PROPOSAL TO MEASURE THE A-DEPENDENCE OF J/ψ AND ψ' PHOTOPRODUCTION E160

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Representing the E160 Collaboration

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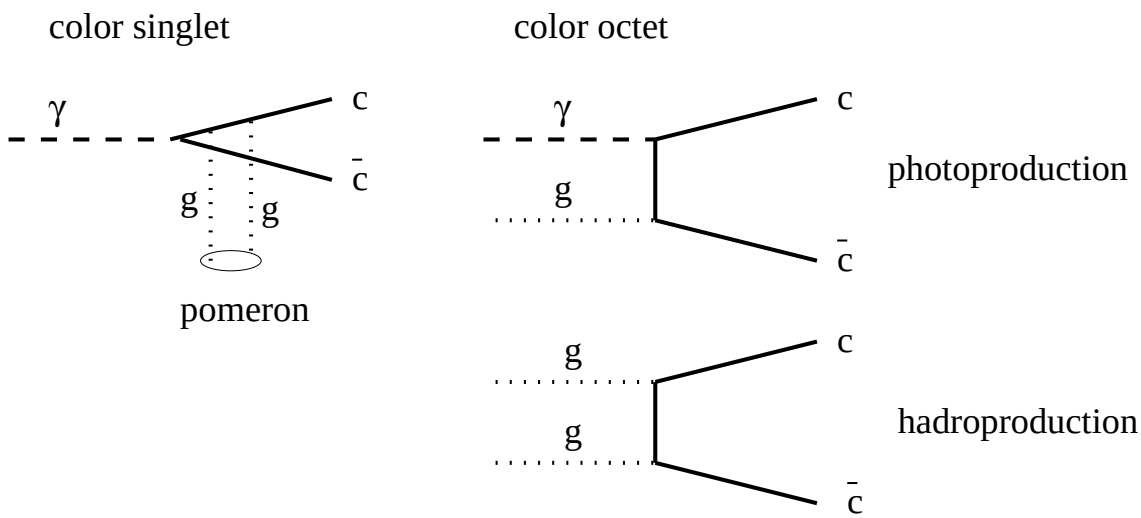
- What do we know about J/ψ and ψ' production and their interactions with hadrons?
- What can SLAC contribute?
- Details of the E160 experiment.

E160 Collaboration

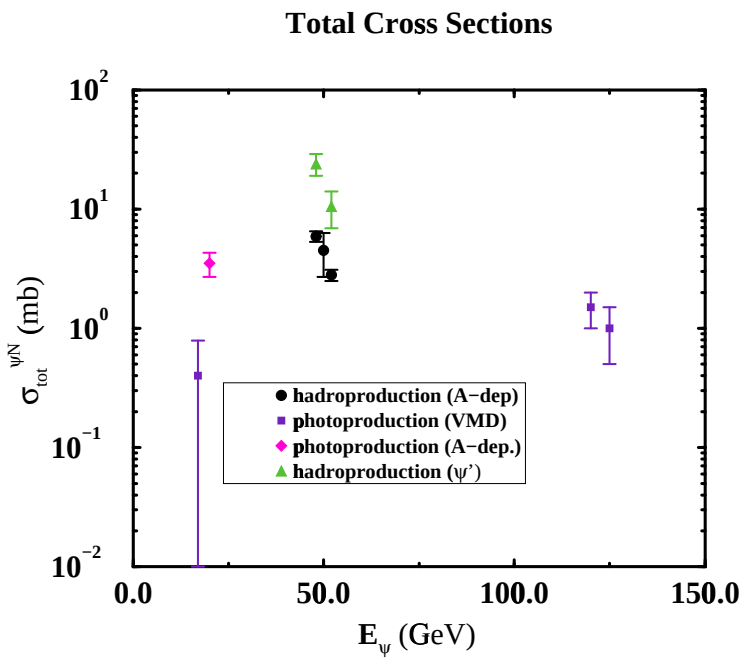
- University of California Los Angeles
- Jefferson Lab
- University of Massachusetts
- DAPNIA-Saclay
- Institut für Kernphysik Mainz
- Los Alamos National Laboratory
- Mississippi State University
- Old Dominion University
- Ruhr-Universität Bochum
- Smith College
- Stanford Linear Accelerator Center
- University of Virginia
- College of William and Mary
- Yerevan Physics Institute

Motivation



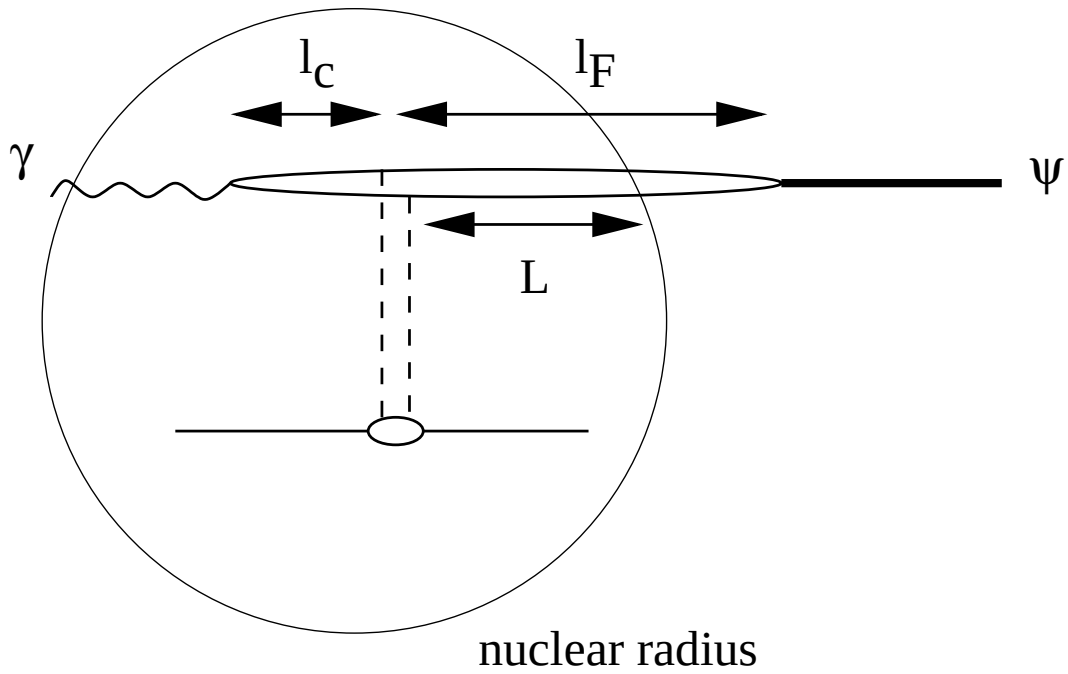
- Charmonium production: perturbative interactions, non-perturbative formation.
- Cross sections: perturbative → kinematic dependence; non-perturbative → uncalculable magnitude.
- No direct evidence for correct perturbative diagrams (e.g. photoproduction explained by both color singlet and octet models).
- Charmonium-nucleon interaction cross sections are not well known or understood.
- Yet charmonium production is used to probe gluon distributions and hot nuclear matter.

