THE GEORGE WASHINGTON UNIVERSITY
WASHINGTON, DC

The Proton Radius Puzzle: Are We Still Puzzled?

Evangeline J. Downie

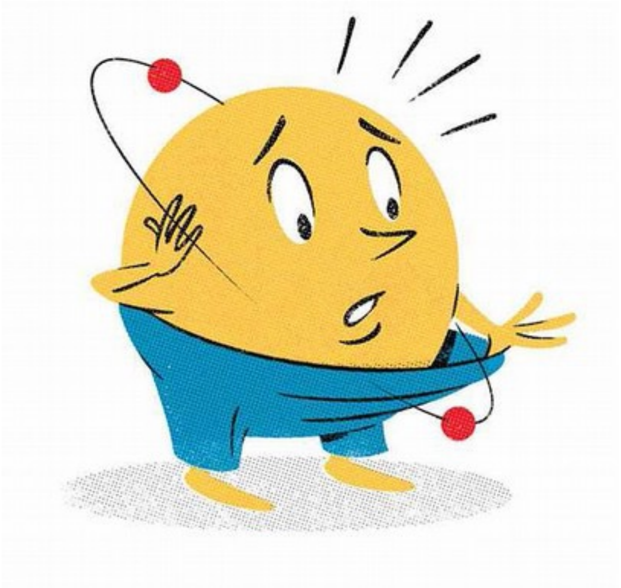
SPIN 2023

Award:
PHY-2310026

The Proton Radius Puzzle (2010)

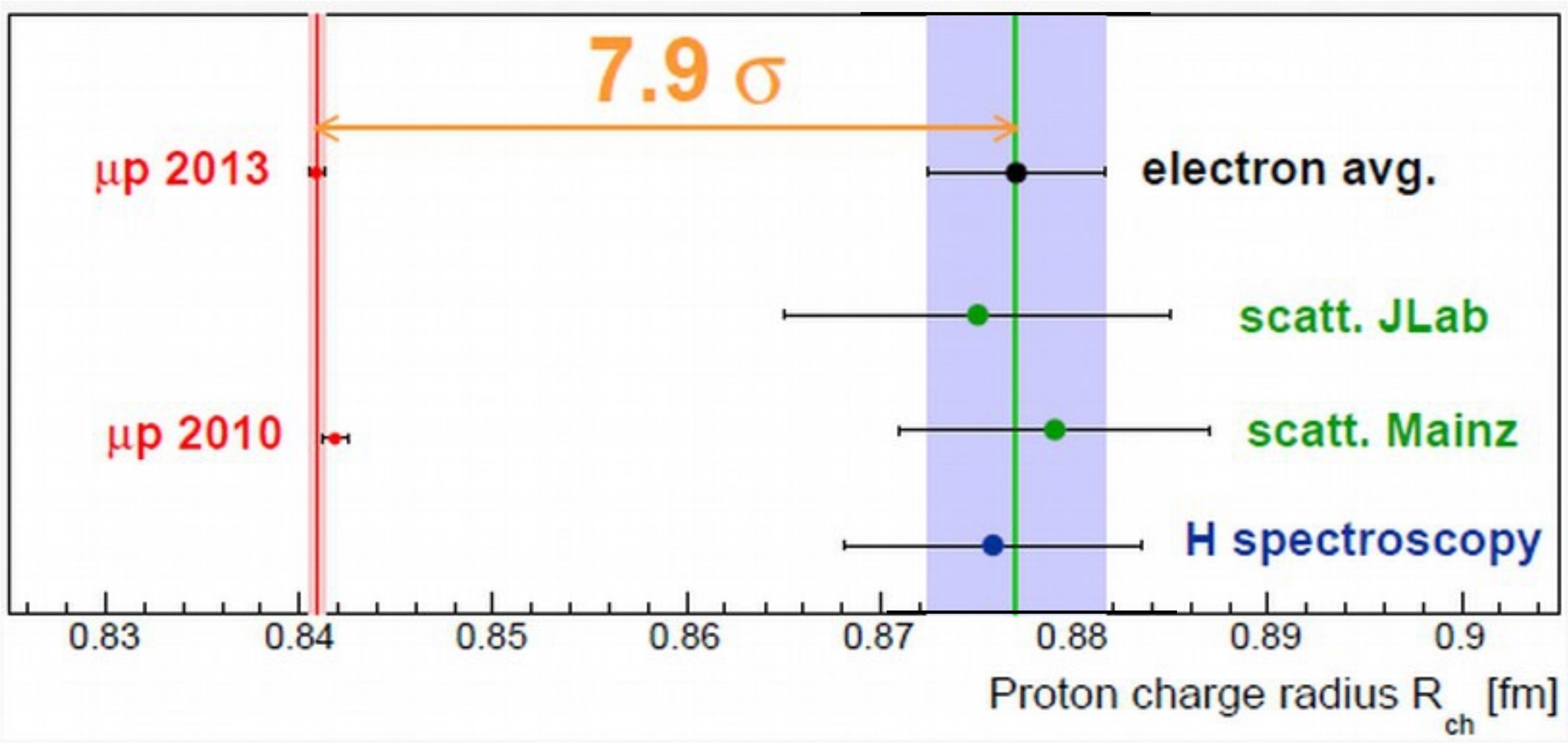
Nature **466**, 213 (2010)

Discrepancy between radius measured with electrons and muons



The New York Times

The Proton Radius Puzzle (2010)



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

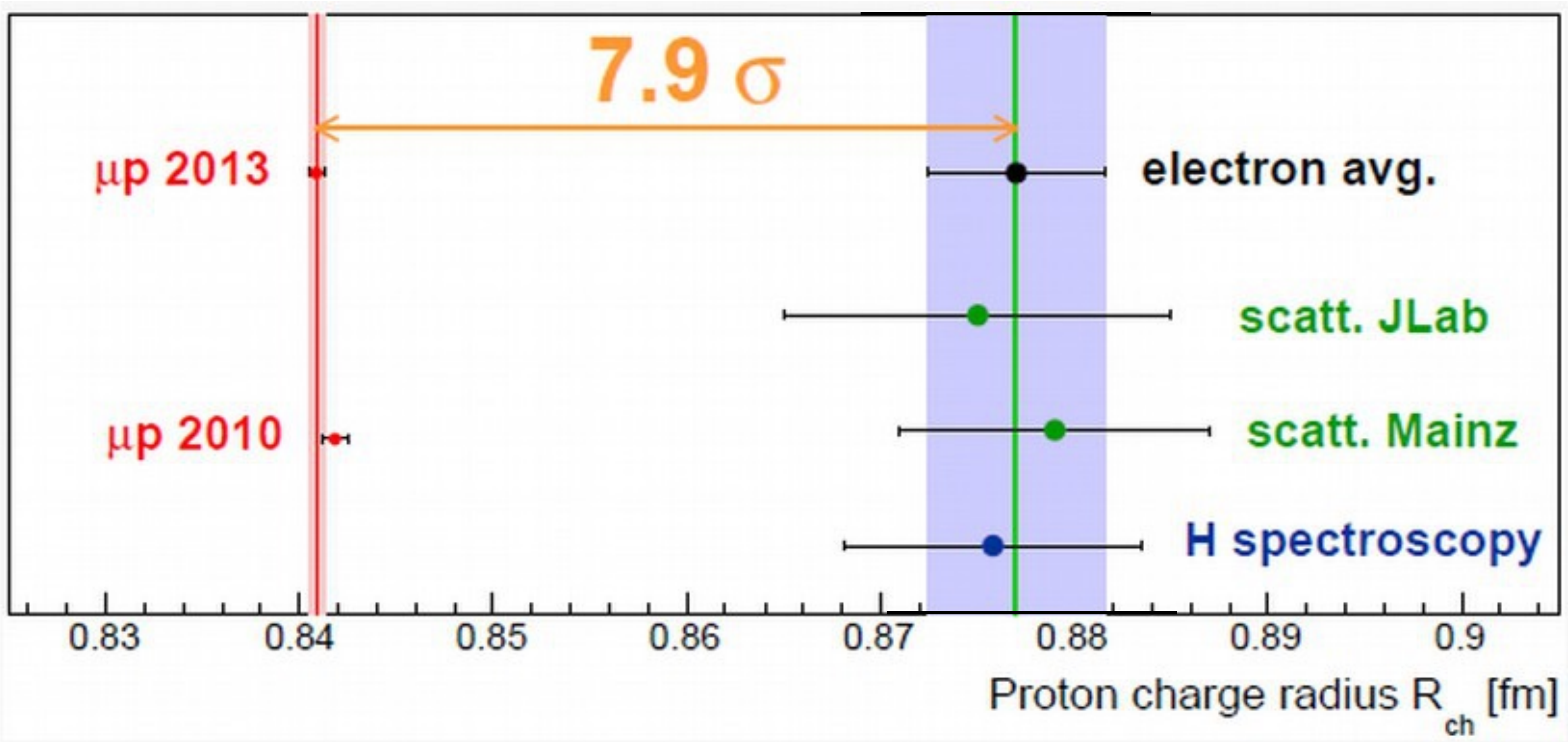
Jlab: Zhan *et al.*
PLB **705,** 59-64 (2011)

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

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

The Proton Radius Puzzle (2013)

THE GEORGE WASHINGTON UNIVERSITY
WASHINGTON, DC



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

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

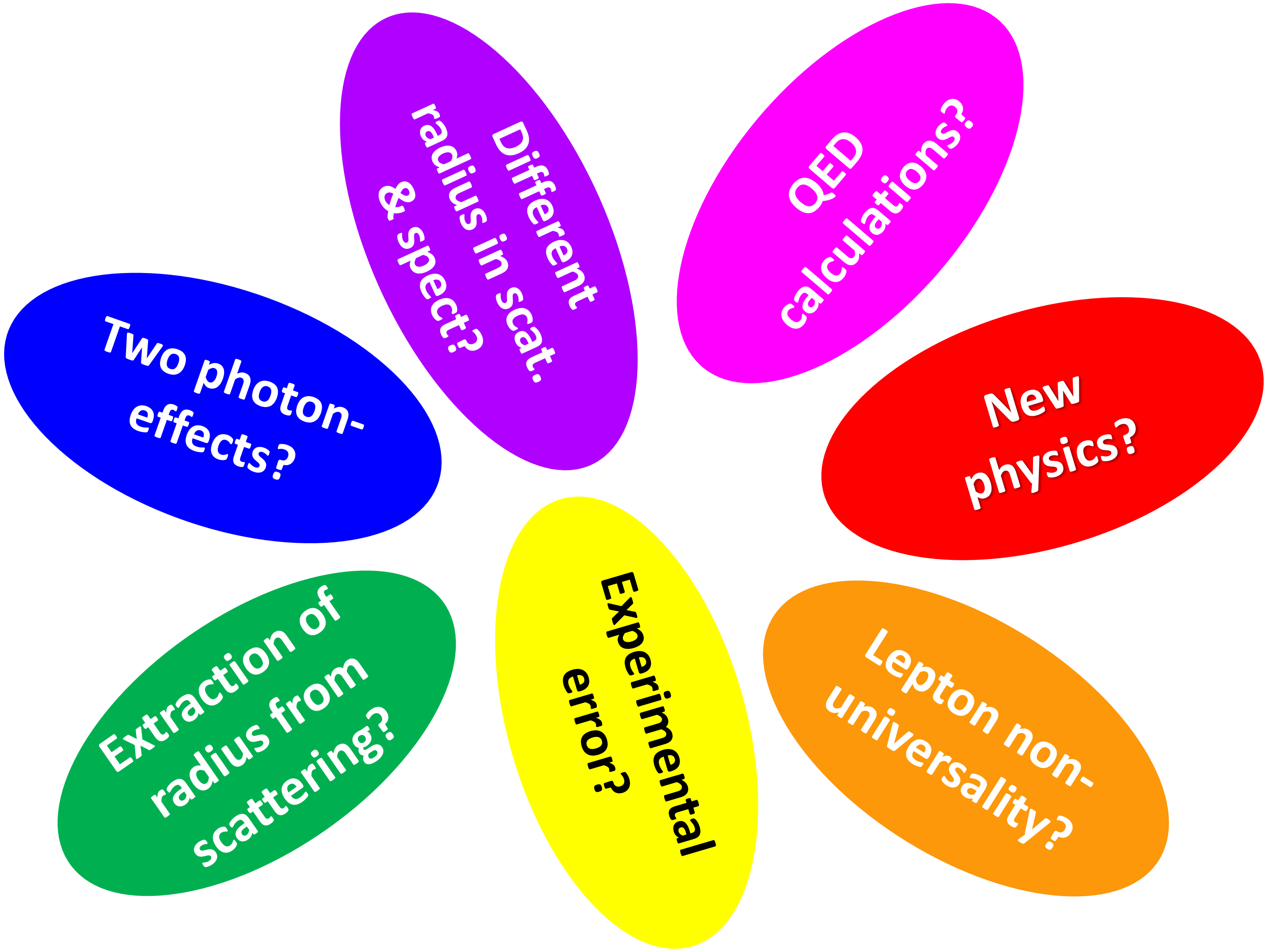
Mainz: Bernauer *et al.*
PRL **105**, 242001 (2010)

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

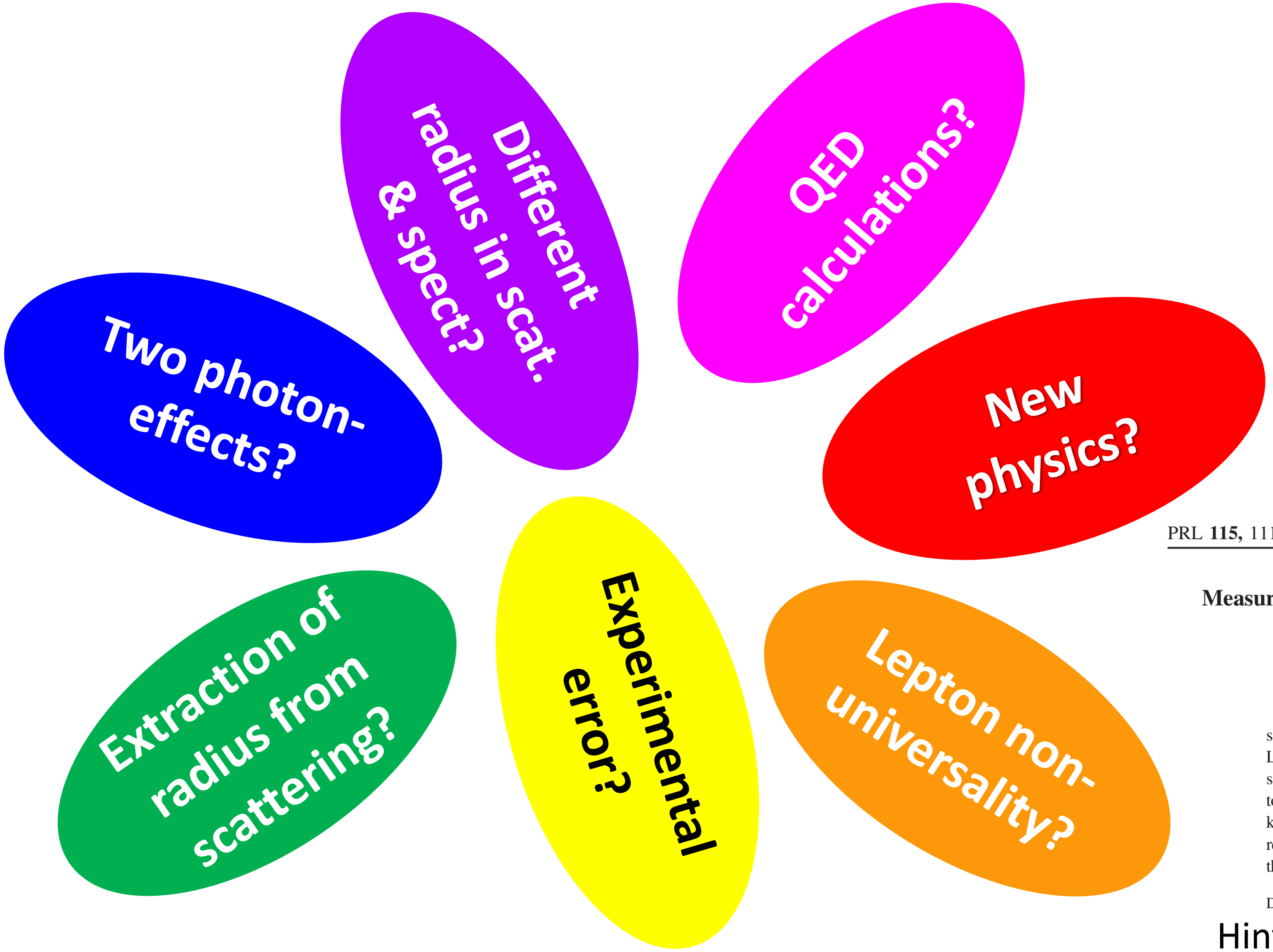
$$R^2 = -6 \left. \frac{dG_e(q^2)}{dq^2} \right|_{q=0}$$

The Proton Radius Puzzle (2013)

How to resolve the PRP?



