MUSE:
The MUon Scattering Experiment

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THE GEORGE WASHINGTON UNIVERSITY
WASHINGTON, DC

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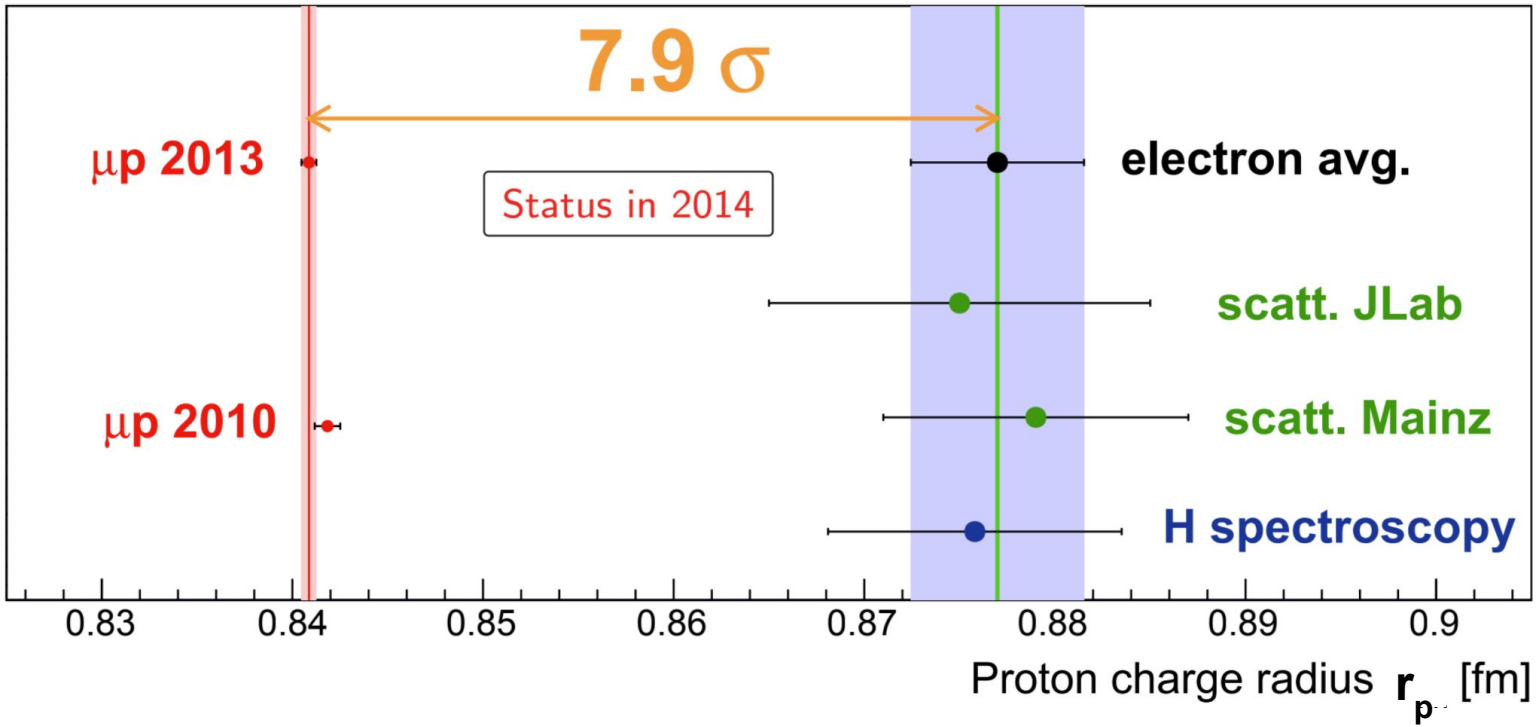
MUSE is supported by the U.S. National Science Foundation, the U.S. Department of Energy, the Paul Scherrer Institute, and the U.S.-Israel Binational Science Foundation

