

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

Outline

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

Lomonosov Conference 2017
Moscow

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on behalf of the
OLYMPUS Collaboration

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_E^p and G_M^p using the Rosenbluth separation

$$\frac{d\sigma / d\Omega}{(d\sigma / d\Omega)_{Mott}} = \frac{\sigma}{\sigma_0} = A(Q^2) + B(Q^2) \tan^2 \frac{\theta}{2}$$
$$= \frac{G_E^2(Q^2) + \tau G_M^2(Q^2)}{1 + \tau} + 2\tau G_M^2(Q^2) \tan^2 \frac{\theta}{2}$$

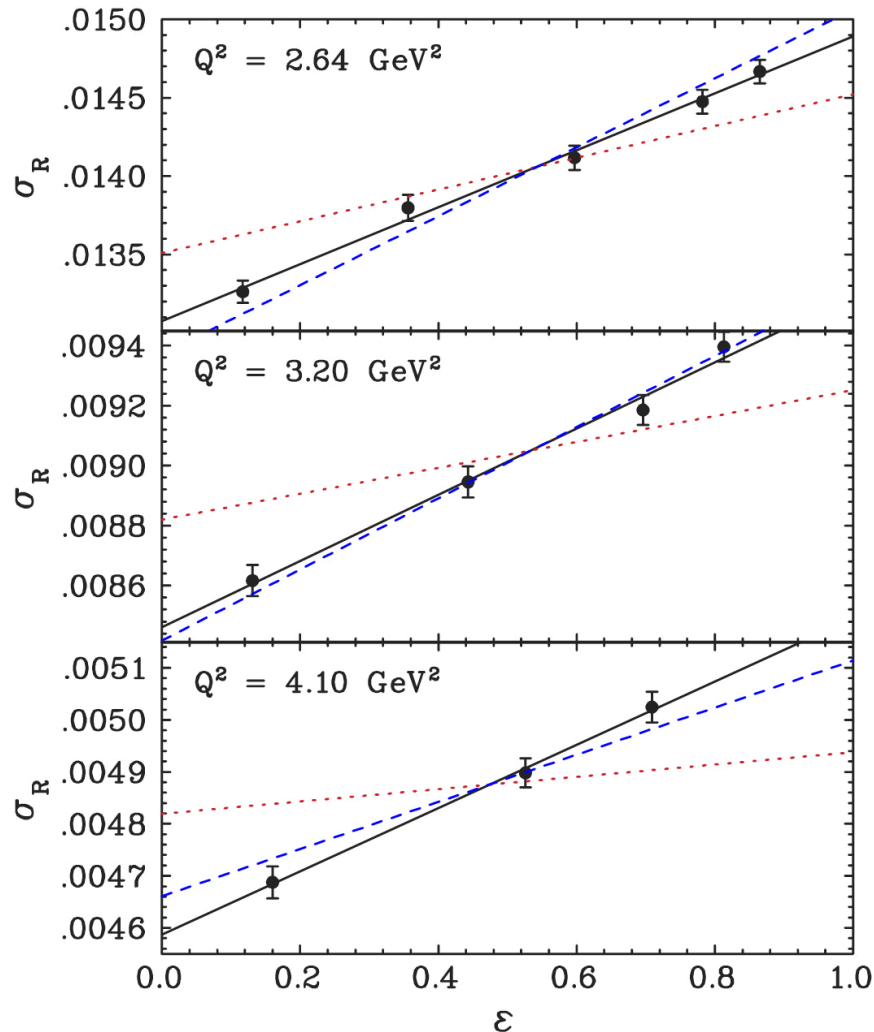
$$\sigma_{red} = \frac{d\sigma}{d\Omega} \frac{\varepsilon(1 + \tau)}{\sigma_{Mott}} = \tau G_M^2 + \varepsilon G_E^2$$

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

(ε transverse virtual photon polarization)

Form Factors - Rosenbluth Method

Reduced cross section



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

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

- > Slope $\rightarrow G_E^2$
- > Intercept $\rightarrow G_M^2$
- > G_M dominates at high Q^2
- > σ_R decreases quickly with Q^2

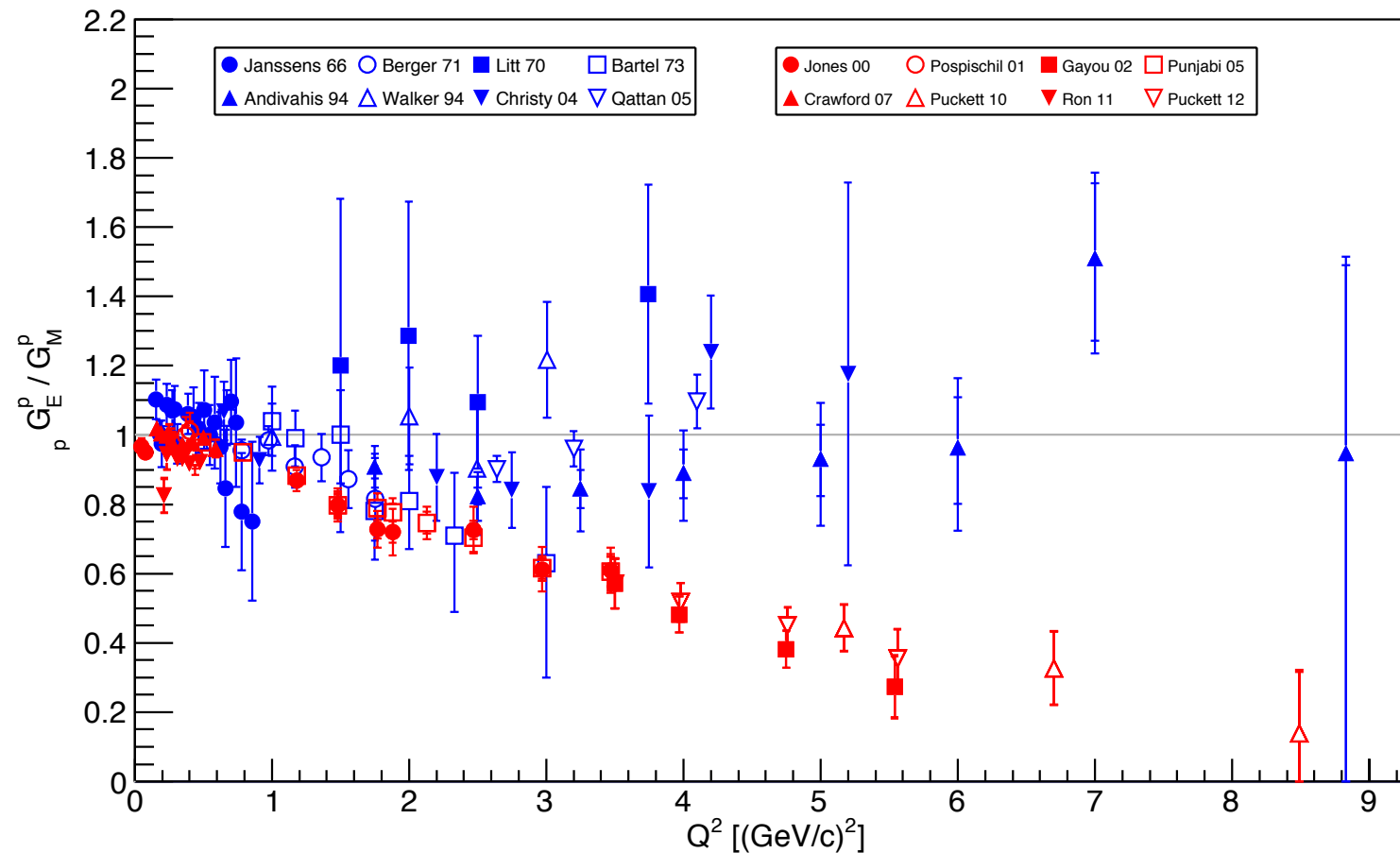
Blue dashed: FF ratio = 1

Red dotted: pol. measurements

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

Discrepancy in Form Factor Ratio

Proton Form Factor Ratio vs. Q^2



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

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

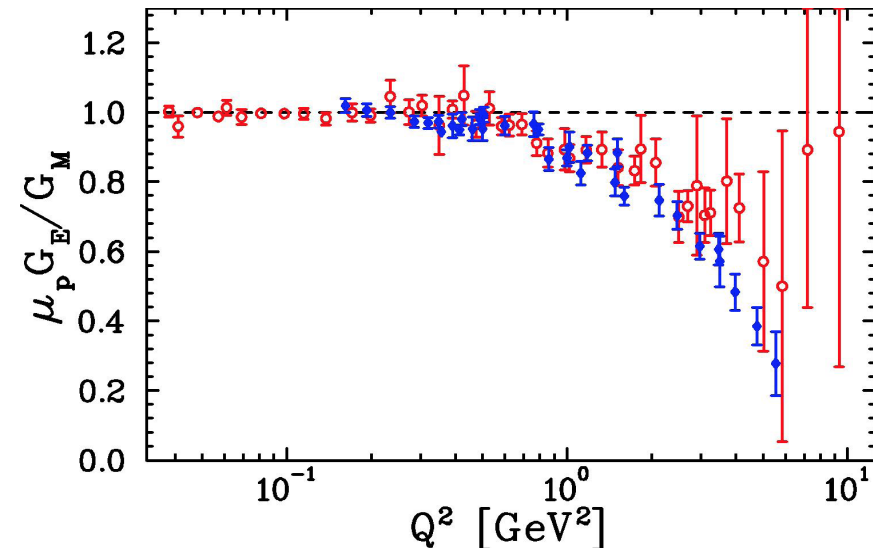
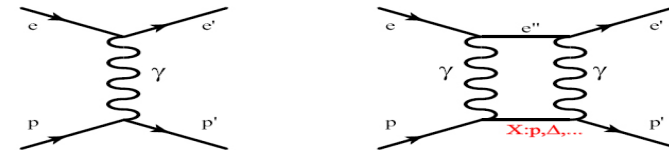
$$\mu_p \frac{G_E}{G_M} = -\mu_p \sqrt{\frac{\varepsilon(1+\varepsilon)}{2\varepsilon}} \frac{P_T}{P_L}$$

