Проблема формфактора протона и эксперимент *OLYMPUS*

Proton elastic form factors
(traditional, before JLAB data)

- *Fundamental observables describing the distribution of charge and magnetism in the proton and neutron*

- *Determined by quark structure of proton, will be calculable in lattice QCD, also important input for GPDs analysis (quark orbital motion)*

- *Experimentally, data satisfactory described by an exponential spatial fall off of nucleon charge and magnetism* $\sim e^{-\mu r}$ *=> dipole form form factor*
  $G_D(Q^2) \sim (1 + Q^2/0.71)^{-2}$ *, with node in time-like domain*

- *Commonly expected that* $\mu_p G_E(Q^2)/G_M(Q^2) \approx 1$

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???

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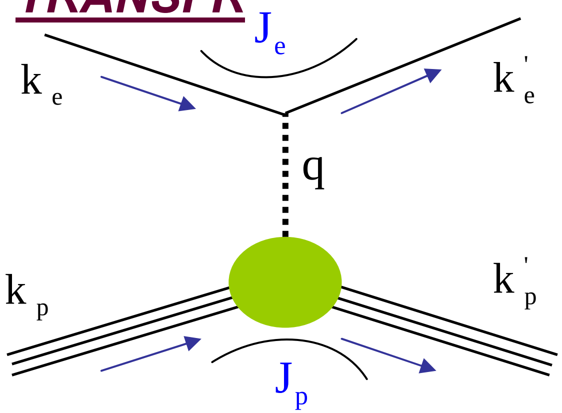
OUTLINE

- Theoretical introduction
- Rosenbluth (LT) separation
- JLAB polarization experiments
- TPE mechanism as possible explanation of LT separation/polarization disagreement
- Experiments to measure e^+/e^- asymmetry, OLYMPUS et al
- Conclusion

ELASTIC ep SCATTERING AMPLITUDE ,CROSS SECTION AND POLARIZATION TRANSFR



In plane wave Born (OPE) approximation e-p scattering invariant amplitude

$$M \sim \underbrace{e_e \cdot \bar{u}(k'_e)\gamma^\mu u(k_e)}_{J_e} \cdot \underbrace{\left(-\frac{1}{q^2}\right)}_{\gamma} \cdot \underbrace{e_p \bar{u}(k'_p)\left[G_E(Q^2)\gamma^\mu + G_M(Q^2) i\sigma^{\mu\nu} q_\nu\right] u(k_p)}_{J_p}$$

*Using **M** one may calculate all necessary observables:*

- *Unpolarized cross section*

$$\frac{d\sigma}{d\Omega} = \frac{d\sigma}{d\Omega}_{Mott} \frac{1}{\varepsilon(1+\tau)}\left[\varepsilon G_E^2(Q^2) + \tau G_M^2(Q^2)\right], \quad \tau = \frac{Q^2}{4M_p},$$

photon polarization $\varepsilon = \dfrac{1}{1+2(1+\tau)\tan^2(\theta_e/2)}, \quad 0 < \varepsilon < 1.$

under study

$$\sigma_r = \varepsilon G_E^2(Q^2) + \tau G_M^2(Q^2)$$

- *Spin transfer from longitudinally polarized electron to recoil proton*

Longitudinal polarization component (along recoil proton momentum) $P_\parallel$

Transverse polarization component (in scattering plane perp. to recoil proton momentum) $P_\perp$

$$\frac{G_E^2(Q^2)}{G_M^2(Q^2)} = -\frac{P_\perp}{P_\parallel} \cdot \frac{E_e + E'_e}{2M_p} \tan(\theta_e/2)$$

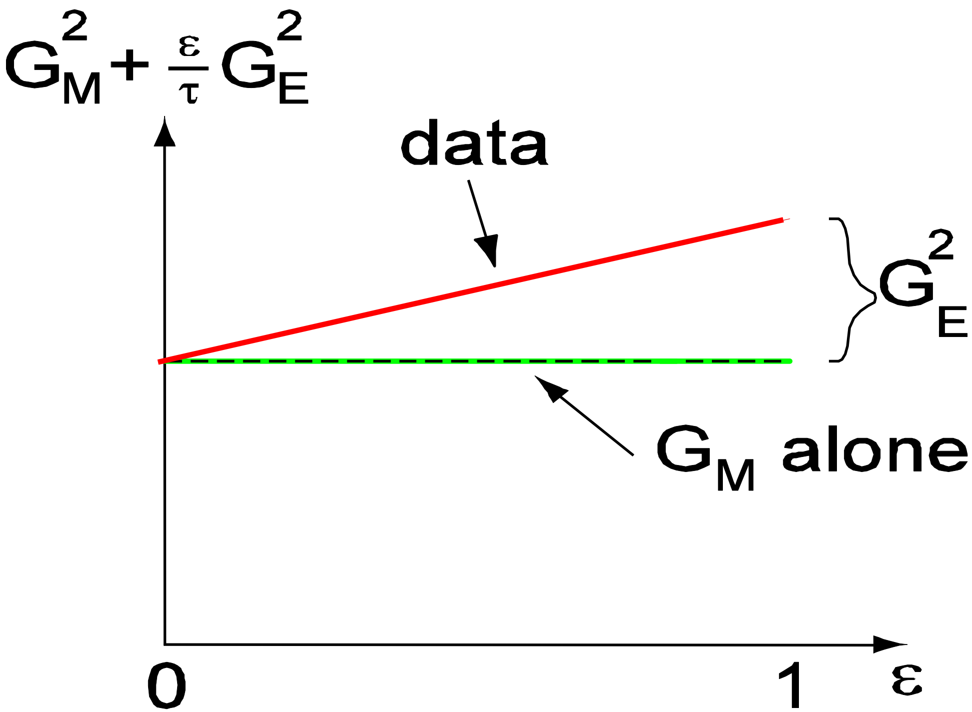
Rosenbluth separation (L-T separation)

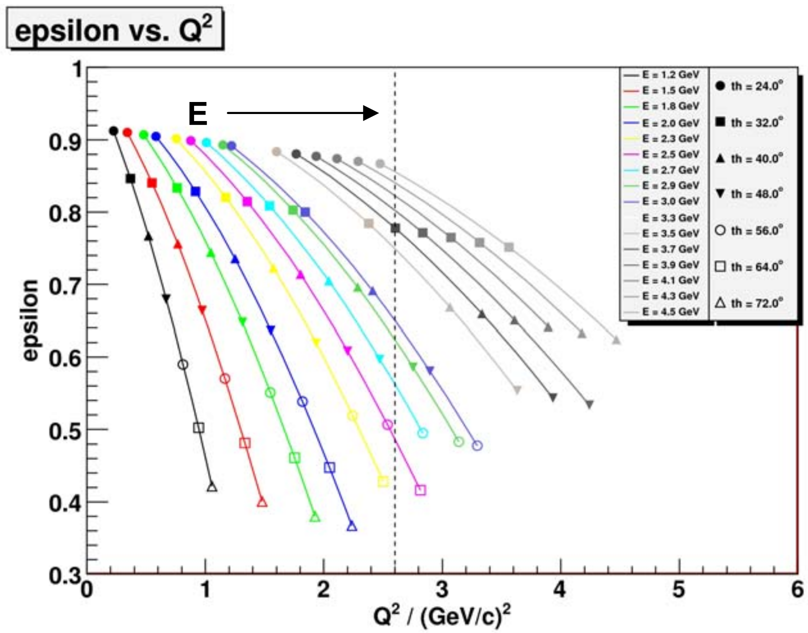
$$\sigma_r = \varepsilon G_E^2(Q^2) + \tau G_M^2(Q^2)$$

$$\textit{scan} \quad \varepsilon = \frac{1}{1+2(1+\tau)\tan^2(\theta_e/2)} \quad \textit{at fixed} \quad \tau = \frac{Q^2}{4M_p}$$

$$Q^2 = -q^2 = 4E_e E_e' \sin^2\frac{\theta_e}{2} \qquad E_e \searrow, (E_e' \searrow), \theta_e \to 2\pi, \ \varepsilon \to 0$$

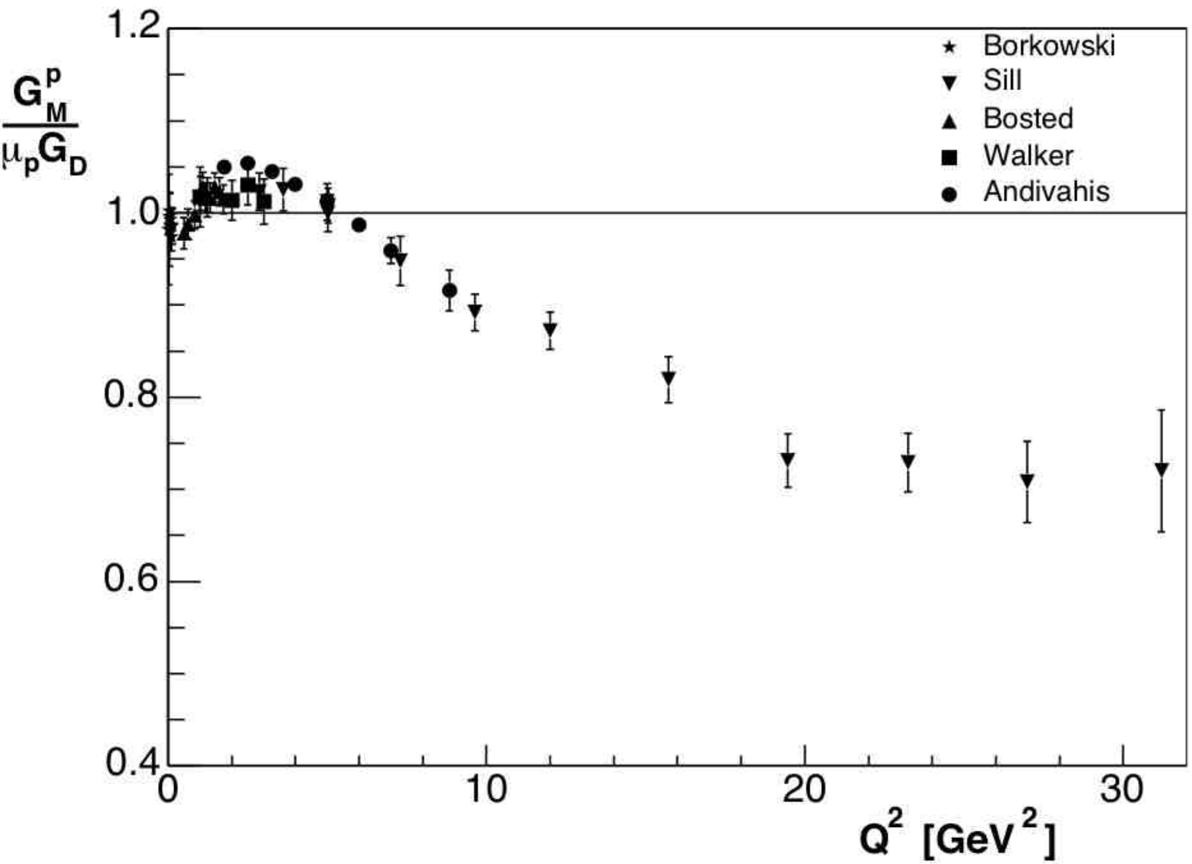
scalar photon fraction $\to 1$





Extraction of FFs from Unpolarized Elastic e-p Scattering

Proton magnetic form factor



Dipole parametrization $G_D(Q^2)$

$$\frac{\Lambda^3}{8\pi}\int e^{-\Lambda R} e^{i\vec{q}\vec{x}}\, d^3x =$$

$$\frac{\Lambda^3}{2}\int_0^\infty e^{-\Lambda R}\frac{\sin qR}{q} R dR = G_D(Q^2)$$

