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The Proton Radius Puzzle: Are We Still Puzzled?

Evangeline J. Downie

Bormio 2024

MUSE

NSF
Award:
PHY-2310026

PAUL SCHERRER INSTITUT PSI

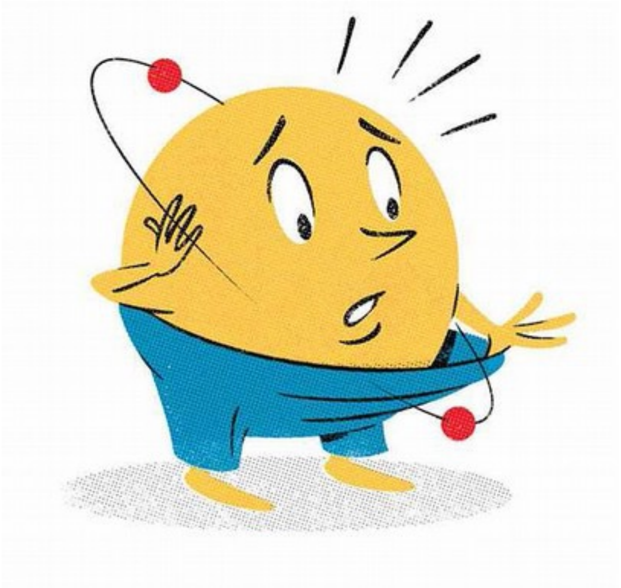
BSF

DEPARTMENT OF ENERGY UNITED STATES OF AMERICA

The Proton Radius Puzzle (2010)

Nature **466**, 213 (2010)

Discrepancy between radius measured with electrons and muons



The New York Times

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The Proton Radius Puzzle (2010)

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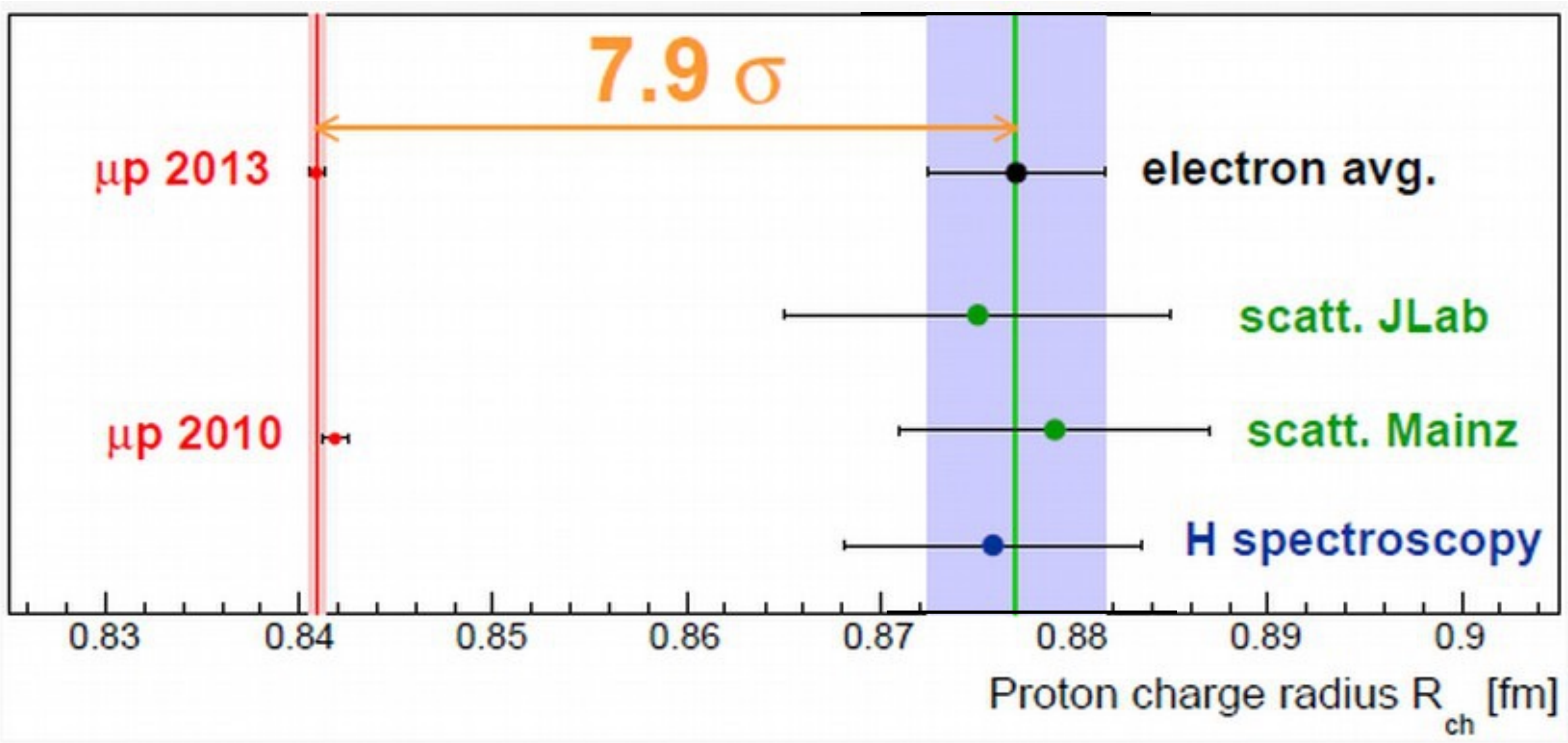

μp 2013: Antognini *et al.*
Science **339,** 417 (2013)

Jlab: Zhan *et al.*
PLB **705,** 59-64 (2011)

Mainz: Bernauer *et al.*
PRL **105**, 242001 (2010)

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

The Proton Radius Puzzle (2013)

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Radius from Scattering

Differential cross section

Mott cross section

Form Factor

$$\frac{d\sigma}{d\Omega} = \left(\frac{d\sigma}{d\Omega}\right)_{Mott} G^2(Q^2)$$

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Radius from Scattering

$$r^2 = -6 \left(\frac{dG(Q^2)}{d(Q^2)} \right) \Bigg|_{Q^2=0}$$

Proton radius squared

Slope of the form factor as a function of momentum transfer

Evaluated at momentum transfer = 0

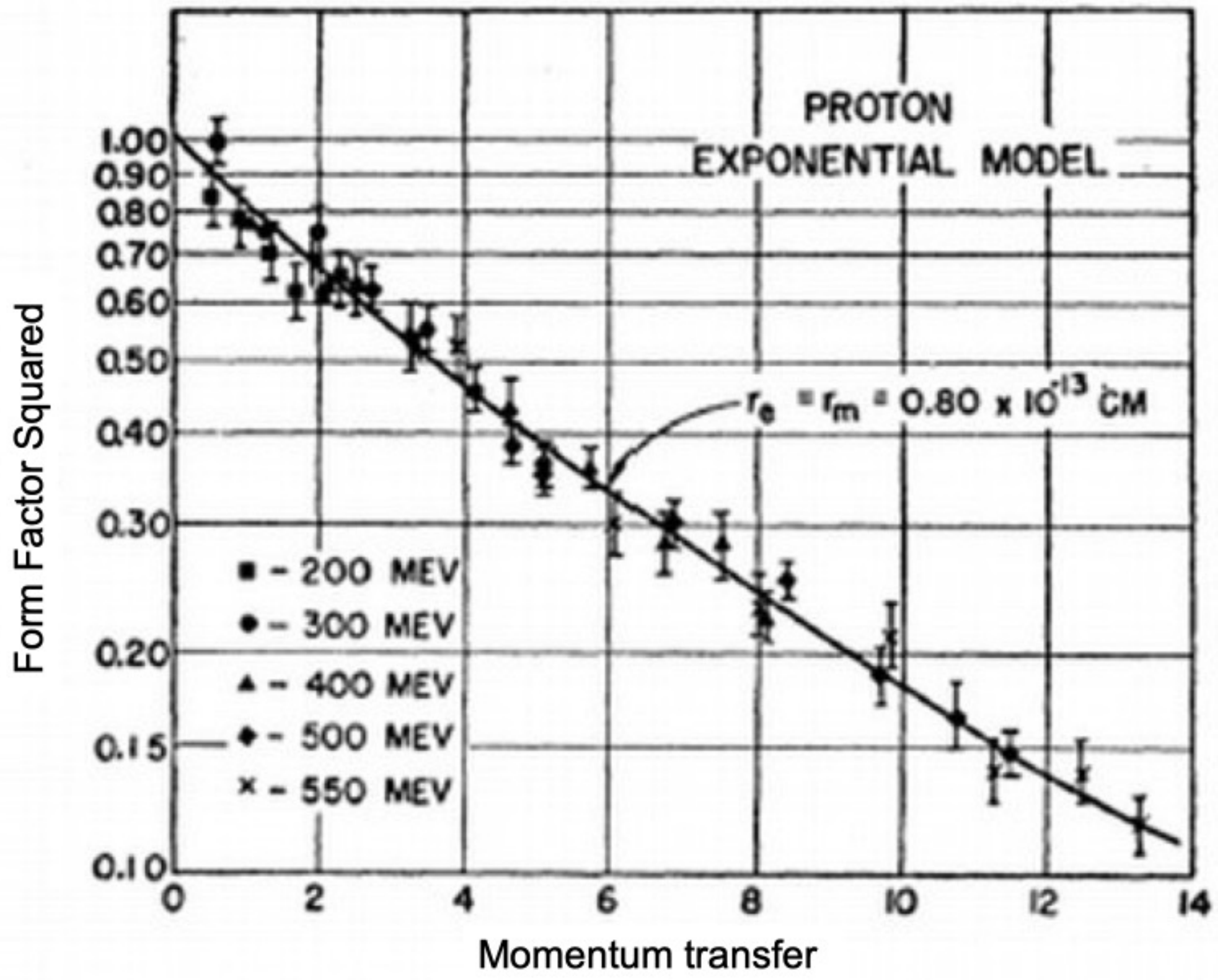
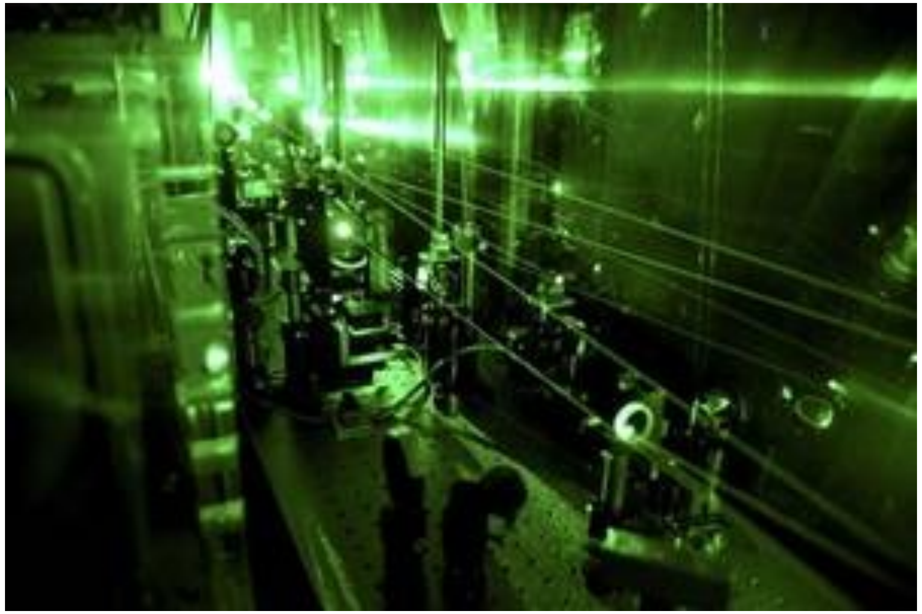
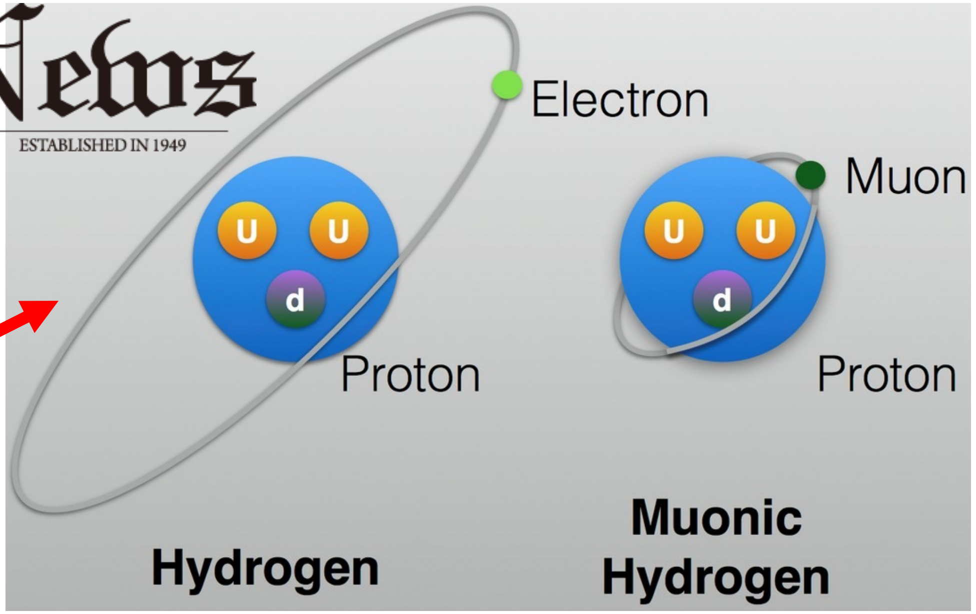


Figure from:
Chambers & Hofstadter
PRL **103** 1454 (1956)

Radius from Scattering

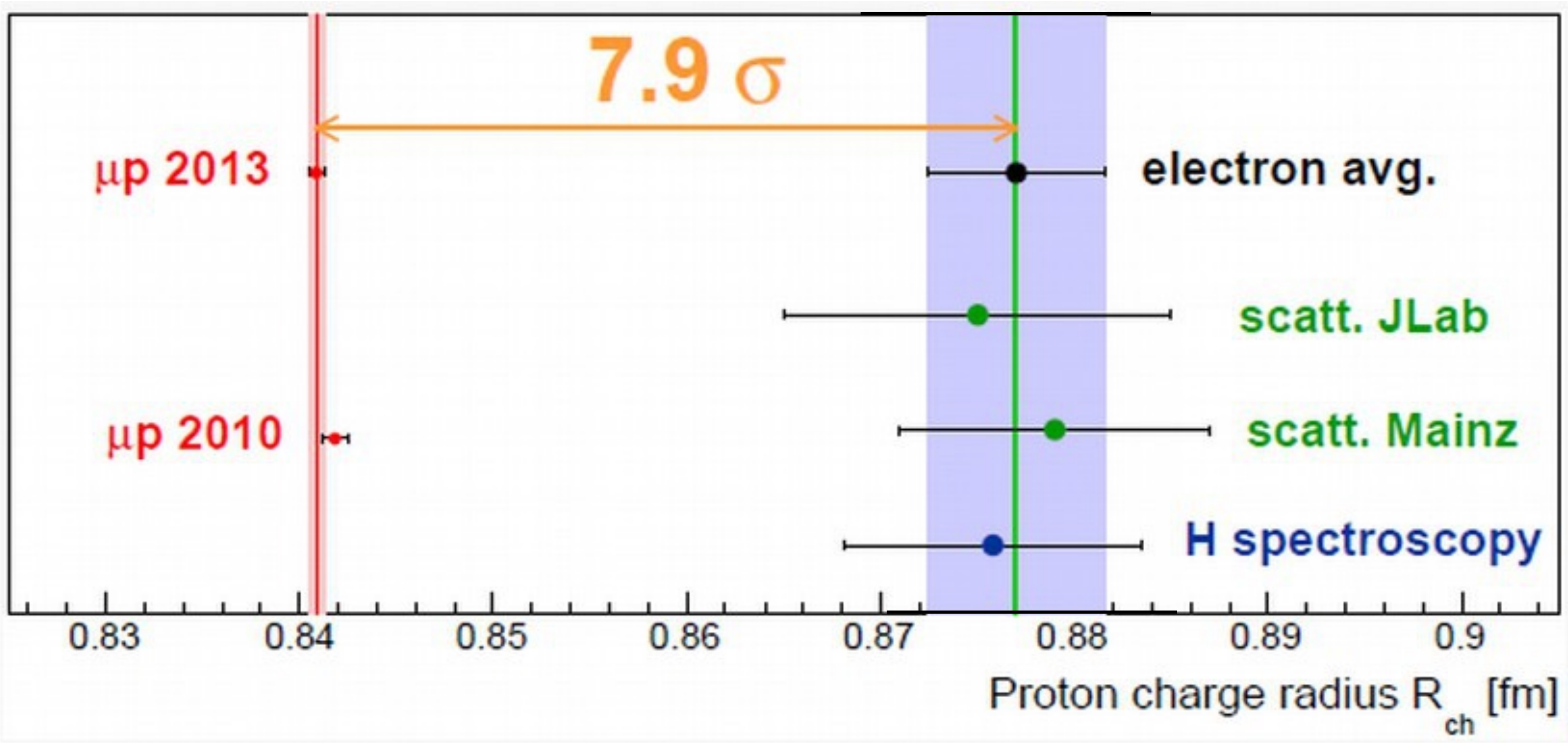


Not to scale!



