JLab Experiment E08-007
Proton Electromagnetic Form Factor Ratio at Low Q^2

Ron Gilman*

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Outline

- Stuff we (should ?) know
- E08-007 form factor measurements
  - Motivation
  - Analysis

The E08-007 Collaboration:

Guy Ron, spokesperson

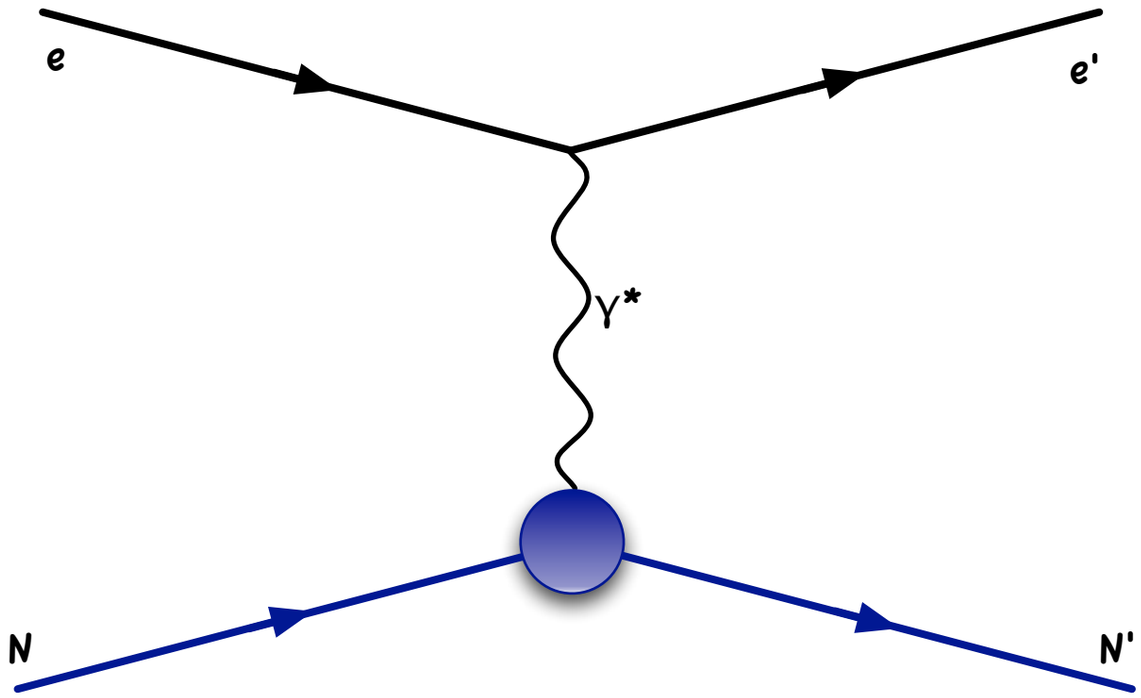
Moshe Friedman, Ph.D. student

et al.

Mainz, June 2014

*Thanks to: US NSF grant PHY 09-69239, 12-63280, JLab, MITP, ...

Stuff We Know: EM scattering from 1γ Exchange



Cross section formulas derived and put in modern form ≈ 60 years ago - Rosenbluth separation.

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

Rosenbluth - Spin-1/2 with Structure

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

Assumptions: one-photon exchange, electron mass small

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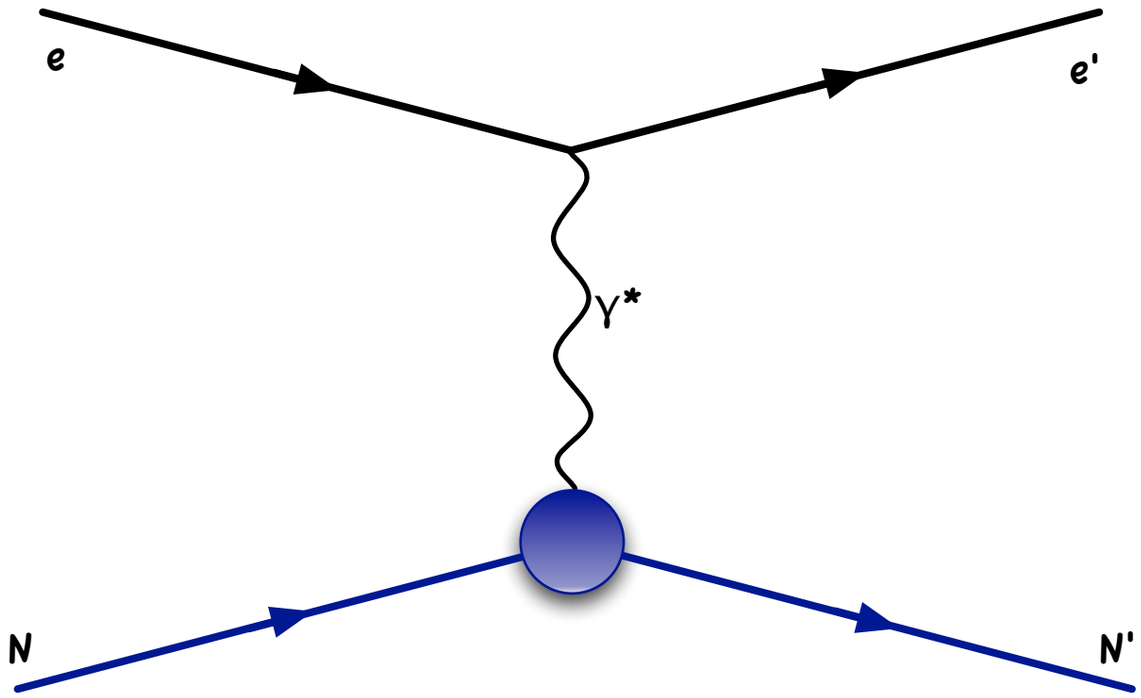
Stuff We Know: Form Factors



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Rosenbluth - Spin-1/2 with Structure

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

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

Two relativistic-invariant functions of four-momentum transfer Q^2

G_M's roughly follow the dipole form, $(1+Q^2/\Lambda^2)^{-2}$, which has no theoretical significance

Sometimes written using:

$$G_E = F_1 - \tau F_2$$

$$G_M = F1 + F_2$$

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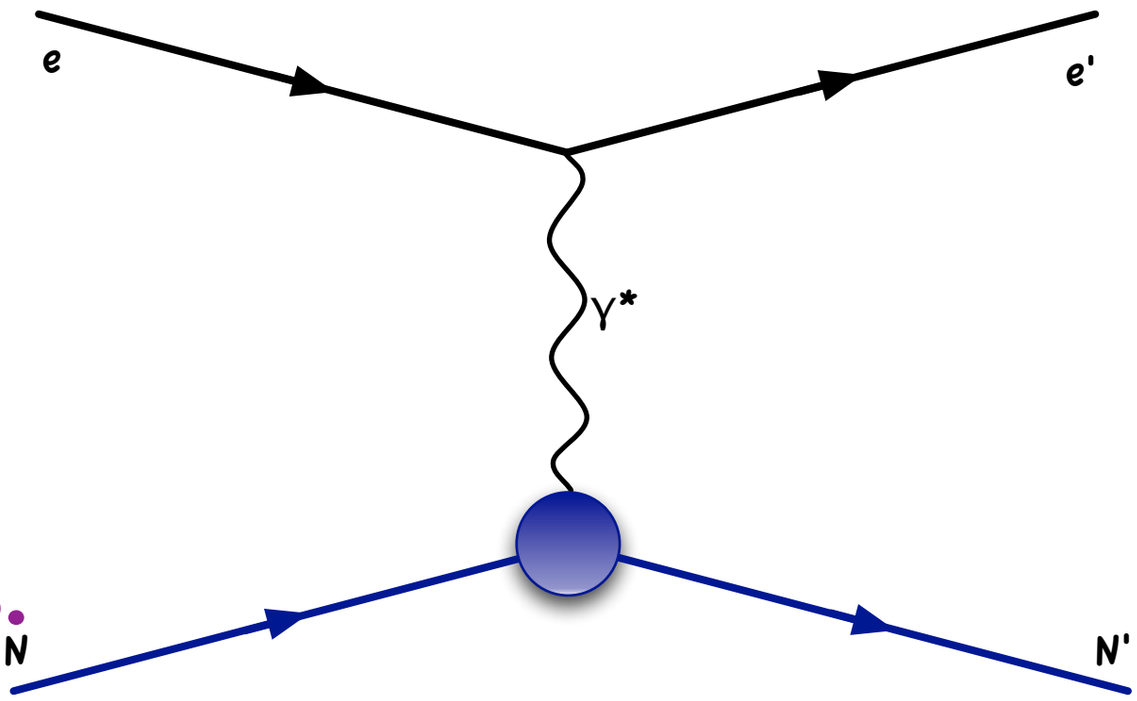
Stuff We Know: Radius means slope of FF at $Q^2 = 0$, it does not mean radius.



In NRQM, scattering theory, F.T. 3d spatial distributions, small-Q^2 expansion:

$$G_{E,M}(Q^2) = 1 - \frac{1}{6}\left\langle r^2_{E,M}\right\rangle Q^2 + \frac{1}{120}\left\langle r^4_{E,M}\right\rangle Q^4 - \frac{1}{5040}\left\langle r^6_{E,M}\right\rangle Q^6 + \cdots$$

Sometimes you get the "right" answer despite the wrong approach

$$-6\frac{dG_{E,M}}{dQ^2}\bigg|_{Q^2=0} = \left\langle r^2_{E,M}\right\rangle \equiv r^2_{E,M}$$

Overall factor of μ taken out of G_M

Slope of $G_{E,M}$ at Q^2=0 defines the radii. This is what FF experiments quote.

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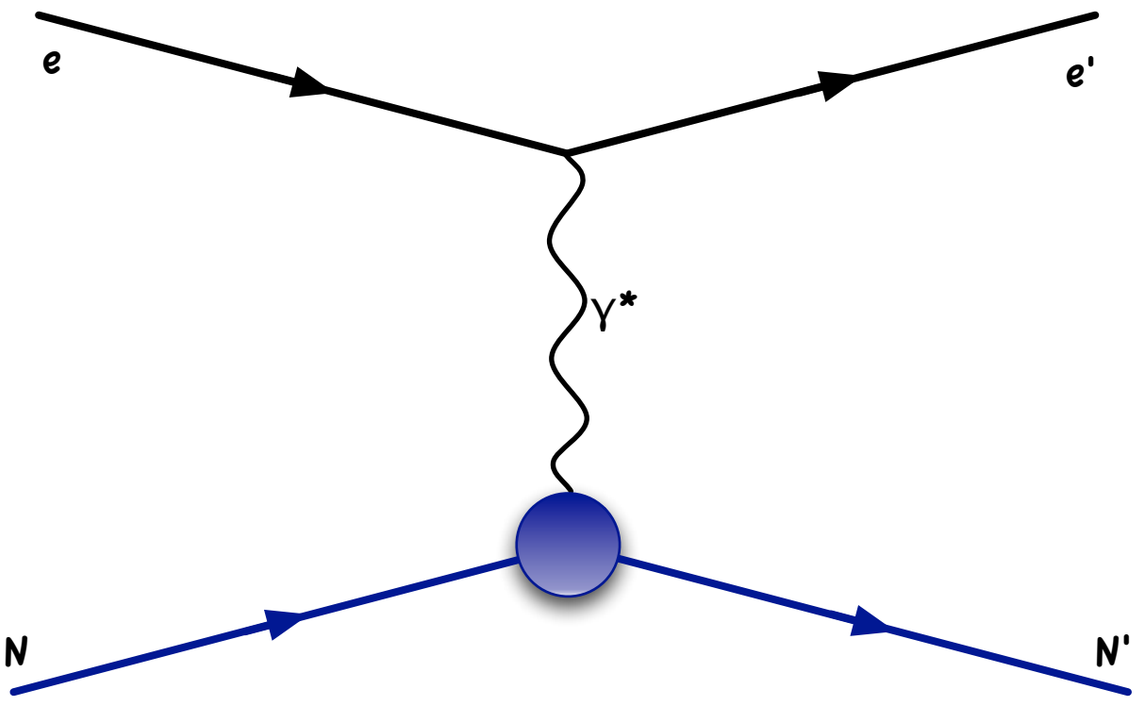
Stuff We Know: Rosenbluth separations do not determine FF with small contribution to cross section well



