Two Photon Exchange (TPE) and the Proton Form Factor Problem

Larry Weinstein

Old Dominion University

With Dasuni Adikaram, Dipak Rimal, Robert Bennett, Puneet Khetarpal, Mauri Ungaro, Brian Raue, Will Brooks, John Arrington, …

1. Problem: Factor of 3 discrepancy in G_E^p
2. Solution: Compare H(e±,e±) cross sections to measure TPE
   1. Important problem ➔ high profile competition
3. Aggressive Measurement: make high energy e+ in Hall B
4. Challenging Analysis
5. Preliminary Results (much better than published data)
6. Summary

The Proton Charge Formfactor
Why do we care?

To compare to models of the proton:

- The ratio of the electric and magnetic formfactors, $G_{\mathbf{E}}(Q^2)/G_{\mathrm{M}}(Q^2)$, gives information about the relative distributions of the **quark longitudinal momenta** and **transverse positions**
- Nonrelativistically, ${G_{\mathrm{E}}}^2(Q^2)$ is the Fourier transform of the charge distribution.

To build models of the nucleus and answer questions like:

- is the proton modified in the nucleus?
- where does color transparency start?

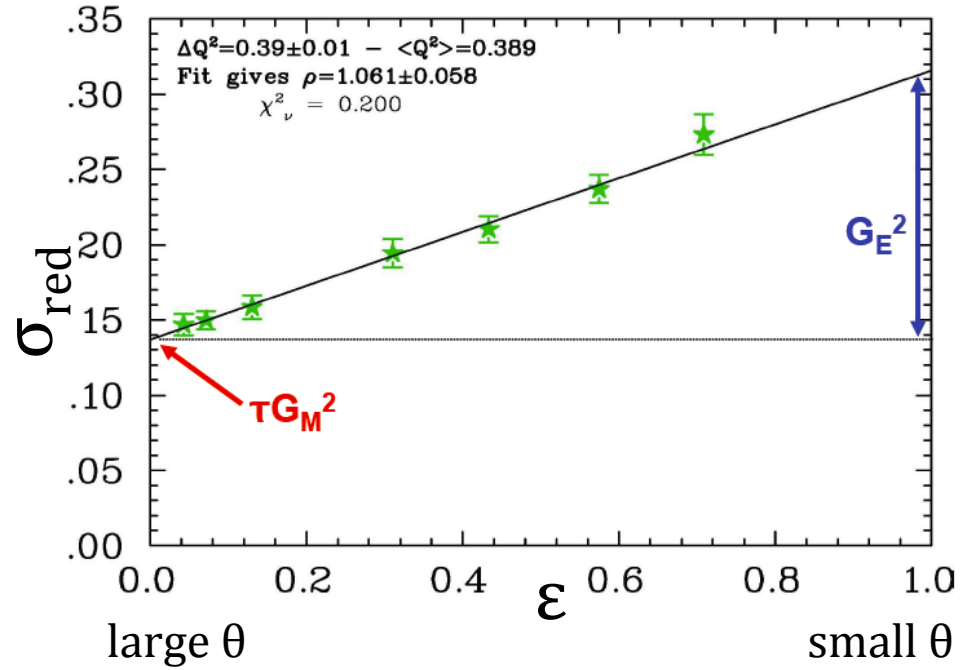
G_E^p and Rosenbluth Separation

$$\sigma_R = \left[\varepsilon G_E^2\left(Q^2\right) + \tau G_M^2\left(Q^2\right)\right]$$

$$\tau = \frac{Q^2}{4m_p}$$

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

Measure H(*e,e'*) reduced cross section as a function of ε (angle) for fixed values of Q^2.

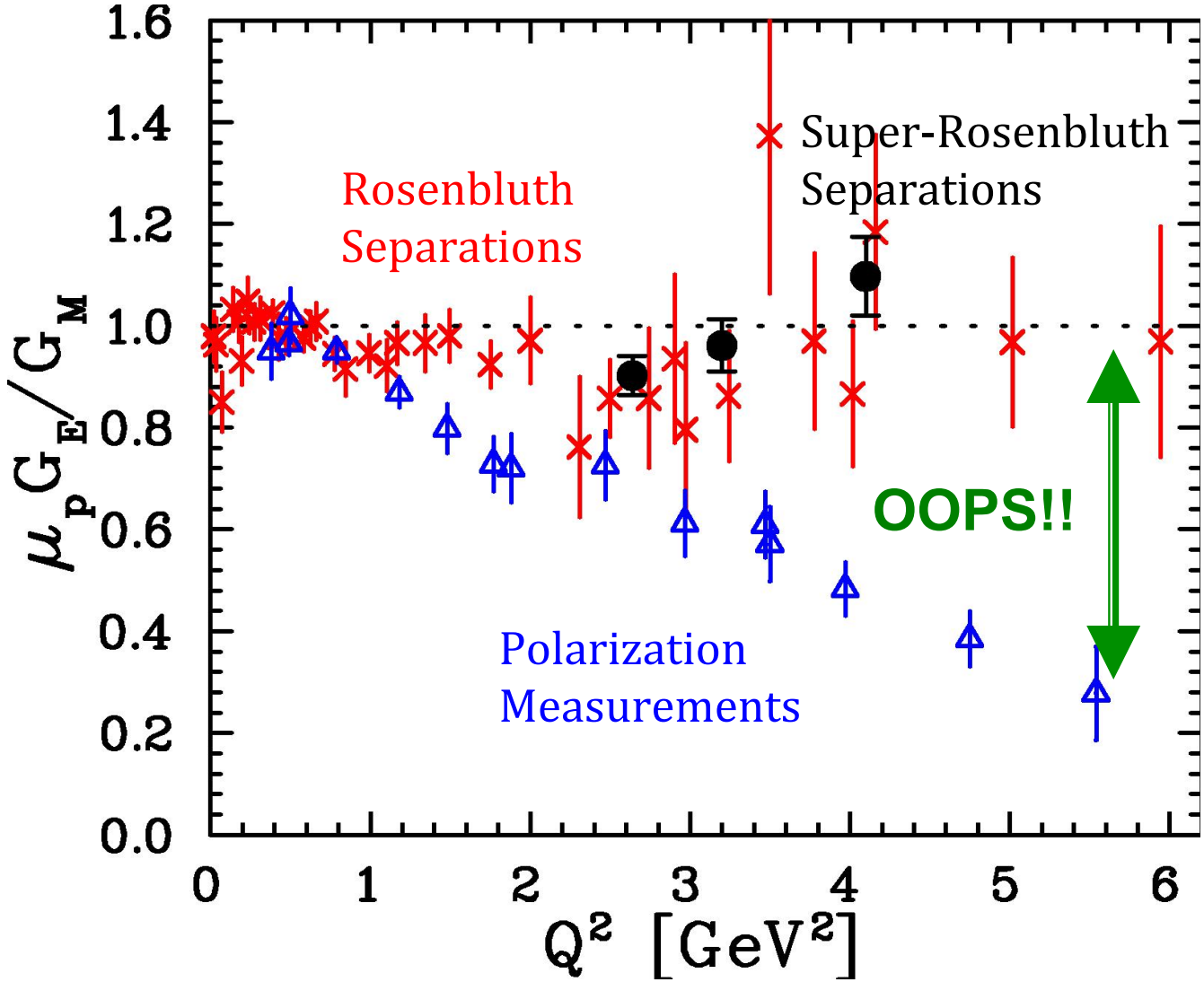


G_E^p and Polarization Transfer

Measure transverse (P_T) and longitudinal (P_L) polarization of outgoing proton.

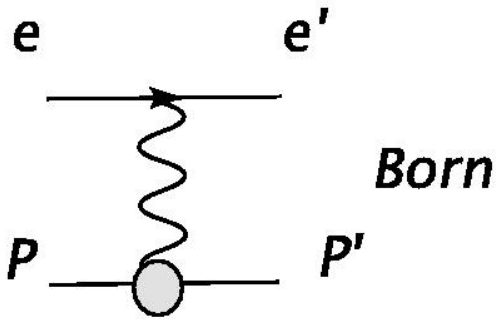
$$\mathrm{H}(\vec{e}, e'\vec{p}) \qquad \frac{G_E}{G_M} = -\frac{P_T}{P_L}\frac{\left(E+E'\right)}{2m_p}\tan\frac{\theta}{2}$$

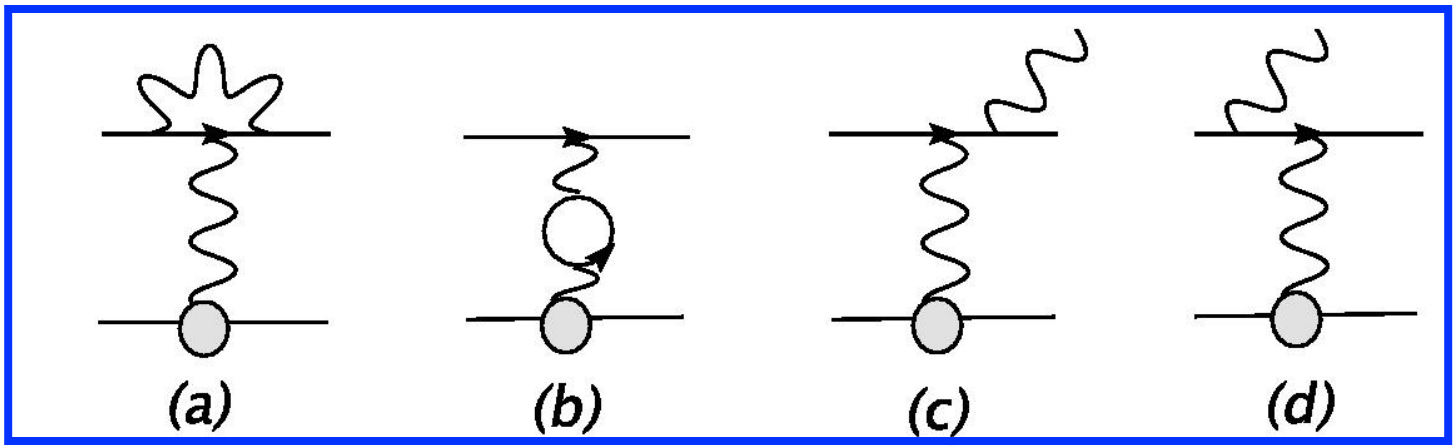
The Proton Charge Form Factor G_E^p



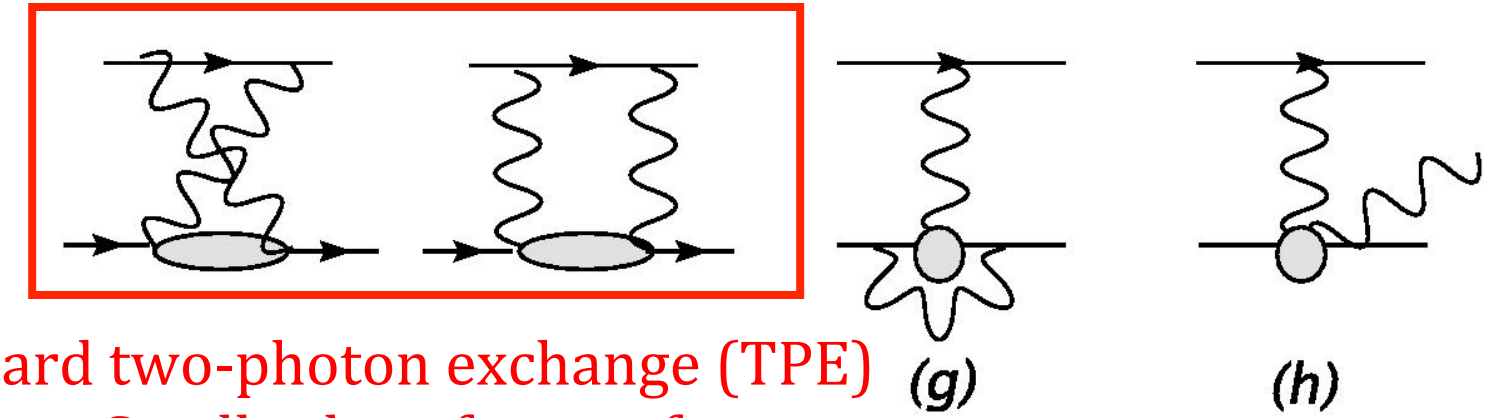
This discrepancy needs to be resolved

Radiative Corrections to Single Photon Exchange





Standard radiative corrections



Hard two-photon exchange (TPE)
Smaller by a factor of α

The TPE Formalism

General 1- and 2-photon exchange amplitude

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

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

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

General 1- and 2-photon exchange cross section

1: $$\frac{d\sigma}{d\Omega} \propto [\tau G_m^2 + \epsilon G_E^2]$$

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

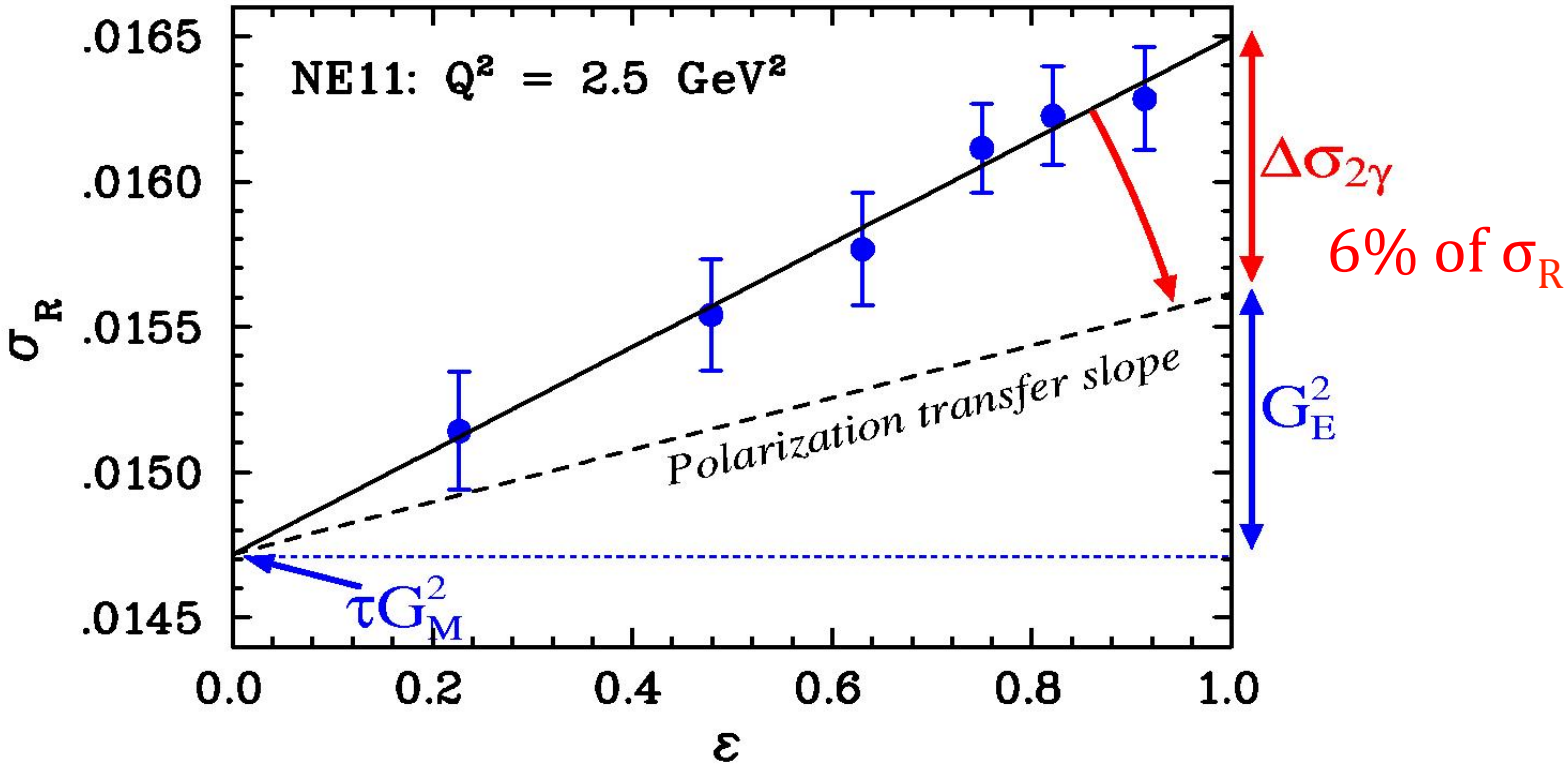
$$Y_{2\gamma} \propto \mathcal{R}\left(\frac{\tilde{F}_3}{|\tilde{G}_m|}\right)$$

Thus we have

- Another ε dependent term
- Modified G_E and G_M

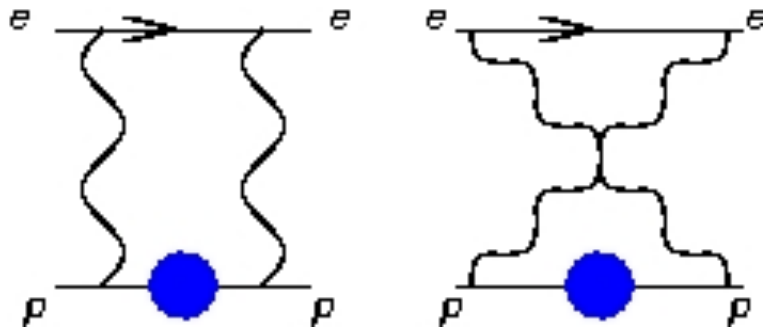
Guichon and Vanderhaegen, PRL 91 (03) 142303

Possible Effect of Two Photon Exchange on Rosenbluth Separation



Small (few %) TPE effects can dramatically change $G_E{}^2$

TPE Calculations are Hard



Doubly-virtual Compton scattering (VVCS)!

