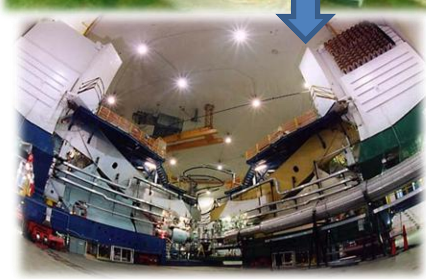

High Precision Measurement of the Proton Elastic Form Factor Ratio at Low Q^2

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Argonne National Lab

12th International Conference on Meson-Nucleon Physics and the Structure of the Nucleon

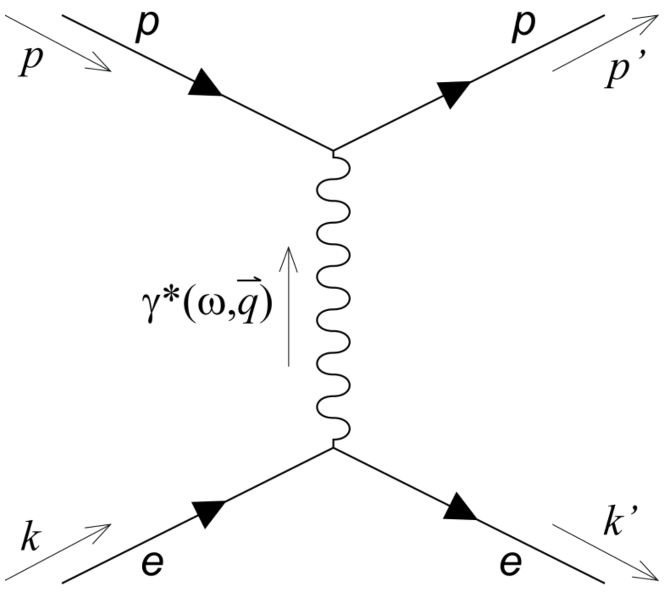
- Introduction
- E08-007
- Analysis
- Results & Discussions
- Future Outlook & Summary

Electron Elastic Scattering Formalism

- 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



single photon exchange
(Born approximation)

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

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

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

Sachs Form Factors

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

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

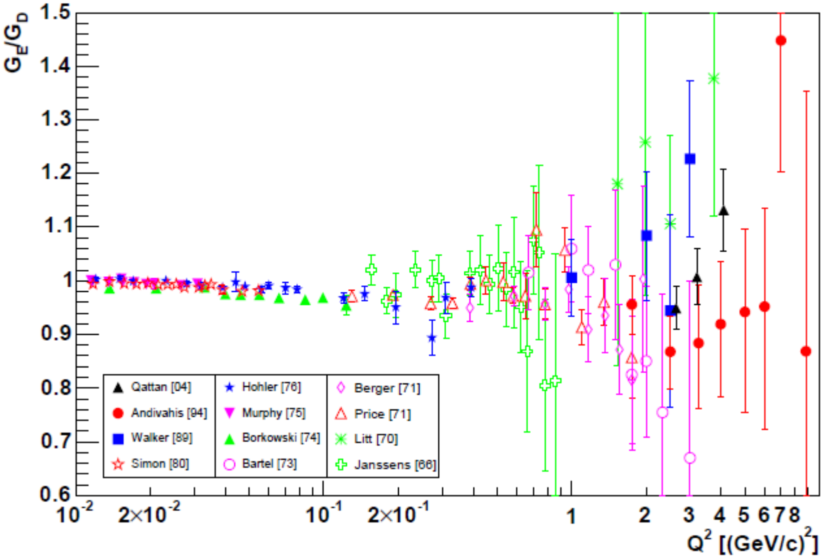
Electric: $G_E \equiv F_1 - \tau F_2$

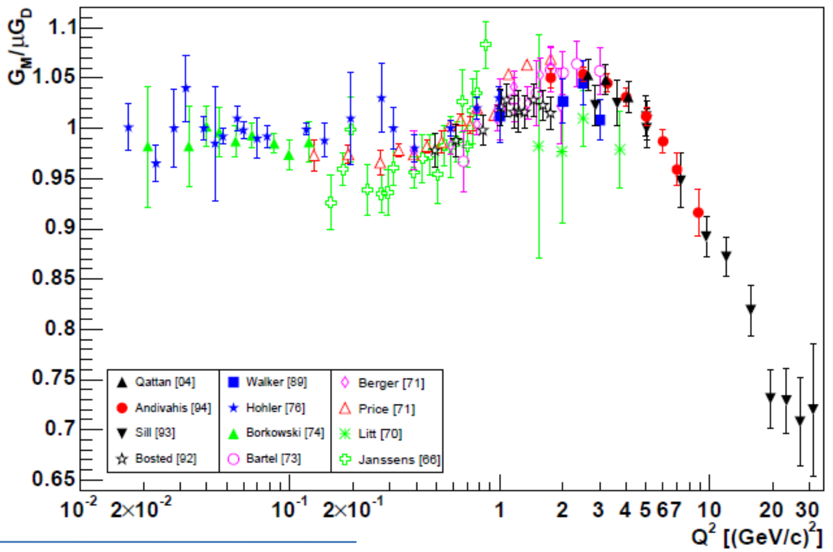
Magnetic: $G_M \equiv F_1 + F_2$

- Early experiments found ~ dipole form ($Q^2 < 2$ GeV^2), naively corresponds to an exponential shape in space.

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

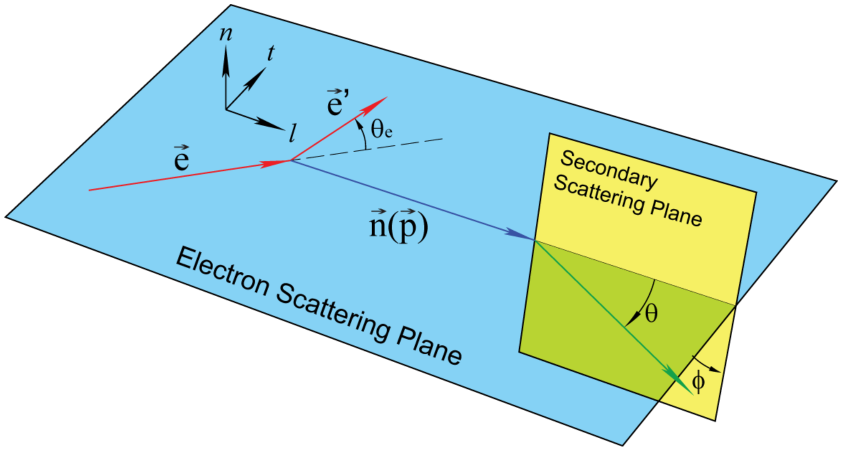
$$\mu_P \frac{G_E}{G_M} = 1$$





Recoil Polarimetry

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



$$I_0 P_t = -2\sqrt{\tau(1+\tau)}G_E G_M \tan\frac{\theta_e}{2}$$

$$I_0 P_l = \frac{E_e + E_{e'}}{M}\sqrt{\tau(1+\tau)}G_M^2 \tan^2\frac{\theta_e}{2}$$

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

Advantages:

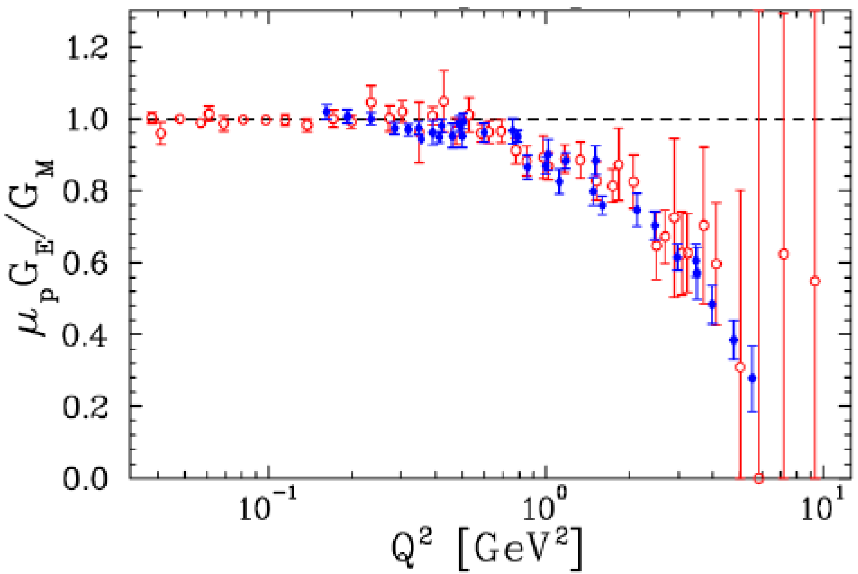
• Only one measurement is needed for each Q^2.

• Much better precision than a cross section measurement.

• Complementary to XS measurements.

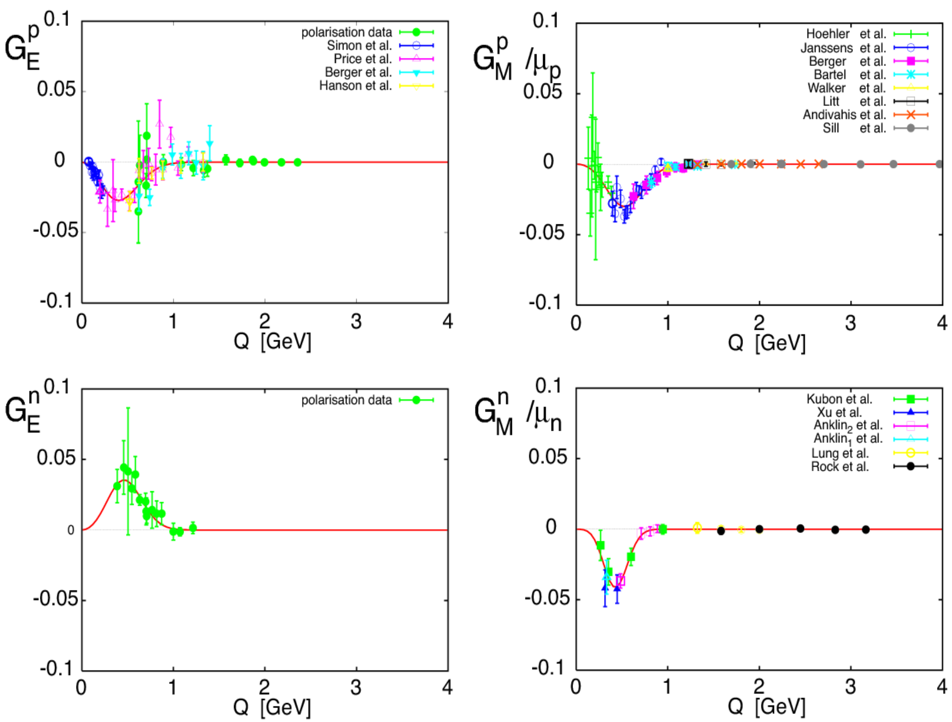
• Famous discrepancy between Rosenbluth and polarized measurement, mostly explained by 2-γ exchange.

