The proton charge-radius puzzle

What is the size of the proton?

1. The puzzle
2. Results from electron scattering experiments
3. Results from spectroscopy experiments
4. New experiments

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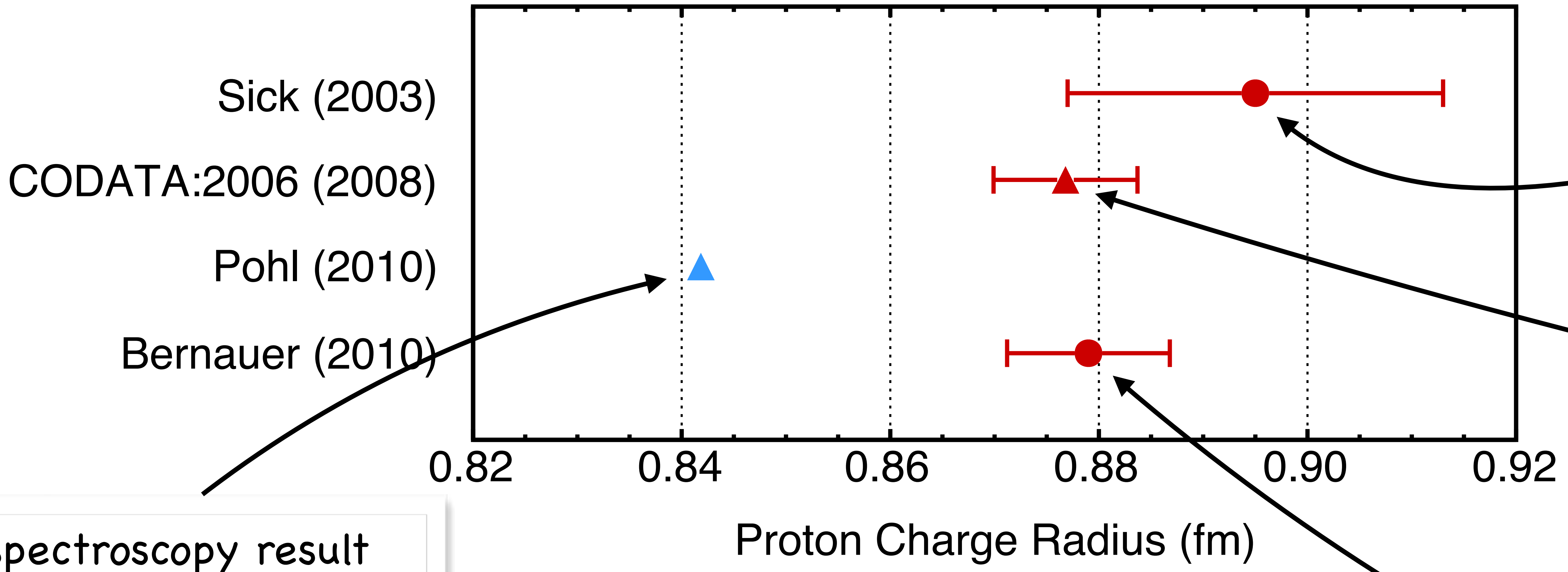
University of Aveiro, Portugal, June 24 - 26, 2019

The proton radius puzzle (2010): Muonic and electronic measurements give different proton charge radii



Analysis of world electron-scattering data

Analysis of hydrogen spectroscopy data Committee on Data for Science and Technology (CODATA)

r_p = 0.8768(69) fm

Muonic-hydrogen spectroscopy result

ten times more precise, but 4% smaller than previously accepted value

r_p = 0.84184(67) fm

Analysis of MAMI electron-scattering experiment

In 2010, the discrepancy between muonic and electronic measurements of the proton charge radius was a 5σ effect and grew to a 7σ effect in 2013. Now? … unclear.

I. Sick, PLB 576, 62 (2003); P.J. Mohr et al., Rev. Mod. Phys. 80, 633 (2008); J.C Bernauer et al., PRL 105, 242001 (2010); R. Pohl et al., Nature 466, 213 (2010)

"This discrepancy has triggered a lively discussion…"

Aldo Antognini et al., Science **339**, 417 (2013)

Possible explanations of the proton-radius puzzle:

- Electron scattering & atomic hydrogen data and radius extraction not as accurate as previously reported.

- Novel Hadronic Physics:
  Strong-interaction effect important for μp but not for ep; two-photon corrections, proton polarizability (effect $\propto m_l^4$), off-shell corrections.

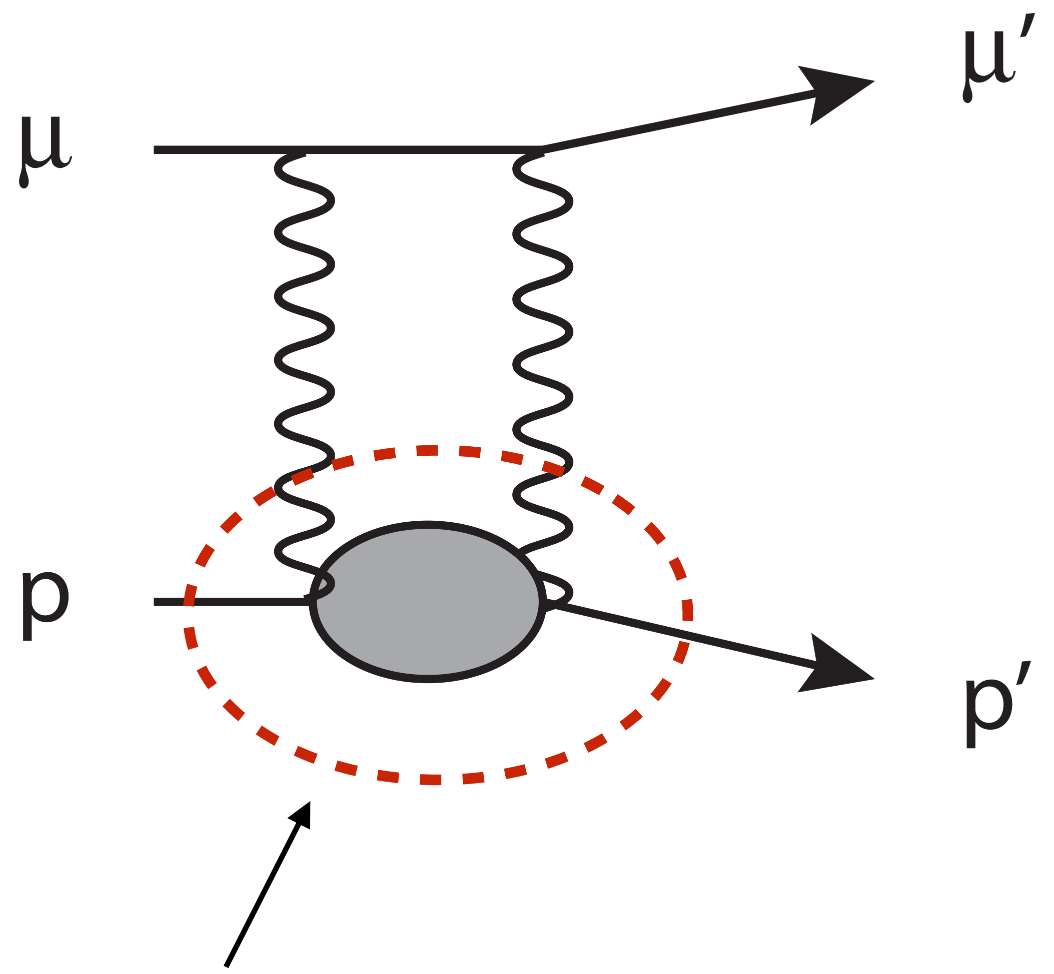
- Beyond Standard Model Physics:
  Violation of μ - e universality.

Pohl, Miller, Gilman, Pachucki, Annu. Rev. Nucl. Part. Sci. **63**, 175 (2013); C. Carlson, Prog. Part. Nucl. Phys. **82**, 59 (2015); G.A. Miller, Phys. Lett. B **718**, 1078 (2013), G.A. Miller, A.W. Thomas, J.D. Carroll, J. Rafelski Phys. Rev. A **84**, 020101 (2011). C.E. Carlson, M. Vanderhaeghen, Phys. Rev. A **84**, 020102 (2011).

New experiments are planned or underway to address the issue

Novel Hadronic Physics: Effect at the intersection between QED and strong interaction effects

Proton polarizability contribution enters in the **two-photon exchange term** of the muonic hydrogen Lamb shift.



Off-shell Compton scattering.

Parts of the scattering amplitude, $T^{\mu\nu}(\nu,q^2)$, are unknown.

Energy shift in the muonic energy level splitting between the 2P and 2S states, proportional to $\mathbf{m^4}$.

Are uncertainties in the contributions large enough to explain the proton-radius puzzle? – probably not.

The two-photon exchange effect will be studied in the MUSE experiment.

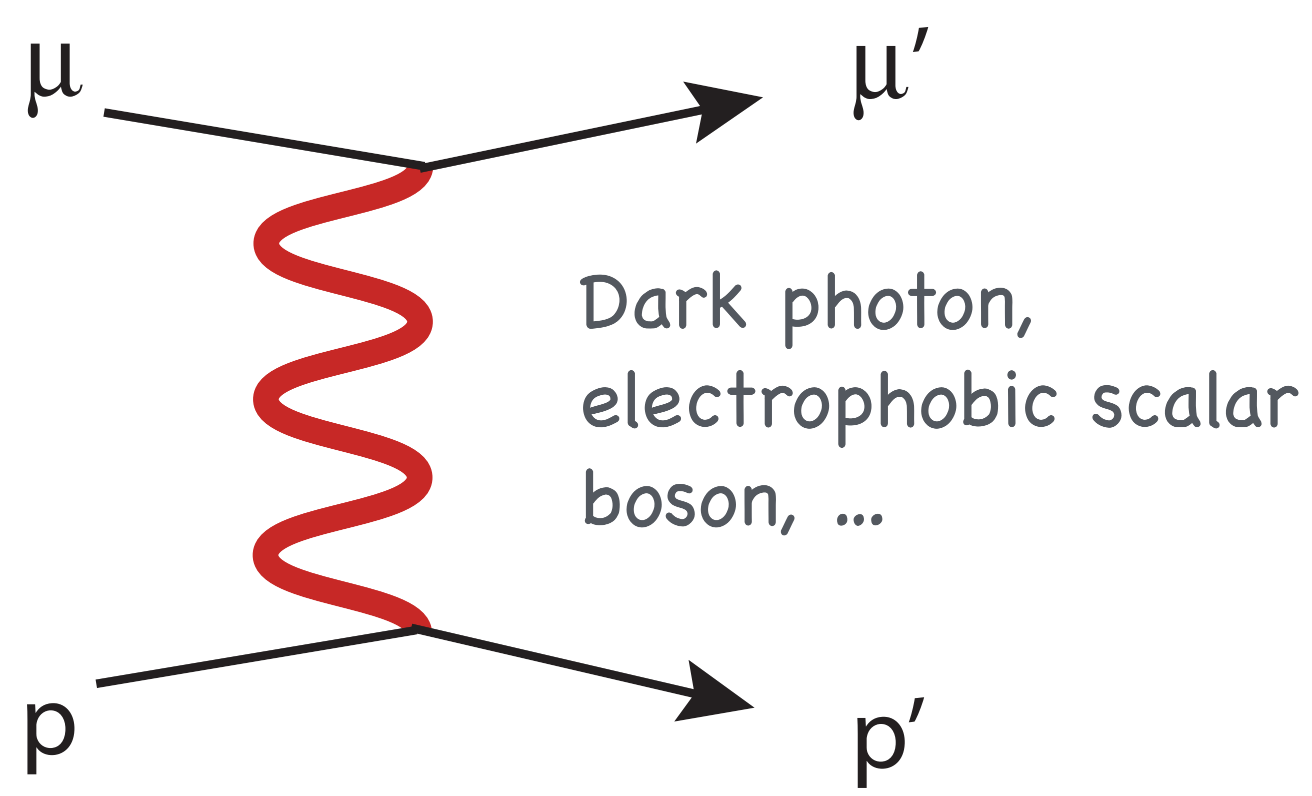
G. A. Miller, A. W. Thomas, J. D. Carroll, and J. Rafelski Phys. Rev. A 84, 020101(R) (2011), G. Miller, Phys. Lett. B 718, 1078 (2012), G. Miller arXiv:1809.09635v1.

Beyond the Standard Model

- An explanation of the proton-radius puzzle involving new particles must include larger couplings to muons than electrons;

  the interactions must **violate lepton universality**;

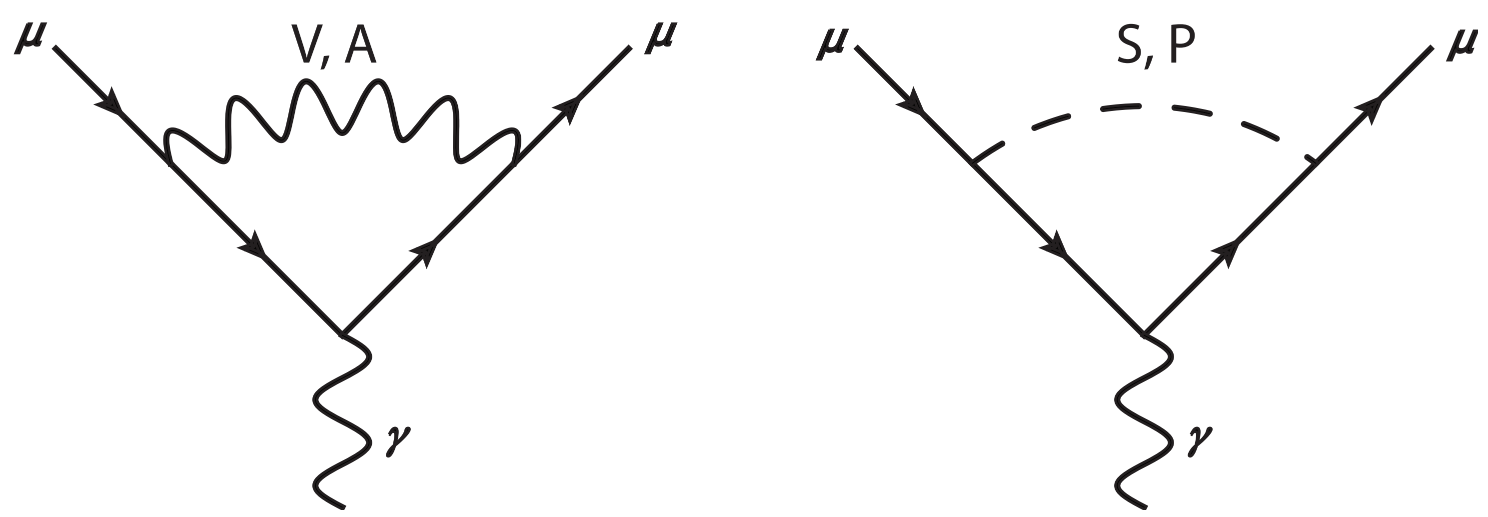
  or maybe a new particle that affects the shape of the form factor without much changing the proton radius.



- Constraints from non-observations in Kaon decays, $K^+ \rightarrow \mu^+ \nu A'$, $A' \rightarrow e^+e^-$

- Constraints from $(g-2)_\mu$

Corrections to the muon magnetic moment due to new particle exchange.

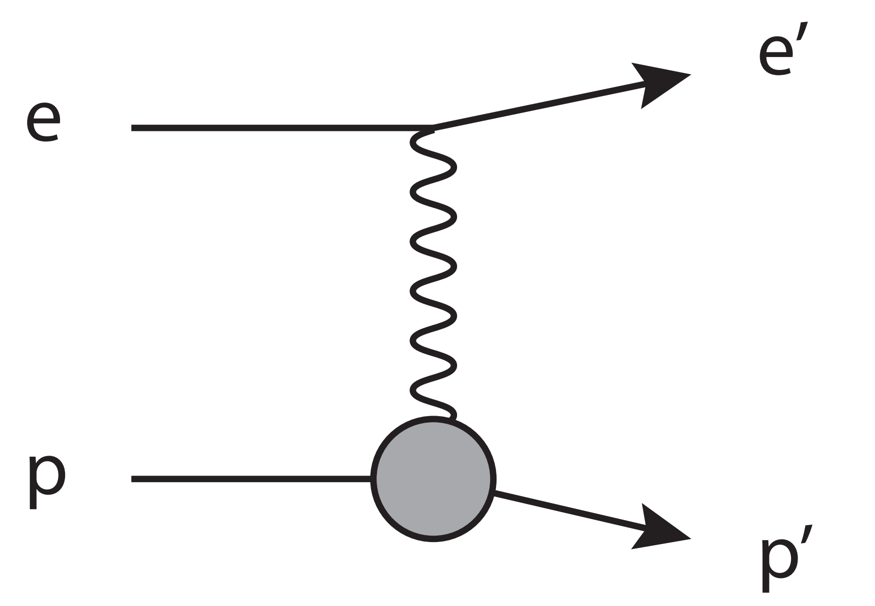


- One cannot claim the theory corrections to $(g-2)_\mu$ are under good control unless the proton radius puzzle is understood.

C. Carlson, Prog. Part. Nucl. Phys. **82**, 59 (2015); Y-S Liu, D. McKeen, and G.A. Miller, Phys., Rev., Lett. **117**, 101801 (2016).

