Beyond the Born Approximation

Measuring the Two Photon Exchange Correction at CLAS

Robert Paul Bennett

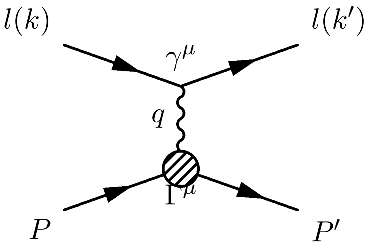
Old Dominion University

D. Adikaram, A. Afanasev, J. Arrington, W. Brooks, K. Joo, P. Khetharpal,
B. Raue, D. Rimal, M. Ungaro, L. Weinstein
CLAS Collaboration

Experimental and Theoretical Aspects of Proton Form Factors
Petersburg Nuclear Physics Institute

July 9, 2012

Elastic Scattering: Born Approximation



ep Kinematics

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

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

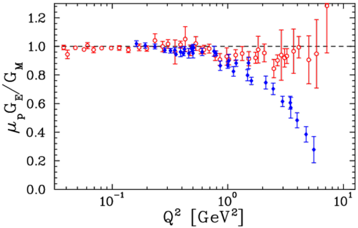
$F_2(q^2)$ Spin flip Pauli Form Factor

F_1 and F_2 are NOT unique

- Electric form factor: $G_{E_P}(Q^2) = F_1^P(Q^2) - \tau\kappa F_2^p(Q^2)$
- Magnetic form factor: $G_{M_P}(Q^2) = F_1^P(Q^2) + \kappa F_2^p(Q^2)$

$$\tau = \frac{Q^2}{4M_P^2} \; ; \quad G_{E_P}\mu_P \approx G_{M_P} \approx G_D$$

The Proton Formfactor Puzzle



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

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

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

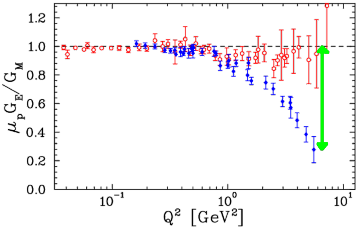
- Separate G_E and G_M contributions at a particular Q^2 using different beam energies and scattered electron angles
- G_M measurement dominates at high Q^2, G_E is suppressed

- 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.)

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

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

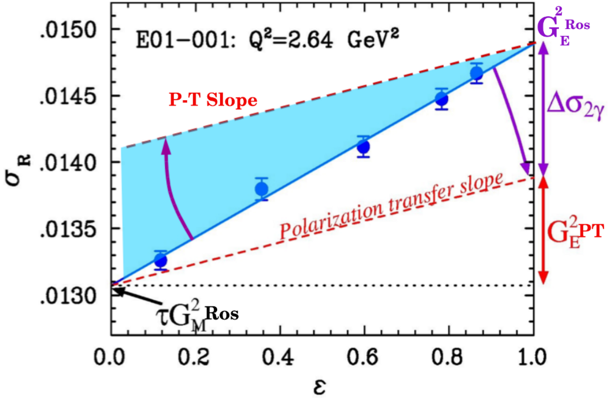
- Separate G_E and G_M contributions at a particular Q^2 using different beam energies and scattered electron angles
- G_M measurement dominates at high Q^2, G_E is suppressed

- Polarization Transfer: (Hall A & C)

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

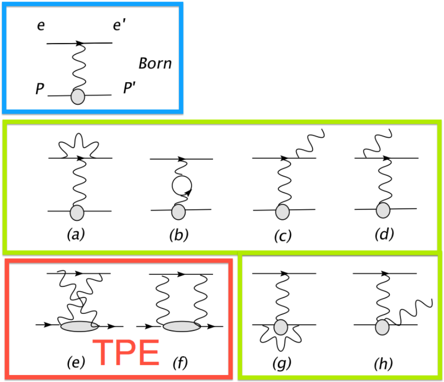
- Longitudinal polarized electrons incident on proton target
- Measure transverse and longitudinal polarization of recoiled proton

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

TPE Contribution



- Modified G_E and G_M
- New ε dependent term

The general $1-\gamma$ and $2-\gamma$ exchange amplitudes

$$A = \frac{e^2}{Q^2}\bar{u}(k')\gamma^\mu u(k)$$

$$1: \times \bar{u}(p')\left[G_M\gamma^\mu - F_2\frac{P^\mu}{M}\right]u(p)$$

$$2: \times \bar{u}(p')\left[\tilde{G}_M\gamma^\mu - \tilde{F}_2\frac{P^\mu}{M} + \tilde{F}_3\frac{\gamma K P^\mu}{M^2}\right]u(p)$$

The general $1-\gamma$ and $2-\gamma$ exchange cross section

$$1: \frac{d\sigma}{d\Omega} \propto \left[\varepsilon G_E^2 + \tau G_M^2\right]$$

$$2: \frac{d\sigma}{d\Omega} \propto \left[\varepsilon \tilde{G}_E^2 + \tau \tilde{G}_M^2\right] + \left[2\varepsilon\left(\tau|\tilde{G}_M| + |\tilde{G}_E\tilde{G}_M|\right)Y_{2\gamma}\right]$$

$$Y_{2\gamma} \propto Re\left(\frac{\tilde{F}_3}{|\tilde{G}_M|}\right)$$

Guichon and Vanderhaeghen, PRL 91 (03) 142303

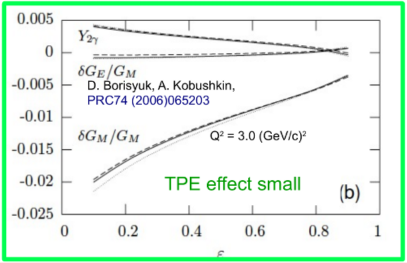
Predictions

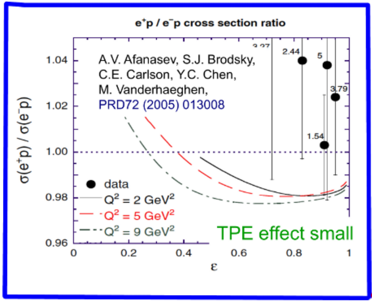
Model Dependent Predictions

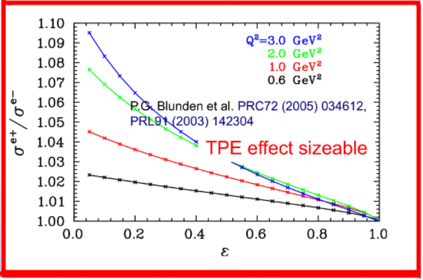
pQCD

GPD

Baryonic

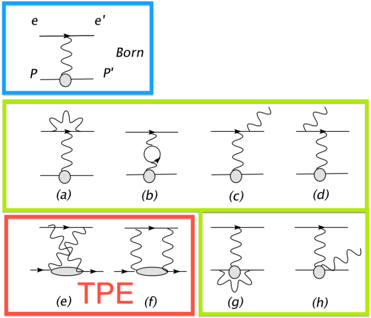






Positrons to the rescue!

