The OLYMPUS Experiment - Two-Photon Exchange in Electron Proton Scattering

Outline

- Introduction and Motivation
- Overview of the Experiment
- Radiative Corrections
- Results
- Conclusions

Lomonosov Conference2017
Moscow

Uwe Schneekloth, DESY

on behalf of the
OLYMPUS Collaboration

HELMHOLTZ ASSOCIATION

Elastic e N Scattering/Form Factors

Nucleon elastic form factors: electric G_E and magnetic G_M

- Fundamental observables describing distribution of charge and magnetism in proton and neutron
- Described by quark structure of proton
- Will be calculable in lattice QCD
- For ~ 50 years unpolarized cross section measurements have determined G^p_E and G^p_M using the Rosenbluth separation

$$\frac{d\sigma / d\Omega}{(d\sigma / d\Omega)_{Mott}} = \frac{\sigma}{\sigma_0} = A(Q^2) + B(Q^2)\tan^2\frac{\theta}{2}$$

$$= \frac{G_E^2(Q^2) + \tau G_M^2(Q^2)}{1+\tau} + 2\tau G_M^2(Q^2)\tan^2\frac{\theta}{2}$$

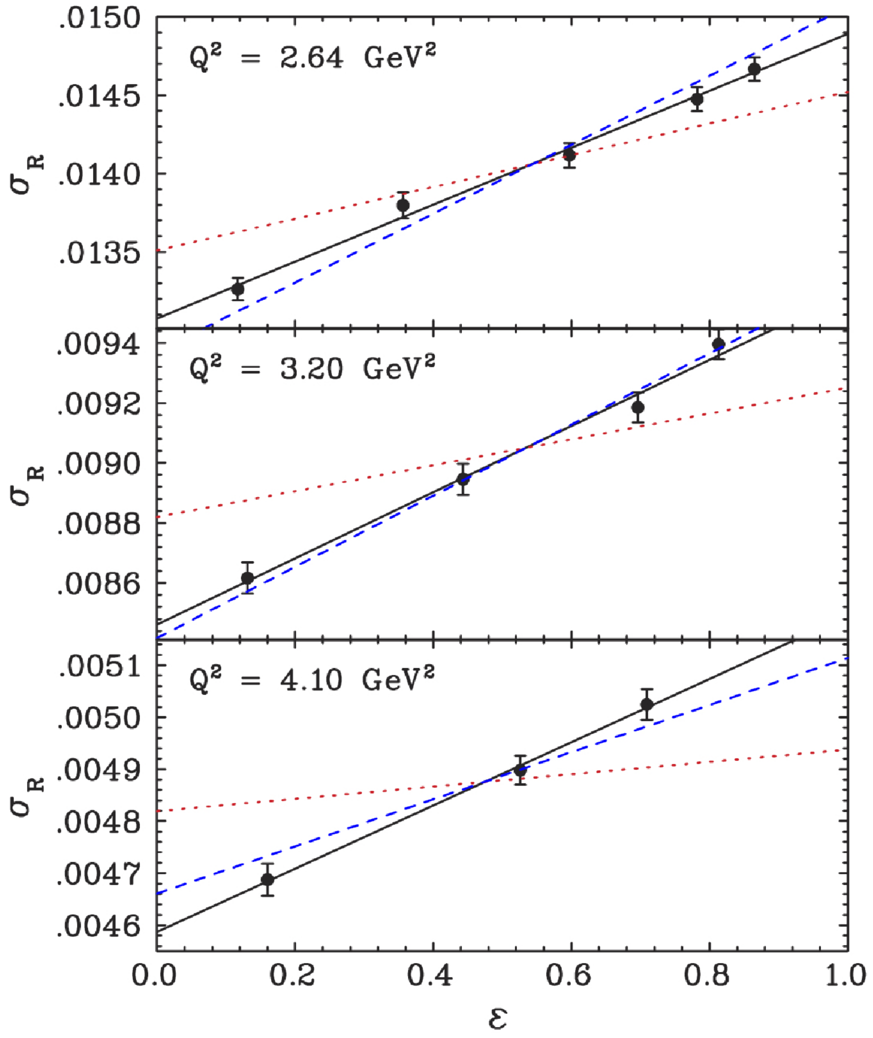
$$\sigma_{red} = \frac{d\sigma}{d\Omega}\frac{\varepsilon(1+\tau)}{\sigma_{Mott}} = \tau G_M^2 + \varepsilon G_E^2$$

$$\tau = Q^2 / 4M_p^2 \qquad \varepsilon = \left[1 + 2(1+\tau)\tan^2\theta/2\right]^{-1}$$

(ε transverse virtual photon polarization)

Form Factors - Rosenbluth Method

Reduced cross section



I.A. Qattan, Phys. Rev. Lett. **94** (2005) 142301.

$$\sigma_{red} = \frac{d\sigma}{d\Omega}\frac{\varepsilon(1+\tau)}{\sigma_{Mott}} = \tau G_M^2 + \varepsilon G_E^2$$

Vary E and θ to measure σ_R different ε but same Q^2 and plot:

- Slope → G_E^2
- Intercept → G_M^2
- G_M dominates at high Q^2
- σ_R decreases quickly with Q^2

Blue dashed: FF ratio = 1

Red dotted: pol. measurements

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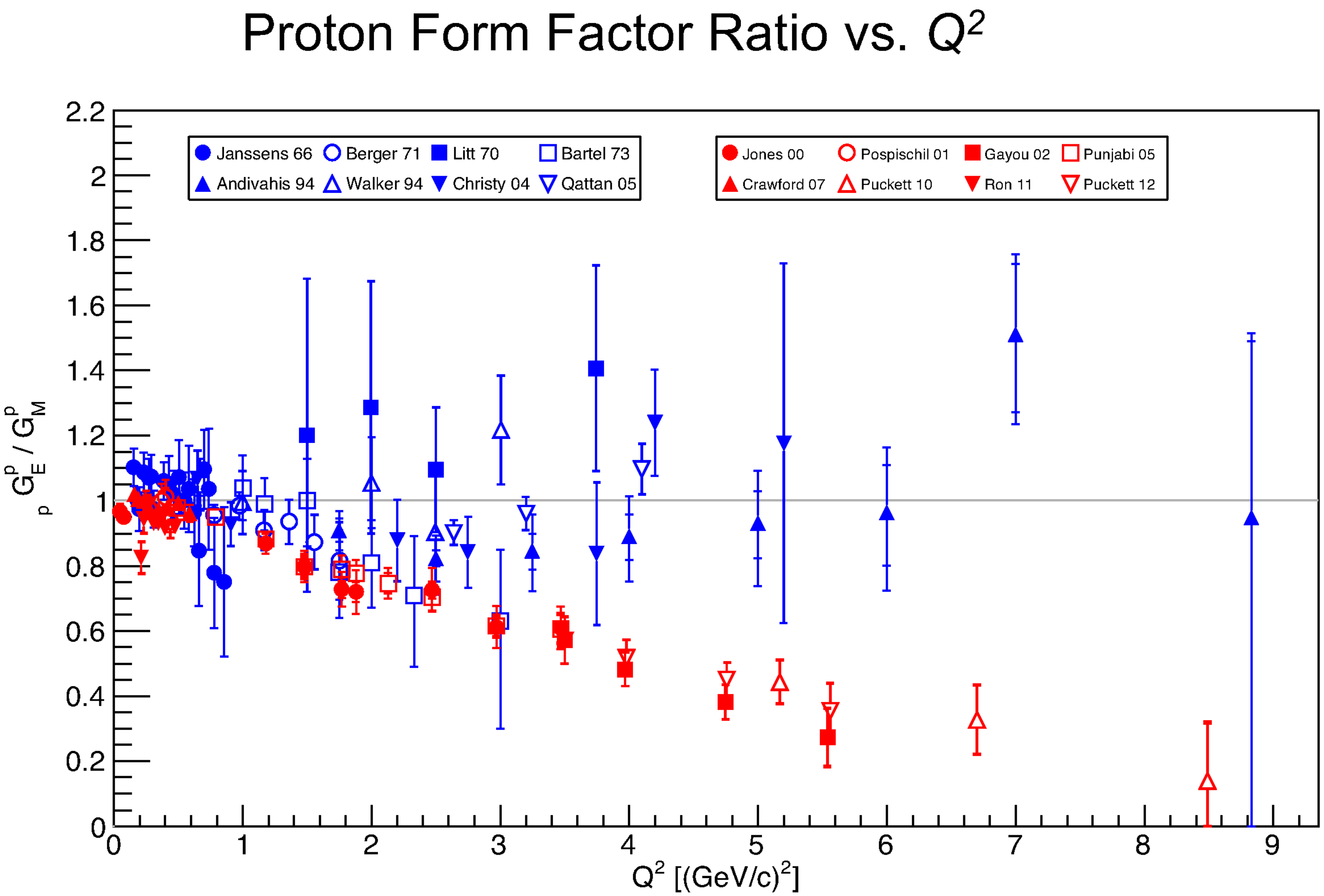
Discrepancy in Form Factor Ratio



- All Rosenbluth data in agreement
- Dramatic discrepancy between Rosenbluth and recoil polarization technique

$$\vec{e}p \rightarrow e\vec{p}$$

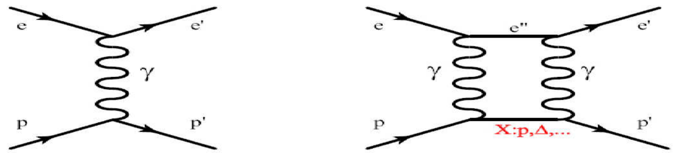
$$\mu_p \frac{G_E}{G_M} = -\mu_p \sqrt{\frac{\varepsilon(1+\varepsilon)}{2\varepsilon}} \frac{P_T}{P_L}$$

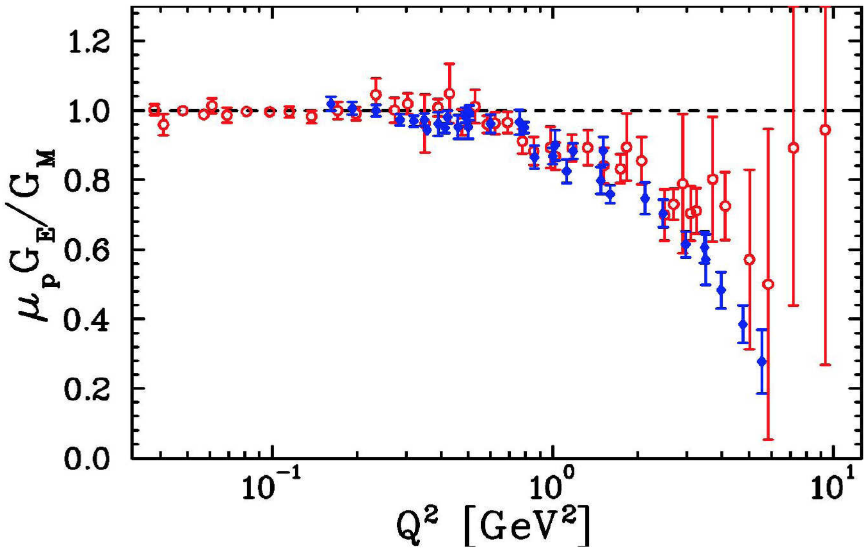
- Interpreted as evidence for two photon contribution to elastic scattering

