University of Glasgow

Form factor measurements in the presence of two-photon exchange

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University of Glasgow
IOP Glasgow, 6 April 2011

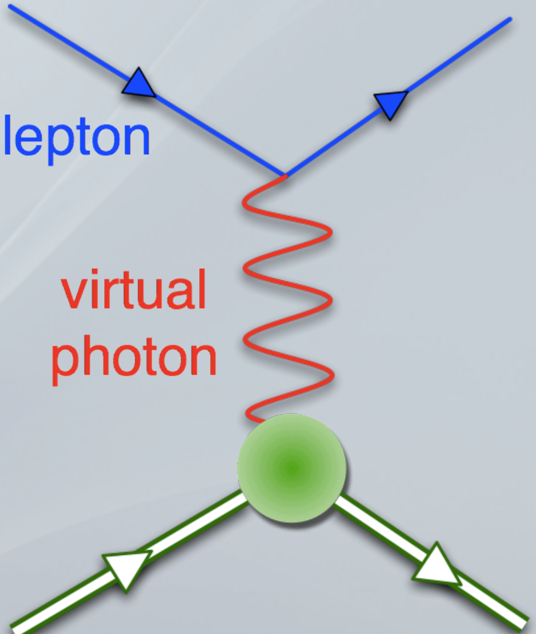
IOP Institute of Physics

OLYMPUS

Form Factors

- Elastic scattering (Born approx.)

$$\langle N(P')|J^{\mu}_{\mathrm{EM}}(0)|N(P)\rangle = \bar{u}(P')\left[\gamma^{\mu}F_1^N(Q^2) + i\sigma^{\mu\nu}\frac{q_\nu}{2M}F_2^N(Q^2)\right]u(P)$$

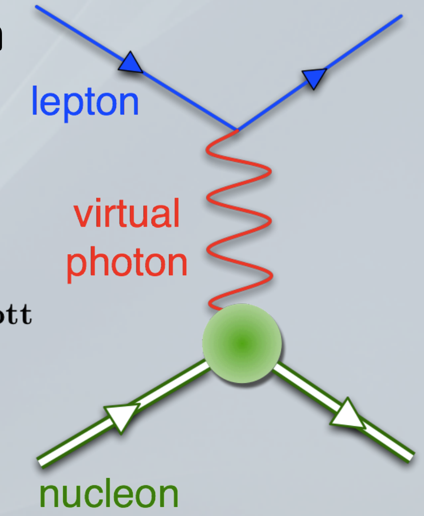


- Electric and magnetic form factors G_E and G_M
  - Fourier transforms of resp. distributions

$$G_E = F_1 - \tau F_2; \quad G_M = F_1 + F_2, \quad \tau = \frac{Q^2}{4M^2}$$

Classical Approach

- Assume single photon exchange – Born approximation
  - Measure cross section (Rosenbluth)



$$\left(\frac{d\sigma}{d\Omega}\right)_{\text{Rosenbluth}} = \left[\frac{|G_E|^2 + \tau|G_M|^2}{1+\tau} + 2\tau|G_M|^2 \tan^2\frac{\theta}{2}\right]\left(\frac{d\sigma}{d\Omega}\right)_{\text{Mott}}$$

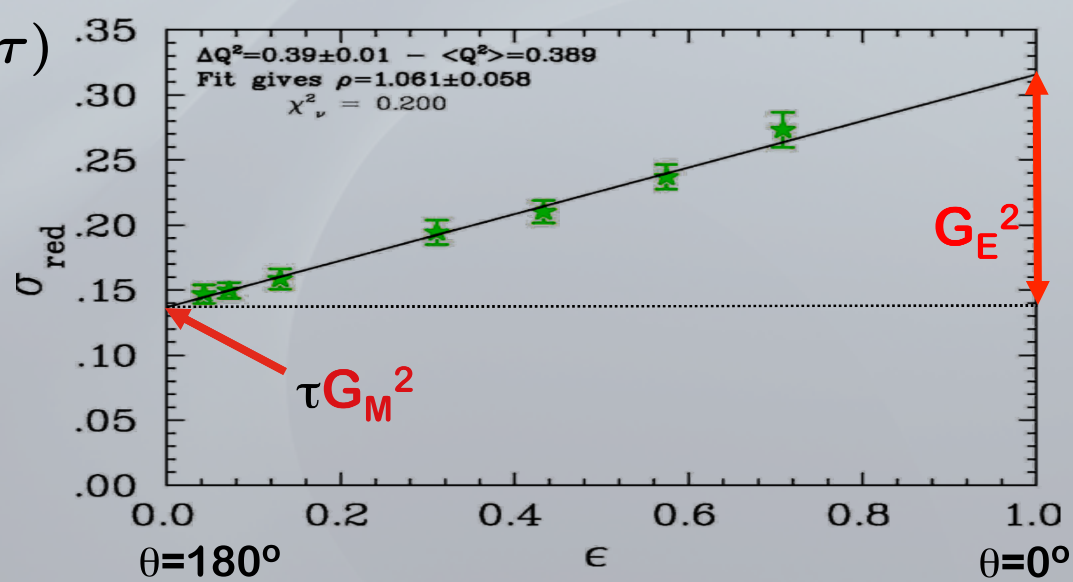
  - Extract G_E and G_M

$$\sigma_{\text{red}} = \frac{\left(\frac{d\sigma}{d\Omega}\right)_{\text{Rosenbluth}}}{\left(\frac{d\sigma}{d\Omega}\right)_{\text{Mott}}}\epsilon(1+\tau)$$

$$= \epsilon|G_E|^2 + \tau|G_M|^2$$

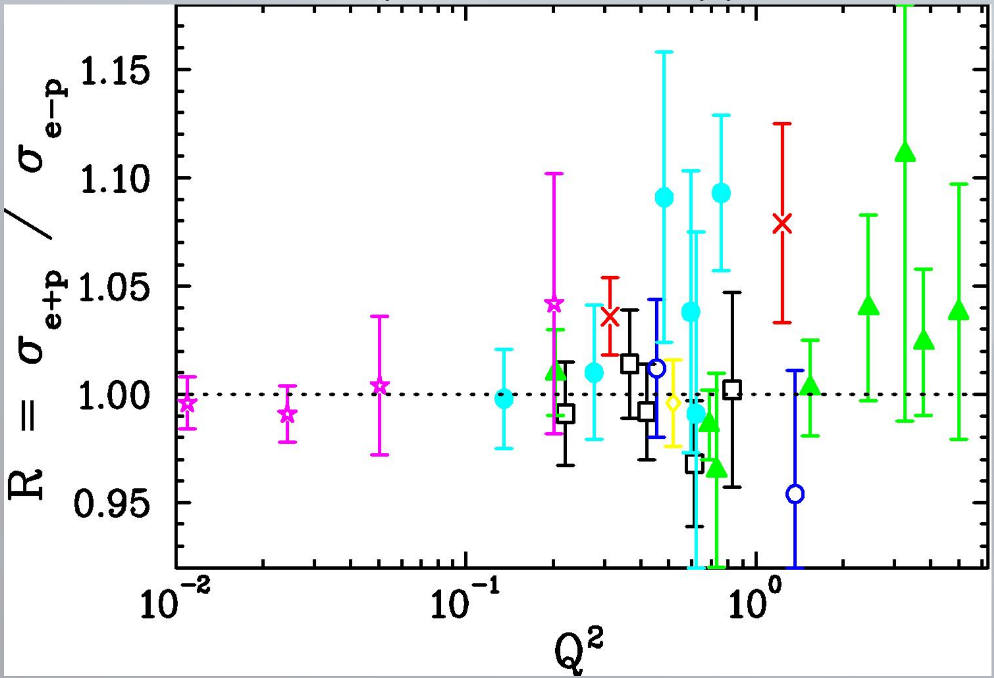
- with $\tau = \frac{Q^2}{4M_p^2}$

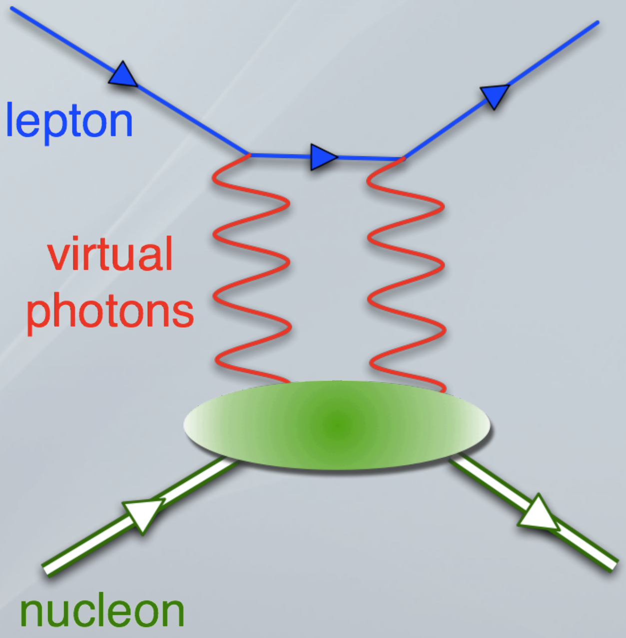
$$\epsilon = \left[1 + 2(1+\tau)\tan^2\frac{\theta}{2}\right]^{-1}$$