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



FFs at Low Q^2

- Small $Q^2 \rightarrow$ larger length scale, closely related to the proton size.

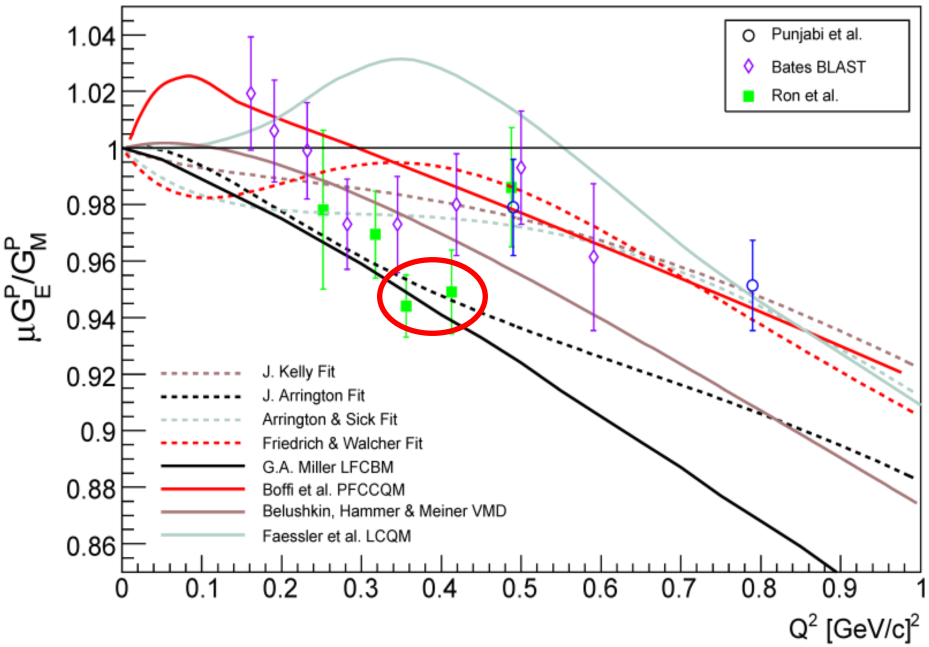


J. Friedrich and Th. Walcher, *Eur. Phys. J.* A 17, 607 (2003)

- 2003 – Fit by Friedrich & Walcher Eur. Phys. J. A17, 607 (2003):
  - Smooth dipole form + "bump & dip"
  - All four FFs exhibit similar structure at small momentum transfer ($Q^2 \sim 0.25$ GeV^2).
  - Proposed interpretation: effect of pion cloud.
- Improved EMFFs:
  - Strange form factors through PV
  - Proton Zemach radius and hydrogen hyperfine splitting
  - Proton charge RMS radius.

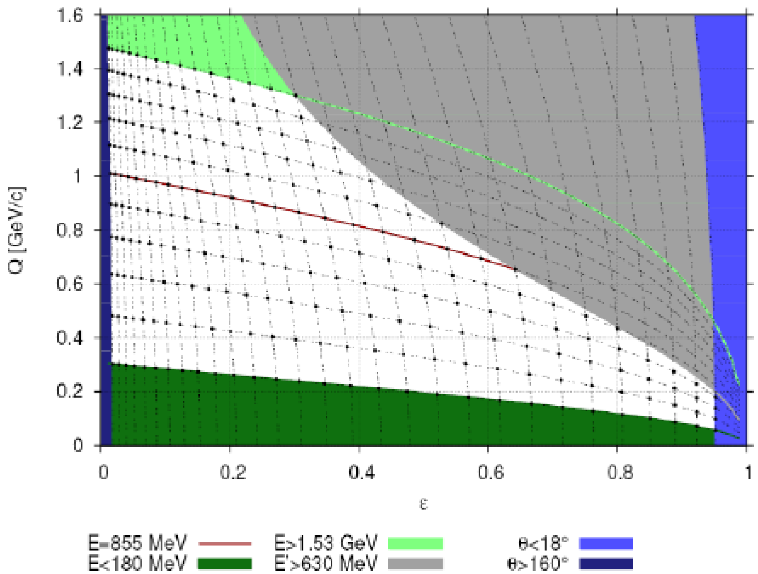
$$\langle r_{E,M}^2 \rangle = \frac{-6}{G_{E,M}(0)} \left[\frac{d}{dQ^2} G_{E,M}(Q^2) \right]_{Q^2=0}$$

World Data



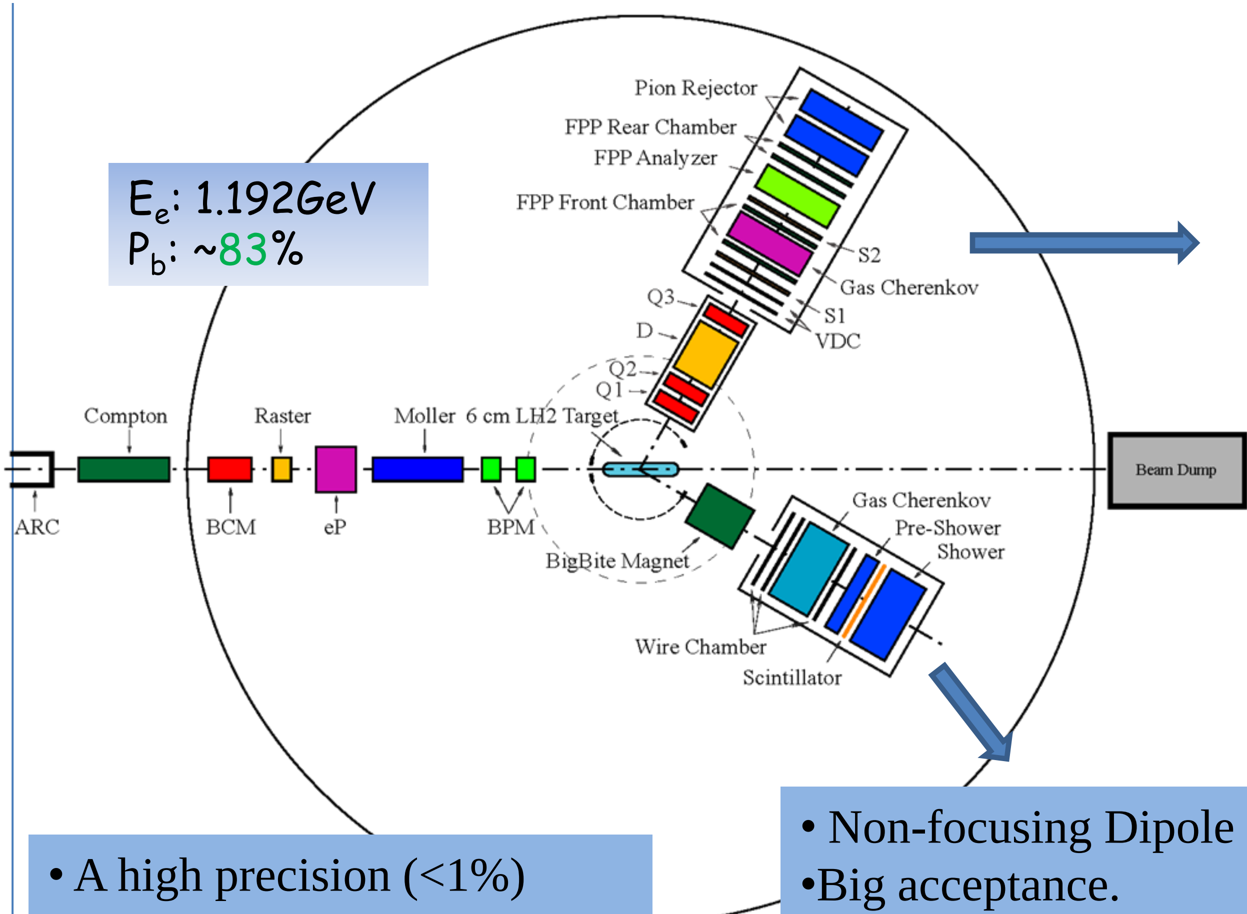
- Bates **BLAST** result consistent with 1. Crawford et al., *Phys. Rev. Lett* 98 052301 (2007)
- Substantial deviation from unity is observed in **LEDEX** (Ron et al.).
- Both data inconsistent with F&W fit.
- New dedicated experiment **E08-007**.

- Complementary to the high precision XS measurement at **Mainz (Q^2~ 0.003 – 1 GeV^2)**.



