Two-photon exchange: experimental tests

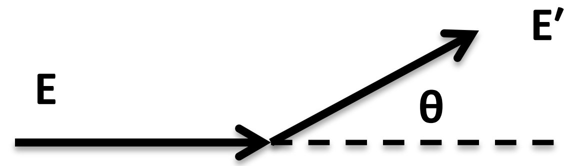
Studying the QED expansion for elastic electron-proton scattering

- Motivation
- The Three Experiments
- Summary

With thanks to R. Bennett and A. Gramolin

Elastic electron-proton scattering

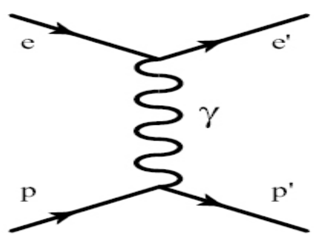
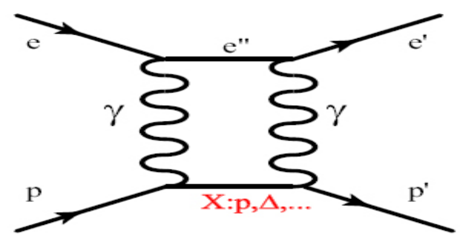
$e + p \longrightarrow e' + p'$



$Q^2 = 4EE' \sin^2 \theta/2$

$Q^2 = 2M_p(E-E')$

- Fundamental process in hadronic physics
- Described in QED ($\alpha = 1/137$) by a perturbative expansion

$\Big|$  +  +.... $\Big|^2$

$\approx\alpha$

$\approx\alpha^2$

Elastic scattering cross section

In the one-photon exchange approximation, the cross section is a product of the Mott cross section and the form factor functions

$$\left(\frac{d\sigma}{d\Omega}\right)_{Mott} = \frac{\alpha^2}{4E^2}\frac{1}{\sin^4\frac{\theta}{2}}\cdot\cos^2\frac{\theta}{2}\cdot\frac{E'}{E}$$

$$\frac{d\sigma/d\Omega}{(d\sigma/d\Omega)_{Mott}} = S_0 = A(Q^2) + B(Q^2)\tan^2\frac{\theta}{2}$$

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

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

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

ε =relative flux of longitudinally polarized virtual photons

Nucleon elastic form factors

- Defined in the context of single photon exchange
- Fundamental observables describing the distribution of charge and magnetism in the proton and neutron
- Experimentally, data approximately described by an exponential fall off of the nucleon's spatial charge and magnetism => dipole form factor

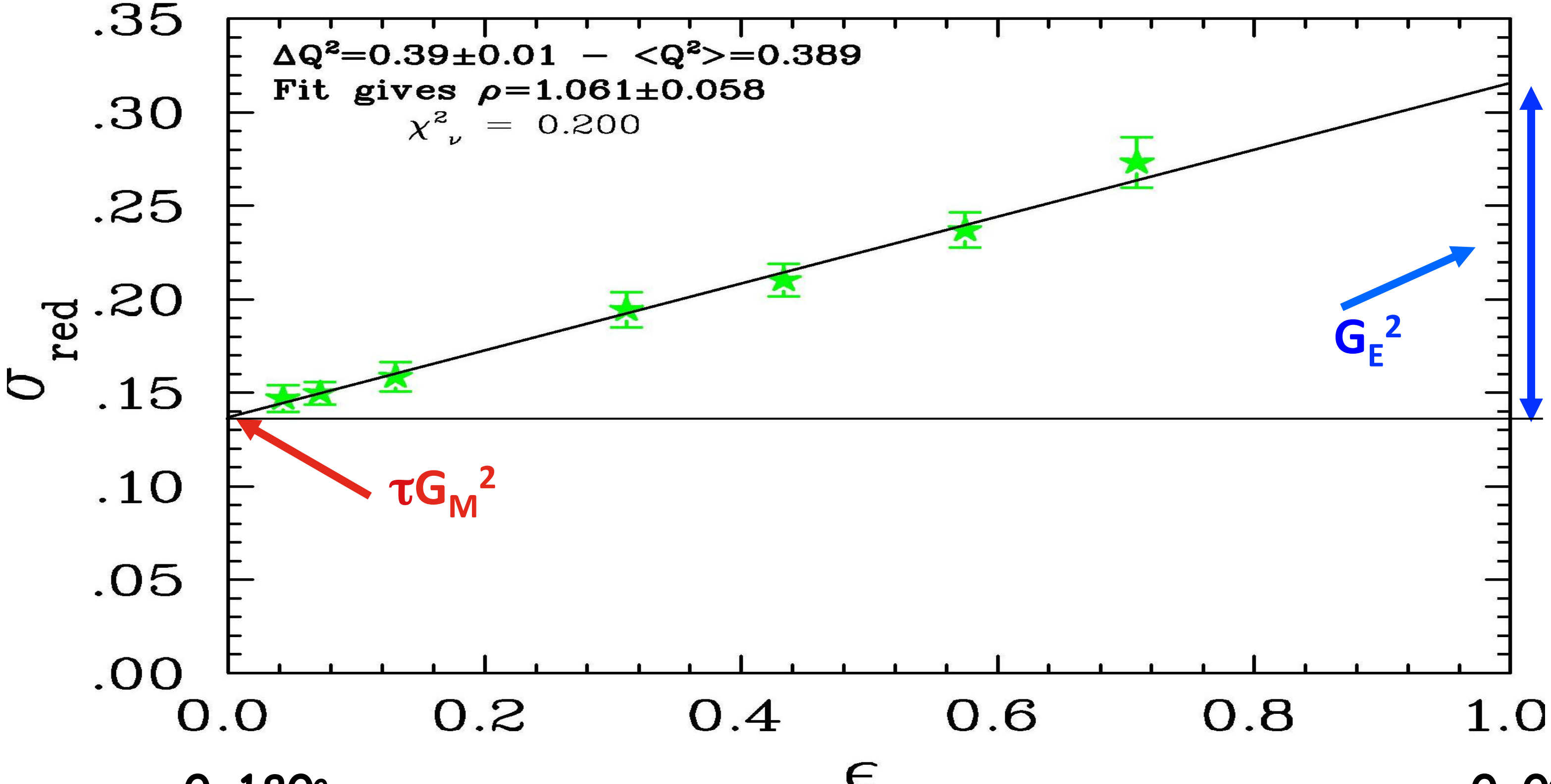
$$G_E^p(Q^2) \approx (1 + Q^2/0.71)^{-2} \qquad G_M^p(Q^2) \approx \mu_p\,(1 + Q^2/0.71)^{-2}$$

- At $Q^2 \Rightarrow 0$, slope of electric form factor determines the proton charge radius
- At $Q^2 >> 1$, $\sigma \approx \sigma_{Mott}\, G^2_D \sim Q^{-12}$
- FF determined by quark structure of proton
- Will be calculable in lattice QCD
- Elastic electron proton scattering can be used to search for new physics beyond the Standard Model, e.g. search for A′ with DarkLight

Form Factors from Rosenbluth Method

One can define the reduced cross section σ_{red}

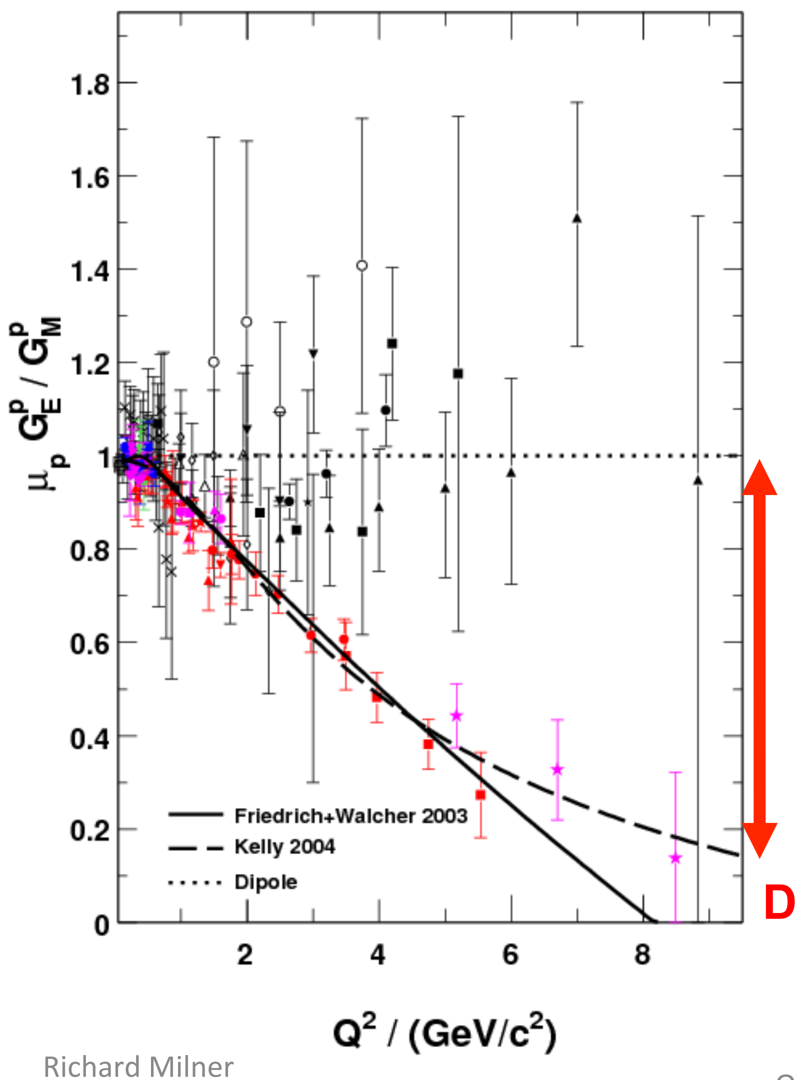
$$\sigma_{red} = \varepsilon G_E^2 + \tau G_M^2$$