- > 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, \dots
 - 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)

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

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

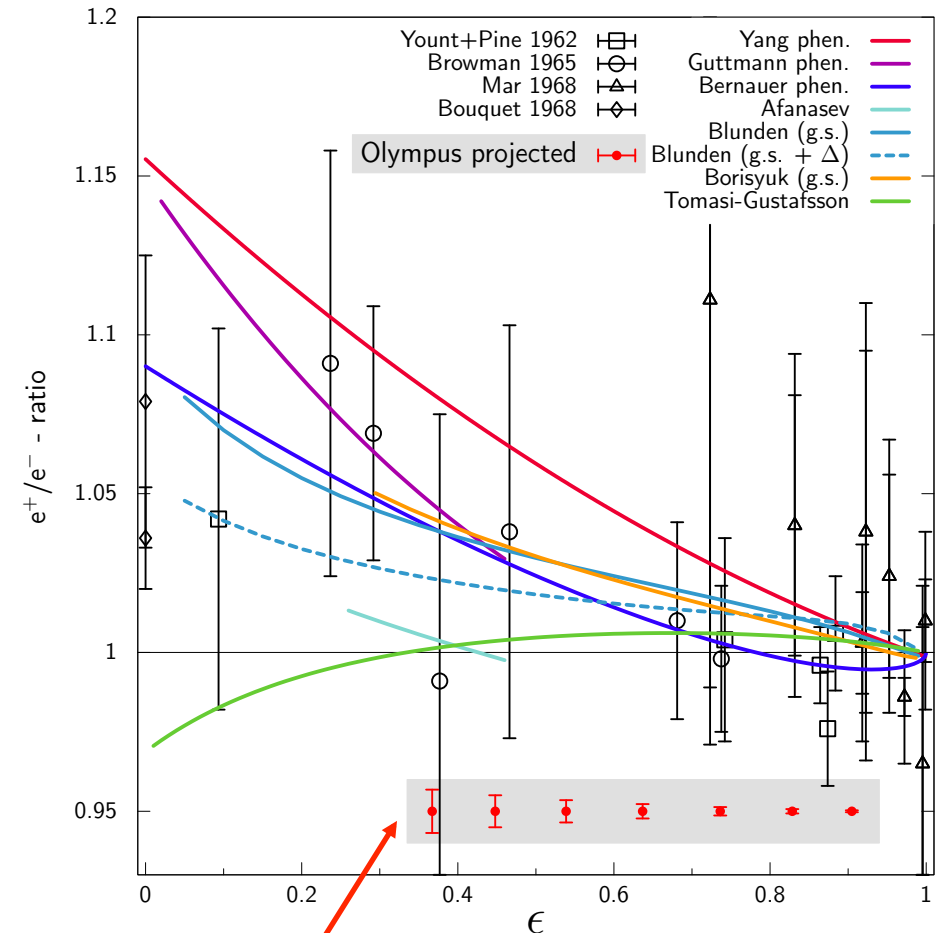
$$R = \frac{\sigma(e^+p)}{\sigma(e^-p)} = 1 + \frac{4 \Re(M_{1\gamma}^\dagger M_{2\gamma})}{|M_{1\gamma}|^2}$$

OLYMPUS Experiment at DORIS

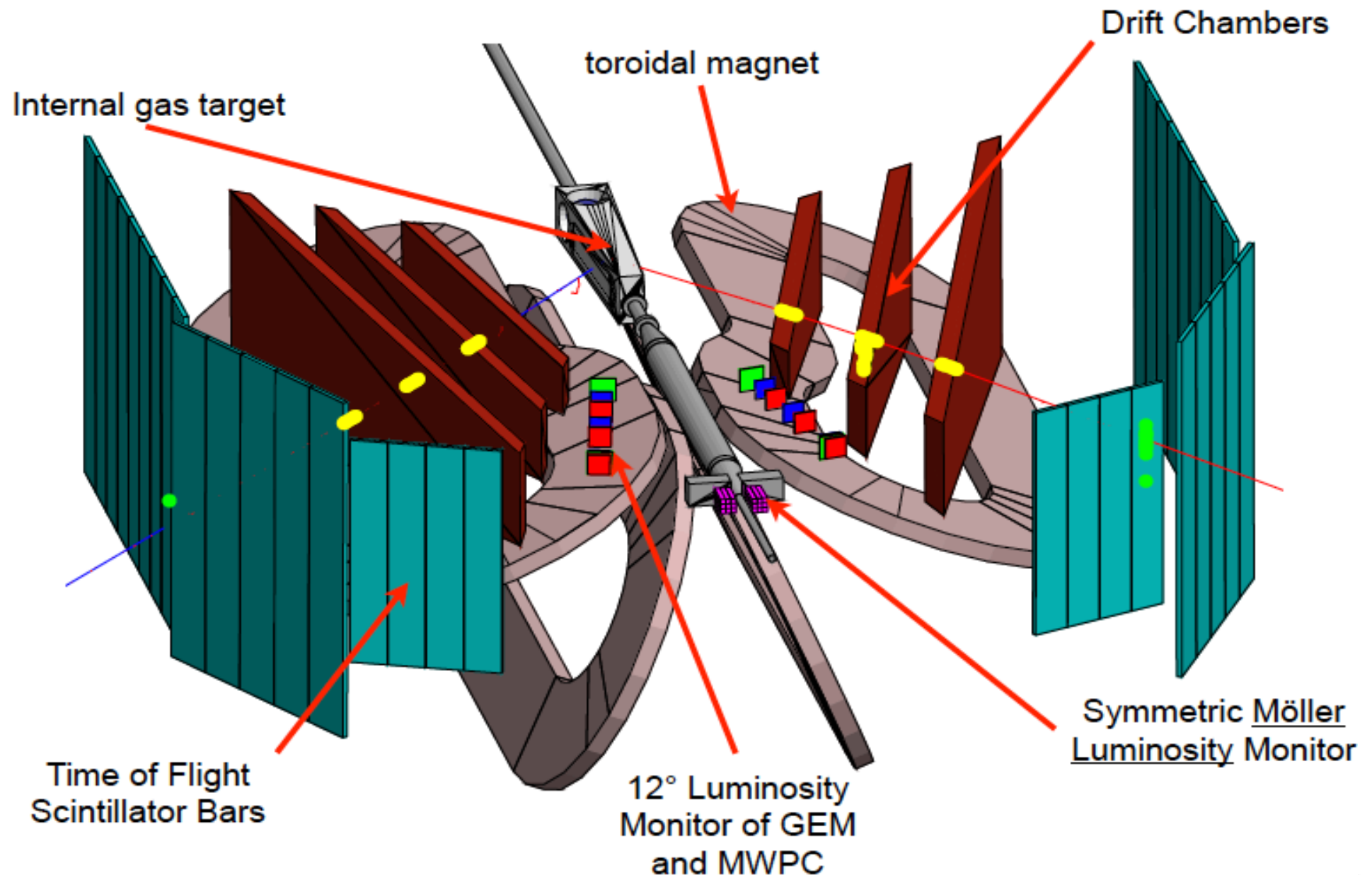
Elastic $e^+(e^-) p$ scattering at 2 GeV beam energy

- Measure ratio of e^+p/e^-p rates with 1% precision
- DORIS 100 mA $e^+(e^-)$ beam
- Unpolarized internal hydrogen target, density 3×10^{15} at/cm²
- Daily change of beam (e^+ or e^-) to minimize systematic error
- Redundant luminosity measurements
- Using former BLAST detector from MIT/Bates. Ideally suited.