ψ-Nucleon Cross Section Data



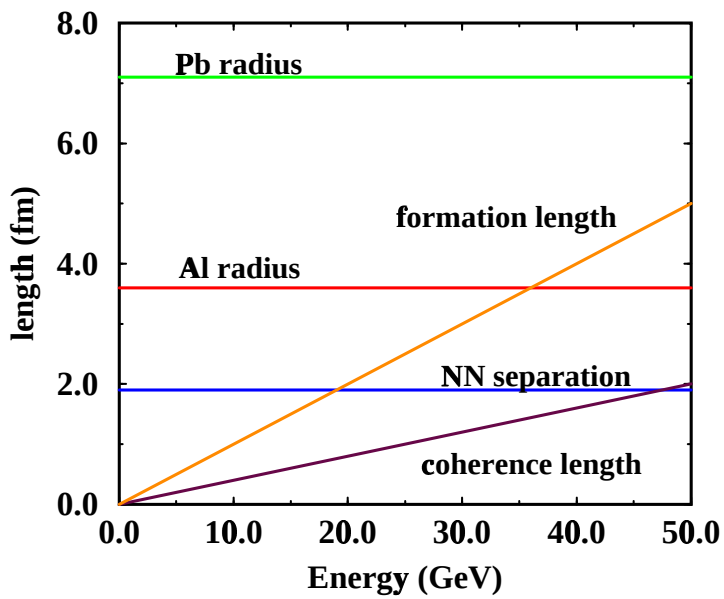
- Estimates of $\sigma_{\rm tot}^{\psi N}$ using vector meson dominance are small.
- Estimates from the A-dependence of J/ψ hadroproduction cluster around 6 mb.
- Estimates from the A-dependence of ψ' hadroproduction are between 7 and 30 mb.
- Estimate from the sole extraction from A-dependent photoproduction measurements is about 4 mb.

Coherence and Formation Lengths



- Coherence length ℓ_c
- Formation length ℓ_F

Length Scales



- Coherence Length: lifetime of a $c\bar{c}$ fluctuation

$$\ell_c \leq \frac{2E_{J/\psi}}{m^2_{J/\psi}} = 0.04 E_{J/\psi} \text{ fm}$$

- Formation Length: time of evolution from point-like perturbative interaction to full on-shell J/ψ.

$$\ell_F \approx \frac{2E_{J/\psi}}{m^2_{\psi'} - m^2_{J/\psi}} = 0.1 E_{J/\psi} \text{ fm}$$

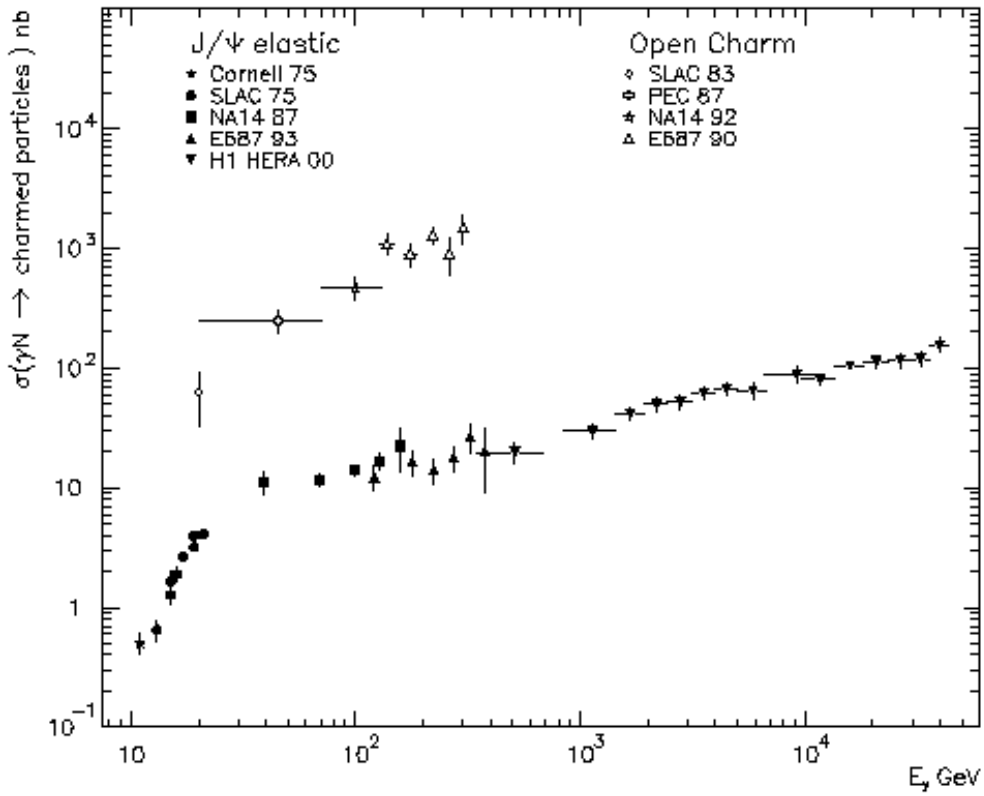
- Nuclear Radius: $R = 1.2 A^{\frac{1}{3}}$ fm $= 4 - 7$ fm

- Internucleon Spacing: $\langle r \rangle = \left(\frac{\frac{4}{3}\pi R^3}{A} \right)^{\frac{1}{3}} = 1.9$ fm

Advantages of Photoproduction

- Photons do not have multiple interactions with the nucleons in a nucleus.
- Elastic ψ production is relatively simple.
- Photons do not appreciably excite the 1P charmonium states χ_c, which radiatively decay into J/ψ's.
- Both ℓ_c and ℓ_F change with E_γ.

Charm Photoproduction



- Representative data
- Star: Cornell, B. Gittelman, *et al.*, Phys. Rev. Lett. **35**(1975)1616.
- Dots: SLAC, U. Camerini, *et al.*, Phys. Rev. Lett. **35**(1975)483.
- Squares: CERN NA14, R. Barate, *et al.*, Z. Phys. **C33**(1987)505.
- Up triangles: FNAL E687, P.L. Frabetti, *et al.*, Phys. Lett. **B316**(1993)197.
- Down triangles: HERA H1, C. Aldoff, *et al.*, Phys. Lett. **B483**(2000)23.