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



PRL **115,** 111803 (2015) PHYSICAL REVIEW LETTERS week ending 11 SEPTEMBER 2015

Measurement of the Ratio of Branching Fractions $\mathcal{B}(\bar{B}^0 \to D^{*+}\tau^-\bar{\nu}_\tau)/\mathcal{B}(\bar{B}^0 \to D^{*+}\mu^-\bar{\nu}_\mu)$

R. Aaij *et al.*[*]
(LHCb Collaboration)

(Received 30 June 2015; published 9 September 2015; corrected 14 September 2015)

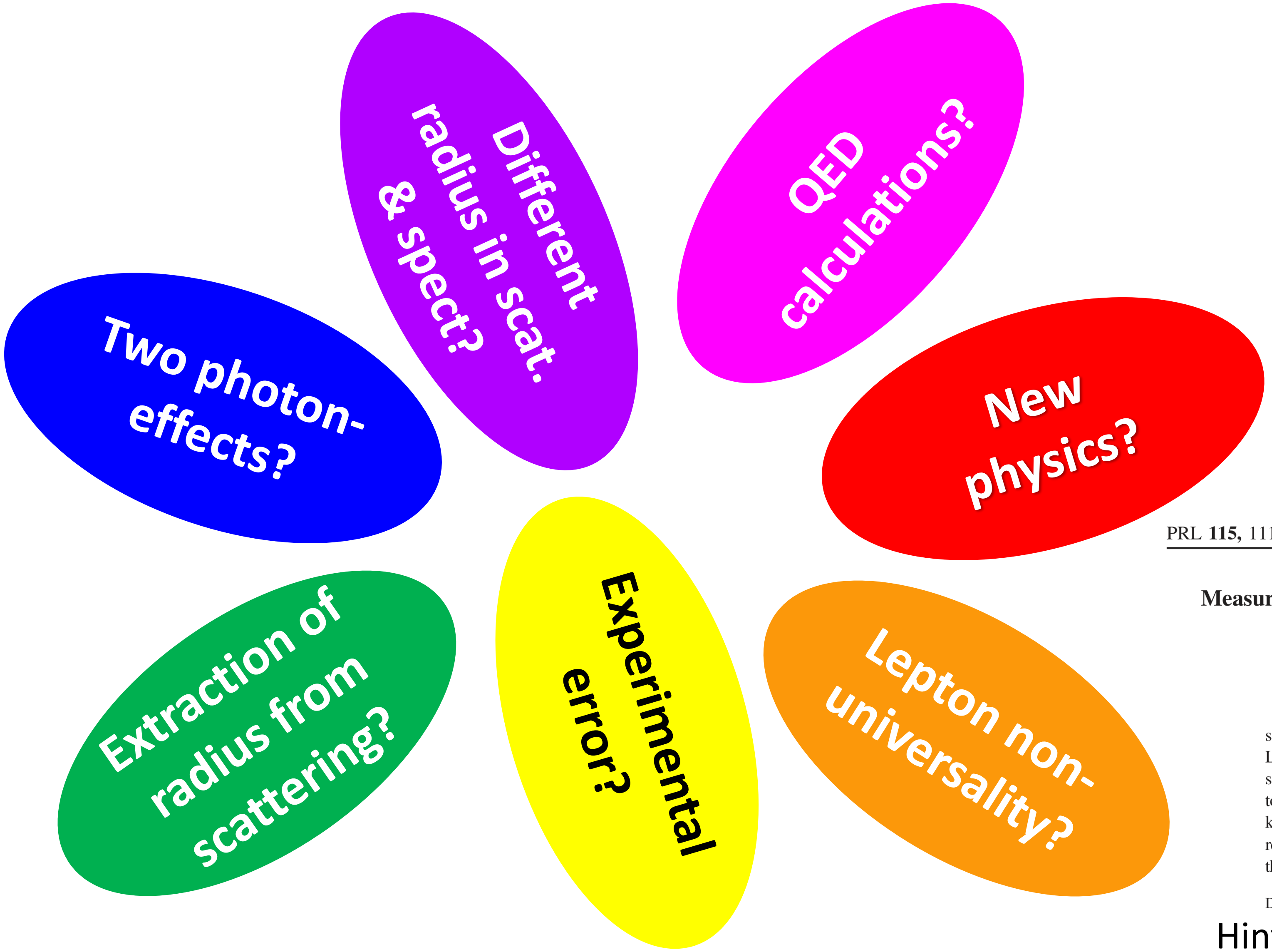
The branching fraction ratio $\mathcal{R}(D^*) \equiv \mathcal{B}(\bar{B}^0 \to D^{*+}\tau^-\bar{\nu}_\tau)/\mathcal{B}(\bar{B}^0 \to D^{*+}\mu^-\bar{\nu}_\mu)$ is measured using a sample of proton-proton collision data corresponding to 3.0 fb^{-1} of integrated luminosity recorded by the LHCb experiment during 2011 and 2012. The tau lepton is identified in the decay mode $\tau^- \to \mu^-\bar{\nu}_\mu\nu_\tau$. The semitauonic decay is sensitive to contributions from non-standard-model particles that preferentially couple to the third generation of fermions, in particular, Higgs-like charged scalars. A multidimensional fit to kinematic distributions of the candidate $\bar{B}^0$ decays gives $\mathcal{R}(D^*) = 0.336 \pm 0.027(\text{stat}) \pm 0.030(\text{syst})$. This result, which is the first measurement of this quantity at a hadron collider, is 2.1 standard deviations larger than the value expected from lepton universality in the standard model.

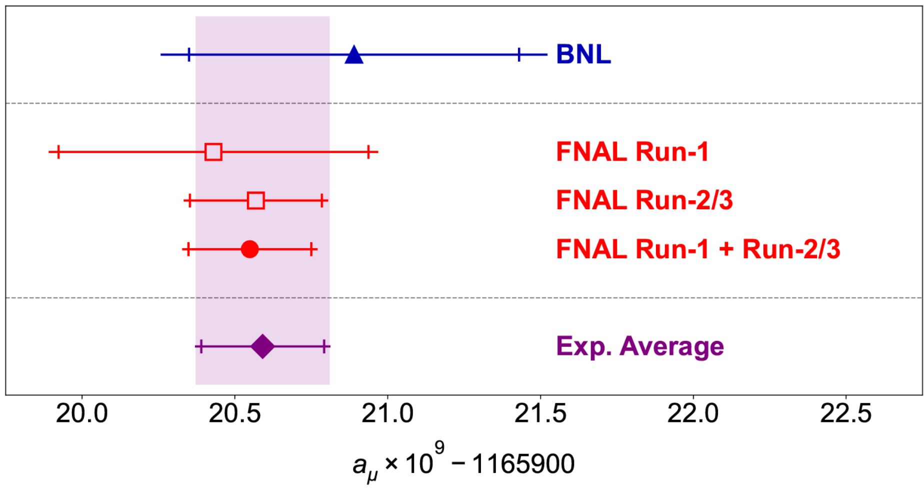
DOI: 10.1103/PhysRevLett.115.111803 PACS numbers: 13.20.He, 14.80.Fd

Hints at lepton non-universality in $\bar{\text{B}}^0$ decays (2015)

How to resolve the PRP?

THE GEORGE WASHINGTON UNIVERSITY
WASHINGTON, DC





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

PRL **115,** 111803 (2015) PHYSICAL REVIEW LETTERS week ending 11 SEPTEMBER 2015

Measurement of the Ratio of Branching Fractions $\mathcal{B}(\bar{B}^0 \to D^{*+}\tau^-\bar{\nu}_\tau)/\mathcal{B}(\bar{B}^0 \to D^{*+}\mu^-\bar{\nu}_\mu)$

R. Aaij *et al.*[*]
(LHCb Collaboration)

(Received 30 June 2015; published 9 September 2015; corrected 14 September 2015)

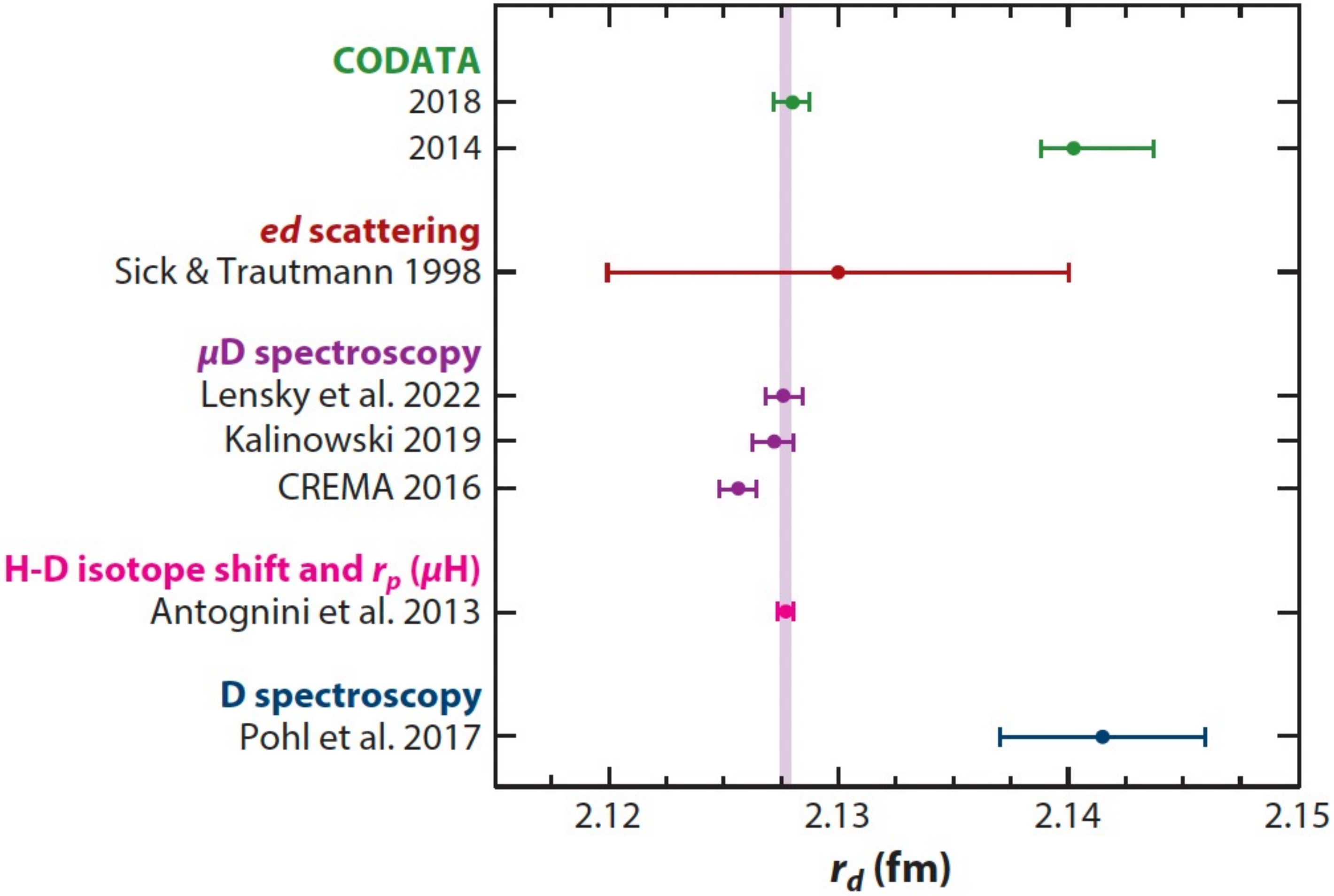
The branching fraction ratio $\mathcal{R}(D^*) \equiv \mathcal{B}(\bar{B}^0 \to D^{*+}\tau^-\bar{\nu}_\tau)/\mathcal{B}(\bar{B}^0 \to D^{*+}\mu^-\bar{\nu}_\mu)$ is measured using a sample of proton-proton collision data corresponding to 3.0 fb^{-1} of integrated luminosity recorded by the LHCb experiment during 2011 and 2012. The tau lepton is identified in the decay mode $\tau^- \to \mu^-\bar{\nu}_\mu\nu_\tau$. The semitauonic decay is sensitive to contributions from non-standard-model particles that preferentially couple to the third generation of fermions, in particular, Higgs-like charged scalars. A multidimensional fit to kinematic distributions of the candidate $\bar{B}^0$ decays gives $\mathcal{R}(D^*) = 0.336 \pm 0.027(\text{stat}) \pm 0.030(\text{syst})$. This result, which is the first measurement of this quantity at a hadron collider, is 2.1 standard deviations larger than the value expected from lepton universality in the standard model.

DOI: 10.1103/PhysRevLett.115.111803 PACS numbers: 13.20.He, 14.80.Fd

Hints at lepton non-universality in $\bar{B}^0$ decays (2015)

How to resolve the PRP?

THE GEORGE WASHINGTON UNIVERSITY
WASHINGTON, DC



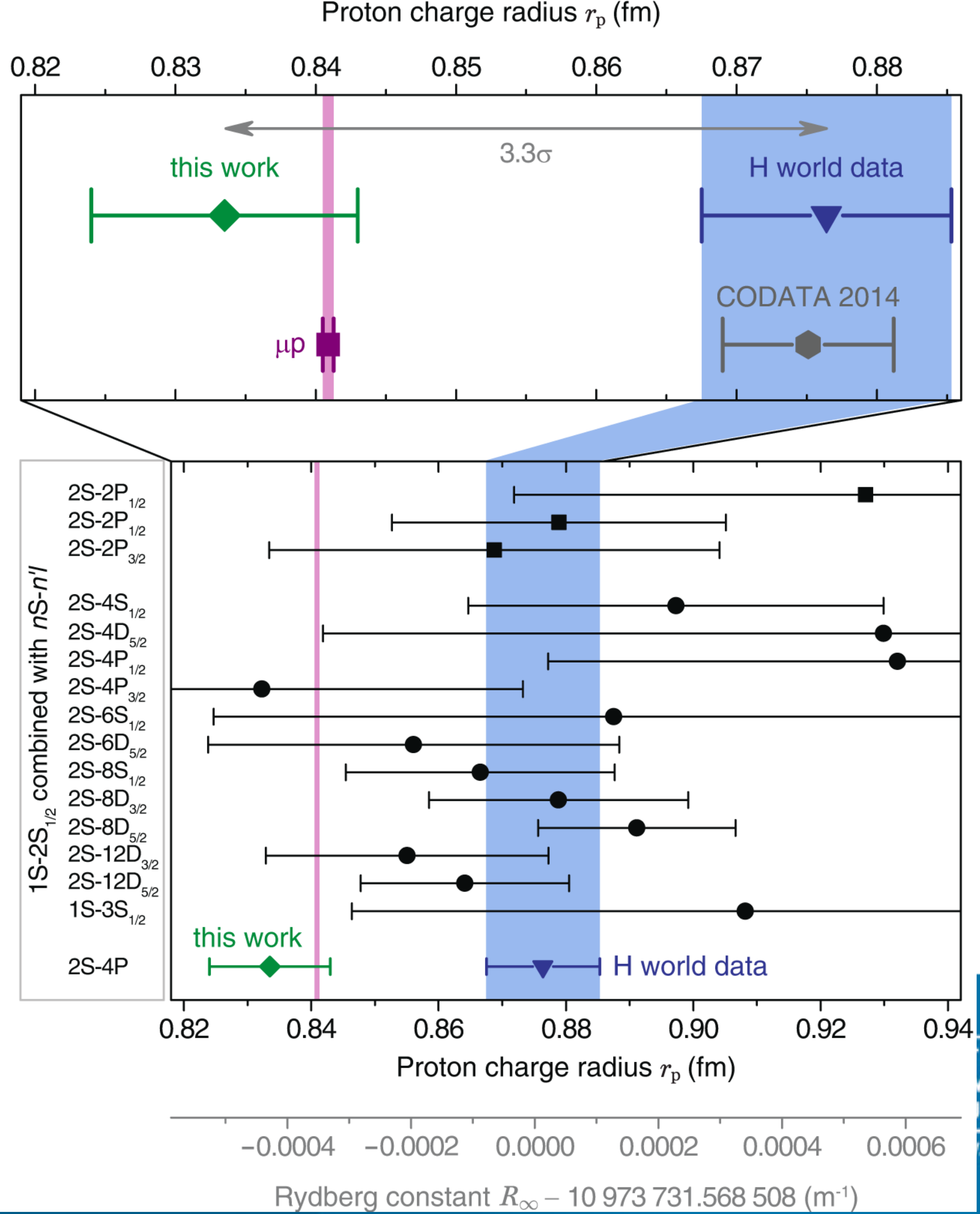
- Muonic deuterium agrees with muonic hydrogen: Pohl *et al.*, (CREMA) Science 353 (2016) 669
- Muonic 4He agrees with electronic helium: Krauth *et al.*, Nature **589**, 527 (2021)
- A Z=1 problem!
- Many new results on hydrogen