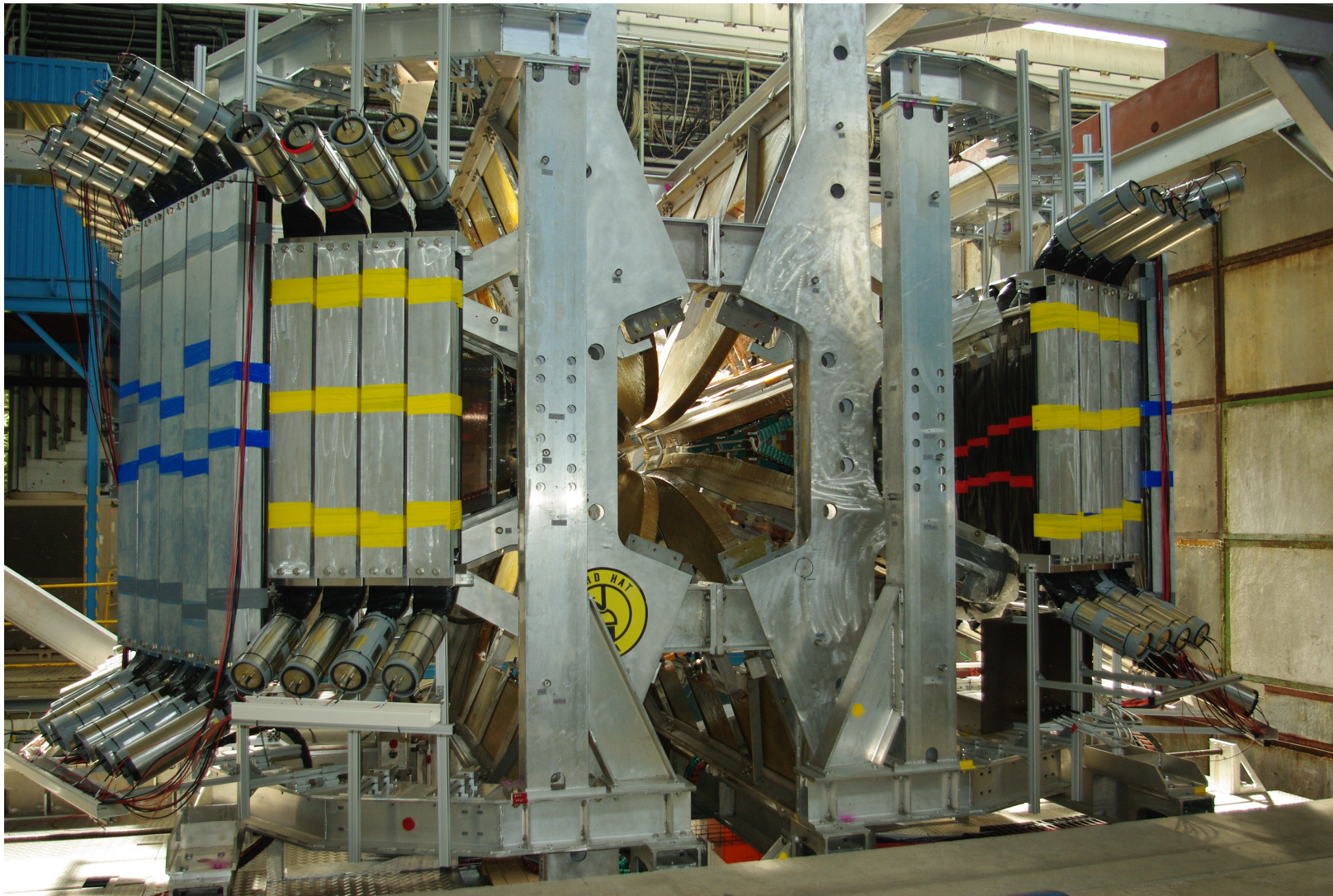
Comparison of data and theory



Detector Overview

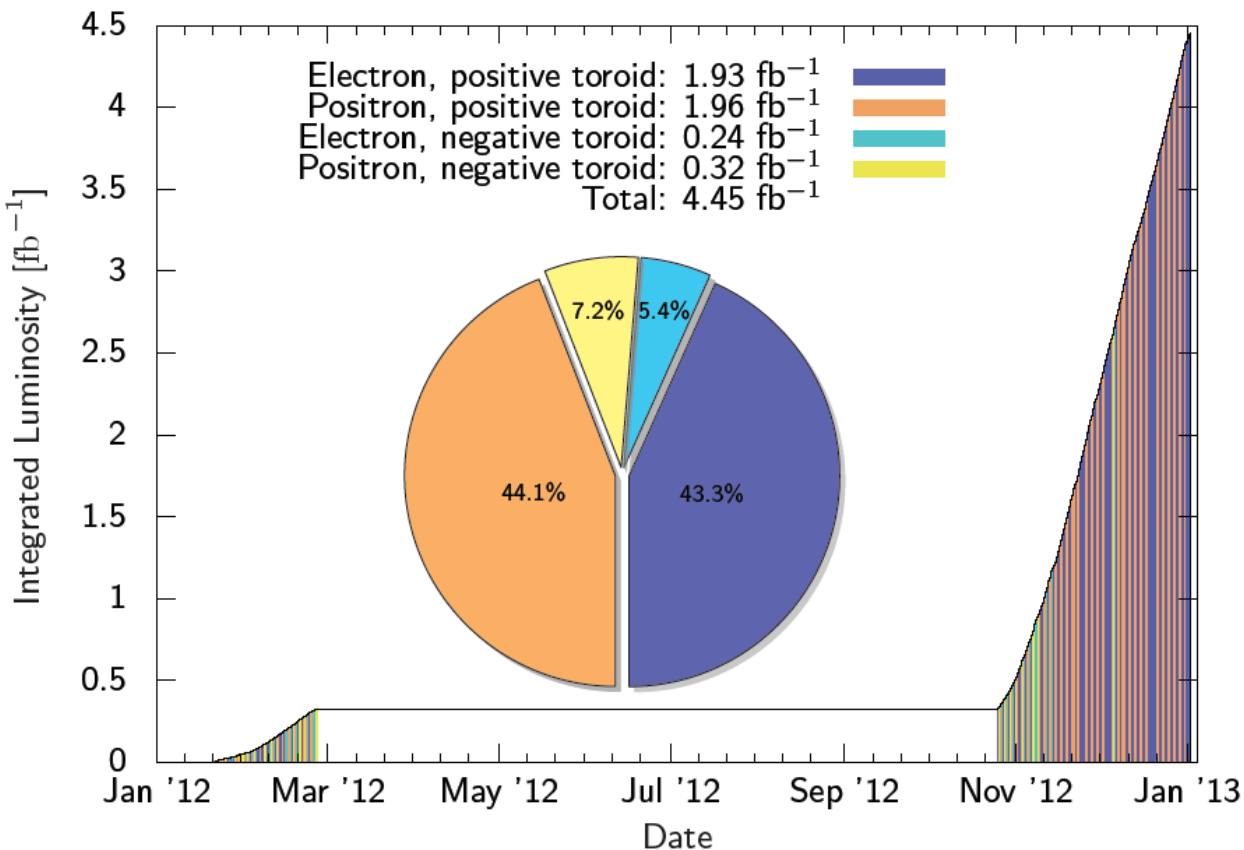


OLYMPUS Detector



DataTaking in 2012

OLYMPUS Luminosity



Limited flow and luminosity in Feb. run

Fall run

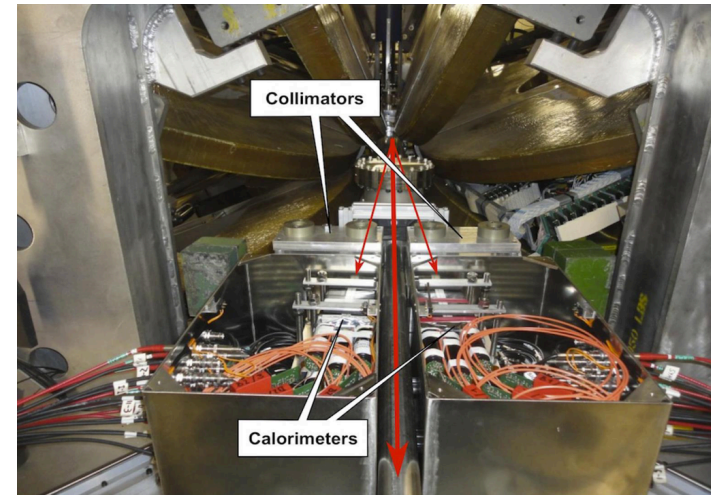
- > Full hydrogen flow
- > DORIS top-up mode
- > Excellent performance
- > Exceeded integrated luminosity:
 - Design 3.6fb⁻¹, achieved 4.45fb⁻¹
- > Daily switch of beam species, good balance
- > Mainly positive toroid polarity due to background
- > Negative field for systematics checks

Luminosity Determination

Three independent measurements

- > Slow Control (beam current and target density)
 - 2% between beam species, 5% absolute
- > Tracking telescopes at 12° (elastic ep scattering at small angles)
 - MWPC with coincident proton in WC
 - 0.46% between beam species, 2.4% absolute
- > Multi-interaction events ($e^\pm e \rightarrow e^\pm e$) + ($e^\pm p \rightarrow e^\pm p$) at 1.29° 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

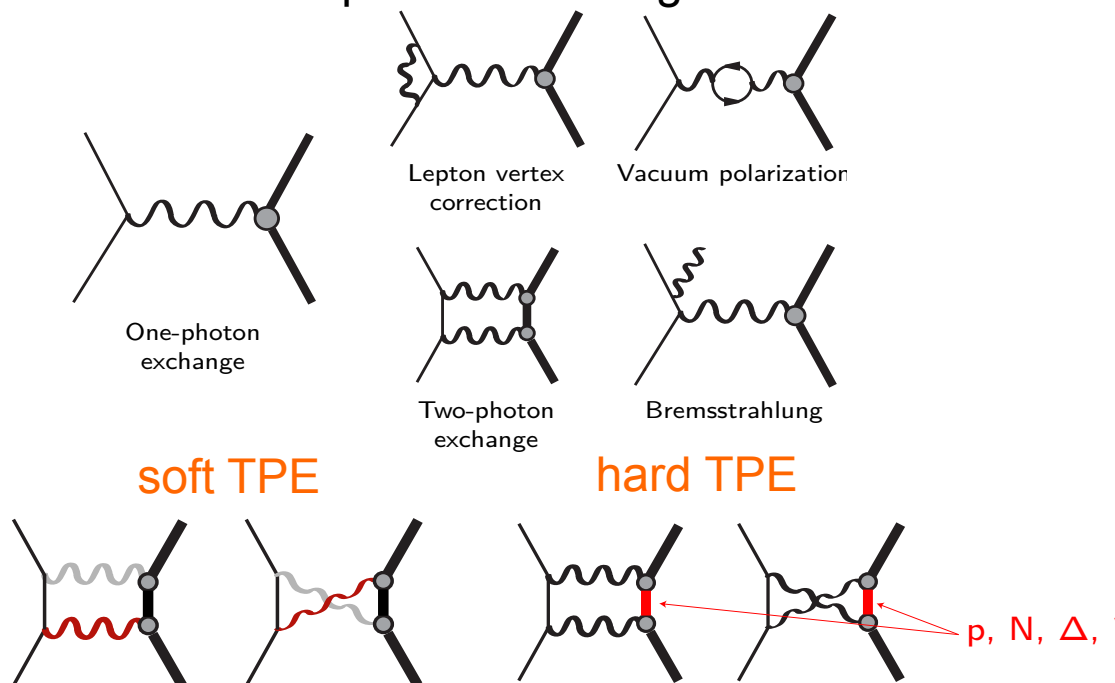
- > Negligible TPE at 1.29°
 - $\langle Q^2 \rangle = 0.002 \text{ GeV}^2$
- > Allows measurement of TPE at 12°
 - $R_{2\gamma} = 0.9975 \pm 0.010 \pm 0.0053$
 - $\langle Q^2 \rangle = 0.165 \text{ GeV}^2, \langle \epsilon \rangle = 0.98$

