Beyond the Born Approximation

Measuring the Two-Photon Exchange Effect at CLAS

Robert Paul Bennett

Old Dominion University
for The CLAS Collaboration

E07-005
PANIC 2011: Cambridge, MA

June 24-29, 2011

Jefferson Lab

1 Motivation

2 Form Factors

3 TPE

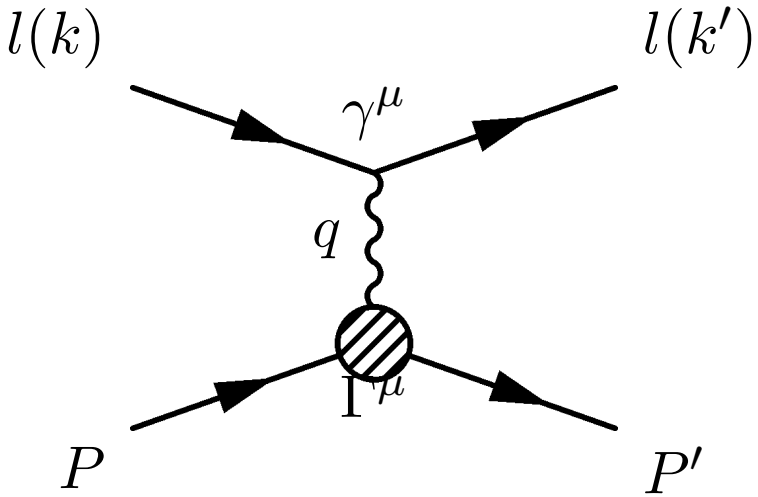
4 Experiment

5 Analysis overview

6 Projections

7 Summary

Elastic Scattering: Born Approximation



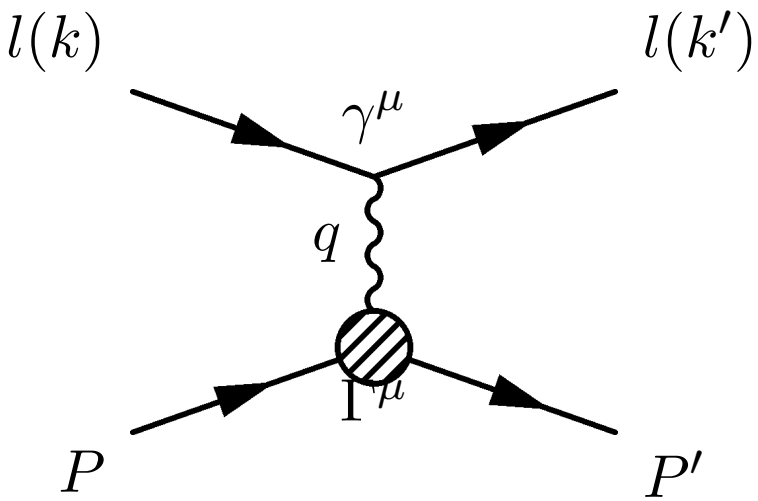
e-p Kinematics

- k (k'): incoming (outgoing) lepton 4-vector
- P (P'): incoming (outgoing) proton 4-vector
- Single virtual photon: $q^2 = (k - k')^2 = -Q^2$, $Q^2 > 0$
- Proton remains intact

Nucleon Current Operator $\Gamma^\mu(q)$

- $\Gamma^\mu(q) = \gamma^\mu F_1(q^2) + \frac{1}{2M_N}\sigma^{\mu\nu}q_\nu F_2(q^2)$
- $F_1(q^2)$ Non-spin flip Dirac Form Factor
- $F_2(q^2)$ Spin flip Pauli Form Factor

Elastic Scattering: Born Approximation



$$\frac{d\sigma}{d\Omega} = \frac{d\sigma_{Mott}}{d_\Omega}\left[G^2_{E_p}(Q^2) + \frac{\tau}{\epsilon}G^2_{M_p}(Q^2)\right]\left(\frac{1}{1+\tau}\right)$$

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

ep Kinematics

- k (k'): incoming (outgoing) lepton 4-vector
- P (P'): incoming (outgoing) proton 4-vector
- Single virtual photon: $q^2 = (k-k')^2 = -Q^2$, $Q^2 > 0$
- Proton remains intact

F_1 and F_2 are NOT unique

- Electric form factor: $G_{E_P}(Q^2) = F_1^P(Q^2) - \tau F_2^p(Q^2)$
- Magnetic form factor: $G_{M_P}(Q^2) = F_1^P(Q^2) + F_2^p(Q^2)$
- $\tau = \frac{Q^2}{4M_P^2}$; $G_{E_P}\mu_P \approx G_{M_P} \approx G_D$

How to extract $G_{E_p}^2(Q^2)$: Rosenbluth Separation Method

- Step 1: Fix Q^2

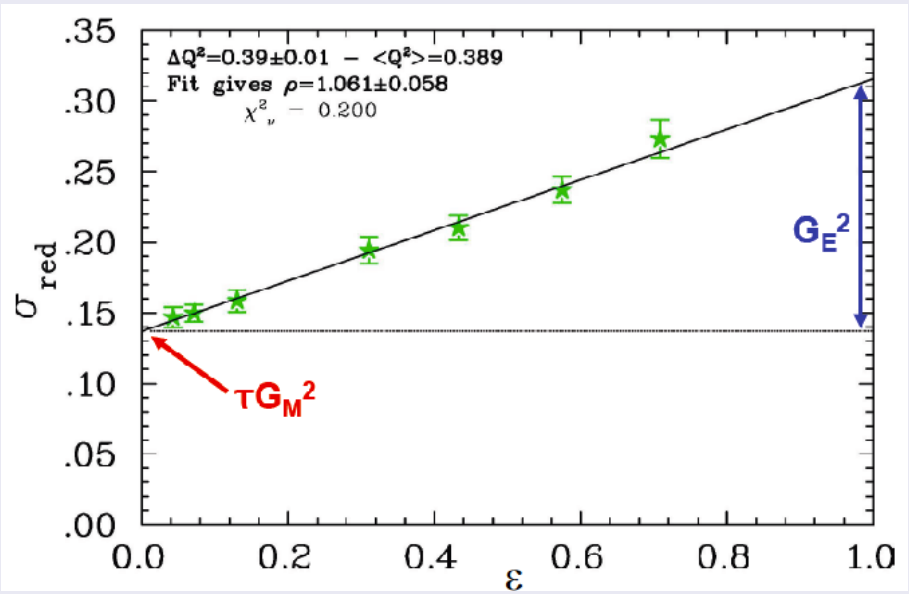
Step 2: Measure $\frac{d\sigma}{d\Omega}$ at large E_e and small θ_e ($\epsilon \to 1$)

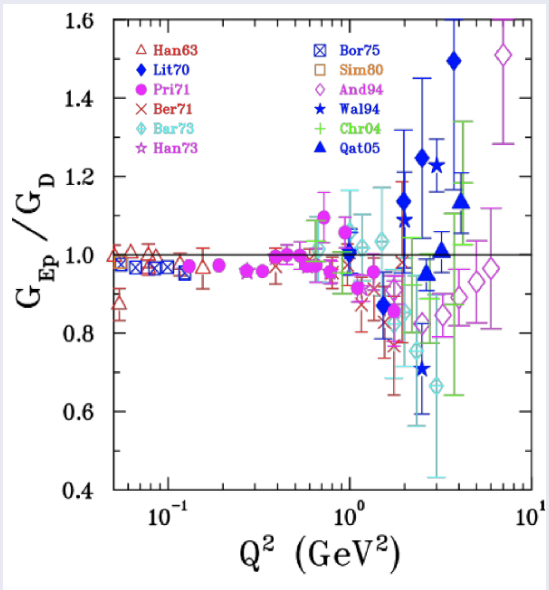
$$\frac{d\sigma}{d\Omega} \propto G_{E_p}^2(Q^2) + \tau G_{M_p}^2(Q^2)$$

Step 3: Measure at small E_e and large θ_e ($\epsilon \to 0$)

$$\frac{d\sigma}{d\Omega} \propto G_{M_p}^2(Q^2)$$

Step 4: Subtract





A Better Way: Polarization Transfer

Formalism

$$I_0 P_t = -2\sqrt{\tau(1+\tau)} G_{E_p} G_{M_p} \tan\frac{\theta_e}{2}$$

$$I_0 P_l = \frac{1}{M}\sqrt{\tau(1+\tau)} G_{M_p}^2 \tan^2\frac{\theta_e}{2}$$

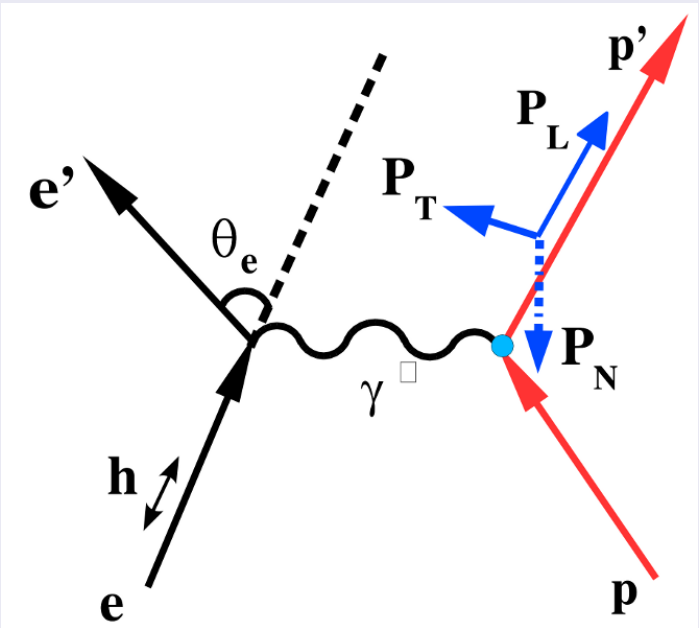
$$I_0 = G_{E_p}^2 + \frac{\tau}{\epsilon} G_{M_p}^2$$

$$\frac{G_{E_p}}{G_{M_p}} = -\frac{P_t}{P_l}\left(\frac{E_e + E_e'}{2M}\right)\tan\frac{\theta_e}{2}$$

A. I. Akhiezer and M. P. Relanko, Sov. J. Part. Nucl. 3, (1974) 277 and Arnold, Carlson and Gross, Phys. Rev. C23 (1981) 363

Method

- Scatter polarized electrons off of an un polarized proton target
- Electron transfers spin to the proton
- Detect the polarization of the outgoing proton

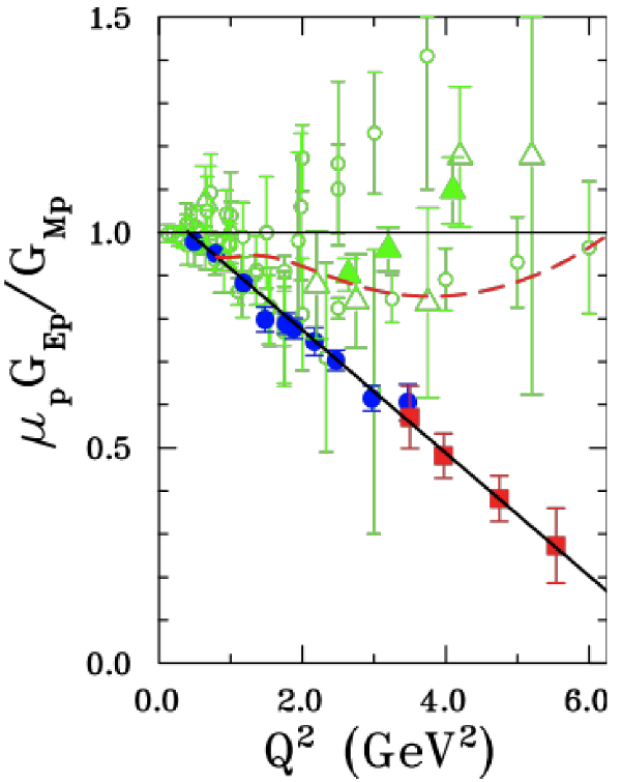


Why this is hard:

- Need polarized electrons (easy at JLab)
- Need to detect the proton, and then let it rescatter and remeasure it to determine the polarization (easy at JLab)
- Need to understand spin precession in the spectrometer
- Need **lots** of events (easy at JLab)

Why this is easy:

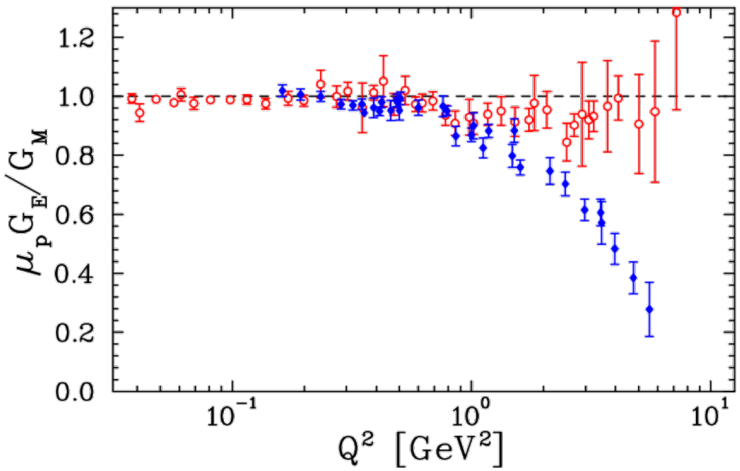
- Almost all errors cancel in the ratio of polarizations



Hall A & C

M.K. Jones et al., Phys. Rev. Lett. 84, 1398 (2000)
O. Gayou et al., Phys. Rev. C64, 038202 (2001)
O. Gayou et al., Phys. Rev. Lett. 88, 092301 (2002)
V. Punjabi et al., Phys. Rev. C71, 055202 (2005)
M.K. Jones et al., Phys. Rev. C74, 035201 (2006)
G. MacLachian et. al., Nucl. Phys. A764, 261 (2006)

The Proton Formfactor Puzzle



- Rosenbluth Separation: (SLAC, MIT BATES, JLab et al.)

