Final Results of the GEp-III Experiment (E04-108)

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on behalf of the GEp-III Collaboration

4th Workshop on Exclusive Reactions at High Momentum Transfer

Jefferson Lab

5/19/2010

Jefferson Lab

Experimental Hall C

Outline

- Nucleon form factors overview
- Experiments E04-108 and E04-019 overview
- Data analysis
- Results
  - E04-108 final results (~~submitted to~~ accepted by PRL)
- Statistical Impact of E04-108 results
- Conclusion

GEp-III Collaboration

Recoil Polarization Measurements of the Proton Electromagnetic Form Factor Ratio to $Q^2 = 8.5$ GeV^2

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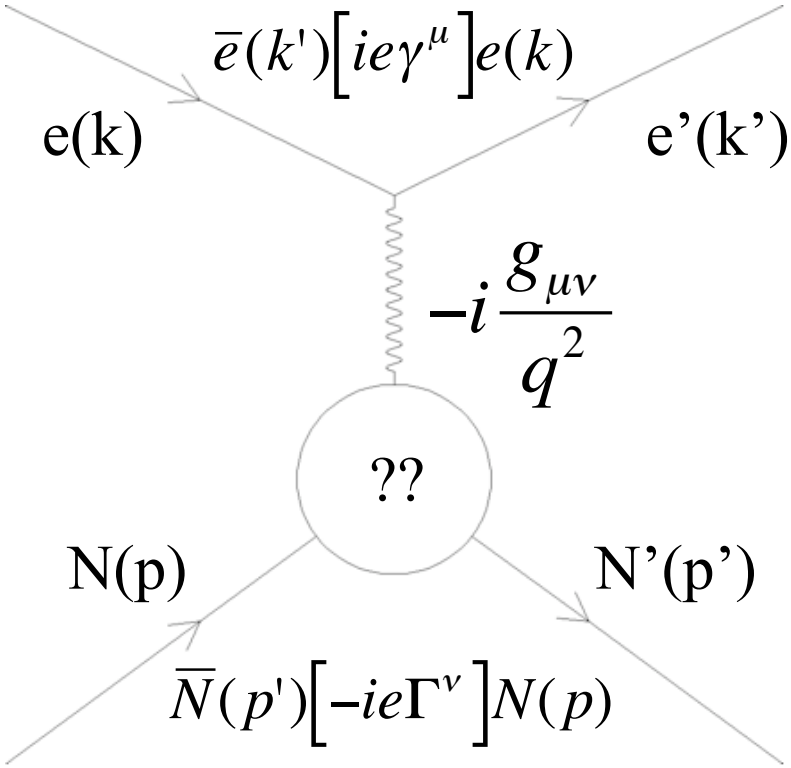
Overview of Nucleon Form Factors



One-photon exchange (OPEX) mechanism for elastic *eN* scattering

Definitions and Formulas:

$$\Gamma^{\mu} = F_1(q^2)\gamma^{\mu} + F_2(q^2)\frac{i\sigma^{\mu\nu}q_{\nu}}{2M}$$

$$Q^2 = -q^2 > 0$$

$$G_E = F_1 - \tau F_2$$

$$G_M = F_1 + F_2$$

$$\tau \equiv \frac{Q^2}{4M^2}$$

$$\frac{d\sigma}{d\Omega_e} = \frac{\alpha^2}{Q^2}\left(\frac{E_e'}{E_e}\right)\left[\frac{G_E^2 + \tau G_M^2}{1+\tau}\cot^2\left(\frac{\theta_e}{2}\right) + 2\tau G_M^2\right]$$

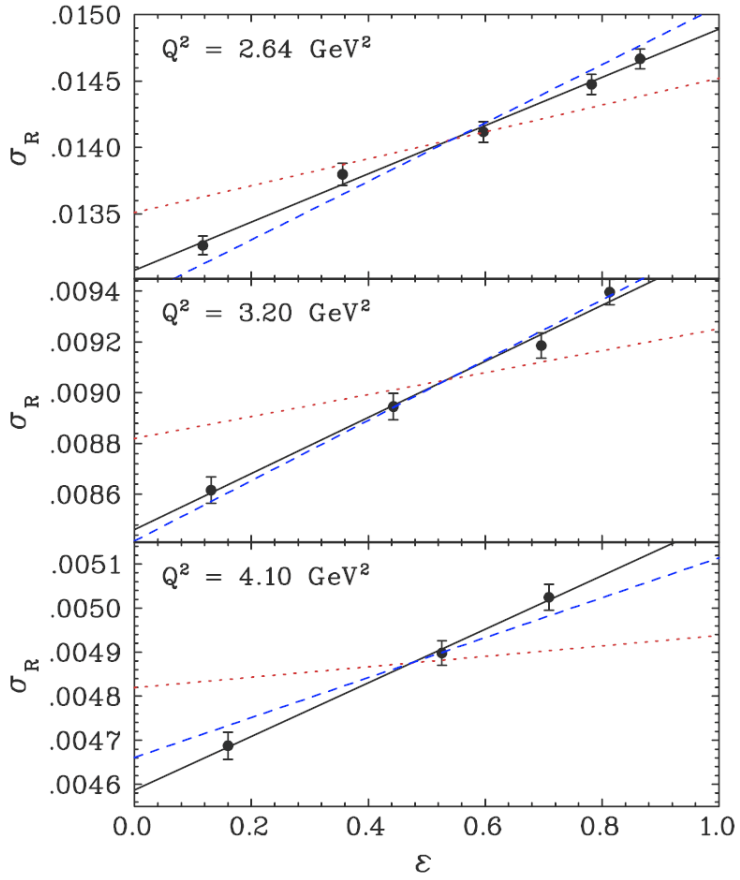
Lab Differential Cross Section: Rosenbluth Formula

Rosenbluth (L/T) Separation

$$\sigma_r \equiv (1+\tau)\varepsilon\frac{\sigma_{eN}}{\sigma_{Mott}} = \varepsilon G_E^2 + \tau G_M^2$$

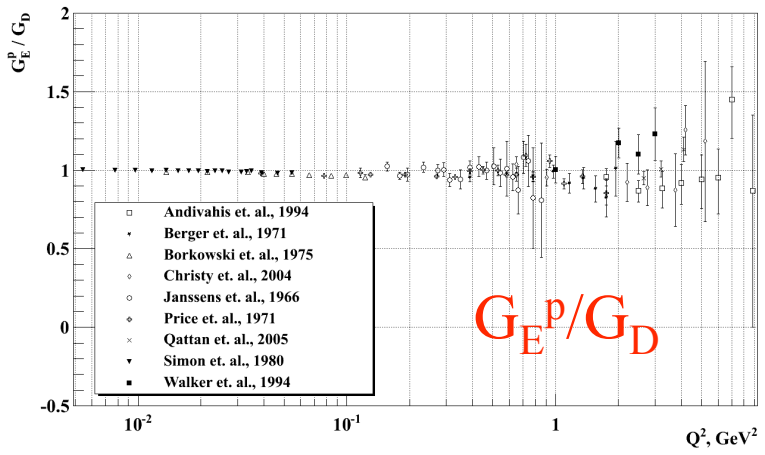
$$\varepsilon = \left[1 + 2(1+\tau)\tan^2\left(\frac{\theta_e}{2}\right)\right]^{-1}$$

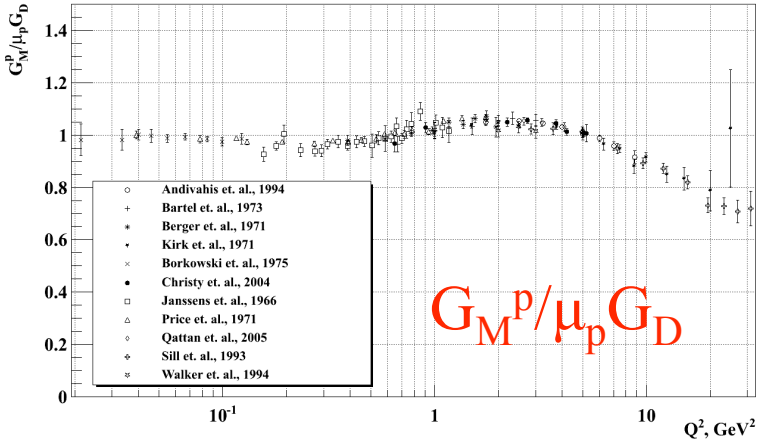
- Measure angular dependence of scattering cross section at fixed Q^2
- In OPEX, "reduced cross section" is linear in ε
- Slope and intercept determine G_E^2, G_M^2 respectively

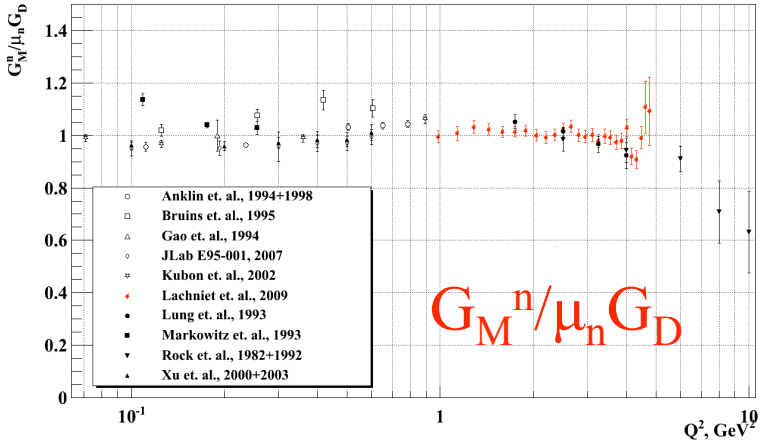


PRL 94, 142301 (2005)

World Cross-Section Data







- Cross section data for G_E^p, G_M^p, G_M^n qualitatively described by dipole form:

$$G_D = \left(1 + \frac{Q^2}{\Lambda^2}\right)^{-2} \qquad \Lambda^2 = 0.71 \text{ GeV}^2$$

- L/T separation becomes insensitive to $G_M(G_E)$ at small (large) Q^2
- Method impractical for (small) G_E^n

Polarization Transfer

$$p(\vec{e},e'\vec{p})$$

$$I_0 P_l = \sqrt{\tau(1+\tau)}\tan^2\left(\frac{\theta_e}{2}\right)\frac{E_e + E'_e}{M}G_M^2$$

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

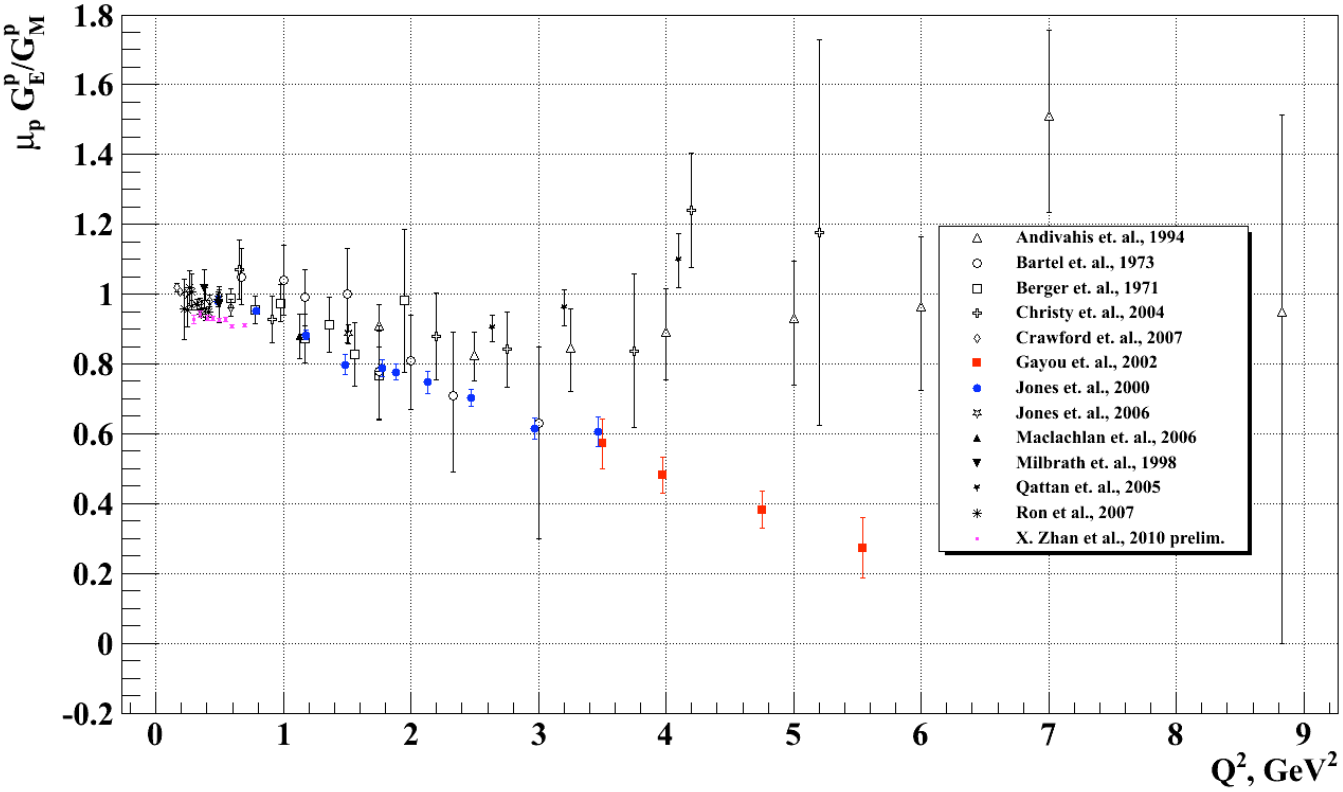
$$P_n = 0$$

$$I_0 \equiv G_E^2 + \frac{\tau}{\varepsilon}G_M^2$$

$$\frac{G_E}{G_M} = -\frac{P_t}{P_l}\frac{E_e + E'_e}{2M}\tan\left(\frac{\theta_e}{2}\right)$$

