Photoproduction of J/ψ on Nuclei

E.Chudakov[1]

[1] JLab

SRC Workshop, Jlab 2007

JLab at 12 GeV

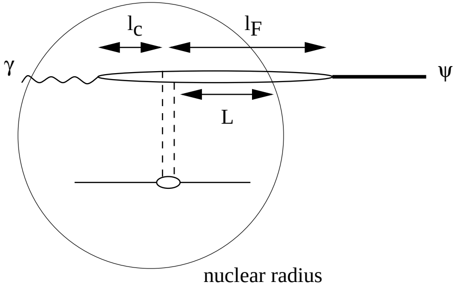
- At 11 GeV $\gamma p \to \eta_c(1S)$, $J/\psi(1S)$, $\overline{D}^0\Lambda_c^+$, $\chi_{c1}(1P)$...
- Cross sections are low:
  $<$ 10 nb for D and $<$ 1 nb for charmonia
- The only detectable particle seems $J/\psi(1S)$ - decays to lepton pairs

Physics

- Photoproduction of $J/\psi(1S)$ close to threshold
- Interaction of $J/\psi(1S)$ - a long living particle - with matter

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

J/ψ photoproduction at 10 GeV: Scales



$$r_\perp \sim \frac{1}{\alpha_s \cdot m_c} = 0.3\ fm$$

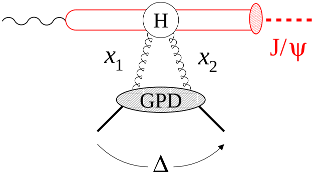
At $E_\gamma = 10$ GeV:

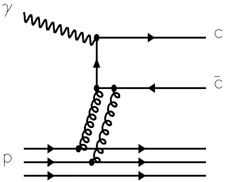
$$\ell_{coh} = \frac{2E_\gamma}{4m_c^2 + Q^2} \approx 0.4\ fm$$

$$\ell_F \cong \frac{2E_\gamma}{m_{\psi'}^2 - m_{J/\psi}^2} \sim 1\ fm$$

- No coherent production on heavy nucleus: $\ell_{coh} \ll R_A$
- No shadowing effects: $\ell_{coh}, \ell_F < R_A$
- VMD not applicable: $\ell_{coh} < 1$ fm

J/ψ photoproduction at 10 GeV: Dynamical models

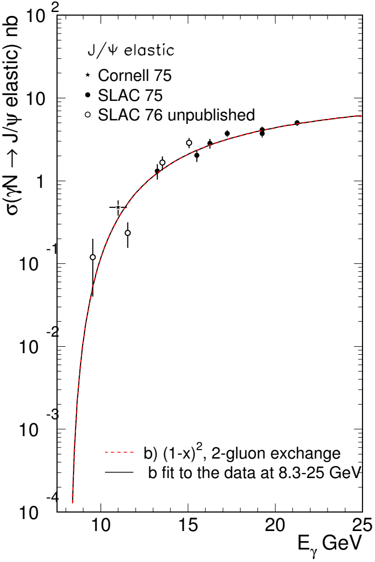




- Partonic soft mechanism Frankfurt..2002..
  - Well tested at high energies
  - 10 GeV: gluons $x_1 \neq x_2 \sim 1$ $|t_{min}| > 0.4$ GeV/c
  - 2-gluon formfactor: $\frac{d\sigma_{\gamma P \to J/\psi p}}{dt} \propto (1 - t/1.0 GeV^2)^{-4}$
- Hard scattering mechanism Brodsky.., 2001
  - 10 GeV: Quark counting rules
  - 2-gluon exchange $\propto (1 - x)^2$
  - 3-gluon exchange $\propto (1 - x)^0$

Unique probe of small-size gluon configurations in proton

J/ψ photoproduction at 10 GeV: Dynamical models



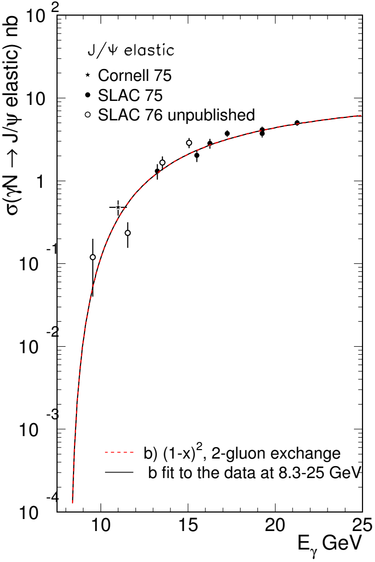
Both models fit the data at 11-25 GeV:

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

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

Jefferson Lab

J/ψ photoproduction at 10 GeV: Dynamical models



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Subthreshold experiment E-03-008

