Status of the Muon proton Scattering Experiment (MUSE)

(On behalf of the MUSE Collaboration)

"10th workshop of APS Topical Group on Hadronic Physics"
Minneapolis, Minnesota
April 12-14, 2023

Ievgen Lavrukhin

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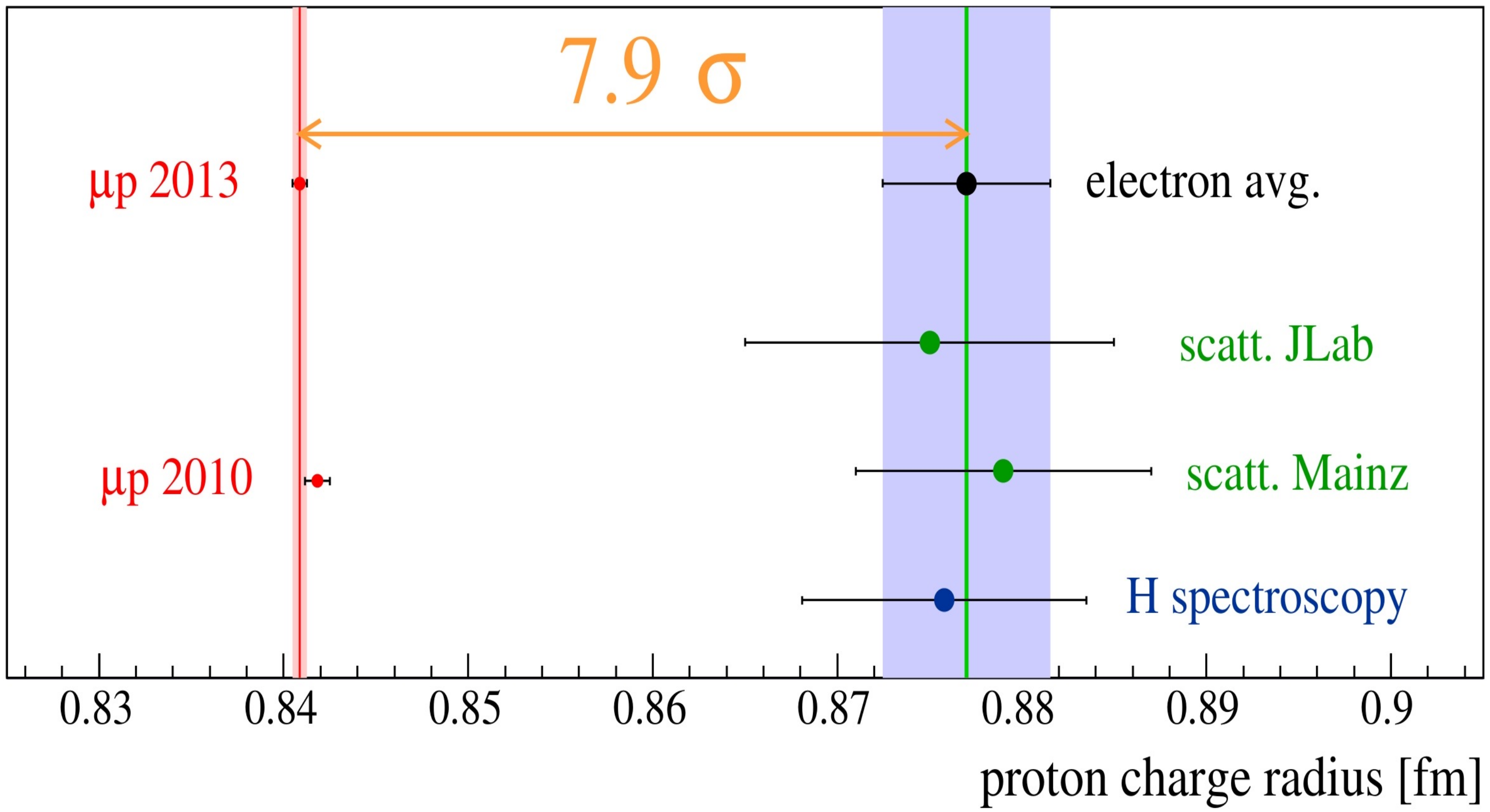
The Proton Radius Puzzle in 2010/2013

The Proton Radius Puzzle : Discrepancy between muonic hydrogen spectroscopy results and electron measurements. (First released → 2010)



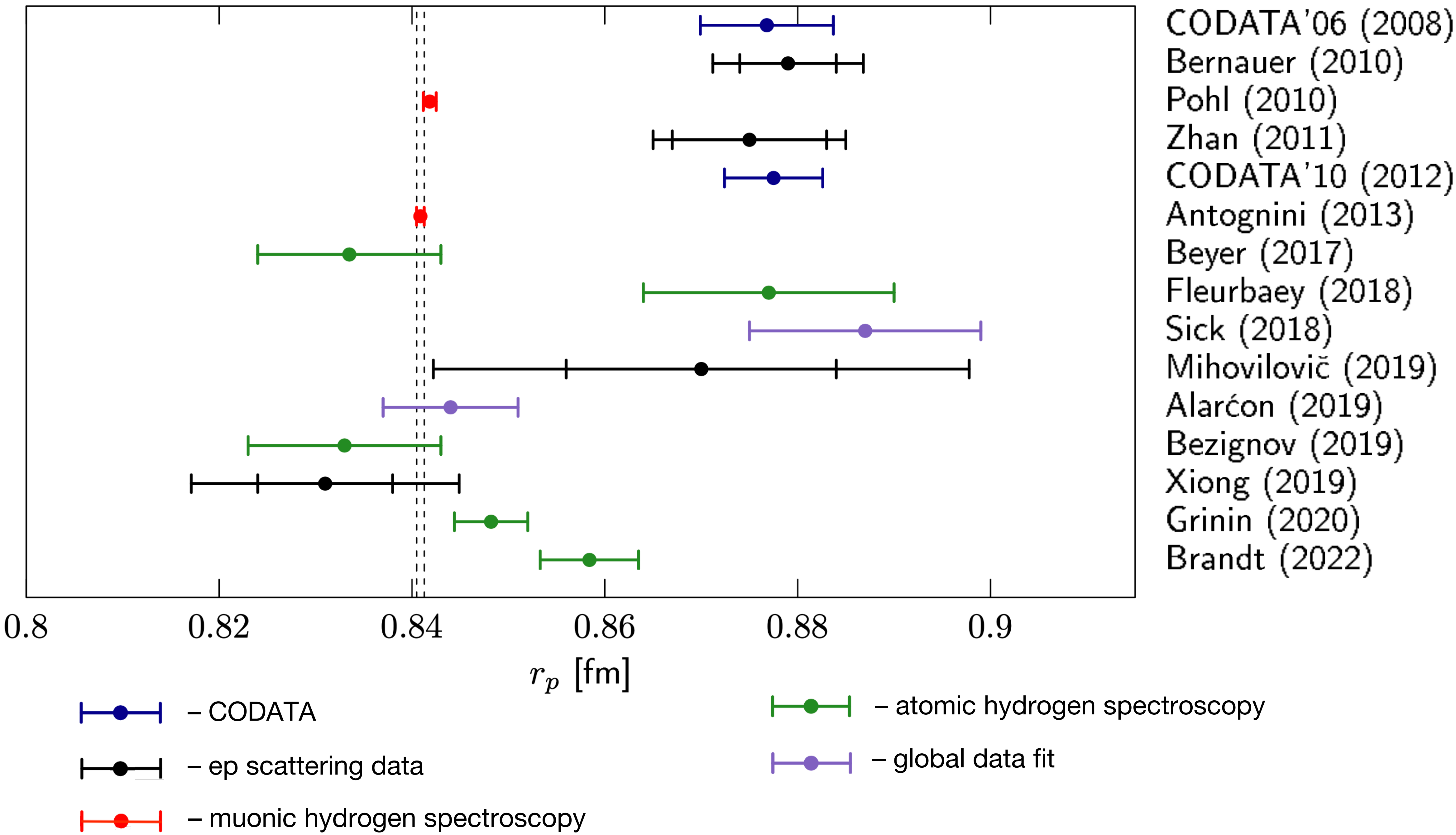
μp 2013: Antognini *et al.*, Science **339,** 417 (2013)
JLab: Zhan *et al.*, PLB **705,** 59-64 (2011)
Mainz: Bernauer *et al.*, PRL **105**, 242001 (2010)
μp 2010: Pohl *et al.*, Nature **466**, 213 (2010)

MUSE Motivation:

- direct comparison of ep and μp scattering results at sub-percent level precision;
- test the two-photon exchange contribution by comparing measurements of both polarities

The Proton Radius Puzzle in 2023

Many hydrogen results over past several years - new experiments and re-analyses:



The Proton Radius Puzzle in 2023

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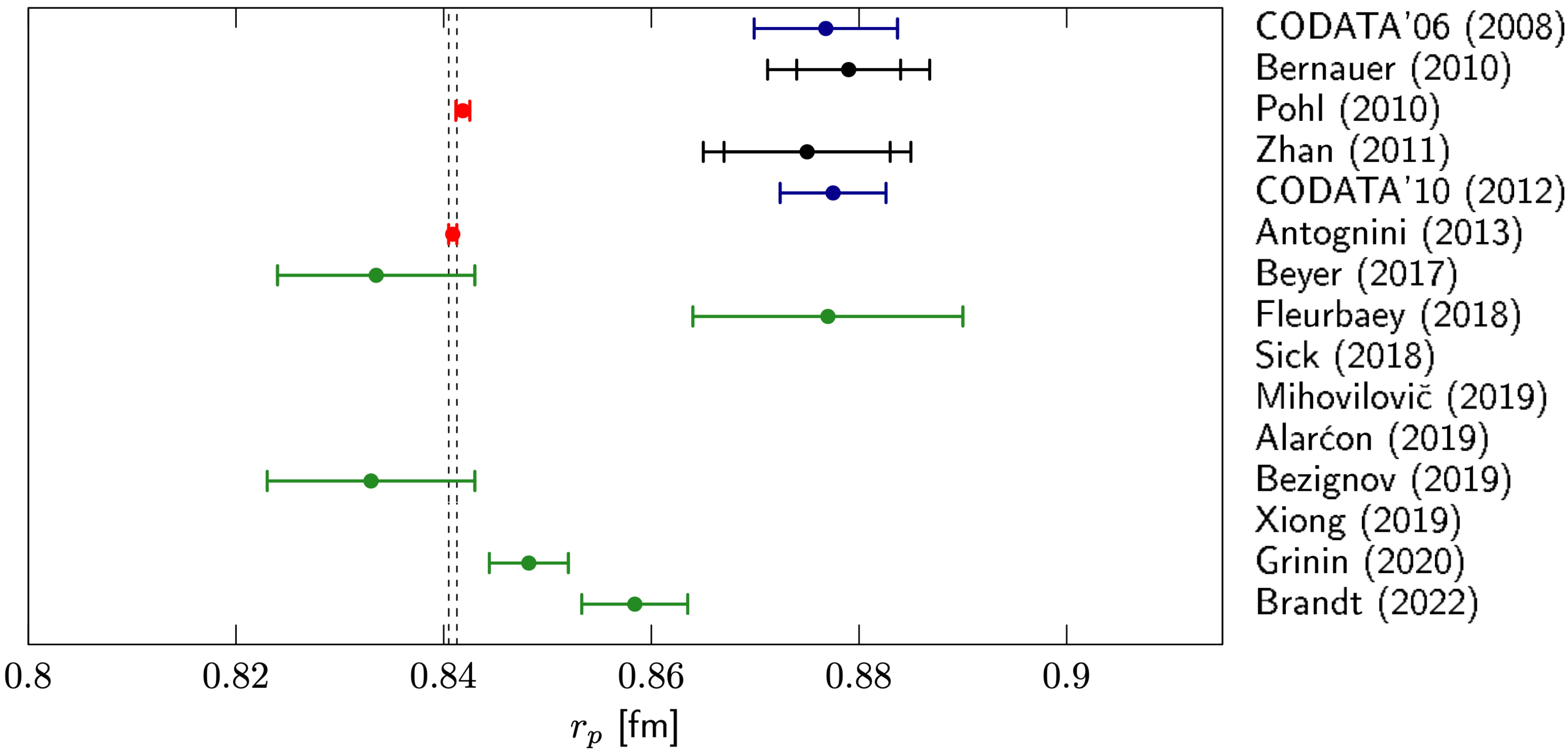

Inconsistency in the recent hydrogen spectroscopy results!

The Proton Radius Puzzle in 2023

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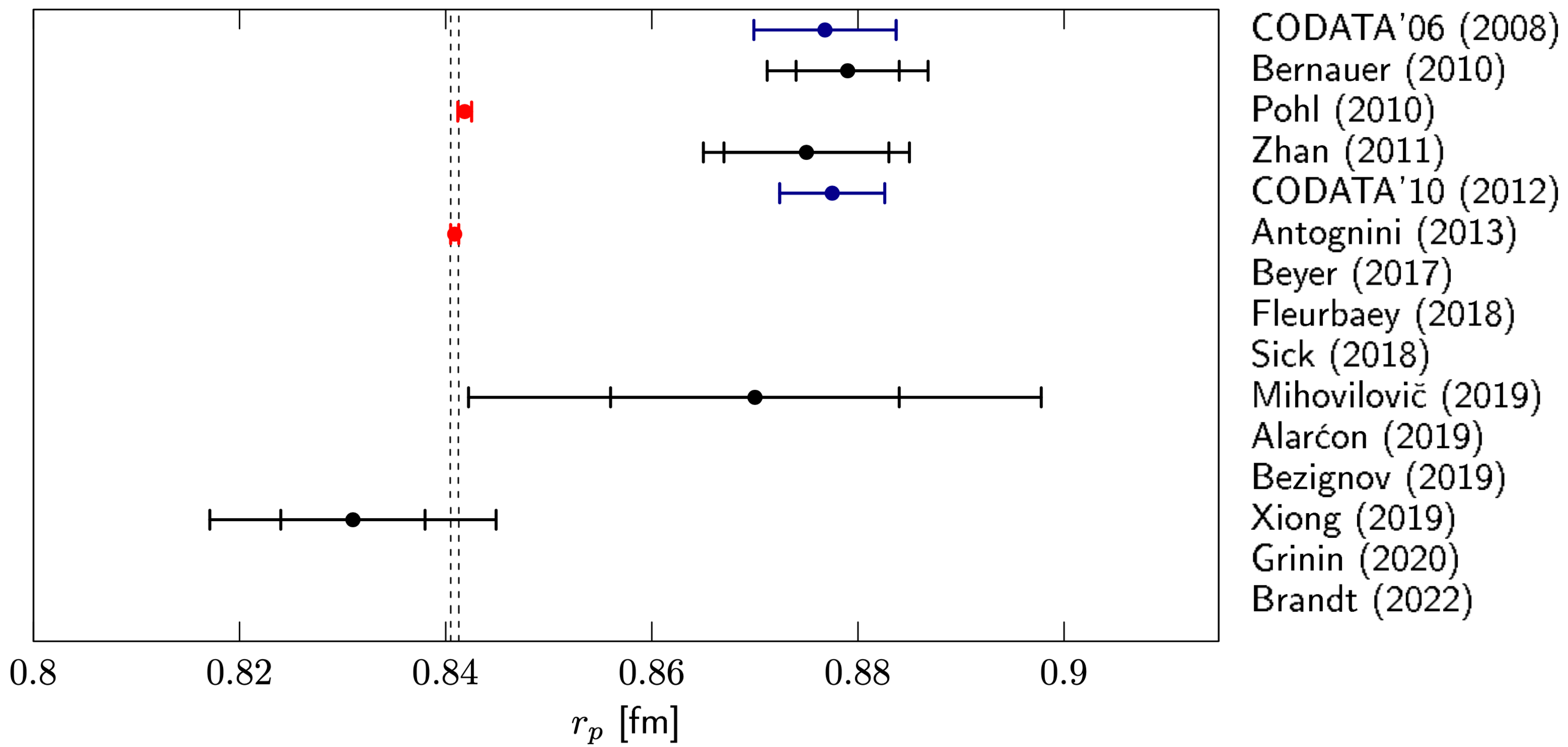
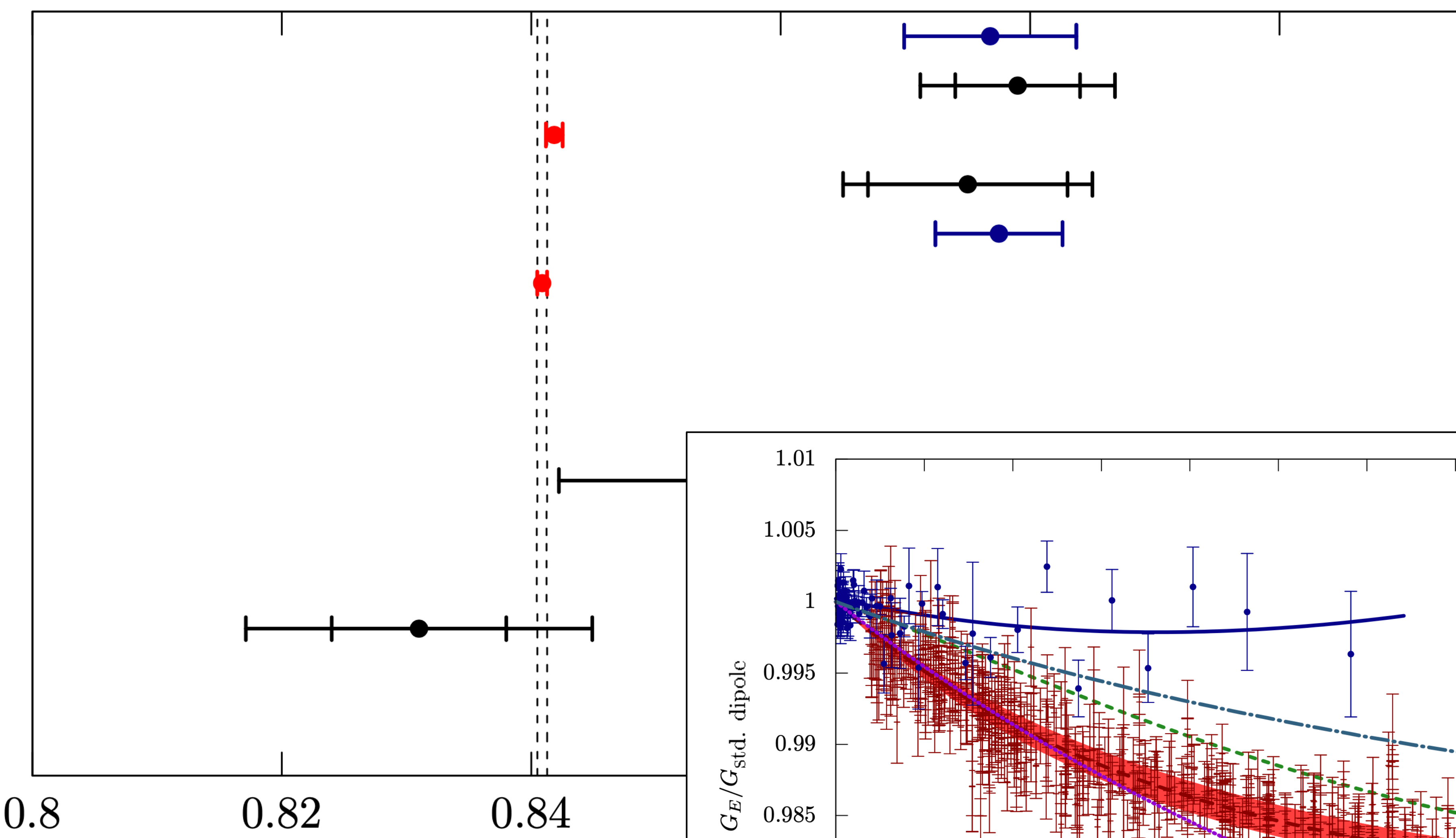
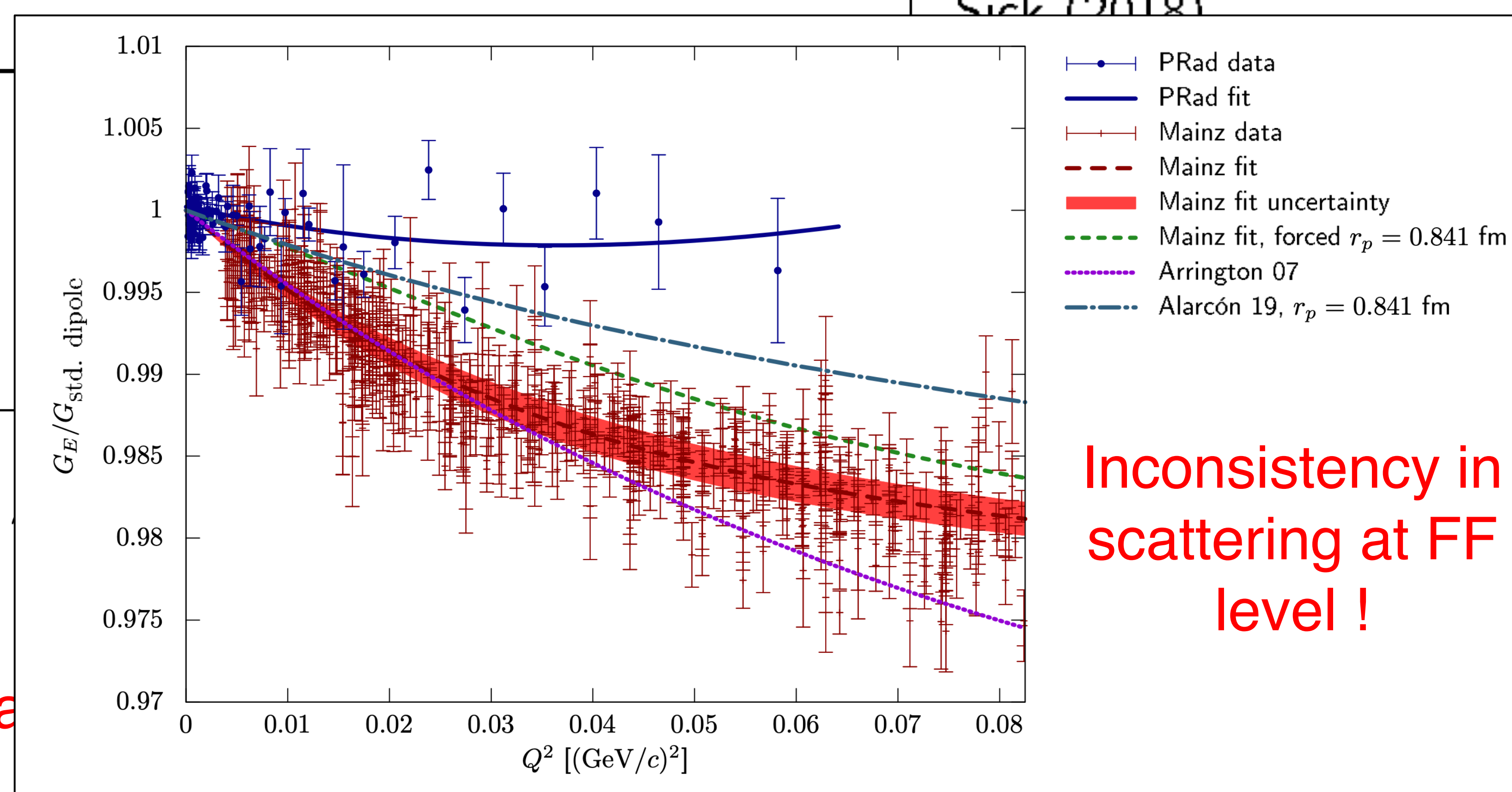


