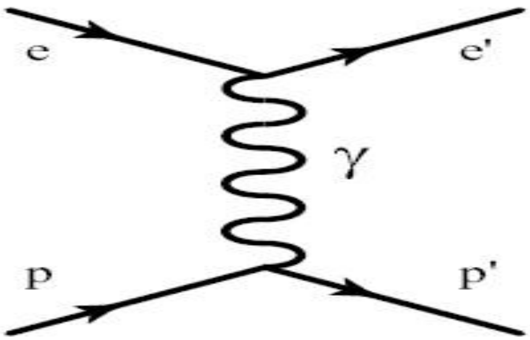
OLYMPUS: physics update

- Introduction
- Novosibirsk experiment
- Vanderhaeghen *et al.* preprint
- Conclusions

Elastic Electron Scattering from Proton



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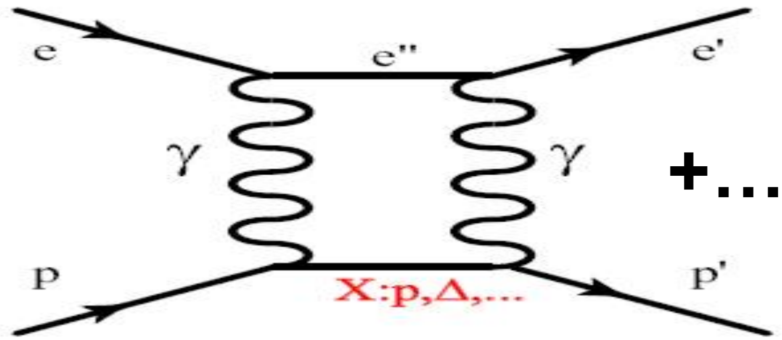


+…

Dirac, Pauli FF

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

Sachs FF

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

Unpolarized Elastic e-N Scattering

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

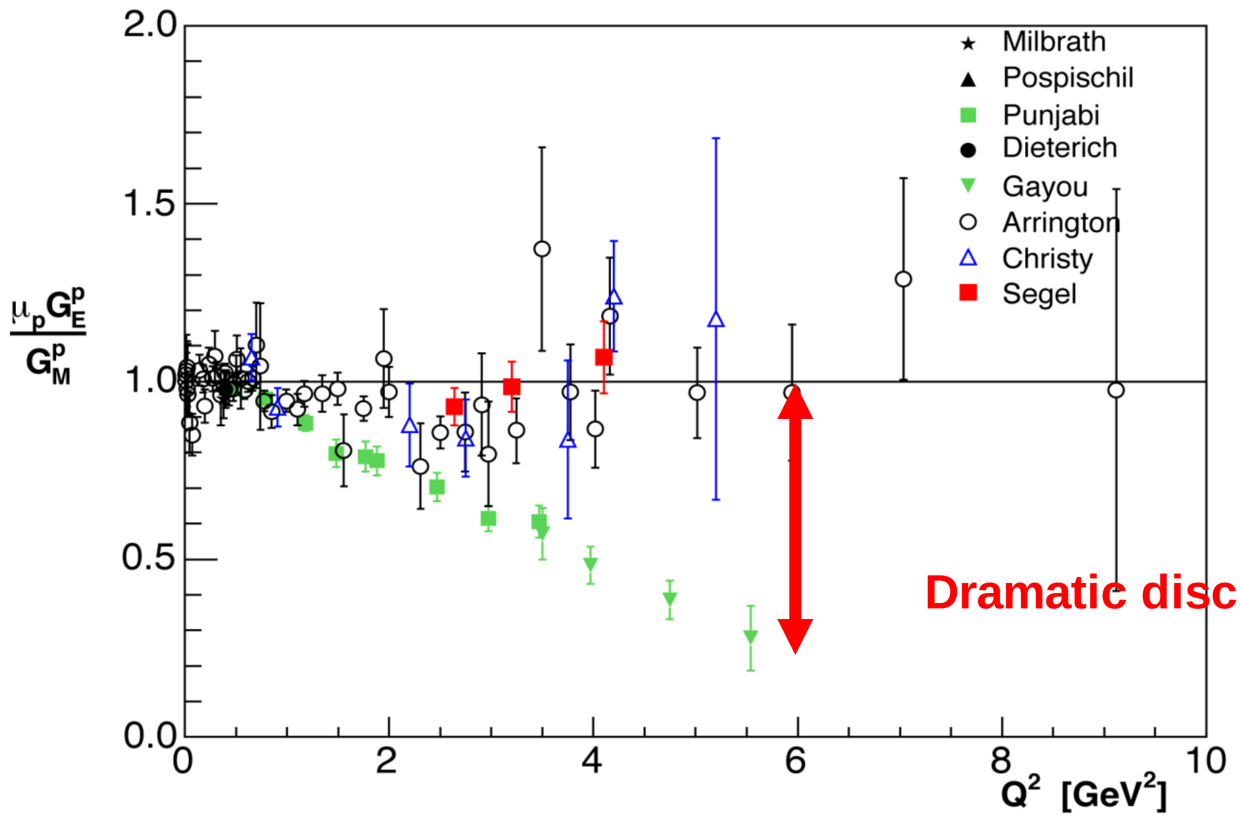
$$= \frac{G_E^2(Q^2) + \tau G_M^2(Q^2)}{1+\tau} + 2\tau G_M^2(Q^2)\tan^2\frac{\theta}{2}$$

For ~ 50 years unpolarized cross section measurements have determined the elastic FF G^p_E and G^p_M using the Rosenbluth separation

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

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

Proton Form Factor Ratio



Jefferson Lab

- **All Rosenbluth data from SLAC and Jlab in agreement.**
- **Dramatic discrepancy between Rosenbluth and recoil polarization technique**
- **Interpreted as evidence for two photon exchange**

Estimation of TPE Contribution

P.G. Blunden et al.,
Phys. Rev. C 72, 034612 (2005)

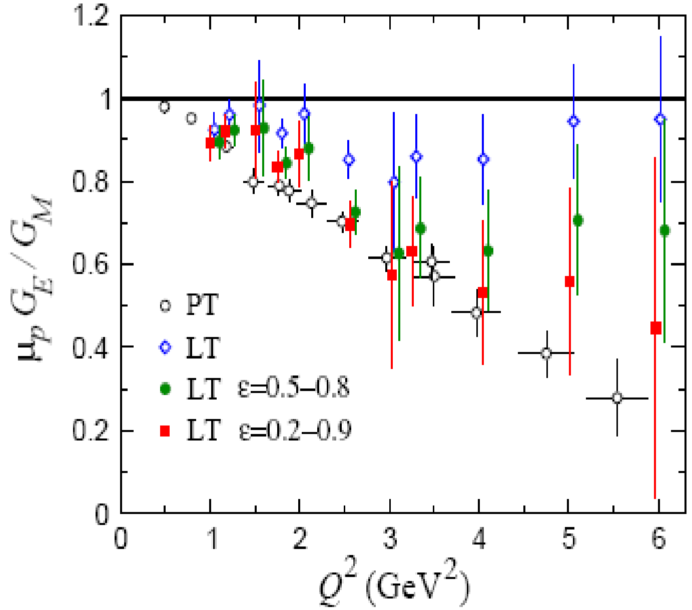
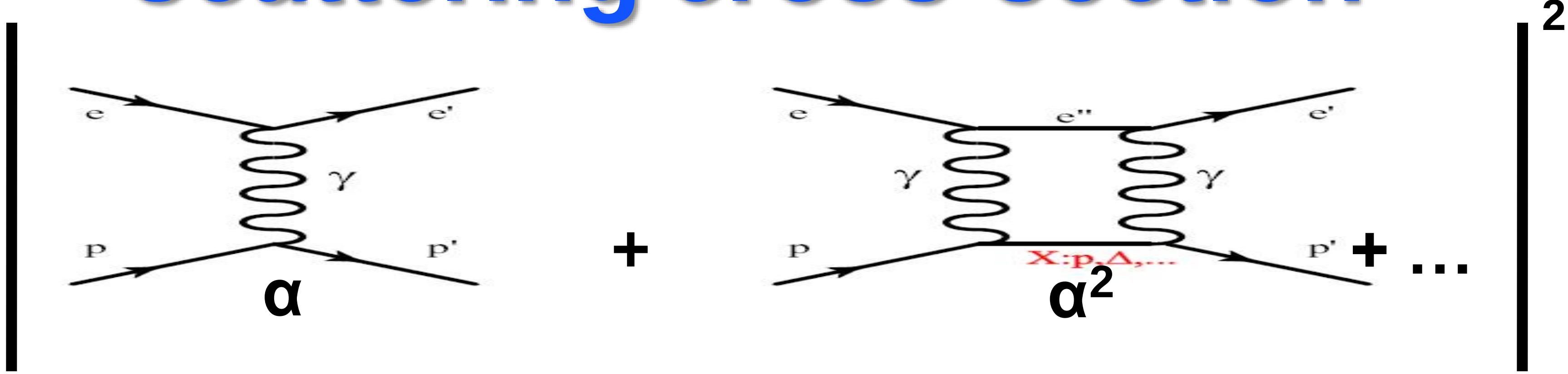


FIG. 5: The ratio of proton form factors $\mu_p G_E/G_M$ measured using LT separation (open diamonds) [2] and polarization transfer (PT) (open circles) [5]. The LT points corrected for 2γ exchange are shown assuming a linear slope for $\varepsilon = 0.2 - 0.9$ (filled squares) and $\varepsilon = 0.5 - 0.8$ (filled circles) (offset for clarity).