Electric and magnetic proton form factors

Cross section for ep scattering (one photon exchange)

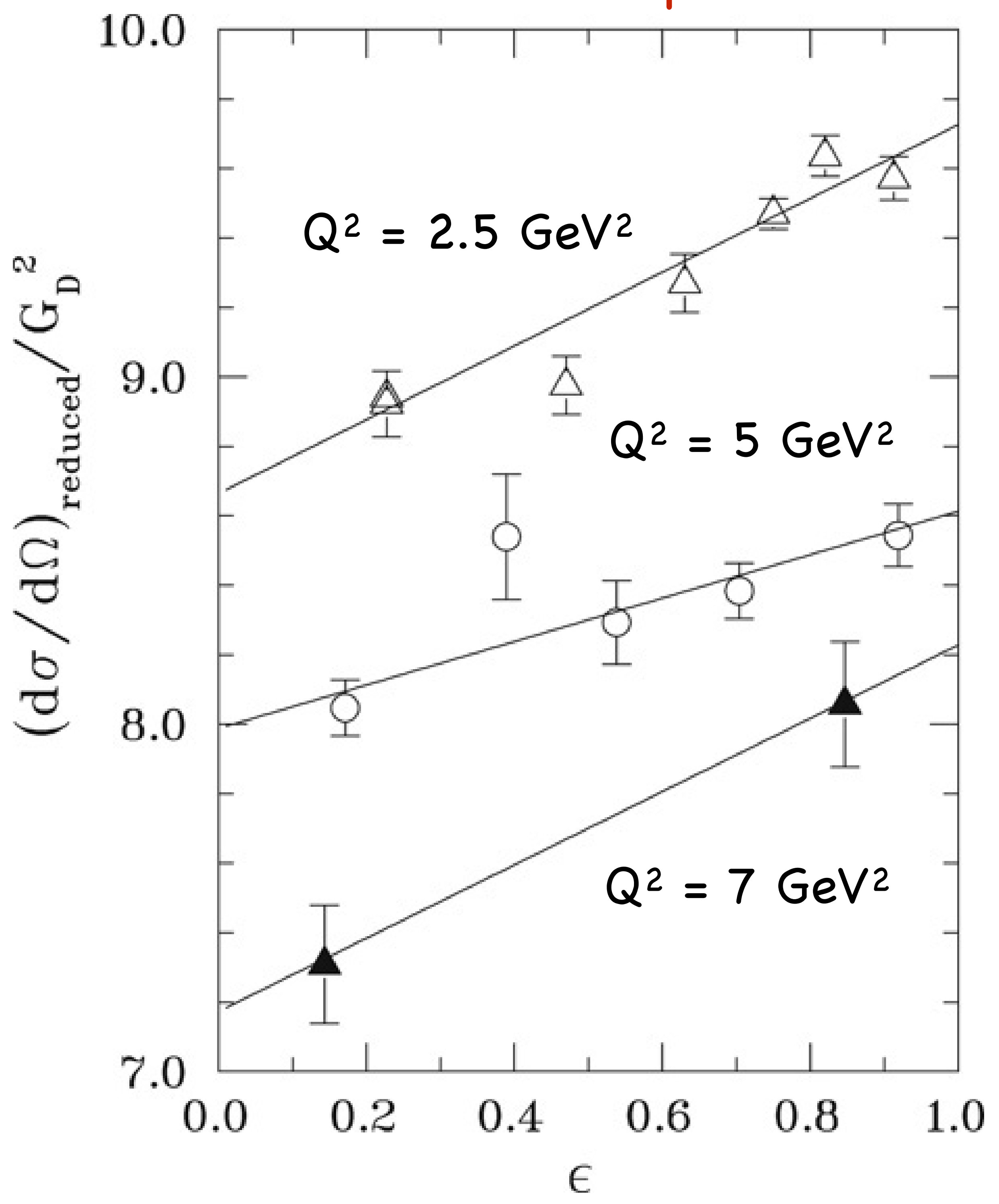


$$\left(\frac{d\sigma}{d\Omega}\right) = \left(\frac{d\sigma}{d\Omega}\right)_{\text{Mott}} \frac{\tau}{\epsilon(1+\tau)} \underbrace{\left[G_M^2 + \frac{\epsilon}{\tau} G_E^2\right]}_{\text{reduced cross section}}$$

- G_E is related to **electric charge** distribution, $G_E(0) = 1$
- G_M is related to **magnetic current density**, $G_M(0) = \mu_p$
  G_M enters cross section as $Q^2 G_M$, and is suppressed at low Q^2

$$\boxed{\langle r_p^2 \rangle := -6\hbar^2 \left.\frac{dG_E(Q^2)}{dQ^2}\right|_{Q^2=0}}$$

Rosenbluth separation



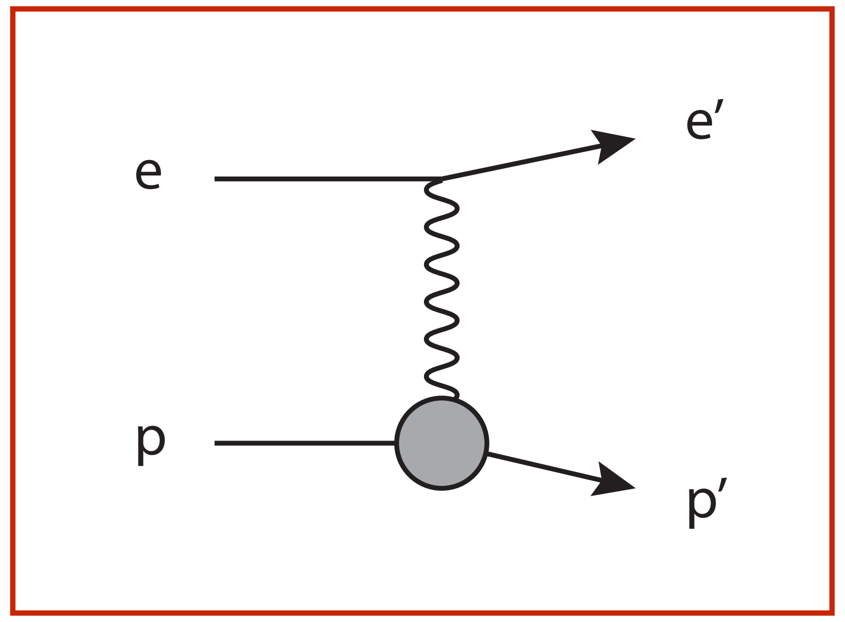
Alternatively:

Direct fits of $G_E(Q^2)$ and $G_M(Q^2)$ to experimental cross-section data.

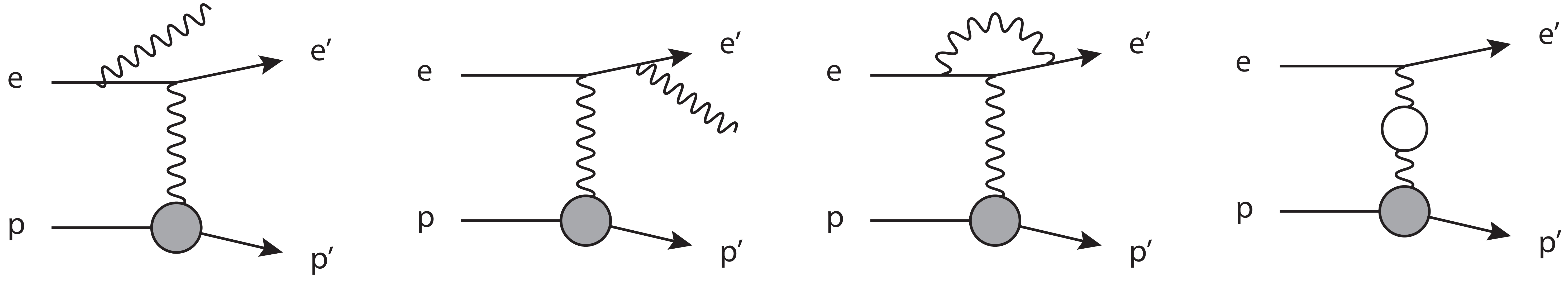
C.F. Perdrisat, V. Punjabi, M. Vanderhaeghen, Progress in Particle and Nuclear Physics **59** (2007) 694-764.
G. Miller, "Defining the proton radius: A unified treatment", PRC 99, 035202 (2019).

Also electromagnetic processes of higher order contribute to the measured cross section

Born term



QED radiative corrections



initial state bremsstrahlung | final state bremsstrahlung | vertex correction | vacuum polarization | …

$$\sigma_{\text{exp}} = \sigma_{\text{Born}}(1+\delta)$$

modify incident and final electron momentum distributions

Approximation for multiple soft-photon emission

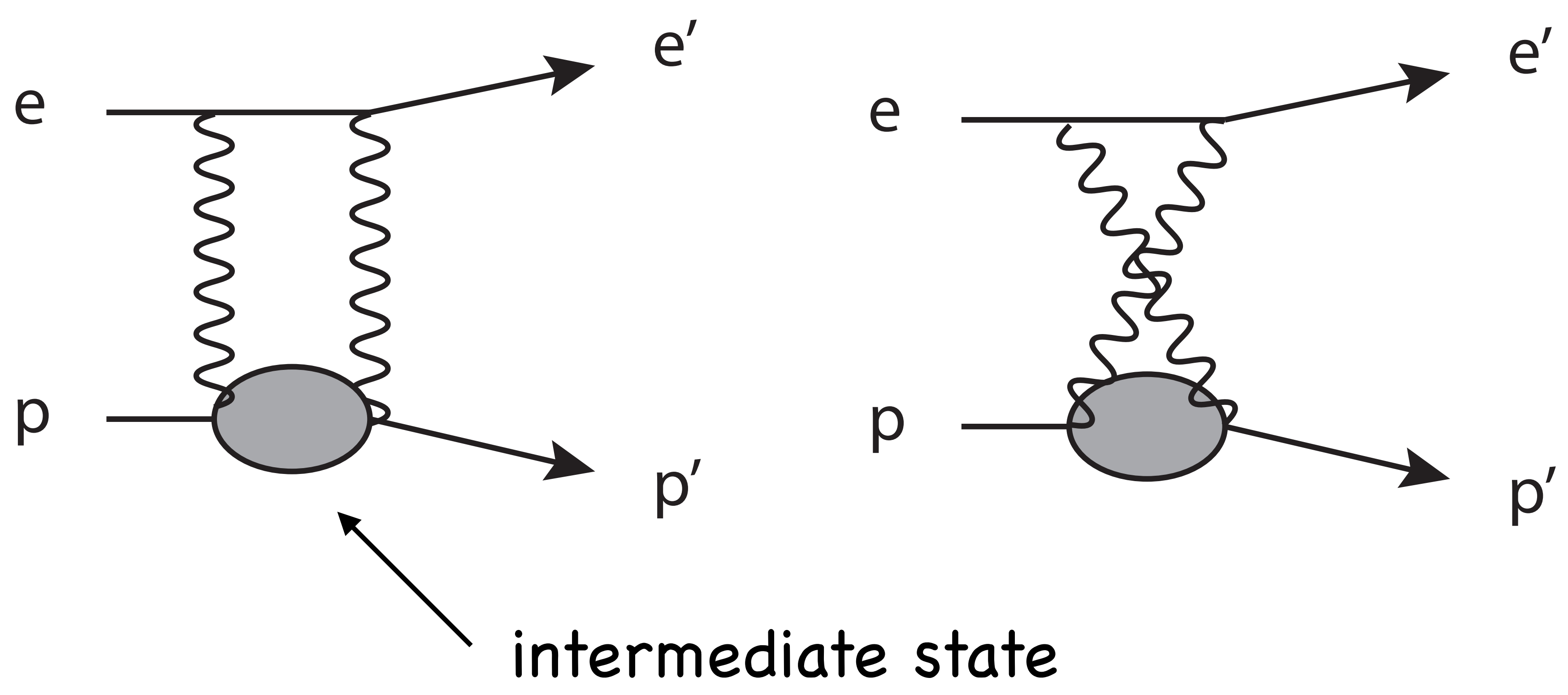
$$(1+\delta) \rightarrow e^{\delta}$$

Recent work include calculations beyond the peaking approximation and also include the lepton mass.

Yung-Su Tsai, Phys. Rev. **122**, 1898 (1961); O. Koshchii and A. Afanasev Phys. Rev. D 96, 016005 (2017), P. Talukdar, F. Myhrer, G. Meher. R. Udit. Eur. Phys. J. A (2018) 54: 195.

Two-photon exchange effects are important

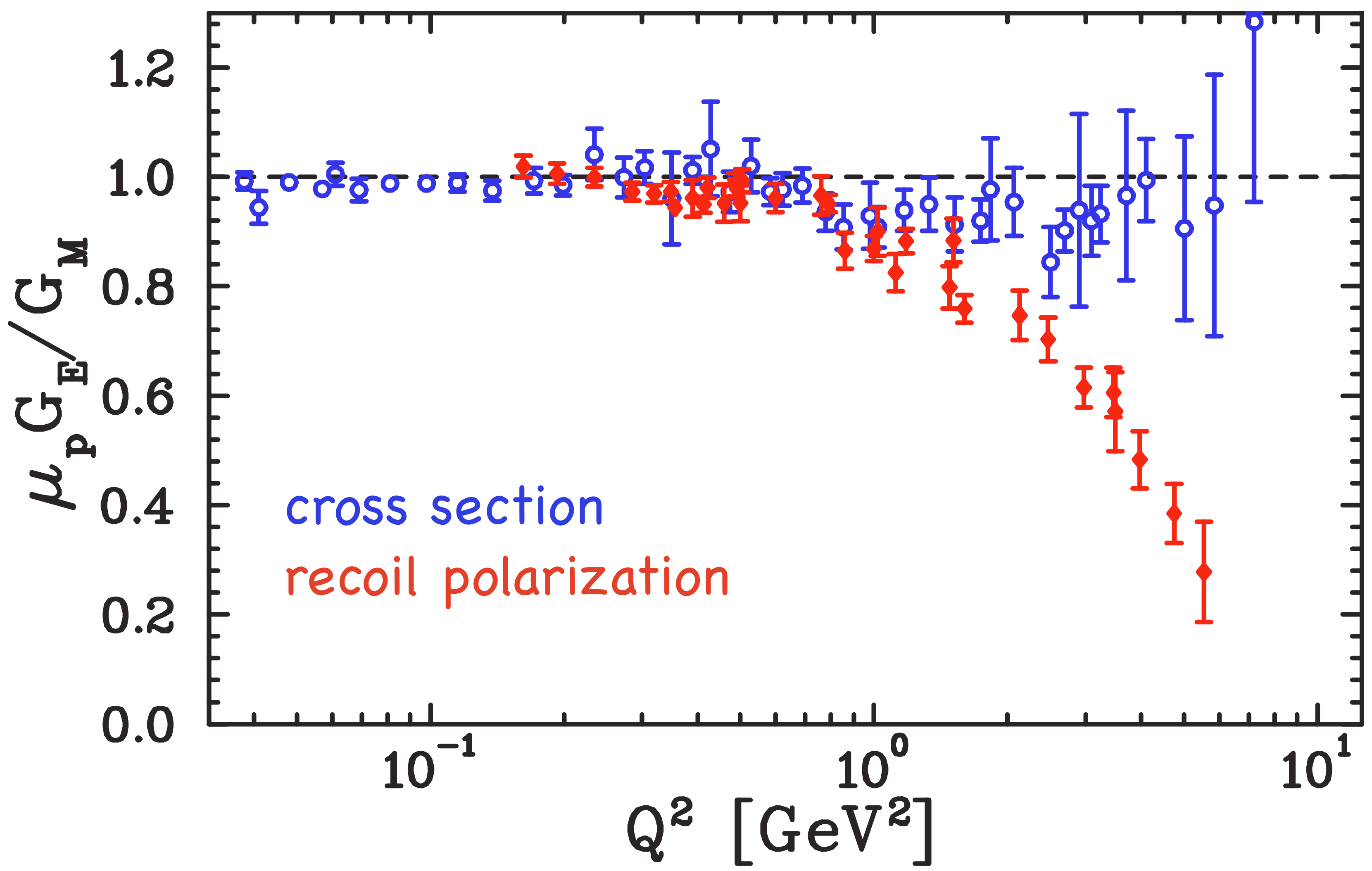
Two-photon exchange terms



The intermediate state can be an unexcited proton, a baryon resonance or a continuum of hadrons.

Two-photon effect expected to be small (< 1%) at low energies but are important for radius determination (move extracted radius **up** by 0.01 - 0.02 fm).

Properly included TPE calculations include Coulomb corrections (otherwise double counting). (A. Afanasev priv. communication)



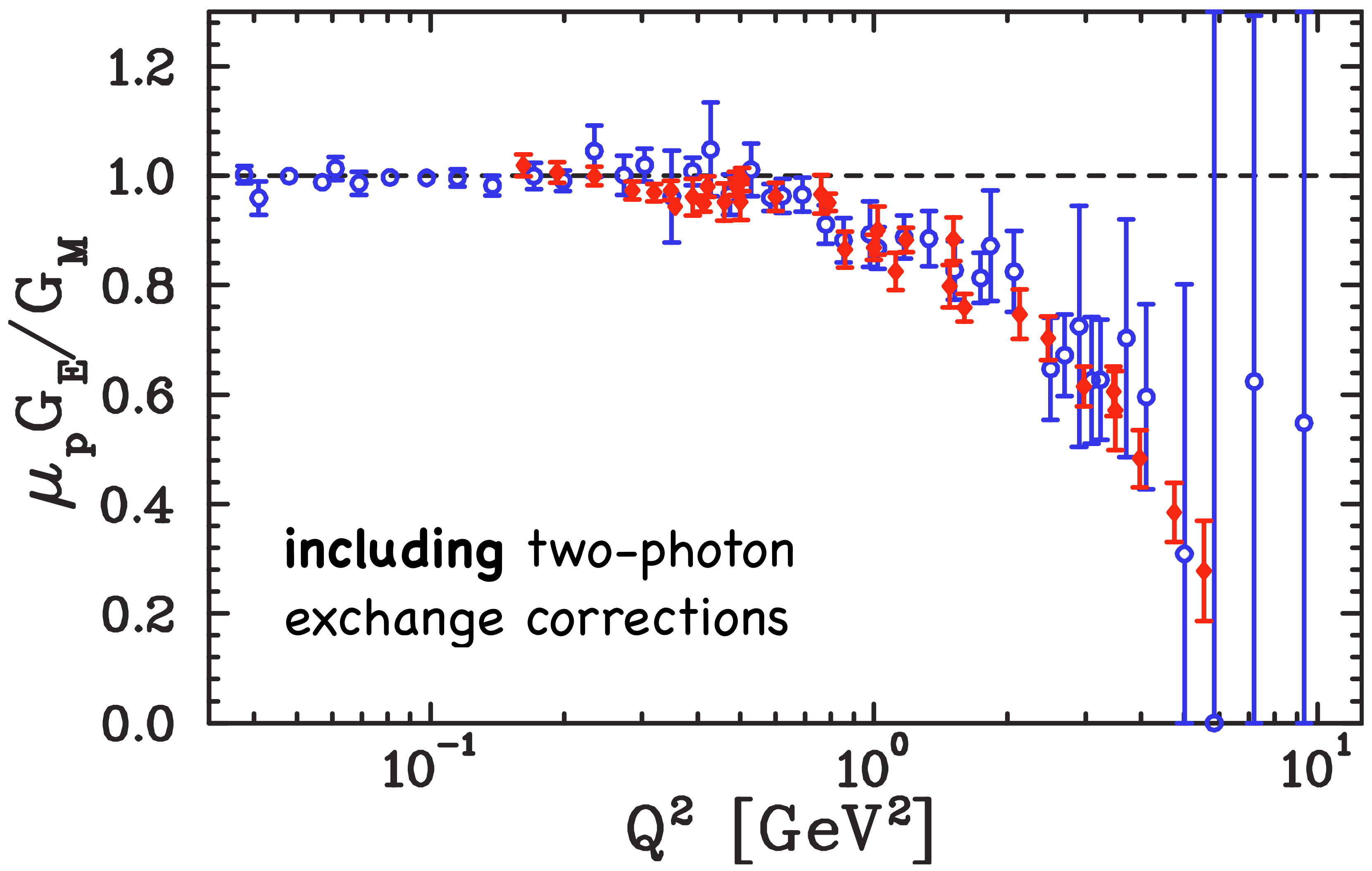
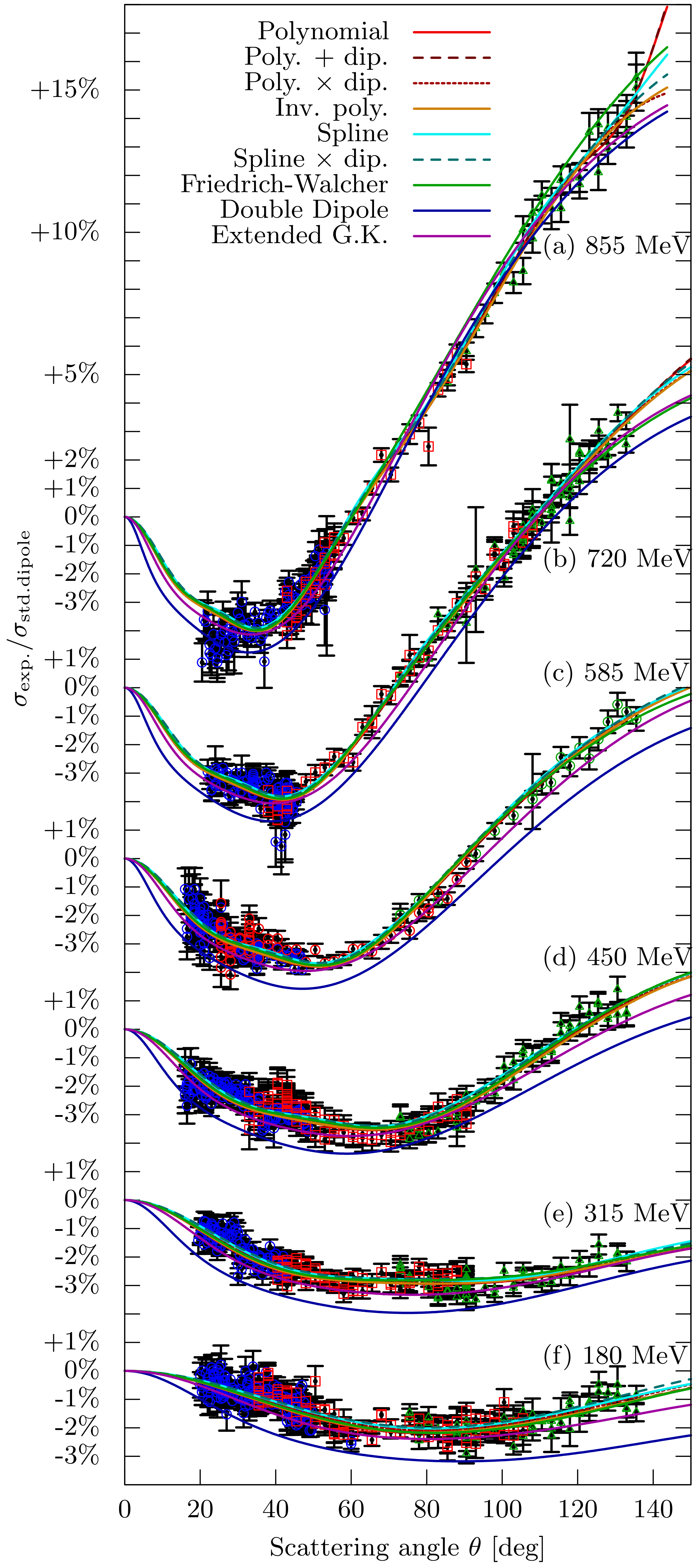