Radiative Corrections

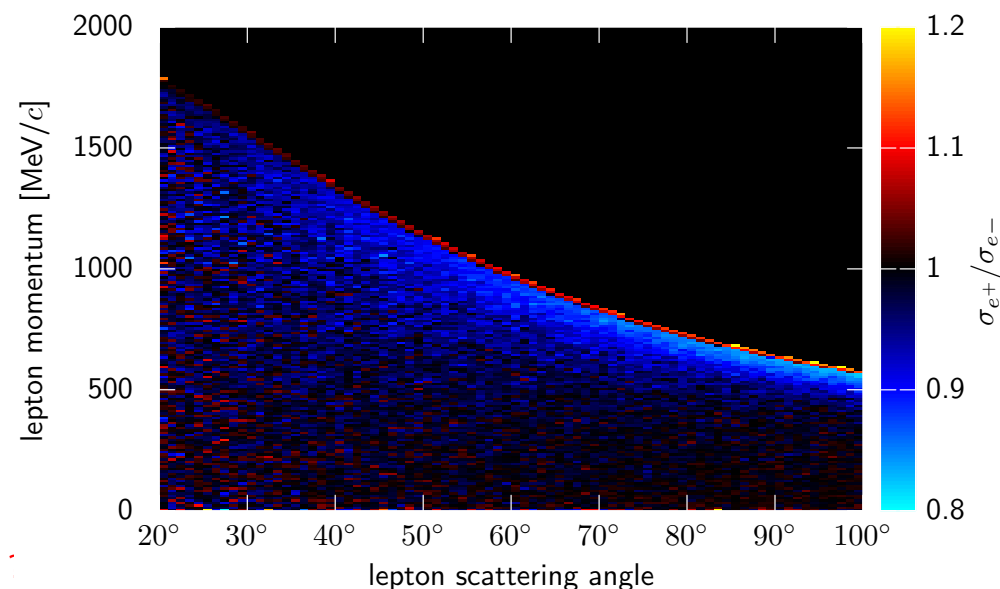
Independent elastic $e^\pm p$ generators written at MIT (weighted)

> Radiative corrections include:

