Results from the OLYMPUS Experiment on the Contribution of Hard Two-Photon Exchange to Elastic Electron-Proton Scattering

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Massachusetts Institute of Technology

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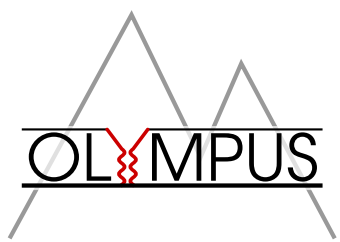


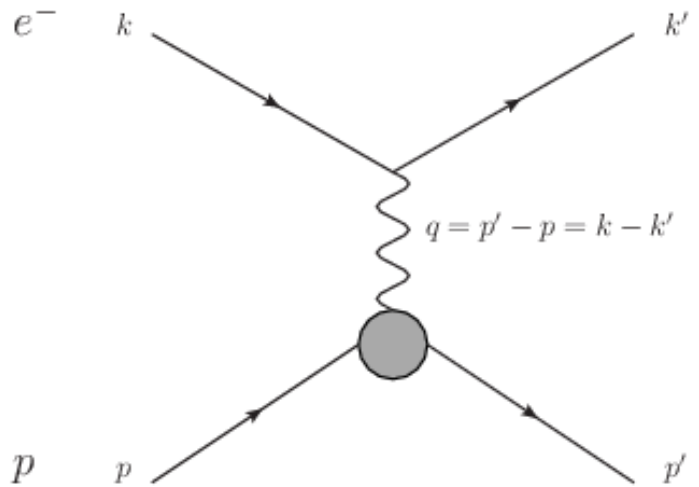
The elastic *ep* cross section and form factors

$$\frac{d\sigma}{d\Omega} = \frac{1}{\varepsilon\left(1+\frac{Q^2}{4m_p^2}\right)} \underbrace{\left(\frac{\alpha^2 E' \cos^2(\theta/2)}{4E^3 \sin^4(\theta/2)}\right)}_{\sigma_{\text{Mott}}} \left(\varepsilon G_E^2\left(Q^2\right) + \frac{Q^2}{4m_p^2} G_M^2\left(Q^2\right)\right)$$

$\theta =$ Lab frame scattering angle of the lepton

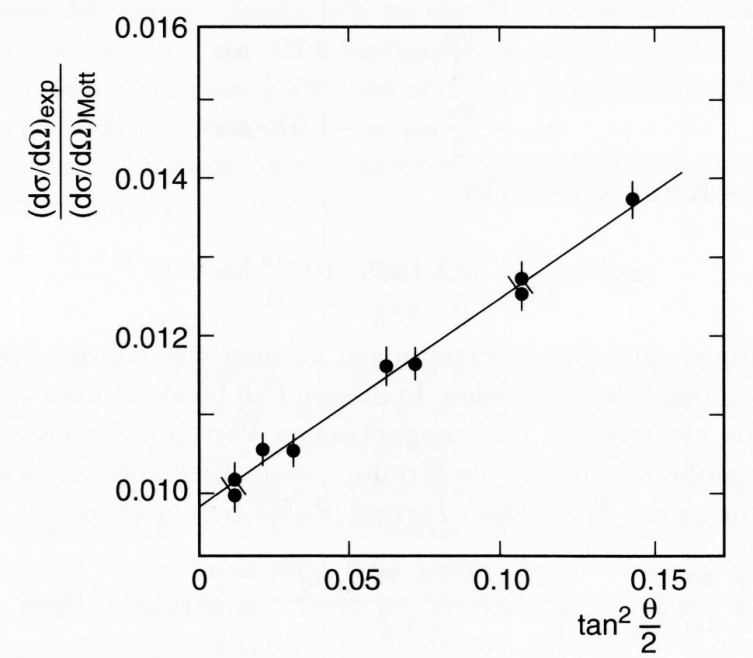
$Q^2 = -q_\mu q^\mu =$ Squared four-momentum transfer

$$\varepsilon = \left(1 + 2\left(1+\frac{Q^2}{4m_p^2}\right)\tan^2\left(\frac{\theta}{2}\right)\right)^{-1}$$



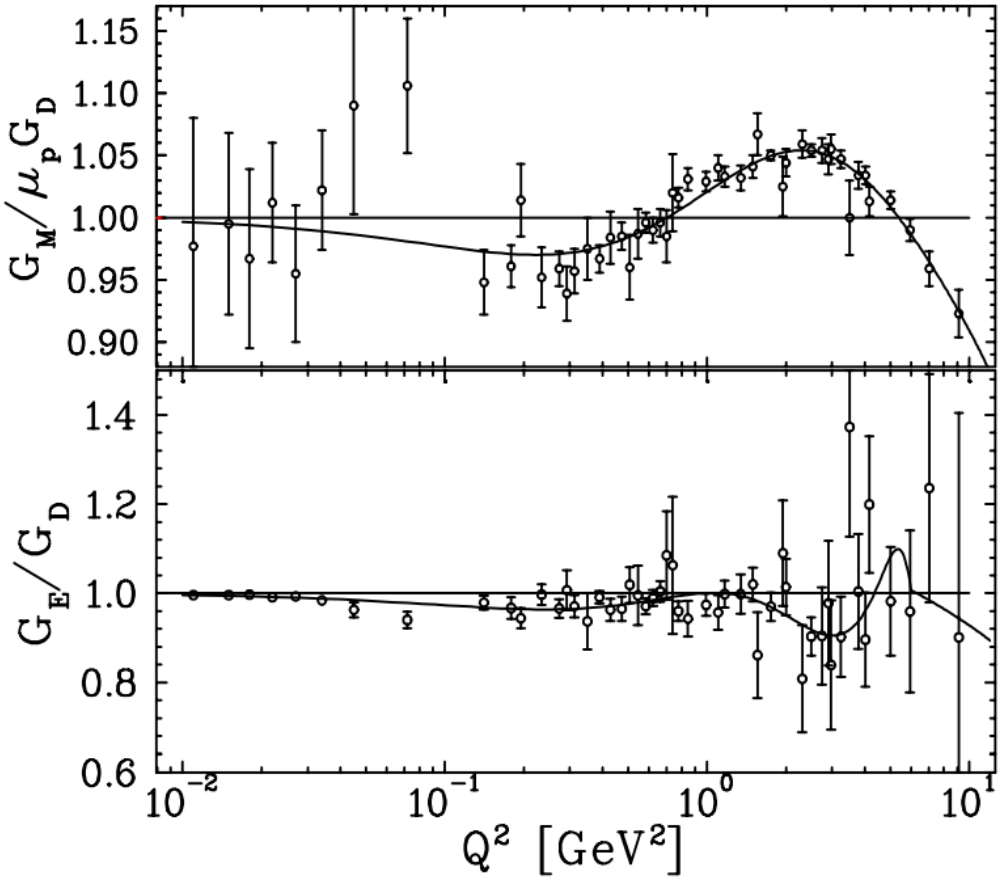
Rosenbluth separation

Form of cross section suggests a straightforward way to measure the form factors: fix Q^2 and vary ε (i.e., θ) using a small-acceptance spectrometer



$G_E^2(Q^2) \propto$ slope, $G_M^2(Q^2) \propto$ cross-section at $\theta = 0$

The form factors from Rosenbluth separation



$$G_D = \left(1 + \frac{Q^2}{0.71\,\mathrm{GeV}^2}\right)^{-2}$$

Polarized beams/targets and G_E/G_M

Availability of highly polarized e^- beams and targets starting in the mid-to-late 1990s provided a new way to measure G_E/G_M

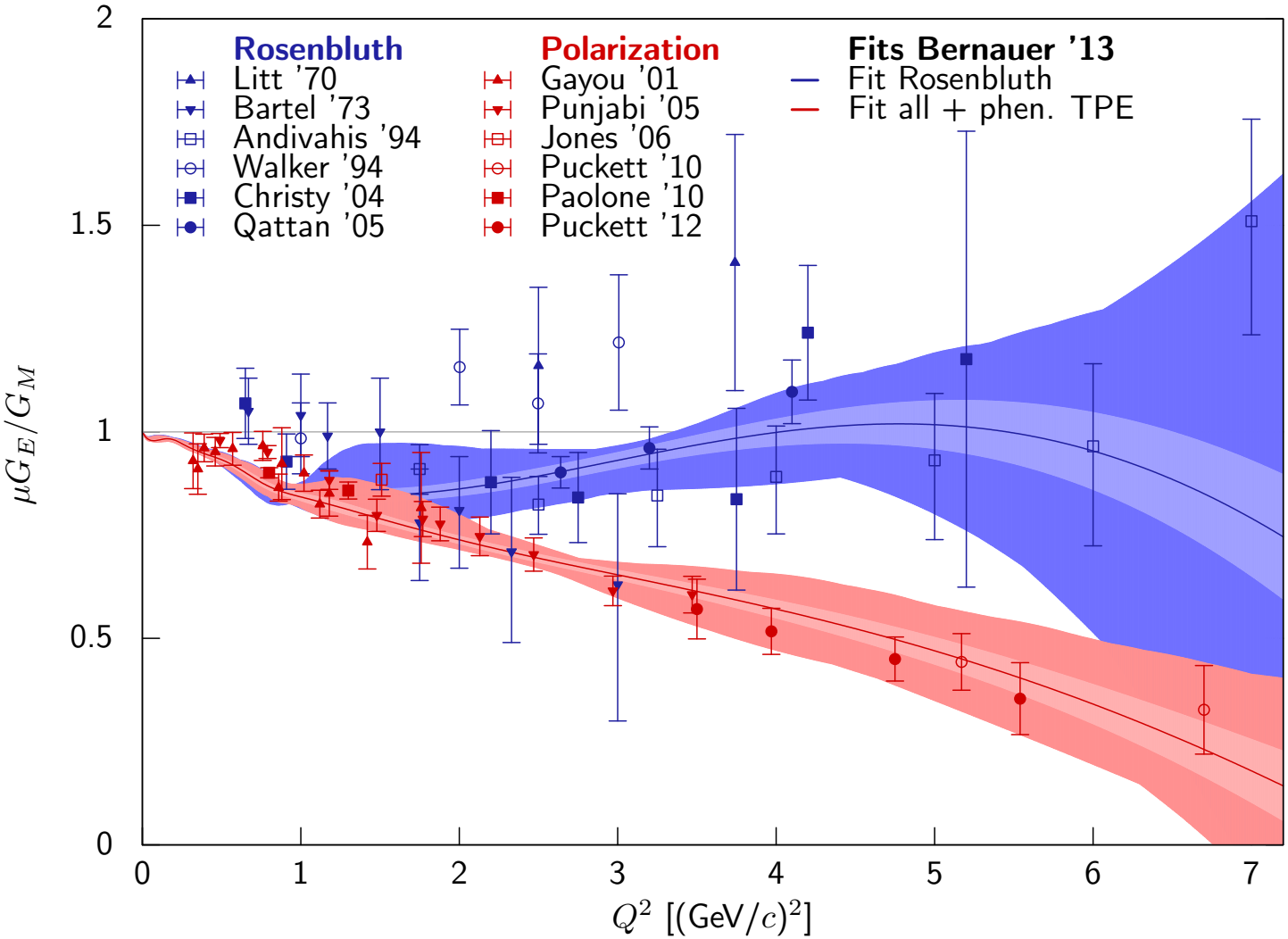
Scatter longitudinally-polarized e^- from unpolarized protons, and measure the cross-sections for the different polarizations of the outgoing lepton

$$\frac{d\sigma^{(L)}}{d\Omega} = h\sigma_{Mott}\frac{E+E'}{m_p}\sqrt{\frac{1}{1+\frac{4m_p^2}{Q^2}}}\tan^2\left(\frac{\theta}{2}\right)G_M^2$$

$$\frac{d\sigma^{(T)}}{d\Omega} = 2h\sigma_{Mott}\sqrt{\frac{1}{1+\frac{4m_p^2}{Q^2}}}\tan\left(\frac{\theta}{2}\right)G_E G_M$$

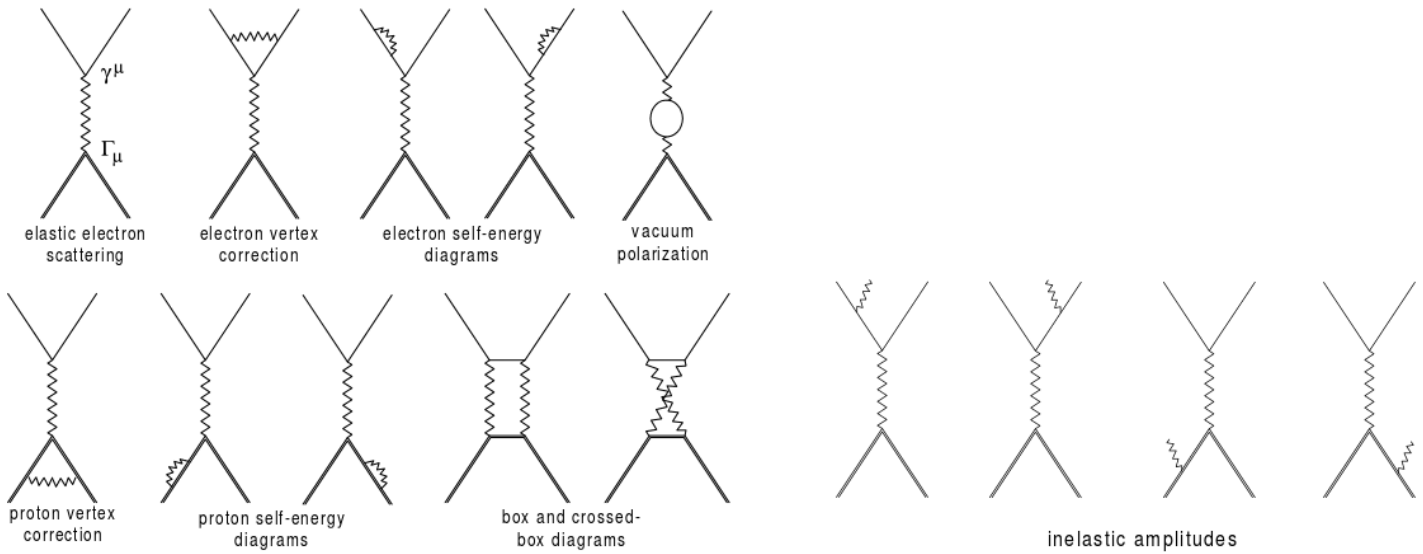
The G_E/G_M ratio discrepancy

The Rosenbluth and polarization form factor ratios show a large discrepancy!



Questioning the Born approximation

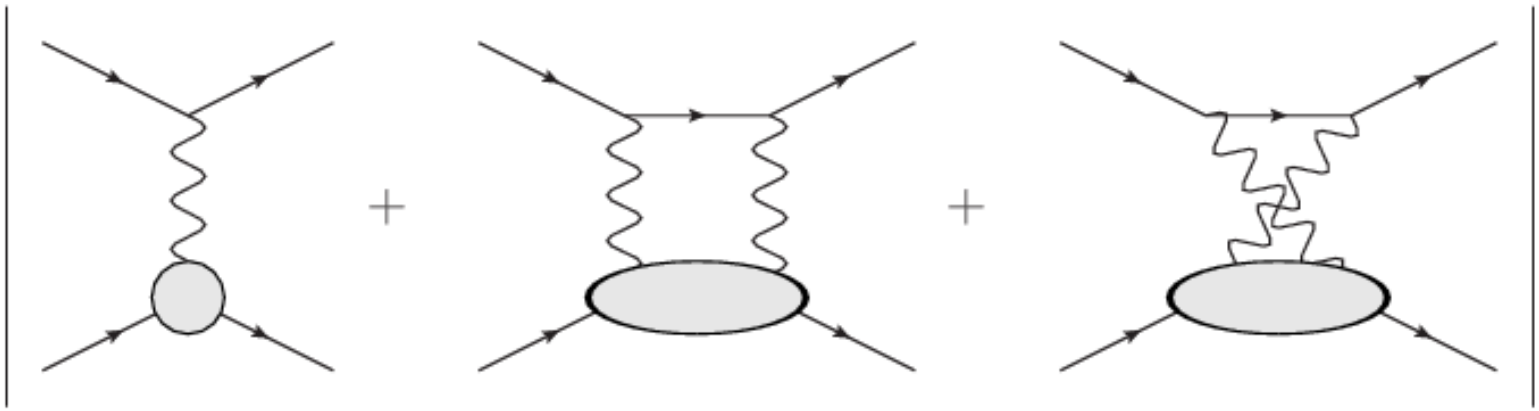
Results from both methods (especially Rosenbluth separation), depend heavily on radiative corrections



Most of these are calculable, but the two photon exchange (TPE) box and crossed-box contributions had always been "assumed to be negligible" due to the challenges of the off-shell proton propagator

Measuring TPE directly with $\sigma_{e^+p}/\sigma_{e^-p}$

A TPE correction could bring the data into agreement, but calculation of the diagrams is highly model-dependent

$|\mathcal{M}|^2 \sim$  ^{2}

Interference of the tree-level and TPE diagrams changes sign with the charge of the lepton $\rightarrow$ comparing e^+ and e^- scattering gives you a direct link to the TPE contribution

$$R_{2\gamma}\left(\epsilon, Q^2\right) = \frac{\sigma_{e^+}}{\sigma_{e^-}} \sim 1 + 4\alpha \frac{\mathcal{M}_{\gamma\gamma}}{\mathcal{M}_{\gamma}}$$

The OLYMPUS experiment

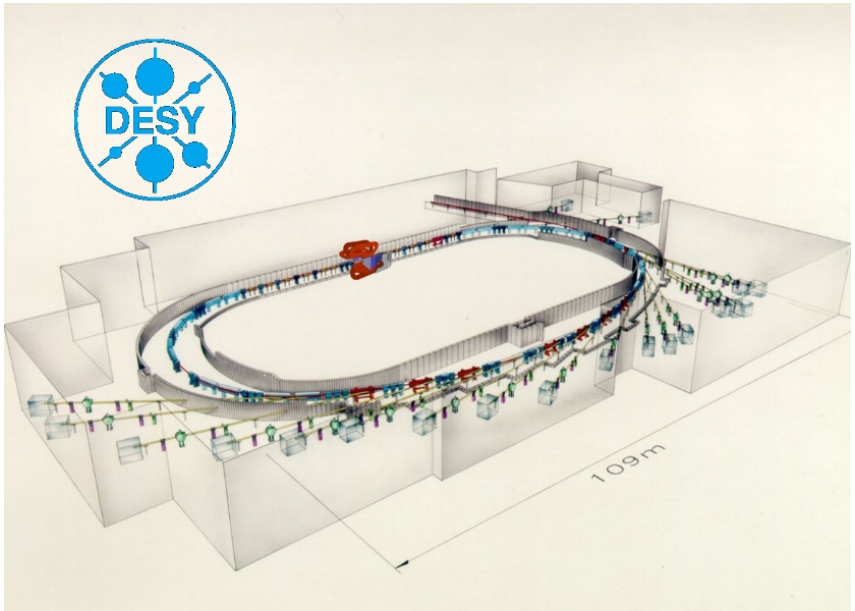
OLYMPUS seeks to provide a measurement of the e^+p/e^-p elastic cross section ratio with better than 1% uncertainty over a range of 0.15 GeV^2 $< Q^2 <$ 2.2 GeV^2 to test the TPE hypothesis

Experiment requirements:

- Strong statistics over a large θ range
- Precise monitoring of the relative e^+/e^- luminosity collected
- Complete understanding of any systematic difference between e^+ and e^- running
  - Acceptance effects
  - Beam conditions
  - Associated background/noise
  - ...
- Careful radiative corrections (especially α^3 soft effects)

OLYMPUS basics

- Located at the DORIS storage ring, DESY, Hamburg, Germany
- 2.01 GeV e^+ and e^- on a fixed internal gaseous hydrogen target
- Main tracking detectors and toroidal magnet from BLAST (MIT Bates)
- New detectors for precision luminosity monitoring
- Two other experiments: CLAS and VEPP-3