Figure from: J. Arrington, W. Melnitchouk, and J. A. Tjon, Phys. Rev. C **76**, 035205 (2007)



A1 MAMI: Most substantial elastic electron-scattering data set

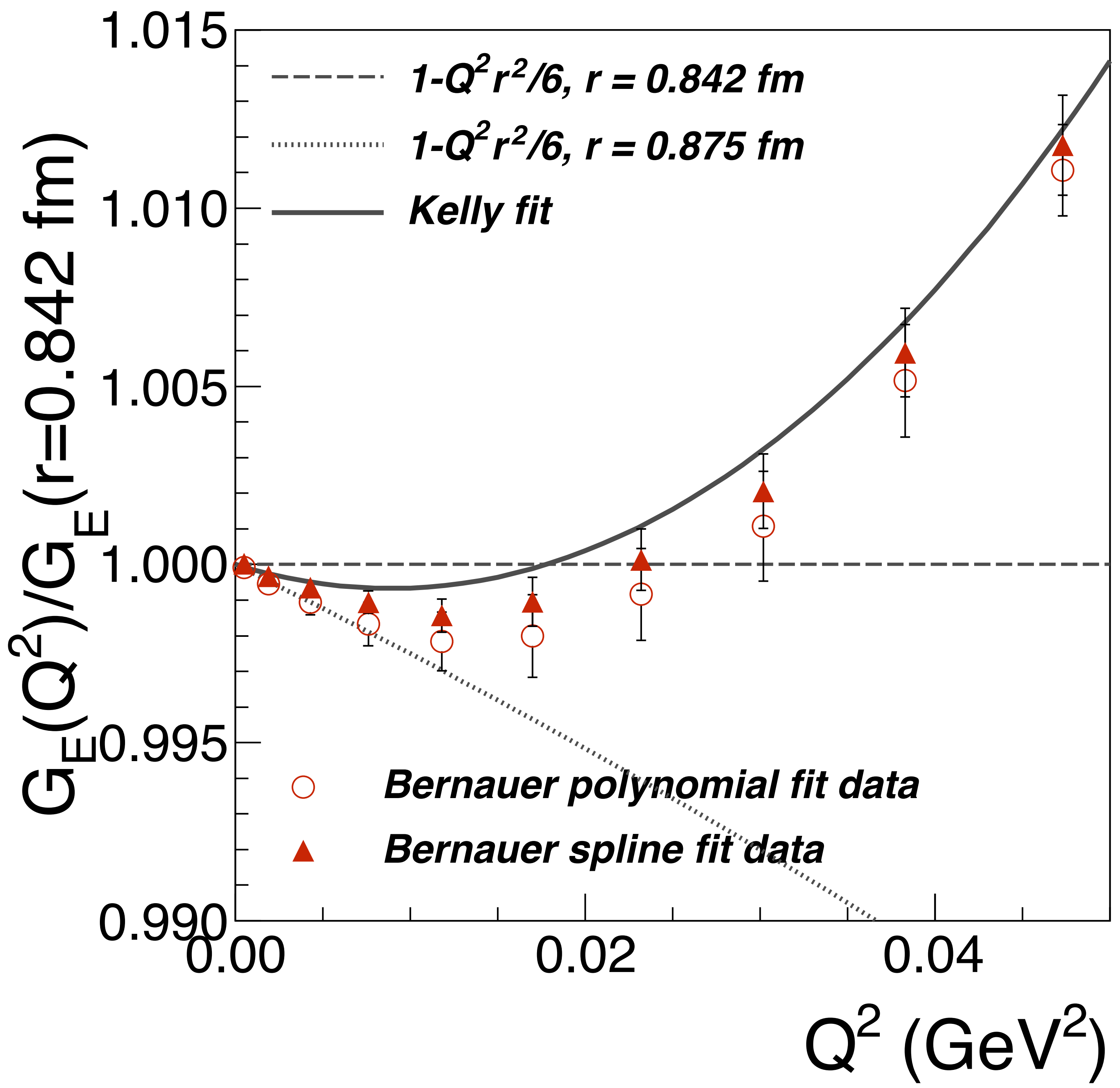
- 1,422 cross sections data points with a statistical uncertainties below 0.2%.
- Fit of a large variety of form factor models to the data: $G_E(Q^2)$, $G_M(Q^2)$ and 31 normalization constants
- Q^2 = 0.003 (GeV/c)^2 to 1 (GeV/c)^2

$\boxed{r_p = 0.879(8) \text{ fm}}$

J. Bernauer et al., PRL **105**, 242001 (2010),
J. Bernauer et al., PRC **90**, 015206 (2014)

Terms beyond the linear term become quickly important

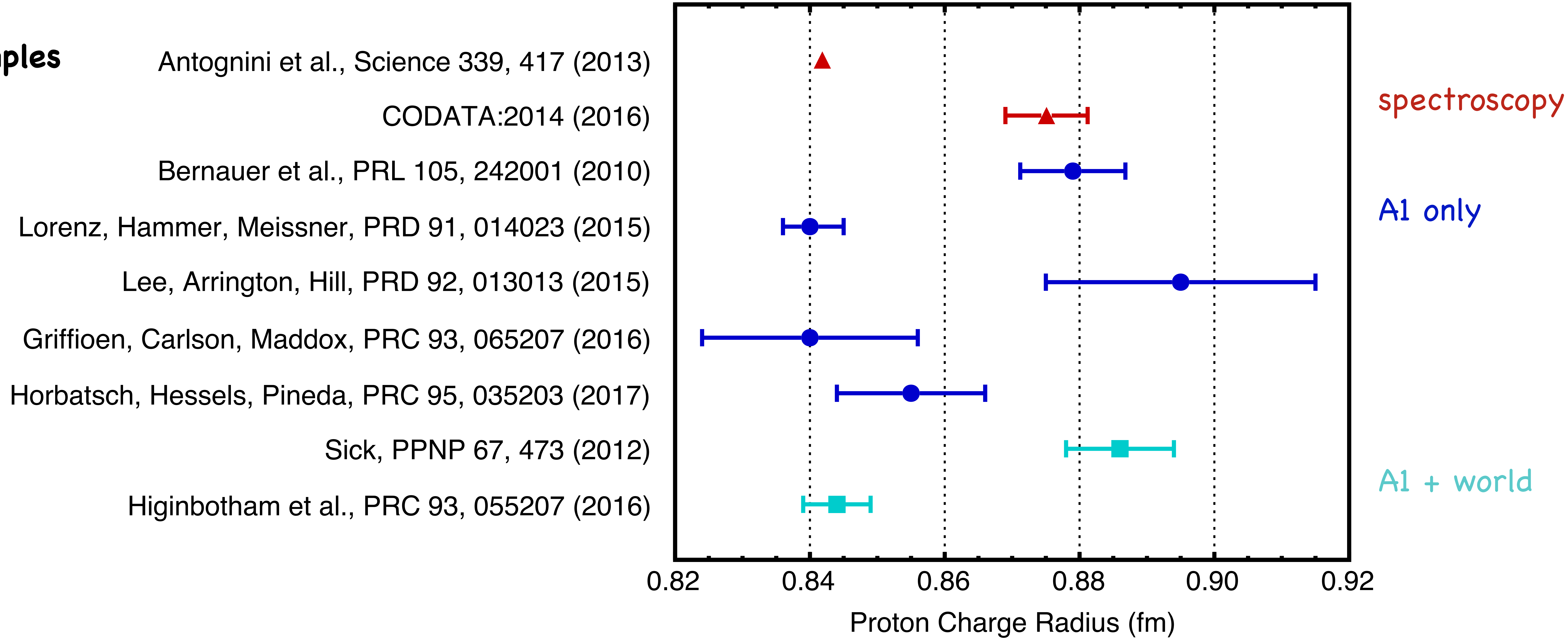
$$G_E = 1 - Q^2 r_p^2/6 + Q^4 r_p^4/120 + \ldots$$



MUSE TDR arXiv:1709.09753 [physics.ins-det]

Controversial proton-radius results from available data

Examples

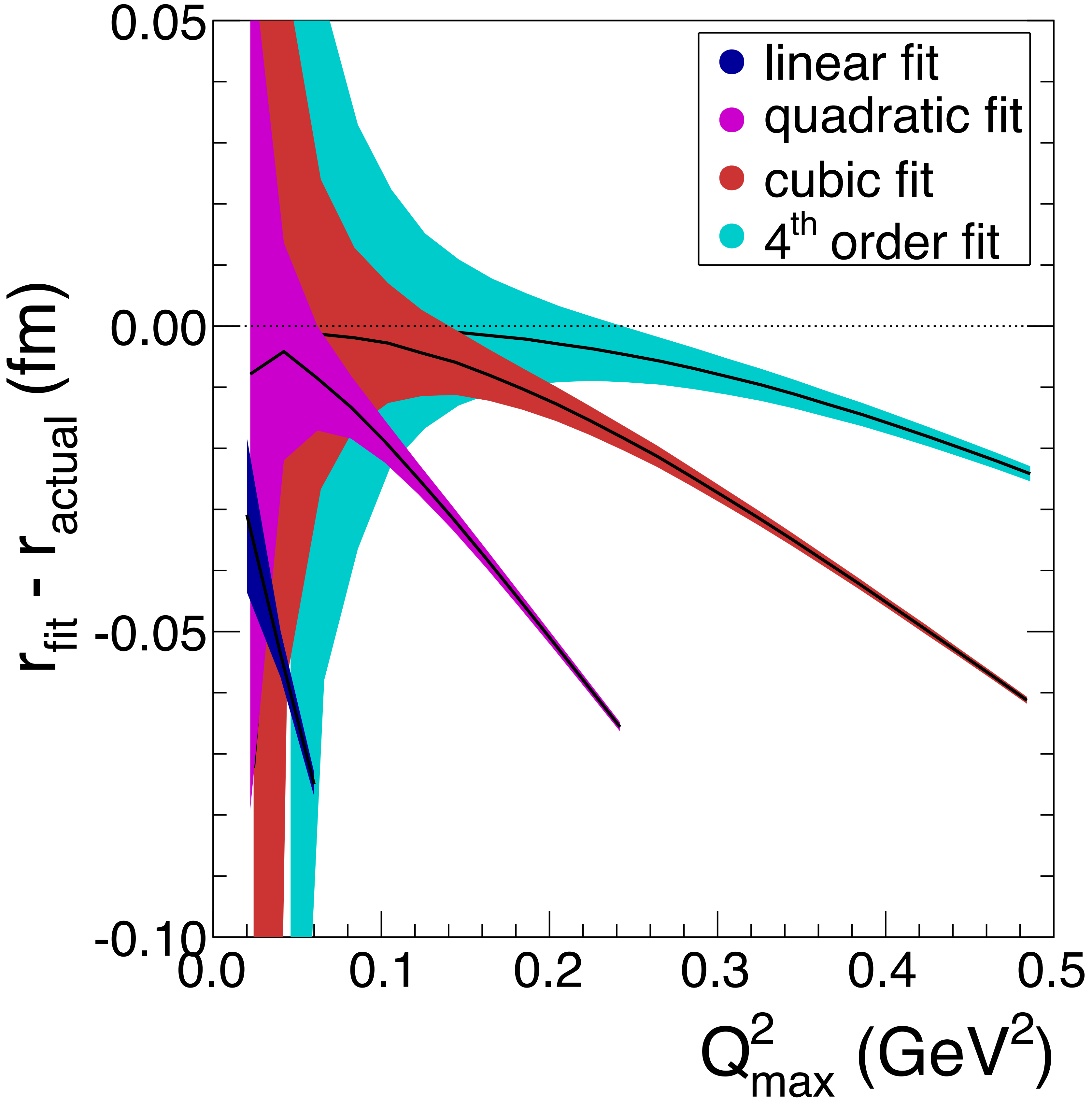


Analyses are critically discussed and no consensus has been reached, yet.

Extracting r_p requires the determination of the slope of an extrapolated function.

Polynomial fits are unreliable for an extrapolation of the form factor to $Q^2 = 0$

Analysis of pseudo data



For the proton: higher-order terms exist and are large.

$$G_E(Q^2) = 1 - \frac{r_p^2\, Q^2}{6\,\hbar^2} + \frac{r_p^4\, Q^4}{120\,\hbar^4} - \ldots$$

Study of truncation error with simulated data:

- The smaller Q^2_{max} the larger the statistical uncertainty.
- The larger Q^2_{max} the larger the truncation error.
- For all realistic form factor parameterizations, the truncation error is negative!
- A polynomial fit with a $\chi^2/\text{dof} \approx 1$ is not a sufficient indication for a reliable result.

E. Kraus, K.E. Mesick, A. White, R. Gilman, and S.S., Phys. Rev. C **90**, 045206 (2014).

The challenges extracting r_p from electron-scattering data

Sick (atoms): "The problem lies in the model dependence of the parameterized G(q) needed for the extrapolation."

Simplified model*: In the non-relativistic limit, the charge density is related to the electric form factor

$$G_E(q) = \frac{4\pi}{q}\int_0^\infty \rho(r)\sin(qr)\,r\,dr$$

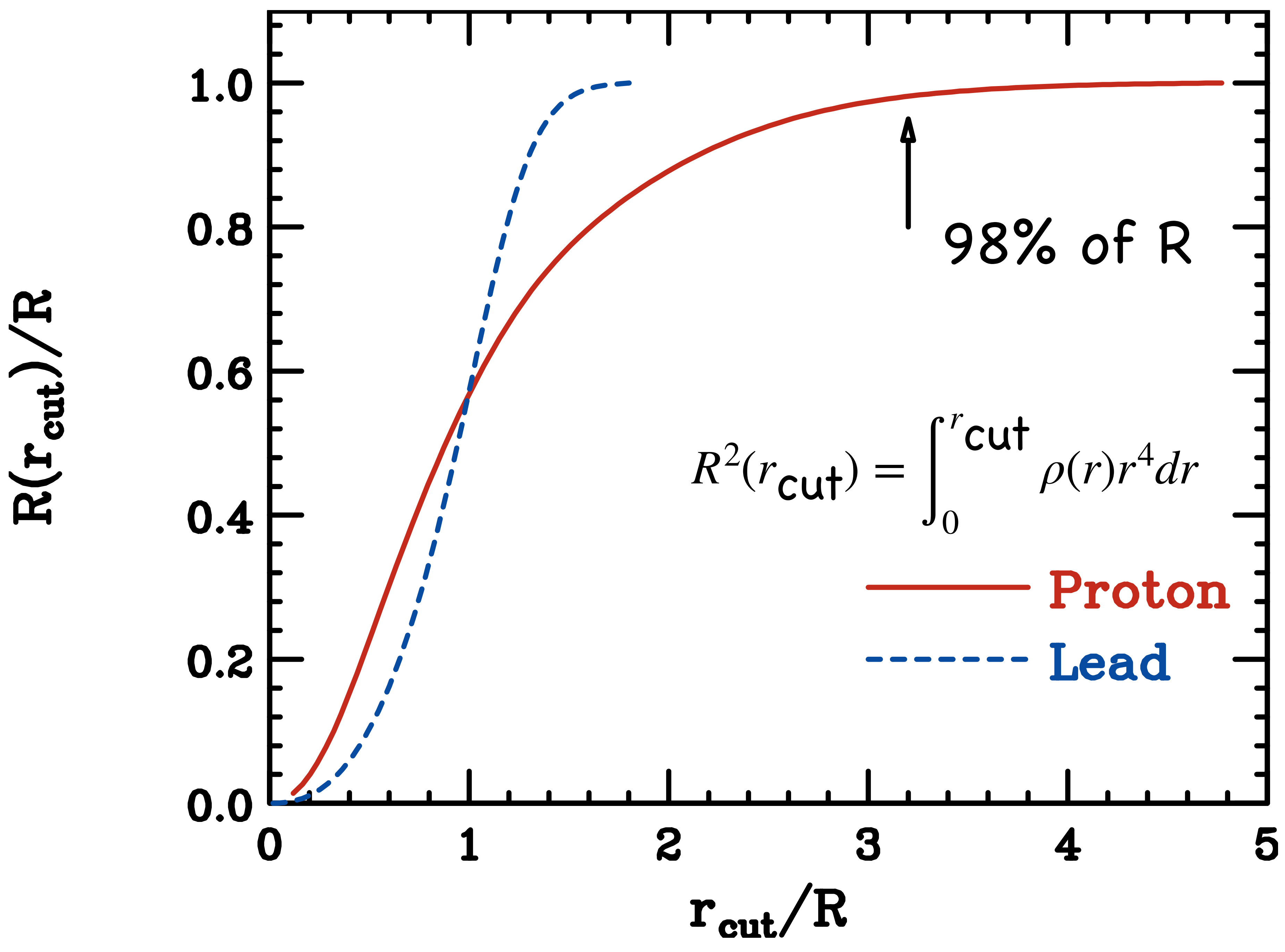
Some G(q) parameterizations result in unphysical charge densities ρ(r).

