



# Measuring the $2\gamma$ exchange effect in $e^+e^-$ – proton elastic scattering at CLAS

Robert Bennett  
Old Dominion University  
MENU 2010  
May 27, 2010



# Proton Form Factor Puzzle

- Rosenbluth Separation Method

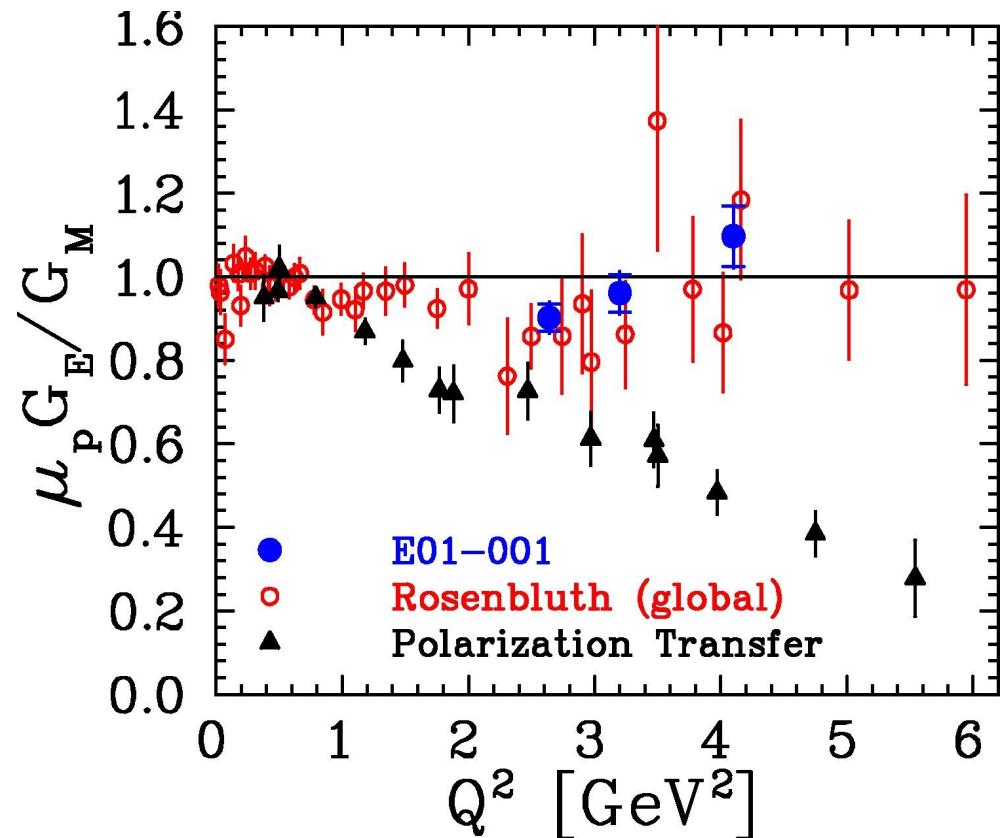
$$\sigma_R = \left( \frac{d\sigma}{d\Omega} \right) \left[ \frac{\epsilon(1+\tau)}{\sigma_{Mott}} \right] = \tau G_M^2 + \epsilon G_E^2$$

$$\epsilon = [1 + 2(1+\tau) \tan^2(\theta_e/2)]^{-1}$$

$$\tau = Q^2 / 4M_P^2$$

- Polarization Transfer Method

$$\frac{P_t}{P_l} = \sqrt{\frac{2\epsilon}{\tau(1+\epsilon)}} \frac{G_E}{G_M}$$



Hall A & C Experiments

Polarized electrons incident on proton target

Measure polarization of recoiled proton



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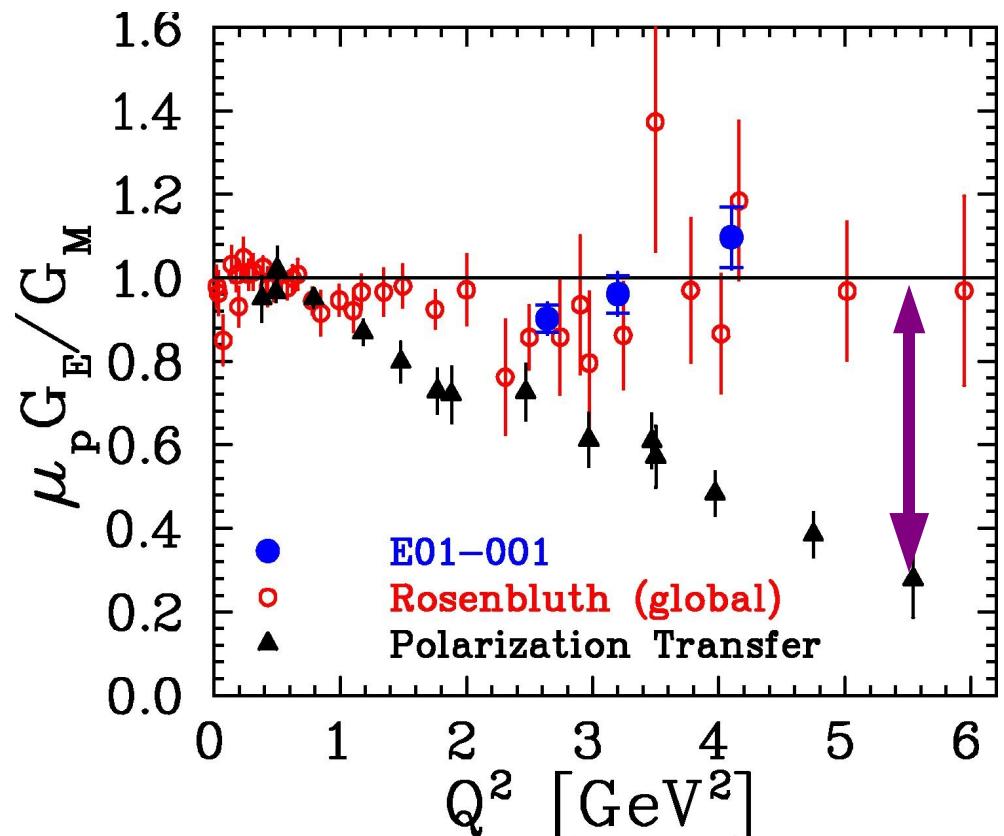
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- Large discrepancy between the two methods
- Grows systematically with Q<sup>2</sup>



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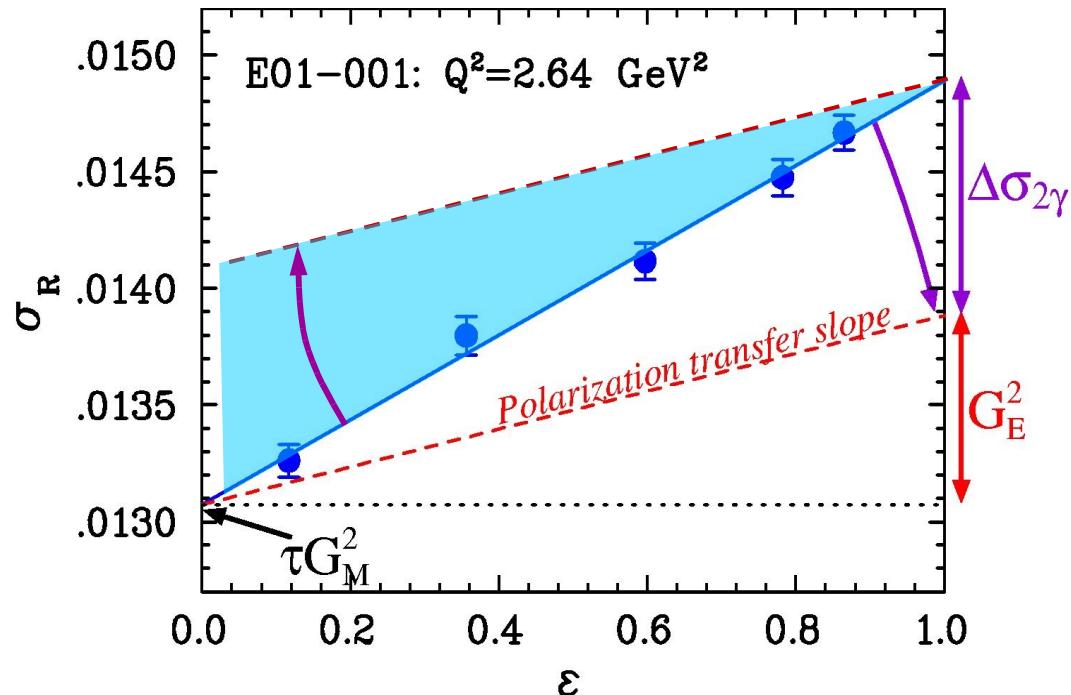
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- Large discrepancy between the two methods
- Grows systematically with  $Q^2$



# TPE Beyond the Elastic Cross Section

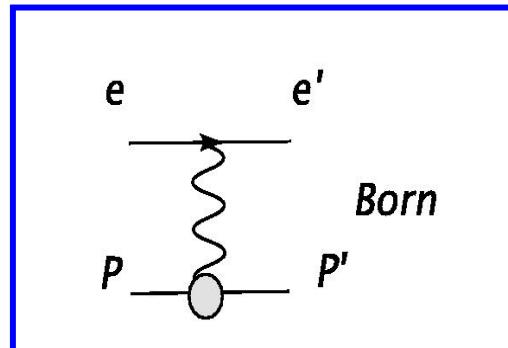
- Precise experimental tests of TPE calculations possible for the proton
  - Necessary to be certain of our knowledge of the form factors
  - Important for validating calculations used for other reactions
- Important direct and indirect consequences on other experiments
  - High-precision quasi-elastic expts. *D.Dutta, et al., PRC 68, 064603 (2003)*
  - $\gamma$ - N scattering measurements *JA, PRC 69, 022201(R) (2004)*
  - Proton charge radius, hyperfine splitting *H.Budd, A.Bodek, and JA hep-ex/0308005*
  - Strangeness from parity violation *P.Blunden and I.Sick, PRC 72, 057601 (2005)*
  - Neutron, Nuclear form factors *S.Brodsky, et al., PRL 94, 022001 (2005)*
  - Transition form factors *A.Afanasev and C.Carlson, PRL 94, 212301 (2005)*
  - Bethe-Heitler, Coulomb Distortion, ... *JA and I.Sick, nucl-th/0612079*
  - *P.Blunden, W.Melnitchouk, and J.Tjon, PRC72, 034612 (2005)*
  - *A.Afanasev, et al., PRD 72, 013008 (2005)*
  - *S. Kondratyuk and P. Blunden, NPA778 (2006)*
  - *V. Paschutska, C. Carlson, M. Vanderhaeghen, PRL96, 012301 (2006)*

Compiled by J. Arrington

Robert Bennett: MENU 2010



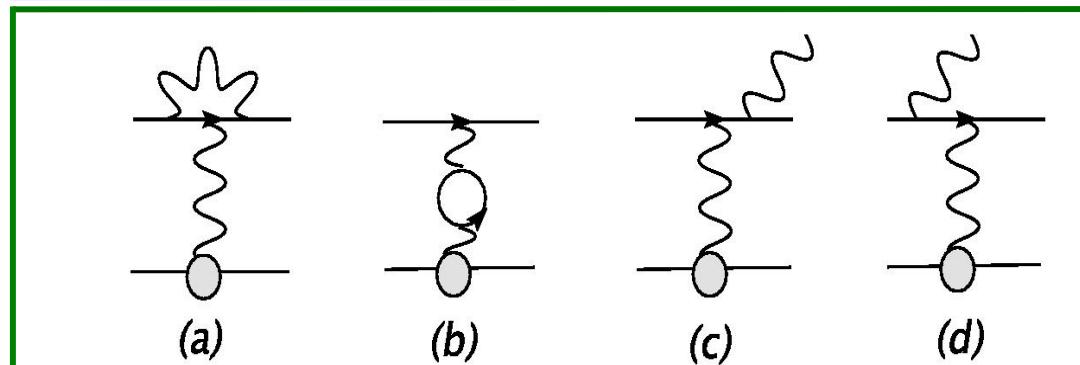
# Two Photon Exchange (TPE) Correction



The elastic  $ep$  scattering cross section:

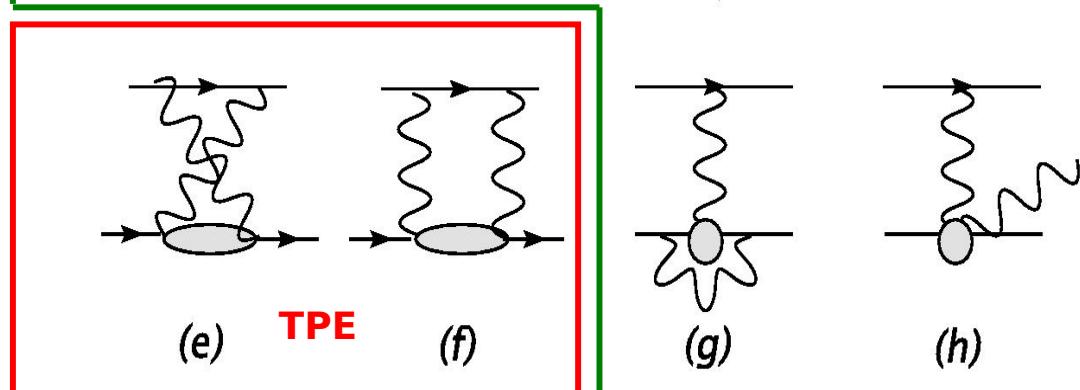
$$\sigma(e^\pm) \propto |A_{ep \rightarrow ep}|^2 = |A_{Born} + \dots + A_{2\gamma}|^2$$

$$\sigma(e^\pm) \propto |A_{Born}|^2 \pm 2A_{Born} \operatorname{Re}(A_{2\gamma})$$



