MENU2023 Conference, Mainz, Oct 15-20, 2023

The Proton Radius Puzzle

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* Supported by NSF PHY-2113436, DOE DE-SC0013941, and JSA

Outline

- **Recent reviews**

- **The Proton Charge Radius**
  – Definition

- **The Puzzle**
  – Spectroscopy
  – Scattering

- **Theory**
  – Quark models
  – Effective theories
  – Lattice QCD

- **Present and future experiments**

- **Conclusion**
  – There has been a trend, however we are not done yet

Recent reviews

- **H. Gao, M. Vanderhaeghen,**
  The proton charge radius,
  Rev. Mod. Phys. 94, 015002 (2022)

- **J.-P. Karr, D. Marchand, E. Voutier,**
  The proton size,
  Nature Reviews Physics 2, 601–614 (2020)

- **C. Peset, A. Pineda, and O. Tomalak,**
  The proton radius (puzzle?) and its relatives,
  Prog. Part. Nucl. Phys. 121, 103901 (2021)

Definition

G. Miller, *Defining the Proton Radius: a Unified Treatment*
Phys. Rev. C 99, 035202 (2019)

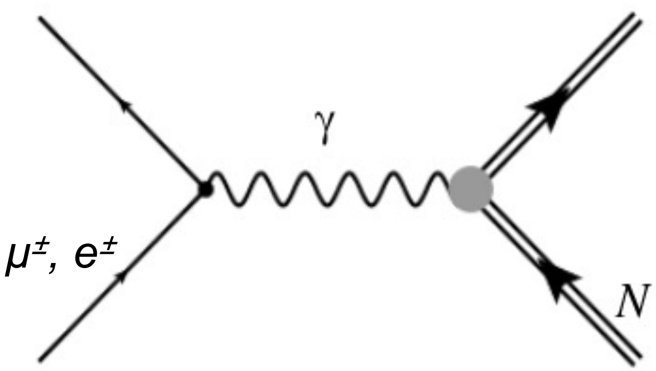
Proton = a rather light, relativistic, composite object
Moment of rest charge distribution not probed by spectroscopy or scattering

Consistent, covariant treatment: $$\langle r_E^2 \rangle = -6 \frac{dG_E^p(Q^2)}{dQ^2}\bigg|_{Q^2 \to 0}$$

Transverse charge density may be considered (relativistically correct)

Lepton scattering and charge radius

Lepton scattering from a nucleon:



Vertex currents:

$$J_e^\mu = -e\overline{u}_e \gamma^\mu u_e$$

$$J_N^\mu = \overline{\psi}_N \left[F_1(Q^2)\gamma^\mu + F_2(Q^2)\frac{i\sigma^{\mu\nu}q_\nu}{2M_N} \right] \psi_N$$

F_1, F_2 are the Dirac and Pauli form factors

Sachs form factors:

$$G_E(Q^2) = F_1(Q^2) - \tau F_2(Q^2)$$
$$G_M(Q^2) = F_1(Q^2) + F_2(Q^2)$$

Fourier transform (in the Breit frame) gives spatial charge and magnetization distributions

Derivative in $Q^2 \rightarrow 0$ limit:

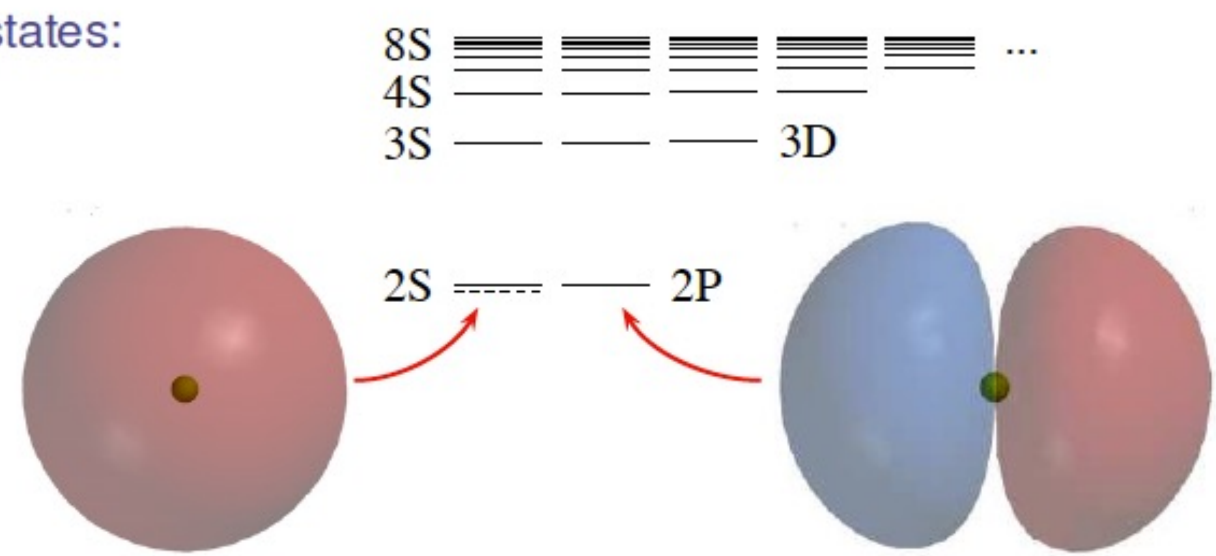
$$\boxed{\langle r_E^2 \rangle = -6 \left. \frac{dG_E^p(Q^2)}{dQ^2} \right|_{Q^2 \rightarrow 0}}$$

$$\langle r_M^2 \rangle = -6 \left. \frac{dG_M^p(Q^2)/\mu_p}{dQ^2} \right|_{Q^2 \rightarrow 0}$$

Expect identical behavior for any charged lepton – e±, μ±

Atomic physics

Wave functions of S and P states:



S states: max. at r=0

Electron sometimes inside the proton.

S states are shifted.

Shift ist proportional to the

size of the proton

P states: zero at r=0

Electron is not inside the proton.

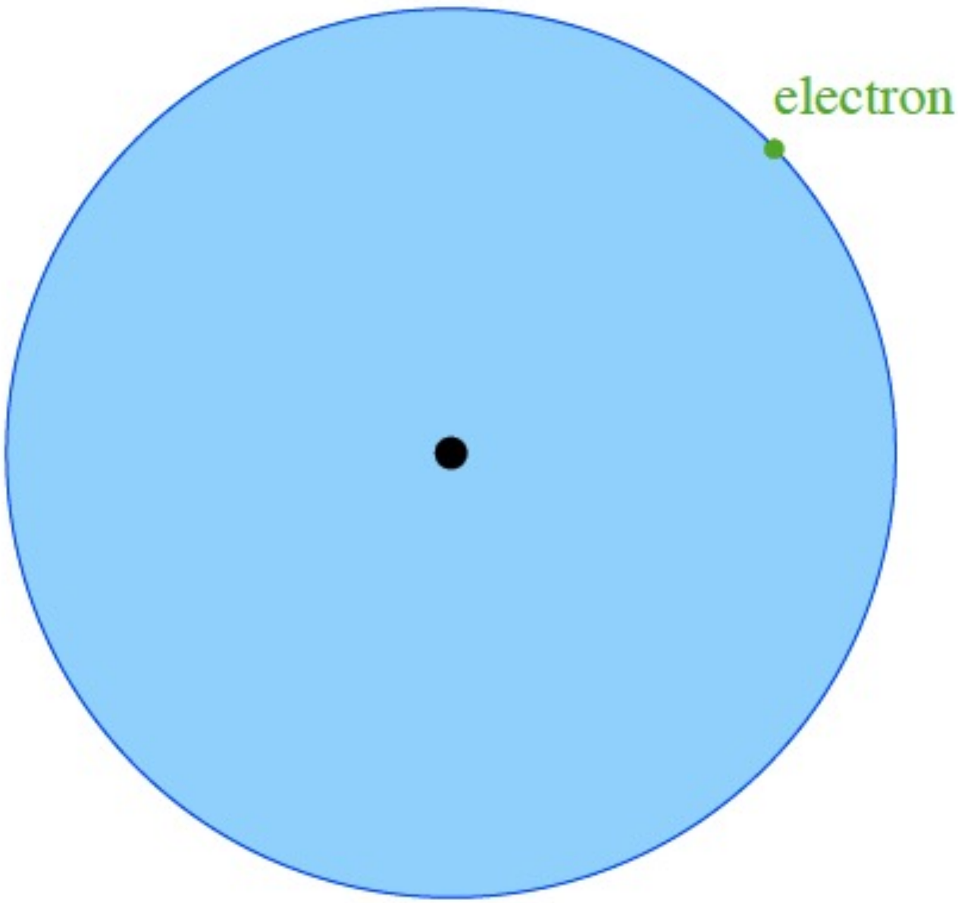
Slide by R. Pohl

Orbital pictures from Wikipedia

Muonic hydrogen

Regular hydrogen:

electron e^- + proton p



Muonic hydrogen:

muon μ^- + proton p

muon mass $m_\mu \approx$ 200 $\times m_e$

Bohr radius $r_\mu \approx$ 1/200 $\times r_e$

μ inside the proton: $200^3 \approx 10^7$

muon **much** is more sensitive to r_p

Slide by R. Pohl

Muonic hydrogen

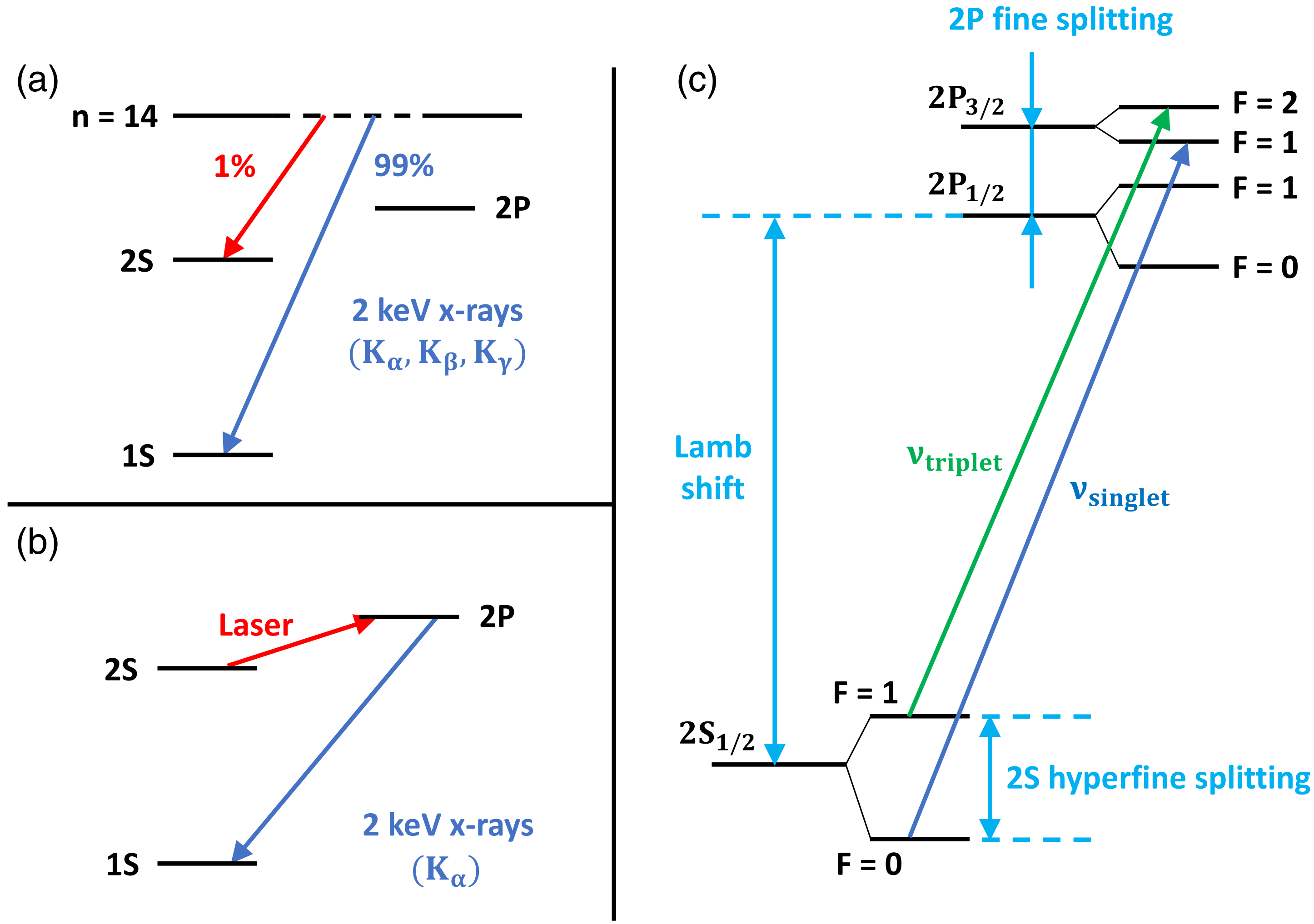


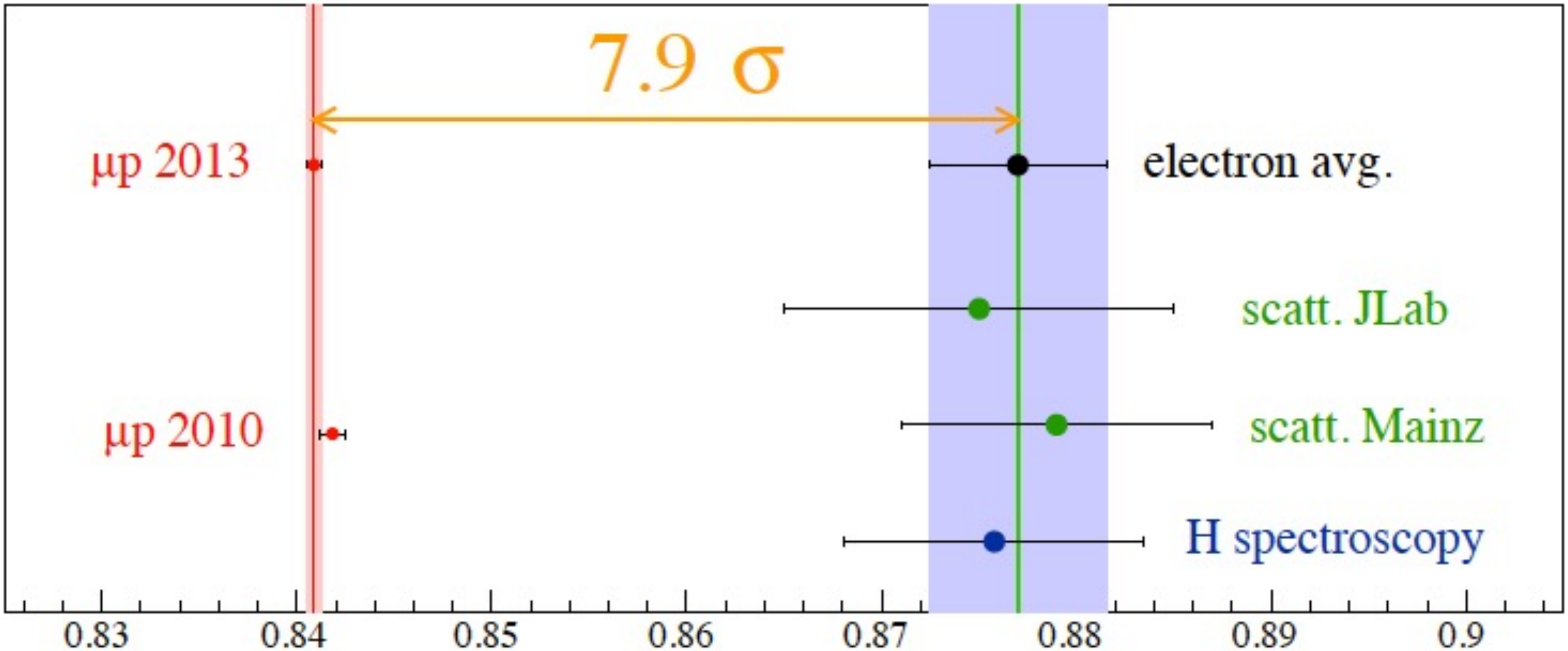
FIG. 20. Muonic hydrogen energy levels relevant to the proton charge radius measurement. From Jingyi Zhou.

The proton radius puzzle in 2010/2013

The proton rms charge radius measured with

electrons: 0.8770 ± 0.0045 fm (CODATA2010+Zhan et al.)