- Energy level differences = precisely known physics (QED) + (tiny) proton size effect
- Muonic hydrogen spectroscopy ~8,000,000 times more sensitive to radius

Radius from Spectroscopy



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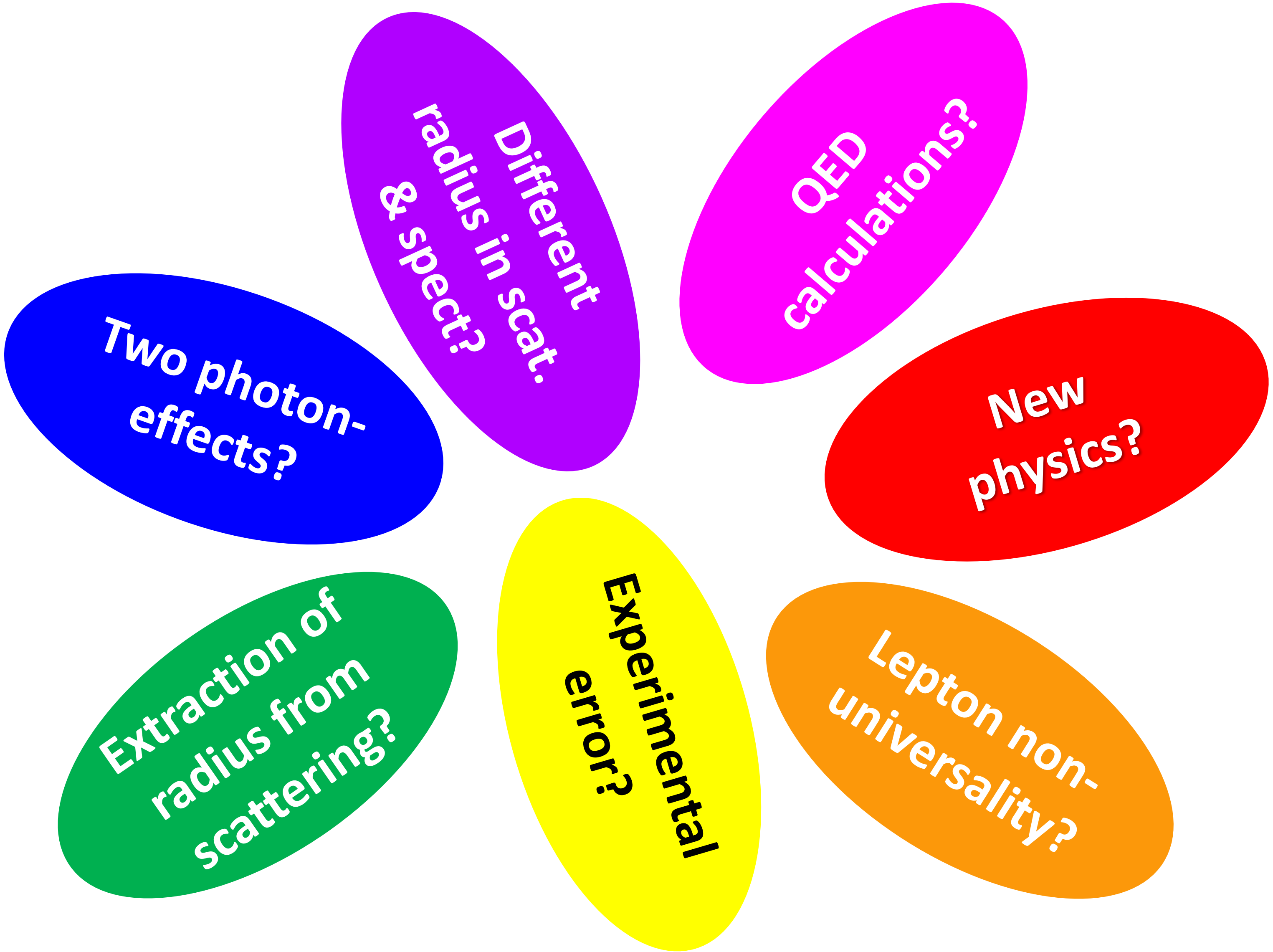
The Proton Radius Puzzle (2013)



For details see:
The Proton Radius, Losinj (2019)
https://indico.cern.ch/event/806319/

How to resolve the PRP?

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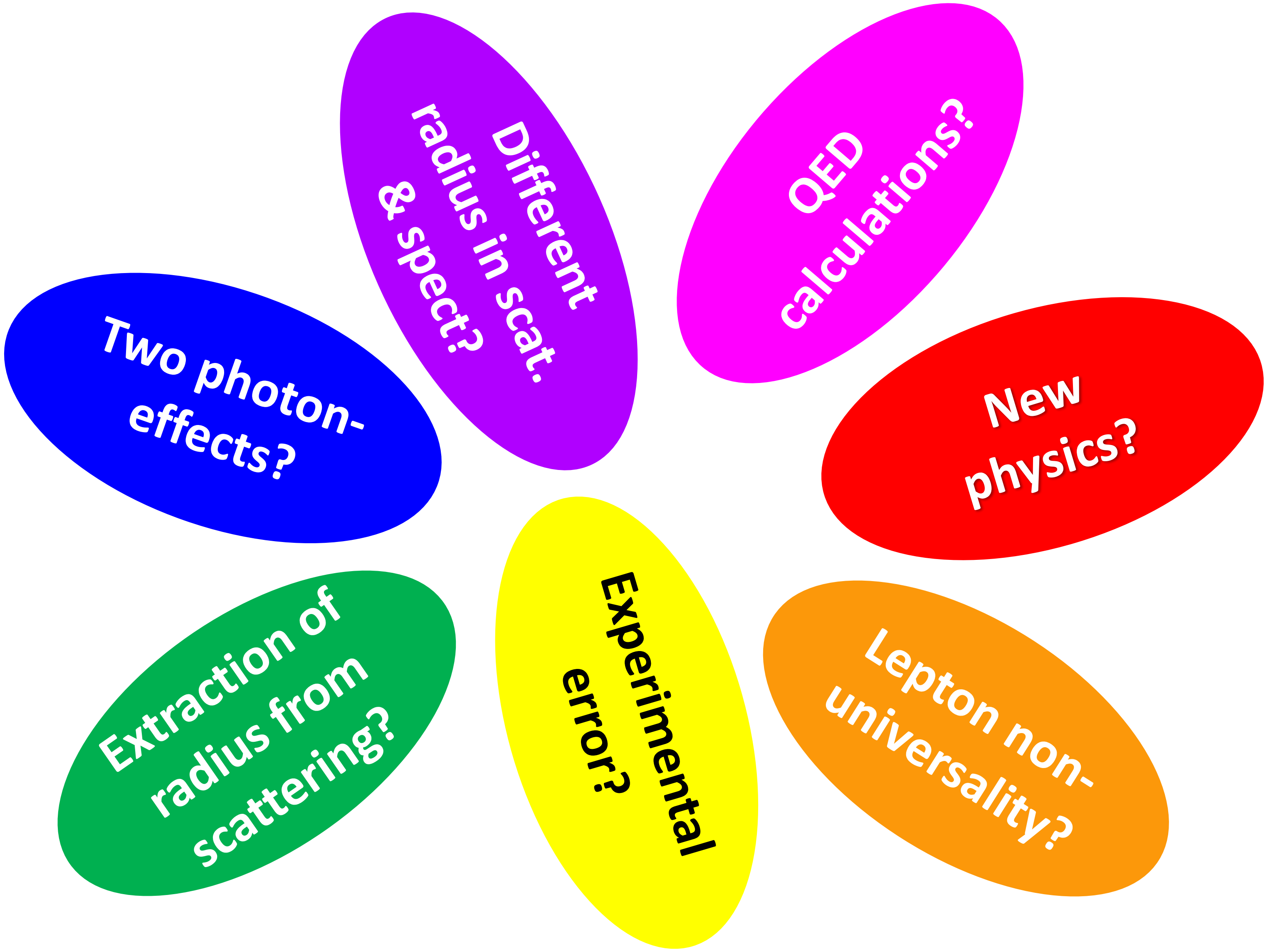
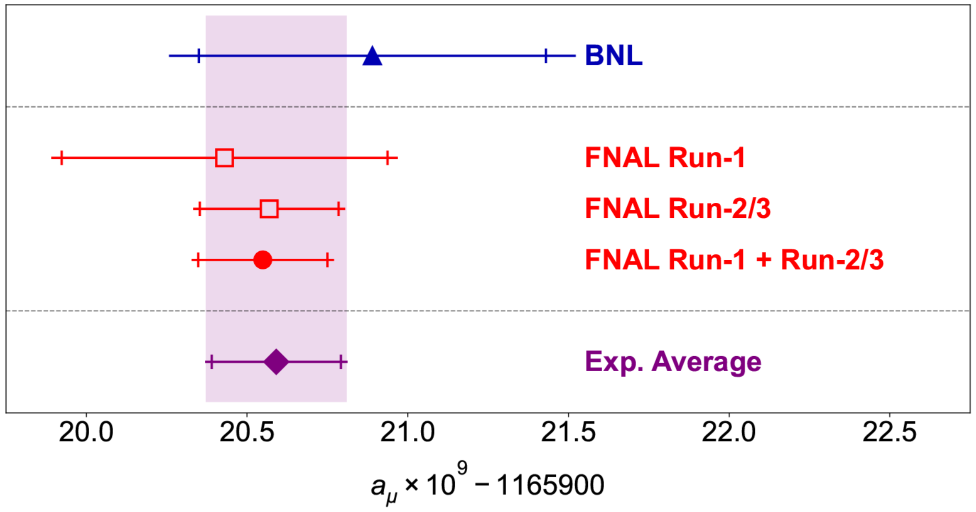
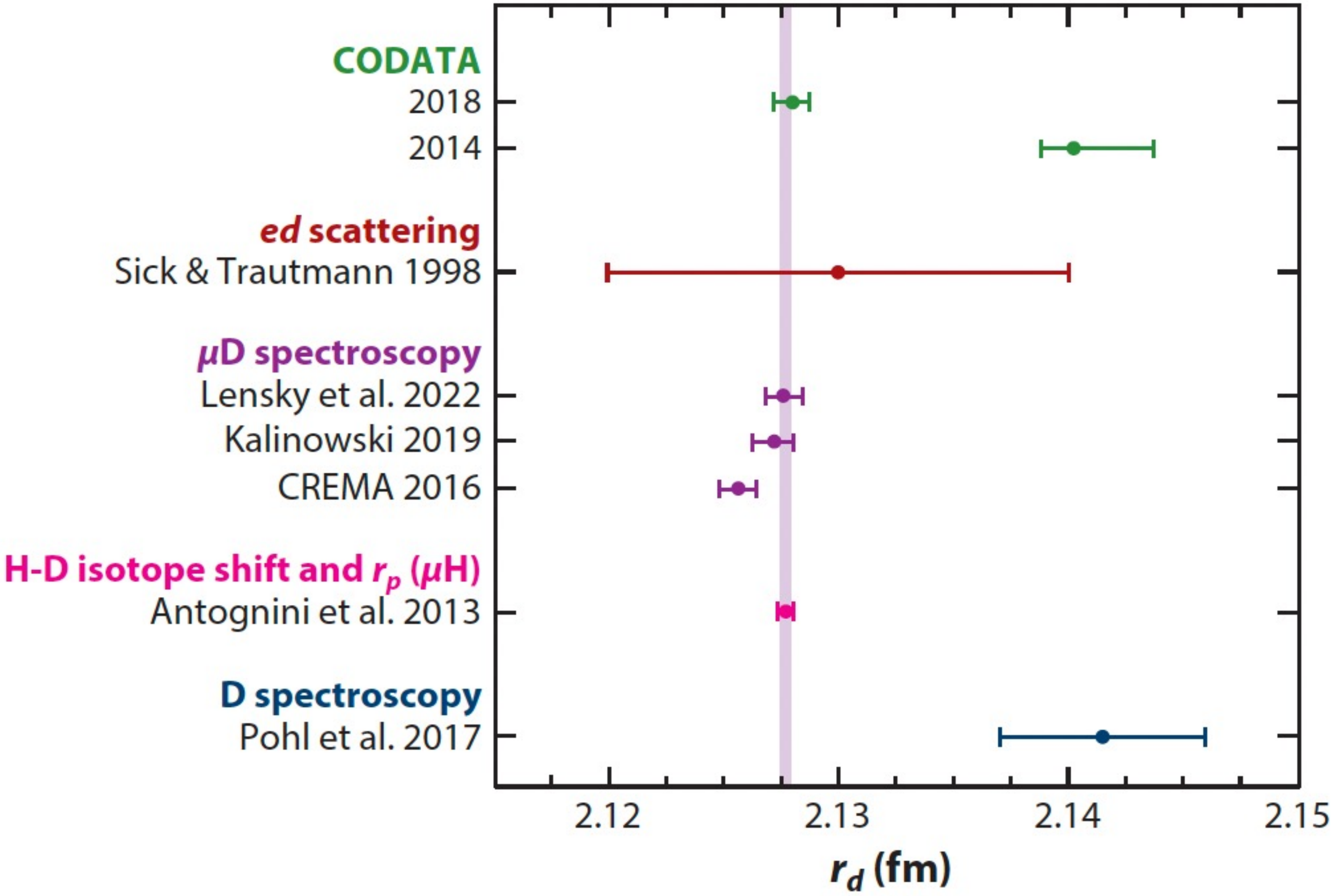




New muon (g-2) result (2023)
arXiv:2308.06230 [hep-ex]

How to resolve the PRP?

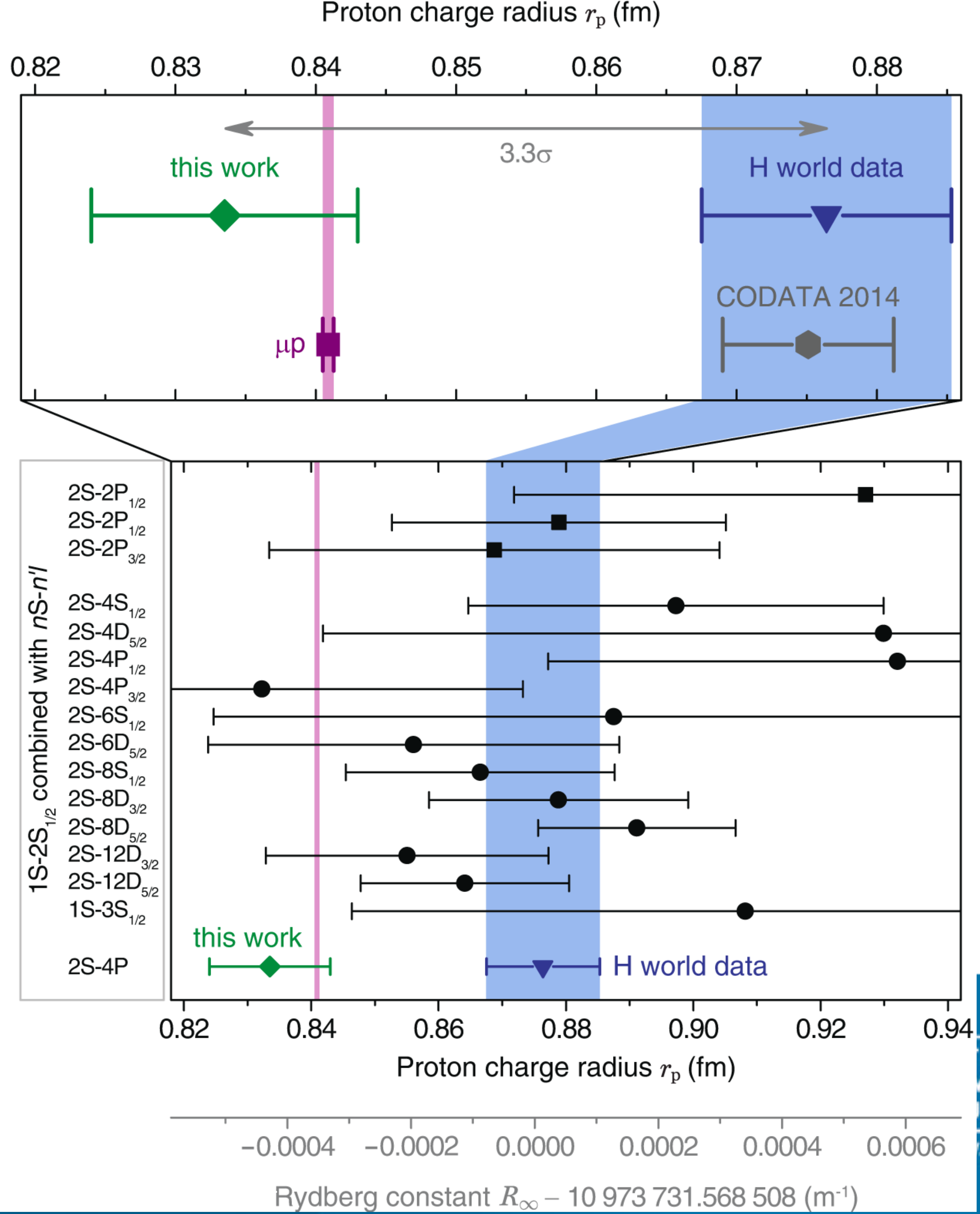
Muonic atom spectroscopy: a Z=1 Problem



- Muonic deuterium agrees with muonic hydrogen: Pohl *et al.*, (CREMA) Science 353 (2016) 669
- Muonic 4He agrees with electronic helium: Krauth *et al.*, Nature **589**, 527 (2021)
- A Z=1 problem!
- Many new results on hydrogen

MPQ Result
2S – 4P

Beyer *et al.*
Science **358**, 79-85 (2017)
6 October 2017



Spectroscopy: 2S-4P

E.

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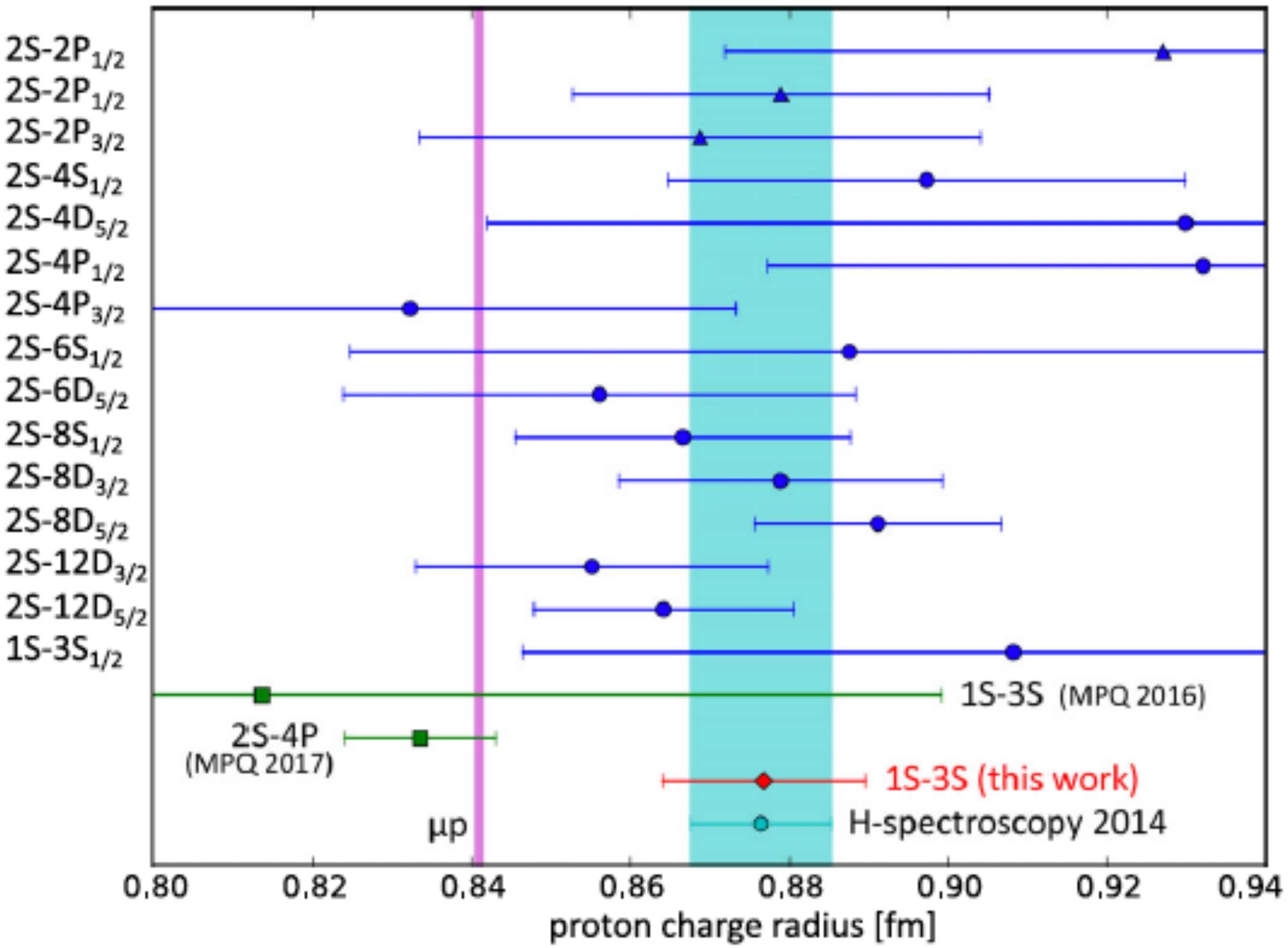
Orsay Result
1S – 3S