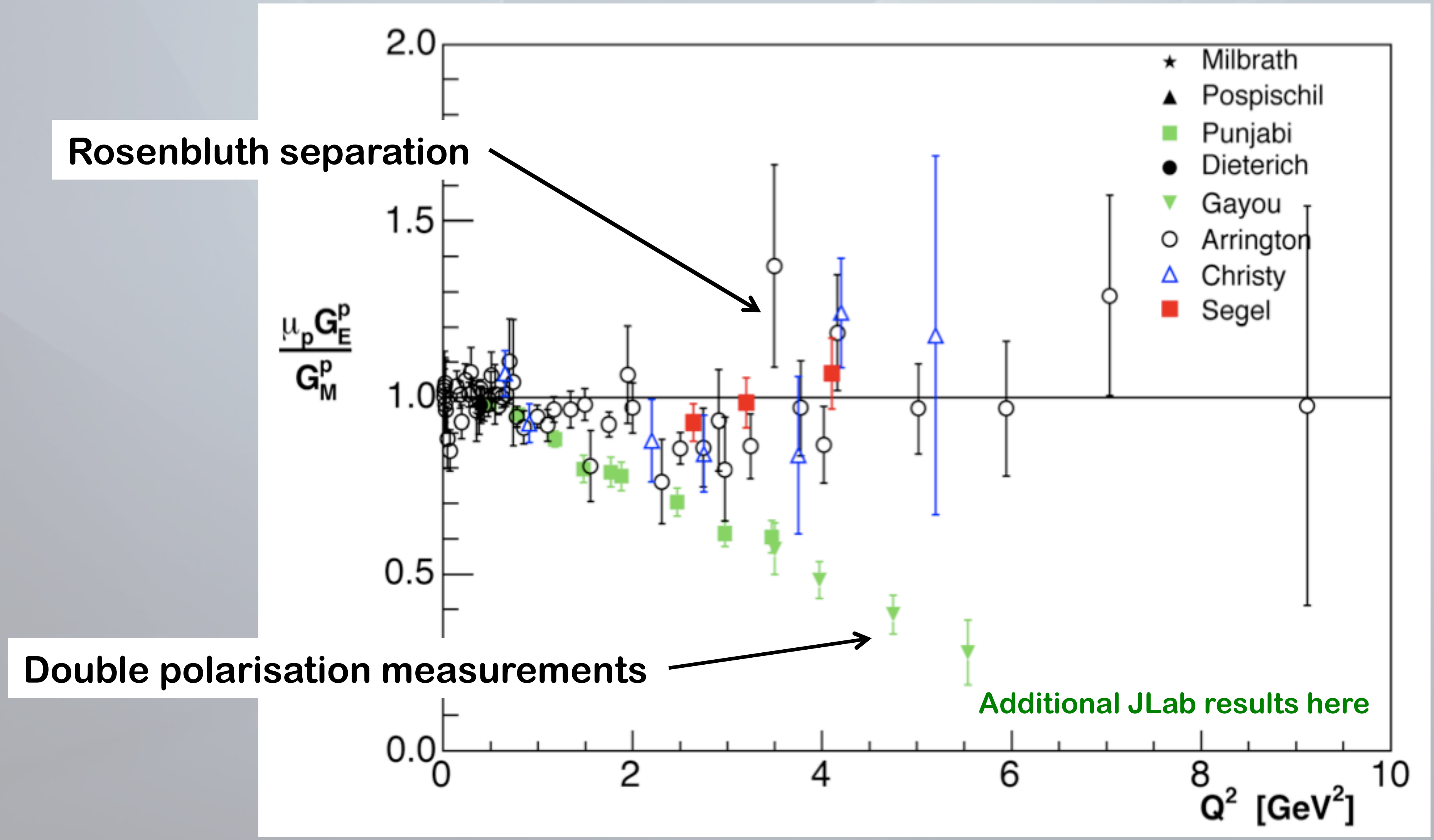
Multi-Photon Contributions?

- Long standing beliefs:
  - $G_E \sim G_M$
  - Multi-photon contribution 1-2% only
- Experimental arguments
  - Linearity of Rosenbluth plot
  - e^+/e^- (and μ^+/μ^-) ratio found to be 1
    - as required in Born approximation





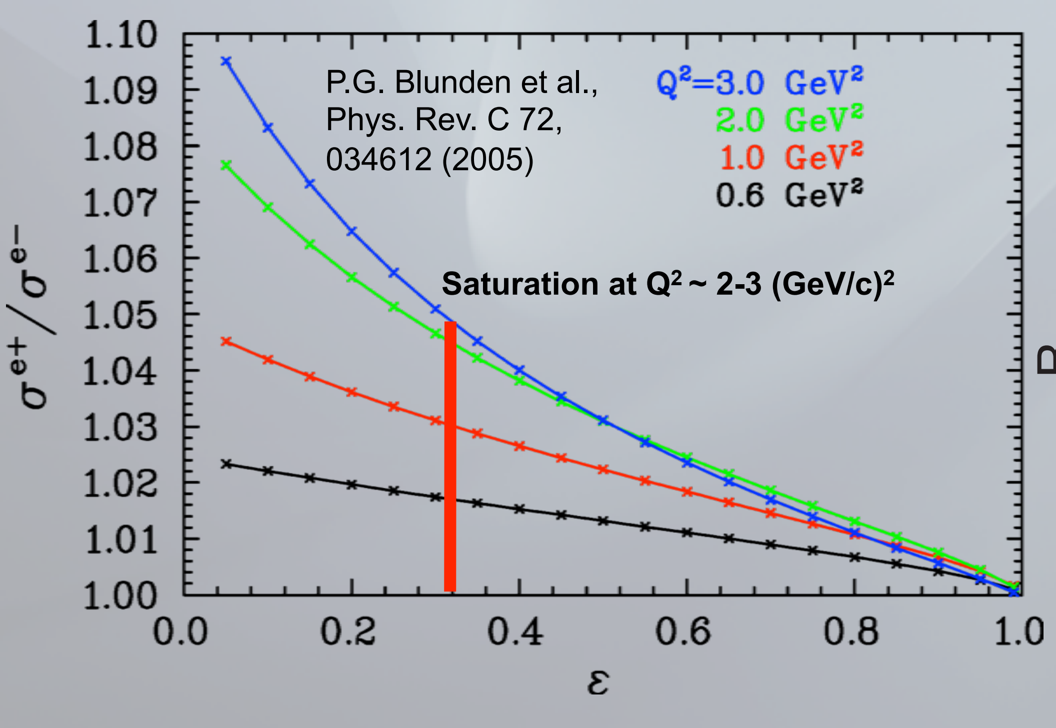
Recent Puzzle in G_E/G_M

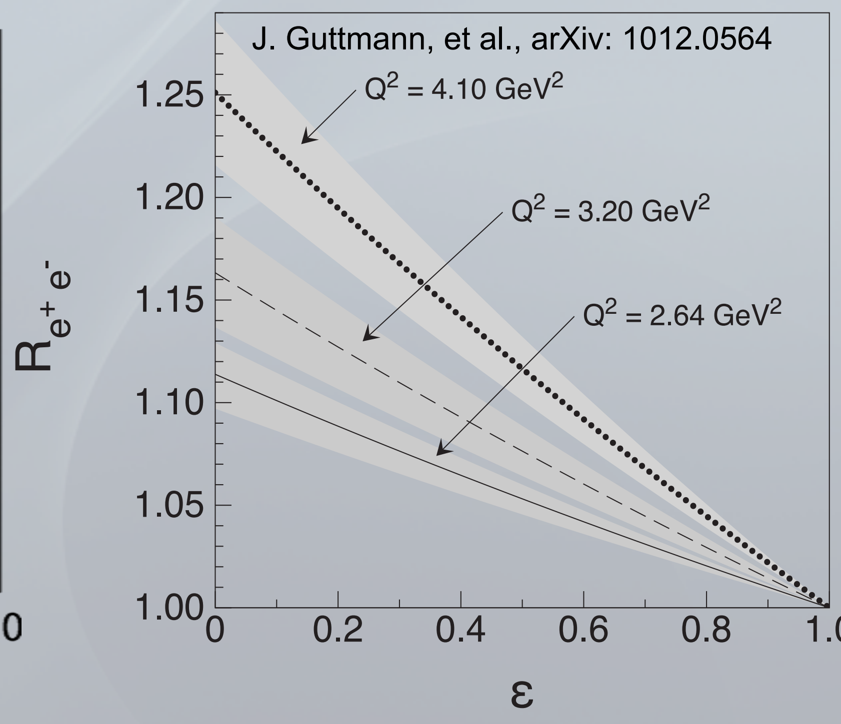


How to address the issue

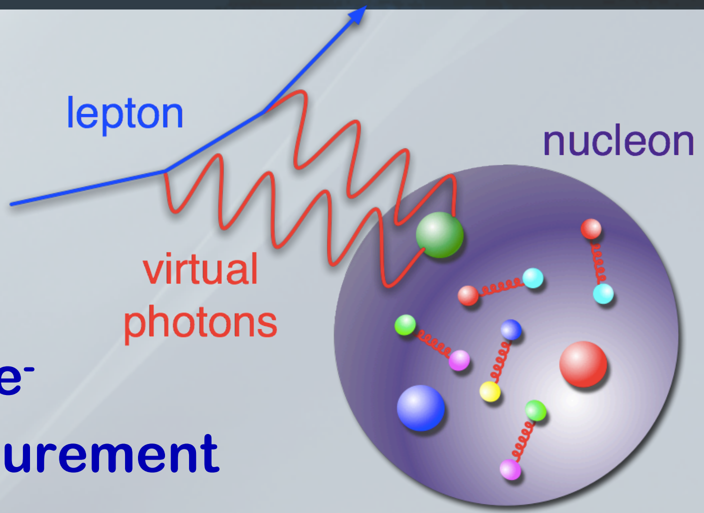
- Measure cross section ratio e^+/e^- versus epsilon
  - exactly unity in Born approximation
  - two-photon effects at low epsilon
  - several percent effect at $Q^2 \sim 2\ \mathrm{GeV}^2$
  - 3 experiments: OLYMPUS, CLAS, VEPP3

$$\epsilon = \left[1 + 2(1+\tau)\tan^2\frac{\theta}{2}\right]^{-1}$$





Measurement Concept



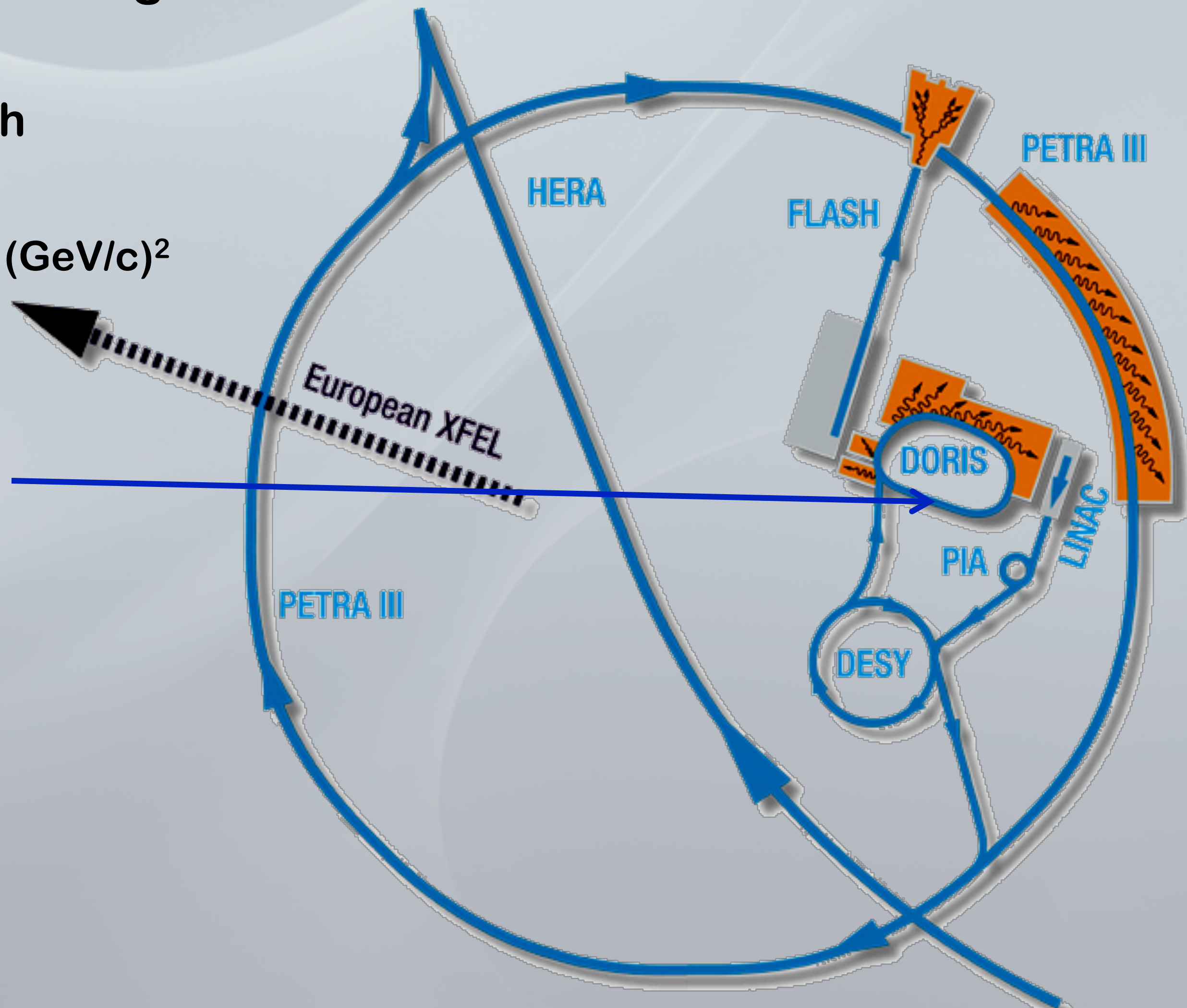
- Electron and positron beams
- Proton target
- OLYMPUS features
  - E ~ 2 GeV
  - Frequent switch between e^+ and e^-
  - Lepton-proton coincidence measurement
  - Windowless, pure proton target
  - Large theta coverage, i.e. epsilon range
  - Minimal systematic uncertainties
    - symmetric arrangement
    - reversible magn. field
  - Precise luminosity measurement
    - ratio e^+ to e^- with precision <1%
  - Redundancy

