LEES Workshop, Tohoku University, Sendai, Japan, Oct. 28 - Nov. 1, 2024

Status and Prospects of the MUSE Project at PSI

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* **Supported by NSF PHY-2113436, PHY-2412757, DOE DE-SC0013941, and JSA**

Outline

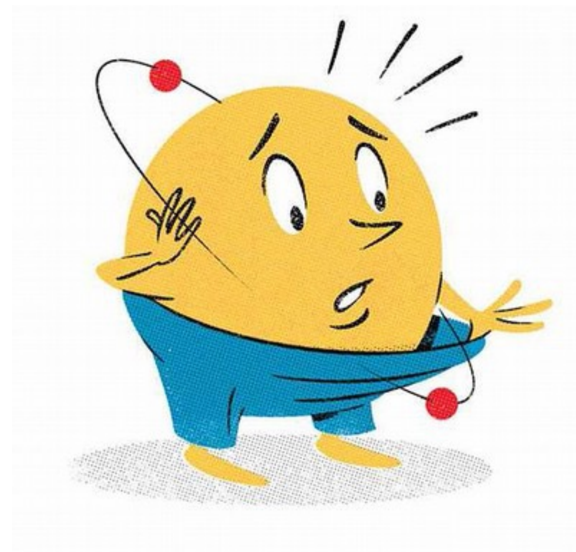
- **The Proton Charge Radius**
  – Definition and recent reviews

- **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

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

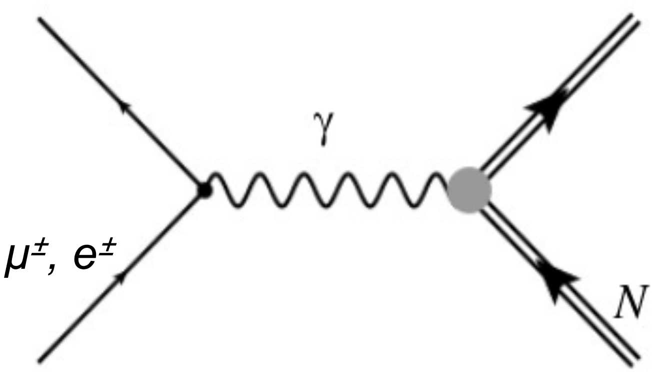
Consistent, covariant treatment: $$\langle r_E^2 \rangle = -6 \frac{dG_E^p(Q^2)}{dQ^2}\bigg|_{Q^2\to 0}$$

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:

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

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

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 $Q^2 \to 0$ limit:

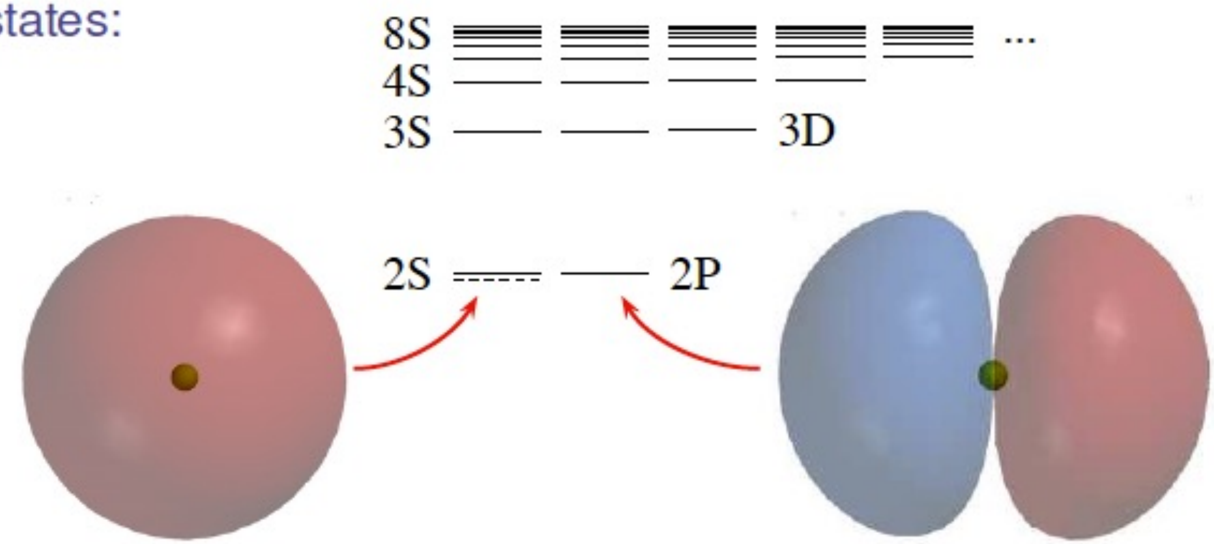
$$\langle r_E^2\rangle = -6\frac{dG_E^p(Q^2)}{dQ^2}\Big|_{Q^2\to 0}$$

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

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.

