# PROPOSAL TO MEASURE THE $A$-DEPENDENCE OF $J/\psi$ AND $\psi'$ PHOTOPRODUCTION
## E160

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**Representing the E160 Collaboration**

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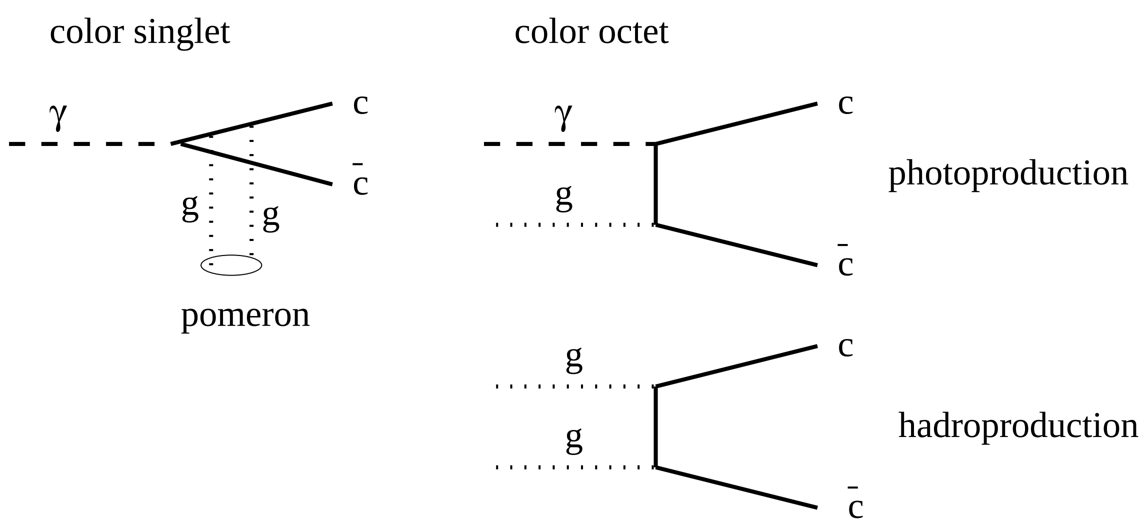
- What do we know about $J/\psi$ and $\psi'$ production and their interactions with hadrons?
- What can SLAC contribute?
- Details of the E160 experiment.

## E160 Collaboration

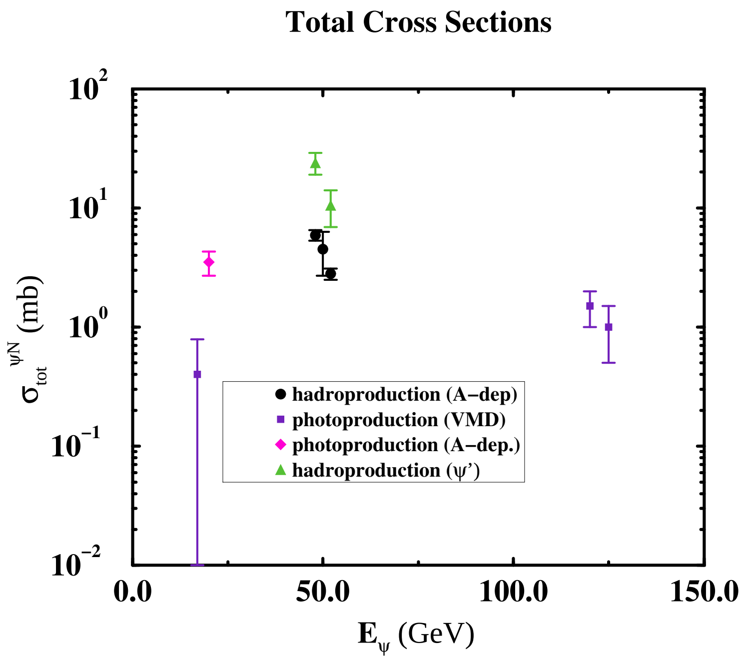
- University of California Los Angeles
- Jefferson Lab
- University of Massachusetts
- DAPNIA-Saclay
- Institut für Kernphysik Mainz
- Los Alamos National Laboratory
- Mississippi State University
- Old Dominion University
- Ruhr-Universität Bochum
- Smith College
- Stanford Linear Accelerator Center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

