

Understanding the Proton with MUSE

Ethan Cline

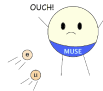
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Cambridge, MA

MENU 2026

This work is supported by the National Science Foundation, grants PHY-2012114 and 2412703 to Stony Brook University. The MUSE experiment is supported by the U.S. Department of Energy, the U.S. National Science Foundation, the Paul Scherrer Institute, and the US-Israel Binational Science Foundation.

October 20, 2026



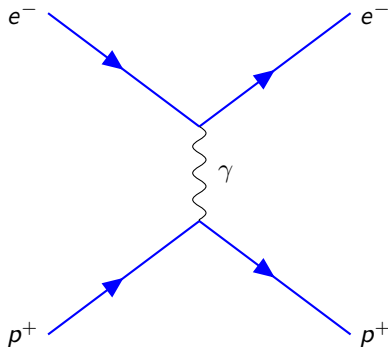
Measuring the Proton Radius with Elastic Scattering

Historically r_p measured via ep scattering

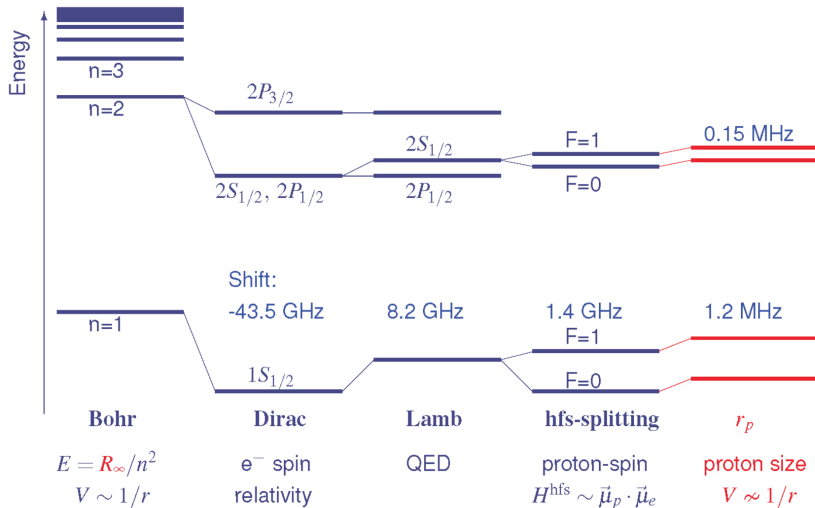
$$\left(\frac{d\sigma}{d\Omega}\right)_{red} = \frac{\tau}{\epsilon(1+\tau)} [G_M^2(Q^2) + \frac{\epsilon}{\tau} G_E^2(Q^2)]$$

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

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

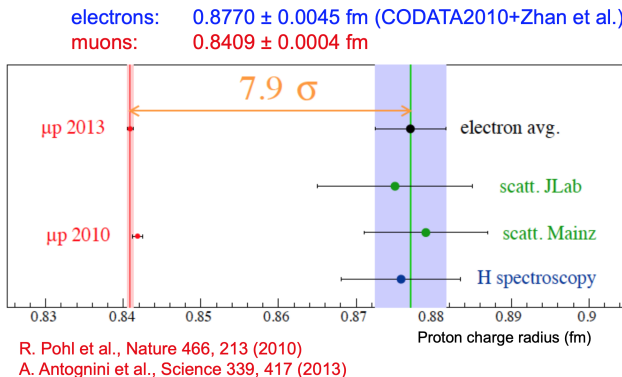


Spectroscopic Measurements



Energy levels in Hydrogen

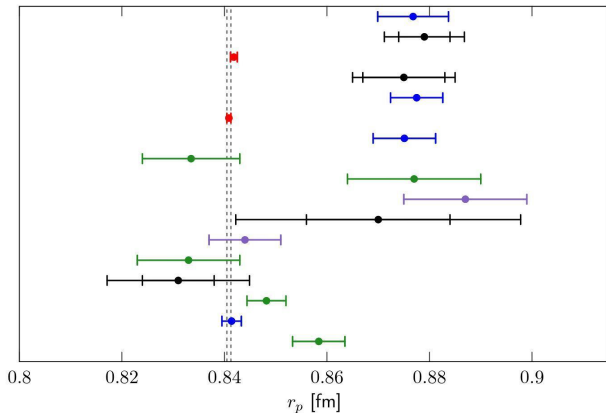
The Original Proton Radius Puzzle



“Although the uncertainty of the muonic hydrogen value is significantly smaller than the uncertainties of these other values, its negative impact on the internal consistency of the theoretically predicted and experimentally measured frequencies . . . was deemed so severe that the only recourse was to not include it in the final least-squares adjustment on which the 2010 recommended values are based.” -

