Muons in Minneapolis, UNM, Minneapolis, Dec 6-8, 2023

The Muon Scattering Experiment (MUSE) at PSI

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

Outline

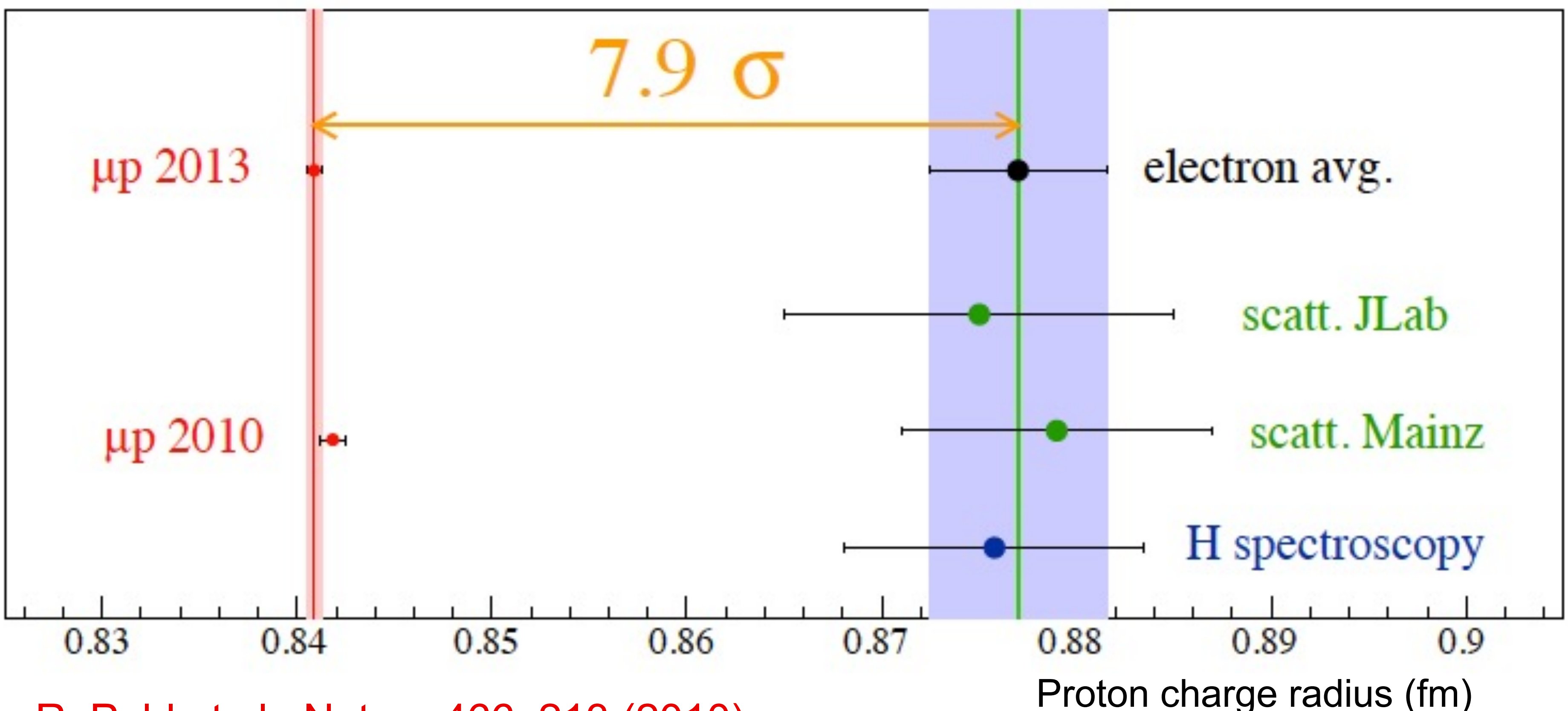
- **The Proton Radius Puzzle: A >7σ discrepancy**
- **Lepton universality**
- **Two-photon exchange**
- **The MUSE experiment**
  - **Sensitivity**
  - **Overview**
  - **Status**

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)

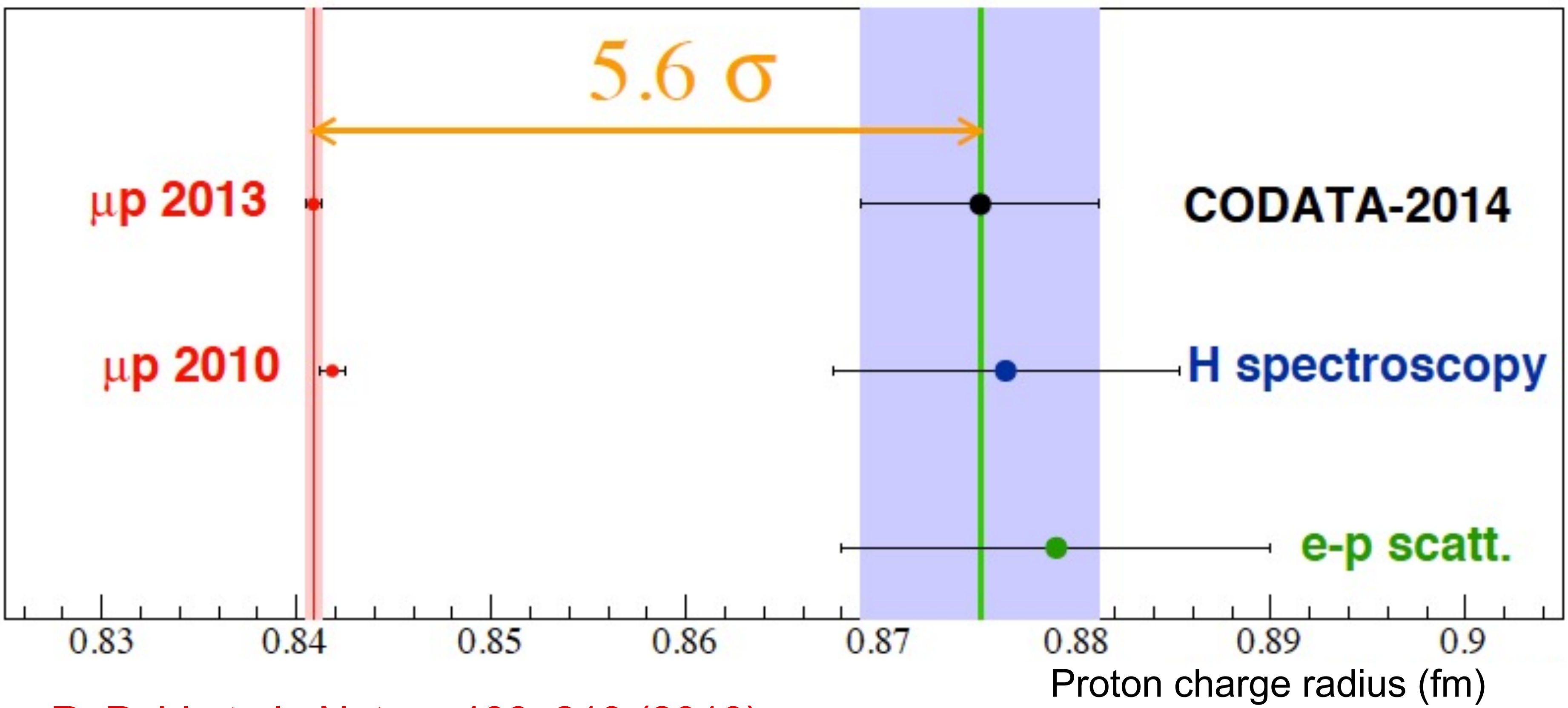
A. Antognini et al., Science 339, 417 (2013)

The proton radius puzzle in 2016

The proton rms charge radius measured with

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

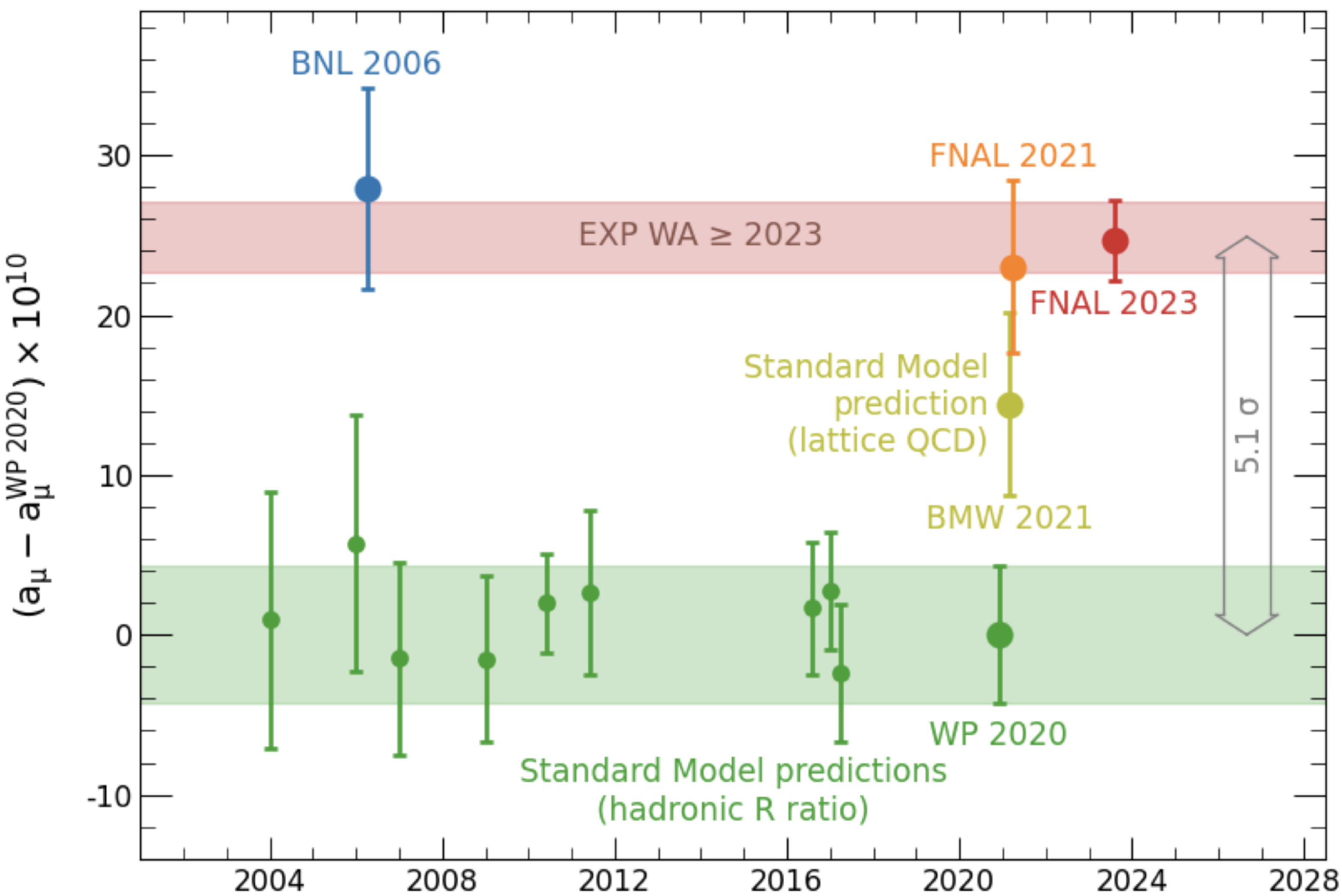
muons: (0.8409 ± 0.0004) fm



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

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

Lepton non-universality: Muon g-2



A. Driutti, MENU23

D.P. Aguillard, PRL 131, 161802 (2023)

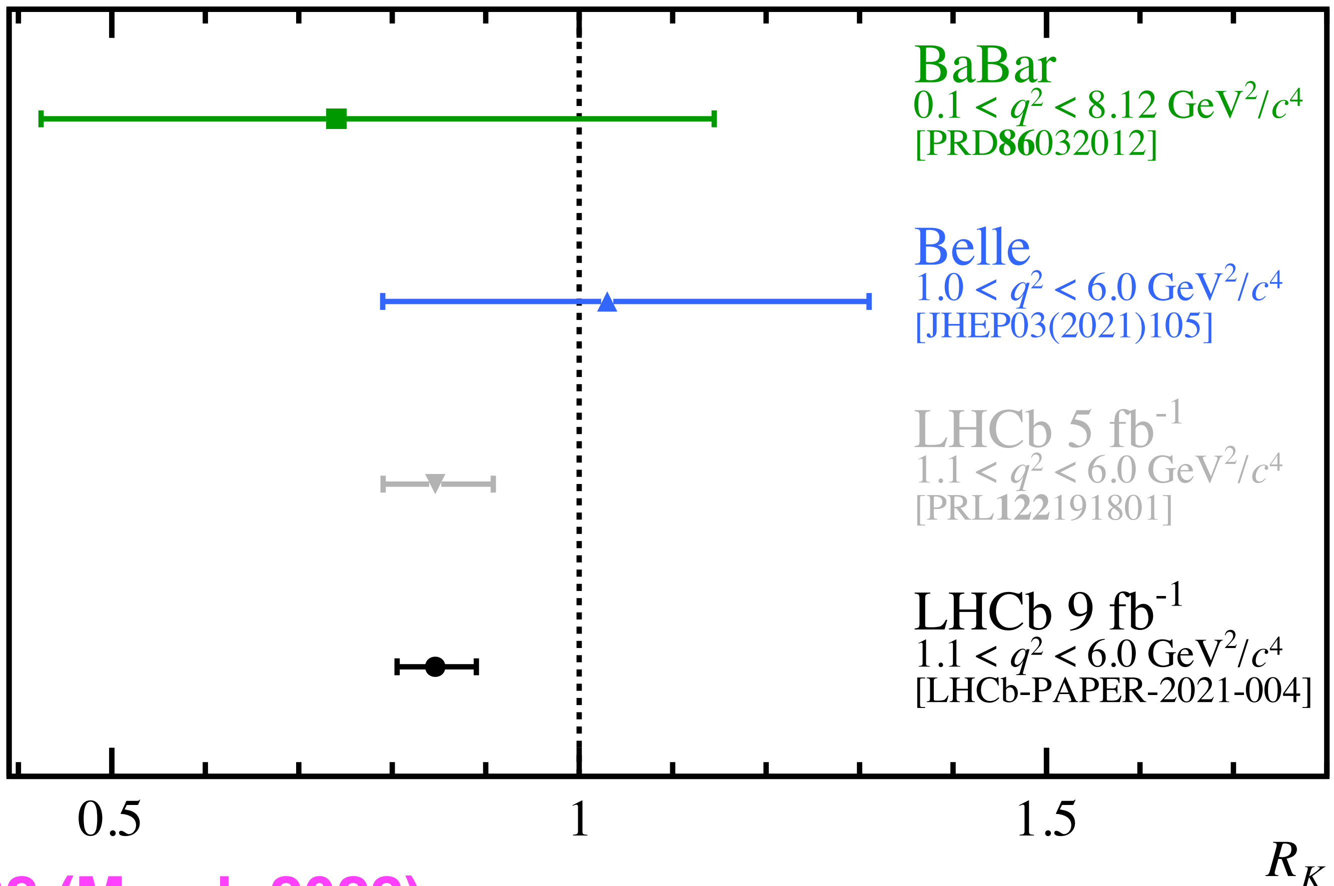
Lepton non-universality in B-decays (μ-e)

- **LHCb: R(K⁺) = Γ(B⁺→K⁺ μ⁺μ⁻) / Γ(B⁺ → K⁺ e⁺e⁻)**
- **Spring 2021: R(K⁺) different from SM at 3.1σ level**

[LHCb, PRL 113 (2014) 151601]
[BaBar, PRD 86 (2012) 032012]
[Belle, PRL 103 (2009) 171801]

R. Aaji, PRL 122, 191801 (2019)

Full Run1 + Run2
arXiv:2103.11769

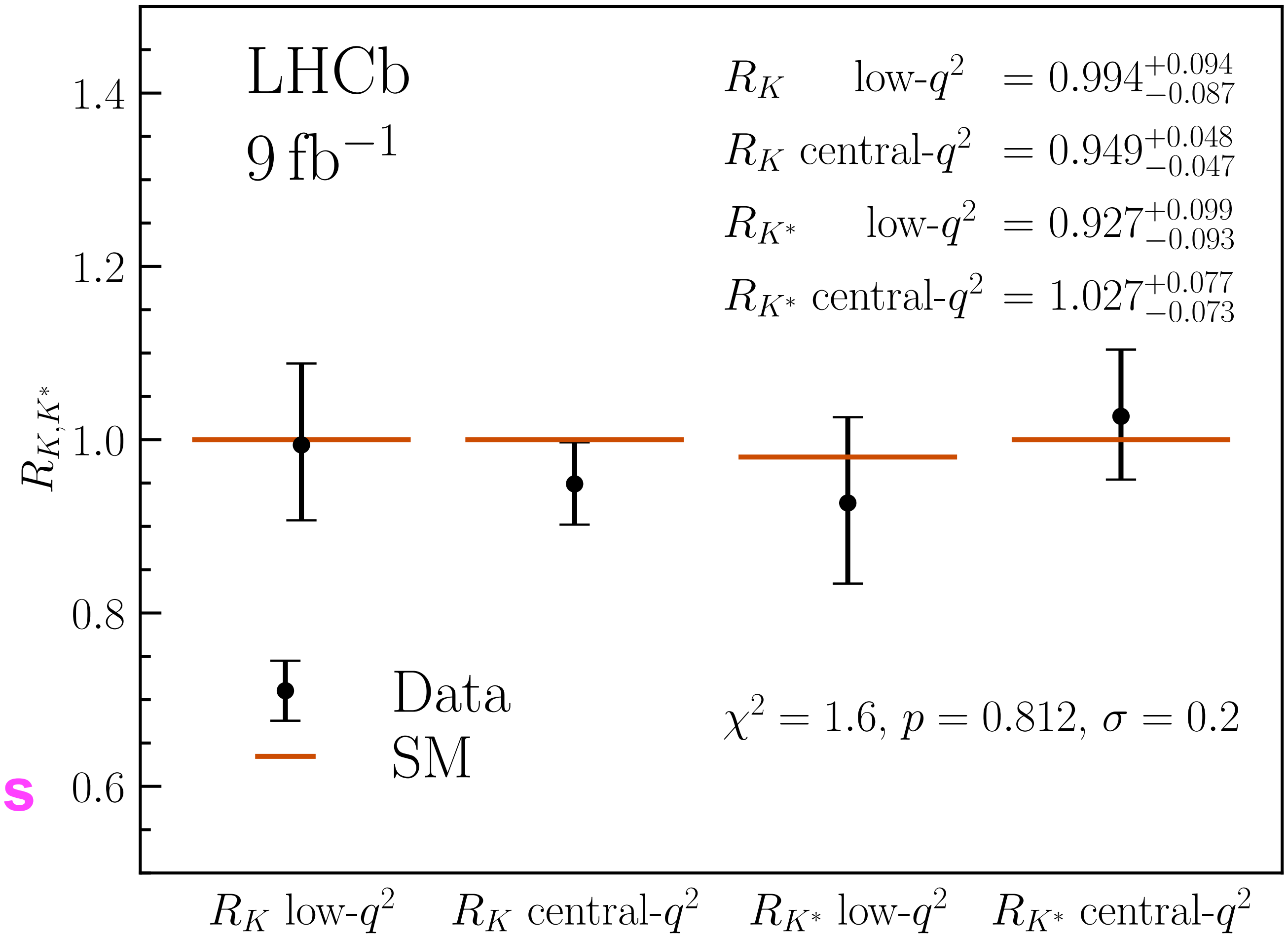


Nature 18, 277–282 (March 2022)

$$R_K = 0.846\ ^{+0.042}_{-0.039}\ (\text{stat})\ ^{+0.013}_{-0.012}\ (\text{syst})$$