E08-007: Low Q^2 GEp

E_e: 1.192GeV
P_b: ~83%



LHRS

- $\Delta p/p0$: $\pm$ 4.5% ,
- out-of-plane: $\pm$ 60 mrad
- in-plane: $\pm$ 30 mrad
- $\Delta\Omega$: 6.7msr
- QQDQ
- Dipole bending angle 45°
- VDC+FPP
- P_p : 0.55 ~ 0.93 GeV/c

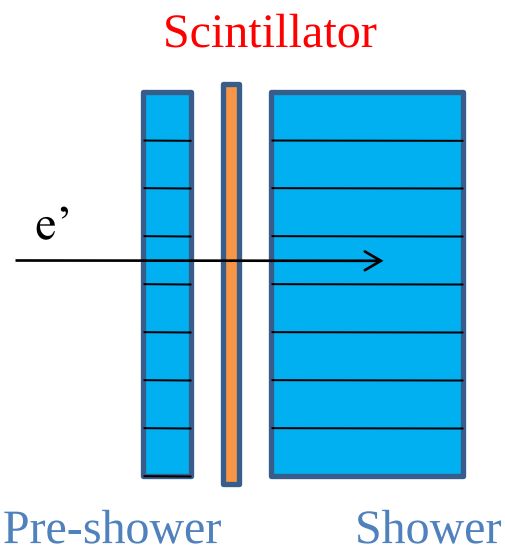
BigBite

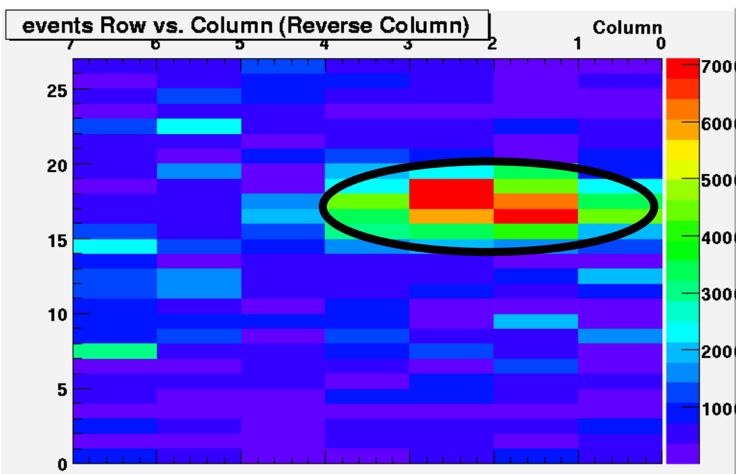
- A high precision (<1%) survey of the proton FF ratio.
- 8 Q^2 data points: 0.3 ~ 0.7 $(GeV/c)^2$.

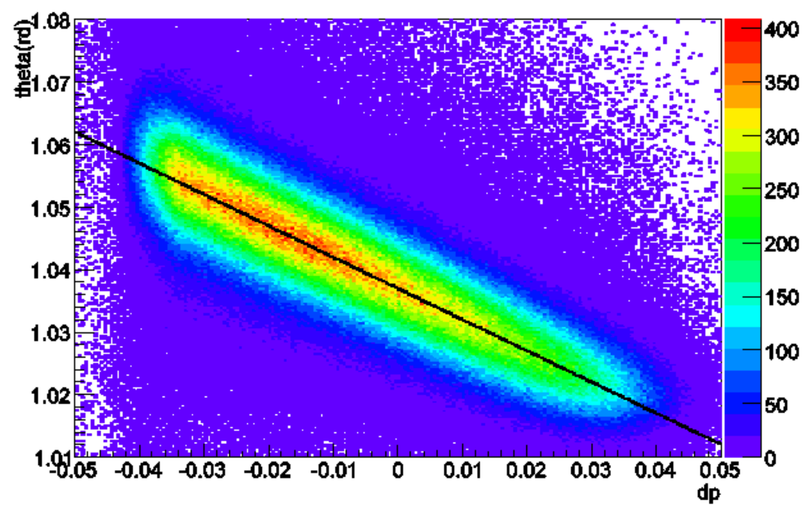
- Non-focusing Dipole
- Big acceptance.
    - Δp: 200-900MeV
    - $\Delta\Omega$: 96msr
- PS + Scint. + SH

BigBite Spectrometer

- Detect scattered electrons.
- Only elastic-peak blocks were in the trigger.
- Background minimized with tight elastic cut.



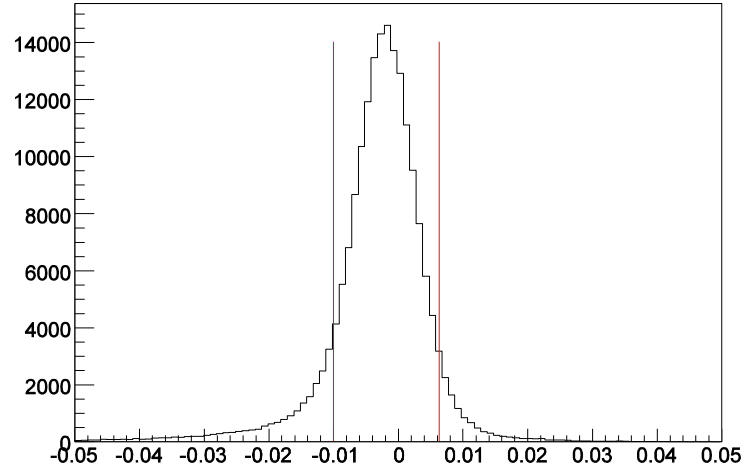


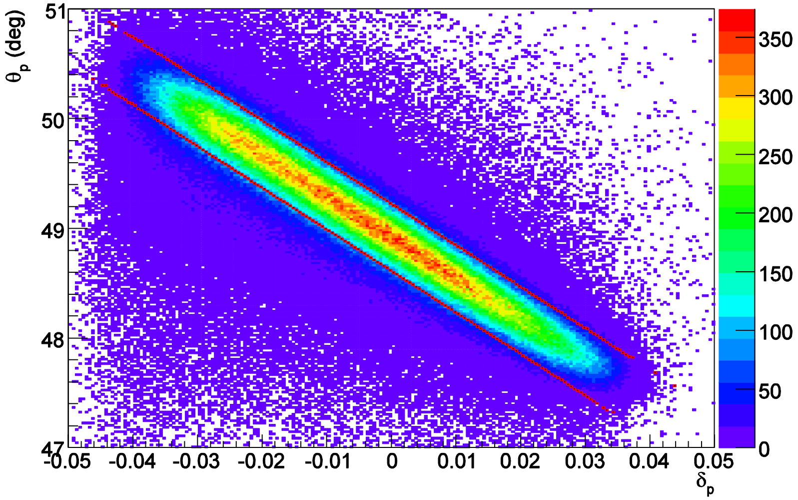


Elastic Events Selection

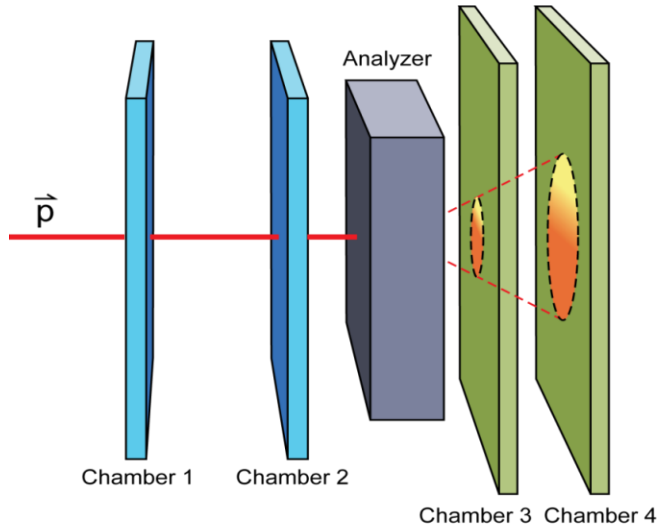
- **HRS acceptance cut:**
  - out of plane: +/- 60 mr
  - in plane: +/-30 mr
  - momentum: +/- 0.04 (dp/p_0)
  - reaction vertex cut
- **FPP cuts:**
  - scattering angle θ_{fpp} $5^o \sim 25^o$
  - reaction vertex (carbon door)
  - conetest cut
- **Other cuts:**
  - Coin. Timing cut
  - Coin. event type (trigger)
  - single track event
  - dpkin (**proton angle vs. momentum)**

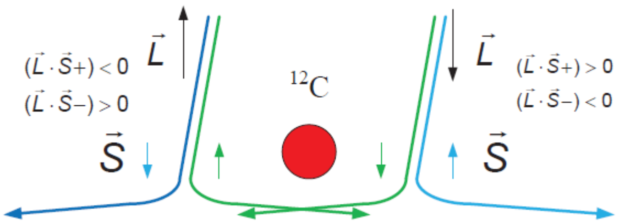
proton dpkin

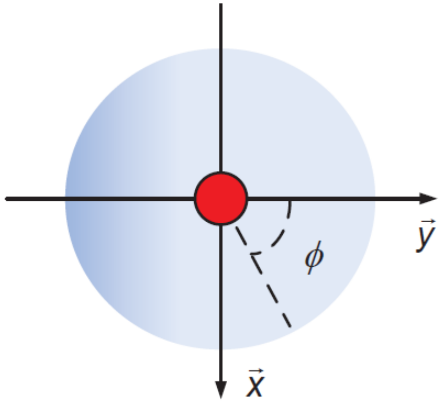


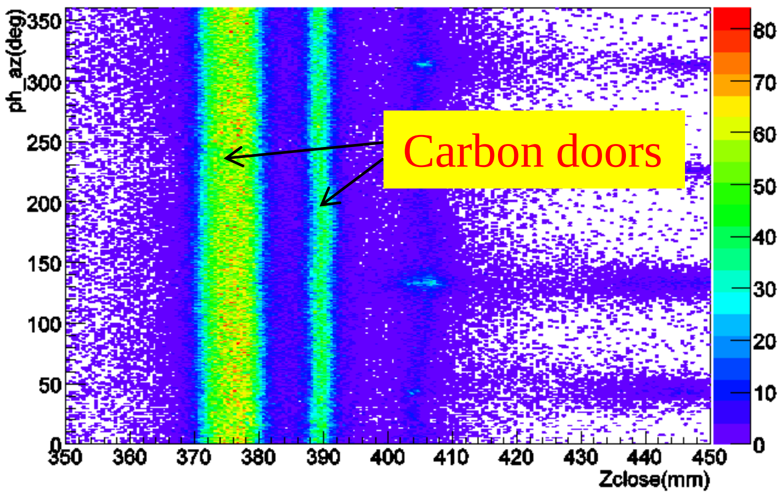


Focal Plane Polarimeter (FPP)







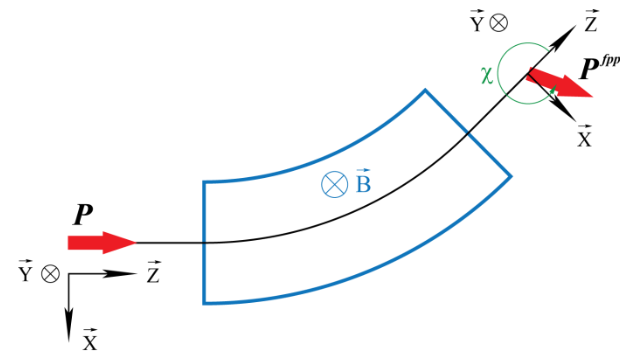


- Left-right asymmetry gives the vertical component while the up-down asymmetry gives the horizontal component.
- Need well determined scattering azimuthal angle ϕ_{fpp}, chamber alignment checked with straight through data.