Inconsistency in the recent ep scattering results!

The Proton Radius Puzzle in 2023

Many hydrogen results over past several years - new experiments and re-analyses:



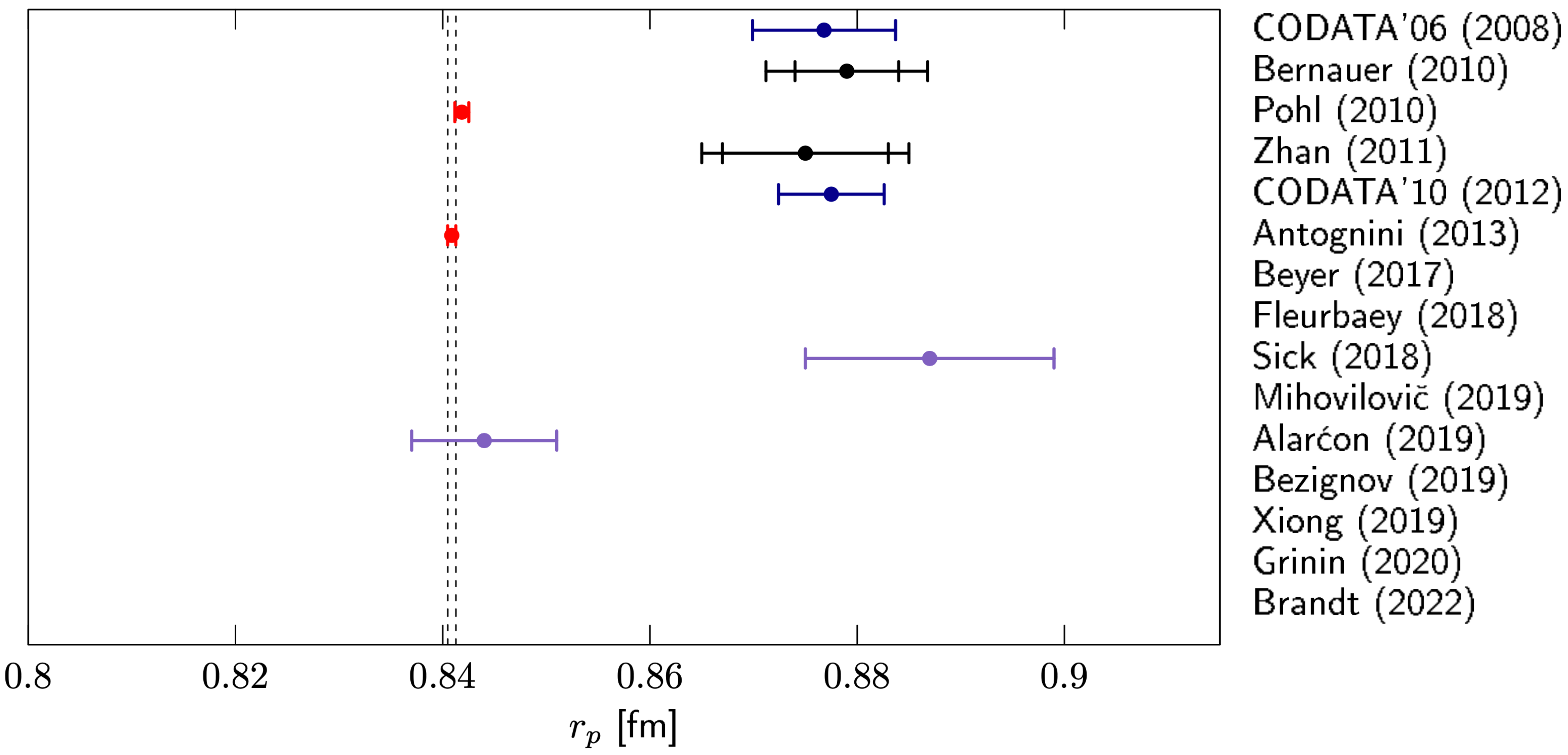


Inconsistency in scattering at FF level !

Inconsistency in the recent ep sca

The Proton Radius Puzzle in 2023

Many hydrogen results over past several years - new experiments and re-analyses:



Inconsistency in the analysis results!

The Proton Radius Puzzle Summary

PRP in 2013:

r_p [fm]	electrons	muons
spectroscopy	0.8758 (77)	0.8409 (4)
scattering	0.8770 (60)	N/A

PRP in 2023:

r_p [fm]	electrons	muons
spectroscopy	Inconsistent	0.8409 (4)
scattering	Inconsistent	N/A

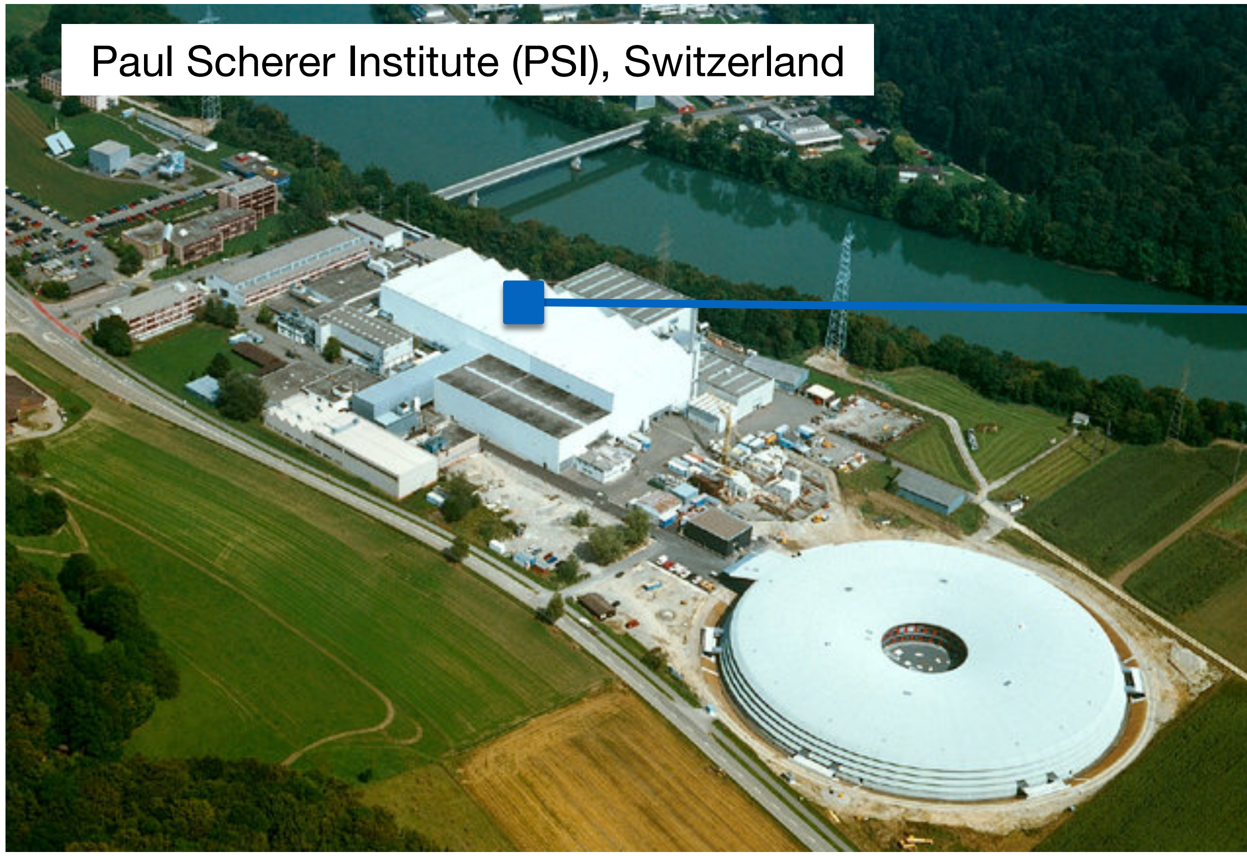
- Proton Radius Puzzle (PRP) is still unresolved!
- No measurements from μp scattering (AMBER and MUSE are coming).

What MUSE can do:

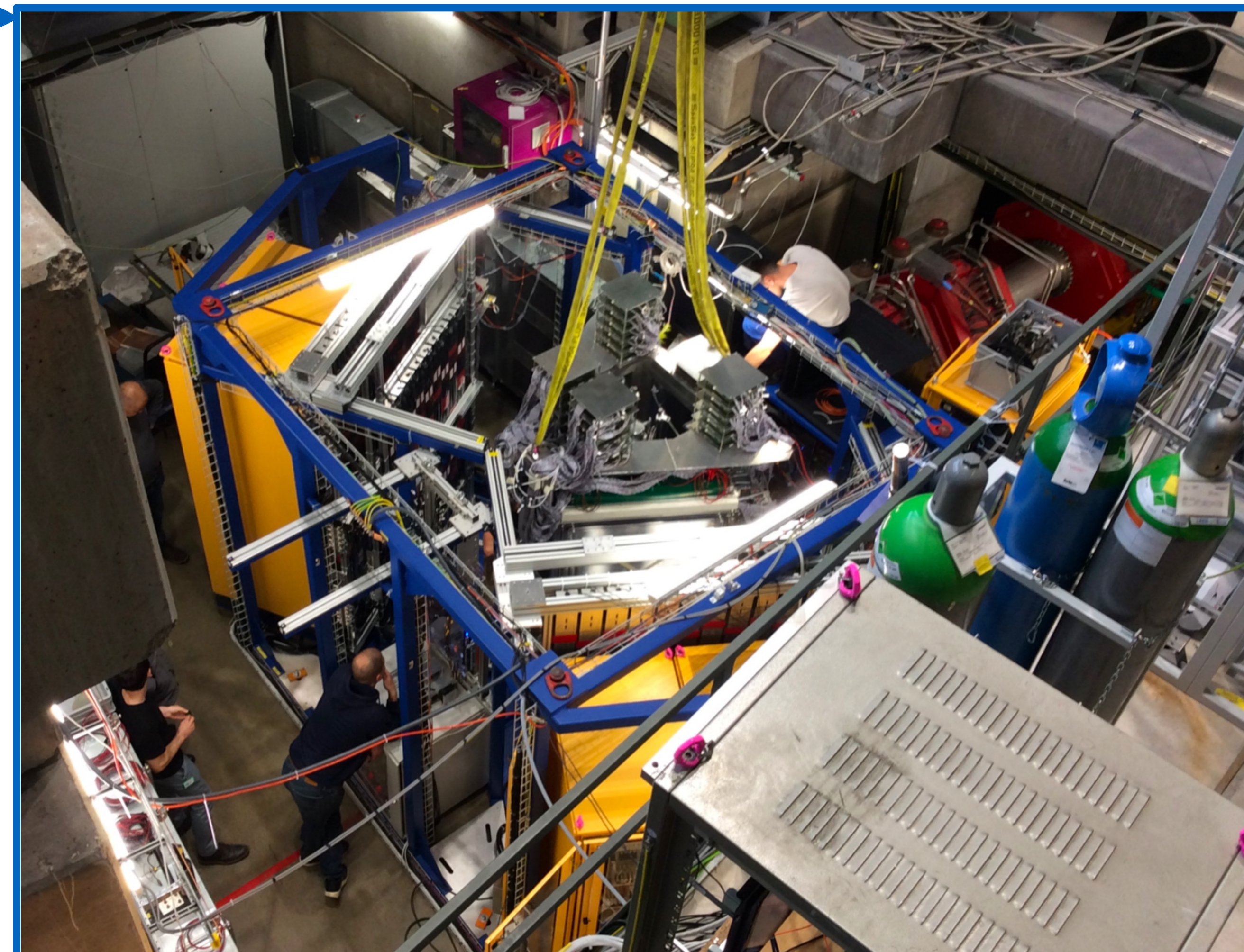
Simultaneous measurement of $e^{\pm}p$ *and* $\mu^{\pm}p$ elastic scattering reactions:

- Simultaneous determination of the **proton radius in both $e^{\pm}p$ and $\mu^{\pm}p$ scatterings**.
- Directly compare of *ep* and μ*p* scatterings at sub-percent level precision.
- Extract **TPE effects** from the $e^{-}p / e^{+}p$ and $\mu^{-}p / \mu^{+}p$ ratios.
- Lepton universality test.

