Electron–proton scattering puzzle

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E-P SCATTERING PUZZLE

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What is the proton radius puzzle?

- 2010: CODATA uses regular hydrogen spectroscopy data (mostly)
- Also: elastic e-p scattering data, to declare R_p=0.8755(51) fm
- Even though: muonic hydrogen Lamb shift (CREMA): R_p=0.84169(66) fm

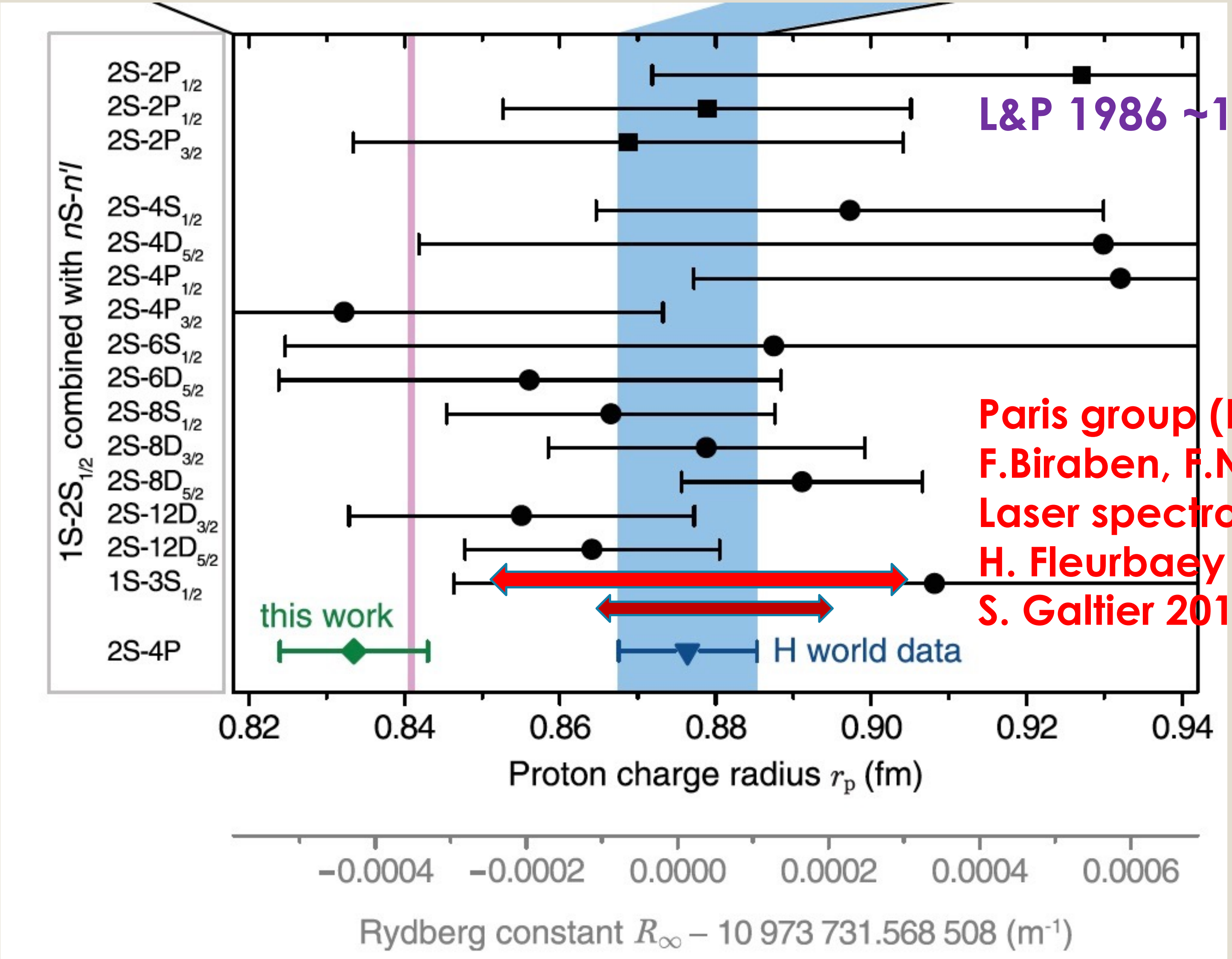
- Triggers: re-analysis of e-p scattering, re-analysis of hydrogen spectroscopy, much debate over 'new' physics (the muon not just a cousin to the electron?)
- Demand for new regular hydrogen spectroscopy!
- 2014 CODATA: doesn't trust the muonic hydrogen result YET!
- Rydberg constant (SI-au conversion!) is severely affected.

Outline

- 1. Spectroscopy overview: Garching vs Paris
- 2. elastic e-p scattering problem: what is the problem?
- 3. using moments from theory? C.Peset and A.Pineda; J.Alarcón and C.Weiss
- 4. need the z-expansion, or the ζ-expansion (shifted z-expansion at fixed Q^2_{max})
- 5. Are 8 parameters sufficient to fit the MAMI data up to 1 GeV^2 ? (instead of 24)
- Will the scattering puzzle come to rest soon? Will the spectroscopy puzzle?

Spectroscopy results (Science **358**, 79)

MPQ Garching:
Fluorescence
following
Laser excitation
Big quantum
interference
systematic!



L&P 1986 ~1GHz ± 9kHz

Paris group (LKB)
F.Biraben, F.Nez et al
Laser spectroscopy
H. Fleurbaey 2017 (5 kHz),
S. Galtier 2014, 2017 (3 kHz)

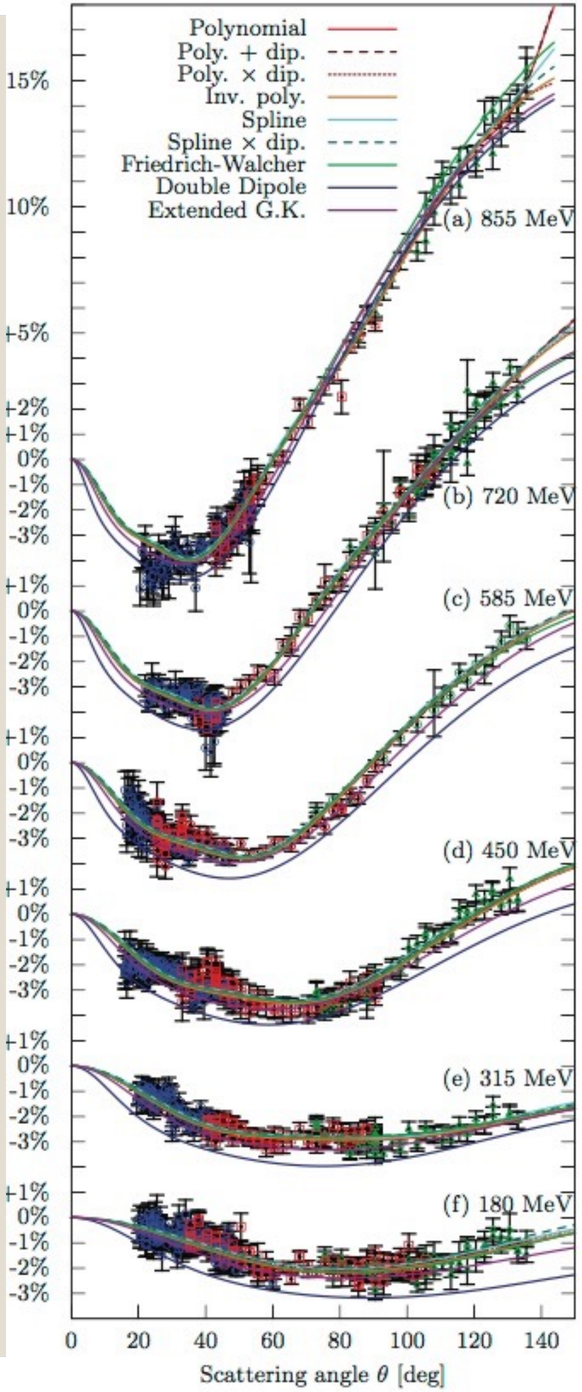
Elastic e-p scattering (post-2010)

- Elastic e-p scattering with relativistic electrons
- De Broglie wavelength chosen to not look inside the proton
- Mainz (MAMI); Jan Bernauer et al.: 1422 data at momentum transfer squared $Q^2 < 1\ GeV^2/c^2$ using 6 beam energies
- Probing electric and magnetic charge distributions at the same time, except when Q^2 small
- Scattering problem: can it be inverted?
- Dispersion relations = analytic property of the form factors!
- Photoproduction (γ-p scattering) of pions has a threshold at twice the pion mass squared!
- Are fits in Q^2 justified when the range exceeds threshold ($0.078\ GeV^2/c^2$)???
- Conformal mapping to the rescue!