Focal Plane Asymmetry

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

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

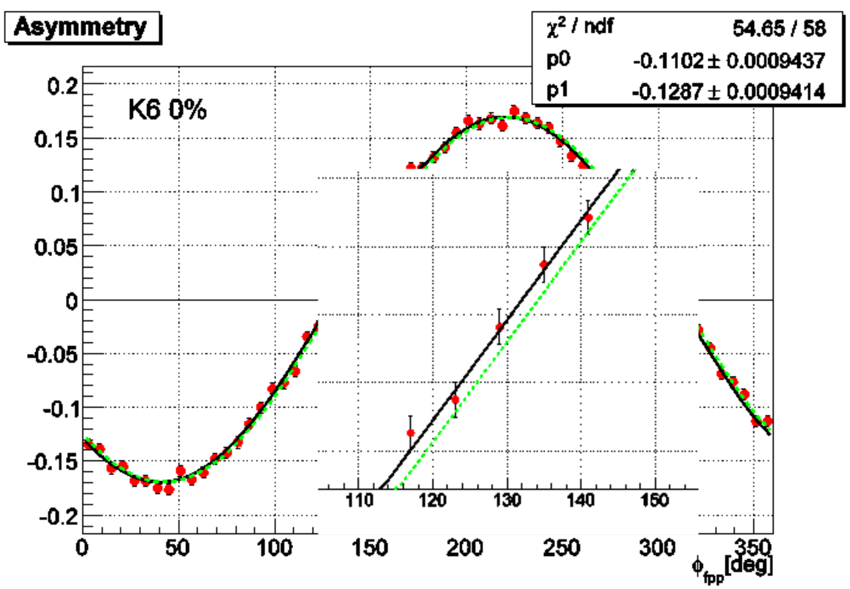


- Helicity difference:

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

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

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

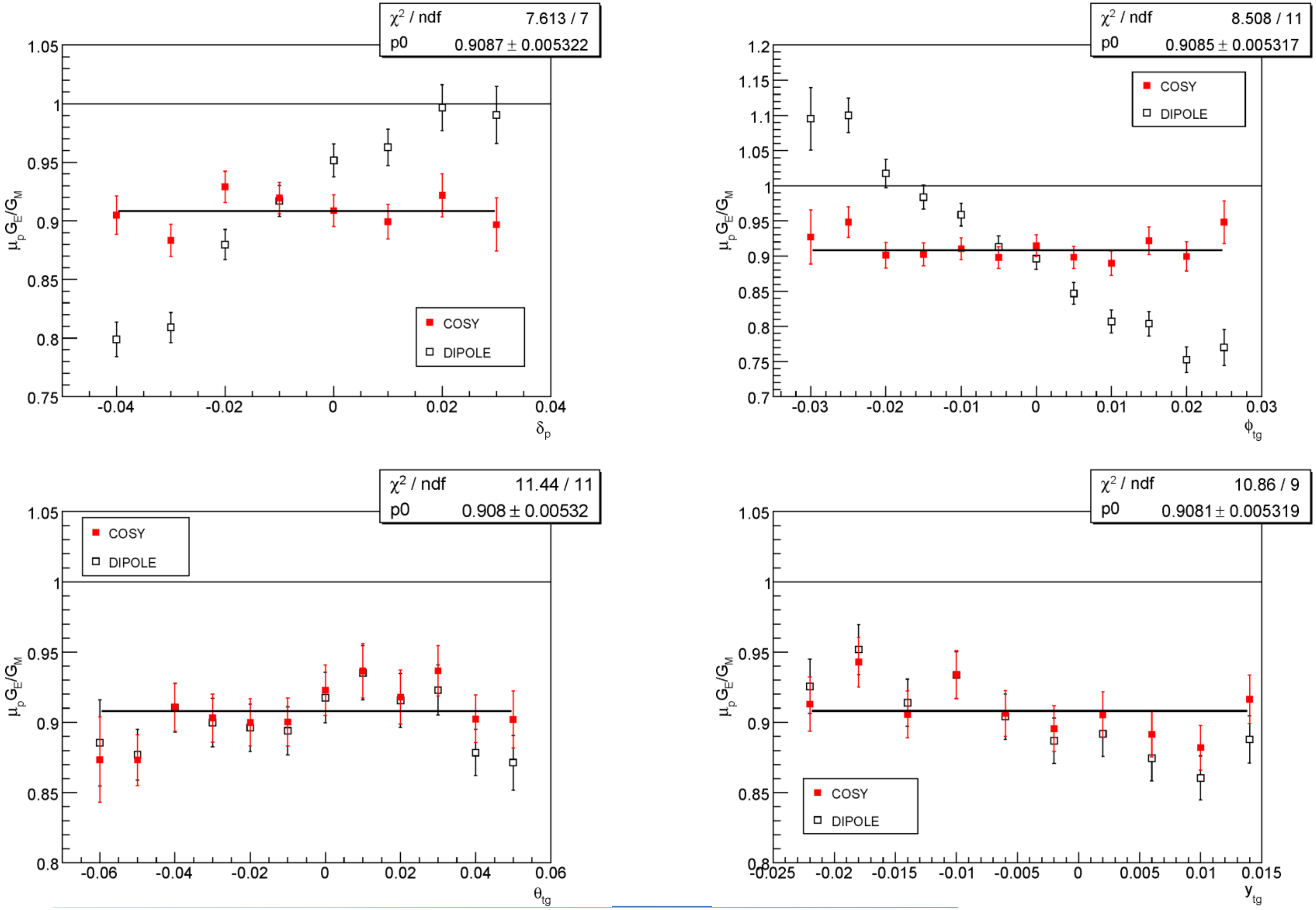


- By dipole approximation:

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

(K: kinematic factor)

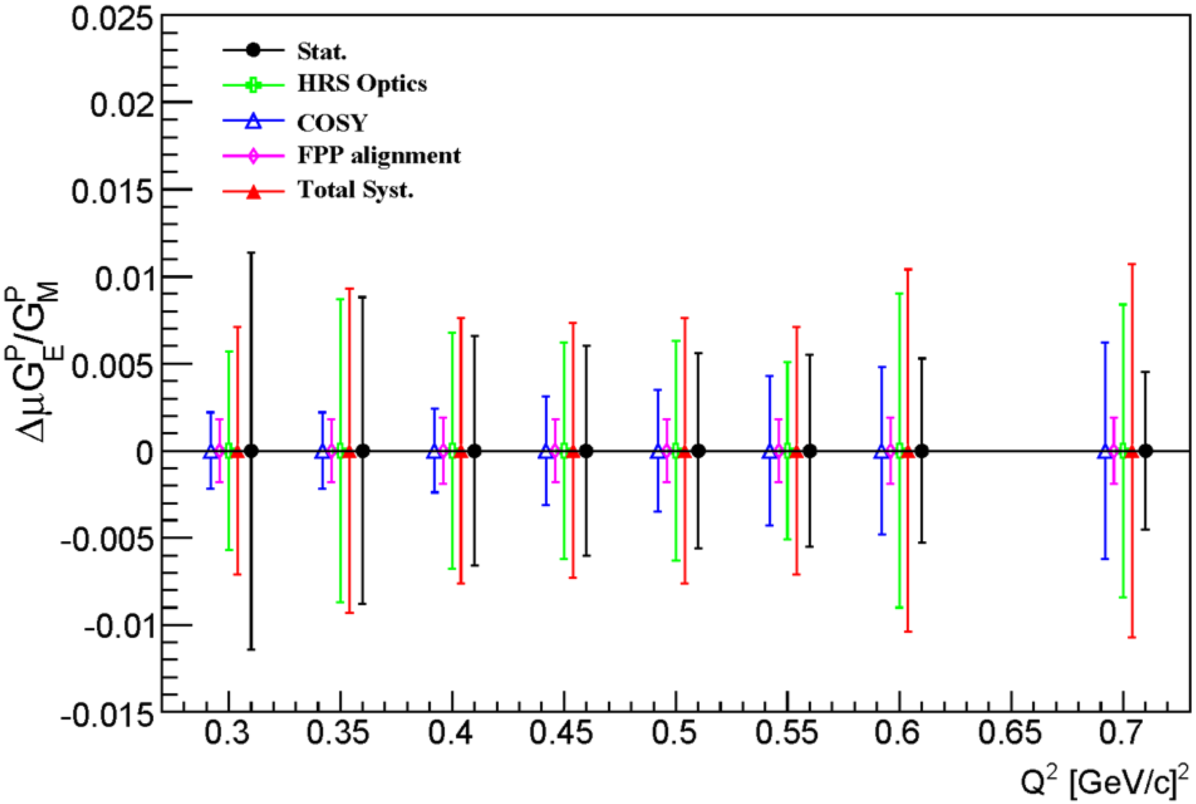
Spin Transport in HRS (COSY)