θ=180° θ=0°

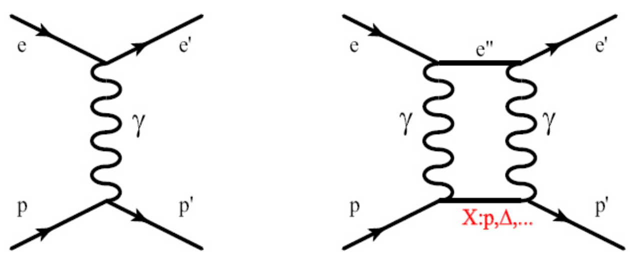
➔**Determine $|G_E|, |G_M|, |G_E/G_M|$**

Proton Form Factor Ratio



Jefferson Lab 2000–today

- **All Rosenbluth data from SLAC and Jlab in agreement**
- **Dramatic discrepancy between Rosenbluth and recoil polarization technique**
- **Contribution of multiple hard photon exchange accepted explanation**

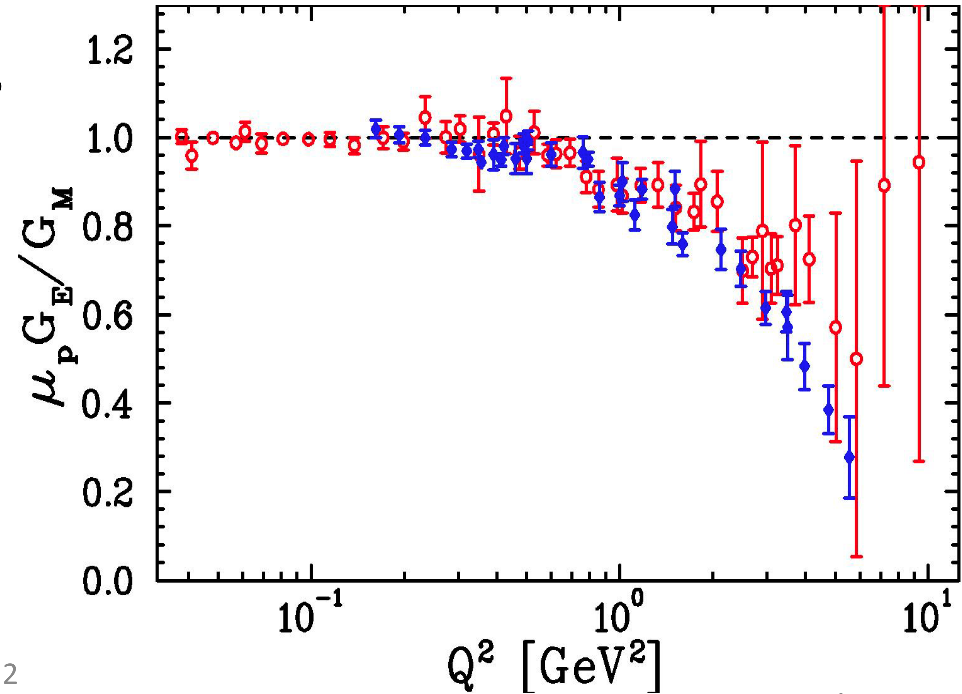


Dramatic discrepancy!

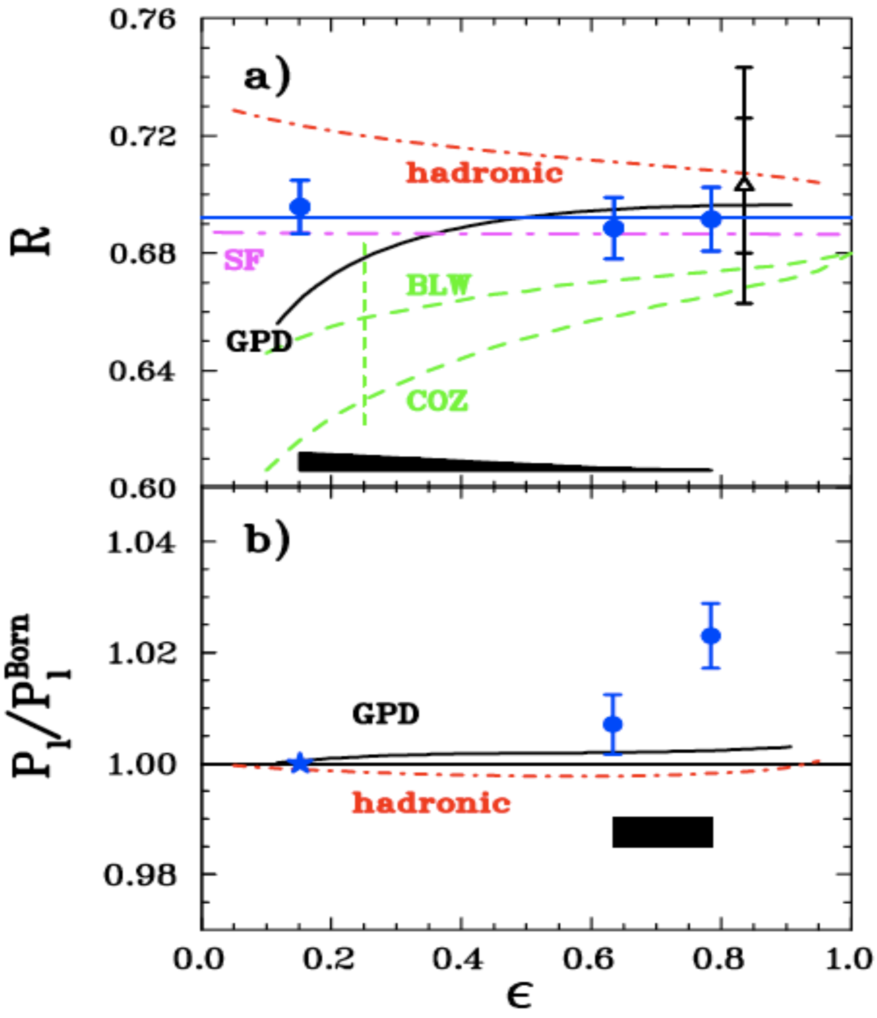
>800 citations

Validity of explanation

- To calculate the contribution of TPE requires a model for the nucleon, e.g. a hadronic description or quark based model (GPDs).
- In general, the hadronic vertex function can be expressed in terms of three independent complex amplitudes, e.g. $\breve{G}_{Ep}(\varepsilon, Q^2)\breve{G}_{Mp}(\varepsilon,Q^2)$, $F_3(\varepsilon,Q^2)$ *Guichon and Vanderhaeghen*, PRL **91**, 142303 (2003).
- There are significant assumptions and large uncertainties.
- A definitive experimental determination of the contributions beyond single photon exchange is demanded.



Jefferson Lab E04-019: TPE effects in Recoil Polarization



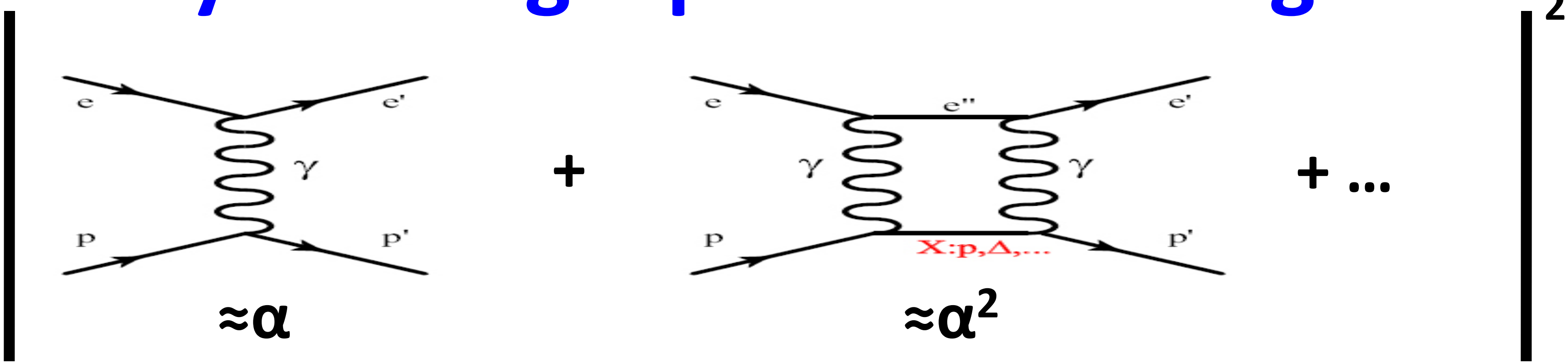
- JLab – Hall C, $Q^2 = 2.5\ (\mathrm{GeV}/c)^2$
- G_E/G_M from P_t/P_l constant vs. ε

