

# Status of the MUon Scattering Experiment (MUSE) at PSI

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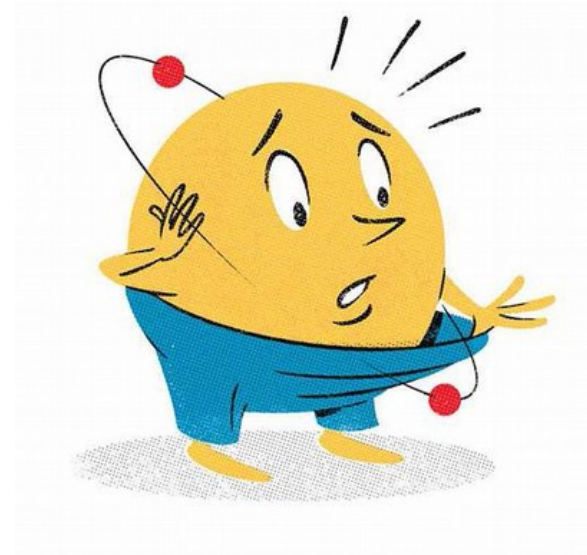


**\* Supported by NSF PHY-2113436, DOE DE-SC0013941, and JSA**

# Outline

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- **The Proton Charge Radius**
  - Definition and recent reviews
- **The Puzzle**
  - Spectroscopy
  - Scattering
- **Theory**
  - Lattice QCD
- **MUSE**
  - Idea, design
  - Radius puzzle, two-photon exchange, lepton universality, radiative corrections
  - Performance, status and timeline
- **Conclusion**
  - There has been a trend, however we are not done yet



**The New York Times**

# Charge radius definition & recent reviews

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**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**

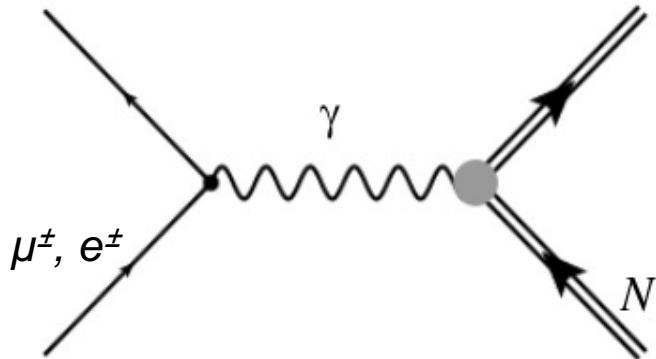
**Consistent, covariant treatment:**  $\langle r_E^2 \rangle = -6 \frac{dG_E^p(Q^2)}{dQ^2} \Big|_{Q^2 \rightarrow 0}$

**Recent reviews:**

- **W. Xiong and C. Peng, *Proton Electric Charge Radius from Lepton Scattering*,  
 Universe 9, no.4, 182 (2023)**
- **H. Gao, M. Vanderhaeghen, *The proton charge radius*,  
 Rev. Mod. Phys. 94, 015002 (2022)**
- **C. Peset, A. Pineda, and O. Tomalak,  
*The proton radius (puzzle?) and its relatives*,  
 Prog. Part. Nucl. Phys. 121, 103901 (2021)**
- **J.-P. Karr, D. Marchand, E. Voutier, *The proton size*,  
 Nature Reviews Physics 2, 601–614 (2020)**

# Lepton scattering and charge radius

Lepton scattering from a nucleon:



Vertex currents:

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

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

$F_1, F_2$  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:

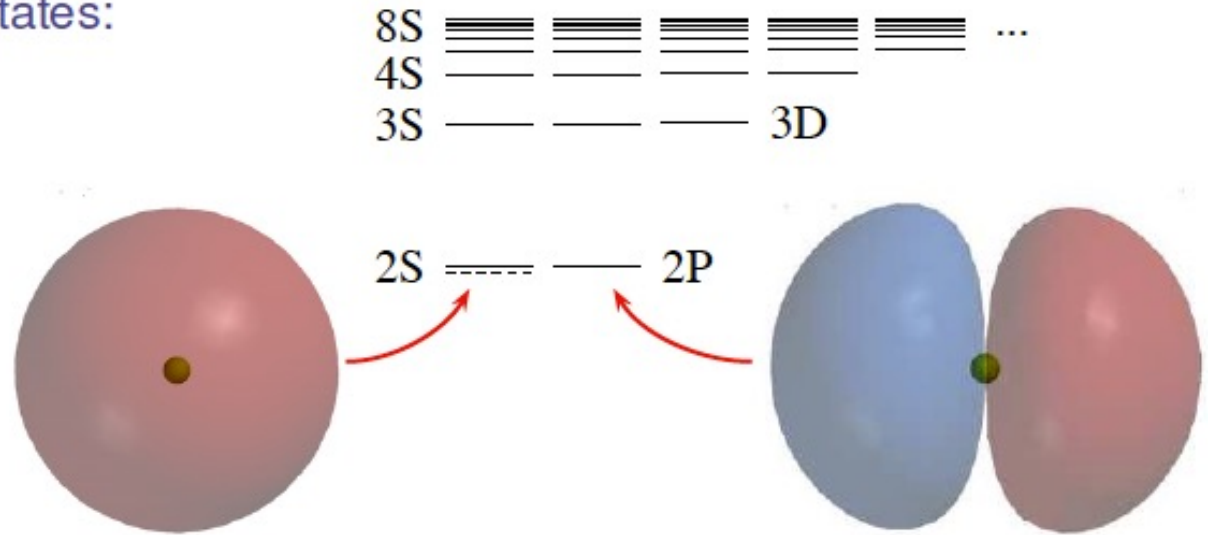
$$\langle r_E^2 \rangle = -6 \left. \frac{dG_E^p(Q^2)}{dQ^2} \right|_{Q^2 \rightarrow 0}$$

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

**Expect identical behavior for any charged lepton –  $e^\pm, \mu^\pm$**

# 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 is proportional to the

**size of the proton**

P states: zero at  $r=0$

Electron is **not** inside the proton.



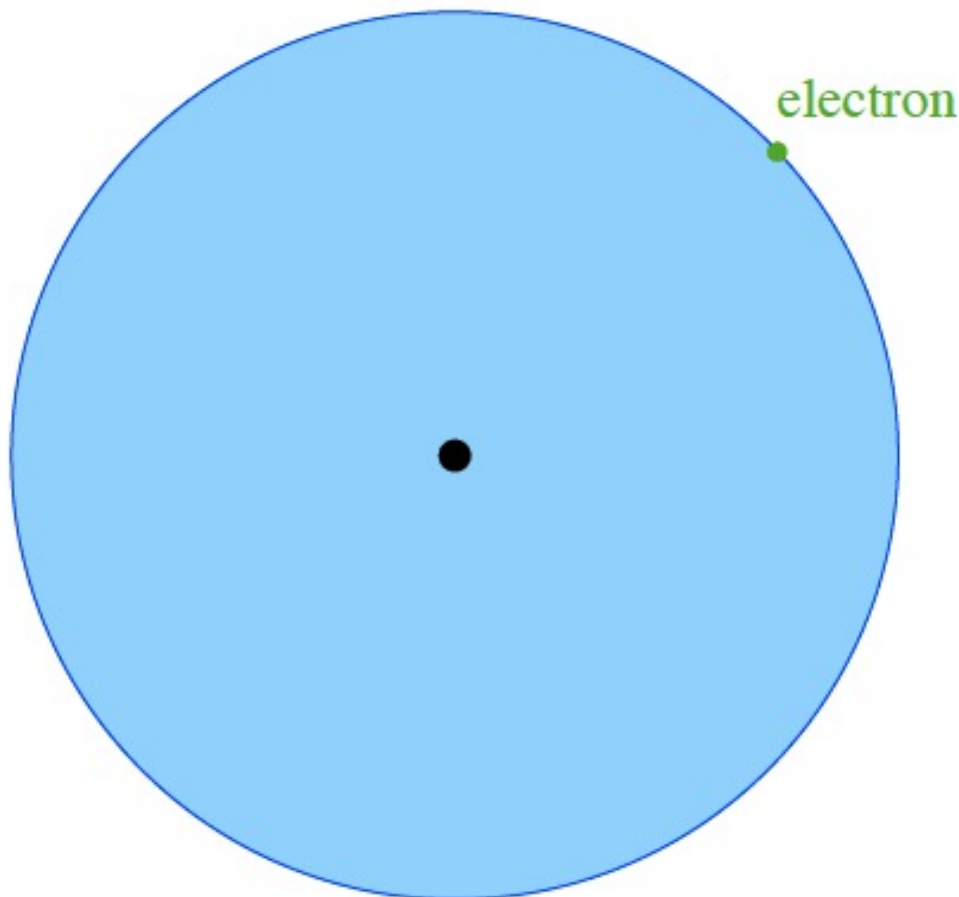
Slide by R. Pohl

Orbital pictures from Wikipedia

# Muonic hydrogen

Regular hydrogen:

electron  $e^-$  + proton  $p$



Muonic hydrogen:

muon  $\mu^-$  + proton  $p$

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

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

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



muon much is more sensitive to  $r_p$

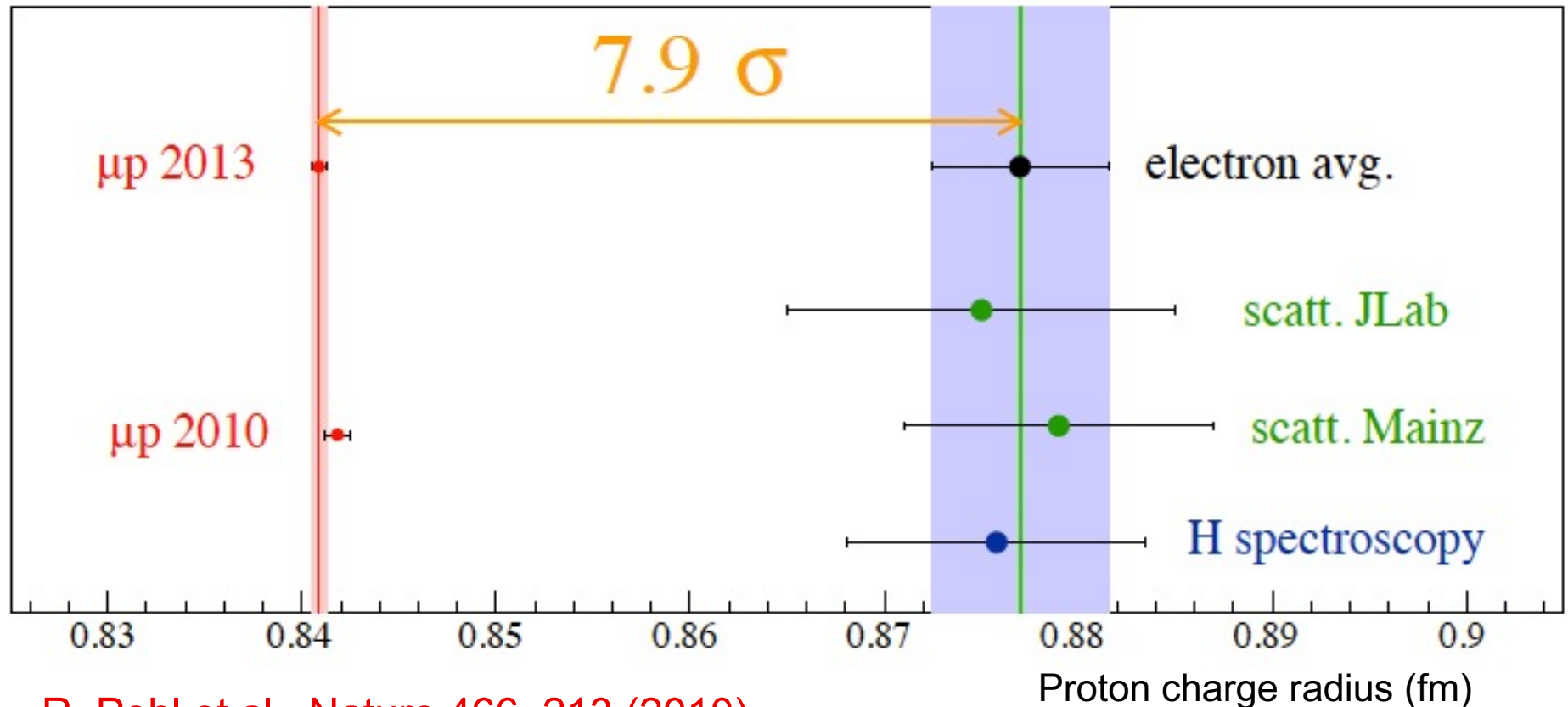
Slide by R. Pohl

# The proton radius puzzle in 2010/2013

The proton rms charge radius measured with

electrons:  $0.8770 \pm 0.0045$  fm (CODATA2010+Zhan et al.)

