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Proton Form Factor Measurements Using Recoil Polarization: Beyond Born Approximation

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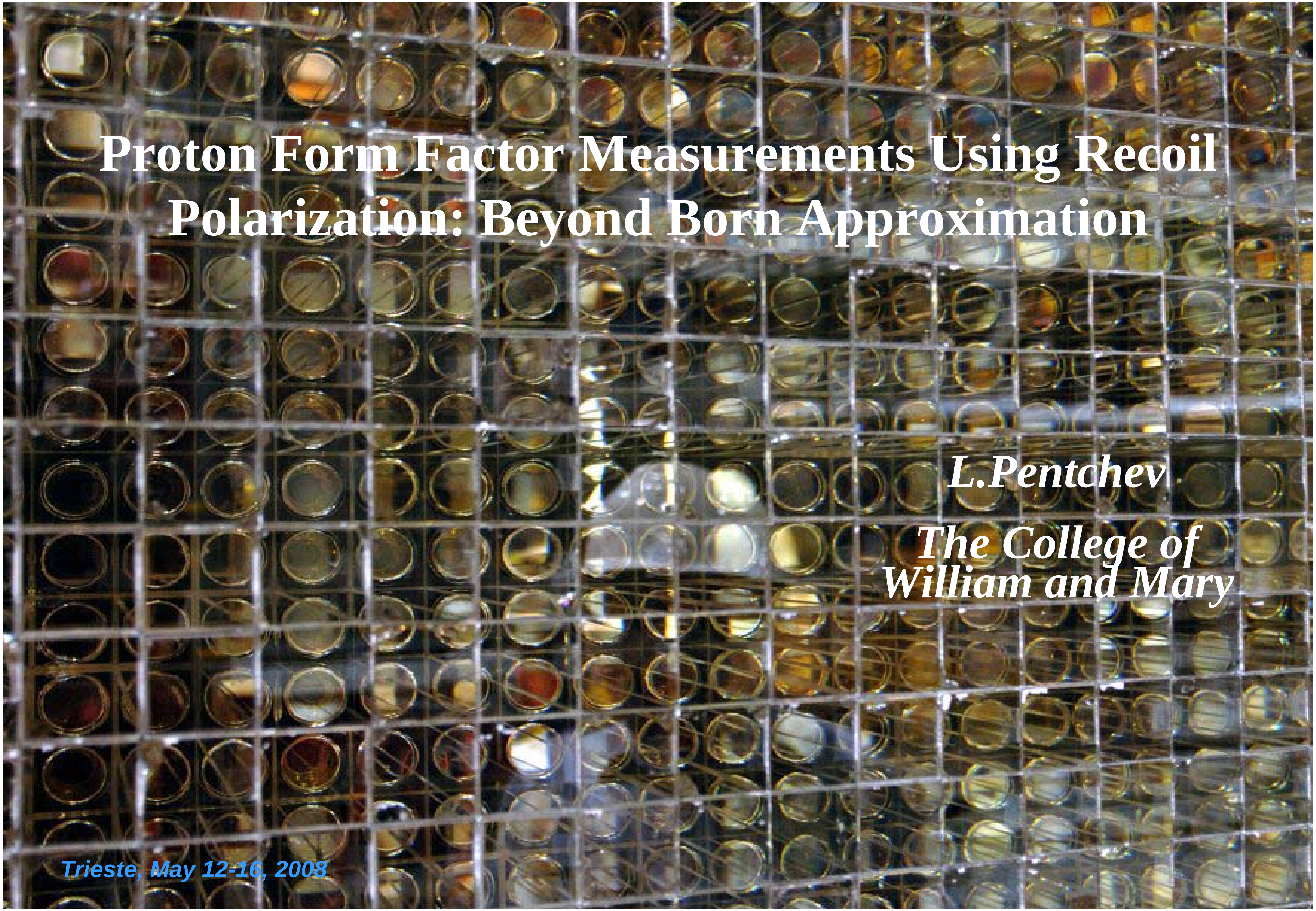

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Trieste, May 12-16, 2008

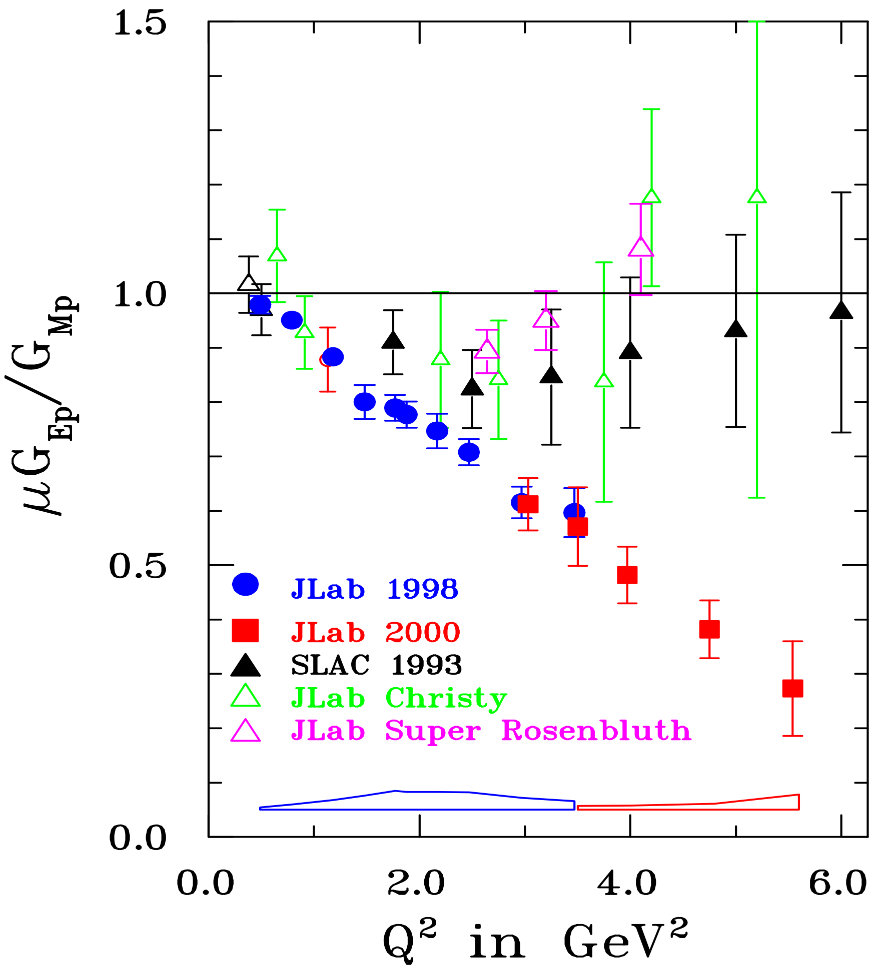
Outline

- Introduction
- GEp crisis: 8 years history
  - Experimental Status
  - Polarization transfer method vs Rosenbluth separation
  - Beyond Born Approximation: theoretical predictions
- GEP-2gamma experiment at JLab: precise (1%) measurement of two polarization quantities; test of the limits of the polarization method
- Preliminary results
- Reconstruction of the real part of the ep elastic amplitudes
- Summary

Introduction

- Nucleon structure as revealed by elastic electron scattering, investigated experimentally and theoretically for over 50 years
- Form factor data of great interest as a testing ground for QCD: lattice QCD becomes increasingly accurate and realistic; testing asymptotic pQCD predictions
- As first GPD moments, form factors measured precisely, provide stringent constraints on the GPD parameterizations
- Sachs form factors, G_E and G_M , traditionally obtained by Rosenbluth separation: G_M known up to 30 GeV^2 but due to decreasing contribution to the cross-section, G_E suffers from inconsistency in the data
- Significant theoretical and experimental efforts have been made over the past 8 years aiming to explain the discrepancy between the proton form factor ratio data obtained at JLab using the polarization method and the previous Rosenbluth measurements

GEp/GMp Crisis: discrepancy in the data



"The discrepancy is a serious problem as it generates confusion and doubt about the whole methodology of lepton scattering experiments"

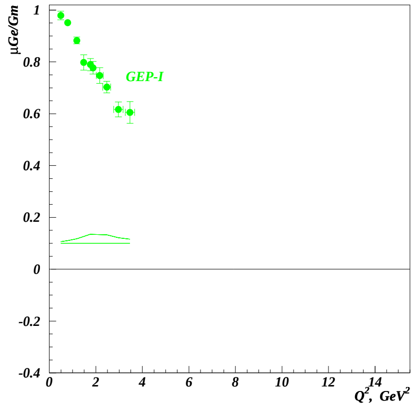
P.A.M. Guichon and

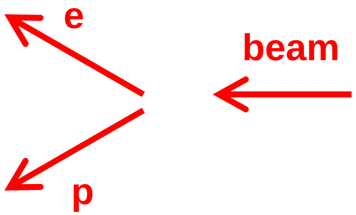
M.Vanderhaeghen

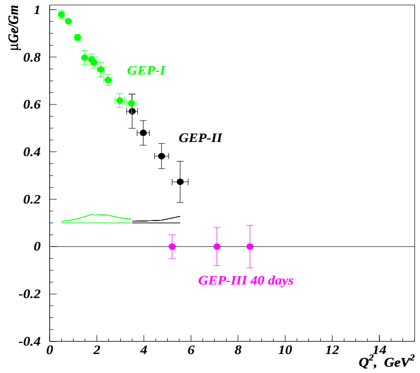
E.M. calorimeter

Electron Spectrometer (HRS)

$\Omega_e = 6msr$ Ω_e *up to* 138 *msr*







Proton spectrometer (HRS)

$\Omega_p = 6msr$

POLARIMETER

Polarization Method

$$\vec{e}\,p \rightarrow e\vec{p} \quad elastic$$

In Born (one-photon exchange) approximation:

$$I_0 P_t = -2\sqrt{\tau(1+\tau)}G_{Ep}G_{Mp}\tan\frac{\vartheta_e}{2}$$

$$I_0 P_l = \frac{1}{M_p}(E_{beam}+E_e)\sqrt{\tau(1+\tau)}G_{Mp}^2\tan^2\frac{\vartheta_e}{2}$$

$$I_0 = G_{Ep}^2 + \frac{\tau}{\varepsilon}G_{Mp}^2 \qquad \tau = Q^2/4M_p^2 \qquad \varepsilon = \frac{1}{1+2(1+\tau)\tan^2\frac{\theta_e}{2}}$$

$$\frac{G_{Ep}}{G_{Mp}} = -\frac{P_t}{P_l}\frac{(E_{beam}+E_e)}{2M_p}\tan\frac{\vartheta_e}{2}$$

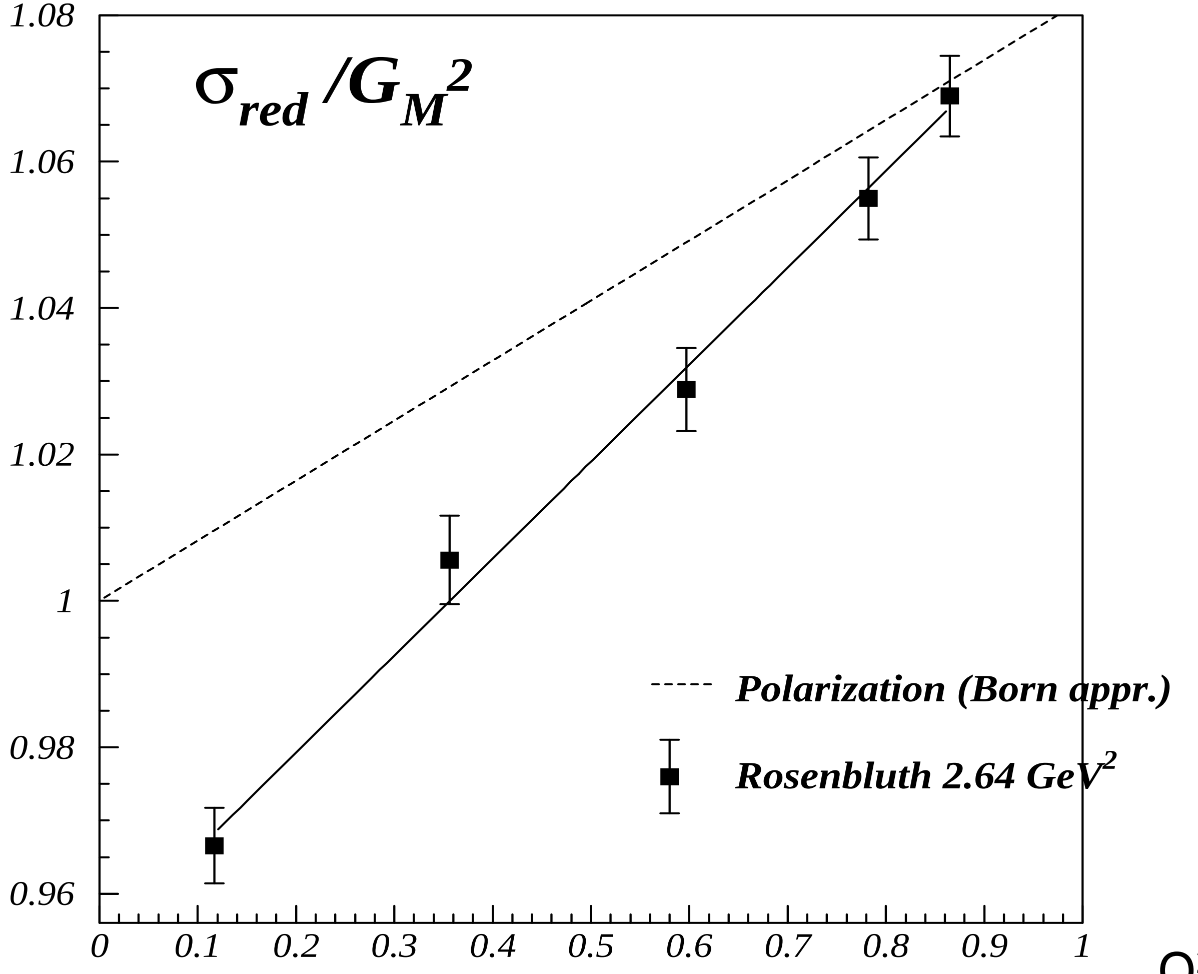
•Form Factor ratio can be obtained without knowing analyzing power, Ay, and beam helicity, h, (both cancel out in the ratio), and without measuring cross-section.