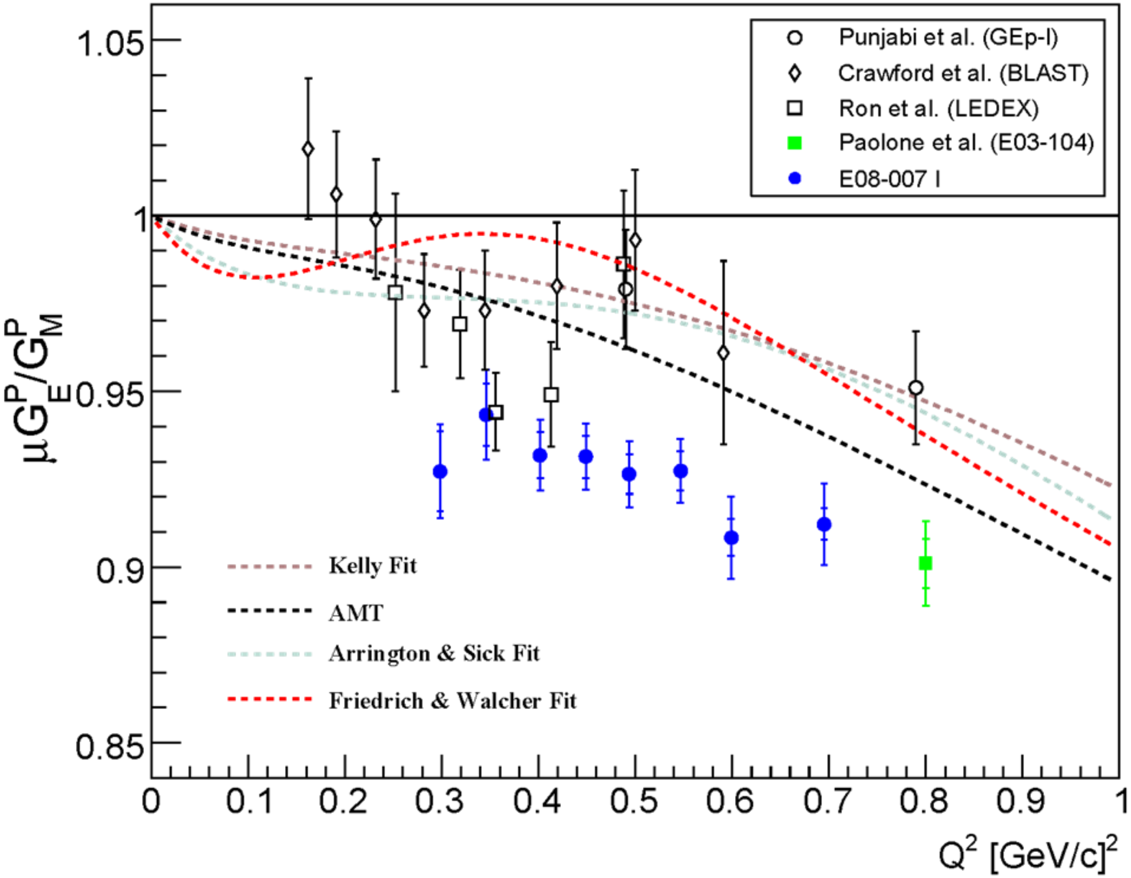
Systematic Budget

• 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.

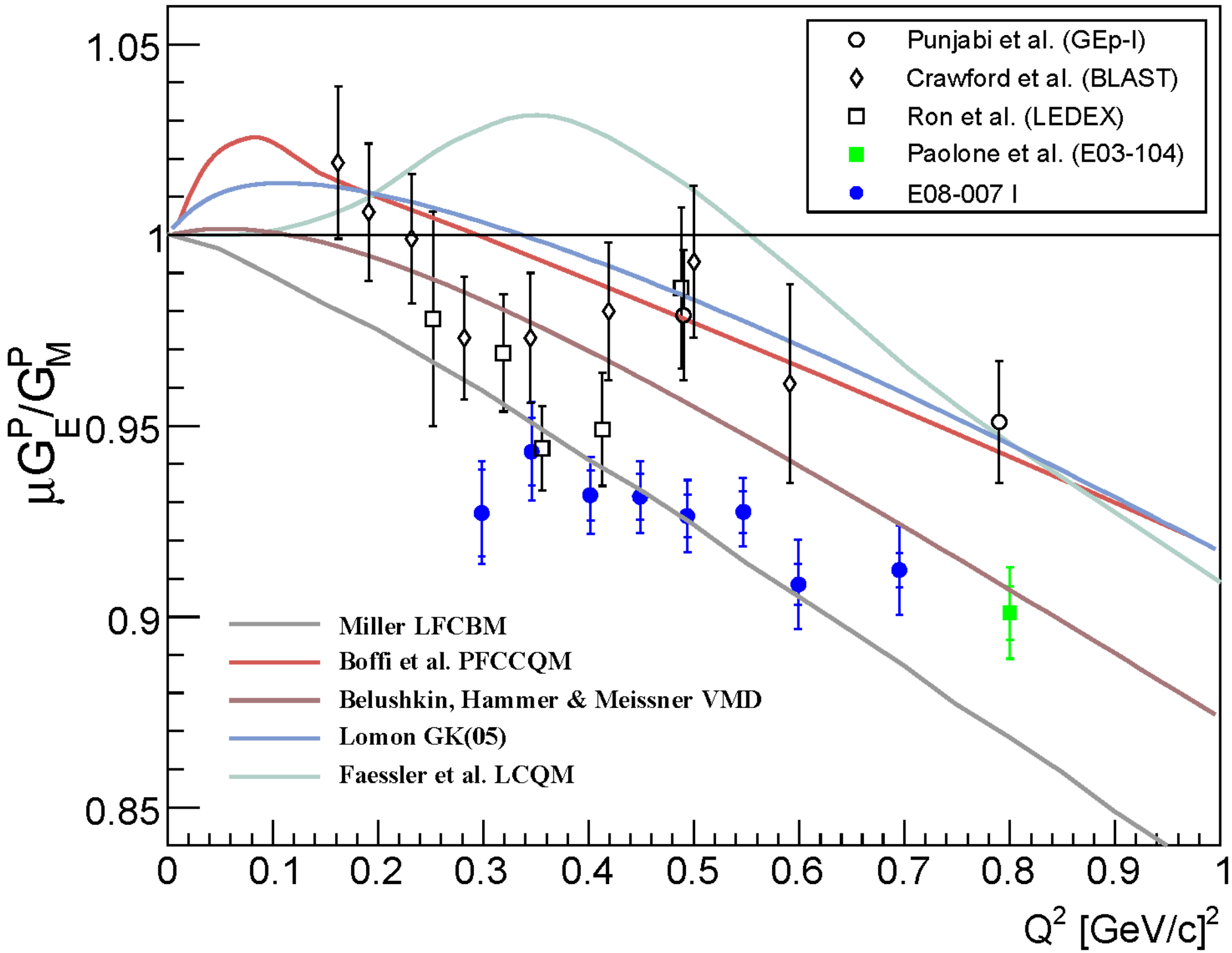


E08-007 Final Results

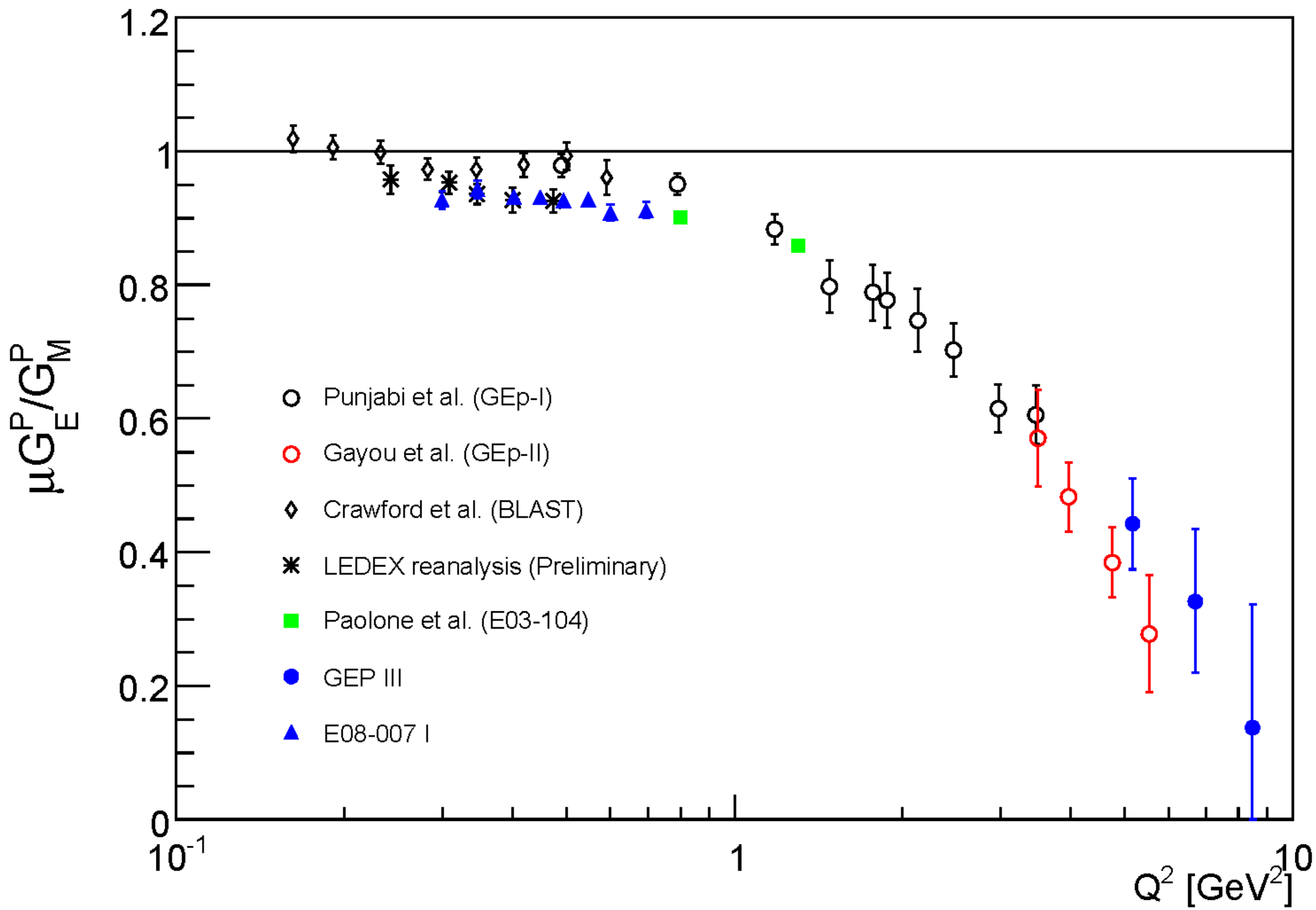


- Agreement with independent analysis of Paolone *et al.* at 0.8 GeV^2.
- Slow decrease with Q^2. A few percent below typical expectations.
- No obvious indication of "Structure", inconsistent with F&W fit.
- No obvious trend to rise quickly to unity at the lowest Q^2 point.