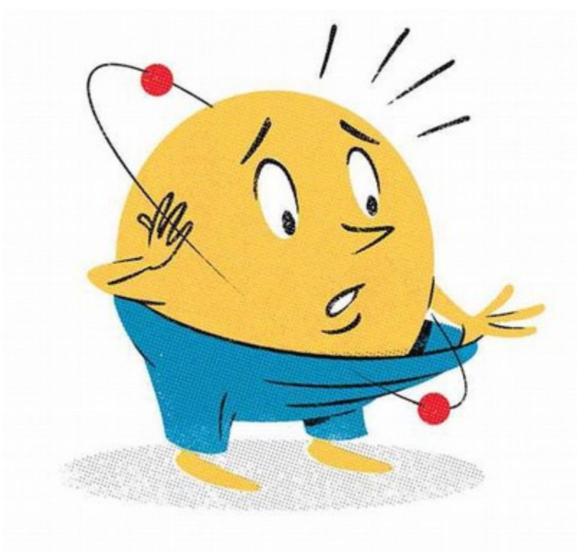
muons: 0.8409 ± 0.0004 fm



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

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

Proton radius puzzle has drawn attention



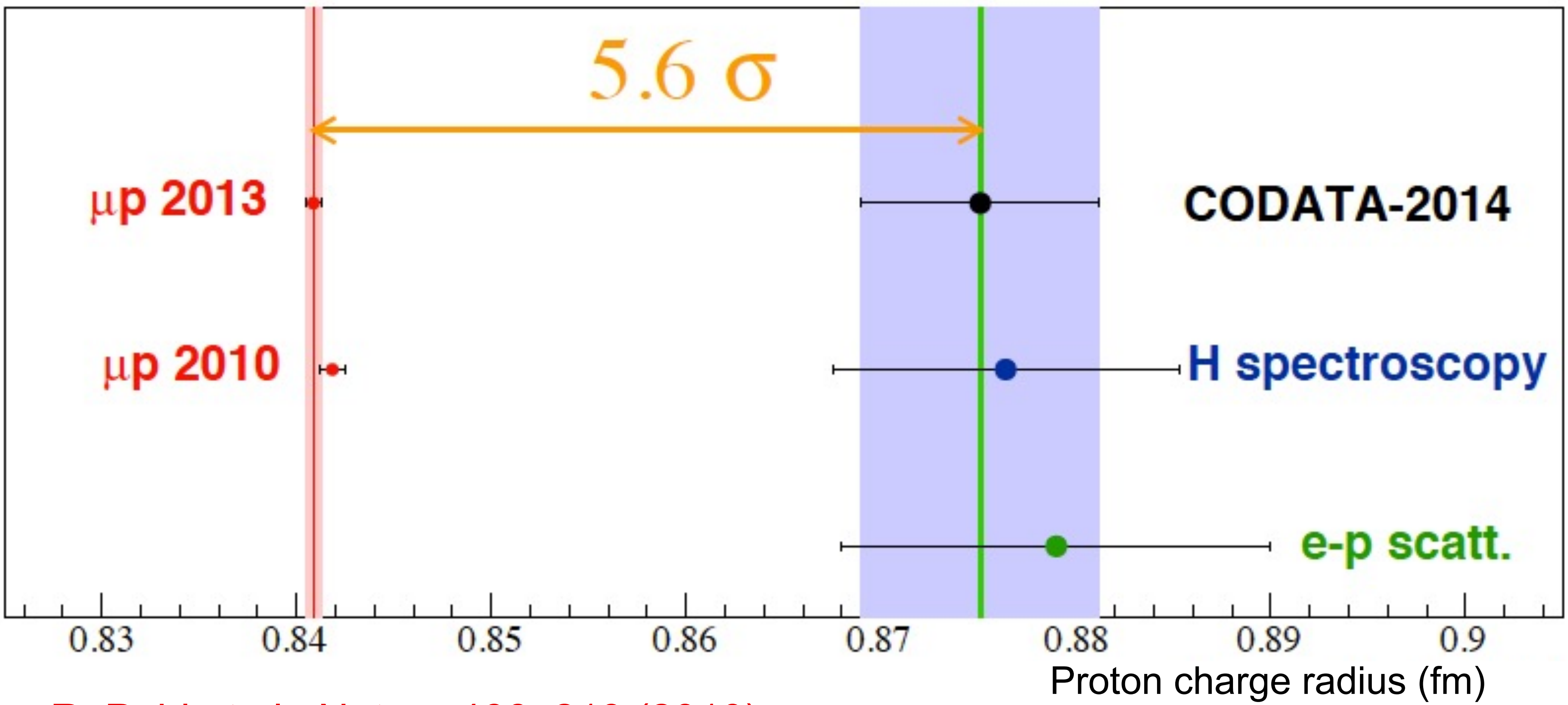
The New York Times

The proton radius puzzle in 2016

The proton rms charge radius measured with

electrons: (0.8751 ± 0.0061) fm **(CODATA2014)**

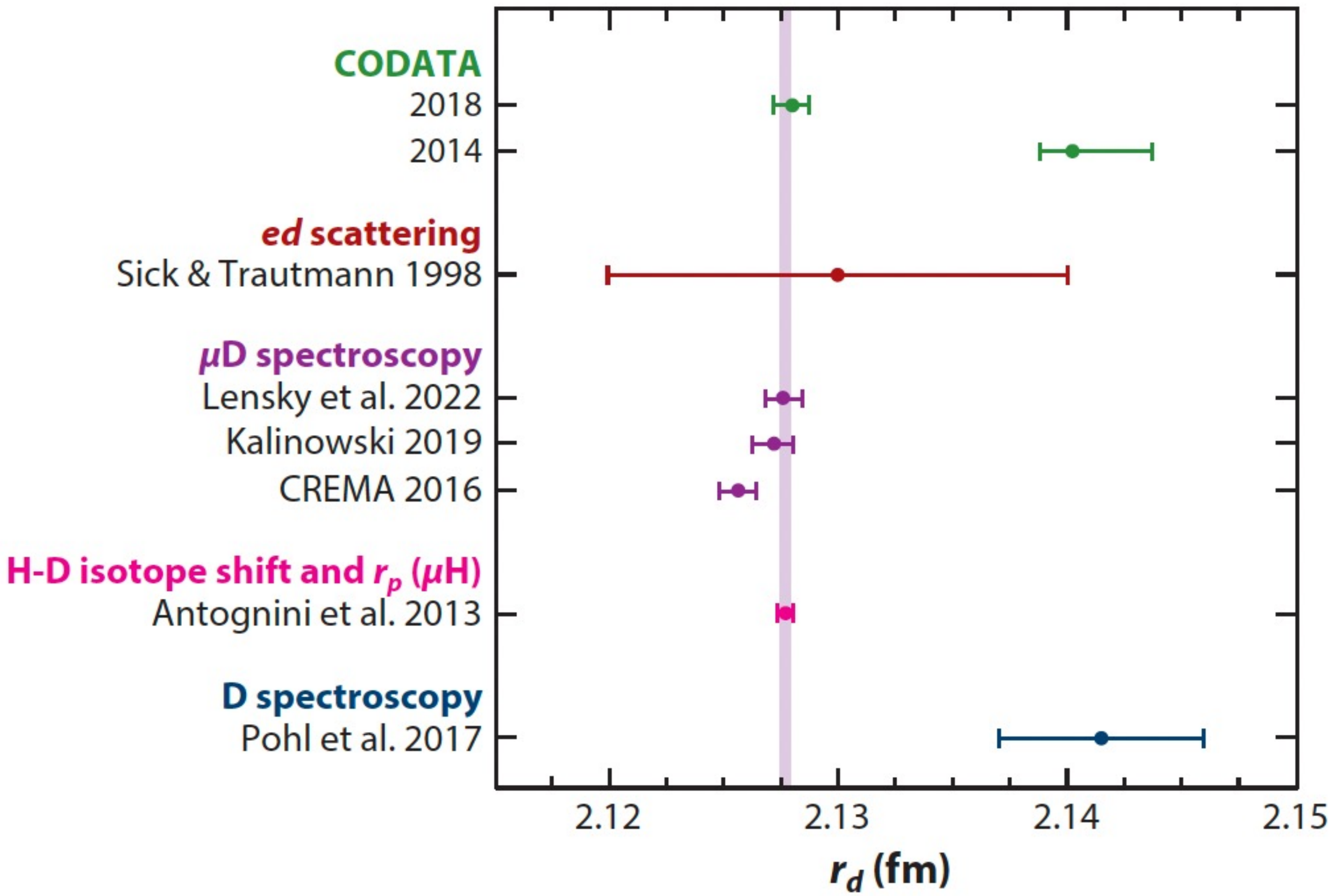
muons: (0.8409 ± 0.0004) fm



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

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

There is also a deuteron radius puzzle



- **Muonic deuterium agrees with muonic hydrogen w/ istope shift:**
  R. Pohl *et al.,* (CREMA) Science 353, 669 (2016)
- **Electron scattering not (yet) conclusive**
- **Muonic ^{4}He agrees with electronic helium:**
  J. Krauth *et al.*, Nature 589, 527 (2021)

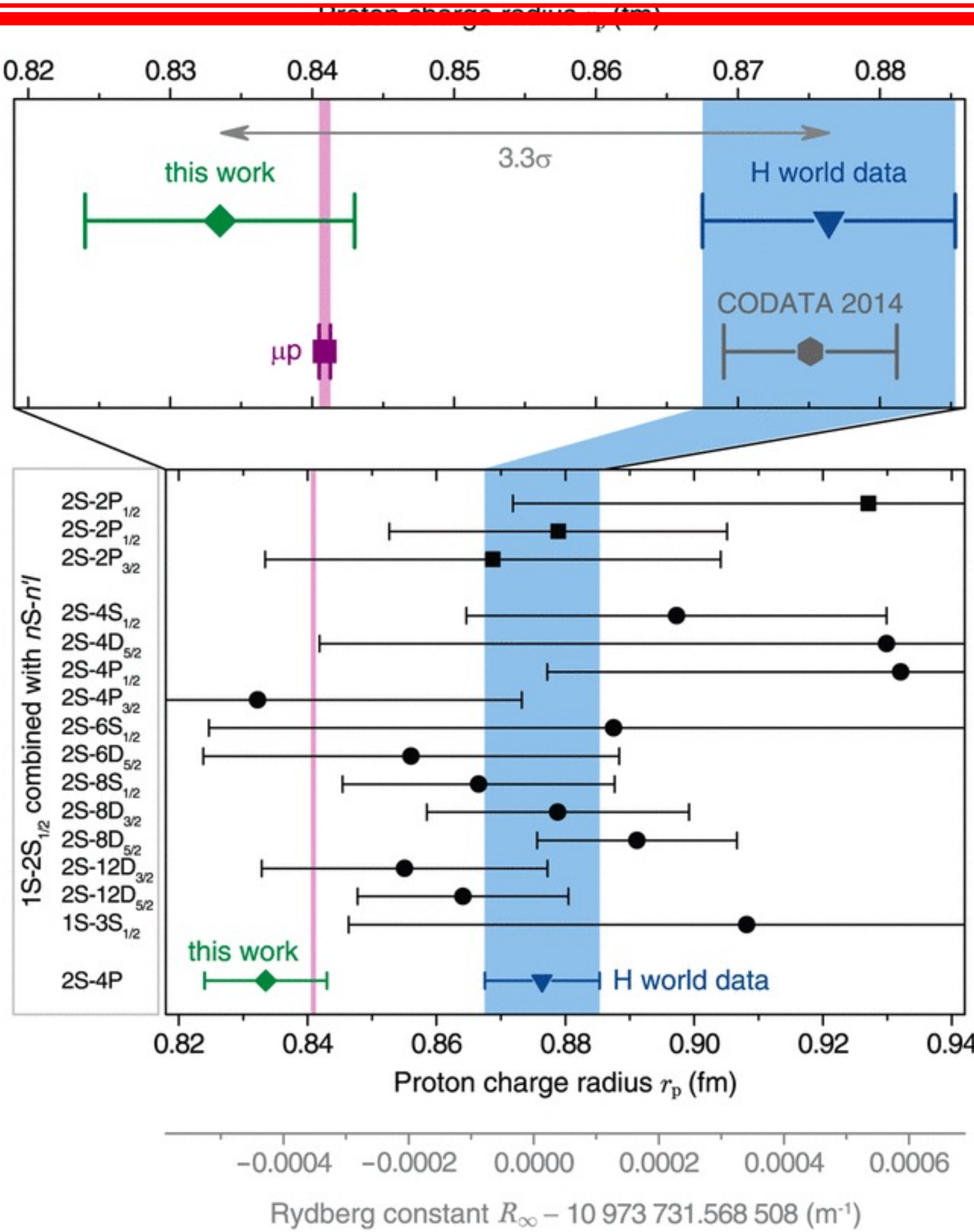
The community got engaged

- **Workshops and conferences**
  2012, 2016 ECT*
  2014, 2018 Mainz
  2019 Losinj
  2022, 2023 PREN (Paris, Mainz)
- **Special sessions of many other major conferences**
- **Re-analyses**
- **Theoretical efforts**
- **New experiments**
  Spectroscopy
  Scattering

Possible resolutions to the puzzle

- **The μp (spectroscopy) result is wrong**
  Discussion about theory and proton structure for extracting the proton radius from muonic Lamb shift measurement
- **The ep (spectroscopy) results are wrong**
  Accuracy of individual Lamb shift measurements?
  Rydberg constant could be off by ~5 sigma
- **The ep (scattering) results are wrong**
  Fit procedures not good enough
  Q^2 not low enough, structures in the form factors
- **Proton structure issues in theory**
  Off-shell proton in two-photon exchange leading to enhanced effects differing between μ and e
  Hadronic effects different for μp and ep:
  e.g. proton polarizability ($effect \propto m_l^4$)
- **Physics beyond Standard Model differentiating μ and e**
  Lepton universality violation, light massive gauge boson(s)
  Constraints on new physics from meson decays and spectroscopy

New spectroscopy results: 2S-4P (Garching)



A. Beyer *et al.*
Science 358, 79 (Oct. 6, 2017)

$\delta\nu \sim \Gamma / 10^4$

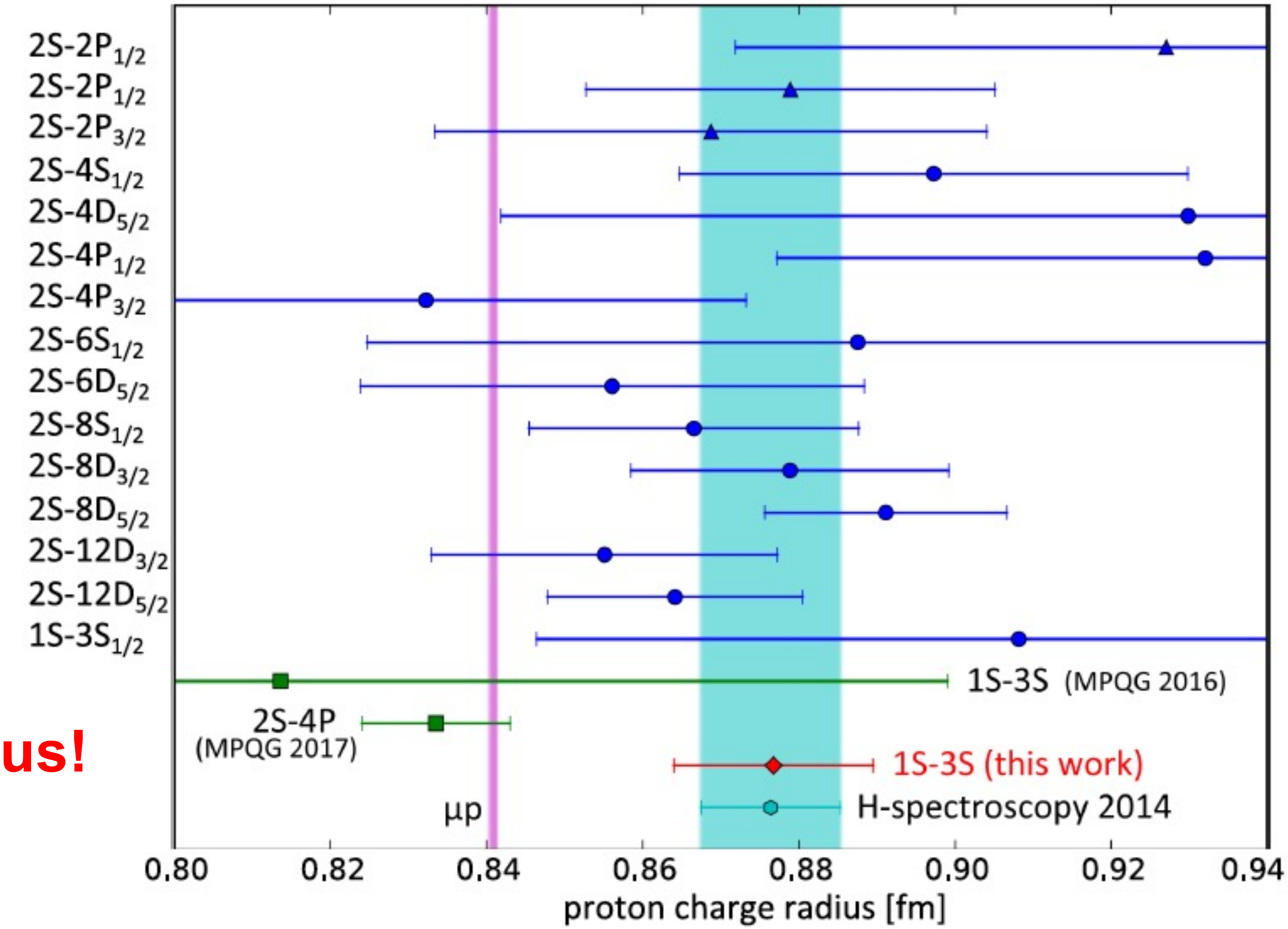
→ Small radius

Puzzle solved?

No!

Why different?