Proposed Explanation – Two Photon Exchange

Two-Photon-Exchange

- Thought to be small effect
  - Suppressed by order α
- Hard TPE difficult to calculate
  - Intermediate p, Δ,…
  - Large theoretical model uncertainties
- Calculations suggest TPE can resolve discrepancy
- Only experiment can definitively resolve contributions beyond single photon exchange
- Determine TPE by measuring ratio of e^+p/e^-p, i.e. ratio of rates, no absolute cross section measurements





J. Arrington, W. Melnitchouk, J.A. Tjon, Phys. Rev. C 76 (2007)

$$\sigma(e^- p) = |M_{1\gamma}|^2\,\alpha^2 - 2\,|M_{1\gamma}|\,|M_{2\gamma}|\,\alpha^3 + \dots$$

$$\sigma(e^+ p) = |M_{1\gamma}|^2\,\alpha^2 + 2\,|M_{1\gamma}|\,|M_{2\gamma}|\,\alpha^3 + \dots$$

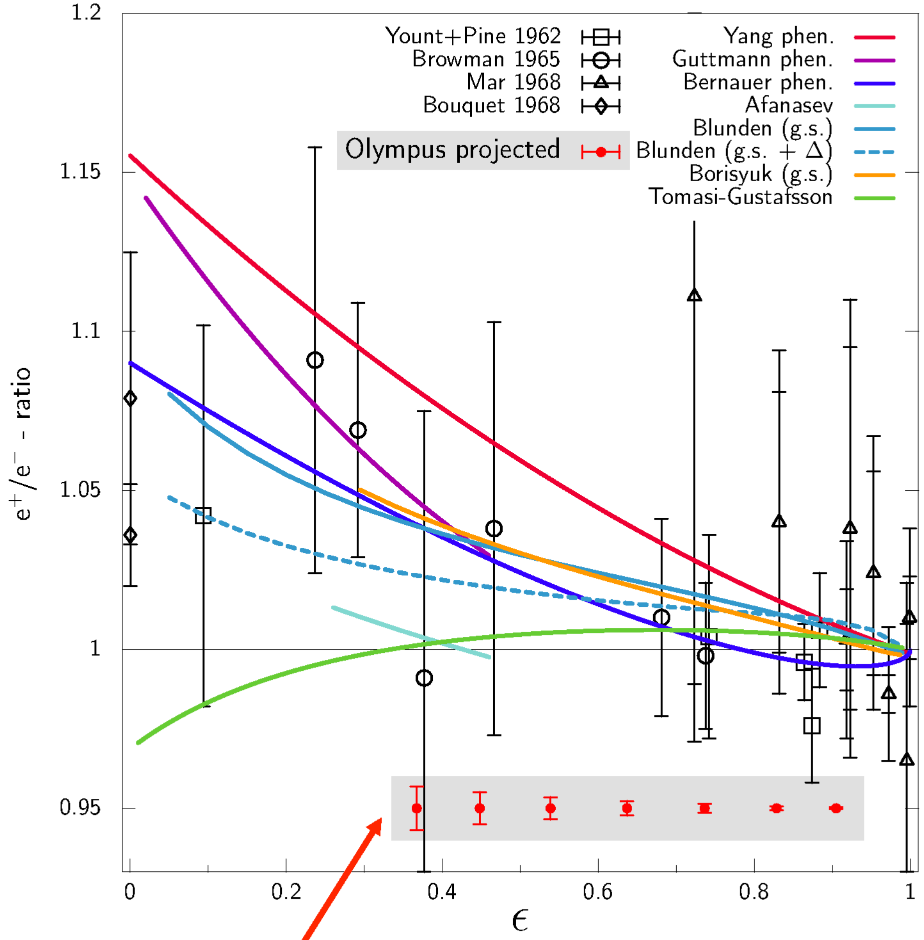
$$R = \frac{\sigma(e^+ p)}{\sigma(e^- p)} = 1 + \frac{4\,\Re(M_{1\gamma}^\dagger M_{2\gamma})}{|M_{1\gamma}|^2}$$

OLYMPUS Experiment at DORIS

Elastic $e^+(e^-)$ p scattering at 2 GeV beam energy

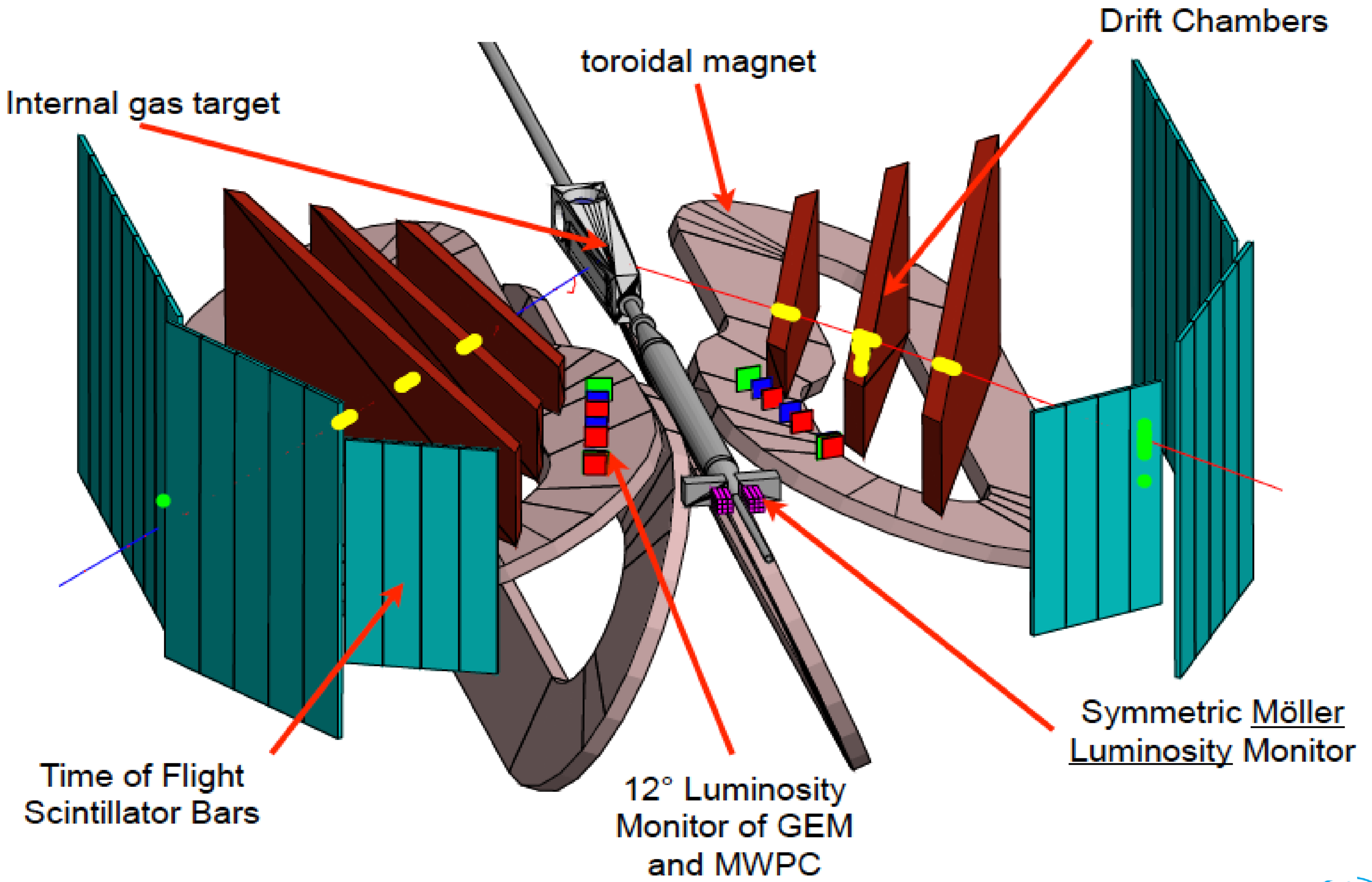
- Measure ratio of e^+p/e^-p rates with 1% precision
- DORIS 100 mA $e^+(e^-)$ beam
- Unpolarized internal hydrogen target, density 3 x 10^{15} at/cm^2
- Daily change of beam (e^+ or e^-) to minimize systematic error
- Redundant luminosity measurements
- Using former BLAST detector from MIT/ Bates. Ideally suited.