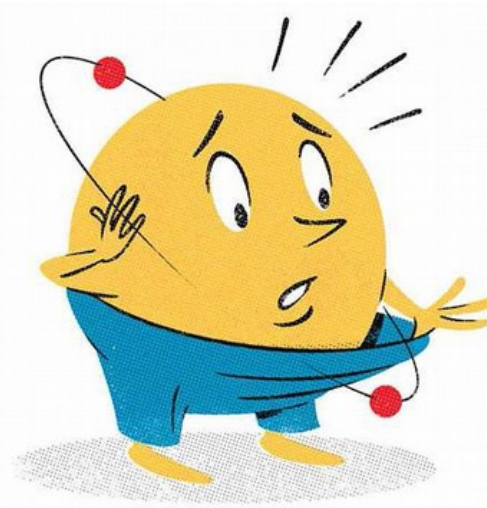
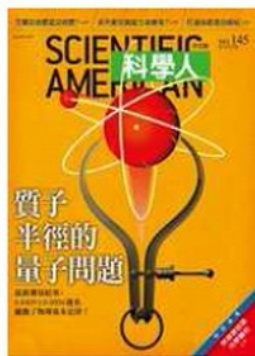
muons:  $0.8409 \pm 0.0004$  fm



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

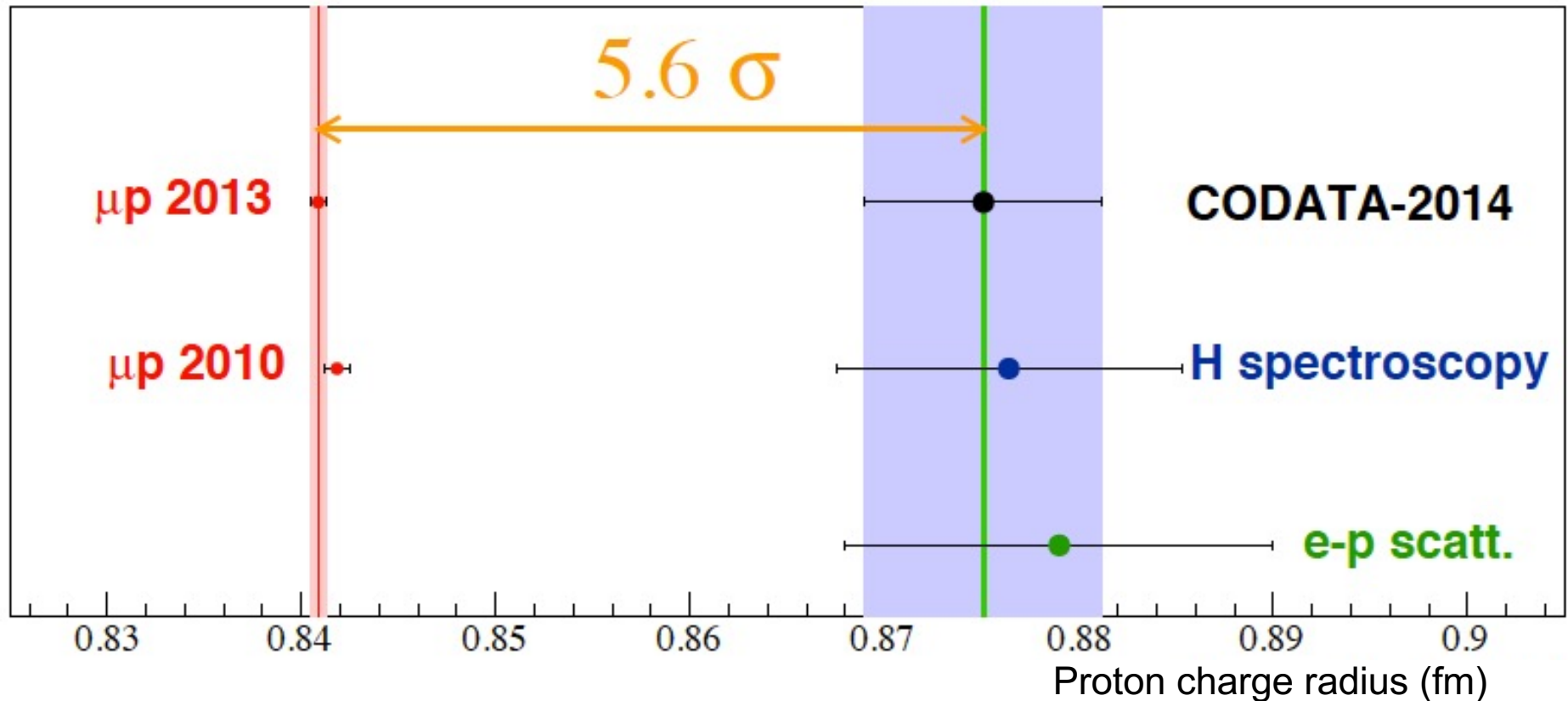


# The proton radius puzzle in 2016

The proton rms charge radius measured with

electrons:  $(0.8751 \pm 0.0061)$  fm (CODATA2014)

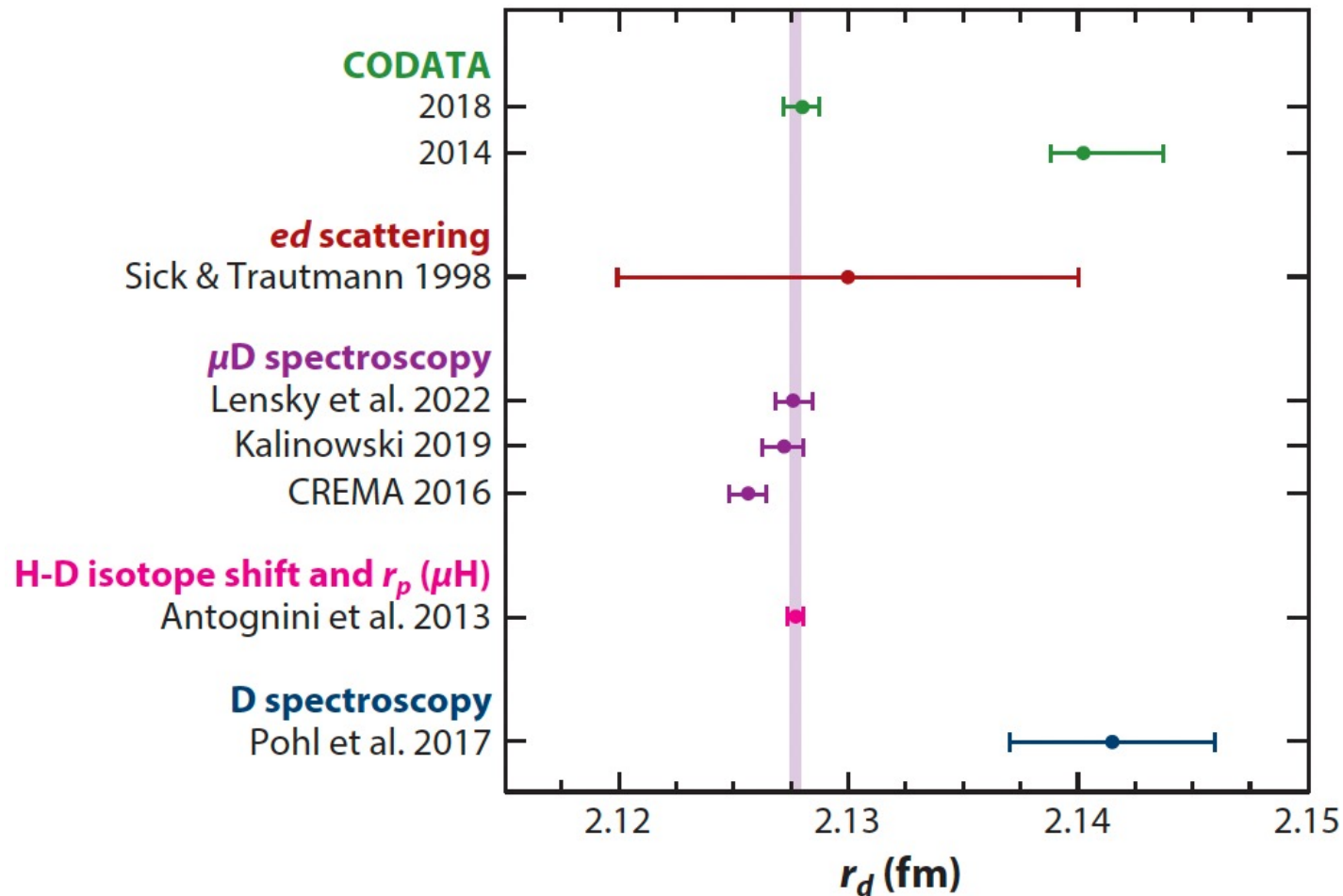
muons:  $(0.8409 \pm 0.0004)$  fm



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

# The community got engaged

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- **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  $\mu p$  (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  $\sim 5$  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  $\mu$  and  $e$   
Hadronic effects different for  $\mu p$  and  $ep$ :  
e.g. proton polarizability (*effect*  $\propto m_l^4$ )
- **Physics beyond Standard Model differentiating  $\mu$  and  $e$**   
Lepton universality violation, light massive gauge boson(s)  
Constraints on new physics from meson decays and spectroscopy

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Constraints on new physics from meson decays and spectroscopy

**MUSE**  
**will test**

# CODATA2018 new recommended values

← → ↻ [https://physics.nist.gov/cgi-bin/cuu/Value?rp|search\\_for=proton](https://physics.nist.gov/cgi-bin/cuu/Value?rp|search_for=proton)

Apps Halliday, Resnick, W. Blackboard Hugenwiki WhatsApp 13NEWS TREK ELOG MUSE

The NIST Reference on Constants, Units, and Uncertainty

**May 20, 2019**  
**RMP 93, 025010 (2021)**

## Fundamental Physical Constants

### proton rms charge radius

$$r_p$$

Numerical value	<b>8.414 x 10<sup>-16</sup> m</b>
Standard uncertainty	<b>0.019 x 10<sup>-16</sup> m</b>
Relative standard uncertainty	<b>2.2 x 10<sup>-3</sup></b>
Concise form	<b>8.414(19) x 10<sup>-16</sup> m [-5.5σ]</b>
	CODATA2014: 8.751(61) x 10 <sup>-16</sup> m

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**

# CODATA2018 new recommended values

← → ↻ [https://physics.nist.gov/cgi-bin/cuu/Value?rydchz|search\\_for=rydberg](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  
RMP 93, 025010 (2021)

## Fundamental Physical Constants

Click symbol for equation

### Rydberg constant times $c$ in Hz

$$R_{\infty}c$$

Numerical value	<b>3.289 841 960 2508 x 10<sup>15</sup> Hz</b>
Standard uncertainty	<b>0.000 000 000 0064 x 10<sup>15</sup> Hz</b>
Relative standard uncertainty	<b>1.9 x 10<sup>-12</sup></b>
Concise form	<b>3.289 841 960 2508(64) x 10<sup>15</sup> Hz [-5.5σ]</b>
	<b>CODATA2014: 3.289 841 960 355 (19) x 10<sup>15</sup> Hz</b>