Fleurbaey *et al.*, Phys. Rev. Lett. **120**, 183001 (2018)

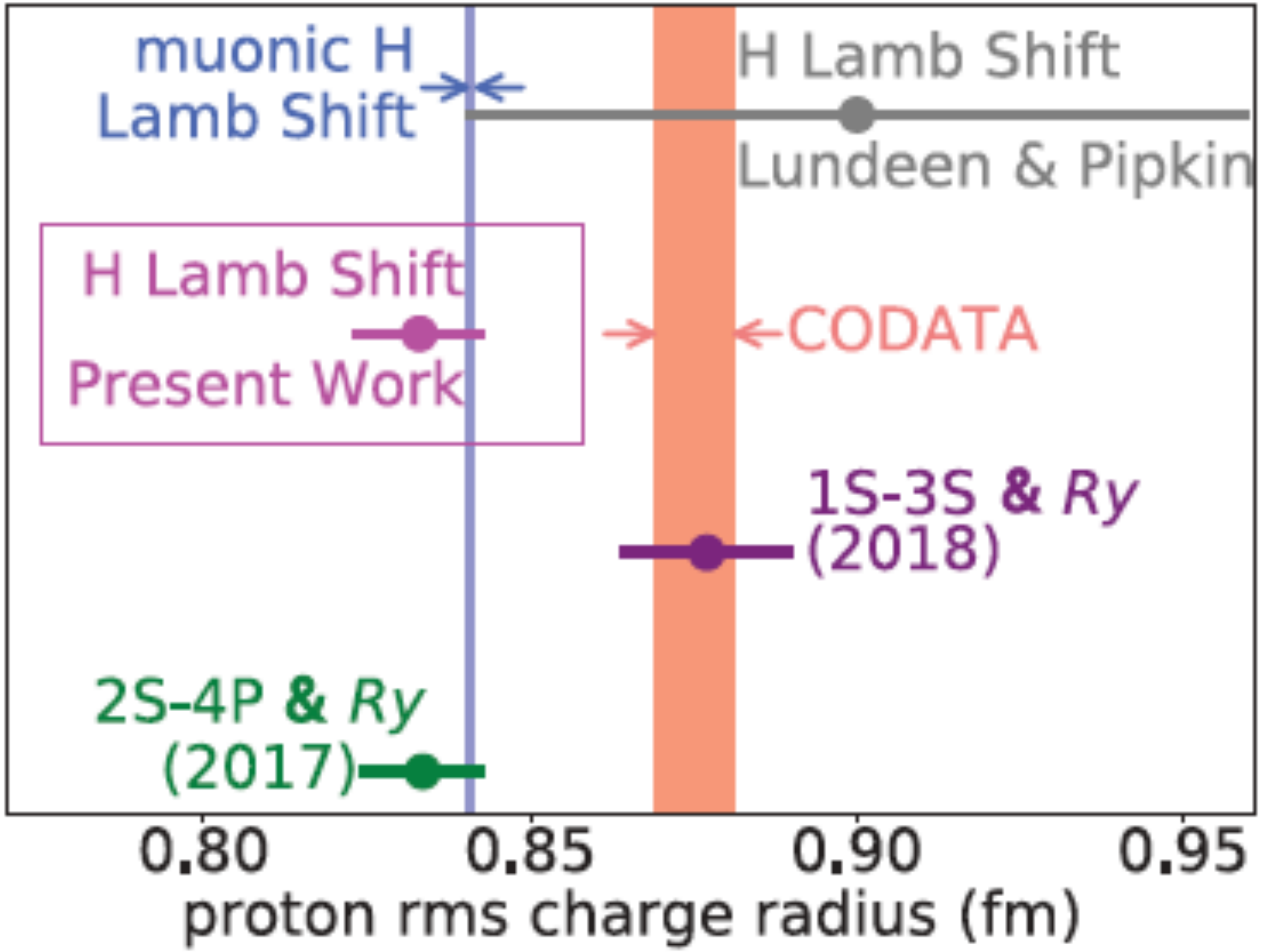


Spectroscopy: 1S – 3S

York Result
2S – 2P
(Lamb Shift)

Bezginov *et al.*, Science **365**, 1007–1012 (2019)

No involvement of Rydberg



Spectroscopy: 2S – 2P, Rydberg Independent

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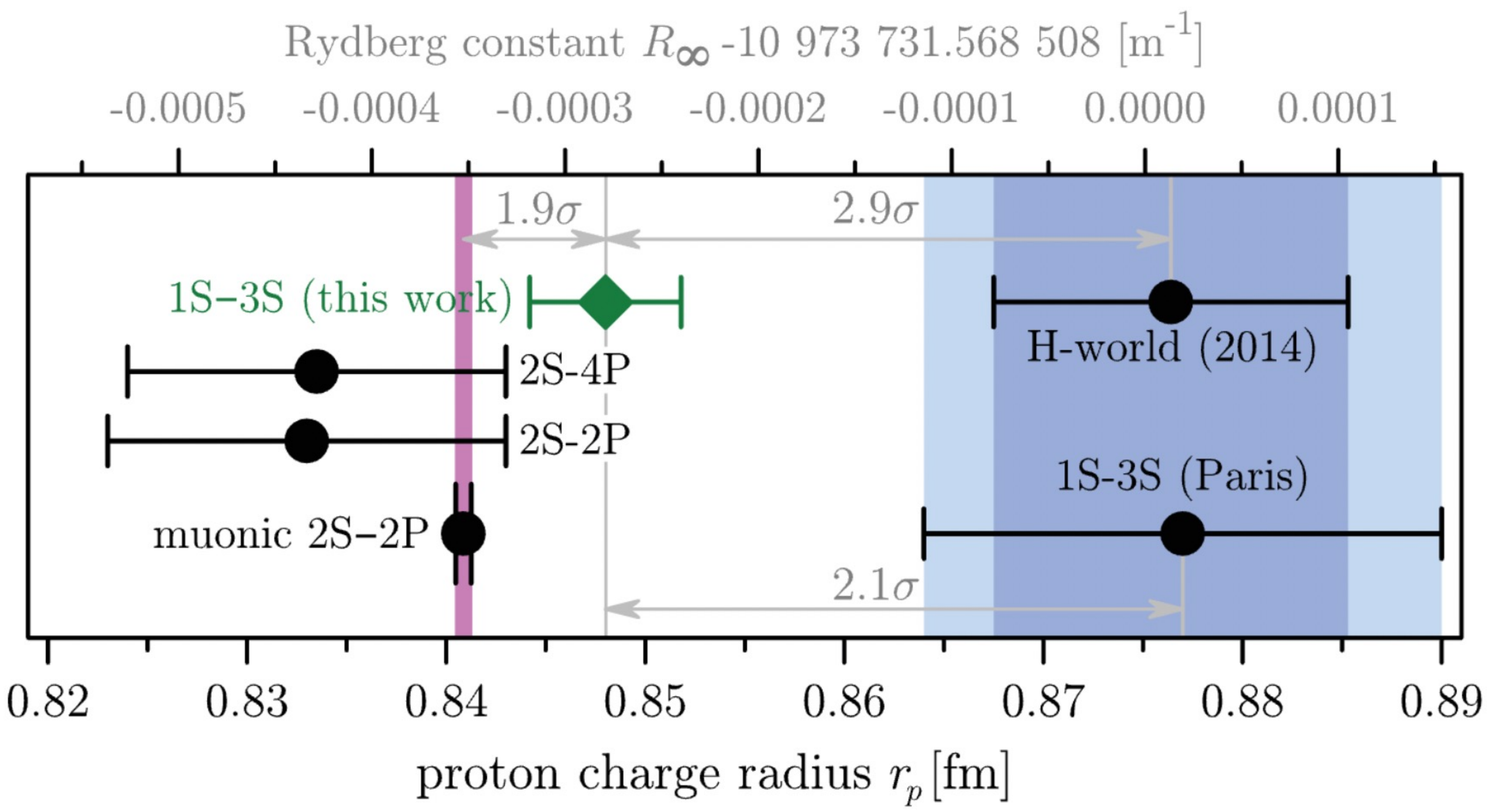
MPI Garching Result 2S – 3S

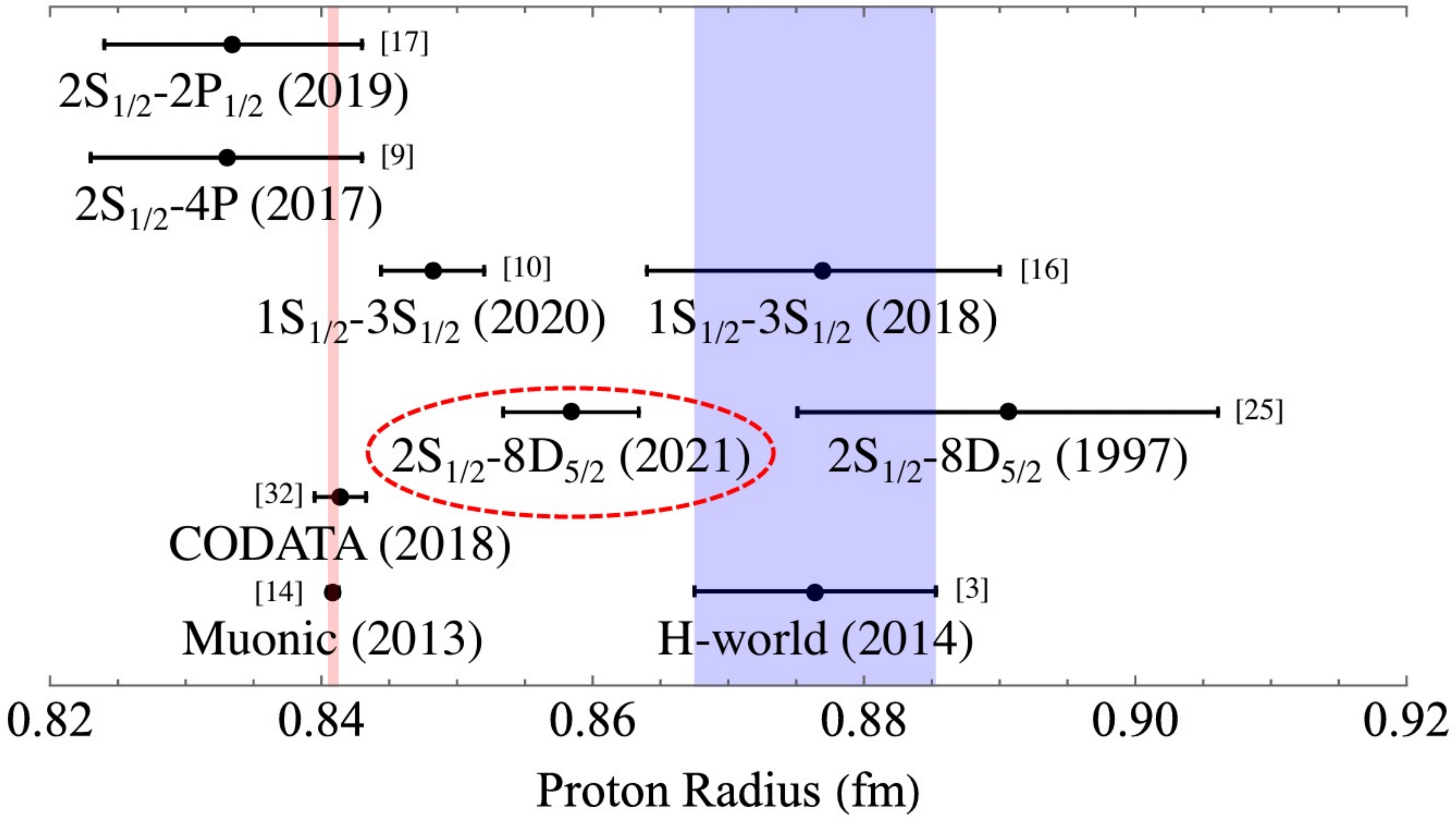
Grinin *et al.*, Science **370**, 1061–1066 (2020)



Spectroscopy: 2S – 3S

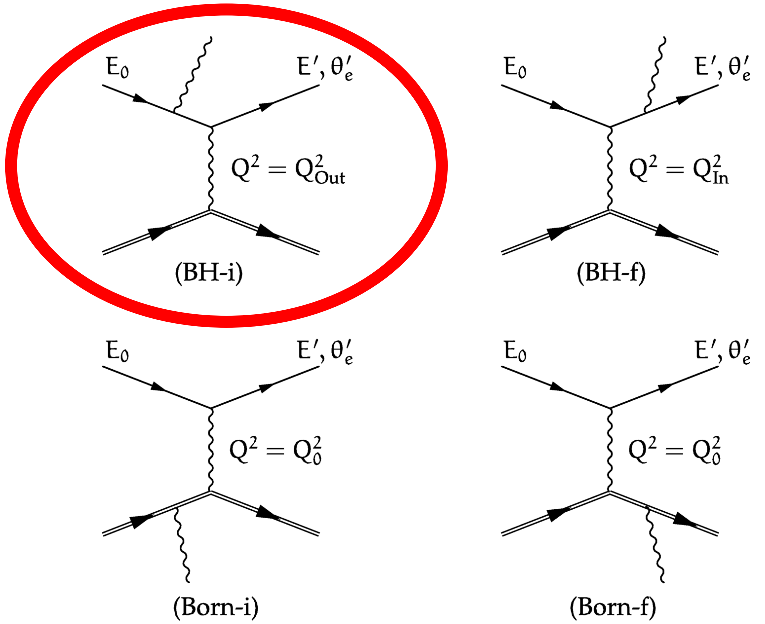
Colorado Result 2S – 8D

Brandt *et al.*, PRL **128**, 023001 (2022)



Spectroscopy: 2S – 8D

Mihovilovič *et al.*,
PLB **771**, 194 (2017)
Eur. Phys. J. A **57** 107 (2021)



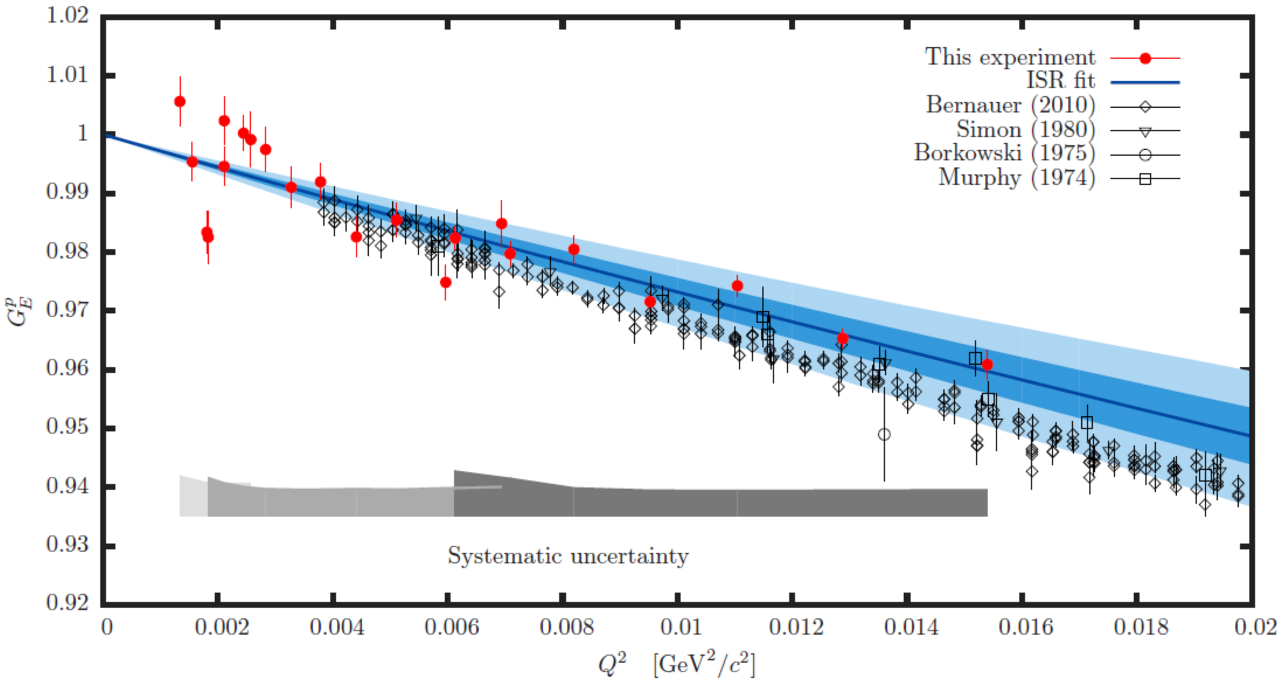


FIG. 3. (Color on-line) The proton electric form factor as a function of $Q^2 (= Q^2_{\mathrm{Out}})$. Empty black points show previous data [19–22]. The results of this experiment are shown with full red circles. The error bars show statistical uncertainties. Gray structures at the bottom shows the systematic uncertainties for the three energy settings. The curve corresponds to a polynomial fit to the data defined by Eq. (2). The inner and the outer bands around the fit show its uncertainties, caused by the statistical and systematic uncertainties of the data, respectively.