  ➔ no effect in P_t/P_l
  ➔ some effect in P_l

- Discrepancy in FF ratio is all in TPE correction to the cross section

M. Meziane et al., hep-ph/1012.0339v2
Phys. Rev. Lett. 106, 132501 (2011)

Definitive determination of contributions beyond single photon exchange



$$\sigma = (1\gamma)^2\alpha^2 + (1\gamma)(2\gamma)\alpha^3 + ...$$

$$e^- \Longleftrightarrow e^+ \Rightarrow \alpha \Longleftrightarrow -\alpha$$

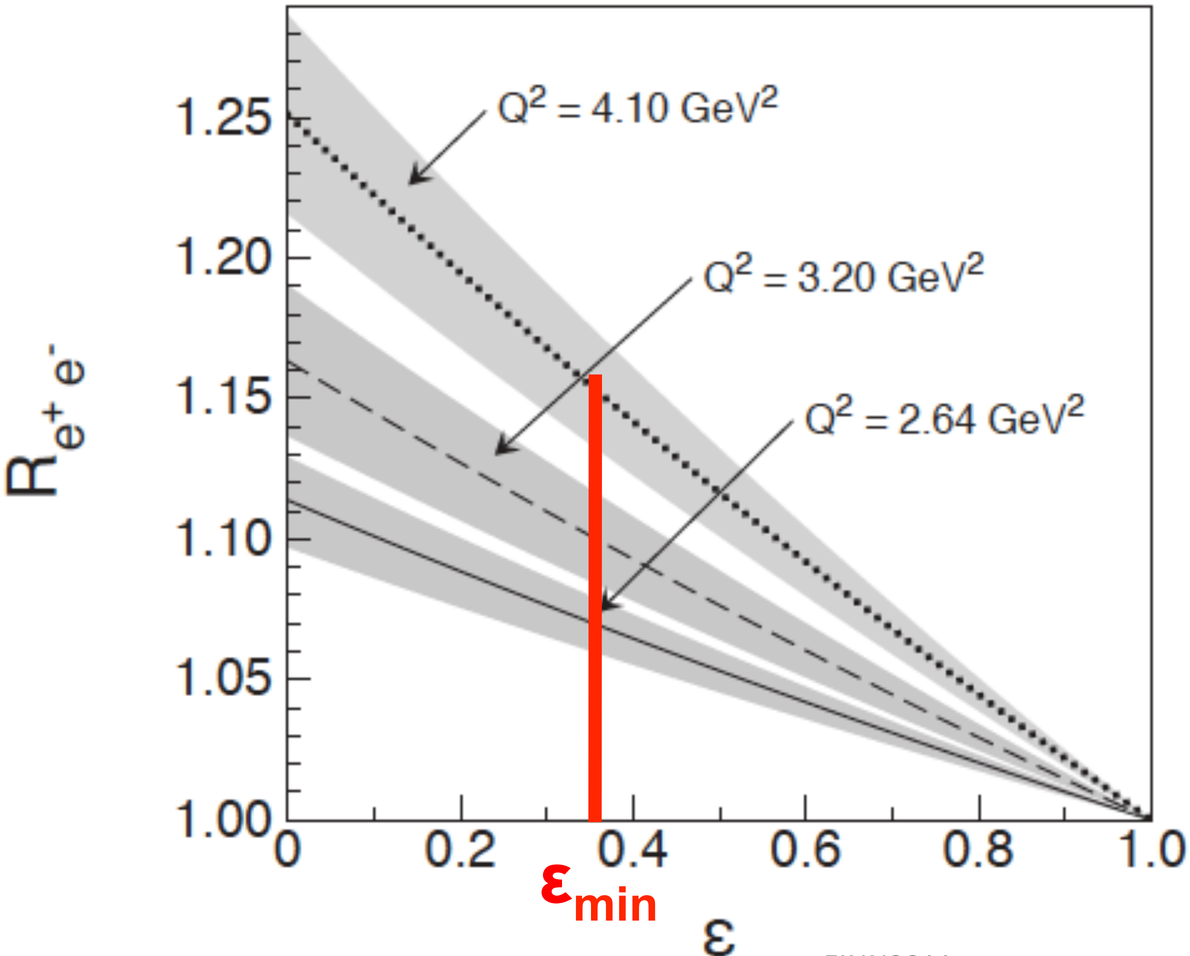
$$\sigma(\text{electron-proton}) = (1\gamma)^2\alpha^2 - (1\gamma)(2\gamma)\alpha^3 + ..$$

$$\sigma(\text{positron-proton}) = (1\gamma)^2\alpha^2 + (1\gamma)(2\gamma)\alpha^3 + ..$$

$$\frac{\sigma(e^+p)}{\sigma(e^-p)} = 1 + (2\alpha)\frac{2\gamma}{1\gamma}$$

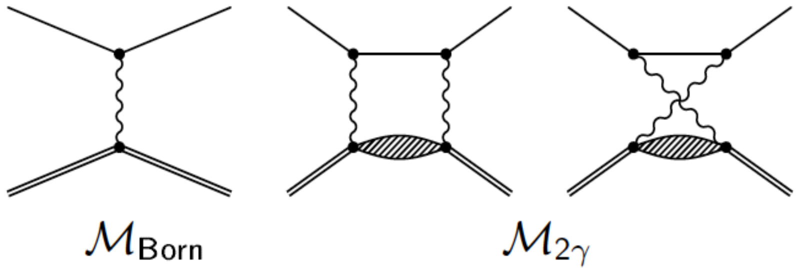
Empirical Extraction of TPE Amplitudes

J. Guttmann, N. Kivel, M. Meziane, and M. Vanderhaeghen, hep-ph/1012.0564v1

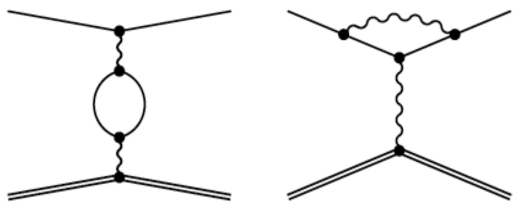


- ~6% effect for OLYMPUS@2.0GeV and Q^2 ~2.2 $(GeV/c)^2$
- grows with Q^2!

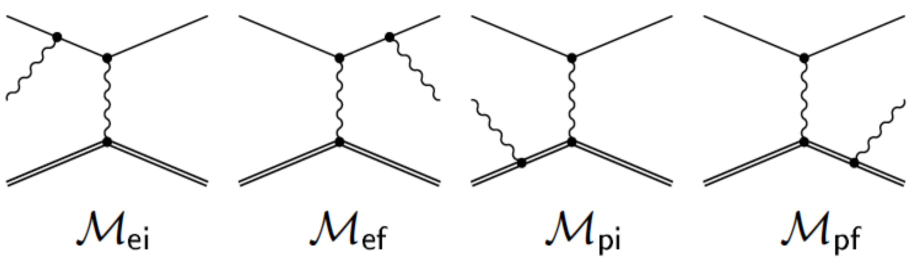
Radiative corrections



The diagrams of *ep* scattering in the 1γ and 2γ approximations.



Virtual photon corrections, which don't depend on the detector geometry.



Corrections related to the bremsstrahlung of the first order. Their contribution is determined by the detector geometry!

The experimentally measured ratio $R = \sigma(e^+p)/\sigma(e^-p)$:

$$R \approx \frac{e^4|\mathcal{M}_{\mathrm{Born}}|^2 + 2e^6\mathcal{M}_{\mathrm{Born}}\mathrm{Re}(\mathcal{M}^*_{2\gamma}) + e^6|\mathcal{M}_{\mathrm{ei}} + \mathcal{M}_{\mathrm{ef}} + \mathcal{M}_{\mathrm{pi}} + \mathcal{M}_{\mathrm{pf}}|^2 + \ldots}{e^4|\mathcal{M}_{\mathrm{Born}}|^2 - 2e^6\mathcal{M}_{\mathrm{Born}}\mathrm{Re}(\mathcal{M}^*_{2\gamma}) + e^6|-\mathcal{M}_{\mathrm{ei}} - \mathcal{M}_{\mathrm{ef}} + \mathcal{M}_{\mathrm{pi}} + \mathcal{M}_{\mathrm{pf}}|^2 + \ldots}$$

Radiative Corrections for e+/e-

- Radiative correction of cross section is sizable – it depends on the details of the experiment, *e.g.* momentum cutoff => resolution, whether photons are detected, etc.
- Existing prescriptions (e.g. Maximon and Tjon) ignore the off-shell nature of the γ^*p interaction.
- The deviation from unity of the measured ratio of positron to proton yields vs. angle requires a substantial correction

(~ 50%) for *soft* multiple photon effects before the contribution due to *hard* multiple photon exchange (the purported explanation of the discrepancy) can be isolated.

