Two-Photon Exchange at MUSE

R Gilman, Rutgers

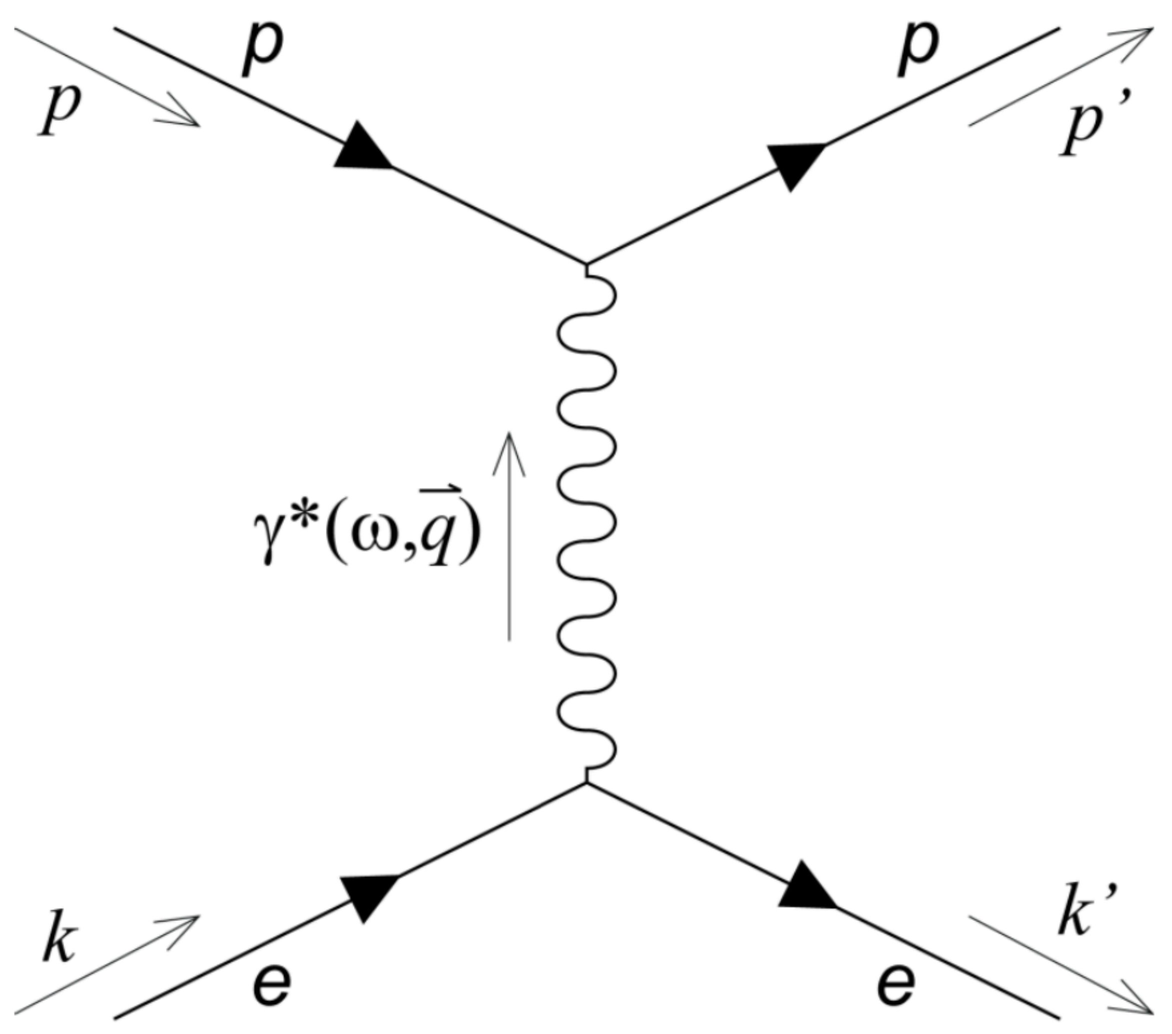
7/20/22

Supported in part by US National Science Foundation grant 1913653

- Some TPE history - my apologies to the experts familiar with the story
- TPE in MUSE
- Conclusions

Background 1

- I grew up in pion scattering, etc., then moved to electromagnetic scattering as a postdoc
- I learned that electron scattering was well understood, with some small, well-understood, “radiative correction” hardly worth discussing



Lowest order perturbation theory in QED (single photon exchange)

Background 2

- At Rutgers, I* built the Jefferson Lab Hall A FPP for many experiments, especially, for our purposes here at Trento, the proton electric form factor G_E^p (Perdrisat Bonner Prize).
- Initial G_E^p goals: proton structure at high Q^2, determine G_E^p and Q^2F_2/F_1, look for approach to pQCD
- Neglecting here the Bates and Mainz FPP efforts.

*Rutgers: Bimbot^, Gilman, Glashausser, Kumbartzki, Ransome, Rutt

William and Mary: Jones, Perdrisat, Wijesooriya

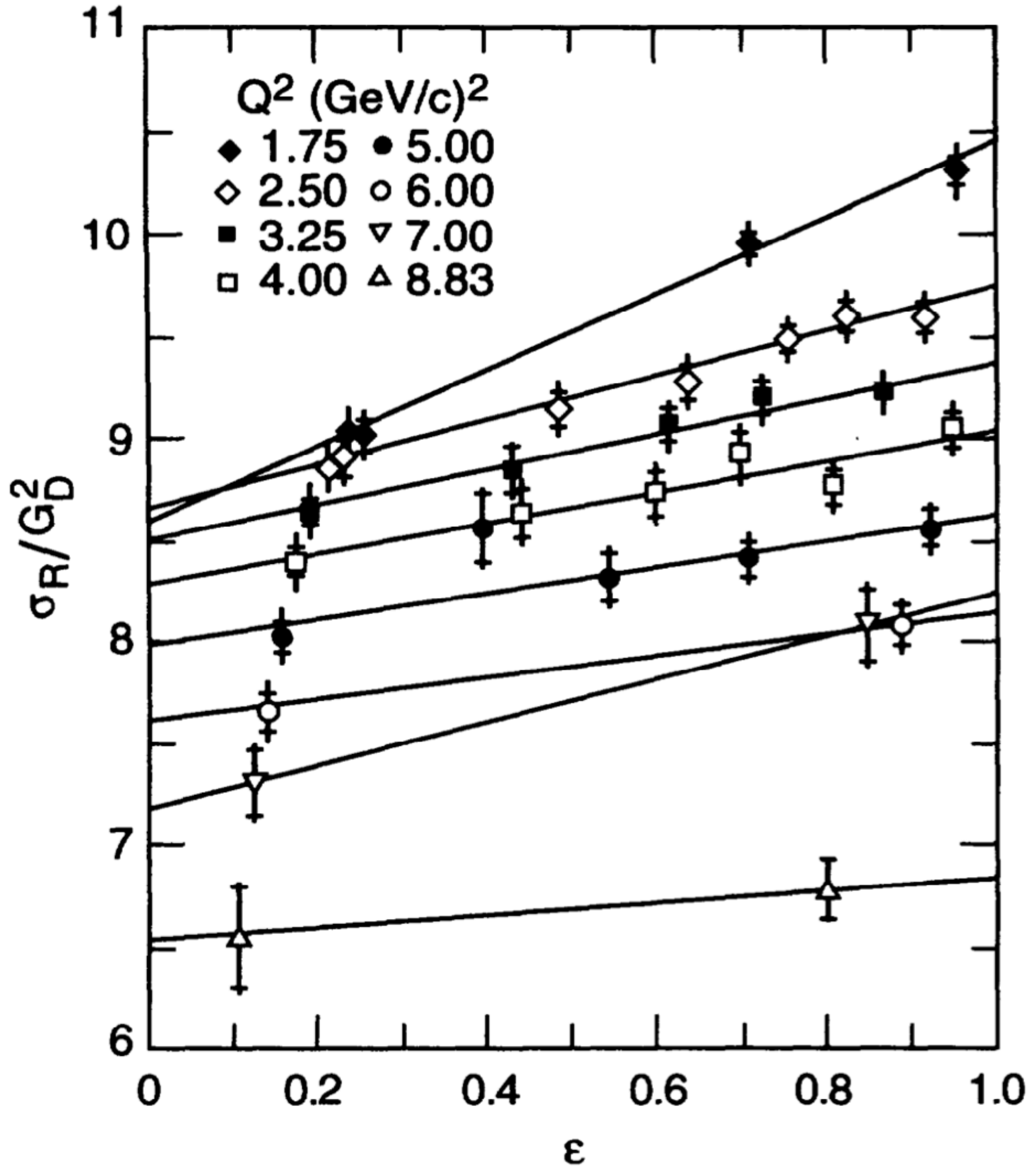
Norfolk State: Punjabi

Regina: Brash

JLab: Nanda

G_E^p

- The electron scattering cross section depends mainly on G_M^p (G_E^p) at high (low) Q^2, making precise extractions of the small G_E^p (G_M^p) contribution difficult.

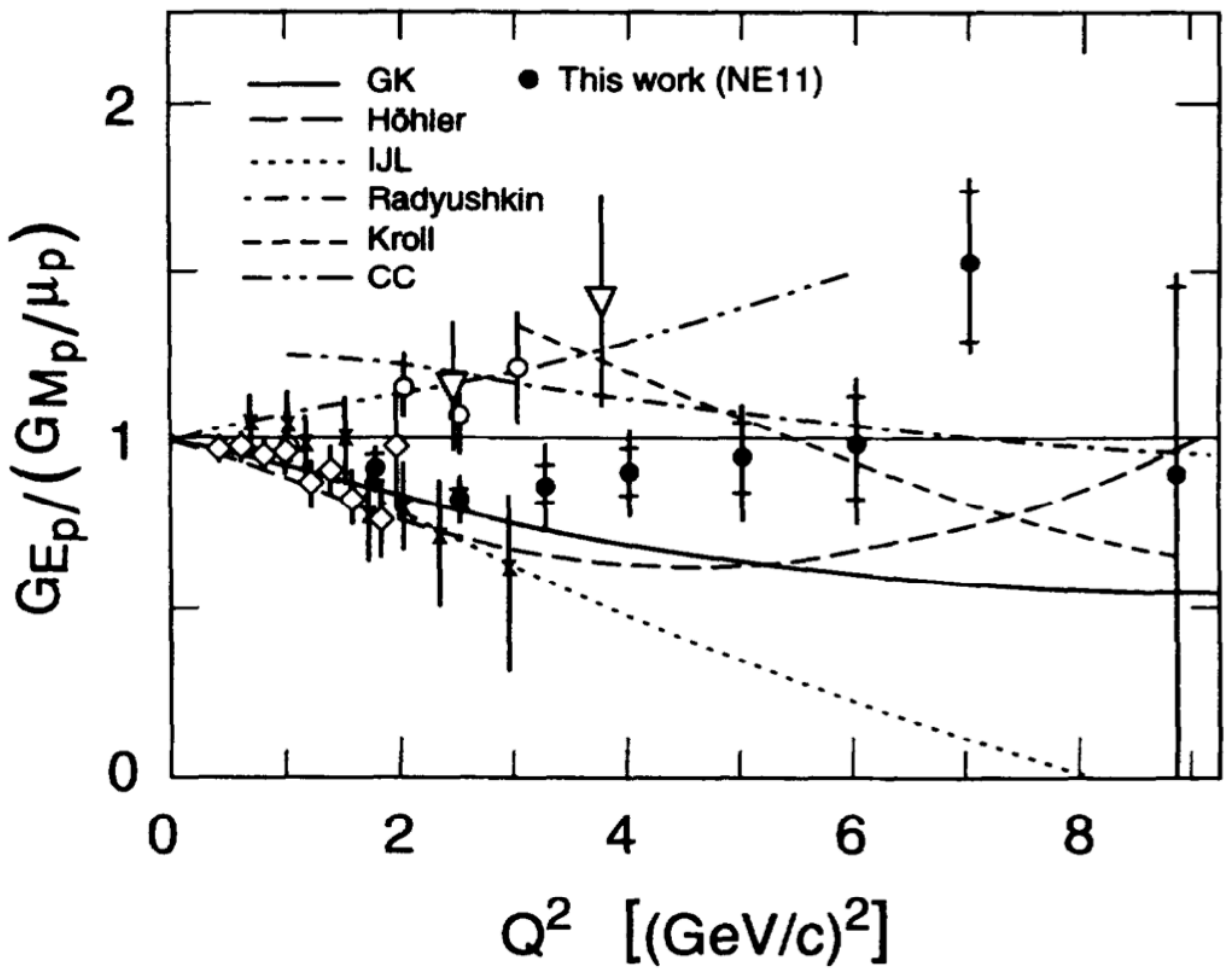


Best high Q^2 result before the polarization measurements: Andivahis et al., PRD 50, 5491 (1994)

Left: Fig 22, Rosenbluth separations

Slope from G_E^p, intercept from G_M^p

Right: Fig 25, form factor ratio



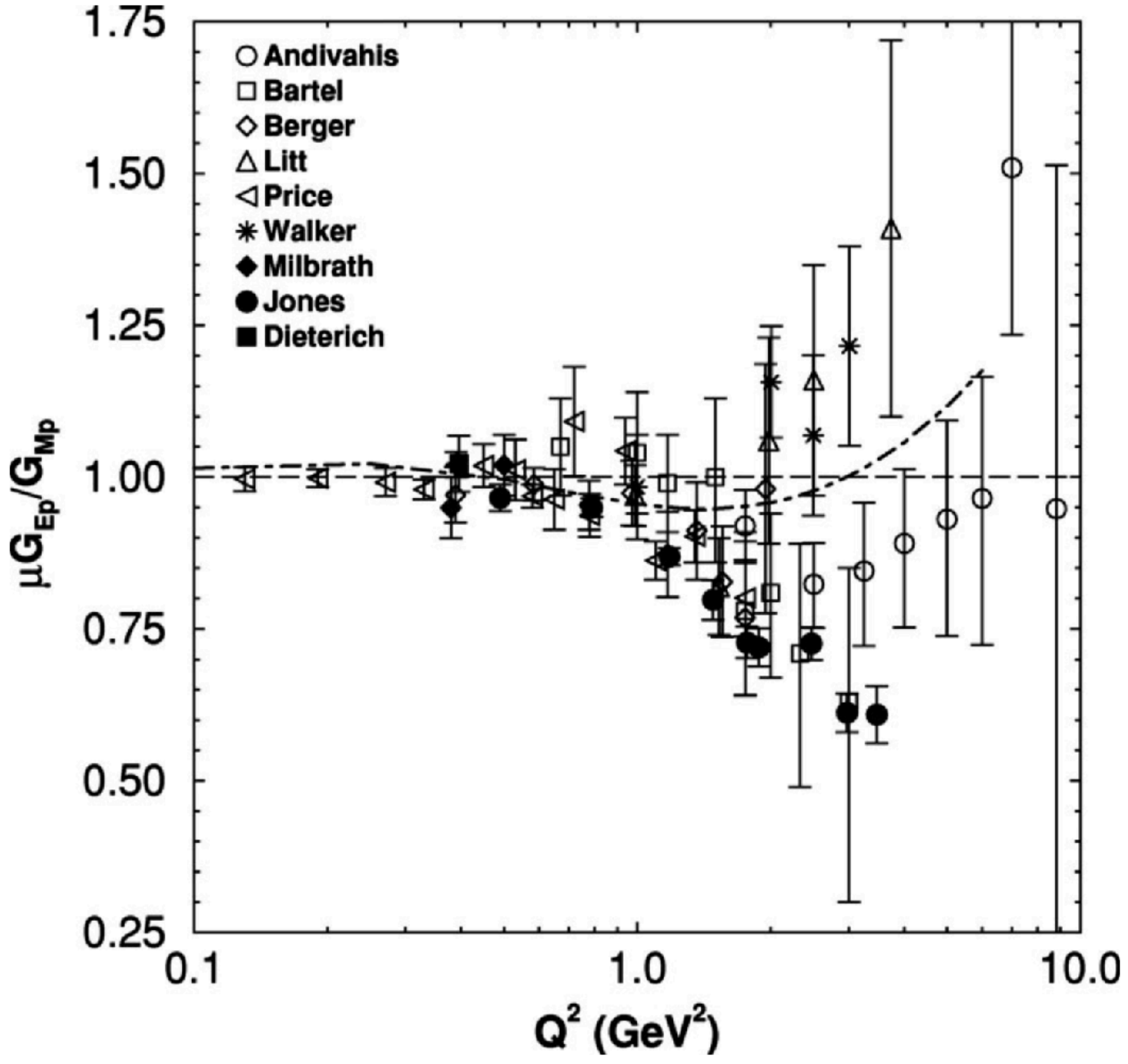
- Since the late 1950s / early 1960s, “known” that polarization techniques could be used instead for linear (vs quadratic) contribution.
- “Popularized” by Arnold, Carlson, and Gross in PRC 23, 363 (1981), using formulas from Dombey (1969), Scofield (1959, 1966), and Akhiezer and Rekalo (1973, 1974).