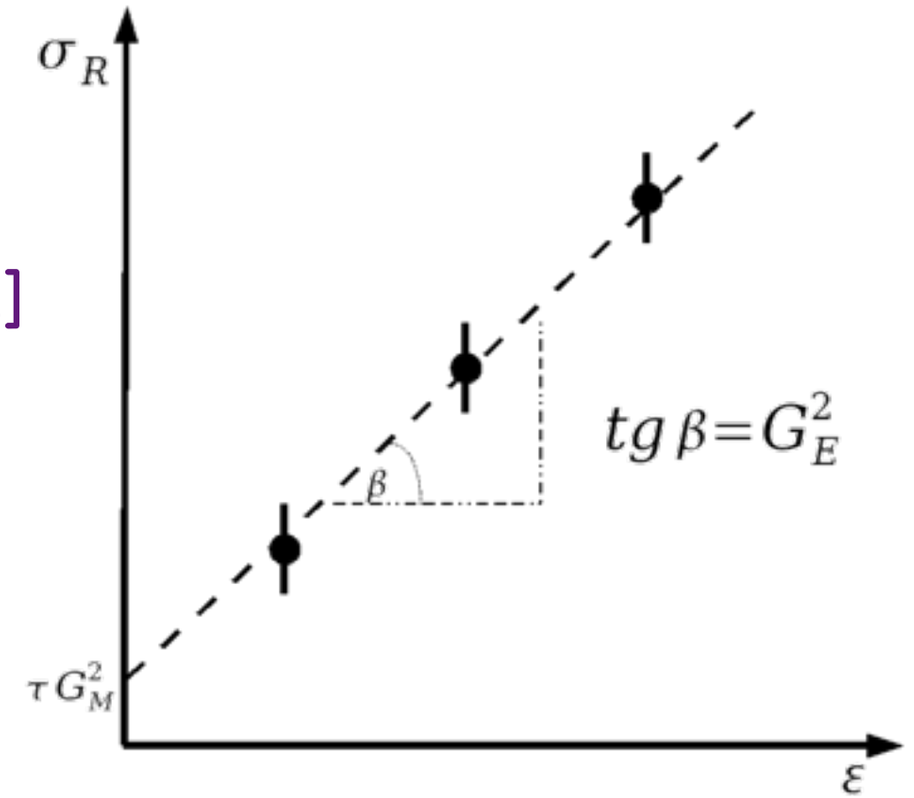
$$\frac{d\sigma_{Str}}{d\Omega} = \frac{d\sigma_M}{d\Omega} \times \left[G_E^2(Q^2) + \frac{\tau}{\varepsilon} G_M^2(Q^2)\right]$$

For Rosenbluth, multiply RHS by ε/ε and use $\sigma_R = \varepsilon[\ldots]$

At high Q^2, τ is large and G_E is hard to determine

At low Q^2, τ is small and G_M is hard to determine (except for $\theta \approx 180^\circ$)

Solution already known by early 1960s ➪ polarization measurements



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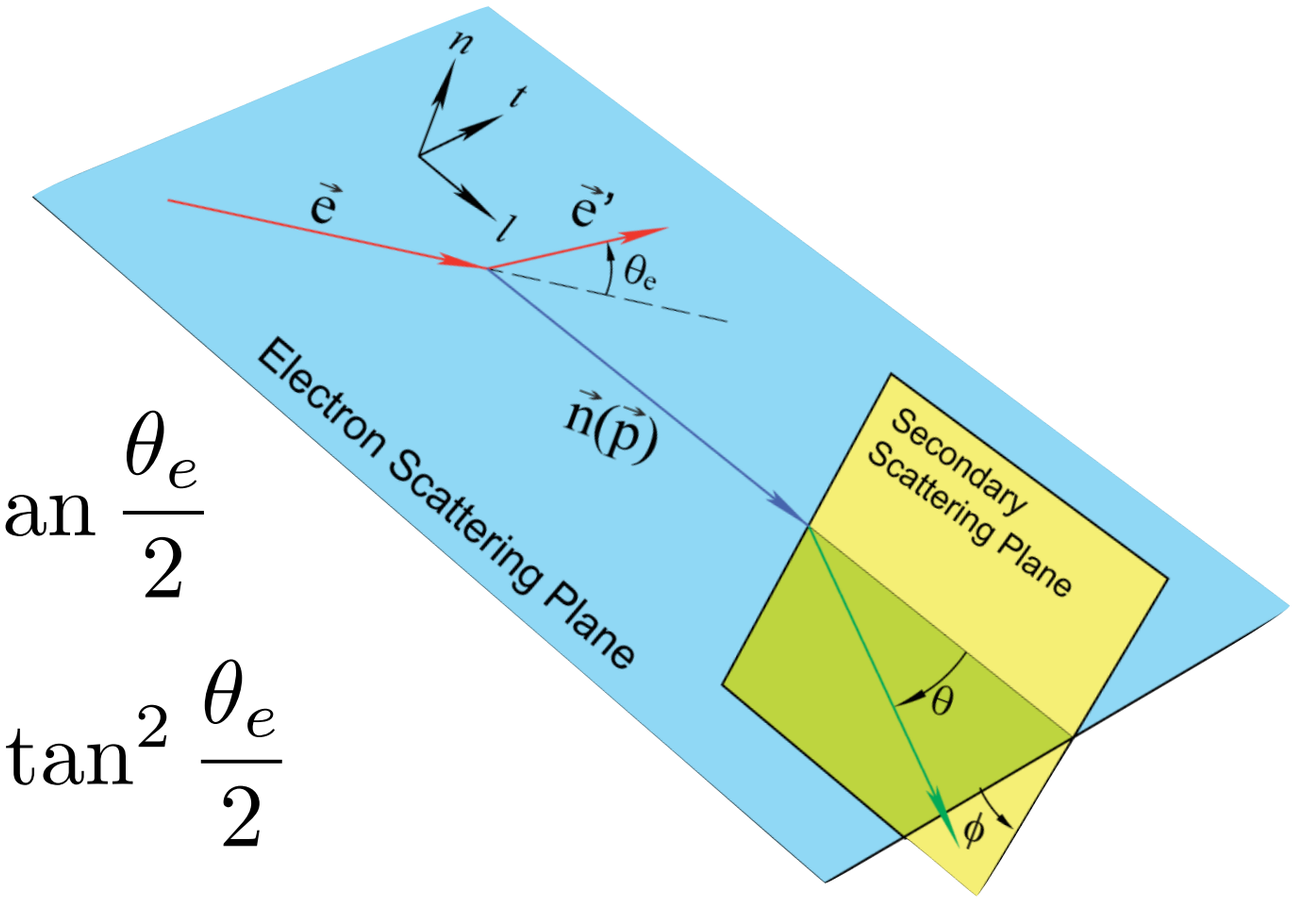
Stuff We Know: Polarization Transfer

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

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

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



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

Polarizations worked on by many. Put in modern form first by Akhiezer & Rekalo (1973). "Popularized" in US by Arnold, Carlson & Gross (1981).

Polarizations measure the ratio G_E/G_M, not the individual form factors.

I_0 is the structure part of the cross section, the [...].

Done at Mainz, MIT Bates, and JLab.

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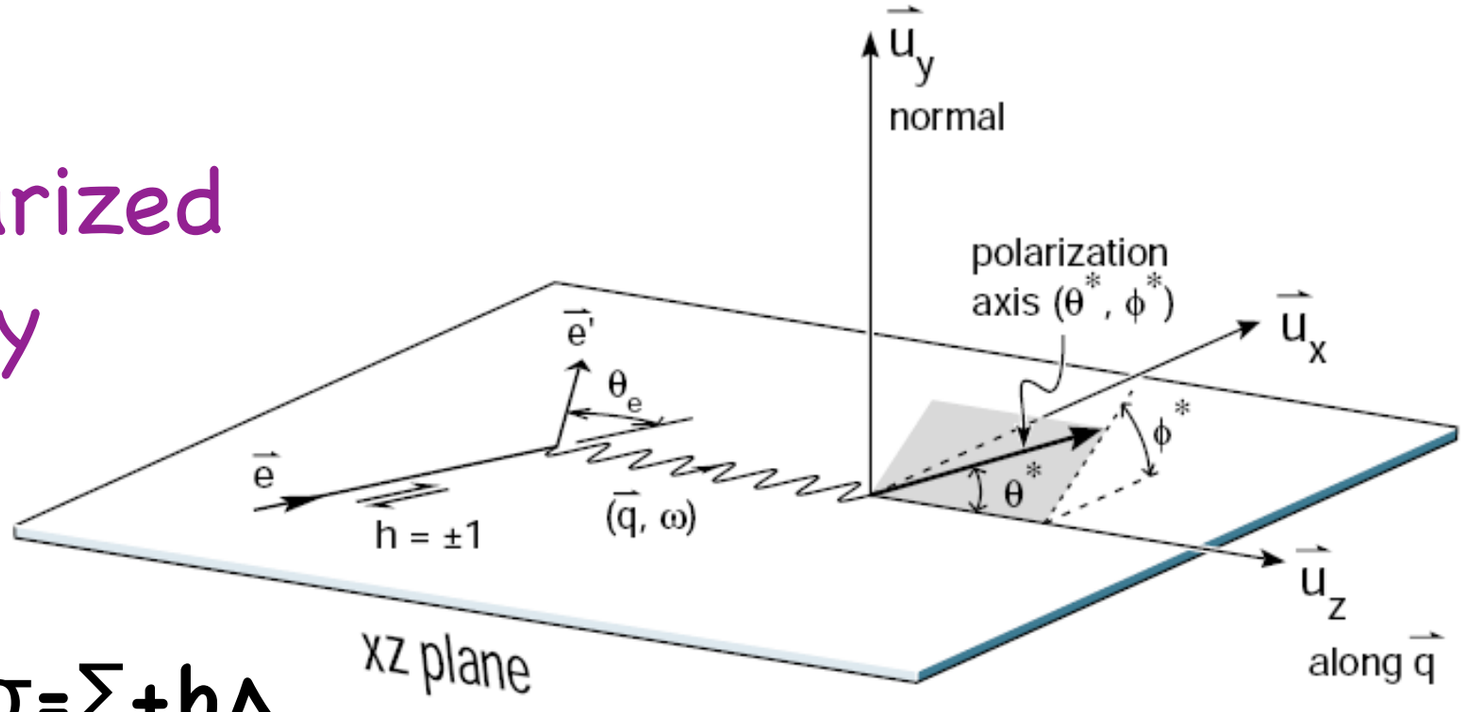
Stuff We Know: Polarized Beam - Polarized Target Asymmetry



Polarized Cross Section: $\sigma = \Sigma + h\Delta$

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

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

For a single polarization measurement, uncertainties can be limited by polarimetry, to a few percent.

For two simultaneous polarization measurements, these uncertainties can cancel in the ratio of the two.

Can swap between systematic & statistical uncertainties.

a, b, c, d are kinematic factors

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Why E08-007?

Back in 2008, we perceived a need for better low Q^2 form factors

- Measure to better precision the low Q^2 form factor ratio, and how it starts deviating from unity
- Check claims of structure in the low Q^2 form factors (Friedrich & Walcher)
- Work by Carlson, Griffeoen, et al., pointed out that leading uncertainties in hyperfine splitting theory were related to nucleon structure - improved elastic form factors to calculate a better Zemach radius, and improved polarized inelastic scattering to calculate a better polarizibility correction - the subject of our polarized target "sister" experiment, E08-027, by Slifer et al.

We did not anticipate a proton radius puzzle. But neither did the JLab PAC.
We did not anticipate the quality and quantity of the Mainz data.