## Motivation



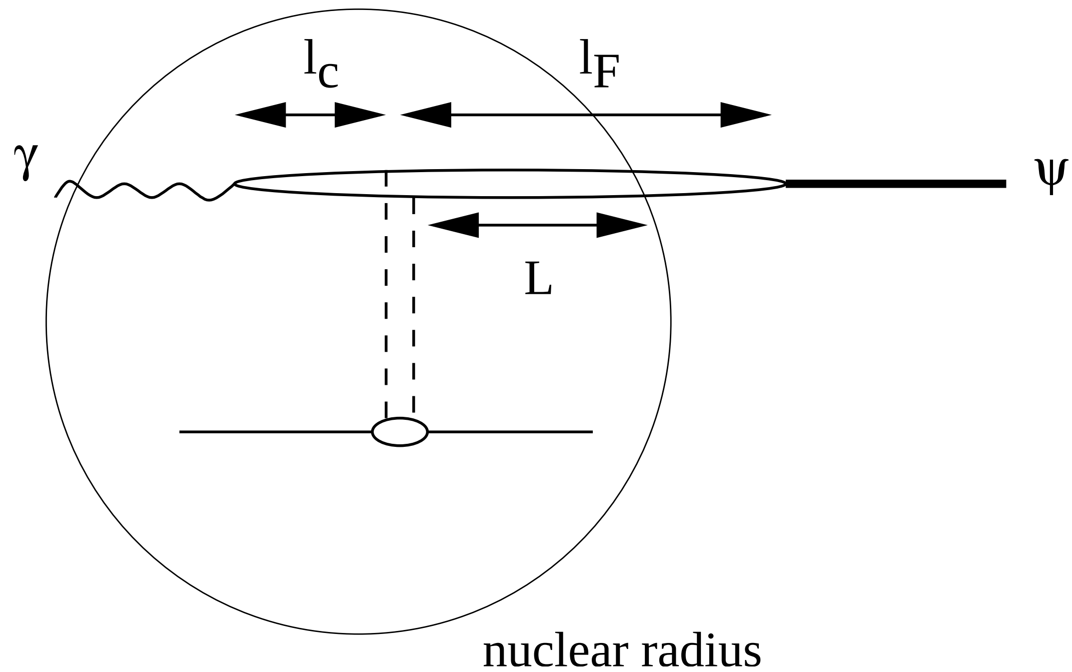

- Charmonium production: perturbative interactions, non-perturbative formation.
- Cross sections: perturbative $\rightarrow$ kinematic dependence; non-perturbative $\rightarrow$ uncalculable magnitude.
- No direct evidence for correct perturbative diagrams (e.g. photoproduction explained by both color 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.

# $\psi$-Nucleon Cross Section Data



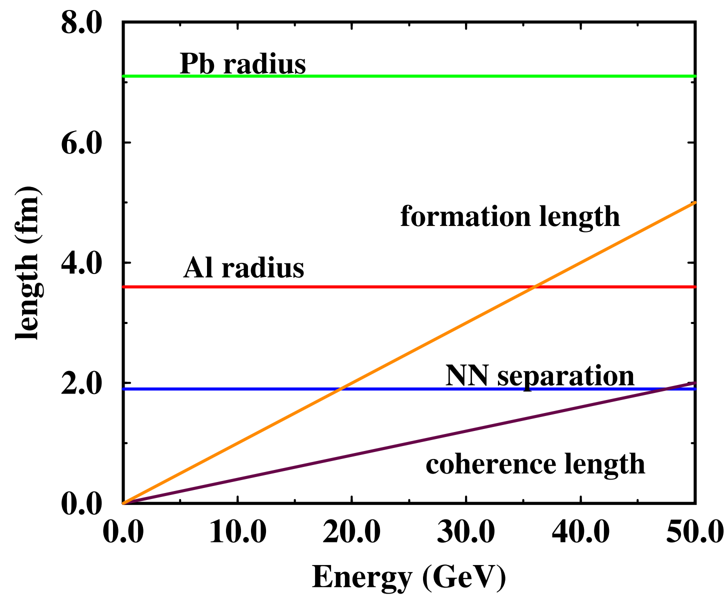

- Estimates of $\sigma_{\rm tot}^{\psi N}$ using vector meson dominance are small.
- Estimates from the $A$-dependence of $J/\psi$ hadroproduction cluster around 6 mb.
- Estimates from the $A$-dependence of $\psi'$ hadroproduction are between 7 and 30 mb.
- Estimate from the sole extraction from $A$-dependent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

## Coherence and Formation Lengths




- Coherence length $\ell_c$
- Formation length $\ell_F$

# 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 $J/\psi$.

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

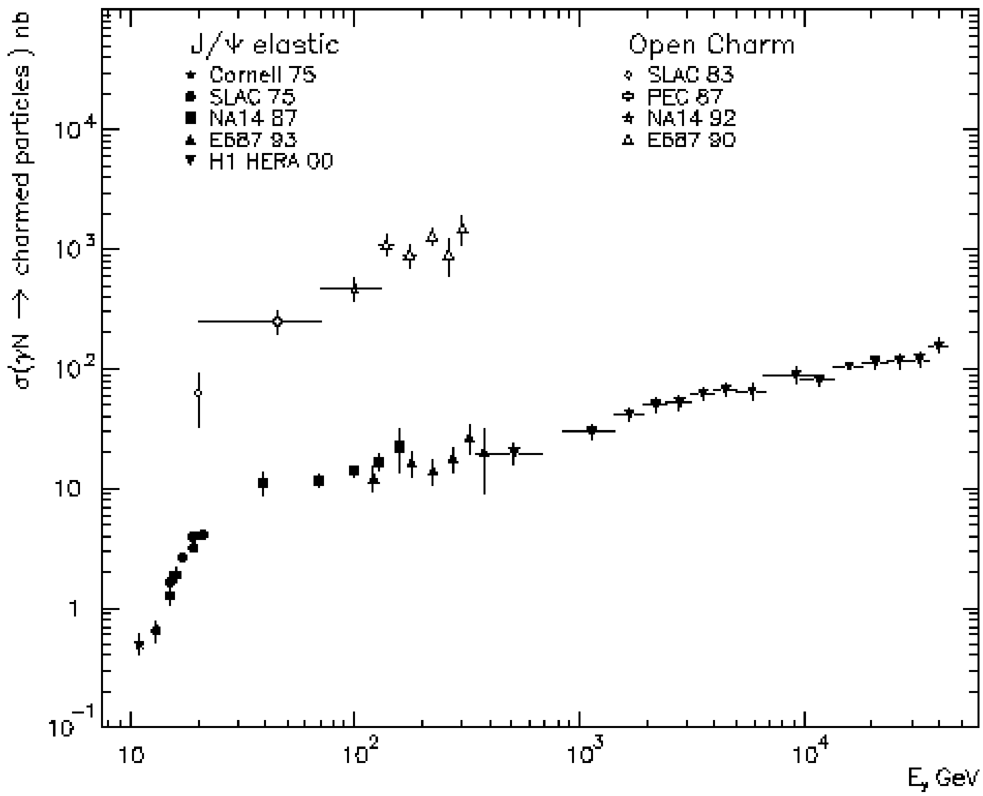
- Nuclear Radius: $R = 1.2 A^{\frac{1}{3}} \text{ fm} = 4 - 7 \text{ fm}$

