Physics from MUSE: Beyond the Radius

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GHP April Meeting 2021

Funding acknowledgment: This material is based upon work supported by the National Science Foundation under Grant No. PHY 1614456 and 2012114. The MUSE experiment is supported by Stony Brook University, the Department of Energy, NSF, PSI, and the US-Israel Binational Science Foundation.

April 13, 2021

MUon proton Scattering Experiment

72 MUSE collaborators from 25 institutions in 5 countries:

A. Afanasev, A. Akmal, A. Atencio, J. Arrington, H. Atac, C. Ayerbe-Gayoso, F. Benmokhtar, K. Bailey, N. Benmouna, J. C. 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, T. Patel, E. Piasetzky, R. Ransome, R. Raymond, D. Reggiani, H. Reid, P.E. Reimer, 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

George Washington University, Montgomery College, Argonne National Lab, Temple University, College of William & Mary, Duquesne University, Massachusetts Institute of Technology, Christopher Newport University, Rutgers University, Hebrew University of Jerusalem, Tel Aviv University, Paul Scherrer Institut, Johannes Gutenberg-Universität, Hampton University, University of Michigan, University of Virginia, University of South Carolina, Jefferson Lab, Los Alamos National Laboratory, Norfolk State University, Technical University of Darmstadt, St. Mary's University, Soreq Nuclear Research Center, Weizmann Institute, Old Dominion University

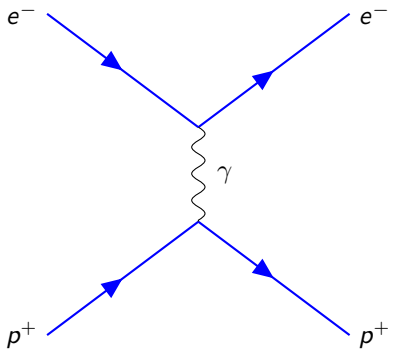
Measuring the Proton Radius with Elastic Scattering

Historically r_p measured via ep scattering

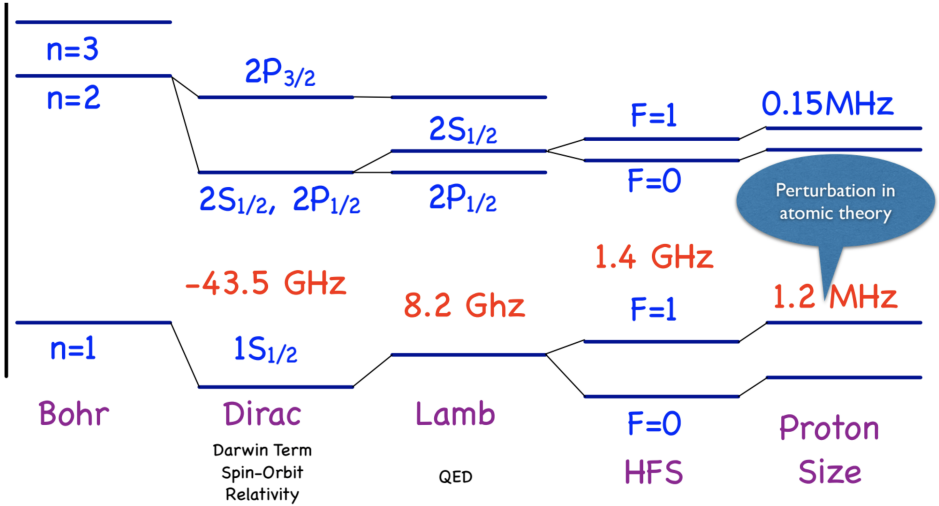
$$\left(\frac{d\sigma}{d\Omega}\right)_{red} = \epsilon G_E^2(Q^2) + \tau G_M^2(Q^2)$$