Where to go

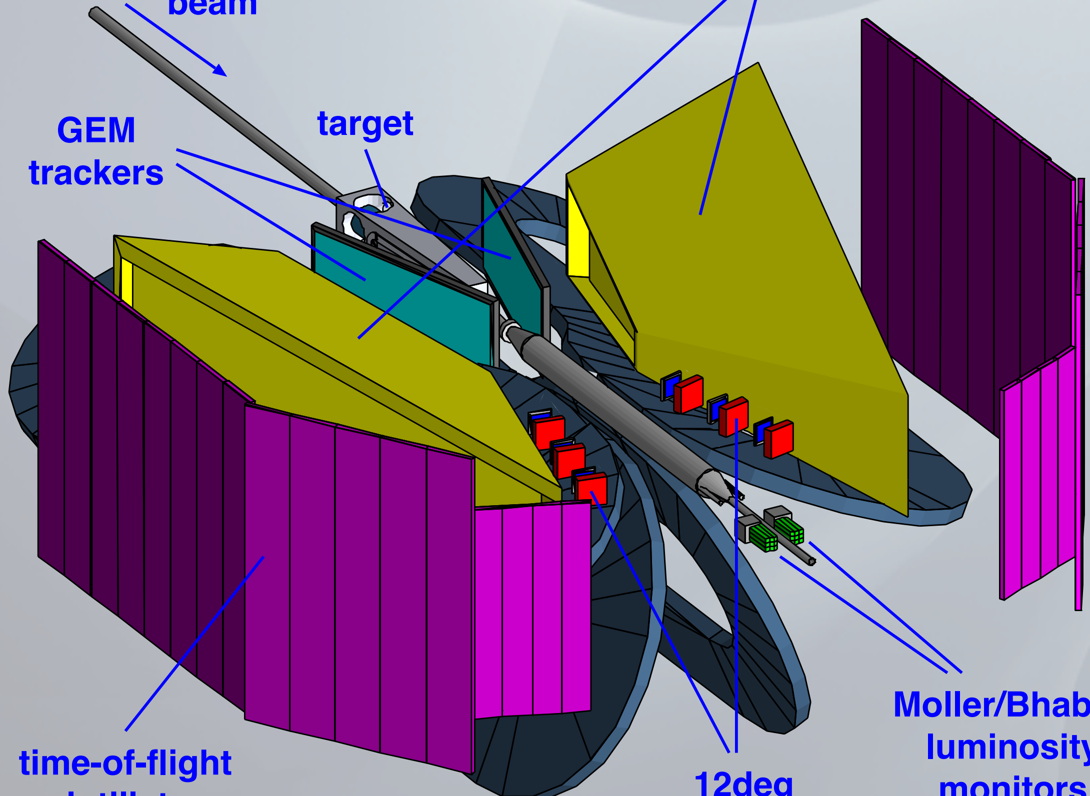
DORIS at DESY, Hamburg

- e^+ and e^- beams
  - frequent switch
- E = 2.0 (4.5)GeV
  - $Q^2 = 0.6\text{-}2.4(4.1)\ (\text{GeV}/c)^2$

- ARGUS location



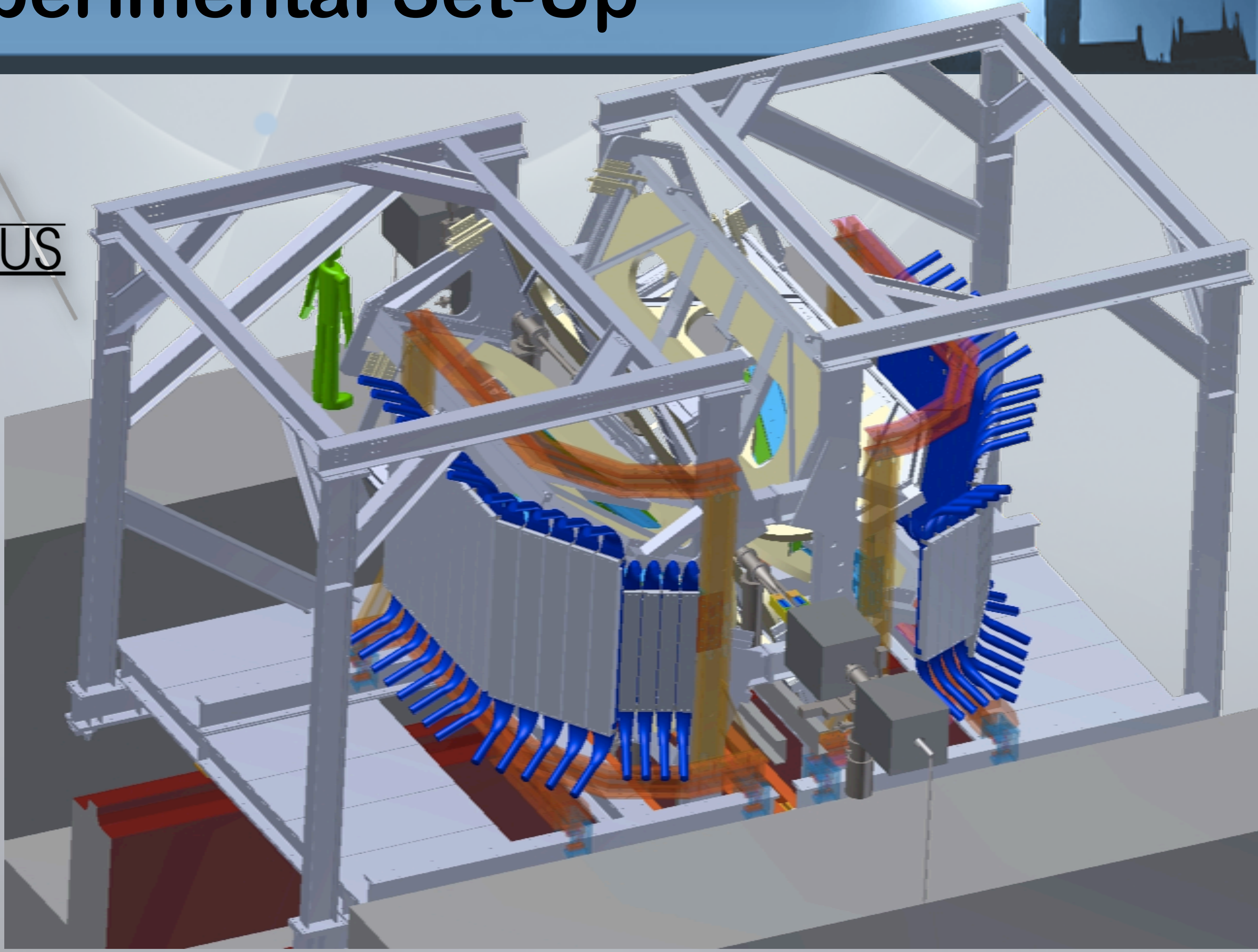
Experimental Set-Up



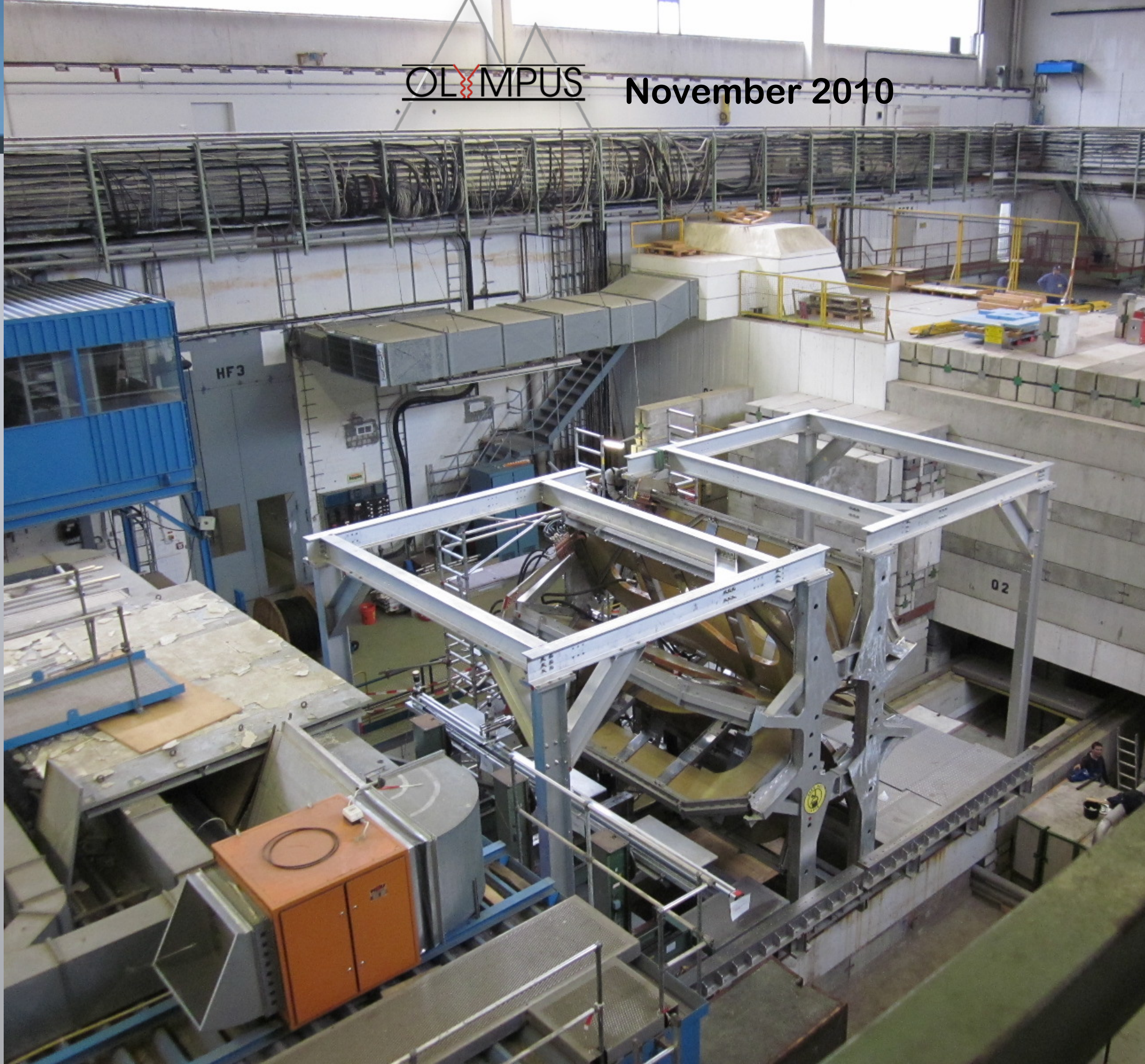
- **Use BLAST detector from MIT-Bates**
  - refurbished
  - add-ons
- **Symmetric spectrometer**
- **Luminosity monitors**
  - precise + redundant
- **Toroidal field**
  - frequent reversal