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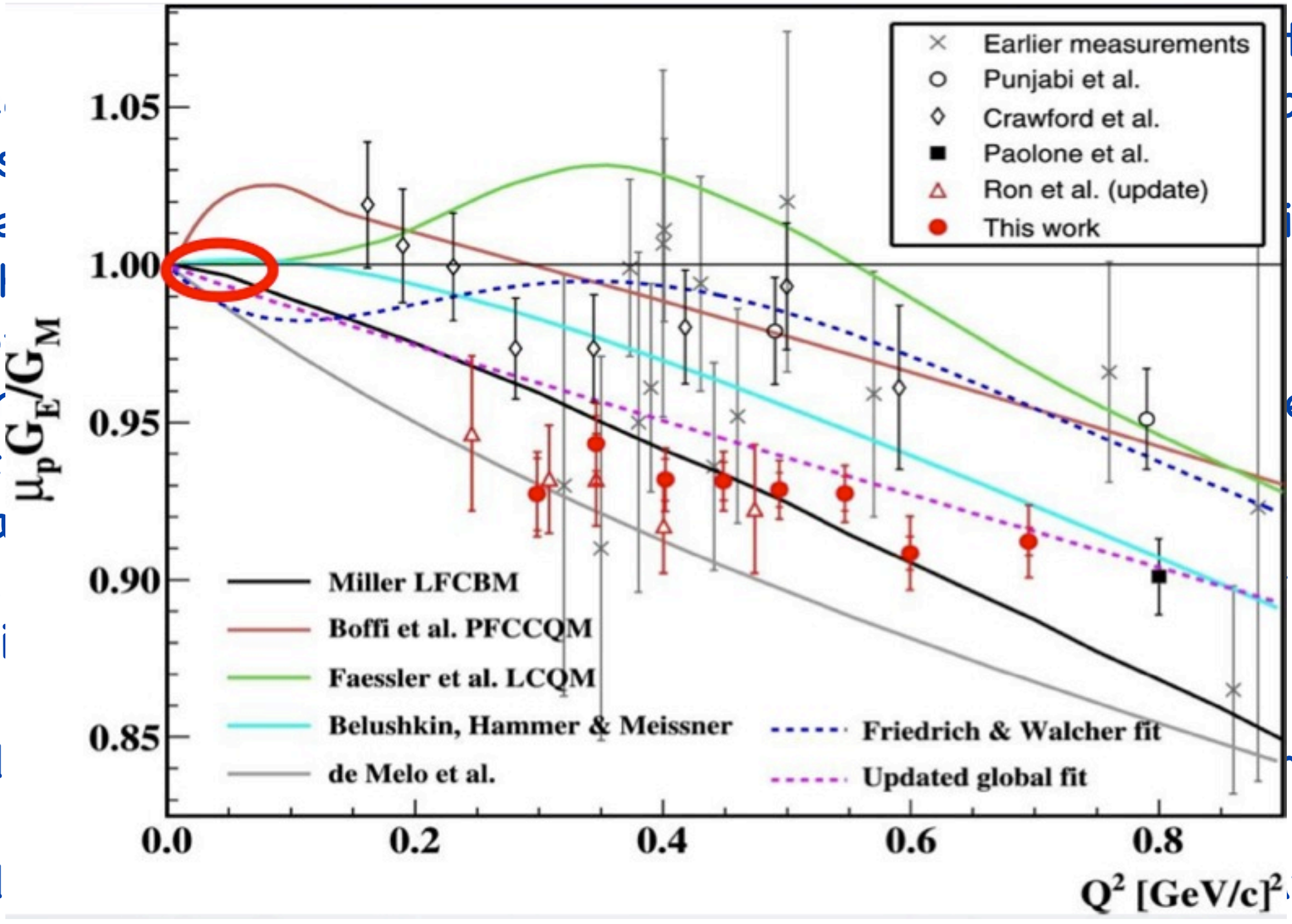
Why E08-007?

Back tors

- Me ow it starts
- Che ich & Walcl
- Wo uncer eon struc Zema calcu polari

We d ne JLab We d ta.



But polarizations only measure ratios... ?

While the polarization data only measure ratios, they help constrain the normalization of cross section data sets, leading to improved form factors.

The number of polarization data points is comparable to the amount of non-Bernauer et al cross section data points.

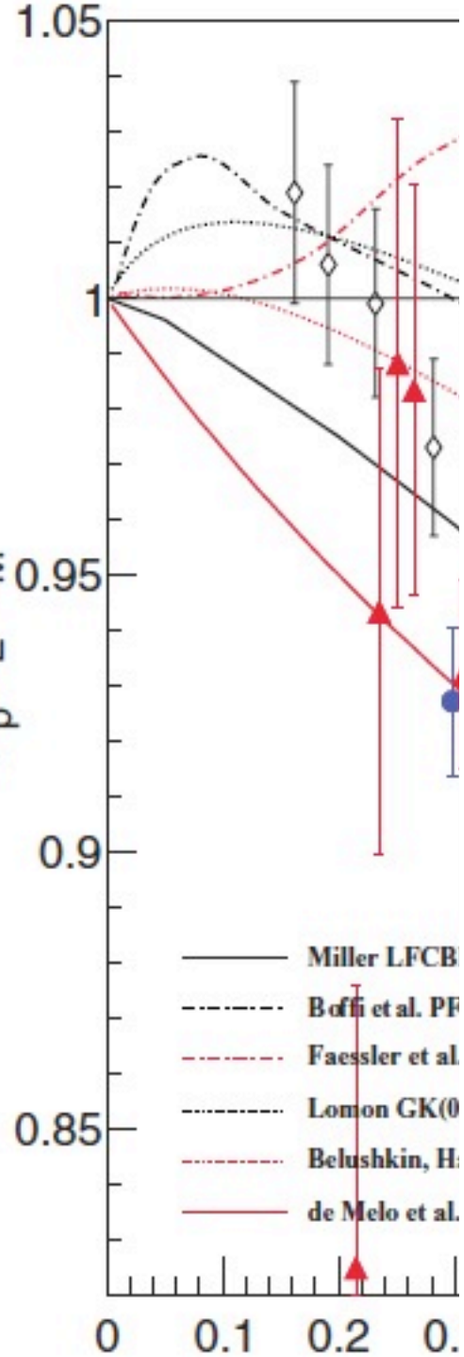
E08-007 Overview

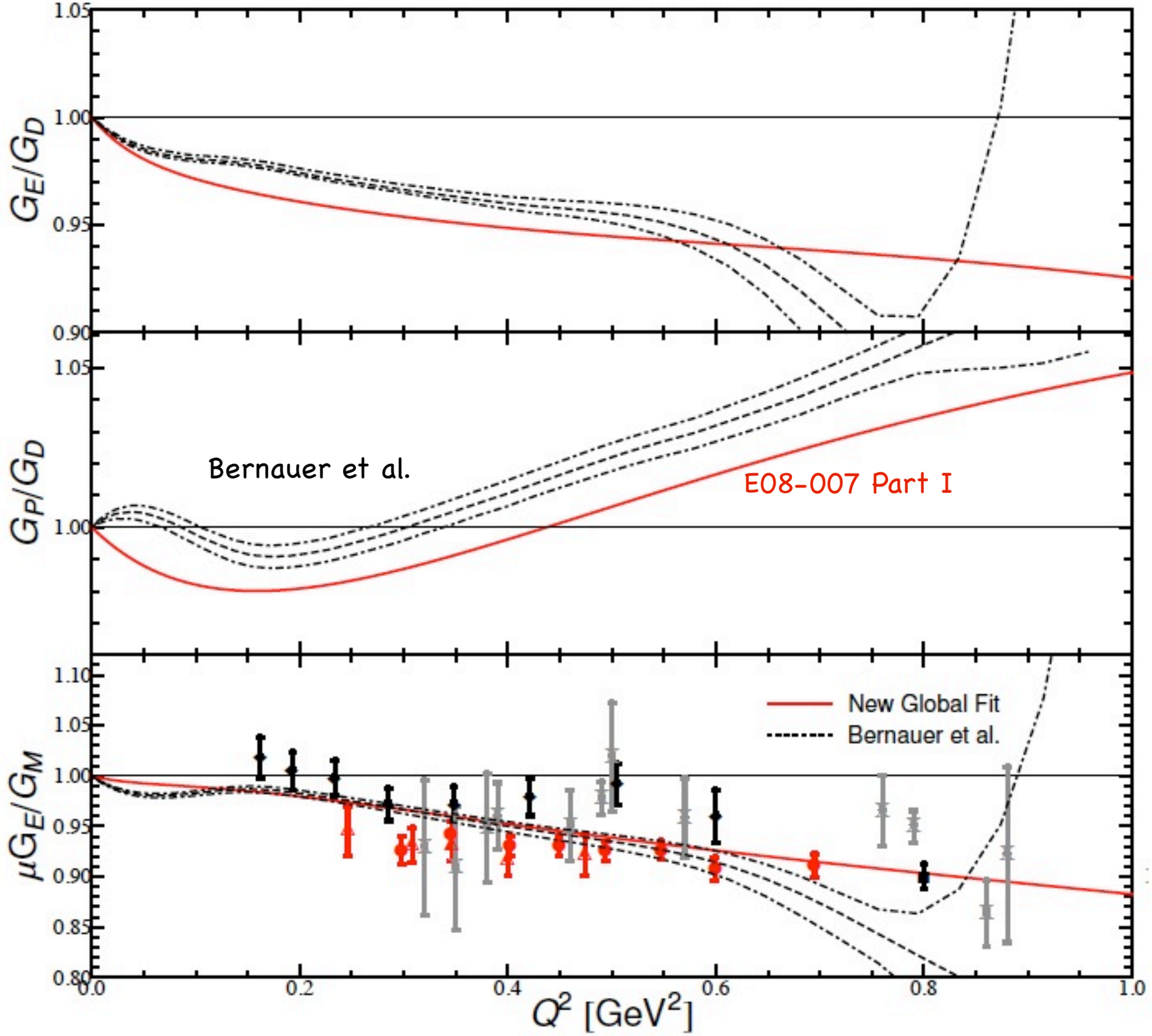
Proposed in 2008 by G Ron et al. as a two-part measurement:

- Part I:
  - Recoil polarization for $Q^2 \approx 0.3$ - 0.7 GeV^2
  - Ran 2008
  - Published as Zhan et al., PLB, 2011

- Part II:
  - Polarized target asymmetries for lower Q^2
  - …

E08-007 Part I





GR et al., PRC84, 055204(2011)

Bernauer et al, PRL105, 242001 (2010)

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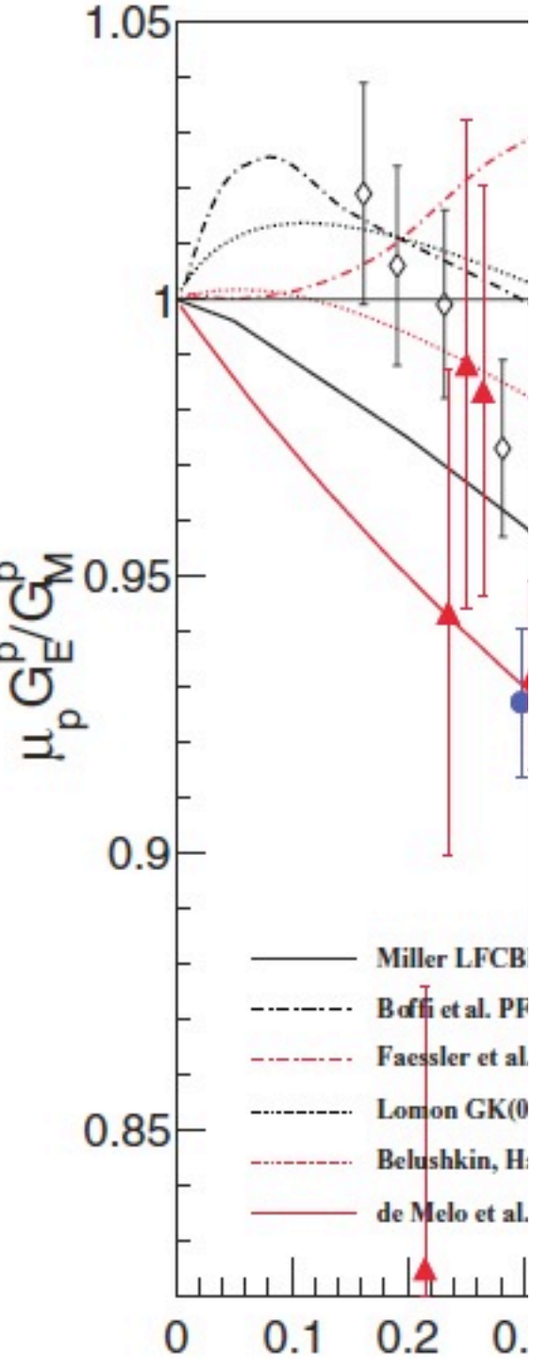
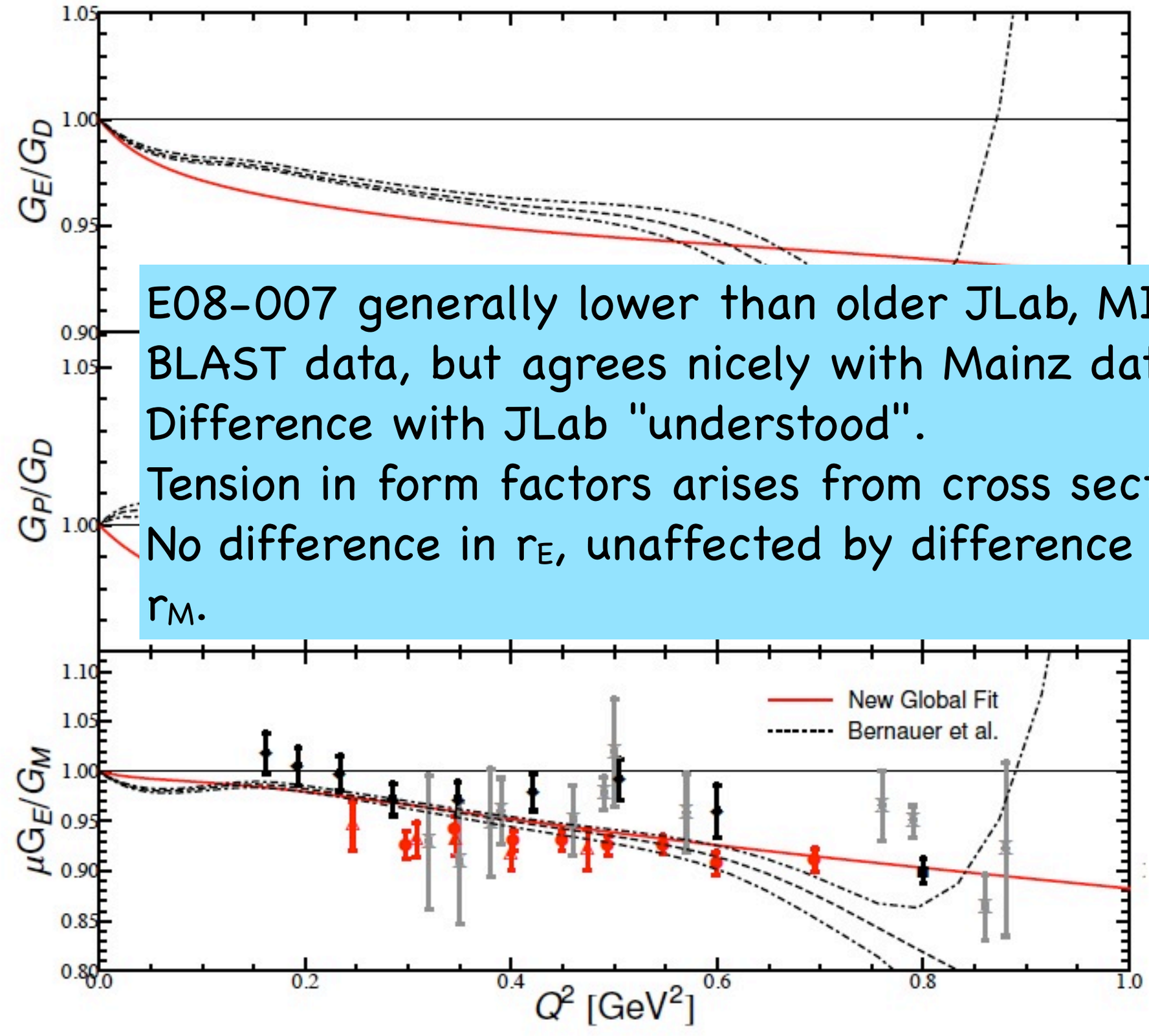
E08-007 Part I