- G_E related to charge distribution, $G_E(0) = 1$
- G_M related to magnetic distribution, $G_M(0) = \mu_p$

$$\langle r_p^2 \rangle \equiv -6 \frac{dG_E(Q^2)}{dQ^2}\bigg|_{Q^2=0}$$

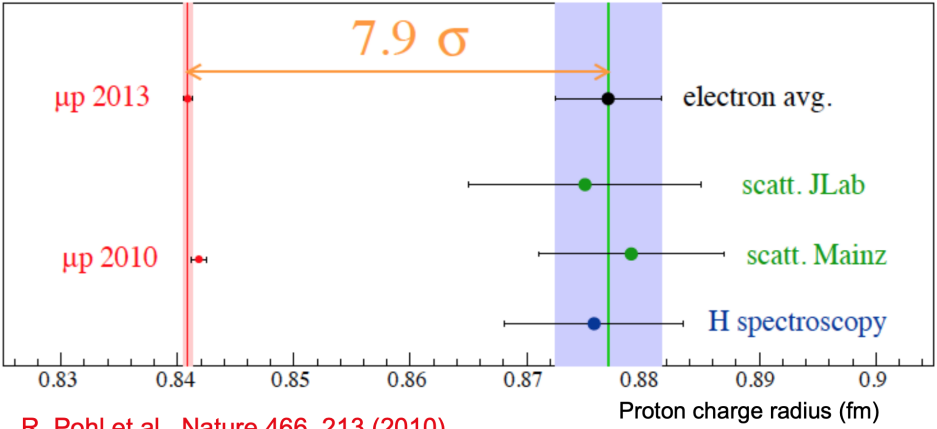


Measuring the Proton Radius with Spectroscopy



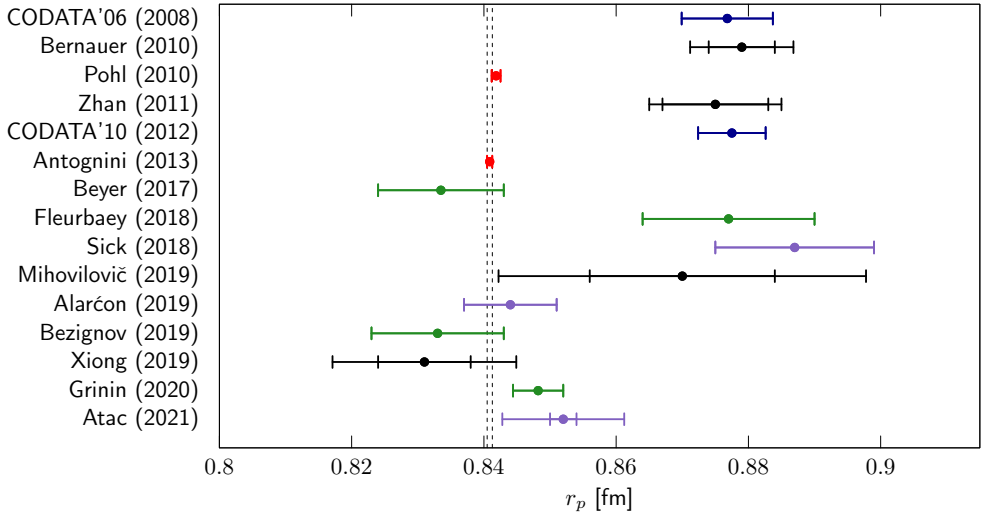
The Original Proton Radius Puzzle

electrons: 0.8770 ± 0.0045 fm (CODATA2010+Zhan et al.)
muons: 0.8409 ± 0.0004 fm



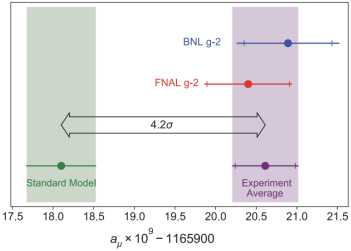
R. Pohl et al., Nature 466, 213 (2010)
A. Antognini et al., Science 339, 417 (2013)