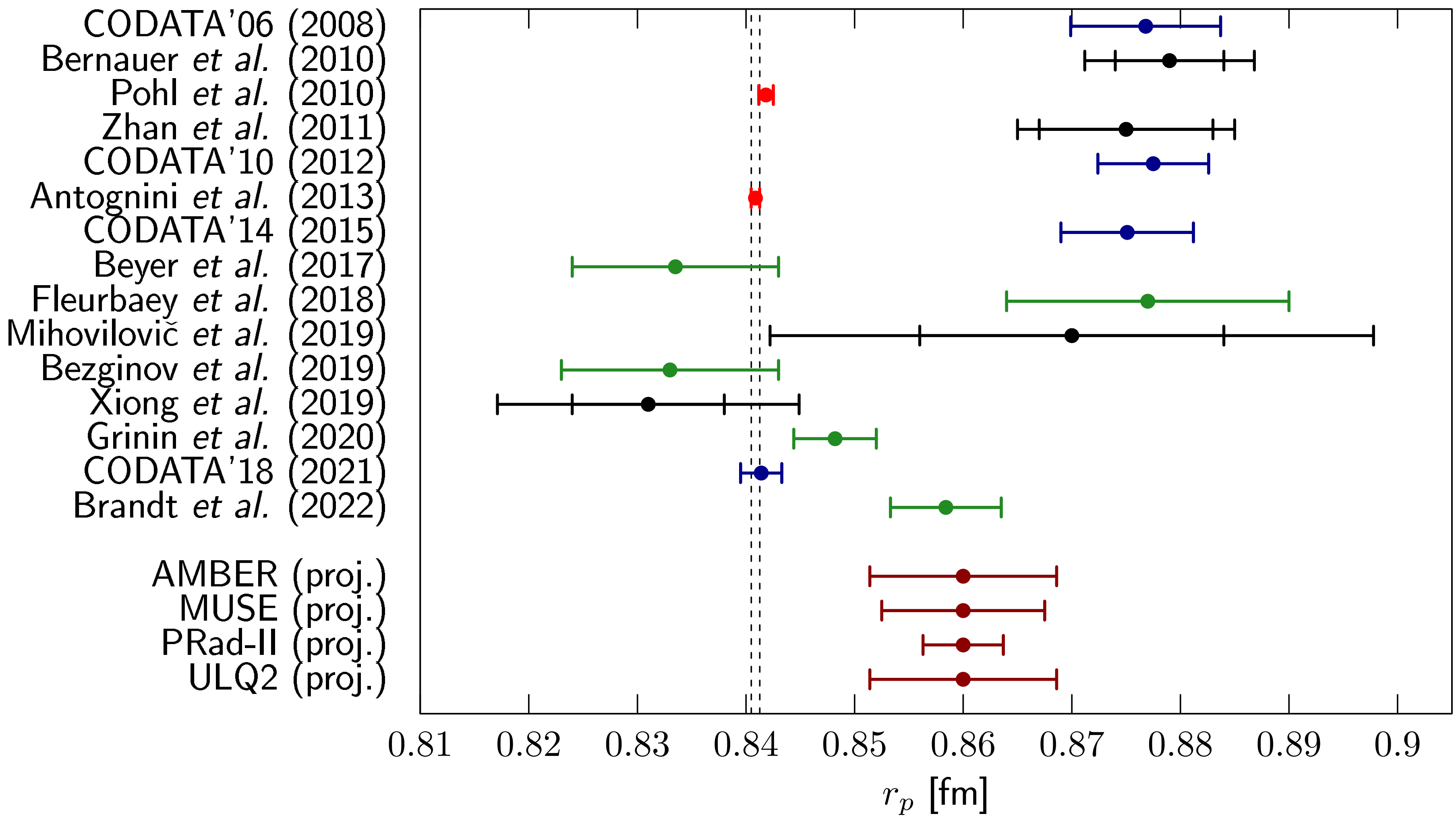
Lepton non-universality in B-decays (μ-e)

- **LHCb: $R(K^{(+,*)}) = \Gamma(B^{(+,0)} \rightarrow K^{(+,*)} \mu^+\mu^-) / \Gamma(B^{(+,0)} \rightarrow K^{(+,*)} e^+e^-)$**
- **December 2022: $R(K^{(+,*)})$ consistent with Standard Model**



Full Run1 + Run2
arXiv:2212.09153
Supersedes previous results!

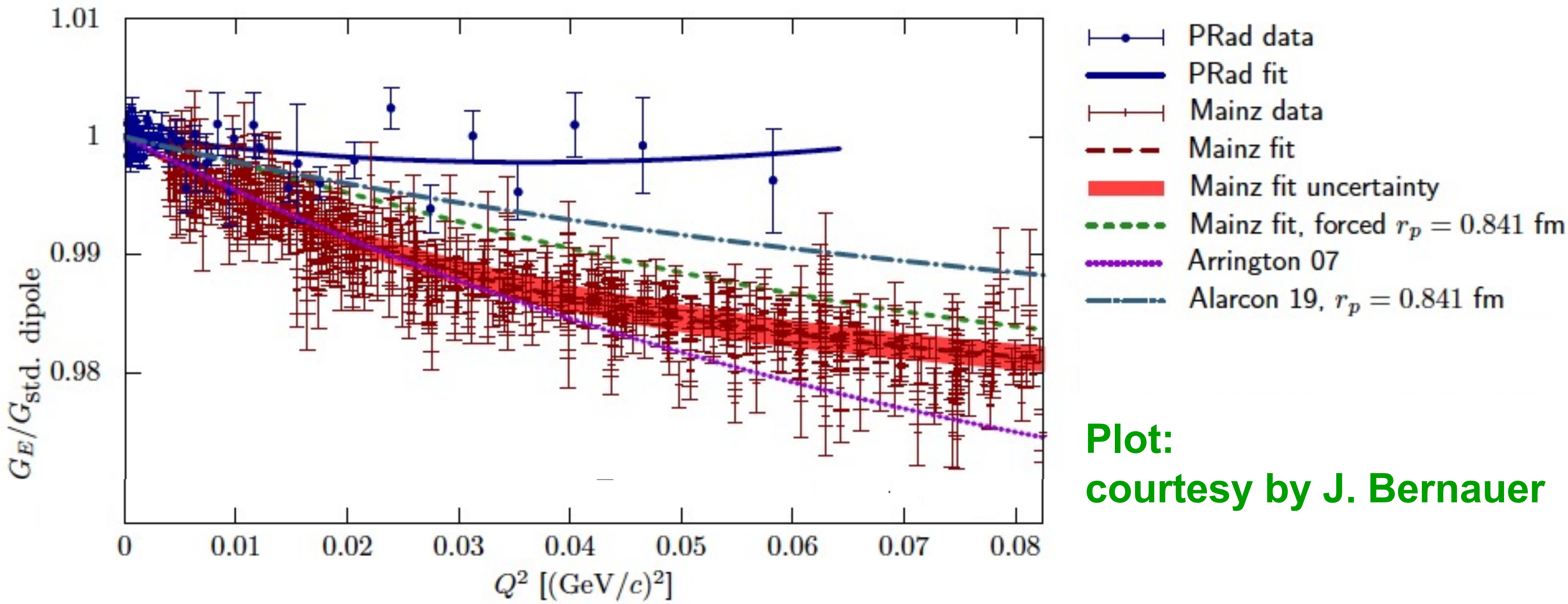
The proton radius puzzle in 2023



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)**

Motivation for μp scattering

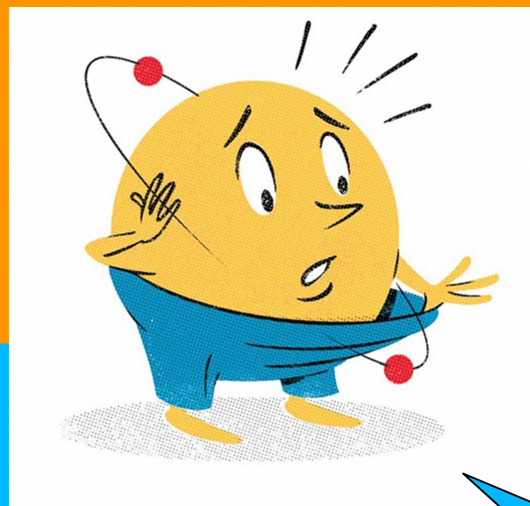
Spectroscopy

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

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
  Constraints on new physics e.g. from kaon decays (TREK@J-PARC)

MUSE will test

MUon Scattering Experiment (MUSE) at PSI

PAUL SCHERRER INSTITUT PSI

Appollo and the nine muses

MUSE: MUon Scattering Experiment at PSI

Use the world's most powerful low-energy separated e/π/μ beam for a direct test if μp and ep scattering are different:

- **Simultaneous, separated beam of (e+/π+/μ+) or (e-/π-/μ-) on liquid H_2 target**

→ **Separation by time of flight**

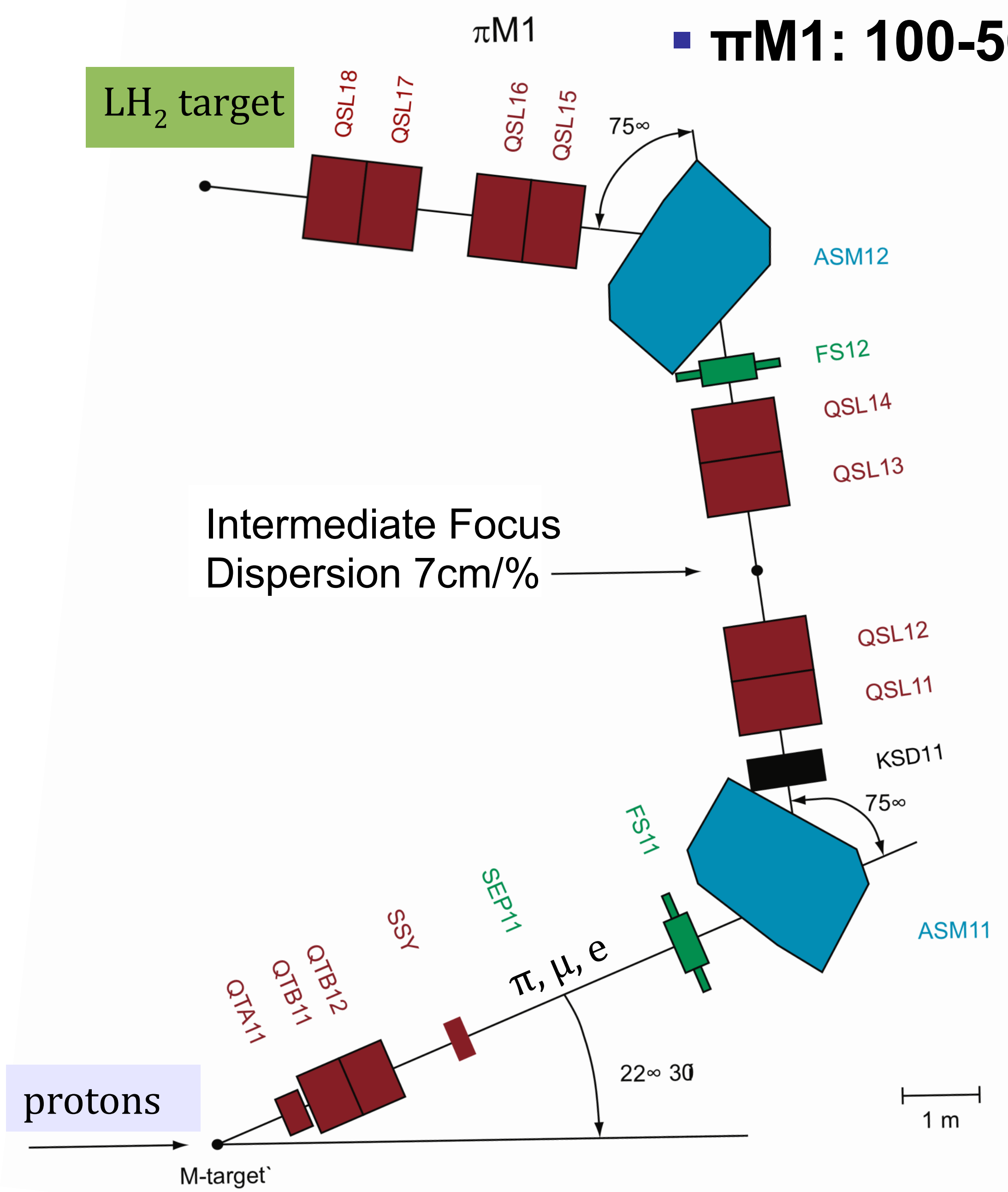
→ **Measure absolute cross sections for ep and μp**

→ **Measure e+/μ+, e-/μ- ratios to cancel certain systematics**

→ **If radii differ by 4%, then form factor slope by 8%, x-section slope by 16%**

- **Directly disentangle effects from two-photon exchange (TPE) in e+/e-, μ+/μ-**
- **Multiple beam momenta 115-210 MeV/c for broad low-Q^2 range to be covered**

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

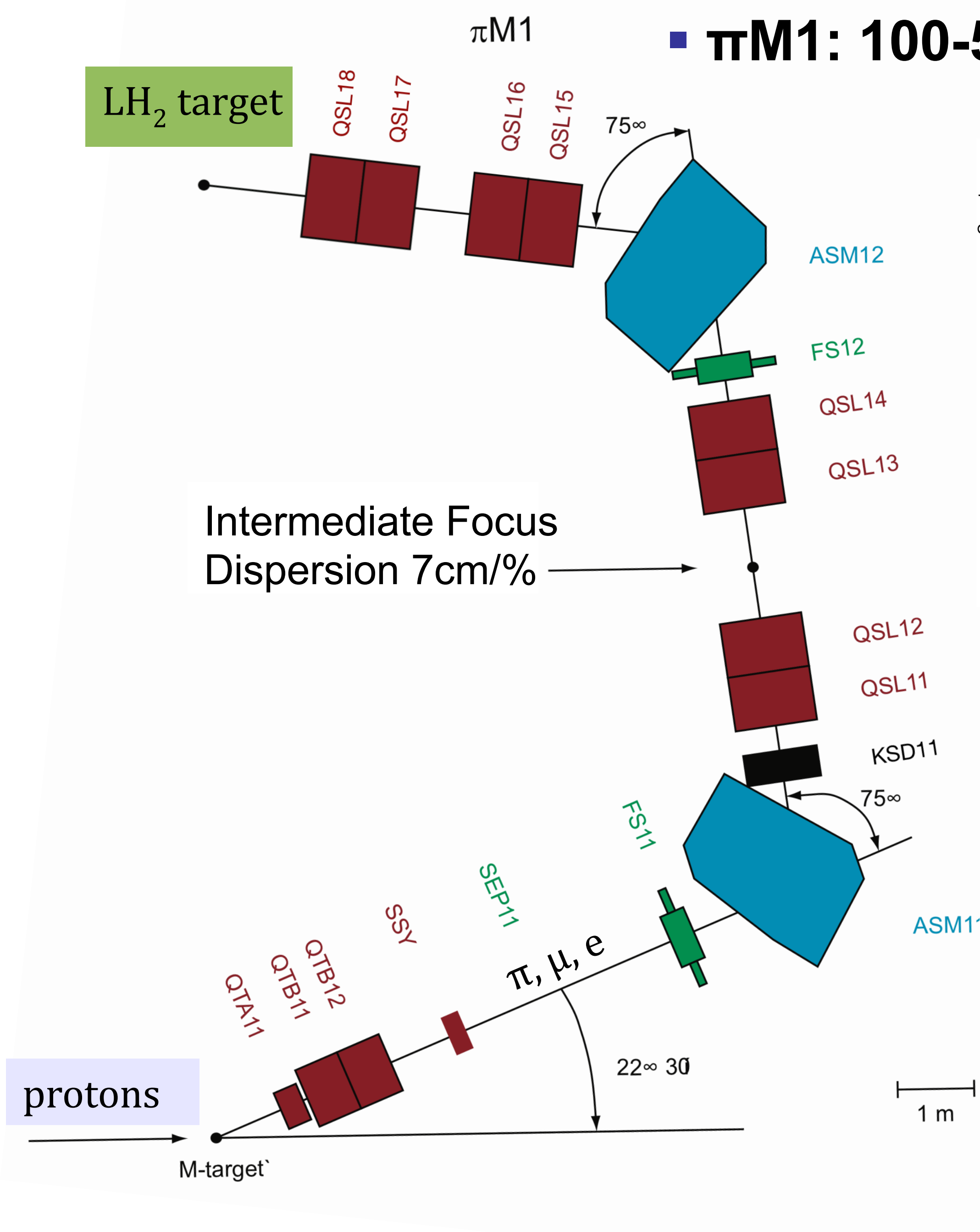
- **$\mu^{\pm}$ from $\pi^{\pm}$ decay in flight *O(cm)* transv., *O(m)* longit.**

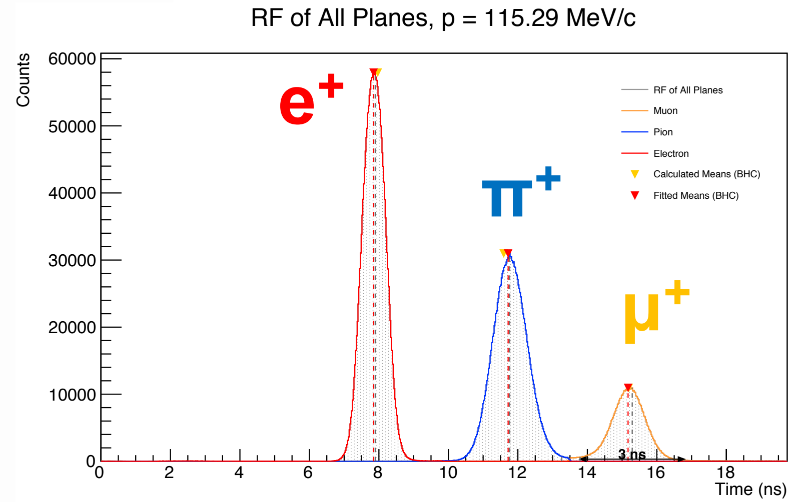
Beam properties well understood with TRANSPORT, TURTLE, and G4Beamline

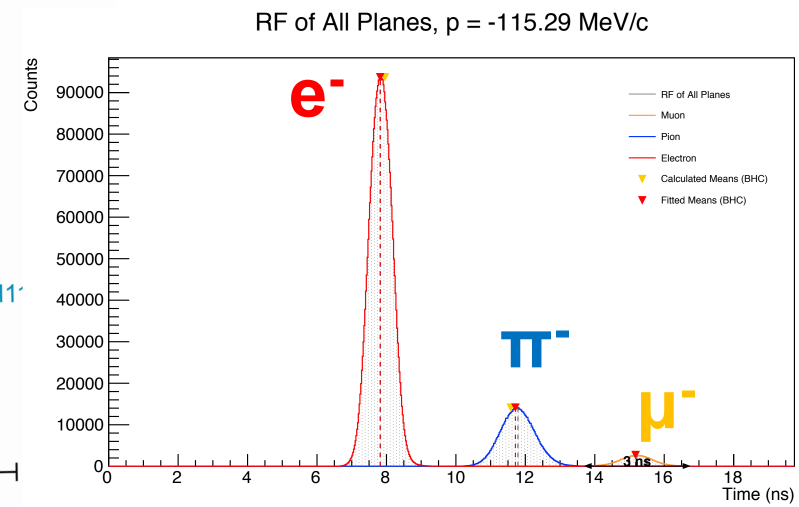
E. Cline et al., PRC105, 055201 (2022)

