free

Tagger rate:
0.4 GeV: 100 MHz
bucket: 0.2/2 ns

Tagger $<$11.4 GeV
Upgrade to $\sim$11.8 ?

High beam rate
J/ψ rate: $\sim$50 / day
Low beam rate
J/ψ rate: $\sim$5 / day

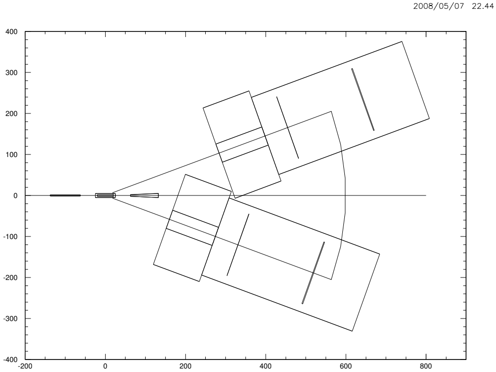
Hall B Potential for Heavy Quark Physics

1. CLAS-12 standard: 10^2 nb^{-1}s^{-1}: $\sim 10^9$ photons/s potentially a good measurement of $\frac{d\sigma}{d\Omega}(E, t, \cos\theta)$
2. Polarized target: ammonia $<$ 100 nA.
3. Large acceptence (? - need a number)
4. Asymmetry $\sim 0.05 \Rightarrow >1$ M events needed

LOI by M.Osipenko et al

1. $\times$10 luminosity: 100 nA, 3 cm target
2. About 10^6 events in 6 months:
3. Acceptance?

MPS layout



8.2-11 GeV:
Acceptance for J/ψ: 0.02
Acceptance for $J/\psi, p$: 0.003

20 μA on 20 cm LH2: 2000/h
for e, μ 10^5 nb^{-1}s^{-1}
radiator ?
20 days $\Rightarrow$ 1 M events

Energy reconstruction?

Summary

1. The cross section for ψN and for photoproduction (limited coverage): Hall C has an advantage
2. Hall D: first 2 years (240 days $\times 0.7$) - low flux beam on LH
   - Well tagged events, in parallel with the main program
   - Expected J/ψ: $\sim$ 800 events total, $\sim$ 50 for $E_{beam} < 9.5$ GeV
   - Measurements:
     - "elastic"/"inelastic"
     - $\frac{d\sigma}{d\Omega}(E, t, cos\theta)$ for $9.5 < E_{beam} < 11.4$ GeV, accuracy $\sim$10% / bin
     - Linear polarization in $8 < E_{beam} < 9$ GeV is unusable
3. Hall D: running at high flux($\sim$ 240 days $\times 0.7$) - on LH, LD
   - Options: linear polarization vs good tagging with wide collimation
   - Cross section mapping down to low energies, better accuracy
   - Production on LD - hidden color?

Summary

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 $J/\psi(1S)$ 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) SHMS+HMS in 2 months
- The part (2) - longer time (several options)

ψN Interaction: Proposed Experiment

1. Measure the A-dependence of $\gamma A \to J/\psi X$, extract $\sigma_{\rm abs}^{\psi N}$ compared with SLAC 1977:
   - low background for J/ψ
   - no coherent production
   - smaller effects from ℓ_{coh},ℓ_F
   - several targets used
   - reconstructed kinematics of J/ψ

   - steeper $\sigma(E_\gamma)$ dependence $\Rightarrow$ stronger effect from Fermi motion (need $\sigma(E_\gamma)$ to make correction)
   - EMC effect could make a stronger impact $x \sim 0.3 \to 0.5$
2. Measure $\frac{d\sigma}{dt}(E)$ for γp$\to$J/ψp
   - Provide Fermi-motion correction for the A-dependence
   - Measurement in a new energy range

Spectrometers

spectr.	P range GeV/c	$\Delta P/P$	$\sigma P/P$	θ^{in} range	$\Delta\theta^{in}$ mrad	$\Delta\theta^{out}$ mrad	$\Delta\Omega$ msr	$\sigma\theta^{in}$ mrad	$\sigma\theta^{out}$ mrad
HMS	0.4–7.4	$-10+10\%$	0.1%	10.5°–90°	±24	±70	8	0.8	1.0
SHMS	2.5–11.	$-15+25\%$	0.1%	5.5°–25°	±20	±50	4	1.0	1.0