The Puzzle Deepens

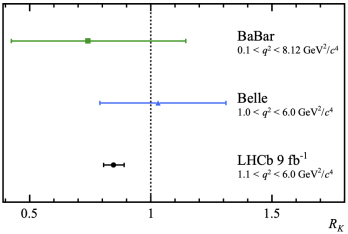


Possible Explanations

- Beyond the standard model physics
- Two photon exchange/hadronic structure effect
- Extrapolation Uncertainty
- Experimental Error



https://doi.org/10.1103/PhysRevLett.126.141801



https://arxiv.org/pdf/2103.11769.pdf

What's the Next Experiment?

r_p (fm)	ep	μp
Spectroscopy	0.877 ± 0.007	0.841 ± 0.0004
Scattering	0.875 ± 0.006	**??**

- No high precision muon-proton scattering experiment to date
- Highly desirable to perform another electron-proton scattering experiment
- Measure two-photon exchange in muons and electrons
- MUSE!

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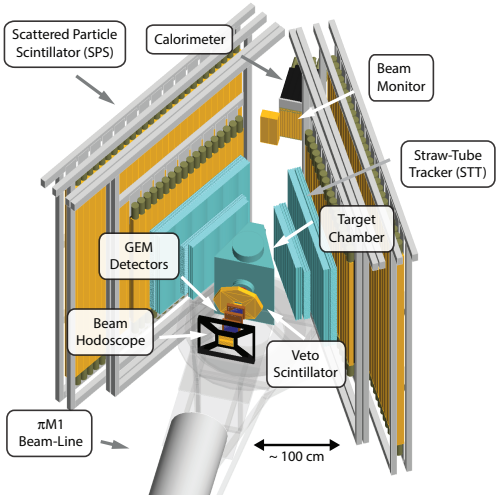
Paul Scherrer Institute

- HIPA provides 590 MeV protons
- 2.2 mA current
- World's most powerful continuous proton beam
- PiM1 secondary beam line

MUSE



- Secondary beam line with e's, μ's, and π's
- Can select positive or negative charge polarities
- Measure incoming beam event by event
- Use RF signal for PID
- Veto π's in the trigger, accept e's and μ's
- Active Veto to reject decay events

T. Rostomyan *et al.*, *Timing Detectors with SiPM read-out for the MUSE Experiment at PSI*, NIM A
P. Roy *et al.*, *A Liquid Hydrogen Target for the MUSE Experiment at PSI*, NIM A

Kinematics of MUSE

Quantity	Coverage
Beam momenta	115, 160, 210 MeV/c
Scattering angle range	20° - 100°
Azimuthal coverage	30% of 2π typical
ε	$0.26 - 0.94$
Q^2 range for electrons	0.0016 GeV^2 - 0.0820 GeV^2
Q^2 range for muons	0.0016 GeV^2 - 0.0799 GeV^2

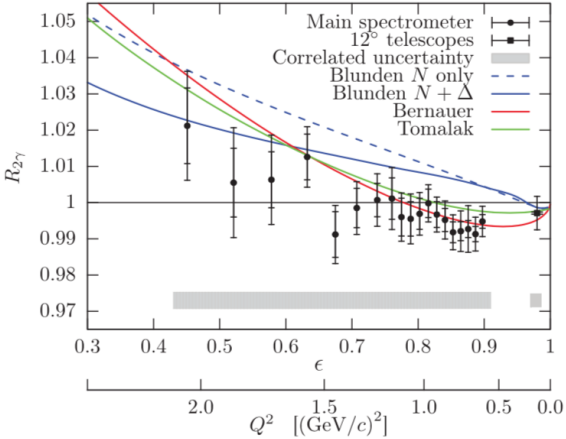
- Simultaneous elastic ep and μp scattering $\rightarrow$ can test lepton universality
- Can measure both lepton charge polarities $\rightarrow$ direct test of two photon exchange effect
- Some systematic uncertainties cancel in comparisons
- Precisely capture difference in cross sections and in radii

Physics Coverage of MUSE

- First high precision measurement of μp scattering for TPE and at precision necessary to inform PRP
- Direct comparison between ep and μp scattering at cross section level to test rad. corr. and lepton universality
- Low energy πp scattering important for χPT
- Search for $\sigma(\pi^+ p)/\sigma(\pi^- p)$ resonances