•Systematic uncertainty dominated by the spin transport from the polarimeter to the target.

A.I.Akhiezer and M.P.Rekalo, Sov.J.Part.Nucl. 3, 277 (1974)

R.Arnold, C.Carlson, and F.Gross, Phys. Rev. C 23, 363 (1981)

Discrepancy at fixed Q^2



$$d\sigma_{red} / G_M^2 = 1 + \frac{\varepsilon R^2}{\tau}$$

Q^2 = 2.64 GeV ^{2}

Experimental Status

- Polarization method

• Experimental errors are well understood

• Experimental errors are small and can't explain the discrepancy between Rosenbluth and polarization measurements; it would require significant uncertainties in the trajectory bending angles, totally inconsistent with the optical studies

• Consistency of different measurements:

  - two experiments in HallA (GEP-1 and GEP-2) overlapping at 3.5 GeV^2
  - ongoing GEP-3/GEP-2Gamma experiments using different (HallC) detectors; overlapping measurements at 2.5, 2.7 and 5.2 GeV^2

- Rosenbluth method

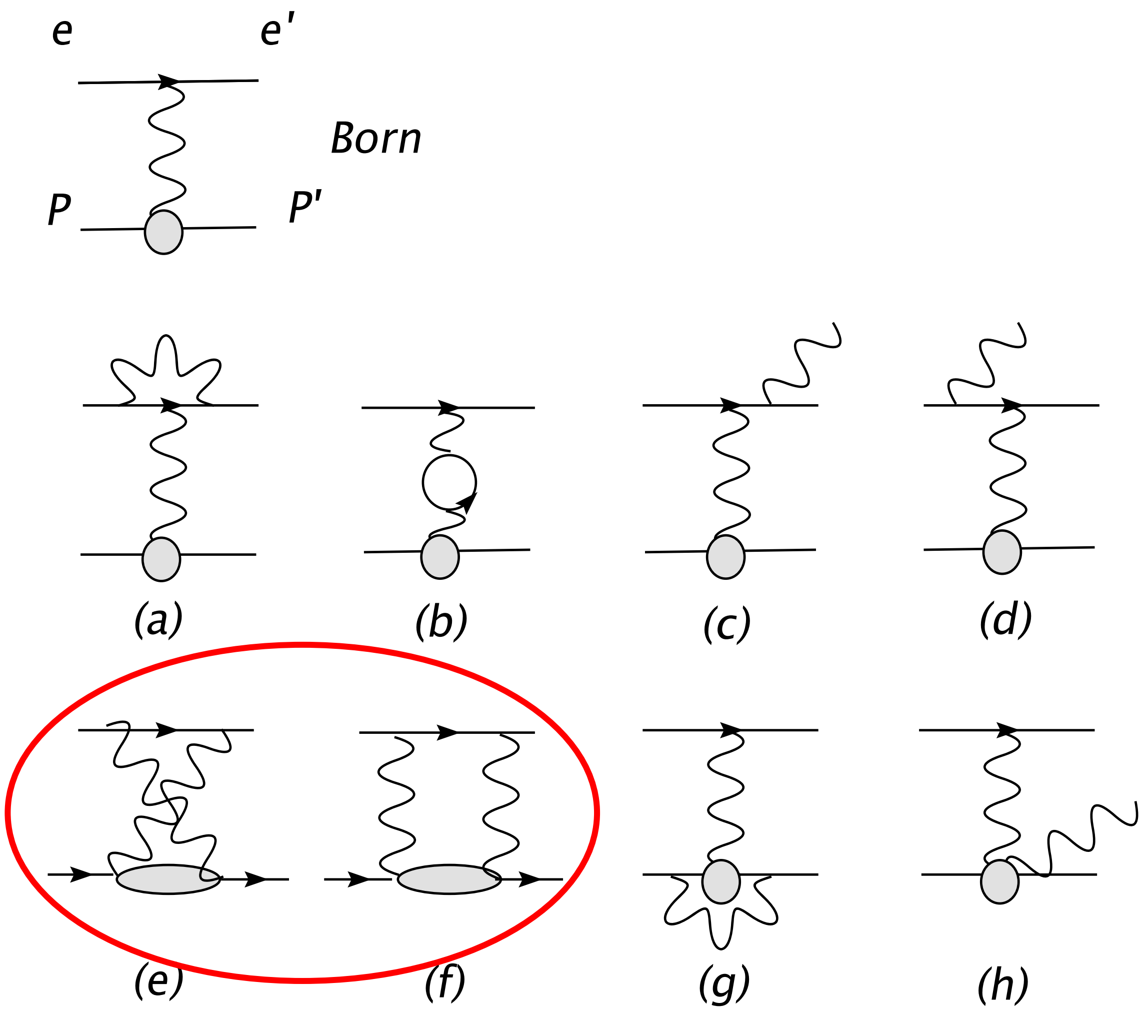
•JLab experiment (Super Rosenbluth) confirmed previous SLAC results: registering proton instead of electron; different radiative corrections

• Recent JLab experiment collected data over large Q^2 and ε range

• The method has reduced sensitivity for Q^2 > ~3 GeV^2

NO EXPERIMENTAL EXPLANATION OF THE DISCREPANCY FOUND

Beyond Born Approximation



Mo and Tsai, and others:

- prescriptions for radiative corrections commonly used
- two-photon exchange: (e), (f) – only with one soft photon, neglecting proton structure

Generalized Form Factors (ep elastic amplitudes)

$$P_t = -\sqrt{\frac{2\varepsilon(1-\varepsilon)}{\tau}}\frac{G_M^2}{d\sigma_{red}}\left\{R + R\frac{\Re(\delta\tilde{G}_M)}{G_M} + \frac{\Re(\delta\tilde{G}_E)}{G_M} + Y_{2\gamma}\right\}$$

$$P_l = \sqrt{(1+\varepsilon)(1-\varepsilon)}\frac{G_M^2}{d\sigma_{red}}\left\{1 + 2\frac{\Re(\delta\tilde{G}_M)}{G_M} + \frac{2}{1+\varepsilon}\varepsilon Y_{2\gamma}\right\}$$

this experiment

$$d\sigma_{red}/G_M^2 = 1 + \frac{\varepsilon R^2}{\tau} + 2\frac{\Re(\delta\tilde{G}_M)}{G_M} + 2R\frac{\varepsilon\Re(\delta\tilde{G}_E)}{\tau G_M} + 2\left(1+\frac{R}{\tau}\right)\varepsilon Y_{2\gamma}$$

e^+/e^- x-section ratio

Rosenbluth non-linearity

$$\Re(\tilde{G}_M) = G_M(Q^2) + \Re(\delta\tilde{G}_M(Q^2,\varepsilon))$$

$$\Re(\tilde{G}_E) = G_E(Q^2) + \Re(\delta\tilde{G}_E(Q^2,\varepsilon))$$

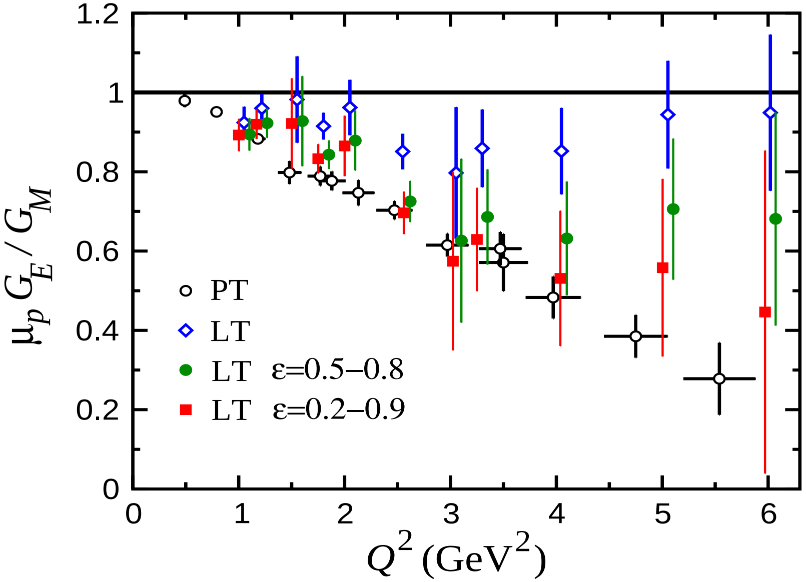
$$R = G_E/G_M \qquad Y_{2\gamma} = 0 + \sqrt{\frac{\tau(1+\tau)(1+\varepsilon)}{1-\varepsilon}}\frac{\Re(\tilde{F}_3(Q^2,\varepsilon))}{G_M}$$

Born Approximation | Beyond Born Approximation

P.A.M. Guichon and M.Vanderhaeghen, Phys.Rev.Lett. 91, 142303 (2003)

M.P. Rekalo and E. Tomasi-Gustafsson, E.P.J. A 22, 331 (2004)

theoretical predictions

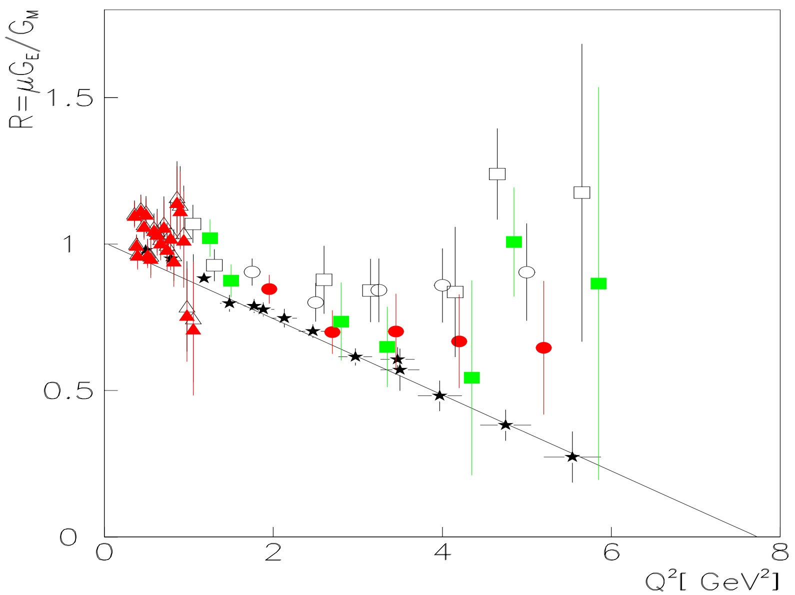


Hadronic calculations

•**P.Blunden et al., Phys.Rev.C72: 034612 (2005)** elastic (Figure)

•**S.Kondratyuk et al., Phys.Rev.Lett. 95: 172503 (2005)** including Delta reduces the effect

• **S.Kondratyuk et al., nucl-th/0701003** (**2007)** including 1/2 and 3/2 resonances – no effect

