MUSE - Status of proton radius measurement

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- MUSE experiment
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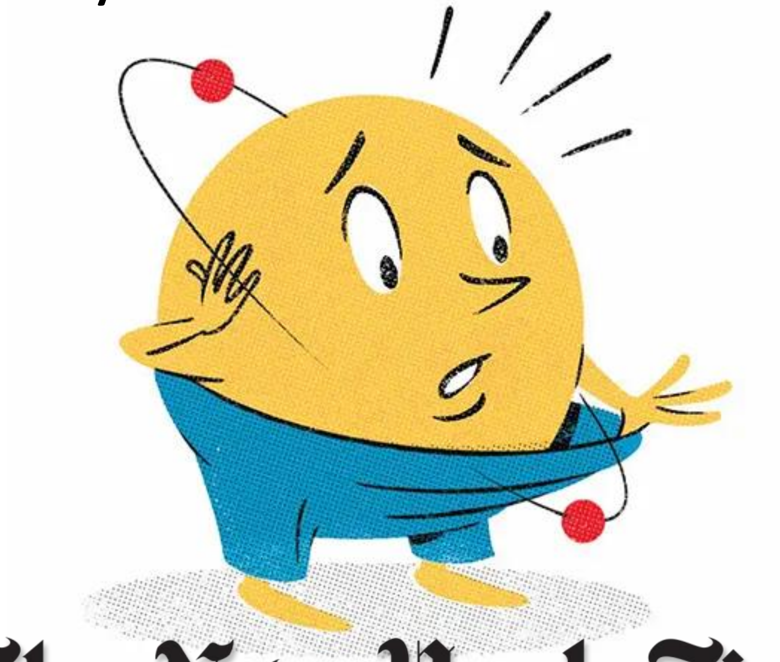
Proton Radius Puzzle

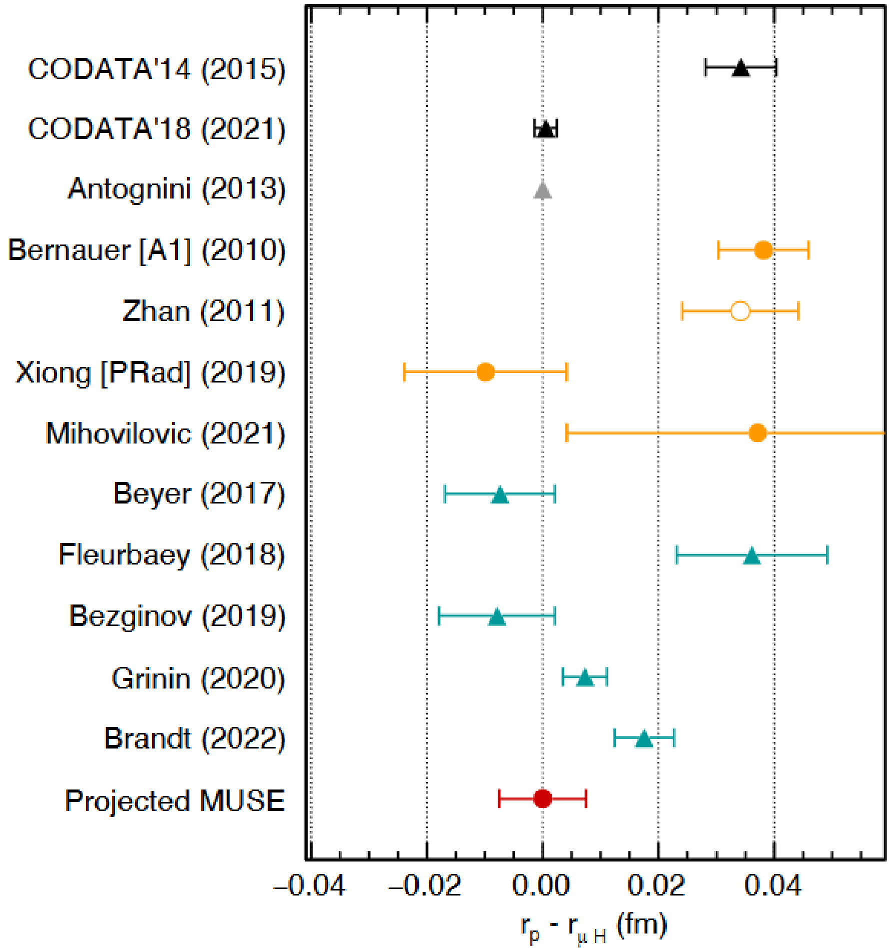
Discrepancy between radius measured by electrons and muons



The New York Times

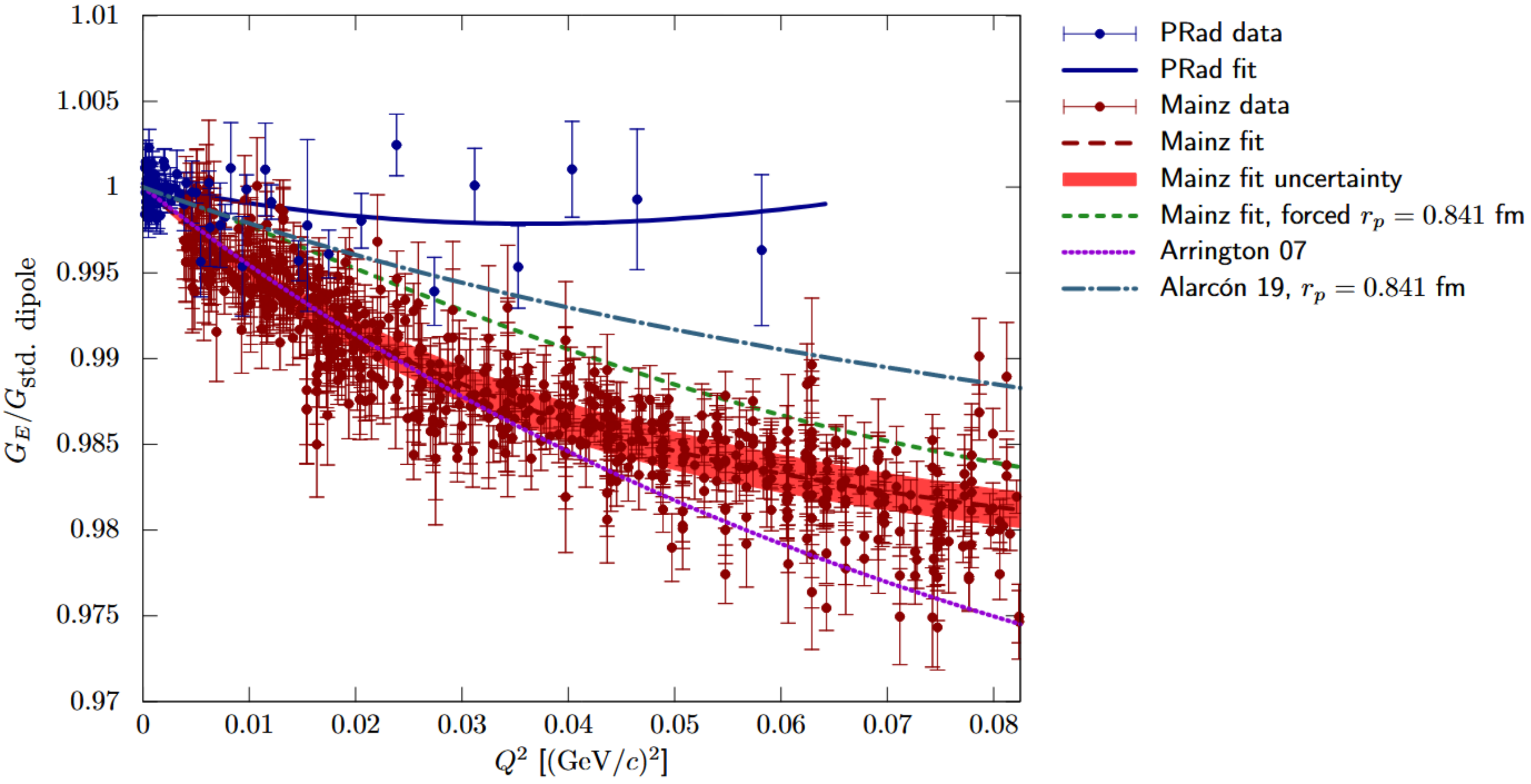
Nature 466, 213 (2010)