Muonic atom spectroscopy: a Z=1 Problem

THE GEORGE WASHINGTON UNIVERSITY
WASHINGTON, DC

MPQ Result
2S – 4P

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

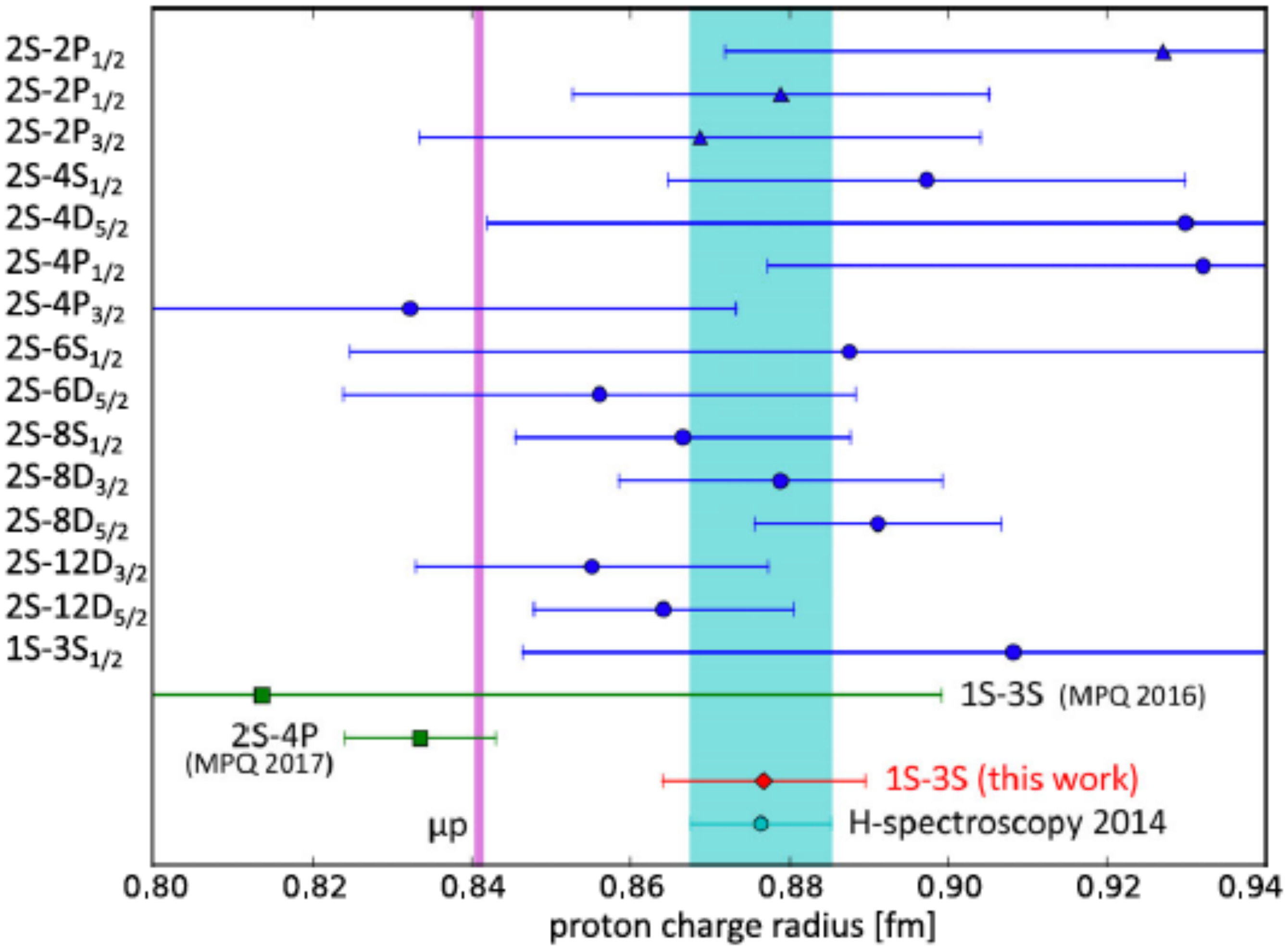


Spectroscopy: 2S-4P

THE GEORGE WASHINGTON UNIVERSITY
WASHINGTON, DC

Orsay Result
1S – 3S

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



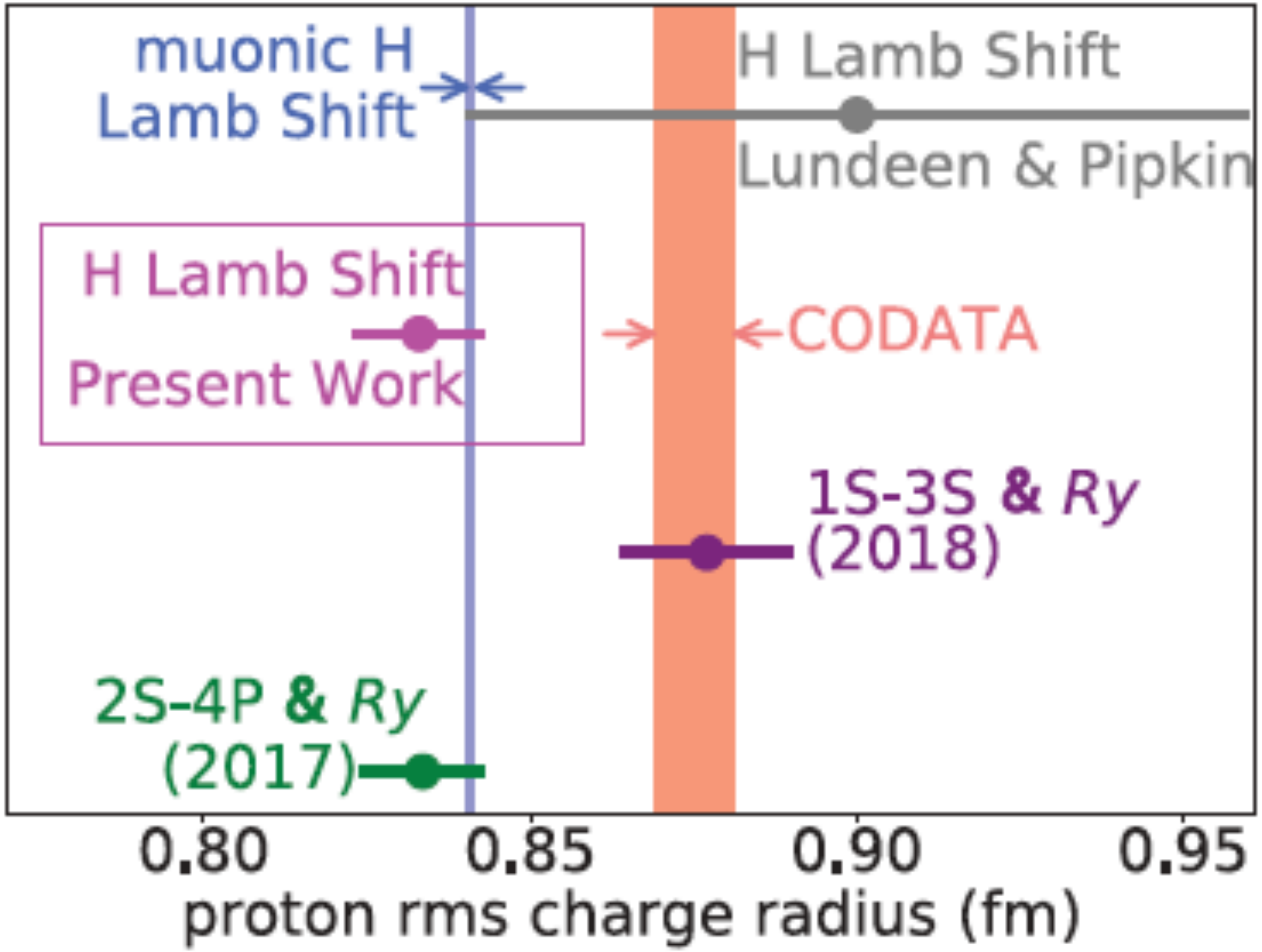
Spectroscopy: 1S – 3S

THE GEORGE WASHINGTON UNIVERSITY
WASHINGTON, DC

York Result
2S – 2P
(Lamb Shift)

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

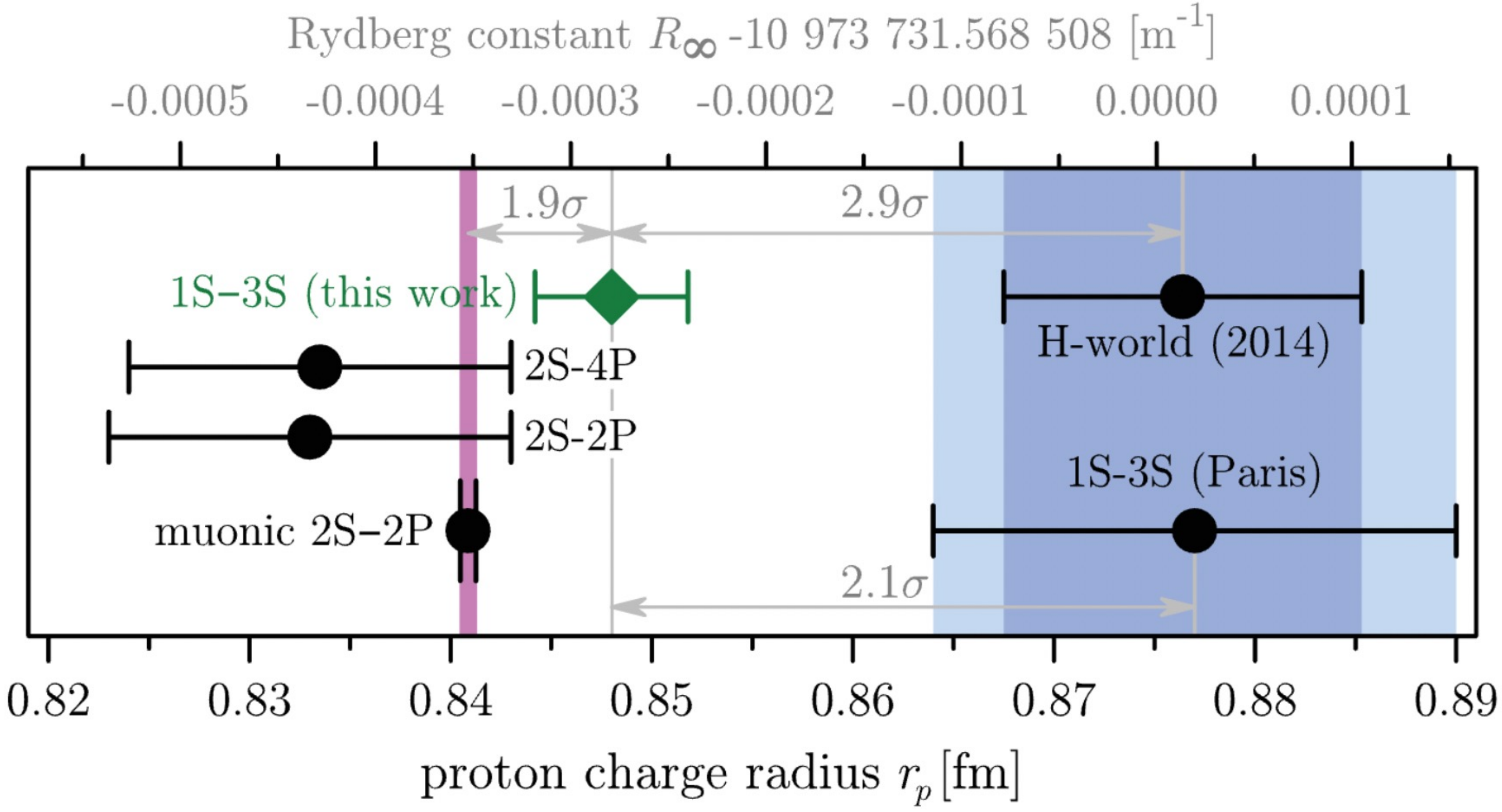
No involvement of Rydberg



Spectroscopy: 2S – 2P, Rydberg Independent

MPI Garching Result 2S – 3S

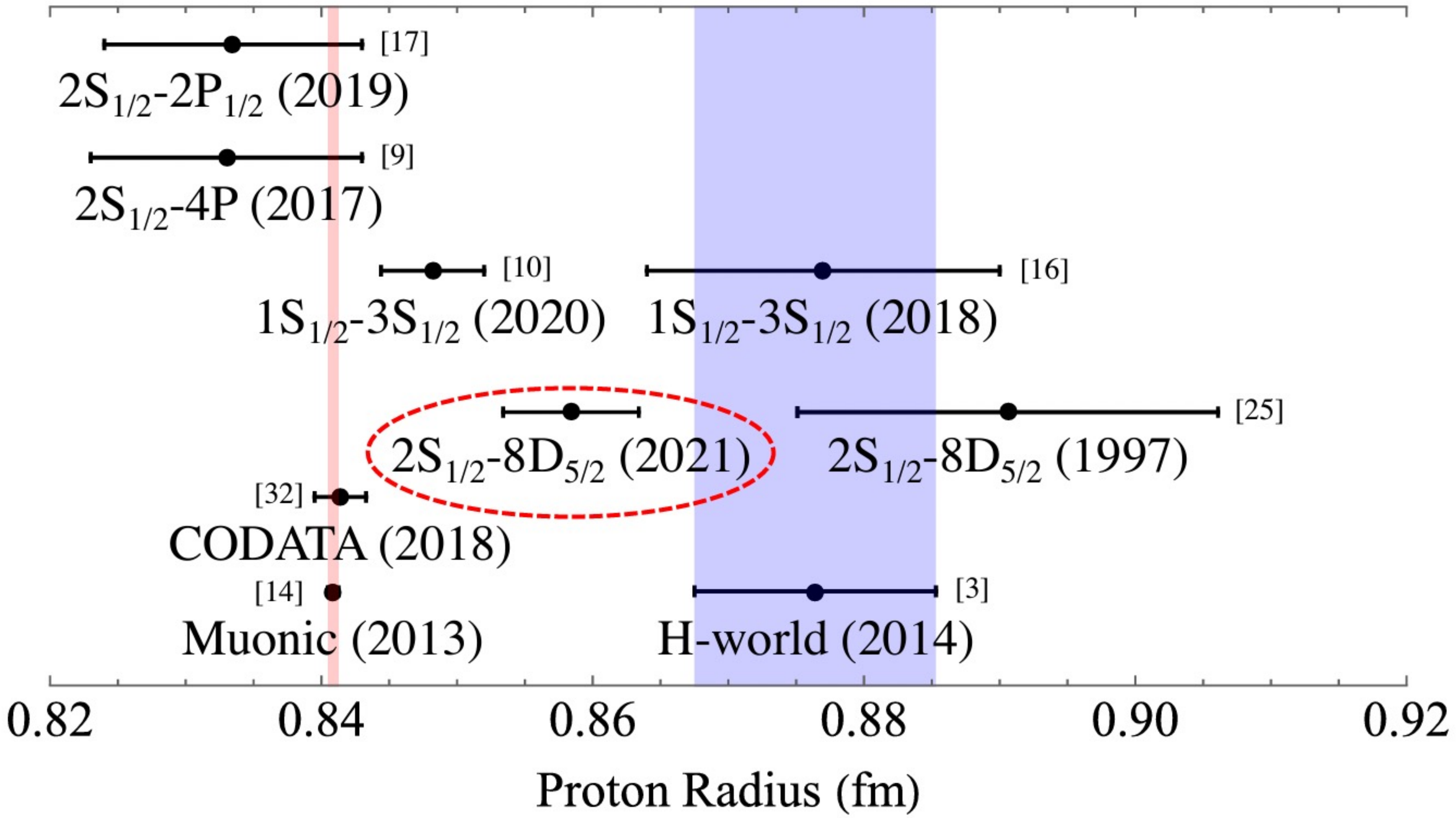
Grinin *et al.*, Science **370**, 1061–1066 (2020)



