Results from the Hall A GMp12 Experiment (E12-07-108)

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on behalf of the GMp collaboration

2021 Hall A Winter Workshop
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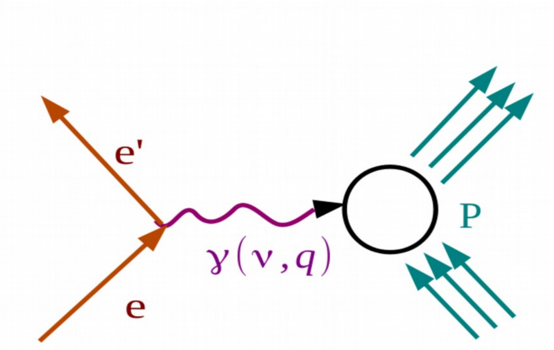
Proton magnetic form factor

- Form factors encode electric and magnetic structure of the nucleon

  → Form factors characterize the spatial distribution of the electric charge and the magnetization current in the nucleon

$$|\text{Form Factor}|^2 = \frac{\sigma(\text{Structured object})}{\sigma(\text{Point like object})}$$



- In one photon exchange approximation the cross section in *ep* scattering when written in terms of G_M^p and G_E^p takes the following form:

$$\frac{d\sigma}{d\Omega} = \sigma_{Mott} \frac{\epsilon (G_E^p)^2 + \tau (G_M^p)^2}{\epsilon (1+\tau)}, \quad \sigma_{Mott} = \frac{\alpha^2 \cos^2 \frac{\theta}{2}}{4E^2 \sin^4 \frac{\theta}{2}} \frac{E'}{E}$$

$$\mathcal{J}_{\text{proton}} = e\bar{N}(p') \left[\gamma^\mu F_1(Q^2) + \frac{i\sigma^{\mu\nu} q_\nu}{2M} F_2(Q^2) \right] N(p)$$

Where,

$$G_E = F_1 - \tau F_2 \qquad G_M = F_1 + F_2$$

$$\tau = \frac{Q^2}{4M^2}, \qquad \epsilon = \left[1 + 2(1+\tau) \tan^2\left(\frac{\theta}{2}\right) \right]^{-1}$$

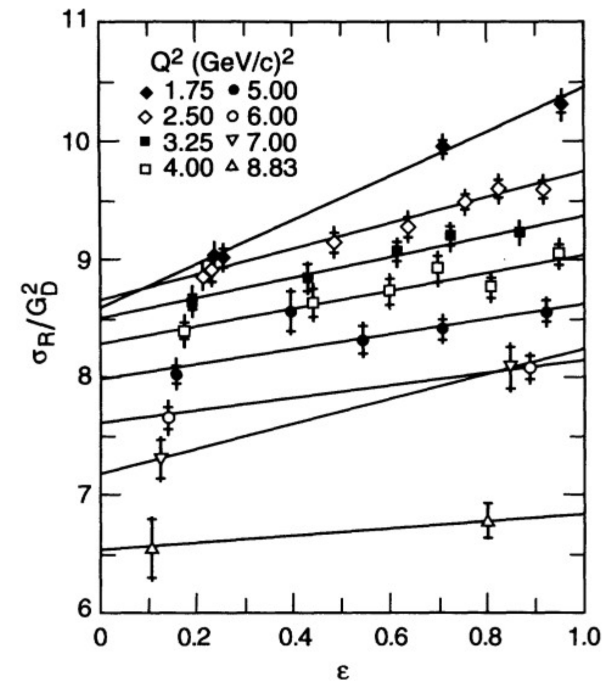
Methods of measurements

- **Rosenbluth separation method:**
  → This method uses different beam energies and angle at fixed Q^2

$$\sigma_R = \frac{d\sigma}{d\Omega}\frac{\varepsilon(1+\tau)}{\tau\sigma_{Mott}} = \frac{\varepsilon}{\tau}\left(G_E^p\right)^2 + \left(G_M^p\right)^2,$$

The slope of $\sigma_R(\varepsilon)$ is directly related to G_E^p and the intercept to

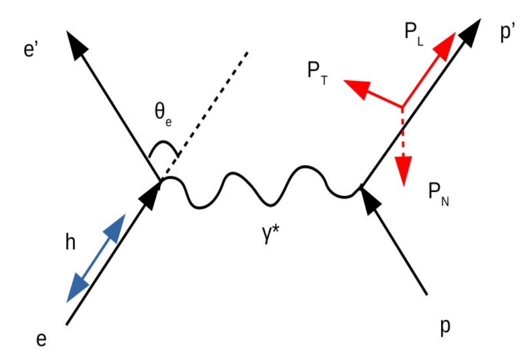
SLAC NE11



- **Recoil polarization technique:**

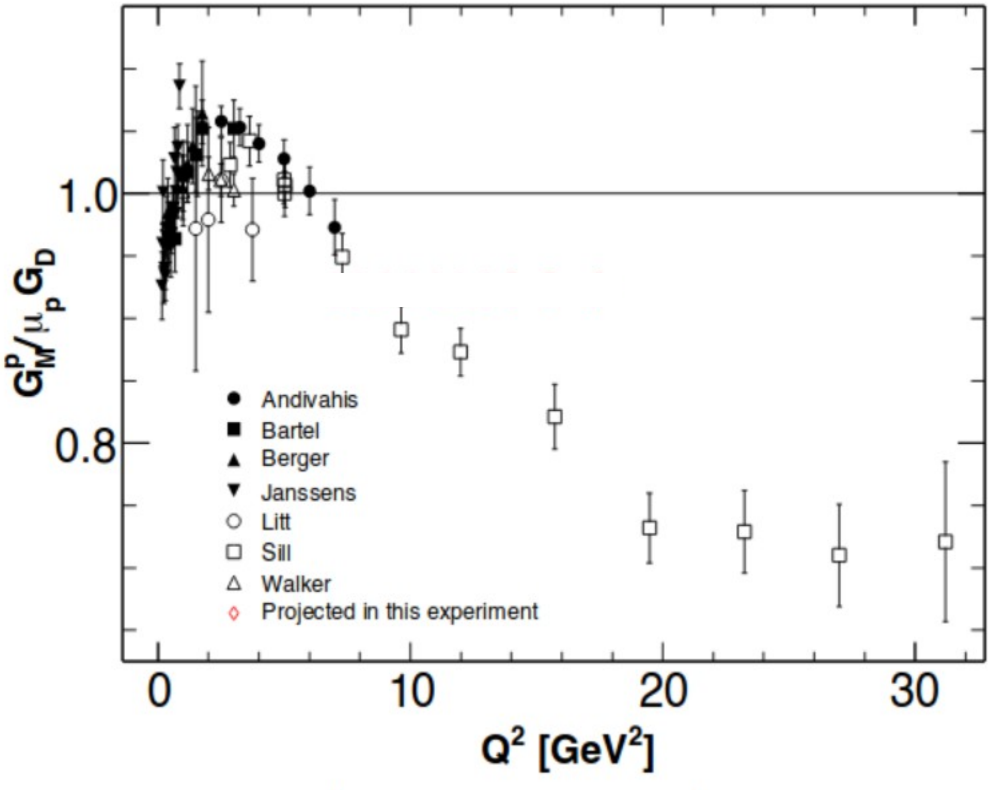
Polarized electron transfers longitudinal polarization to G_E^p, but transverse polarization to G_M^p

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

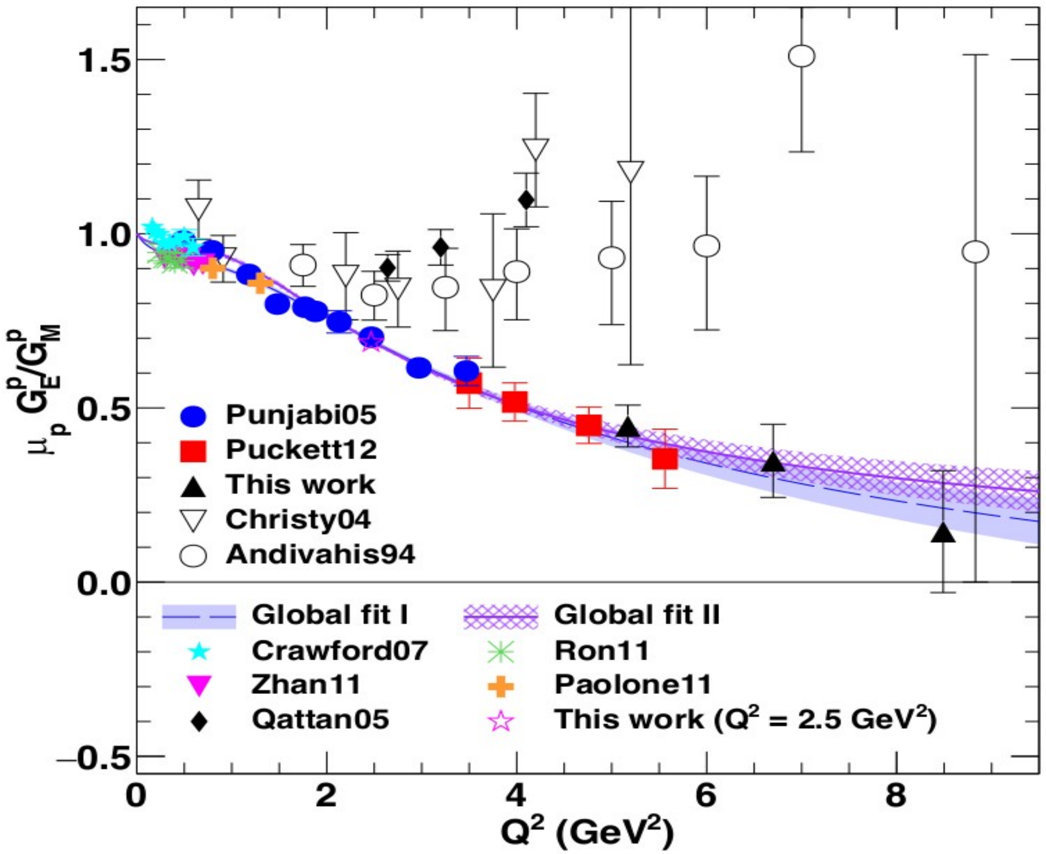


Polarization transfer cannot determine the values of G_E and G_M but can determine the from factor ratio.

Experimental Status of Proton Form Factors



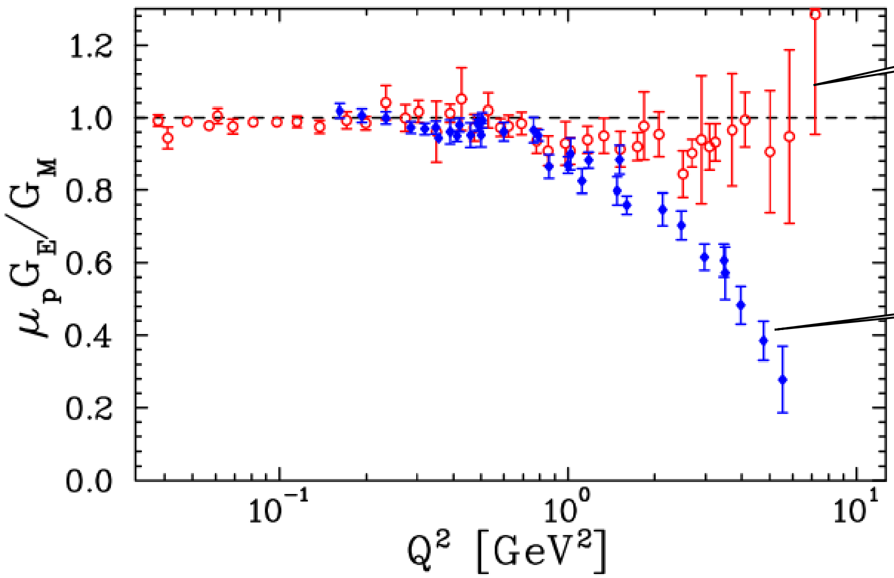
JLab Hall C GEP-III PRC 96, 055203 (2017)