Comparison of data and theory

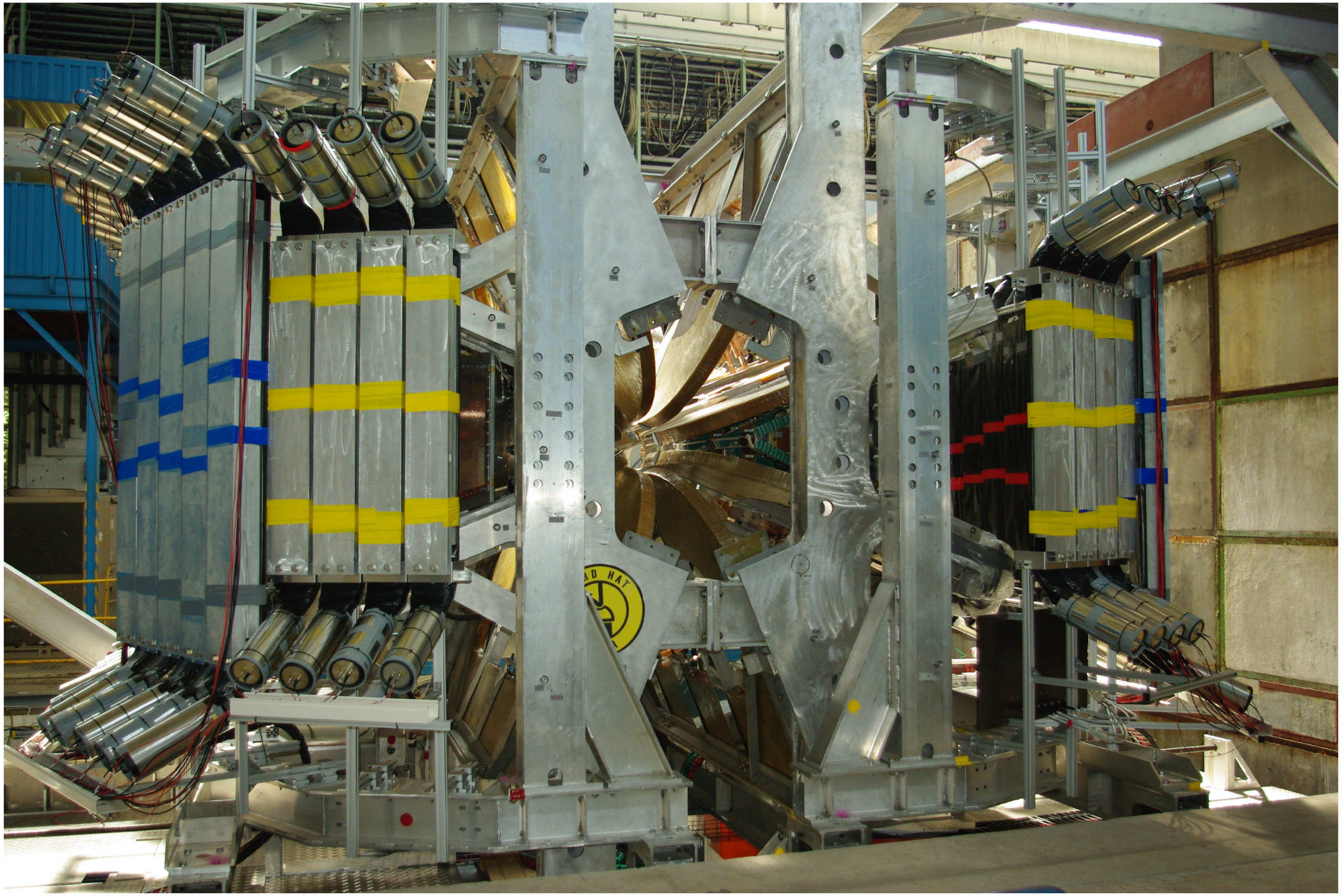


expected OLYMPUS sensitivity

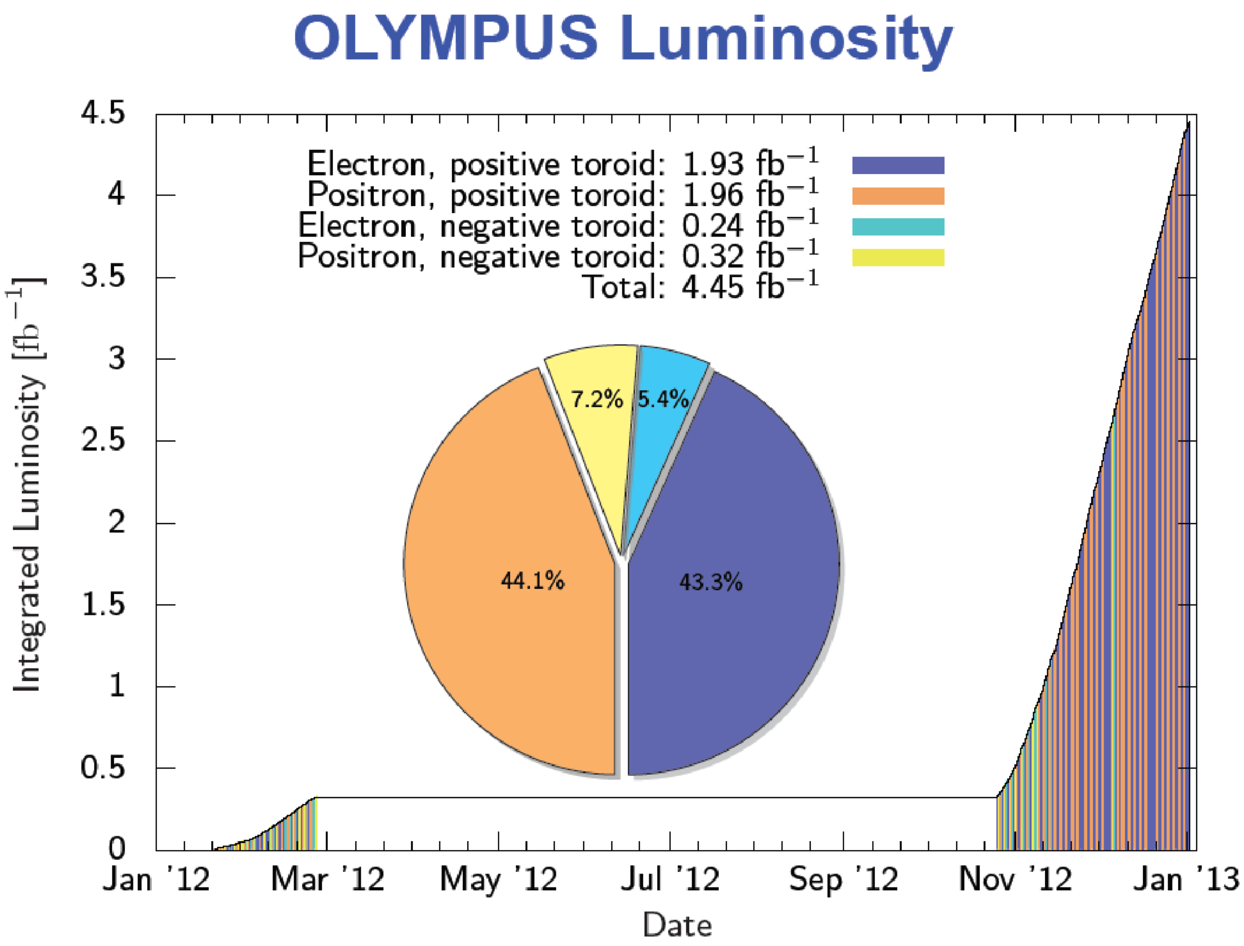
Detector Overview



OLYMPUS Detector



DataTaking in 2012



Limited flow and luminosity in Feb. run

Fall run

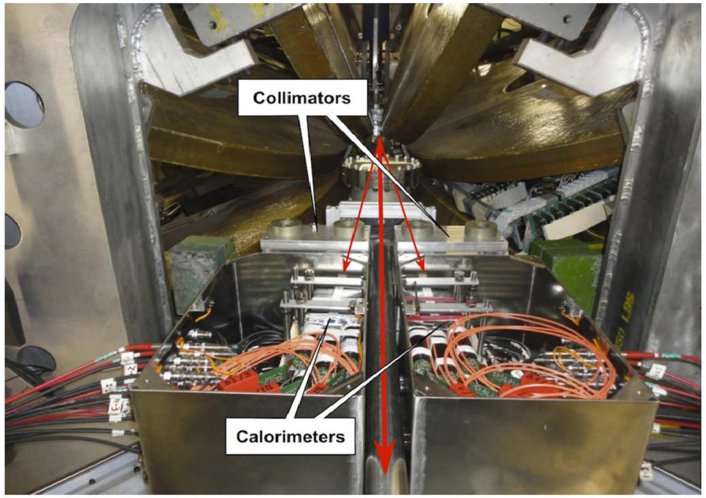
- Full hydrogen flow
- DORIS top-up mode
- Excellent performance
- Exceeded integrated luminosity:
  - Design $3.6fb^{-1}$, achieved $4.45fb^{-1}$
- Daily switch of beam species, good balance
- Mainly positive toroid polarity due to background
- Negative field for systematics checks

Luminosity Determination

Three independent measurements

- Slow Control (beam current and target density)
  - 2% between beam species, 5% absolute
- Tracking telescopes at 12^{o} (elastic ep scattering at small angles)
  - MWPC with coincident proton in WC
  - 0.46% between beam species, 2.4% absolute
- Multi-interaction events ($e^{\pm}$ e → $e^{\pm}$ e) + ($e^{\pm}$ p → $e^{\pm}$ p) at 1.29^{o} in SYMB monitor
  - High statistics measurement, no dead time
  - 0.1% statistical, 0.27% systematic

Need $e^{+}p/e^{-}p$ luminosity ratio, not precise absolute luminosity



Chose multi-interaction events, most accurate

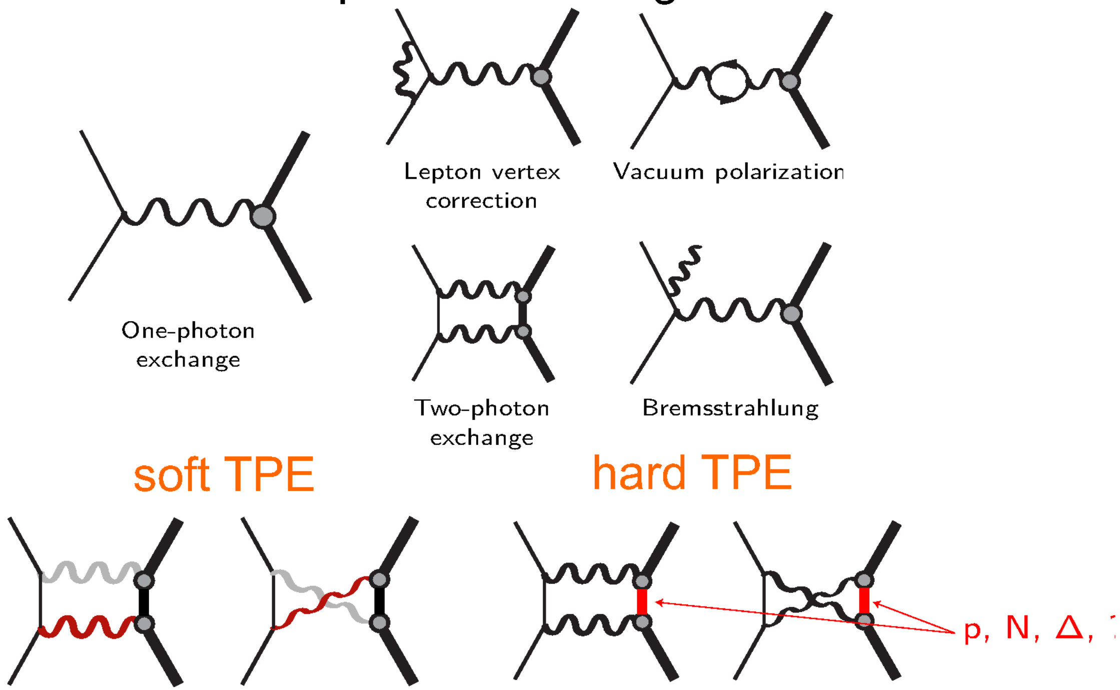
- Negligible TPE at 1.29^{o}
  - $\langle Q^2 \rangle = 0.002 \mathrm{GeV}^2$
- Allows measurement of TPE at 12^{o}
  - $R_{2\gamma} = 0.9975 \pm 0.010 \pm 0.0053$
  - $\langle Q^2 \rangle = 0.165 \mathrm{GeV}^2, \langle \varepsilon \rangle = 0.98$

Radiative Corrections

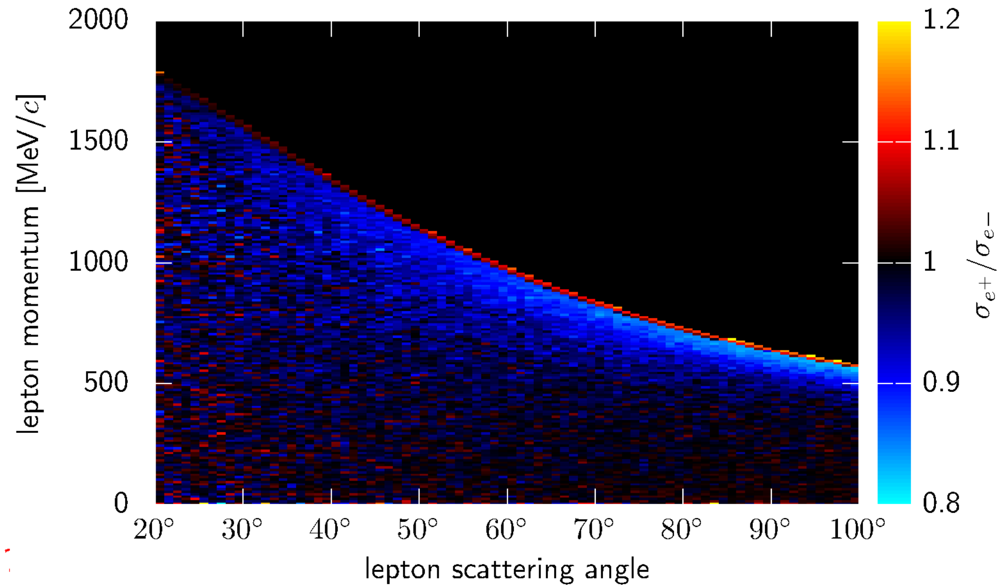
Independent elastic e±p generators written at MIT (weighted)

