Nucleon Form Factors at the (M)EIC/MeRHIC

Guy Ron

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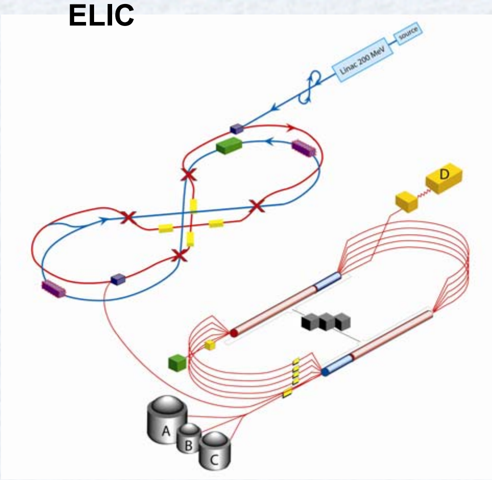
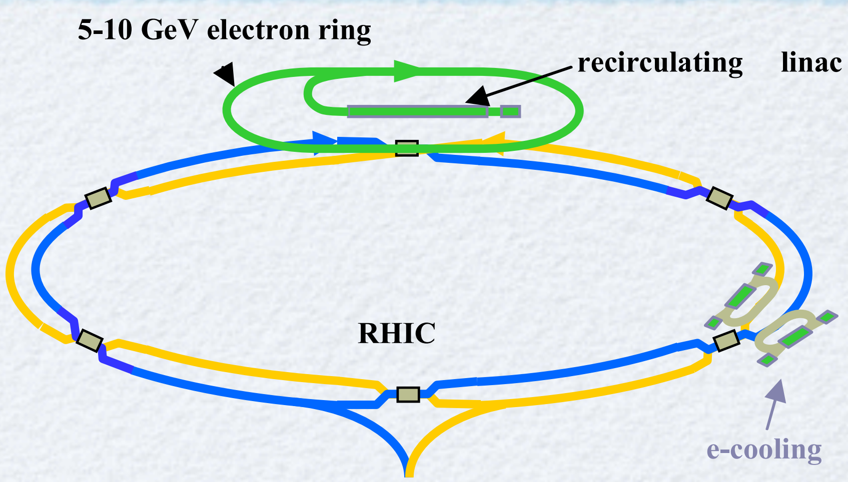
ELIC



EIC Workshop

Rutgers University

Mar. 14, 2010



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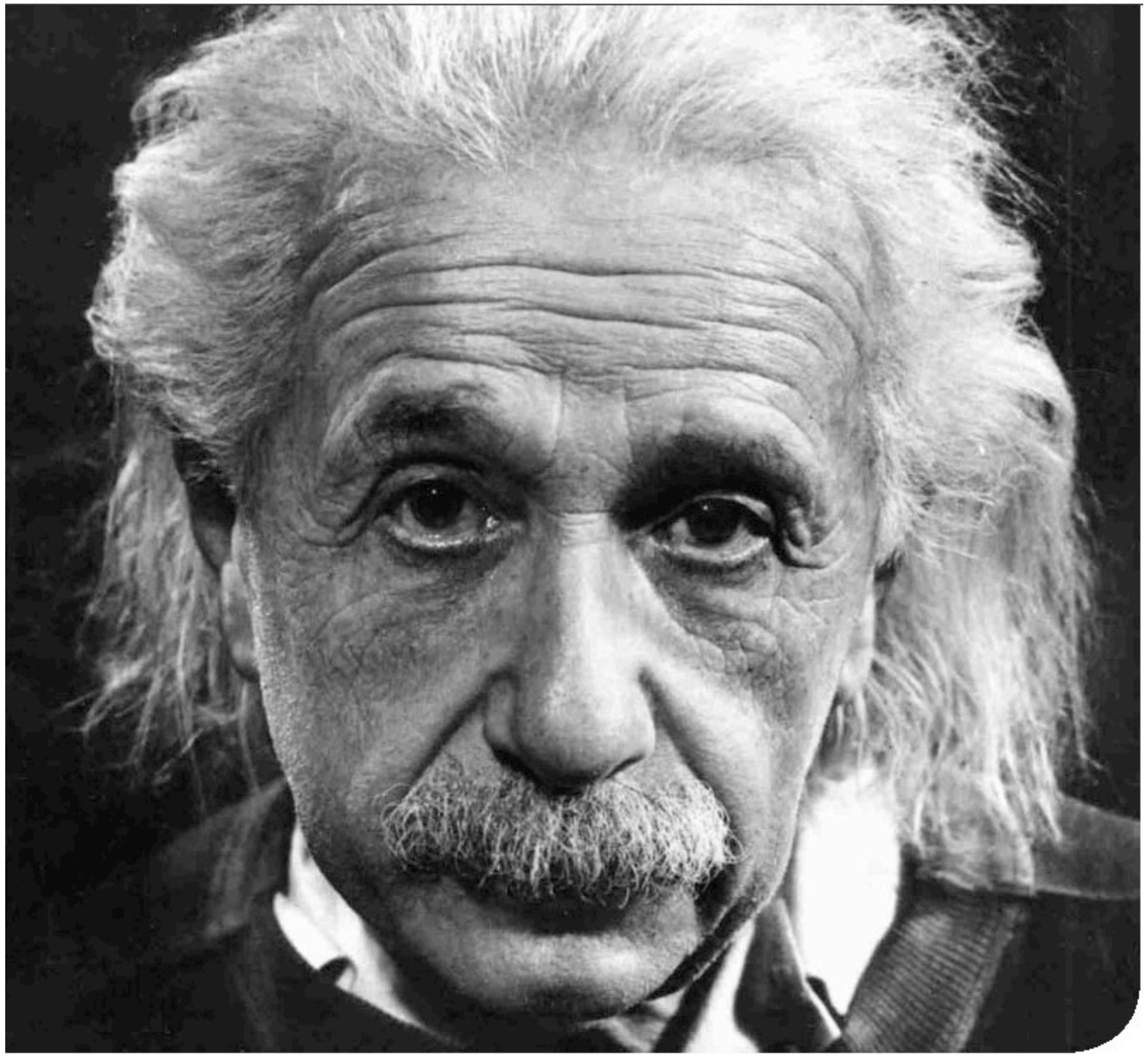
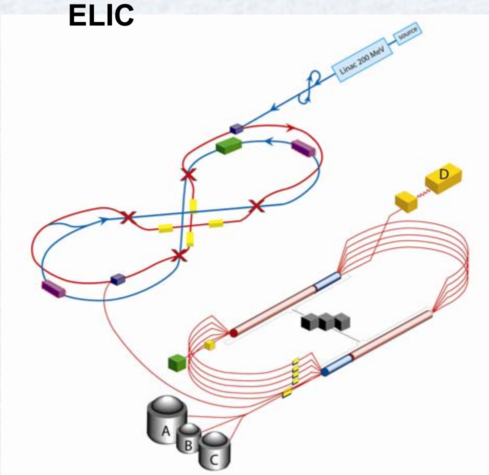
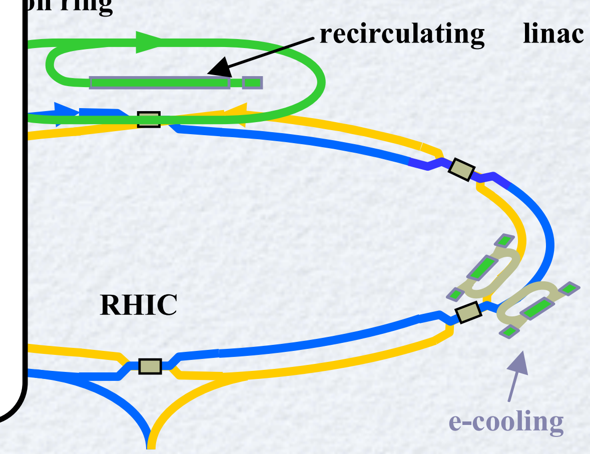


Happy π Day

ELIC





OUTLINE

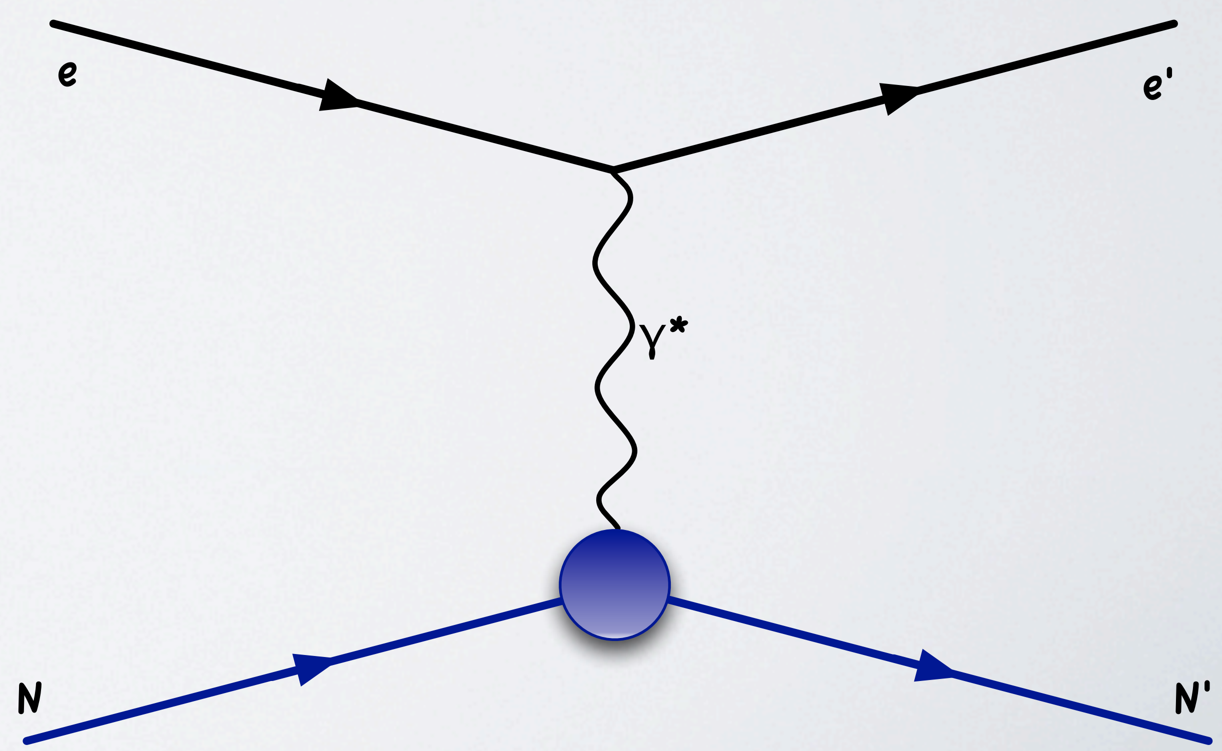
- Form Factors 101.
- High Q^2
  - Motivation
  - Possibilities
- Low Q^2
  - Motivation
  - Possibilities
- Summary

Electron Scattering Cross-Section (1-γ)

$$\frac{d\sigma_R}{d\Omega} = \frac{\alpha^2}{Q^2}\left(\frac{E'}{E}\right)^2 \frac{\cot^2\frac{\theta_e}{2}}{1+\tau}$$

Rutherford - Point-Like

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



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$$\frac{d\sigma_M}{d\Omega} = \frac{d\sigma_R}{d\Omega} \times \left[1 + 2\tau\tan^2\frac{\theta}{2}\right]$$