Proton Radius Puzzle



- Inconsistent electron-scattering data
- Inconsistent hydrogen-spectroscopy data
- No adequate muon-scattering data yet

Update on scattering experiments



Why are form factors different for Prad?

- Which result should be favoured and why?
- Inaccurate radiative corrections?
- Incorrect methodology?

Independent checks needed:

ISR, ULQ2, MUSE

Update on scattering experiments

- Many different scattering experiments underway and to come
- MUSE is the only simultaneous electron- and muon-scattering experiment
- MUSE is first muon-scattering experiment
  - AMBER to follow soon

Beam	e^-	e^+	μ^-	μ^+	
PRad	✓				Data taken
Mainz 2010	✓				
Mainz ISR	✓				
Mainz Jet	✓				
MUSE PSI	✓	✓	✓	✓	Running
ULQ2 ELPH	✓				
AMBER CERN			✓	✓	Future
MAGIX MESA	✓				
PRES MAMI	✓				
PRad-II JLab	✓				

MUSE – Accessing further physics

Lepton-universality

- Simultaneous electron and muon scattering experiment
- Comparison gives direct test of lepton non-universality

Radiative Corrections

- Muons have a mass approximately 200 times that of an electron
  - Radiative effects are much smaller
- Comparing these results can provide a greater understanding of these effects

Two Photon Exchange

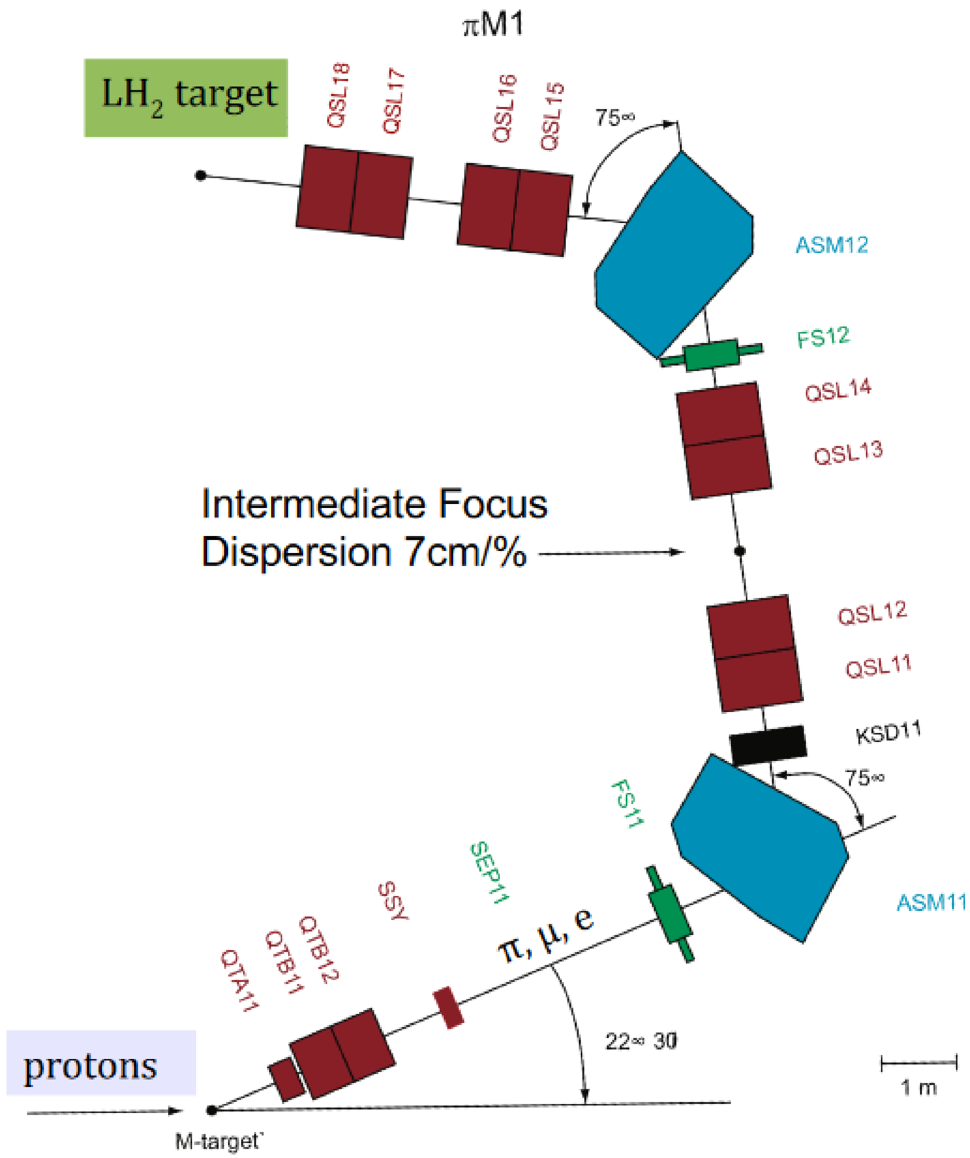
- Both polarities provide access to explore two-photon contributions

W. Xiong and C. Peng, ``Proton Electric Charge Radius from Lepton Scattering,'' Universe 9, no.4, 182 (2023), doi:10.3390/universe9040182, [arXiv:2302.13818 [nucl-ex]].