OLYMPUS

Experimental Set-Up

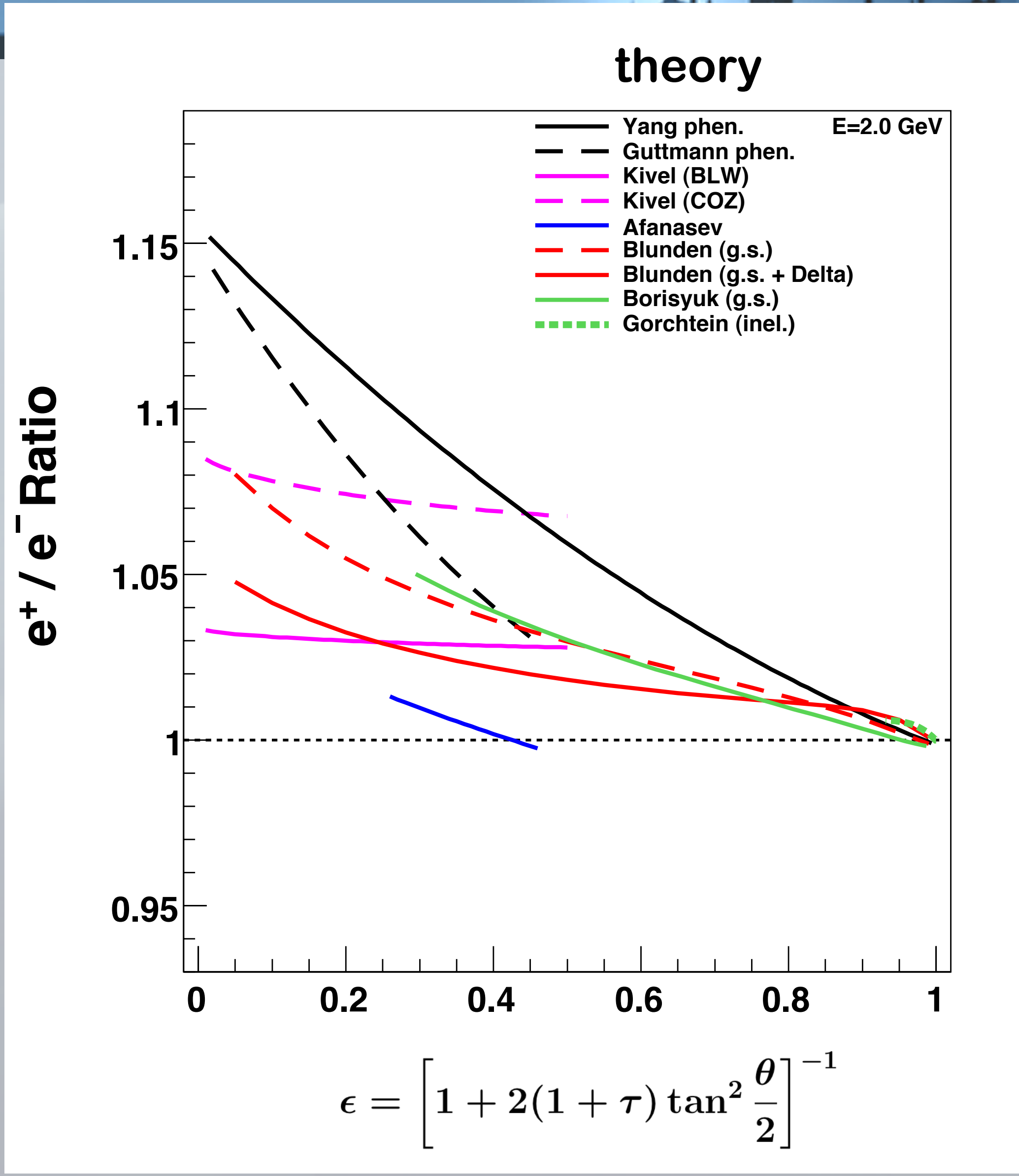


November 2010



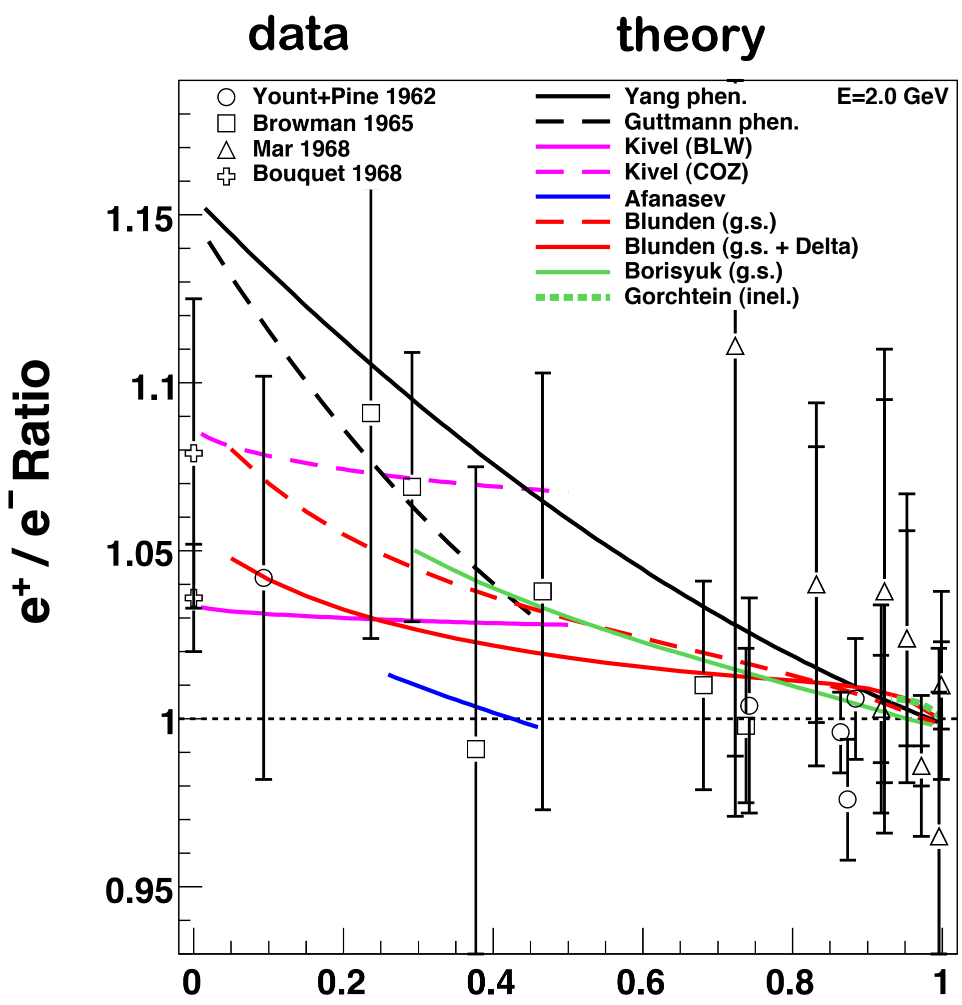
Expected Performance

- Theoretical predictions
  - large variations



Expected Performance

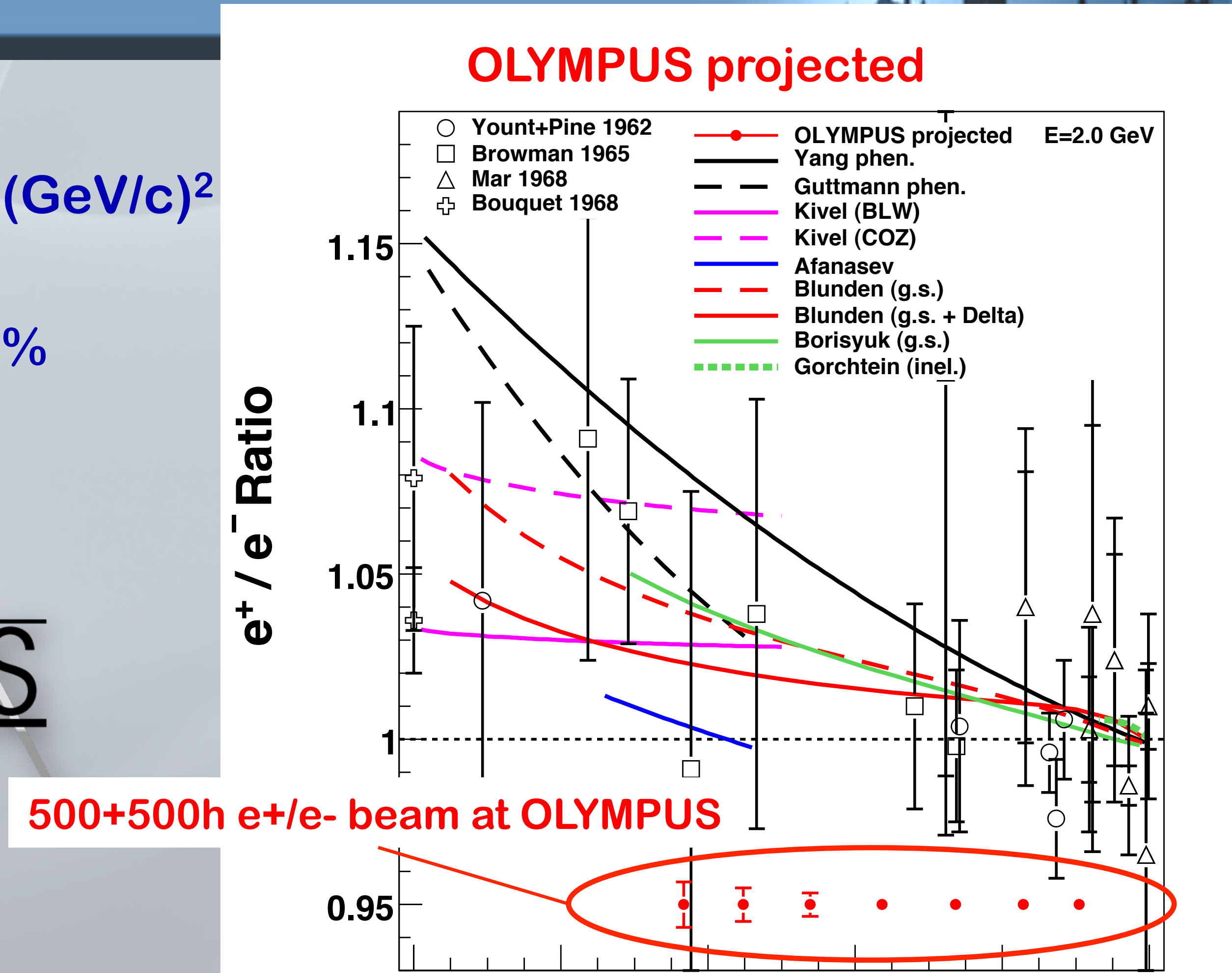
- Theoretical predictions
  - large variations
- Existing data
  - not conclusive