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

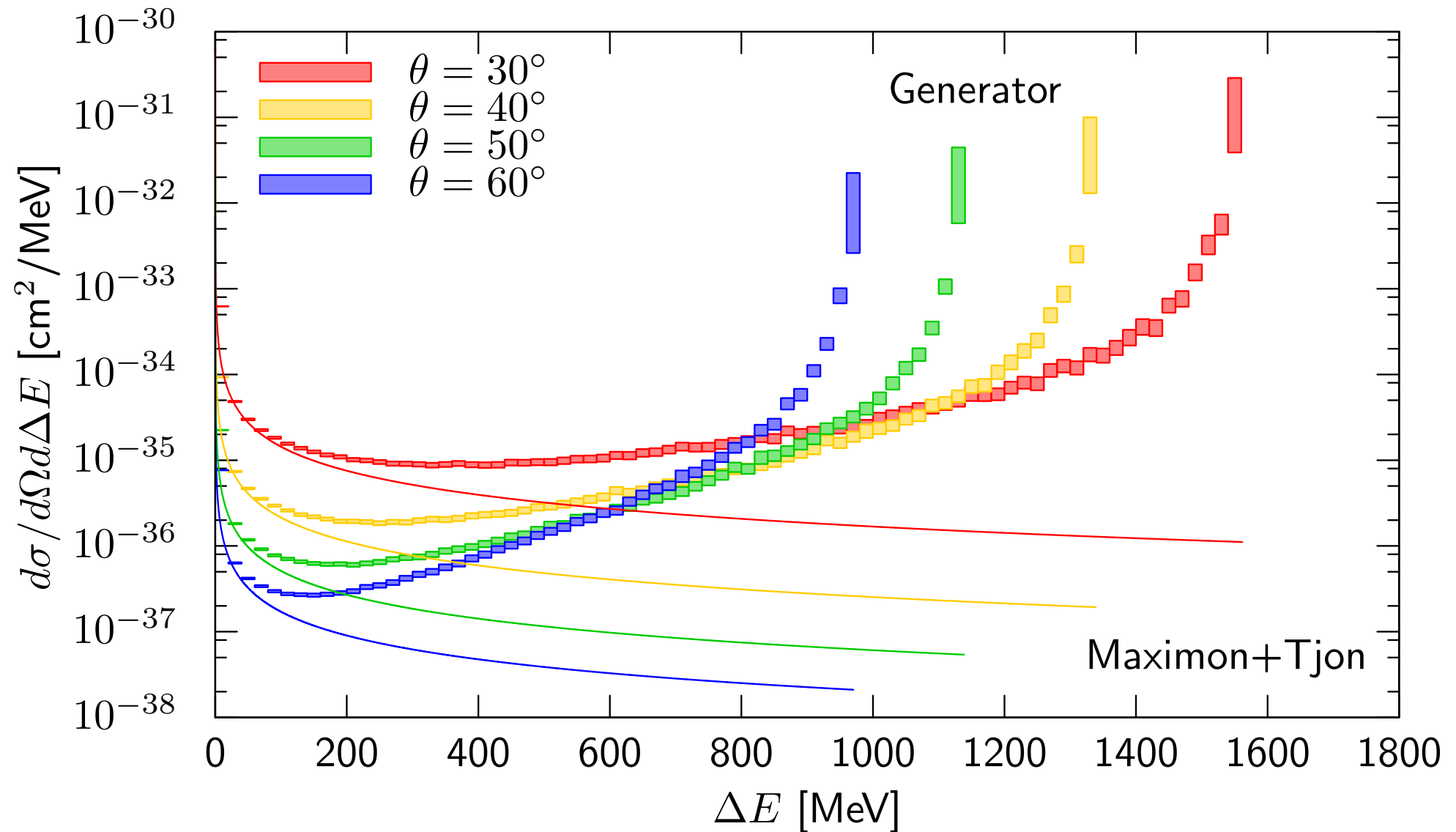


Even powers of z same for e^+ and e^- scattering, cancel in ratio

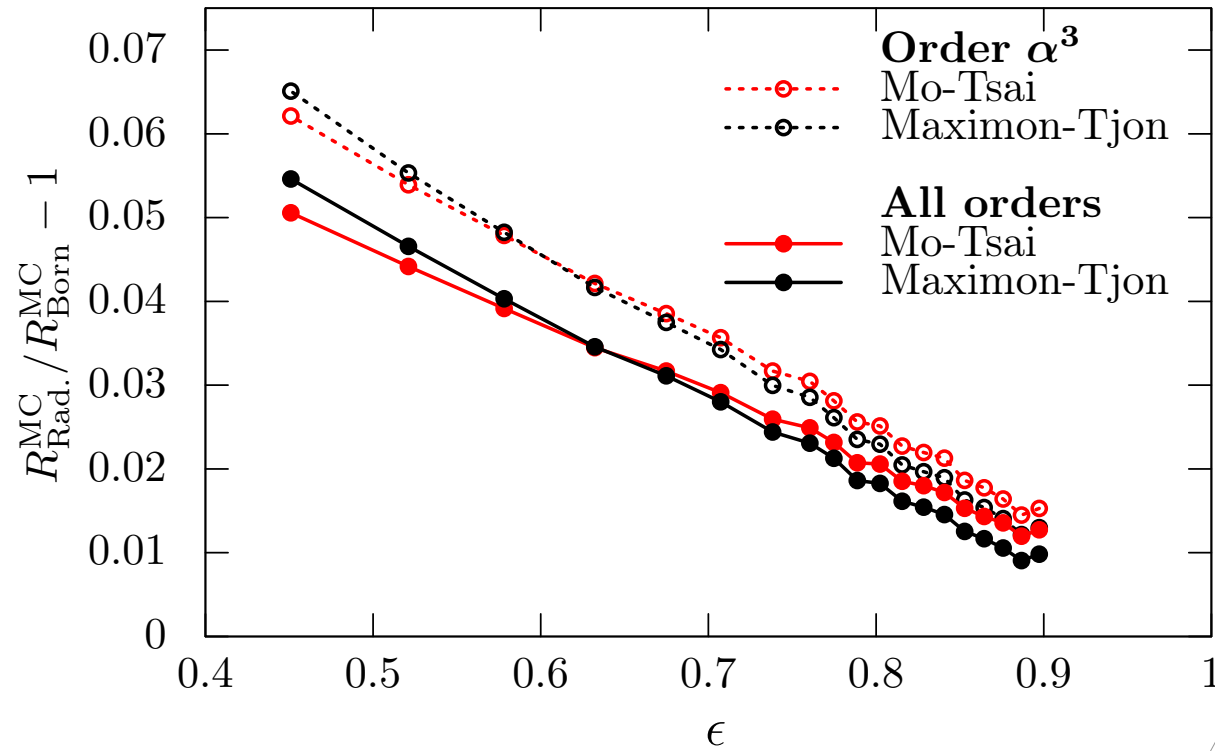


New Møller/Bhabha generator with radiative corrections

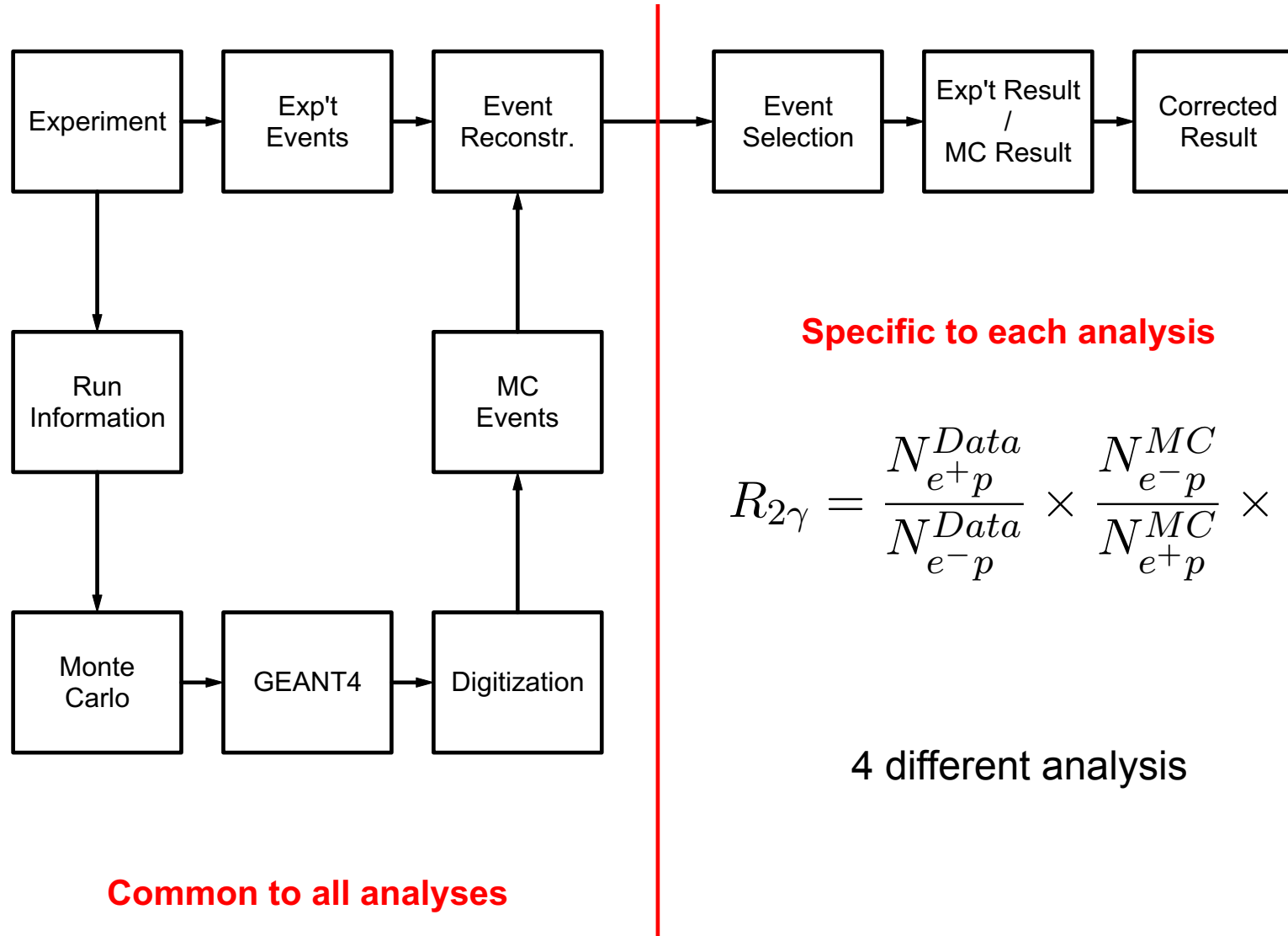
Radiative Corrections Depend on Experiment



Radiative Corrections in OLYMPUS



Schematic of Analysis Procedure



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

4 different analysis

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

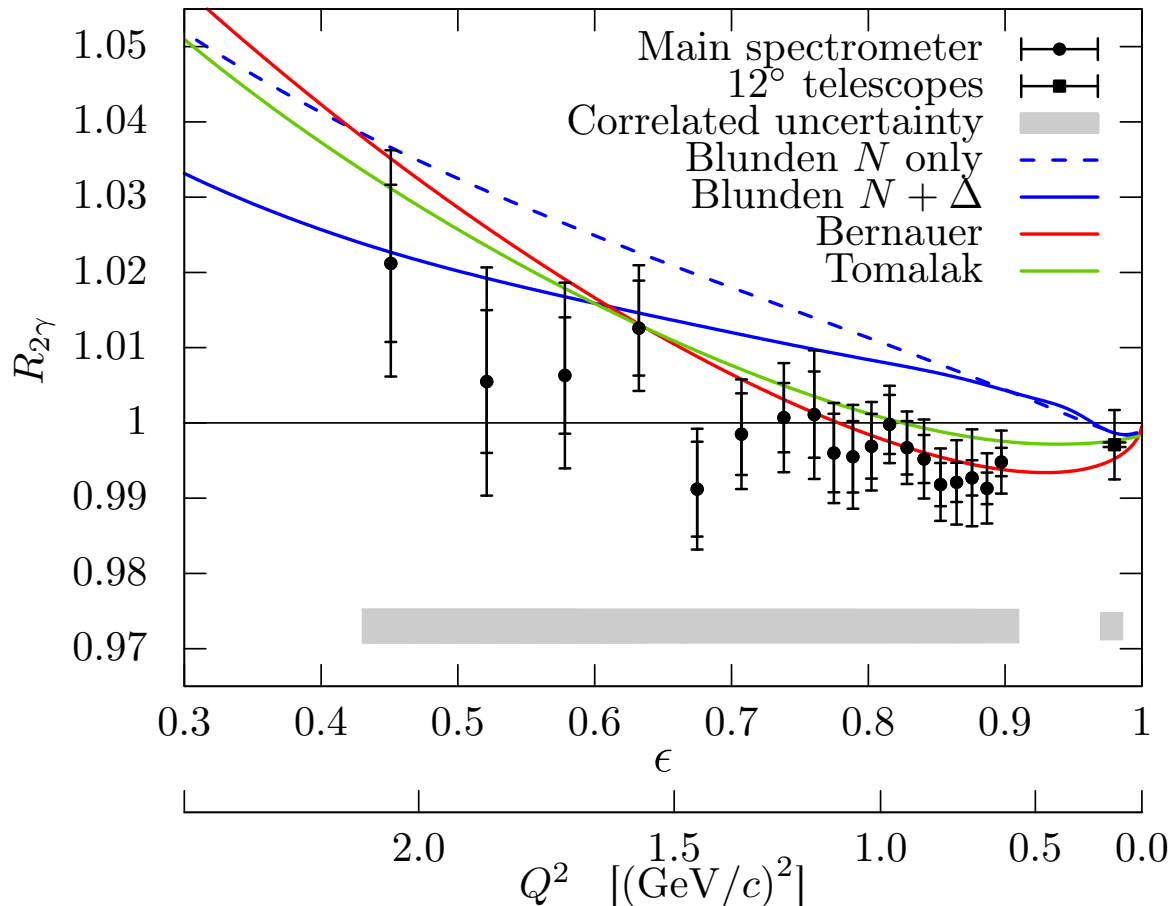
- > Luminosity (MIE): 0.36%
- > Beam energy: 0.04 – 0.13%
- > Beam position and detector position/geometry: 0.25%
- > Total: 0.46%

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)