MUSE: MUon Scattering Experiment at PSI

The world's most powerful low-energy separated p beam

- Simultaneous, separated beam of (π^-, e^-, μ^-) or (π^+, e^+, μ^+) on liquid H_2 target
- Beam momentum of 100 – 500 MeV available gives a broad low Q^2 range



πM1 MUSE Beamline

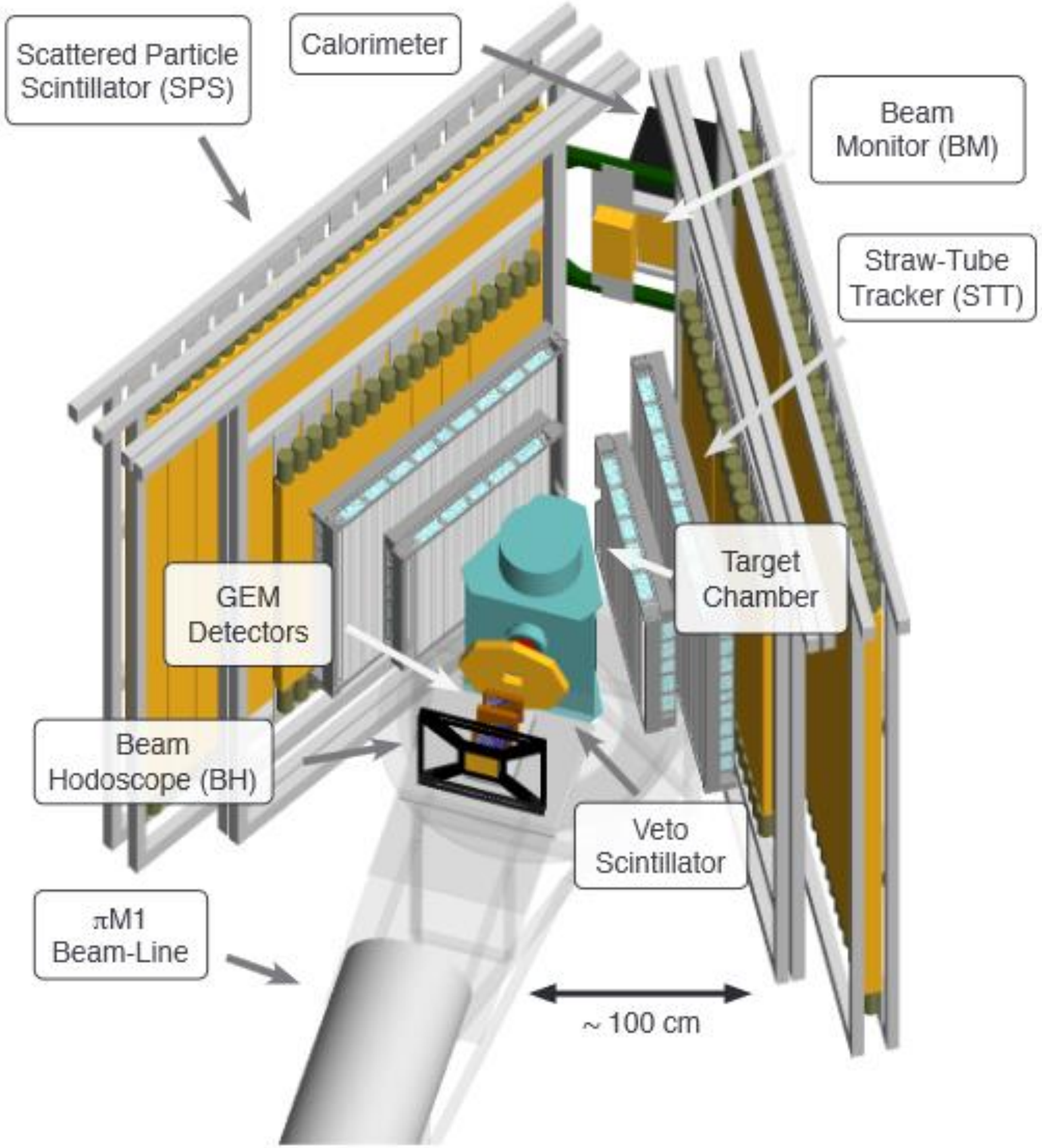
- Secondary beams of π,e,μ produced at M-target with 590 MeV protons

- Beam properties well understood with TRANSPORT, TURTLE, and G4Beamline (E. Cline et al., PRC105, 055201 (2022))