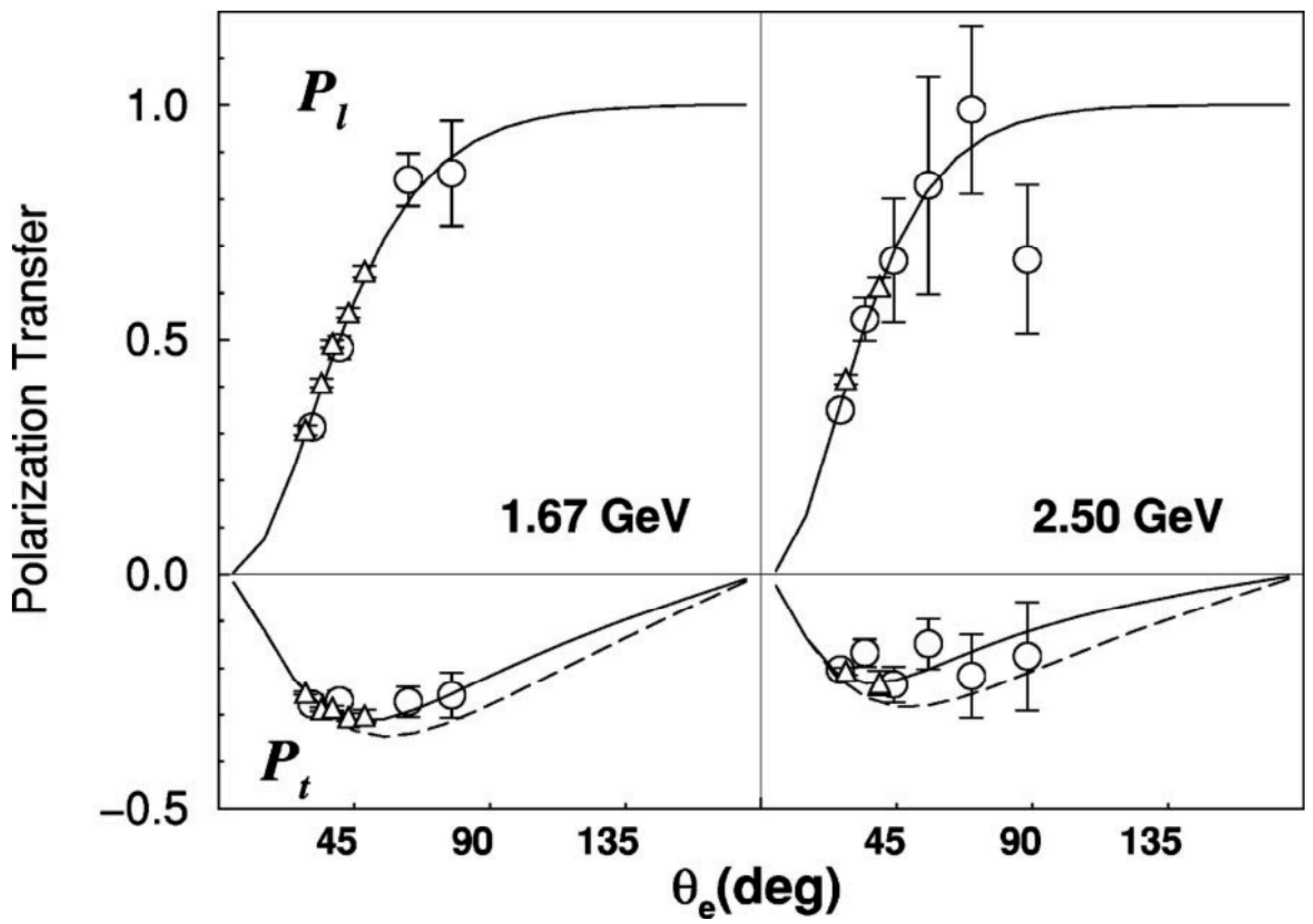
G_E^p - I and First Confirmation

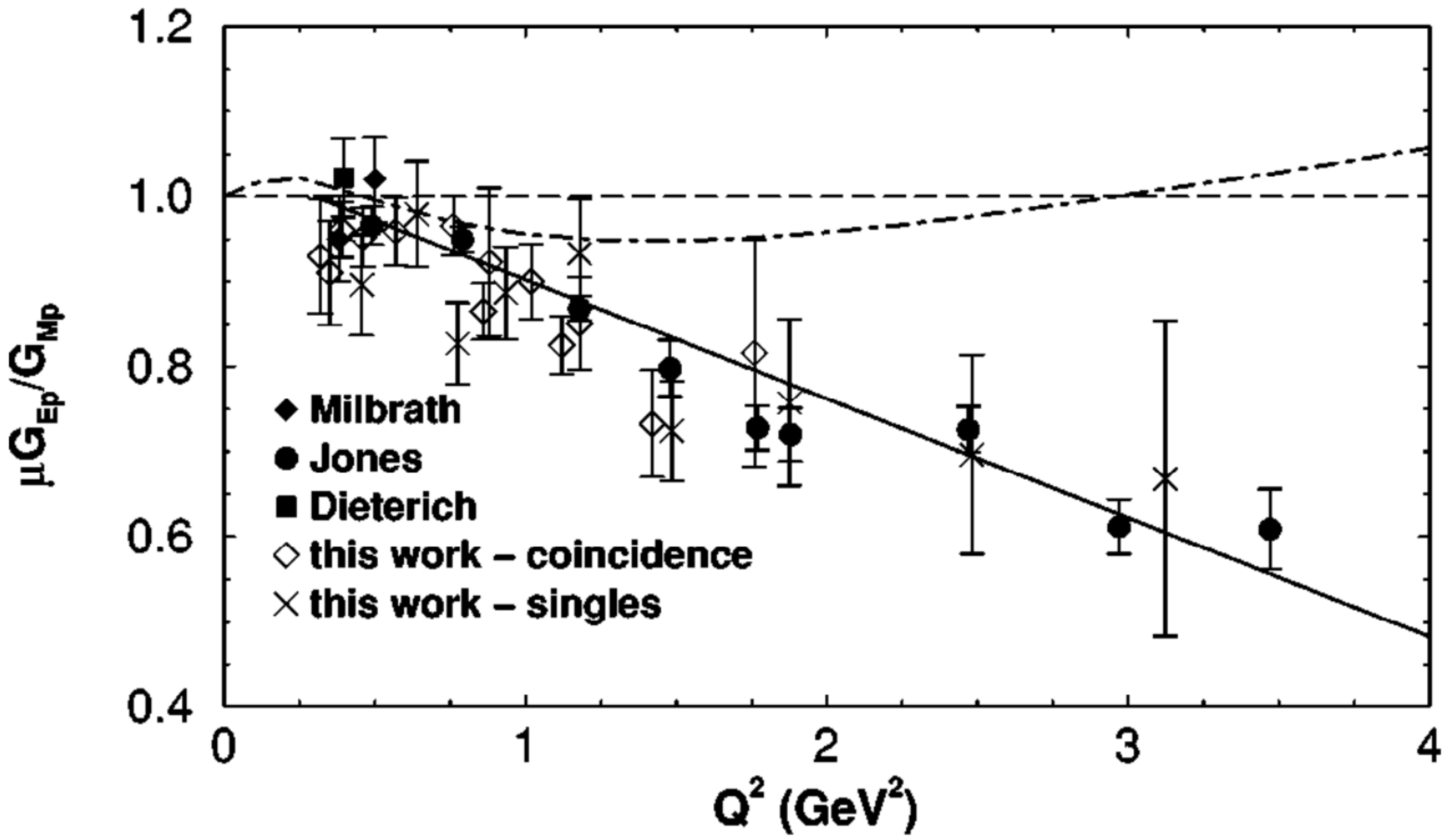
- G_E^p-I (B+), G_E^p-II (A), etc. showed and confirmed $\mu G_E^p/G_M^p$ decreases ~ linearly with Q^2, contradicting what was believed — the results of Andivahis et al.
- Experimenters initially focussed on: what could the others have done wrong

From O. Gayou, K. Wijesooriya et al., PRC 64, 038202 (2001)

Pre-existing data, measurements, form factor ratio polarization data







G_E^p - I and II

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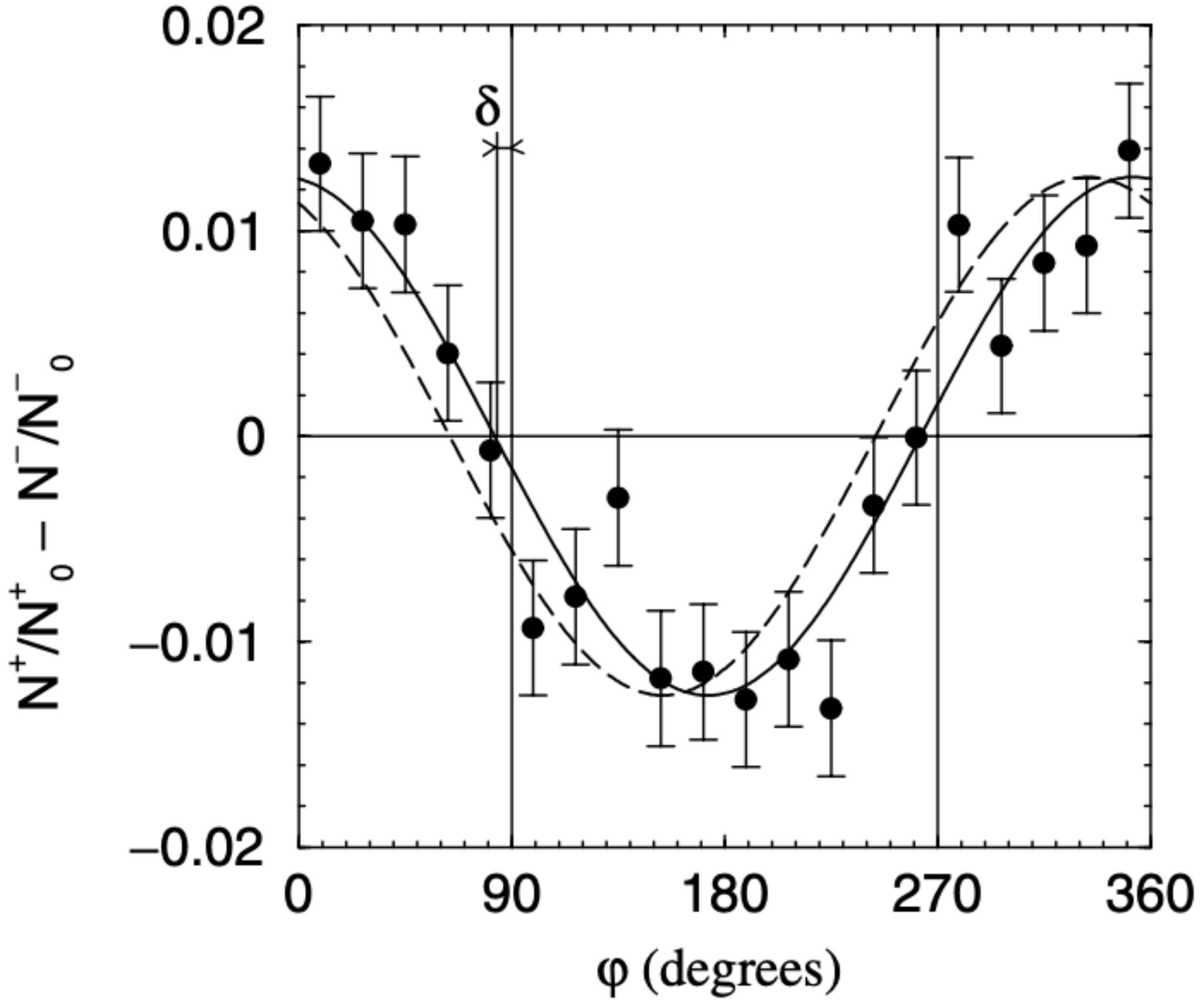
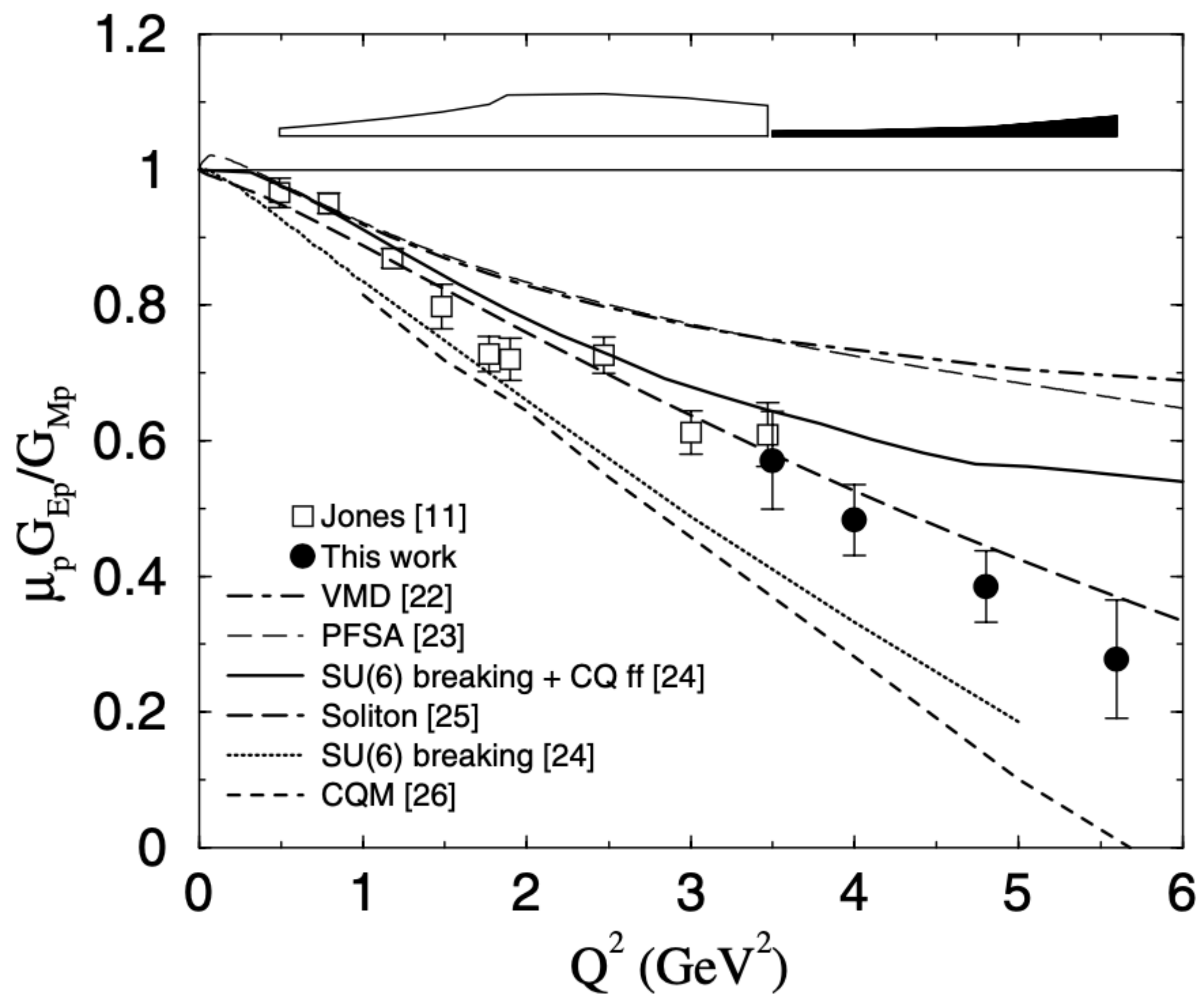
From O. Gayou, K. Wijesooriya, et al., PRL 88, 092301 (2002)

