Precision Measurement of the Proton Elastic Form Factor Ratio at Low Q^2

Shalev Gilad, MIT

- Nucleons Form Factors
- Recoil polarimetry
- World data
- New results
- Impact
- Outlook and summary

Dirac and Pauli Form Factors

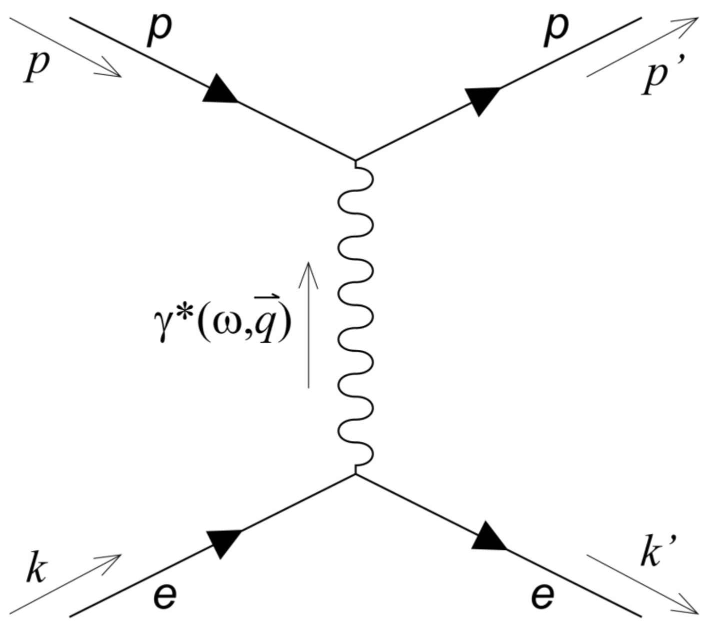
- Pioneered by Hofstadter *et. al* at Stanford in 1950s, first proton form factor measurement reported in 1955

- As theory for Strong force, QCD has been tested well in the asymptotic region, understanding hadron structure in confinement region still challenging

- Dirac and Pauli form factors: F_1 , F_2

$$J^{\mu}_{hadronic} = e\bar{u}(p')[\gamma^{\mu}F_1(Q^2) + \frac{i\sigma^{\mu\nu}q_{\nu}}{2M}F_2(Q^2)]u(p)$$

$$Q^2 = -q^2$$



single photon exchange
(Born approximation)

$$\frac{d\sigma}{d\Omega} = \sigma_{Mott}\frac{1}{1+\tau}\{F_1^2(Q^2) + \tau[F_2^2(Q^2) + 2(F_1(Q^2) + F_2(Q^2))^2\tan^2\frac{\theta_e}{2}]\}$$

Sachs Form Factors

- Linear combination of F_1 and F_2
- Fourier transform of the charge (magnetization) densities in the Breit frame at the non-relativistic limit

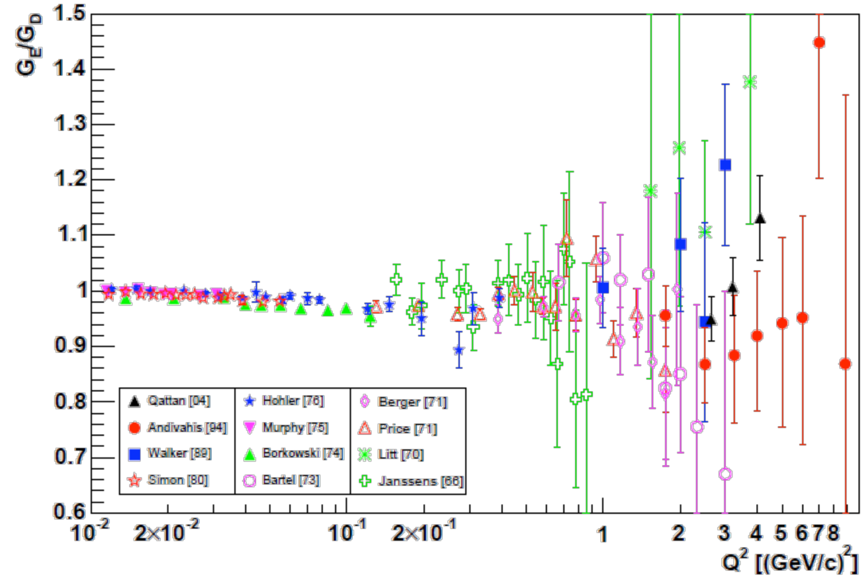
Electric: $G_E \equiv F_1 - \tau F_2$

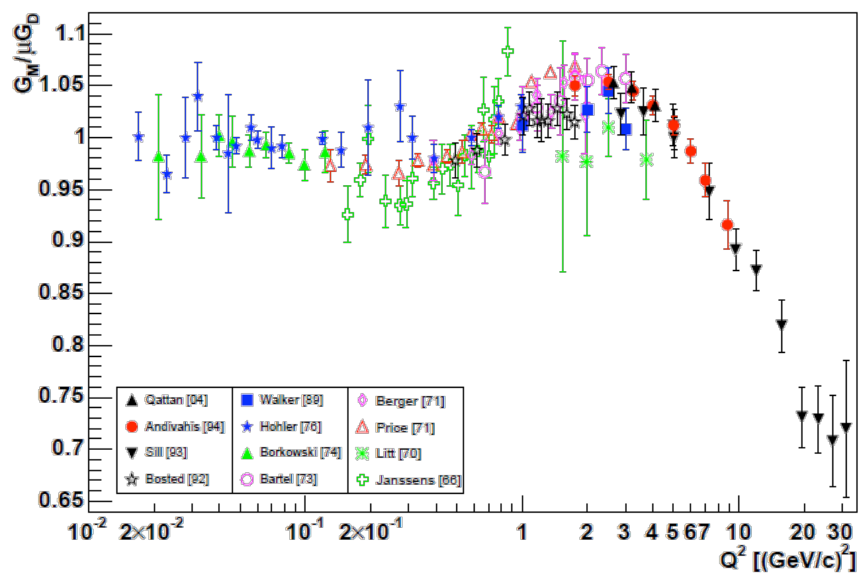
Magnetic: $G_M \equiv F_1 + F_2$

$$\frac{d\sigma}{d\Omega} = \sigma_{Mott} \frac{1}{1+\tau}\left[G_E^2 + \frac{\tau}{\varepsilon} G_M^2\right]$$

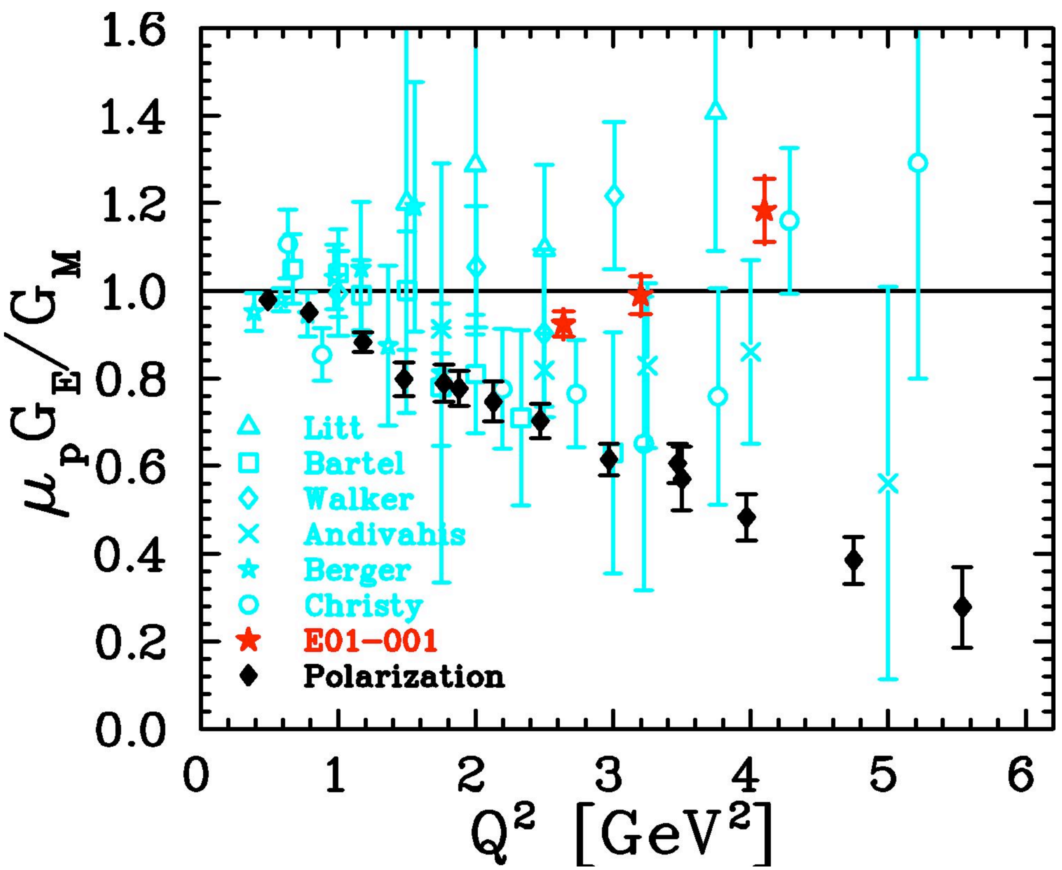
- Rosenbluth separation
  Hard to determine G_E at large Q^2, G_M at low Q^2 (except at $\theta_{e'} \approx 90°$)
- Early experiments found ~ dipole form ($Q^2 < 2$ GeV^2), naively corresponds to an exponential shape in space

$$G_D(Q^2) = (1 + \frac{Q^2}{0.71 GeV^2})^{-2} \qquad \mu_P \frac{G_E}{G_M} = 1$$

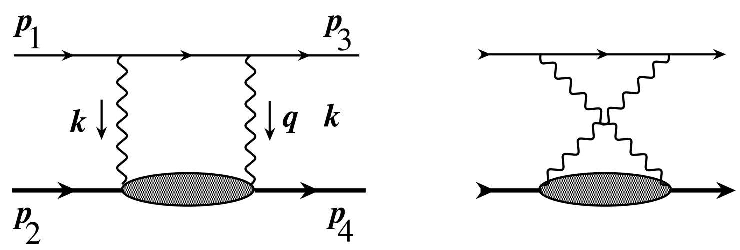




Rosenbluth vs. Polarimetry



M.K.Jones, et al., PRL ***84****, 1398 (2000)*
O.Gayou, et al., PRL ***88****, 092301 (2003)*
I.A.Qattan, et al., PRL ***94****, 142301 (2005)*



P.A.M.Guichon and M.Vanderhaeghen, PRL 91, 142303 (2003)

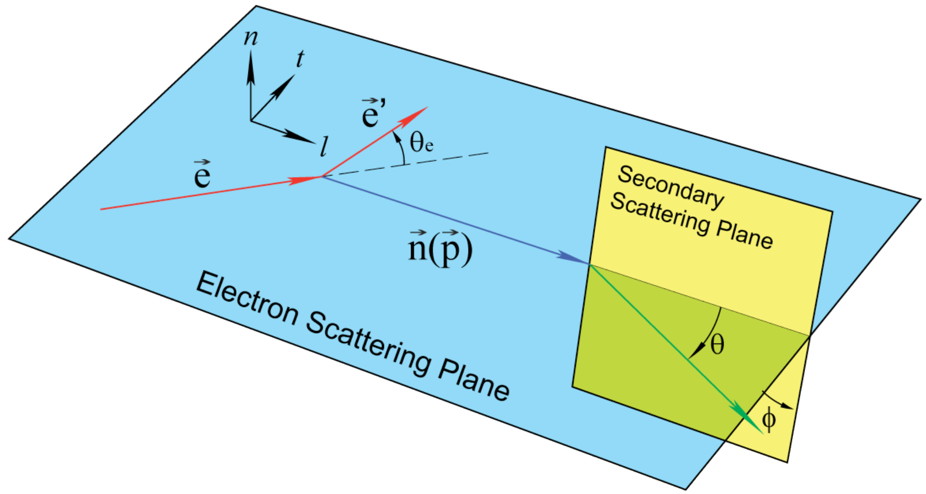
Recoil Polarimetry

- Direct measurement of form factor ratios by measuring the ratio of the transferred polarization P_t and P_l

$$l_0 P_t = -2\sqrt{\tau(1+\tau)} G_E G_M \tan\frac{\theta_e}{2}$$

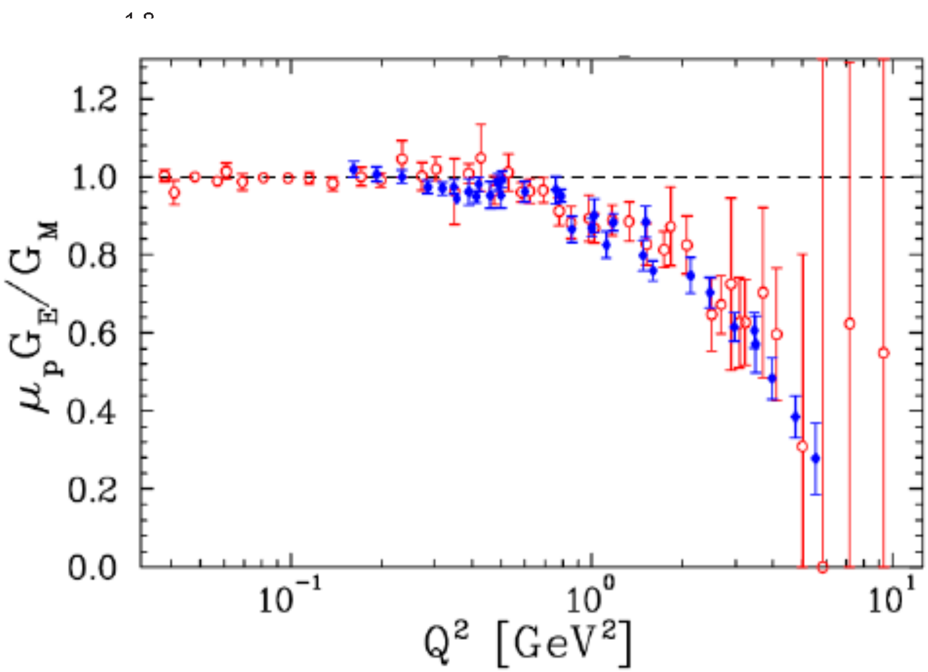
$$l_0 P_l = \frac{E_e + E_{e'}}{M}\sqrt{\tau(1+\tau)} G_M^2 \tan^2\frac{\theta_e}{2}$$

$$\frac{G_E}{G_M} = -\frac{P_t}{P_l}\frac{(E_e + E_{e'})}{2M}\tan\frac{\theta_e}{2}$$