Paradox of Vector Meson Dominance

- $\sigma_{\rm tot}^{\psi N} \propto \frac{d\sigma}{dt}(\gamma N \to \psi N)|_{t=0}$ by the optical theorem.
- This results in $\sigma_{\rm tot}^{\psi N} \leq 1$ mb which is much less than the 3-10 mb values obtained from A-dependence studies.
- A virtual meson of mass m must have a transverse size $\sim \frac{1}{m}$ by uncertainty-principle arguments.
- Interaction cross sections scale as the square of the transverse size. Therefore,

$$\frac{\sigma_{\rm tot}^{\psi' N}}{\sigma_{\rm tot}^{\psi N}} = \left(\frac{m_{J/\psi}}{m_{\psi'}}\right)^2 \approx 0.7$$

- By the same scaling argument,

$$\sigma_{\rm tot}^{\psi N} = \left(\frac{r_{J/\psi}}{r_\pi}\right)^2 \sigma_{\rm tot}^{\pi N} = 2 - 5 \text{ mb}$$

  - $r_\pi \approx 0.65$ fm; $\sigma_{\rm tot}^{\pi N} \approx 25$ mb.
  - $r_{J/\psi} \approx 0.2 - 0.3$ fm.
  - $r_{\psi'} \approx 2 r_{J/\psi}$.
  - $\sigma_{\rm tot}^{\psi' N} / \sigma_{\rm tot}^{\psi N} \approx 4$

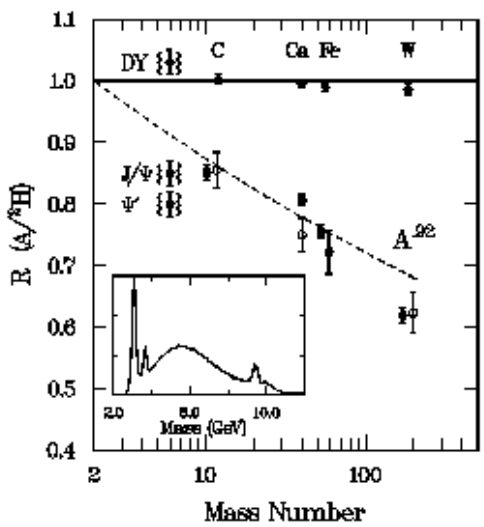
Why Might VMD Fail?

- The fluctuation of a photon might not always be a vector meson.
- Frankfurt and Strikman: Color transparency insures that the pre-meson is of small size at the time of interaction with the nucleon.
- Hüfner and Kopeliovich: The $c\bar{c}$ fluctuation has a wavefunction $|c\bar{c}\rangle = \alpha_1|J/\psi\rangle + \alpha_2|\psi'\rangle + ...$
- Ducati and Mariotto: Elastic J/ψ photoproduction could originate from color octet states rather than pomeron exchange.

How can one study the problem?

- E160 uses nuclei of various sizes to probe the J/ψ at a range of times during its formation.

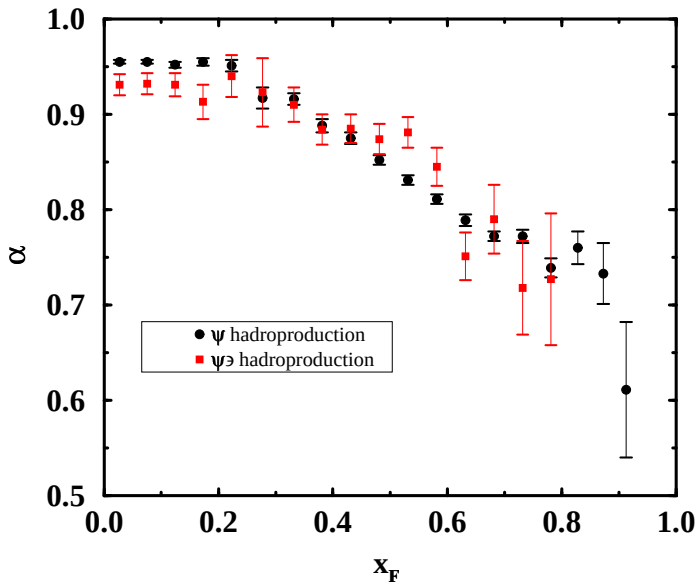
A-Dependence of J/ψ Production



- From D.M. Alde, *et al.*, Phys. Rev. Lett. **66**(91)133.
- Comparisons to Drell-Yan data indicate that shadowing does not explain the suppression of J/ψ's in nuclei.
- Data are fit to a universal form A^{α}, which is roughly the same for J/ψ and ψ'.
- If the error bars on the FNAL data are realistic, the A-dependence of J/ψ production is not a power law.
- $\sigma^{pA\to\psi}/A\sigma^{pN\to\psi} = \exp\left(-L\rho_0\sigma_{\rm tot}^{\psi N}\right)$ with $L \propto A^{\frac{1}{3}}$ fits approximately to a power law in A as long as $\sigma_{\rm tot}^{\psi N}$ is constant.

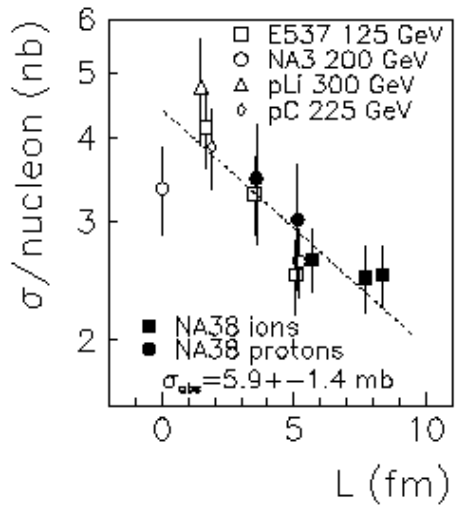
A-Dependence with x_F

FNAL E866/NuSea



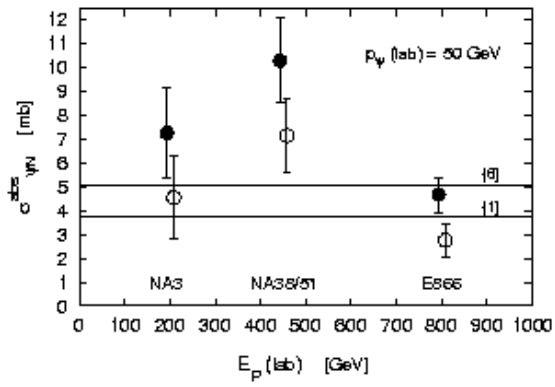
- FNAL E866/NuSea Collaboration, Phys. Rev. Lett. **84**(00)3256.
- ψ' has stronger A-dependence than J/ψ at $x_F \approx 0$, suggesting that $\sigma_{\rm tot}^{\psi' N} > \sigma_{\rm tot}^{\psi N}$.
- J/ψ and ψ' have similar, but enhanced A-dependencies at large x_F, suggesting that $\sigma_{\rm tot}^{\psi' N} = \sigma_{\rm tot}^{\psi N}$.
- α is small for large x_F and also for small p_T^2.