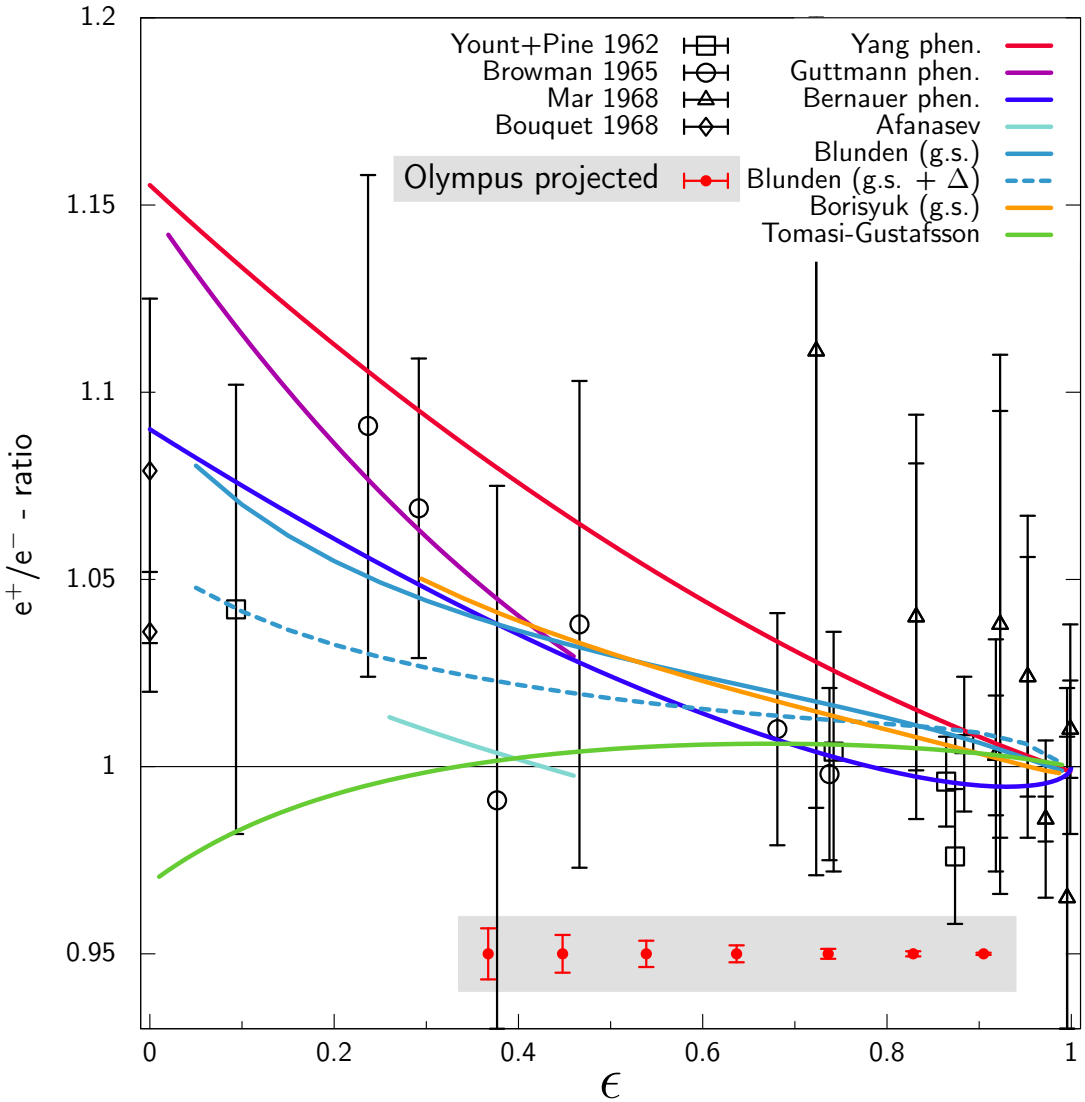


OLYMPUS basics

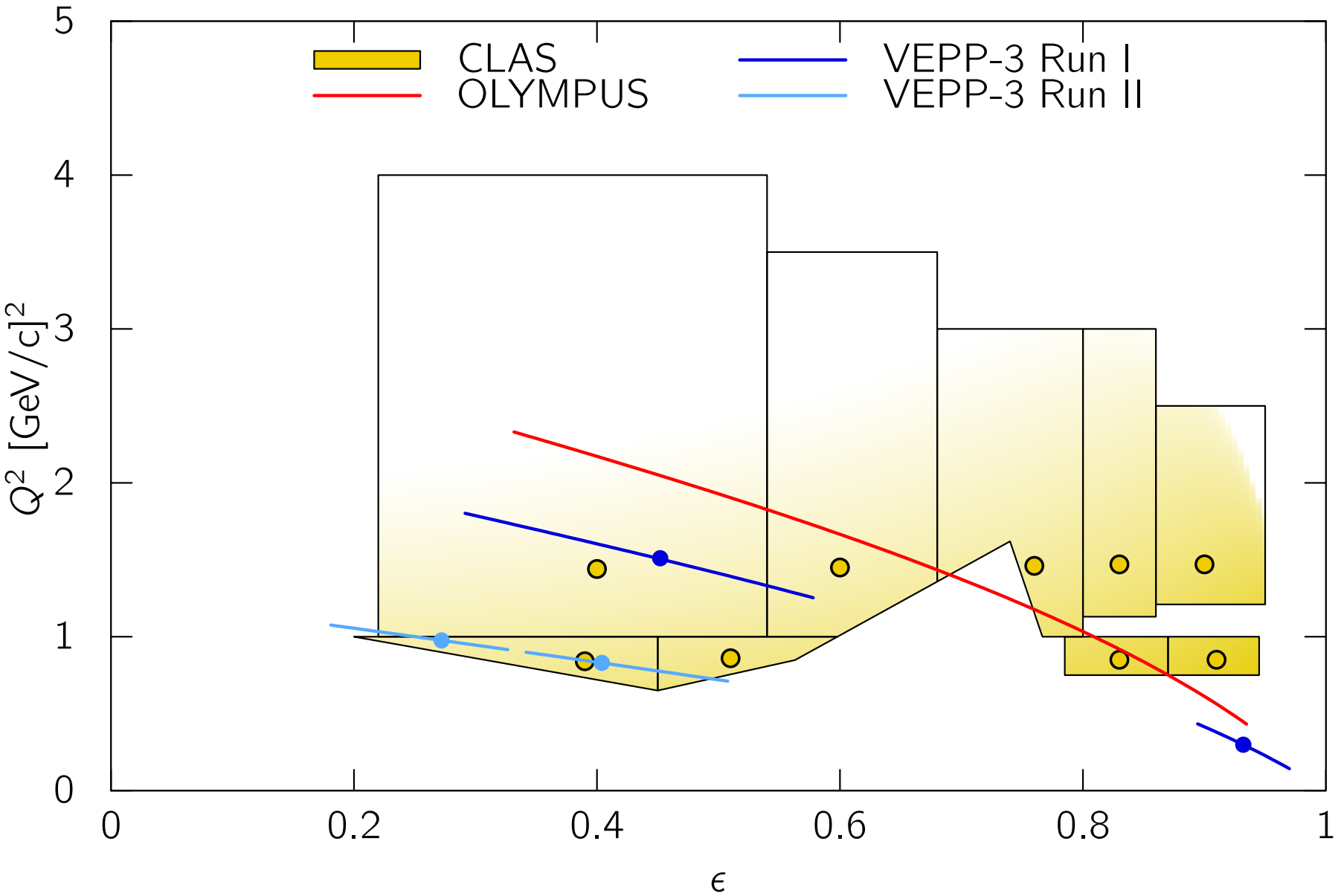
- Exclusively reconstruct elastic $e^{\pm}p$ events from $\theta \approx 20°$–$70°$
- Switch beam species approximately daily to control long-period systematics
- Construct an extremely detailed Monte Carlo simulation including detector efficiencies and acceptance, radiative corrections, and experiment conditions (beam current, target density, beam position, etc.)

$$R_{2\gamma} = \frac{\sigma_{e^+p}(\theta)}{\sigma_{e^-p}(\theta)} = \frac{N_{e^+,data}(\theta)}{N_{e^-,data}(\theta)} \cdot \frac{N_{e^-,MC}(\theta, \mathcal{L}_{e^-})}{N_{e^+,MC}(\theta, \mathcal{L}_{e^+})}$$

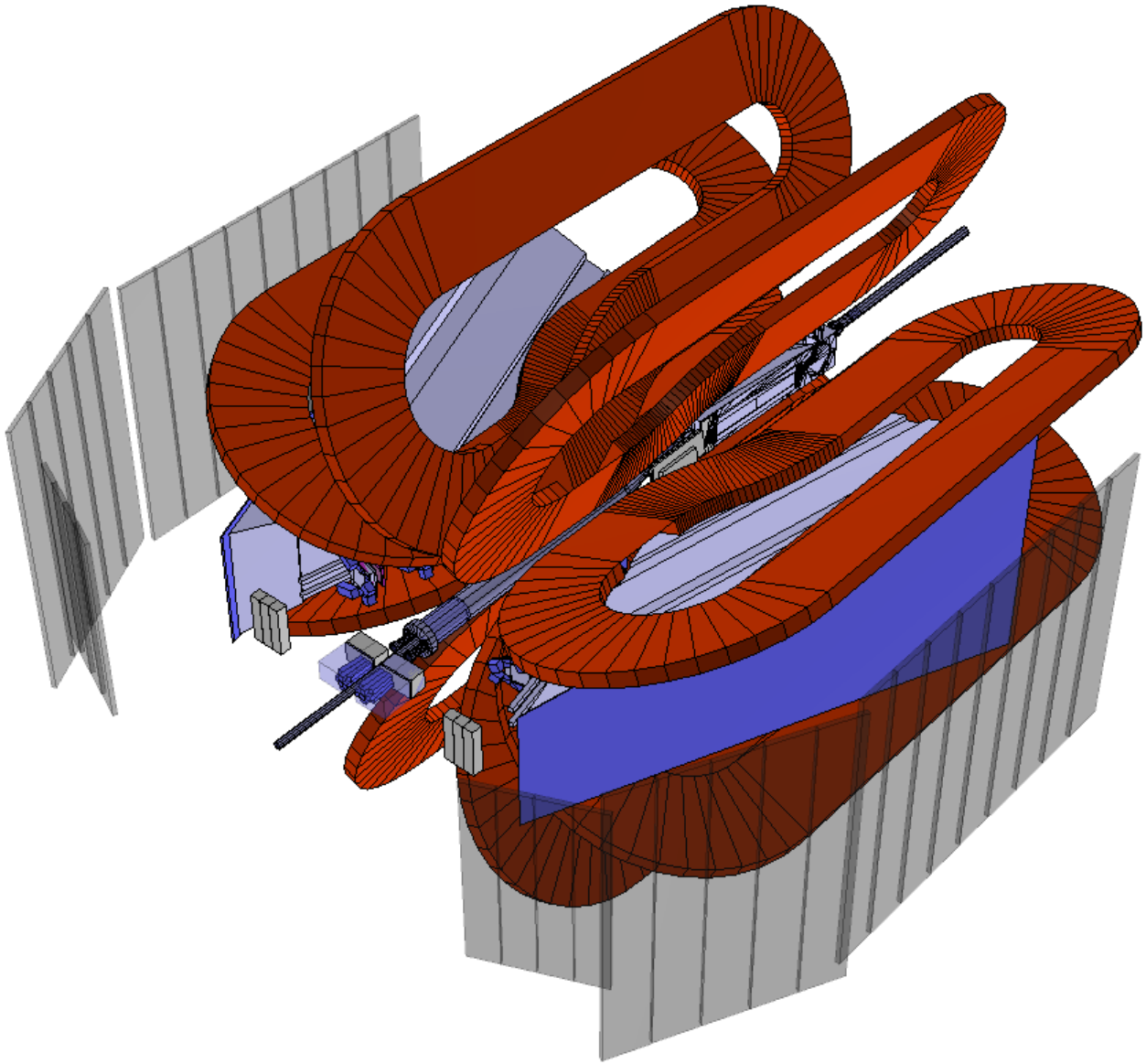
Projected reach and previous data



Reach of the modern TPE experiments



The OLYMPUS detector



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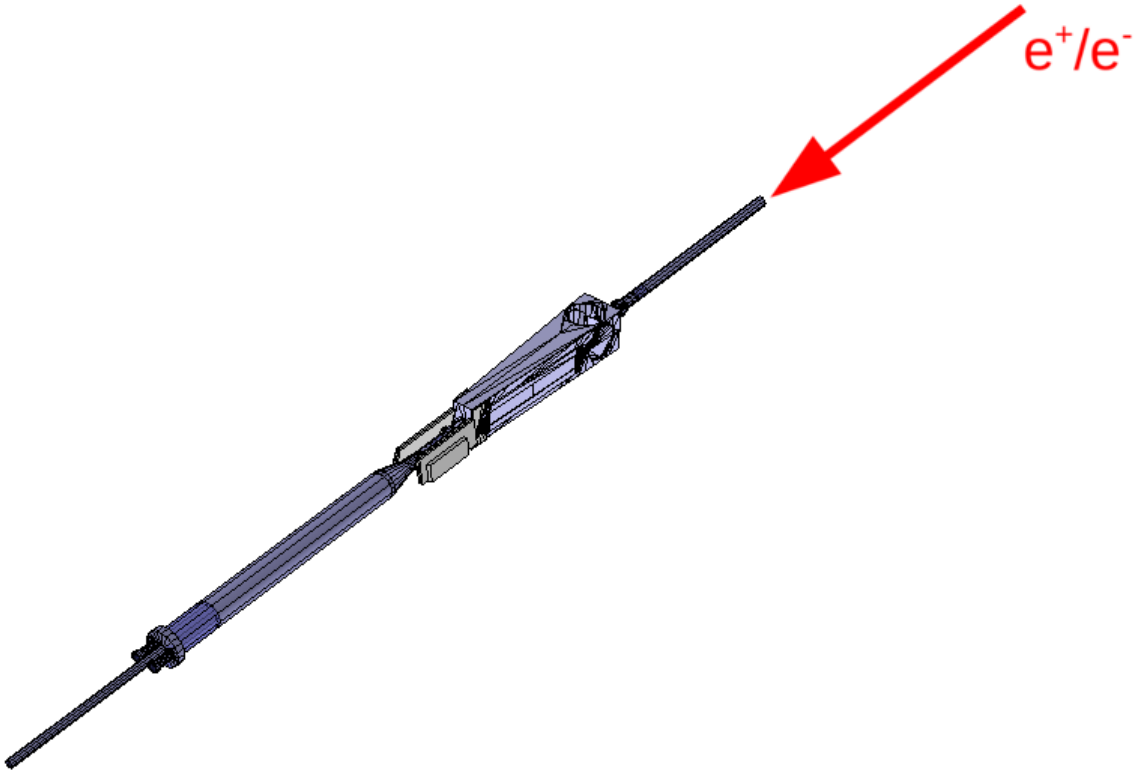

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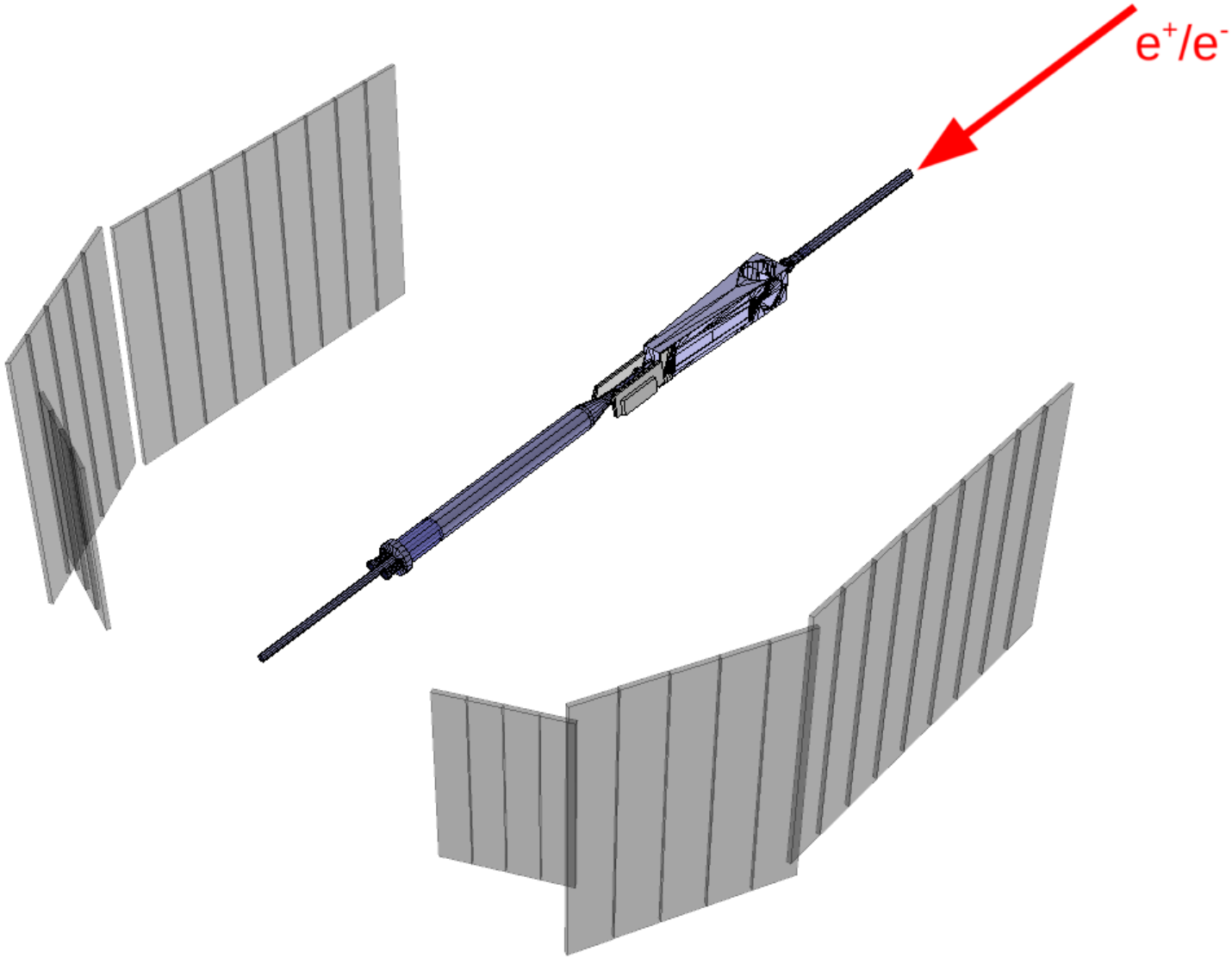