πM1 / MUSE beamline

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







MUSE experiment layout

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

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

$p = 115, 153, 210$ MeV/c

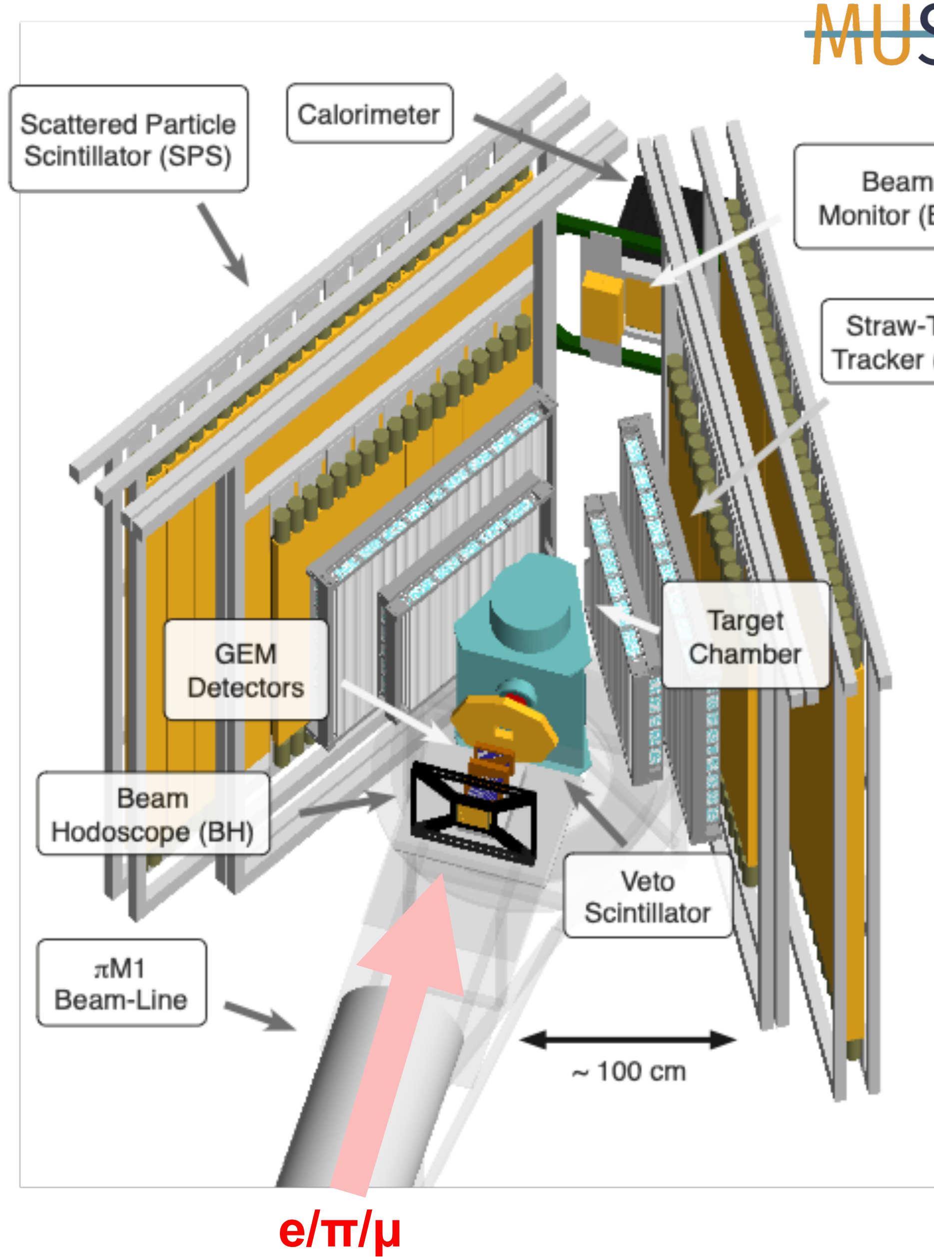
$\theta = 20^o$ to 100^o

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

$\varepsilon = 0.256 - 0.94$

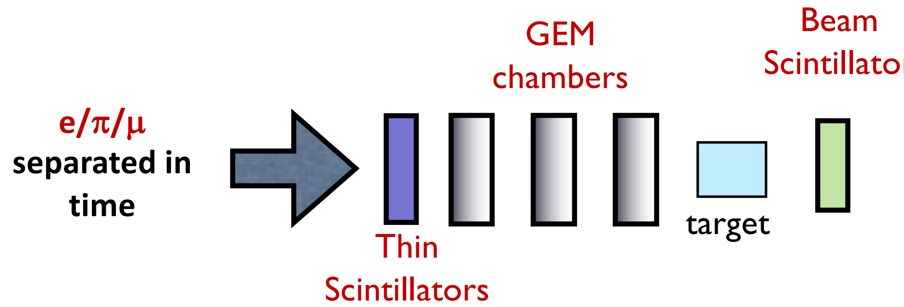
Challenges

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

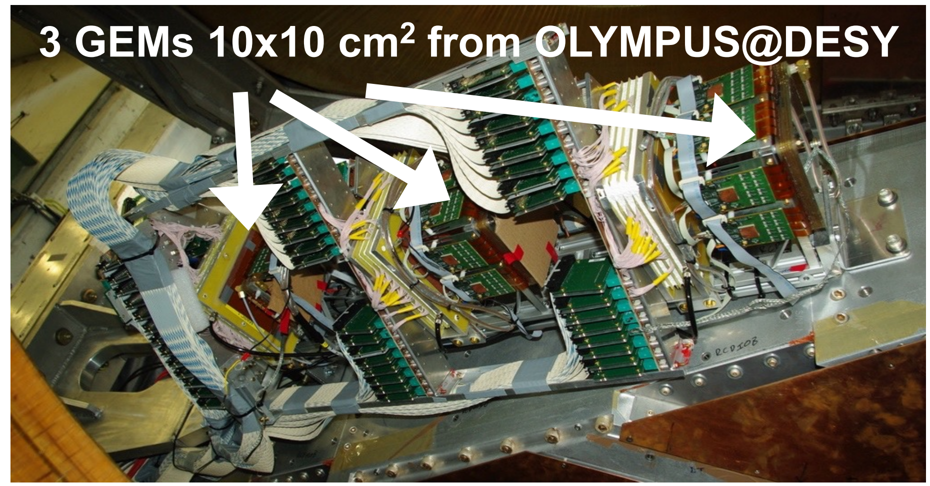


Beamline instrumentation

Beamline Elements:



GEM telescope
(Hampton University)
→ Incident track angle to ~0.5 mr intrinsic; <5 mr mult.sc.
→ Third GEM to reject ghost tracks
→ Existing chambers from OLYMPUS



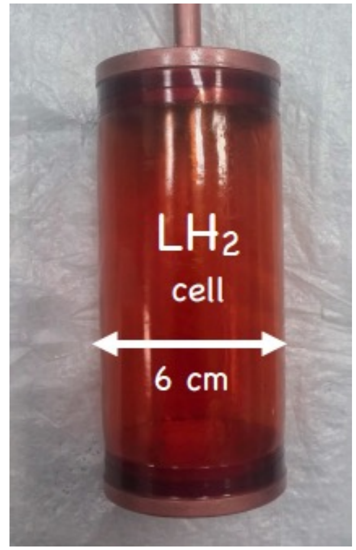
SiPM + 2 mm thin scintillators

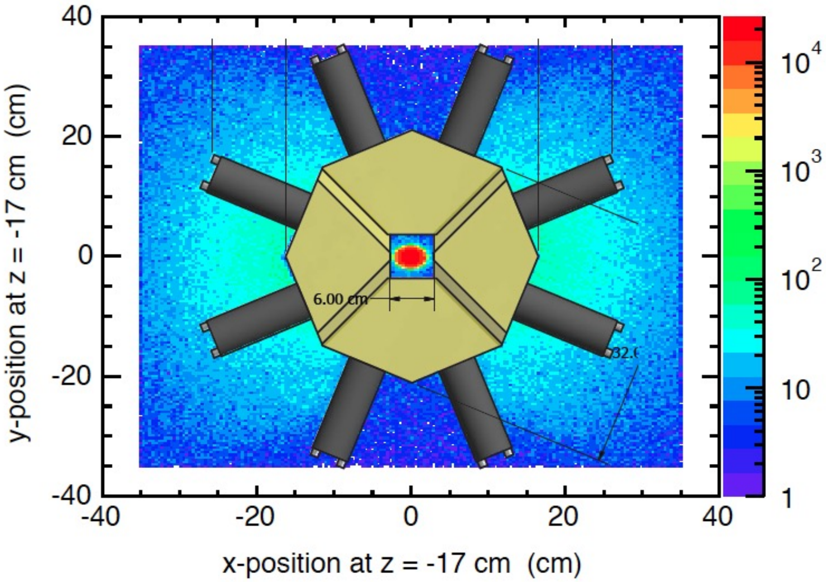
Thin scintillators with SiPM+CFD readout (PSI/Rutgers/TAU)
→ Fast timing (~60ps): RF time and scattered particle TOF
→ Flux, PID, Trigger, TOF, momentum
→ Reject false tracks in GEMs

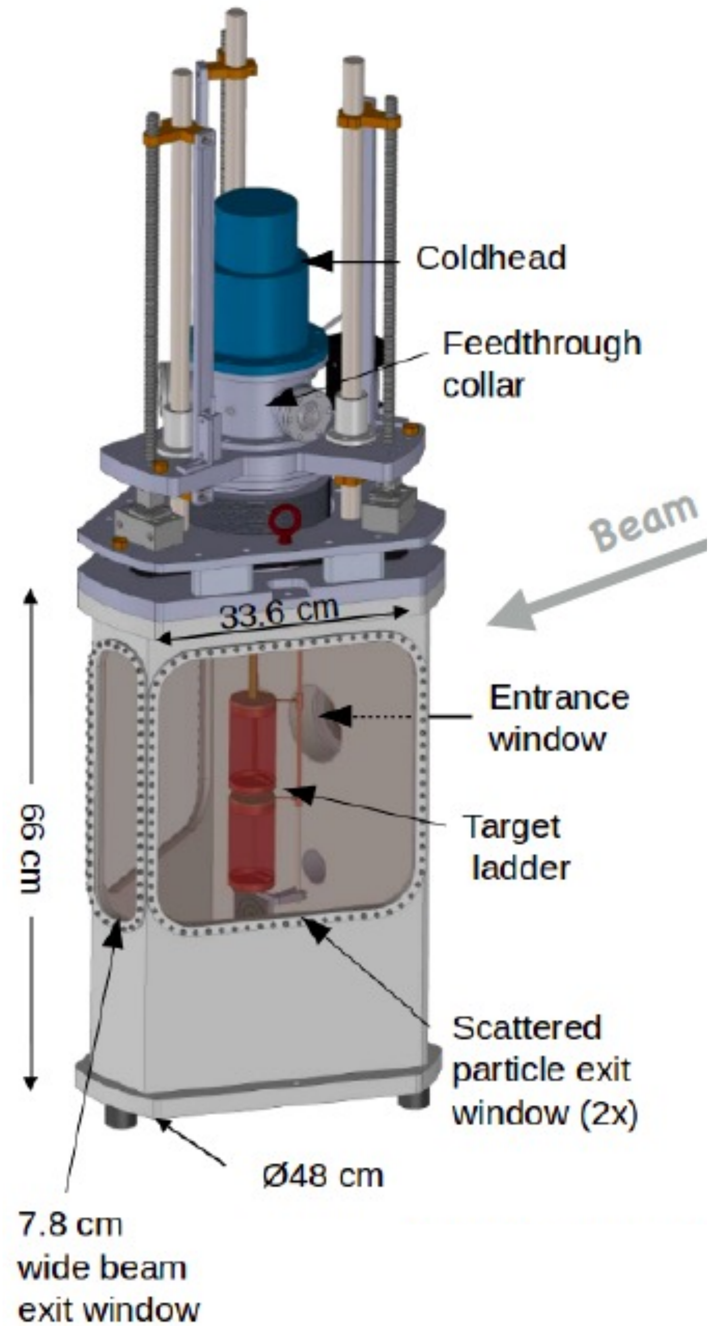
Target and veto

Low-power liquid hydrogen target
(UMich, GWU, Creare, PSI)

Target cell prototype







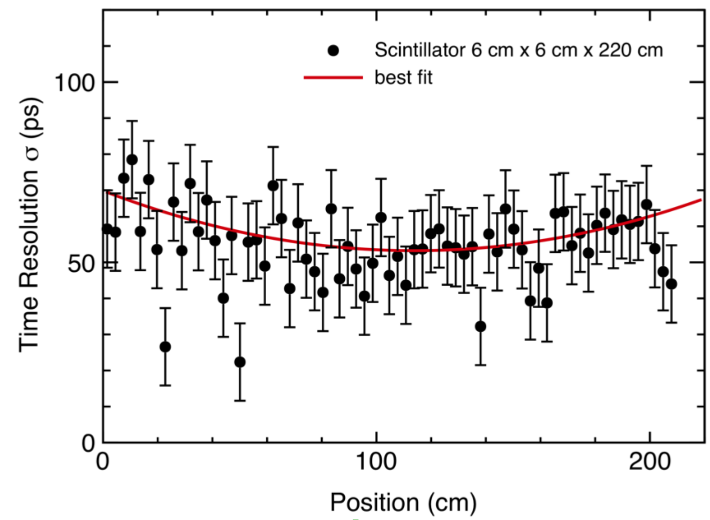
Veto scintillators (USC):

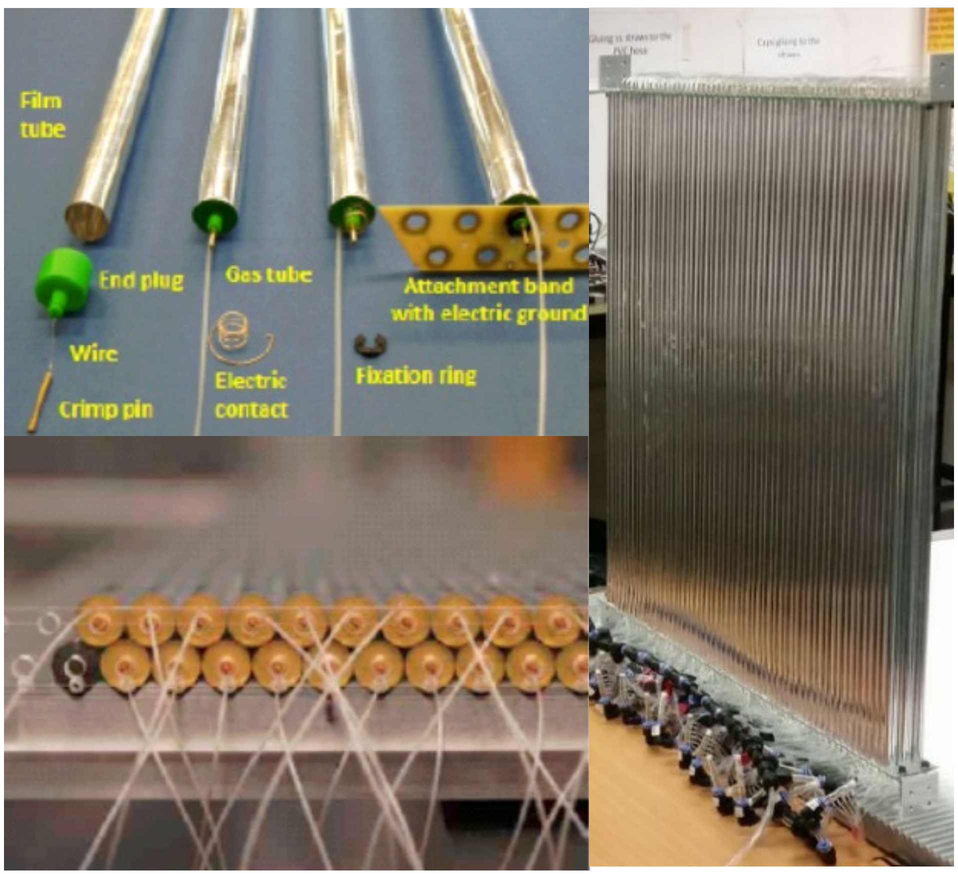
Annullar veto ring defines accepted beam aperture, smaller than transverse target cell diameter (6 cm)

Main detector instrumentation

Scattered particle scintillators (USC)

- 2 planes of scintillators (CLAS12 design)
- 94 bars (2 sides + beam)
- High precision (~50 ps) timing
- PID and trigger, background rejection



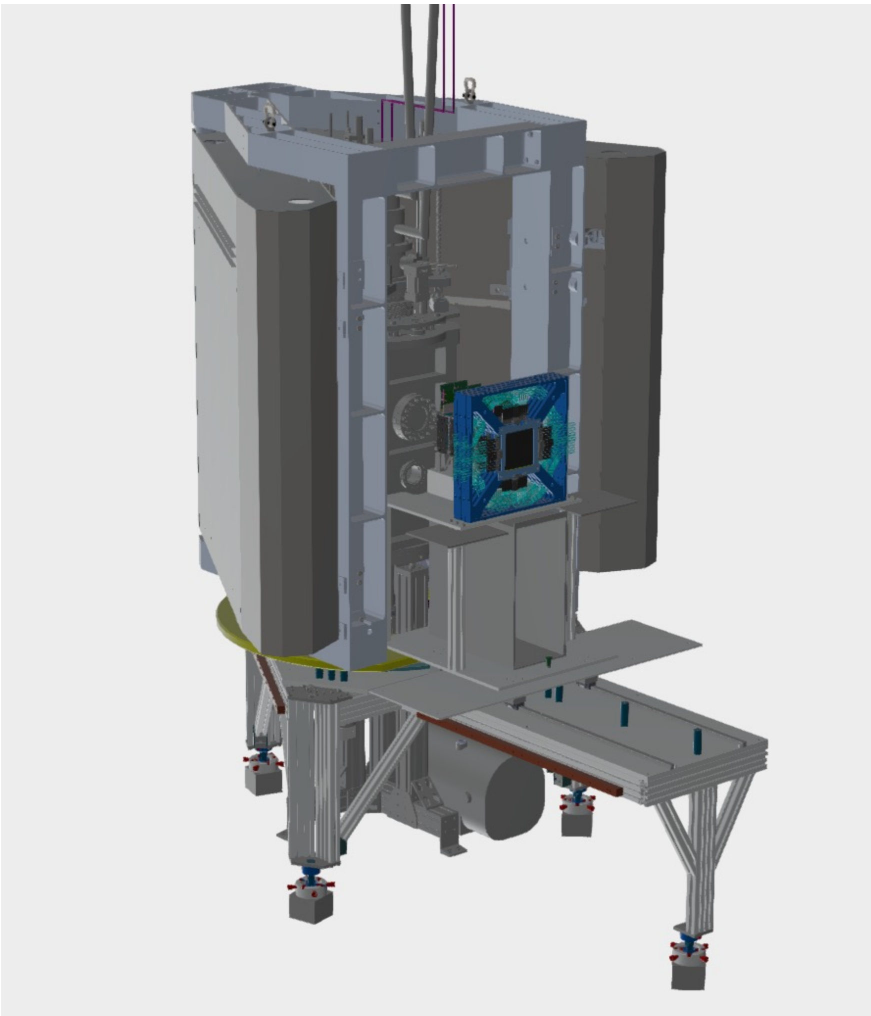


Straw tube tracker (HUJI, Temple)

- Straw Tube Tracker (STT), ~3000 straws
- Determine scattered particle trajectory
- Existing PANDA design – 140 μm resol.
- Thin walls (25μm), overpressured (2 bar)
- Directly coupled to fast readout boards

Mechanical assembly

T. O'Connor **(ANL)**

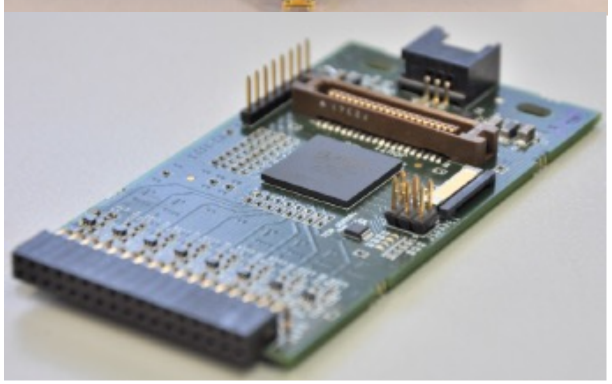


Rotating table
Retractable beam tracker
Dedicated alignment procedures

DAQ and trigger

DAQ system (GWU and Montgomery Coll.)