Mott - Spin-1/2

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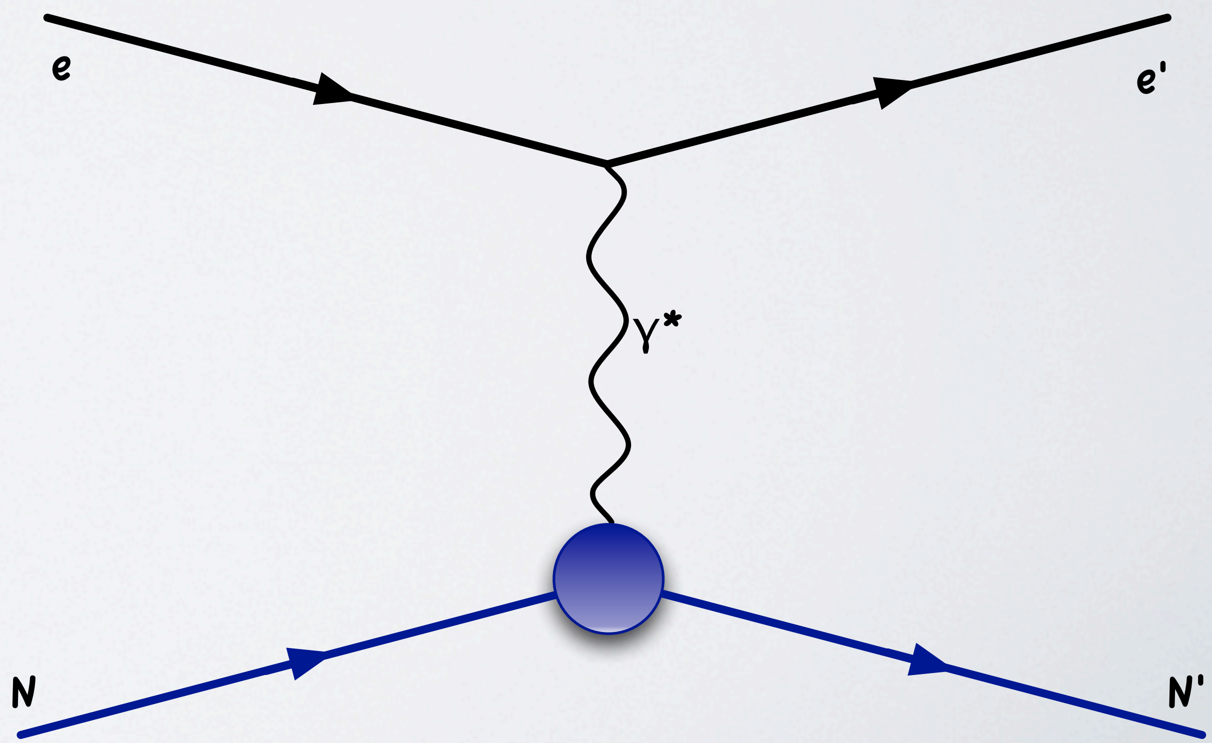

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$$\frac{d\sigma_{Str}}{d\Omega} = \frac{d\sigma_M}{d\Omega} \times \left[G_E^2(Q^2) + \frac{\tau}{\varepsilon}G_M^2(Q^2)\right]$$

Rosenbluth - Spin-1/2 with Structure

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

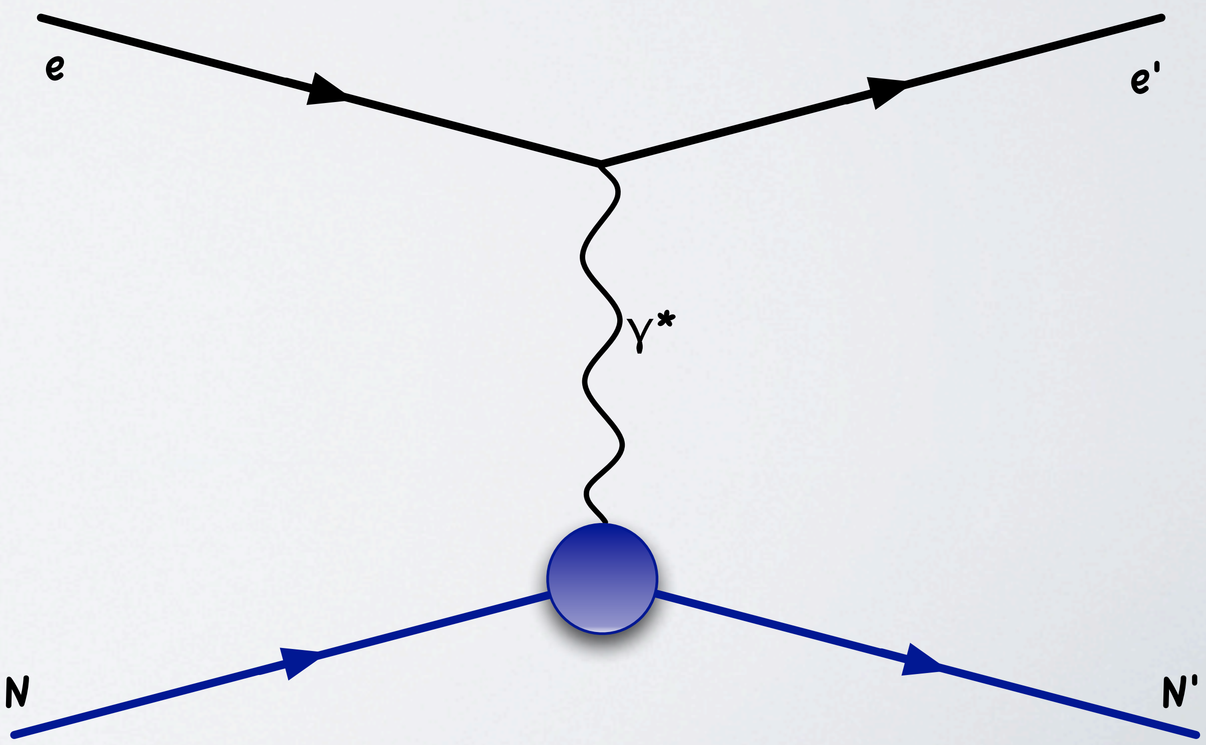
$$G_E^p(0) = 1 \qquad G_E^n(0) = 0$$

$$G_M^p = 2.793 \quad G_M^n = -1.91$$

Sometimes written using:

$$G_E = F_1 - \tau F_2$$

$$G_M = F1 + F_2$$



Electron Scattering Cross-Section (1-γ)

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$$\frac{d\sigma_M}{d\Omega} = \frac{d\sigma_R}{d\Omega} \times \left[1 + 2\tau\tan^2\frac{\theta}{2}\right]$$

$$\frac{d\sigma_{Str}}{d\Omega} = \frac{d\sigma_M}{d\Omega} \times \left[G_E^2(Q^2) + \frac{\tau}{\varepsilon}G_M^2(Q^2)\right]$$

Everything we don't know goes here!

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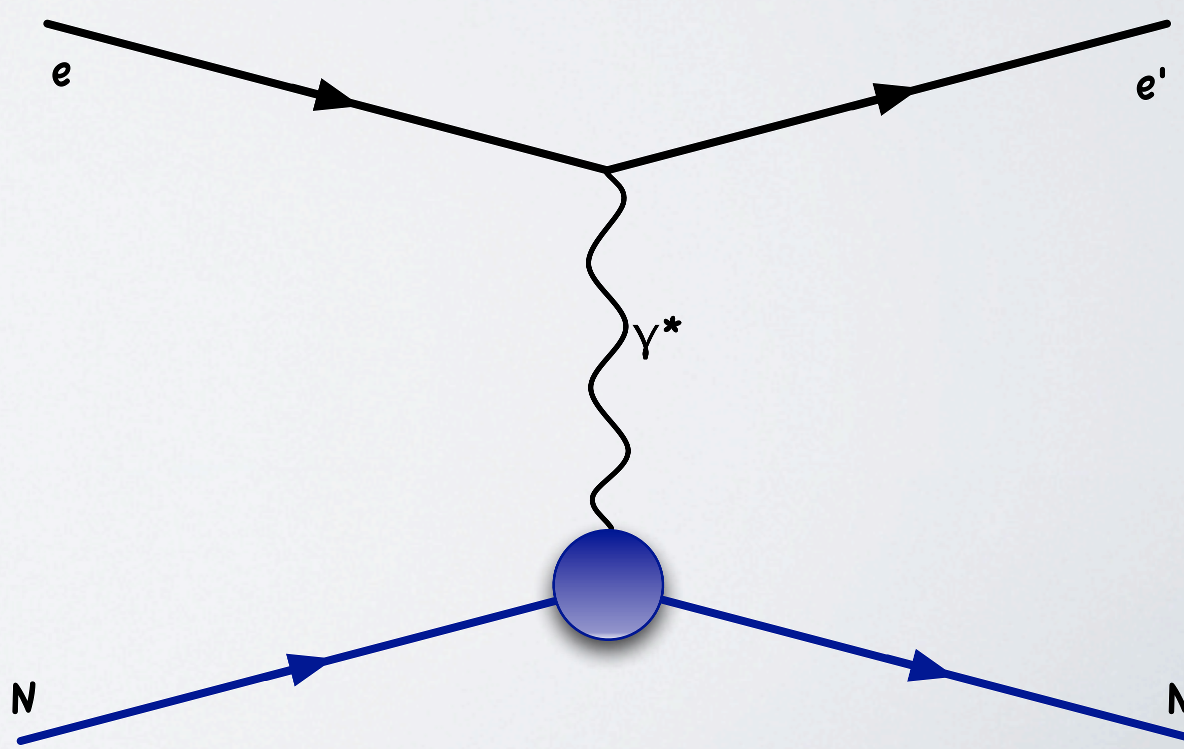


Measurement Techniques

Rosenbluth Separation

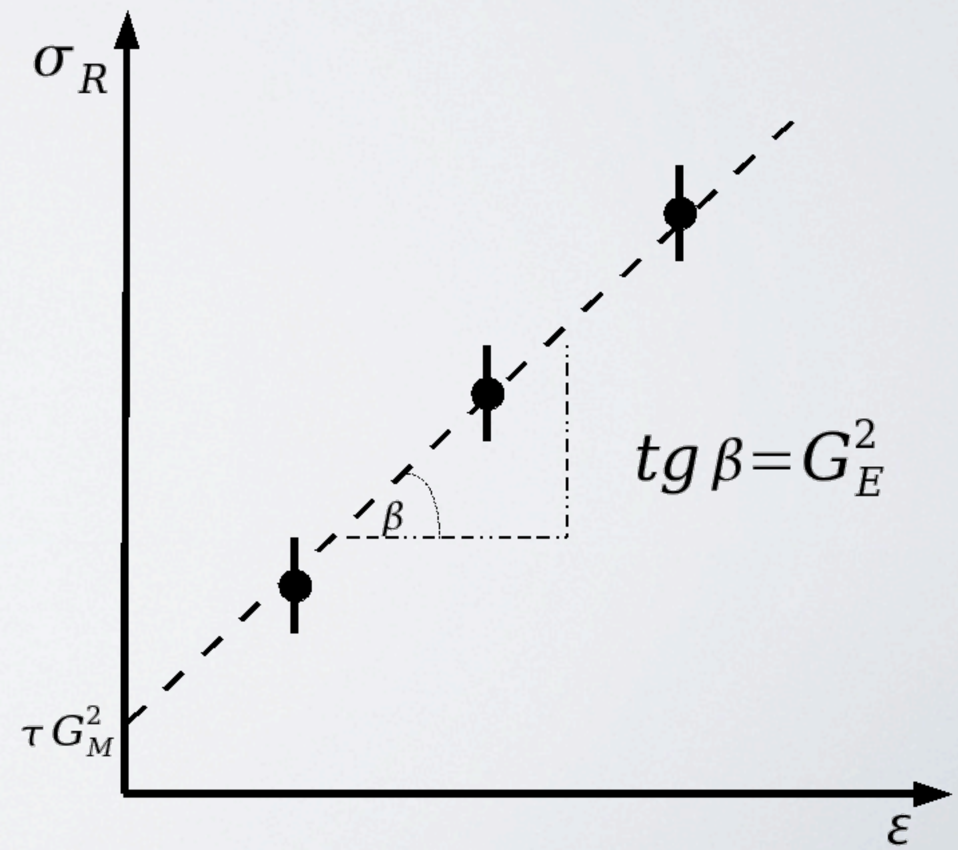
$$\sigma_R = (d\sigma/d\Omega)/(d\sigma/d\Omega)_{\text{Mott}} = \tau G_M^2 + \varepsilon G_E^2$$

- Measure the reduced cross section at several values of ε (angle/beam energy combination) while keeping Q2 fixed.

- Linear fit to get intercept and slope.

- But... G_M suppressed for low Q^2 (and G_E for high).