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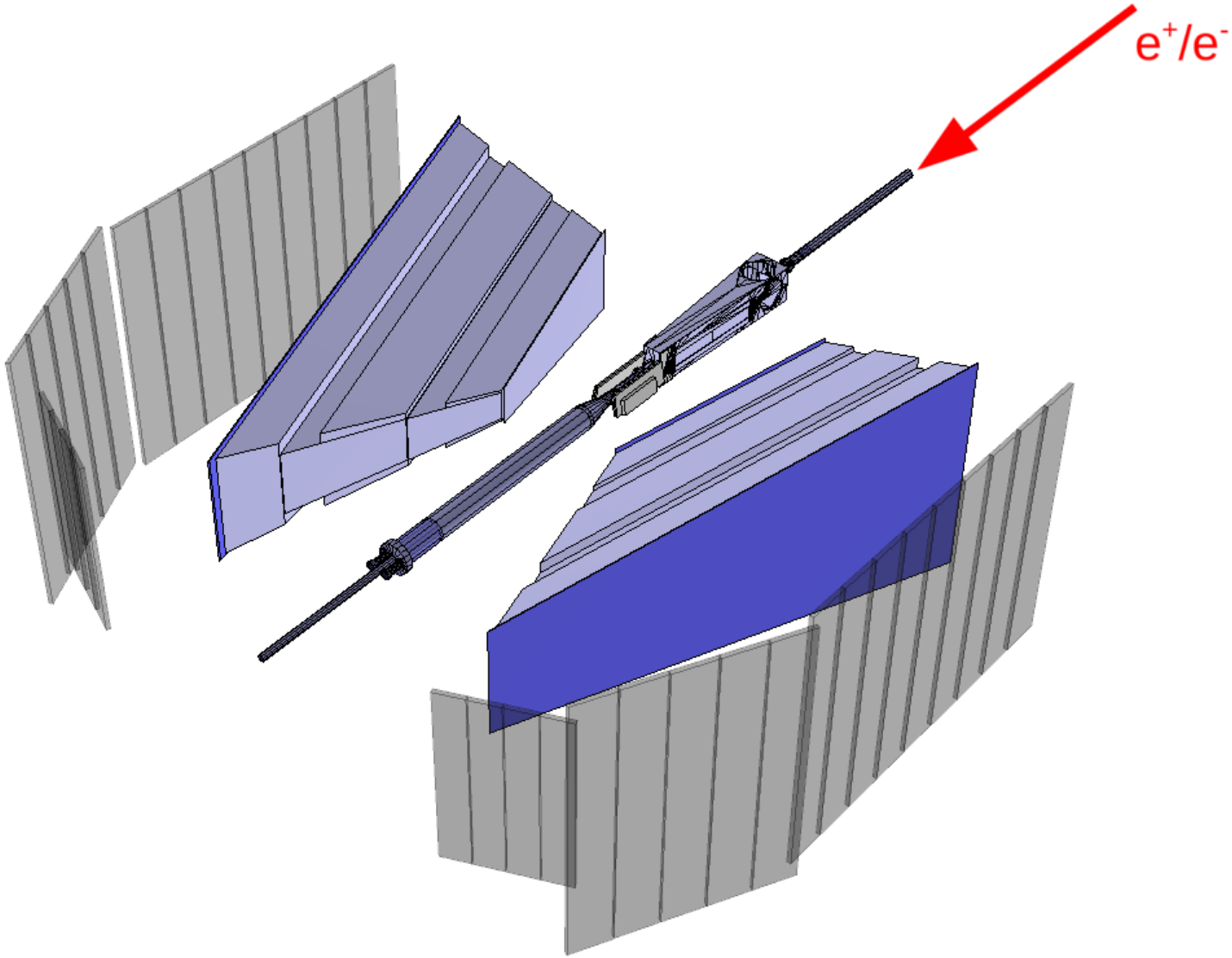
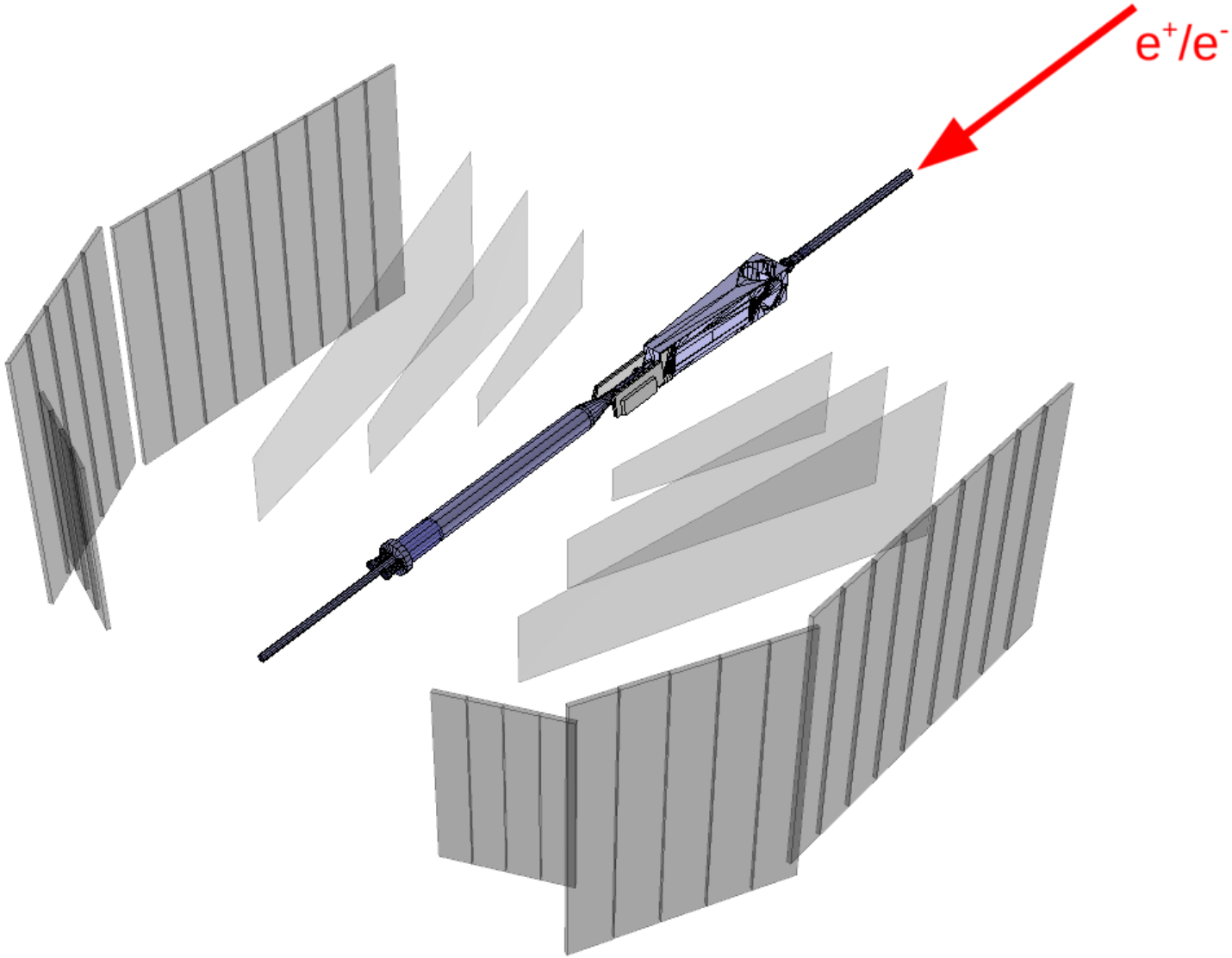
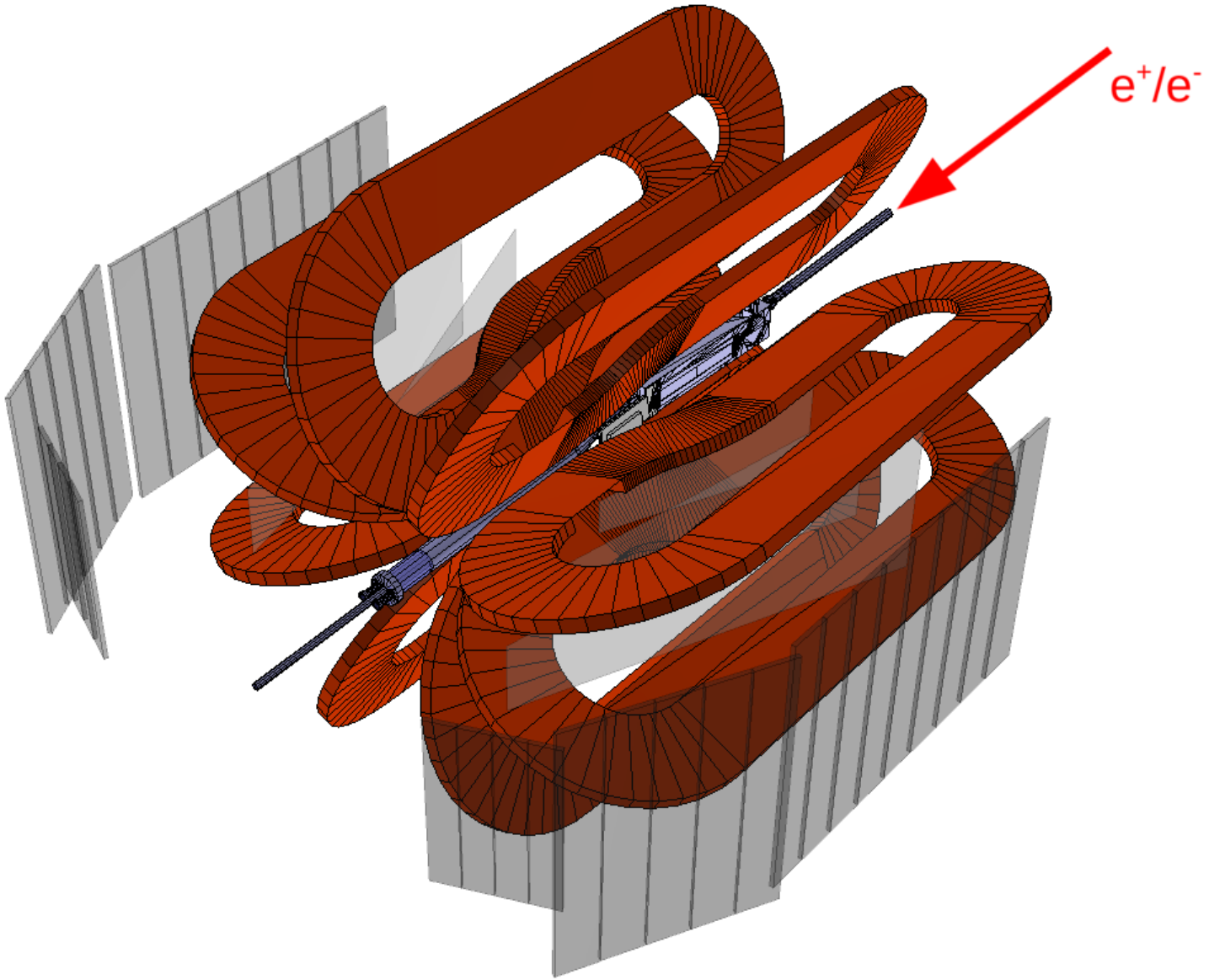


The OLYMPUS detector



The OLYMPUS detector



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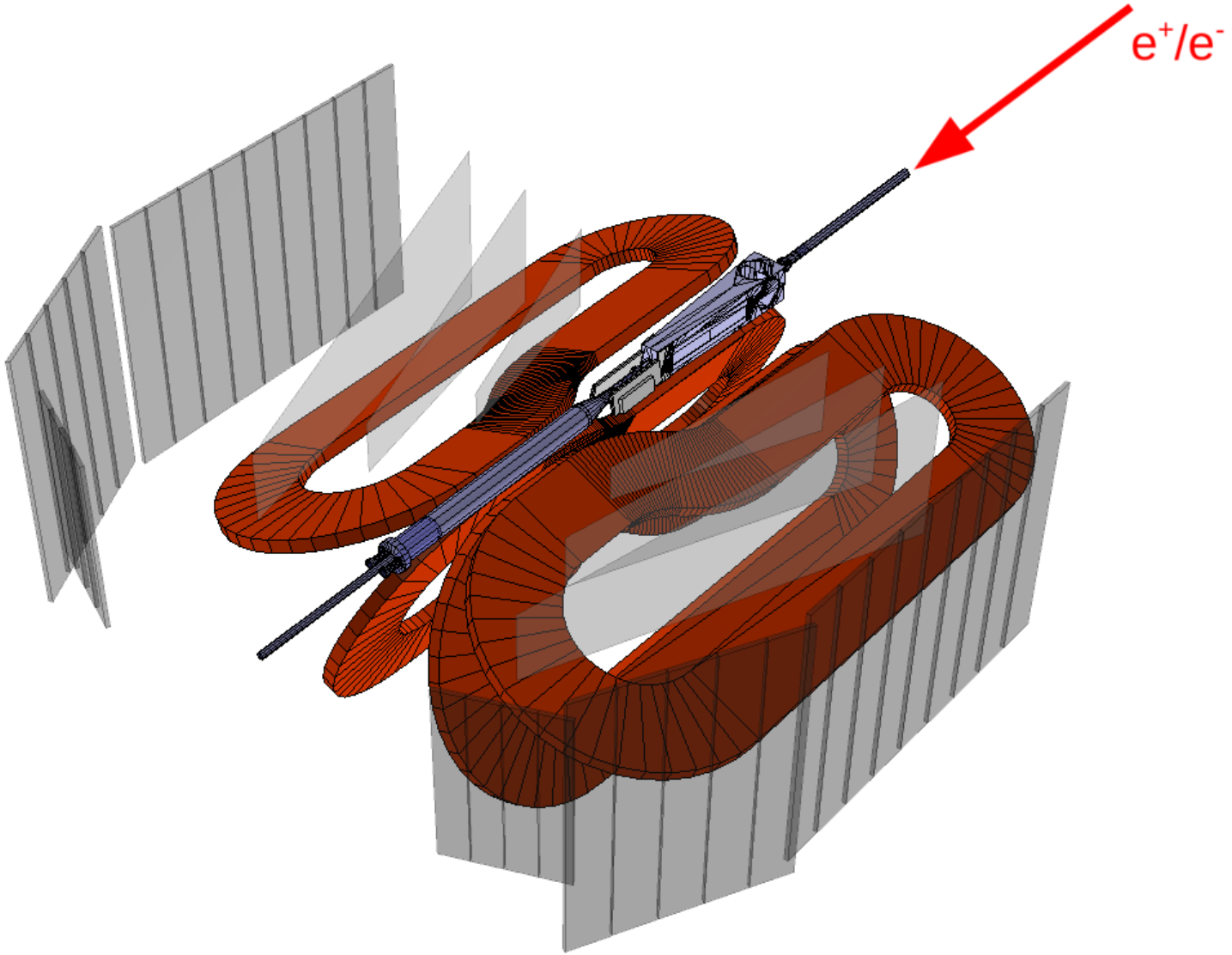

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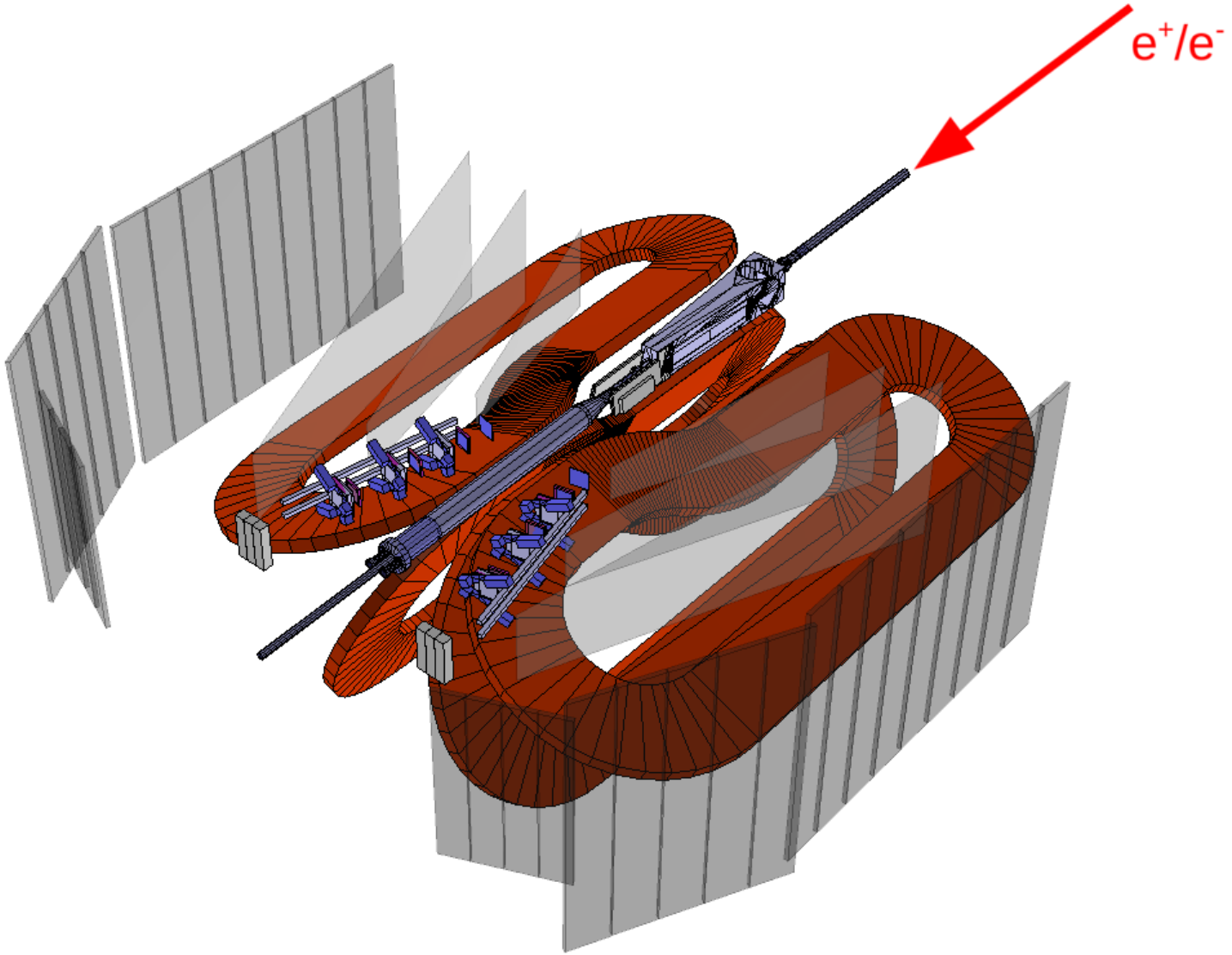
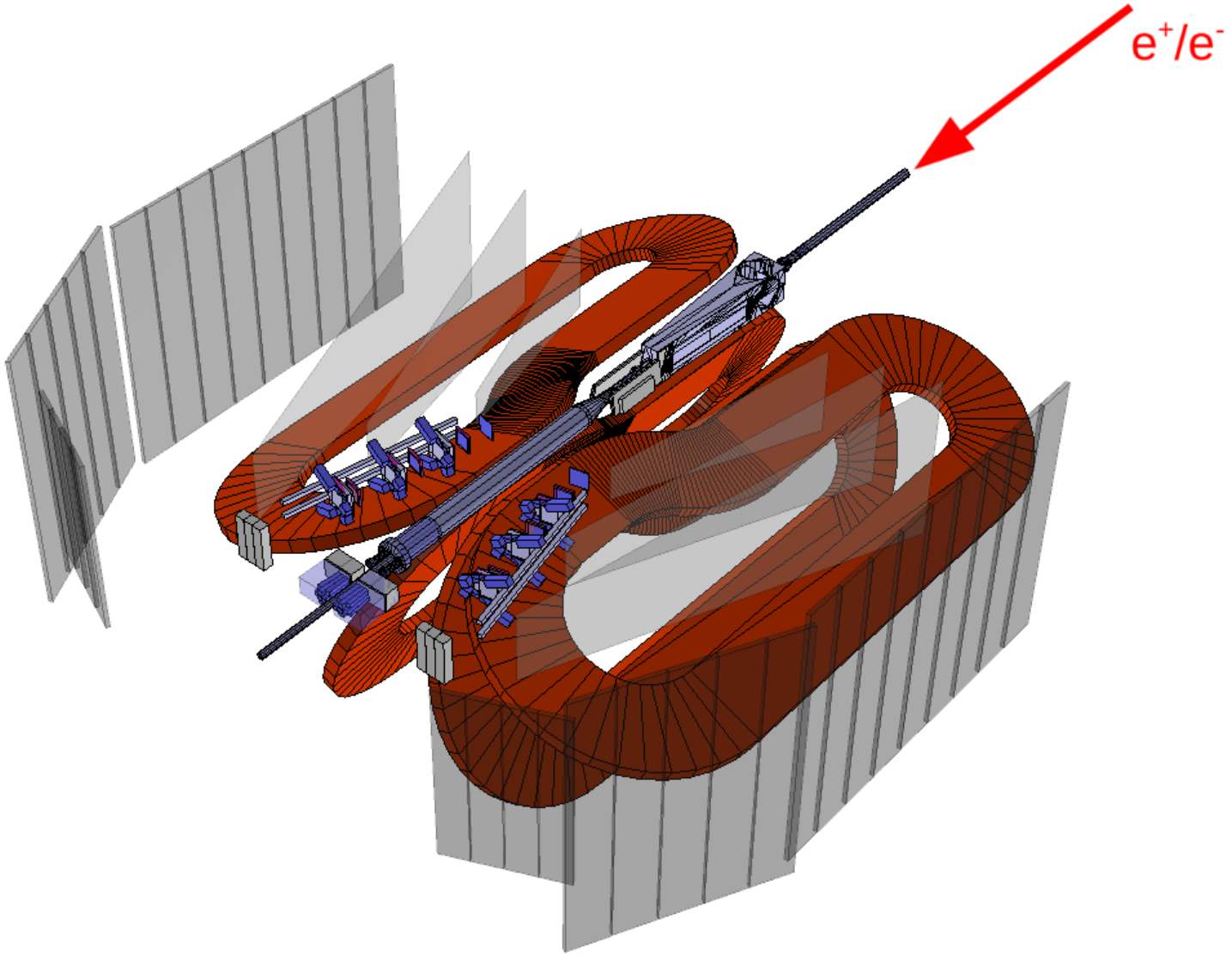