- The Born amplitude changes sign as the the charge of the incident beam.
- The leading TPE terms of the elastic scattering cross section are sensitive to the lepton charge



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

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

The ratio of the cross sections isolates the TPE correction term

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

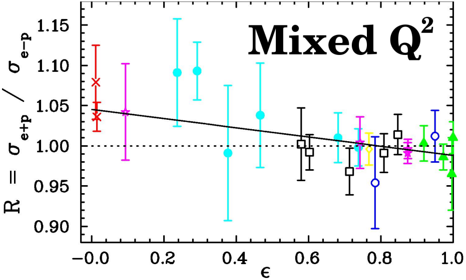
- We can calculate this very well (QED)
- Theoretical calculation of the diagram is hard : Need to integrate over all baryon states
- The e^-p/e^+p ratio measures the real part of the TPE contribution

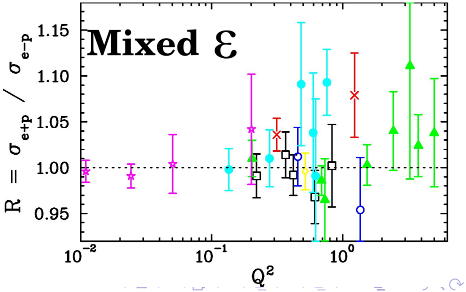
Limited Previous e^+p/e^-p Data

TPE was a known issue

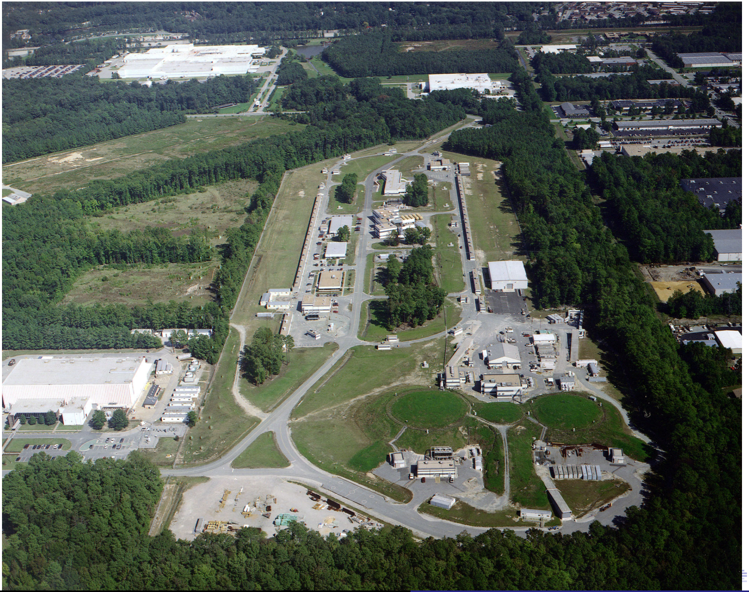
- TPE expected to be on order α $\sim 1\%$ effect
- Previous e^+p/e^-p data consistent with this assumption
- Reanalysis of the existing world data is inconclusive, but indicates a few % ε depenence
- Negligible Q^2 dependence of the ratio

J. Arrington, PRC69, 032201 (2004) →

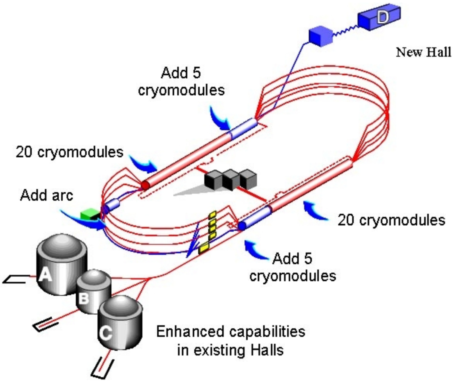




Jefferson Laboratory

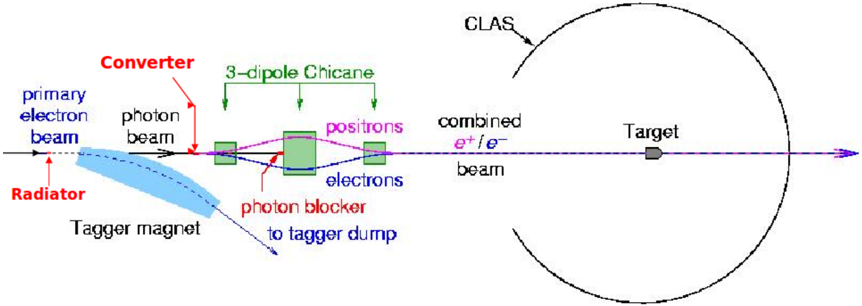


Continuous Electron Beam Accelerator Facility (CEBAF)



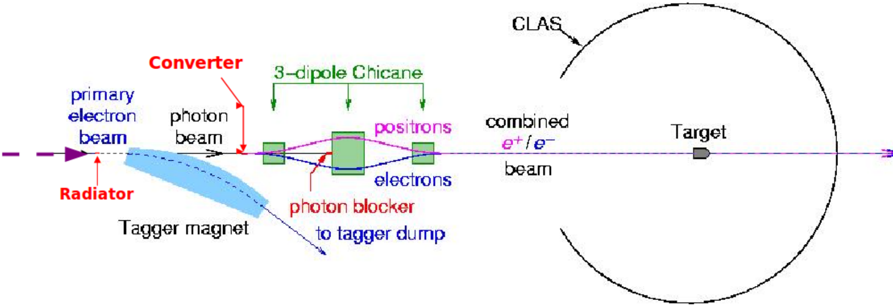
- 5 pass super-conducting accelerator
- Polarized electrons up to 6 GeV
- Maximum Current $\sim 100\ \mu$ A
- Upgrading to 12 GeV
- 3 experimental halls running (A, B, & C) (D is coming soon)

