MEASUREMENT OF THE A-DEPENDENCE OF J/ψ AND ψ' PHOTOPRODUCTION AT SLAC (E160)

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International Workshop
Charm Production: from Threshold via SPS to RHIC and LHC
ECT Trento
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- About J/ψ and ψ' Production
- About Real Photons at SLAC
- About the E160 Experiment

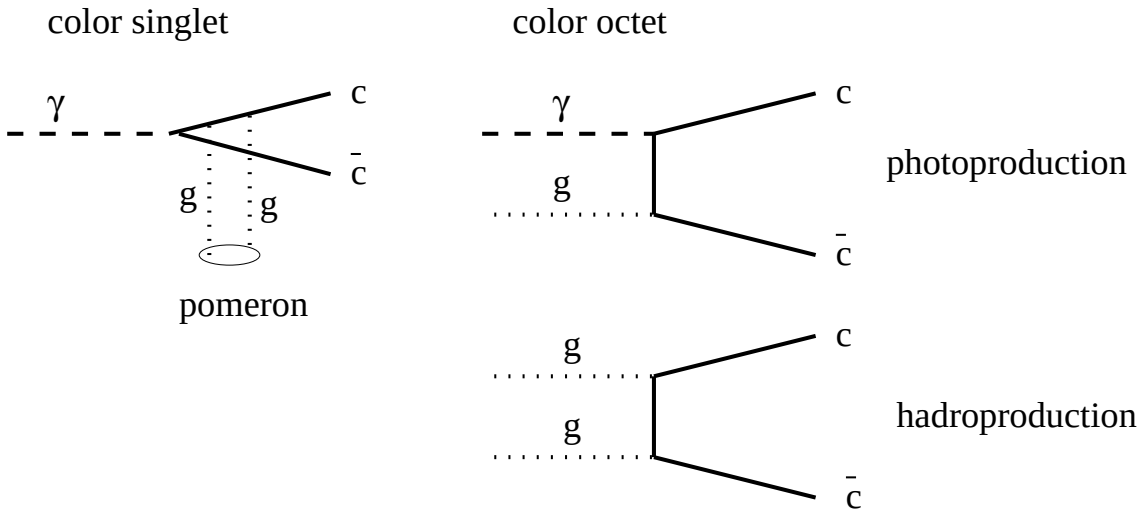
E160 Collaboration

- 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

E160: Measurement of the A-dependence of J/ψ and ψ' photoproduction

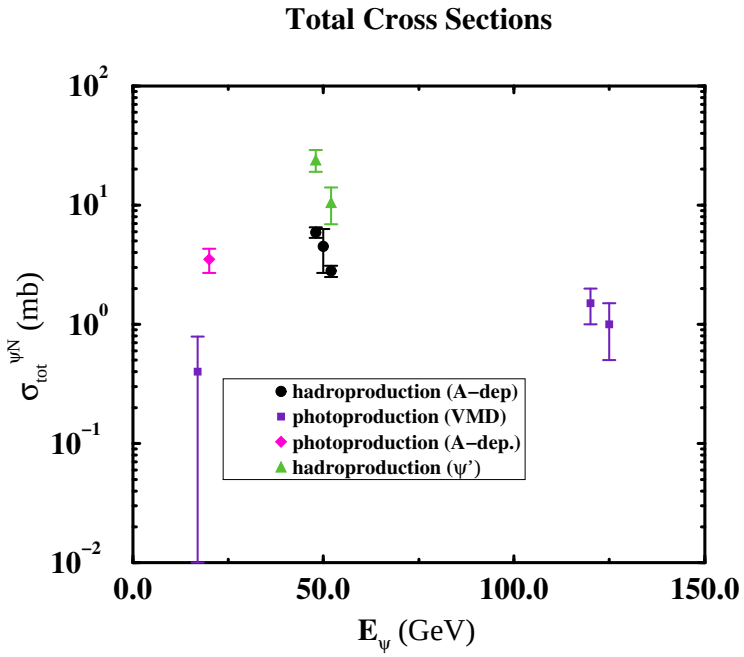
- Goals:
  - Accurately measure the fundamental cross sections $\sigma_{\rm tot}^{\psi N}$. (VMD and geometrical expectations are at odds.)
  - Understand interplay of pQCD and color transparency in creation and interaction of J/ψ and ψ' in nuclei.
  - Constrain causes for J/ψ suppression in relativistic heavy-ion collisions.
- Measurement:
  - Reconstruct J/ψ and ψ' from $\mu^+\mu^-$ pairs.
  - ^{6}LiD, Be, Al, Cu, Sn, Pb targets
  - 15–45 GeV photons
- Results:
  - p_T^2-distributions (coherent, elastic, inelastic)
  - α from $\sigma_A \propto A^\alpha$
  - ψ-nucleon cross section $\sigma_{\rm tot}^{\psi N}$
- http:www.slac.stanford.edu/exp/e160/

Motivation



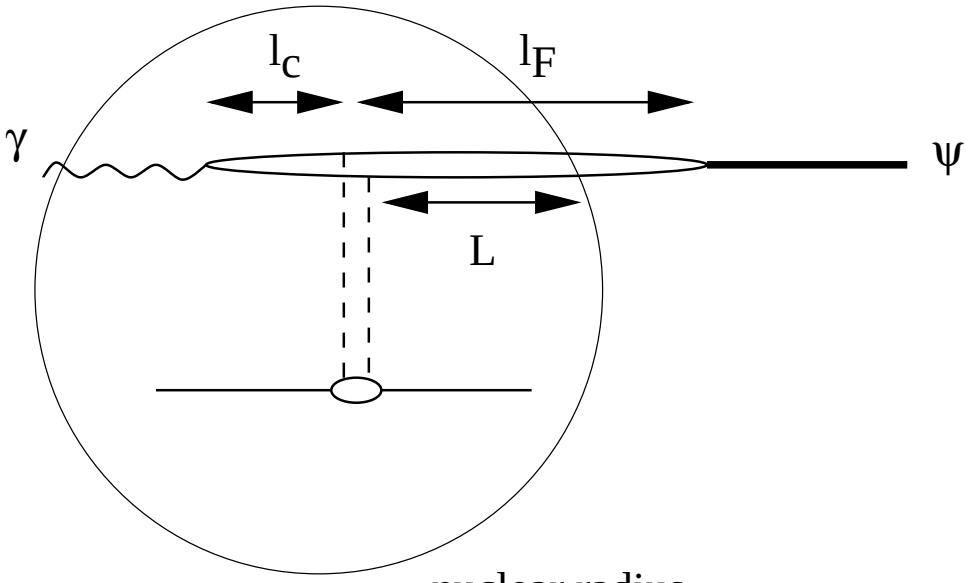
- Charmonium production: perturbative interactions, non-perturbative formation.
- Cross sections: perturbative → kinematic dependence; non-perturbative → uncalculable magnitude.
- No direct evidence for correct perturbative diagrams (e.g. photoproduction explained by both color singlet and octet models).
- 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 (lifetime of a $c\bar{c}$ fluctuation):

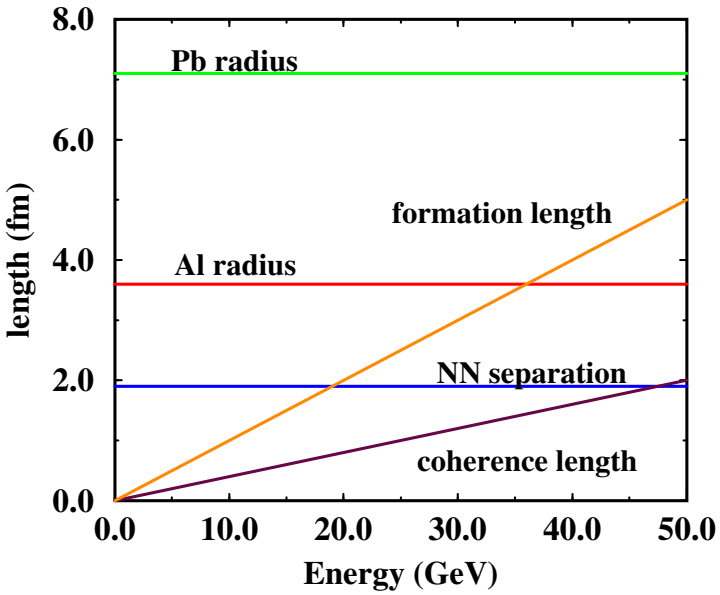
$$\ell_c = \frac{2\nu}{Q^2+m_V^2}$$

- Formation length (evolution time from point-like configuration to normal hadron):

$$\ell_F = \frac{2\nu}{m'^2_V - m_V^2}$$

  - $\nu =$ photon energy
  - $m_V =$ vector meson mass
  - $m'_V =$ excited vector meson mass
  - $Q^2 =$ negative 4-momentum transfer squared