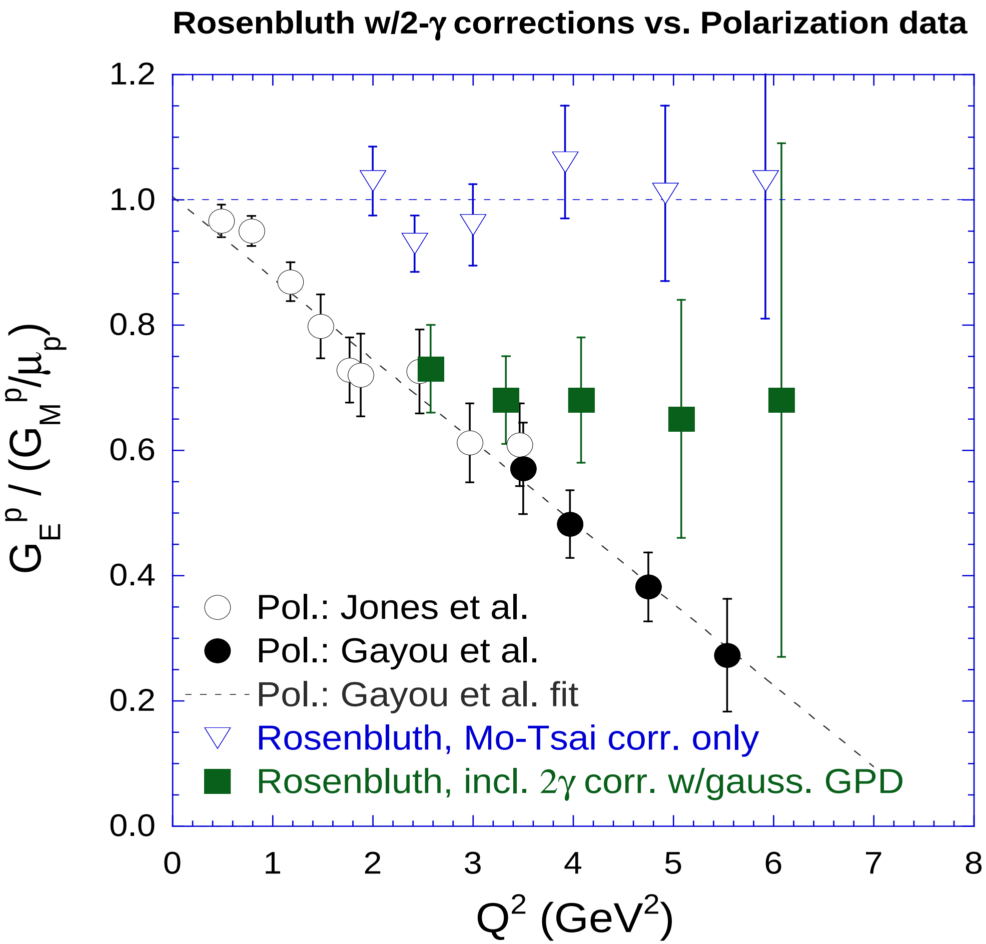


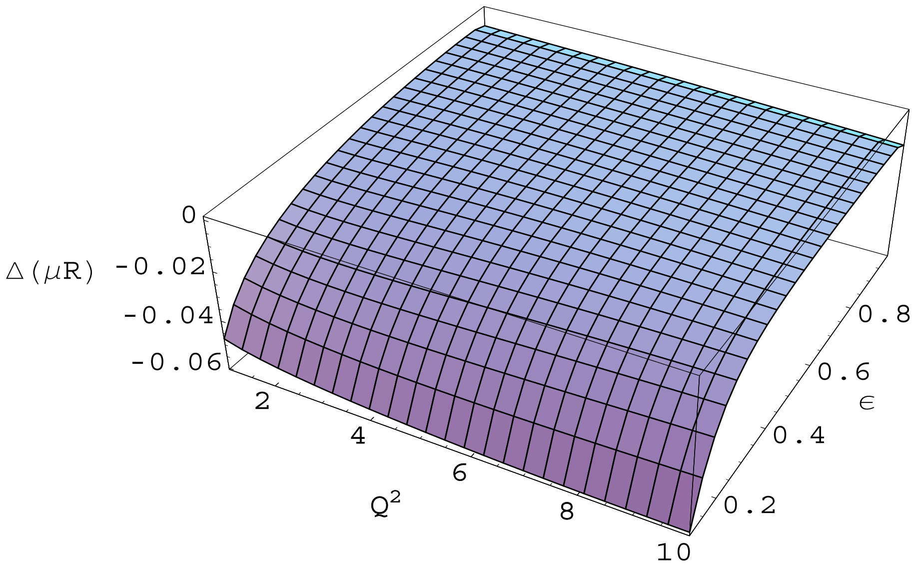
•**Yu. Bystricky, E.A.Kuraev, E. Tomasi-Gustafsson Phys. Rev. C75, 015207 (2007)** structure function method: 2γ effects small, higher orders change Rosenbluth slope (Figure)

•**D.Borisuyk, A.Kobushkin** arXiv:0804.4128: proton off-shell form factors are not needed to calculate TPE amplitudes

Two-Photon Exchange: theoretical predictions

GPD calculations





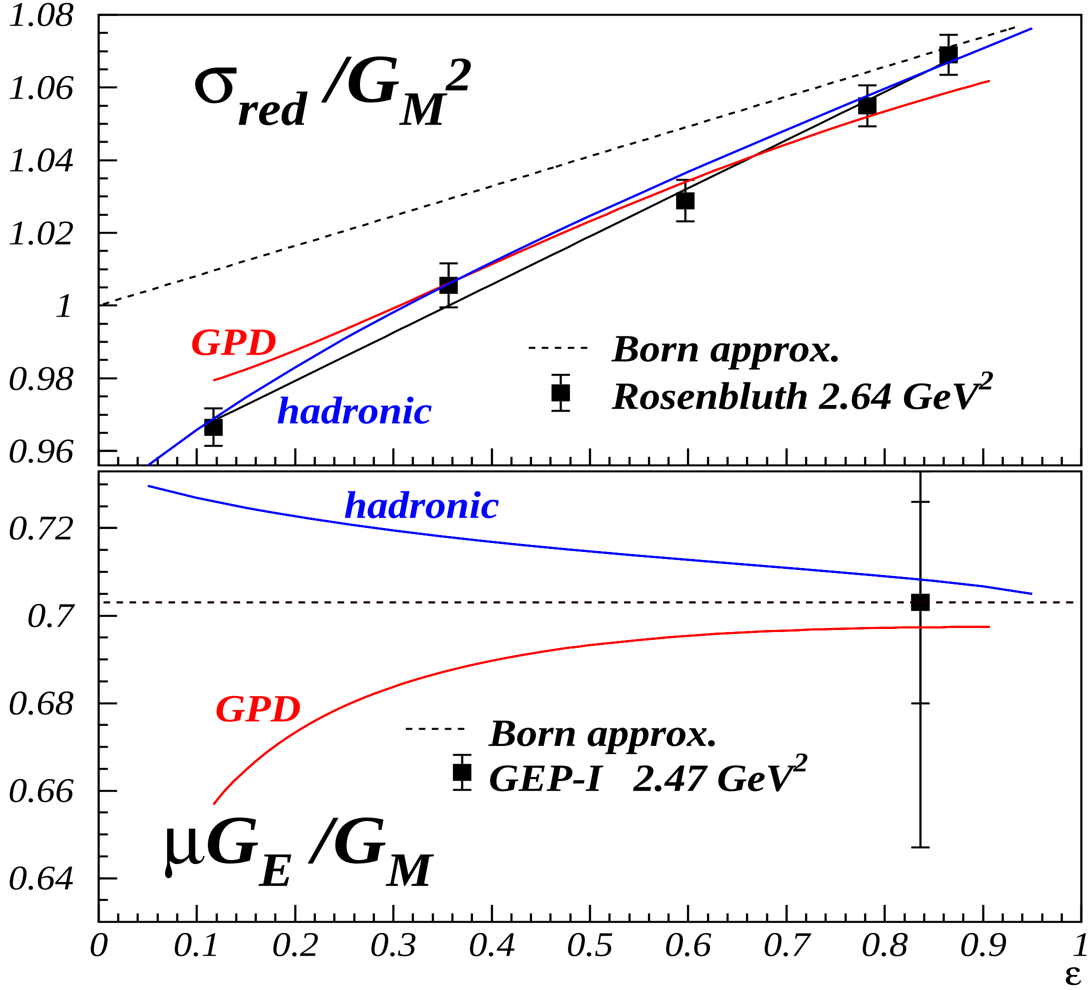
Absolute correction to FF ratio μGe/Gm:

•slow Q^2 variation, strong effects at low ε

• valid for high Q^2 or high ε

•**A.Afanasev et al., Phys.Rev.D72:013008 (2005)** – GPD models: Gauss on Fig., smaller effect with Regge, or non-zero quark mass

Two-Photon Exchange: theoretical predictions



hadronic (elastic): dominated by correction to G_M

GPD (includes inelastic): dominated by Y2γ and correction to G_E

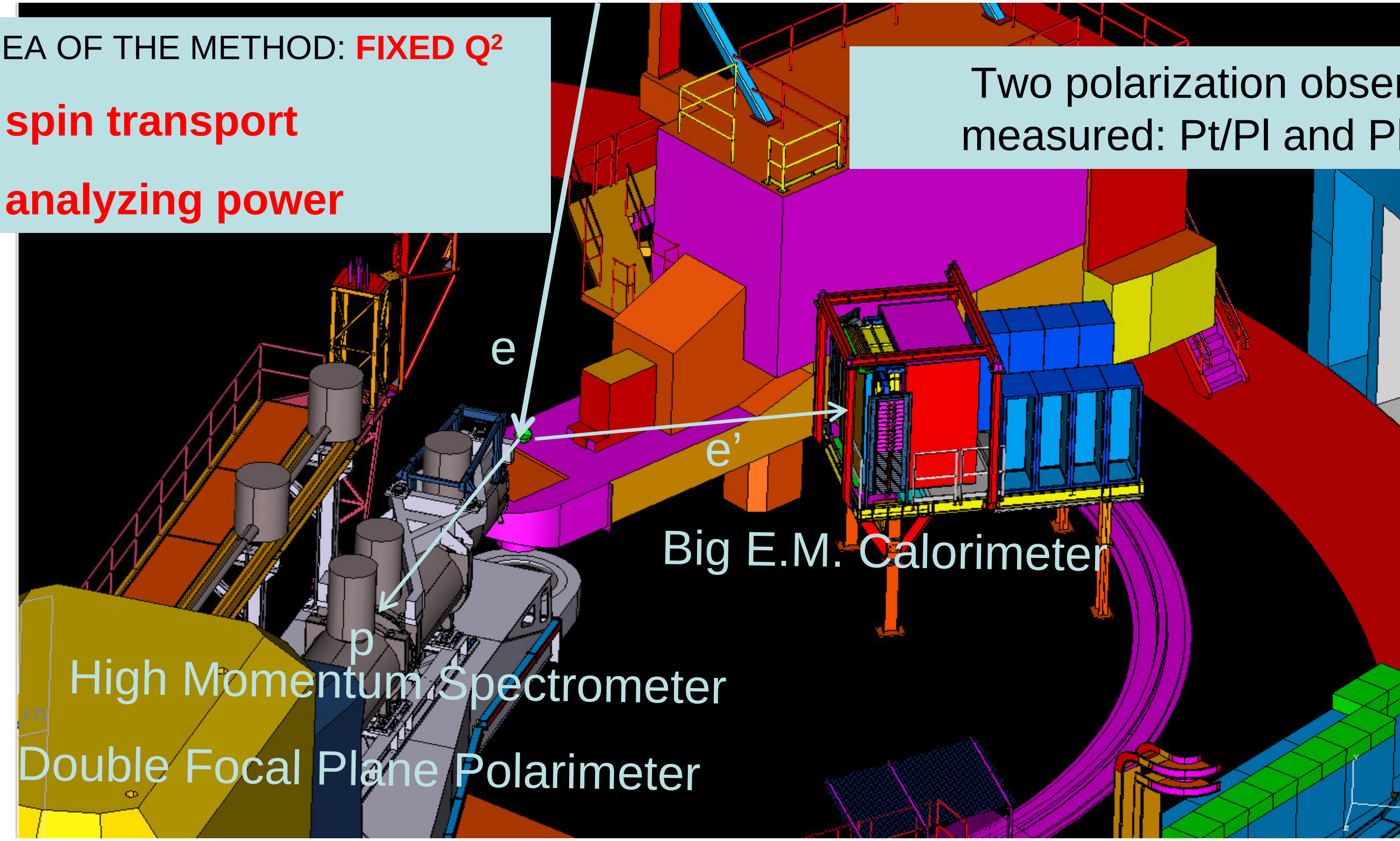
Both theories describe Rosenbluth data but have opposite predictions for $\mu G_E/G_M$

Goal of This Experiment: ε dependence of R at 2.5 GeV^2

KEY IDEA OF THE METHOD: **FIXED Q^2**

- **same spin transport**
- **same analyzing power**

Two polarization observables are measured: Pt/Pl and Pl separately



80 uA beam current

85% pol.