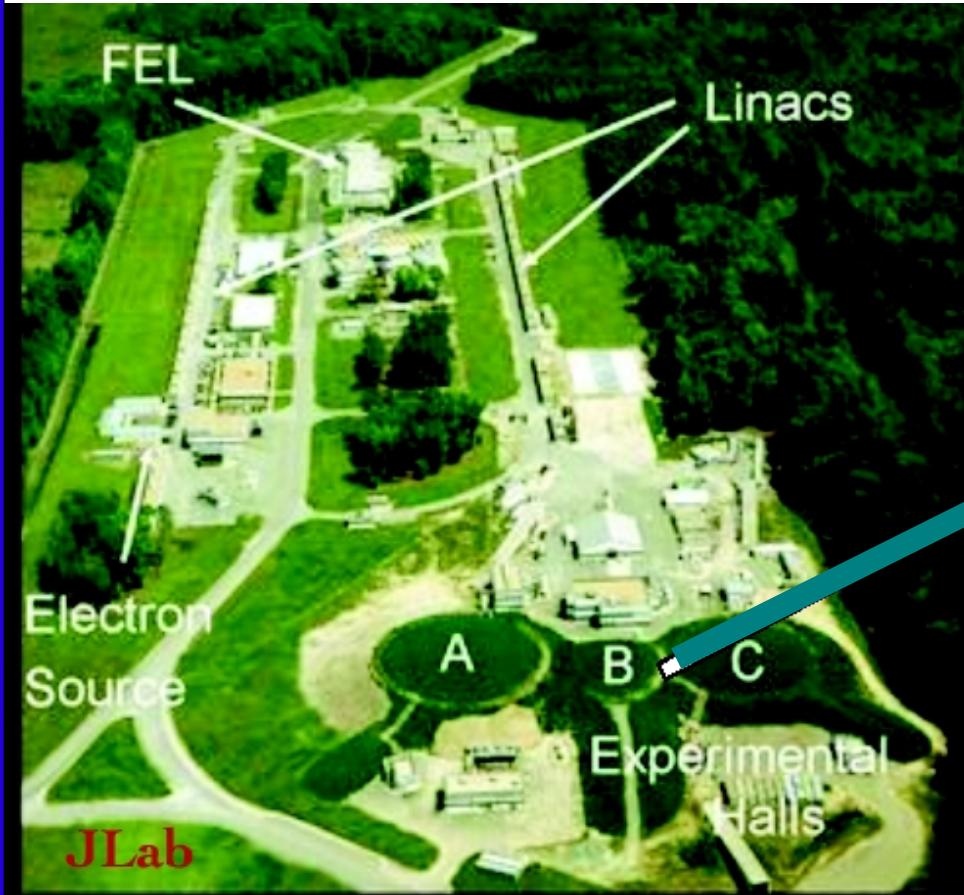
$$R = \frac{\sigma(e^+)}{\sigma(e^-)} = 1 - 2\delta_{2\gamma}$$

$$\text{where } \delta_{2\gamma} = \frac{2\operatorname{Re}(A_{2\gamma})}{A_{Born}}$$





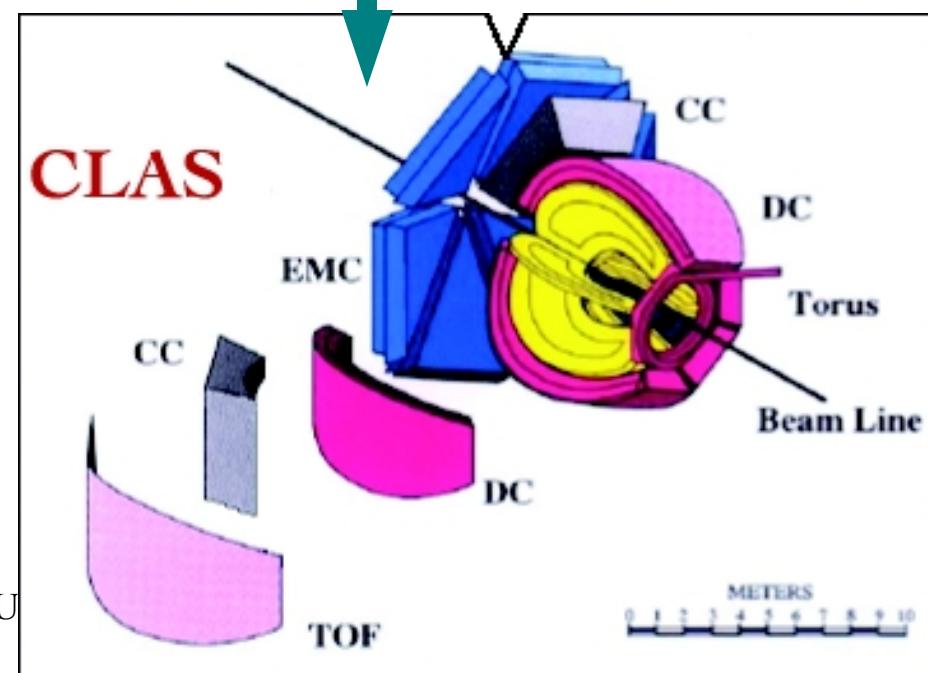
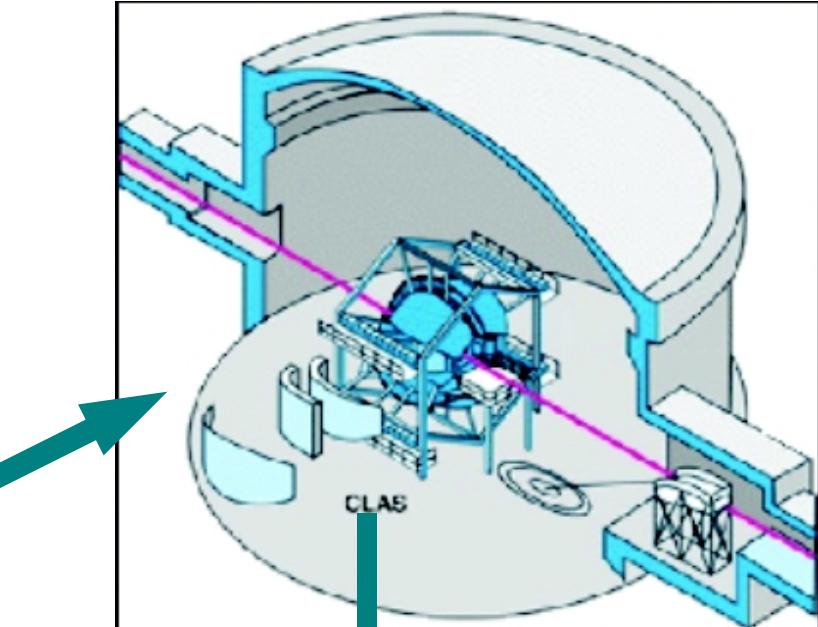
# JLab and CLAS



CEBAF  
Capable of accelerating electrons  
 $0.7 \text{ GeV} < E < 6 \text{ GeV}$   
Maximum Current  $\sim 100 \mu\text{A}$

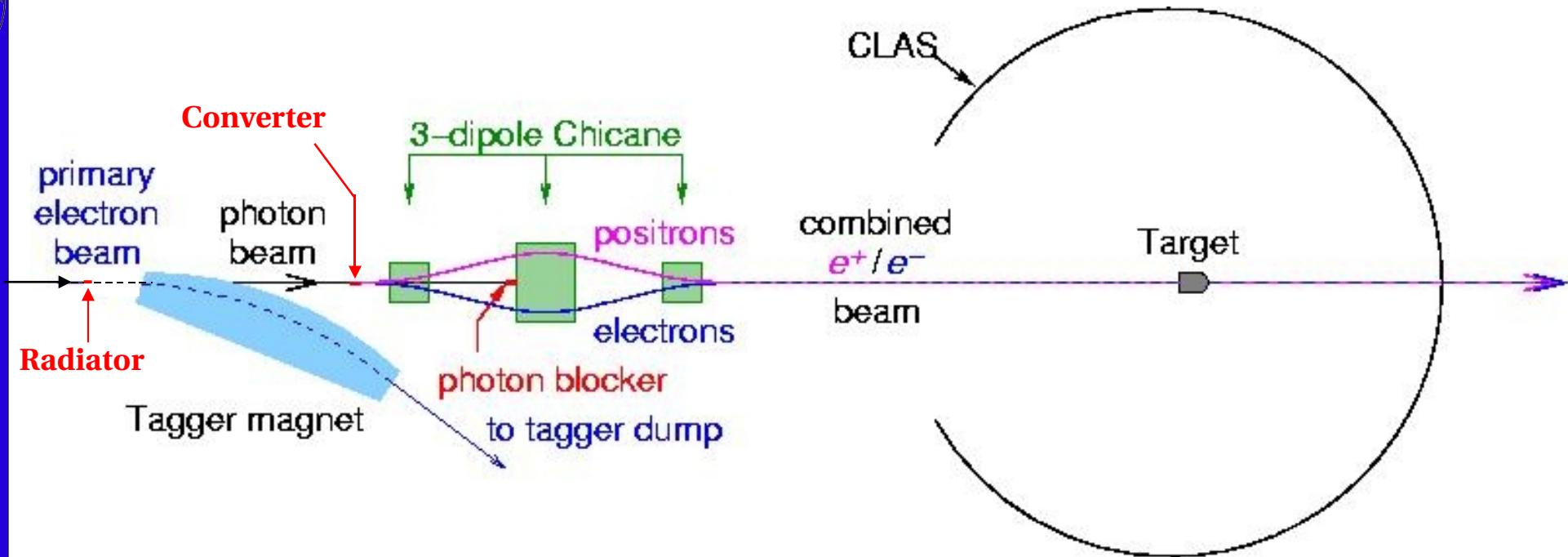
CLAS Coverage  
 $8^\circ < \theta < 142^\circ$   
 $\sim 2\pi$  in  $\phi$

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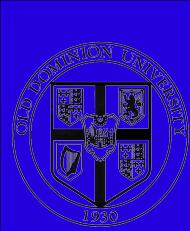




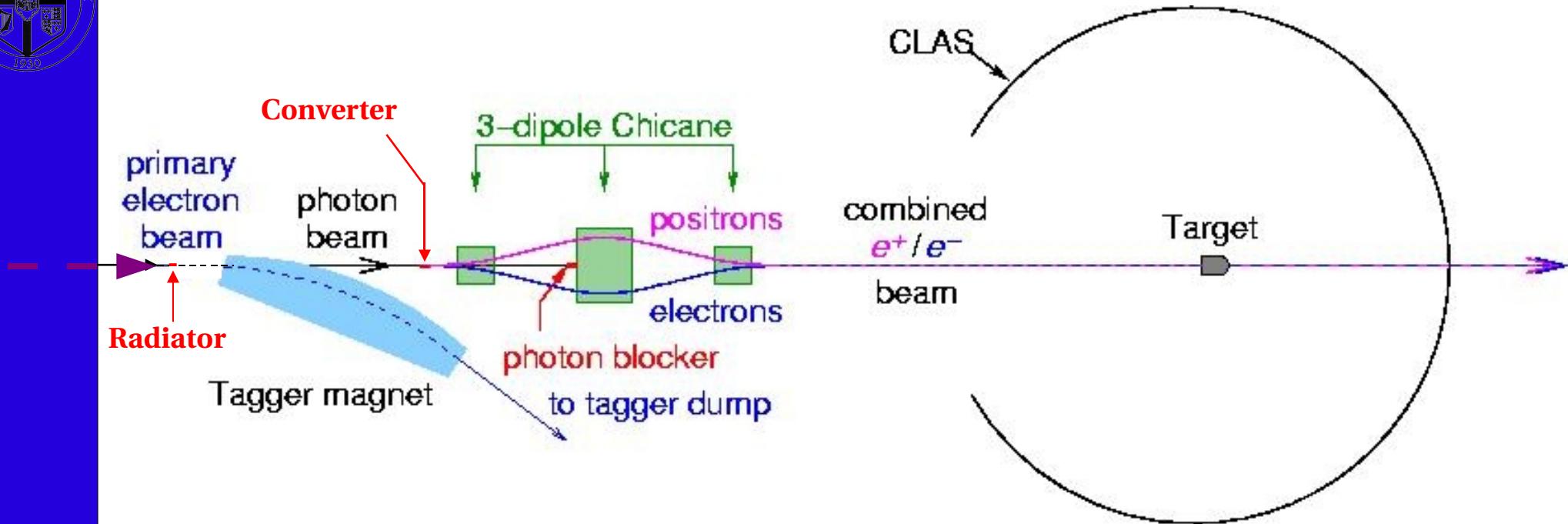
# TPE Experimental Method



- Primary electron beam: 3.2 GeV & ~80nA (2006) 5.5 GeV and 100 nA (projected)
- Radiator: 0.5 % ( 2%) of primary electrons radiate high energy photons
- Tagger magnet: transport electrons tagger dump
- Converter: 5% ( 5%) of photons are converted to electron/positron pairs
- Chicane: separate the lepton beams
  - Remaining photons are stopped at the photon blocker
  - $e^+$  and  $e^-$  beams are then recombined and continue to the target
- Target: liquid hydrogen: length = 18cm (30 cm) & diameter = 6cm (6 cm)
- Detector: CLAS (DC, TOF)