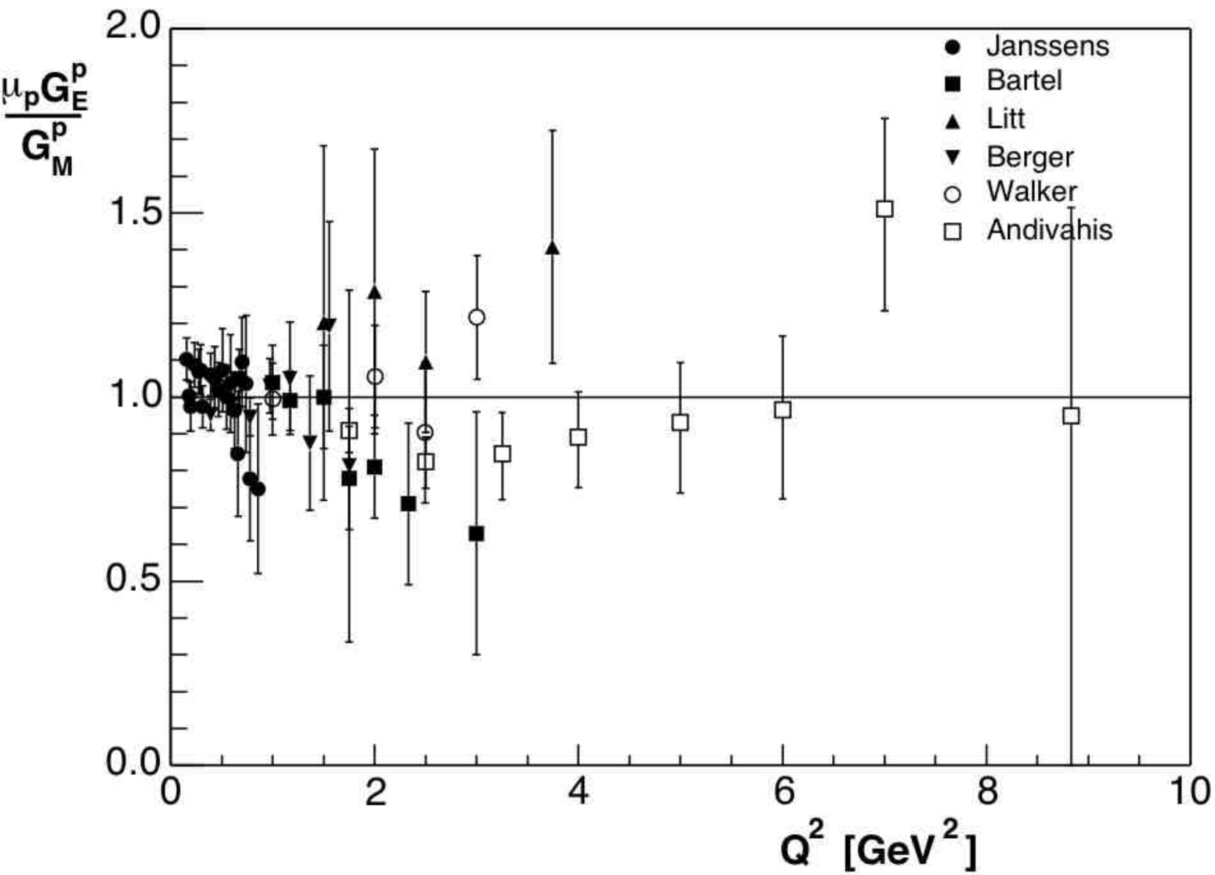
$$G_D(Q^2) = \left(\frac{\Lambda^2}{\Lambda^2 + Q^2}\right)^2, \quad Q^2 = |\vec{q}|^2$$

with $\Lambda = 0.84\,\text{GeV}$

By far not ideal but acceptable parameterization

Extraction of FFs from Unpolarized Elastic e-p Scattering

Proton electric form factor



Under study

$$\sigma_r = \varepsilon G_E^2(Q^2) + \tau G_M^2(Q^2)$$

Note that $0 < \varepsilon < 1$

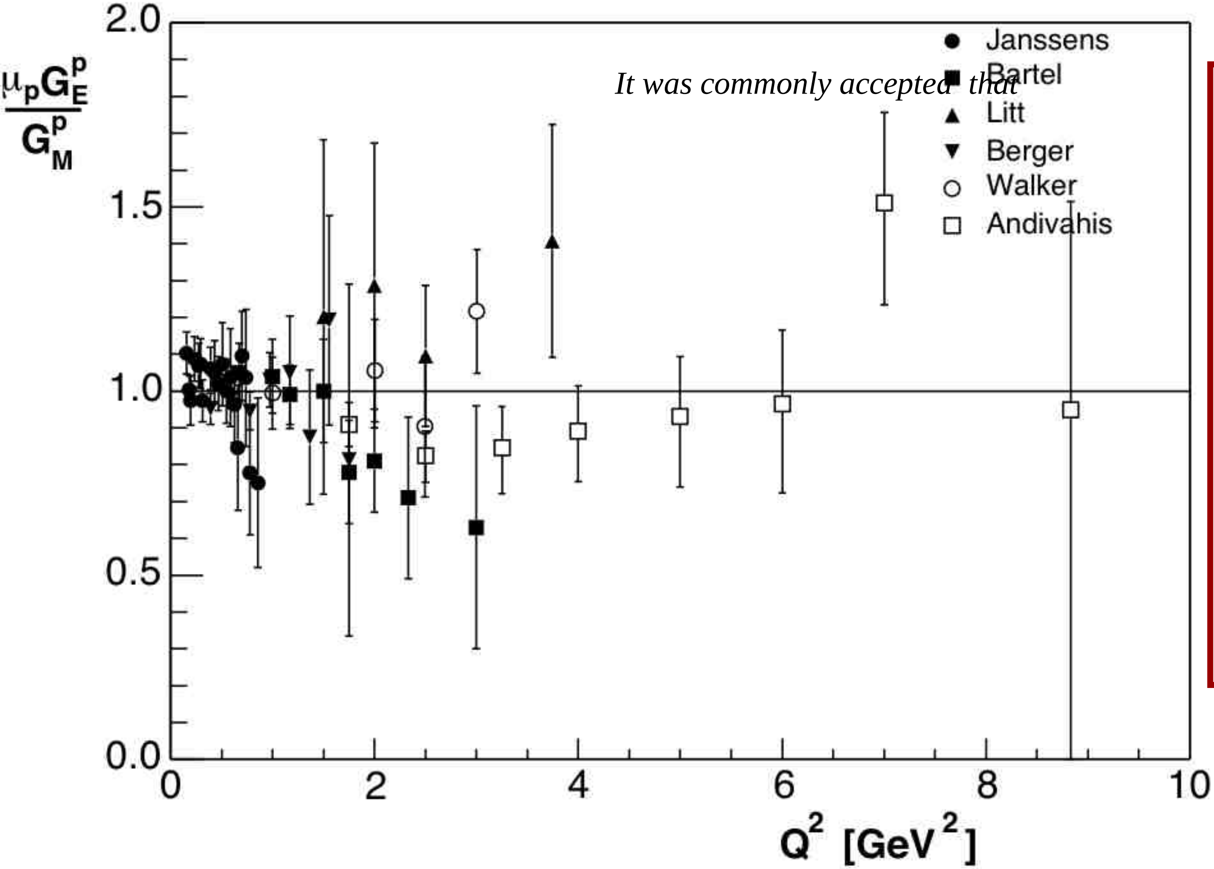
while $0 < \tau \equiv \frac{Q^2}{2M_p} < 15$

$\Rightarrow$ *problems to extract* $G_E^2(Q^2)$ *at high* Q^2

Additional problem →
cross section normalization uncertainty (included in error bars)

Extraction of FFs from Unpolarized Elastic e-p Scattering

Proton electric form factor



It was commonly accepted that

$$\frac{\mu_p G_E^2(Q^2)}{G_M^2(Q^2)} \approx 1$$

JLAB measurements of recoil proton polarization in contradiction with Rosenbluth (LT) separaton results

$$\frac{\mu_p G_E(Q^2)}{G_M(Q^2)} = ???$$

JLAB Polarization Transfer experiment

(V.Punjabi, C.F.Perdrisat, et al. Phys.Rev. C71, 2005)

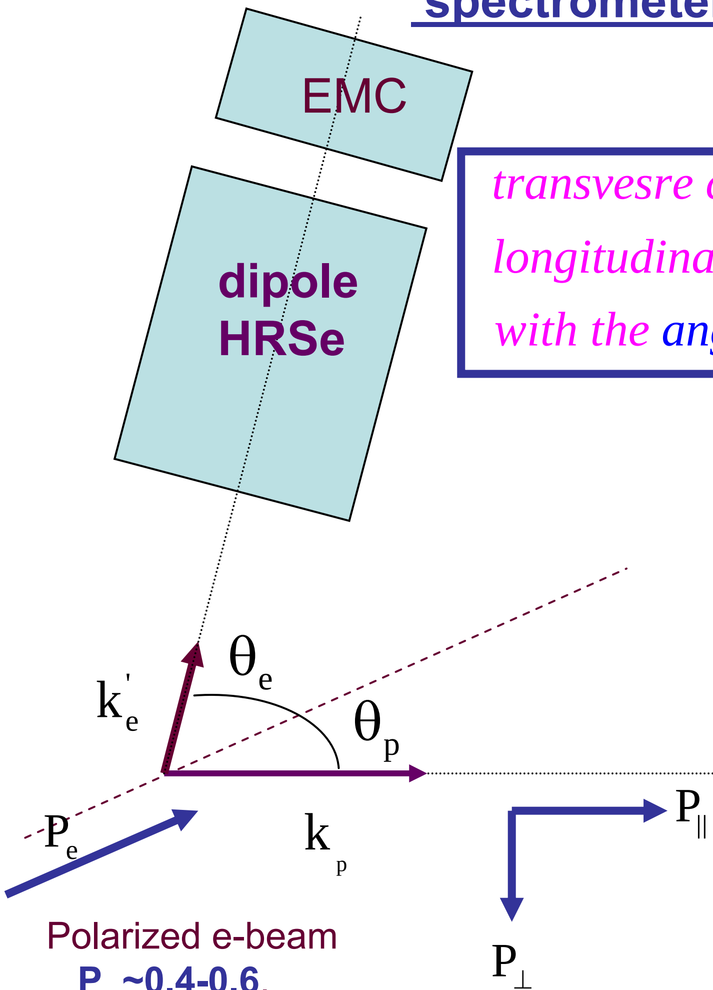
$$\frac{G_E^2(Q^2)}{G_M^2(Q^2)} = -\frac{P_\perp}{P_\parallel}\cdot\frac{E_e+E_e'}{2M_p}\tan(\theta_e/2)$$

JLAB Hall A two-arm spectrometer (top view)

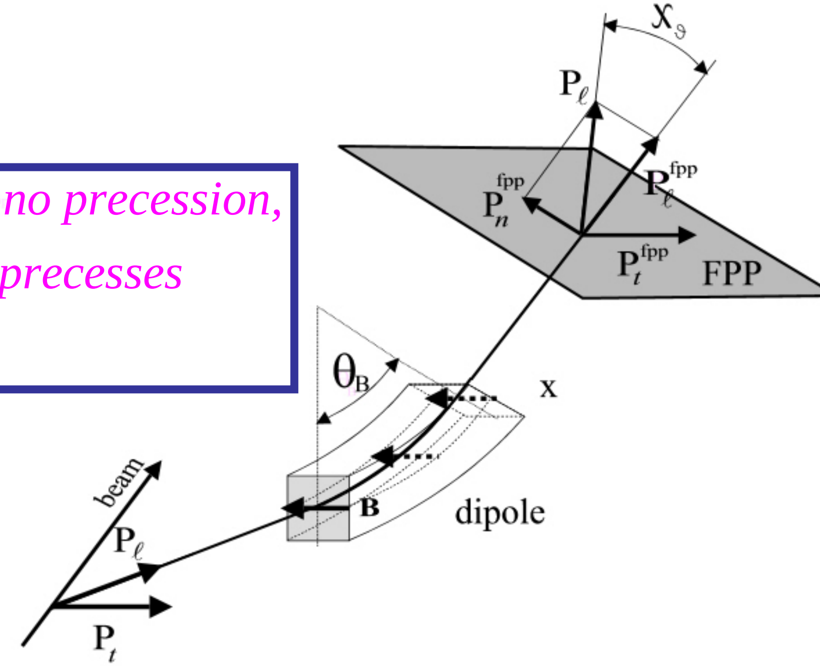
transvesre component $P_\perp$ *no precession,*

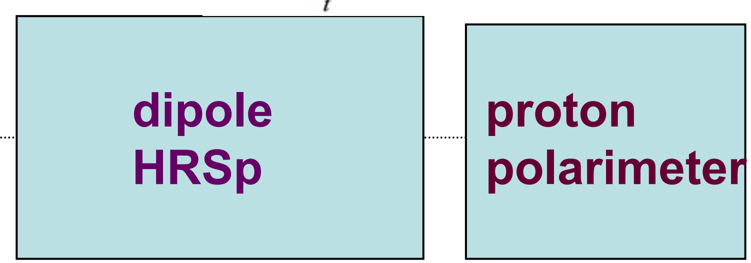
longitudinal component $P_\parallel$ *precesses*

with the angle $=\gamma(\mu_p-1)\Theta_B$



Polarized e-beam
P_e ~0.4-0.6,
0.934-4.091 GeV,
5-15 μA.





Vertical bending
Θ_B=45 deg.