Only experiment can definitively resolve the contributions beyond single photon exchange

Lepton-proton elastic scattering cross-section



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

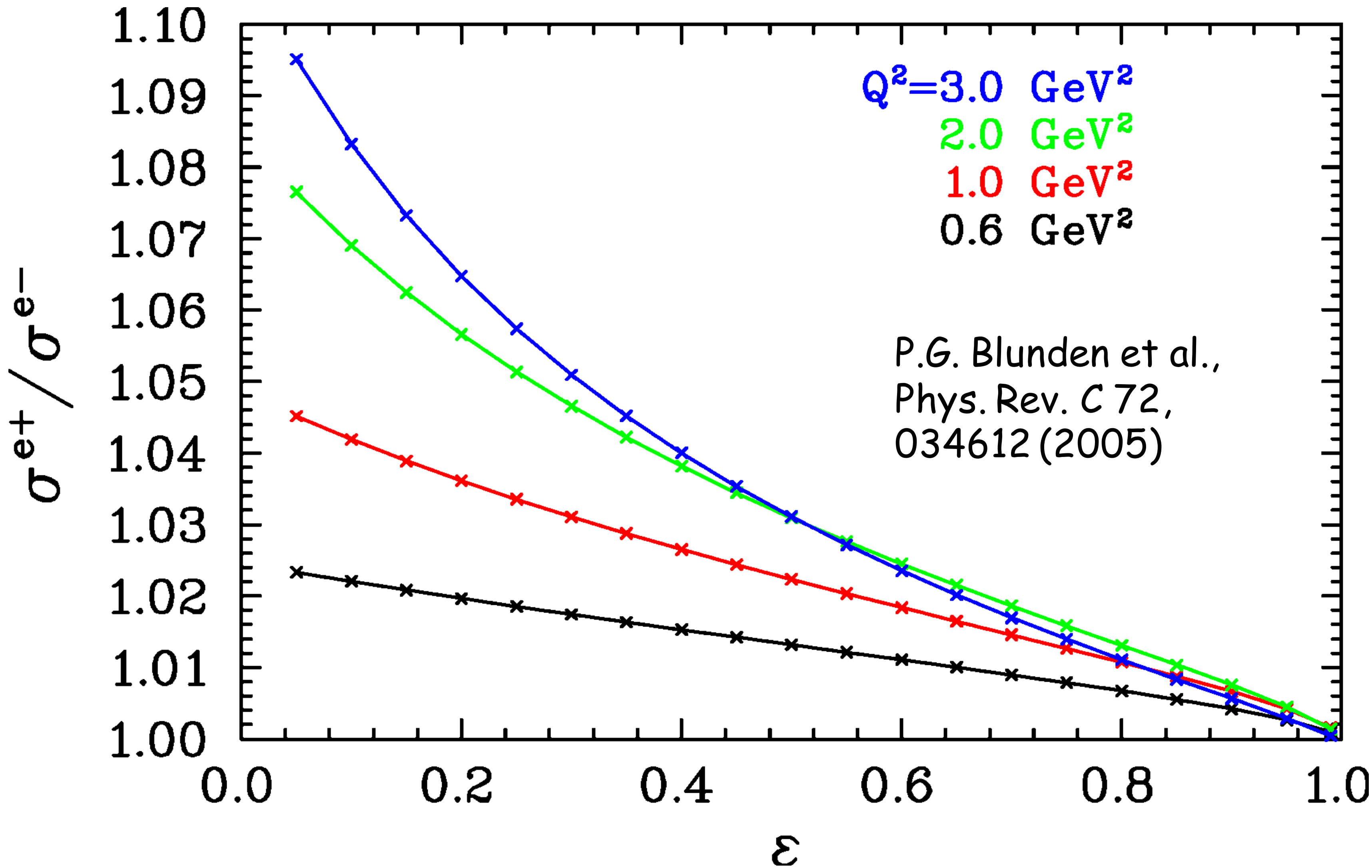
$$e^- \Longleftrightarrow e^+ \Rightarrow \alpha \Longleftrightarrow -\alpha$$

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

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

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

e^+p/e^-p cross section ratio



OLYMPUS kinematics

E_0 [GeV]	θ_e	$p_{e'}$ [GeV/c]	θ_p	p_p [GeV/c]	Q^2 [(GeV/c)^2]	ϵ	Counts
2.0	24	1.69	56.4	2.45	0.6	0.905	22613100
	32	1.51	48.1	2.26	0.9	0.828	4321570
	40	1.46	41.3	2.07	1.2	0.736	1141960
	48	1.27	35.7	1.89	1.6	0.636	389822
	56	1.10	31.0	1.73	1.8	0.538	162355
	64	0.97	27.1	1.59	2.0	0.447	78744
	72	0.85	23.8	1.47	2.2	0.367	42954

Table 1.3: Kinematics for 2.0 GeV beam energy and count estimate per 8° bin for 500 h at $2 \cdot 10^{33}$ / (cm^{2}s).

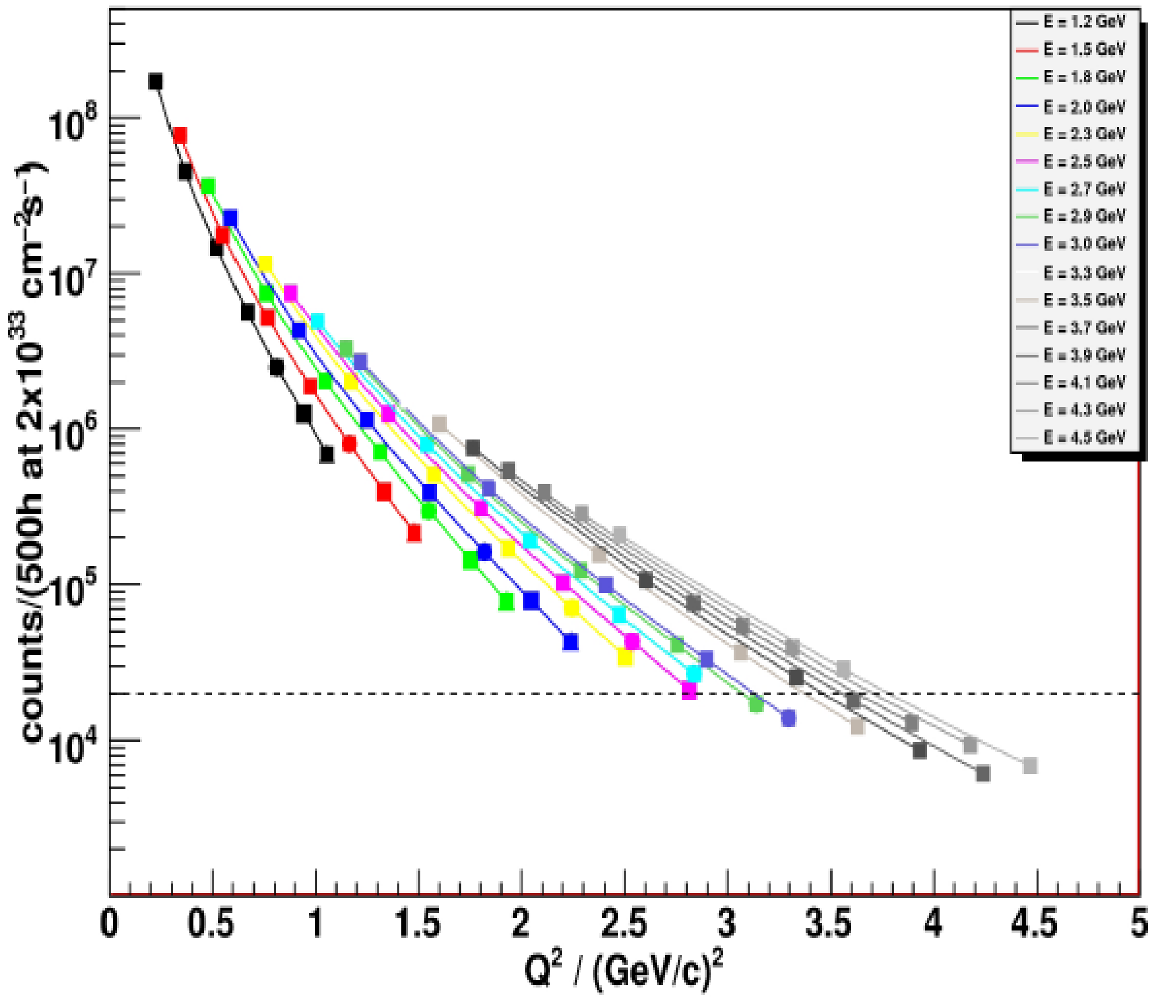


Figure 1.10: Expected distribution of counts per marked angle bin for the BLAST detector for various beam energies, as a function of Q^2. The assumed luminosity is $2 \cdot 10^{33}/(\mathrm{cm}^2\mathrm{s}) \times$ 500 hours.