Making Positrons at CLAS



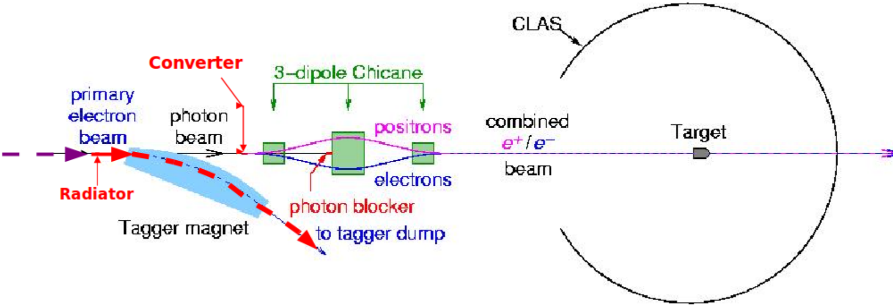
- Primary electron beam: 5.5 GeV and 100-120 nA
- Radiator: 0.9% of primary electrons radiate high energy photons
- Tagger magnet: Transport electrons tagger dump
- Converter: 9% of photons are converted to electron/positron pairs
- Chicane: separate the lepton beams
  – Remaining photons are stopped 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)

Making Positrons at CLAS



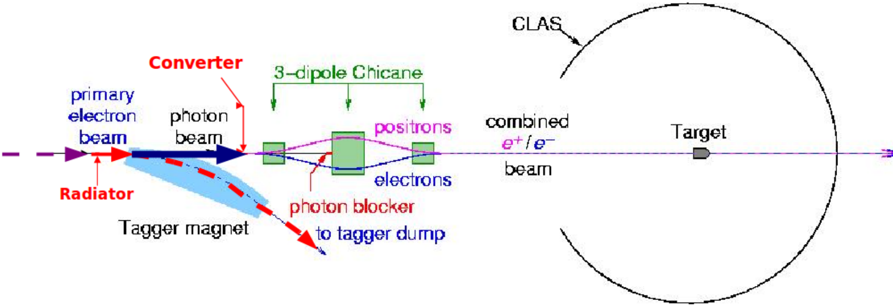
- Primary electron beam: 5.5 GeV and 100 nA
- Radiator: 0.9% of primary electrons radiate high energy photons
- Tagger magnet: Transport electrons tagger dump
- Converter: 9% of photons are converted to electron/positron pairs
- Chicane: separate the lepton beams
  – Remaining photons are stopped at 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)

Making Positrons at CLAS



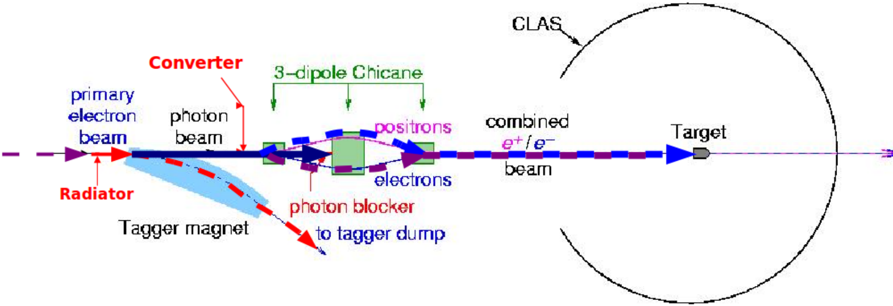
- Primary electron beam: 5.5 GeV and 100 nA
- Radiator: 0.9% of primary electrons radiate high energy photons
- Tagger magnet: Transport electrons tagger dump
- Converter: 9% of photons are converted to electron/positron pairs
- Chicane: separate the lepton beams
  - Remaining photons are stopped at 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)

Making Positrons at CLAS



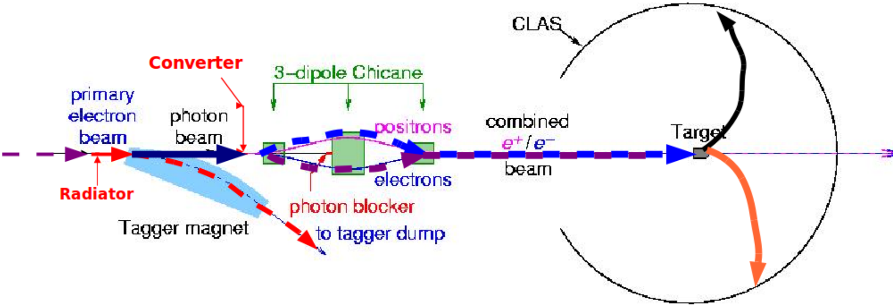
- Primary electron beam: 5.5 GeV and 100 nA
- Radiator: 0.9% of primary electrons radiate high energy photons
- Tagger magnet: Transport electrons tagger dump
- Converter: 9% of photons are converted to electron/positron pairs
- Chicane: separate the lepton beams
  – Remaining photons are stopped at 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)

Making Positrons at CLAS



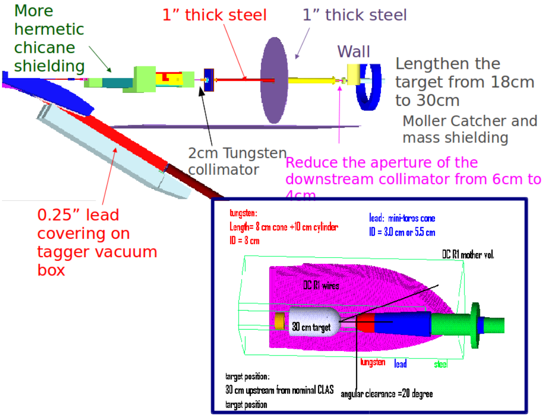
- Primary electron beam: 5.5 GeV and 100 nA
- Radiator: 0.9% of primary electrons radiate high energy photons
- Tagger magnet: Transport electrons tagger dump
- Converter: 9% of photons are converted to electron/positron pairs
- Chicane: separate the lepton beams
  – Remaining photons are stopped at 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)