E08-007 generally lower than older JLab, MIT BLAST data, but agrees nicely with Mainz data.
Difference with JLab "understood".
Tension in form factors arises from cross sections.
No difference in r_E, unaffected by difference in r_M.

GR et al., PRC84, 055204(2011)

Bernauer et al, PRL105, 242001 (2010)

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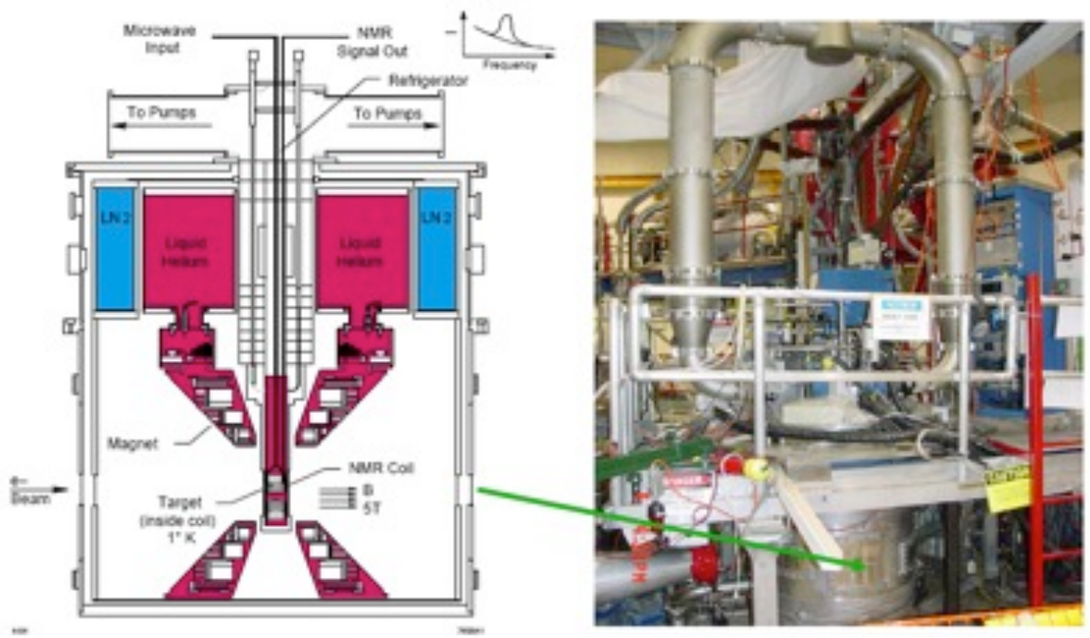
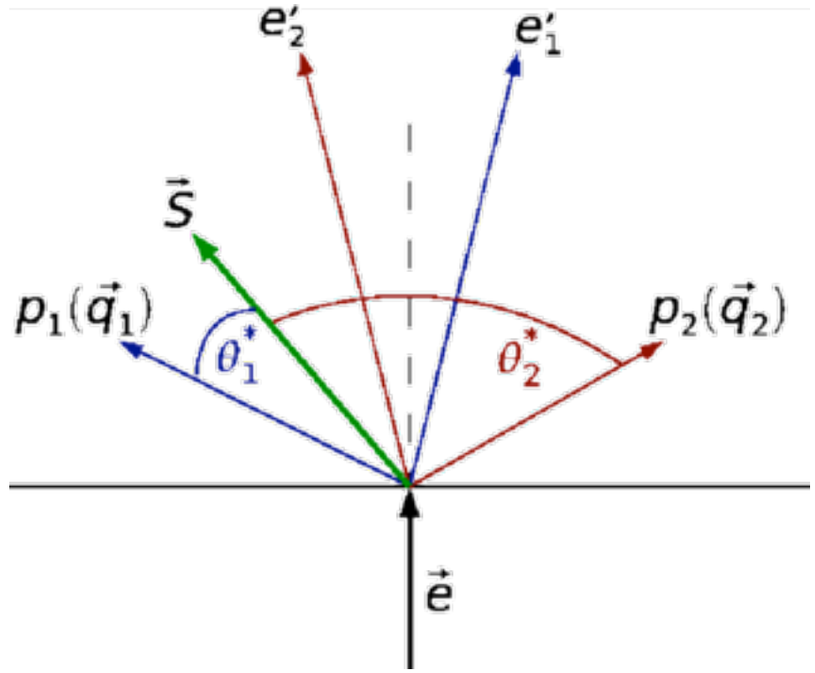
E08-007 Part II Overview

Experiment ran along with E08-027 in "late 2011 / early 2012".

Due to numerous technical problems, particularly with polarized target magnet, this was reduced to Feb - May 2012.



The data range was much reduced. Planned for high precision (≈1%) survey of the FF ratio at Q^2=0.01 - 0.16 GeV^2. Lost "high" Q^2 points.



Moshe Friedman (HUJI) Thesis project, work in progress

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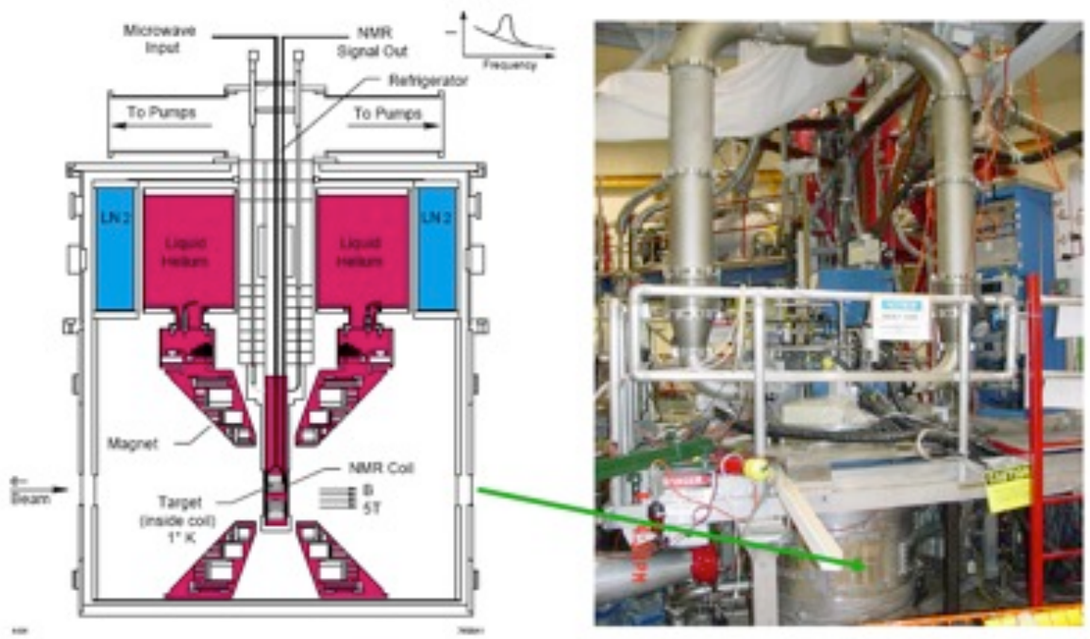
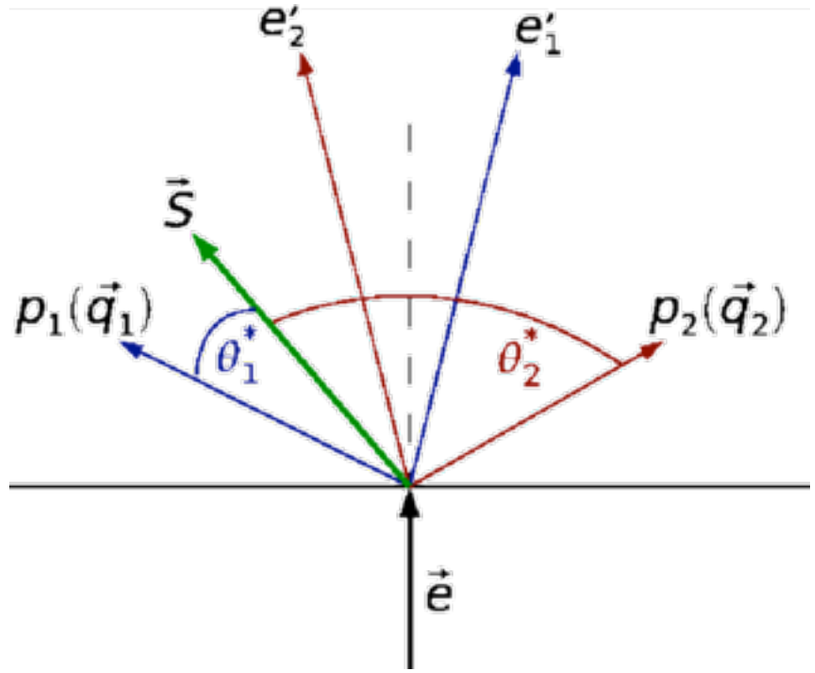
E08-007 Part II Overview



- Measured Beam-target asymmetry in electron scattering from polarized NH_3 target.



- Electrons detected in JLab Hall A's two matched HRS spectrometers.
- Ratio of asymmetries cancels systematic errors → only one target setting to get FF ratio.