Sick and D. Trautmann, PRC **89**, 012201(R) (2014).
*) for a proper treatment of the nucleon charge distribution, see, e.g., G. Miller PRL **99**, 112001 (2007)

Similarly: enforcement of a realistic spectral function

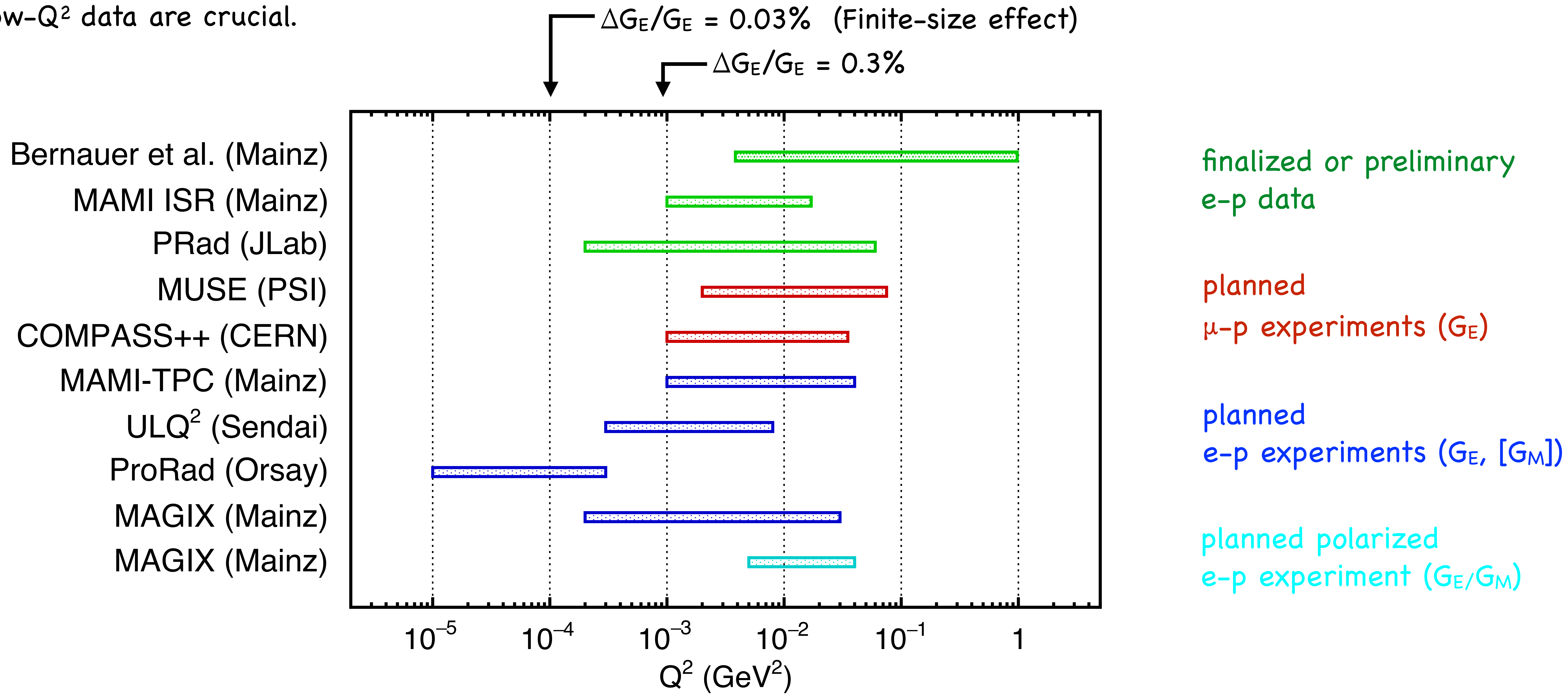
I. T. Lorenz, Ulf-G. Meißner, H.-W. Hammer, and Y.-B. Dong, PRD **91**, 014023 (2015).

The charge density at large values of r contribute to the RMS value of the proton radius.



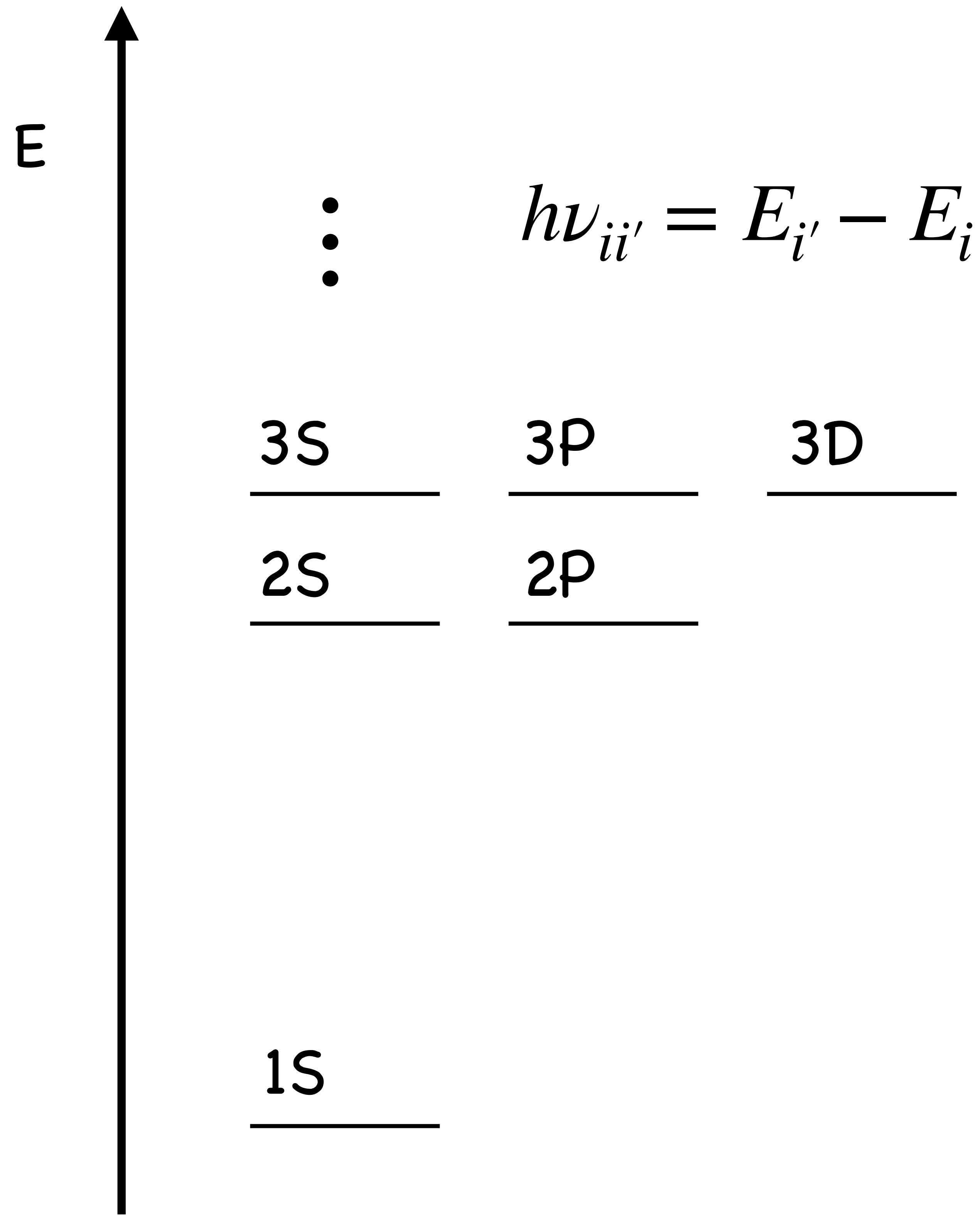
The quest for low Q^2 data: will the sensitivity be sufficient?

Low-Q^2 data are crucial.



Hydrogen Spectroscopy

L. Maisenbacher, Proton Radius Workshop, Mainz, 2018



$$h\nu_{ii'} = E_{i'} - E_i$$

$$E_{nlj} \approx hcR_\infty \left(-\frac{m_{red}}{m_e} \frac{1}{n^2} + f_{nlj}(\alpha, \frac{m_e}{m_p}, \ldots) + \delta_{l0} \frac{C_{NS}}{n^3} r_p^2 \right)$$

Bohr $\gg$ QED Corrections $\gg$ Finite size

Rydberg constant	Parameters	Proton charge radius
Determined from H spectroscopy	measured independently	Determined from H spectroscopy

Finite Size effect

$$\Delta E_{\text{finite size}} = \frac{2\pi\alpha}{3} r_p^2 \left|\psi(0)\right|^2$$

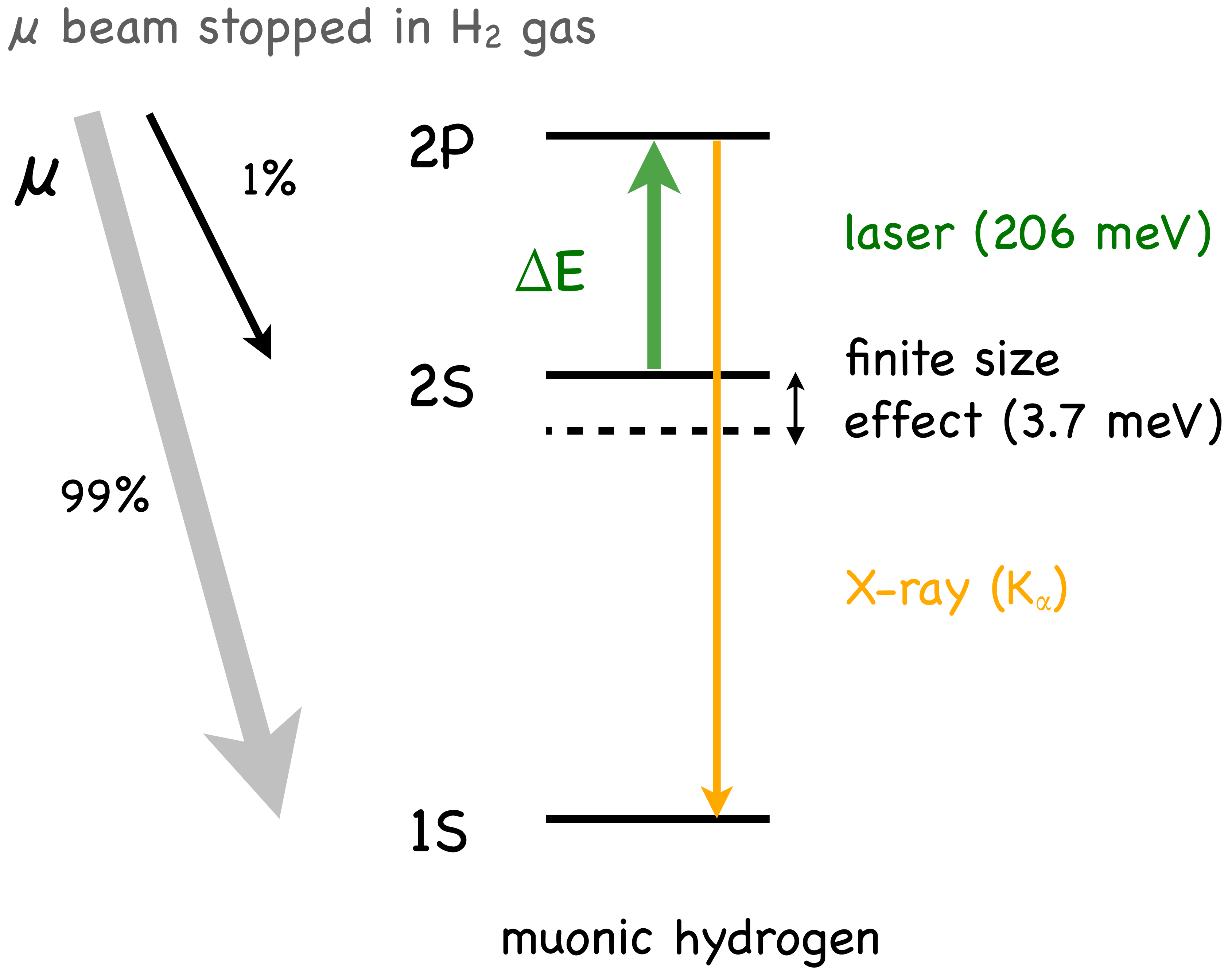
$\left|\psi(0)\right|^2 \propto m_\ell^3$ for S shell

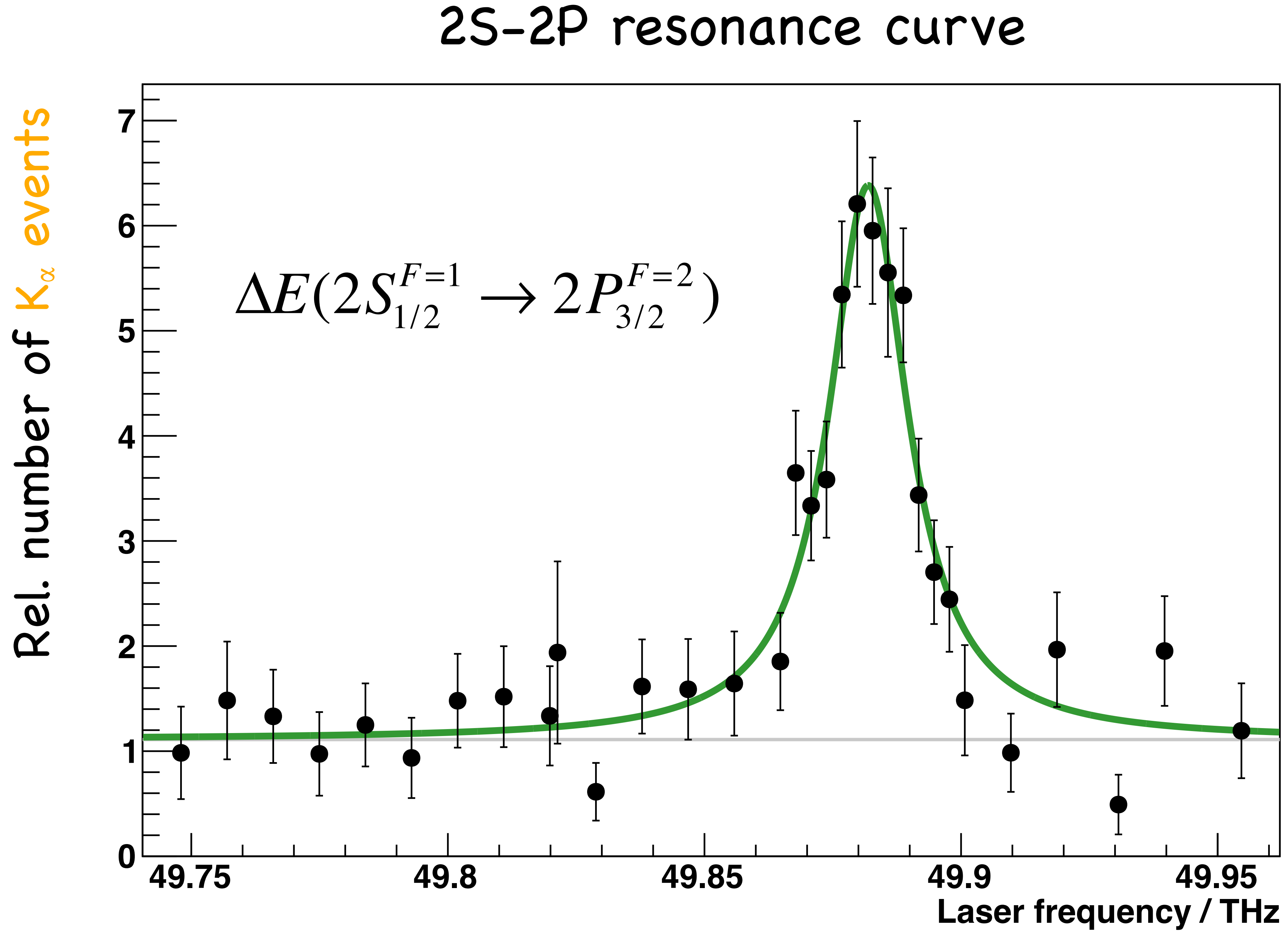
$\left|\psi(0)\right|^2 \approx 0$ for other shells

Muonic hydrogen is 8 x 10^6 more sensitive to r^2_p than electronic hydrogen

A. Antognini et al., Science **339**, 417 (2013)

Spectroscopy of muonic hydrogen 2S-2P





Lamb shift

$$\Delta E = 209.9779(49) - 5.2262 r_p^2 + 0.0347 r_p^3 \text{ meV}$$

r_p = 0.84184(67) fm

R. Pohl et al., Nature **466**, 213 (2010)

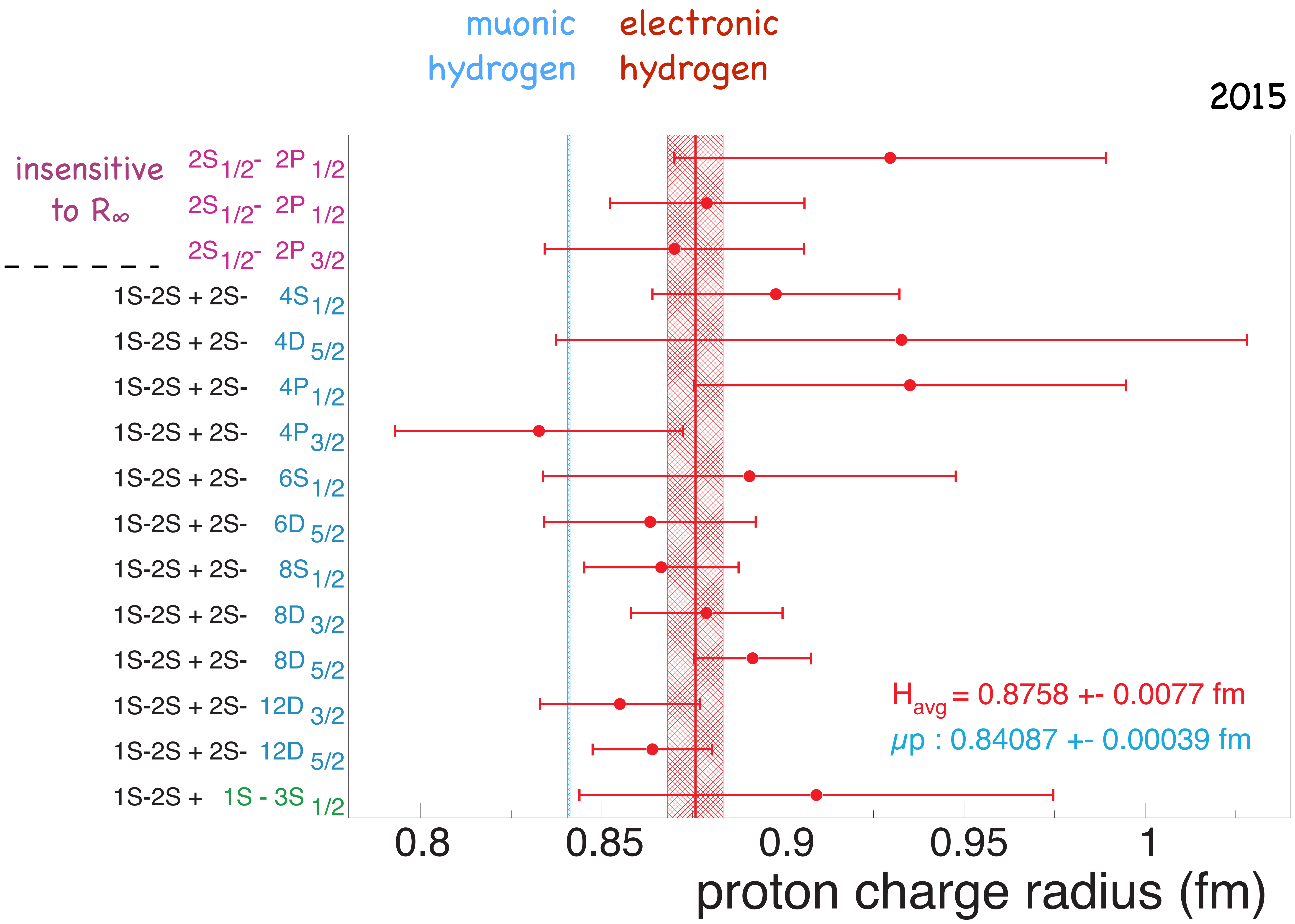
r_p = 0.84087(39) fm

A. Antognini et al., Science **339**, 417 (2013)

Determine r_p from spectroscopic data and QED calculations

R. Pohl et al., Nature **466**, 213 (2010); Fig. adapted from Pohl, Miller, Gilman, Pachucki, Annu. Rev. Nucl. Part. Sci. 63, 175 (2013).