- Result: r_p=(0.810 ±0.035 stat. ±0.074 syst. ±0.003 ΔaΔb)fm, not precise enough to differentiate
- Re-analysed 2021: r_p=(0.878 ±0.011 stat. ±0.031 syst. ±0.002 mod.)fm
- New experiment with jet target (and MESA) planned

Scattering: Mainz Initial State Radiation

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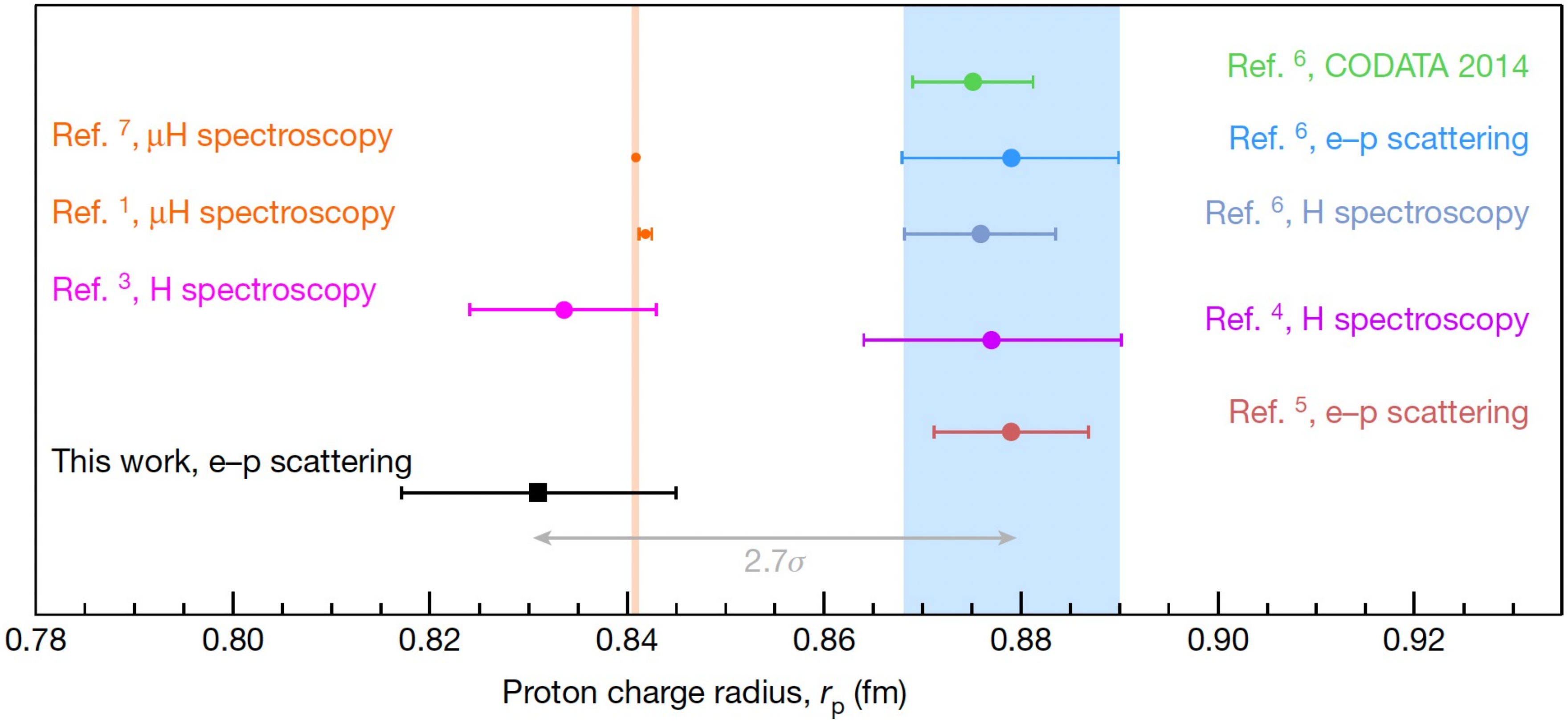
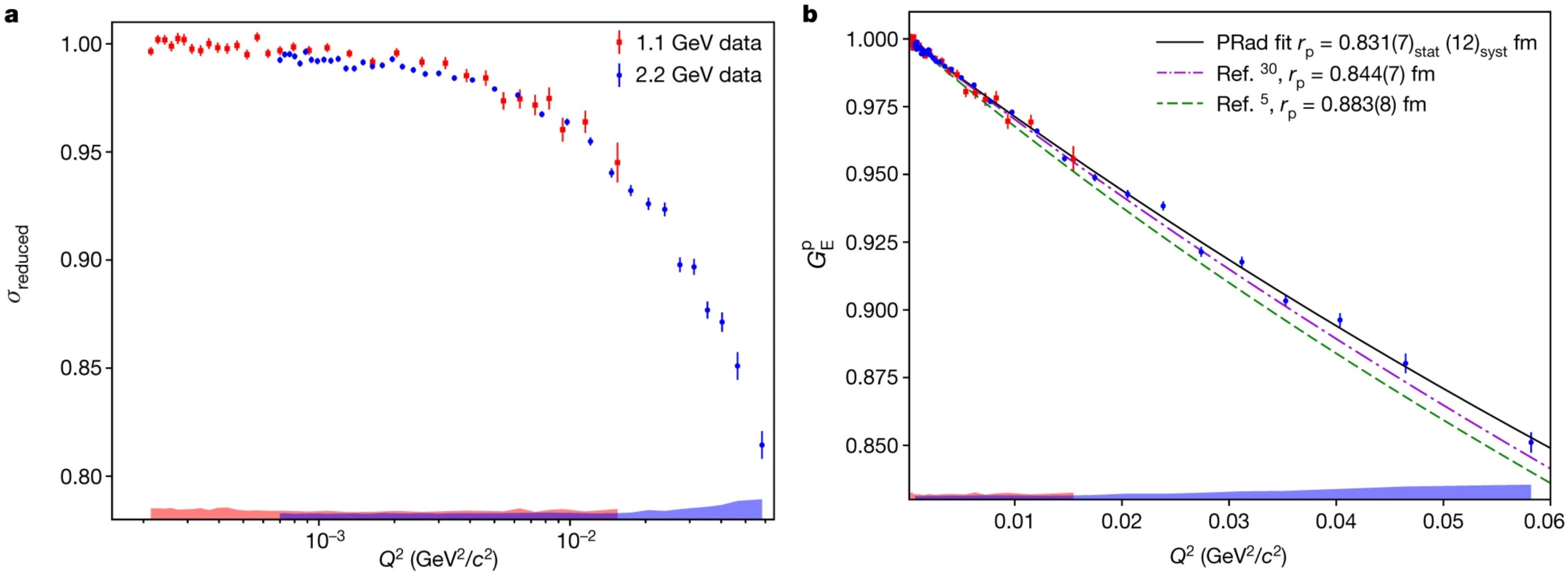
PRad Result Electron Scattering

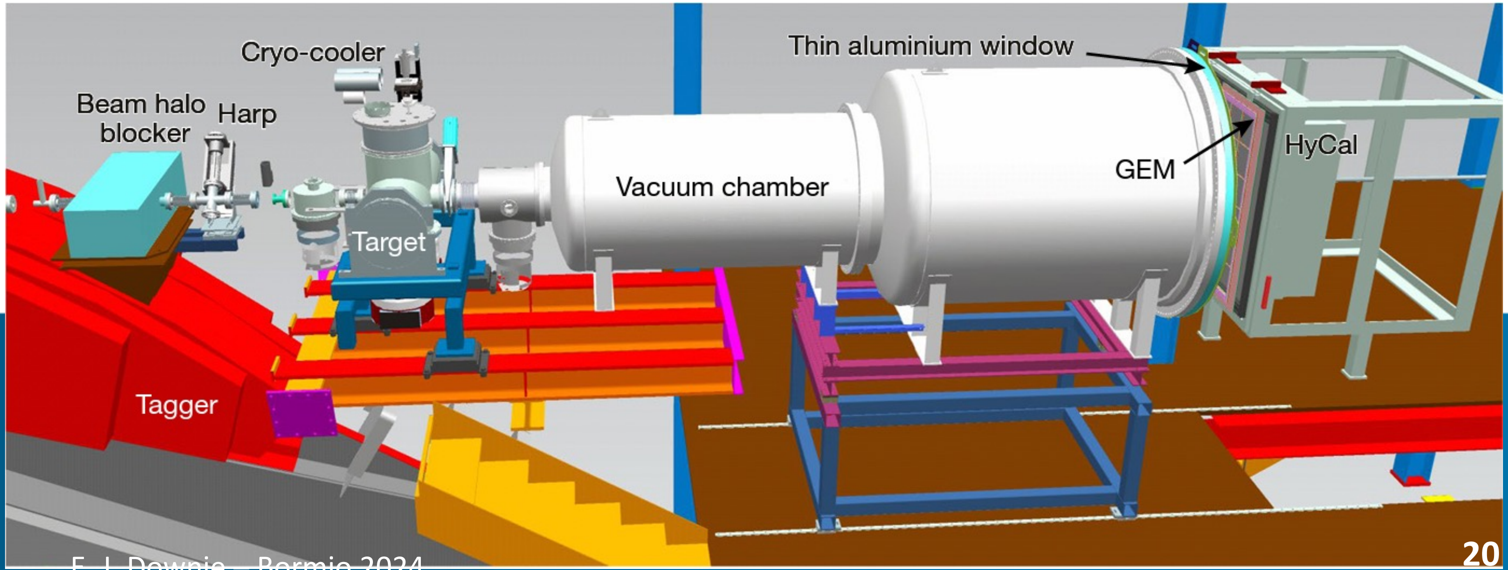
Xiong *et al.*, Nature **575**, 147 - 150 (2019)



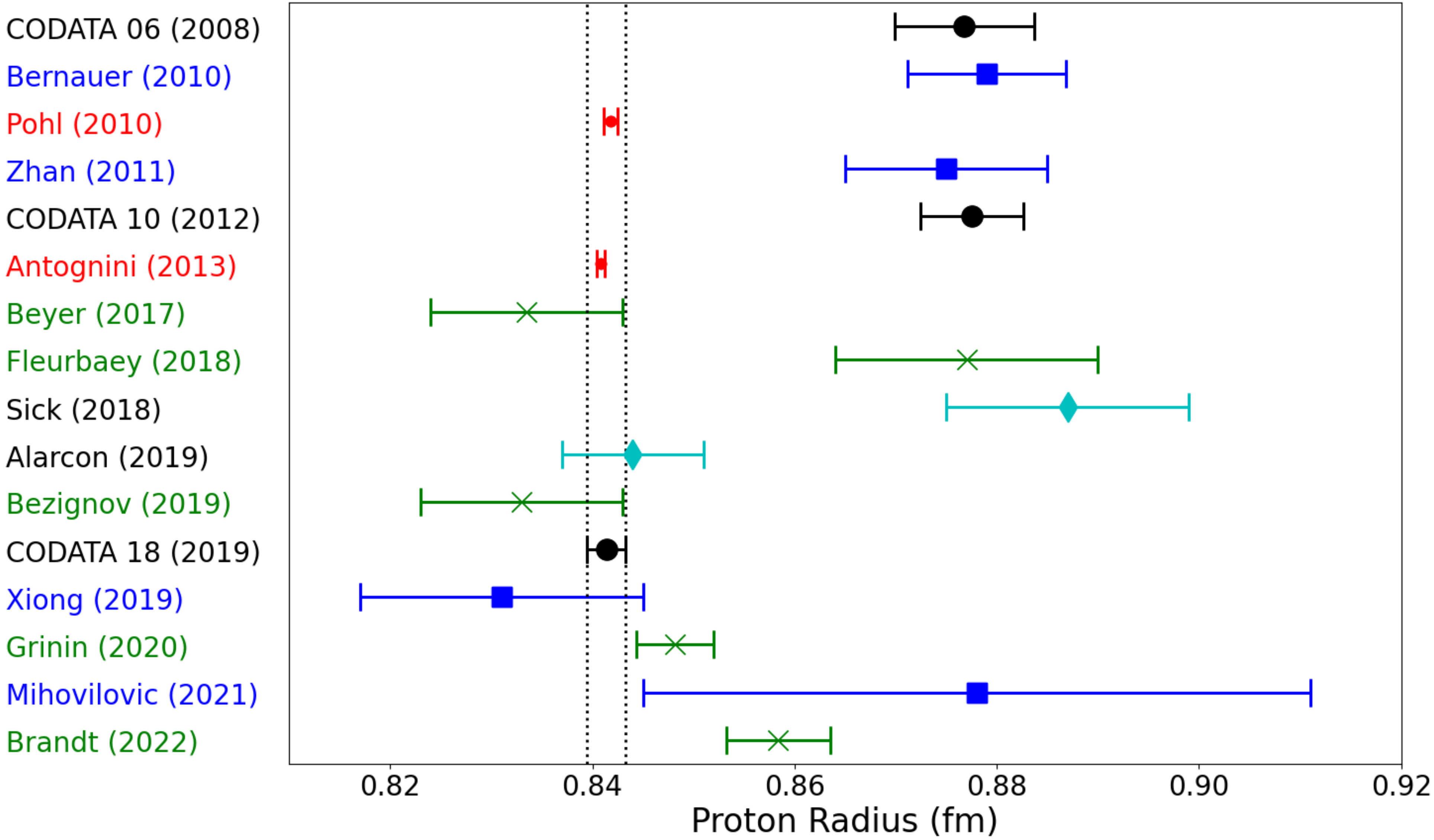
Scattering: PRad @ JLab



Xiong *et al.*, Nature **575**, 147 - 150 (2019)



Scattering: PRad



Muon Measurements:
Spectroscopy – μH

Electron Measurements:
Scattering – e
Spectroscopy – H

Analysis of Measurements:
Re-fitting of e scattering
CODATA

Proton Radius Puzzle Status (2024)

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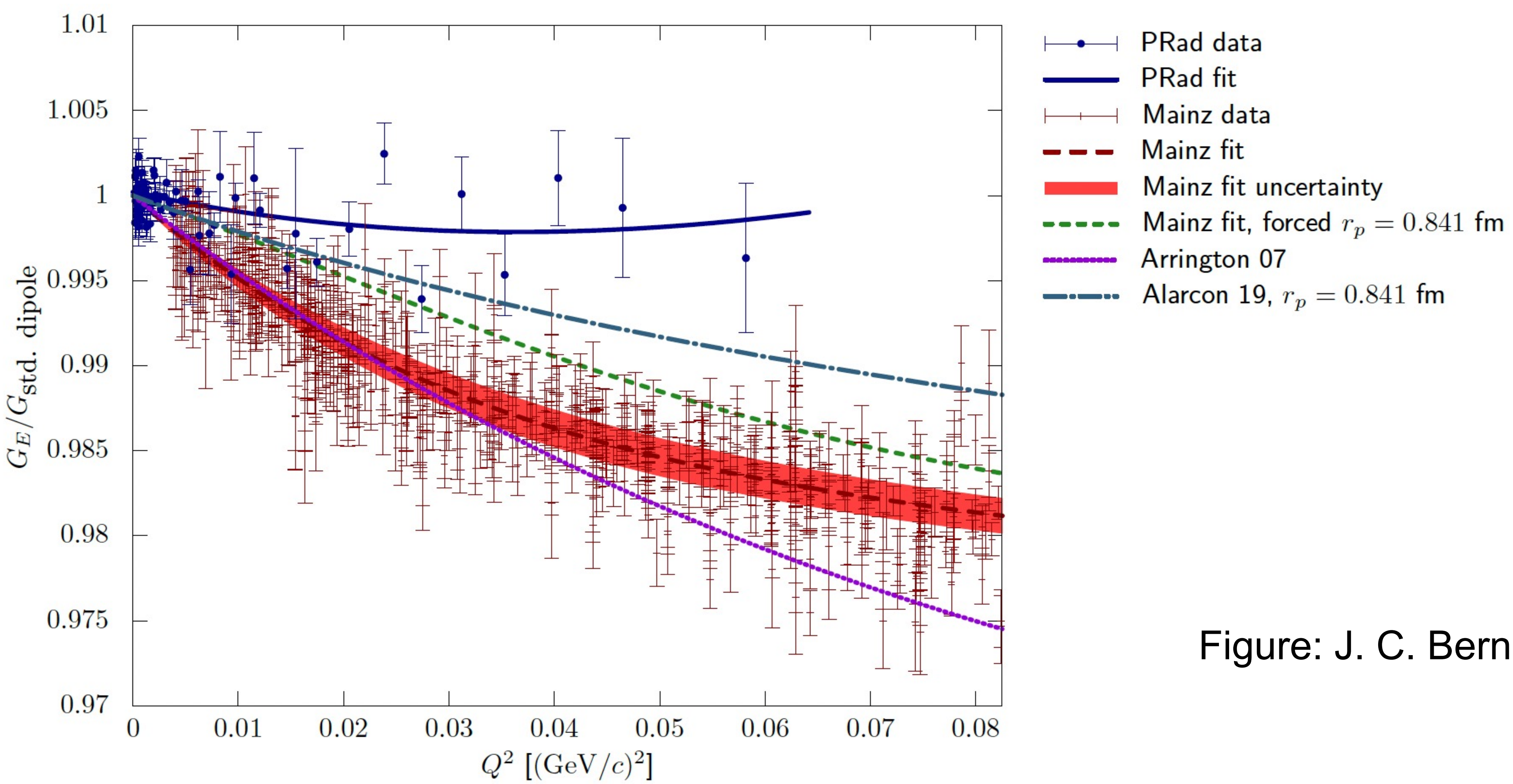
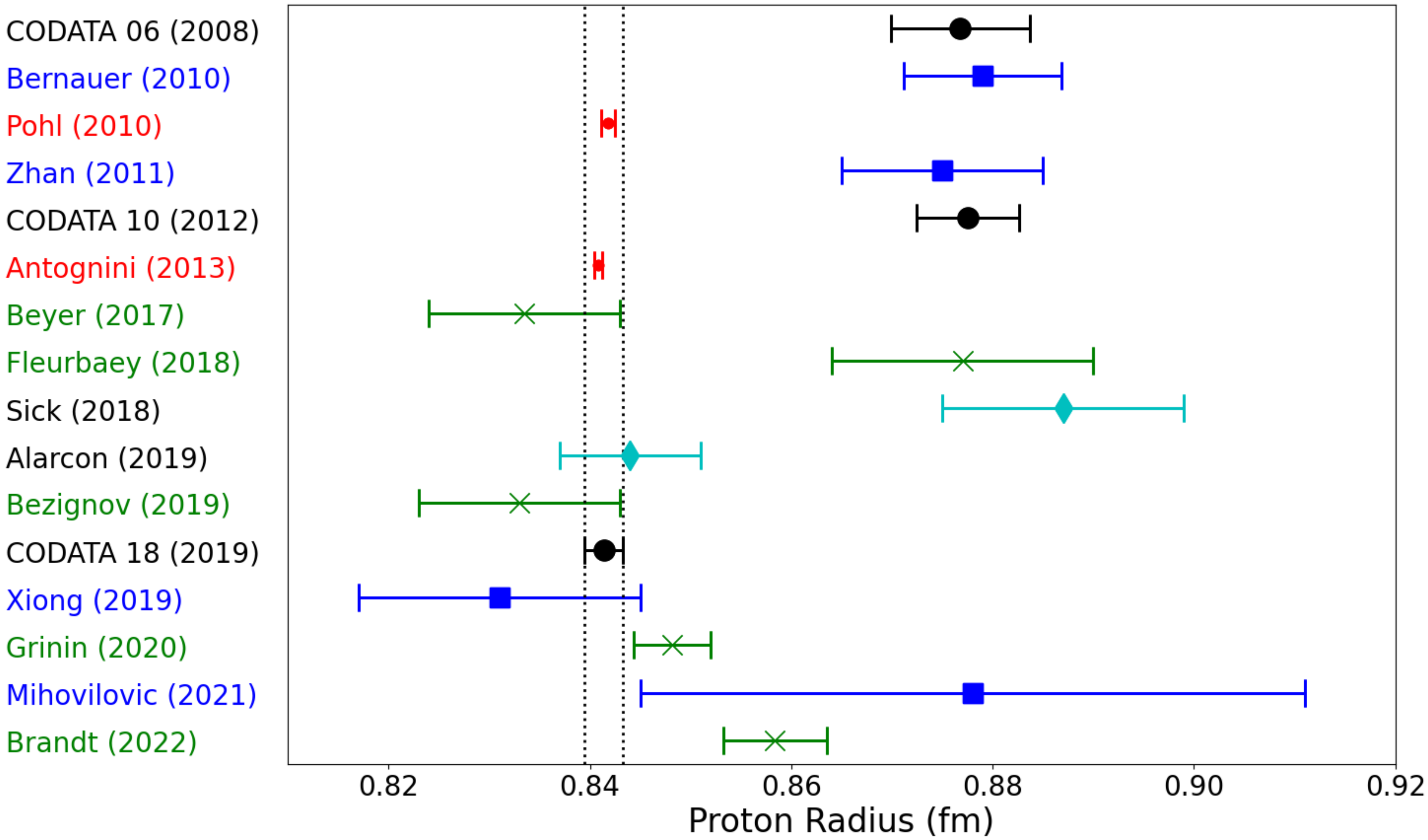


Figure: J. C. Bernauer

Comparison of PRad & Mainz



Muon Measurements:
Spectroscopy – μH

Electron Measurements:
Scattering – e
Spectroscopy – H

Analysis of Measurements:
Re-fitting of e scattering
CODATA

Proton Radius Puzzle Status (2024)

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Proton Radius Puzzle Status (2024)

Rev. Mod. Phys., Vol. 93, No. 2, April–June 2021 025

Eite Tiesinga *et al.*: CODATA recon

The tension between the two approaches determining r_p and r_d has not been fully resolved. In fact, to obtain consistency among the many input data that contribute to the determination of R_∞, r_p, and r_d, a multiplicative expansion factor of 1.6 is applied to their uncertainties. Further experiments are needed.