> Radiative corrections include:

- Initial and finale state beamsstrahlung for lepton and proton, vertex corrections, vacuum polarization and soft two photo exchange
- Hard two photon exchange not included

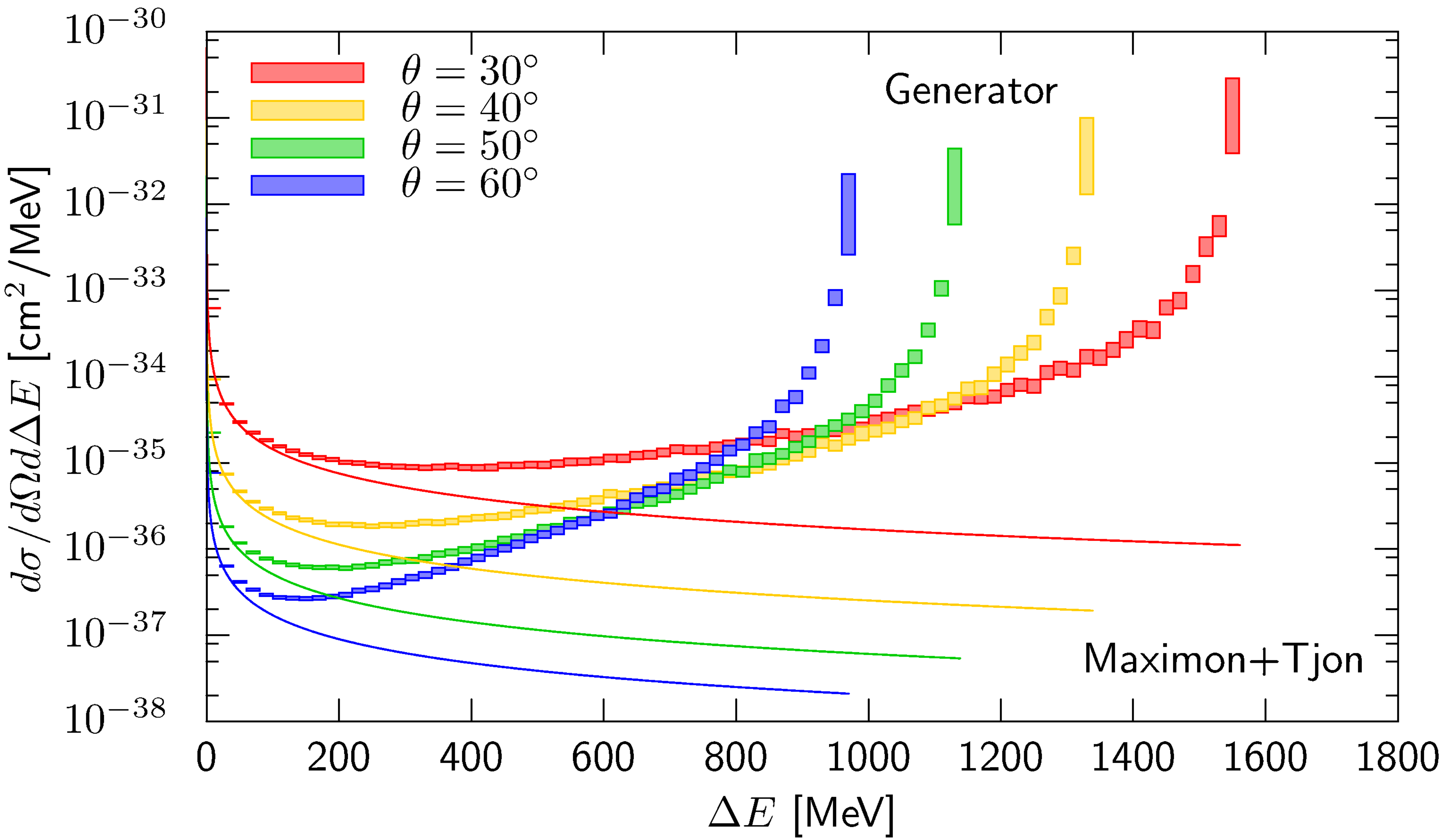


Even powers of z same for e⁺ and e⁻ scattering, cancel in ratio



New Møller/Bhabha generator with radiative corrections

Radiative Corrections Depend on Experiment



Inelastic OLYMPUS

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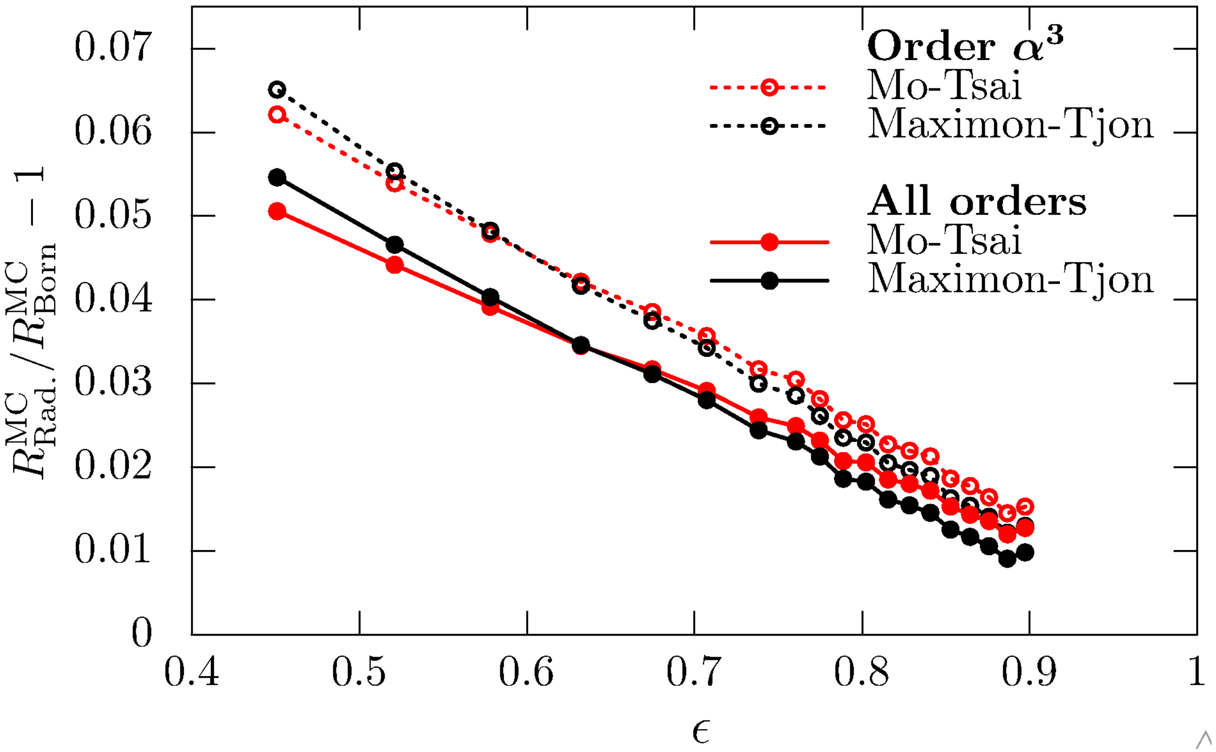
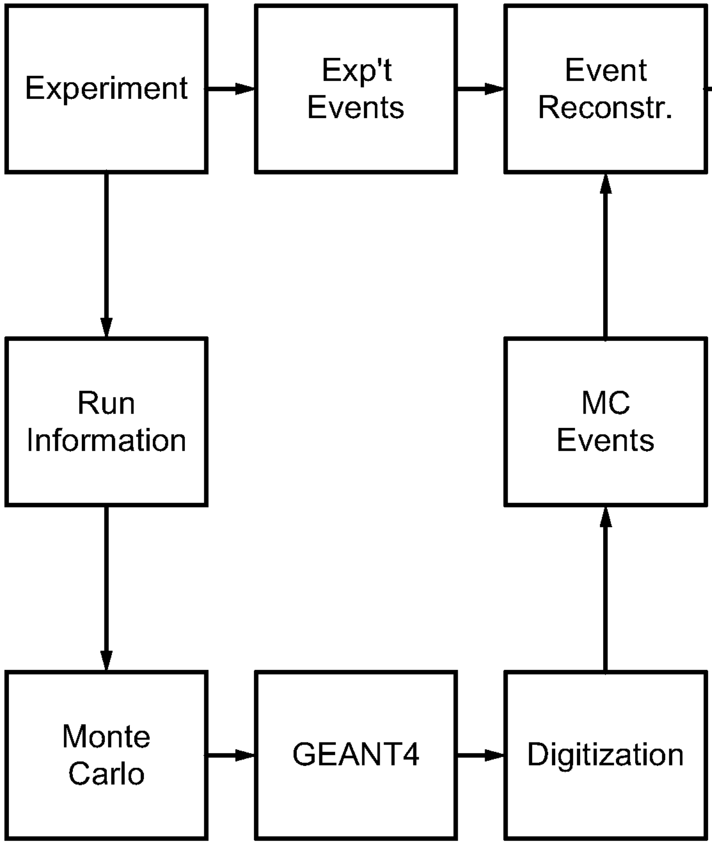
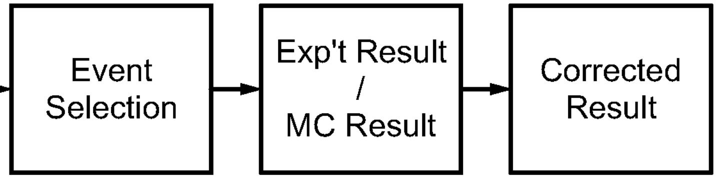
Radiative Corrections in OLYMPUS



Schematic of Analysis Procedure





Specific to each analysis

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

4 different analysis

Common to all analyses

Analysis Procedure

All analyses share the following:

- Based on same run list and same tracked data files
- Use same tracked, radiatively generated, Monte Carlo files
  - Based on same detector calibration, simulation and digitization
- Results normalized with multi-interaction events
- Binned in same Q^2 and ε bins

Analyses are independent in the following:

- Philosophy in selecting elastic candidates vary
- Different order, selection, and size of applying cuts

Four analysis combined for final result

- Results and statistical uncertainty simply averaged
- Variance added to uncorrelated uncertainty in quadrature

Systematic Uncertainties

OLYMPUS control of systematics

- Left / right symmetric detector → two independent measurements
- $R_{2\gamma}$ is a ratio → many efficiencies cancel (or reduced)
- Four independent analyses examined and combined