Length Scales



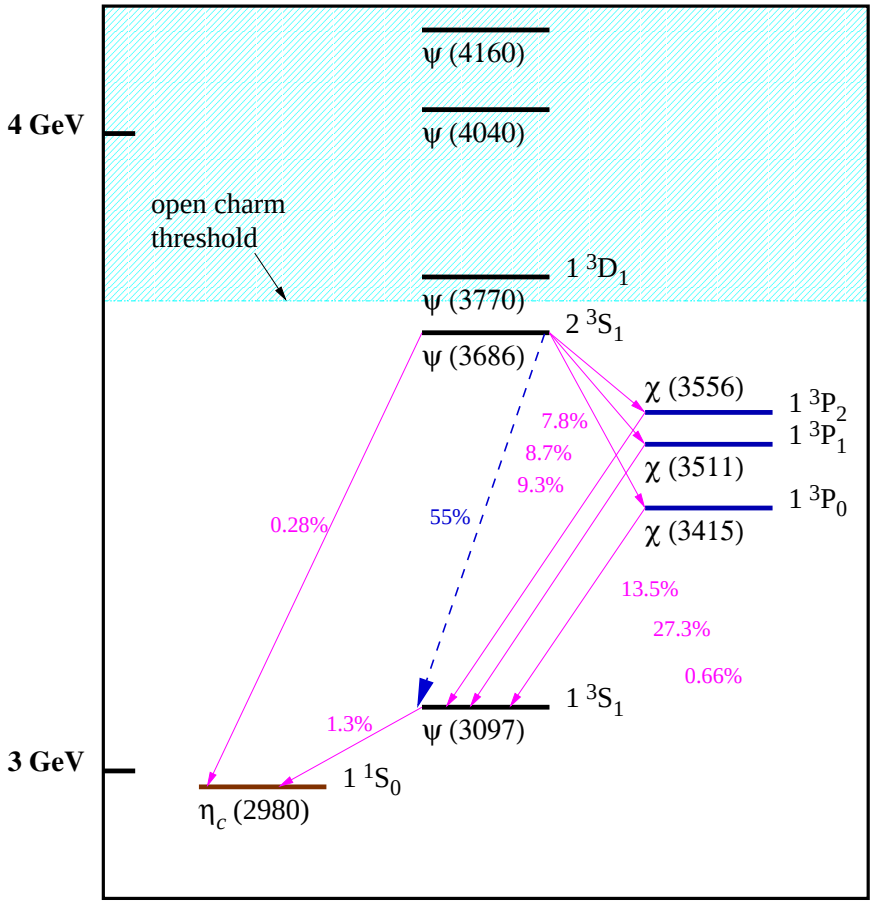
	ℓ_c	ℓ_F
ρ	0.66ν	0.26ν
J/ψ	0.04ν	0.10ν

- ℓ_c and ℓ_F in fm; ν in GeV.
- Nuclear Radius: $R = 1.2A^{\frac{1}{3}}$ 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

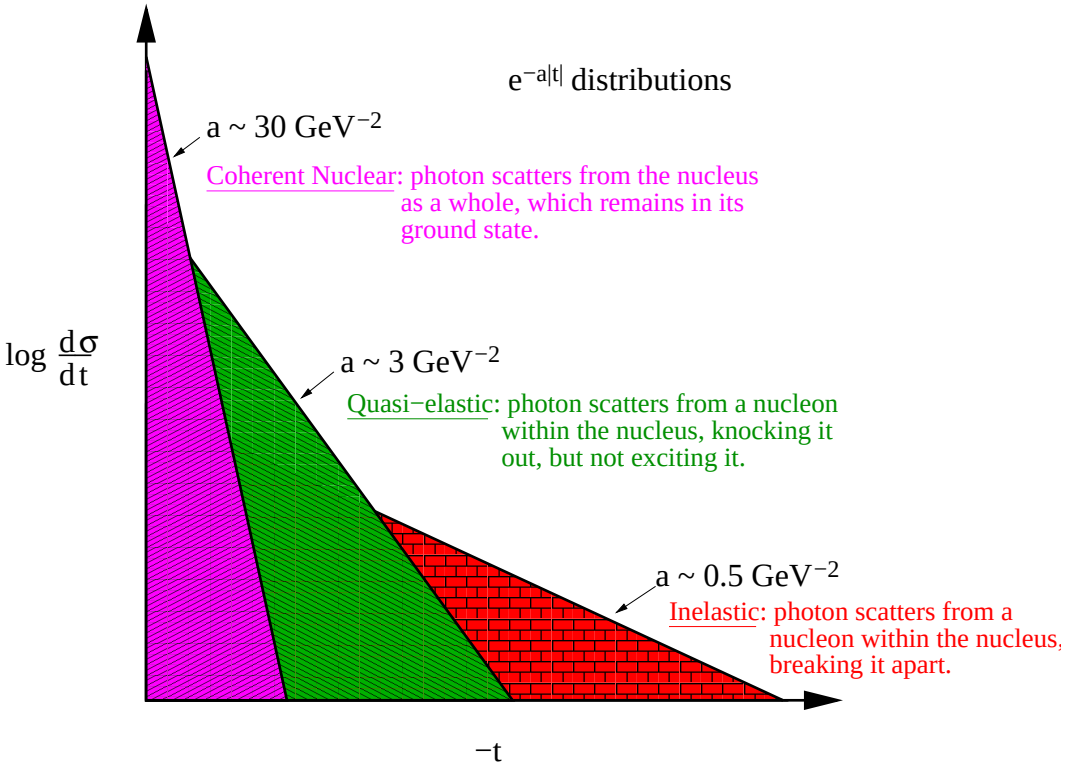
- Photons do not have multiple interactions with the nucleons in a nucleus.
- Elastic ψ production is relatively simple.
- Photons do not appreciably excite the 1P charmonium states χ_c, which radiatively decay into J/ψ's.
- ℓ_c is smaller than the NN separation
- ℓ_F varies with E_γ over the size of typical nuclei.
- Linear polarization provides additional sensitivity to underlying mechanisms.

Charmonium States



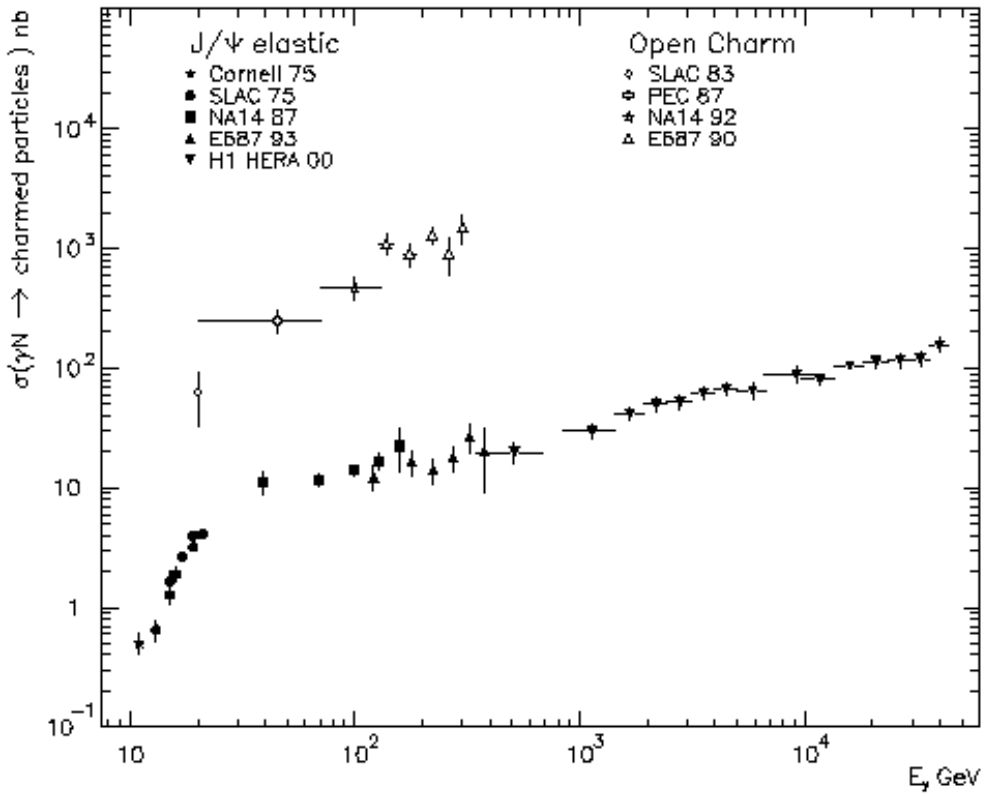
- Shaded region shows the continuum for decays into open charm ($D\bar{D}$) states.
- Photons excite $J^\pi = 1^-$ states (*e.g.* $^3S_1$).

Schematic J/ψ t-Distributions



- size of nucleus (nucleon) $\sim 1/\sqrt{\langle t \rangle} \sim \sqrt{a}$
- Coherent nuclear and quasi-elastic: vector meson dominance, pomeron exchange, diffractive processes.
- Inelastic: photon-gluon fusion.

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

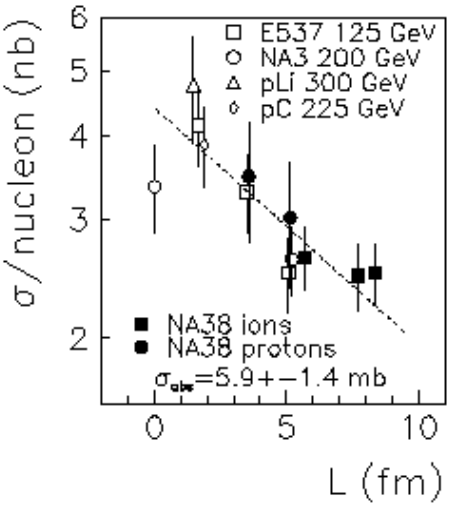
Why Might VMD Fail?

- 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?