→ Discrepancy in G_E/G_M P-T and Rosenbluth (ε) separations

Resolving the Rosenbluth vs P-T discrepancy

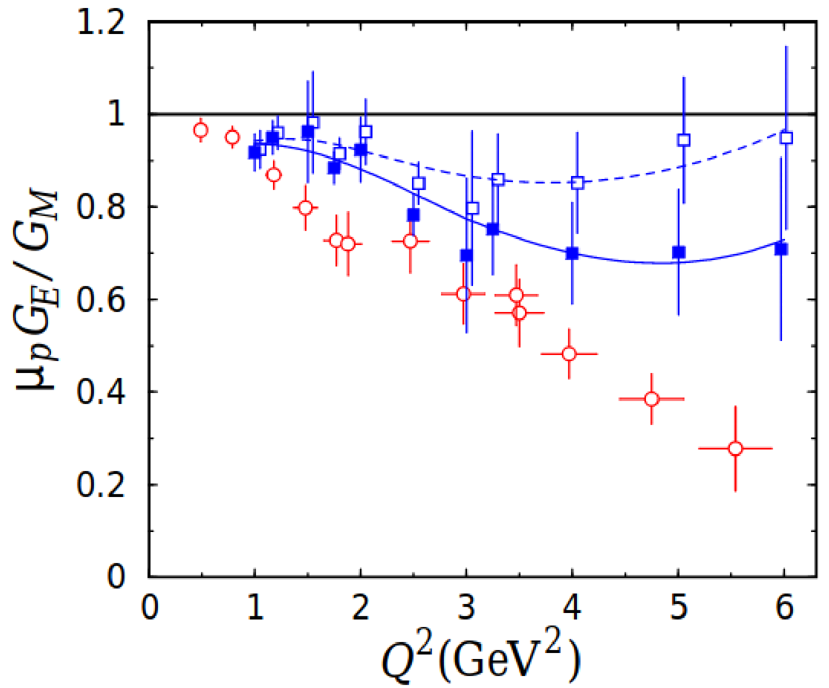
Arrington, Melnitchouk, Tjon, Phys.Rev. C76 (2007) 035205



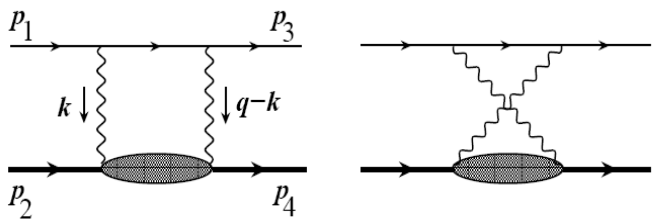
Rosenbluth data (RS)

Polarization data (PT)

Effect of Hadronic 2-γ corrections of Blunden, Melnitchouk, Tjon Phys.Rev.Lett. 91 (2003) 142304



Leading explanation is hard 2-γ exchange, *not* included
In *standard* radiative corrections of Mo-Tsai, etc.



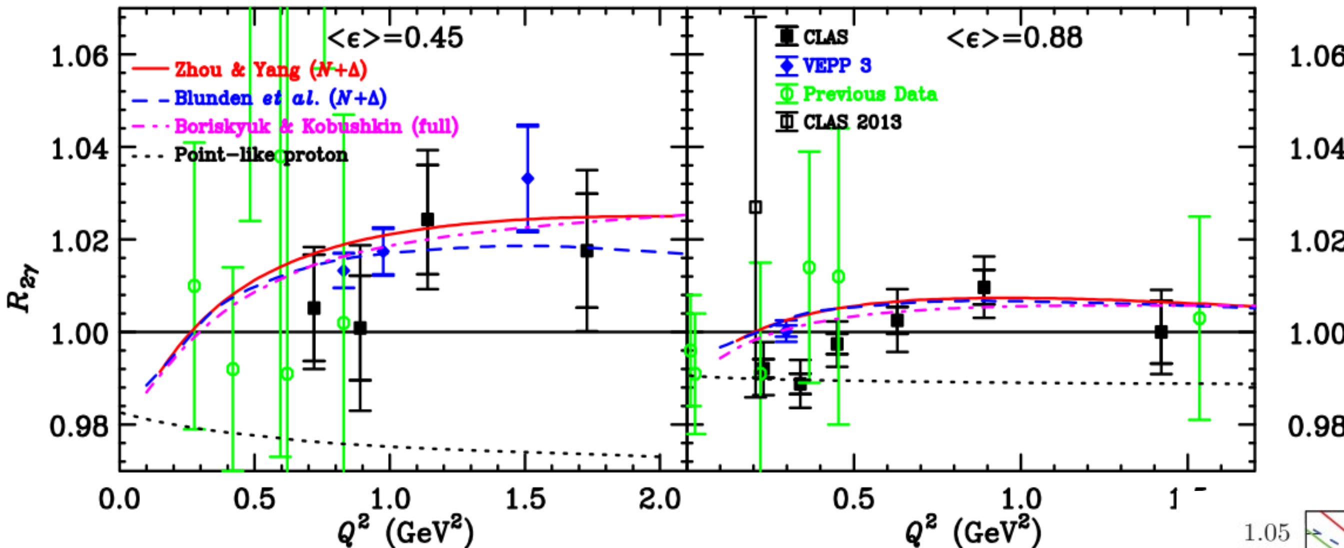
→ Expected to be relatively small for P-T method

2-γ contributions from e+p / e-p ratios

Hard 2-γ contribution comes in with different signs for e+p and e-p =>

$$\sigma+/\sigma- = R_{2\gamma} \sim 1-2\delta_{2\gamma}$$

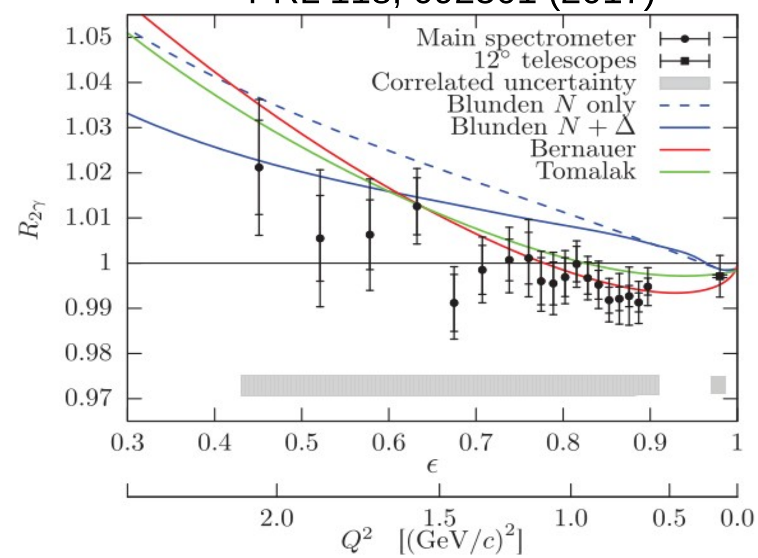
D. Rimal et. al [PRC]



New data from

- VEPP-3
- CLAS
- OLYMPUS

OLYMPUS
PRL 118, 092501 (2017)



Conclusions from combined analysis of
A. Afanasev, P. G. Blunden, D. Hasell, and B. A. Raue:

→ CLAS and VEPP-3 and OLYMPUS data exclude no TPE hypothesis at >95% confidence level

→ Data of insufficient precision to distinguish calculations of 2-γ contributions

→ Renormalization of OLYMPUS results required at twice the estimated uncertainty

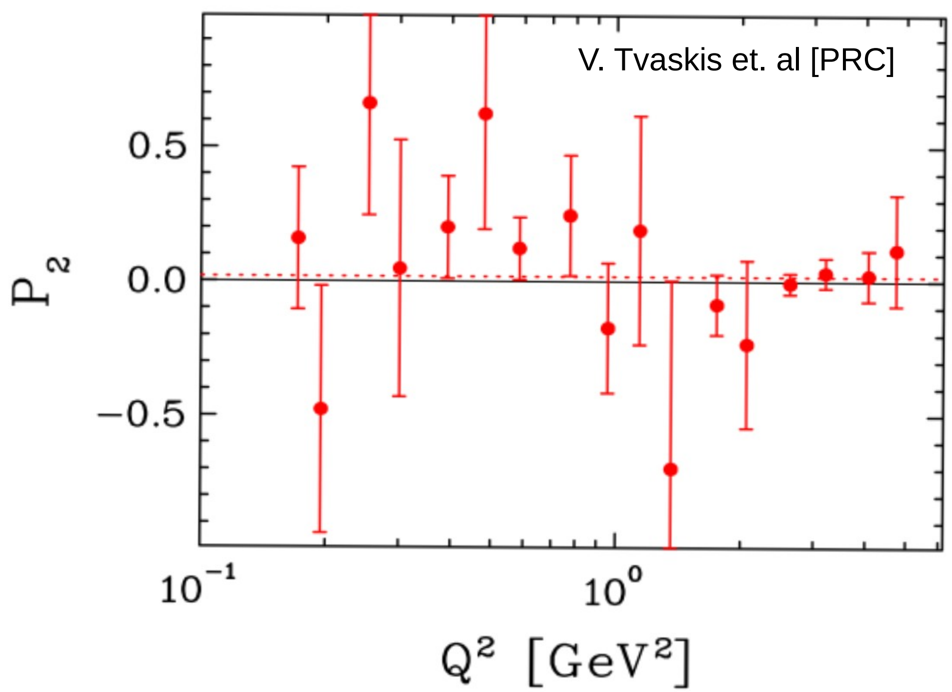
Non-linearities in existing Rosenbluth data

→ Existing data indicate *no significant* non-linearities vs ε

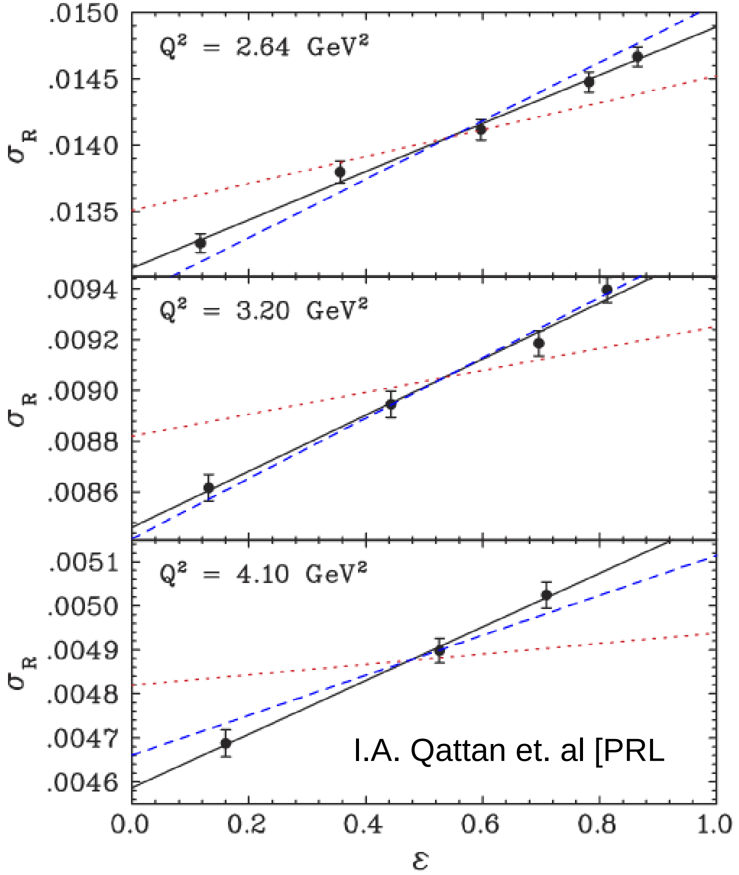
Fit of elastic data to quadratic form

$$\sigma_r = P_0 + P_1(\varepsilon - 0.5) + P_2\,(\varepsilon - 0.5)^2$$

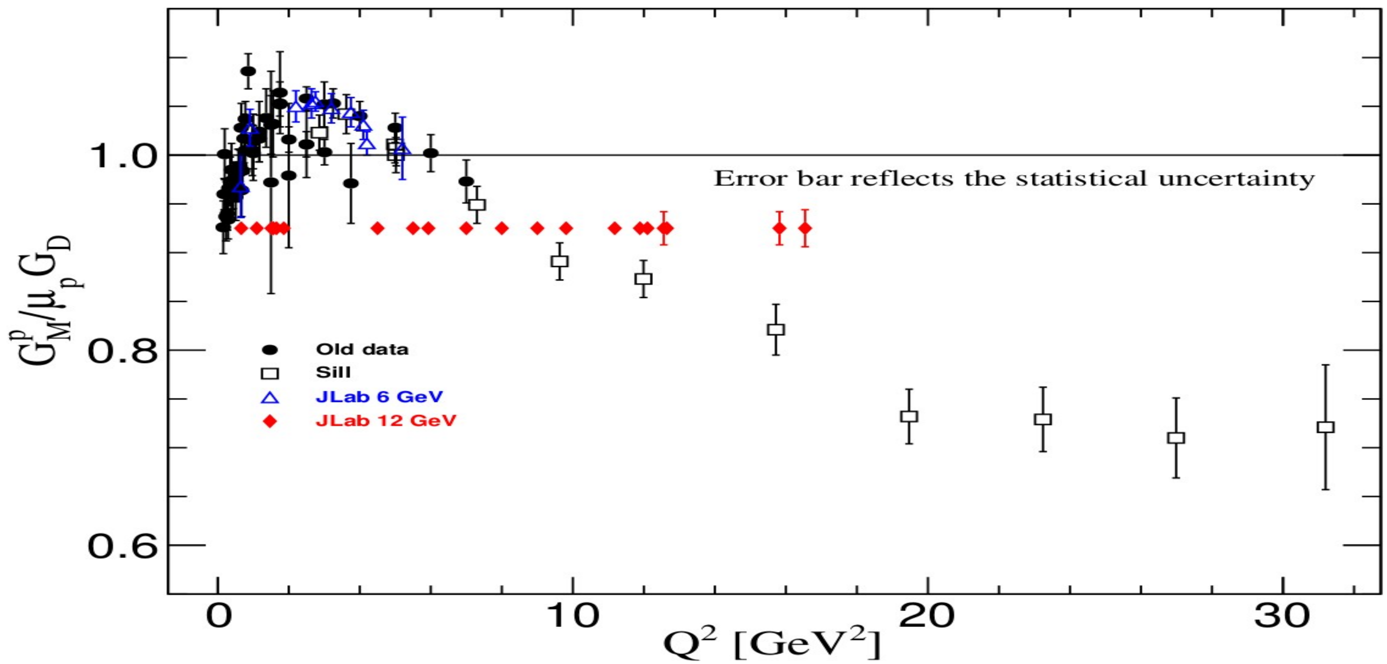
$$\langle P_2 \rangle = 0.019 \pm 0.027$$