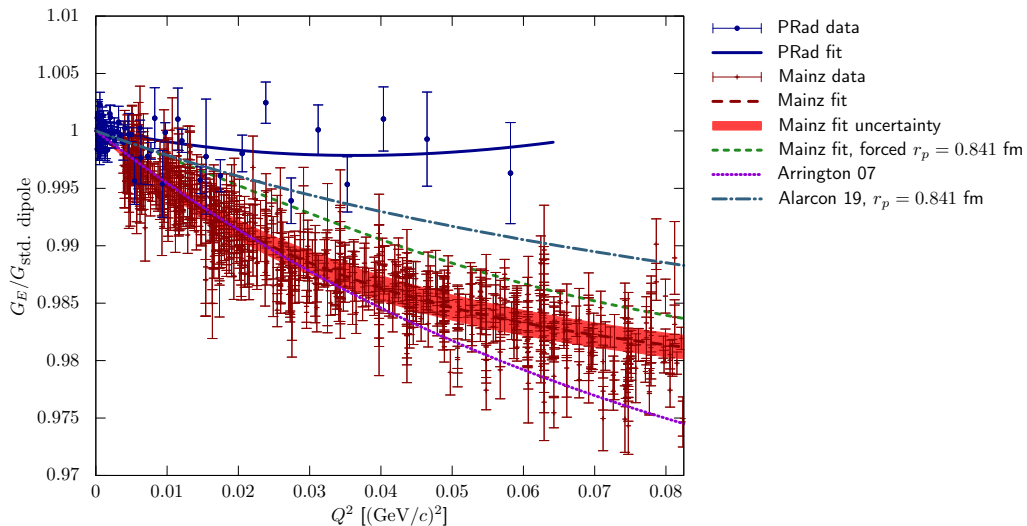
<https://physics.nist.gov/cuu/Constants/Preprints/lsa2010.pdf>

The Puzzle Deepens



CODATA'06 (2008)
Bernauer (2010)
Pohl (2010)
Zhan (2011)
CODATA'10 (2012)
Antognini (2013)
CODATA'14 (2015)
Beyer (2017)
Fleurbaey (2018)
Sick (2018)
Mihovilović (2019)
Alarcón (2019)
Bezginov (2019)
Xiong (2019)
Grinin (2020)
CODATA'18 (2021)
Brandt (2022)

PRad Compared to Mainz



What's the Next Experiment?

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

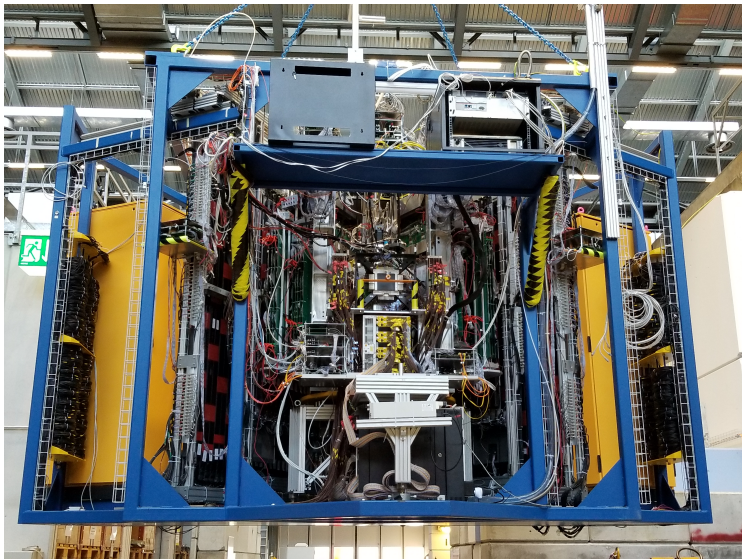
- No high precision muon-proton scattering experiment to date
- Highly desirable to perform another electron-proton scattering experiment
- Measure two-photon exchange in muons and electrons
- MUSE!

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MUSE

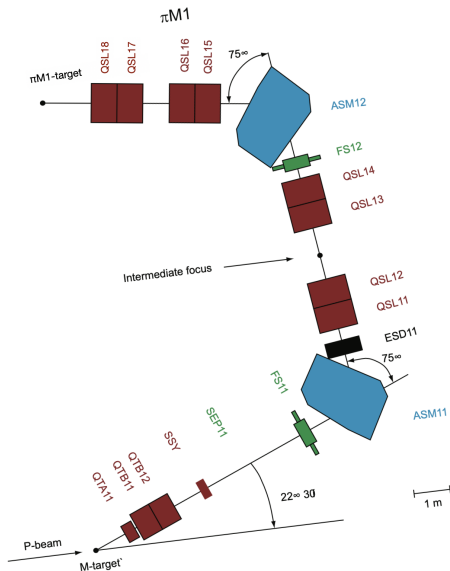


Paul Scherrer Institute



- High-Intensity Proton Accelerator provides 590 MeV protons
- 2.2 mA current
- PiM1 secondary beam line

PiM1 Secondary Beam Line



- Simulated in G4beamline and TURTLE
- Muons from weak decays $\pi^\pm \rightarrow \mu^\pm \nu_\mu$
- Electrons from $\pi^0 \rightarrow \gamma\gamma$ followed by $\gamma C \rightarrow e^+e^-X$ and from Dalitz decays $\pi^0 \rightarrow e^+e^-\gamma$
- Pions and electrons have point-like source
- Muons have an extended source size
- Intermediate Focal Point (IFP)
 - 7cm/% dispersion in x
 - 21 cm wide
 - Can select momentum bite with copper collimator

