G_{Ep}/G_{Mp} with an 11 GeV Electron Beam in Hall C

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and the GEp-IV Collaboration

(Update to E12-09-101)

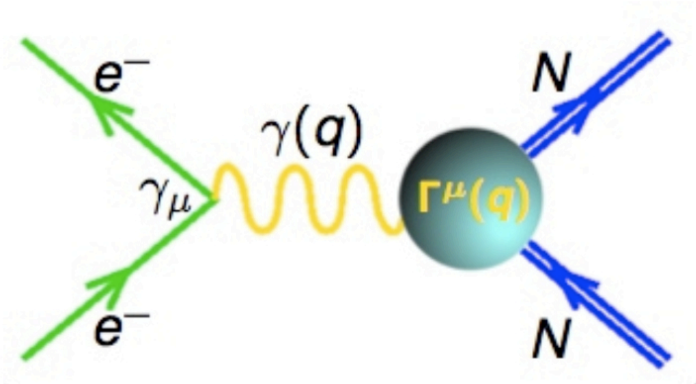
Elastic EM Form Factors

- Fundamental to our understanding of nucleon structure
  - At low Q^2 (larger distance), they shed information on the pion cloud.
  - At intermediate/large Q^2 (shorter distance), they contain information on the quark and gluon structure

- At JLab energies, we gain knowledge about the non-perturbative structure of the nucleon

- Together with other observables (in DIS, SIDIS, DVCS, RCS, etc.), we develop a greater understanding of the nucleon's rich internal structure

Elastic *ep* Scattering: Form Factors



(Born Term)

Nucleon current operator (Dirac & Pauli)

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

$$F_1^p(0) = 1 \qquad F_1^n(0) = 0$$
$$F_2^p(0) = \kappa_p \qquad F_2^n(0) = \kappa_n$$

$F_1(Q^2)$: non spin-flip Dirac form factor

$F_2(Q^2)$: spin-flip Pauli form factor

Electric form factor: $G_E(Q^2) = F_1(Q^2) - \tau \cdot F_2(Q^2)$

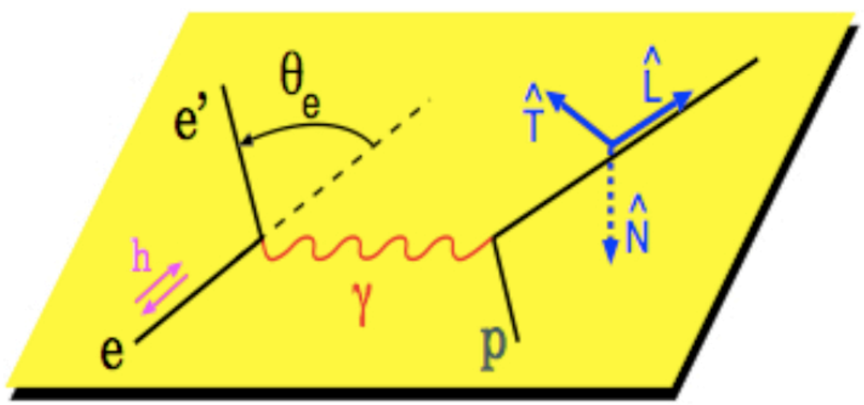
Magnetic form factor: $G_M(Q^2) = F_1(Q^2) + F_2(Q^2)$

where $\tau = \frac{Q^2}{4M_p^2}$

Details of nucleon substructure are in the Q^2 evolution of *$F_1(Q^2)$* and *$F_2(Q^2)$*

Recoil Polarization Method

Elastic $\vec{e}p \rightarrow e\vec{p}$ (A.I. Akheizer and M.P. Rekalo, Sov. J. Part. Phys. 3 (1974) 277; and Arnold, Carlson, and Gross, Phys. Rev. C23 (1981) 363):



$$P_n = 0$$

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

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

$$I_0 = G_{Ep}^2 + \tau \cdot G_{Mp}^2 \left[1 + 1(1+\tau)\tan^2\frac{\vartheta_e}{2}\right]$$

Relative Measurement:

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

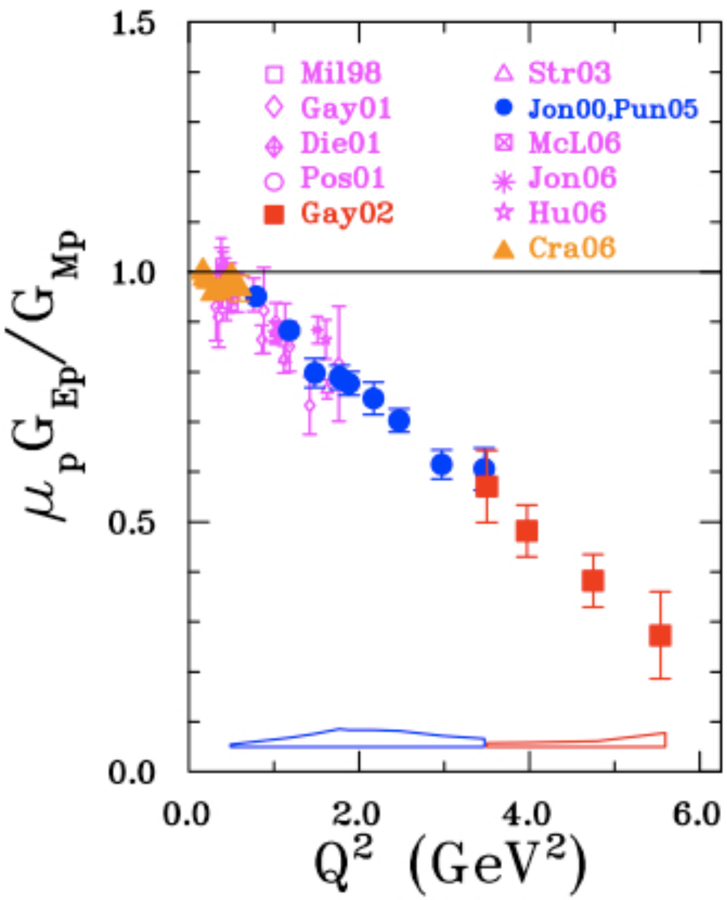
A measurement of G_{Ep}/G_{Mp} allows a direct determination of F_{2p}/F_{1p}:

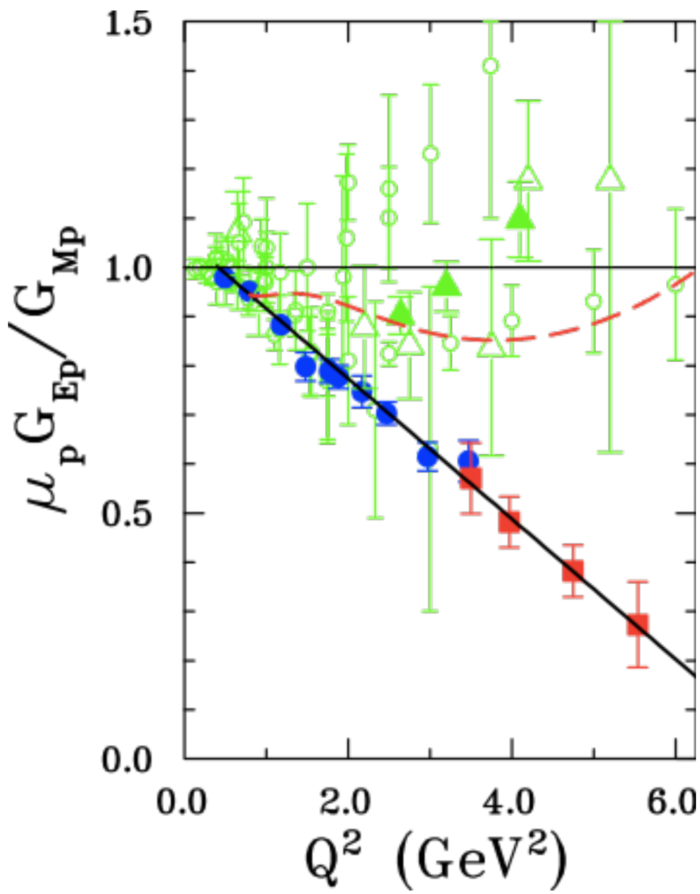
$$\boxed{\frac{F_{2p}}{F_{1p}} = \left(1 - \frac{G_{Ep}}{G_{Mp}}\right) \Big/ \left(\tau + \frac{G_{Ep}}{G_{Mp}}\right)}$$

Recoil Polarization Measurements

M.K. Jones et al., Phys.Rev.Lett., 84 (2000) 1398 (G_{Ep}-I)
O. Gayou et al., Phys.Rev.Lett., 88 (2002) 092301. (G_{Ep}-II)

(935 total citations!!!)