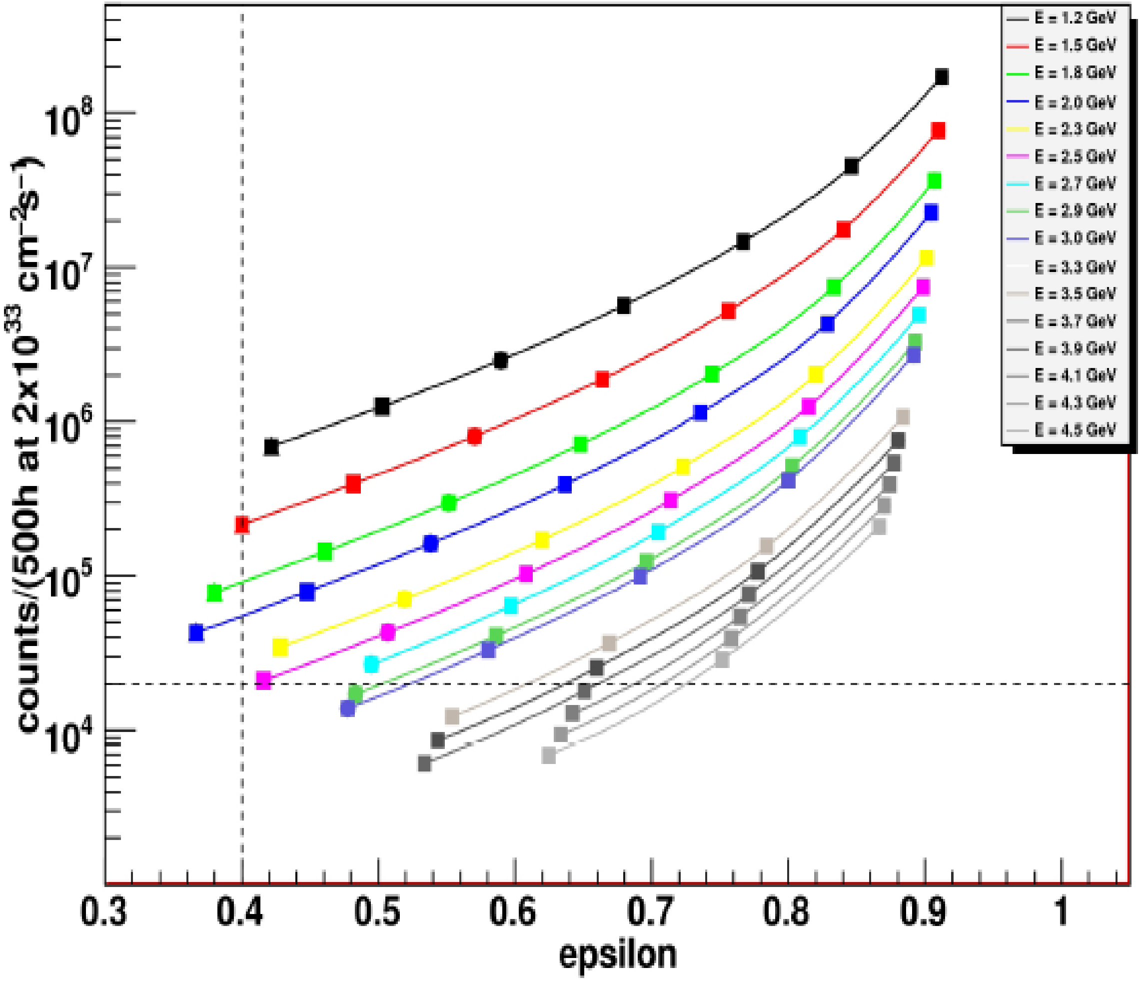
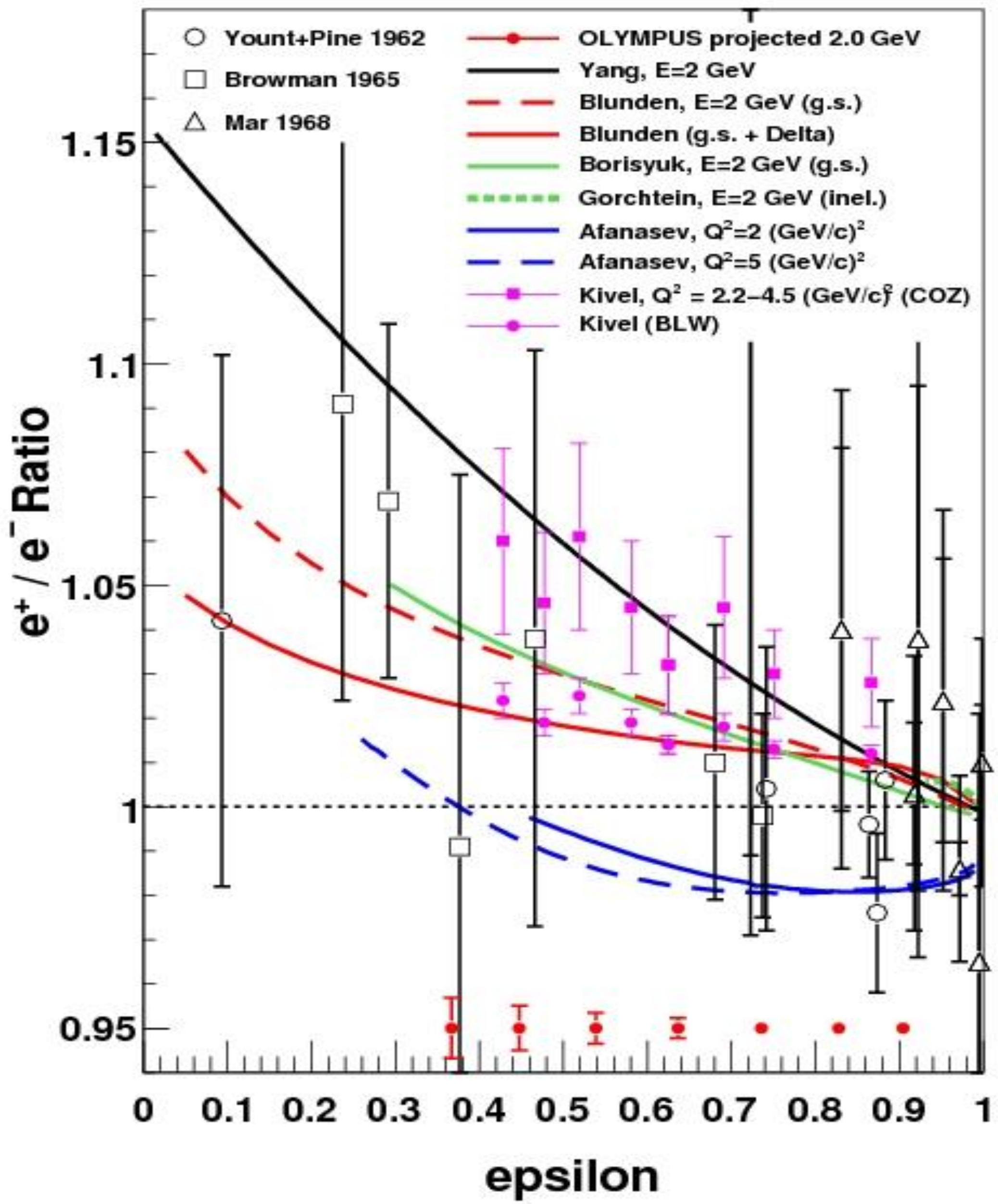


Figure 1.11: Expected distribution of counts per marked angle bin for the BLAST detector for various beam energies, as a function of ϵ. The assumed luminosity is $2 \cdot 10^{33}/(\mathrm{cm}^2\mathrm{s}) \times 500$ hours.