Correlated Systematic uncertainties

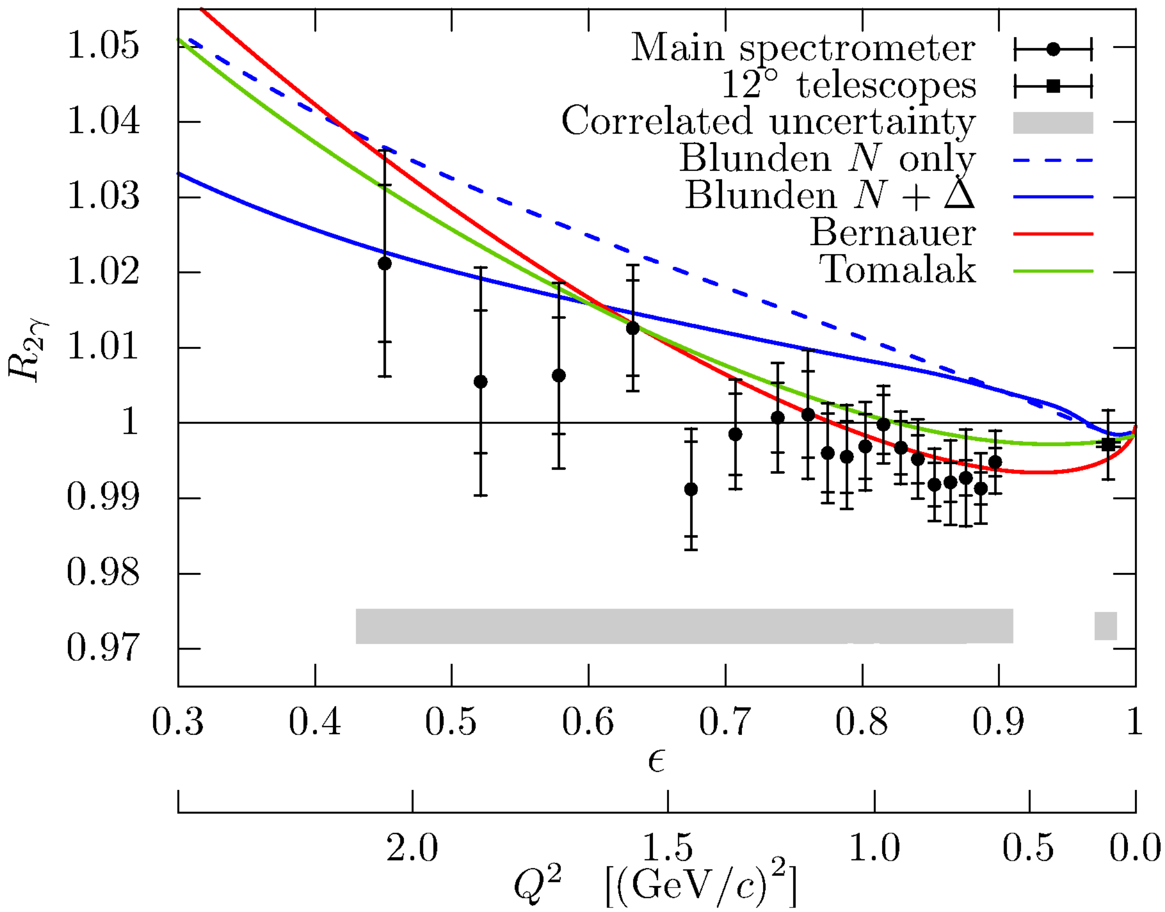
- Luminosity (MIE): 0.36%
- Beam energy: 0.04 – 0.13%
- Beam position and detector position/geometry: 0.25%
- Total: 0.46%

Uncorrelated systematic uncertainties

- Tracking efficiency: 0.25%
- event selection and background subtraction: 0.25 – 1.17%
- Total: 0.37 – 1.20%

OLYMPUS Results

Cross section ratio vs. ε (Q^2)



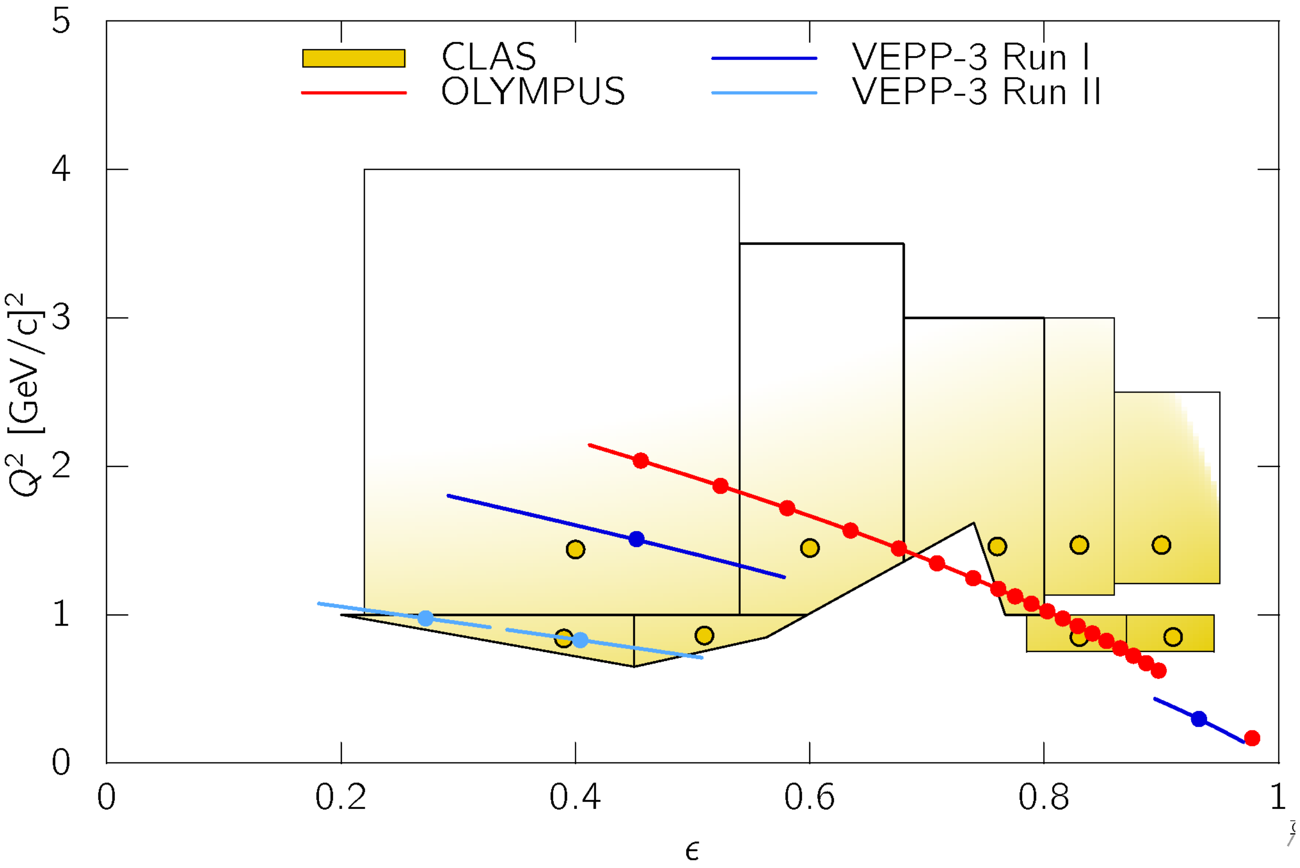
OLYMPUS, B.S. Henderson et al., PRL 118, 092501 (2017)

OLYMPUS results:

- "Hard" two-photon exchange is small, < 1%, at these energies
- Significantly below theoretical calculations
- Reasonable agreement with phenomenological predictions
- Positive slope with decreasing ε or increasing Q^2
  - Suggest TPE may be present
  - May become more important at higher energies

Kinematic Reach – Recent Measurements

Kinematic reach Q^2 vs. ε

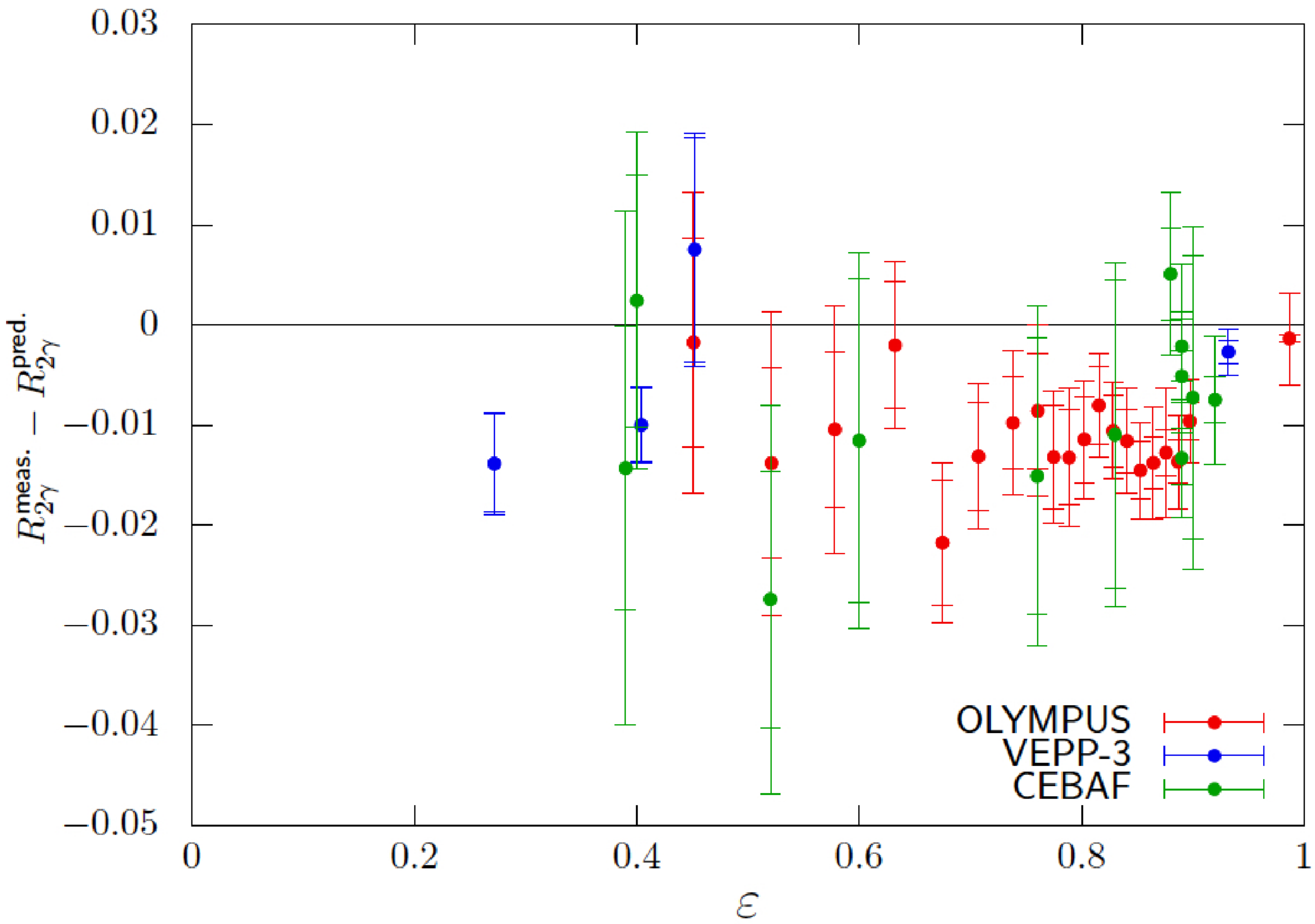


Other recent experiments

- VEPP-3
  - E storage ring in Novosibirsk
- CAST
  - Fixed target, secondary beam experiment at JLAB
- Comparison of experiments difficult due to different ε and Q^2

Comparison of Results with Theory

Difference measurements and theory (Blunden N + Δ)