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

$$\varepsilon = \left[1 + 2(1+\tau)\tan^2\theta_e/2\right]^{-1} \quad \tau = \frac{Q^2}{4M^2}$$

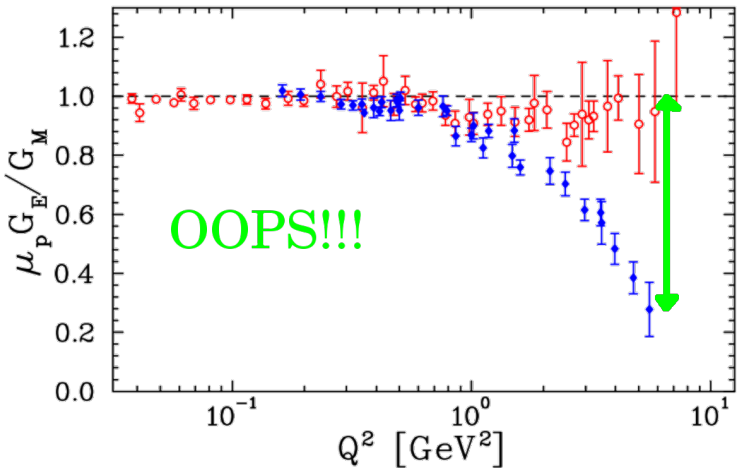
- Separate G_E and G_M contributions at a particular Q^2 using different beam energies and scattered electron angles
- G_M measurement dominates at high Q^2, G_E is suppressed

- Polarization Transfer: (Hall A & C)

$$\frac{G_E}{G_M} = -\frac{P_t}{P_l}\frac{(E_e + E_{e'})}{2M}\tan\frac{\theta_e}{2}$$

- Longitudinal polarized electrons incident on proton target
- Measure transverse and longitudinal polarization of recoiled proton

The Proton Formfactor Puzzle



- Rosenbluth Separation: (SLAC, MIT BATES, JLab et al.)

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

$$\varepsilon = \left[1 + 2(1+\tau)\tan^2\theta_e/2\right]^{-1} \quad \tau = \frac{Q^2}{4M^2}$$

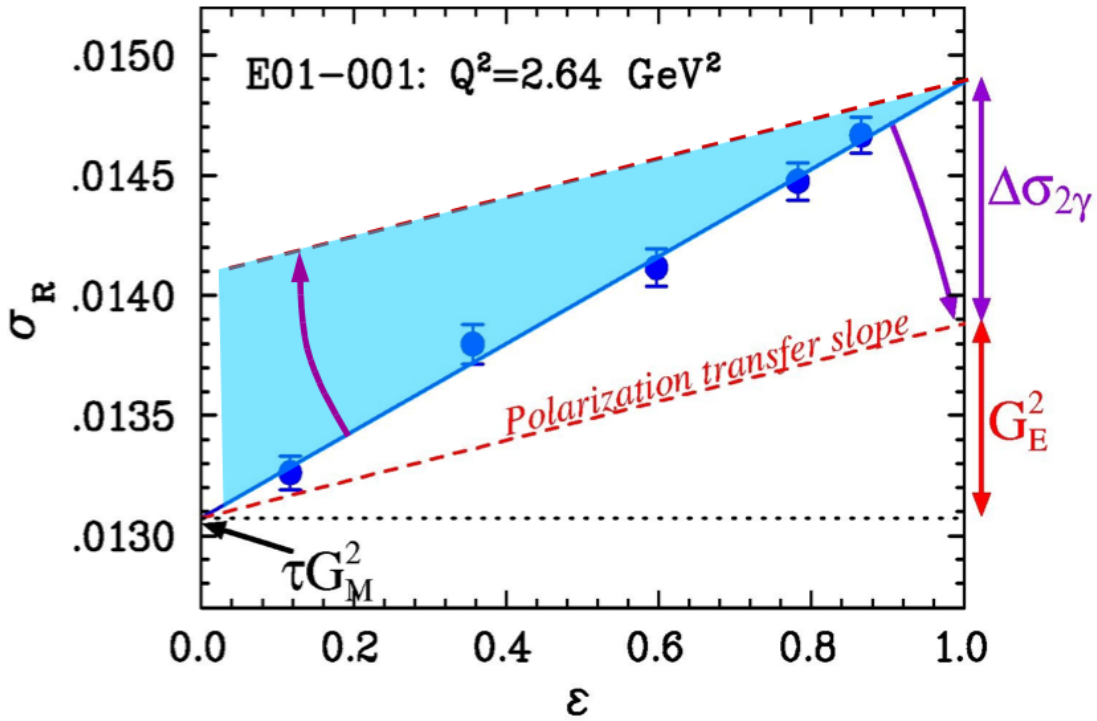
- Separate G_E and G_M contributions at a particular Q^2 using different beam energies and scattered electron angles
- G_M measurement dominates at high Q^2, G_E is suppressed

- Polarization Transfer: (Hall A & C)

$$\frac{G_E}{G_M} = -\frac{P_t}{P_l}\frac{(E_e + E_{e'})}{2M}\tan\frac{\theta_e}{2}$$

- Longitudinal polarized electrons incident on proton target
- Measure transverse and longitudinal polarization of recoiled proton

Beyond the Born Approximation



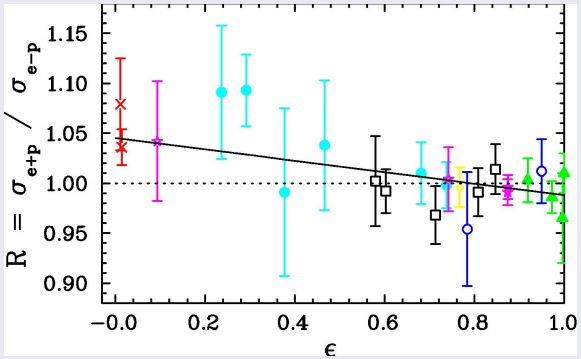
- Use G_M from Rosenbluth Separation and G_E from Polarization Transfer
- To account for the difference we need a ε dependent correction to the cross section on the order of a few percent: The TPE contribution expected to be $\sim 5 - 8\%$
- We've known about this for a long time – Just ask Sydney Drell **Phys. Rev. 113, 741744 (1959)** or Leon Lederman and Mike Tannenbaum **Advances in Particle Physics Vol 1 1967 pp 1–70**

Limited Previous Data

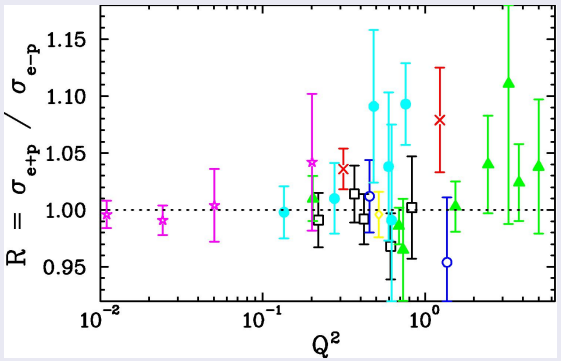
TPE was a known issue

- All of the data indicated that it was small so it was ignored.
- Reanalysis of the existing world data (2004) shows a slight ε dependence but not well constrained.
- Effect increases at low ε
- Negligible Q^2 dependence of the ratio is seen for these data.
- Large error bars limit our knowledge of the correction, especially at low ε and high Q^2.
- A high precision measurement is required as TPE is only a few percent of the cross section

Mixed Q^2



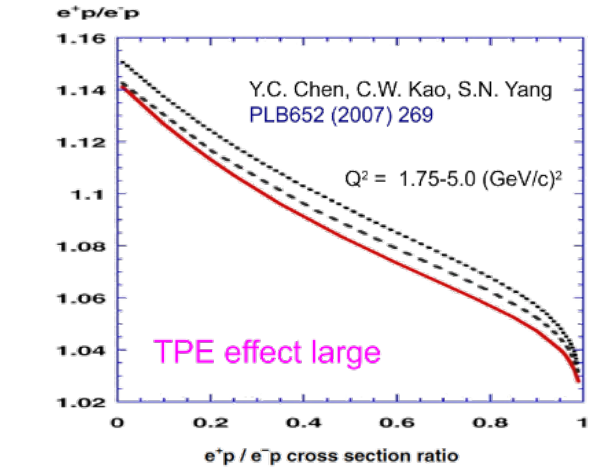
Mixed ε

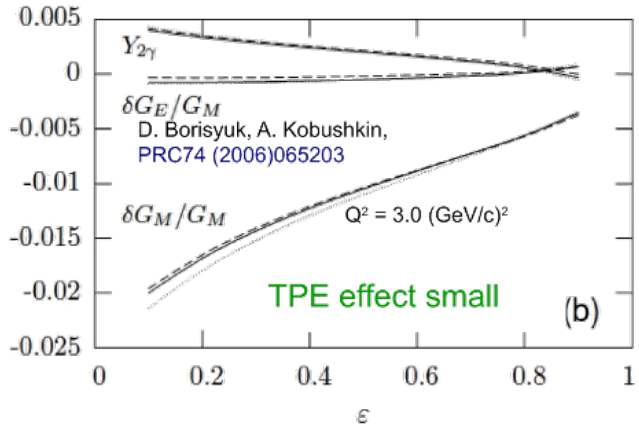


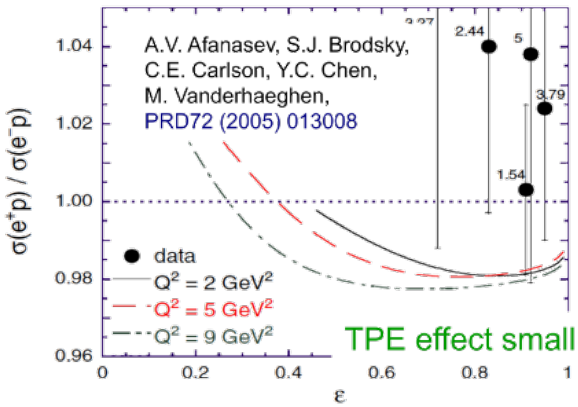
J. Arrington, PRC69, 032201 (2004)

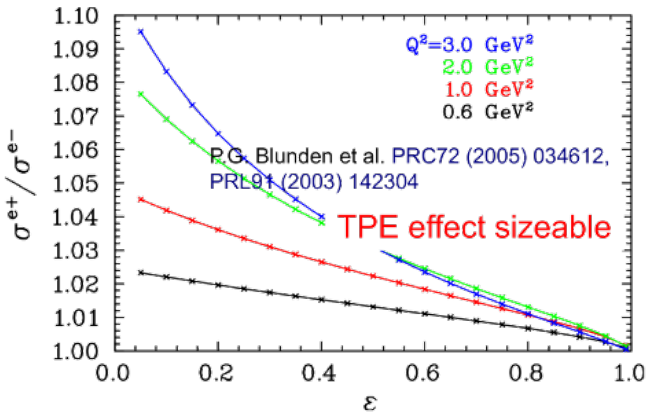
Predictions

There are several model dependent predictions of the TPE effect on the market



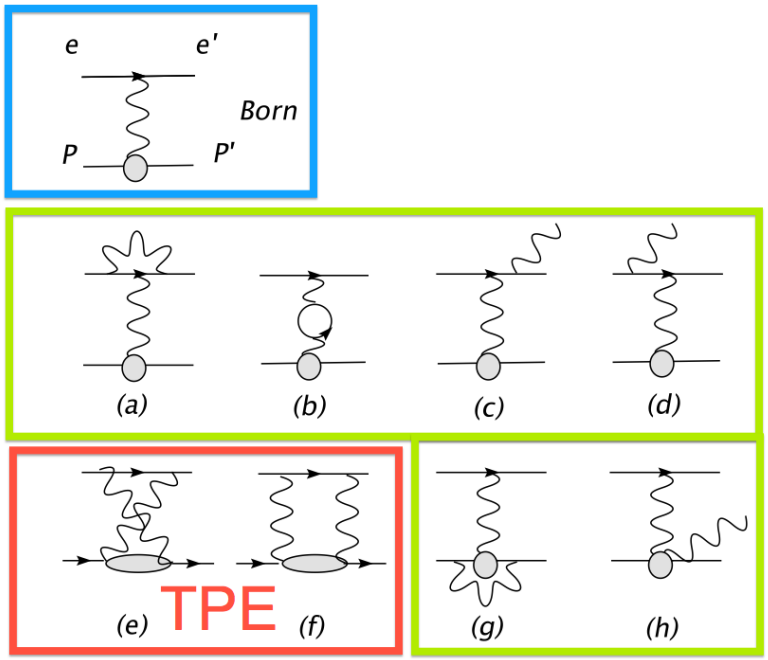






Positrons to the rescue!