MUSE @ Paul Scherer Institute (PSI)



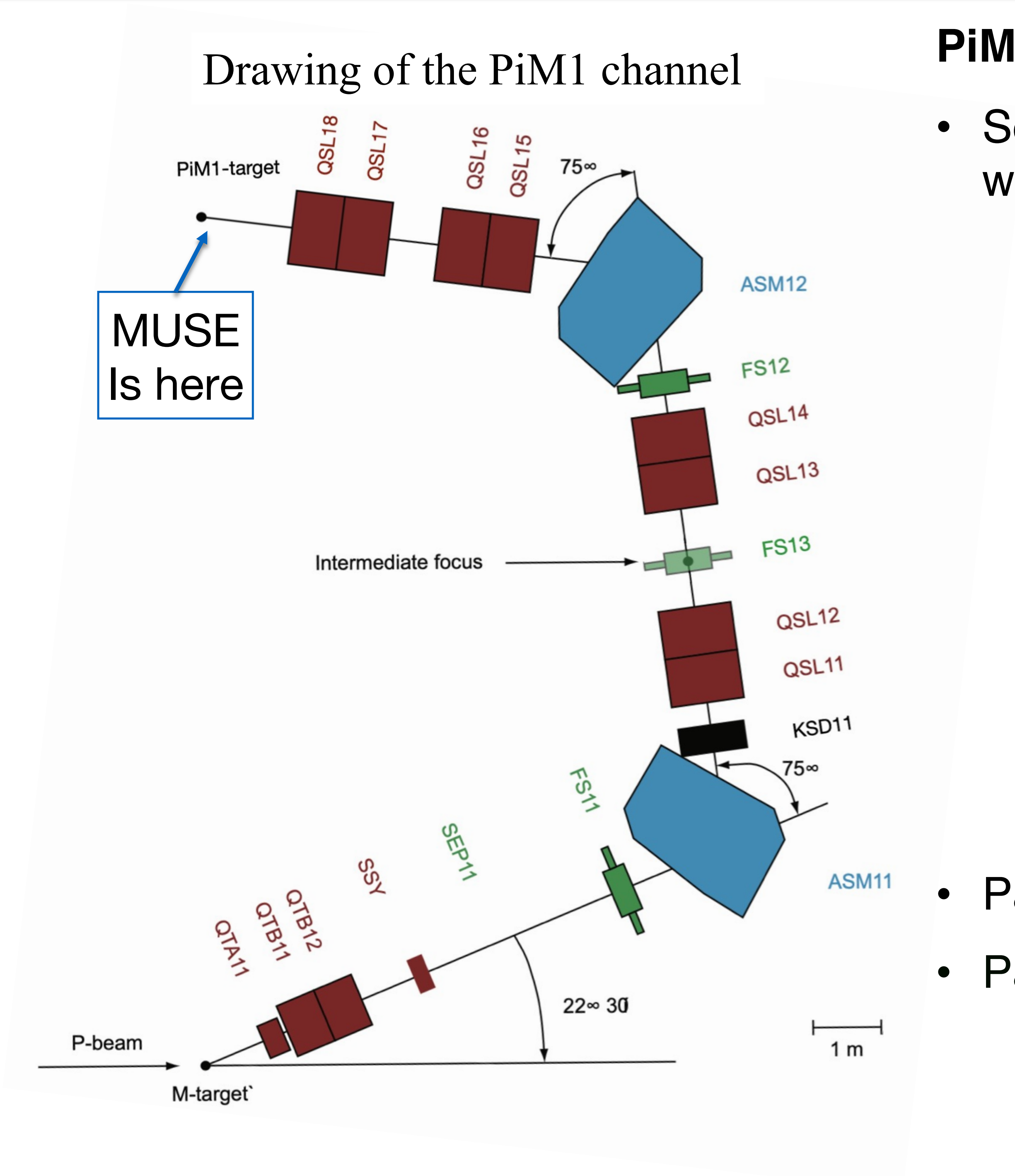
MUSE apparatus installed at PiM1 beam line:



PiM1 Secondary Beam Line:

- 100-500 MeV/c beam momentum;
- 3.3 MHz beam flux (MUSE):
  - $\approx$ 2–15% $\mu^{\pm}$
  - $\approx$ 10–98% $e^{\pm}$
  - $\approx$ 0–80% $\pi^{\pm}$

PiM1 Beam Line @ PSI



PiM1: 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):

  ⇒ π – Production:

  $p + p \to p + n + \pi^+$ $\quad p + n \to p + n + \pi^0$ $\quad p + n \to d + \pi^0$

  $p + p \to p + p + \pi^0$ $\quad p + n \to p + p + \pi^-$

  $p + p \to d + \pi^+$ $\quad p + n \to n + n + \pi^+$

  ⇒ μ – Production:

  $\pi^+ \to \mu^+ + \nu_\mu$ $\quad \pi^- \to \mu^- + \bar{\nu}_\mu$

  ⇒ e – Production:

  $\pi^\pm \to e^\pm + \nu_e$

  $\pi^0 \to^{\approx 98.8\%} 2\gamma$ ⟶ $\gamma + A \to e^+ + e^- + A'$

  $\pi^0 \to^{\approx 1.2\%} e^+ + e^- + \gamma$

- Particle flux varies with beam momentum.
- Particle types are separated in time.

Detailed simulation was done!
Beam is well understood!

[E. Cline et al., Phys. Rev. C 105, 055201]

PiM1 Beam Line @ PSI

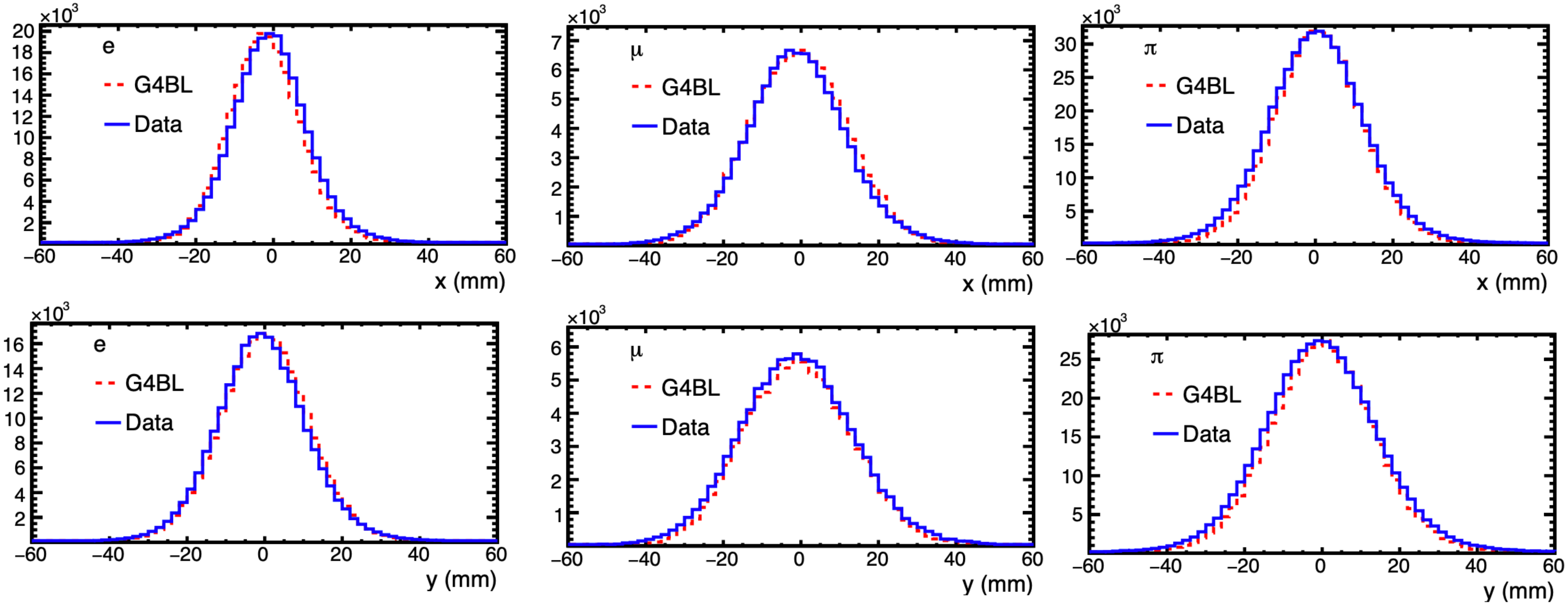
Comparison of the PiM1 beam profile from G4beamline simulations data at the MUSE target:

=> PiM1 beam profile for +160 MeV/c beam momentum.

Electrons | Muons | Pions

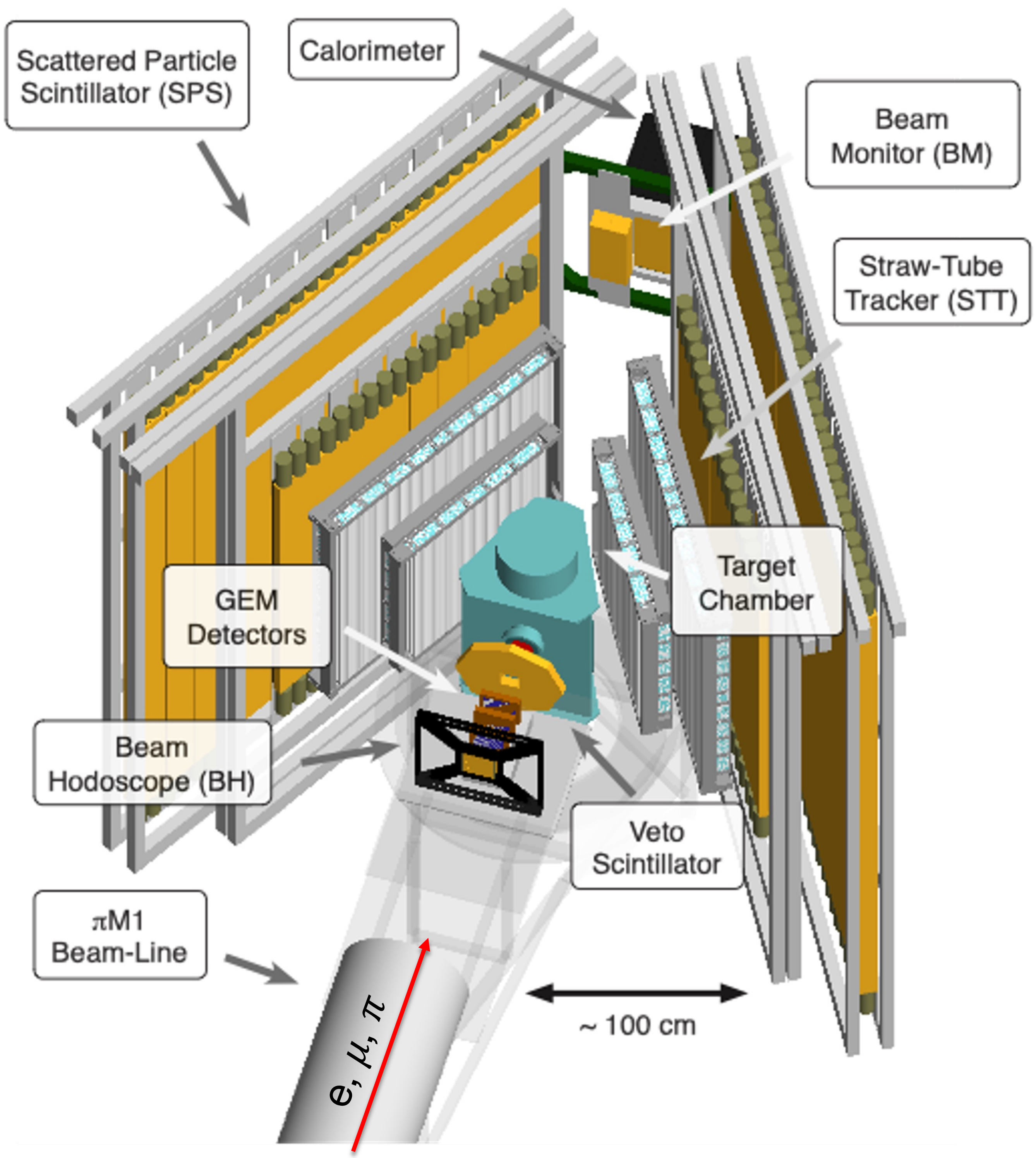
Horizontal distribution

Vertical distribution



[E. Cline et al., Phys. Rev. C 105, 055201]

MUSE Detector Setup and Kinematics



Beam line detectors:

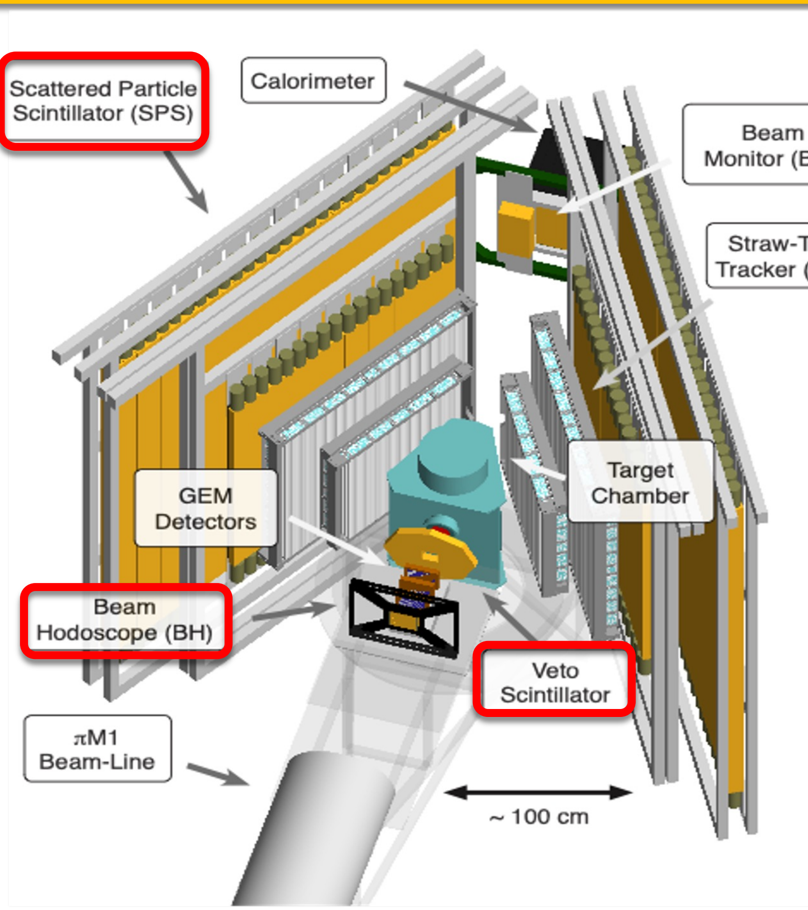
- **Beam Hodoscope** (beam particle ID);
- **GEM Detectors** (beam particle trajectory);
- **Veto Scintillator** (reject scattering and decay events);
- **Beam Monitor** (beam current and beam momentum).
- **Calorimeter** (hard photons suppression).

Scattered particle detectors:

- **Straw-Tube Tracker** (scattering particle track)
- **Scattered Particle Scintillator** (scattered particle ID)

Parameter	Value
Beam momentum, GeV/c	0.115, 0.160, 0.210
Scattering angle rage	$20^0 - 100^0$
Q^2 range for electrons, GeV^2	0.0016 – 0.0820
Q^2 range for muons, GeV^2	0.0016 – 0.0799

MUSE Event Selection

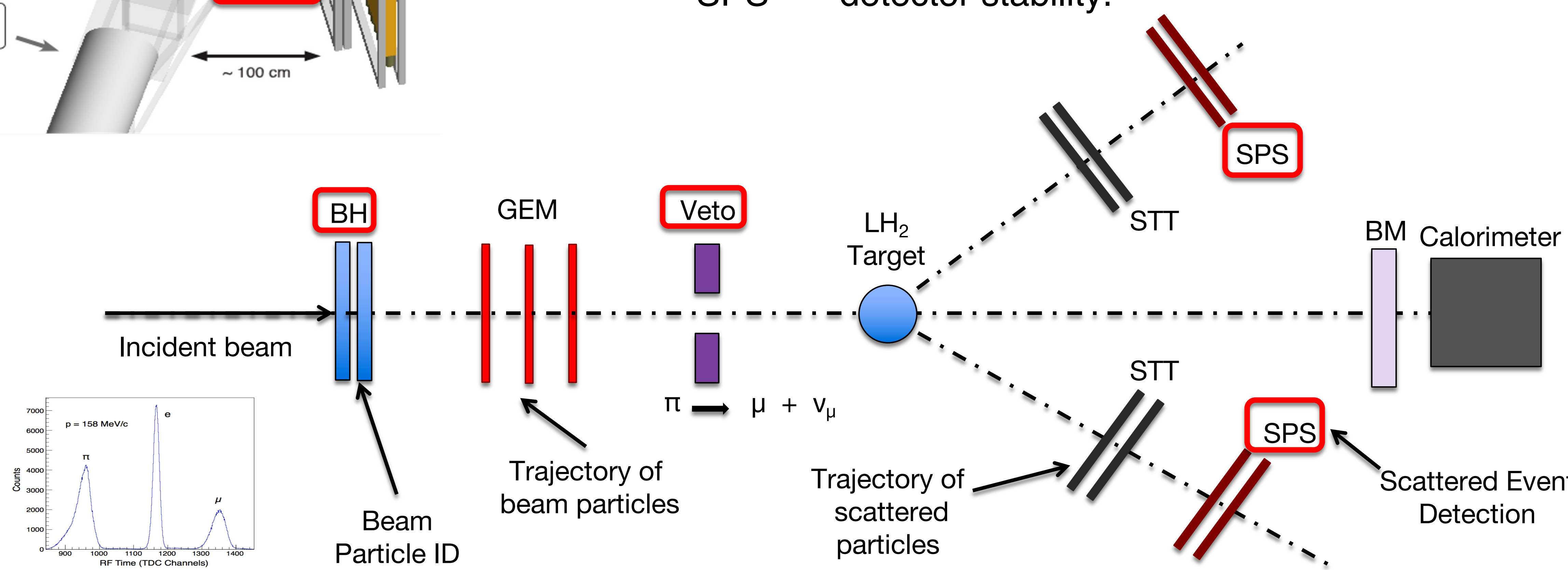


- Primary (Scattering) Triggers:

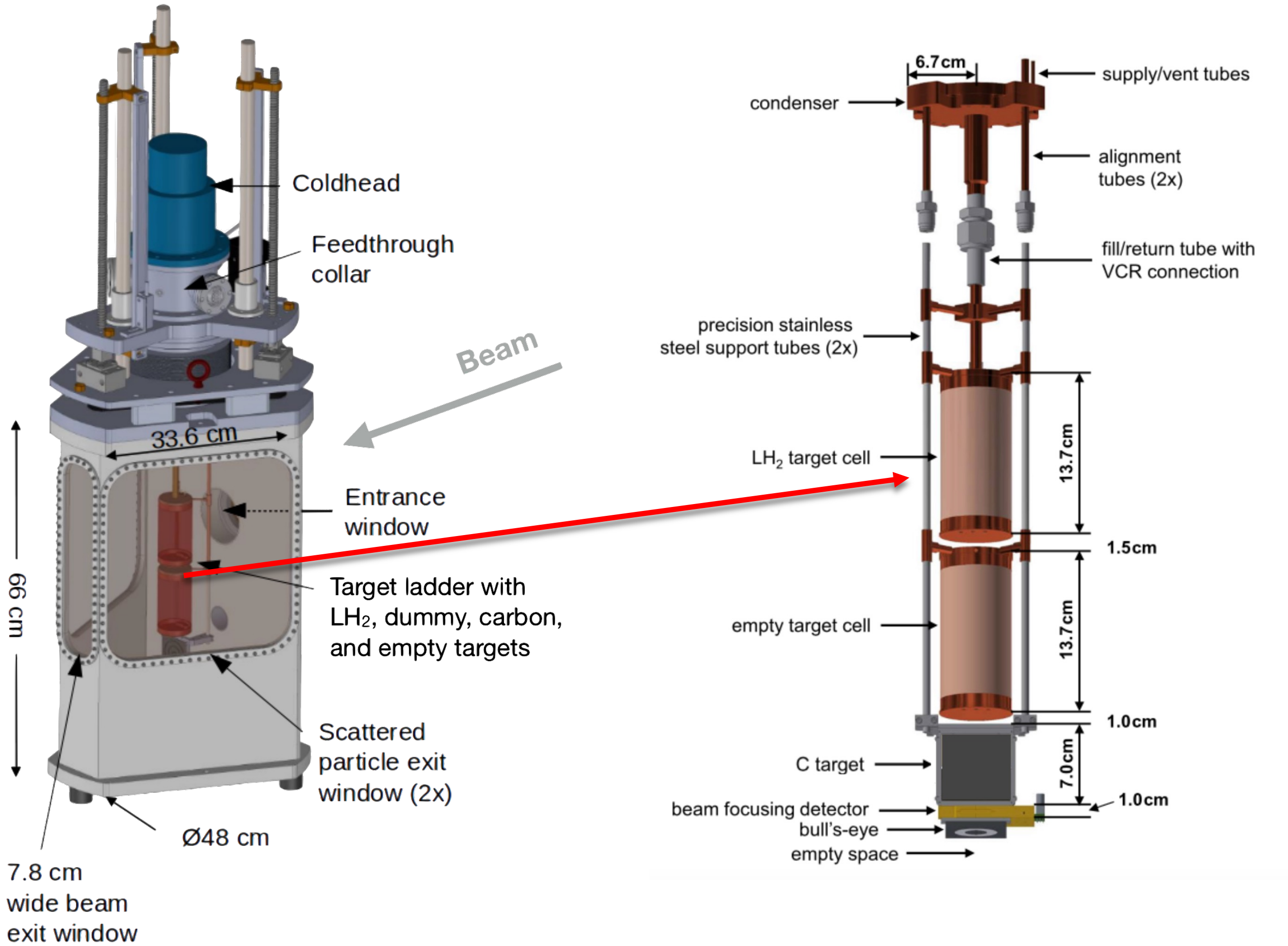
  PID(e OR μ) AND (scatter) AND (no veto)

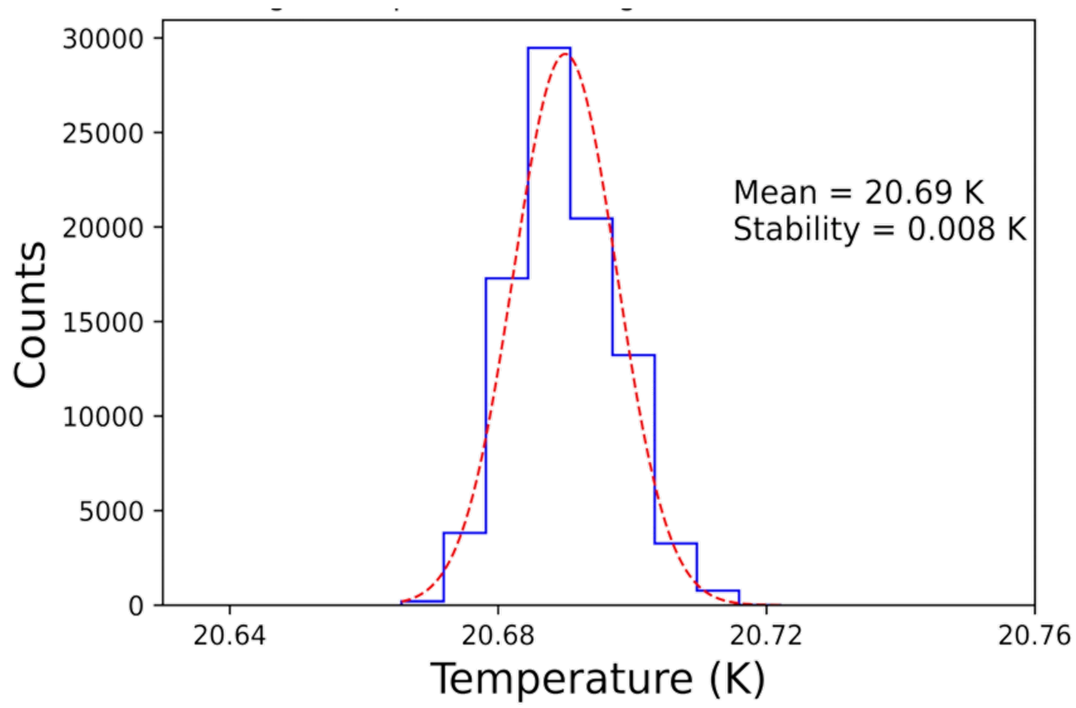
  PID(π) AND (scatter) AND (no veto) => pre-scaled!

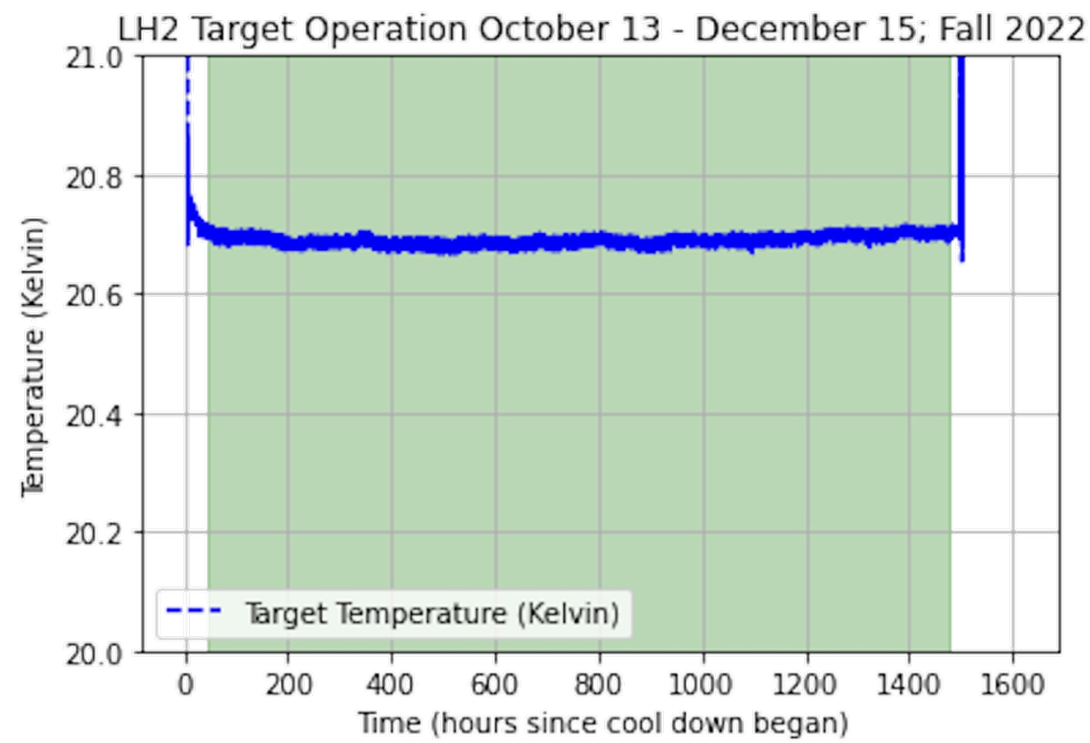
- Calibration Triggers (pre-scaled):
  - random pulser – unbiased detector backgrounds;
  - PID (e, μ, π) – luminosity and beam stability;
  - BM – beam momentum measurements and stability.
  - SPS – detector stability.



MUSE Target and Vacuum Chamber







LH_2 Target Operation in 2022:

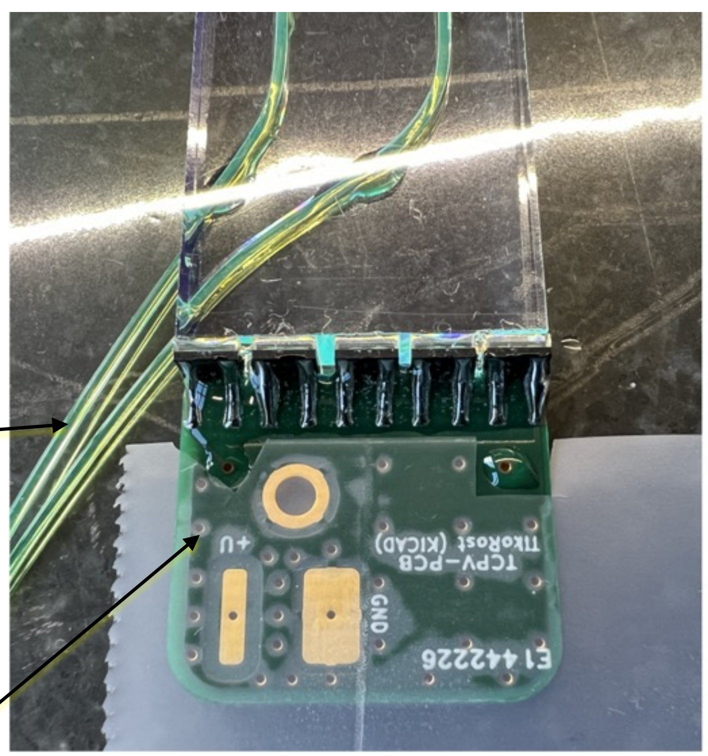
- Target operated with LH_2 for 9 weeks (100% uptime)
  - 1450 hours (60 days w/o cool down and warmup)
- Target Temperature (bottom end cap):
  - stable at 0.008 K level over entire beam time
- Across full operating time:
  - Temperature = 20.69 ± 0.008 K

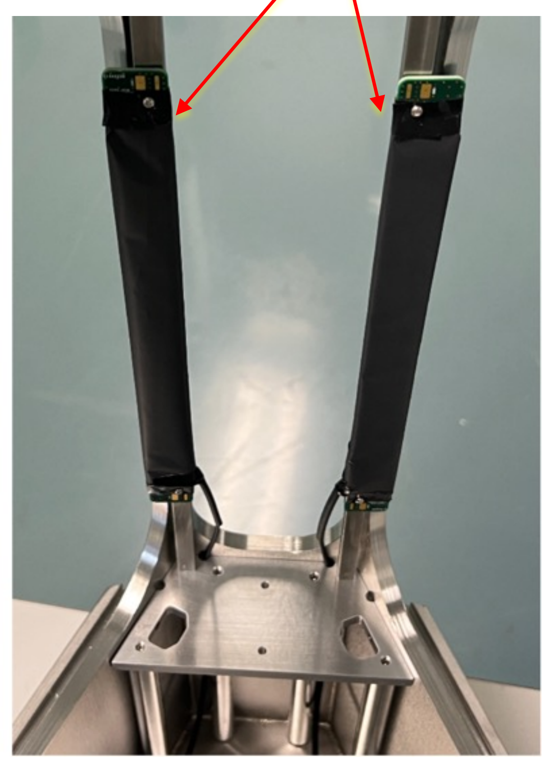
[P. Roy, et al., NIM A A949 (2020) 162874]

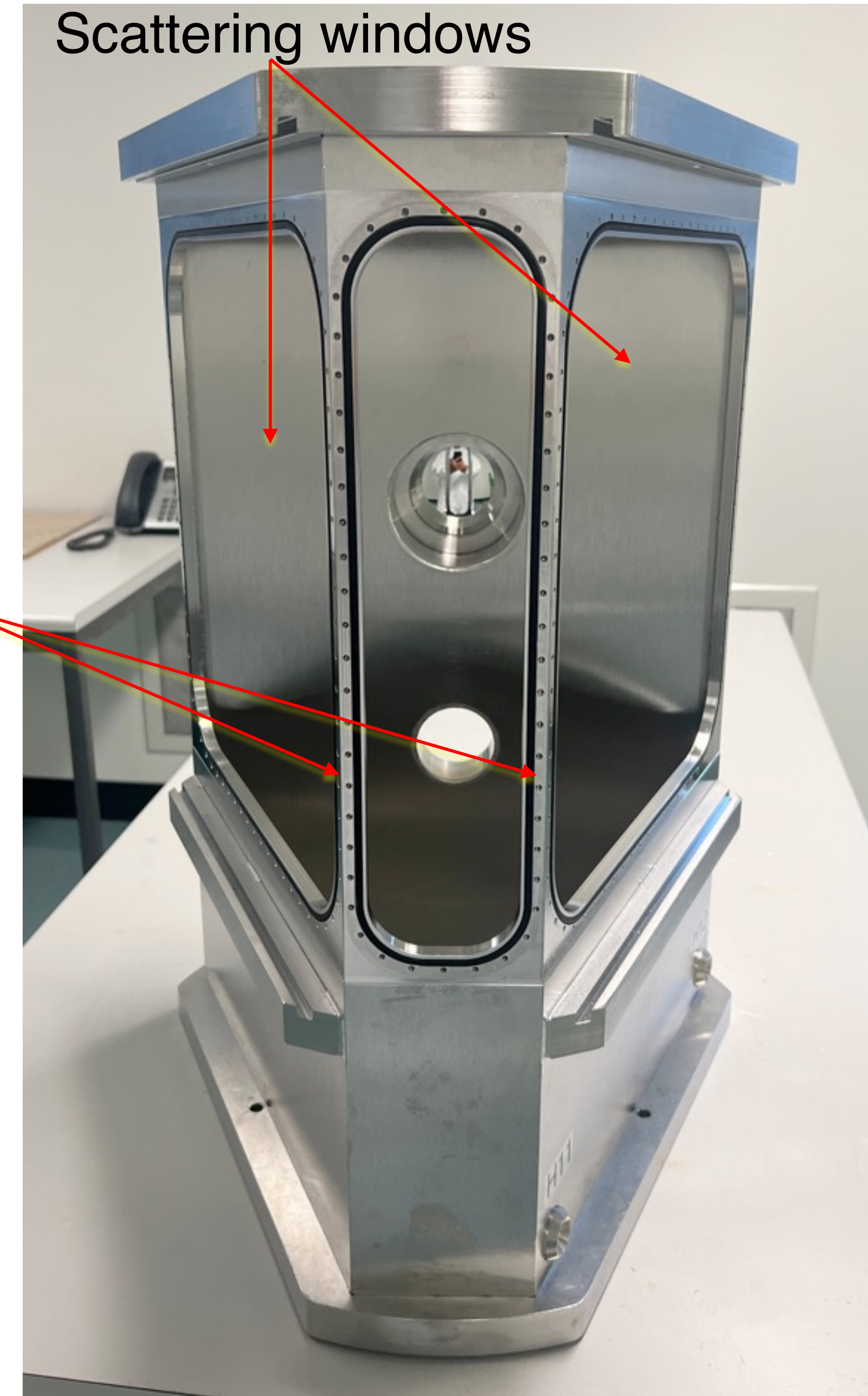
MUSE Vacuum Chamber (Upgrade 2022)

- GEM-STT vertex reconstruction shows many triggers from scattering from target chamber support posts
- A new **Target Post Veto** detector was developed and installed.

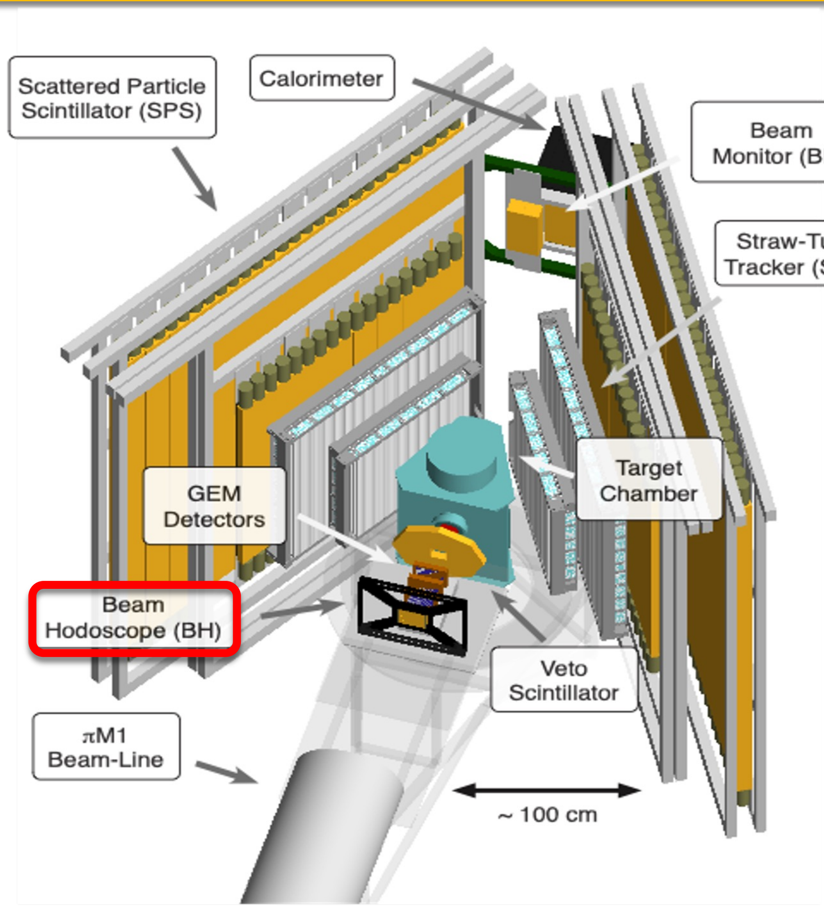
  => 10% reduction of trigger rate

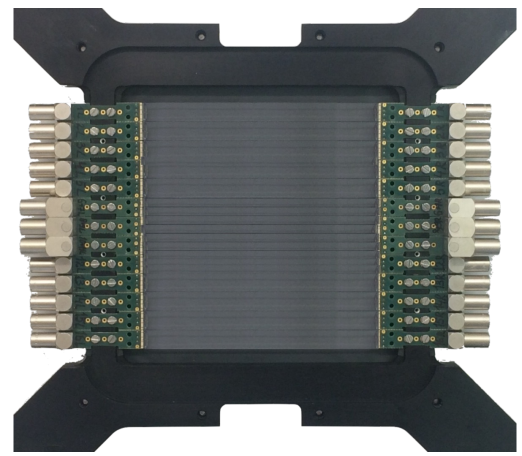






Beam Hodoscope (BH)