$$\epsilon = \left[1 + 2(1+\tau)\tan^2\frac{\theta}{2}\right]^{-1}$$

Expected Performance

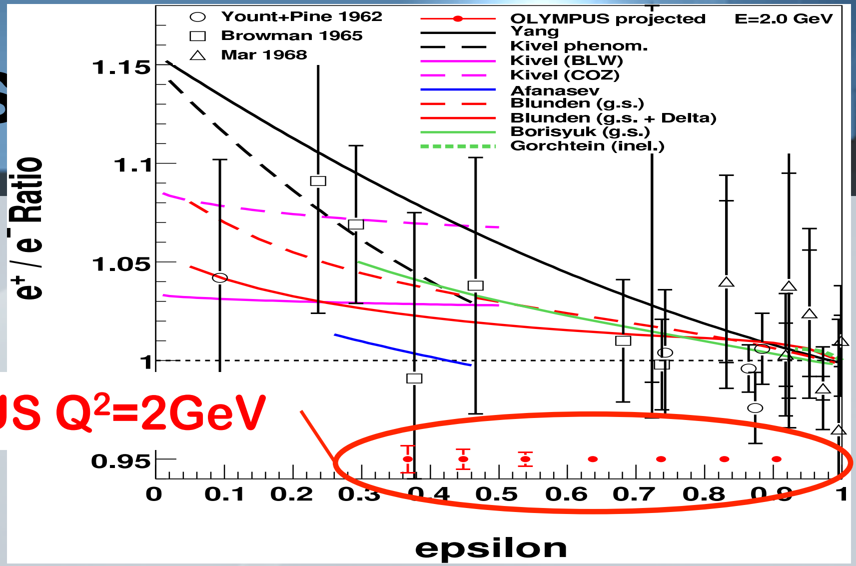
- Beam E = 2 GeV
  - $Q^2 = 0.6 - 2.2\ (\mathrm{GeV}/c)^2$
  - $\varepsilon = 0.37 - 0.9$
  - sys. uncert. 1%

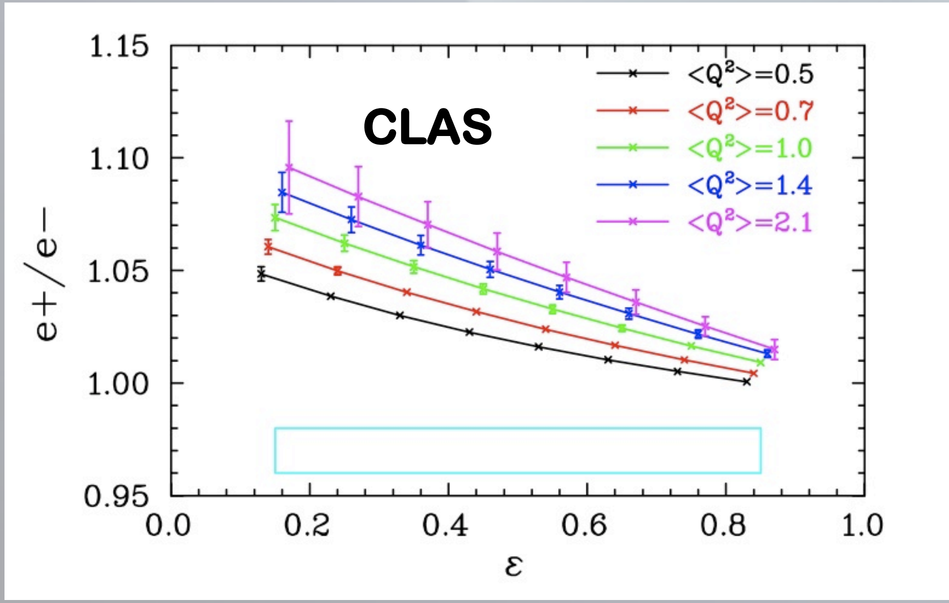


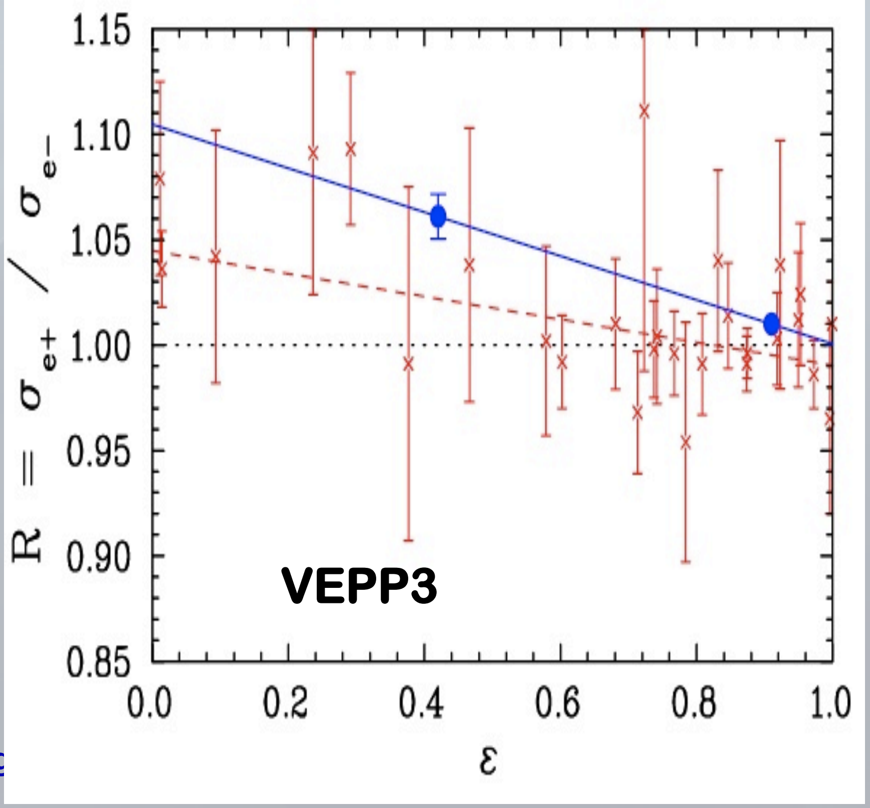
$$\epsilon = \left[1 + 2(1+\tau)\tan^2\frac{\theta}{2}\right]^{-1}$$

Other Experiments

- Projected resolutions
  - scaled to fit scales
- CLAS/PR04-116
  - secondary e⁺/e⁻ beam
  - syst. challenging
- Novosibirsk/VEPP-3
  - storage ring/intern. target
  - low statistics

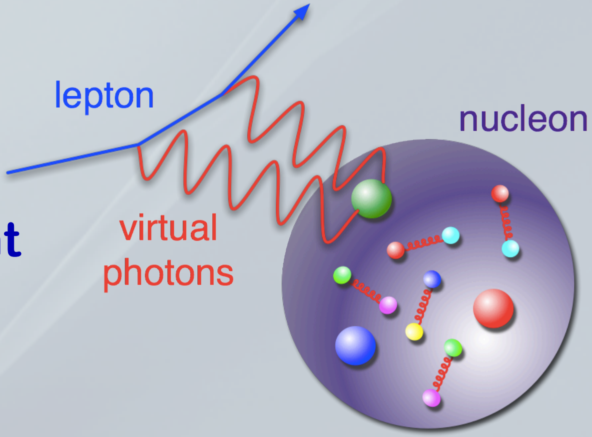






Conclusions

- Form factors
  - old but still hold surprises
- Discrepancy in G_E/G_M
  - unpredicted, 2-photon exch. not sufficient
  - no experimentally verified explanation
- Experimental approach
  - measure e^+/e^- ratio over large ε range
  - systematic uncertainties ~1%
- The OLYMPUS experiment
  - symmetric toroidal spectrometer at DESY
  - preparation progressing well and in time
  - measurements in 2012
- Decisive information
  - nature of discrepancy
  - sensitivity to nucleon EM structure
- Further future: time-like form factors (PANDA)



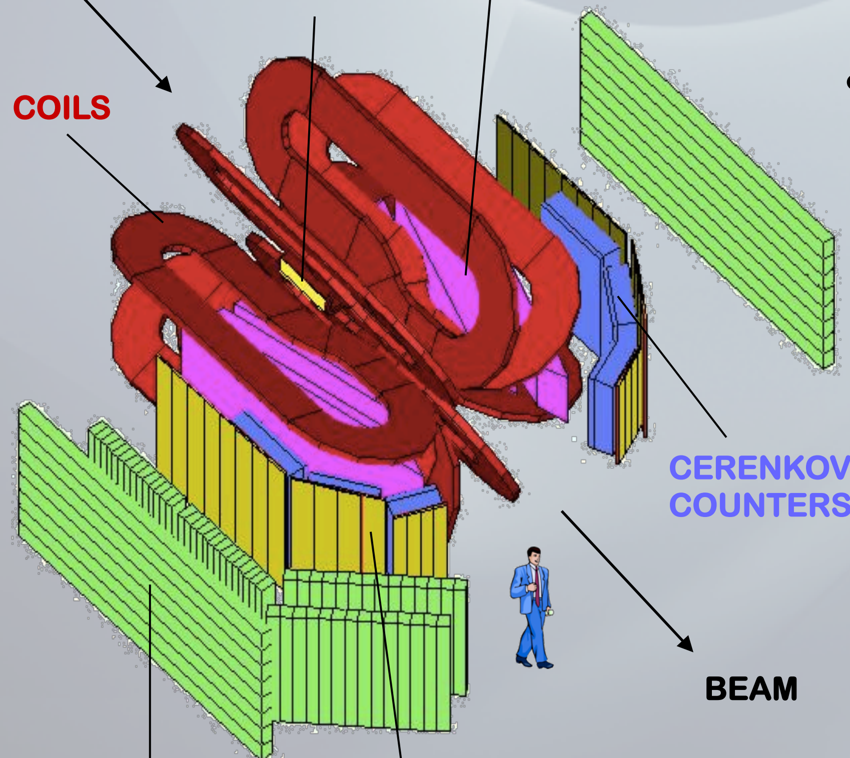
OLYMPUS

Olympus Collaboration

- Arizona State University
- DESY Hamburg
- Hampton University
- INFN Bari
- INFN Ferrara
- INFN Rome
- Massachusetts Institute of Technology
- Petersburg Nuclear Physics Institute
- Universität Bonn
- University of Colorado
- University of Glasgow
- University of Kentucky
- Universität Mainz
- University of New Hampshire
- Yerevan Physics Institute