JLAB Polarization Transfer Results

(V.Punjabi, C.F.Perdrisat, et al. Phys.Rev. C71, 2005)

disagreement with LT separation results

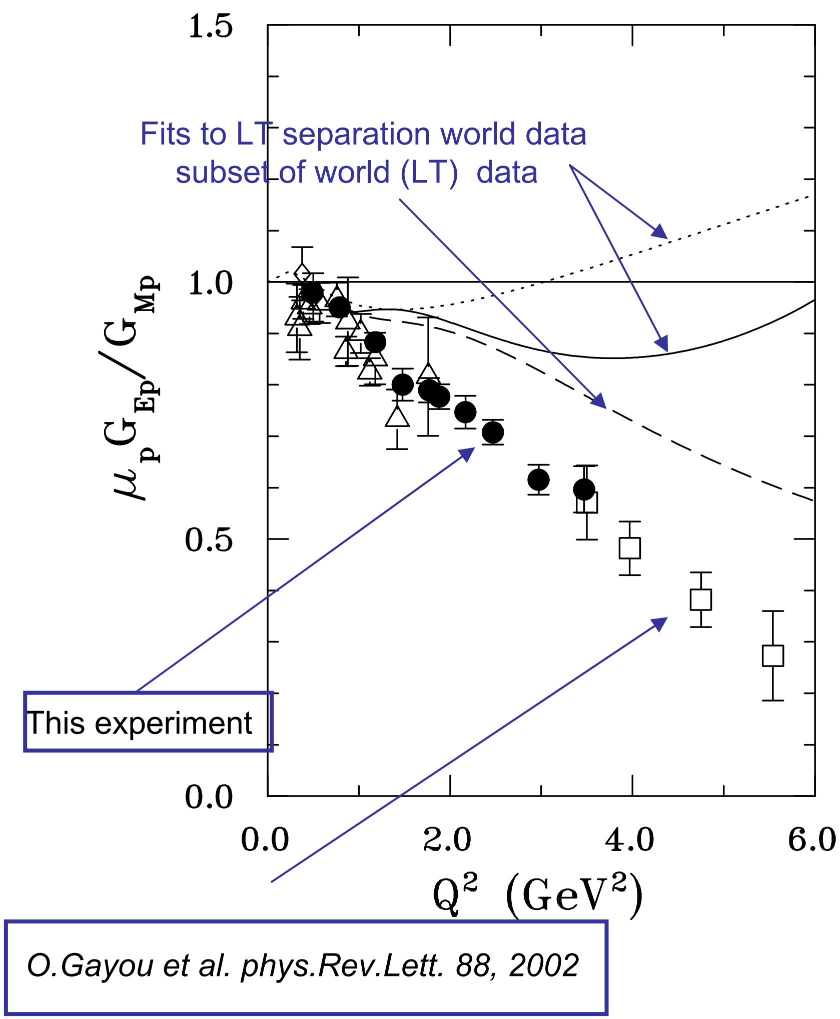
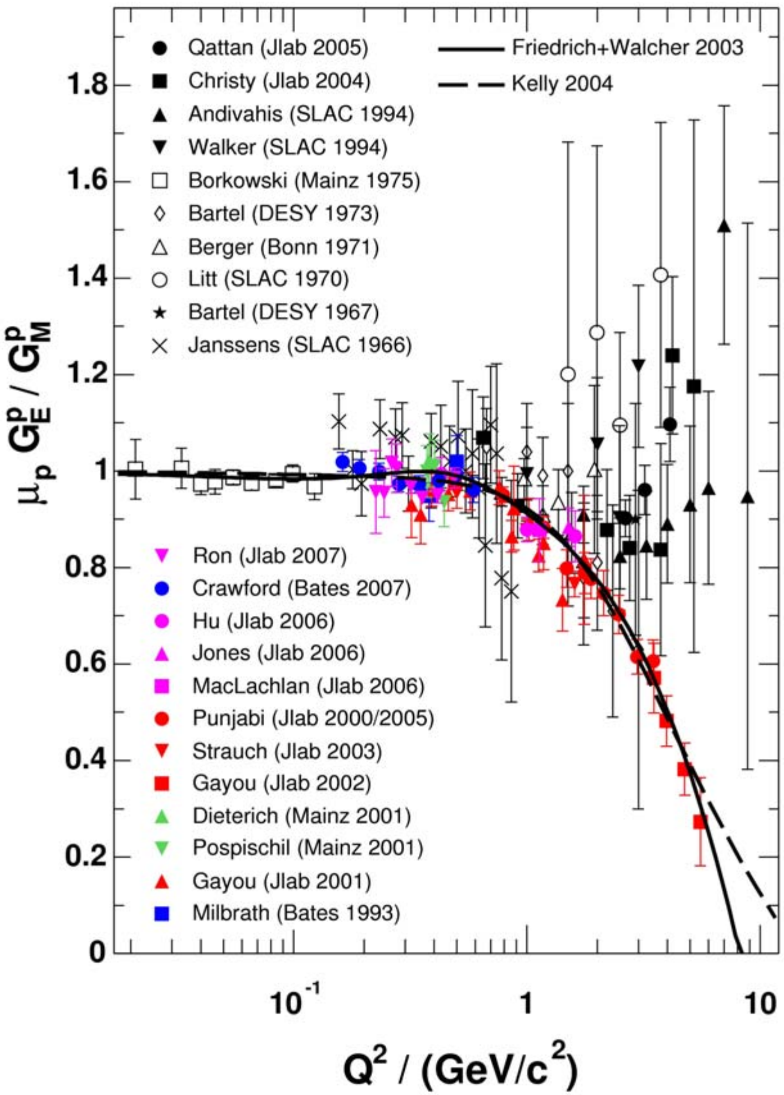


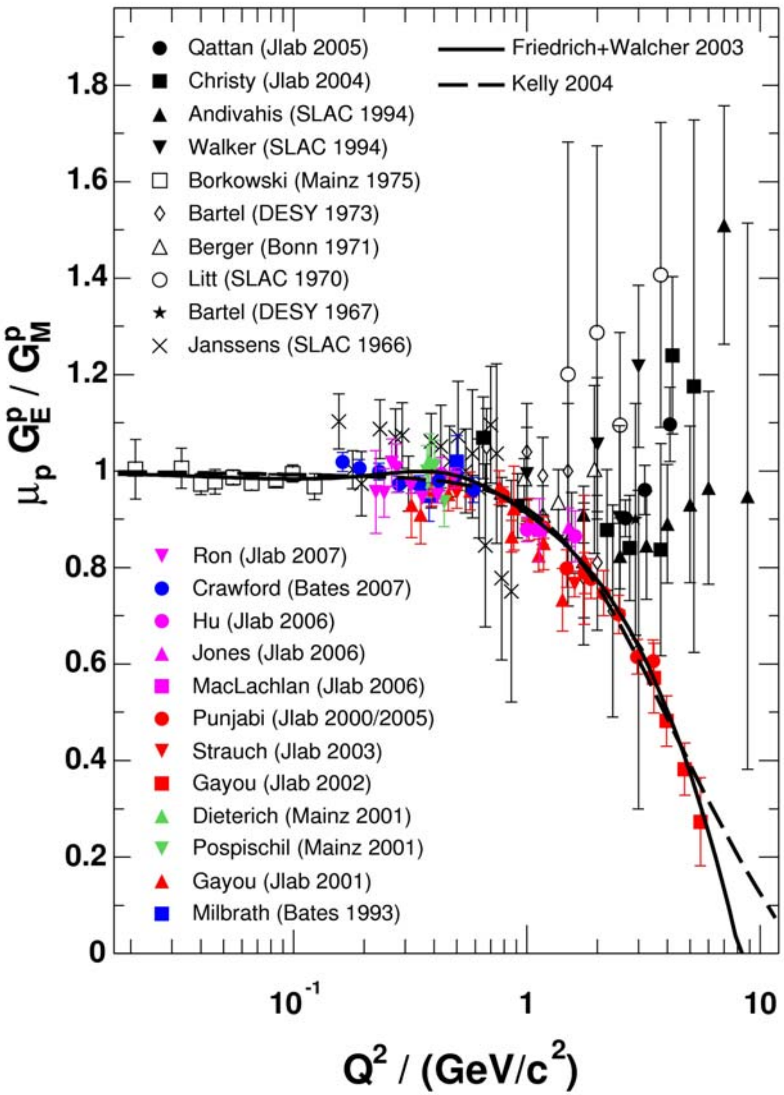
TABLE VI: The ratio $\mu_p G_{Ep}/G_{Mp} \pm$ statistical uncertainty (1σ). Δ_{sys} is the systematic uncertainty from Table VII. $\overline{Q}^2$ and $\overline{\chi}_\theta$ are the weighted average four momentum transfer squared and spin precession angle, respectively. ΔQ^2 is half the Q^2 acceptance. The last column P_t/P_ℓ is the ratio of measured polarization components at the target, the relative uncertainty is the same as for $\mu_p G_{Ep}/G_{Mp}$.

$\overline{Q}^2 \pm \Delta Q^2$ (GeV^2)	$\overline{\chi}_\theta$ (deg)	$\mu_p G_{Ep}/G_{Mp}$ (± stat. uncert.)	Δ_{sys}	P_t/P_ℓ
0.49±.04	105	0.979 ± 0.016	0.006	-0.822
0.79±.02	118	0.951 ± 0.012	0.010	-0.527
1.18±.07	136	0.883 ± 0.013	0.018	-0.492
1.48±.11	150	0.798 ± 0.029	0.026	-0.422
1.77±.12	164	0.789 ± 0.024	0.035	-0.381
1.88±.13	168	0.777 ± 0.024	0.033	-0.368
2.13±.15	181	0.747 ± 0.032	0.034	-0.329
2.47±.17	196	0.703 ± 0.023	0.033	-0.284
2.97±.20	218	0.615 ± 0.029	0.021	-0.224
3.47±.20	239	0.606 ± 0.042	0.014	-0.198

Rosenbluth (LT) separation and polarization measurement data compilation

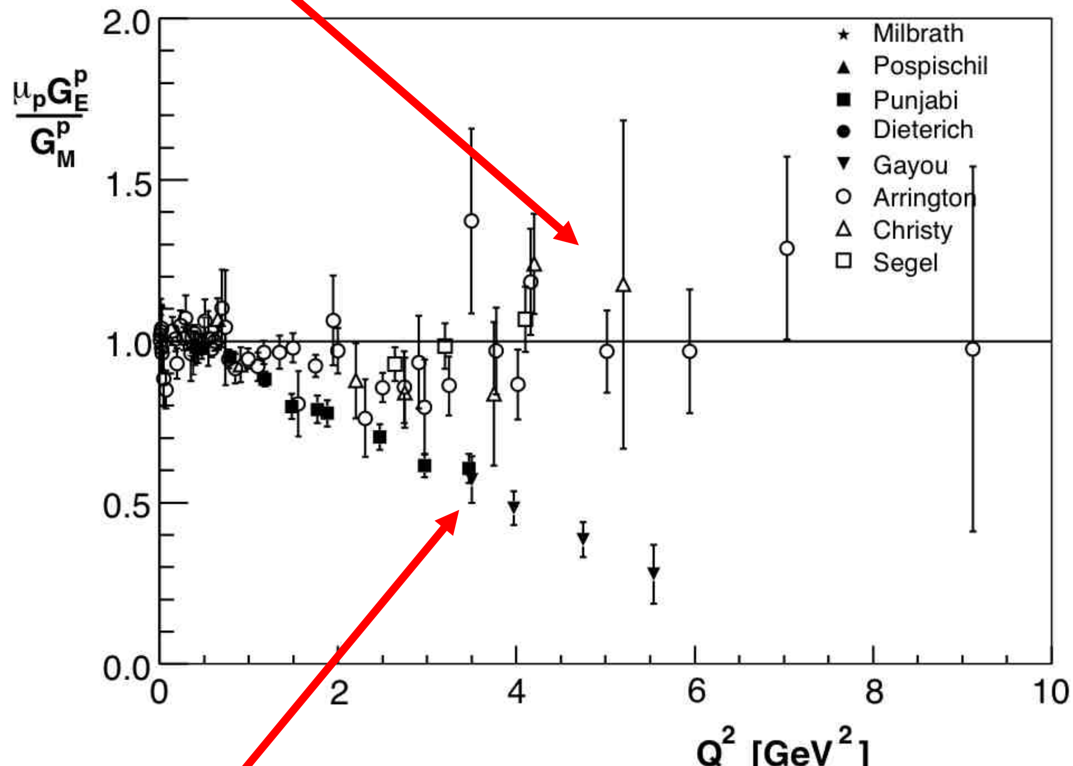


Rosenbluth (LT) separation and polarization measurement data compilation



Christy, Segel→recent LT data
Arrington →reanalized older LT data
Punjabi,Gayoy… → recoil proton polarization measurements

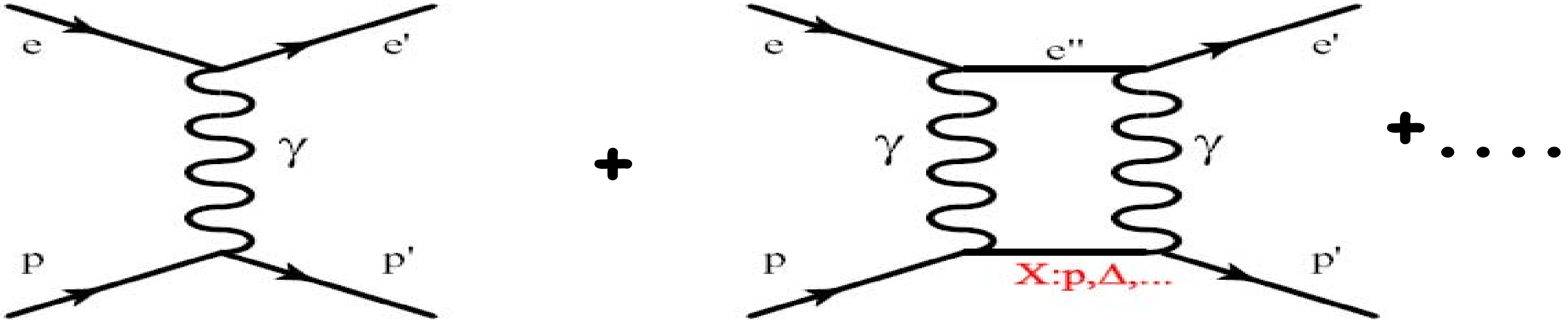
LT separation



Recoil polarization

Apparent disagreement !!