MUSE

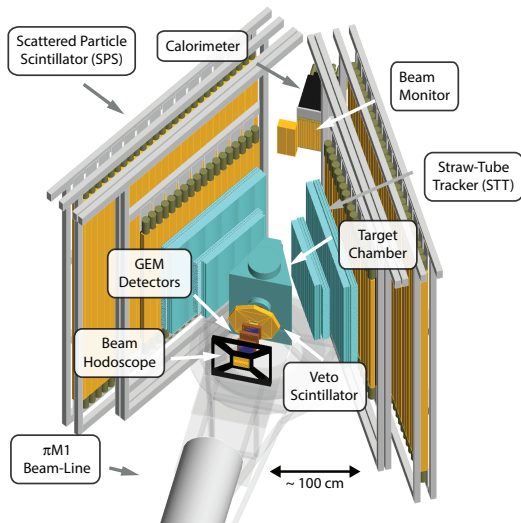


Figure from S. Strauch

- Secondary beam line

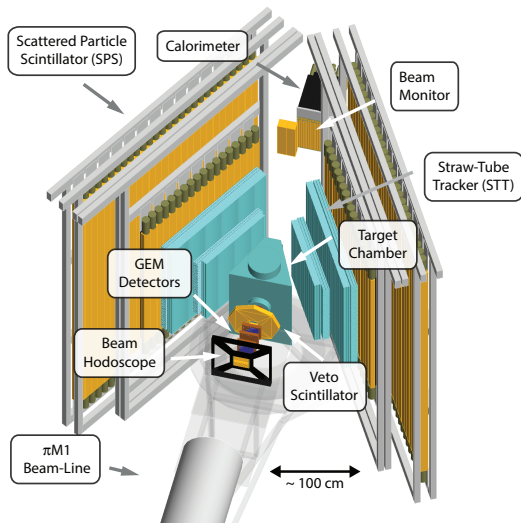


Figure from S. Strauch

MUSE

- Secondary beam line
- Measure incoming beam event by event

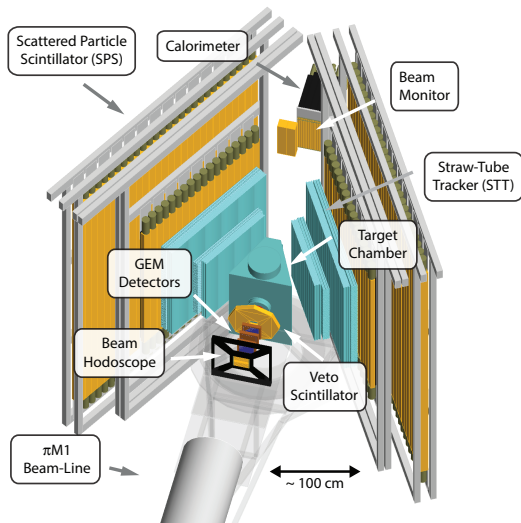


Figure from S. Strauch

MUSE

- Secondary beam line
- Measure incoming beam event by event
- Beam contains e 's, μ 's, and π 's

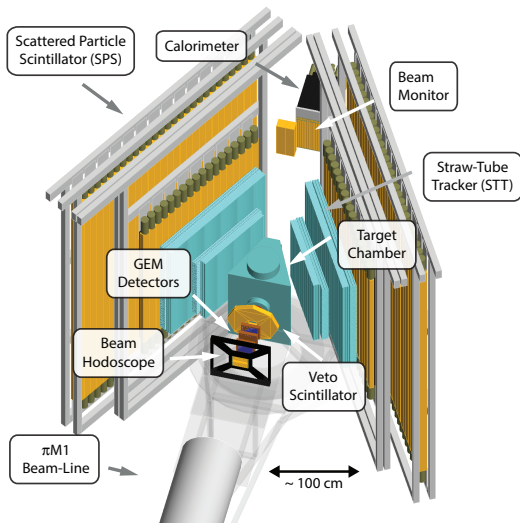


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MUSE

- Secondary beam line
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- Beam contains e 's, μ 's, and π 's
- Can select positive or negative charge polarities

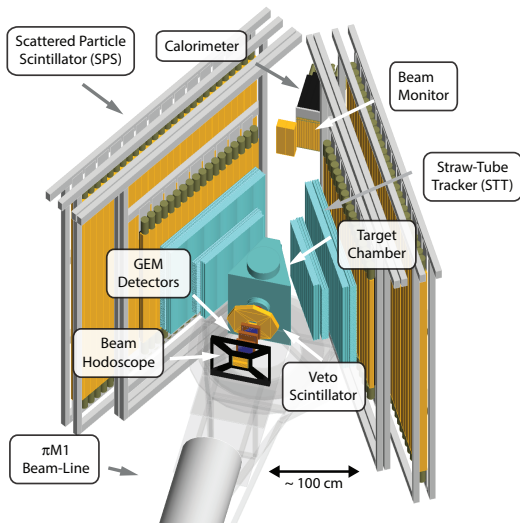
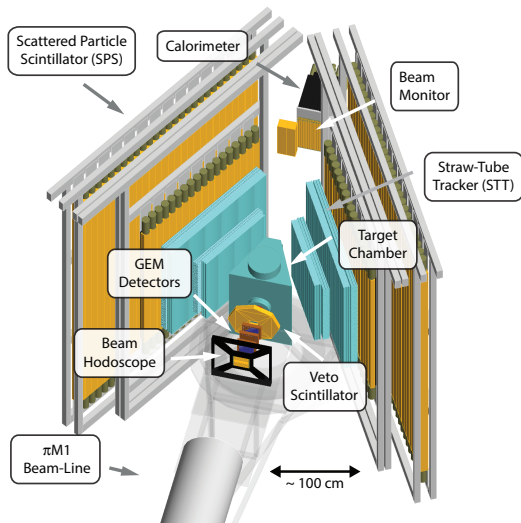