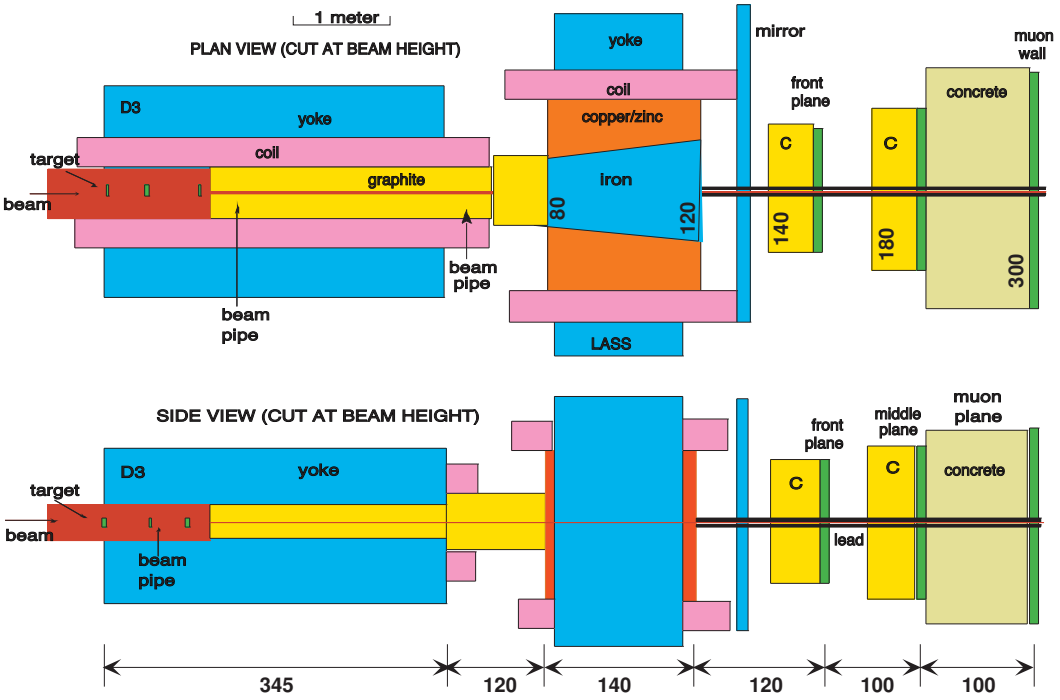
- E160 uses nuclei of various sizes to probe the J/ψ at a range of times during its formation.

$\psi - N$ Cross Sections



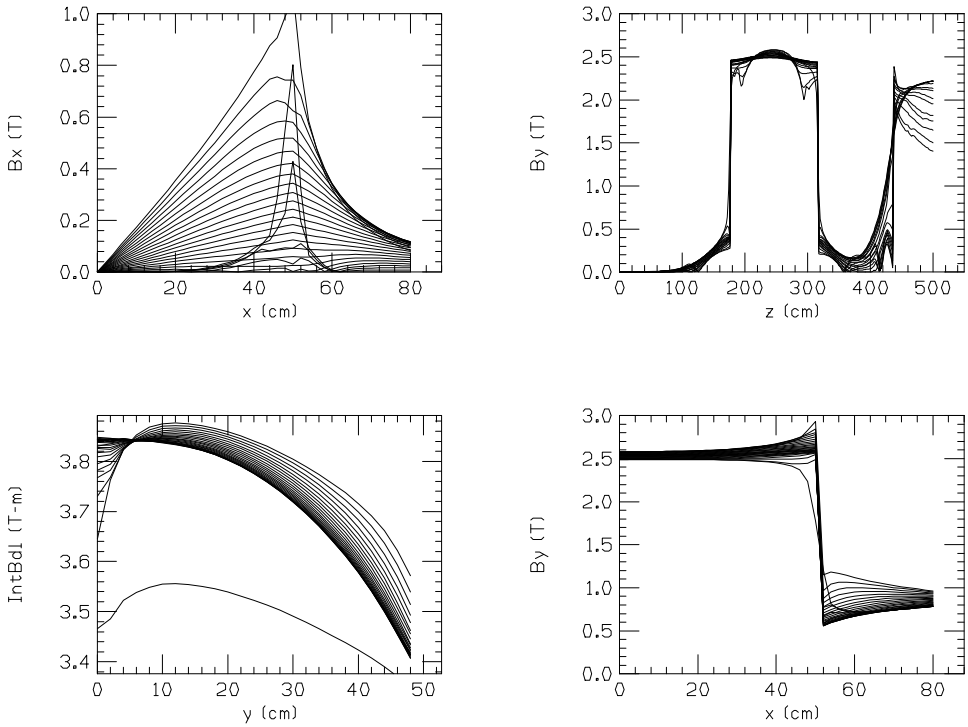
- Data: nucl-th/9806023 review
- Glauber:
$$\frac{\sigma^{pA\to\psi}}{A\sigma^{pN\to\psi}} = e^{-L\rho_0\sigma_{\rm tot}^{\psi N}}.$$
in which L is the length of absorption trajectory, ρ_0 is nuclear density. If $L \propto A^{\frac{1}{3}}$ then $\sigma_{\rm tot}^{\psi N} \propto A^{\alpha}$. $\sigma_{\rm tot}^{\psi N} \approx 6$ mb, $\alpha \approx 0.92$.
- Vector Meson Dominance: $\sigma_{\rm tot}^{\psi N} \propto \frac{d\sigma}{dt}(\gamma N \to \psi N)|_{t=0}$ by the optical theorem. $\sigma_{\rm tot}^{\psi N} \leq 1$ mb.
- Geometry: $\sigma_{\rm tot}^{\psi N}$ is proportional to the square radius. $\sigma_{\rm tot}^{\psi N} = 2 - 5$ mb.

E160 Spectrometer



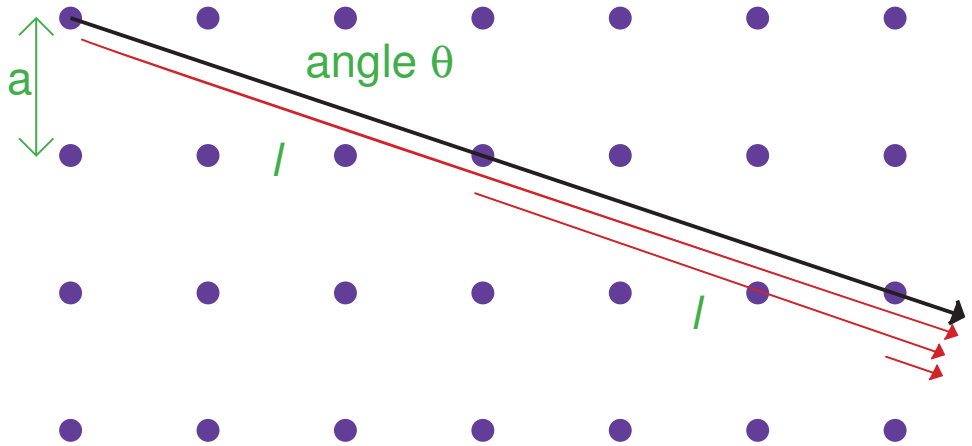
- 29D36 D3 Dipole Magnet
  - $55 \times 35 \times 220$ cm.
  - $\int \mathbf{B} \cdot \mathbf{d}\ell = 50$ kG-m.
  - graphite absorber
- 70D43 LASS Dipole Magnet
  - iron wedge $80 \rightarrow 120 \times 100 \times 140$ cm
  - $\int \mathbf{B} \cdot \mathbf{d}\ell = 35$ kG-m.
- 3 planes of scintillator hodoscopes.

LASS Fieldmap



- 3D modeling with TOSCA and Mermaid
- 2.5 T in wedge
- Realistic calculations of fringe fields

Coherent Bremsstrahlung

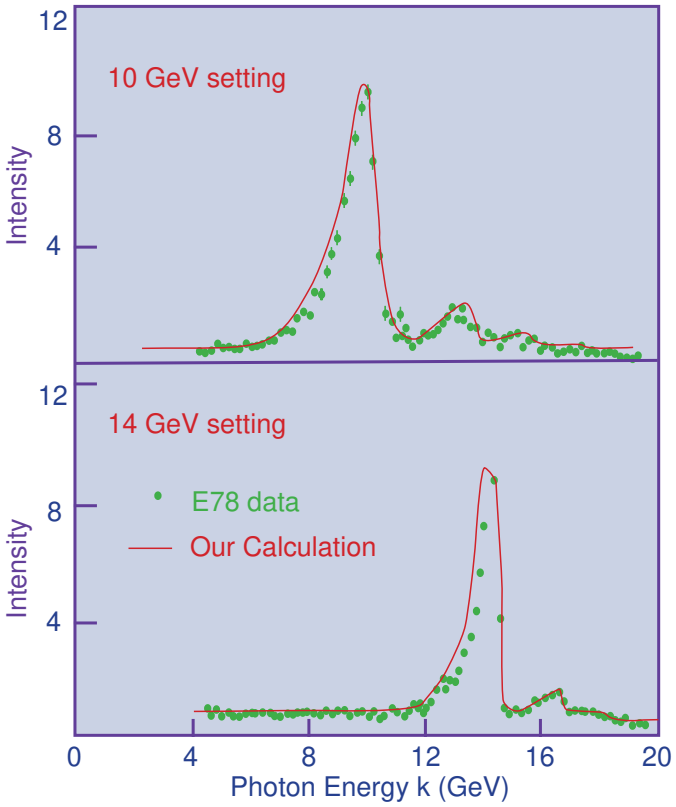


photon waves, velocity=1.
Want to be in phase.

electron, velocity=β.
Lag by one photon wavelength over distance a/θ

- High flux quasi-monoenergetic circularly polarized real photon beam.
- Thin diamond crystal radiators: low mosaic spread, low Z, small lattice spacing.
- Outperforms laser backscattering (emittance growth limits intensity) and tagging (rates are too low with 10^{-4} duty cycle).

Coherent Bremsstrahlung Spectra



- Calculations using formulas from Diambrini Palazzi, Rev. Mod. Phys. 40, 611 (1968).
- Data from SLAC E78, W. Kaune et al., Phys. Rev. D11, 478 (1975)
- Calculations are shown to be reliable for 19.7 GeV electron beams. Plotted is intensity—photon flux times energy.