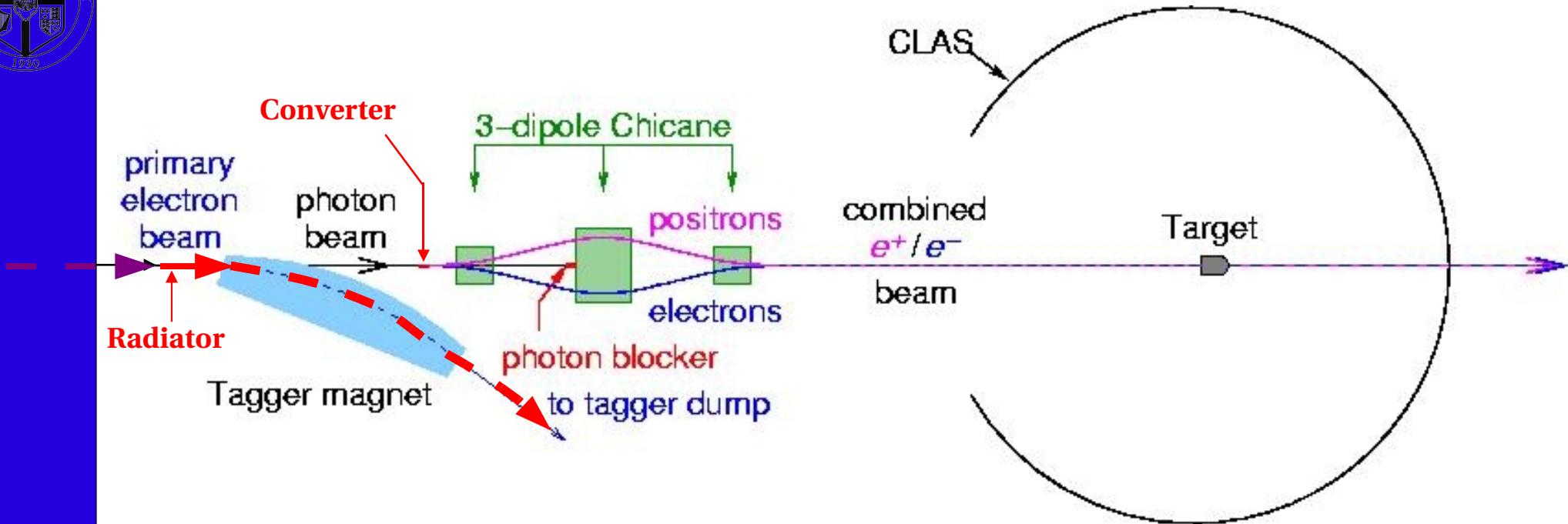
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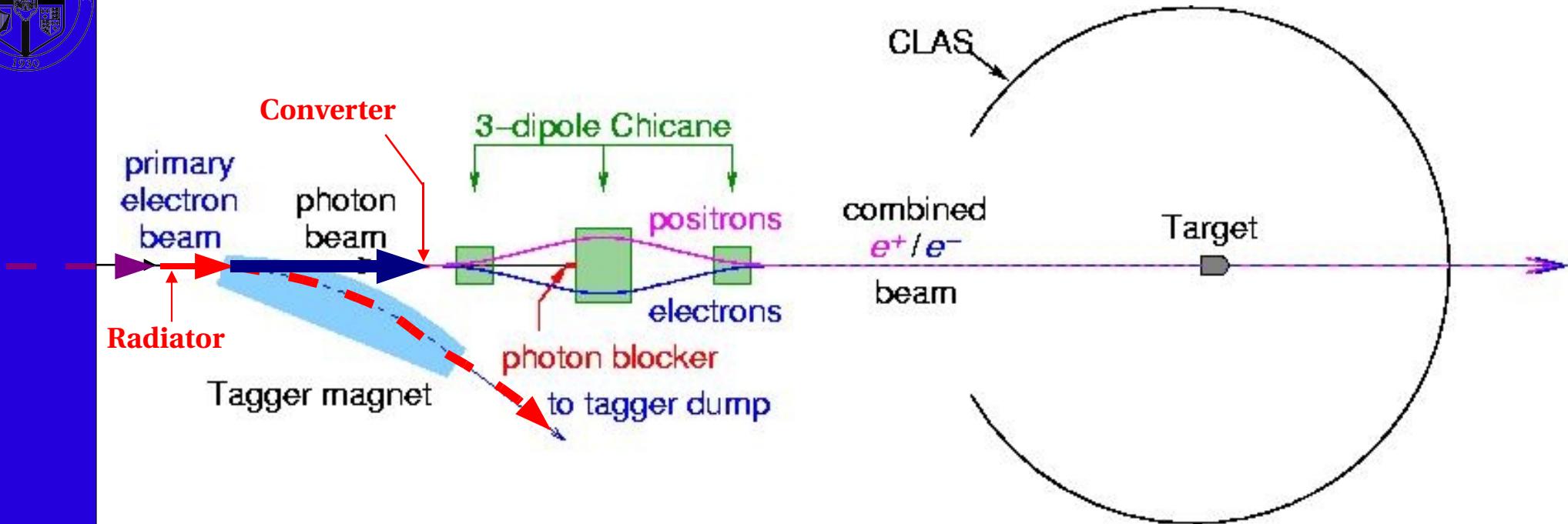
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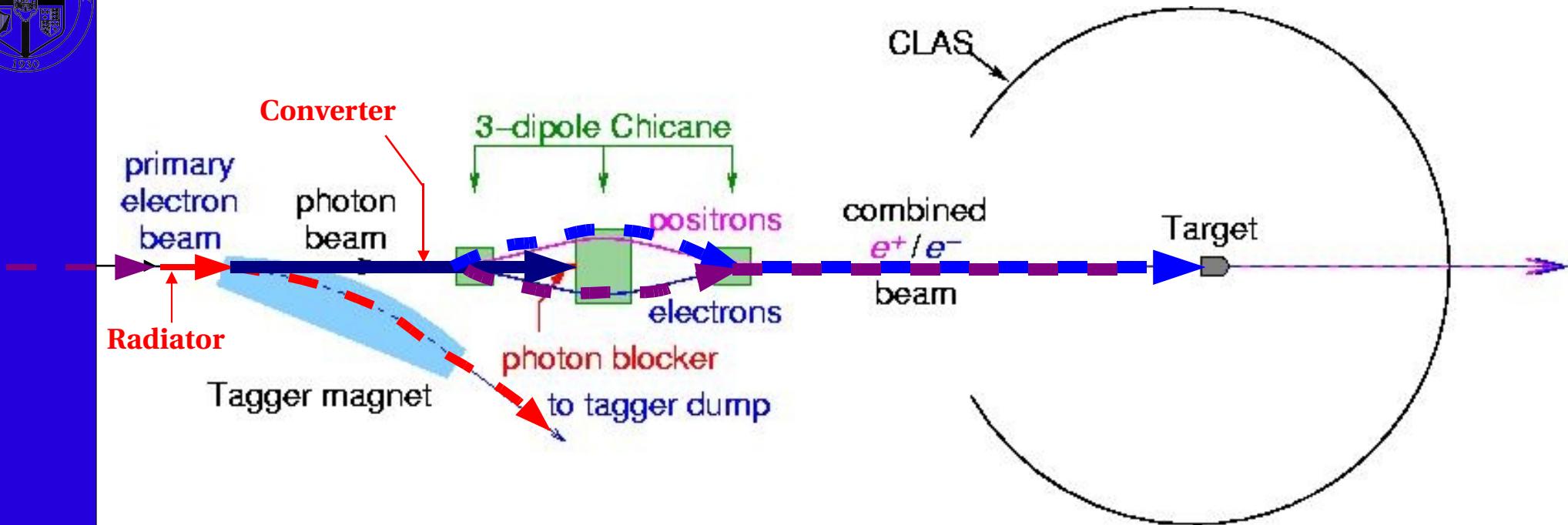
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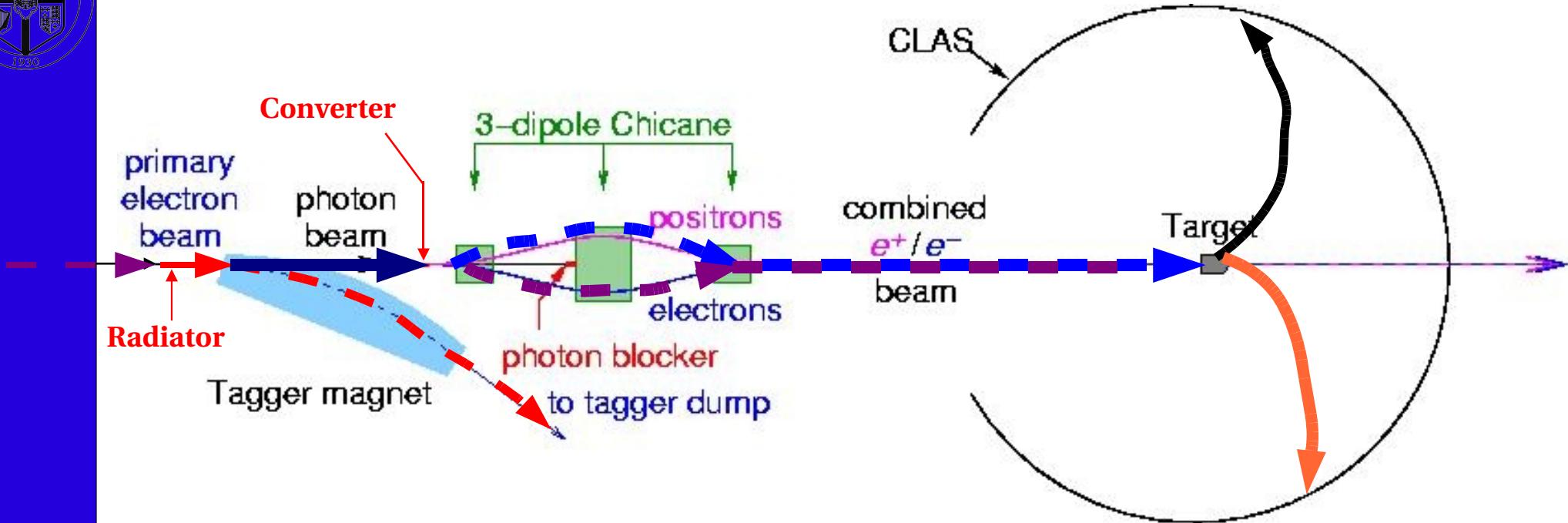
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# The Basics

1. Measure elastic scattering ratio
2. Systematics checks/corrections
  - Flip chicane polarity
  - Flip torus polarity
  - Extensive beam profiling
3. Analysis Issues
  - Unknown beam energy for a given event
  - Non-standard particle ID (no CC or EC for lepton ID)
4. Analysis solutions
  - Look for co-planar particle pairs (opposite sectors).
  - Identify ++ and -- pairs.
  - Exploit elastic-scattering kinematics and other cuts to identify events of interest.

$$R = \frac{\sigma_{e^+ p}}{\sigma_{e^- p}}$$



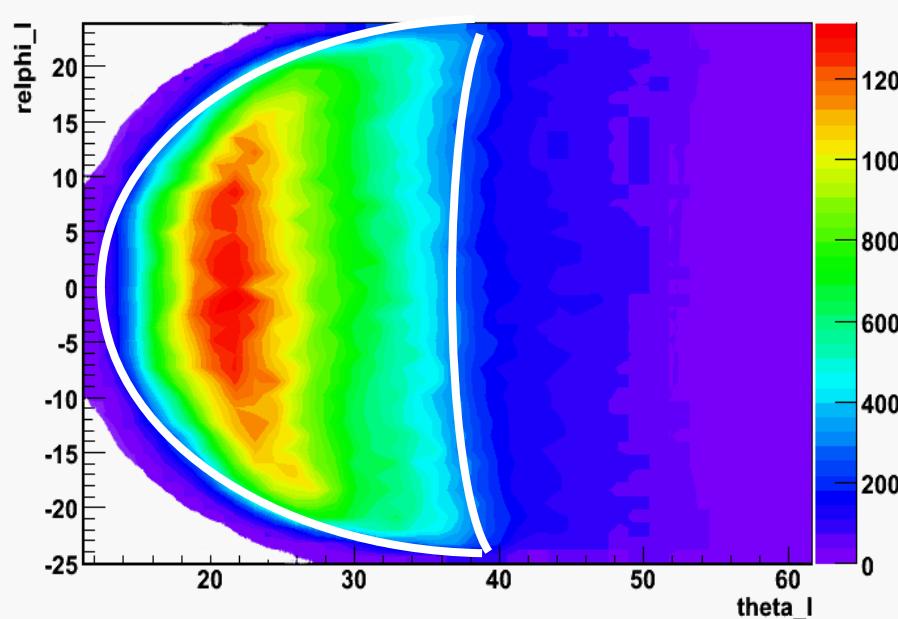
# Data Analysis Summary

- 1.) Two particles in opposite sectors.
- 2.) For ++ events, positrons  $0.95 < \beta < 1.05$ , protons  $\beta < 0.90$
- 3.) Target vertex cut for lepton candidate.
- 4.) Bad TOF paddles removed.
- 5.) Azimuthal angle between proton and lepton ( $\Delta\phi$ ) cut.
- 6.) Transverse momentum relative to beam direction cut.
- 7.) Beam-energy difference cut.
- 8.) Beam polar angle cut.
- 9.) Distance of closest approach (DOCA) between tracks.
- 10.) Fiducial cuts (selects “good” acceptance region of CLAS)
- 11.) Acceptance matching between ++ and +- events.



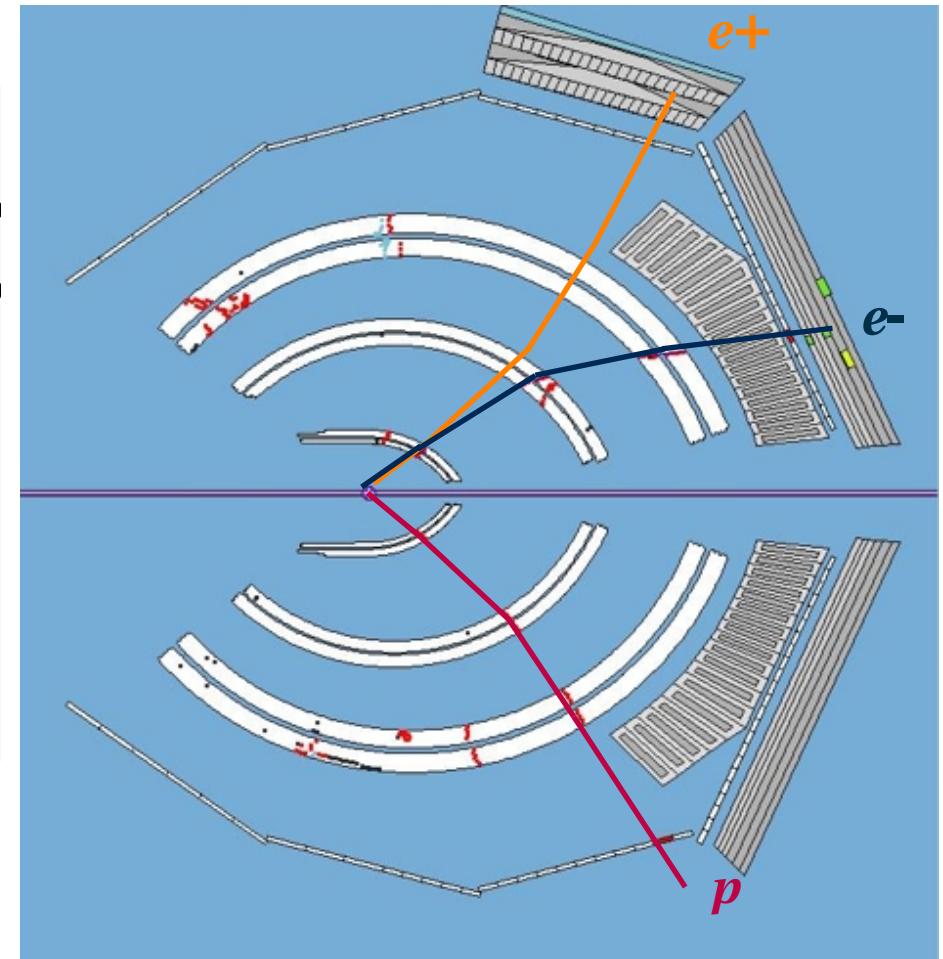
# Data Analysis: Acceptance

Largest systematic uncertainties arise from relative luminosity and detector acceptance