Figure from S. Strauch

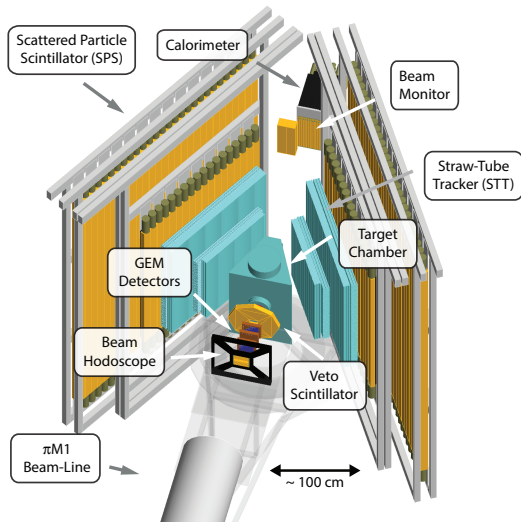
MUSE



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- Beam contains e 's, μ 's, and π 's
- Can select positive or negative charge polarities
- Veto to reject beam halo and decay events

Figure from S. Strauch

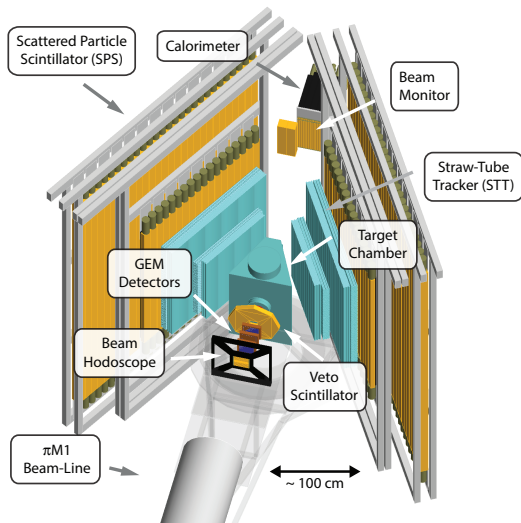
MUSE



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Figure from S. Strauch

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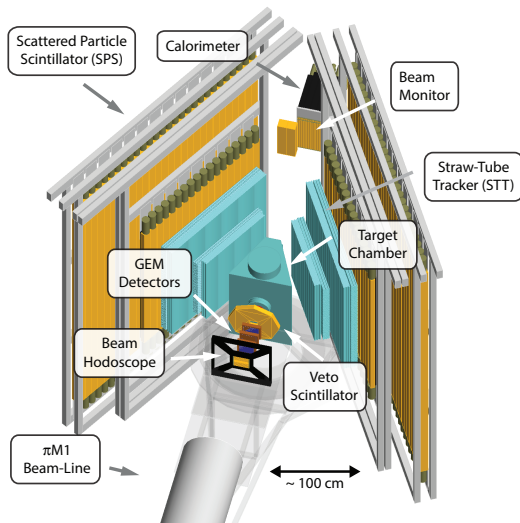
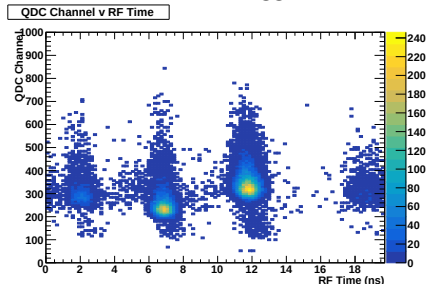


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Kinematics of MUSE

Quantity	Coverage
Beam momenta	115, 160, 210 MeV/c
Scattering angle range	$20^\circ - 100^\circ$
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

What has MUSE Measured?

- Data taking from 2022 - 2025
- All statistics have been acquired, final systematic studies last summer
- Blinded analysis underway

What do we Blind?

What do we blind?

- Proton charge radius
- Cross sections
 - $e^{\pm}$, $\mu^{\pm}$, and $\pi^{\pm}$
- Cross section ratios
 - Data and simulation

How do we blind?