MUSE Experiment

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

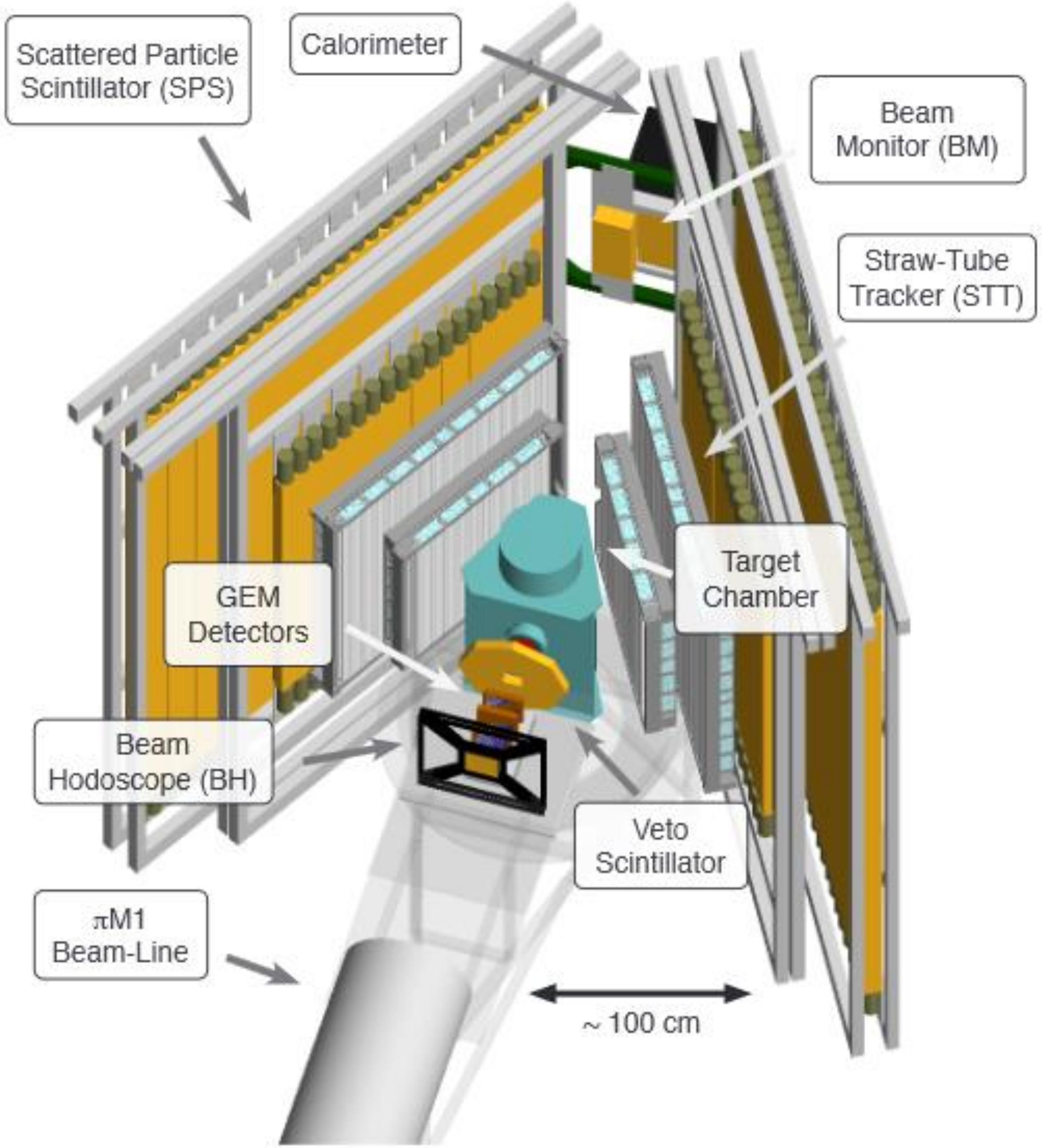
- 3.3 MHz total beam flux
  - ≈ 2-15% μ's
  - ≈ 10-98% e's
  - ≈ 0-80% π's
- p = 115, 160, 210 MeV/c



MUSE Experiment

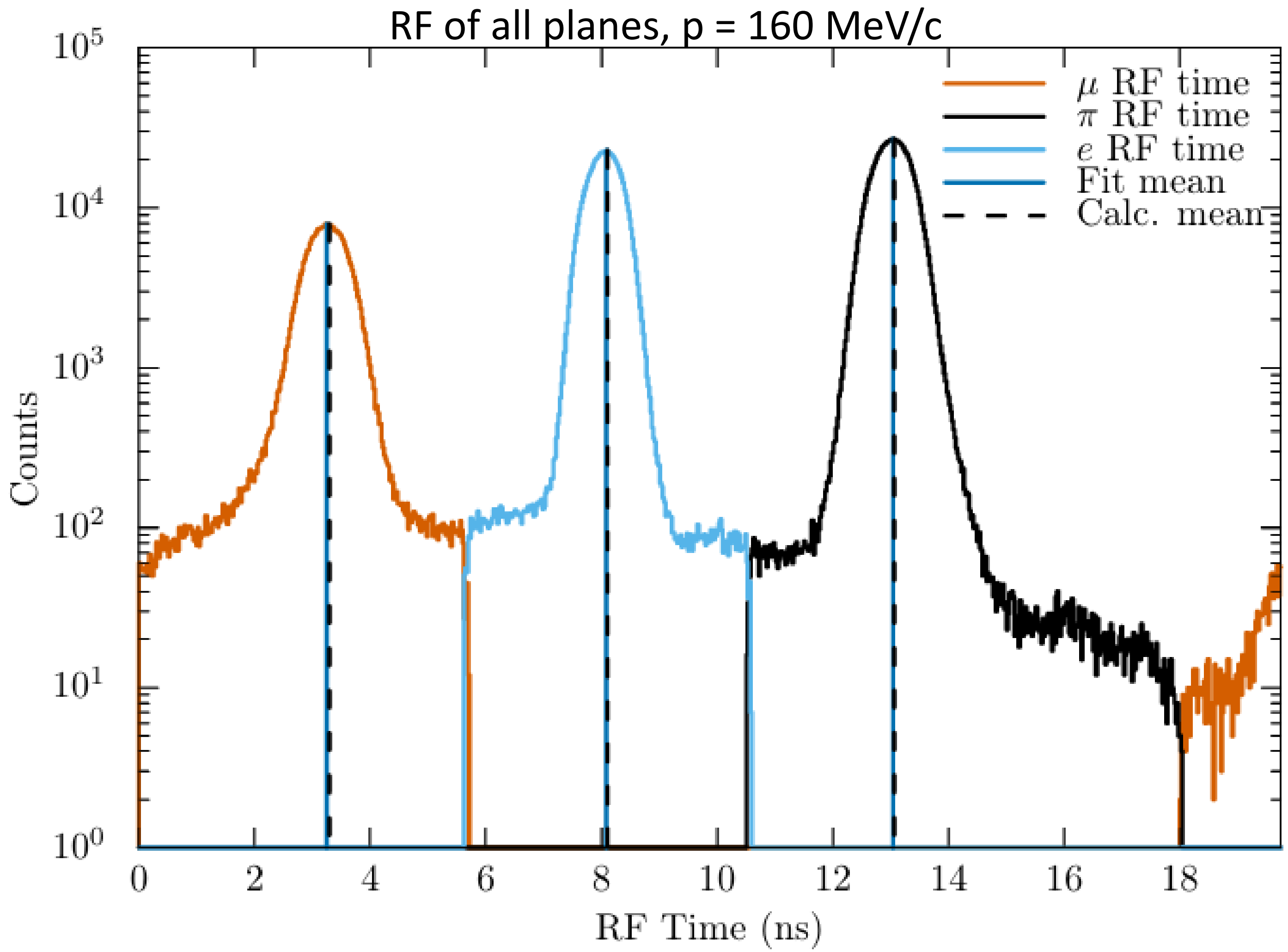
- **Beam particle tracking**
- **Liquid hydrogen target**
- **Scattered lepton tracking**

- $Q^2 \approx 0.002$ - 0.07 GeV^2
- $\theta \approx 20°$ - $100°$
- 180° coverage in Ø