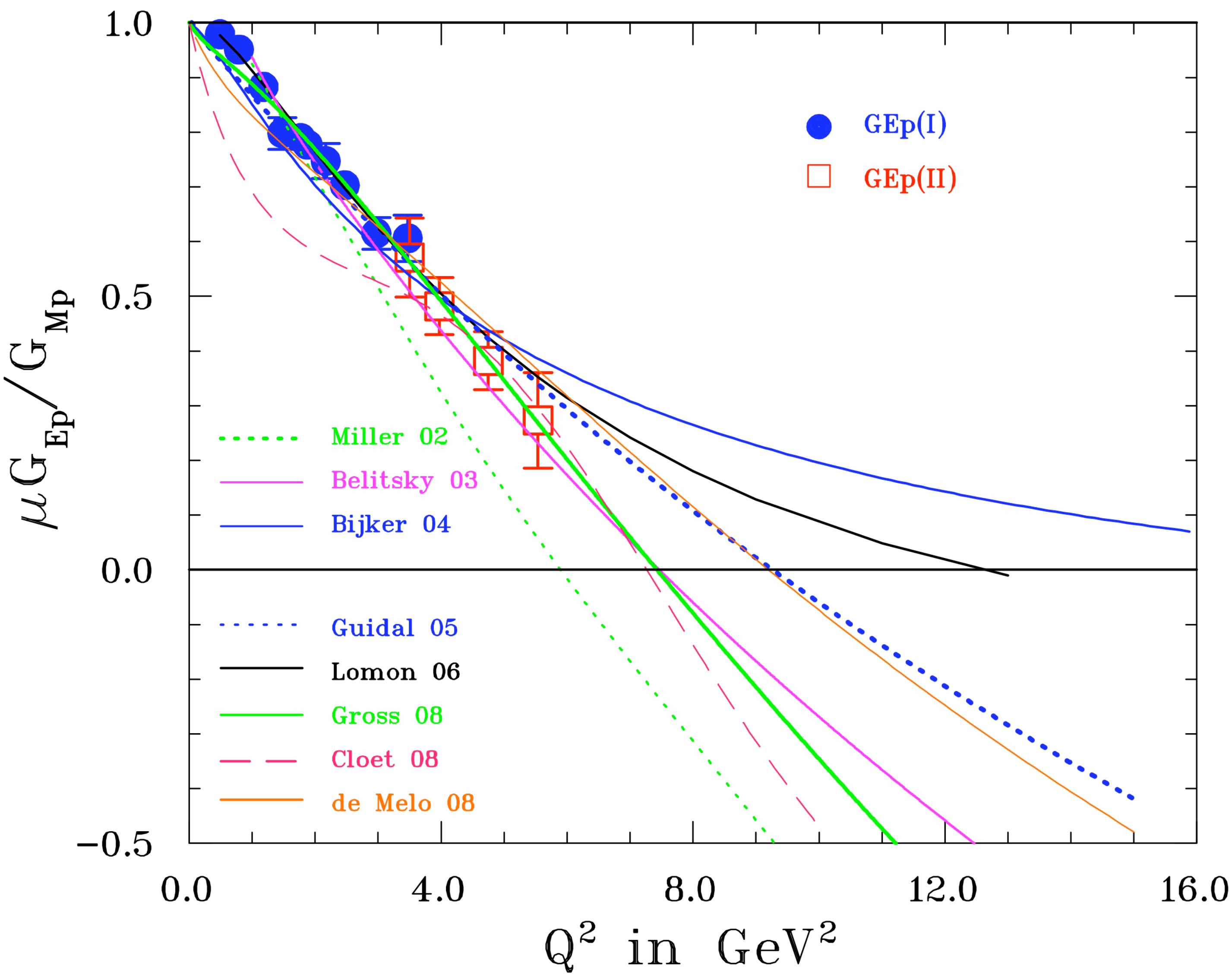




Theoretical Progress

- VMD-based models
  - Describe all four nucleon FF's well
  - Tend to favour ratio reaching a constant value at intermediate Q^2
- rCQM
  - Show the importance of relativistic dymamics, and allow to separate dynamical from nucleon structure effects
- pQCD-inspired models
  - Predict logarithmic scaling behaviour of F_2/F_1 at intermediate Q^2 (Belitsky and Ji) -> related to quark OAM
- GPD-inspired models
  - Show a connection with OAM of the quarks in the nucleon
  - FF's provide important constraints on GPD's
  - Behaviour of G_{Ep}/G_{Mp} at intermediate Q^2 related to u/d ratio at small distances (Miller)
- Lattice QCD Models
  - Good progress already, and will get much better in the future

Recoil Polarization Measurements



G_{Ep}-III Experiment at JLab

The ratio G_{Ep}/G_{Mp} was measured with the recoil polarization technique at Q^2 of 5.2, 6.8 and 8.54 GeV^2 in Hall C at JLab, between October 2007 and June 2008. Also G_{Ep}/G_{Mp} at a constant Q^2 of 2.49 GeV^2 for 3 kinematics (3 values of ε).

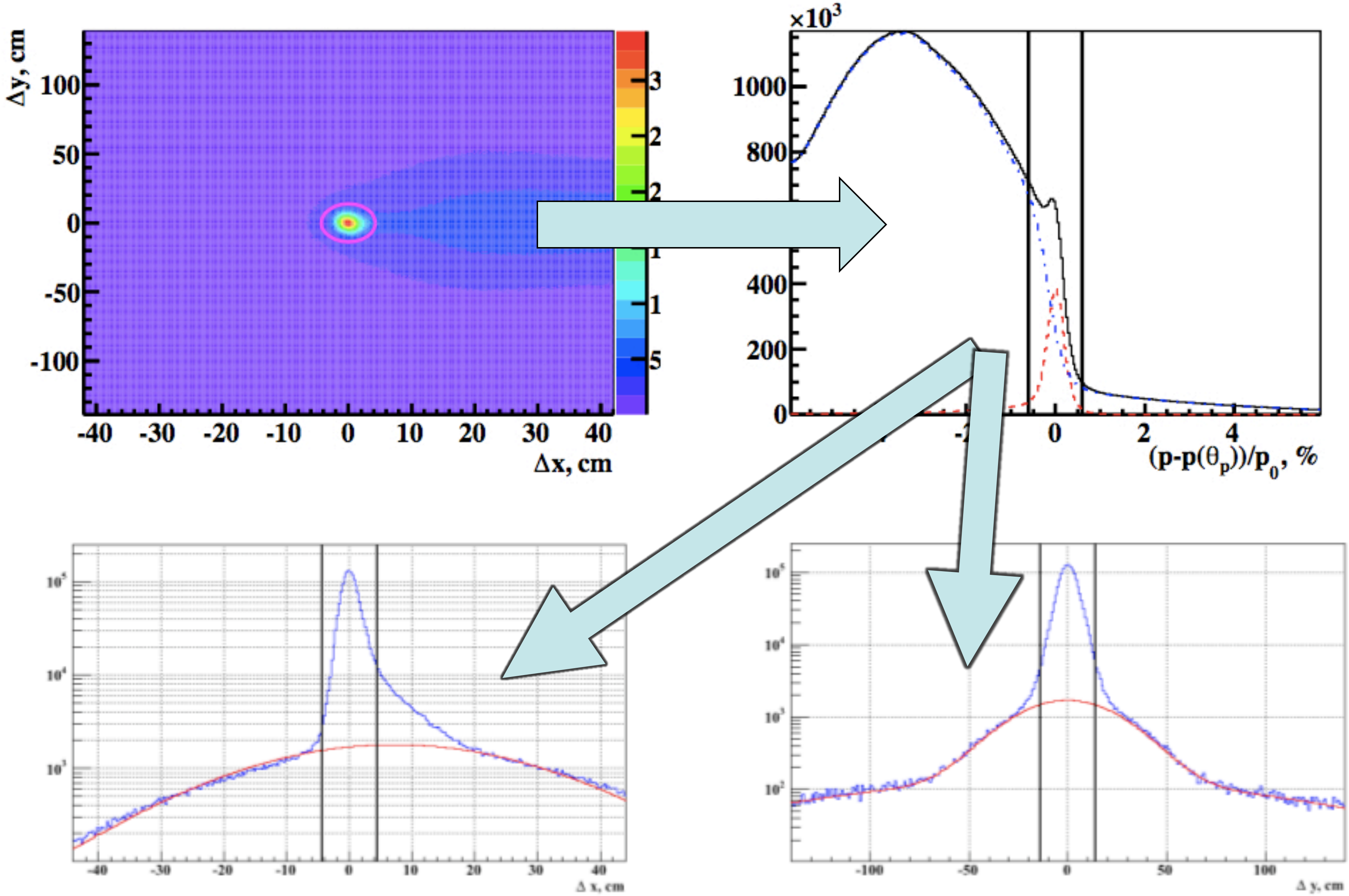
These experiments used the High Momentum Spectrometer (HMS) to detect proton; a new double focal plane polarimeter (FPP) in the focal plane of the HMS measured the polarization of the recoil proton.

A large area Electromagnetic Calorimeter (BigCal) assembled for the experiment was used to detect the elastically scattered electrons in coincidence with the protons.

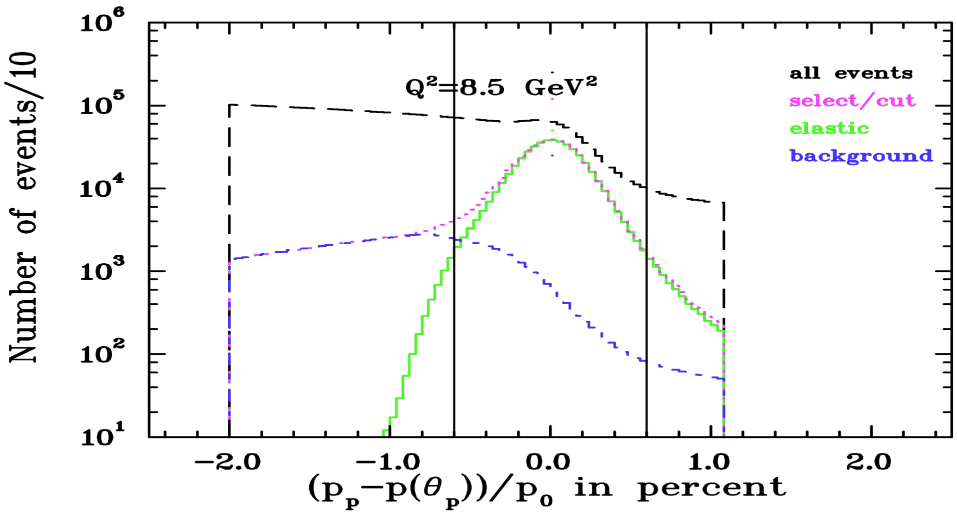
BigCal in Hall C

Focal Plane Polarimeter

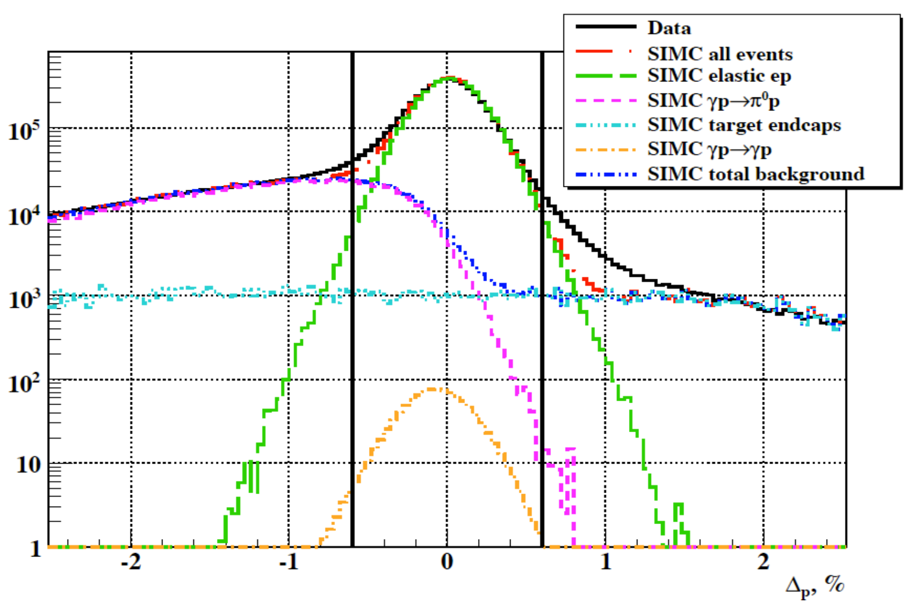
Identification of Elastic Events and Background