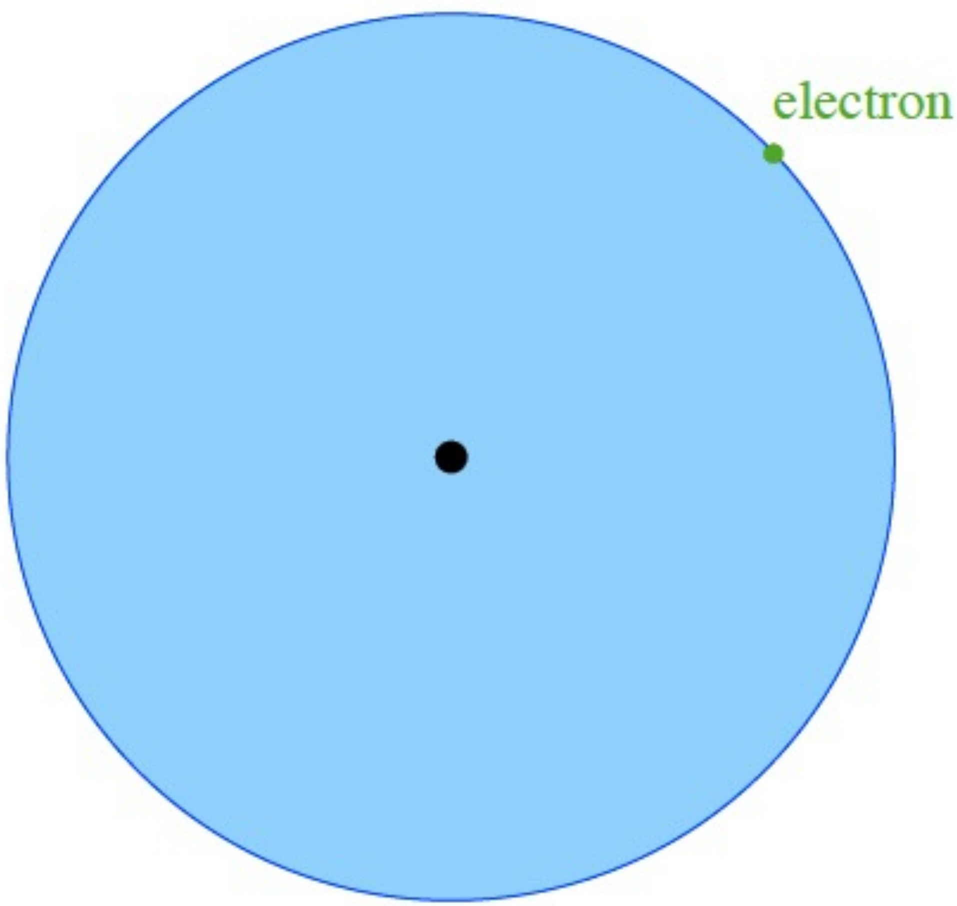
Slide by R. Pohl

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

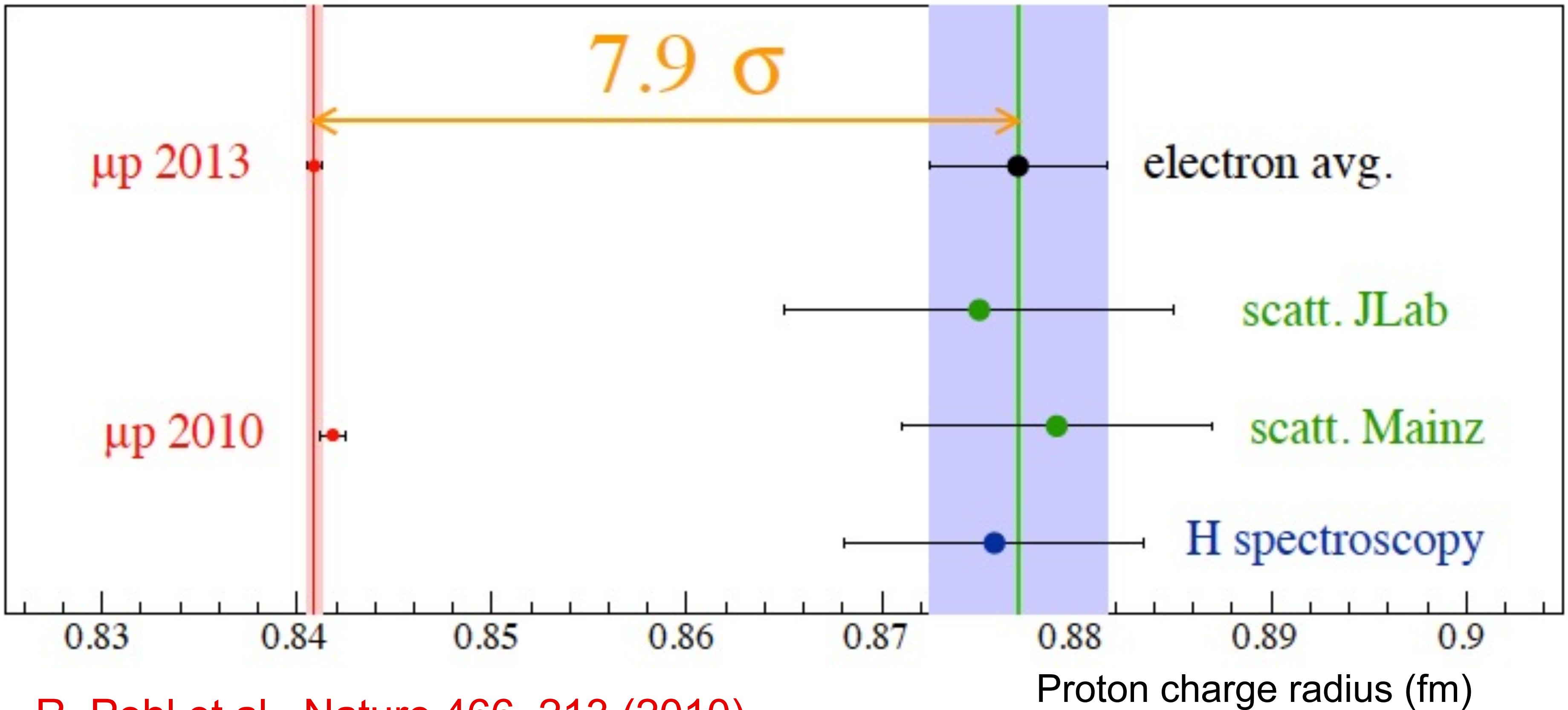
Slide by R. Pohl

The proton radius puzzle in 2010/2013

The proton rms charge radius measured with

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

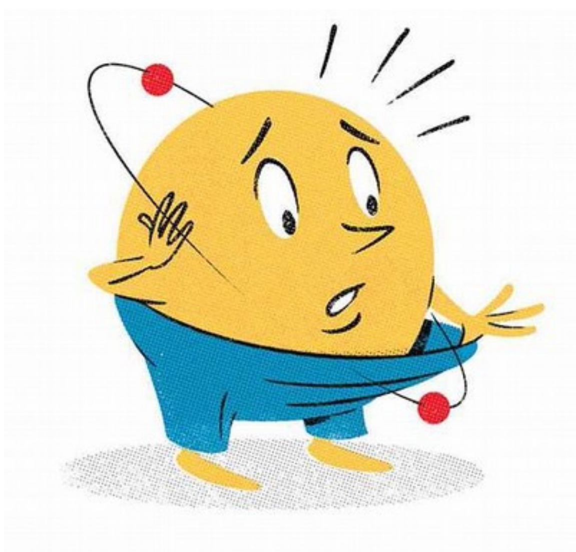
muons: 0.8409 ± 0.0004 fm



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

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

Proton radius puzzle has drawn attention



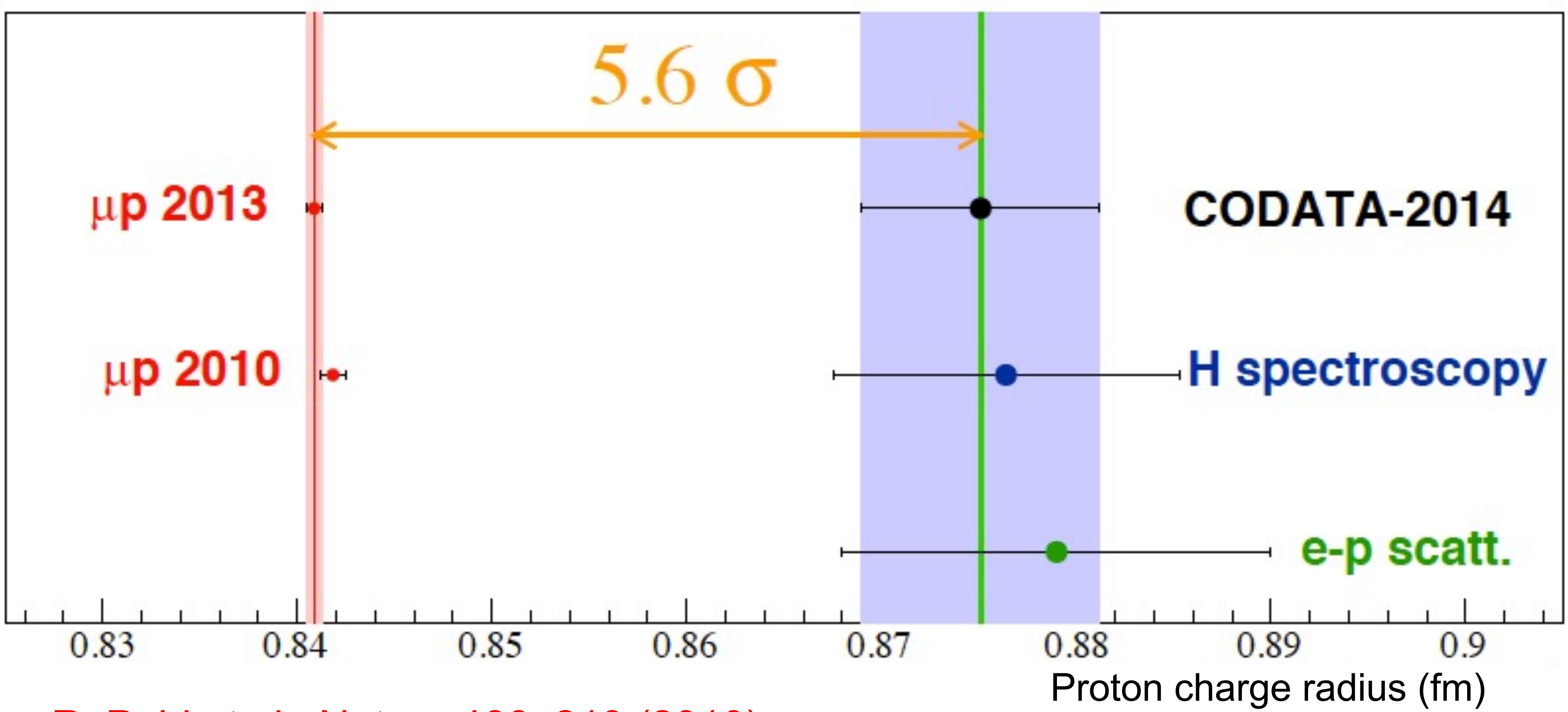
The New York Times

The proton radius puzzle in 2016

The proton rms charge radius measured with

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

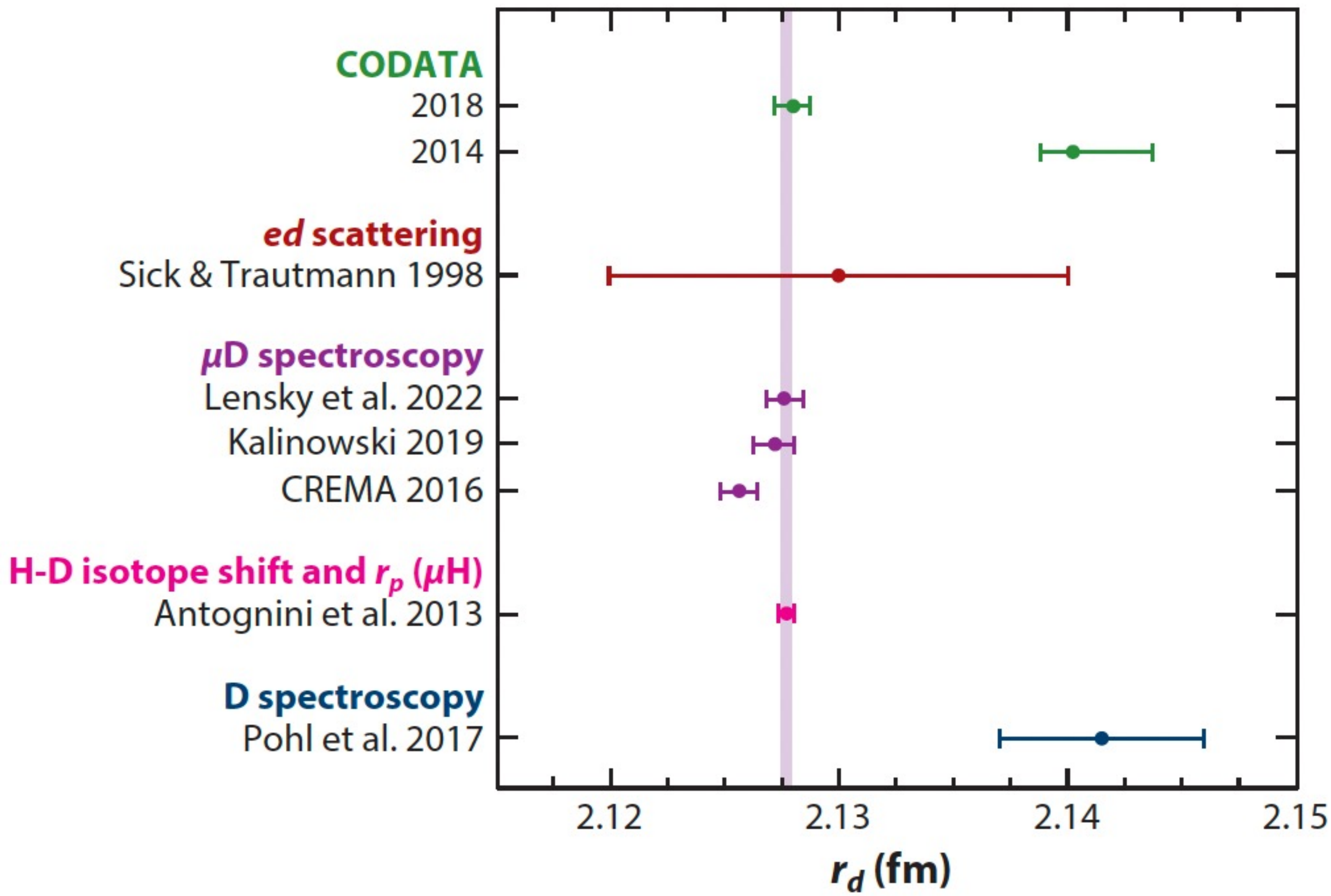
muons: (0.8409 ± 0.0004) fm



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 → Mainz, ULQ2, DRAD**
- **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

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MUSE will test

CODATA2018 new recommended values

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

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

Constants Topics:
- Values
- Energy Equivalents
- Searchable Bibliography
- Background
- Constants Bibliography
- Constants, Units & Uncertainty home page

proton rms charge radius

r_p

Numerical value	8.414×10^{-16} m
Standard uncertainty	0.019×10^{-16} m
Relative standard uncertainty	2.2×10^{-3}
Concise form	$8.414(19) \times 10^{-16}$ m [-5.5σ]

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

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

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RMP 93, 025010 (2021)

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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

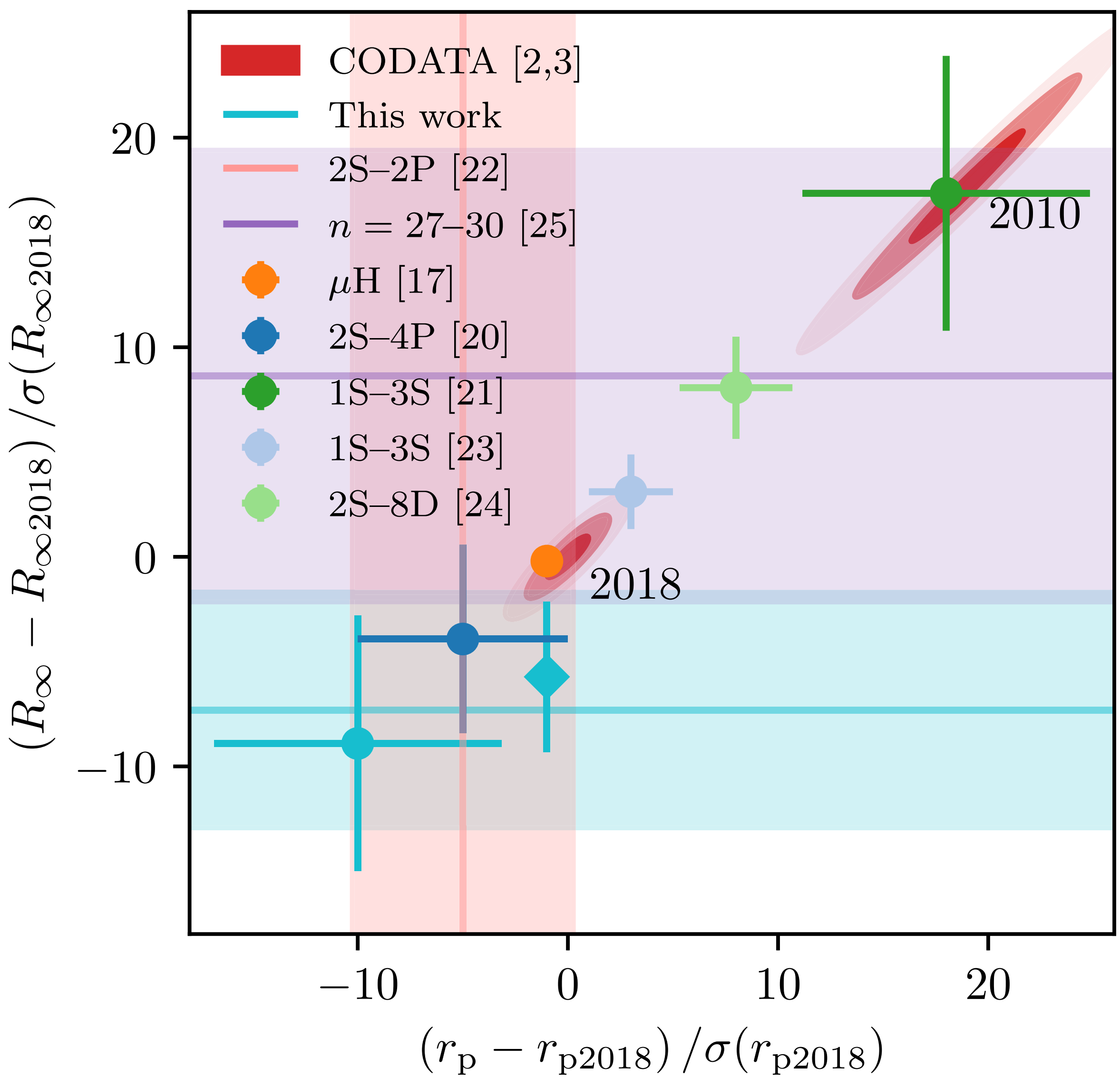
Click here for **correlation coefficient** of this constant with other constants

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

3x more precise

Return to List | Go to New Search

New, independent Rydberg measurement



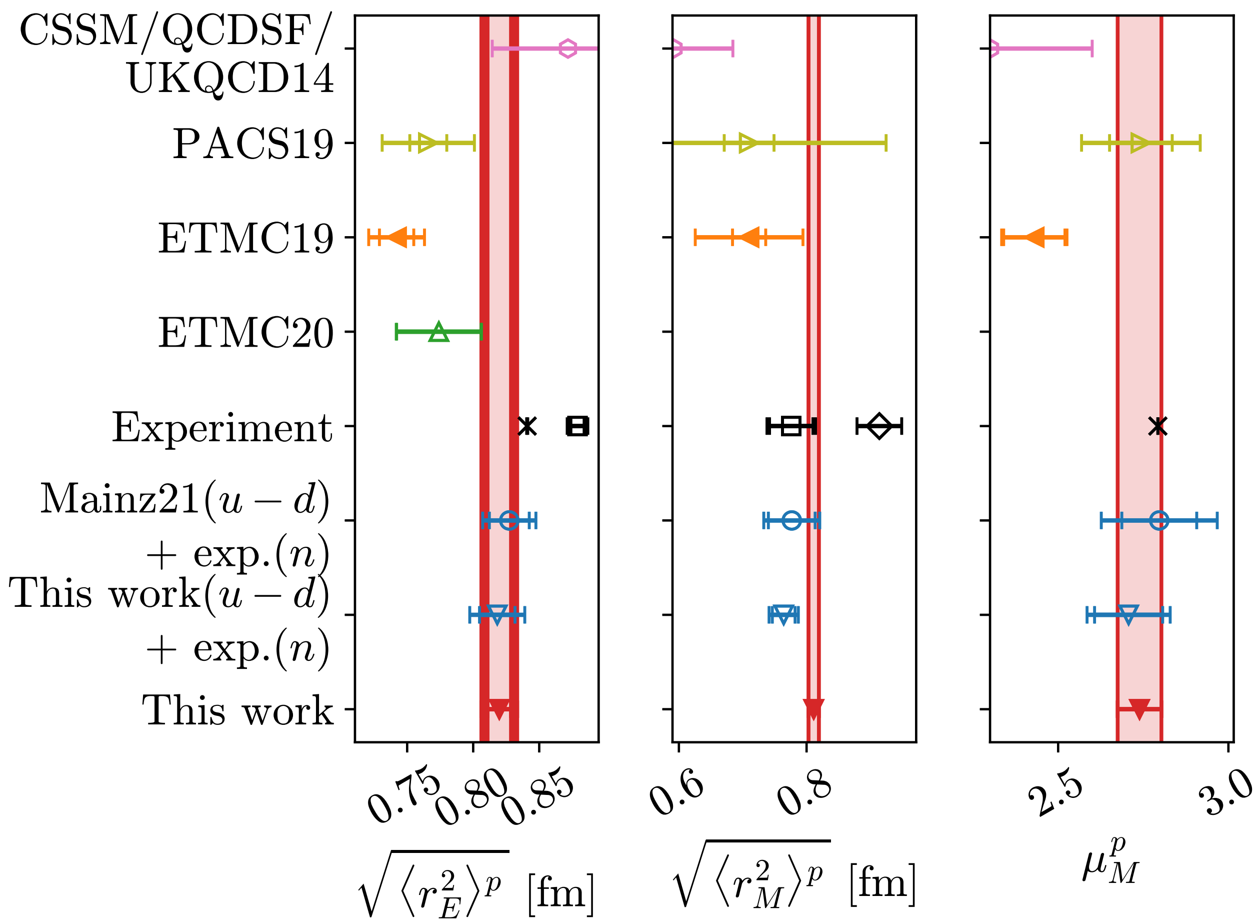
Spectroscopy: Rydberg constant and proton radius are correlated