Larger proton charge radius from hydrogen level-splitting measurements



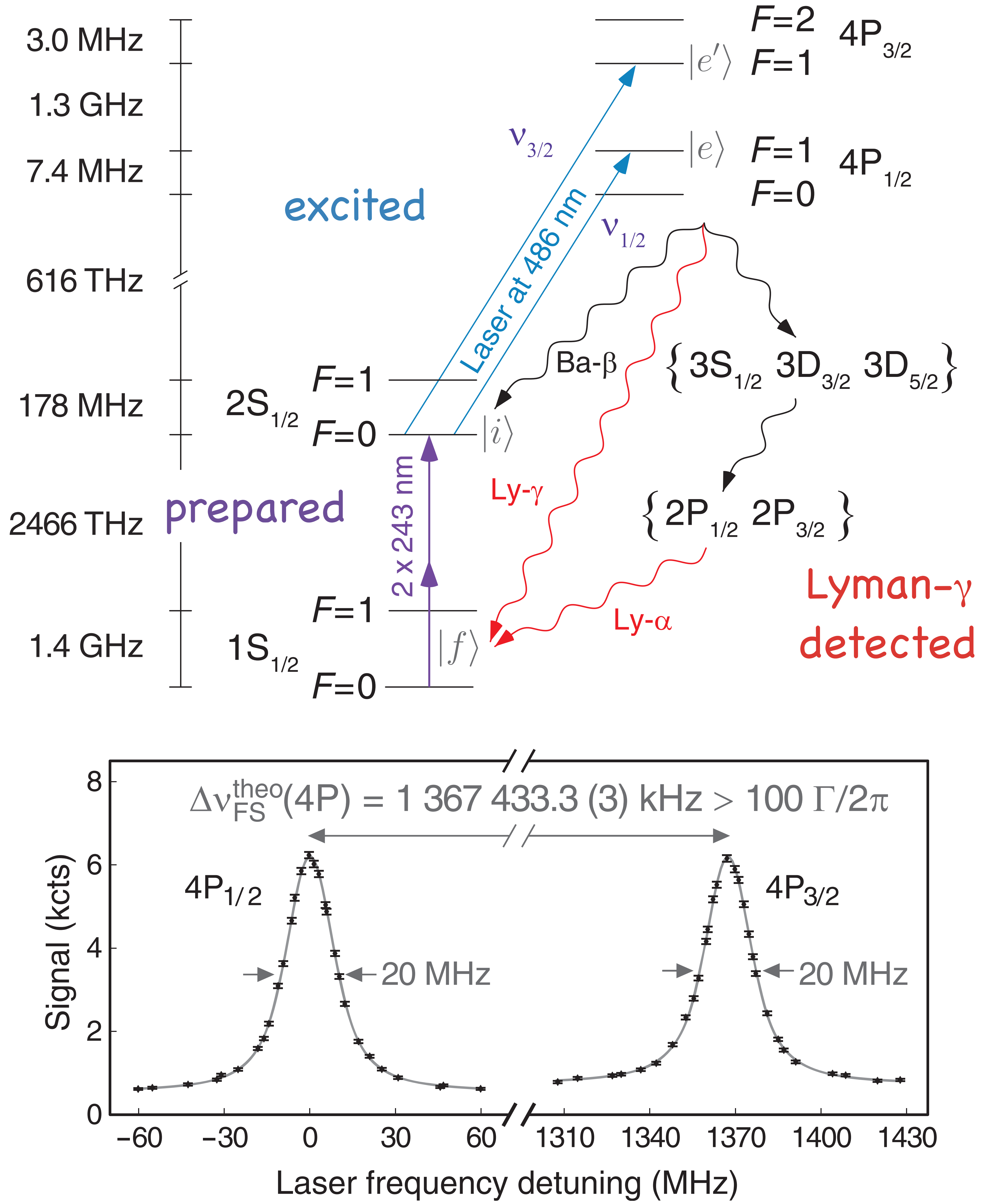
$$\Delta E = aR_\infty + br_p^2$$

- Determination of R_∞ and r_p requires two measurements in H:
  - 1S-2S (relative accuracy of 4×10^{-15})
  - 2S-nl
- μH and eH difference is only significant when results are averaged.
- Common systematic uncertainties?

Systematic effect would amount to only a tiny fraction of 10^{-3} of the line width.

Pohl, Miller, Gilman, Pachucki, Annu. Rev. Nucl. Part. Sci. **63**, 175 (2013), C. Carlson, Prog. Part. Nucl. Phys. **82**, 59 (2015).

New Garching results: The Rydberg constant and proton size from atomic hydrogen



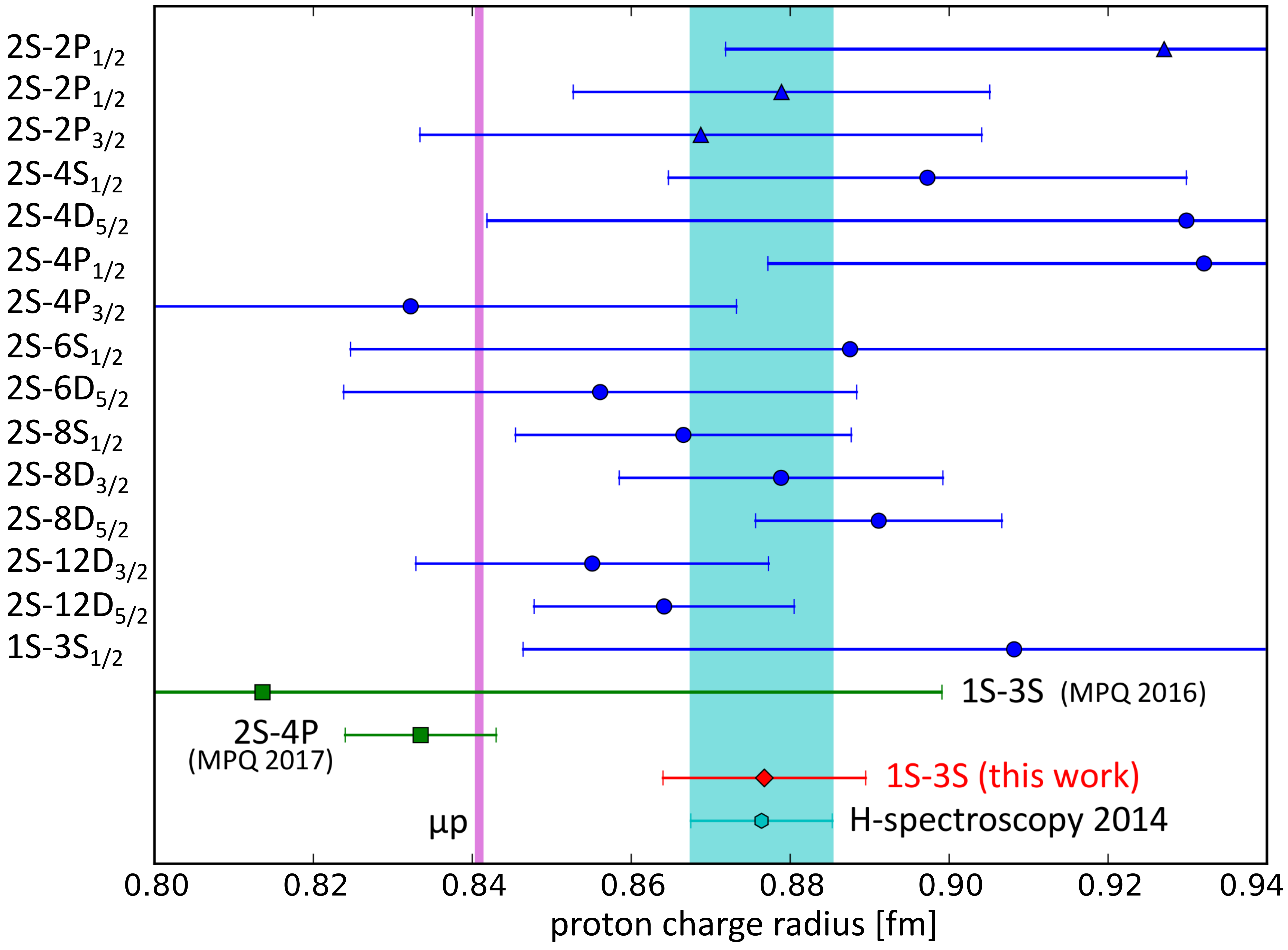
- Using a cryogenic beam of H atoms
- Uncertainty dominated by Doppler shift, which is measured in-situ
- Measurement of 2S-4P transition frequency in H
- Combined with the precisely measured 1S–2S transition frequency
- Result

$\boxed{r_p = 0.8335(95)\ \text{fm}}$

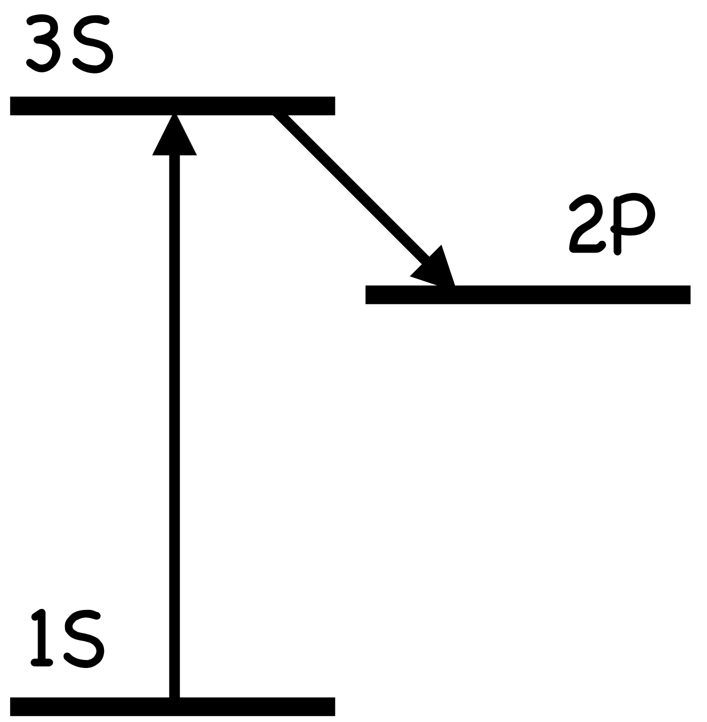
is 3.3 combined standard deviations smaller than the previous H world data, but in good agreement with the μp value.

A. Beyer et al., Science 358, 79 (2017).

New Paris Measurement of the 1S–3S Transition Frequency of Hydrogen: Contribution to the Proton Charge Radius Puzzle



1S-3S two-photon hydrogen transition frequency



Detection through Balmer-α fluorescence

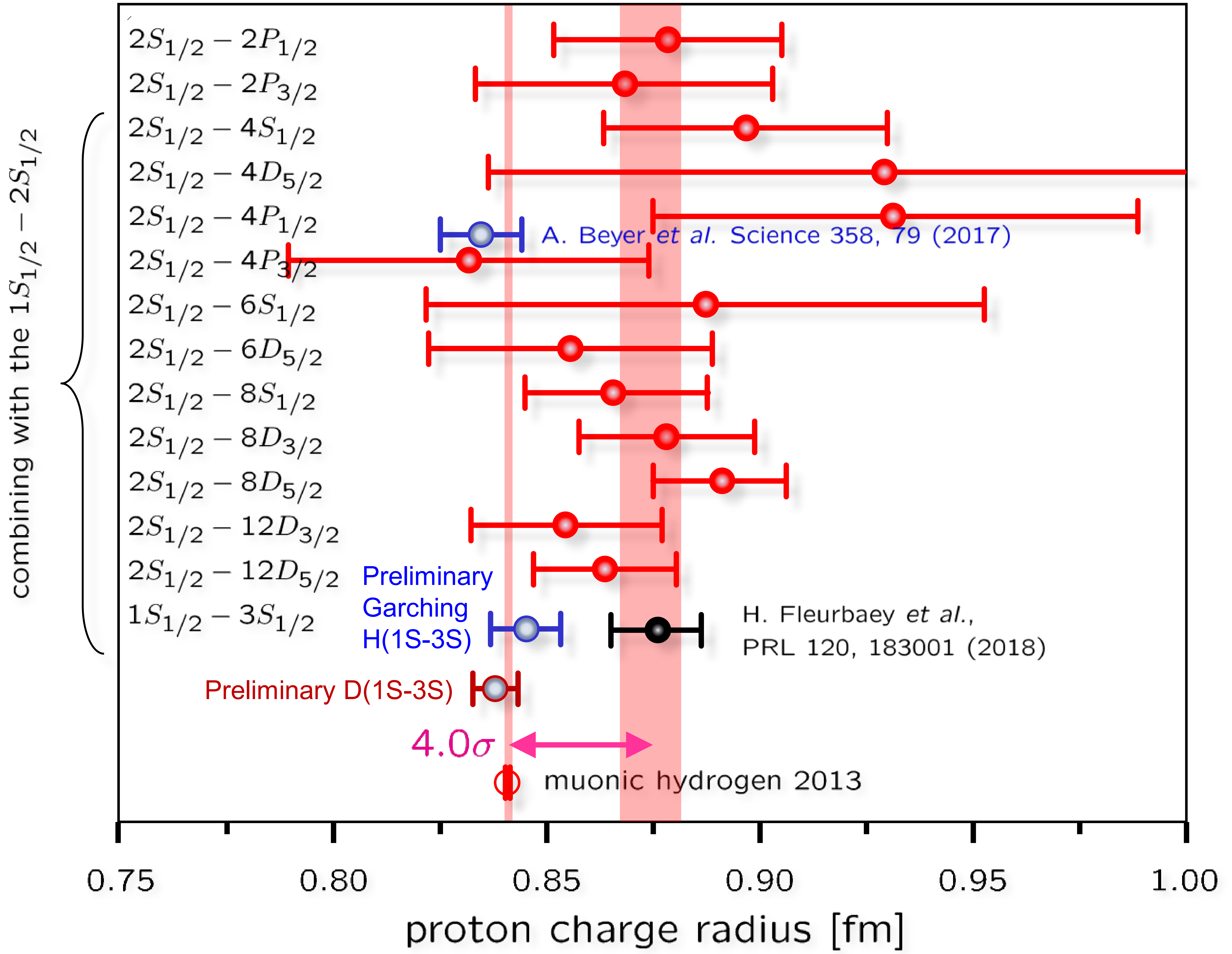
r_p = 0.877(13) fm

- Result in very good agreement with the current CODATA-recommended value
- Ongoing work:
  - cooled H beam to reduce the second-order Doppler shift
  - 1S–3S transition in deuterium
  - entirely new effusive beam

H. Fleurbaey et al., PRL 120, 183001 (2018); S. Thomas et al., Ann. Phys. (Berlin) 531, 1800363 (2019)

Preliminary Garching H/D(1S-3S) results

- Preliminary **H(1S-3S)** and **D(1S-3S)** r_p results from Garching are consistent with μH result. (PSAS2018)
- Different systematic effects of the Garching **H(1S-3S)** and Paris **H(1S-3S)** measurements
- Known systematic effects much too small to explain the difference between presented result and CODATA value.
- Also the preliminary H(2S-2P) result (E. Hessels, Toronto, 2018) for r_p is consistent with the μH result.



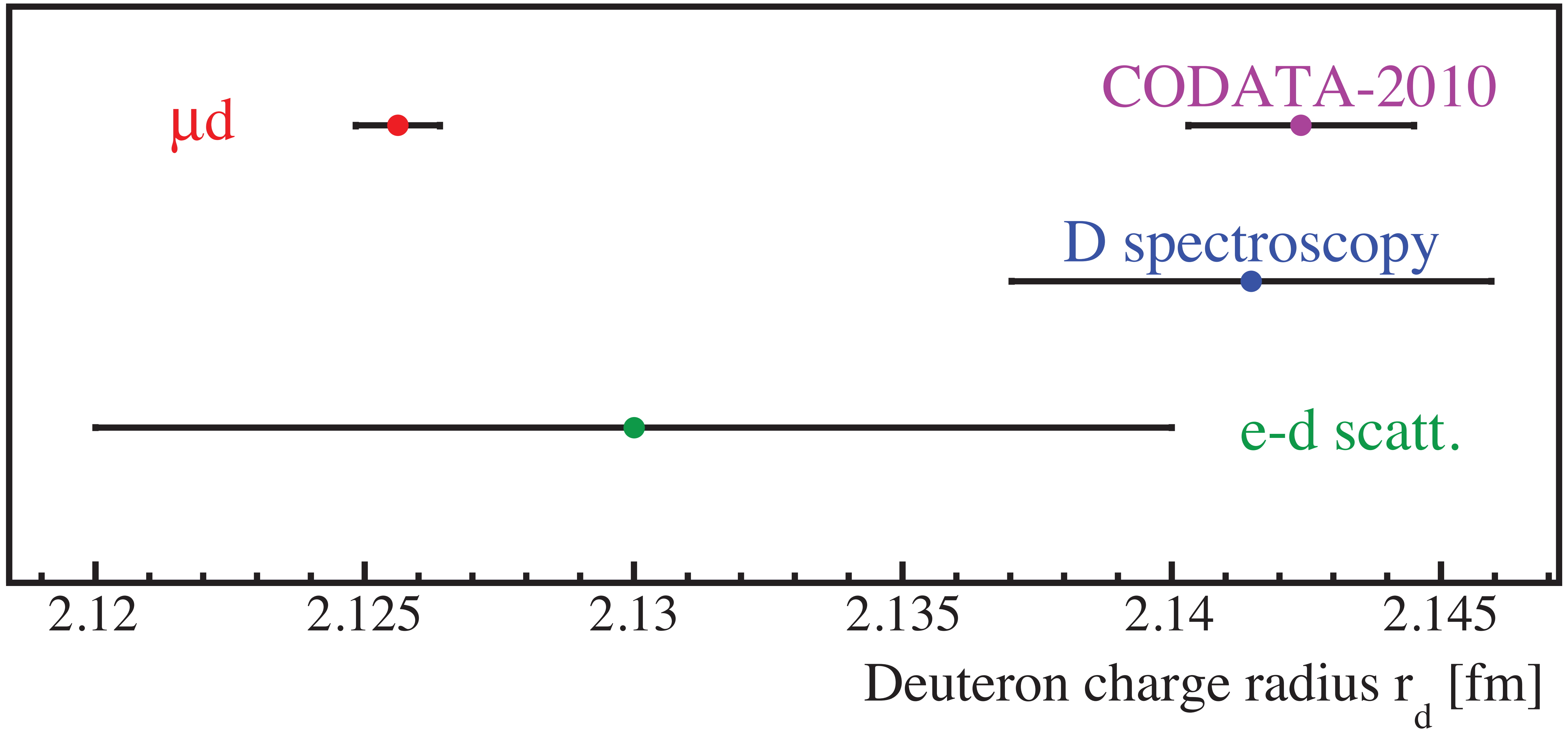
A. Matveev et al., talk at the "Precision Measurements and Fundamental Physics; The Proton Radius Puzzle and Beyond" workshop, Mainz, July 2018.