New spectroscopy results: 1S-3S (Paris)

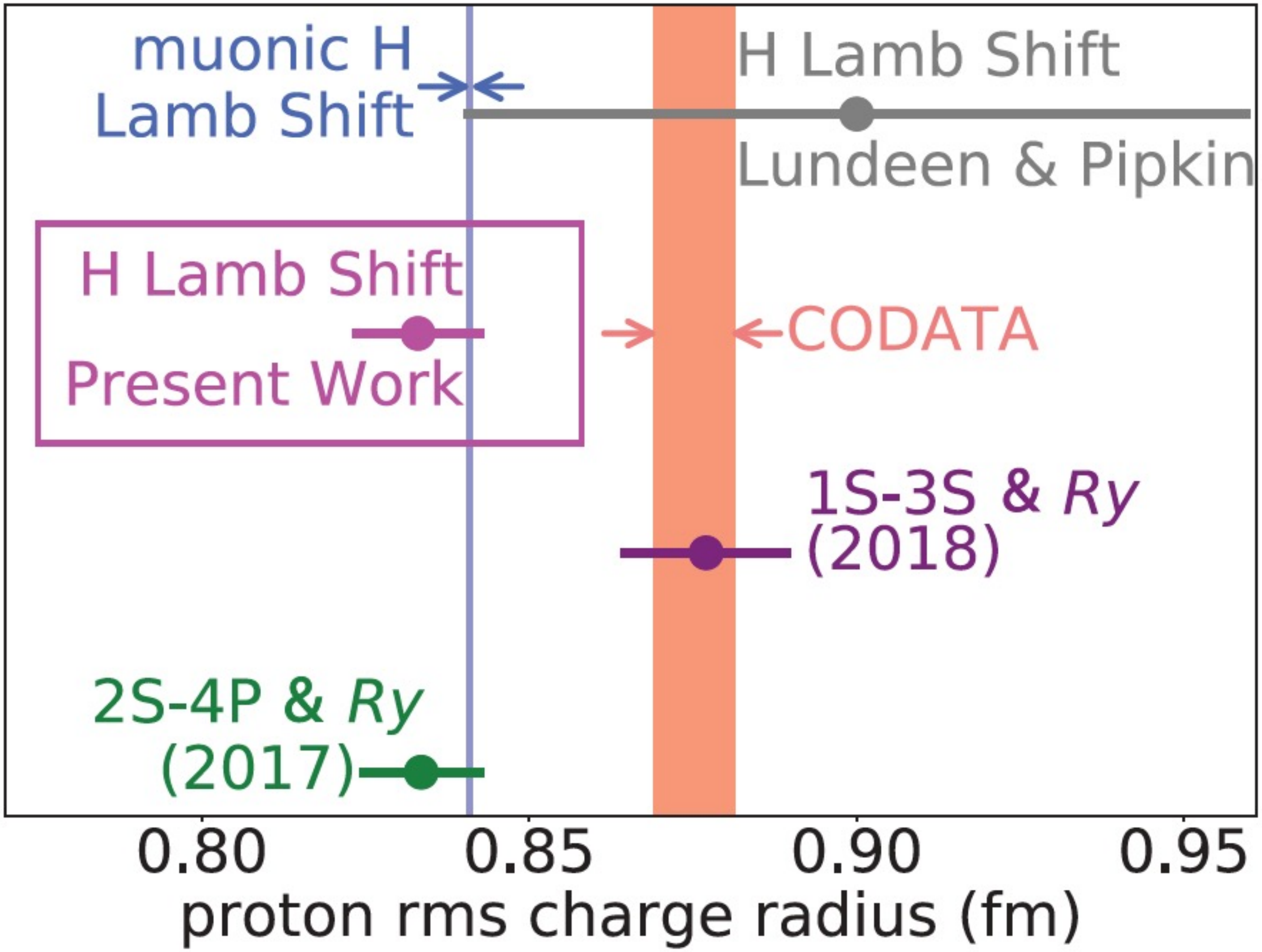


→ **Large radius!**

Hélène Fleurbaey *et al.*, PRL 120, 183001 (2018)

G. Miller @ INT: Is there still a proton radius puzzle?
Is electron-hydrogen spectroscopy accurate enough?

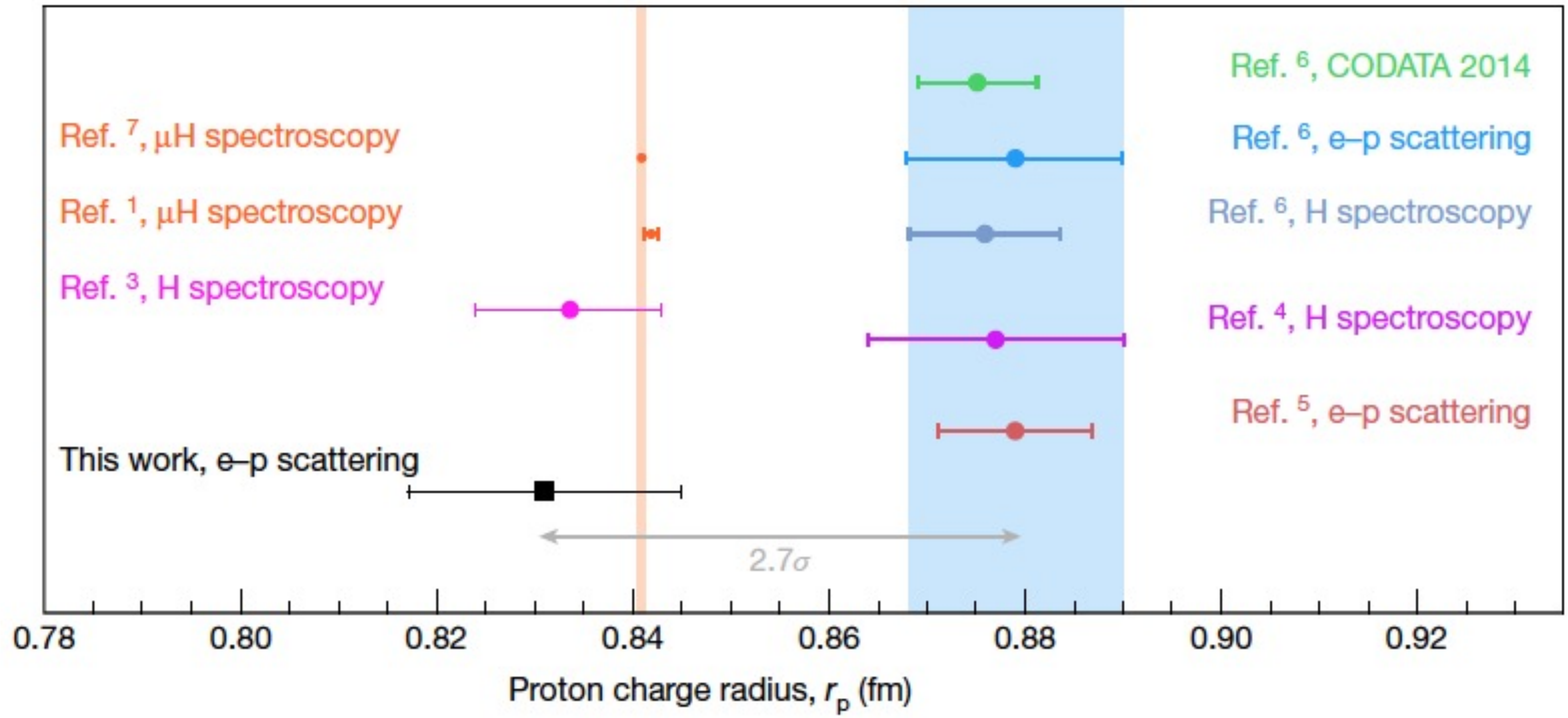
New spectroscopy results: 2S-2P (York)



→ Small radius! Independent of Rydberg

N. Bezginov *et al.*, Science 365, 1007 (2019) – published Sep 5, 2019

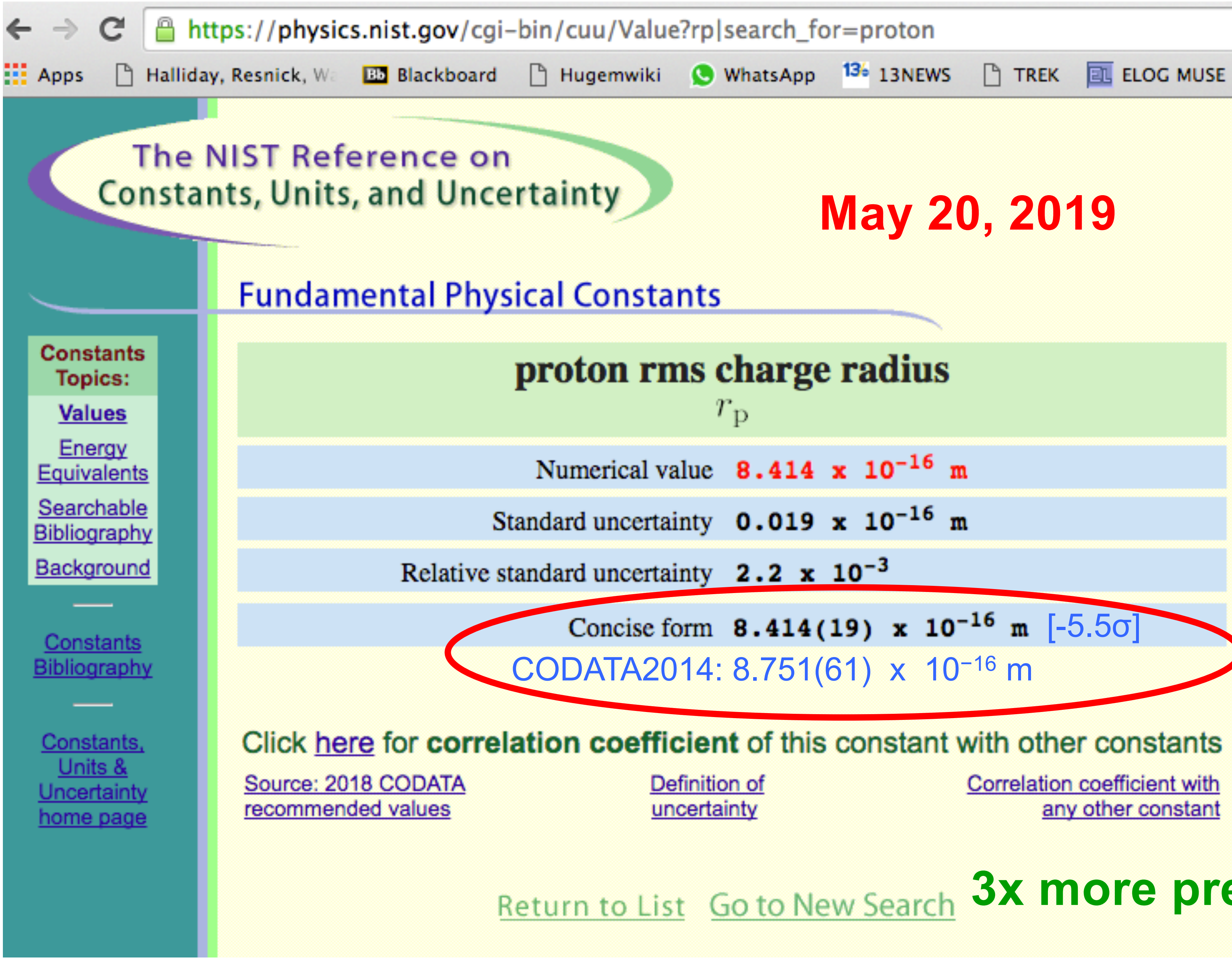
New electron scattering: PRad



"A small proton charge radius from an electron–proton scattering experiment"

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

CODATA2018 new recommended values



May 20, 2019

[-5.5σ]

CODATA2014: $8.751(61) \times 10^{-16}$ m

3x more precise

CODATA2018 new recommended values

https://physics.nist.gov/cgi-bin/cuu/Value?rydchz|search_for=rydberg

Apps | Halliday, Resnick, W | Blackboard | Hugemwiki | WhatsApp | 13NEWS | TREK | ELOG MUSE

The NIST Reference on Constants, Units, and Uncertainty

May 20, 2019

Fundamental Physical Constants

Constants Topics:
- Values
- Energy Equivalents
- Searchable Bibliography
- Background

Constants Bibliography

Constants, Units & Uncertainty home page

Click symbol for equation

Rydberg constant times c in Hz

$R_\infty c$

Numerical value	3.289 841 960 2508 x 10^{15} Hz
Standard uncertainty	0.000 000 000 0064 x 10^{15} Hz
Relative standard uncertainty	1.9 x 10^{-12}
Concise form	3.289 841 960 2508(64) x 10^{15} Hz [-5.5σ]

CODATA2014: 3.289 841 960 355 (19) x 10^{15} Hz

Click here for **correlation coefficient** of this constant with other constants

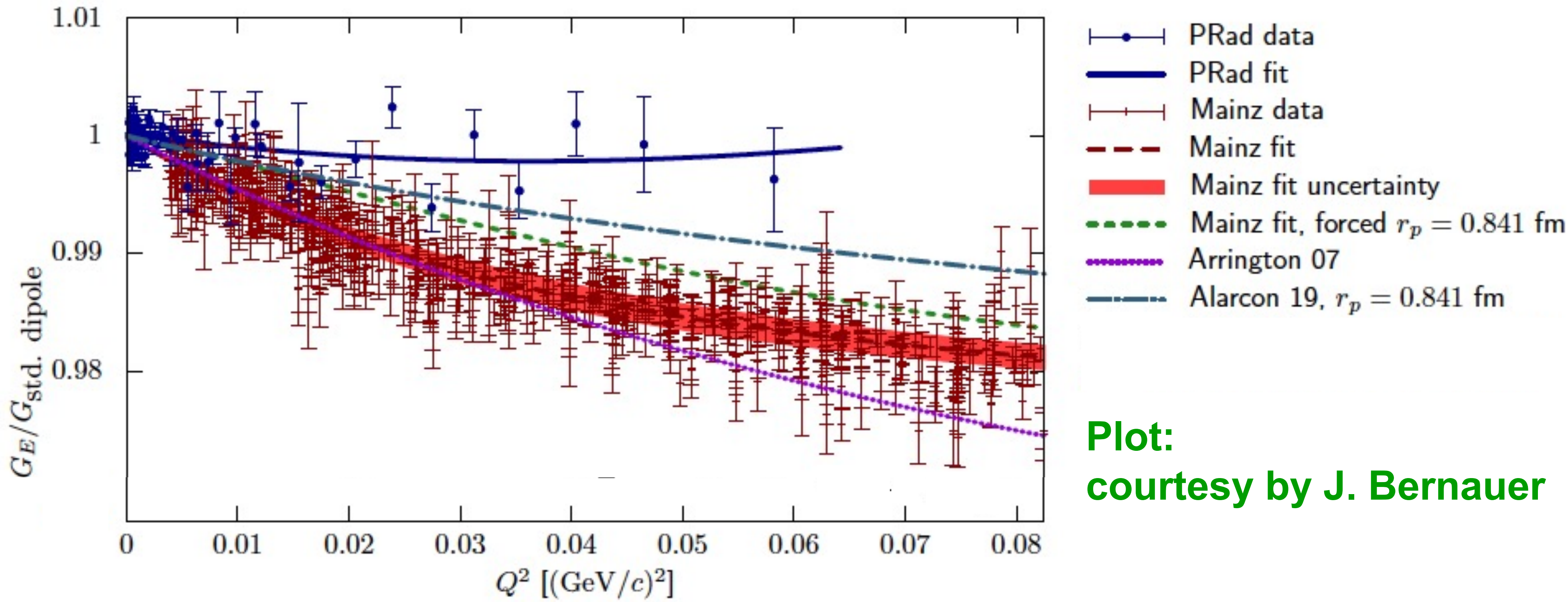
Source: 2018 CODATA recommended values | Definition of uncertainty | Correlation coefficient with any other constant

Return to List | Go to New Search

3x more precise

Puzzle solved?