Advantages:

- Only one measurement is needed for each Q^2
- Much better precision than a cross section measurement
- Complementary to cross section measurements
- Discrepancy between Rosenbluth and polarized measurement, mostly explained by 2-γ exchange



(J. Arrington, et al., Phys. Rev. C **76** 035205 (2007))

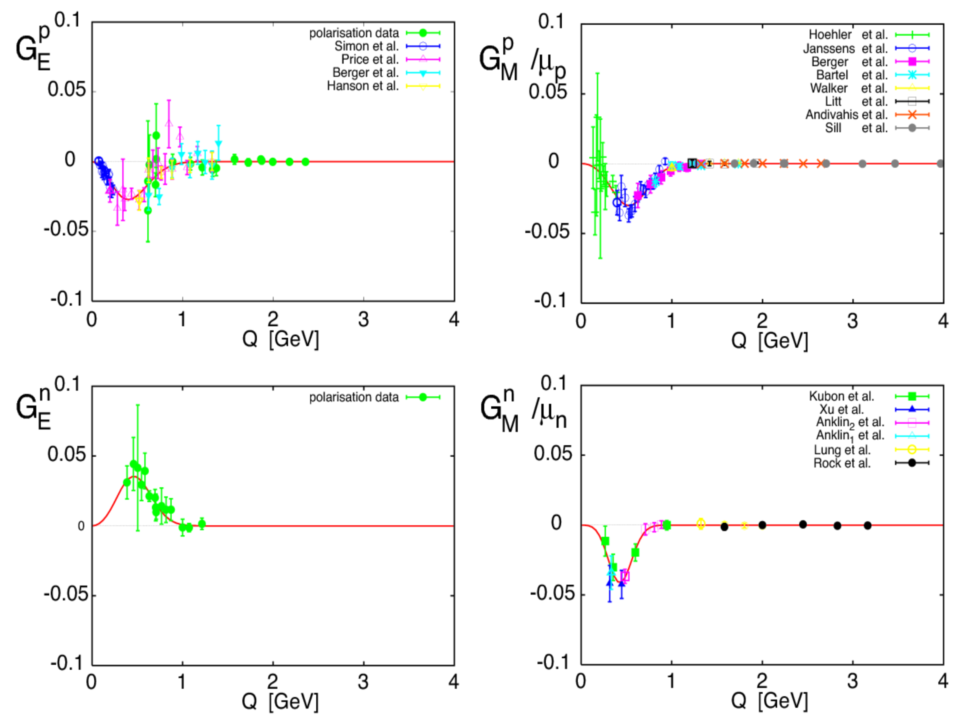
Form Factors at Low Q^2

- Small Q^2 → larger length scale, closely related to proton size

- Improved EMFFs:
  - Strange form factors through PV
  - Proton Zemach radius and hydrogen hyperfine splitting
  - Isoscalar and isovector form factors for Lattice QCD
  - Proton RMS radius

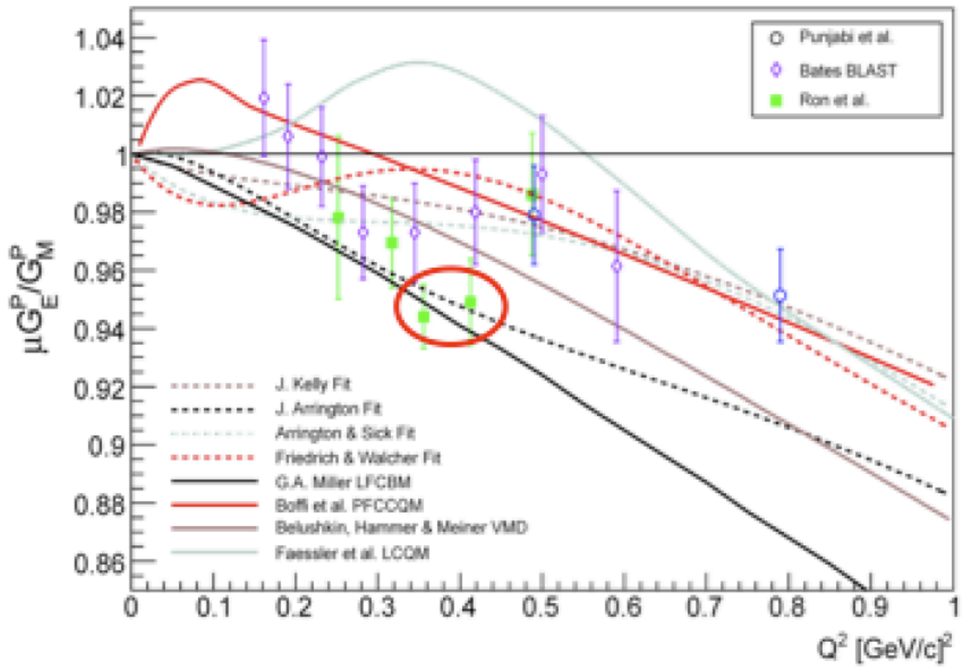
$$\langle r^2_{E,M}\rangle = \frac{-6}{G_{E,M}(0)}\left[\frac{d}{dQ^2}G_{E,M}(Q^2)\right]_{Q^2=0}$$

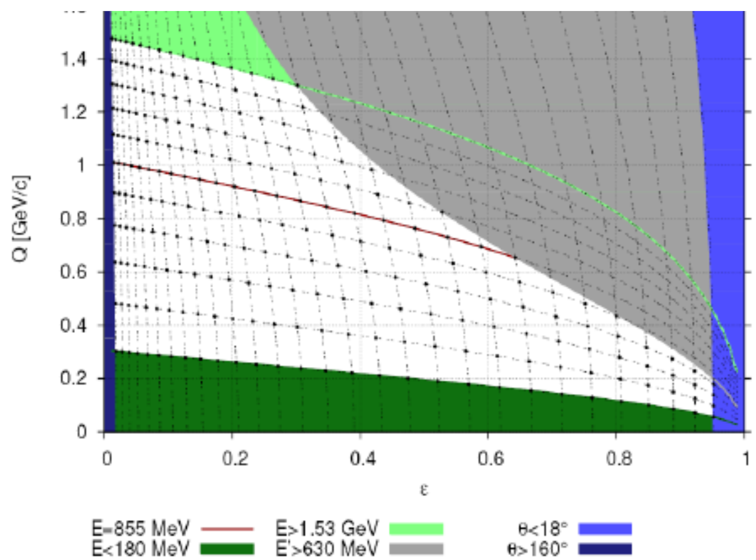
- 2003 – Fit by Friedrich & Walcher
  - Smooth dipole form + "bump & dip"
  - All four FFs exhibit similar structure at small momentum transfer (Q^2 ~ 0.25 GeV²)
  - Interpretation: effect of pion cloud



J. Friedrich and Th. Walcher, *Eur. Phys. J.* A **17**, 607 (2003)

World Data at Low Q^2

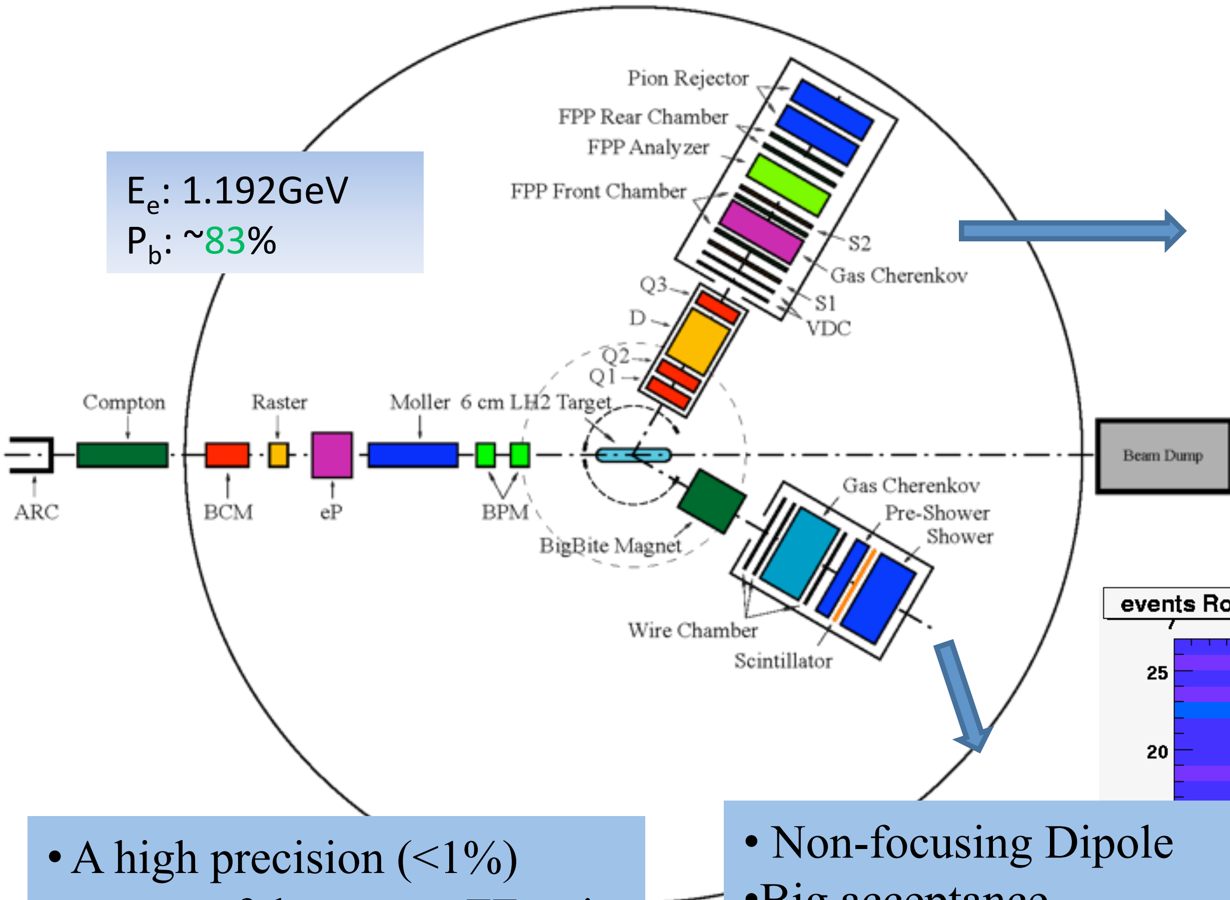




- Bates BLAST result consistent with 1
  Crawford et al., *Phys. Rev. Lett* **98** 052301 (2007)
- Substantial deviation from unity observed in LEDEX – smaller G_E
  G. Ron et al., *Phys. Rev. Lett* **99** 202002 (2007)
- Both data inconsistent with F&W fit
- Complementary to high precision XS measurement at Mainz (Q^2~ 0.003 – 1 GeV^2)
- New dedicated experiment JLAB E08-007

E08-007: Low Q^2 GEp/GMp

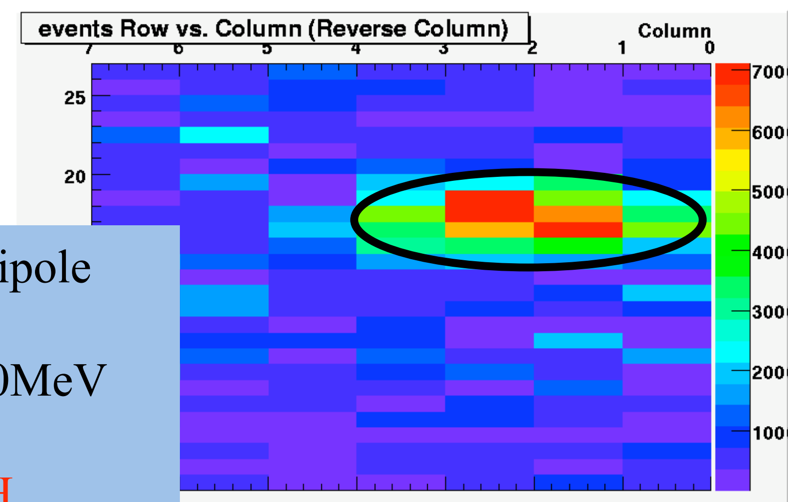
E_e: 1.192GeV
P_b: ~83%



LHRS

- Δp/p0: ± 4.5% ,
- out-of-plane: ± 60 mrad
- in-plane: ± 30 mrad
- ΔΩ: 6.7msr
- QQDQ
- Dipole bending angle 45^o
- **VDC+FPP**
- P_p : 0.55 ~ 0.93 GeV/c