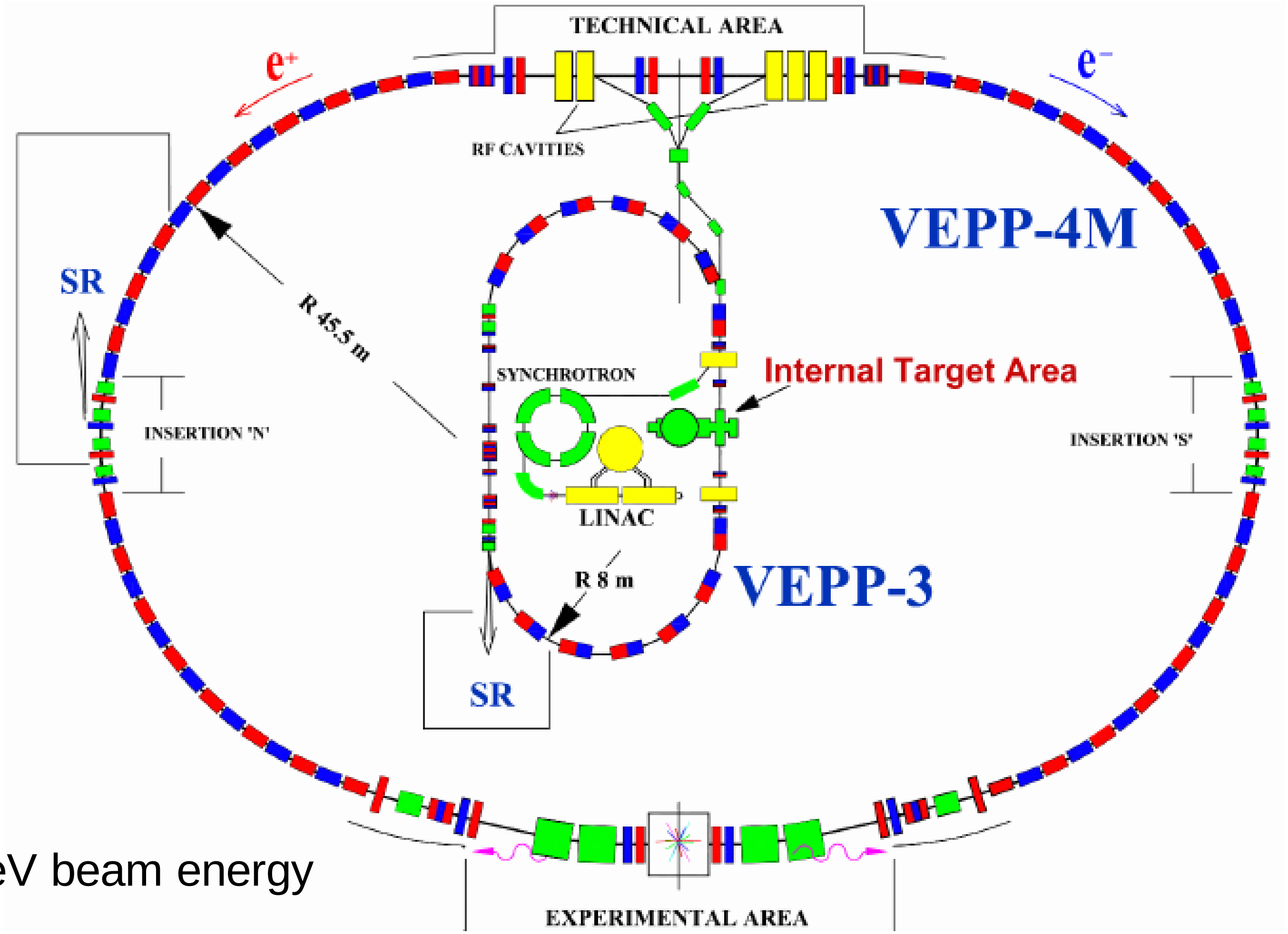
Projected OLYMPUS uncertainties

- Luminosity = 2 x 10^{33} cm^{-2} s^{-1}
- 500 hours each for e+ and e-
- 2 GeV energy