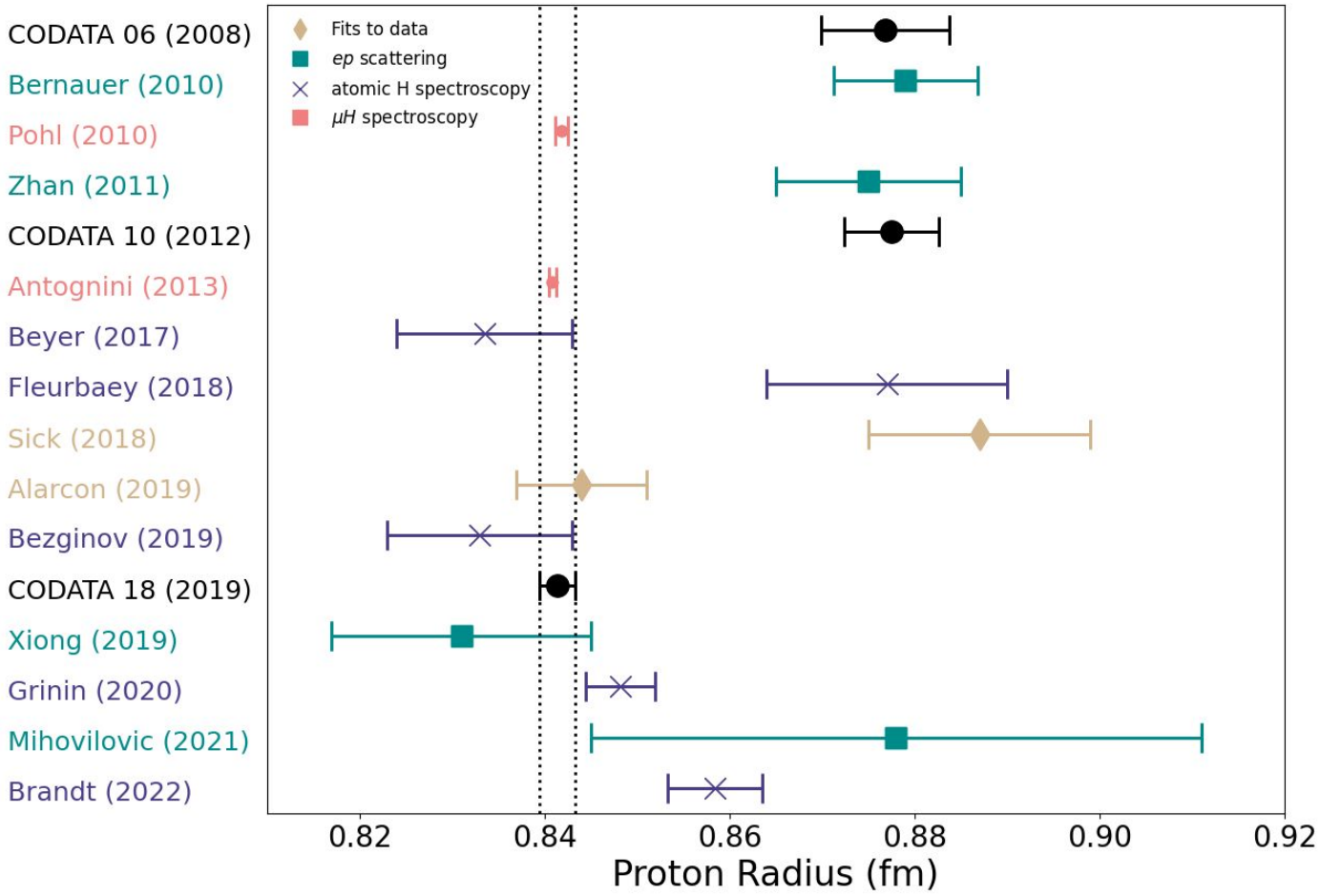
MUSE

Proton Charge Radius

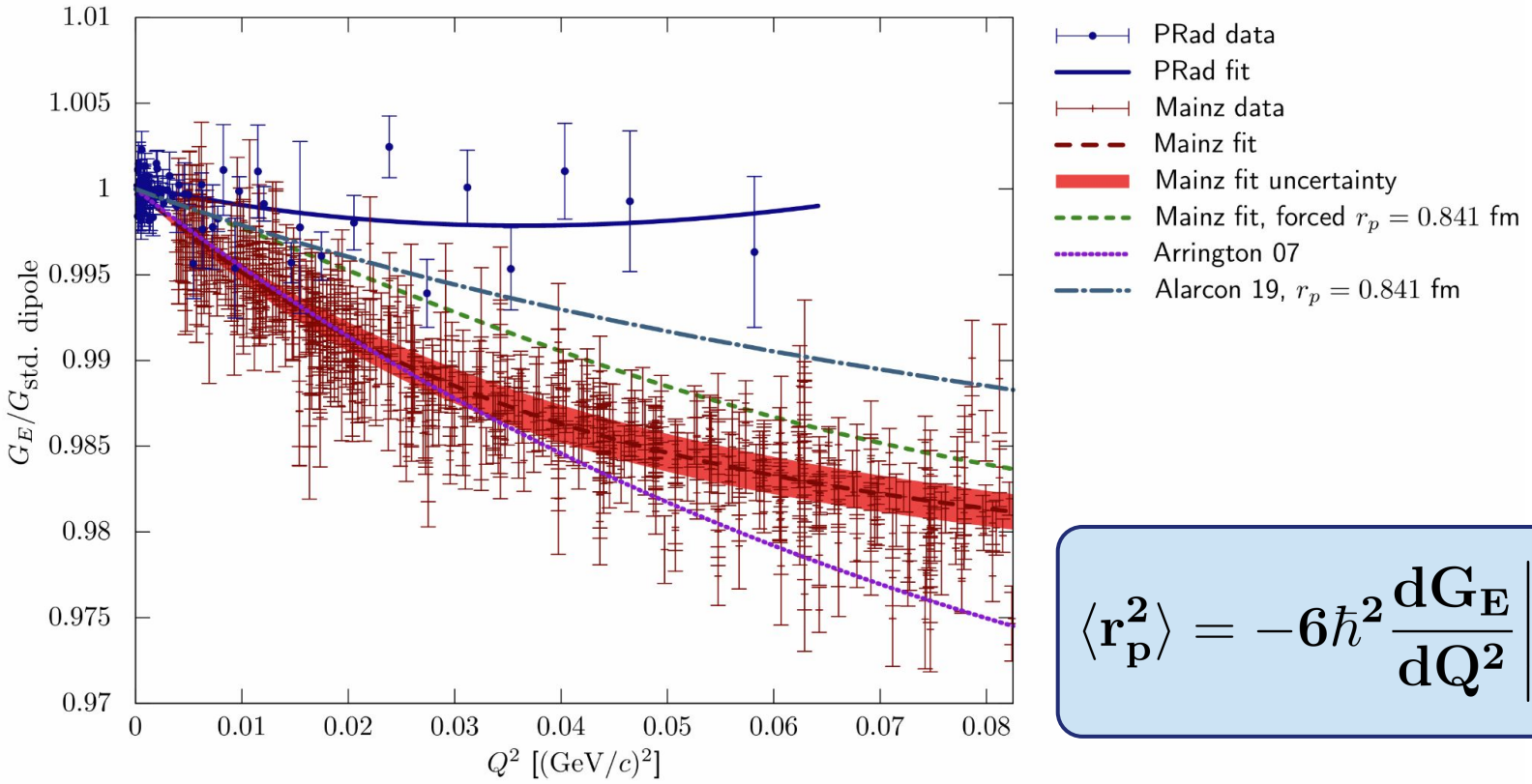


2010: Muonic hydrogen spectroscopy results bring proton charge radius into question

Current Status of the Proton Charge Radius



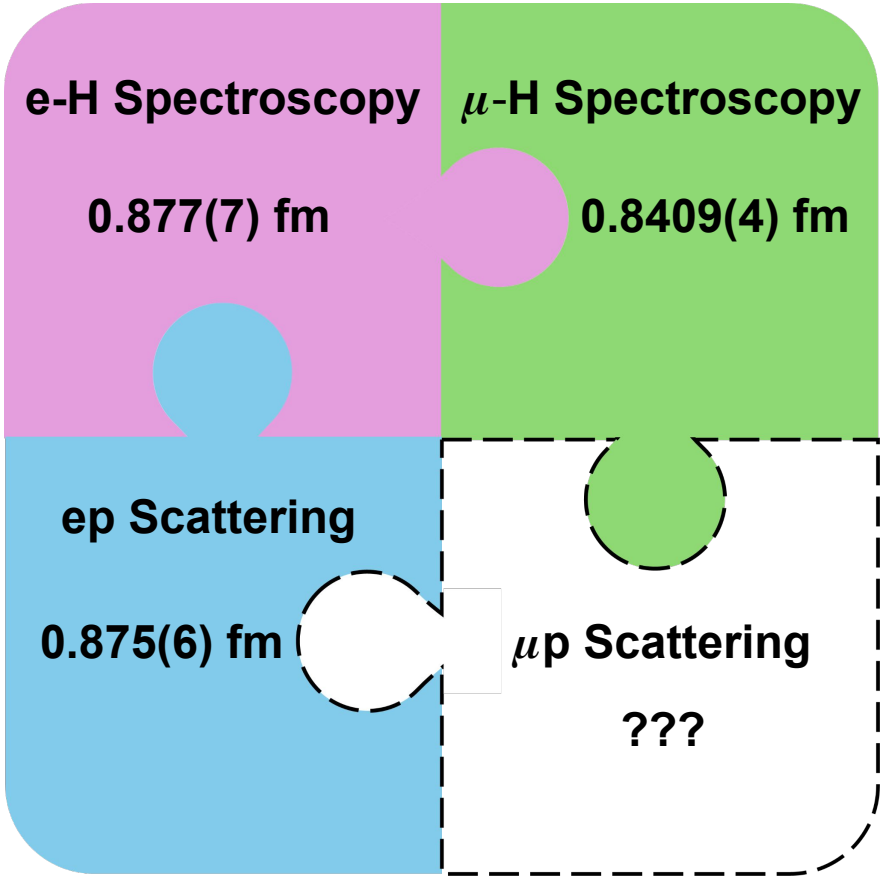
Form Factors for Radius Extraction



$$\langle r_p^2 \rangle = -6\hbar^2 \left. \frac{dG_E}{dQ^2} \right|_{Q^2=0}$$

Discrepancies exist at the form factor level

Muon-Proton Scattering - The Missing Piece?

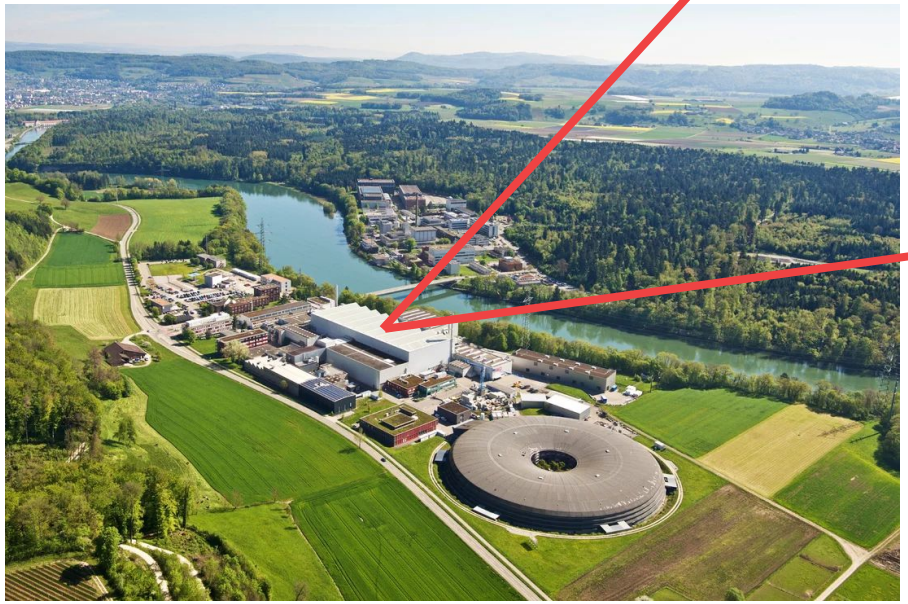


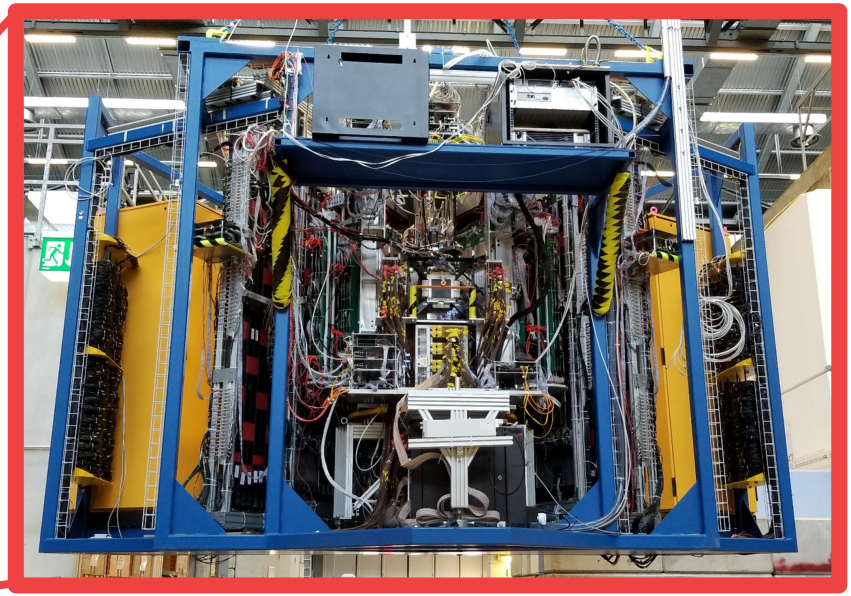
Original Motivations for MUSE

- Muon-proton scattering to address the proton charge radius
- Muon vs Electron Divergence?
- Two Photon Exchange

MUSE: The MUon Scattering Experiment

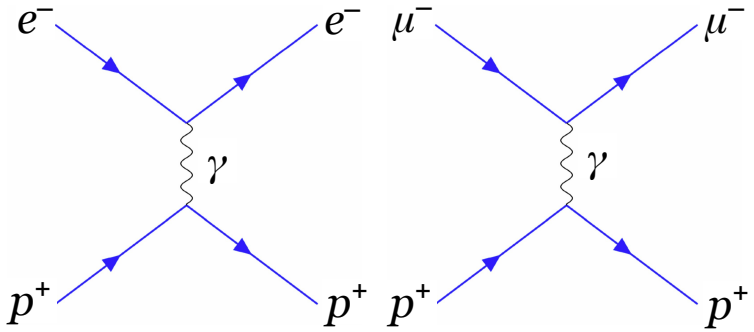
- Simultaneous **electron** and **muon scattering** experiment at Paul Scherrer Institute (PSI)
- PiM1 Secondary Beamline