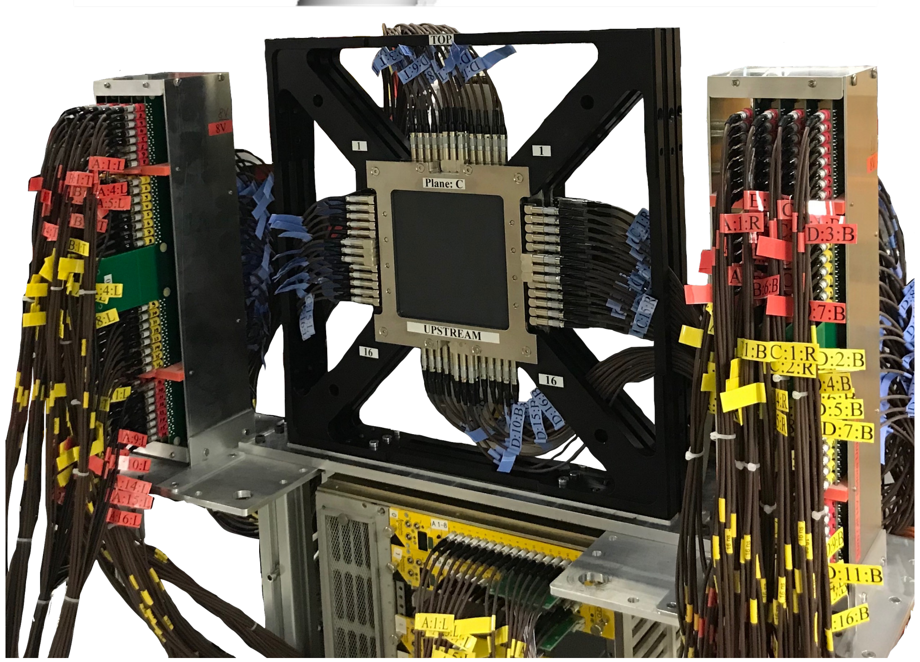


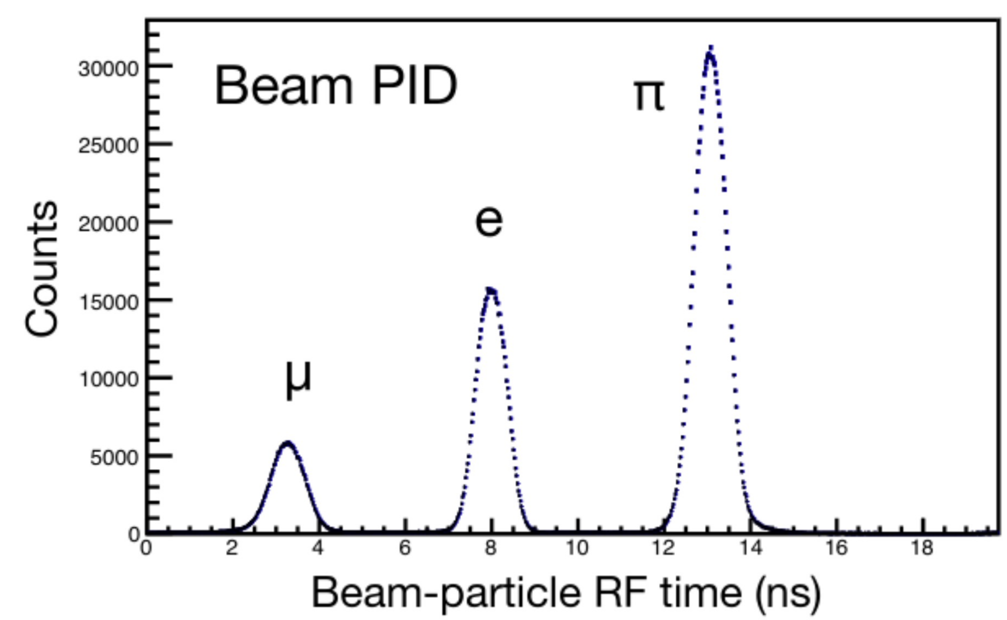


- 2x BH-Planes : 16 & 13 paddles per plane;
- 2 (3) mm thick x 4&8 mm wide x 100 mm long **BC404** + Hamamatsu **S13360-3075PE;**
- σ_T < 100 ps; $\varepsilon \geq 99$ %.

- The beam hodoscope counts the total incident beam **flux** and provides precise **timing** and **position** information for beam particles:

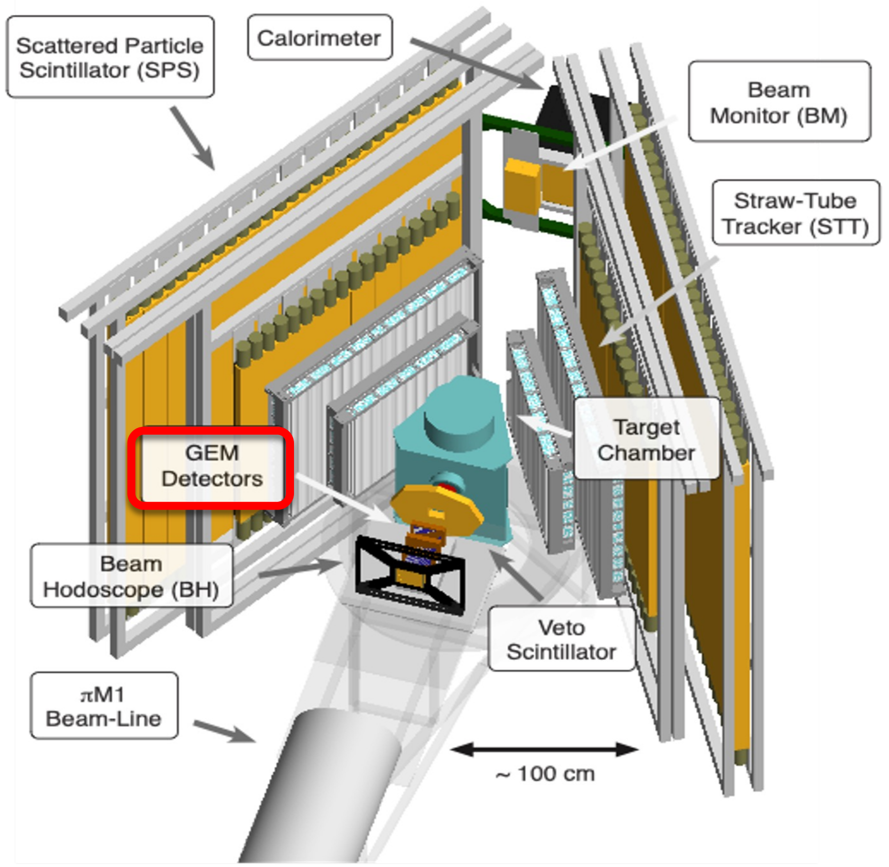
  => beam RF time to hodoscope: beam-particle ID.

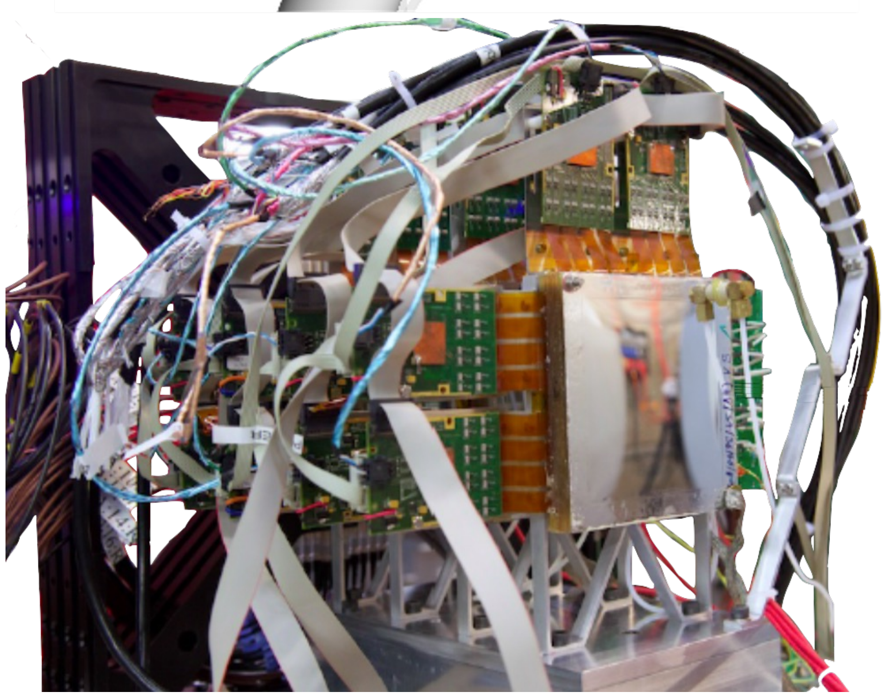




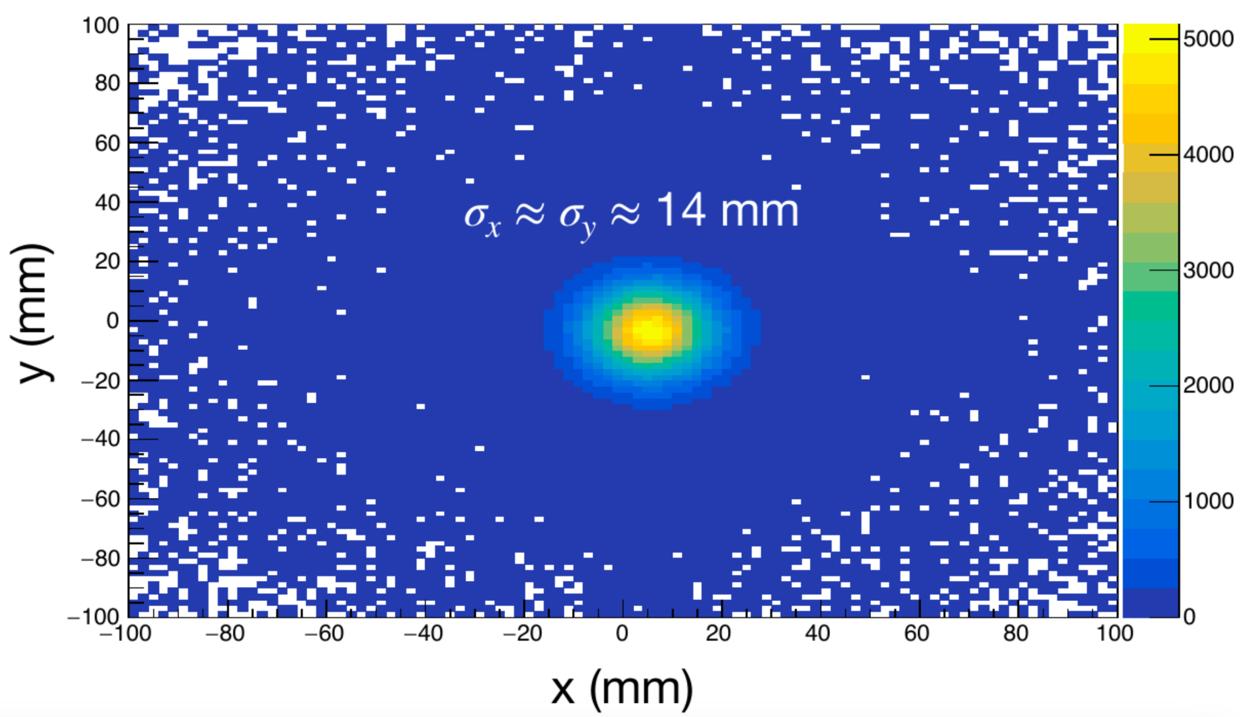
[T. Rostomyan, et al., Nucl.185 Instrum. Methods Phys. Res., Sect. A 986, 164801 (2021) .]

GEM detector

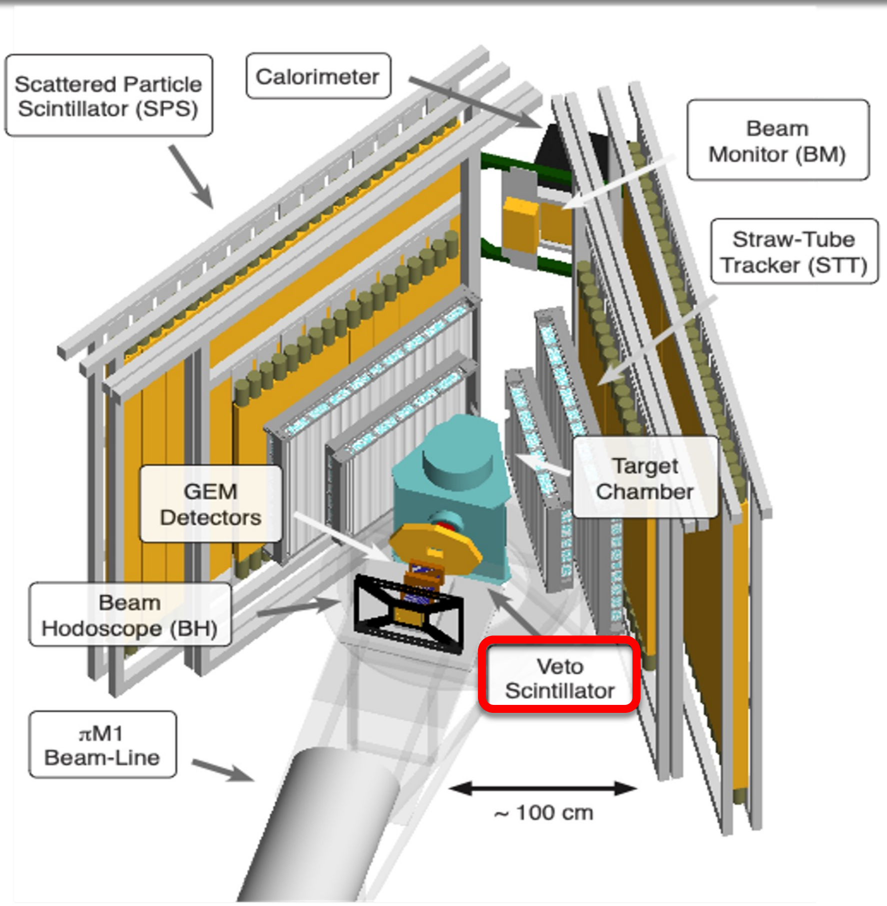


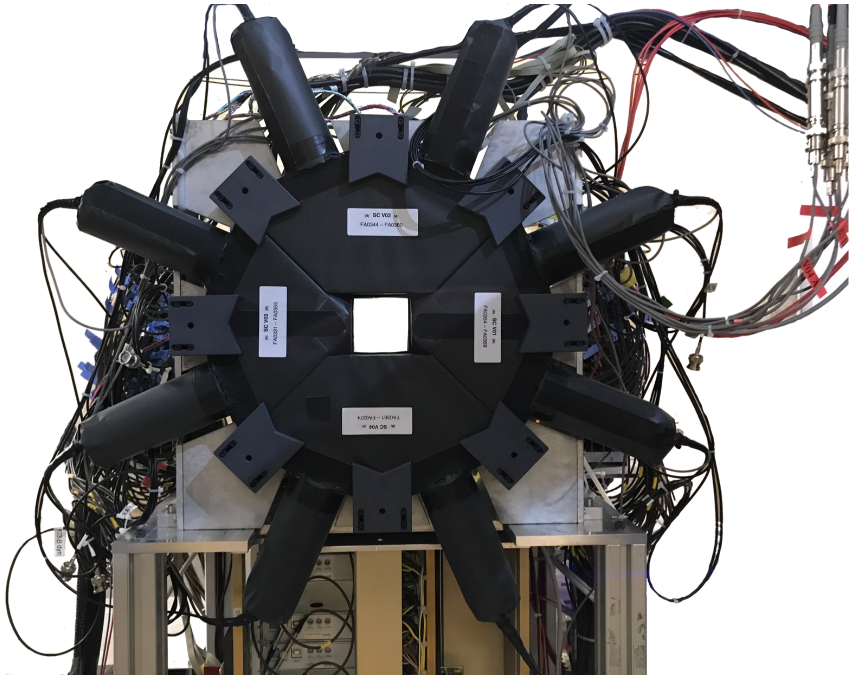


- Set of 3x (10cm x 10cm) **GEM** detectors (from OLYMPUS);
- measure trajectories into the target to reconstruct the scattering angle;
- $\sigma_S \approx 70\ \mu m$, $\varepsilon = 97 - 99\ \%$.