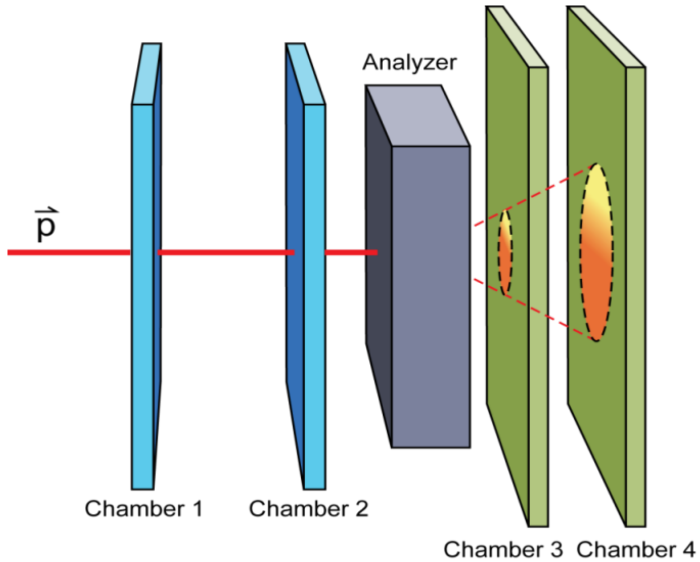
BigBite

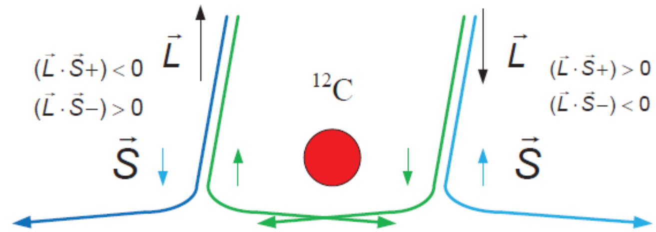


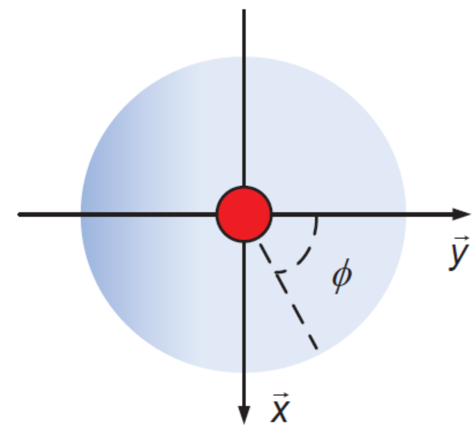
- A high precision (<1%) survey of the proton FF ratio
- 8 Q^2 data points: 0.3 ~ 0.7 $(GeV/c)^2$

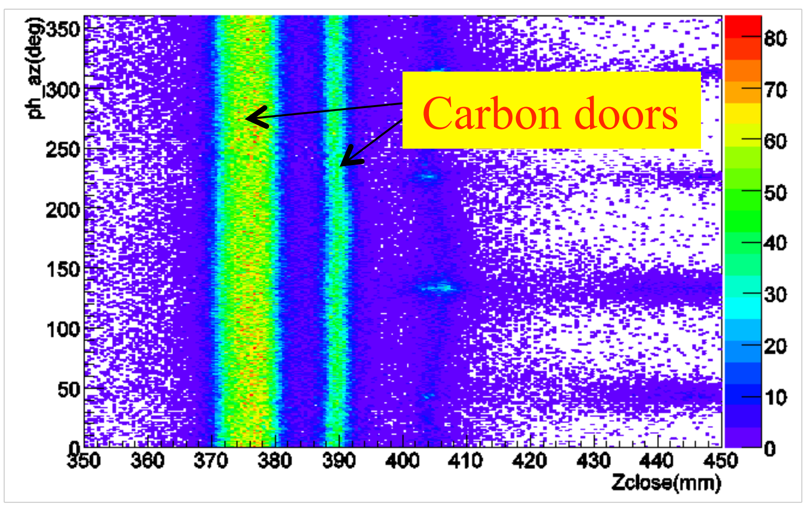
- Non-focusing Dipole
- Big acceptance.
  - Δp: 200-900MeV
  - ΔΩ: 96msr
- PS + Scint. + SH

Focal Plane Polarimeter (FPP)





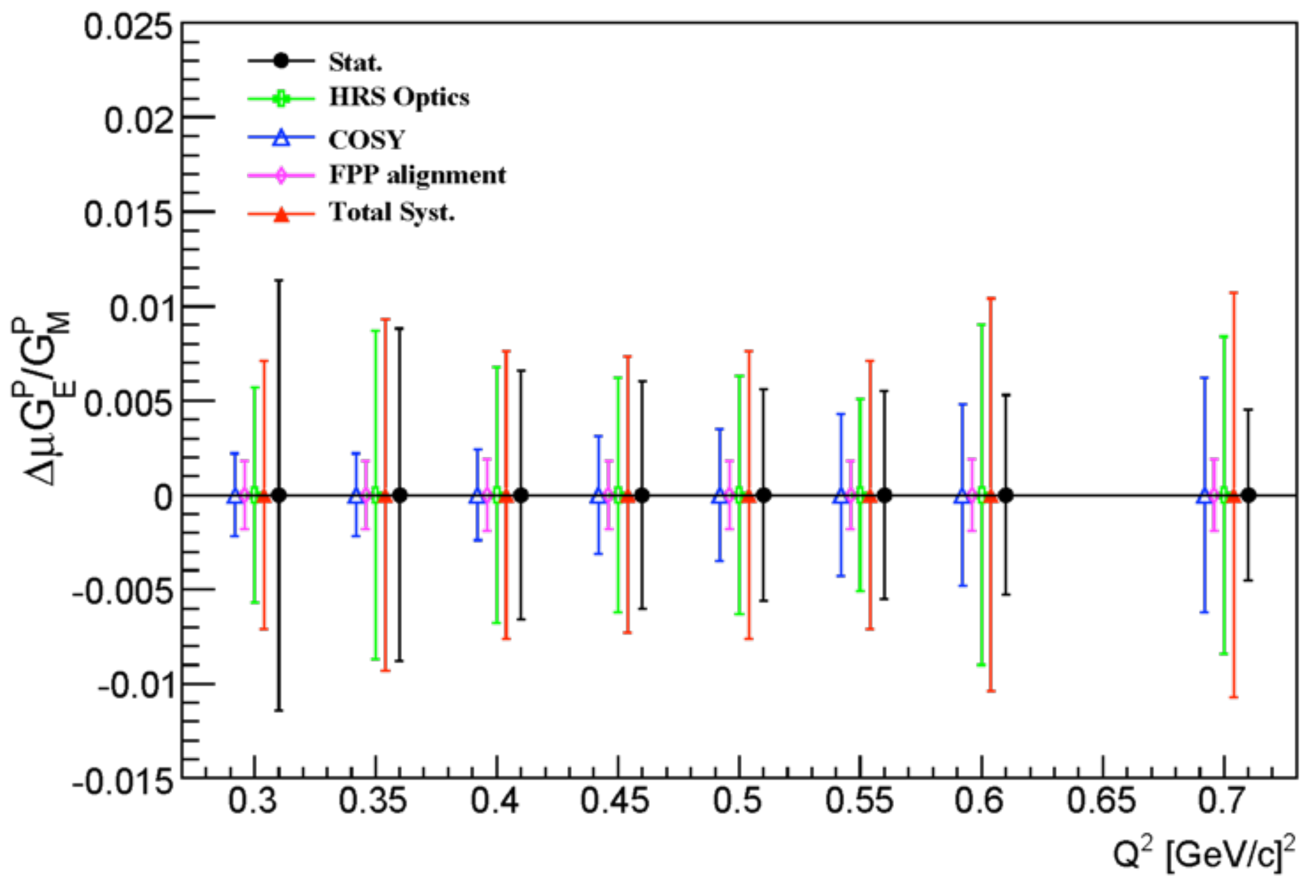




- Left-right asymmetry gives the vertical component while the up-down asymmetry gives the horizontal component
- Need well determined scattering azimuthal angle, ϕ_{fpp} , chamber alignment checked with straight through data

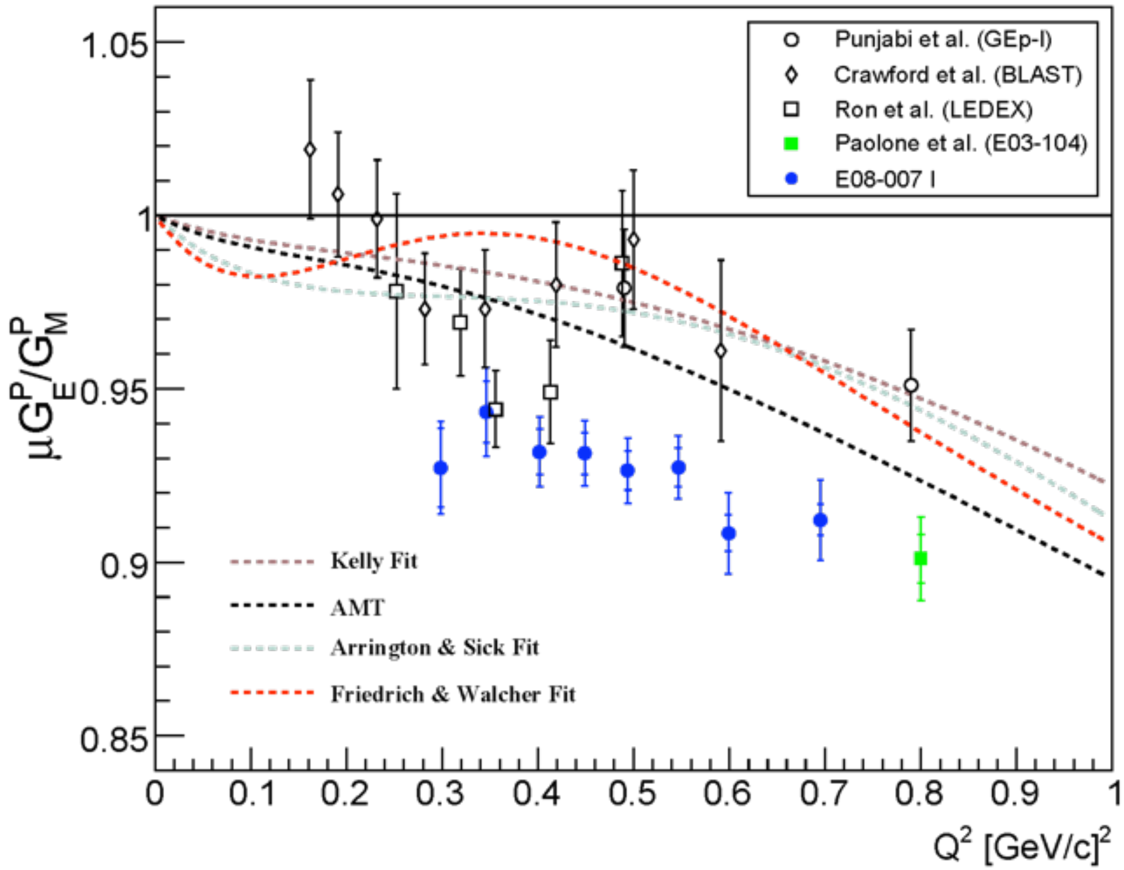
Systematic Budget

- Spin transport: OPTICS and COSY---major uncertainty (0.7 ~ 1.2 %)
- Others negligible: FPP alignment, Al end cap contamination, VDC reconstruction, spectrometer settings, beam energy, charge asymmetry, pion contamination, etc.