2024: Small Rydberg reconfirmed

Consistent w/ small radius

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

New milestone: Precision Lattice QCD

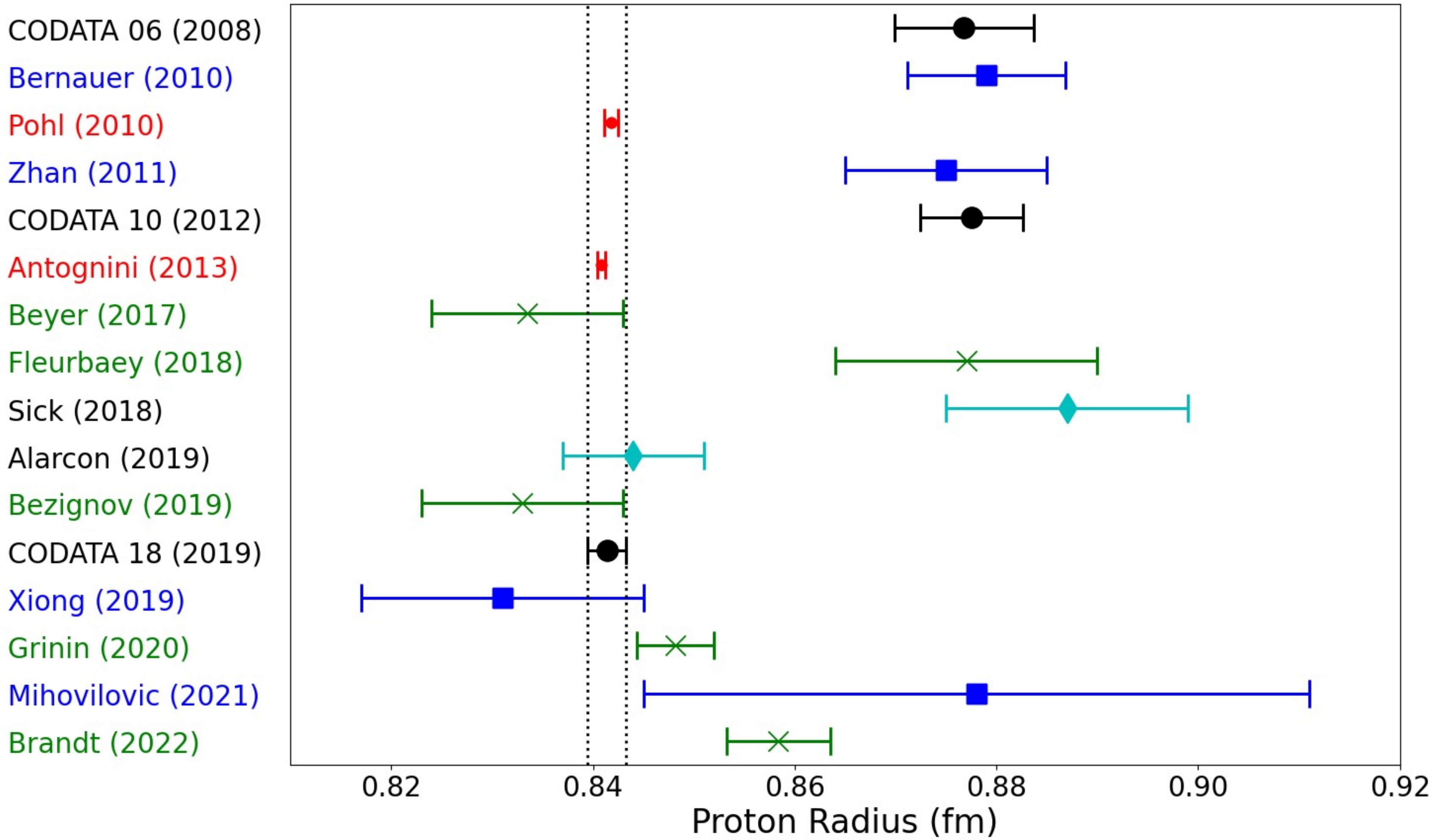


$$\sqrt{\langle r_E^2\rangle^p} = 0.820(14)\ \text{fm},\ \sqrt{\langle r_M^2\rangle^p} = 0.8111(89)\ \text{fm, and}\ \mu_M^p = 2.739(66)$$

Consistent with small radius

D. Djukanovic, G. von Hippel, H.B. Meyer, K. Ottnad, M. Salg, and H. Wittig, PRL 132, 211901 (2024) [May 22, 2024]

The proton radius puzzle in 2023

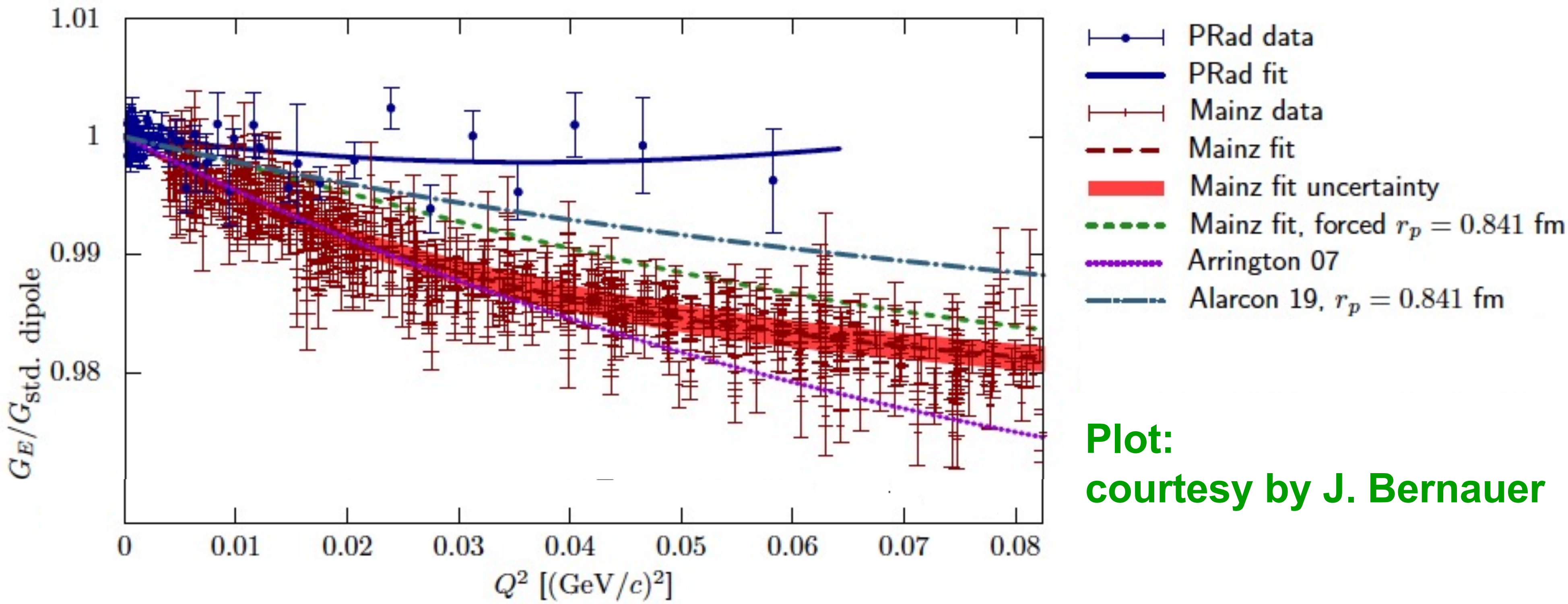


Red = μp spectroscopy
Blue = ep scattering
Light blue = re-fitting of e scattering
Green = ep spectroscopy
Black = CODATA

Plot: courtesy by J. Bernauer

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, …)

Ongoing and future scattering experiments

Experiment	Probe	Q^2 / $(GeV/c)^2$	Status
PRad II	e^-	0.00004 – 0.06	Approved by JLab PAC, running in 2025
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

Motivation for μp scattering

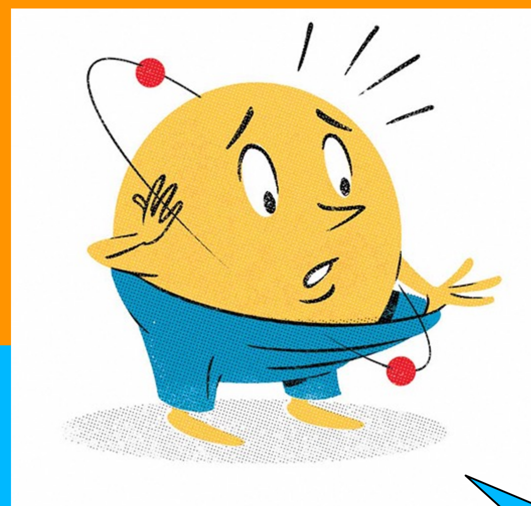
Spectroscopy

Electronic hydrogen

0.8758 ± 0.0077

Muonic hydrogen

0.84184 ± 0.00067
0.84087 ± 0.00039



Electron scattering

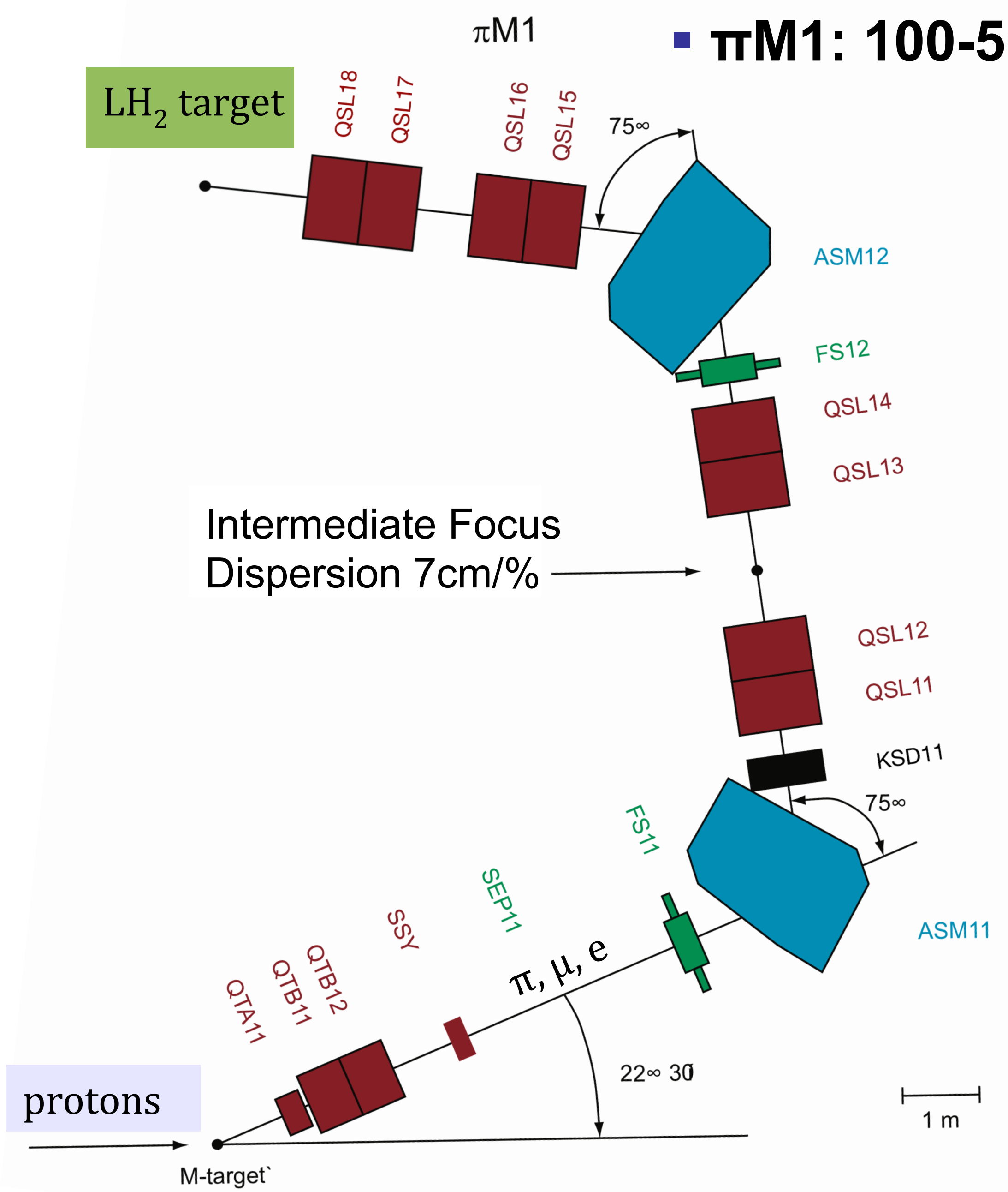
0.8770 ± 0.0060

Scattering

Muon scattering
???

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

πM1 / MUSE beamline



- **πM1: 100-500 MeV/c RF+TOF sep. π, μ, e**

Secondary beams of π, μ, 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 π^0 decay + conv.**