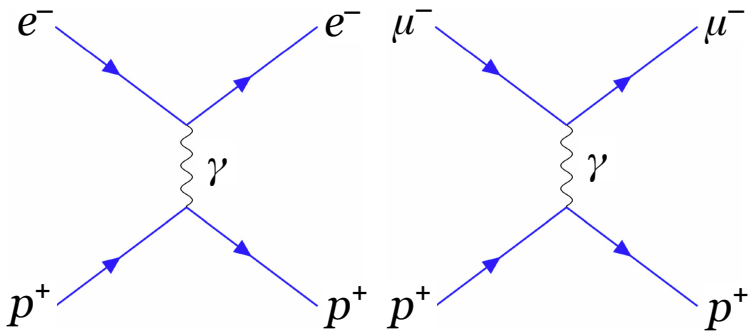
- Mixed particle species beam: e, μ, π
- Positive and negative particle charge polarities

Simultaneous ep and μp



- Extraction of **proton charge radius from μp scattering**
- Direct comparison of ep and μp **cross section** and $\mathbf{G_E}$ results
- Test of **lepton universality**

Simultaneous ep and μp



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- Direct comparison of ep and μp **cross section** and **G_E** results
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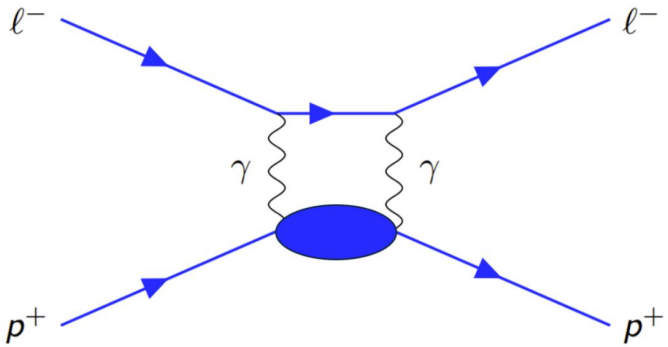
Two Photon Exchange

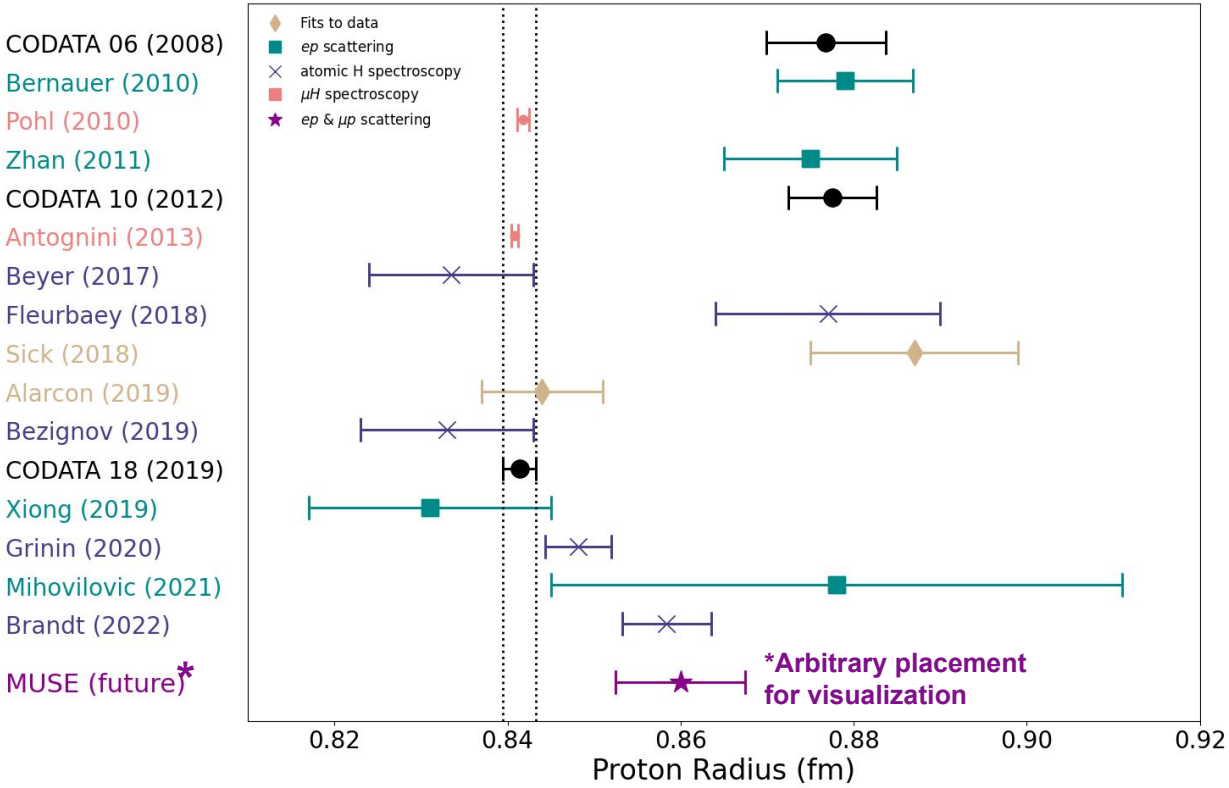


- Extract **TPE effects** with access to both lepton charge polarities

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

$$\frac{\sigma(l^{+}p)}{\sigma(l^{-}p)} \approx 1 + 2\delta_{2\gamma}$$

Precision Goals of MUSE



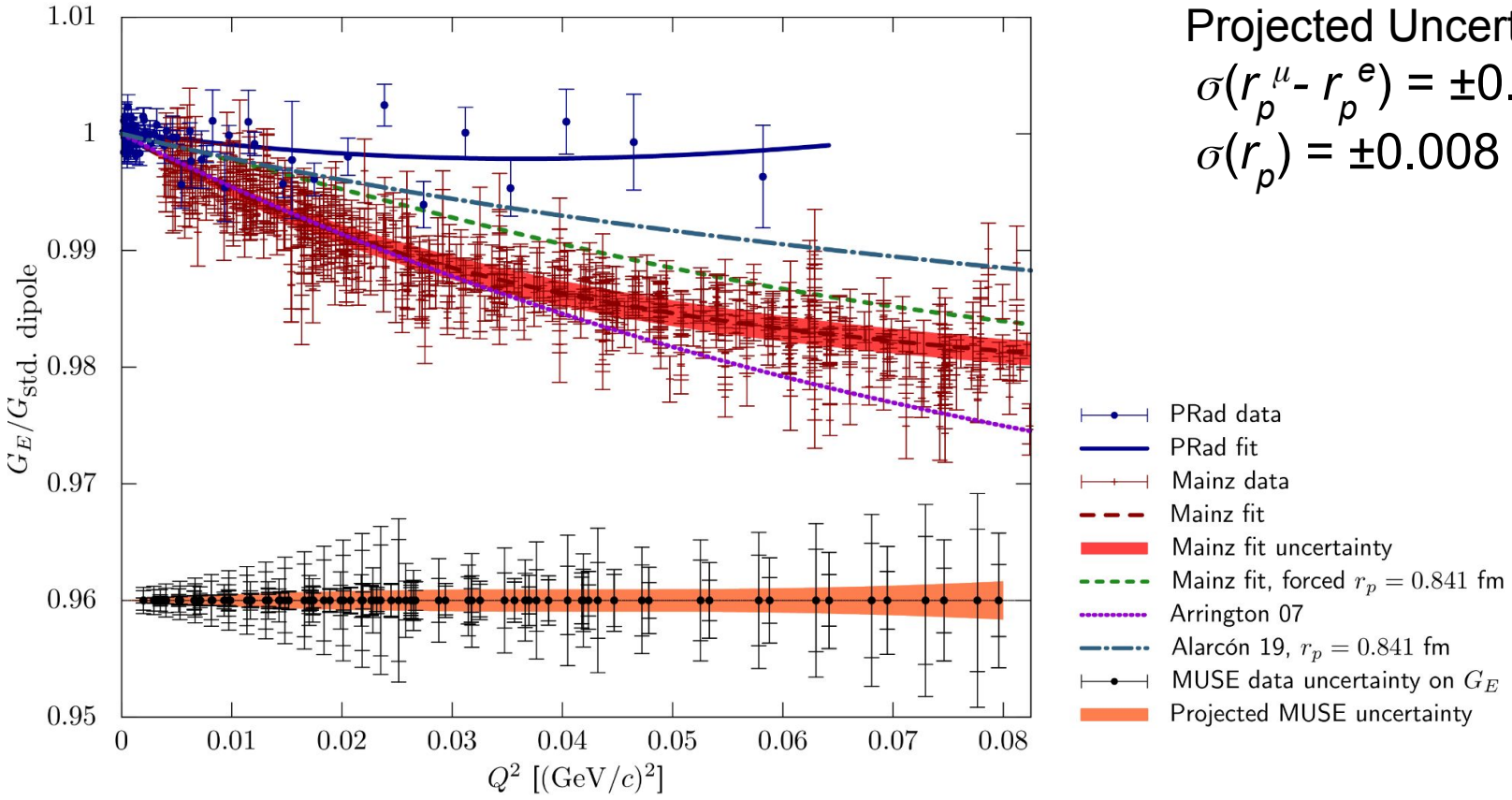
Projected Uncertainties:

$\sigma(r_p^{\mu} - r_p^{e}) = \pm 0.005$ fm

$\sigma(r_p) = \pm 0.008$ fm

*Projected MUSE measurement placed arbitrarily for visualization

Precision Goals of MUSE



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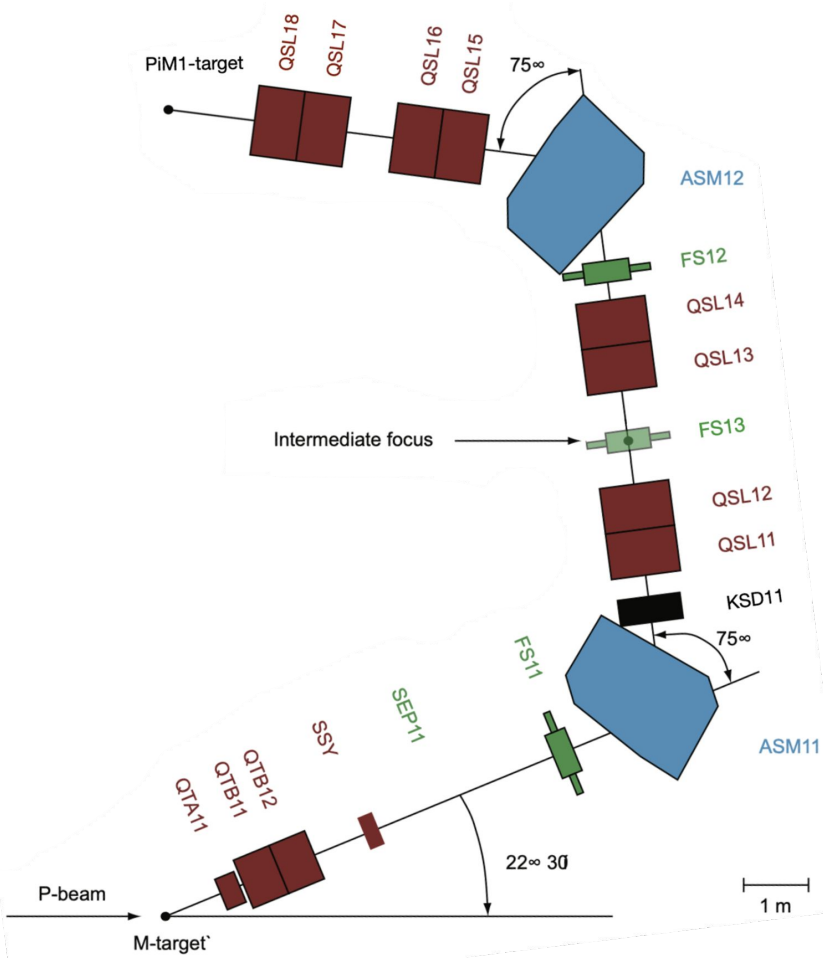
PiM1 Beam at PSI

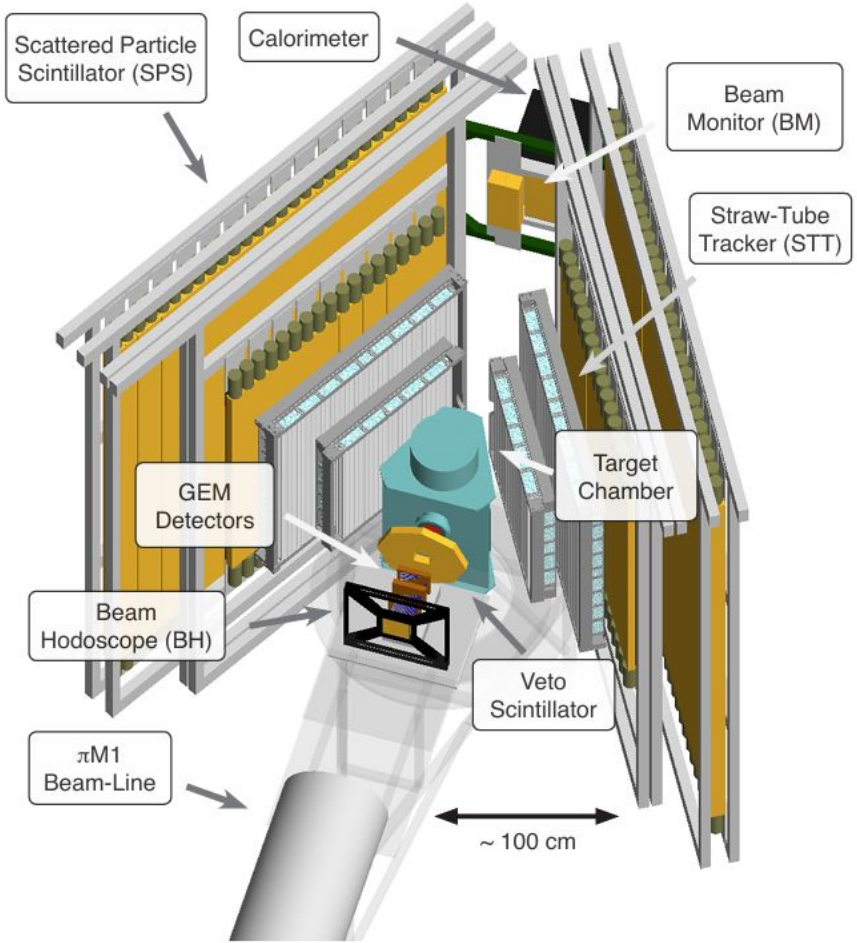


HIPA: 2 mA proton beam, 590 MeV
PiM1: e, μ, π beam, 100-500 MeV/c

- Mixed particles species beam (e, μ, π) produced from M-target (graphite)
- e's and π's generated in point-like source; μ's from π decay - extended source
- Particle species separated in time - PID
- MUSE constructed with PiM1 beam properties in mind

E. Cline *et al.*, PRC 105, 055201 (2022) [arXiv]

MUSE Apparatus

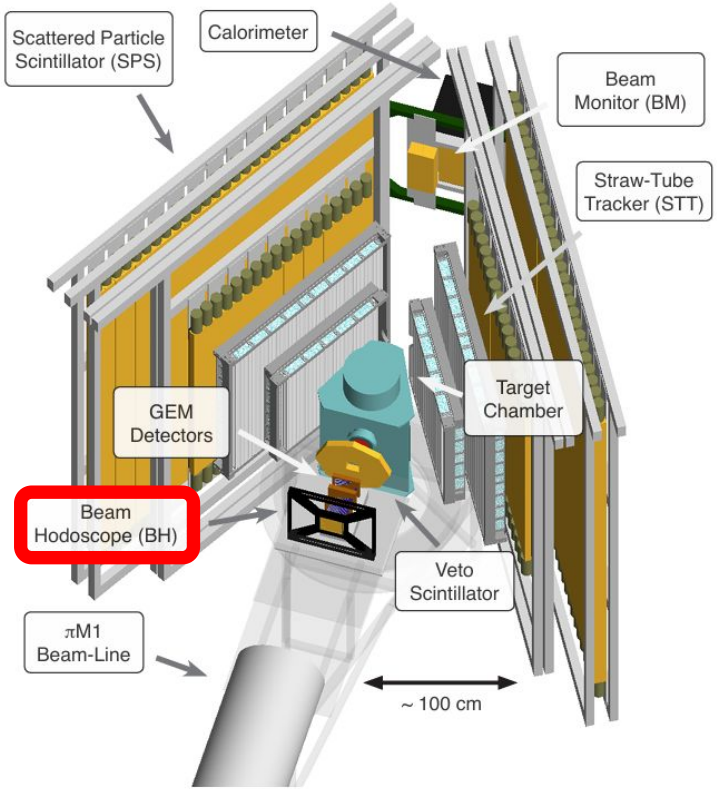


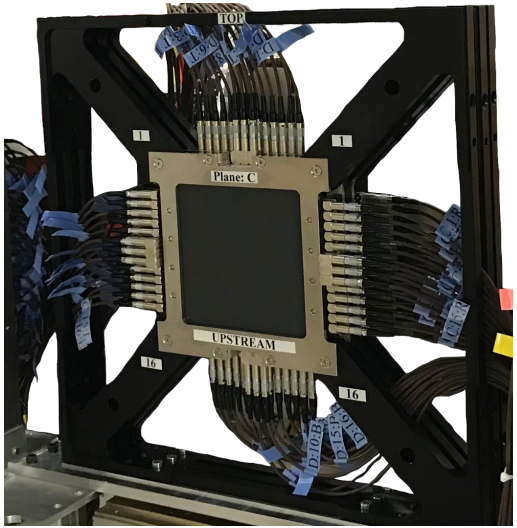
- Large acceptance, non-magnetic spectrometer
- High precision timing for PID
- Incident and scattered particle tracking
- Control of radiative corrections

Kinematic Coverage of MUSE

- $p_{e,\mu,\pi}$ = 115, 160, 210 MeV/c
- $\theta_{e,\mu,\pi}$ = 20° - 100°
- 0.0016 GeV^2 < Q^2_e < 0.0820
- 0.0016 GeV^2 < Q^2_μ < 0.0799