- Protect CPU intensive parts of the analysis - tracking
- Encrypt scattered tracks with an angular dependence
- Encrypted tracks are secured by three public/private key pairs
 - Key pairs are taken from senior members of the collaboration
- Require two-of-three keys to decrypt
 - Requires collaboration approval
 - Attempt to reduce risk of lost key

Blinding Probability on Tracks

- Encrypt STT tracks with angular dependence
- A, B are generated from fixed seed and are unique for charge, species, momentum, data vs. simulation
- $A = [0.25..1]$, $B = [3..10]$

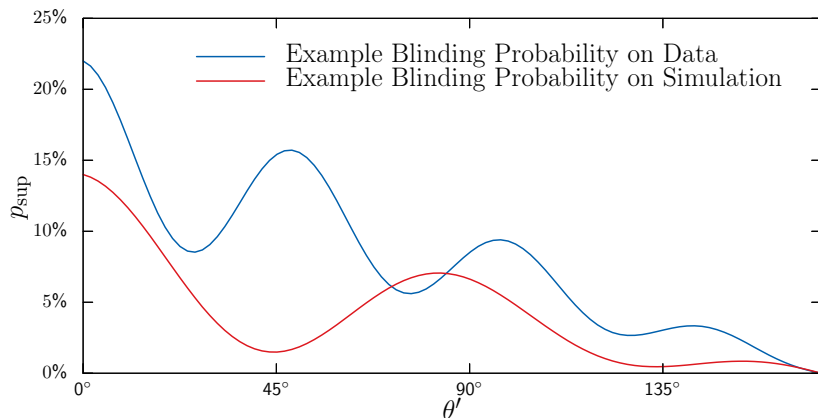
$$s = 0.2(A + 0.3 \cos(B \times \theta'))$$

$$P = s \times \frac{3 - \theta'}{3}$$

- if $P \leq R$, where R is a uniformly distributed random number between 0 and 1, encrypt the track
- Can blind up to 25 % of tracks at any given angle

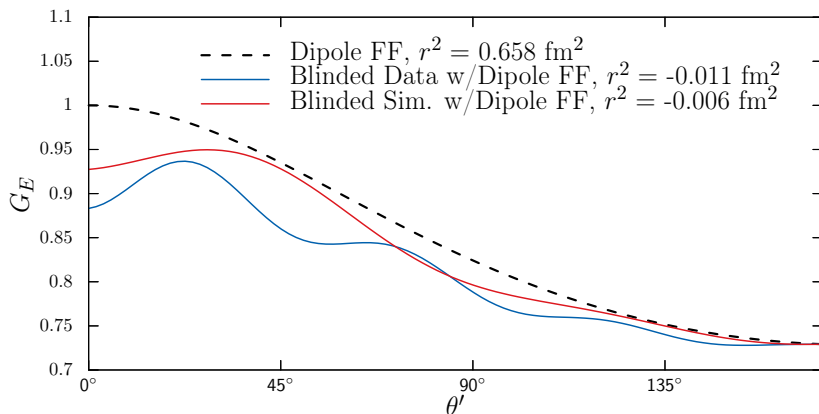
Detailed scheme presented in: J. C. Bernauer, EWC, *et al.*, [arxiv:2310.11469](https://arxiv.org/abs/2310.11469), submitted to PRC

Example Blinding Curve



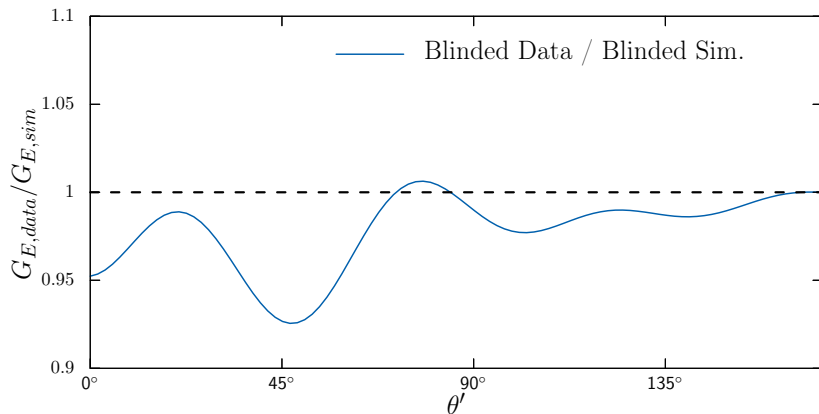
Two example distributions for blinding simulation or data as a function of θ' . For simulation (data) the values of $A = 0.4$ (0.8) and $B = 4.1$ (7.2) are used.

Effect of Blinding on G_E



The r^2 denotes the proton charge radius from the associated form factors. Note that the blinding directly changes the extracted radius from the true radius.

Effect of Blinding on G_E



The ratio of data to simulation of the extracted form-factor, assuming a dipole shape.

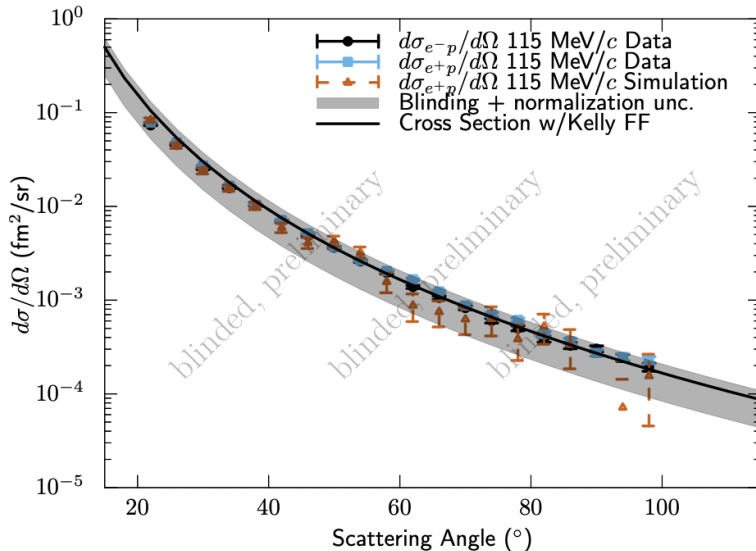
“Traditional” Cross Section Extraction

- Measured cross section for $e^{\pm}, \mu^{\pm}, \pi^{\pm}-p$
- Presenting results for $e^{\pm}p$ and $\mu^{\pm}p$ at 115 and 160 MeV/c scattering