MAMI (J. Bernauer et al)

- Used many fits to arrive at [Phys Rev C90, 015206 (2014)]
- R_p=0.879(5)$_{stat}$ (4)$_{sys}$ (2)$_{model}$ (4)$_{group}$ fm
- Magnetic radius: ~0.80 fm (depends on TPE model)
- Problem: reduced χ^2 of 1.14 ! (problem with error bars)

- Disputed by a number of different analyses:
- Horbatsch&Hessels: different models can give 0.84 and 0.89 fm
- Low-Q^2 data fits: favor small radius (Higinbotham et al, Griffioen et al)
- I. Sick and D. Trautmann fight back (PRC 95, 012501) defending large R_p, and defending the need to go to high Q^2.



Low-Q^2 fit: using moments from χPT

- H&H&Pineda: PRC 95, 045203 (2017)
- Peset&Pineda: effective field theory: QCD reduced to heavy baryons (p, Δ) and π
- Cannot predict $< R_p{}^2>$, but $< R_{mag}{}^2>$ and $< R_p{}^4>$, etc., really the form factors minus R_p
- Fit low-Q^2 MAMI data to: and please note the VIRTUAL PHOTON POLARIZATION ε !!!

$$\sigma_{\rm red} = (1+\tau)\frac{d\sigma}{d\Omega}\Big/\frac{d\sigma_{\rm Mott}}{d\Omega} = G_E^2 + \frac{\tau G_M^2}{\epsilon},$$

$$G_E(Q^2) = 1 - \frac{R_p^2}{3!}Q^2 + \frac{\langle r^4\rangle_E}{5!}Q^4 - \frac{\langle r^6\rangle_E}{7!}Q^6 + \cdots$$

$$\frac{G_M(Q^2)}{\mu_p} = 1 - \frac{\langle r^2\rangle_M}{3!}Q^2 + \frac{\langle r^4\rangle_M}{5!}Q^4 - \frac{\langle r^6\rangle_M}{7!}Q^6 + \cdots$$

$$\tau = Q^2/(4m_p^2)$$

$$\epsilon = \left[1 + \frac{4Q^2 + \frac{Q^4}{m_p^2}}{8E^2 - 2\frac{Q^2}{m_p}(2E+m_p)}\right]^{-1}$$

Note:
At the lowest Q^2 G_E only, but…

$$R_p = \sqrt{-3\frac{d\sigma_{\rm red}}{dQ^2}\Big|_{Q^2=0} + \frac{3\mu_p^2}{4m_p^2}}$$

One-parameter R_p fits? - 'kind of'; show 'G_E^2 '

χPT moments come with substantial uncertainties. Fits work up to some Q^2_{max} with χ^2_{red}<1.14

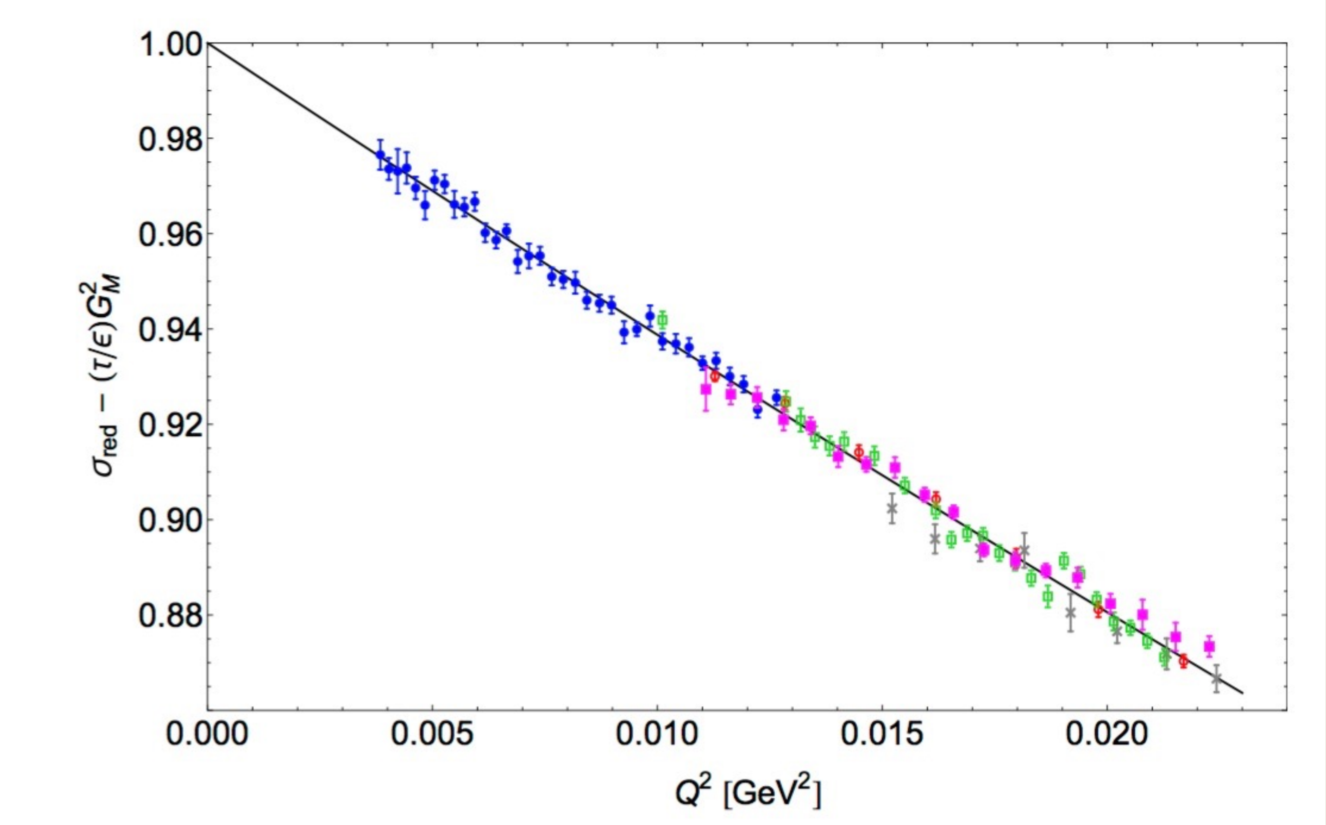
Data come in groups (here five) with floating normalization constants (less than 1 % different from 1).

Extracted charge proton radius R_p has **statistical** and **systematic** uncertainties

Beam energies:
180 MeV: blue, red, green
315 MeV: magenta
450 MeV: gray (Rosenbluth method?)
(270/1422 MAMI data)

For R_p we need the slope at Q^2=0 !

Big question: are the predicted χPT moments (incl. uncertainties) reasonable?



What do we get when using less vs more data?