Laser spectroscopy of muonic deuterium: The deuteron is consistently smaller

μd: R. Pohl et al., Science **353**, 669 (2016);
μ^4He: A. Antognini et al., talk at the "Precision Measurements and Fundamental Physics; The Proton Radius Puzzle and Beyond" workshop, Mainz, July 2018.

The CREMA collaboration measured three 2S-2P transitions in µd

r_d = 2.12562(78) fm



7.5σ smaller than the CODATA-2010 value (CODATA contains proton data).

3.5σ smaller than the r_d value from electronic deuterium spectroscopy.

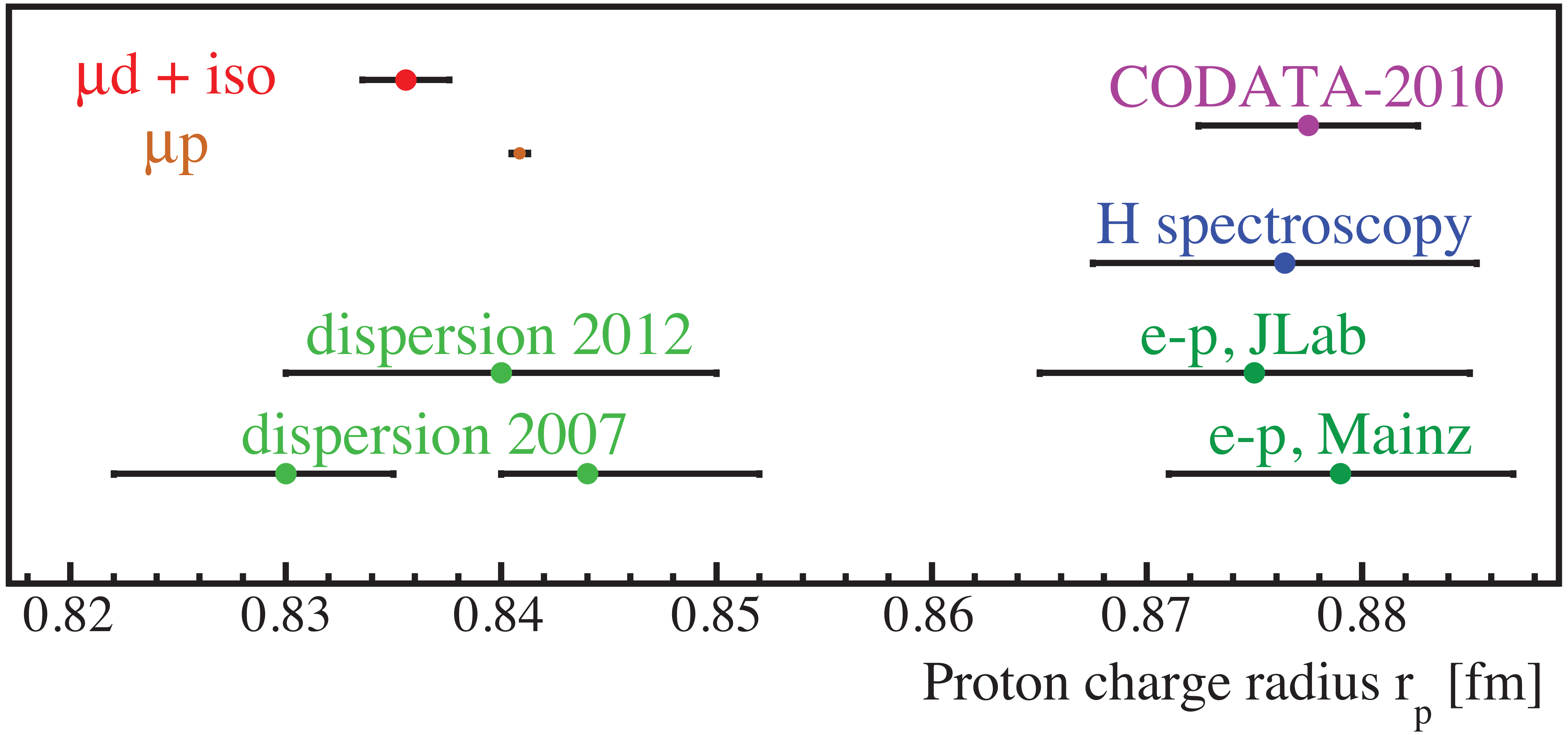
μd and preliminary μ^4He^+ spectroscopy results in excellent agreement with electron-scattering results

Deuteron data amplify the proton-radius puzzle

Using the measured muonic deuteron charge radius and the electronic isotope shift, $r_d^2 - r_p^2 = 3.82007(65)\ \mathrm{fm}^2$, a new value for the proton radius

$$\boxed{r_p(\mu d + \mathrm{iso}) = 0.8356(20)\ \mathrm{fm}}$$

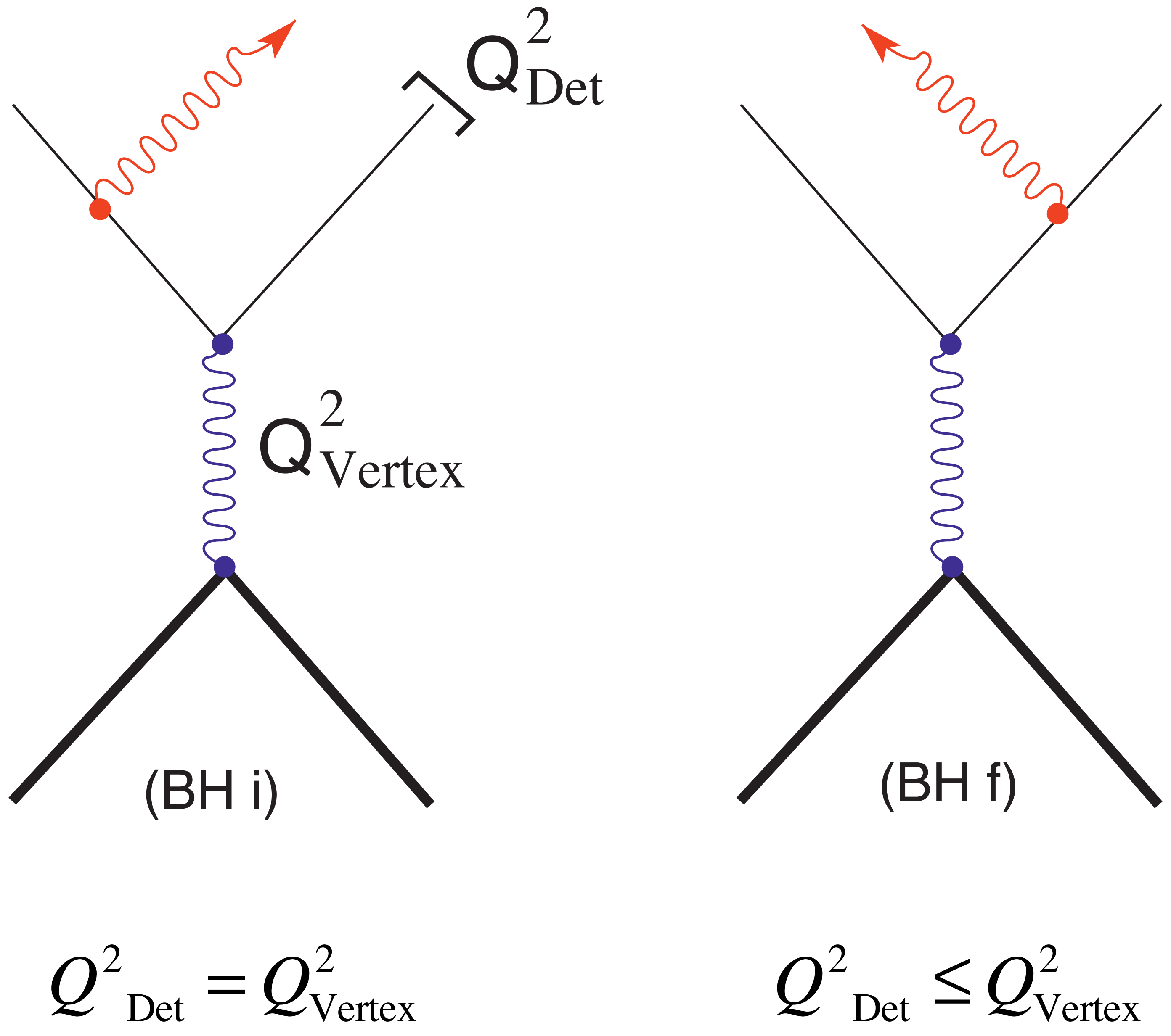
- Results from μd + iso and μp are consistent within 2.5σ
- Small value of the proton radius is confirmed from μd

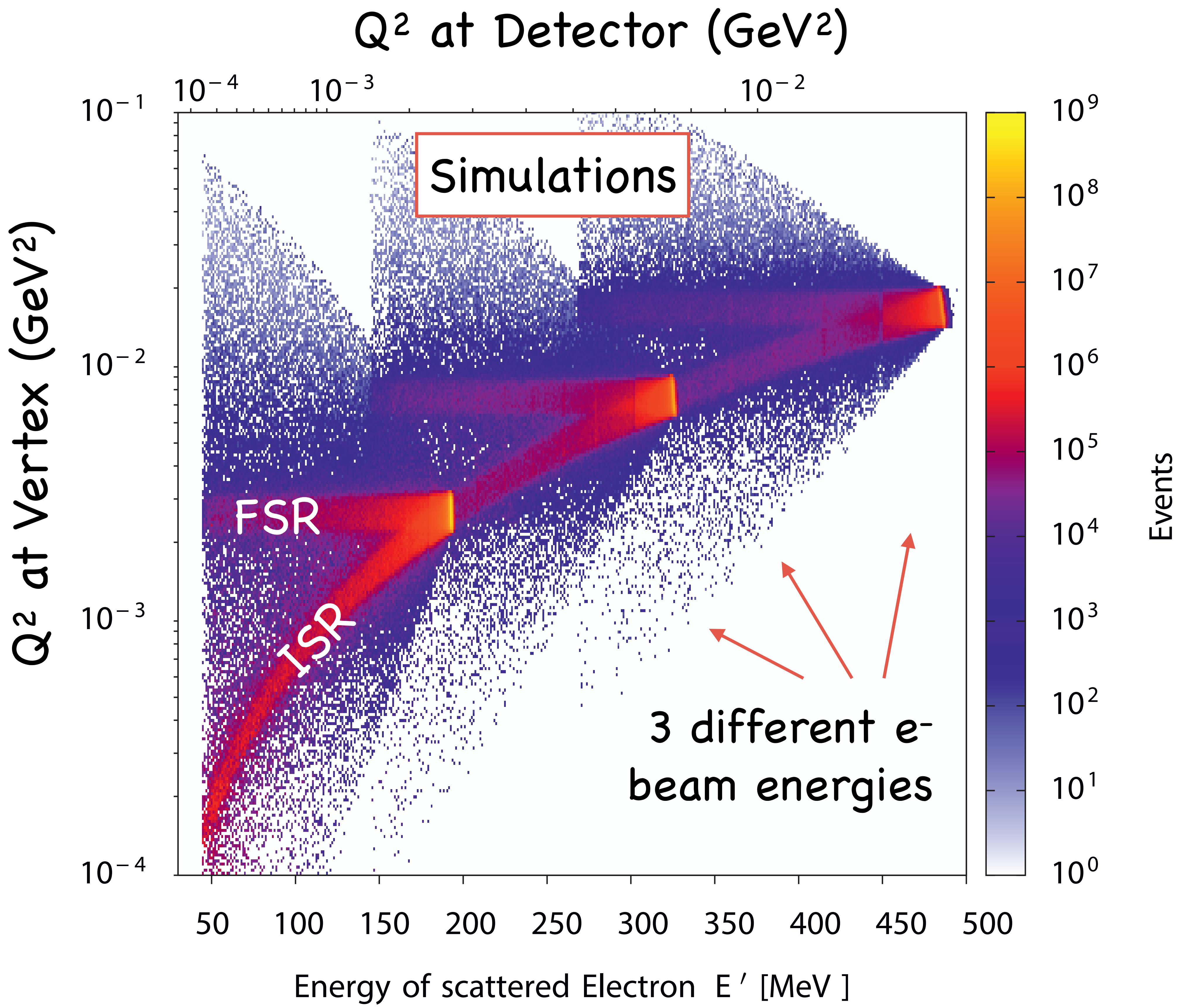


R. Pohl et al., Science **353**, 669 (2016)

MAMI Initial-State Radiation in elastic electron-proton scattering

Radiative tail dominated by coherent sum of two Bethe-Heitler diagrams

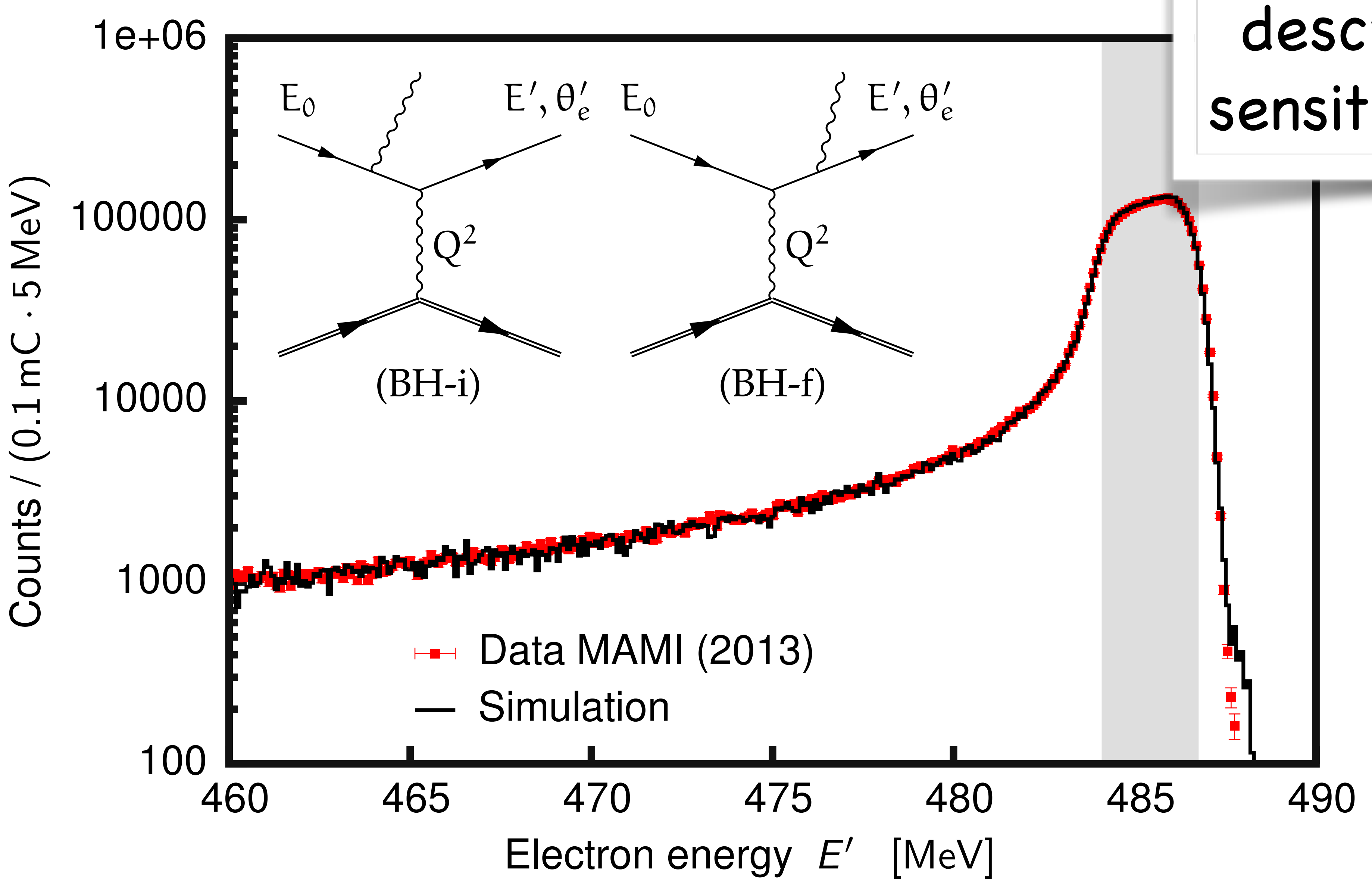




- Only Q^2_{Det} can be measured.
- In data, ISR can not be distinguished from FSR
- Combining data and simulation, ISR and form factor can be extracted
- Experiment aimed to extract G_{Ep} in the range $10^{-4} \leq Q^2 \leq 0.005\ (GeV/c)^2$

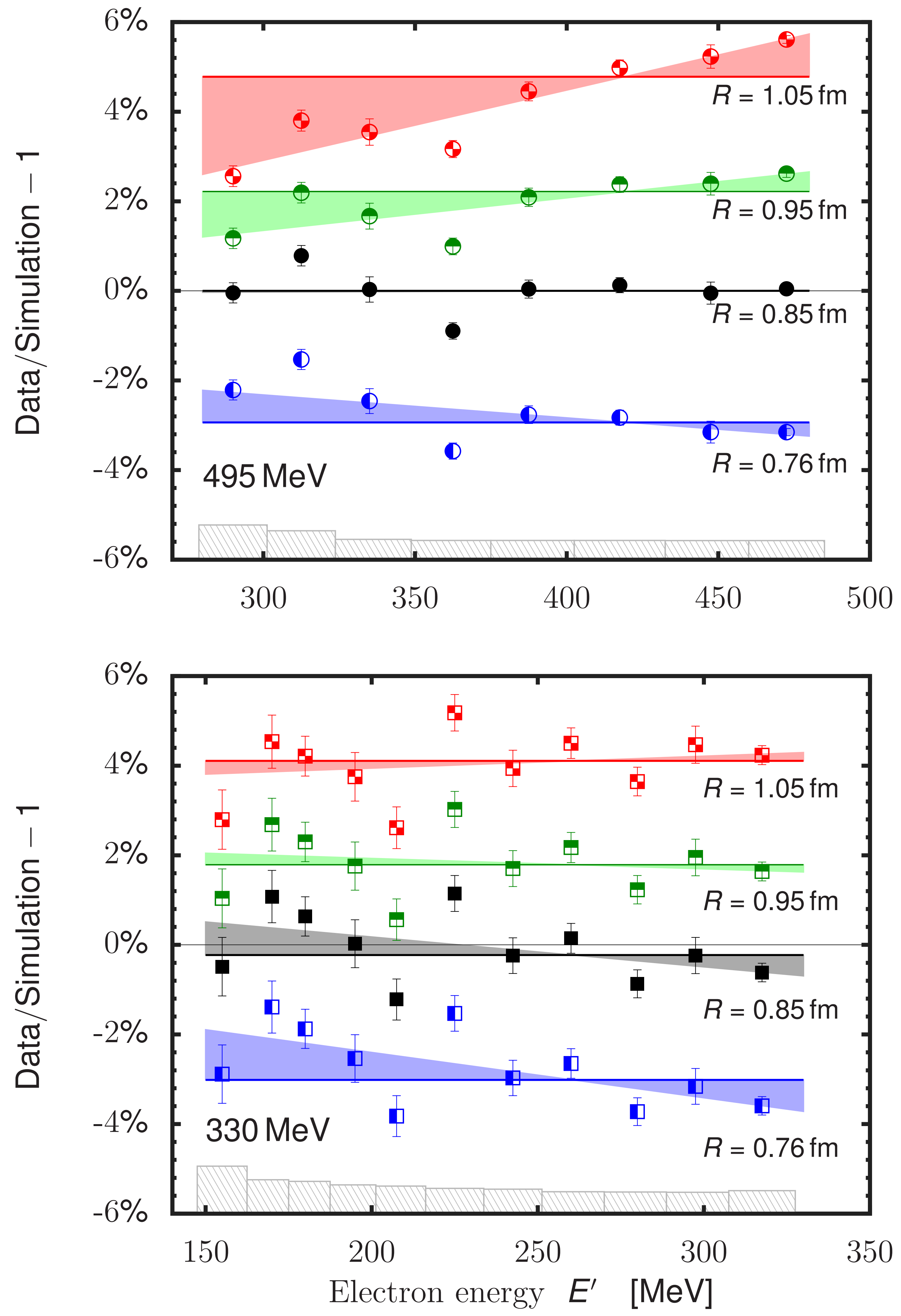
M. Mihovilovič et al., EPJ Web of Conferences 72, 00017 (2014)

MAMI Initial-State Radiation in elastic electron-proton scattering



description of the radiative tail sensitive (via G_E) to proton radius.