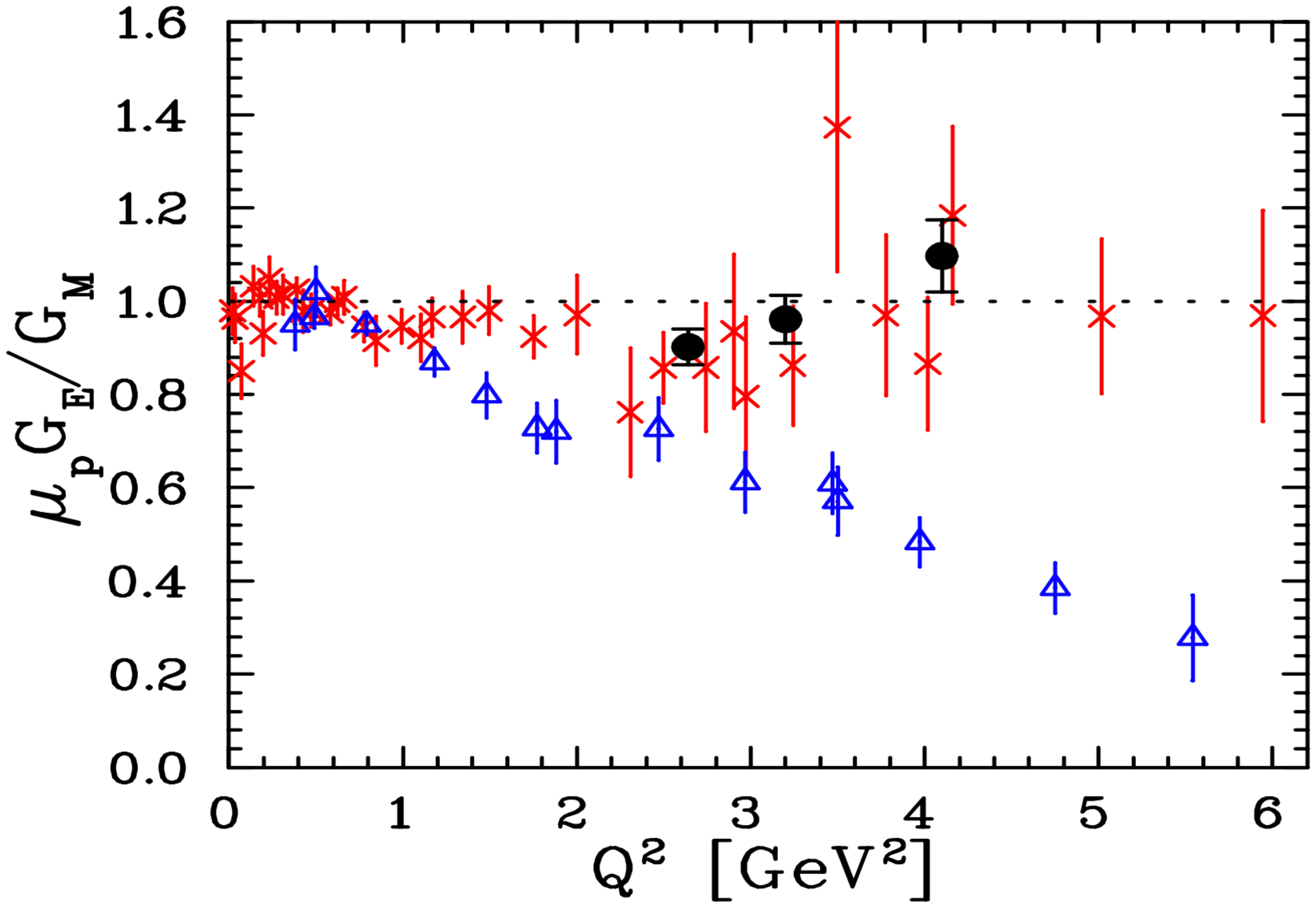
Measurement, form factor ratio polarization data





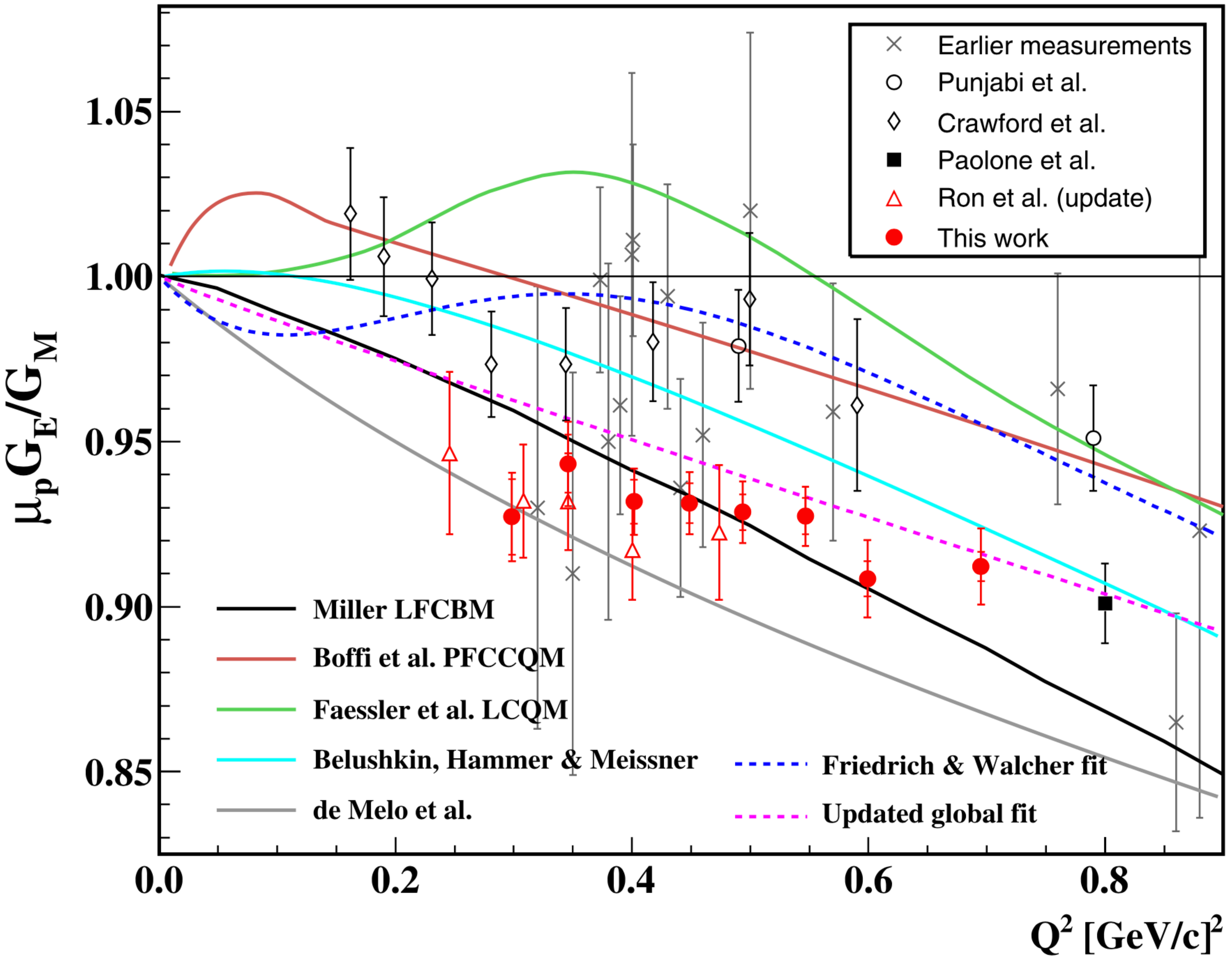
Discrepancy Reconfirmed

- (Skipping a little forward in time…) I. Qattan et al., PRL 94 (2005) 142301 Rosenbluth separation measuring recoil protons rather than scattered electrons



Radiative Corrections to Polarizations?

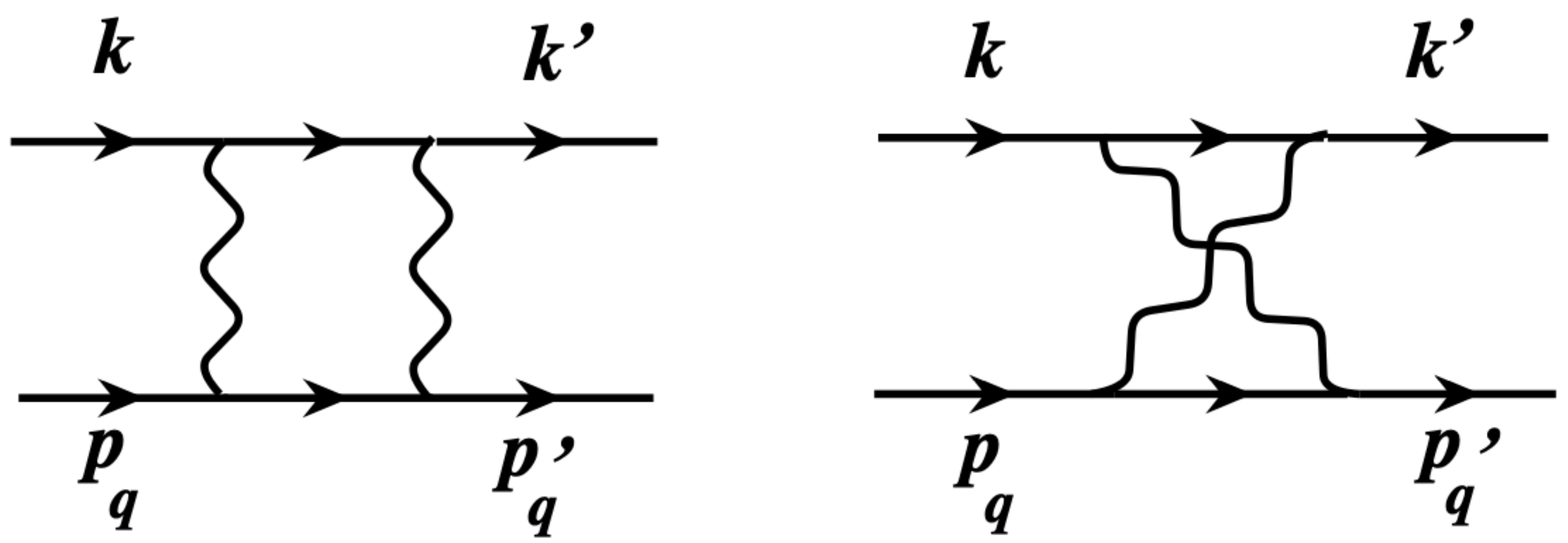
- We believed that radiative corrections were small for polarizations, as we only analyzed the elastic peak. Soft Brem should not affect the proton polarization → integrate over the elastic peak to maximize statistics — but be careful for inelastic backgrounds.
- (Still skipping forward in time...) Highest statistics polarization measurements were in X. Zhan et al., PLB 705, 59 (2011)
- We found small, percent level effects → limit how far we integrate.
- Still offset from Crawford et al.
- It has always bothered me that our data does not curve towards 1 at $Q^2 = 0$.



Main systematic is the solved problem of spin transport. We used COSY.

What was wrong?

- ~2003 we started to hear about two-photon exchange corrections:
  - P. G. Blunden, W. Melnitchouk, and J. A. Tjon, PRL 91, 142304 (2003); PRC 72 034612 (2005).
  - P. A. M. Guichon and M. Vanderhaeghen, PRL 91, 142303 (2003).
  - M. P. Rekalo and E. Tomasi-Gustafsson, EPJA 22, 331 (2004).
  - Y. C. Chen, A. V. Afanasev, S. J. Brodsky, C. E. Carlson, M. Vanderhaeghen, PRL 93, 122301 (2004); ABCCV PRD 72, 013008 (2005).