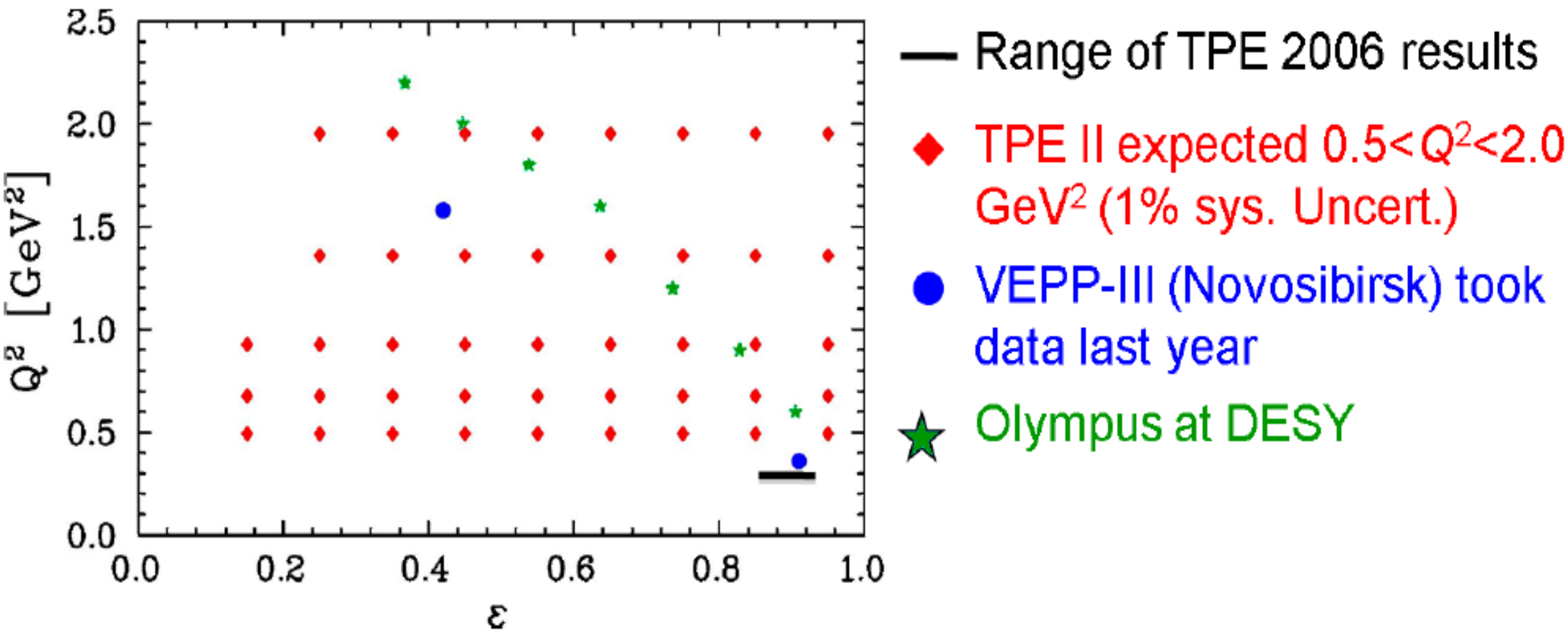
The Three Experiments

- **EG5 CLAS/JLab**
  - secondary e+/e- beams
  - data taking completed
  - acquired approx. 12 million elastic events
  - analysis in progress

- **Novosibirsk**
  - 1-1.6 GeV e+/e- beams in VEPP-3 storage ring
  - large acceptance non-magnetic detector
  - design luminosity 5 $\times 10^{31}$ cm^{-2} s^{-1}
  - result reported, additional data taking underway

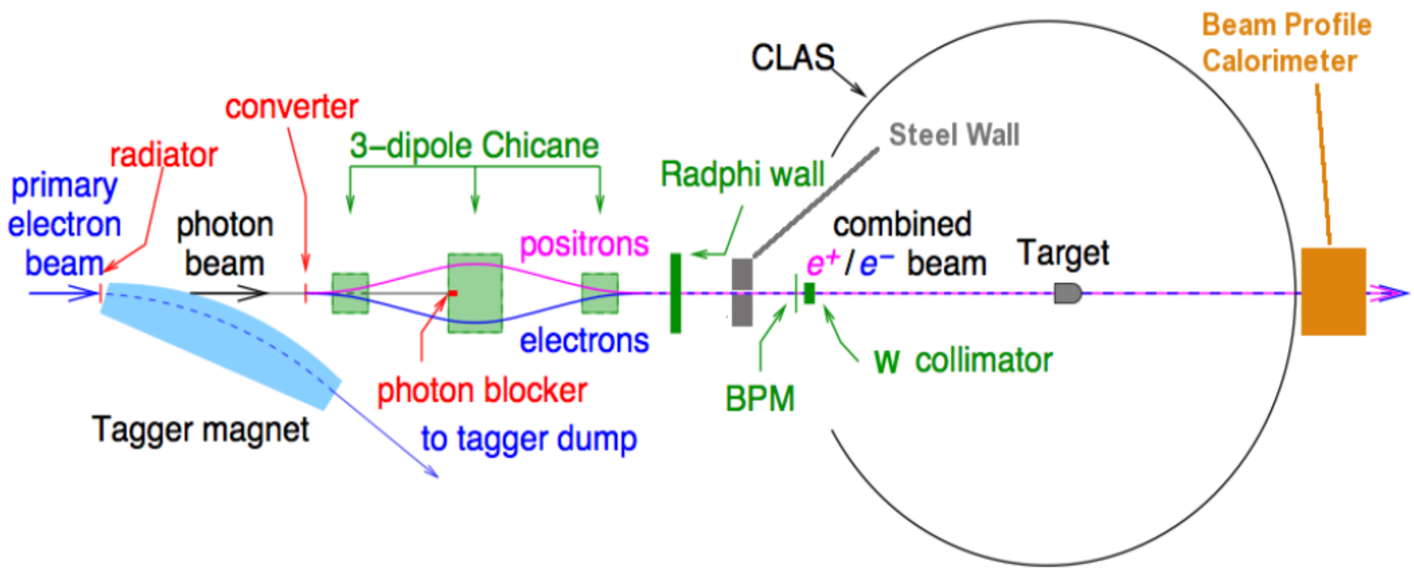
- **OLYMPUS/DESY**
  - 2 GeV e+/e- beams in DORIS storage ring
  - large acceptance toroidal spectrometer
  - design luminosity 2 $\times$ 10^{33} cm^{-2} s^{-1} => 30 million events for each of e+ and e-
  - in preparation for data taking in 2012

Kinematics



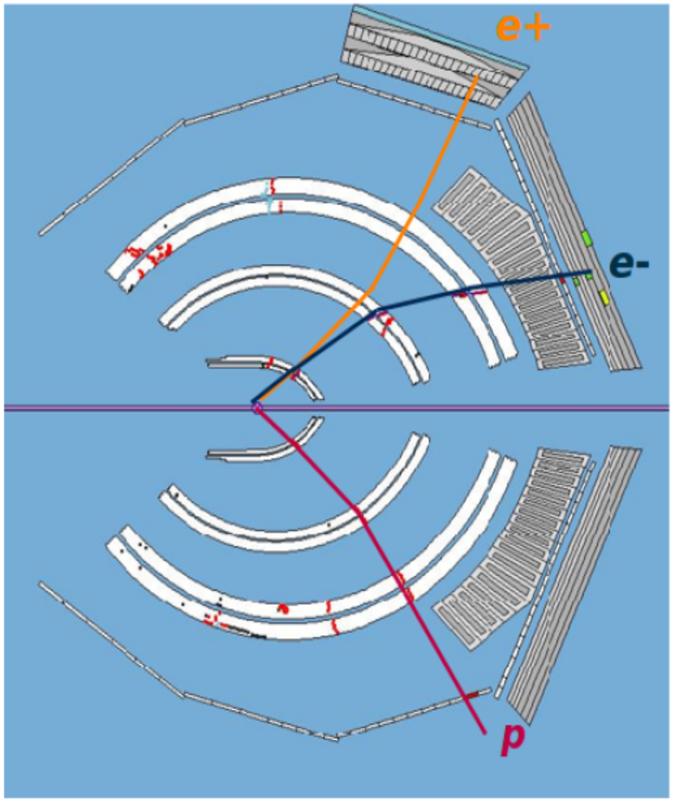
2.5
2.0
1.5
1.0
0.5
0.0
0.0
0.2
0.4
0.6
0.8
1.0
Q^2 [GeV^2]
ε
Range of TPE 2006 results
TPE II expected $0.5<Q^2<2.0$ GeV^2 (1% sys. Uncert.)
VEPP-III (Novosibirsk) took data last year
Olympus at DESY

EG5: CLAS TPE Experiment



- Primary electron beam: 5.5 GeV and 100 nA
- Radiator: 1% of primary electrons radiate high energy photons
- Tagger magnet: Transport electrons tagger dump
- Converter: 10% of photons are converted to electron/positron pairs
- Chicane: separate the lepton beams
- Remaining photons are stopped at the photon blocker
- e^+ ande^- beams are then recombined and continue to the target
- Target: liquid hydrogen: length = 18cm (30 cm) & diameter = 6cm (6 cm)
- Detector: CLAS (DC, TOF)