CODATA inflate uncertainties by 1.6 and say that further experiments are needed. (2021)

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Proton Radius Puzzle Status (2024)

the muonic hydrogen results. We believe more experiments, especially those with improved precision from electron scattering, and new results from muon scattering will be essential to fully resolve this puzzle. To answer a more provocative question, whether there is a difference in the proton charge radius determined from experiments involving electronic (e-p and ordinary

tems, significantly improved p

and also measurements from o

with precision comparable to t

be critical. Pushing the precisi

proven to be the harbinger of

REVIEWS OF MODERN PHYSICS, VOLUME 94, JANUARY–MARCH 2022

The proton charge radius

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Institut für Kernphysik and PRISMA[+] Cluster of Excellence, Johannes Gutenberg Universität, D-55099 Mainz, Germany

(published 21 January 2022)

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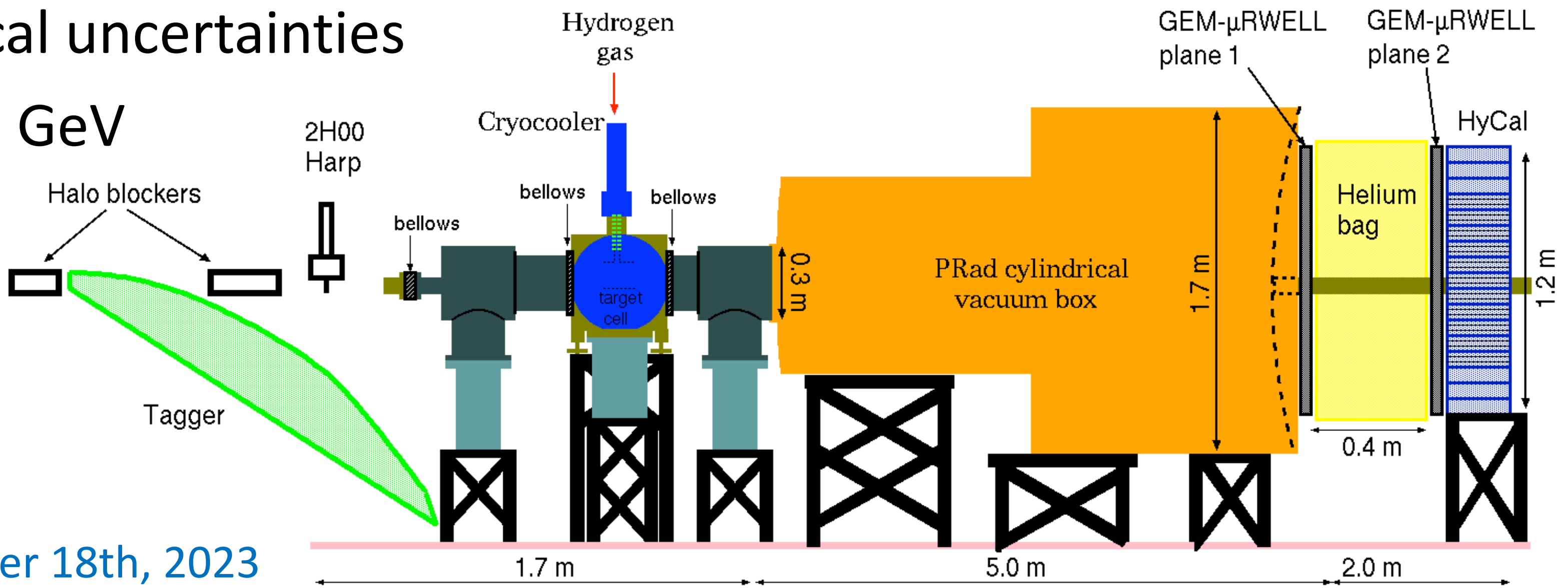
- Improvements for PRad-II:
  - ✓ Better upstream vacuum and halo rejection
  - ✓ Add second GEM plane
  - ✓ Upgrade HyCal: $PbW0_4$, FADC readout
  - ✓ Added scintillators: separate Moller from ep in elect. scattering angular range of 0.5° - 0.8°
  - ✓ Factor of 4 reduction in statistical uncertainties
  - ✓ Beam energies: 0.7, 1.4 and 2.1 GeV

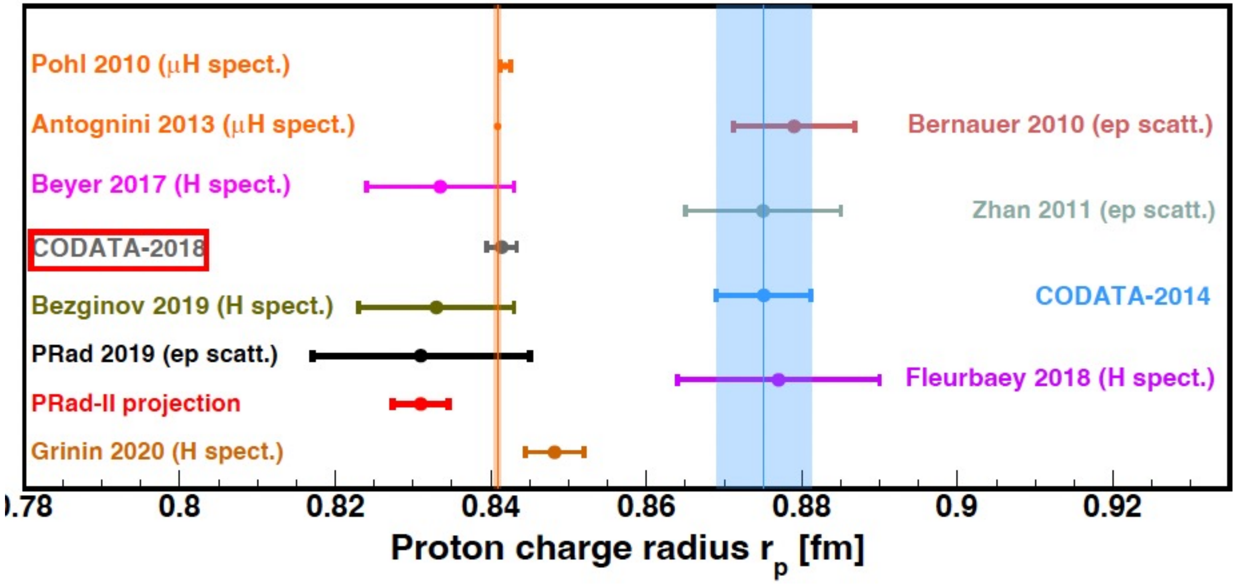
PRad-II Experimental Setup (Side View)

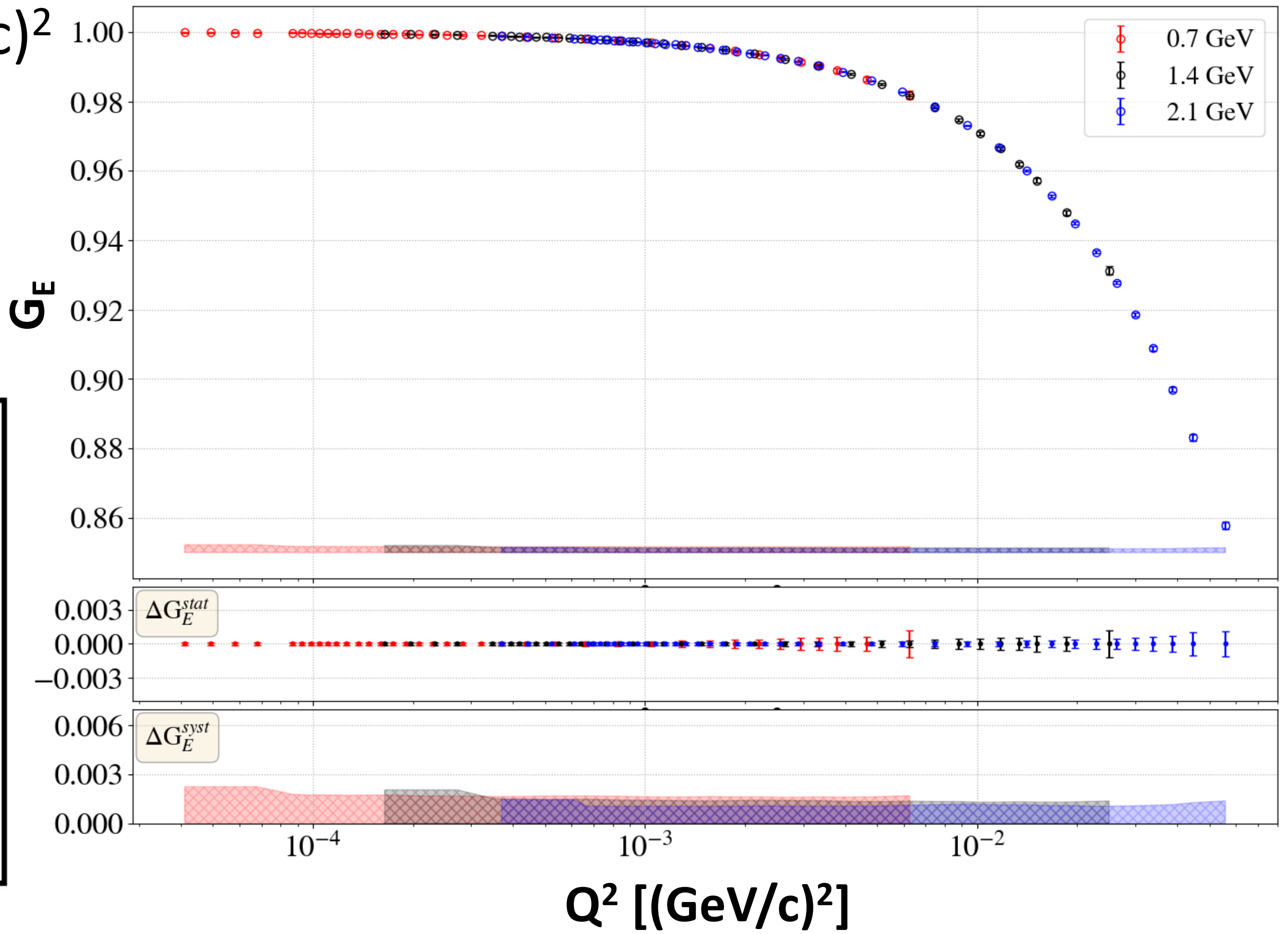


H. Gao: ERICE School on Nuclear Physics, September 18th, 2023

PRad II @ JLab

- Unprecedented low Q^2 : 4×10^{-5} – 0.06 $(GeV/c)^2$
- Aiming for total uncertainty: 0.0036 fm
- Highest rating from JLab PAC 2020





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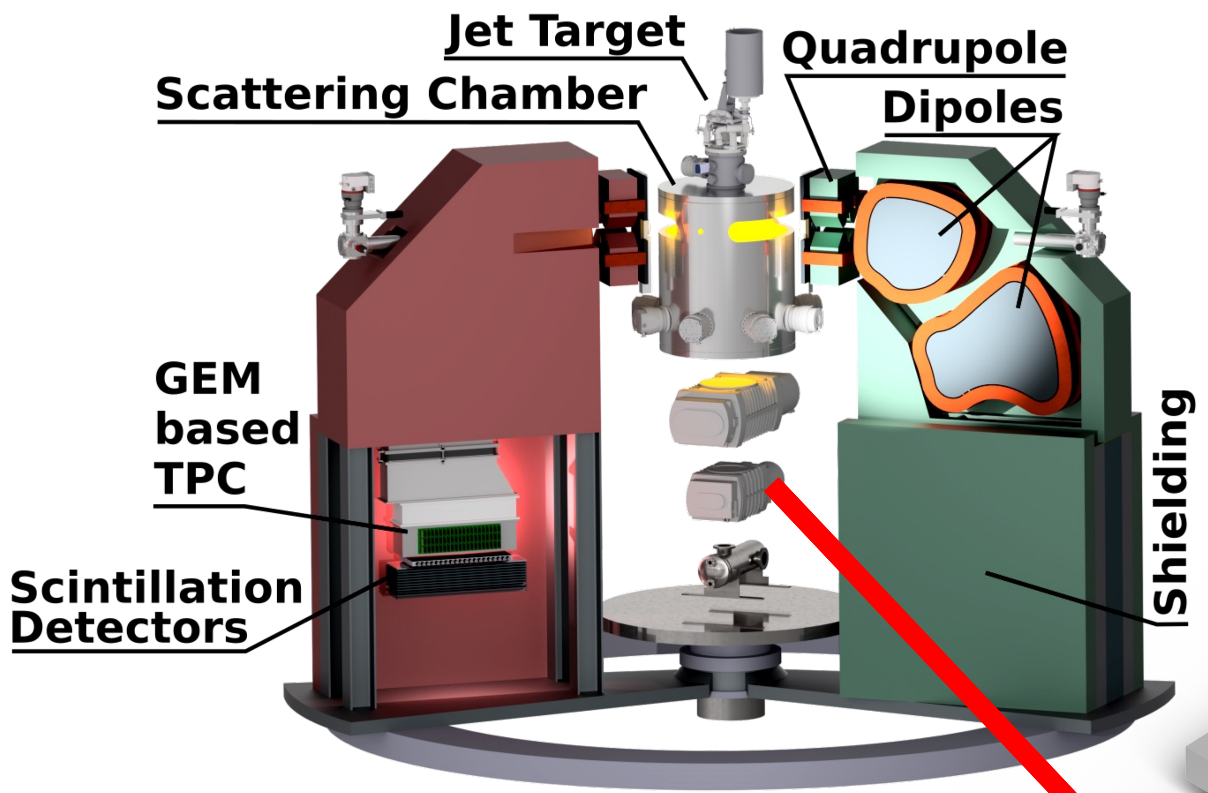
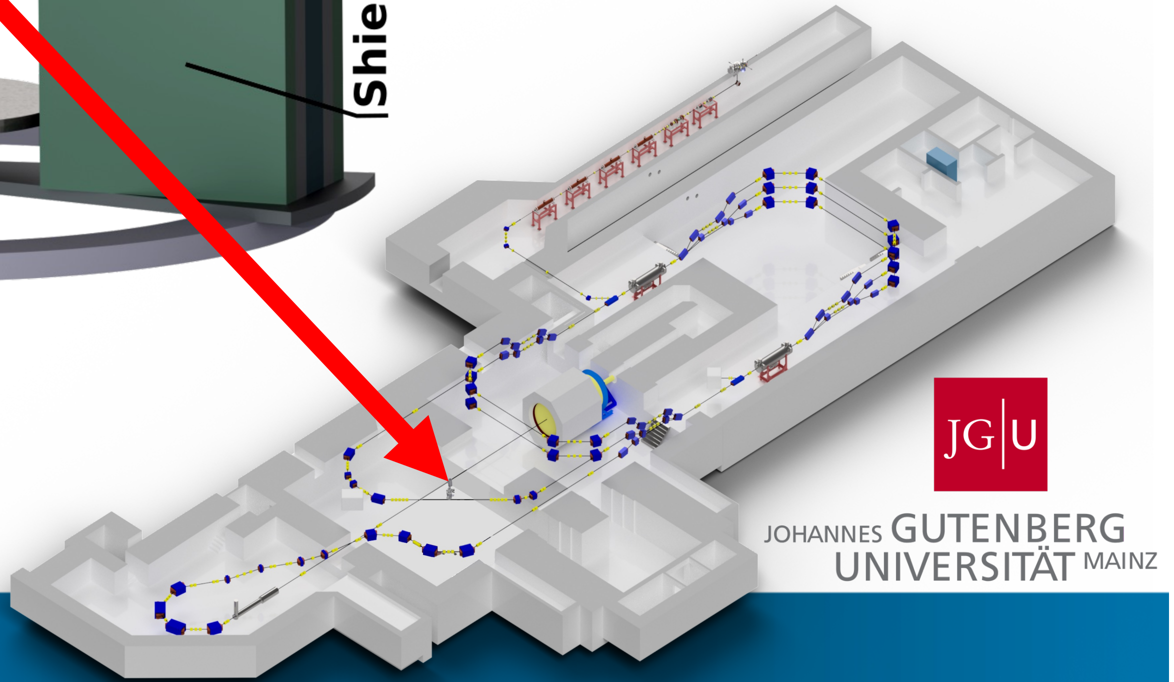
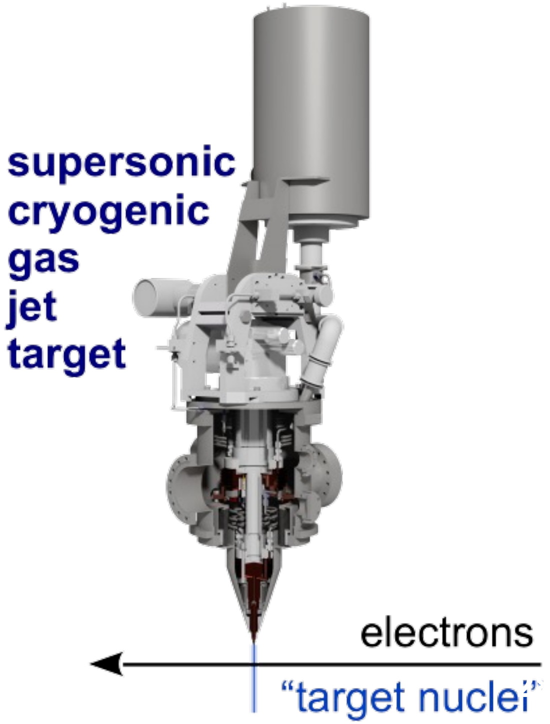
PRad II @ JLab

MAGIX Collaboration @ MESA

- MESA accelerator (first beam 2024/25)
- ERL mode up to 1—10mA, 20 - 105 MeV
- Electron scattering with supersonic cryogenic gas target
- Coverage from $Q^2 = 1.10^{-5}$ to 0.03 $GeV^2 \Rightarrow$ proton radius!