- **Cross sections and form factors of PRad are different – why?**



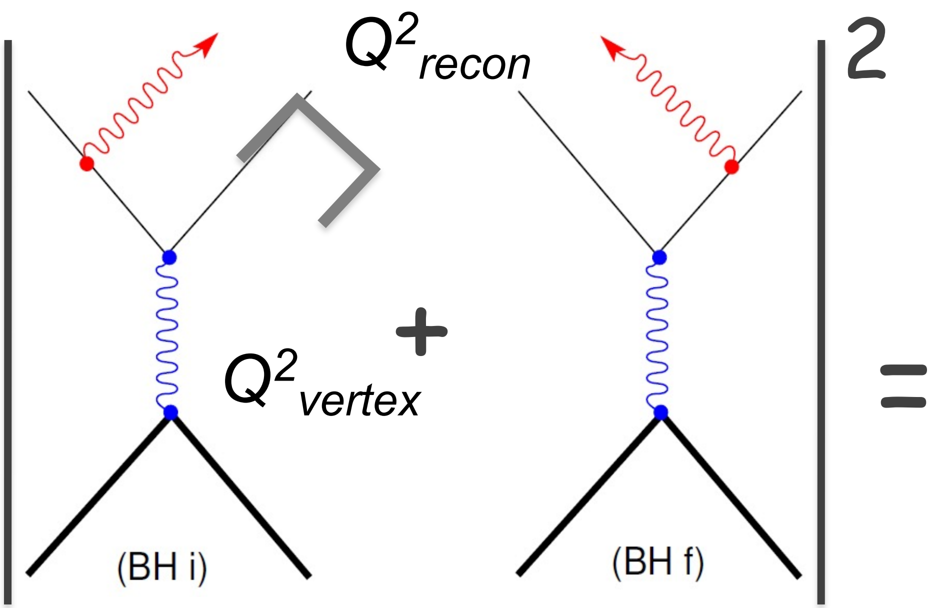
Plot: courtesy by J. Bernauer

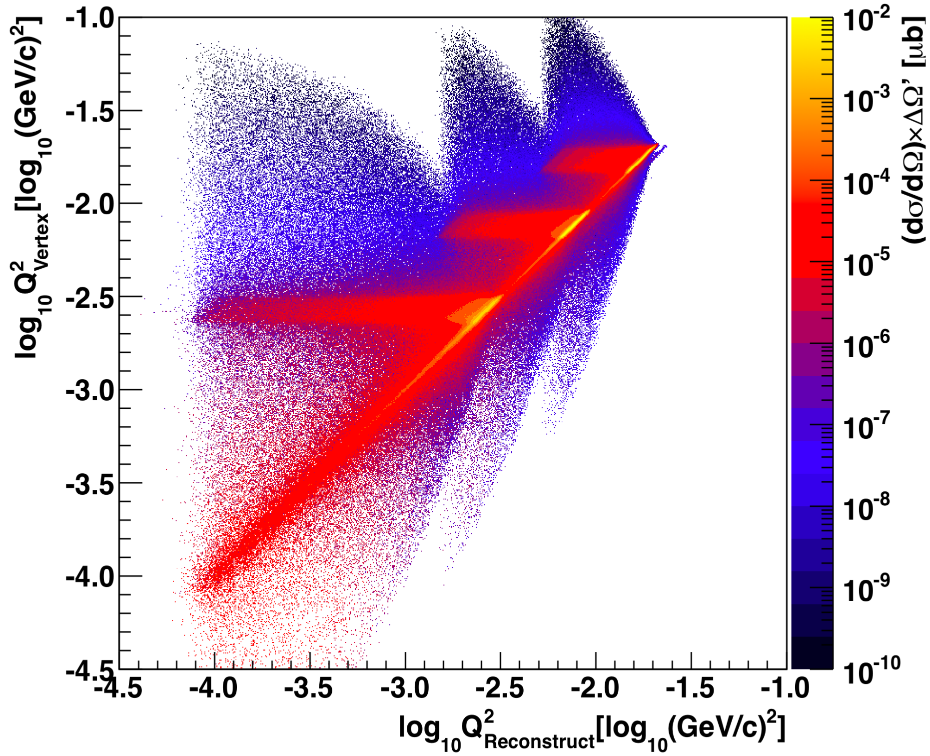
- **Accuracy of radiative corrections?**
- **What did previous experiments do wrong?**
- **Which result is to be preferred, and why?**

- **Need independent checks and validations**
  (→ ISR, ULQ2, MUSE, AMBER, PRad-II, MAGIX, …)

Initial state radiation (ISR) at MAMI

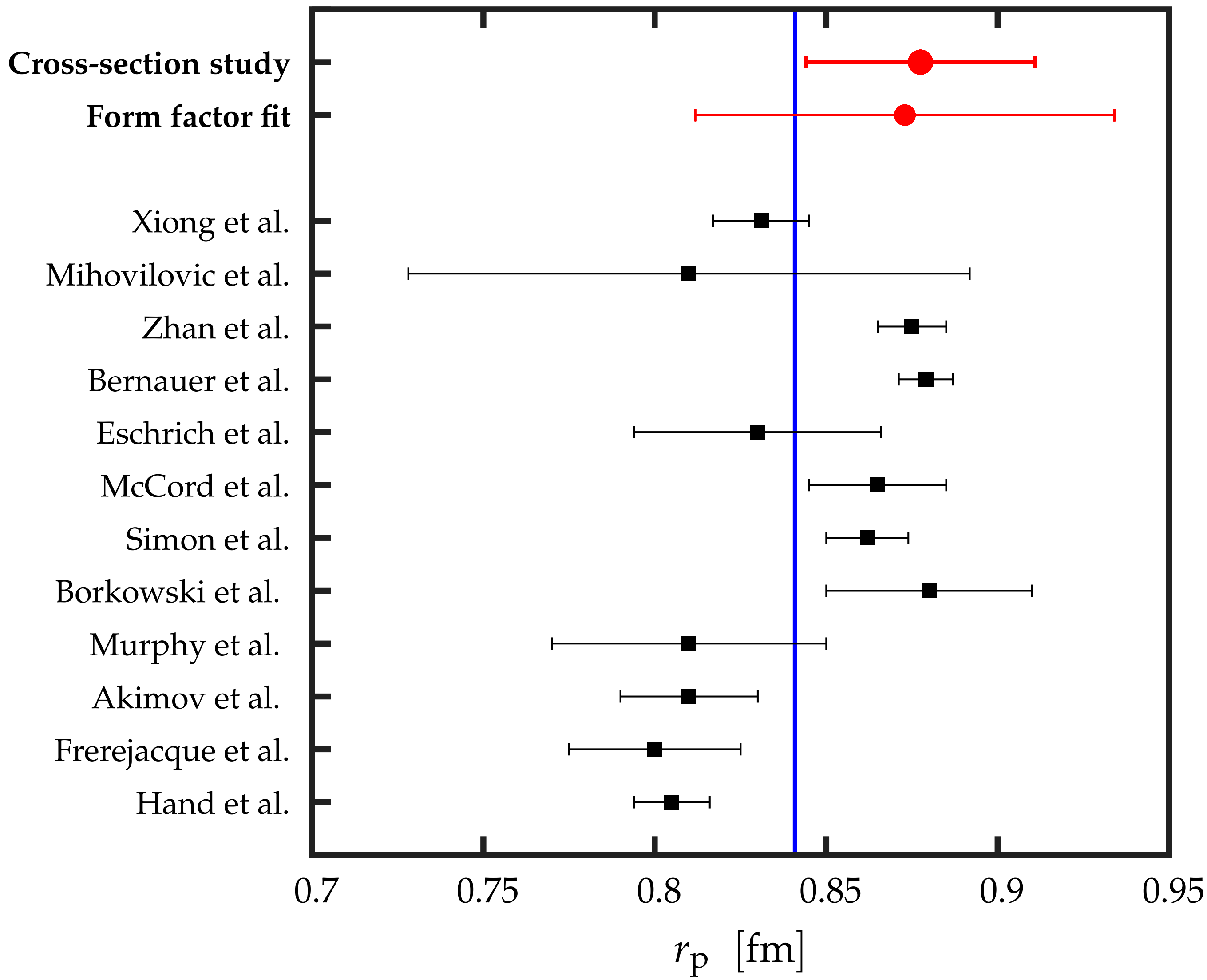
- Radiative tail dominated by coherent sum of two Bethe-Heitler diagrams





- <u>New MAMI experiment</u> to extract $\mathbf{G_E^p}$ at **lowest $Q^2 \sim 10^{-4}$ (GeV/c)^2**
- In the data ISR can not be distinguished from FSR, Q^2 (Recon) > Q^2 (ISR)
- **Combining data and simulation, ISR and form factor can be extracted**
- Method tested at higher Q^2
- Pilot pub. 2017, prel. result May 2019, **M. Mihovilovic, EPJA 57, 107 (2021)**
- Improvements underway (jet target), **Y. Wang et al., PRC 106, 044610 (2022)**

Initial state radiation (ISR) at MAMI



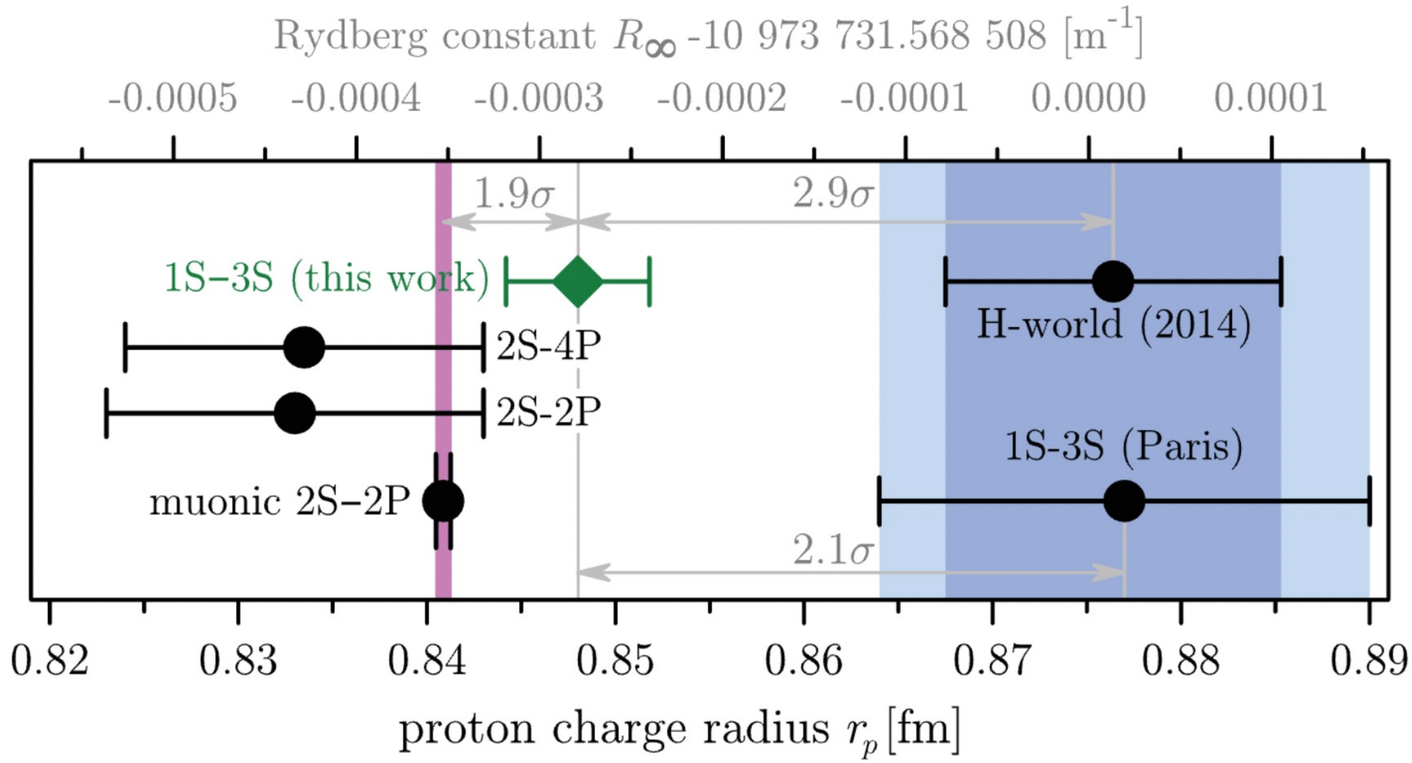
→ **Large radius!**

M. Mihovilovic *et al.*, EPJA 57, 107 (2021)

New spectroscopy results: 1S-3S (Garching)

MPI Garching Result 1S – 3S

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

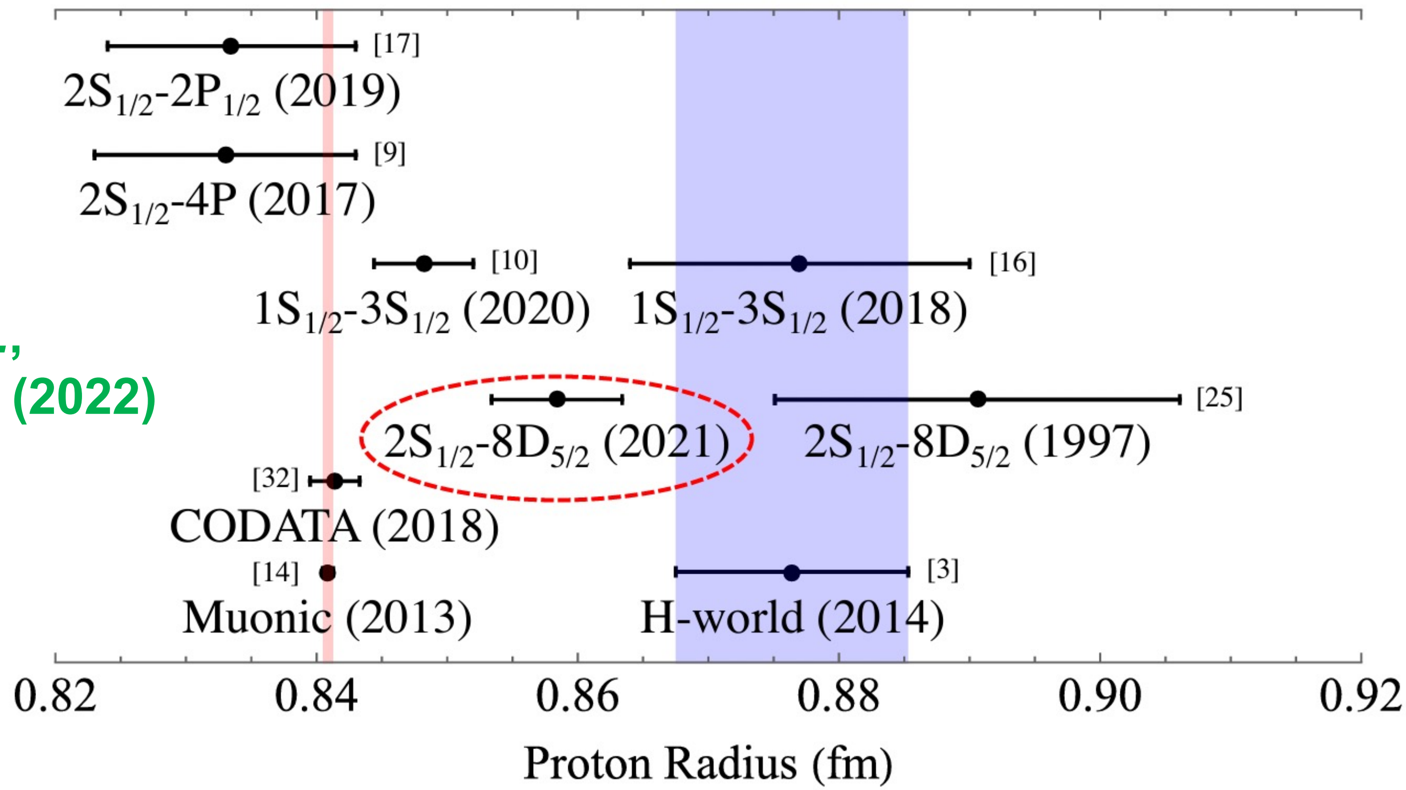


→ Intermediate radius!

New spectroscopy results: 2S-8D (Colorado)

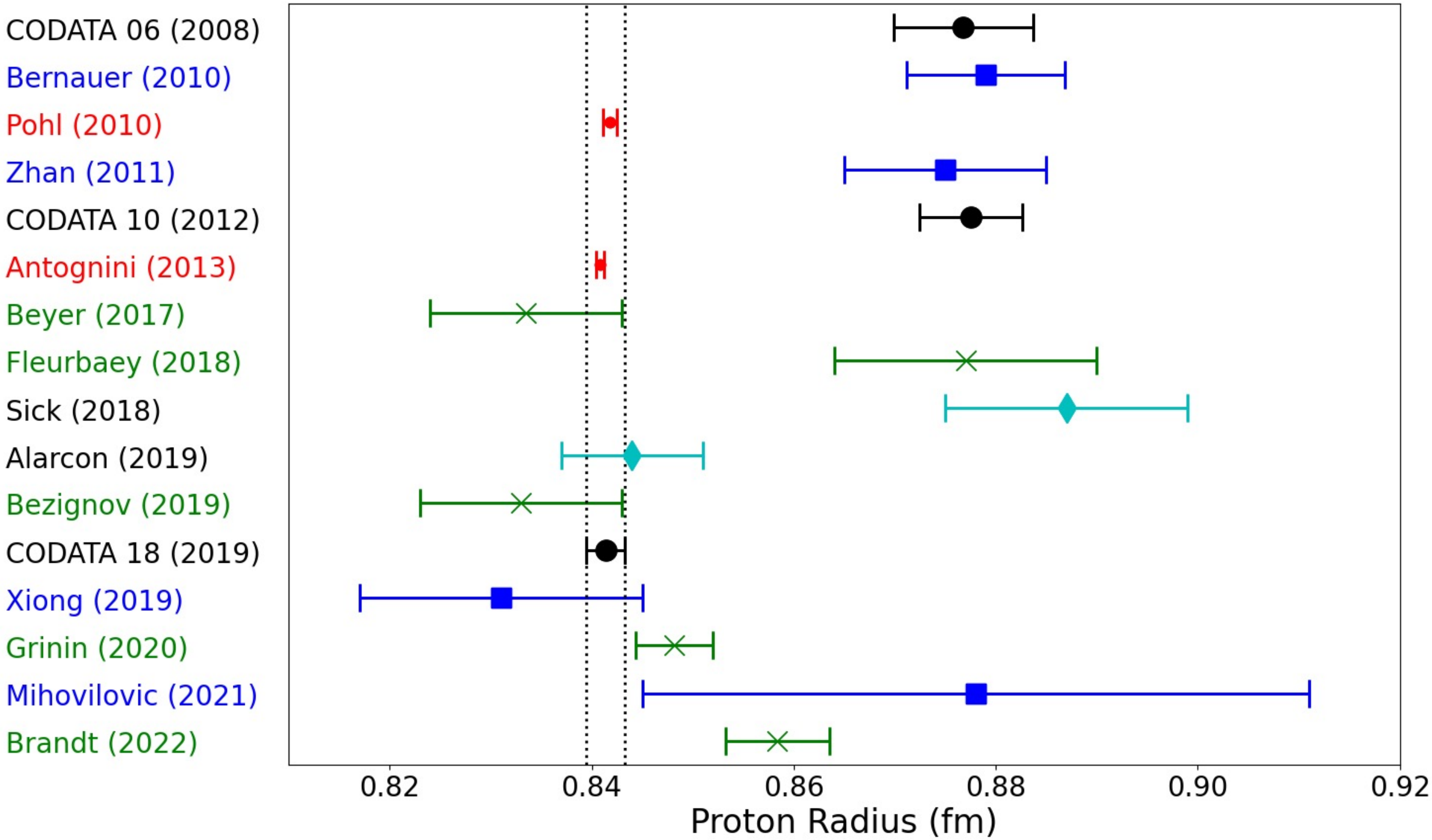
Colorado Result 2S – 8D

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



→ Intermediate radius!