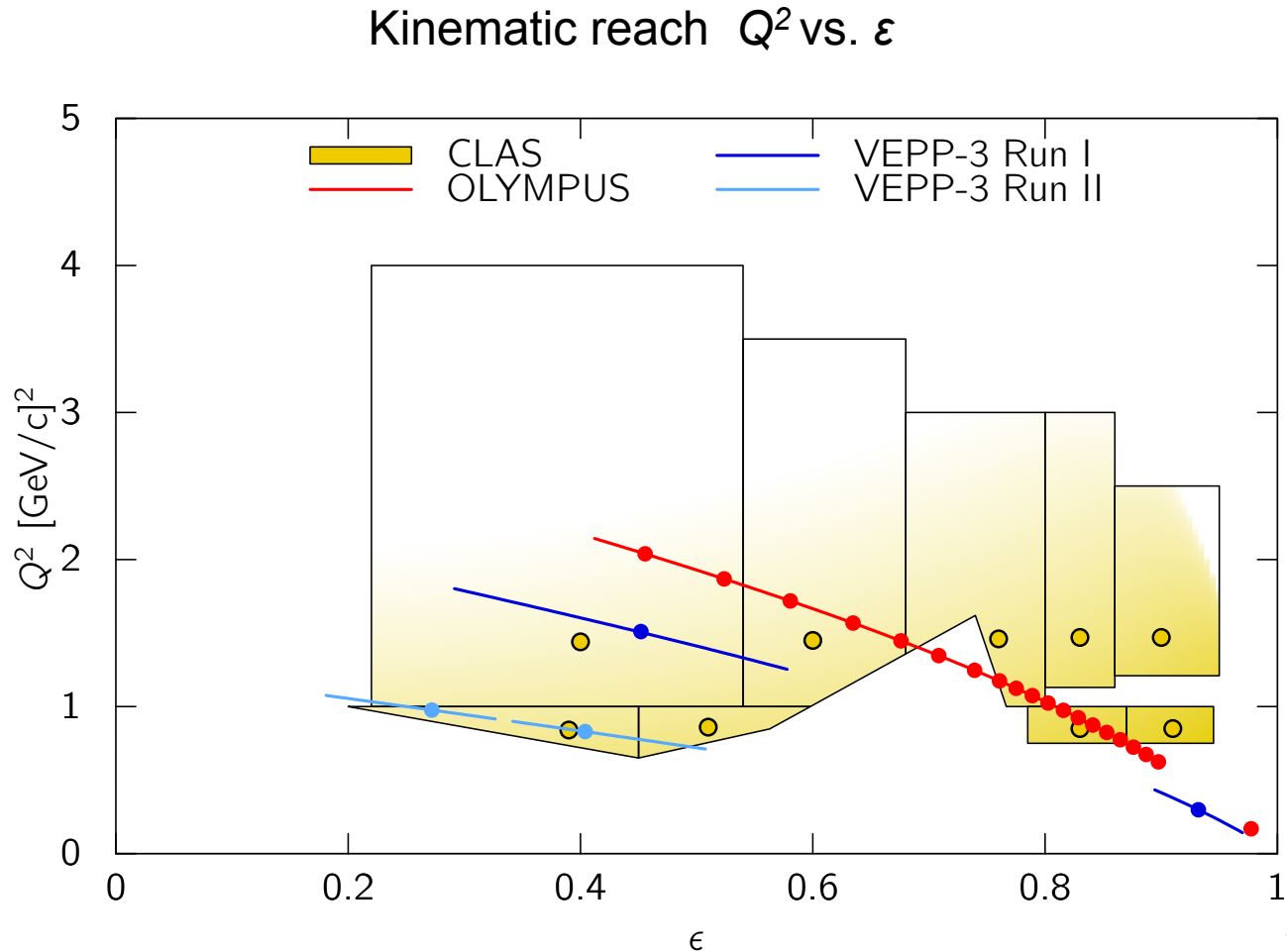


OLYMPUS, B.S. Henderson et al., PRL 118, 092501 (2017)

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



Other recent experiments

> VEPP-3

- E storage ring in Novosibirsk

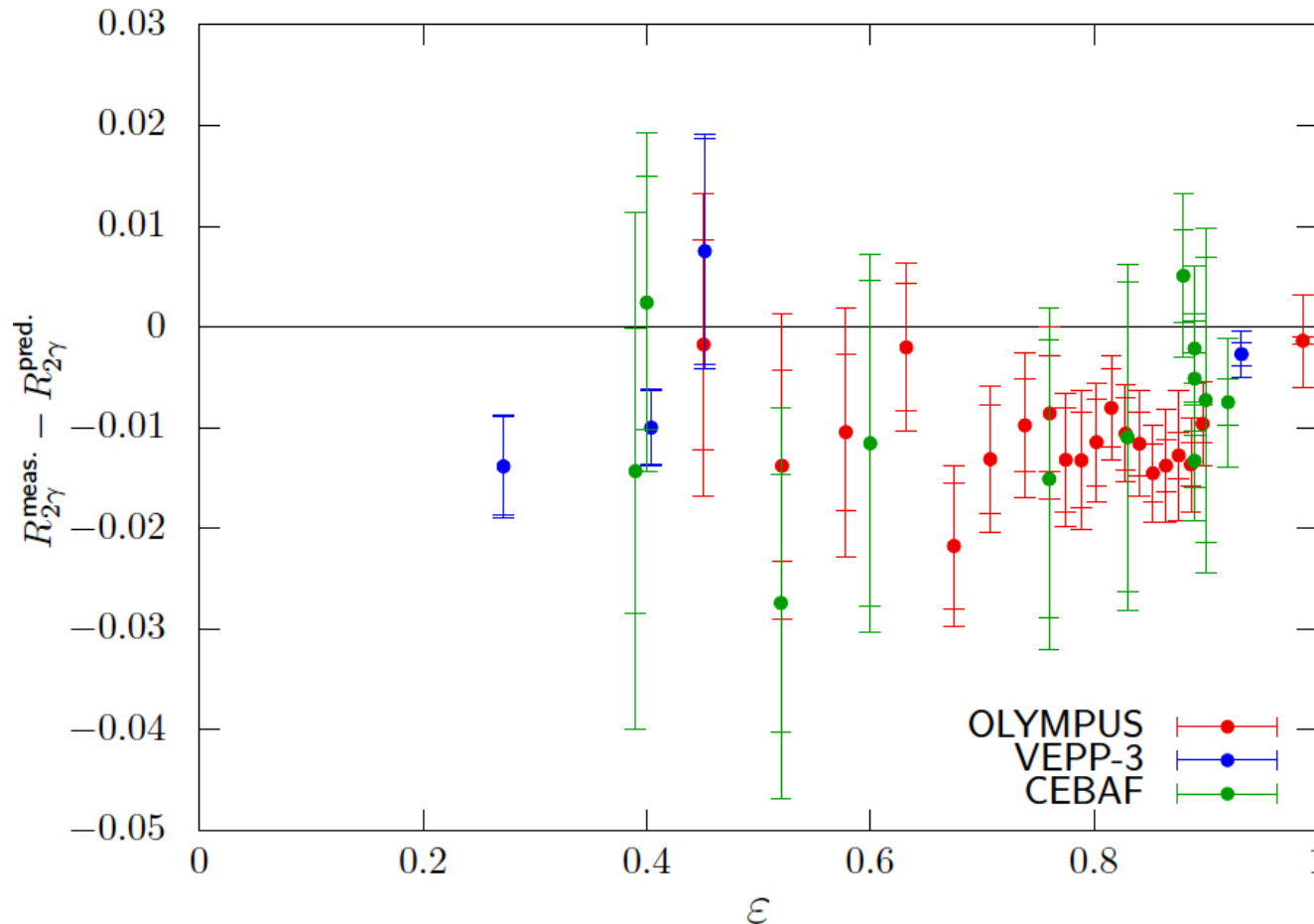
> CAST

- 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 $N + \Delta$)

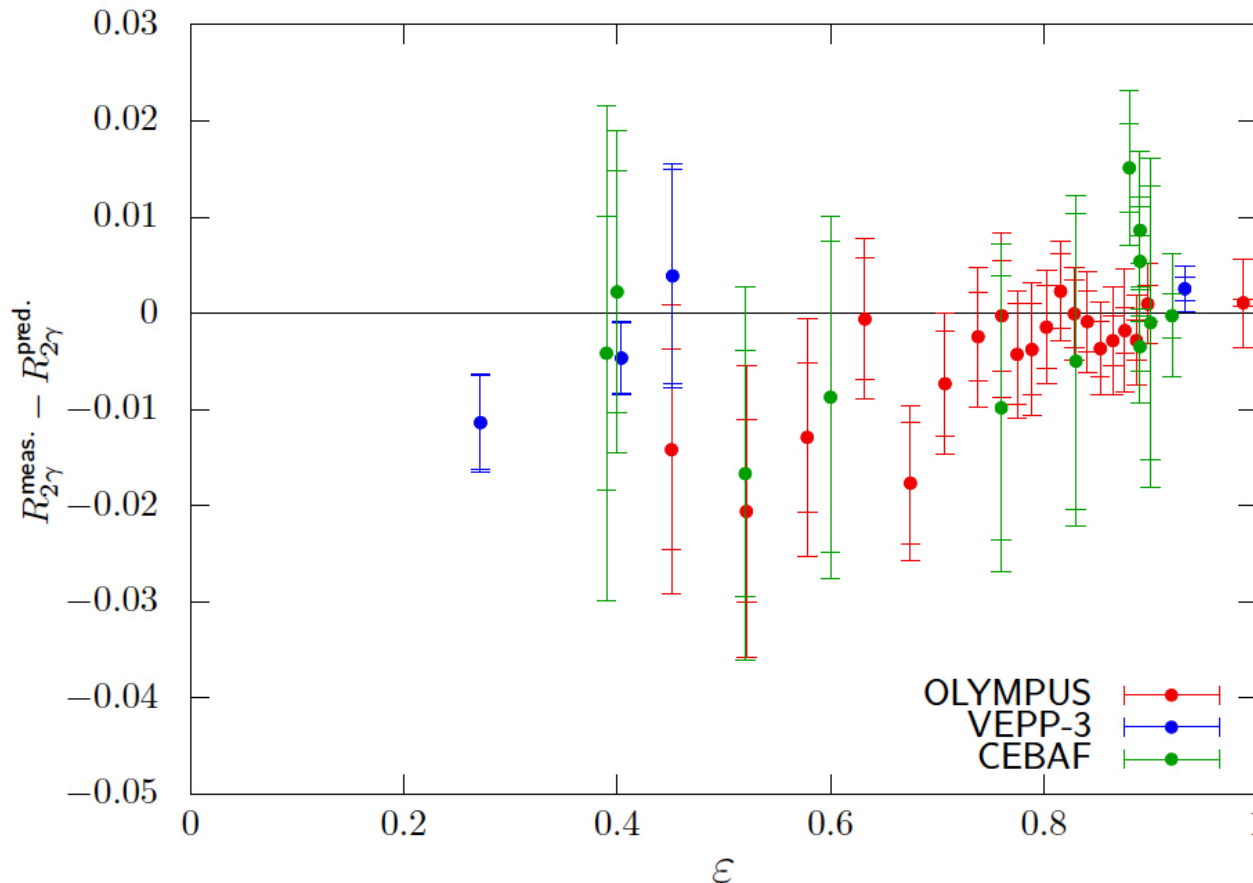


Comparison of results

- > 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 $Q^2 < 2.3 \text{ GeV}^2$
- > 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
- 2nd 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