At leading order, the TPE term of the elastic scattering cross section changes sign as the charge of the incident beam



The elastic $e^{\pm}p \to e^{\pm}p$ scattering contribution:

$$\sigma(e^{\pm}) \propto |A_{born} + \cdots \pm A_{2\gamma}|^2$$
$$\sigma(e^{\pm}) \propto |A_{born}|^2 \pm 2A_{born}\mathrm{Re}(A_{2\gamma})$$

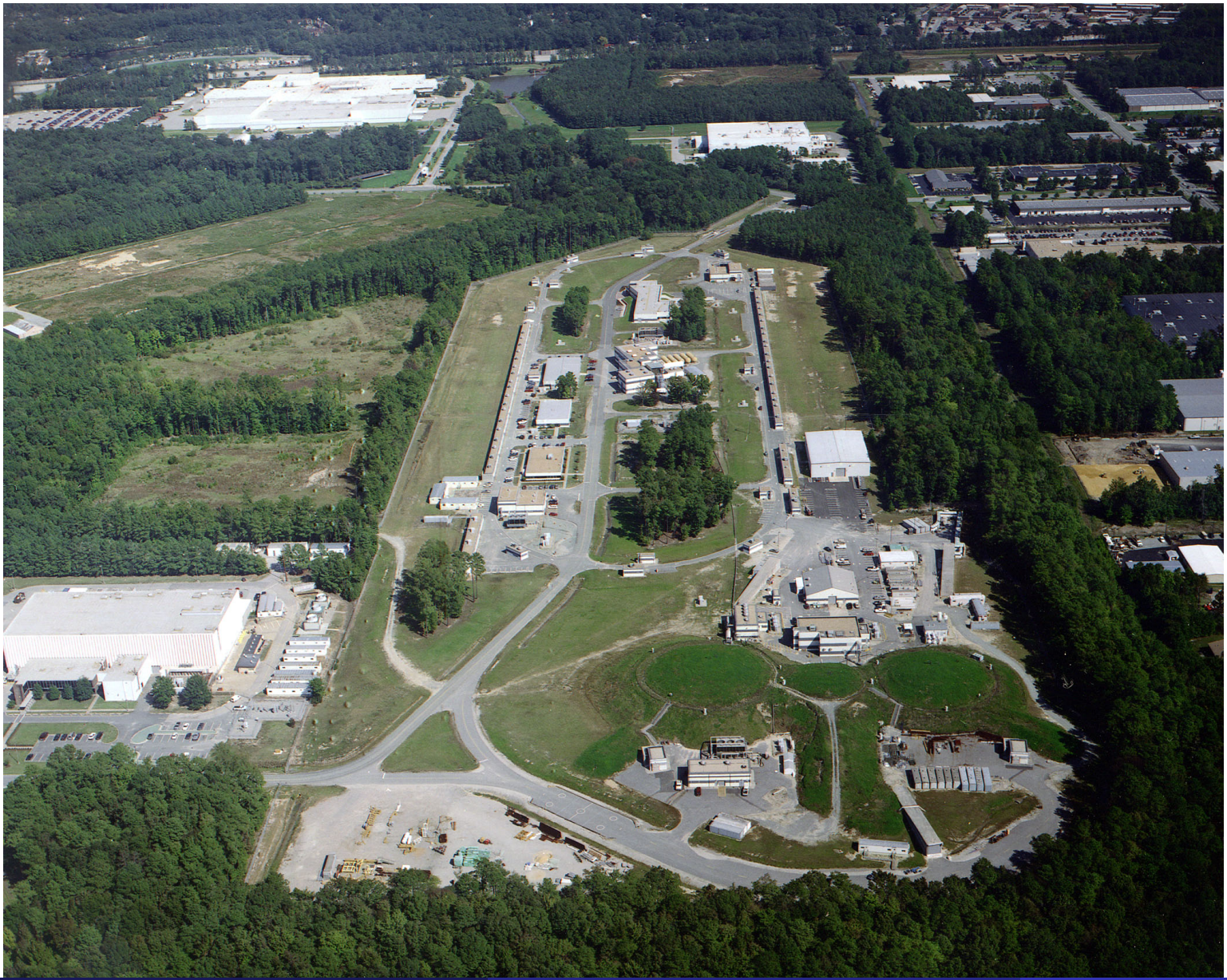
$$e^- \leftrightarrow e^+ \Rightarrow \alpha \leftrightarrow -\alpha$$

The ratio of the cross sections isolates the TPE correction term

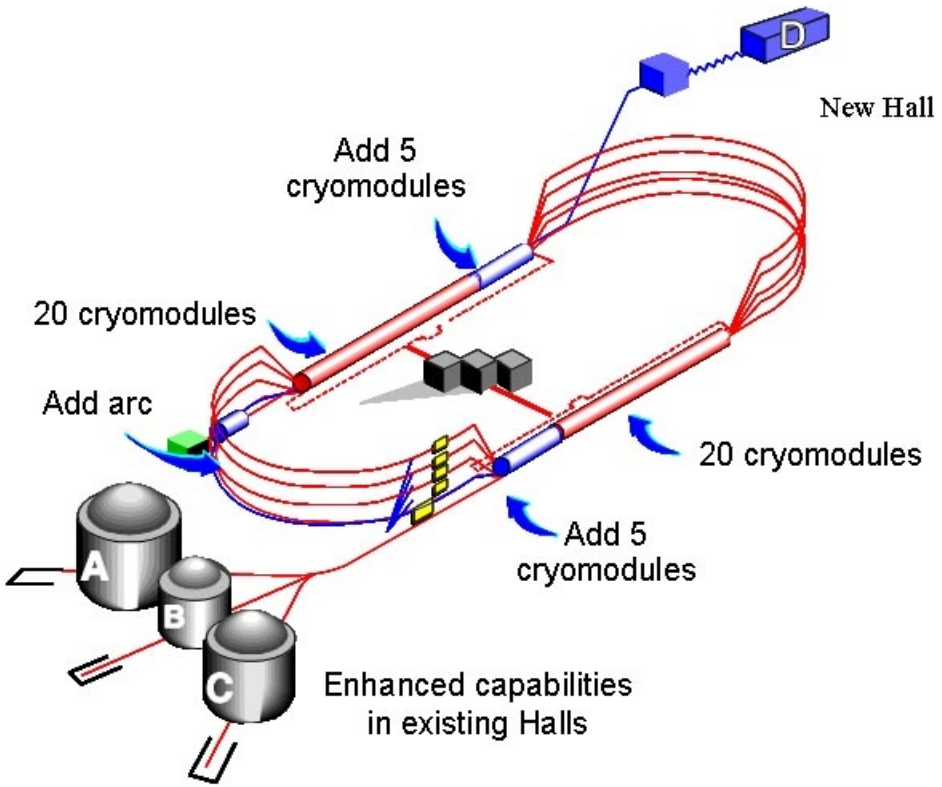
$$R = \frac{\sigma(e^+)}{\sigma(e^-)} = 1 - 2\delta_{2\gamma}$$
$$\delta_{2\gamma} = \frac{2\mathrm{Re}(A_{2\gamma})}{A_{born}}$$

- We can calculate this very well (QED)
- Theoretical calculation of the diagram is hard : Need to integrate over all baryon states
- The e^-P/e^+P ratio provides a model independent measurement of the TPE contribution

Jefferson Laboratory



Continuous Electron Beam Accelerator Facility (CEBAF)



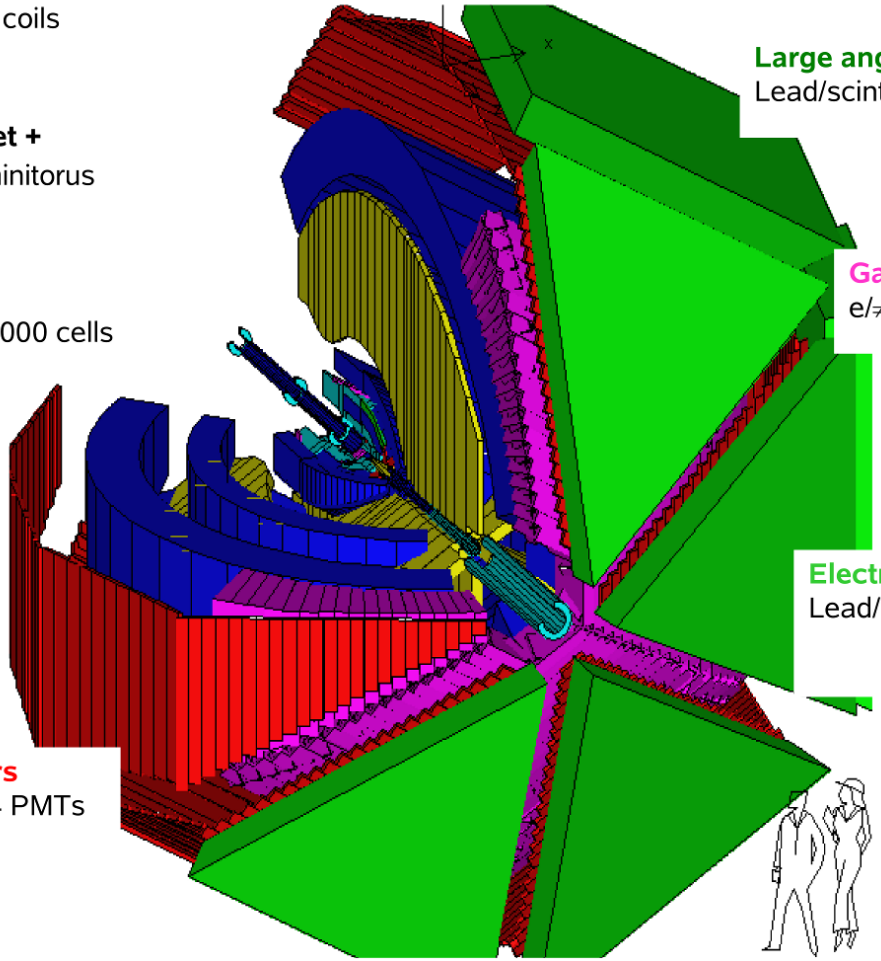
- 5 pass super-conducting accelerator
- Polarized electrons up to 6 GeV
- Maximum Current $\sim 100\ \mu$ A
- Upgrading to 12 GeV
- 3 experimental halls running (A, B, & C) (D is coming soon)

CEBAF Large Acceptance Spectrometer

Torus magnet
6 superconducting coils

Liquid D_2 (H_2)target +
γ start counter; e minitorus

Drift chambers
argon/CO_2 gas, 35,000 cells



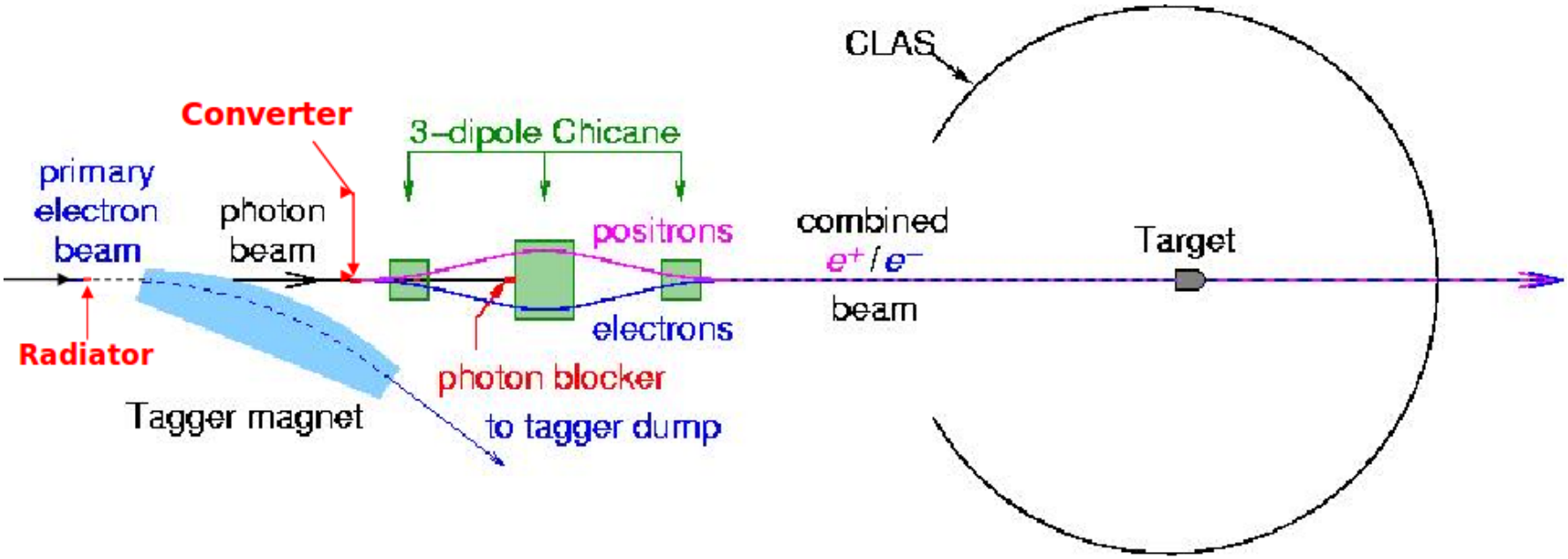
Large angle calorimeters
Lead/scintillator, 512 PMTs

Gas Cherenkov counters
e/$\neq$ separation, 216 PMTs

Electromagnetic calorimeters
Lead/scintillator, 1296 PMTs

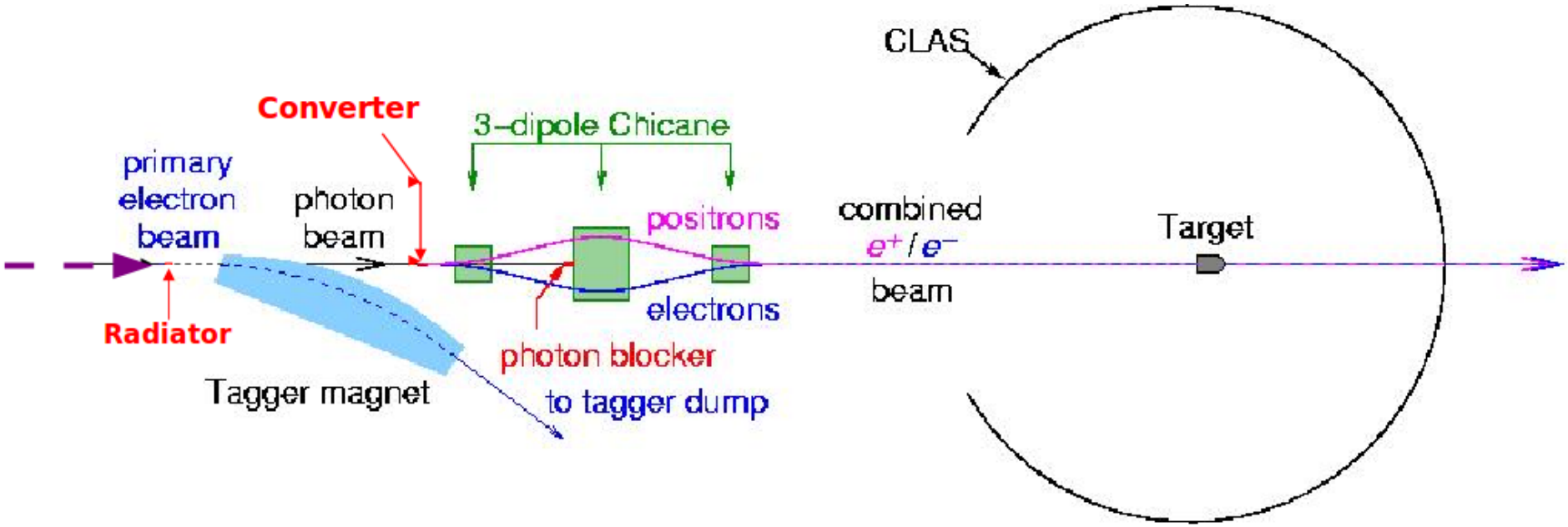
Time-of-flight counters
plastic scintillators, 684 PMTs