Glauber Approximation for $\sigma_{\rm tot}^{\psi N}$



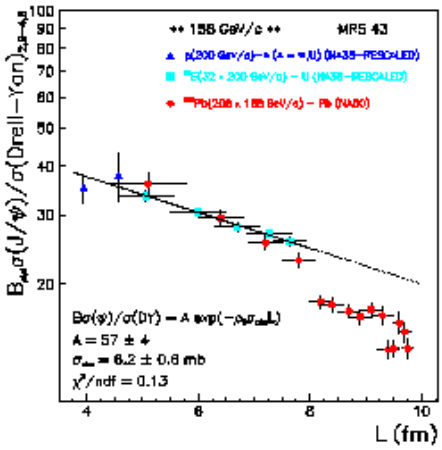
- Data as shown in B. Müller, nucl-th/9806023
- $$\frac{\sigma^{pA\to\psi}}{A\sigma^{pN\to\psi}} = e^{-L\rho_0\sigma_{\rm tot}^{\psi N}}.$$
- L: length of the absorption trajectory.
- ρ_0: the nuclear density.
- $\sigma_{\rm tot}^{\psi N}$ is assumed to be constant.
- Procedure works for nucleus-nucleus collisions.

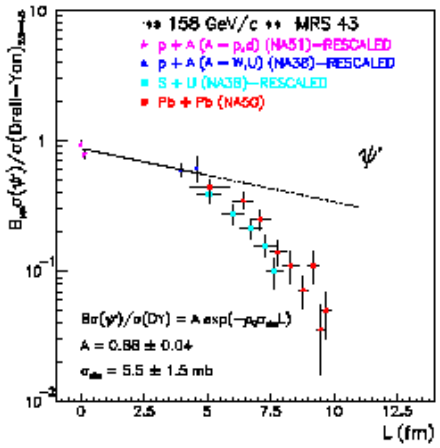
Glauber Approximation (con't)



- Fits to pA data from Hüfner, Kopeliovich and Polleri, hep-ph/0010282
- Open circles: Glauber-model fit.
- Solid circles: with corrections for gluon anti-shadowing.
- Lines: theoretical expectations for color singlet (lower) and octet (upper) absorption mechanisms.
- $\sigma^{\psi N}_{\rm tot}$ is clearly not well-known.

J/ψ Suppression for Heavy Ions



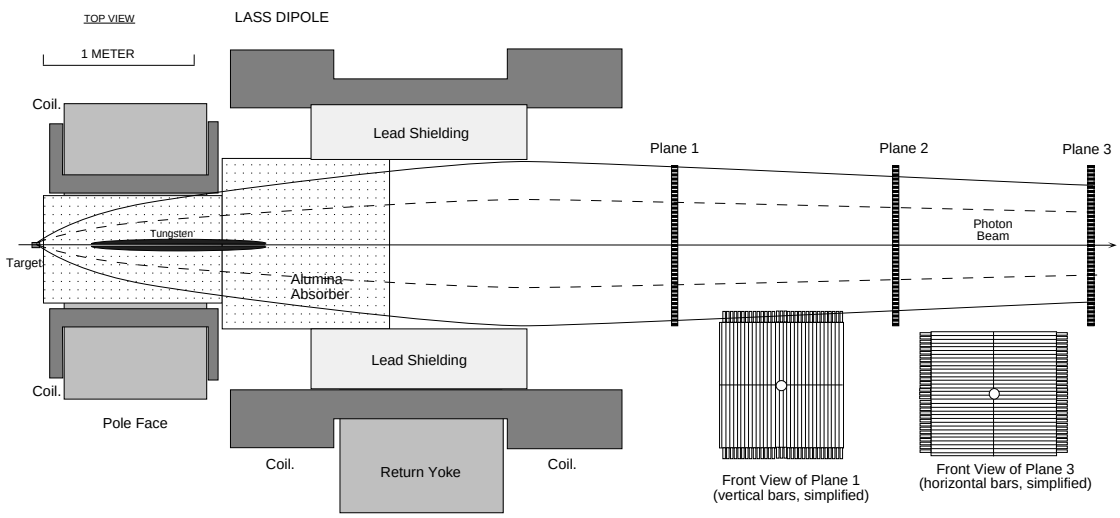


- From B. Müller, nucl-th/980623:
- It's still unclear whether J/ψ is a reliable probe for quark-gluon plasmas.
- Suppression in light targets is the result of the $A^{0.92}$ dependence of the $pA \to J/\psi X$ cross section.
- The color octet model provides a credible mechanism, but there is no direct evidence for it.
- Available evidence points toward a novel suppression in Pb+Pb collisions.
- Color singlet absorption on hadronic comovers does not explain the Pb+Pb data.

Experiment E160

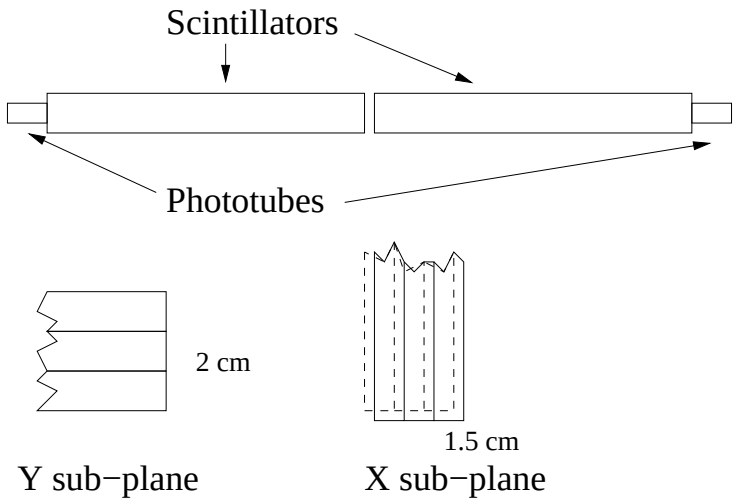
- SLAC can make a significant contribution to the understanding of charmonium production and propagation using a coherent bremsstrahlung photon beam with maximum energy 50 GeV.
- The proposed experiment E160 eliminates the overwhelming hadronic backgrounds with an absorber that only muons can penetrate.
- J/ψ's and ψ''s are reconstructed from $\mu^+\mu^-$ pairs.
- Muon angles and momenta are determined by two dipole magnets and 3 planes of hodoscopes.

E160 Spectrometer



- 29D32 Dipole Magnet
  - 25.4 cm gap; ±36 cm width; ≈ 1 m length.
  - $\int \mathbf{B} \cdot \mathbf{d}\ell = 22$ kG-m.
- 70D43 LASS Dipole Magnet
  - 102 cm gap; ±45 cm width; 109 cm length.
  - $\int \mathbf{B} \cdot \mathbf{d}\ell = 25$ kG-m.
  - 4000 A from 2 existing 1.6 MW power supplies.
  - mirror plates removed.
- 2.2 m alumina (Al_2O_3) absorber with tungsten core.
- 3 planes of scintillator hodoscopes.