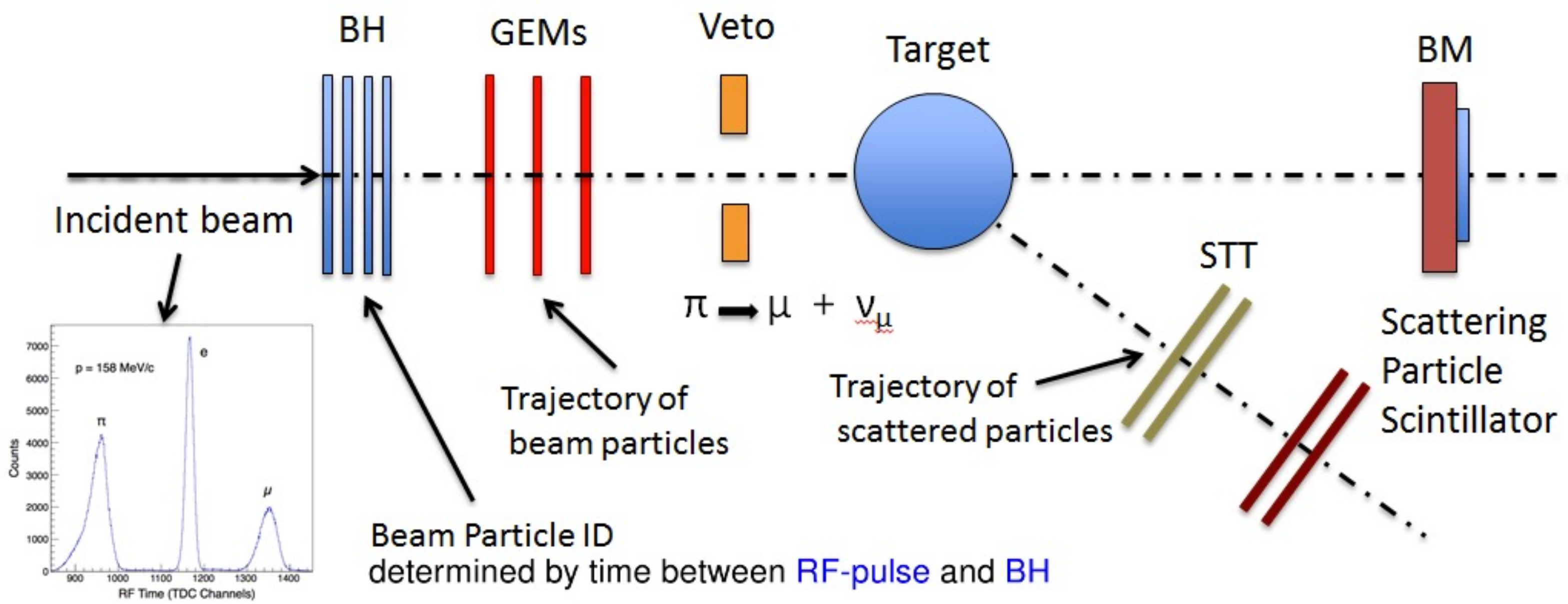
- FPGAs as frontend discriminator/amplifier, custom designed TDCs (PADIWA/TRB3)
- High channel density (192ch/board)
- VME QDCs (MESYTEC)



Trigger (Rutgers)

- FPGA design for beam PID (TRB3)
- Beam hodoscope + beam RF → beam PID
- Count particles and reject pions
- e or μ beam part. + scattered part. + no veto

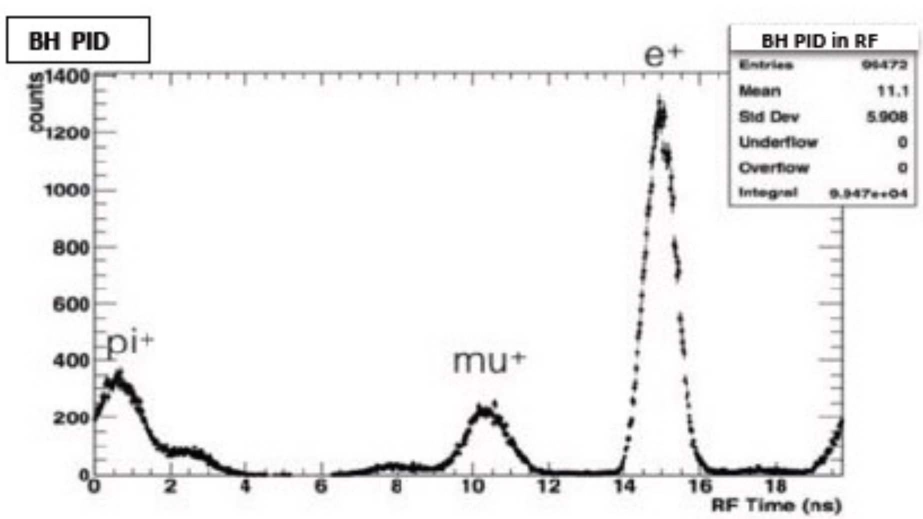
Trigger with pion rejection

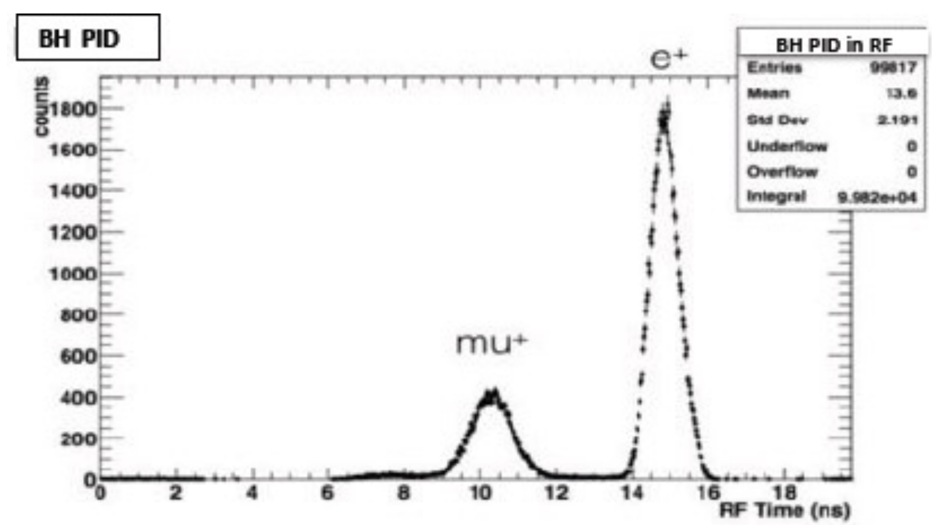


Trigger Logic: TRB3 FPGA-based:

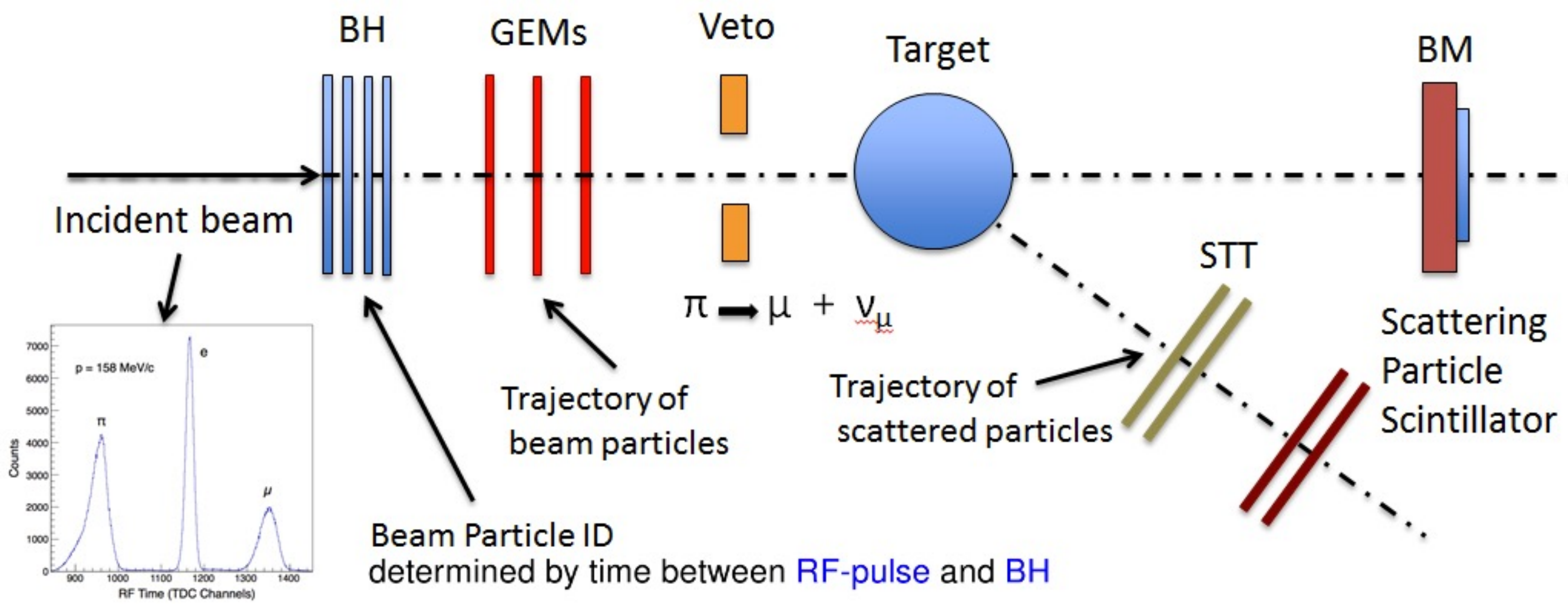
accept $e^{\pm}, \mu^{\pm}$, reject $\pi^{\pm}$

(e OR μ) AND (no π) AND (scatter) AND (no veto)





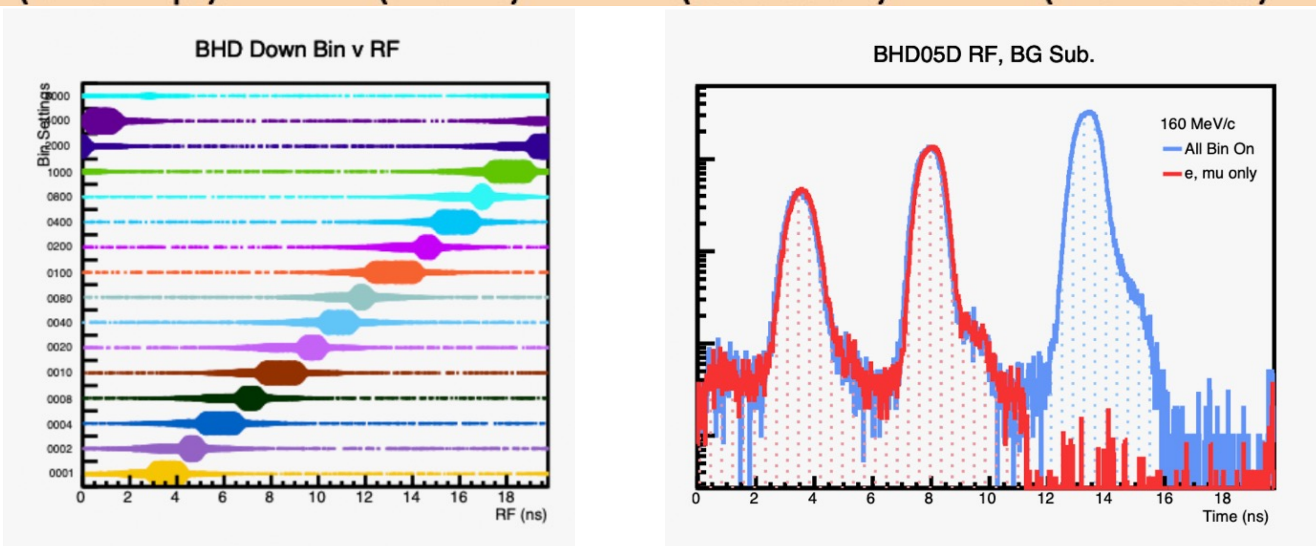
Trigger with pion rejection



Trigger Logic: TRB3 FPGA-based:

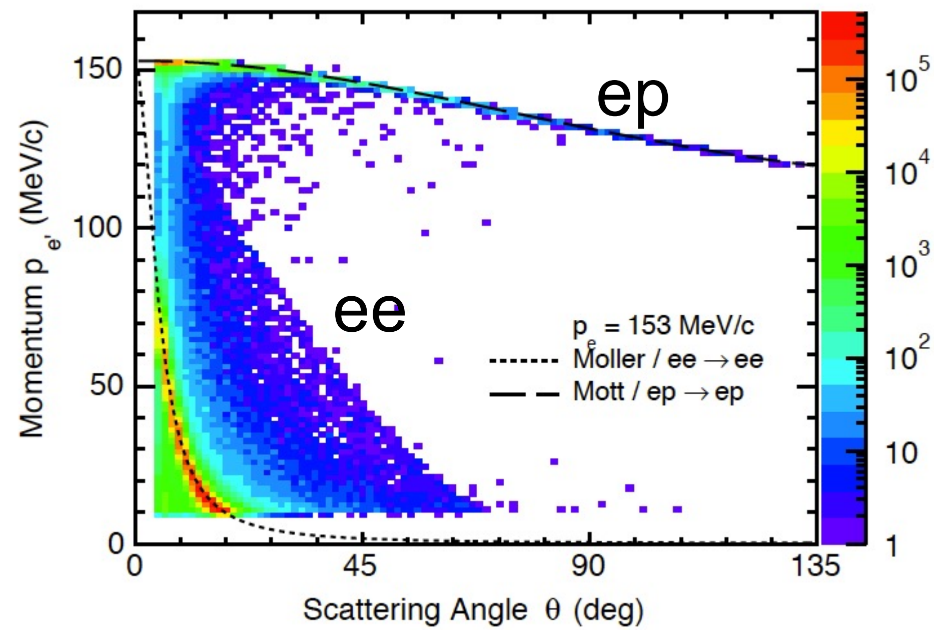
accept $e^{\pm}, \mu^{\pm}$, reject $\pi^{\pm}$

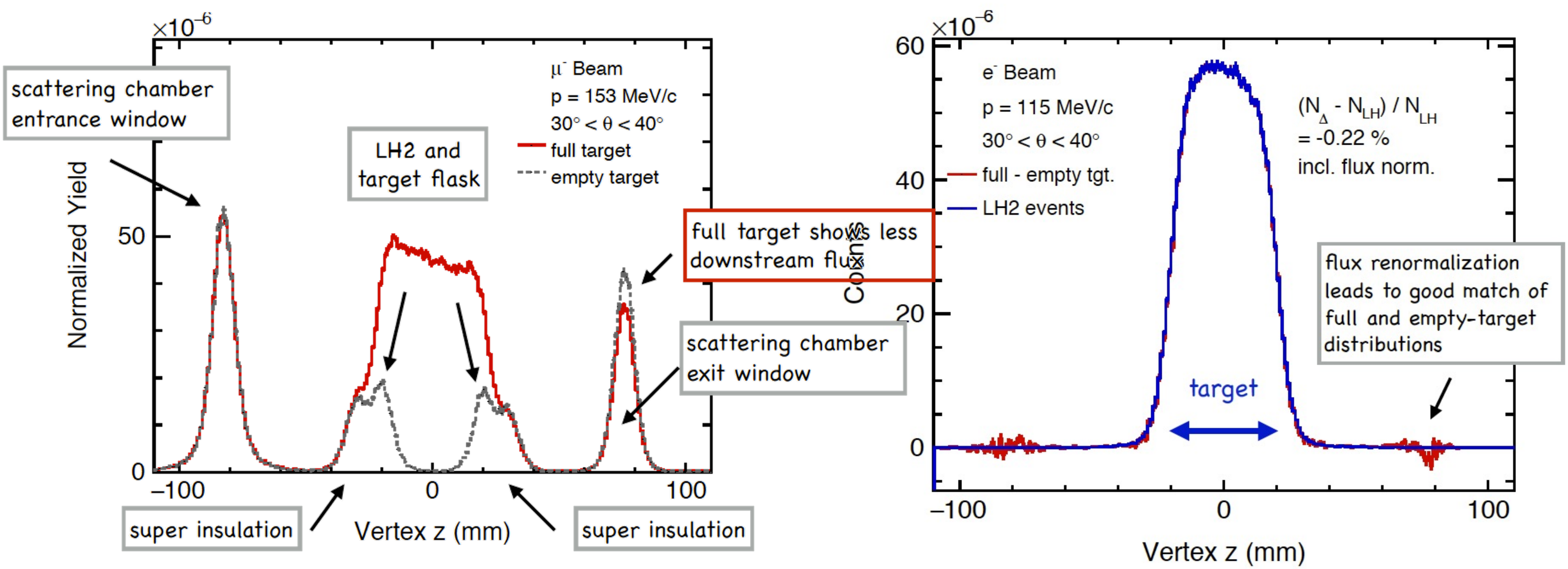
(e OR μ) AND (no π) AND (scatter) AND (no veto)