Contribution of Two Photon Exchange Effects ??



Estimation of TPE effect on LT and polarization data

- ✓ *significant effect on LT separation results*
- ✓ *a few per cent effect on polarization data*

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

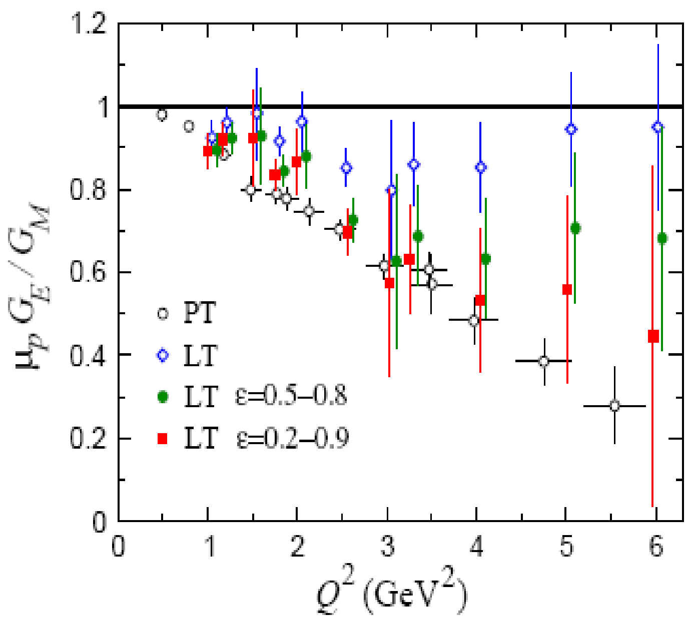


FIG. 5: The ratio of proton form factors $\mu_p G_E/G_M$ measured using LT separation (open diamonds) [2] and polarization transfer (PT) (open circles) [5]. The LT points corrected for 2γ exchange are shown assuming a linear slope for $\varepsilon = 0.2 - 0.9$ (filled squares) and $\varepsilon = 0.5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

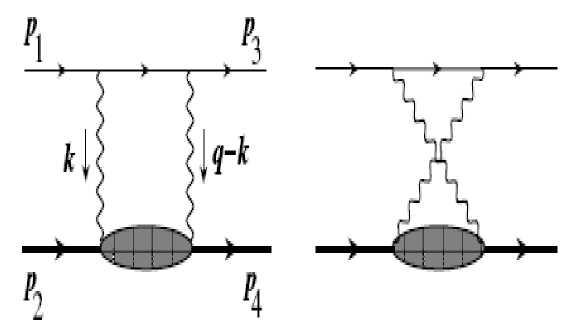
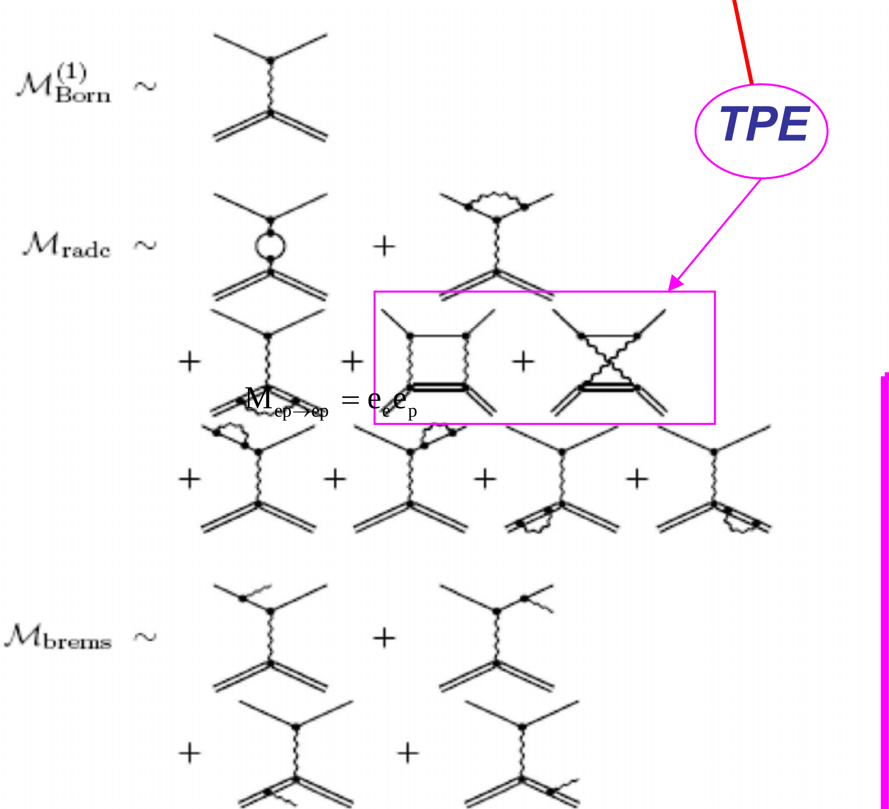


FIG. 1. Two-photon exchange box and crossed box diagrams for elastic electron-proton scattering.

Radiative Corrections & TPE graphs

Contribution from two photon exchange diagram not taken into account in traditional analysis may be an explanation

$$\left|M_{ep\to ep}\right|^2 = e_e^2 e_p^2 \left[\left|M_{Born}\right|^2 + 2e_e e_p M_{Born}\, \mathrm{Re}\left(M^*_{2\gamma}\right) + 2e_e e_p \left(M_{e-bremm} M^*_{p-bremm}\right) \right]$$



$$2e_e e_p M_{Born}\, \mathrm{Im}\left(M^*_{2\gamma}\right) \sim P_{transverse}$$

perpendicular to the production plane, not related neither beam nor target helicity (spontanious)

another indication of TPE

small, not measured yet

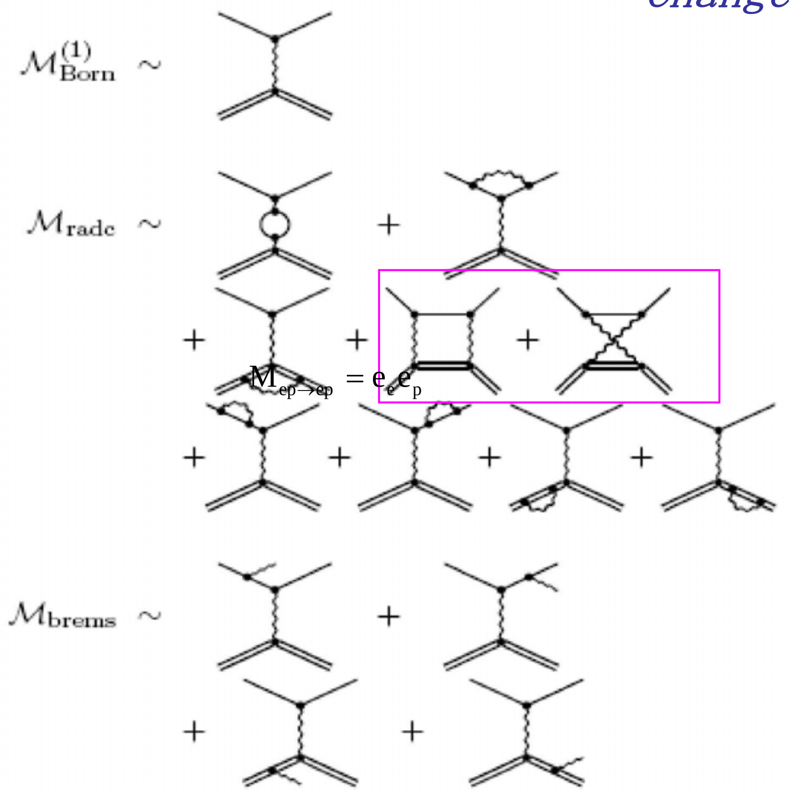
Radiative Corrections & TPE graphs

Contribution from two photon exchange diagram not taken into account in traditional analysis may be an explanation

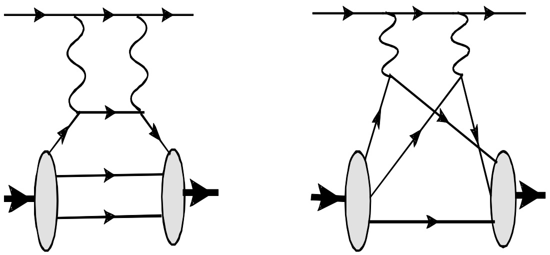
$$\left|M_{ep\to ep}\right|^2 = e_e^2 e_p^2 \left[\left|M_{Born}\right|^2 + 2e_e e_p M_{Born}\, \mathrm{Re}\left(M^*_{2\gamma}\right) + 2e_e e_p \left(M_{e-bremm}\ M^*_{p-bremm}\right) \right]$$

Change sign

Calculable standard radiative correction



Charge asymmetry & TPE graph theoretical calculations



Charge asymmetry

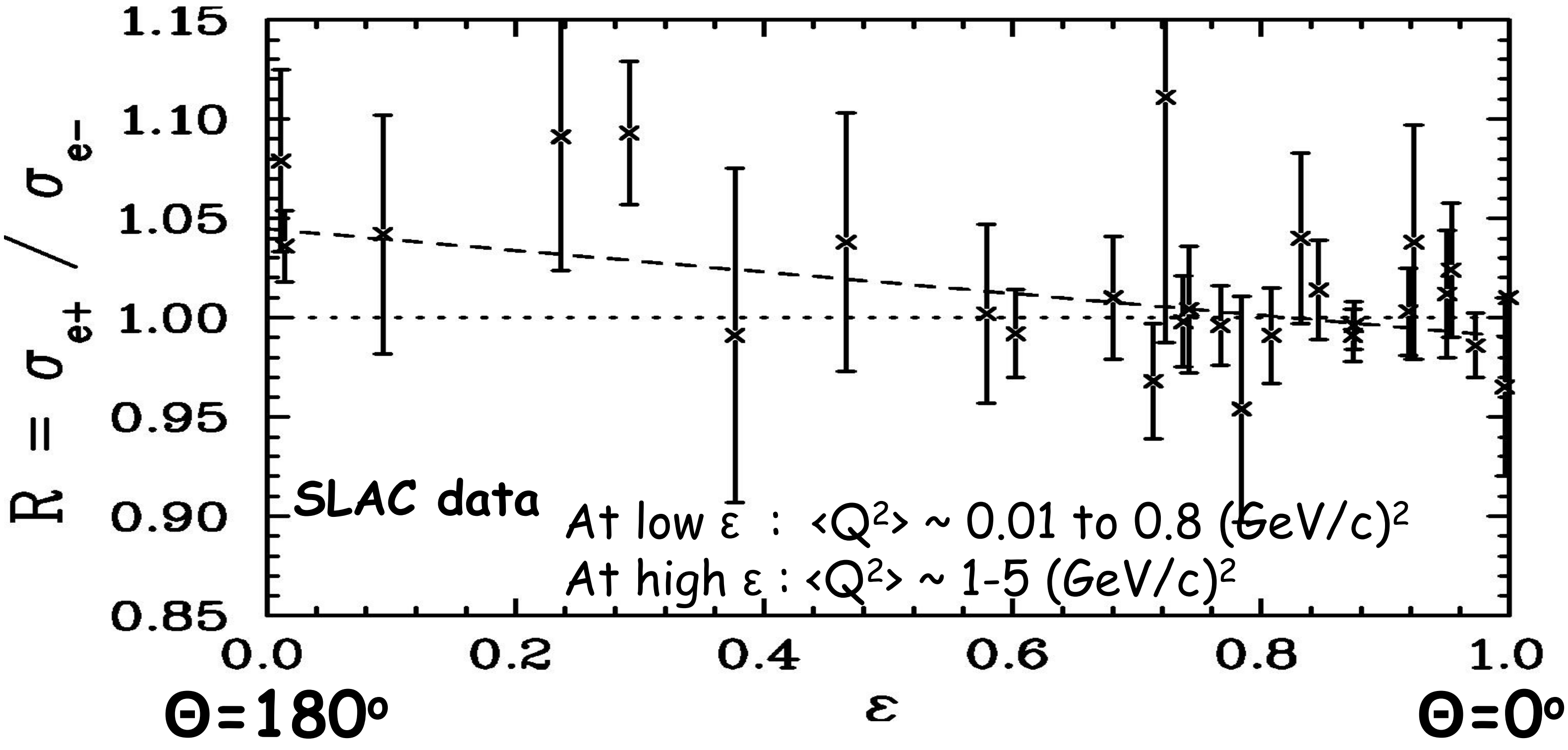
$$\frac{\sigma^+}{\sigma^-} \simeq \frac{|M_{Born}|^2 + 2e_e e_p M_{Born}\,\mathrm{Re}(M^*_{2\gamma}) + 2e_e e_p\,\mathrm{Re}(M_{e-bremstr} M^*_{p-bremstr})}{|M_{Born}|^2 - 2e_e e_p M_{Born}\,\mathrm{Re}(M^*_{2\gamma}) - 2e_e e_p\,\mathrm{Re}(M_{e-bremstr} M^*_{p-bremstr})}$$