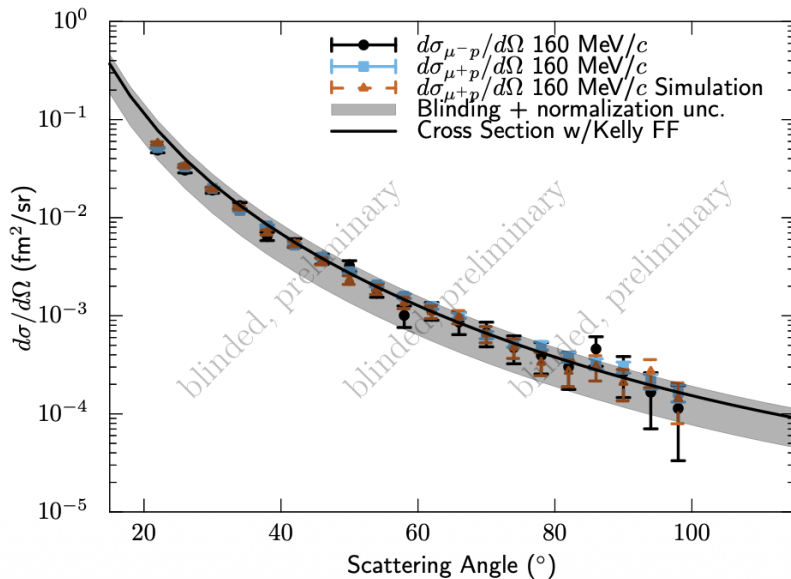
$$\frac{d\sigma}{d\Omega_i} = \frac{\text{counts}_i}{x\rho N_{beam} \Delta\Omega_i \epsilon_{DAQ} \epsilon_{fiducial} \epsilon_{rad}},$$

- counts_i given from reconstructed vertices binned in angle
- N_{beam} calculated from BH trigger rates
- $x\rho$ target areal density
- $\Delta\Omega_i$ simulation-driven estimate of acceptance
- ϵ_{DAQ} (reconstruction efficiency, detector efficiency, live time, etc.) known from analysis
- $\epsilon_{fiducial}$ imposed in analysis of sim and data
- ϵ_{rad} radiative corrections, taken to be 1 for this analysis

Extracted Cross Sections $e^\pm p$ at 115 MeV/c



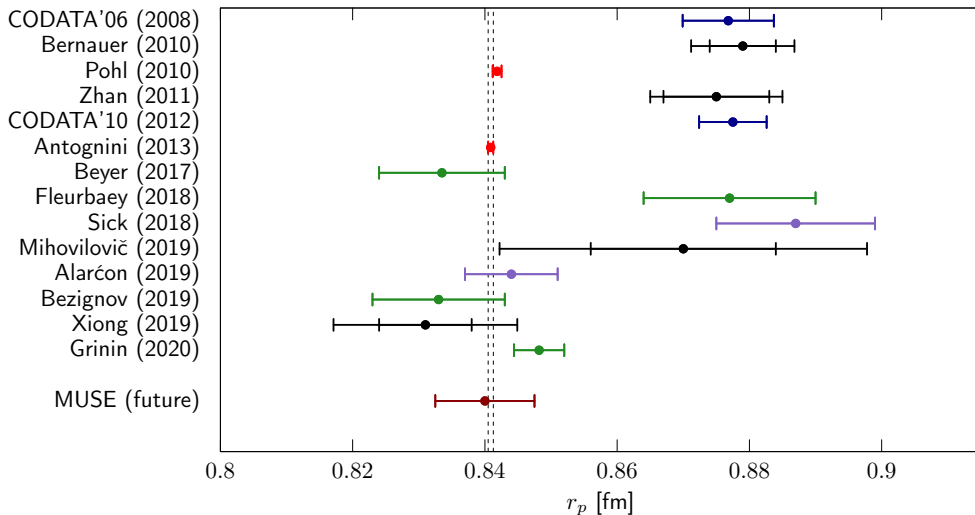
Extracted Cross Sections $\mu^\pm p$ at 160 MeV/c