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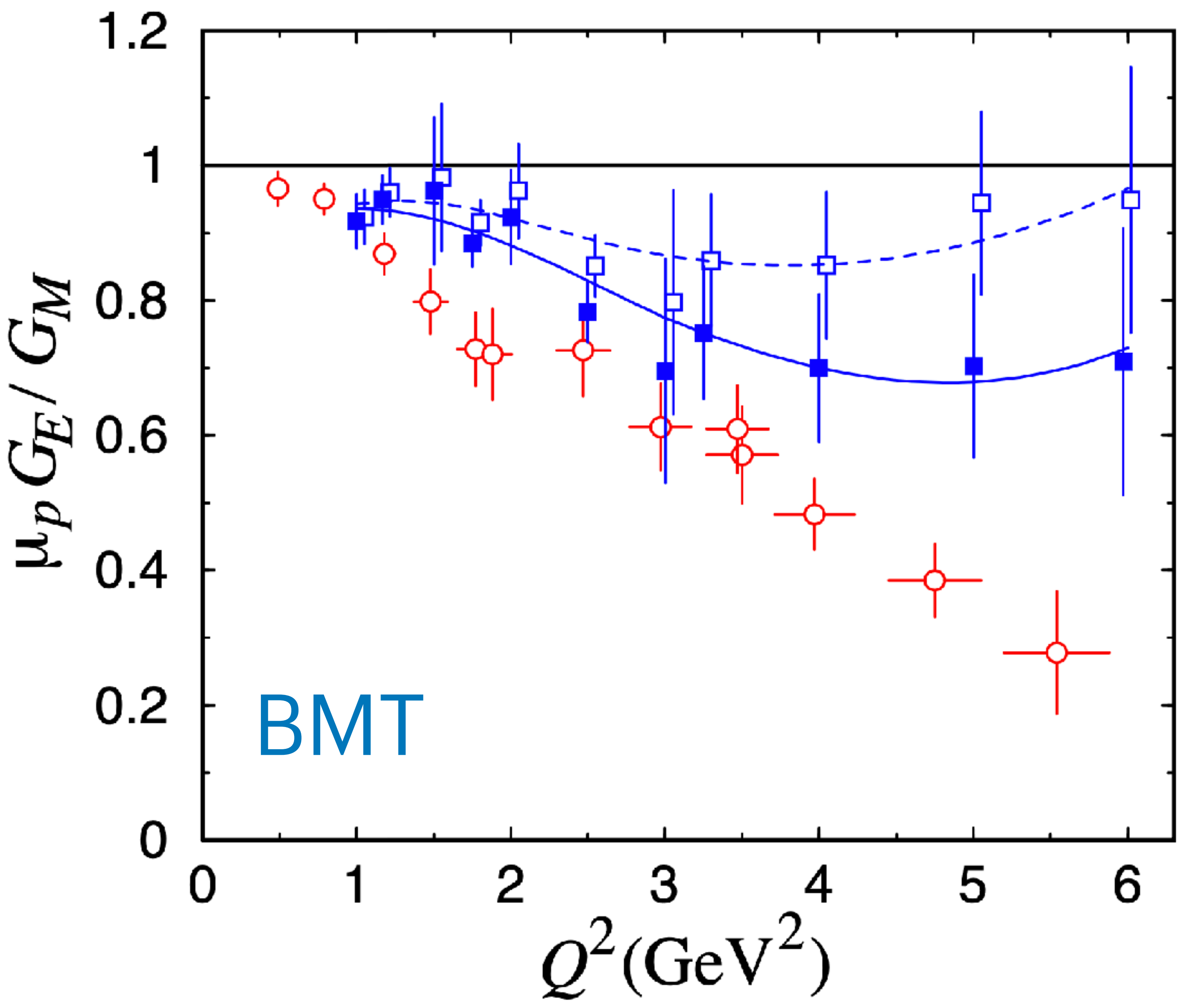
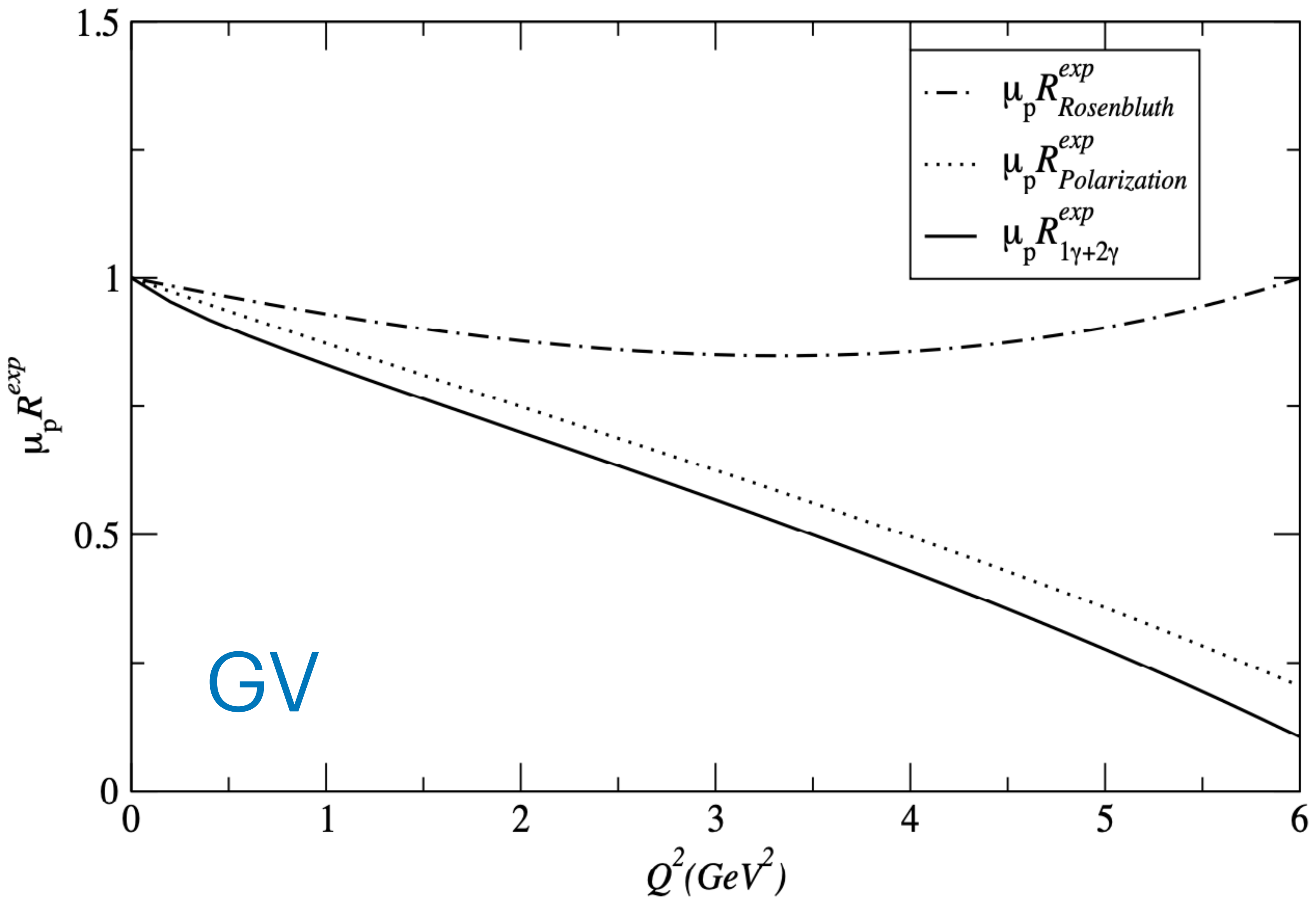
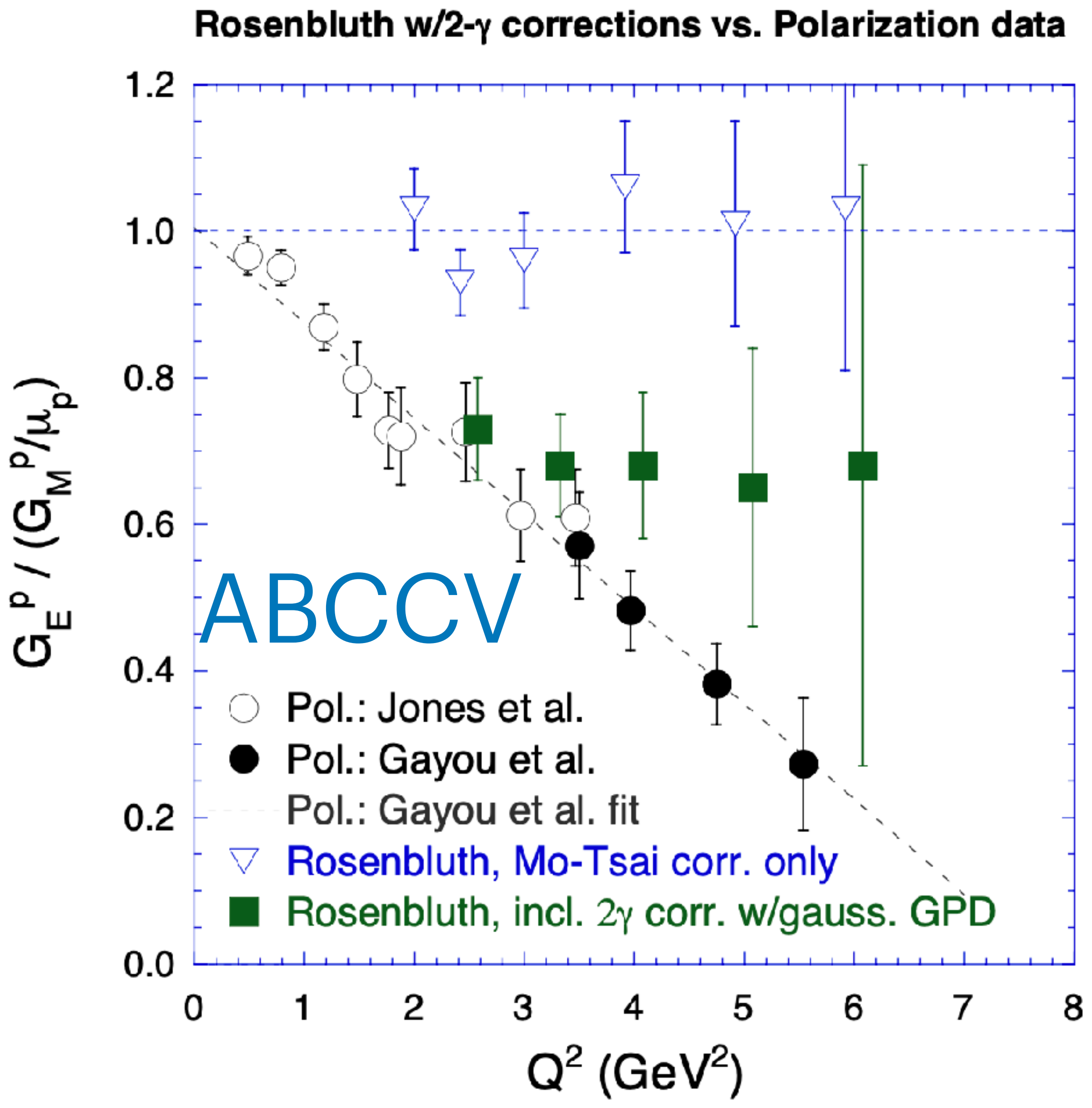
TPE is a plausible explanation







Experimental Tests?

- Data mining
- At JLab: Nonlinear Rosenbluth separations, angle dependence to P_l, non-zero normal polarizations P_n / A_n (SSA from imaginary part of TPE)
- Not easily at JLab: Positron / electron cross section ratios

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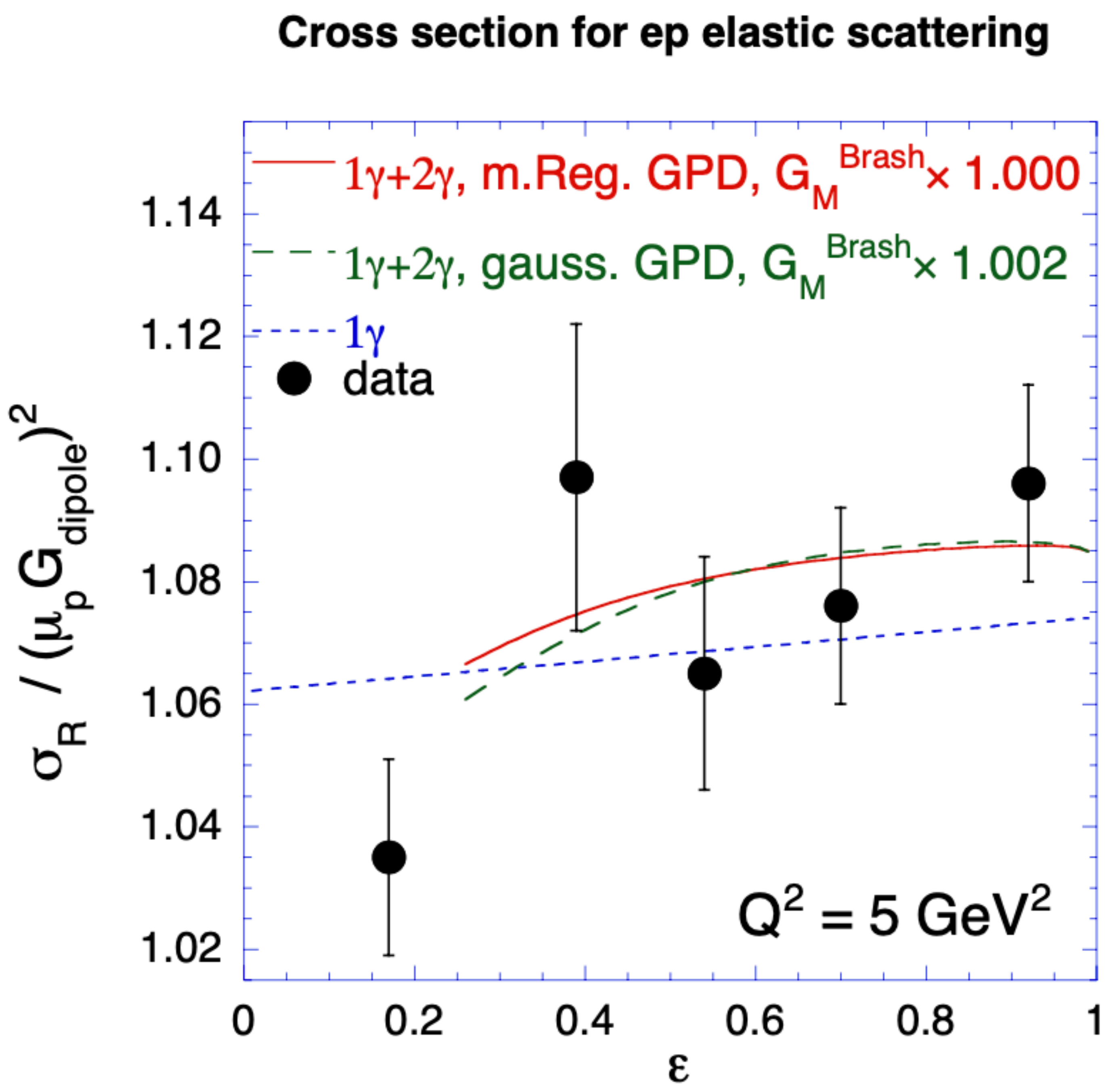
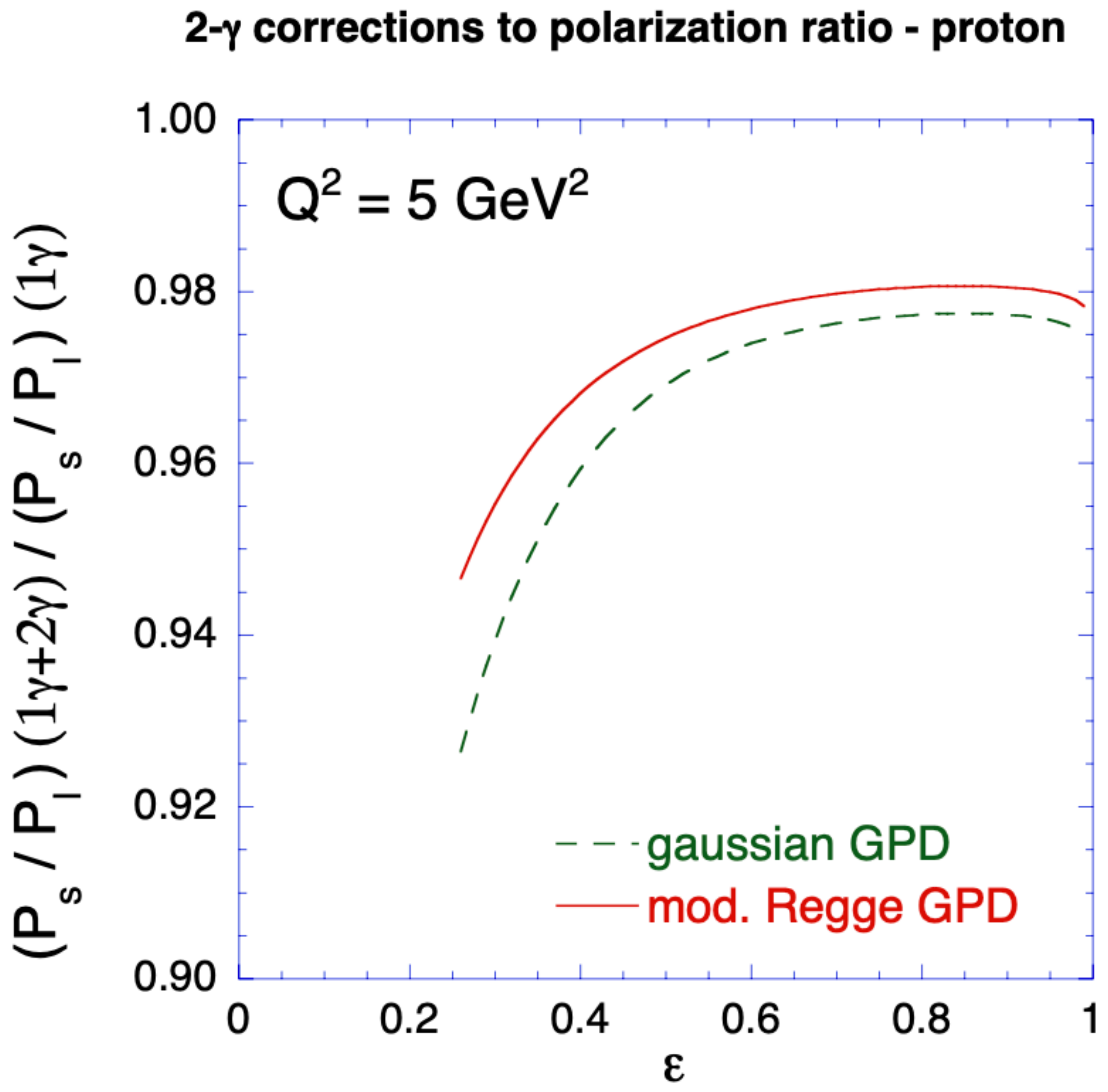
ABCCV



Nonlinear Rosenbluth hard to see.