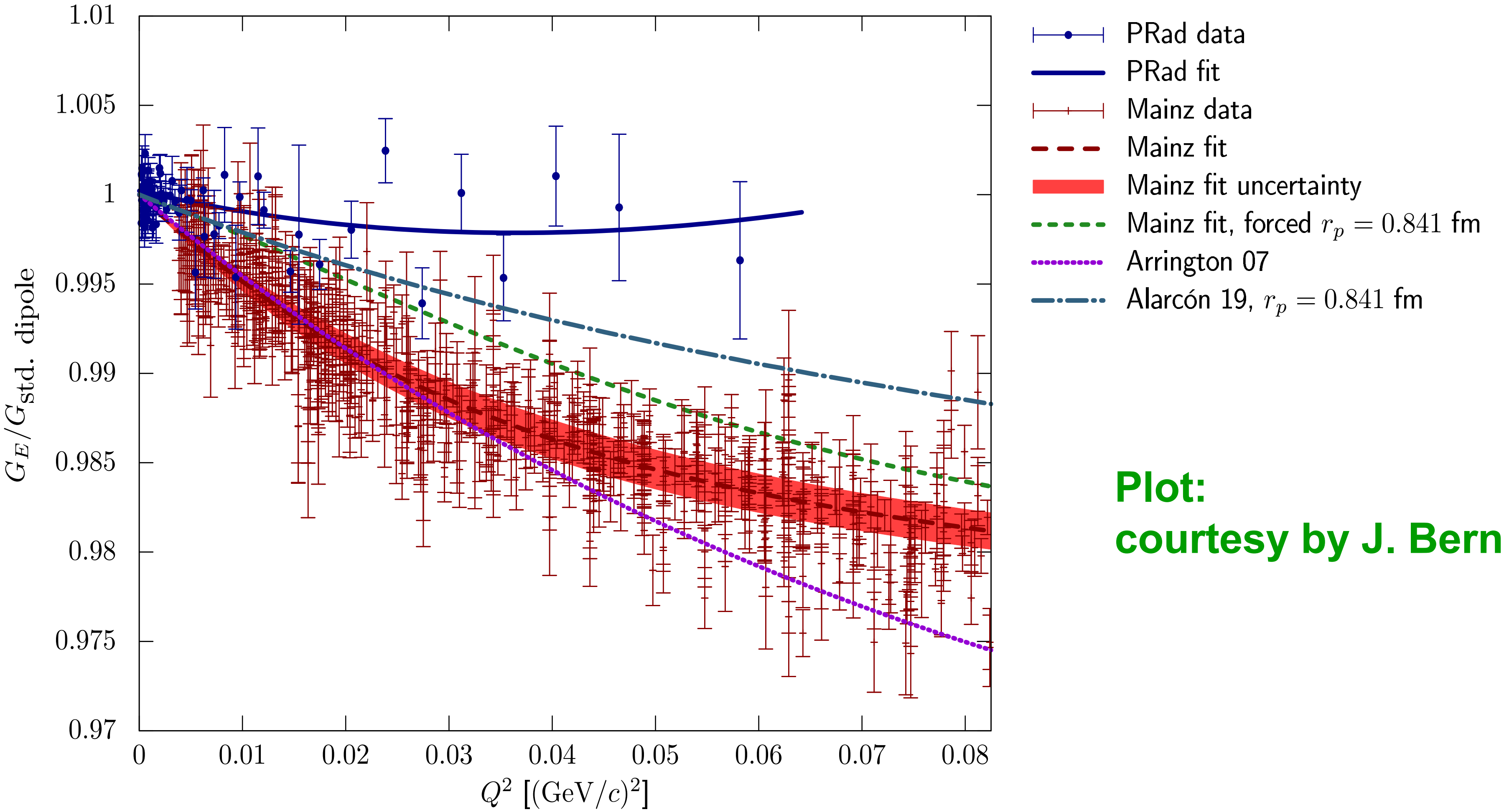
Simulations (S. Strauch, USC)

- Particle vertex and scattering-angle reconstruction meet MUSE requirements
- Background from target walls and windows can be cleanly eliminated or subtracted



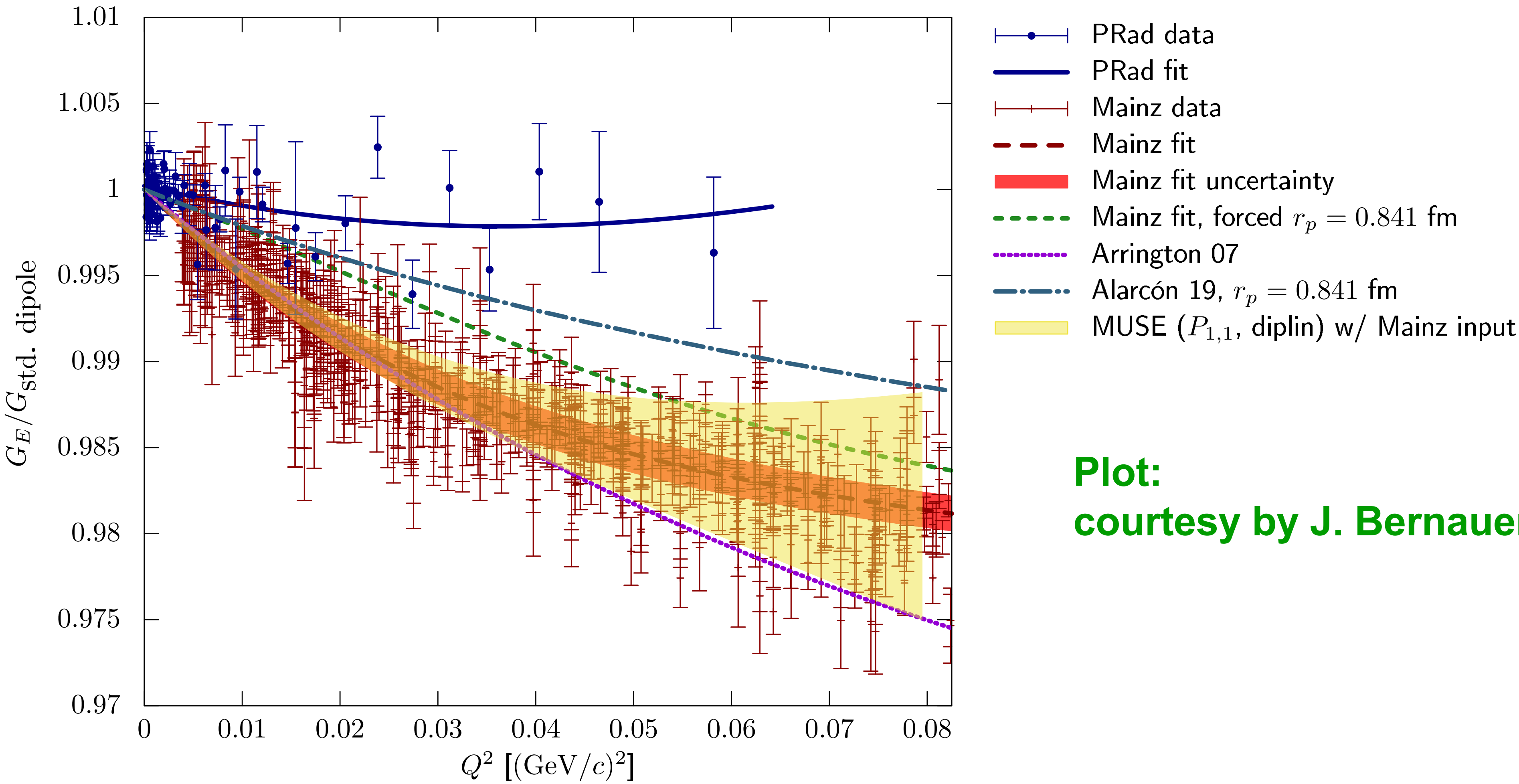


MUSE projected sensitivity: G_E



Plot: courtesy by J. Bernauer

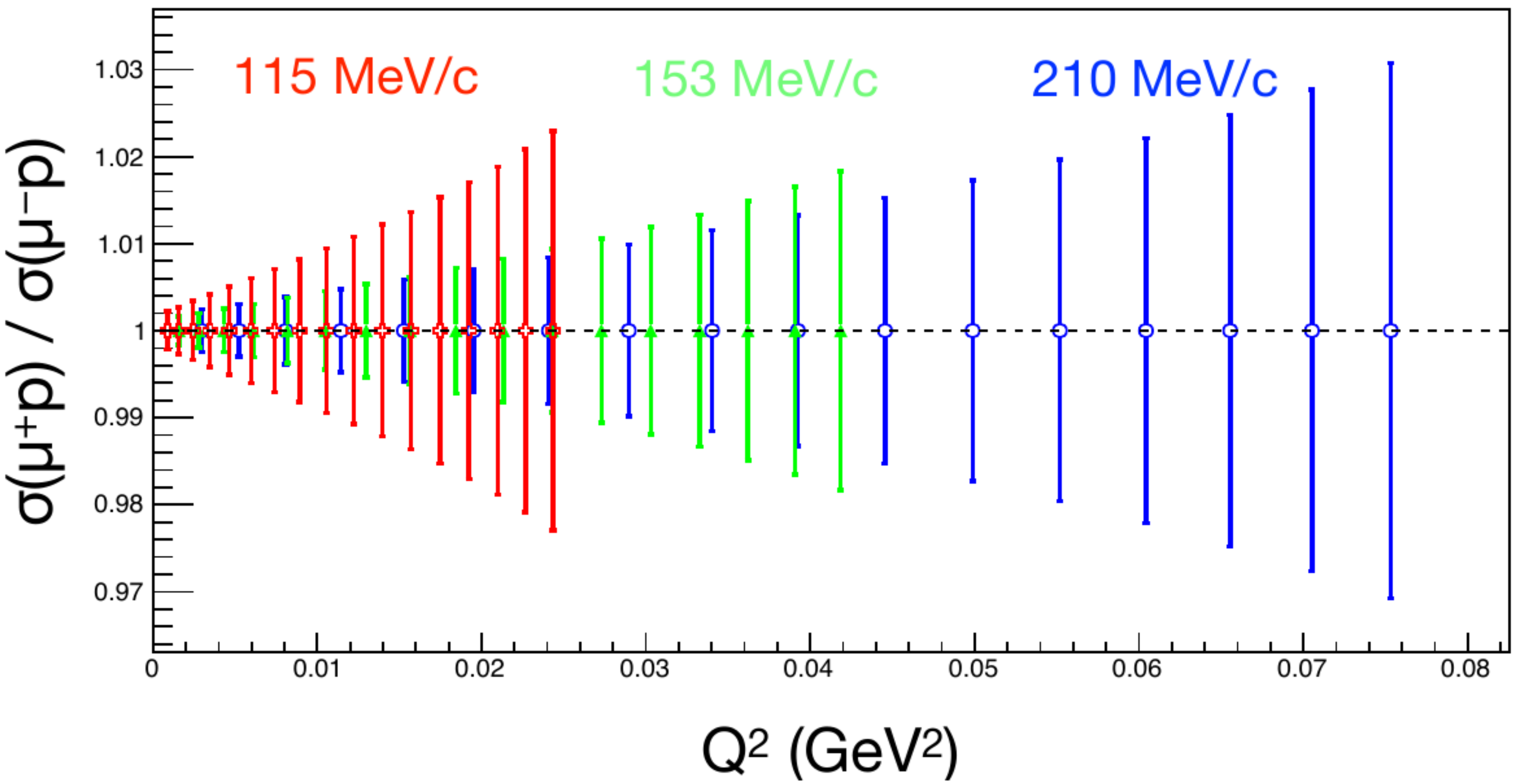
MUSE projected sensitivity: G_E



Plot: courtesy by J. Bernauer

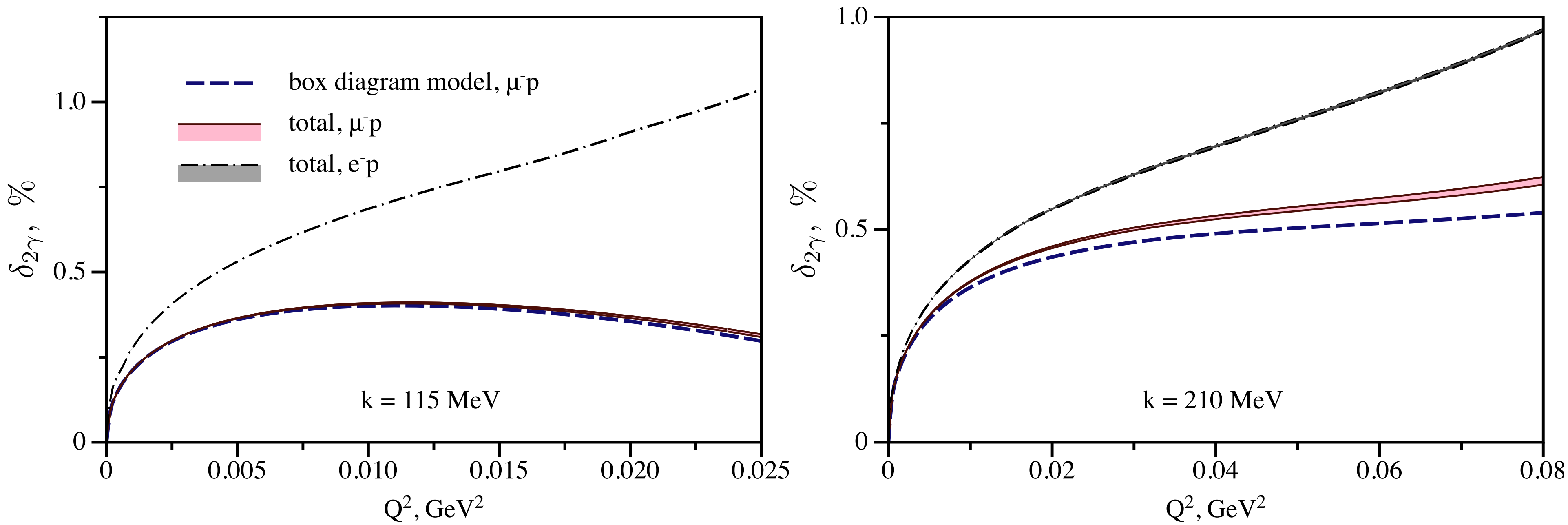
- **Error band projected for MUSE data, using G_E and G_M from Mainz**

MUSE: expected precision for TPE (muons)



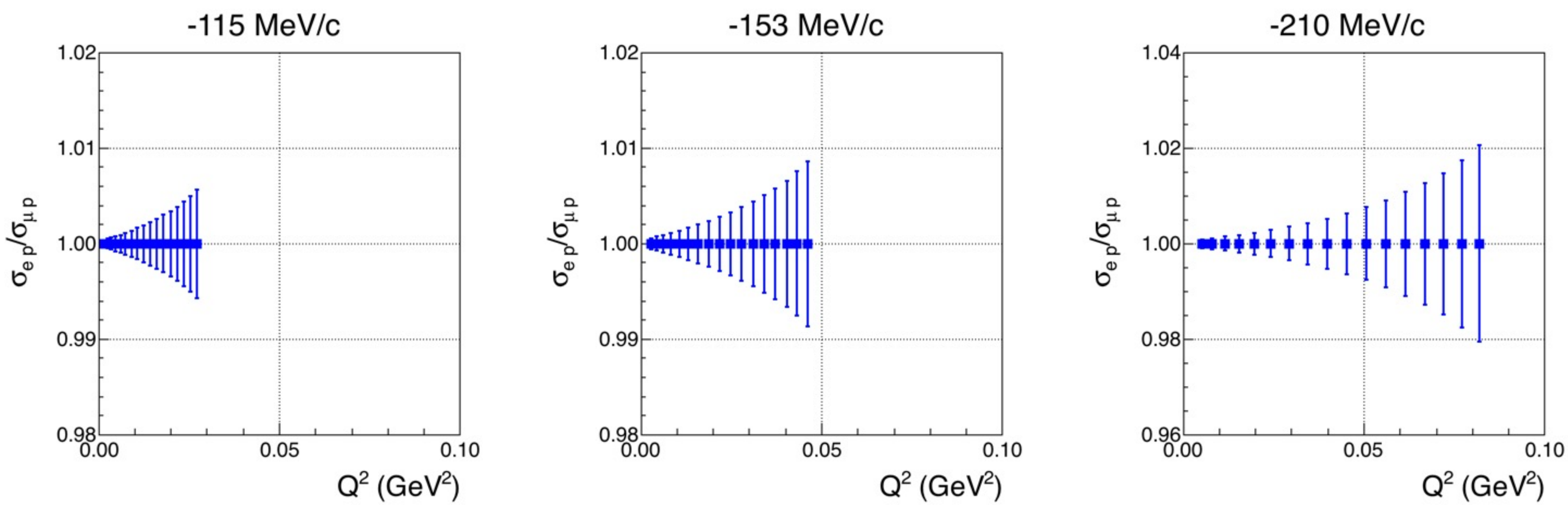
- **Investigation of e+/e-, μ+/μ-**
- **Direct measurement of 2-photon effects**
- **TPE for muons could be sizable; for e+/e- expect sub-percent**

MUSE: expected theory for TPE



- **Investigation of e+/e-, μ+/μ-**
- **Direct measurement of 2-photon effects**
- **TPE for muons could be sizable; for e+/e- expect sub-percent**
- **TPE even smaller for muons (helicity-flip and non-flip cancel)**
  O. Tomalak, Few-Body Systems, 59, 87 (2018)

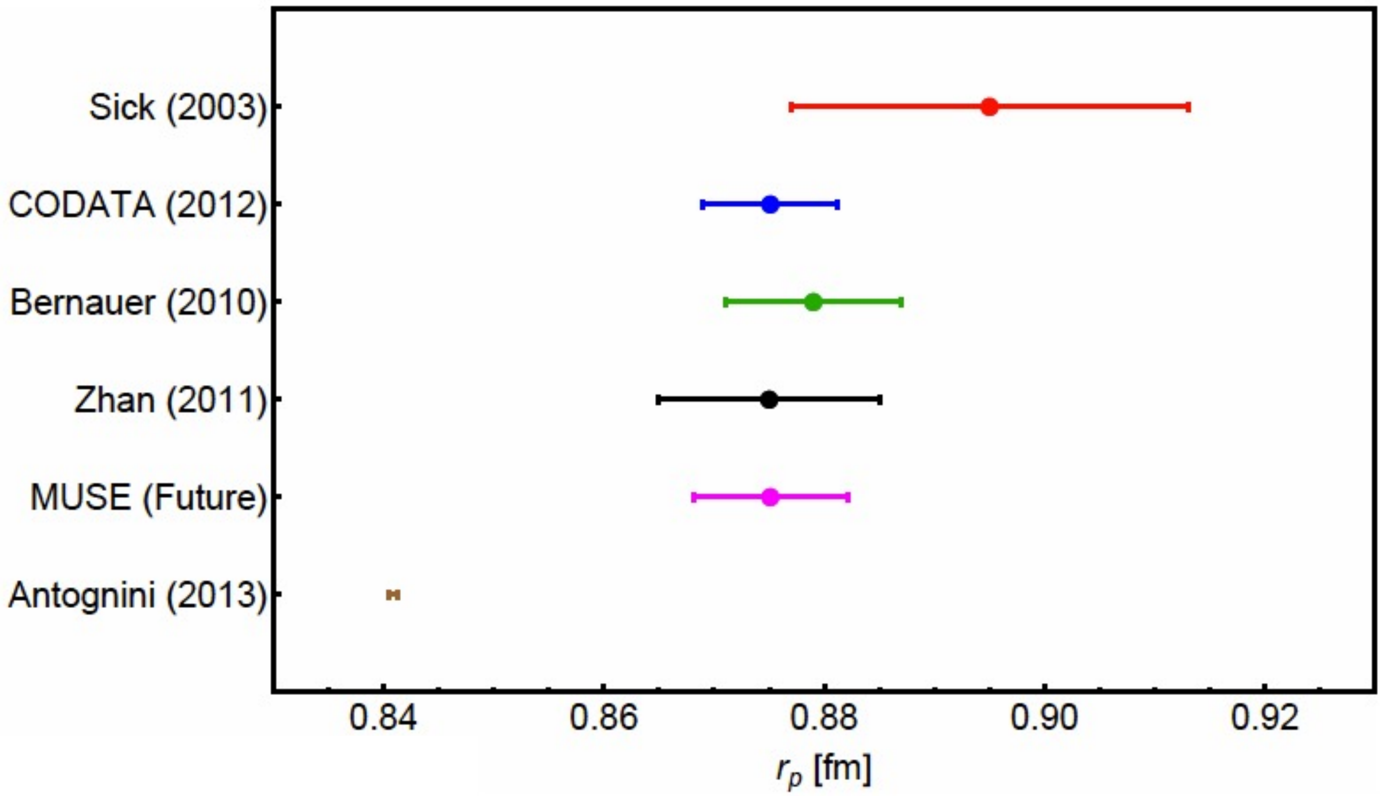
MUSE: expected precision for LU ratio



- **Comparison of ep and μp cross section statistical uncertainty, systematic better than 0.5%**
- ***The MUon Scattering Experiment at PSI (MUSE),* MUSE Technical Design Report, arXiv:1709.09753 [physics.ins-det]**