MUSE Apparatus: Beam Hodoscope

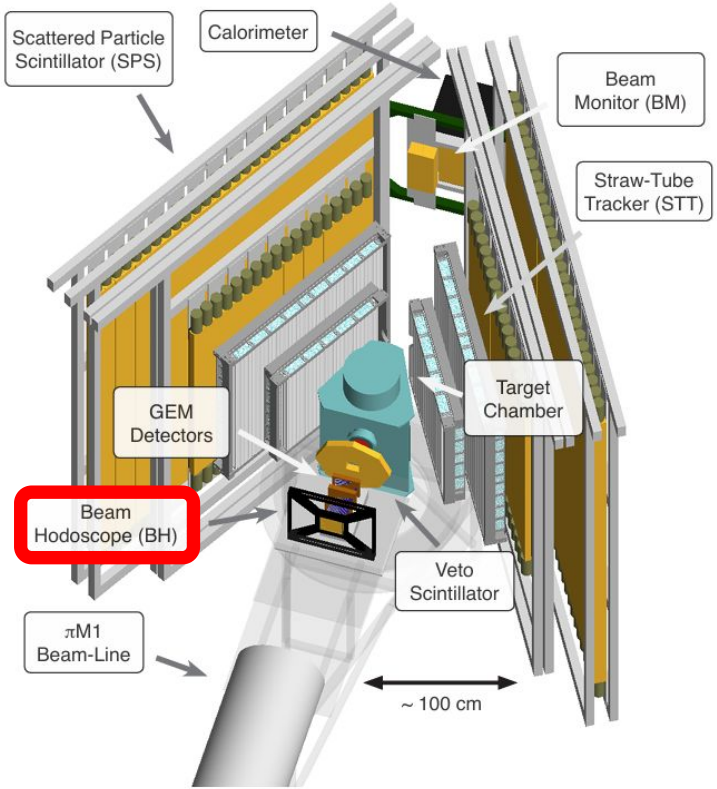


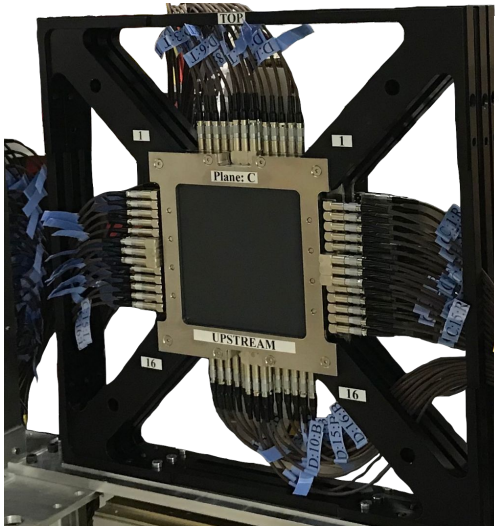


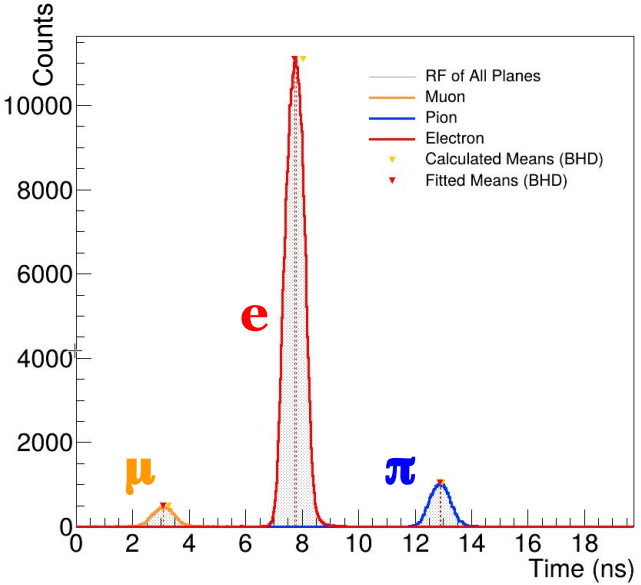
- Thin scintillating paddles with double-ended SiPM readout
- Precision timing of incident particles, combined with accelerator RF signal for PID

T. Rostomyan *et al.*, NIM A 986, 164801 (2021) [arXiv]

MUSE Apparatus: Beam Hodoscope







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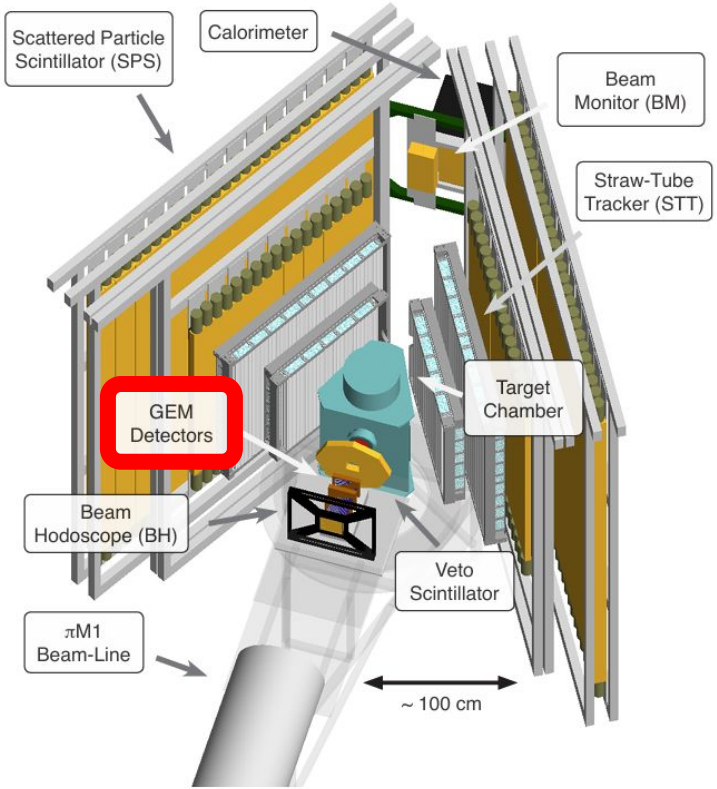
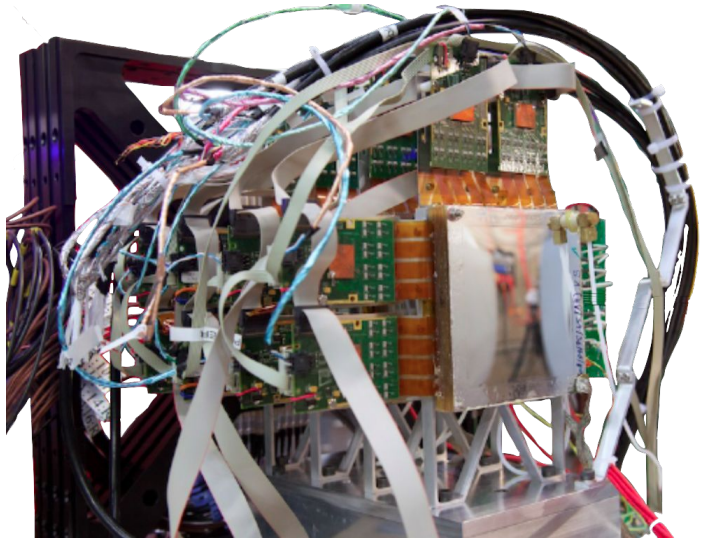
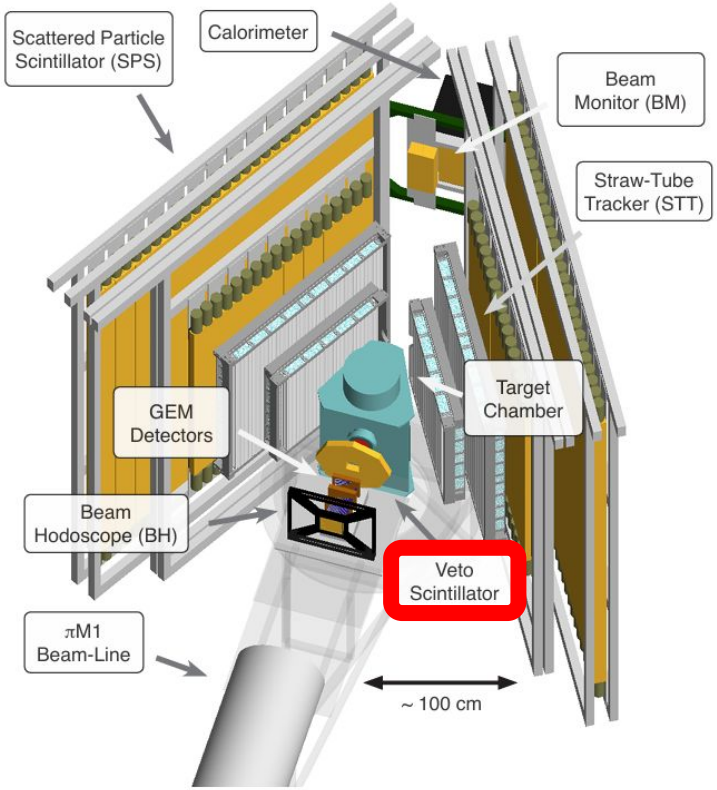
MUSE Apparatus: GEM Detectors