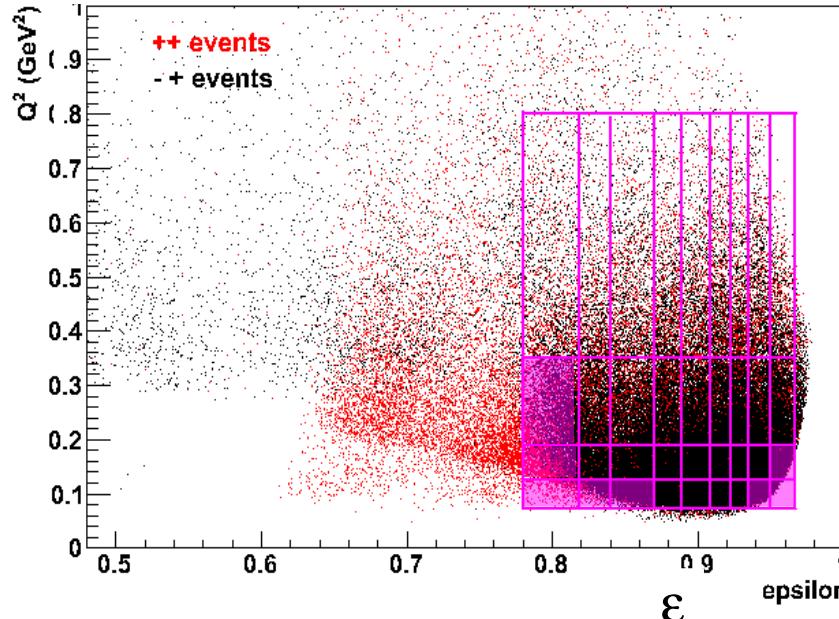
- Fiducial cuts to select regions of overlap between electrons and positrons for different torus settings.  
Varied cuts to est. sys. Uncertainty.
- Most of these effects can be mitigated with swimming and newly proposed beamline components

Acceptance matching (swimming)

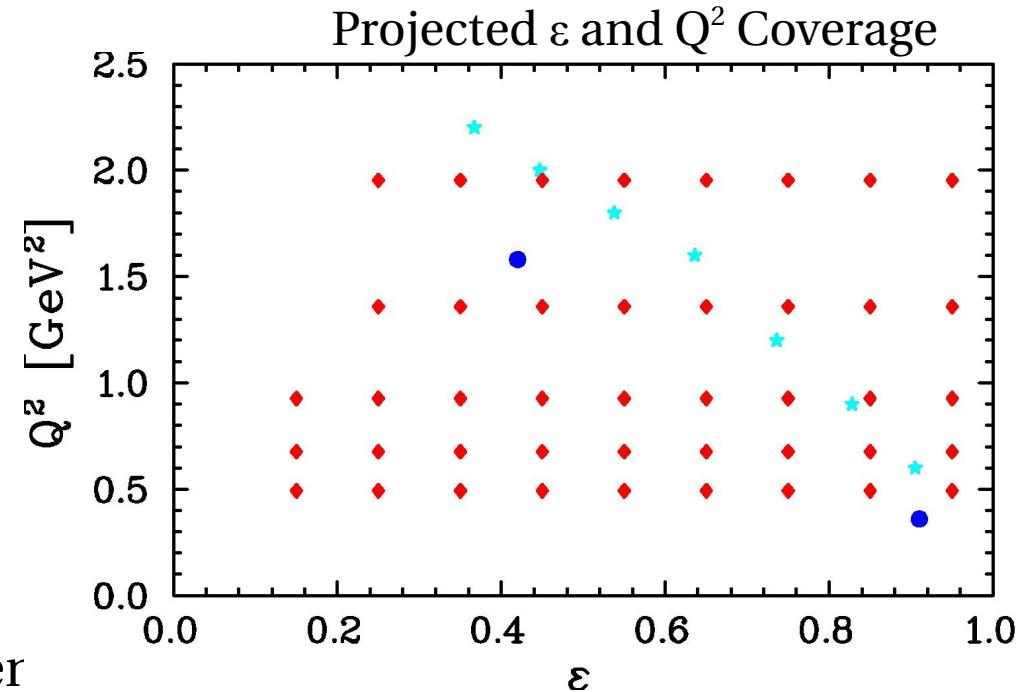




# 2006 Test Run Data Analysis: Binning



Roughly equal statistics in  $\epsilon$  for given  $Q^2$  (*Thesis: Maryam Motteabbed*)



[VEPP-III, DESY-Olympus, CLAS]

$$\langle Q^2 \rangle = 0.472 \text{ GeV}^2$$

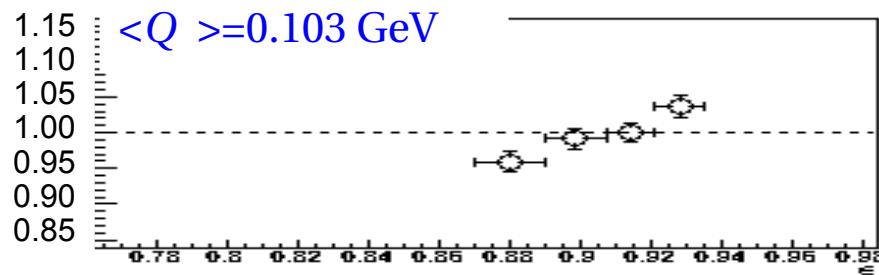
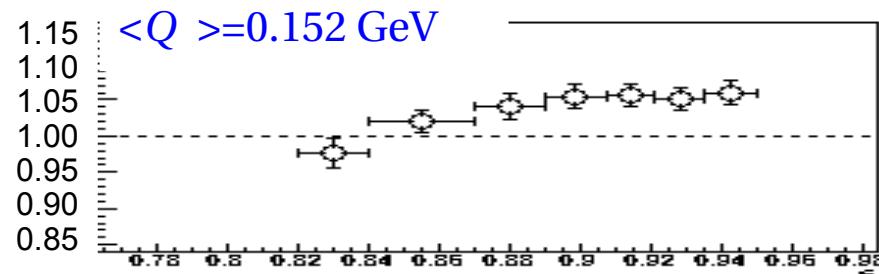
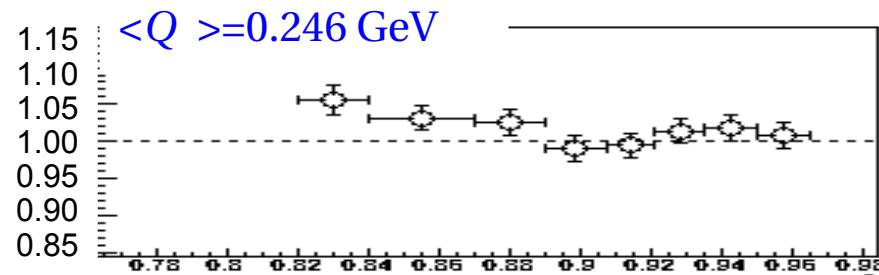
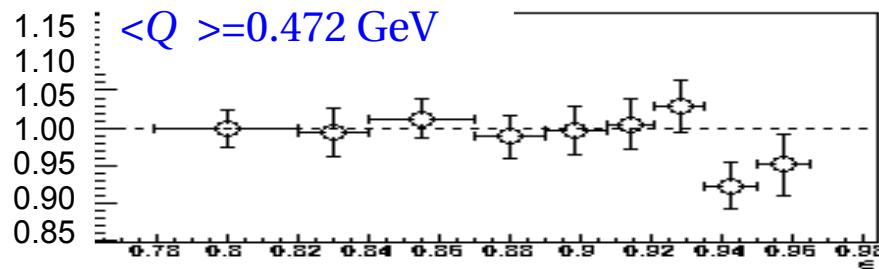
$$\langle Q^2 \rangle = 0.246 \text{ GeV}^2$$

$$\langle Q^2 \rangle = 0.152 \text{ GeV}^2$$

$$\langle Q^2 \rangle = 0.103 \text{ GeV}^2$$



# Test Run Results: Double Ratio vs $\epsilon$

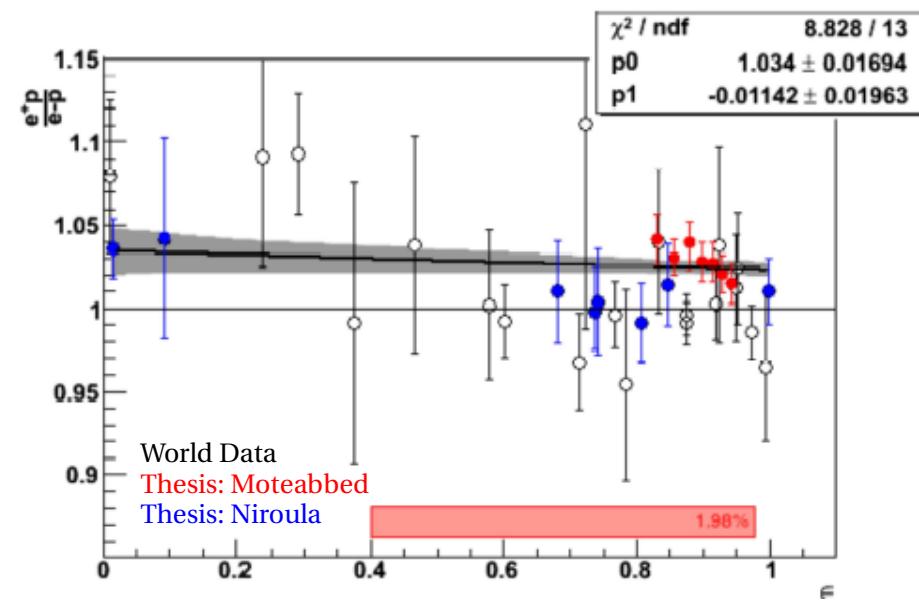


$\epsilon$  scale from 0.76 to 0.985

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$$R = \sqrt{\frac{Y_{e^+ p}^+}{Y_{e^- p}^+} \times \frac{Y_{e^+ p}^-}{Y_{e^- p}^-}}$$

Positive torus polarity  $e^+ / e^-$ -ratio      Negative torus polarity  $e^+ / e^-$  ratio



- Detector efficiency and acceptance drop out in double ratio
- Systematic uncertainties ~1-2%
- Systematics will improve with full run

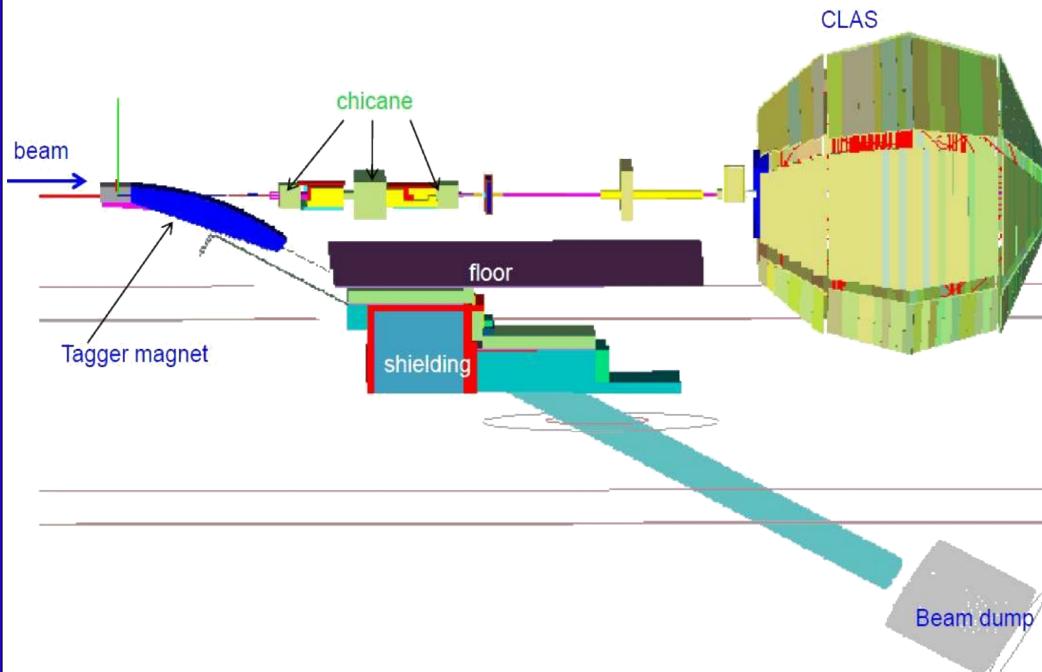


# Maximizing Luminosity

- Constraints
  - DC occupancy < 3%
  - TOF occupancy
  - Tagger Radiation Dose
    - Detector < 0.1 MRad
    - Window < 100 MRad
- Tools
  - Collimation
  - Beam current, radiator + convertor
  - Mass shielding
  - Magnetic shielding
  - Large team (Larry Weinstein, Jeff Lachniet, Maurizio Ungaro, Will Brooks, Brian Raue, Maryam Moteabbed, Megh Niroula, Dasuni Adikaram, Robert Bennett, Cristian Peña, and Hayk Hakobyan)



# Test Run Setup



Primary Beam Energy	3.2 GeV
Primary Beam Current	80 nA
Radiator Thickness	0.5 % $X_0$
Converter Thickness	5 % $X_0$
Downstream Collimator ID	6cm
Target Length	18 cm
Target Diameter	6 cm
Target Material	$H_2$

- Bunker at tagger dump
- Chicane shielding: lead, concrete, BPE
- Concrete wall at insertion cart
- Lead rad-phi wall
- Approximately 75 % of the beam time was used to identify sources of background
- A pair of PMTs were placed at several locations to measure backgrounds for simulation validation



# Calculating Occupancy & Vertex Plots

- Drift Chamber Occupancy

- In order to compare test run data to simulations, we need to normalize the number of hits in our simulation by the beam current.