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

## Advantages of Photoproduction

- Photons do not have multiple interactions with the nucleons in a nucleus.
- Elastic $\psi$ production is relatively simple.
- Photons do not appreciably excite the 1P charmonium states $\chi_c$, which radiatively decay into $J/\psi$'s.
- Both $\ell_c$ and $\ell_F$ change with $E_\gamma$.

# 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.
  - $r_{\psi'} \approx 2 r_{J/\psi}$.
  - $\sigma_{\rm tot}^{\psi' N}/\sigma_{\rm tot}^{\psi N} \approx 4$

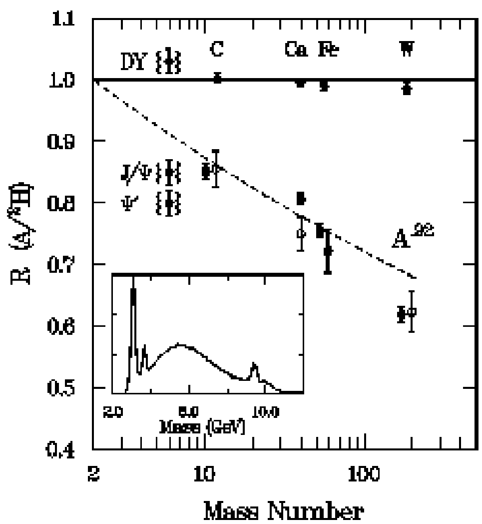
## Why Might VMD Fail?

- 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 $J/\psi$ photoproduction could originate from color octet states rather than pomeron exchange.

## How can one study the problem?

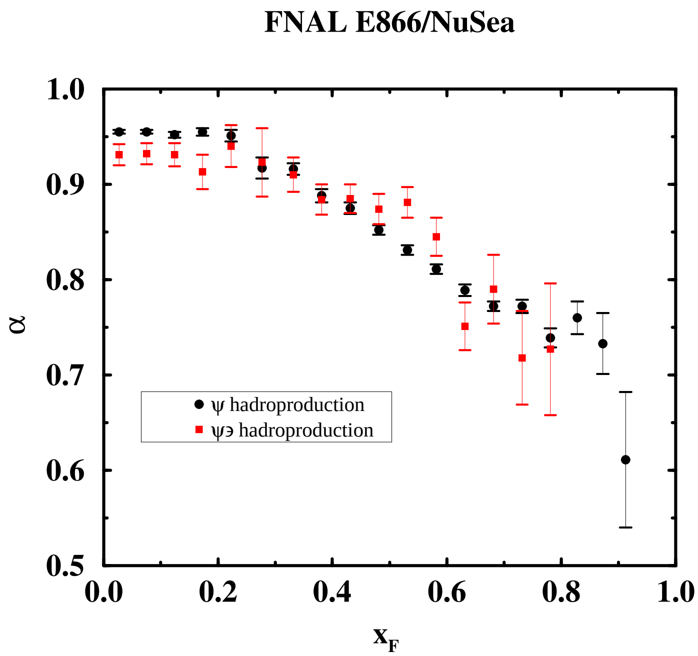
- E160 uses nuclei of various sizes to probe the $J/\psi$ at a range of times during its formation.