Making Positrons at CLAS



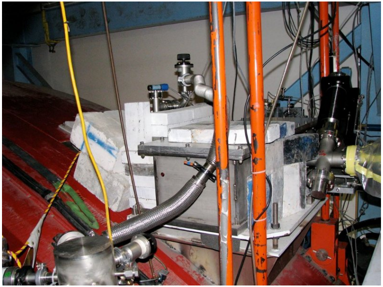
- Primary electron beam: 5.5 GeV and 100 nA
- Radiator: 0.9% of primary electrons radiate high energy photons
- Tagger magnet: Transport electrons tagger dump
- Converter: 9% of photons are converted to electron/positron pairs
- Chicane: separate the lepton beams
  – Remaining photons are stopped at 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)

Beam Line Modification for TPE



- Extensive GEANT simulations of detector backgrounds.
- Confirmed simulation with test run data
- A lot of shielding added on tagger, tagger dump and chicane.
- Improved luminosity by a $\approx$ factor 100

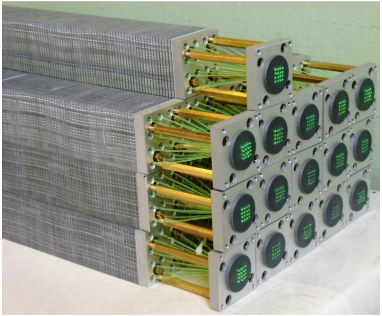
Beam Line Modification for TPE

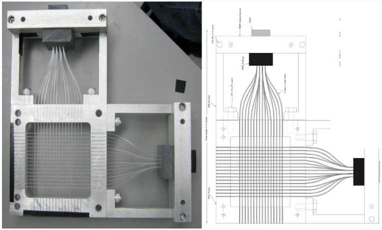


Beam Profiling

TPE Calorimeter

- Measure beam energy vs position during low luminosity run
- 30 module Shashlik (Pb/Scint) calorimeter
- Located directly downstream of CLAS on the forward carriage

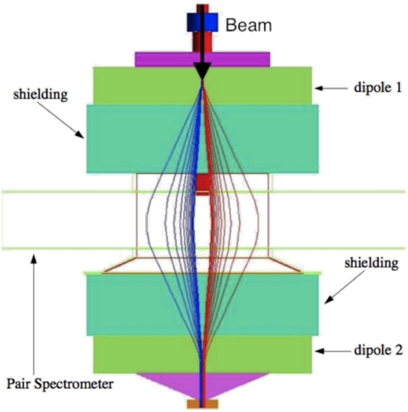


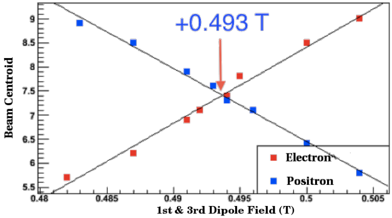


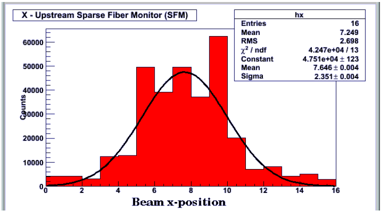
Fiber Monitors

- 16x16 Sparse fiber monitor continually monitoring beam profile before the target
- 64x64 Dense fiber monitor mounted on TPE Calorimeter face for beam profiling during low luminosity runs
- Bicron fibers spaced 5 mm (1mm) apart glued to a Hamamatsu PMT
- Beam size $\sim$ 15 mm radius

Systematic Beam Checks

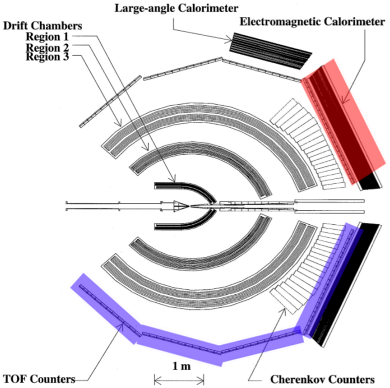






- Flipped chicane polarity about once a week
- Check for geometric alignment of e^-/e^+ on target – Varied steering magnet currents and measured individual beam positions at sparse fiber monitor
- Reproducible crossing for all chicane flips

Triggering, Cuts and Corrections



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

1. Trigger on particle in forward 45^0 and anything in opposite sector
2. Target vertex cut (-45 cm $\leq V_z \leq -15$ cm)
3. Momentum Corrections
4. Proton energy loss corrections
5. Fiducial Cuts
6. Swimming – Acceptance matching $++$ and $+-$ events

Non-Standard PID & Elastic Event Selection

1. Select ++ and +− track pairs
2. Coplanarity cut ($\phi_{proton} - \phi_{lepton} \approx 180^0$)
3. Reconstructed Beam Energy:

$$\begin{aligned} E_1 &= M_P \left[\frac{1}{\tan(\theta_e/2)\tan(\theta_P)} - 1.0 \right] \\ E_2 &= P_e \cos(\theta_e) + P_p \cos(\theta_P) \\ \Delta E_{Beam} &= E_1 - E_2 \end{aligned}$$

4. Scattered lepton Energy:

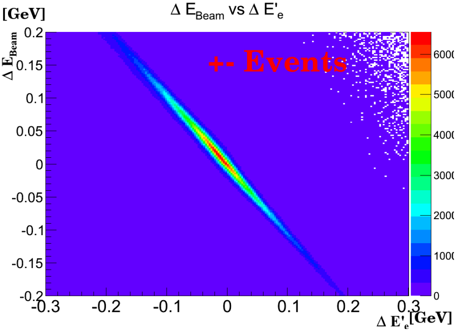
$$\Delta E'_e = E^e_{measured} - E^e(\theta_e, \theta_p)$$