Simultaneous, Idential e^+/e^- Beams



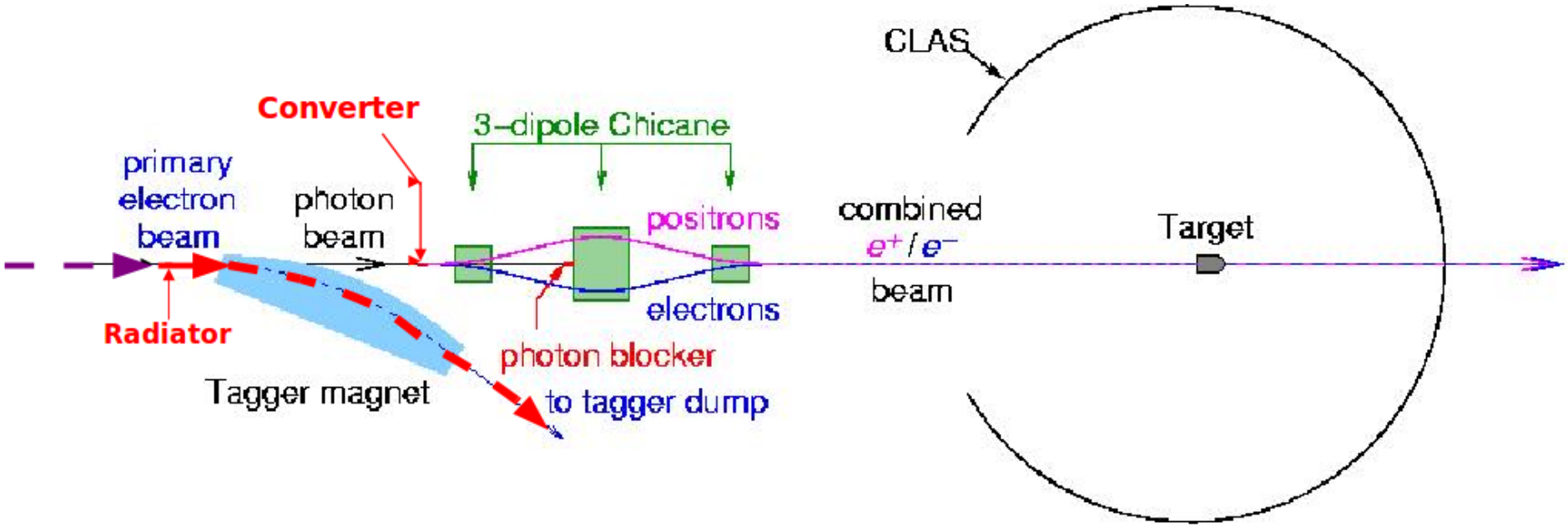
- Primary electron beam: 5.5 GeV and 100 nA
- Radiator: 1% of primary electrons radiate high energy photons
- Tagger magnet: Transport electrons tagger dump
- Converter: 10% of photons are converted to electron/positron pairs
- Chicane: separate the lepton beams
- Remaining photons are stopped at the photon blocker
- e^+ ande^- beams are then recombined and continue to the target
- Target: liquid hydrogen: length = 18cm (30 cm) & diameter = 6cm (6 cm)
- Detector: CLAS (DC, TOF)

Simultaneous, Idential e^+/e^- Beams



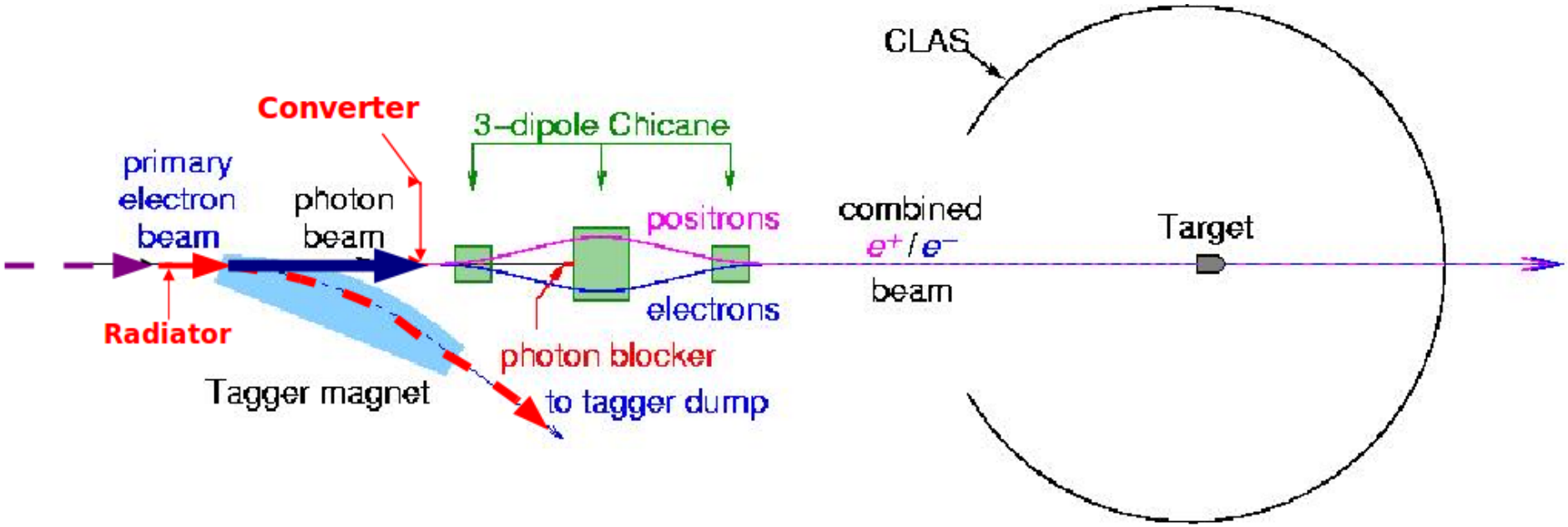
- Primary electron beam: 5.5 GeV and 100 nA
- Radiator: 1% of primary electrons radiate high energy photons
- Tagger magnet: Transport electrons tagger dump
- Converter: 10% of photons are converted to electron/positron pairs
- Chicane: separate the lepton beams
- Remaining photons are stopped at the photon blocker
- e^+ ande^- beams are then recombined and continue to the target
- Target: liquid hydrogen: length = 18cm (30 cm) & diameter = 6cm (6 cm)
- Detector: CLAS (DC, TOF)

Simultaneous, Idential e^+/e^- Beams



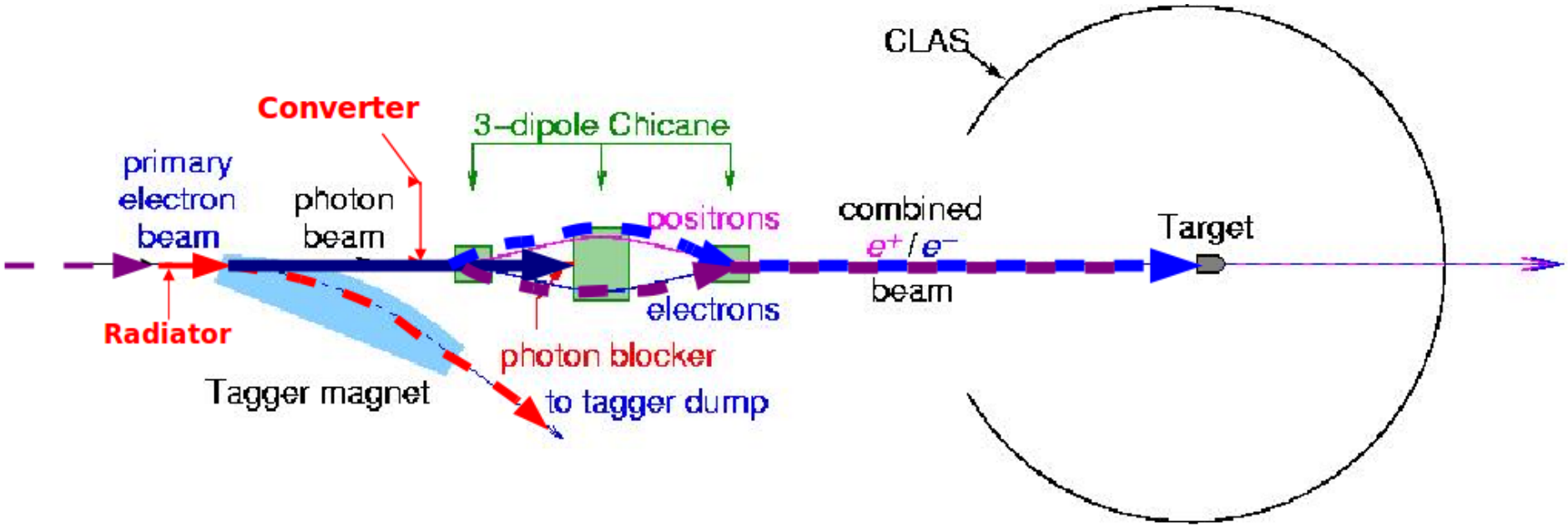
- Primary electron beam: 5.5 GeV and 100 nA
- Radiator: 1% of primary electrons radiate high energy photons
- Tagger magnet: Transport electrons tagger dump
- Converter: 10% of photons are converted to electron/positron pairs
- Chicane: separate the lepton beams
- Remaining photons are stopped at the photon blocker
- e^+ ande^- beams are then recombined and continue to the target
- Target: liquid hydrogen: length = 18cm (30 cm) & diameter = 6cm (6 cm)
- Detector: CLAS (DC, TOF)

Simultaneous, Idential e^+/e^- Beams



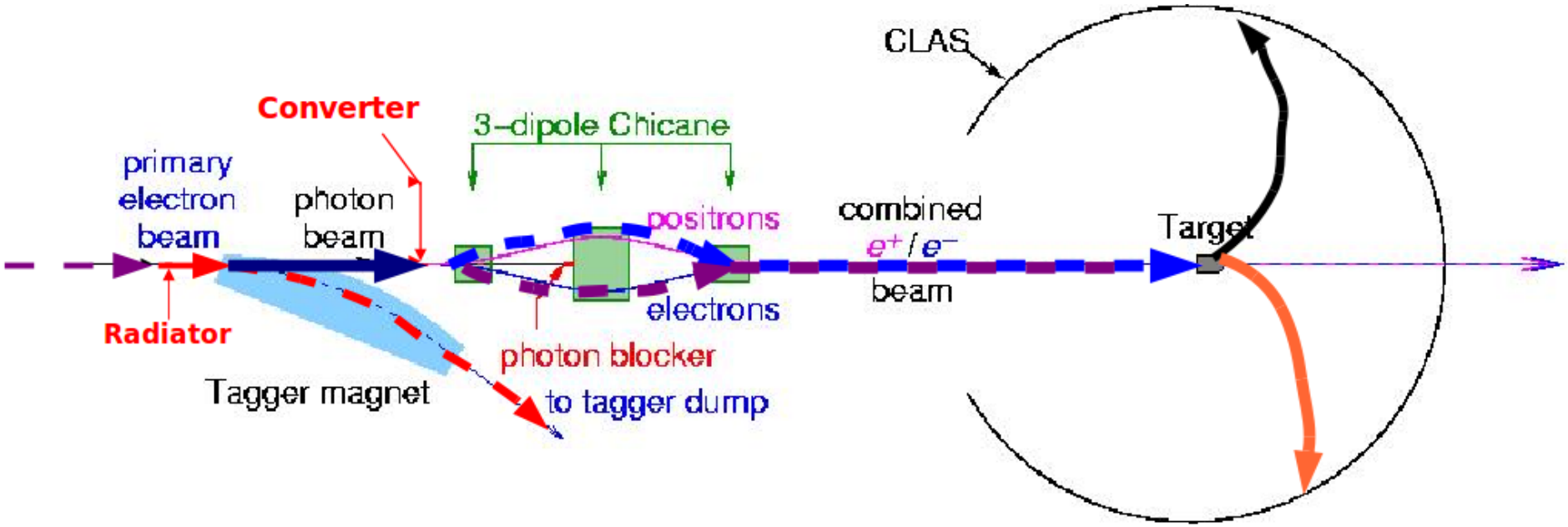
- Primary electron beam: 5.5 GeV and 100 nA
- Radiator: 1% of primary electrons radiate high energy photons
- Tagger magnet: Transport electrons tagger dump
- Converter: 10% of photons are converted to electron/positron pairs
- Chicane: separate the lepton beams
- Remaining photons are stopped at the photon blocker
- e^+ ande^- beams are then recombined and continue to the target
- Target: liquid hydrogen: length = 18cm (30 cm) & diameter = 6cm (6 cm)
- Detector: CLAS (DC, TOF)

Simultaneous, Idential e^+/e^- Beams



- Primary electron beam: 5.5 GeV and 100 nA
- Radiator: 1% of primary electrons radiate high energy photons
- Tagger magnet: Transport electrons tagger dump
- Converter: 10% of photons are converted to electron/positron pairs
- Chicane: separate the lepton beams
- Remaining photons are stopped at the photon blocker
- e^+ ande^- beams are then recombined and continue to the target
- Target: liquid hydrogen: length = 18cm (30 cm) & diameter = 6cm (6 cm)
- Detector: CLAS (DC, TOF)

Simultaneous, Idential e^+/e^- Beams



- Primary electron beam: 5.5 GeV and 100 nA
- Radiator: 1% of primary electrons radiate high energy photons
- Tagger magnet: Transport electrons tagger dump
- Converter: 10% of photons are converted to electron/positron pairs
- Chicane: separate the lepton beams
- Remaining photons are stopped at the photon blocker
- e^+ ande^- beams are then recombined and continue to the target
- Target: liquid hydrogen: length = 18cm (30 cm) & diameter = 6cm (6 cm)
- Detector: CLAS (DC, TOF)