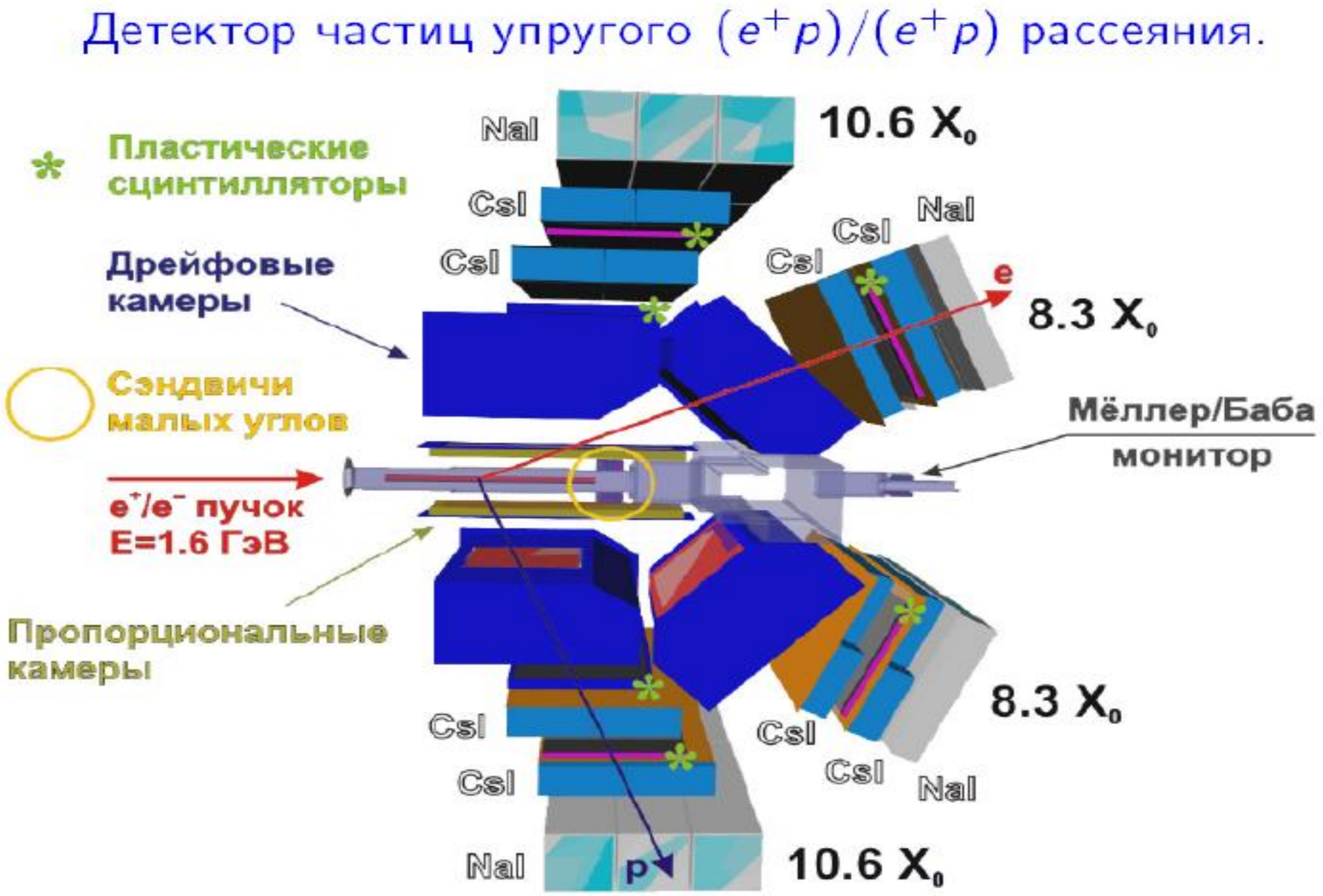
M. Kohl

Novosibirsk experiment

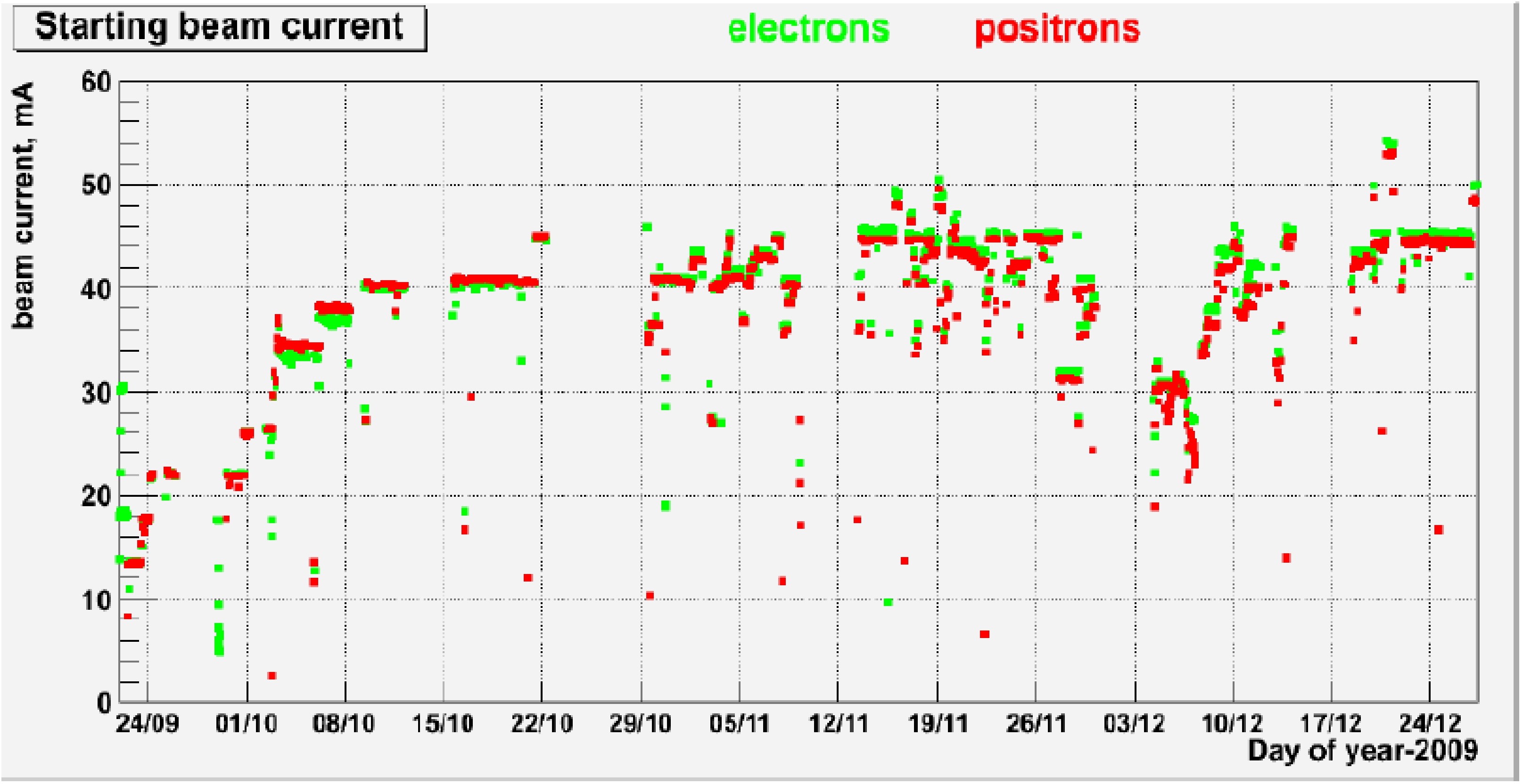


1.6 GeV beam energy

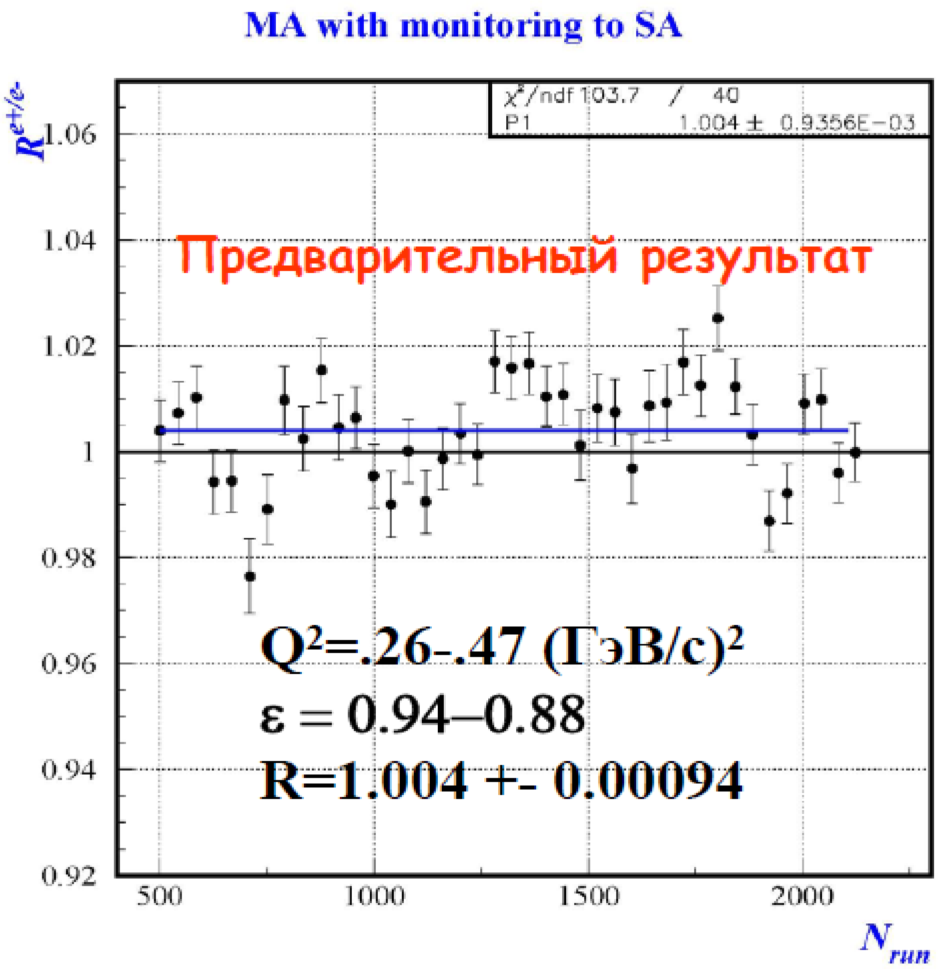
Non-magnetic detector system



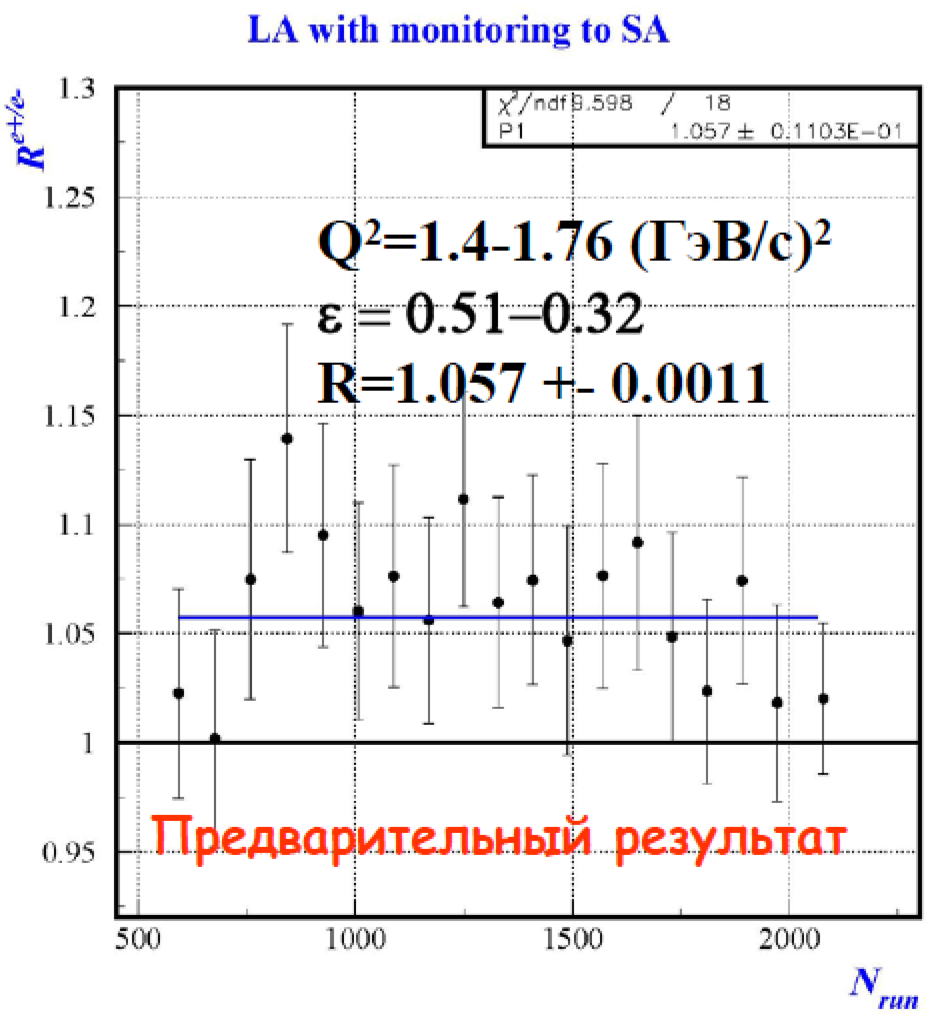
50 mA beams


Starting beam current
electrons
positrons
beam current, mA
60
50
40
30
20
10
0
24/09
01/10
08/10
15/10
22/10
29/10
05/11
12/11
19/11
26/11
03/12
10/12
17/12
24/12
Day of year-2009