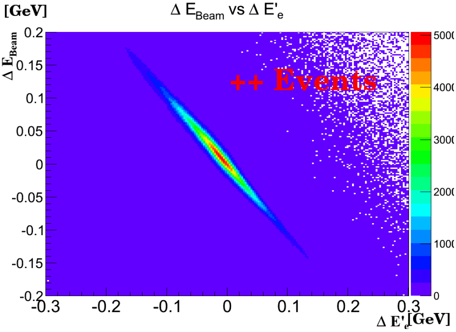
5. Proton Momentum:

$$\Delta P(p) = P_p - \frac{P_e \sin(\theta_e)}{\sin(\theta_p)} \quad (1)$$

ΔE_{Beam} vs $\Delta E'_e$

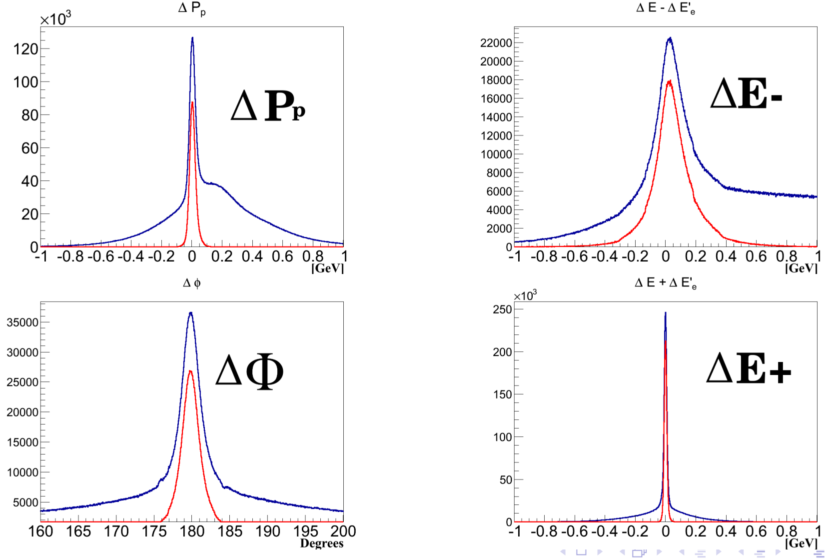
Δ E and Δ E'$_e$ are correlated, so we cut on the sum (Δ E+) and difference (Δ E−)



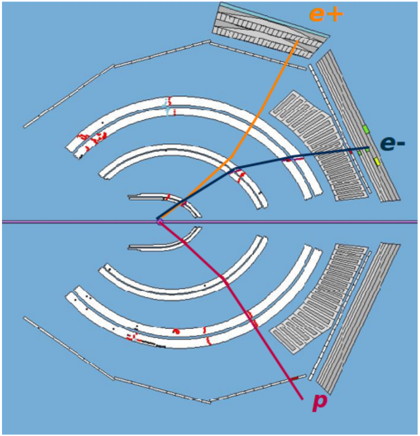


Kinematic Cuts

No cuts Apply other 3 kinematic cuts

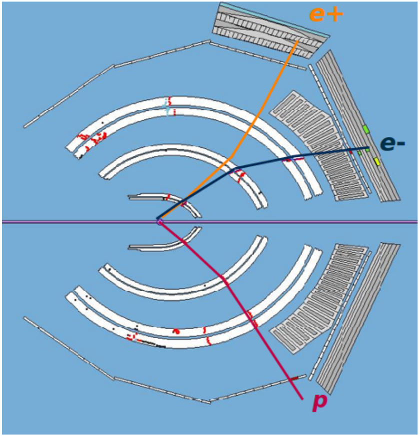


Ratios



1. Apply fiducial cuts to select regions where both e^- and e^+ can both be detected

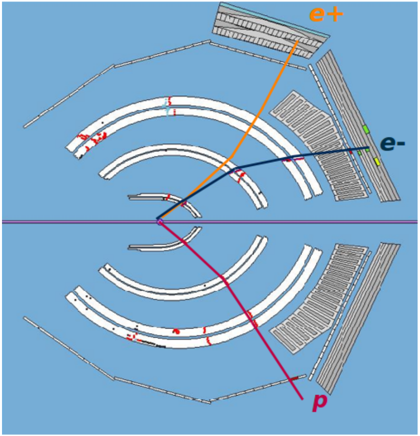
Ratios



1. Apply fiducial cuts to select regions where both e^- and e^+ can both be detected
2. Measure Elastic Scattering Ratio : Proton acceptance cancels in the ratio

$$R = \frac{Y(e^+P)}{Y(e^-P)}$$

Ratios



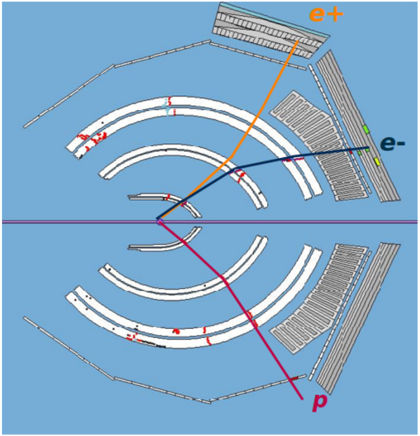
1. Apply fiducial cuts to select regions where both e^- and e^+ can both be detected
2. Measure Elastic Scattering Ratio : Proton acceptance cancels in the ratio

$$R = \frac{Y(e^+P)}{Y(e^-P)}$$

3. Flip torus polarity : Lepton acceptance cancels in double ratio

$$R_2 = \sqrt{\left[\frac{Y_{e^+P}}{Y_{e^-P}}\right]^+ \times \left[\frac{Y_{e^+P}}{Y_{e^-P}}\right]^-}$$