MUSE: expected precision for charge radius

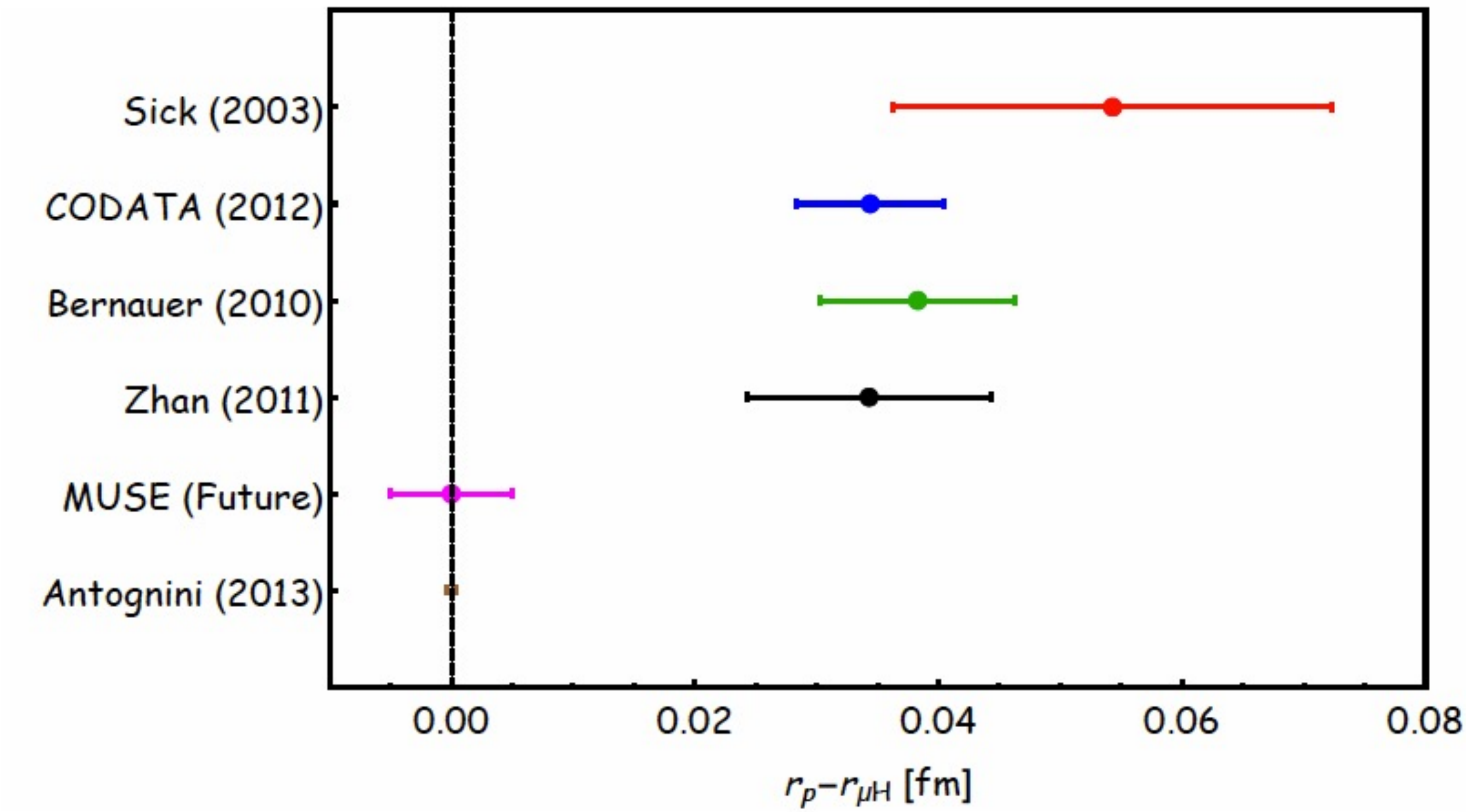
- **Cross sections** to <1% stat. for backward μ, <<1% for e and forward μ
  Absolute 2%, point-to-point relative uncertainties **few x10^{-3}**
- **Individual radius extractions** from $e^{\pm}$, $\mu^{\pm}$ each to **0.010 fm**
- Compare $e^{\pm}p$ and $\mu^{\pm}p$ for TPE. Charge-average to eliminate TPE.
- From e/μ xsec ratios: extract **e-μ radius difference** with minimal truncation error to **0.0045 fm or ~8σ** (1st-order fits)
- If no difference, extract **combined radius to 0.007 fm** (2nd-order fit)



MUSE: expected precision for radius diff.

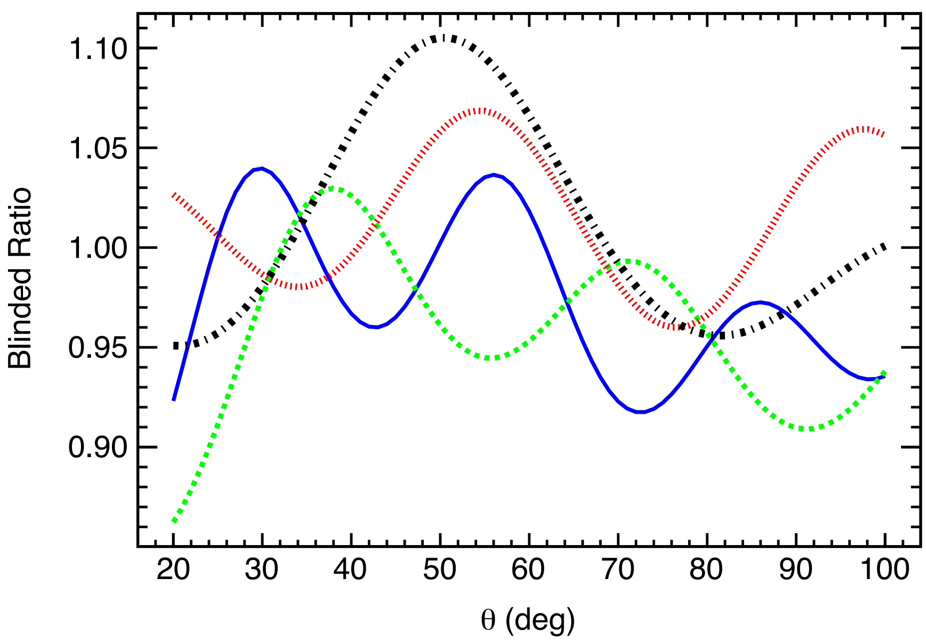
- Charge radius extraction limited by systematics, fit uncertainties
- Many uncertainties are common to all extractions in the experiment: Cancel in e+/e-, μ+/μ-, and μ/e comparisons
- R_e-R_μ = 0.034±0.006 fm (5.6σ), **MUSE: δ(R_e-R_μ) = 0.0045 fm (7.6σ)**

MUSE suited to verify 5.6σ effect (CODATA2014) with 7.6σ significance



MUSE performance: data are blinded

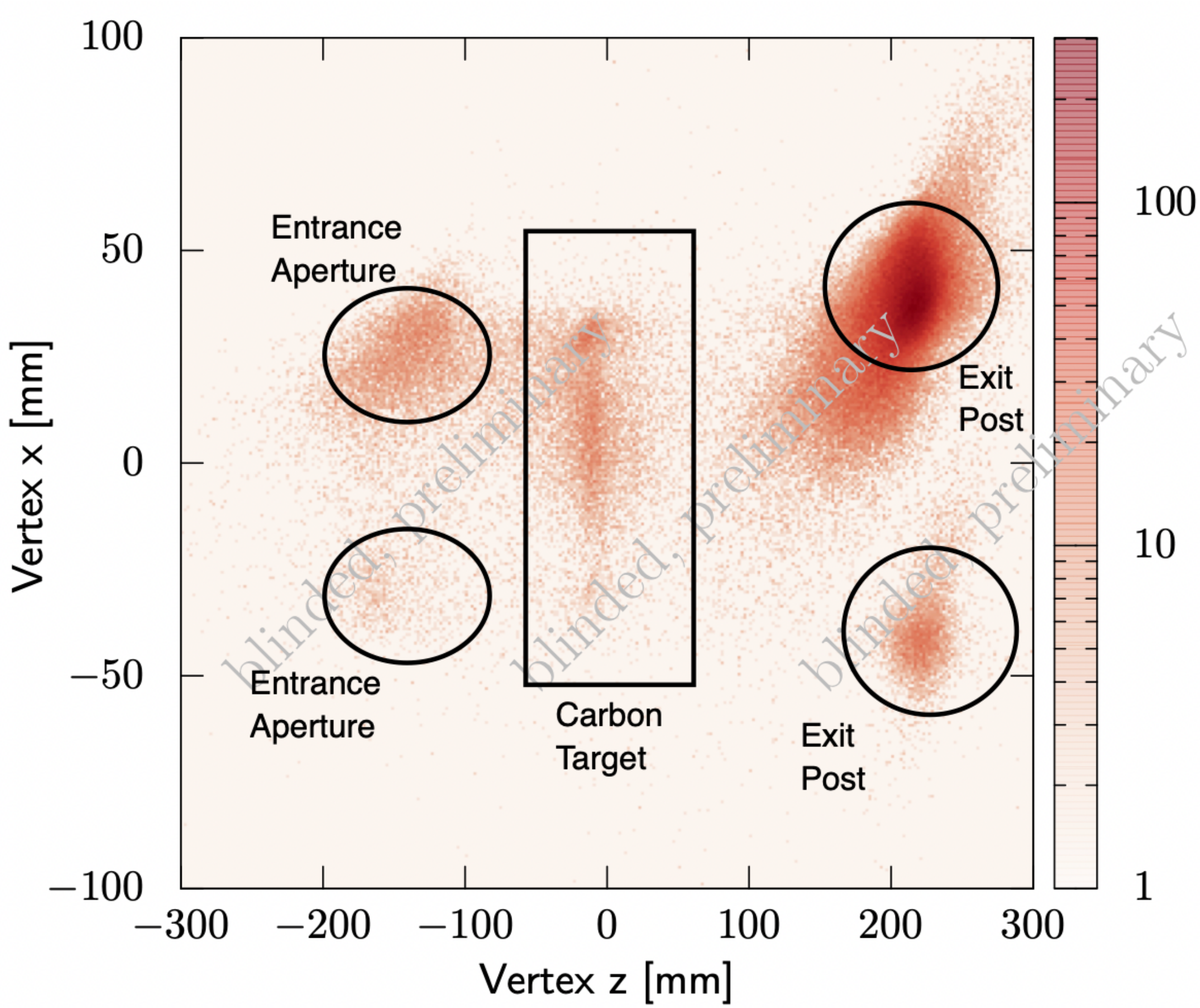
J.C. Bernauer *et al.*,
Blinding for precision scattering experiments: The MUSE approach as a case study
https://doi.org/10.48550/arXiv.2310.11469



- Four randomly generated blinding examples
- Randomized fractions of tracks suppressed
- Data and simulation blinded independently
- Change of ratios >> expected size of physics
- Data/MC, TPE (+/-), LU (e/μ)

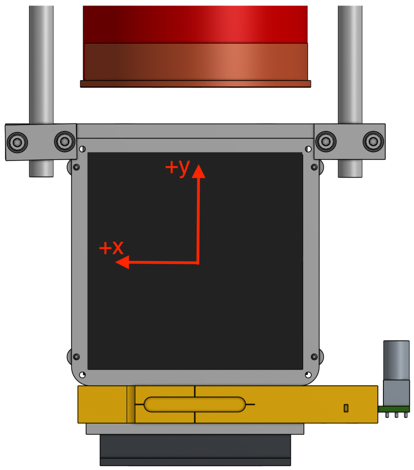
MUSE performance: $e^{\pm}$ scattering from C

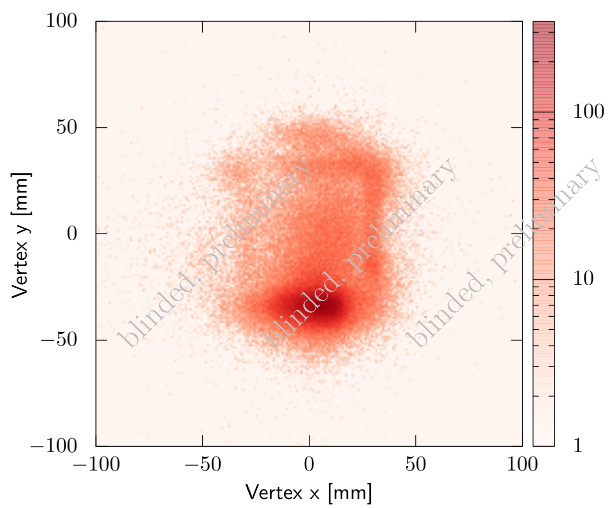
e^{-}C and e^{+}C scattering at 115 MeV/c , 14M events (7 runs, 2022 data)

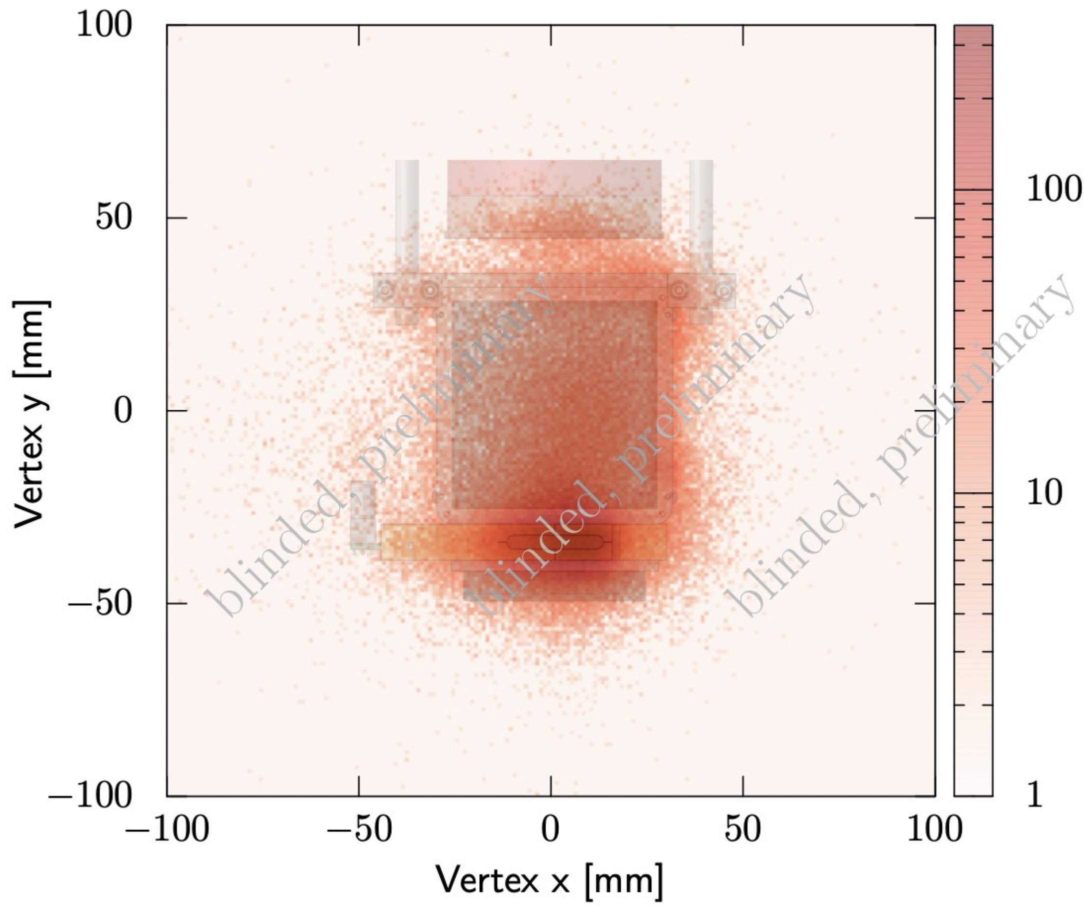


Cut on |y| < 25 mm. Carbon target x y z vertex reconstruction

MUSE performance: e$^{\pm}$ scattering from C



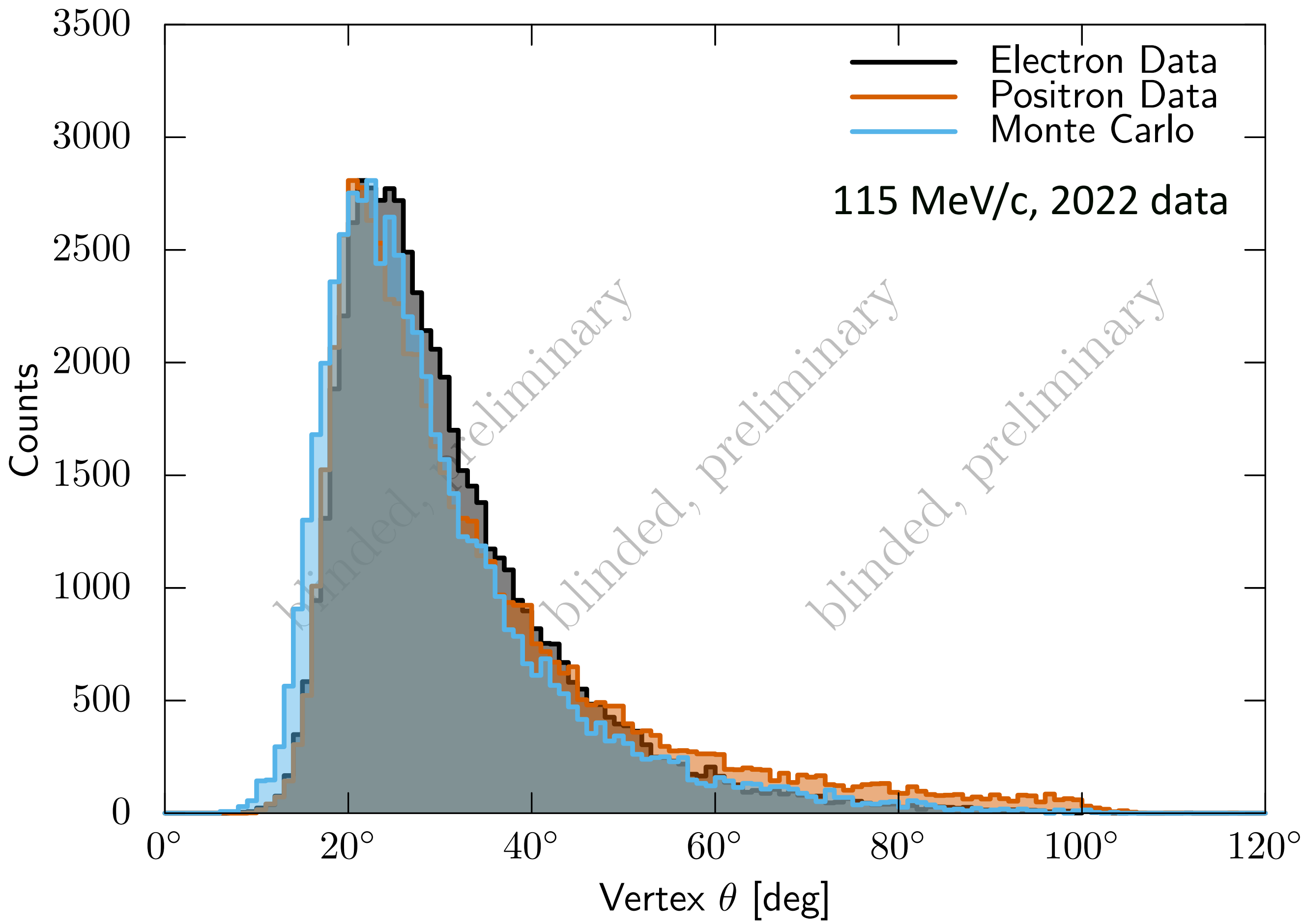




Cut on |z| < 80 mm. Carbon target y vs. x vertex reconstruction (+x toward beam-left)

MUSE performance: e± scattering from C

Counts vs. scattering angle



Cut on |x| < 25 mm, |y| < 25 mm, and |z| < 80 mm

Blinded data!