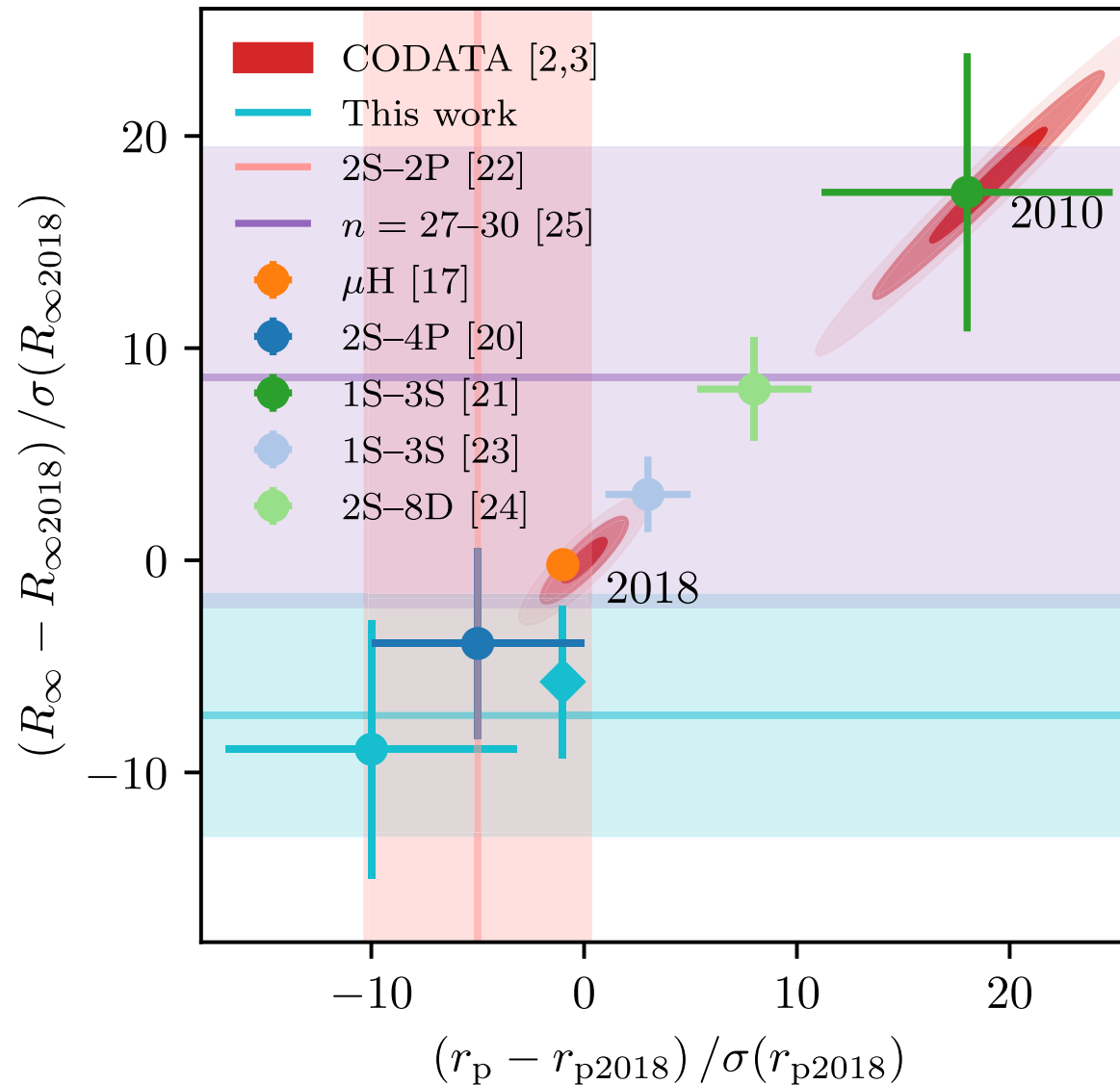
Click [here](#) for **correlation coefficient** of this constant with other constants

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**3x more precise**

# New, independent Rydberg measurement



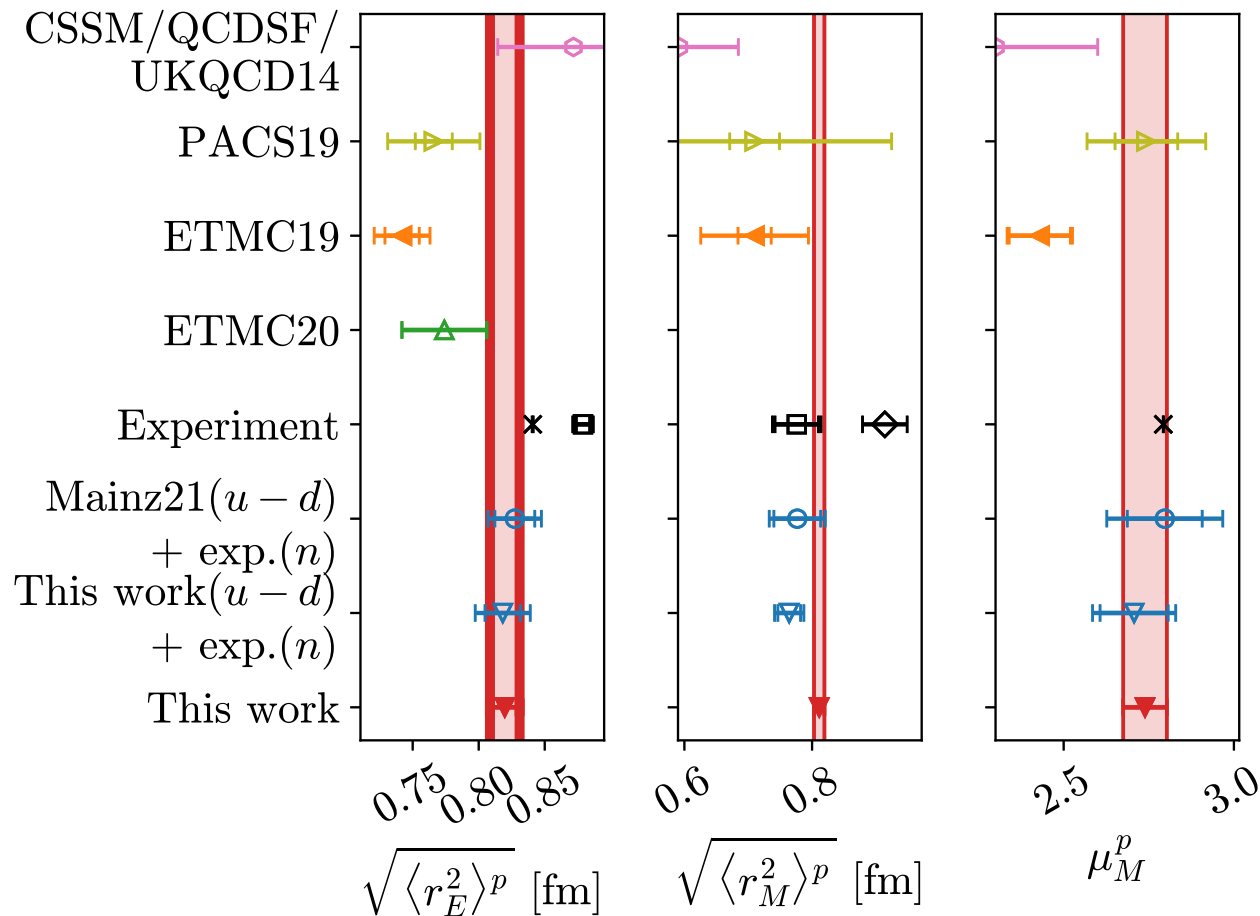
**Spectroscopy:  
Rydberg constant and  
proton radius  
are correlated**

**2024: Small Rydberg  
reconfirmed**

**S. Scheidegger and F. Merkt, PRL 132, 113001 (2024) [March 11, 2024]**



# New milestone: Precision Lattice QCD



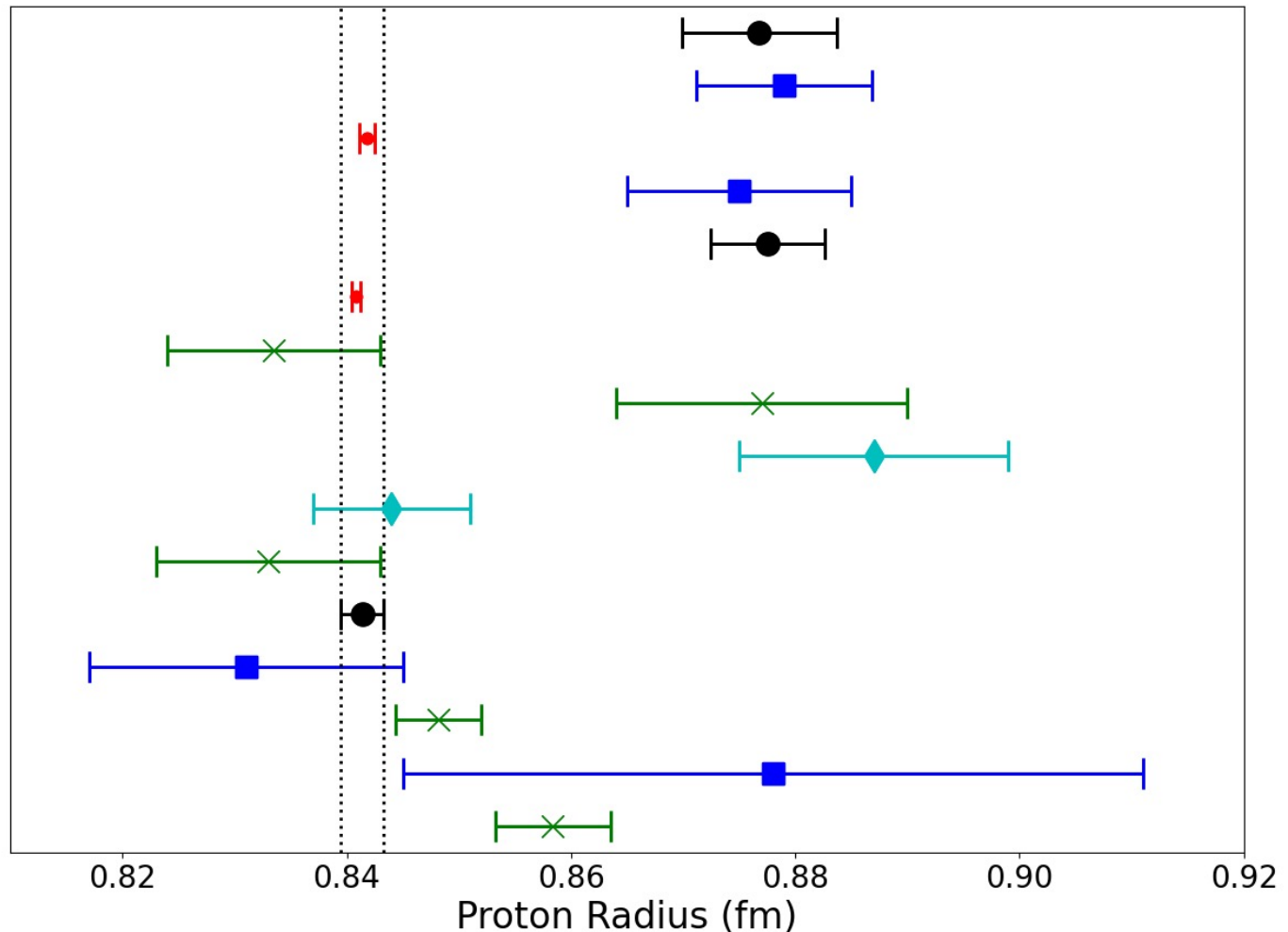
$$\sqrt{\langle r_E^2 \rangle^p} = 0.820(14) \text{ fm}, \quad \sqrt{\langle r_M^2 \rangle^p} = 0.8111(89) \text{ fm}, \quad \text{and} \quad \mu_M^p = 2.739(66)$$

**Consistent with small radius**

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

# The proton radius puzzle in 2023

CODATA 06 (2008)  
 Bernauer (2010)  
 Pohl (2010)  
 Zhan (2011)  
 CODATA 10 (2012)  
 Antognini (2013)  
 Beyer (2017)  
 Fleurbaey (2018)  
 Sick (2018)  
 Alarcon (2019)  
 Bezninov (2019)  
 CODATA 18 (2019)  
 Xiong (2019)  
 Grinin (2020)  
 Mihovilovic (2021)  
 Brandt (2022)