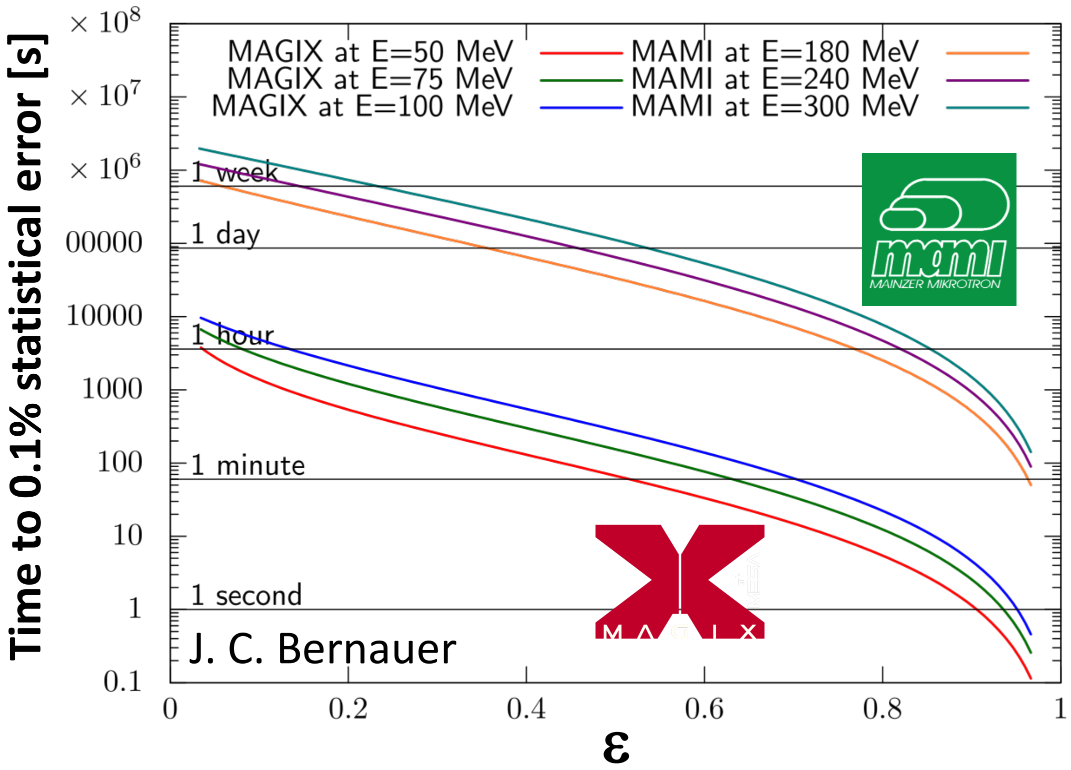


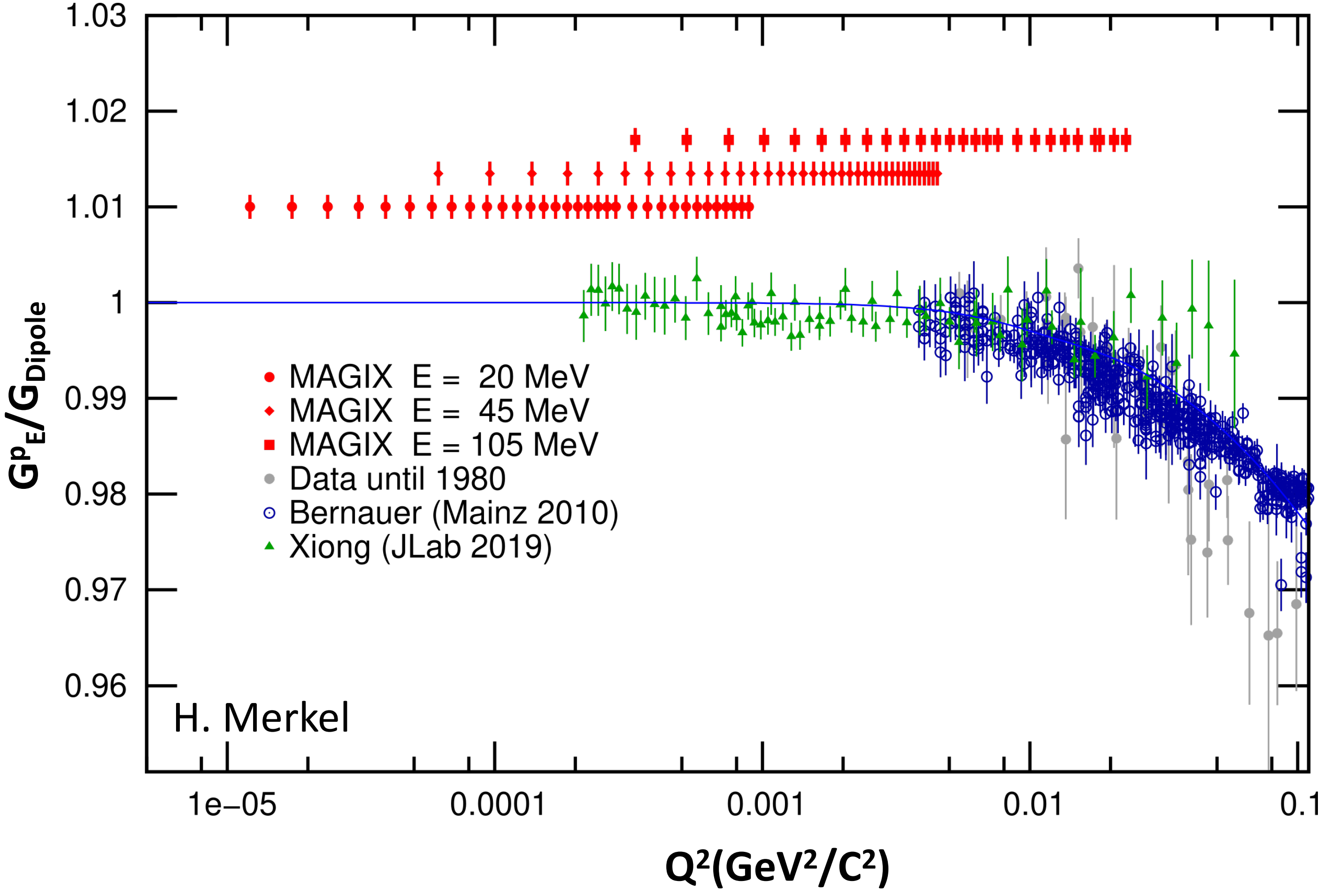


MAGIX info: S. Schlimme

JOHANNES GUTENBERG UNIVERSITÄT MAINZ

- First beam on solid target: 2025
- First data on proton: 2027

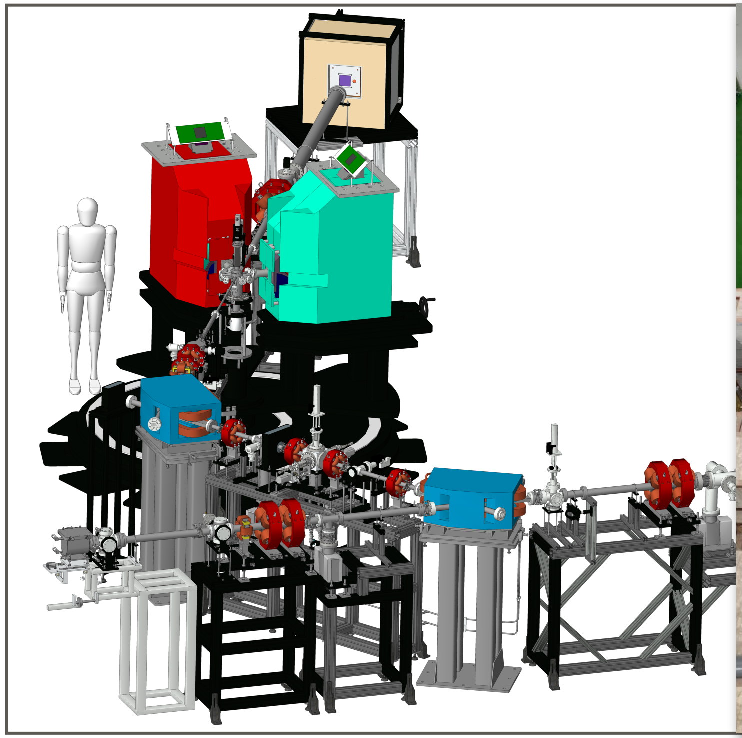


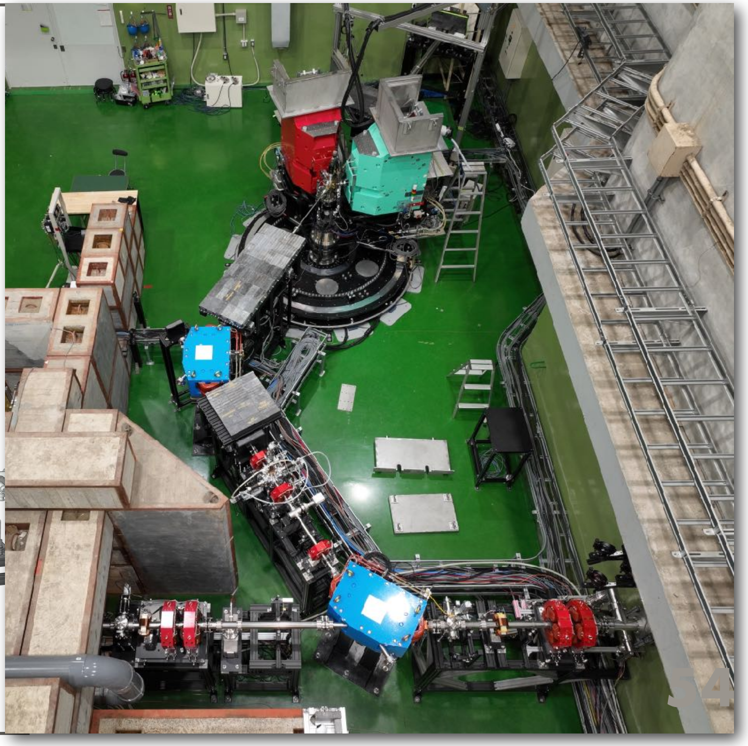


MAGIX info: S. Schlimme

ULQ2 @ ELPH Tohoku

- E_0 ~10–60 MeV; θ_e ~ 30°–150°;
- Q^2 ~ 0.0003 – 0.008 $(GeV/c)^2$
- Twin magnetic spectrometers
- Commissioning since 2019
- Production running 2023 – 2024
- Production running with CH_2 target
- Normalization to ^{12}C elastic scattering
- Expected errors 10^{-3} on σ_{ep}, 1% on r_p





ULQ2 info by T. Suda and Y. Honda

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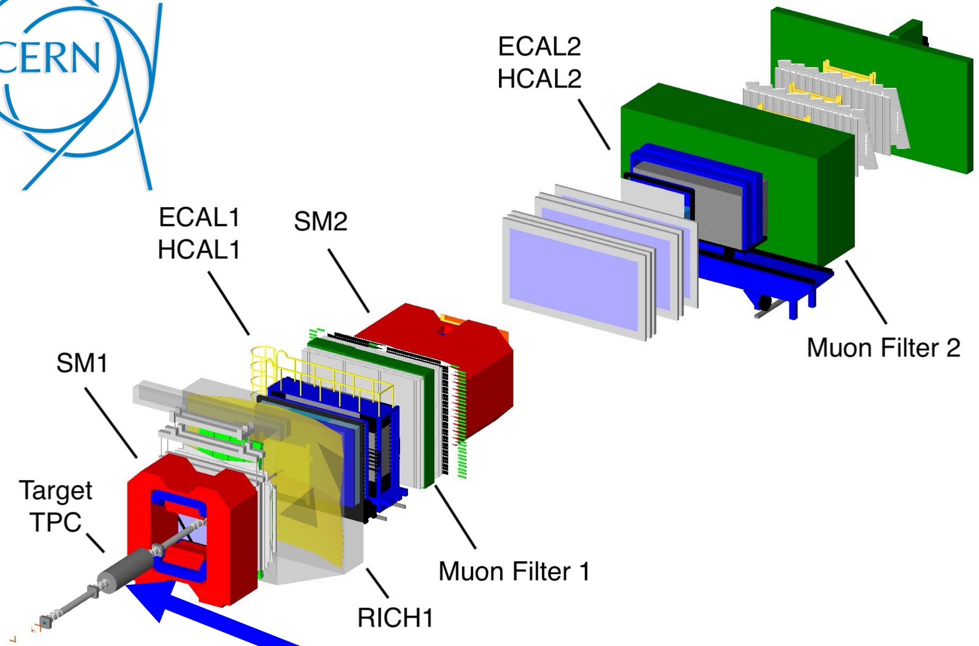
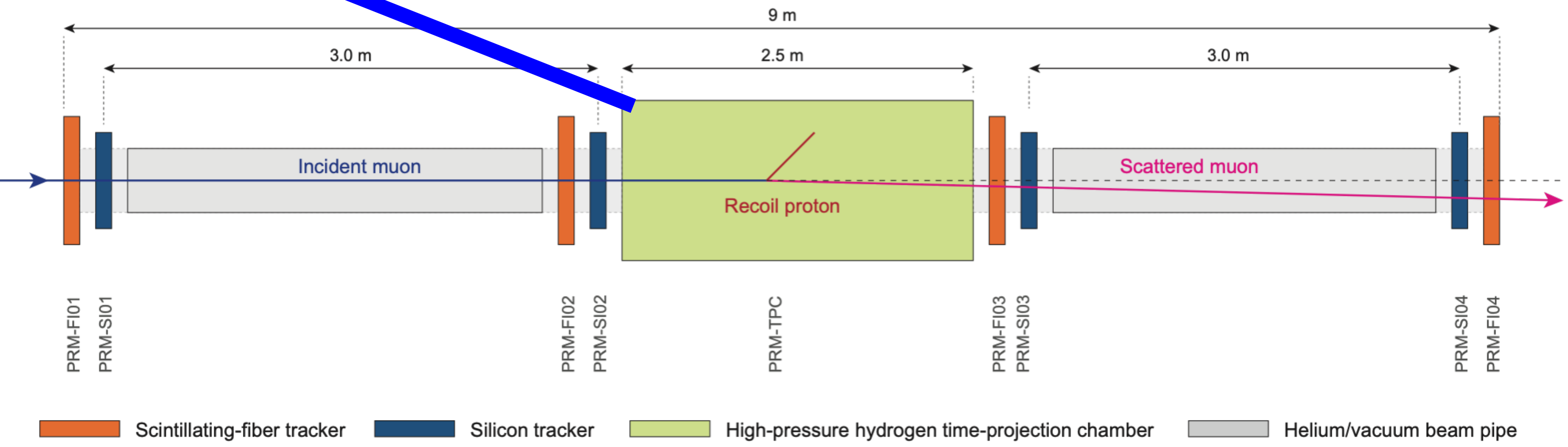
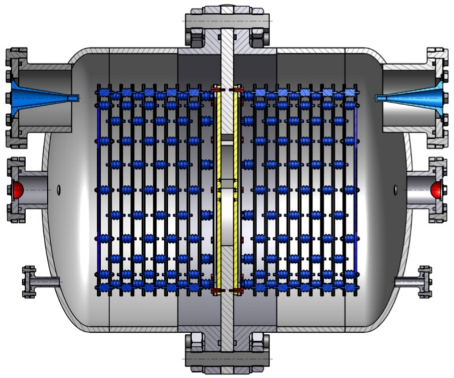


- 100 GeV **muon** beam, CERN SPS M2 beam line
- Active-target TPC with high-pressure H_2
- high-precision tracking and spectrometer for muon reconstruction
- Goal: 70 million elastic scattering events in the range $10^{-3} < Q^2 < 4x10^{-2}$ $(GeV/c)^2$
- Precision on the proton radius ~0.01 fm