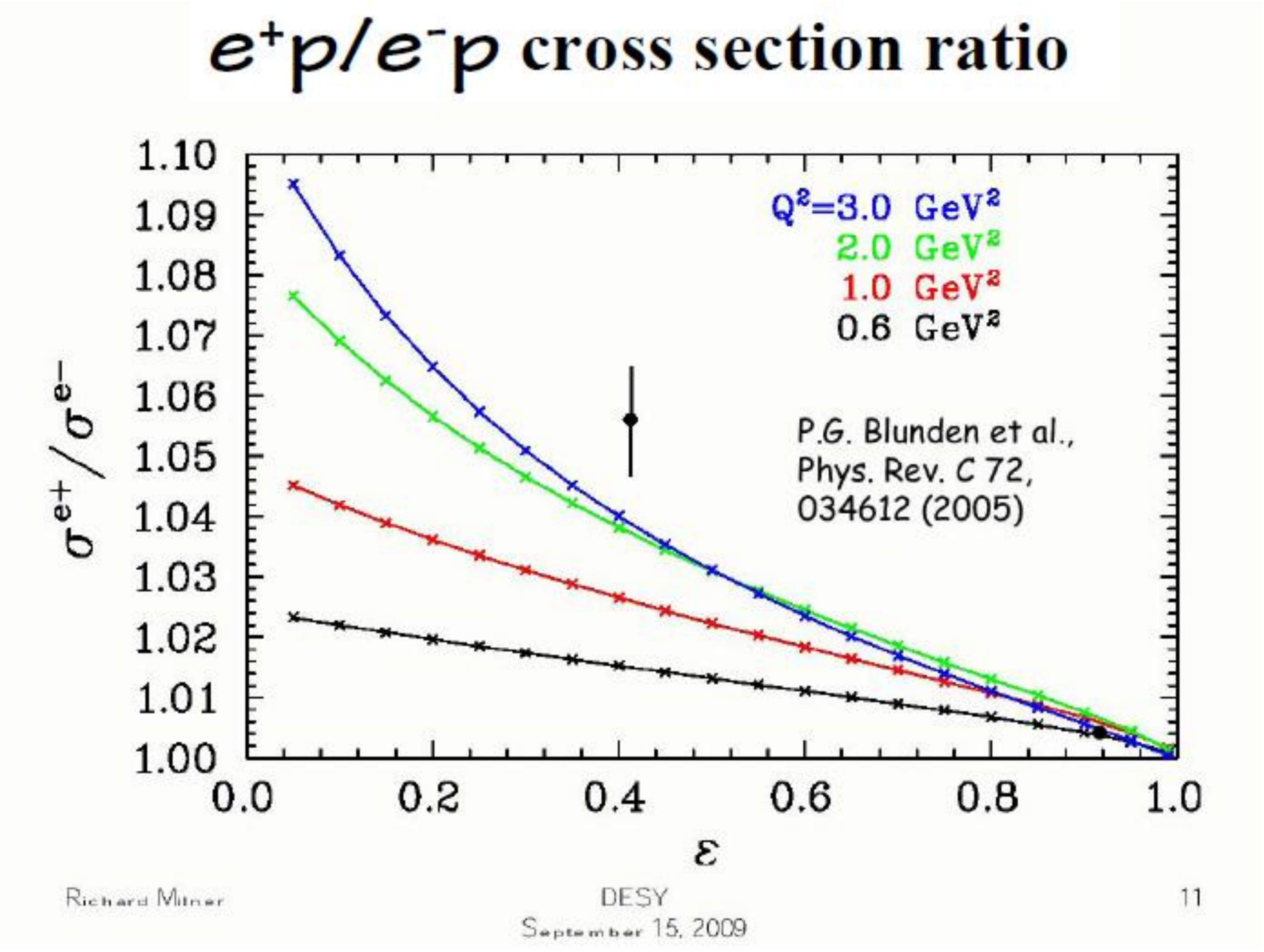
Forward angle measurement



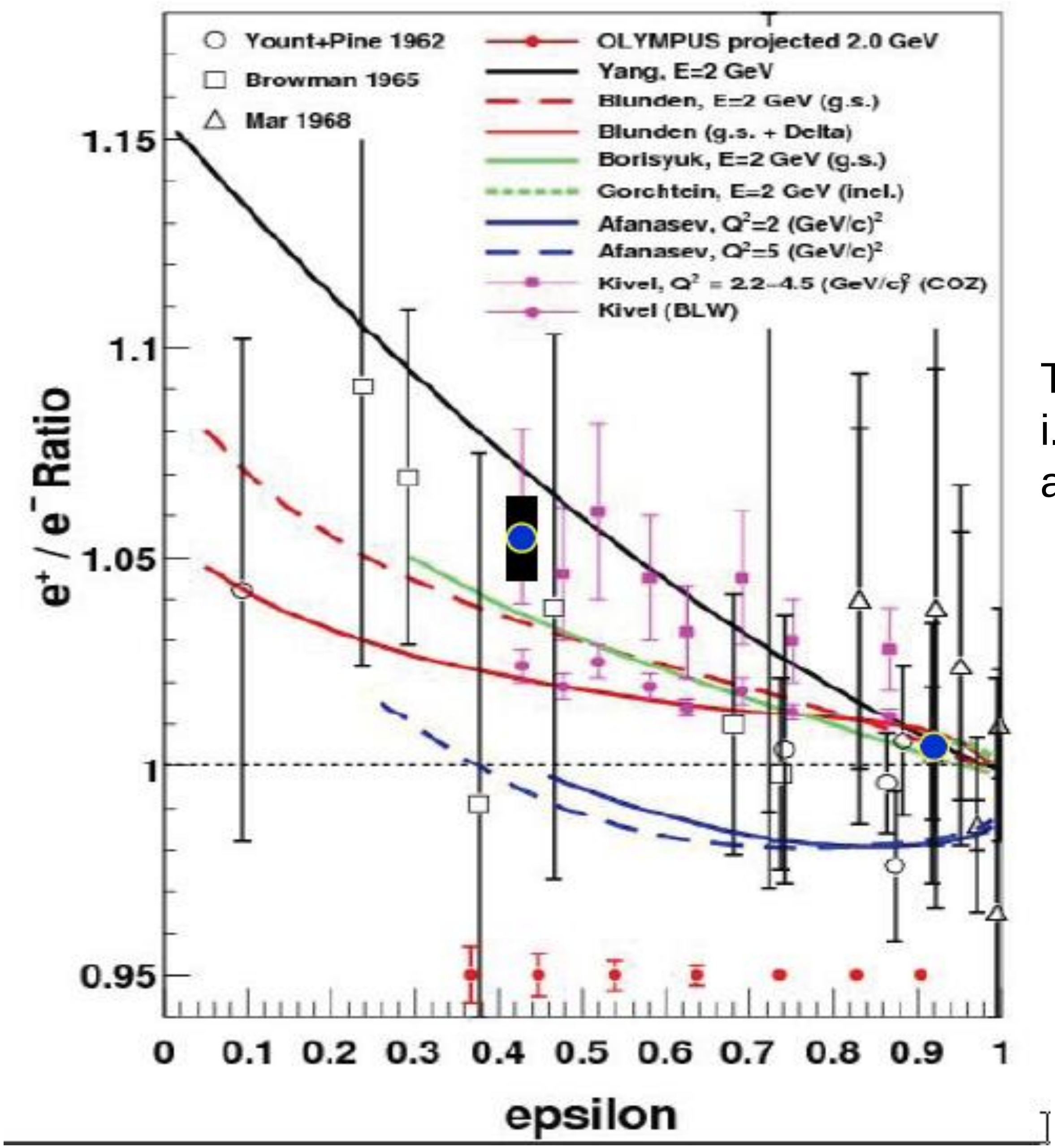
Back angle measurement



Result



e^+p/e^-p cross section ratio
σ^{e+}/σ^{e-}
1.10
1.09
1.08
1.07
1.06
1.05
1.04
1.03
1.02
1.01
1.00
0.0
0.2
0.4
0.6
0.8
1.0
ε
Q²=3.0 GeV²
2.0 GeV²
1.0 GeV²
0.6 GeV²
P.G. Blunden et al.,
Phys. Rev. C 72,
034612 (2005)
Richard Milner
DESY
September 15, 2009
11



Total integrated charge = 54 kC
i.e. 5 days of continuous running
at 100 mA

Empirical extraction of two-photon amplitudes

Preprint MKPH-T-10-06

First empirical determination of two-photon exchange amplitudes from elastic electron-proton scattering data

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(Dated: April 13, 2010)

We provide a first complete empirical extraction of the two-photon exchange amplitudes to elastic electron-proton scattering based on measurements of cross sections and polarization observables at a common value of four-momentum transfer, $Q^2 = 2.64$ GeV^2. This analysis also provides an empirical prediction for the ratio of e^+p/e^-p elastic scattering, which will be measured by forthcoming experiments.

$$T_{h,\lambda'_N\lambda_N} = \frac{e^2}{Q^2}\bar{u}(k',h)\gamma_\mu u(k,h) \times \bar{u}(p',\lambda'_N)\left(\tilde{G}_M\gamma^\mu - \tilde{F}_2\frac{P^\mu}{M} + \tilde{F}_3\frac{\gamma\cdot K P^\mu}{M^2}\right)u(p,\lambda_N), \tag{1}$$

$$Y_{2\gamma}^M(\nu,Q^2) \equiv \mathcal{R}\left(\frac{\delta\tilde{G}_M}{G_M}\right), \quad Y_{2\gamma}^E(\nu,Q^2) \equiv \mathcal{R}\left(\frac{\delta\tilde{G}_E}{G_M}\right),$$

$$Y_{2\gamma}^3(\nu,Q^2) \equiv \frac{\nu}{M^2}\mathcal{R}\left(\frac{\tilde{F}_3}{G_M}\right), \tag{3}$$

where $\mathcal{R}$ stands for the real part.

$$\frac{\sigma_R}{G_M^2} = 1 + \frac{\varepsilon}{\tau}\frac{G_E^2}{G_M^2} + 2\,Y_{2\gamma}^{M} + 2\varepsilon\frac{G_E}{\tau G_M}\,Y_{2\gamma}^{E} + 2\varepsilon\left(1+\frac{G_E}{\tau G_M}\right)Y_{2\gamma}^{3} + \mathcal{O}(e^4), (4)$$