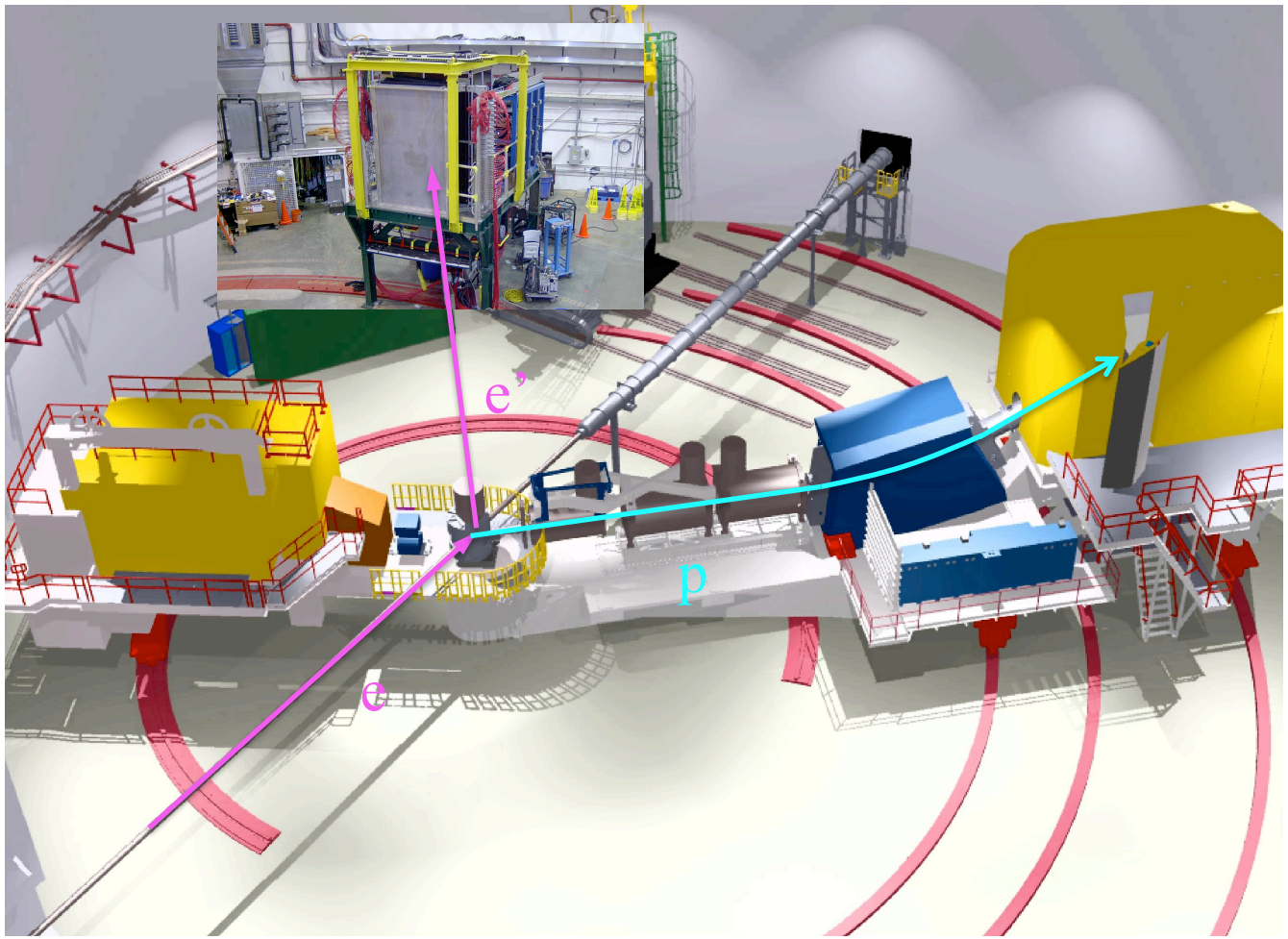
- Elastic scattering of polarized electrons from unpolarized nucleons transfers polarization to scattered nucleons
- Better sensitivity to G_E, especially at high Q^2
- Determines sign of G_E/G_M
- Much lower sensitivity to radiative corrections and two-photon-exchange (TPEX) than cross section

Polarization Transfer and G_E^p/G_M^p



Precise recoil polarization data for $R=\mu_p G_E^p/G_M^p$ conclusively revealed a strong deviation from $R \approx 1$ scaling of cross section data

Experiments E04-108 & E04-019



New recoil polarization measurements of G_E^p/G_M^p in Hall C at JLab

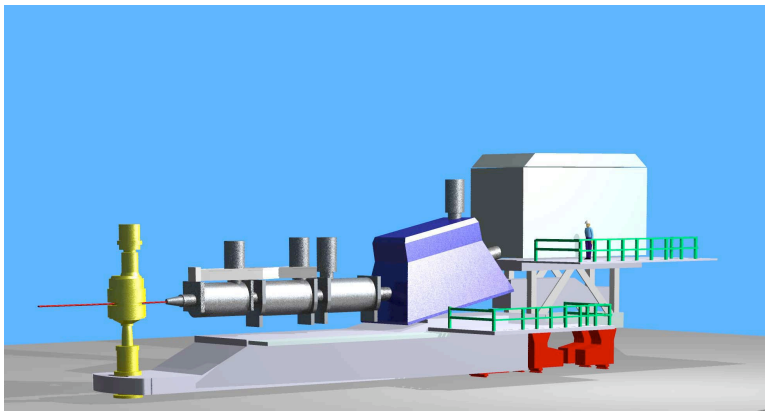
Kinematics

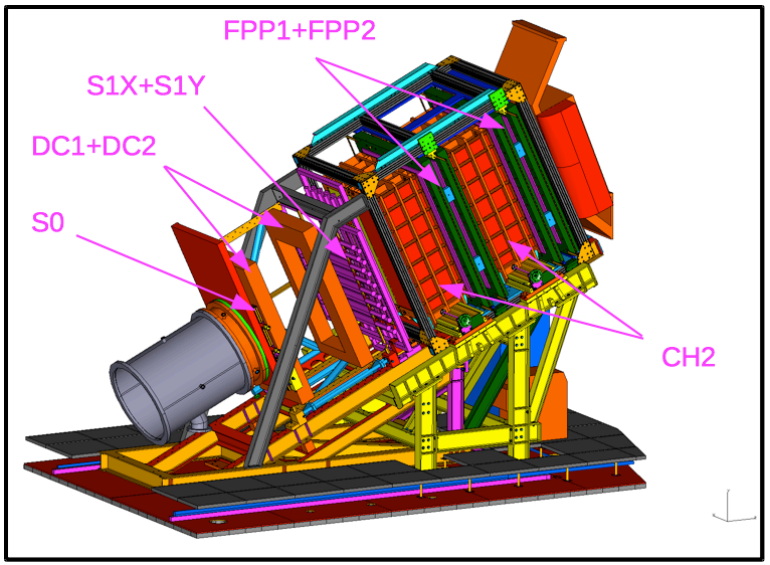
Q^2, GeV^2	ε	E_{beam}, GeV	θ_p, $^\circ$	p_p, GeV	E_e, GeV	θ_e,$^\circ$
2.5	0.154	1.873	14.495	2.0676	0.532	105.2
2.5	0.633	2.847	30.985	2.0676	1.51	44.9
2.5	0.789	3.680	36.10	2.0676	2.37	30.8
5.2	0.377	4.053	17.94	3.5887	1.27	60.3
6.8	0.507	5.714	19.10	4.4644	2.10	44.2
8.5	0.236	5.714	11.6	5.407	1.16	69.0

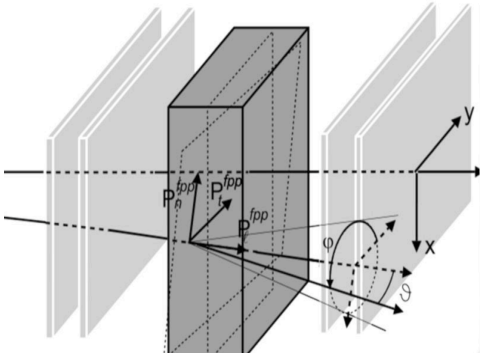
- E04-108: three new high Q^2 measurements
- E04-019: precision measurements at Q^2=2.5 GeV^2 for three ε values; look for signatures of TPEX
- Beam: ~60-100 μA CW, 80-85% polarized (Moller)
- Target: 20 cm LH_2, nominal luminosity ~4×10^{38} s^{-1}cm^{-2}

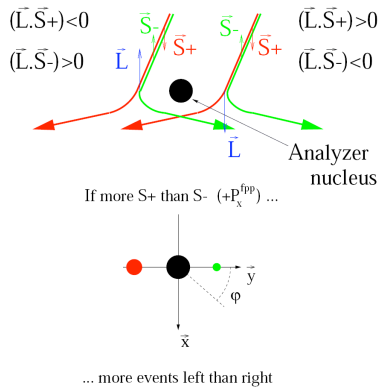
HMS+FPP

- High Momentum Spectrometer (HMS), superconducting, 25° vertical bend magnetic spectrometer measures proton:
  - Angles
  - Momentum
  - Vertex
- Focal Plane Polarimeter:
  - Measure transverse components of proton polarization at the focal plane

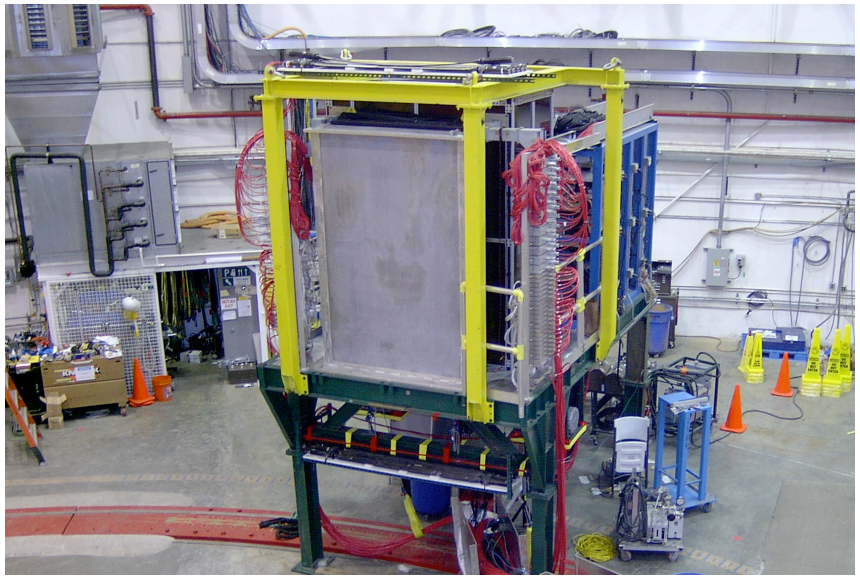








BigCal

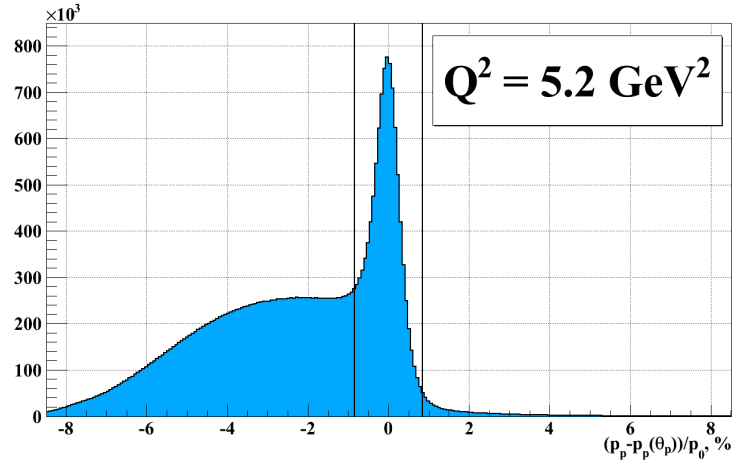


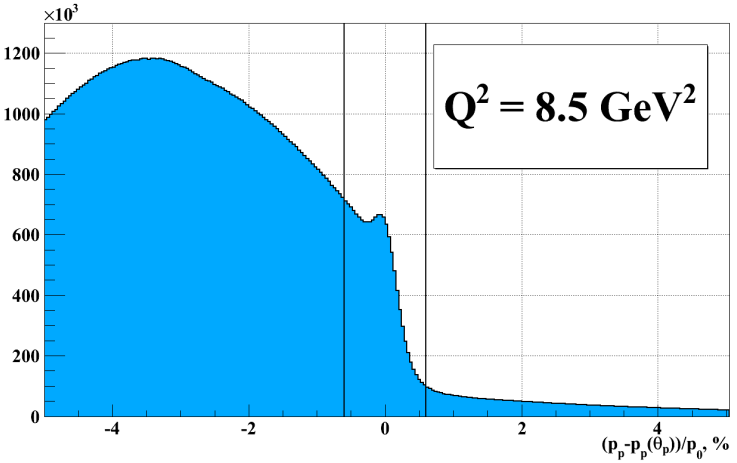
- Measure electron angles, energy
- Separate elastic from inelastic using angular correlation
- Large Jacobian in elastic ep scattering—large acceptance to match proton arm
- For $Q^2 = 8.5$ GeV^2, $\Omega_e = 143$ msr to $\Omega_p = 6.7$ msr

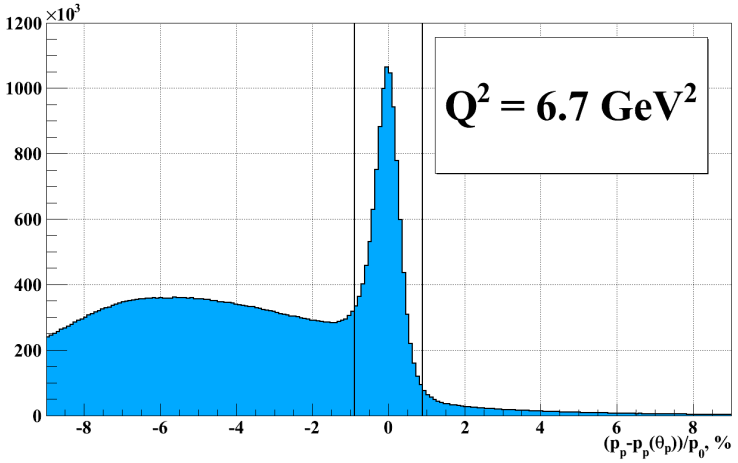
Data Analysis

- Elastic Event Selection
  - Inelasticity variable definitions
  - Cut selection and background estimation
- Extraction of Polarization Observables
  - Focal plane asymmetry extraction
  - Spin precession calculation

Elastic Event Selection, I



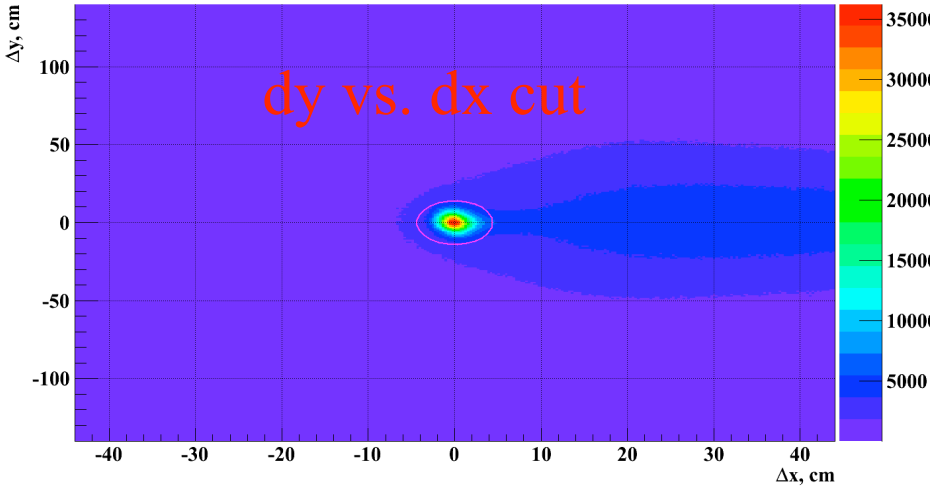


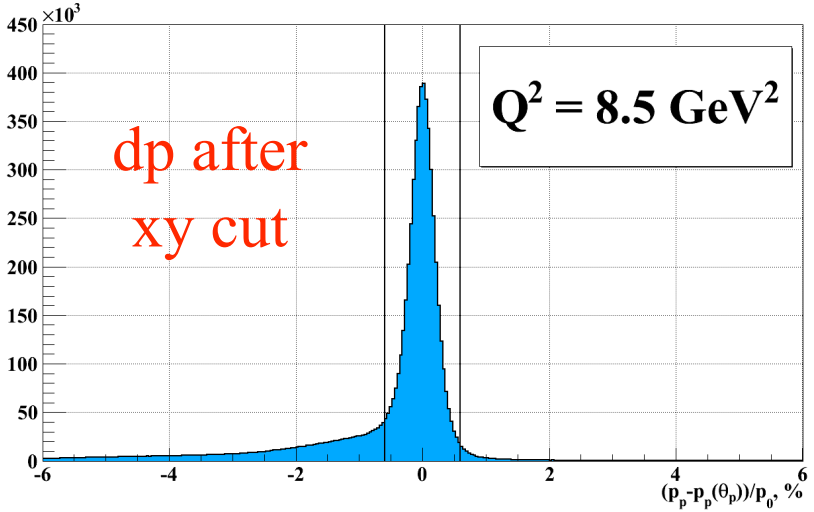


$$p_p(\theta_p) = \frac{2M_p E_e (E_e + M_p)\cos\theta_p}{M_p^2 + 2M_p E_e + E_e^2 \sin^2\theta_p}$$

- Proton angle-momentum correlation in elastic scattering
- p-p(θ) spectra before applying cuts to BigCal electron position