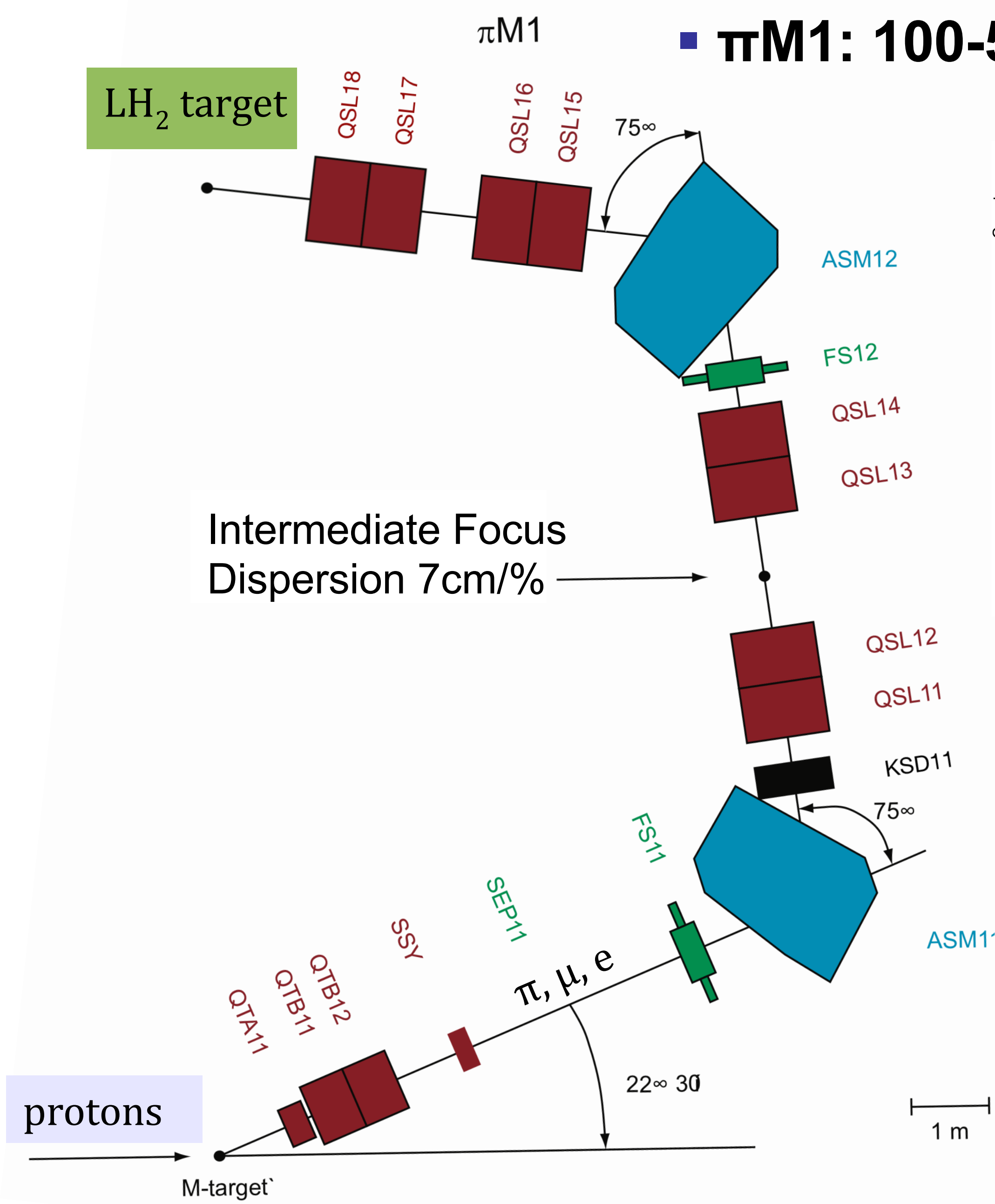
Extended source

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

Beam properties well understood with TRANSPORT, TURTLE, and G4Beamline

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

πM1 / MUSE beamline



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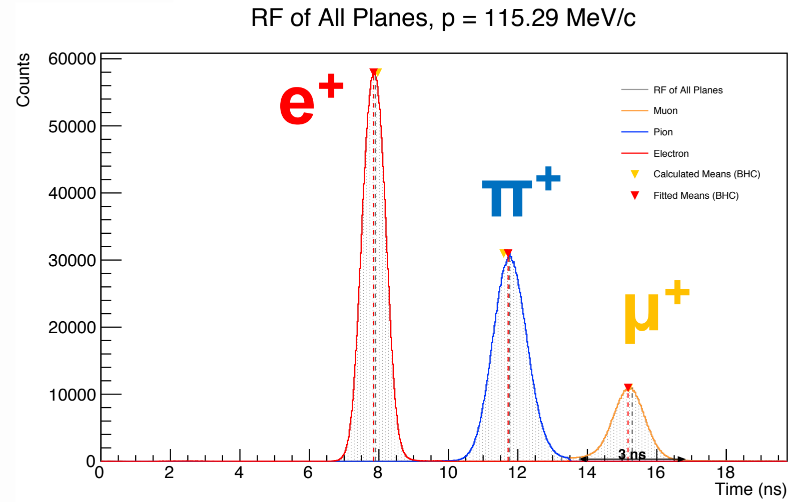
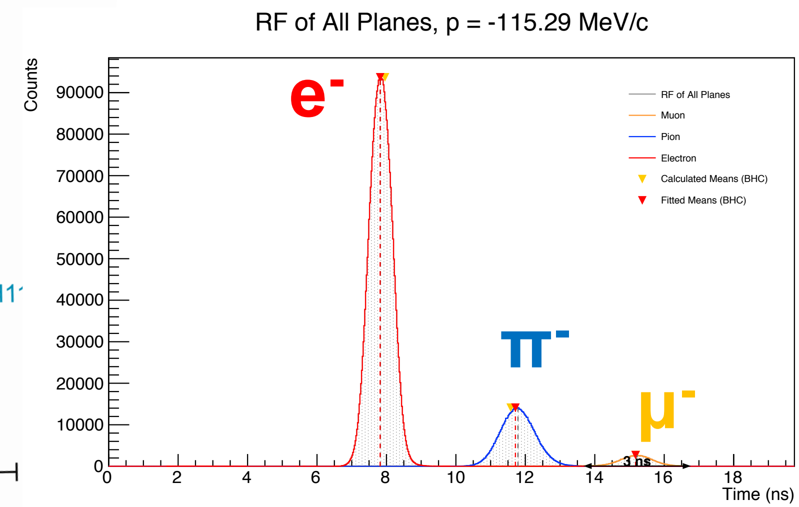




MUSE at PSI

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

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

p = 115, 160, 210 MeV/c

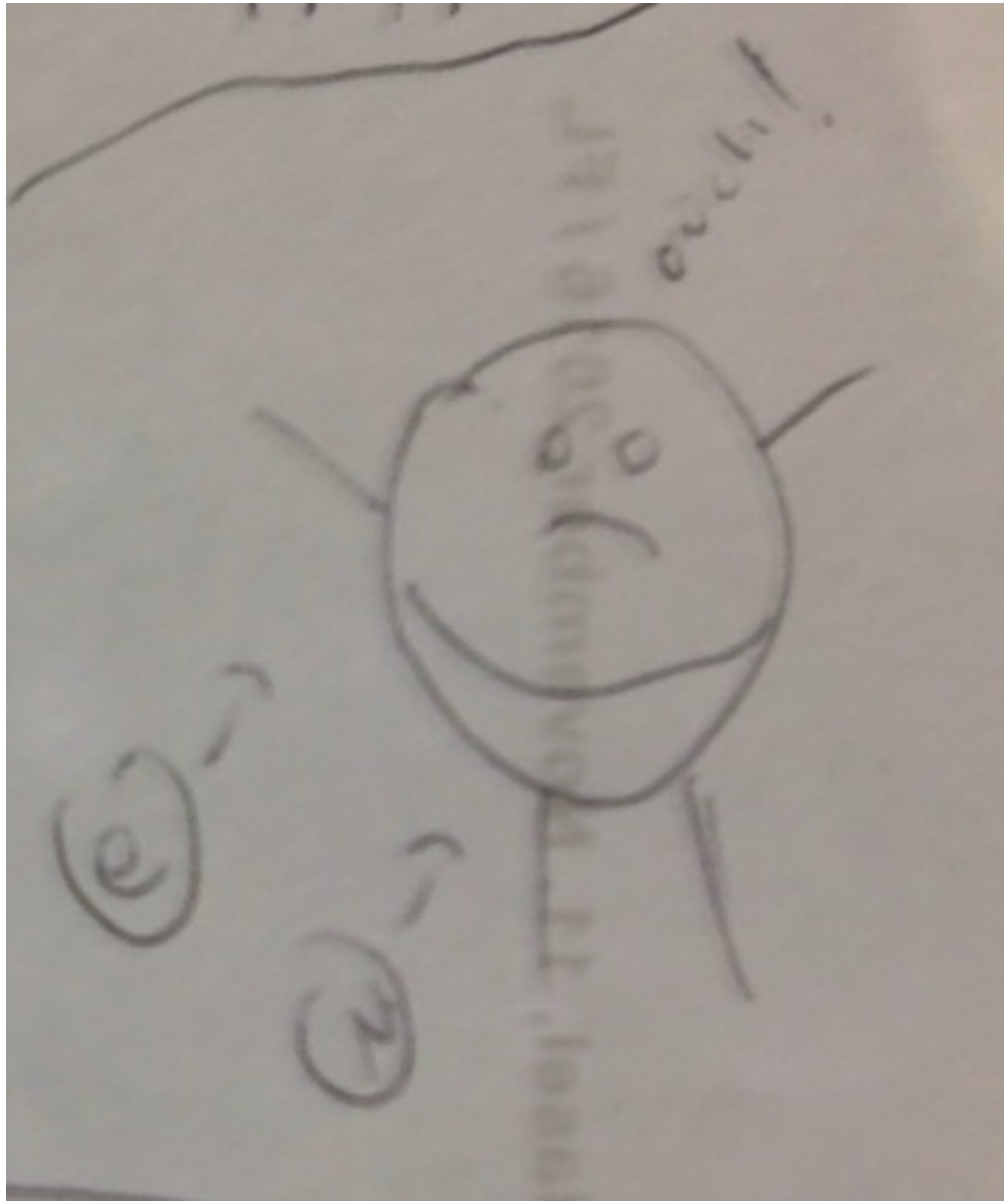
$\theta = 20^o$ to 100^o

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

$\varepsilon = 0.256 - 0.94$

Challenges

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



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

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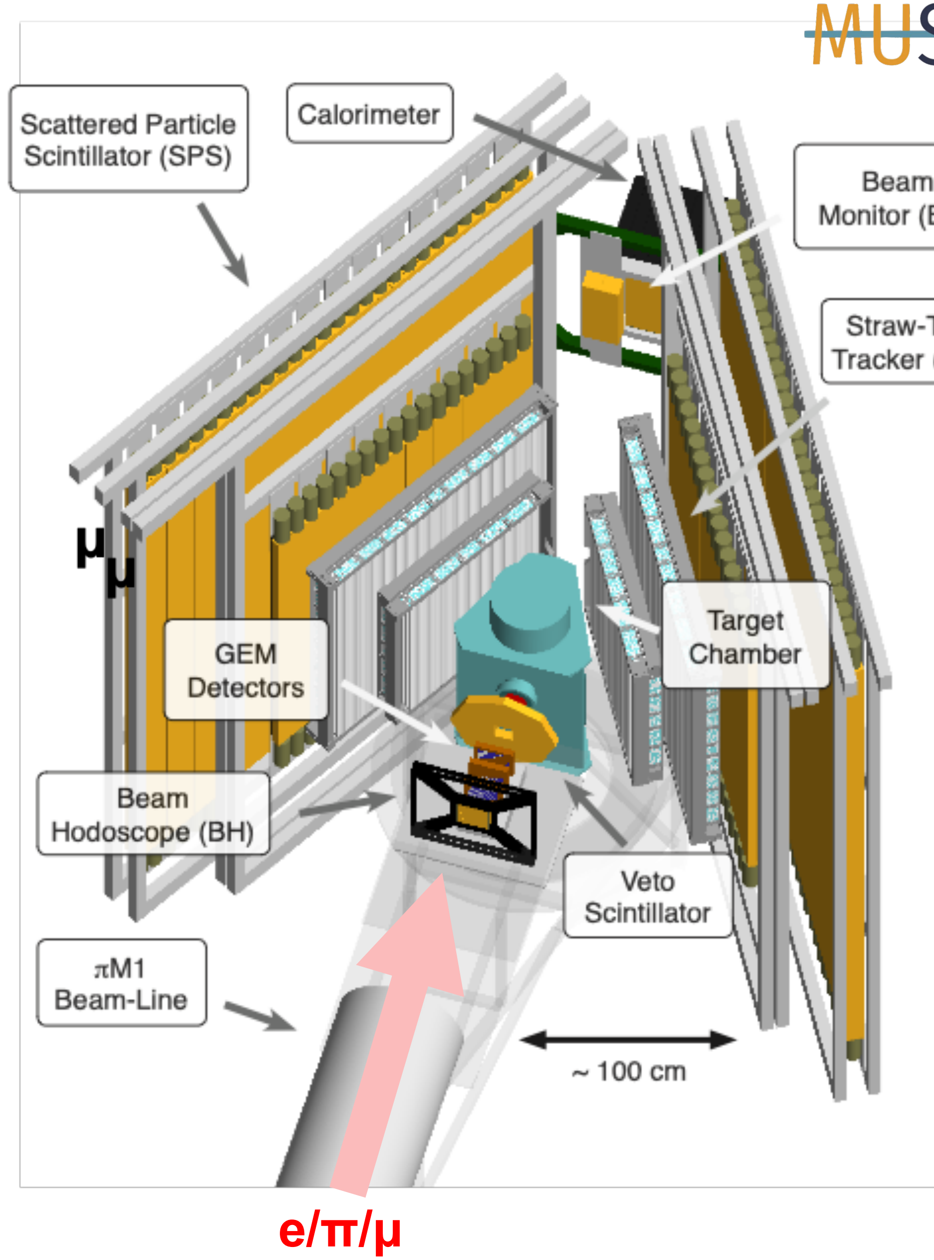
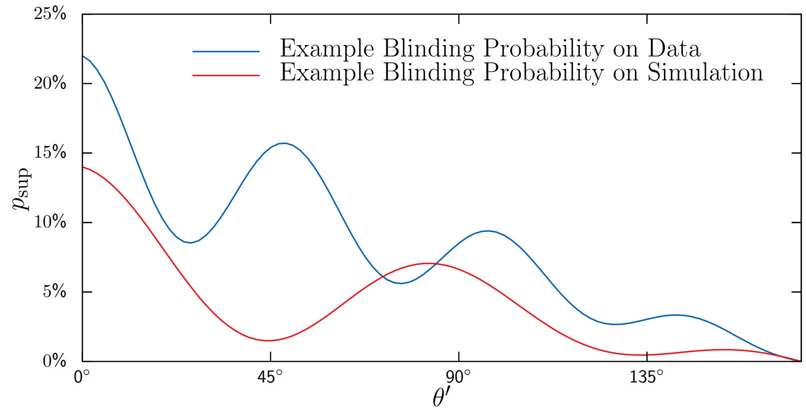


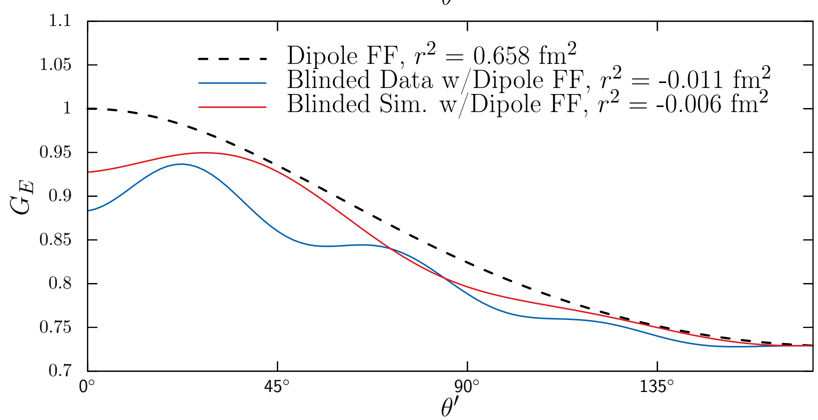
MUSE analysis status

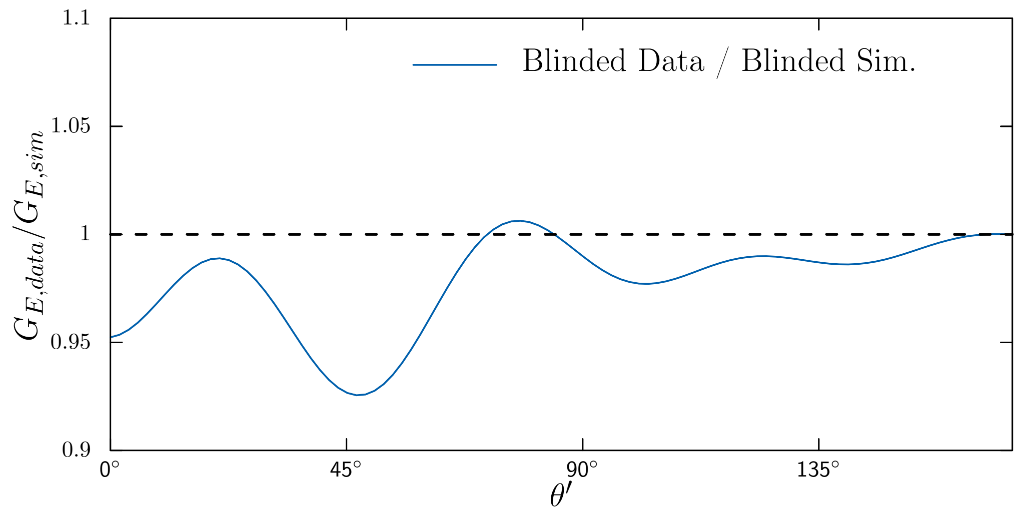
- **Preliminary analysis of scattering data at 115, 160, 210 MeV/c: Good agreement between data and simulation within blinding (all observed ratios agree to within 20%)**
- **Analysis and simulation framework established (Cooker, g4PSI): same reconstruction routines for data and pseudo data**
  - **Detector 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**