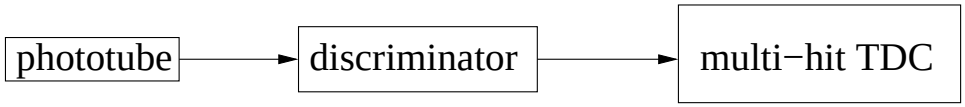
E160 Hodoscopes



- 3 planes at 4.2, 5.7 and 7.0 m from target; 1 phototube per plastic scintillator finger.
- 2 X sub-planes with 2/3 overlap of 1.5 cm thick fingers; segmented into top and bottom halves.
- 1 Y sub-plane with 2 cm thick fingers; segmented into left and right halves.

Plane	x (cm)	y (cm)	fingers
1	± 60	± 60	300
2	± 55	± 80	300
3	± 50	± 100	300

E160 Hodoscopes (con't)



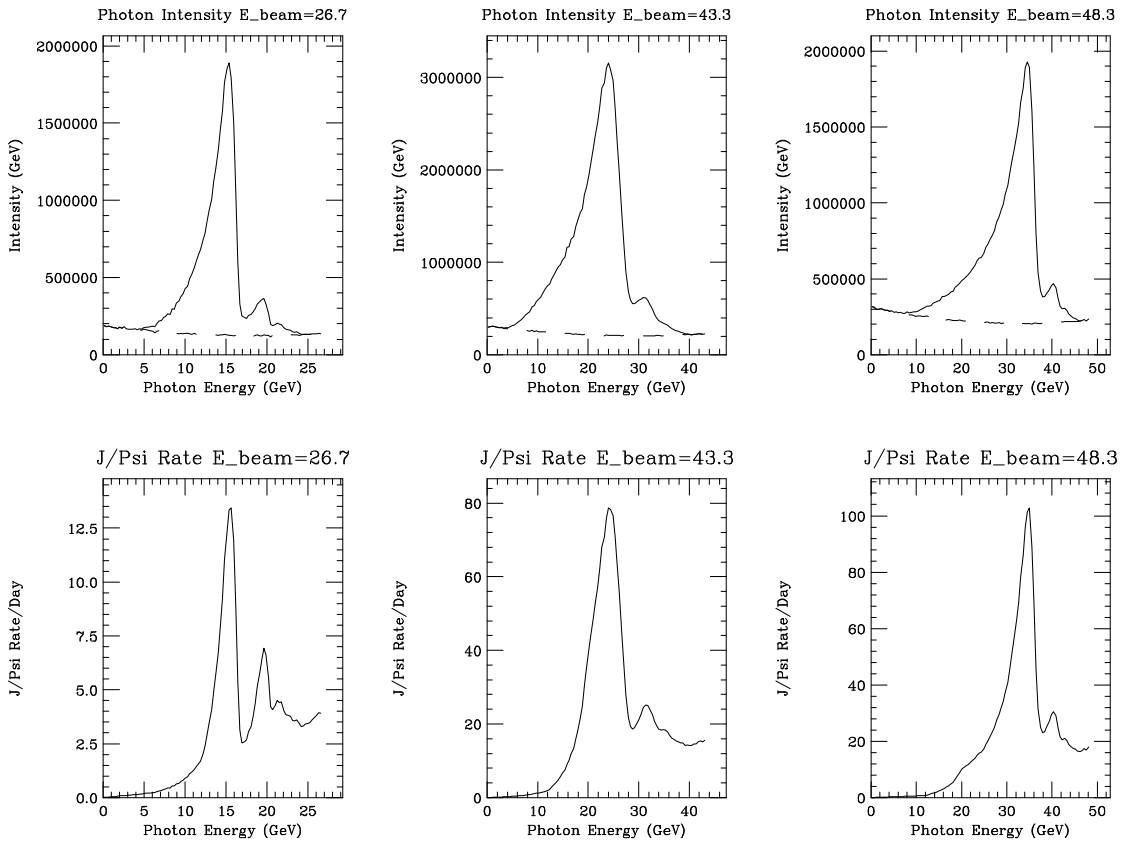
- leading-edge discriminators
- multi-hit TDC's:
  - 0.5 ns granularity
  - leading-edge triggers only
  - $<$ 7 ns input pulse width
  - $\approx$ 11 ns dead time
- $\sigma_x = 0.15$ cm; $\sigma_y = 0.6$ cm.
- 100 hits per plane per 500 ns spill.
- muon tracks every 10-30 ns.
- Muons with $p_T^2 < 0.5\,\mathrm{GeV}^2$ rarely trigger all 3 planes.

Targets

element	Z	A	ρ (g/cm^3)	g/cm^2
Be	4	9.012	1.848	3.26
Al	13	26.980	2.700	3.36
Cu	29	63.546	8.960	2.57
Pb	82	207.200	11.350	1.27
element	cm	rad. lengths	int. lengths	b^{-1}
Be	1.764	0.050	0.043	1.96
Al	1.245	0.140	0.032	2.02
Cu	0.287	0.200	0.019	1.55
Pb	0.112	0.200	0.007	0.77

- Targets mounted on a movable target ladder
- Thicknesses chosen to obtain up to 2 b^{-1} without exceeding 0.2 radiation length.

Beam Intensity and Rates

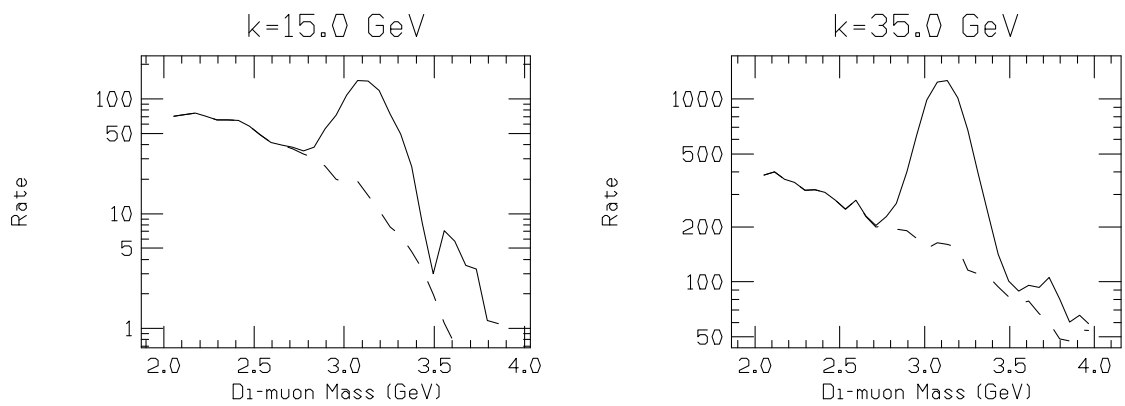


- Electron beam energies: 26.7, 43.3 and 48.3 GeV.
- Upper: photon intensities (flux times energy).
- Lower: quasi-elastic J/ψ events per day.
- Dashed lines: incoherent radiation.