Ratios



1. Apply fiducial cuts to select regions where both e^- and e^+ can both be detected
2. Measure Elastic Scattering Ratio : Proton acceptance cancels in the ratio

$$R = \frac{Y(e^+P)}{Y(e^-P)}$$

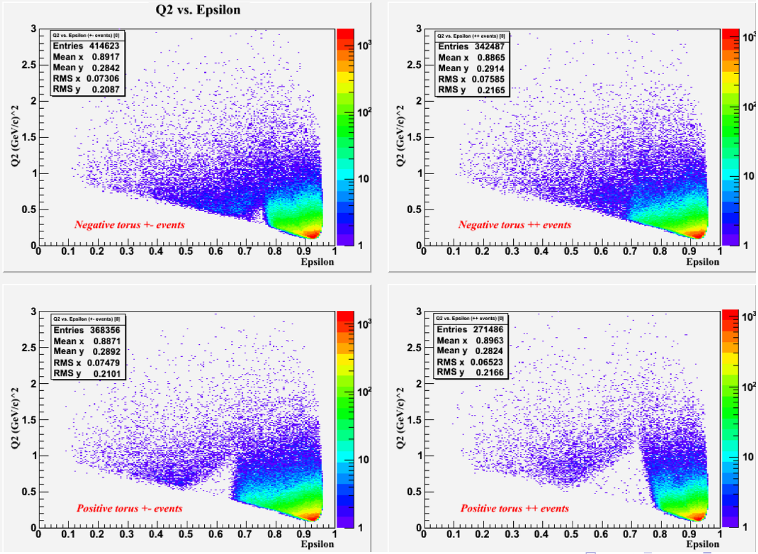
3. Flip torus polarity : Lepton acceptance cancels in double ratio

$$R_2 = \sqrt{\left[\frac{Y_{e^+P}}{Y_{e^-P}}\right]^+ \times \left[\frac{Y_{e^+P}}{Y_{e^-P}}\right]^-}$$

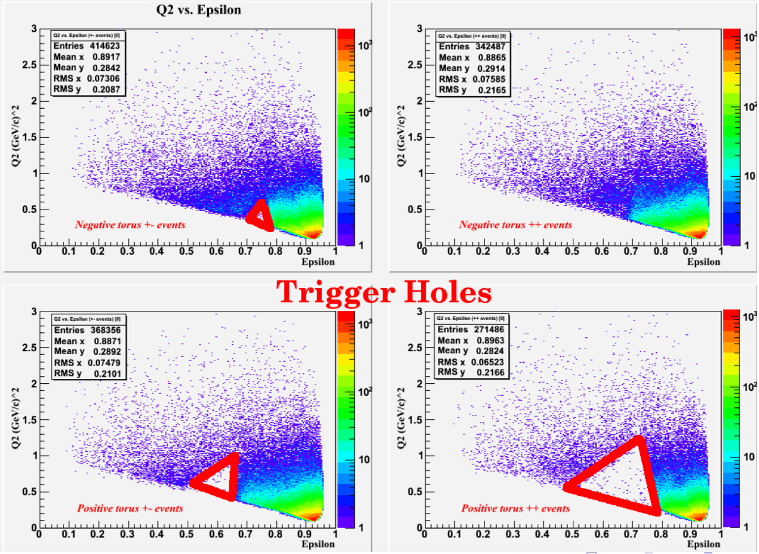
4. Flip chicane polarity: Beam asymmetries cancel in quadruple ratio

$$R_4 = \sqrt{R_2^+ \times R_2^-}$$

Q^2 vs ε (TPE II 2010-2011)



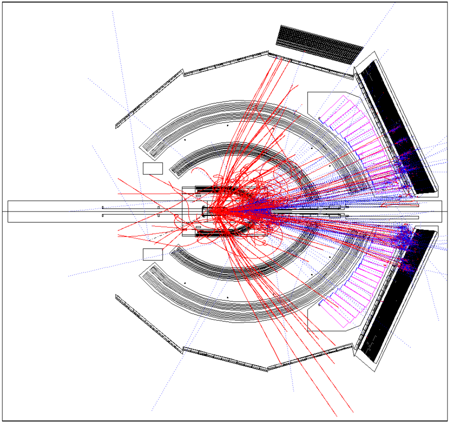
Q^2 vs ε (TPE II 2010-2011)

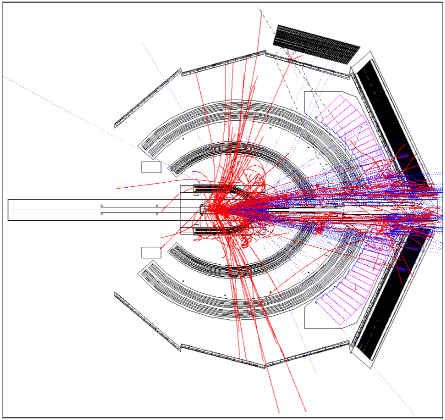


Analysis Issues [In Progress]

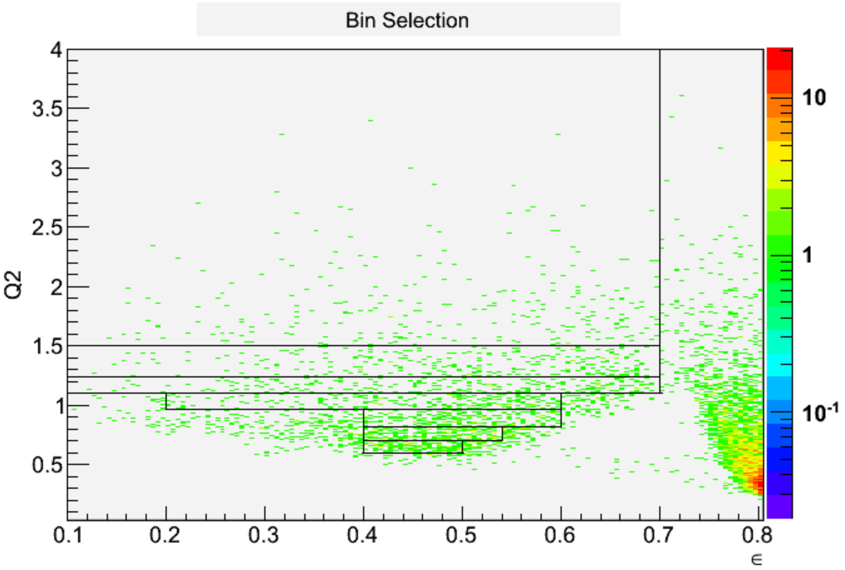
1. High background rates $10 - 15\%$ losses for relative timing. Will use timing for systematic error checks only.
2. Need to account for dead detector channels
   - Swimming
   - Simulations
3. Background subtraction
   - Fitted
   - Sampled
   - Mixed Events

GSIM [In Progress]