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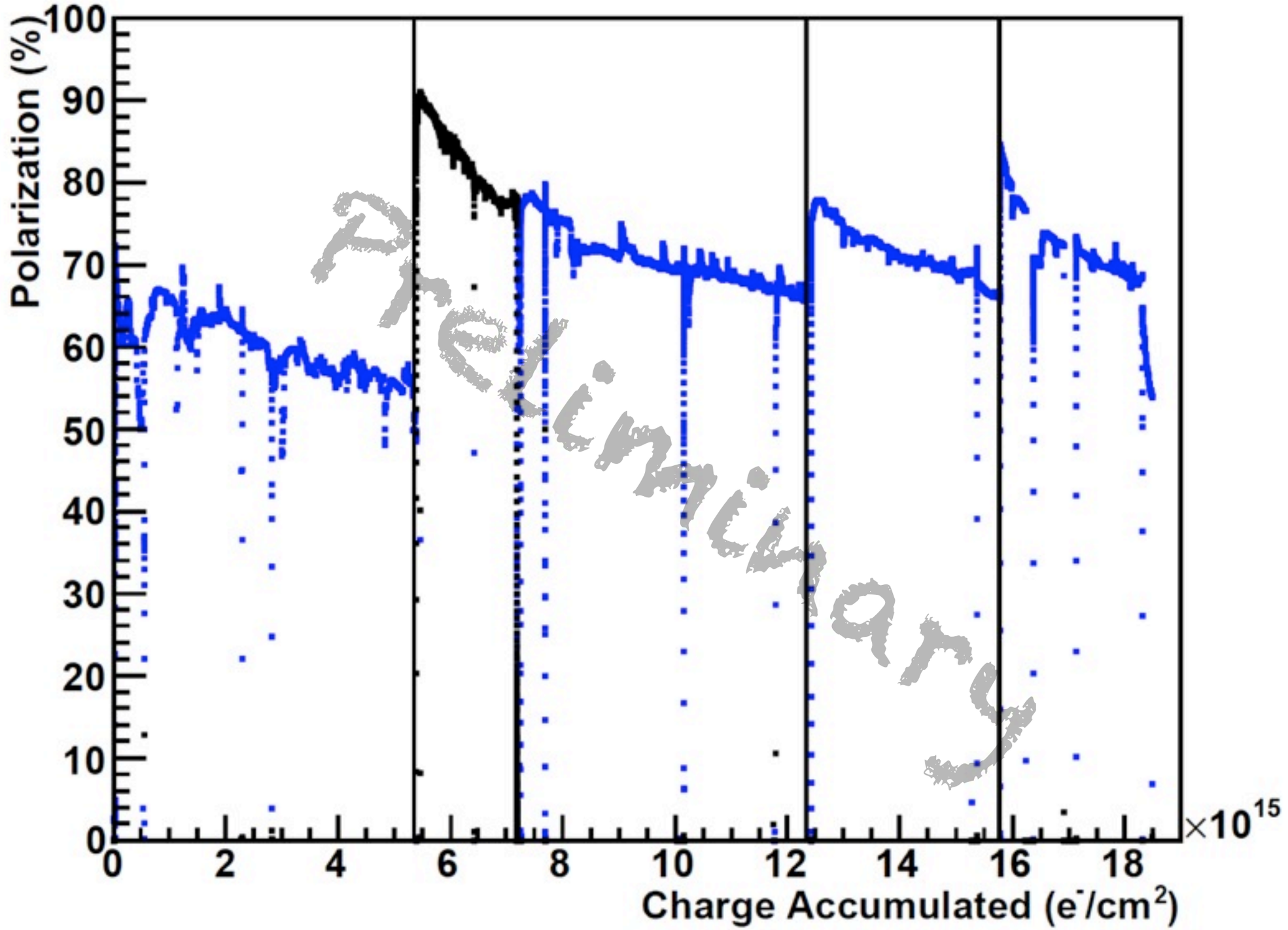
E08-007 Part II Preliminary Results

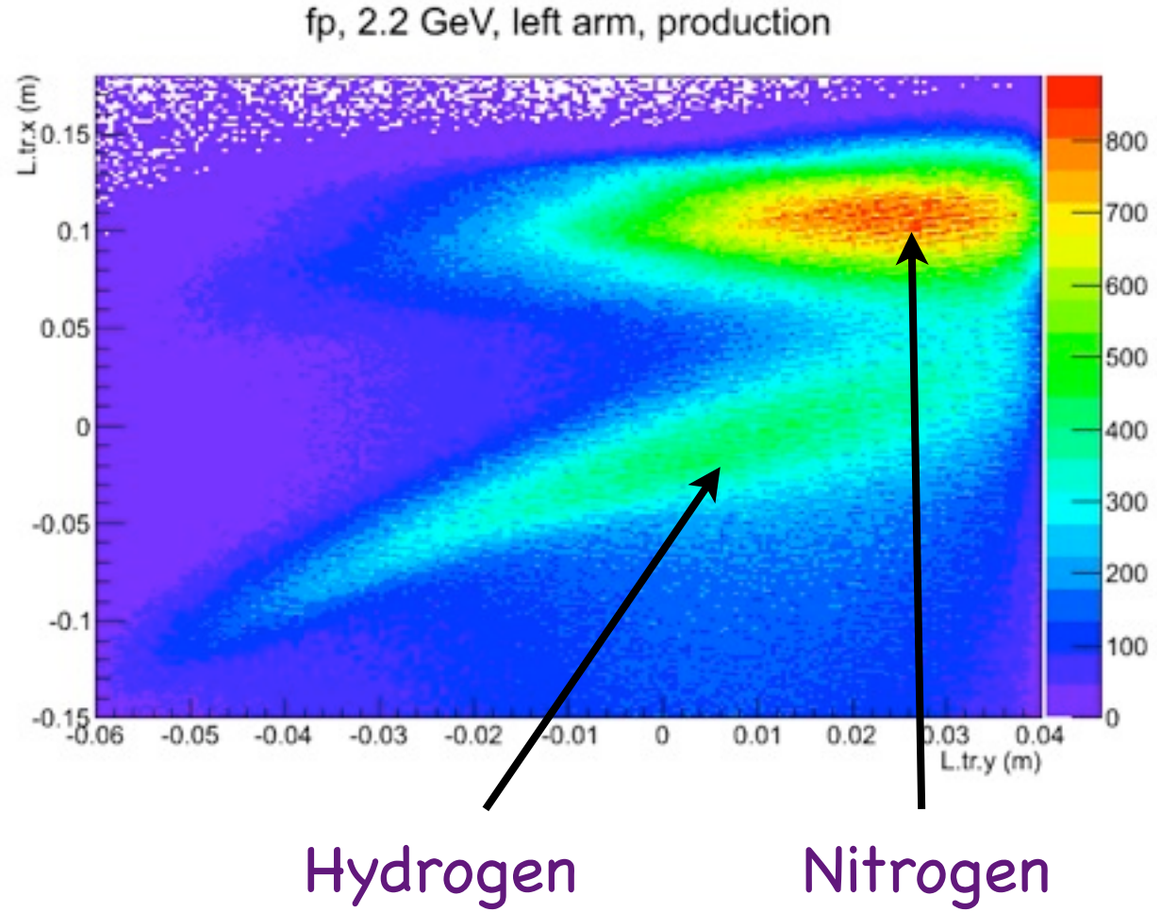
Target polarization vs time.

Absolute polarization known to ≈ 3%.



E08-007 Part II Preliminary Results

Event distribution on focal plane. Roughly momentum vs scattering angle.



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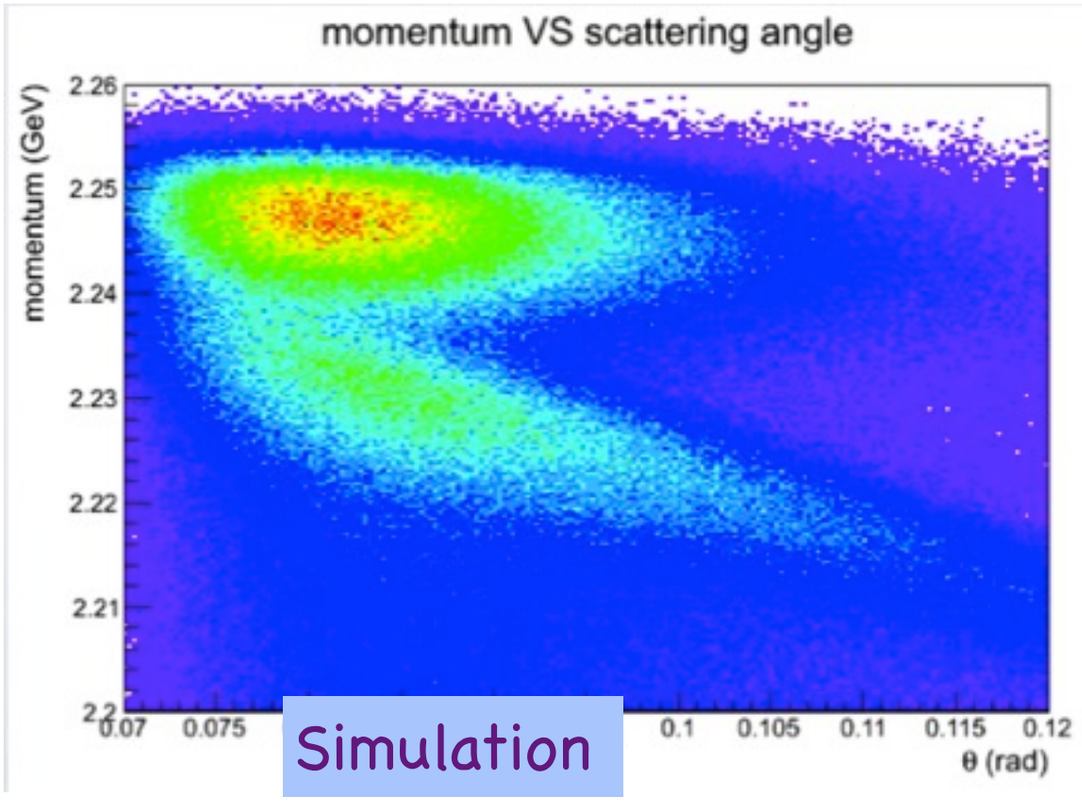
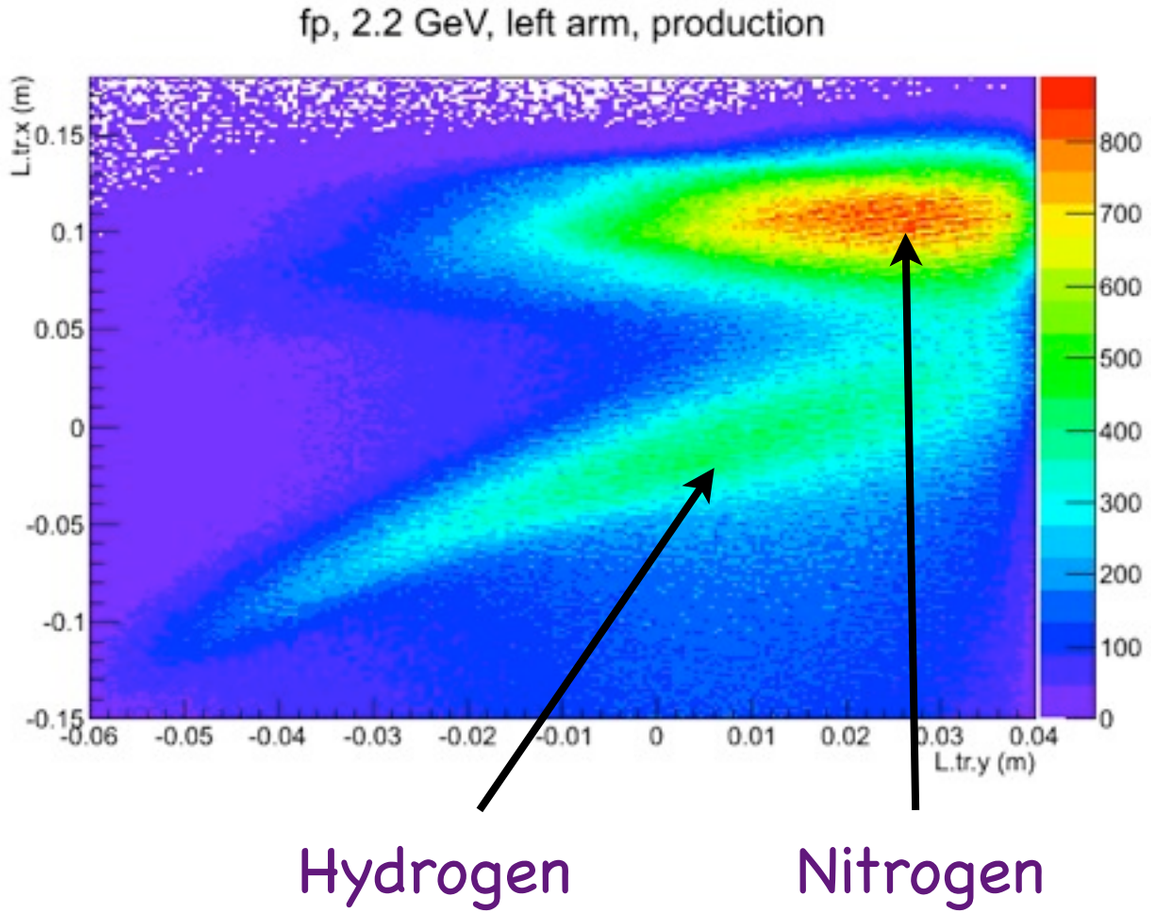