Physics Coverage of MUSE

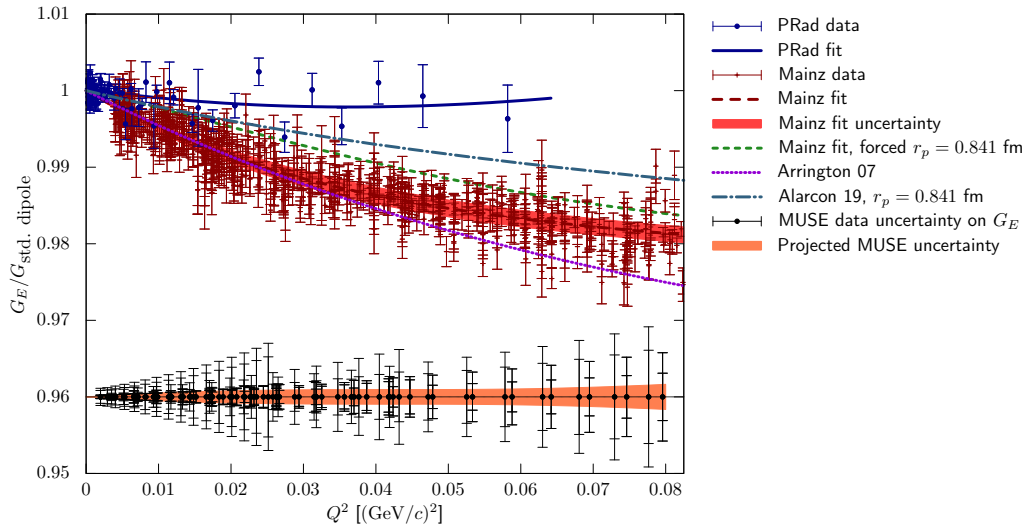
- First high precision measurement of μp scattering for TPE and at precision necessary to inform PRP
- Direct comparison between ep and μp scattering at cross section level to test rad. corr. and lepton universality
- Low energy πp scattering important for χPT
- Search for $\sigma(\pi^+ p)/\sigma(\pi^-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

Projected Resolution of MUSE



MUSE value arbitrarily placed at 0.84 fm for visualization

Comparing PRad and MUSE



Unblinding Plan

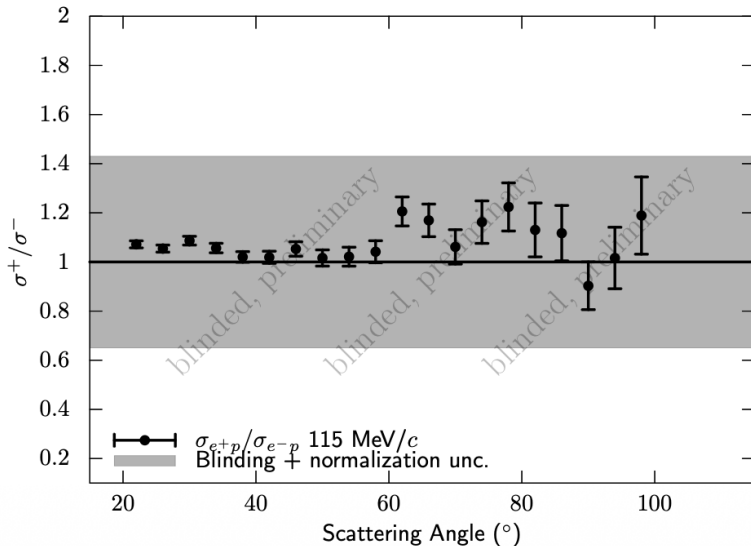
- Unblinding is species, momentum, charge polarity specific
- Plan to blind run periods differently
- Unblind πp scattering first, less contentious
 - First 10 %
 - Remainder of data
- Depending on analysis status, either ep or μp
 - Similarly, first 10 %
 - Remainder of data
 - *Anticipate* TPE first, then e/μ universality, then radius

Conclusion

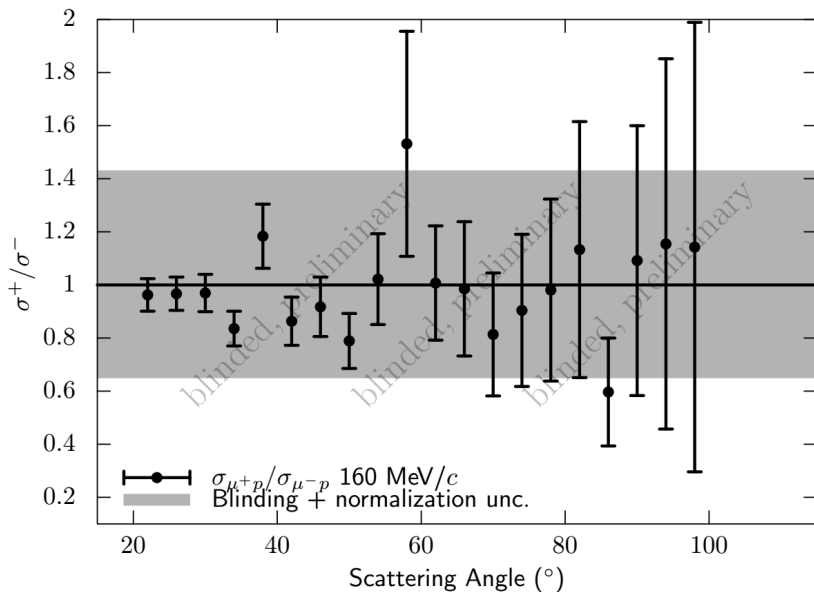
- Proton Radius Puzzle remains unsolved
- MUSE uniquely suited to address the puzzle
- MUSE can precisely measure difference between extracted radii
- Wide variety of interesting physics possible
- Achieved statistics goal, may do some systematic studies this summer
- Lots of analysis work to do!