Elastic Event Selection, II

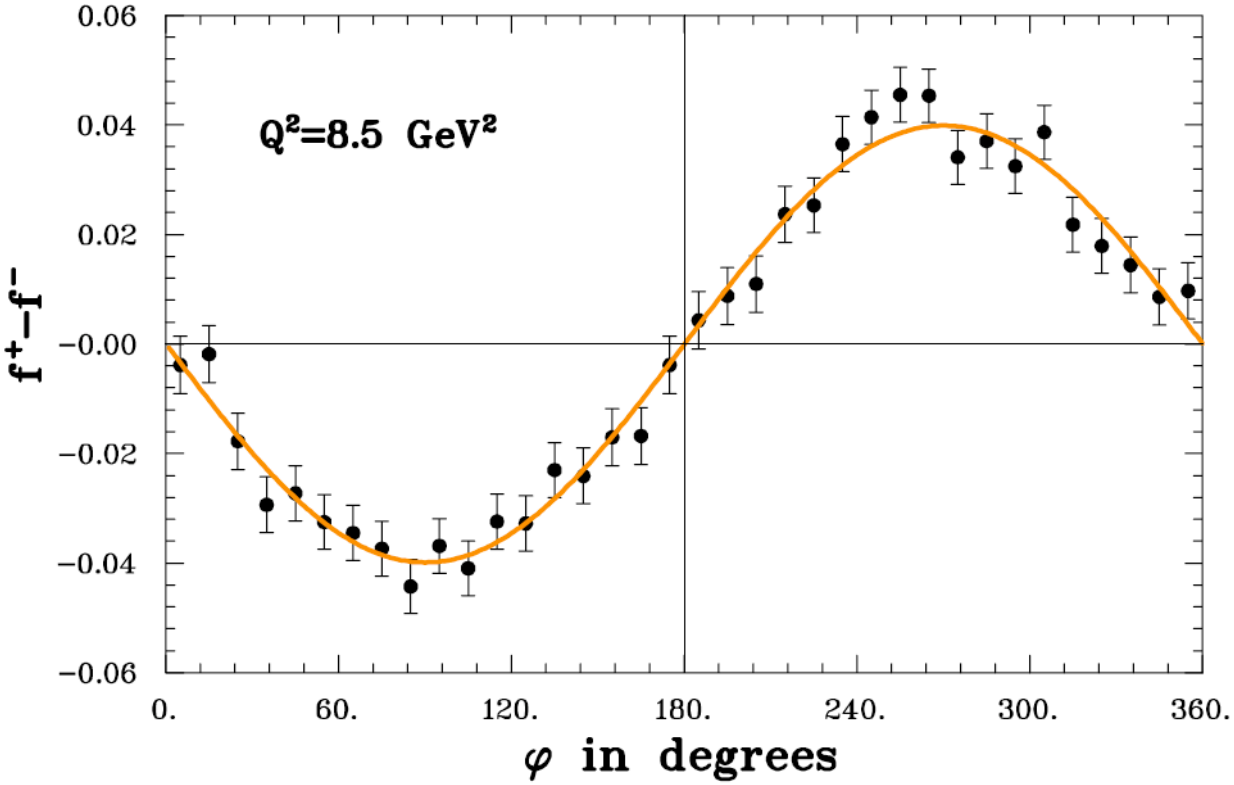




$$\left(\frac{\Delta x}{x_{\max}}\right)^2 + \left(\frac{\Delta y}{y_{\max}}\right)^2 \leq 1$$

- Elliptical cut at BigCal cleans up "dp" spectrum rather efficiently
- Fat tail on inelastic side of peak indicates "leftover" background
- Tight cuts to dx, dy, dp needed
- Still ~6% background for final cuts at Q^2=8.5 GeV^2

Polarization Observables—FPP Asymmetry



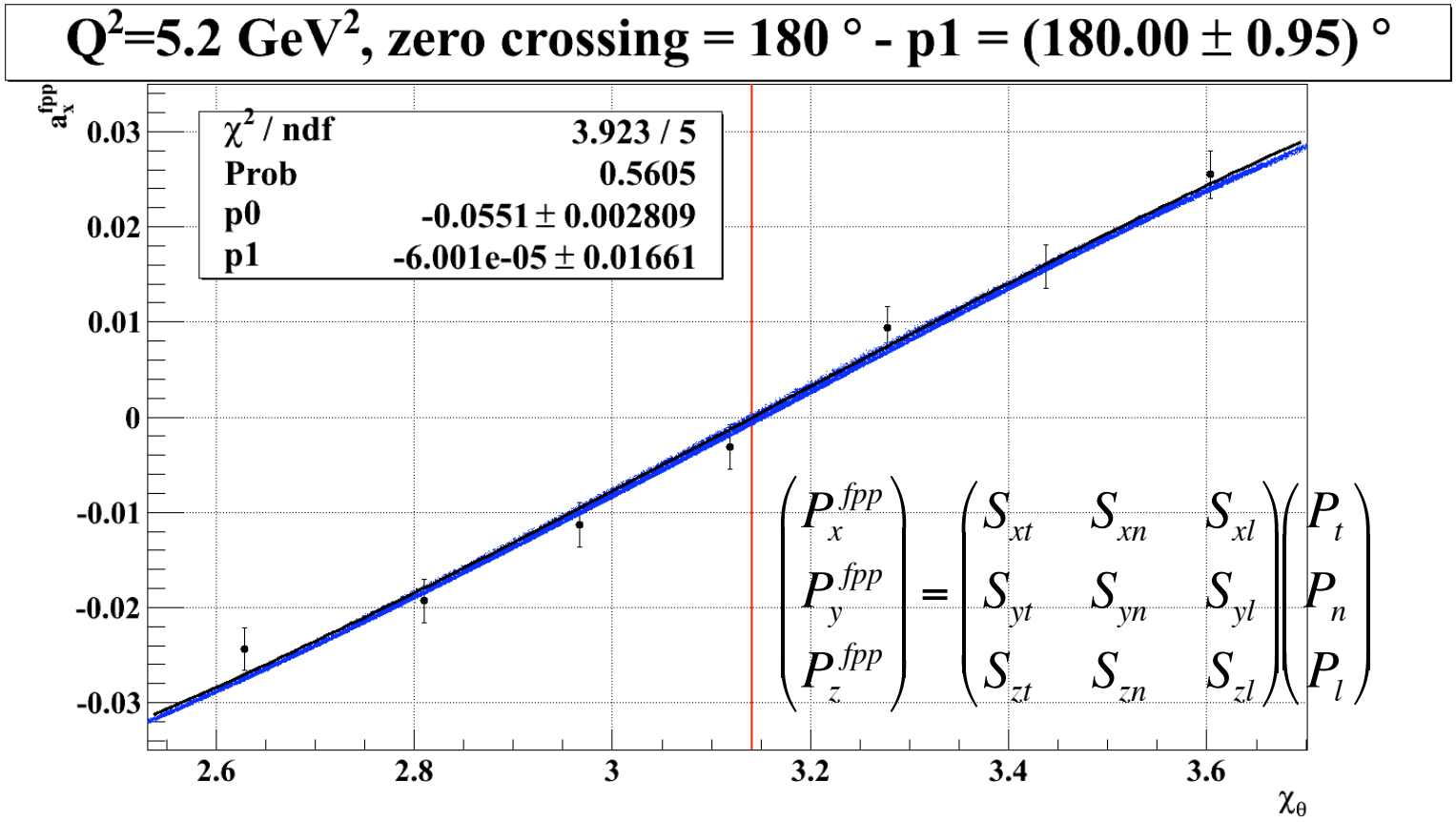
$$f_+ - f_- = A\sin(\varphi + \delta)$$

$$A = \overline{A_y}\sqrt{\left(P_x^{fpp}\right)^2 + \left(P_y^{fpp}\right)^2}$$

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

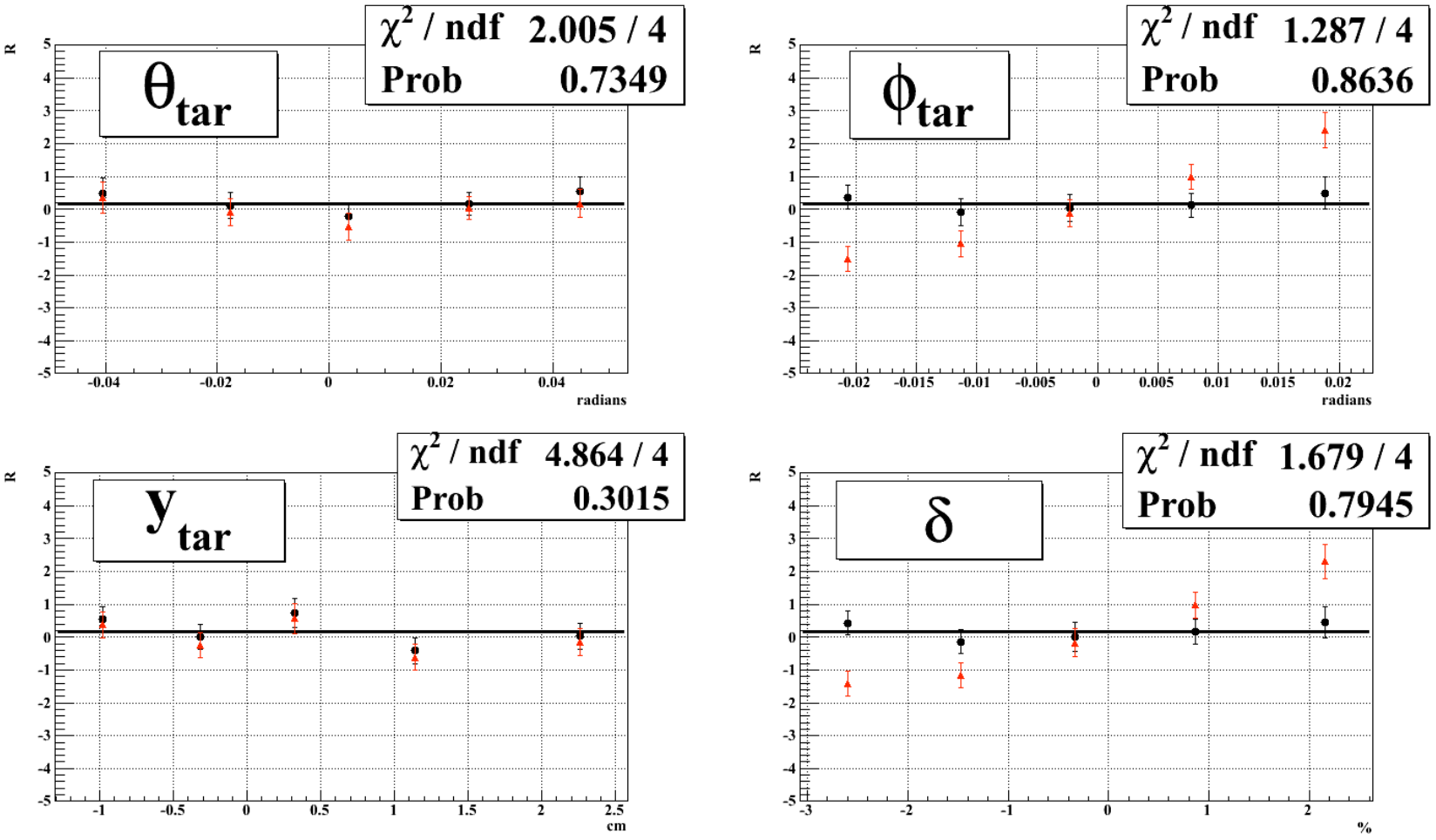
Helicity difference asymmetry, $Q^2 = 8.5$ GeV^2, $0.5° \le \theta \le 14.0°$

Spin Precession, I



- Normal asymmetry at focal plane should cross zero at χ=180°
- Within statistics, data compatible with this prediction
- Fit: $a_x = p0\ \sin(\chi + p1)$, $\langle hA_y \rangle S_{xl} P_l$ from COSY agrees with χ-dependence of the data

Spin Precession, II



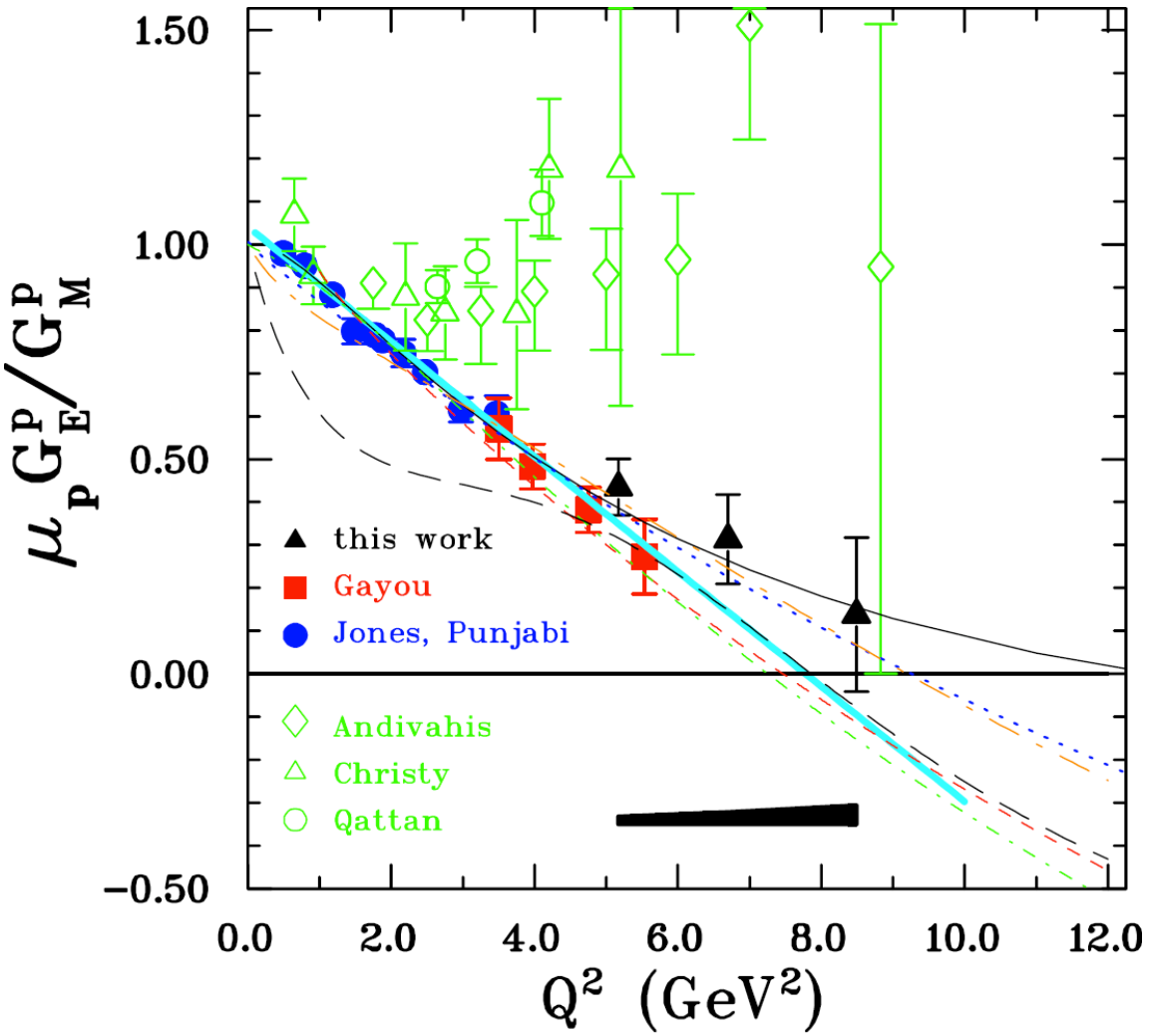
R vs. reconstructed kinematics, **$Q^2 = 8.5$ GeV², DIPOLE/COSY**