The OLYMPUS detector



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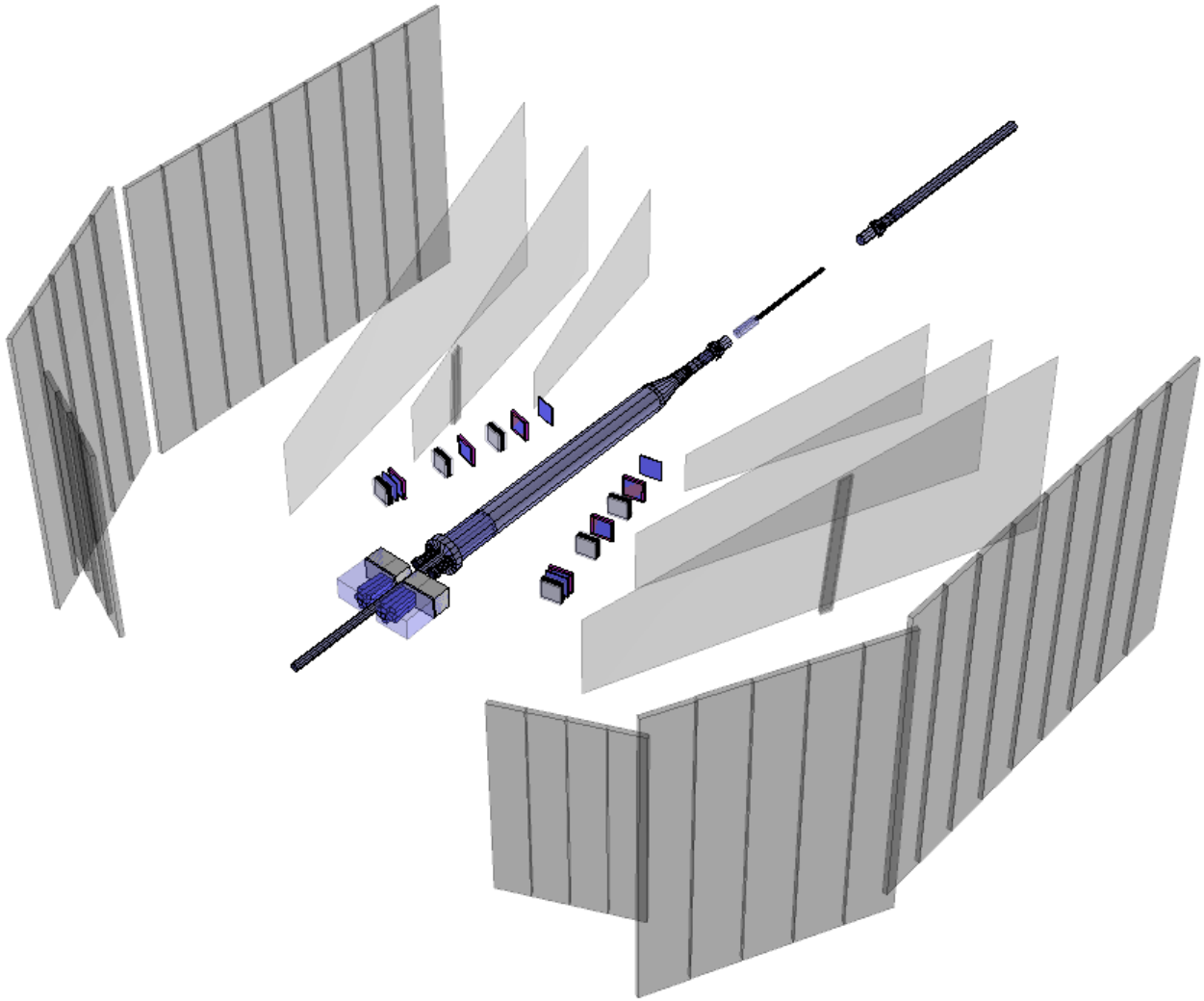
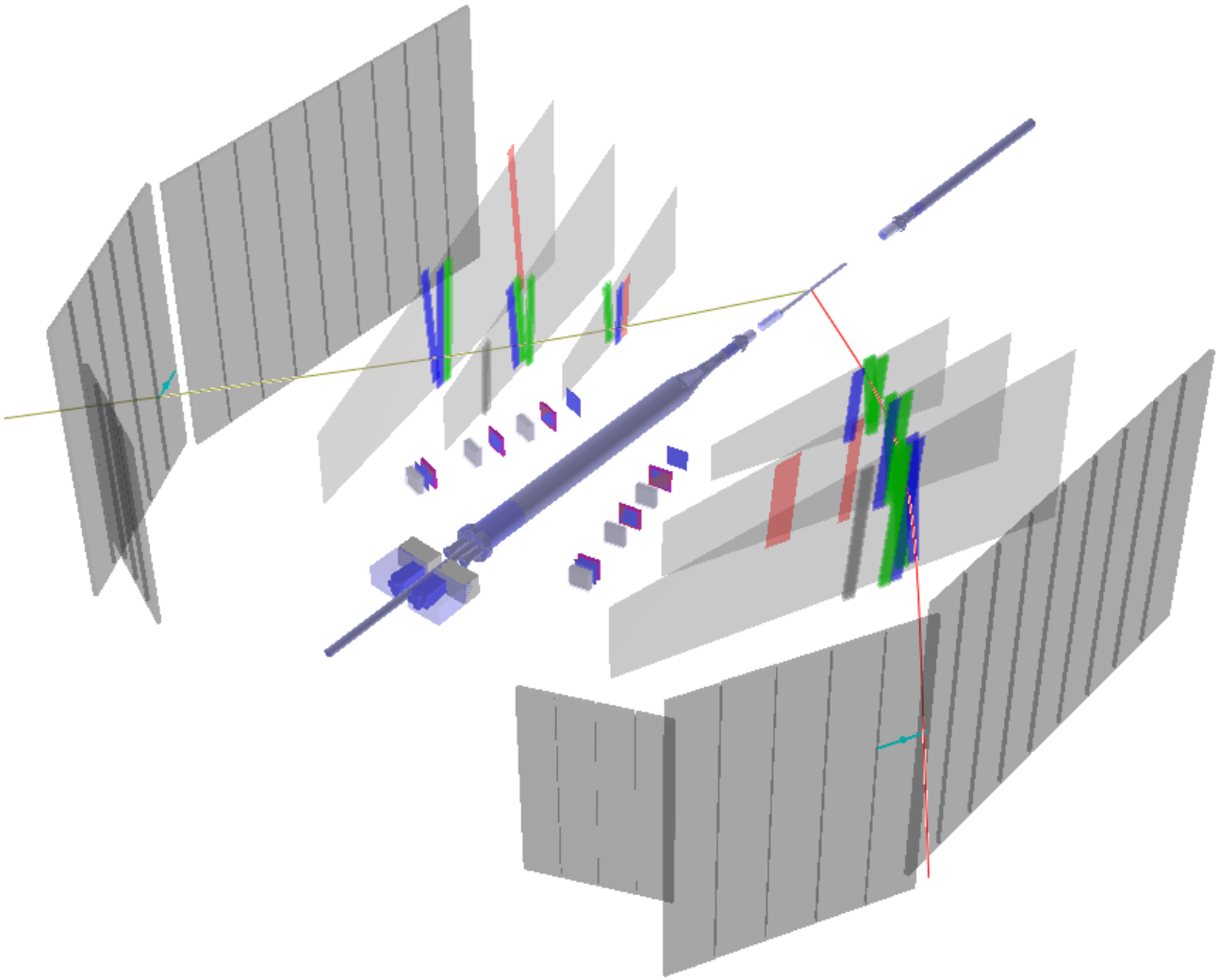
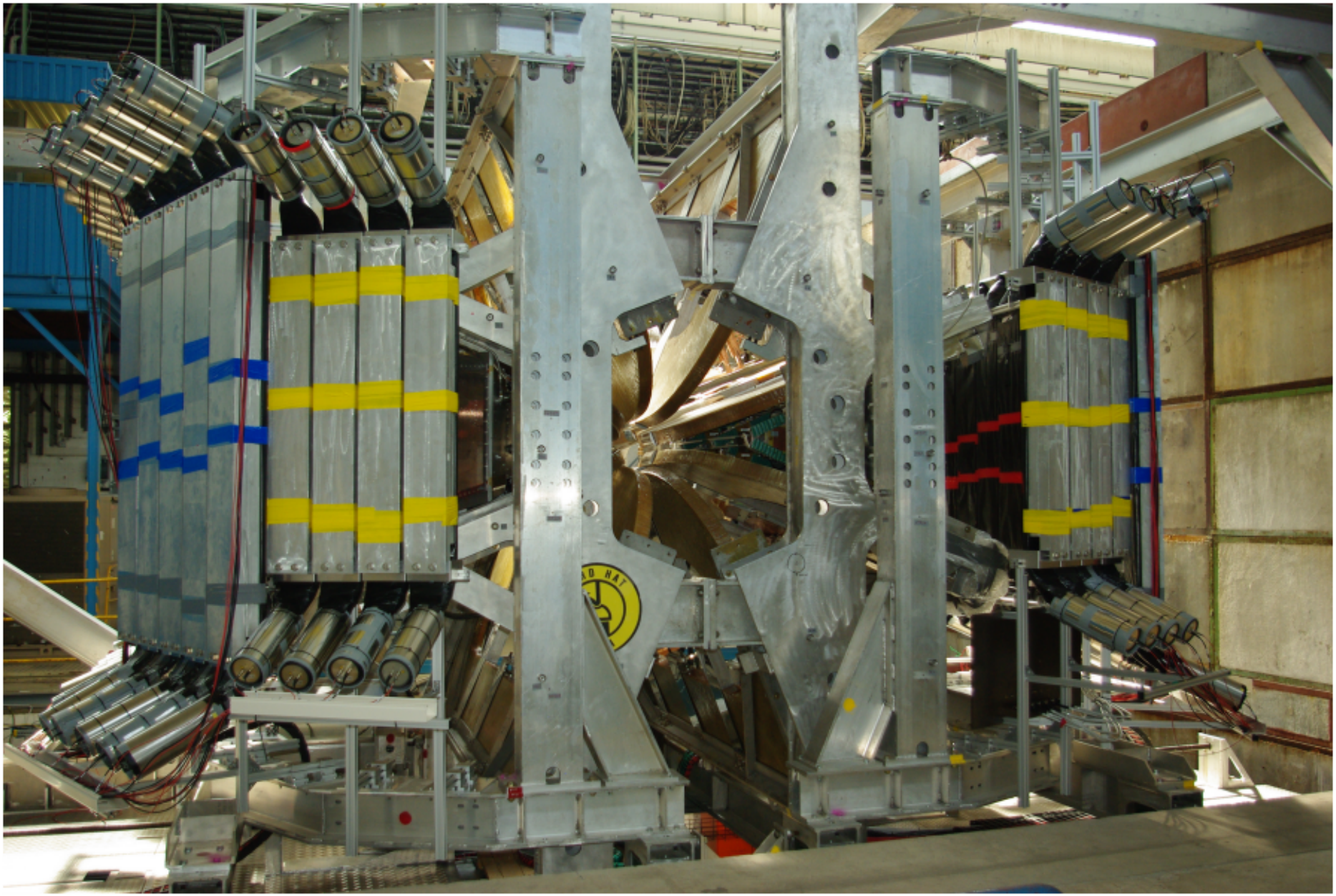


The OLYMPUS detector

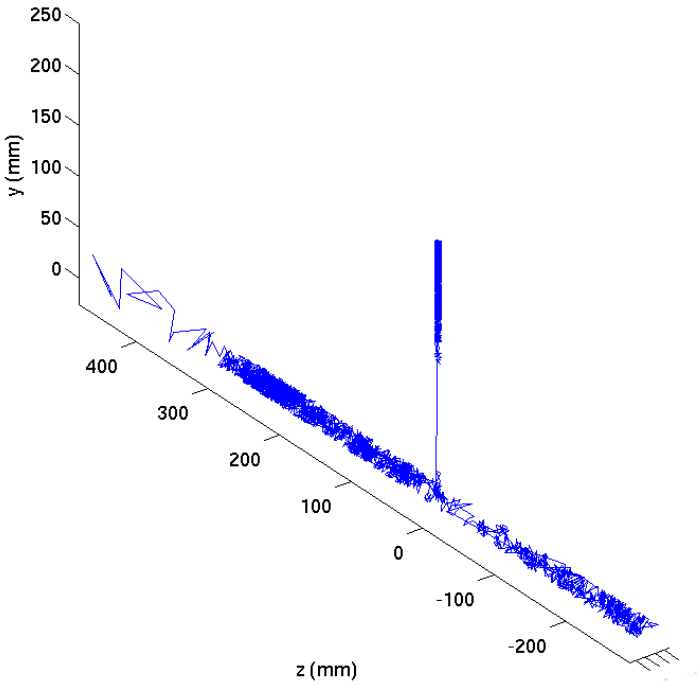


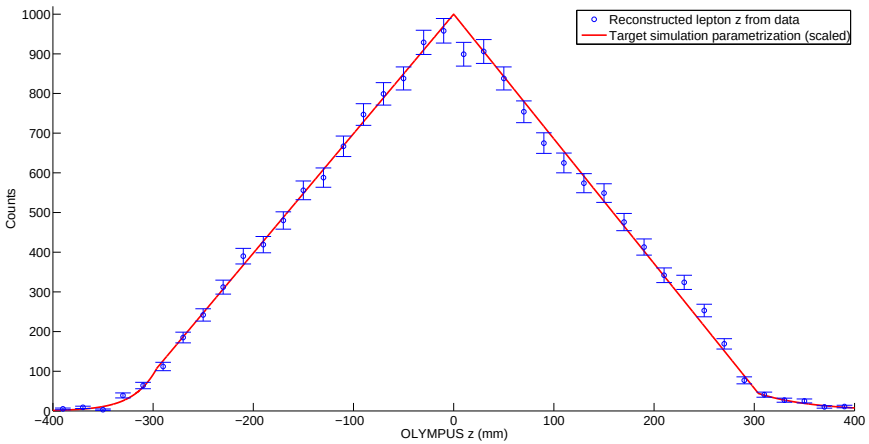
The OLYMPUS detector



Luminosity determination

Three independent monitors of the e^+/e^- relative luminosity:



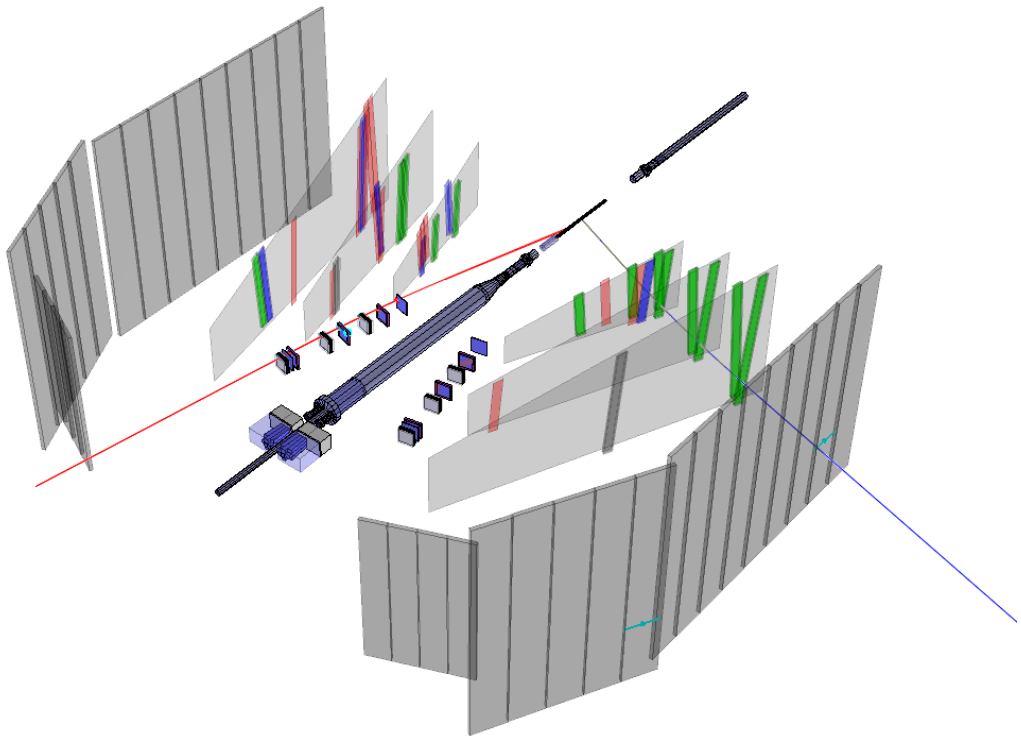


Beam current + molecular flow modeling of target density

~5% absolute, ~1% species-relative uncertainty

Luminosity determination

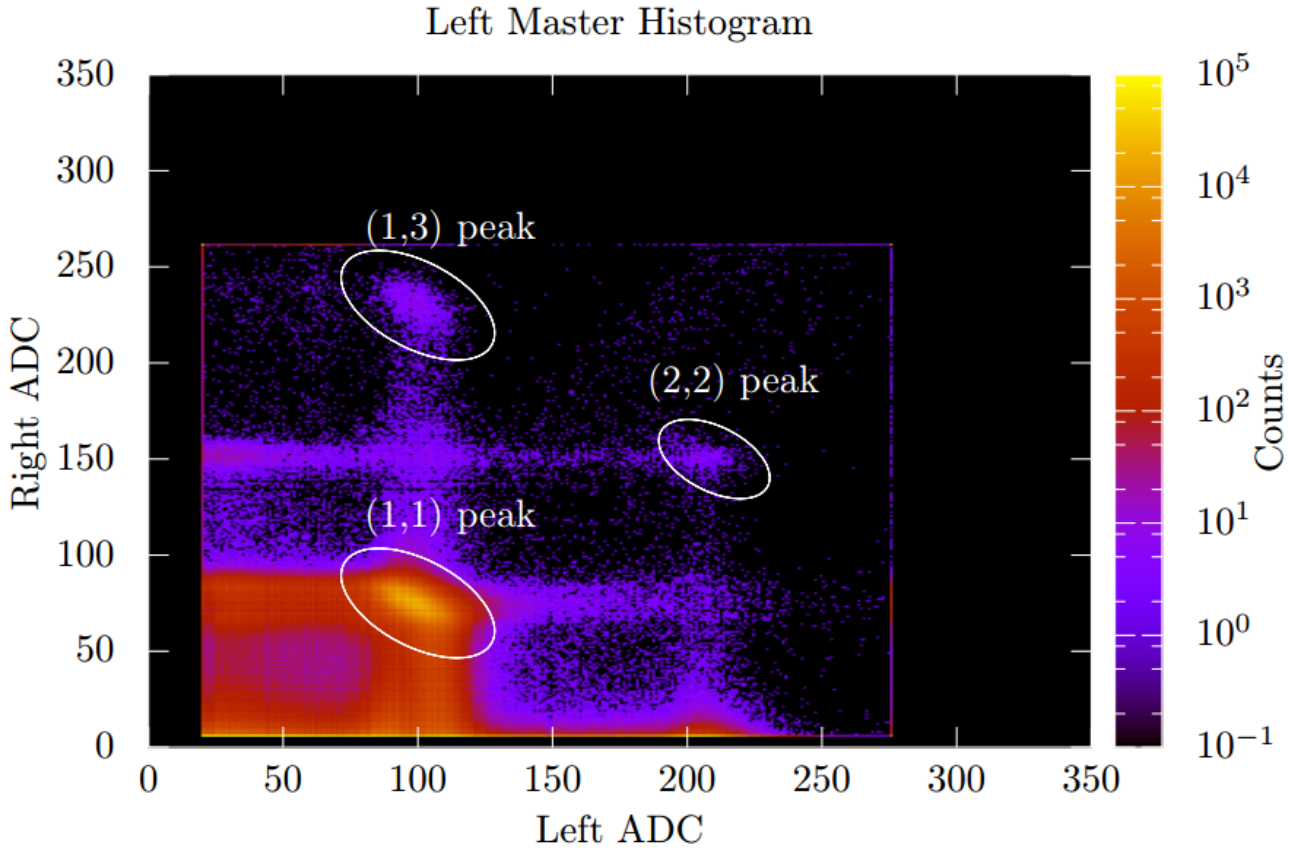
Three independent monitors of the e^+/e^- relative luminosity:



12 Degree Elastic Scattering ($R_{2\gamma} \approx 1$ at high ε)
$\sim$2% absolute, $\sim$0.4% species-relative uncertainty

Luminosity determination

Three independent monitors of the e^+/e^- relative luminosity:

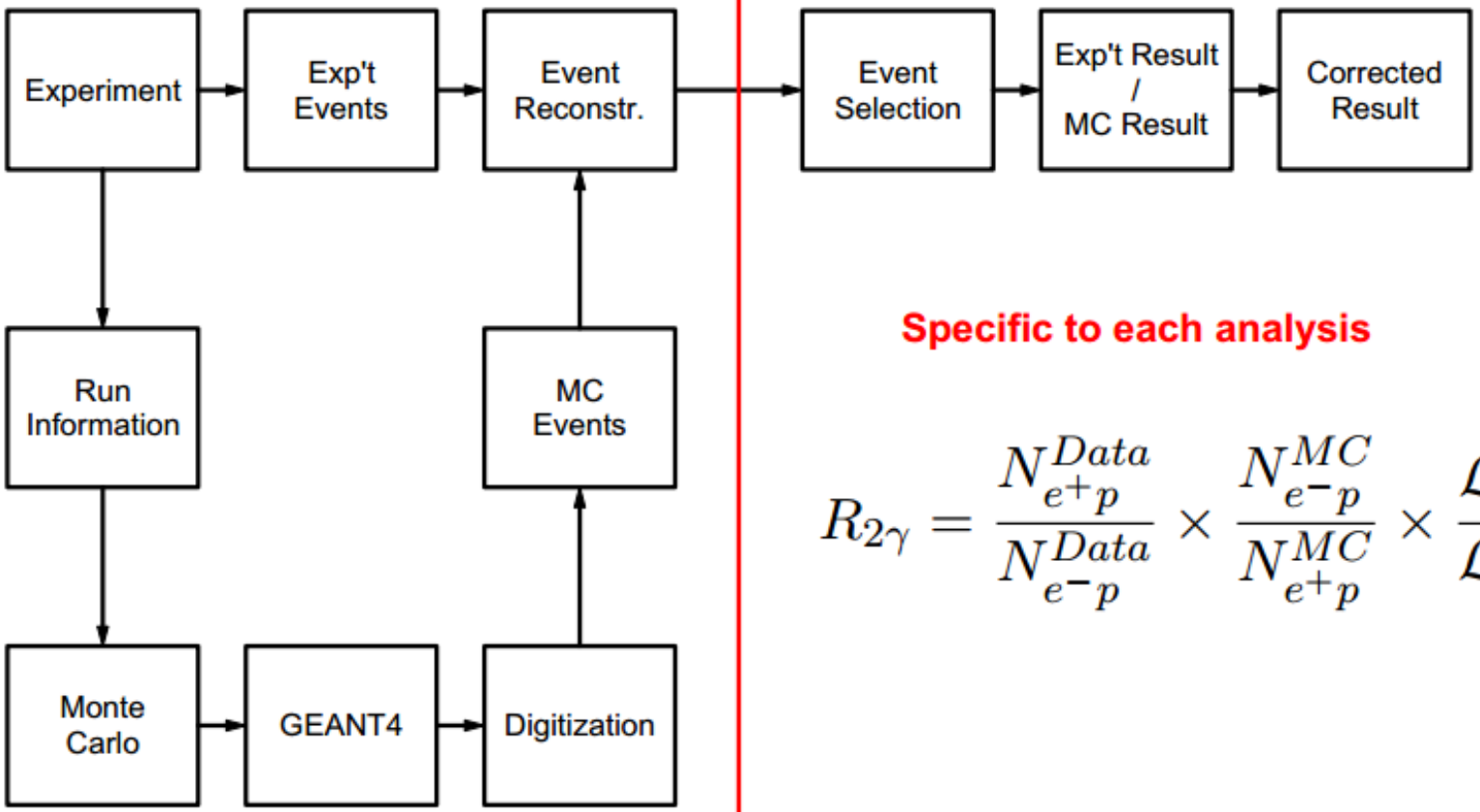


Multi-Interaction Events in Forward Calorimeter

$\sim$10% absolute, $\sim$0.35% species-relative uncertainty

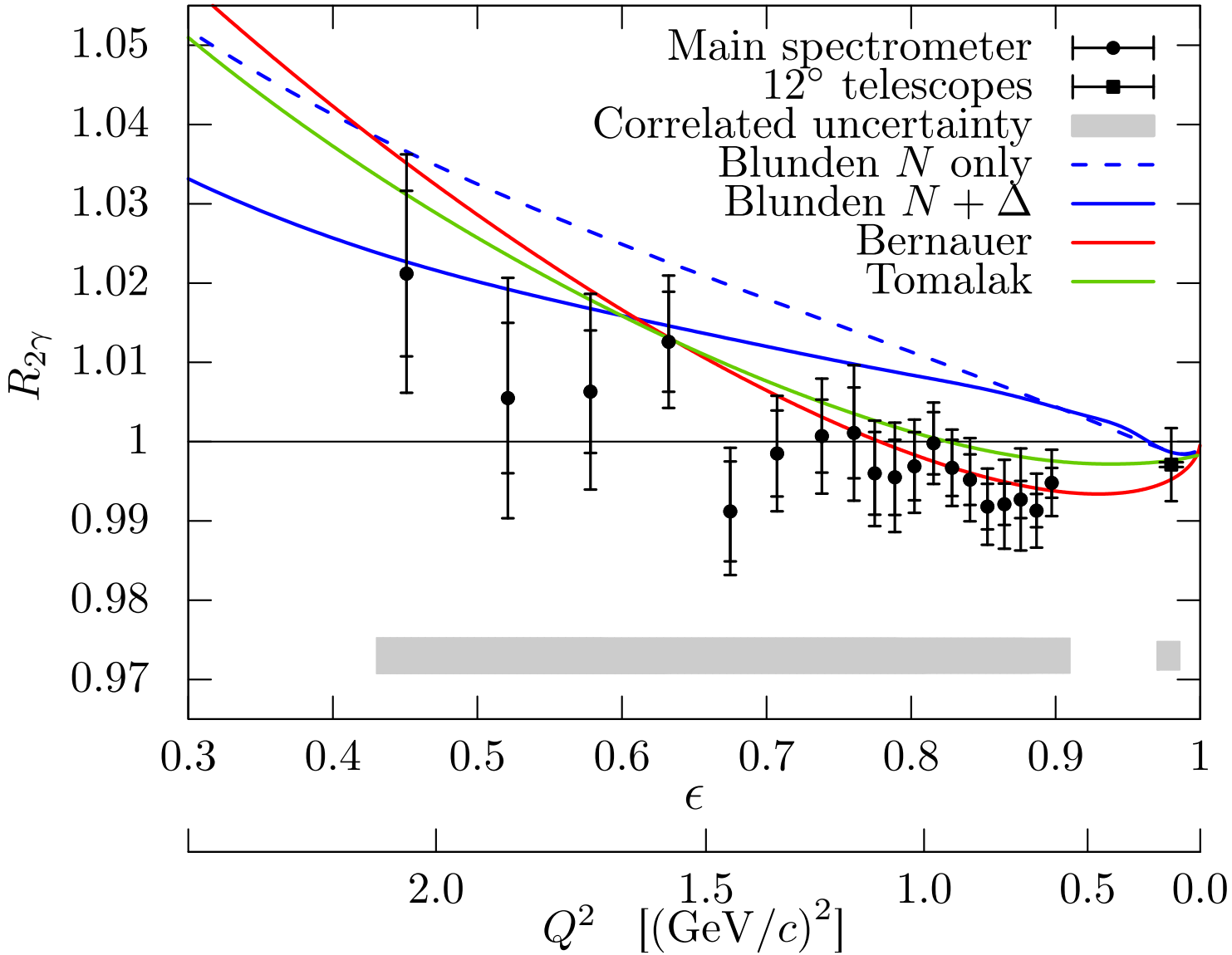
A. Schmidt *et al.*, arXiv:1708.04616 (physics.ins-det)

Main analysis



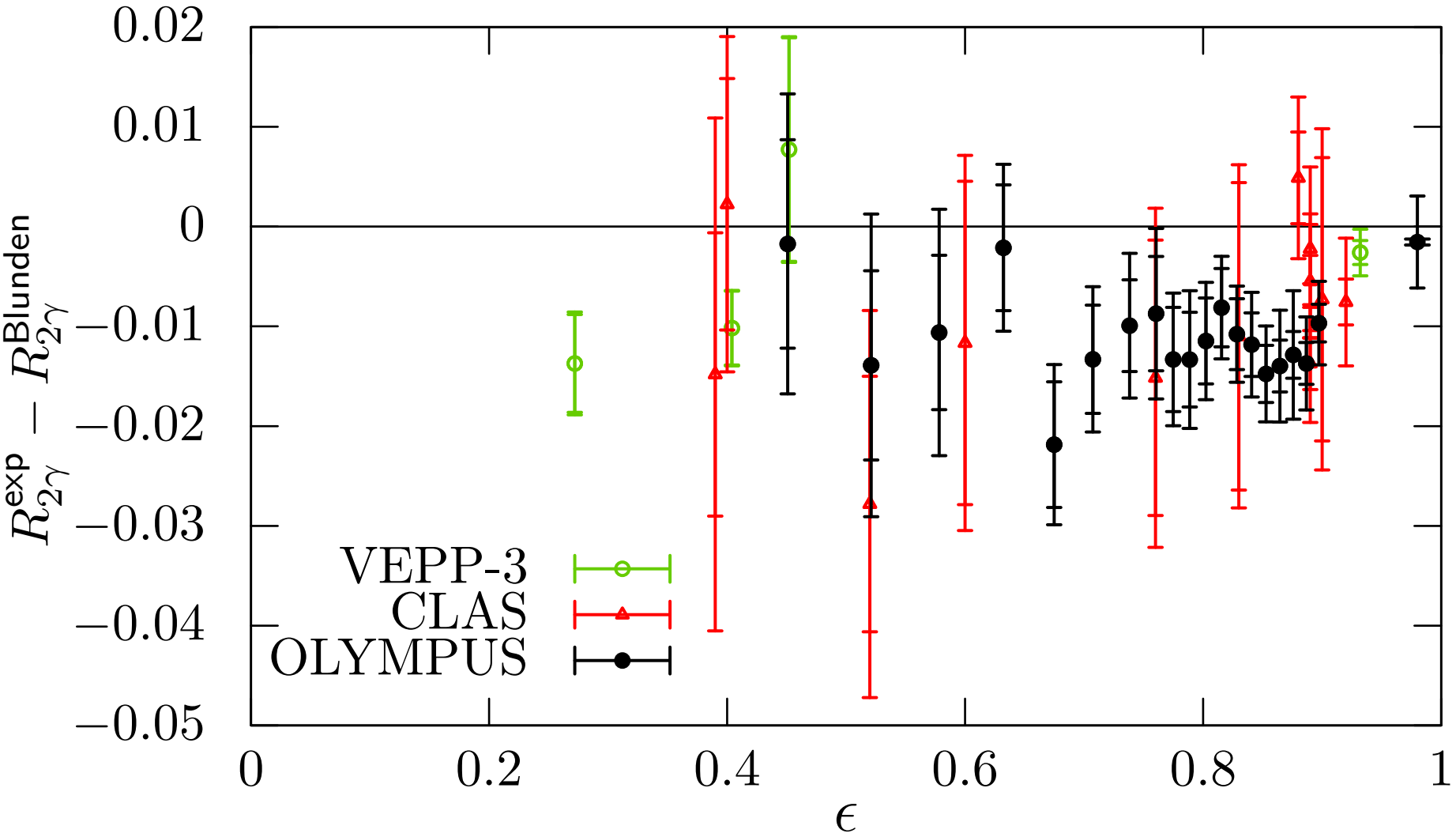
$$R_{2\gamma} = \frac{N^{Data}_{e^+p}}{N^{Data}_{e^-p}} \times \frac{N^{MC}_{e^-p}}{N^{MC}_{e^+p}} \times \frac{\mathcal{L}_{e^+p}}{\mathcal{L}_{e^-p}}$$

$R_{2\gamma}$, Mo-Tsai radiative correction model



B. S. Henderson *et al.*, Phys. Rev. Lett. 118, 092501 (2017).

Comparison to Blunden $N + \Delta$ model



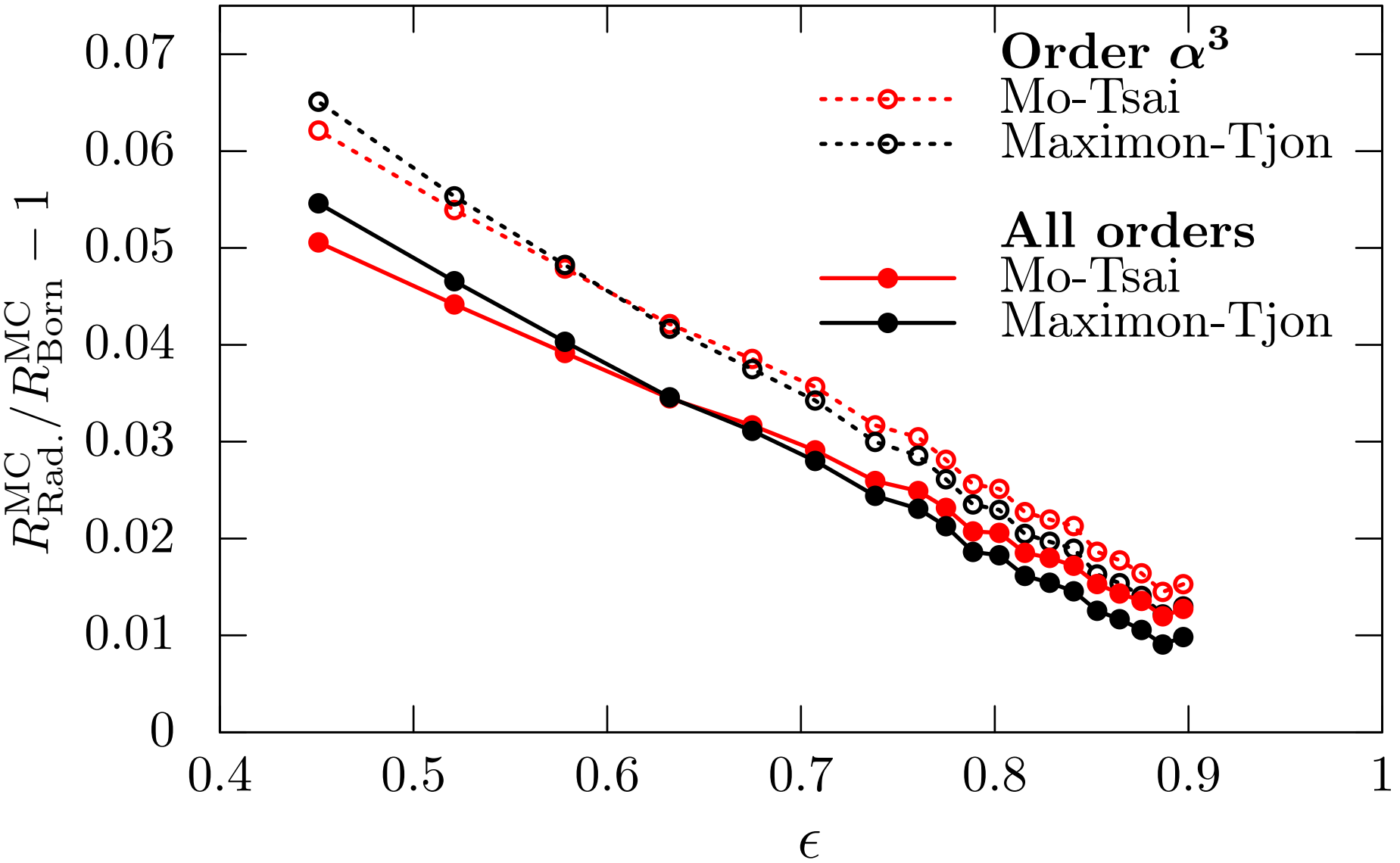
Conclusions

- OLYMPUS achieved measurement of $\sigma_{e^+p}/\sigma_{e^-p}$ for 0.15 GeV^2 $< Q^2 <$ 2.2 GeV^2, with $\lesssim$1% uncertainty
- In general, the three modern TPE experiments agree; the effect is small at low Q^2, consistent with the slope of theoretical models, and roughly consistent with the magnitude of some phenomenological models
- The definitive answer may be at higher Q^2, plans are forming to explore this region experimentally