Acceptance and Resolution Calculations

- Monte Carlo simulation for muons only
- Accounts for:
  - Multiple scattering in absorber and detectors
  - energy loss in absorber
  - beam size
  - target length
  - quasi-elastic sample of J/ψ and ψ' events
  - e^{3t} distribution with no A-dependence
  - $1 + \cos\theta^*$ angular distribution of $\mu^+\mu^-$
  - Bethe-Heitler backgrounds

Invariant Mass Spectra



- Invariant mass of $\mu^+\mu^-$ pairs.
- Dashed line: quasi-elastic, elastic and inelastic Bethe-Heitler backgrounds.
- Solid line: total spectrum with J/ψ and ψ' peaks.
- Cuts on each muon: $\theta > 40$ mr; $p > 2.5$ GeV.

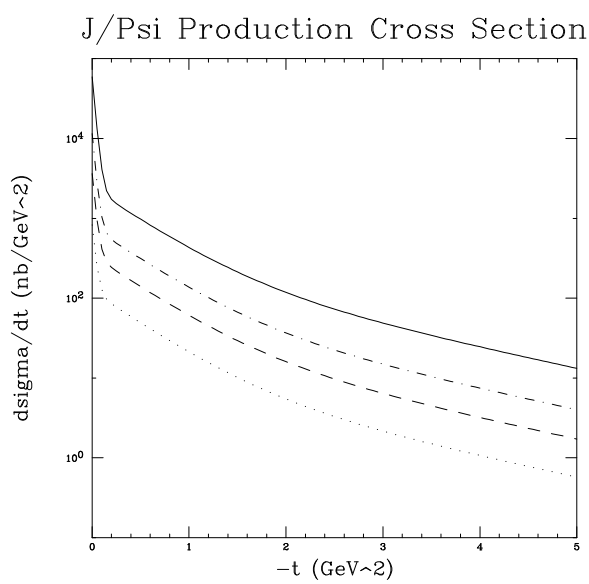
Peak Photon Energy (GeV)	15.0	25.0	35.0
J/ψ Mass Resolution (GeV)	0.120	0.127	0.142
J/ψ Energy Resolution (GeV)	0.54	1.04	1.80
J/ψ p_T^2 Resolution (GeV^2)	0.09	0.11	0.14
J/ψ Acceptance	0.07	0.17	0.24
ψ' Acceptance	0.01	0.16	0.23

Physics Model

$$\frac{d\sigma}{dt} = \sigma_0 \sum_i A^{\alpha_i} r_i a_i e^{a_i t}$$

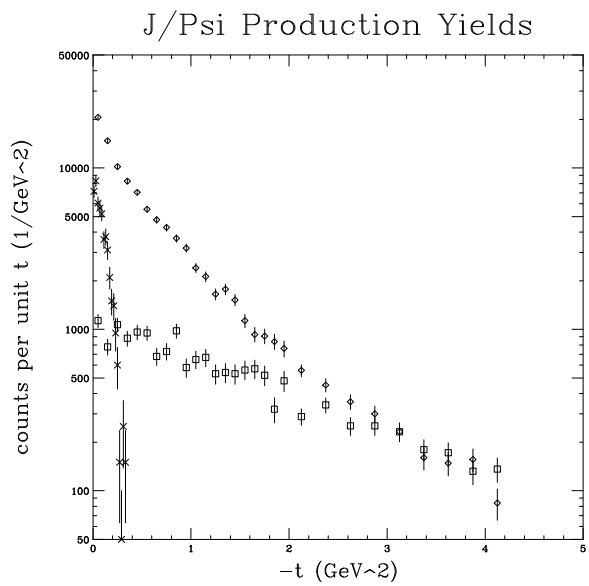
$$\sigma(\gamma N \to J/\psi N) = (10.3 \pm 0.7 \text{ nb}) \left[\frac{\sqrt{s}}{10 \text{ GeV}}\right]^{0.80 \pm 0.04}$$

i	process	α_i	r_i	a_i (GeV^{-2})
1	coherent	1.4	0.14	33
2	quasi-elastic	0.94	1	2.0
3	inelastic	1	0.30	0.6



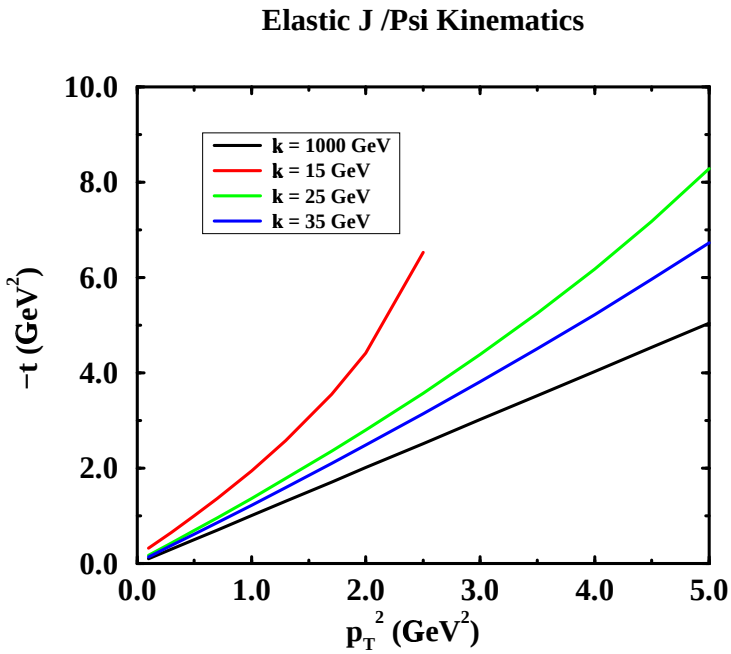
Curves for Be (dotted), Al (dashed), Cu (dot-dashed) and Pb (solid) and $E_\gamma = 20$ GeV.