Polarization changed ~ 1%

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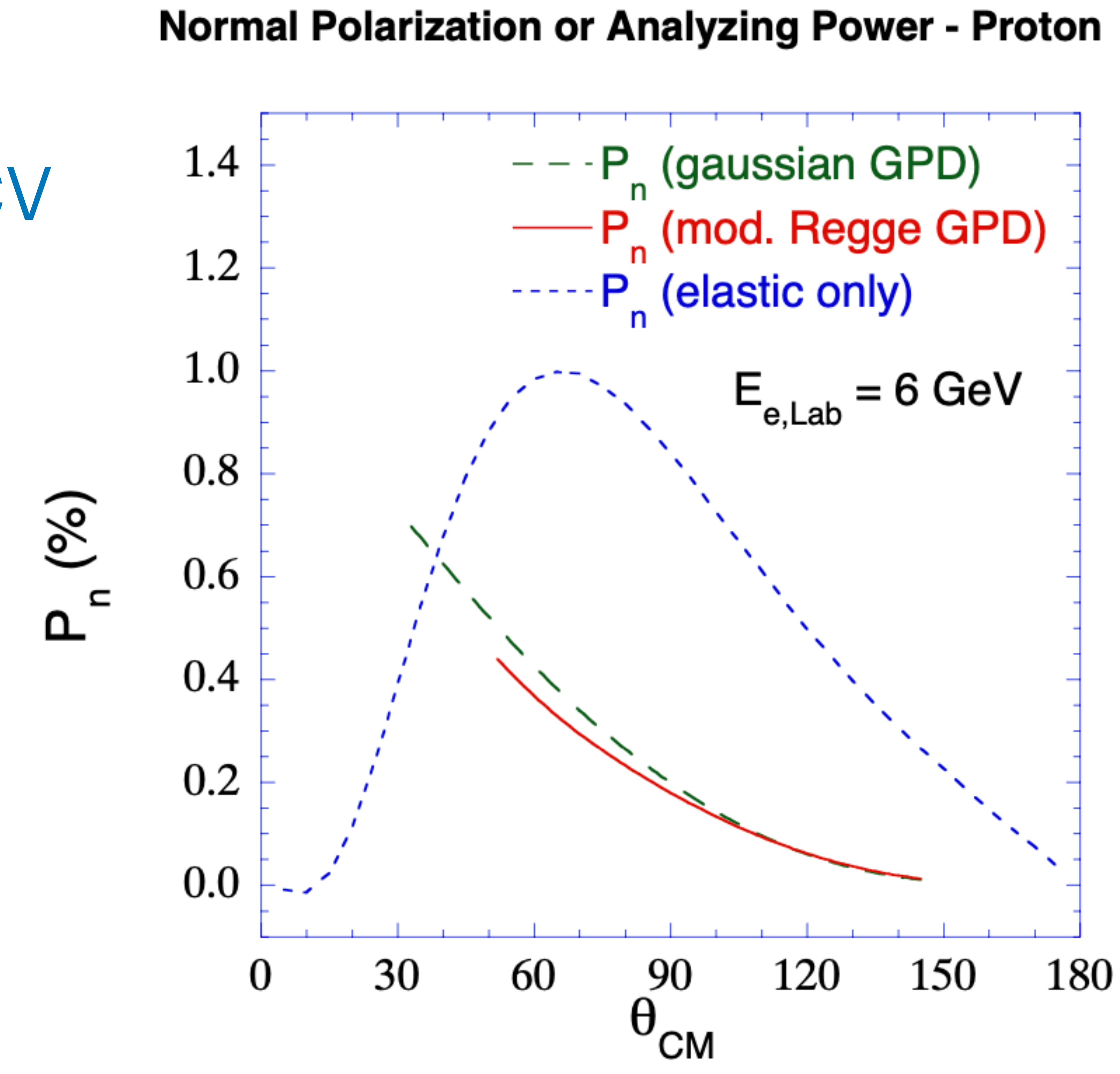
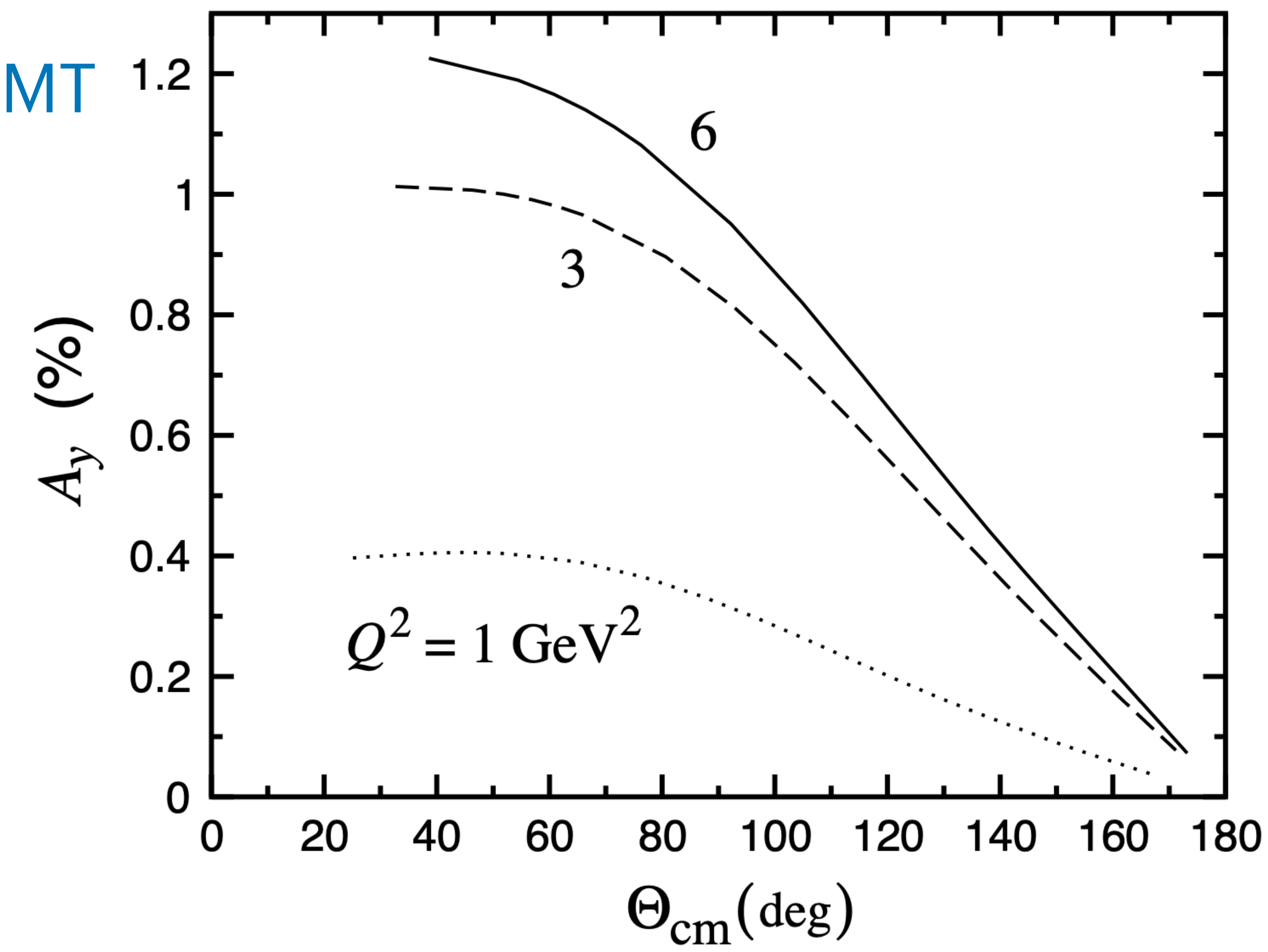


BMT



SSA small

Experimental Tests?

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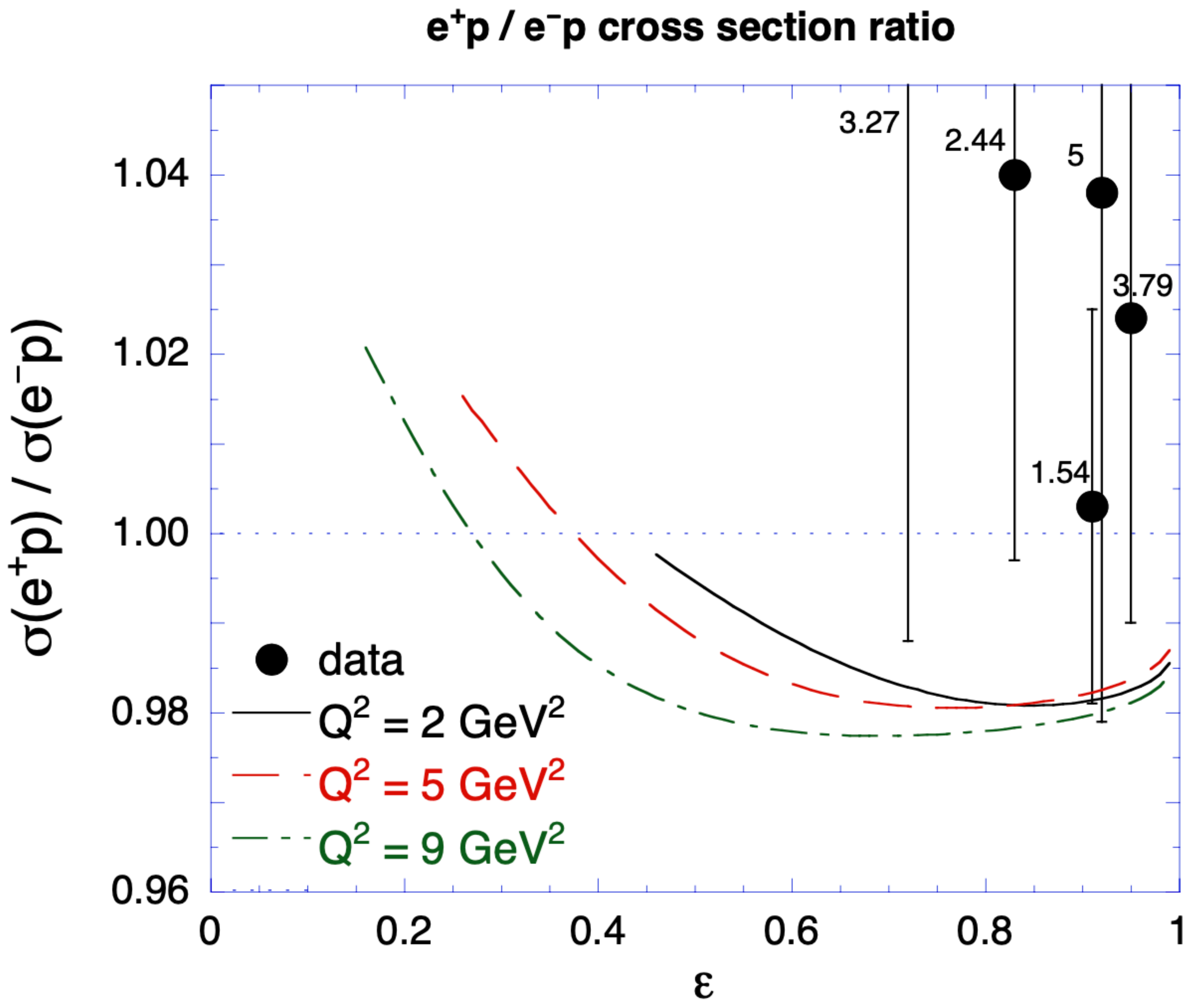

e⁺p/e⁻p ratio / asymmetry is the favored observable, most directly related to the Rosenbluth results being off

Experimental Tests?

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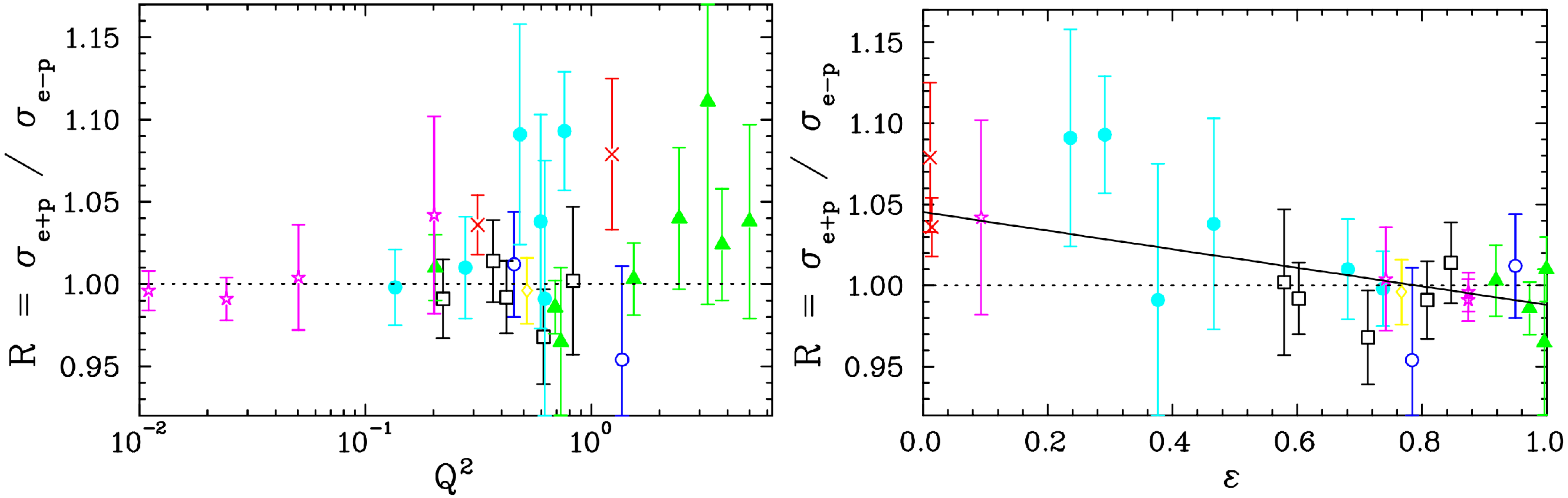
J. Arrington, Phys.Rev. C69 (2004) 032201



Indications of TPE, but not very compelling. Led to VEPP-3, CLAS, and OLYMPUS measurements.

Experimental Tests?