20cm LH target

E_e, GeV	p_p	E_e'	Θ_p, deg	θ_e	ε range	<Q^2>
1.867	2.068	0.527	14.13	106	.130-.160	2.49
2.839	2.068	1.507	30.76	45.3	.611-.647	2.49
3.549	2.068	2.207	35.39	32.9	.765-.786	2.49
3.650	2.068	2.307	36.14	31.7	.772-.798	2.49

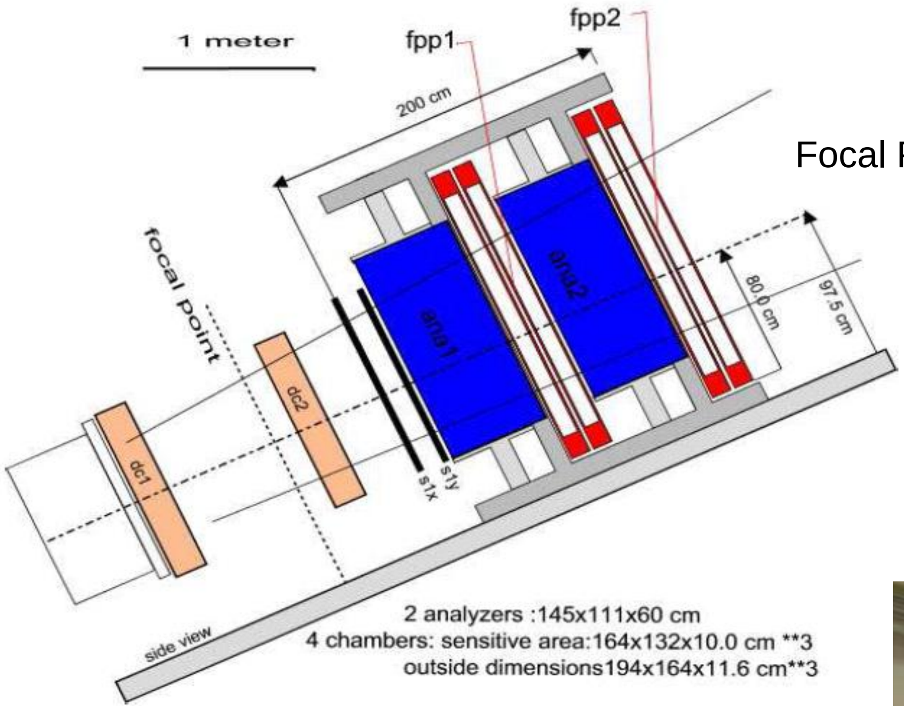
precision limited only by statistics (~ 1%), unlike Rosenbluth,

very small p.t.p systematics:

Ay , h cancel out in the Pt/Pl ratio

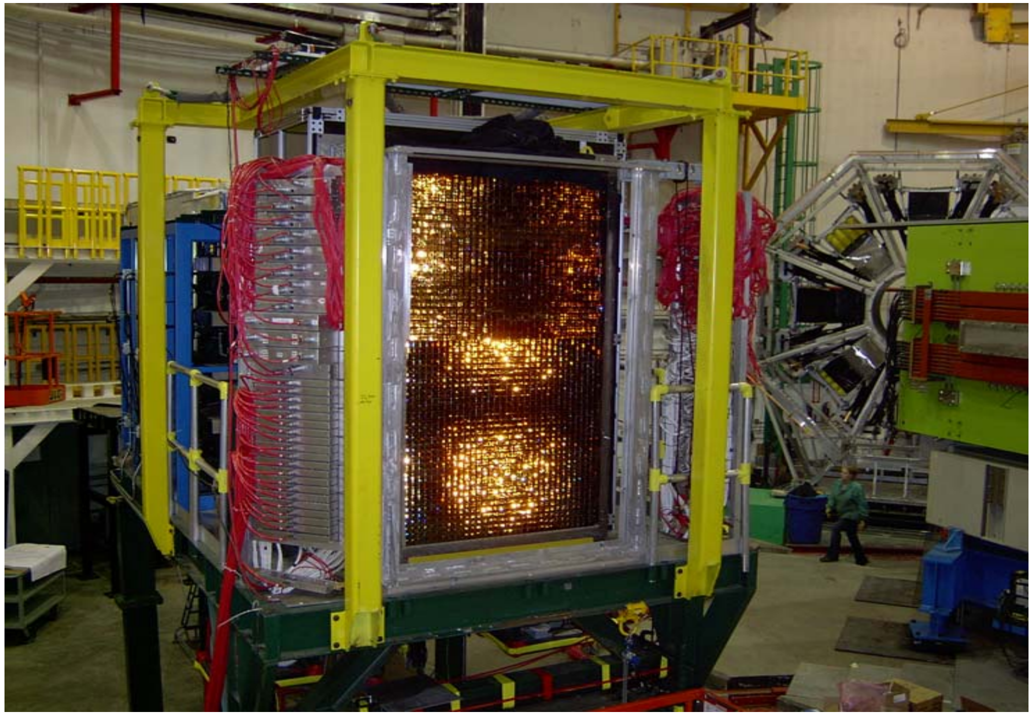
Q^2 fixed, Pp fixed, spin precession fixed

Detectors

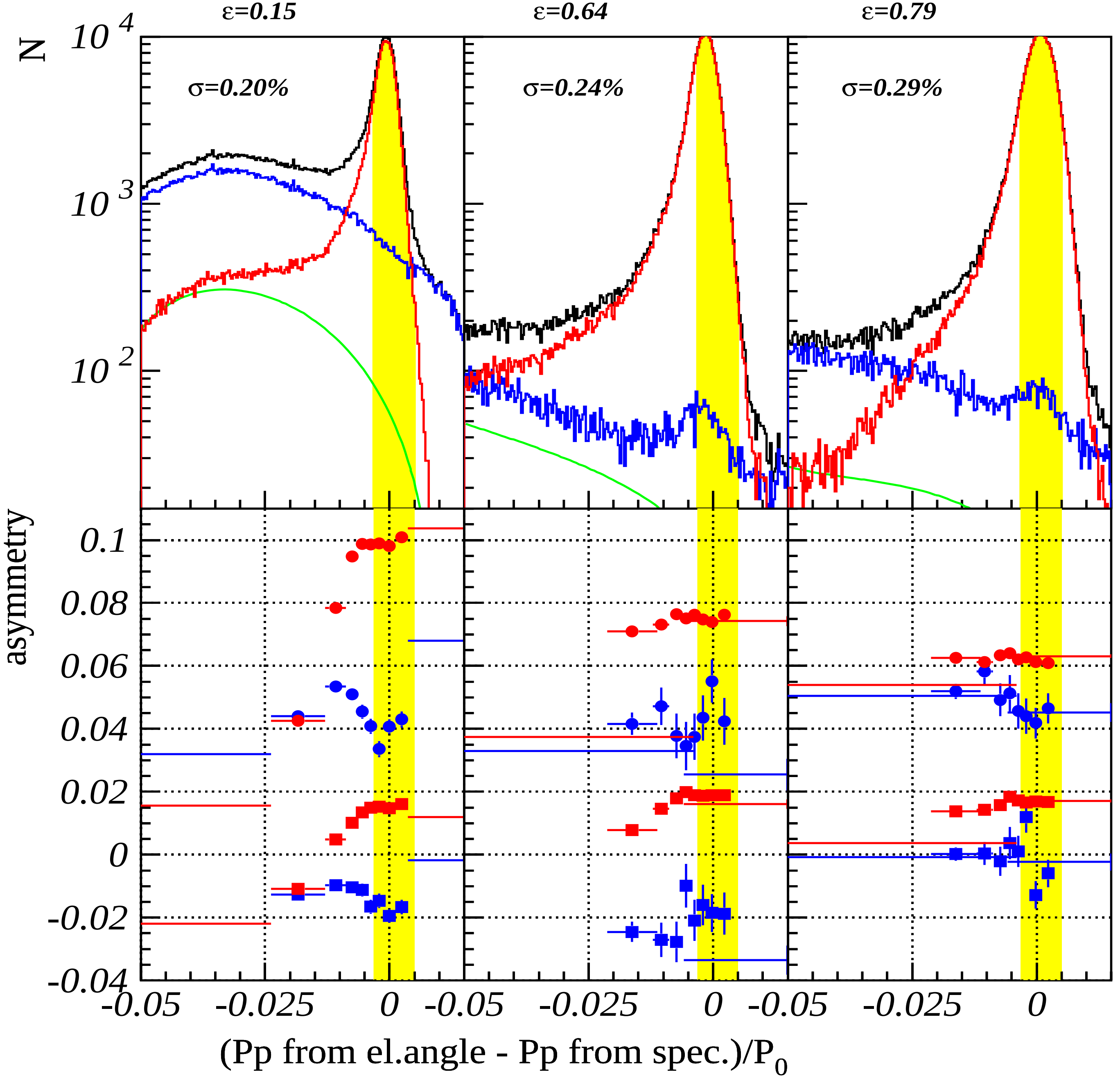


Focal Plane Polarimeter with double Analyzer

1744 channel E.M. Calorimeter



Data analyses: elastic separation



All triggers

Inelastics

Elastics after ep kinematical correlation

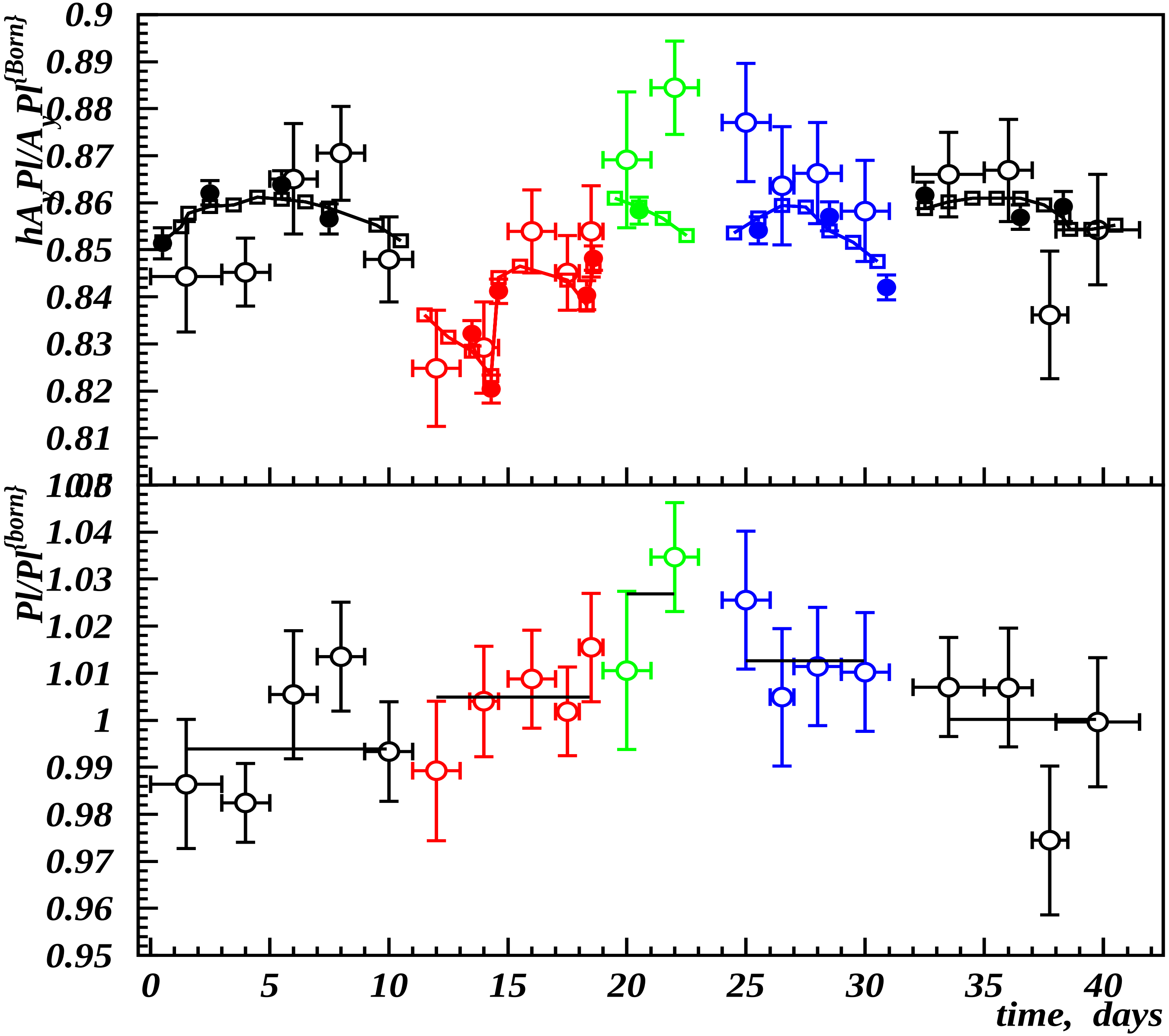
Estimated background

Circles –longitudinal asymmetry at target

Boxes – transverse asymmetry at target

Background contribution max of 0.5% for ε=0.15

Longitudinal transferred polarization: stability of the measurements



•open circles: this experiment

(hAyPl)^meas/(Plborn Ay(θ))

• filled circles – Moller measurements of beam polarization (h)

• open boxes (connected with line): beam polazrization predicted from quantum efficiency measurements (Dave Gaskell, private comm.)