Intermediate state contributions → model dependent calculations

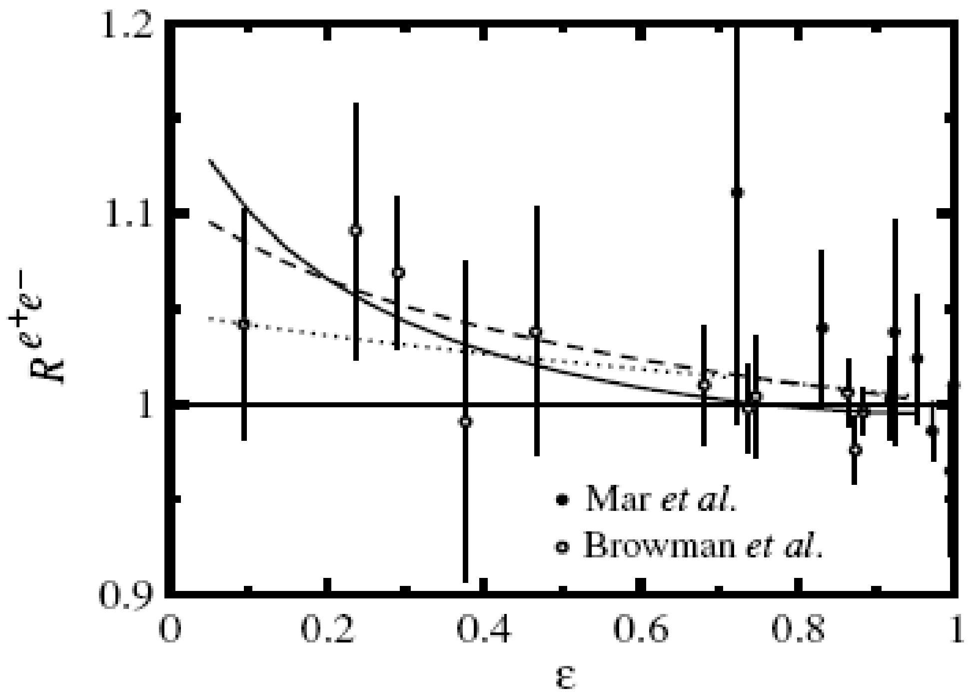
- *P.A.M. Guichon and M. Vanderhaeghen, PRL91, 142303 (2003)*
- *P.G. Blunden, W. Melnitchouk, and J.A. Tjon, PRC72, 034612 (2005), PRL91, 142304 (2003)*
- *M.P. Rekalo and E. Tomasi-Gustafsson, EPJA22, 331 (2004)*
- *Y.C. Chen et al.,PRL93, 122301 (2004)*
- *A.V. Afanasev and N.P. Merenkov, PRD70, 073002 (2004)*
- *……….*

Measured and estimated TPE effect on charge asymmetry

J. Arrington PRC 69, 032201(R) (2004)



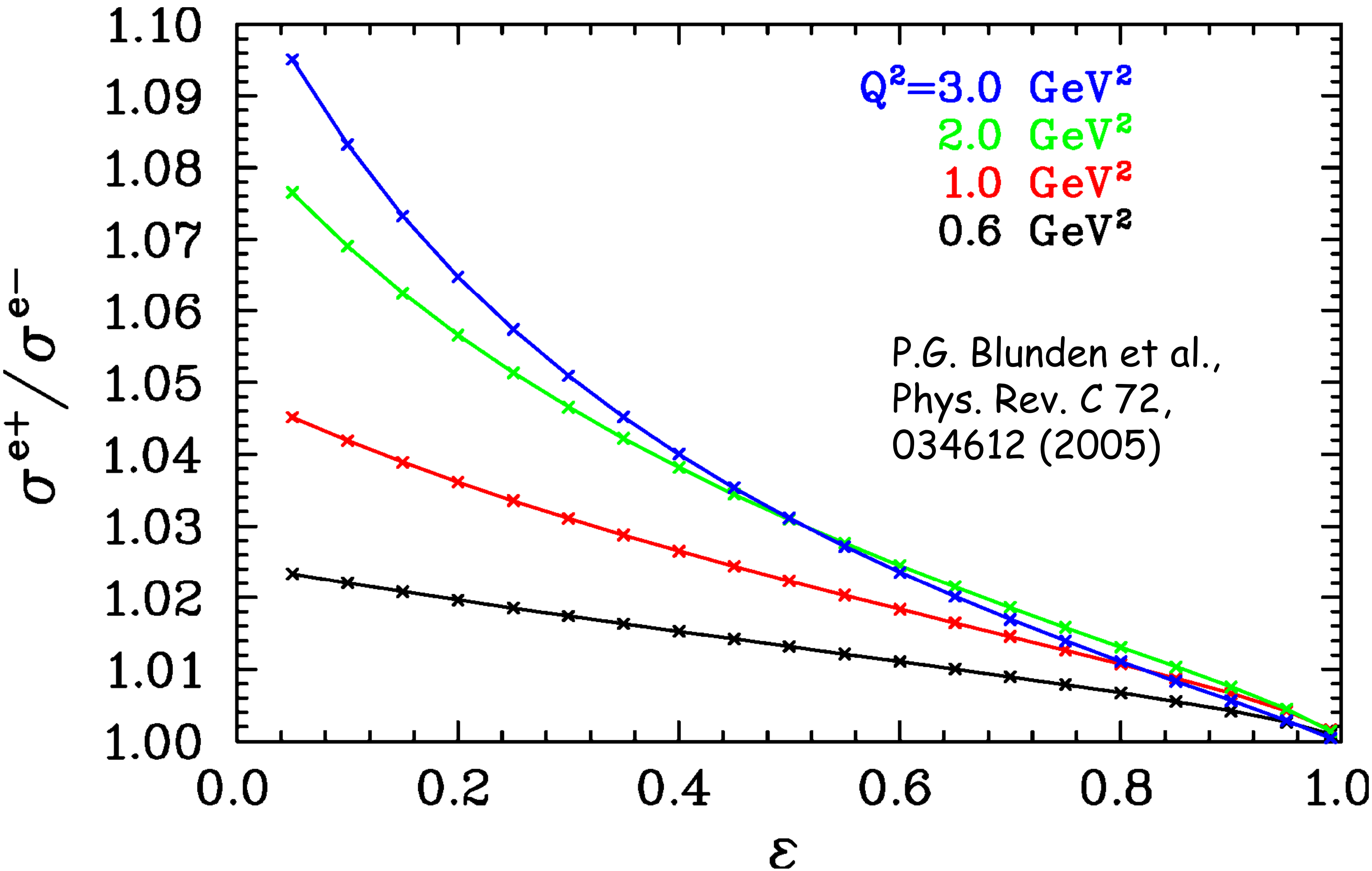
Measured and estimated TPE effect on charge asymmetry



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

FIG. 7. Ratio of elastic e^+p to e^-p cross sections. The data are from SLAC [31,32], with Q^2 ranging from 0.01 to 5 GeV^2. The results of the 2γ exchange calculations are shown by the curves for $Q^2 = 1$ (dotted), 3 (dashed), and 6 GeV^2 (solid).

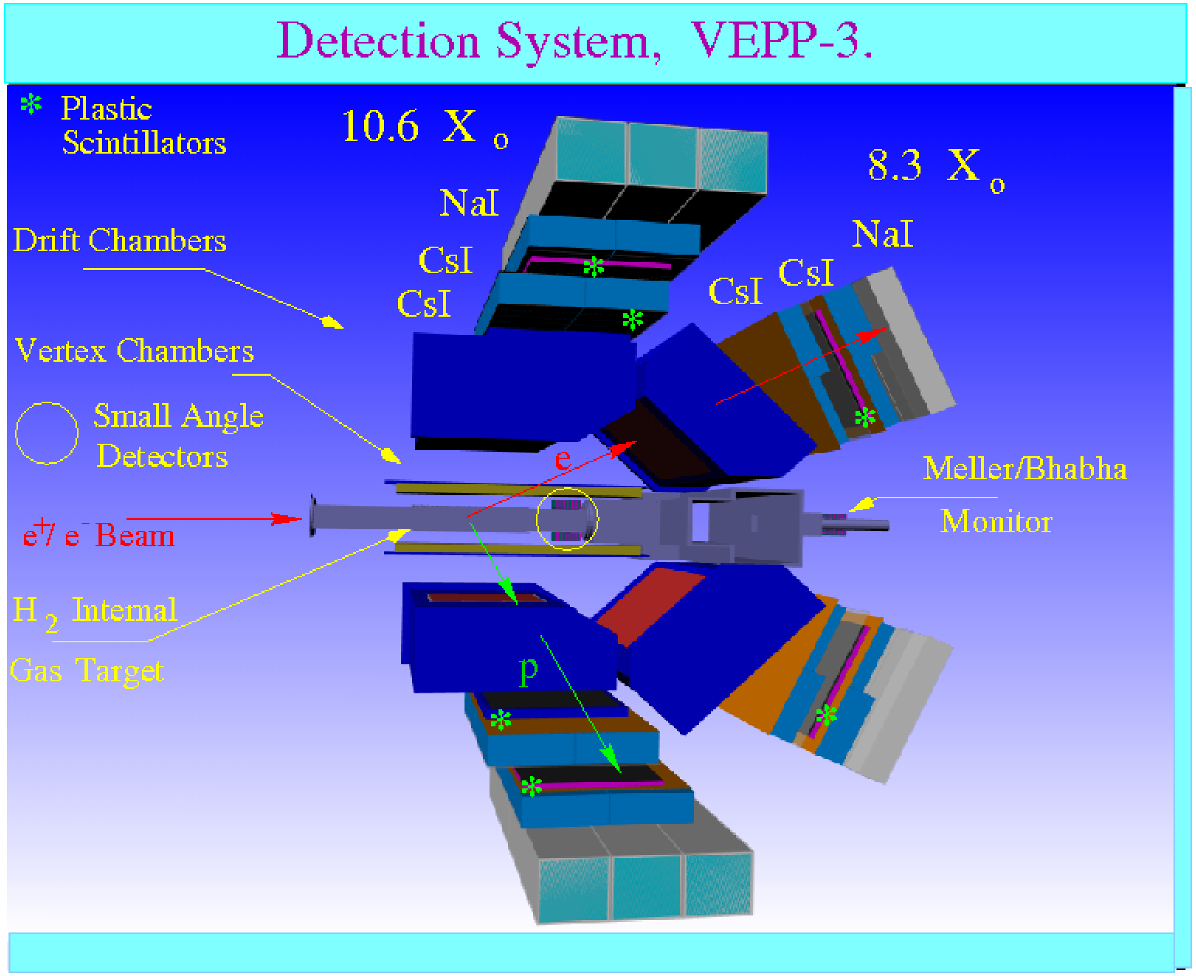
e^+p/e^-p cross section ratio



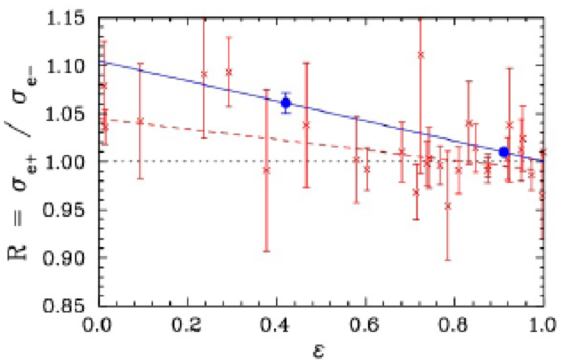
Experiments planned to measure e^+e^- asymmetry at per cent level