Comparison with Models

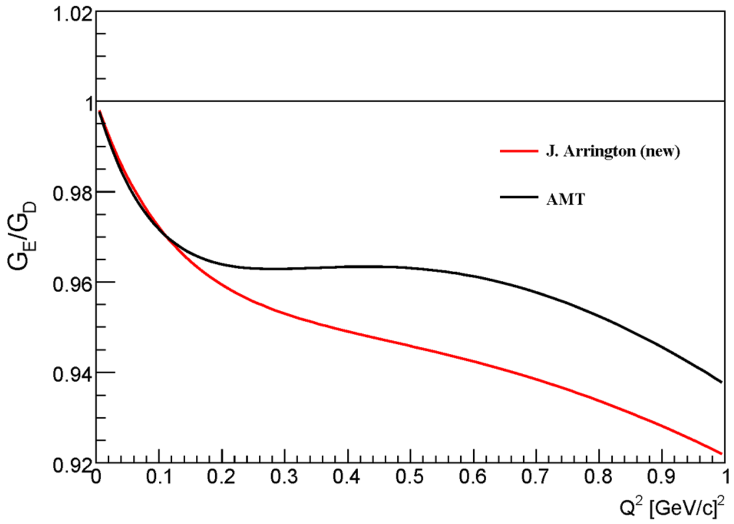


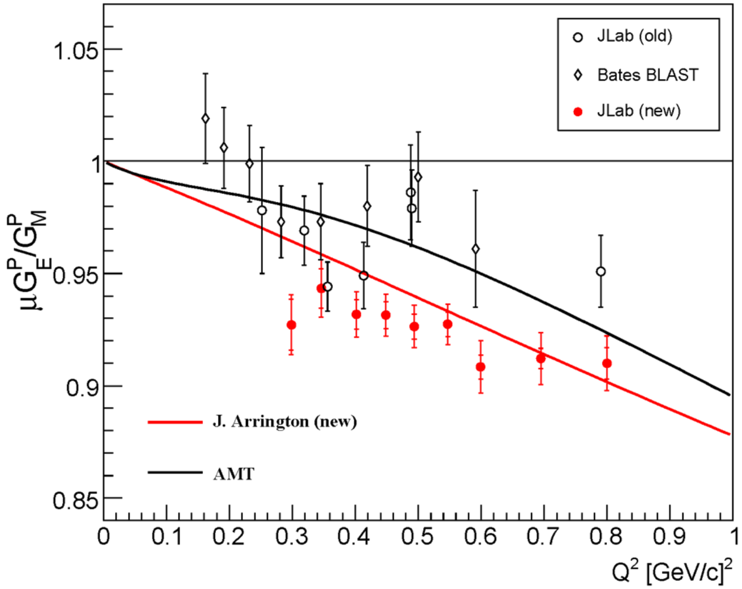
Results with World Polarization Data

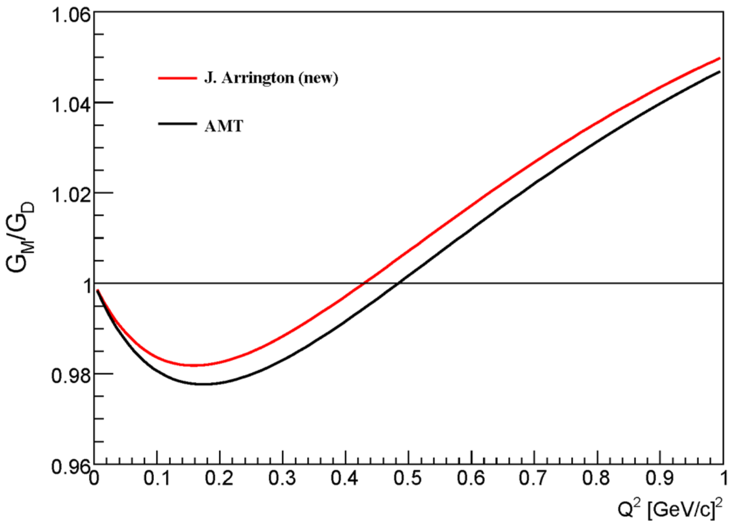


Global Fits

- Combined global fits (John Arrington).
- AMT fit (black) : include all previous data with TPE correction.
- New fit (red) : same procedure, include new data.
- Preliminary fits suggest lower G_E (~2%).







Impacts I

- Strangeness form factor by PV: asymmetry arises from the interference between EM and neutral weak current.

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

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

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

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

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

- 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.

Impacts II

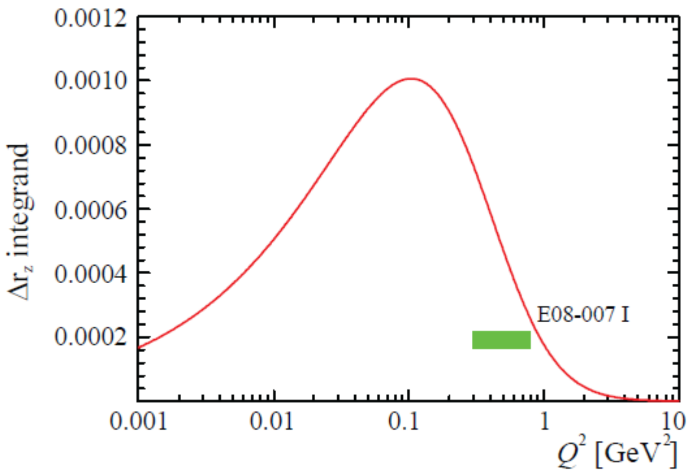
- Proton Zemach radius:

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

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

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

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



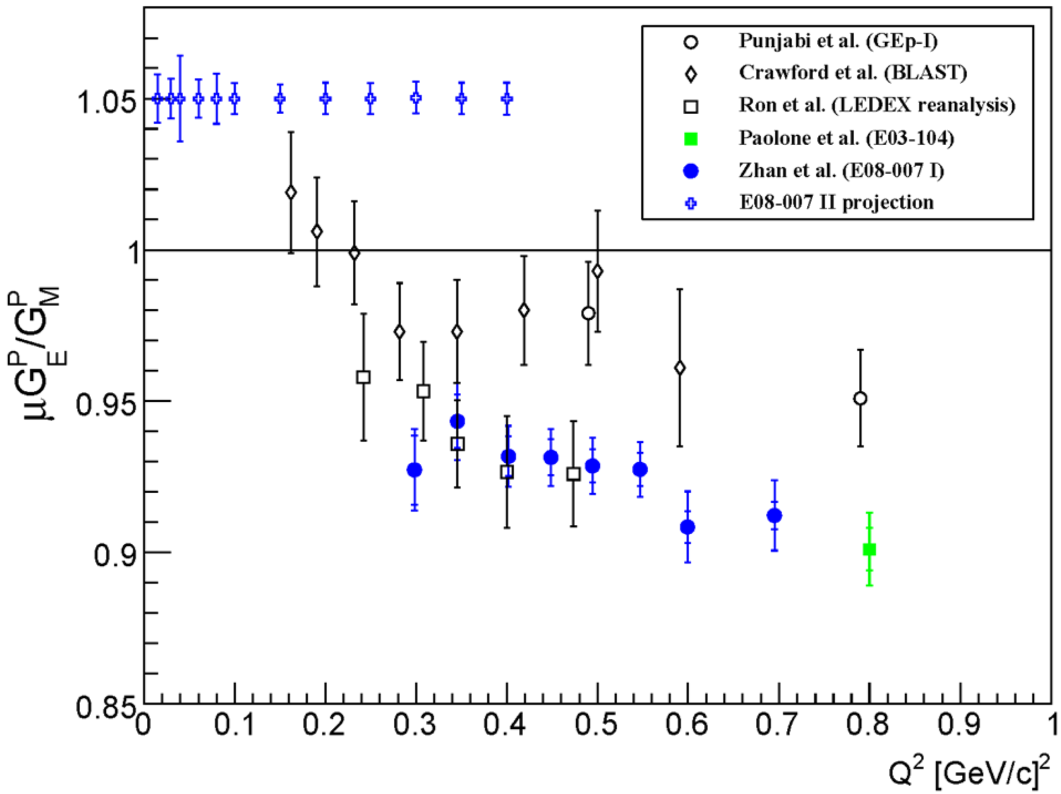
Quantity	value (ppm)	uncertainty (ppm)
$(E_{hfs}(e^- p)/E^p_F) - 1$	1 103.48	0.01
Δ_{QED}	1 136.19	0.00
$\Delta^p_{\mu vp} + \Delta^p_{hvp} + \Delta^p_{weak}$	0.14	
Δ_Z (using [31])	−41.43	0.44
Δ^p_R (using [31])	5.85	0.07
Δ_{pol} (this work, using [31])	1.88	0.64
Total	1102.63	0.78
Deficit	0.85	0.78

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

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

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

- 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.

Summary

• Nucleon FFs are fundamental quantities describing the nucleon internal structure, and has been a longstanding subject of interest in nuclear and particle physics.