Systematic Uncertainties

Q^2, GeV^2	5.2	6.7	8.5
ϕ_{bend} (±.5 mrad)	.0162	.0202	.0378
θ_{bend} (±2 mrad)	.0009	.0006	.0002
δ (±0.3%)	.0029	.0027	.0024
φ_{fpp} (±.14 mrad/ $\sin(\vartheta_{fpp})$)	.0003	.0057	.0178
E_{beam} (±.05%)	.00027	.00009	.00025
False asym.	.0069	.0057	.0018
Background	.0015	.0013	.0130
Rad. Corr. (% of R)	0.05% ($\Delta R \approx -.0002$)	0.12% ($\Delta R \approx -.0004$)	0.13% ($\Delta R \approx -.0002$)
Total ΔR_{syst}	.018	.022	.043

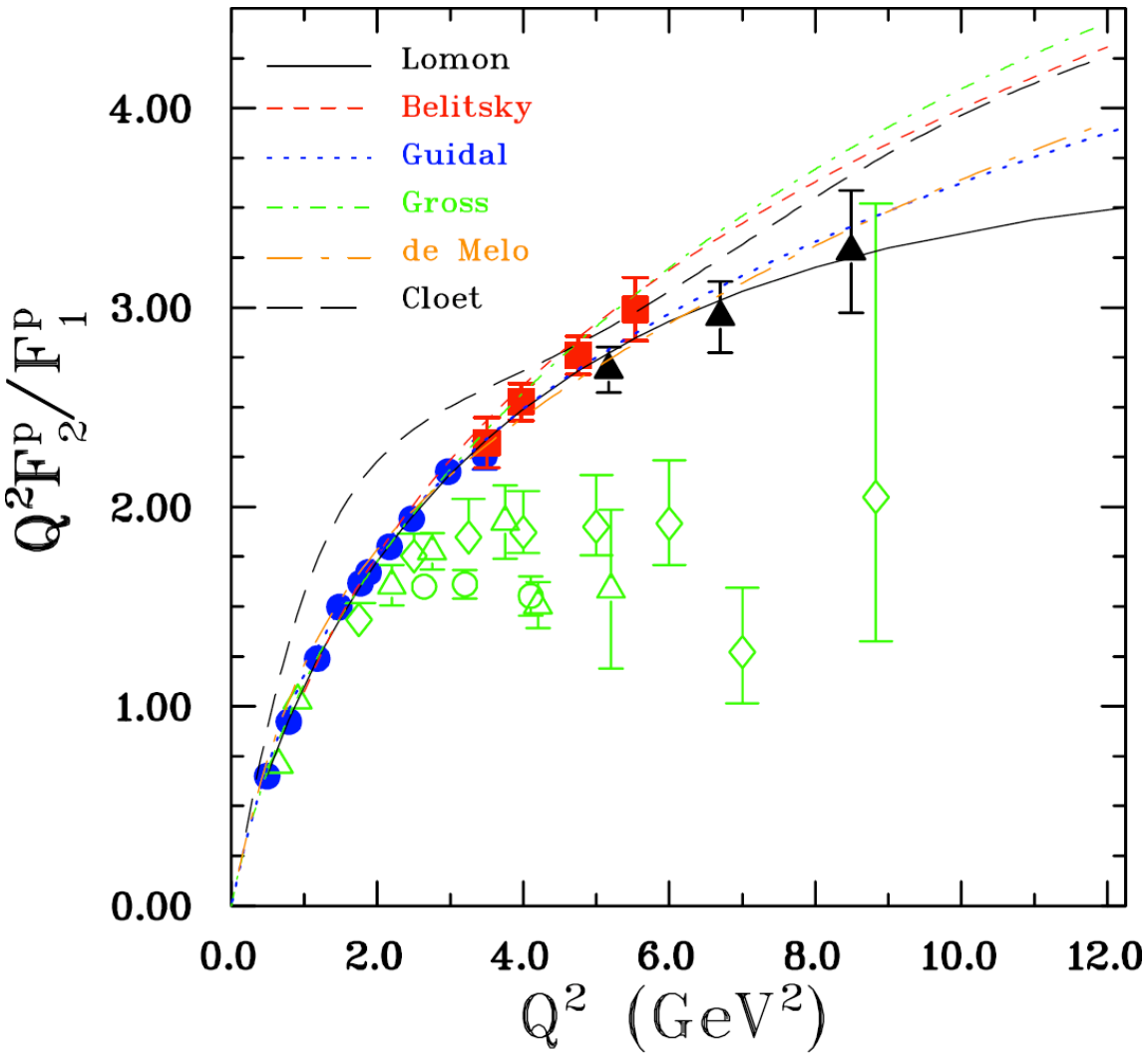
- Non-dispersive precession uncertainty dominates the systematic uncertainty in R
- **A_y, h cancel**, no uncertainty for R
- Standard radiative corrections (not applied) **negligible** compared to other uncertainties

Final Results, I



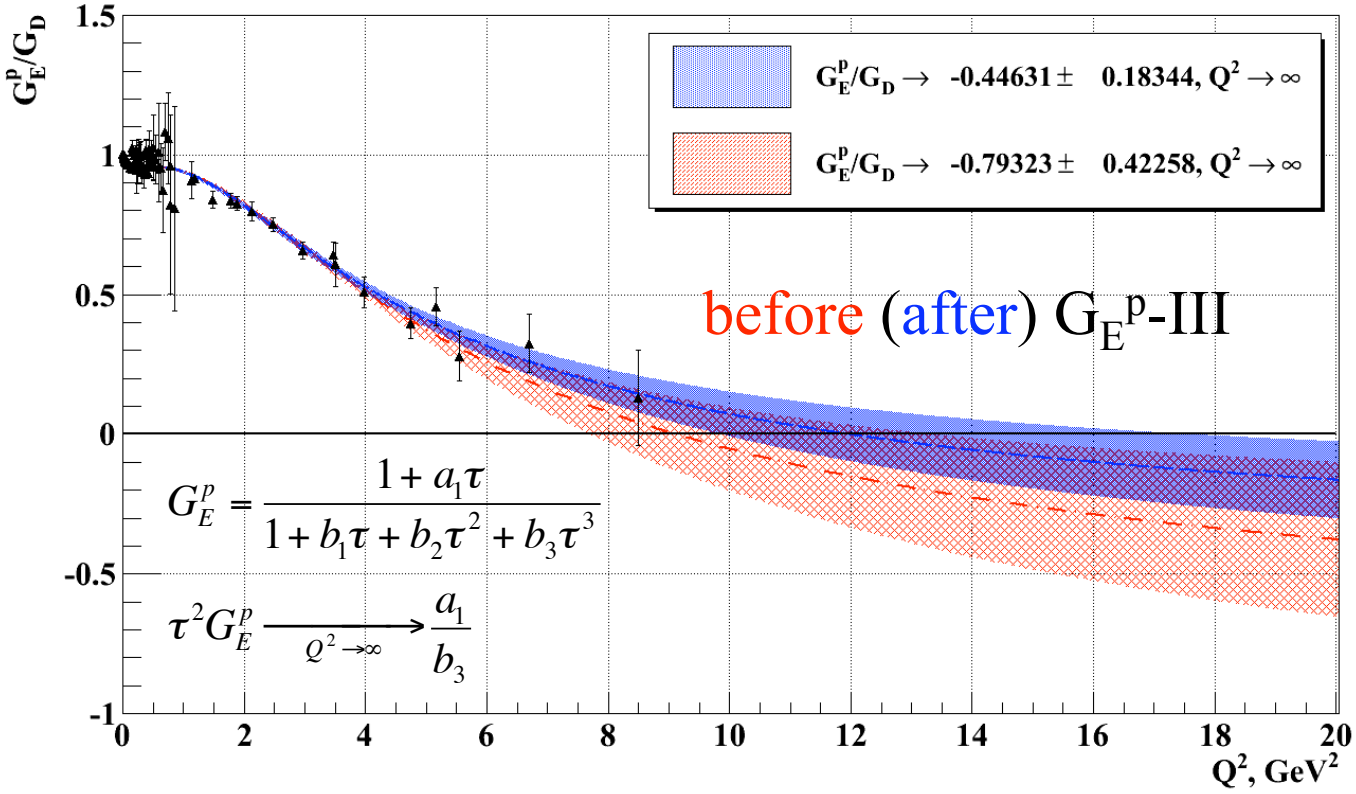
- Results finalized, accepted for publication in PRL
- 50% increase in Q^2 coverage
- New data favor a slowing rate of decrease of R

Final Results, II



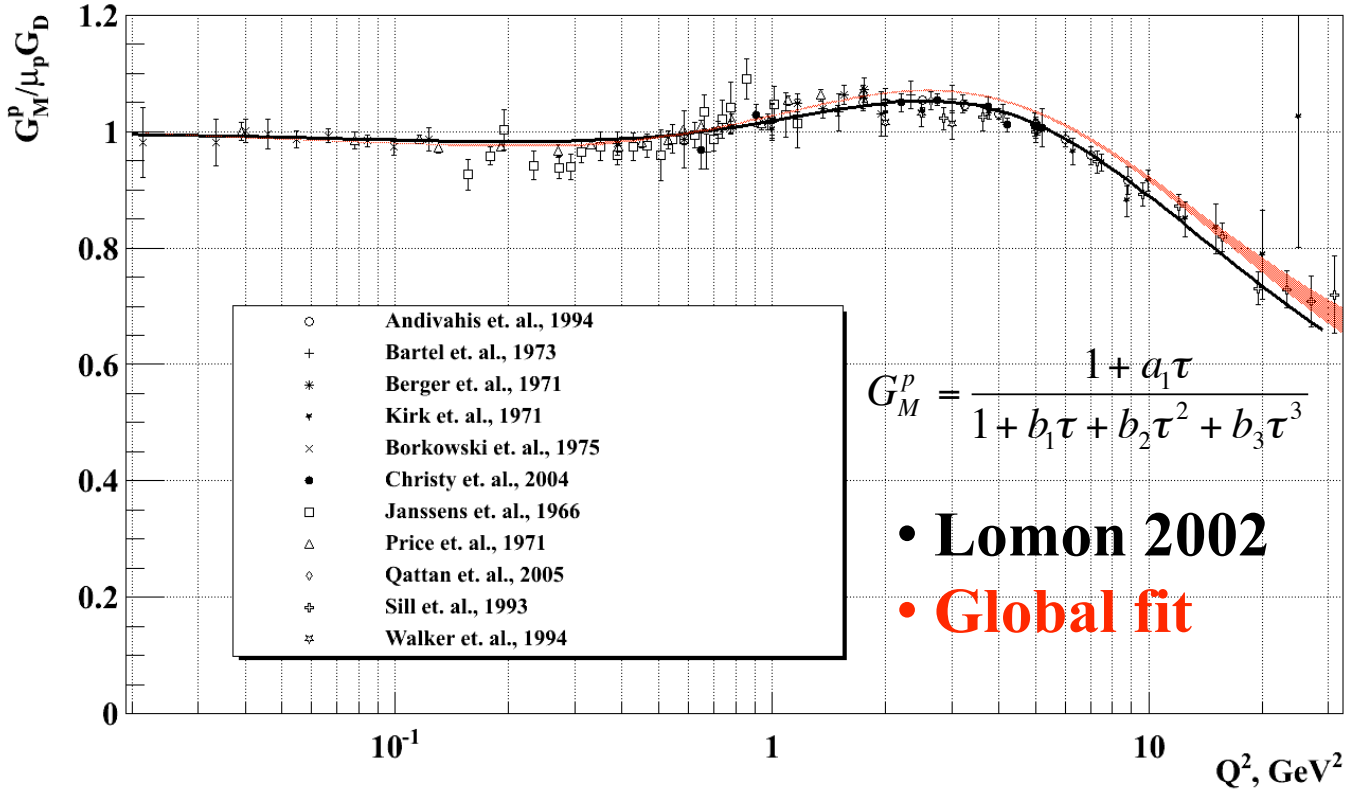
- **Theory curves:**
- Lomon 2002, 2006 (VMD)
- Belitsky 2003 (pQCD scaling)
- Guidal 2005 (GPD)
- Gross 2006, 2008 (covariant spectator model)
- de Melo 2009 (Bethe-Salpeter Amplitude)
- Cloet 2009 (Dyson-Schwinger/Faddeev/quark-diquark)

Statistical Impact of GEp-III



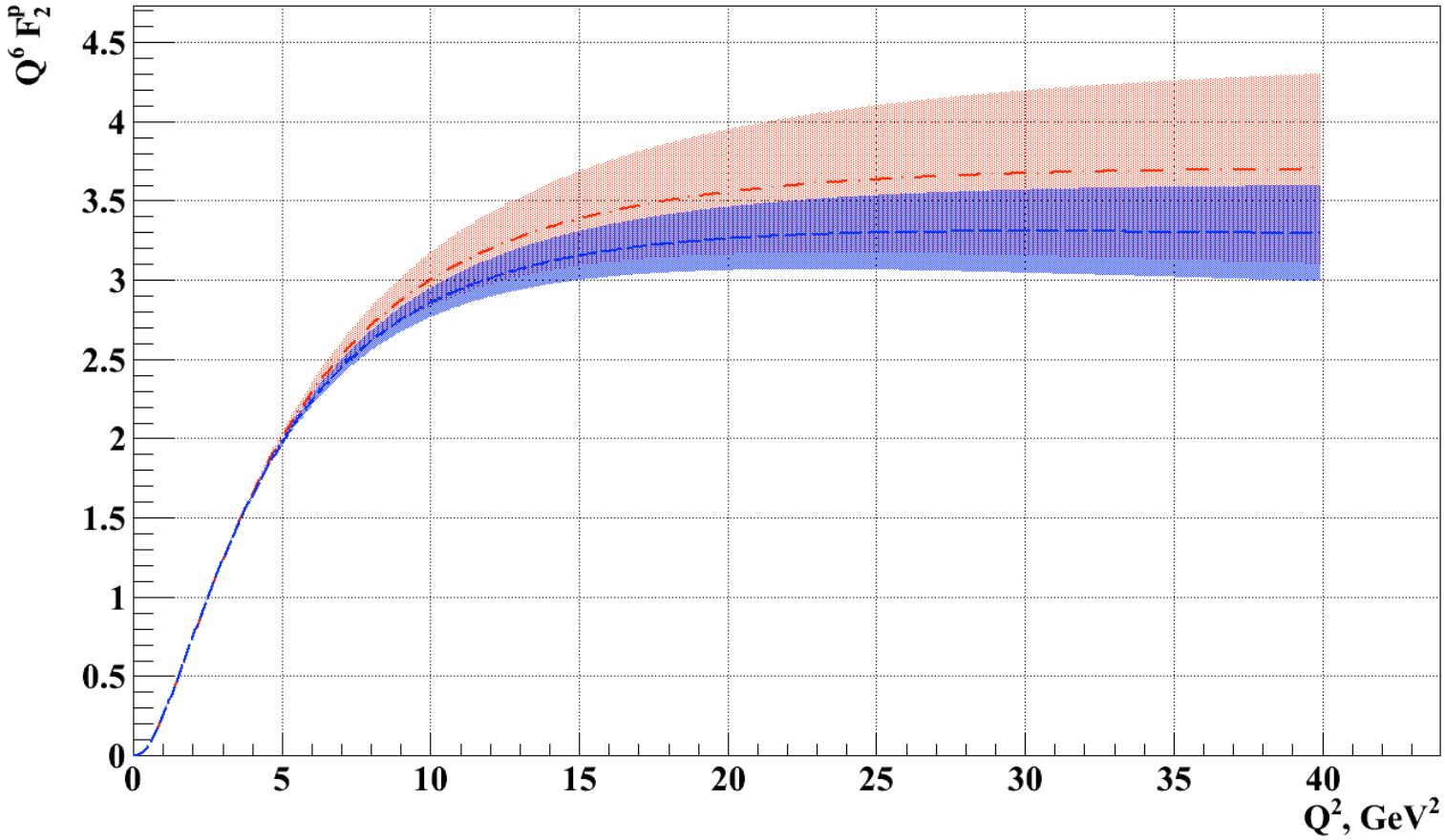
- Global fit of G_E^p and G_M^p using Kelly parametrization: PRC 70, 068202 (2004)
- Including GEp-III data pushes zero crossing from ~9 to ~12 GeV^2, reduces uncertainty in asymptotic G_E^p/G_D by a factor of more than 2.