Blinding of MUSE data and simulation

$$p_{\mathrm{sup}} = \frac{0.2}{3}\left(A_i + 0.3\cos B_i\theta'\right)\left(3-\theta'\right) \qquad A_i \in [0.25, 1] \qquad B_i \in [3, 10]$$



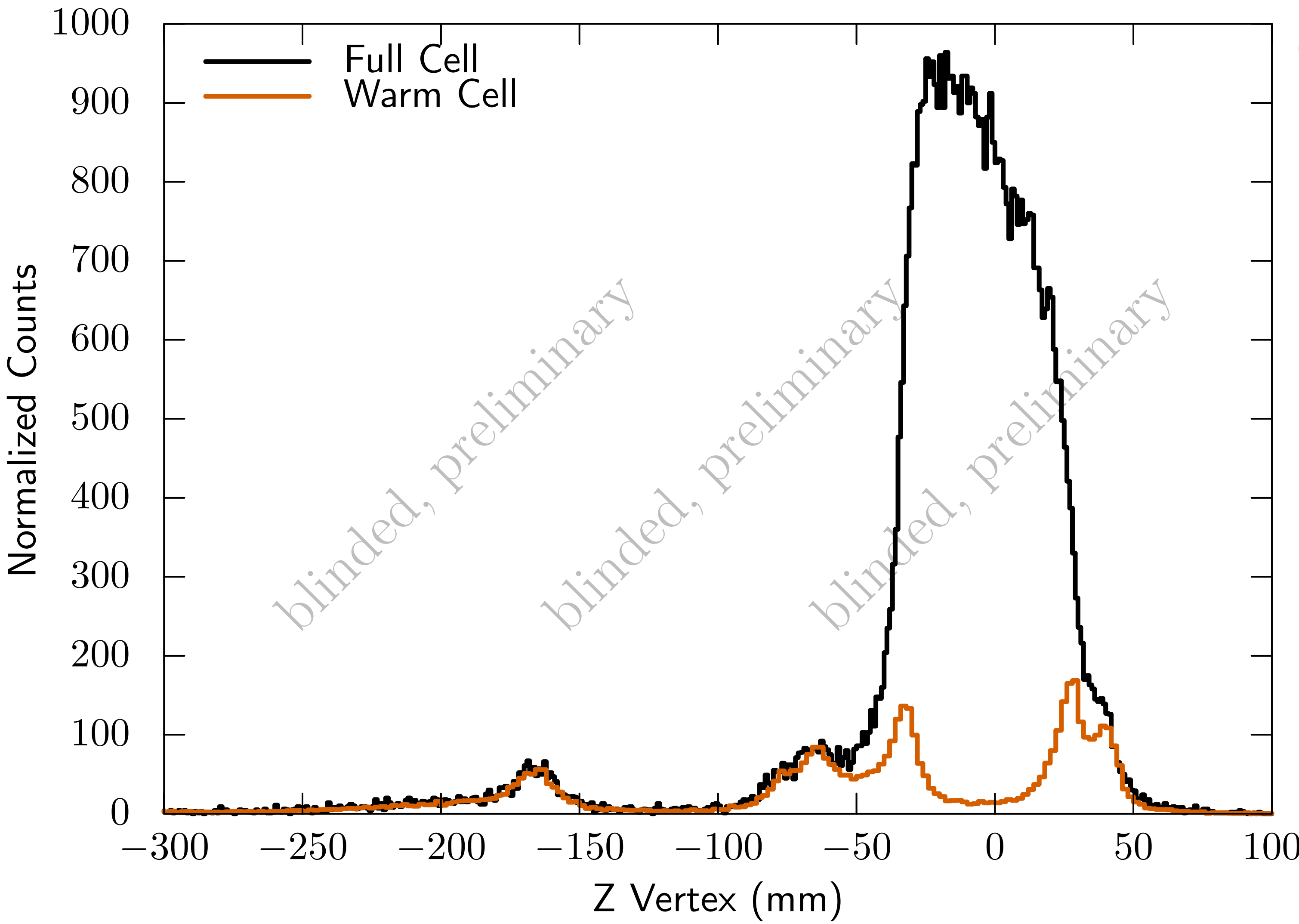




J.C. Bernauer *et al.*,
***Blinding for precision scattering experiments: The MUSE approach as a case study,* Phys. Rev. C, under review; arXiv:2310.11469v1 [physics.data-an]**

Angular dependent O(20%) blinding by stochastic event suppression for all beam species, polarity, beam momenta, data & simulation

MUSE performance: Full vs empty

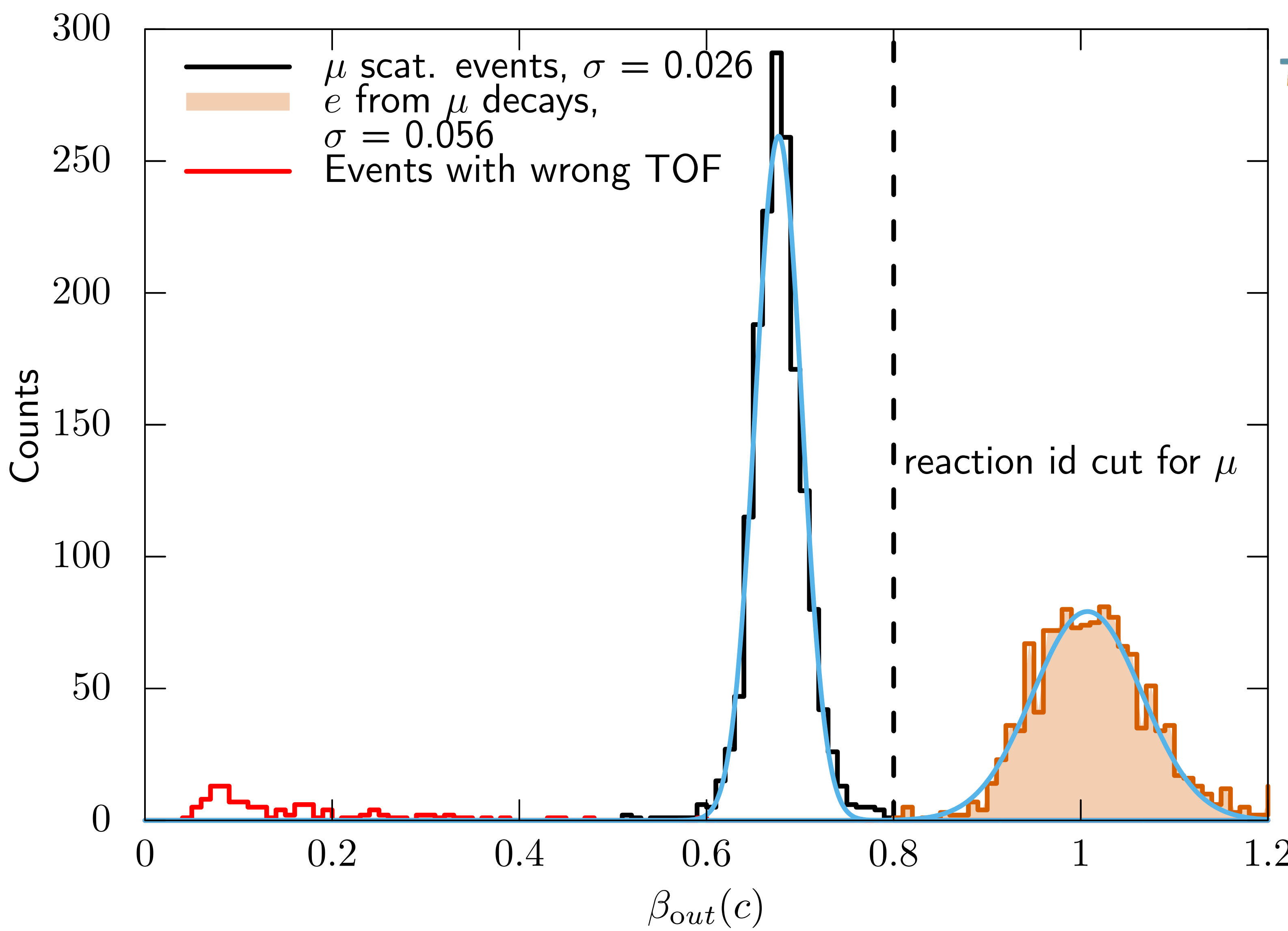


+210 MeV/c beam

“Full” cell (lq H_2) and “warm” cell (are the same cell)

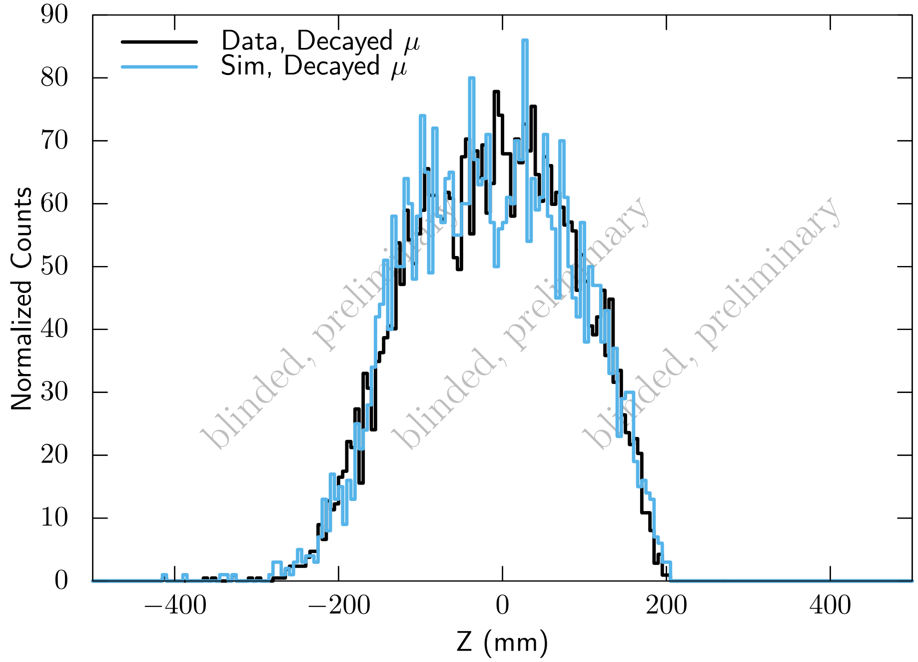
Cell wall structures due to aluminized mylar

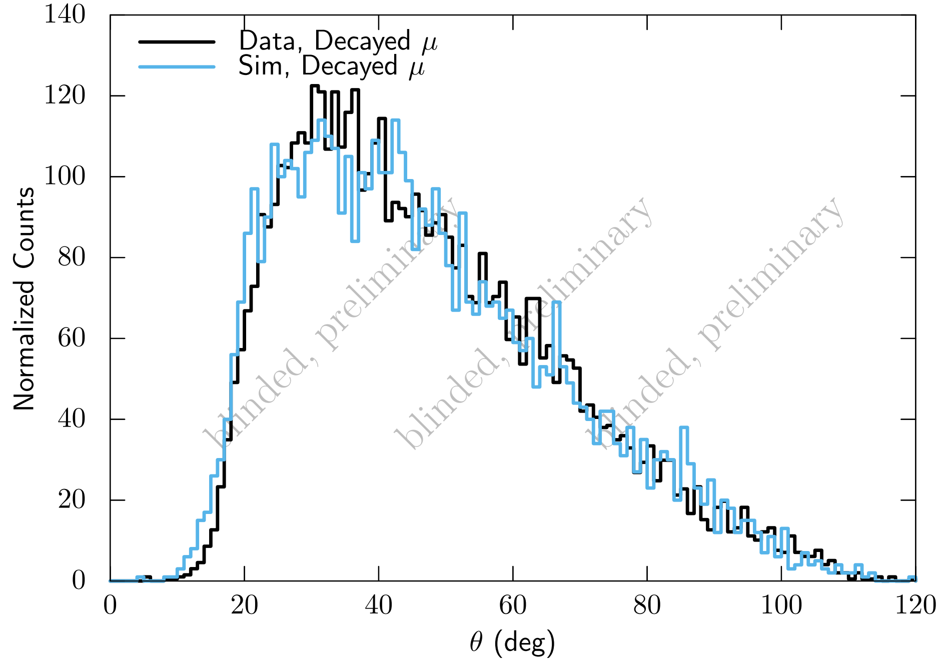
Reaction identification



β_{out} from reaction vertex to SPS, *p* = –115 MeV/c
Clean separation of μp scattering vs μ beam decay-in-flight events