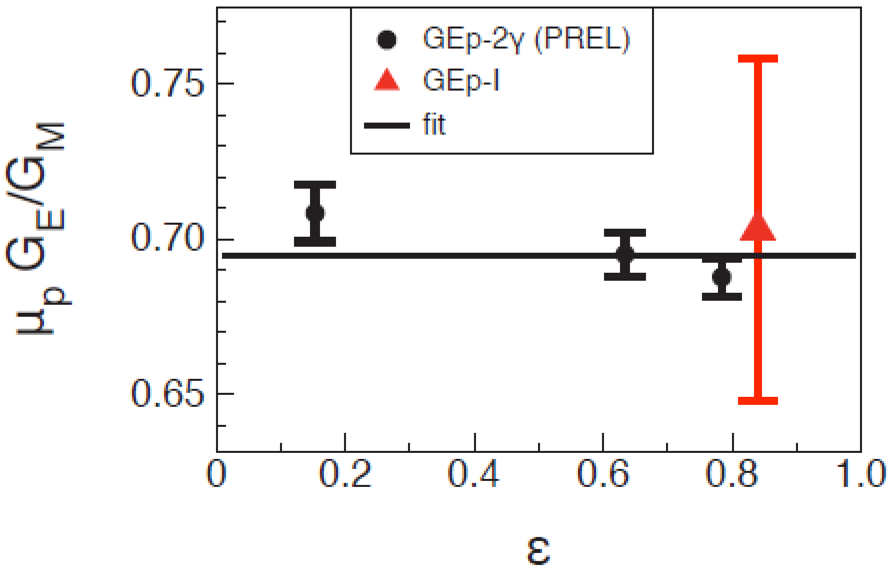

FIG. 1: The ratio $-\mu_p\sqrt{\frac{\tau(1+\varepsilon)}{2\varepsilon}}\frac{P_t}{P_l}$, which equals $\mu_p\frac{G_E}{G_M}$ in the 1γ-approximation, as a function of ε for $Q^2 = 2.5$ GeV^2. The data points are from the GEp-I experiment (red triangle) [1, 2], and from the GEp-2γ experiment (black circles) [12]. The solid curve is an ε-independent fit, given by Eq. (11).

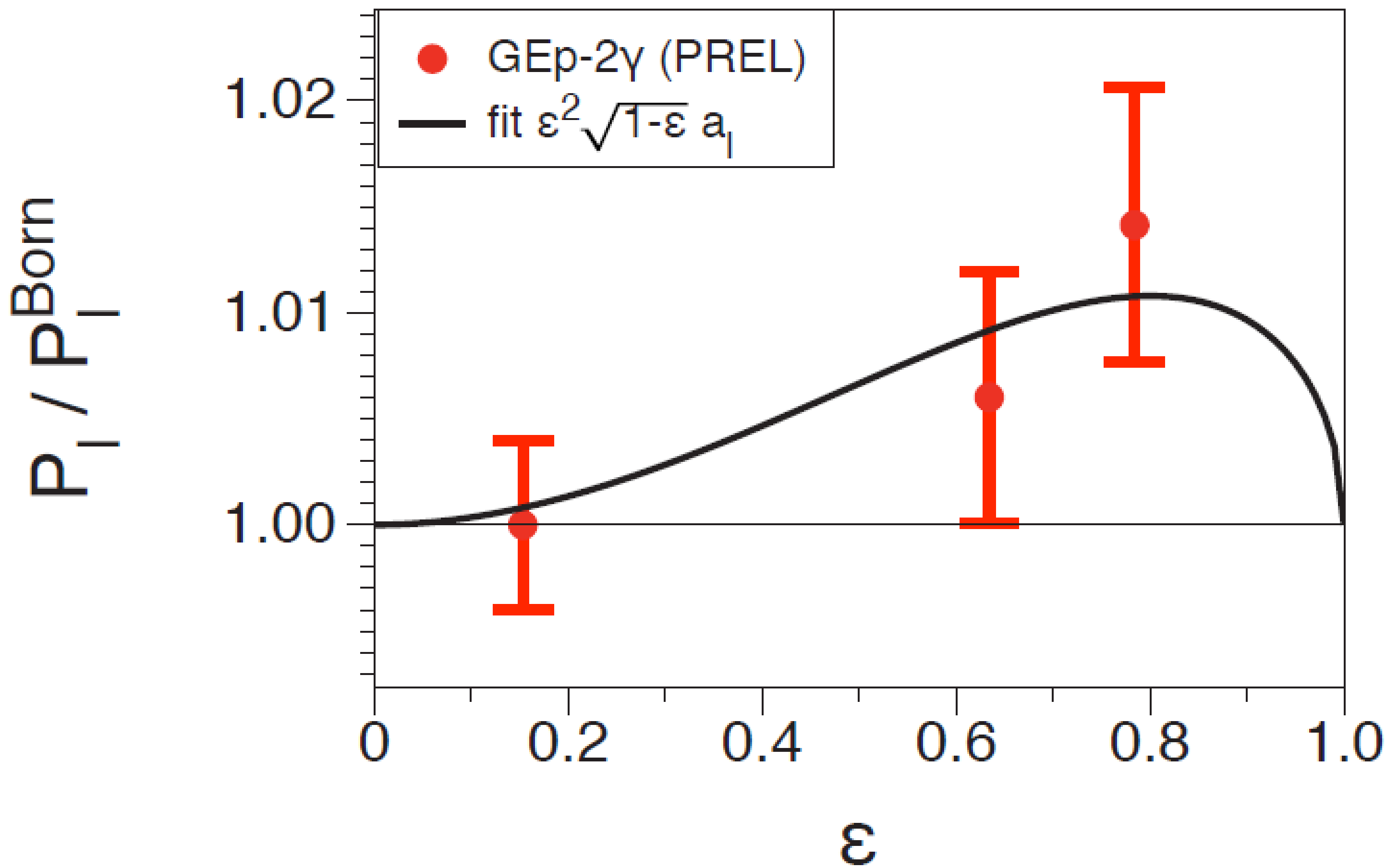

FIG. 2: The ratio P_l/P_l^{Born} as a function of ε for $Q^2 = 2.5\ \text{GeV}^2$. The data points are from the GEp-2γ experiment (black circles) [12]. The solid curve is a fit according to Eq. (12).

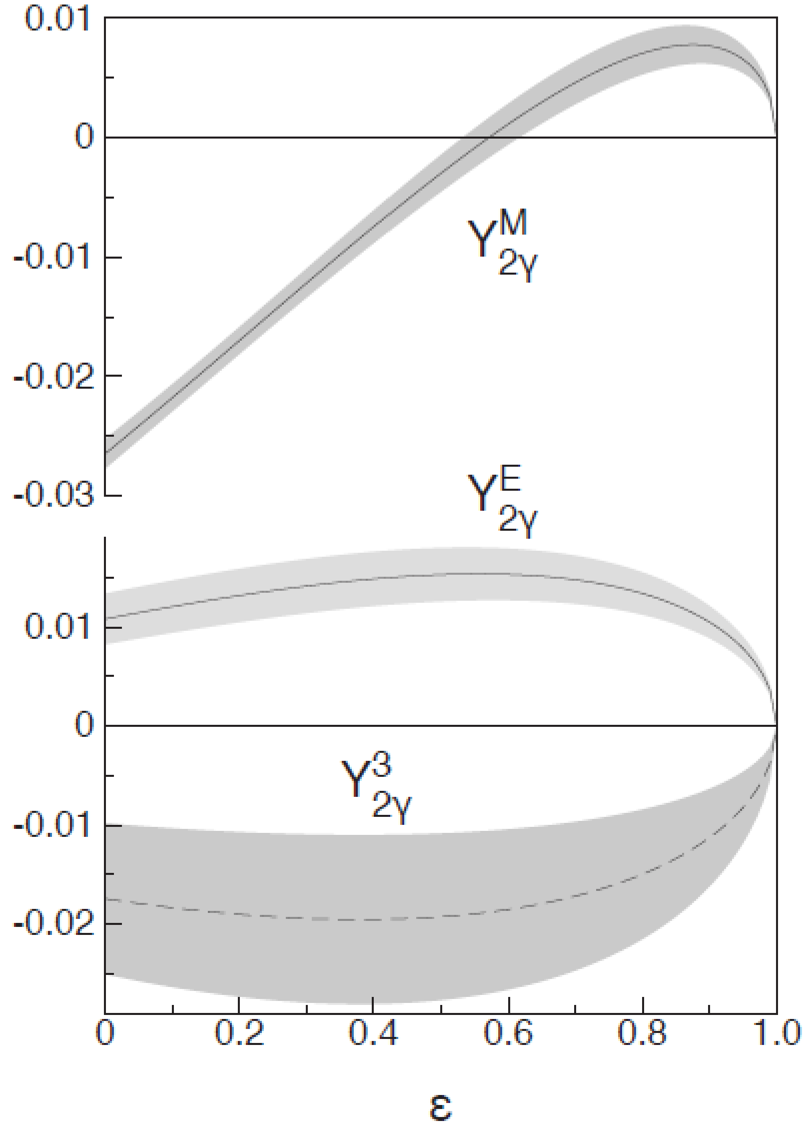

FIG. 4: The extracted 2γ amplitudes as a function of ε for $Q^2 = 2.64$ GeV^2, together with their 1σ error bands.