Blue band: statistical
Pink: syst.: $\langle r^2 \rangle_M$
Green syst. Higher

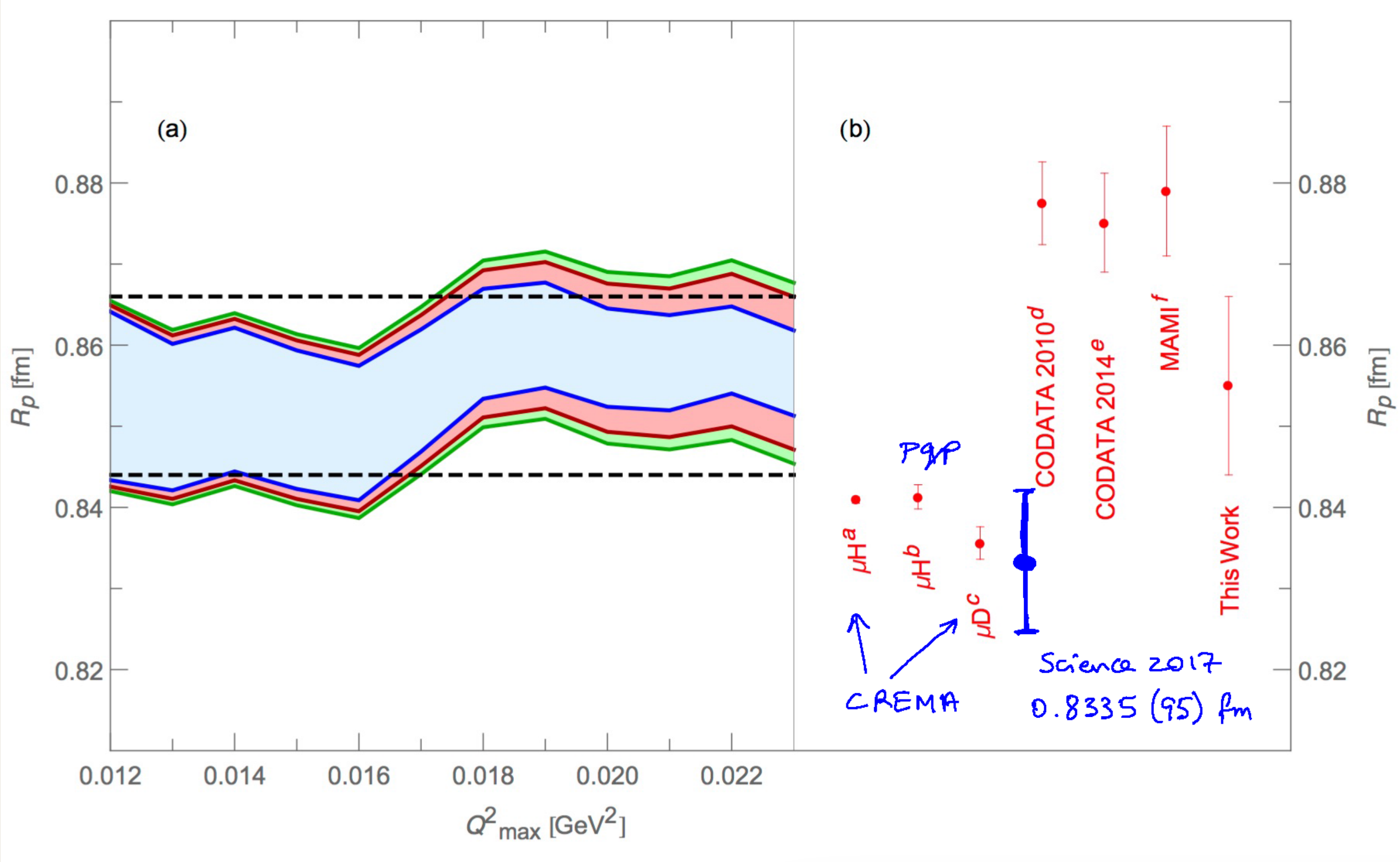
Note:
We are far from the branch cut (0.078 GeV^2)

χPT bound in fm^2:

$0.28 < \langle r^2 \rangle_M < 0.60$

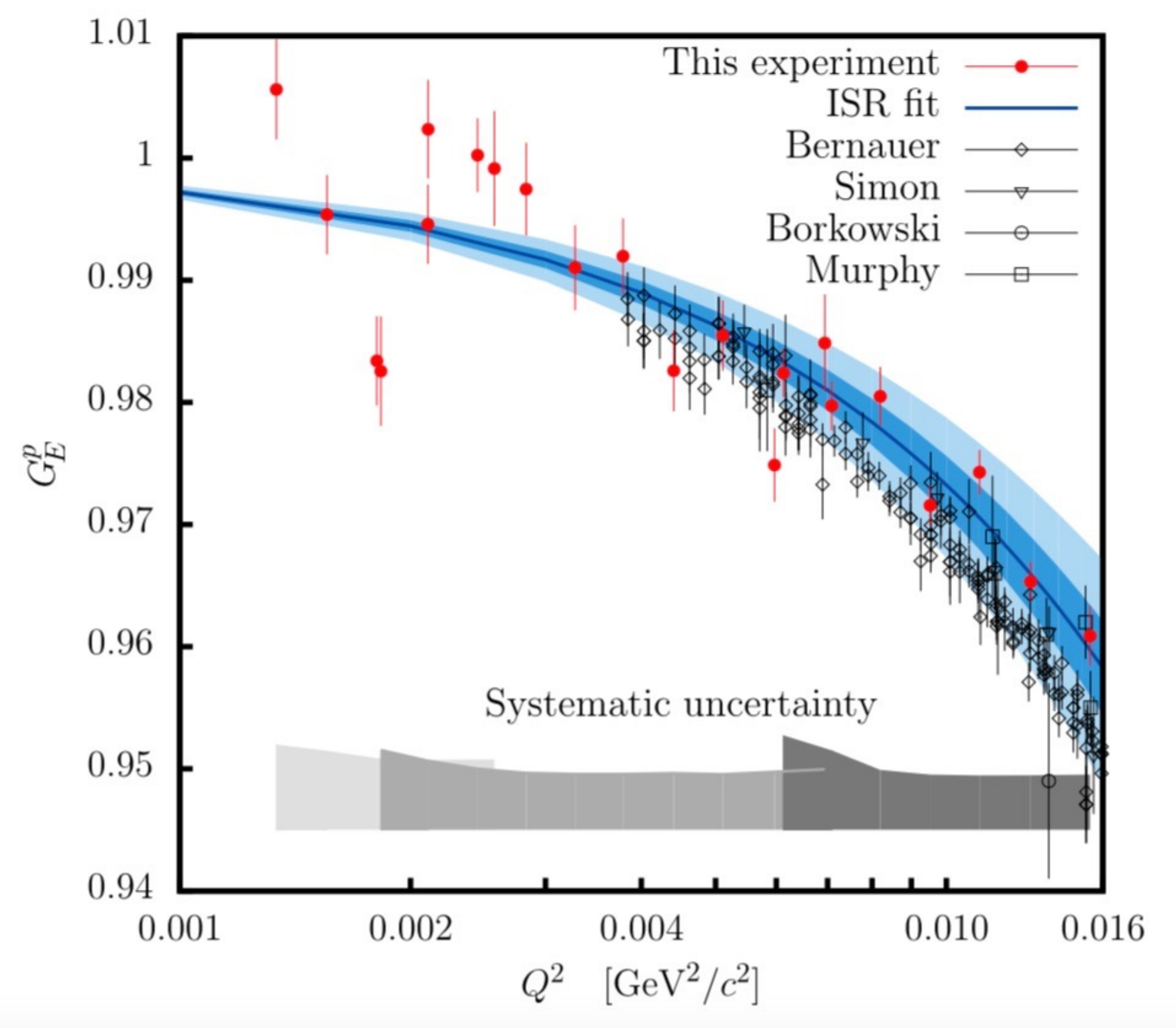
Current R_M = 0.8 fm
(χPT marginal ?)

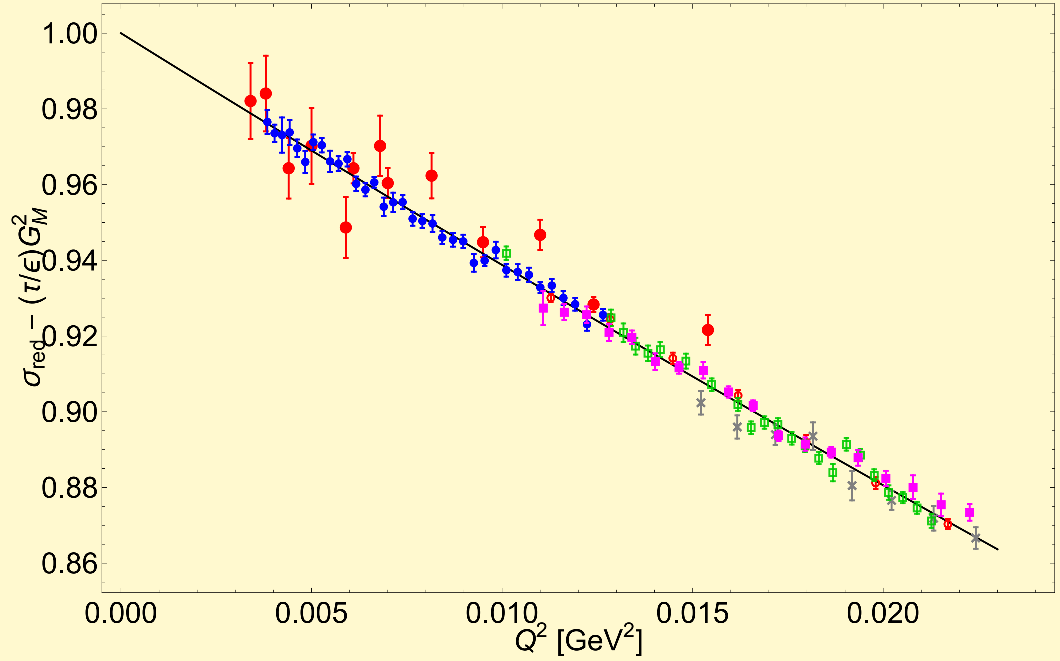
Main reason why we stop at 0.023 GeV^2, but $\langle r^4 \rangle_E$ is also 'small'.