E08-007 Final Results

X-H. Zhan, MIT Ph.D. thesis (2010), to be submitted

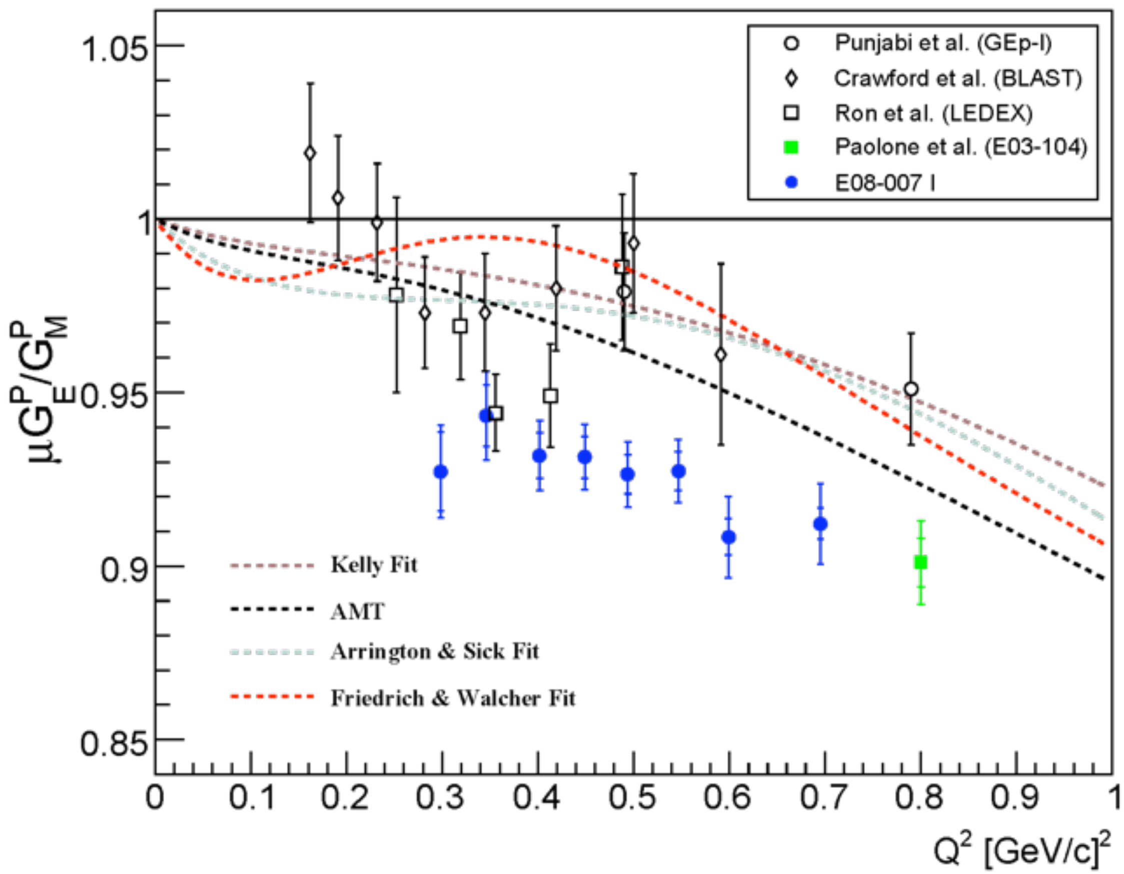


AMT - W. Melnitchouk J. Arrington and J.A. Tjon, Phys. Rev. C **76**,035205 (2007)
J. Arrington and I. Sick. Phys. Rev. C, **76**, 035201 (2007)

- Agreement with independent analysis of Paolone *et al.* at 0.8 GeV^2
- Slow decrease with Q^2. A few percent below previous data, fits
- Suggests that R = $\mu_p G_{Ep}/G_{Mp} < 1$ even at low Q^2
- No obvious indication of "Structure", inconsistent with F&W fit

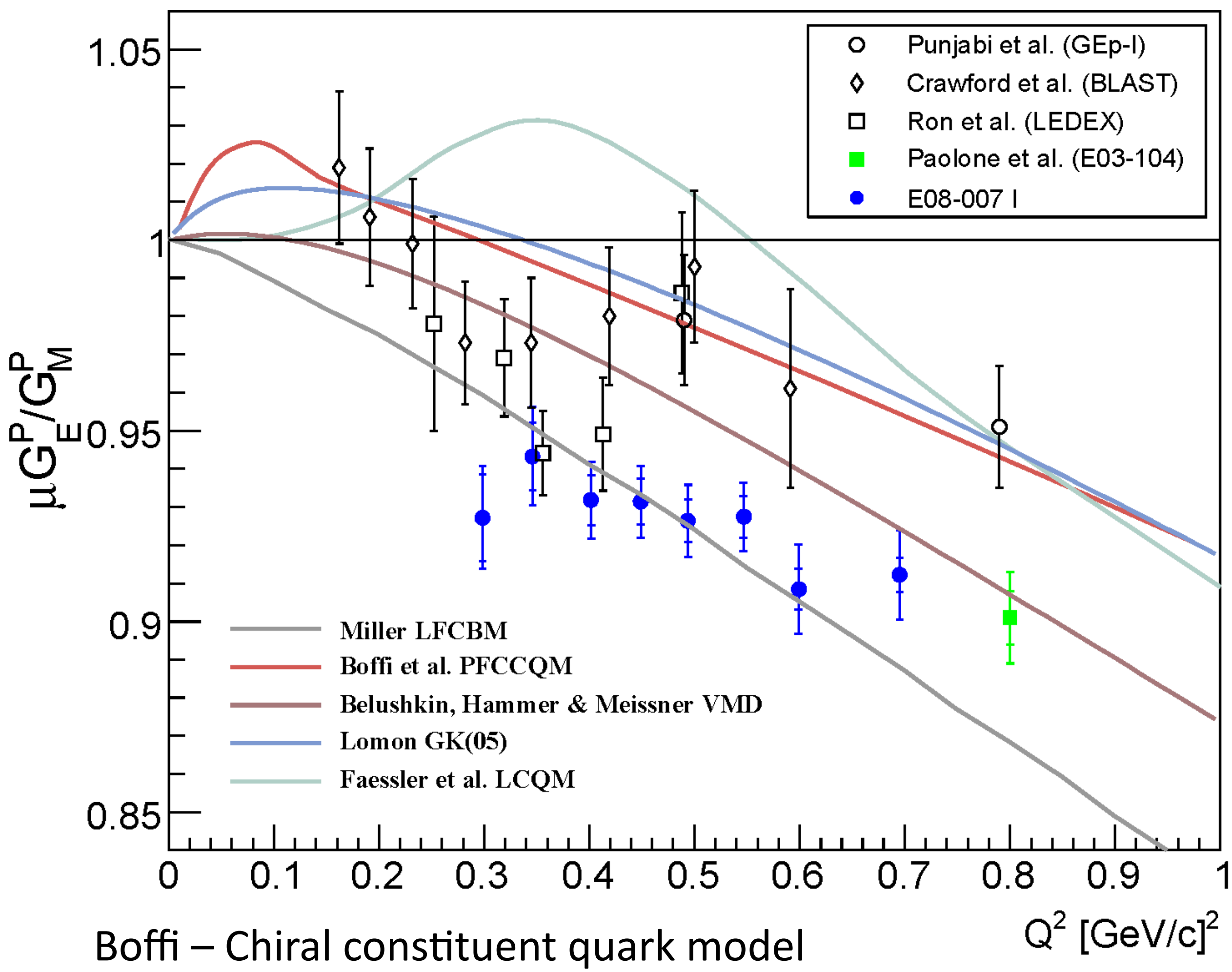
Comparison to Previous Data

X-H. Zhan, MIT Ph.D. thesis (2010), to be submitted



- Disagreement with GE_p-I, BLAST, LEDEX
- Agreement with independent analysis of Paolone *et al.* at 0.8 GeV^2
- LEDEX re-analysis consistent with new data
- Indictions of cut dependence in GE_p-I point
- No current plans to re-examine BLAST data

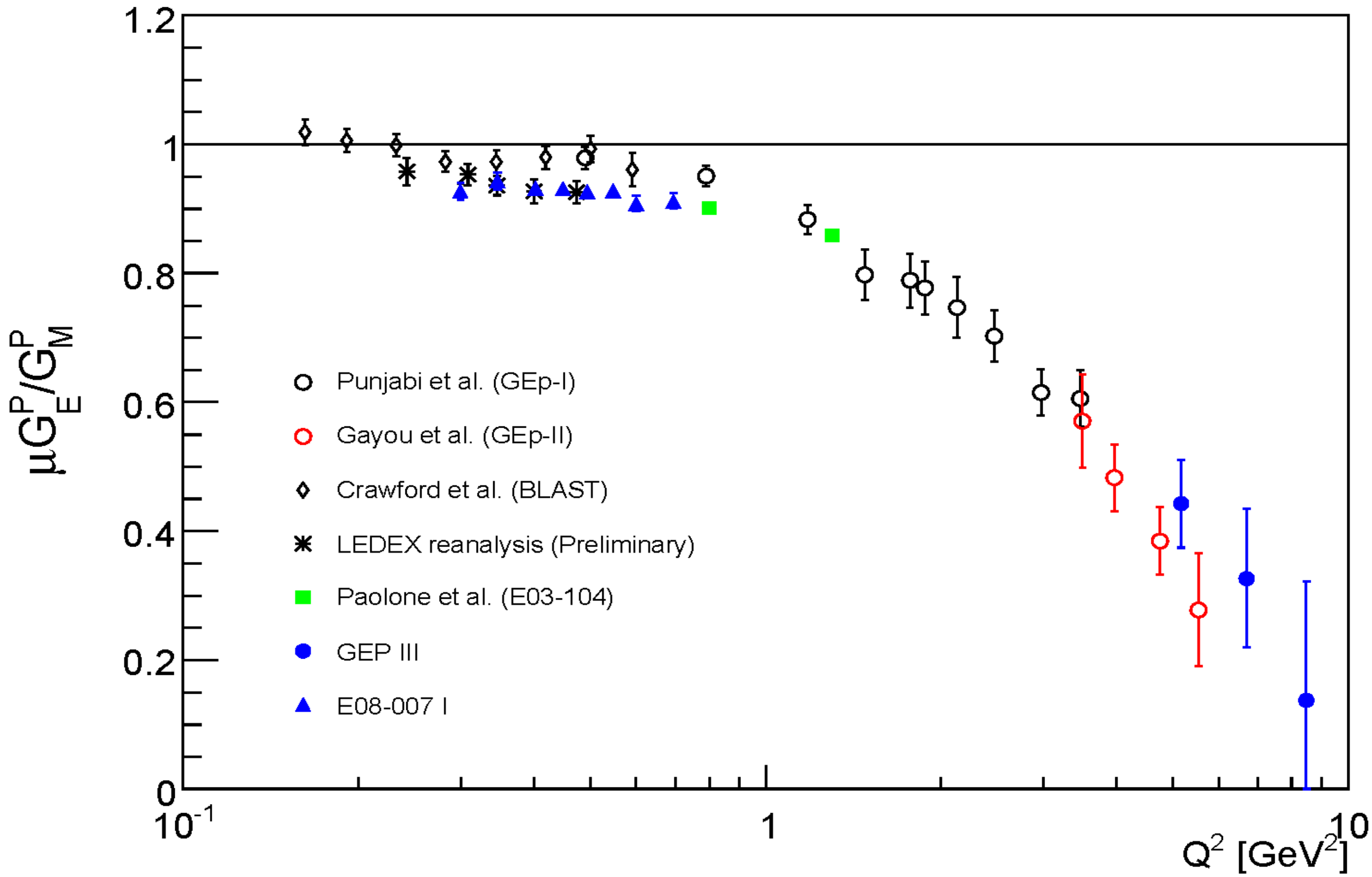
Comparison with Models



Boffi – Chiral constituent quark model
Faessler – Lorentz covariant chiral quark model
Belushkin, Lomon – VMD
Miller – Light front cloudy bag model

◆No model consistent with data!

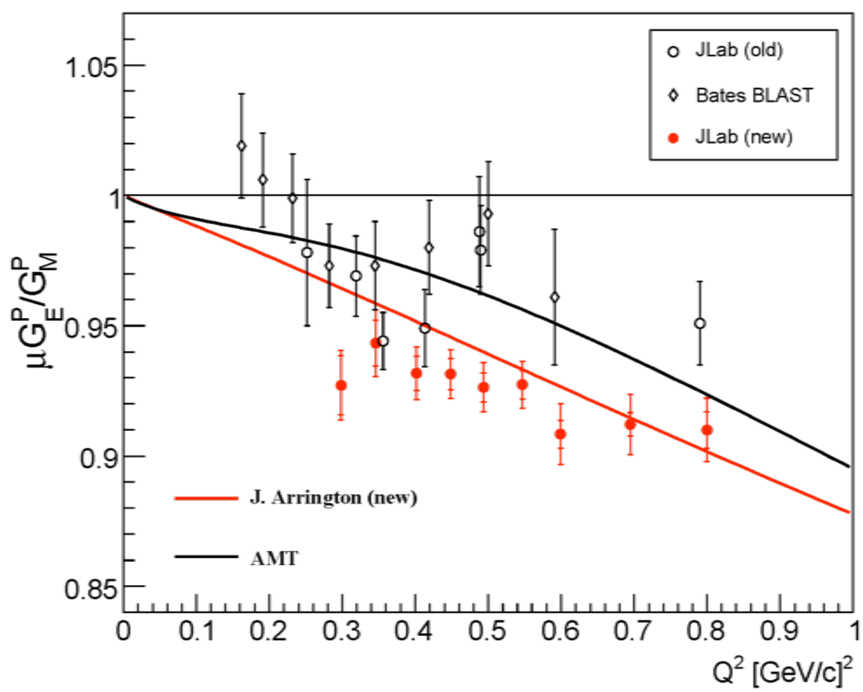
World Data with Polarization

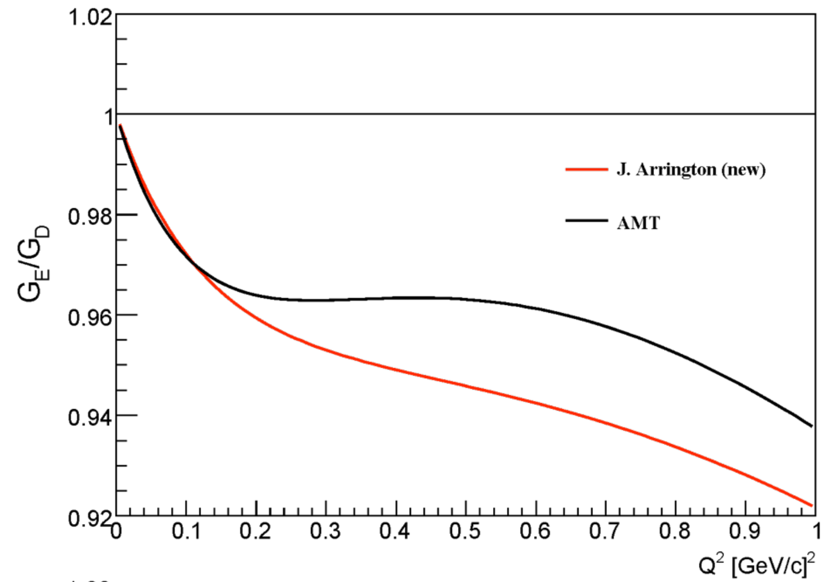


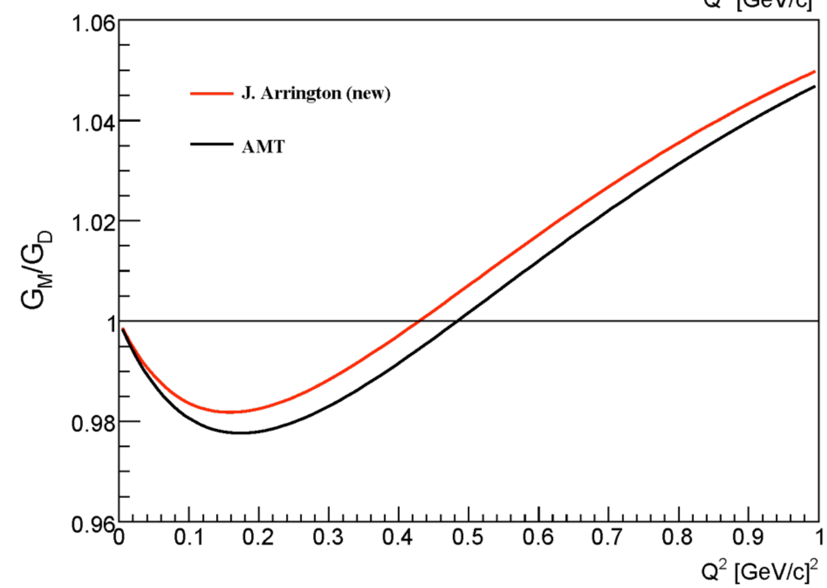
Note: LEDEX re-analysis
Examination of Gep-I, Gep-II