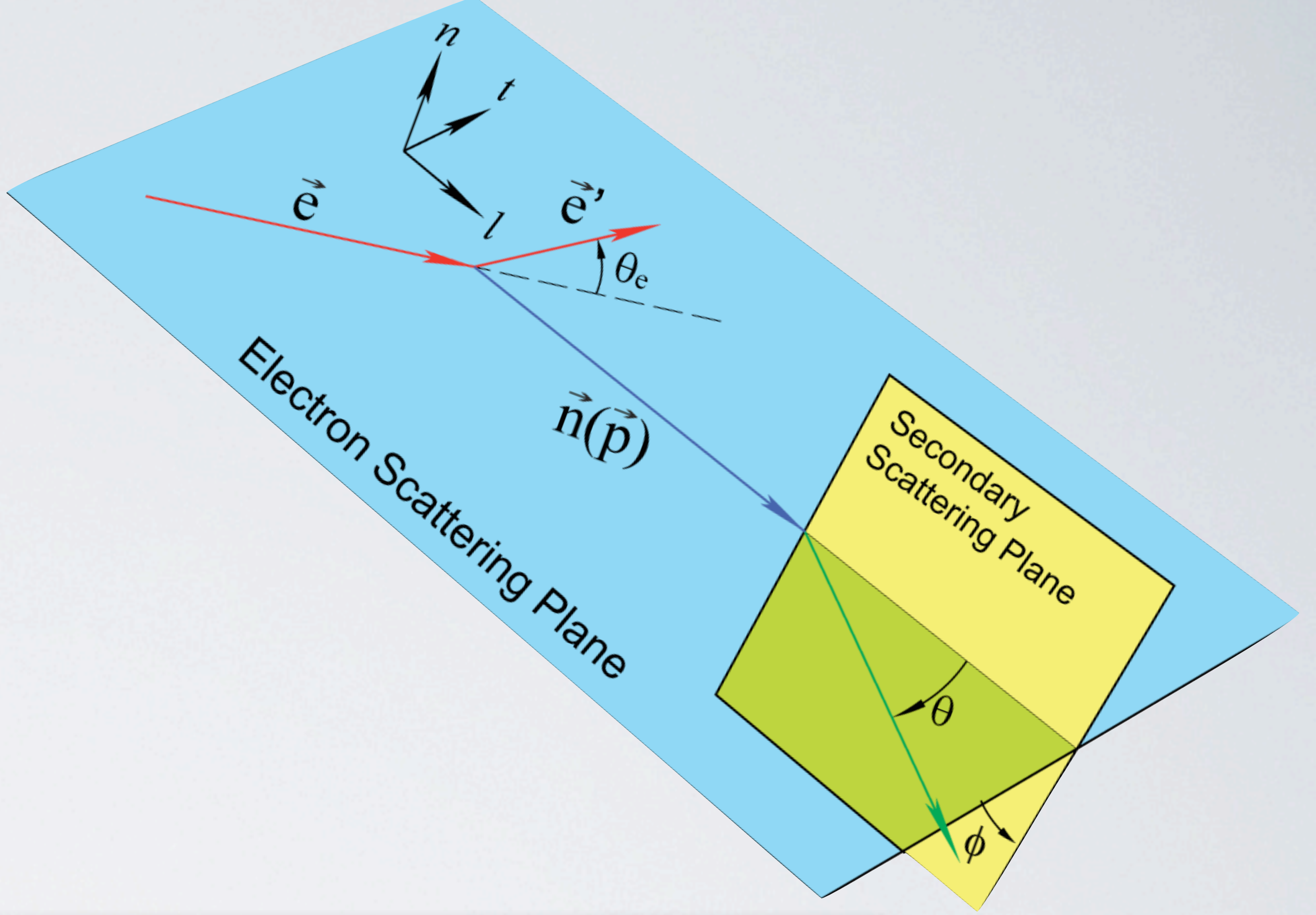
- Also normalization issues/acceptance issues/etc. make it hard to get high precision.



Measurement Techniques

Recoil Polarization

(Secondary scattering of nucleon)



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

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

$$P_n = 0 \ (1\gamma)$$

$$\mathcal{R} \equiv \mu_p \frac{G_E}{G_M} = -\mu_p \frac{P_t}{P_l} \frac{E_e + E_{e'}}{2M} \tan\frac{\theta_e}{2}$$

- A single measurement gives ratio of form factors.
- Interference of "small" and "large" terms allow measurement at practically all values of Q^2.

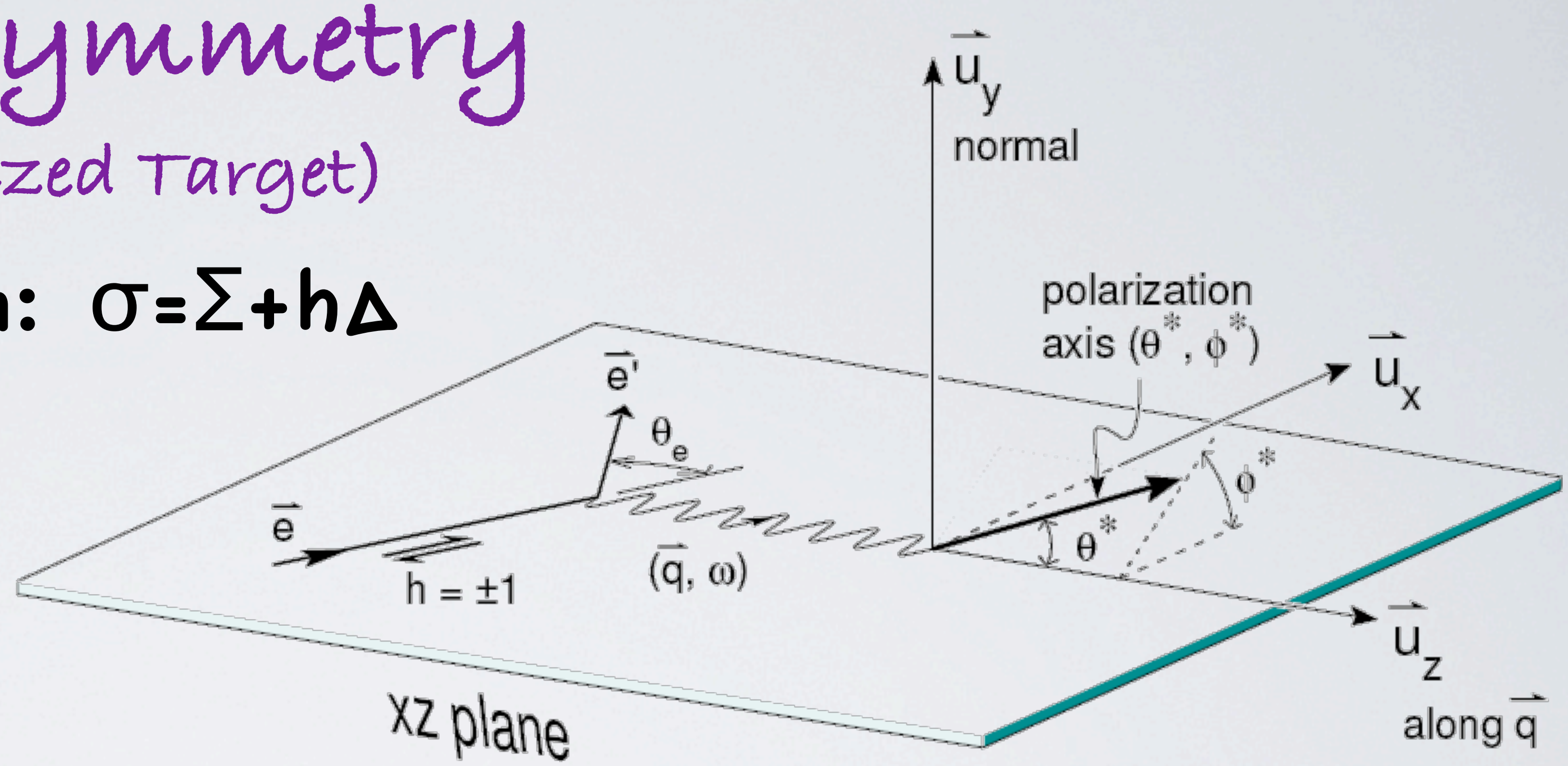
Measurement Techniques

Beam-Target Asymmetry

(Polarized Beam Polarized Target)

Polarized Cross Section: σ=Σ+hΔ

$$\mathcal{A} = \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-}$$



$$\mathcal{A} = P_b P_t \frac{\overbrace{a\,cos\theta^* G_M^2}^{A_T} + \overbrace{b\,sin\theta^*\,cos\phi^* G_E G_M}^{A_{LT}}}{cG_M^2 + dG_E^2}$$

Measure asymmetry at two different target settings, say θ*=0, 90.
Ratio of asymmetries gives ratio of form factors.
Functionally identical to recoil polarimetry measurements.

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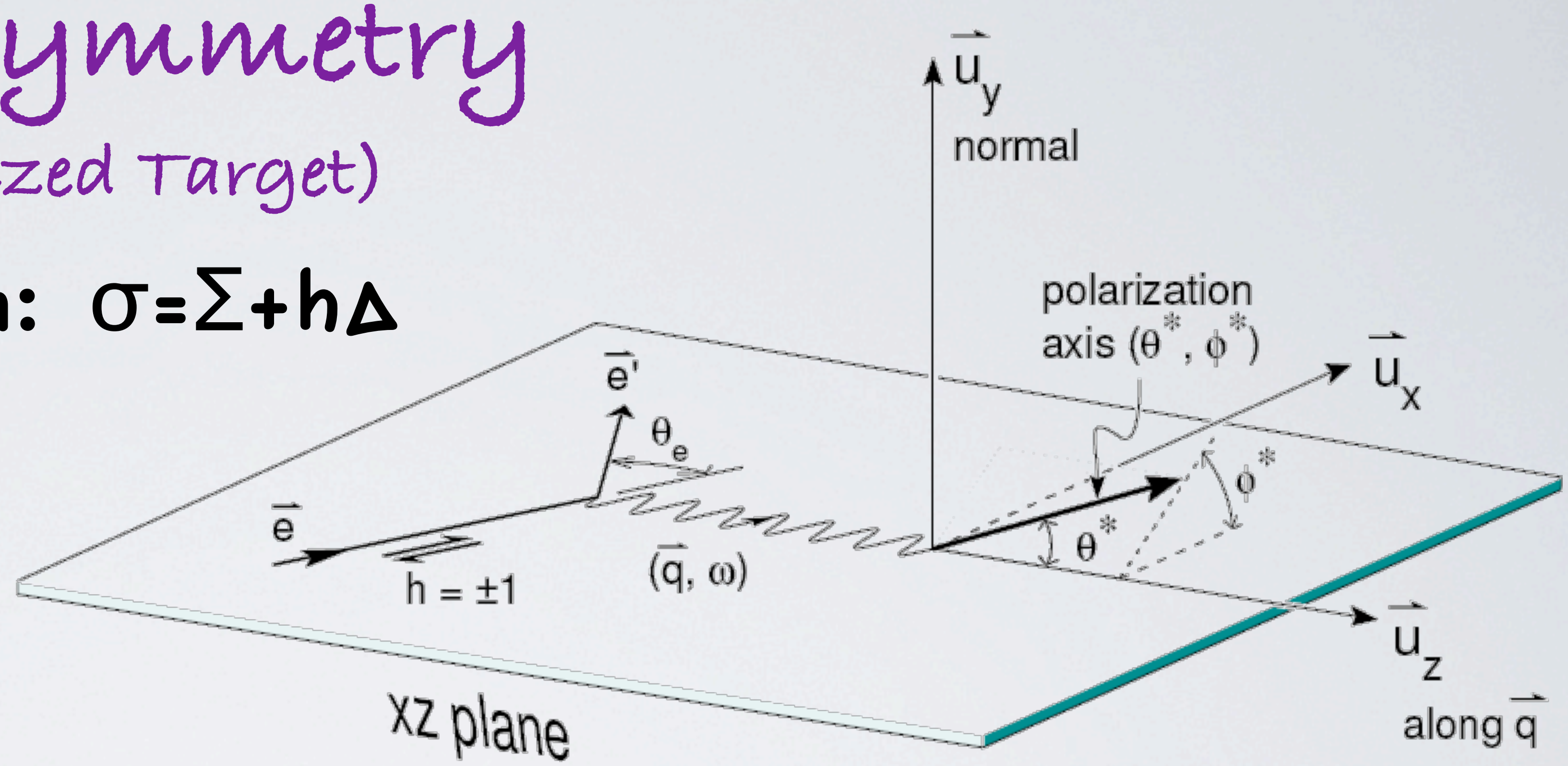

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Relevant for EIC

$$\mathcal{A} = P_b P_t \frac{\overbrace{a\, cos\theta^* G_M^2}^{A_T} + \overbrace{b\, sin\theta^*\, cos\phi^* G_E G_M}^{A_{LT}}}{cG_M^2 + dG_E^2}$$

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Canceling (some of) the uncertainties