Need to integrate over

- All intermediate virtual baryonic states
- All photon energy sharing ➔ wide range of masses of those states

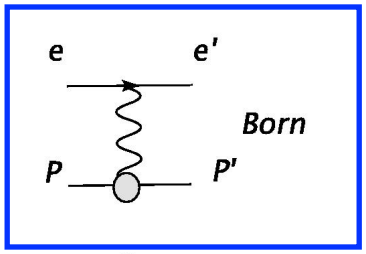
Photocouplings of most states are not known

Typical approximations

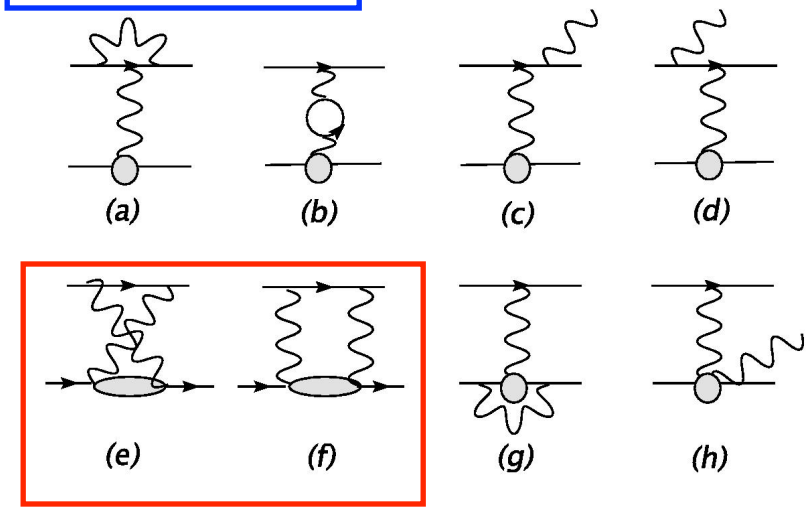
1. Consider only the nucleon and the delta
2. Use GPDs for baryon structure

We need to measure it!

Compare H(e±,e±') to Measure TPE



$A_{\mathrm{Born}} \sim e^{\pm}$
➔changes sign



$A_{2\gamma} \sim (e^{\pm})^2$
➔always positive

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

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

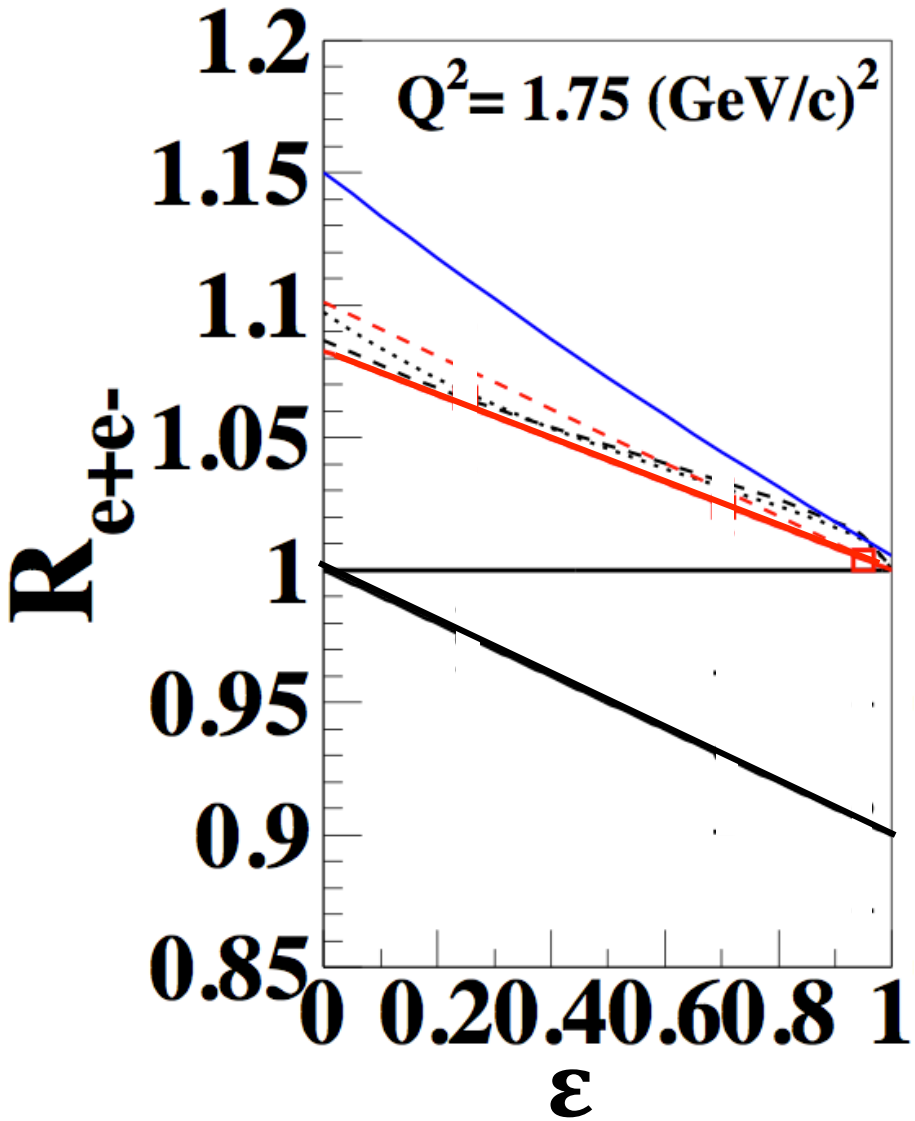
$$R = \frac{\sigma(e^+p)}{\sigma(e^-p)} \approx 1 + \frac{4A_{Born}Re(A_{2\gamma})}{|A_{Born}|^2}$$

R measures the real part of the two photon amplitude

The real part contributes directly to the G_E^p problem.

Phenomenological TPE Extractions

(to make Rosenbluth and Polarization Transfer G_E^p agree)



Parametrize the TPE amplitude and then fit the *e*+/*e*- ratio to the Rosenbluth and polarization transfer data

Different *e*+/*e*- ratios can explain the G_E^p discrepancy

Qattan, Alsaad and Arrington, ArXiv arXiv:1109.1441

Recap:

The Problem:
Rosenbluth/Polarization Transfer discrepancy in $G_{\mathrm{E}}(Q^2)$

The Probable Cause:
Two-Photon Exchange contributions of a few percent

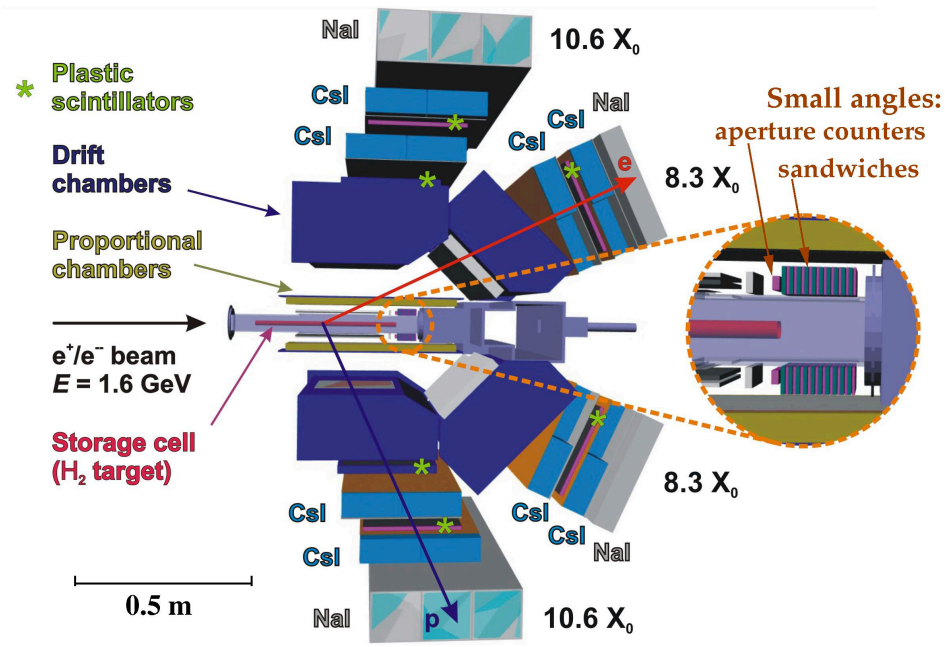
How to test it:
Compare electron and positron elastic scattering from the proton to better than a few percent

- existing data is at low Q^2 and too imprecise

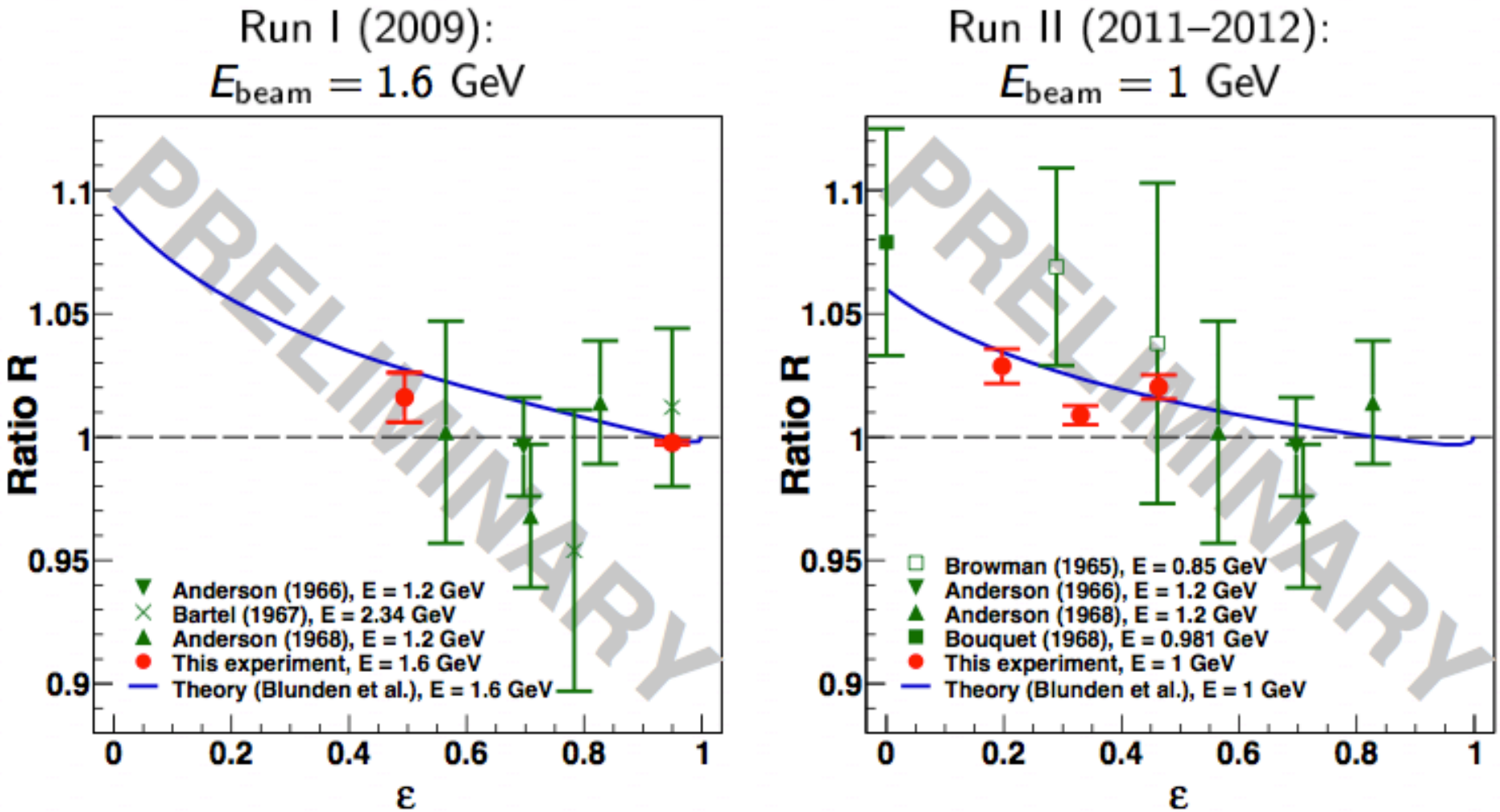
Now where did I leave those positrons …

The Competition: VEPP-3 (Novosibirsk) 2009-2012

- E = 0.6, 1 and 1.6 GeV
- Alternating e+ and e- beams
- Internal target
- Separate large and small angle detectors
- Non-magnetic spectrometer: identical e+/e- detector acceptance
- Preliminary results arXiv: 1112.5369