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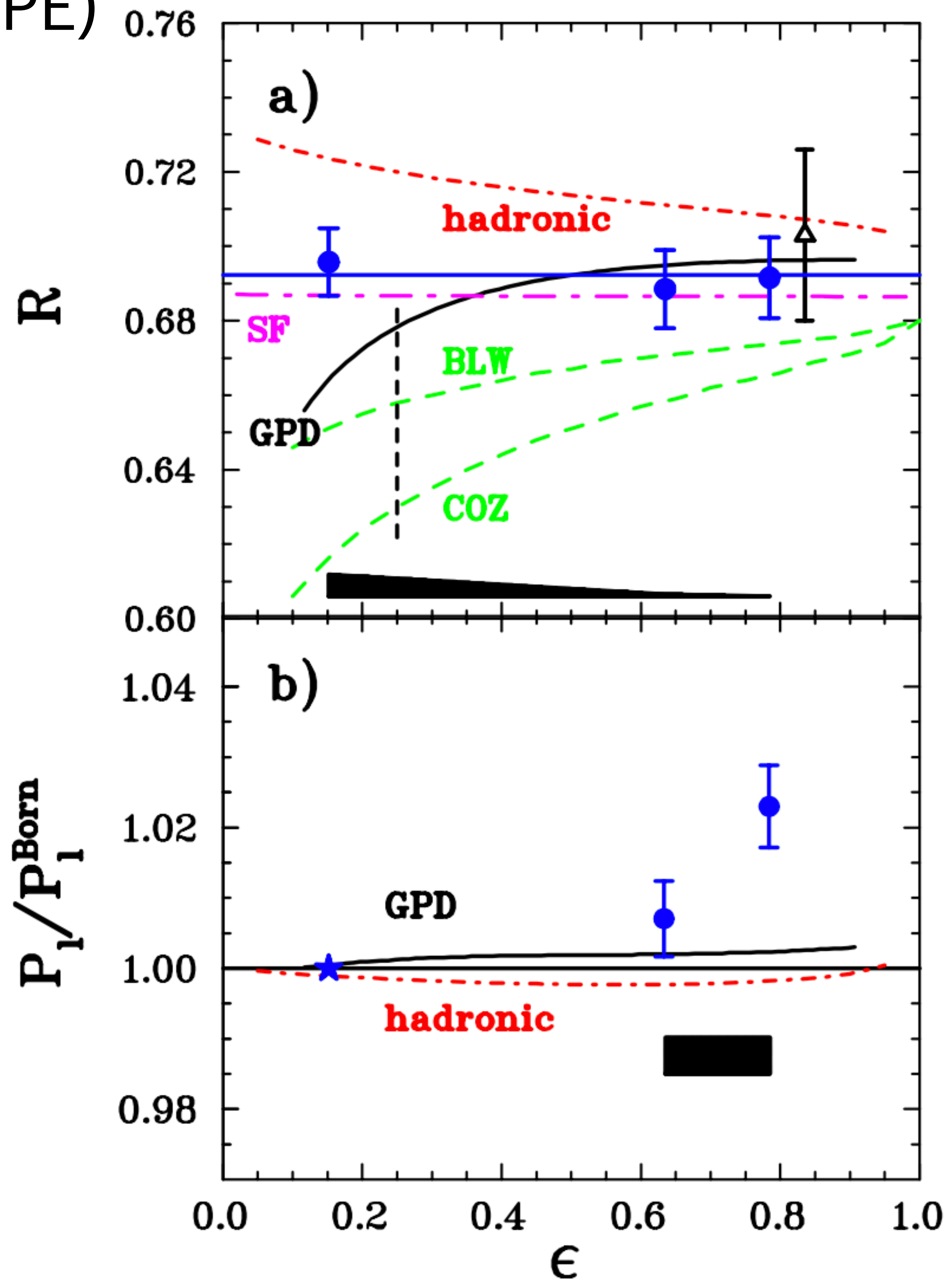

M. Meziane (L. Pentchev) et al. PRL 106, 132501 (2011)

Polarization transfer shows little ϵ dependence.

It is clear that experimenters should as best as possible only measure asymmetries / ratios / polarizations, not cross sections.

Experimental Tests?

- Data mining
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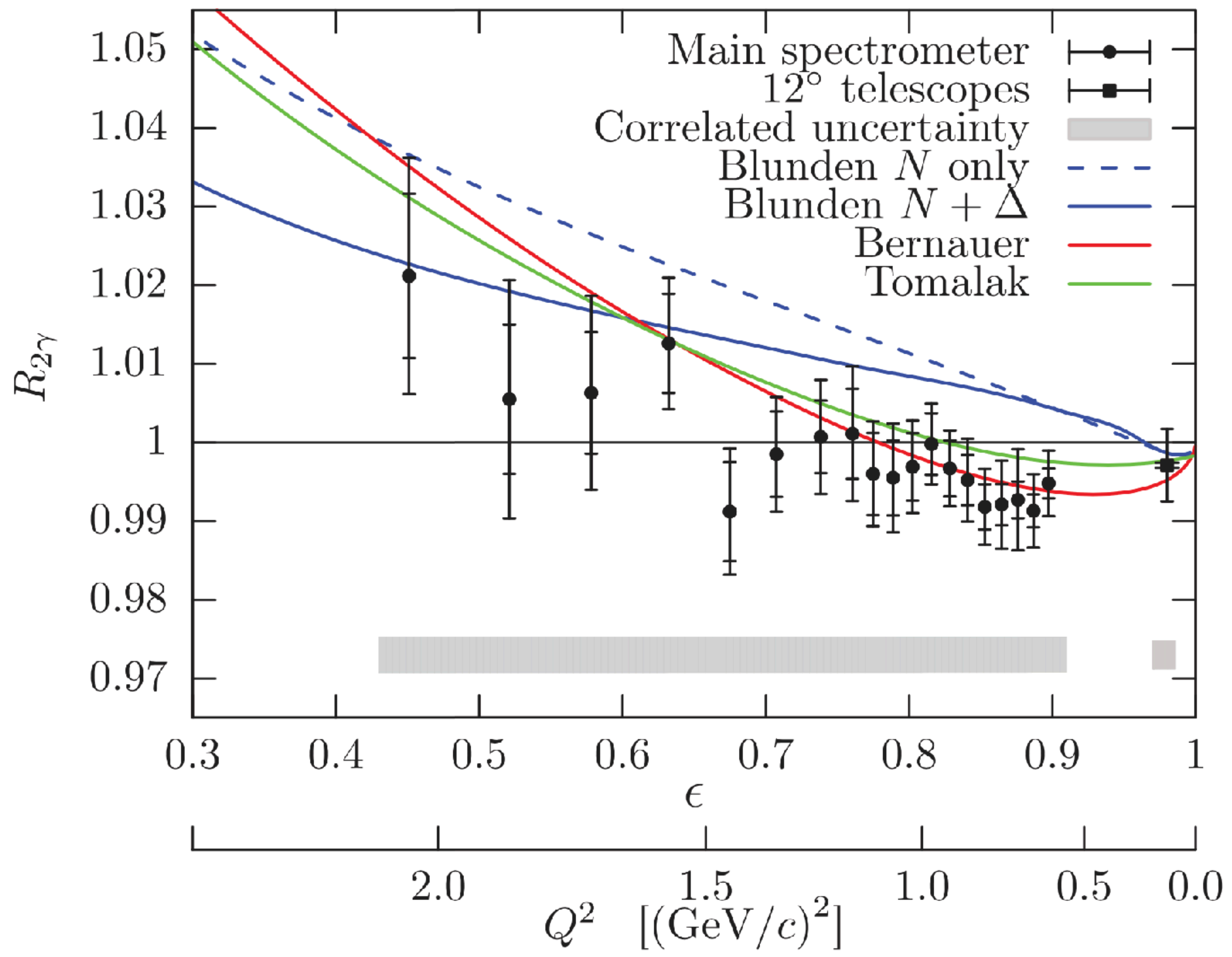
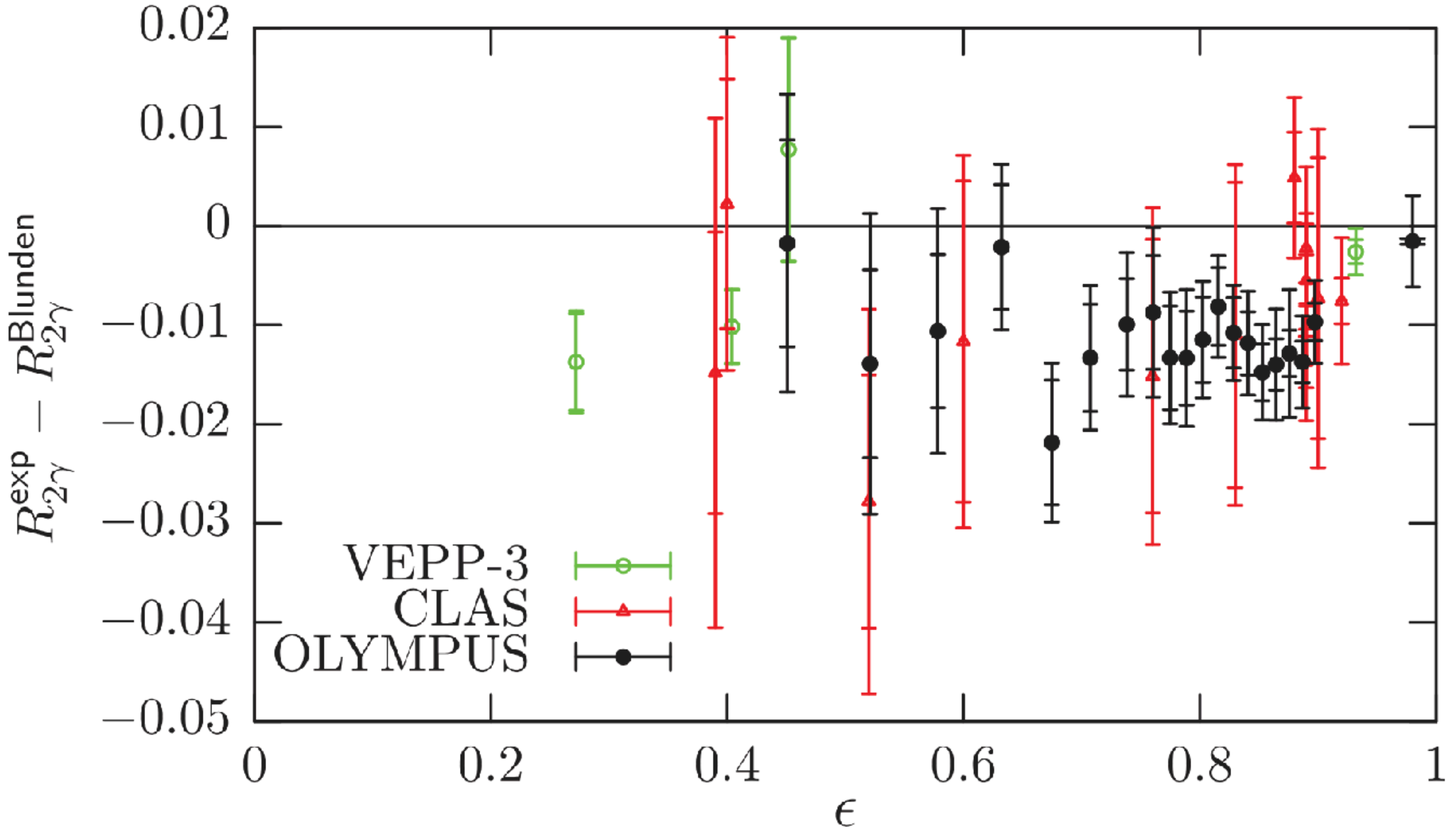
Only showing the OLYMPUS result: B.S. Henderson et al., PRL 118, 092501 (2017).

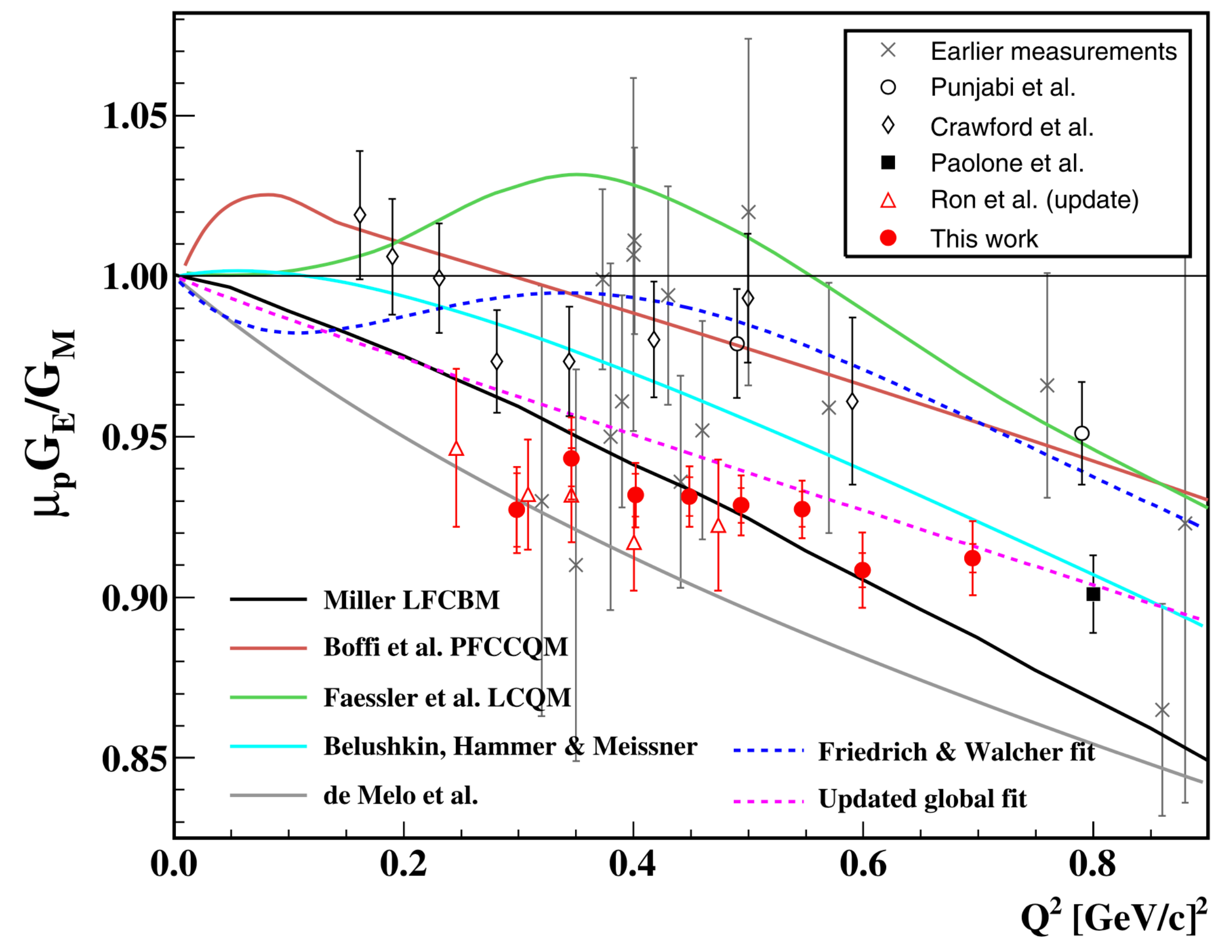




TPE data and theory agree to about the size of the effect.