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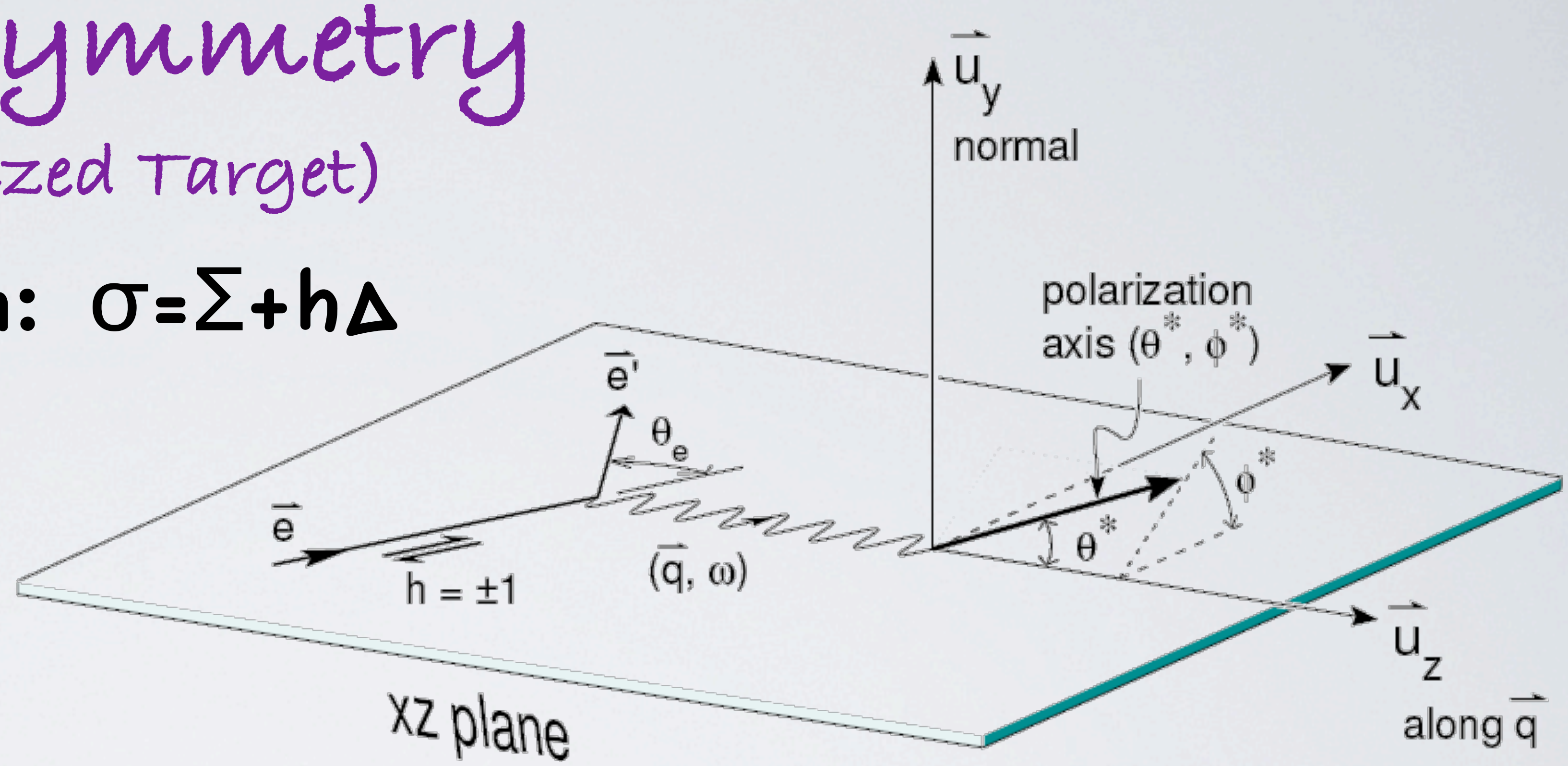

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$$\mathcal{A} = P_b P_t \frac{\overbrace{a\,cos\theta^* G_M^2}^{A_T} + \overbrace{b\,sin\theta^*\;cos\phi^* G_E G_M}^{A_{LT}}}{c G_M^2 + d G_E^2}$$

Simultaneous measurement with two different values of θ*.
Ratio of asymmetries related to FF ratio and cancels systematics.

$$\frac{G_E}{G_M} = -\frac{a(\tau,\theta_e)\cos\theta_1^* - \Gamma a(\tau,\theta_e)\cos\theta_2^*}{\cos\phi_1^*\sin\theta_1^* - \Gamma\cos\phi_2^*\sin\phi_2^2}$$

$$a(\tau,\theta_e) = \sqrt{\tau(1+(1+\tau)\tan^2(\theta_e/2))}$$

$$\Gamma = \mathcal{A}_1/\mathcal{A}_2$$

Set p beam polarization to intermediate angle such that $\theta_1^* \neq \theta_2^*$.

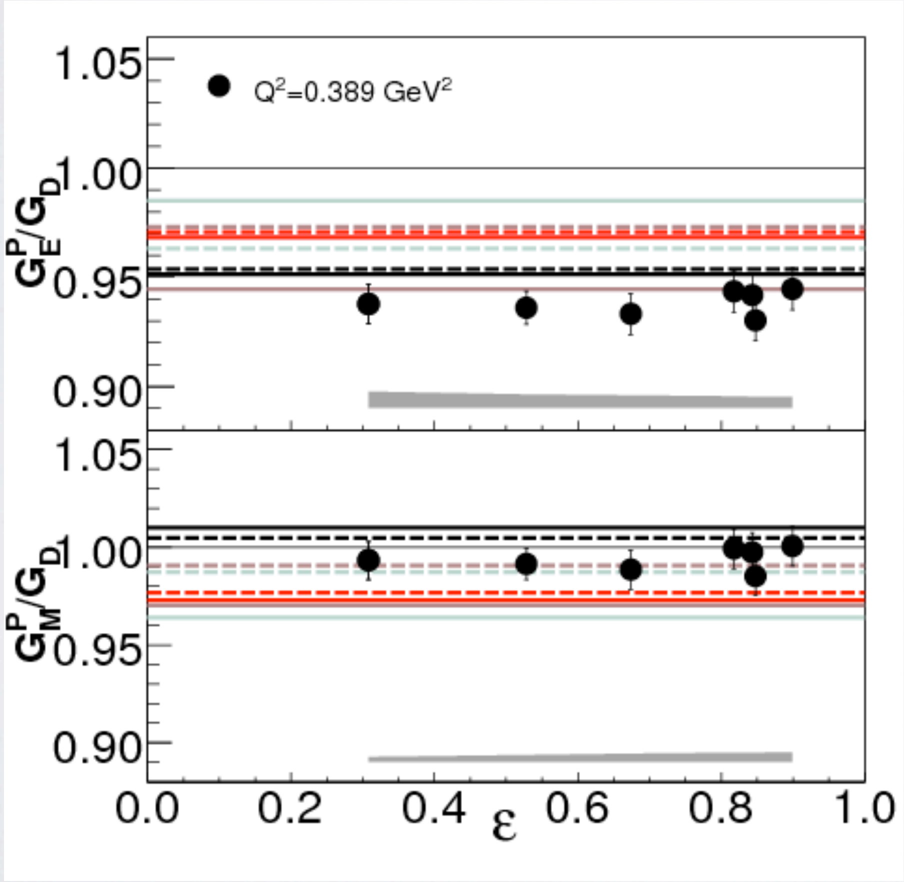
Getting G_E & G_M from Ratios + Cross Sections

Cross section at high/low Q^2 dominated by one term (Rosenbluth separation not feasible).

Ratio gives second equation

➛ Can now solve 2 equations in two variables to get both FFs.

Multiple cross section measurements at the same Q^2 give cross check.



$$\sigma_R = \tau G_M^2 + \varepsilon G_E^2$$

$$\mathcal{R} = \mu \frac{G_E}{G_M}$$

$$\sigma_R = \tau G_M^2 + \varepsilon \frac{G_M^2 \mathcal{R}^2}{\mu^2}$$

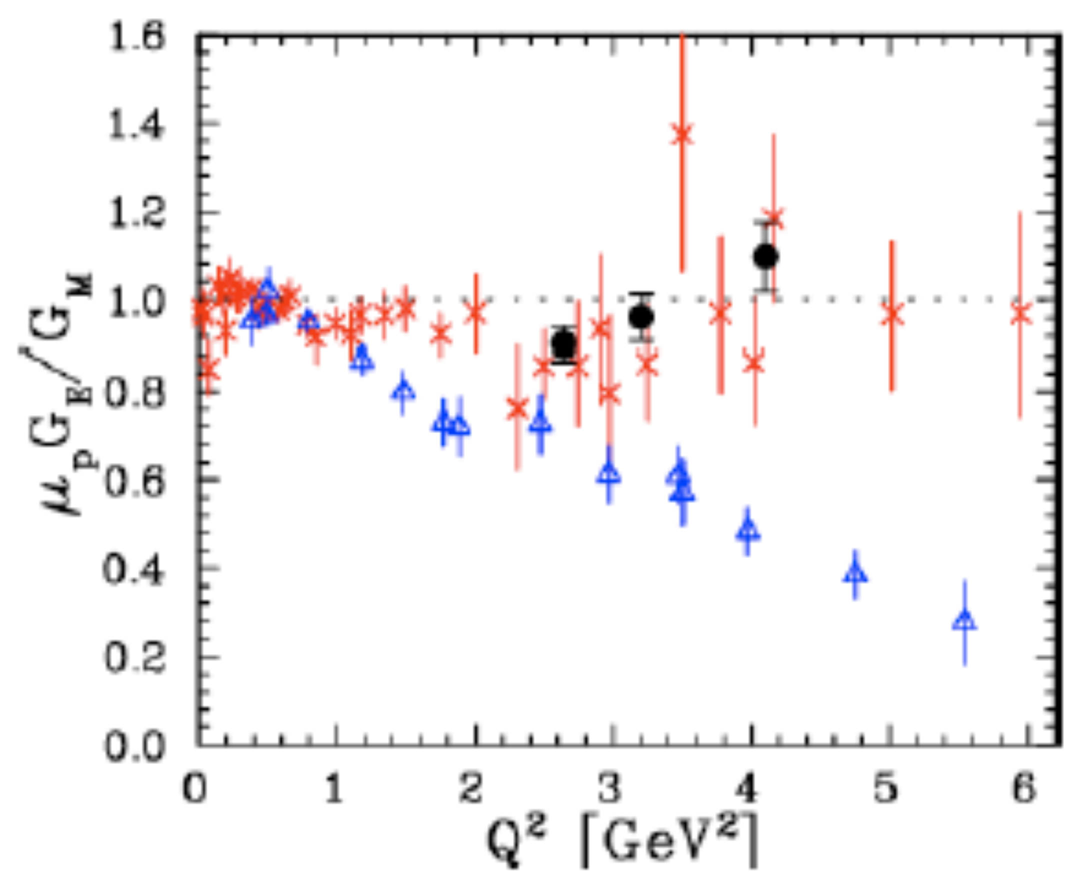
$$G_M^2 = \sigma_R / \left(\tau + \varepsilon \mathcal{R}^2 / \mu^2\right)$$

G. Ron et al., Phys. Rev. Lett. 99, 202002 (2007)

High Q^2 Measurements

The high Q^2 discrepancy

- At high Q^2 Rosenbluth and polarization measurements for the proton are in violent disagreement.



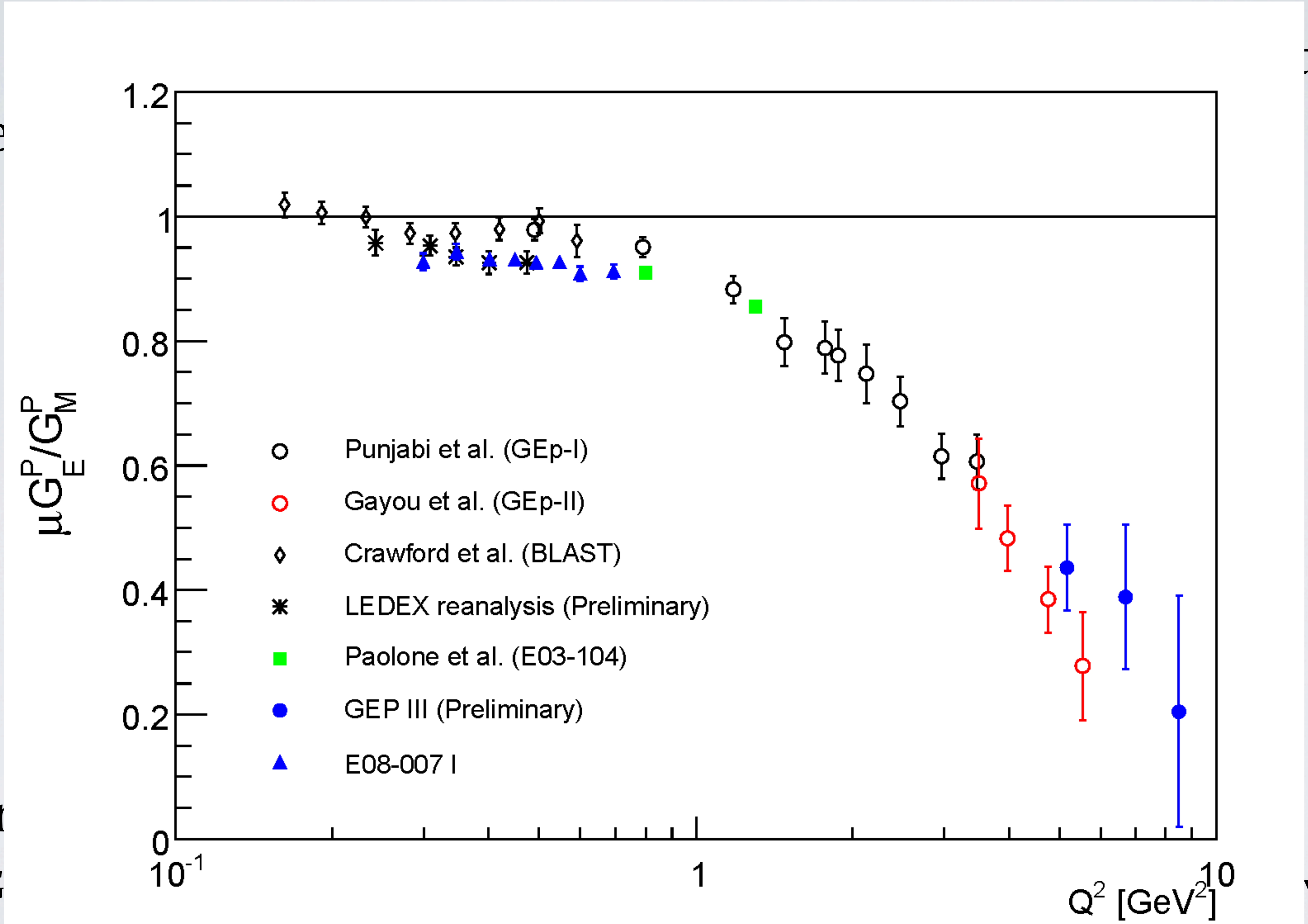
I. Qattan *et al.*, Phys. Rev. Lett. **94**, 142301 (2005).