Identification of Elastic Events and Background

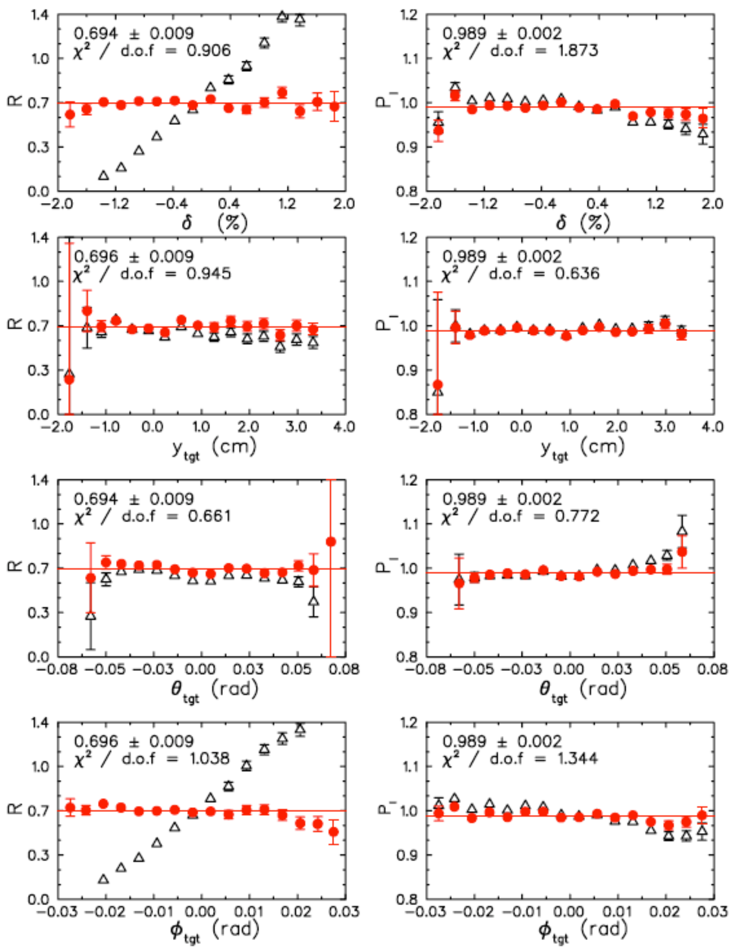


Extrapolation procedure is carried out bin by bin in $(p_p-p(\theta_p))/p_0$ in order to measure background



Simulations reproduce well the total background based on the above procedure

Spin Precession



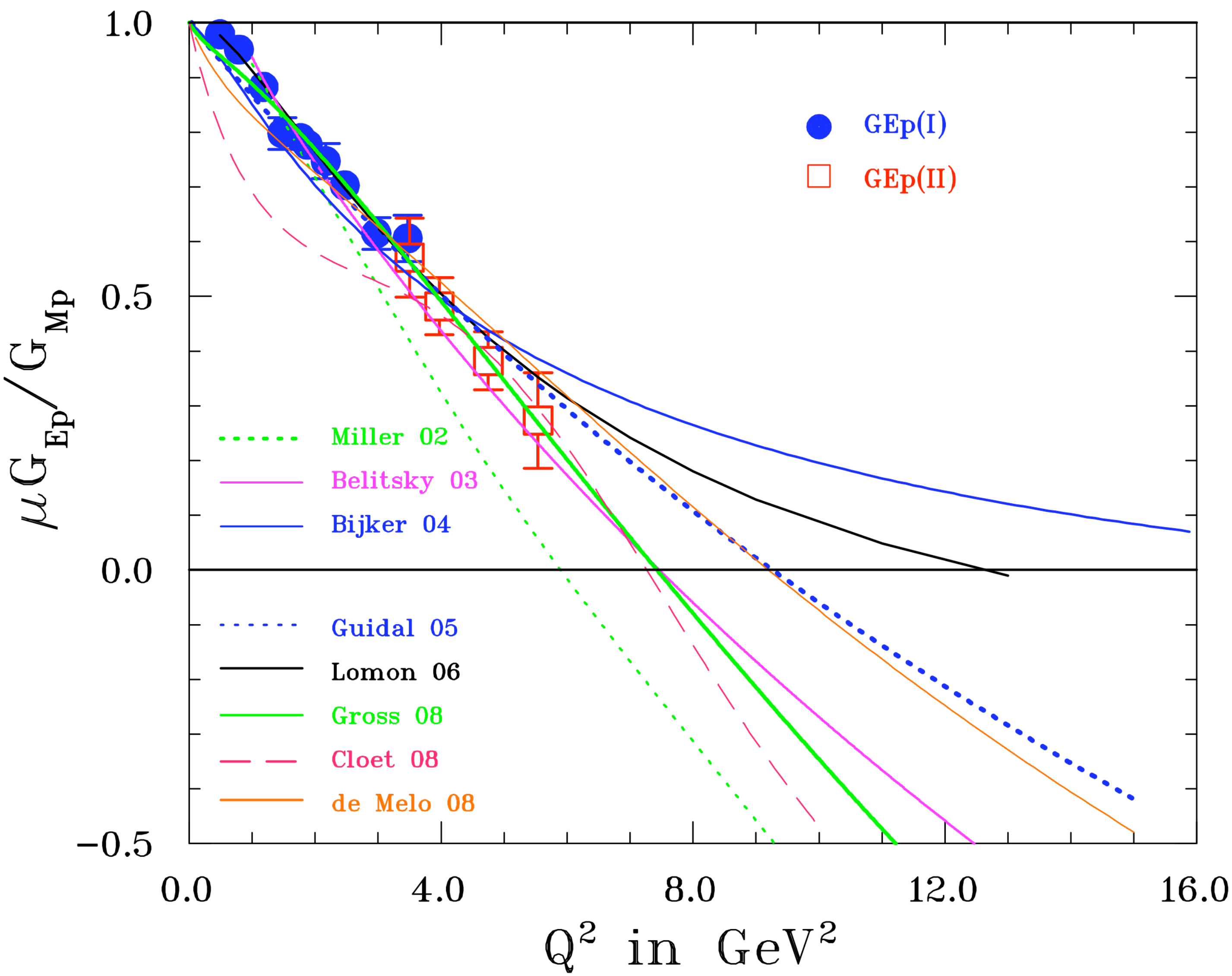
Black – dipole, Red - COSY

- High-precision data at Q^2=2.5 GeV^2 provide a strong test of spin transport calculation.

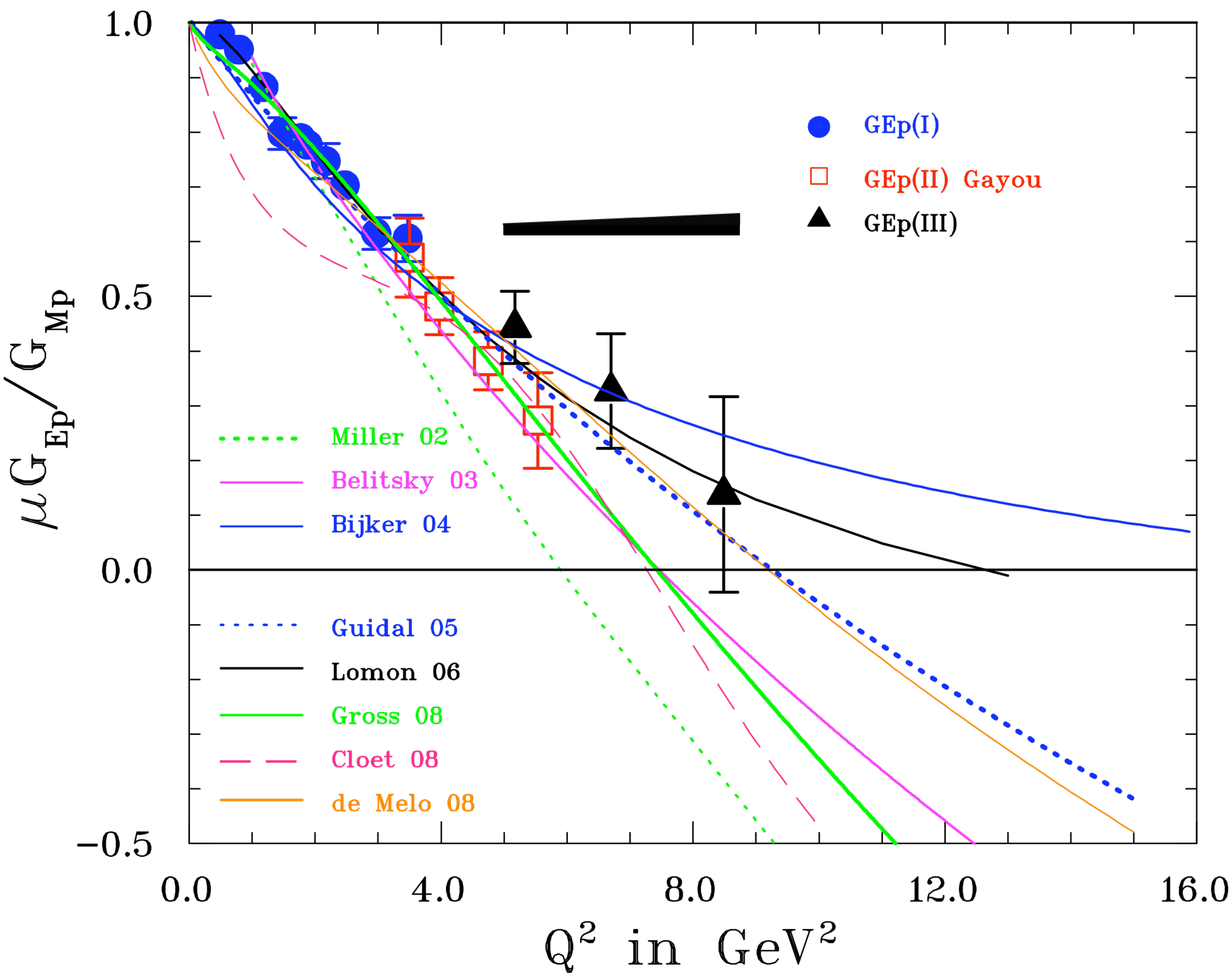
- Benchmark test: extracted form factor ratio is independent of reconstructed kinematics

- χ^2 of constant fit close to one for all four target variables:
    - δ = percent deviation from central momentum
    - θ_{tar}= vertical angle
    - ϕ_{tar}= horizontal angle
    - y_{tar} = vertex