Measured Two Photon Effect

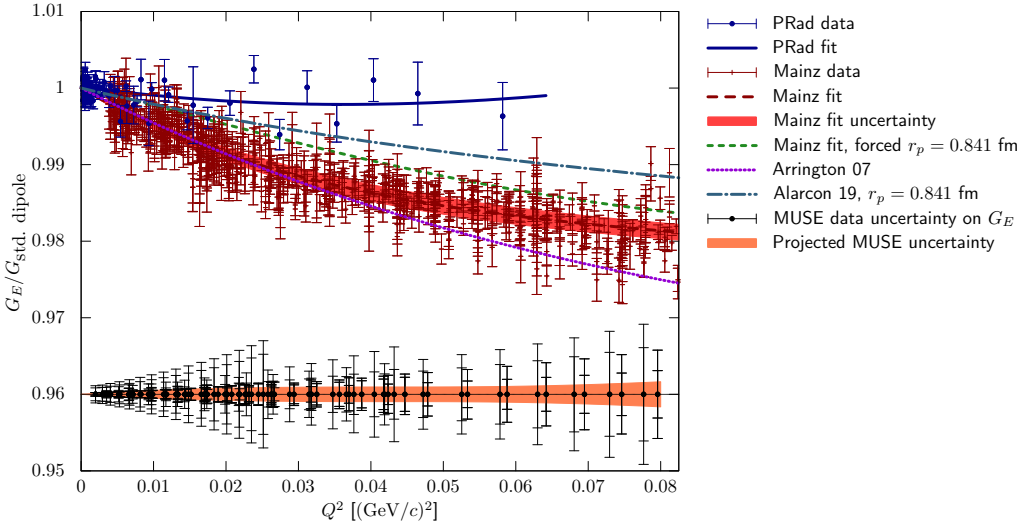
- TPE leading explanation for proton form factor ratio discrepancy
- CLAS-12, VEPP-3, OLYMPUS
- More data needed
- MUSE covers wide ϵ range, smaller Q^2 range



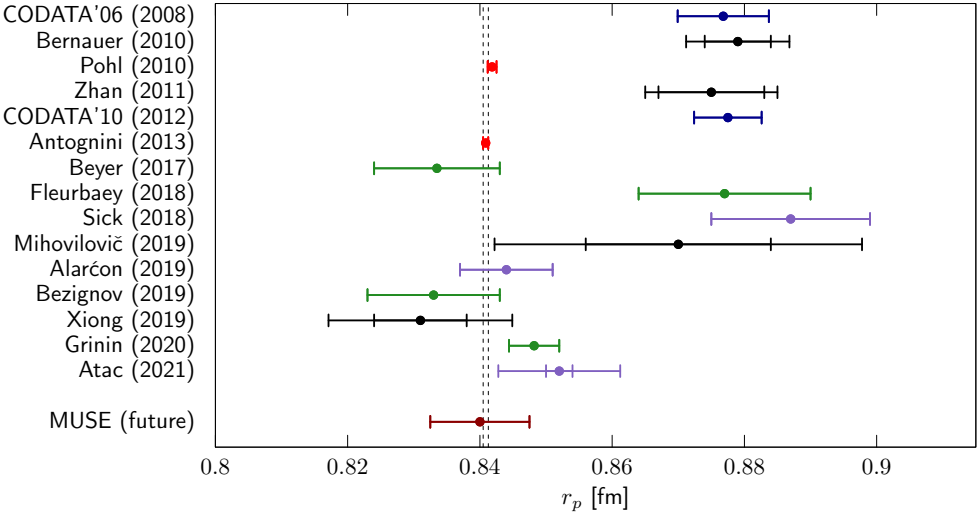
OLYMPUS $R_{2\gamma} = \sigma_{e^+}/\sigma_{e^-}$ measurement*.