- Almost certainly explained by multi-γ effects.

"As $G_E = F_1 - \tau F_2$, it is a priori quite likely that G_E becomes negative for large values of k^2" - *N. Dombey, Rev. Mod. Phys.* 41, 1 (1969). – **Not supported by new results.**

The high Q^2 discrepancy

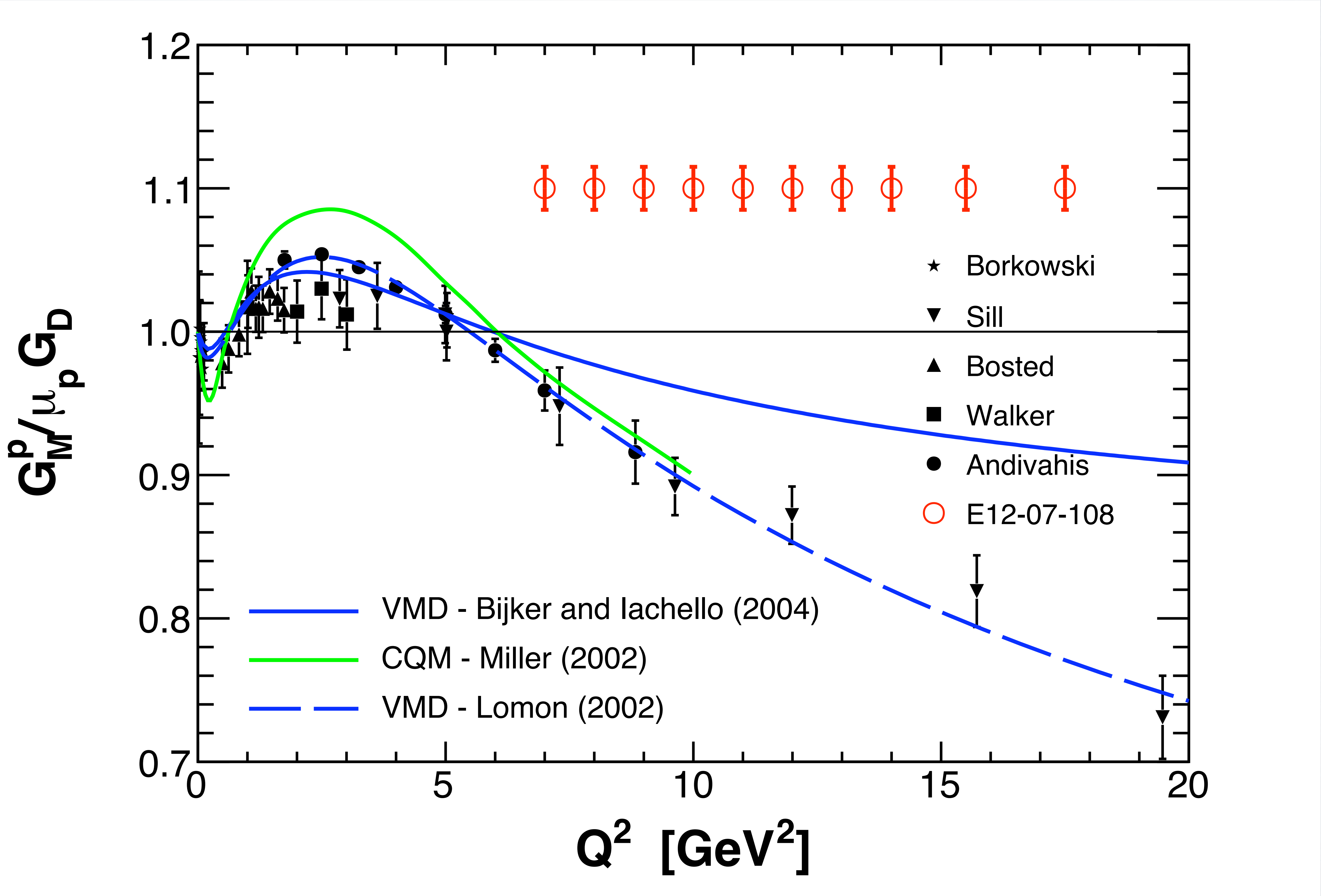
- At … ts for the



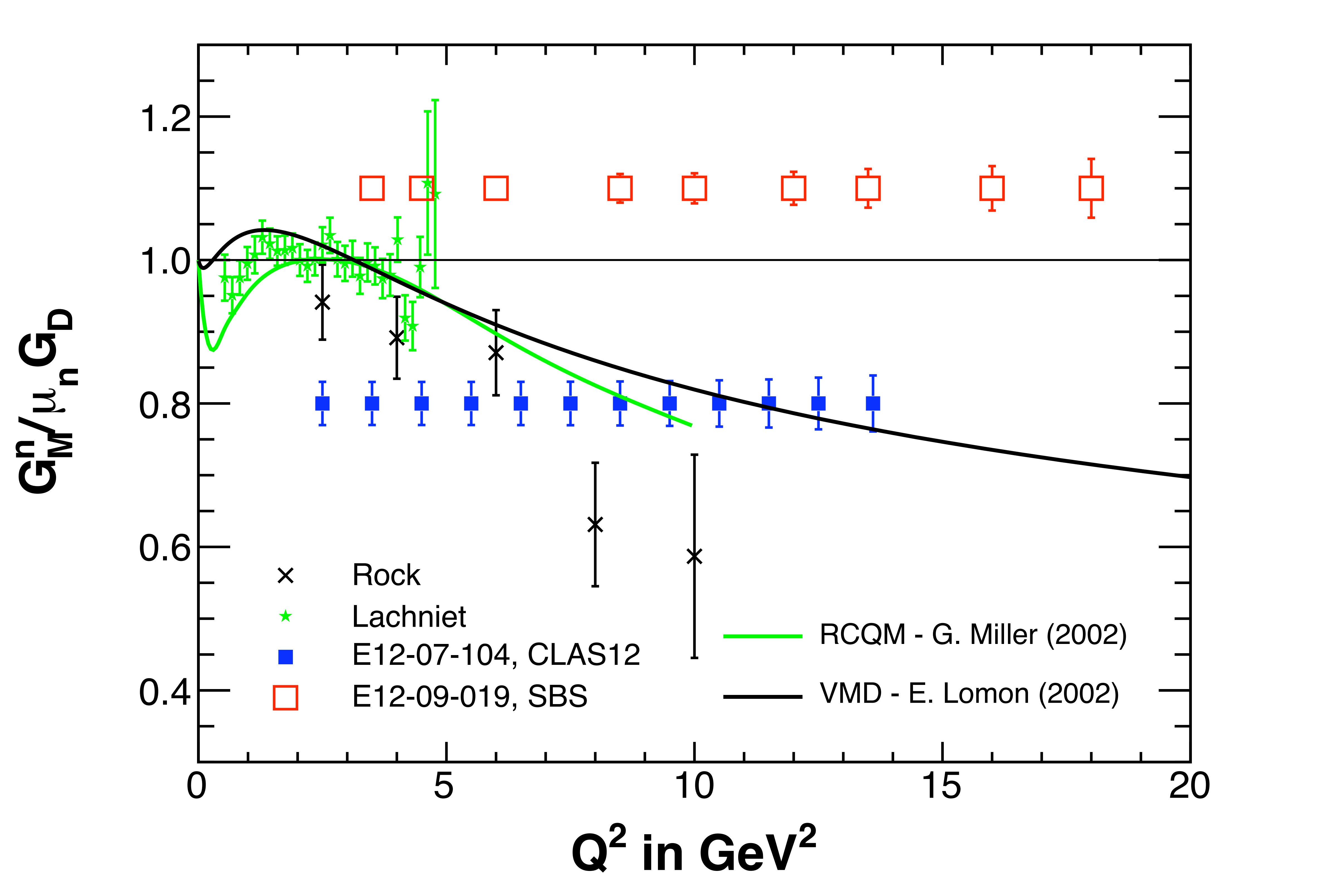
- Al…

"As G … values of k^2" - N. Dombey, Rev. Mod. Phys. 41, 1 (1969). – **Not supported by new results.**

12 GeV G_{Mp} @JLab



12 GeV GMn @JLab



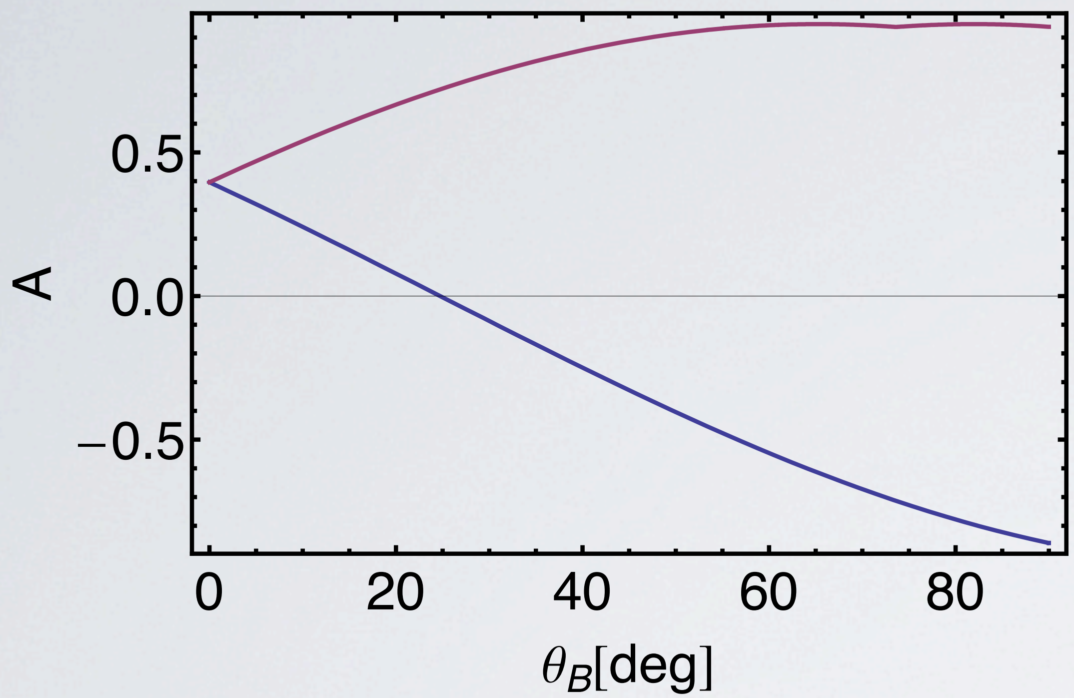
Prospects for High Q^2 ep with EIC

- 3GeV Electron + 30 GeV Proton.
- $\mathcal{L} = 10^{34}$ cm^{-1} sec^{-1}.
- Full angular (φ) detector coverage.
- $\Delta Q^2/Q^2 = 0.1$.