$$Occupancy(\%) = \frac{N_{hits} \times T_{detector}}{T_{events}} \frac{1}{N_{wire}} \times 100$$

- Vertex Plots

- Location where particles are originally produced which hit the CLAS detectors

$N_{hits}$	Number of DC wires hit
$N_{wire}$	Number of wires per DC sector
$T_{events}$	Time to produce the number of thrown electrons with a given beam current
$T_{detector}$	Detector time window DC R1: 0.625 $\mu$ s DC R3: 2.4 $\mu$ s TOF: 100 ns



# Validating the Simulation

- Beamlne components and shielding were varied
  - The effect of these modifications were compared to simulation
  - Nominal Configuration:
    - 24 concrete block on the floor above the tagger dump
    - Rad-phi collimator ID = 2 cm
    - Down stream collimator ID = 6 cm
- Modifications
- Beam blocked at Rad-Phi collimator
  - Extra shielding wall placed on insertion cart
  - Beam blocked at the DS collimator

## Drift Chamber Occupancy

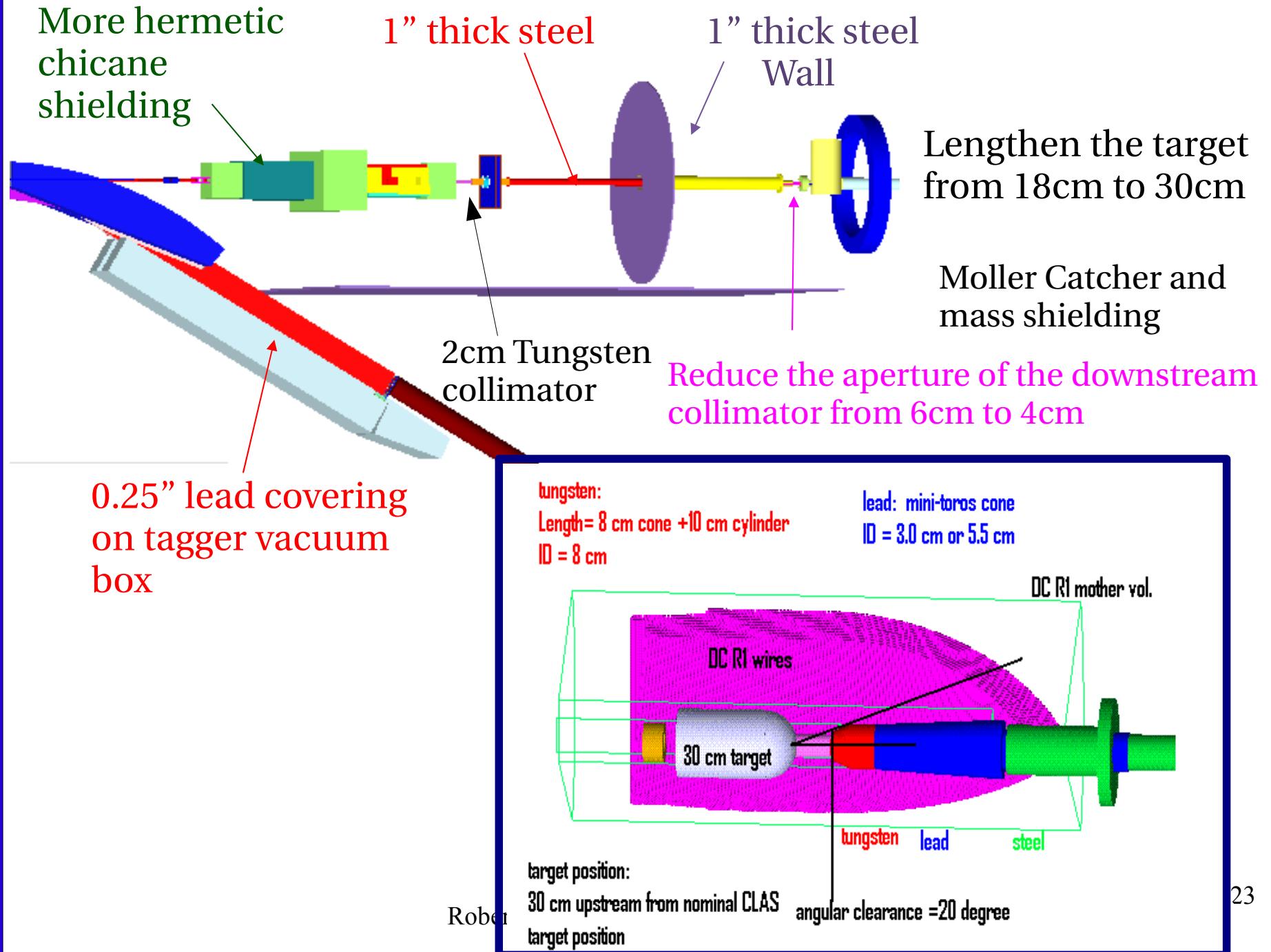
	Data	Region 1	Region 3	R3 Nominal/Mod
Nominal	Data	2.05	0.97	1
	Simulation	2.54	3.57	1
Beam blocked @ Rad-phi	Data	0.04	0.49	2.0
	Simulation	0.14	1.97	1.8
Icart Wall	Data	1.27	0.38	2.5
	Simulation	1.91	2.55	1.4
Beam blocked @ DS coll	Data	0.14	0.34	2.8
	Simulation	0.10	1.84	1.9

– The simulation describes R1 occupancy quantitatively

– The simulation describes changes in the R3 occupancy



# Summary of Planned Shielding





# Down Stream Collimator



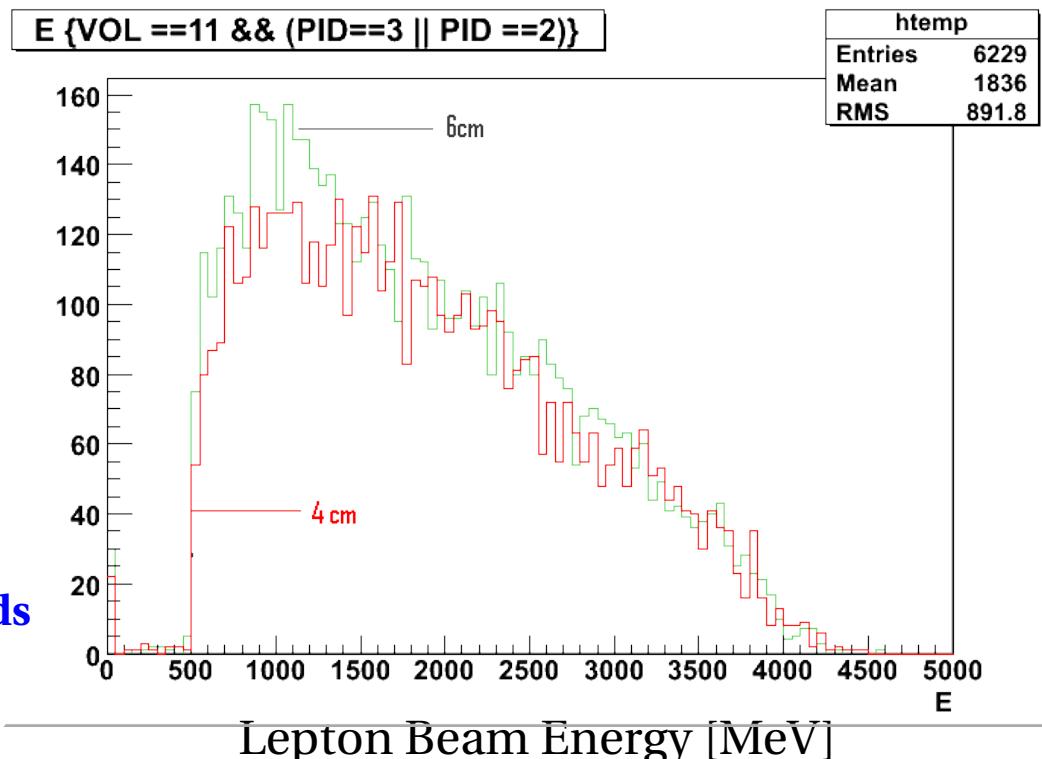
Target cooler + condenser apertures  
are too small

- 1) Enlarge cooler + condenser aperture  
(too expensive)
- 2) Reduce collimator aperture from  
6cm to 4cm

Negligible loss of  $e^+ / e^-$  beam

~10%, but is it mostly low energy

Dramatic decrease in detector backgrounds

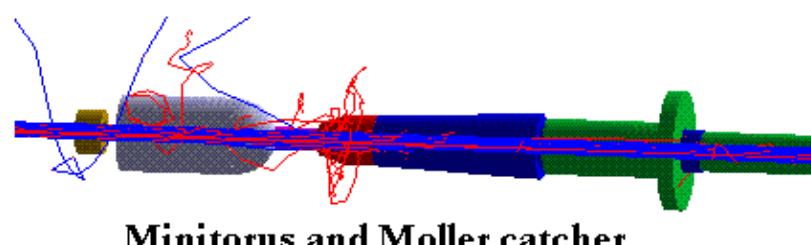
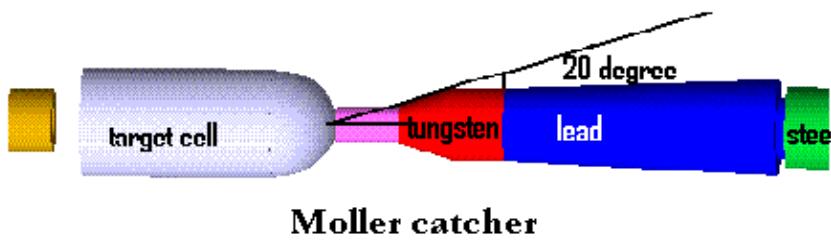
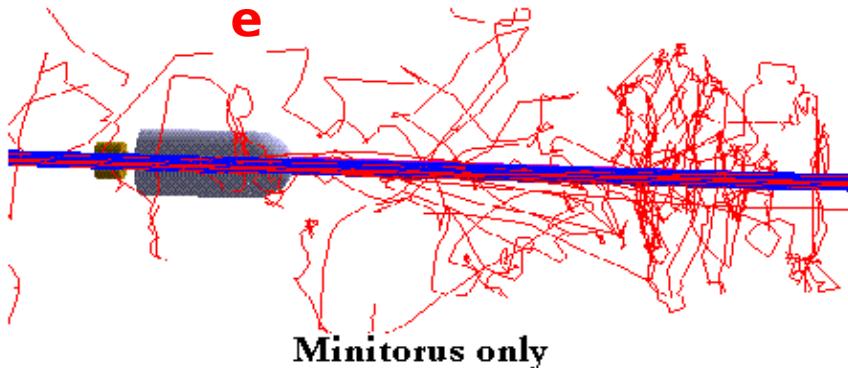


DS Coll. ID	R1 Improvement Factor	R3 Improvement Factor
6cm → 4 cm	7.0	1.7

Improvement Factor = Nominal Occupancy / Improved Occupancy  
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# Mini-torus & Møller Catcher



Minitorus and Møller catcher

- Low-energy Møller electrons produce a significant background in inner drift chamber.
- Tungsten
  - ID= 8 cm
  - Length = 8 cm cone + 10 cm cyl.
- Lead mini-torus cone
  - ID = 5.5 cm

Addition of Mini-torus field

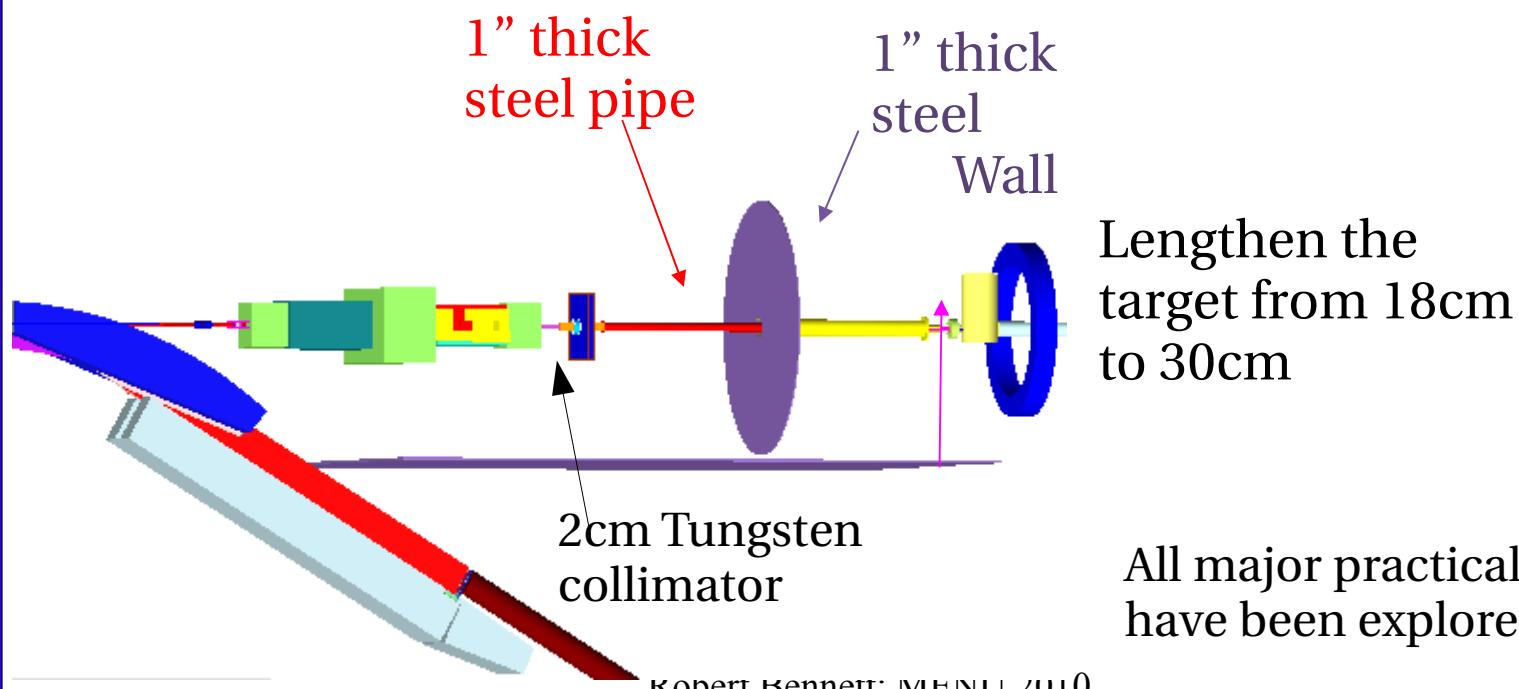
R1 Improvement Factor	R3 improvement Factor
2.20	2.00