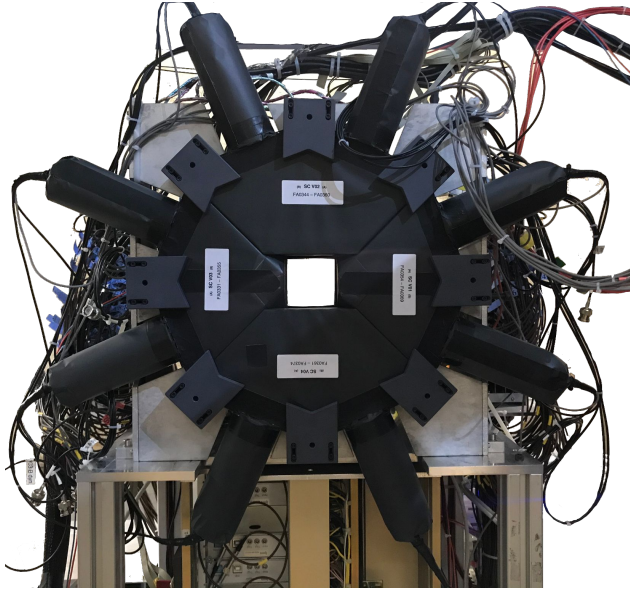




- 4-plane GEM detector (10 cm x 10 cm)
- Incident beam tracking for vertex reconstruction

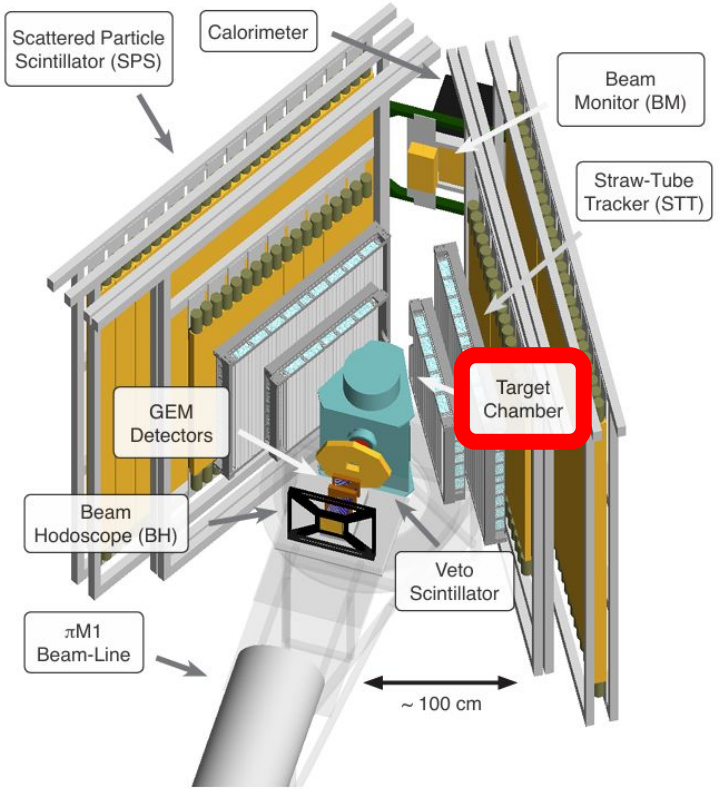
MUSE Apparatus: Veto

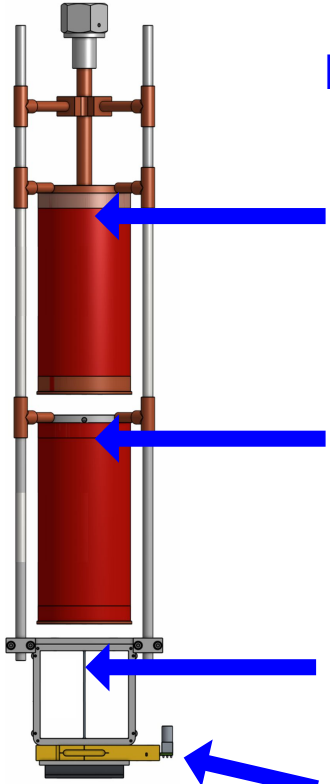




- 4-piece octagonal scintillator PMT readout
- Reduction of triggers induced by background events (upstream scattering, beam decay)

MUSE Apparatus: Target





Movable MUSE Target Ladder

Full Cell:
LH_2 target, 6 cm inner diameter

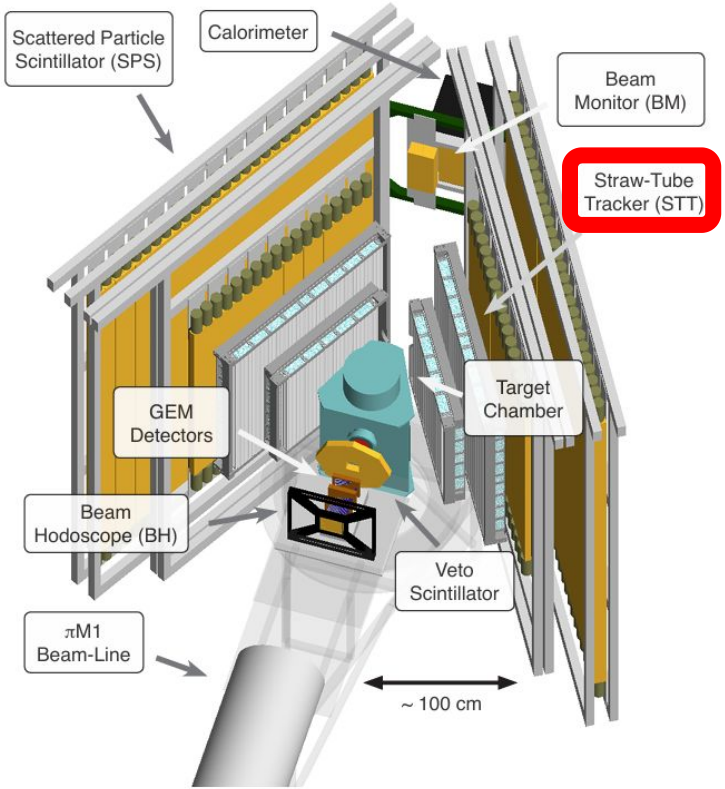
Empty Cell:
Background scattering measurements

Rod Target:
Vertex resolution studies

Beam Focus Monitor:
Beam monitoring at target position

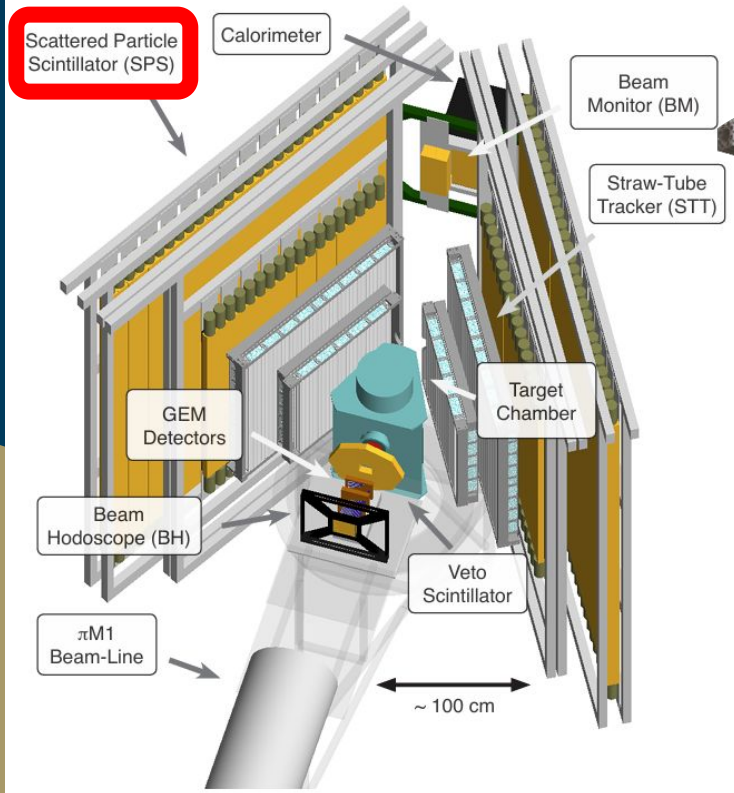
P. Roy *et al.*, NIM A 949, 162874 (2020) [arXiv]