# $A$-Dependence of $J/\psi$ Production



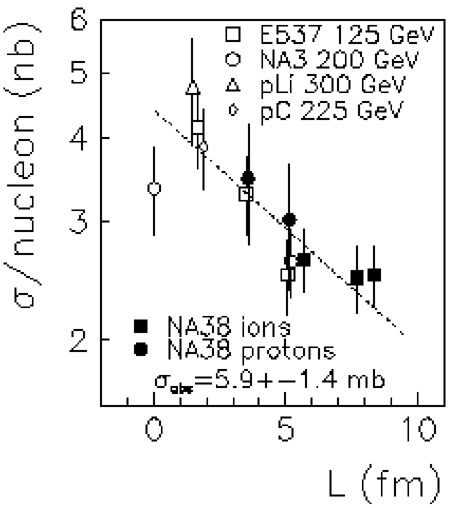

- From D.M. Alde, *et al.*, Phys. Rev. Lett. **66**(91)133.
- Comparisons to Drell-Yan data indicate that shadowing does not explain the suppression of $J/\psi$'s in nuclei.
- Data are fit to a universal form $A^\alpha$, which is roughly the same for $J/\psi$ and $\psi'$.
- If the error bars on the FNAL data are realistic, the $A$-dependence of $J/\psi$ 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 $x_F$



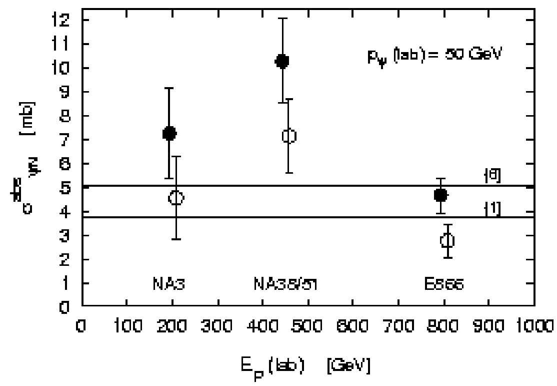

- FNAL E866/NuSea Collaboration, Phys. Rev. Lett. **84**(00)3256.
- $\psi'$ has stronger $A$-dependence than $J/\psi$ at $x_F \approx 0$, suggesting that $\sigma_{\rm tot}^{\psi' N} > \sigma_{\rm tot}^{\psi N}$.
- $J/\psi$ and $\psi'$ have similar, but enhanced $A$-dependencies at large $x_F$, suggesting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

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



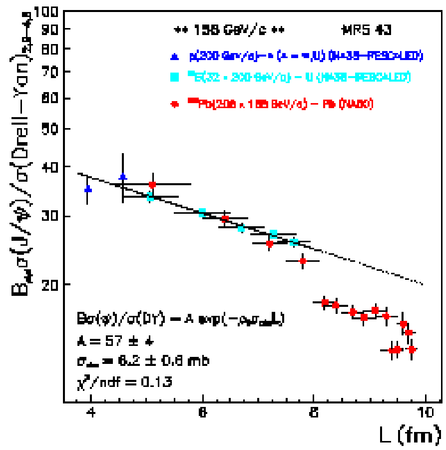

- Data as shown in B. Müller, nucl-th/9806023
-
$$\frac{\sigma^{pA\to\psi}}{A\sigma^{pN\to\psi}} = e^{-L\rho_0\sigma_{\rm tot}^{\psi N}}.$$
- $L$: length of the absorption trajectory.
- $\rho_0$: the nuclear density.
- $\sigma_{\rm tot}^{\psi N}$ is assumed to be constant.
- Procedure works for nucleus-nucleus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

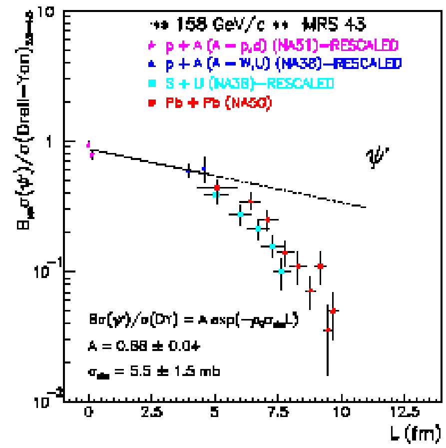
# Glauber Approximation (con't)




- 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.
- $\sigma_{\rm tot}^{\psi N}$ is clearly not well-known.

# $J/\psi$ Suppression for Heavy Ions



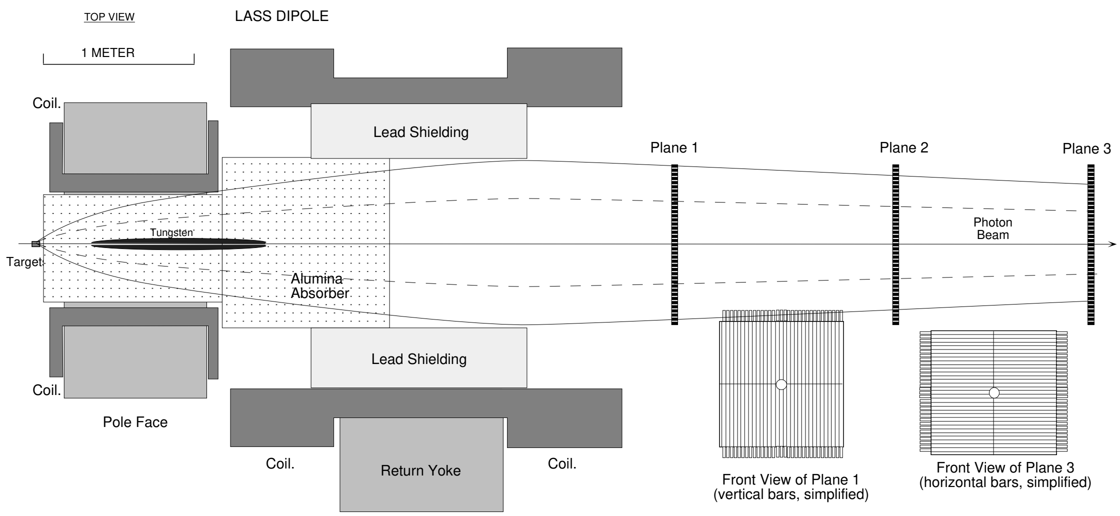




- From B. Müller, nucl-th/980623:
- It's still unclear whether $J/\psi$ is a reliable probe for quark-gluon plasmas.
- Suppression in light targets is the result of the $A^{0.92}$ dependence of the $pA \to J/\psi X$ cross section.
- The color octet model provides a credible mechanism, but there is no 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