Spectroscopy: 2S – 3S

Colorado Result 2S – 8D

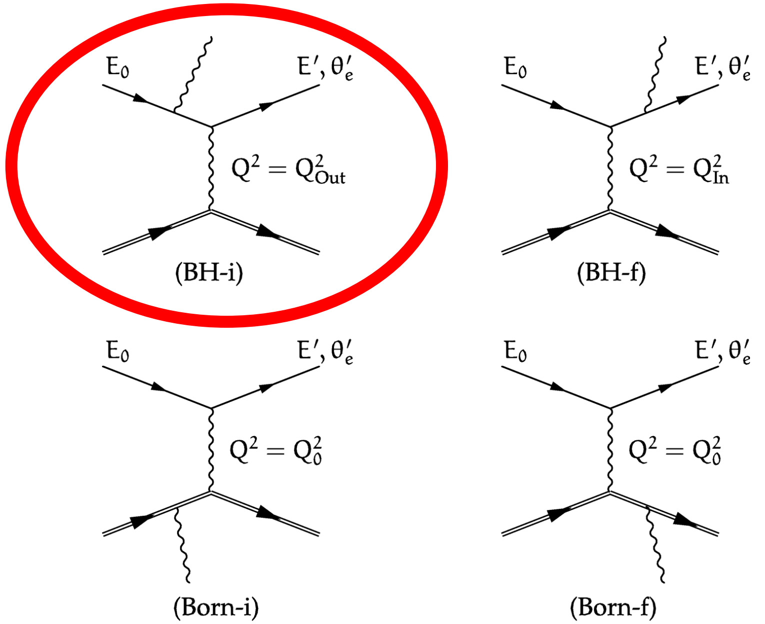
Brandt *et al.*, PRL **128**, 023001 (2022)



Spectroscopy: 2S – 8D

THE GEORGE WASHINGTON UNIVERSITY
WASHINGTON, DC

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



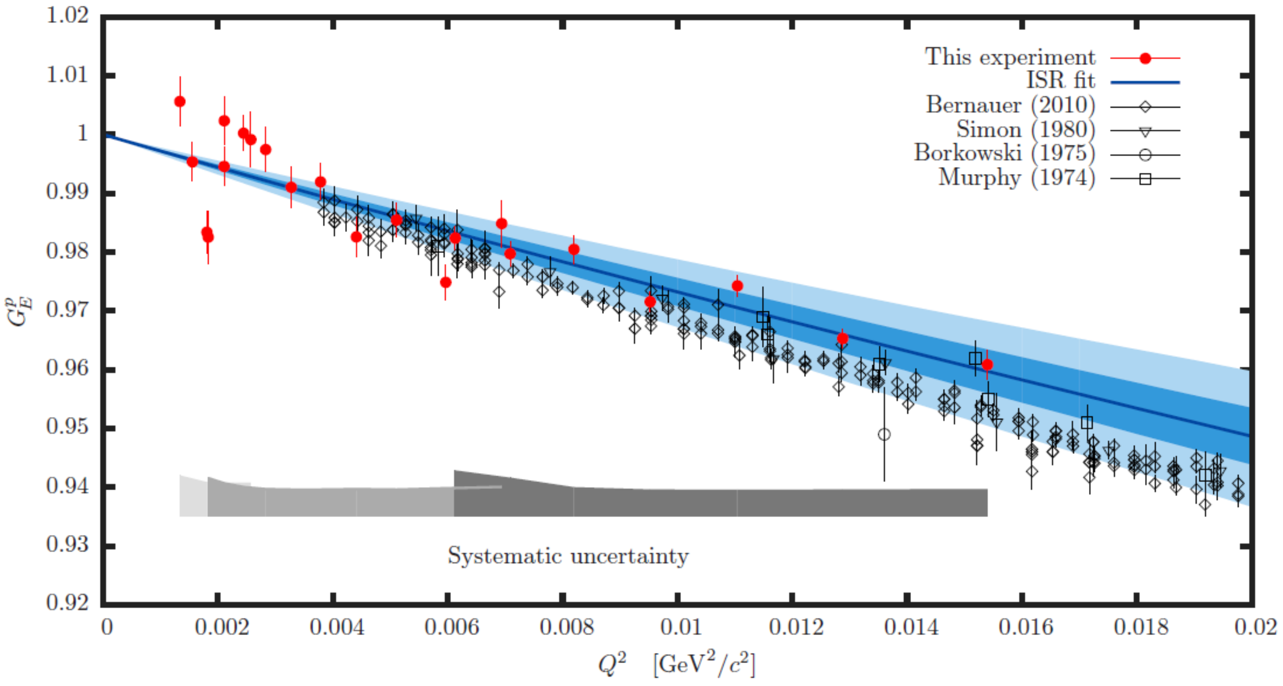


FIG. 3. (Color on-line) The proton electric form factor as a function of $Q^2 (= Q^2_{\mathrm{Out}})$. Empty black points show previous data [19–22]. The results of this experiment are shown with full red circles. The error bars show statistical uncertainties. Gray structures at the bottom shows the 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.

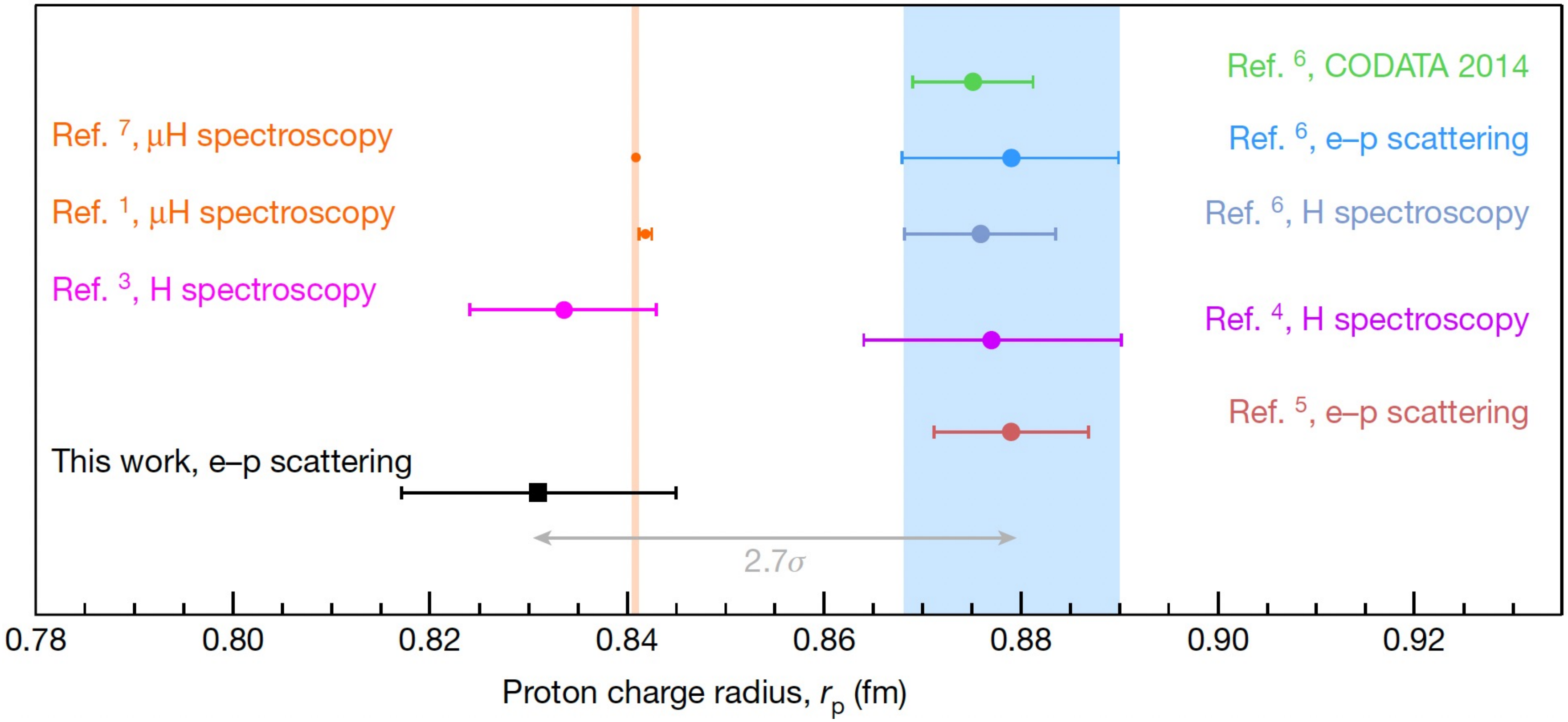
- Result: r_p=(0.810 ±0.035 stat. ±0.074 syst. ±0.003 ΔaΔb)fm, not precise enough to differentiate
- Re-analysed 2021: r_p=(0.878 ±0.011 stat. ±0.031 syst. ±0.002 mod.)fm
- New experiment with jet target (and MESA) planned

Scattering: Mainz Initial State Radiation

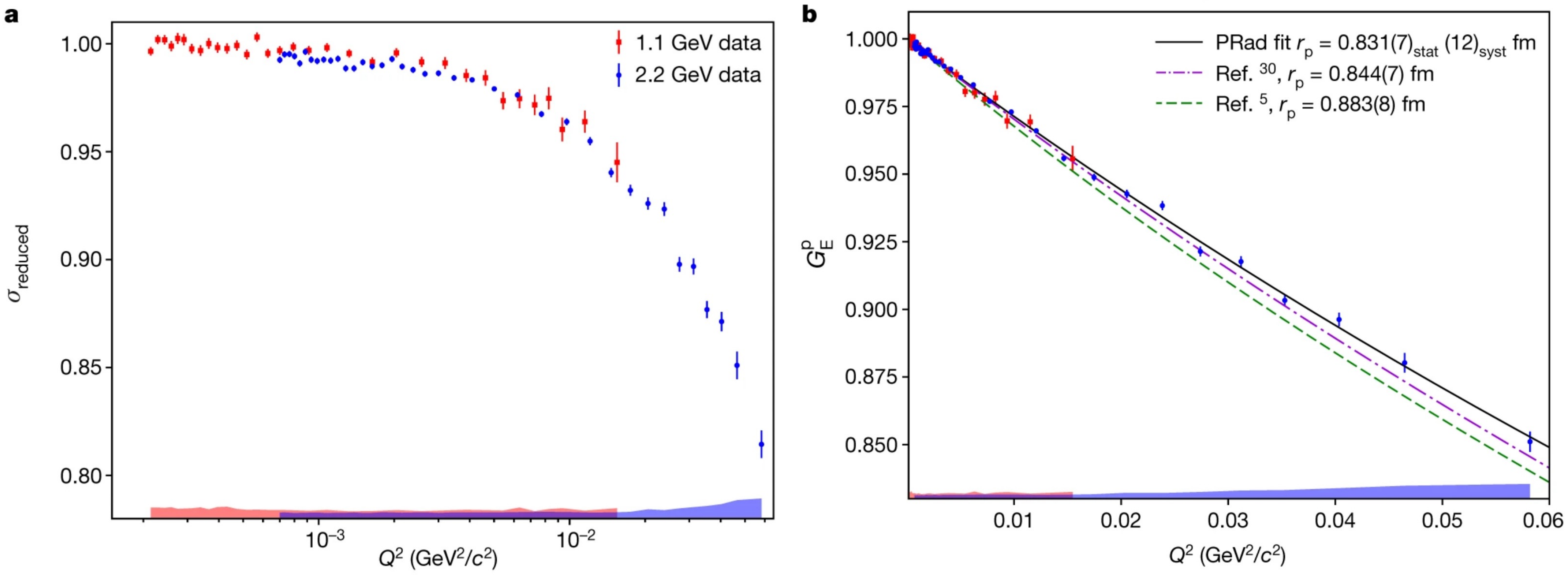
THE GEORGE WASHINGTON UNIVERSITY
WASHINGTON, DC

PRad
Result
Electron Scattering

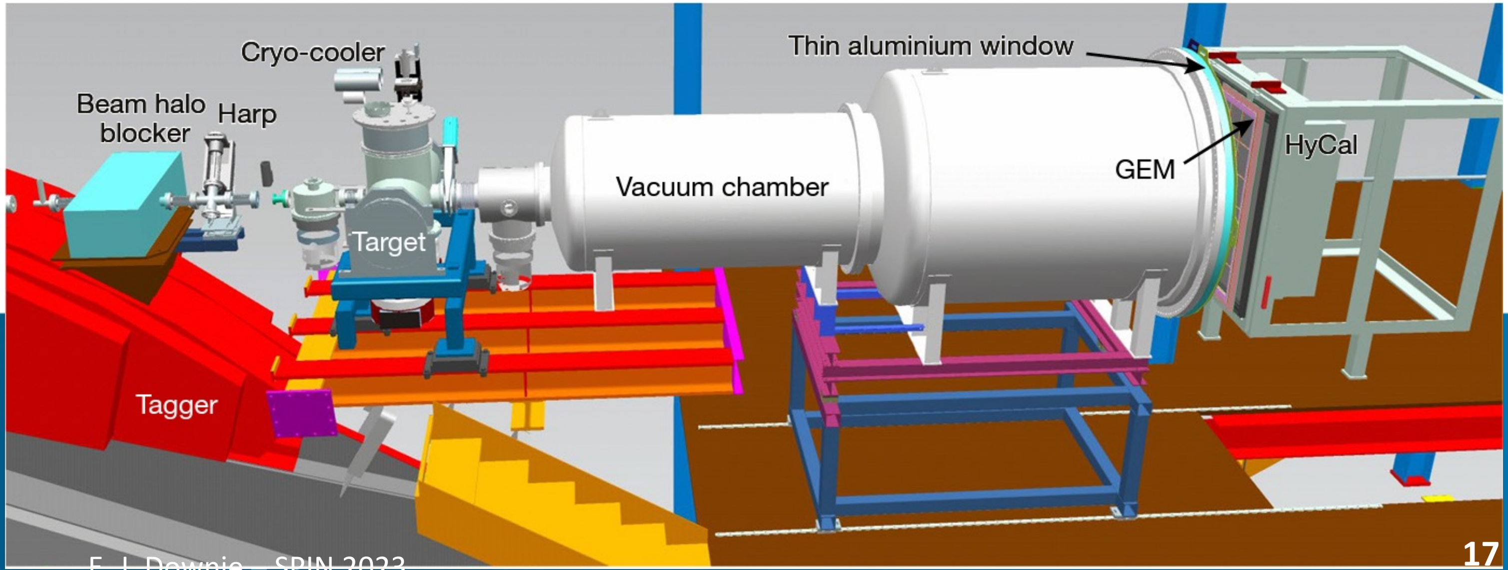
Xiong *et al.*, Nature **575**, 147 - 150 (2019)