Monte Carlo in progress

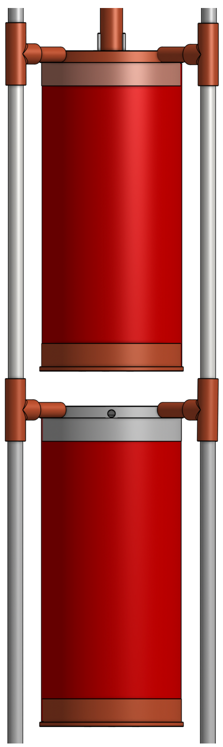
MUSE performance: e^+ scattering from LH2

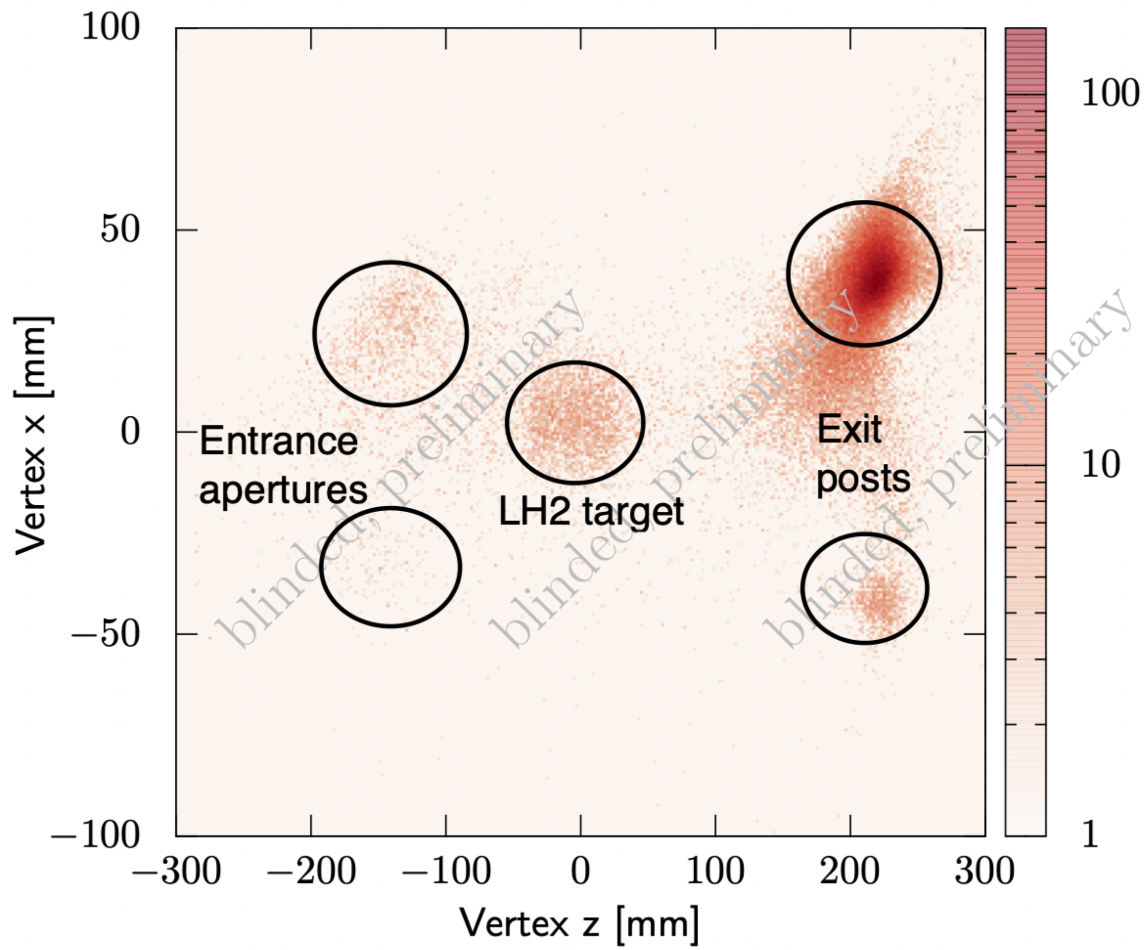
e^+ scattering from LH2 at +160 MeV/c
2022 data: initial vertex analysis

Top:
filled with LH_2

Bottom:
empty cell

6 cm diameter
13.7 cm tall



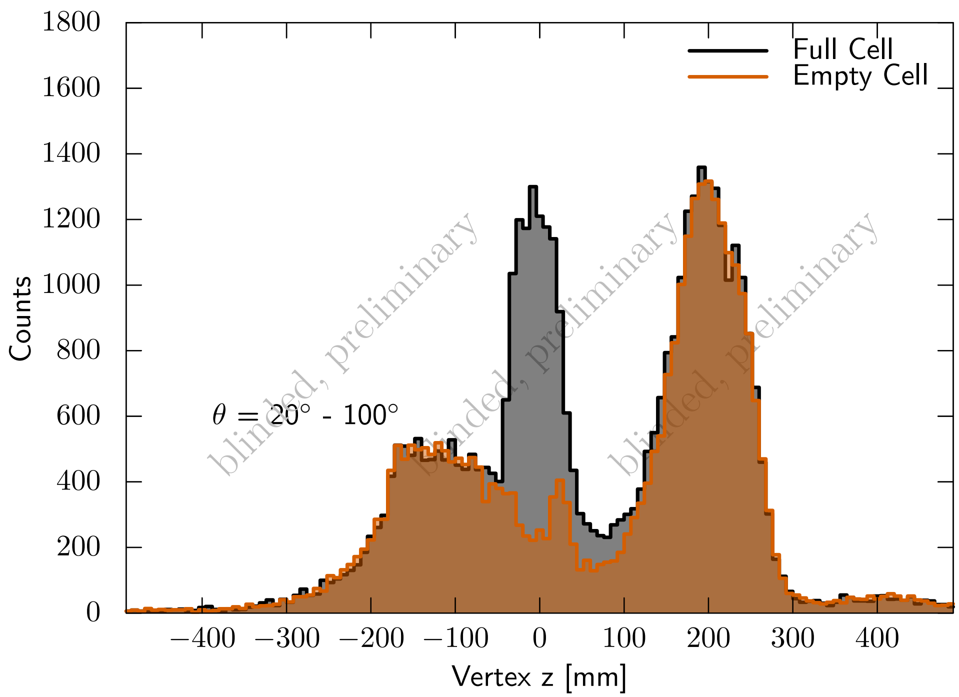


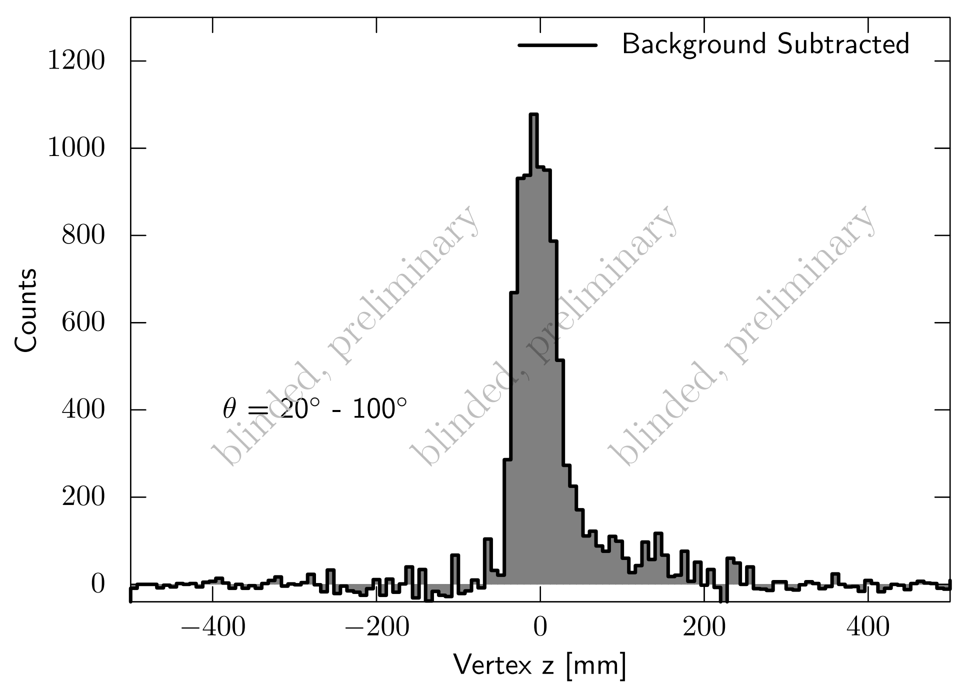
Cut on |y| < 50 mm

MUSE performance: scattering from LH2

+160 MeV/c, full vs. empty target, reconstructed vertices

2022 data: initial vertex analysis





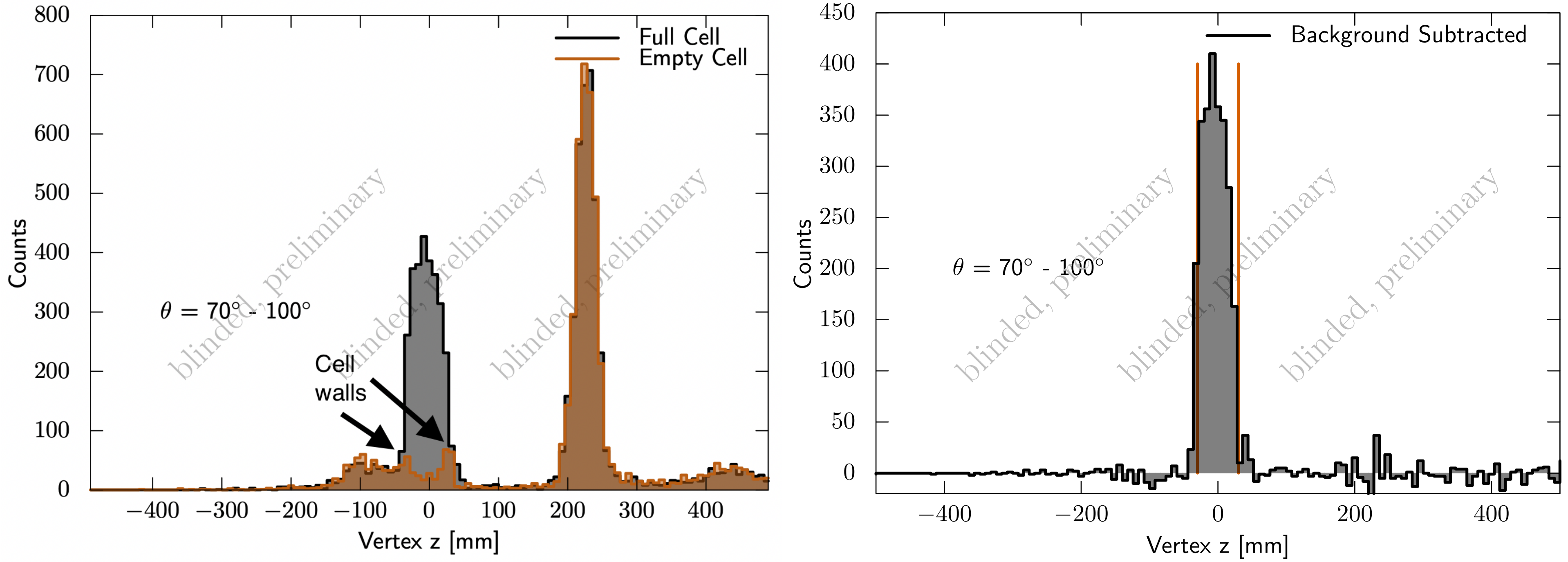
Cut on |x| < 25 mm, |y| < 25 mm, 20 < θ < 100

Localized backgrounds, more pronounced at forward angles

MUSE performance: scattering from LH2

+160 MeV/c, full vs. empty target, reconstructed vertices

2022 data: initial vertex analysis



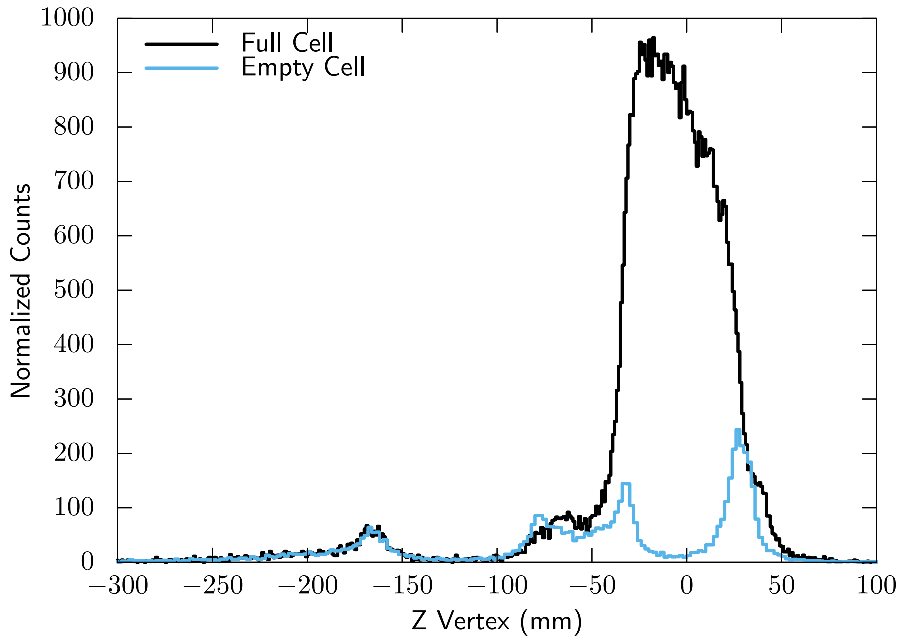
Cut on |x| < 25 mm, |y| < 25 mm, 70 < θ < 100

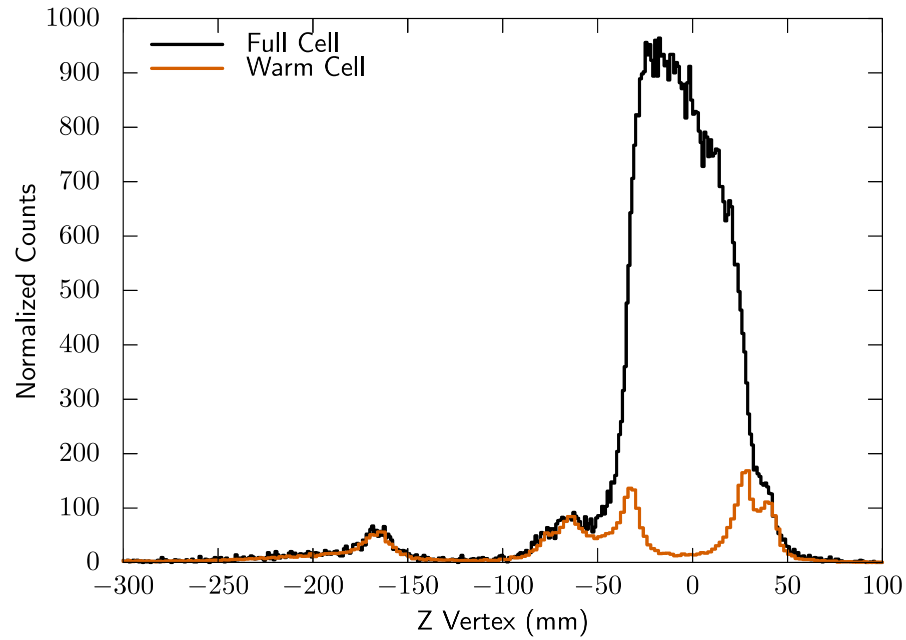
Localized backgrounds, more pronounced at forward angles

MUSE performance: scattering from LH2

+210 MeV/c, full vs. empty and warm target, reconstructed vertices

2023 data: improved vetoing, improved vertex analysis





Cut on |x| < 20 mm, no |y| cut, max angular range 20 < θ < 100

MUSE performance: scattering from LH2

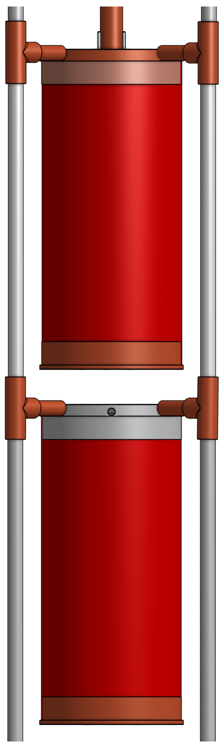
+210 MeV/c, full vs. empty and warm target, reconstructed vertices