Global Fit and G_M^p



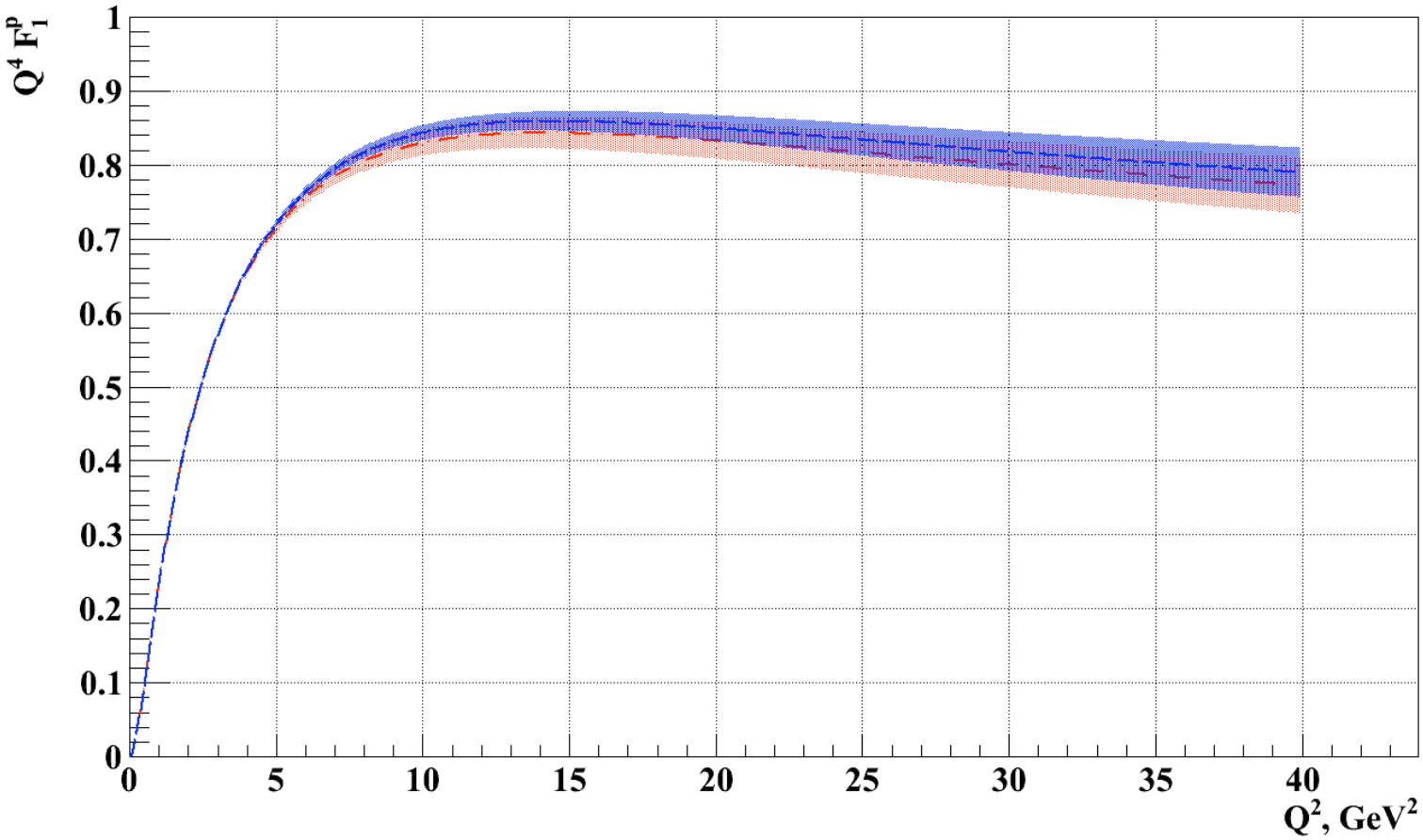
• Global analysis using constraint on R from polarization data brings a small systematic increase in G_M^p, consistent with Brash 2001 and Arrington, Melnitchouk, Tjon 2007 (TPEX effects neglected in our analysis), due to smaller G_E^{p2} contribution to σ_r.

Global Fit and F_2^p



Global fit of $Q^6F_2^p$ **before**/**after** GEp-III

Global Fit and F_1^p



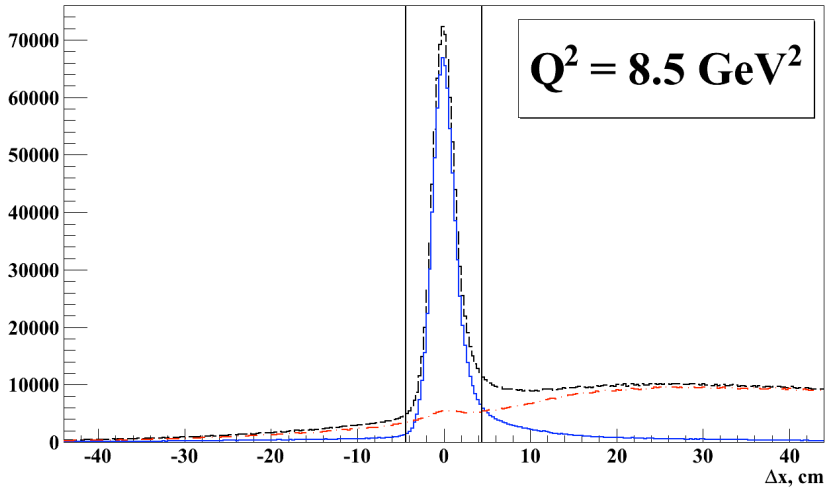
Global fit of $Q^4F_1^p$, **before**/**after** GEp-III

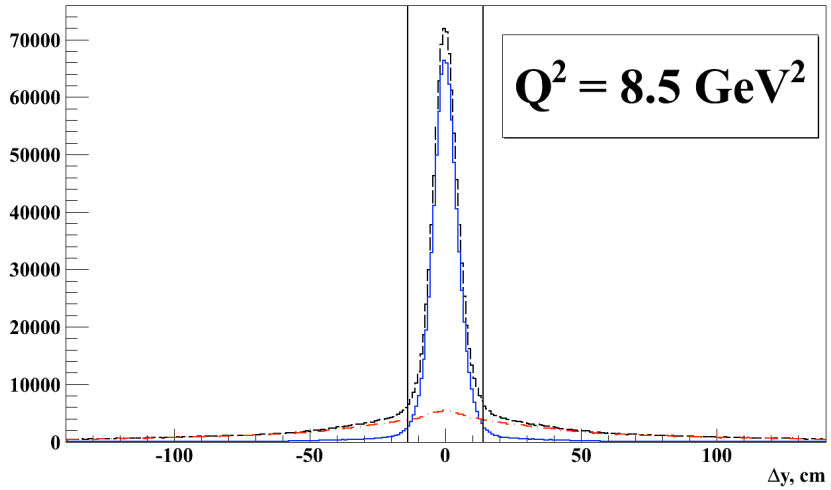
Conclusion

- GEp-III results finalized, accepted for publication in PRL
- Extended recoil polarization data to $Q^2 = 8.5$ GeV^2
- Significant new constraints on high-Q^2 behavior of F. F. models, GPD moments, transverse charge and magnetization densities, etc.
- GEp-2γ results not far behind!

Backup Slides

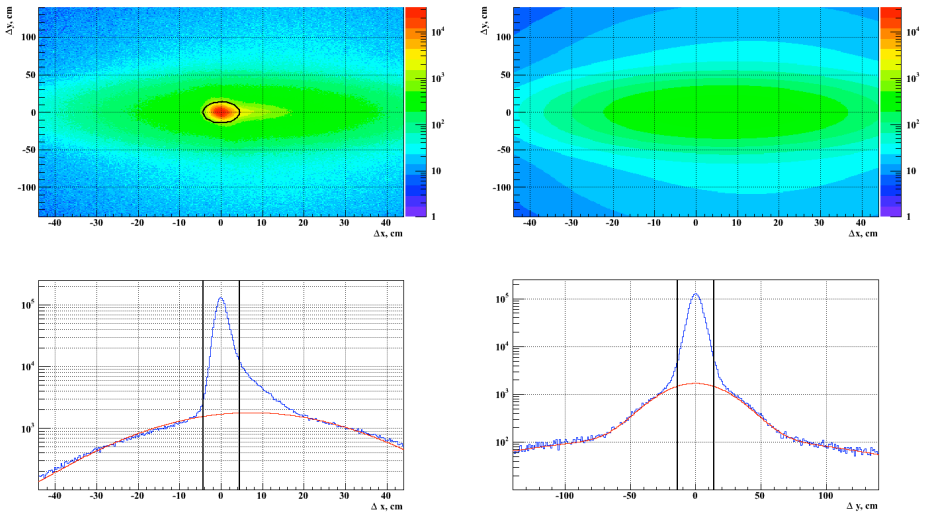
Elastic Event Selection

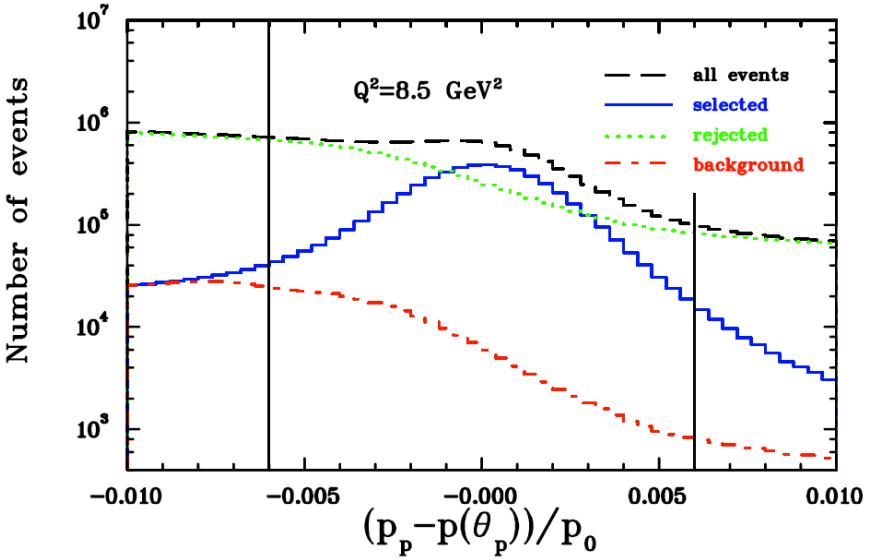




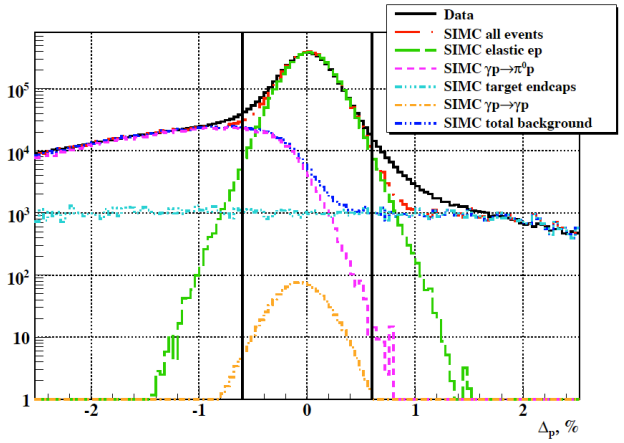
- Electron coordinates/angles + proton momentum measured with excellent resolution; use these quantities to define cut variables
- Calculate θ_e from E_e, p_p
- Calculate φ_e from φ_p (coplanarity)
- Project from vertex to BigCal, compare to measured electron coordinates
- Above: projections of horizontal (dx) and vertical (dy) coordinate differences:
  - **No cut, 3σ dp cut, 3σ dp anticut**
  - Tight dp cut rejects some small fraction of elastic events (small "bumps")

Background Estimation

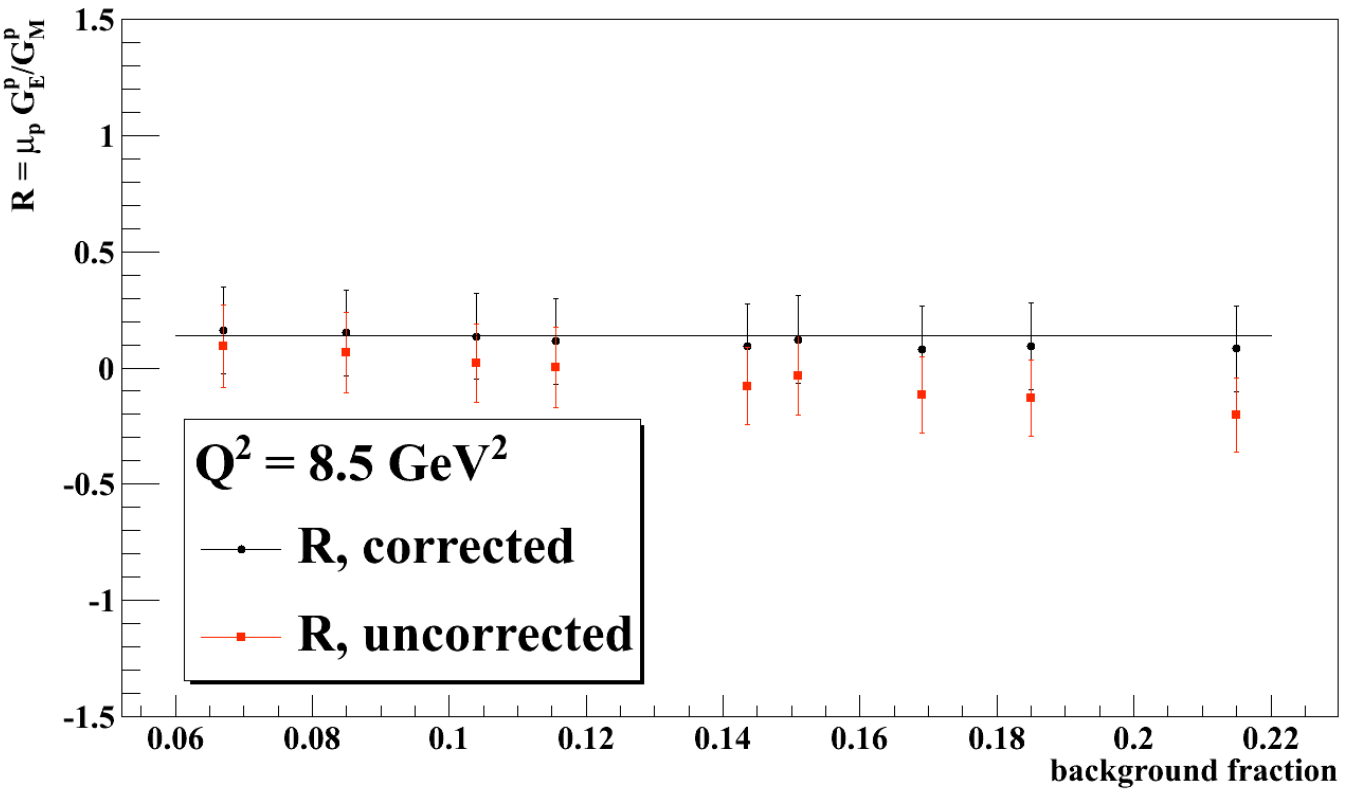




- Estimate background directly from data by extrapolating dx, dy distribution under the peak (above):
  - Data, fitted background and projections
- Compare data (top right) and MC (bottom right) for dp