VEPP-3 Preliminary Results

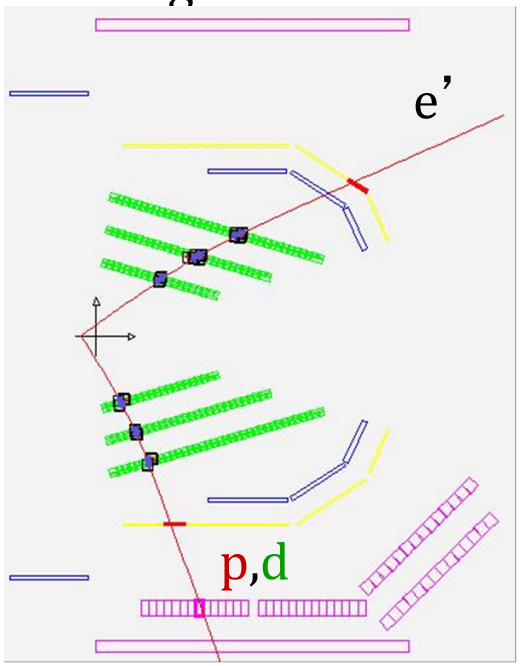


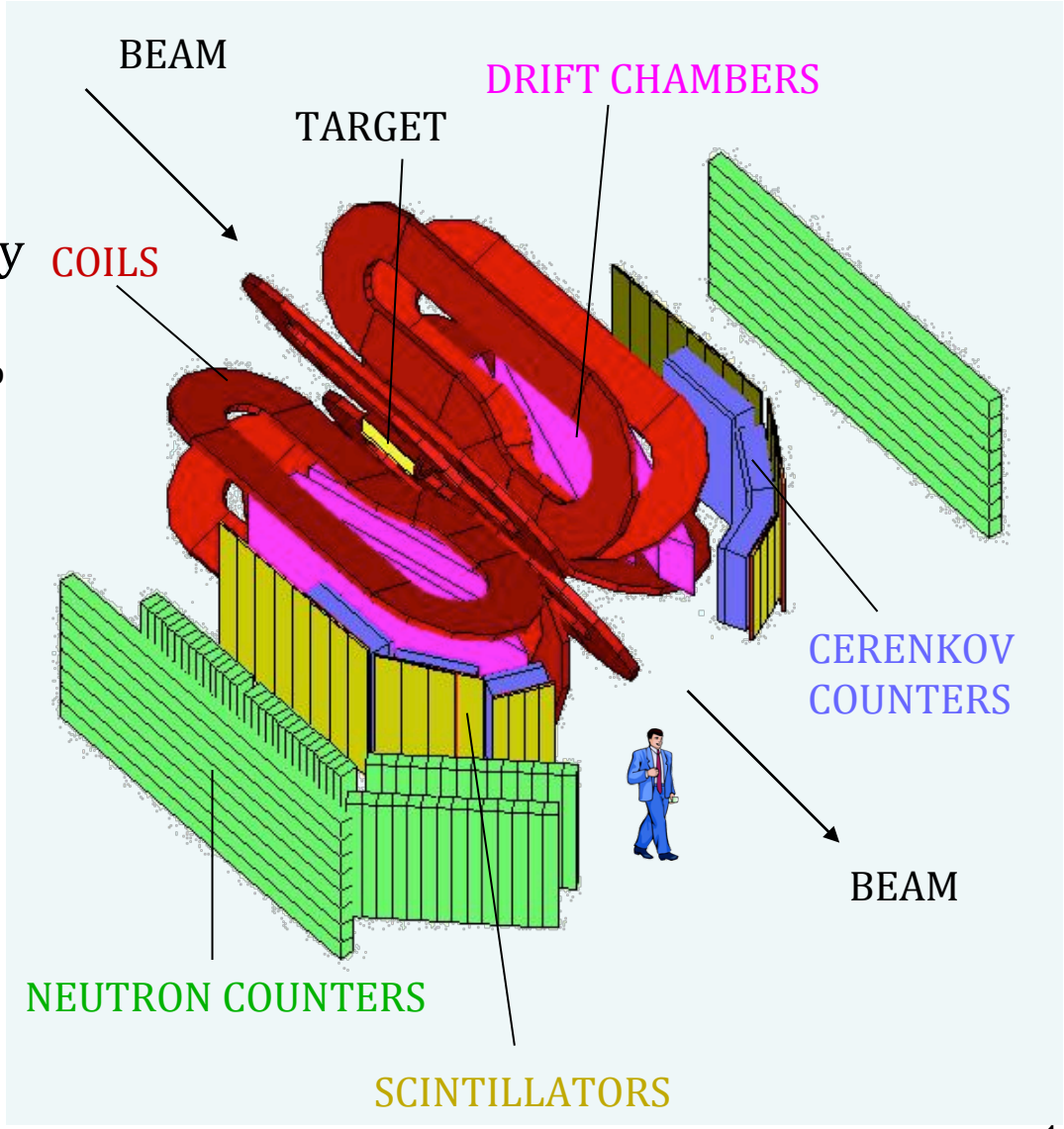
Theory: Blunden et al, Phys. Rev. C 72, 034612 (2005)

Radiative corrections have been applied.
Systematic uncertainties (0.3%) not shown.

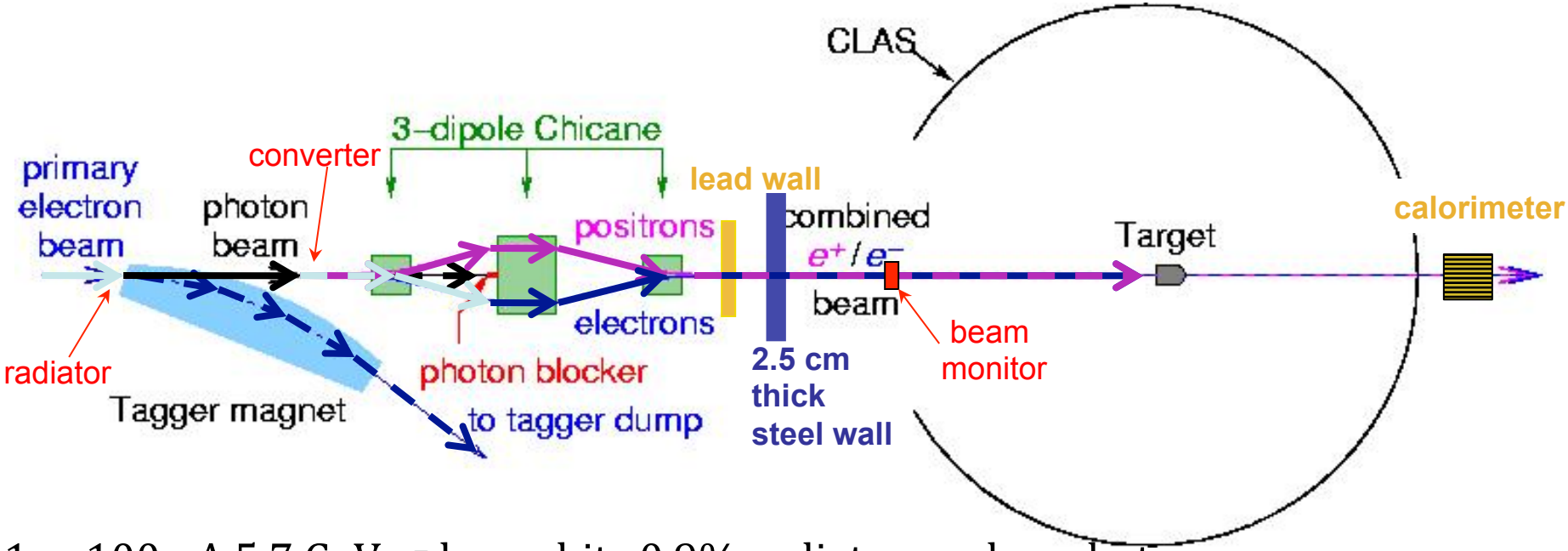
OLYMPUS: BLAST Detector at DESY

- E = 2 GeV
- Alternating e+ and e- beams
- Internal target 10^{15} atom/cm^3
- Forward angle (12°) luminosity monitor
- Continuous coverage 20°—80°
- Taking data NOW!





CLAS: Making Positrons in Hall B



1. 100 nA 5.7 GeV e^- beam hits 0.9% radiator, makes photons
   - Electrons dumped in tagger dump
2. Photon beam hits 9% converter, makes e+/e− pairs
   - e+/e− beams split by 3-dipole chicane
   - Photon beam blocked
   - Low energy leptons blocked
   - Lepton beams recombined
3. Simultaneous e+/e− beams hit 30-cm×6-cm diam hydrogen target in CLAS

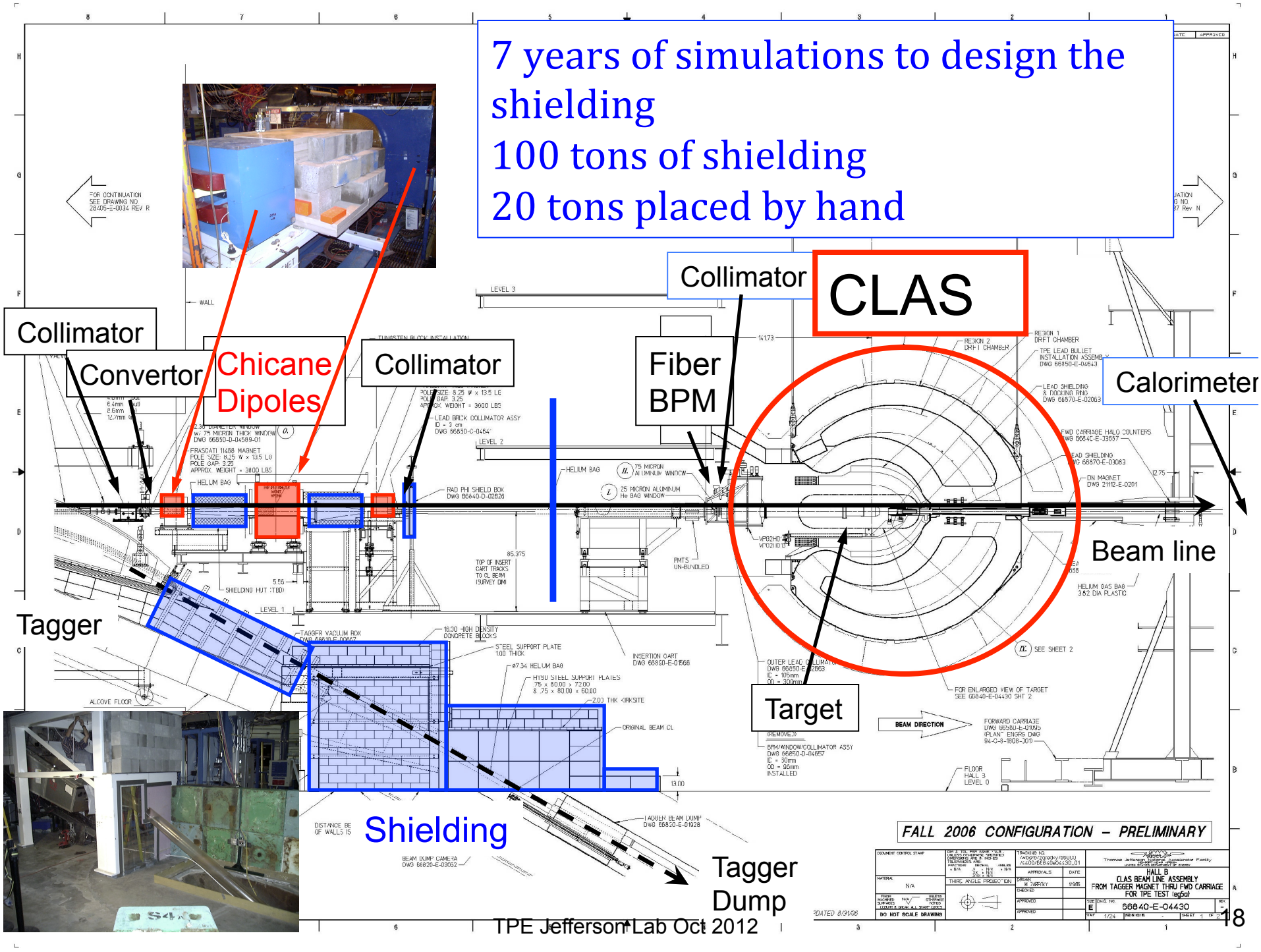
Experiment Features/Bugs

- Simultaneous $e+/e-$ beams (~100 pA each)
- Continuous beam energy distribution
  - Wide Q^2 and angle (ε) coverage
- $e+$ and $e-$ beam position and energy measurements
- Simultaneous e^+p and e^-p cross section measurements
  - Minimize systematic uncertainty
- Reverse Torus magnetic field to cancel acceptance effects
- Reverse chicane magnetic field to cancel beam asymmetries
- Six independent measurements in the 6 CLAS sectors
- Overdetermined *ep* kinematics allows background rejection

Experiment Comparison

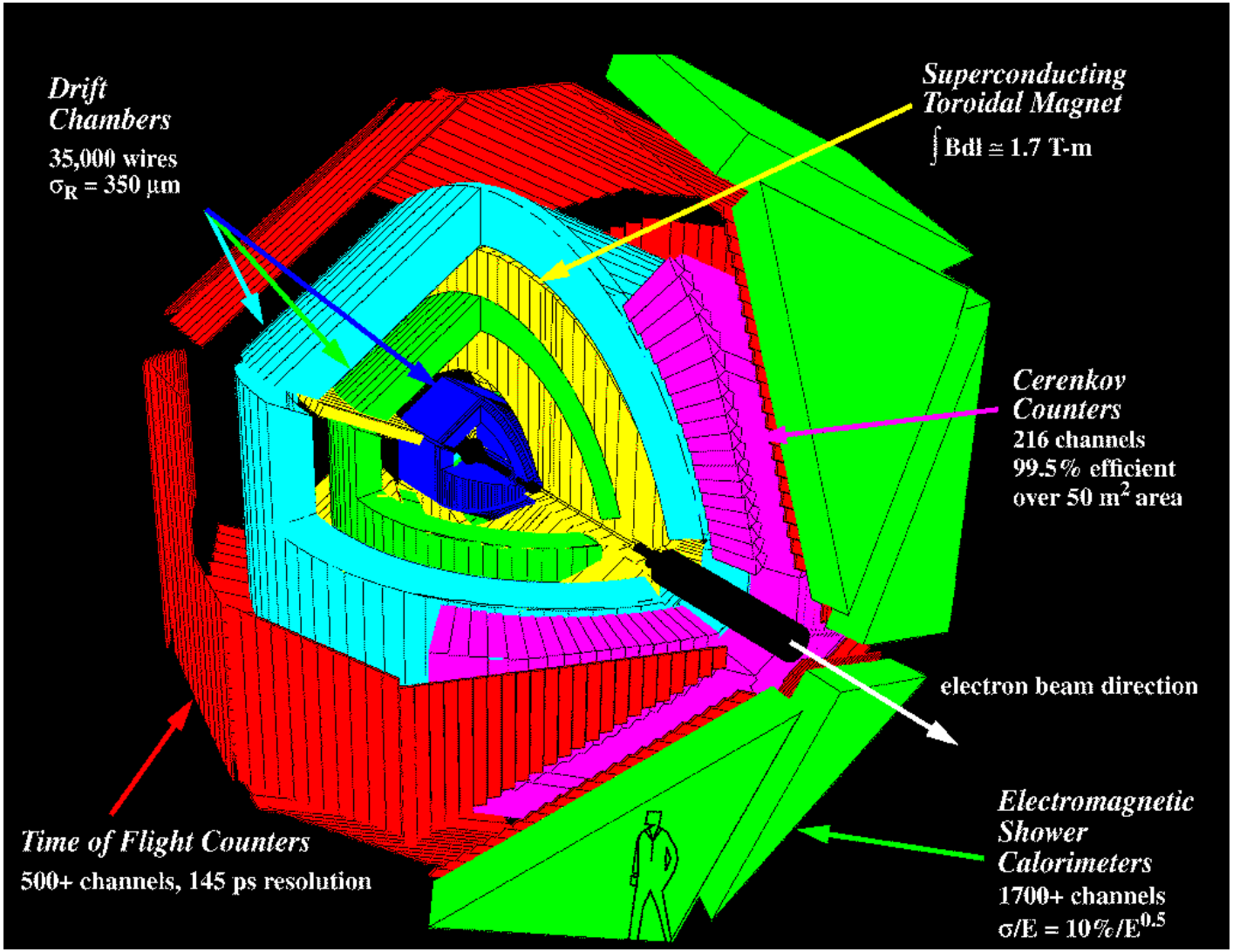
	CLAS	VEPP-3	OLYMPUS
Beam energy	0.8 to 4 GeV	0.6, 1, 1.6 GeV	2 GeV
e+/*e*- swapping frequency	simultaneous	0.5 hour	8 hour
e+/e- luminosity	Calorimeter	Elastic low Q^2	Elastic low Q^2 Moller/Bhabha
ε (angular) coverage	0.2—0.9 25°—140°	Discrete 0.4, 0.9	0.3—0.9 20°—80°
Scattered *e* energy	magnet	calorimeter	magnet
Proton PID	kinematics	ΔE/E, TOF	TOF
e+/*e*- detector acceptance	Not-identical	Identical	Not-identical
Luminosity $cm^{-2}s^{-1}$	2×10^{32}	10^{32}	2×10^{33} (projected)

7 years of simulations to design the shielding
100 tons of shielding
20 tons placed by hand