The proton radius puzzle in 2023



Red = μp spectroscopy
Blue = ep scattering
Light blue = re-fitting of e scattering
Green = ep spectroscopy
Black = CODATA

Plot: courtesy by J. Bernauer

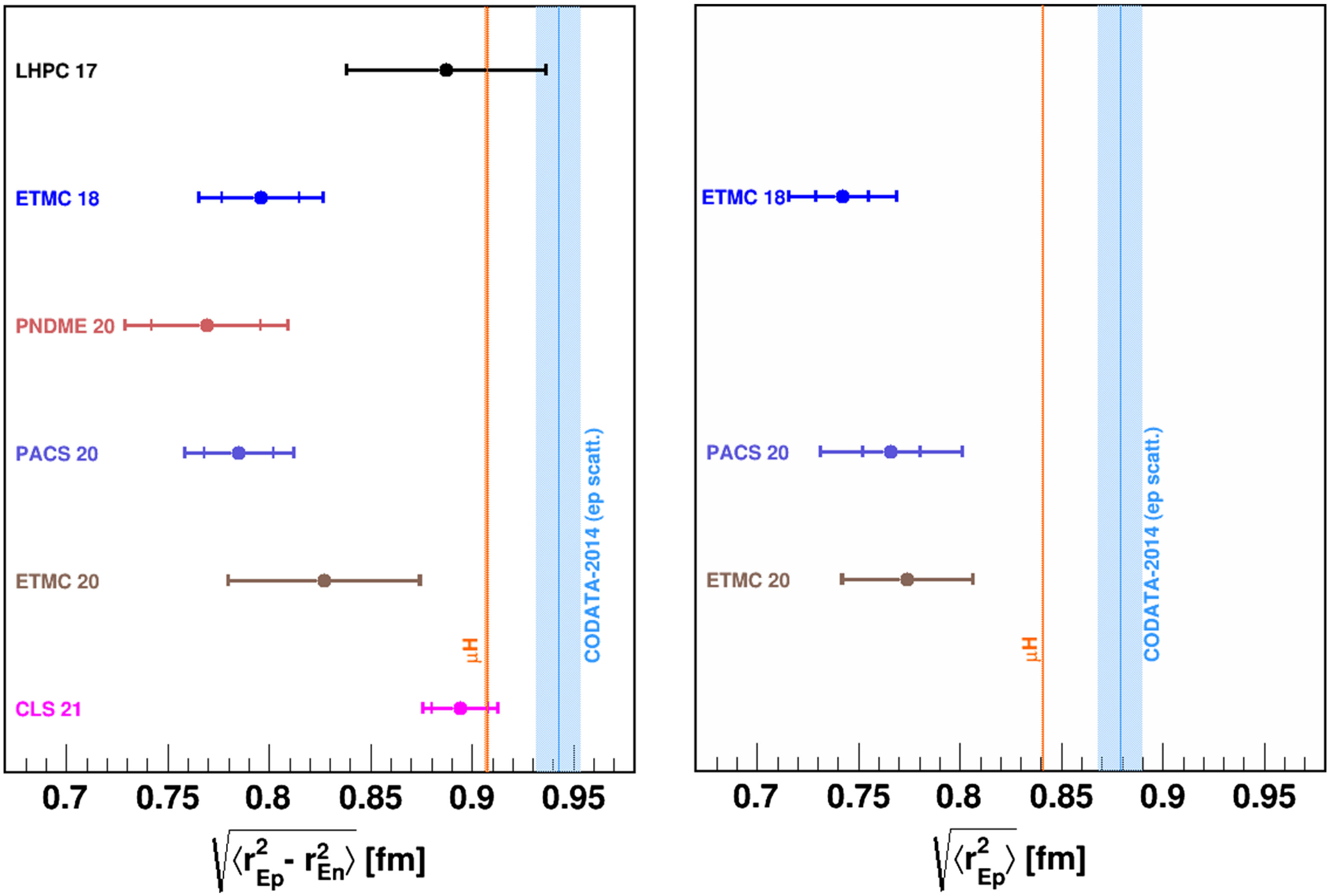
Theoretical efforts

- **Advanced models, e.g. RCQM, light-front, …**
  - rather accurate, increasingly sophisticated
  - inspired by effective degrees of freedom
  - model-dependent, as the name says
  - assumptions often ad hoc and not dynamically generated

- **Effective theories and phenomenology**
  - Phenomenological parameterizations
  - Advanced fits (e.g. z-expansion) with physics constraints
  - Dispersion Theory
  - Chiral Effective Field Theory, HBCPT, …
  - DSE, quark orbital momentum, di-quark correlations
  - Increasingly dynamic

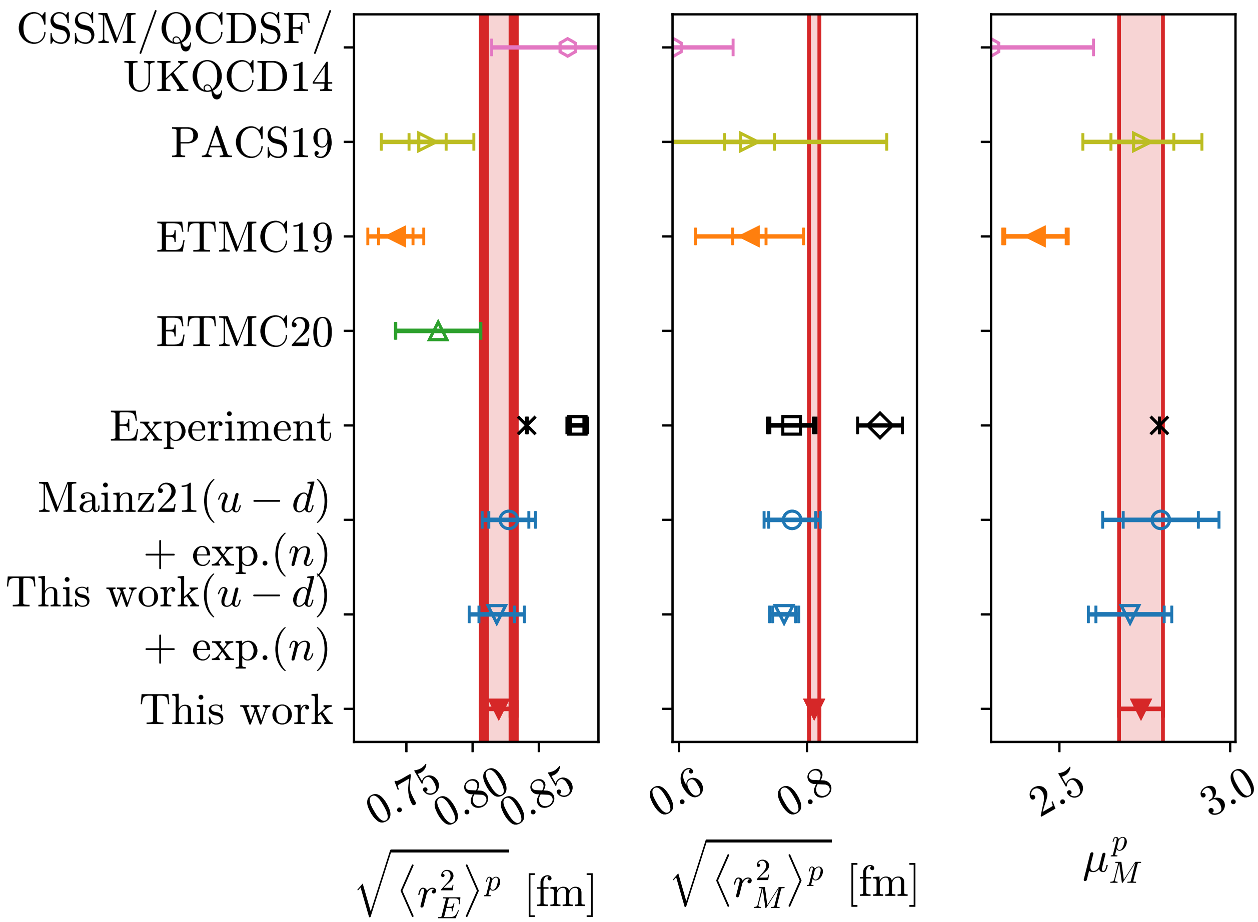
- **QCD = "Exact" theory of Strong Interaction, non-perturbative**
  - Lattice QCD
  - Uses first principles, phenomena dynamically generated

Recent Lattice QCD results



Isovector observables: no disconnected diagrams
Radii typically come out too small (pion mass, lattice box size)
Figure: from H. Gao, M. Vanderhaeghen, Rev. Mod. Phys. 94, 015002 (2022)

New milestone: Precision Lattice QCD



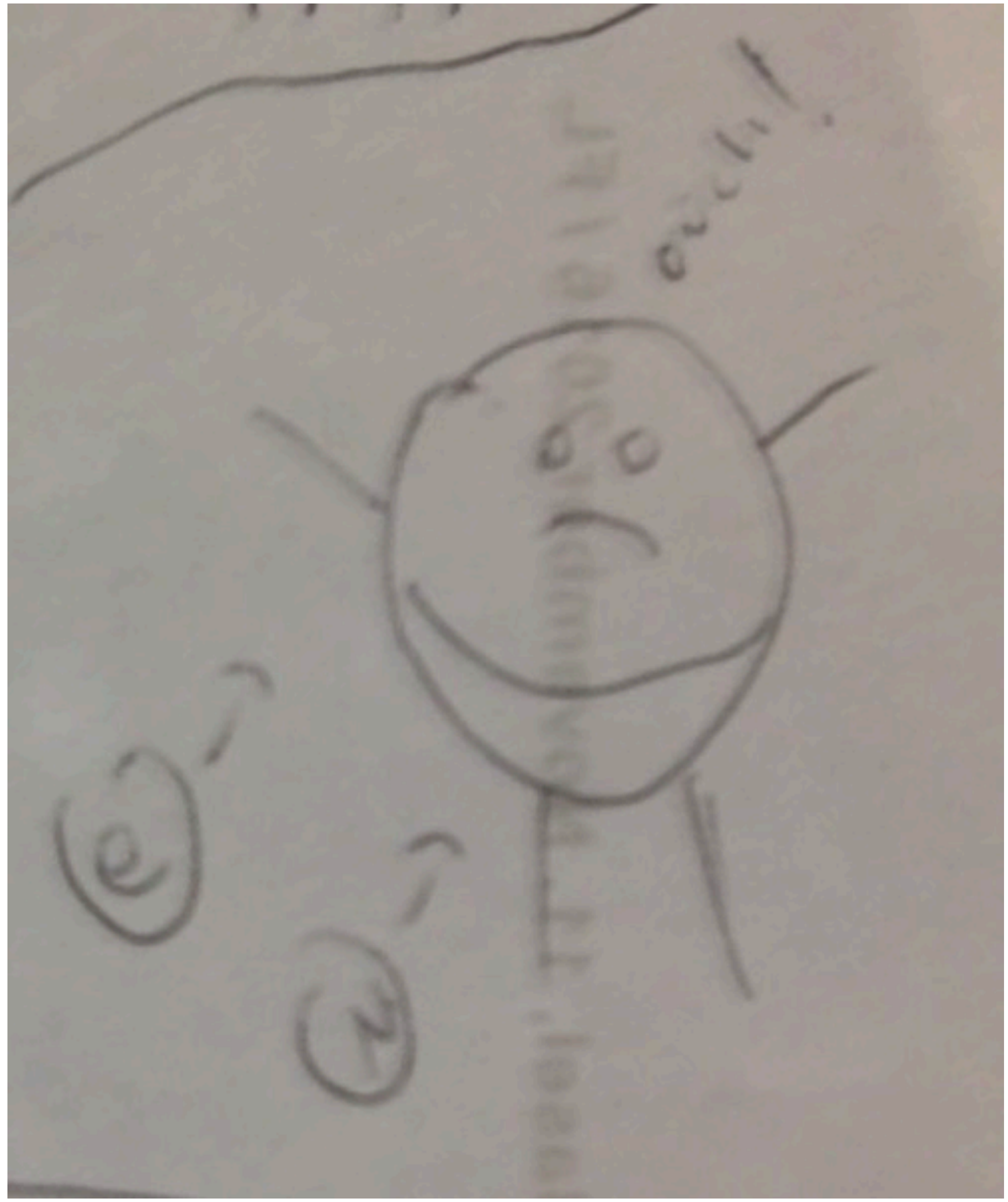
$$\sqrt{\langle r_E^2\rangle^p} = 0.820(14)\ \text{fm},\ \sqrt{\langle r_M^2\rangle^p} = 0.8111(89)\ \text{fm, and}\ \mu_M^p = 2.739(66)$$

Consistent with small radius

D. Djukanovic, G. von Hippel, H.B. Meyer, K. Ottnad, M. Salg, and H. Wittig, arXiv:2309.07491v1

Ongoing and future scattering experiments

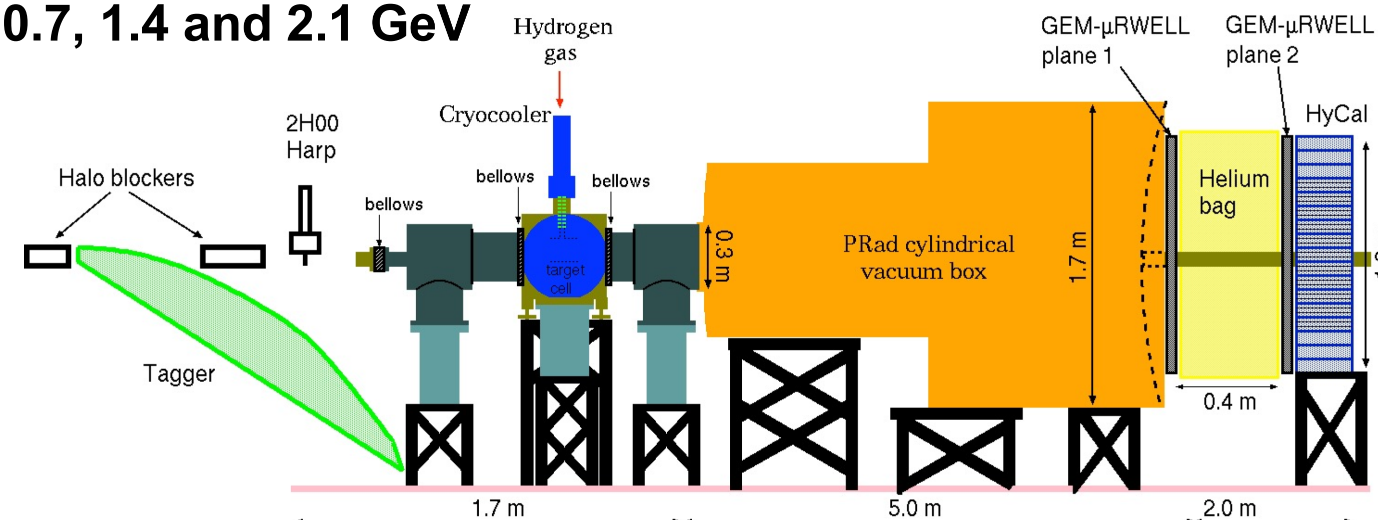
- **PRad-II @ JLab**
- **ULQ2 @ ELPH**
- **MAGIX @ MESA**
- **MUSE @ PSI**
- **AMBER @ CERN**



R. Gilman’s draft scribbling for the MUSE logo contest on the back of an envelope

PRad-II at JLab

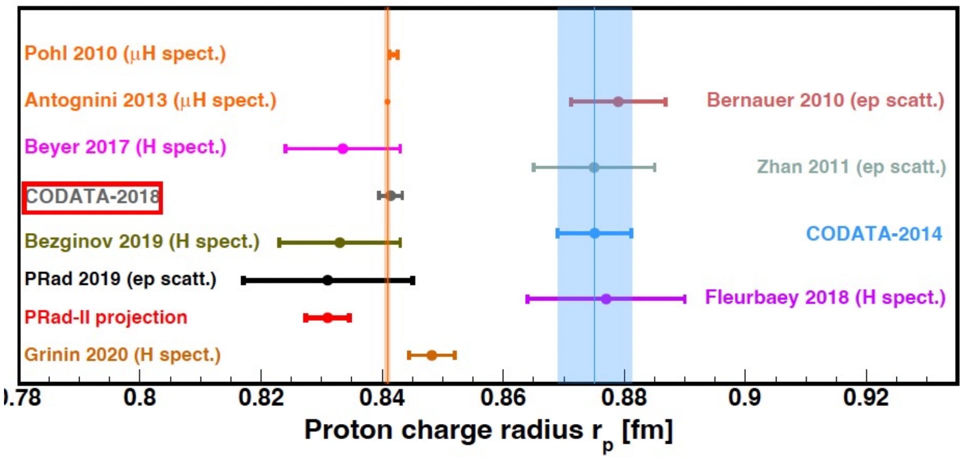
- **Improvements for PRad-II:**
  - ✓ **Better upstream vacuum and halo rejection**
  - ✓ **Add second GEM plane**
  - ✓ **Upgrade HyCal: $PbW0_4$, FADC readout**
  - ✓ **Added scintillators: separate Moller from ep in elect. scattering angular range of 0.5° - 0.8°**
  - ✓ **Factor 4 reduction of statistical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