New MAMI on the horizon (PRad competition?)

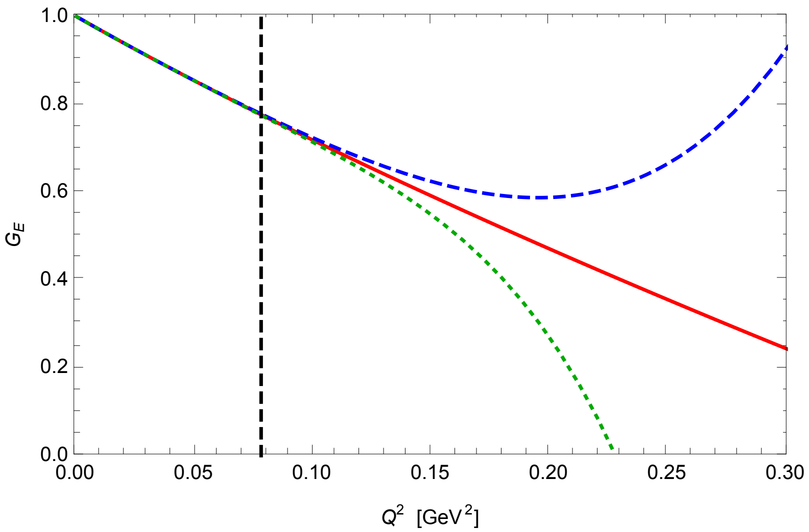
- Initial-state radiation, Phys Lett B771,194 (2017), arXiv1612.06707

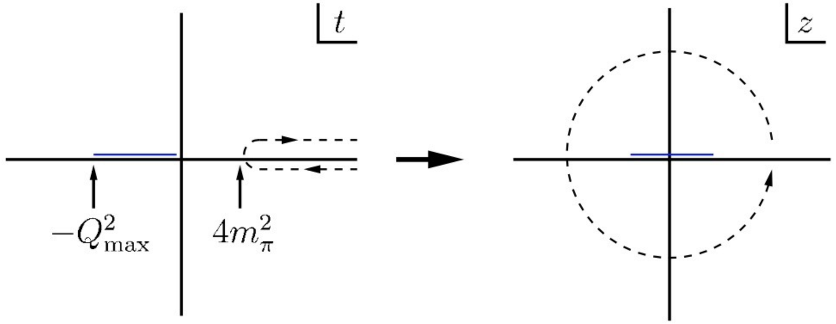


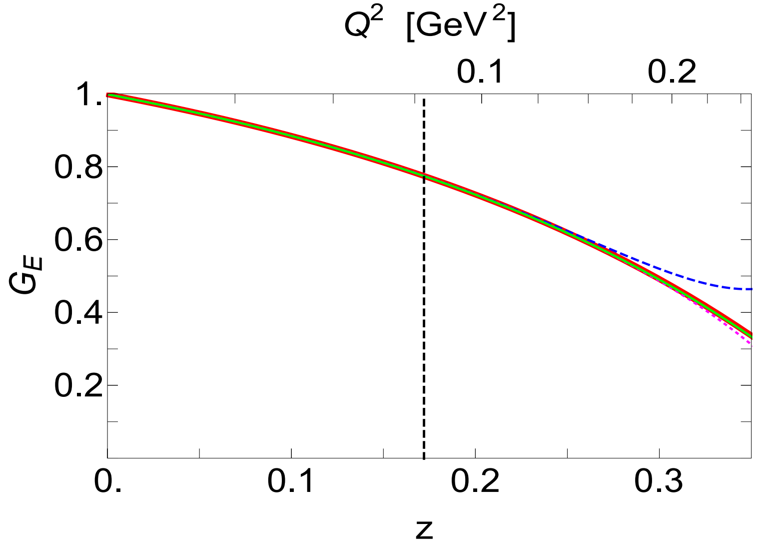


R_p small, after all ?

G_E and G_M from effective theory (Peset and Pineda)







R.J. Hill and G. Paz re-introduce this (forgotten?) method!

$$z = \frac{\sqrt{t_c - t} - \sqrt{t_c}}{\sqrt{t_c - t} + \sqrt{t_c}}$$

Moment expansion in Q^2 fails beyond 0.078 due to branch cut (charged pions) at Q^2=-0.078=-t_c

γ-p scattering, dispersion relations

Note: we had to put in R_p^2 = <r^2>$_E$ (here R_p=0.85 fm)!

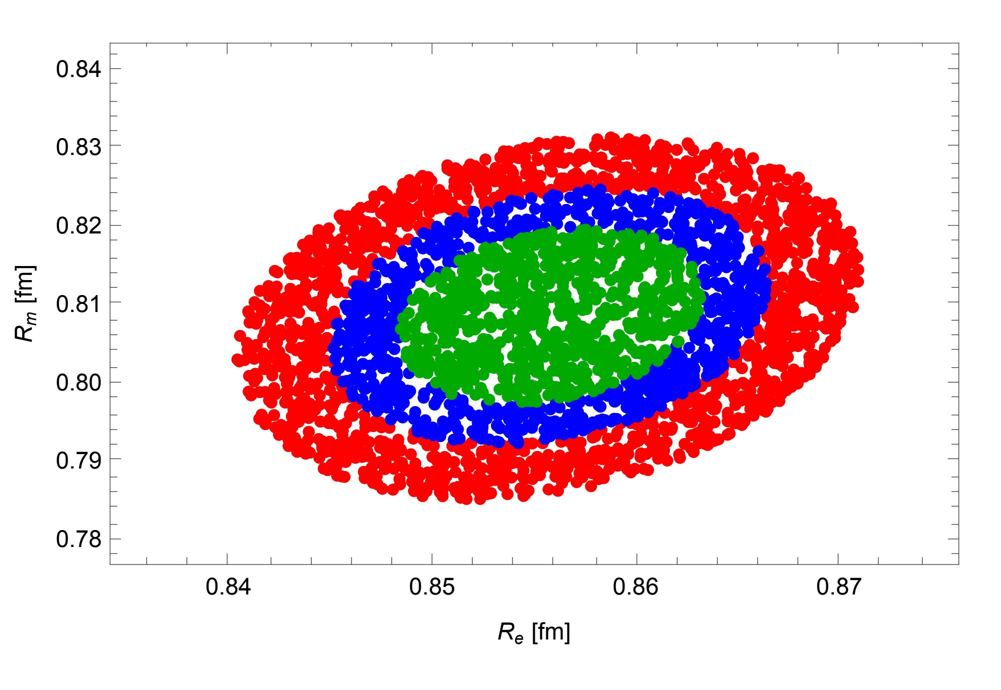
But:
We can fix that using conformal mapping