Physics Model (con't)



- Simulated t distribution for J/ψ production
  - counts per GeV^2 vs. t
  - t-resolution of 0.1 GeV^2
  - 8000 quasi-elastic events
  - 1000 coherent events (x)
  - 2000 inelastic events (squares)
  - total events shown as diamonds

Elastic J/ψ Kinematics



$k(GeV)$	$s(\mathrm{GeV}^2)$	$k^*(\mathrm{GeV})$	$k'^*(\mathrm{GeV})$	$E^*_\psi(\mathrm{GeV})$	$t_{\min}(\mathrm{GeV}^2)$
15	29.0	2.61	1.63	3.50	-0.170
25	47.8	3.39	2.67	4.09	-0.036
35	66.5	4.02	3.42	4.61	-0.024

* indicates CM frame

k: incident photon lab momentum

k': ψ momentum

p_T^2: ψ transverse momentum squared

s, t: Mandelstam variables

E_ψ: ψ energy

Conservative Statistical Error Estimates

variable	stat. error coherent	QE	inelastic
a	± 1 GeV^{-2}	± 0.04 GeV^{-2}	± 0.2 GeV^{-2}
$\sigma_{\gamma A \to \psi}$	11%	3%	12%
$\alpha_{J/\psi}$	± 0.044	± 0.004	± 0.017
$\alpha_{\psi'}$		± 0.044	
	total		
$\sigma_{\rm tot}^{\psi N}$	± 0.3 mb		
$\sigma_{\rm tot}^{\psi' N}$	± 3 mb		

- Expected statistical accuracy is based on the simple 3-component model and 10,000 J/ψ events for each target and energy.
- a: exponential slope parameter of t-distribution
- $\sigma_{\gamma A \to \psi}$: ψ photoproduction cross section
- $\alpha_{J/\psi}$: A^α fit to $\sigma_{\gamma A \to \psi}$
- $\sigma_{\rm tot}^{\psi N}$: extraction of ψN total cross section from A-dependence of $\sigma_{\gamma A \to \psi}$

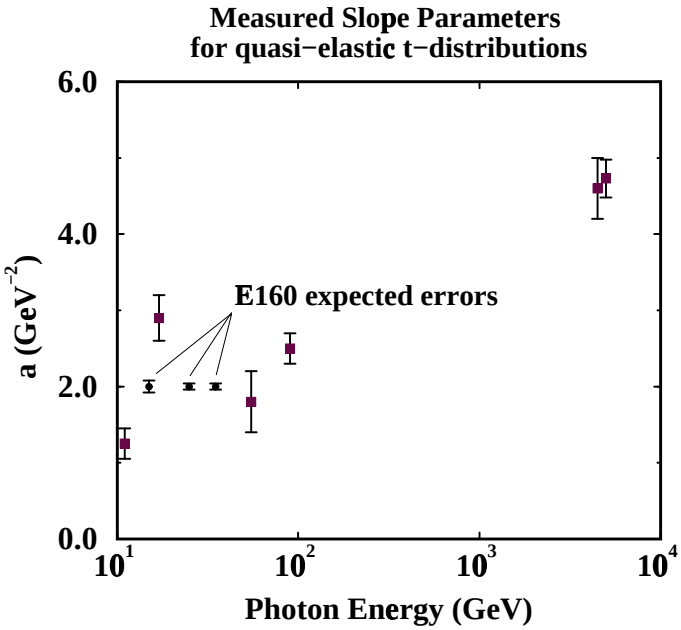
Statistical Error Estimates (con't)

- Δa: extracted from fits to Monte Carlo data
- $\Delta\sigma_{\gamma A\to\psi}$ (quasi-elastic and inelastic): obtain $\sigma_{\gamma A\to\psi}$ from measured counts in $0.3 < -t < 2$ GeV^2; use systematics of a to correct for events with $-t < 0.3$ and $-t > 2$.
- $\Delta\sigma_{\gamma A\to\psi}$ (coherent): QE counts subtracted from $0 < -t < 0.3$ GeV^2.
- $\Delta\alpha$: errors on a linear fit to $\sigma_{\gamma A\to\psi}$ Monte Carlo data for 4 targets.
- $\Delta\sigma_{\rm tot}^{\psi N}$: propagation of errors for the form

$$\frac{\sigma_{\gamma Pb\to\psi}/207}{\sigma_{\gamma Be\to\psi}/9} = e^{-(L_{Pb}-L_{Be})\rho_0\sigma_{\rm tot}^{\psi N}}$$

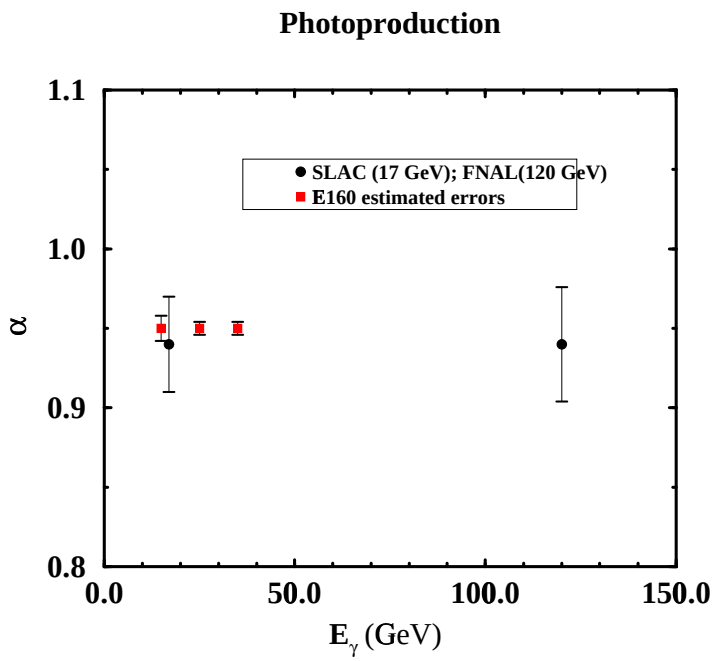
(with 4 targets errors will be proportionately smaller if $\sigma_{\rm tot}^{\psi N}$ does not change with ℓ_F).

Expected Quasi-Elastic Results



- Slope of the quasi-elastic t-distribution extracted from photoproduction experiments (square points):
  - 11 GeV, Cornell75, Gittelman, *et al.*
  - 13-21 GeV, SLAC75, Camerini, *et al.*
  - 55 GeV, FNAL76, Nash, *et al.*
  - 90 GeV, CERN NA14, Barate, *et al.*
  - 850-32400 GeV, ZEUS97, Breitweg, *et al.*
  - 360-43300 GeV, H1-00, Aldoff, *et al.*
- Estimated errors for E160 at 15, 25, and 35 GeV photon beam energies (dots).