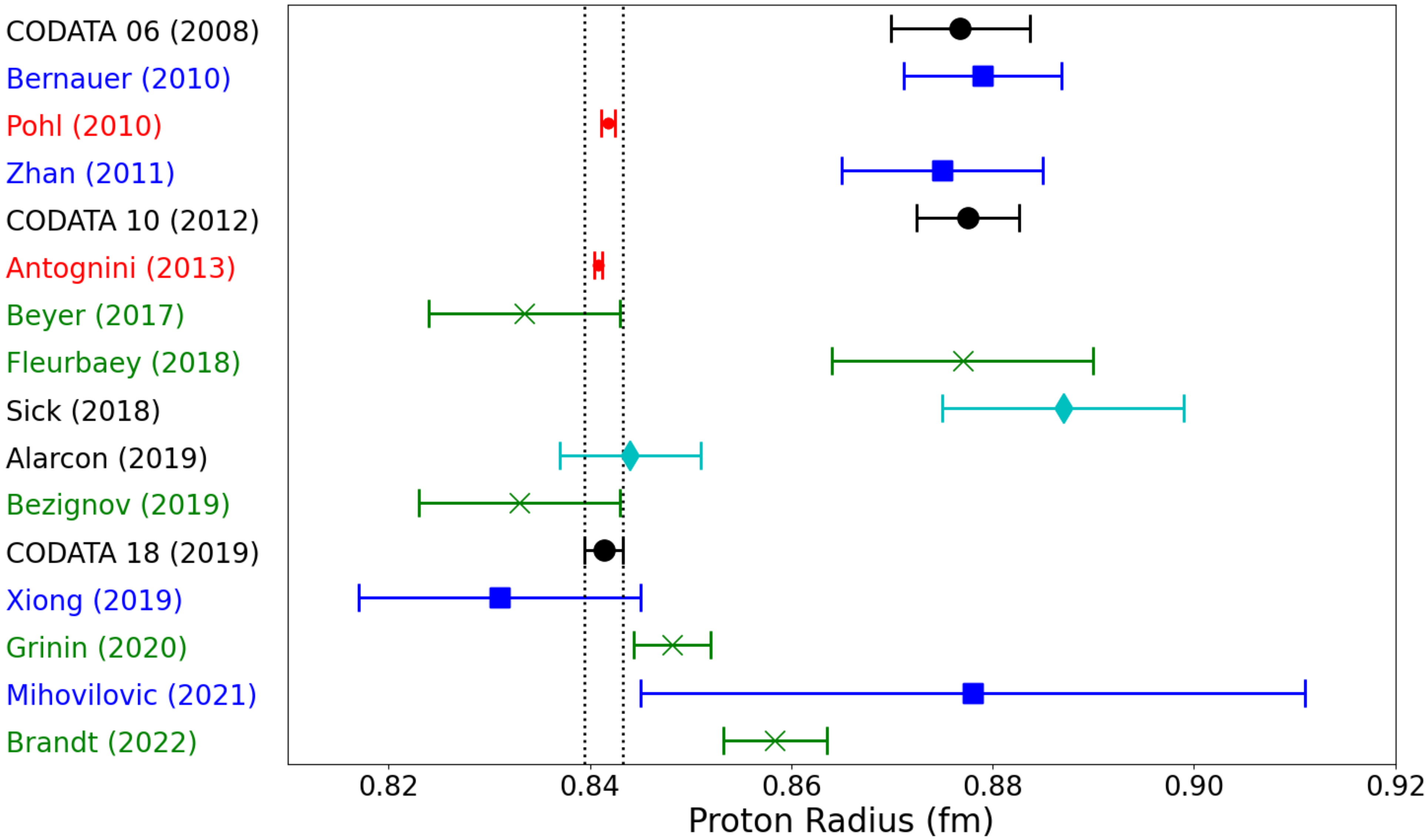
Scattering: PRad @ JLab



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 (2023)

THE GEORGE WASHINGTON UNIVERSITY
WASHINGTON, DC

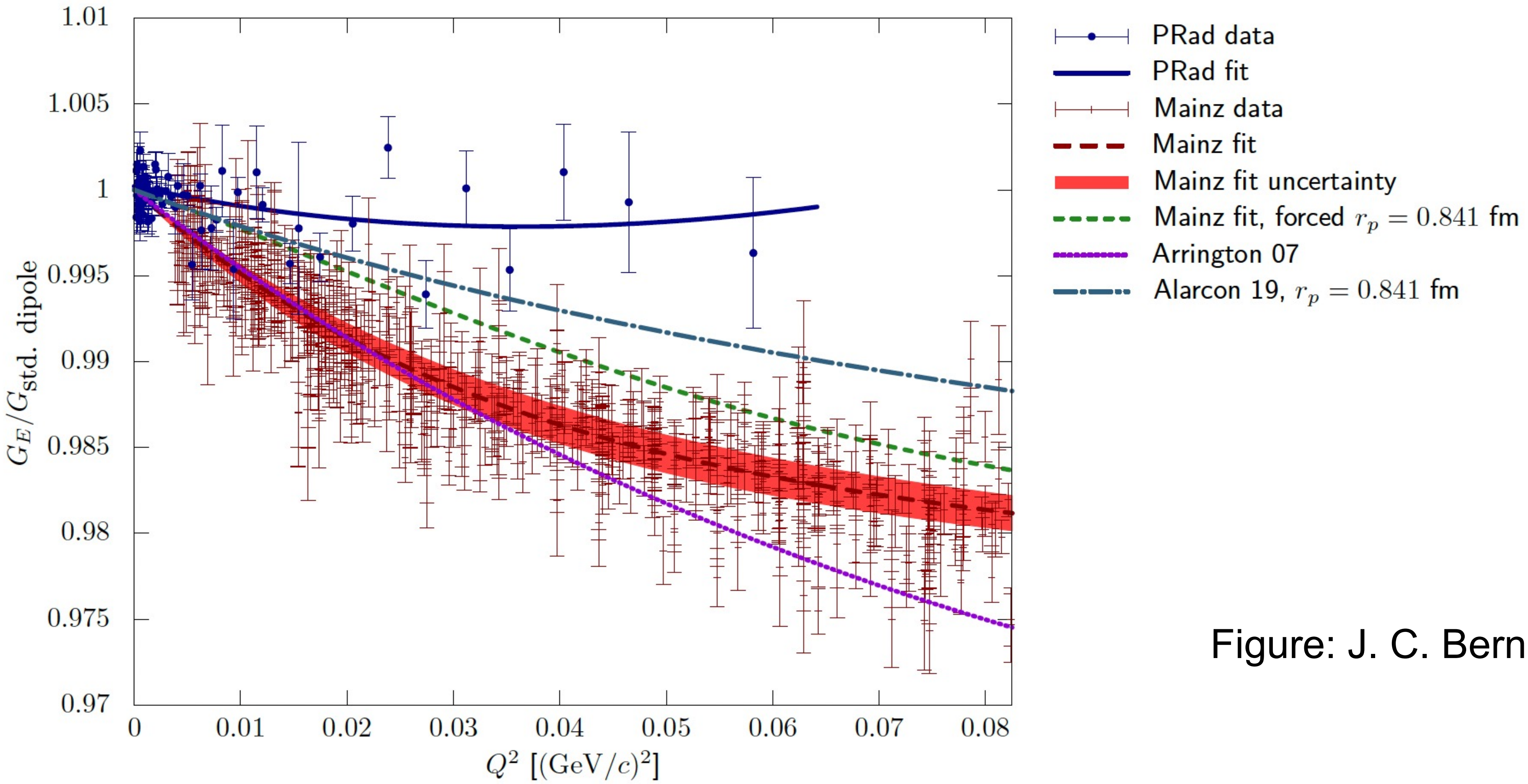
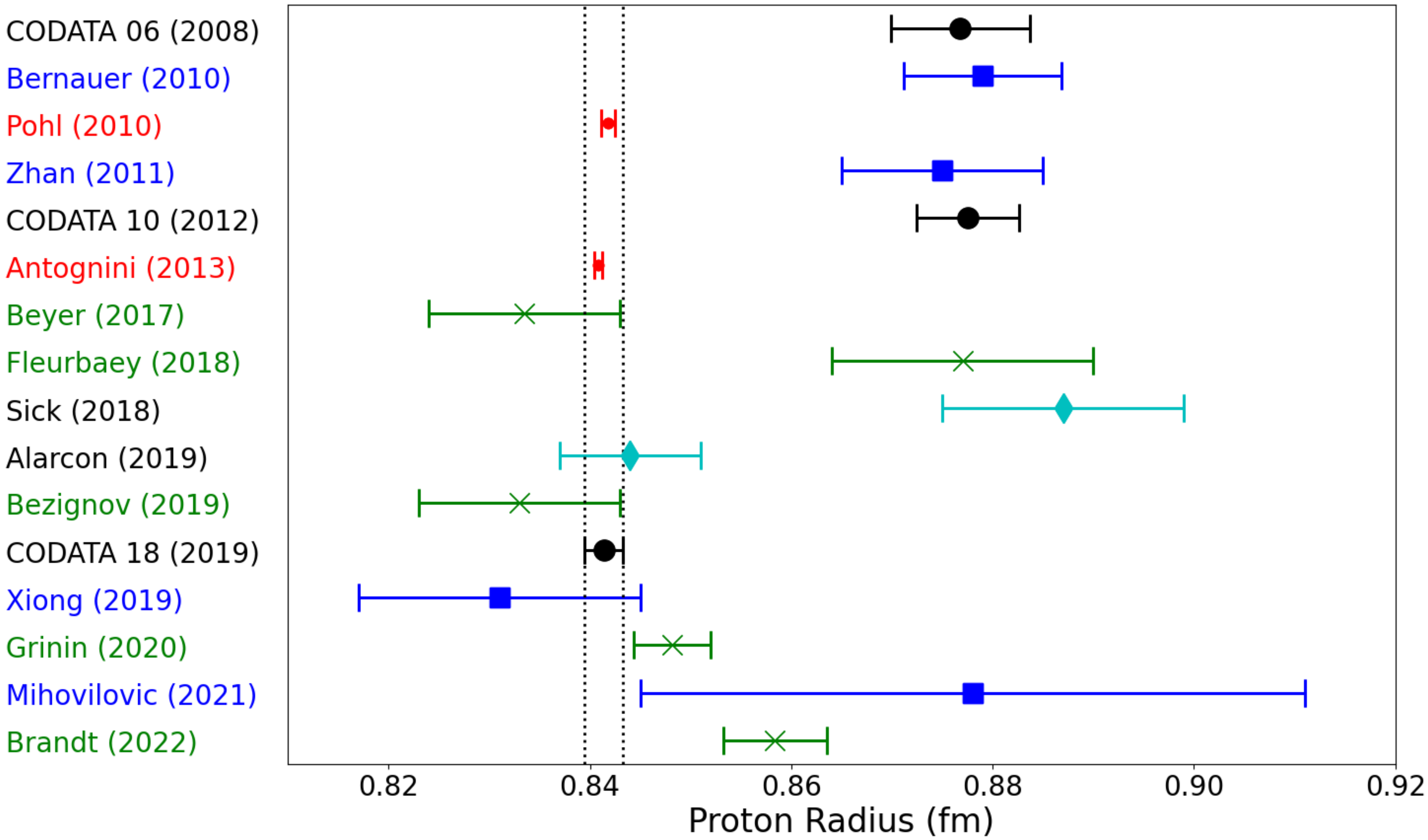


Figure: J. C. Bernauer

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 (2023)

THE GEORGE WASHINGTON UNIVERSITY
WASHINGTON, DC

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)

Proton Radius Puzzle Status (2023)

THE GEORGE WASHINGTON UNIVERSITY
WASHINGTON, DC

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

H. Gao*

Department of Physics, Duke University and the Triangle Universities Nuclear Laboratory, Science Drive, Durham, North Carolina 27708, USA

M. Vanderhaeghen†

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

(published 21 January 2022)

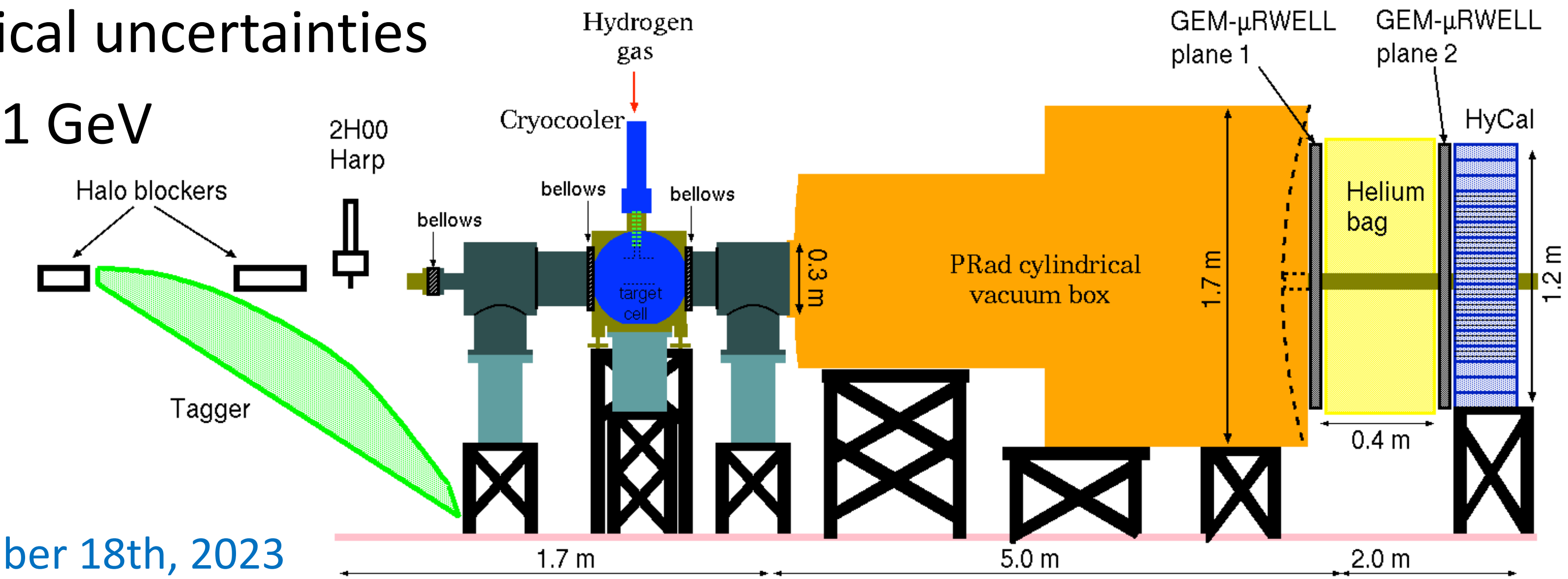
Proton Radius Puzzle Status (2023)

THE GEORGE WASHINGTON UNIVERSITY
WASHINGTON, DC

- 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

Jefferson Lab
Exploring the Nature of Matter

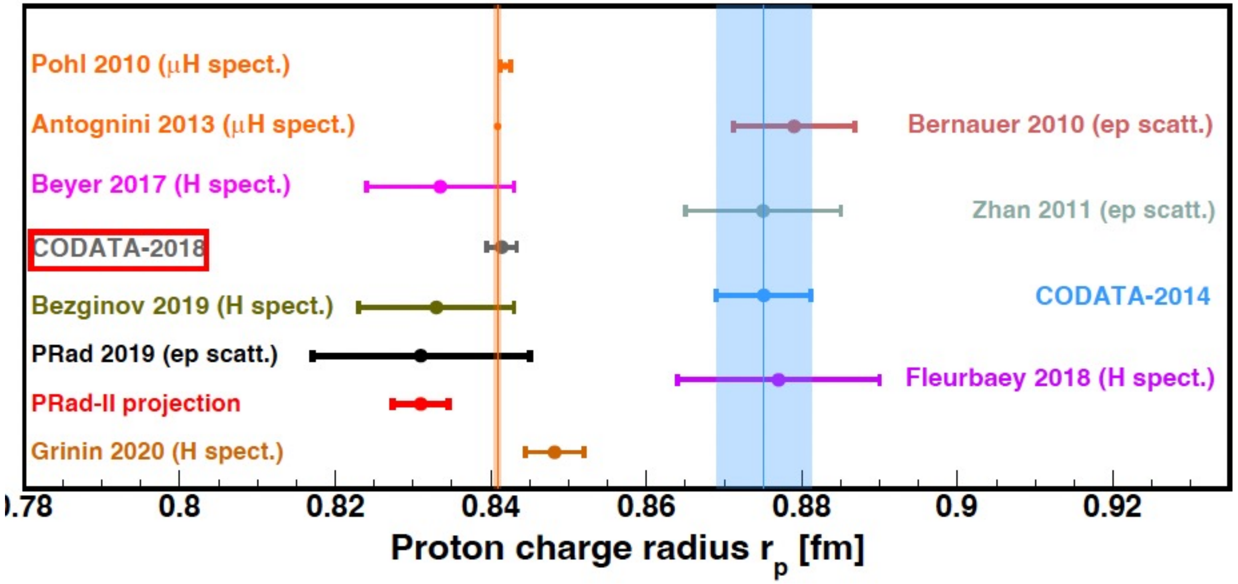
PRad-II Experimental Setup (Side View)