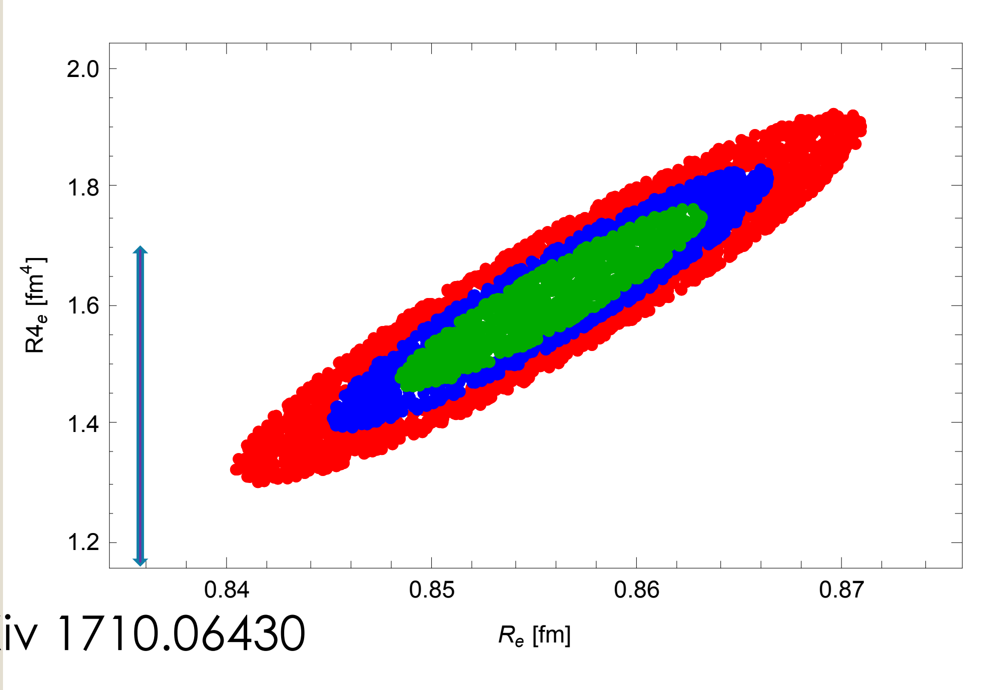
Moment expansion equals semi-analytic answer to high accuracy out to reasonable Q^2=-t !

Testing fits up to moderate Q^2_{max}

- Situation: Effective theory predictions: nothing useful on charge radius, rather small quartic moment, smallish magnetic radius.
- Thus: attempt fits where R_p=R_e and R_m float, as well as $\langle r^4\rangle_e$ with sampling of $\langle r^6\rangle_e$ and $\langle r^4\rangle_m$ in an extended range compared to predictions. Show reduced chi-squared for three-parameter fits with chosen $\langle r^6\rangle_e$ and $\langle r^4\rangle_m$ and observe correlations.
- If we went for the minimum chi-squared in these, then we'd do a total 5-parameter fit
- Higher moments up to order 20 are used as the central-value predictions. Without that, no reasonable function out to Q^2_{max} = 0.2 GeV^2.
- Note: we are forced to expand beyond the predictions for $\langle r^6\rangle_e$ and $\langle r^4\rangle_m$, but not by too much.
- We use heavy-baryon effective theory including as degrees: π, p, and the Δ. (by C. Peset and A. Pineda)

(Q^2_{max} = 0.2 GeV^2) χ_{red}^2 : green<1.08, blue<1.10,red<1.14





J.A & C.W arXiv 1710.06430

Is lowest reduced chi-squared χ_{red}^2 the answer?

If not, why not?

Are there systematic problems with the MAMI data?

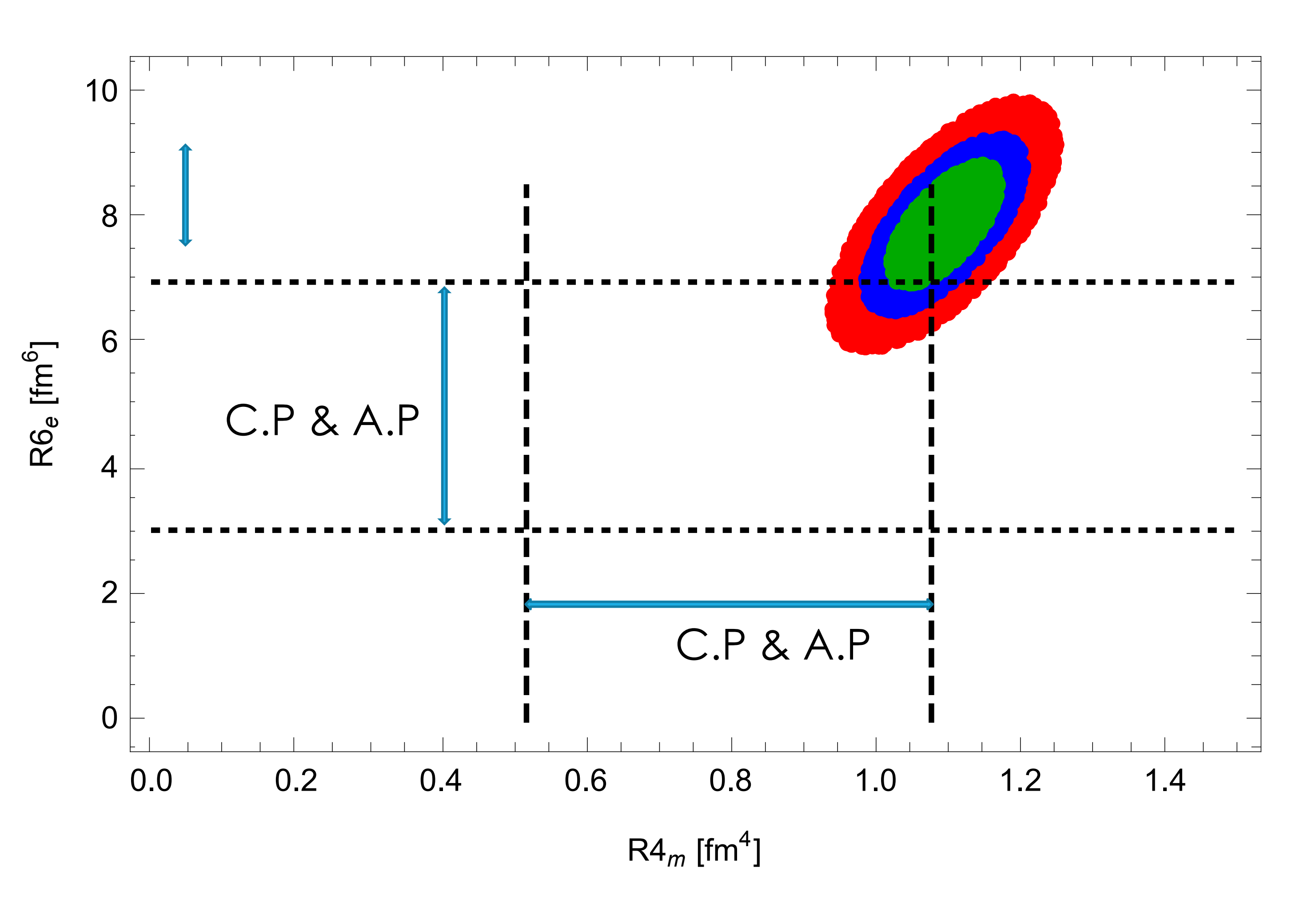
Clearly: P&P prediction 0.6(3) = No Go

I. Sick & D. Trautmann: 2.01(5) PRC 2017
M. Distler: 2.6 fm^4

Note the R_e vs $\langle r^4\rangle_e$ correlation !!