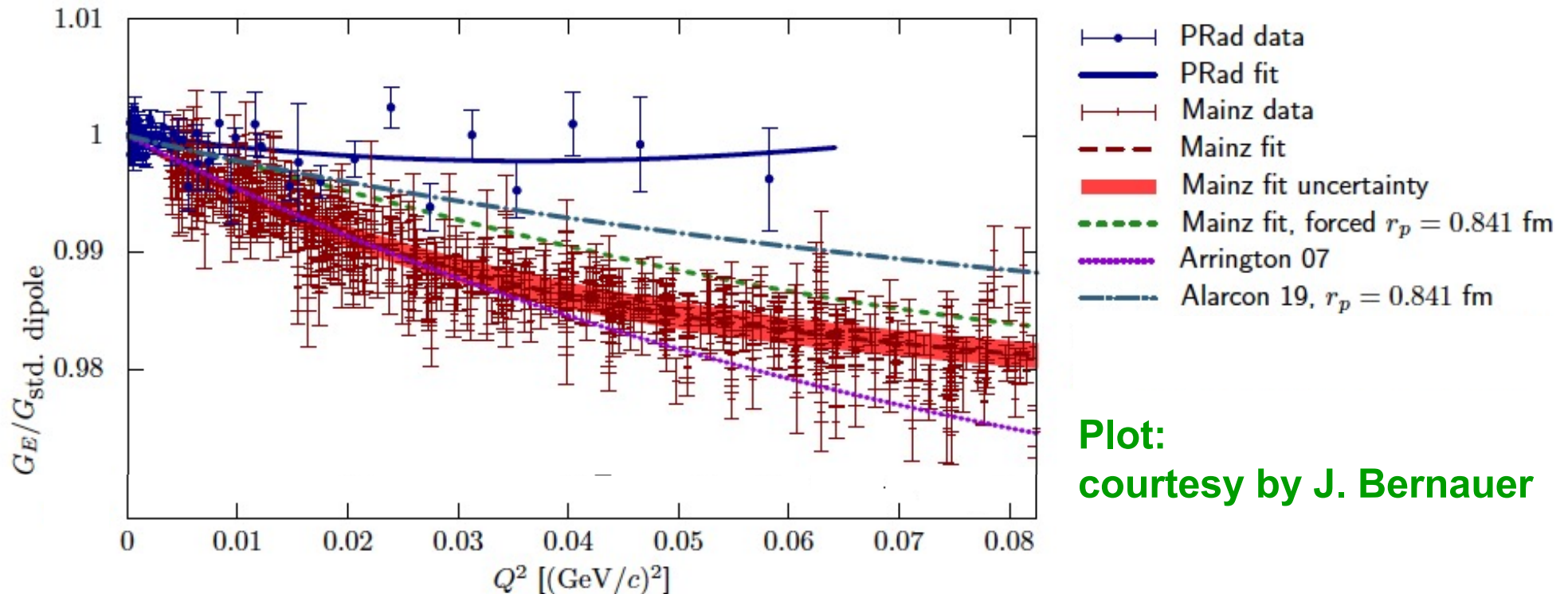


**Red** =  $\mu p$  spectroscopy  
**Blue** = ep scattering  
**Light blue** = re-fitting of e scattering  
**Green** = ep spectroscopy  
**Black** = CODATA

Plot: courtesy by J. Bernauer

# Puzzle solved?

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



- 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, ...)

# Ongoing and future scattering experiments

Experiment	Probe	$Q^2 / (\text{GeV}/c)^2$	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	$e^+, e^-, \mu^+, \mu^-$	0.002 – 0.07	Physics running 2023-25
AMBER	$\mu^+, \mu^-$	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  $\mu$
- Each with different beam / systematics; expected precision 0.004-0.010 fm
- Many further spectroscopy efforts underway

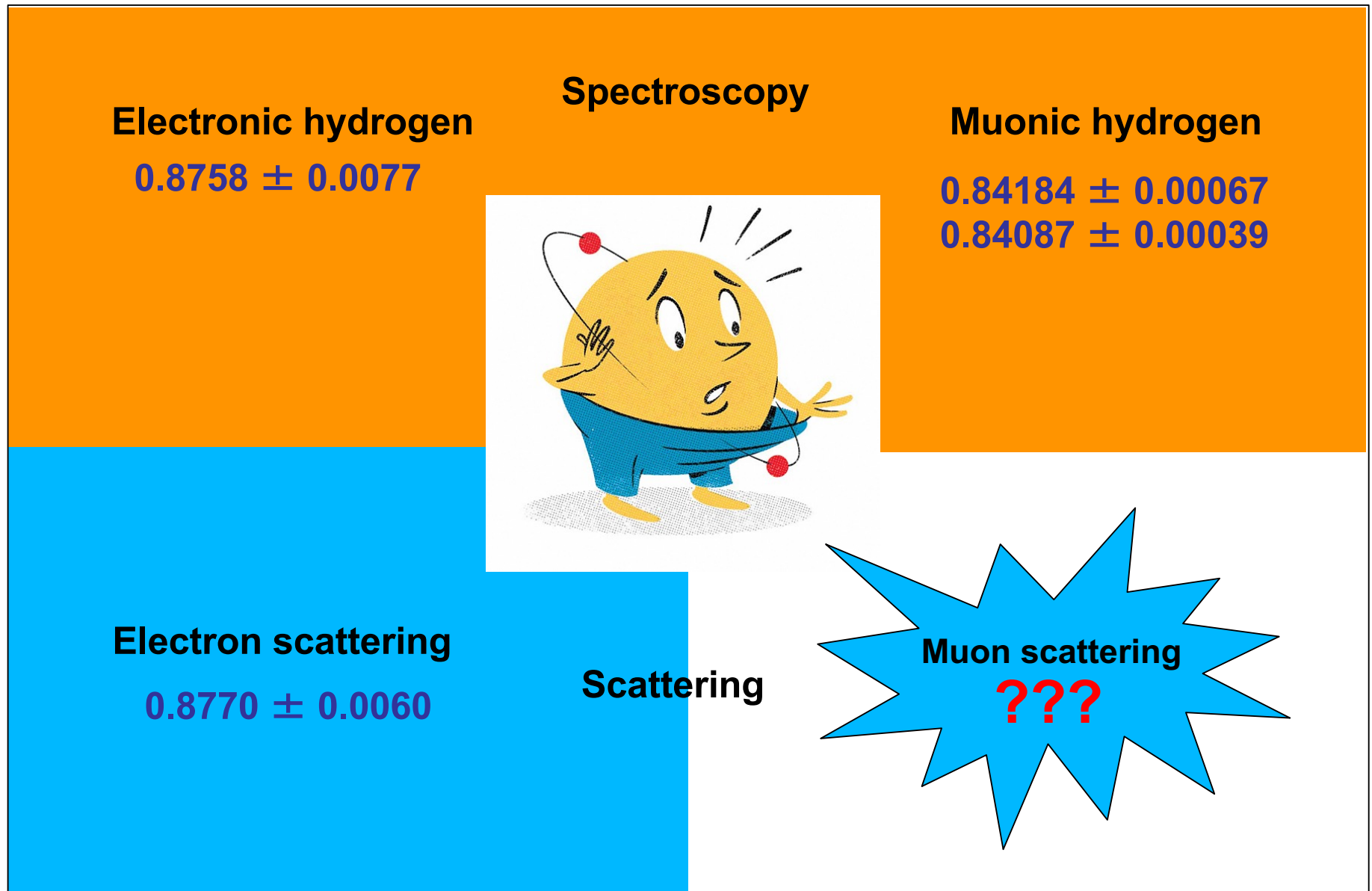
**PR**oton  
Radius

**A**MBER  
Apparatus for Meson and Baryon  
Experimental Research

**M**AGIX  
MESA

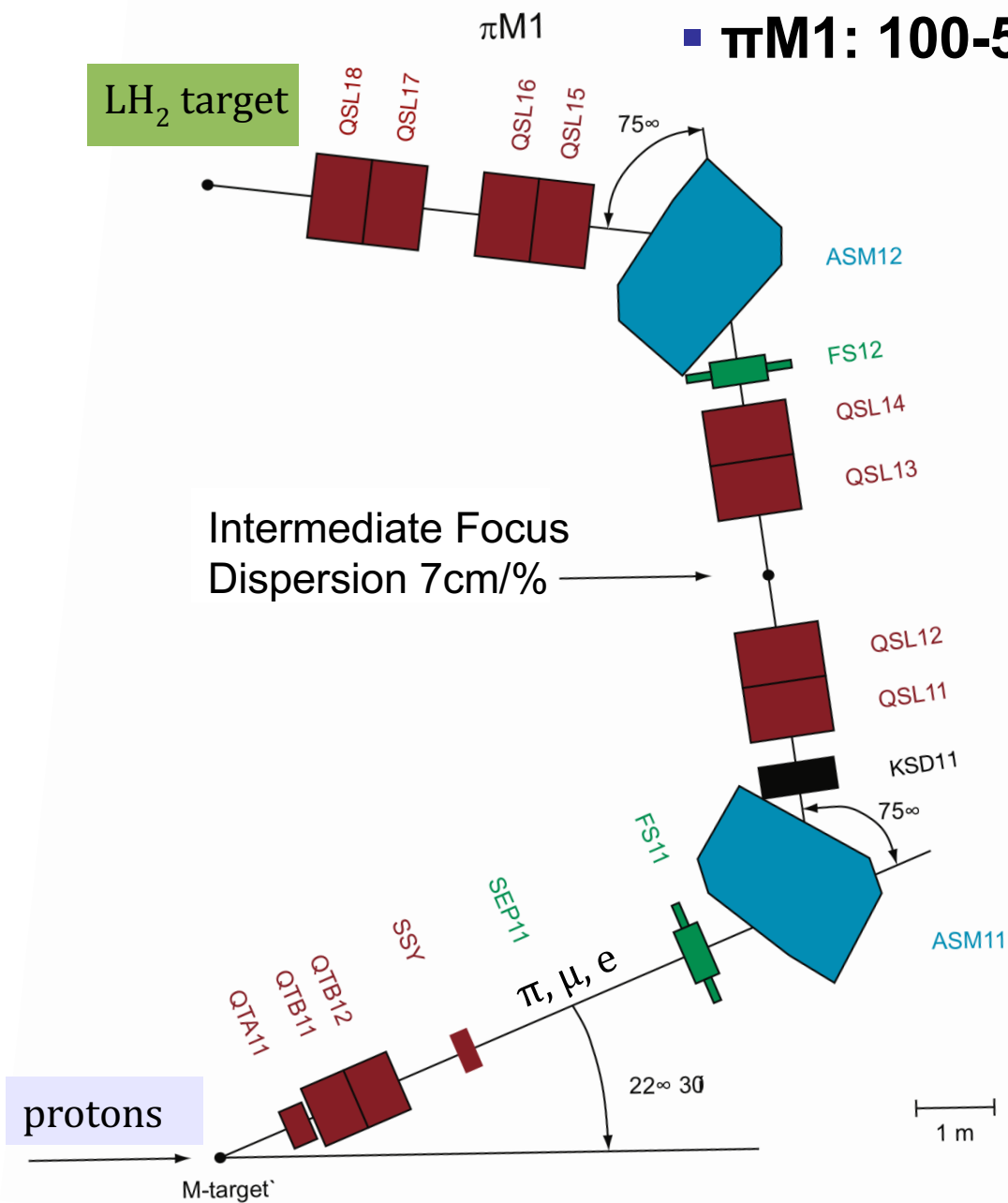
**MUSE**

# Motivation for $\mu p$ scattering



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

# $\pi$ M1 / MUSE beamline



- $\pi$ M1: 100-500 MeV/c RF+TOF sep.  $\pi, \mu, e$

Secondary beams of  $\pi, \mu, e$  produced at M-target with 2 mA protons (590 MeV), 1-10 MHz flux collected with quads, jaws, and double-C

Point-like source

- $\pi^\pm$  produced directly
- $e^\pm$  from  $\pi^0$  decay + conv.