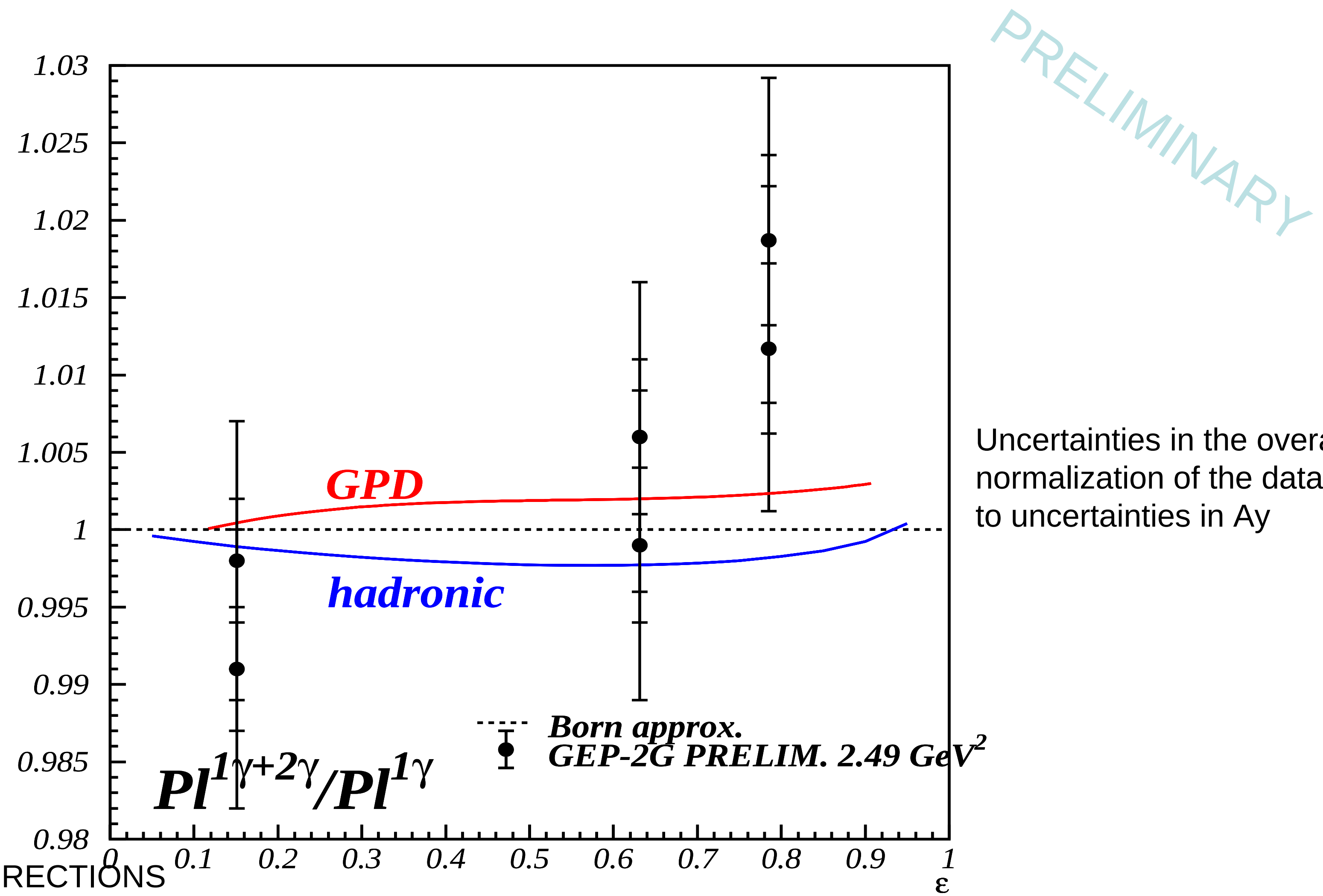
• 1.873 GeV beam energy, ε=0.15

• 2.846 GeV e=0.64

• 3.549 GeV e=0.78

•3.680 GeV e=0.79

Preliminary results: longitudinal polarization



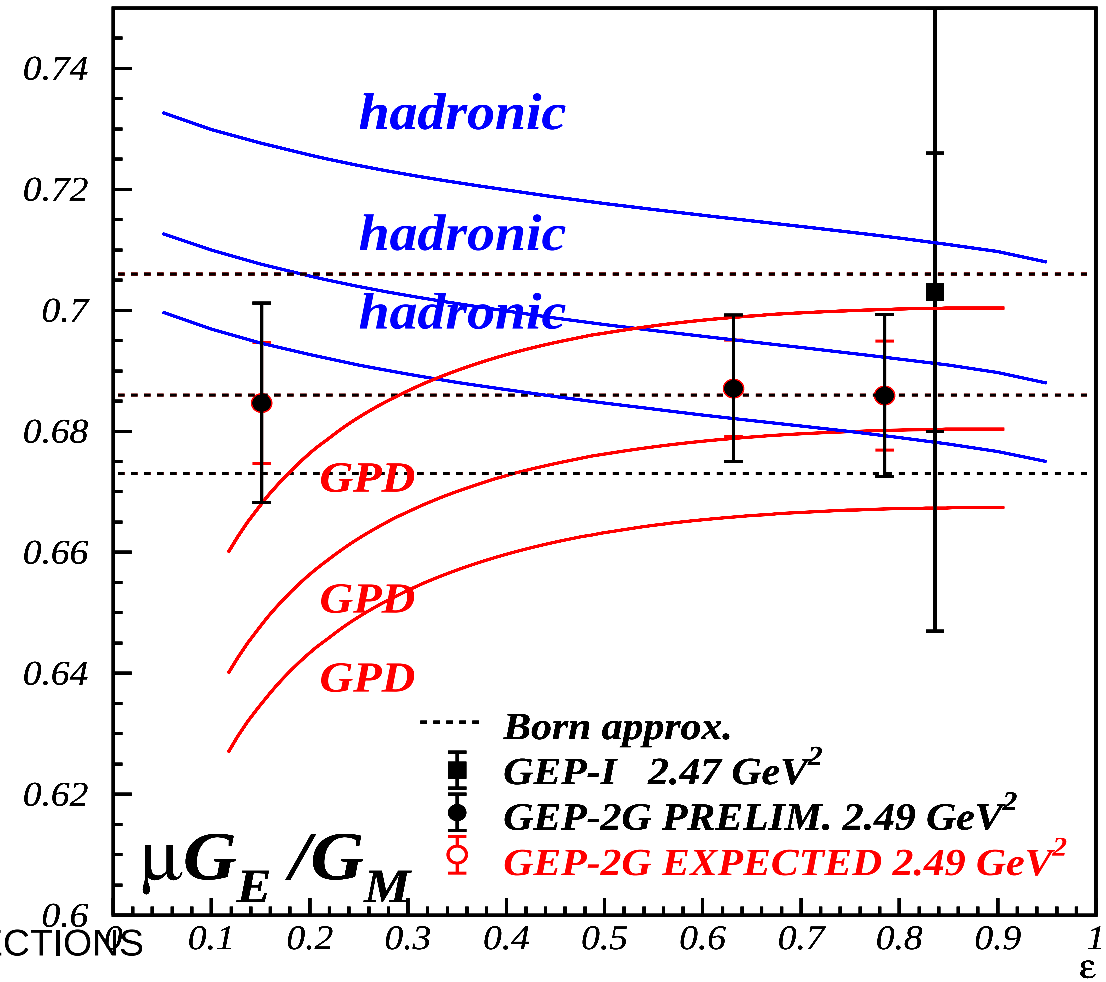
Uncertainties in the overall normalization of the data due to uncertainties in Ay

NO RADIATIVE CORRECTIONS APPLIED,

Less than 1% (Afanasev et.al, Phys.Rev. D64 (2001) 113009)

Beam polarization p.t.p. systematics 0.5%

Preliminary results: form factor ratio



Theoretical predictions are with respect to the Born approximation

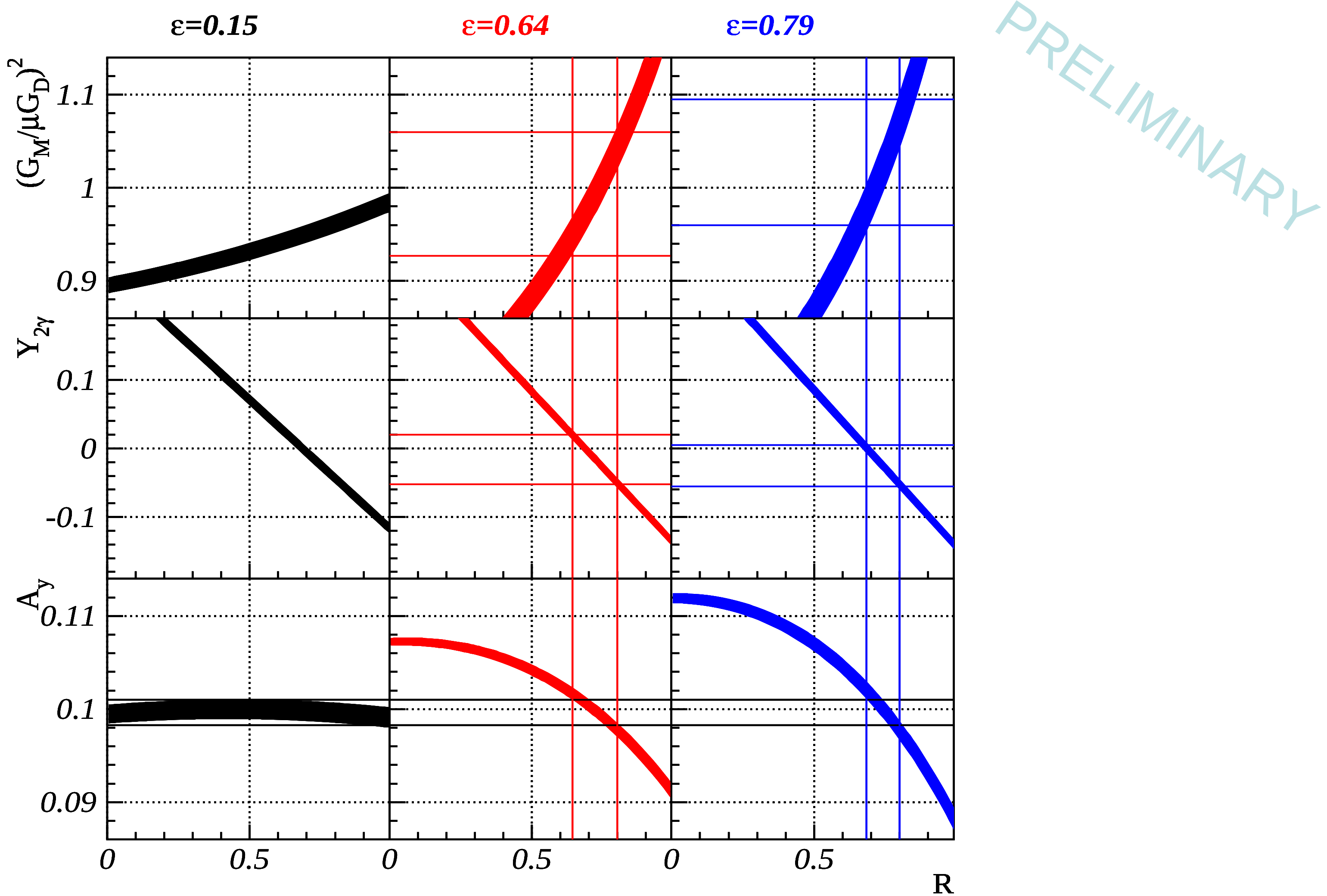
NO RADIATIVE CORRECTIONS APPLIED,

Less than 1% (Afanasev et.al, Phys.Rev. D64 (2001) 113009)