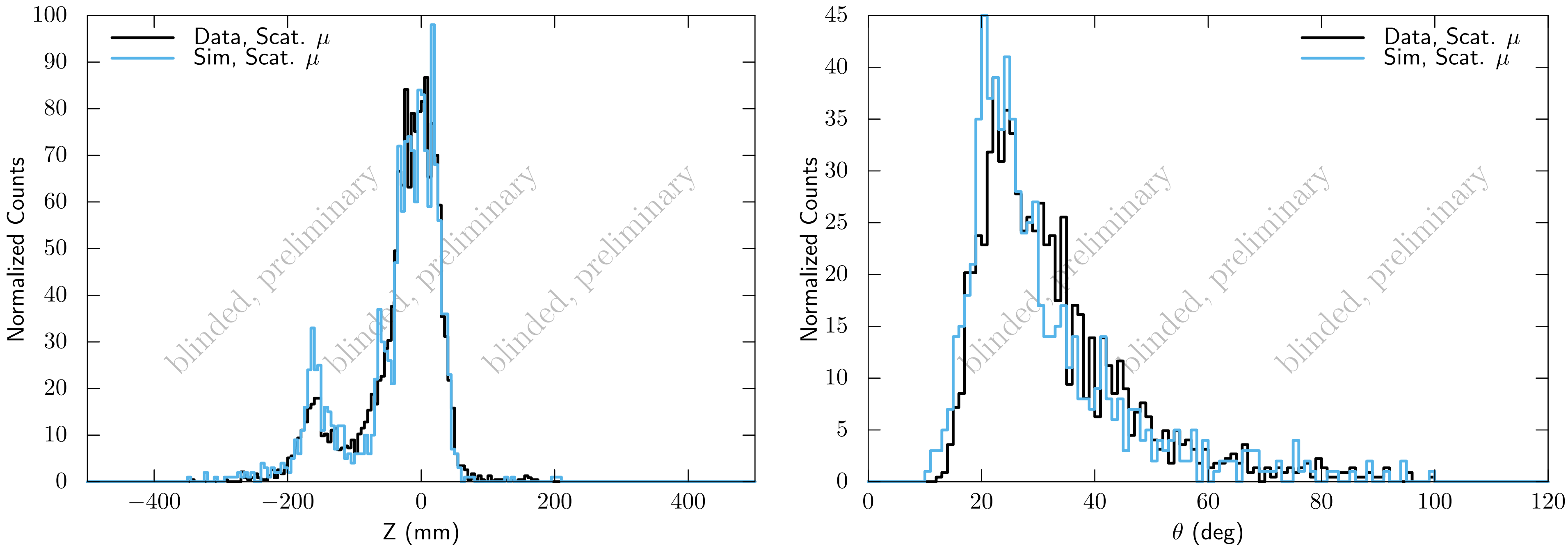
Muon beam decay events data vs sim





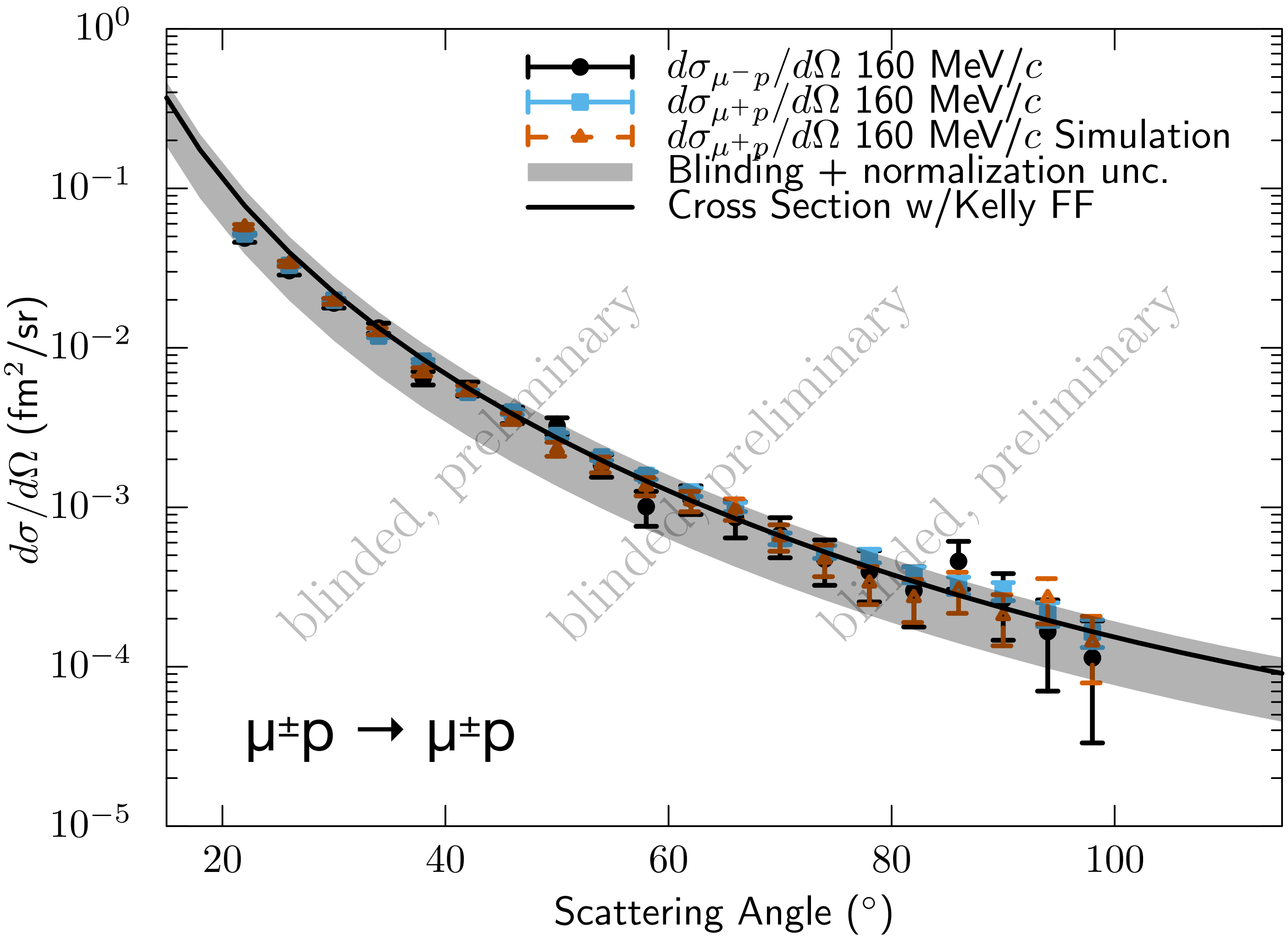
- ***p*** **= + 115 MeV/c; left: vertex; right: reconstructed angle**
- **Good agreement between data and simulation for muon beam decay-in-flight events**
- **Both data and simulation are blinded**

Muon scattering events data vs sim



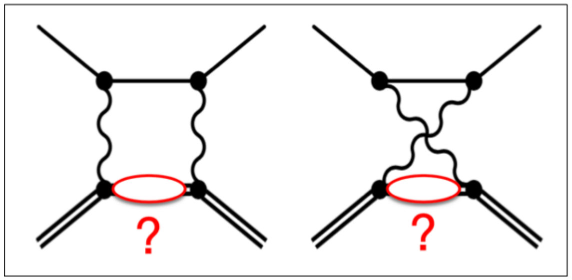
- ***p* = + 115 MeV/c; left: vertex; right: reconstructed angle**
- **Good agreement between data and simulation for muon scattering events**
- **Both data and simulation are blinded**
- **Similar findings for all data sets**
  $\mu^{\pm}$, $e^{\pm}$, $\pi^{\pm}$ @ 115, 160, 210 MeV/c

Preliminary cross sections at 160 MeV/c



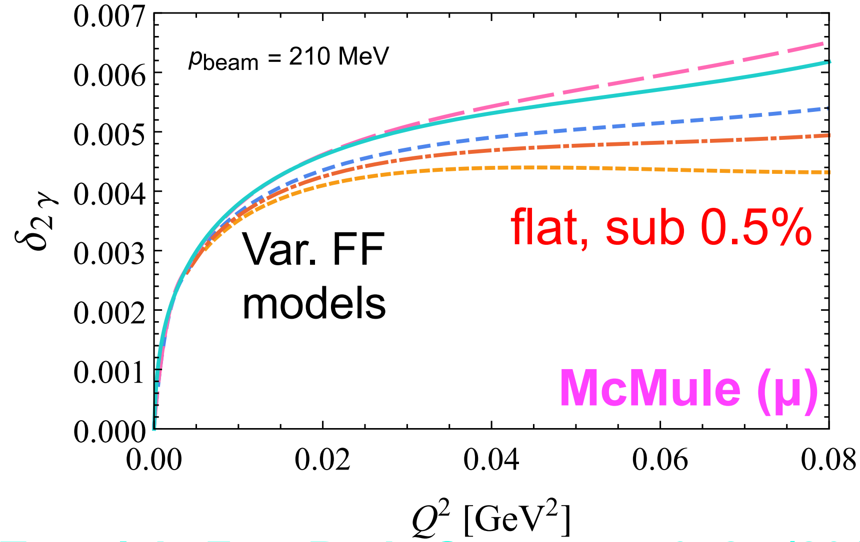
- **Preliminary analysis of 2023 $\mu^{\pm}p$ scattering data**
- ***p* = 160 MeV/c, target thickness experimentally determined**
- **Both data and simulation are blinded**

Two-photon exchange



$$\sigma^{\pm} = \sigma_{1\gamma}(1 \pm \delta_{2\gamma})$$

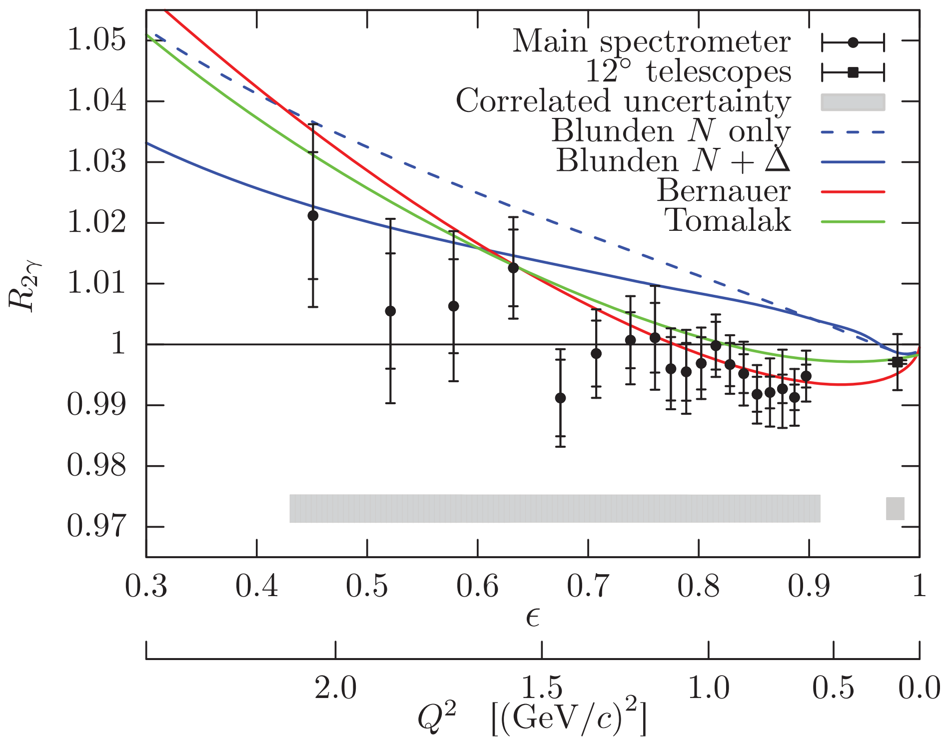
$$\frac{\sigma^{+}}{\sigma^{-}} \approx 1 + 2\delta_{2\gamma}$$



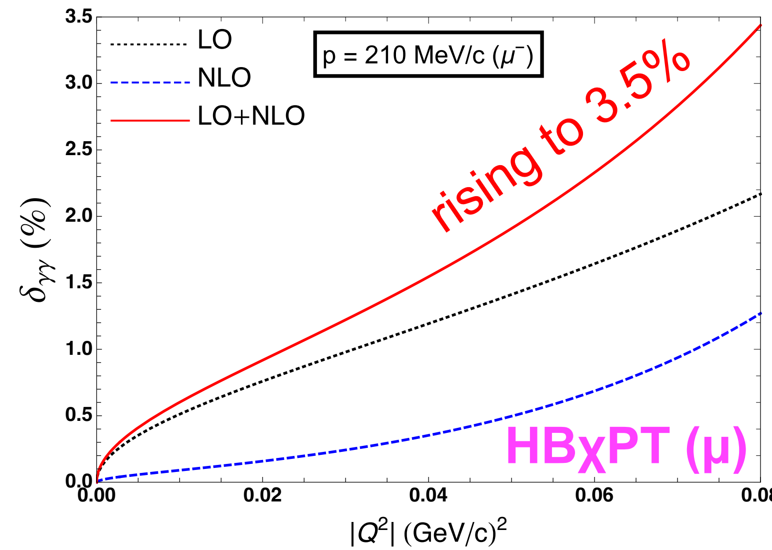
O. Tomalak, Few-Body Systems, 59, 87 (2018)