VEPP-3 experiment

E_e=1.6 GeV (up to 2 GeV)
electron current ~ 30mA, positron current limited to ~ 9mA
HERMES type gas target 10^{15} atoms/cm^2, L≈10^{31}cm^{-2}s

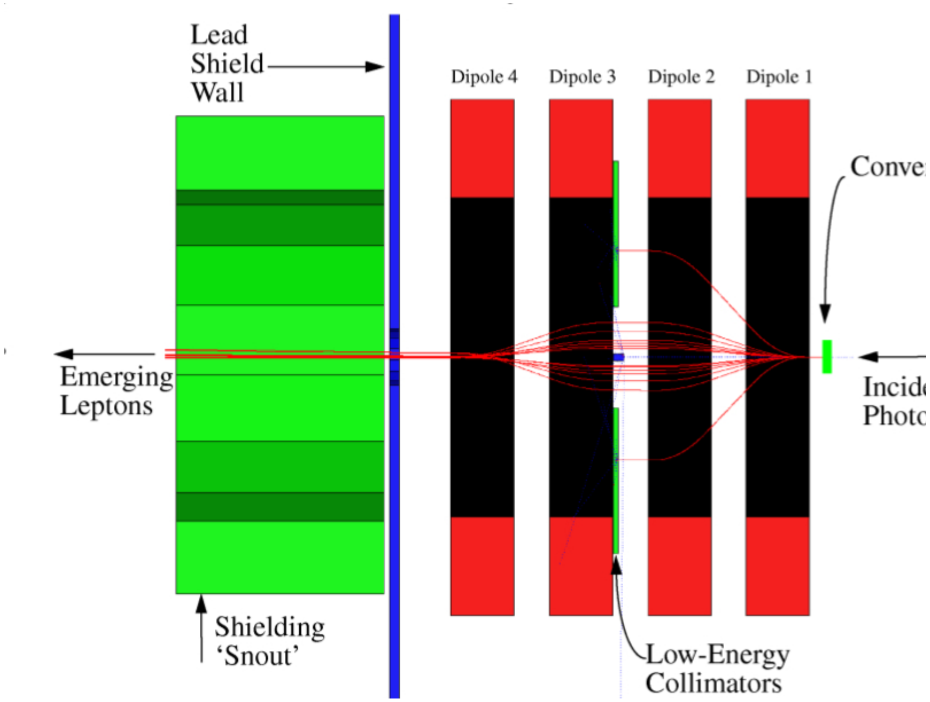


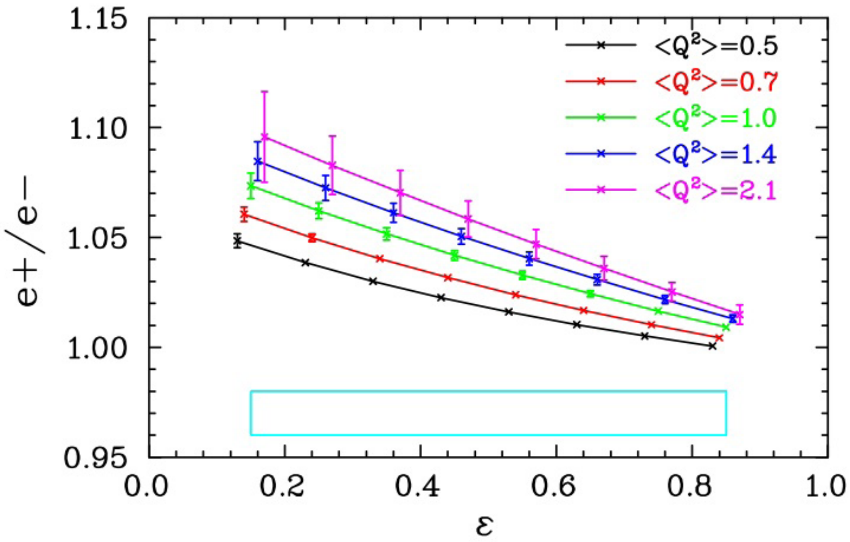
Planned for 2009-11



JLAB Polarization Transfer Results

Hall B, CLAS spectrometer,
primary 5.7Gev e-beam 1мA→ γ-beam → e+e- beam 250 pA→
thick hydrogen target→L=1.3x10^{33} cm^{-2}sec^{-1}
Major challenge hard background conditions related to e+e- production target





A PROPOSAL TO DEFINITIVELY DETERMINE THE CONTRIBUTION OF MULTIPLE PHOTON EXCHANGE IN ELASTIC LEPTON-NUCLEON SCATTERING

THE OLYMPUS COLLABORATION

June 23, 2008

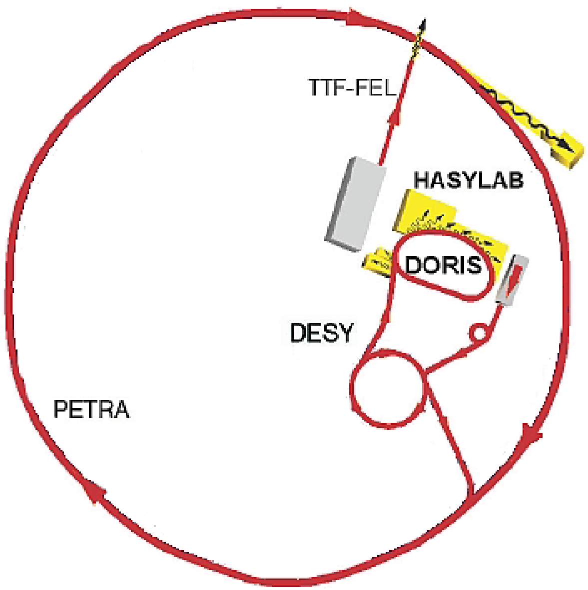
THE OLYMPUS COLLABORATION

Arizona State University, USA
DESY, Hamburg, Germany
Hampton University, USA
INFN, Ferrara, Italy
INFN, Frascati, Italy
INFN, Rome, Italy
Massachusetts Institute of Technology, USA
St. Petersburg Nuclear Physics Institute, Russia
Universität Bonn, Germany
University of Colorado, USA
Universität Erlangen-Nürnberg, Germany
University of Glasgow, United Kingdom
University of Kentucky, USA
Universität Mainz, Germany
University of New Hampshire, USA

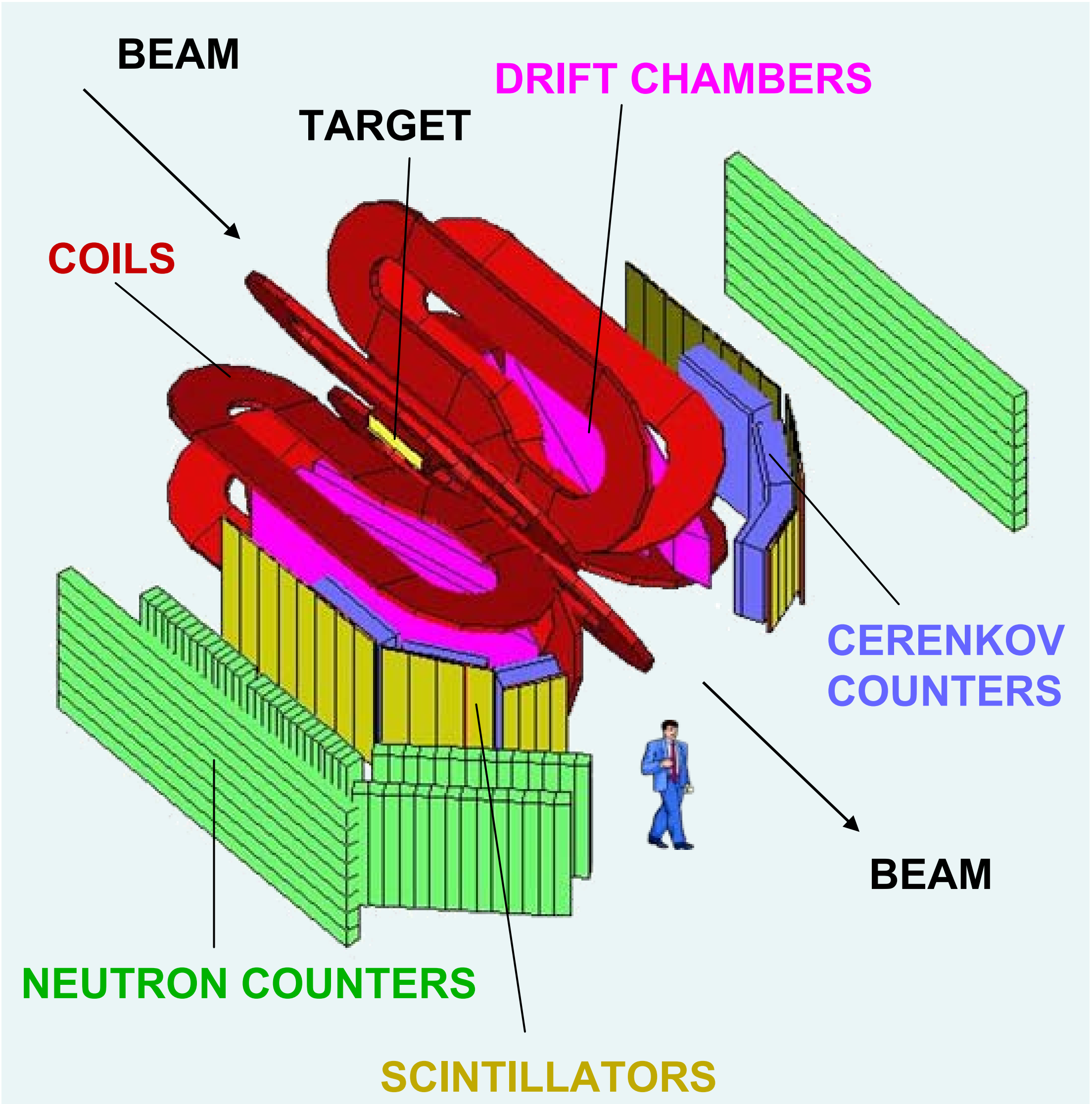
The OLYMPUS Experiment

- Electrons/positrons (100mA) in multi-GeV storage ring DORIS at DESY, Hamburg, Germany
- Unpolarized internal hydrogen target (like HERMES) 3×10^{15} at/cm^2 @ 100 mA $\rightarrow$ L = 2×10^{33} / (cm^{2}s)
- Measure elastic e^+/e^- proton scattering to 1% precision at 2 GeV energy with ε range from 0.4 to 1 at high $Q^2 \sim$ 2-3 (GeV/c)^2 using the existing Bates Large Acceptance Spectrometer Toroid
- Experiment requires switching from e^+ beam to e^- beam on timescale of $\leq$ 1 day.
- Redundant monitoring of luminosity, pressure, temperature, flow, current measurements - small-angle elastic scattering at high ε and low Q^2