Beam Parameters

Experiment	Photon Energies	Photons/Spill	Polarization
E159	4 to 40 GeV	10^5 to 10^7	circular
E160	15, 25, 35 GeV	$< 10^{10}$	linear
E161	35, 40, 45 GeV	$< 10^{10}$	circular

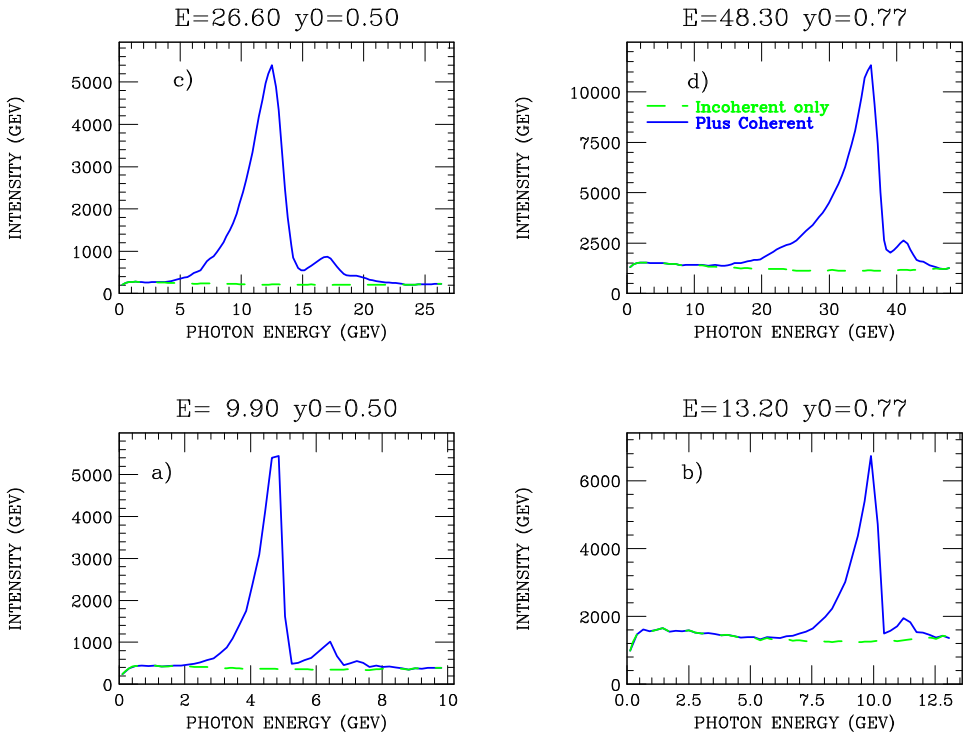
- Limit current to about 5×10^{10} e^- per 500 ns spill. At 120 spills/s, this avoids breaking diamonds and limits radiation damage.
- Tight collimation and thin diamond enhances coherent peak when high flux is not needed.
- Lower $y = k/E$ gives better coherent/incoherent ratio for given k, but also lower polarization.
- Higher k/E reduces effect of higher energy spikes.
- Linear polarization $\approx (1 - y)$
- Circular polarization

$$P_\gamma = P_e \frac{1 - (1-y)^2 - \frac{2}{3}y(1-y)}{1 + (1-y)^2 - \frac{2}{3}y(1-y)}$$

is nearly the same for coherent and incoherent.

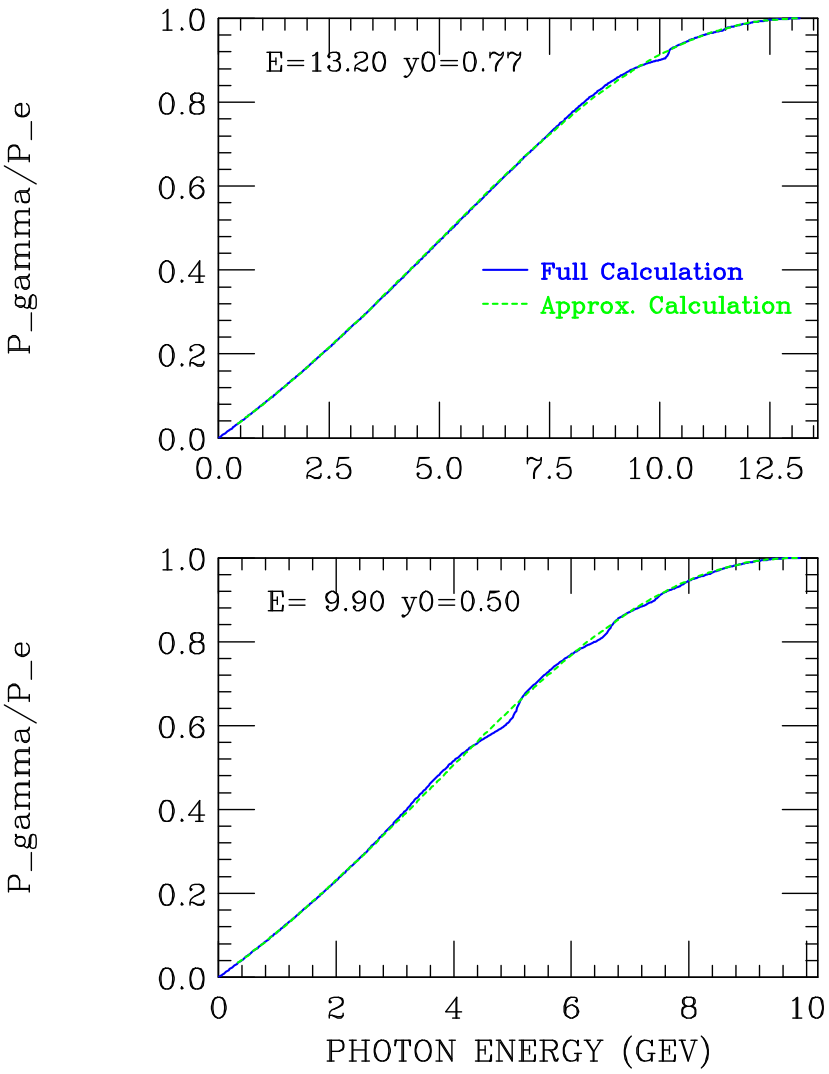
I.M. Nadzhafov, Bull. Acad. Sci. USSR, Phys. Ser. Vol. 14, No. 10, p. 2248 (1976).

Representative Photon Intensities

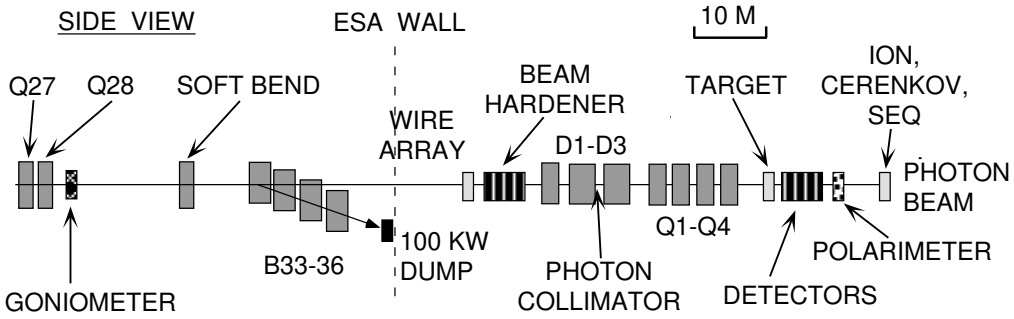


- Coherent contribution (blue lines)
- Incoherent contribution (green dashed lines)
- $y_0 = k/E$

Circular Polarization

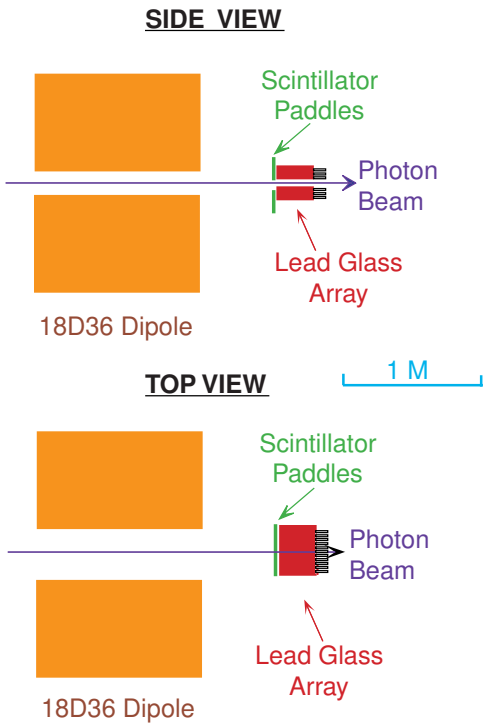


Beamline Overview



- Goniometer
- Sweeping magnets to dump electron beam
- Beam dump
- Hardener
- Collimator and position monitors
- Polarimeter
- Flux and intensity measuring devices

Compton Polarimeter



- Designed to measure flux, energy distribution, and circular polarization of beam photons.
- Helicity-dependent $\gamma e \to \gamma e$ cross section:

$$\frac{d\sigma}{d\Omega} = \frac{\alpha^2}{2m_e^2}\left(\frac{k}{k_0}\right)^2\left[\frac{k}{k_0}+\frac{k_0}{k}-\sin^2\theta - P_\gamma P_e(1-\cos\theta)\cos\theta\frac{(k+k_0)}{m_e}\right]$$

- Iron target with $P_e \approx 0.08$.
- Photon energy measurement to 3%-5%.
- Polarization measurement to 3% in about 1 hour.