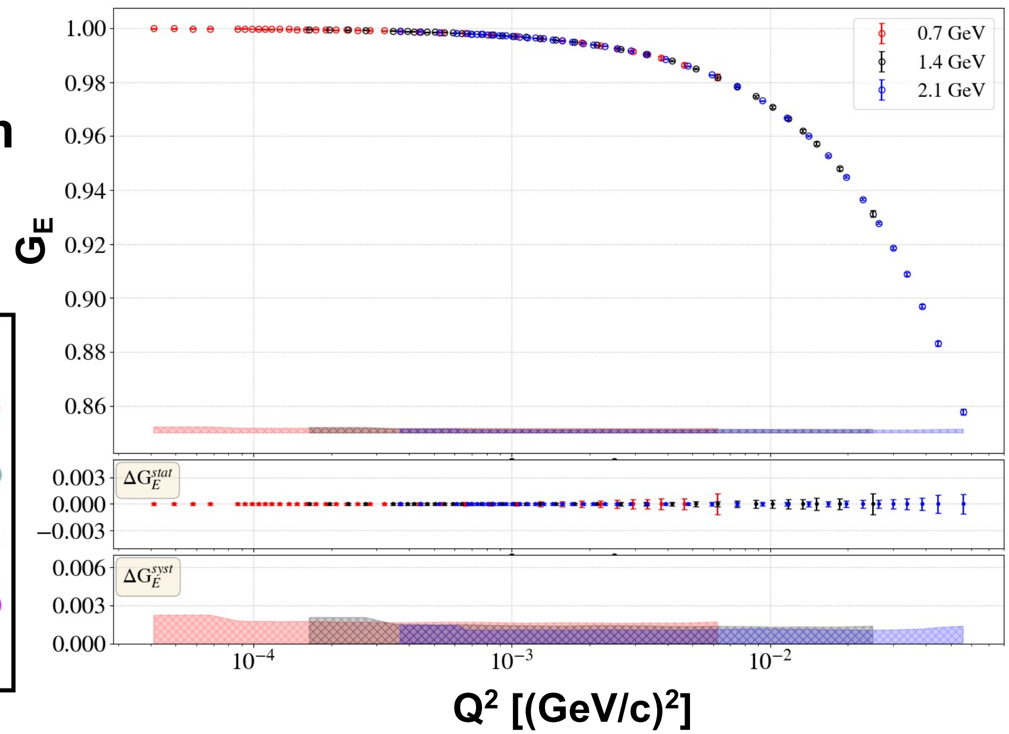


PRoton PRadius **PRad II @ JLab**

PRad-II at JLab

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





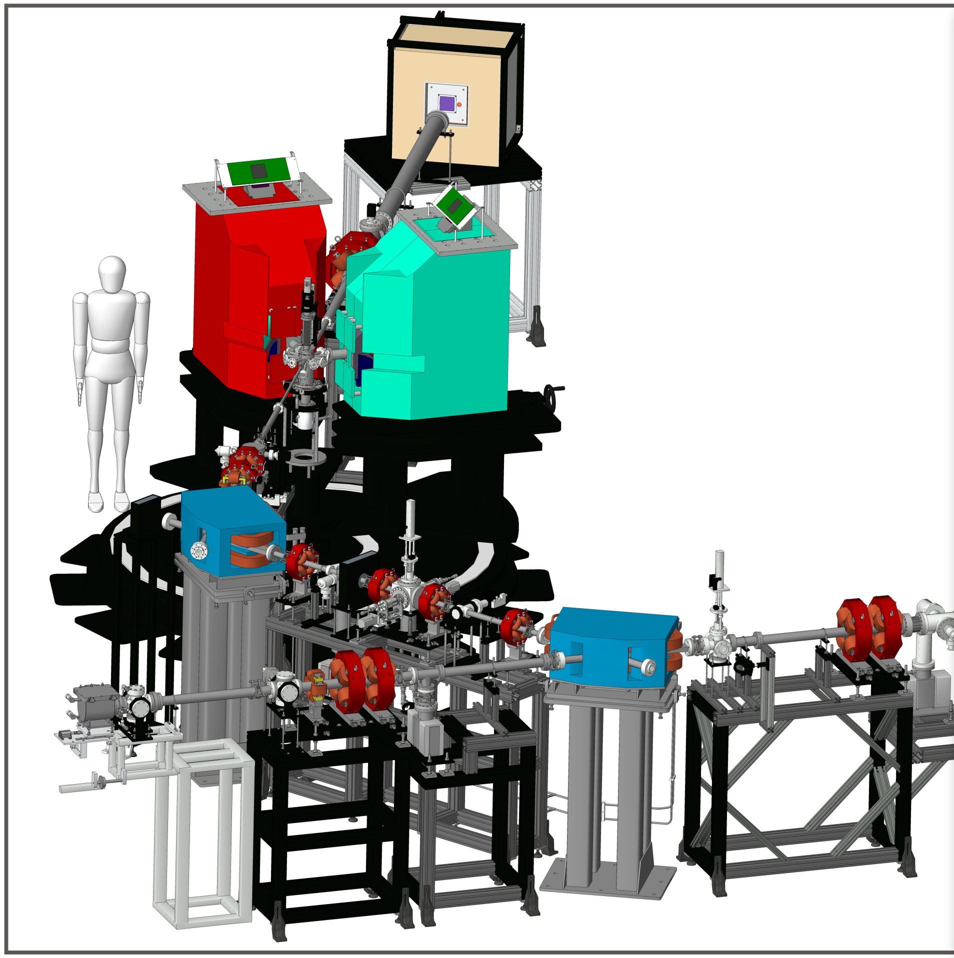
H. Gao: ERICE School on Nuclear Physics, September 18th, 2023

PRoton PRadius

PRad II @ JLab

ULQ2 @ ELPH

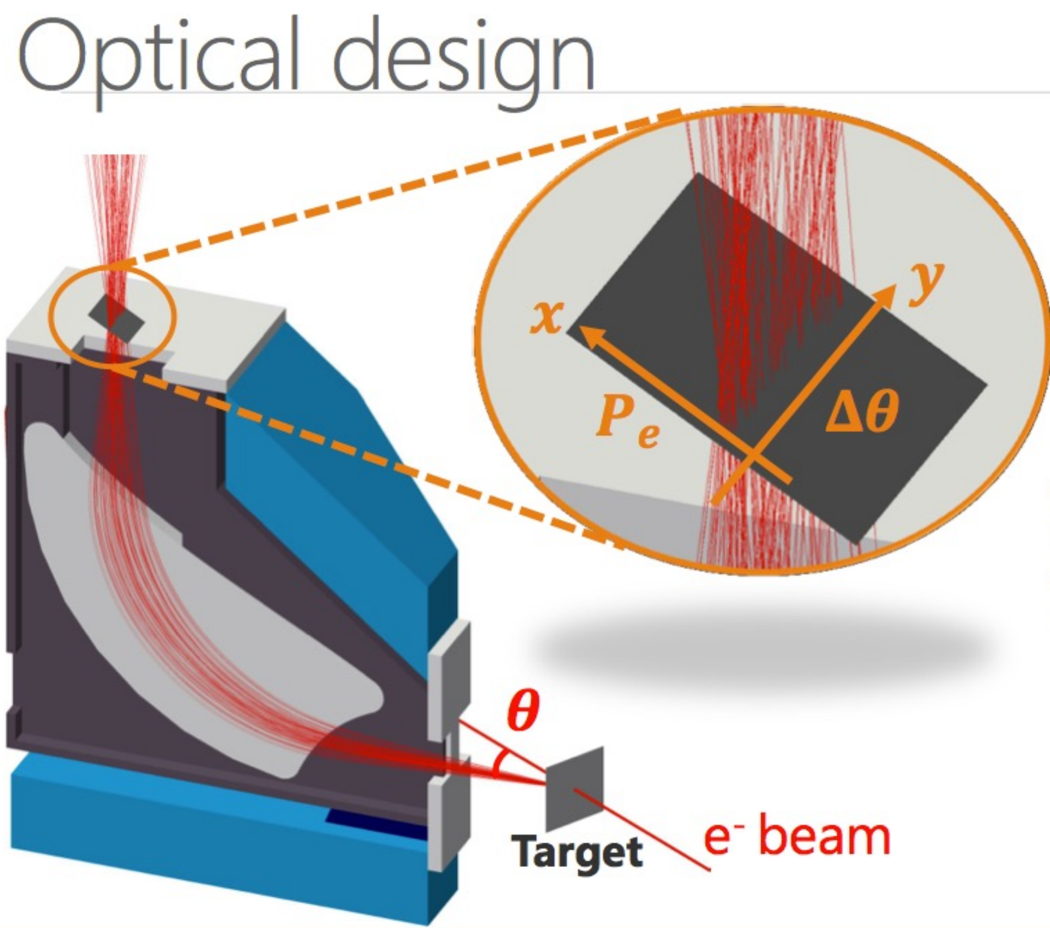
- ULQ2: E_0 ~ 10–60 MeV; θ_e ~ 30°–150°; Q^2 ~ 3×10^{-5} – 0.013 $(GeV/c)^2$
- Twin magnetic spectrometers (2019+2021)
- Commissioning since 2019, production running 2023-24

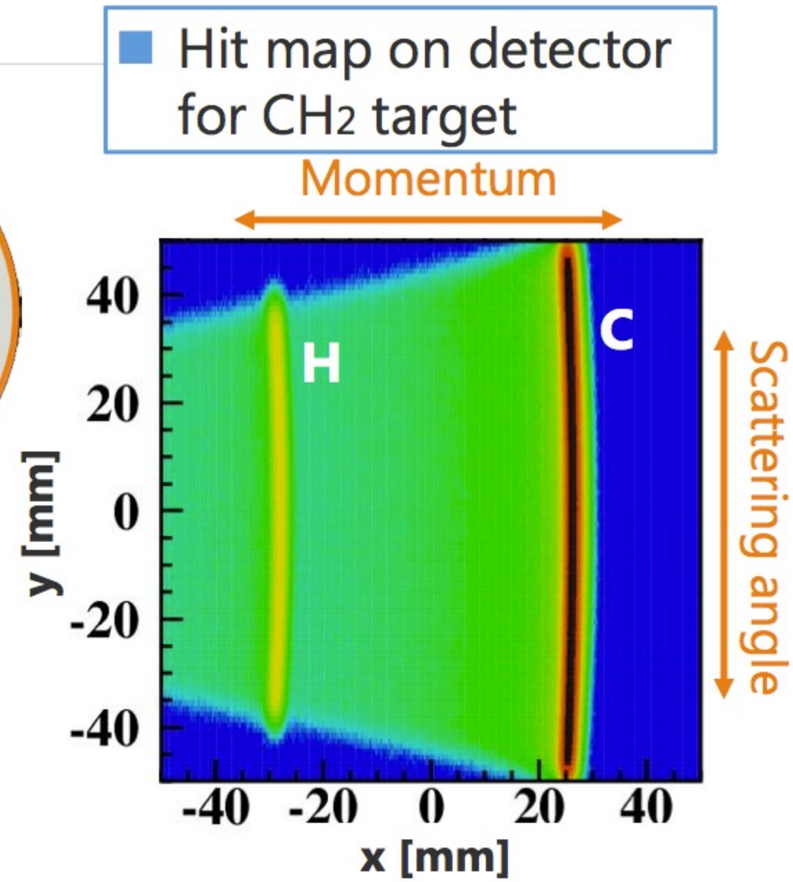


ULQ2 info by T. Suda and Y. Honda

ULQ2 @ ELPH

- ULQ2: E_0 ~ 10–60 MeV; θ_e ~ 30°–150°; Q^2 ~ 3×10^{-4} – 0.008 $(GeV/c)^2$
- Twin magnetic spectrometers (2019+2021)
- Commissioning since 2019, production running 2023-24

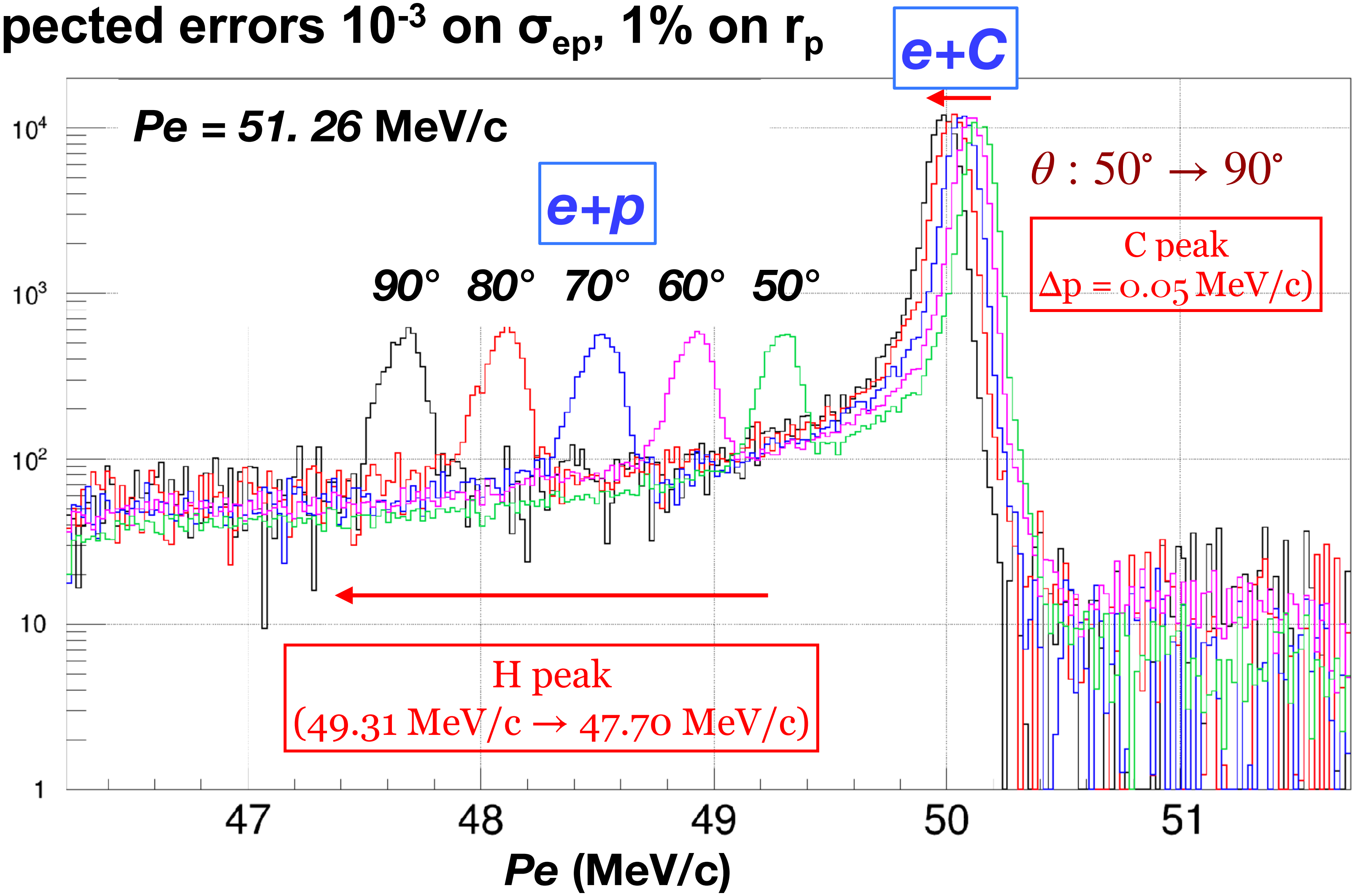




ULQ2 info by T. Suda and Y. Honda

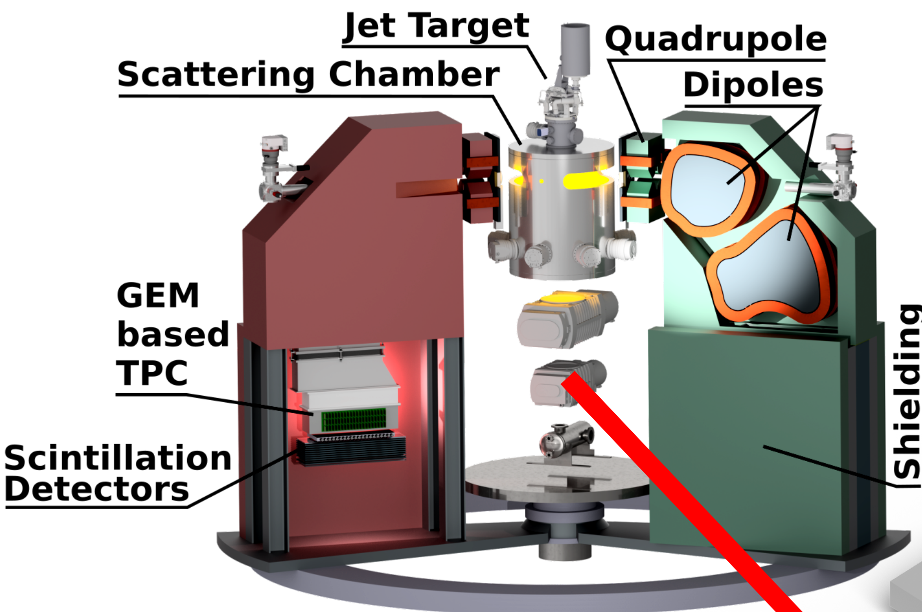
ULQ2 @ ELPH

- Production running just started with CH_2 target
- Normalization to ^{12}C elastic scattering
- Expected errors 10^{-3} on σ_{ep}, 1% on r_p

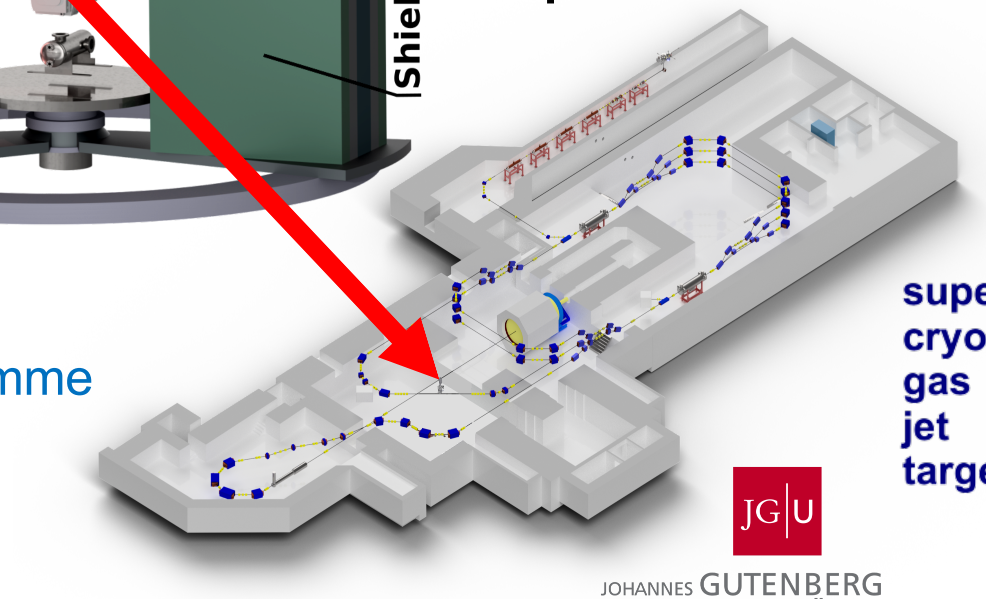


ULQ2 info by T. Suda and Y. Honda

MAGIX at 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 $Q^2 = 1\times10^{-5}$ to 0.03 GeV^2 ⇒ proton radius!