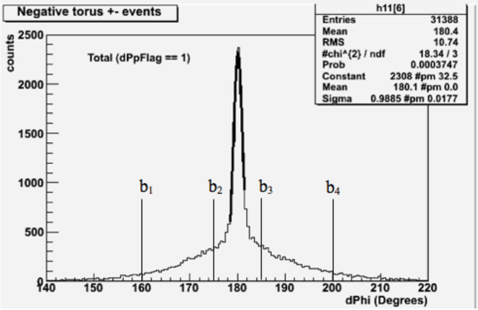


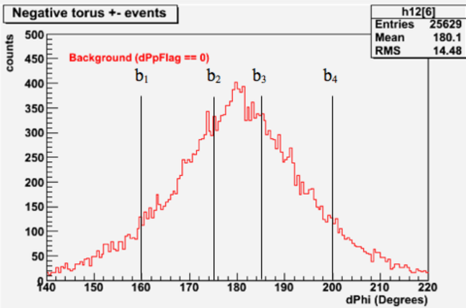


Low ε Bins



Background Subtraction [Method I]

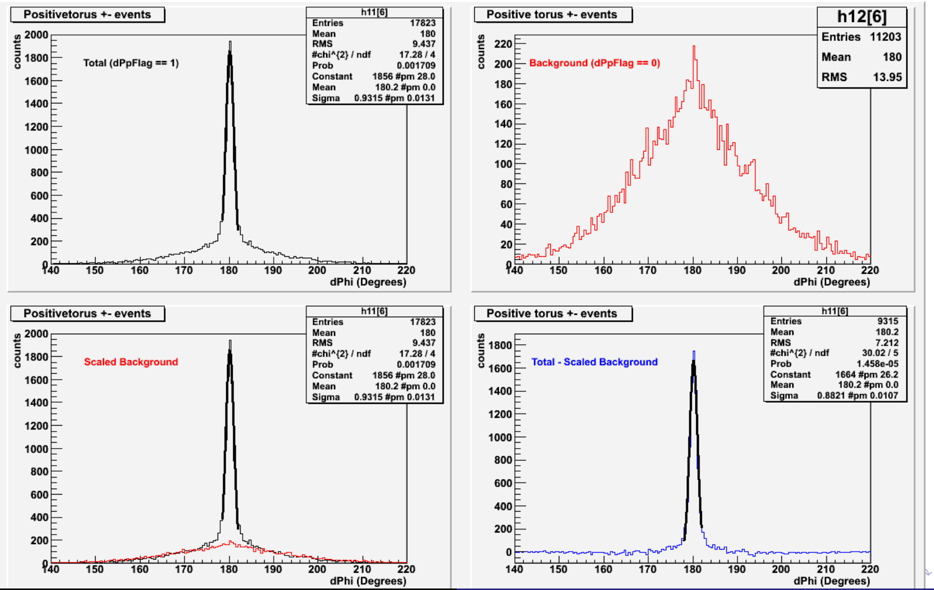




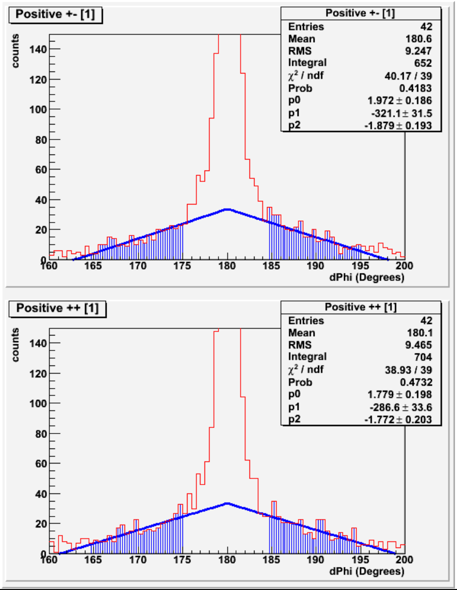
- p_1 = no. of events in bins b1 - b2 in total (signal)
- p_2 = no. of events in bins b3 - b4 in total (signal)
- bg_1 = no. of events in bins b1 - b2 in background
- bg_2 = no. of events in bins b3 - b4 in background
- Scale Factor

$$S = \frac{(p_1 + p_2)}{(bg_1 + bg_2)}$$

Background Subtraction [Method I]

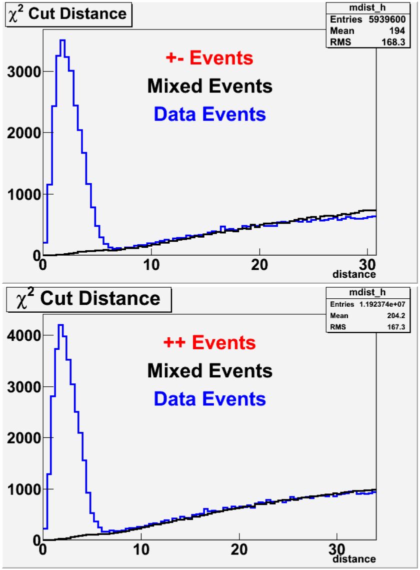


Background Subtraction [Method II]



- Fit back ground
- Polynomial fits to wings
- Subtract fits from ditstribution

Background Subtraction [Method III: Event Mixing]

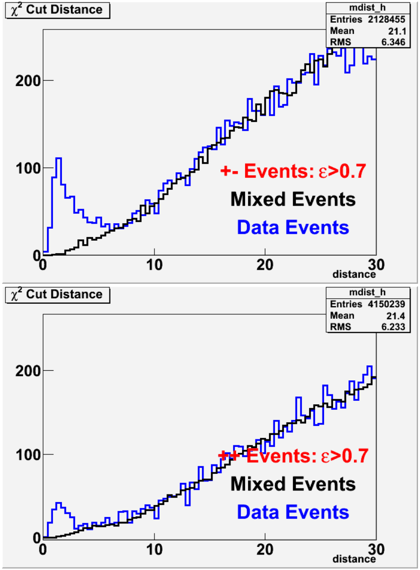


- Define distance:

$$d = \sqrt{N(\sigma_\phi)^2 + N(\sigma_{E+})^2 + N(\sigma_{E-})^2 + N(\sigma_{Pp})^2}$$