Personal Note

X. Zhan et al., PLB 705, 59 (2011)



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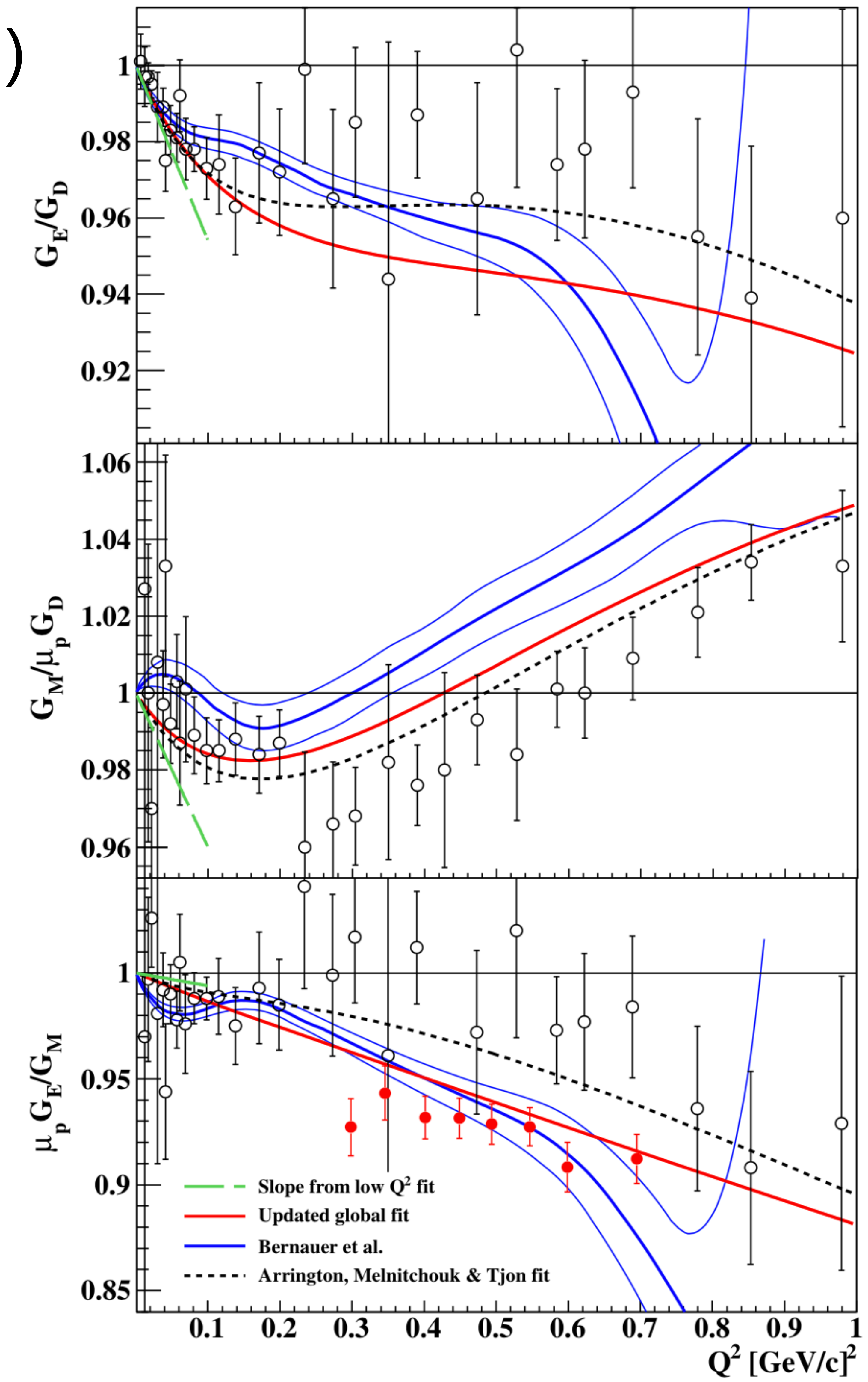

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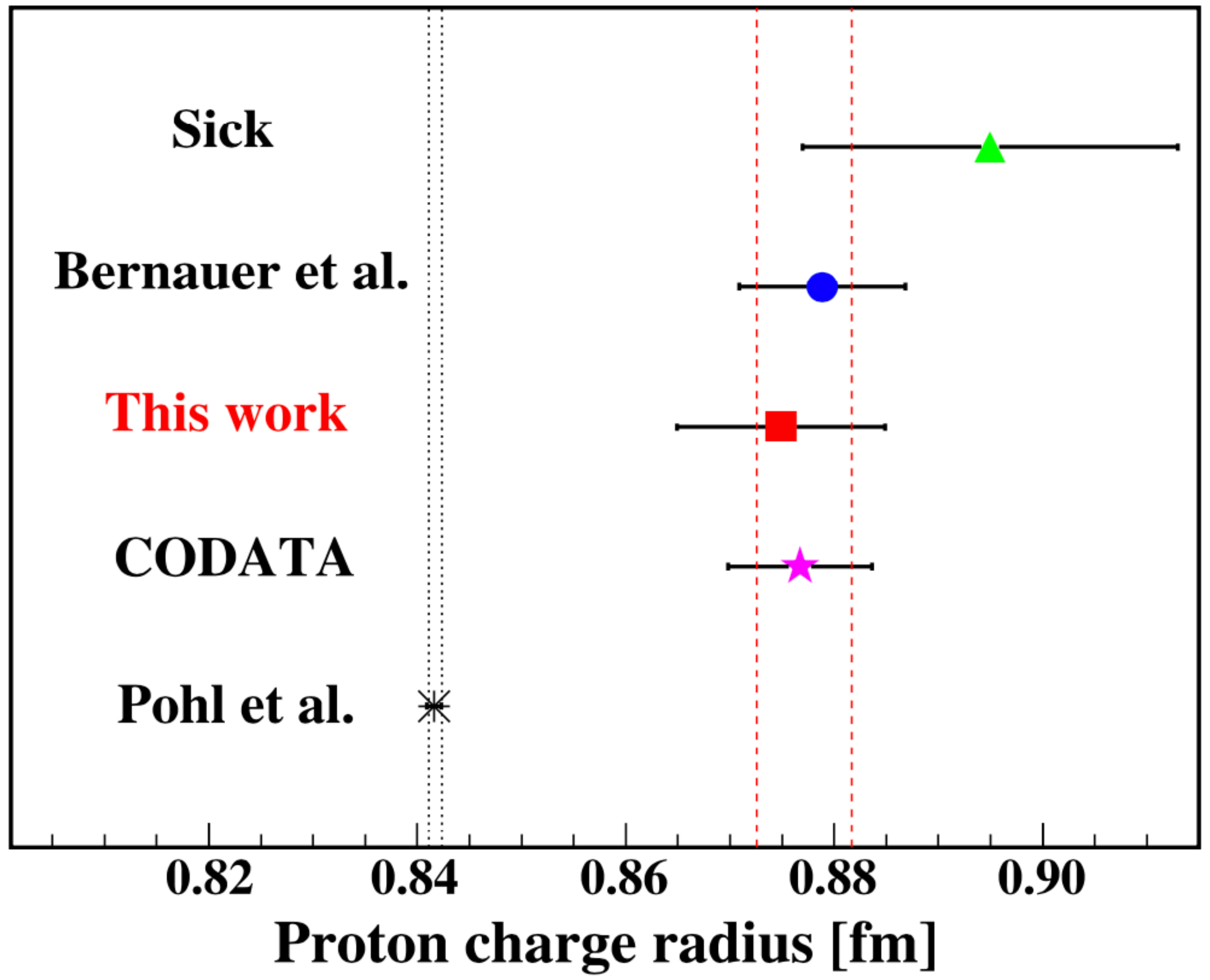

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Nice coffee break chat between Michael Kohl and me at Marrakech 2011

↓

MUSE

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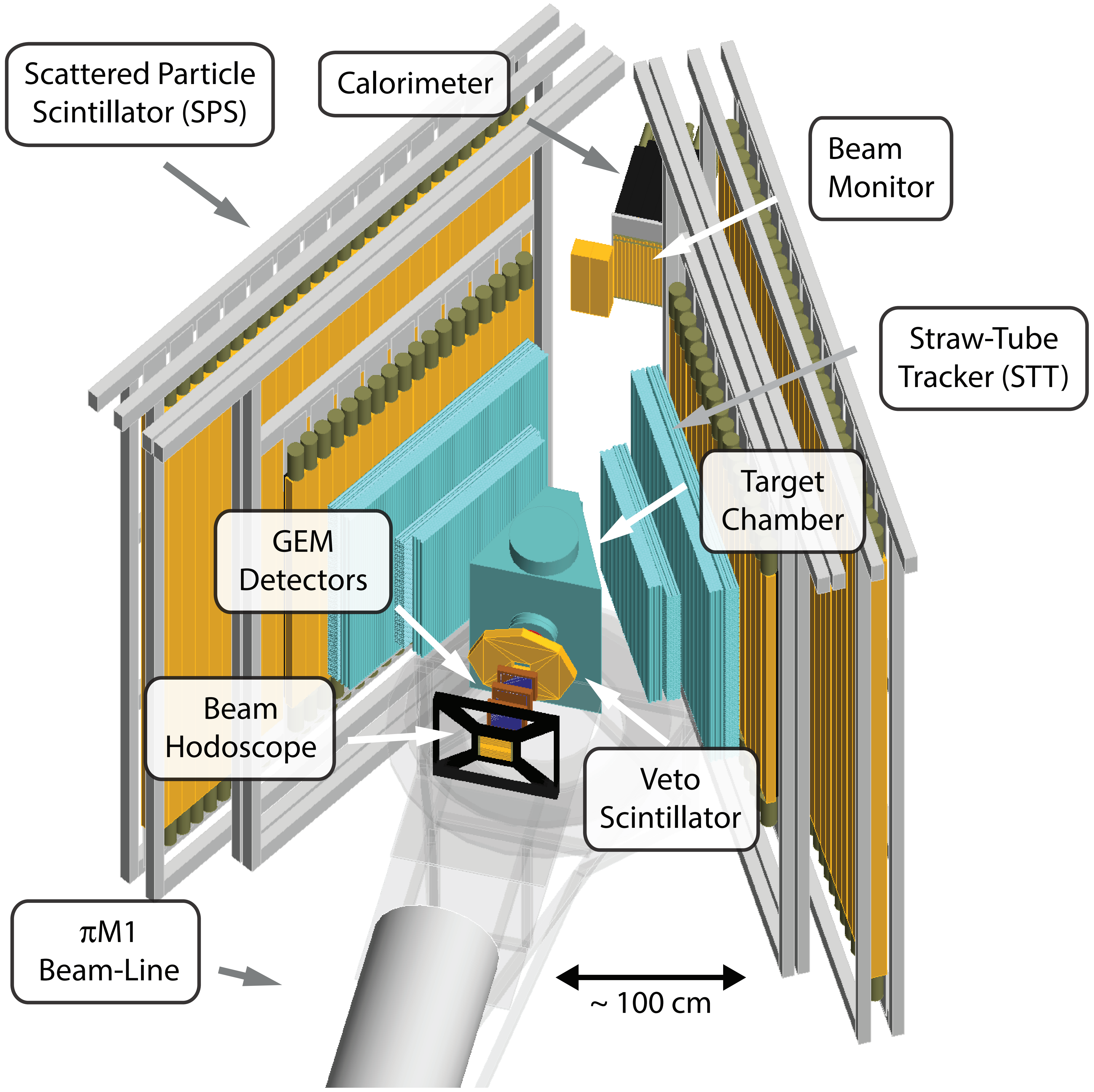


Use ep and μp scattering at the same time to compare cross sections*, form factors, and proton radii with reduced systematics.

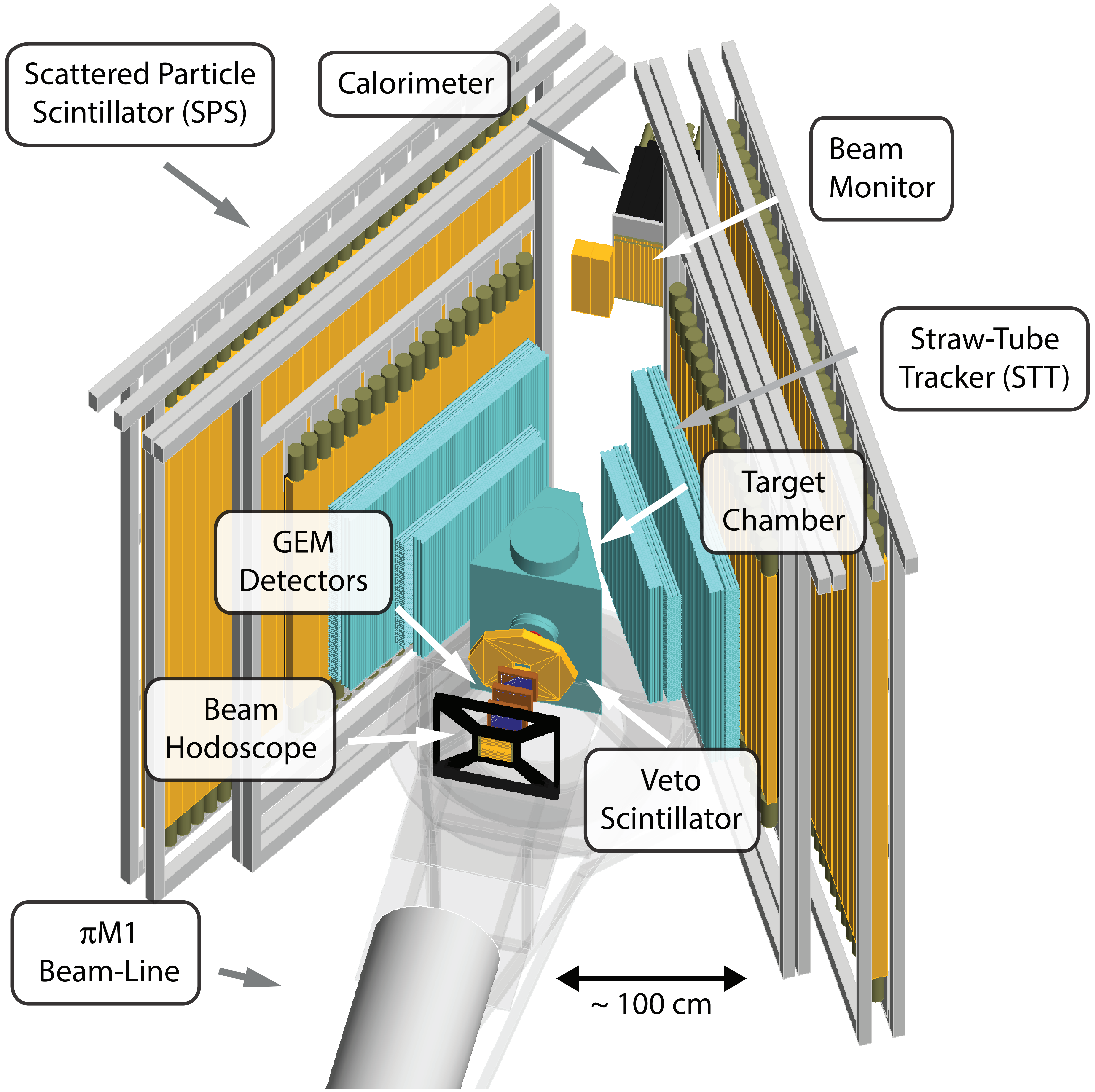
Beams of both polarities for two-photon exchange measurement.

Check of conventional “initial-state” radiative corrections.

Pion backgrounds also for πp phase shifts.

* Mass terms in the cross section — see B. M. Preedom and R. Tegen, PRC 36. 2466 (1987).

MUSE



Standard beam momenta: 115, 160, 210 MeV/c.

Angle range: ~ 20° - 100°.

Q^2 range: ~ 0.002 - 0.08 GeV^2

ϵ range: ~ 0.94 - 0.27

(Slightly different for μ's vs e's.)

MUSE - Why TPE?

OLYMPUS comparison suggests the actual TPE correction is about the size predicted by theory, but might be opposite in sign.