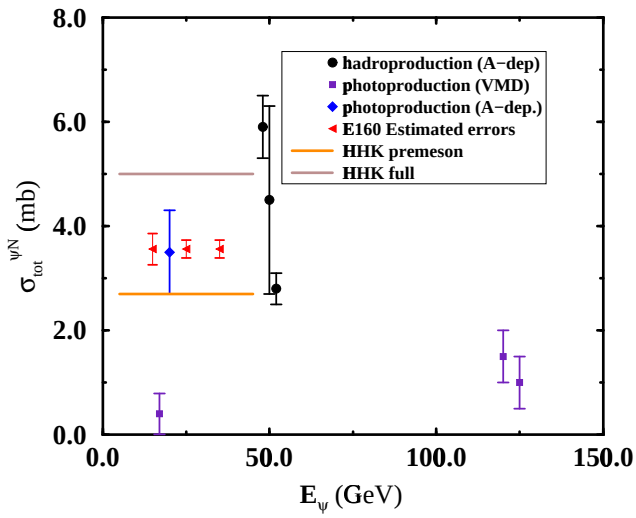
α from Photoproduction

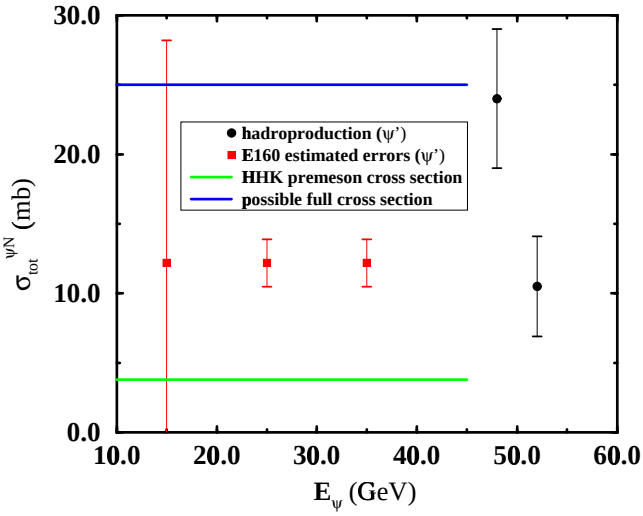


- Photoproduction data from SLAC at 17 GeV and FNAL at 120 GeV
- Estimated errors for E160

Error Estimates on $\sigma_{\rm tot}^{\psi N}$

Total Cross Sections





Request

- 2 weeks of checkout at low rates
- 2 months of production running at 120 Hz
- Resources to obtain scintillator material for hodoscopes
- Use of the LASS and 29D36 dipole magnets
- Resources to obtain several hundred phototubes for hodoscopes
- Upgrade to the data acquisition system to handle 16kB per spill
- Commissioning of a coherent bremsstrahlung beam line for ESA

Request (con't)

Electron Energy (GeV)	26.7	43.3	48.3
Electron Current (10^{10}/spill)	2.0	1.2	1.0
Peak Photon Energy (GeV)	15.0	25.0	35.0
Linear Polarization	0.69	0.69	0.48
J/ψ per day total	1494.	9755.	10025.
J/ψ per day in Peak	423.	2988.	3713.
J/ψ goal per target	2000.	8000.	8000.
days (at 100% efficiency)	9.5	10.7	8.6

- Summary of beam parameters, J/ψ rates, and running time:
- 0.0007 radiation length diamond
- 3 mm diameter collimator
- Average 1 b^{-1} target thickness
- Spectrometer as described
- Linear polarization is given at the main coherent peak.

Conclusions

- E160 will study J/ψ and ψ' production and propagation through nuclei with error bars small enough to make a difference for interpretations of J/ψ suppression in relativistic heavy-ion collisions. This suppression remains one of the most promising indicators of quark-gluon plasma formation.
- E160 will measure fundamental charmonium cross sections $d\sigma/dt$ and $\sigma_{\rm tot}^{\psi N}$ with at least a factor of three improvement in accuracy over an energy range where one would be surprised not to find large variations produced by ℓ_F.
- E160 will provide data using a simple probe, the results of which are easier to interpret than hadron-induced reactions.
- E160 will make the first ever measurement of the A-dependence of ψ' photoproduction and test the claim that $\sigma_{\rm tot}^{\psi' N}$ is as large as 25 mb.
- E160 will constrain models for the creation and interaction of J/ψ and ψ' particles, and shed light on the VMD mystery.

Elastic J/ψ Kinematics (con't)

$$
\begin{aligned}
E_\psi &= \sqrt{m_\psi^2 + k'^2} \\
E_\psi^* &= \sqrt{m_\psi^2 + k'^{*2}} \\
s &= M^2 + 2Mk \\
u &= -2ME_\psi + M^2 + m_\psi^2 \\
k^* &= \frac{(s-M^2)}{2\sqrt{s}} \\
k'^{*2} &= \frac{(s-M^2-m_\psi^2)^2 - 4M^2 m_\psi^2}{4s} \\
t &= -2M(k - E_\psi) \\
t &= m_\psi^2 - 2k(E_\psi - k'\cos\theta) \\
t &= m_\psi^2 - 2k^*(E_\psi^* - k'^*\cos\theta^*) \\
t_{\min} &= m_\psi^2 - 2k^*(E_\psi^* - k'^*) \\
-(t - t_{\min}) &= 4k^*k'^*\sin^2\frac{\theta^2}{2} \\
p_T^2 &= (k'^*\sin\theta^*)^2 \\
p_T^2 &= 4k'^{*2}\sin^2\frac{\theta^*}{2}\cos^2\frac{\theta^*}{2} \\
k_{\text{muon}}^* &= \sqrt{m_\psi^2/4 - m_{\text{muon}}^2}
\end{aligned}
$$

M is the nucleon mass; m_ψ is the ψ mass; k_{muon}^* is the momentum of a decay muon in the ψ CM frame.

Charmonium States

- $\eta_c(1S)$ $I^G(J^{PC}) = 0^+(0^{-+})$ $m = 2979.8$ MeV
  - $\Gamma = 13.2$ MeV
- $J/\psi(1S)$ $I^G(J^{PC}) = 0^-(1^{--})$ $m = 3096.88$ MeV
  - $\Gamma = 87$ keV
  - $BR(\to \mu^+\mu^-) = (6.01 \pm 0.19)\%$
- $\chi_{c0}(1P)$ $I^G(J^{PC}) = 0^+(0^{++})$ $m = 3417.3$ MeV
  - $\Gamma = 14$ MeV
  - $BR(\to \gamma J/\psi) = (6.6 \pm 1.8) \times 10^{-3}$
- $\chi_{c1}(1P)$ $I^G(J^{PC}) = 0^+(1^{++})$ $m = 3510.53$ MeV
  - $\Gamma = 0.88$ MeV
  - $BR(\to \gamma J/\psi) = (27.3 \pm 1.6)$
- $\chi_{c2}(1P)$ $I^G(J^{PC}) = 0^+(2^{++})$ $m = 3556.17$ MeV
  - $\Gamma = 2.00$ MeV
  - $BR(\to \gamma J/\psi) = (13.5 \pm 1.1)$
- $\psi'(2S)$ $I^G(J^{PC}) = 0^-(1^{--})$ $m = 3686.00$ MeV
  - $\Gamma = 277$ keV
  - $BR(\to \mu^+\mu^-) = (7.7 \pm 1.7) \times 10^{-3}\%$
  - $BR(\to \gamma J/\psi) = (54.2 \pm 3.0)\%$