Concept



1. Measure Elastic Scattering Ratio

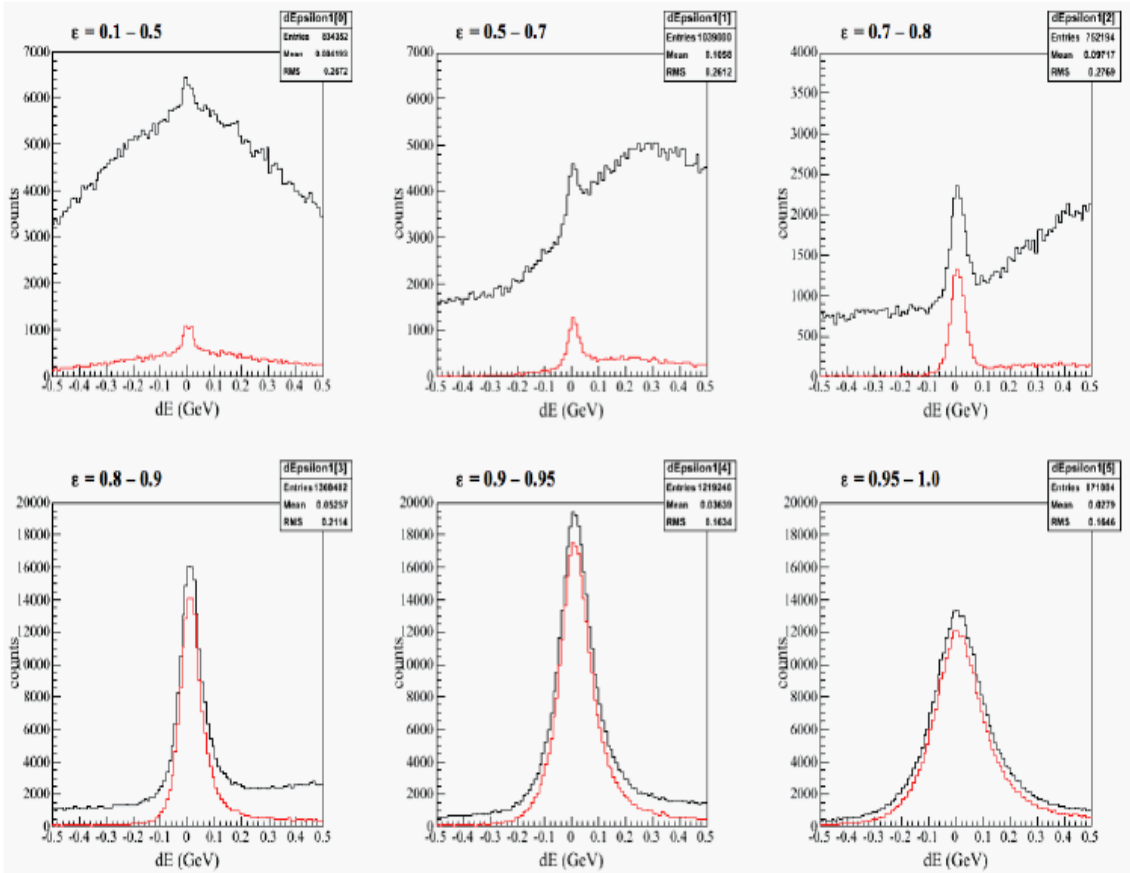
$$R = \sqrt{\frac{Y^{+}_{e^{+}P}}{Y^{+}_{e^{-}P}} \times \frac{Y^{-}_{e^{+}P}}{Y^{-}_{e^{-}P}}}$$

2. **Systematics**
   - Extensive beam profiling
   - Flip torus polarity
   - Flip chicane polarity

3. **Analysis Issues**
   - Beam energy for a given event is unknown
   - Non-standard particle identification
   - Different efficiency for ID'ing in-bending and out-bending tracks

4. **Analysis Solutions**
   - Look for coplanar pairs (opposite sectors)
   - Identify ++ and +− pairs
   - Exploit over constrained kinematics
   - Straight through running of primary beam

Negative Torus Polarity: Electron-Proton Events



$\Delta E = E_1 - E_2$ · Before $\Delta\phi$ cuts · After $\Delta\phi$ cuts

$$E_1 = M\left[\cot\frac{\theta_e}{2}\cot\theta_p - 1\right],\ E_2 = p_e\cos\theta_e + p_p\cos\theta_p$$

Preliminary · Explore other kinematics

CLAS TPE Experiment

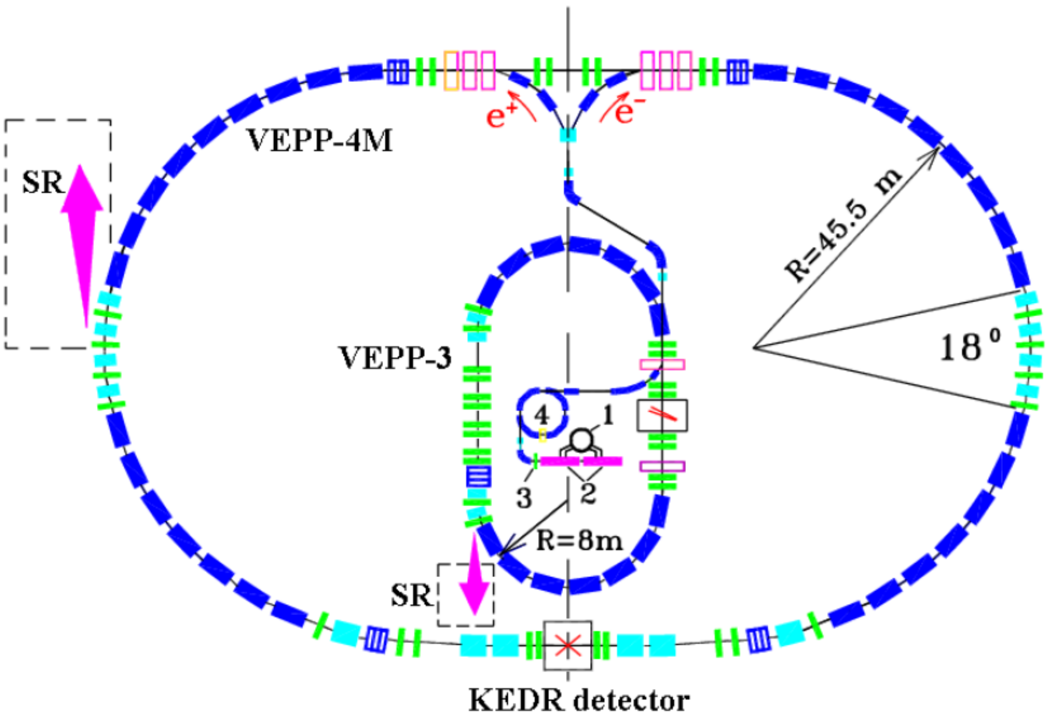
- Nov 30, 2010 - Feb 25, 2011 (30 PAC days)
- 5.6 GeV @ $\sim 100 - 120$ nA unpolarized electron beam
  - $\rightarrow$ Photon beam
  - $\Rightarrow$ Electron-positron beam ~ 50 pA
  - $\Rightarrow$ 30 cm Liquid Hydrogen target (-30 cm from CLAS center)
- Luminosity limitations:
  - DC occupancies
  - Trigger rate
- Systematic error control:
  - Flipped torus polarity weekly
  - Flipped lepton beam line magnet (chicane) polarity weekly
  - Zero field mini-torus runs
  - Half-field torus runs
  - Compare six different sector results
  - 2.2 GeV run
    - Electron beam run at 0.3 nA directly on target ($\sim$ 1 day)
    - Two different torus polarities
    - In-bending and out-bending particle reconstruction
- $\sim$ 12 billion triggers $\Rightarrow$ 12 million elastic events over all kinematics
- No accurate measure of luminosity, estimates: $\sim 2.5 \times 10^{32}$ cm^{-2}s^{-1} for electron and positron separately (Simulation)

The Novosibirsk Experiment

A. V. Gramolin,[1] J. Arrington,[2] L. M. Barkov,[1] V. F. Dmitriev,[1] V. V. Gauzshteyn,[3] R. A Golovin,[1] R. J. Holt,[2] V. V. Kaminsky,[1] B. A. Lazarenko,[1] S. I. Mishnev,[1] N. Yu. Muchnoi,[1] V. V. Neufeld,[1] D. M. Nikolenko,[1] I. A. Rachek,[1] R. Sh. Sadykov,[1] Yu. V. Shestakov,[1] V. N. Stibunov,[3] D. K. Toporkov,[1] H. de Vries,[4] S. A. Zevakov,[1] and V. N. Zhilich[1]

[1]Budker Institute of Nuclear Physics, Novosibirsk, Russia
[2]Argonne National Laboratory, Argonne, USA
[3]Nuclear Physics Institute at Tomsk Polytechnical University, Tomsk, Russia
[4]NIKHEF, Amsterdam, The Netherlands

The VEPP-3 Electron Storage Ring

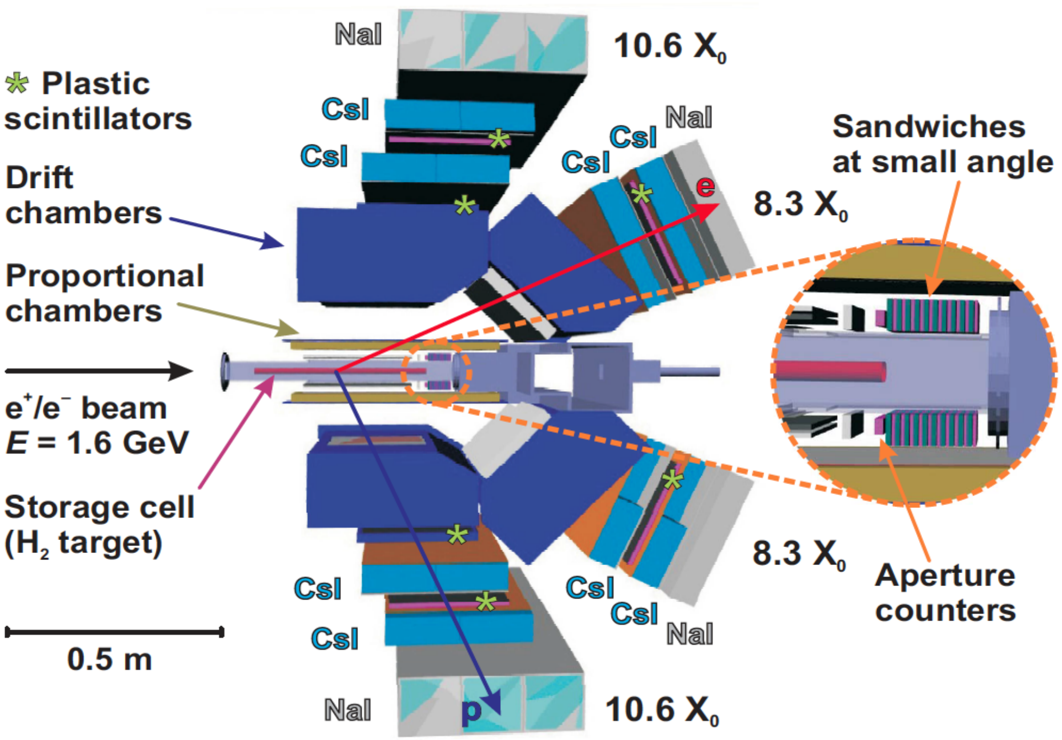


1 — Girokon (430 MHz)
2 — Linac (50 MeV)
3 — Electron to positron converter
4 — Synchrotron B–4 (350 MeV)