Simulation



Hydrogen

Nitrogen

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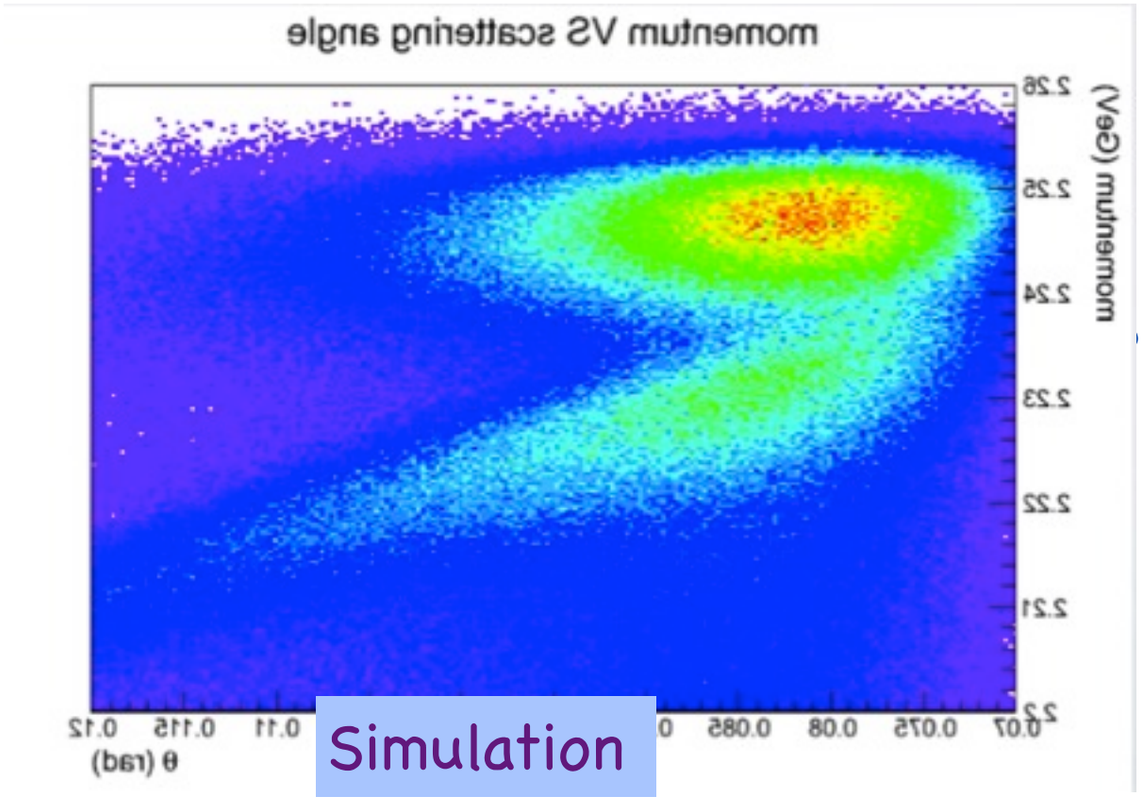
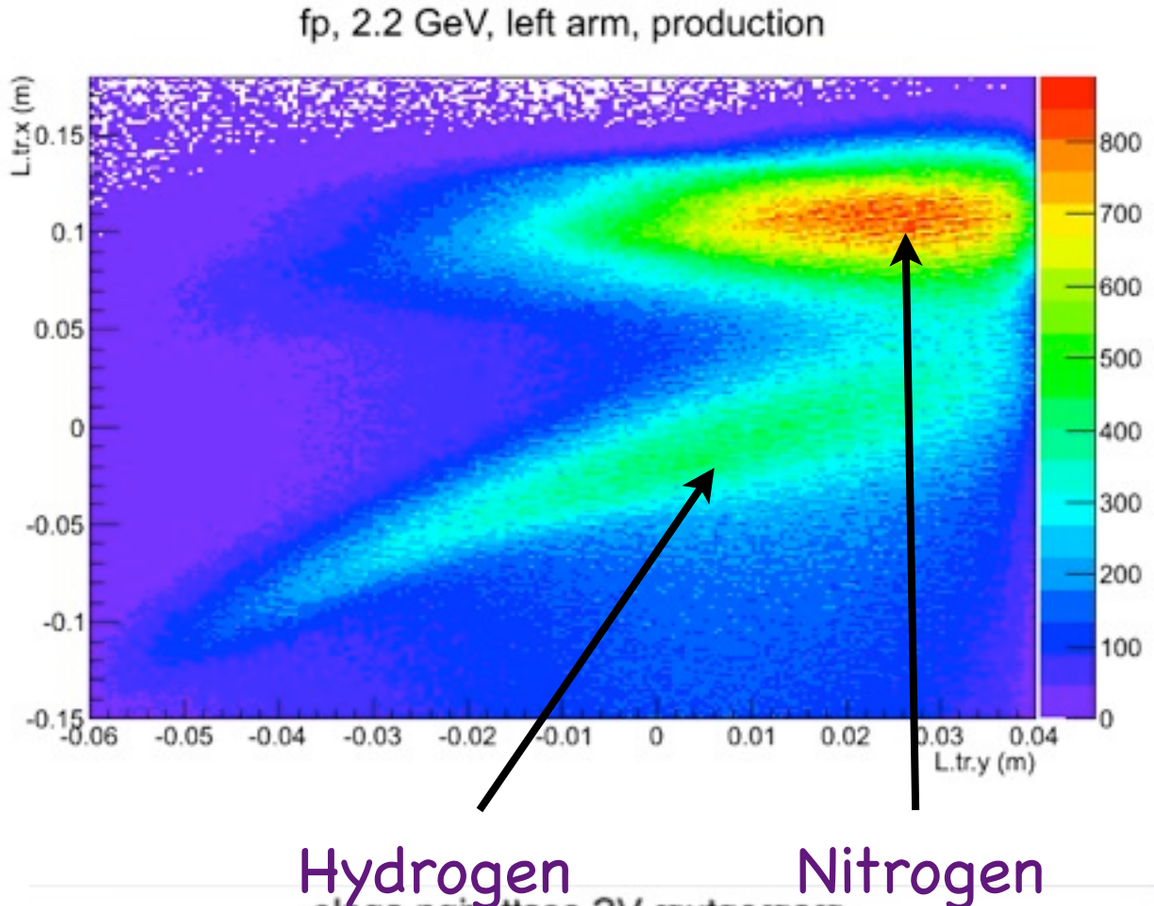
E08-007 Part II Preliminary Results





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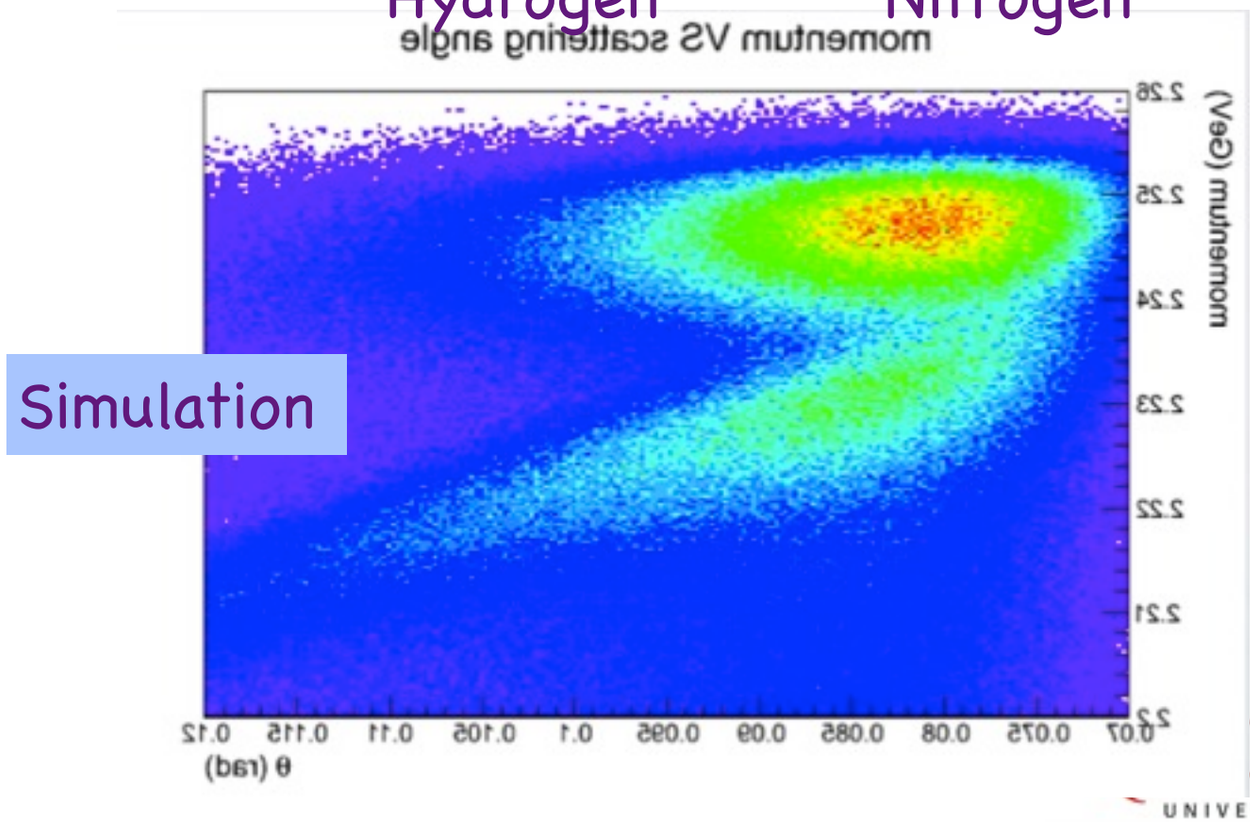
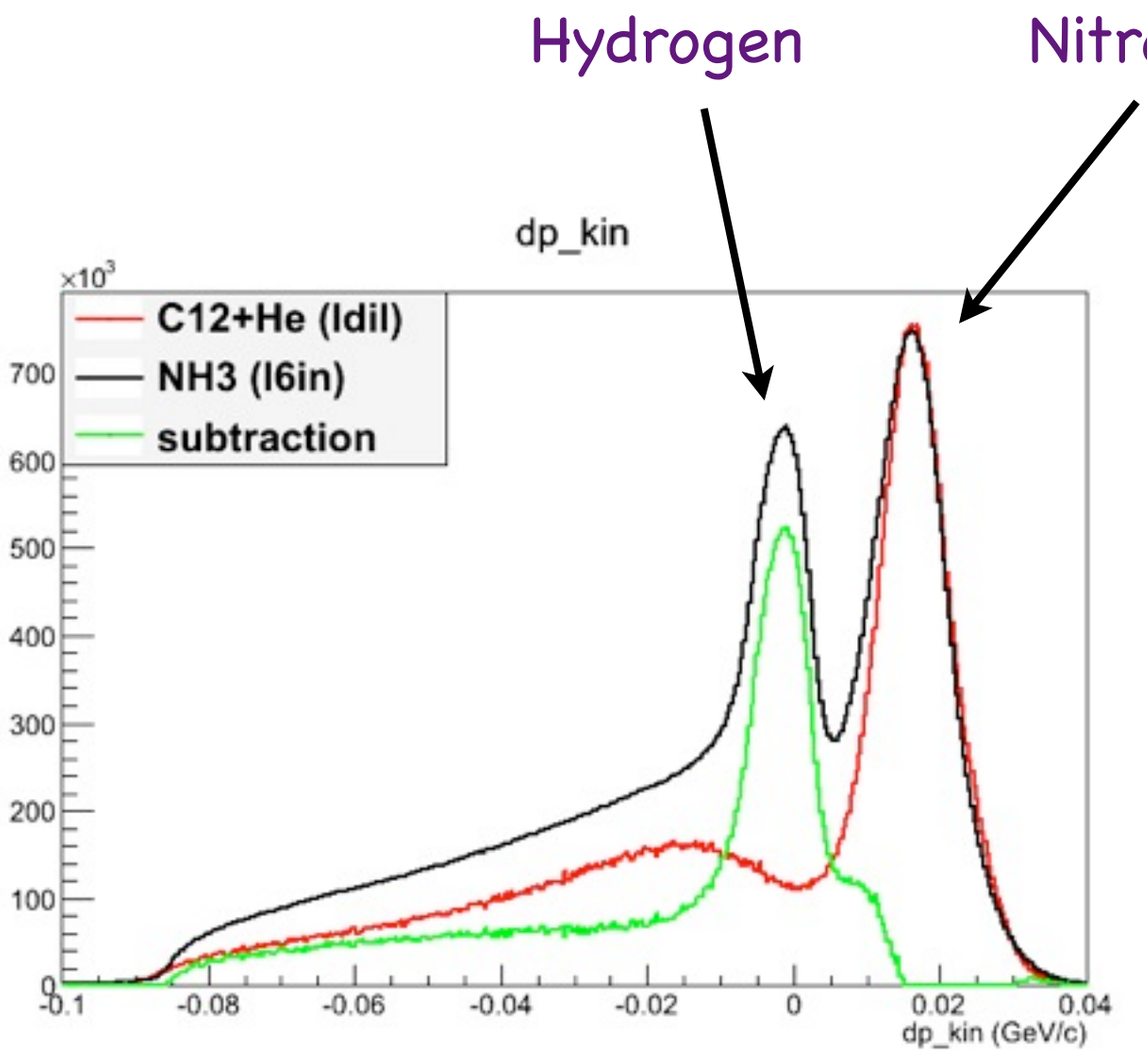
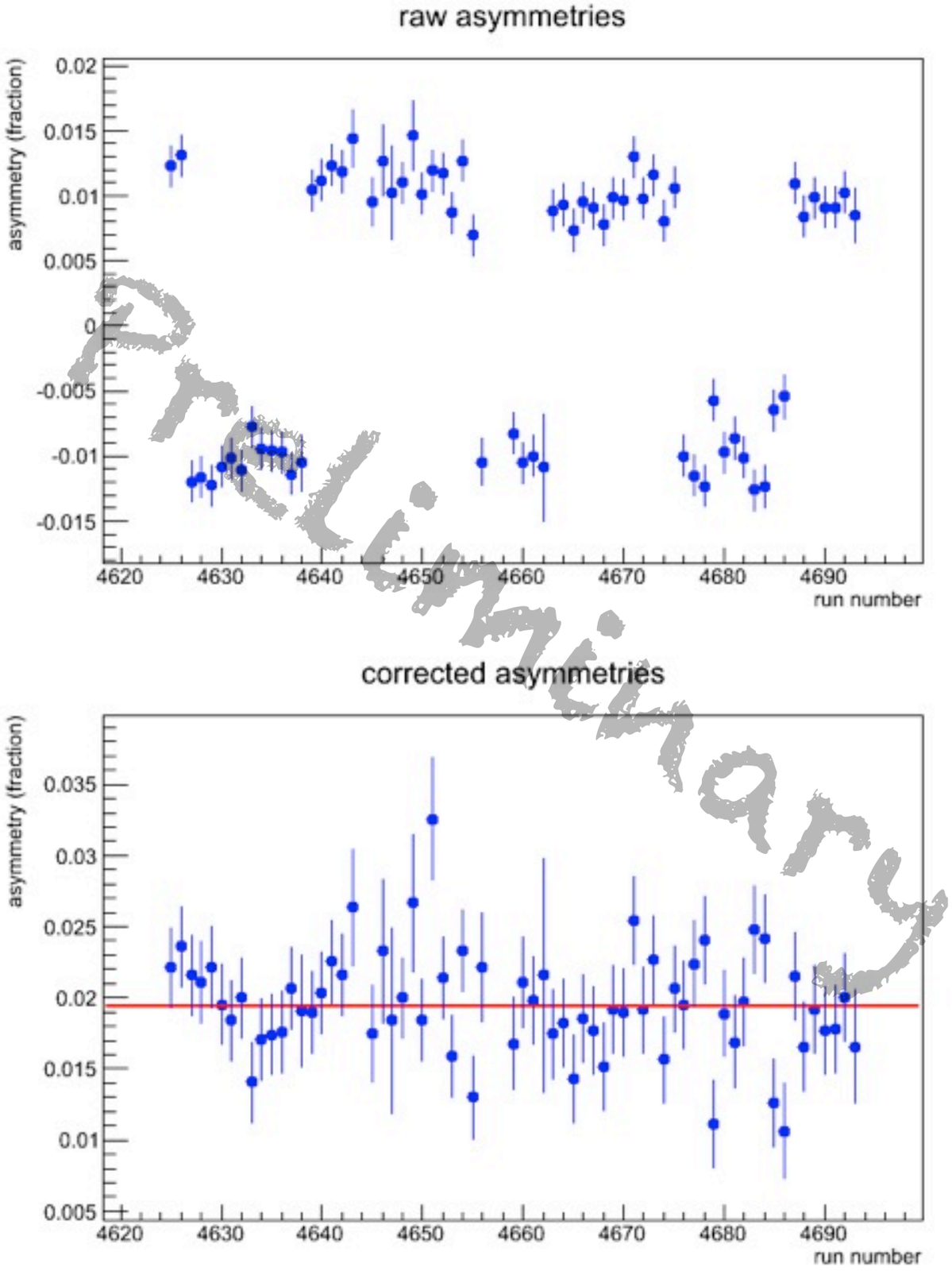