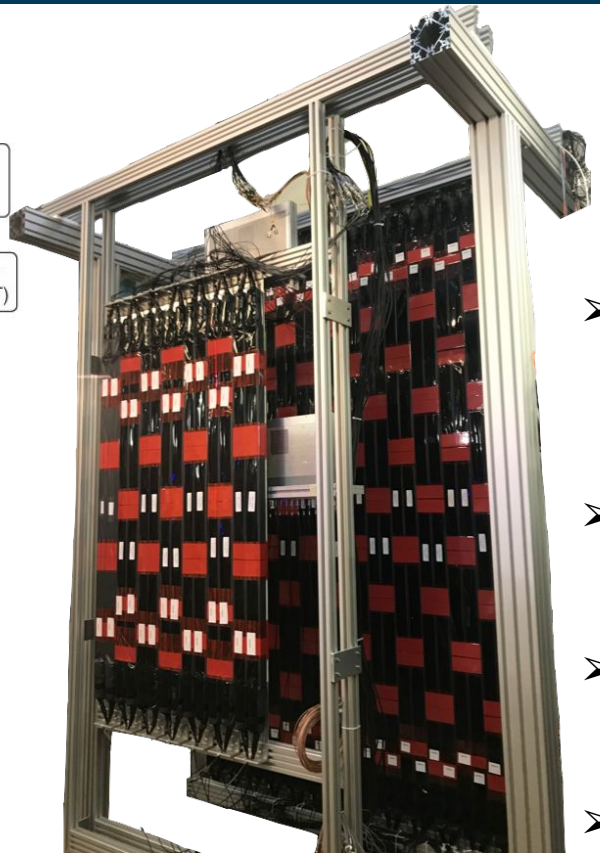
MUSE Apparatus Straw-Tube Tracker



- 2 chambers per side; 5 vertical straw planes, 5 horizontal straw planes per chamber
- Tracking of scattered particles

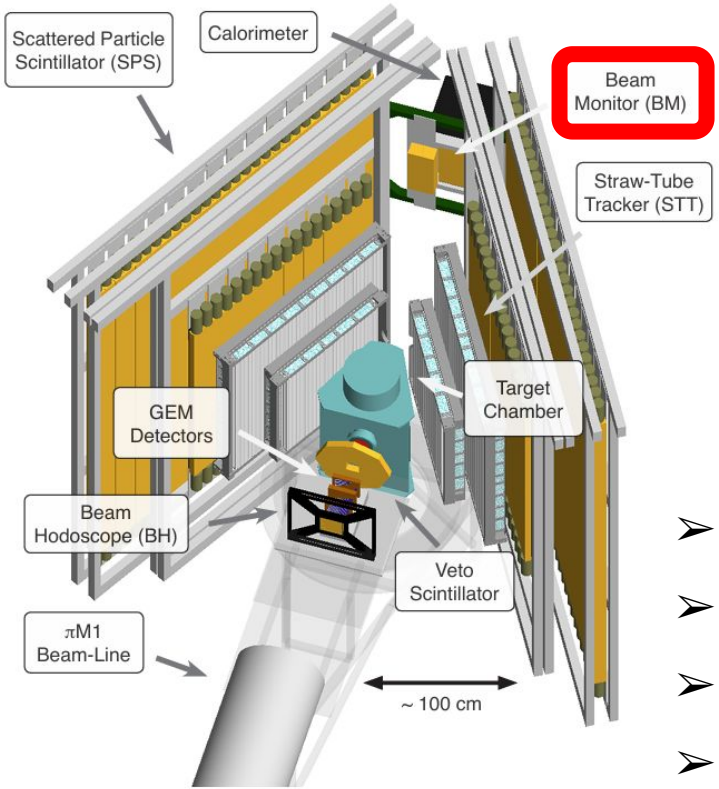
MUSE Apparatus: Scattered Particle Scintillator

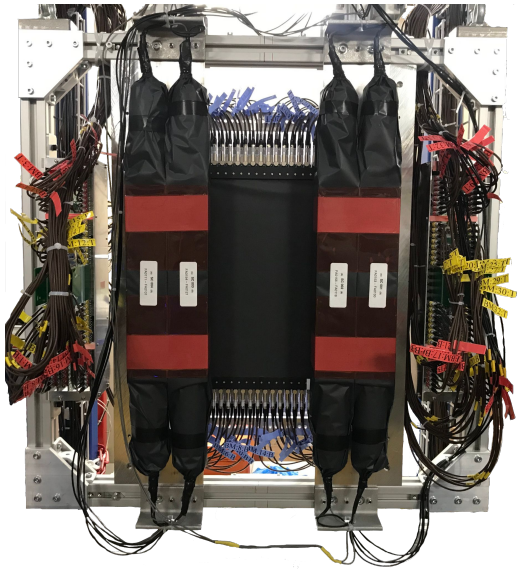




- 2 walls of plastic scintillator bars on each side of MUSE
- Front Wall : 18 Bars
  Rear Wall: 28 Bars
- Scattered particle trigger - lookup table
- TOF measurements

MUSE Apparatus: Beam Monitor

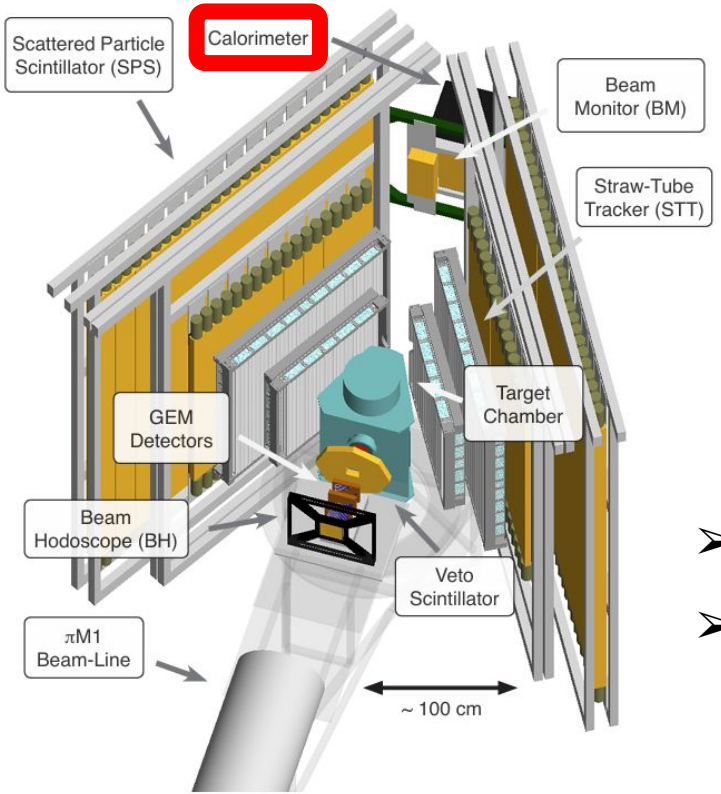


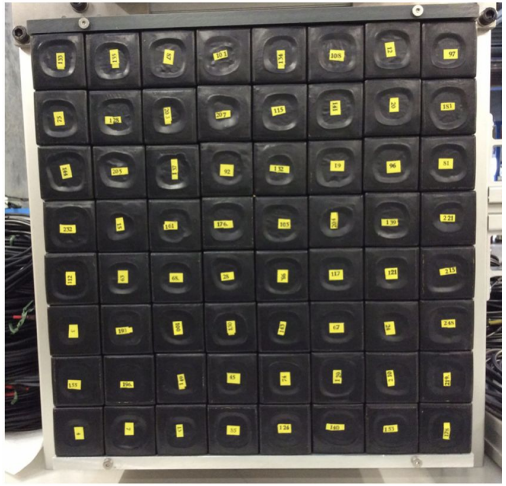


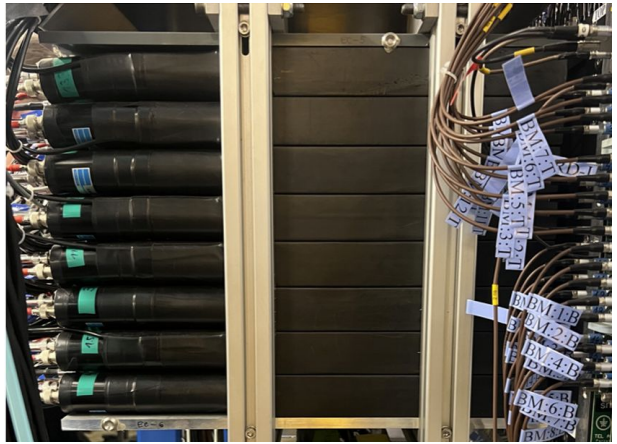
- 2 planes of 16 scintillator bars with SiPM readout
- Additional adjustable plane, 4 paddles with PMT readout
- Monitoring of beam luminosity
- TOF measurements for calibrations