Perimeter: 74.4 m
Injection energy: 350 MeV
Maximal energy: 2000 MeV
Maximal e^+ current: 50 mA

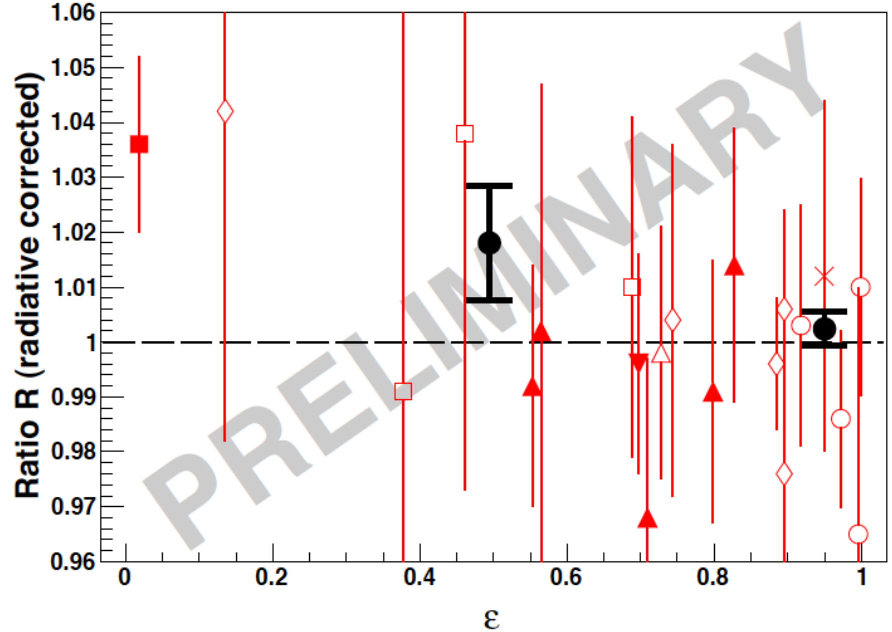
Schematic view of detector system

	θ_ℓ (°)	Q^2 (GeV^2)	ε	$\Delta R/R$ (%, stat.)
SA	8.4÷12.9	0.05÷0.13	0.99÷0.97	—
MA	15.5÷22.4	0.18÷0.34	0.96÷0.92	0.09
LA	57.5÷71.0	1.32÷1.61	0.55÷0.40	1.08



Preliminary results

Middle angle ($\varepsilon = 0.95,\ Q^2 = 0.23\ \text{GeV}^2$): $R = 1.0024 \pm 0.0009 \pm 0.003$,
Large angle ($\varepsilon = 0.5,\ Q^2 = 1.43\ \text{GeV}^2$): $R = 1.018 \pm 0.011 \pm 0.003$.

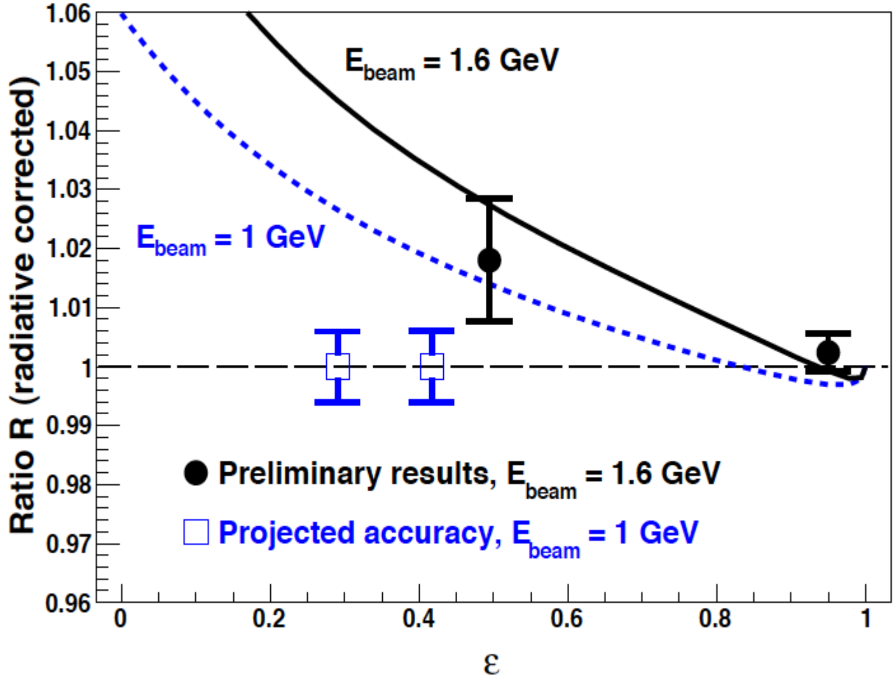


Integrated luminosity: 0.27 fb^{-1}

Our preliminary results and the previous measurements (for $Q^2 < 2\ \text{GeV}^2$):
◊ Yount (1962); □ Browman (1965), run 1; △ Browman (1965), run 2;
▼ Anderson (1966); × Bartel (1967); ■ Bouquet (1968); ▲ Anderson (1968);
○ Mar (1968); ● this experiment.

Next phase

The measurement will be continued at other kinematics:
$\varepsilon = 0.42,\ Q^2 = 0.82\ \text{GeV}^2$ & $\varepsilon = 0.29,\ Q^2 = 0.96\ \text{GeV}^2$.



The figure shows projected statistical accuracy (blue squares) and our preliminary results (black circles). The lines represent the corresponding results of the theoretical prediction by Blunden, et al.

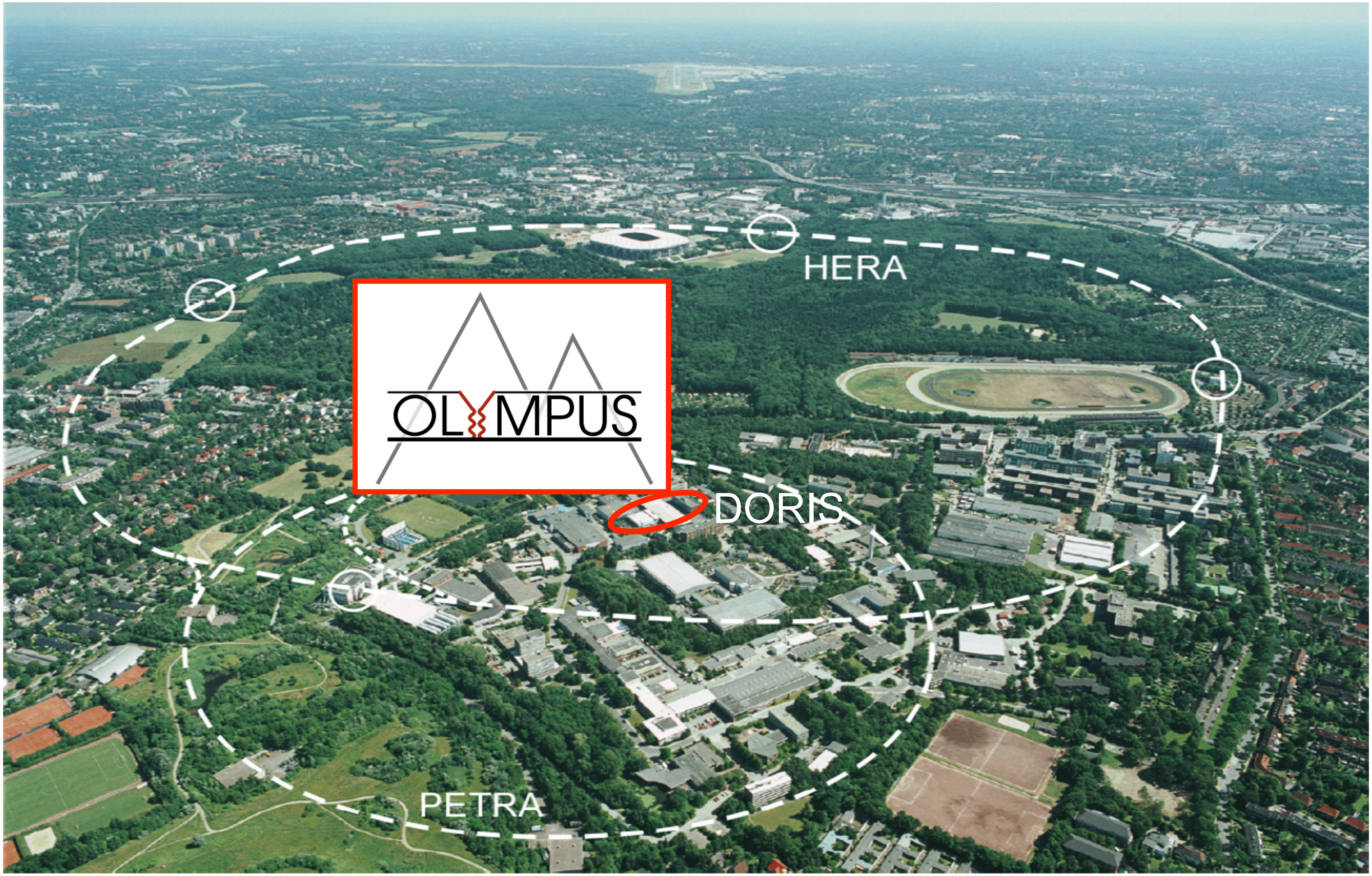
- *P. G. Blunden, W. Melnitchouk, and J. A. Tjon.* PRC **72** (2005) 034612.