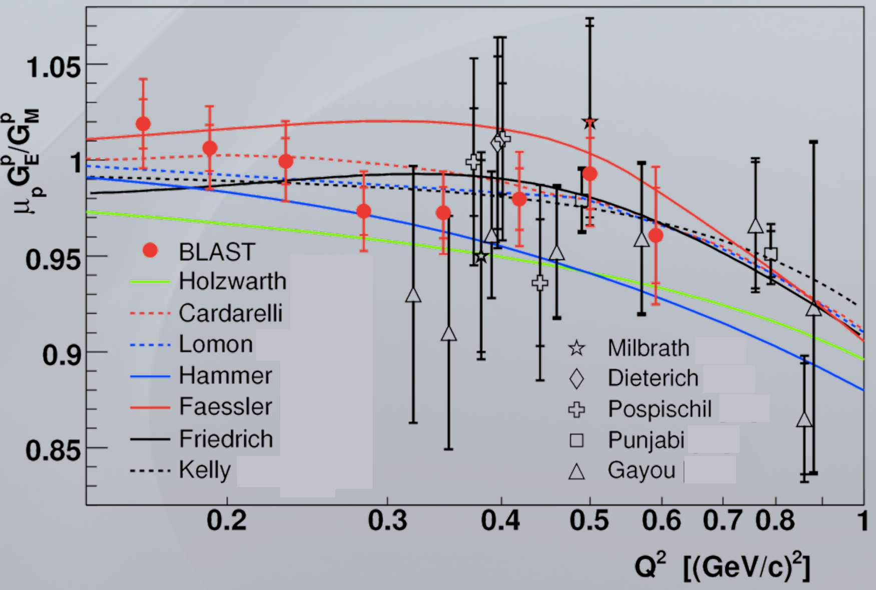
Backup

BLAST at MIT-Bates



- BLAST Detector Set-Up
  - Fulfils most criteria
- MIT-Bates South Hall Ring
  - Too low Q^2 to study the observed effect

C.B. Crawford et al., PRL 98 (2007) 052301



Normalisation

- 2 symmetric luminosity monitors
  - 12deg telescopes: GEMs + MWPCs (coincident)
  - Moller/Bhabha calorimeters
- Regular change of both
  - particle type: i = e^+ or e^-
  - magnet polarity: j= pos or neg
- Combination
  - efficiency and acceptance effects cancel to first order

$$N_{ij} = L_{ij}\sigma_i\kappa_{ij}^{p}\kappa_{ij}^{l}$$

lumi proton, lepton efficiency

acceptance

$$\frac{\sigma_{e+}}{\sigma_{e-}} = \left[\left(\frac{N_{e++}\,N_{e+-}}{N_{e-+}\,N_{e--}} \Big/ \frac{A_{e++}\,A_{e+-}}{A_{e-+}\,A_{e--}}\right) \Big/ \left(\frac{N^{fwd}_{e++}\,N^{fwd}_{e+-}}{N^{fwd}_{e-+}\,N^{fwd}_{e--}} \Big/ \frac{A^{fwd}_{e++}\,A^{fwd}_{e+-}}{A^{fwd}_{e-+}\,A^{fwd}_{e--}}\right)\right]^{\frac{1}{2}}$$

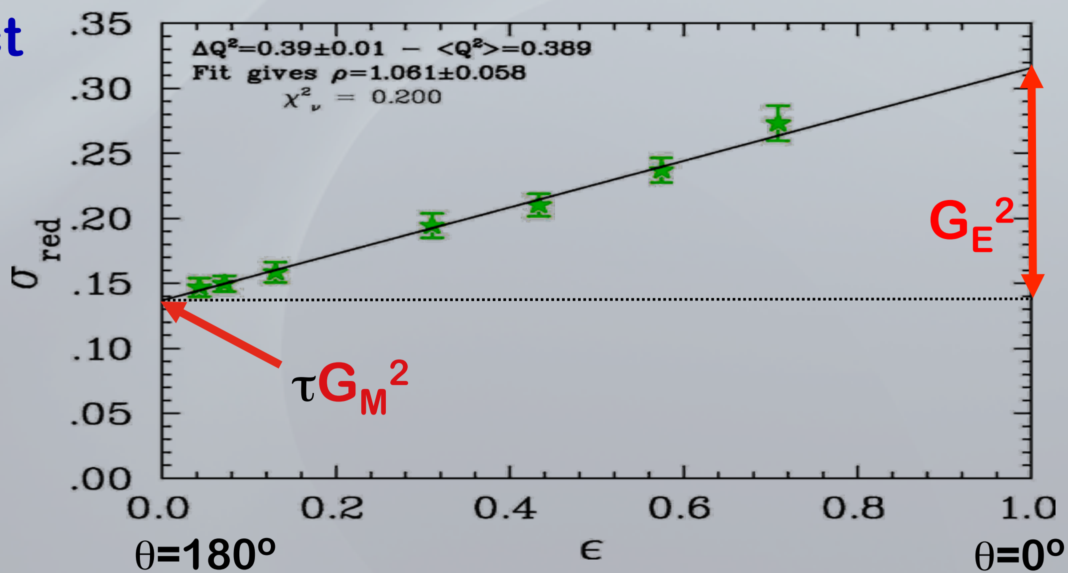
Recent Puzzle in G_E/G_M

- Nobody predicted this effect
- Polarization measurements
  - measure asymmetry ratio

$$\frac{P_\perp}{P_\parallel} = \frac{A_\perp}{A_\parallel} \propto \frac{G_E}{G_M}$$

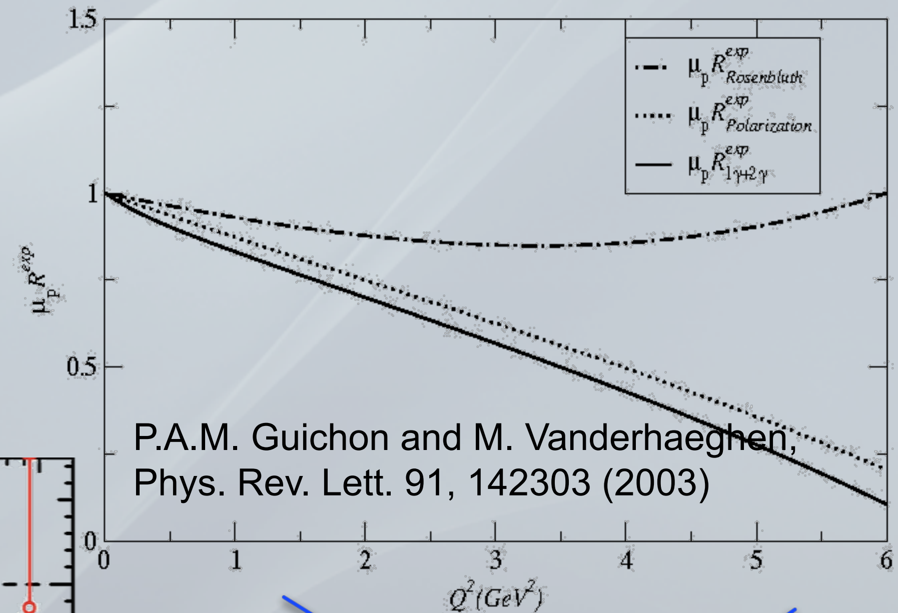
$$-\sigma_0 \vec{P}_p \cdot \vec{A} = \sqrt{2\tau\epsilon(1-\epsilon)} G_E G_M \sin\theta^* \cos\phi^* + \tau\sqrt{1-\epsilon^2} {G_M}^2 \cos\theta^*$$

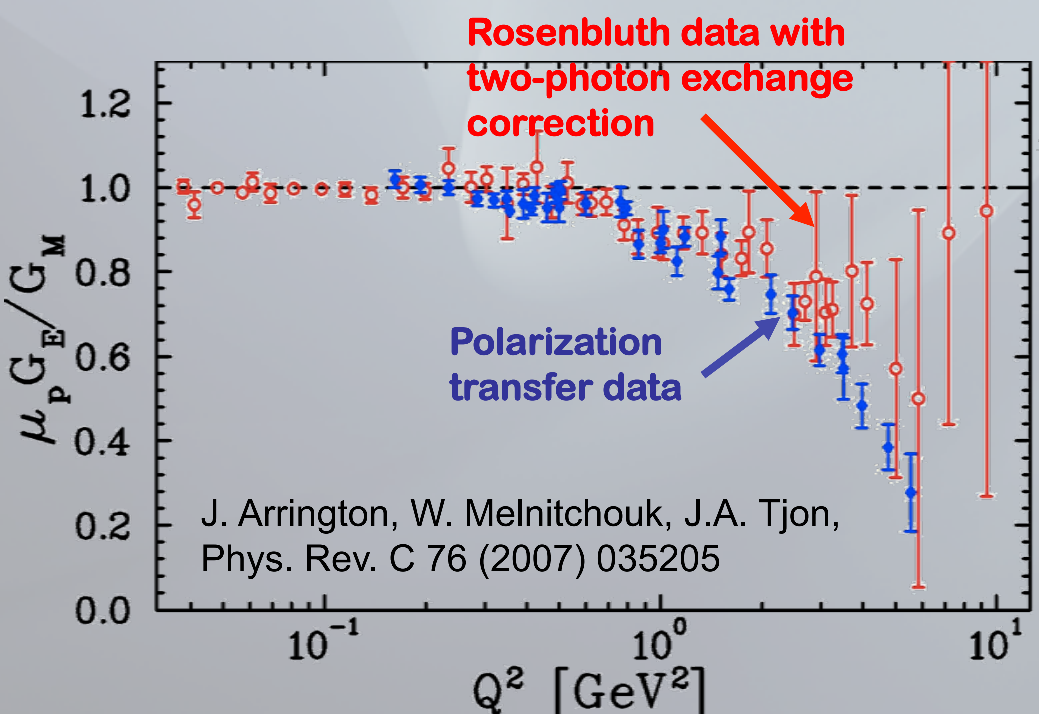
- Rosenluth separation at high Q^2
  - G_E difficult to extract
  - 2γ corrections large