Beam Profiling

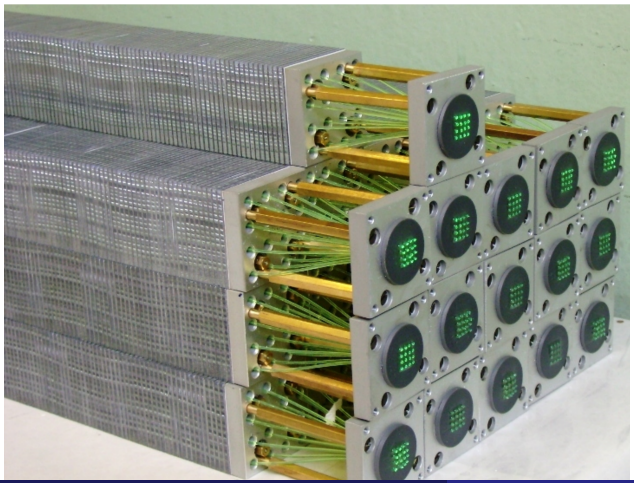
TPE Calorimeter

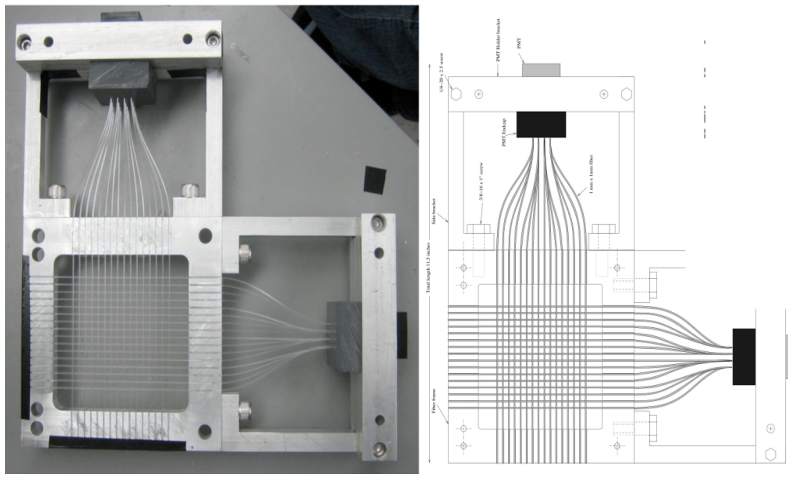
- 5x6 tower,

  $3.8mm \times 3.8mm \times 450mm$ Shashlik type calorimeter

- Located directly downstream of CLAS on the forward carriage

- Dense fiber monitor mounted on the face of TPEcal.





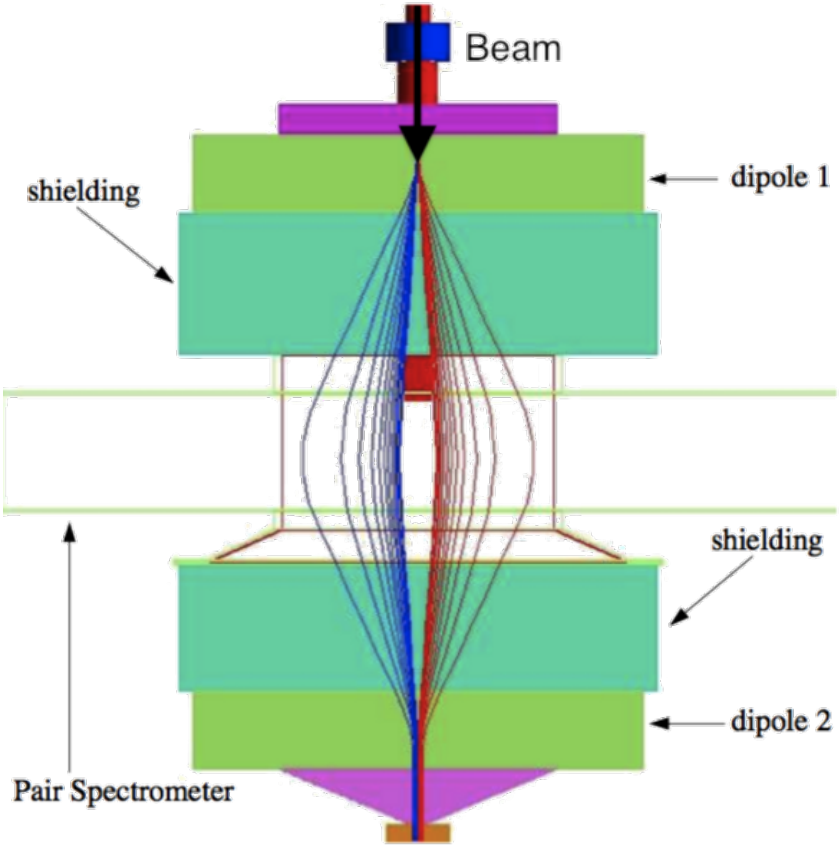
Fiber Monitors

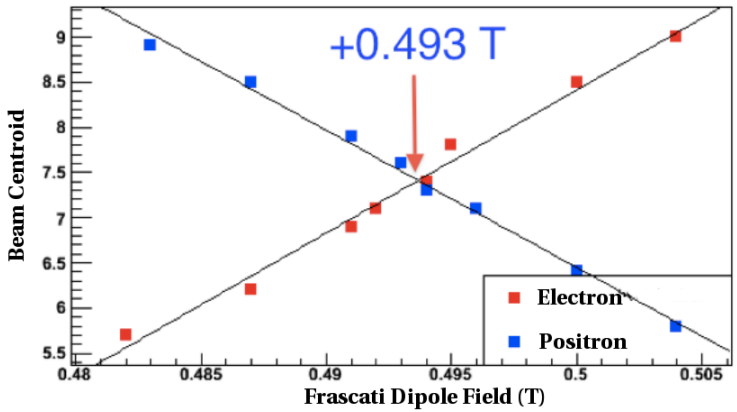
- 16x16 (64x64) channel Upstream Sparse Fiber Monitor

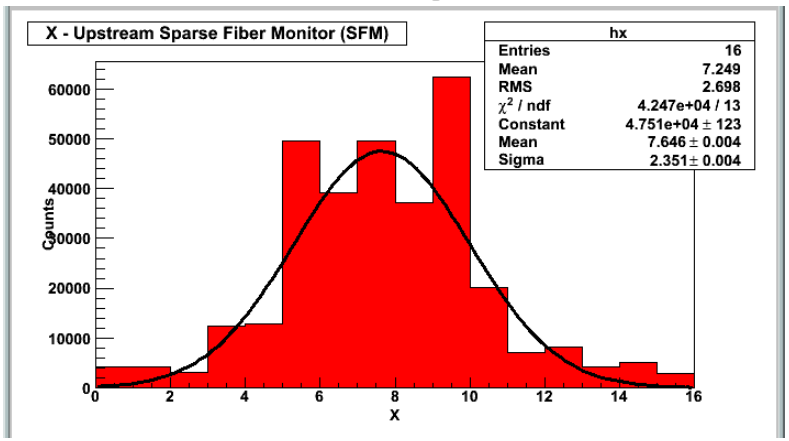
- Bicron fibers spaced 5 mm (1mm) apart glued to a Hamamatsu PMT

- Beam size $\sim$ 15 mm radius

Systematic Checks

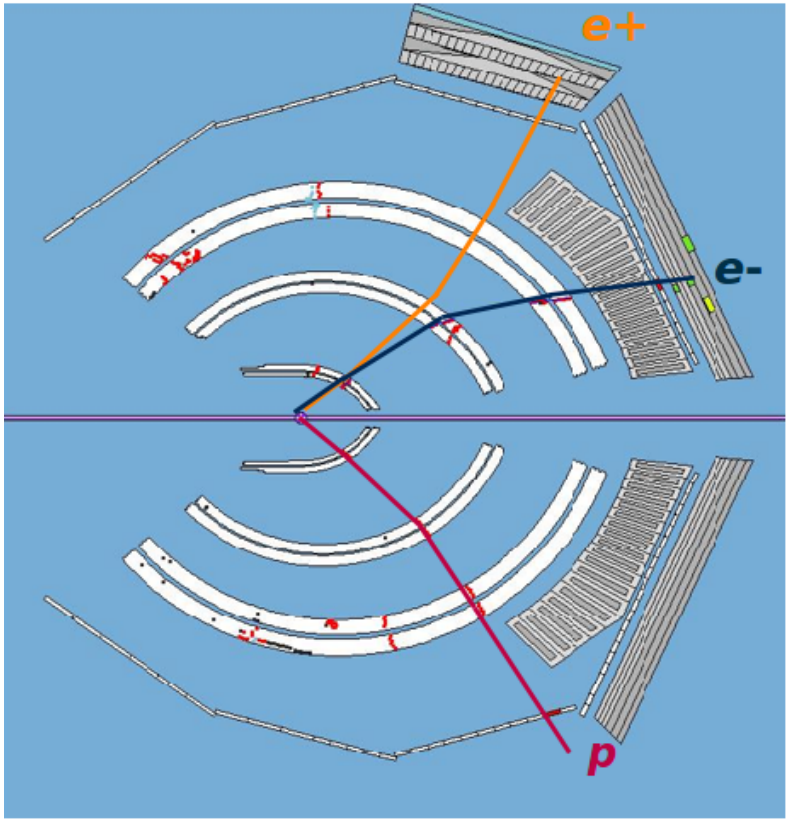






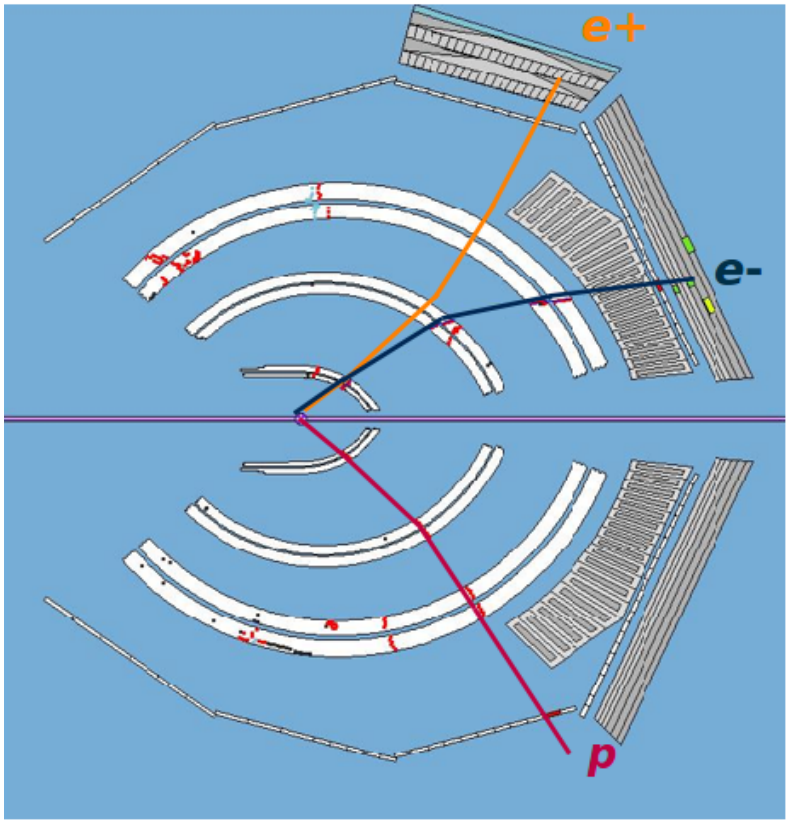
- Flipped chicane polarity about once a week
- Check for geometric alignment of e^-/e^+ on target
- Varied steering magnet currents
- Measured individual beam positions at Sparse Fiber Monitor
- Reproducible crossing for all chicane flips

The Basics



1. Measure Elastic Scattering Ratio

The Basics

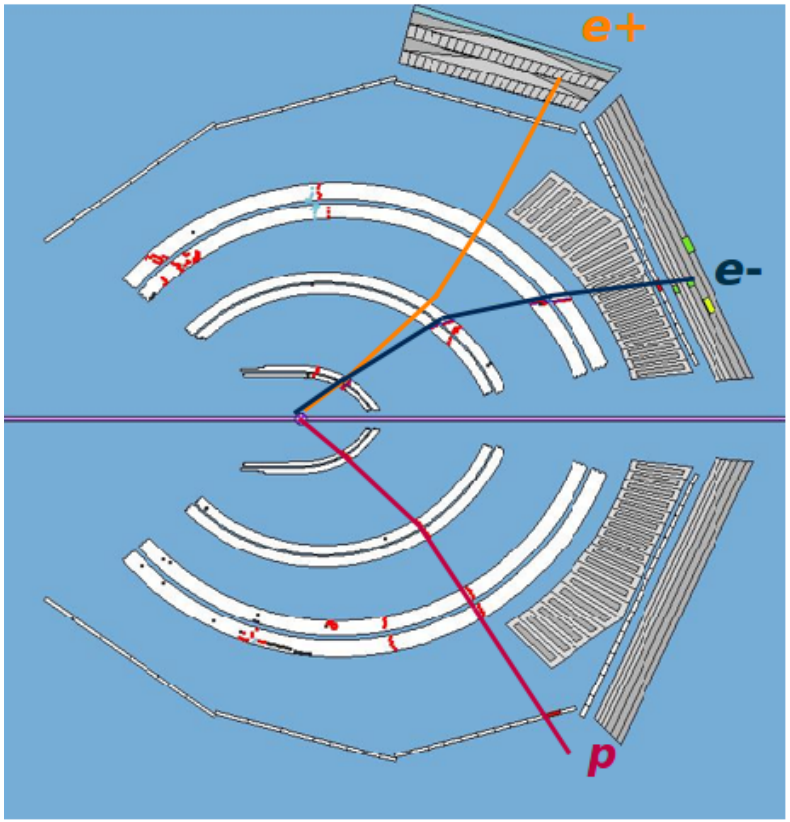


1. Measure Elastic Scattering Ratio

$$R = \sqrt{\frac{Y^{+}_{e^+P}}{Y^{+}_{e^-P}} \times \frac{Y^{-}_{e^+P}}{Y^{-}_{e^-P}}}$$

2. **Systematics**
   - Extensive beam profiling
   - Flip torus polarity
   - Flip chicane polarity