Extended source

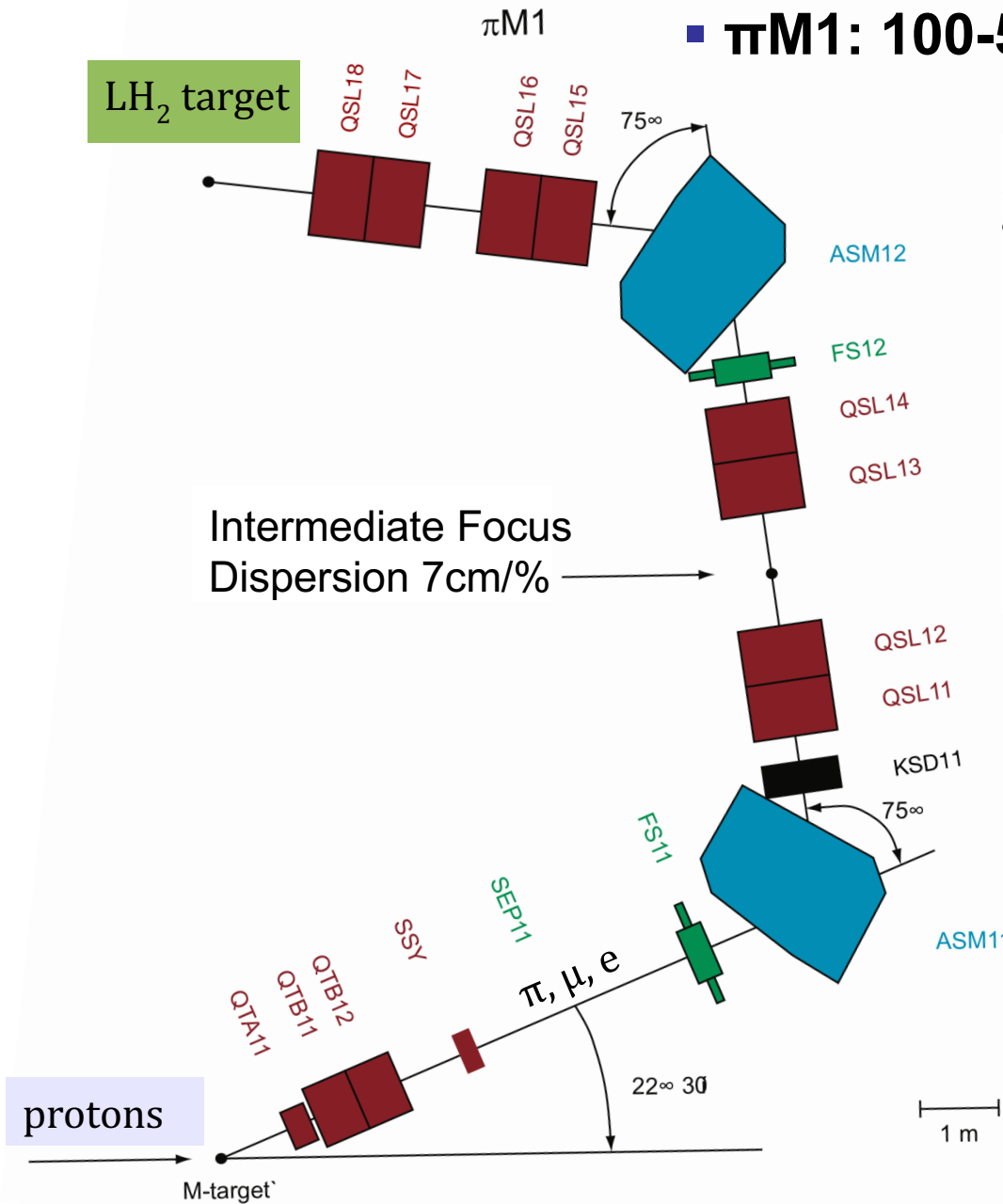
- $\mu^\pm$  from  $\pi^\pm$  decay in flight  
 $O(\text{cm})$  transv.,  $O(\text{m})$  longit.

Beam properties well understood with TRANSPORT, TURTLE, and G4Beamline

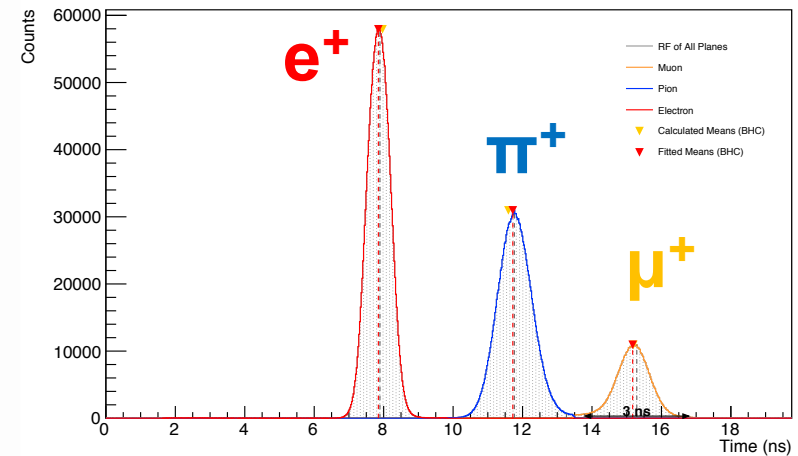
E. Cline et al., PRC105, 055201 (2022)

# $\pi$ M1 / MUSE beamline

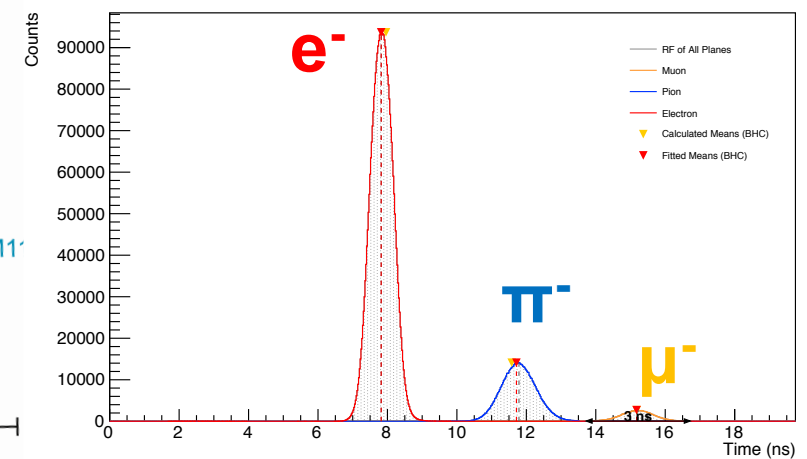
■  $\pi$ M1: 100-500 MeV/c RF+TOF sep.  $\pi$ ,  $\mu$ , e



RF of All Planes,  $p = 115.29$  MeV/c



RF of All Planes,  $p = -115.29$  MeV/c



# MUSE at PSI

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

## Measure $e^\pm p$ and $\mu^\pm p$ elastic scattering

$p = 115, 160, 210 \text{ MeV}/c$

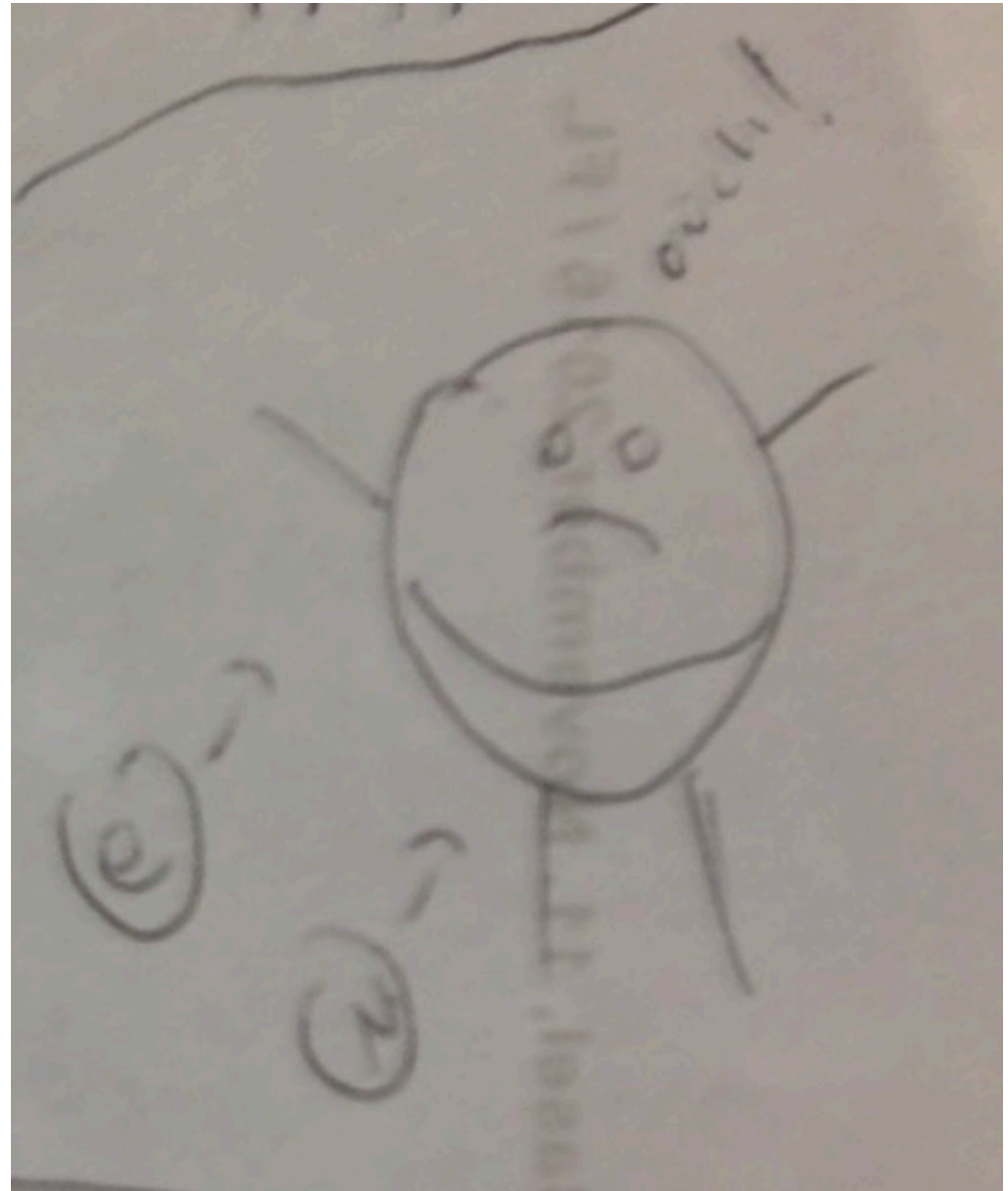
$\theta = 20^\circ \text{ to } 100^\circ$