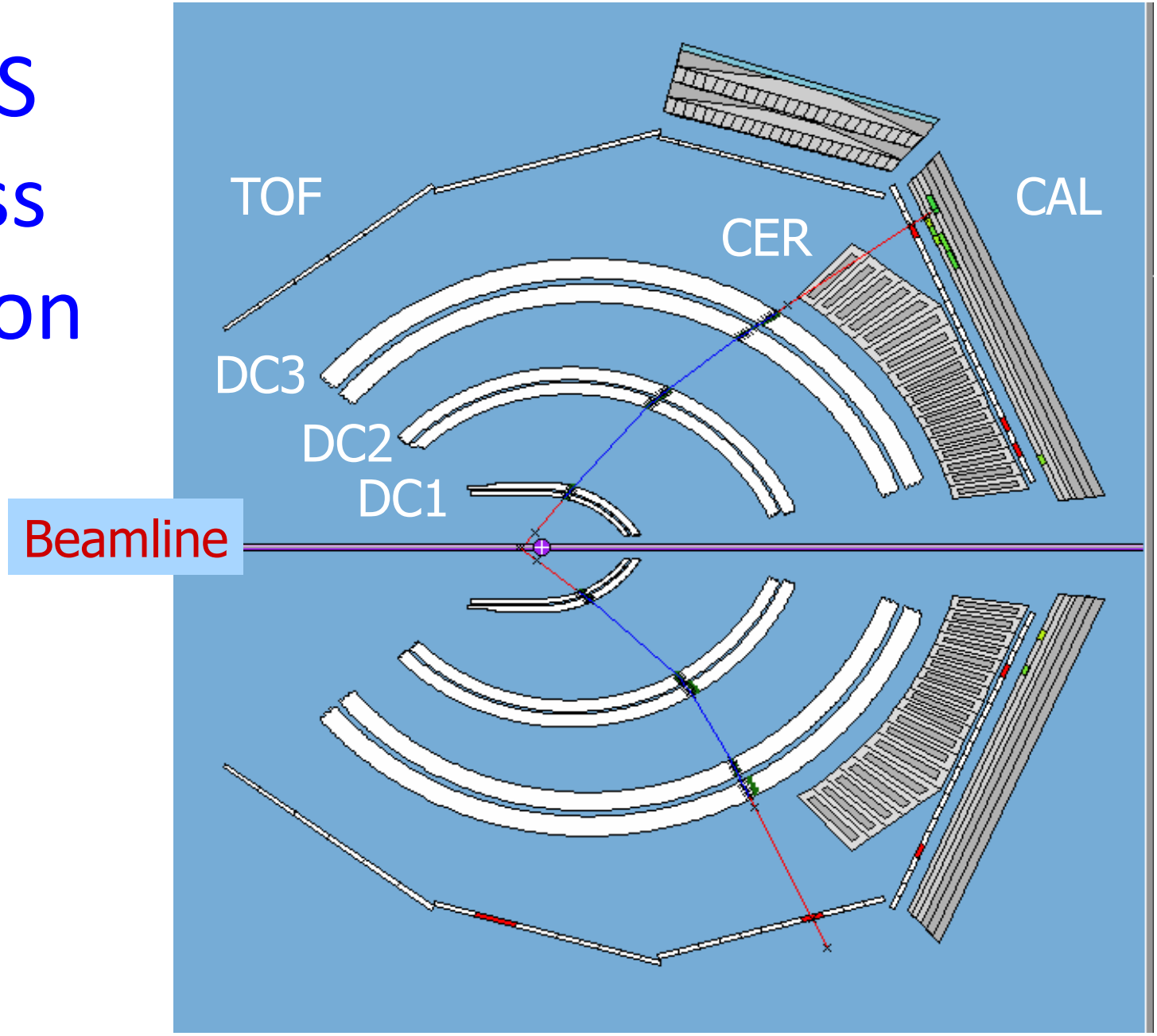
The JLab CLAS

Almost 4π coverage
Six independent sectors



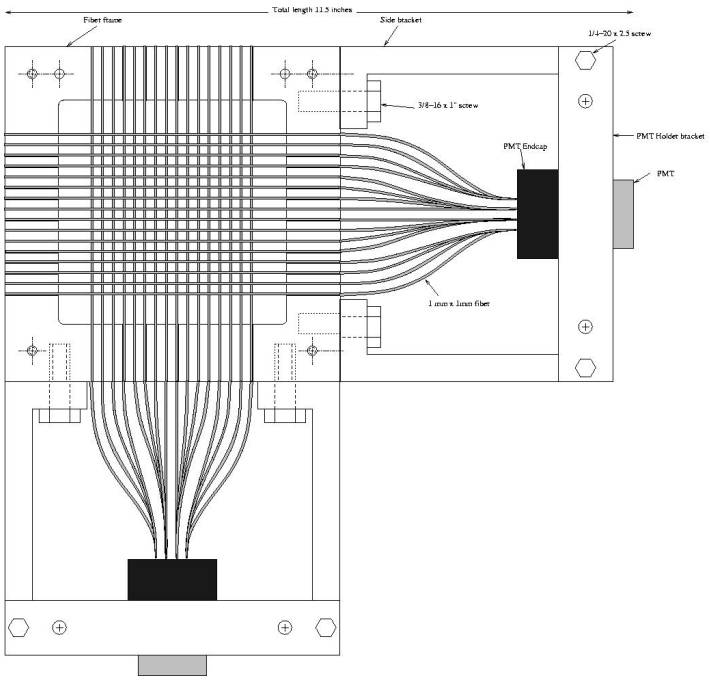
CLAS Cross Section

Sectors 1 and 4

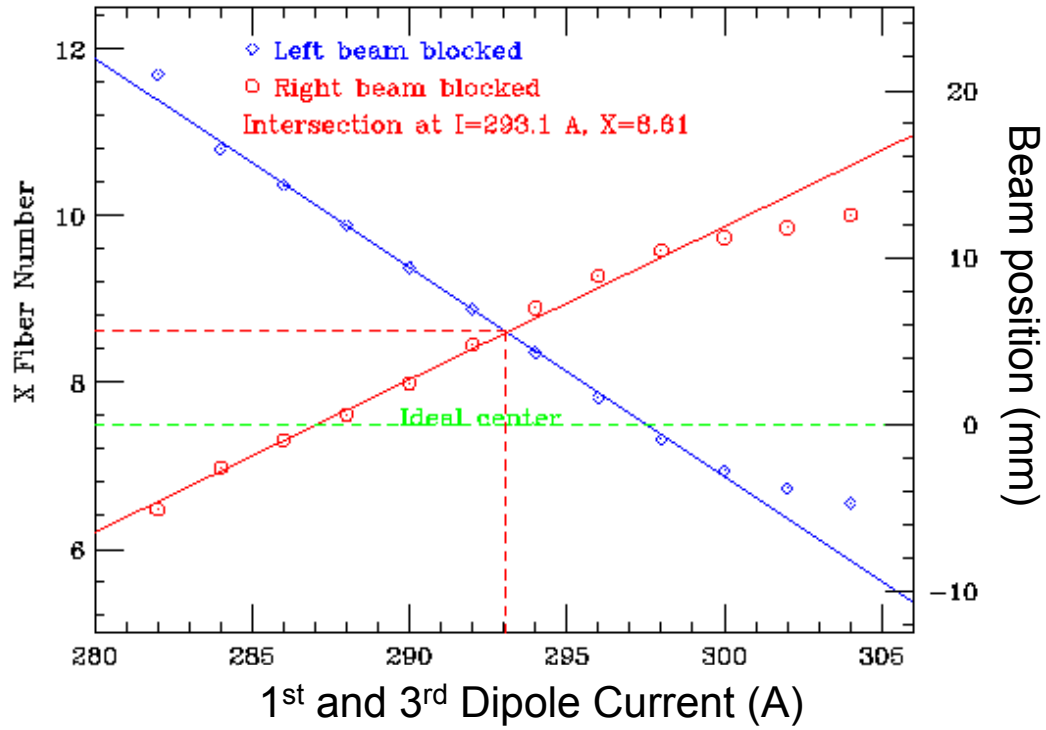


Centering the Lepton Beams

Beam Profile
Fiber Monitor (FIU)

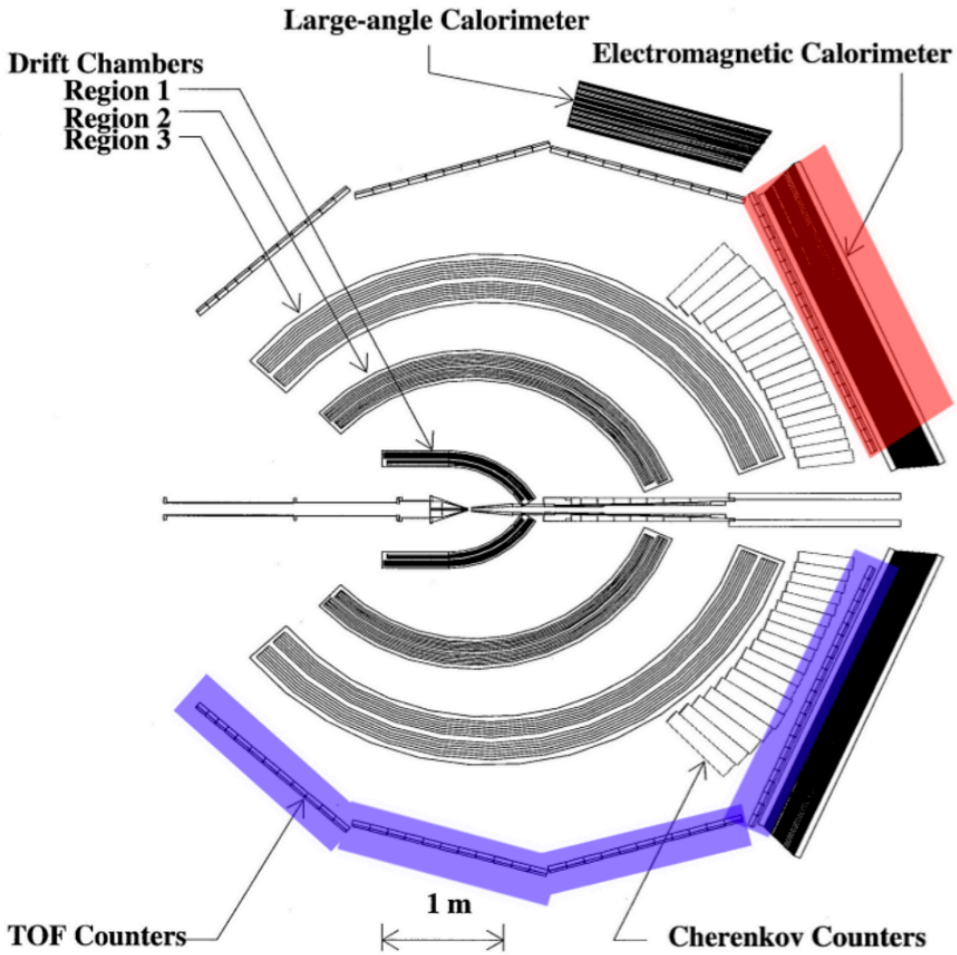


- Block one lepton beam
- Scan chicane dipoles 1&3
- Watch the beam move
- Repeat for the other beam



Repeated each chicane flip
Chicane currents were reproducible

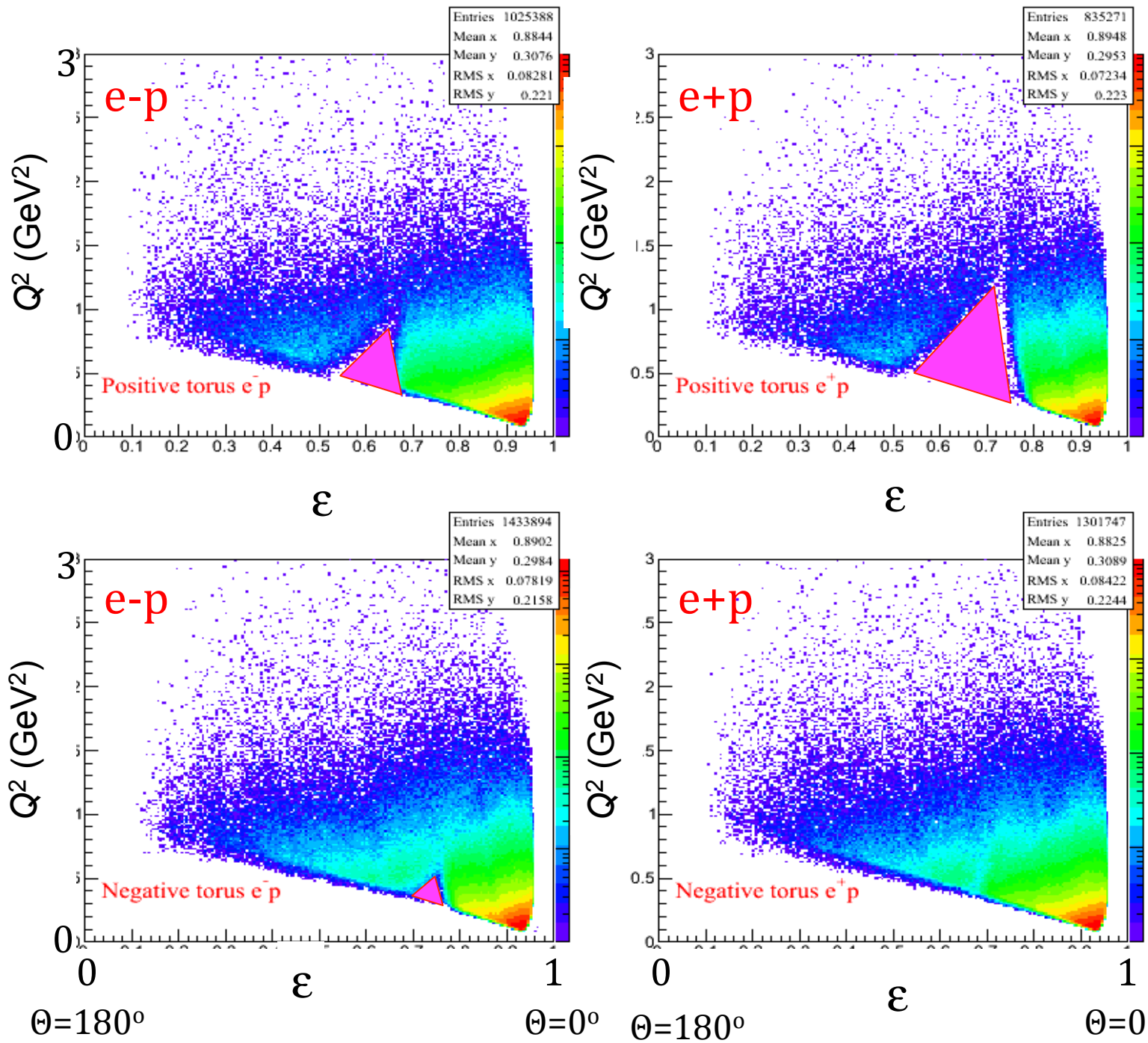
Trigger



- EC (minimum ionizing) & TOF ($\theta<45^o$)
- Any opposite sector TOF

EC needed in trigger to reduce rates

Elastic Kinematic Coverage



Positive torus B field

Trigger holes (no particles with θ<45°)

Negative torus B field

Identifying Elastic Events

Analysis issues:

- Unknown beam energy for a given detected event
- Non-standard particle ID (no CC or EC for lepton ID)
- Need charge-symmetric event analyzer

Analysis solutions:

- Rewrote event analyzer to eliminate electron bias
- Select two charged particles (++ or +-) in opposite sectors
- Elastic kinematic cuts
  - 6 measured quantities ($\theta_l, \varphi_l, p_l, \theta_p, \varphi_p, p_p$)
  - 3 free quantities (e.g., $\theta_l, \varphi_l, \theta_p$)
  - ➔ 3 orthogonal cuts (actually we make 4 cuts)

Elastic Event Identification

1. Reconstructed beam energy: $$E_1 = m_p\left(\cot\frac{\theta_e}{2}\ \cot\theta_p - 1\right)$$

$$E_2 = p_e\cos\theta_e + p_p\cos\theta_p$$

$$\Delta E_{beam} = E_1 - E_2$$

2. Scattered lepton energy: $$\Delta E'_e = E'^{meas}_e - \frac{m_p E_1^{beam}}{E_1^{beam}\left(1-\cos\theta_e\right)+m_p}$$