MUSE Experiment – Beam Particle Separation

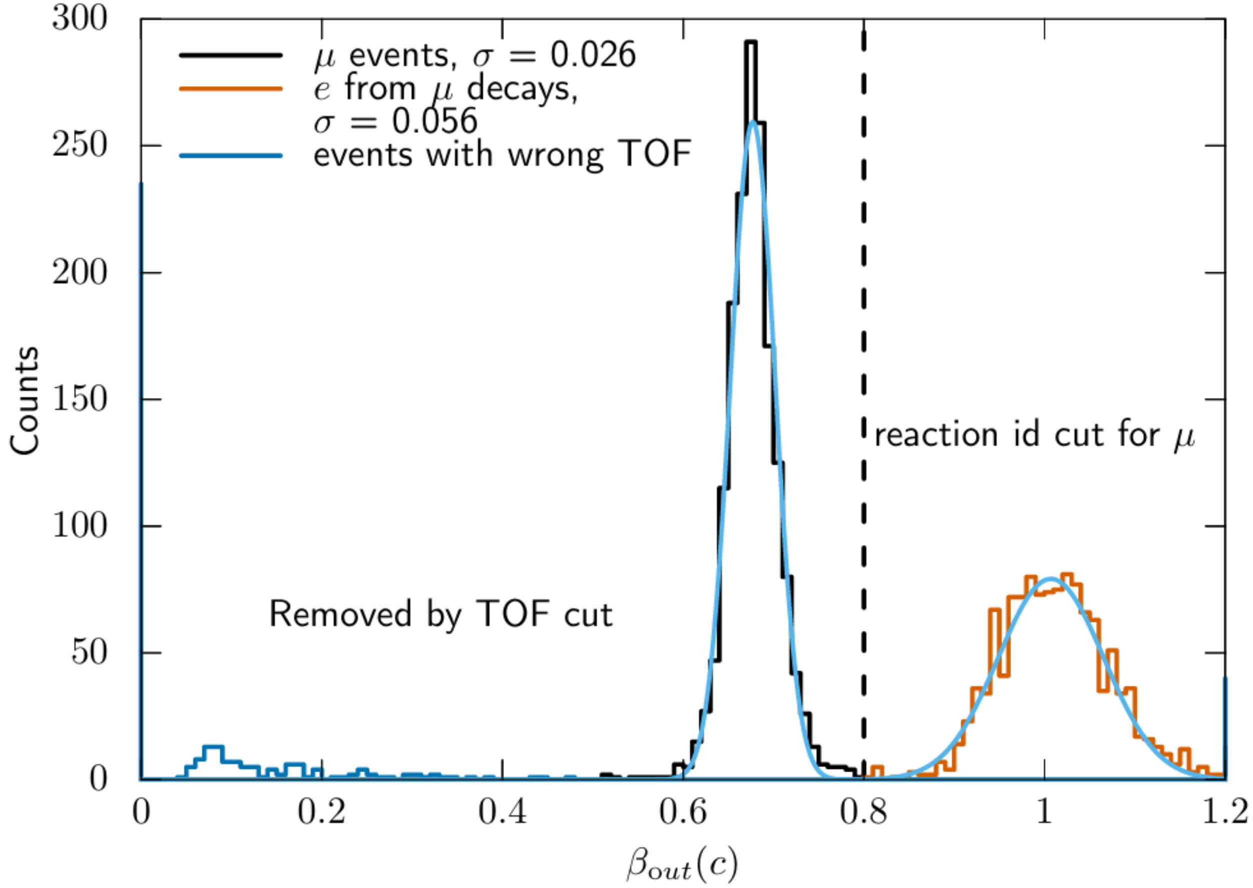
π,e,μ beam particles separated by RF



MUSE Experiment – Reaction Identification

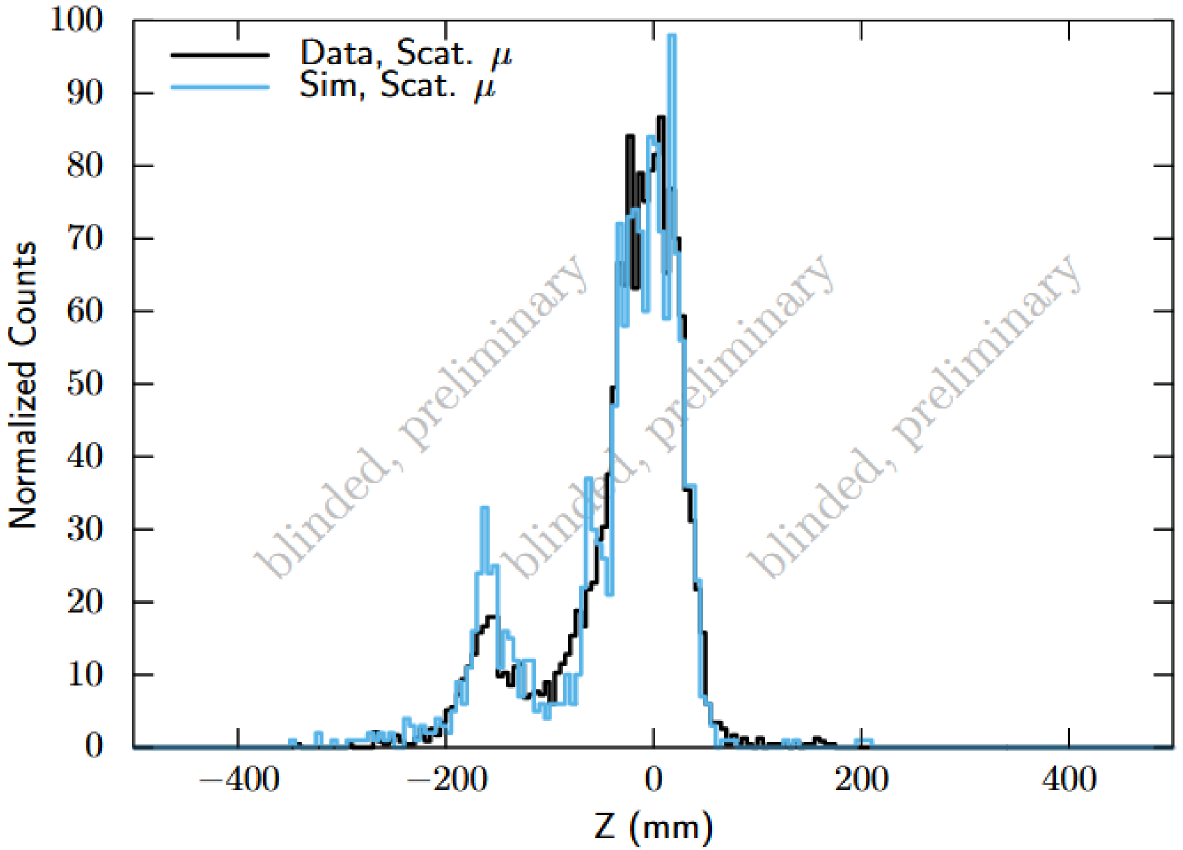
- Muons decay after identification in beamline detectors
- Time of Flight used for reaction identification