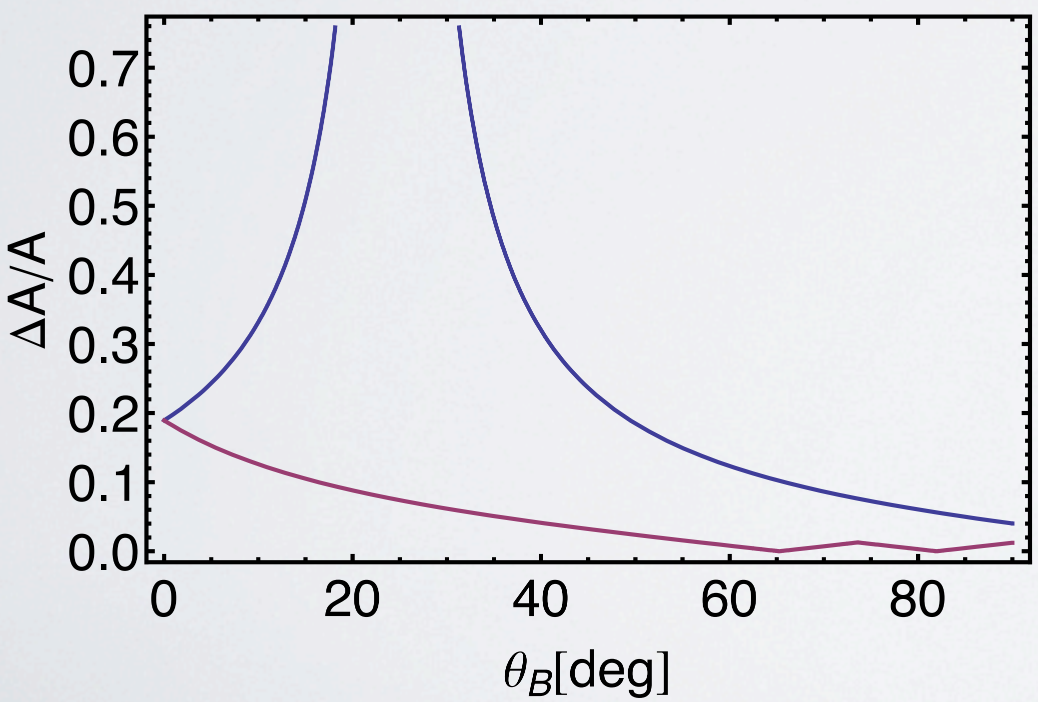
Systematics Limited ⟷ Statistics Limited

Q^2 (GeV^2)	10	20	30	40	50	60
θ_e	56.25	74.97	87.28	96.4	103.6	109.5
θ_p	6.12	8.77	10.9	12.76	14.5	16.1
E'_e	3.74	4.5	5.24	6	6.74	7.5
E'_p	28.3	27.56	26.81	26.06	25.31	24.56
Events / year	186000	7300	1000	250	80	30
$(\Delta\sigma/\sigma)_{stat}$	0.2%	1.2%	3.1%	6.3%	11.2%	18.2%
$(\Delta A/A)_{stat}$	0.3%	1.6%	4.4%	9%	15.8%	25.8%

Prospects for High Q^2 ep with EIC



Asymmetry as a function of proton polarization angle for $Q^2 = 10$ GeV^2



Systematic Uncertainty in asymmetry as a function of proton polarization angle for $Q^2 = 10$ GeV^2.

$\Delta\theta_{pol} = 5^0$

Low Q^2 Measurements

Why Low Q^2?

- Deviations from dipole form evident.
- Probe static properties ($Q^2 \rightarrow 0$) and peripheral structure.
- Small Q^2 does not allow for pQCD, many competing EFTs.
- Hitting the π mass region (2π-cut in Pauli/Dirac FFs).
- Potentially impacts many high precision measurements (nucleon GPDs, parity violation, Zemach radius,...).

Some Models

VMD

$$F(Q^2) = \Sigma \frac{C_{\gamma V_i}}{Q^2 + M^2_{V_i}} F_{V_i N}(Q^2)$$

Breaks down at high Q^2

Lattice QCD *(not really a model....)*

RCQM

Point Form

Light Front

di-Quark

CBM/LFCBM

pQCD

Helicity Conservation

Counting rules $\frac{Q^2 F_2}{F_1} \rightarrow \text{Constant}$

State of the Art

- **Rosenbluth:**
  - Mainz has concluded a high precision cross section survey.
  - Measured cross sections downto $Q^2 \approx 0.01 GeV^2$.

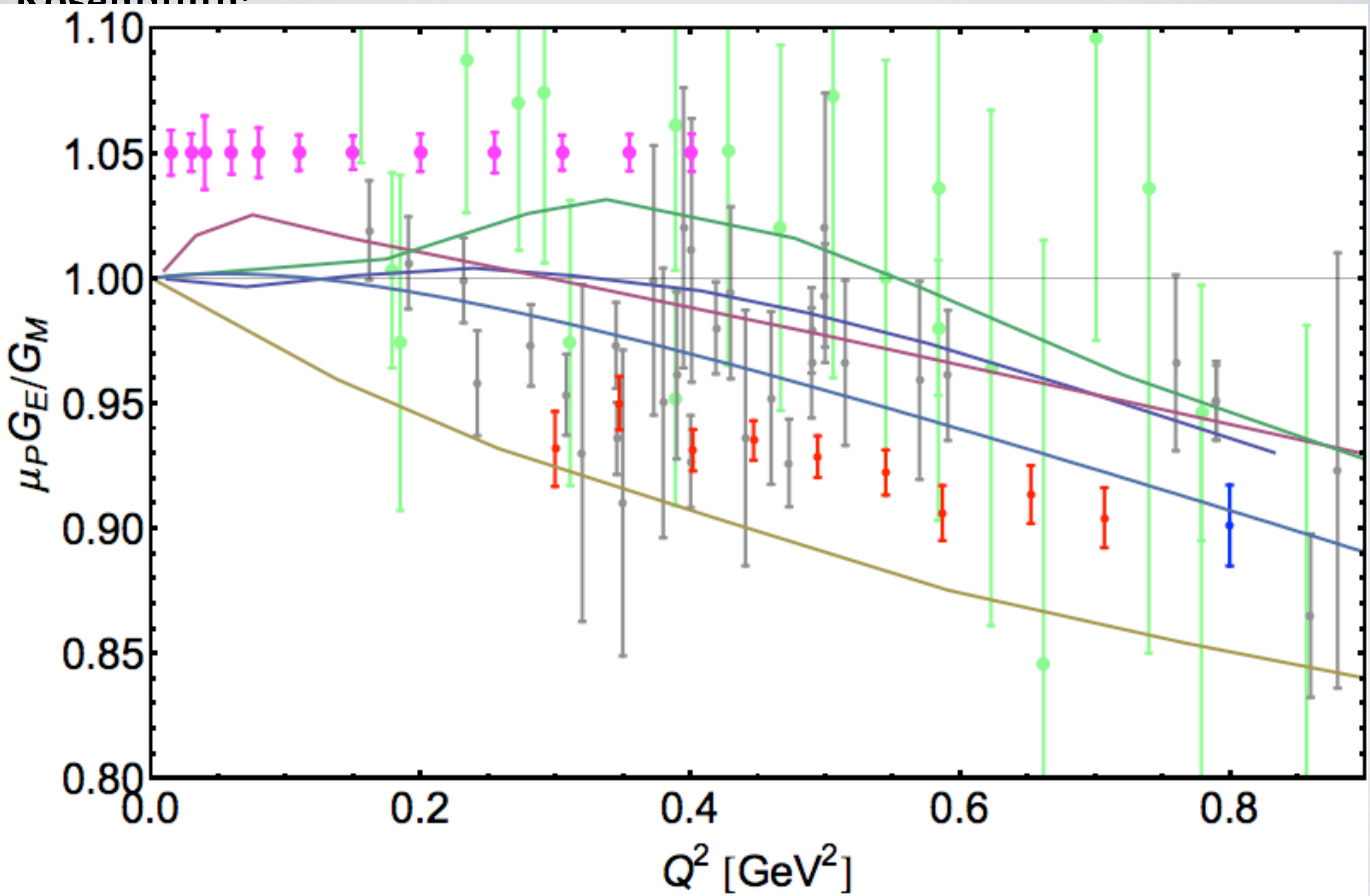
- **Polarization Data (FF Ratio):**
  - **Bates BLAST** (Beam-Target Asymmetry) - $Q^2 = 0.16 - 0.6$ GeV^2, C. B. Crawford et al., Phys. Rev. Lett. 98, 052301 (2007).
  - **JLab LEDEX** (Recoil Polarization) - $Q^2 = 0.22 - 0.5$ GeV^2, G. Ron et al., Phys. Rev. Lett. 99, 202002 (2007).
  - **JLab E08007 Part I** (Recoil Polarization) - $Q^2 = 0.25 - 0.7$ GeV^2 (Very high precision), X. Zhan PhD Thesis.
  - **JLab E08007 Part II** (Beam-Target Asymmetry) - $Q^2 = 0.01 - 0.4$ GeV^2 (Very high precision) Tentative 2012.

- **Strong deviation fron unity at low** Q^2**.**

- **Attributed to** $G_{Ep} \langle G_D$**.**

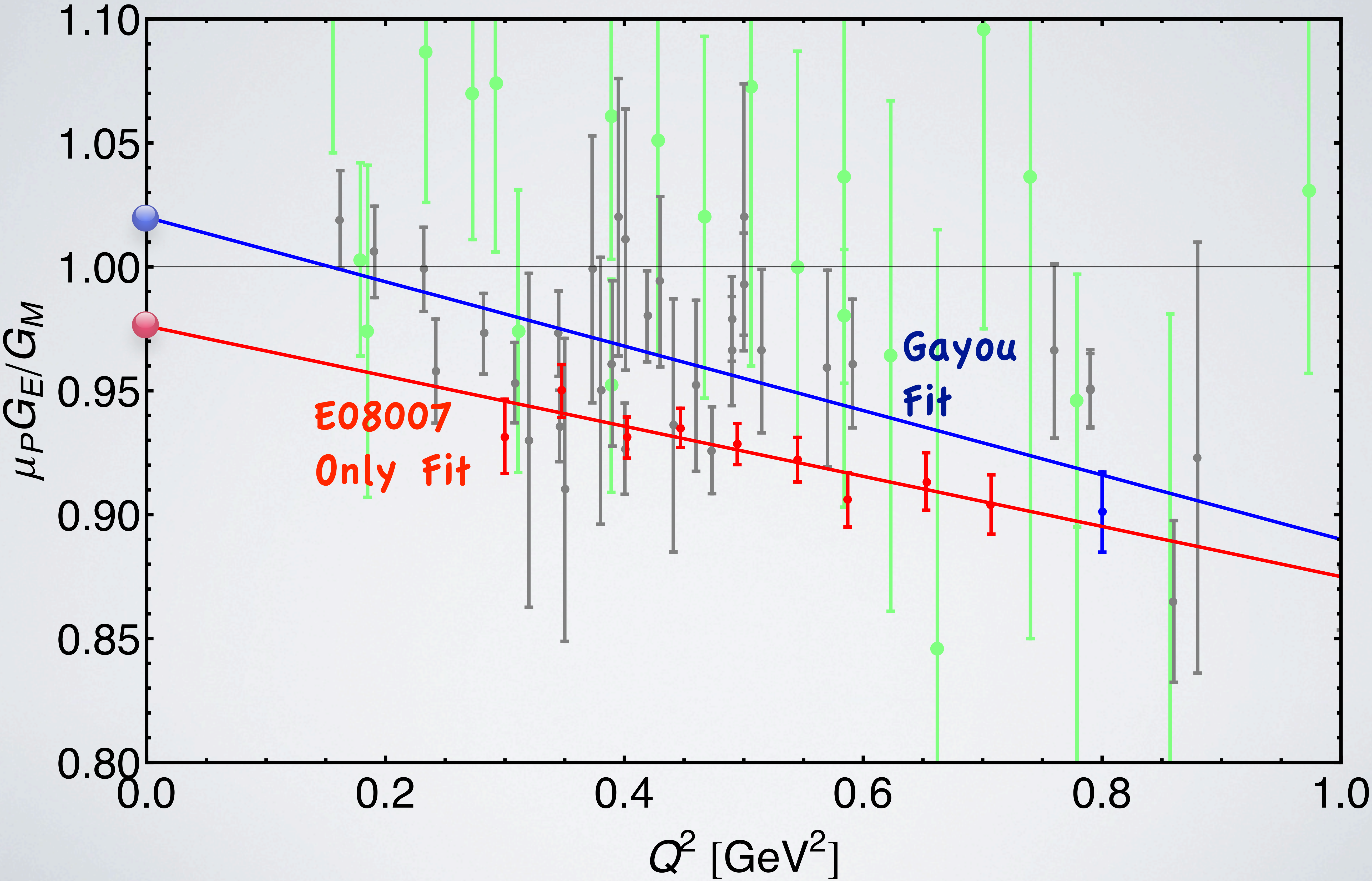
State of the Art

- Rosenbluth:
-



-
- Attributed to $G_{Ep} < G_D$.