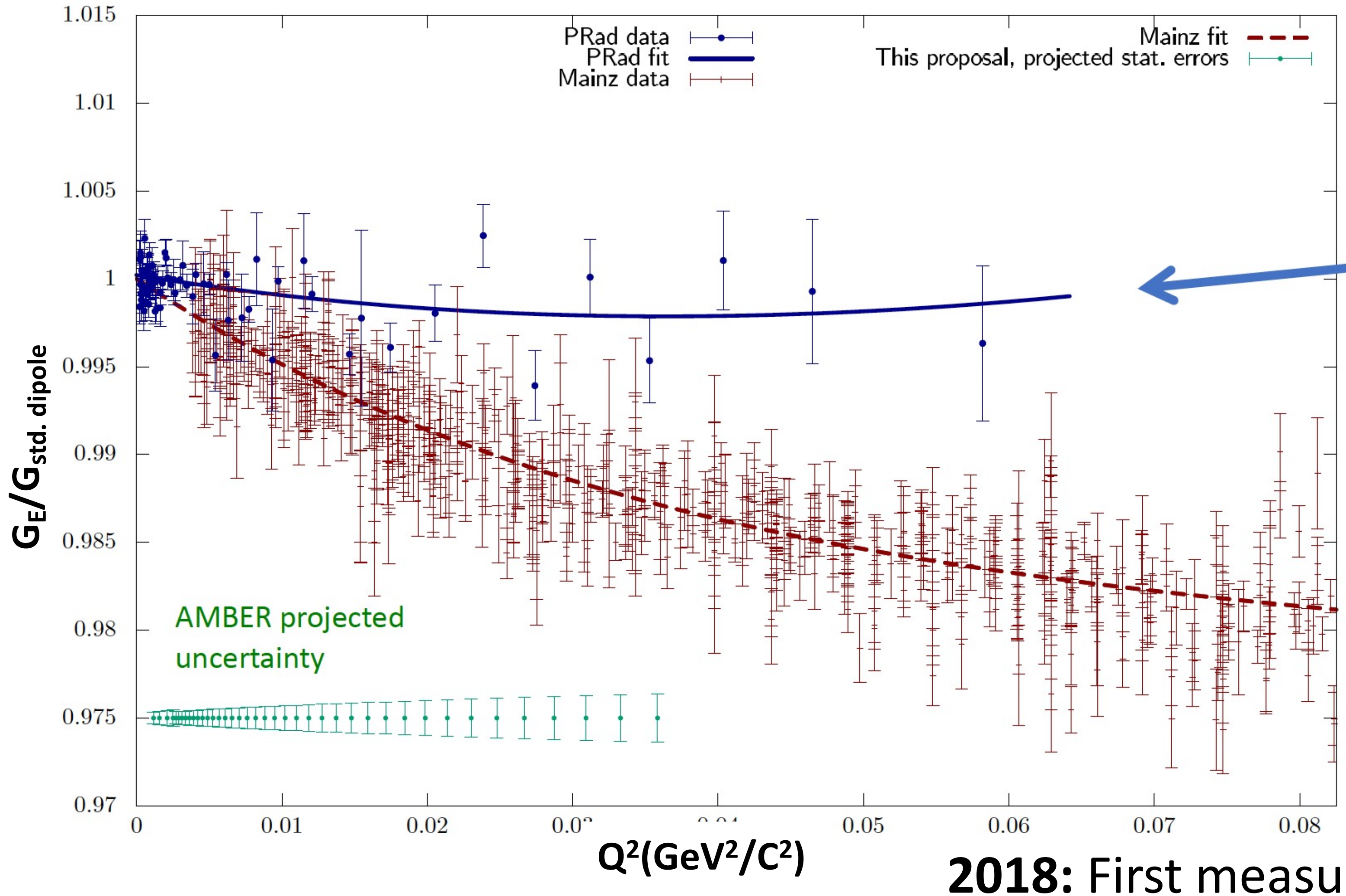


TPC, 20 bar, ~ 50 keV precision on recoiling proton

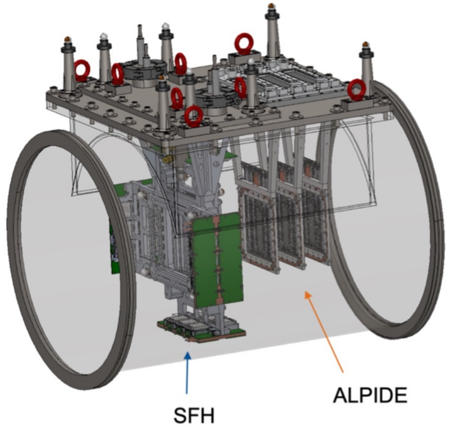
AMBER info: J. Friedrich

AMBER — Apparatus for Meson and Baryon Experimental Research

AMBER @ CERN



New Si and SciFI
Unified Tracking System (UTS)



Proton Radius Experiment at Jefferson Lab

PRoton Radius

MAMI MAINZER MIKROTRON

Figure: J. C. Bernauer

AMBER info: J. Friedrich

AMBER Apparatus for Meson and Baryon Experimental Research @ CERN

2018: First measurement H_2 TPC in high energy μ beam

2021: First test run with IKAR TPC and existing tracking detectors from COMPASS

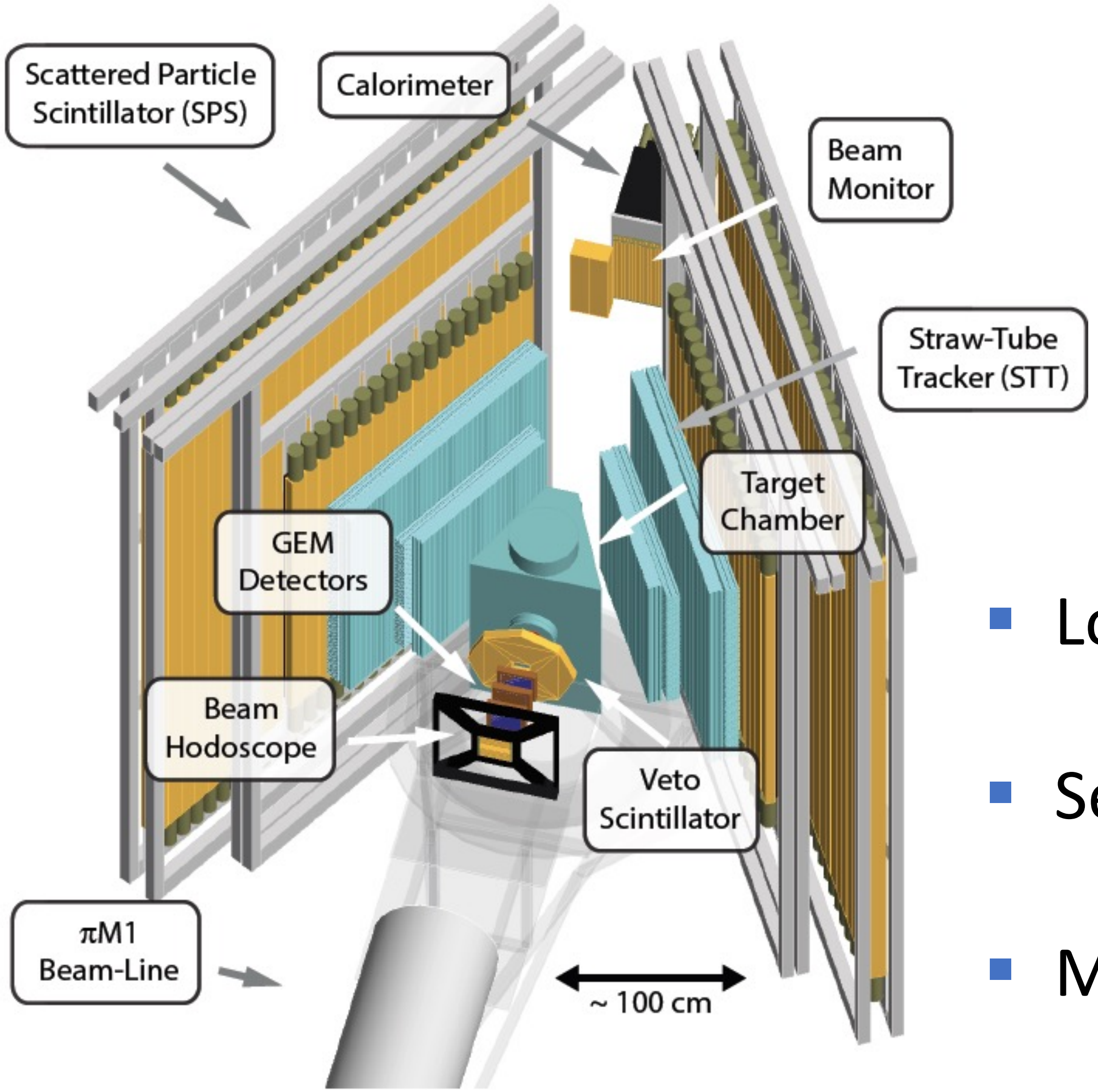
2023: Test run with new free-running DAQ

2024: Test run with IKAR TPC and UTS prototypes

2025: Physics run with new TPC and final UTS

- MUSE in PiM1 beamline of Paul Scherrer Institute (mixed μ/e/π beam)
- Allows direct comparison of μ and e, cross sections, form factors
- Comparison of charge states, μ^+/μ^-, e^+/e^-, two photon effects
- Extraction of radii using e and μ in same experiment

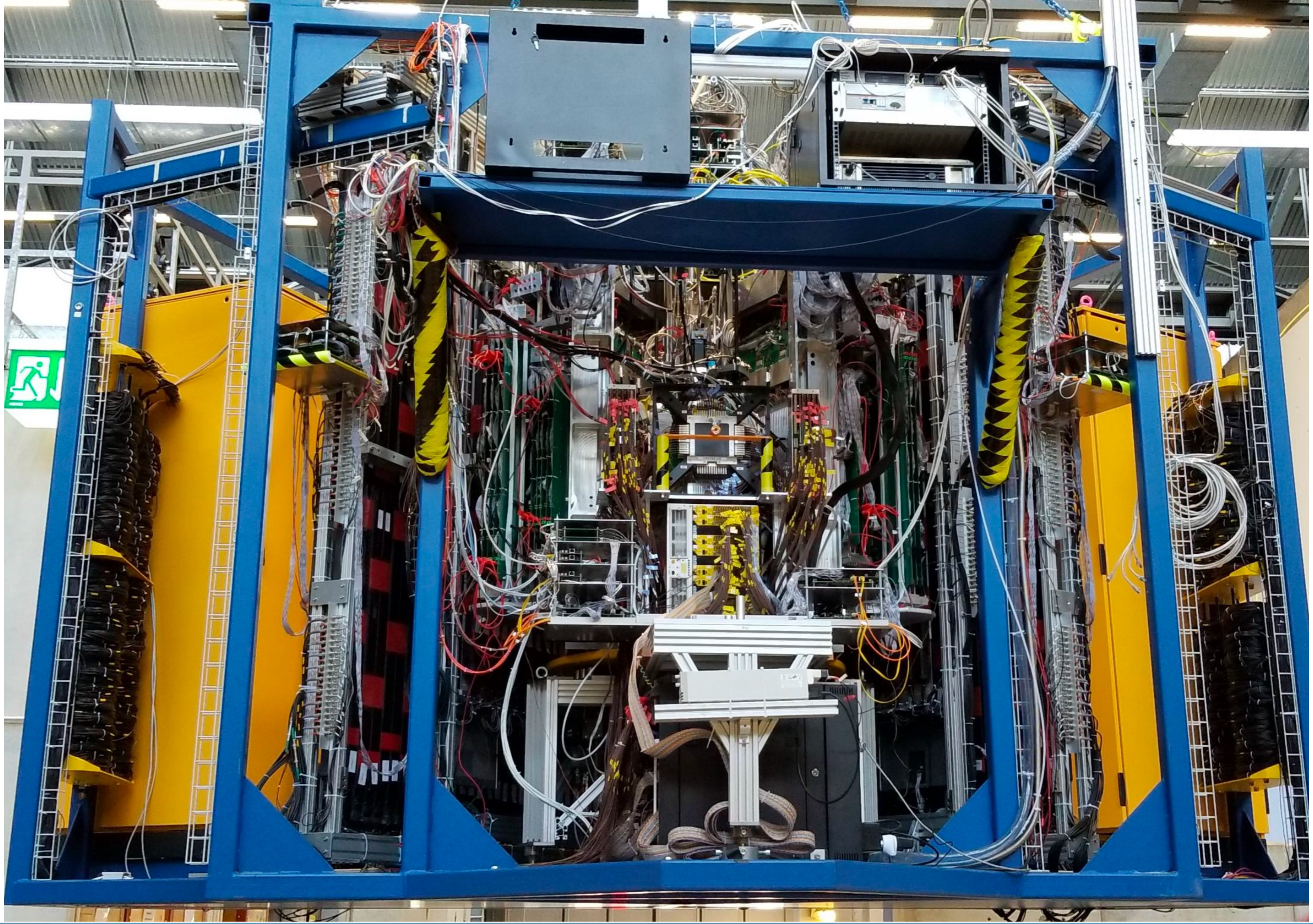
MUSE



θ ≈ 20° – 100°
$Q^2 \approx 0.002 - 0.07\ GeV^2$
3.3 MHz total beam flux
≈ 2-15% μ's
≈ 10-98% e's
≈ 0-80% π's

- Low beam flux
  - ✓ Large angle, non-magnetic detectors
- Secondary beam
  - ✓ Tracking of beam particles to target
- Mixed beam
  - ✓ Identification of beam particle in trigger

MUSE



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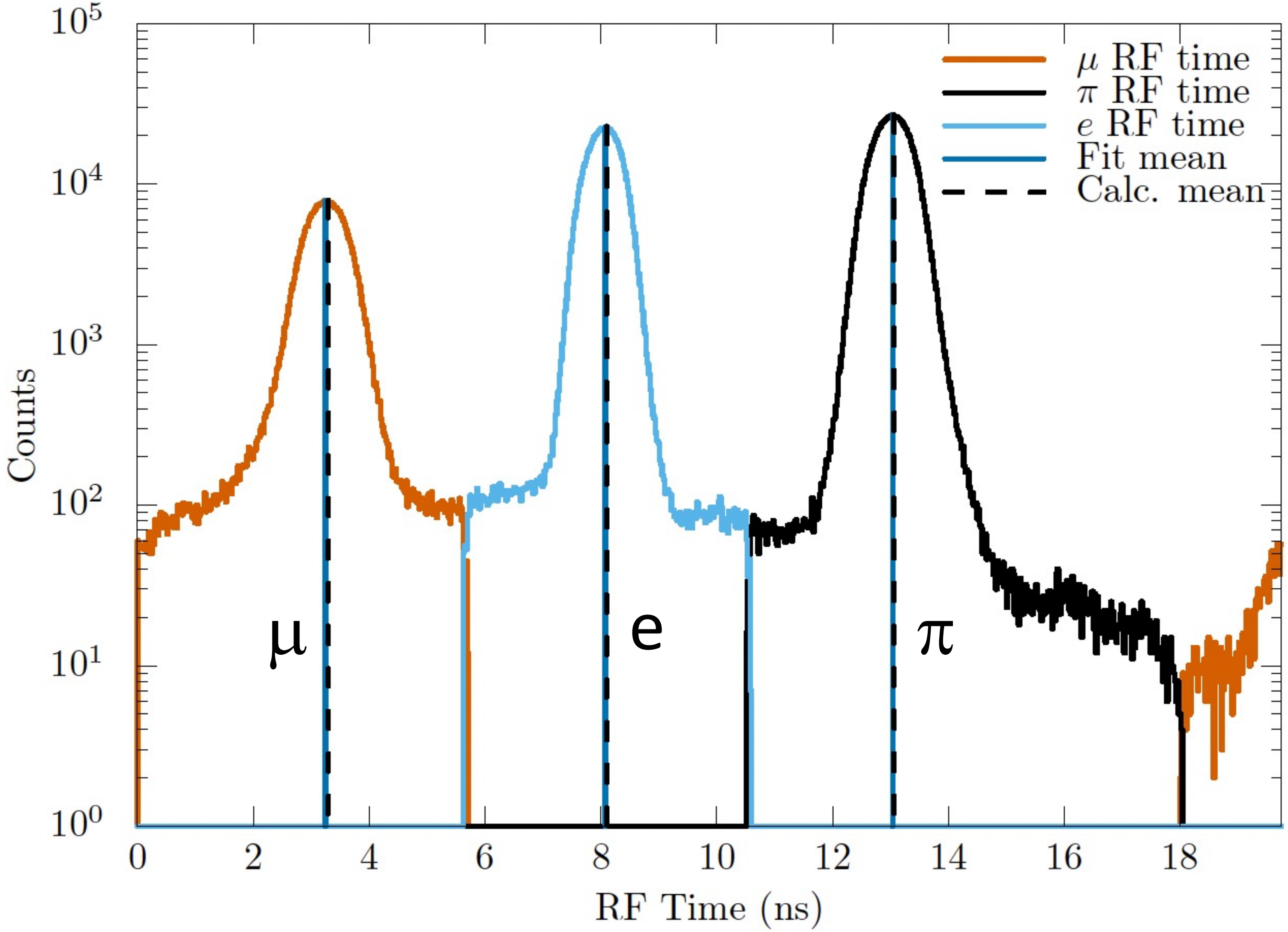
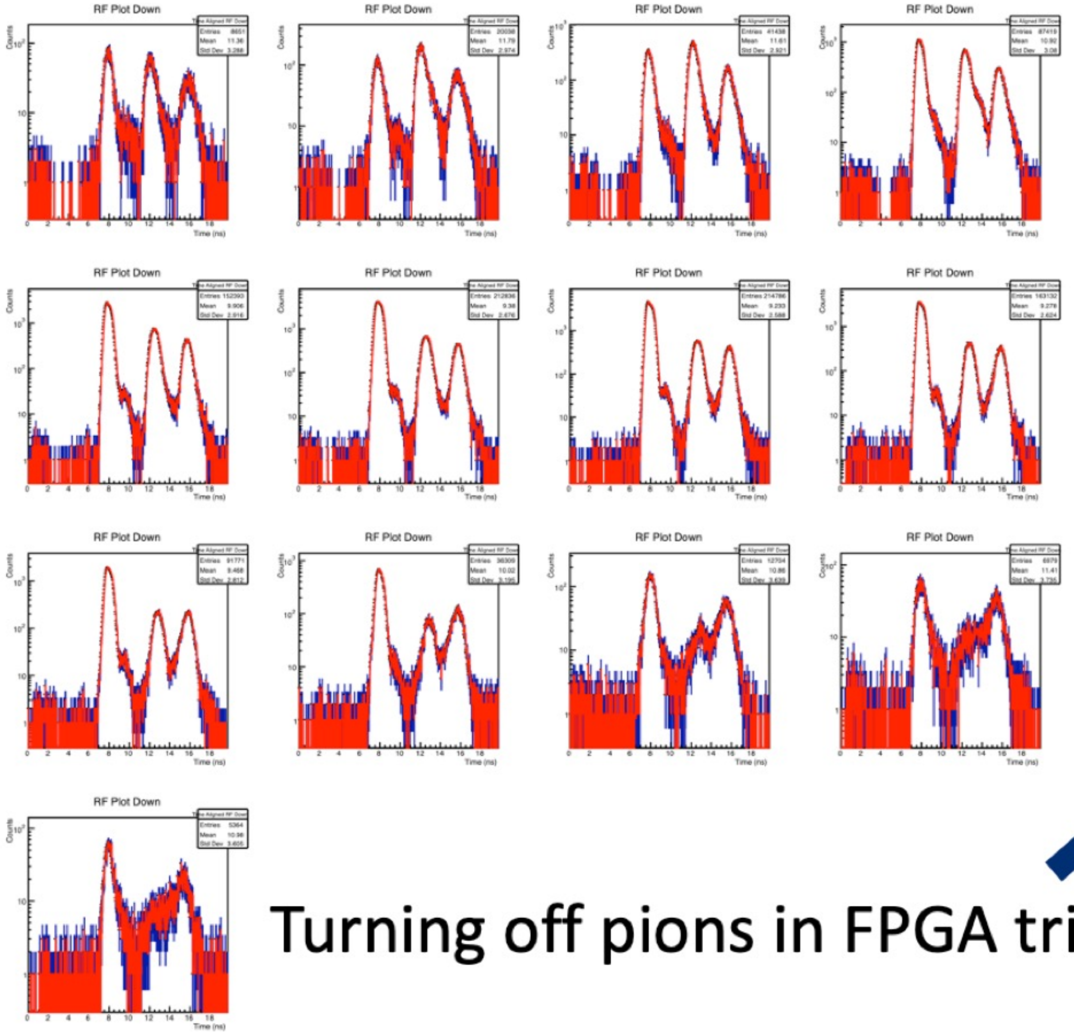