Relative differences between the data and simulations



M. Mihovilovič et al., Phys. Lett. B 771, 194 (2017), M. Mihovilovič et al., arXiv:1905.11182 [nucl-ex]

- refined external energy corrections after 2017 result
- r_p extraction relies on knowledge of higher-order terms, a and b

$$G(Q^2) = n_{E_0}\left[1 - \frac{r_p^2\,Q^2}{6\,\hbar^2} + \frac{a\,Q^4}{120\,\hbar^4} - \frac{b\,Q^6}{5040\,\hbar^6}\right]$$

r_p = (0.870 ± 0.014 stat. ± 0.024 sys. ± 0.003 mod.) fm

PRad Experiment at Jefferson Lab Hall B:

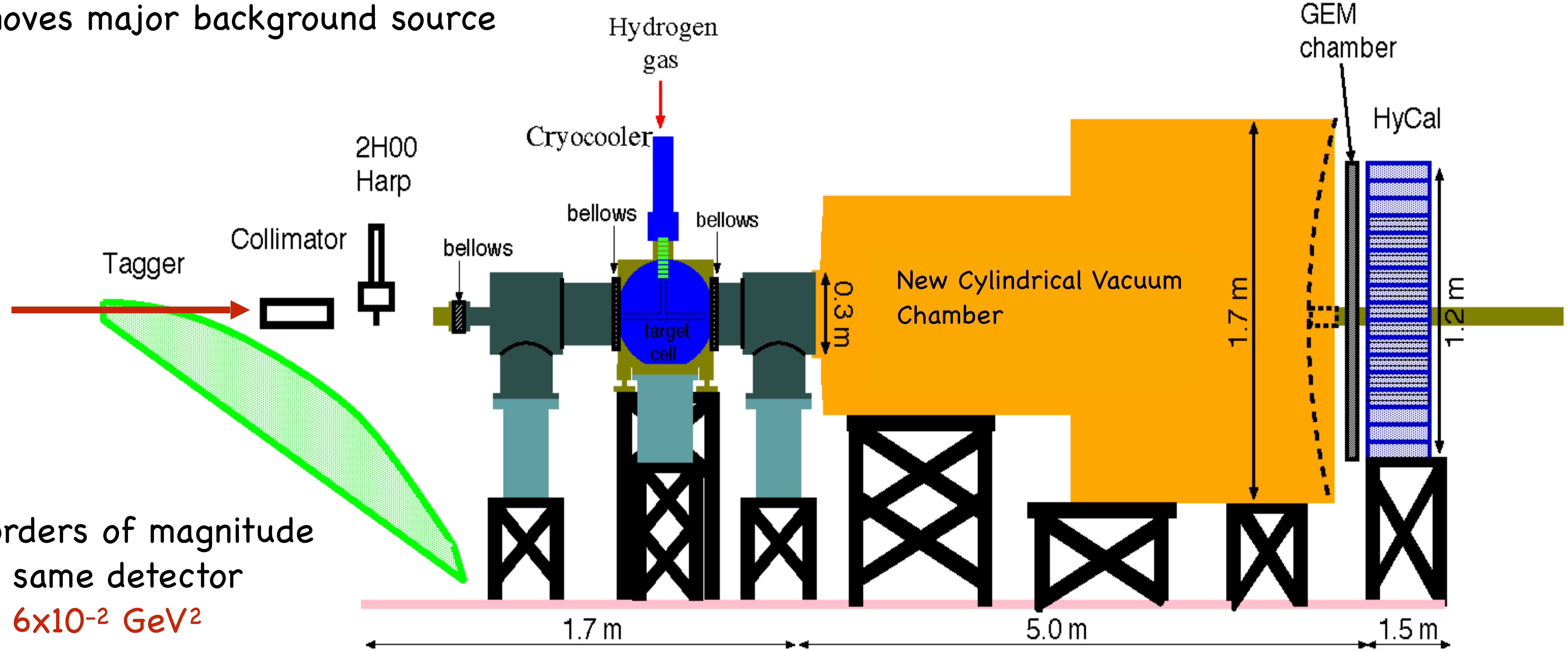
Apparatus (side view, not to scale)

Non-magnetic-spectrometer method:
high resolution, high acceptance crystal calorimeter and GEM detector

Windowless H_2 gas-flow target
removes major background source

Electron beam

E_0 = 1 GeV
E_0 = 2 GeV

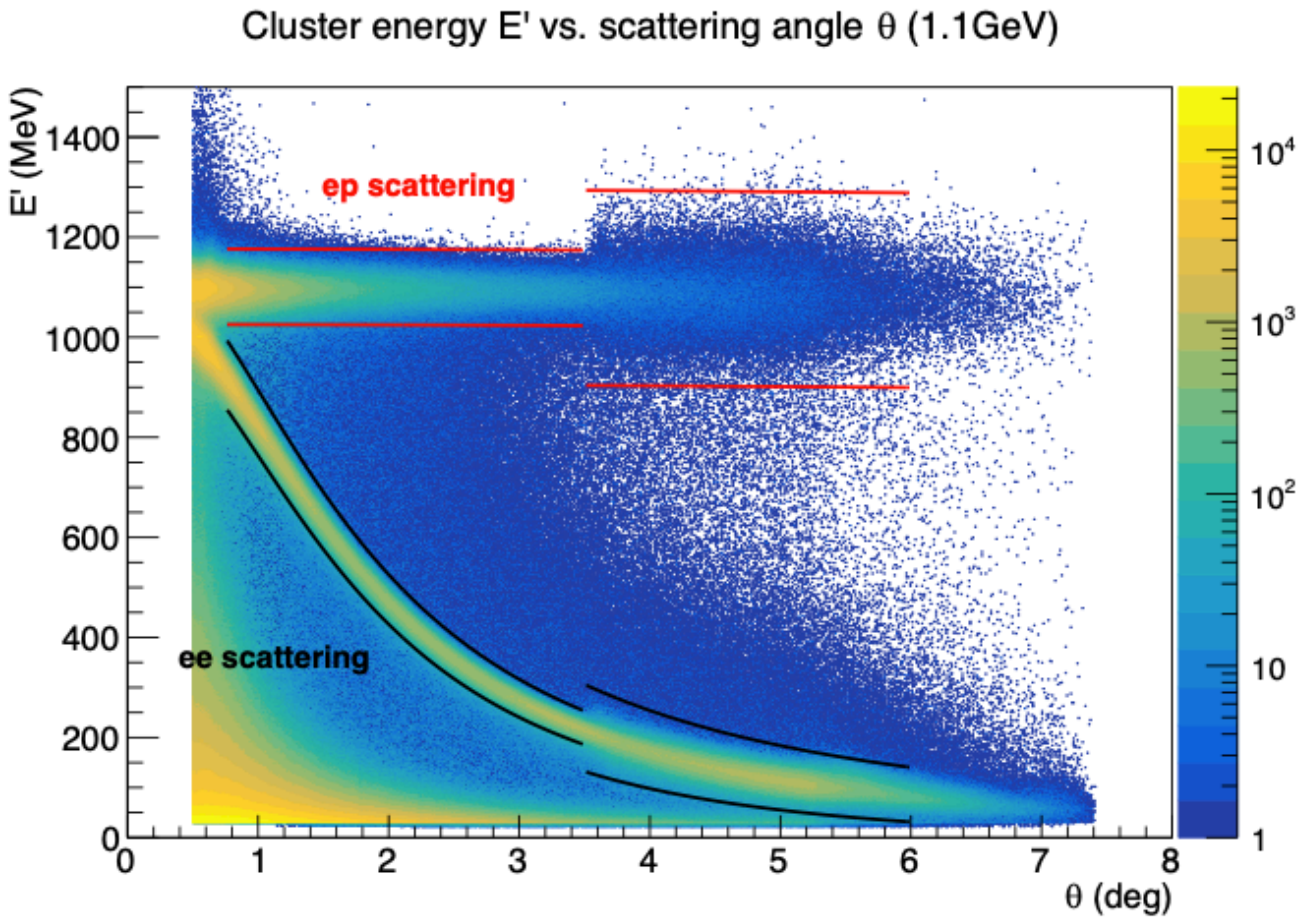


PRad covers two orders of magnitude in low Q^2 with the same detector setting: $\approx 2\times10^{-4} - 6\times10^{-2}$ GeV^2

JLab Experiment E12-11-106, A. Gasparian, H. Gao, M. Khandaker, and D. Dutta spokespeople; A. Gasparian and W. Xiong, priv. communication (2019).

PRad Analysis - Event Selection Method

- Normalize to the simultaneously measured Møller scattering process
- For all events, require hit matching between GEMs and HyCal
- For ep and ee events, apply detector-resolution dependent energy cuts based on kinematics
- For ee, if requiring double-arm events, apply additional cuts
  - Elasticity
  - Co-planarity
  - Vertex z



JLab Experiment E12-11-106, A. Gasparian, H. Gao, M. Khandaker, and D. Dutta spokespeople; A. Gasparian and W. Xiong, priv. communication (2019).

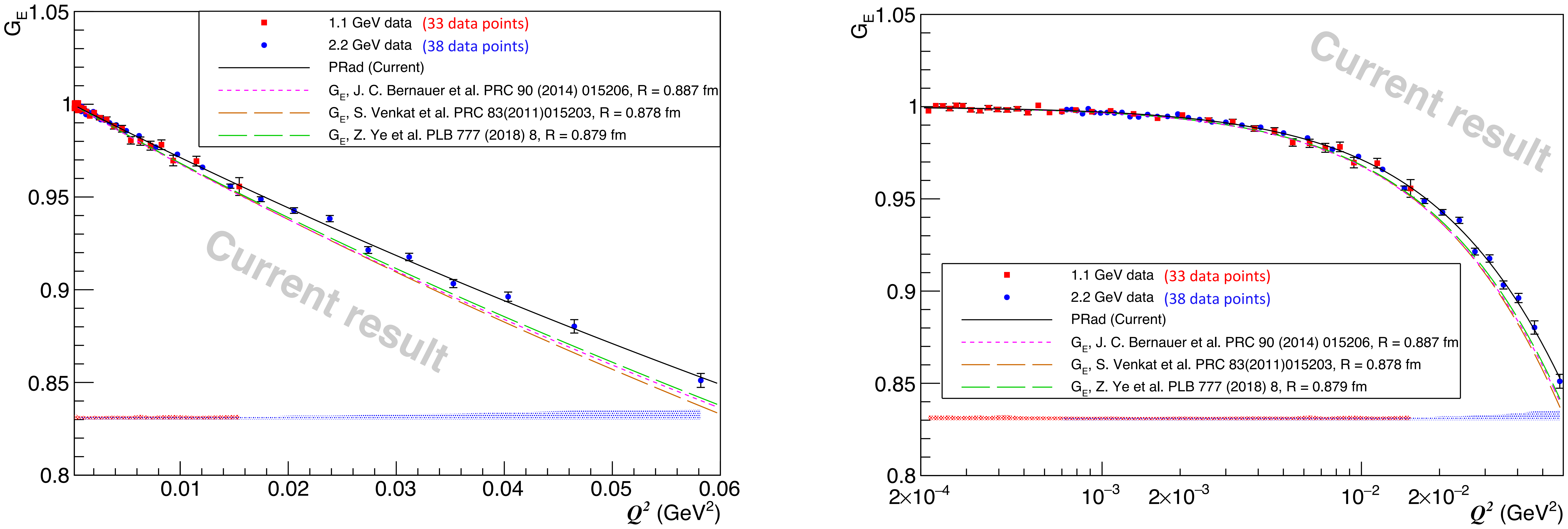
PRad: Proton Electric Form Factor G_E

Fitting PRad G_E to $\begin{cases} n_1 f(Q^2), & \text{for 1 GeV data} \\ n_2 f(Q^2), & \text{for 2 GeV data} \end{cases}$ using rational (1,1): $f(Q^2) = \dfrac{1 + p_1 Q^2}{1 + p_2 Q^2}$

X. Yan et al., PRC 98, 025204 (2018)

Extracted proton radius is consistent with μH result within ±0.007 (stat.) ± 0.012 (syst.) fm

Proton Electric Form Factor G_E



Normalization constants n_1 and n_2 are consistent with one within uncertainties of ±0.002.

JLab Experiment E12-11-106, A. Gasparian, H. Gao, M. Khandaker, and D. Dutta spokespeople; A. Gasparian and W. Xiong, priv. communication (2019).

MUon Scattering Experiment (MUSE) at PSI

Direct test of μp and ep interactions in a scattering experiment:

- higher precision than previously,
- low-Q^2 region for sensitivity to the **proton charge radius**, Q^2 = 0.002 to 0.07 GeV^2,
- with μ^+,μ^- and e^+,e^- to study possible **2γ mechanisms**,
- with μp and ep to have direct **μ/e comparison**

MUSE

$$e^- p \rightarrow e^- p$$

$$e^+ p \rightarrow e^+ p$$

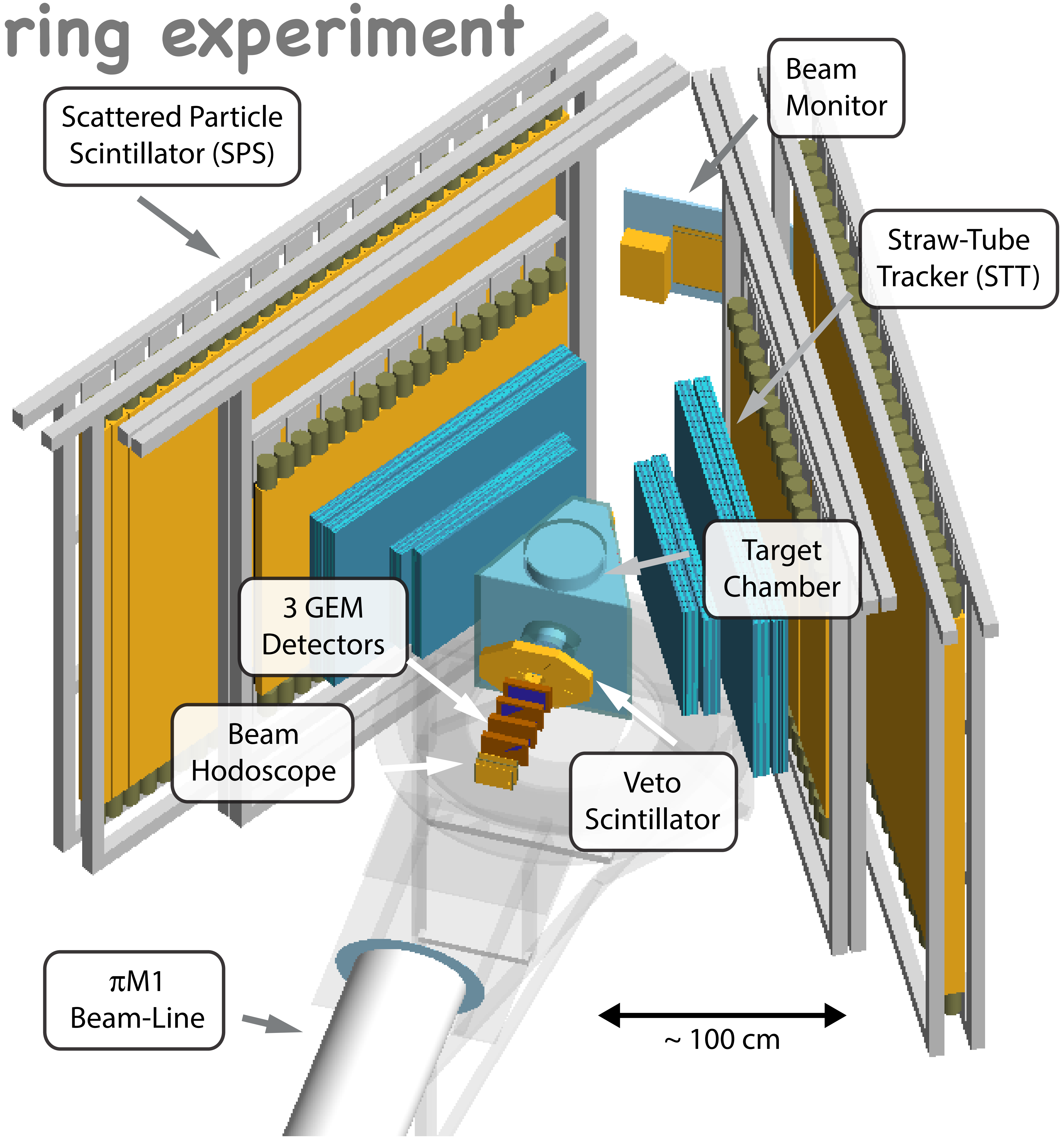
$$\mu^- p \rightarrow \mu^- p$$

$$\mu^+ p \rightarrow \mu^+ p$$

The MUon Scattering Experiment at PSI (MUSE), MUSE Technical Design Report, arXiv:1709.09753 [physics.ins-det].