# Improvement Factors from Beamline Shielding and Target Length

	R1 Improvement Factor	R3 Improvement Factor
Target: 18cm → 30 cm	1.2	1.6
Steel Pipe & Wall	1	1.8
Tungsten Rad-phi coll.	1	1.5

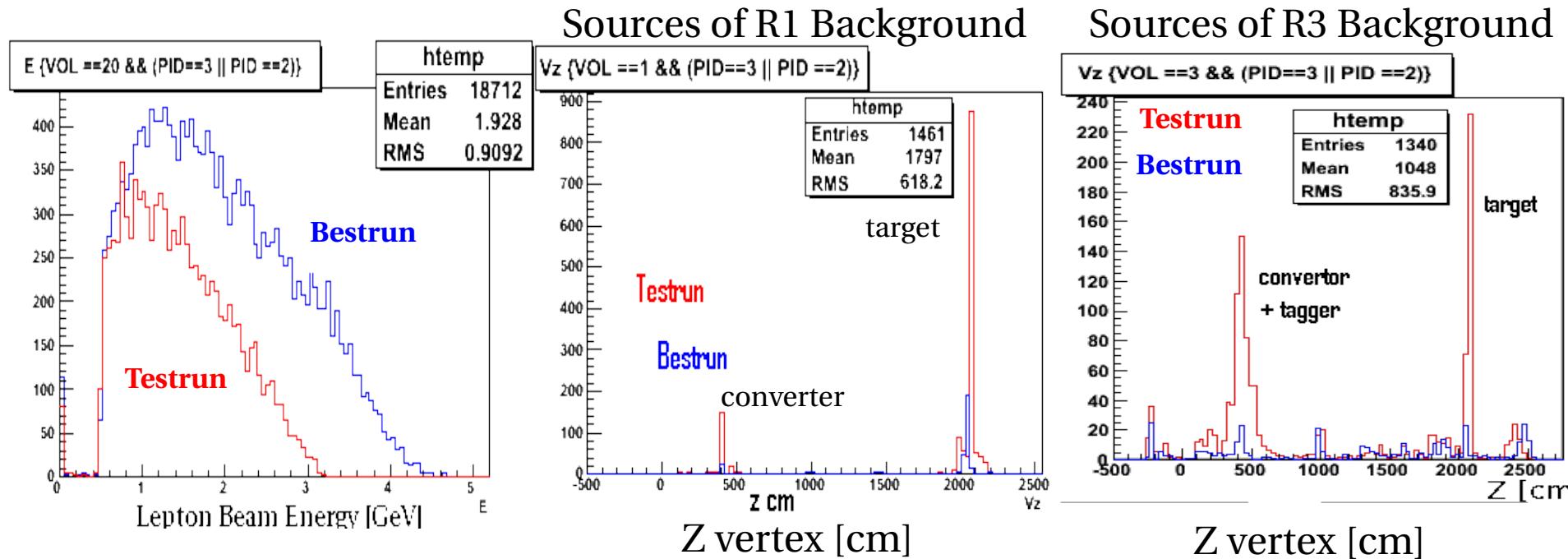
$$I.F. = \frac{Occ(18\text{ cm})}{Occ(30\text{ cm})} \times \frac{30\text{ cm}}{18\text{ cm}}$$



All major practical shielding options have been explored



# Test Run vs. Best Run



	Test Run	Best Run
E <sub>Beam</sub>	3.2 GeV	5.5 GeV
Target Length	18 cm	30 cm
DS Collimator	6 cm	4 cm
Mini-torus(5.5cm aperture) Moller catcher, lead covering on vacuum box and shielding wall		



# Maximum Luminosity

- Scale measured test run occupancies by the ratio of simulated occupancies
- Test Run: 80 nA / 0.5% Rad / 5% Conv. / 18 cm Target
- Projected Run: 100 nA / 2 % Rad / 5% Conv. / 30 cm Target

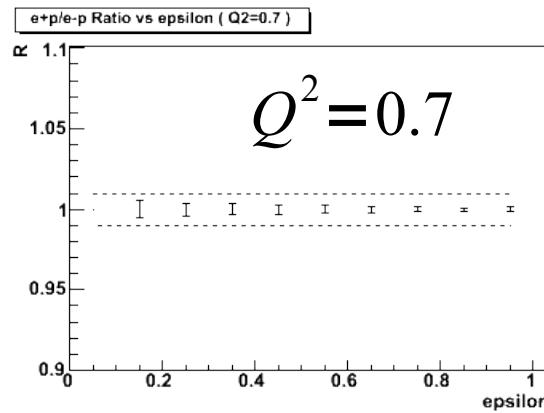
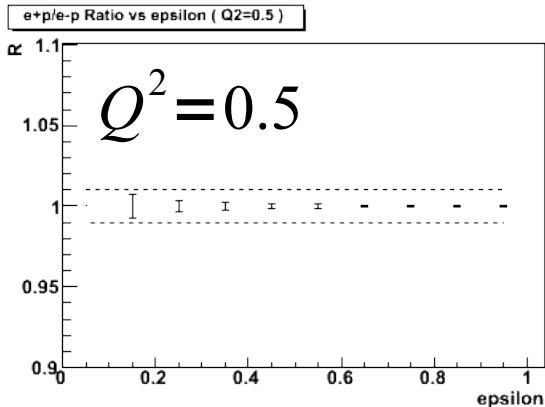
$$Best\ Run = Test\ Run\ Data \times \frac{Best\ Simulation}{Test\ Run\ Simulation}$$

Normalized to 40 nA	Test Run Data	Best Simulation	Test Run Simulation	Best Run	Projected Run (100nA)
DC R1 Occ(%)	1.3	1.7	1.9	1.2	<b>3.0</b>
DC R3 Occ (%)	0.4	3.5	2.0	0.7	<b>1.8</b>
TOF	0.67	0.80	2.6	2.1	<b>5.3</b>

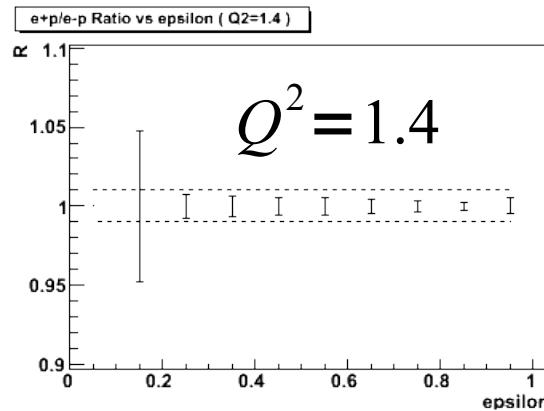
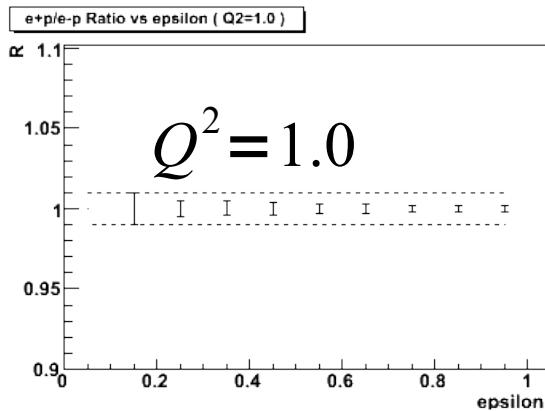
- We expect 3.0% R1 occupancy at 100 nA beam current.
- We also expect a factor of three increase in the TOF rate at the same beam current
  - → factor of 9 increase in the trigger rate
  - Test run trigger rate was 800 Hz at 80 nA → 10 kHz at 100 nA



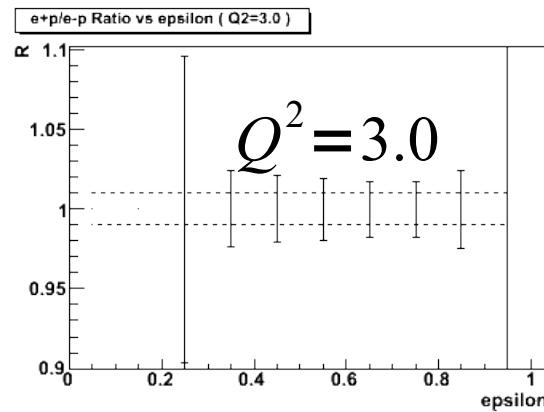
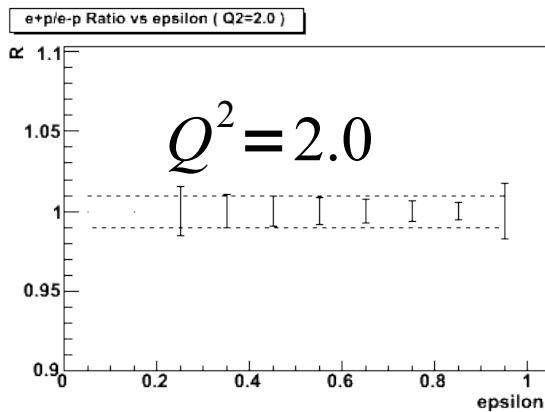
# Expected Uncertainties in $e^+/e^-$ Ratio



Primary beam 5.5 GeV/100 nA  
Radiator 2%  
Converter 5%  
Target length 30 cm  
beam days 30



R1 occupancy ~ 3.0%  
R3 occupancy ~ 1.8%  
Trigger rate 10 kHz



Convolution of GEANT lepton flux with H( $ee'p$ ) cross section

Uncertainties calculated using double ratios

Calculation reproduces test run

Dashed line show expected systematic uncertainty of  $\pm 1\%$



# Conclusions

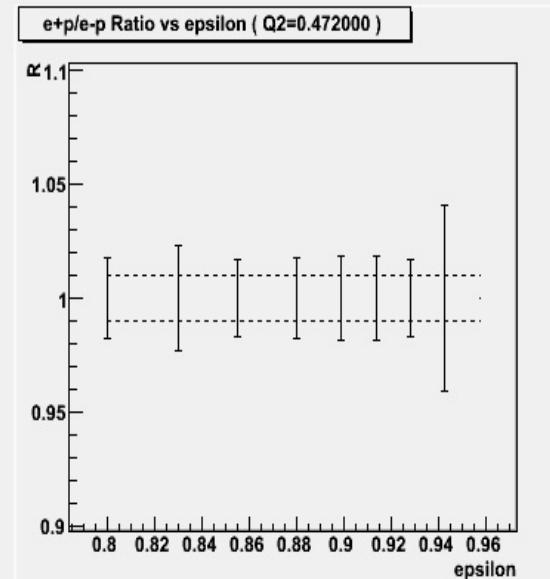
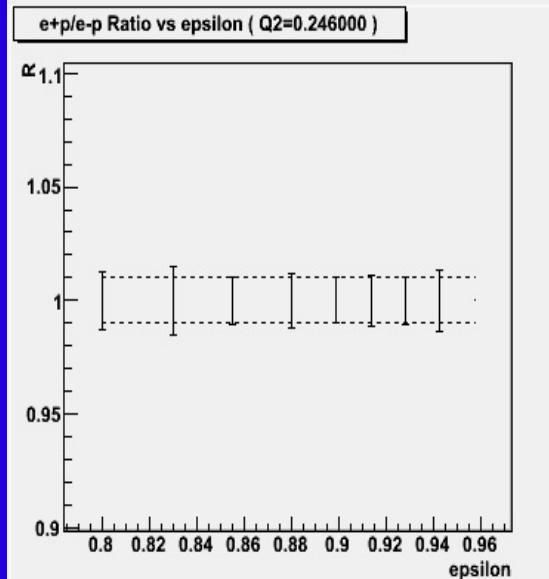
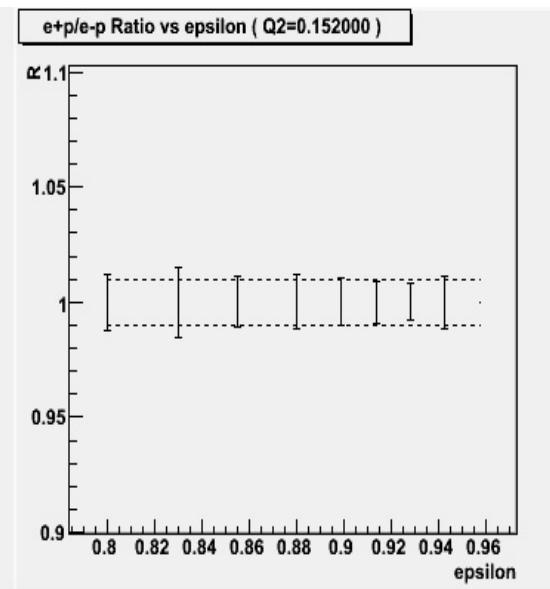
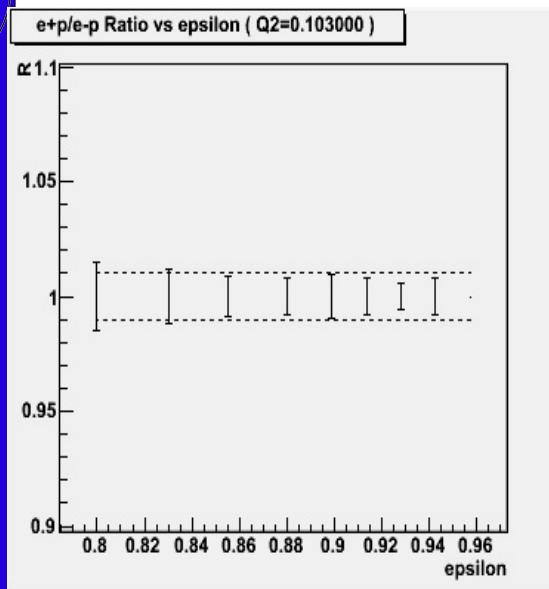
- 2006 Test Run data analysis exceeded expectations
- Intensive simulation efforts
  - Over 1000 elements simulated
  - Validated simulation with test run data
  - Showed how to increase luminosity dramatically
  - No more major improvements anticipated
- 100nA on a 2% radiator and 5% converter
- No adverse impact on CLAS detectors
- No major engineering or complicated fabrication required
- The TPE experiment can achieve statistical uncertainties equal to or smaller than the expected 1% systematic uncertainties for  $Q^2 \leq 2 \text{ GeV}^2$  with the proposed 30 days of beam time



# Backups



# Test Run Statistical Uncertainties



Test run parameters  
Input spectrum from simulation

Fit parameters for  $G_E$  and  $G_M$   
for elastic  $eP$  cross section  
Phys. Rev. C 76, 035205(2007)

We are able to reproduce  
the statistical uncertainties  
found in the test run data.