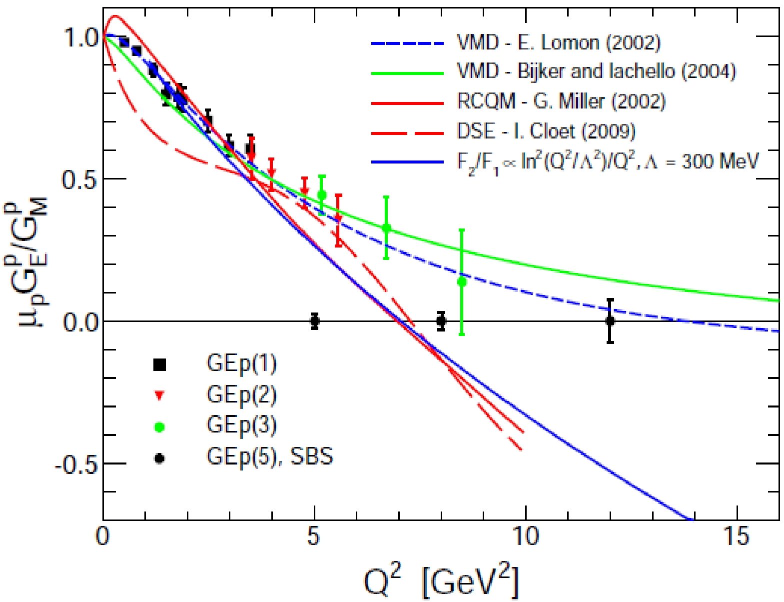


Super-Rosenbluth data also consistent with linear ε dependence of σ_r



Precision GMp is part of the 12 GeV Form Factor Program





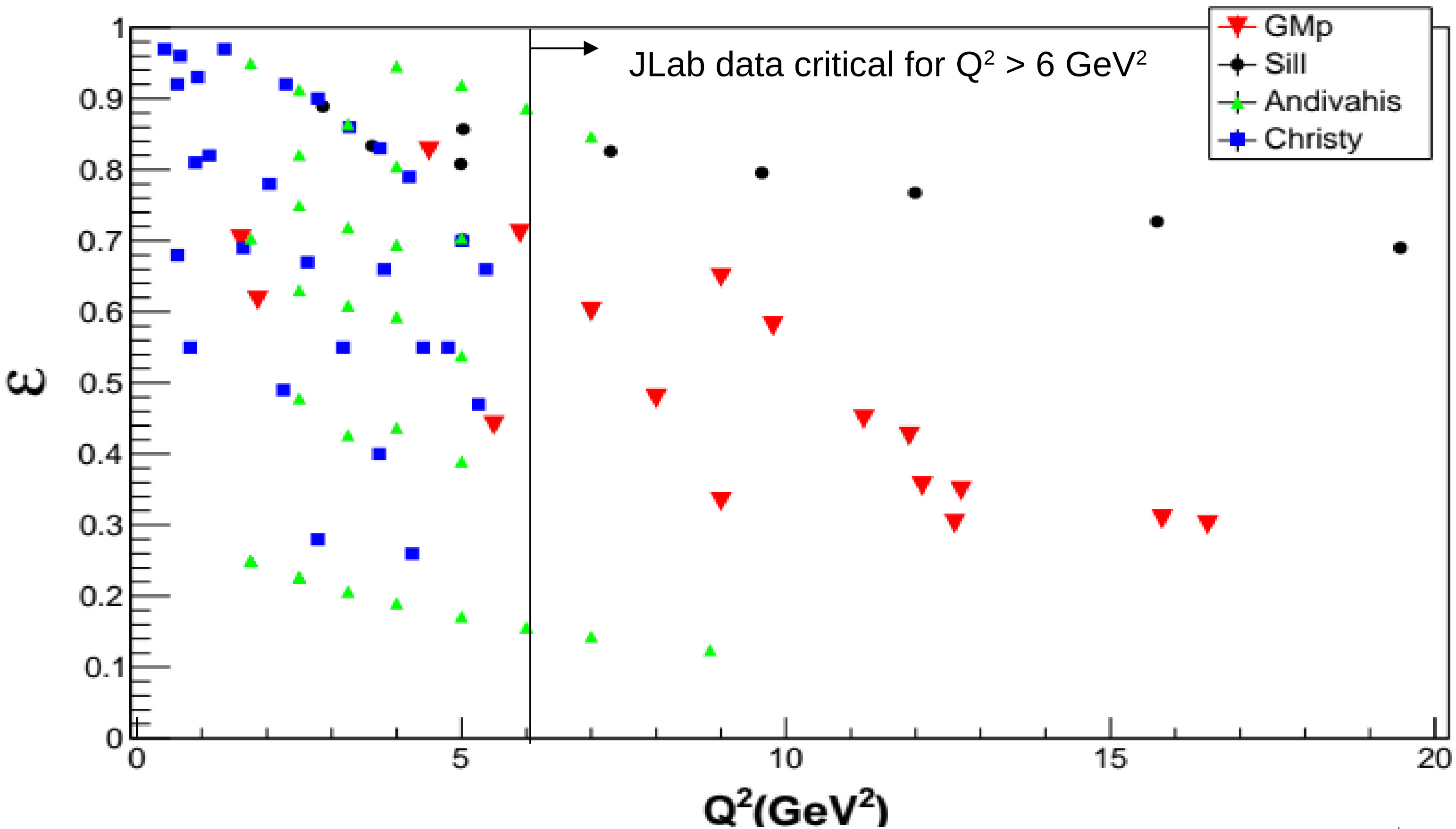
→ Precision G_M required to study approach of QCD scaling in Dirac F_1

$$F_1 = (G_E + Q^2/4M_N^2 \times G_M)/(1 + Q^2/4M_N^2)$$

→ F_2 provides constraint on E(x,t) GPD at high-x, high-t via sum rules

→ Precision G_M up to Q^2 ~12 GeV^2 complementary to 12 GeV polarization Transfer measurements of G_E/G_M

GMp and other High Q^2 data



→ GMp12 data at much smaller ε than Sill data

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

- Less sensitivity to G_E in extracting G_M
- Lever arm in ε provides sensitivity to:
  - 2γ from global fit utilizing G_E / G_M from polarization transfer

E12-07-108 Experiment Overview

- Precision measurement of the elastic *ep* cross-section over the wide range of the Q^2 and extraction of proton magnetic form factor

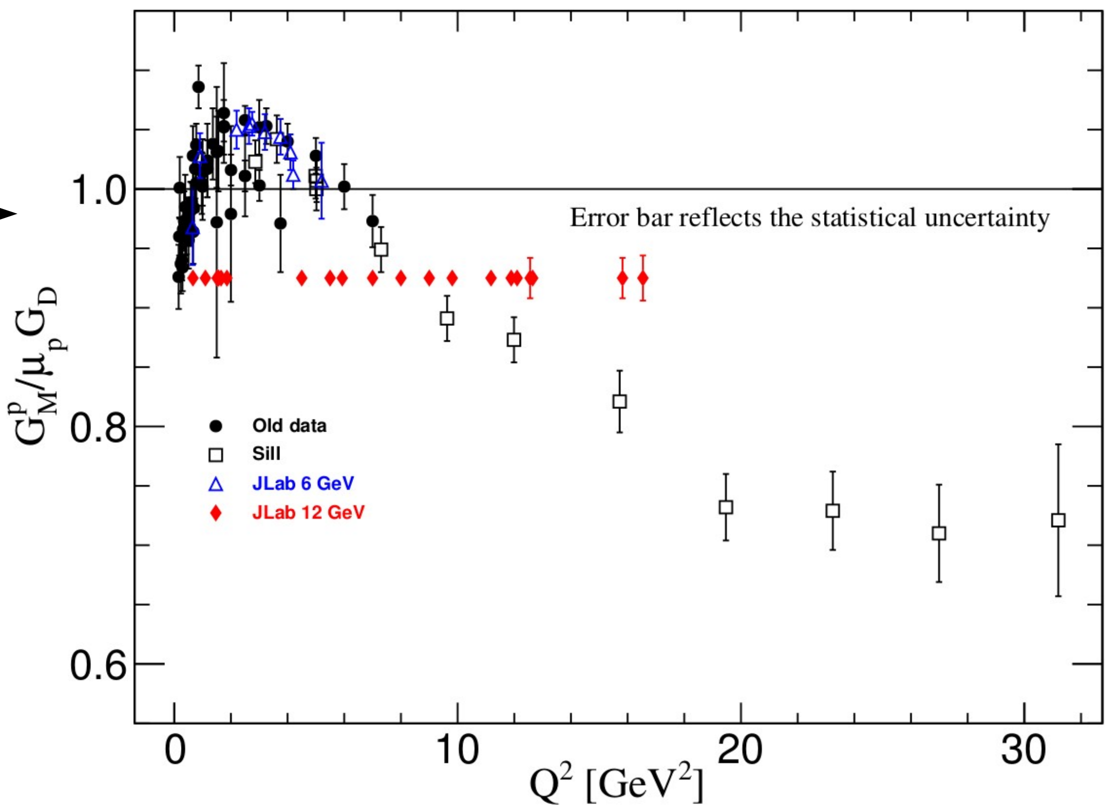
➢ To improve the precision of cross section at high Q^2 by a factor of 3

➢ To provide insight into scaling behavior of the form factors at high Q^2

GMp Uncertainties:

Statistical: Significant improvement over existing data for $Q^2 > 6$

Systematic Goals:
Point to point: 0.8-1.1%
Normalization: 1.3%

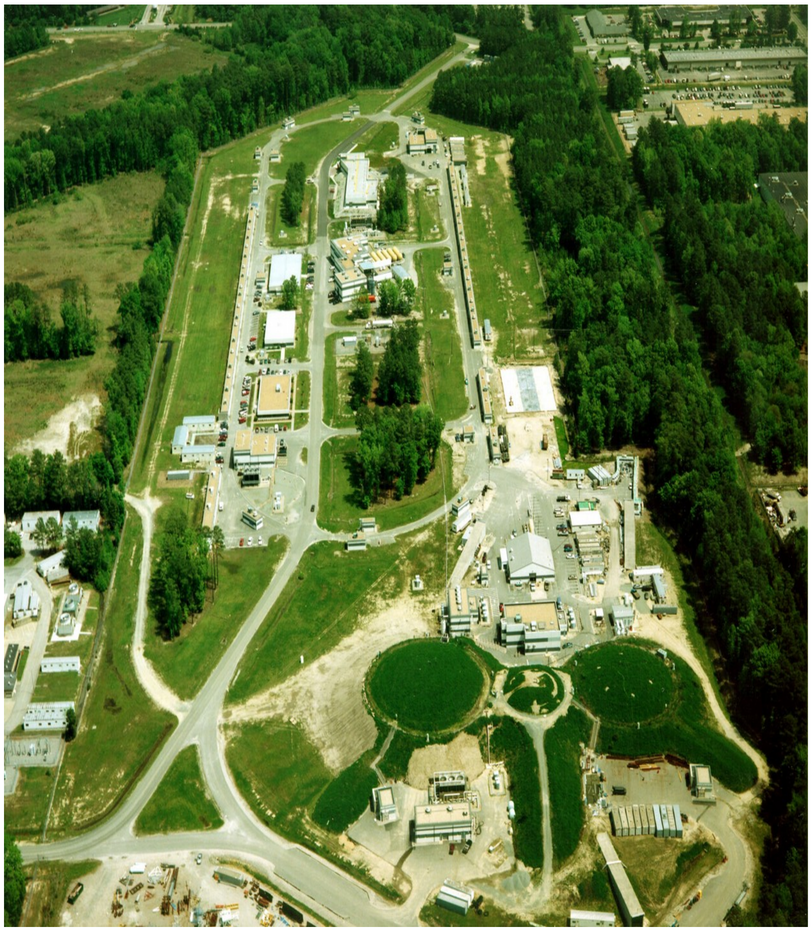


Need a good control on:

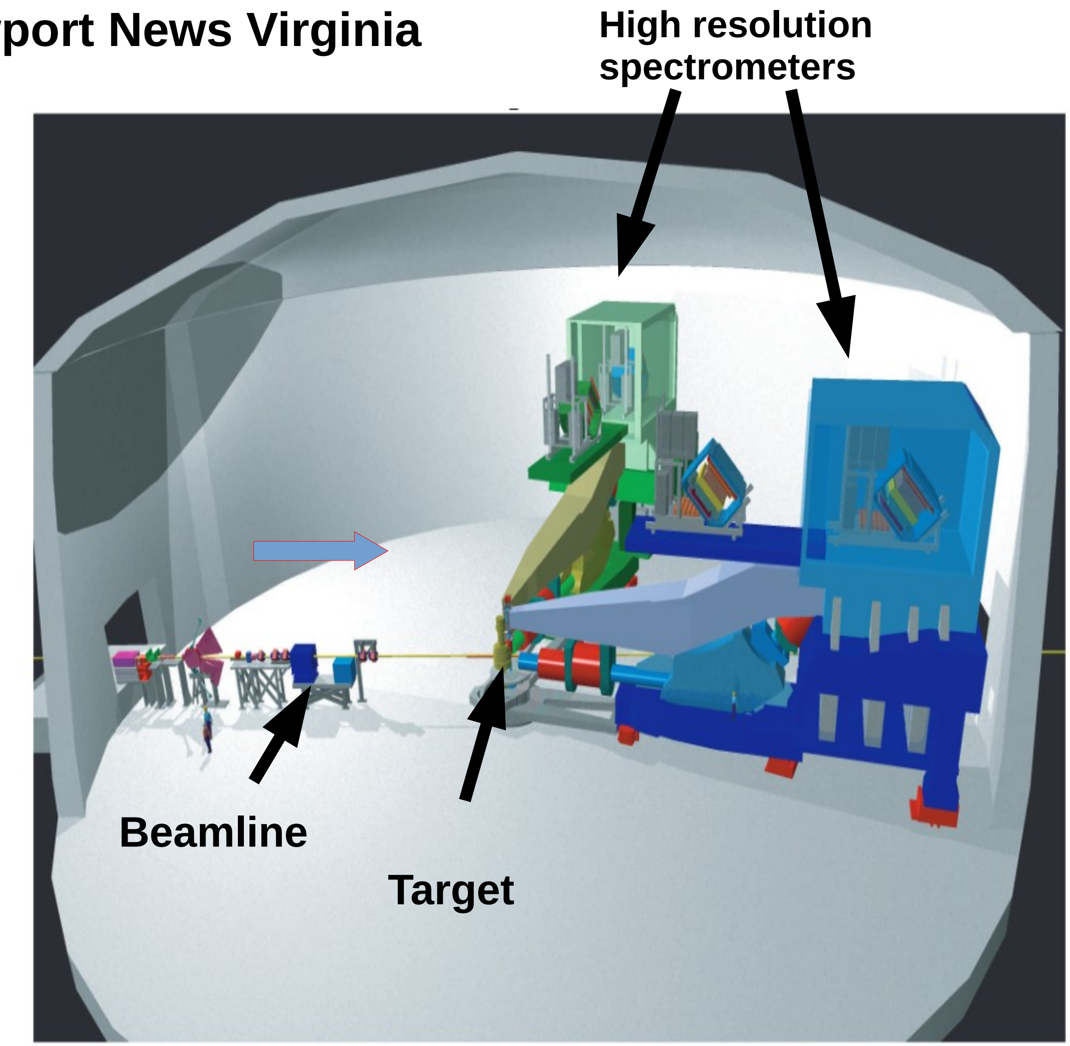
- Beam charge
- Beam position
- Scattering angle
- target density, ...

Experimental setup

Jefferson Lab at Newport News Virginia

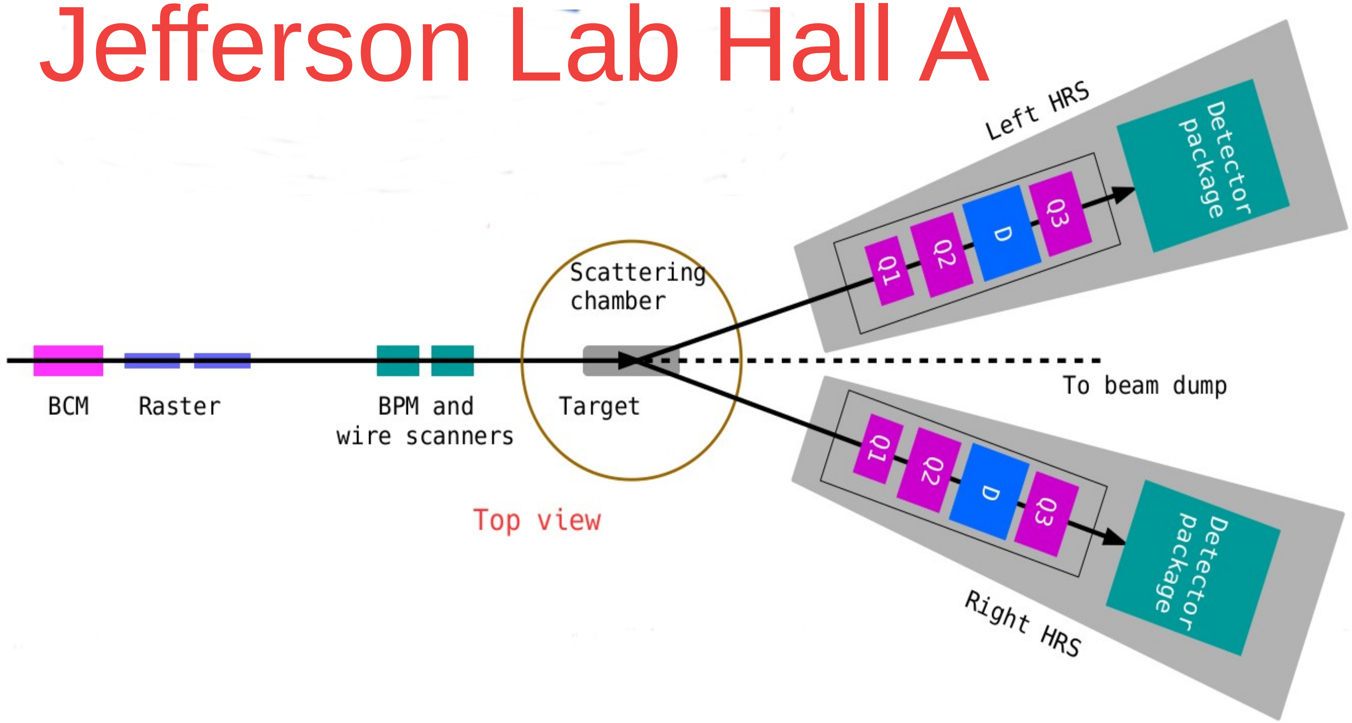


CEBAF: Continuous Electron Beam Accelerator Facility



Experimental Hall A

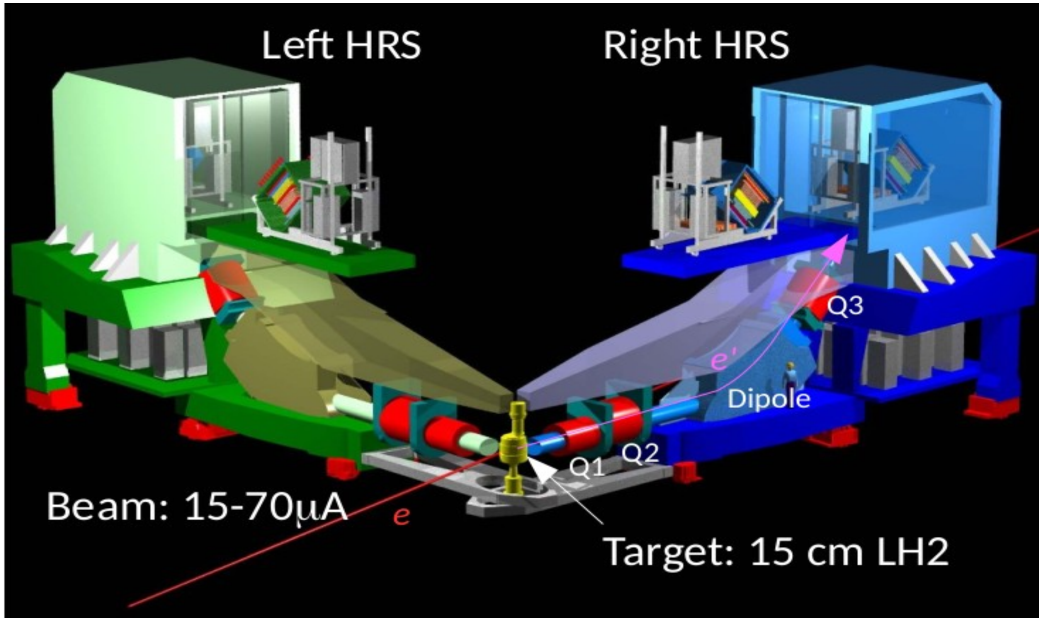
Jefferson Lab Hall A

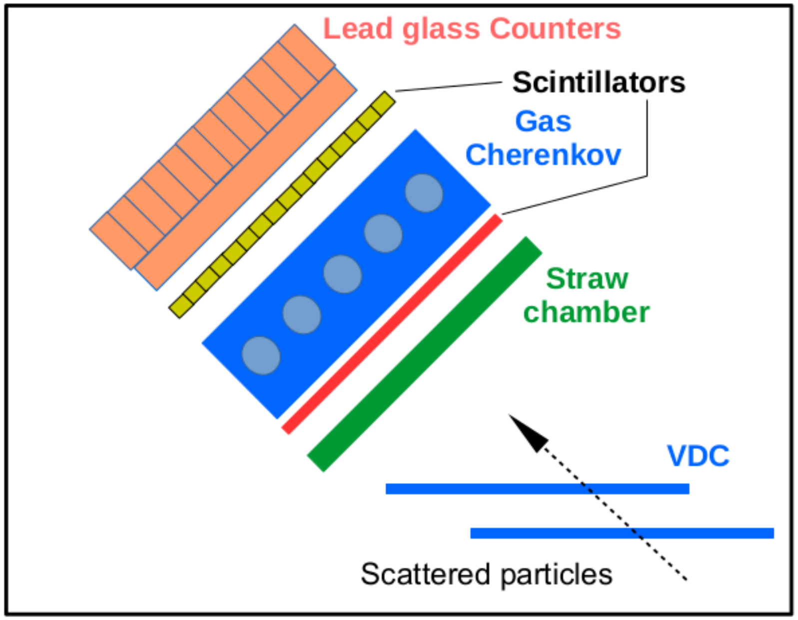


HRS Parameters:

Acceptance: $-4.5\%<\Delta p/p<4.5\%$, 6 msr

Resolution: $\delta p/p \leq 2\times10^{-4}$
$\Delta x'_{tar}$= 0.5 mrad (Horizontarl)
$\Delta y'_{tar}$= 1.0 mrad (Vertical)





Data collected during GMp

Spring 2015:

E_{beam} (GeV)	HRS	P_0 (GeV/c)	Θ_{HRS} (deg)	Q^2 $(GeV/c)^2$	Events(k)
2.06	R	1.15	48.7	1.65	157
2.06	L	1.22	45.0	1.51	386
2.06	L	1.44	35.0	1.1	396
2.06	L	1.67	25.0 *	0.66	405

Spring 2016:

* Surveyed angles

E_{beam} (GeV)	HRS	P_0 (GeV/c)	Θ_{HRS} (deg)	Q^2 $(GeV/c)^2$	Events(k)
4.48	R	1.55	52.9	5.5	108
8.84	R	2.10	48.8*	12.7	8
8.84	L	2.50	43.0*	11.9	11
11.02	R	2.20	48.8*	16.5	0.7

Fall 2016: *Most complete systematic studies during this period

E_{beam} (GeV)	HRS	P_0 (GeV/c)	Θ_{HRS} (deg)	Q^2 $(GeV/c)^2$	Events(k)
2.22	R	1.23	48.8*	1.86	356
2.22	L	1.37	42.0*	1.57	2025
8.52	L	2.53	42.0*	11.2	18.9
8.52	L	3.26	34.4	9.8	57.6
8.52	L	3.69	30.9*	9.0	11.6
6.42	L	3.22	30.9*	5.9	48.6
6.42	L	2.16	44.5*	8.0	27.2
6.42	L	3.96	24.3	4.5	30.5
6.42	L	2.67	37.0	7.0	41.4
6.42	R	1.59	55.9*	9.0	11.6
8.52	R	2.06	48.6*	12.1	11
8.52	R	1.80	53.5*	12.6	3.4
10.62	R	2.17	48.8*	15.8	3.6