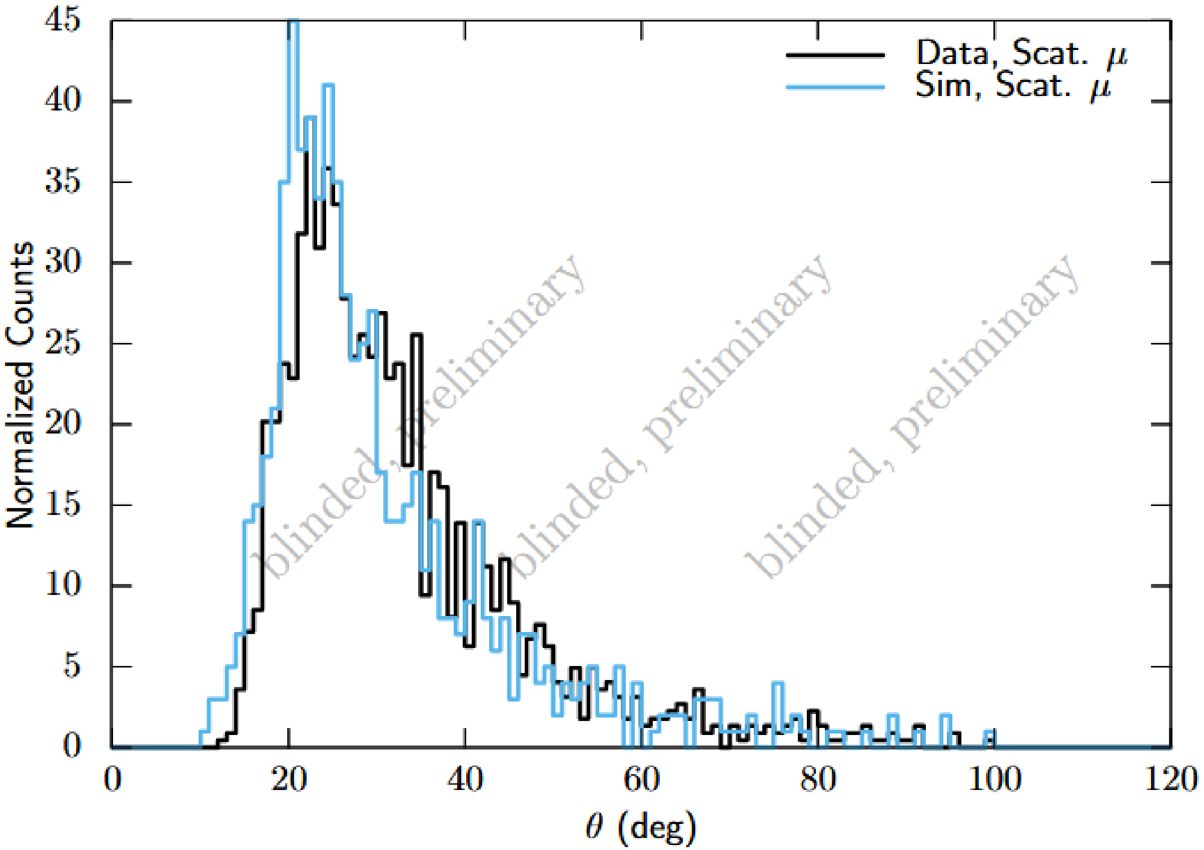
Outgoing beta of particles identified as muons, p = +115 MeV/c



Muon scattering events

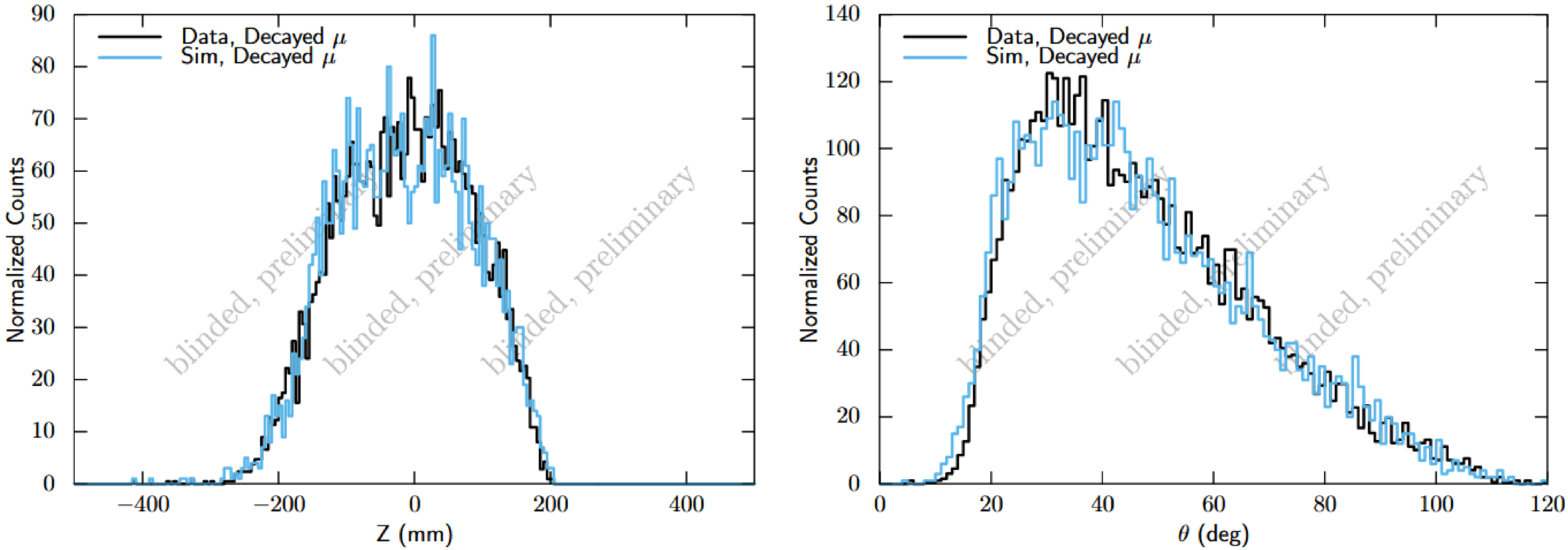
p = +115 MeV/c, Left: Reconstructed Z vertex, Right: Reconstructed angle