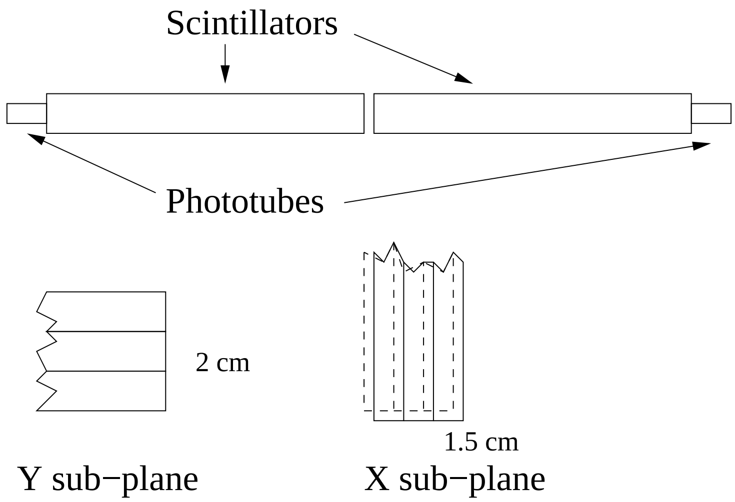
- SLAC can make a significant contribution to the understanding of charmonium production and propagation using a coherent bremsstrahlung photon beam with maximum energy 50 GeV.
- The proposed experiment E160 eliminates the overwhelming hadronic backgrounds with an absorber that only muons can penetrate.
- $J/\psi$'s and $\psi'$'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; $\pm 36$ cm width; $\approx$ 1 m length.
  - $\int \mathbf{B} \cdot \mathbf{d}\ell = 22$ kG-m.
- 70D43 LASS Dipole Magnet
  - 102 cm gap; $\pm 45$ 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 | $\pm 60$ | $\pm 60$ | 300 |
| 2 | $\pm 55$ | $\pm 80$ | 300 |
| 3 | $\pm 50$ | $\pm 100$ | 300 |

# E160 Hodoscopes (con't)

phototube $\rightarrow$ discriminator $\rightarrow$ multi−hit TDC

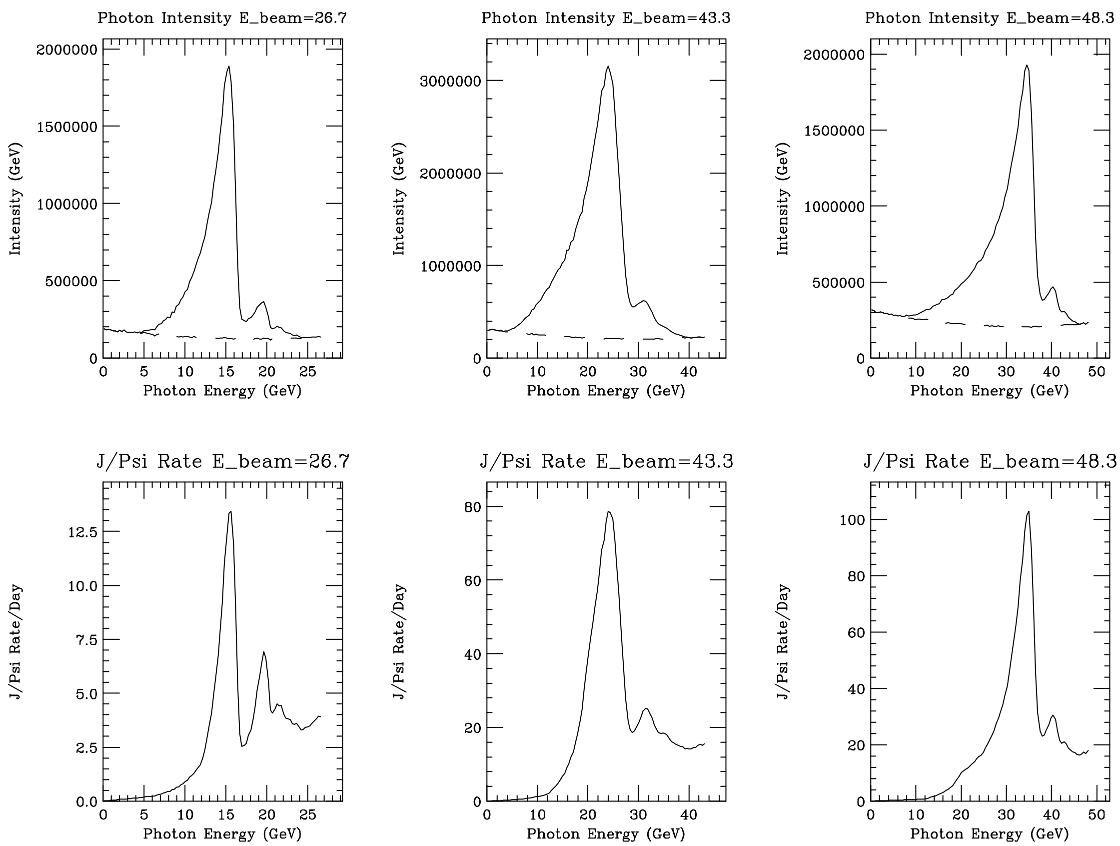
- leading-edge discriminators
- multi-hit TDC's:
  - 0.5 ns granularity
  - leading-edge triggers only
  - $<$ 7 ns input pulse width
  - $\approx$ 11 ns dead time
- $\sigma_x = 0.15$ cm; $\sigma_y = 0.6$ cm.
- 100 hits per plane per 500 ns spill.
- muon tracks every 10-30 ns.
- Muons with $p_T^2 < 0.5$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