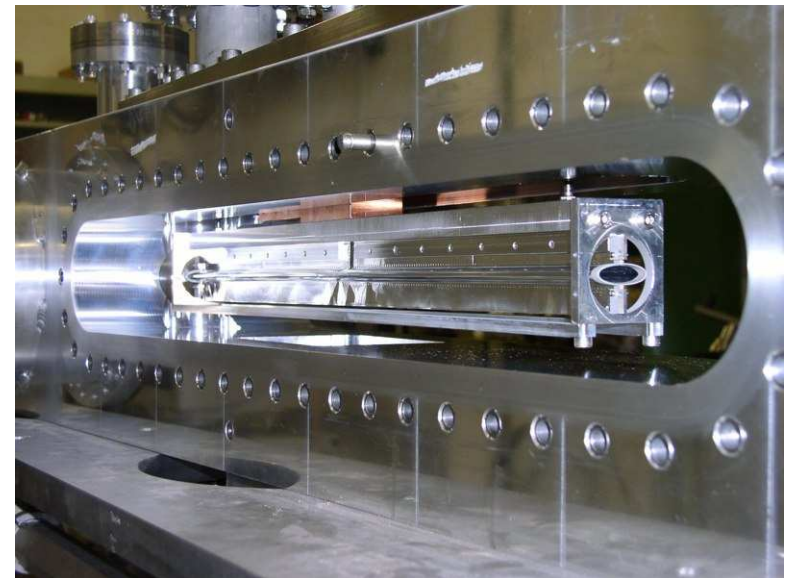
> 2017

- Ratio paper published in PRL

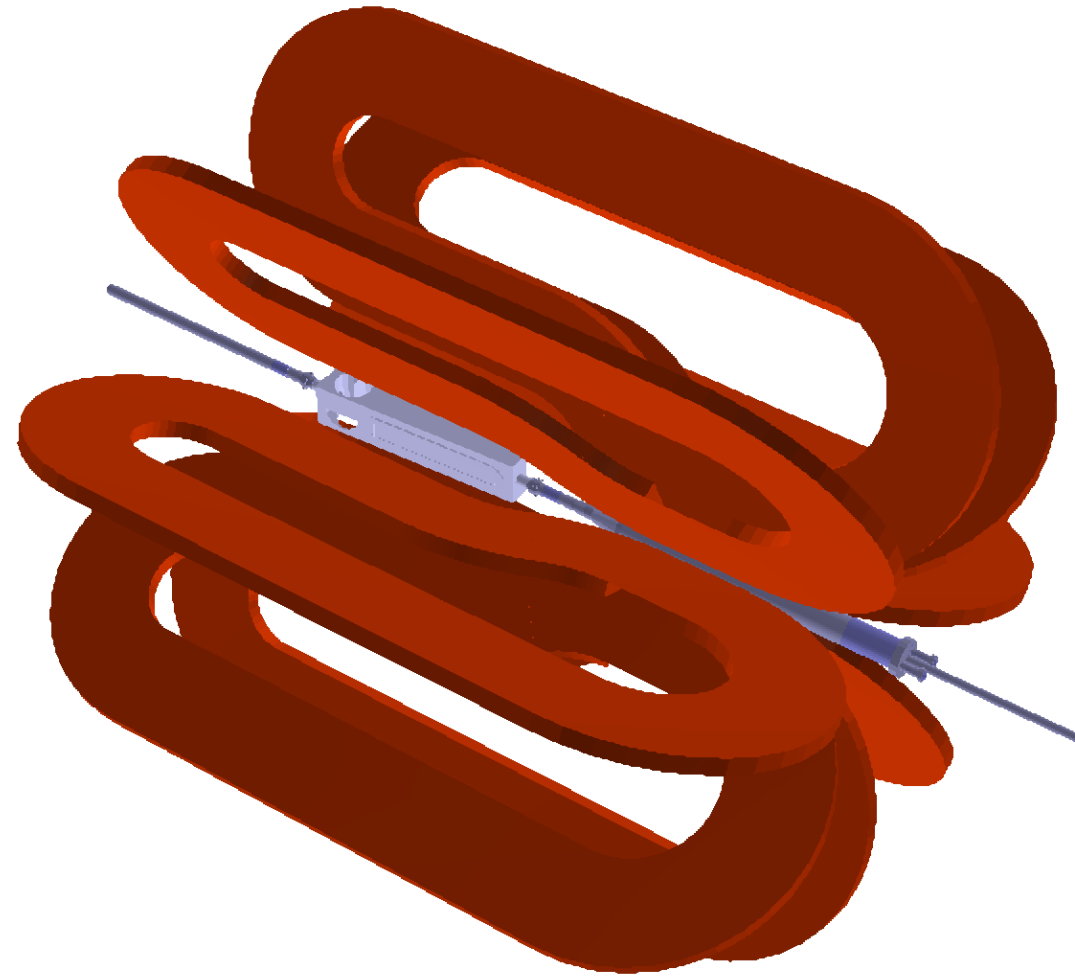
Target System

- 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 $\sim 45\text{ K}$
- $\text{O}(10^{15})\text{ atoms/cm}^2$
- Hydrogen produced by generator (electrolysis)