Elastic amplitude reconstruction

Three observables measured at 2.5 GeV^2:

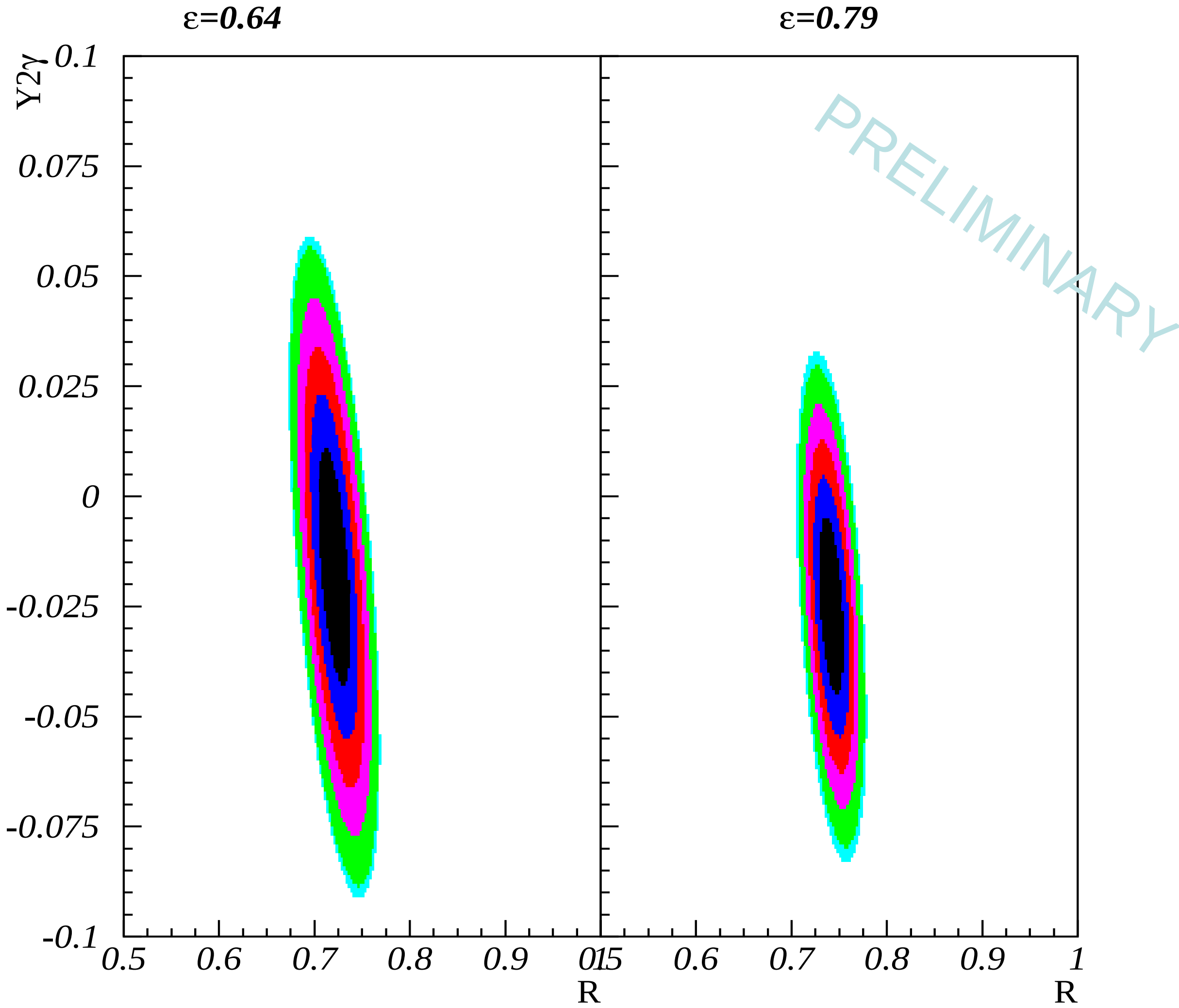
- Pt/Pl
- Ay*Pl
- dσ



Three amplitudes (Re parts): $R=\mu Re(G_E)/Re(G_M)$, $Y2\gamma$, $Re(G_M)$ and Ay unknown

Plotted: $Re(G_M)$ (dσ, Pt/Pl,R), Y2g(Pt/Pl,R), Ay(Ay*Pl,R)

Elastic Amplitude Reconstruction



Y2γ vs R=μ*Re*(G_E)/*Re*(G_M) reconstructed from this experiment (1σ area)

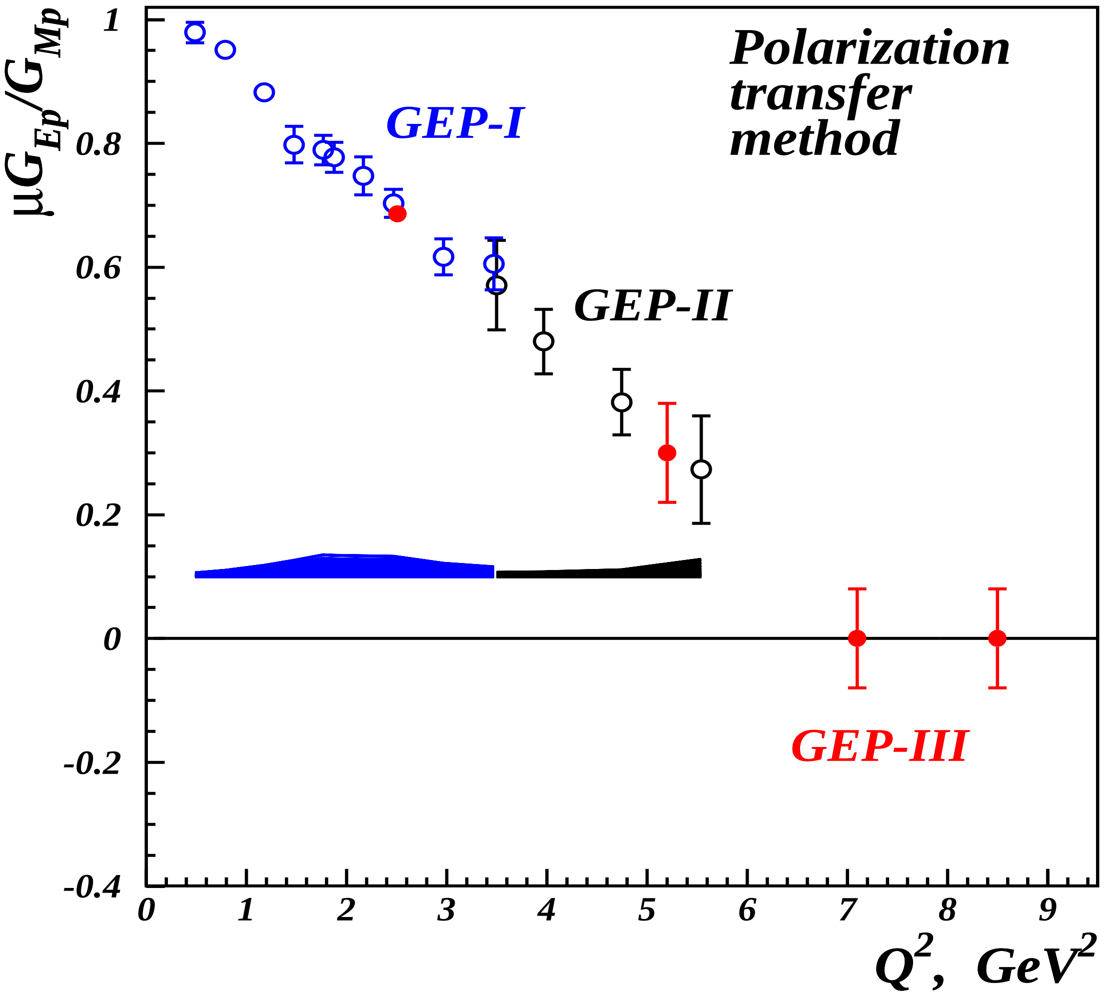
Important note:

Elastic amplitude reconstruction is different from full Born / non-Born separation: need e+/e- data and triple polarization observables (M.P.Rekalo and E. Tomasi-Gustafsson Nucl.Phys.A740:271-286,2004**)**

Still here one can constrain the contribution from the third non-Born amplitude Y2γ.

GEP results

GEP preliminary results at 2.5 and 5.2 GeV^2



CONCLUSIONS

- POLARIZATION METHOD PASSED THE TEST : no evidence for effects beyond Born approximation at 1% level in the polarization data at Q^2 of 2.5 GeV^2

- Slight deviation from Born approximation at a two sigma level for longitudinal polarization requires attention

- Discrepancy between Rosenbluth and polarization method

• No experimental explanation was found

• Radiative corrections (two-photon exchange and/or higher order corrections) are the most likely candidate but it requires further experimental and theoretical investigation

- Measuring two polarization observables for a fixed Q^2 in a wide kinematical range with 1% precision allows to constrain the real parts of both, ratio of the generalized electric to magnetic form factors, and the third non-Born amplitude contribution $Y_{2\gamma}$, without model assumptions. Including precise cross-section data will constrain also the real part of the magnetic form factor.

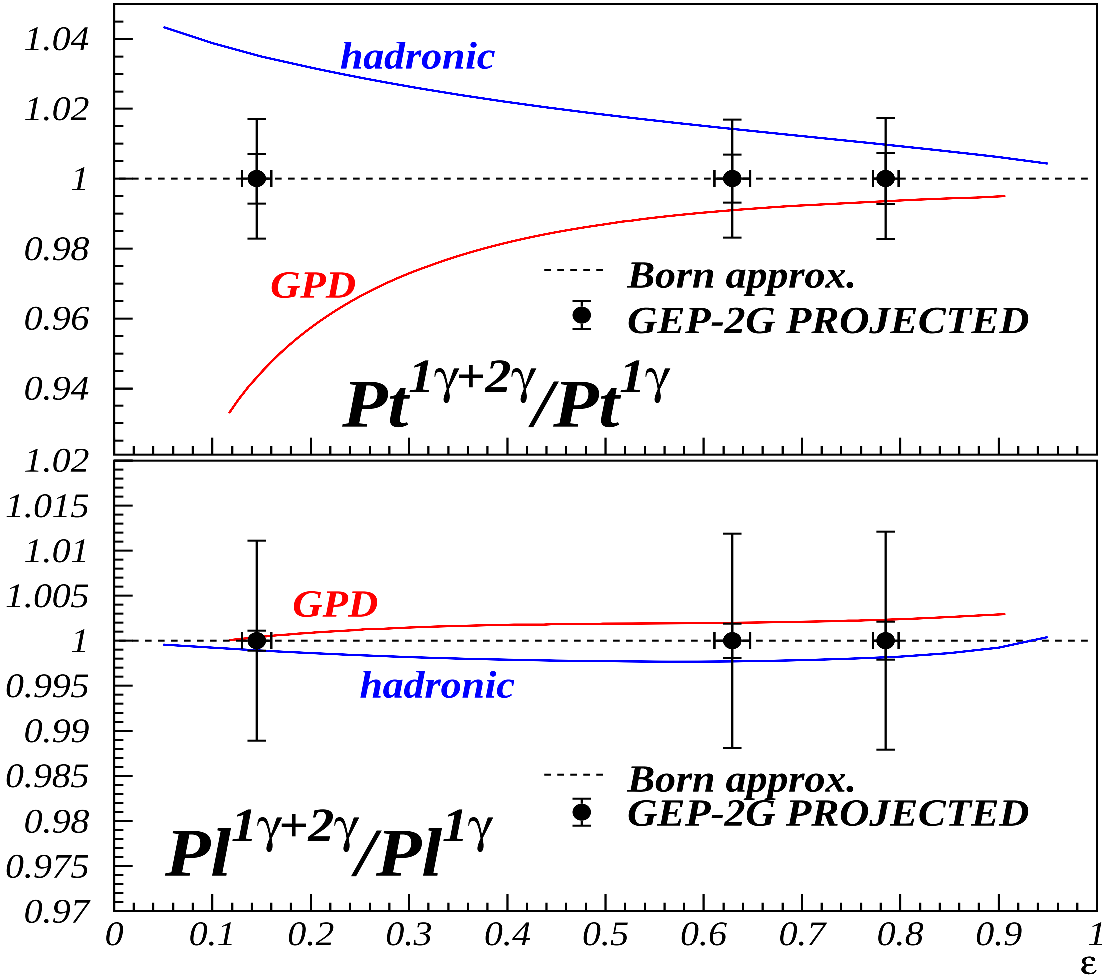
Preliminary results

No radiative corrections applied (<1%)