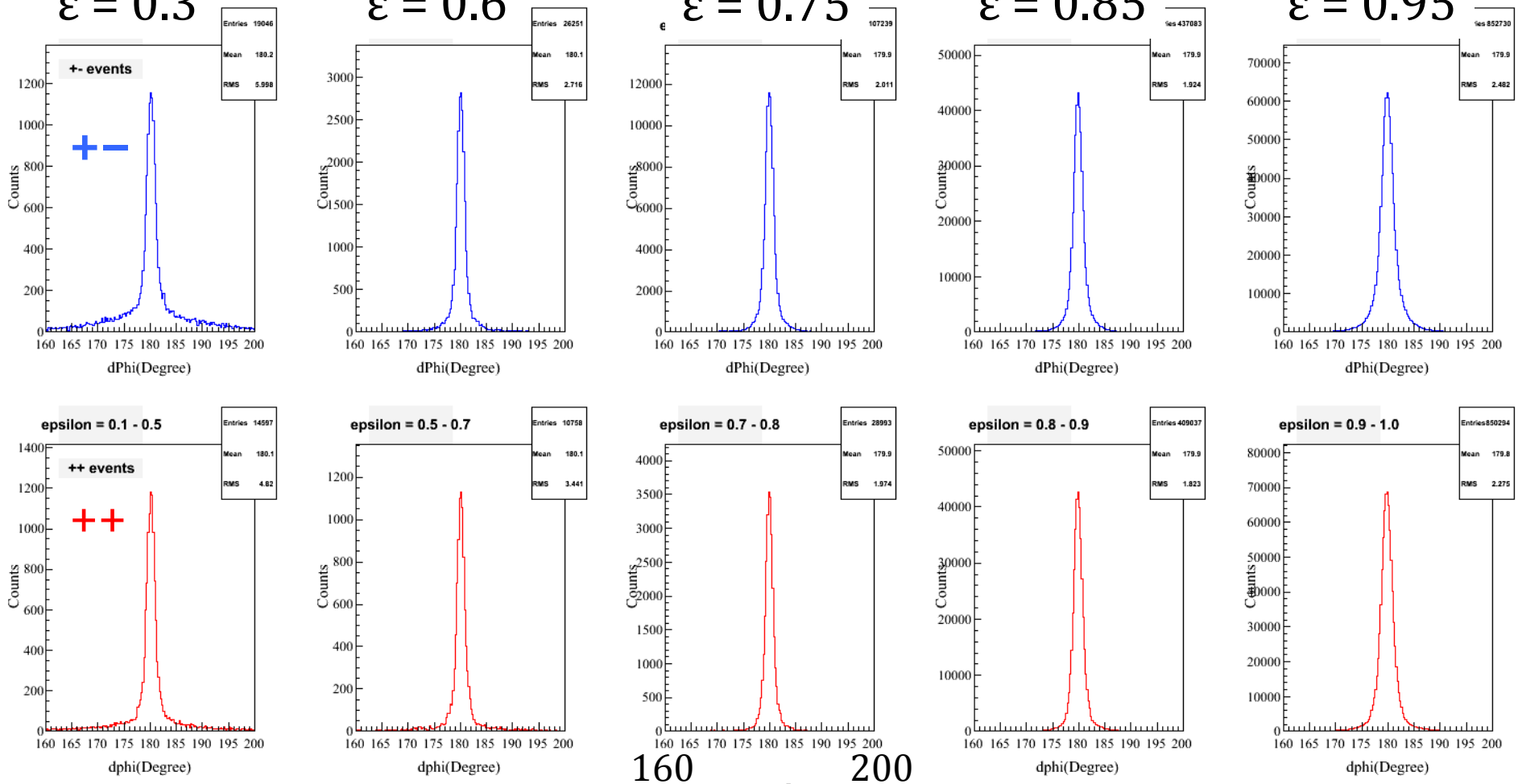
3. Proton momentum: $$\Delta p_p = p_p^{meas} - \frac{p_e\sin\theta_e}{\sin\theta_p}$$

4. Coplanarity: $$\Delta\phi = \phi_p - \phi_e$$

ΔΦ: Cut on other 3

(backward angle) (forward angle)

ε = 0.3 ε = 0.6 ε = 0.75 ε = 0.85 ε = 0.95



160 200

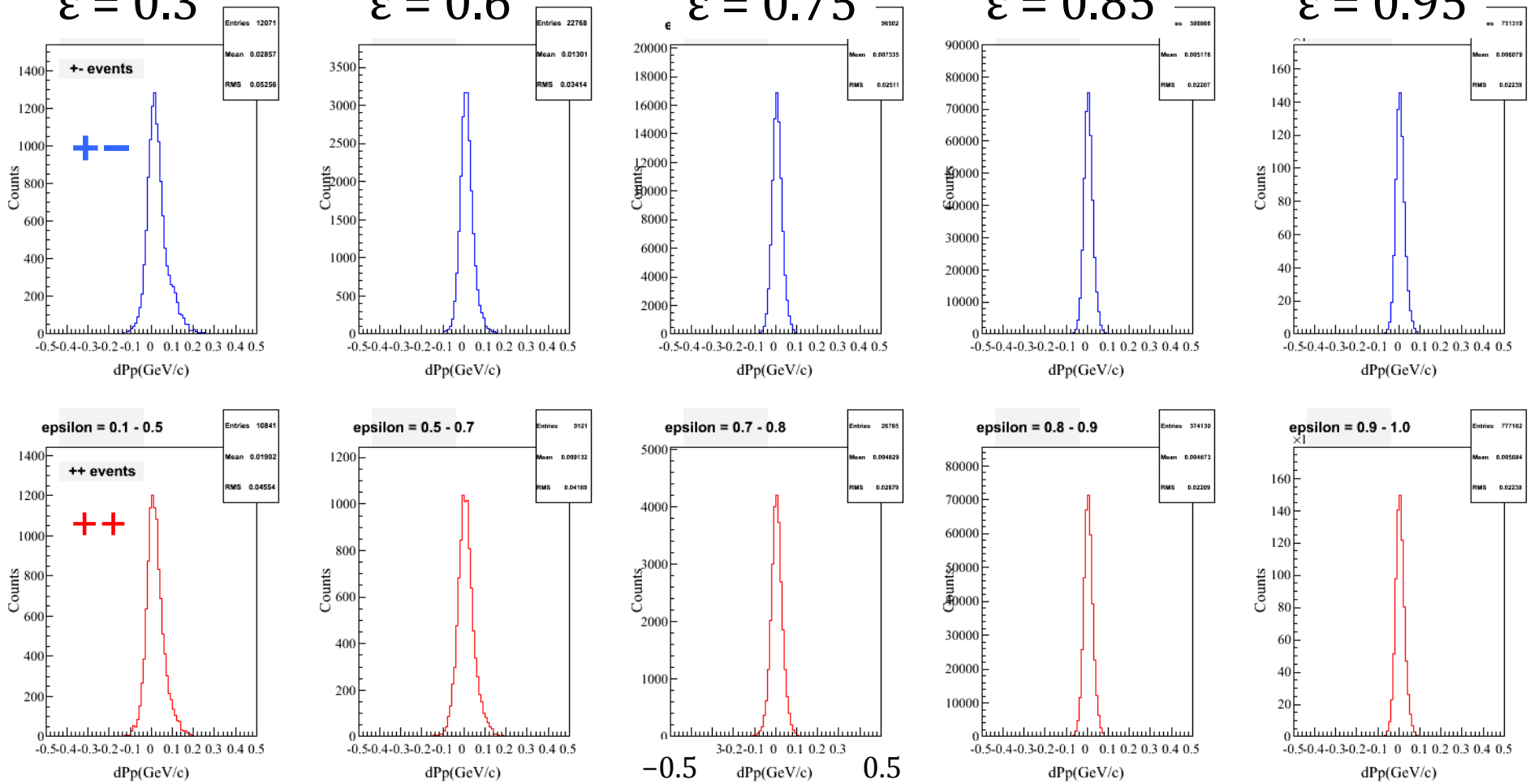
Δϕ

Very little background for ε > 0.7

ΔP_p: Cut on other 3

(backward angle) (forward angle)

ε = 0.3 ε = 0.6 ε = 0.75 ε = 0.85 ε = 0.95



−0.5 0.5

ΔP_p (GeV/c)

Elastic Event Identification

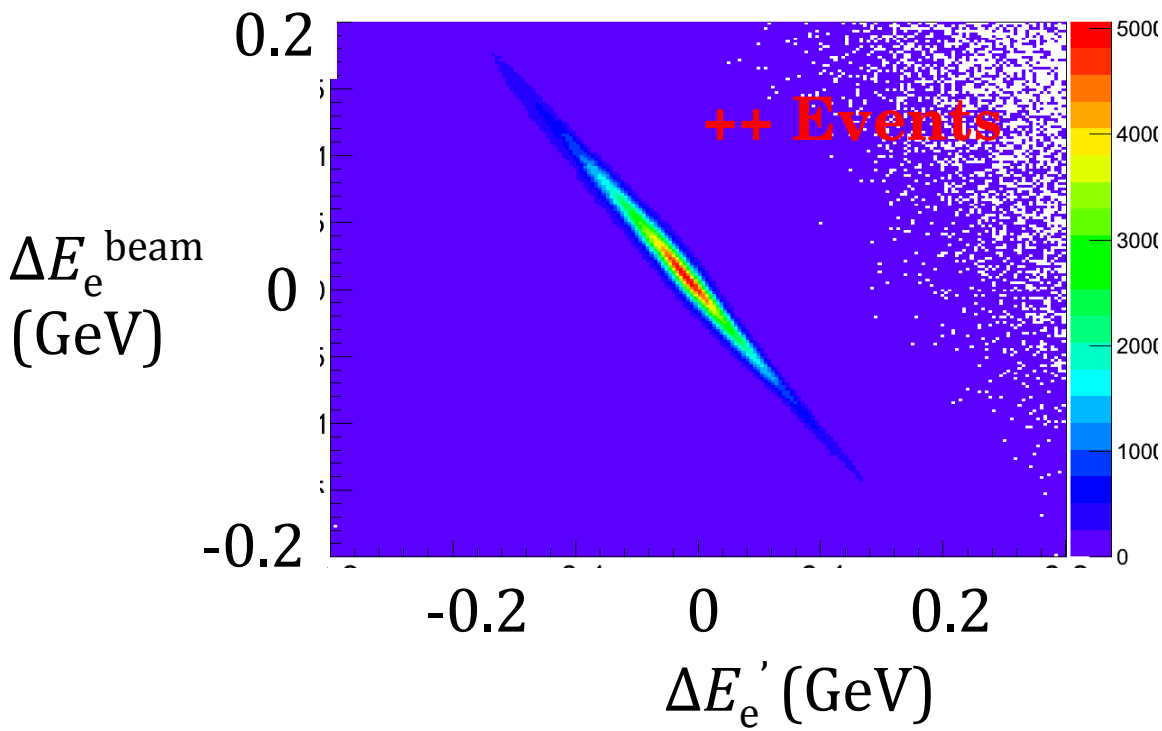
ΔE_{beam} and ΔE_{e} are correlated so make cuts on

$$\Delta E+ = \Delta E_{beam} + \Delta E'$$

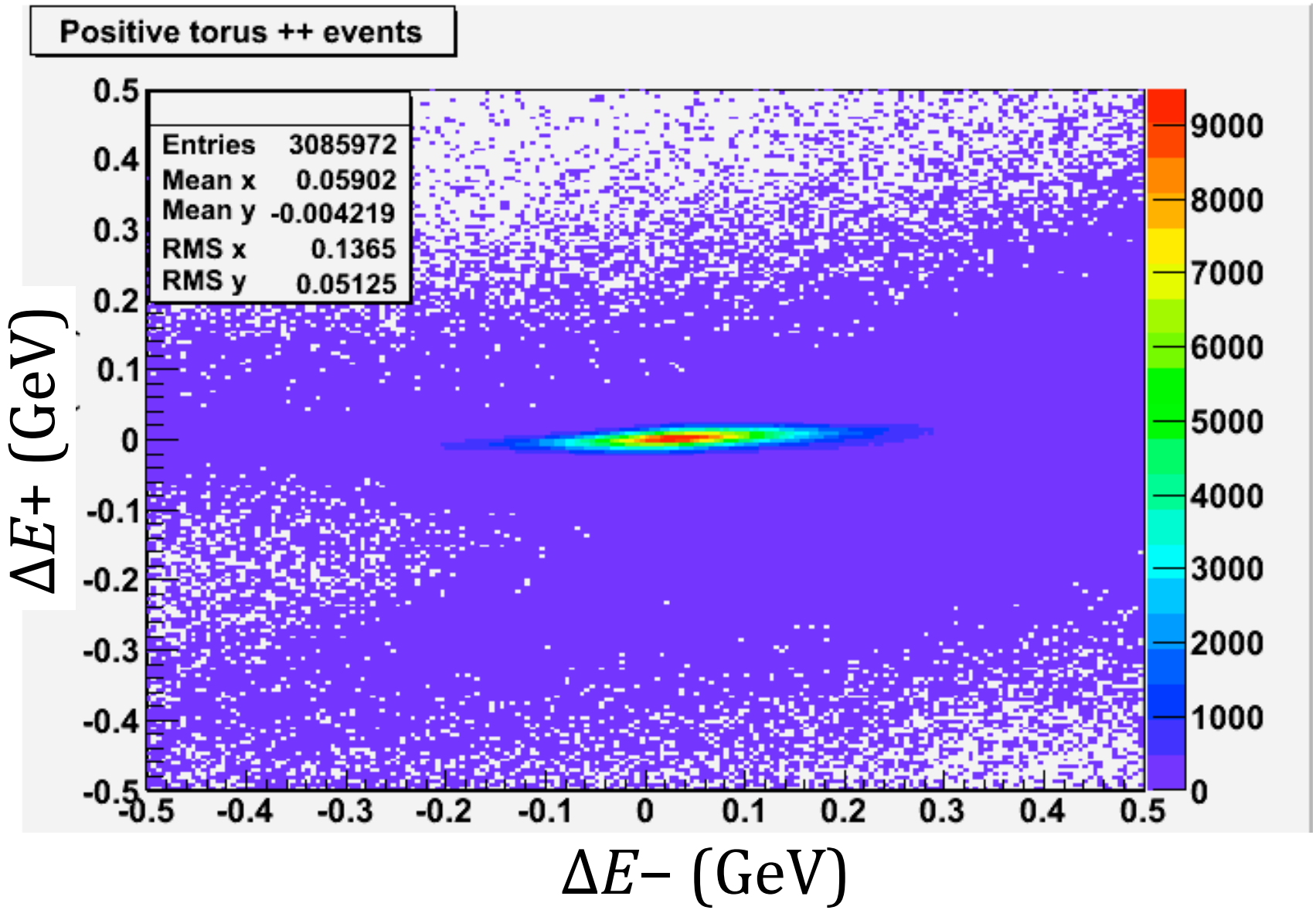
$$\Delta E- = \Delta E_{beam} - \Delta E'$$

$$\Delta E'_e = E'^{meas}_e - \frac{m_p E_1^{beam}}{E_1^{beam}(1-\cos\theta_e)+m_p}$$

$$\Delta E_{beam} = E_{beam}(\theta_e,\theta_p) - E_{beam}(p_e^z + p_p^z)$$



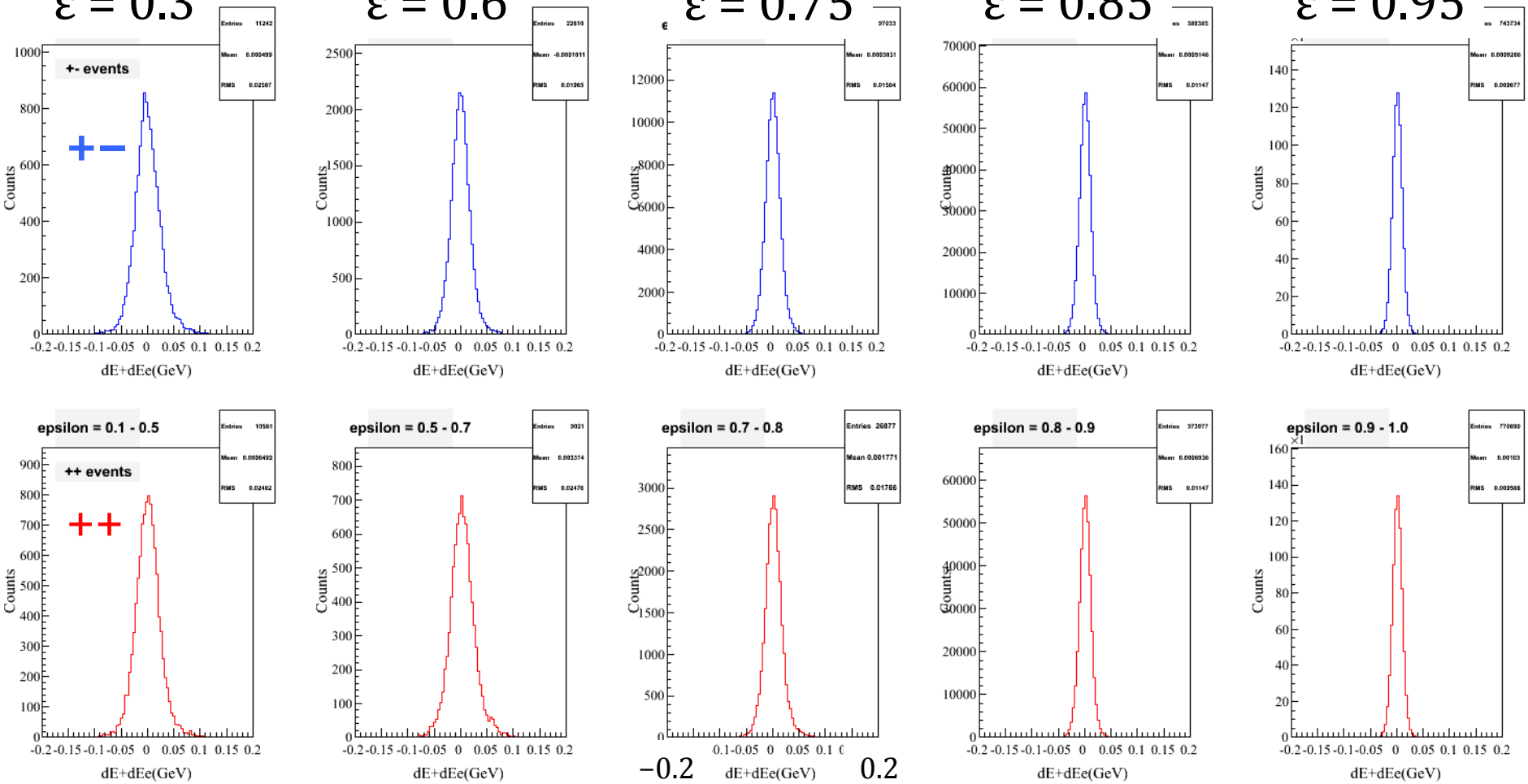
Elastic Event Identification



$\Delta E+ = \Delta E_{\text{beam}} + \Delta E'$ Cut on other 3

(backward angle) (forward angle)