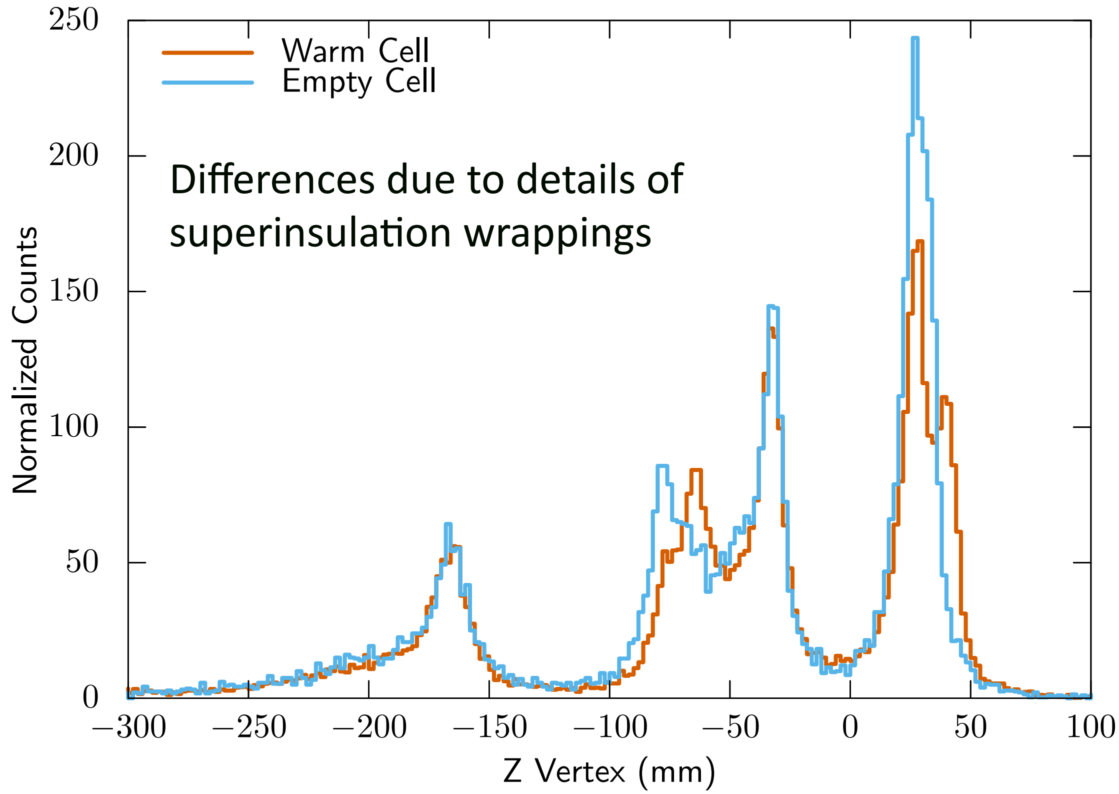
2023 data: Improved target post vetos, improved vertex analysis

Top:
warm cell

Bottom:
empty cell

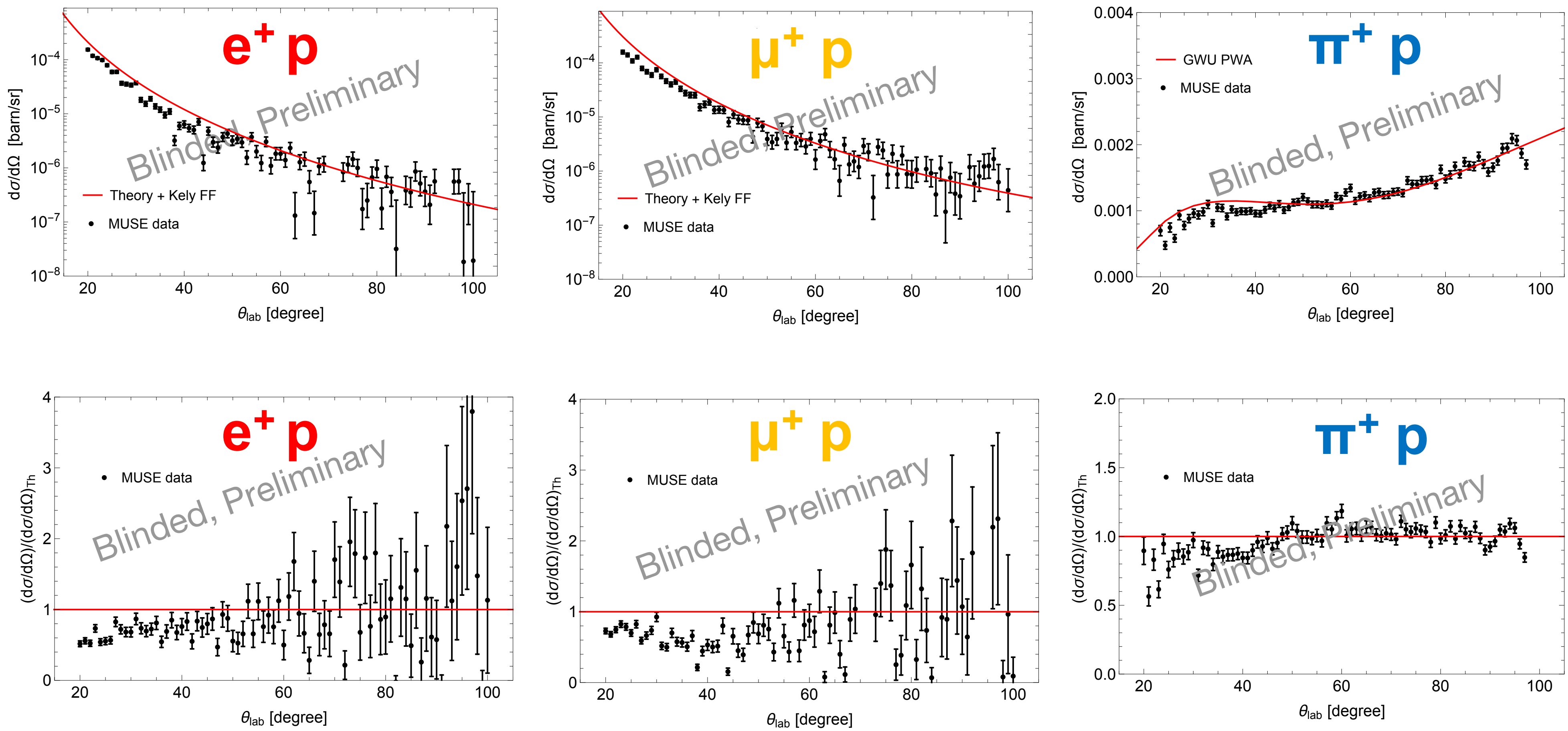
6 cm diameter
13.7 cm tall





Cross sections for +160 MeV/c

Two independent analyses: W. Lin (Rutgers); I. Lavrukhin (U Mich., shown here)



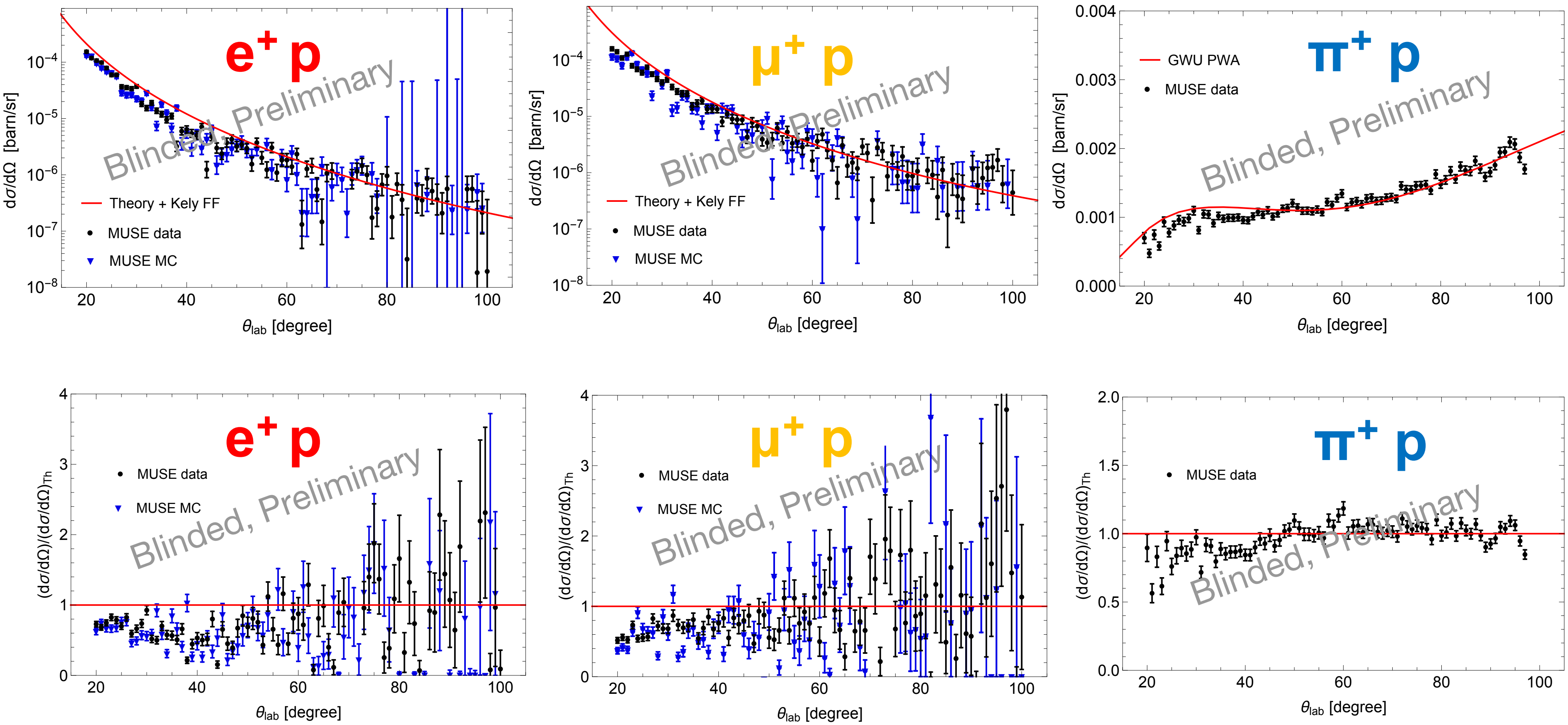
Data:

Acceptance, target thickness nominal

$$\frac{d\sigma}{d\Omega} = \frac{N_{scat}(p,\theta)}{N_{inc} \times (x\rho)_{target} \times \Omega_D \times \epsilon_{total}}$$

Cross sections for +160 MeV/c

Two independent analyses: W. Lin (Rutgers); I. Lavrukhin (U Mich., shown here)

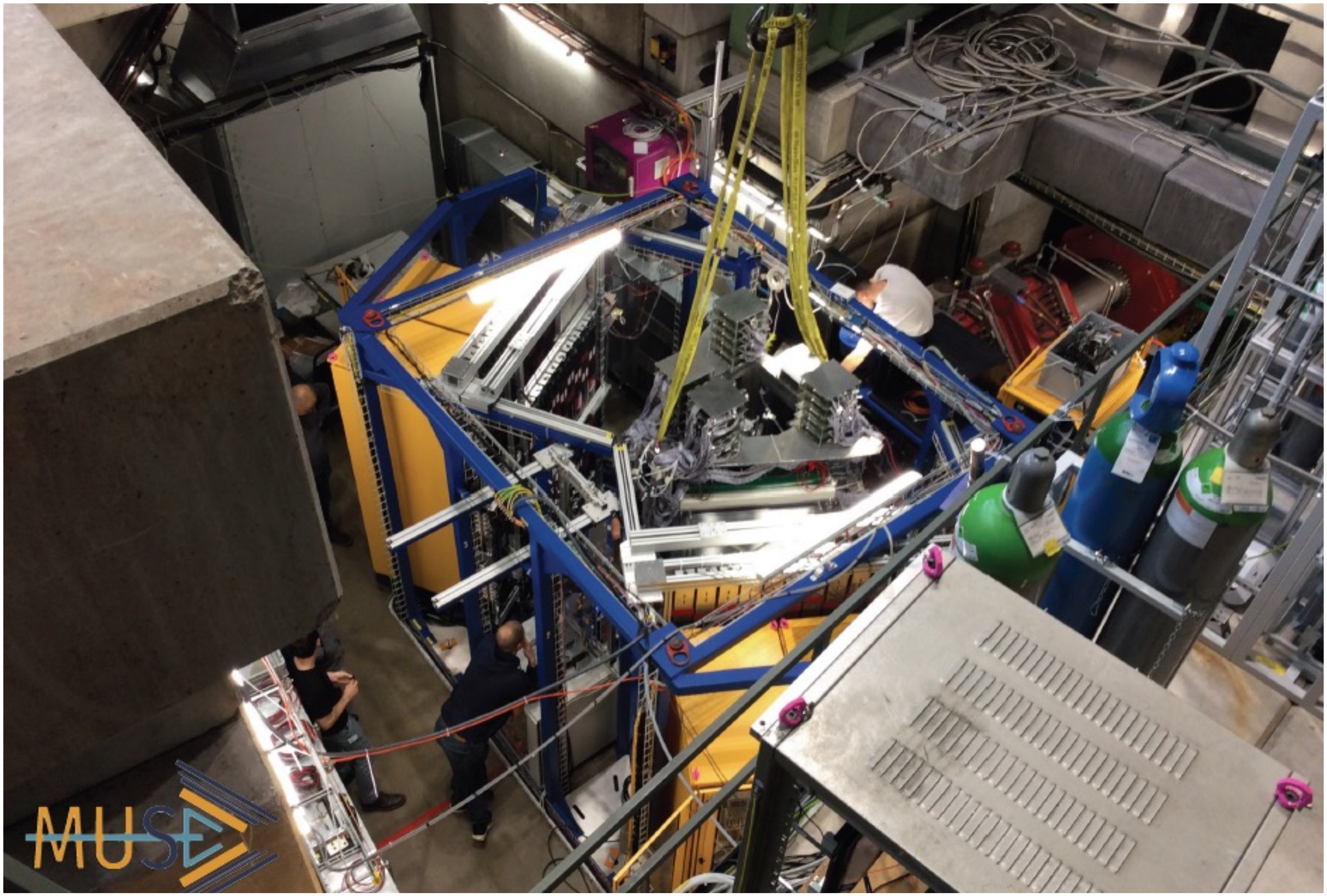


MC:
Acceptance, target thickness nominal, without radiative correction

$$\frac{d\sigma}{d\Omega} = \frac{N_{scat}(p,\theta)}{N_{inc}\times(x\rho)_{target}\times\Omega_D\times\epsilon_{total}}$$

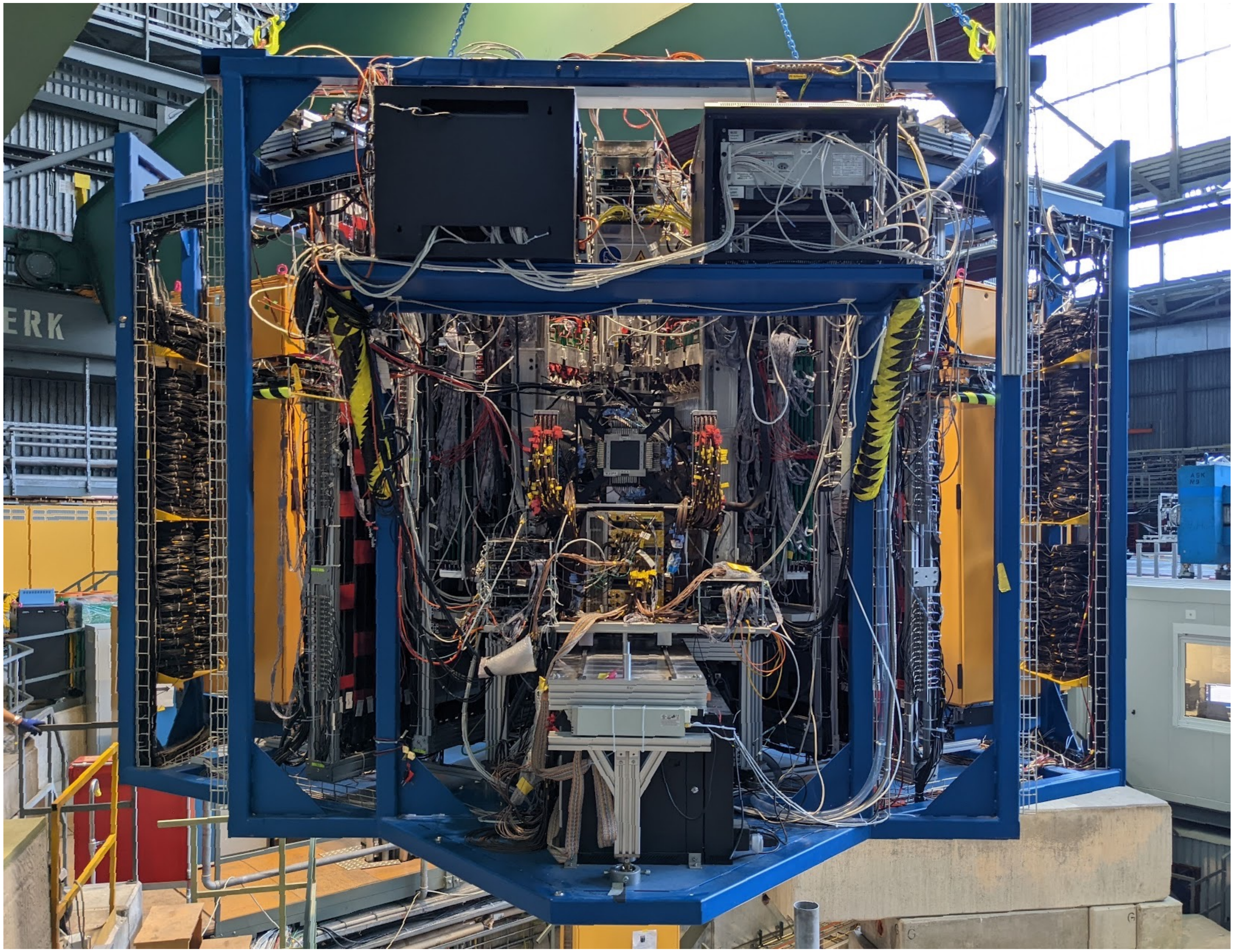
2018-2022 installation and commissioning

Dec. 2018: Assembly complete; Summer/fall 2019: Initial commissioning
Fall 2020-2022: Commissioning cont'd under Covid-19 constraints
From Sum. 2023: Start production data for 12 beam months over ~2 years



2023-2025: production data taking

Dec. 2018: Assembly complete; Summer/fall 2019: Initial commissioning
Fall 2020-2022: Commissioning cont'd under Covid-19 constraints
From Sum. 2023: Start production data for 12 beam months over ~2 years



MUSE

MUSE timeline and status

- Proton radius puzzle not solved in 2023 – 13 years later
- Lepton non-universality in the center of beyond-SM effects

- MUSE first proposed in 2012, PAC-approved in 2013
- R&D program with NSF, BSF, and DOE support 2014 – 2016

- Technical design report November 2015
- Collaborative funding proposal to NSF in Nov 2015: Mid-scale
- NSF technical review February 2016

- Target conceptual design March 2016
- MOU with PSI April 2016
- Project management review May 2016 → award recommendation!

- Funding for construction has begun in fall 2016
- Construction and commissioning of MUSE 2016-2022
- Initial scattering data collected in Fall 2021 and Fall 2022

- Data taking for 12 calendar months – 5 months in 2023 approved

MUSE current status

- **MUSE took 14 weeks of production data taking since June 2023**
- **Additional 3 weeks scheduled in late Nov/early Dec 2023**
- **Took initial data at 115 MeV/c in Fall 2022**
- **This year (2023) focused on 210 and 160 MeV/c, under analysis**
- **Plan to continue data taking in 2024 and 2025**

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 experimen**t, 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

MUon Scattering Experiment – MUSE

MUSE

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. 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

PAUL SCHERRER INSTITUT

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, Technical University of Darmstadt, St. Mary's University, Soreq Nuclear Research Center, Weizmann Institute, Old Dominion University (April 2020)

Thank you!