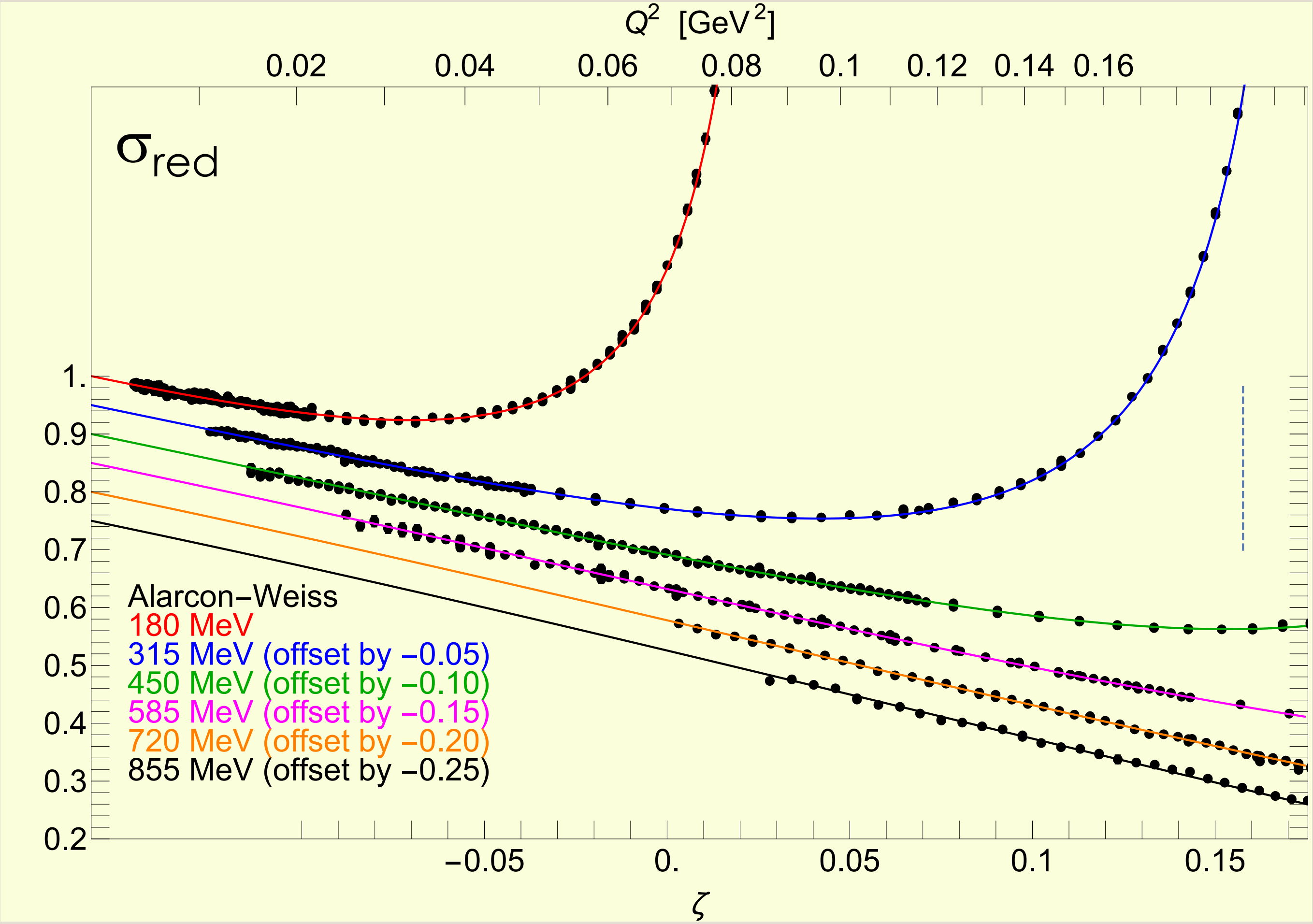
Is it consistent for the higher moments ?

J.A & C.W arXiv 1710.06430



Strategy: use ‘χPT+’ (J.Alarcón & C.Weiss) with a trick:

- Turn moment expansions into fit functions:



here is how:

Given a max. Q^2 (here 0.2, dashed line):
Spread the data in the conformal range
Power series about ζ=0. ζ = generalized z.

Use predicted moments (up to 10th order in ζ)

Replace the lowest-order moments by fit parameters (here a 4-parameter fit)

Fit works for some range above max. Q^2.

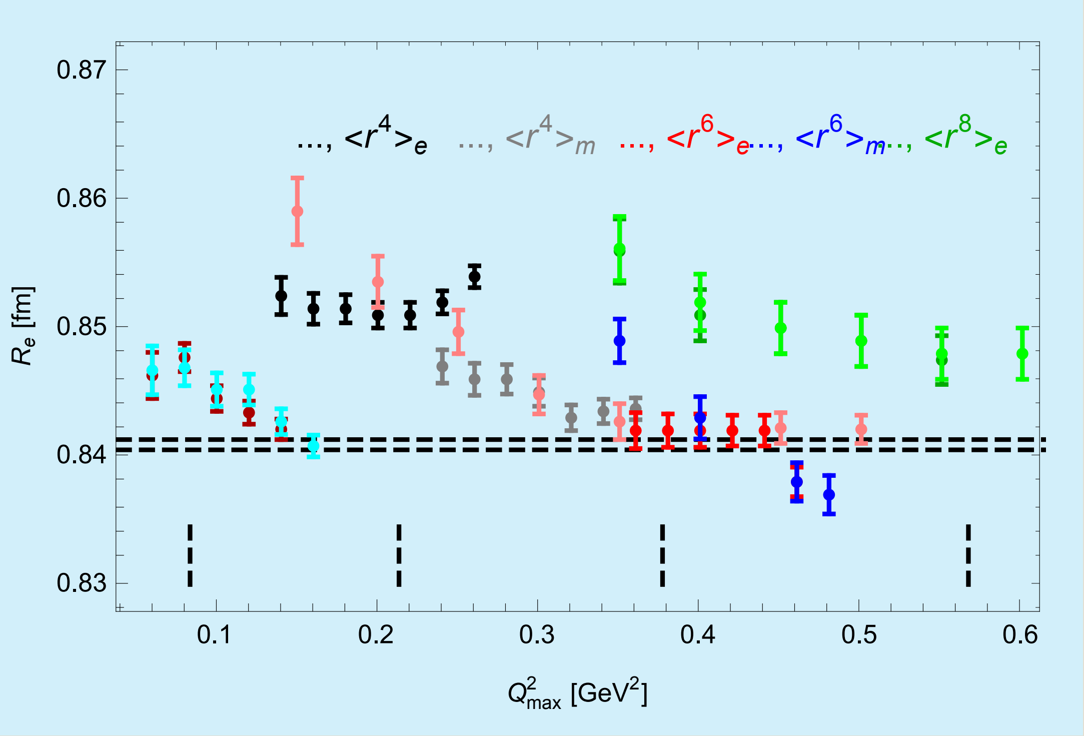
Reduced chi-squared of 1.08 here

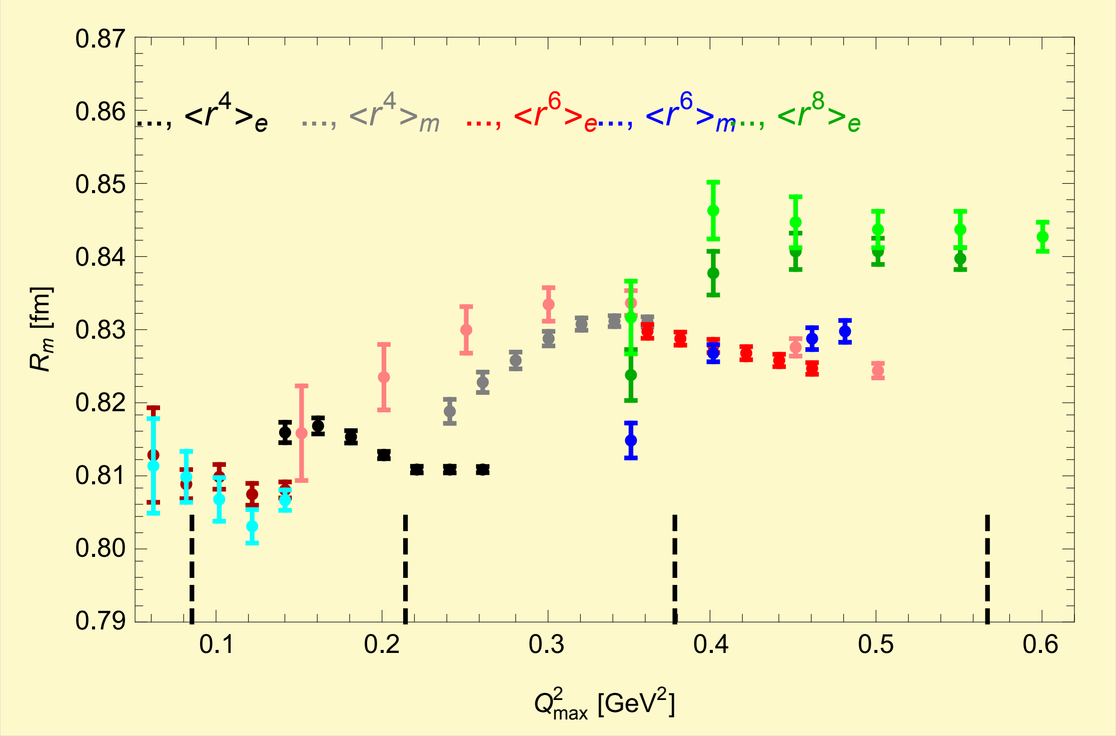
Good sensitivity to magnetic effects. Why?