ε = 0.3 ε = 0.6 ε = 0.75 ε = 0.85 ε = 0.95



−0.2 0.2

$\Delta E+$ (GeV)

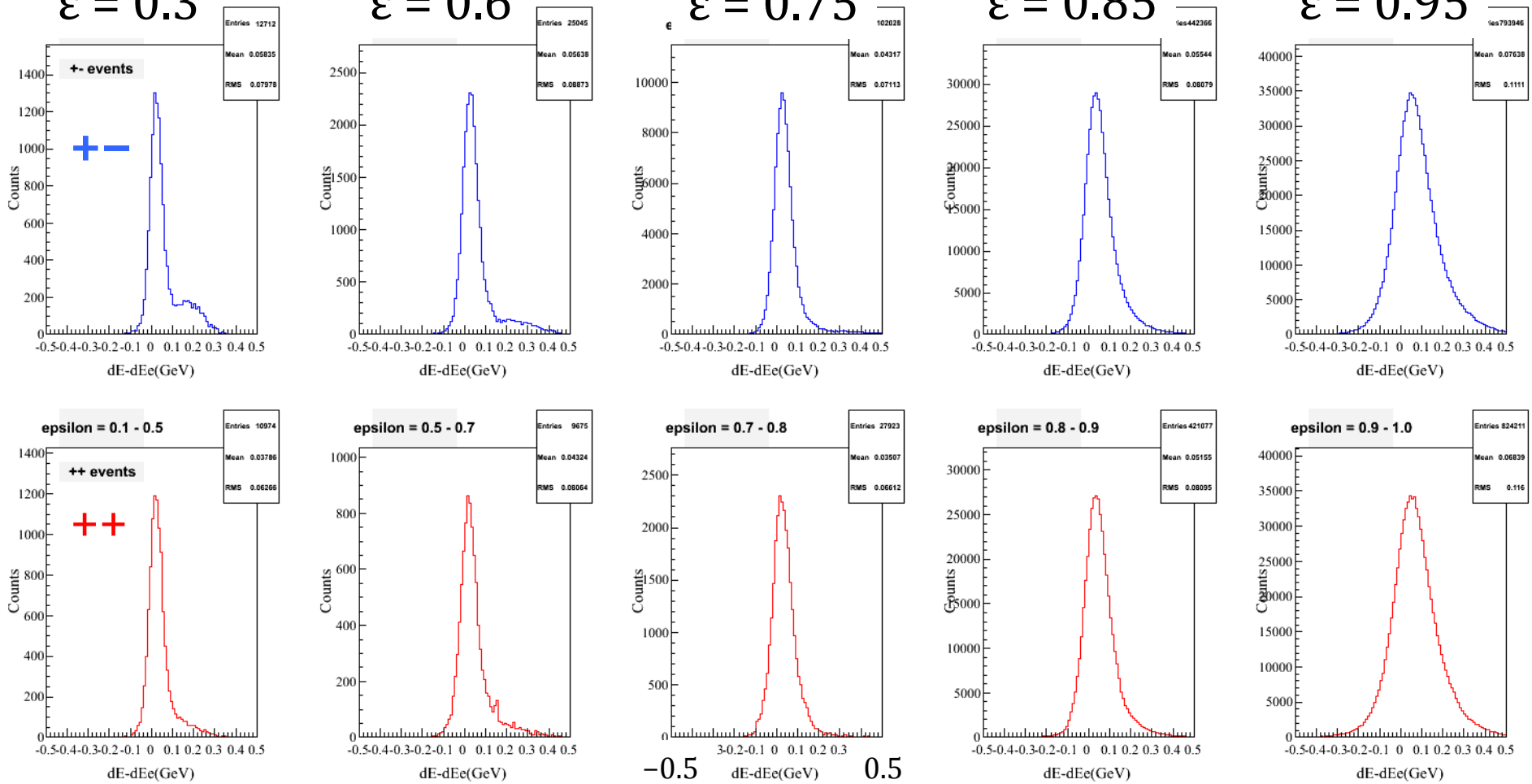
Fit gaussians to determine peak widths for each bin

Make 3-sigma cuts on each variable

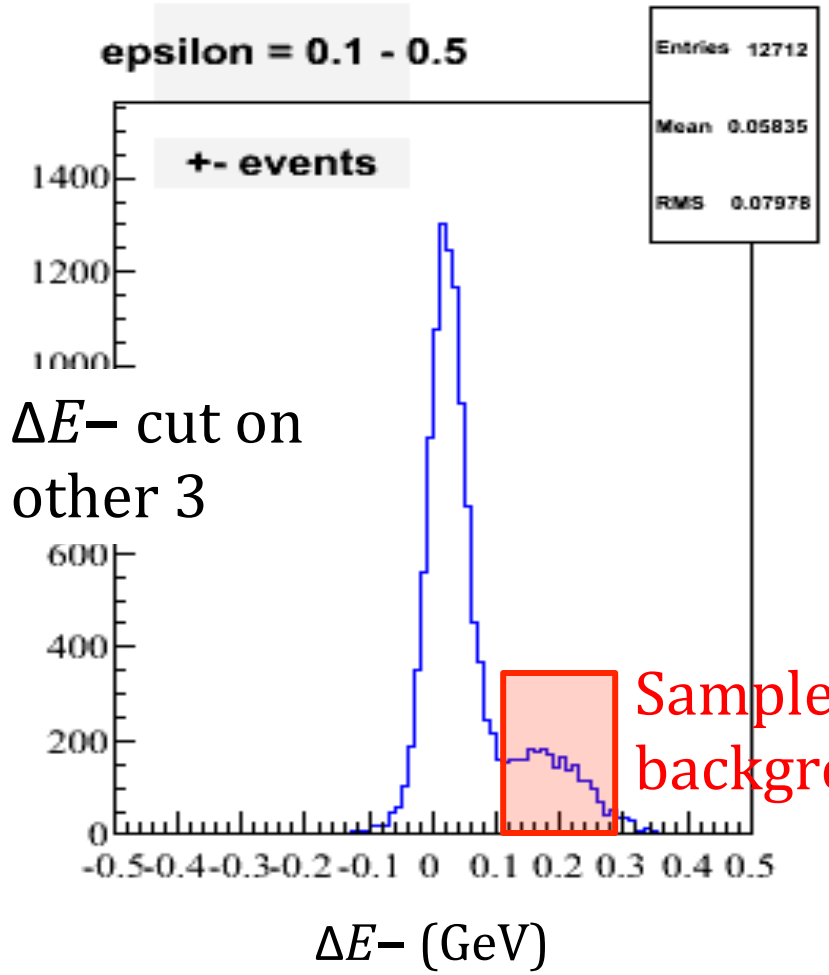
$\Delta E\text{-} = \Delta E_{beam} - \Delta E'$ Cut on other 3

(backward angle) (forward angle)

ε = 0.3 ε = 0.6 ε = 0.75 ε = 0.85 ε = 0.95

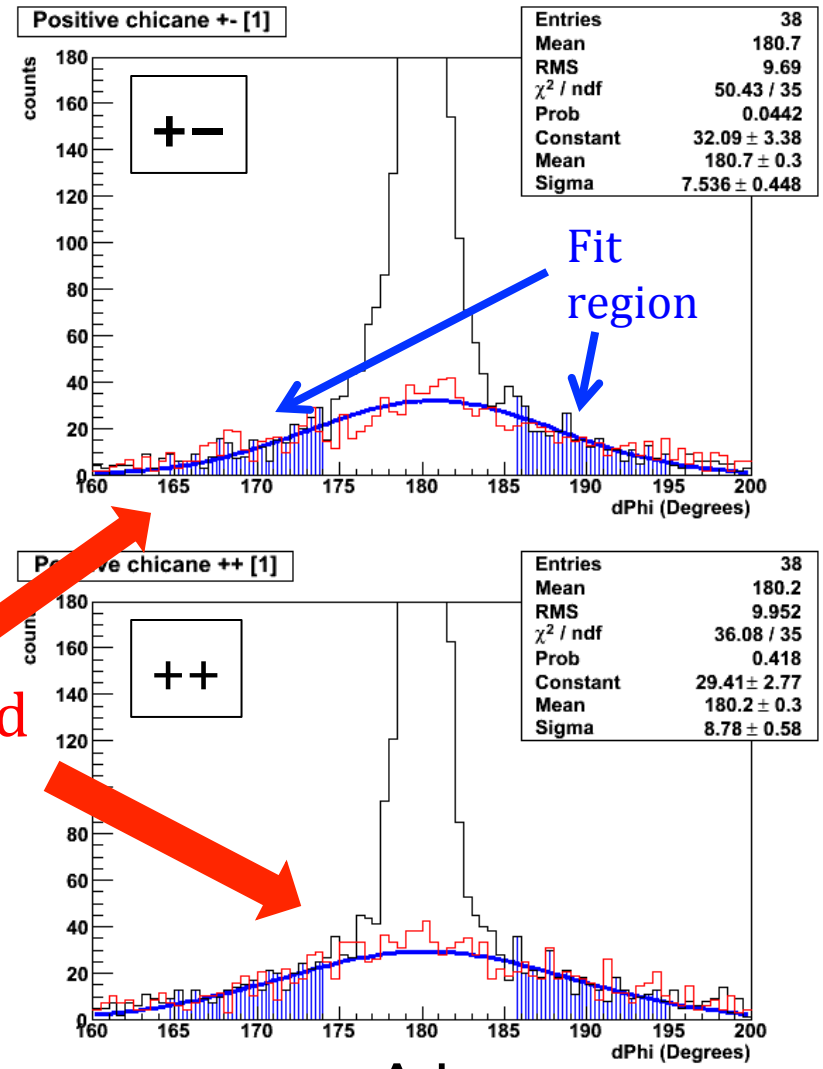


Background Subtraction – Worst Case



ΔE− cut on other 3

Sampled background



ΔΦ

1. Measure background in ΔE- tails
2. Fit height to ΔΦ tails
3. Subtract from peak

(gaussian fit also shown)

Data Analysis: Acceptance

- Fiducial cuts to select regions of high detector efficiency and complete overlap between e^+ & e^-
- Elastic ratio for given torus polarity:

$$R_1^{\pm} = \frac{N^+}{N^-}$$

Proton acceptance cancels

- Flip torus polarity, form double ratio for given chicane setting:

$$R_2^{\pm} = \sqrt{R_1^+ R_1^-}$$

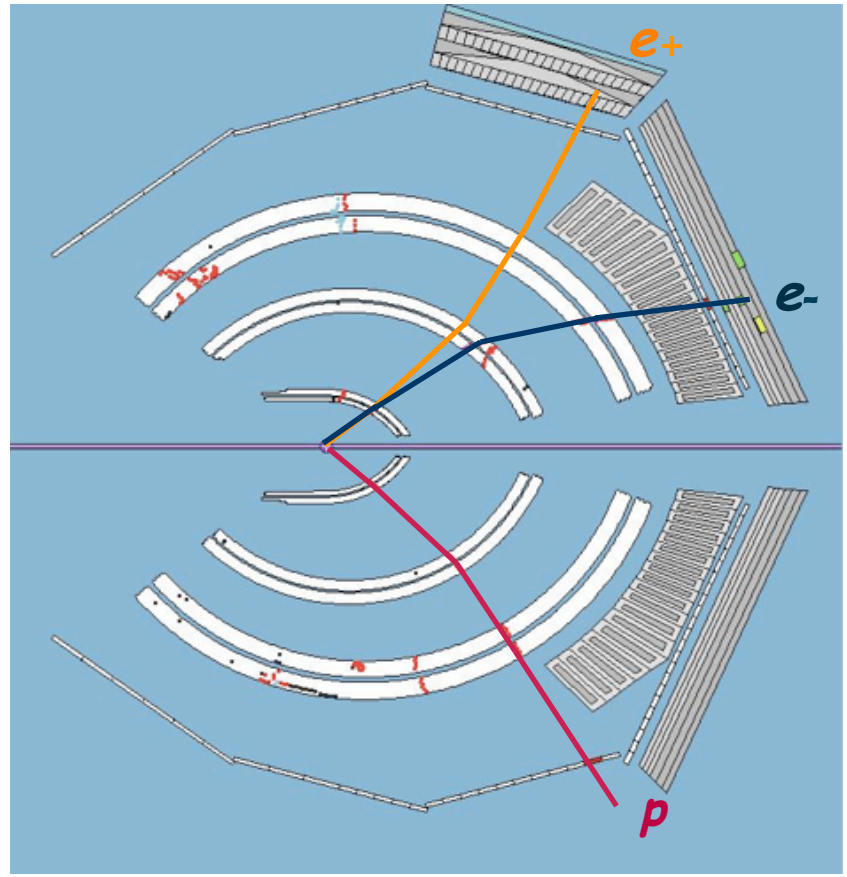
Lepton acceptance cancels

- Flip chicane polarity, form quadruple ratio:

$$R = \sqrt{R_2^+ R_2^-} = \sigma(e^+ p) \big/ \sigma(e^- p)$$

Beam asymmetries cancel

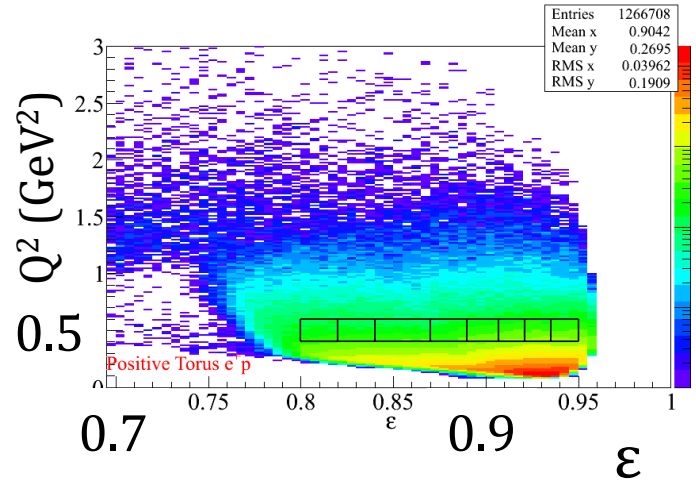
Acceptance matching (swimming)