Background Subtraction



$$f = \frac{N_{inel.}}{N_{el.} + N_{inel.}}$$

$$P_{obs} = (1 - f)P_{el} + fP_{inel}$$

$$P_{el} = \frac{P_{obs} - fP_{inel}}{(1 - f)}$$

- Background and signal polarizations differ, F. F. ratio decreases as elastic cuts are relaxed
- Stability of background-subtracted F. F. ratio w.r.t. cut variations including more background validates background subtraction method

Extraction of Polarization Observables

$$N^{\pm}(\vartheta,\varphi) = N_0^{\pm}\frac{\varepsilon(\vartheta)}{2\pi}\begin{bmatrix}1+\left(c_1(\vartheta)\pm A_y(\vartheta)P_y^{fpp}\right)\cos\varphi\\ +\left(s_1(\vartheta)\mp A_y(\vartheta)P_x^{fpp}\right)\sin\varphi+\\ c_2(\vartheta)\cos(2\varphi)+s_2(\vartheta)\sin(2\varphi)+\ldots\end{bmatrix}$$

$$f_{\pm} = \frac{N^{\pm}(\vartheta,\varphi)}{N_0^{\pm}}$$

$$f_+ + f_- = \frac{\varepsilon(\vartheta)}{\pi}\begin{bmatrix}1+c_1\cos\varphi+s_1\sin\varphi+\\ c_2\cos(2\varphi)+s_2\sin(2\varphi)+\ldots\end{bmatrix}$$

$$f_+ - f_- = \frac{\varepsilon(\vartheta)A_y(\vartheta)}{\pi}\left[P_y^{fpp}\cos\varphi - P_x^{fpp}\sin\varphi\right]$$

Angular distribution and azimuthal asymmetry definitions

Spin Precession, I

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

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

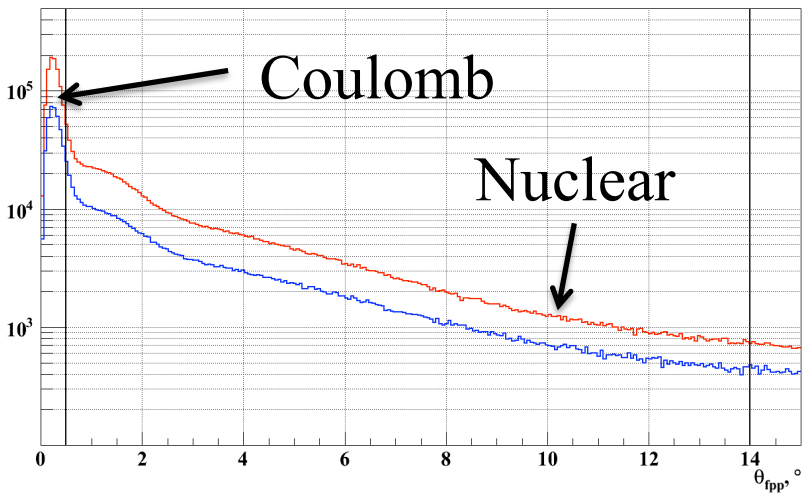
$$\left(\frac{d\vec{S}}{dt}\right)_{comoving} \xrightarrow{B_{\parallel}=0} \gamma\left(\frac{g}{2}-1\right)\frac{e}{m\gamma}\vec{S}\times\vec{B}$$

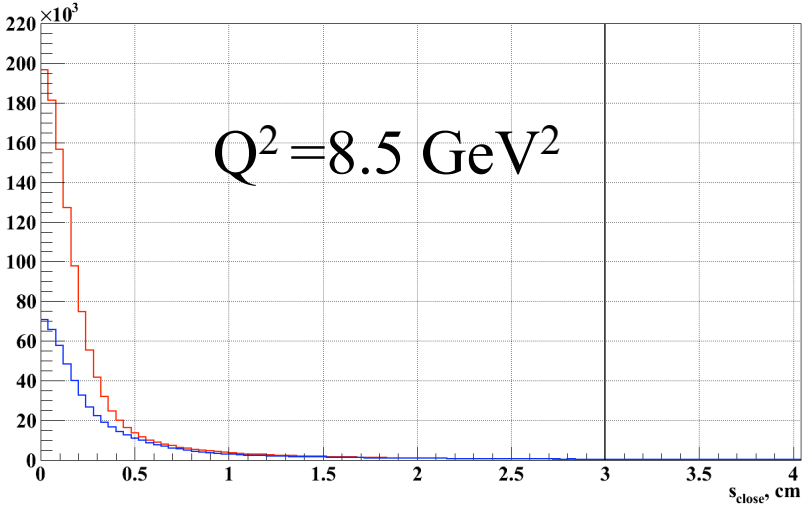
$$\chi = \gamma\kappa\theta_{bend}$$

Q^2, GeV^2	p_0, GeV/c	χ_θ, °
2.5	2.0676	108.5
5.2	3.5887	177.2
6.7	4.4644	217.9
8.5	5.4070	262.2

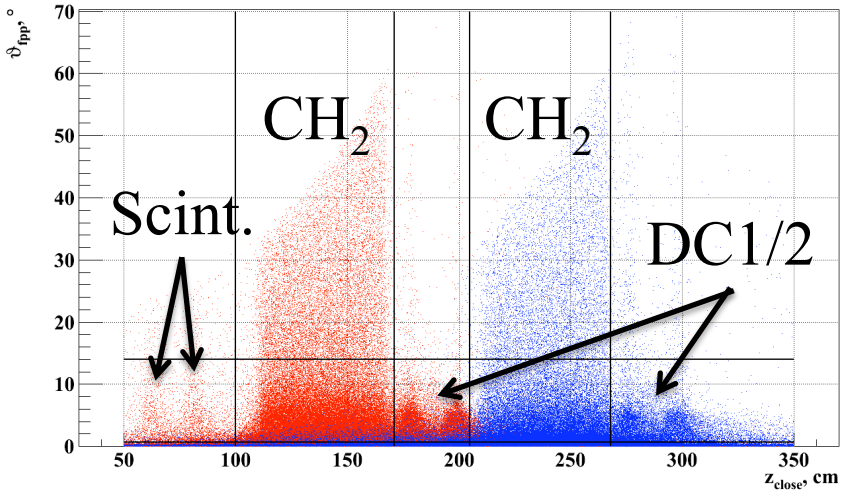
- BMT equation (1959): relativistic spin precession in a magnetic field
- χ = precession angle relative to velocity in a constant, uniform magnetic field
- Precession angles corresponding to HMS 25° central bend for this experiment shown in table
- Unique spin rotation for each event, calculated using HMS COSY model

FPP Reconstruction



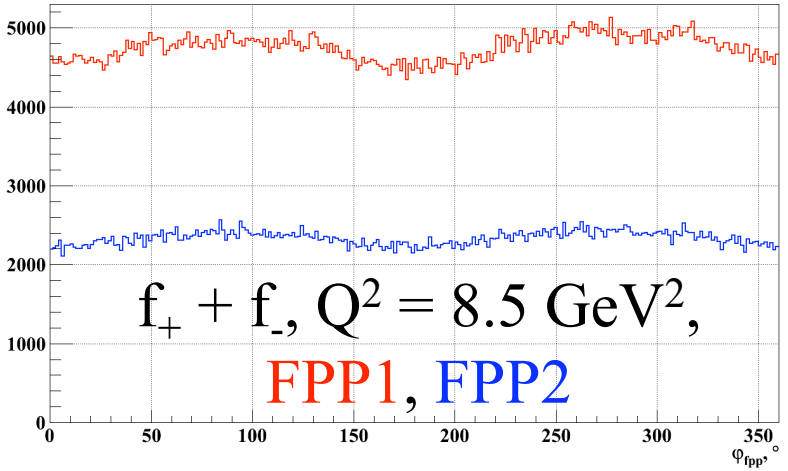


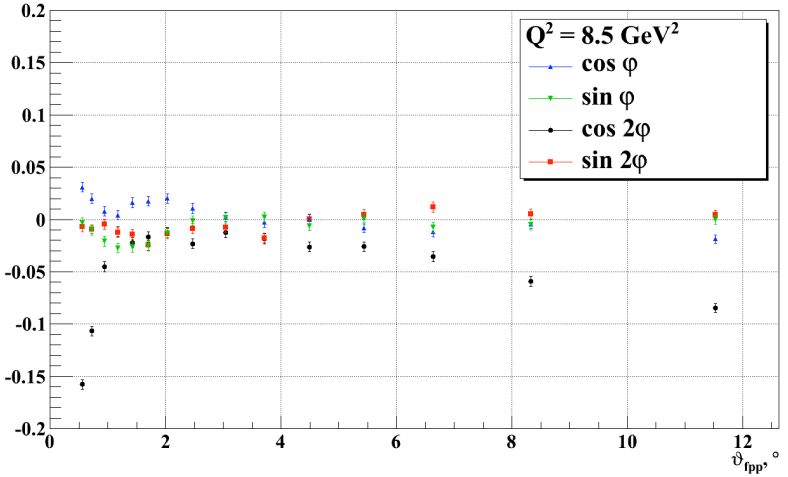
- FPP1 (FPP2) event distributions:
  - Polar angle θ (top left)
  - Closest approach distance s_{close} (top right)
  - θ vs point of closest approach z_{close} (bottom right)
- Black lines represent analysis cuts



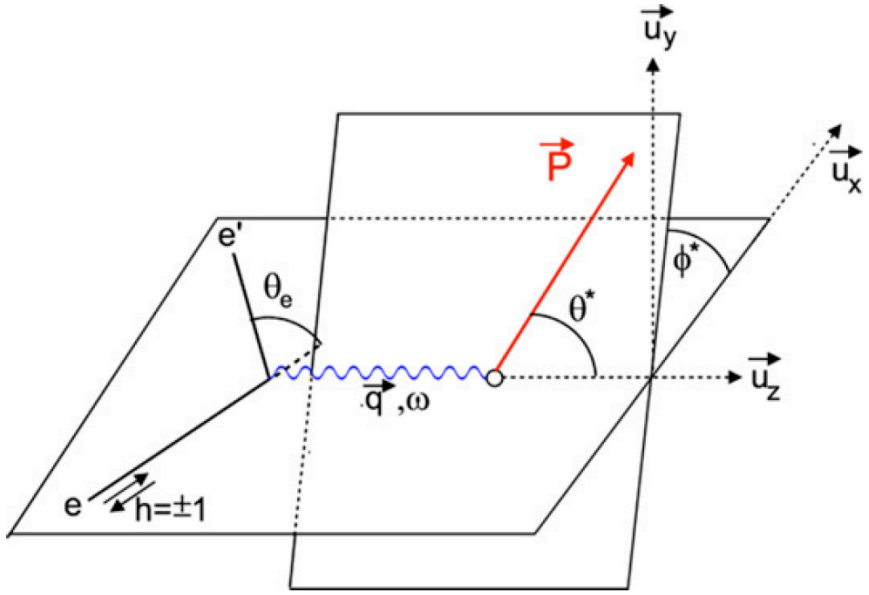
False Asymmetries

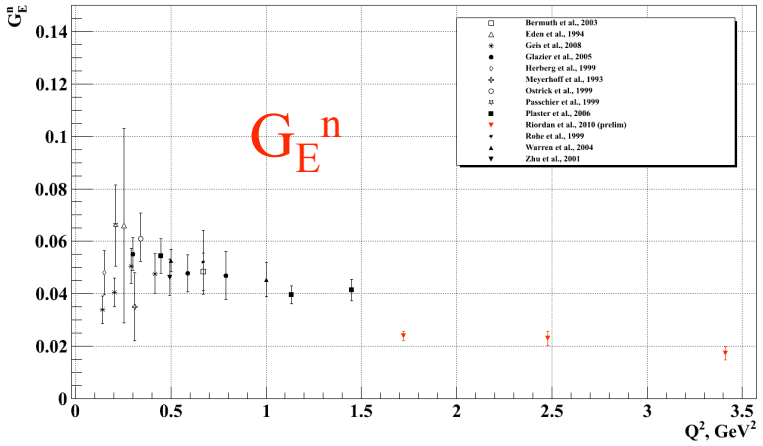
- Helicity-independent false/ instrumental asymmetries caused by:
  - FPP acceptance/efficiency
  - φ misreconstruction:
    - Misalignment (1φ)
    - xy resolution asymmetry (2φ)
- θ-dependent (bottom right)
- Cancelled by helicity reversal to first order
- Second-order effects small
- ***Measured*** using sum distribution and ***corrected*** in analysis





Polarized Target Asymmetry and G_E^n



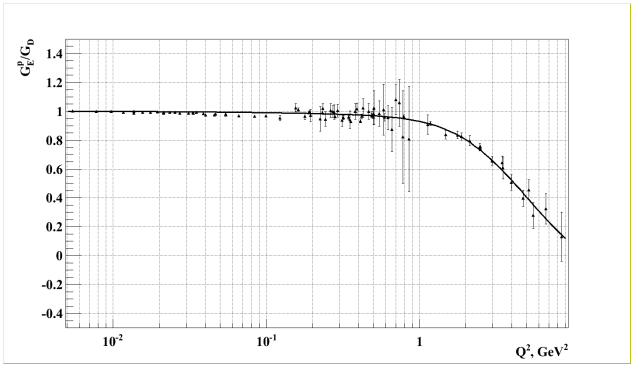


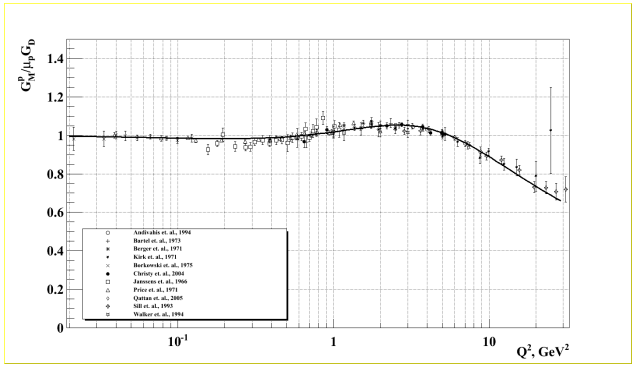
$$A_{phys} = -\frac{2\sqrt{\tau(1+\tau)}\tan\frac{\theta_e}{2}}{\frac{G_E^2}{G_M^2}+\frac{\tau}{\epsilon}}\left[\sin\theta^*\cos\phi^*\frac{G_E}{G_M} + \sqrt{\tau\left[1+(1+\tau)\tan^2\frac{\theta_e}{2}\right]}\cos\theta^*\right]$$

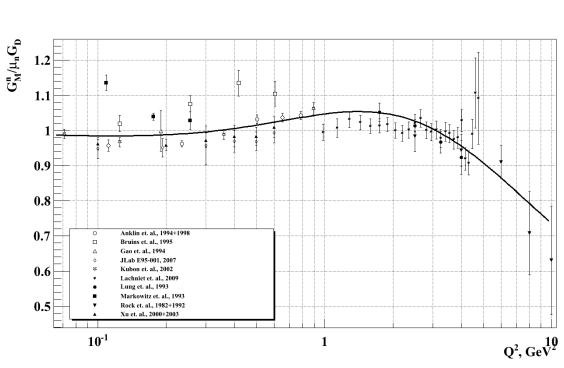
- Polarized beam on polarized target
- Beam helicity asymmetry sensitive to G_E/G_M
- Maximal sensitivity for target polarization perp. to q in scattering plane
- Nearly all G_E^n data obtained from:

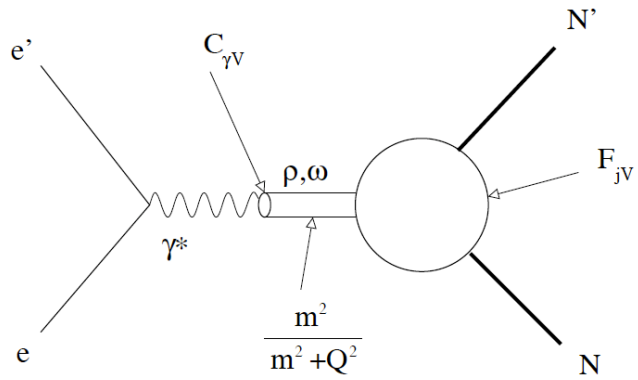
$$^3\overrightarrow{He}(\vec{e},e'n),\ ^3\overrightarrow{He}(\vec{e},e'),\ ^2H(\vec{e},e'\vec{n})$$