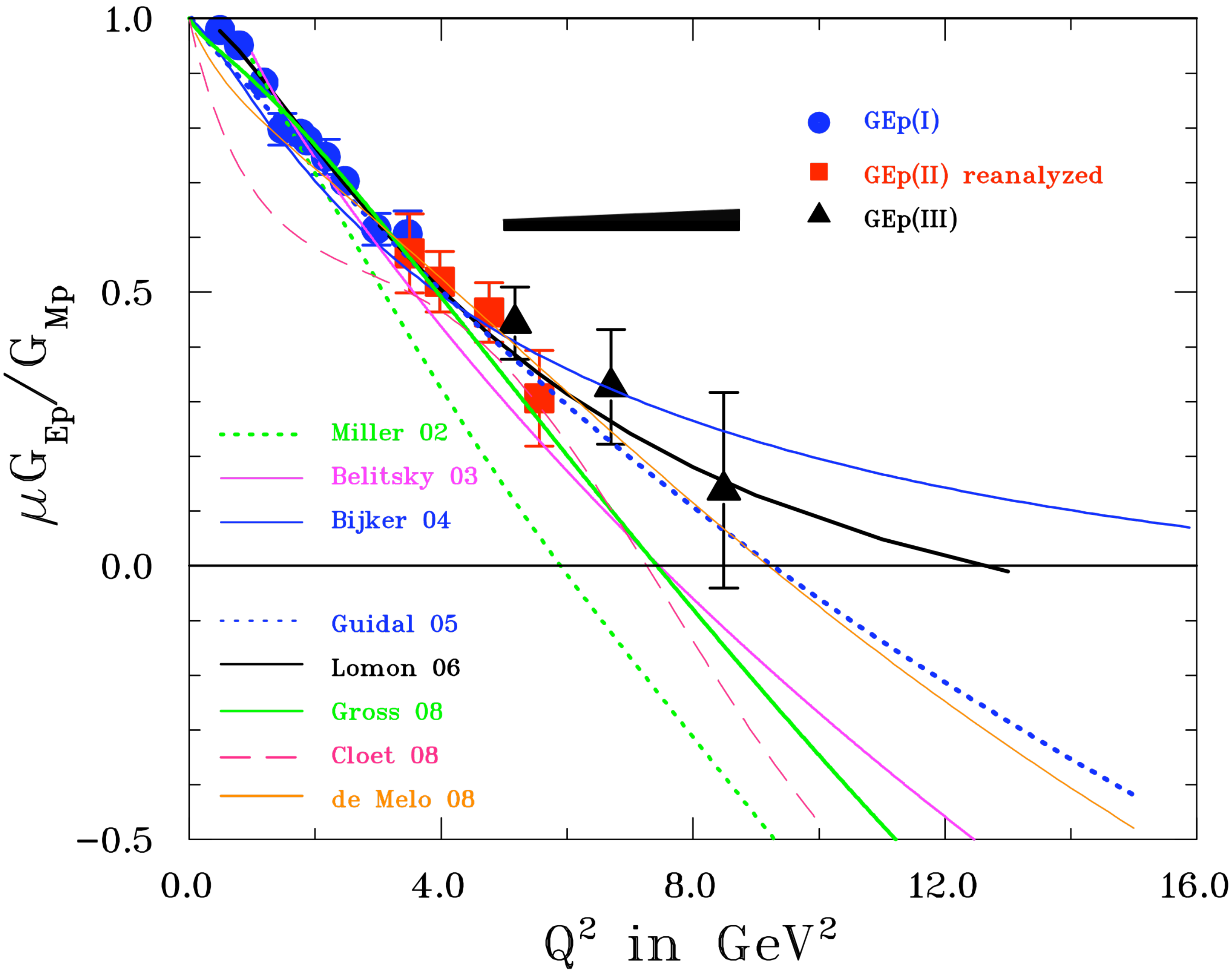
Recoil Polarization Measurements



Recoil Polarization Measurements



Recoil Polarization Measurements



G_{Ep}-IV and G_{Ep}-V

"While [the proponents] consider both experiments to be complementary (high resolution and small acceptance vs. small resolution and large acceptance), the PAC is not convinced that both of them should be pursued. The PAC therefore asks the two collaborations to either come up with one common proposal or to make an extremely compelling case as to why both of them need to be done."

G_{Ep}-IV and G_{Ep}-V

We strongly believe that both experiments should be pursued, since:

1. G_{Ep}-V is the only experiment capable of reaching ~14.5 GeV^2; this would maximize the G_{Ep}-related potential of the 12 GeV upgrade

2. Realization of SBS enables a broad new physics program beyond G_{Ep}

3. G_{Ep}-IV will provide timely, reliable data of excellent precision in a currently unexplored region of Q^2, and will provide two comparison points to the G_{Ep}-V data, which will lay the foundation for absolute confidence in the eventual higher Q^2 G_{Ep}-V result

G_{Ep}-IV and G_{Ep}-V: Potential Performance

Hall C

1. Radiation Damage to BigCal (mitigated with UV curing, as in GEp-III)
2. Target Boiling

N.B. Both of these effects apply to a larger extent in Hall A (factor of 1/3)

Hall A

1. BigCal trigger efficiency [Hall C at ½ of ep elastic energy (~10% radiative losses), Hall A at 85% of full energy (~18% radiative losses)] -> gain matching/radiation damage present more of a challenge in Hall A

2. Placement of HCAL behind FPP analyzer -> potential for helicity-independent asymmetries in the FPP, which cancel only to first order with helicity flip of the electron beam. At the same time, use of HCAL may offer higher analyzing power (due to use of high threshold on proton signal)

3. FPP multiple tracks-> estimate 10% occupancy in FPP chambers, leading to ~15% loss of events

GEp-IV and GEp-V: Systematics

- Clean identification of elastic events is of crucial importance; the limiting source of resolution is different in the two experiments
  - HMS has excellent momentum resolution (0.1%), good angular resolution (1.0 mrad) and vertex resolution (~1mm)
    - Elastic identification as in GEp-III:
      - Correlation between p_p and θ_e -> resolution dominated by p_p
      - Correlation between p_p and θ_p -> resolution dominated by θ_p
      - Missing energy with moderate resolution dominated by BigCal energy resolution
      - Coplanarity with resolution dominated by ϕ_p
  - SBS has excellent angular resolution (0.2 mrad), good vertex resolution (1mm), and momentum resolution (0.5% at 9 GeV/c)
    - Elastic identification using:
      - Electron proton angular correlation -> similar contributions from θ_p and θ_e resolutions
      - Proton angle-momentum correlation -> moderate resolution dominated by p_p
      - Missing energy with moderate resolution dominated by BigCal energy resolution
      - Coplanarity with similar resolution in ϕ_e and ϕ_p

GEp-IV and GEp-V: Systematics

- Systematic uncertainty due to background is expected to be small compared the statistical uncertainty in both experiments (as a direct result of higher beam energy)

- At similar values of Q^2, the SHAPE of the background, and its overlap with the elastic peak is very different for different classes of two-body correlations (angle-angle, angle-energy, and energy-energy), and for different ratios of solid angle to momentum acceptance

- While the prediction of elastic yield is very reliable, the prediction of π^0 photoproduction yield has more uncertainty -> the effect that this can have has already been witnessed in GEp-II -> in that case, the eventual background correction was several times the original systematic uncertainty

G_{Ep}-IV and G_{Ep}-V: Summary

When SBS performance is realized, then G_{Ep}-V will achieve superior statistical precision at similar Q^2 to G_{Ep}-IV, and will reach its goal at high Q^2

However, some uncertainties in SBS performance remain until construction

The projections for G_{Ep}-IV are based on extensive experience with the same apparatus in G_{Ep}-III.

Thus, there is virtually no downside risk, and some upside potential based on planned upgrades and improvements.

G_{Ep}-IV requires zero new equipment, and can be run immediately post upgrade.

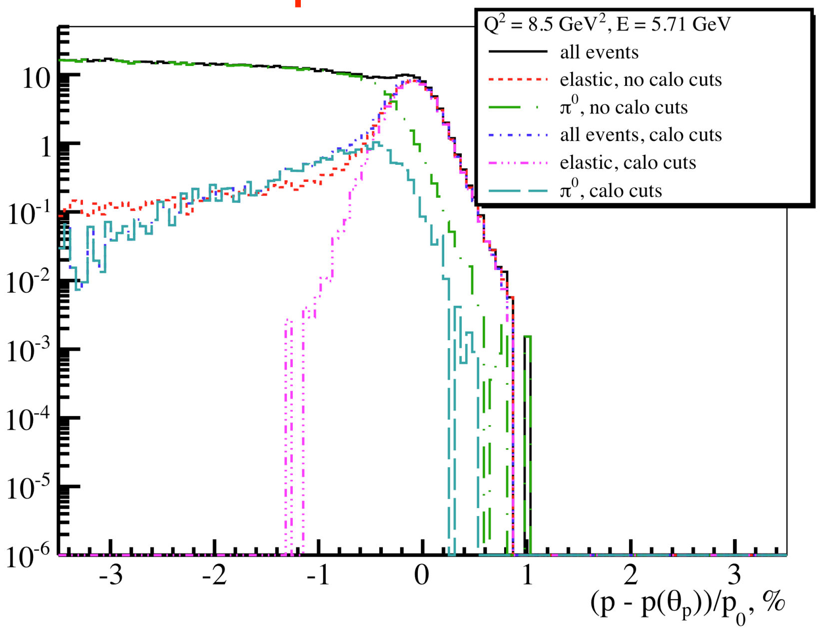
It is better to have two measurements, with different apparati, and different systematics, in two different halls, than to combine into one experiment in one hall … if the results are consistent with one another in the end, they can be combined