No J/ψ observed

Spectral functions $\otimes$ σ not large

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Photoproduction on nucleons

1. Measure $\frac{d\sigma}{dt}(E)$ for γ+p$\rightarrow$J/ψ+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 $D\overline{D}$, $\psi + N \rightarrow \Lambda_c^+ \overline{D}$

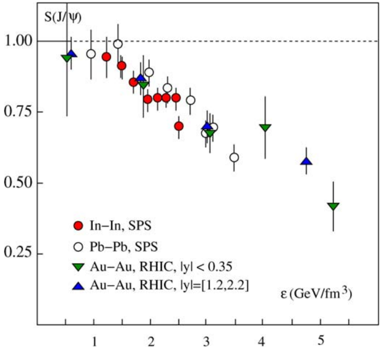
ψN Interaction: Signature for QGP

J/ψ suppression in *AA* collisions $\Rightarrow$ signature for QGP

Range: $\sqrt{s} \sim 5 - 400$ GeV

deficiency found, using

experiment	$\sigma_{abs}^{\psi N}$
SPS	4.18 mb
RHIC	$\sim$ 3. mb



Interpretation: not resolved yet

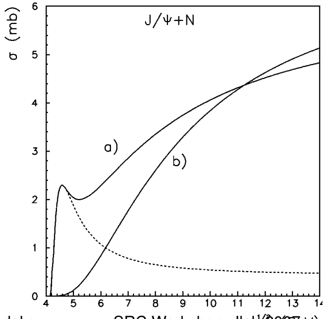
mixture ψ, χ_c...; regeneration at RHIC

- JLab experiment - measure $\sigma_{abs}^{\psi N}$ at lower energy $\sqrt{s} \sim 5$ GeV, in different conditions

ψN Interaction: $\sigma^{\psi N}$ Theoretical Calculations

Various models: VMD, exchange meson currents, etc.

authors	model	$\sqrt{s}$, GeV	$\sigma^{\psi N}$, mb
Brodsky,Miller,1997	Van-der-Waals potential	small	7
Kopeliovich...,1994	GVMD, wave functions	10–400	3–10
Gerland..., 1998	VMD, data for VM	>7	3.6
Sibirtsev..., 2001	boson exchange	>4	2.2
	Lattice		



ψN Interaction: Experimental Access

1. Calculated from photoproduction on nucleons using VMD/GVMD

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

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

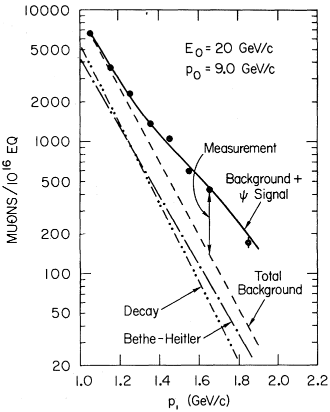
   γA 20 GeV $\sigma_{\rm abs}^{\psi N} = 3.5 \pm 0.9$ mb clean interpretation
   poor accuracy

   pA $>$100 GeV $\sigma_{\rm abs}^{\psi N} = 4.2 \pm 0.4$ 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 $\sigma_{\rm abs}^{\psi N}$ at $\sqrt{s} \sim$ 5 GeV
Much improved accuracy and a cleaner interpretation.

Program at JLab

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.

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)
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

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: 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 $(\text{GeV/c})^{-2}$ 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: Rates on Nuclear Targets

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

	^{1}H	^{2}H	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

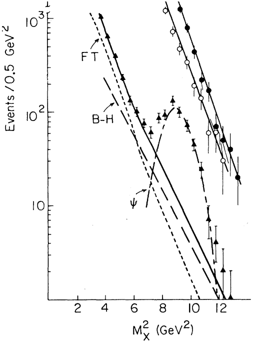
- 200 hours on nuclear targets

Experiment: Counting rates, Backgrounds

Rates

- Single arm: < 250 kHz
- Coincidence $\Delta t \sim 100$ ns: ~ 200 Hz

Cornell



Resolutions

- Mass 7.4 MeV/c^2
  For γ+p$\rightarrow$J/ψ+p:
- Photon energy 0.2%
- t: $\sigma_t \sim 0.015$ (GeV/c)$^{-2}$