Settings for hydrogen measurements

set	HMS θ	HMS P GeV/c	SHMS θ	SHMS P GeV/c	selection $\langle P_\psi \rangle$ GeV/c	selection $\langle P_t^2 \rangle$ (GeV/c)^2	selection $\langle \cos\theta_{CM} \rangle$	selection $\langle E_\gamma \rangle$ GeV	rate J/ψ per hour total	rate J/ψ per hour elas.
$E_{e^-} = 11$ GeV										
1	21.0°	4.20	15.0°	5.80	9.7	0.08	-0.15	10.8	170	66
2	21.5°	4.00	16.3°	5.90	9.7	0.12	-0.15	10.8	106	17
3	28.0°	2.95	10.7°	7.50	9.7	0.08	-0.45	10.8	136	65
4	37.0°	1.90	8.0°	8.50	9.7	0.08	-0.65	10.8	72	40
5	23.4°	3.89	16.3°	5.30	8.9	0.08	-0.15	9.8	60	
$E_{e^-} = 10.2$ GeV										
5	23.4°	3.89	16.3°	5.30	8.9	0.08	-0.15	10.0	60	30
$E_{e^-} = 8.8$ GeV										
6	28.1°	3.24	19.1°	4.50	7.3	0.08	-0.15	8.7	0.70	0.70

Experiment: γA – kinematics optimization

- $\frac{d\sigma}{dt} = C(E_\gamma) \cdot e^{b \cdot t}$, 2–gluon exchange, fit to data
- t-slope b varied in 1.1-3.0 $(\mathrm{GeV/c})^{-2}$ range
- Decay distribution $(1 + \cos^2\theta_{CM})$
- Fermi motion - spectral functions for C, Fe and Au used
- Beam energy 11 GeV

Acceptance optimized for γA

set	HMS		SHMS	
	θ	P, GeV/c	θ	P, GeV/c
1	21.0°	4.20	15.0°	5.80

Experiment: Expected Results on $\sigma^{\psi N}$

Total error per target $\sim$3%

- beam flux $\sim$ 1%
- target thickness $<$ 1.5%
- Fermi correction $<$ 1.%
- statistics $\sim$ 1.5%
- acceptance: nearly cancels
- other $\sim$ 0.5%

Glauber model used to extract $\sigma^{\psi N}$

Expected transparencies $T_N(A) = \sigma_A / A\sigma_N$

	$\sigma^{\psi N}$ mb	A: 9	12	27	63	108	197	$\delta(\sigma^{\psi N})$ mb
T	1.0	0.982	0.980	0.974	0.963	0.952	0.931	0.29
	3.5	0.938	0.931	0.908	0.870	0.833	0.760	0.25
	7.0	0.876	0.863	0.816	0.740	0.665	0.519	0.18

$\sigma^{\psi N} \approx (3.5) \pm 0.12 \pm 0.20$ mb at $\sqrt{s} \sim 5$ GeV

SLAC: 0.80 ± 0.60

Experiment: Photoproduction

1. Main measurements on hydrogen
   - 3 endpoints: 8.8,10.2 and 11.0 GeV
     expected accuracy $\sigma_\psi \sim 3\%$ for 10.2 and 11 GeV
2. Additional measurements at 11 GeV
   - Increase the range of t to measure $\frac{d\sigma}{dt}$
   - Increase the range of θ_{decay} to measure the absolute cross section
   - LD_2 - for isoscalarity correction

In total 290 hours are requested

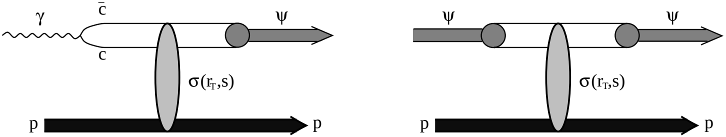
Request

- Standard Hall C spectrometers
- New nuclear targets
- Radiators for cryo targets

beam		
11.0 GeV	standard	16 days
10.8 GeV	non-standard	2 days
8.8 GeV	standard	3 days
		21 days

ψ Photoproduction and ψ-N interaction

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



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

$\sigma^{\psi N}$ Theoretical Calculations

Various models used ⇒ exchange meson currents, color dipole interactions etc.

- Low energy (Van-der-Waals): $\sigma^{\psi N}_{\text{tot}} \sim$ 7 mb (Brodsky,Miller,1997), falling with energy
- Scaling from other VM: $\sigma^{\psi N}_{\text{abs}} \sim$ 3.6 mb (Gerland et al,1998)
- GVMD, wave func, $\sigma^{\psi N}_{\text{tot}} \sim$ 3 mb (Kopeliovich,Raufeisen,1994)
- Exclusive reactions

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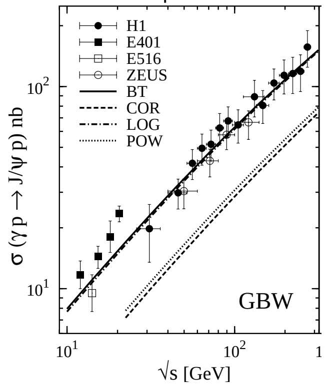
Kopeliovich



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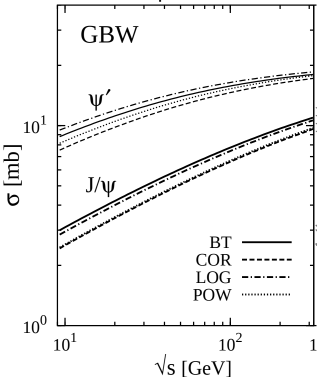