Global Fits

- Combined global fits (John Arrington).
- AMT fit (black) : include all previous data with TPE correction
- New fit (red) : same procedure, includes new data, remove lowest point of GEp-I, (and highest point of LEDEX)
- Preliminary fits suggest lower G_E (~2%), higher G_M (0.5%)







Impact I – Strangeness Form Factors by PV

$$A_{PV} = -\frac{G_F Q^2}{4\pi\alpha\sqrt{2}}\Big[(1-4\sin^2\theta_W) - \frac{\varepsilon G_{Ep}(G_{En}+G_{Es})+\tau G_{Mp}(G_{Mn}+G_{Ms})}{\varepsilon(G_{Ep})^2+\tau(G_{Mp})^2} - \frac{(1-4\sin^2\theta_W)\varepsilon' G_{Mp} G_A^Z}{\varepsilon(G_{Ep})^2+\tau(G_{Mp})^2}\Big]$$

- Asymmetry arises from the interference between EM and neutral weak currents

$$\sigma \propto |\mathcal{M}_\gamma + \mathcal{M}_Z|^2$$

$$\mathcal{M}^R = \mathcal{M}_\gamma + \mathcal{M}_Z^R,$$
$$\mathcal{M}^L = \mathcal{M}_\gamma + \mathcal{M}_Z^L.$$

$$A_{PV} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} = \frac{|\mathcal{M}^R|^2 - |\mathcal{M}^L|^2}{|\mathcal{M}^R|^2 + |\mathcal{M}^L|^2}$$

- Rely on knowledge of EMFFs
- With New FF parameterization, HAPPEX III results shift ~ 0.5σ

Q^2	ΔA	ΔA/σ	ΔA/A	Exp.
0.38	-0.178	0.42	1.6%	G0 FWD
0.56	-0.347	0.50	1.6%	G0 FWD
1.0	-0.414	0.30	0.8%	G0 FWD
0.50	-0.299	0.50	1.7%	HAPPEX III
0.231	+0.038	0.12	0.2%	G0 BCK
0.65	0.142	0.14	0.3%	G0 BCK

Table: Difference in the extracted asymmetries.

Impact II – Proton Zemach Radius

Hyperfine splitting of hydrogen ground state

$$E_{hfs} = (1 + \Delta_{QED} + \Delta^p_{hvp} + \Delta^p_{\mu vp} + \Delta^p_{weak} + \Delta_S) E^p_F$$

$$\Delta_S = \Delta_Z + \Delta^p_R + \Delta_{pol}, \quad \Delta_Z = -2\alpha Z \frac{m_e m_p}{m_e + m_p} r_Z$$

$$r_Z = -\frac{4}{\pi}\int_0^\infty \frac{dQ}{Q^2}[G_E(Q^2)G_M(Q^2)/(1+\kappa_p) - 1]$$

- Leading theoretical uncertainty
- FFs at Low Q^2 (<1 GeV^2) accounts for >70% of r_Z, and also dominate the uncertainty

Quantity	value (ppm)	uncertainty (ppm)
$(E_{hfs}(e^-p)/E^p_F) - 1$	1 103.48	0.01
Δ_{QED}	1 136.19	0.00
$\Delta^p_{\mu vp} + \Delta^p_{hvp} + \Delta^p_{weak}$	0.14	
Δ_Z (using [31])	−41.43	0.44
Δ^p_R (using [31])	5.85	0.07
Δ_{pol} (this work, using [31])	1.88	0.64
Total	1102.63	0.78
Deficit	0.85	0.78

Carlson, Nazaryan, and Griffioen, *arXiv:0805.2603v1* (2009)

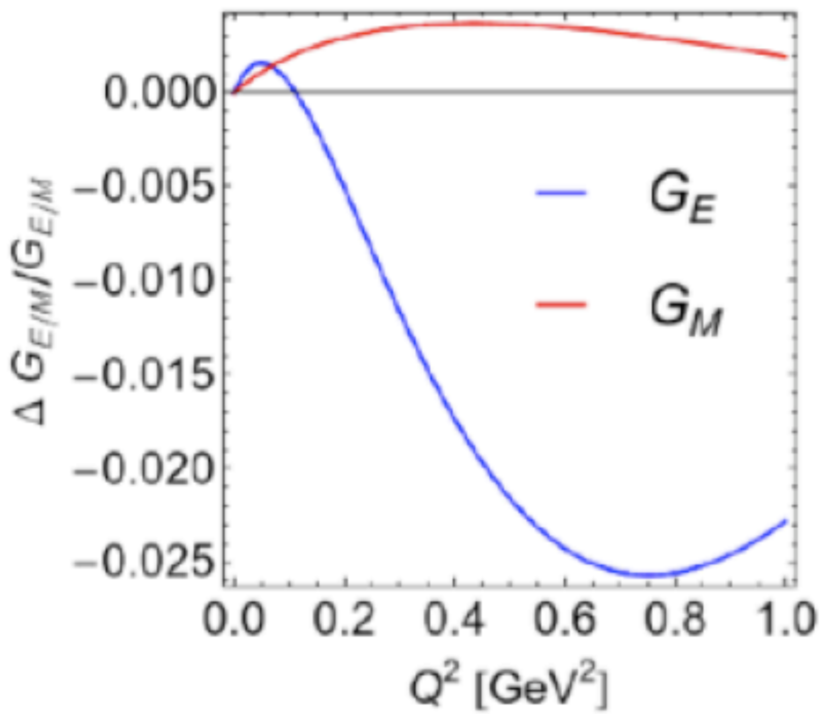
FFs	r_z (fm)	Δz	year
Dipole	1.025	-39.29	-
FW	1.049	-40.22	2003
Kelly	1.069	-40.99	2004
AS	1.091	-41.85	2007
AMT	1.080	-41.43	2007
New fit	1.075	-41.21	2009

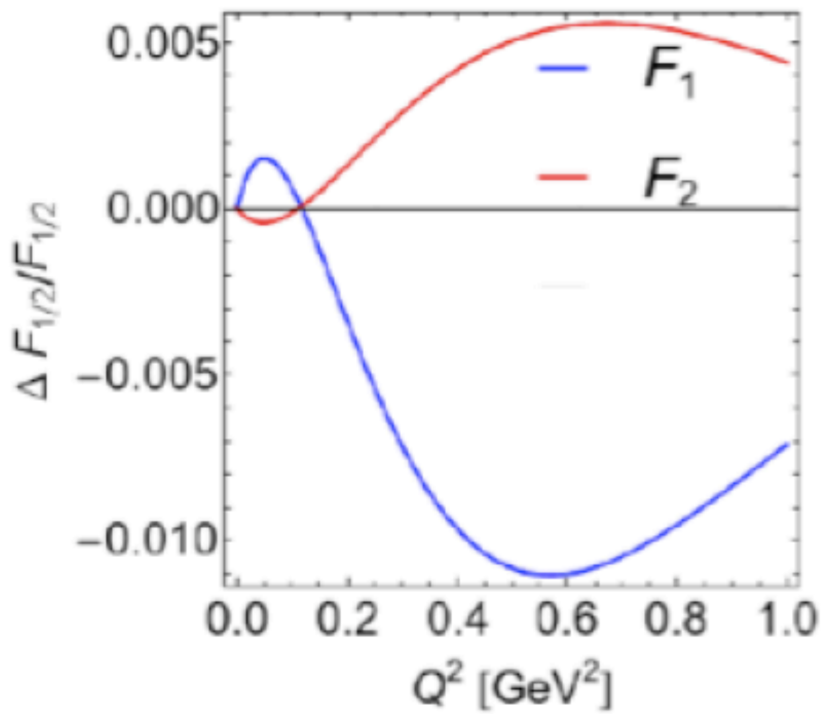
Impact III – Isoscalar & Isovector FFs

- Isoscalar & Isovector FFs (important for Lattice QCD):

$$F_J^S = \frac{1}{2}(F_J^p + F_J^n) \qquad F_J^V = \frac{1}{2}(F_J^p - F_J^n)$$

- Change in FFs by using new parameterization vs. old parameterization





Impact IV - e-d Elastic Cross Section

$$\frac{d\sigma}{d\Omega} = \sigma_{Mott} * \frac{E'}{E} * [A(Q^2) + B(Q^2)\tan^2(\theta/2)]$$

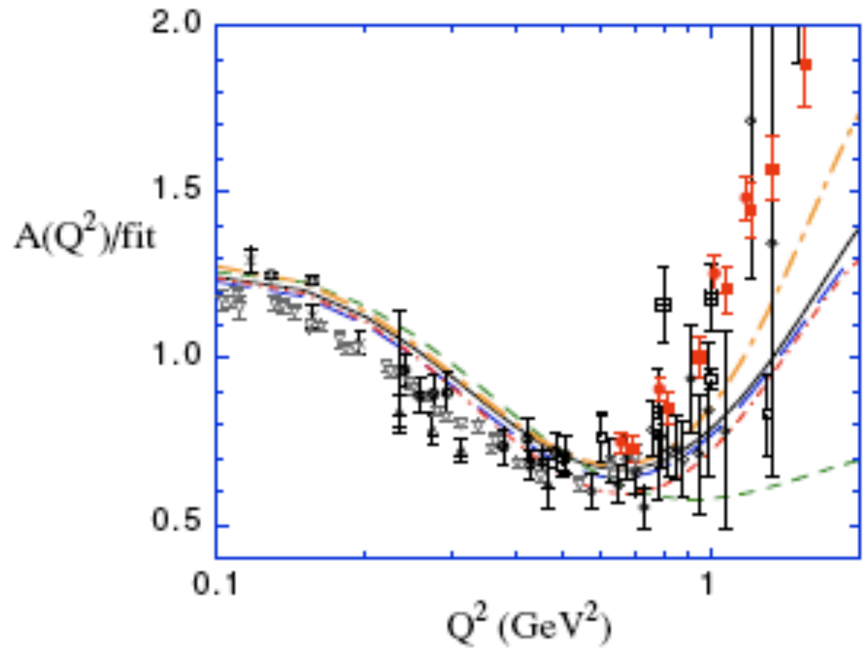
Where

$$A(Q^2) = G_C^2(Q^2) + \frac{8}{9}\eta^2 G_Q^2(Q^2) + \frac{2}{3}\eta G_M^2(Q^2)$$

$$B(Q^2) = \frac{4}{3}\eta(1+\eta)G_M^2(Q^2)$$ Small except at $\theta \approx 180°$

and

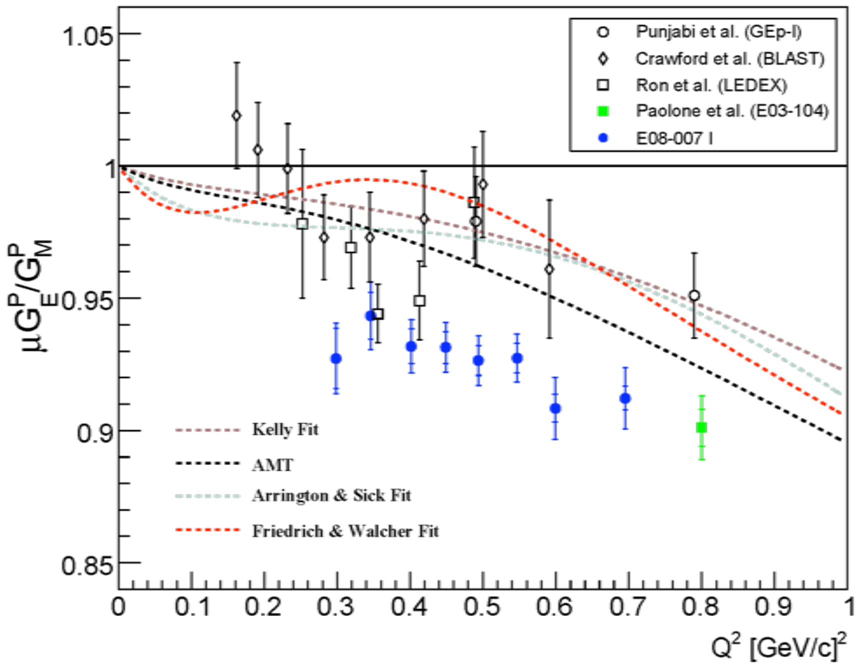
$$\eta = Q^2/4m_d^2$$ Very small at low Q



At low Q^2, elastic e-d cross section depends mainly on GE_p

New results change model cross sections by a few percent!