G_{Ep}-IV: Basic Plan

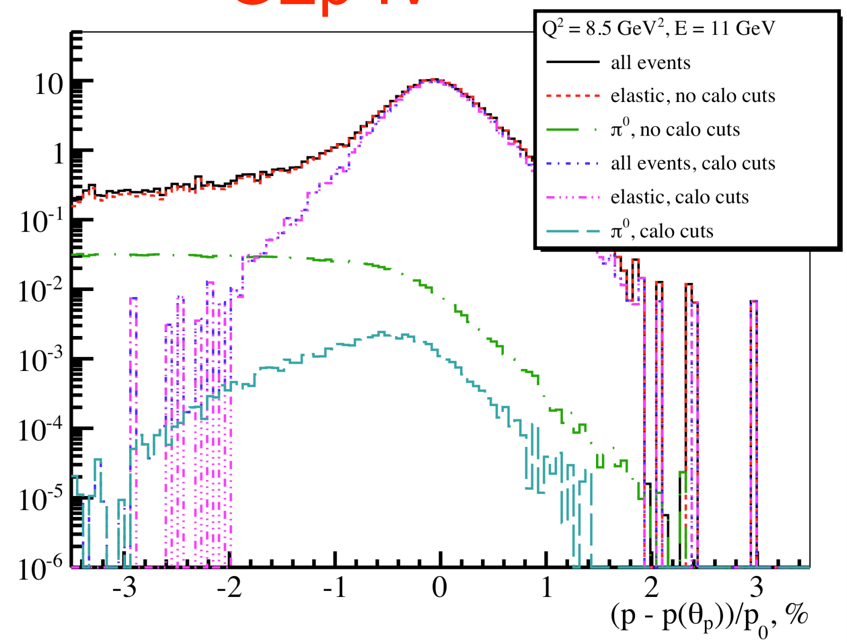
- Extend the measurement of G_{Ep}/G_{Mp} to larger Q^2 using existing equipment in Hall C
  - Largest Q^2 = 11.0 GeV^2 is determined by a desire to have statistical error bars of ~0.12
  - Repeat the Q^2 = 8.5 GeV^2 point of G_{Ep}-III to reduce statistical error bar when data points are combined
- Use the Hall C HMS spectrometer, equipped with the existing FPP, for proton detection and polarization measurement
- Use the existing BigCal detector for electron detection

Background (Q^2=8.5 GeV^2)

GEp-III



GEp-IV



Increase in beam energy from 5.7 to 11.0 GeV reduces inelastic background contribution (at the same Q^2) dramatically

Background in G_{Ep}-IV

Q^2, GeV^2	6.0	8.5	8.5	11.0
E_{beam}, GeV	8.8	5.71	11.0	11.0
L_{tgt}, cm	30	20	30	30
SIMC rate, mC^{-1}	761	91	184	60
bkgr. fraction, 3σ cuts	0.02 %	10.6%	0.03%	0.15%
bkgr. fraction, 6σ cuts	0.11 %	36.7%	0.12%	0.61%
bkgr. fraction, no cuts	0.52%	97.5%	2.16%	10.1%
cut efficiency, 3σ cuts	79.5%	74.7%	78.1%	77.3%
cut efficiency, 6σ cuts	87.1%	79.9%	86.3%	85.7%

Gep-III

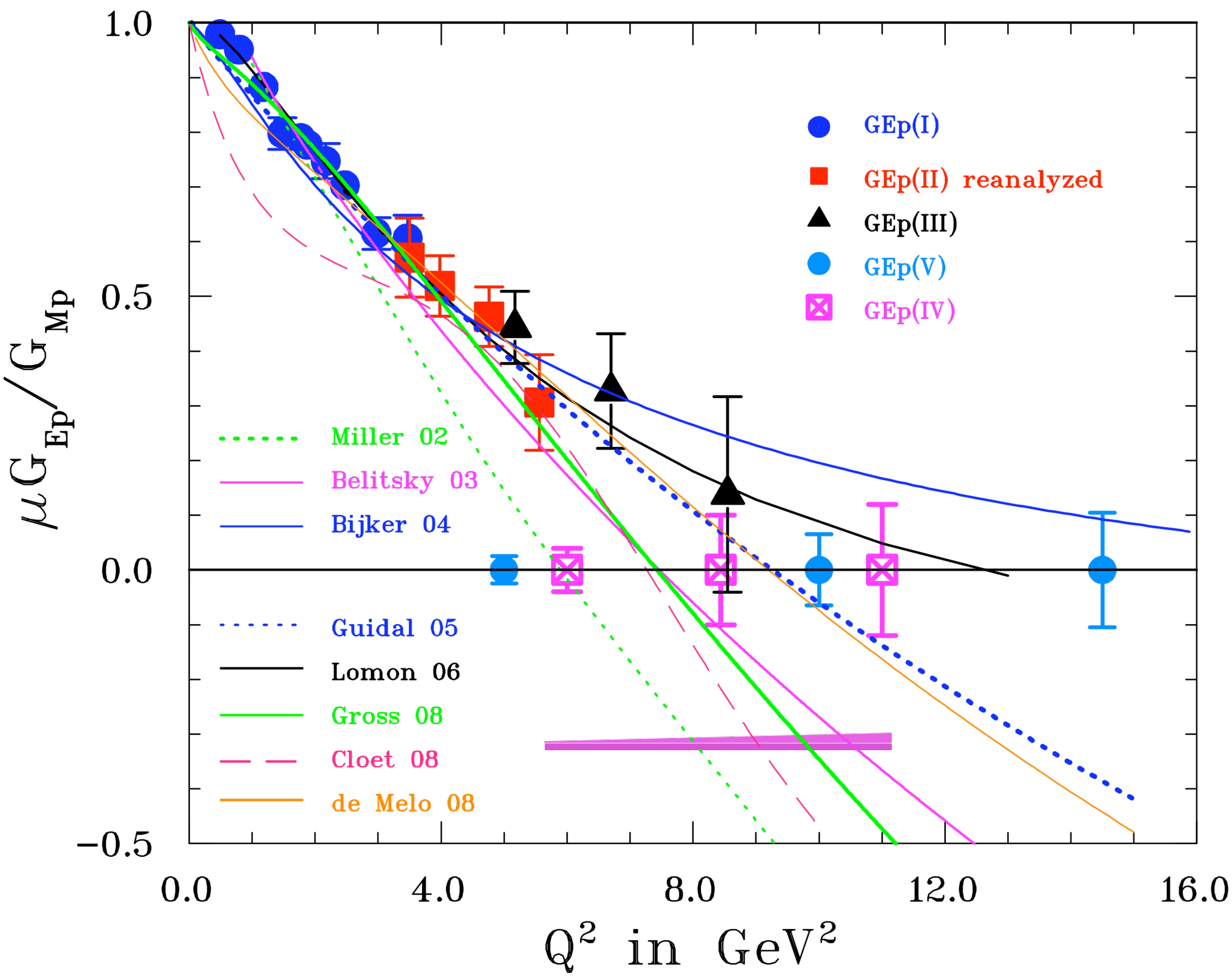
G_{Ep}-IV: Kinematics

Q^2	E_e	θ_e	$E_{e'}$	θ_p	p_p	$d\sigma/d\Omega_e$	ϵ	χ	$\Delta\Omega_e$
GeV^2	GeV	deg	GeV	deg	GeV/c	cm^2/sr		deg	msr
6.0	8.8	20.1	5.60	28.5	4.03	$3.2*10^{-35}$	0.85	197.6	4.1
8.5	11.0	19.9	6.47	24.4	5.39	$6.5*10^{-36}$	0.83	261.2	5.3
11.0	11.0	25.5	5.14	19.2	6.74	$0.9*10^{-36}$	0.70	324.8	12.7

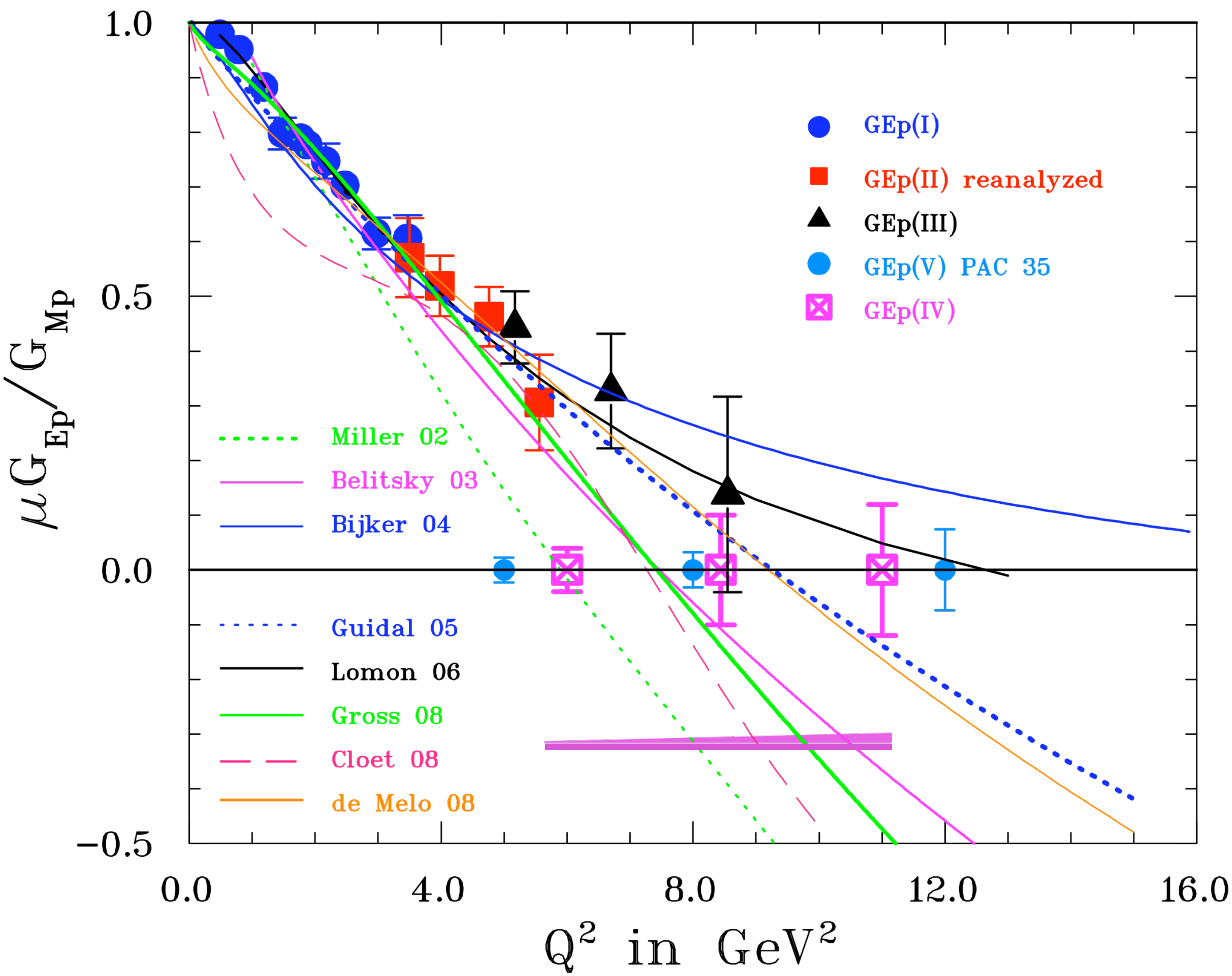
Table 3: The proposed kinematics. Assumed HMS spectrometer solid angle: 7 msr. Assumed beam characteristics: 75 μA, 85% polarization. Assumed target: 30 cm LH_2.