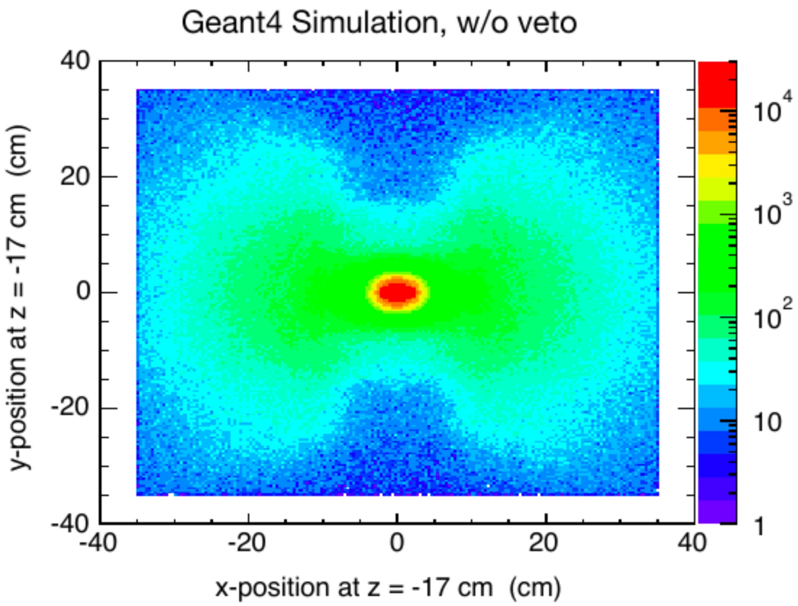


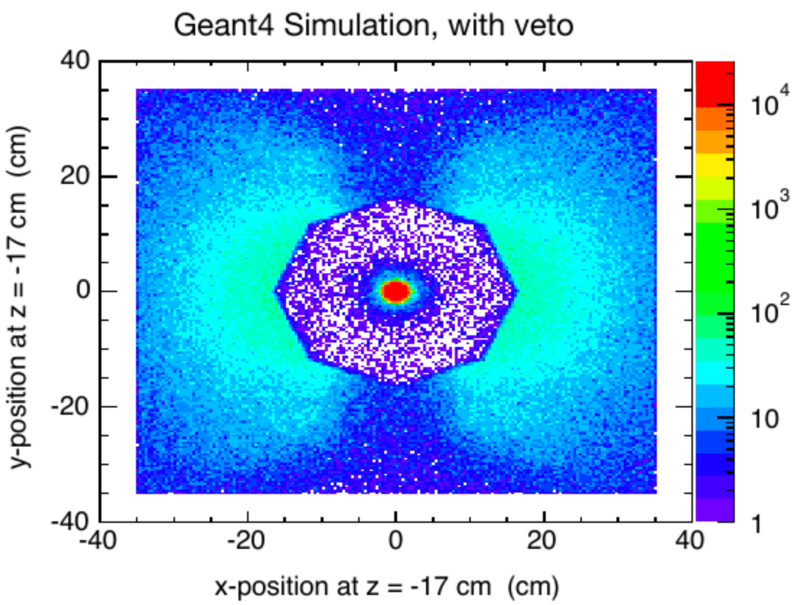
Veto Scintillator



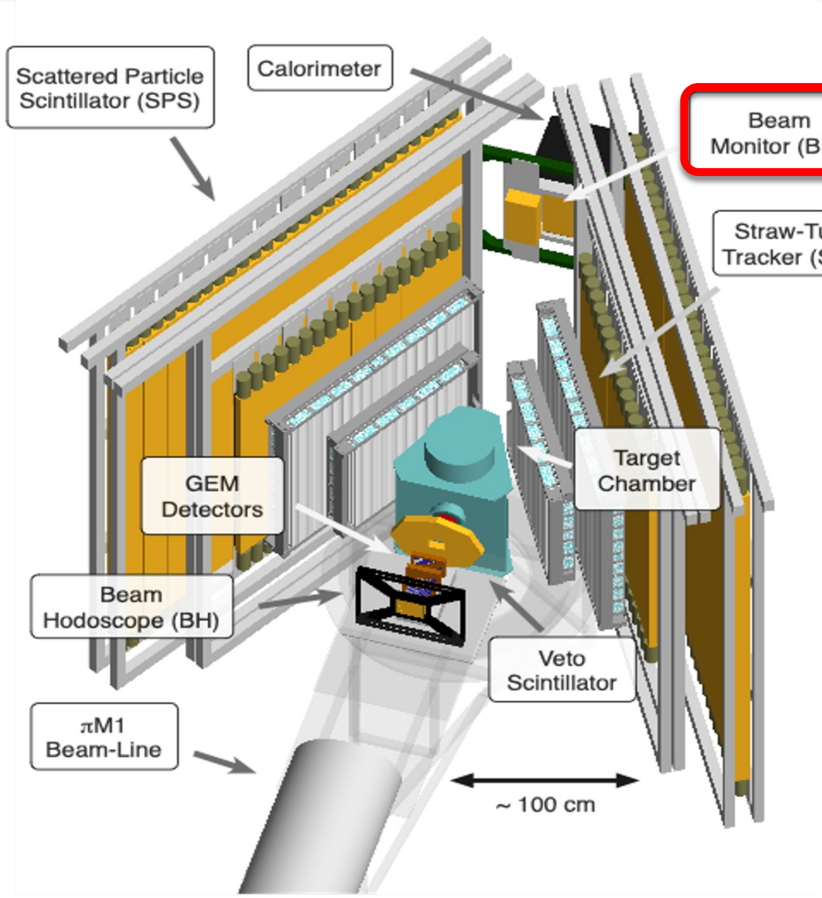


- Angular 4-element **VETO** detector, surrounding target entrance window;
- Reduces trigger rate from background events (upstream scattering and beam decays) by ~ 25%;
- $\sigma_T \leq 200$ ps, $\varepsilon > 99$ % .



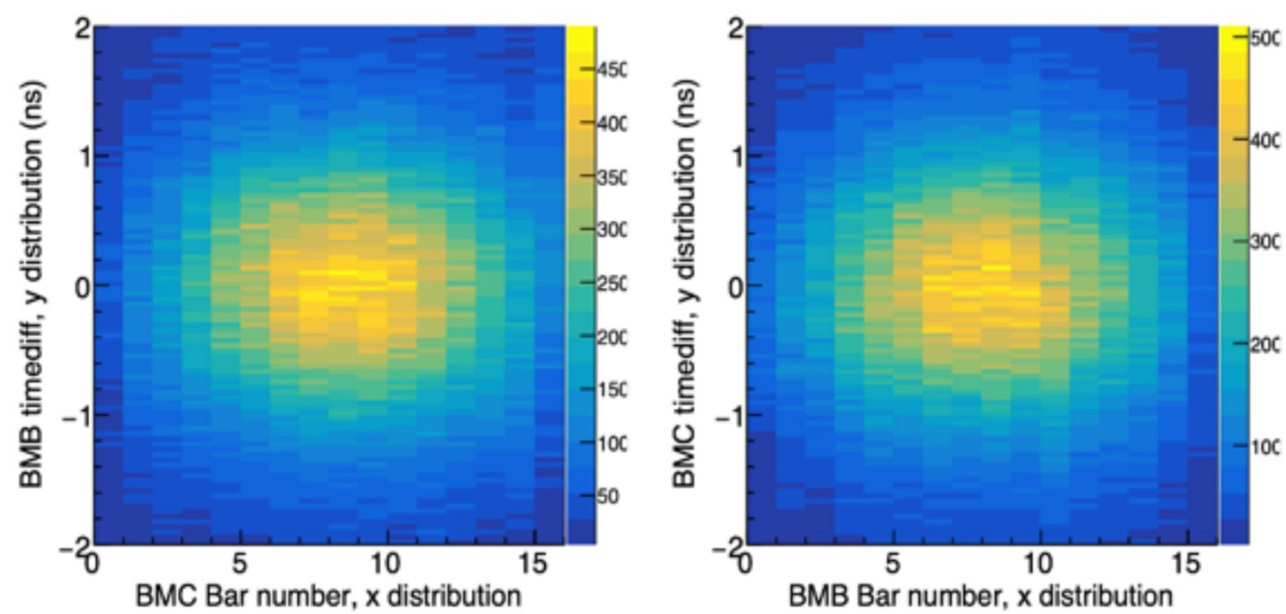


Beam Monitor (BM)



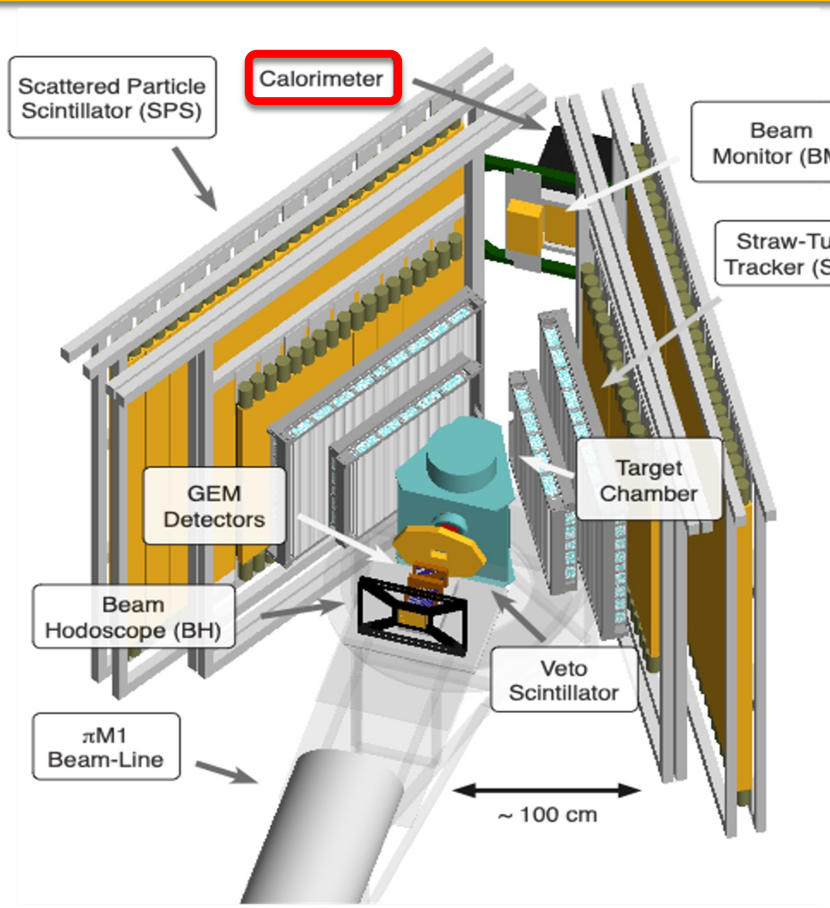
- 3 mm x 12 mm x 300 mm **BC404** + **S13360-3075PE**
- 6 mm shifted 2 planes:
  - =>16 paddles per plane(σ_T < 100 ps; ε ≥ 99 %)
  - => + 4 front scintillator bars ($\sigma_T \approx$ 50 ps; ε ≥ 99%)
- determines particle flux downstream of the target
- monitors beam **stability**
- Acts as Veto for **Møller / Bhabha scattering background**
- **BH** to **BM** → independent beam-particle ID & muon and pion beam momenta ($dp/p \lesssim$ 0.2%)

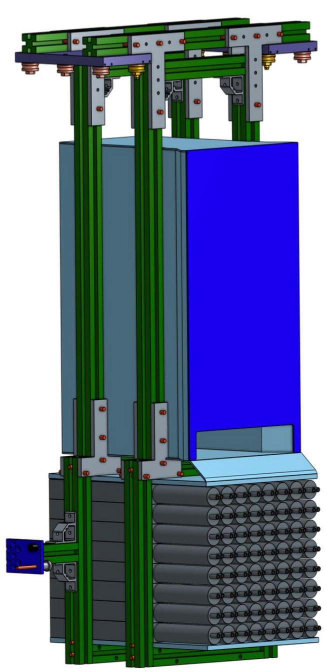
Beam distribution in BM hodoscope



[T. Rostomyan, et al.,Nucl.185 Instrum. Methods Phys. Res., Sect. A 986, 164801 (2021) .]

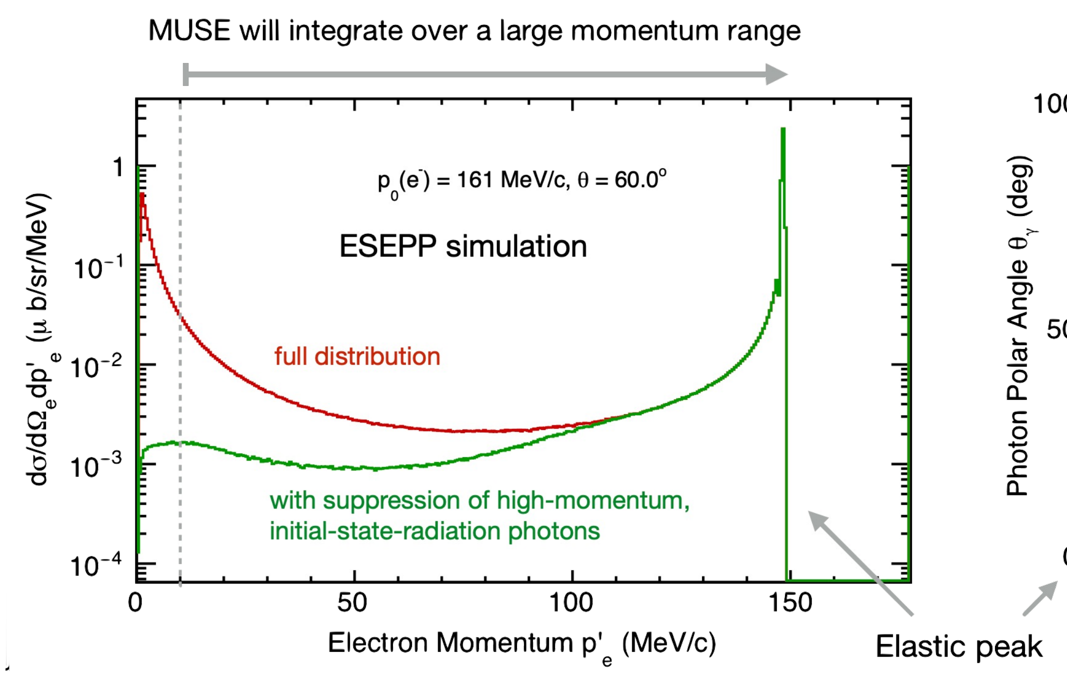
Calorimeter

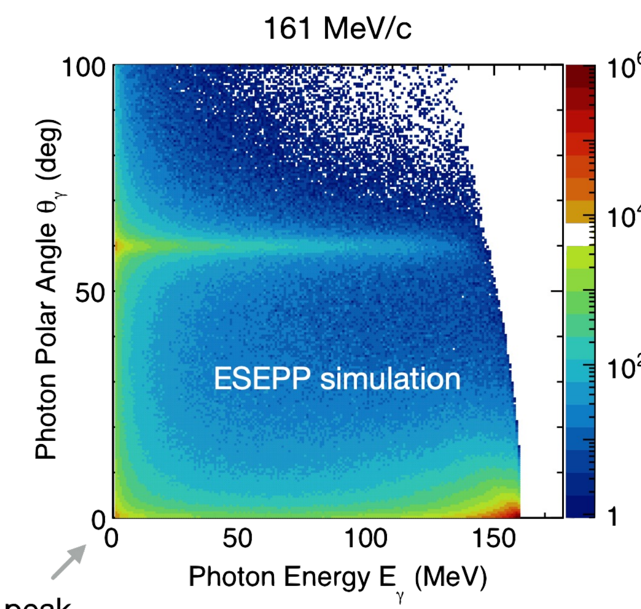




- **64x** (4 cm x 4 cm x 30 cm) **Lead-Glass** crystals
- Removes events with high-energy γ in beam direction

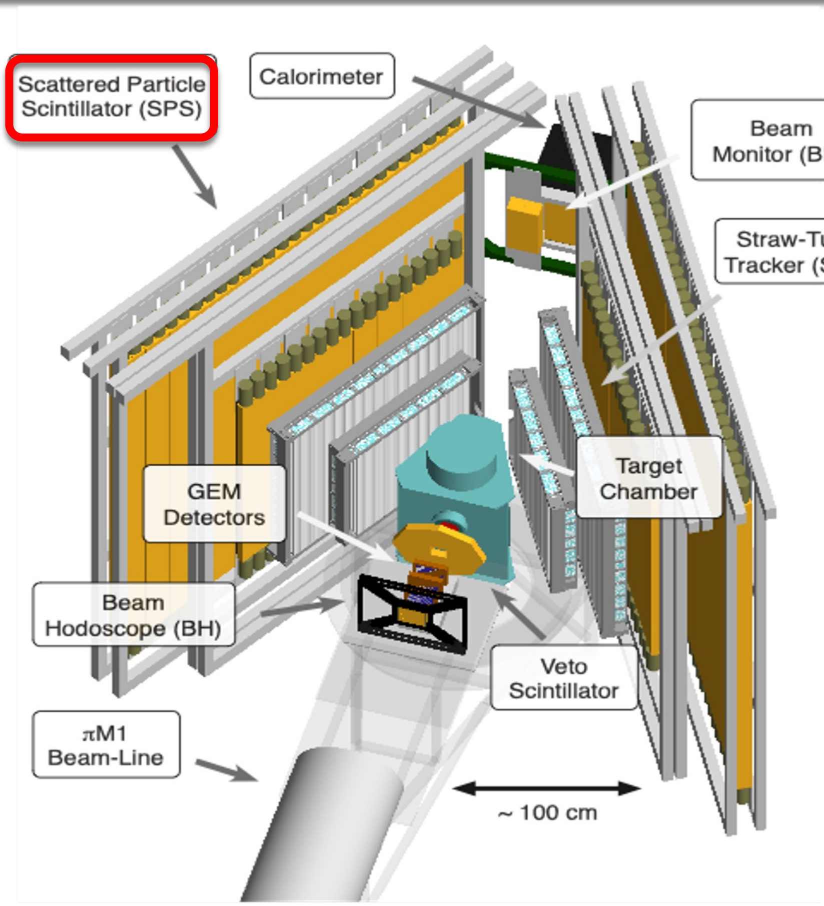
$ep \to e'p\gamma$ Cross section in MUSE kinematics



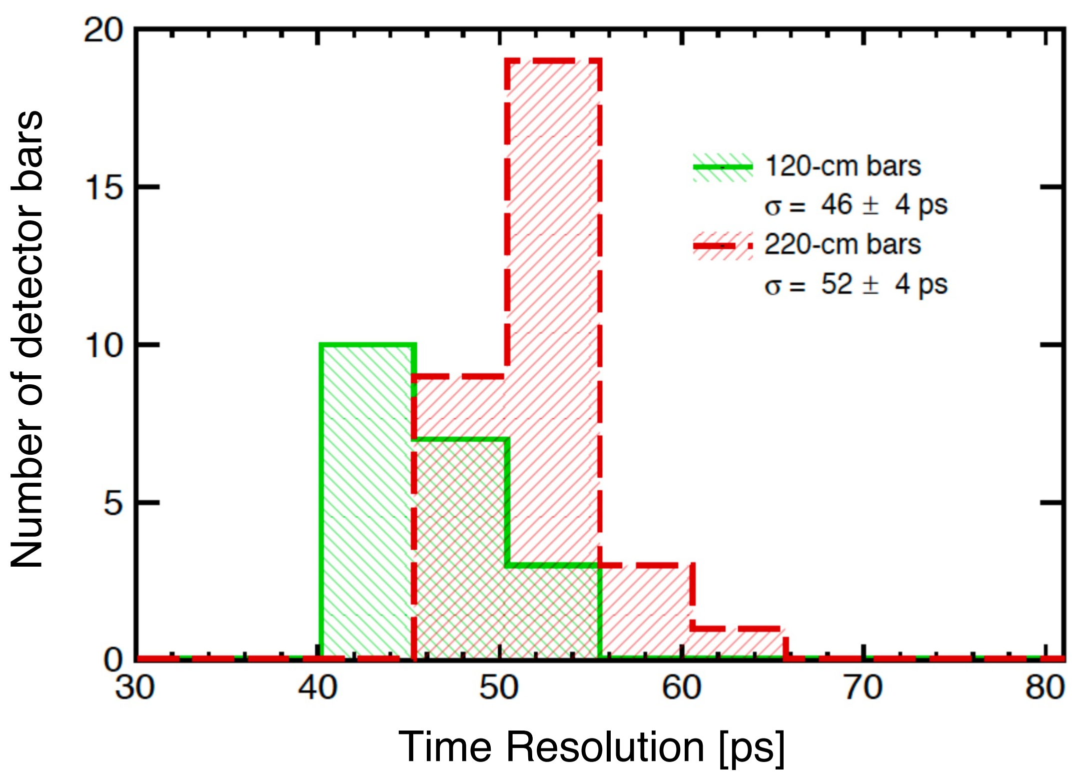


CAL veto on downstream photons reduces radiative corrections and p'_{min} dependence, reducing uncertainty.