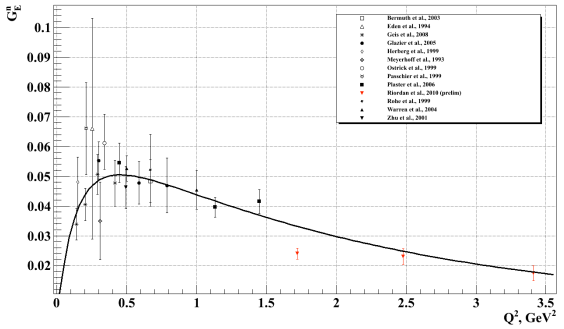
VMD





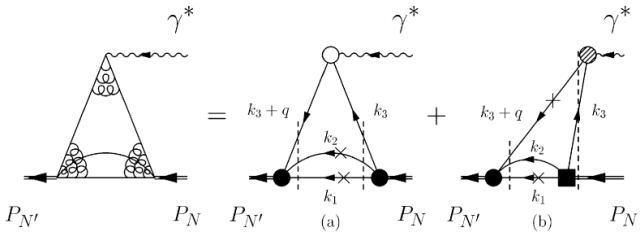




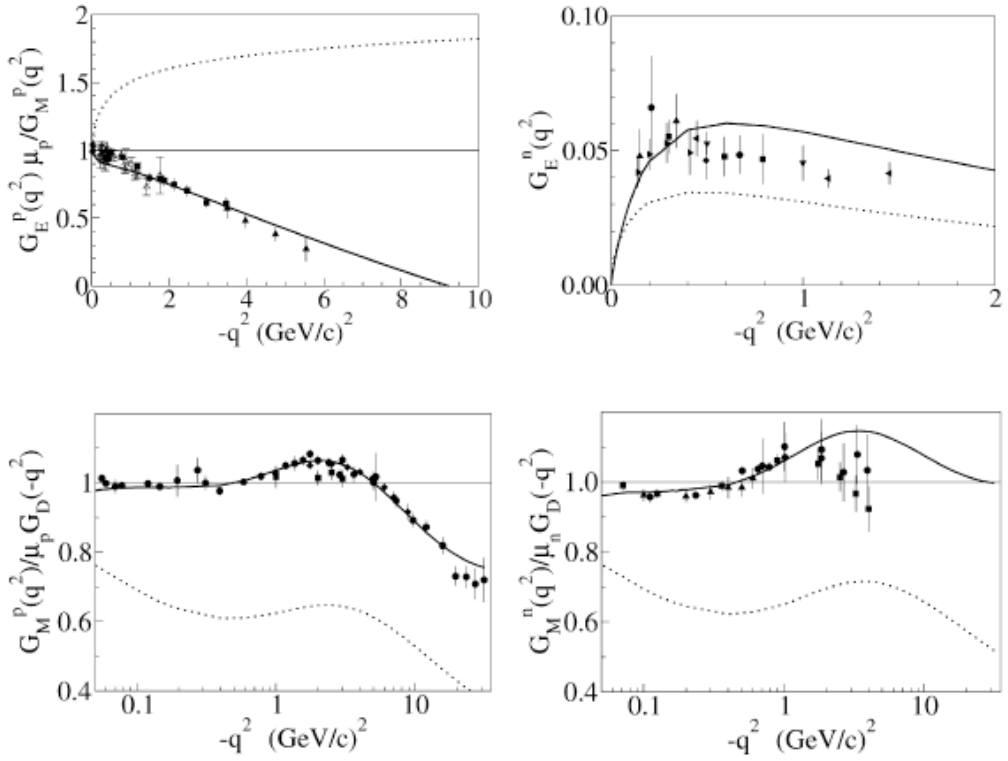


- Fits by Lomon in extended Gari-Krumpelmann model, nucl-th/0609020
- ρ, ω, ϕ, ρ', ω' mesons + "direct coupling" enforces pQCD asymptotic behavior

Bethe-Salpeter Amplitude

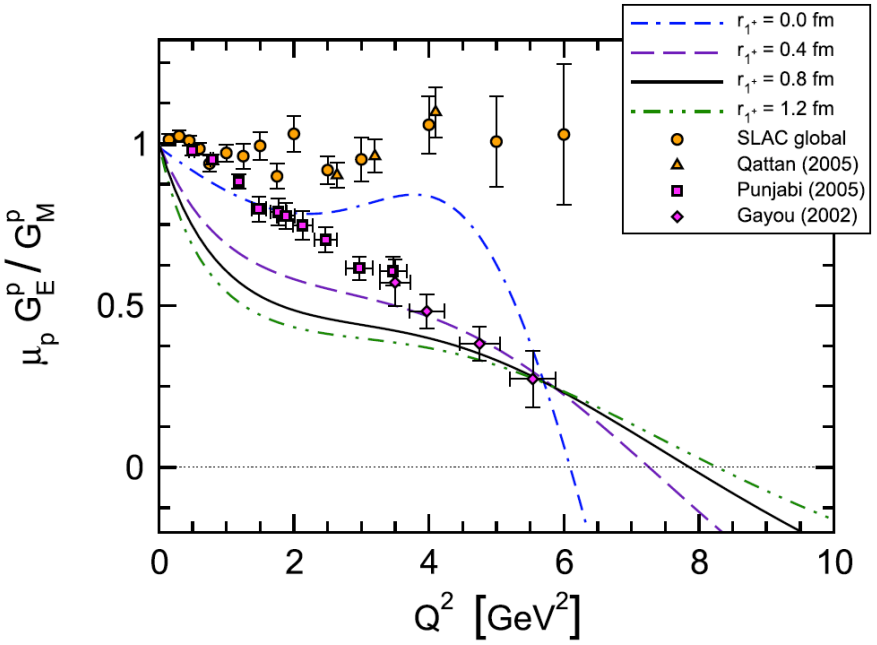


Combined Ansatz for nucleon Bethe-Salpeter amplitude and microscopic VMD model, consider valence and non-valence components of the nucleon state in light-front dynamics



de Melo et al. PLB 671, 153 (2009)

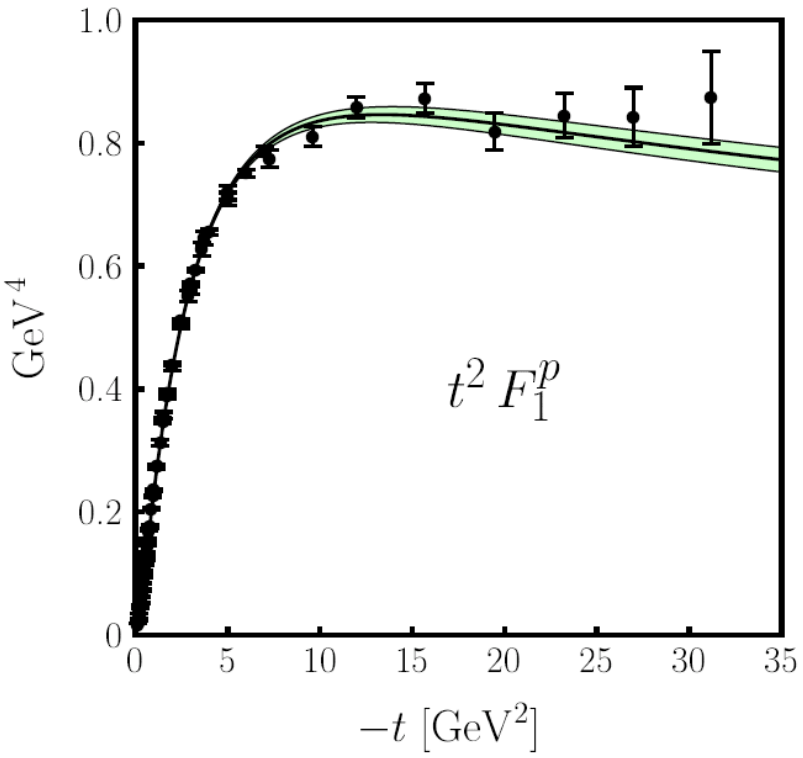
Dyson-Schwinger/Faddeev/q(qq)

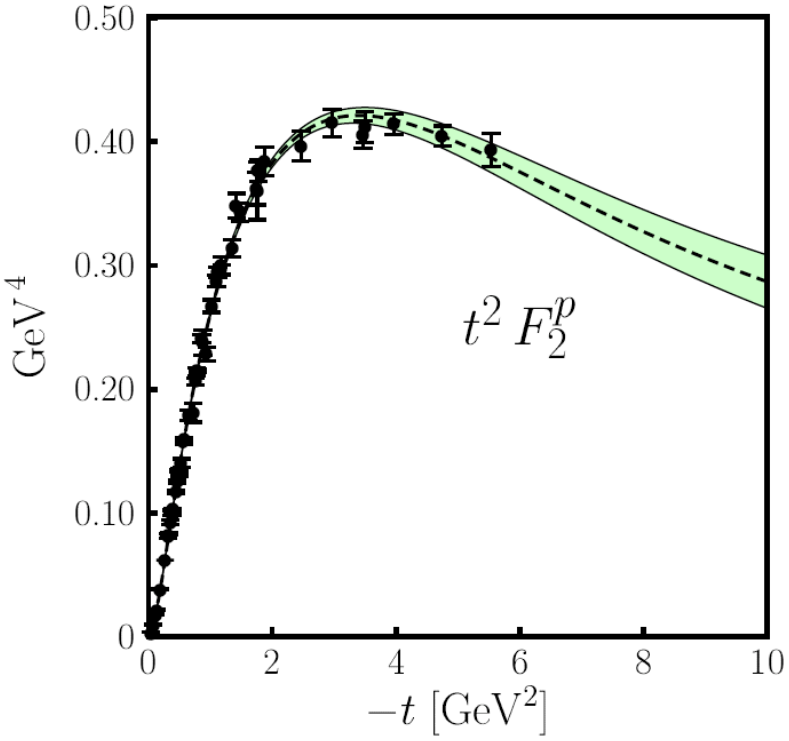


Dressed-quark core contribution to R_p for different diquark radii

- Cloet et al., Few Body Systems, 46, 1 (2009)
- Dressed quarks are fundamental degrees of freedom
- diquark correlations
- Solution of Poincare-covariant Faddeev equations based on rainbow-ladder truncation of DSEs of QCD
- photon-nucleon vertex depends on a single parameter: diquark charge radius
- G_{Ep} and G_{En} both possess a zero

GPDs, I





$$\int_{-1}^{1} dx H^q(x,\xi,t) = F_1^q(t)$$

$$\int_{-1}^{1} dx E^q(x,\xi,t) = F_2^q(t)$$

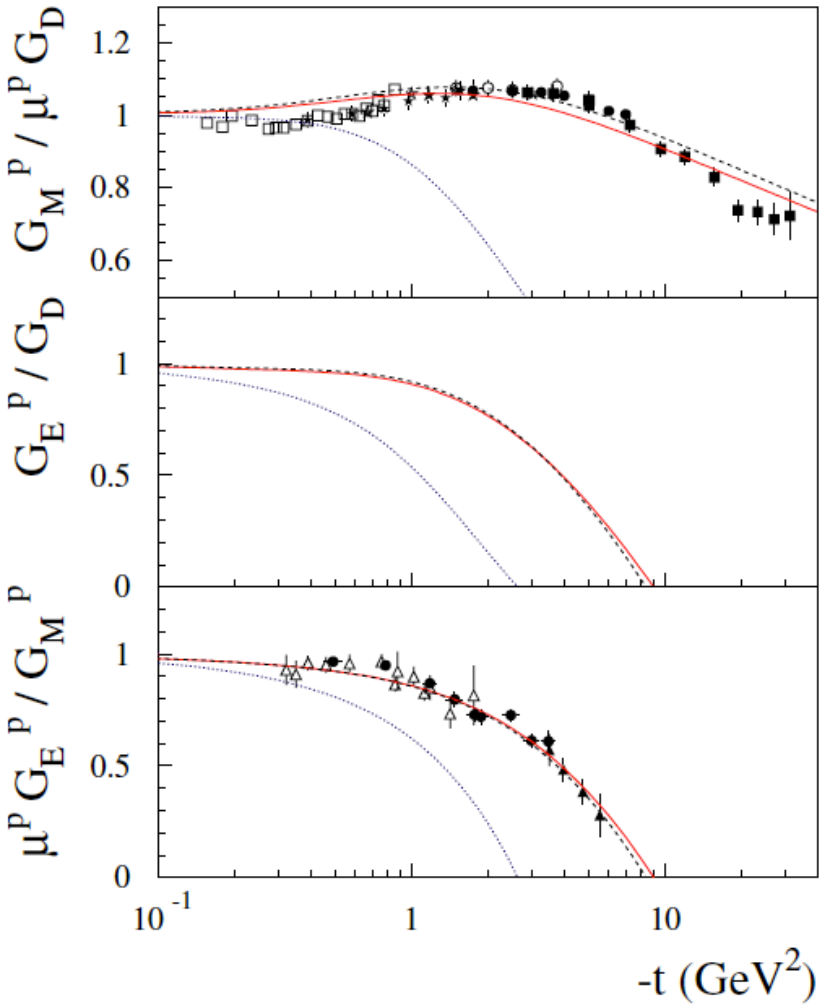
- Form factors constrain GPDs through sum rules: 0th moments of vector (H) and tensor(E) GPDs equal e.m. form factors
- Above: Diehl et al; EPJ C, 39, 1 (2005)

GPDs, II

- Guidal et al., PRD 72, 054013 2005: Modified Regge parametrization of valence quark GPDs
- Three-parameter fit to nucleon form factor data
- Constraint on E from precise F_{2p} data allowed evaluation of Ji sum rule:

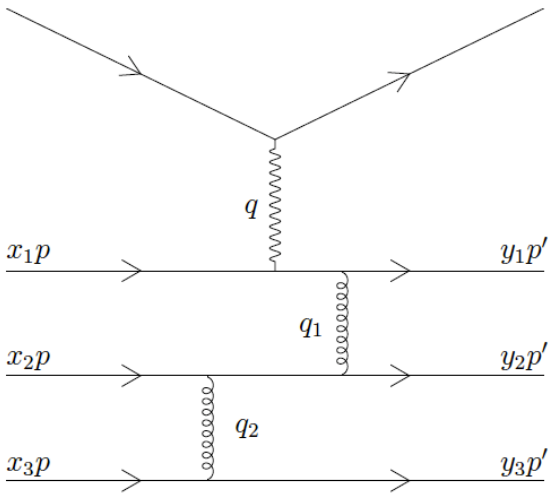
$$2J^q = \int_{-1}^{1} dx x\{H^q(x,0,0) + E^q(x,0,0)\},$$