The Basics



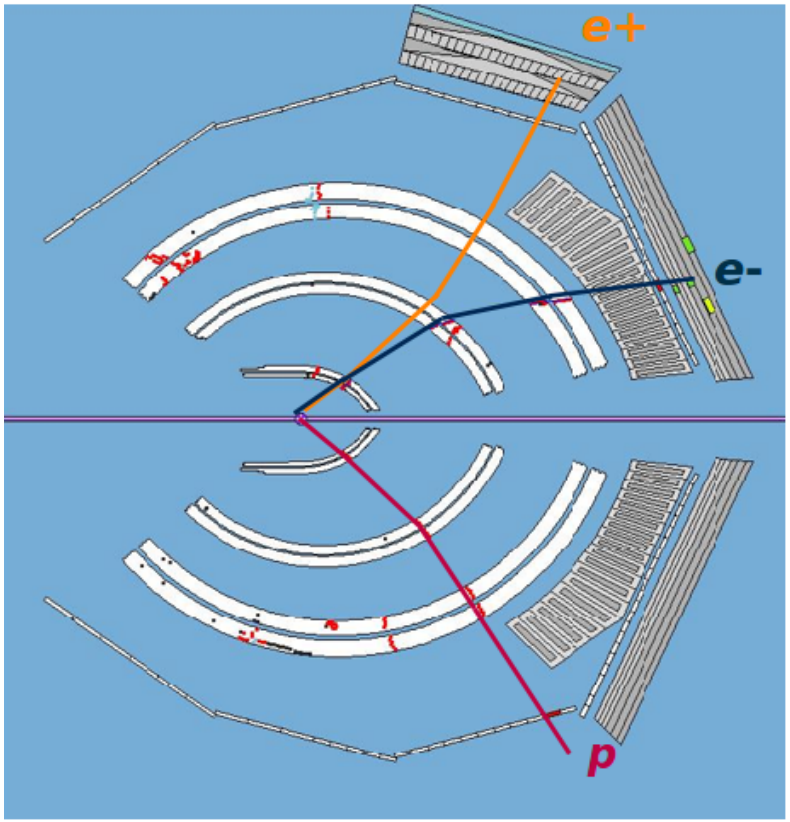
1. Measure Elastic Scattering Ratio

$$R = \sqrt{\frac{Y^{+}_{e^+P}}{Y^{+}_{e^-P}} \times \frac{Y^{-}_{e^+P}}{Y^{-}_{e^-P}}}$$

2. **Systematics**
   - Extensive beam profiling
   - Flip torus polarity
   - Flip chicane polarity

3. **Analysis Issues**
   - Beam energy for a given event is unknown
   - Non-standard particle identification
   - Different efficiency for ID'ing in-bending and out-bending tracks

The Basics



1. Measure Elastic Scattering Ratio

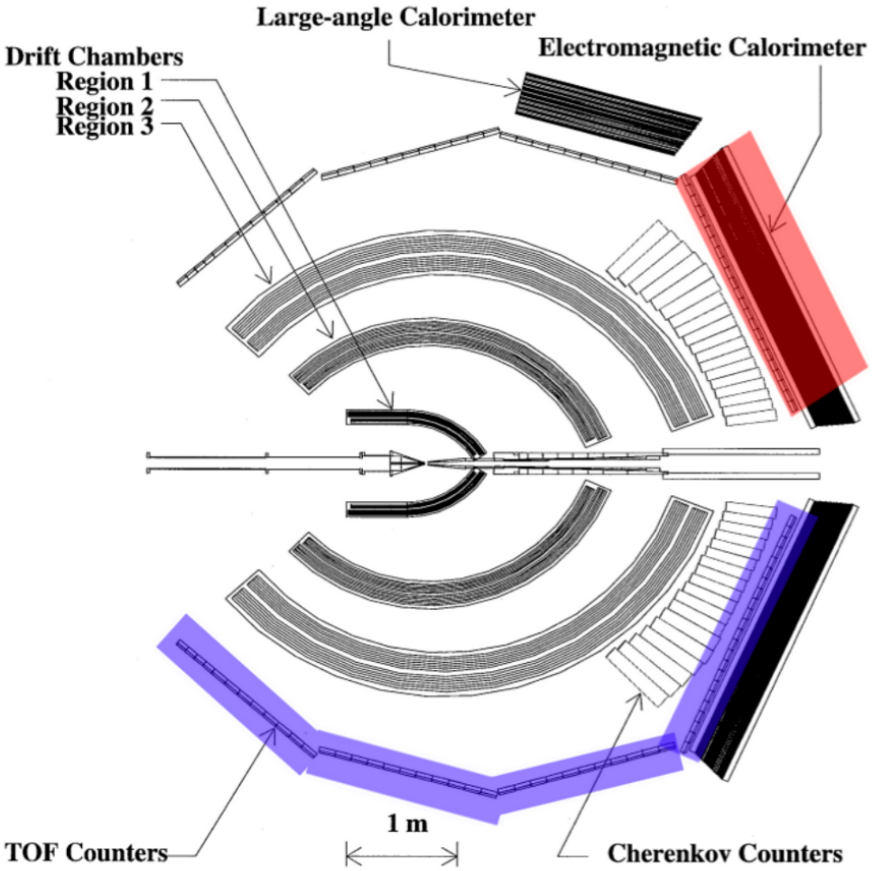
$$R = \sqrt{\frac{Y^{+}_{e^+P}}{Y^{+}_{e^-P}} \times \frac{Y^{-}_{e^+P}}{Y^{-}_{e^-P}}}$$

2. **Systematics**
   - Extensive beam profiling
   - Flip torus polarity
   - Flip chicane polarity

3. **Analysis Issues**
   - Beam energy for a given event is unknown
   - Non-standard particle identification
   - Different efficiency for ID'ing in-bending and out-bending tracks

4. **Analysis Solutions**
   - Look for coplanar pairs (opposite sectors)
   - Identify $++$ and $+-$ pairs
   - Exploit over constrained kinematics
   - Straight through running of primary beam

Summary of Data Analysis

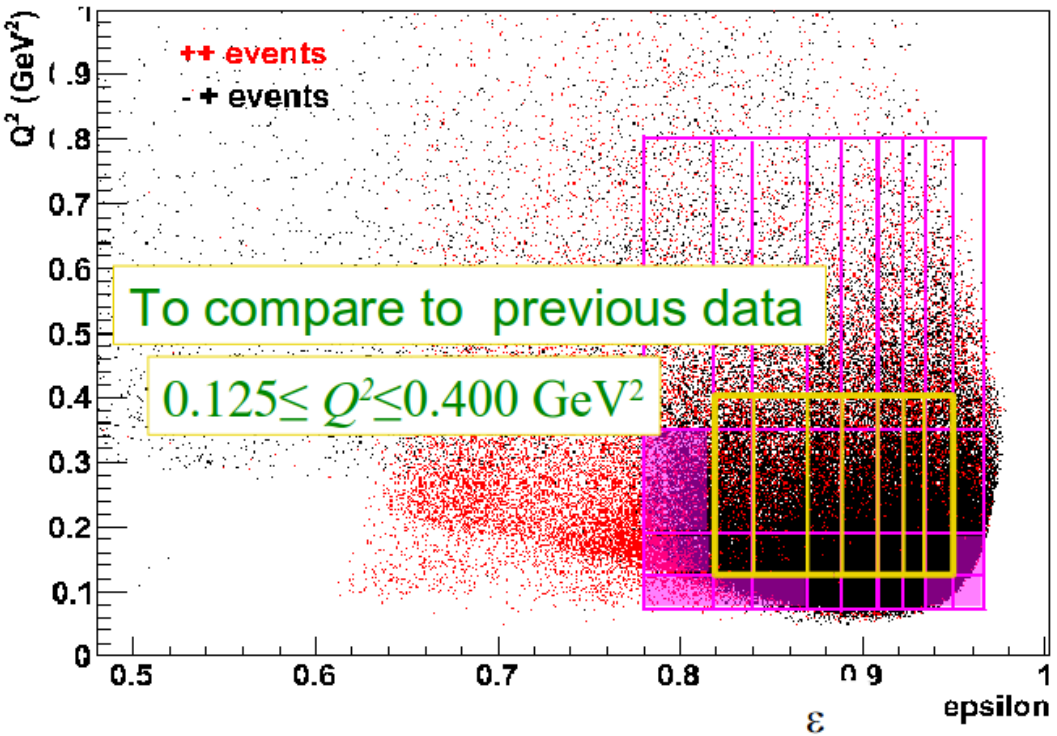


EC and TOF ($\theta < 45°$) and opposite sector TOF

1. Trigger on particle in forward 45^0 and anything in opposite sector
2. Vertex cut $(-45cm \leq V_z \leq -15cm)$
3. Azimuthal angle cut $(\phi_{proton} - \phi_{lepton} \approx 180^0)$
4. Transverse Momentum cut $(P_T \approx 0)$
5. Beam Energy cut $(E_{beam}(angles) \approx E_{beam}(PConsv.))$
6. Fiducial Cuts
7. DOCA cut between tracks
8. Swimming – Acceptance matching ++ and +− events

2006 Test Run

1.5 days of low luminosity beam



<Q^2>=0.472 GeV^2

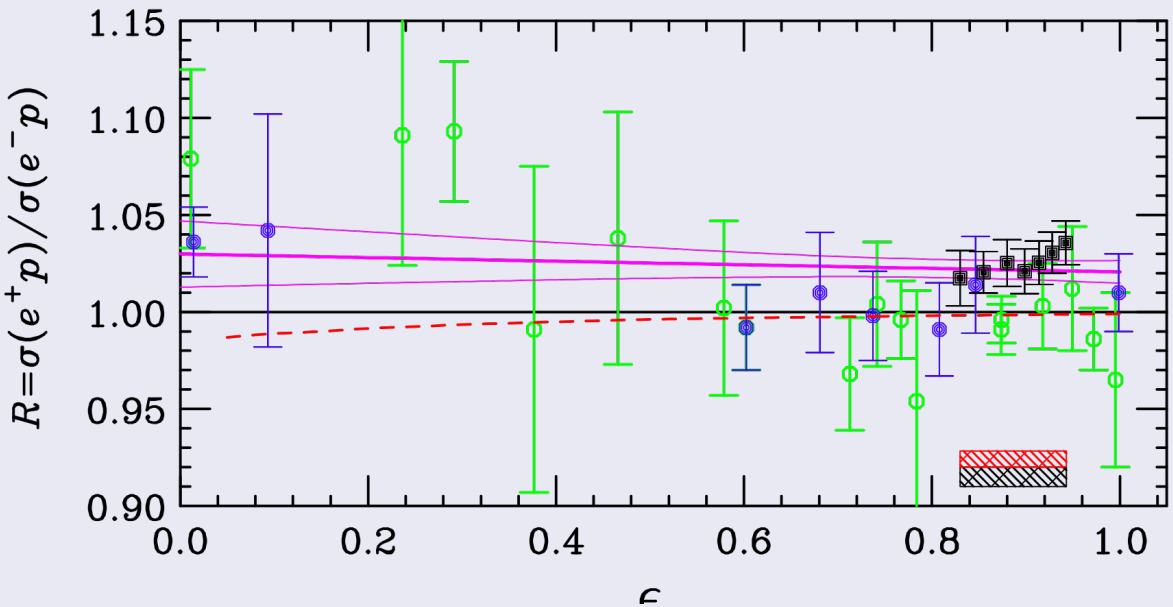
<Q^2>=0.246 GeV^2

<Q^2>=0.152 GeV^2

<Q^2>=0.103 GeV^2

2006 Test Run Results

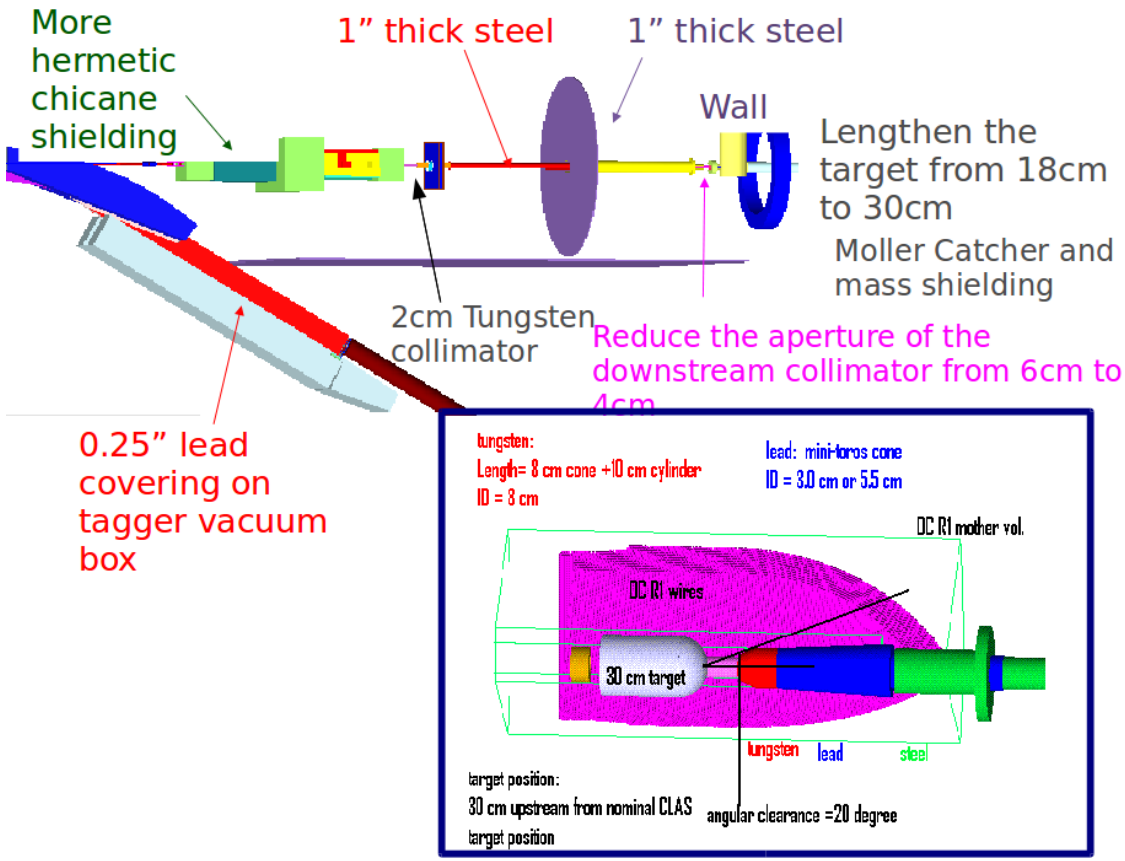
Cross Section Ratio



- Scale-type systematic uncert. ~ 0.010 (e+/e- relative luminosity)
- Point-to-point systematic uncert. ~ 0.0080 (acceptance & effects of cuts, coupled to statistical precision)