E08-007 Part II Preliminary Results



Momentum spectrum of data. C+He is similar to N, but not enough. N data in ≈ same kinematics being analyzed.

E08-007 Part II Preliminary Results



Hydrogen asymmetries reverse sign when target polarization reversed.

Nitrogen asymmetries (not shown) consistent with 0.

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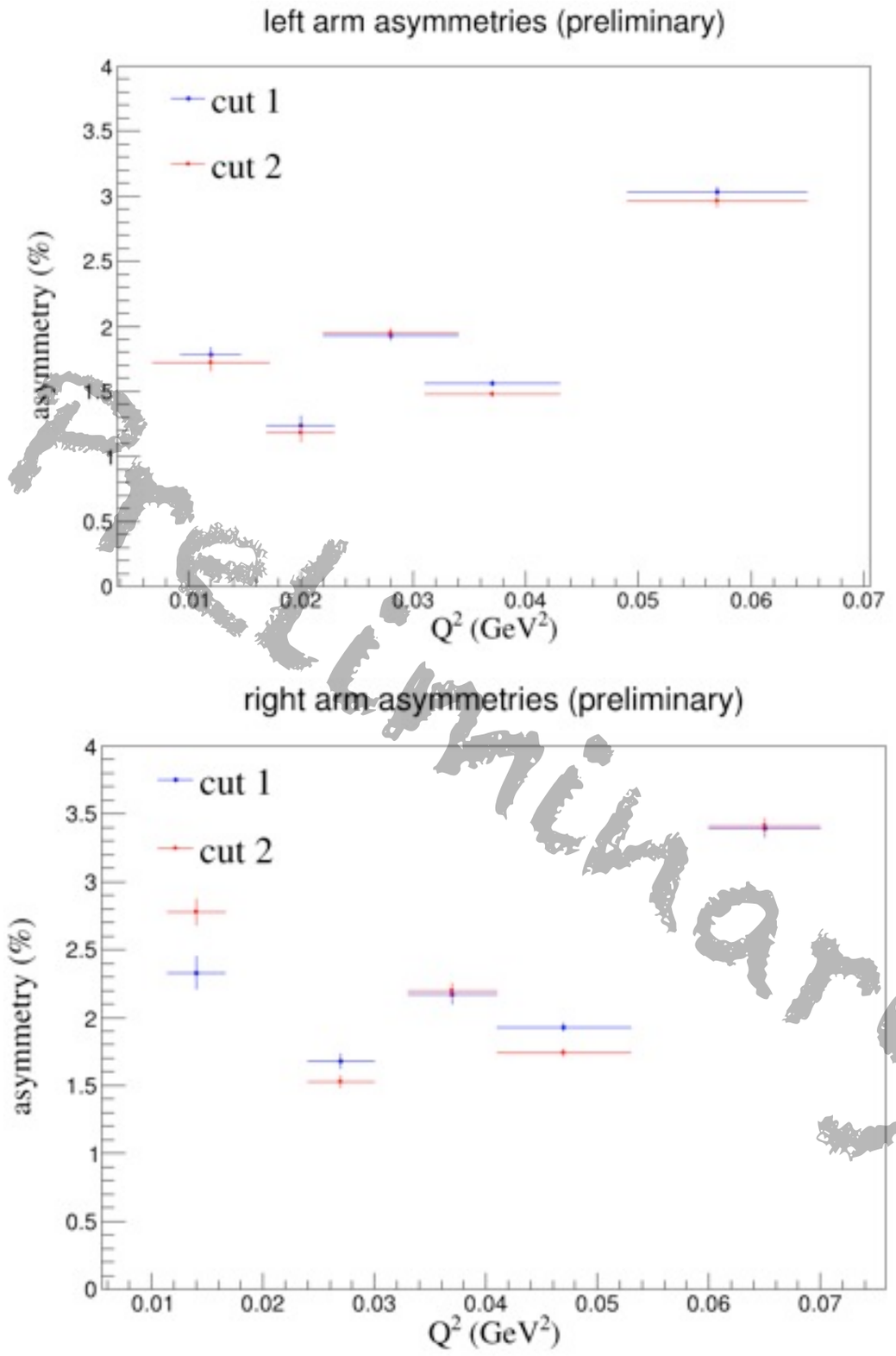
E08-007 Part II Preliminary Results



Left arm less insensitive to N vs H cut than right arm.

Statistical uncertainties becoming small. Need to better evaluate systematic uncertainties.

Cut 1 is a tighter cut.

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E08-007 Part II Issues & Improvements

Optics not finalized. Should get better signal/background separation and thus statistical uncertainty.

Helicity decoder messes up, diluting asymmetry. Fixing will increase asymmetry and improve ΔA/A.

Nitrogen data should allow better background subtraction.

All these are approaching final, and the analysis should be completed later this year.

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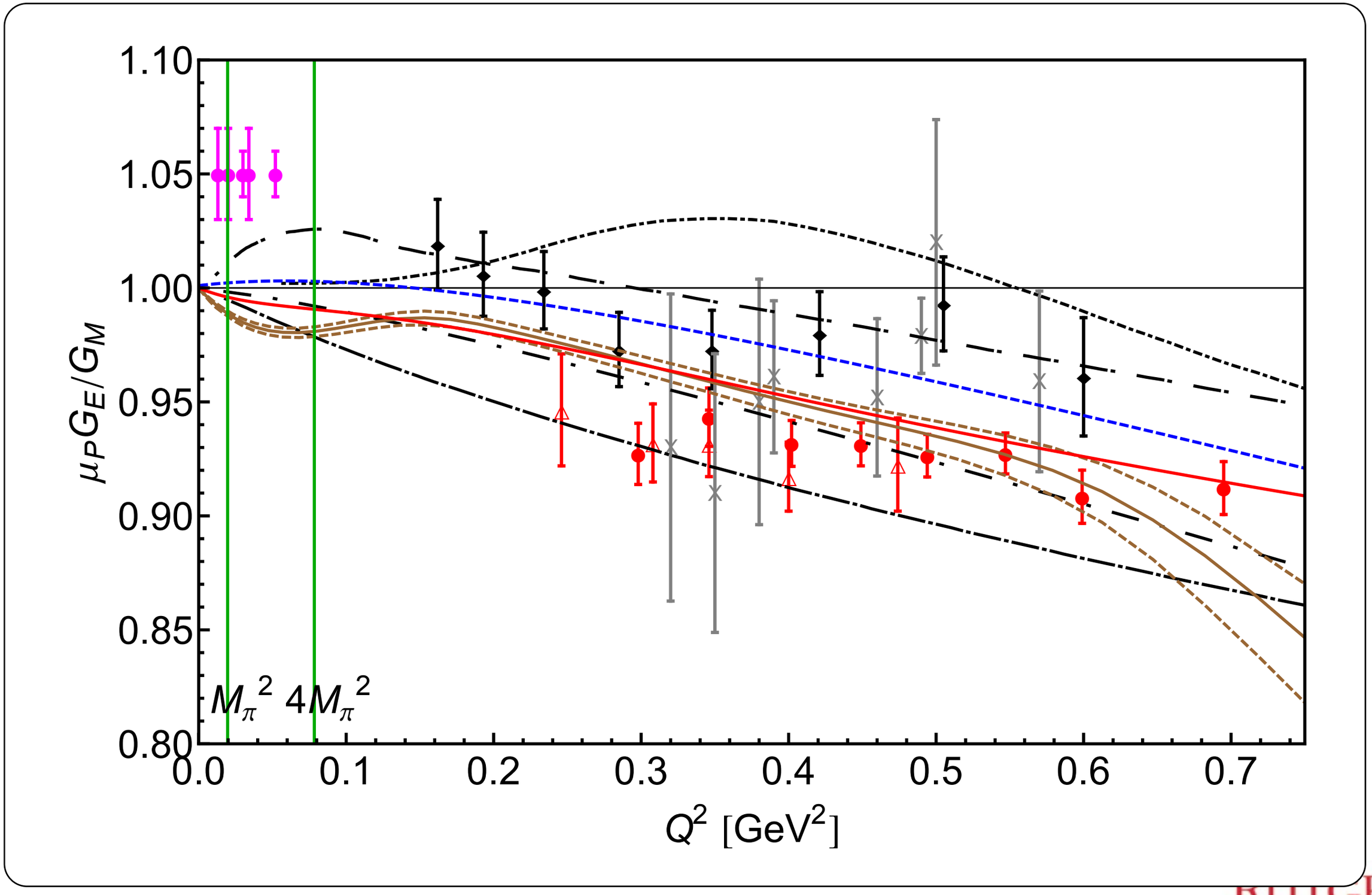
E08-007 Part II Projected Uncertainties