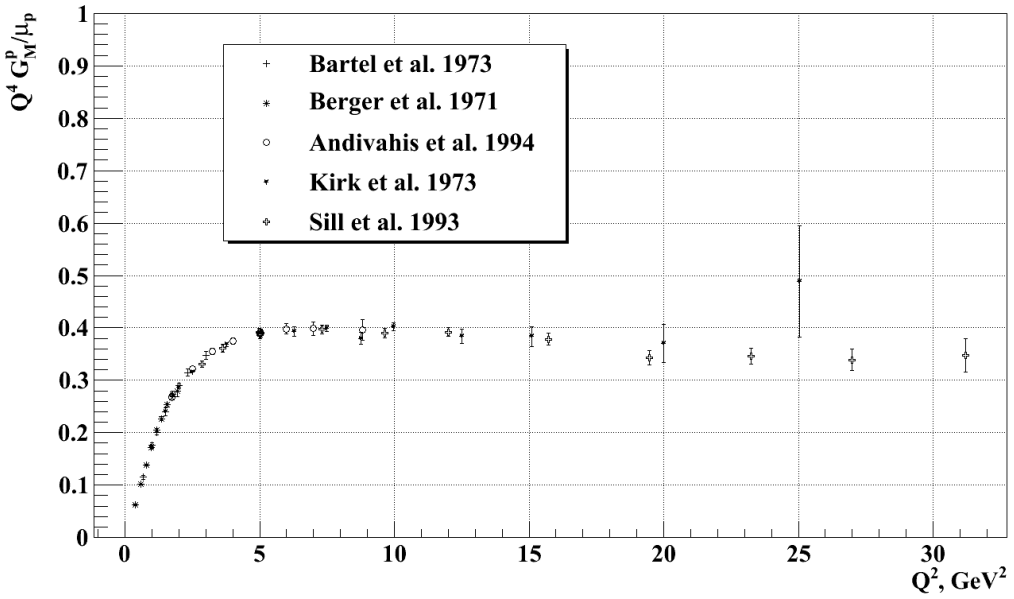
	M_2^q (MRST2002)	$2J^q$ (R2 model)	$2J^q$ (lattice [40])
u	0.37	0.58	0.74 ± 0.12
d	0.20	-0.06	-0.08 ± 0.08
s	0.04	0.04	
$u + d + s$	0.61	0.56	0.66 ± 0.14



pQCD, I

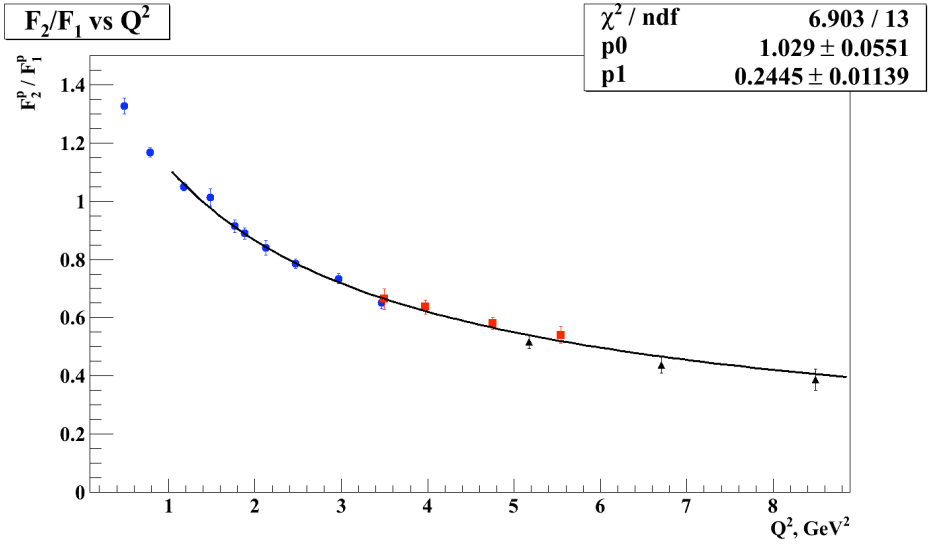
- Based on dimensional scaling laws for high-Q^2 exclusive reactions:
  - Brodsky, Farrar, PRD 11, 1309 (1975)
  - Brodsky, Lepage PRL 43, 545 (1979)
- Expect $F_{1p} \sim 1/Q^4$, $F_{2p} \sim 1/Q^6$, as $Q^2 \rightarrow \infty$

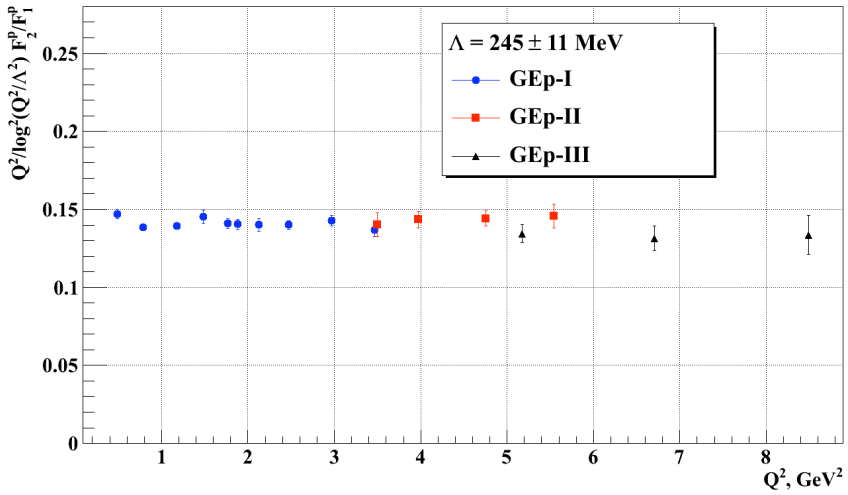




Approximately satisfied by G_{Mp} starting at $Q^2 \approx$ 5-10 GeV^2

pQCD, II



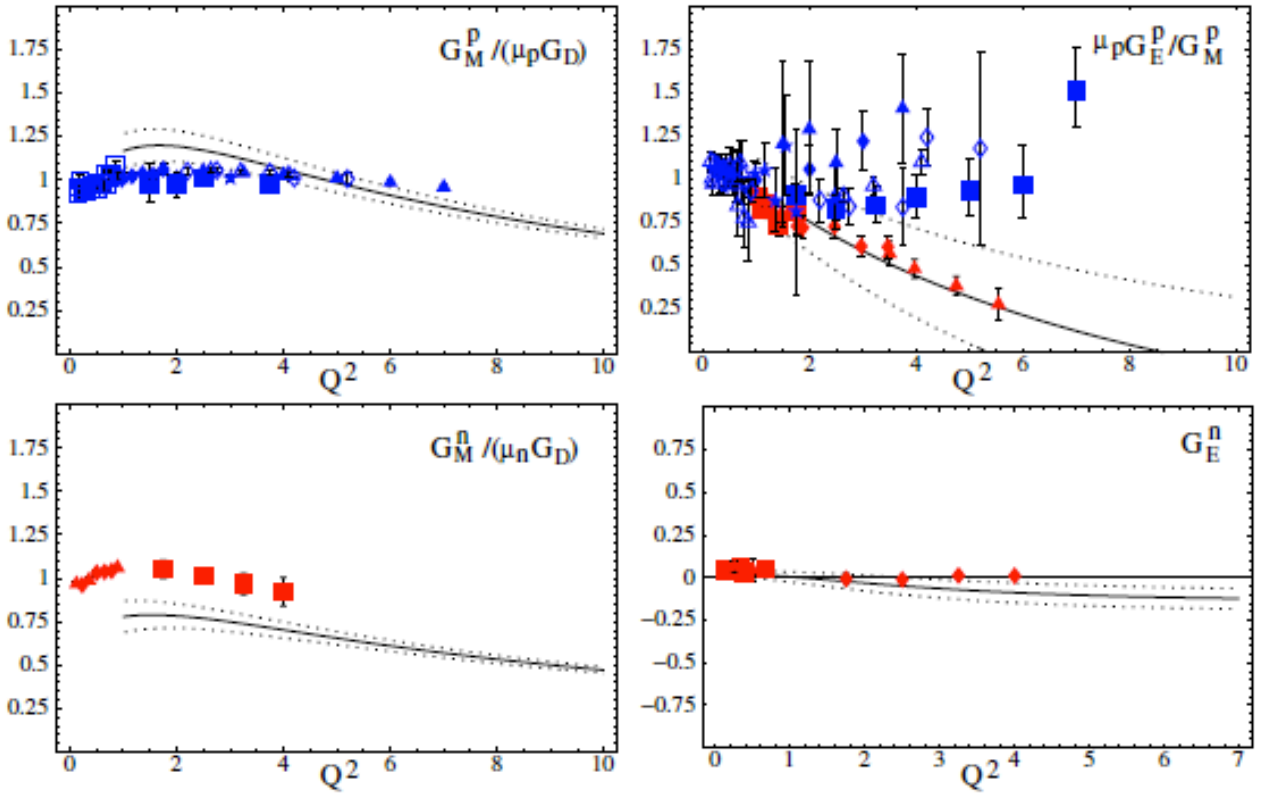


- Belitsky, Ji, Yuan, PRL 91, 092003 (2003)
- pQCD analysis of Pauli form factor F_2
- Subleading-twist component of light cone nucleon D. A. leads to logarithmic modification of asymptotic scaling of F_2 relative to F_1

- Proton data for the ***ratio*** F_2/F_1 well described by this modified scaling
- Necessary, but not sufficient condition for validity of pQCD form factor description
-

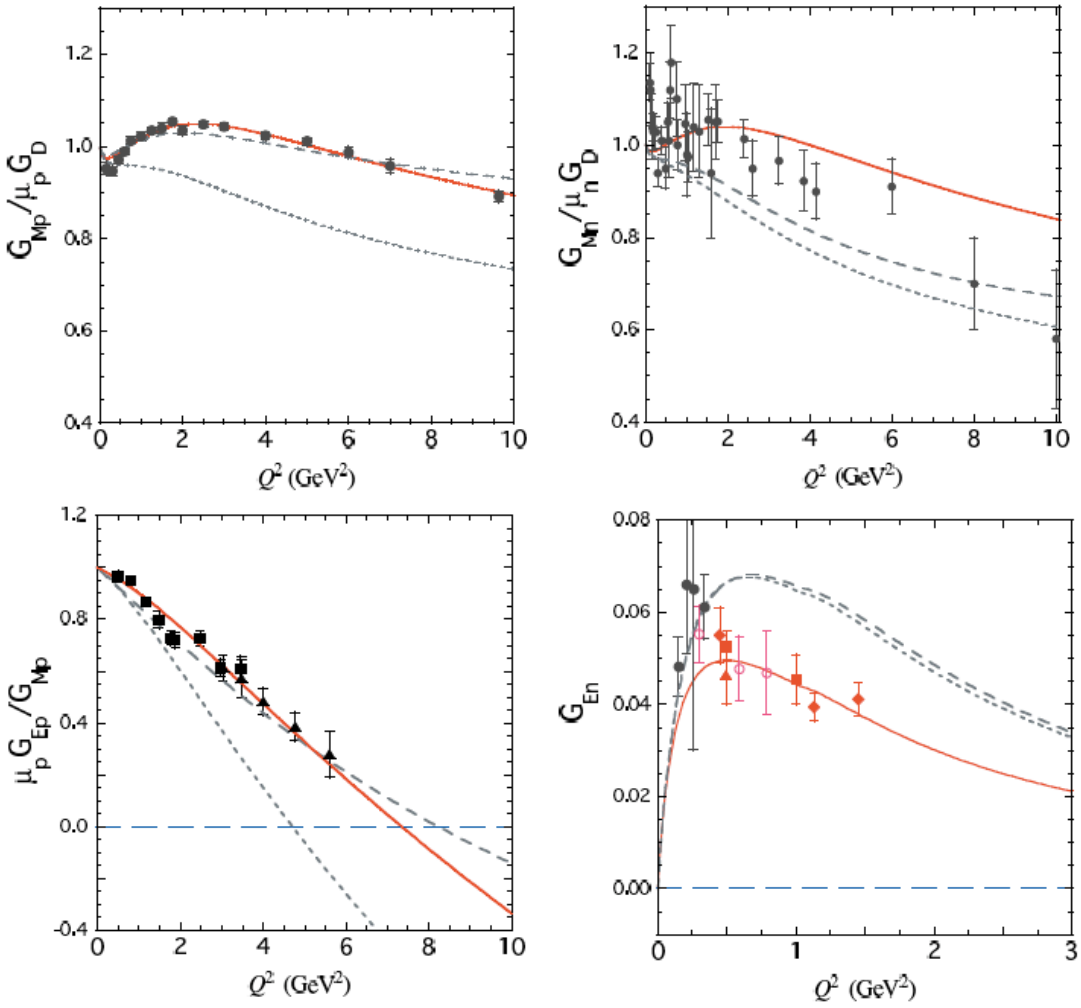
$$Q^2 \frac{F_2}{F_1} \propto \ln^2\left(\frac{Q^2}{\Lambda^2}\right)$$

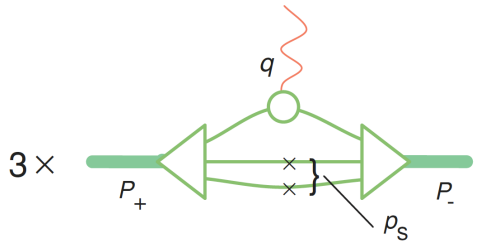
pQCD, III



Light cone QCD sum rule calculation of nucleon form factors: Braun, Lenz, and Wittmann, PRD 73, 094019 (2006)

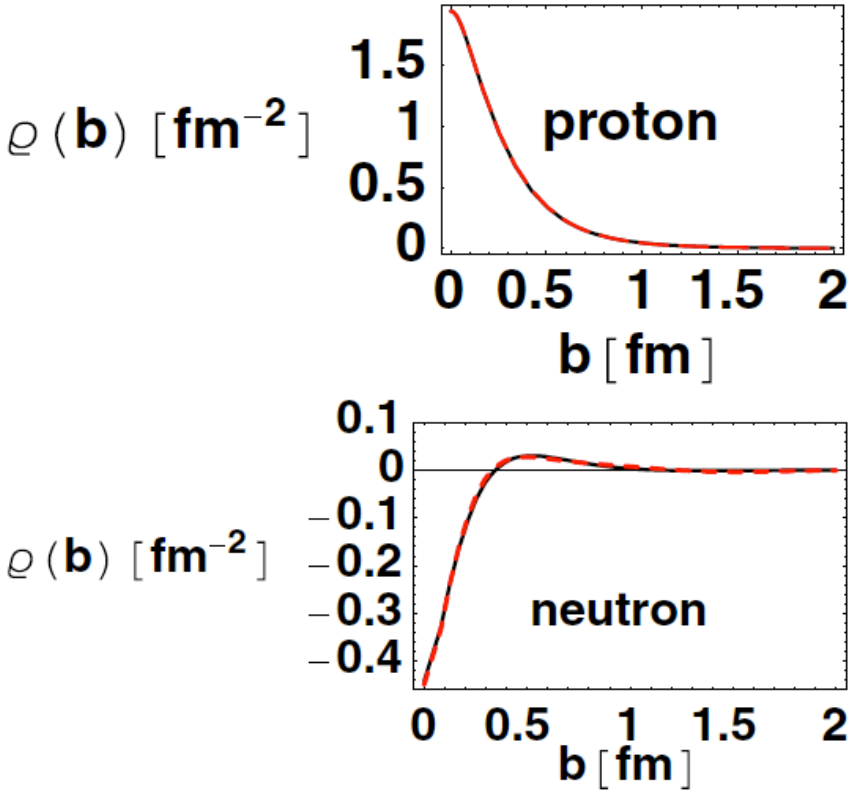
Covariant Spectator Model





- Gross and Agbakpe, PRC 73, 015203 (2006)
- Model nucleon as bound state of three dressed, valence constituent quarks
- Covariant spectator "diquark" on shell

Transverse Densities



• Burkardt, Int. J. Mod. Phys. A 18, 173 (2003)—GPDs related to impact-parameter distributions:

$$q(x,\mathbf{b}) = \int \frac{d^2q}{(2\pi)^2} e^{i\mathbf{q}\cdot\mathbf{b}} H_q(x, t=-\mathbf{q}^2),$$

• Miller, PRL 99, 112001 (2007)—model-independent transverse charge density from 2D Fourier transform of F_{1p}

• Miller, Piasetzky, Ron, PRL 101, 082002 (2008)—model-independent magnetization density from F_{2p}

$$\rho(b) \equiv \sum_q e_q \int dx q(x,\mathbf{b}) = \int \frac{d^2q}{(2\pi)^2} F_1(Q^2=\mathbf{q}^2) e^{i\mathbf{q}\cdot\mathbf{b}}.$$

$$\rho_M(b) = \int \frac{d^2q}{(2\pi)^2} F_2(t=-\mathbf{q}^2) e^{i\mathbf{q}\cdot\mathbf{b}}.$$