T. Rostomyan *et al.*, NIM A 986, 164801 (2021) [arXiv]

MUSE Apparatus: Electromagnetic Calorimeter



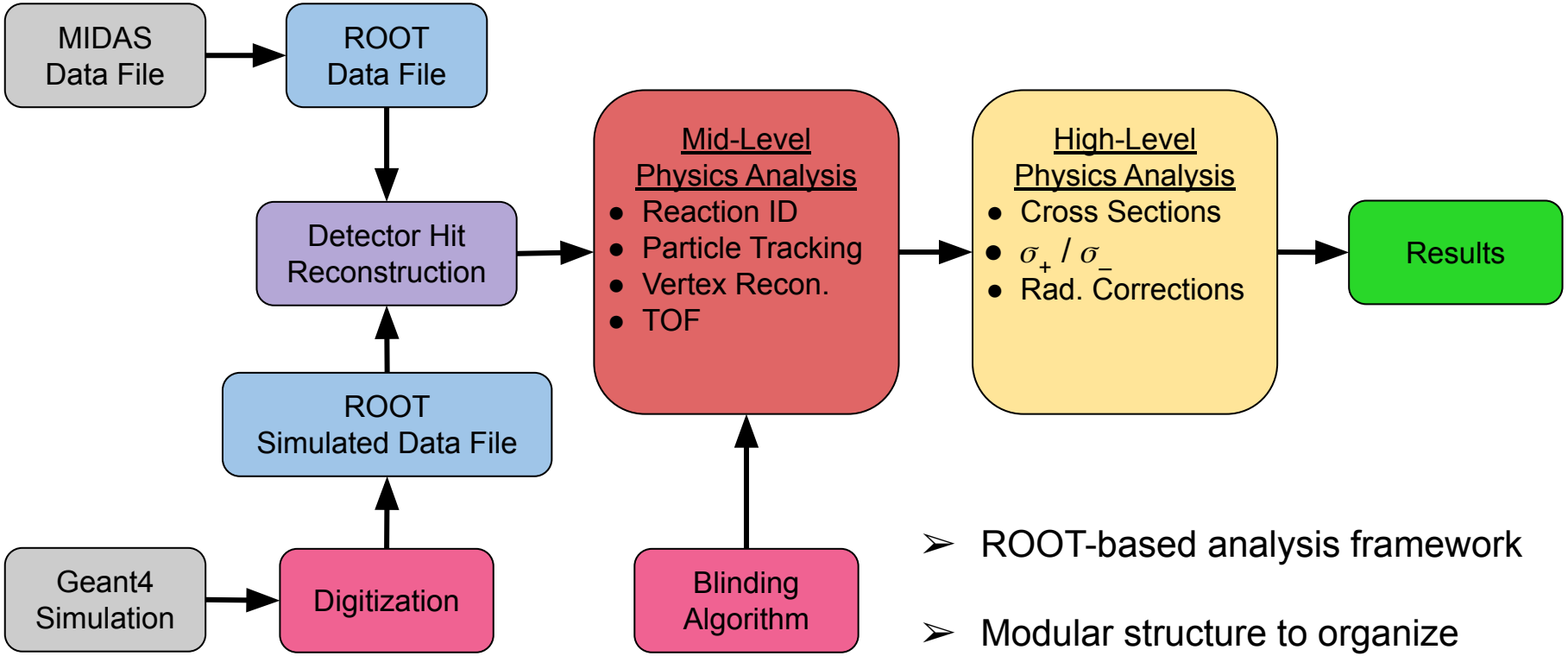




- 64 lead-glass bars with PMT readout
- Measurement of radiative photons downstream of target for better control of radiative corrections

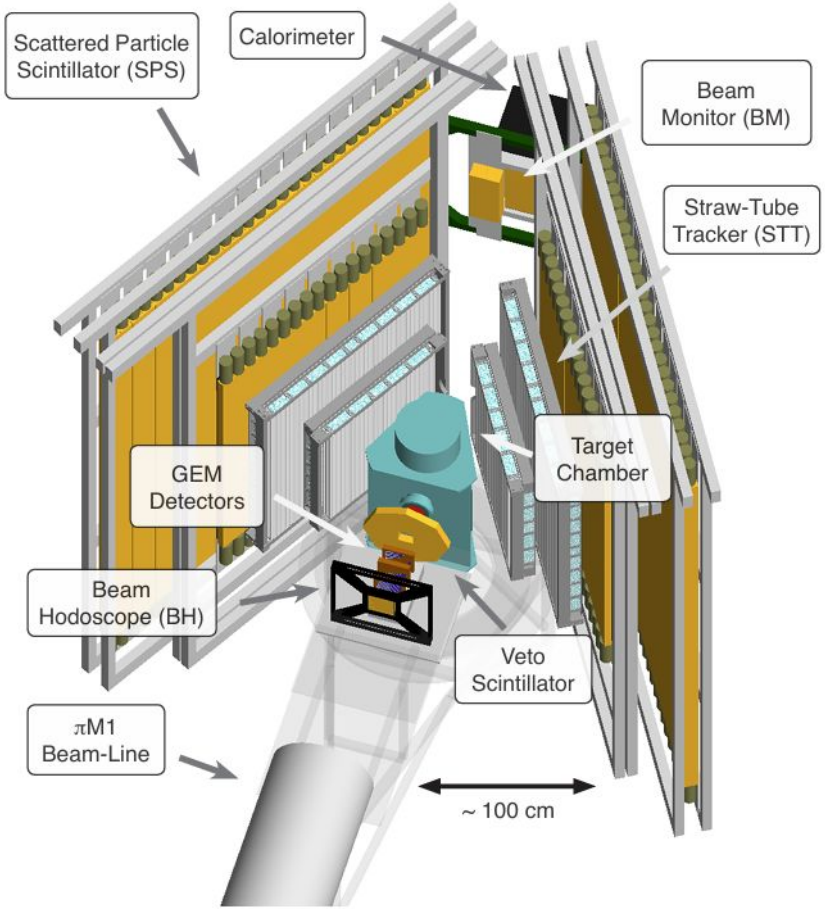
W. Lin *et al.*, NIM A 1080, 170754 (2025) [arXiv]

Analysis Chain



- ROOT-based analysis framework
- Modular structure to organize different levels of analysis

Geant4 Simulation



- Full Geant4 simulation of MUSE to support analysis
- Realistic detector responses
- Radiative corrections incorporated into simulation with custom physics model from Olympus (RadGen)
- Realistic beam characterization from data

Blinding

- Scattered tracks stochastically blinded to prevent bias
- Tracks encrypted with angular dependence:

$$P = 0.2\Big(A + 0.3\cos(B\theta)\Big)\left(\frac{3-\theta}{3}\right)$$

for $\mathrm{A} = [0.25, 1], \mathrm{B} = [3, 10]$

- Track encrypted when P ≤ R for randomly generated R = [0,1]
- Decryption requires collaboration approval and 2 keys from senior members

- Detailed review: Bernauer *et al.*, (2023) arxiv:2310.11469
- NREC talk: “Blinding Precision Scattering Experiments” by Ethan Cline

Systematics in MUSE

Estimated MUSE Relative Systematic Cross Section Uncertainties

Systematic Uncertainty	Angular Distributions (%)	μ/e (%)	+/– (%)
Radiative Corrections	0.1 (μ) , 0.5 (e)	0.5	1γ - *small*
Detector Efficiencies	0.1	0.1	0.1
Scattering Angle Offset	0.2	*small*	*small*
Beam Momentum Offset	0.1	0.1	0.1
Subtraction of μ Decay	0.1	0.1	*small*
Target Wall Subtraction	0.3	*small*	*small*
Beam PID/Reaction ID	0.1	0.1	0.1
Total	0.5 (μ) , 0.7 (e)	0.5	0.2

The MUon Scattering Experiment at PSI (MUSE), MUSE Technical Design Report, arXiv:1709.09753

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Detector Efficiencies	0.1	0.1	0.1
Scattering Angle Offs			*mall*
Beam Momentum Off			0.1
Subtraction of μ Deca			*mall*
Target Wall Subtraction	0.3	*small*	*small*
Beam PID/Reaction ID	0.1	0.1	0.1
Total	0.5 (μ) , 0.7 (e)	0.5	0.2

NREC Talk:
"Instrumental Uncertainties in Radiative Corrections for the MUSE Experiment"
by Steffen Strauch

The MUon Scattering Experiment at PSI (MUSE), MUSE Technical Design Report, arXiv:1709.09753

MUSE Run Status

Completed

- 15 Months Production Data-Taking
  - 2022-2025
  - Statistics goals reached
- Systematic studies run in parallel with production data-taking:
  - Time-of-flight measurements
  - Detector efficiency and resolution studies
  - Beam characterization and stability studies

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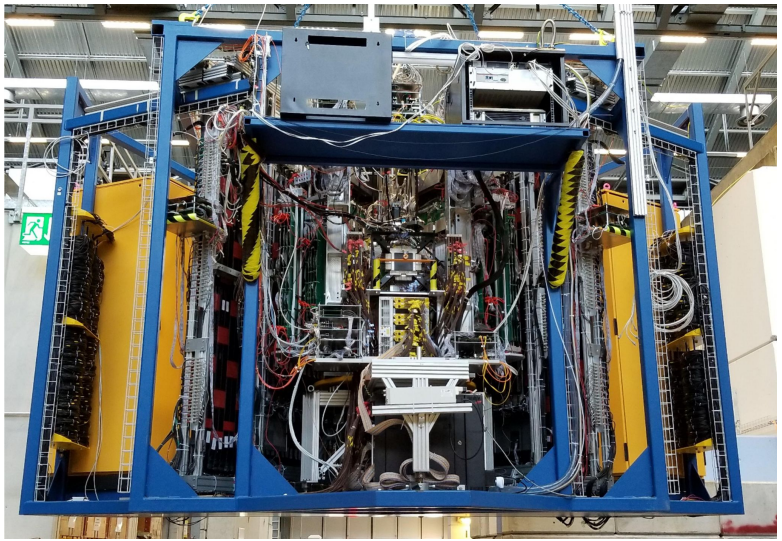
In Progress

- 12 Weeks Beamtime Summer 2026
- Standalone Systematics Studies:
  - Efficiency measurements
  - Background events
  - Energy-loss corrections
- These studies will accelerate the analysis timeline with better handling of systematics

Summary



- MUSE will provide insight into the proton charge radius (and G_E) through the first <u>simultaneous</u> measurements of *ep* and μp elastic scattering on the proton
- MUSE will measure TPE effect
- Production data collection complete in December 2025 - statistics goals achieved!
- Final systematic studies Summer 2026

Questions?