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

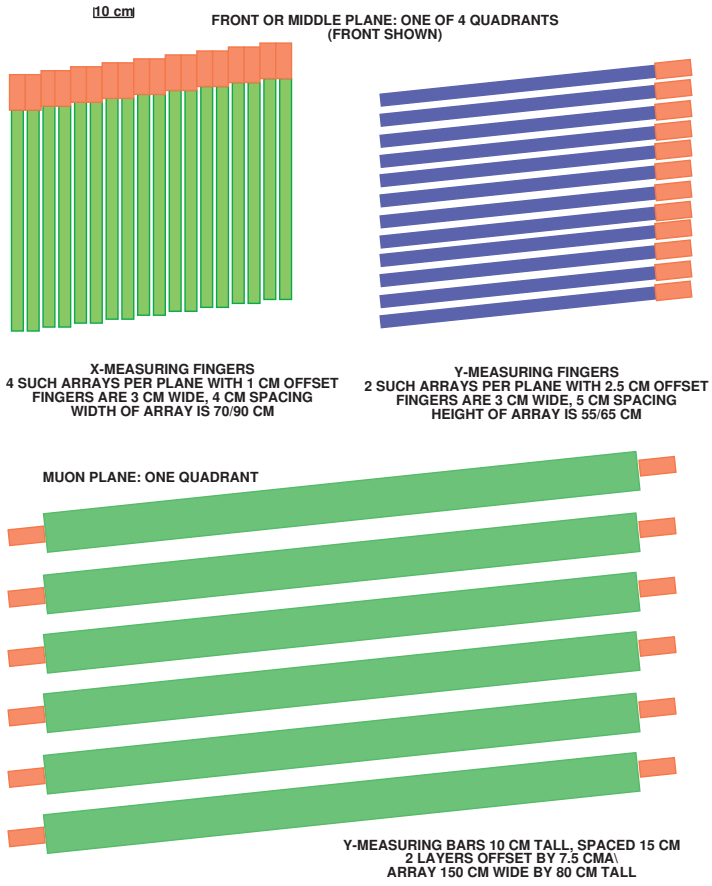
- Targets mounted on a movable target ladder
- Thicknesses chosen to obtain up to 2 b^{-1} without exceeding 0.2 radiation length.

Experimental Conditions

Electron Energy (GeV)	45.0	45.0	48.3
Electron Current (10^{10}/spill)	5.0	5.0	5.0
$k > 2.5$ GeV Photons/spill	8.3×10^9	2.8×10^9	1.8×10^9
Peak Photon Energy (GeV)	14.8	26.5	35.2
Diamond angle (μrad)	305	888	1587
C37 opening (mm)	± 2	± 2	± 2
Photon Beam Power (kW)	1.7	0.9	0.7
Diamond thickness (mm)	1.5	1.5	1.5
Linear Polarization	0.91	0.68	0.47
J/ψ/day total	78K	124K	132K
J/ψ/day in Peak	11K	45K	48K
J/ψ goal per target	10K	30K	30K
ψ' goal per target	-	1000	1000
days (at 100% efficiency)	4	5	10

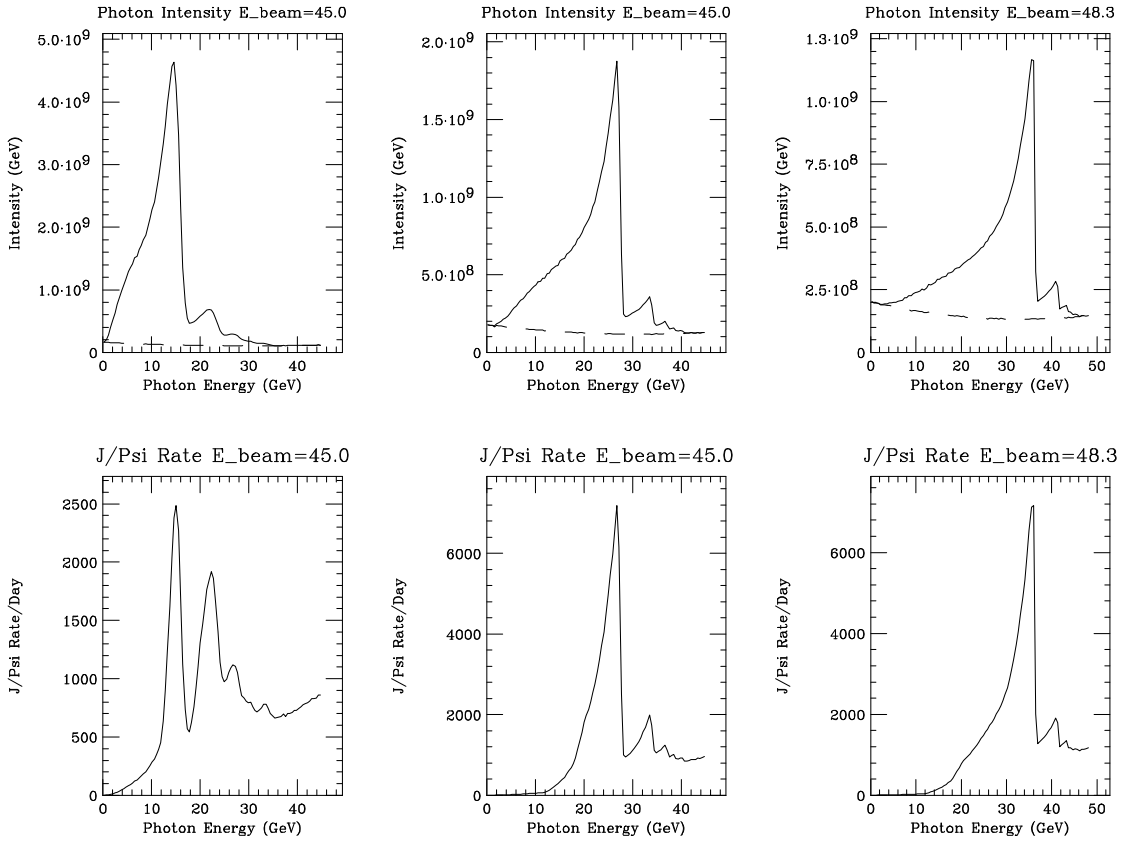
- Summary of beam parameters, J/ψ rates, and running time.
- 120 spills per second
- Spectrometer as described
- Linear polarization is given at the main coherent peak.

Hodoscope Schematic Design



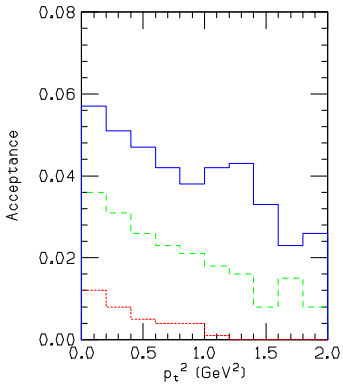
Layer	x	y	x fingers	y fingers
Front	± 70 cm	± 60 cm	280	75
Middle	± 90 cm	± 70 cm	360	90
Muon	± 150 cm	± 80 cm	16	36

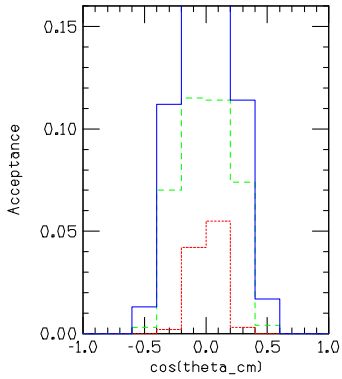
Beam Intensity and Rates

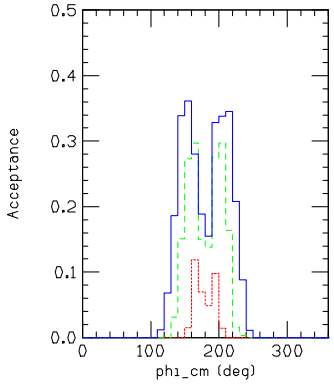


- Electron beam energies: 45 and 48.3 GeV.
- Upper: photon intensities (flux times energy).
- Lower: quasi-elastic J/ψ events per day.
- Dashed lines: incoherent radiation.