Backgrounds

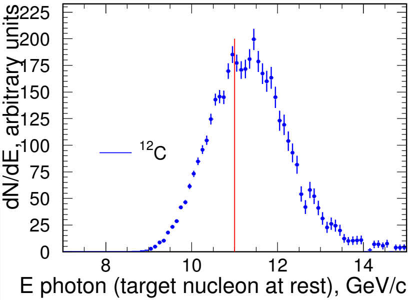
- Accidentals < 0.2 per hour

Physics: Bethe-Heitler dominated

- Calculated
- Scaled using Cornell, SLAC $< 2\%$

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%

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

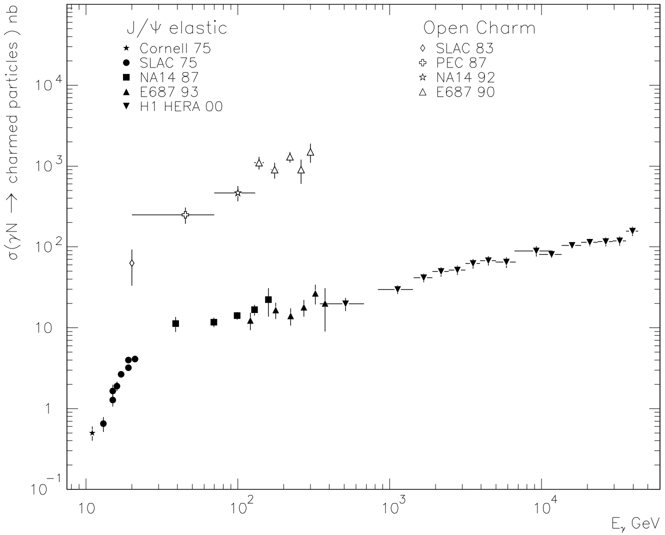
Spectrometers

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

Photoproduction measurements



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

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

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

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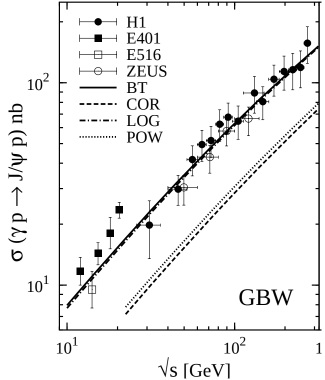

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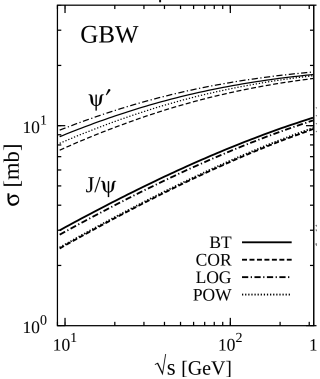

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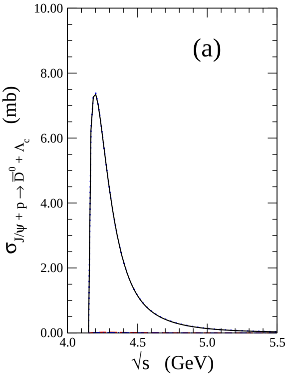
Oh, Liu,Ko 2007 ψ+N$\rightarrow\Lambda_c^+\overline{D}$



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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

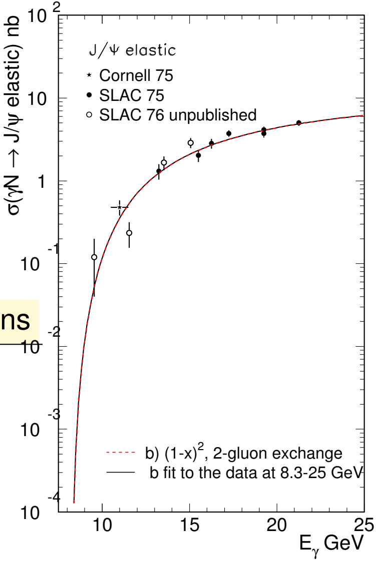
$$\frac{d\sigma}{dt} = \mathcal{N}_{2g} v \frac{(1-x)^2}{R^2 \mathcal{M}^2} F_1(\tfrac{t}{4})(s - m_p^2)^2$$

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



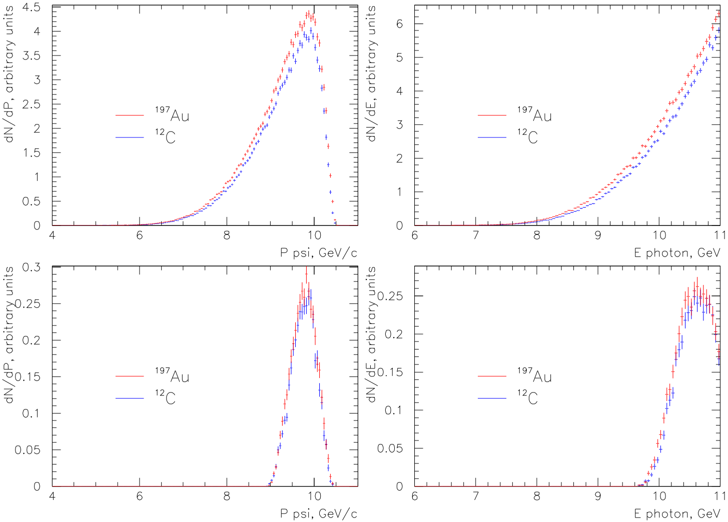
Frankfurt, Strikman, Weiss 2002-2004

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

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

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

Spectra



Produced

Detected

P_ψ

E_γ

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