Measurement of Elastic Cross Section

- Cross section:

$$\frac{d\sigma}{d\Omega}(\theta) = \int dE' \frac{N_{\rm det}(E',\theta) - N_{\rm BG}(E',\theta)}{\mathcal{L}\cdot\epsilon_{\rm eff}\cdot {\rm LT}} \cdot A(E',\theta)\cdot {\rm RC}$$

- Reduced cross section:

$$\sigma_{\rm red} = \frac{d\sigma}{d\Omega}\frac{\epsilon(1+\tau)}{\sigma_{\rm Mott}} = \frac{4E^2\sin^4\frac{\theta}{2}}{\alpha^2\cos^2\frac{\theta}{2}}\frac{E}{E'}\epsilon(1+\tau)\frac{d\sigma}{d\Omega}$$

- Parameters:
  - N_{det}: number of scattered elastic electrons detected
  - N_{BG}: events from background processes
  - $\mathcal{L}$: Integrated luminosity
  - ϵ : Corrections for efficiencies
  - LT: live time correction
  - A(E',θ): spectrometer acceptance
  - RC: radiative correction factor
  - E: beam energy
  - θ: Scattering angle

A thorough understanding of all these parameters is crucial for a precision cross section measurement

Extraction of Elastic *ep* Cross Section

$$\frac{d\sigma}{d\Omega}^{data}(\theta) = \int dE' \boxed{\frac{N^{data}(E',\theta) - N_{BG}(E',\theta)}{\mathcal{L}^{data}.\epsilon.LT}} \cdot \frac{RC^{data}}{A^{data}(E',\theta)} \qquad (1)$$

$$\frac{d\sigma}{d\Omega}^{mod}(\theta) = \int dE' \frac{N^{MC}(E',\theta)}{\mathcal{L}^{MC}} \cdot \frac{RC^{MC}}{A^{MC}(E',\theta)}$$

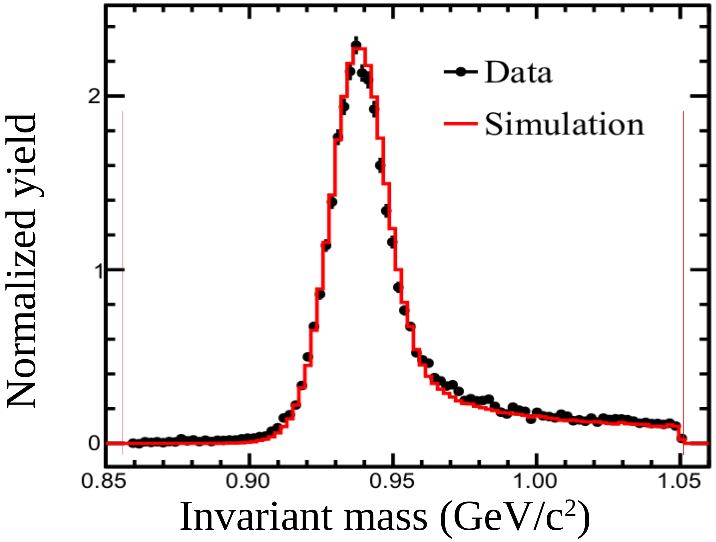
Radiative effects in Monte-Carlo based on improved Mo-Tsai from

R. Ent *et. al Phys.Rev. C64 (2001) 054610*

$$\frac{d\sigma}{d\Omega}^{data}(\theta) / \frac{d\sigma}{d\Omega}^{mod}(\theta) = \frac{\int^{E_{max}} (N^{data}(E',\theta) - N_{BG}(E',\theta))dE'}{\int^{E_{max}} N^{MC} dE'} \cdot \frac{A^{MC}(E',\theta)}{A^{data}(E',\theta)} \cdot \frac{RC^{data}}{RC^{MC}}$$

Assuming acceptance and ratiative contributions are correctly modeled:

$$\frac{d\sigma}{d\Omega}^{data}(\theta) = \frac{d\sigma}{d\Omega}^{mod}(\theta) . \frac{\boxed{Y^{data}}}{Y^{MC}}$$

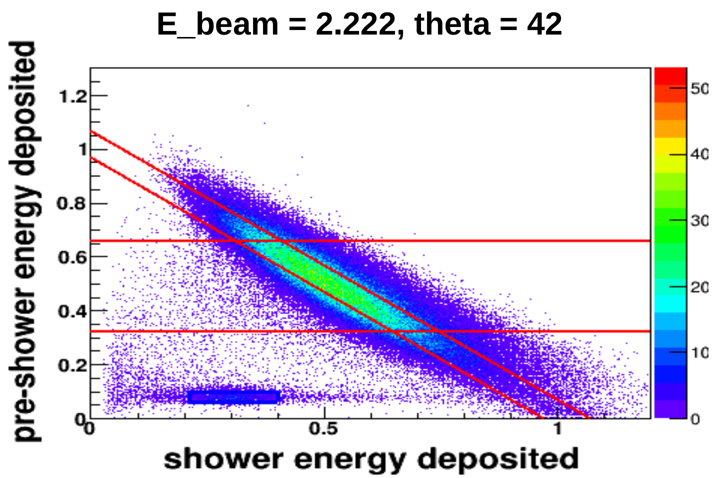


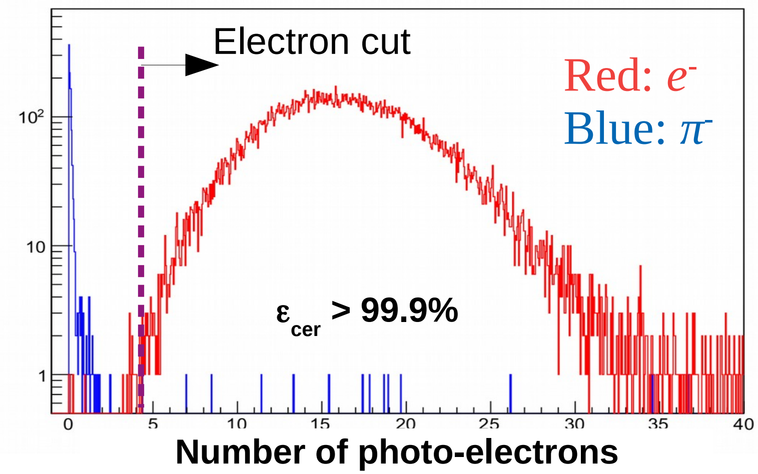
→ **Results were cross checked with acceptance correction method (eq 1) using Rad Cor based on code utilized for later SLAC experiments.**

Detector efficiencies

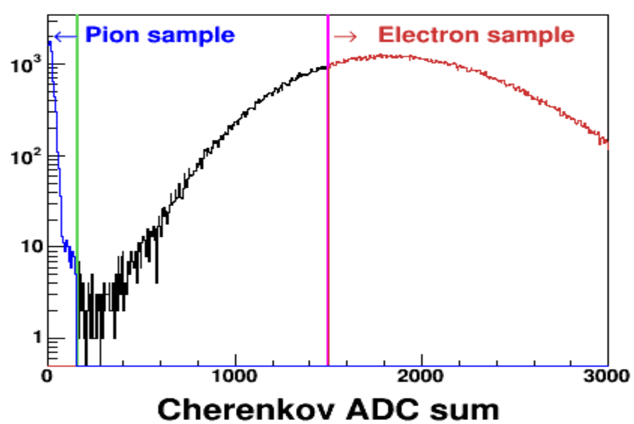
e^- sample selection in other detector

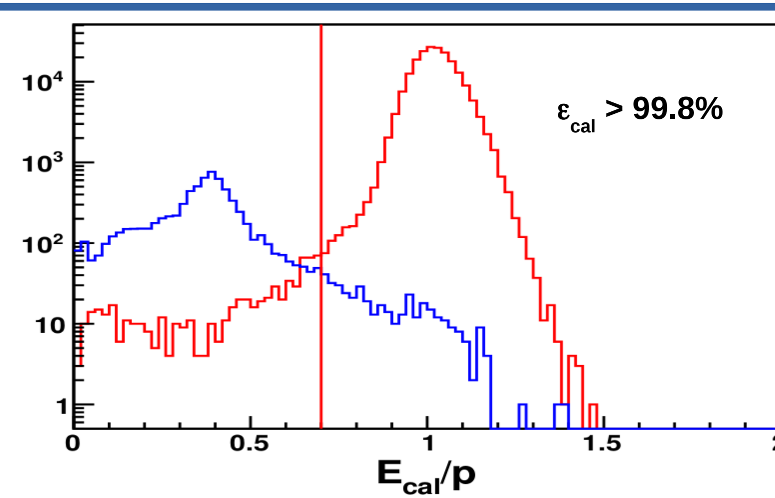
e^- cut efficiency





Cherenkov cut efficiency



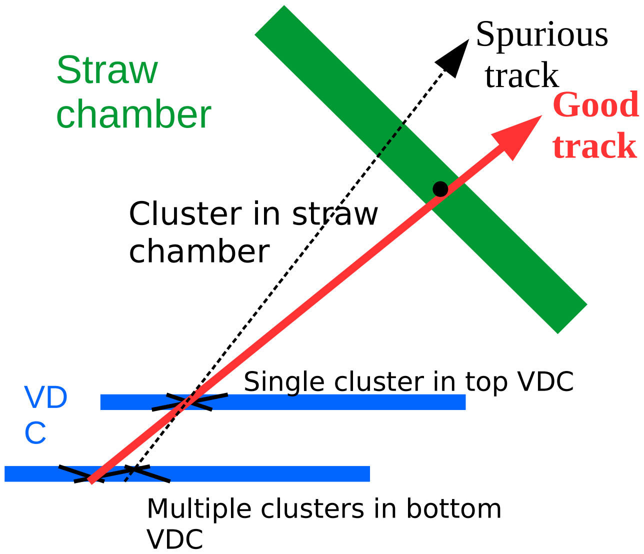


Calorimeter cut efficiency

$$\frac{\delta\epsilon}{\epsilon} < 0.1\,\%$$

VDC Track Reconstruction Efficiency

- Standard Tracking for HRS VDCs utilizes single cluster only in each chamber
- GMp utilized additional Straw Chamber to perform precise checks on efficiency determination



- Elastic events were reconstructed with:

  1. single cluster in both VDCs
  2. single cluster in 1 VDC + SC

Longwu Ou (MIT)

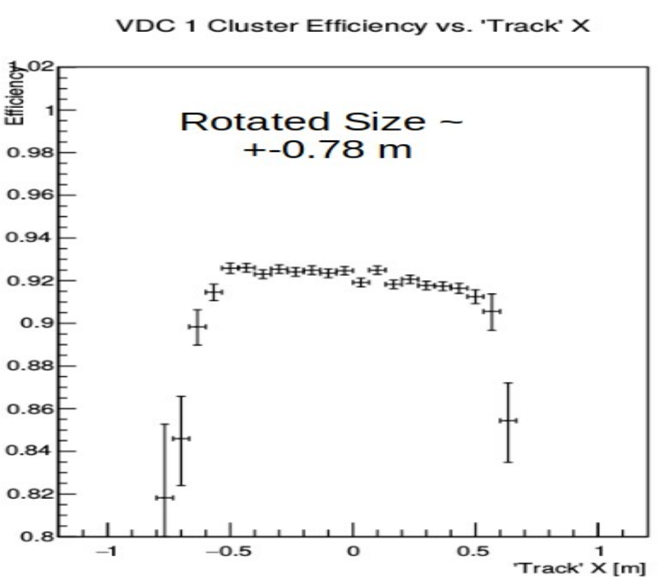
Kinematic	K3-4	K3-6	K3-7	K3-8	K4-9	K4-10	K4-11
Corrected Yield ratio	1.0016	0.9994	0.9993	0.9985	1.0007	1.0021	0.9997

Corrected yields agree to better than 0.2%

- A “coarse” track was formed using scintillator hit and straw chamber. This method enables us to estimate the track intercept at the focal plane without using VDC hits

Barak Schmookler (MIT)

Bashar Aljawrneh (NC A&T)