Resolution and Acceptance



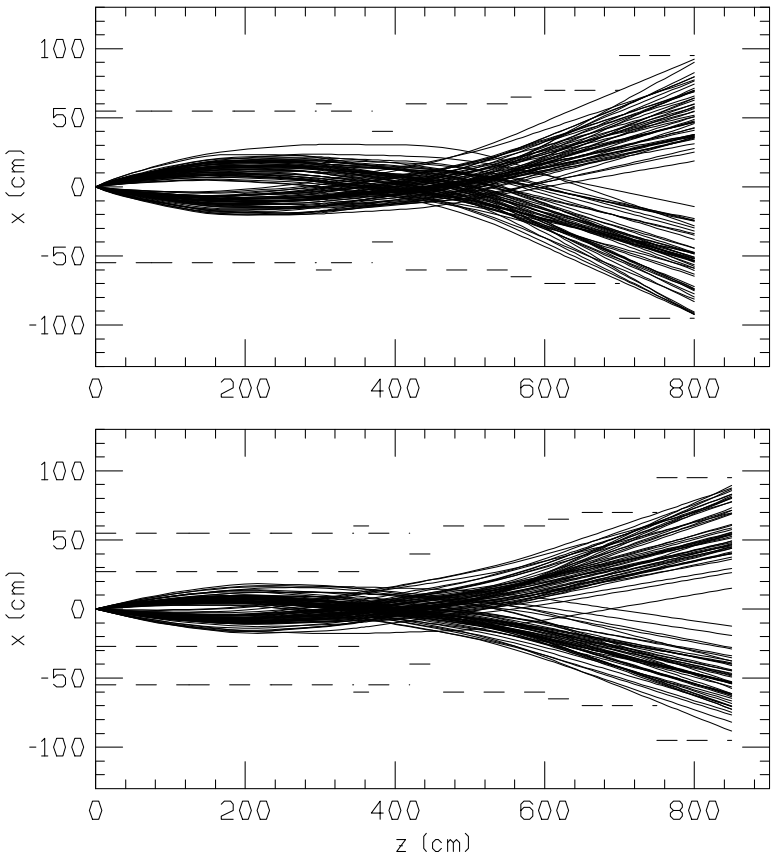




J/ψ momentum	15 GeV	25 GeV	35 GeV
Mass Resolution J/ψ (%)	3.5	2.5	2.5
Mass Resolution ψ' (GeV)	4.4	2.5	2.5
J/ψ Energy Resolution (%)	9.6	7.0	6.9
p_T Resolution (GeV)	0.12	0.11	0.12
J/ψ Acceptance	0.009	0.025	0.035
ψ' Acceptance	0.002	0.022	0.035

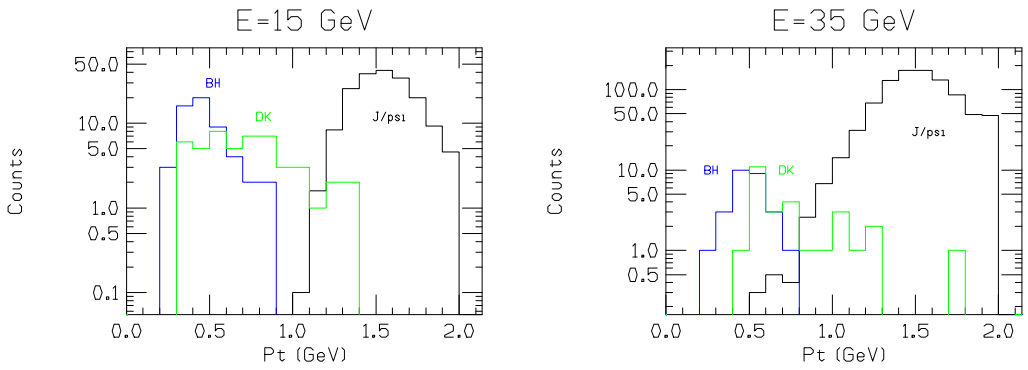
- Monte Carlo simulation of detector.
- Full height of detector not used at 25-35 GeV to get better resolution.

Beam Intensity and Rates



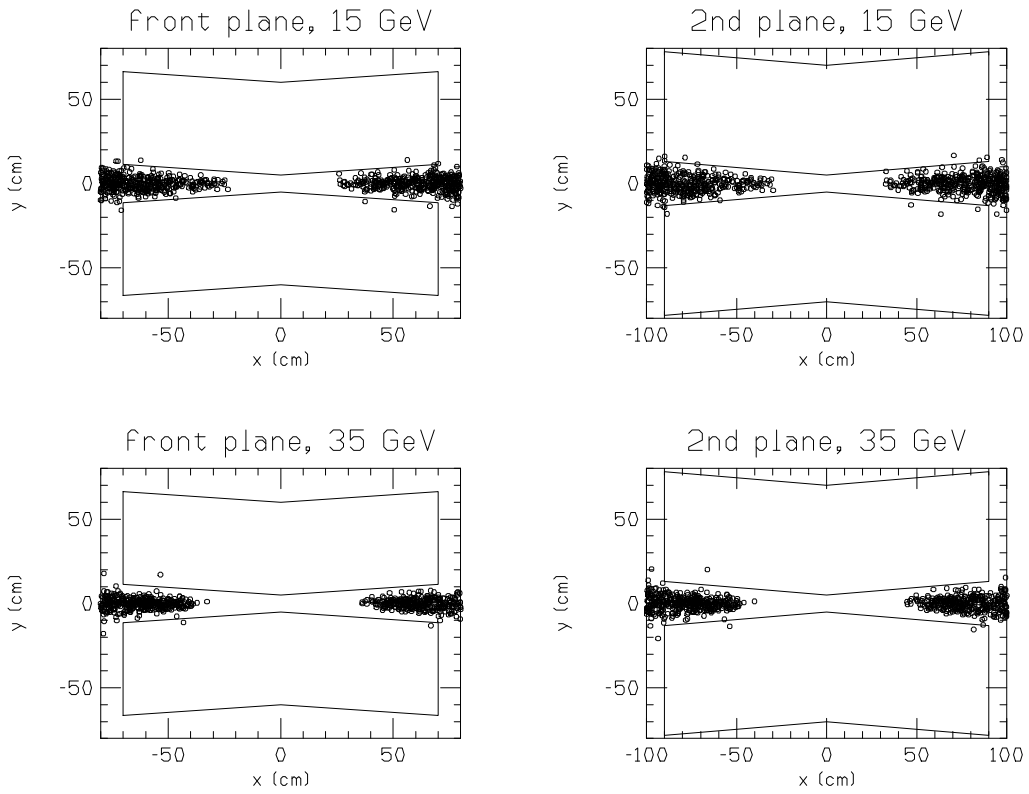
- 15 GeV (top); 35 GeV (bottom).
- Field bends in the x-direction (horizontal).
- Detected trajectories cross the central axis.

Separation of Signal and Background



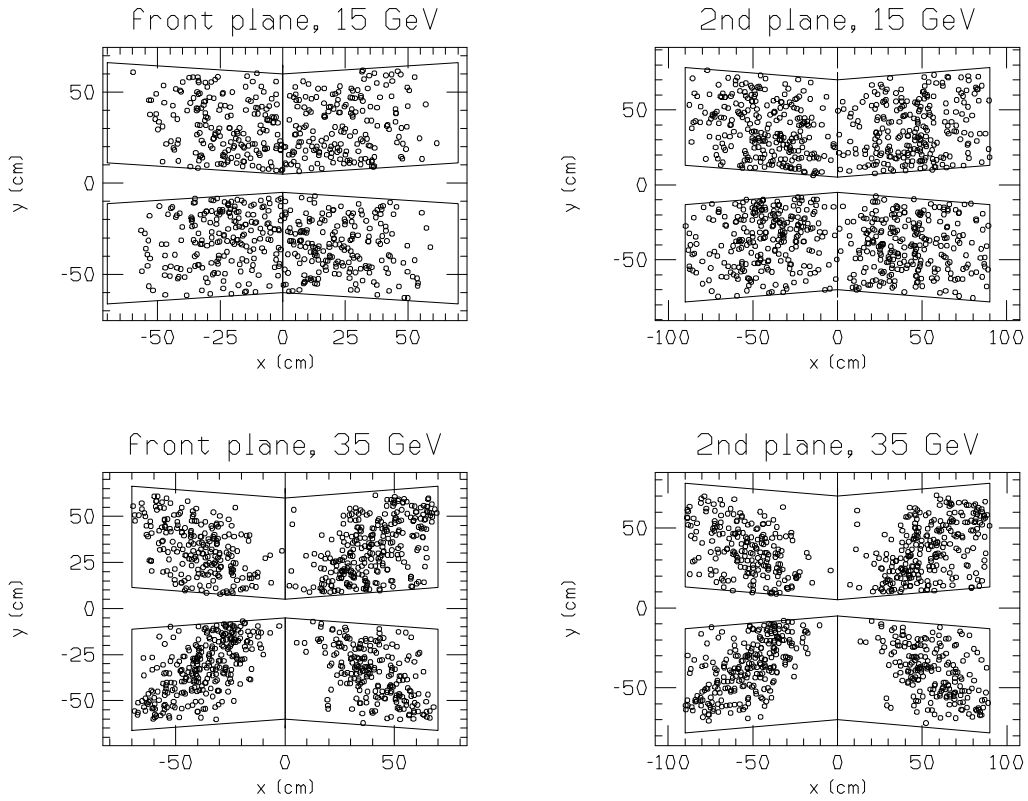
- p_T distribution of μ tracks.
- Blue line: Bethe-Heitler.
- Green line: Decay muons.
- Solid line: J/ψ.