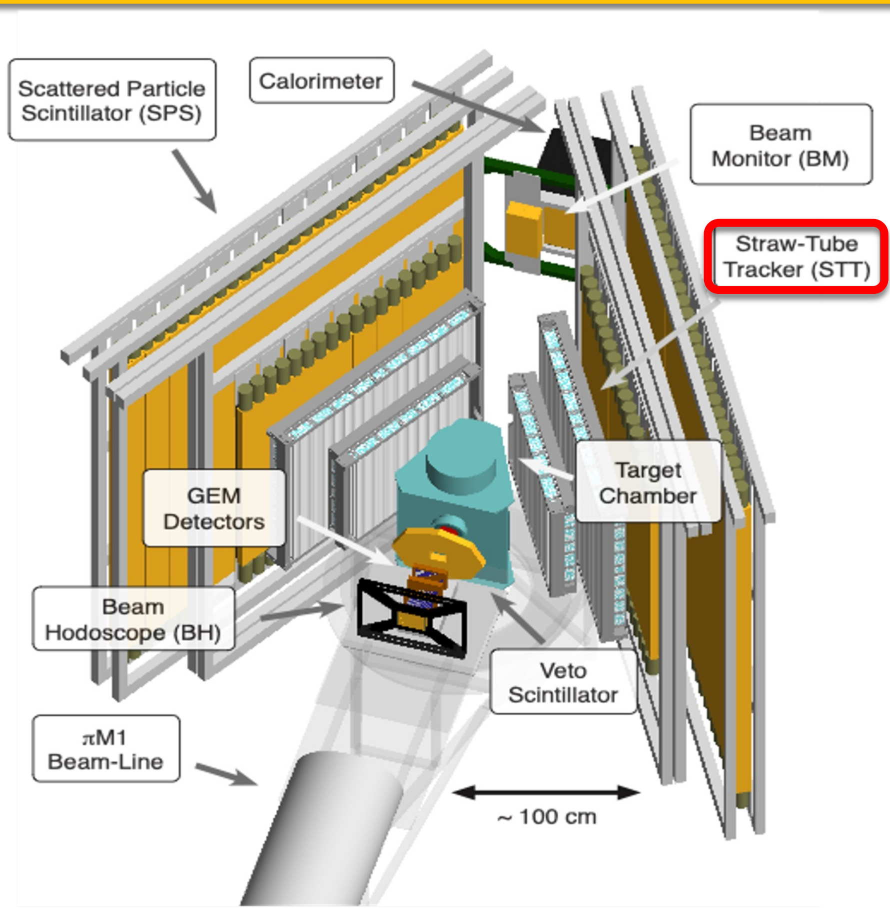
Scattered Particle Scintillators (SPS)



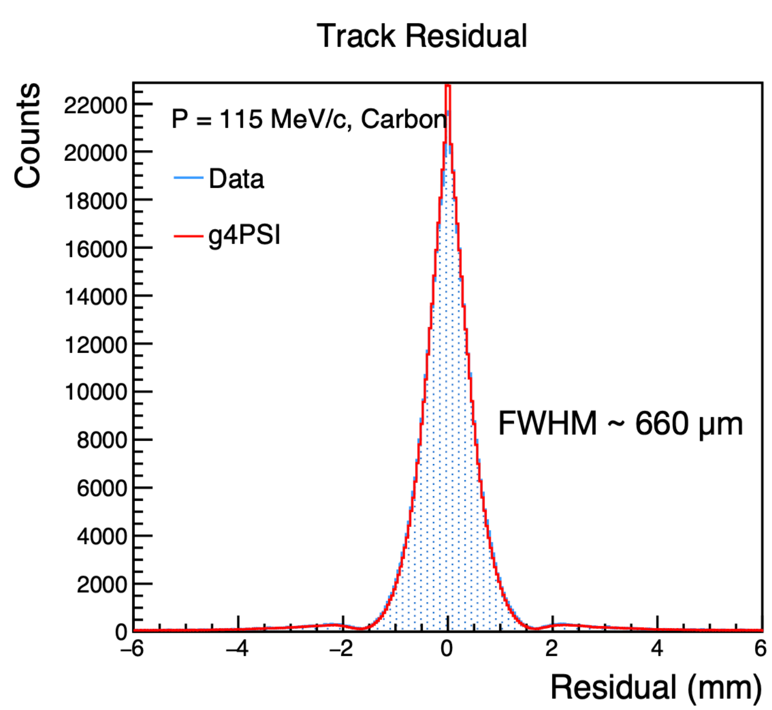
- 2 sides x 2 planes of scintillators:
  - Front wall: 18 bars (6 cm x 3 cm x 120 cm)
  - Rear wall: 28 bars (6 cm x 6 cm x 220 cm)
- CLAS12 design;
- High precision timing and efficiency:
  - $\sigma_T^{(Front)} < 50$ ps, $\sigma_T^{(Rear)} < 60$ ps;
  - $\varepsilon \geq 98\%$.

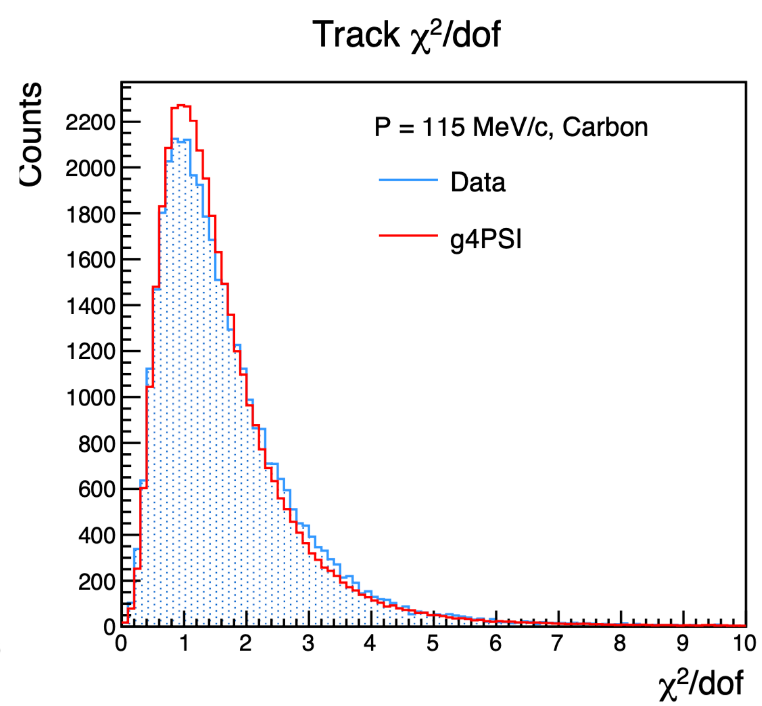


Straw Tube Tracker (STT)



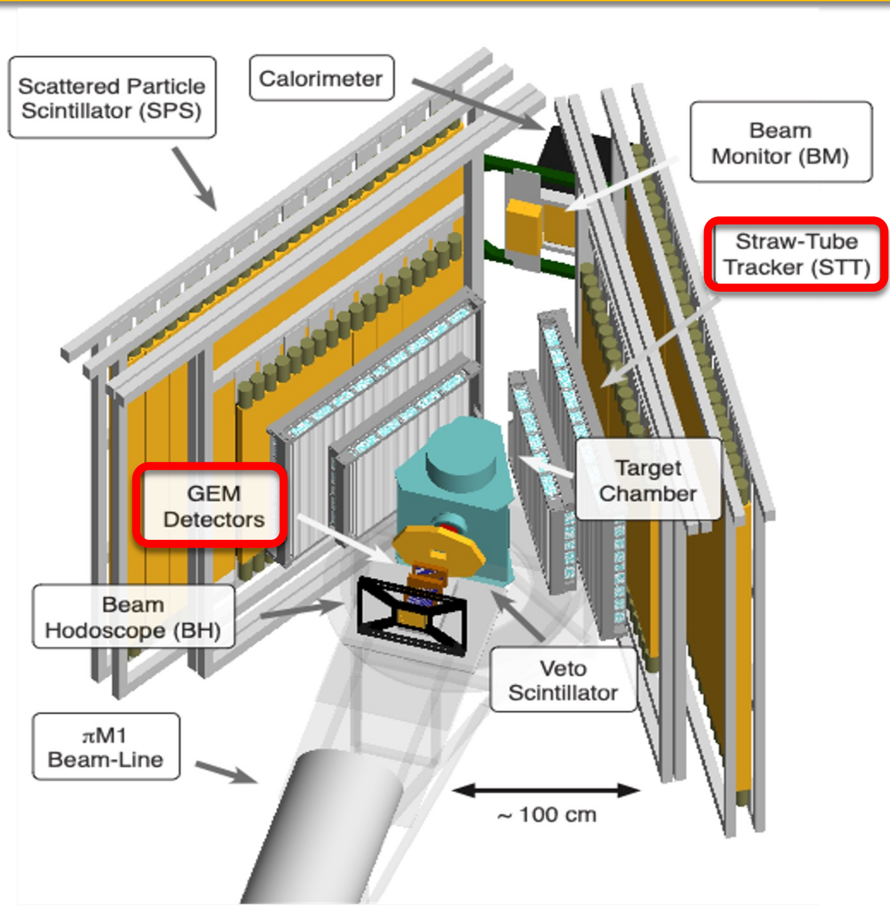
- Based on PANDA STT – design
- 4 chambers x 5 planes x 2 orientations (**x and y)**
- In total **2850** Straws.
- **STT** provides high-resolution and high-efficiency tracking of the particles scattered from the target.

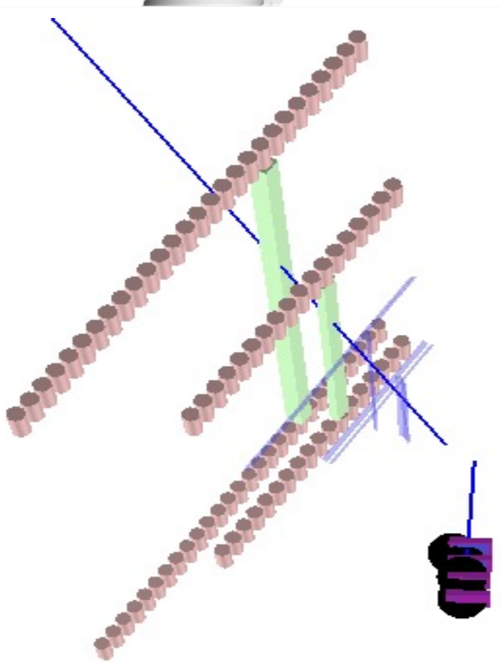




- MC studies confirmed that STT tracking efficiency is nearly angle independent and close to 99%!

Muse Tracking and Vertex Reconstruction

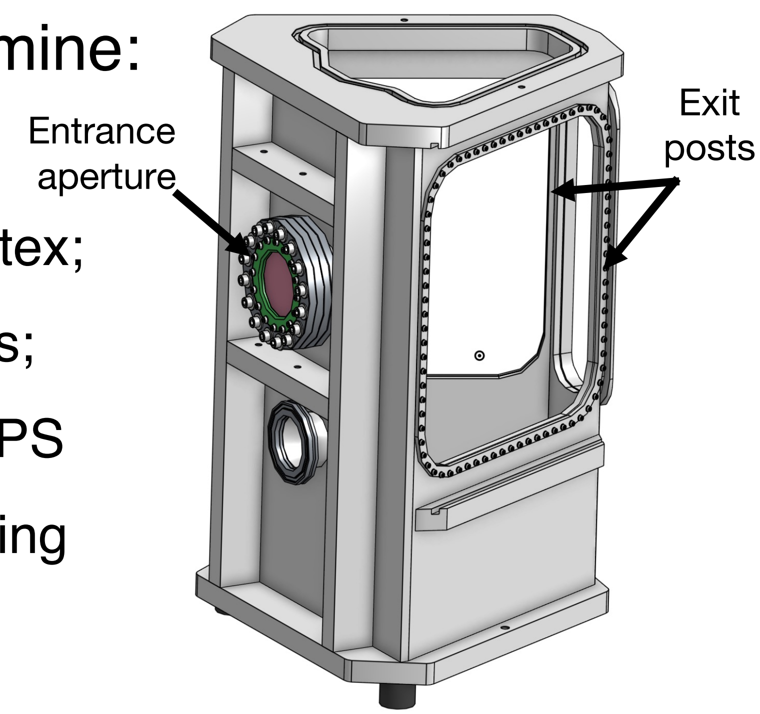




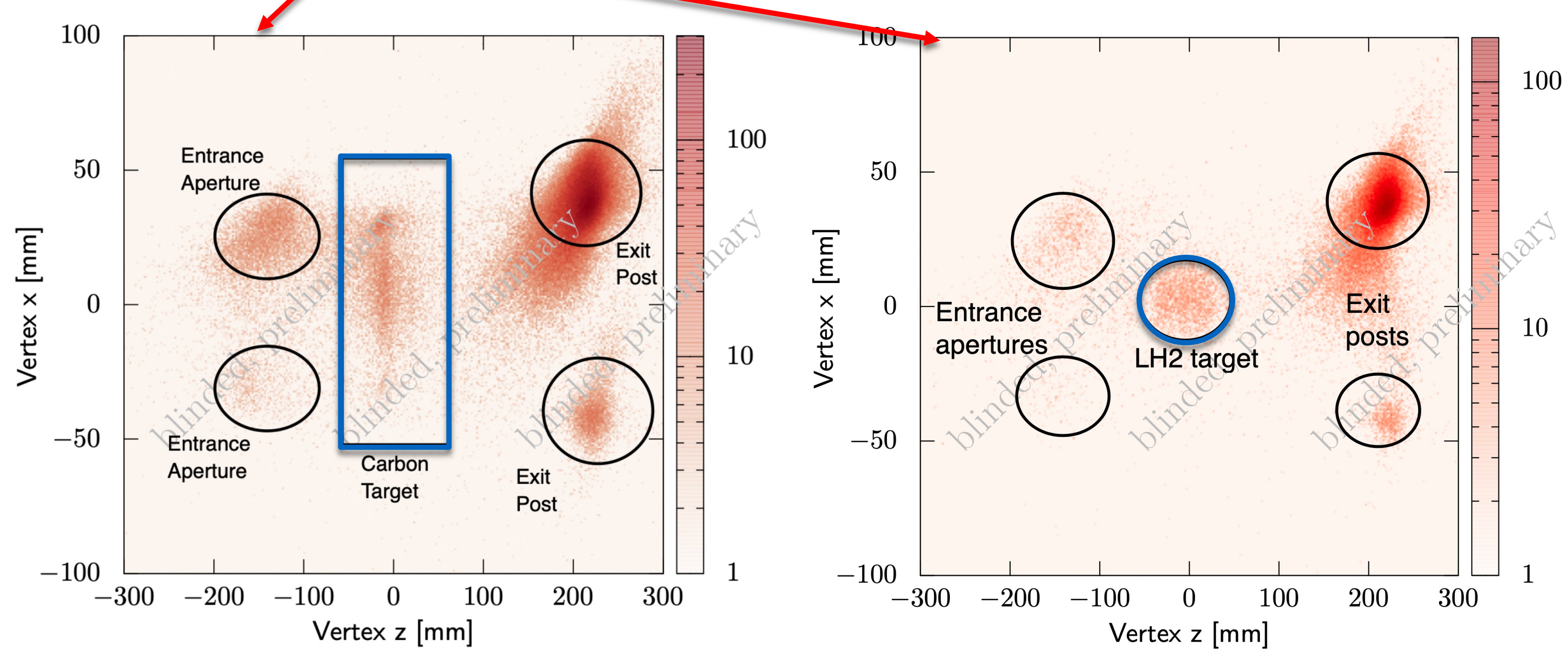
GEM and STT together determine:

- interaction vertex;
- quality of the reconstructed vertex;
- scattering and azimuthal angles;
- path length between BH and SPS

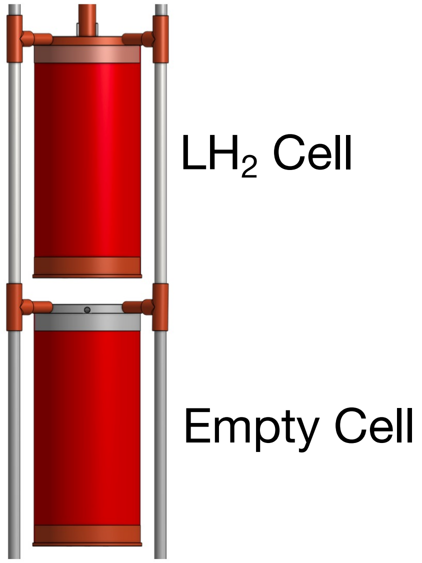
=> Reaction ID (using timing information).