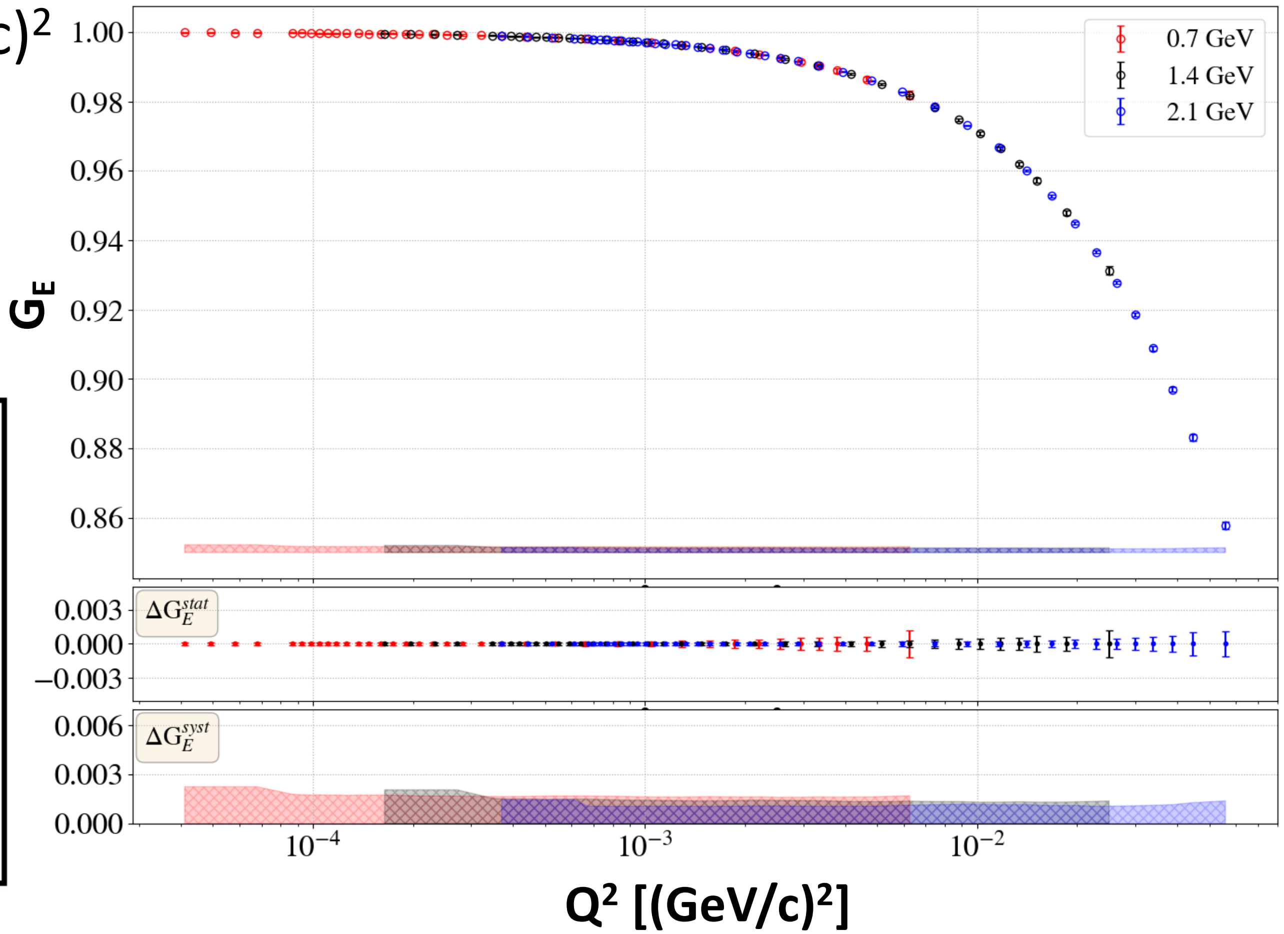


H. Gao: ERICE School on Nuclear Physics, September 18th, 2023

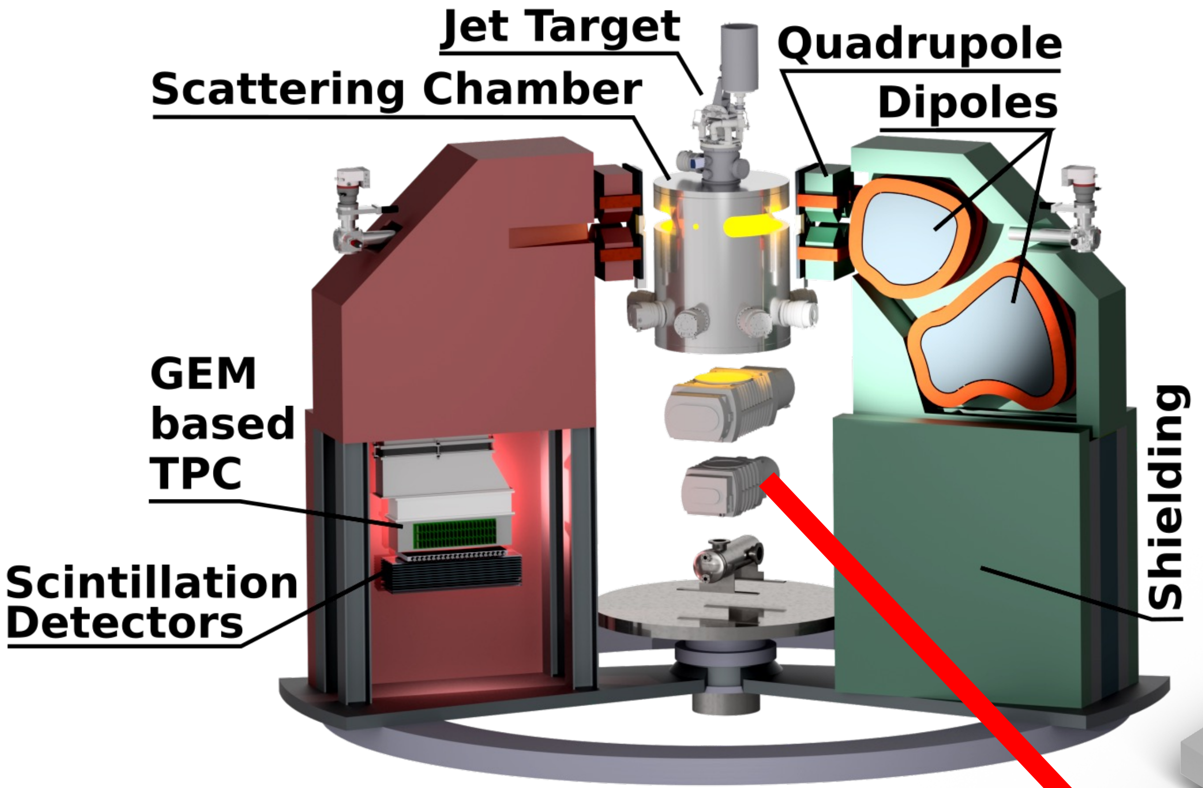
PRad II @ JLab

- Unprecedented low Q^2 : $4x10^{-5} – 0.06$ $(GeV/c)^2$
- Aiming for total uncertainty: 0.0036 fm
- Highest rating from JLab PAC 2020

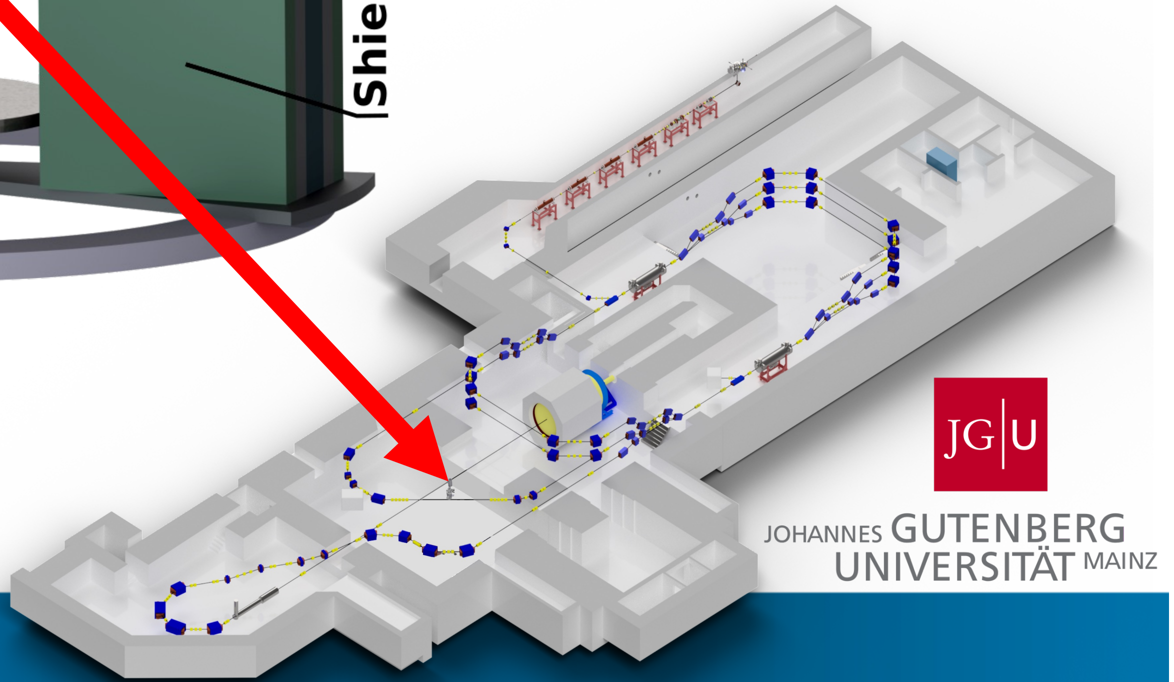




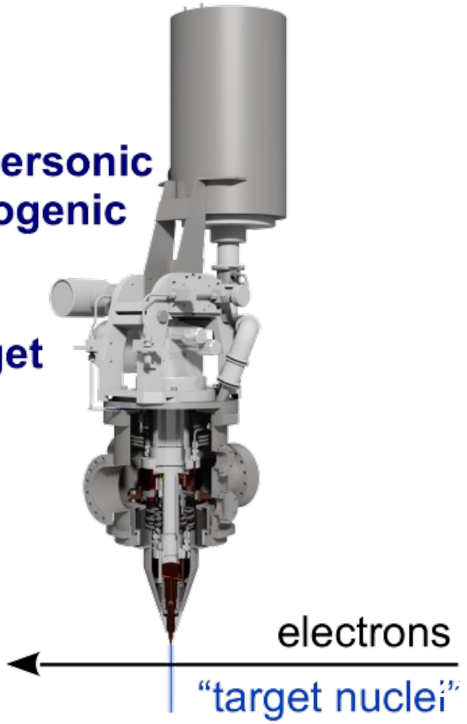
H. Gao: ERICE School on Nuclear Physics, September 18th, 2023



- 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!