DORIS 4.45 GeV, 120 mA

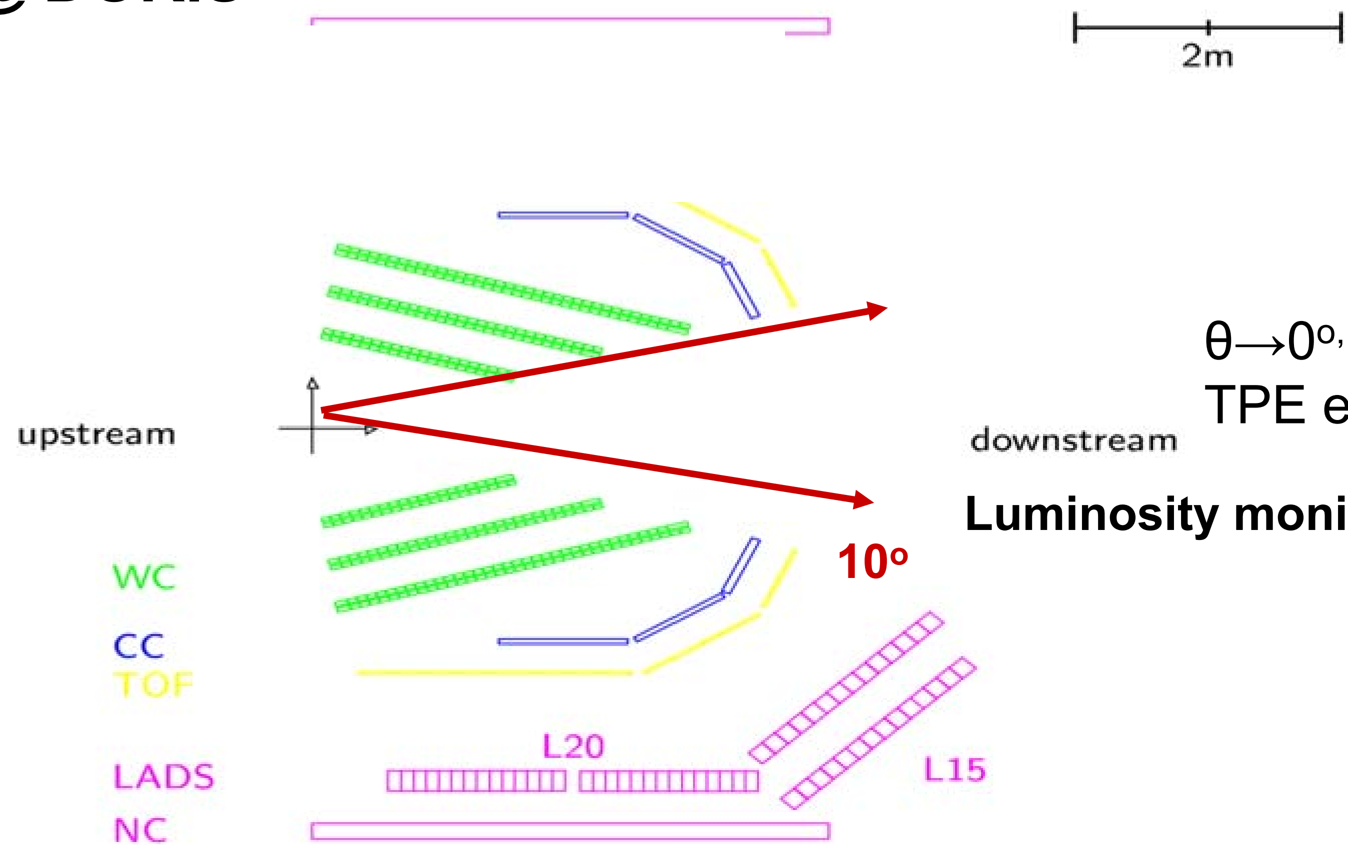


BLAST detector



Control of systematics

BLAST @ DORIS



θ→0°, ε→1
TPE effects → 0

Luminosity monitors

- **Change BLAST polarity once a day**
- **Change between electrons and positrons regularly**
- **Left-right symmetry**

Projected OLYMPUS uncertainties

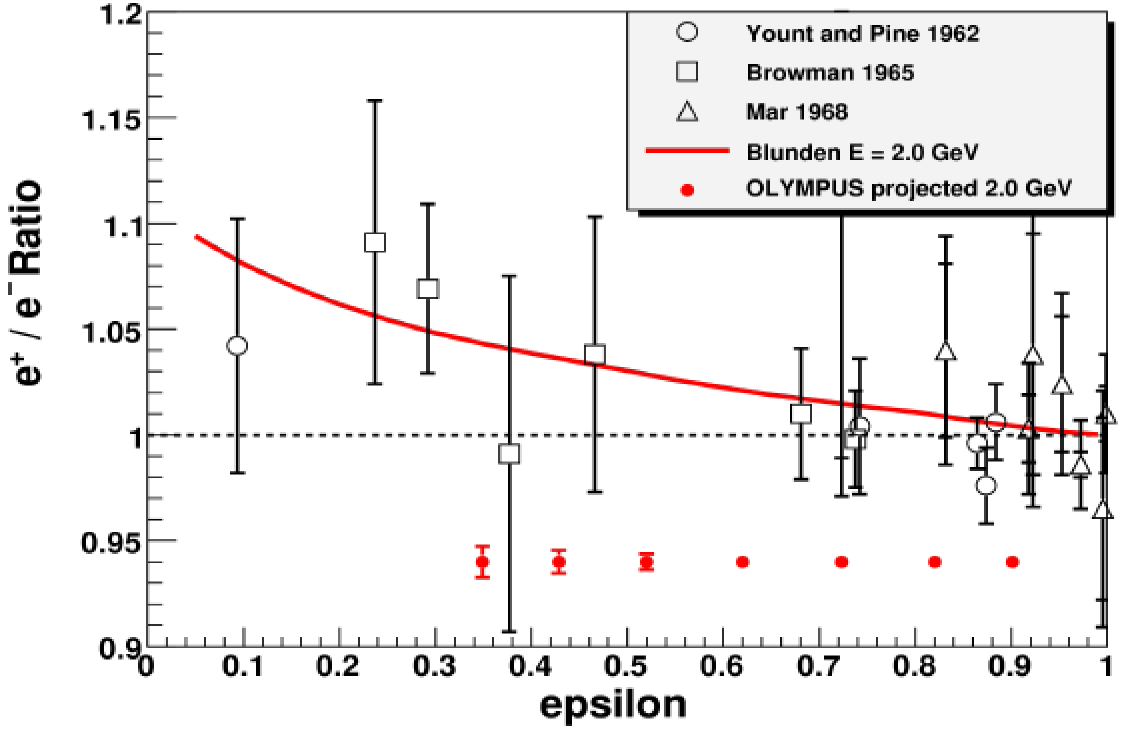


Figure 1.12: Projected uncertainties in the determination of the cross section ratio e^+p/e^-p for the BLAST detector for a beam energy of 2.0 GeV, as a function of ϵ. The assumed luminosity is $2 \cdot 10^{33}$ /(cm ^{2}s) $\times$ 500 hours each for running with electrons and positrons, respectively.

Conclusion & outlook

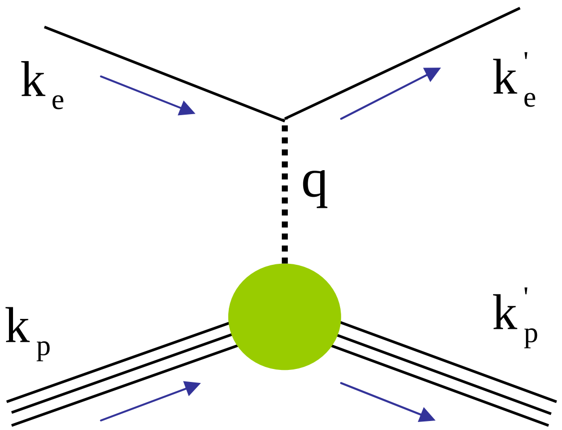
Experiments designed to measure charge asymmetry at per cent level

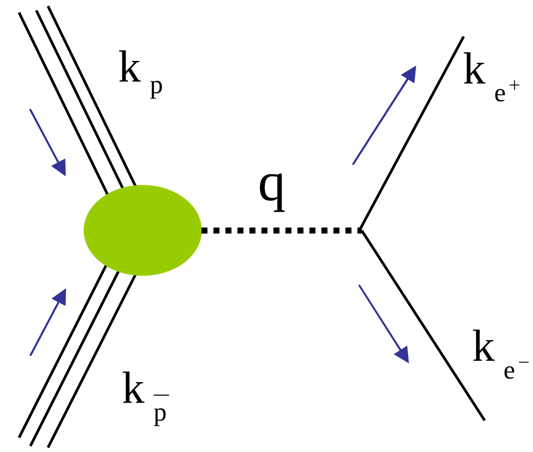
Experiment	E_{beam} GeV	Luminosity $cm^{2} sec^{-1}$	ε_{min}	Q^2 GeV	Planned for	Challenge
VEPP-3	1.6	10^{31}	0.4	0.1-1.76	2010-2012	Low lumi
JLAB	5.7	$1.3x10^{33}$	0.2	0.5-2.1	2012-….??	High bgr level
Olympus	2	$2.x10^{33}$	0.4	2-3	2011-2012	Continuation after 2012

BACKUP SLIDES

FF DEFINITION.

FFs are defined in context of one photon exchange





space-like photon $Q^2 > 0$

$$m_\gamma = q^2 = \left(k_e^{'} - k_e\right)^2 = \left(k_p^{'} - k_p\right)^2, \quad t = Q^2 = -q^2$$

$$q = q_0, \vec{q}$$

In CM frame $q_0 = 0,\ q^2 = q_0^2 - \vec{q}^{\,2} = -\left(\vec{p}^{\,'} - \vec{p}\right)^2 = -4k^2 \sin^2\frac{\theta_{CM}}{2}$. *No energy transfer* $\rightarrow$ *equivalent to Breit frame*

time-like photon $Q^2 < 0$

$$m_\gamma = q^2 = \left(k_{e^+} + k_{e^-}\right)^2 = \left(k_p + k_{\bar{p}}\right)^2, \quad s = Q^2 = -q^2$$

$$q = q_0, \vec{q}$$

In CM frame $q_0 = 2k,\ \vec{q} = 0,\ q^2 = 4k^2$

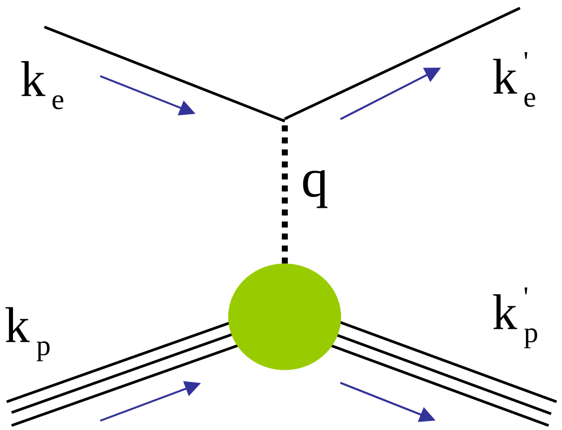
poorly studied till now

$$q_0 = 0 \rightarrow J_p^\mu = G_E(Q^2)\gamma^\mu + G_M(Q^2) i\sigma^{\mu\nu} q_\nu \rightarrow \rho_{E,M}\left(\vec{x}\right) = \int G_{E,M}\left(-q^2\right) e^{-i\vec{q}\vec{x}}\, d^3x$$

$$G_E^p(0) = 1 \quad G_E^n(0) = 0 \quad G_M^p(0) = \mu_p \quad G_E^n(0) = \mu_n$$

FF DEFINITION.

FFs are defined in context of one photon exchange



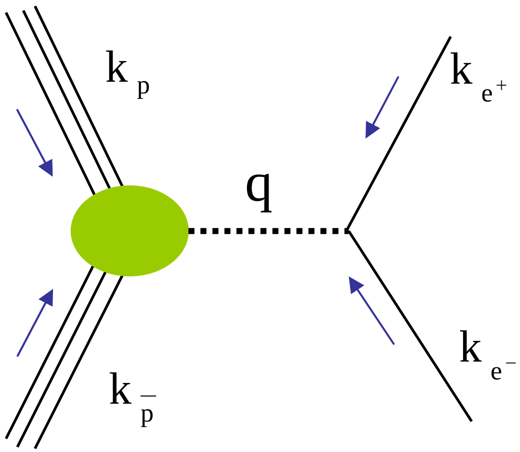
space-like photon $Q^2 > 0$

$$q^2 = \left(k'_e - k_e\right)^2 = \left(k'_p - k_p\right)^2, \quad t = Q^2 = -q^2$$

$$q = q_0, \vec{q}$$

In CM frame $q_0 = 0,\ q^2 = q_0^2 - \vec{q}^{\,2} = -\left(\vec{p}^{\,'} - \vec{p}\right)^2 =$

$-4k^2 \sin^2 \frac{\theta_{CM}}{2}$. *No energy transfer* $\rightarrow$ *equivalent to Breit frame*



time-like photon $Q^2 < 0$

$$q^2 = \left(k_{e^+} + k_{e^-}\right)^2 = \left(k_p + k_{\bar{p}}\right)^2, \quad s = Q^2 = -q^2$$

$$q = q_0, \vec{q}$$

In CM frame $q_0 = 2k,\ \vec{q} = 0,\ q^2 = 4k^2$

Till now poorly studied

$$q_0 = 0 \rightarrow J_p^\mu = G_E(Q^2)\gamma^\mu + G_M(Q^2) i\sigma^{\mu\nu} q_\nu \rightarrow \rho_{E,M}\left(\vec{x}\right) = \int G_{E,M}\left(-q^2\right) e^{-i\vec{q}\vec{x}}\, d^3x$$

$$G_E^p(0) = 1 \quad G_E^n(0) = 0 \quad G_M^p(0) = \mu_p \quad G_E^n(0) = \mu_n$$

<u>*Comment: in general case (any frame)*</u>

$$G_E(Q^2) \rightarrow F_1\left(Q^2\right) = \frac{G_E\left(Q^2\right) + \tau G_M\left(Q^2\right)}{1+\tau}, \quad G_M\left(Q^2\right) \rightarrow \frac{G_E\left(Q^2\right) + \tau G_M\left(Q^2\right)}{\mu(1+\tau)},$$