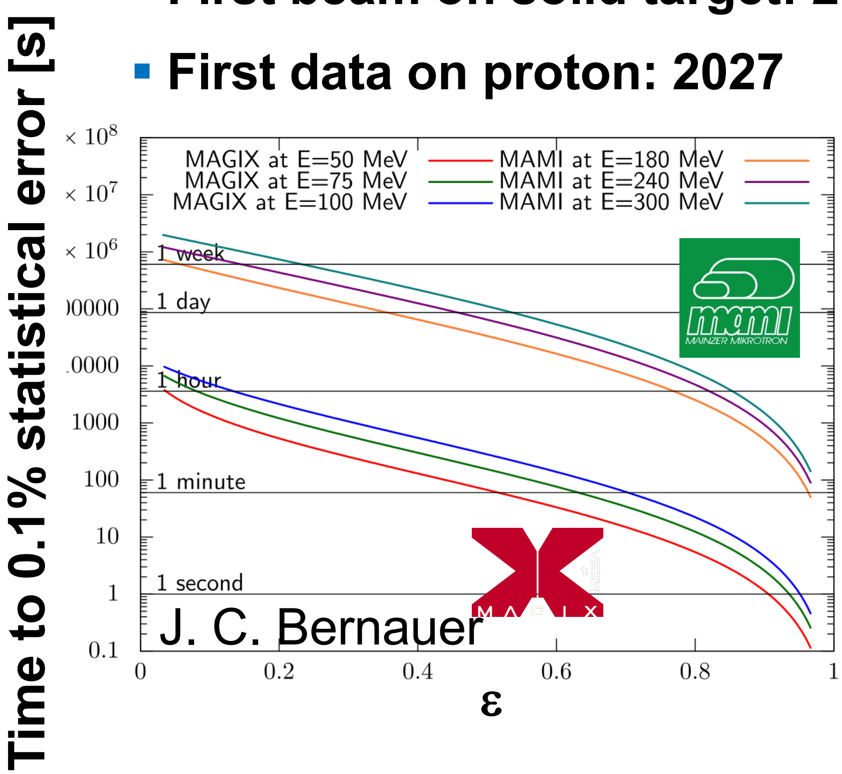
MAGIX info: S. Schlimme

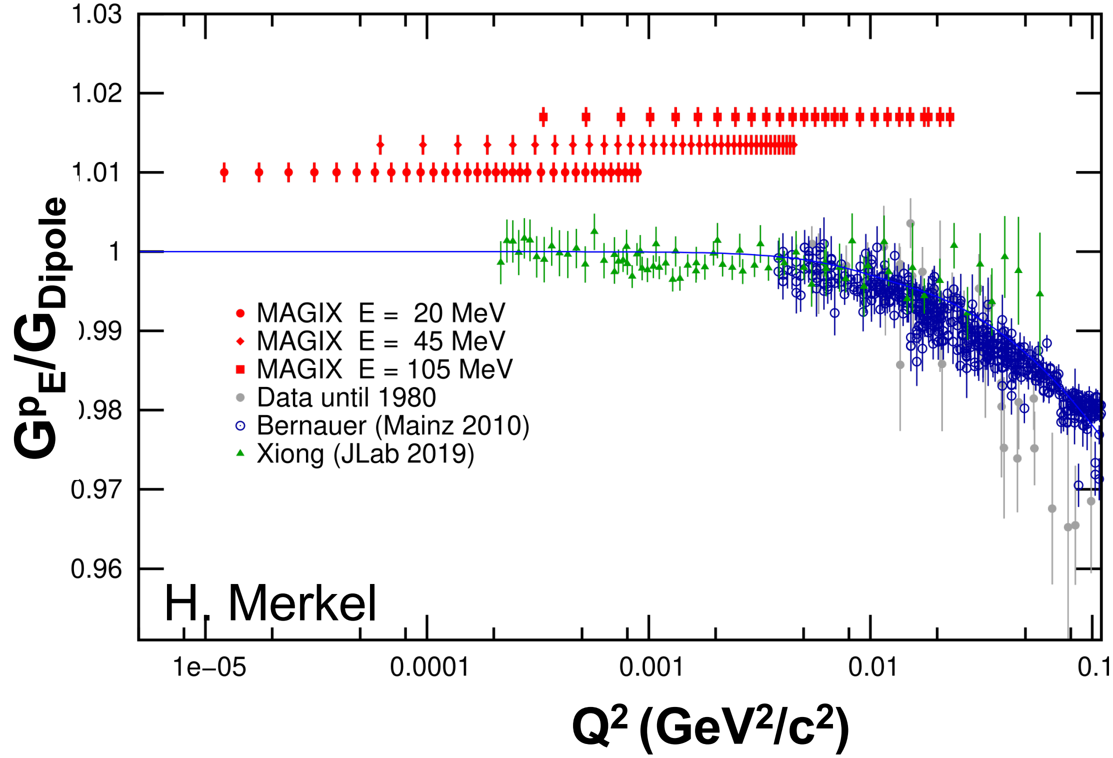
JOHANNES GUTENBERG UNIVERSITÄT MAINZ

MAGIX Collaboration @ MESA

MAGIX at MESA

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





MAGIX info: S. Schlimme

MAGIX Collaboration @ MESA

Motivation for μp scattering

Spectroscopy

Electronic hydrogen

0.8758 ± 0.0077

Muonic hydrogen

0.84184 ± 0.00067
0.84087 ± 0.00039

Electron scattering

0.8770 ± 0.0060

Scattering

Muon scattering
???

Idea for MUSE developed by R. Gilman, G. Miller, and M.K. at PINAN2011, Morocco

MUSE at PSI

- **Beam particle tracking**
- **Liquid hydrogen target**
- **Scattered lepton detected**

Measure $e^{\pm}p$ and $\mu^{\pm}p$ elastic scattering

p = 115, 153, 210 MeV/c

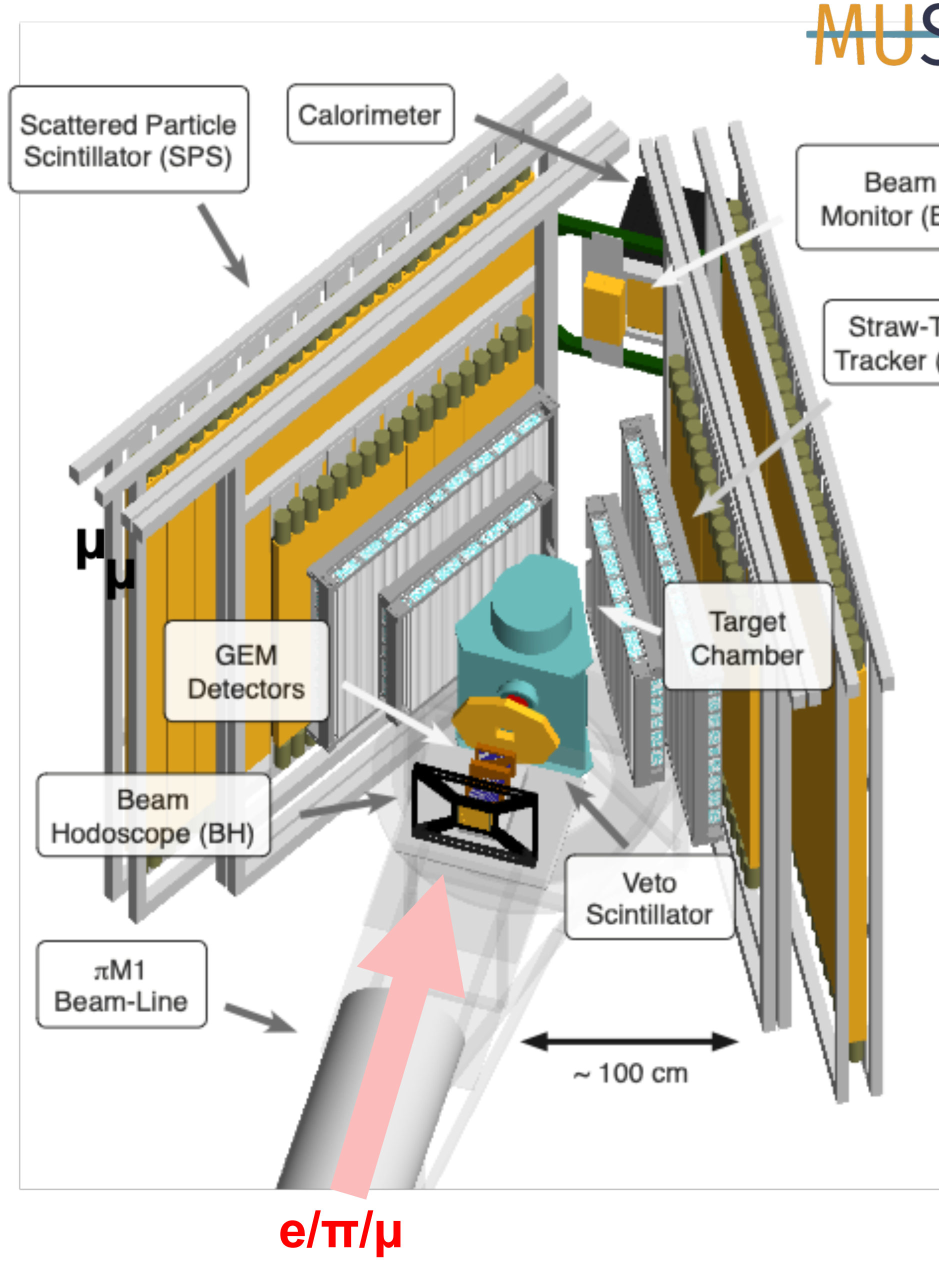
$\theta = 20^o$ to 100^o

$Q^2 = 0.002 - 0.07\ (GeV/c)^2$

$\varepsilon = 0.256 - 0.94$

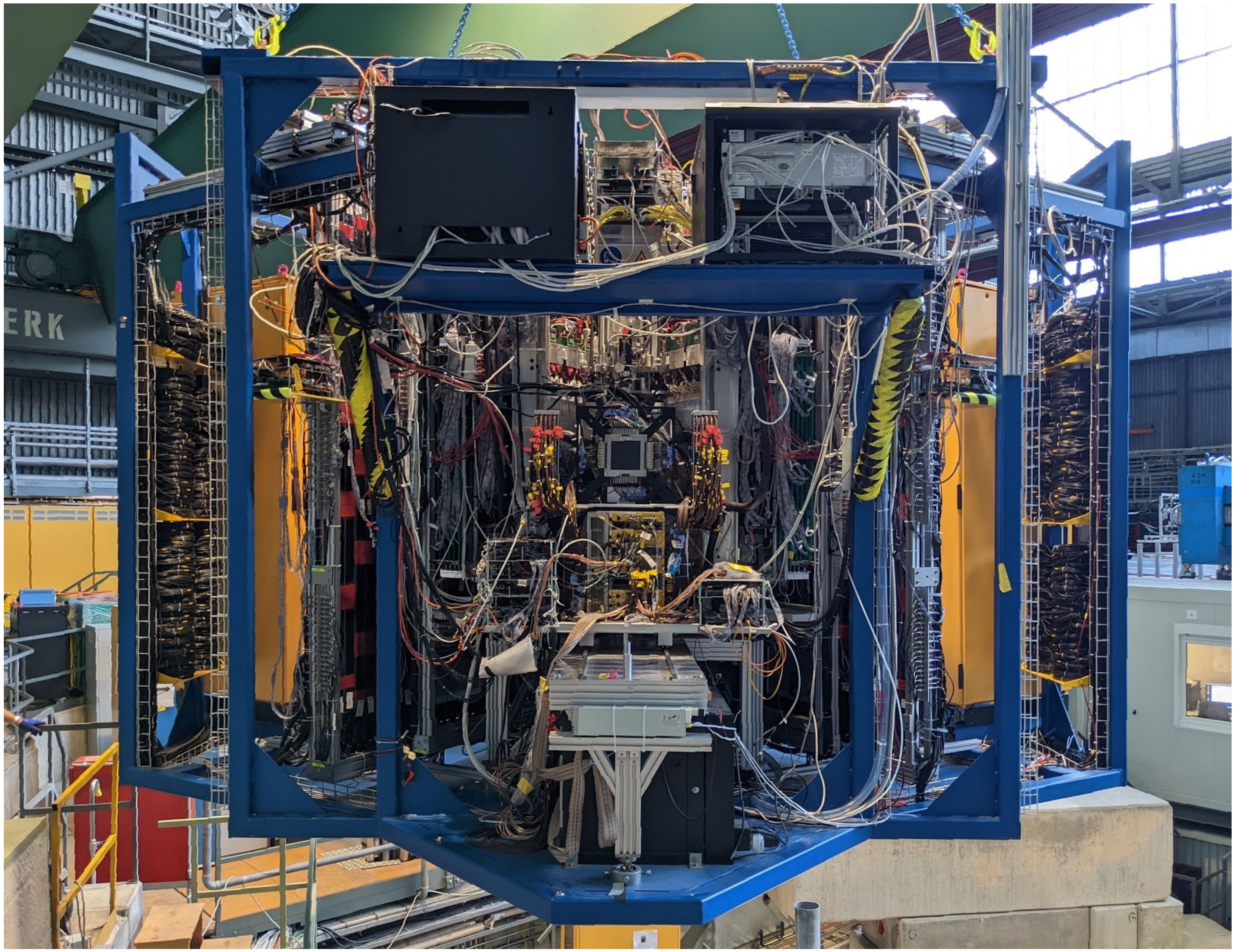
Challenges

- Secondary beam with π background – PID in trigger
- Non-magnetic spectrometer
- Background from Møller scattering and muon decay in flight