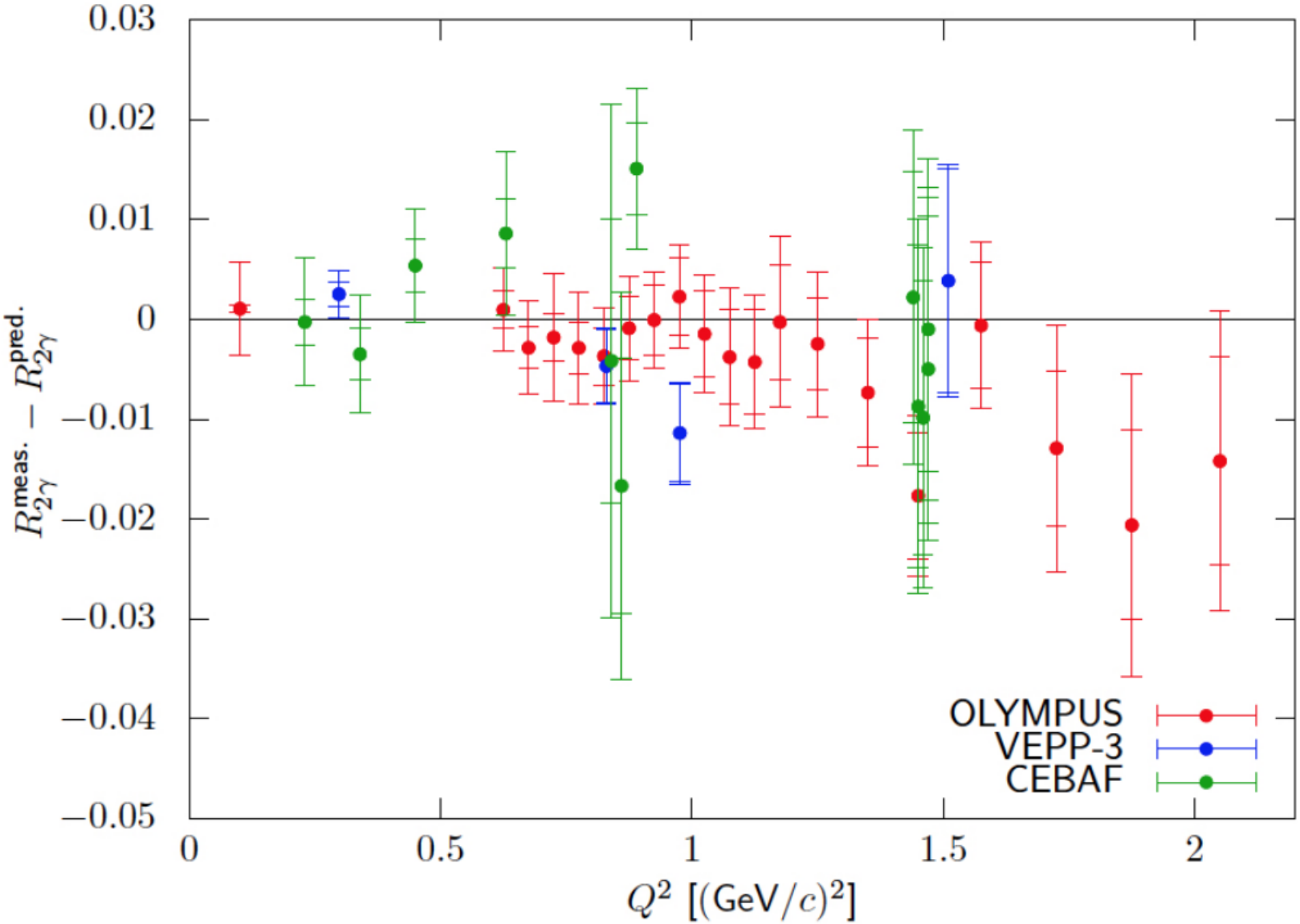
The OLYMPUS collaboration

- Arizona State University
- DESY
- INFN Bari
- INFN Ferrara
- INFN Rome
- Hampton University
- Massachusetts Institute of Technology
- Petersburg Nuclear Physics Institute
- University of Bonn
- University of Glasgow
- University of Mainz
- University of New Hampshire
- A. Alikhanyan National Laboratory (Yerevan Physics Institute)

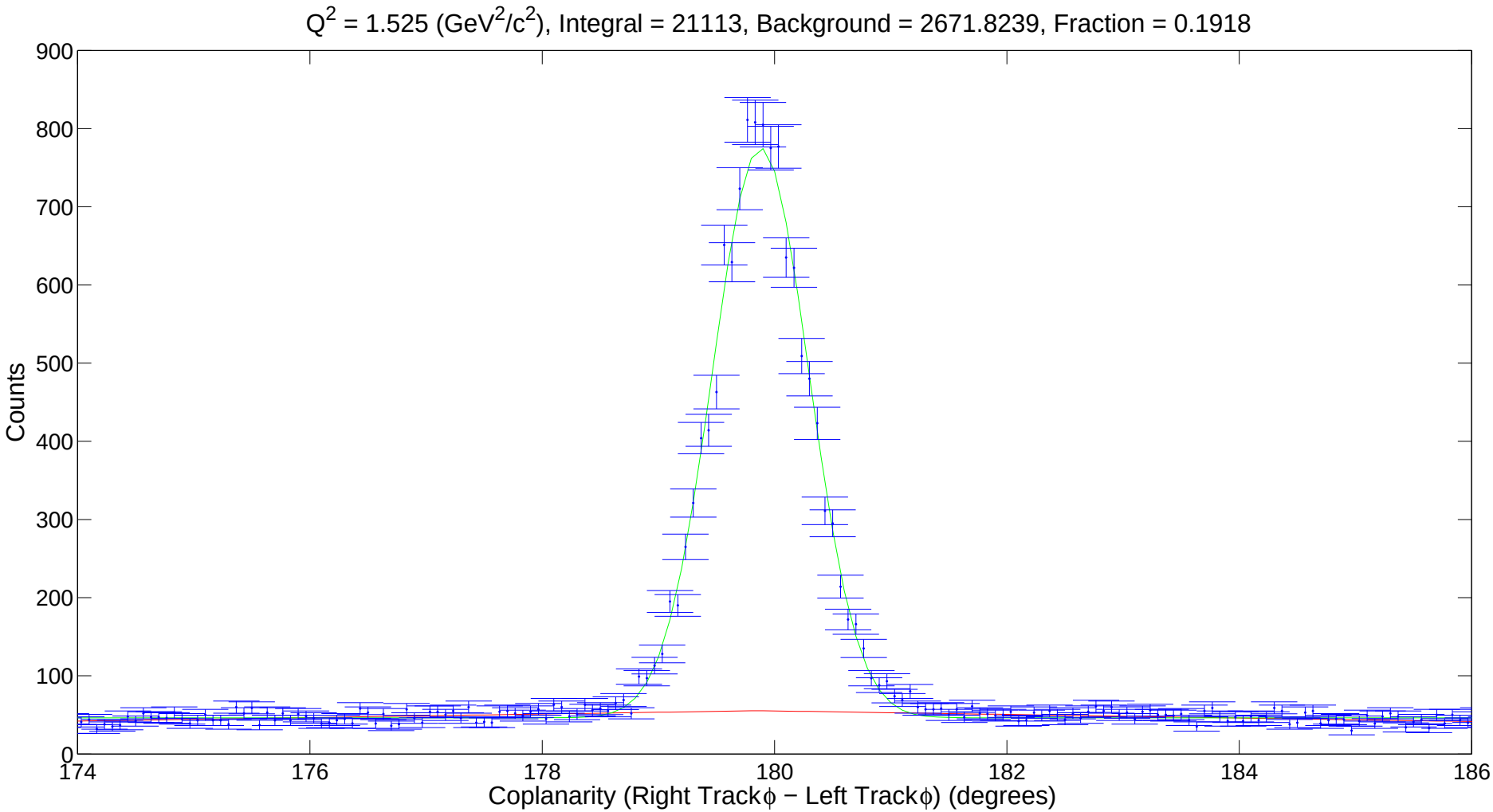
$R_{2\gamma}$, Mo-Tsai Radiative Correction Model



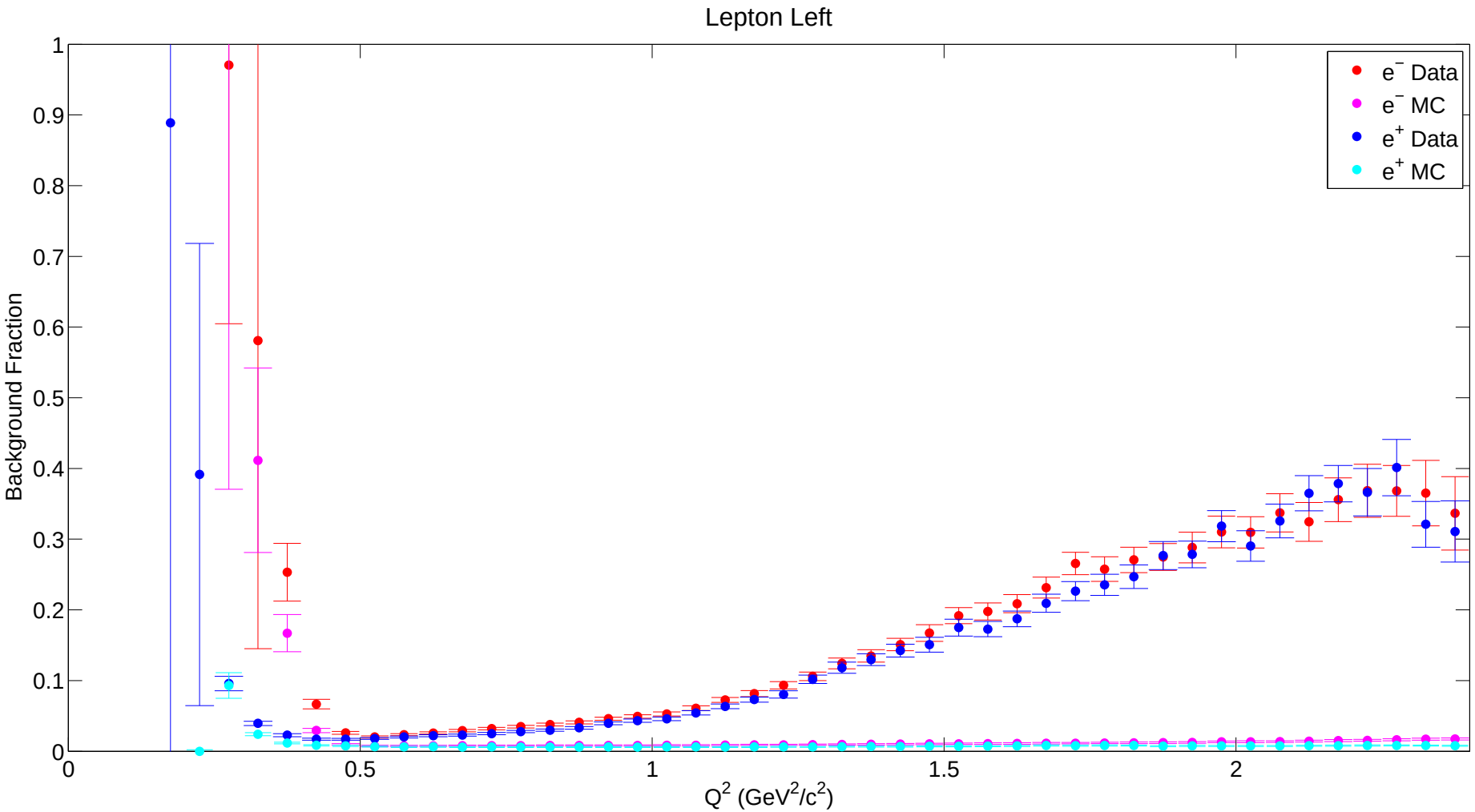
Comparison to Bernauer phen. model



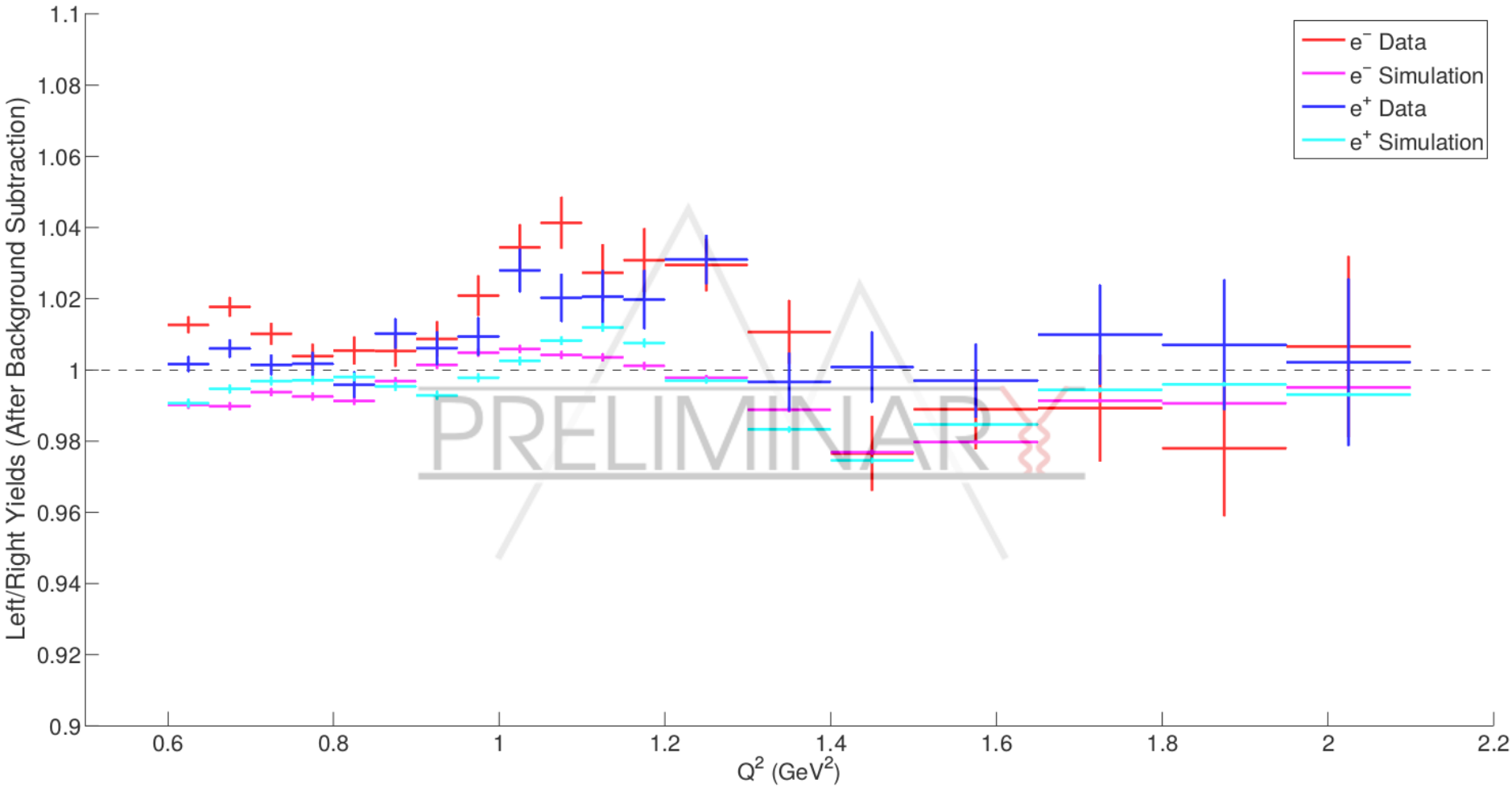
Background Subtraction



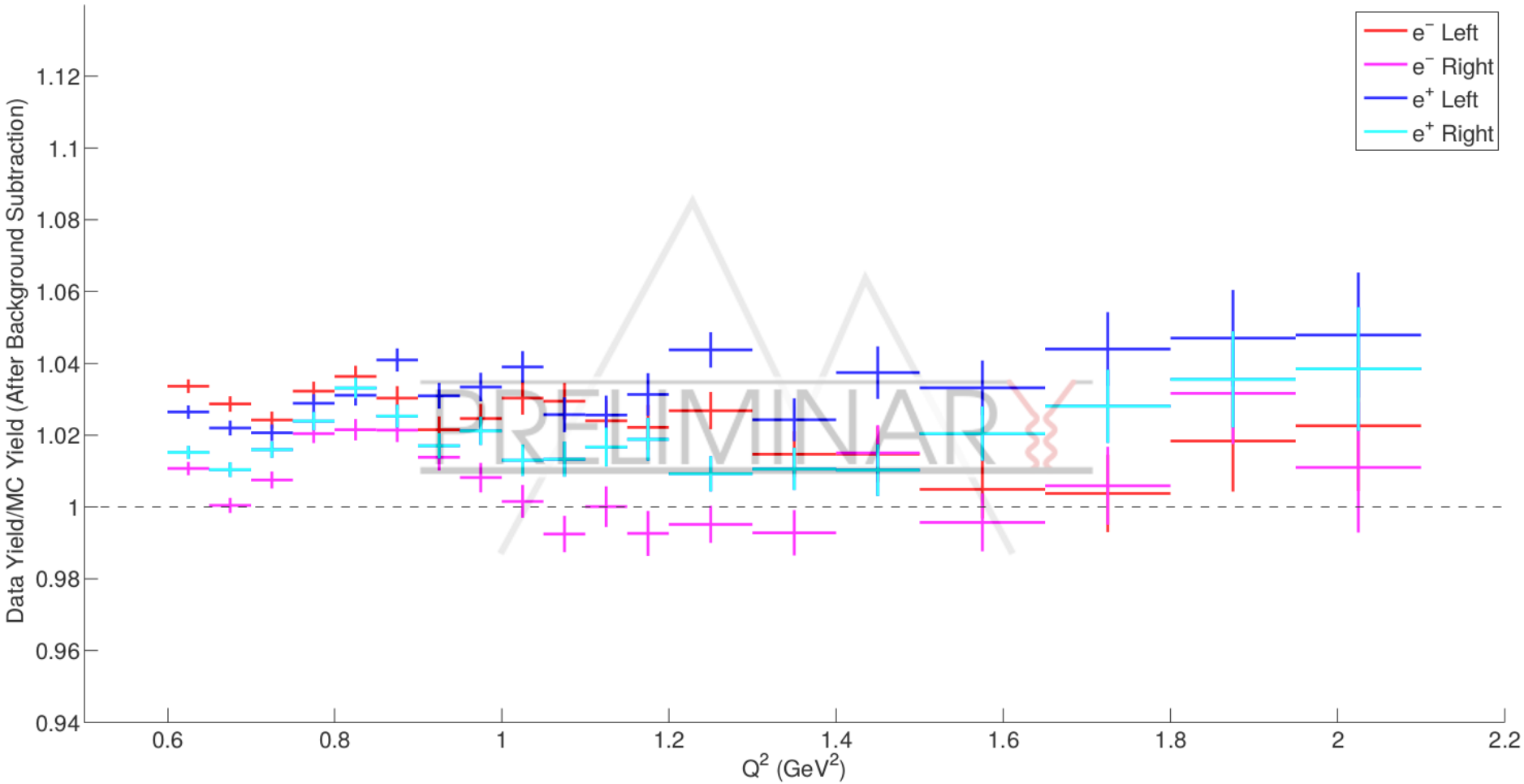
Background Fraction for Lepton Left



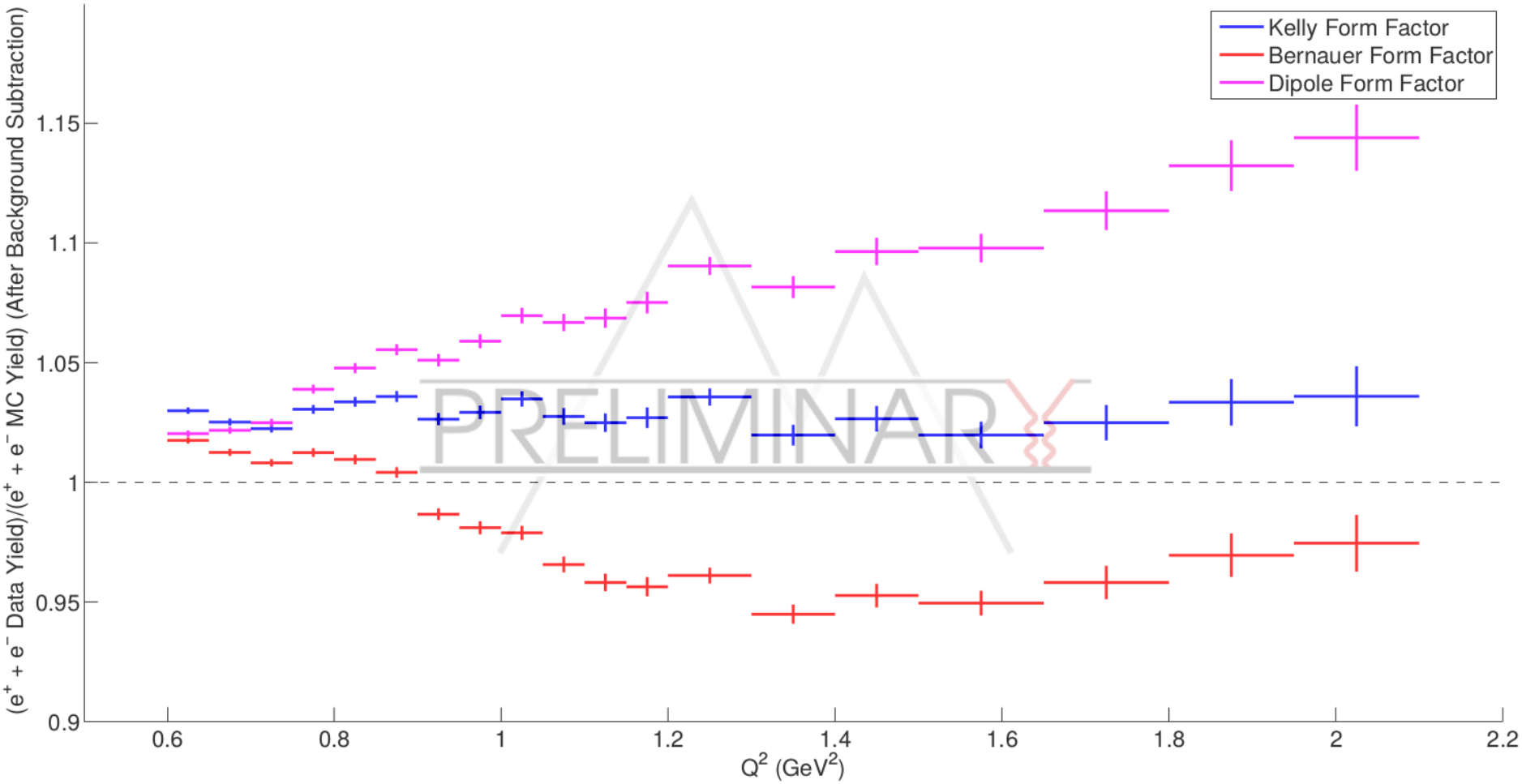
Lepton left/right yields



Data/simulation yields (Kelly form factor)