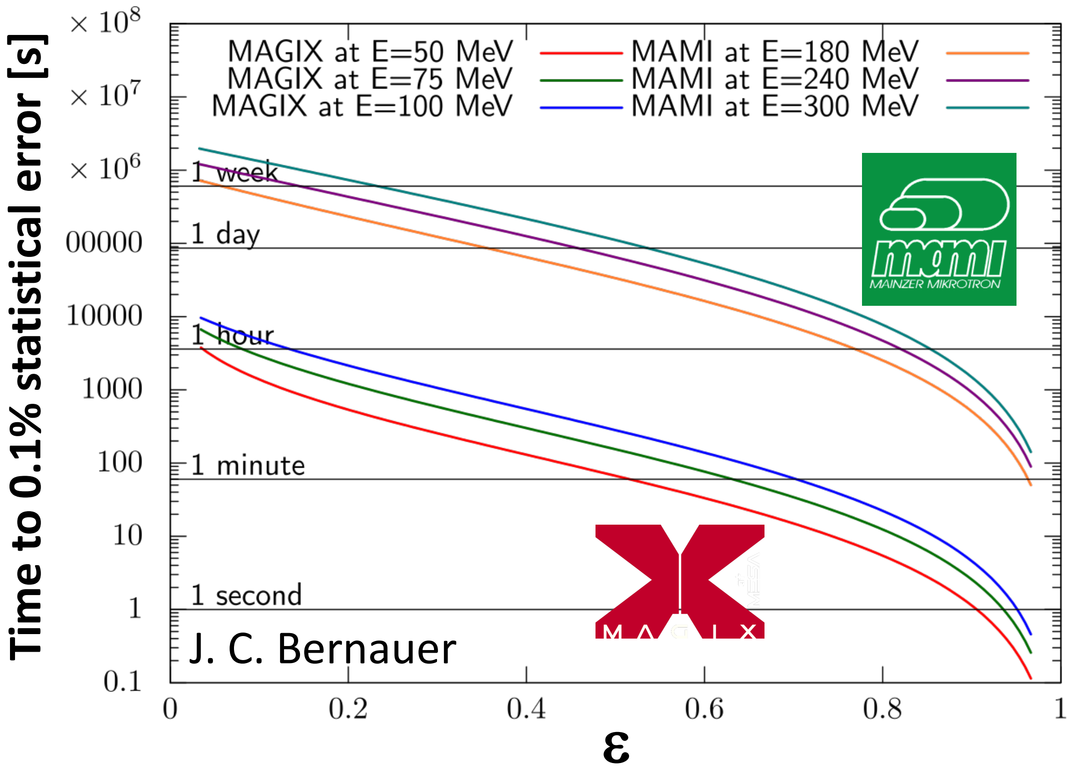
JOHANNES GUTENBERG UNIVERSITÄT MAINZ

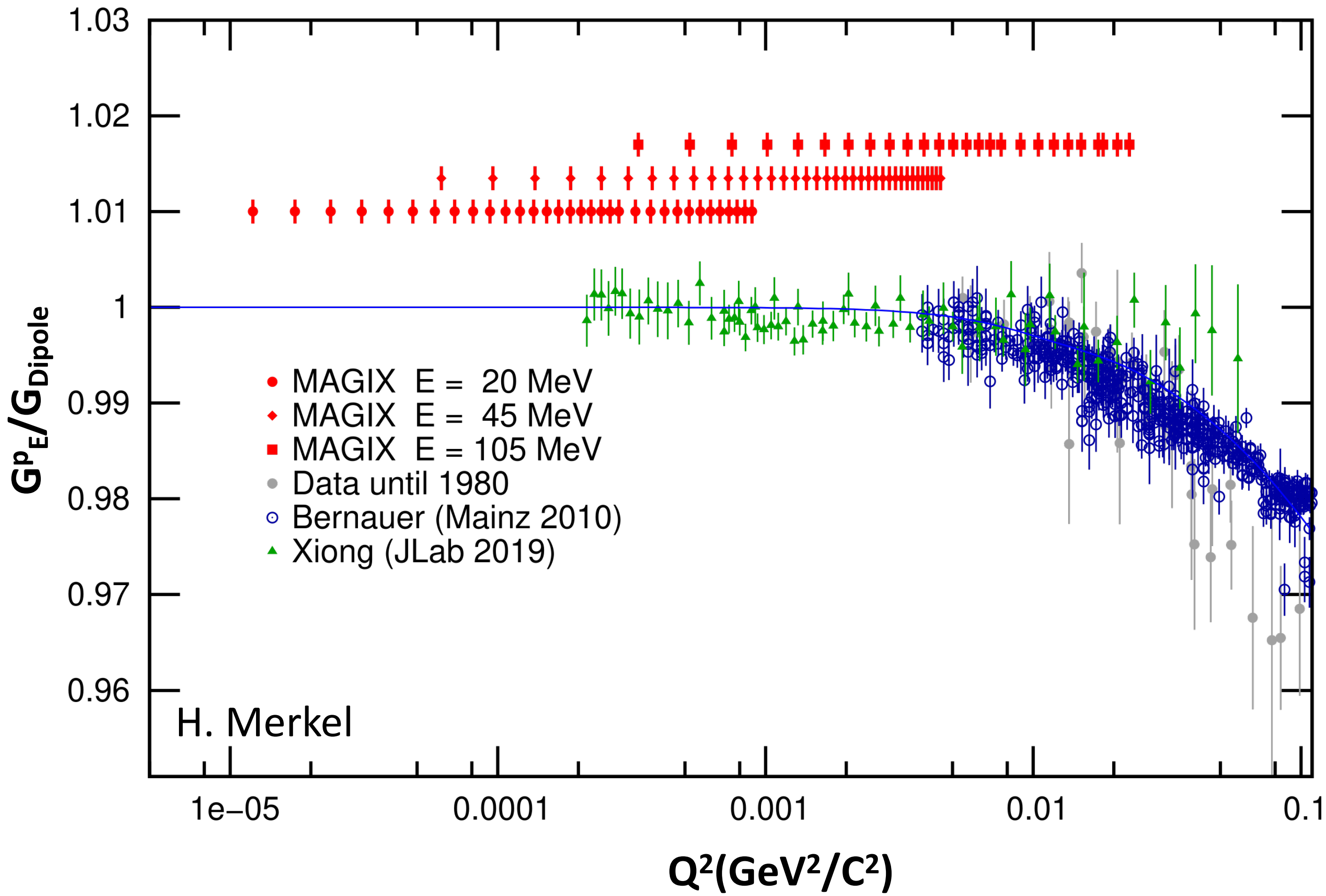


MAGIX info: S. Schlimme

MAGIX Collaboration @ MESA

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

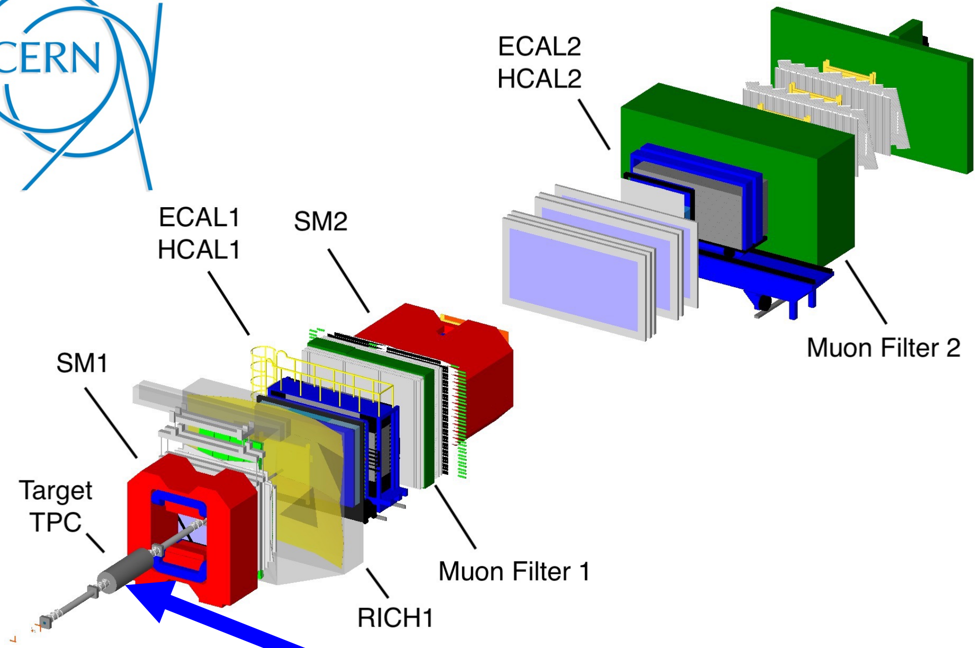


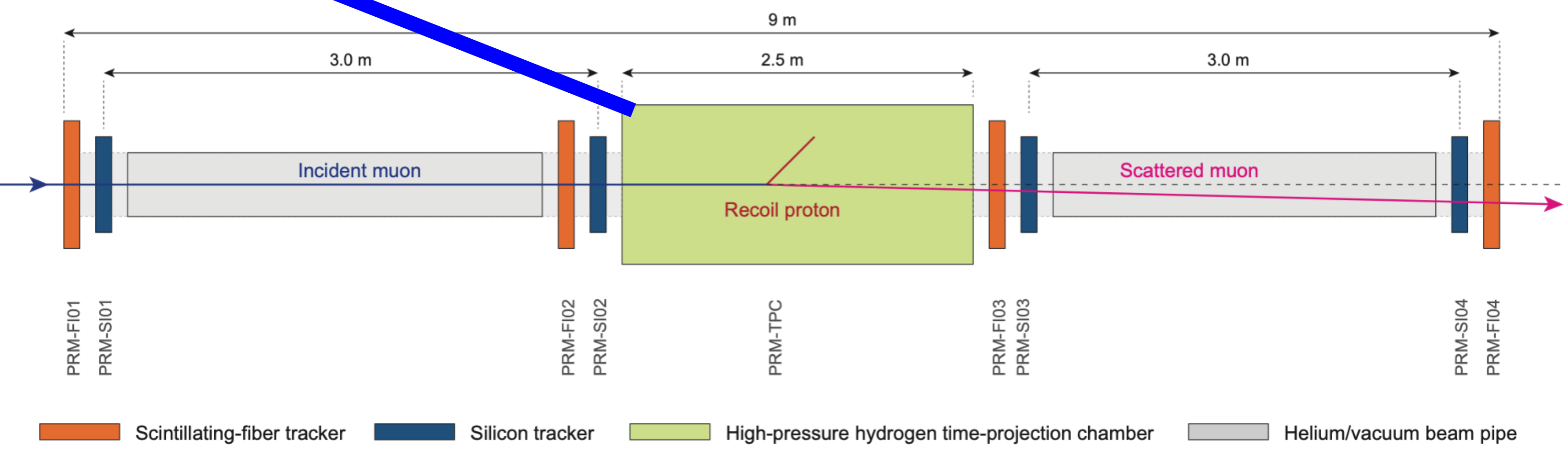


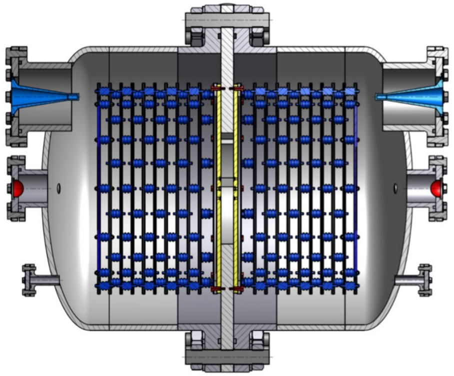
MAGIX info: S. Schlimme

AMBER @ CERN

- 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





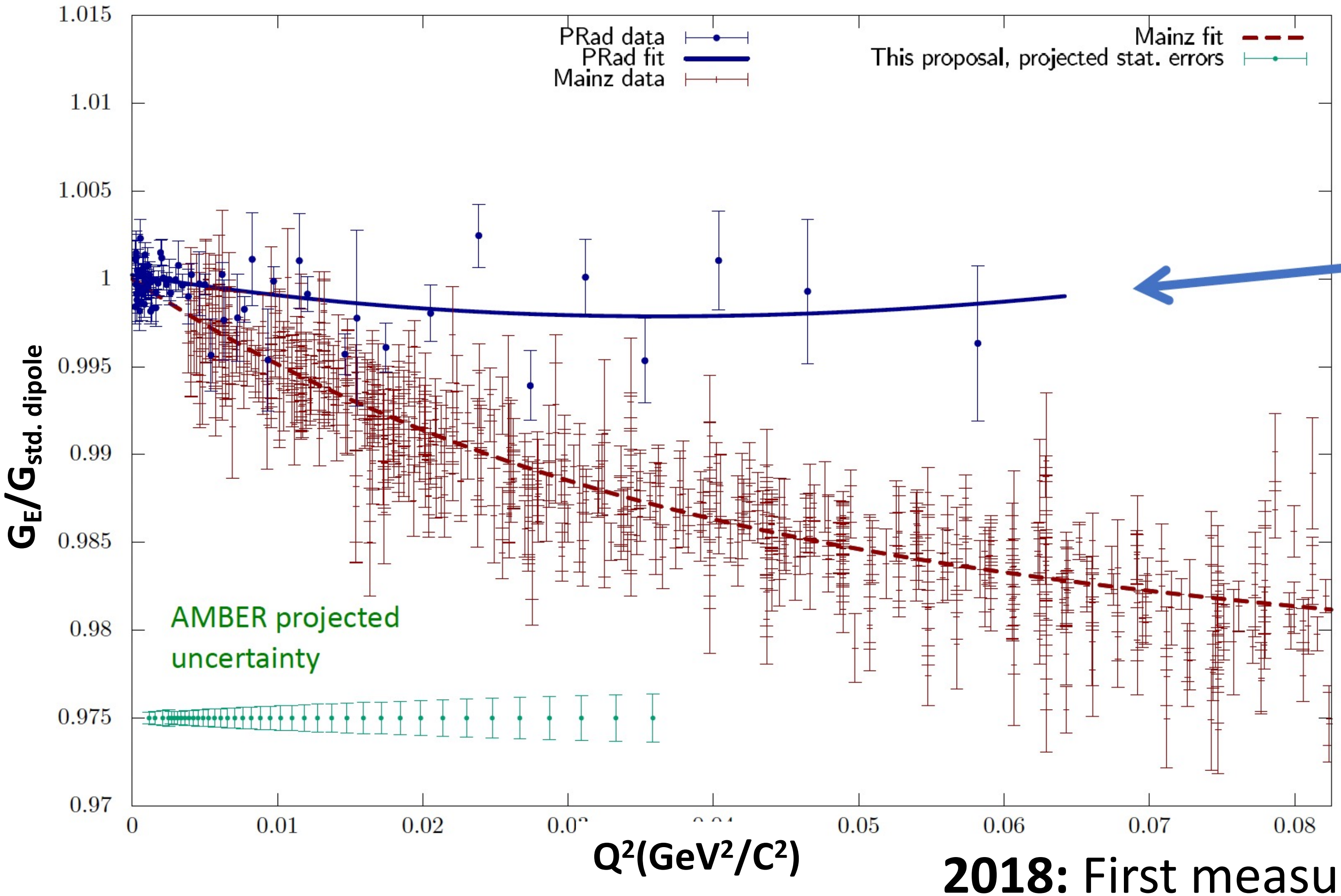


TPC, 20 bar, ~ 50 keV precision on recoiling proton

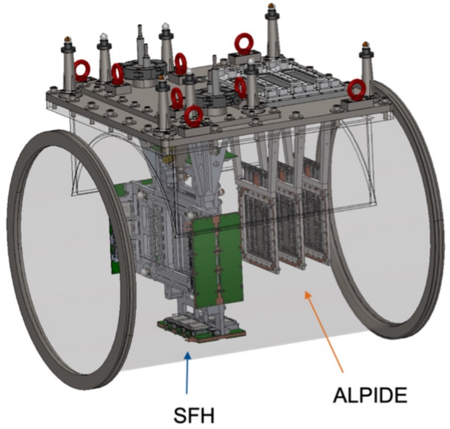
AMBER info: J. Friedrich

AMBER Apparatus for Meson and Baryon Experimental Research

THE GEORGE WASHINGTON UNIVERSITY WASHINGTON, DC



New Si and SciFI
Unified Tracking System (UTS)



Proton Radius Experiment at Jefferson Lab
PRoton Radius

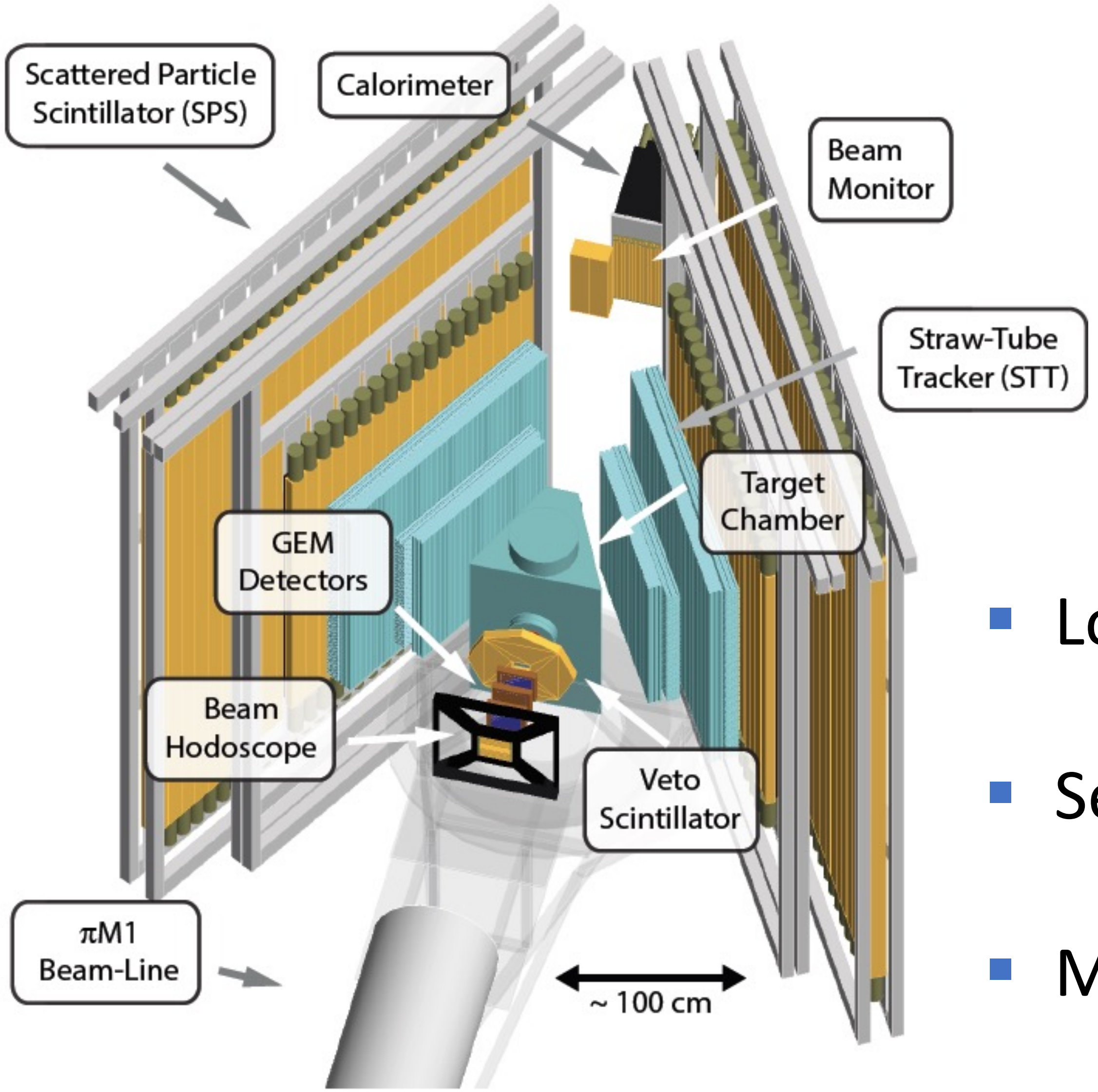
mami
MAINZER MIKROTRON

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

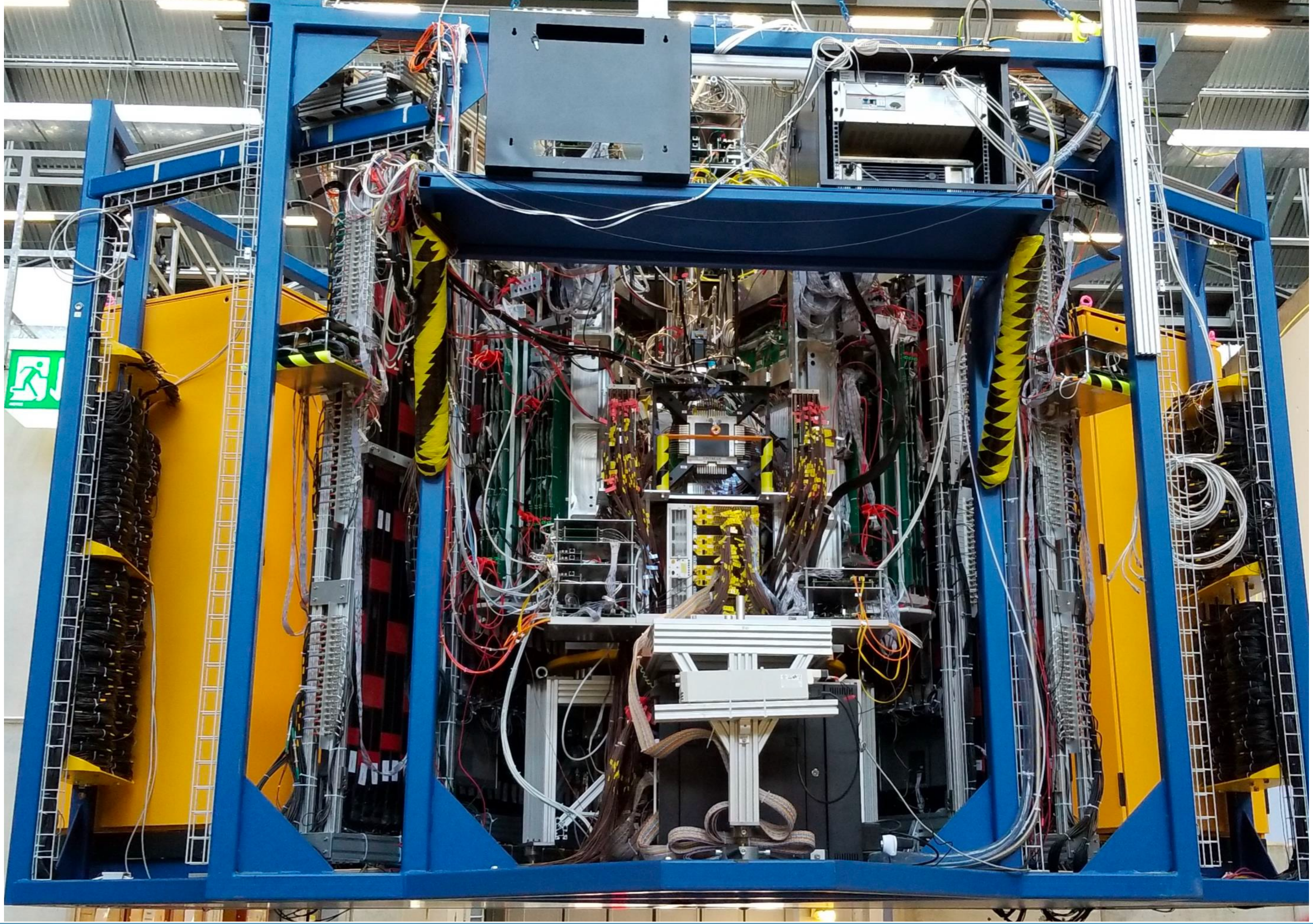
- MUSE in PiM1 beamline of Paul Scherrer Institute (mixed μ/e/p beam)
- Allows direct comparison of μ and e, cross sections, form factors
- Comparison of charge states, μ^+/μ^-, e^+/e^-, two photon effects
- Extraction of radii using e and μ in same experiment