Impact V – Proton RMS Radius



Increased interest in proton radius with new very precise muonic hydrogen data (significantly lower: ~ 0.840 fm

New Global fit with TPE (Arrington):

$\langle r_p^2 \rangle$ = 0.873(14) fm

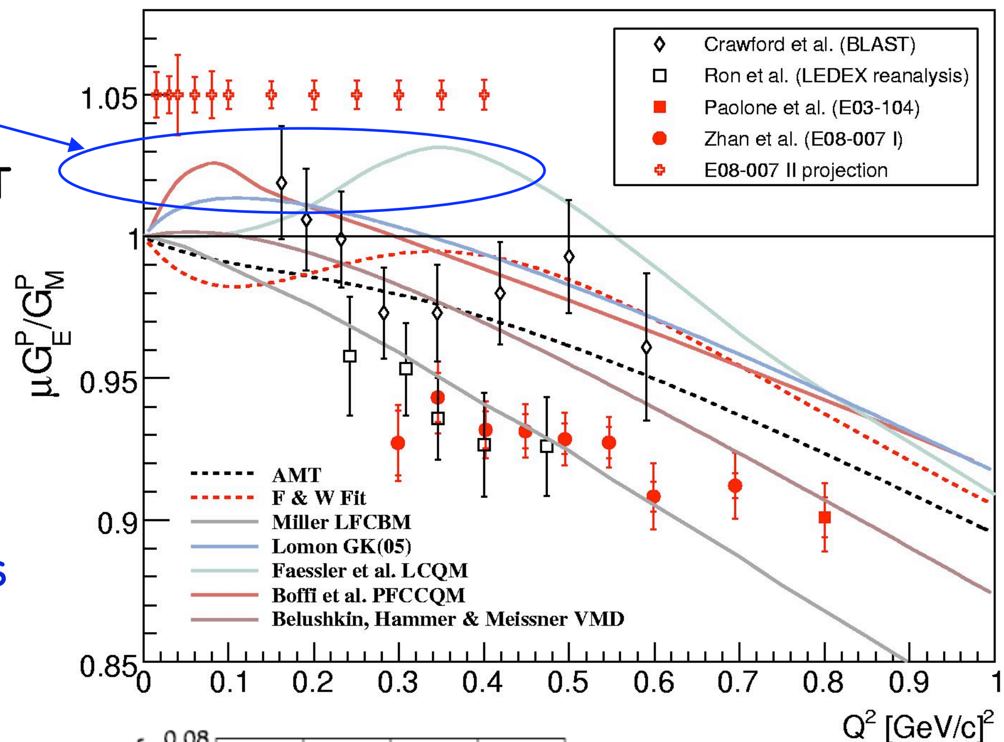
3% below previous value (Sick): 0.897(18) fm
CODATA(2006) value: 0.877(7) fm

If R=1 as Q^2 approaches zero, yields
0.015 fm change in charge radius

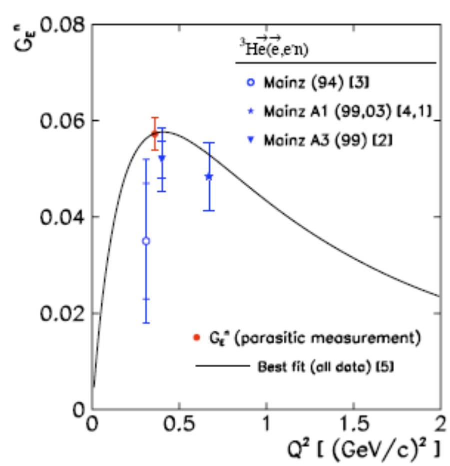
Near Future Outlook

LEDEX re-analysis almost complete; consistent with X-H. Zhan et al.

- Phase-II (pol. Target - 2012)
  - Extract R down to Q^2=0.015
  - Good overlap with Phase-I, BLAST
  - First precise extraction of magnetic radius
  - Linear approach to Q^2=0 ?
    - ~3% smaller magnetic radius
    - No region where magnetization, charge are simply sum of quarks
    - Disagreement with muonic hydrogen radius?



- New G_{En} measurement
  - One data point was measured parasitically in Hall A during experiment E05-102.
  - Data in analysis



Summary

- Nucleon FFs are fundamental quantities describing the nucleon internal structure
- A new high precision measurement was conducted in Jefferson Lab Hall A at low Q^2, new data strongly deviate from unity, systematically lower than previous world data
- While adding further constraints on theoretical models, the new high precision data also impact determination of other physics quantities: proton Zemach radius, strange form factor through PV, proton RMS radius etc.
- Near-future experiment with polarized target accessing very low Q^2:
  - ✓ Precisely determine magnetic radius for the first time
  - ✓ Important for precisely determining proton RMS radius, check possible disagreement with determination from muonic hydrogen data
  - ✓ Help to settle disagreement between blast (pol. target) and JLAB (recoil polarization) data

E08-007 Collaboration

- Argonne National lab
- Jefferson Lab
- Rutgers University
- St. Mary's University
- Tel Aviv University
- UVa
- CEN Saclay
- Christopher Newport University
- College of William & Mary
- Duke University
- Florida International University
- Institut de Physique Nuclaire d'Orsay
- Kent State University
- MIT
- Norfolk State University
- Nuclear Research Center Negev
- Old Dominion University
- Pacific Northwest National Lab
- Randolph-Macon College
- Seoul National University
- Temple University
- Universite Blaise Pascal
- University of Glasgow
- University of Maryland
- University of New Hampshire
- University of Regina
- University of South Carolina

Thank you!

Acknowledgements

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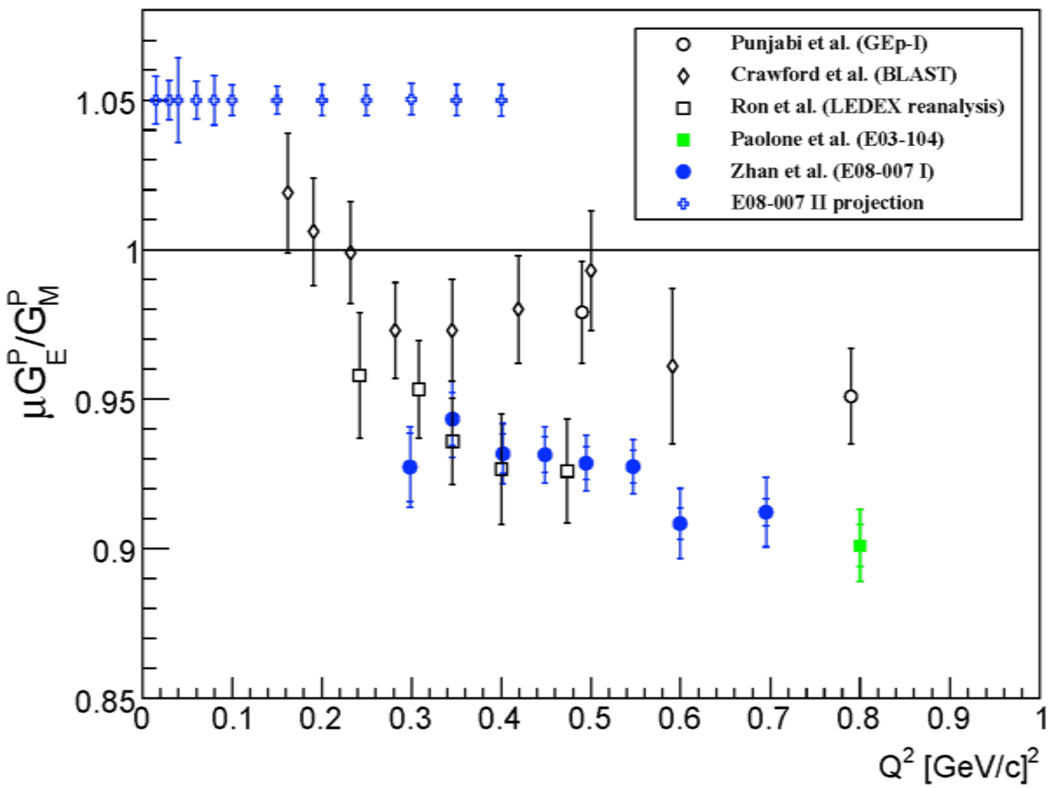
&

Jefferson Lab Hall A Collaboration

Back up slides

Future Outlook

• E08007 analysis finalized.
• Publication in preparation.
• Updated paper for LEDEX (G. Ron *et al.*) in preparation.



• Second half of the experiment (DSA) is tentatively scheduled in early 2012

$$A_{phys} = \frac{v_z \cos\theta' G_M^2 + v_x \sin\theta' \cos\varphi' G_E G_M}{\left(\varepsilon G_{Ep}^2 + \tau G_{Mp}^2\right) / \left[\varepsilon\left(1+\tau\right)\right]}$$

• Opportunity to see the FFR behavior at even lower Q^2 (0.015-0.4 GeV^2) region.

• Third independent measurement, direct comparison with BLAST, examine any unknown systematic errors for previous measurements.

• Challenges: Solid polarized proton target & effect of target field to septum magnets.

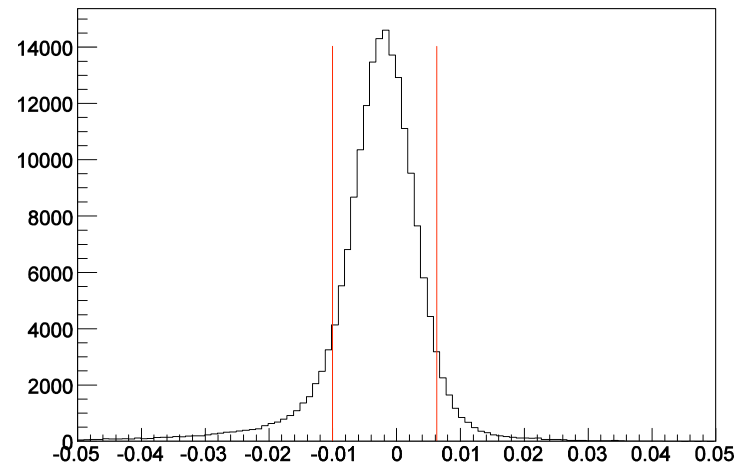
Elastic Events Selection

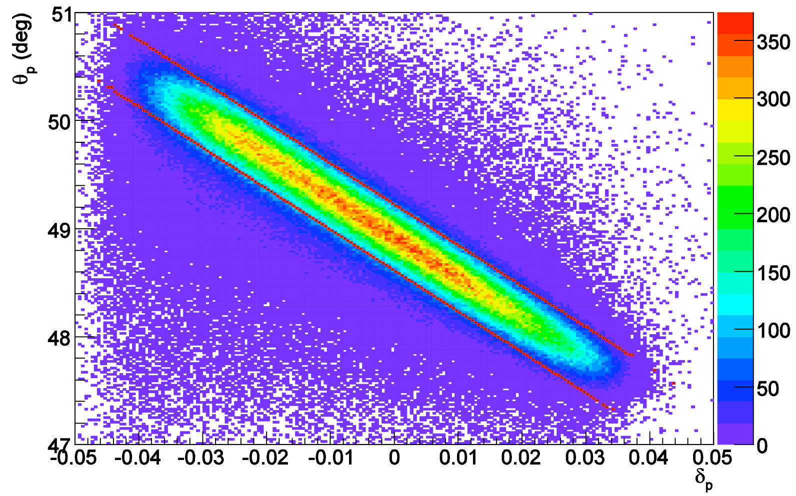
- **HRS acceptance cut:**
  - out of plane: +/- 60 mr
  - in plane: +/-30 mr
  - momentum: +/- 0.04 (dp/p_0)
  - reaction vertex cut

- **FPP cuts:**
  - scattering angle θ_{fpp} $5^o \sim 25^o$
  - reaction vertex (carbon door)
  - conetest cut

- **Other cuts:**
  - Coin. Timing cut
  - Coin. event type (trigger)
  - single track event
  - dpkin **(proton angle vs. momentum)**

proton dpkin

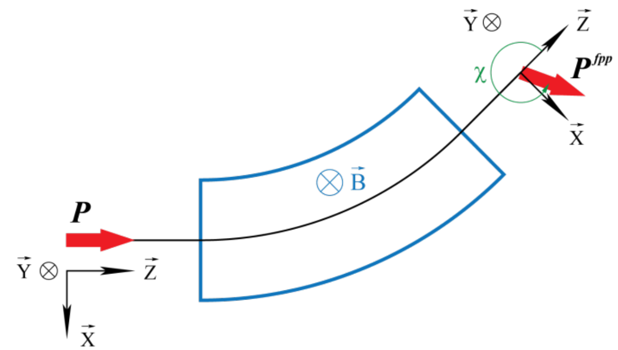




Focal Plane Asymmetry

- Detection probability at focal plane with azimuthally angle ϕ_{fpp}

$$f^{\pm} = \frac{1}{2\pi}\xi[1 \pm A_y(\theta_{fpp})(P_x^{fpp}\sin(\phi_{fpp}) - P_y^{fpp}\cos(\phi_{fpp}))]$$