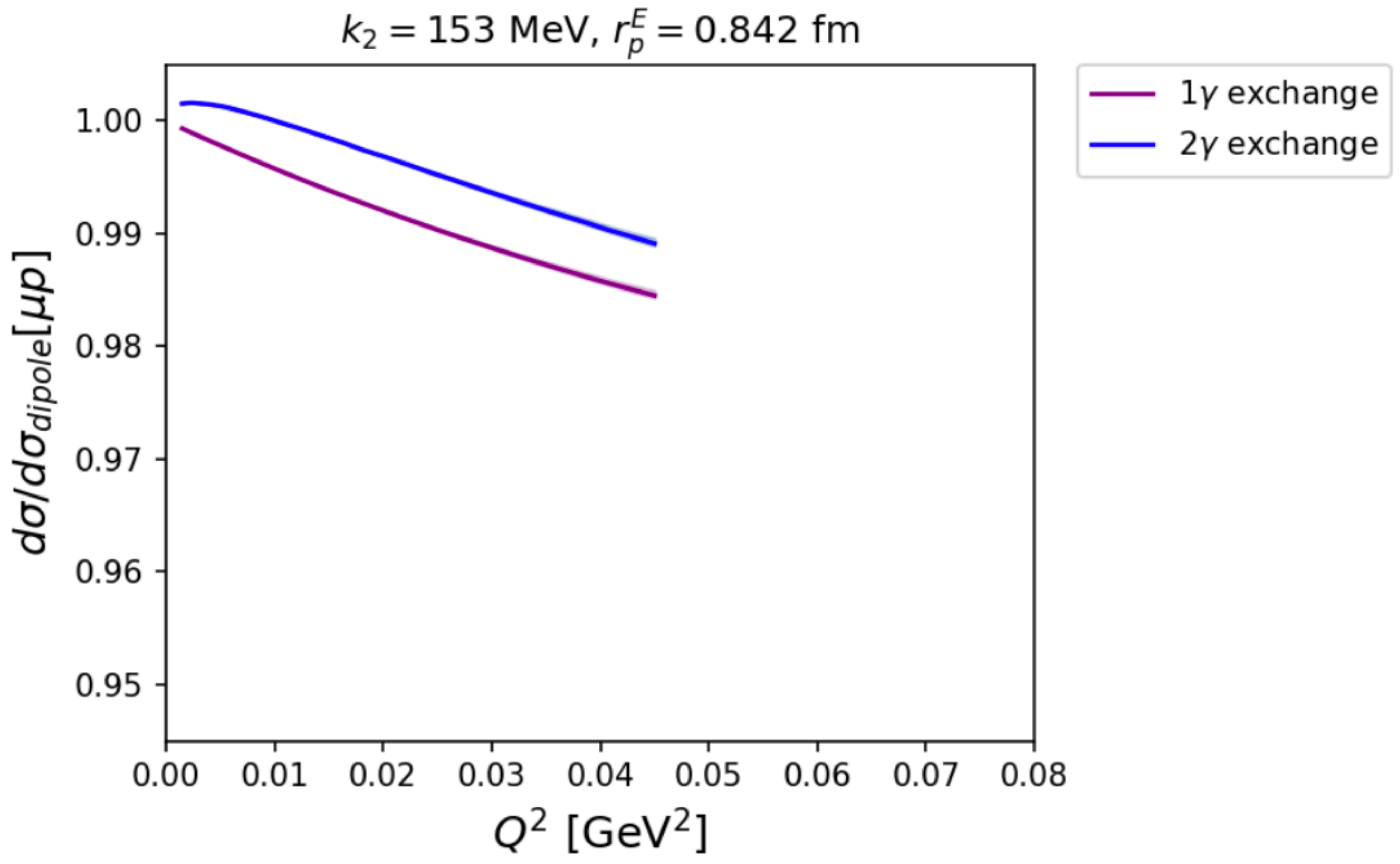
TPE corrections seem to be typically calculated to be O(1%), with a slope near $\epsilon = 1$, so have the potential to significantly affect a radius extraction.

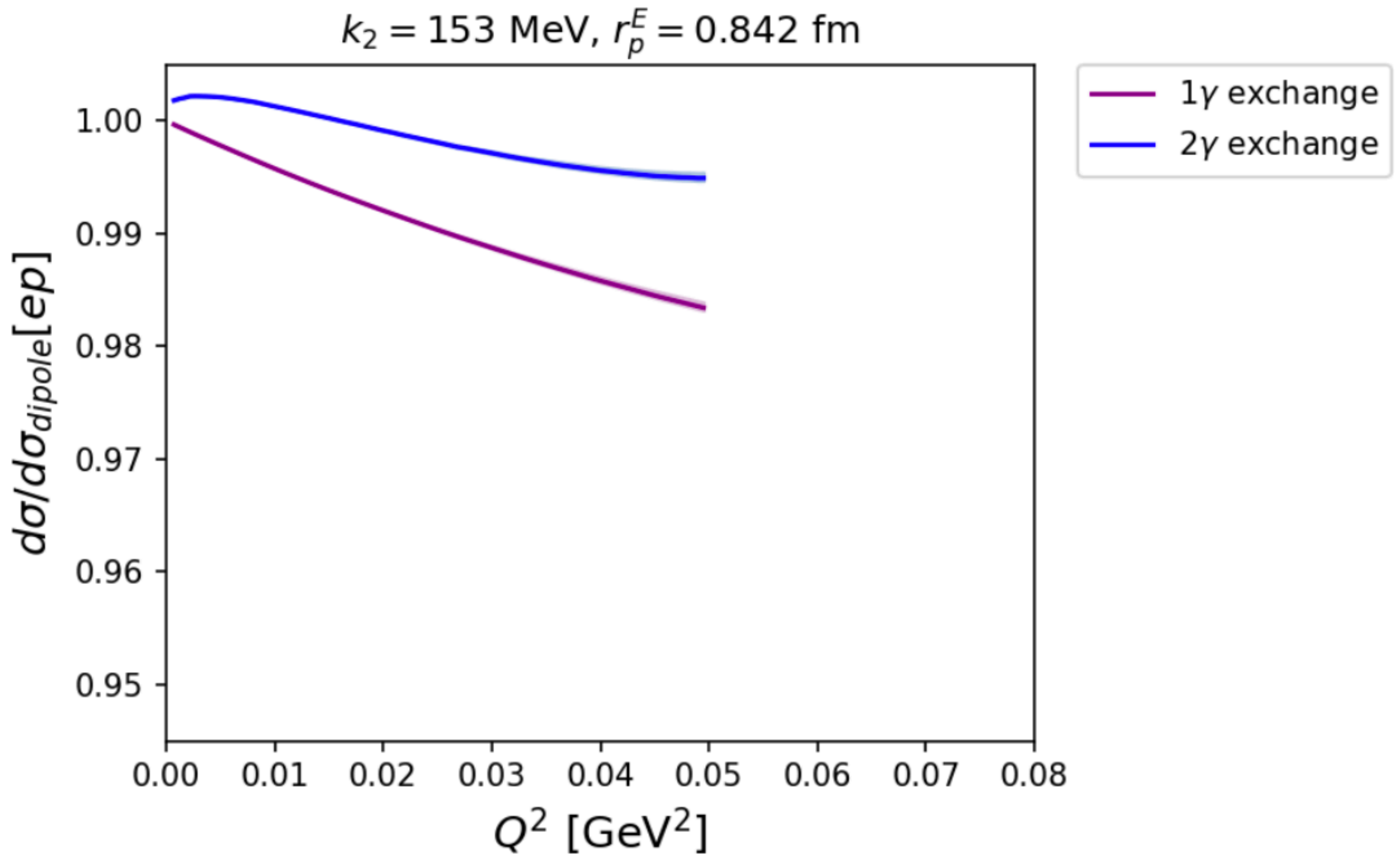
If you can measure the correction, you should.

MUSE - Why TPE?

We recently received calculations of the sensitivity of MUSE to the radius in DIχEFT, by F. G. Dominguez, J. M. Alarcon, and C. Weiss: ~ 0.75 % / 0.01 fm — the TPE correction is a potentially significant fraction of the proton charge radius puzzle.

"The cross section is computed by evaluating Eq. (42) of [6] with the DIχEFT form factors; the TPE corrections are added according to Eq. (44), and their values are extracted from Fig. 14 of the same article." Ref [6]: O. Tomalak and M. Vanderhaeghen, EPJC 78, 514 (2018).





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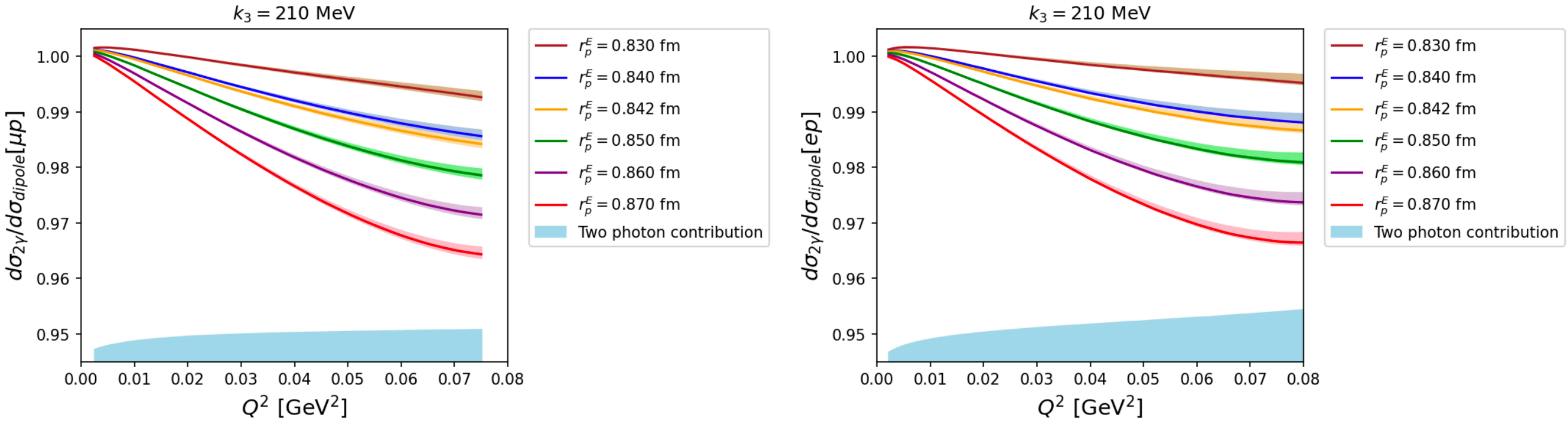
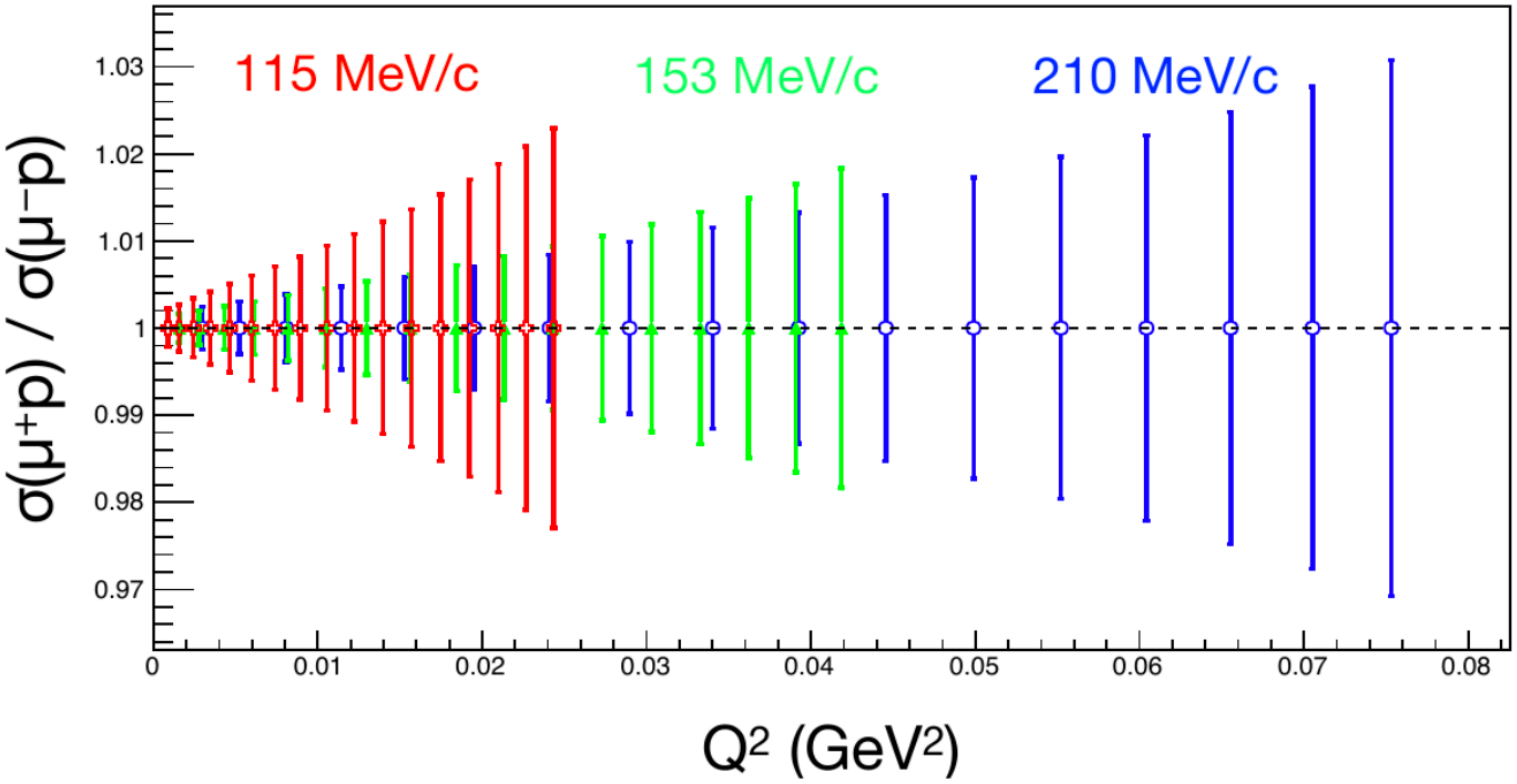


MUSE - Projected Data



ep statistics 2 - 3 x better

systematics at ~ 0.2%.

Conclusions

TPE is important for precision ep (and μp) cross section experiments.

The level of agreement between theory and data is not yet sufficient. Could be there is some interesting theory to learn, but could be experimental issues.

The corrections are significant for a precise proton radius, and we will measure them.

Formulas

Cross sections – $\sigma_r = \epsilon G_E^2 + \tau G_M^2$

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

$$P_n = 0 \text{ (OPE)}$$
$$I_0 P_t = -2\sqrt{\tau(1+\tau)}G_E^p G_M^p \tan\frac{\theta_e}{2}$$
$$I_0 P_l = \frac{(E_e + E_e')}{M_p}\sqrt{\tau(1+\tau)}G_{Mp}^2 \tan^2\frac{\theta_e}{2}$$

$$\theta_{rot} = \gamma\kappa\theta_{bend}$$
$$I_0 = \sigma_r/\epsilon$$

We measure $\frac{G_{Ep}}{G_{Mp}} = \frac{P_t}{P_l}\frac{(E_e + E_e')}{2M_p}\tan\frac{\theta_e}{2}$

Formulas

Free to divide both numerator and denominator by G_M^2, and using $R = G_E/G_M$:

$$P_t \propto \frac{R}{\frac{\tau}{\epsilon} + R^2}$$

$$P_l \propto \frac{1}{\frac{\tau}{\epsilon} + R^2}$$

$$\frac{P_t}{P_l} \propto R$$

Polarizations only measure the form factor ratio.