## Targets

| element | $Z$ | $A$ | $\rho$ (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

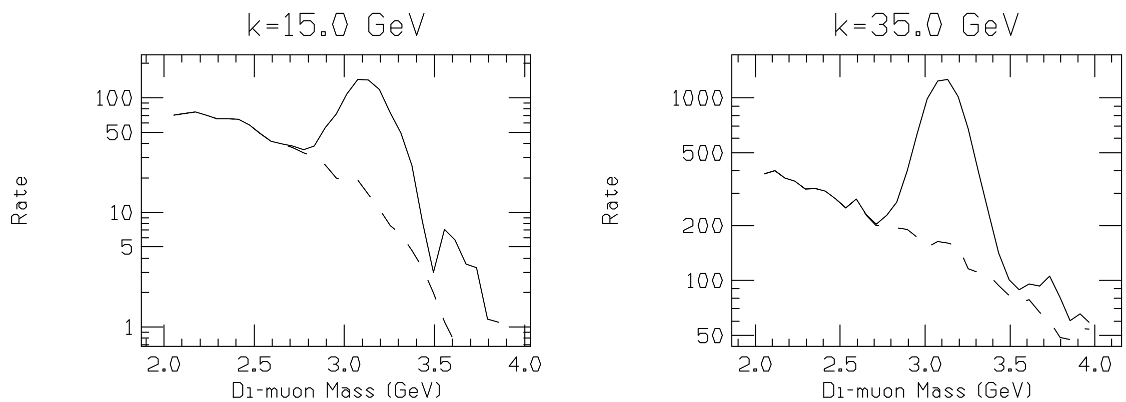



- Electron beam energies: 26.7, 43.3 and 48.3 GeV.
- Upper: photon intensities (flux times energy).
- Lower: quasi-elastic $J/\psi$ events per day.
- Dashed lines: incoherent radiation.

## 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 $J/\psi$ and $\psi'$ 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 $J/\psi$ and $\psi'$ peaks.
- Cuts on each muon: $\theta > 40$ mr; $p > 2.5$ GeV.

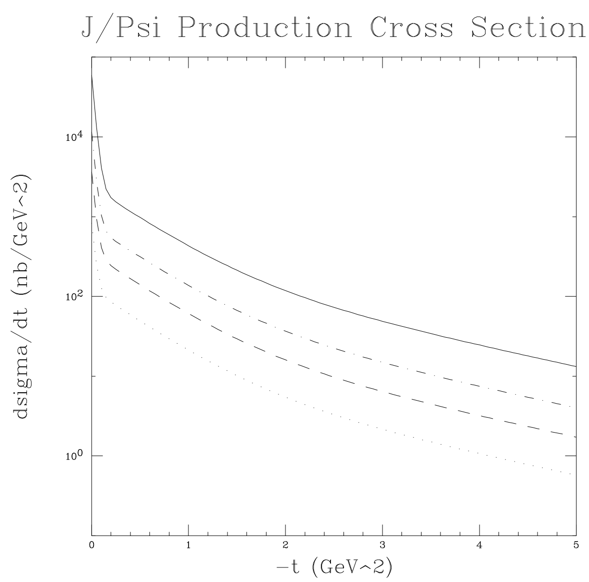
| Peak Photon Energy (GeV) | 15.0 | 25.0 | 35.0 |
|---|---|---|---|
| $J/\psi$ Mass Resolution (GeV) | 0.120 | 0.127 | 0.142 |
| $J/\psi$ Energy Resolution (GeV) | 0.54 | 1.04 | 1.80 |
| $J/\psi$ $p_T^2$ Resolution (GeV$^2$) | 0.09 | 0.11 | 0.14 |
| $J/\psi$ Acceptance | 0.07 | 0.17 | 0.24 |
| $\psi'$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