Q^2	E_e	COM	absolute $\Delta(G_{Ep}/G_{Mp})^*$	time
GeV^2	GeV			days
6.0	**8.8**	$\mathbf{3.9 \times 10^{-3}}$	**0.04**	**10**
8.5	**11.0**	$\mathbf{1.5 \times 10^{-3}}$	**0.10**	**20**
11.0	**11.0**	$\mathbf{1.1 \times 10^{-3}}$	**0.12**	**65**

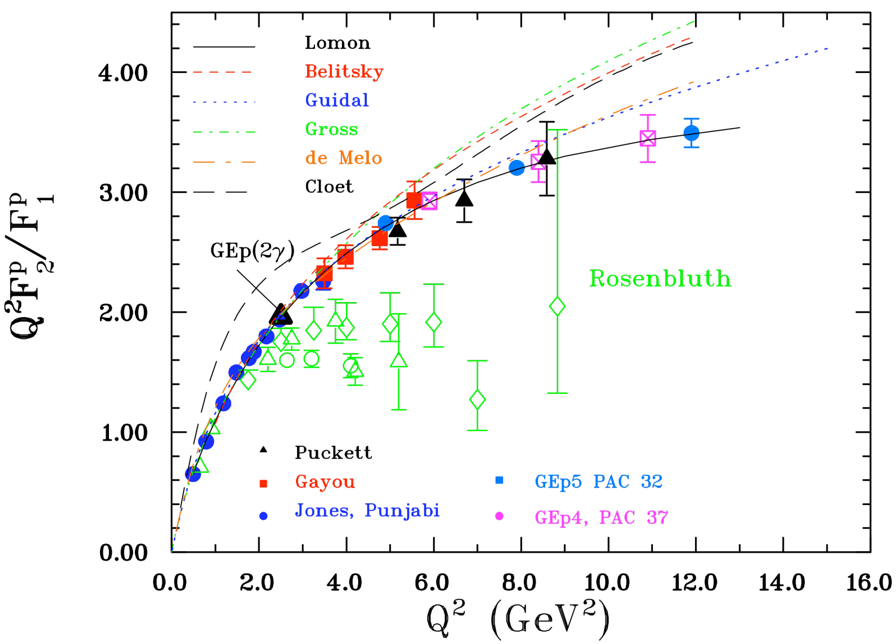
Recoil Polarization Measurements

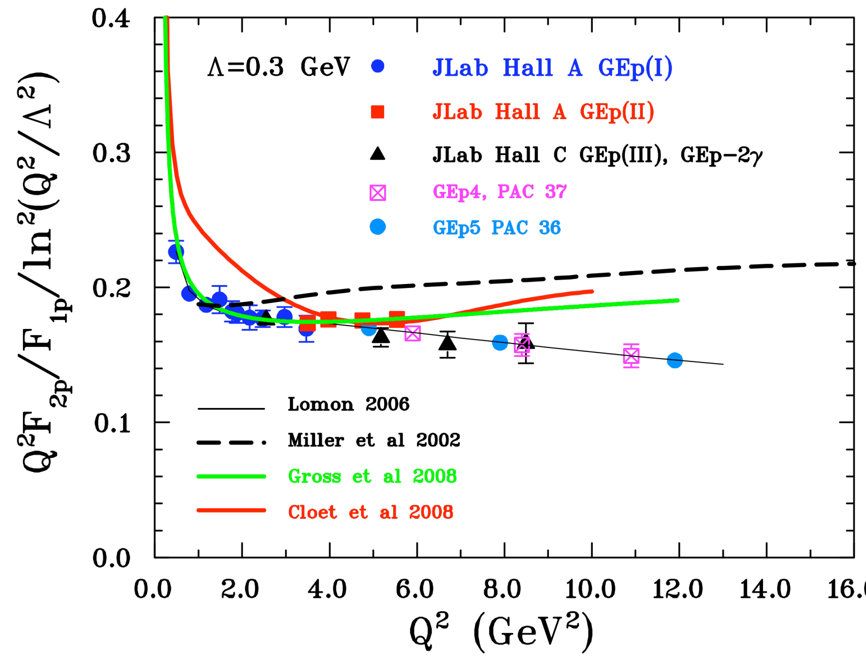


Recoil Polarization Measurements



Proton: F2 /F1 and pQCD





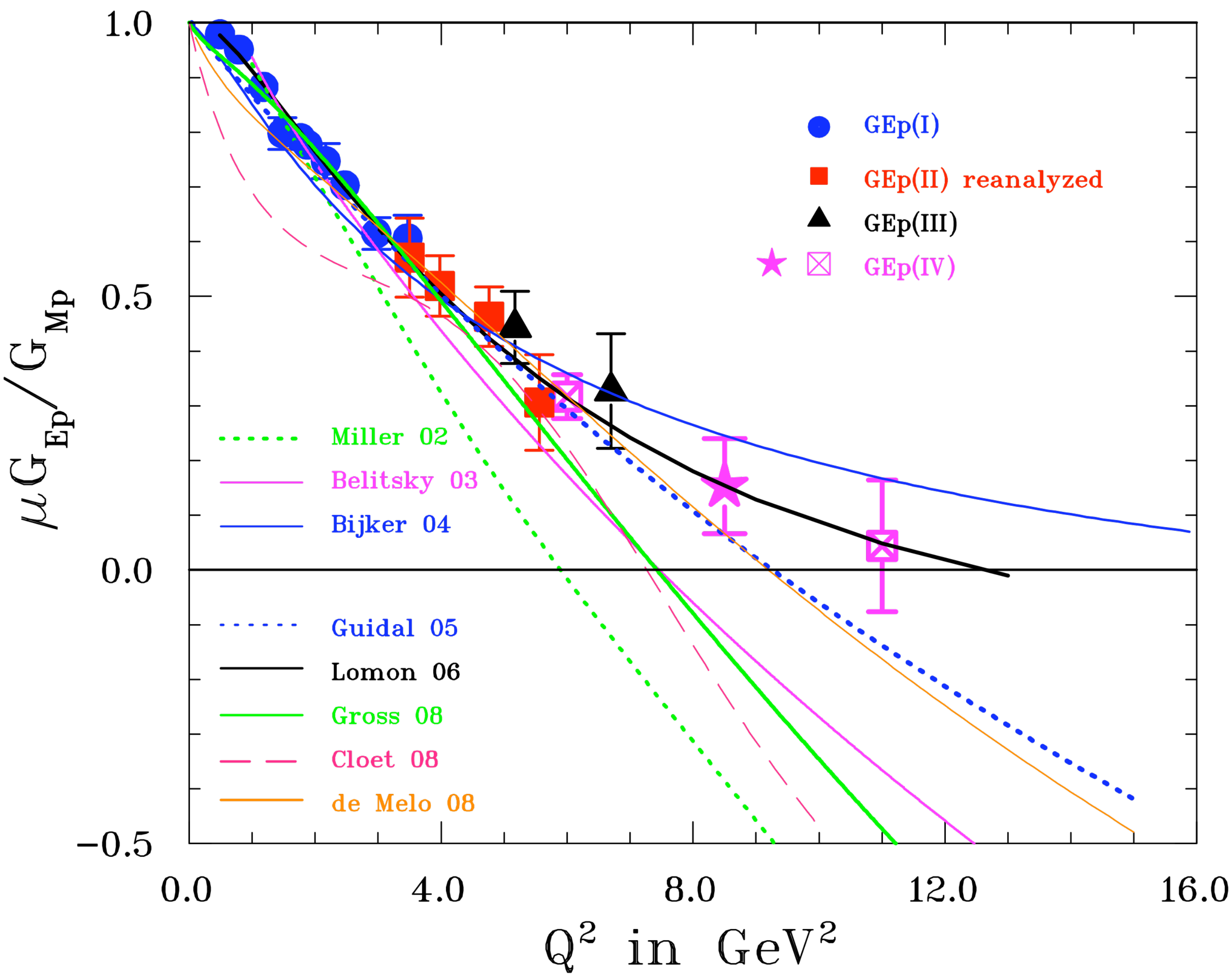
Brodsky and Farrar (75):

$Q^2F_2/F_1 \rightarrow$ constant

Belitsky, Ji and Yuan (03):