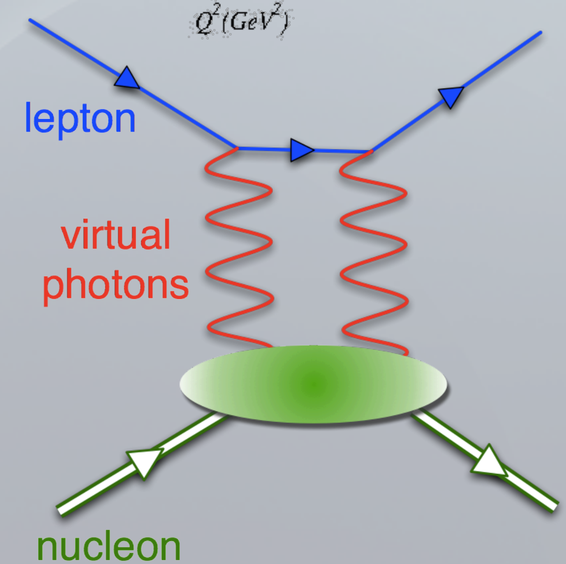


Recent Puzzle in G_E/G_M

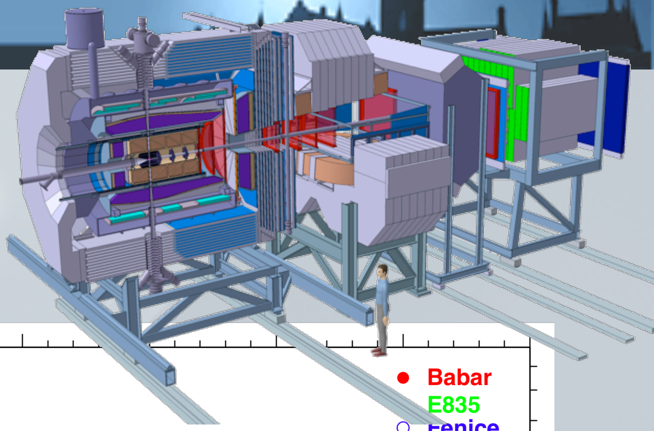
- Observed effect
  - mostly explicable by 2-photon exchange
  - experimental proof missing