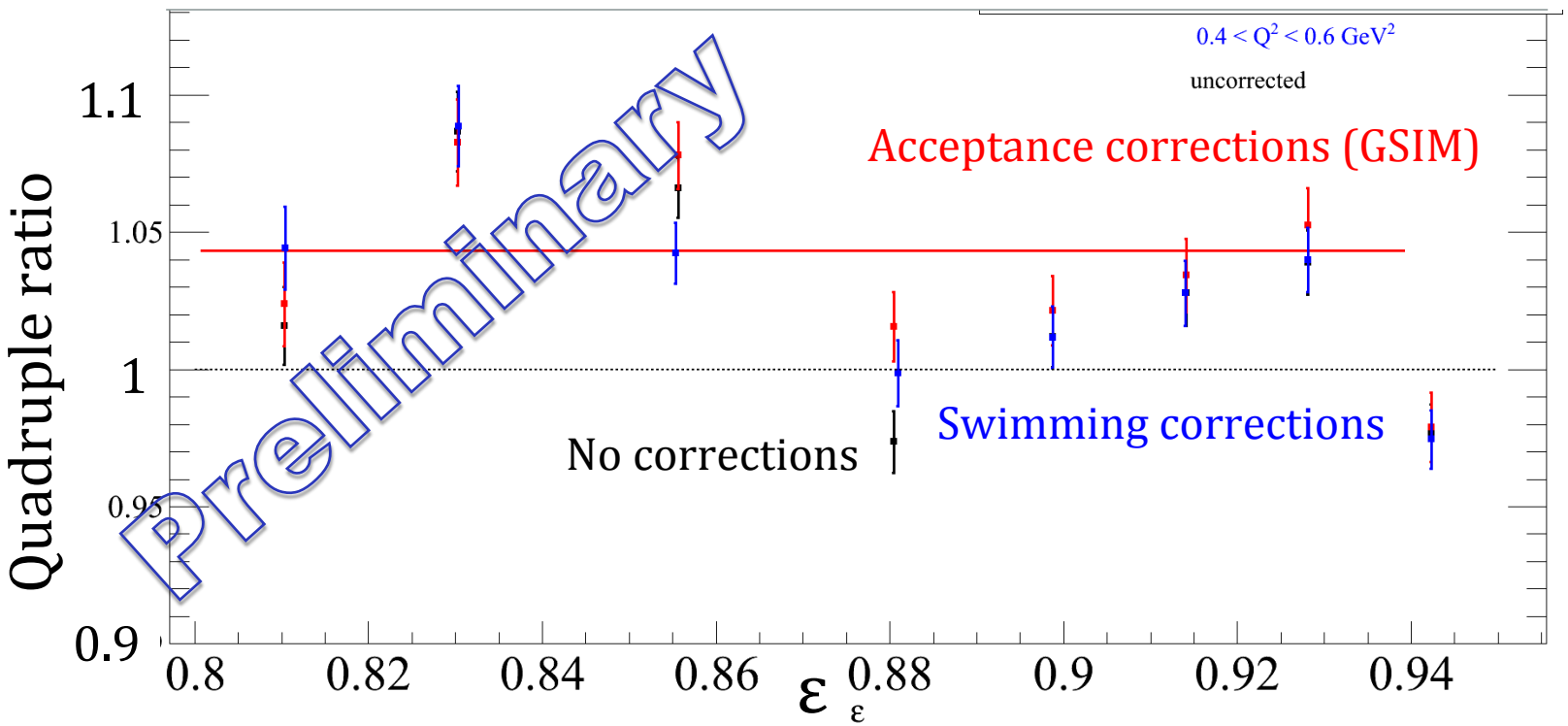


Also doing acceptance corrections using GSIM (simulation)

Data: Low Q^2 and High ε Acceptance Corrections

$0.4 < Q^2 < 0.6$ GeV^2
$0.8 < \varepsilon < 0.95$ (forward angle)

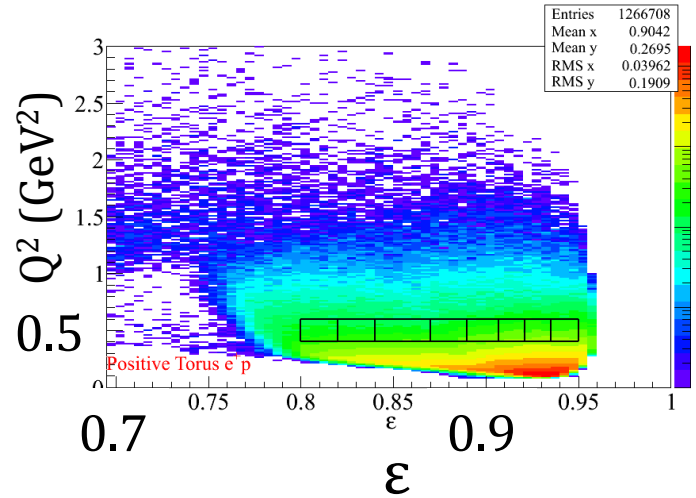


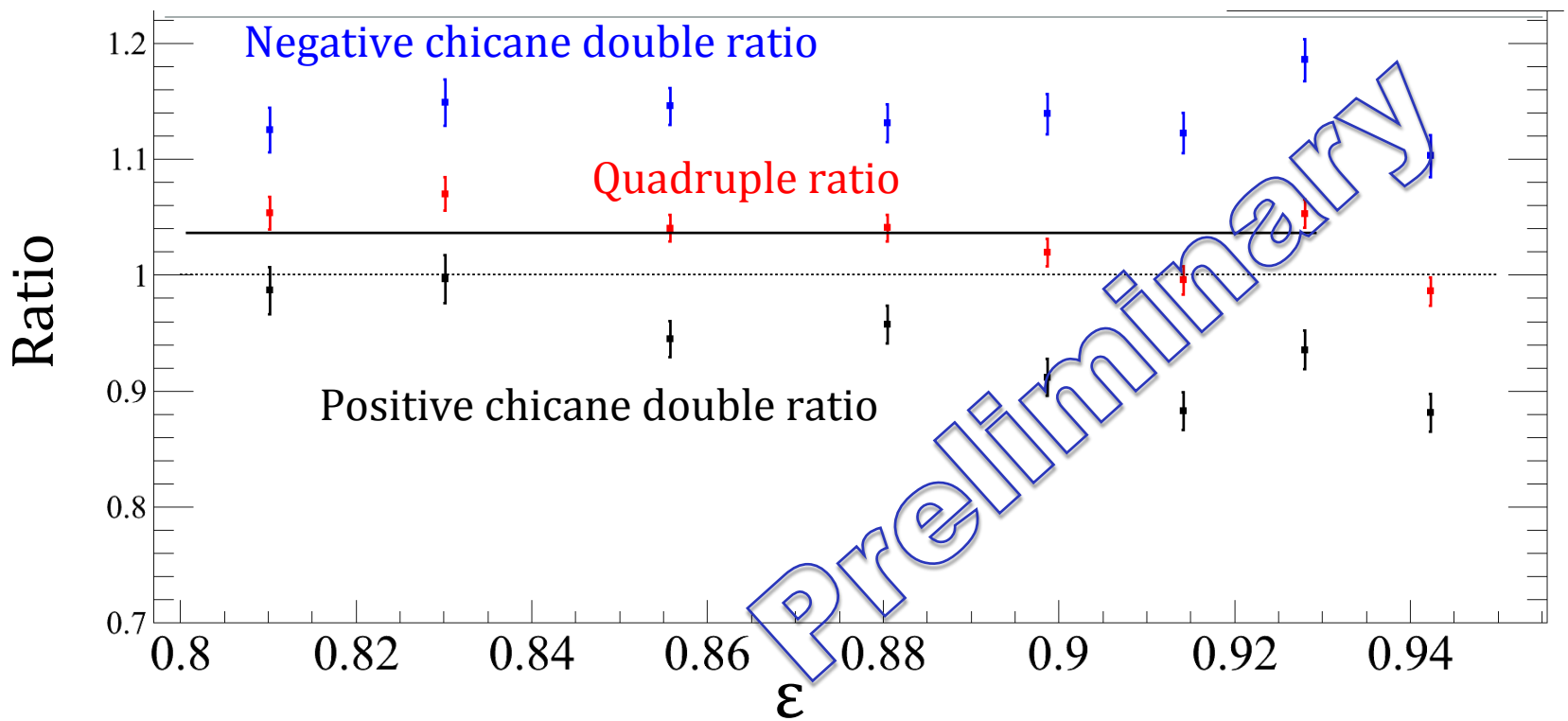


Acceptance corrections are small, even in small bins.

Data: Low Q^2 and High ε Beam Asymmetries

$0.4 < Q^2 < 0.6$ GeV^2
$0.8 < \varepsilon < 0.95$ (forward angle)

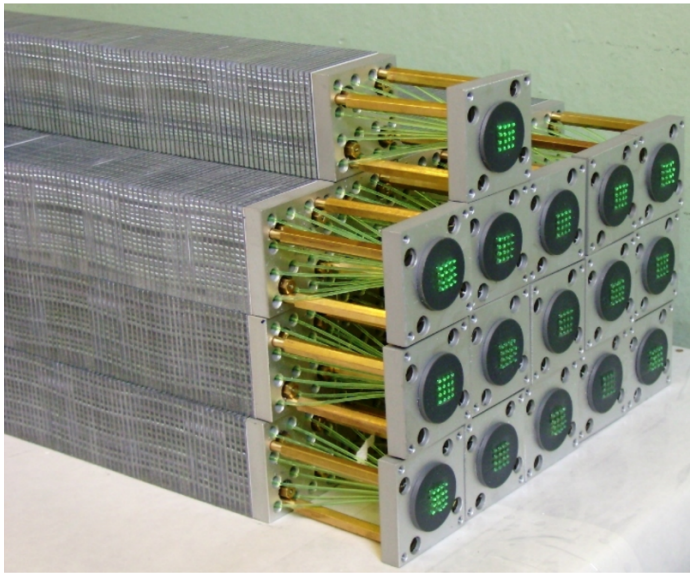


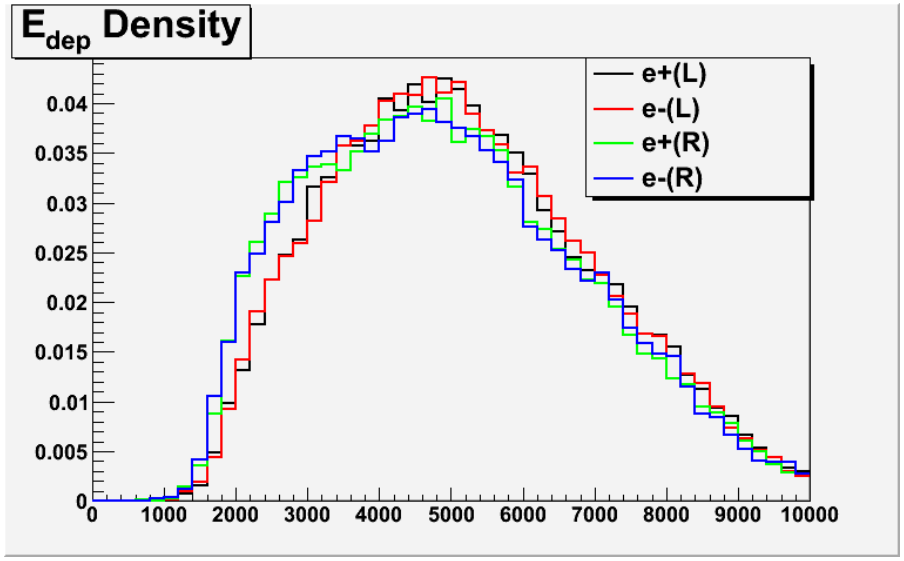


Does the beam asymmetry cancel in the super ratio?

Beam energy measurements USM/ODU Calorimeter

- 30 module shashlik (Pb/scint) calorimeter
- Positioned downstream of CLAS on forward carriage
- Measure beam energy during low luminosity runs
- Measure beam energy for *e*+ and *e*- separately every time we flipped the chicane
- Calibrated with cosmic rays (~450 MeV *e*- equivalent) centered at channel 1000

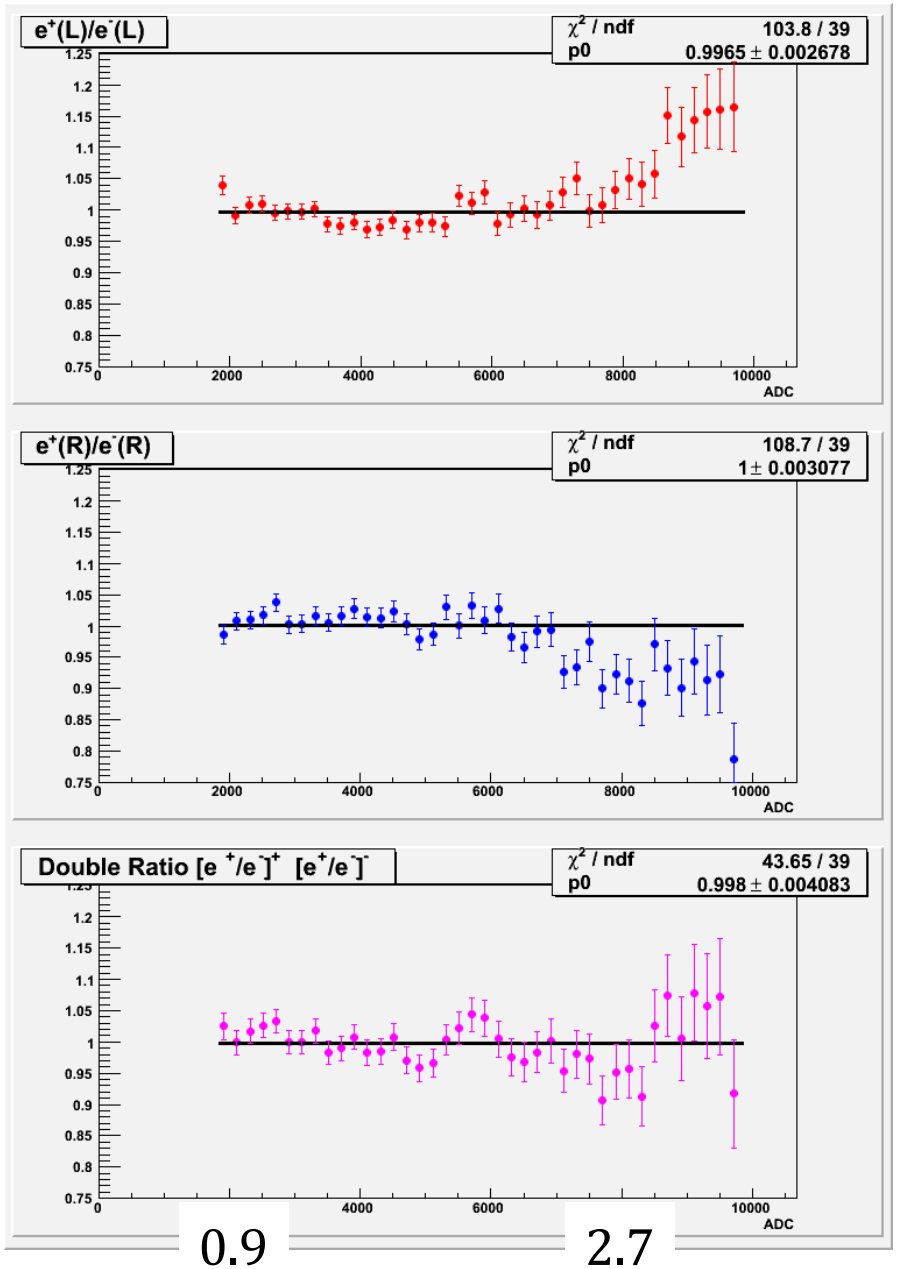




Incident Lepton Energy (Channel #)

Beam asymmetries cancel in the super ratio

Normalized to incident beam charge



0.9 2.7

Incident lepton energy (GeV approx)