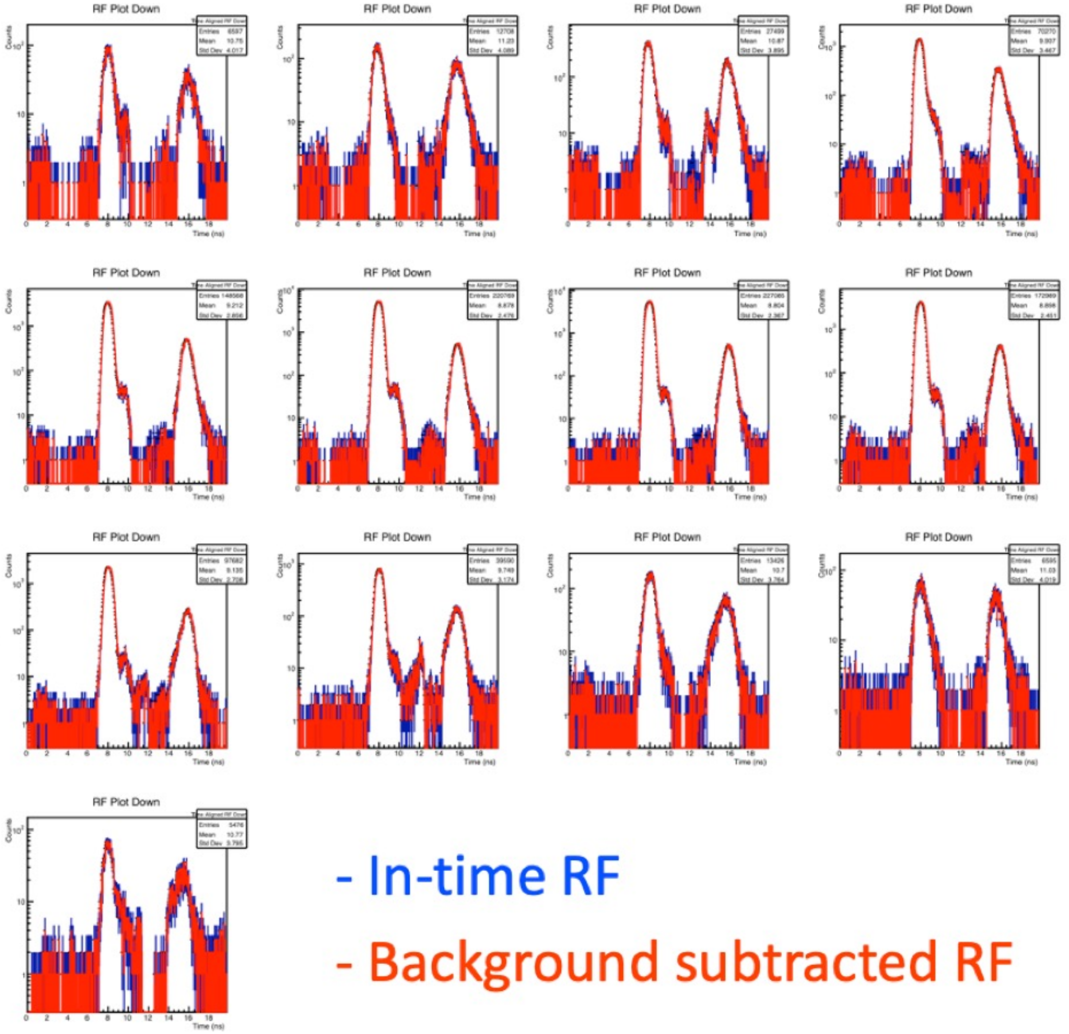
BH – RF Time @ 160 MeV/c
Used for Particle ID

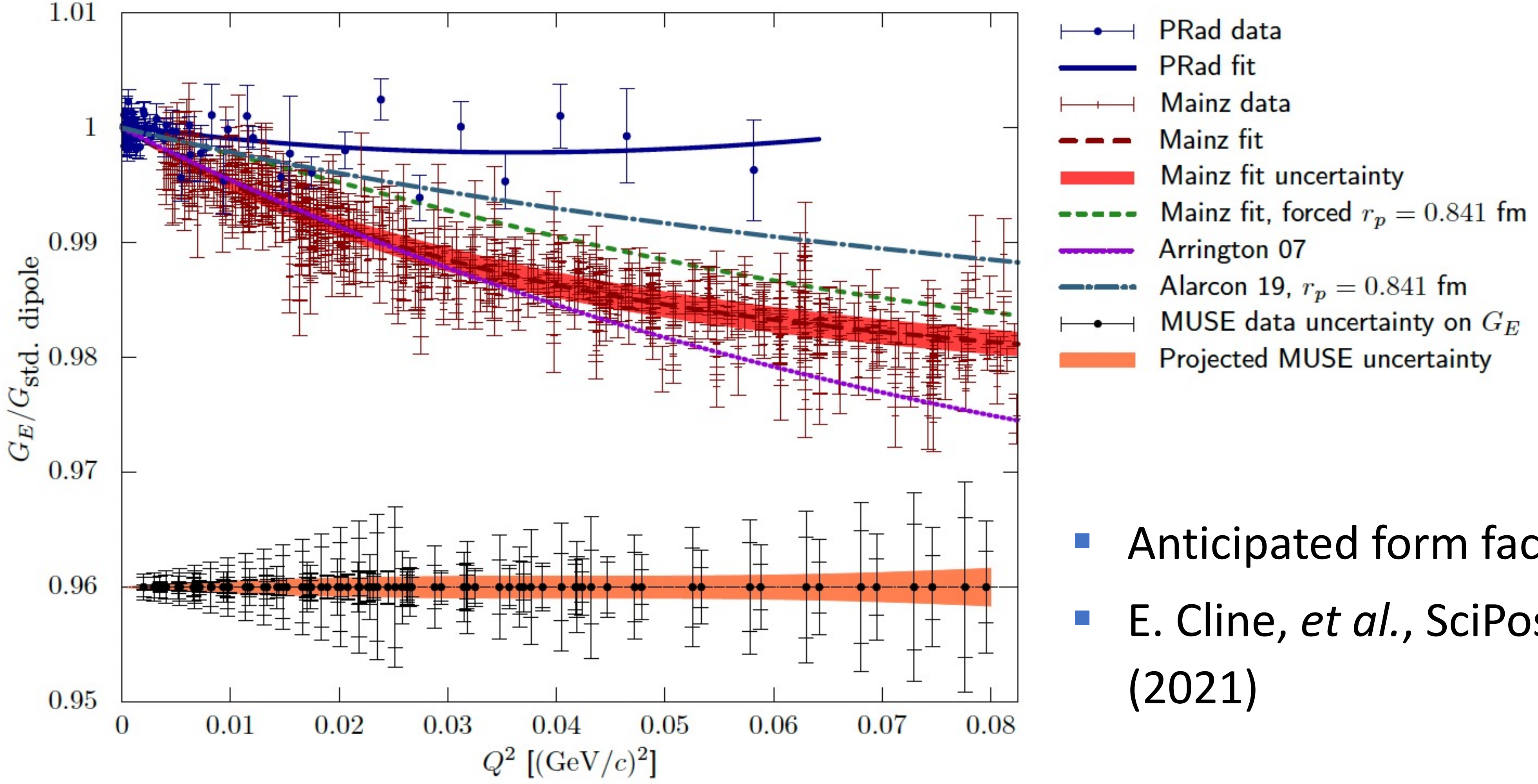
Figure from:
MUSE Analysis Report
December 2023

MUSE Beam momenta:
115, 160, 210 MeV/c



Turning off pions in FPGA trigger

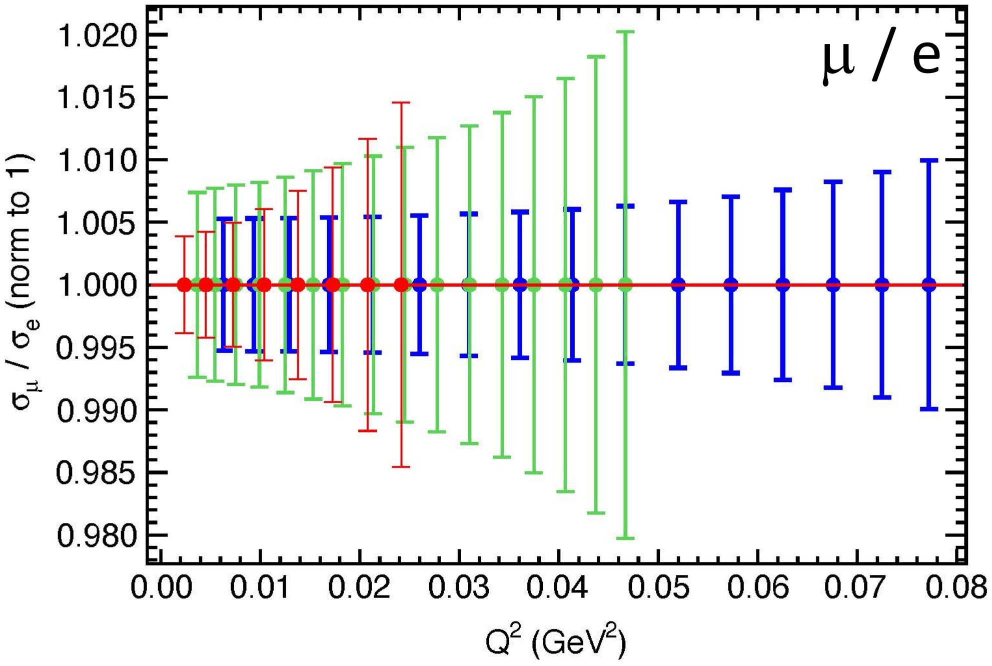


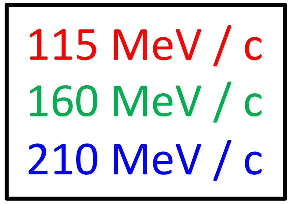


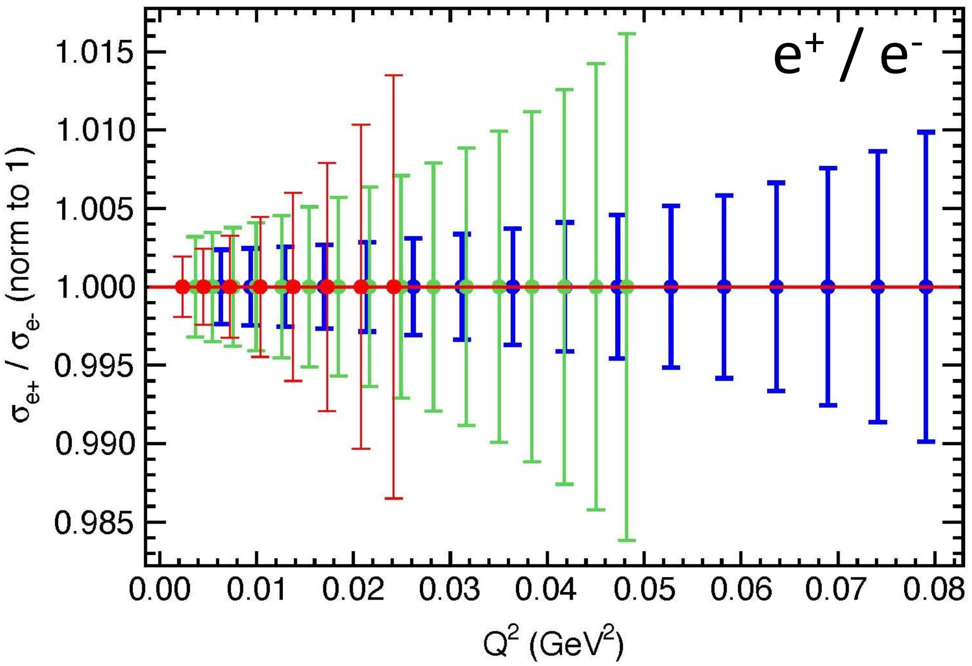
- Anticipated form factor uncertainty
- E. Cline, *et al.*, SciPost Phys. Proc. 5, 023 (2021)

Anticipated Results

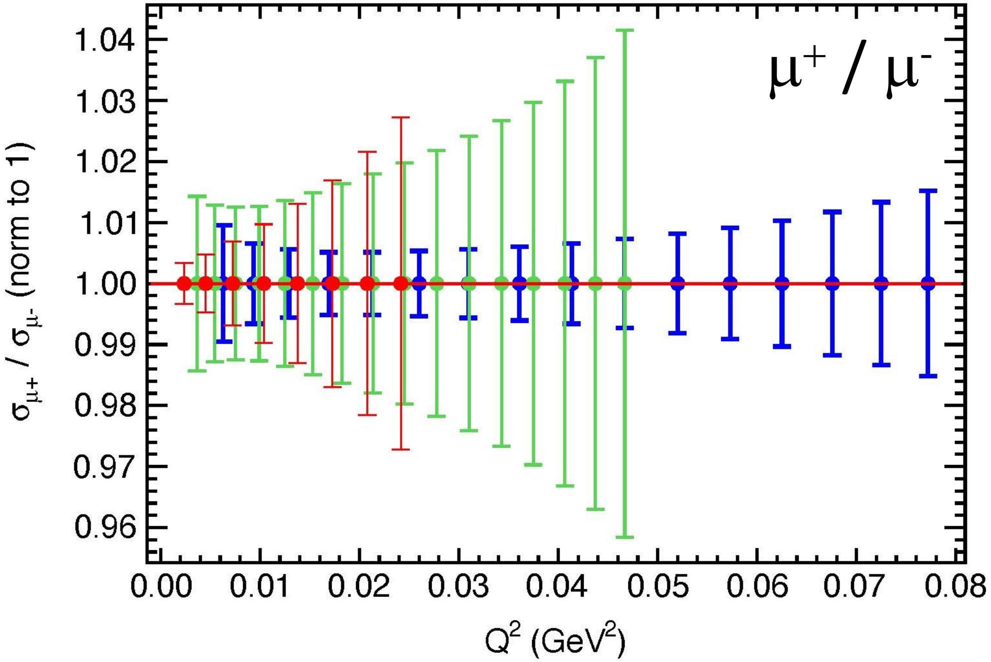
Anticipated Results



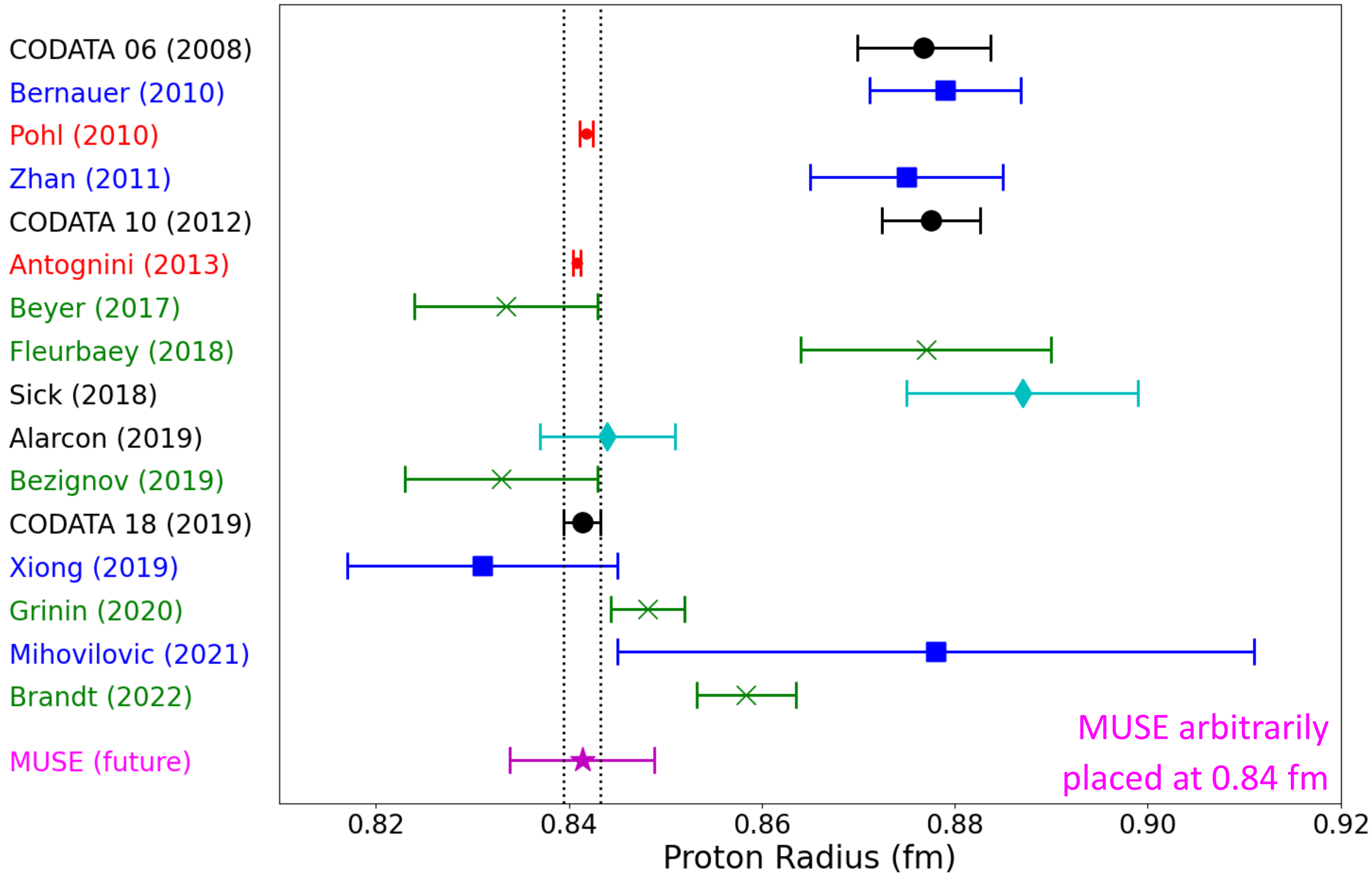




- Stat. uncertainty plotted, systematic better than 0.5%
- Based on assumption of one year of running
- ~20% of scattering data needed taken in first 2023 run



Anticipated Results



- Currently taking production data (2022 – 2025)
- MUSE only experiment measuring with e and μ in same experiment
- MUSE accesses both charge states
- Cancellation of uncertainties gives

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

Experiment	e / μ	Q^2 (GeV/c)^2	Status
AMBER	μ^+, μ^-	0.001 – 0.04	Test runs ongoing, physics run 2025
MAGIX	e^-	0.00001 – 0.03	Beam 2025, data on proton 2027
MUSE	e^+,e^-, μ^+, μ^-	0.002 – 0.07	Physics running, unblinding 2025/6
PRad II	e^-	0.00004 – 0.06	Approved by JLab PAC
ULQ2	e^-	0.0003 – 0.008	Production running 2023-24

- Proton Radius Puzzle remains unresolved
- Vibrant array of scattering experiments, e and μ
- Each with different beam / systematics
- Many spectroscopy efforts underway!

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Conclusion

PRoton Radius

AMBER Apparatus for Meson and Baryon Experimental Research

MAGIX MESA

MUSE

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