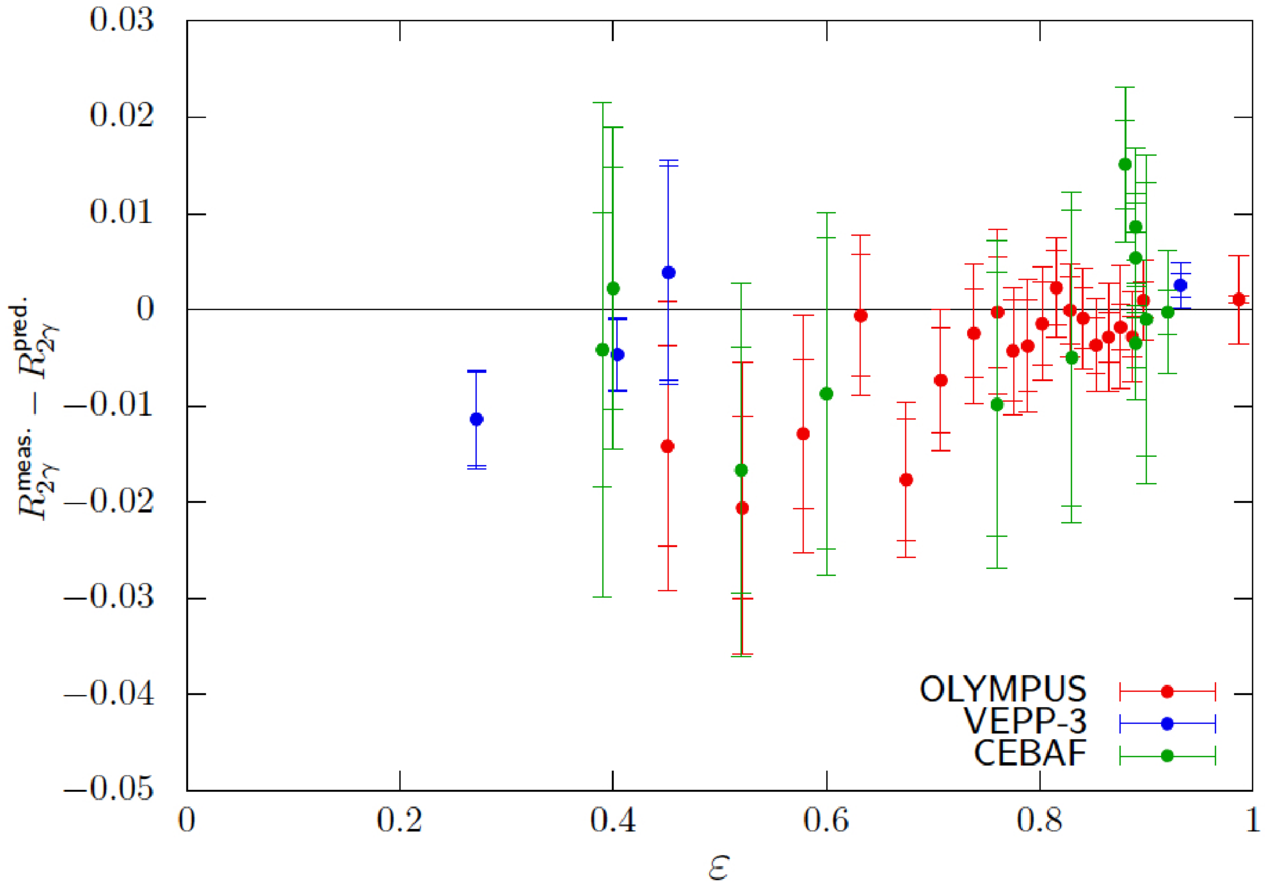


Comparison of results

- Calculate difference between data and theory calculated at ε and Q^2 for each point
- Data are consistent
- Mostly below calculation of Blunden

Comparison with Phenomenological Prediction

Difference measurements and Phenomenological Prediction(J.Bernauer)



Comparison of results

- Data in good agreement with phenomenological prediction of Bernauer

Summary of OLYMPUS Results

- Precision measurement of $R_{2\gamma}$ for $Q^2 < 2.3$ GeV^2
- Radiative corrections for “soft” TPE important
- Small, <1%, hard TPE observed
- Evidence for effect increasing with Q^2
- Results lower than theoretical calculations, but in reasonable agreement with phenomenological predictions
- Further theoretical effort on radiative corrections needed
- Experiments at higher energy required to resolve discrepancy
  - Difficult due to rapidly decreasing cross section

OLYMPUS Collaboration

Institutes

- Arizona State University, USA
- DESY
- Hampton University, USA
- INFN, Bari, Italy
- INFN, Ferrara, Italy
- INFN, Rome, Italy
- MIT, USA
- Petersburg Nucl. Phys. Inst.
- Universität Bonn, Germany
- University of Glasgow
- Universität Mainz, Germany
- Univ. of New Hampshire, USA
- Yerevan Physics Inst., Armenia

45 physicists

Backup Slides

OLYMPUS Monte Carlo

> Utilizing advanced Monte Carlo simulation to account for:
  - Beam position/slope
  - Detector acceptance/geometry
  - Detector resolution and response
  - Detector efficiencies
  - Radiative corrections (radiative $e^{\pm}$ p and Møller/Bhabha generators developed)

> Recent improvements:
  - Refinement of detector geometry model
  - Implementation of multiple generator weights for radiative generator systematic studies
  - Molecular flow Monte Carlo simulation of target gas flow to improve MC target distribution

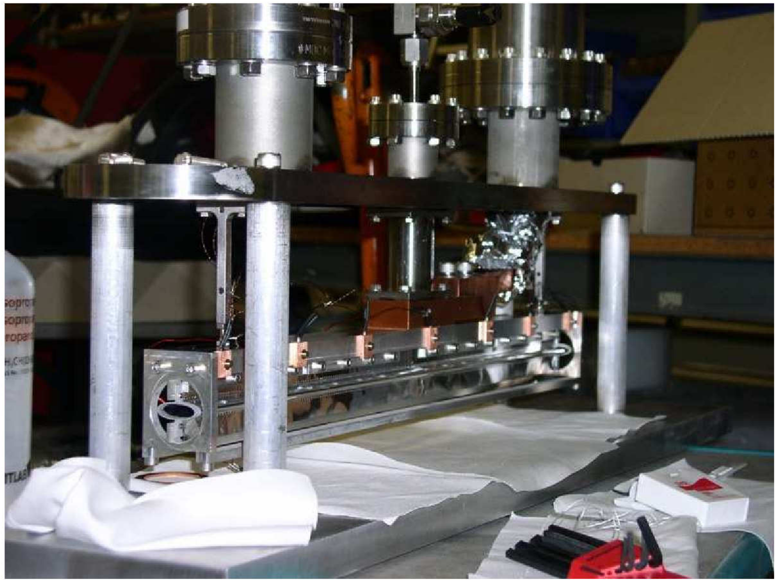
Schedule

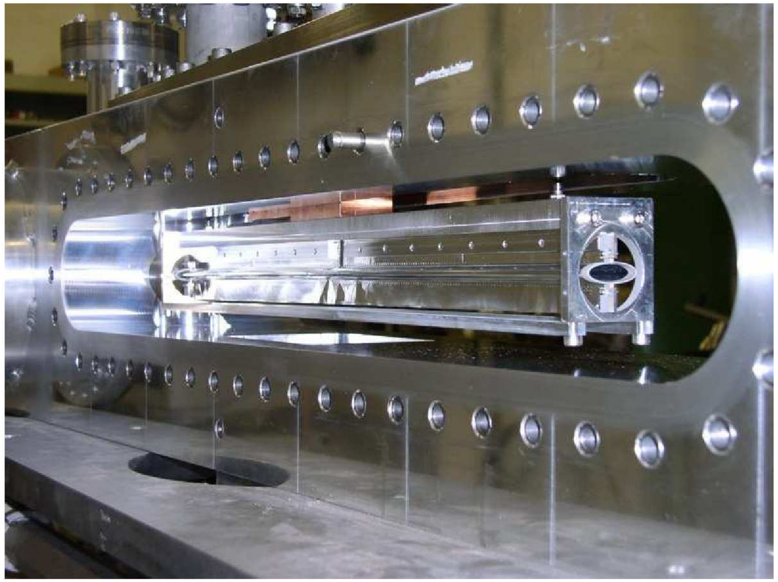
- 2005
  - End of BLAST / Bates experiment
- 2007
  - Letter of Intent
- 2008
  - OLYMPUS proposal
  - Conditional approval DESY
- 2009
  - Technical Design Report
  - Technical Review
- 2010
  - Approval and funding
  - Disassemble Blast detector at MIT ship to DESY,
  - Assembly at DORIS, parking position
- 2011
  - Interaction region modified, test experiment
  - Detector moved to beam position
- 2012
  - February: first data taking period
  - 2^{nd} data taking period Oct. – Dec.
  - Exceeded integrated luminosity: design 3.6 fb^{-1}, achieved 4.45 fb^{-1}
- 2013
  - Cosmic ray run
  - Complete survey
  - New magnetic field map
  - Beam position monitor calibration
  - Reconstruction/data analysis
- 2016
  - Most of analysis finished
- 2017
  - Ratio paper published in PRL

Target System

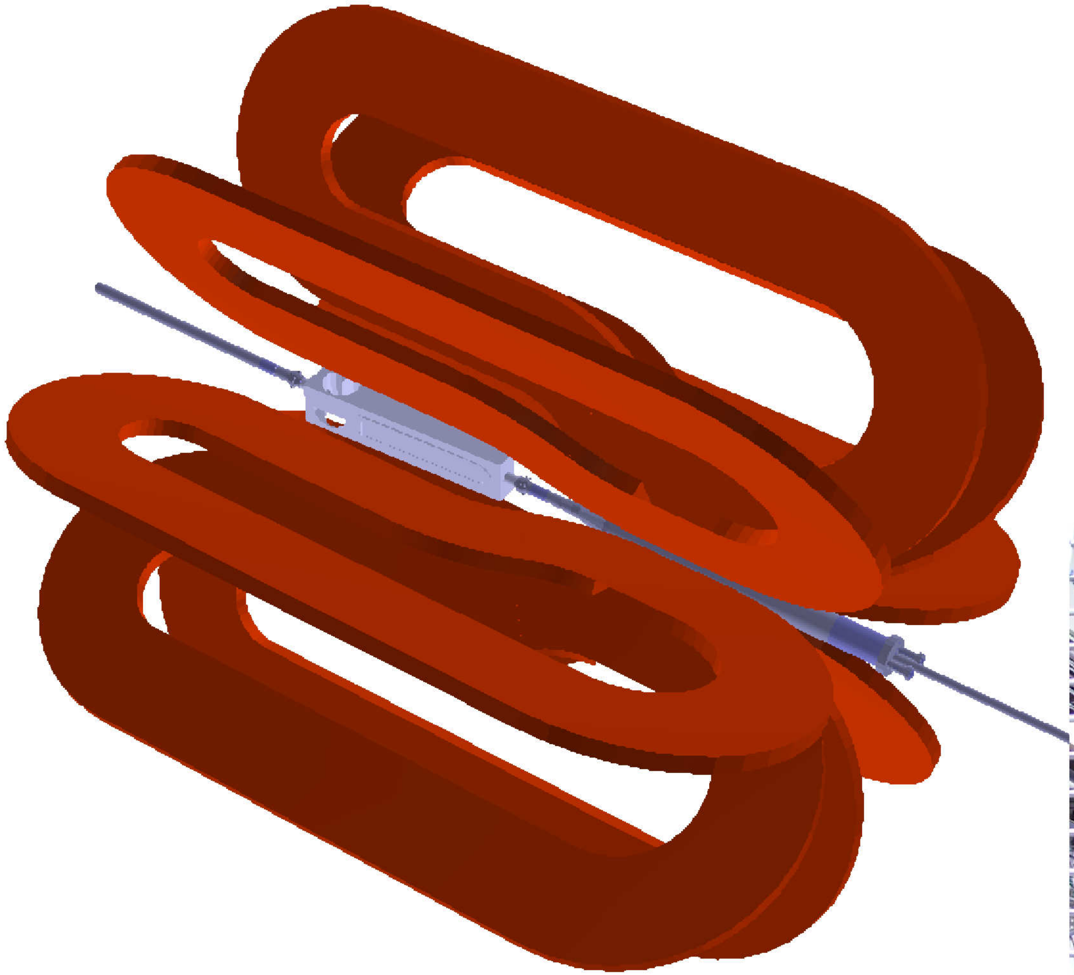
- Internal, windowless gas target
- 60 cm long storage cell
- Elliptical cross section (27 mm x 9 mm)
- 100 µm thick aluminum wall
- H_2 flows up to 1 sccm
- Cryo cooled ~45 K
- $O(10^{15})$ atoms/cm^2
- Hydrogen produced by generator (electrolysis)