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

$\varepsilon = 0.256 - 0.94$

## Challenges

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



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



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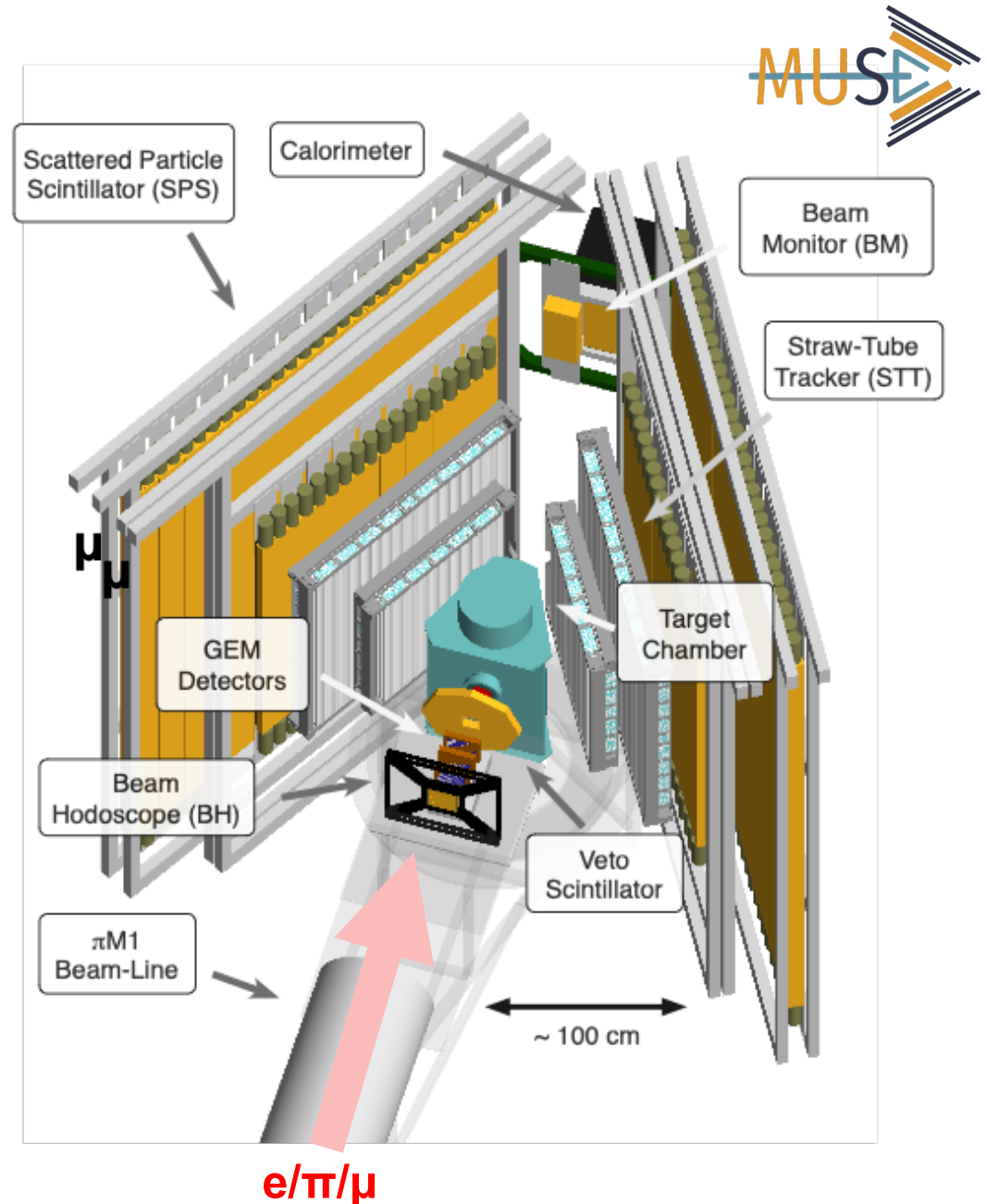
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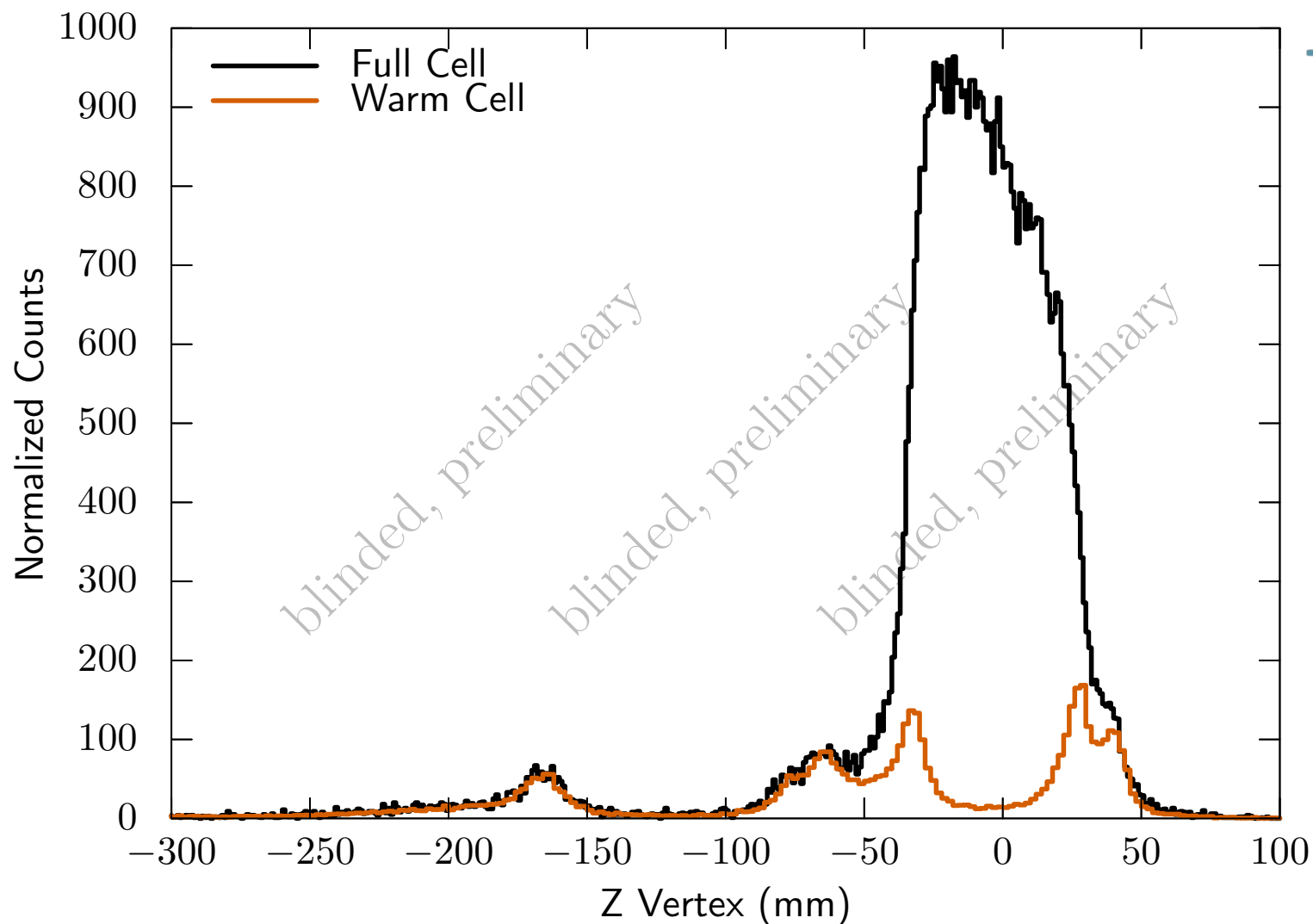
# MUSE analysis status

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- Preliminary analysis of scattering data at 115, 160, 210 MeV/c:  
Good agreement between data and simulation within blinding  
(all observed ratios agree to within 20%)
- Analysis and simulation framework established (Cooker, g4PSI):  
same reconstruction routines for data and pseudo data
  - Detector plugins: calibrated raw data
  - Multiple tracking methods
  - Higher-level analysis plugins
- In progress:
  - Calibrations, time-dependent
  - Alignment calibration, time-dependent  
→ improve tracking and internal data consistency
  - Simulations: Radiative generators, digitization, trigger, PID,  
beam properties, theoretical modeling of xsec, ff, TPE, LU
  - Error propagation and systematic errors