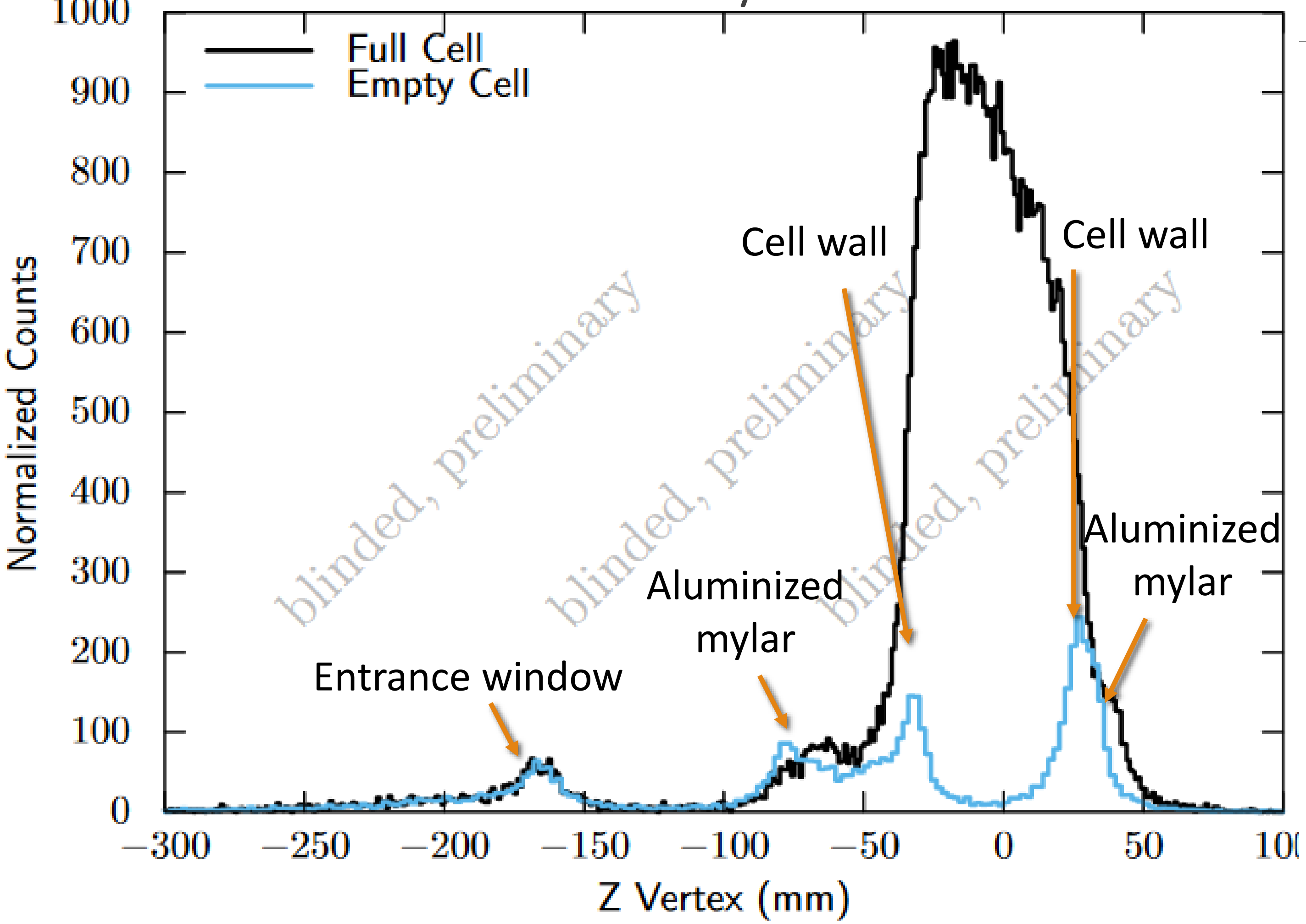
Muon decay events

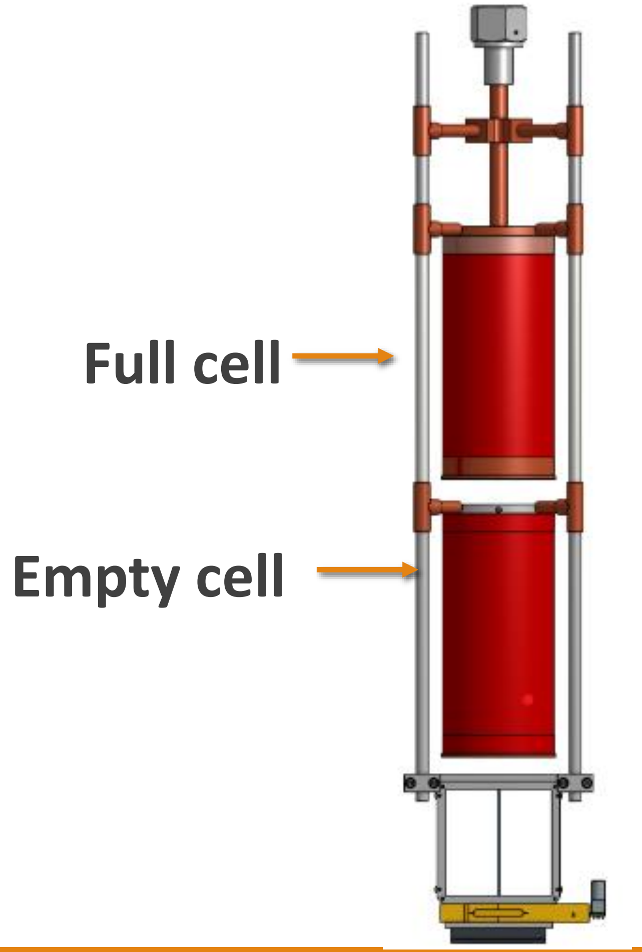
p = +115 MeV/c, Left: Reconstructed Z vertex, Right: Reconstructed angle