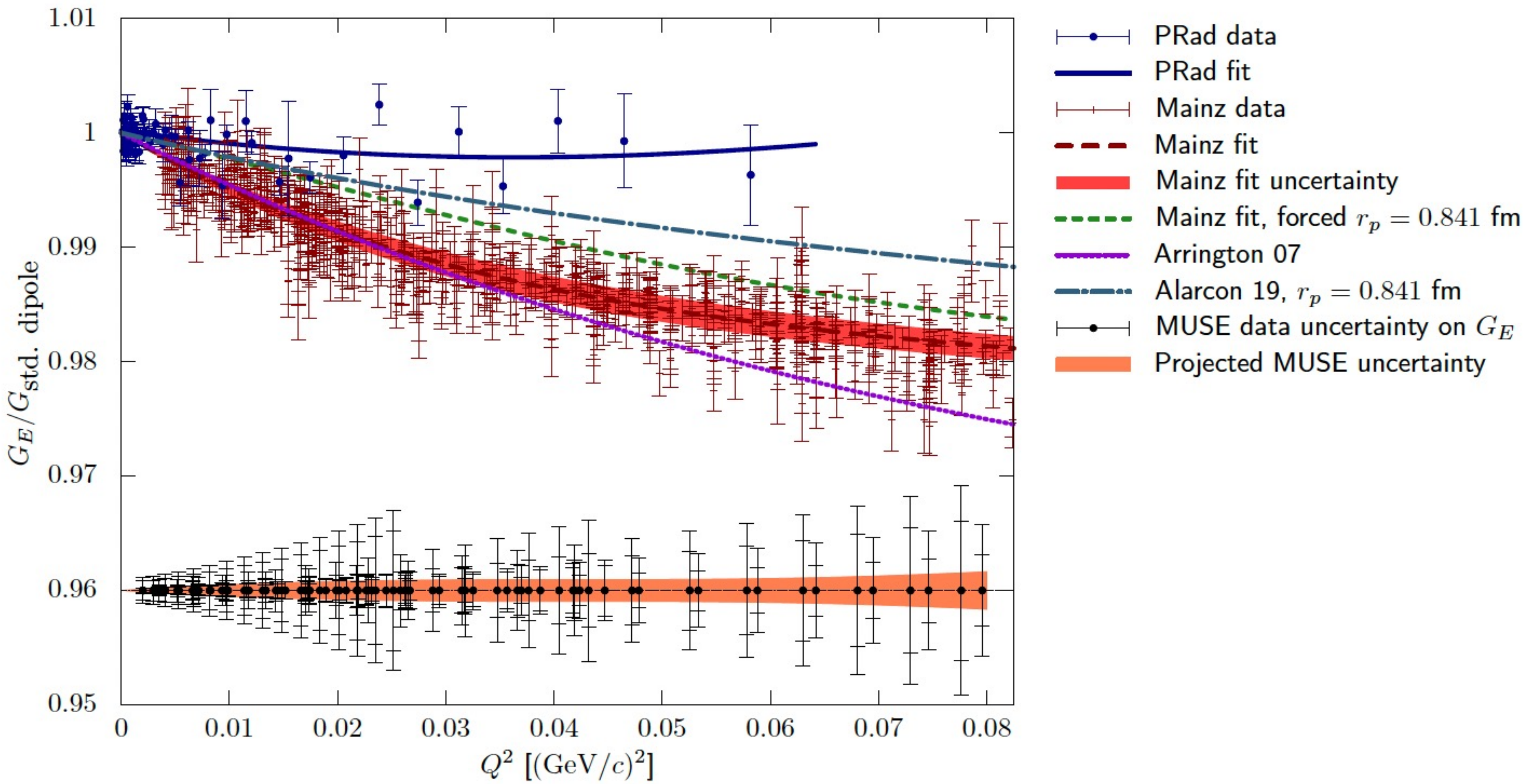
2023-2025: MUSE production data taking

2016-2019: Assembly complete; Initial commissioning
2020-2022: Commissioning cont'd under initial Covid-19 constraints
2023: Started production data for 12 beam months over ~2 years



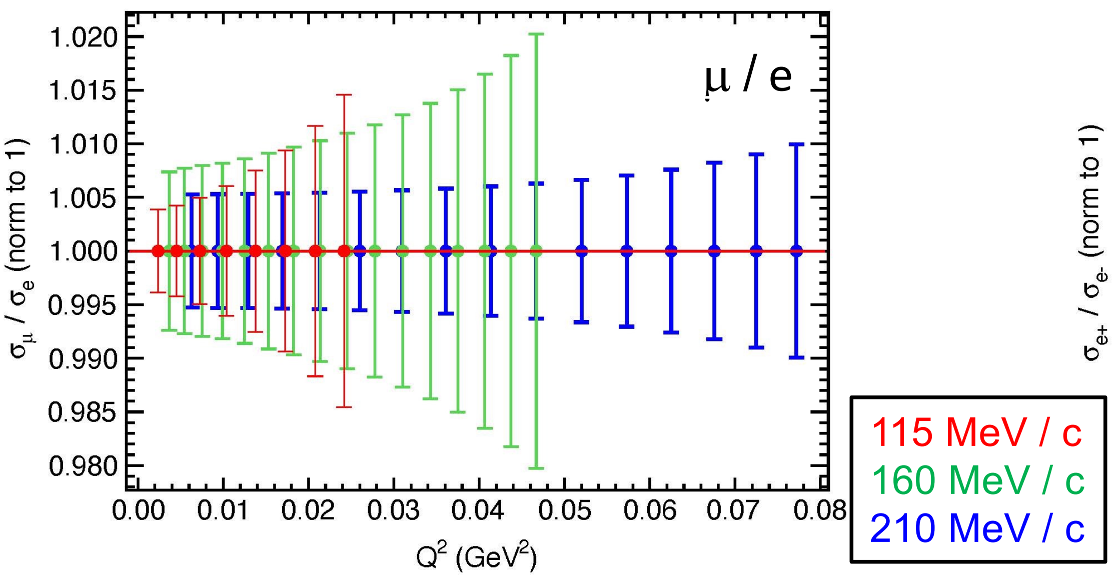
MUSE

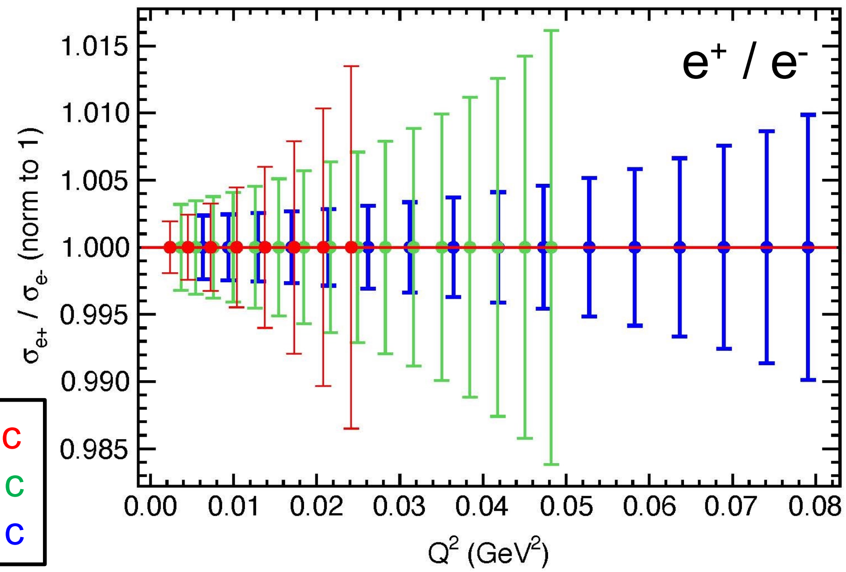
MUSE coverage and expected errors



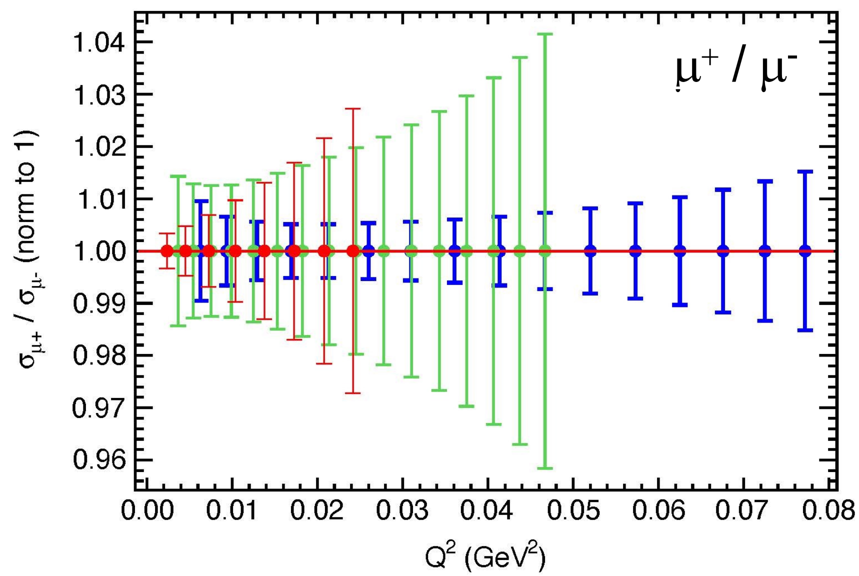
- **Anticipated form factor uncertainty**
- E. Cline, *et al.*, SciPost Phys. Proc. 5, 023 (2021)

MUSE coverage and expected errors

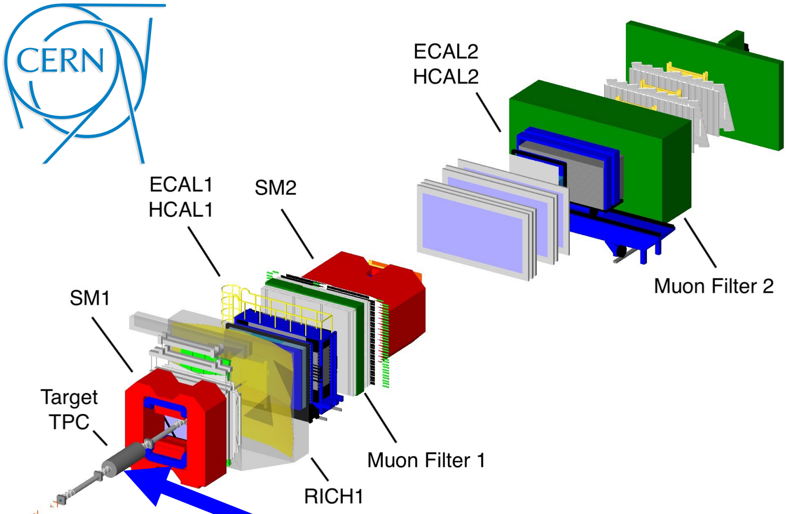




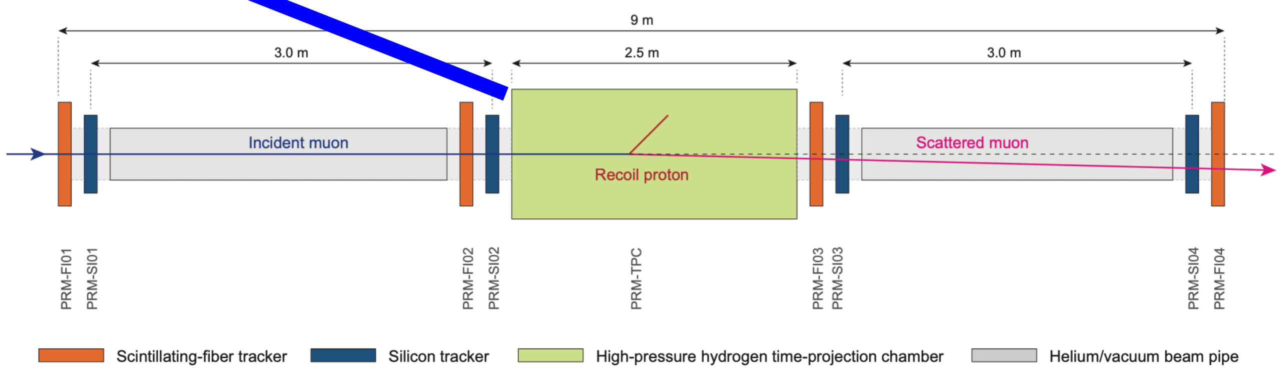
- **Stat. errors plotted, systematics <0.5%**
- **Based on assumption of 1 year of running**
- **~20% of scattering data taken in 2023**
- **Radius to 0.007 fm, R_μ–R_e to 0.005 fm**

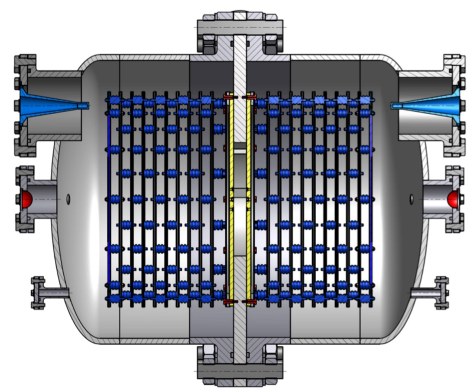


AMBER at CERN



- 100 GeV μ beam, CERN SPS M2 beamline
- Active-target TPC with high-pressure H_2
- High-precision proton tracking and forward spectrometer for muon reconstruction
- Goal: 70 million elastic scattering events in the range $10^{-3} < Q^2 < 4 \times 10^{-2}$ $(GeV/c)^2$
- Precision on the proton radius ~0.010 fm





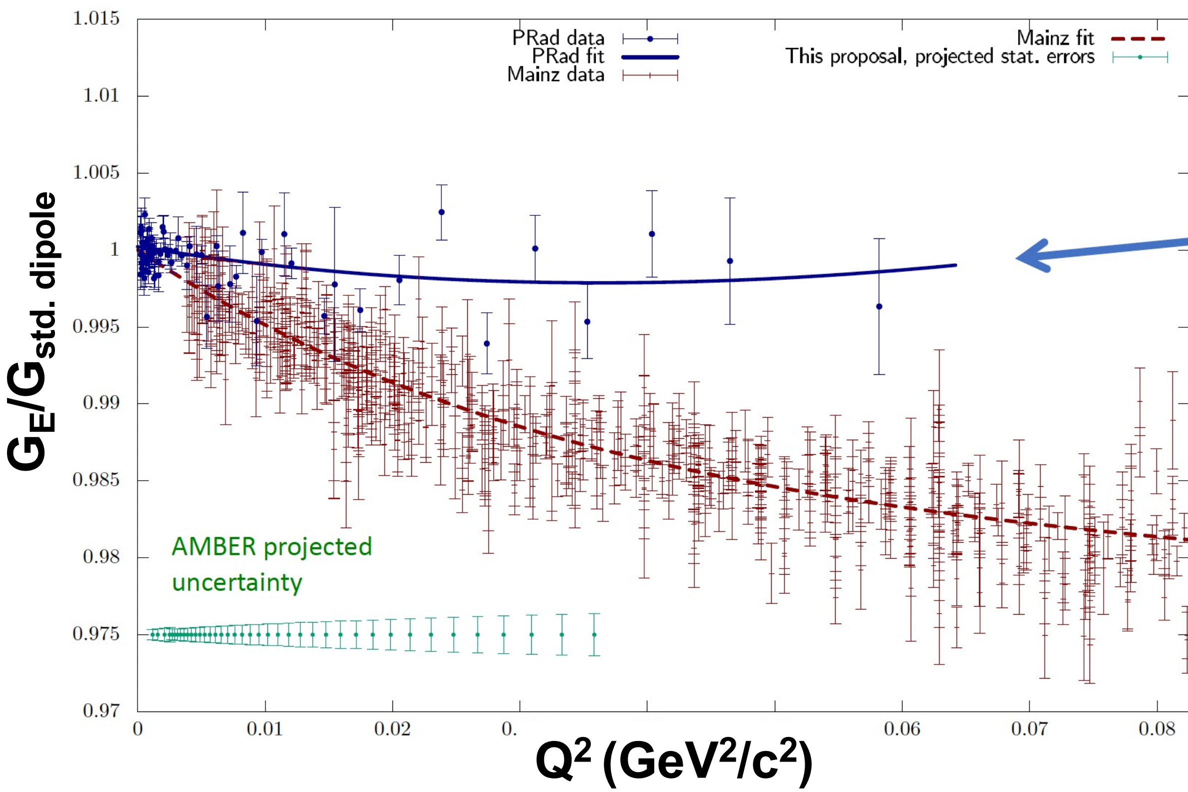
TPC, 20 bar
~50 keV precision for recoiling proton

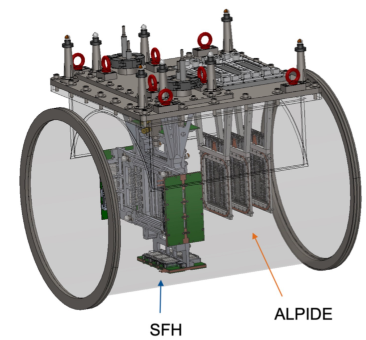
AMBER info: J. Friedrich

AMBER
Apparatus for Meson and Baryon Experimental Research

AMBER at CERN

New Si and SciFI
Unified Tracking System (UTS)





Proton Radius Experiment at Jefferson Lab

MAINZER MIKROTRON

Figure: J. C. Bernauer

AMBER info: J. Friedrich

Apparatus for Meson and Baryon Experimental Research

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

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Ongoing and future scattering experiments

Experiment	Probe	Q^2 / $(GeV/c)^2$	Status
PRad II	e^-	0.00004 – 0.06	Approved by JLab PAC
ULQ2	e^-	0.0003 – 0.008	Commissioning 2019-22, running 2023-24
MAGIX	e^-	0.00001 – 0.03	Beam 2025, data on proton 2027
MUSE	e^+, e^-, μ^+, μ^-	0.002 – 0.07	Physics running 2023-25
AMBER	μ^+, μ^-	0.001 – 0.04	Test runs ongoing, physics run 2025

Thanks to: S. Schlimme, J. Friedrich, H. Gao, T. Suda, Y. Honda, and E. Downie

- Proton Radius Puzzle remains unresolved
- Diverse array of scattering experiments, e and μ
- Each with different beam / systematics; expected precision 0.004-0.010 fm
- Many further spectroscopy efforts underway

PRoton Radius

AMBER Apparatus for Meson and Baryon Experimental Research

MAGIX

MUSE

Summary

- PRP not resolved, 13 years later
- 2016-2019 trend favored smaller radius, resulting in CODA2018, supported by theory (most recent Lattice QCD)
- 2020-2022 trend not stringently reconfirming a small radius, tension
- Unclear why larger radii should be considered wrong
- Phase space for BSM physics has been narrowed by work of many
- TPE exists but is too small to explain PRP
- PRad-Mainz discrepancy points to potential issues with radiative corrections

- Await results from new experiments within near future:
  – e-scattering w/ (ULQ2, MAGIX) and w/o magnetic field (PRad, MUSE)
  – μ-scattering: smaller rad. corr., cleaner than e? (MUSE, AMBER)
- MUSE allows for comparison of ep and μp, as well as TPE for both

- Conclusion
  – There has been a trend, however we are not done yet

Backup