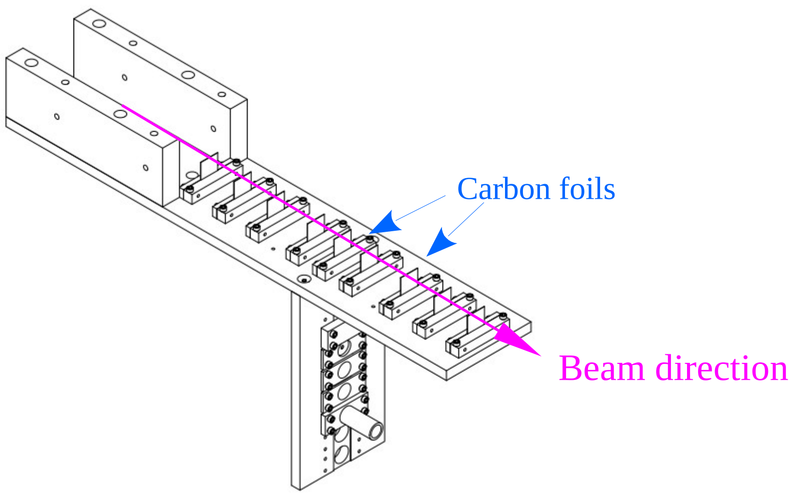


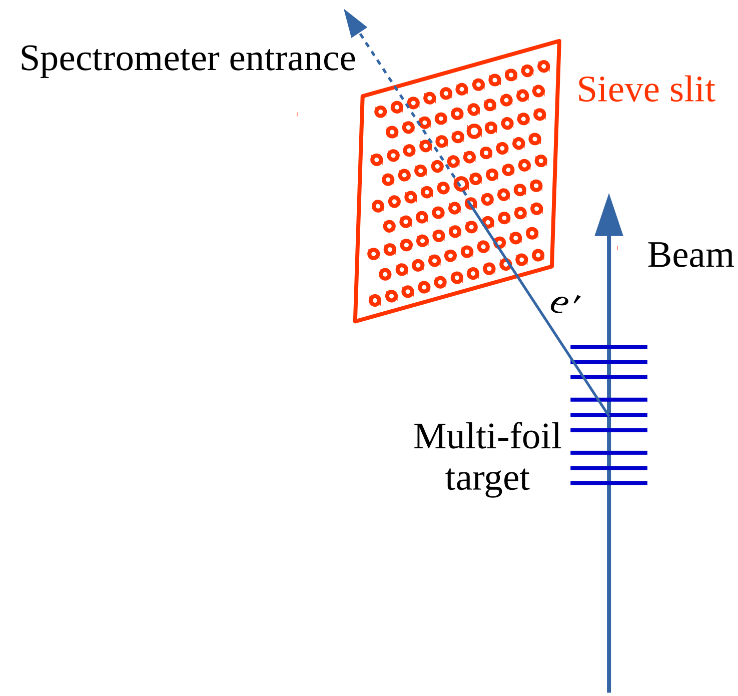
Significant Effort to Improve Optics Calibration

Longwu Ou (MIT)

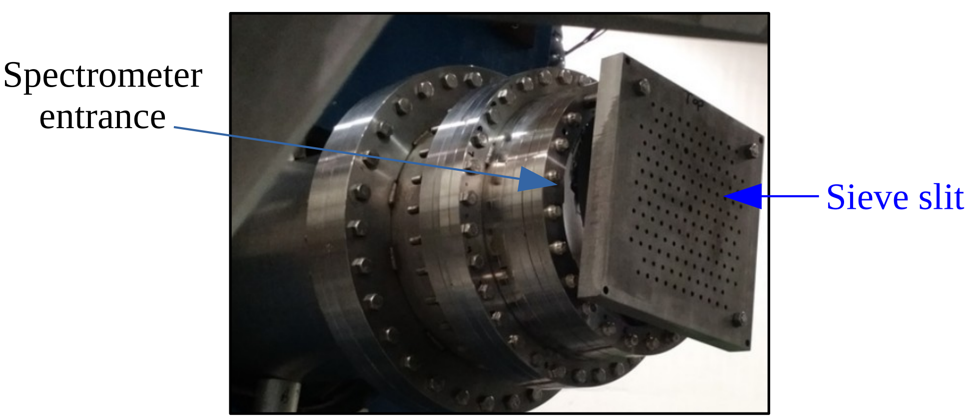
- **Angle and vertex calibration:** used deep inelastic electrons from multi-foil carbon target

A 9-foil carbon target covers a total length of 20 cm along the beam direction





A 1-inch-thick tungsten sieve slit with high density holes at the spectrometer entrance selects scattered electrons in specific directions



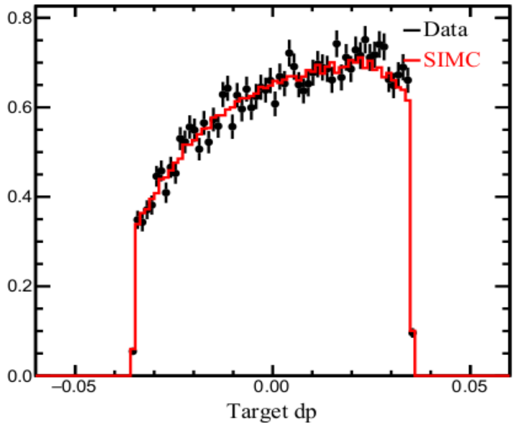
- Algorithm: Minimization of χ^2 by varying the optics coefficients

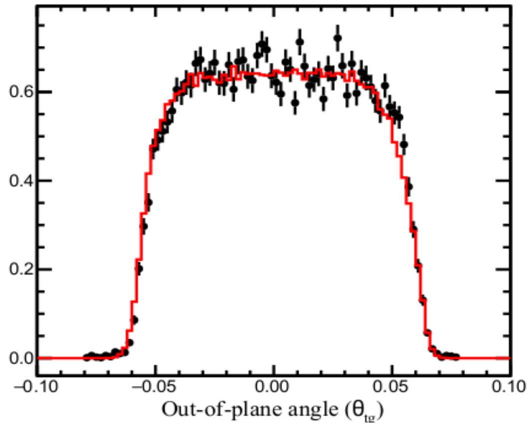
$$\chi^2(y_{tg}) = \sum_{\text{events}} \left(Y_{ijkl} x^i_{fp} \theta^j_{fp} y^k_{fp} \phi^l_{fp} - y^{\text{survey}}_{tg}\right)^2$$

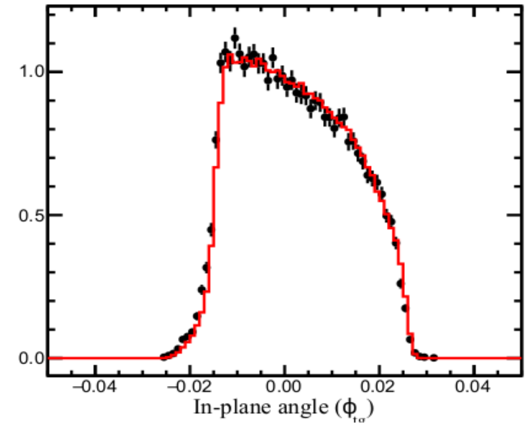
- **Momentum calibration:** used elastic electrons from liquid hydrogen target

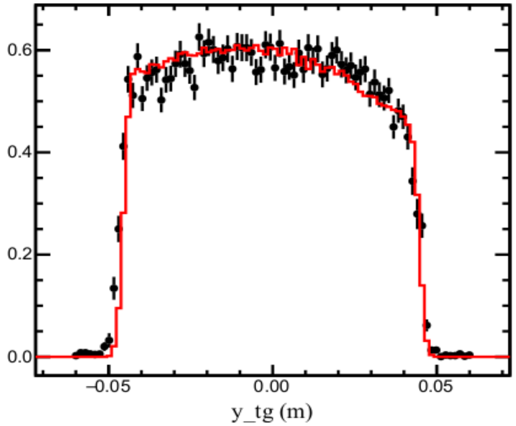
Example Data to Monte Carlo Comparison: LHRS

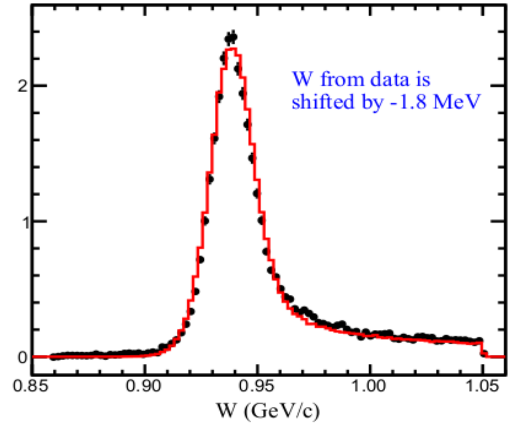
K3-7











Data to MC ratio: 1.0102

P_0: 2.6720 GeV/c

Beam energy = 6.427 GeV

Scattering angle = 37.01 deg

Q^2 = 6.99 $(GeV/c)^2$

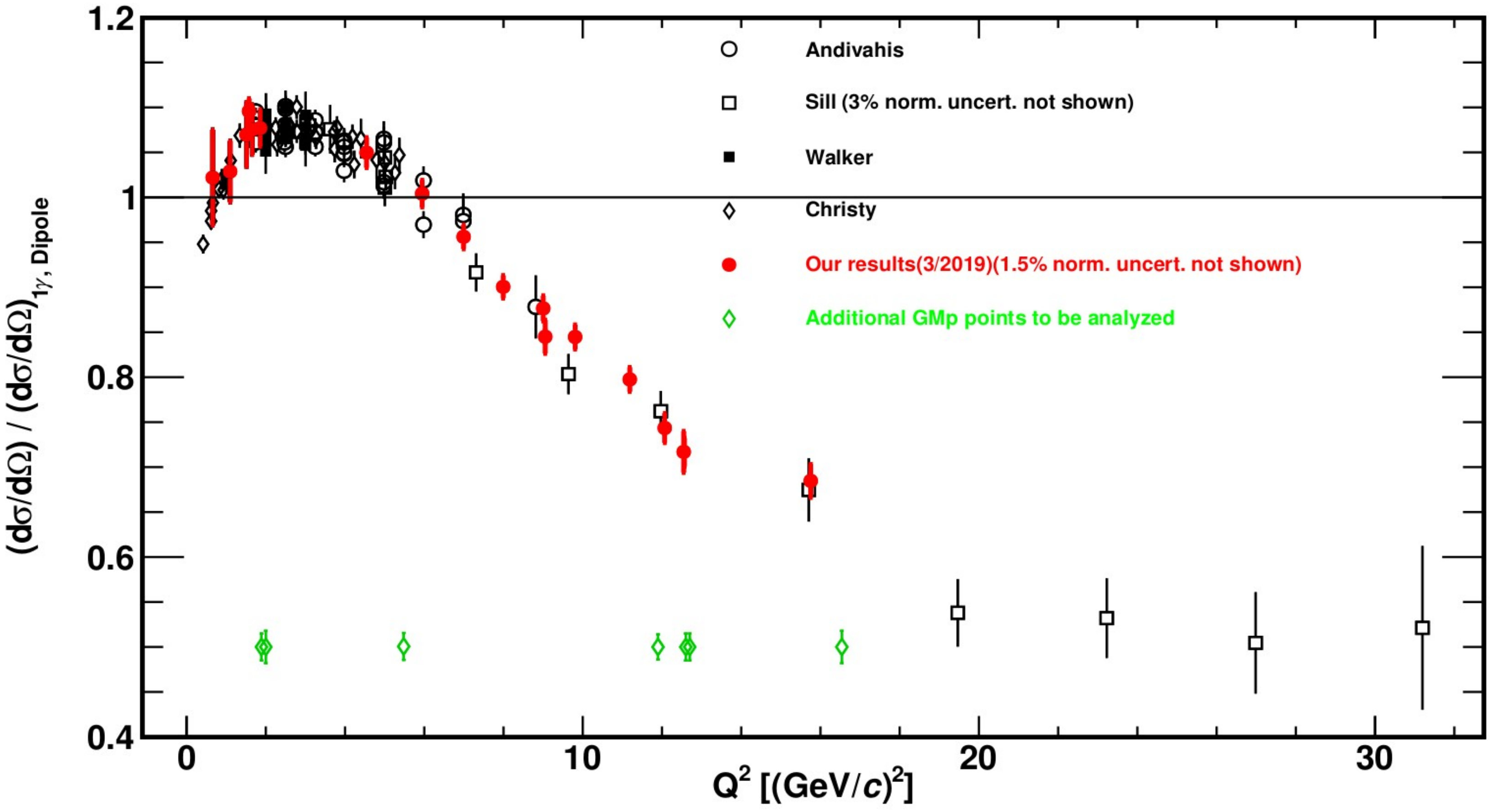
Cross section = 2.89e-06 ub/sr

- Excellent comparison after subtraction of target cell endcaps via dummy (~3%)
- Small offsets in W consistent with estimated kinematic uncertainties

Error Budget (LHRS Fall 2016)

Source	$d\sigma/\sigma$ (%) (pt-pt)	$d\sigma/\sigma$ (%) (Norm.)
Beam charge ($\Delta I = 0.06\ \mu A$)	0.6(at 10 μA) - 0.1(at 65 μA)	0.1
Scattering angle ($\Delta\theta = 0.2$ mrad)	0.1 - 0.4	0.1 - 0.4
Beam energy ($\Delta E = 5 \times 10^{-4}$)	0.3	0.3
Boiling	<0.35 (at 10 μA) - 0(at 60 μA)	0.35 (at 60 μ A)
Optics	0.3	0.3
Track Reco	0.2	0.2
PID	0.1	0.1
Trigger	0.2	0.1
Target Length		0.1
Spectrometer acceptance	0.7	0.8
Radiative correction	0.8	1.0
Background subtraction	0.2	0.2
Cross section model		0.1
Total	1.2 - 1.3%	1.4- 1.6%

GMp - E012-07-108 final cross sections



- Cross section relative to 1-γ cross section calculated with $G_E = G_M/\mu = G_{dip}$
- Significant improvement in precision for $Q^2 > 6$.
- Systematic uncertainties on Fall 2016 LHRS data ~1.3% (pt-pt), 1.5% (norm)
  RHRS (additional 2% from optics)

Status of 1st paper

- A draft of an intended PRL Letter was circulated Summer 2020.