Left side of chicane:
Ratio of e+ to e-

Right side of chicane:
Ratio of e+ to e-

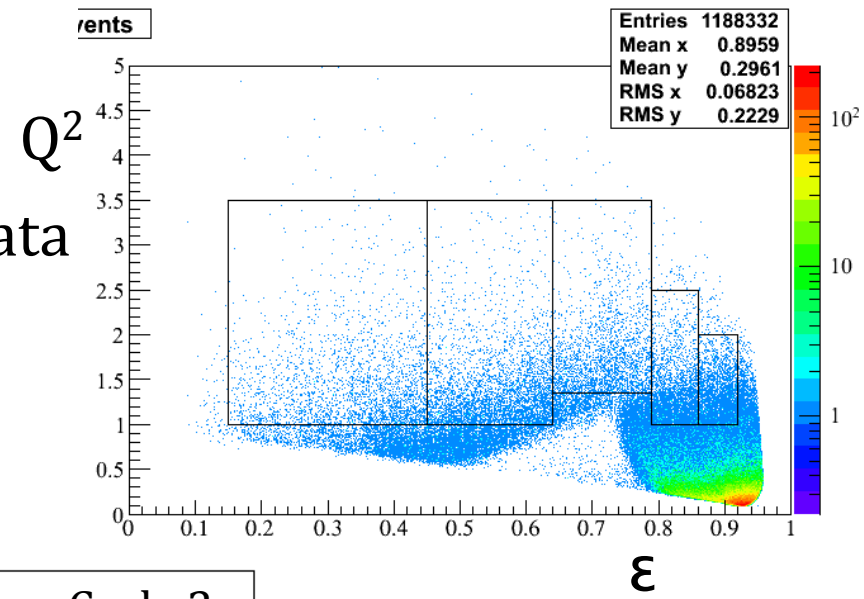
Combined e+/e- ratio
χ^2/ndf = 44/39
p0 = 0.998±0.004

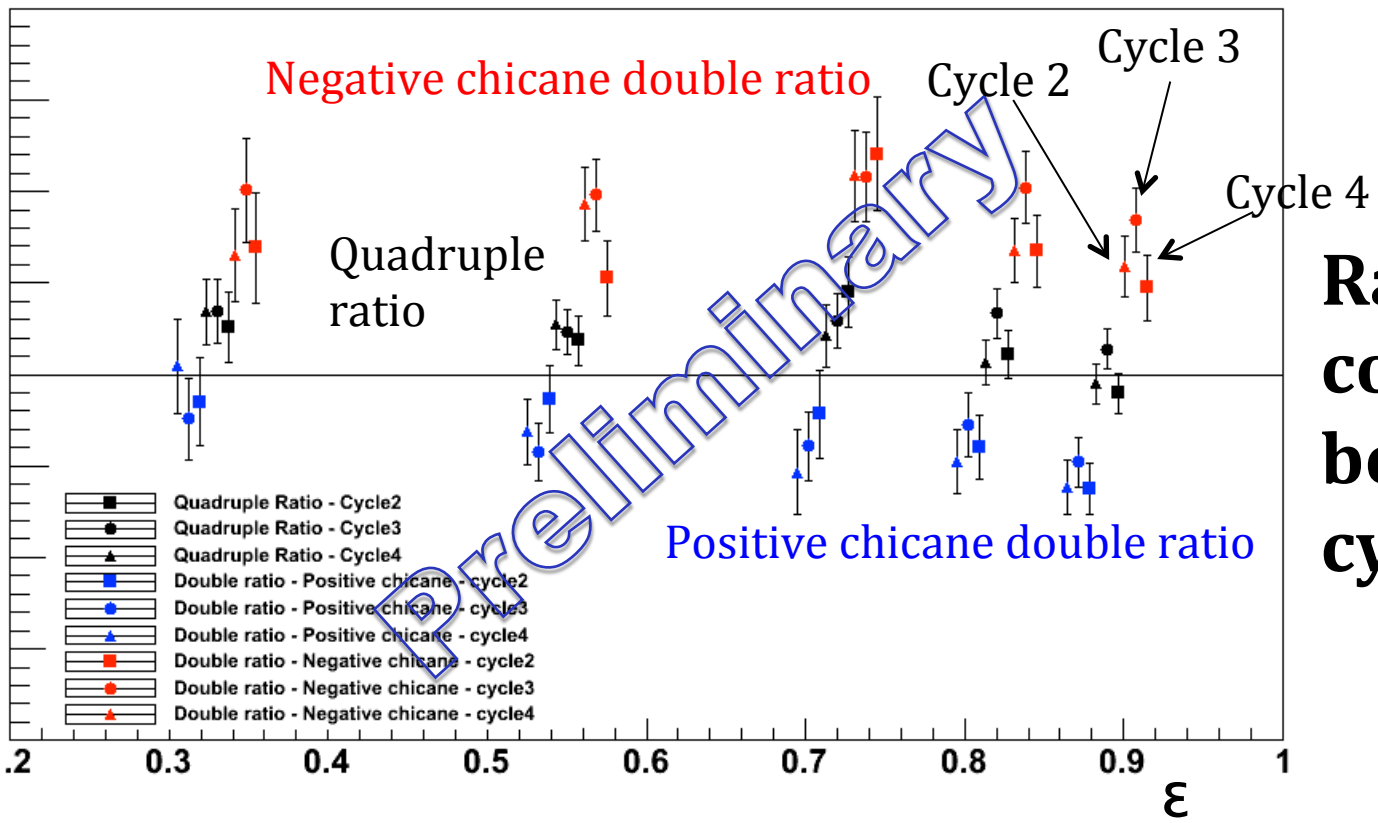
The chicane has a left/right asymmetry, not an e+/e- asymmetry

Stability: cycles 2, 3, 4

We took four full magnet cycles of data

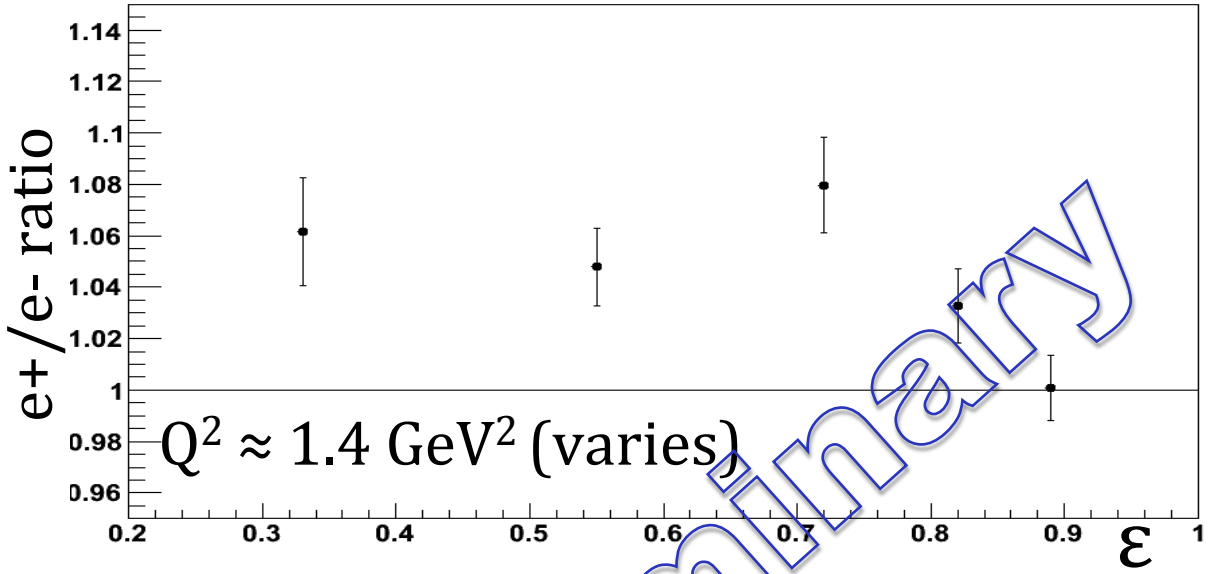
- torus −/+
- chicane −/+

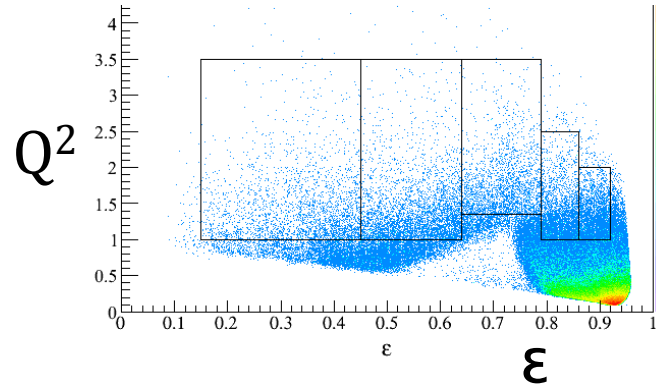




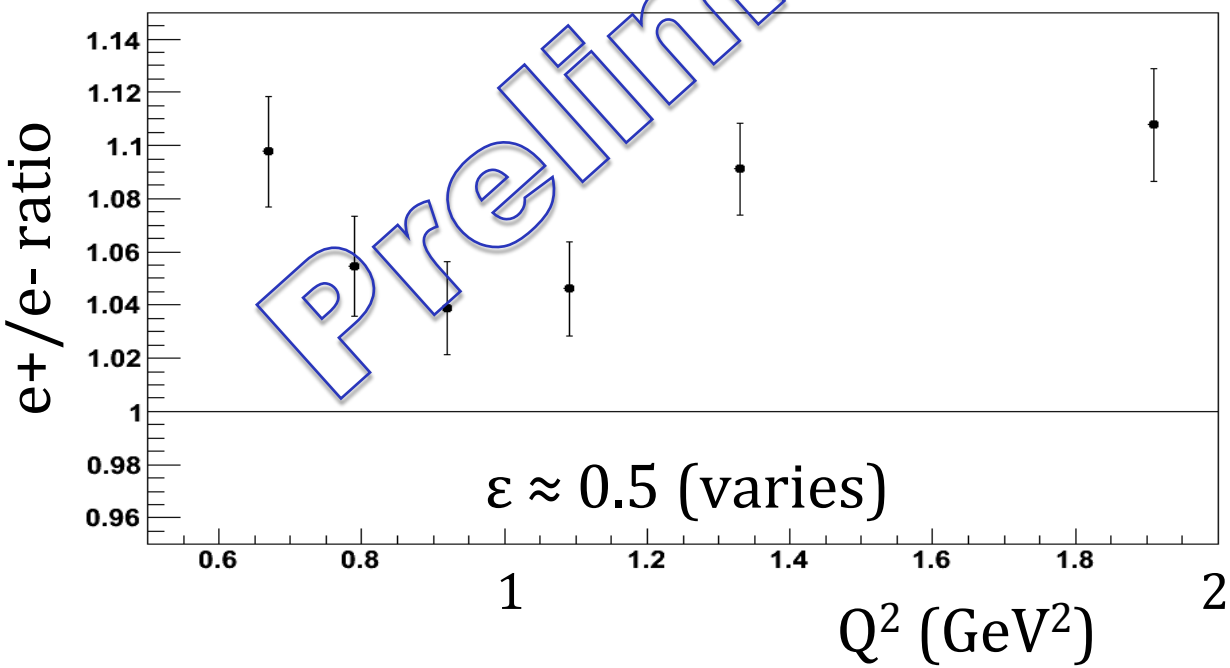
Ratios consistent for both magnet cycles

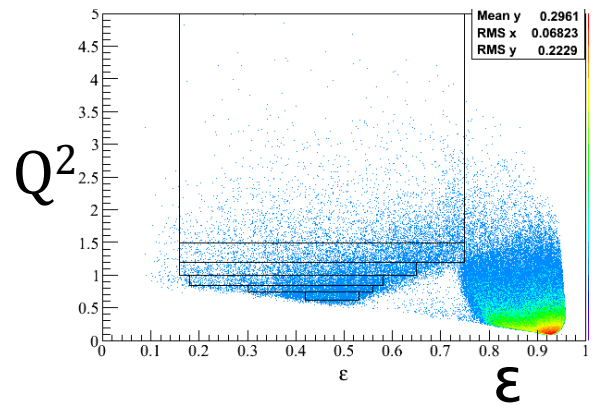
Preliminary Results





Binning

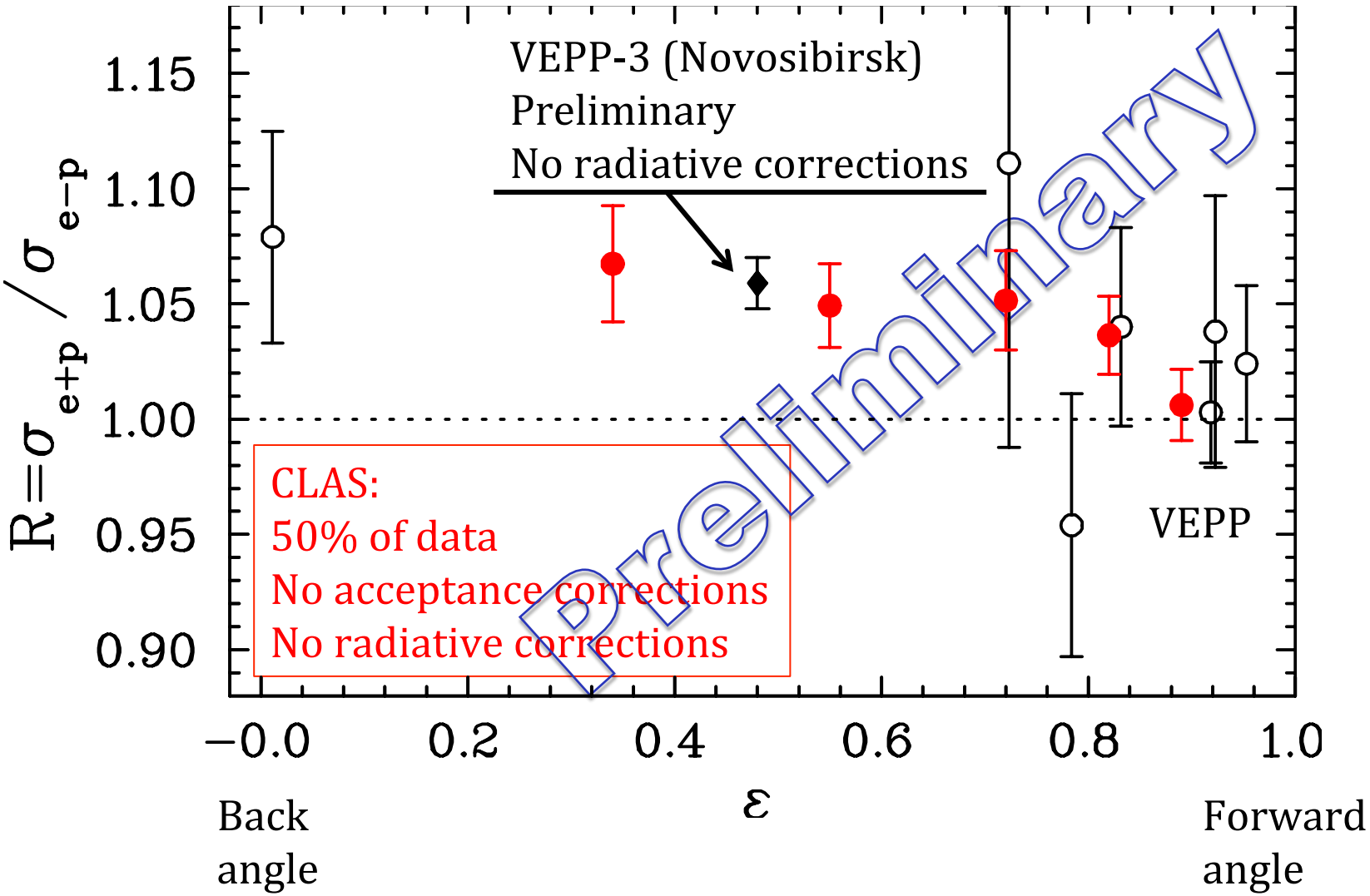




Preliminary

75% of data
No acceptance corrections
No radiative corrections

Comparison to world data at $Q^2 > 1$



Tasks to do:

1. Include remaining data
2. Lots more data points at large ε and varied Q^2
3. Acceptance corrections for all bins
   1. Swimming
   2. GSIM-based
4. Charge dependent radiative corrections
5. Determine systematic uncertainties (anticipate 1-2%)
6. Get CLAS analysis approval
7. Publish
8. Enjoy the plaudits of an admiring populace!

Summary

1. Very serious discrepancy in G_e^p, resolvable by H(e±,e±)
2. Major competition from OLYMPUS@DESY and Novosibirsk
3. **First ever** experiment using simultaneous beams of high energy e+ and e-
4. Measured σ(e+p)/σ(e-p) over a wide range of Q^2 and ε
   1. Our measurements can be applied directly to correct the Rosenbluth G_e^p measurements
5. Innovative analysis
   1. CLAS charge dependent acceptances cancel when torus magnet polarity flipped
   2. Beam charge asymmetries cancel when chicane polarity flipped
6. Initial results appear consistent with e+/e- ratios needed to explain the G_E^p discrepancy
7. Final results expected in 3-6 months