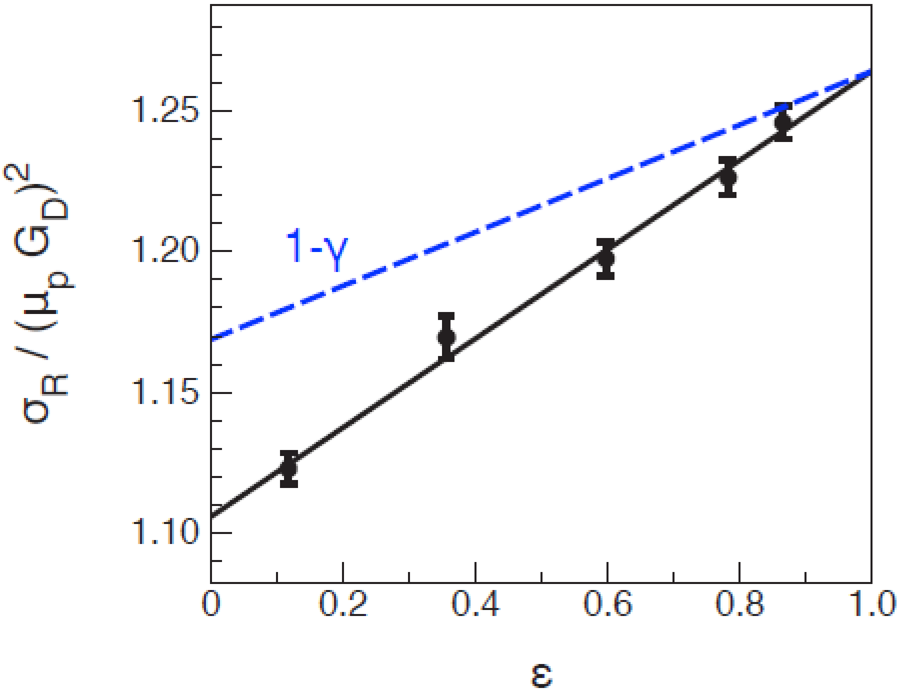

FIG. 3: Rosenbluth plots for elastic $e^- p$ scattering: σ_R divided by $\mu_p^2/(1+Q^2/0.71)^4$ at $Q^2 = 2.64$ GeV^2. Solid curve : fit to the JLab/Hall A cross section data (circles) [6], according to Eq. (13). Dashed curve : 1γ result, using the slope from the polarization data for G_E/G_M [1–3].

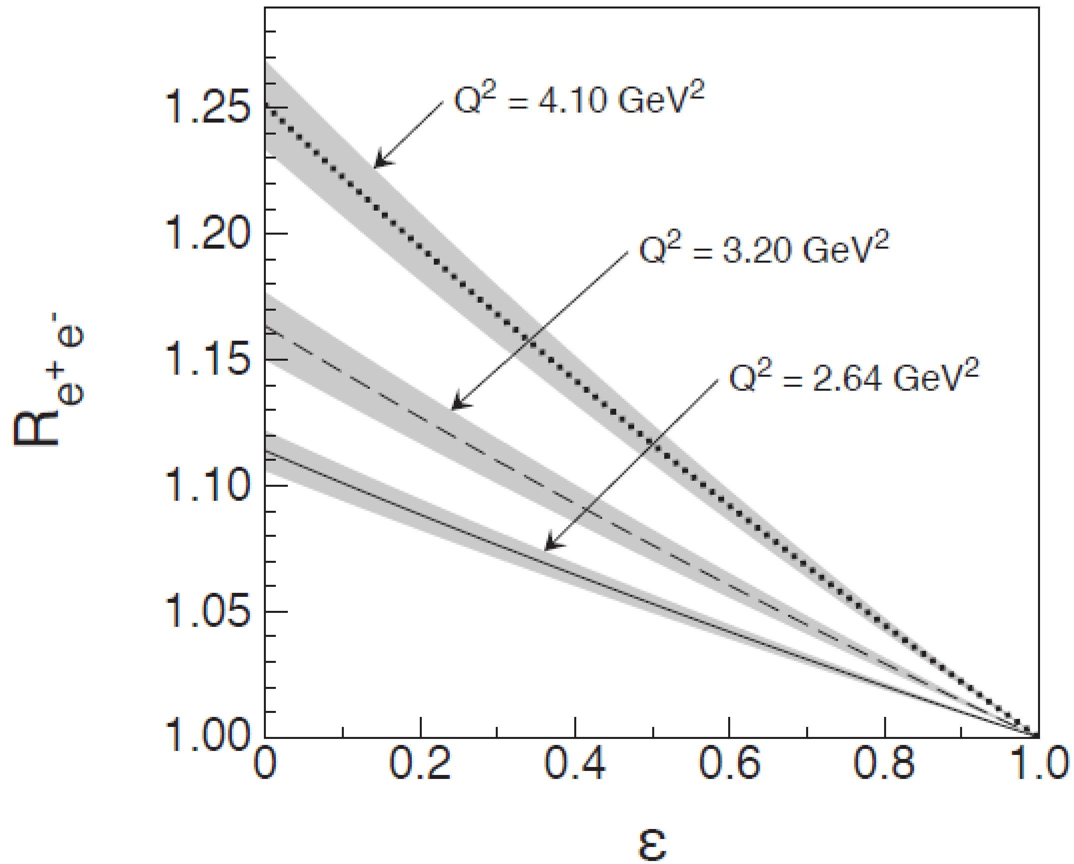

FIG. 5: Predictions for the e^+p/e^-p elastic cross section ratio $R_{e^+e^-}$ as a function of ε, together with their 1σ error bands. The results are based on the fits of the JLab/Hall A cross section data [6], together with the P_t/P_l, and P_l/P_l^{Born} data from Ref. [12] at $Q^2 = 2.5$ GeV^2.

Conclusions

- Empirical analysis of all data by Vanderhaeghen *et al.* suggests a large effect for the positron-to-electron ratio
- It predicts that the effect grows with Q^2
- The optimal energy to take production data with OLYMPUS needs to be reconsidered
- Unofficial data from the Novosibirsk experiment is in qualitative agreement with this prediction

An Experiment to Definitively Determine the Contributions of Multi-Photon Exchange in Elastic Lepton-Nucleon Scattering

D. Hasell, M. Kohl, R. Milner, V. Ziskin

MIT Laboratory for Nuclear Science and Bates Linear Accelerator Center

J. Arrington

Argonne National Laboratory

December 5, 2006

E_0 [GeV]	θ_e	$p_{e'}$ [GeV/c]	θ_p	p_p [GeV/c]	Q^2 [(GeV/c)^2]	ϵ	Counts
4.5	22	3.33	41.6	4.17	2.2	0.891	121357
	26	3.03	36.8	3.85	2.8	0.840	37382
	30	2.74	32.8	3.56	3.3	0.782	13924
	34	2.47	29.4	3.28	3.8	0.720	6046
	38	2.23	26.6	3.03	4.3	0.656	2971
	42	2.01	24.2	2.80	4.7	0.593	1614
							183294
3.0	22	2.43	50.8	3.24	1.1	0.910	1463770
	26	2.27	45.9	3.06	1.4	0.871	500148
	30	2.10	41.6	2.89	1.7	0.825	196674
	34	1.94	37.9	2.72	2.0	0.774	87256
	38	1.79	34.7	2.56	2.3	0.719	42907
	42	1.65	31.8	2.41	2.5	0.663	23025
	46	1.52	29.3	2.27	2.8	0.608	13304
	50	1.40	27.1	2.14	3.0	0.554	8183
	54	1.29	25.1	2.02	3.2	0.502	5306
	58	1.20	23.3	1.92	3.4	0.454	3599
							2344172
2.3	22	1.95	56.1	2.73	0.7	0.918	5842290
	26	1.84	51.5	2.62	0.9	0.883	2203890
	30	1.73	47.2	2.50	1.1	0.842	927333
	34	1.62	43.5	2.38	1.3	0.797	429793
	38	1.51	40.1	2.26	1.5	0.748	216921
	42	1.41	37.1	2.15	1.7	0.697	117977
	46	1.31	34.3	2.05	1.8	0.645	68486
	50	1.23	31.9	1.95	2.0	0.594	42073
	54	1.14	29.6	1.86	2.2	0.544	27146
	58	1.07	27.6	1.77	2.3	0.496	18276
	62	1.00	25.8	1.69	2.4	0.450	12765
	66	0.94	24.1	1.62	2.6	0.407	9204
							9916154

Table 3: Kinematics for three beam energies and count estimate per 4°-angle bin for 1000h at $6 \cdot 10^{32}$ / (cm^{2}s). For the higher beam energy the backward lepton angle acceptance is limited by the forward proton angle.