# Varying Converter and Radiator

## Study of radiator thickness

Radiator (%)	Converter (%)	No. of leptons at the target (N <sub>target</sub> )	R3_Occu / N <sub>target</sub> (10 <sup>-4</sup> )	R3_Occu / N <sub>target</sub> (10 <sup>-4</sup> )	TOF/ N <sub>target</sub> (10 <sup>-4</sup> )
0.5	5.0	1905	2.41	3.78	1.10
1.0	5.0	3520	1.70	5.43	1.25
2.0	5.0	6958	2.44	5.03	1.20
5.0	5.0	14939	2.53	6.98	1.55

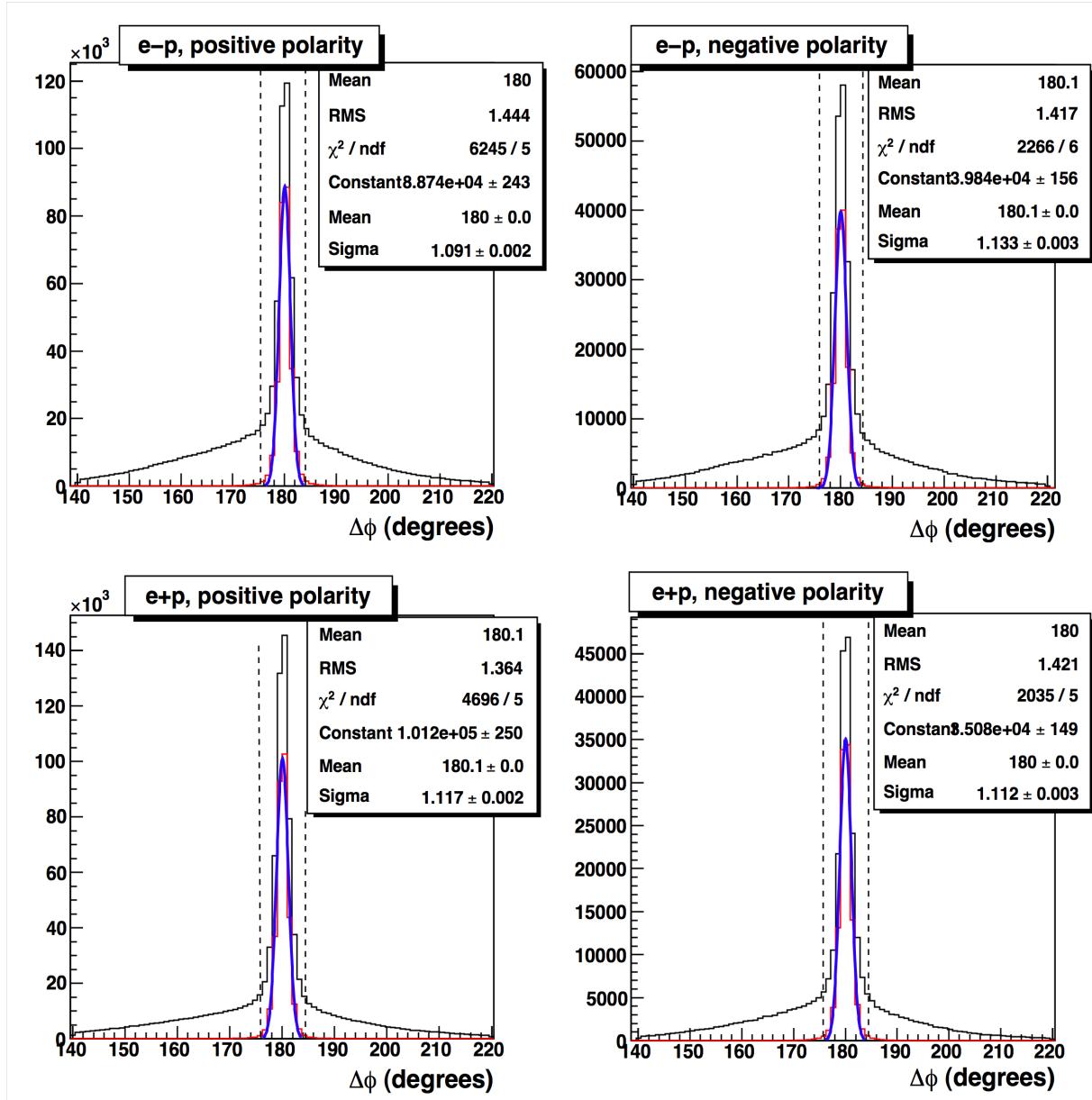
## Study Converter thickness

Radiator (%)	Converter (%)	No. of leptons at the converter (N <sub>converter</sub> )	No. of leptons at the target (N <sub>target</sub> )	R1_Occu / N <sub>target</sub> (10 <sup>-4</sup> )	R3_Occu / N <sub>target</sub> (10 <sup>-4</sup> )	TOF/ N <sub>target</sub> (10 <sup>-4</sup> )
5.0	0.0	9299	1372	3.06	51.38	10.06
5.0	0.5	13980	3546	2.85	22.02	4.26
5.0	1.0	18517	5326	2.65	15.67	3.02
5.0	2.0	27923	8474	2.43	10.38	2.09
5.0	5.0	55105	14939	2.53	6.98	1.55
5.0	10.0	96866	20895	3.07	6.55	1.42

2% Radiator and 5 % Converter is the optimal configuration



# Data Analysis: $\Delta \phi$ Cut



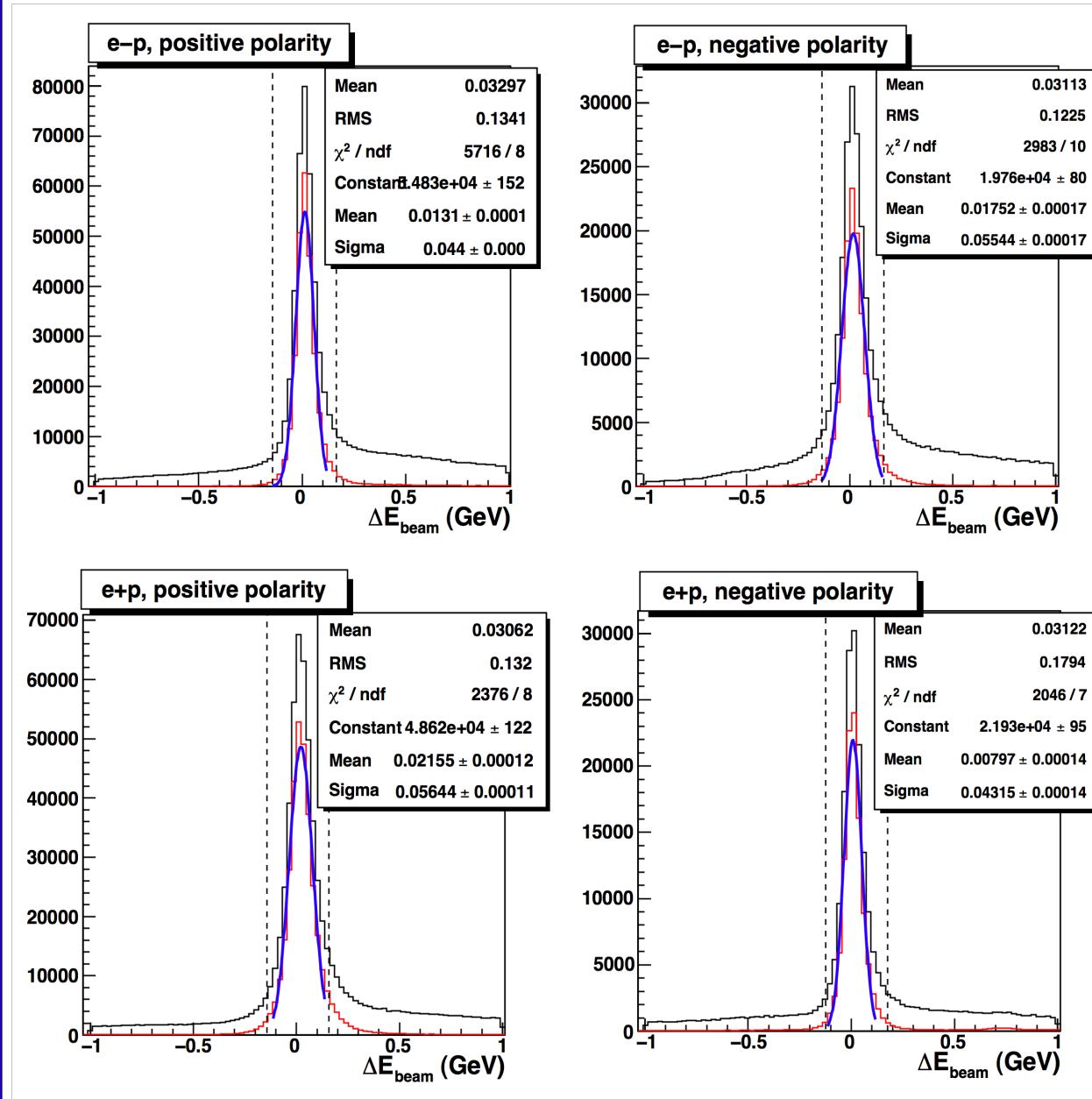
Before any cuts

After all other cuts

Gaussian fit

$3\sigma$  (used  $4\sigma$  cut in analysis and  $3\sigma$  for sys. error estimation)

# Data Analysis: Beam Energy Diff.



$$E1 = m_p \frac{q_e}{2} \cot q_p - 1$$

$$E2 = p_e \cos q_e + p_p \cos q_p$$

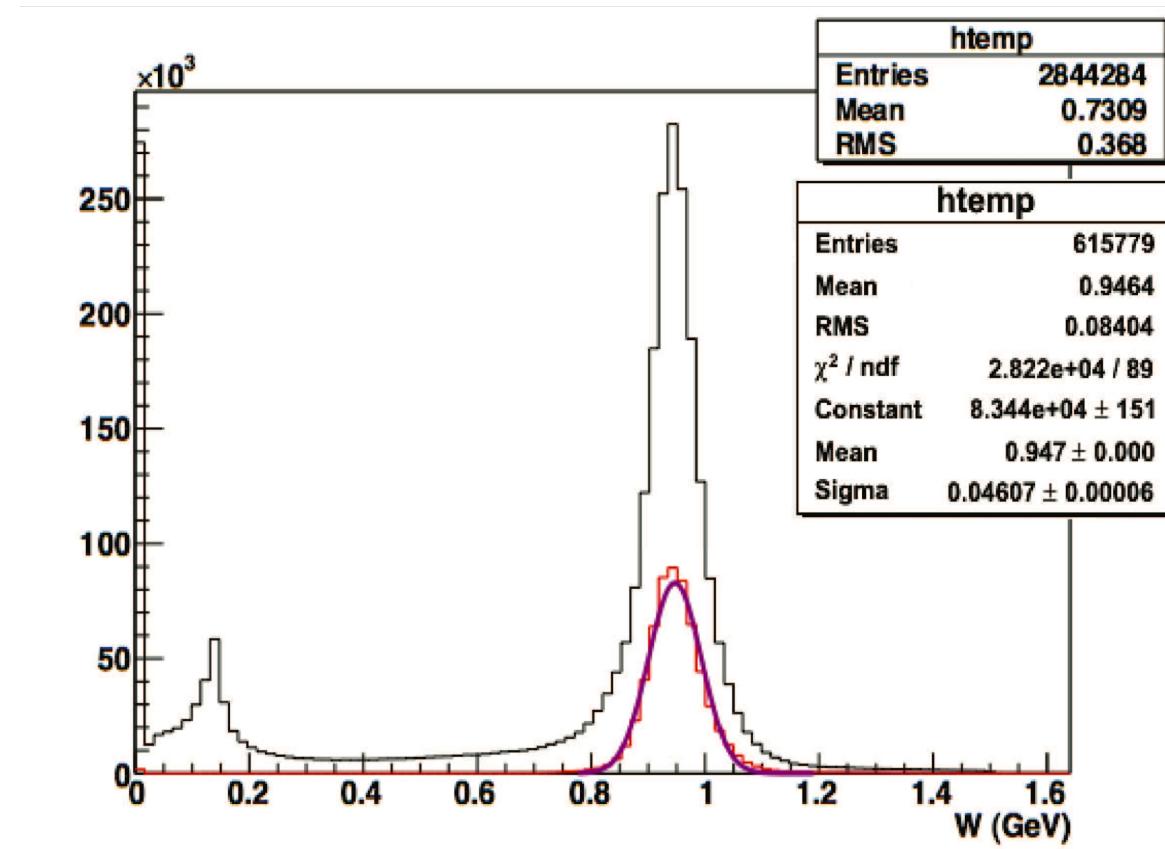
Before any cuts

After all other cuts

Gaussian fit

$3\sigma$  (used  $4\sigma$  cut in analysis and  $3\sigma$  for sys. error estimation)

# Data Analysis: $W$ distribution



Before any cuts  
After all other cuts  
Gaussian fit

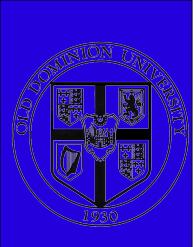
Extremely clean  
distribution!

Calculated from deduced  
 $E_{\text{beam}}$  and measured  $E'$ .