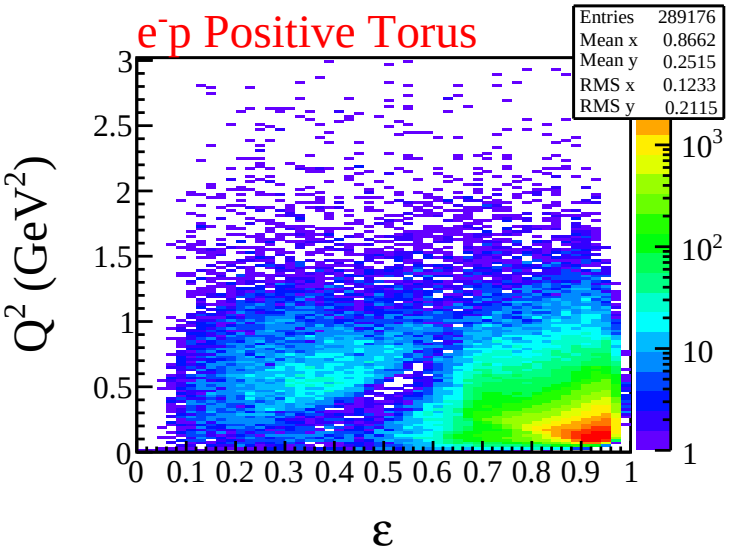
- Maryam Moteabbed Thesis (FIU) $< Q^2 >= 0.206\ GeV^2$
- Megh Niroula Thesis (ODU)
- World data

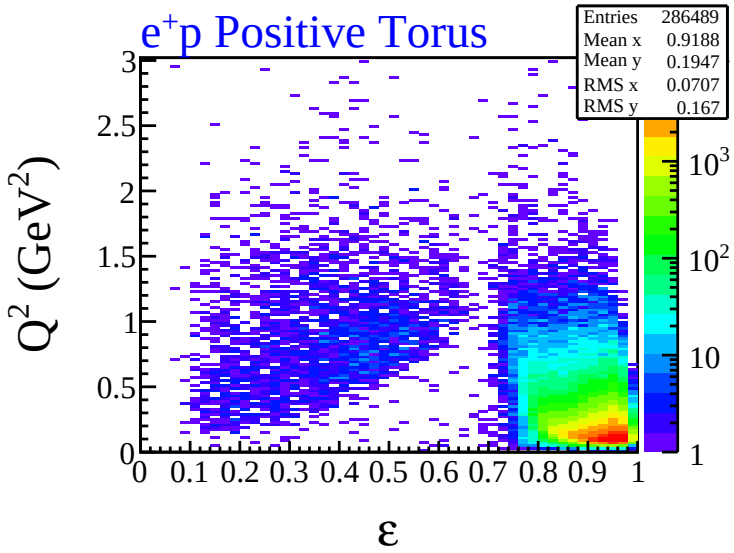
Beam Line Modification for TPE

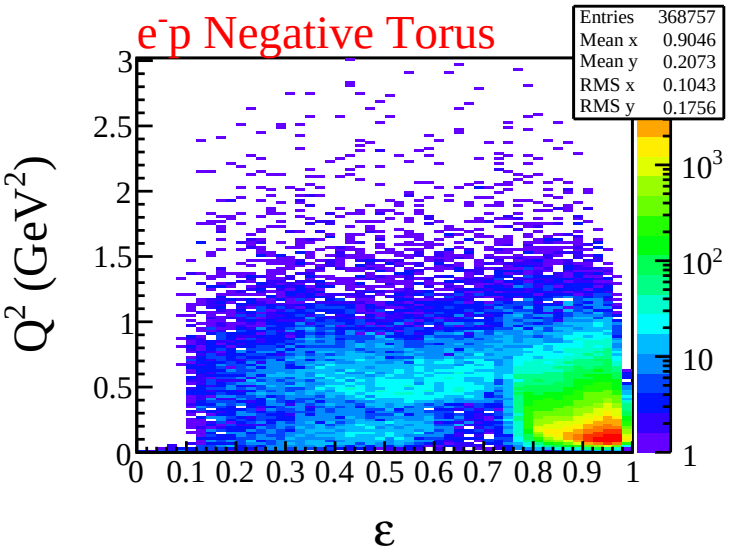


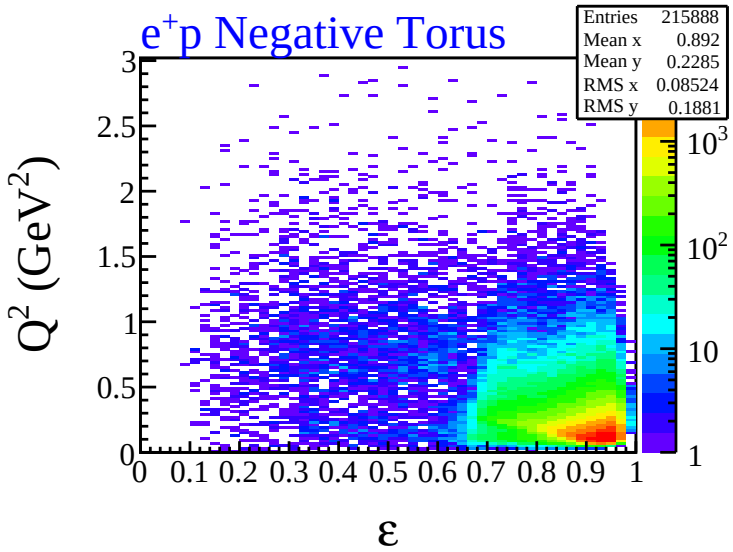
- The biggest hindrance to increasing beam luminosity is the drift chamber occupancy.
- Extensive GEANT simulations to optimize shielding
- Factor of 10 in luminosity + 70 days of beam

Q^2 vs ε (TPE II 2010-2011)

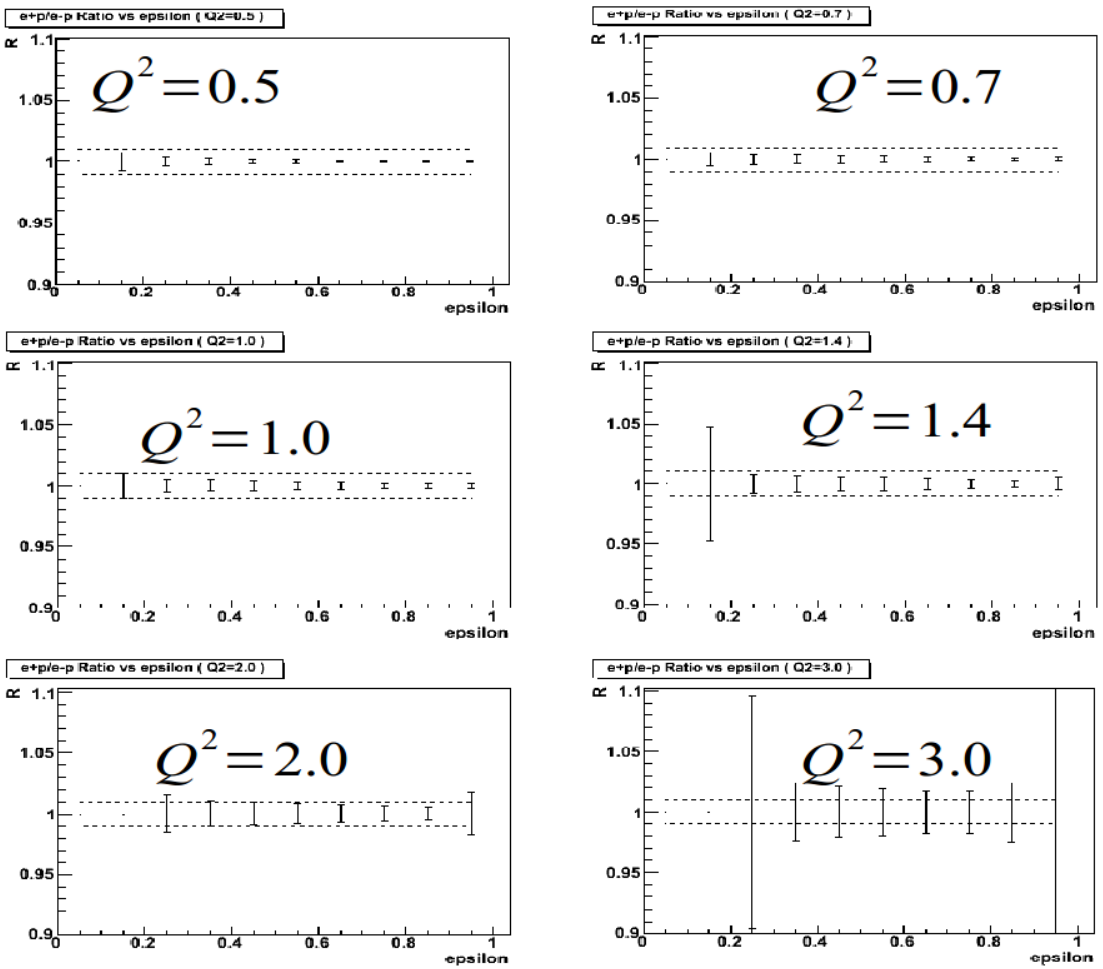


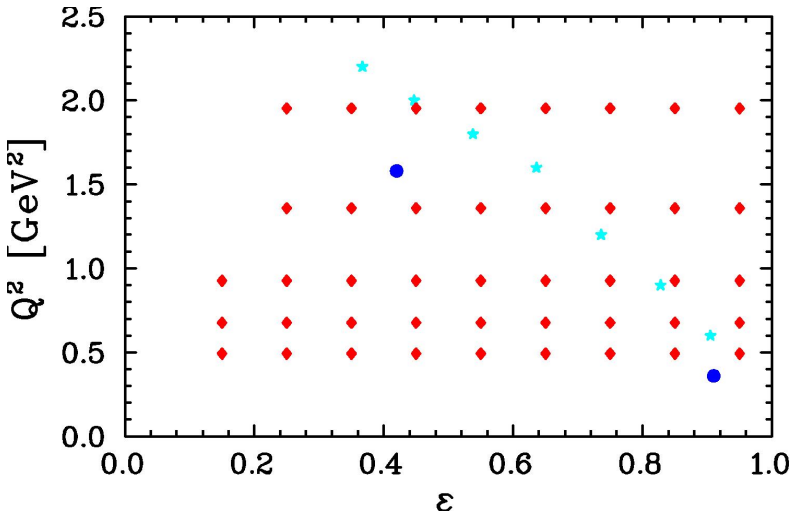






Projections





- CLAS will map out the TPE effect over large areas of Q^2 and ϵ
- Not the only game in town: Olympus at DESY and VEP-III at Novosibirsk
- 30 PAC day (Nov 2010 - Feb 2011), collected more events in 1 hour than the entire test run in 2006
- CLAS will be able to obtain $< 1\%$ statistical and systematic uncertainties out to $Q^2 = 2GeV^2$

Summary

- Rosenbluth and Polarization transfer experiments measure G_{E_P} that differ by a factor of 3 at $Q^2 = 6$
- Understanding the origin of this discrepancy is essential to many other measurement in nuclear physics
- Two Photon Exchange may be able to explain the discrepancy
- The e^+p/e^-p ratio is the only way to measure the real part of the TPE amplitude
- CLAS was able to produce simultaneous, nearly identical beams of electrons and positrons
- Test run results showed promise but were severely statistics limited
- This year we significantly increase our luminosity, through shielding and engineering
- We should expect small ($< 1\%$ stat. and $< 1\%$ sys.) uncertainties for in R over a large area in $Q^2 - \varepsilon$ space