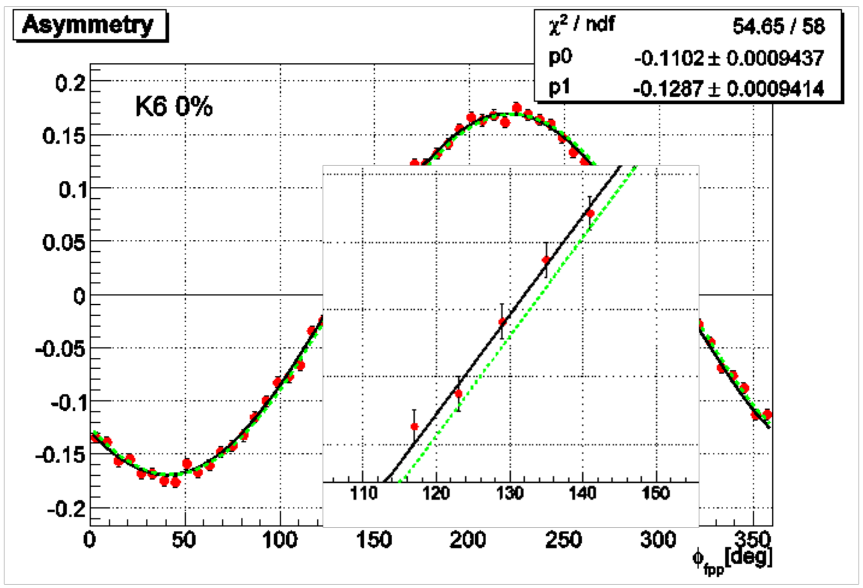


- Helicity difference:

$$f^{diff} = f^+ - f^- \approx \frac{1}{\pi}[A_y(P_x^{fpp}\sin(\phi_{fpp}) - P_y^{fpp}\cos(\phi_{fpp}))] = C\cos(\phi + \delta)$$

$$C = \frac{1}{\pi}A_y\sqrt{(P_x^{fpp})^2 + (P_y^{fpp})^2}$$

$$\tan\delta = \frac{P_y^{fpp}}{P_x^{fpp}}$$

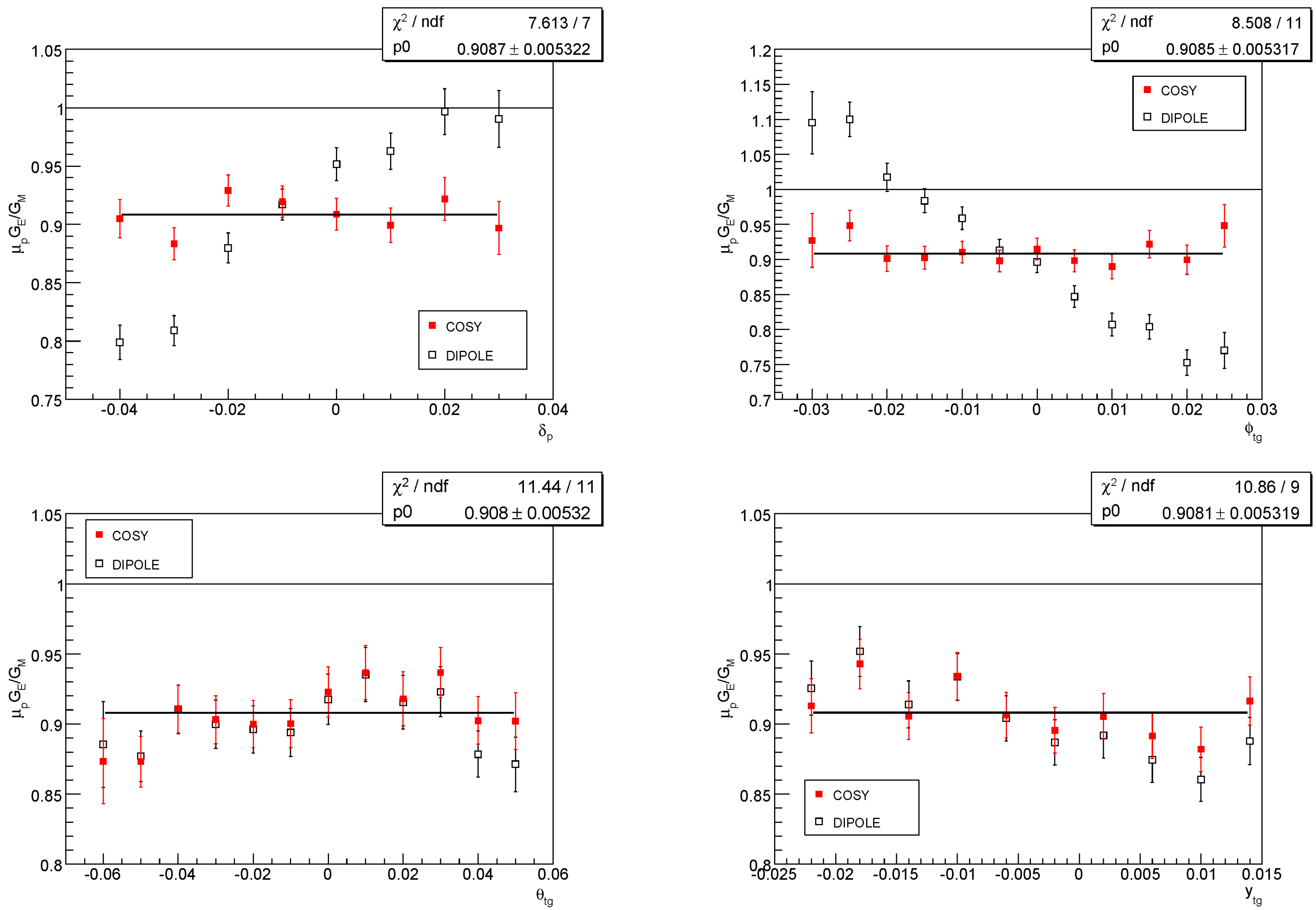


- By dipole approximation:

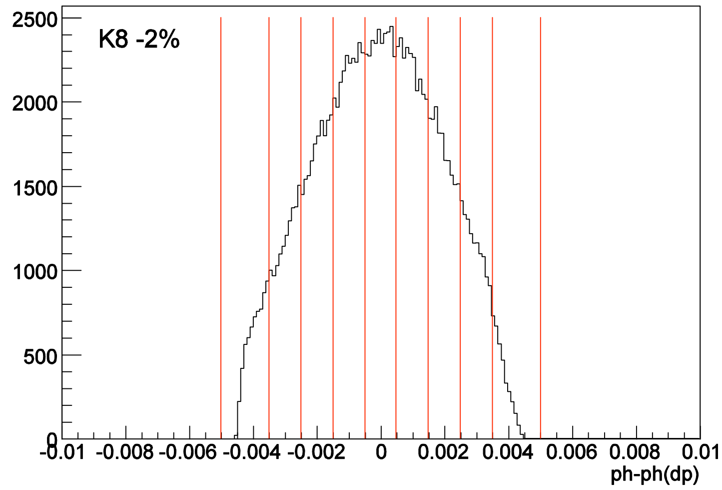
$$R = \mu_p \frac{G_E}{G_M} \approx \sin\chi \frac{P_x^{fpp}}{P_y^{fpp}} \times K$$

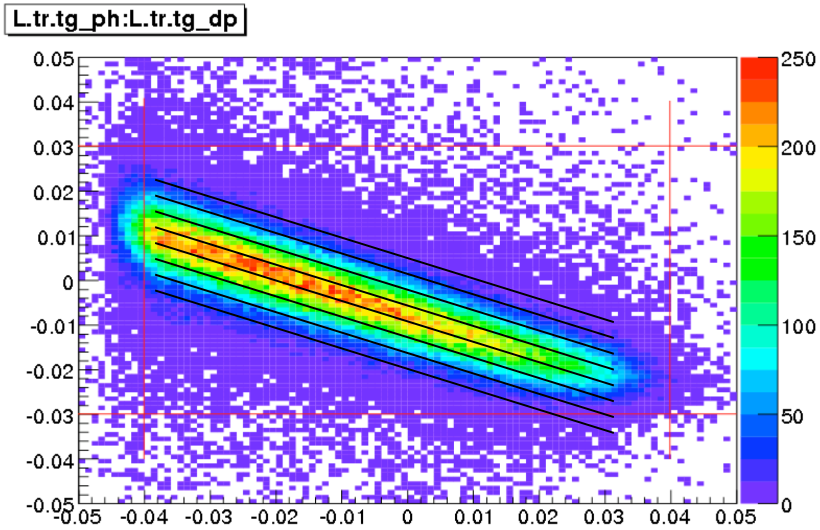
(K: kinematic factor)

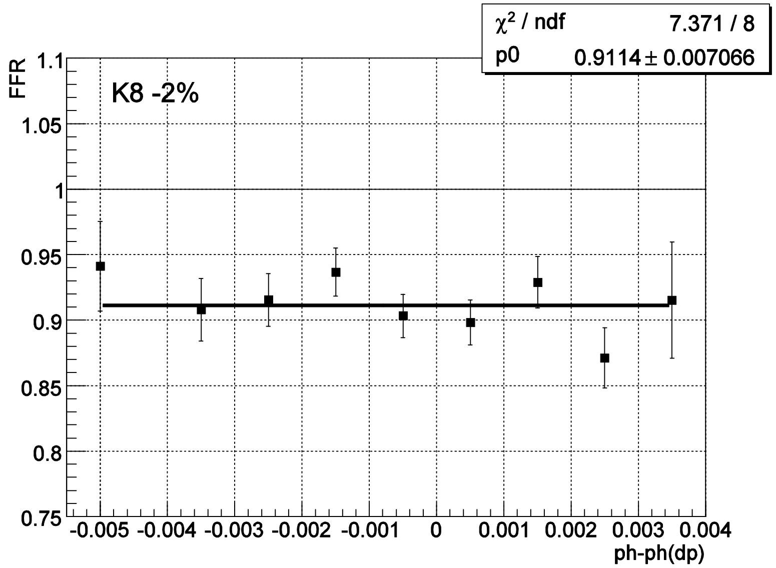
Spin Transport in HRS (COSY)



Spin Transport in HRS

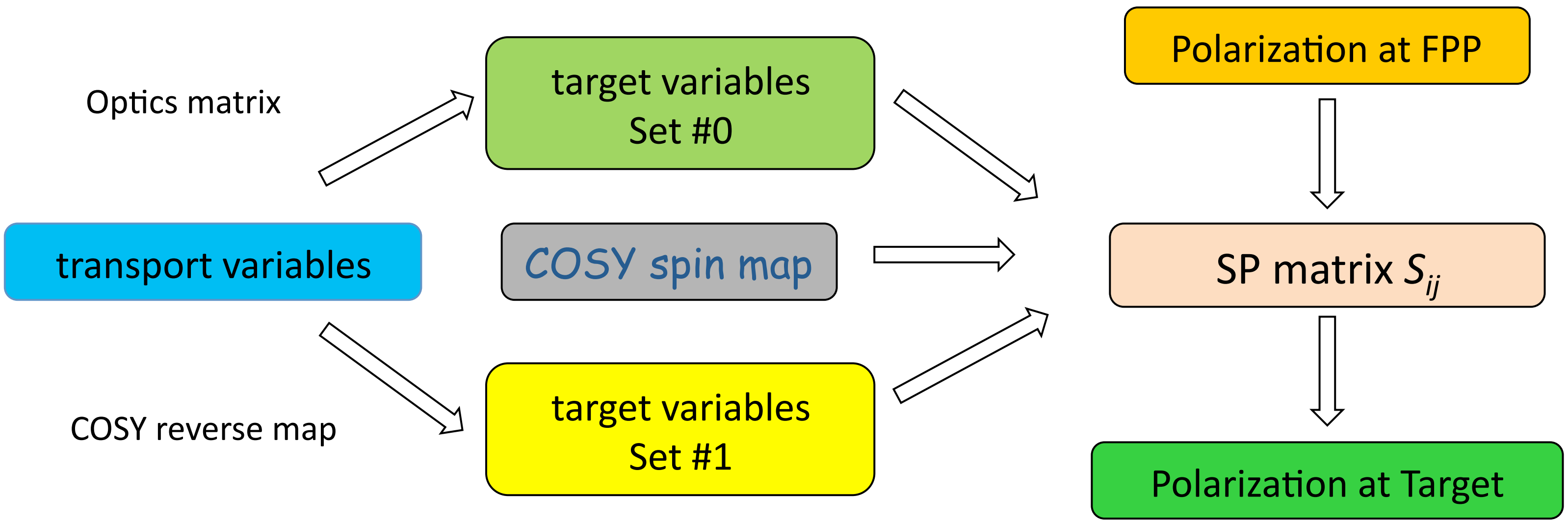






- Binning test for graphical cut.
- A rough check for existence of any possible background under elastic peak.
- No obvious indication of dependence on such variable.