# MUSE performance: Full vs empty

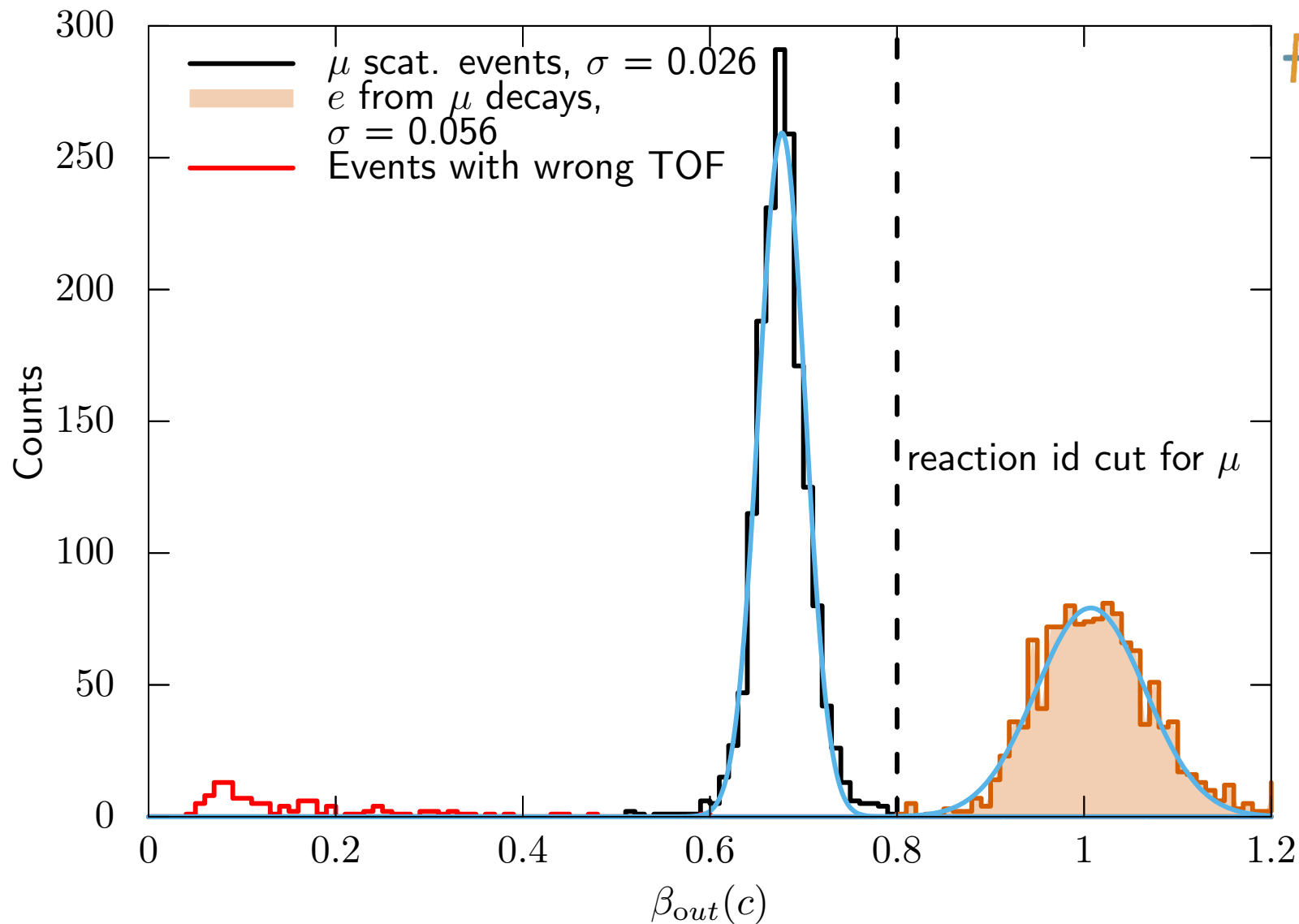


**+210 MeV/c beam**

**“Full” cell (lq H<sub>2</sub>) and “warm” cell (are the same cell)**

**Cell wall structures due to aluminized mylar**

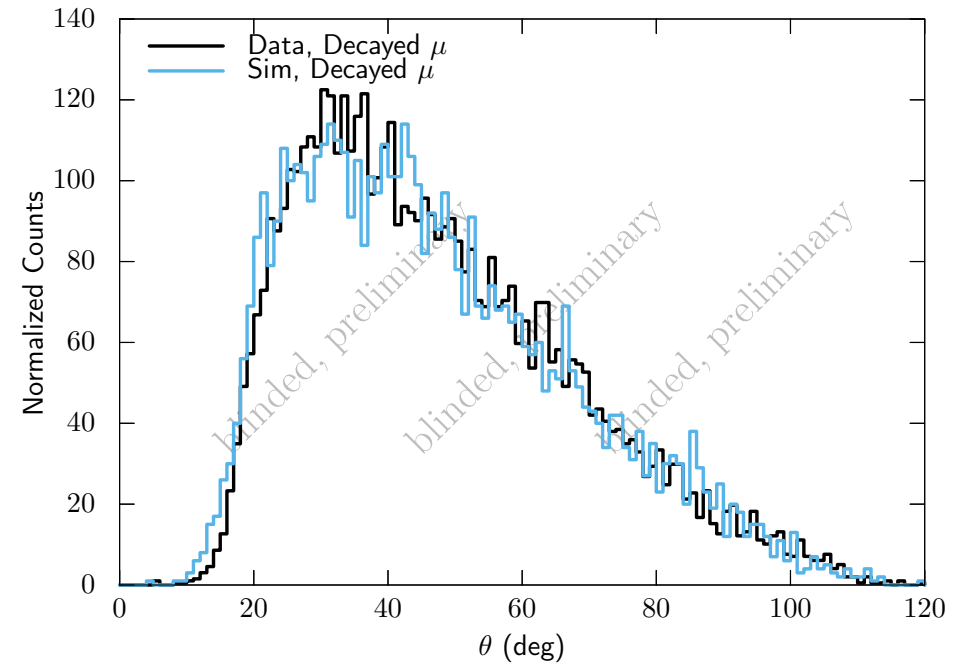
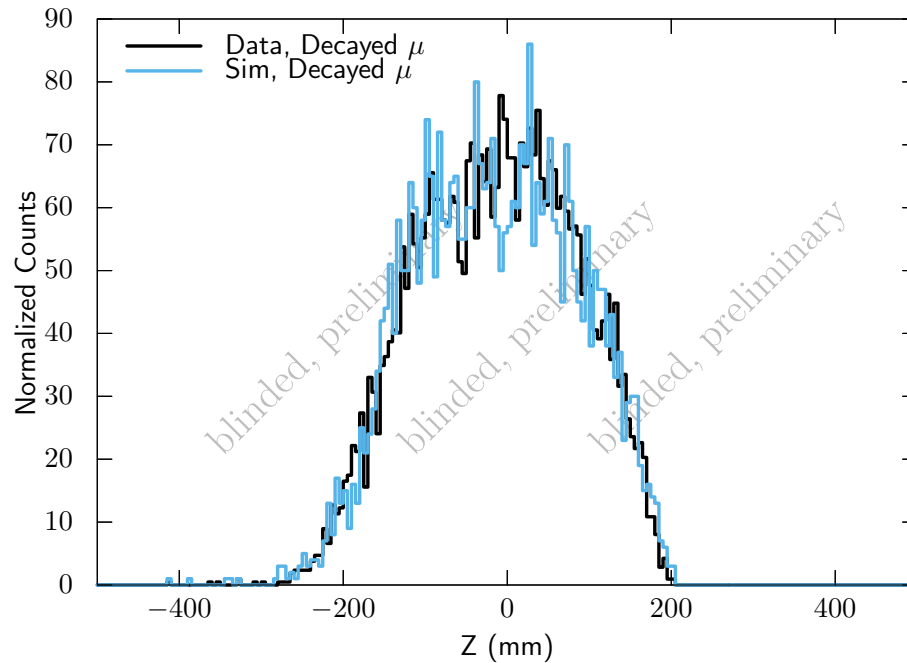
# Reaction identification



$\beta_{out}$  from reaction vertex to SPS,  $p = -115$  MeV/c

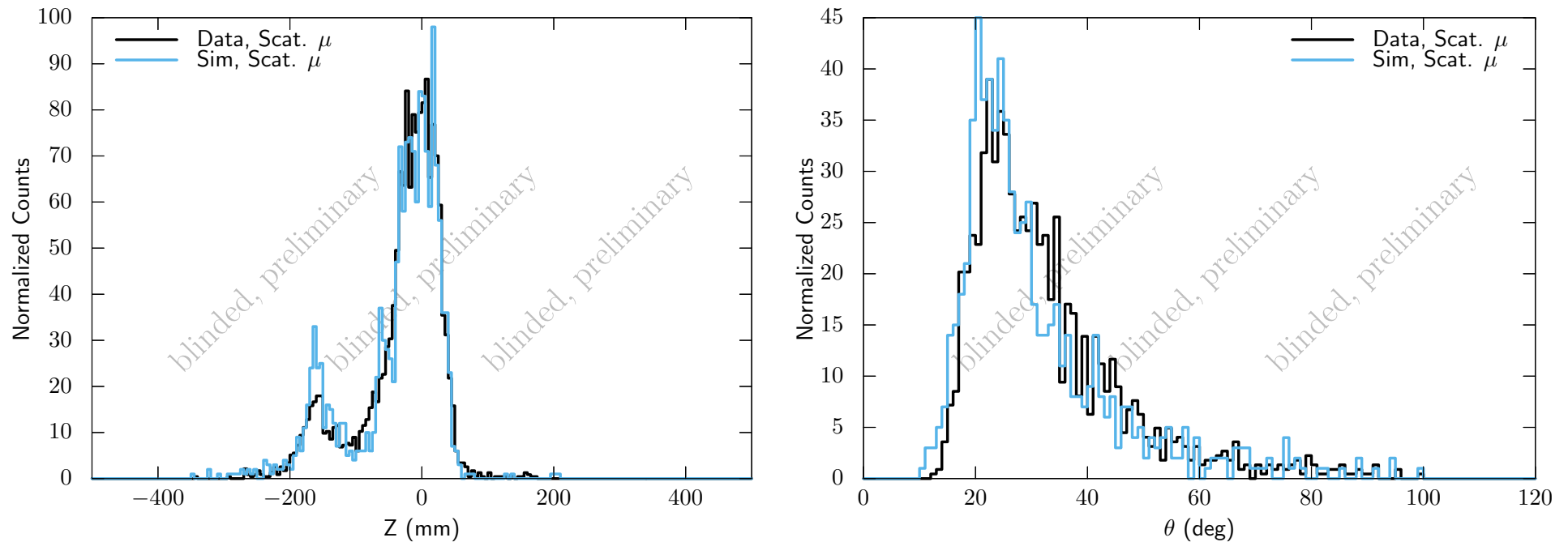
Clean separation of  $\mu p$  scattering vs  $\mu$  beam decay-in-flight events

# Muon beam decay events data vs sim



- $p = + 115$  MeV/c; left: vertex; right: reconstructed angle
- Good agreement between data and simulation for muon beam decay-in-flight events
- Both data and simulation are blinded

# Muon scattering events data vs sim



- $p = + 115 \text{ MeV}/c$ ; left: vertex; right: reconstructed angle
- Good agreement between data and simulation for muon scattering events
- Both data and simulation are blinded
- Similarly findings for all data sets  $\mu^\pm, e^\pm, \pi^\pm @ 115, 160, 210 \text{ MeV}/c$

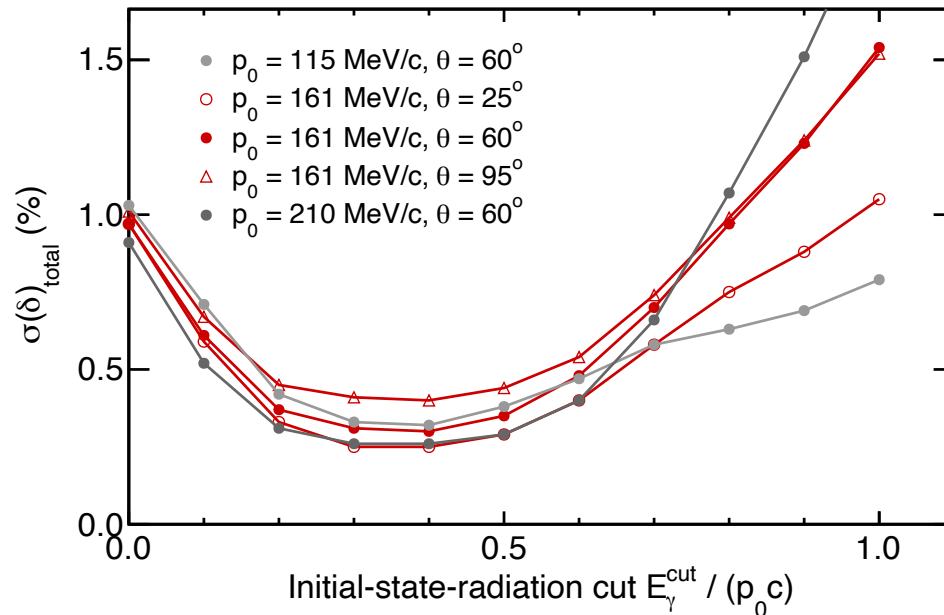
# MUSE publications

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- E.O. Cohen *et al.*,  
*Development of a scintillating-fiber beam detector for the MUSE experiment*, NIM A  
<https://doi.org/10.1016/j.nima.2016.01.044>
- P. Roy *et al.*,  
*A Liquid Hydrogen Target for the MUSE Experiment at PSI*, NIM A  
<https://doi.org/10.1016/j.nima.2020.164801>
- T. Rostomyan *et al.*,  
*Timing Detectors with SiPM read-out for the MUSE Experiment at PSI*, NIM A  
<https://doi.org/10.1016/j.nima.2019.162874>
- E.Cline, J. Bernauer, E.J. Downie, R. Gilman,  
*MUSE: The MUon Scattering Experiment*, Review of Particle Physics at PSI  
<https://doi.org/10.21468/SciPostPhysProc.5>
- E. Cline *et al.*,  
*Characterization of Muon and Electron Beams in the Paul Scherrer Institute PiM1 Channel for the MUSE Experiment*  
PRC 105, 055201 (2022); arXiv: 2109.09508  
<https://doi.org/10.1103/PhysRevC.105.055201>



# Recent MUSE publications



- **L. Li et al.,**  
*Instrumental uncertainties in radiative corrections for the MUSE experiment,*  
*Eur. Phys. J. A 60, 8 (2024)*

**Forward calorimeter to control ISR**

- **J.C. Bernauer et al.,**  
*Blinding for precision scattering experiments: The MUSE approach as a case study,*  
*Phys. Rev. C, in press; arXiv:2310.11469v1 [physics.data-an]*