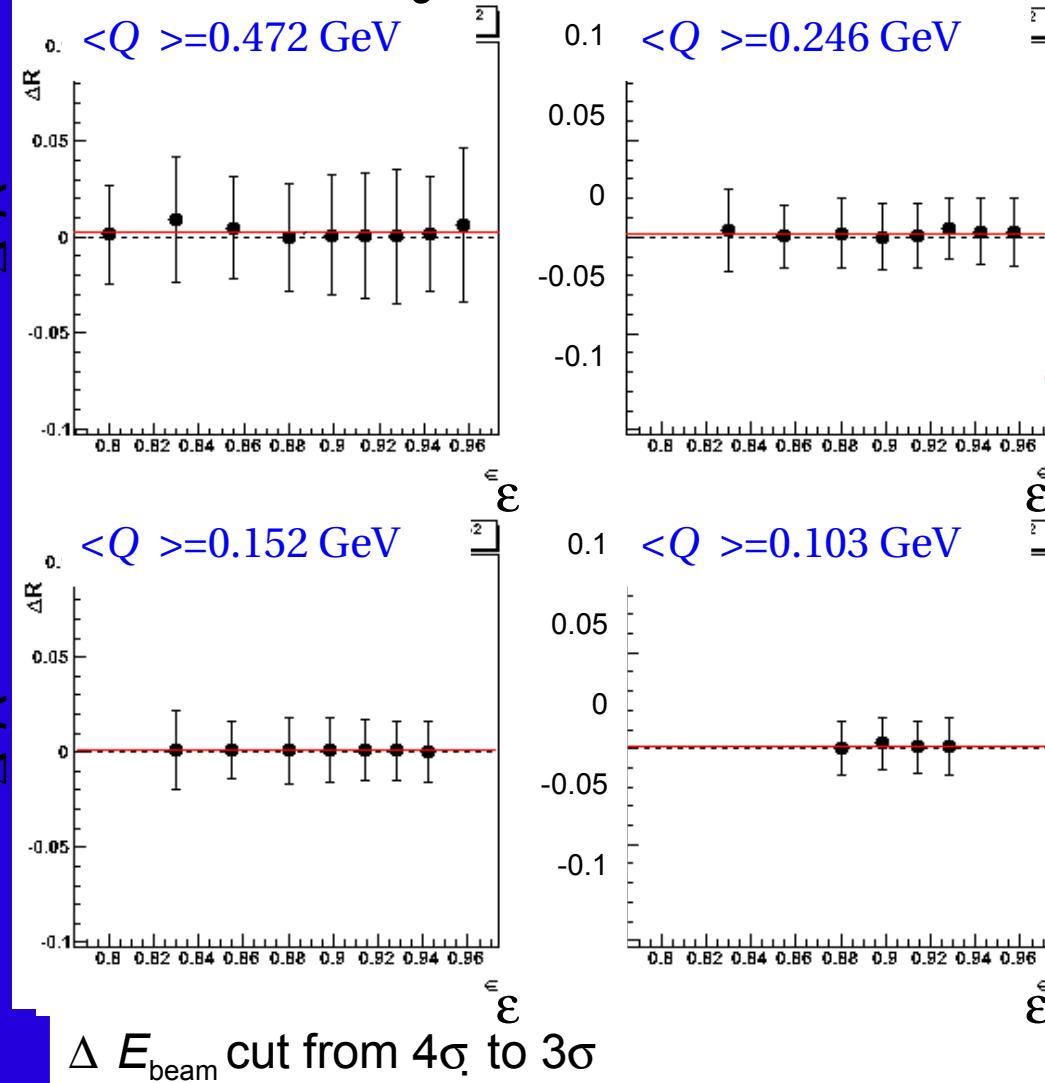


# Double Ratio Method

Use results from two different torus polarities in a double ratio to cancel out any remaining acceptance-related effects.



# Systematic Uncertainties



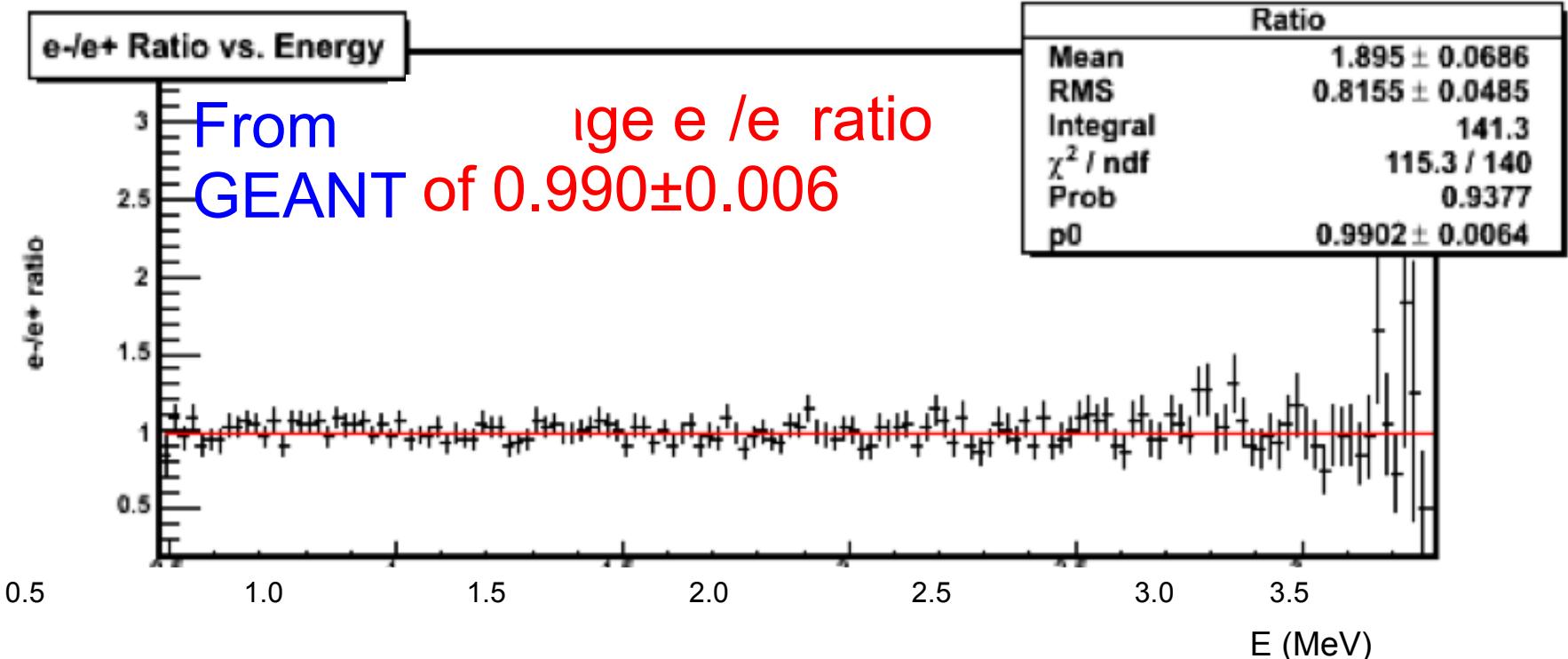
Compared ratios from varied technique (cuts or method) to nominal. Weighted average deviation from zero used as estimated systematic uncertainty related to given cut/method.

$$\Delta R = R_{\text{nom}} - R_{\text{var}}$$

Estimate of systematic uncertainty tied to statistical uncertainty.



# Relative $e^+ / e^-$ Luminosity



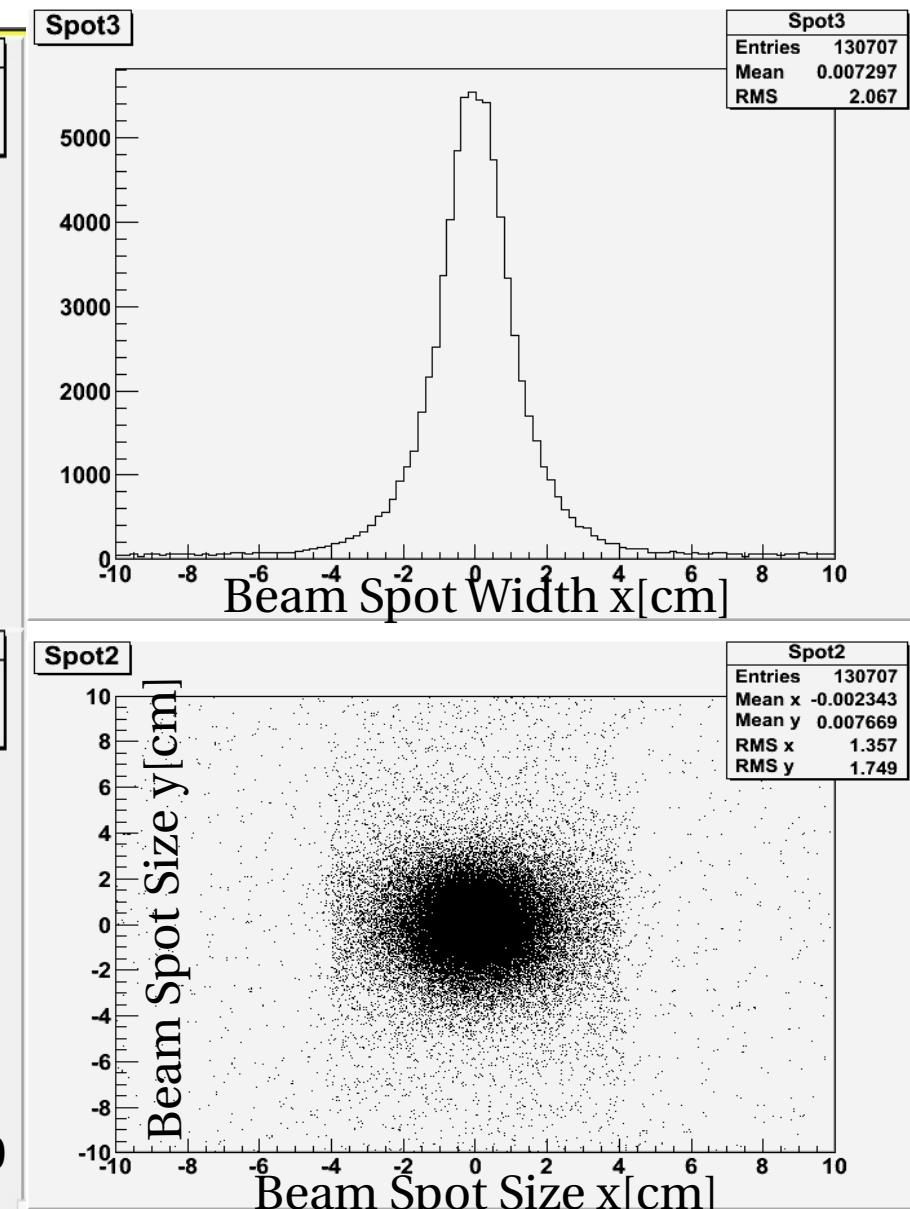
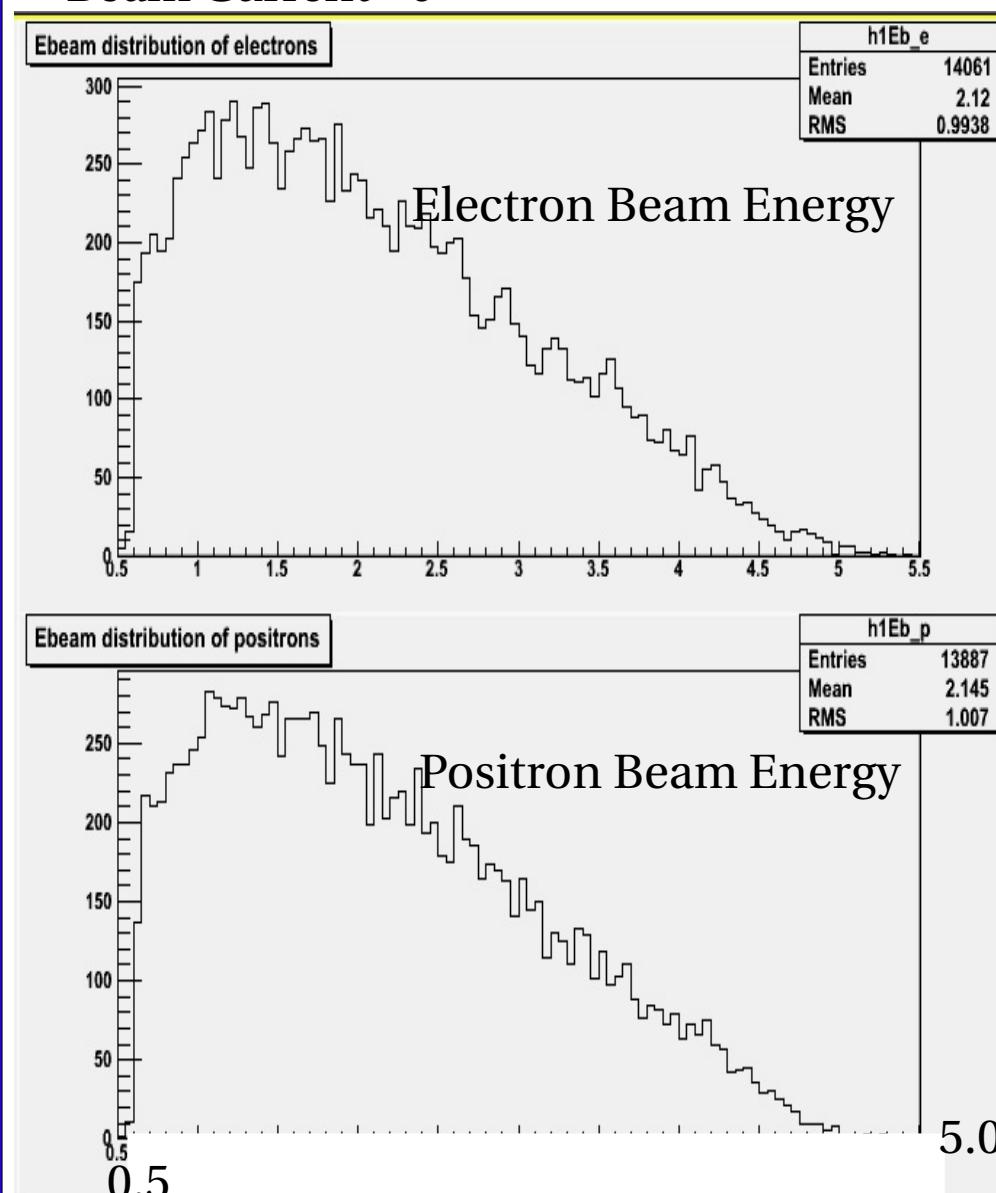
Ratio nearly consistent with unity.

Full experiment will measure this.



# Lepton Beam at the Target

Beam Current =0



Beam Energy at the Target [GeV]

Beam spot ~2cm x 2cm FWHM at target