*B. S. Henderson *et al.* (OLYMPUS Collaboration) Phys. Rev. Lett. 118, 092501 – Published 3 March 2017

Projected Resolution of MUSE



Projected Resolution of MUSE



MUSE value arbitrarily placed at 0.84 fm for visualization

Current Status

- Proton Radius Puzzle remains unsolved
- MUSE uniquely suited to address the puzzle
- MUSE can precisely measure difference between extracted radii
- Wide variety of interesting physics possible
- Two recent theses: E. C. (beam properties), I. Lavrukhin (pion scattering)

T. Rostomyan *et al.*, *Timing Detectors with SiPM read-out for the MUSE Experiment at PSI*, https://doi.org/10.1016/j.nima.2020.164801

P. Roy *et al.*, *A Liquid Hydrogen Target for the MUSE Experiment at PSI*, https://doi.org/10.1016/j.nima.2019.162874

R. Gilman *et al.*, *Technical Design Report for the Paul Scherrer Institute Experiment R-12-01.1: Studying the Proton "Radius" Puzzle with μp Elastic Scattering*, https://arxiv.org/abs/1709.09753

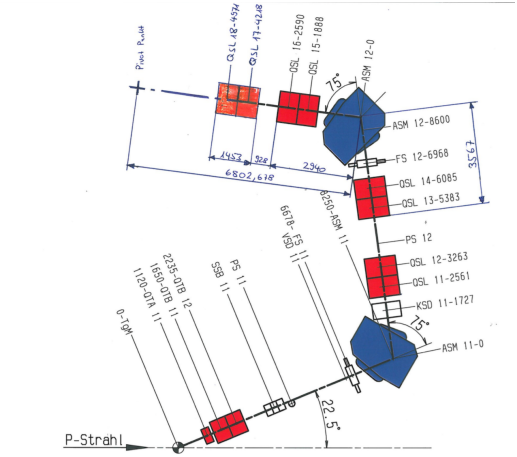
E. O. Cohen *et al.*, *Development of a scintillating-fiber beam detector for the MUSE experiment*, https://doi.org/10.1016/j.nima.2016.01.044

Back up

Required Systematic Uncertainties on Cross Section

Uncertainty	angular distribution (%)	μ/e (%)	$+/-$ (%)
Detector efficiencies	0.1	0.1	0.1
Solid angle	0.1	small	small
Scattering angle offset	0.2	small	small
Multiple scattering	0.15	small	small
Beam momentum offset	0.1	0.1	0.1
Radiative correction	0.1 (μ), 0.5 (e)	0.5	1γ small
Magnetic contribution	0.15	small	small
Subtraction of μ decay	0.1	0.1	small
Target Subtraction	0.3	small	small
Beam PID	0.1	0.1	0.1
TOTAL	0.5 (μ), 0.7 (e)	0.5	0.2

PiM1 Secondary Beam Line

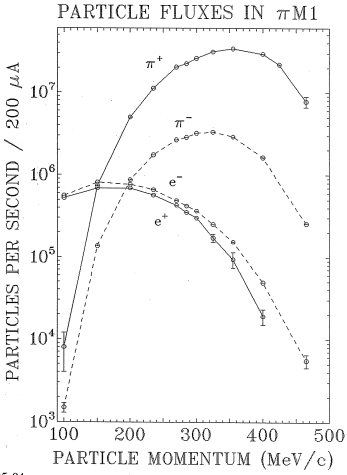


Distanz	Target M → Pivot Punkt	23'652,678
Distanz	Eintritt QSL 18 → Pivot Punkt	10'369,678
Distanz	Eintritt QSL 18 → Austritt QSL 18	8'888

PiM 1

- Designed as pion beam line
- Muons from weak decays $\pi^{\pm} \to \mu^{\pm}\nu_{\mu}$
- Electrons from $\pi^0 \to \gamma\gamma$ followed by $\gamma C \to e^+e^-X$ and Dalitz decays $\pi^0 \to e^+e^-\gamma$
- Pions and electrons have point-like source
- Muons have an extended source size
- Intermediate Focal Point (IFP) (PS-12)
  - 7cm/% dispersion in x
  - 21 cm wide
  - Can select momentum bite with copper collimator

Particle Flux



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PiM1 TRANSPORT