Back up

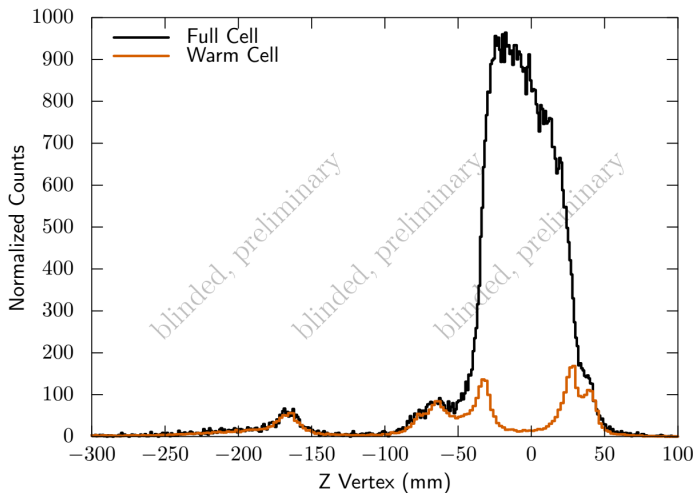
Extracted Cross Sections $e^\pm p$ at 115 MeV/c



Extracted Cross Sections $\mu^\pm p$ at 160 MeV/c

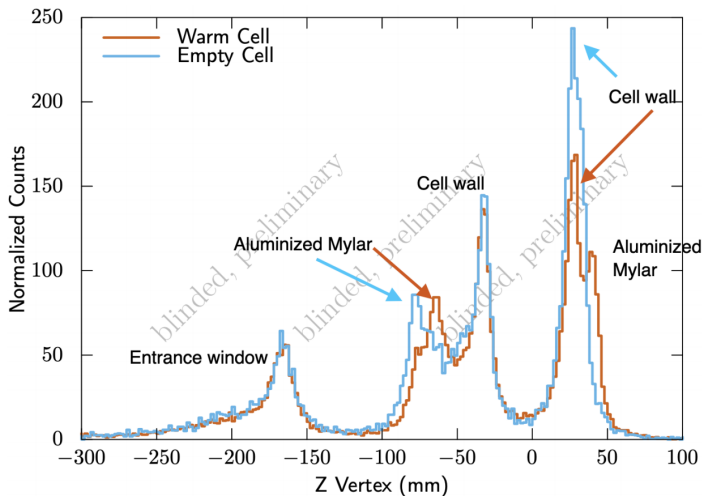


Reconstructed Blinded Vertices



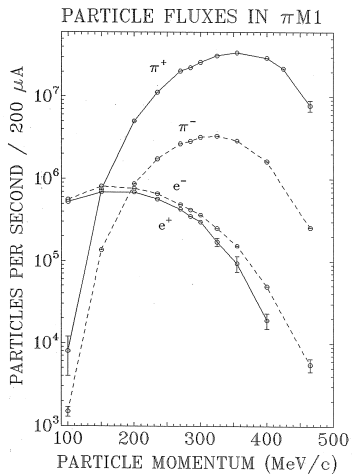
Comparison between luminosity-normalized full and warm cells for +210 MeV/ c π beam.

Aluminized Mylar Wrapping Differences



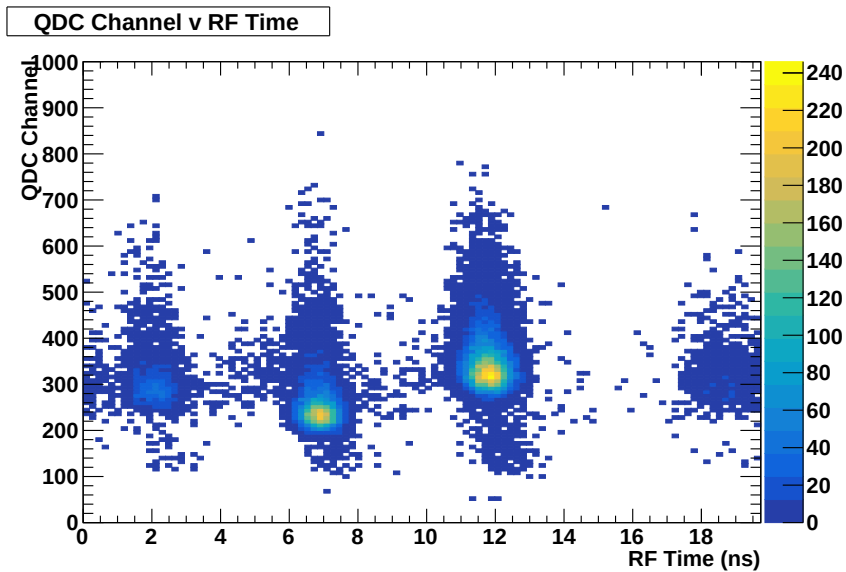
Comparison between luminosity-normalized warm and empty cells for $+210 \text{ MeV}/c \pi$ beam. Note that *cell walls* are in almost identical positions, $z = \pm 30 \text{ mm}$.

Particle Flux



Time: 30-JUN-87 18:35:01

RF V QDC



PiM1 TRANSPORT