Low/High Q^2 Data Matching



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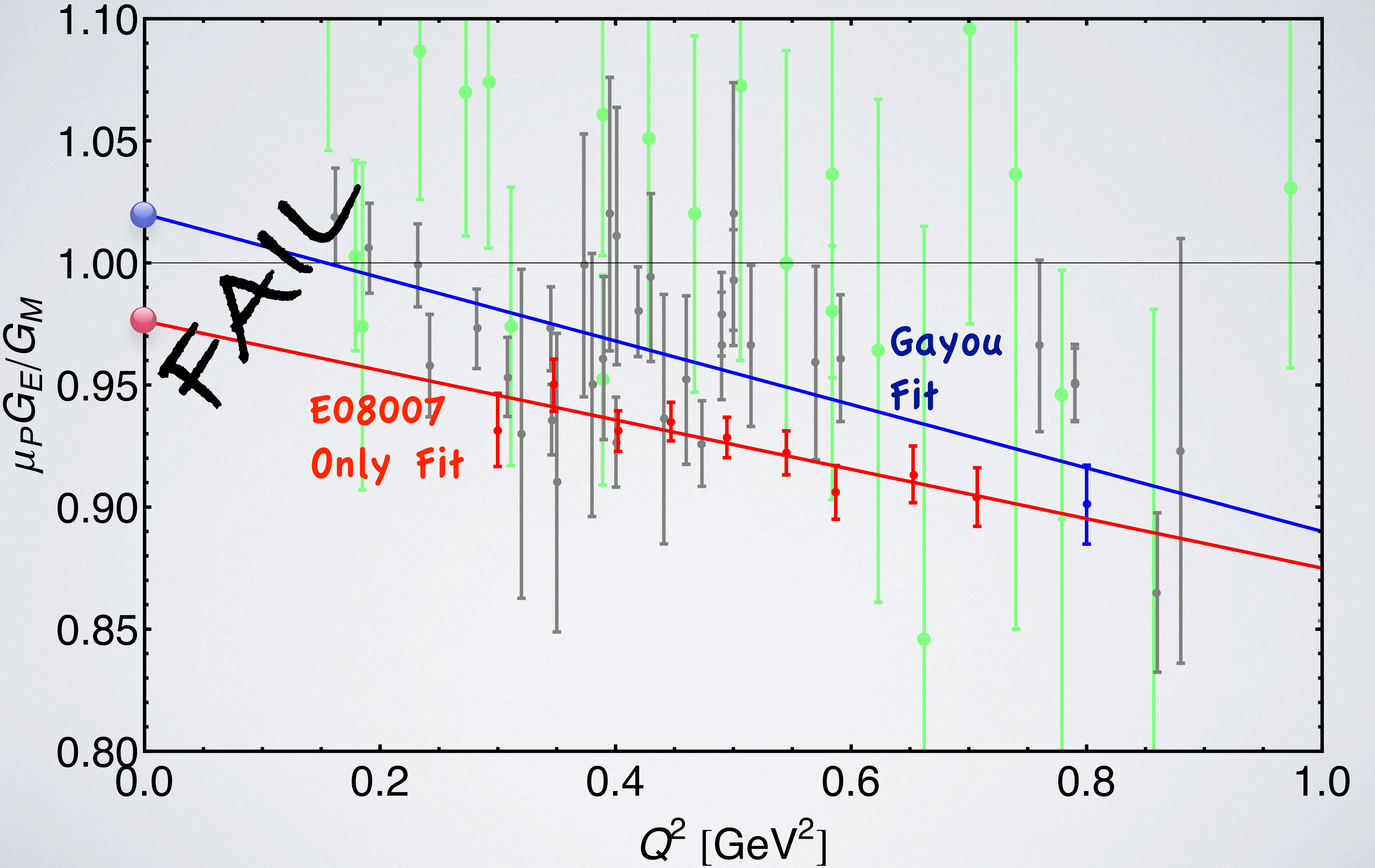

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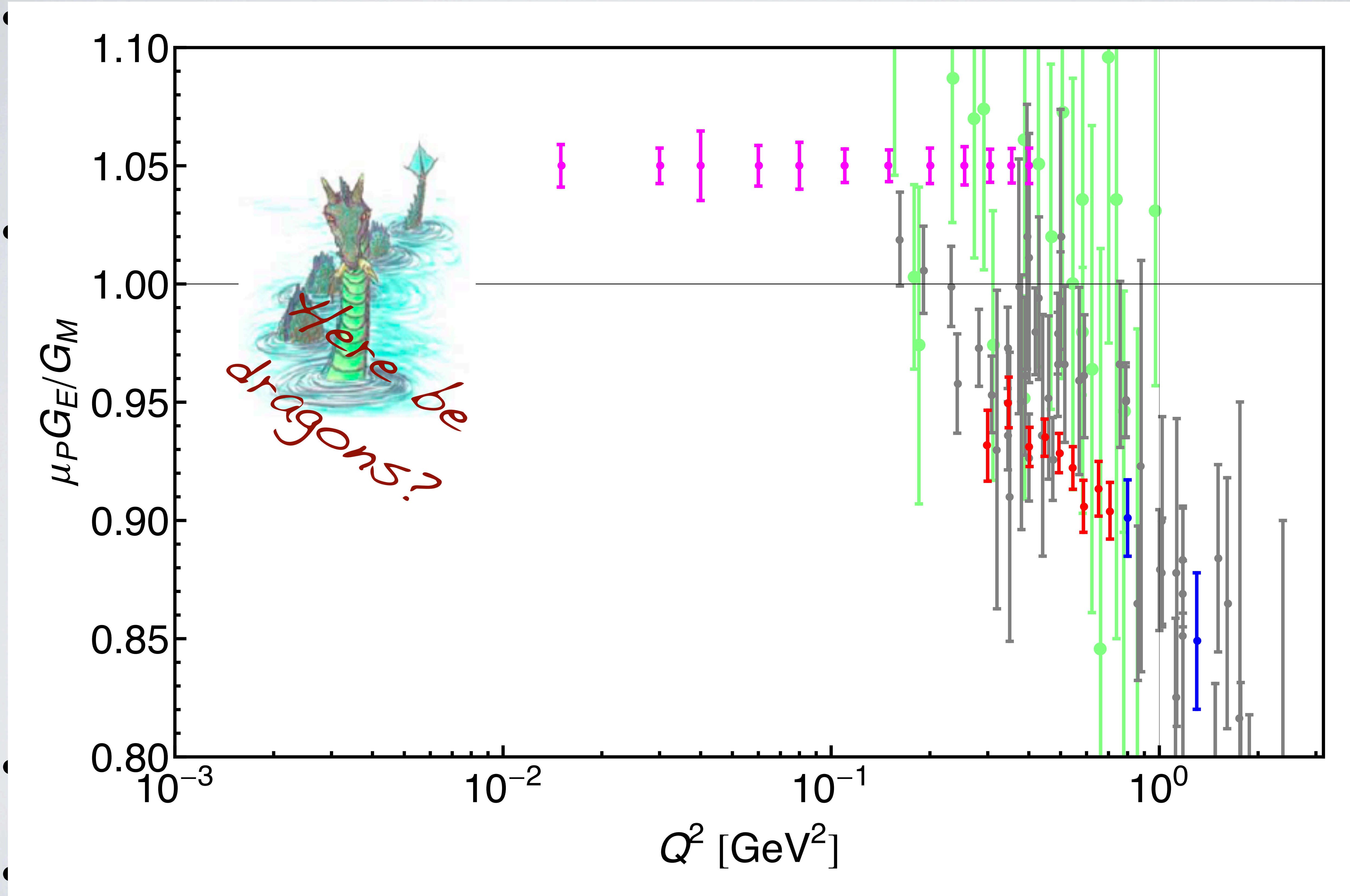


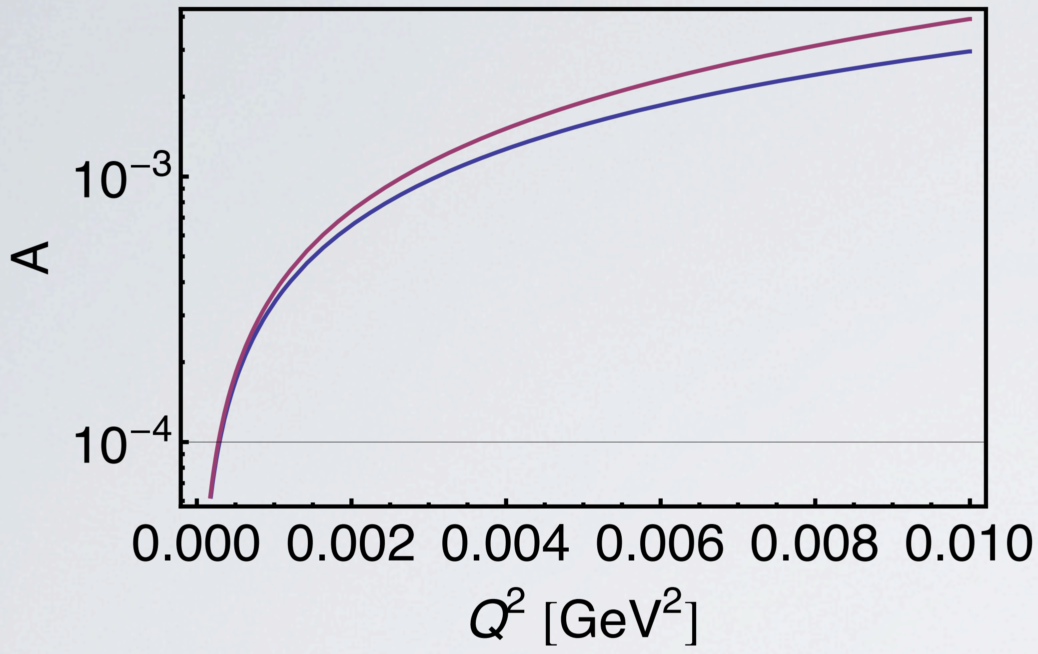
Prospects for Low Q^2 ep with EIC

- Proton polarimetery not feasible for high proton beam energies ($T_p \sim T_{p'}$).
- Very forward scattered electron.
- Luminosity drop significantly when lowering beam energies.
- Cross section measurement gives essentially G_E (charge radius).
- But.... Statistics not an issue.
- Limiting factor is systematic uncertainties (in particular proton beam polarization direction).

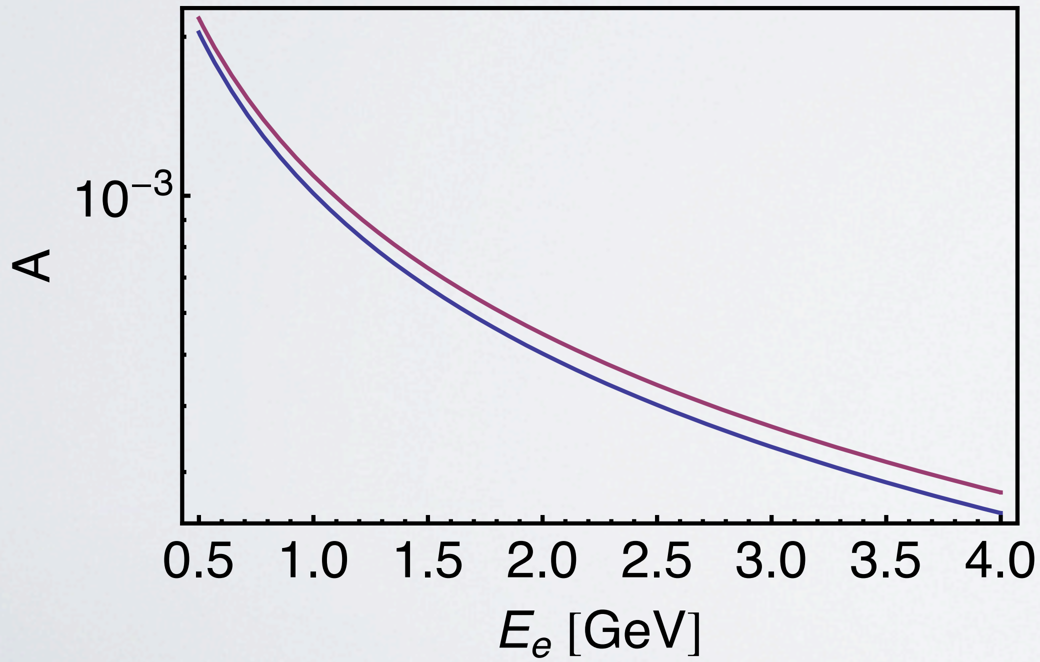
Q^2 (GeV^2)	10^{-4}	$5 \cdot 10^{-4}$	10^{-3}	$5 \cdot 10^{-3}$	0.01
θ_e	0.19	0.427	0.6	1.35	1.9
XS (cm^{-2})	2.60E-23	1.00E-24	2.50E-25	1.00E-26	2.50E-27
Rate (Hz)	9.1	1.75	0.875	0.175	0.0875
$T_{0.5\%}$ (hr)	1.22	6.35	12.7	63.5	127

- $\Delta Q^2/Q^2 = 0.01$.
- Assuming "CDF Style" roman pots detectors 1m from intersection point.
- Smallest possible angle ~0.2deg.
- Lowest possible $Q^2 \sim 10^{-4}$ GeV^2.
- Uncertainties always dominated by systematics - In particular proton beam polarization direction.