$\theta \approx 20^o – 100^o$
$Q^2 \approx 0.002$ - $0.07\ GeV^2$
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

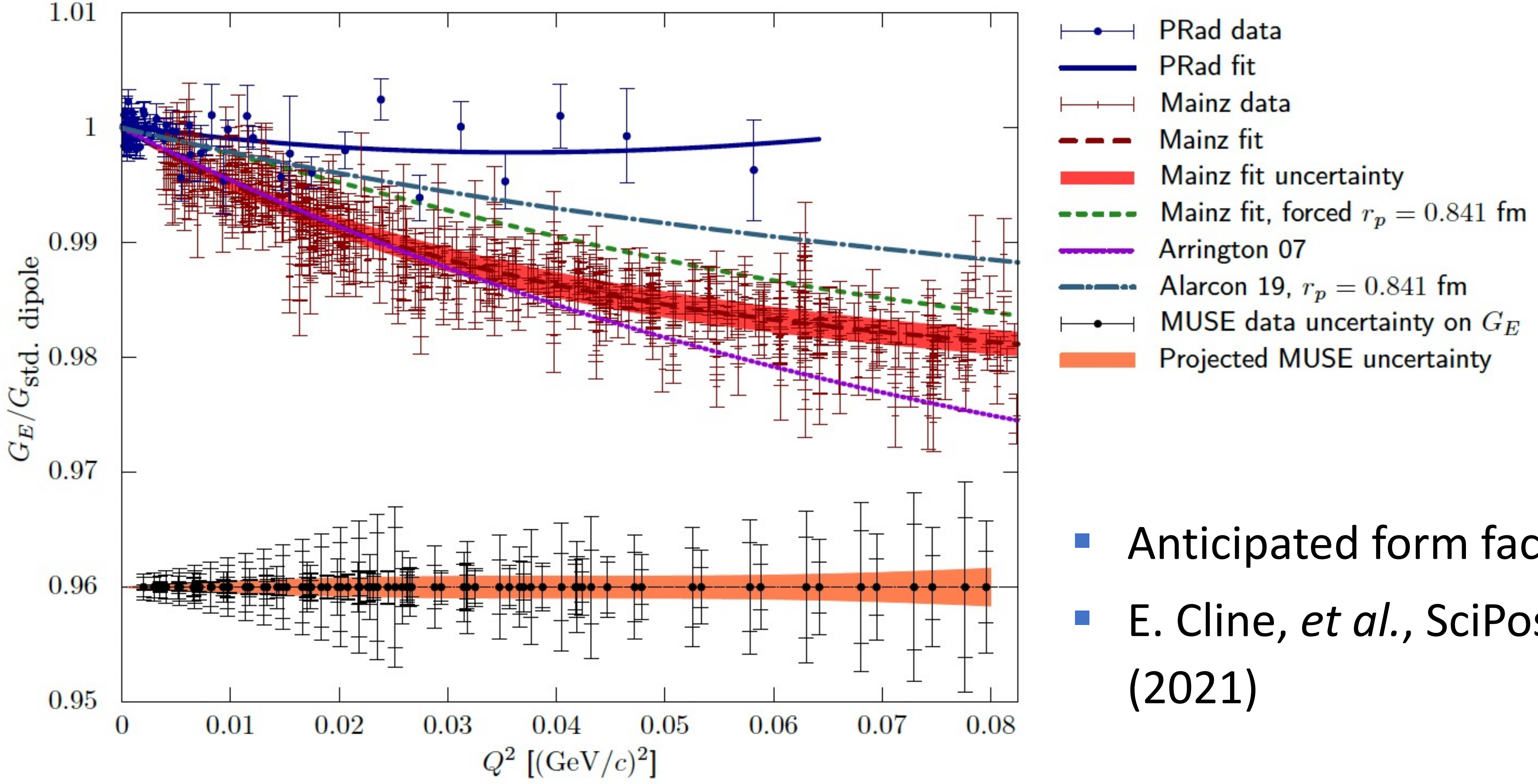
MUSE



MUSE

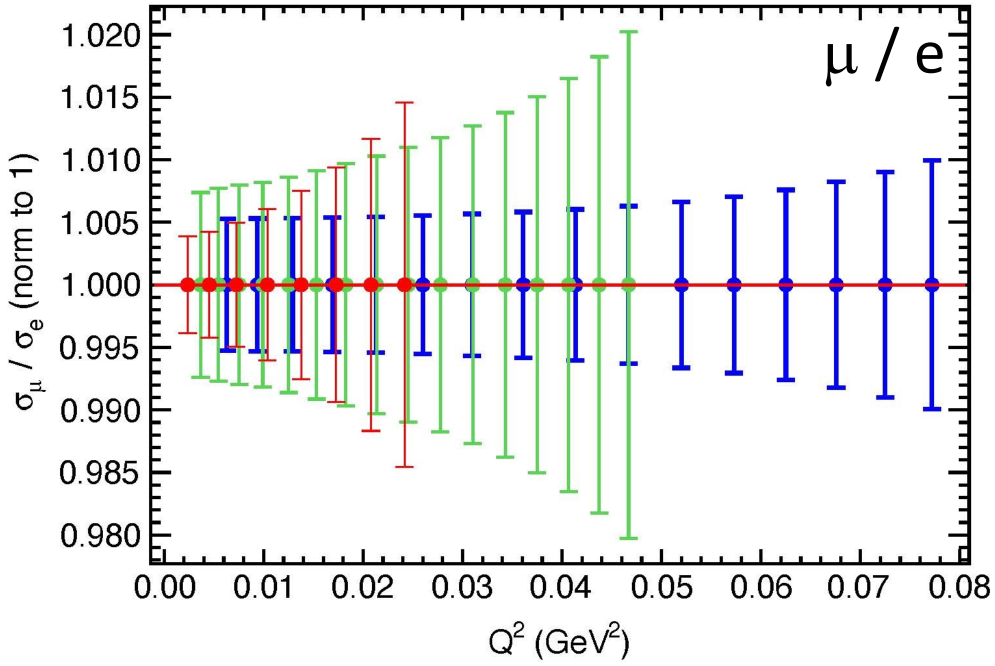
PAUL SCHERRER INSTITUT

THE GEORGE WASHINGTON UNIVERSITY
WASHINGTON, DC

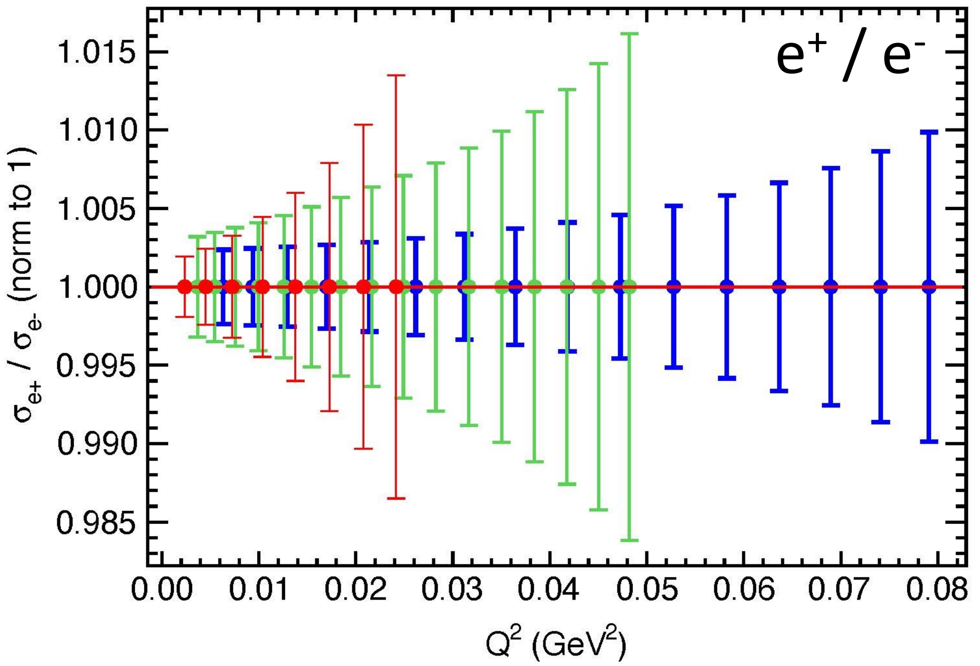


- Anticipated form factor uncertainty
- E. Cline, *et al.*, SciPost Phys. Proc. 5, 023 (2021)

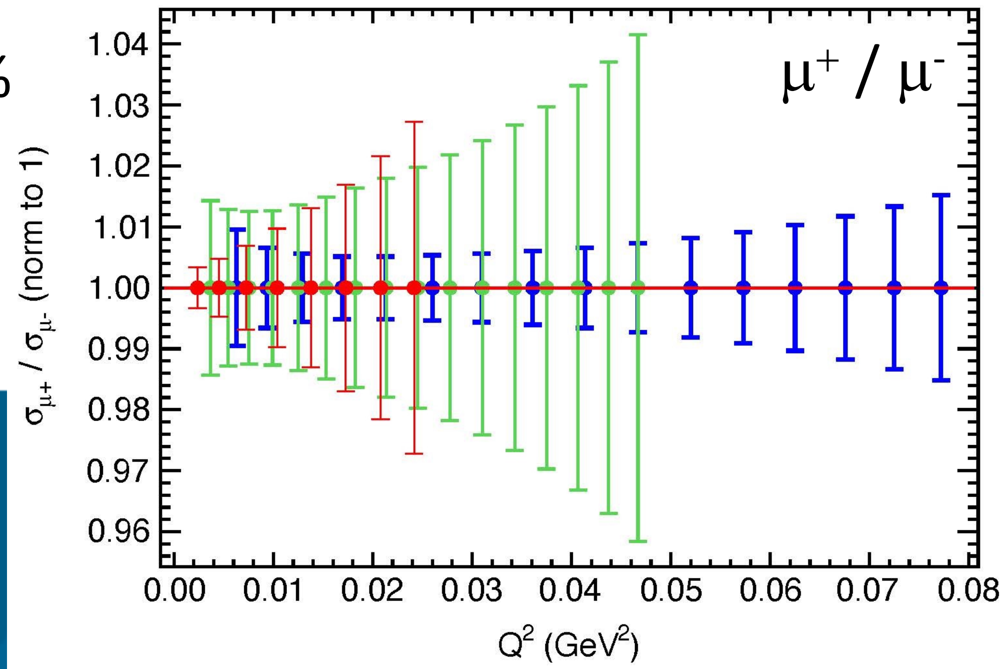
Anticipated Results



115 MeV / c
160 MeV / c
210 MeV / c



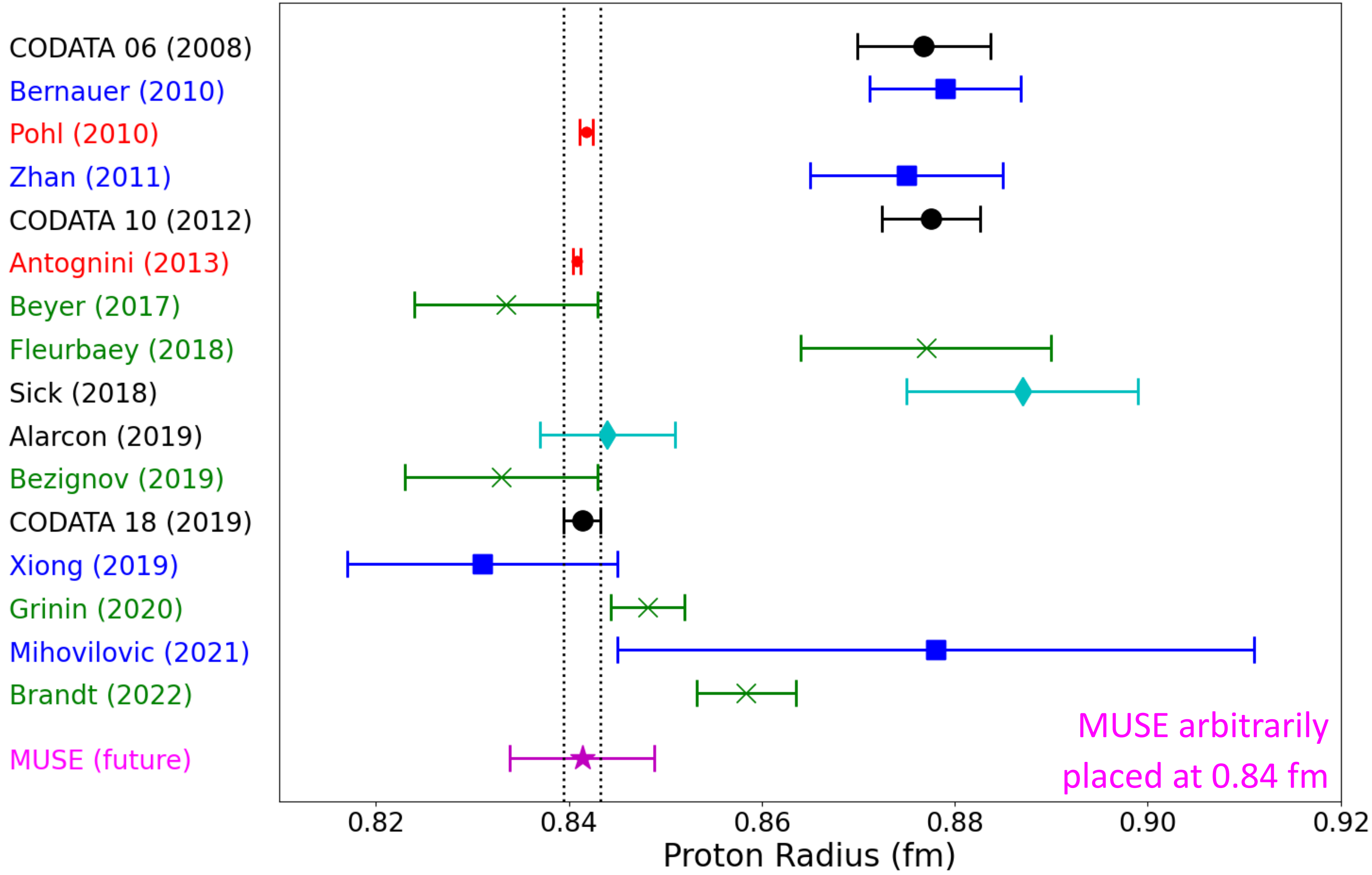
- Stat. uncertainty plotted, systematic better than 0.5%
- Based on assumption of one year of running
- 20% of scattering data taken in 2023 so far…



MUSE

Anticipated Results

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

$\sigma(r_e\text{-}r_\mu) \cong 0.005$ 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

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

Thanks to: S. Schlimme, J. Friedrich, H. Gao, MUSE collaboration

Conclusion

PRoton Radius

AMBER Apparatus for Meson and Baryon Experimental Research

MAGIX at MESA

MUSE

THE GEORGE WASHINGTON UNIVERSITY WASHINGTON, DC