BACK-UP SLIDES

STARTING HERE

GEP-2G goals: ε dependence of p_t, p_l at Q^2=2.5 GeV^2



p.t.p. sytematic uncertainties:

- 1% beam polarization
- 0% analyzing power :

  Q^2 fixed, p_p fixed, A_y fixed

0.75% absolute systematic error: (0.45% non-dispersive bend angle, 0% dispersive (108^0 prec. angle), 0.3% FPP chambers misalignment)

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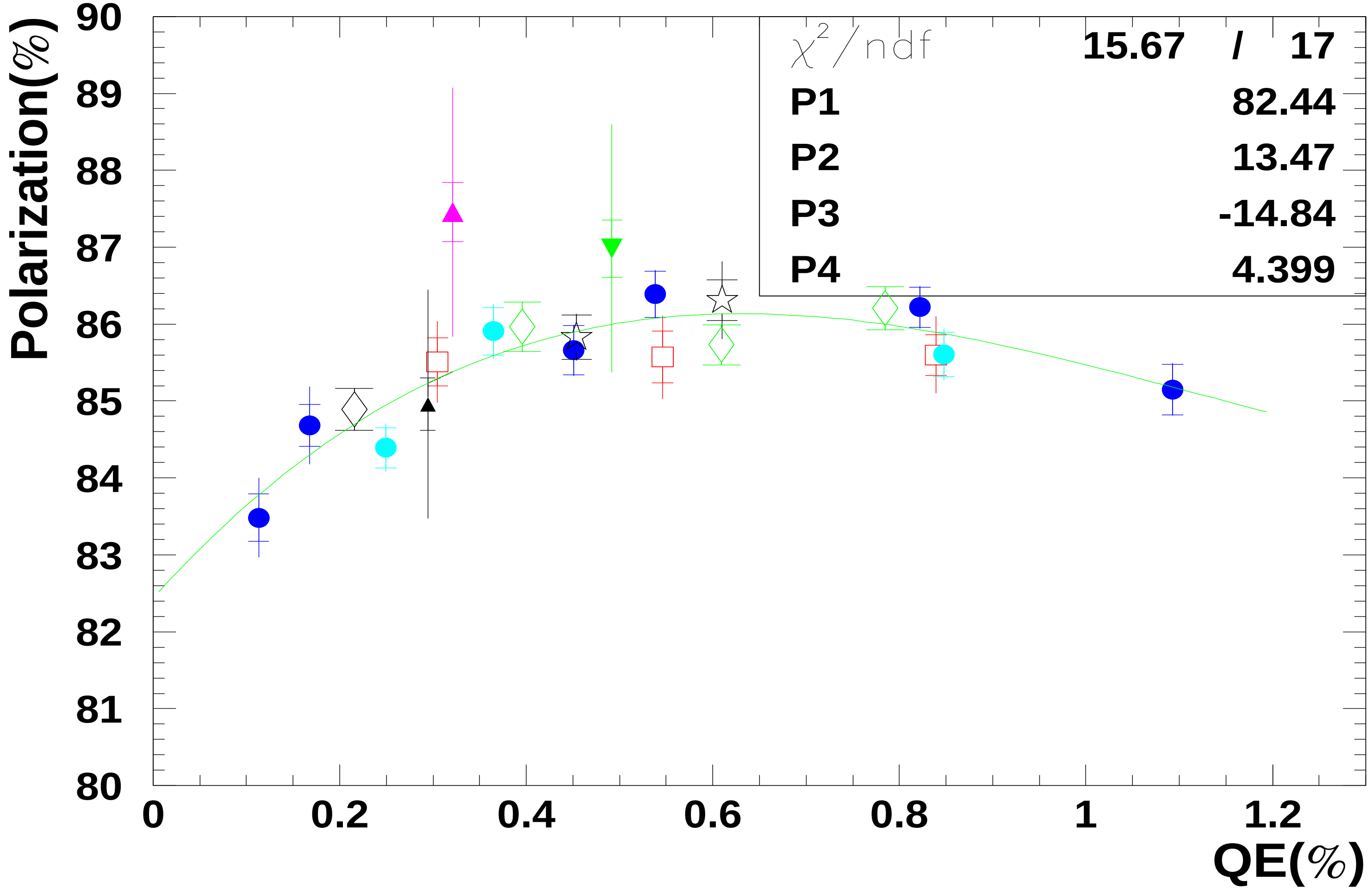
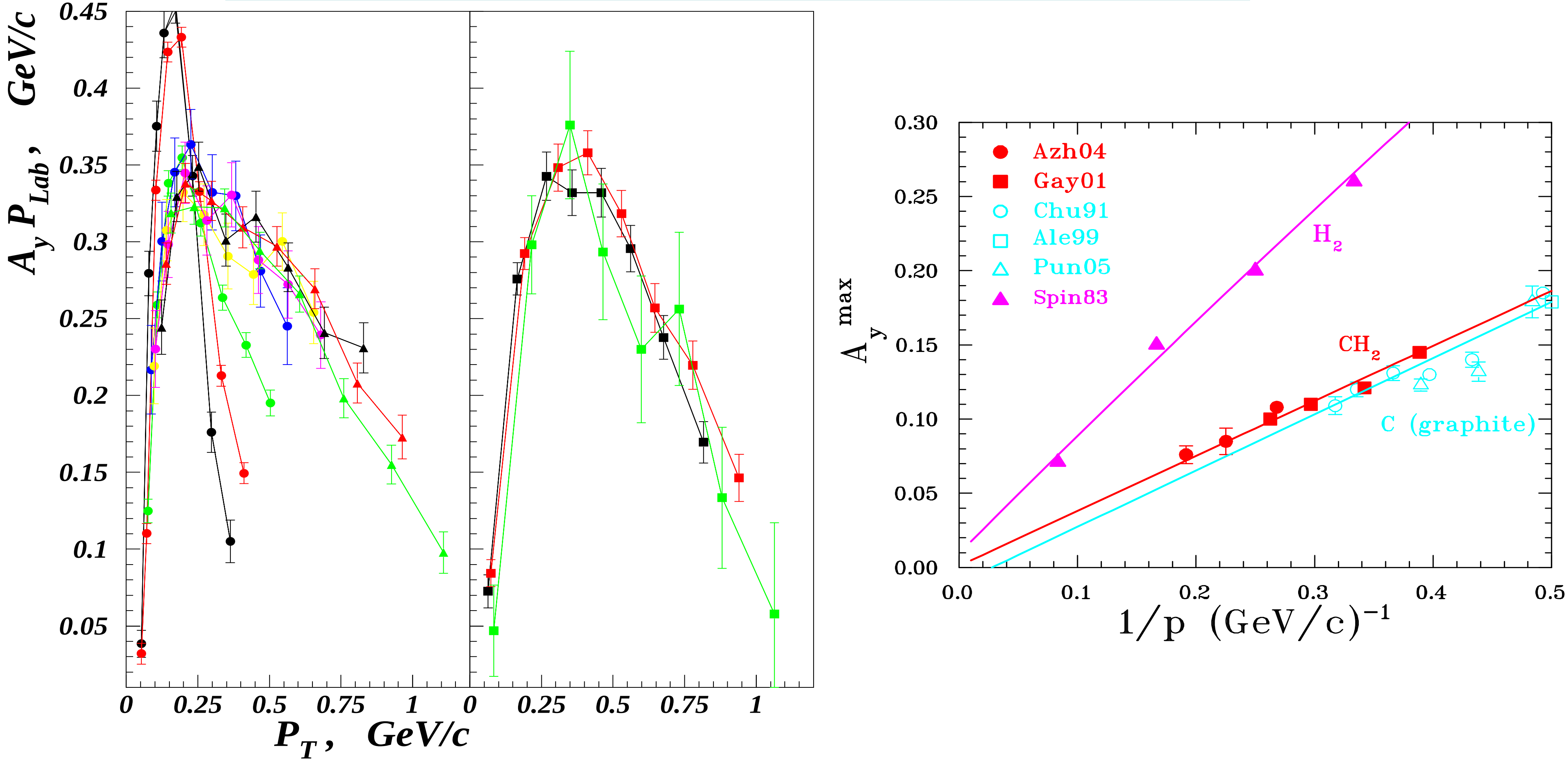


Analyzing Power

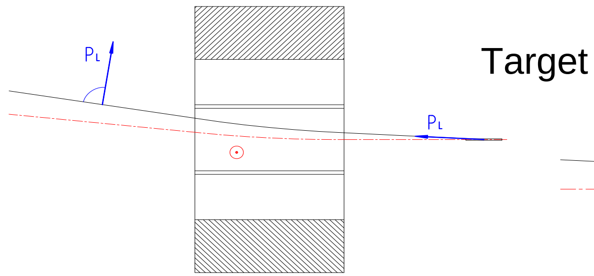


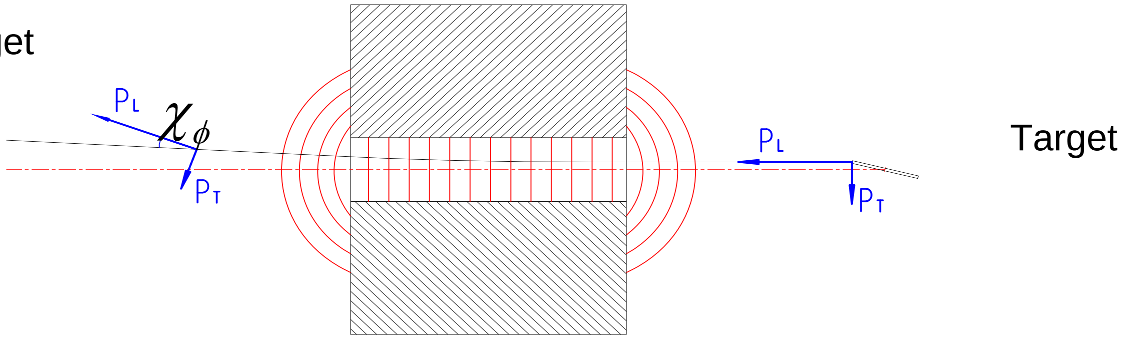
Polarization Method: Spin Transport

Dispersive precession $\chi_\vartheta = \gamma(\mu - 1)\Delta\vartheta$

Non-dispersive precession $\chi_\phi = \gamma(\mu - 1)\Delta\phi$

χ_ϑ



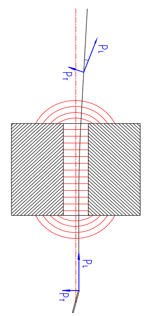


to Reaction Plane

Reaction Plane

$\perp$

$$\mu \frac{G_{Ep}}{G_{Mp}} = -\mu \frac{P_t}{P_l} \frac{(E_{beam} + E_e)}{2M_p} \tan \frac{\vartheta_e}{2}$$



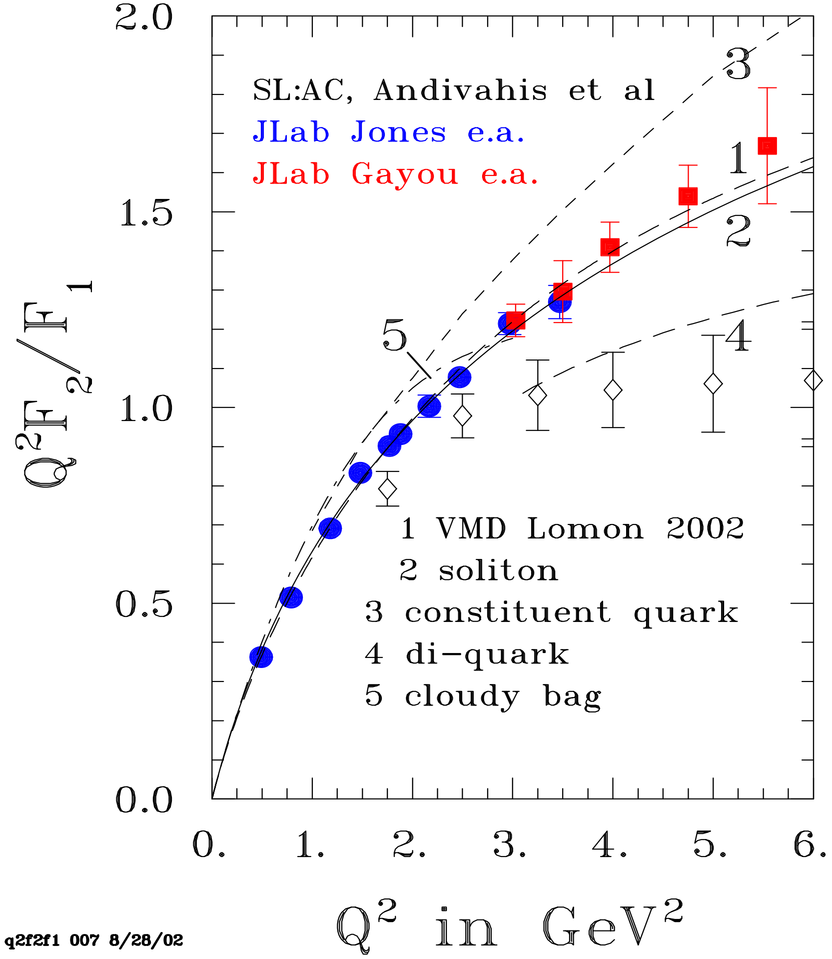
Longitudinal and transverse polarizations Pt and Pl are helicity dependent (transferred)