# Physics Model

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

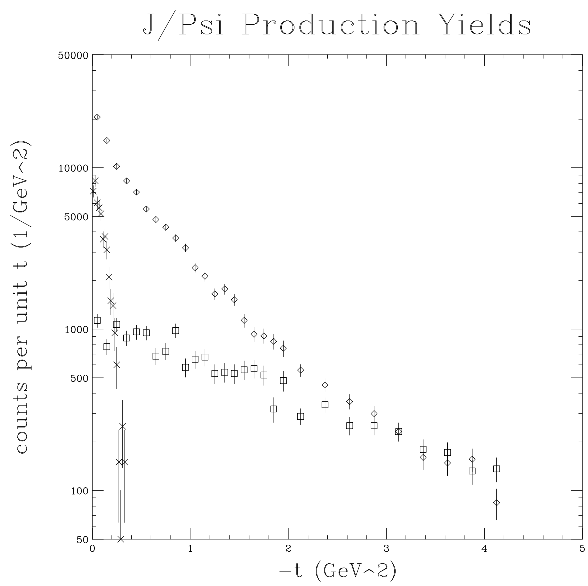
$$\sigma(\gamma N \to J/\psi N) = (10.3 \pm 0.7 \text{ nb}) \left[\frac{\sqrt{s}}{10 \text{ GeV}}\right]^{0.80\pm0.04}$$

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



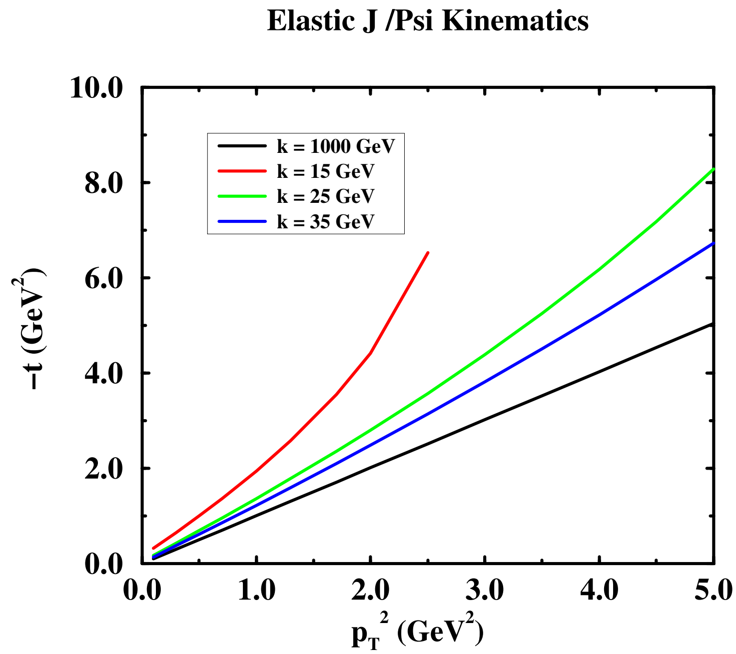

Curves for Be (dotted), Al (dashed), Cu (dot-dashed) and Pb (solid) and $E_\gamma = 20$ GeV.

# Physics Model (con't)




- Simulated $t$ distribution for $J/\psi$ 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 $J/\psi$ Kinematics




| $k(GeV)$ | $s(\mathrm{GeV}^2)$ | $k^*(\mathrm{GeV})$ | $k'^*(\mathrm{GeV})$ | $E^*_\psi(\mathrm{GeV})$ | $t_{\mathrm{min}}(\mathrm{GeV}^2)$ |
|---|---|---|---|---|---|
| 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

$k'$: $\psi$ momentum

$p_T^2$: $\psi$ transverse momentum squared

$s, t$: Mandelstam variables

$E_\psi$: $\psi$ energy

## Conservative Statistical Error Estimates

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

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

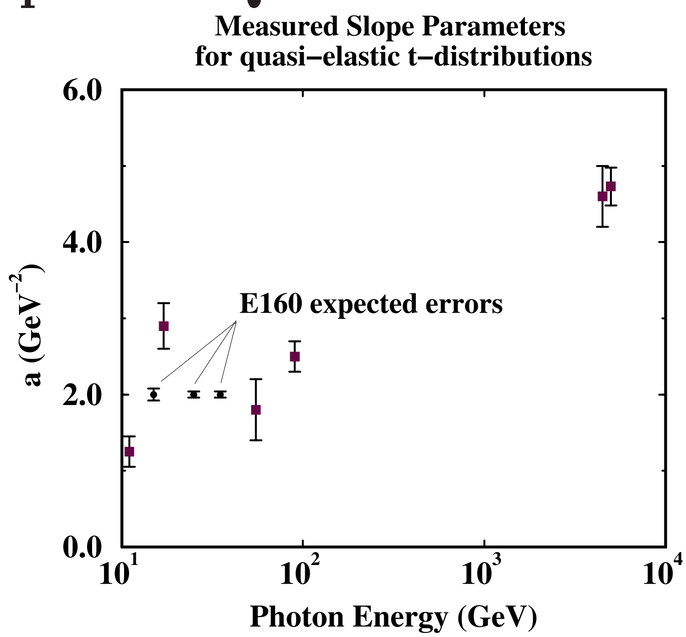
## Statistical Error Estimates (con't)