• pQCD not applicable at low momentum transfer region, precision FF measurements are needed for all the experimental accessible region to test various models.

• A new high precision measurement was conducted in Jefferson Lab Hall A at low Q^2, new results strongly deviate from unity, systematically lower than previous world data.

• While adding further constraints on various models, high precision data also have impacts to other physics quantities: proton Zemach radius, strange form factor through PV, etc.

• Future experiments accessing extremely lower Q^2 are necessary, more "unexpected" results? …

Acknowledgements

J. Arrington, D. Higinbotham, J. Glister, R. Gilman, S. Gilad, E. Piasetzky, M. Paolone, G. Ron, A. Sarty, S. Strauch and the entire E08-007 collaboration

&

Jefferson Lab Hall A Collaboration

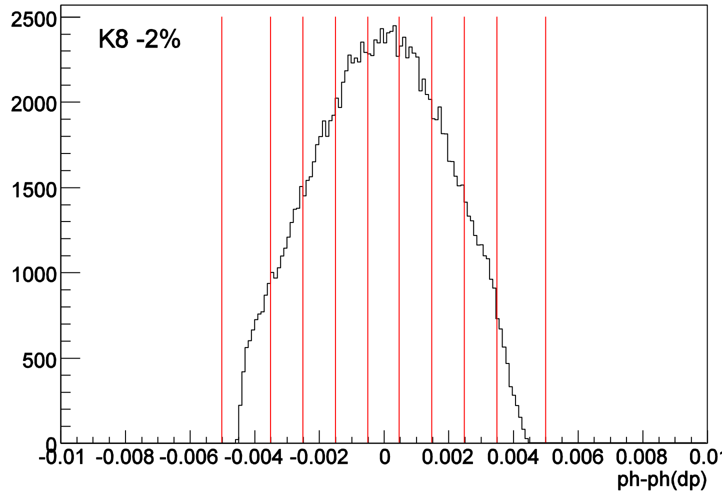
E08-007 Collaboration

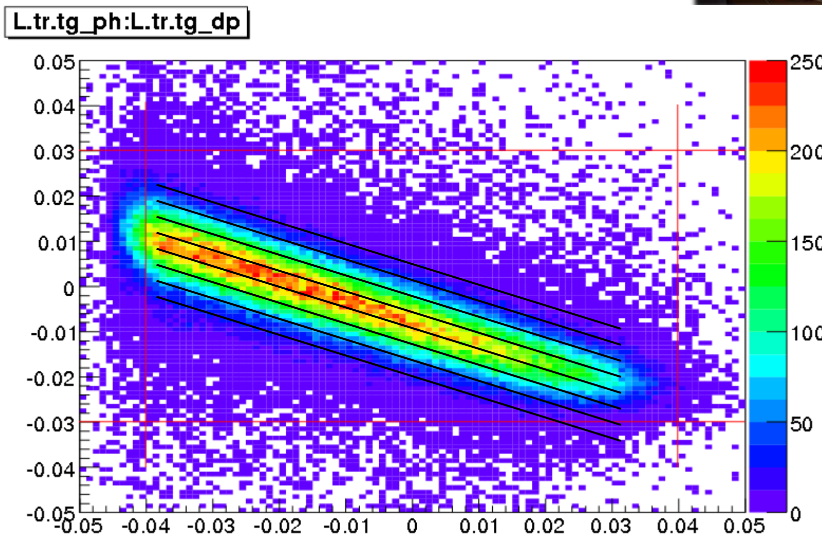
- Argonne National lab
- Jefferson Lab
- Rutgers University
- St. Mary's University
- Tel Aviv University
- UVa
- CEN Saclay
- Christopher Newport University
- College of William & Mary
- Duke University
- Florida International University
- Institut de Physique Nuclaire d'Orsay
- Kent State University
- 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

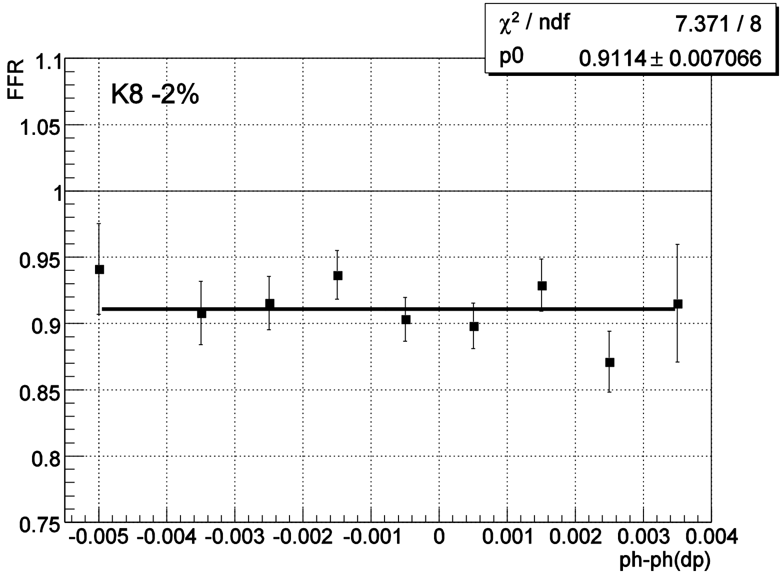
Thank you!

Back up slides

Spin Transport in HRS

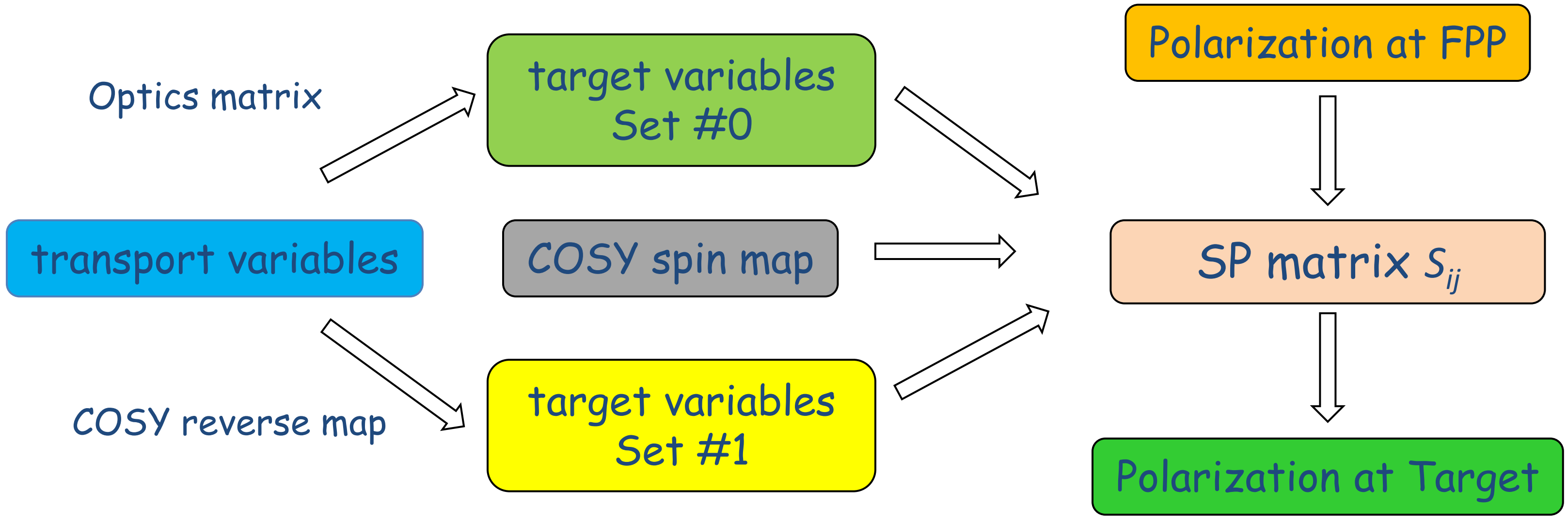






- Binning test for graphical cut.
- A rough check for existence of any possible background under elastic peak.
- No obvious indication of dependence on such variable.