Thank you

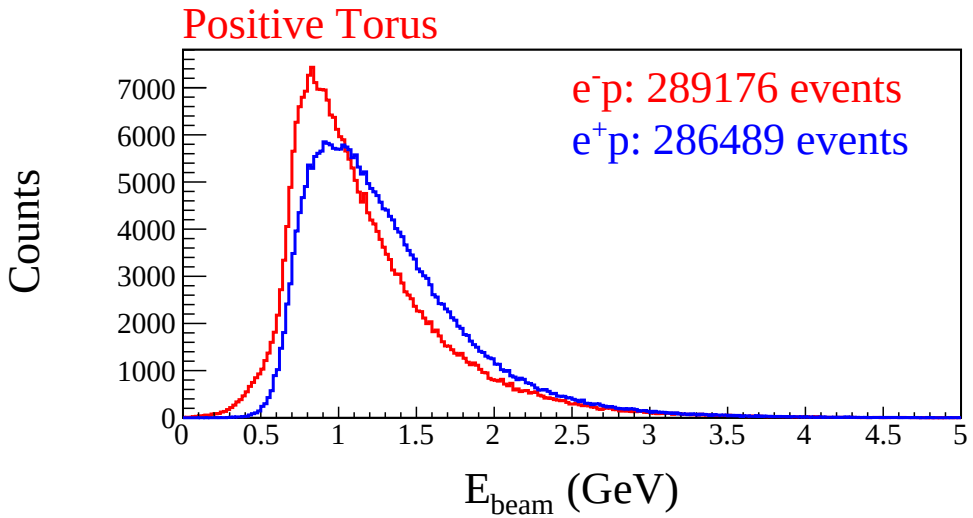
Thank you

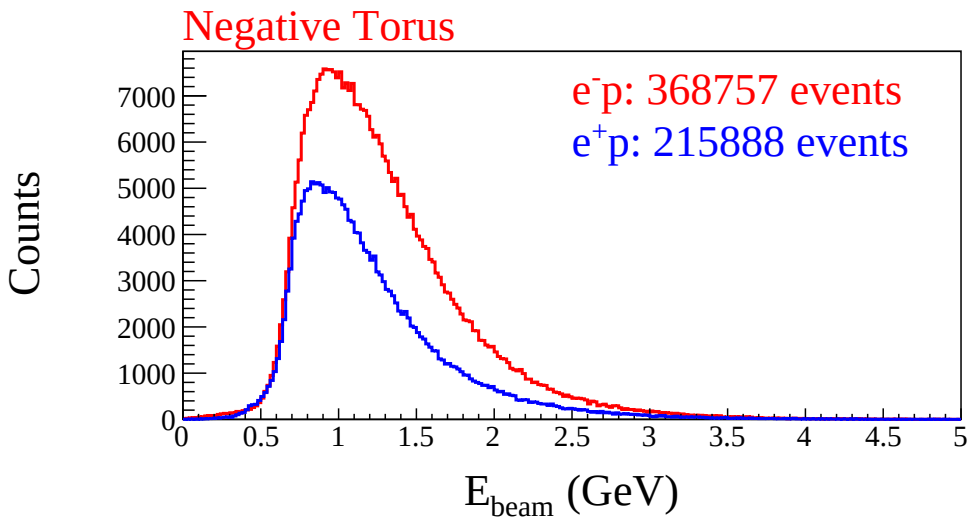
$$E_{Beam} = M_P\left(\frac{1.0}{(tan(\theta_e/2.0) * tan(\theta_P))} - 1.0\right) \quad (1)$$

$$E_{Beam} = (P_{z1} + P_{z2}) \quad (2)$$

$$E_{Beam} = E_e E_p - P_e P_p cos(\theta_e + \theta_p)/M_p \quad (3)$$

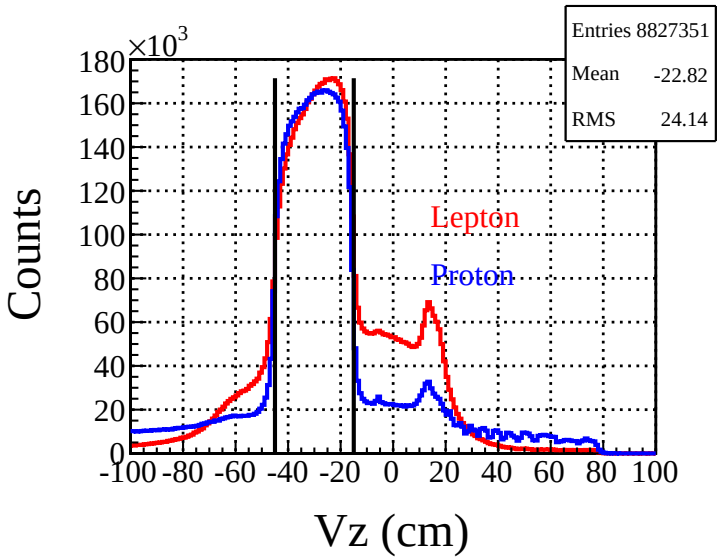
Beam Energy

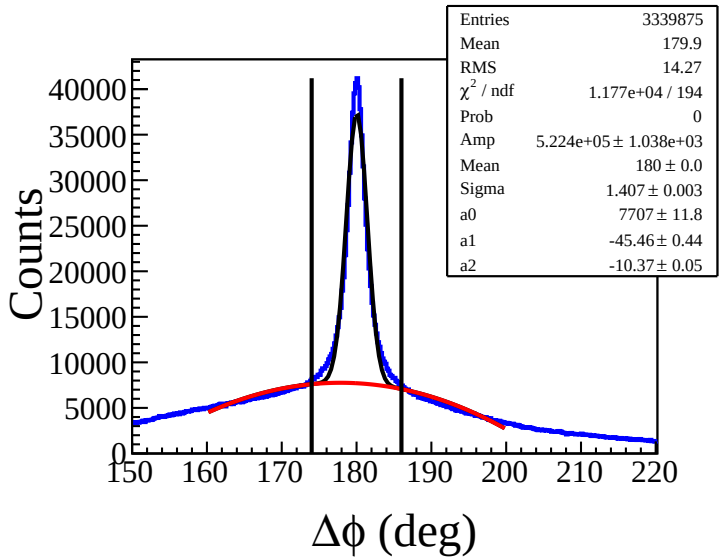


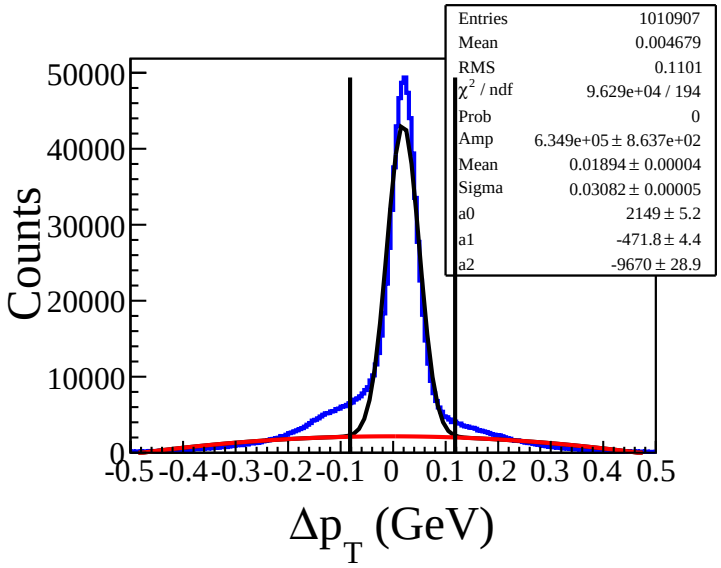


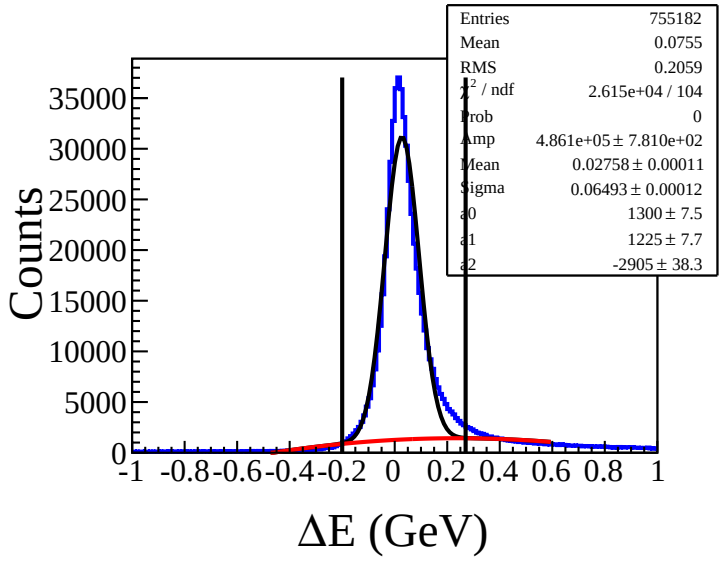
Very Preliminary

Analysis Cuts

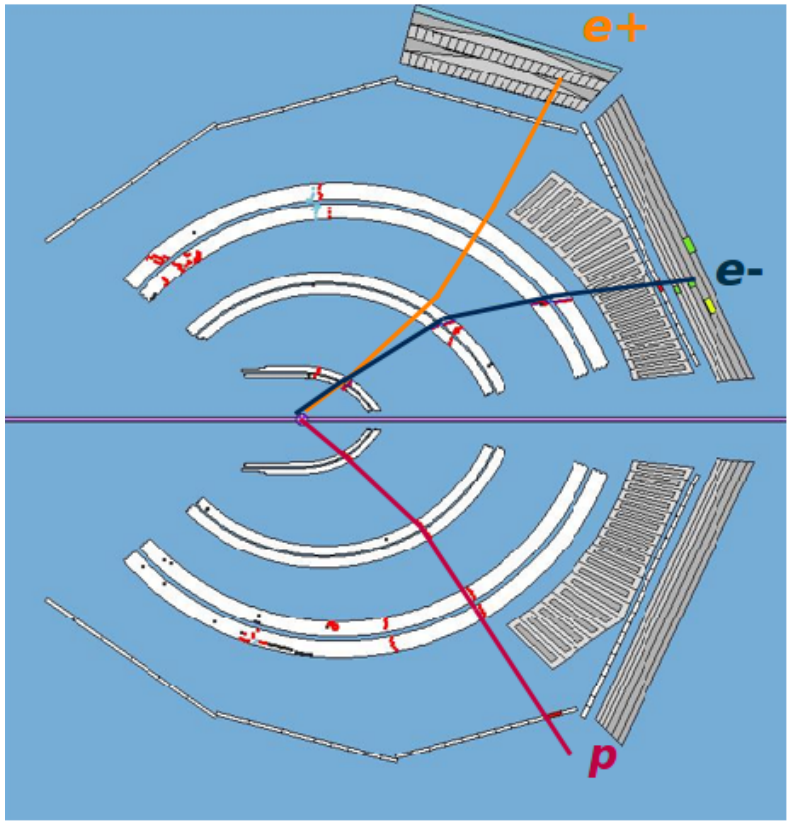








Swimming

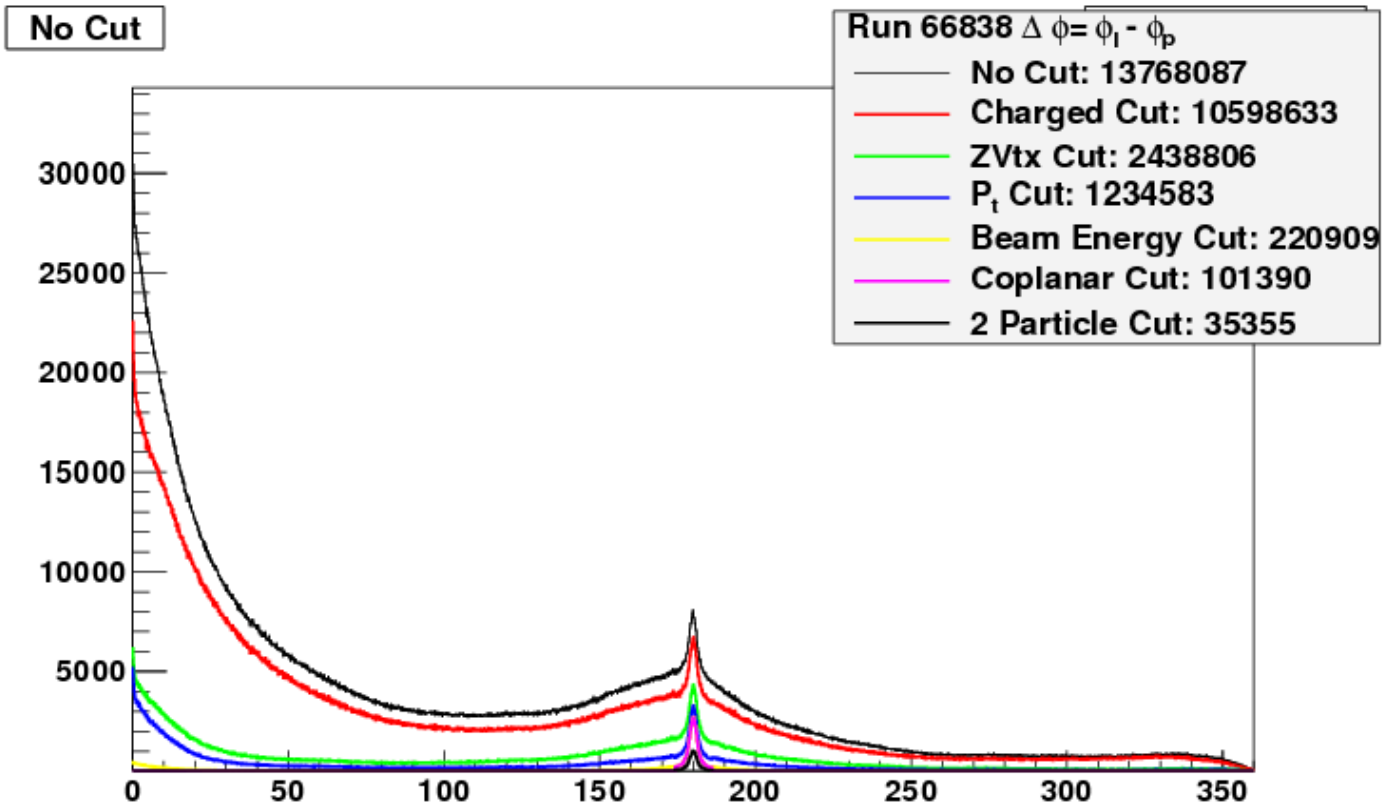


To reduce acceptance effects we utilize a swimming algorithm.

- Reverse the charge of the detected lepton
- Trace track of reversed lepton through CLAS
- Keep tracks which would have produced a good hit in the TOF, discard the rest

Analysis Cuts Summary

- Summary of analysis cuts



Triggers

Trigger Setup

Description	Trigger Bit	Rates (Hz) @ 100nA
Low Threshold EC and TOF ($\theta < 45°$) and opposite sector TOF ($\theta > 45°$)	1 2 3 4 5 6	500 500 400 650 800 800
High Threshold EC and TOF ($\theta < 45°$) and opposite sector TOF ($\theta < 45°$)	7	1700
TOF ($45° < \theta < 60°$) and opposite sector TOF ($45° < \theta < 60°$)	8	40,000 (disabled)
3 Hz Pulser	10	3
Low Threshold EC any sector	12	100 (Prescaled)

- Bit 8: Needed to fill kinematic hole - Rates too high!
- Could not implement Level 2 trigger due to hardware restrictions

Personnel

1. **Spokespersons**
   - Larry Weinstein, Brian Raue, Will Brooks, John Arrington, Andrei Afanasev & Kyungseon Joo
2. **Post Docs**
   - Puneet Khetarpal
   - Mauri Ungaro
   - Robert Bennett
3. **Graduate Students**
   - Dasuni Adikaram
   - Dipak Rimal
   - Cristian Peña
   - Hashir Rashad