**Angular dependent O(20%) blinding for all beam species, polarity, beam momenta, data & simulation**



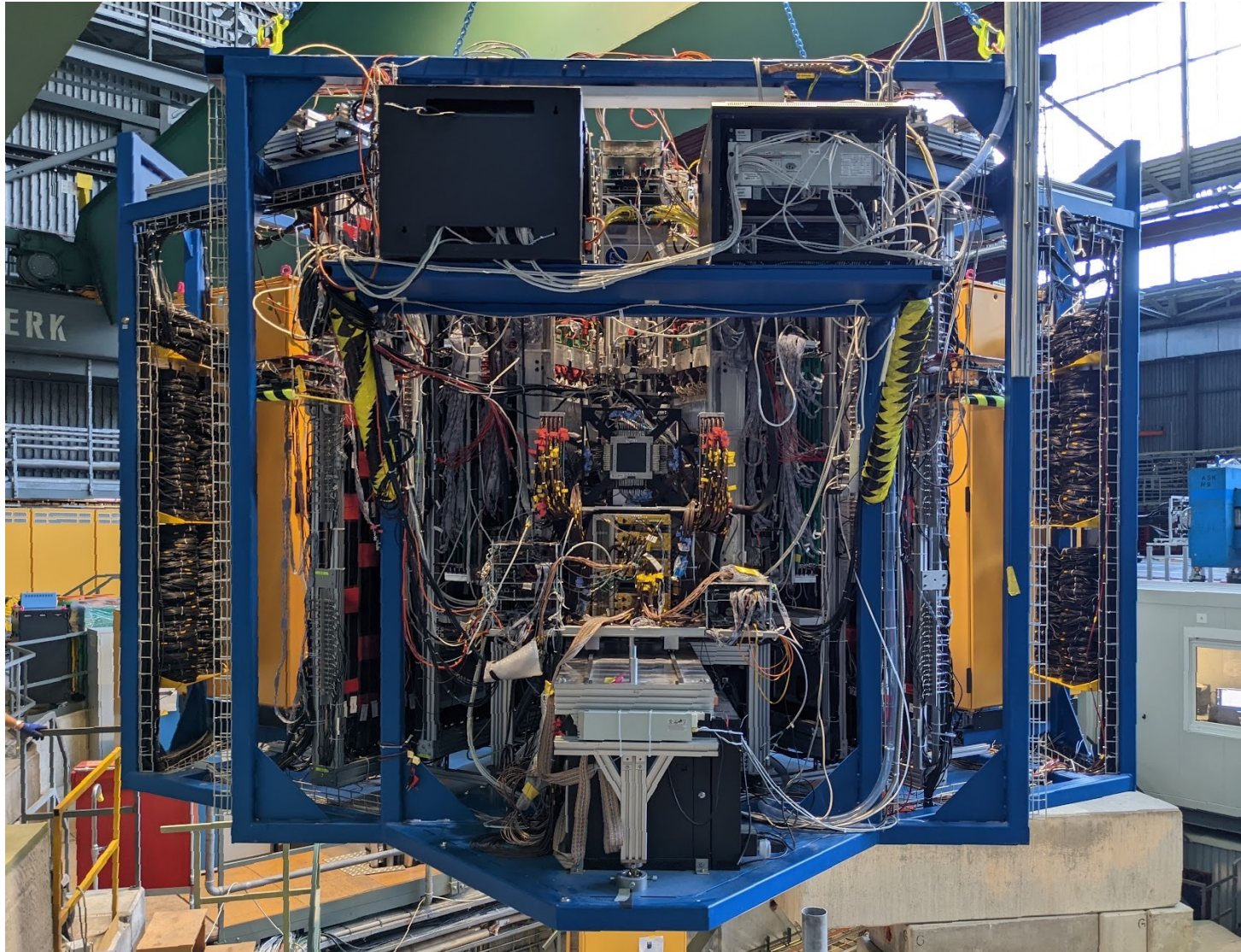


# 2023-2025: MUSE production data taking

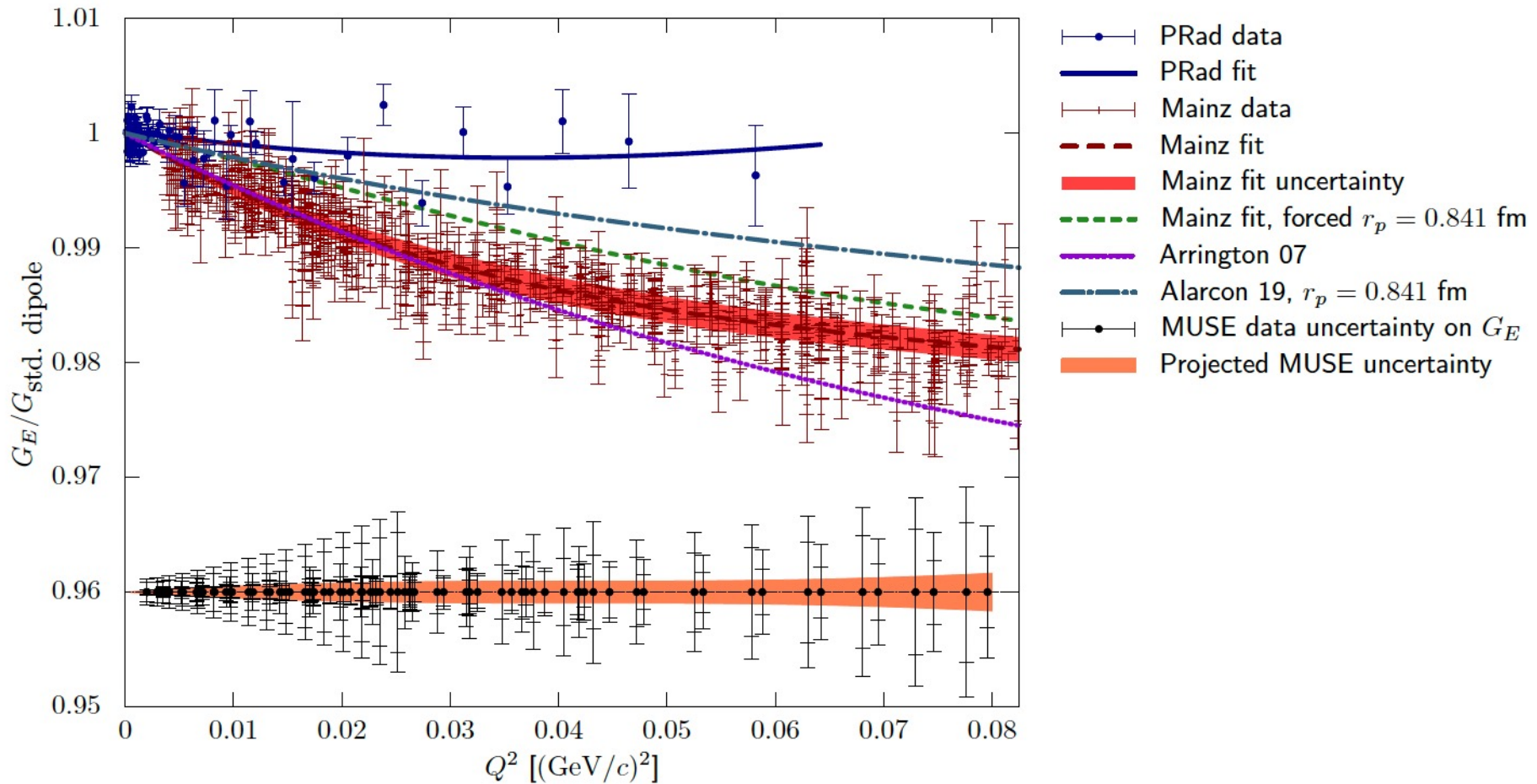
**2016-2019: Assembly complete; Initial commissioning**

**2020-2022: Commissioning cont'd under initial Covid-19 constraints**

**2023: Started production data for 12 beam months over ~2 years**

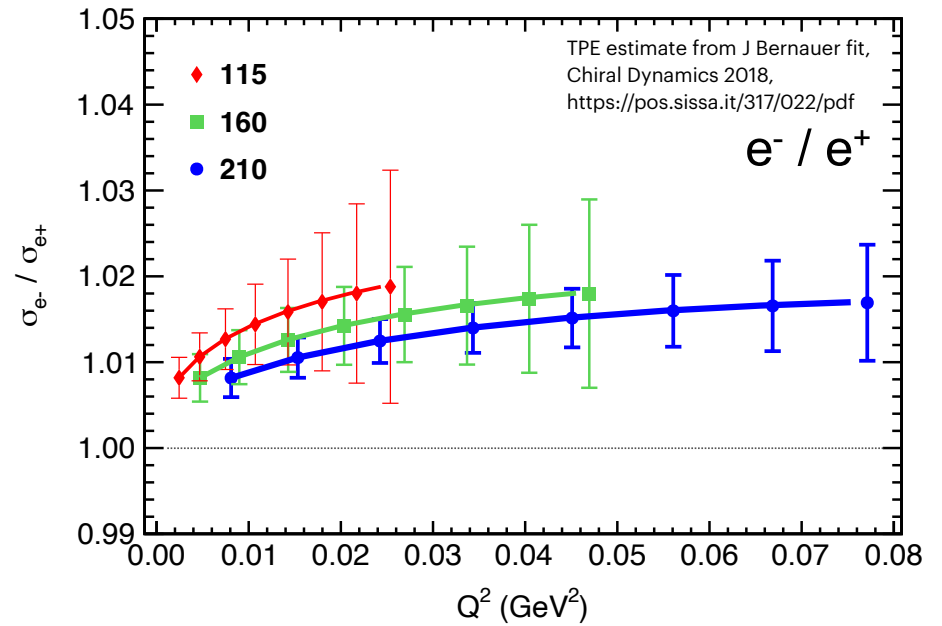
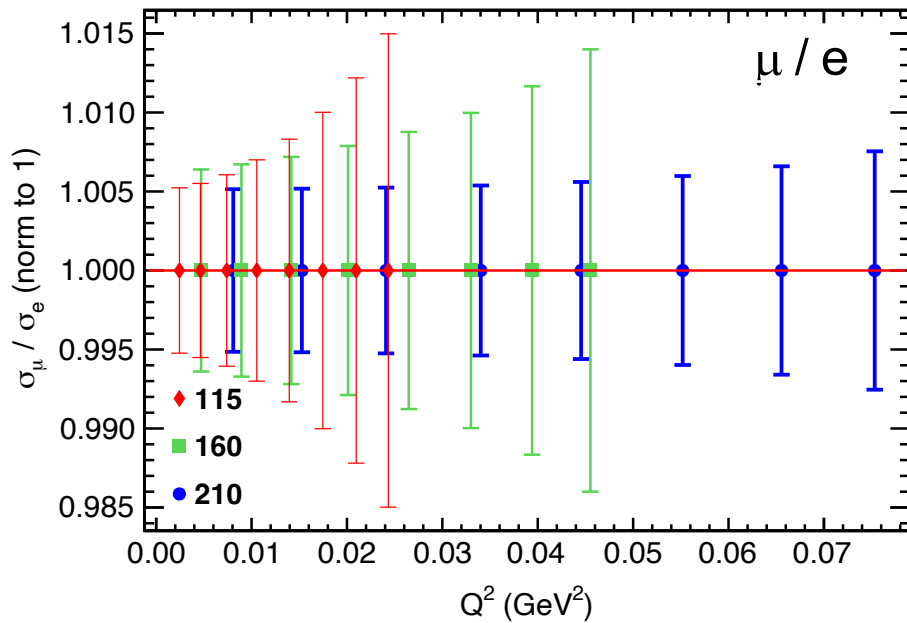


# MUSE coverage and expected errors

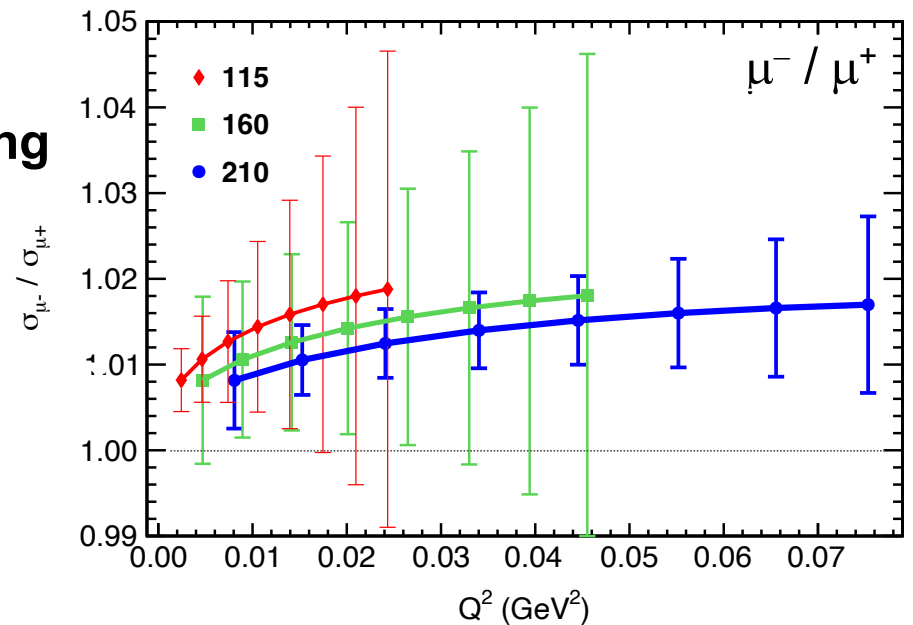


- Anticipated form factor uncertainty
- E. Cline, *et al.*,  
SciPost Phys. Proc. 5, 023 (2021)

# 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,  $R_\mu - R_e$  to 0.005 fm



# Summary

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- **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/o (PRad-II, MUSE), and w/ magn. field (ULQ2, MAGIX)
  - $\mu$ -scattering: smaller rad. corr., cleaner than e? (MUSE, AMBER)
- MUSE allows for comparison of  $e p$  and  $\mu p$ , as well as TPE for both
  
- Conclusion
  - There has been a trend, however we are not done yet



# MUon Scattering Experiment – MUSE

## 75 MUSE collaborators from 23 institutions in 5 countries:

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# Backup

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