7 kC of 60 kC collected in present run: A. Gramolin, Oct 13, 2011

OLYMPUS

Arizona State University, USA
DESY, Hamburg, Germany
Hampton University, USA
INFN, Bari, Italy
INFN, Ferrara, Italy
INFN, Rome, Italy
Massachusetts Institute of Technology, USA
Petersburg Nuclear Physics Institute, Russia
Universität Bonn, Germany
University of Glasgow, United Kingdom
Universität Mainz, Germany
University of New Hampshire, USA
Yerevan Physics Institute, Armenia

OLYMPUS @ DESY

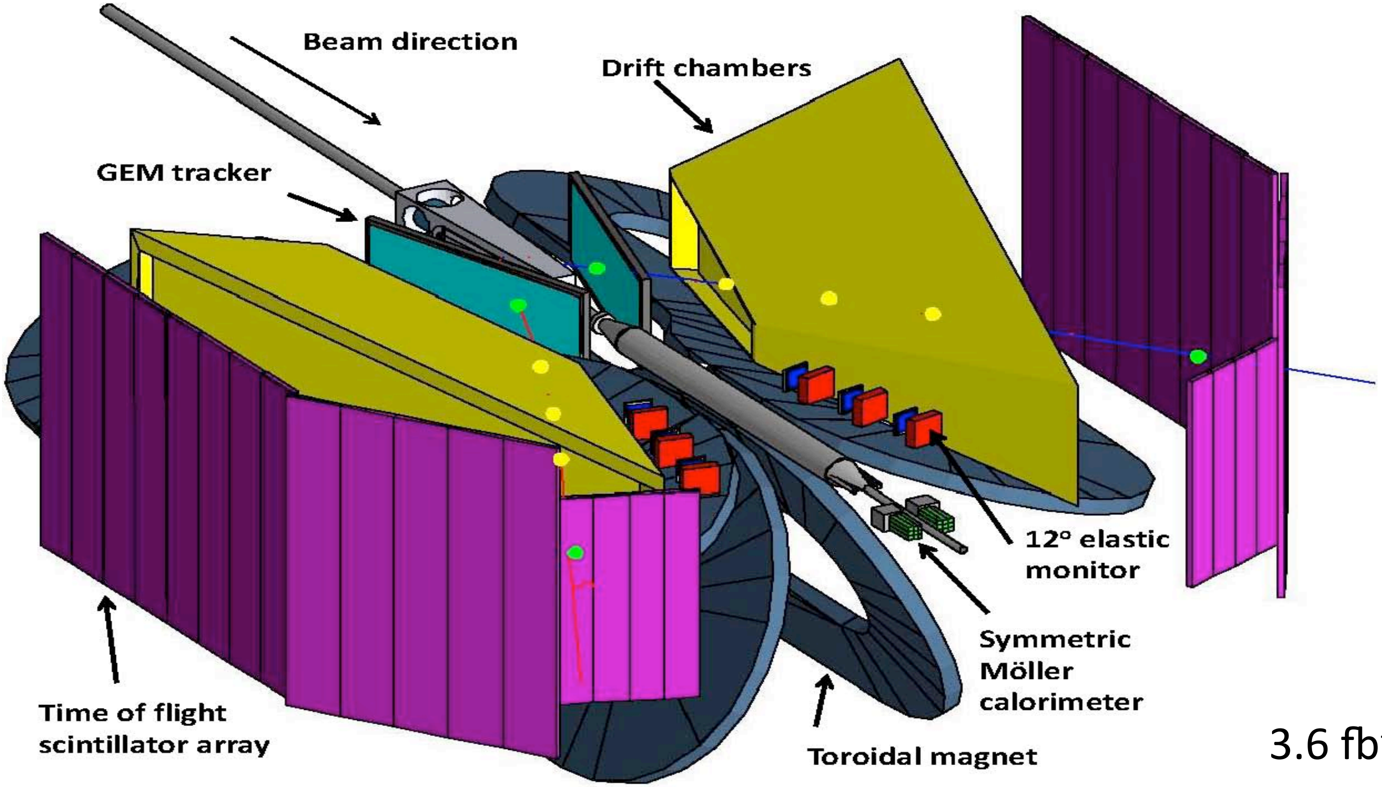


The OLYMPUS Experiment

- Electrons/positrons (100mA) in multi-GeV storage ring DORIS at DESY, Hamburg, Germany
- Unpolarized internal hydrogen gas target 3×10^{15} at/cm^2 @ 100 mA $\rightarrow$ $L = 2 \times 10^{33} / (cm^2 s)$
- Large acceptance detector for e-p in coincidence: utilize existing BLAST detector from MIT-Bates
- Redundant monitoring of luminosity:
  Pressure, temperature, flow, current measurements
  Small-angle elastic scattering at high epsilon / low Q^2
  Symmetric Moller/Bhabha scattering

- **Measure ratio of positron-proton to electron-proton unpolarized elastic scattering to 1% stat.+sys.**