- $\Delta a$: 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

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

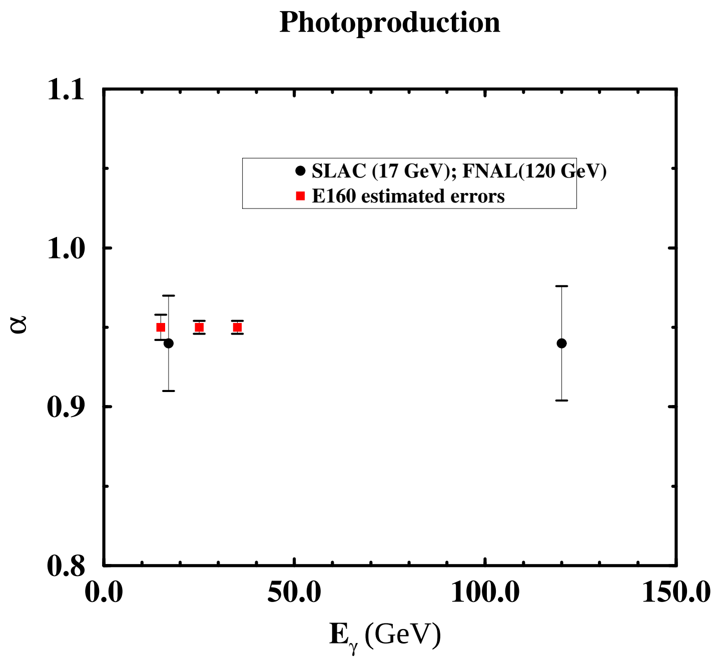
(with 4 targets errors will be proportionately smaller if $\sigma_{\rm tot}^{\psi N}$ does not change with $\ell_F$).

# 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).

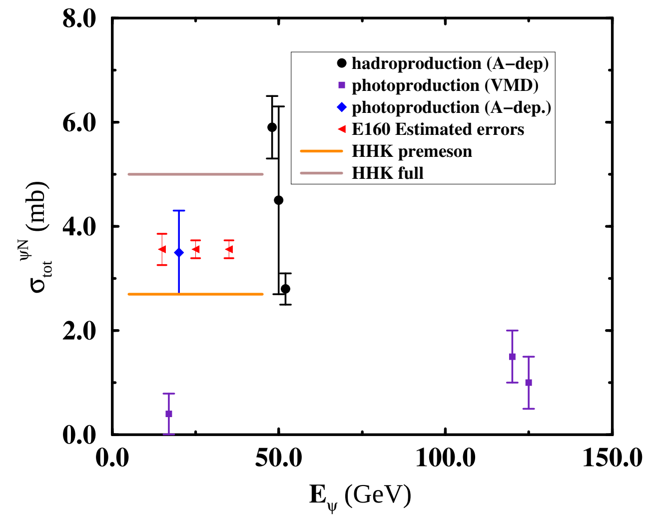
# $\alpha$ from Photoproduction

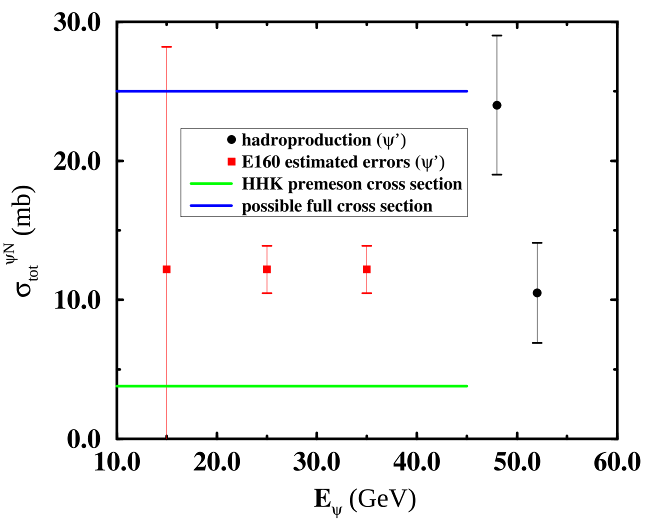



- Photoproduction data from SLAC at 17 GeV and FNAL at 120 GeV
- Estimated errors for E160

# 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 |
| $J/\psi$ per day total | 1494. | 9755. | 10025. |
| $J/\psi$ per day in Peak | 423. | 2988. | 3713. |
| $J/\psi$ goal per target | 2000. | 8000. | 8000. |
| days (at 100% efficiency) | 9.5 | 10.7 | 8.6 |

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

# Conclusions

- E160 will study $J/\psi$ and $\psi'$ production and propagation through nuclei with error bars small enough to make a difference for interpretations of $J/\psi$ 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 $\ell_F$.

- 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 $\psi'$ 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 $J/\psi$ and $\psi'$ particles, and shed light on the VMD mystery.

## Elastic $J/\psi$ Kinematics (con't)

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

$M$ is the nucleon mass; $m_\psi$ is the $\psi$ mass; $k^*_{\text{muon}}$ is the momentum of a decay muon in the $\psi$ 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
  - $BR(\to \mu^+\mu^-) = (7.7 \pm 1.7) \times 10^{-3}\%$
  - $BR(\to \gamma J/\psi) = (54.2 \pm 3.0)\%$