INFN Ferrara, MIT



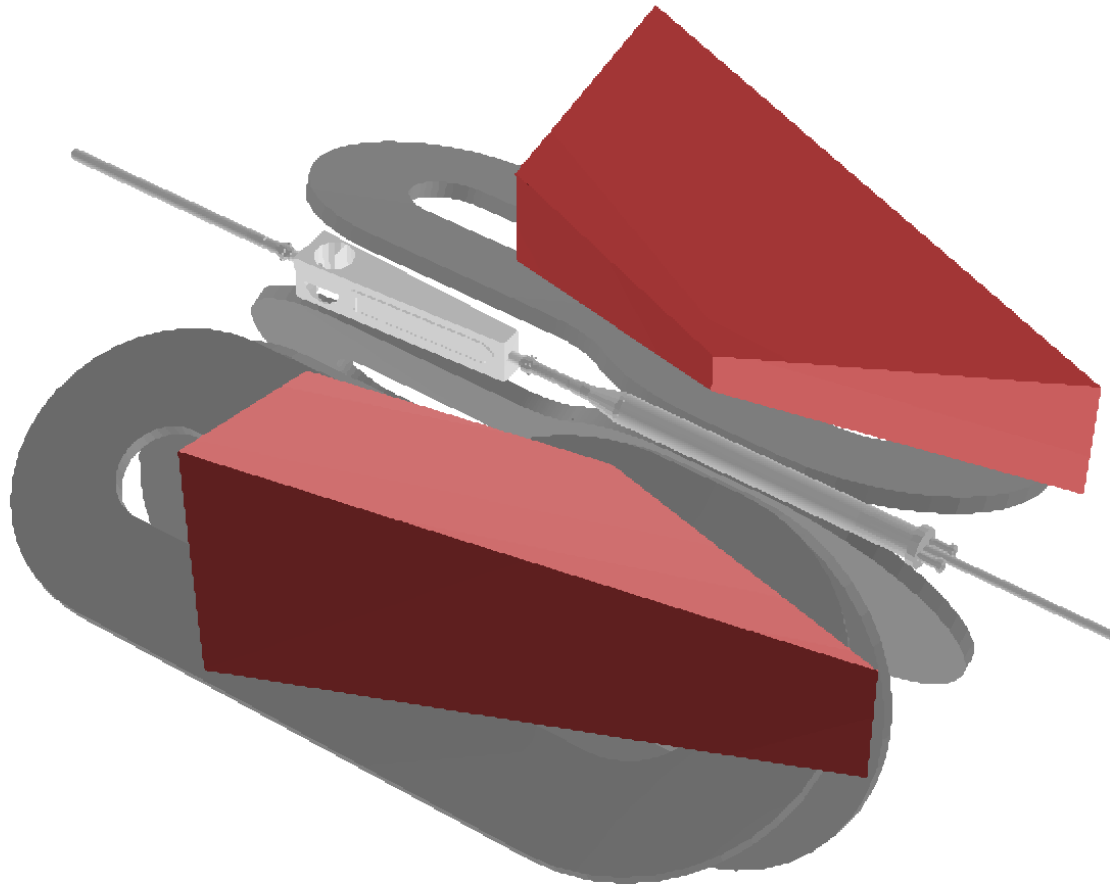
Toroidal Magnet



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



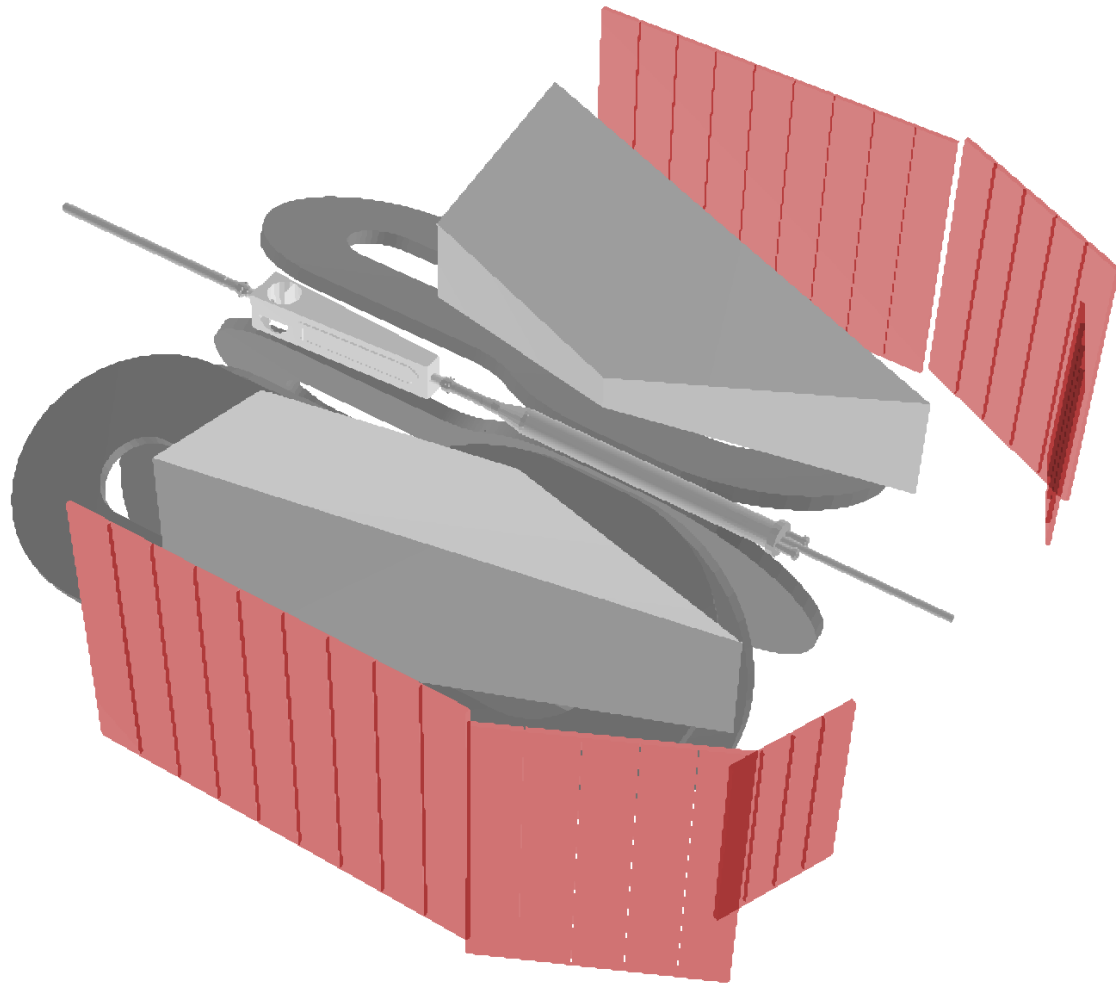
Drift Chambers



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

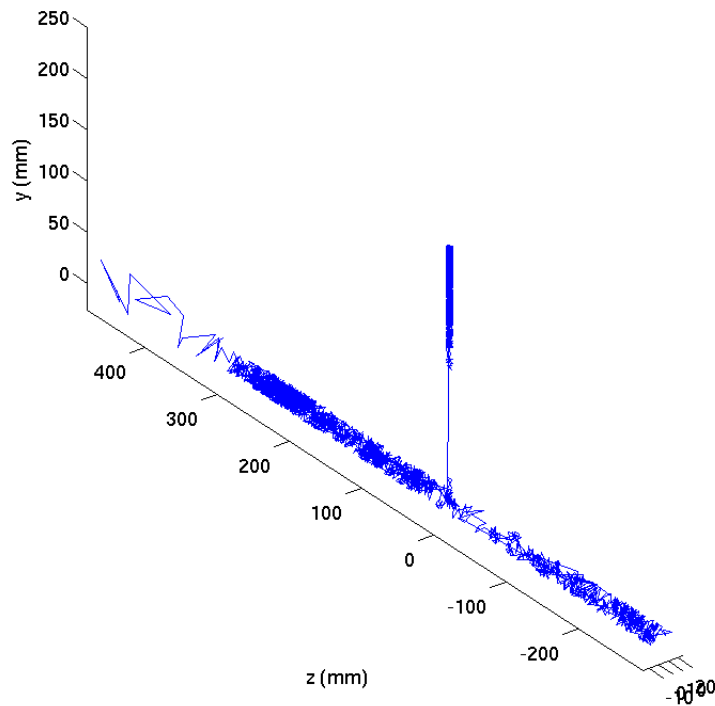


Time – of - Flight Counters

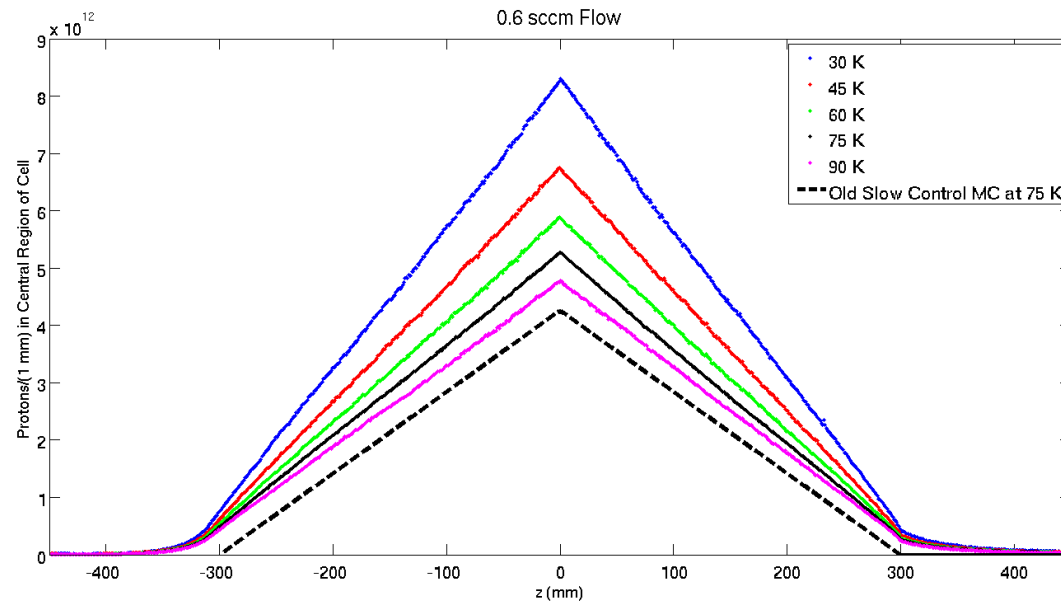


- > Scintillation counters from BLAST
- > Trigger
 - Top/bottom coincidence
 - Kinematic constraint
 - + 2nd level wire chamber
- > Time-of-flight for particle ID

Target Gas Simulation



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



Radiative Corrections in Elastic Cross Section

$$\begin{aligned}
 \frac{d\sigma}{d\Omega} = & \left| \text{tree} \right|^2 \\
 & + 2 \operatorname{Re} \left[\text{tree}^\dagger \left(\text{tree} + \text{self-energy} + \text{vertex} + \text{box} \right) \right] \quad \left. \vphantom{\frac{d\sigma}{d\Omega}} \right\} z^2 \\
 & + 2 \operatorname{Re} \left[\text{tree}^\dagger \left(\text{box} + \text{box} \right) \right] \quad \left. \vphantom{\frac{d\sigma}{d\Omega}} \right\} z^3 \\
 & + 2 \operatorname{Re} \left[\text{tree}^\dagger \left(\text{box} + \text{box} + \text{box} \right) \right] \quad \left. \vphantom{\frac{d\sigma}{d\Omega}} \right\} z^4 \\
 & + \mathcal{O}(\alpha^4)
 \end{aligned}$$

Rebecca Russell, MIT

Even powers of z same for electron and positron scattering

Radiative Corrections from Inelastic Processes

$$\begin{aligned}
 \frac{d\sigma_{\text{inel}}}{d\Omega} = & \left| \begin{array}{c} \text{diagram 1} \\ + \\ \text{diagram 2} \end{array} \right|^2 \quad \left. \vphantom{\left| \begin{array}{c} \text{diagram 1} \\ + \\ \text{diagram 2} \end{array} \right|^2} \right\} z^2 \\
 & + 2 \operatorname{Re} \left[\left(\begin{array}{c} \text{diagram 3} \\ + \\ \text{diagram 4} \end{array} \right)^\dagger \left(\begin{array}{c} \text{diagram 5} \\ + \\ \text{diagram 6} \end{array} \right) \right] \quad \left. \vphantom{2 \operatorname{Re} \left[\left(\begin{array}{c} \text{diagram 3} \\ + \\ \text{diagram 4} \end{array} \right)^\dagger \left(\begin{array}{c} \text{diagram 5} \\ + \\ \text{diagram 6} \end{array} \right) \right]} \right\} z^3 \\
 & + \left| \begin{array}{c} \text{diagram 7} \\ + \\ \text{diagram 8} \end{array} \right|^2 \quad \left. \vphantom{\left| \begin{array}{c} \text{diagram 7} \\ + \\ \text{diagram 8} \end{array} \right|^2} \right\} z^4 \\
 & + \mathcal{O}(\alpha^4)
 \end{aligned}$$

Inelastic IR divergences 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