- It was decided that we needed to address the impact of updated radiative corrections to older data studied by Gramolin et. al. Utilizing the formalism of Maximon & Tjon

  => This was found to reduce the tension with the P-T results.

- A. Gramolin provided corrections for data set of higher Q^2 data for which enough information on external materials was available.

=> This data set of 121 data points were included in a global fit

And Rosenbluth separations were updated.

Form factors and two-photon exchange in high-energy elastic electron-proton scattering

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Global fit: Maximizing information from the data

A global fit to the modern higher Q^2 cross section data (> 0.5) to:

- Provide good description of cross section
- Utilize for analysis of global Rosenbluth separations at large Q^2
- Study signal of 2-γ contributions at larger Q^2 by comparing to P-T data

Fit was performed to the reduced cross section utilizing:

- Rosenbluth form $$\sigma_R = \frac{d\sigma}{d\Omega}\frac{\varepsilon(1+\tau)}{\tau\sigma_{Mott}} = \frac{\varepsilon}{\tau}\left(G_E^p\right)^2 + \left(G_M^p\right)^2,$$
- Updated radiative corrections from Gramolin *et. al* applied for 'modern' data (121 data points with $Q^2 > 0.4$).
- Normalization factors determined as nuisance parameters.

Global fitting results: Fit comparisons

We have studied the systematics for different fit choices:

1. **Form Factor fit to full Q^2 data set (467 data points):**

$$\sigma_R = \frac{d\sigma}{d\Omega}\frac{\varepsilon(1+\tau)}{\tau\sigma_{Mott}} = \left(G_M^p\right)^2 + \frac{\varepsilon}{\tau}\left(G_E^p\right)^2$$

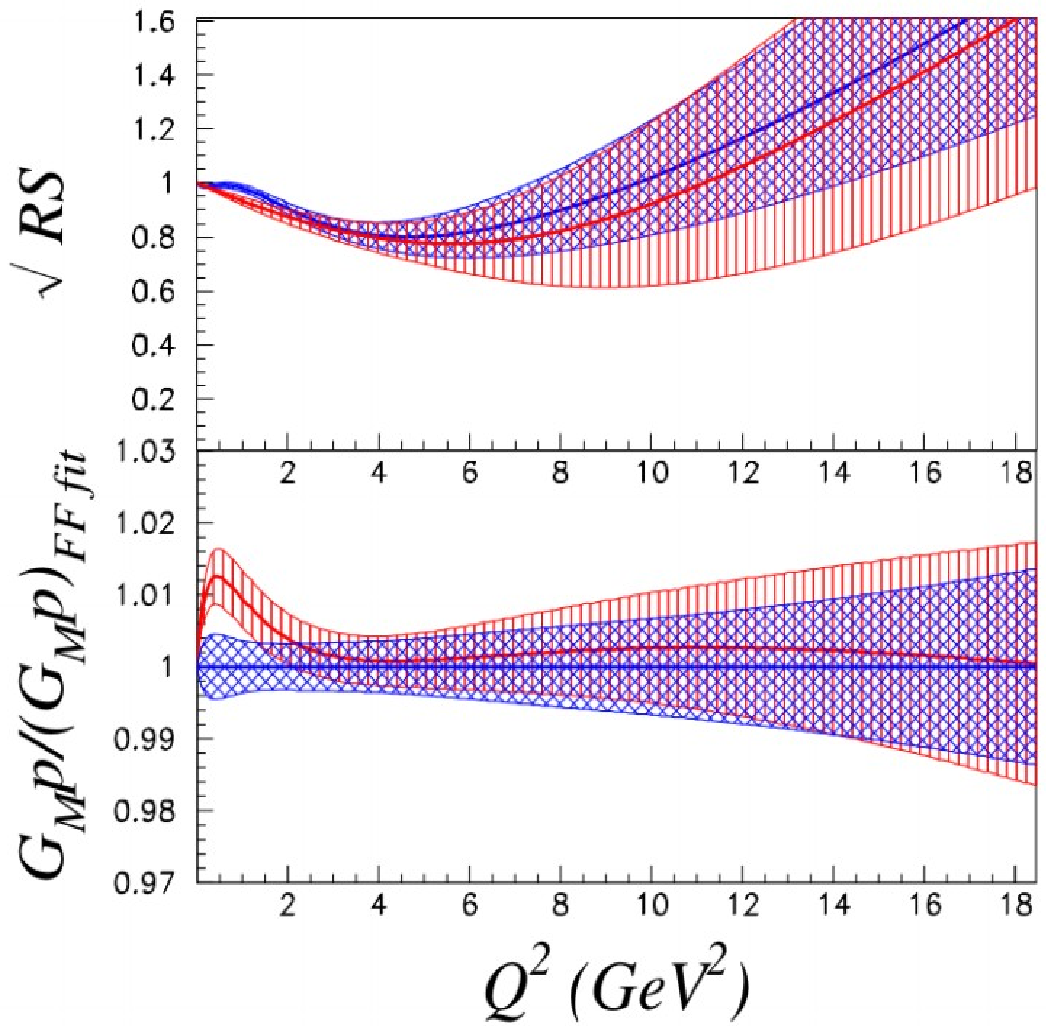
Form factors utilize Kelly-like form

1. **G_M / RS fit to restricted data set with new RCs (121 data points):**

$$\sigma_R = \frac{d\sigma}{d\Omega}\frac{\varepsilon(1+\tau)}{\tau\sigma_{Mott}} = \left(G_M^p\right)^2\left(1+\frac{\epsilon}{\mu^2}RS\right)$$

$$RS = 1 + c_1\tau + c_2\tau^2$$

<u>Comparison of fit results</u>

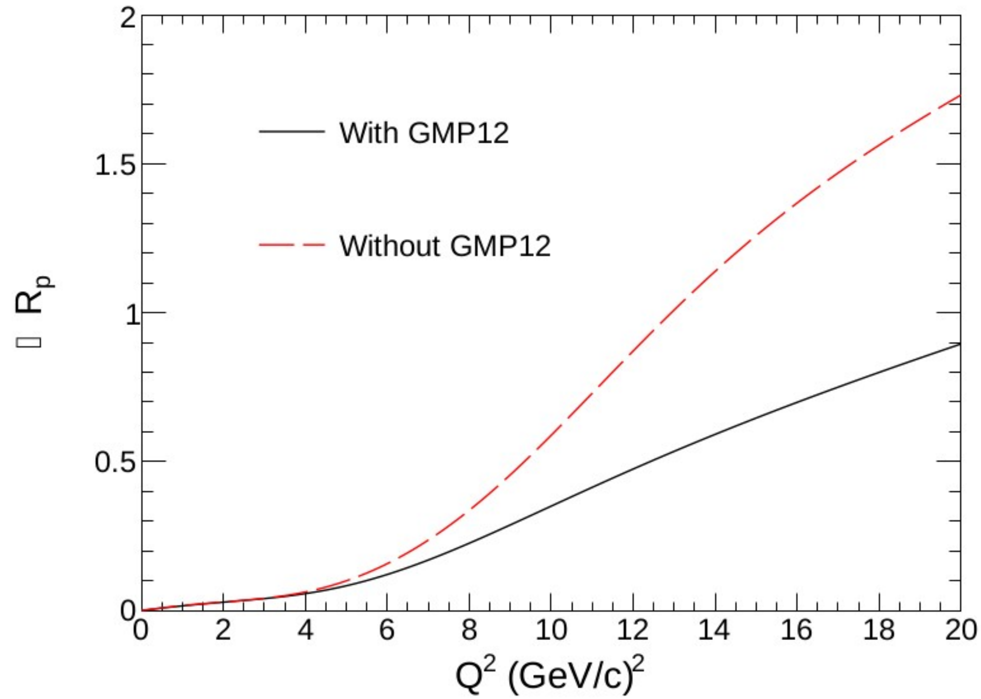


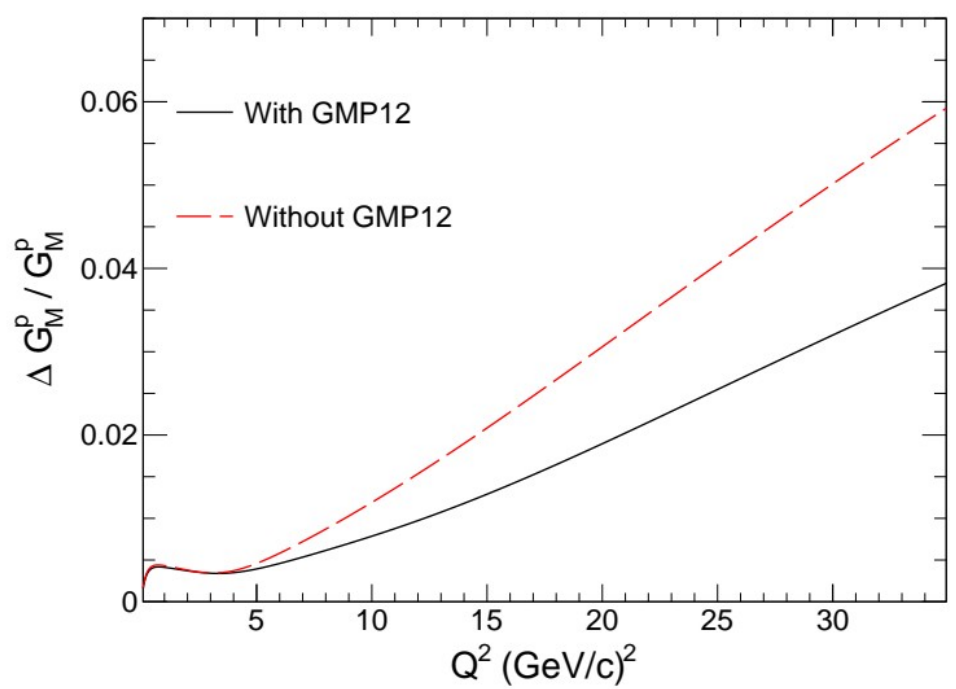
Global fitting results: Impact of GMp12 data

$$\sigma_R = \frac{d\sigma}{d\Omega}\frac{\varepsilon(1+\tau)}{\tau\,\sigma_{Mott}} = \left(G_M^p\right)^2\left(1+\frac{\epsilon}{\mu^2}RS\right)$$

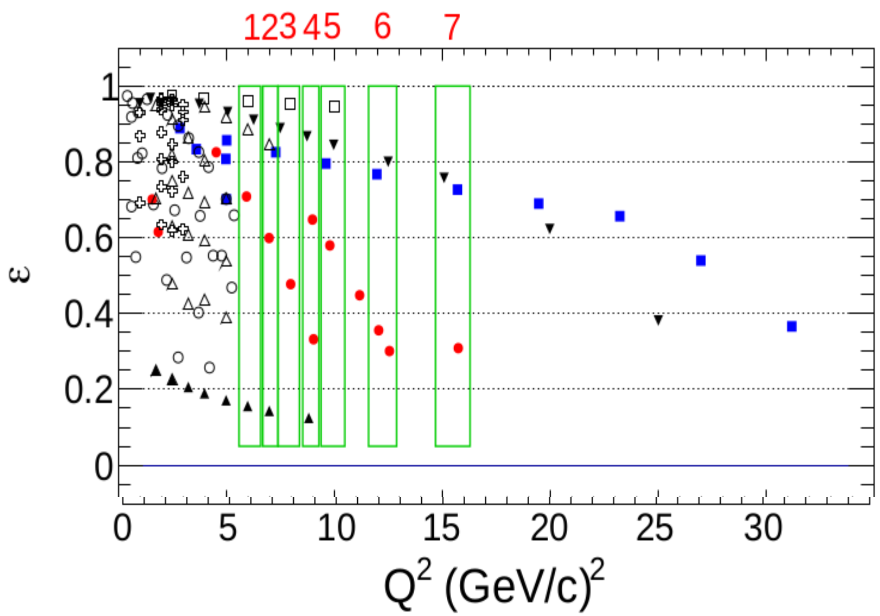
GMp12 data reduces FF ratio uncertainty by factor of **~2** for **Q^2 > 8**

For large fraction of JLab 12 GeV Region GMp12 data reduces G_M^p uncertainty by **~40%**