Vertex Reconstruction

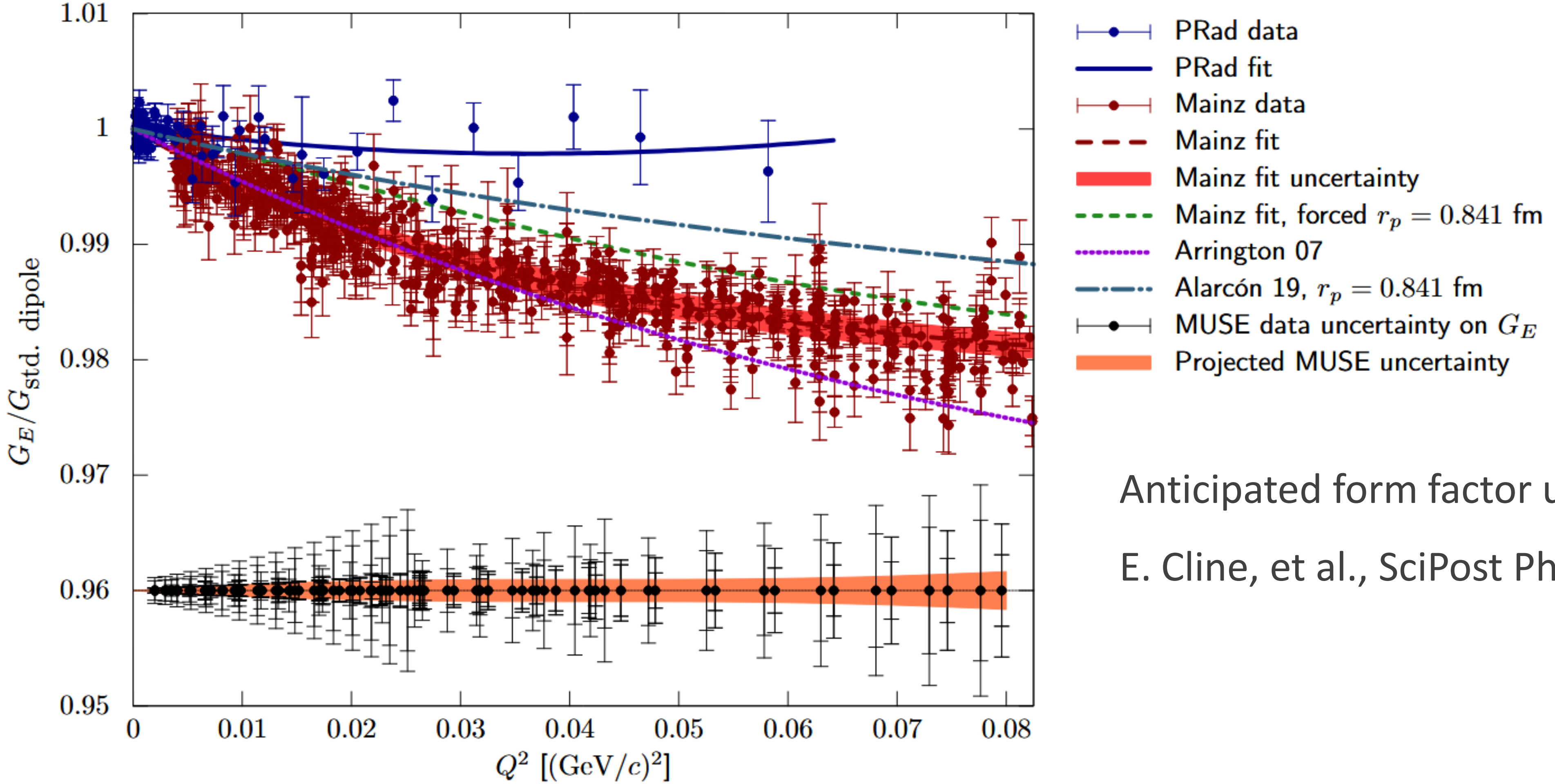
Luminosity-normalised full and empty cells for 210 MeV/c π^+ beam





P. Roy et al., A Liquid Hydrogen Target for the MUSE Experiment at PSI, NIM A, 2019, https://doi.org/10.1016/j.nima.2019.162874

Anticipated results



Anticipated form factor uncertainty

E. Cline, et al., SciPost Phys. Proc. 5, 023(2021)

Status of MUSE

Currently taking data

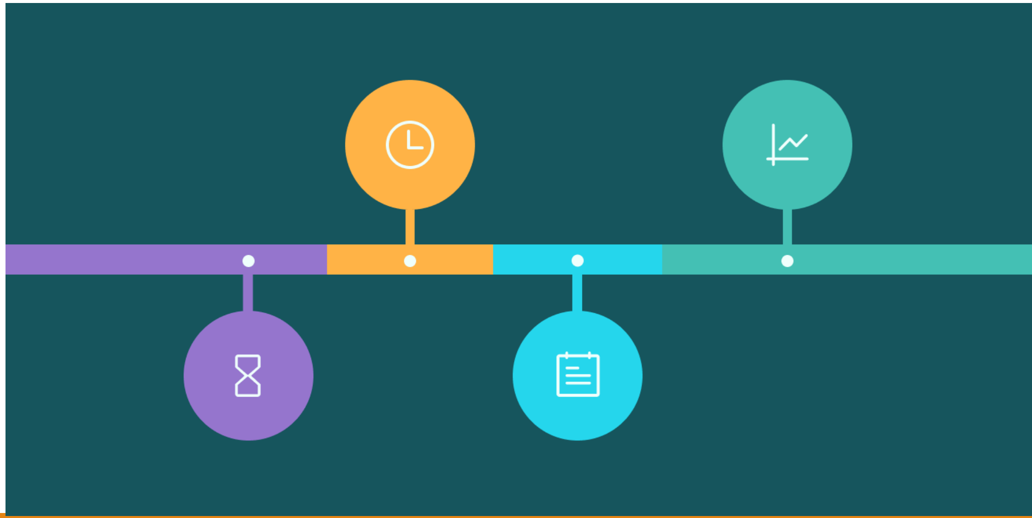
- ~5 months beamtime allocation received this year
- 2 years data taking left

Ongoing:

- Extracting preliminary, blinded cross sections with good agreement to simulation within blinding

Future:

- Calibrations and alignment
- Simulations (radiative corrections, digitization, trigger)
- Systematic errors



MUSE Publications

- R. Gilman, E. J. Downie, G. Ron, et al.,Technical Design Report for the Paul Scherrer Institute Experiment, arXiv, 2017, https://doi.org/10.48550/arXiv.1709.09753
- A. Liyanage, M. Kohl, J. Nazeer, T. Patel, Development of GEM Detectors at Hampton University, arXiv, 2018, https://doi.org/10.48550/arXiv.1803.00132
- E.O. Cohen et al., Development of a scintillating-fiber beam detector for the MUSE experiment, NIM A, 2016, 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, 2019, https://doi.org/10.1016/j.nima.2019.162874
- T. Rostomyan et al., Timing Detectors with SiPM read-out for the MUSE Experiment at PSI, NIM A, 2020, https://doi.org/10.1016/j.nima.2020.164801
- E. Cline, J. Bernauer, E.J. Downie, R. Gilman, MUSE: The MUon Scattering Experiment, Review of Particle Physics at PSI, 2021, 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
- J.C. Bernauer et al., Blinding for precision scattering experiments: The MUSE approach as a case study, arXiv, 2023, https://doi.org/10.48550/arXiv.2310.11469

Conclusion

- Proton radius puzzle still unsolved
- Large variety of scattering experiments, e and μ

- MUSE will play a crucial role in the proton radius puzzle
- MUSE will expand our understanding in other areas
  - Lepton universality
  - Radiative corrections
  - Two photon exchange

Thank You!