MUSE is an unusual scattering experiment

Measure $e^{\pm}$ and $\mu^{\pm}$ elastic scattering off a liquid hydrogen target.

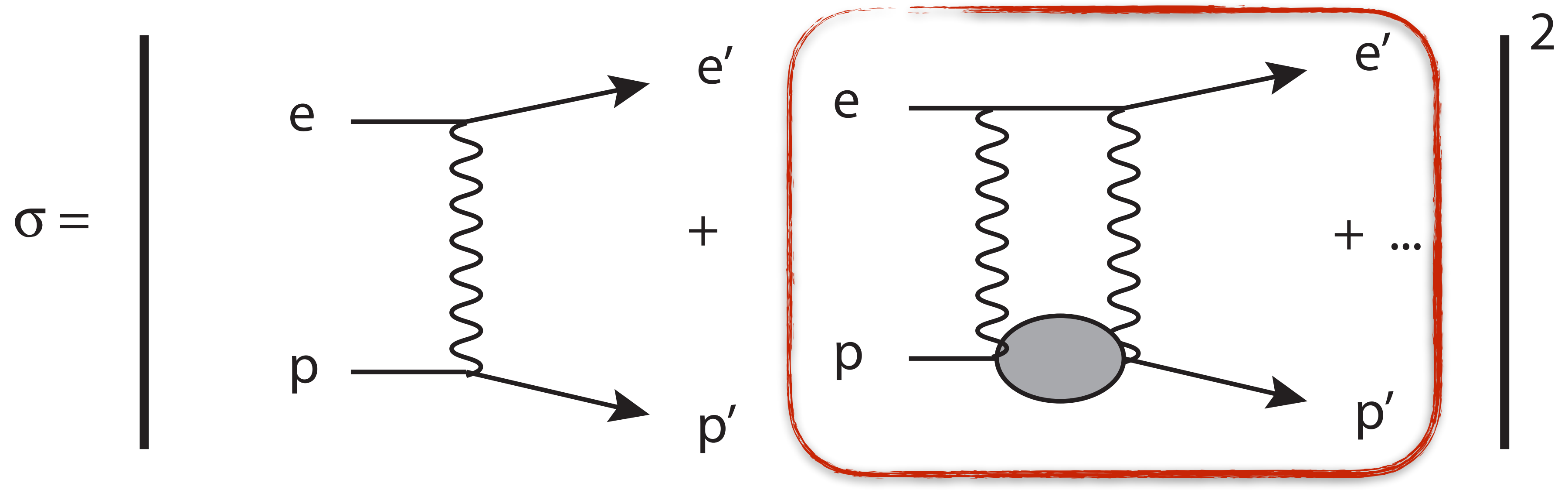


Challenges

- Secondary beam: identifying and tracking beam particles to target,
- Low beam flux: large angle, non-magnetic spectrometer,
- Background: e.g., Møller scattering and muon decay in flight.

The MUon Scattering Experiment at PSI (MUSE), MUSE Technical Design Report, arXiv:1709.09753 [physics.ins-det].

MUSE provides a high precision test of two-photon exchange for electrons and muons at low Q^2



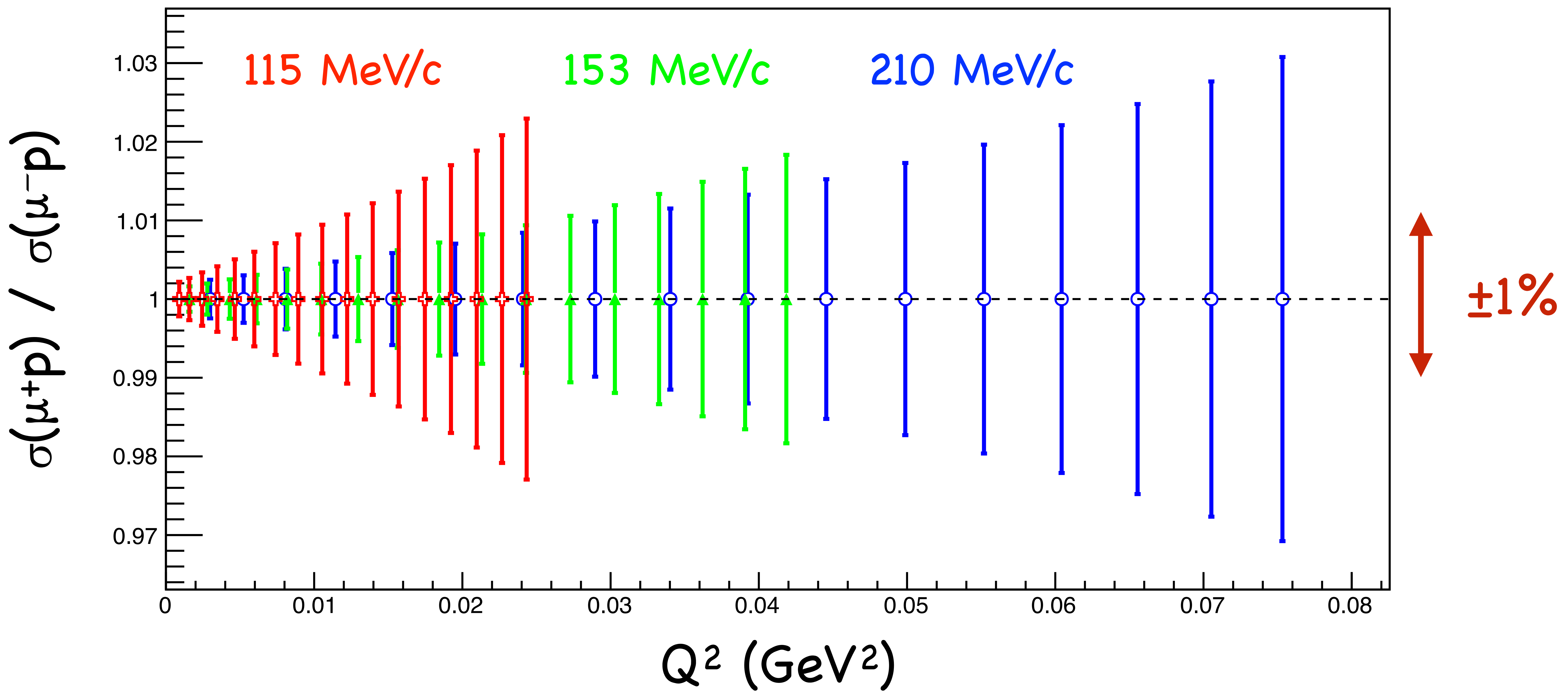
TPE: largest theoretical uncertainty in low-energy proton structure

$$\sigma_{e^\pm p} = |\mathscr{M}_{1\gamma}|^2 \pm 2\Re\{\mathscr{M}^\dagger{}_{1\gamma}\mathscr{M}_{2\gamma}\} + \cdots$$

sign change with lepton-charge

$$\frac{\sigma_{e^+p}}{\sigma_{e^-p}} = 1 + 4\frac{\Re\{\mathscr{M}^\dagger{}_{1\gamma}\mathscr{M}_{2\gamma}\}}{|\mathscr{M}_{1\gamma}|^2}$$

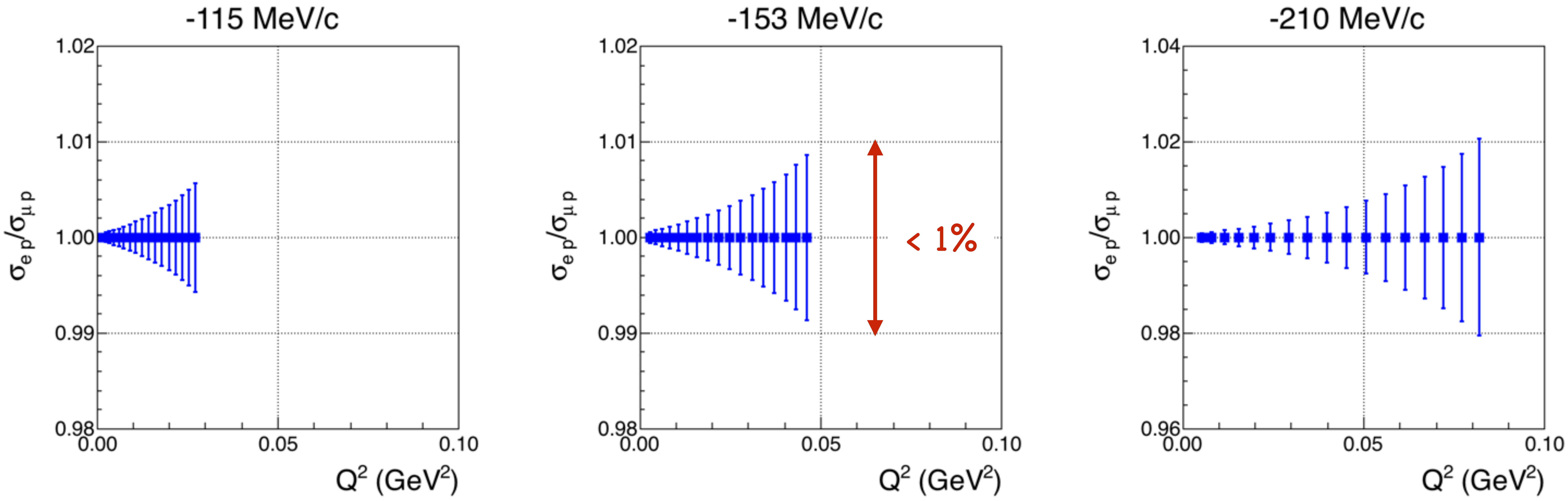
Projected relative uncertainty in the ratio of μ^+p to μ^-p elastic cross sections. Systematics: 0.2%



MUSE Technical Design Report, arXiv:1709.09753 [physics.ins-det].

MUSE directly compares ep to μp cross sections

Projected relative statistical uncertainties in the ratio of ep to μp elastic **cross sections**.
Systematics ≈ 0.5%.



The relative statistical uncertainties in the **form factors** are half as large.

The MUon Scattering Experiment at PSI (MUSE), MUSE Technical Design Report, arXiv:1709.09753 [physics.ins-det].

Projected MUSE proton charge-radius results

How different are the e/μ radii?
(truncation error largely cancels)
Sensitivity to differences in extracted e/μ radii:

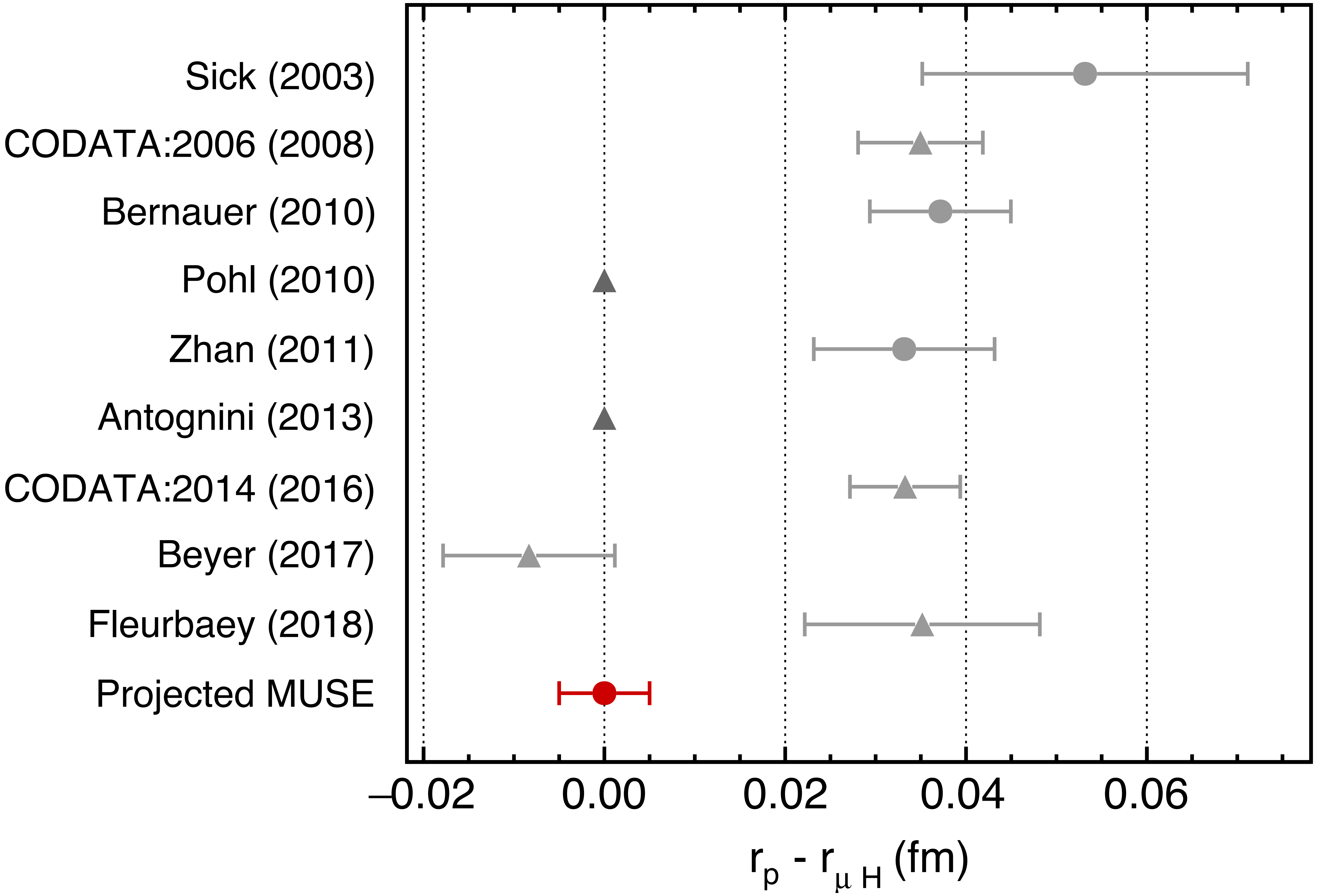
$\sigma(r_e - r_\mu) \approx 0.005$ fm

What is the radius?
Absolute values of extracted e/μ radii (assuming no +/- difference seen):

$\sigma(r_e)$, $\sigma(r_\mu) \approx 0.008$ fm

Comparisons of, e.g., ***e* to *μ*** or of ***μ⁺* to *μ⁻*** are insensitive to many of the systematics

Current discrepancy: $r_e - r_\mu \approx 0.034$ fm

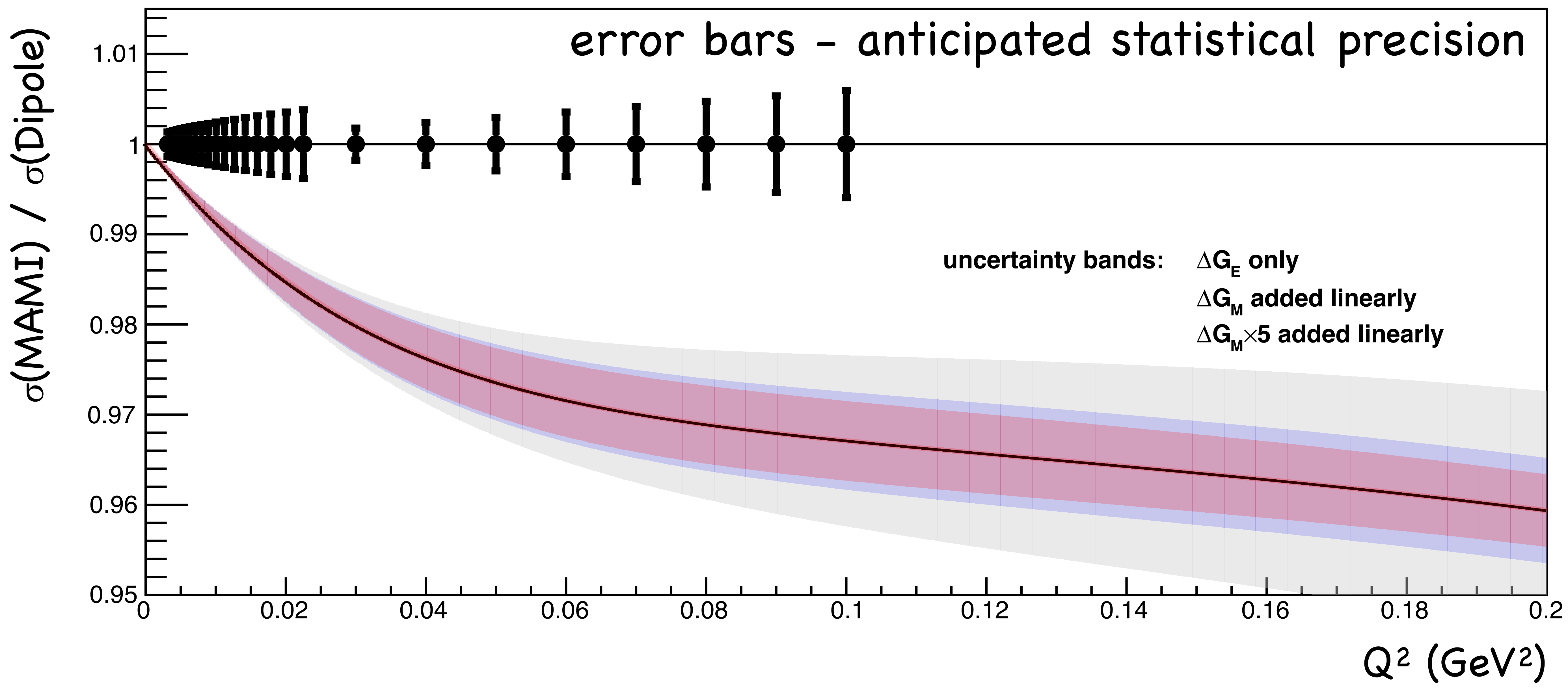


The MUon Scattering Experiment at PSI (MUSE), MUSE Technical Design Report, arXiv:1709.09753 [physics.ins-det].

COMPASS++/AMBER: Elastic μp scattering

Next talk by Christian Dreisbach (TUM)

- 100 GeV SPS muon beam
- Hydrogen high-pressure active TPC target cell
- Broad Q^2 range from 0.001 to 0.02 GeV^2
- Proton radius extraction, $\sigma(r)$ = 0.01 fm, with complementary systematics compared to MUSE



Letter of Intent: A New QCD facility at the M2 beam line of the CERN SPS*
COMPASS++/AMBER, arXiv: 1808.00848v6 [hep-ex]

Summary - the proton charge radius

- **Proton radius puzzle**: The discrepancy between muonic and electronic measurements of the proton radius is a 7σ effect and remains a major problem.
- "Perhaps the discrepancy is due to new physics. Perhaps the explanation is an ordinary physics effect that has been missed. Perhaps, the muonically measured radius will come to be the accepted number." (C. Carlson, 2015)

Scattering

- Conflicting extractions of the proton radius from electron scattering experiments
- Preliminary PRad result consistent with μH spectroscopy result
- Anticipation of new results from elastic muon scattering (MUSE, COMPASS++) and low-Q^2 electron scattering experiments

Spectroscopy

- Muonic hydrogen spectroscopy result scrutinized but unchallenged
- Muonic deuterium result consistent with μH
- New final and preliminary hydrogen-spectroscopy results significant
- All, but one, consistent with μH