Bethe-Heitler μ counts



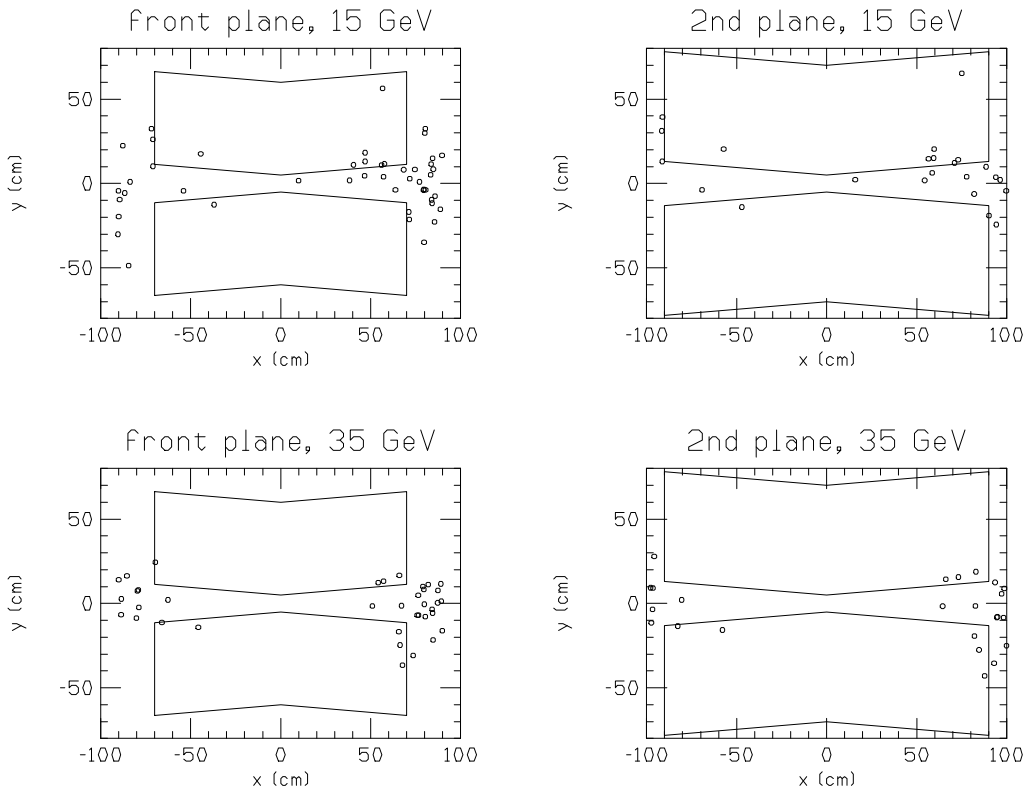
- Chevron detector shape is equivalent to a cut in p_T.
- Bethe-Heitler muons (low p_T) are concentrated in a "sheet of flame" by the dipole spectrometer.
- Most of the Bethe-Heitler muons fall outside the detector acceptance.

Muon counts from J/ψ



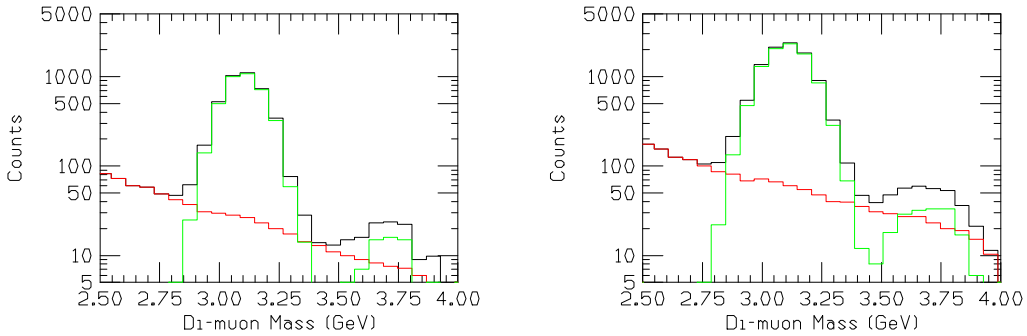
- Chevron detector shape was picked to maximize acceptance of muons from J/ψ decay.
- Forward-focusing at 35 GeV plus horizontal field yields the X pattern.
- The two muons of the pair most likely found in opposite quadrants.

Decay μ Counts



- Muons from hadronic decay.
- Relatively low-energy muons are swept to large x by the magnetic field.
- Few enter the detector acceptance.

Invariant Mass Spectra



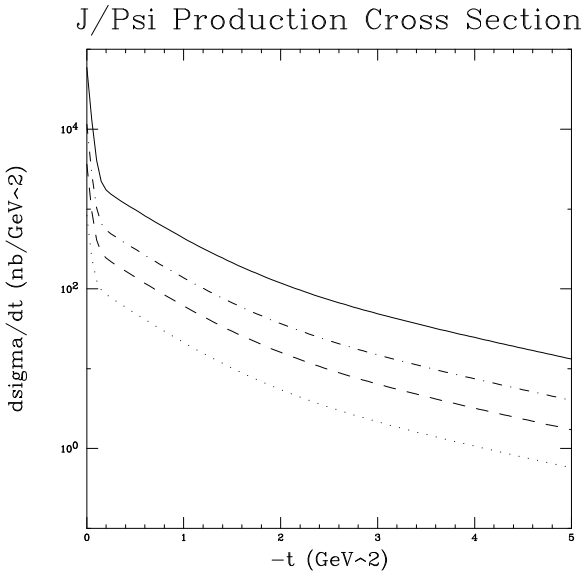
- Invariant mass of $\mu^+\mu^-$ pairs for 25 and 35 GeV.
- Red line: quasi-elastic, elastic and inelastic Bethe-Heitler backgrounds.
- Green line: J/ψ and ψ' peaks.
- Solid line: total spectrum.
- No acceptance for ψ' at 15 GeV.
- J/ψ and ψ' are well-separated.

Physics Model

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

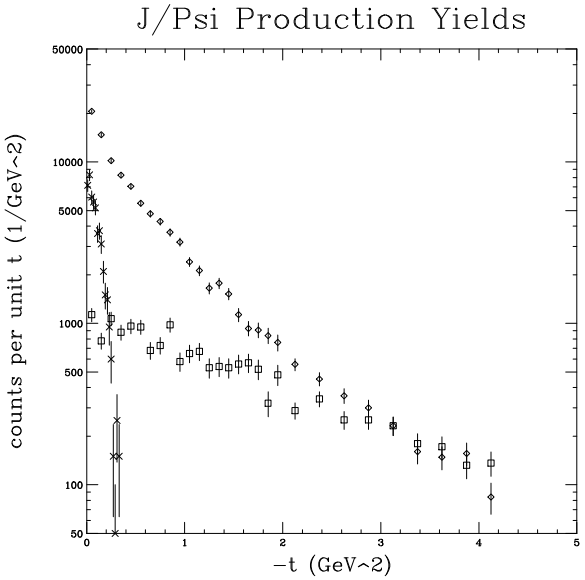
$$\sigma(\gamma N \to J/\psi N) = (10.3 \pm 0.7 \text{ nb}) \left[\frac{\sqrt{s}}{10 \text{ GeV}}\right]^{0.80 \pm 0.04}$$

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



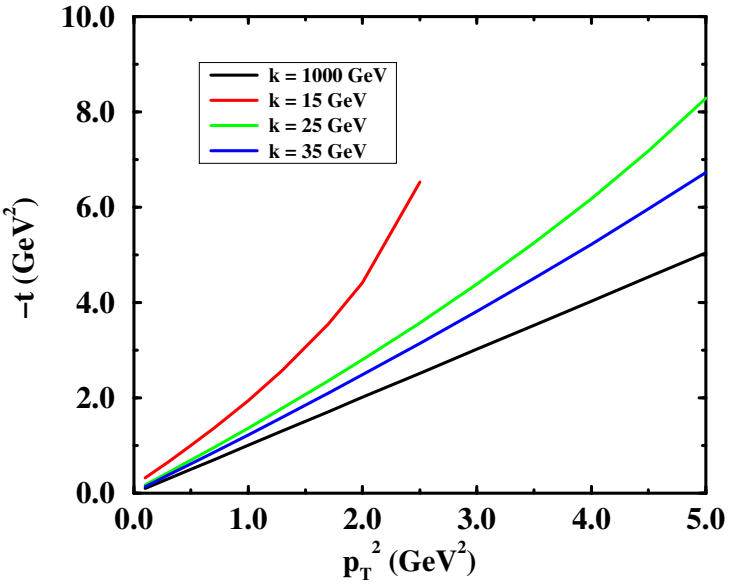
Curves for Be (dotted), Al (dashed), Cu (dot-dashed) and Pb (solid) and $E_\gamma = 20$ GeV.

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

	stat. error		
variable	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

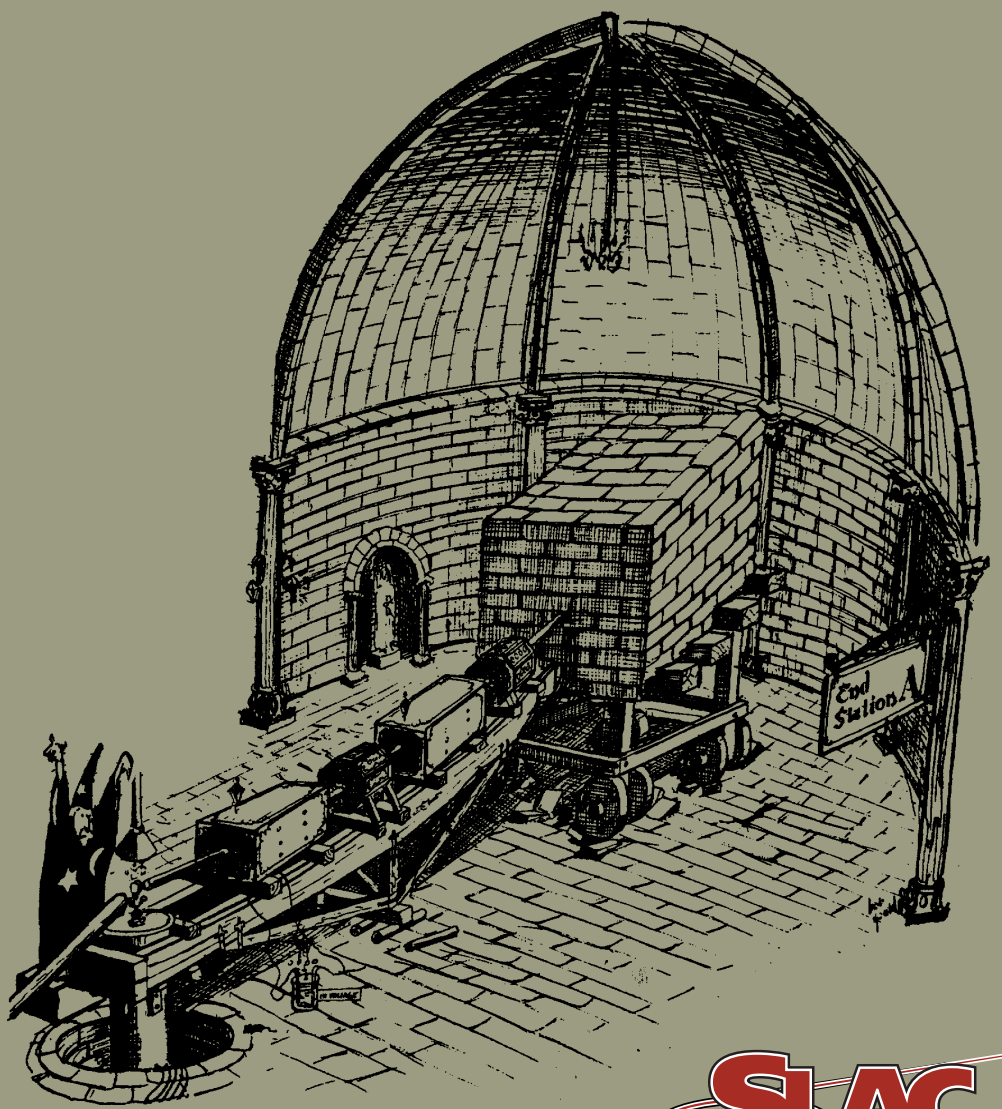
$$\frac{\sigma_{\gamma Pb\to\psi}/207}{\sigma_{\gamma Be\to\psi}/9} = e^{-(L_{Pb}-L_{Be})\rho_0\sigma_{\rm tot}^{\psi N}}$$