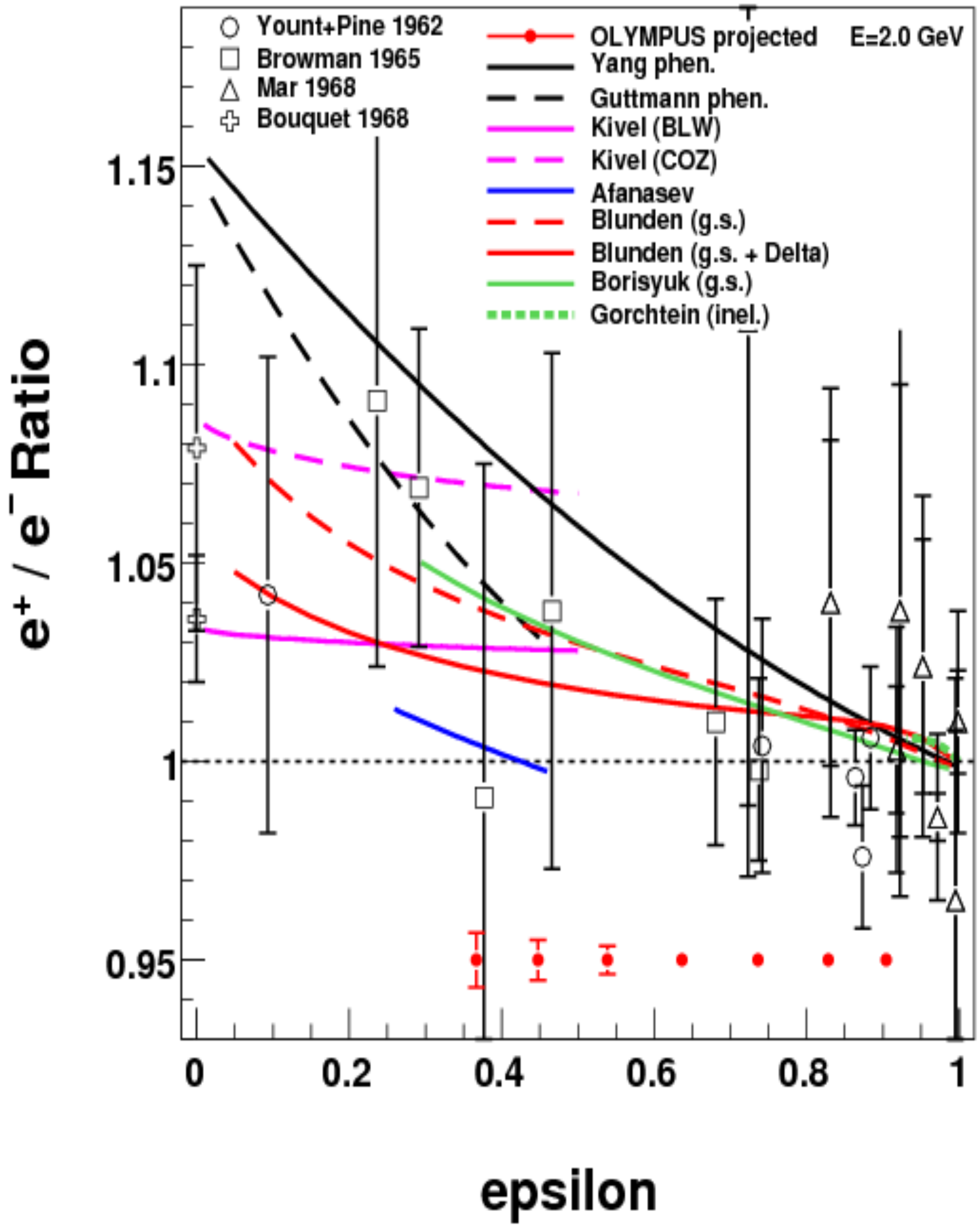
The OLYMPUS Detector



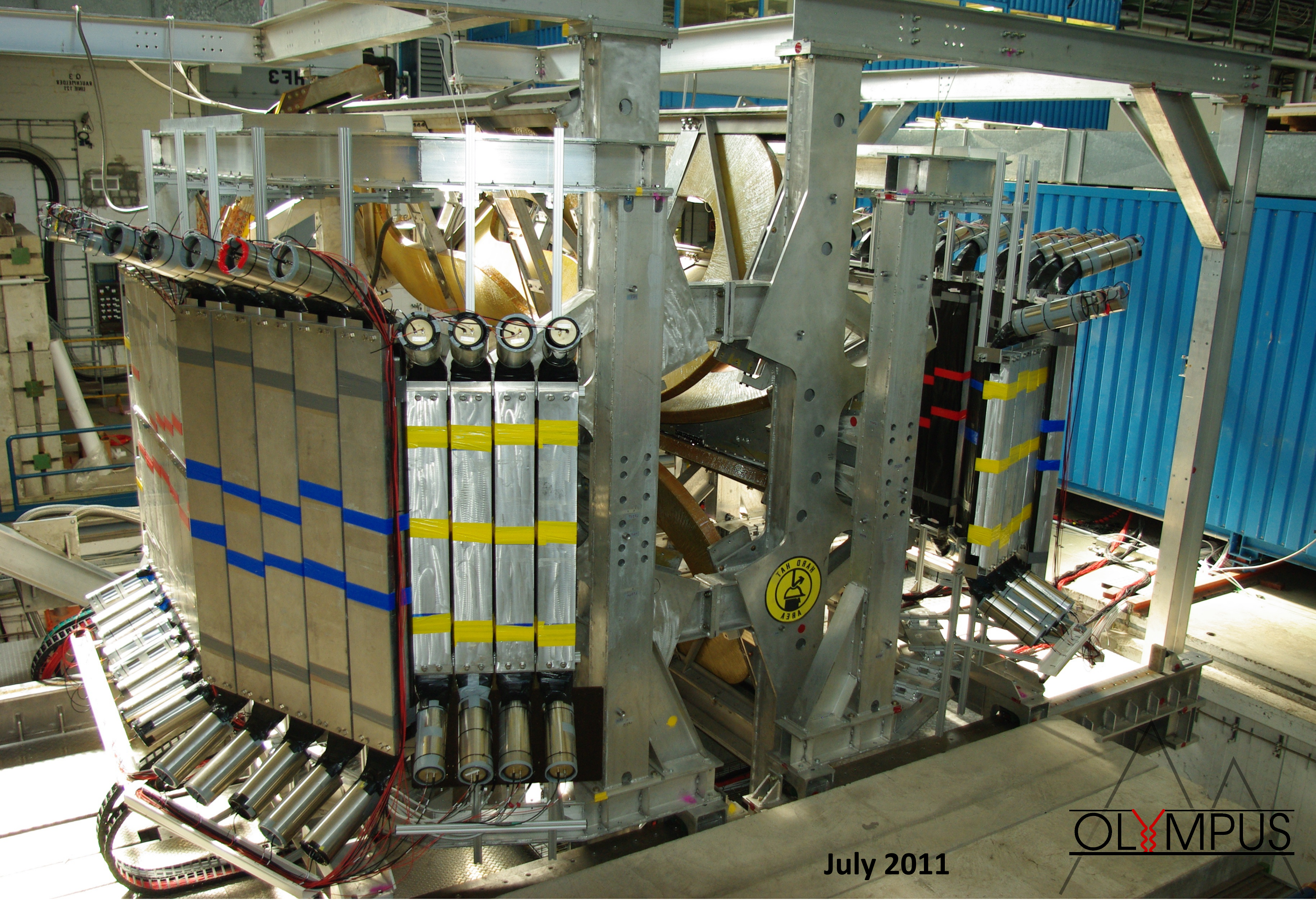
3.6 fb^{-1} integrated luminosity

θ_e deg.	$p_{e'}$ GeV/c	θ_p deg.	p_p GeV/c	Q^2 $(GeV/c)^2$	ε	Counts
24	1.69	57.0	0.82	0.58	0.905	26.5 million
32	1.51	47.8	1.08	0.92	0.828	4.8 million
40	1.33	40.7	1.31	1.26	0.735	1.2 million
48	1.17	35.4	1.50	1.56	0.636	0.4 million
56	1.03	31.0	1.66	1.82	0.538	168 k
64	0.91	27.2	1.79	2.0	0.449	80 k
72	0.81	23.8	1.91	2.23	0.367	43 k

Projected OLYMPUS uncertainties



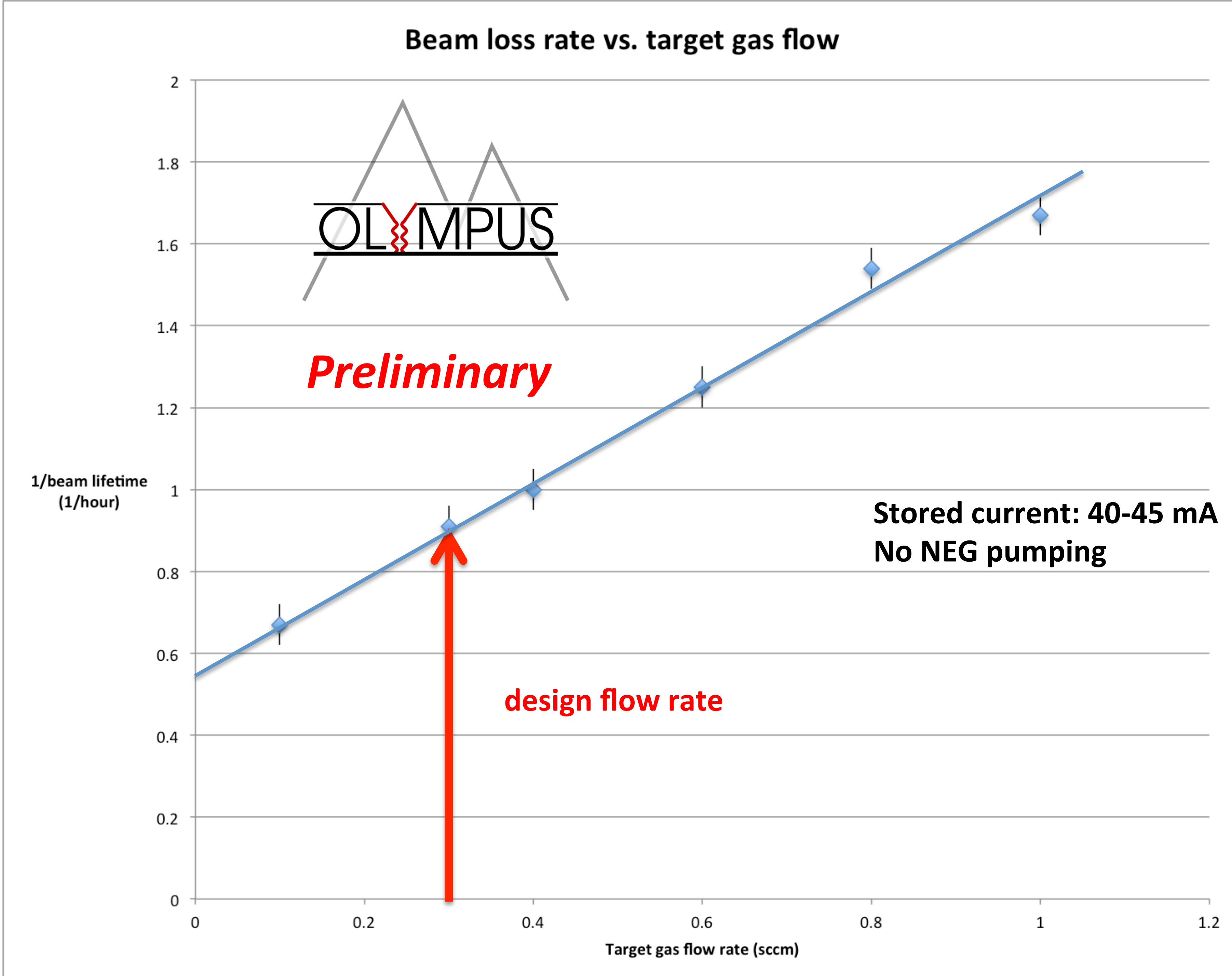
- 2 GeV incident beam energy
- Luminosity = 2 x 10^{33} cm^{-2} s^{-1}
- 500 hours each for e+ and e-
- 3.6 fb^{-1} integrated luminosity


July 2011
OLYMPUS

Status and Plans

- All components installed and operational
- Design luminosity comfortably attained at 2 GeV
- Both e+ and e- beams of 100 mA intensity available
- Internal gas target operates up to x3 above design thickness
- Fast reversal of lepton sign implemented
- Beam quality optimized with tuning and collimation
- Toroid routinely operating up to full field in both directions
- Electronic noise in detectors substantially reduced
- Stable DAQ operation
- Symmetric Moller/Bhabha lumi monitor brought into stable operation
- 12 deg. Elastic lumi monitor (GEMs + MWPCs) in operation
- Several shifts of data at design luminosity with all detectors working obtained

- Analysis of recent data a high priority
- Expect further short beam runs before Christmas
- Access in January 2012
- Data taking run in February 2012
- Subsequent data taking run planned for November and December 2012



Beam loss rate vs. target gas flow
1/beam lifetime (1/hour)
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0
0.2
0.4
0.6
0.8
1
1.2
Target gas flow rate (sccm)
OLYMPUS
Preliminary
Stored current: 40-45 mA
No NEG pumping
design flow rate

Summary

- Major discrepancy in determination of proton form factor ratio has been observed.
- Contributions beyond single photon exchange in QED description of elastic electron proton scattering believed to be source of discrepancy. However, theoretical guidance is only qualitative.
- This undermines the ability to extract unambiguously the proton charge and magnetic form-factors.
- Definitive experimental determination of contributions beyond single photon exchange is demanded.
- Experiments at JLab, Novosibirsk, and DESY are underway to provide definitive precise data to determine contribution beyond single photon exchange.
- Anticipate new experimental data from all experiments within the next year.