Prospects for Low Q^2 ep with EIC



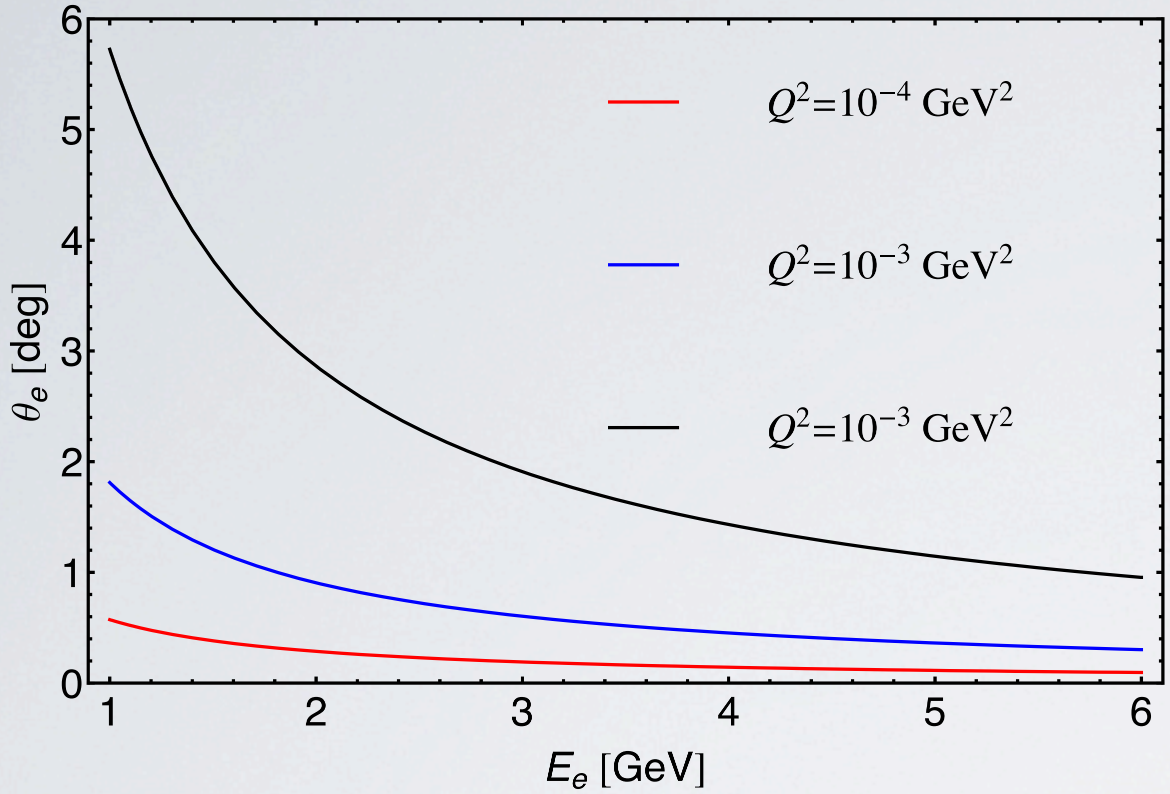
Asymmetry as a function of Q^2 (θ_{pol} = 45).



Asymmetry as a function of electron beam energy (Q^2=0.001 GeV^2, θ_{pol} = 45).

Lower beam energy is better.

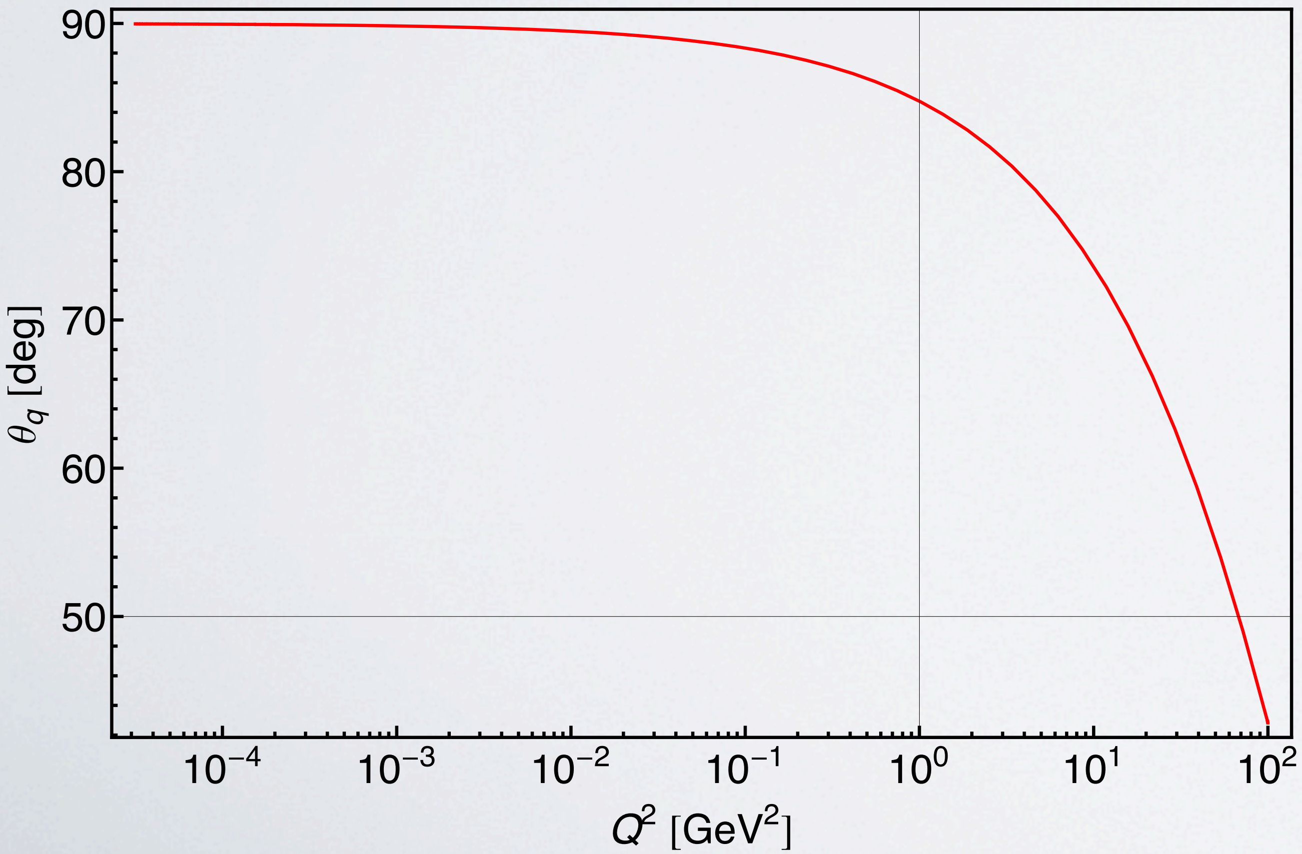
Prospects for Low Q^2 ep with EIC



Electron angle as a function of electron beam energy.

Lower beam energy is better.

Negligible effect from proton beam energy.



q-vector angle as a function of Q^2.

Since for low Q^2 $\theta_q \sim 90$ deg, need intermediate θ polarization.

Prospects for Low Q^2 ep with EIC

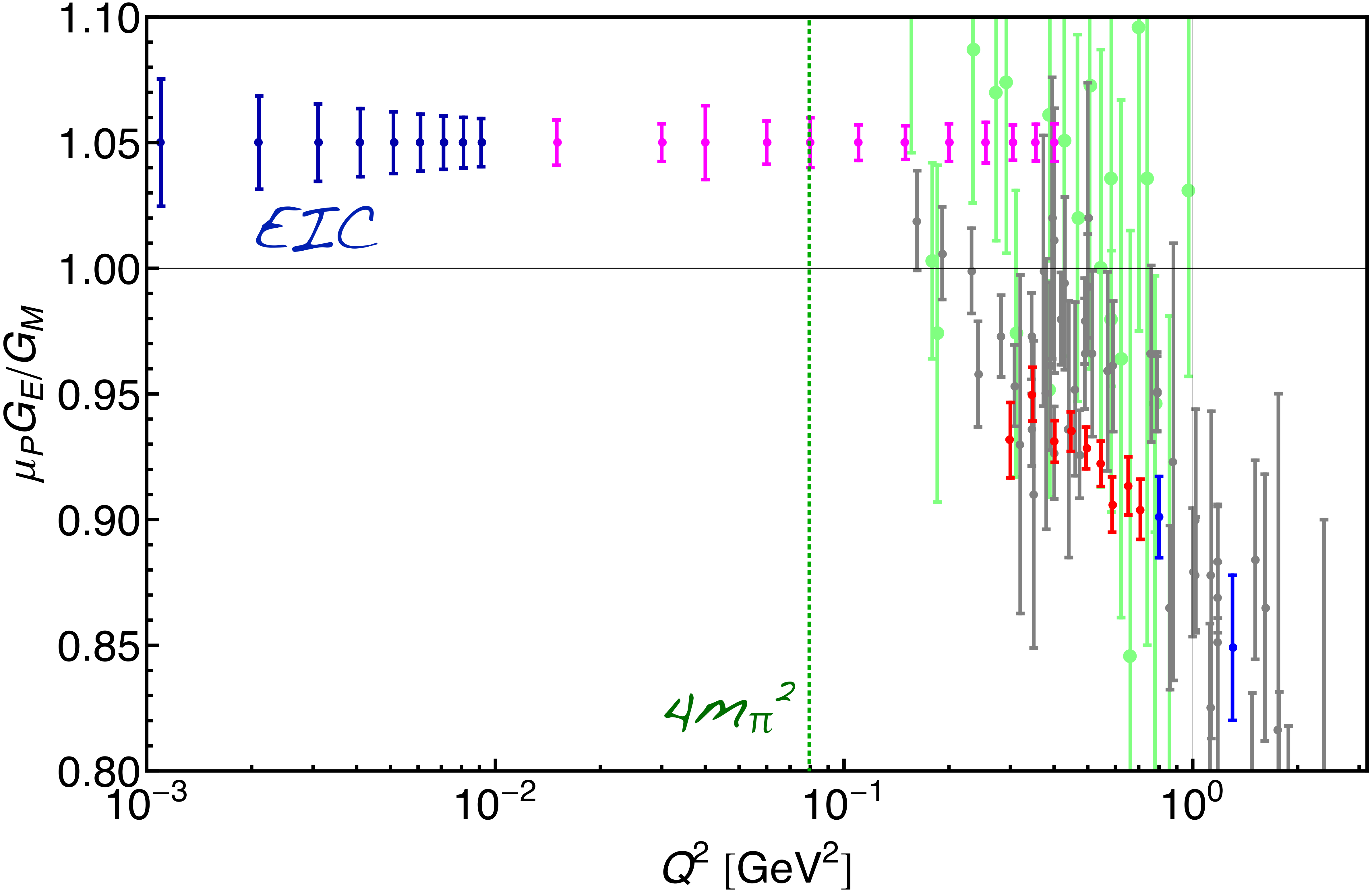
- Possible fix for beam polarization direction uncertainty → Calibrate polarization direction online using measured intermediate Q^2 values.

Q^2 (GeV^2)	10^{-4}	$5 \cdot 10^{-4}$	10^{-3}	$5 \cdot 10^{-3}$	0.01	0.3	0.5
θ_e	0.19	0.427	0.6	1.35	1.9	10.43	13.45
XS (cm^{-2})	2.60E-23	1.00E-24	2.50E-25	1.00E-26	2.50E-27	1.00E-30	2.30E-31
Rate (Hz)	9.1	1.75	0.875	0.175	0.0875	3.25	1.13
$T_{0.5\%}$ (hr)	1.22	6.35	12.7	63.5	127		

Measurable online using standard "barrel" detector.
High precision FF ratio data available.

1% uncertainty on FFR → 0.1 uncertainty on θ_B (at 10 degrees)

What it could look like....



Summary

- EIC feasible for both high and low Q^2 measurements.
- Both ratio of FFs and cross section can (in principle) be simultaneously measured, giving individual form factors.
- Luminosity not an issue for low Q^2 - measurements better with lower electron beam energy.
- For High Q^2 we need $L \sim 10^{34}$ sec^{-1} cm^{-2}.
- Primary concerns:
  - Polarization direction uncertainty for proton beam.
  - Design of "roman pot" style detector for small angles.
- Other things I'd like to see:
  - Polarized positrons for multi-γ studies.
  - Polarized D, ^3He, ^7Li (compare quasi-free/elastic ep):
    - Is D really p+n?
    - Is ^3He(pol) really n(pol)?