To go to higher max. Q^2 we need more predictions replaced by fit parameters

Fits with 2, 3, 4, 5, 6, 7 parameters (& up to 31 norms)

Electric Radius: Magnetic Radius:



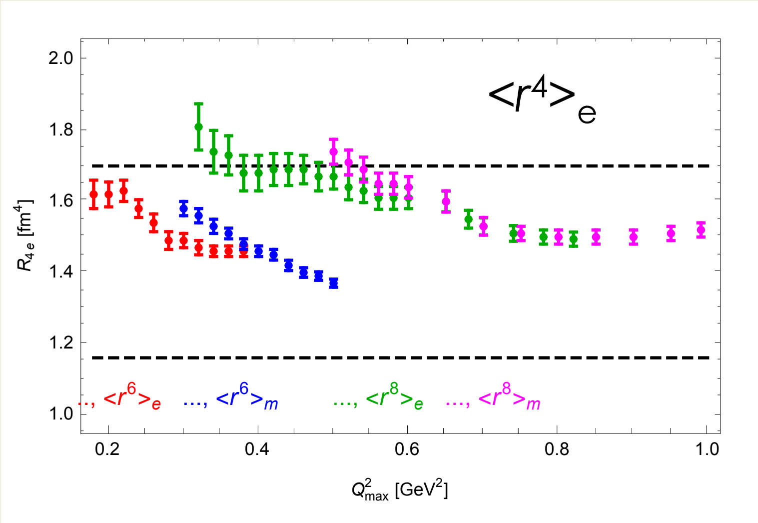


Errors shown are statistical (fit) errors; systematic errors due to predicted moment uncertainties can be inferred from the jump in value when a relevant parameter is added (electric vs magnetic)

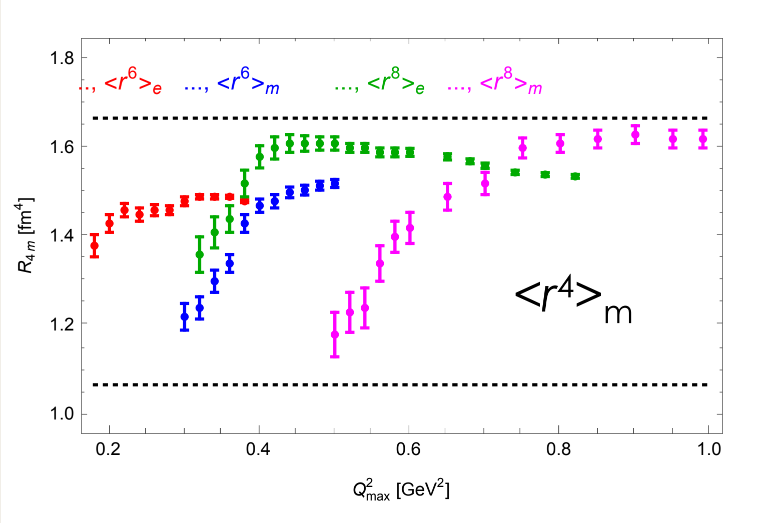
Fits tend towards **small** (μH) radius value when the dust settles! (blue? – no gain in fit quality)

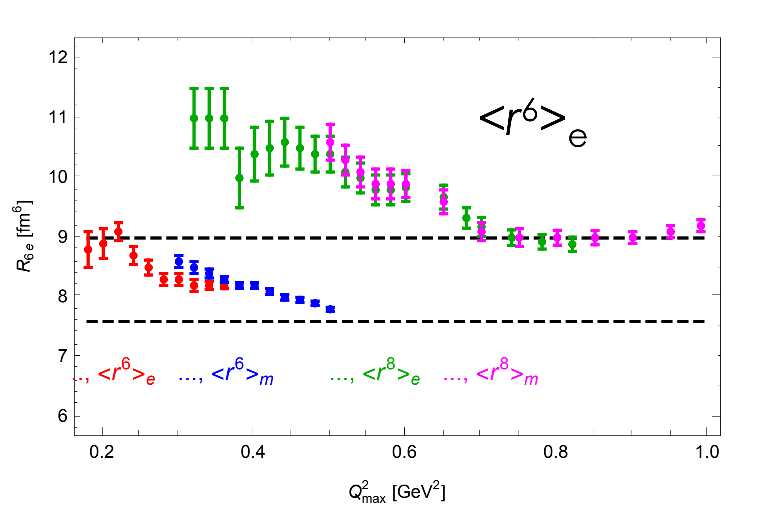
Magnetic radius of ~0.82(1) fm is **higher** than the MAMI analysis of 0.80(2) fm (2014 with TPE)

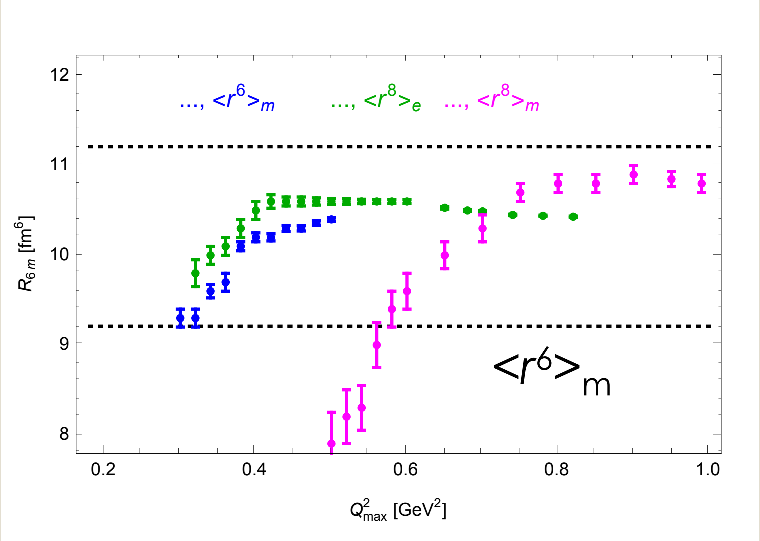
Electric moments (arXiv 1710.06430), magnetic (private c., with uncertainties assumed >= to electric by MH)



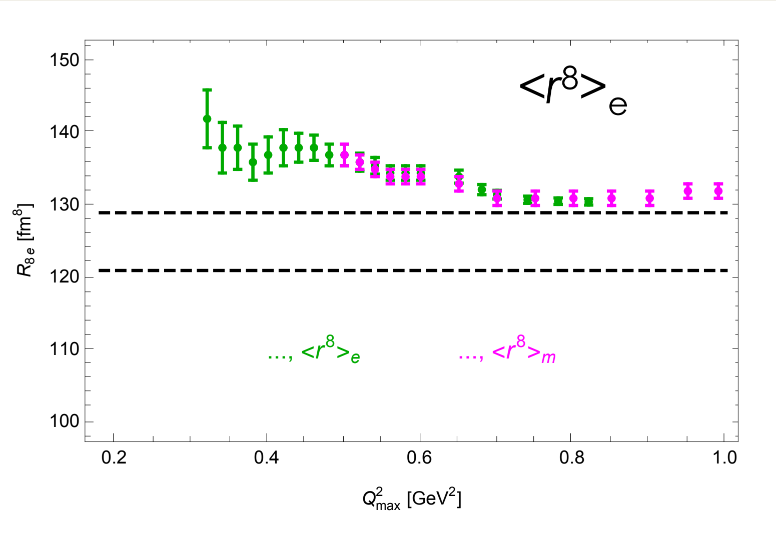
Consistency between predicted ranges and fit findings?