Form factor discrimination power



Slow control luminosity normalization, blinded common slope

Other TPE experiments

Two other experiments have also completed data-taking for e^+p/e^-p ratio measurements; different systematics and kinematic coverages

CLAS, Jefferson Lab, USA

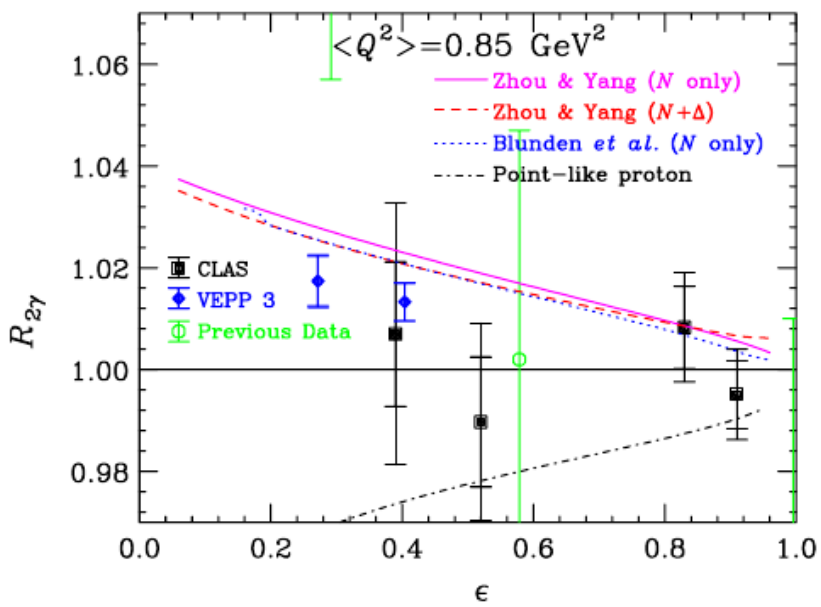
- Unique tertiary beam
- Sensitive to lower Q^2
- Very large acceptance
- Statistics limited
- Results published, long paper pending

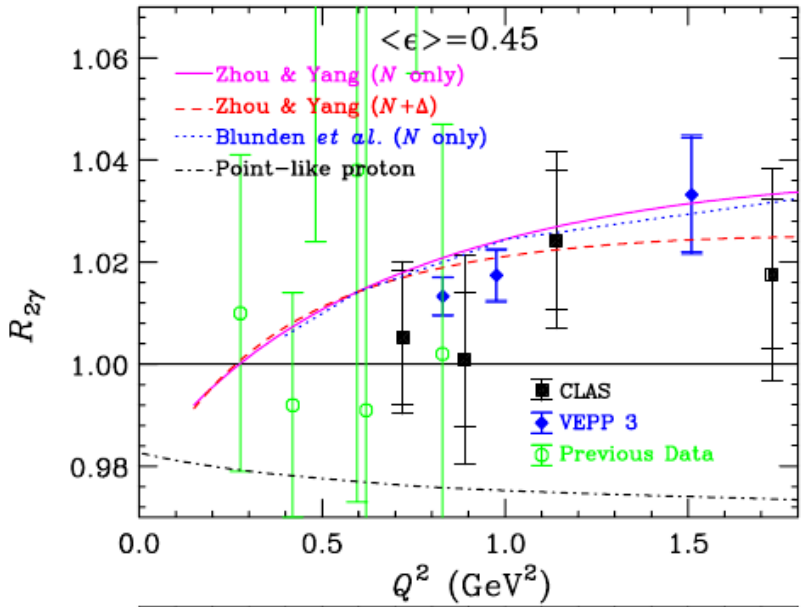
VEPP-3, Novosibirsk, Russia

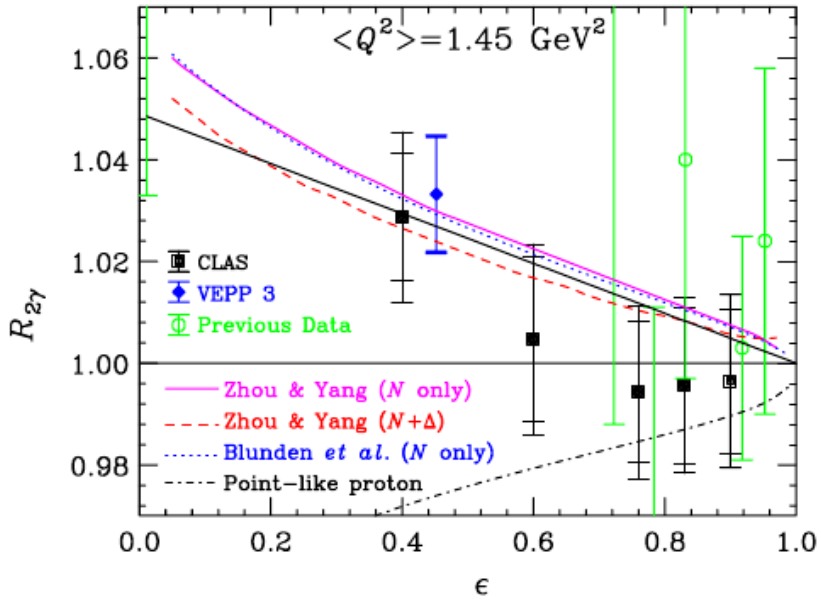
- Sensitive to lower Q^2
- Calorimetry-based detector
- Smaller acceptance
- Relatively advanced results already out

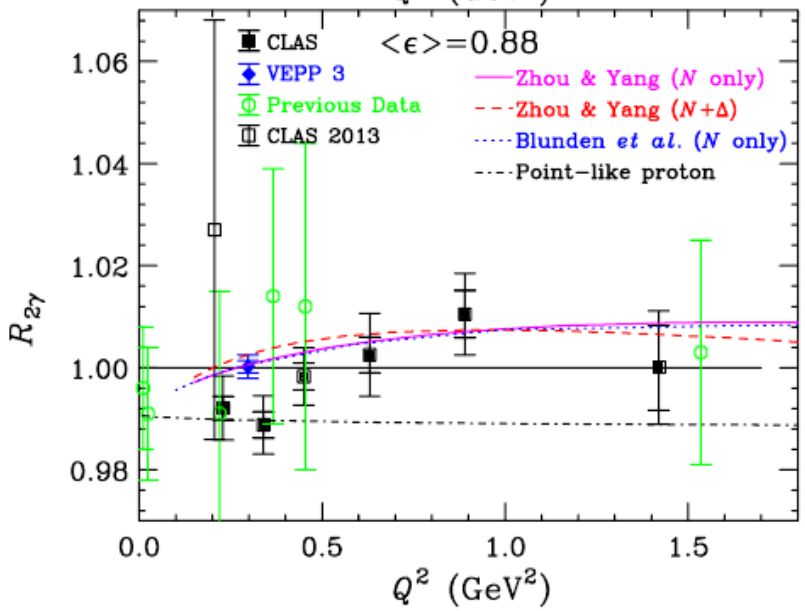
The three experiments are quite complimentary; should provide a definitive answer