Normal polarization Pn is helicity independent; zero in Born approximation

$$\frac{P_t}{P_l} = \frac{P_t^{fp} \sin \chi_\theta}{P_n^{fp}} - \chi_\phi$$

$$\mu \frac{G_{Ep}}{G_{Mp}} = -\mu \frac{(E_{beam} + E_e)}{2M_p} \tan \frac{\vartheta_e}{2} \left(\frac{P_t^{fp}}{P_l^{fp}} \sin \chi_\vartheta + \gamma(\mu - 1)\Delta\phi \right)$$

GEp/GMp Crisis: asymptotic behavior



Dirac and Pauli form factors:

$$F_1 = \frac{\tau G_M + G_E}{1+\tau}$$

$$F_2 = \frac{G_M - G_E}{\kappa(1+\tau)}$$

$$\frac{Q^2 F_2}{F_1} = const. \qquad pQCD\ asymptotic$$

Polarization Method: Systematics

Relate the evolution of the velocity (trajectory) to the evolution of the spin:

$$\frac{d\vec{S}}{dt} = \frac{e}{m\gamma}\vec{S} \times \left[\frac{g}{2}\vec{B}^{\parallel} + \left(1 + \frac{g-2}{2}\gamma\right)\vec{B}^{\perp}\right]$$

$$\frac{d\vec{v}}{dt} = \frac{e}{m\gamma}\vec{v} \times \vec{B}^{\perp}$$

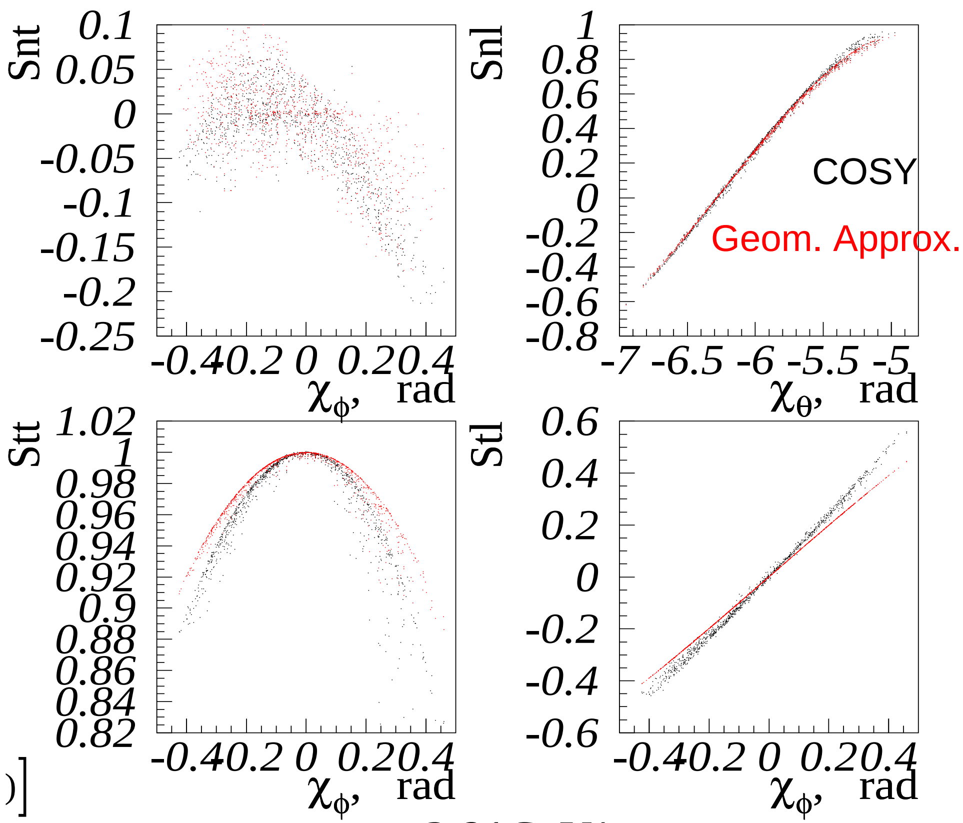
$$\vec{B}^{\parallel} = 0$$

$$\chi_\theta = \gamma\left(\frac{g}{2} - 1\right)\Delta\theta = f \cdot \Delta\theta$$

$$\chi'_\phi(s) = \int_0^s \sin\chi_\theta(s)\, f d\phi(s) \cong -f \cdot (\phi_d - \phi_{fp}) \sin\chi_\theta$$

$$\chi_\phi(s) = \int_0^s \cos\chi_\theta(s)\, f d\phi(s\phi) \cong f \cdot \left[\Delta\phi + (\phi_d - \phi_{fp})(1 - \cos\chi_\theta)\right]$$

$$\begin{pmatrix} P_n^{fp} \\ P_t^{fp} \\ P_l^{fp} \end{pmatrix} = \begin{pmatrix} S_{nn} S_{nt} S_{nl} \\ S_{tn} S_{tt} S_{tl} \\ S_{\ln} S_{lt} S_{ll} \end{pmatrix} \begin{pmatrix} P_n \\ P_t \\ P_l \end{pmatrix}$$



p_0=3.81GeV/c

$$S_{nt} = -\sin\chi_\phi \cos\chi'_\phi \sin\chi_\theta + \cos\chi_\phi \sin\chi'_\phi \cos\chi_\theta$$

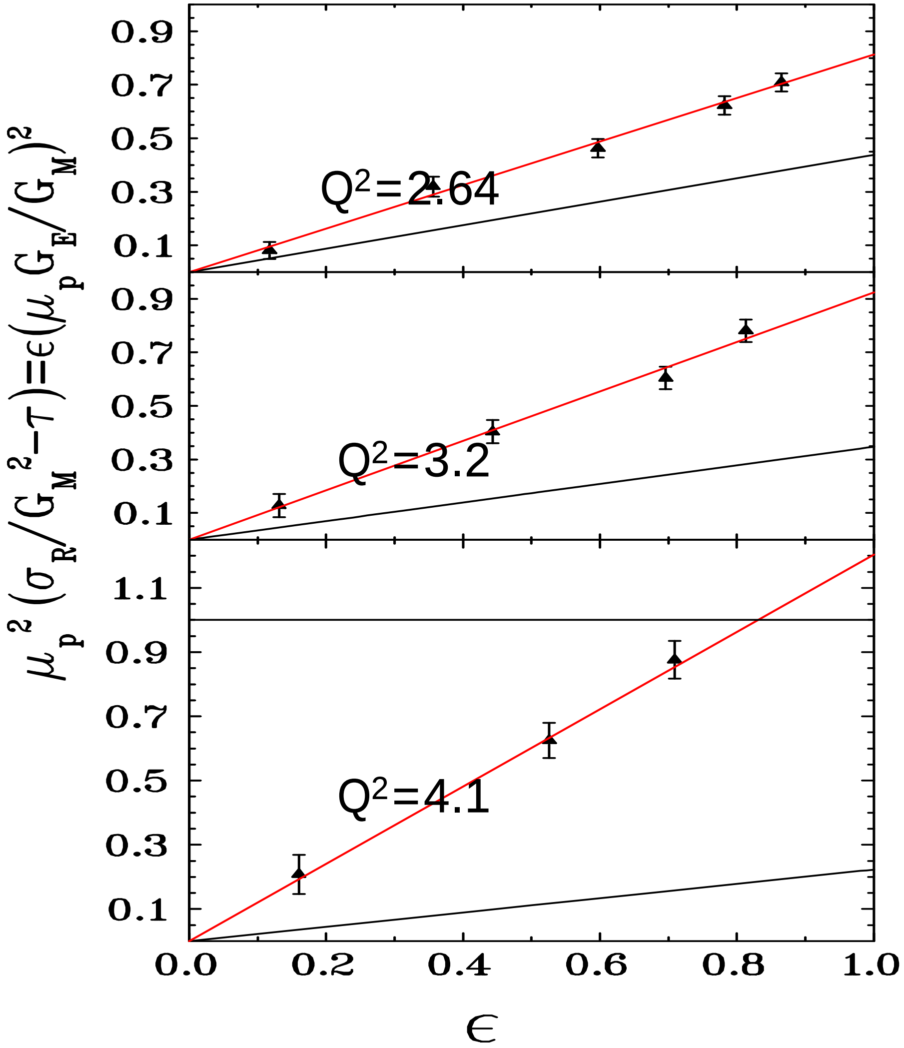
$$S_{nl} = \cos\chi_\phi \sin\chi_\theta$$

$$S_{tt} = \cos\chi_\phi \cos\chi'_\phi$$

$$S_{tl} = \sin\chi_\phi$$

Geometrical Approx.

Rosenbluth method



- Cross section:

  $\frac{d\sigma}{d\Omega} = (\frac{d\sigma}{d\Omega})_{Mott} \times$

  $\left\{F_1^2(Q^2) + \tau\left[F_2^2(Q^2) + 2(F_1(Q^2) + F_2(Q^2))^2 \tan^2\frac{\theta}{2}\right]\right\}$

- F_1 and F_2 relativistic invariants depending on Q^2 only. $G_E = F_1 - \tau\kappa_p F_2$, and $G_M = F_1 + \kappa_p F_2$.

- $\frac{d\sigma}{d\Omega} = (\frac{d\sigma}{d\Omega})_{Mott}\left\{G_E^2 + \frac{\tau}{\epsilon}G_M^2\right\}/(1+\tau)$,

  with $\tau = \frac{Q^2}{4M_p^2}$ and $\epsilon = \frac{1}{1+2(1+\tau)\tan^2\frac{\theta}{2}}$

$$\sigma_R = \epsilon(1+\tau)\frac{d\sigma}{d\Omega}/(\frac{d\sigma}{d\Omega})_{Mott} = \epsilon G_E^2 + \tau G_M^2$$

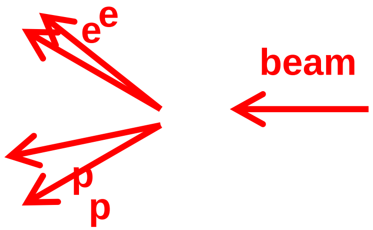
The real FPP

High Q2 Measurements

E.M. calorimeter

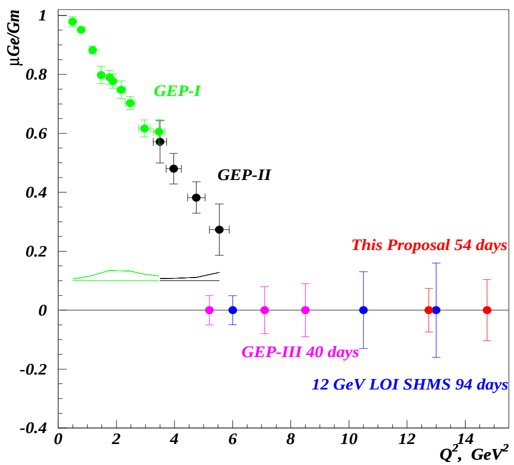
$\Omega_e = 180\,msr$

$\Omega_e\ up\ to\ 138\ msr$



Magnet

$\Omega_p > 33 msr$



POLARIMETER

Proton spectrometer (HRS)

$\Omega_p = 6msr$

HCAL

POLARIMETER

GeP-15 (E12-07-109) Large Acceptance Proton Form Factor Measurements at 13 and 15 GeV² Using Recoil Polarization Method, C.Perdrisat, L.Pentchev, E.Cisbani, V.Punjabi, B.Wojtsekhowski

High Q2 Measurements