INFN Ferrara, MIT



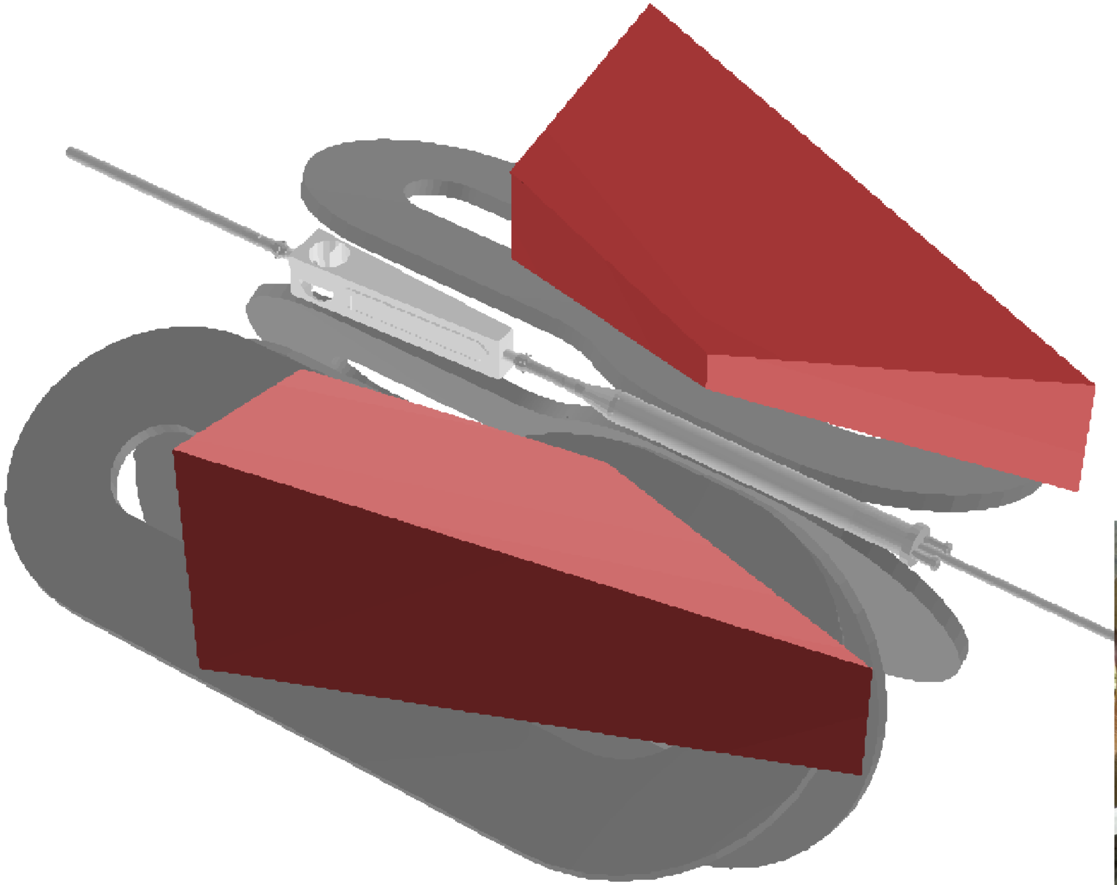


Toroidal Magnet

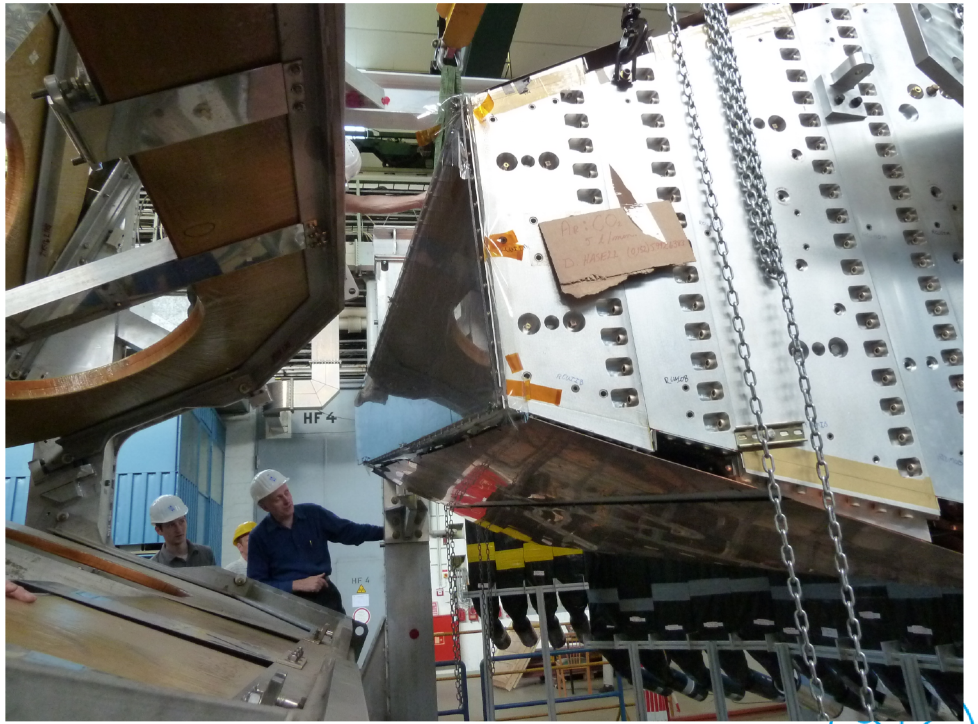


- 8 air coils from BLAST
- Operating at reduced field
- Positive and negative polarity
- Maximum field 0.28 T

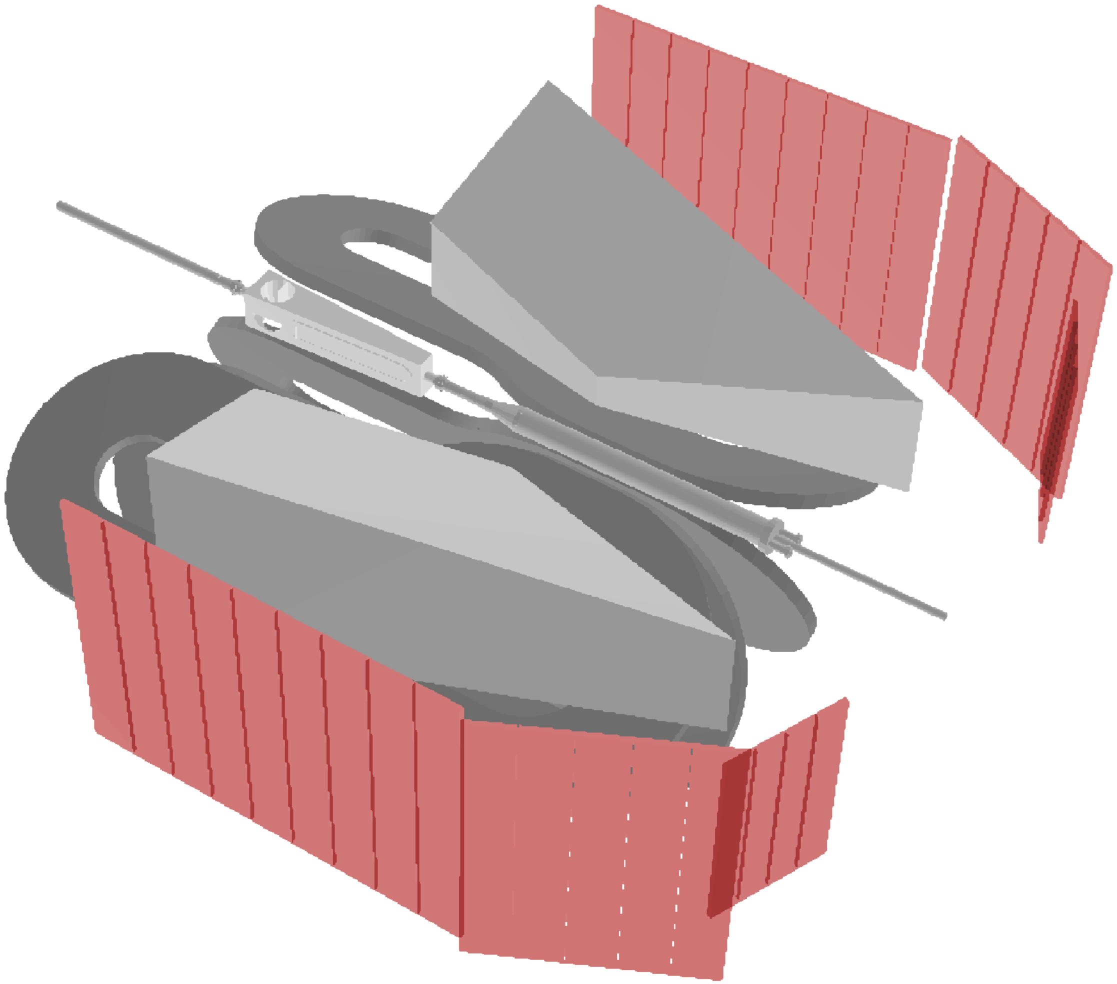
Drift Chambers



- Two chambers, trapezoidal shape
- Jet-style drift cells
- 5000 wires each
- Tracks with 18 hits
- 10^{o} stereo angle