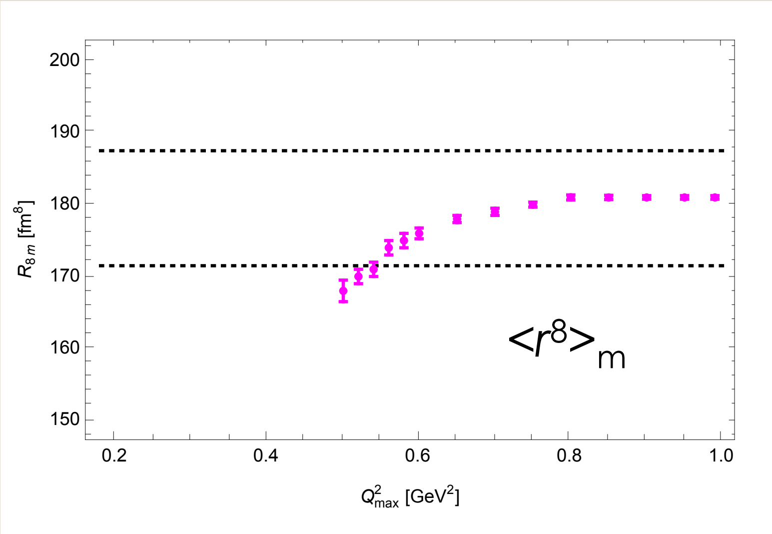






The highest ‘determined’ moments





What have we done ?

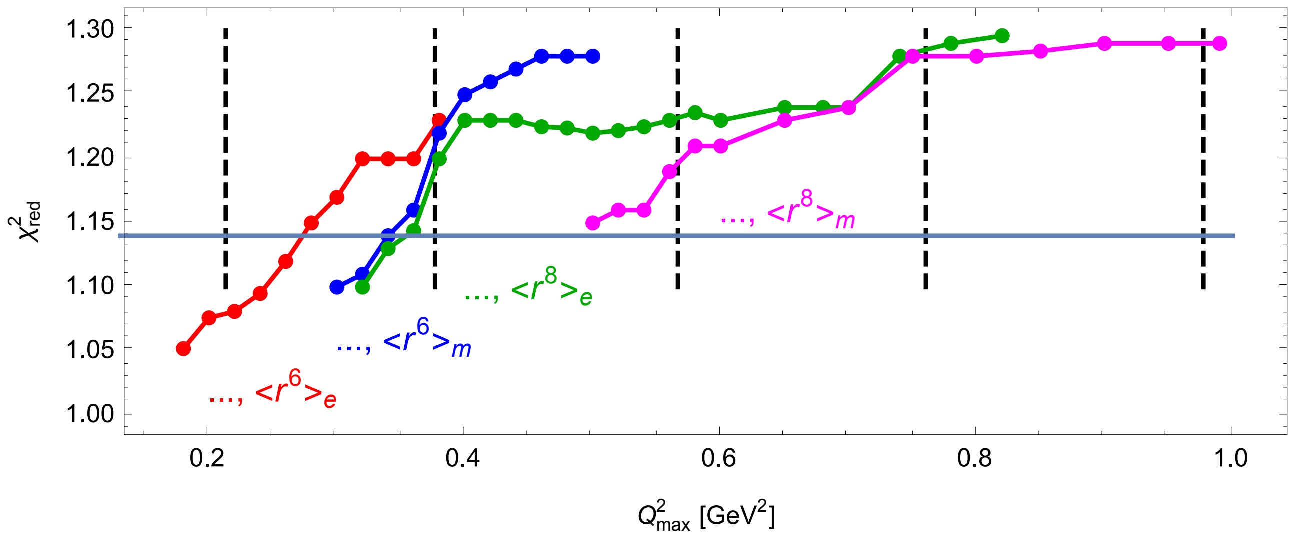
Used theory to yield constraints on the large-Q^2 behavior of the form factors.

Used the only parameters relevant in the given Q^2 range.

Used a physics constraint (π-π threshold in analytic continuation of the FFs).

So, is there any **bad news** ?

Reduced chi-squared is – perhaps - the bad news!



The MAMI fitters are told to stay below 1.14 - line.

This 1.14 is an admission of problems,
For 1422 data points it shouldn't happen.

Now, what if the MAMI troubles are systematic?

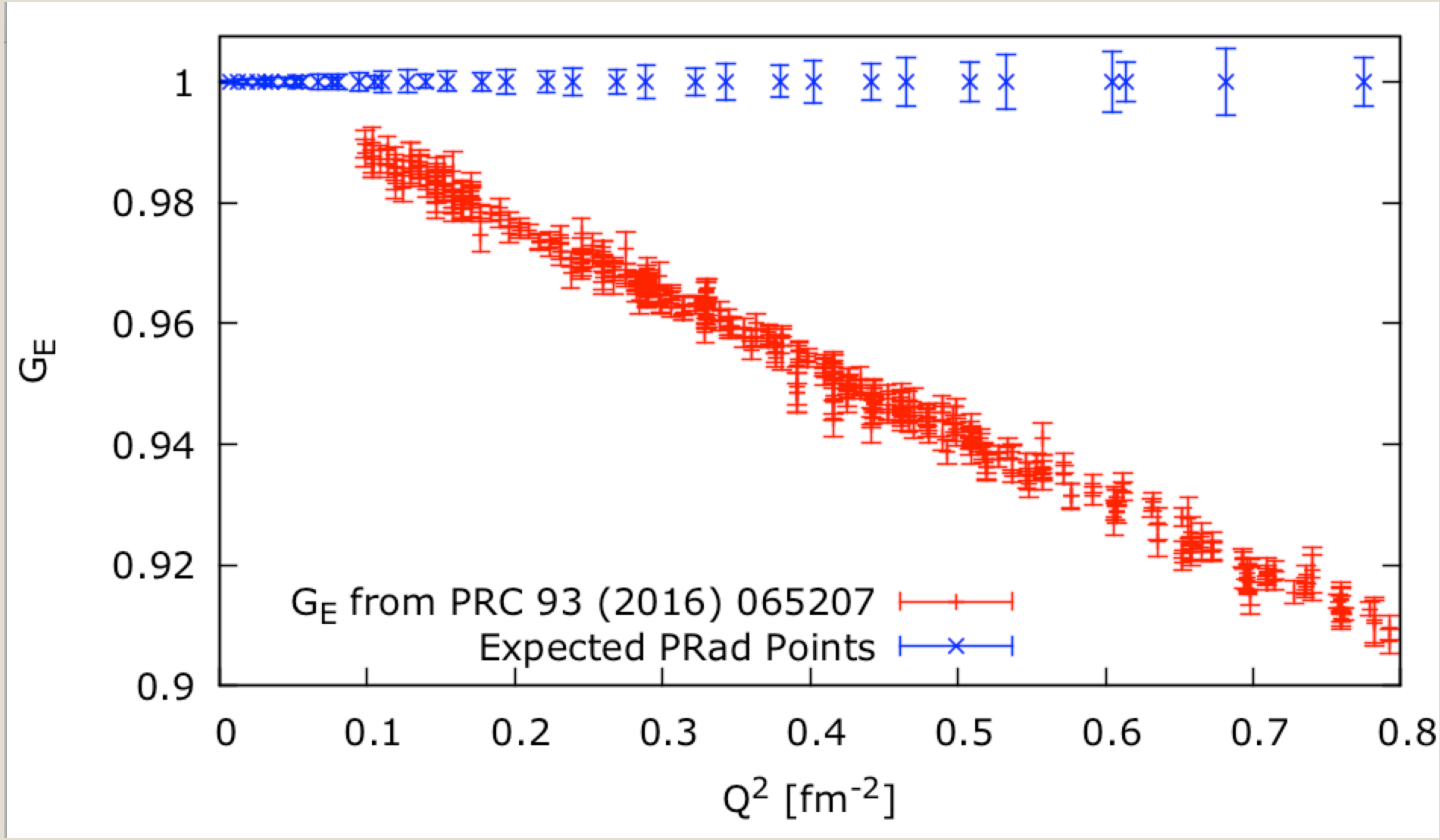
Our analysis: a value of 1.23 for $Q^2_{max} < 0.74$ is OK.
The blue curve is worse (last 6 points, i.e., reject).
Is χ^2 a $1/\varepsilon$ problem??

The MAMI fitters (including ourselves in the past) have managed to achieve 1.14 over the entire data set by using 12 parameters per form factor = 24 parameters. Are these fits just fighting some systematic errors when ε goes small? (at the dashed lines)

7% error vs 14% (Jan's vs our guess)

The future will tell. The weaving is in the MAMI data (from Rosenbluth separations!), G_e and G_m swing a couple of times - is this physics ? If so, what physics ?

Expected Precision of PRad Data



At this point, the community is split.

0.84 fm **0.88 fm**

New electron scattering (PRAD), muon-electron scattering (MUSE), and atomic experiments coming!

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