- Mix Events
  → Pair particle from Event$_i$ with particle from Event$_j$
  → Z-vertex, two charge and minimum energy cuts
- Scale Mixed Events
  Scalefactor = Data Area/Mixed Area

Method III: Event Mixing Low ε



- Define distance:

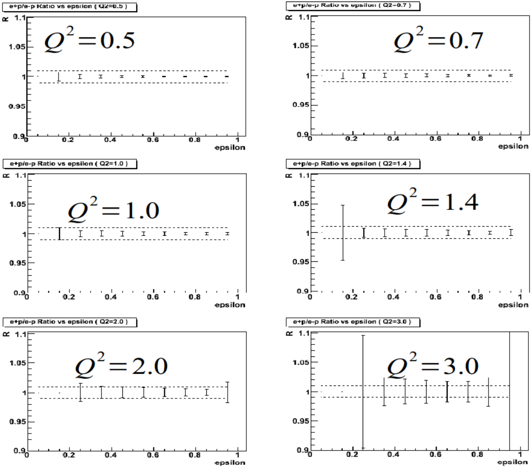
$$d = \sqrt{N(\sigma_\phi)^2 + N(\sigma_{E+})^2 + N(\sigma_{E-})^2 + N(\sigma_{Pp})^2}$$

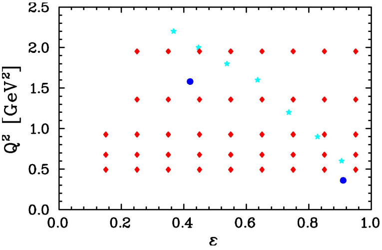
- Mix Events
  $\rightarrow$ Pair particle from Event$_i$ with particle from Event$_j$
  $\rightarrow$ Z-vertex, two charge and minimum energy cuts
- Scale Mixed Events
  Scalefactor = Data Area/Mixed Area

Radiative Corrections [In Progress]

- Standard treatment [known beam energy]:
  - Type I: e-p scattering with the electron detected
  - Type II: e-p scattering with the proton detected
  - Calculate σ_{RC}/σ_B
- CLAS TPE treatment
  - Type III: e-p scattering bremsstrahlung with the electron and proton detected
  - Not trivial due to our cuts non monochromatic beam.
  - Resolution: Simulate & integrate
  - ELRADGEN (hep-ph/088106)

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
- CLAS experiment will be able to obtain $< 1\%$ statistical and systematic uncertainties out to $Q^2 = 2GeV^2$

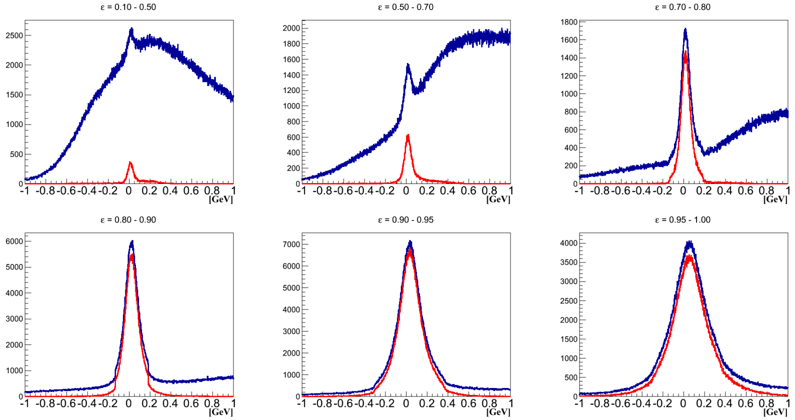
Summary

- TPE Analysis uses non-standard PID & event selection
  $\rightarrow$ Exploit over constrained kinematics
- Working on simulations for detector holes & acceptance
- Trying several background subtraction methods for low ε events
- Special care in radiative correctiosn due to Non-standard experimental setup and elastic cuts
- Expect first results this fall

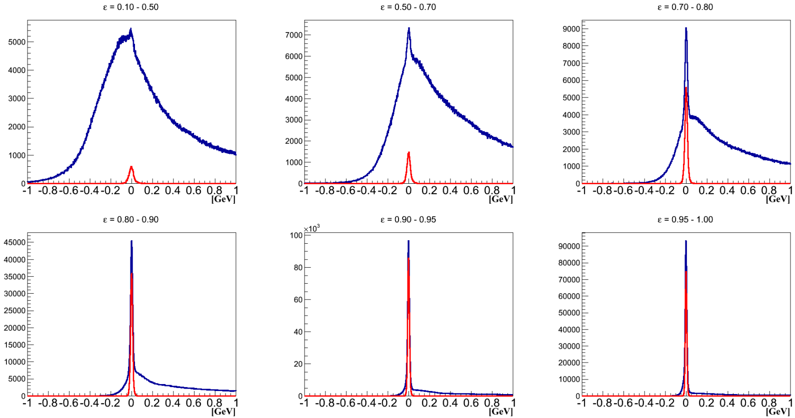
Thank you

Thank you

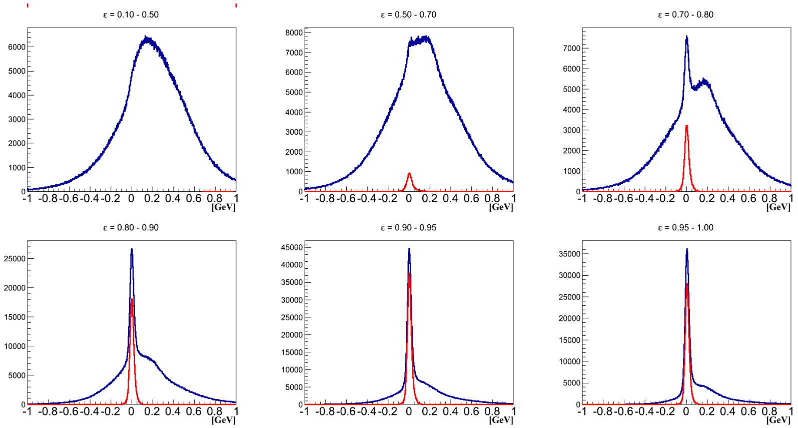
Δ E —: ε Dependence



Δ E +: ε Dependence



Δ P_p : ε Dependence



Personnel

1. **Spokes Persons**
   - 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