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

Conclusions

- E160 will study J/ψ and ψ' production and propagation through nuclei with error bars small enough to test various models.
- 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.

END STATION A



SLAC

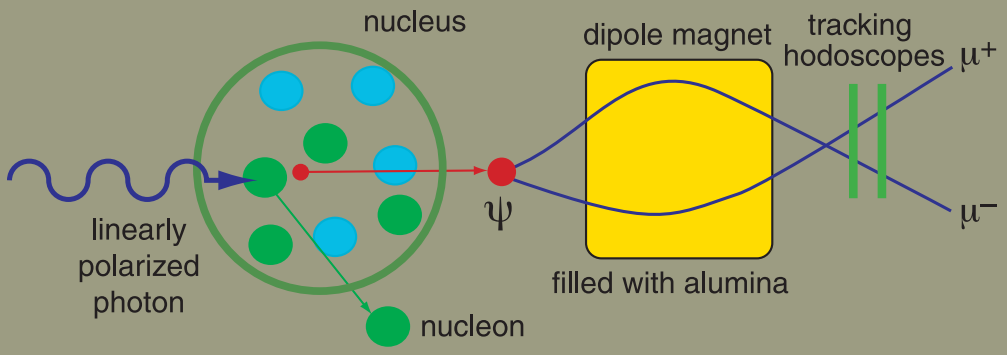
E160

Measurement of the A-Dependence of J/ψ(1S) and ψ(2S) Photoproduction

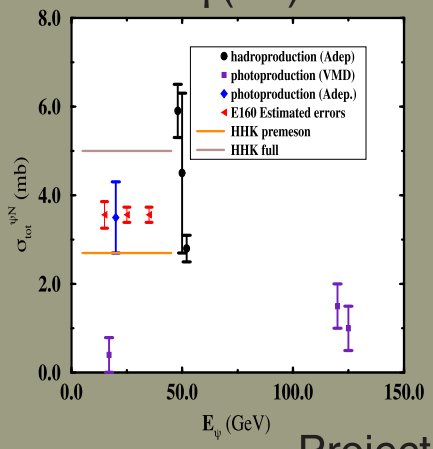
Goals

1) Study production and interaction of charmonium in nuclei from Be to Au at energies from 15 to 35 GeV.

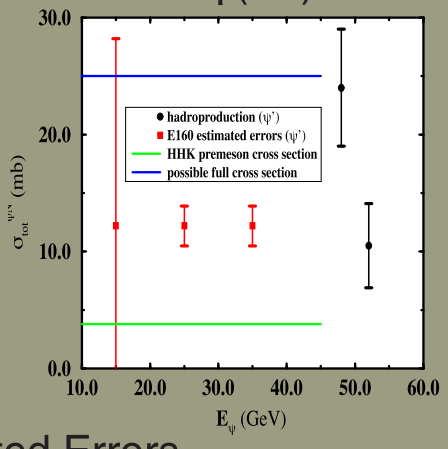
2) Constrain causes for charmonium suppression in heavy ion collisions.



J/ψ(1S)



ψ(2S)



Projected Errors

www.slac.stanford.edu/exp/e160

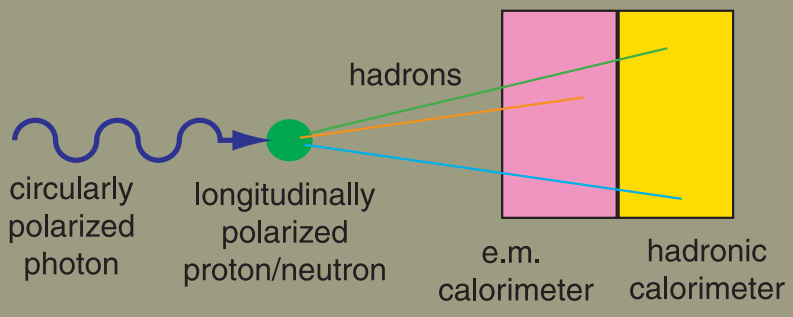
E159

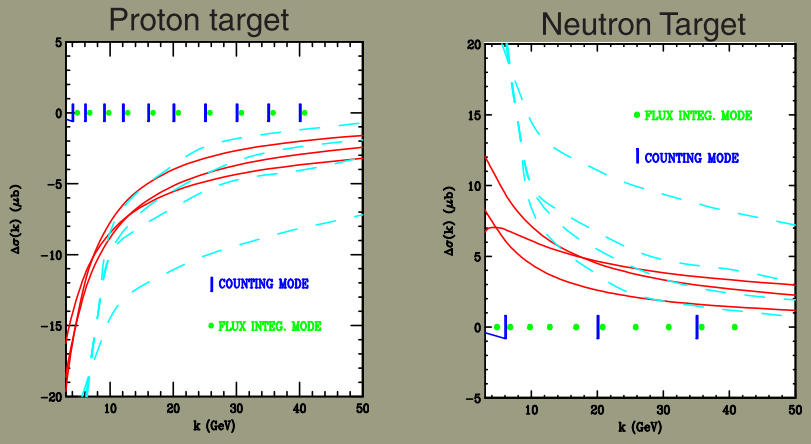
Measurement of $\Delta\sigma(k)$ and the High Energy Contribution to the GDH Sum

Goals

1) Measure helicity dependence of cross section to absorb circularly polarized photons on polarized nucleons in the energy range 5 to 45 GeV.

2) Test the fundamental GDH Sum Rule.





Projected Errors

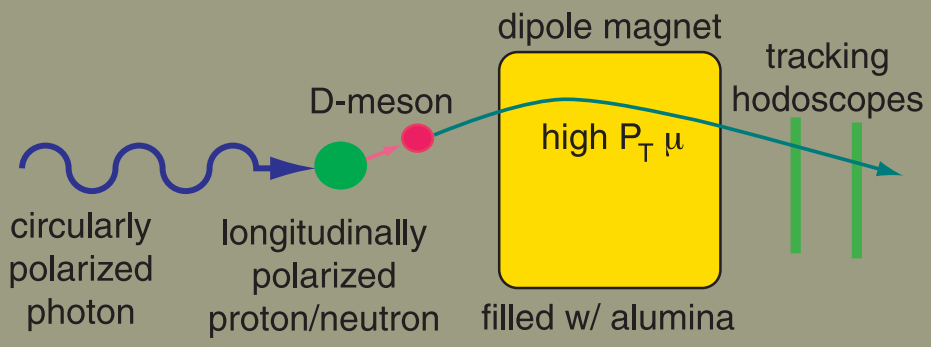
www.slac.stanford.edu/exp/e159

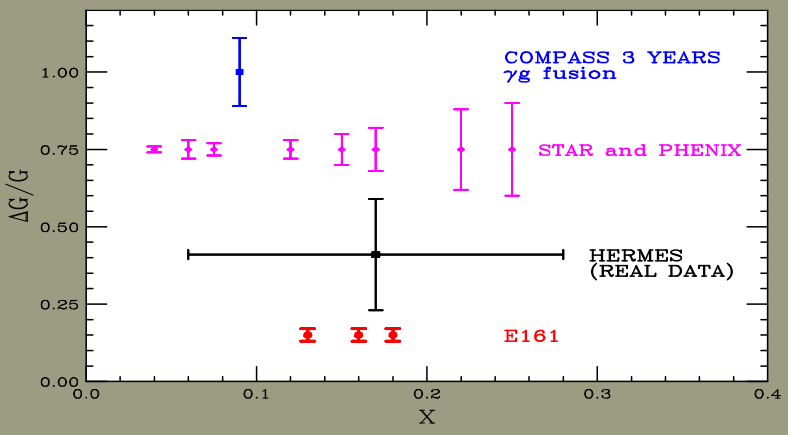
E161

Gluon Spin in Nucleons Using Polarized Open Charm Photoproduction

Goal

Find gluon contribution to the nucleon "Spin Puzzle" using photoproduction of open charm (dominated by photon-gluon fusion diagram). Complementary to measurements at RHIC-Spin and COMPASS.





Projected Errors

www.slac.stanford.edu/exp/e161