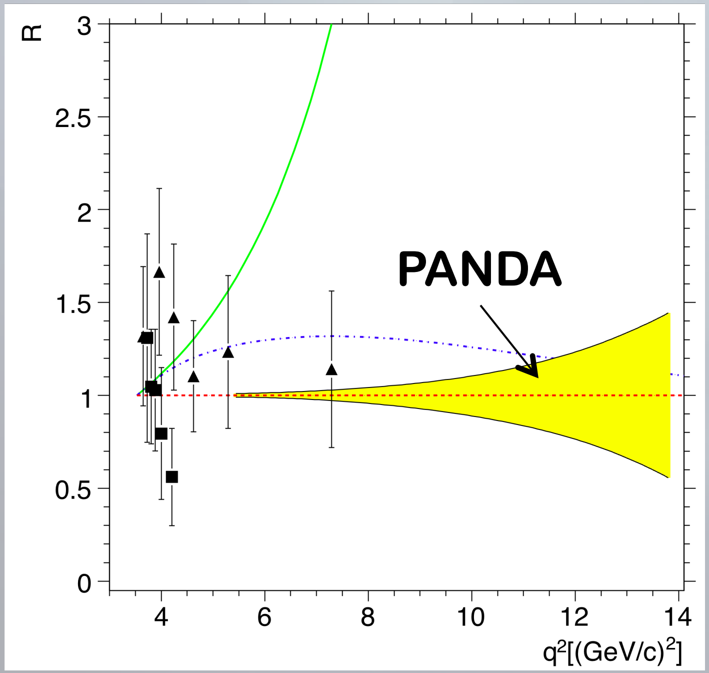




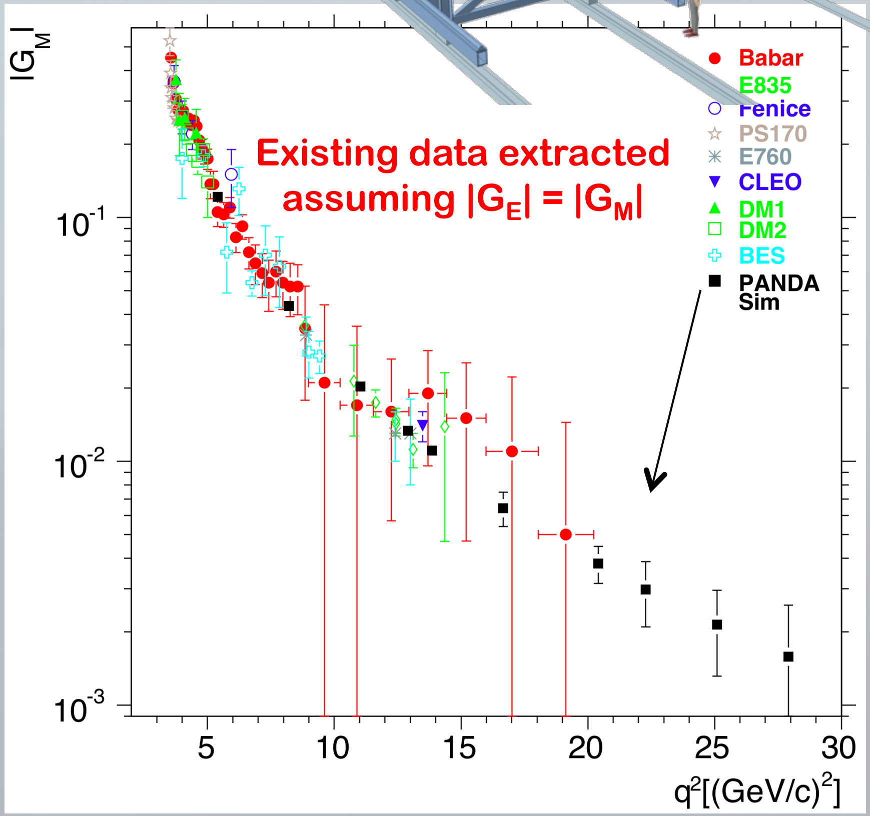
Aside: Time Like Form Factors



- **PANDA (FAIR)**
  - $R = \mu_p G_E / G_M$ with unprecedented precision

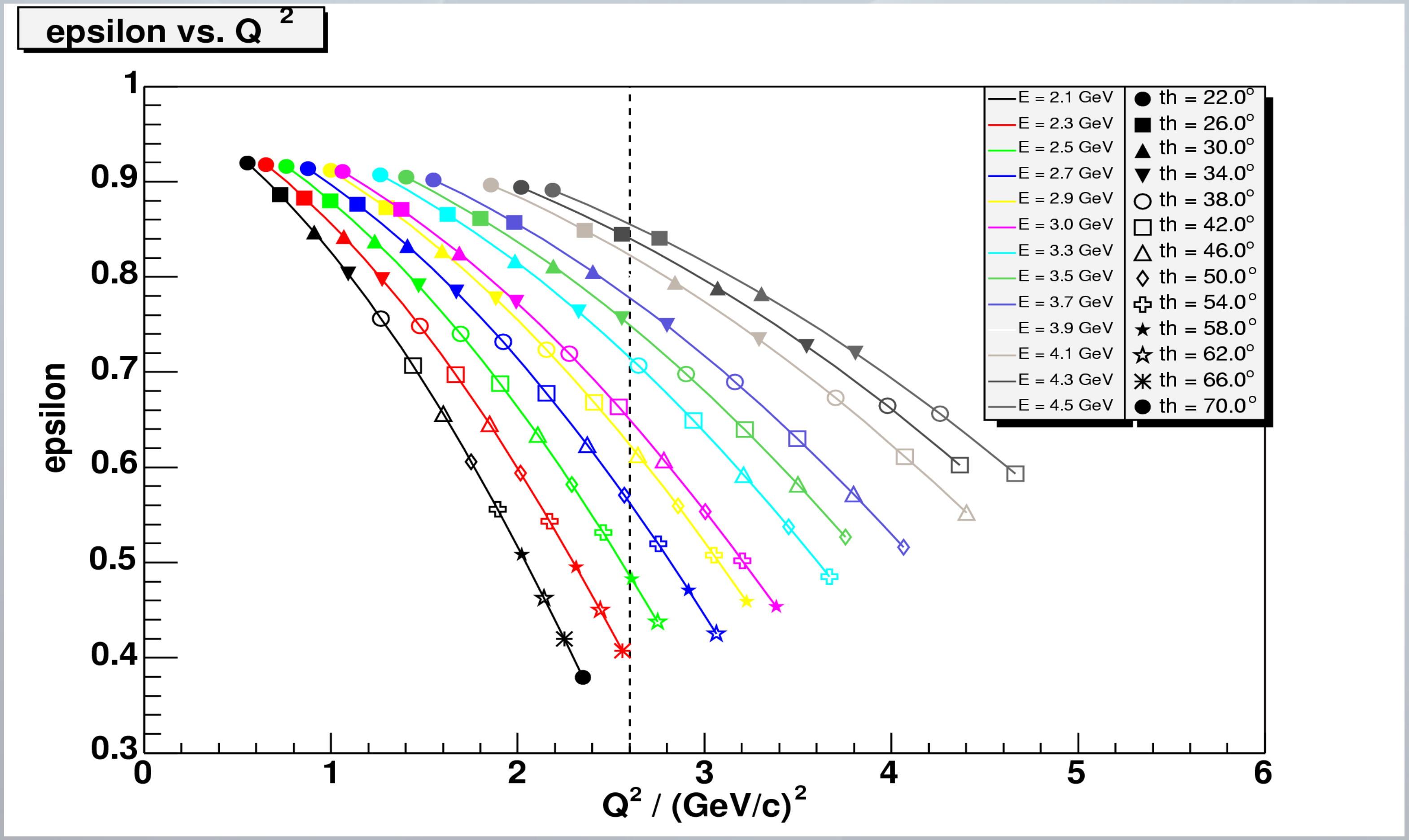


  - absolute value of $|G_M|$ up to $30 (GeV/c)^2$



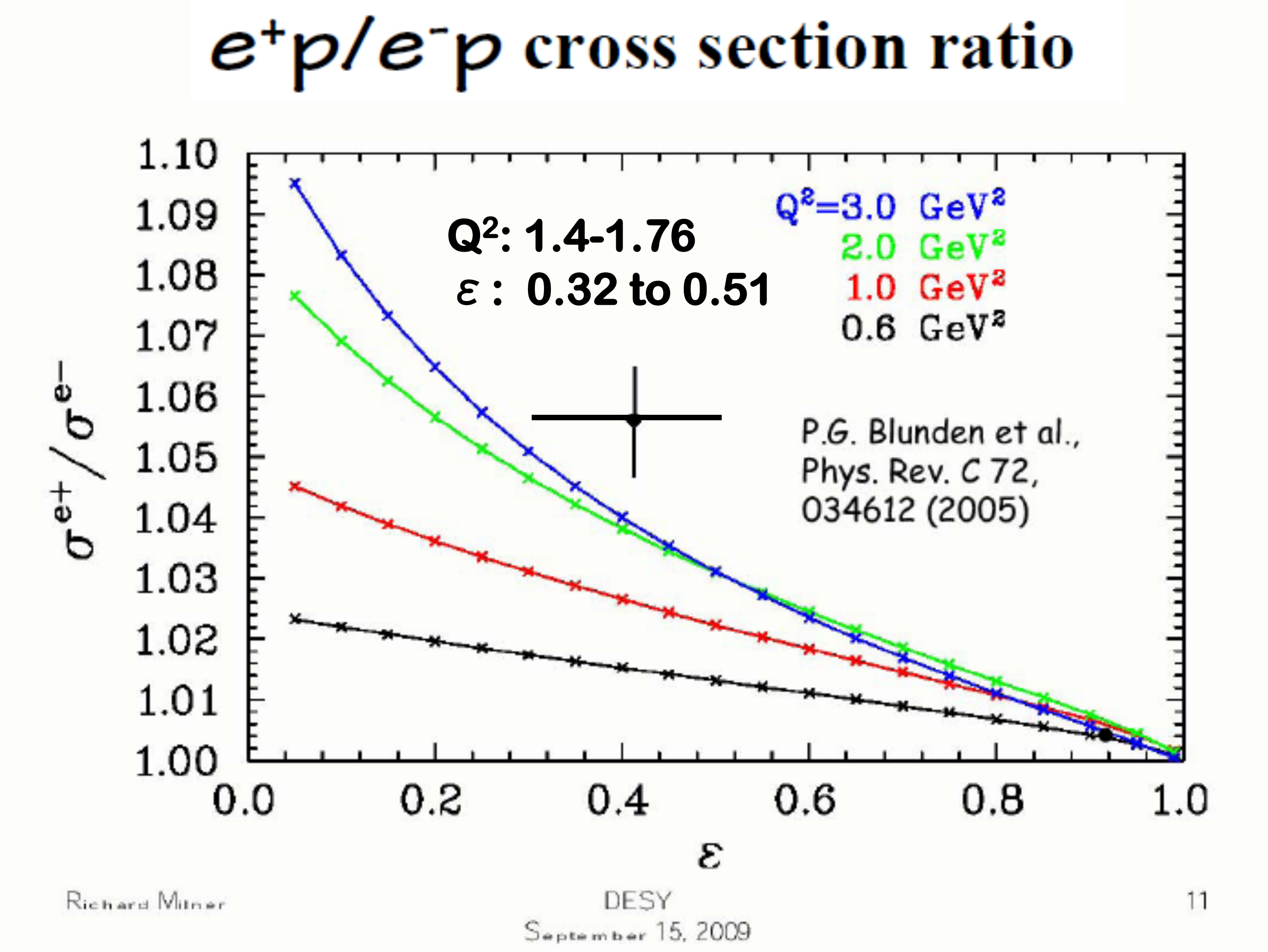
PANDA Physics Performance Report: arXiv:0903.3905

Acceptance with BLAST



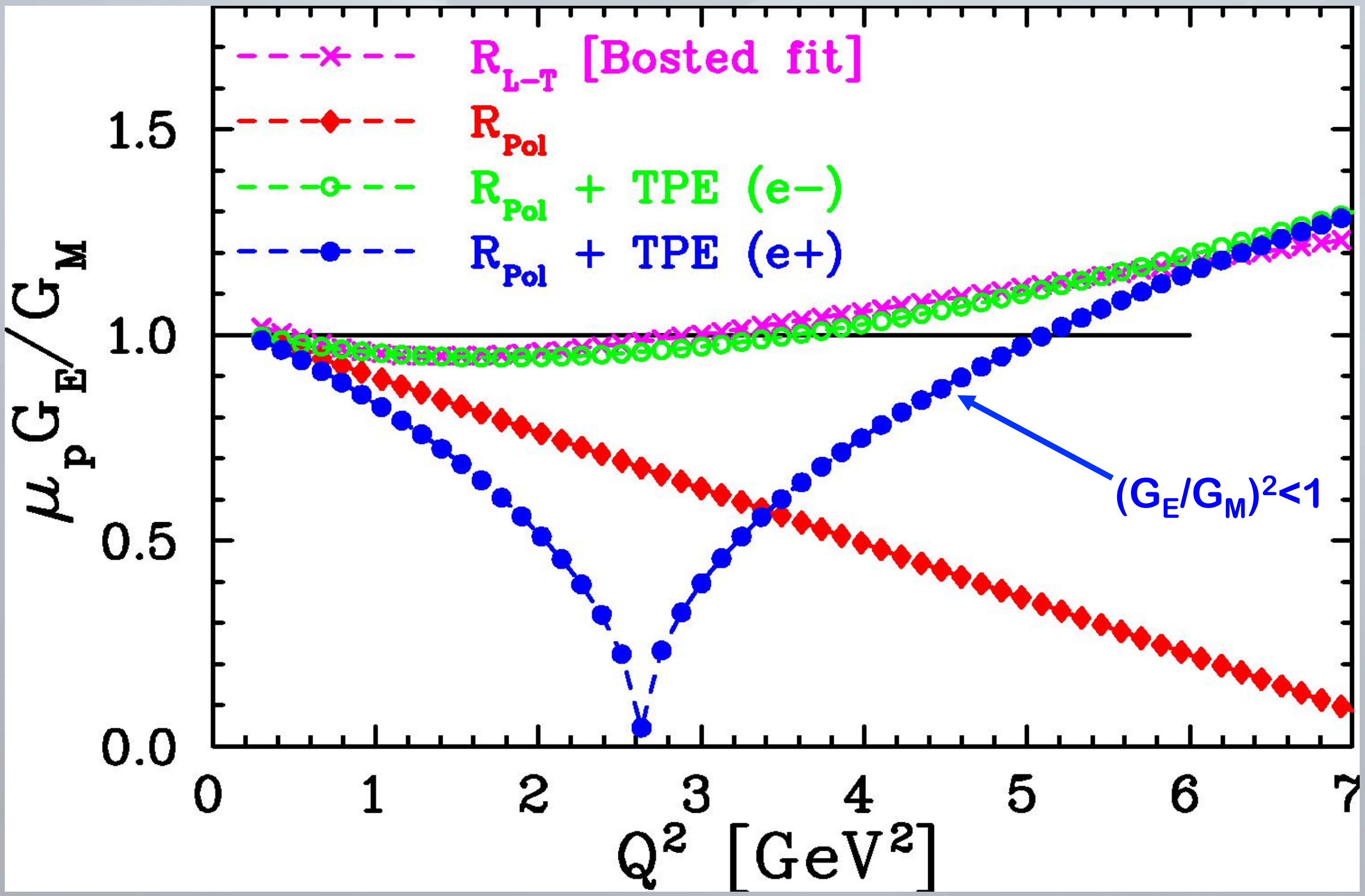
- Lowest epsilon ~0.4 only for E < 2.3 GeV
- At epsilon = 0.4, require E>2 GeV to maintain Q^2 > 2 $(GeV/c)^2$

Unofficial Novosibirsk information



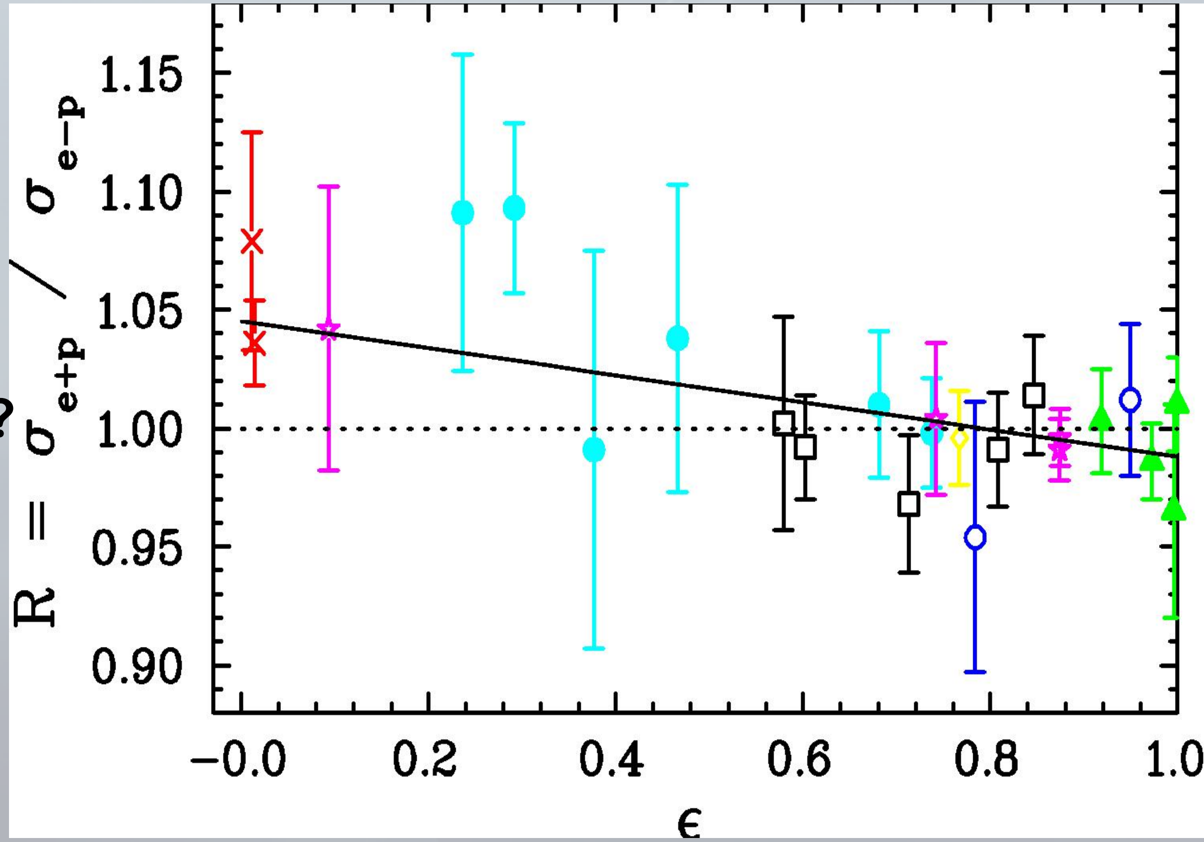
Rosenbluth separation for e^+p

PT results **LT (electron)** **LT (positron)**



Two-Photon Exchange

- Secondary beams
  - low luminosity
- data taken
  - at high Q^2
  - OR large θ
- Unobserved correction?
  - at large θ (small ε)



Further Model Predictions

N.~Kivel and M.~Vanderhaeghen, Phys. Rev. Lett. 103 (2009) 092004