$Q^2F_2/F_1 \rightarrow \ln^2(Q^2/\Lambda^2)$

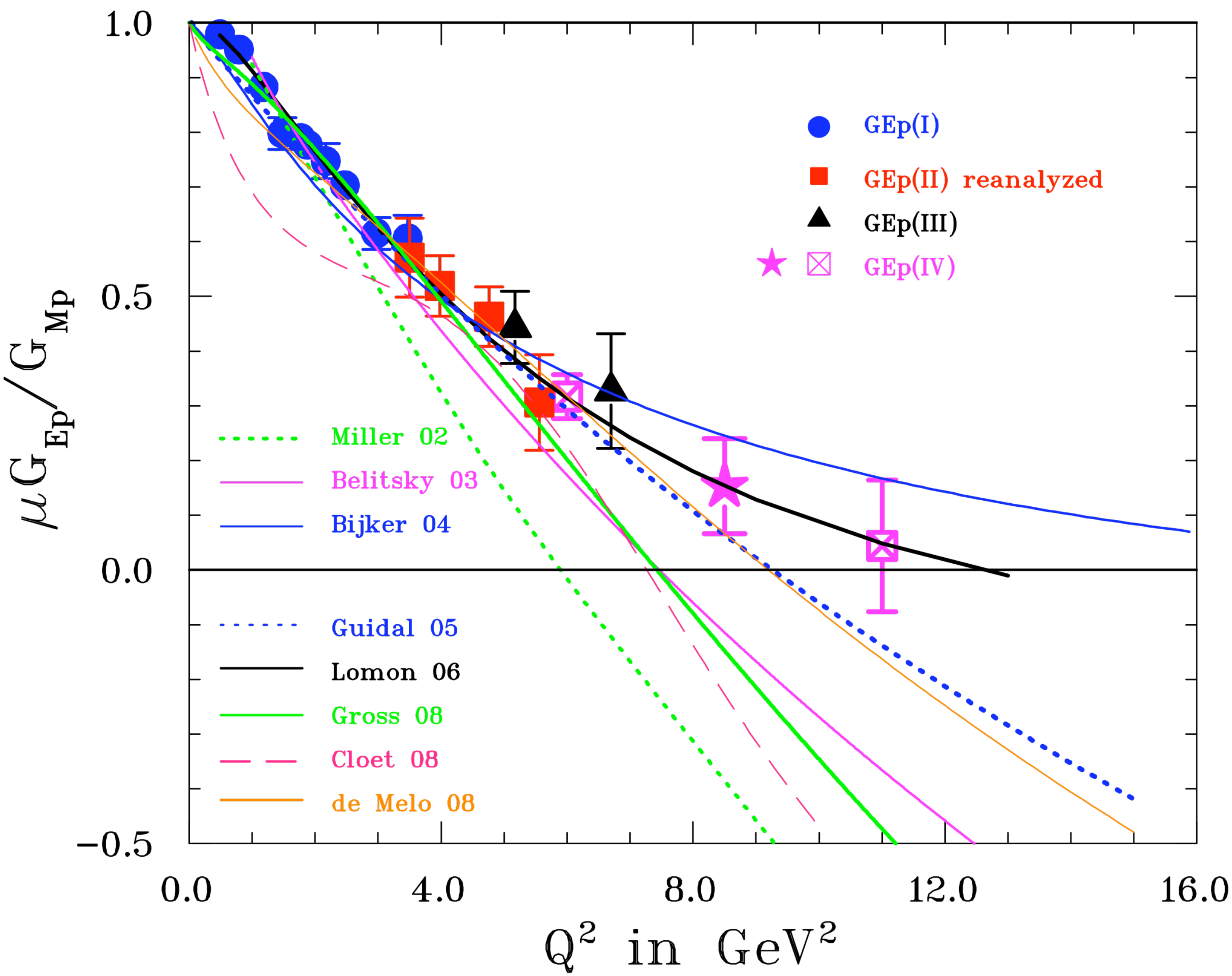
Recoil Polarization Measurements



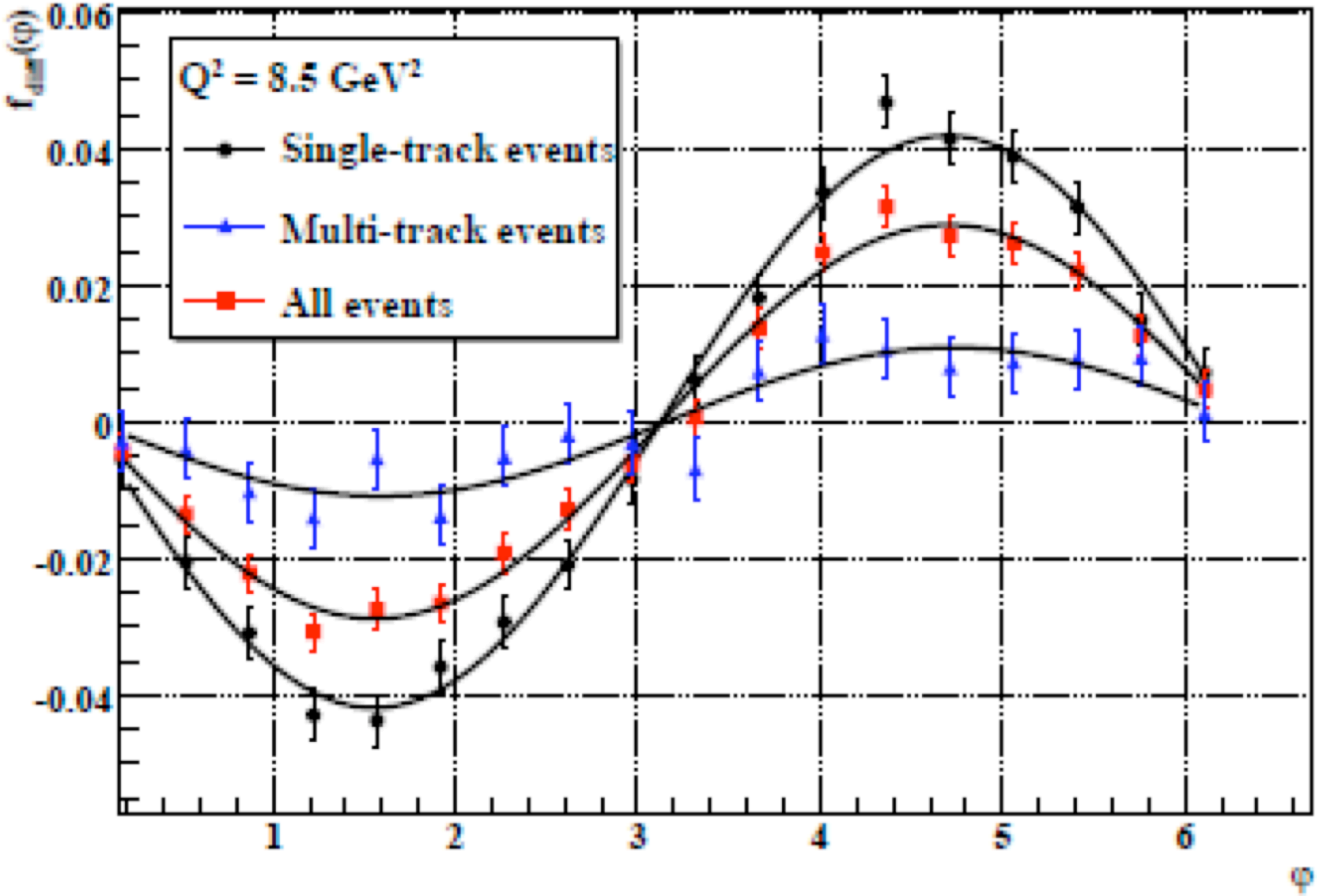
Conclusions

- Many competing/complementary theoretical models, with different approaches.
- While most modern calculations describe the data well in the lower Q^2 regime, they begin to diverge significantly beyond the currently available data.
- New data at higher Q^2 (for both proton and neutron) will place stringent constraints on available models, and will continue to motivate more advanced calculations.
- G_{Ep}-IV will provide high quality data on the form factor ratio up to $Q^2 = 11$ GeV^2, using existing equipment. The experiment can be carried out as soon as the 11 GeV electron beam is available in Hall C. We are also flexible in terms of coordination of the schedule with SHMS commissioning.
- No technical issues face this experiment - hardware and software are "ready to go"

Recoil Polarization Measurements



Backup Slides



$f_{diff}(\varphi)$
$Q^2 = 8.5\ GeV^2$
Single-track events
Multi-track events
All events
0.06
0.04
0.02
0
-0.02
-0.04
1
2
3
4
5
6
φ

G_{Ep}-IV and G_{Ep}-V: Statistical Figure of Merit

	HMS	SBS	Advantage?
Proton Acceptance	7msr	~33msr	Hall A
Luminosity	30 cm target	40 cm target	Slight Hall A
Beam Polarization			Even
Polarimetry	CH_2 Double FPP	CH_2 Double FPP	Even* (*Assumes ideal SBS performance)

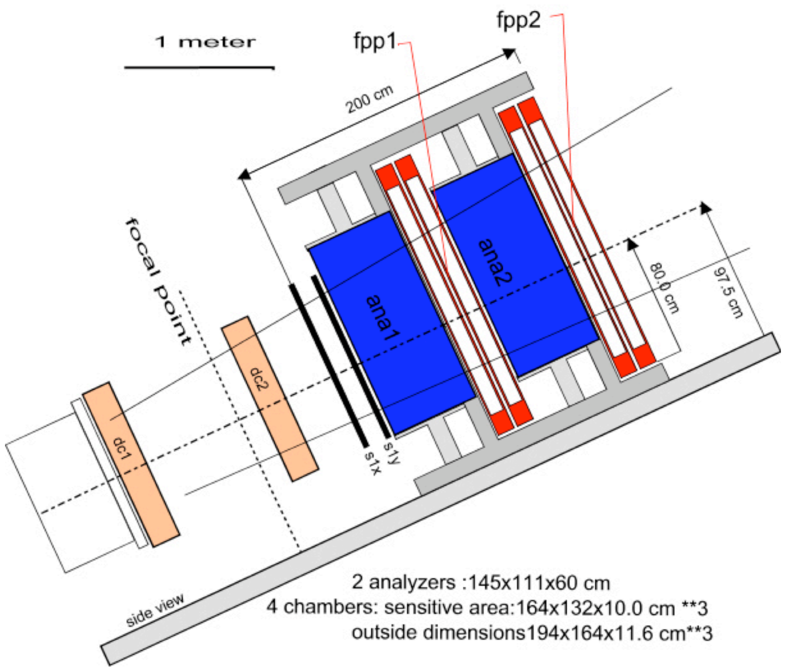
G_{Ep}-IV and G_{Ep}-V: Elastic Event Selection and Background

	HMS	SBS	Advantage?
Electron Detection and Coord./Energy Resolution	BigCal	BigCal with GEMS	Slight Hall A (not the limiting resolution)
Proton Momentum Res.	0.1%	0.5% at p_p = 9 GeV/c	Hall C
Proton Angle Res.	~1 mrad	~.2 mrad	Hall A
Vertex Resolution	~1 mm	~1 mm	Even
Random/Acc. Bkgd.	Negligible (~1.5 ns Coinc. Time)	Higher random rate; similar time res.	Hall C
Event Reconstruction Eff.	Refurb. HMS Drift Chambers; 100% eff.	Irreducible Soft Photon Bkgd.	Slight Hall C (assuming ideal SBS performance)

G_{Ep}-IV and G_{Ep}-V: Systematic Accuracy

	HMS	SBS	Advantage?
Spin Precession	Well understood COSY model with simple quad. precession	Very simple SBS dipole	Even
Elastic Event Selection and Inelastic Background	(see previous slide)	(see previous slide)	Slight Hall C
FPP Angle Reconstruction and False Asymmetry	Well tested and understood + FPP upgrades	New FPP with high background and dead areas	Hall C
Trigger	Scintillators in front of FPP	HCAL behind FPP -> false asymmetry	Hall C

FPP for 01-109 in Hall C



Hall C Focal Plane Polarimeter

Double polarimeter ->
CH2 analyzer (60cm) with two
separate 3-plane (UVX) wire chambers

Lessons learned in Gep-III:

1. Efficiency and Analyzing Power well understood, and consistent with previous data and simulations

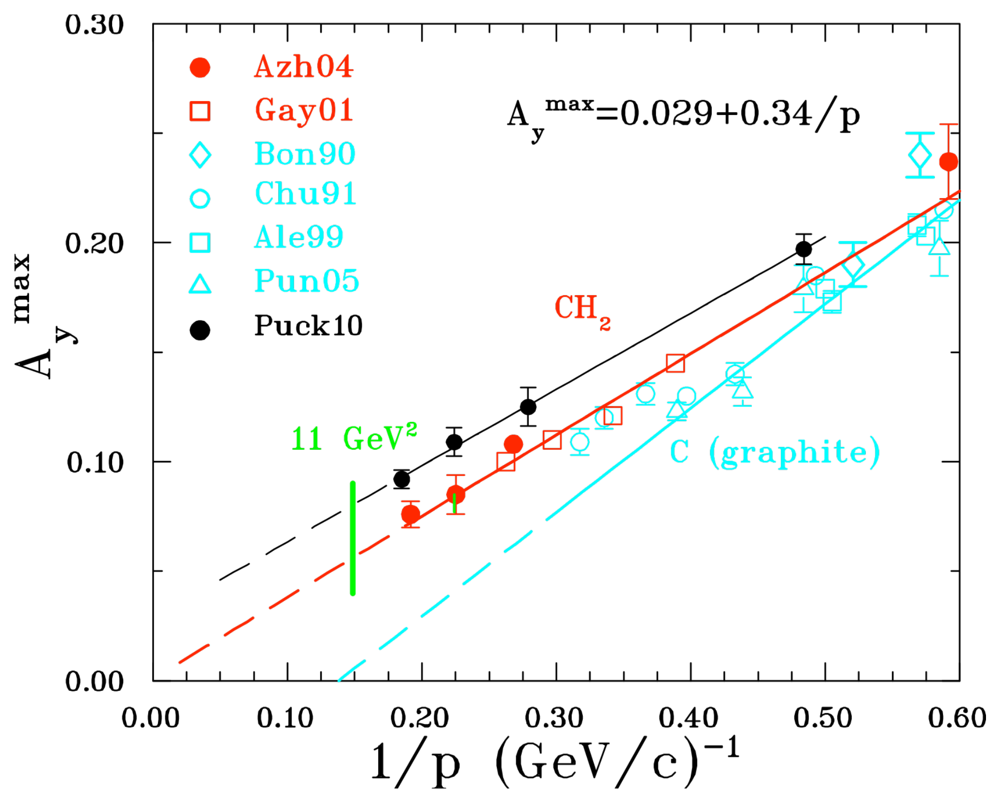
2. Identification of single-track events key to maximizing FPP Figure of Merit

3. Lack of redundancy in wire chambers leads to L/R miss-tracking, resulting in larger than predicted false asymmetries

FPP Wire Chamber Upgrade: add 4th plane to each wire chamber
-> increase overall tracking efficiency, and reduce false asymmetries

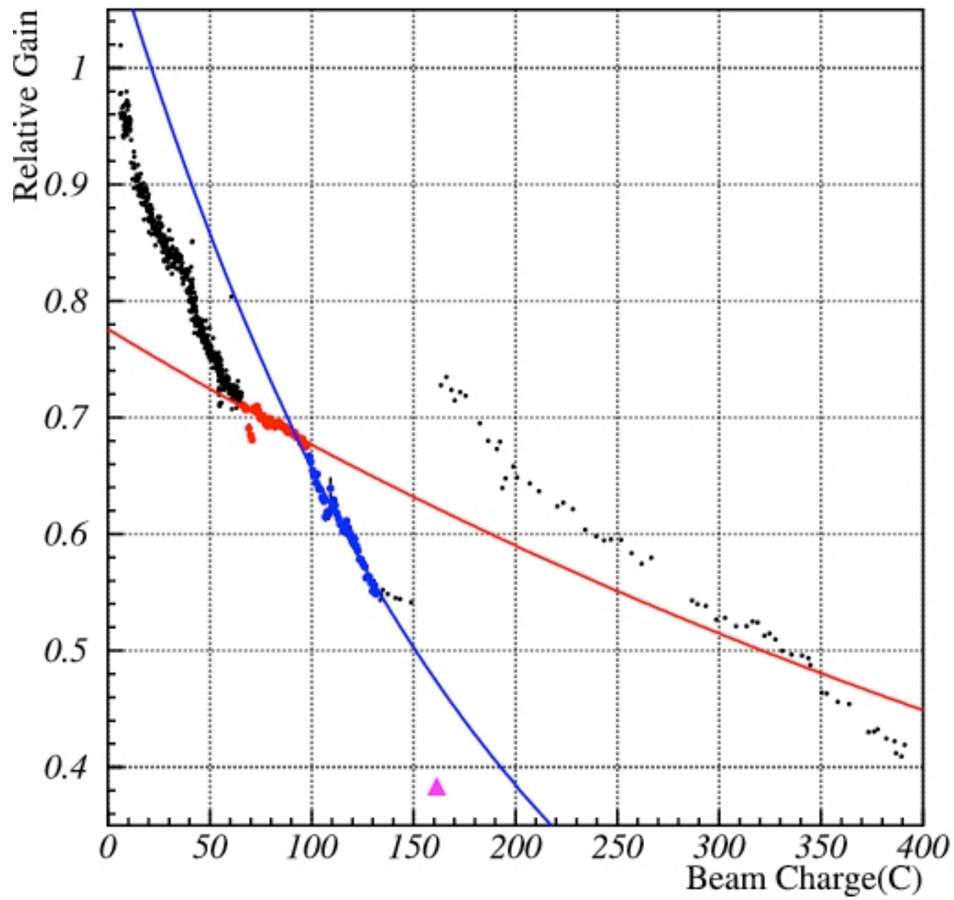
Gep-IV: CH_2 Analyzing Power

- As a by-product of the polarization transfer experiments, we can extract the (average/maximum) CH_2 analyzing power in the FPP
- Empirically, the maximum analyzing power scales as 1/p, the shape of the distribution scales in a similar manner; this allows us to make accurate predictions of the analyzing power at various momenta
- In addition, full GEANT3 as well as toy Monte Carlo simulations have been performed to estimate the scattering efficiency (both describe Gep-III data well)



Gep-IV:BigCal Radiation Damage

- Affects energy resolution
  - we are fairly insensitive to this.
- Main concern:
  - relatively high hardware threshold to keep the BigCal rates low
- Result of GEANT Simulation:
  - Curing about once per week in Gep-IV
- Use maintenance days -
  - need four hours of curing to recover one week of damage



Gep-IV: LH_2 Target

1. Assume current ESR, based on early running scenario. With 75 μA beam on a 30 cm LH_2 target, this equates to 813W of beam heating. Experience tells us that we would need about 1.1kW of cooling power to handle this without significant target boiling.

2. The 1100 W of cooling power needed equates to 28 g/s from the 15K line from the ESR. This flow rate is approximately the maximum cooling power that one could get out of the ESR (which would mean that one could not run an experiment in Hall A that had significant cooling requirements at the same time).

3. However, for Qweak, a recovery HX has been put in place, which actually doubled this limit (to about 50 g/s total). So, assuming we use the recovery HX, we are well under this limit, and one could even, in principle, run another experiment in Hall A simultaneously that required significant target cooling.

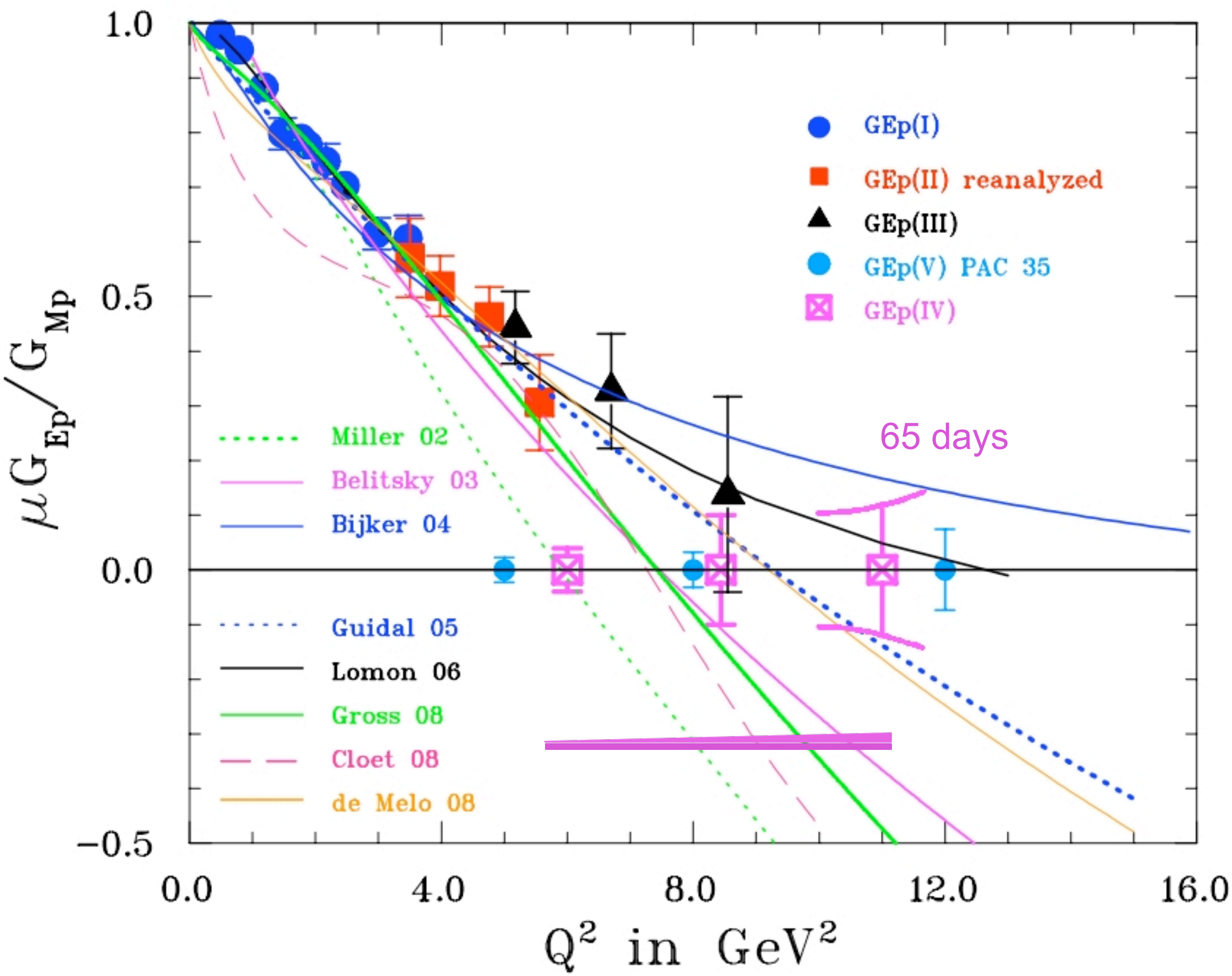
4. In terms of the design of the actual target cell itself, we would obviously rely on the design experience gained during Qweak. We can tolerate significantly more target boiling than can Qweak, and at less than half the beam current. Target boiling only affects event rate; it does not affect the extracted result in any systematic way.

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(ϑ_{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
P_T/P_L	-.095/.934	-0.050/.846	-0.022/.982

- 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

Recoil Polarization Measurements



Recoil Polarization Measurements