T. Engel, et al., Eur. Phys. J. A 59, 253 (2023)

TPE is the leading explanation for the proton form factor ratio discrepancy

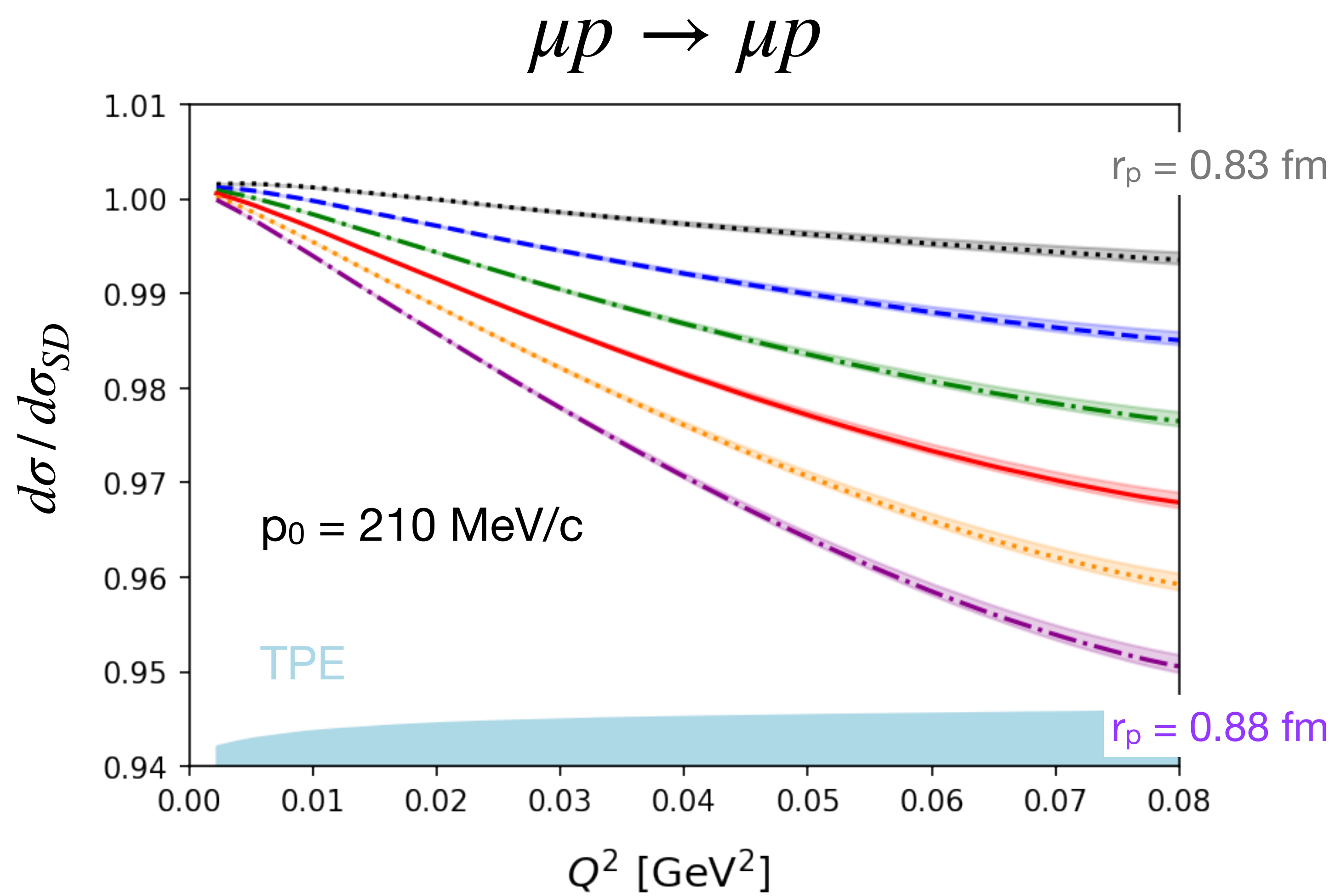


B.S. Henderson et al. [OLYMPUS], PRL 118, 092501 (2017)



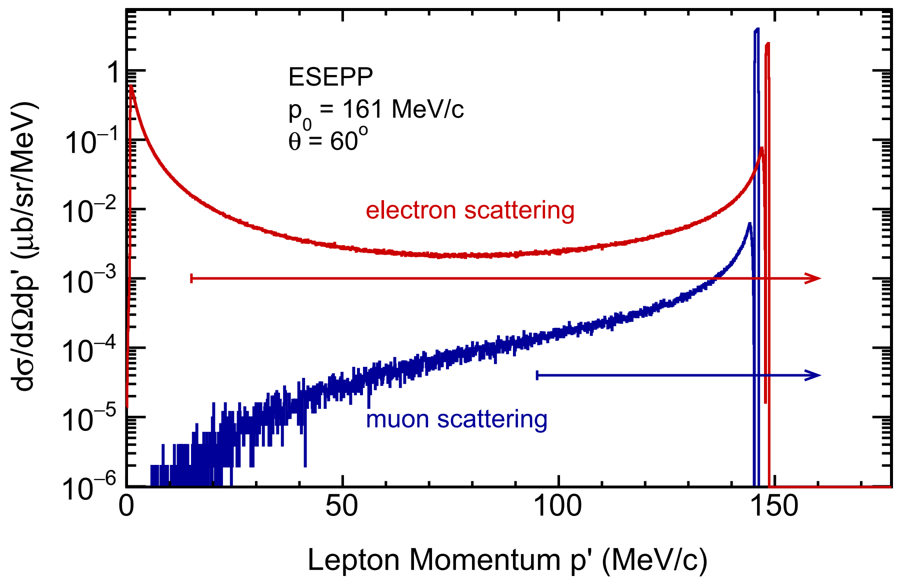
P. Choudhary, et al., EPJA 60, 69 (2024)

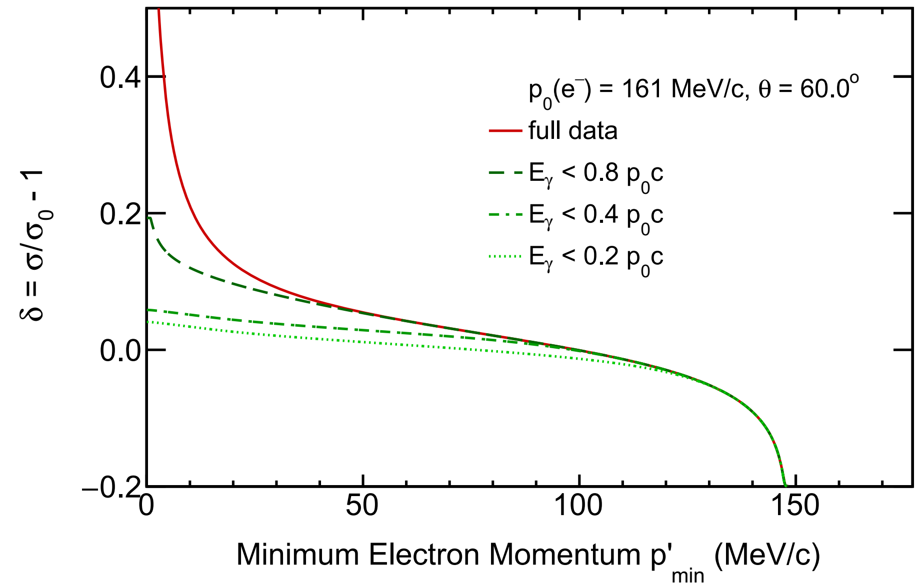
Extraction of radius from muon scattering



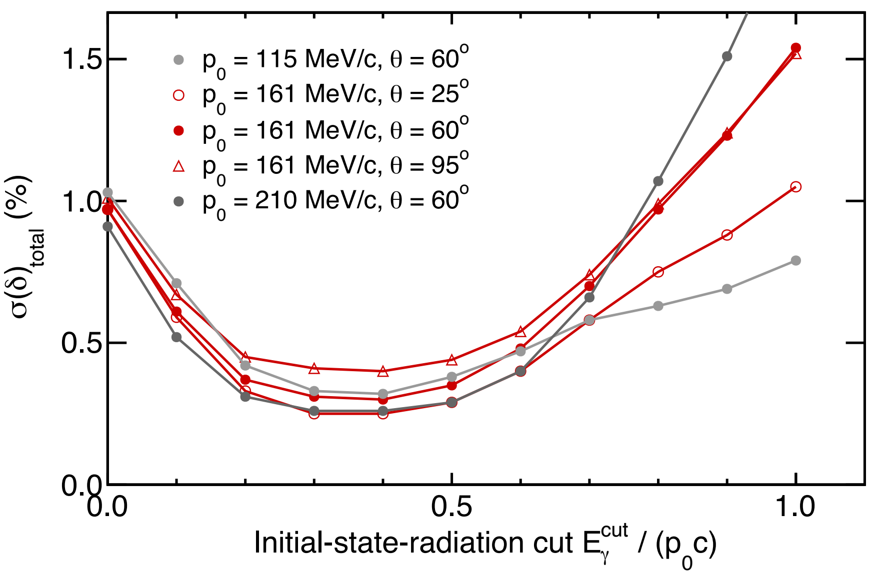
- **Dispersively improved chiral effective field theory:**
  F. Gil-Domingez, J.M. Alarcón, C. Weiss, PRD 108, 074026 (2023)
- **0.01 fm radius change → 0.9% cross sec. change at highest Q^2**
- **Largest MUSE systematic: Radiative corrections for *ep* → *ep***

MUSE can probe radiative corrections





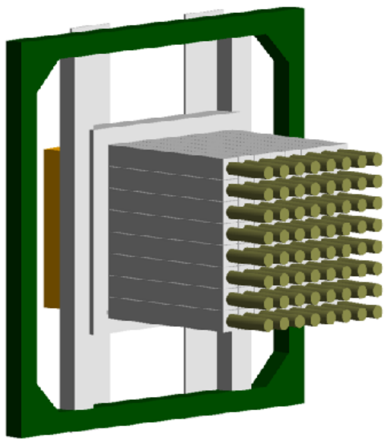
- **MUSE non-magnetic, $e^{\pm}$ detection threshold affects radiative correction**
- **Initial state radiation (ISR): detect & veto hard forward γ to reduce radcorr err.**



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

→ MUSE forward photon calorimeter to control ISR

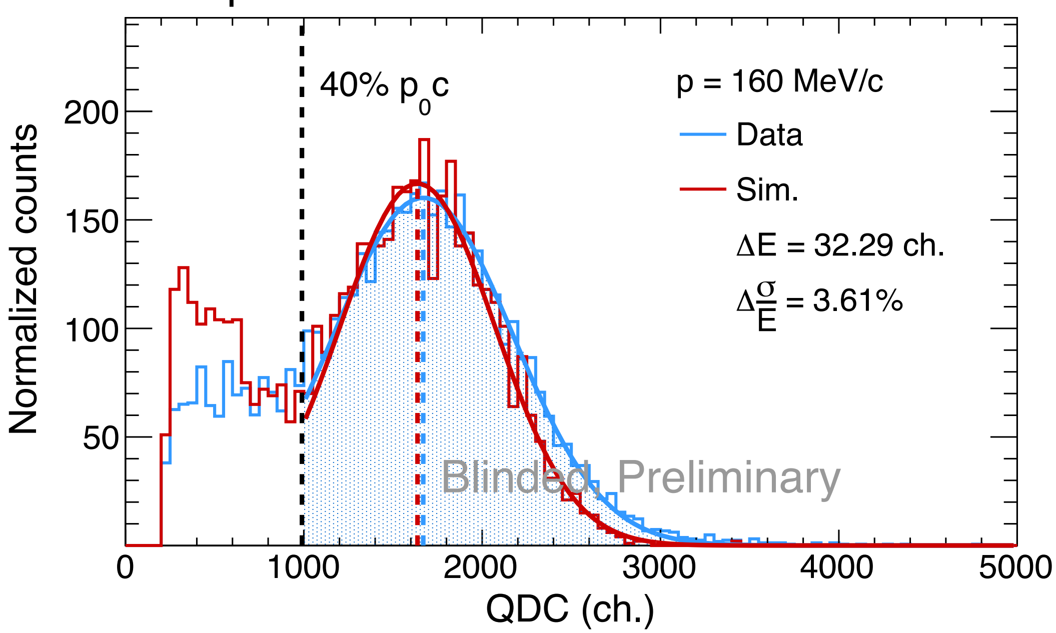
MUSE forward photon calorimeter

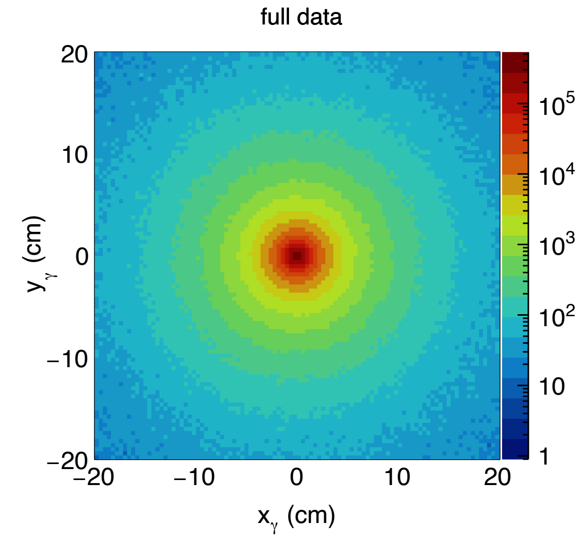


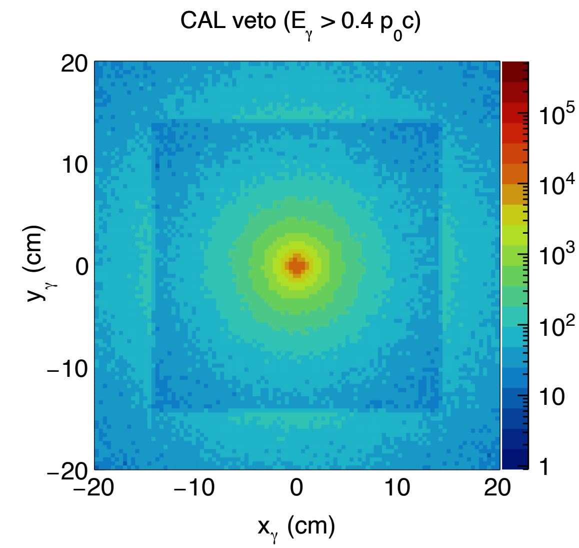
Geant4 rendering

CALO photos

CALO response measured and simulated:



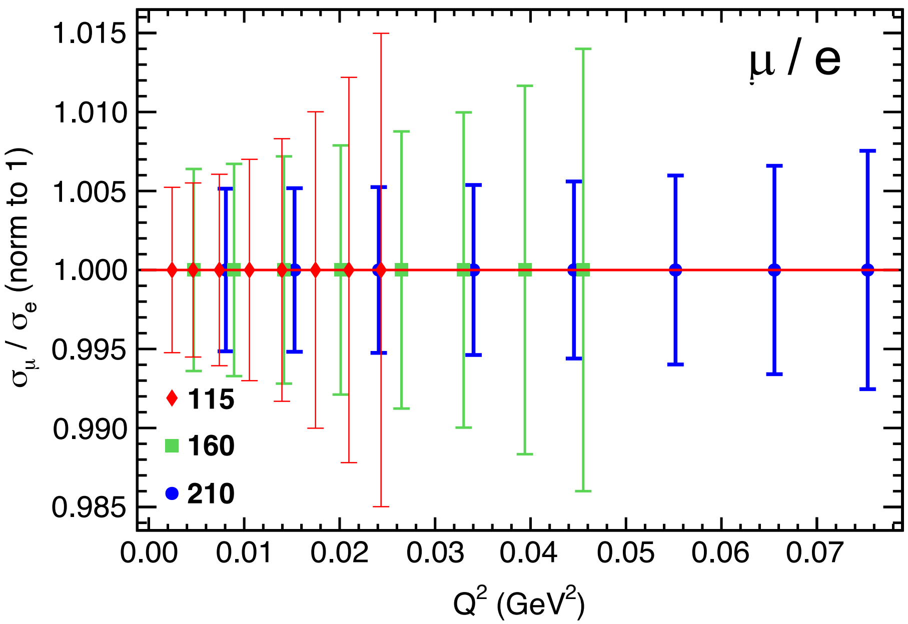


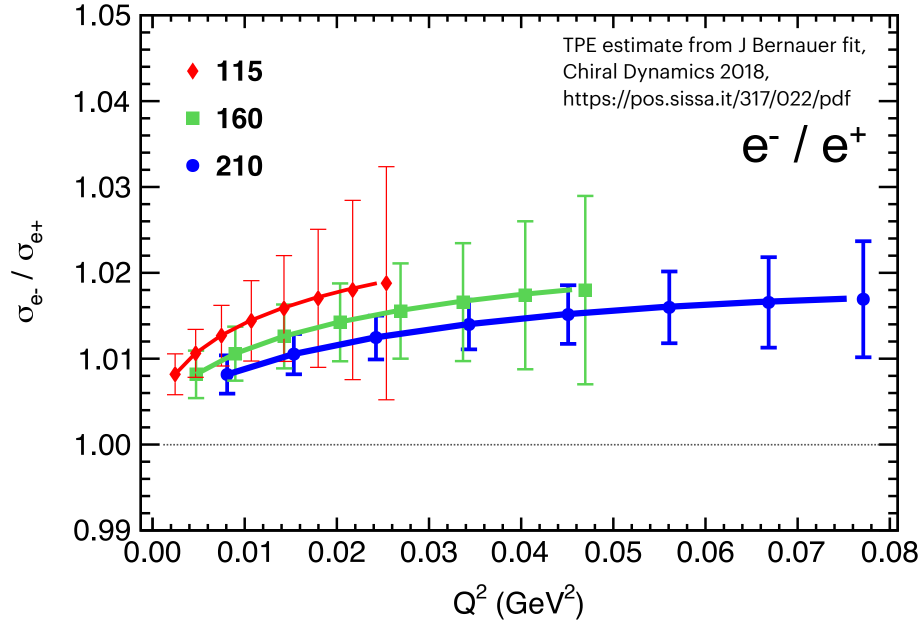


Simulated efficacy of hard photon veto

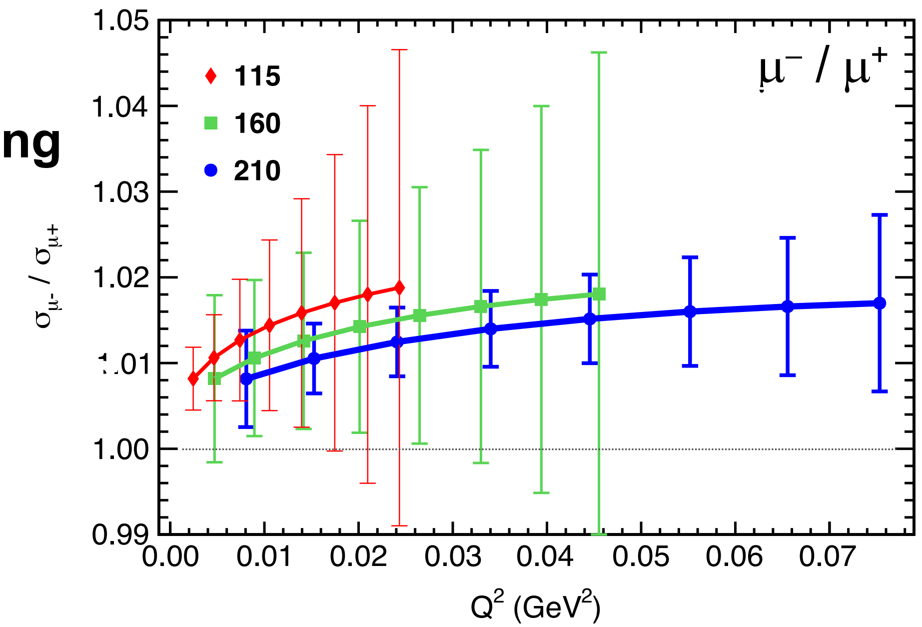
W. Lin et al. (MUSE Collaboration), arXiv:2408.13380 [physics.ins-det]

MUSE coverage and expected errors

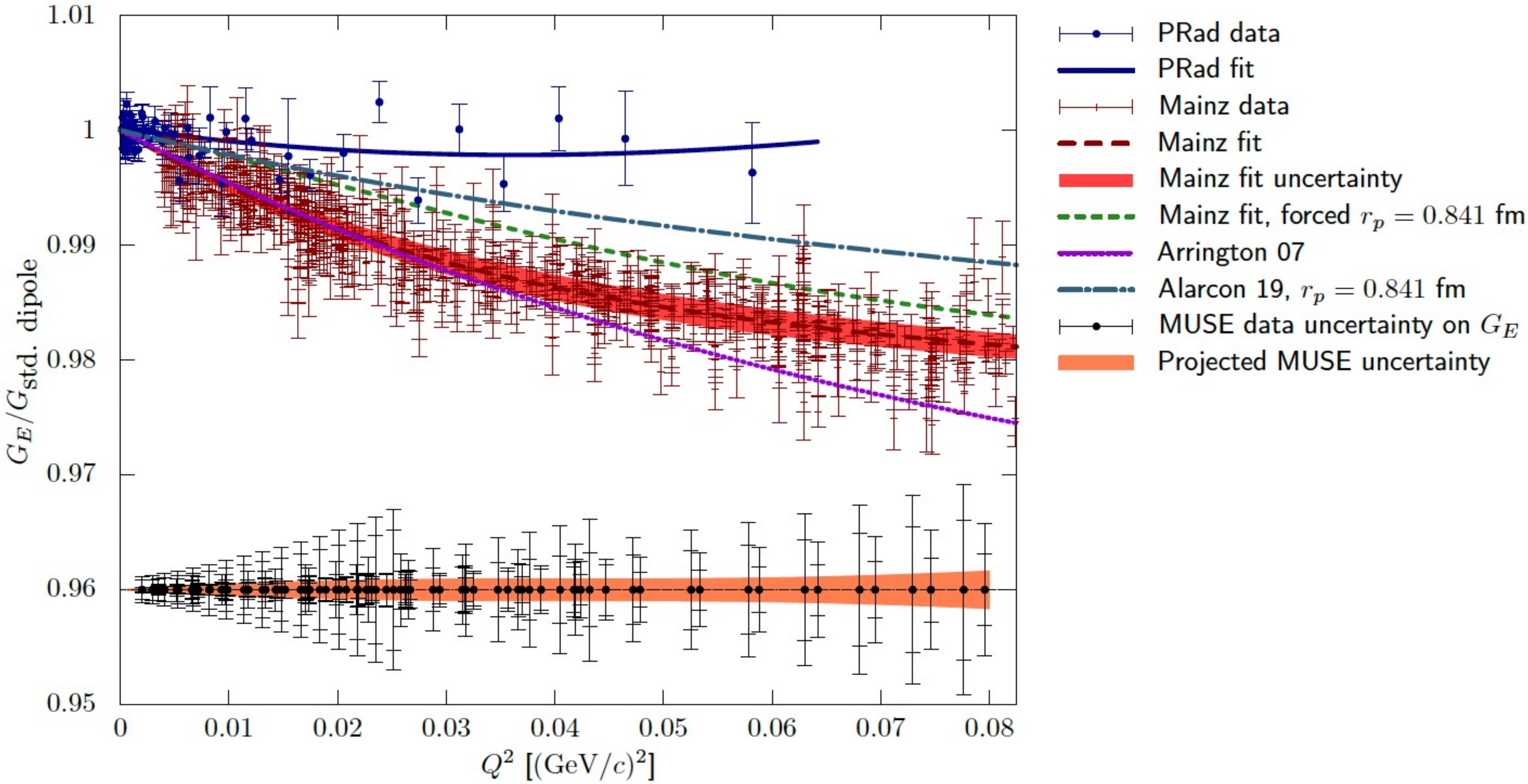




- **Stat. errors plotted, systematics <0.5%**
- **Based on assumption of 1 year of running**
- **~20% of scattering data taken in 2023**
- **Radius to 0.007 fm, R_μ–R_e to 0.005 fm**



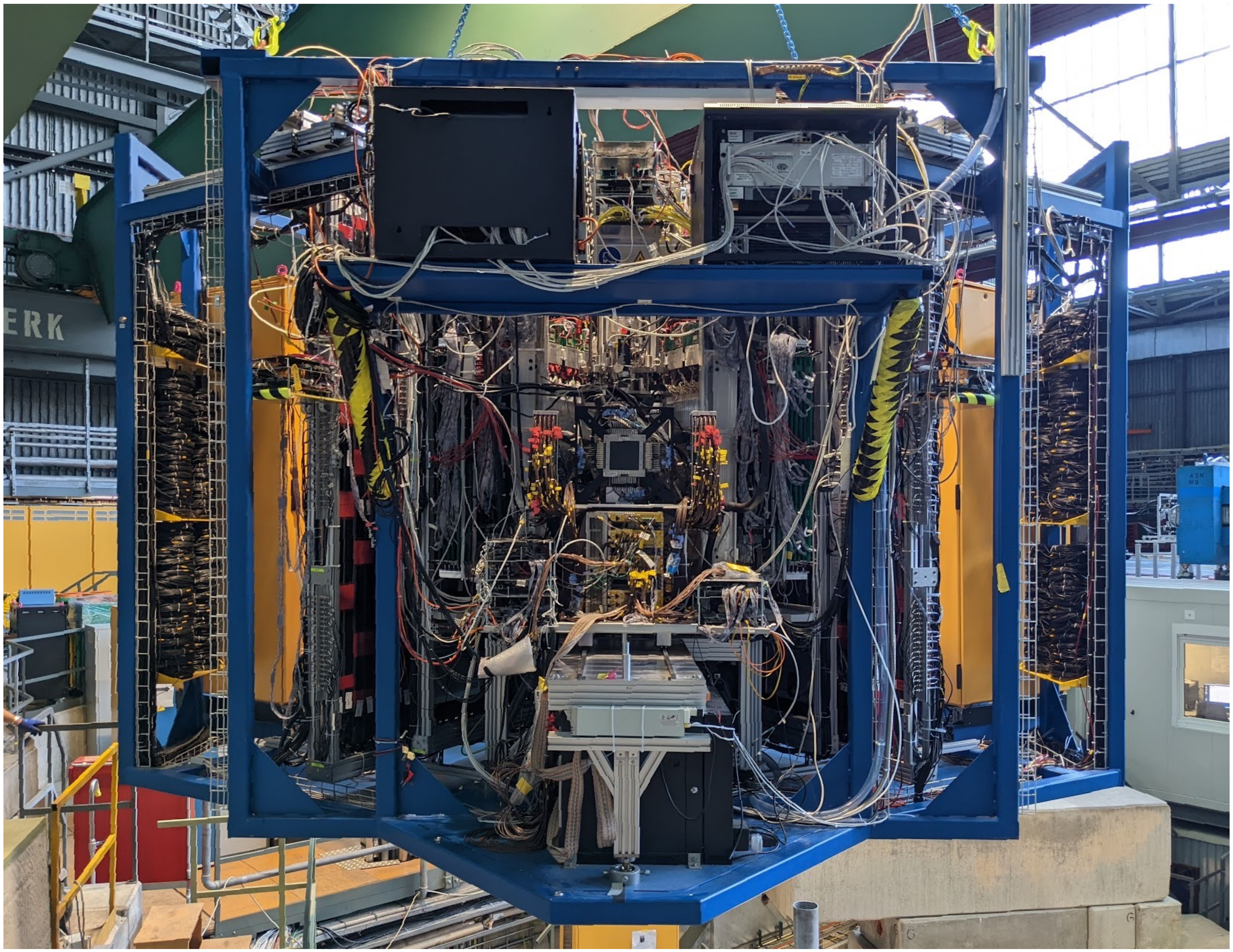
MUSE coverage and expected errors



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

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



Status of data collection

Year	LH2 (millions of events)	Empty (millions of events)	Total (millions of events)
2023	1,473.03	1,260.49	2,733.52
2024	2,259.24	1,556.74	3,815.98

- **In 2023, MUSE started production data taking, anticipated for 12 beam months over 2 years**
- **MUSE aims for ~12 billion events, with a 60/40 split between LH2/Empty Cell scattering events**
- **Continued taking data in 2024**
- **Aim to finish 2025**

MUon Scattering Experiment – MUSE

75 MUSE collaborators from 23 institutions in 5 countries:

A. Afanasev, A. Akmal, M. Ali, A. Atencio, J. Arrington, H. Atac, C. Ayerbe-Gayoso, F. Benmokhtar, K. Bailey, N. Benmouna, J. Bernauer, W.J. Briscoe, T. Cao, D. Cioffi, E. Cline, D. Cohen, E.O. Cohen, C. Collicott, K. Deiters, J. Diefenbach, S. Dogra, E.J. Downie, I. Fernando, A. Flannery, T. Gautam, D. Ghosal, R. Gilman, A. Golossanov, R. Gothe, D. Higinbotham, J. Hirschman, D. Hornidge, Y. Ilieva, N. Kalantarians, M.J. Kim, M. Kohl, O. Koshchii, G. Korcyl, K. Korcyl, B. Krusche, I. Lavrukhin, L. Li, J. Lichtenstadt, W. Lin, A. Liyanage, W. Lorenzon, K.E. Mesick, Z. Meziani, P. M. Murthy, J. Nazeer, T. O'Connor, P. Or, M. Paolone, T. Patel, E. Piasetzky, R. Ransome, R. Raymond, D. Reggiani, H. Reid, P.E. Reimer, R. Richards, A. Richter, G. Ron, P. Roy, T. Rostomyan, P. Salabura, A. Sarty, Y. Shamai, N. Sparveris, S. Strauch, N. Steinberg, V. Sulkosky, A.S. Tadepalli, M. Taragin, and N. Wuerfel

PAUL SCHERRER INSTITUT

PSI

MUSE

George Washington University, Montgomery College, Argonne National Lab, Temple University, Duquesne University, Stony Brook University, Rutgers University, Hebrew University of Jerusalem, Tel Aviv University, University of Basel, Paul Scherrer Institute, Johannes Gutenberg-Universität, Hampton University, University of Michigan, University of South Carolina, Jefferson Lab, Massachusetts Institute of Technology, New Mexico State University, Technical University of Darmstadt, St. Mary's University, Soreq Nuclear Research Center, Weizmann Institute, Old Dominion University (March 2024)

Other MUSE publications

- 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

Summary

- PRP not resolved after 14 years
- 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, tensions
- 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)
  – 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

Thank you for a beautiful conference !