COSY Spin Precession Matrix

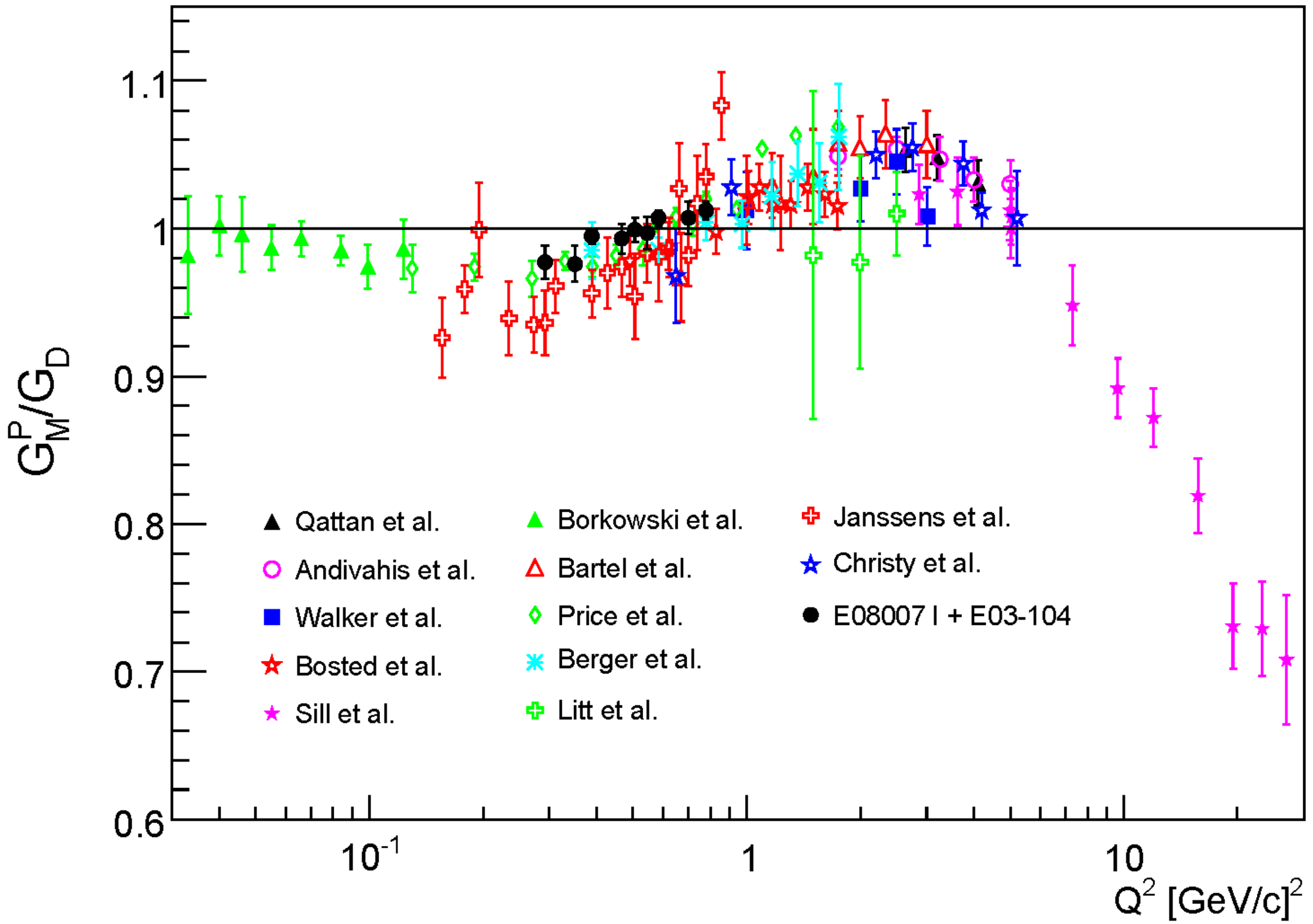


- Different SP matrix were generated by changing the default settings in COSY:
  - dipole radius, drift distances, quadrupoles alignment
  - central bending angle: 5.5 mrad
  - use COSY transport map to reconstruct target variables

- 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.

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

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

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

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

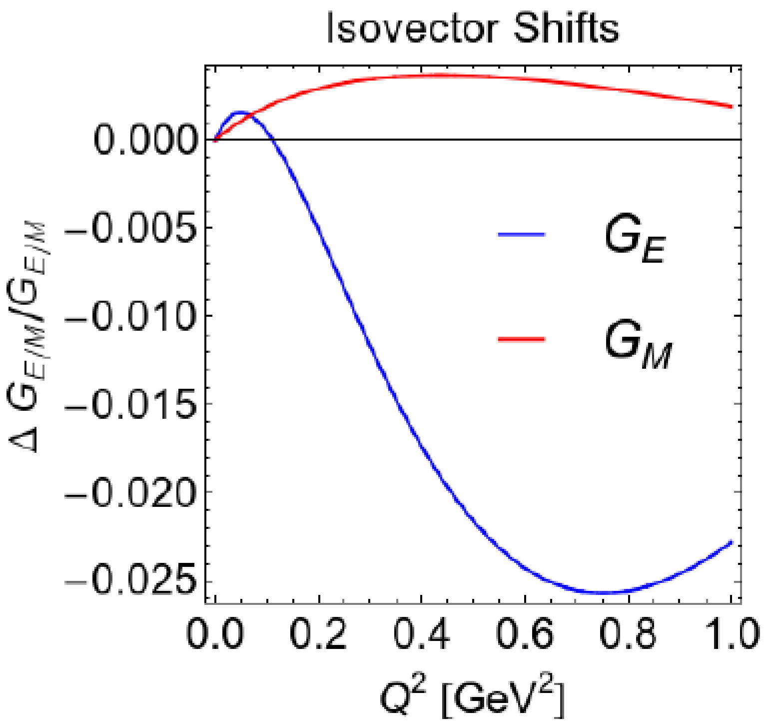
$$\Rightarrow \begin{pmatrix} \sum_i \lambda_{y,i} \\ \sum_i \lambda_{z,i} \end{pmatrix} = \begin{pmatrix} \sum_i \lambda_{y,i}\lambda_{y,i} & \sum_i \lambda_{z,i}\lambda_{y,i} \\ \sum_i \lambda_{y,i}\lambda_{z,i} & \sum_i \lambda_{z,i}\lambda_{z,i} \end{pmatrix} \begin{pmatrix} hP_y^{tg} \\ hP_z^{tg}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

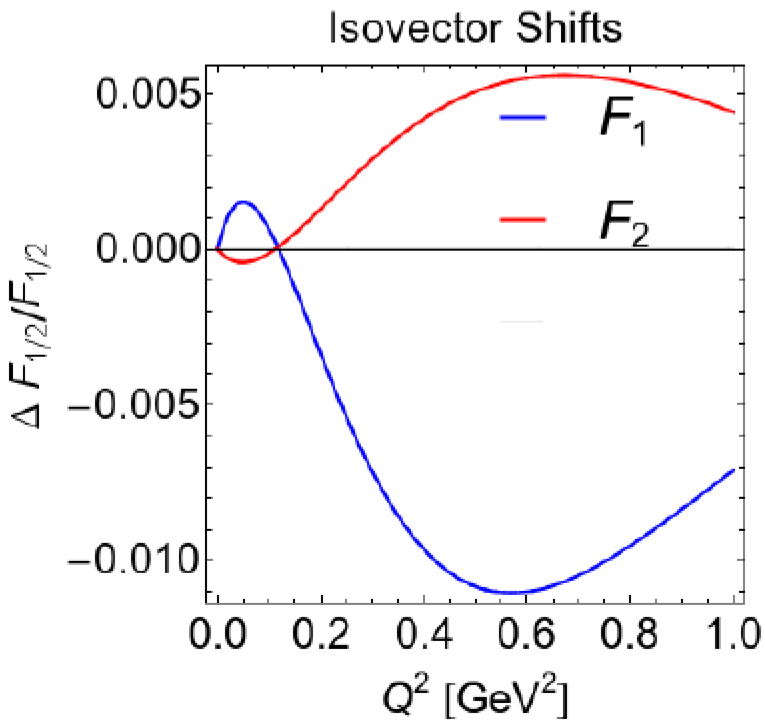
Impacts III

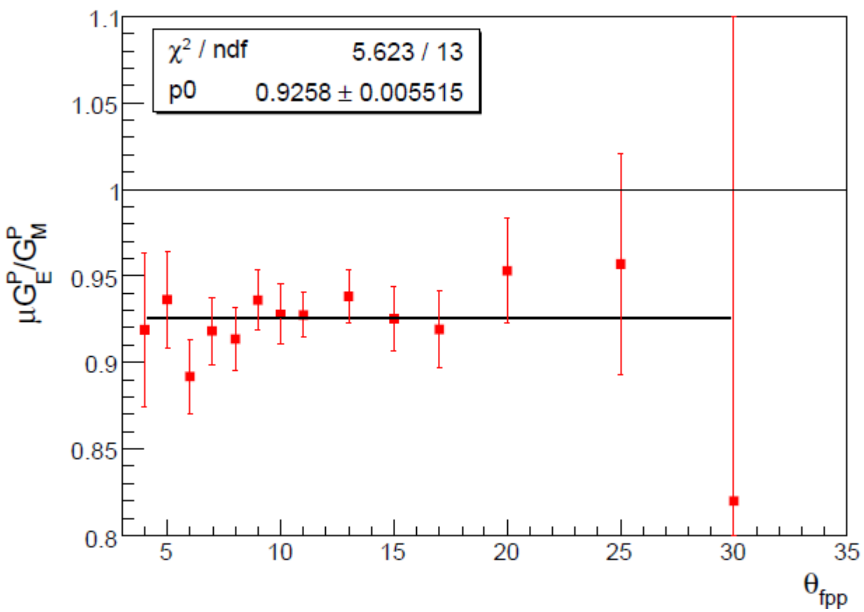
- Isoscalar & Isovector FFs (important for Lattice QCD):

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

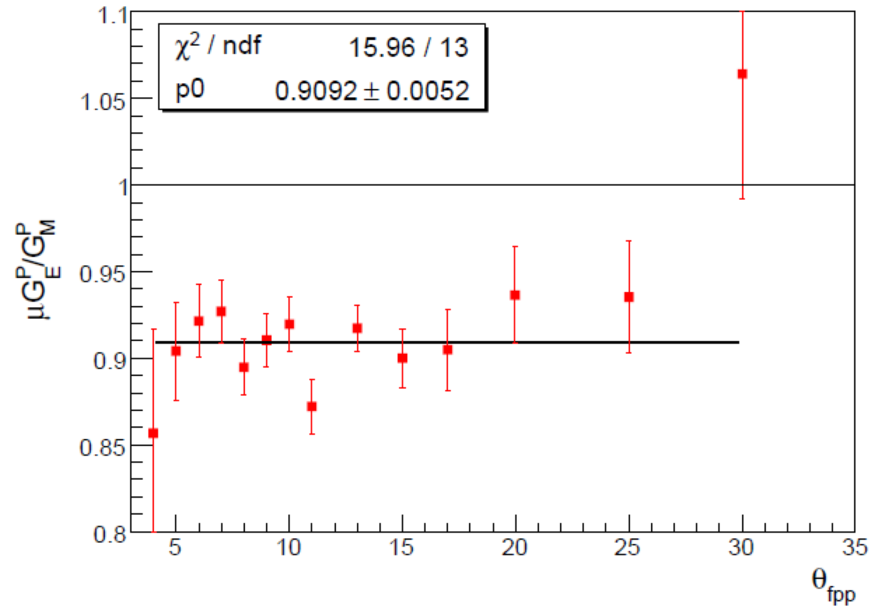
- Plots show fractional change in IS and IV FFs by using the new parameterization vs. the old parameterization.







χ^2 / ndf 5.623 / 13
p0 0.9258 ± 0.005515
$\mu G_E^P/G_M^P$
θ_{fpp}



χ^2 / ndf 15.96 / 13
p0 0.9092 ± 0.0052
$\mu G_E^P/G_M^P$
θ_{fpp}