CLAS and VEPP-3 results

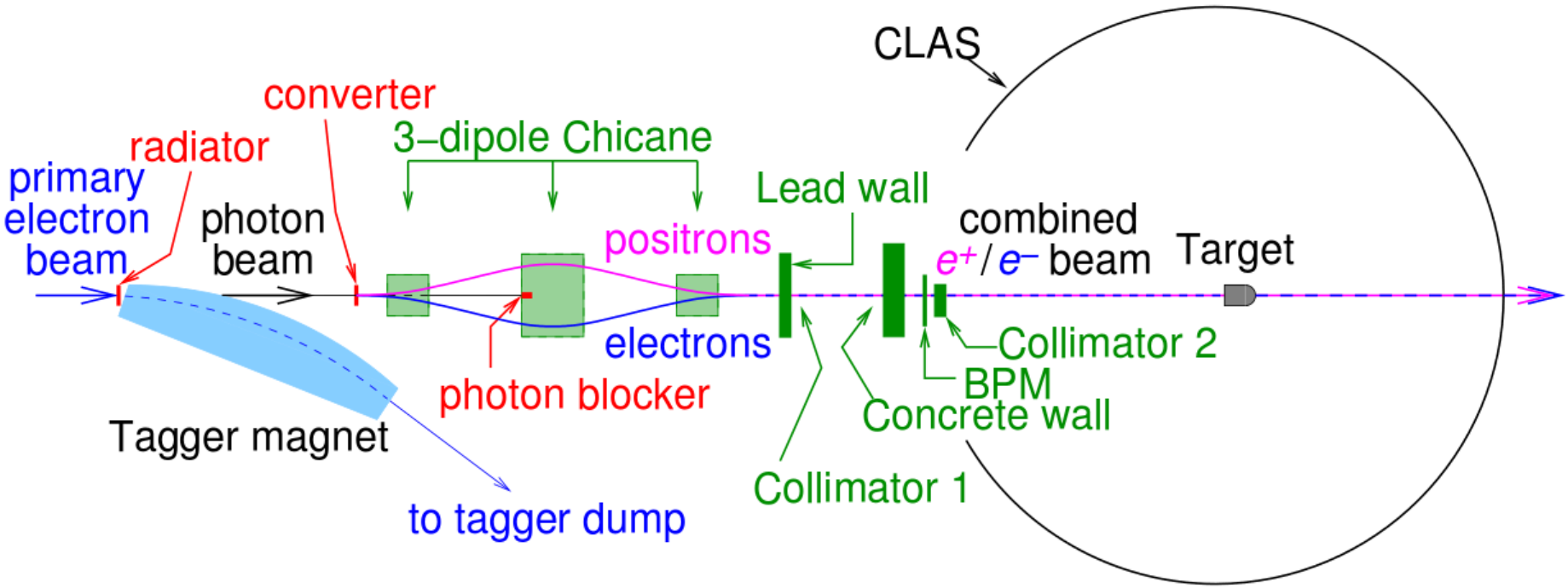




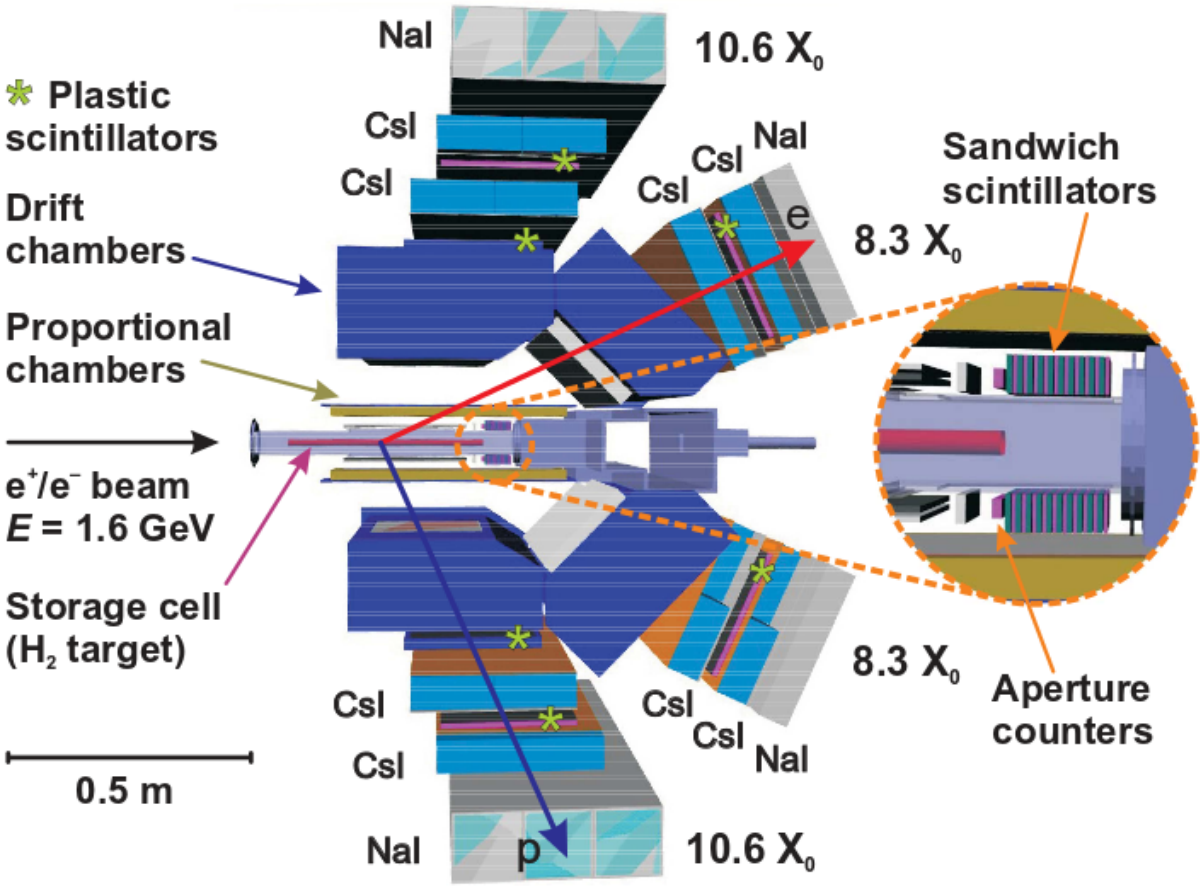




CLAS TPE experiment

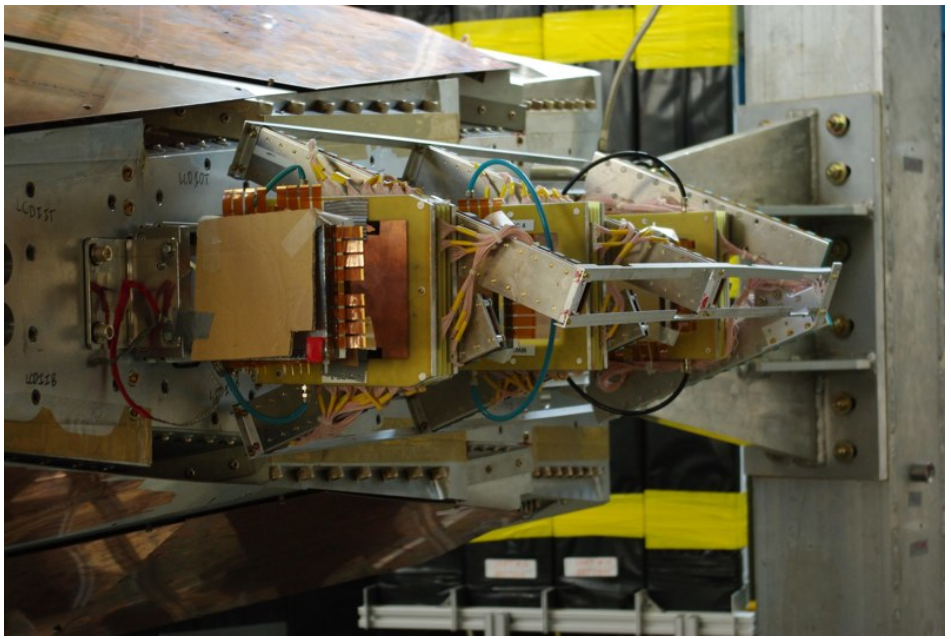


VEPP-3 TPE experiment

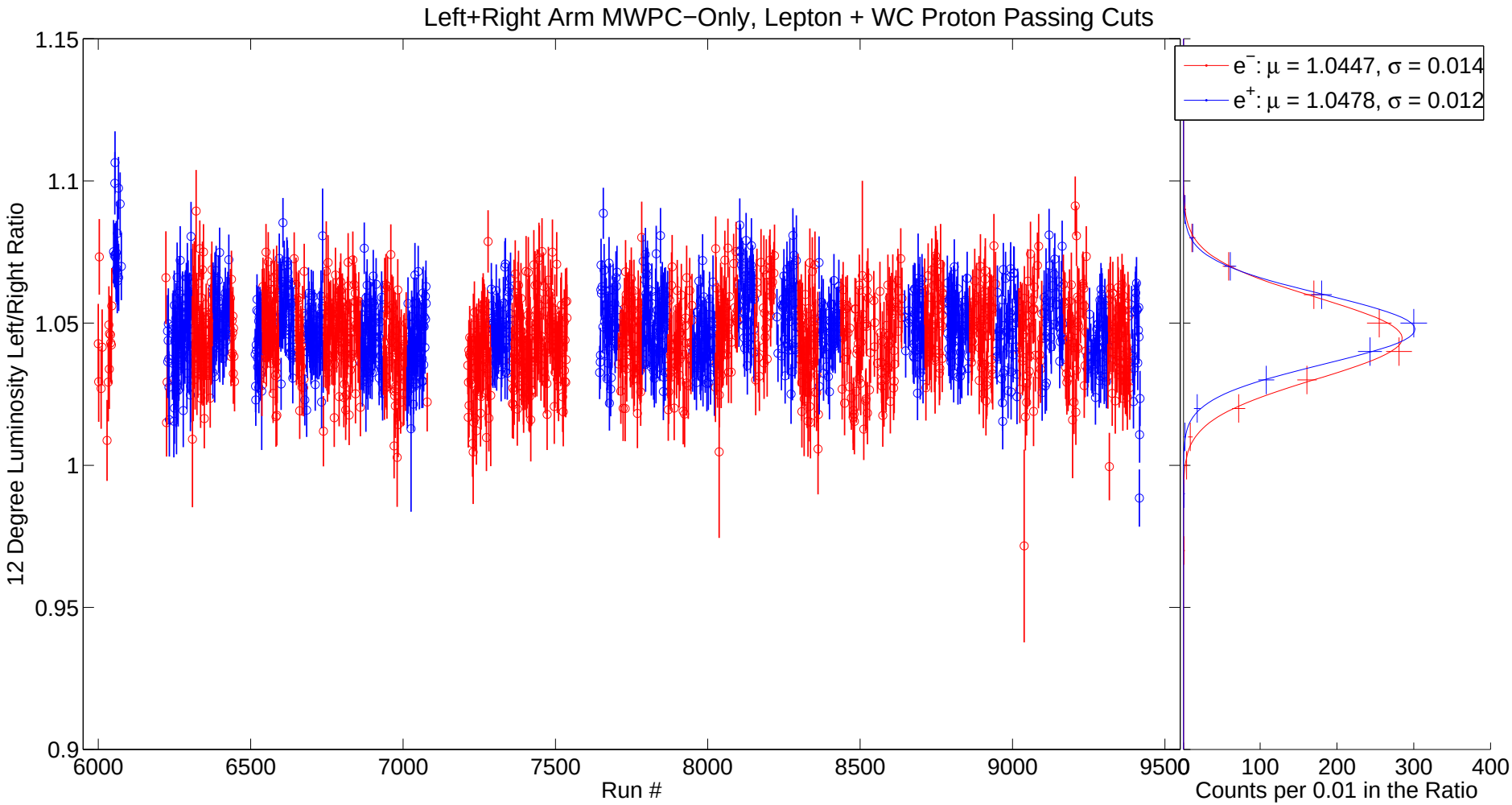


12° $e^{\pm}p$ luminosity monitoring

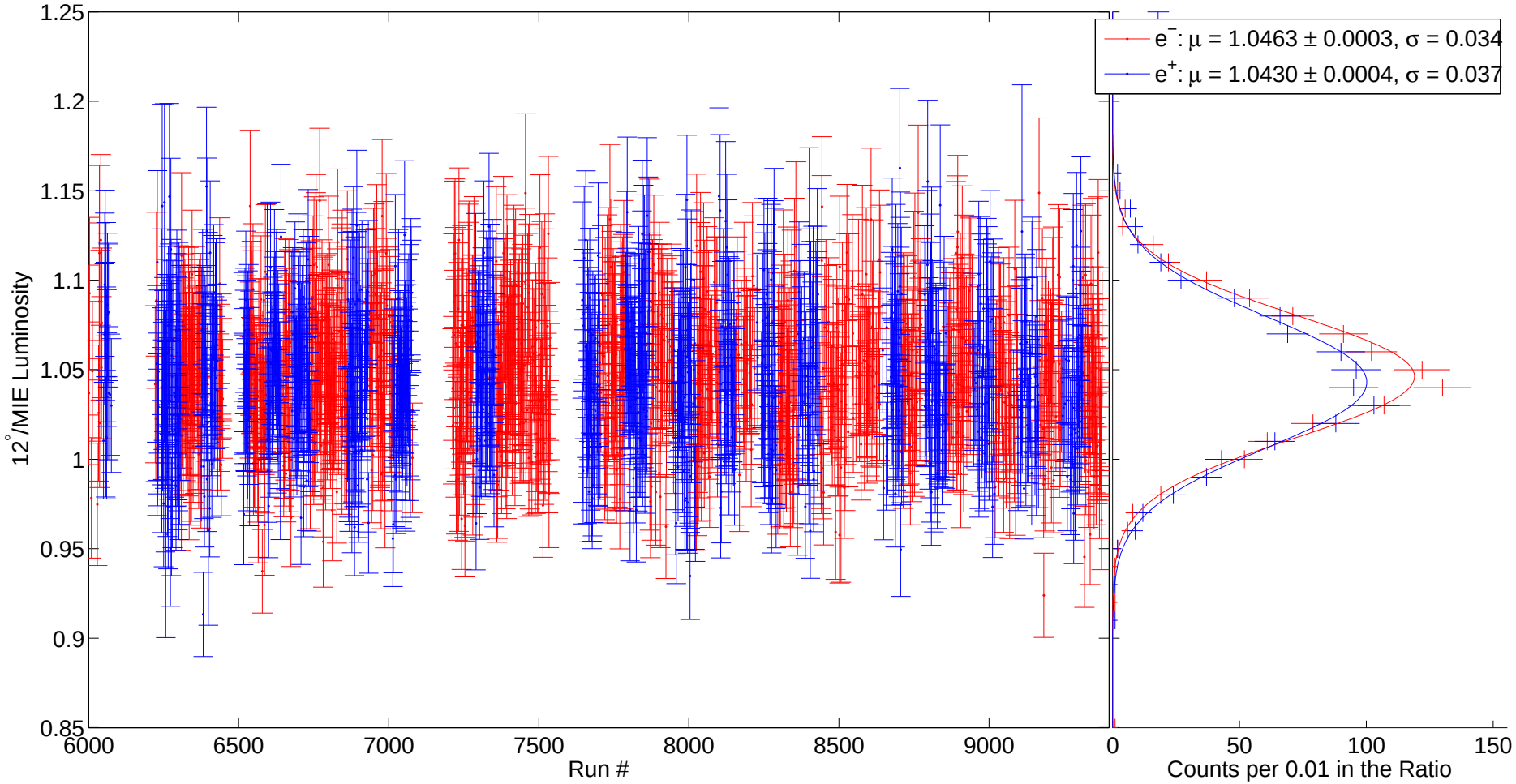
- Broad theory consensus that $R_{2\gamma} \approx 1$ at high ε
- High resolution 12° tracking telescopes with dedicated trigger provide high statistics measurement
  - 3 GEMs + 3 MWPCs per detector side
  - Exclusive $e^{\pm}p$ reconstruction
  - $\sim$1%/hour statistical uncertainty from each telescope
  - Additional $R_{2\gamma}$ point with SYMB luminosity



12° results

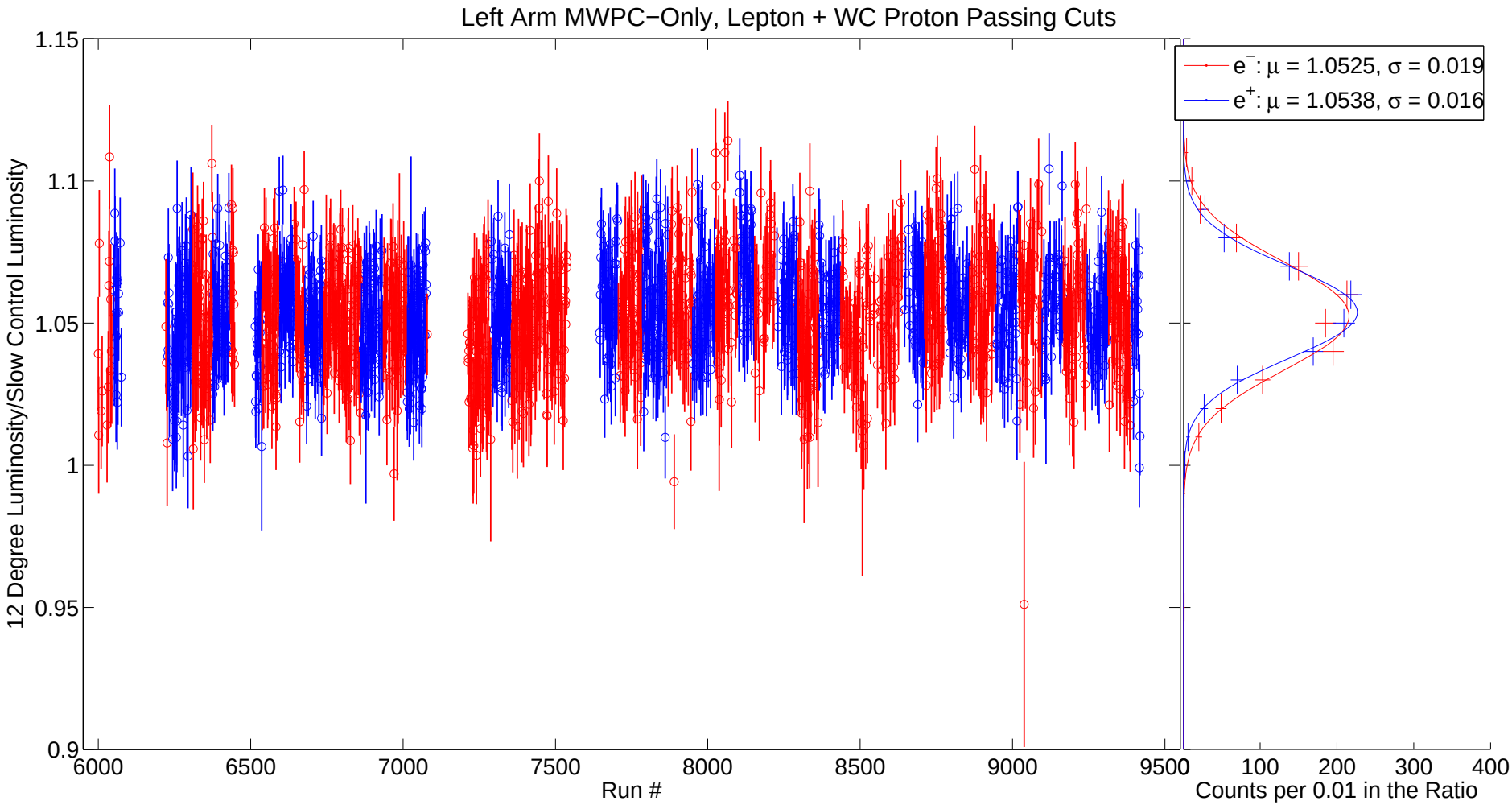

Left+Right Arm MWPC−Only, Lepton + WC Proton Passing Cuts
e⁻: μ = 1.0447, σ = 0.014
e⁺: μ = 1.0478, σ = 0.012
12 Degree Luminosity Left/Right Ratio
Run #
Counts per 0.01 in the Ratio
1.15
1.1
1.05
1
0.95
0.9
6000
6500
7000
7500
8000
8500
9000
9500
100
200
300
400

Measurement of $R_{2\gamma}$ at $\theta \approx 12^\circ$

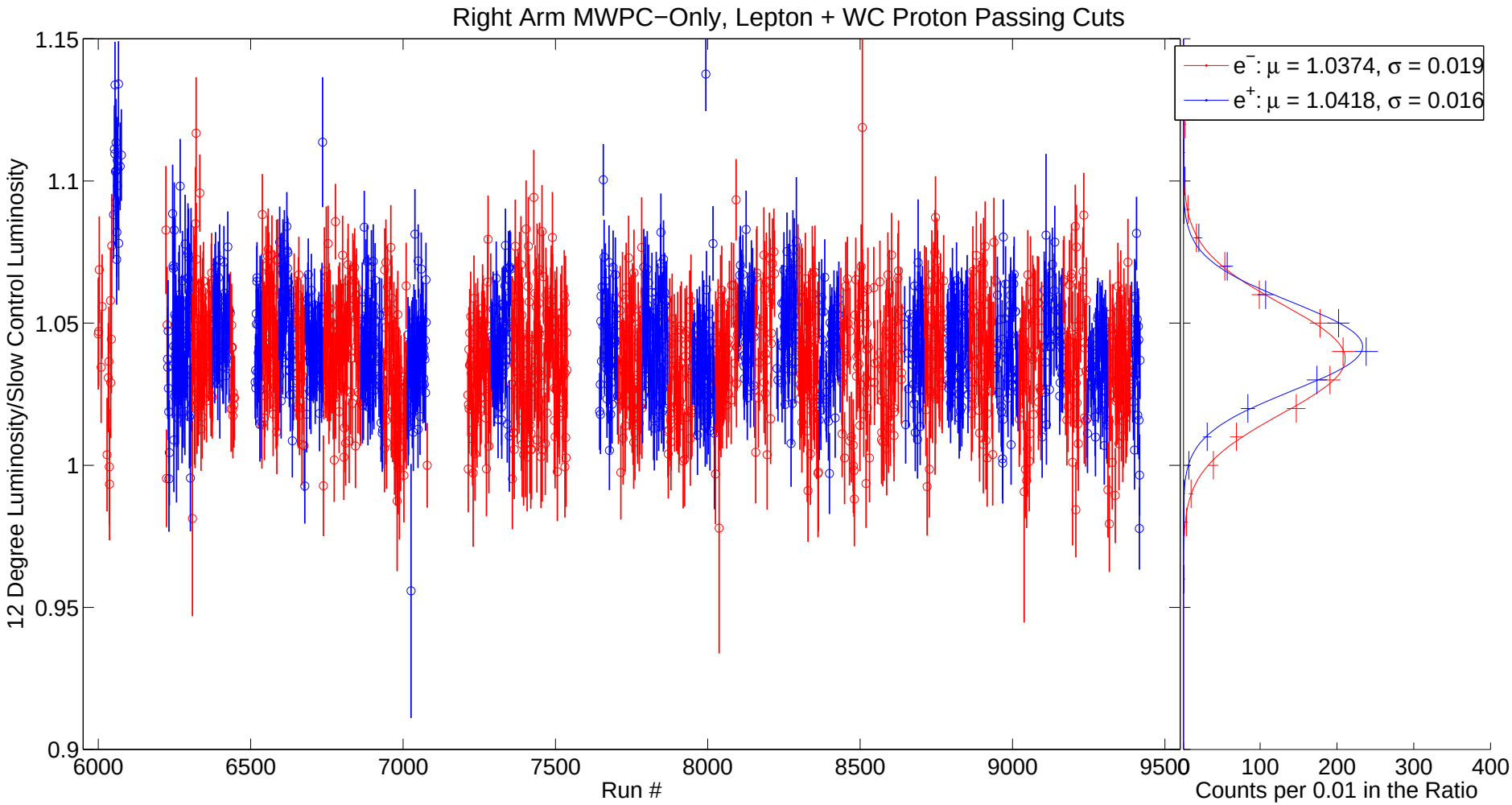


$$R_{2\gamma}\left(\epsilon = 0.98, Q^2 = 0.165\,\mathrm{GeV}^2\right) = 0.9975 \pm 0.0010\,(\mathrm{stat.}) \pm 0.0053\,(\mathrm{syst.})$$

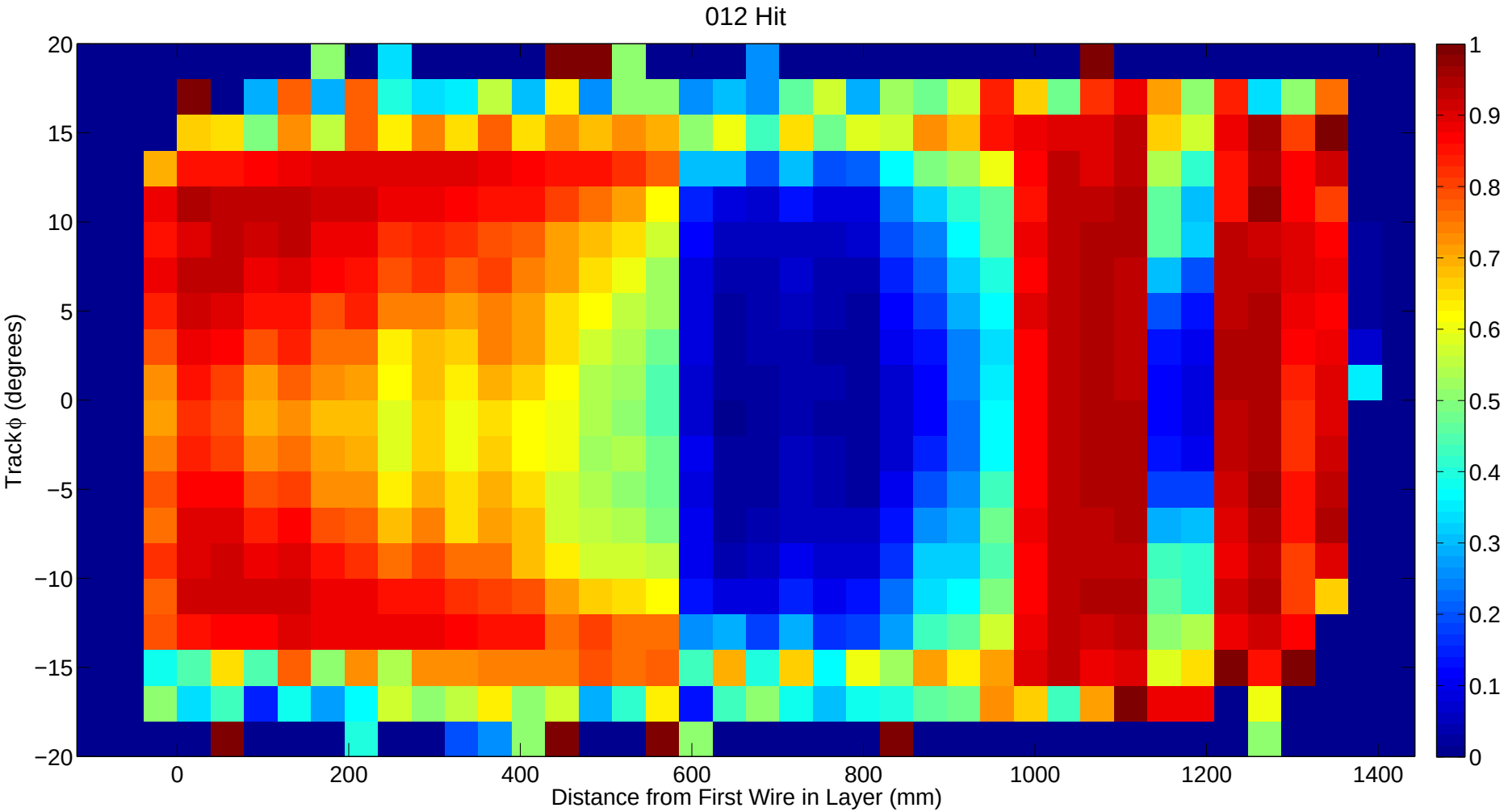
12° left results



12° right results



12° systematics

Uncertainty Source	Relative (%)	Absolute (%)
ToF trigger efficiency ($\delta_{\epsilon_{\text{ToF}}}$)	$\pm$0.19	$\pm$0.25
SiPM trigger efficiency ($\delta_{\epsilon_{\text{SiPM}}}$)	$\pm$0.01	$\pm$0.10
MWPC plane efficiency ($\delta_{\epsilon_{\text{MWPC}}}$)	$\pm$0.01	$\pm$0.05
Magnetic field (δ_B)	$\pm$0.15	$\pm$0.35
Lepton tracking efficiency ($\delta_{\epsilon_{e,\text{track}}}$)	$\pm$0.18	$\pm$0.86
Proton tracking efficiency ($\delta_{\epsilon_{p,\text{track}}}$)	$\pm$0.10	$\pm$0.80
Beam position/slope (δ_{BPM})	$\pm$0.01	$\pm$0.01
Beam energy ($\delta_{E_{\text{beam}}}$)	$\pm$0.02	$\pm$0.02
Detector position (δ_{det})	$\pm$0.02	$\pm$0.20
Fiducial cuts (δ_{fid})	$\pm$0.12	$\pm$0.22
Elastic cuts (δ_{elas})	$\pm$0.27	$\pm$1.63
Radiative corrections (δ_{rad})	$\pm$0.08	$\pm$0.45
Form factors (δ_{ff})	$\pm$0.14	$\pm$1.20
TPE at $\theta = 12°$ (δ_{TPE})*	$\pm$0.10	$\pm$0.10
Total including TPE uncertainty ($\delta_{12°,\text{TPE}}$)	$\pm$0.47%	$\pm$2.44%
Total without TPE uncertainty ($\delta_{12°}$)	$\pm$0.46%	$\pm$2.44%

Cause of left/right difference