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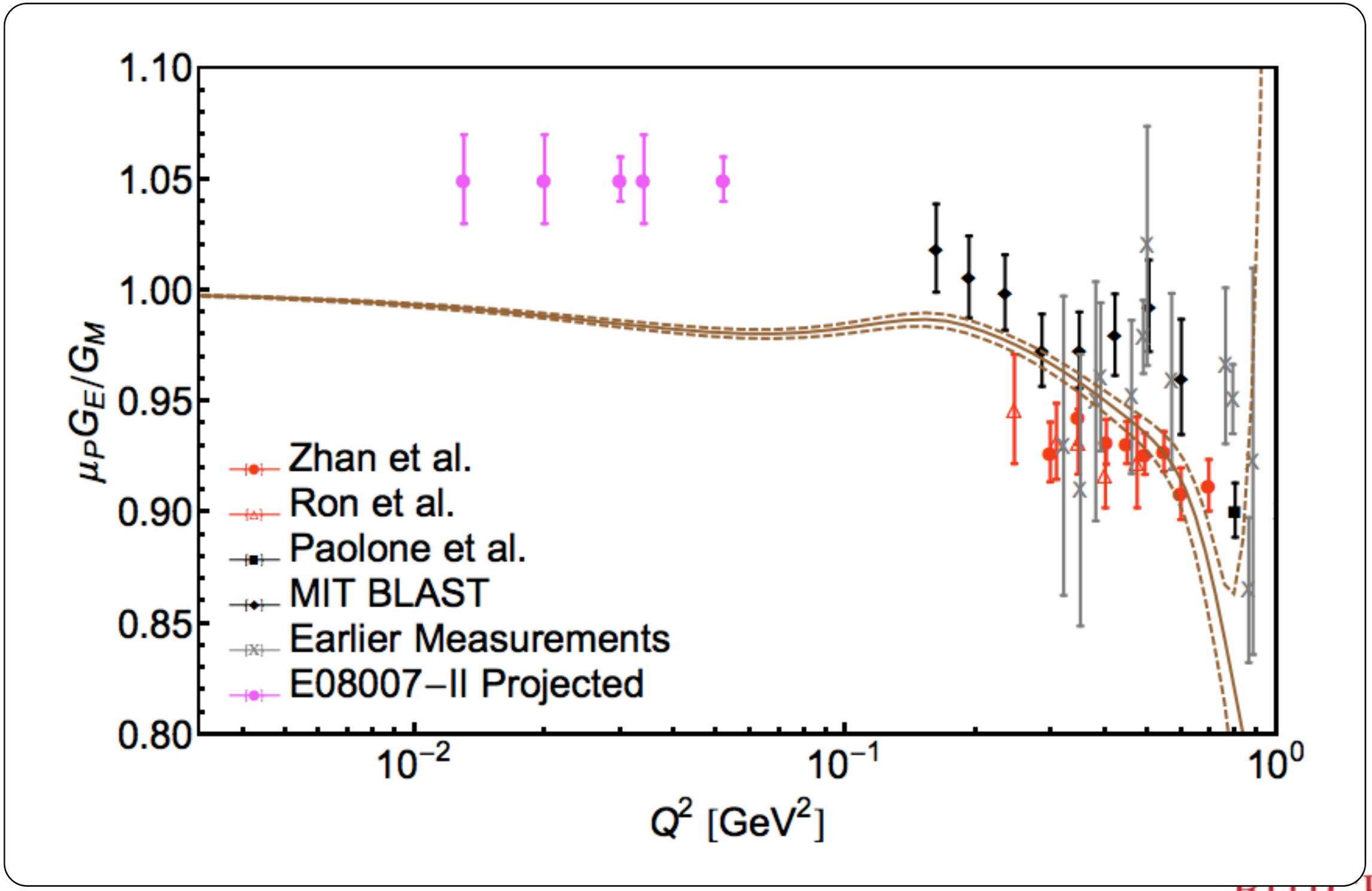

Summary

- Part I: Published in PLB, X. Zhan et al.
  - Improved ratio measurement confirms G_E smaller than previously believed
  - Generally in agreement with Bernauer et al. MAMI data for the ratio
  - Disagreements in detail arise from analysis including old cross section data vs Bernauer data; (in)consistent (r_M) r_E.
- Part II: Data taken in spring 2012
  - Analysis in progress, should be final this year
  - Should obtain statistical uncertainties, systematics to be seen

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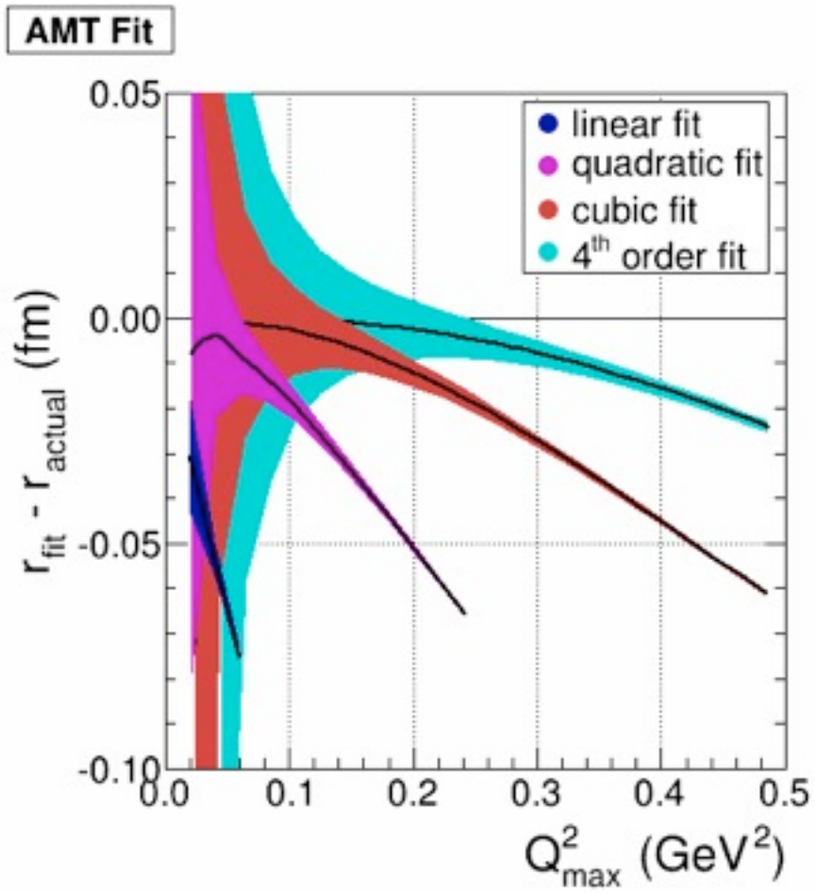
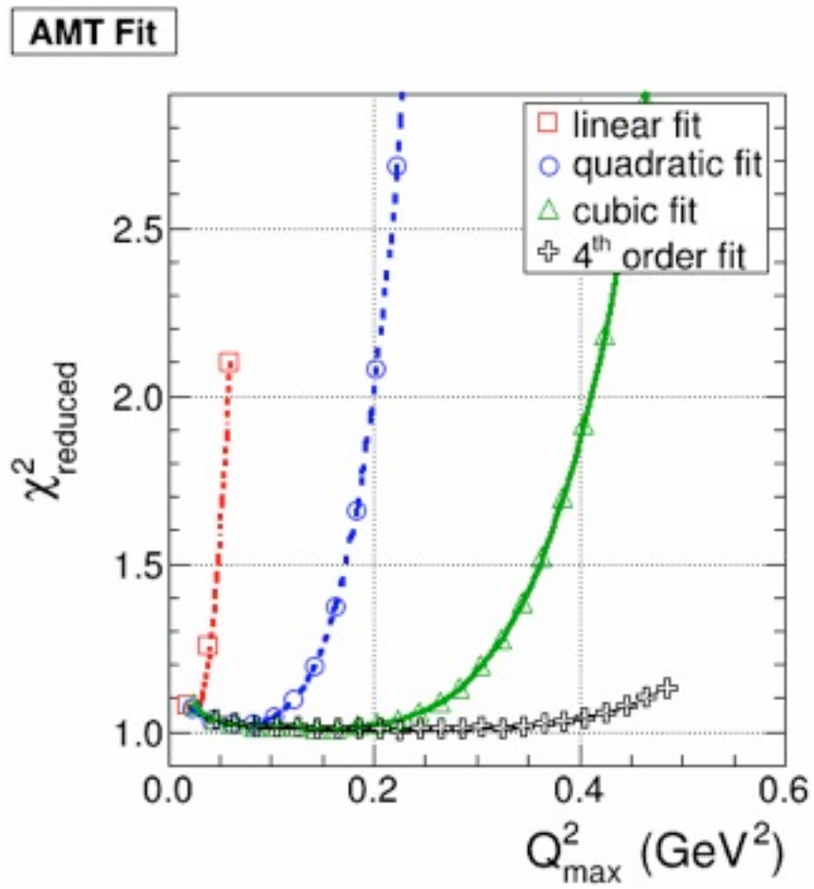
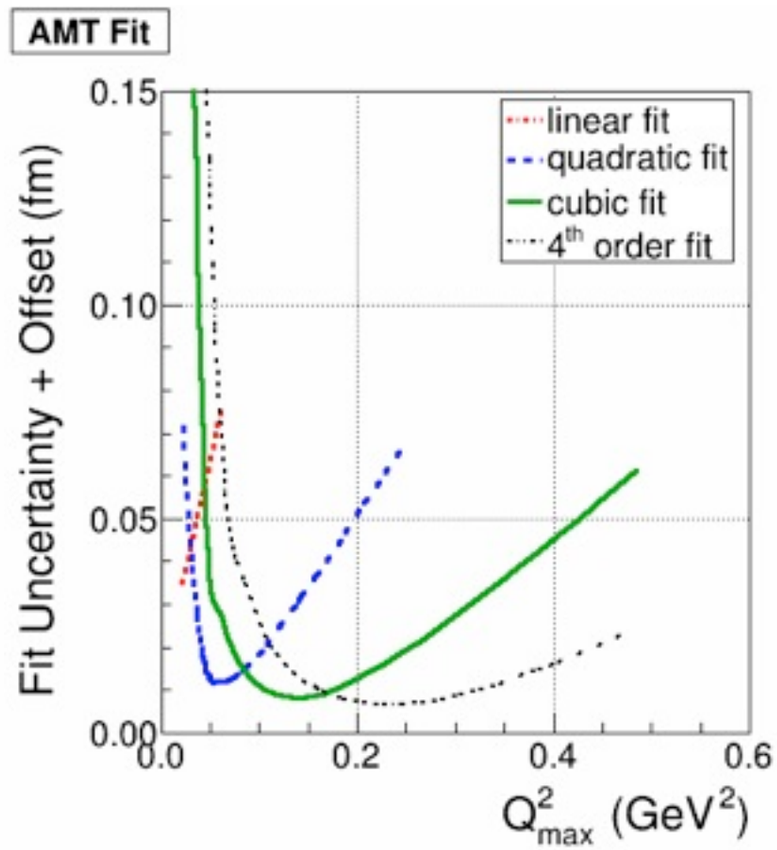
A quick slide on fits

arXiv:1405.4735







Bottom line: Ingo & Michael… have warned us not to do Taylor series fits. We agree.

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