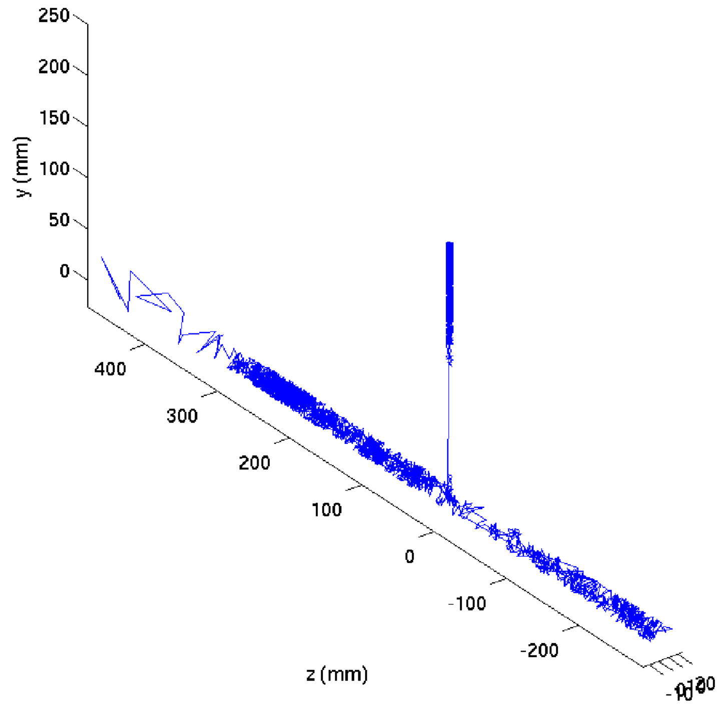


Time – of - Flight Counters

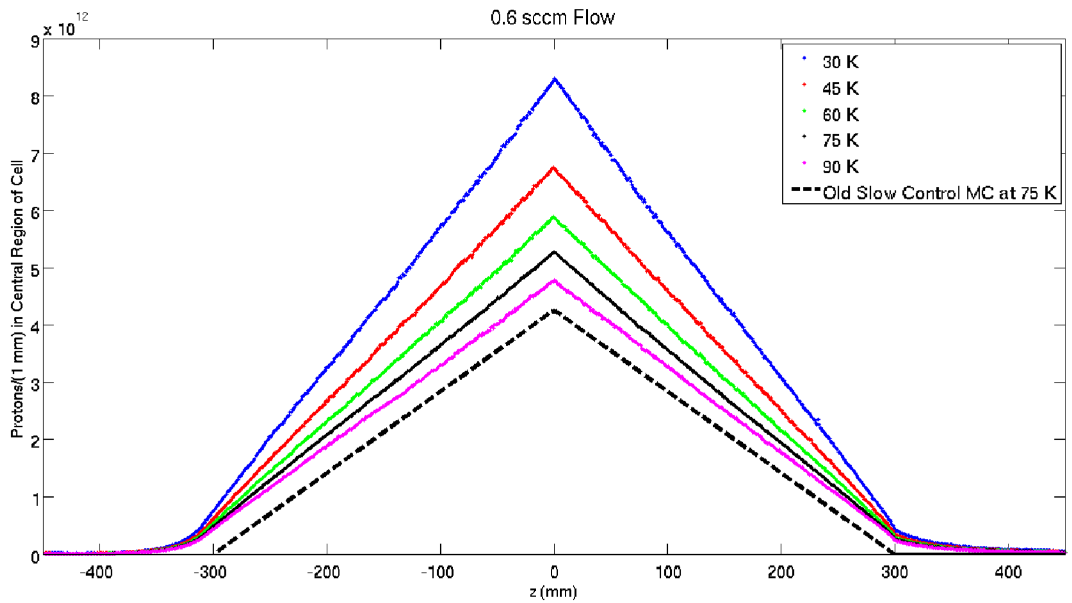


- Scintillation counters from BLAST
- Trigger
  - Top/bottom coincidence
  - Kinematic constraint
  - + 2nd level wire chamber
- Time-of-flight for particle ID

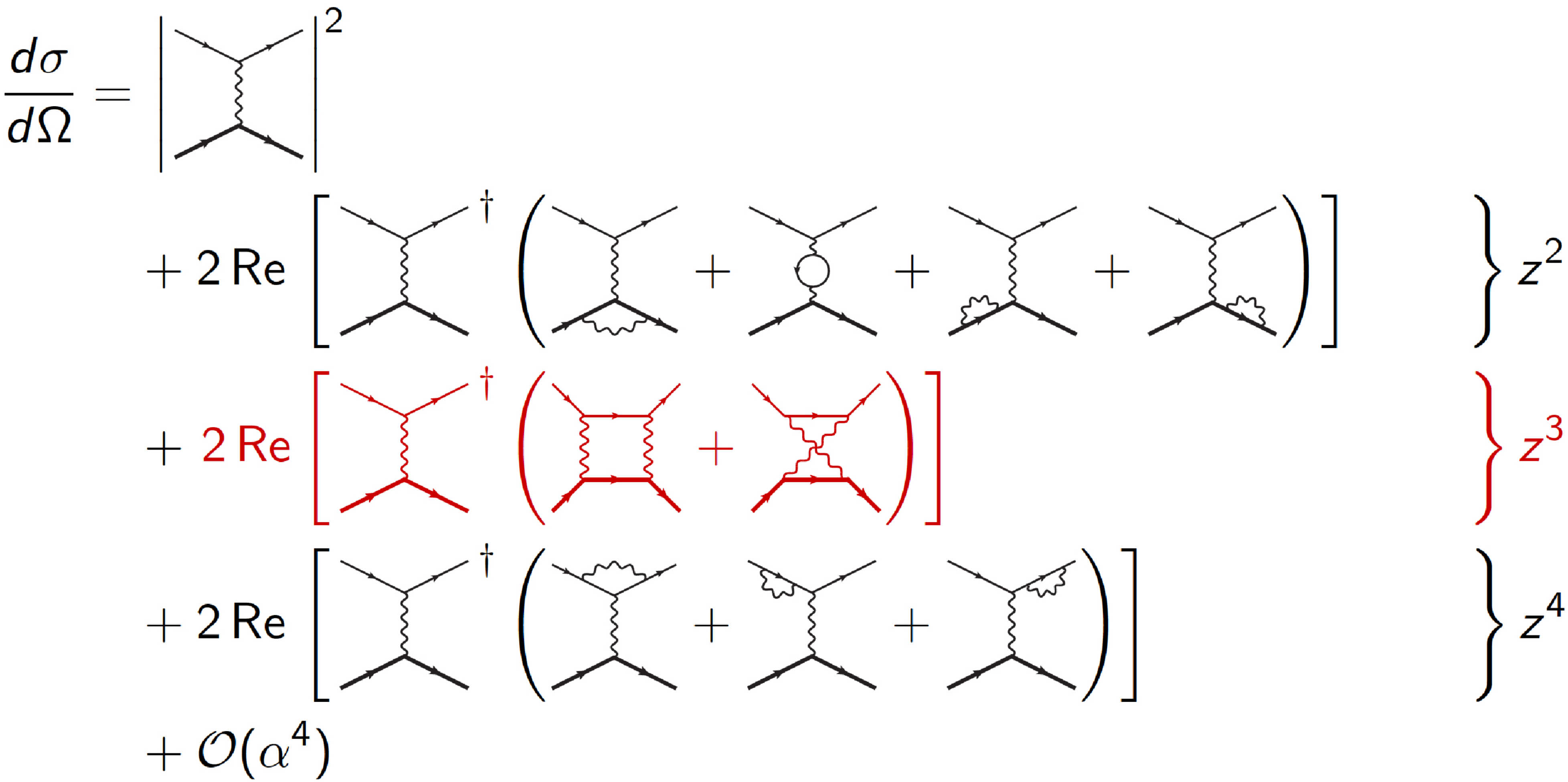
Target Gas Simulation



- Molecular flow Monte Carlo simulaton of target more realistic than conductance-based calculation
- Important to get shape of target distribution correct since e± acceptance can vary along target



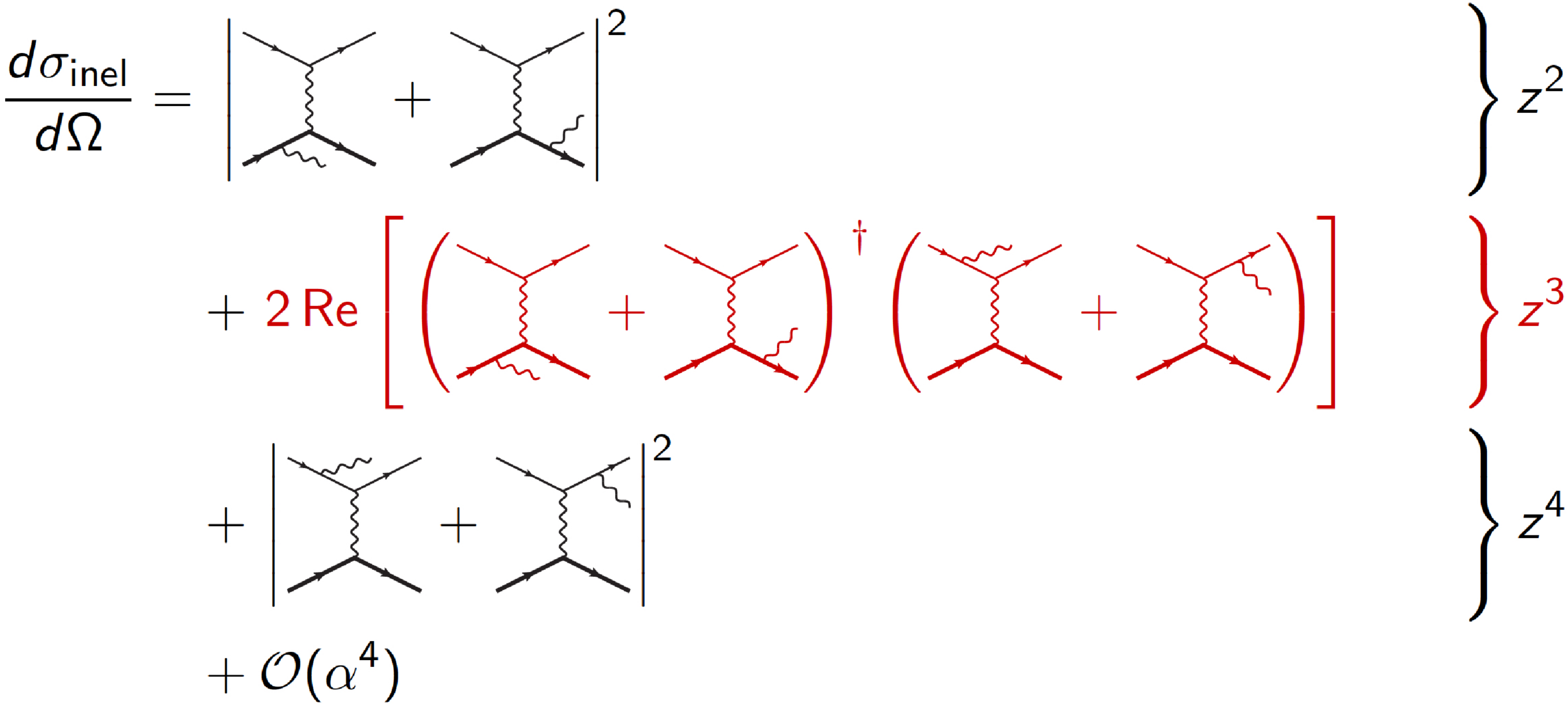
Radiative Corrections in Elastic Cross Section



Rebecca Russell, MIT

Even powers of z same for electron and positron scattering

Radiative Corrections from Inelastic Processes



Inelastic IR diverences cancel with elastic divergences

- Must separate “hard” and “soft” parts in TPE
- “soft” part included in radiative corrections, “hard” part measured
- Prescriptions defining “soft” – e.g. Mo, Tsai and Maximon,Tjon