COSY Spin Precession Matrix

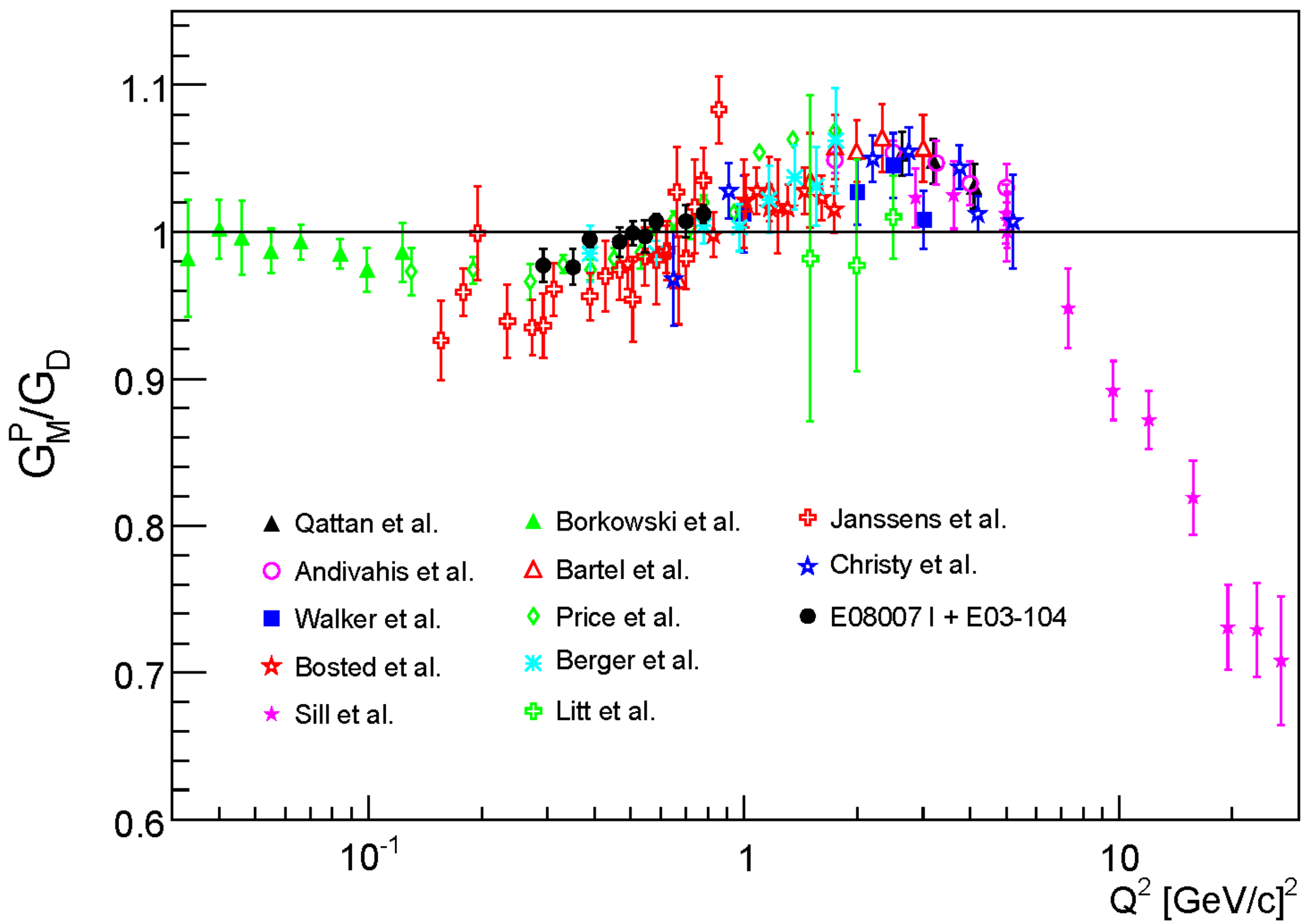


- Different SP matrix were generated by changing the default settings in COSY:
  - dipole radius, drift distances, quadrupoles alignment
  - central bending angle: 5.5 mrad
  - use COSY transport map to reconstruct target variables

- Uncertainties on target variables (OPTICS):
  - dp: 0.001
  - y_tg: 0.001 m
  - ph_tg: 0.7~1.2 mrad
  - th_tg: 1 mrad

Individual Form Factors

- With the extract ratio constraint, refit the world reduced cross section data.



Extraction of Polarization

- Full spin precession by COSY:
  - differential algebra-based.
  - defines the geometry and related setup of magnets.

$$S_{ij} = \sum_{k,l,m,n,p} C_{ij}^{klmnp} x^k \theta^l y^m \phi^n \delta^p$$

$$\begin{pmatrix} P_x^{fpp} \\ P_y^{fpp} \end{pmatrix} = \begin{pmatrix} S_{xx} & S_{xy} & S_{xz} \\ S_{yx} & S_{yy} & S_{yz} \end{pmatrix} \begin{pmatrix} P_x^{tg} \\ \eta h P_y^{tg} \\ \eta h P_z^{tg} \end{pmatrix}$$

focal plane target frame

- Weighted-sum:

$$f(\phi) = \frac{1}{2\pi}\epsilon(1 + \lambda_x P_x^{tg} + \lambda_y h P_y^{tg} + \lambda_z h P_z^{tg}),$$

$$\begin{aligned} \lambda_x &= A_y(S_{yx}\sin\phi - S_{xx}\cos\phi) \\ \lambda_y &= \eta A_y(S_{yy}\sin\phi - S_{xy}\cos\phi) \\ \lambda_z &= \eta A_y(S_{yz}\sin\phi - S_{xz}\cos\phi). \end{aligned}$$

- efficiency cancels with different beam helicity

$$\begin{aligned} \int_0^{2\pi} f(\phi)\lambda_y d\phi &= hP_y^{tg}\int_0^{2\pi} f(\phi)\lambda_y^2 d\phi + \\ & hP_z^{tg}\int_0^{2\pi} f(\phi)\lambda_y\lambda_z d\phi + \\ \int_0^{2\pi} f(\phi)\lambda_z d\phi &= hP_y^{tg}\int_0^{2\pi} f(\phi)\lambda_y\lambda_z d\phi + \\ & hP_z^{tg}\int_0^{2\pi} f(\phi)\lambda_z^2 d\phi. \end{aligned}$$

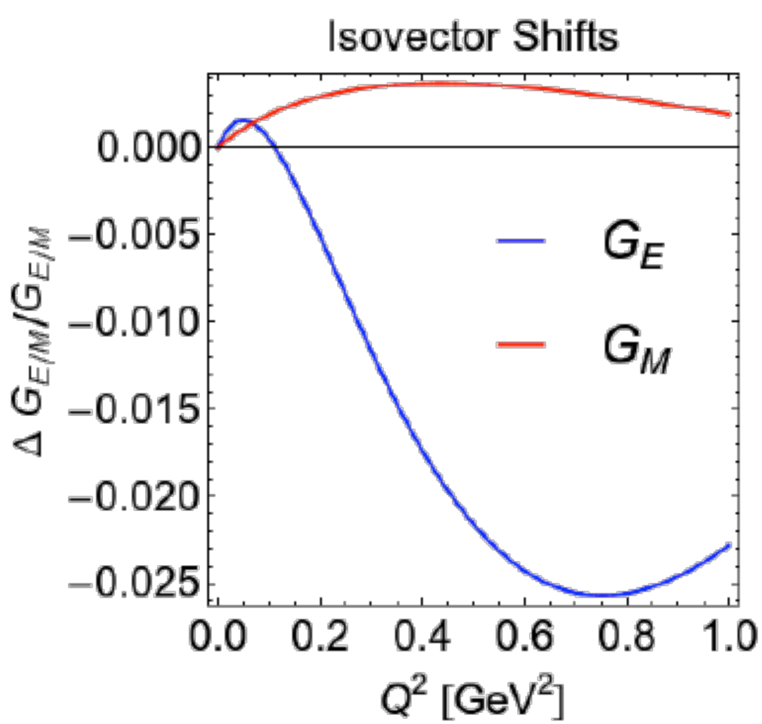
$$\Rightarrow \begin{pmatrix} \sum_i \lambda_{y,i} \\ \sum_i \lambda_{z,i} \end{pmatrix} = \begin{pmatrix} \sum_i \lambda_{y,i}\lambda_{y,i} & \sum_i \lambda_{z,i}\lambda_{y,i} \\ \sum_i \lambda_{y,i}\lambda_{z,i} & \sum_i \lambda_{z,i}\lambda_{z,i} \end{pmatrix} \begin{pmatrix} hP_y^{tg} \\ hP_z^{tg} \end{pmatrix}$$

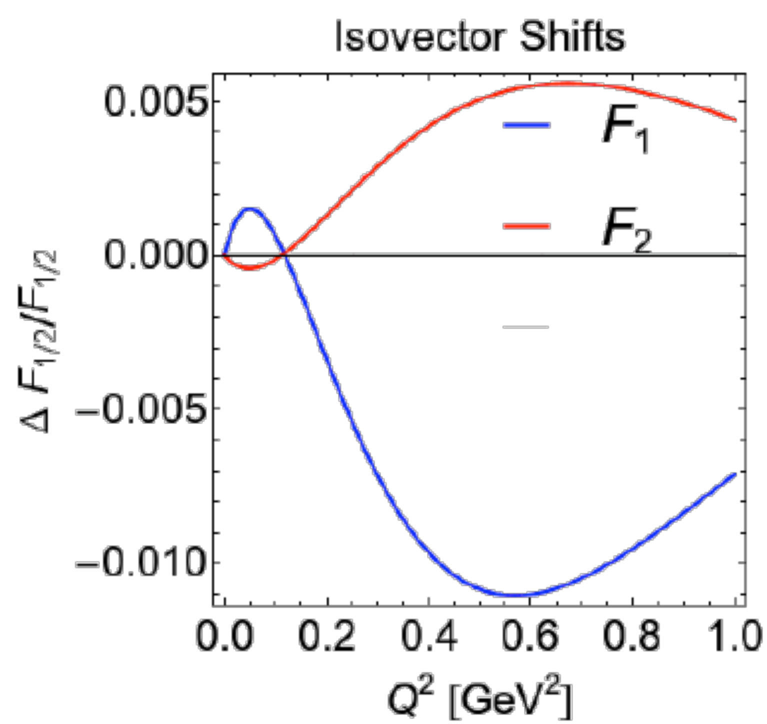
Impacts III

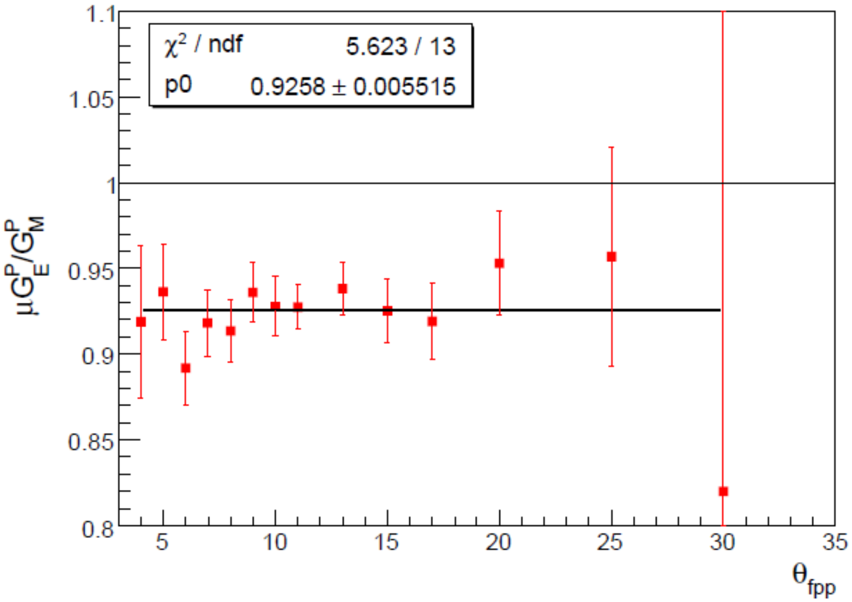
• Isoscalar & Isovector FFs (important for Lattice QCD):

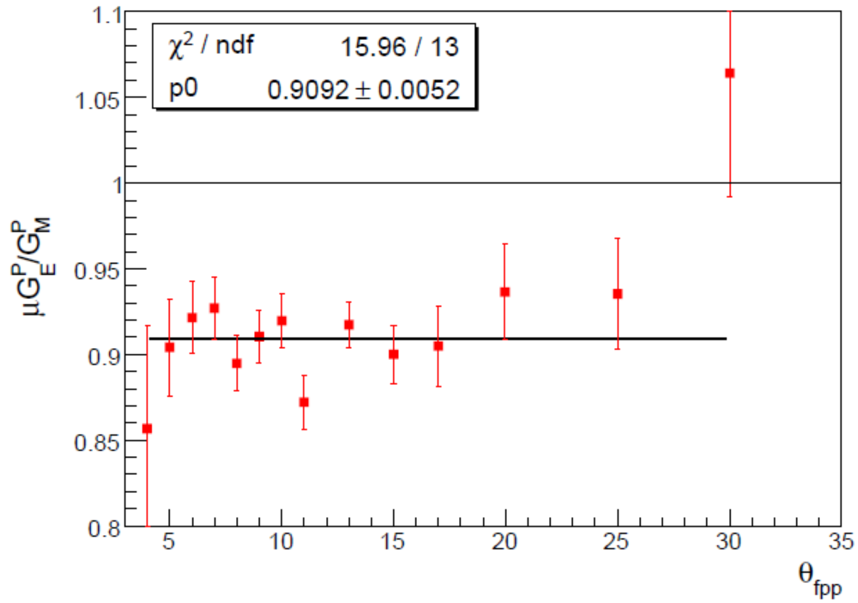
$$F_i^s = \frac{1}{2}(F_i^p + F_i^n), F_i^v = \frac{1}{2}(F_i^p - F_i^n)$$

• Plots show fractional change in IS and IV FFs by using the new parameterization vs. the old parameterization.






χ² / ndf 5.623 / 13
p0 0.9258 ± 0.005515
$\mu G_E^P/G_M^P$
θ_{fpp}


χ² / ndf 15.96 / 13
p0 0.9092 ± 0.0052
$\mu G_E^P/G_M^P$
θ_{fpp}