Rosenbluth separations with GMp12



$$\sigma_R = \frac{d\sigma}{d\Omega}\frac{\varepsilon(1+\tau)}{\tau\sigma_{Mott}} = \frac{\varepsilon}{\tau}\left(G_E^p\right)^2 + \left(G_M^p\right)^2,$$

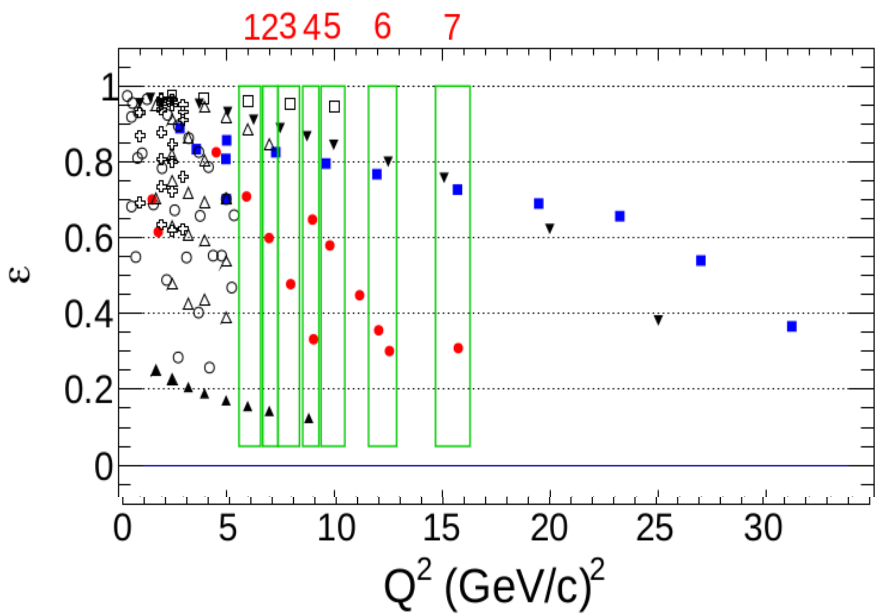
For $Q^2 > 7$, GMp12 data:

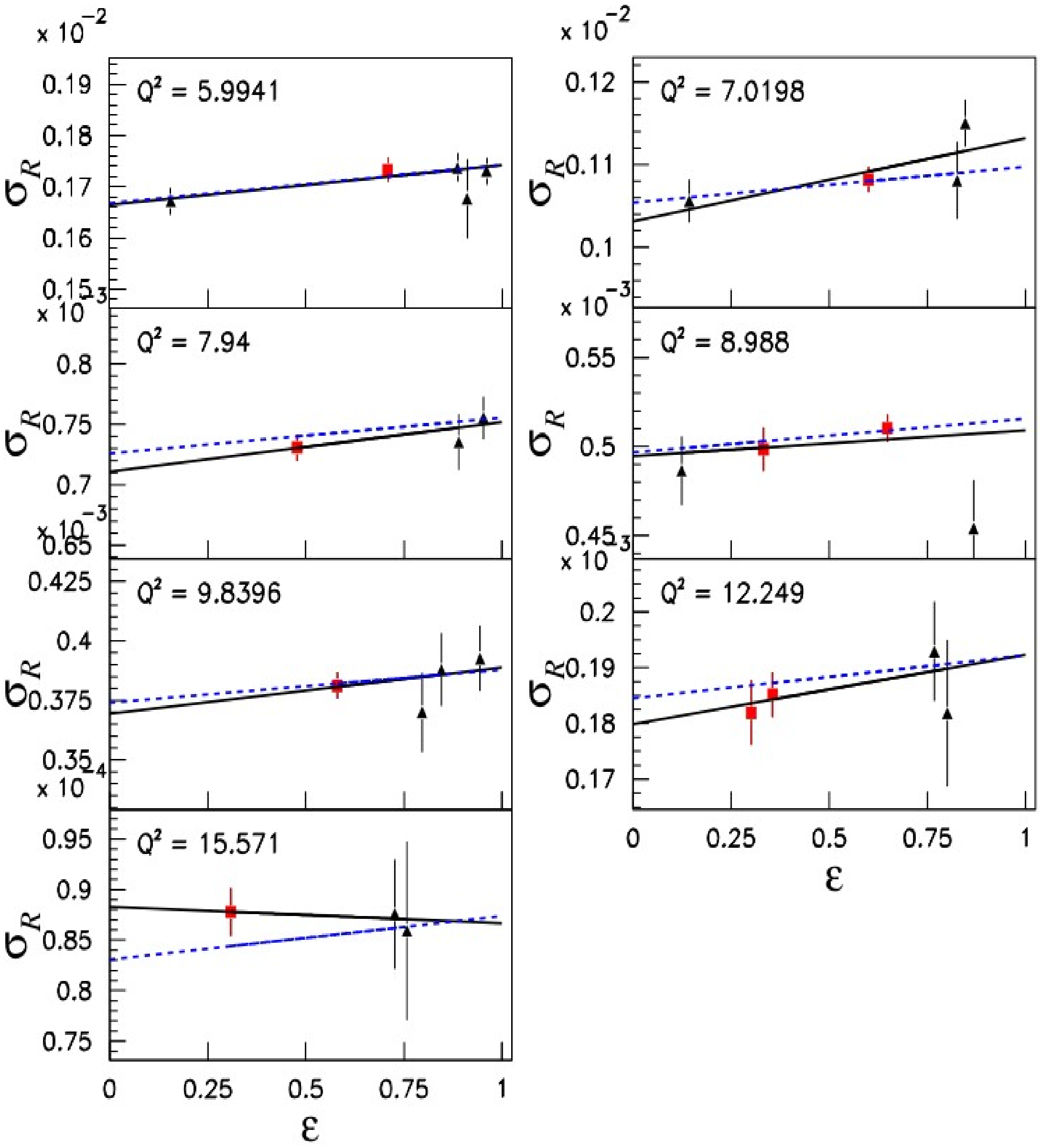
- uncertainties typically 2-4 times smaller than existing data.
- increases lever arm in ε of existing data, allowing Rosenbluth separations for 1st time.

To combine different experiments:

- use global fit to center boxed data to same Q^2
- normalize each data set using global fit results.
- include normalization uncertainties in pt-pt errors for all sets except GMp12.

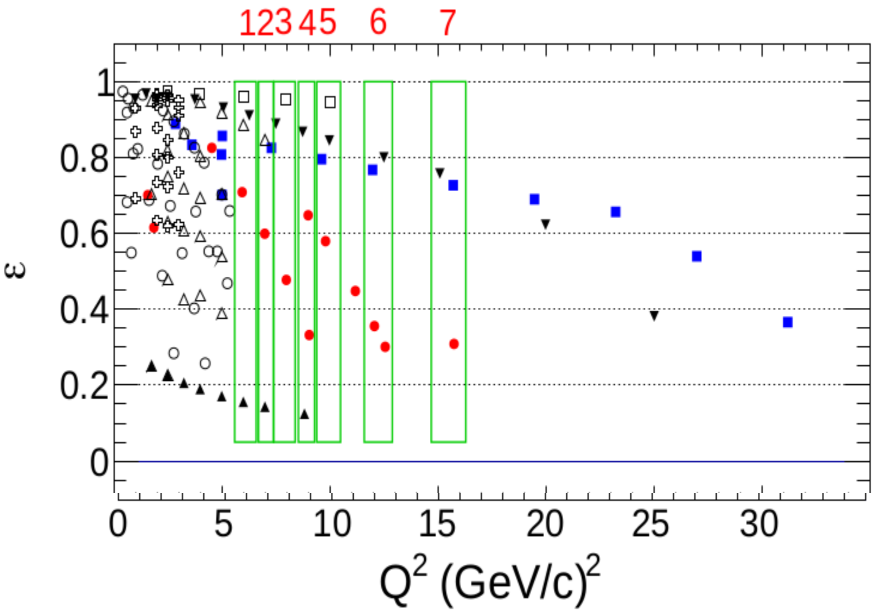
Rosenbluth separations with GMp12

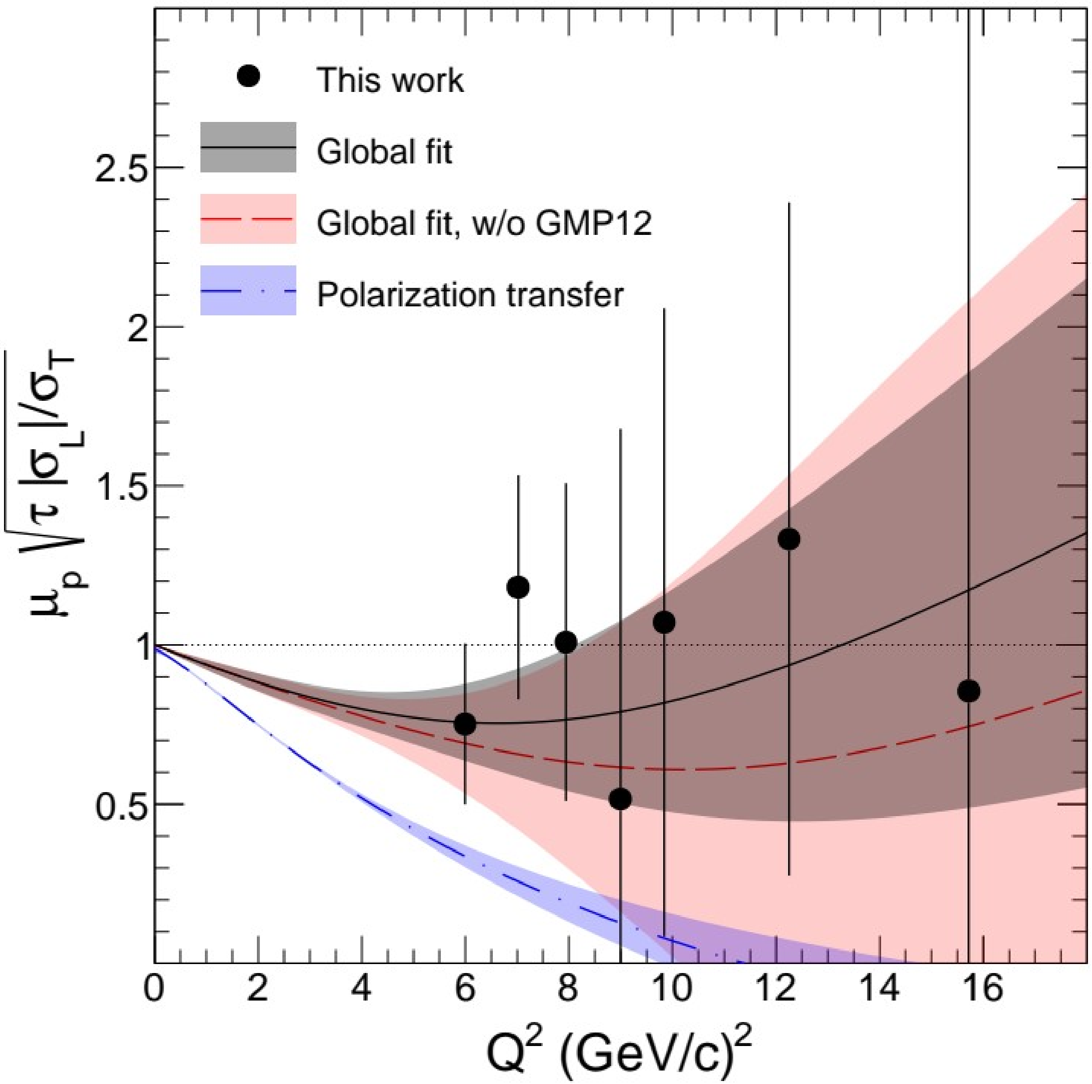




$$\sigma_R = \frac{d\sigma}{d\Omega}\frac{\varepsilon(1+\tau)}{\tau\sigma_{Mott}} = \frac{\varepsilon}{\tau}\left(G_E^p\right)^2 + \left(G_M^p\right)^2,$$

Rosenbluth separations with GMp12





$$\sigma_R = \frac{d\sigma}{d\Omega}\frac{\varepsilon(1+\tau)}{\tau\,\sigma_{Mott}} = \frac{\varepsilon}{\tau}\left(G_E^p\right)^2 + \left(G_M^p\right)^2$$

Significant tension with P-T results is observed for 1st time for $Q^2 > 7$ GeV^2

Summary

- GMp12 provided benchmark for precision inclusive cross sections using HRS spectrometers.
  - → Final Cross sections for Fall2016 data to be published soon with uncertainties of

    1.2 - 2% pt-pt

    1.5% normalization

  - → Uncertainty on GMp for 12 GeV kinematics reduced by ~40% or more.
  - → important for JLab 12 GeV Form Factor and GPD program
  - → provides precision normalization for upcoming 12 GeV experiments at JLab

- Significant evidence for continuing tension with P-T data for $Q^2 > 6$ signaling evidence of 2-γ contributions for 1st time.
- Updated draft of 1st paper coming very soon.

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Thanks!

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