$\tau \equiv \frac{Q^2}{2M}$, F_1 *non-spin-flip Dirac FF*, F_2 *spin-flip Pauli FF*, $F_1(0) = F_2(0) = 1$

Spin-Density Matrix of Virtual Photon in Helicity Representation

$$\varrho^{(\gamma)} = \varrho^{(U)} + P_b \cdot \varrho^{(L)}$$

$$\varrho^{U}_{\lambda_\gamma \lambda'_\gamma} =$$
$$\frac{1}{2}\begin{pmatrix} 1 & \sqrt{\epsilon(1+\epsilon)}e^{-i\Phi} & -\epsilon e^{-2i\Phi} \\ \sqrt{\epsilon(1+\epsilon)}e^{i\Phi} & 2\epsilon & -\sqrt{\epsilon(1+\epsilon)}e^{-i\Phi} \\ -\epsilon e^{2i\Phi} & -\sqrt{\epsilon(1+\epsilon)}e^{i\Phi} & 1 \end{pmatrix},$$

$$\varrho^{L}_{\lambda_\gamma \lambda'_\gamma} =$$
$$\frac{\sqrt{1-\epsilon}}{2}\begin{pmatrix} \sqrt{1+\epsilon} & \sqrt{\epsilon}e^{-i\Phi} & 0 \\ \sqrt{\epsilon}e^{i\Phi} & 0 & \sqrt{\epsilon}e^{-i\Phi} \\ 0 & \sqrt{\epsilon}e^{i\Phi} & -\sqrt{1+\epsilon} \end{pmatrix}. \quad (1)$$

where $\lambda_\gamma = 1,\ 0,\ -1;\ \ \lambda'_\gamma = 1,\ 0,\ -1.$

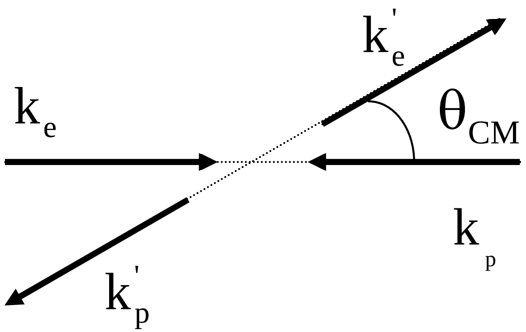
Kinematics of elastic ep scattering

$$t \equiv q^2 = \left(k_e^{'} - k_e\right)^2 = \left(k_p^{'} - k_p\right)^2, \quad Q^2 = -q^2,$$

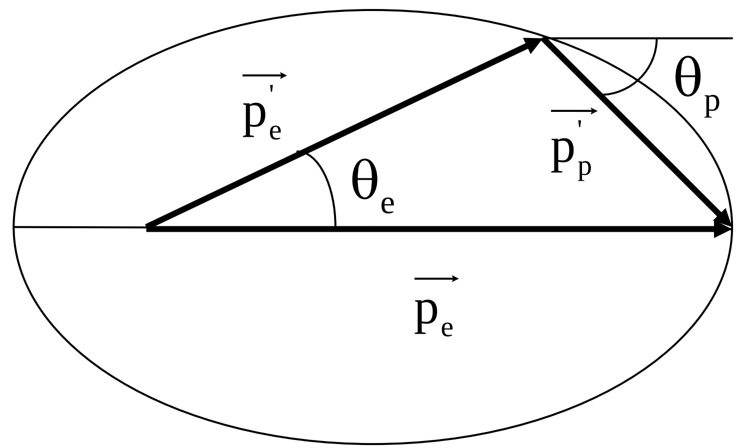
$$s = \left(k_e + k_p\right)^2 = \left(k_e^{'} + k_p^{'}\right)^2, \quad m_e^2 = k_e^2 = k_e^{'2} \quad M_p^2 = k_p^2 = k_p^{'2}$$

in GeV range: $m_e \approx 0 \quad E_e \approx k_e$

CM frame



Lab frame



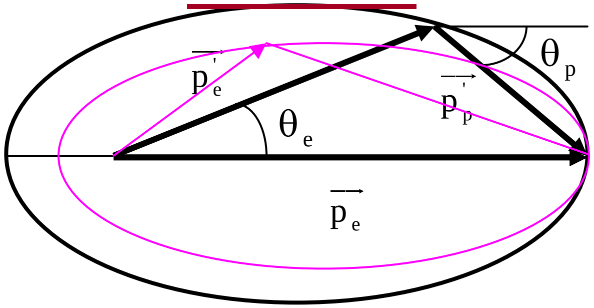
$$k \equiv \left|\vec{k}_e\right| = \left|\vec{k}_e^{\,'}\right| = \left|\vec{k}_p\right| = \left|\vec{k}_p^{\,'}\right| \qquad q = 0, \vec{q}$$

$$q^2 = \left(k_e^{'} - k_e\right)^2 = -\left(\vec{k}_e^{\,'} - \vec{k}_e\right)^2$$

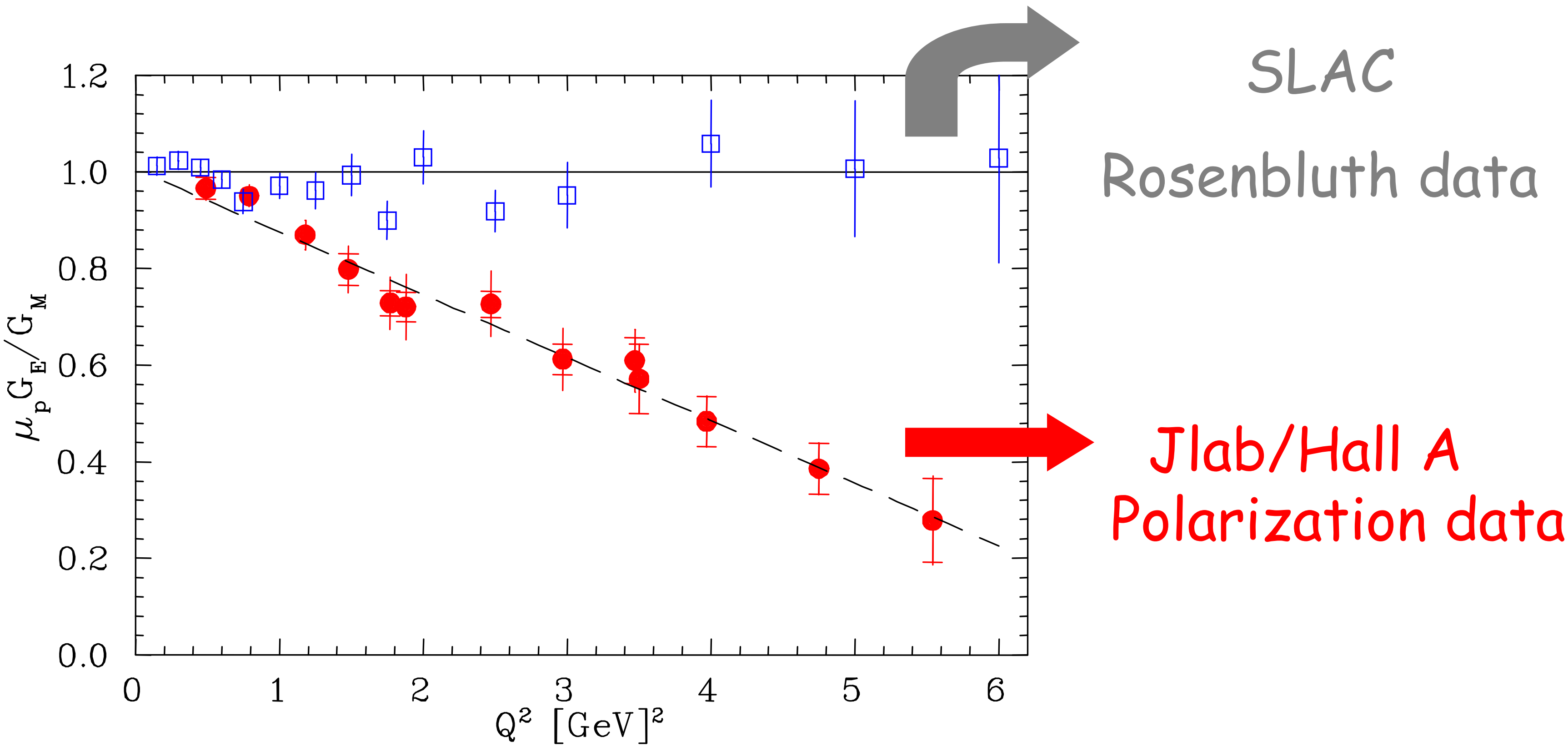
$$q^2 = -4E_e E_e^{'} \sin^2\frac{\theta_{CM}}{2}$$

$$q^2 = -4k \sin^2\frac{\theta_{CM}}{2} \qquad \text{CM = BREIT FRAME}$$

Lab frame

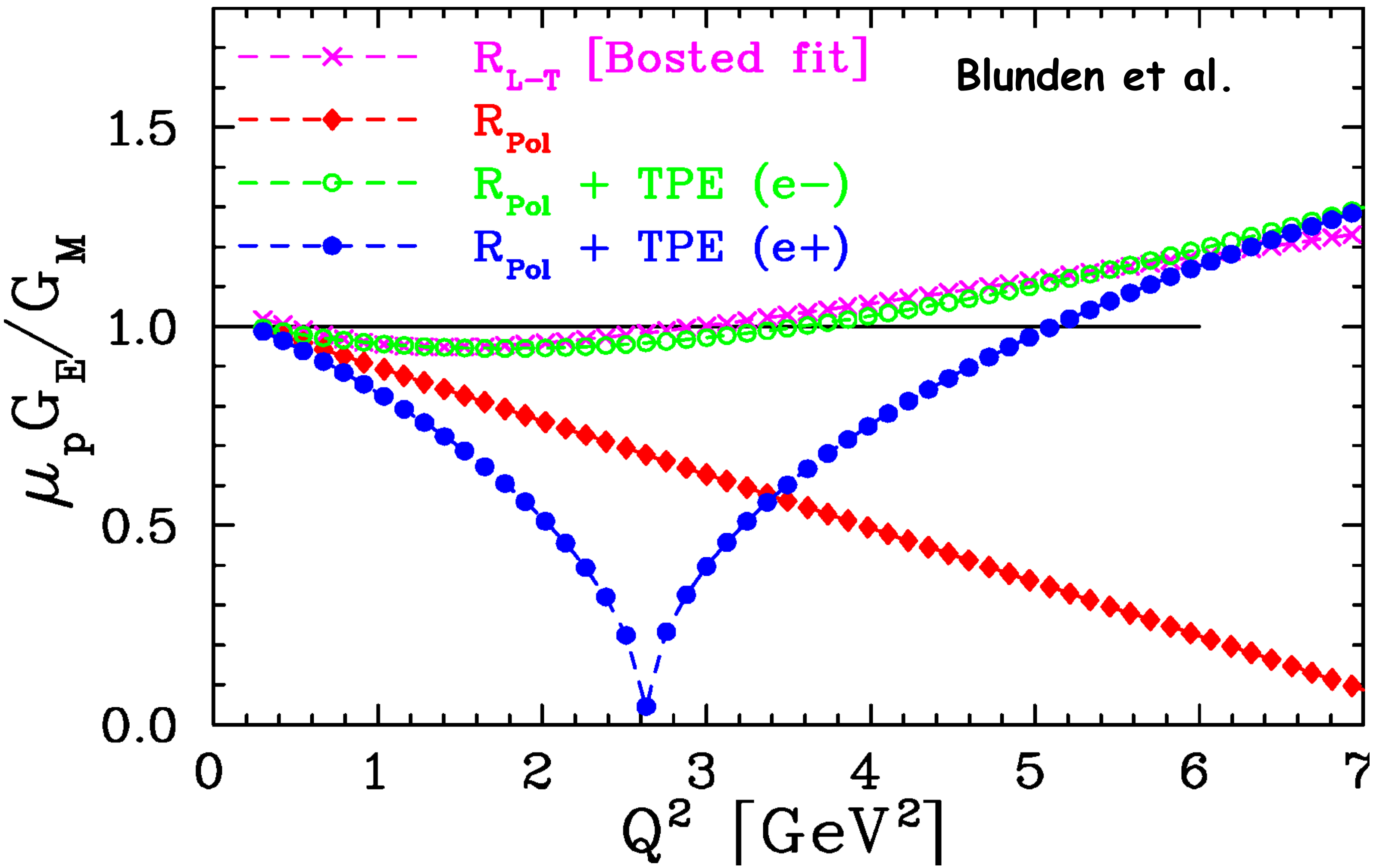


Rosenbluth vs polarization transfer, data



Two methods, two different results !

Proton form factor ratio



OLYMPUS LUMI CONTROL

e_{fwd} p-coincidences, $Q^2<1$ GeV^2 $\varepsilon\approx1$, TPE negligible