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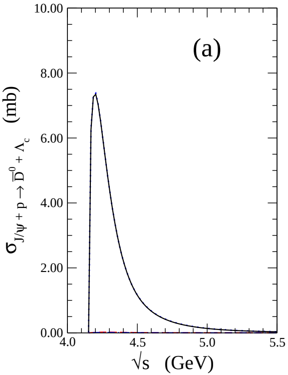
Oh, Liu,Ko 2007 $\psi + N \rightarrow \Lambda_c^+ \overline{D}$



J/ψ photoproduction at 10 GeV: Dynamical models

S. Brodsky et al, 2001:

Quark counting rules at $x = \frac{s_{thresh}-m_p^2}{s-m_p^2} \sim 1$

2-gluon exchange

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

3-gluon exchange

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

$\frac{d\sigma}{dt} \propto e^{b\cdot t}$ from experiments

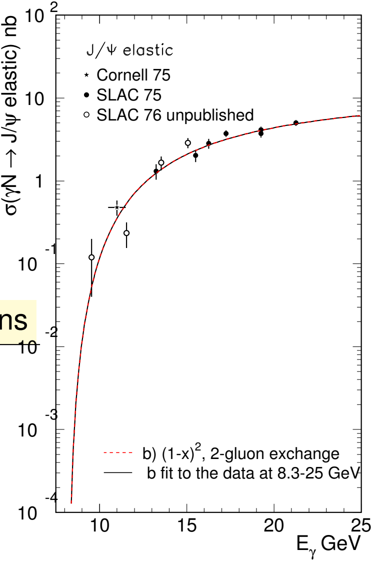
Different energy dependencies for 2,3-gluons

Frankfurt, Strikman, Weiss 2002-2004

$x \ll 1 \quad \frac{d\sigma_{\gamma P\to J/\psi p}}{dt} \propto \frac{H_g(x,t)^2}{H_g(x,0)^2}$

$H_g(x,t) \propto (1 - t/m_g^2)^{-2}$ 2-gluon formfactor

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

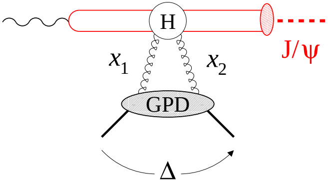


Exclusive J/ψ production in γp and *ep*: High vs. low *W*

Frankfurt, Strikman, Weiss

$W \gg M^2_{c\bar{c}}$ - HERA, FNAL

- Momentum transfer $|\Delta_\perp| <1$ GeV/c, $\Delta_{||}$ - small
- Gluon GPD $x_1 \sim x_2 \ll 1$
- "Transverse gluon imaging"



$W \sim M^2_{c\bar{c}}$ - JLab

- Large $\Delta_{||}$, large $|t_{min}|$
- Gluon GPD $x_1 \neq x_2 \sim 1$ ("skewness")
- Probes transition form factor of gluon dipole moment at high t

- Unique probe of small-size gluon configuration in proton
- Dipole moment $\sim r_{c\bar{c}}$
- "Color transparency"

Theoretical Calculations for J/ψ Production

The full phenomena has not been described.

1. At $E_\gamma > 50$ GeV
   - Models exploiting VMD
2. At threshold $E_\gamma < 12$ GeV
   - No rigorous calculations so far
   - A model based on quark counting rules, used for guidance

$\sigma^{\psi N}$ Theoretical Calculations

At low energy:

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

In a wide range of energies:

- Various models: exchange meson currents, color dipole interaction, etc
- VMD → link to photoproduction

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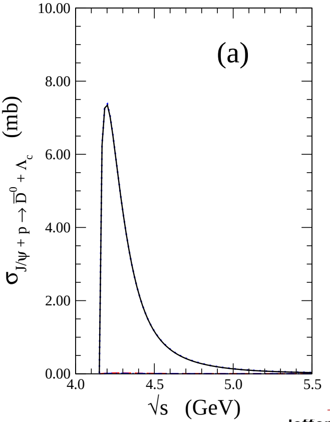
ψ+N→$\Lambda_c^+\overline{\rm D}$
Meson exchange current
Oh, Liu,Ko 2007



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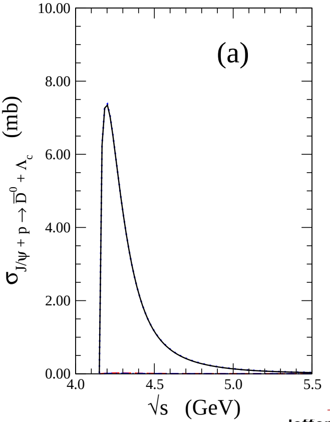

Hall D high intensity beam, wide collimation