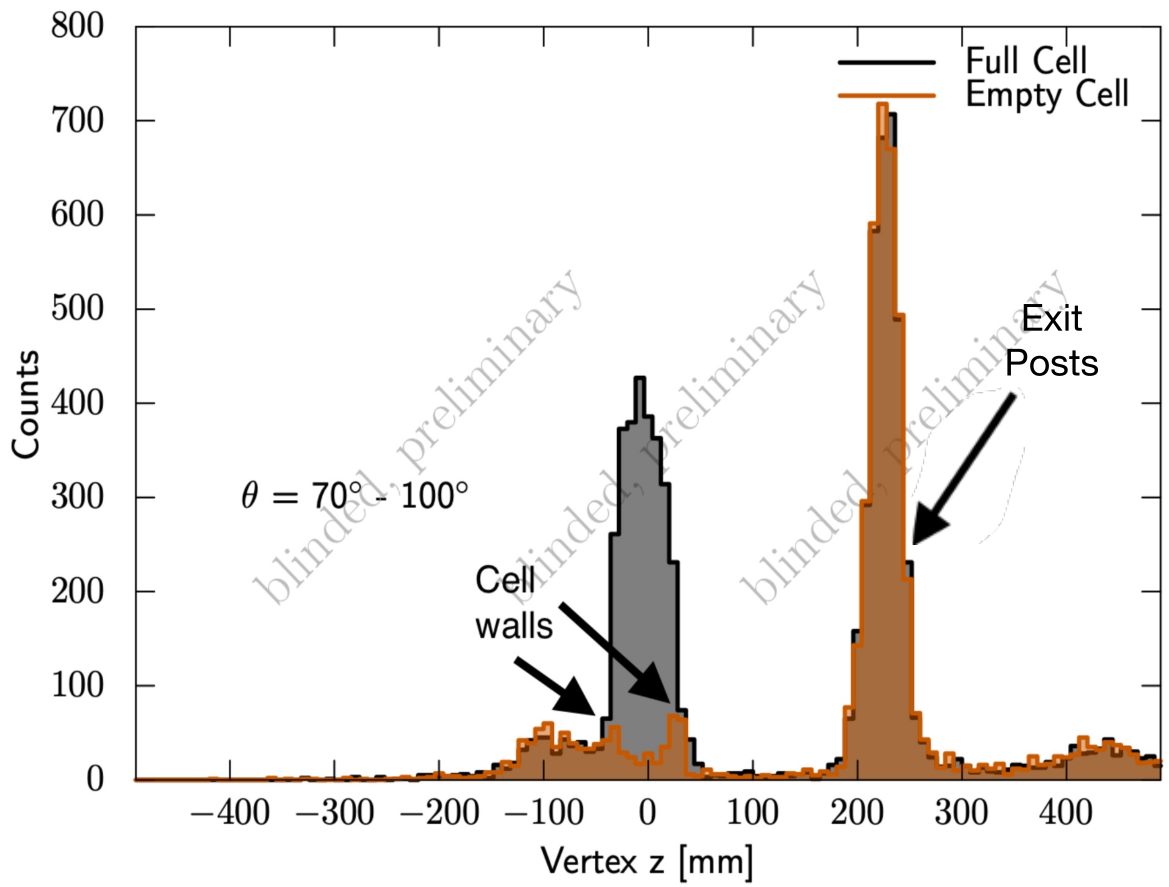
Example of the Top-Down view of the Vertex reconstruction for Carbon and LH_2 data for 160 (+) MeV/c beam momentum:

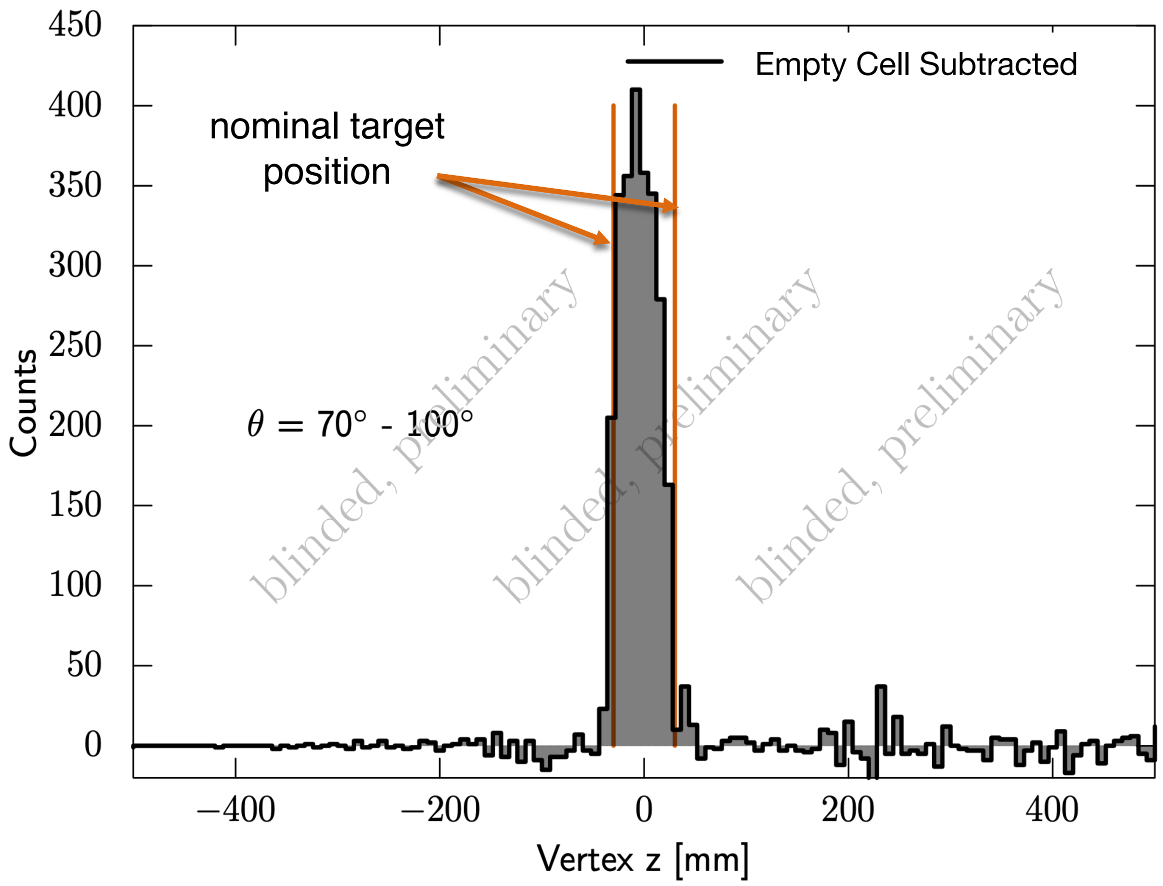


LH_2 Scattering in MUSE

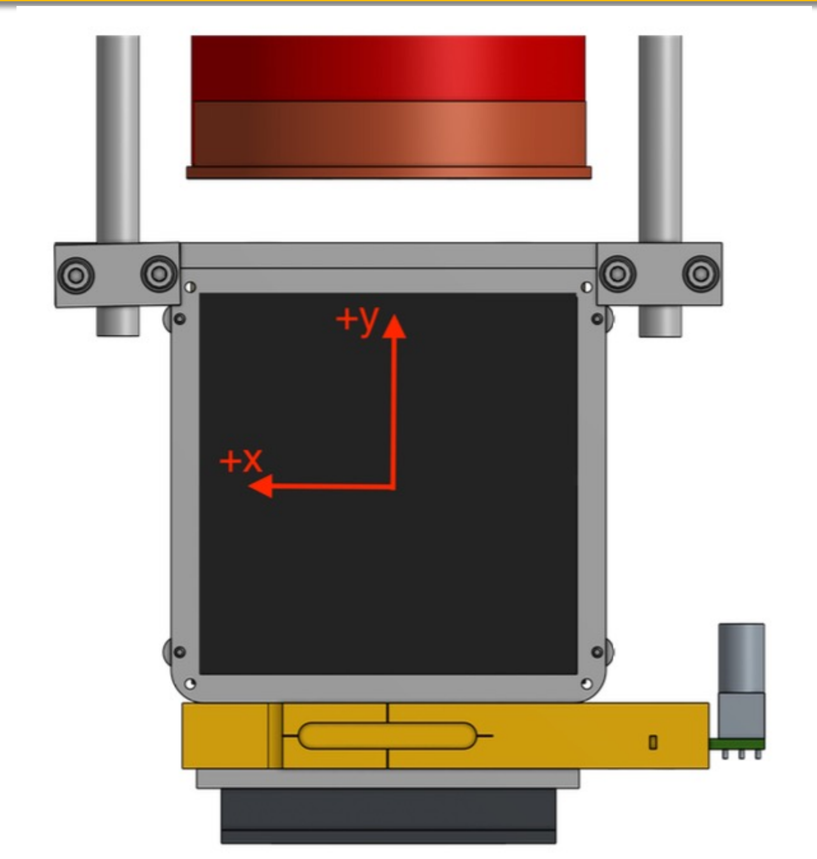


- An example of the Vertex reconstruction for LH_2 and Empty Cells data:
  - => 160 MeV/c beam momentum
  - => All data are blinded!
  - => **Cuts:** |x| < 25 mm, |y| < 25 mm, $70^0 < \theta < 100^0$
- "LH_2 Cell" – "Empty Cell" provides a clean scattering off LH_2!

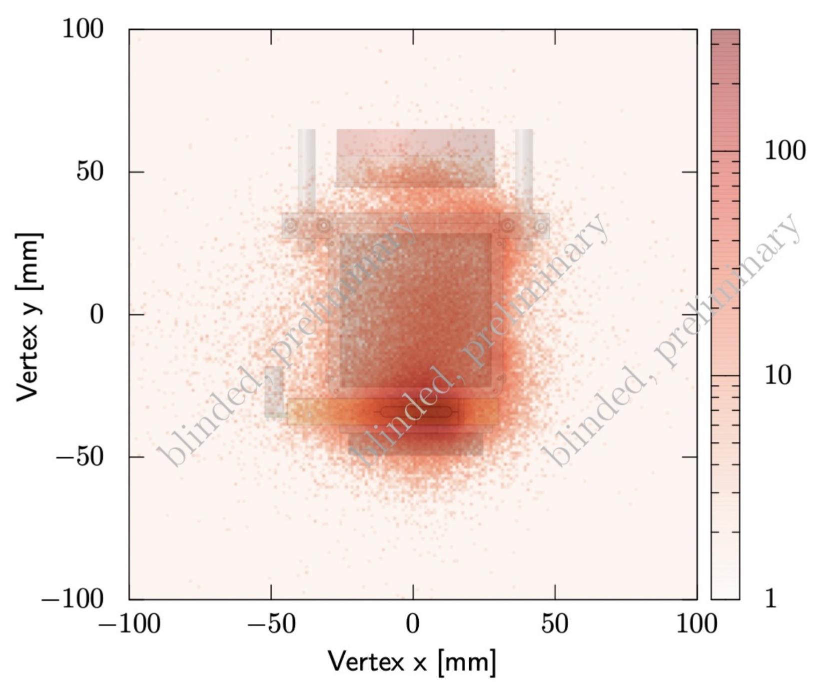


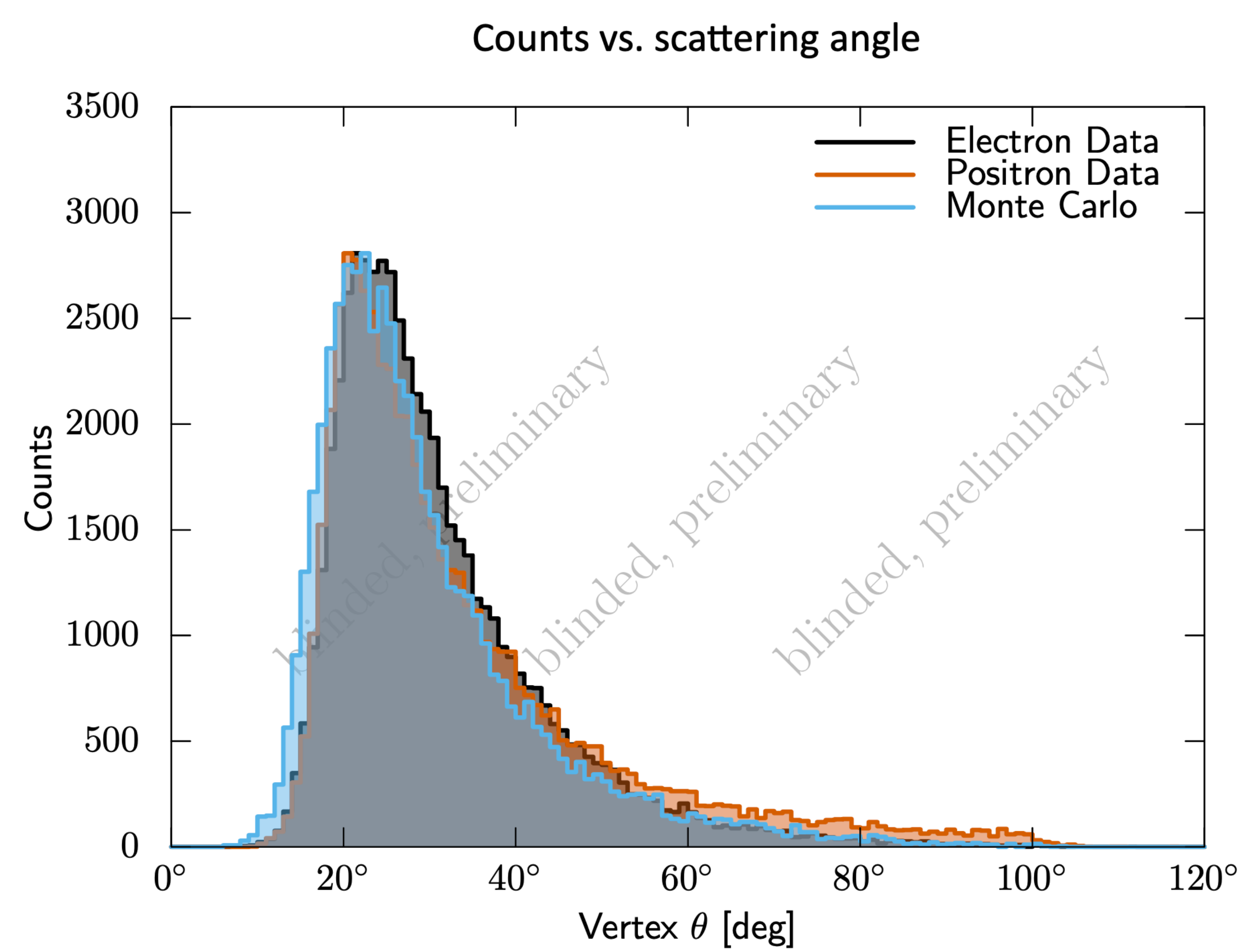


Carbon Scattering in MUSE



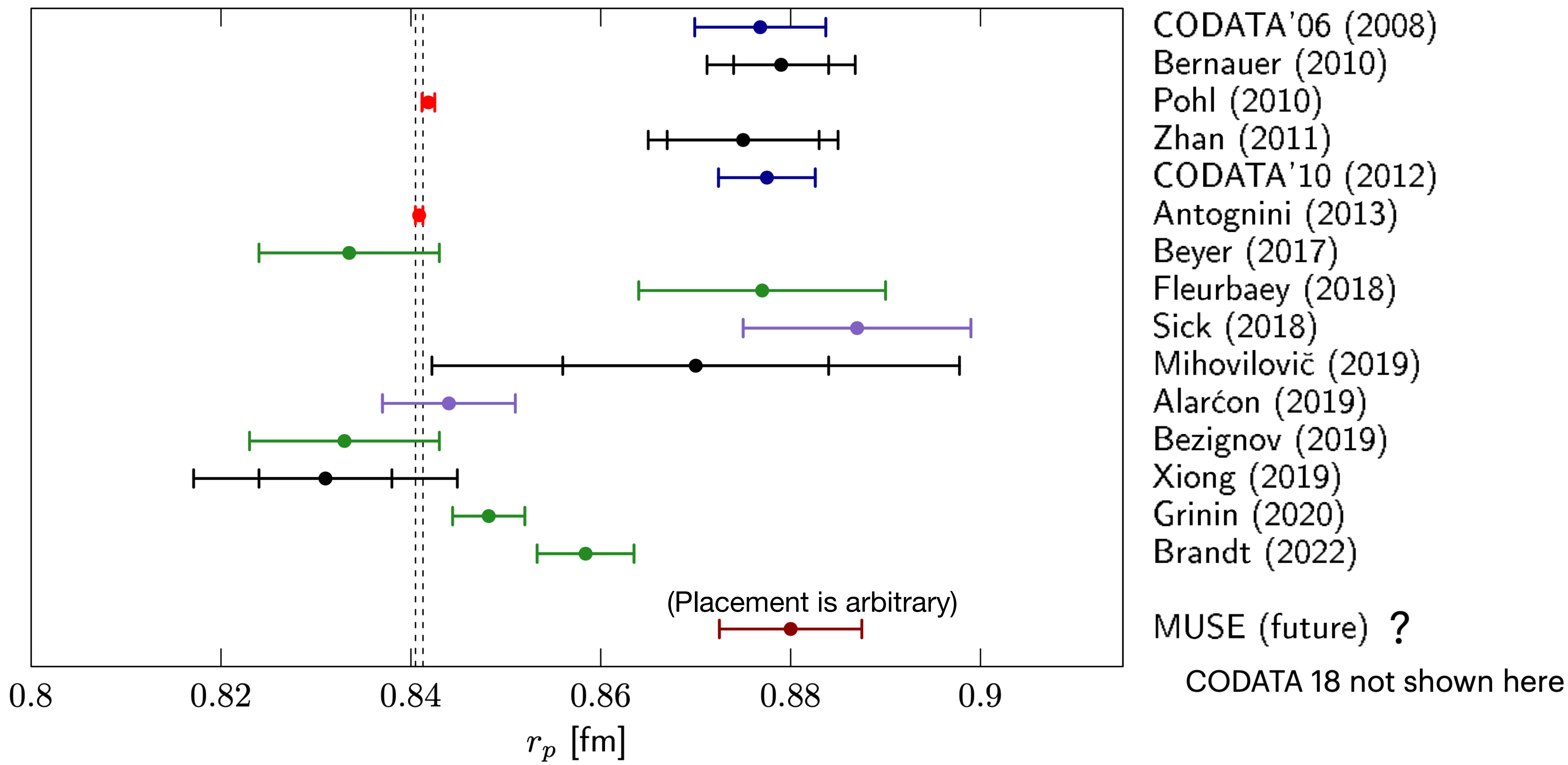
- An example of the scattering angle distribution for electron and position scattering for 160 MeV/c beam momentum compared to simulation.
  => All data are blinded!
  => **Cuts:** |x| < 25 mm, |y| < 25 mm, |z| < 80 mm





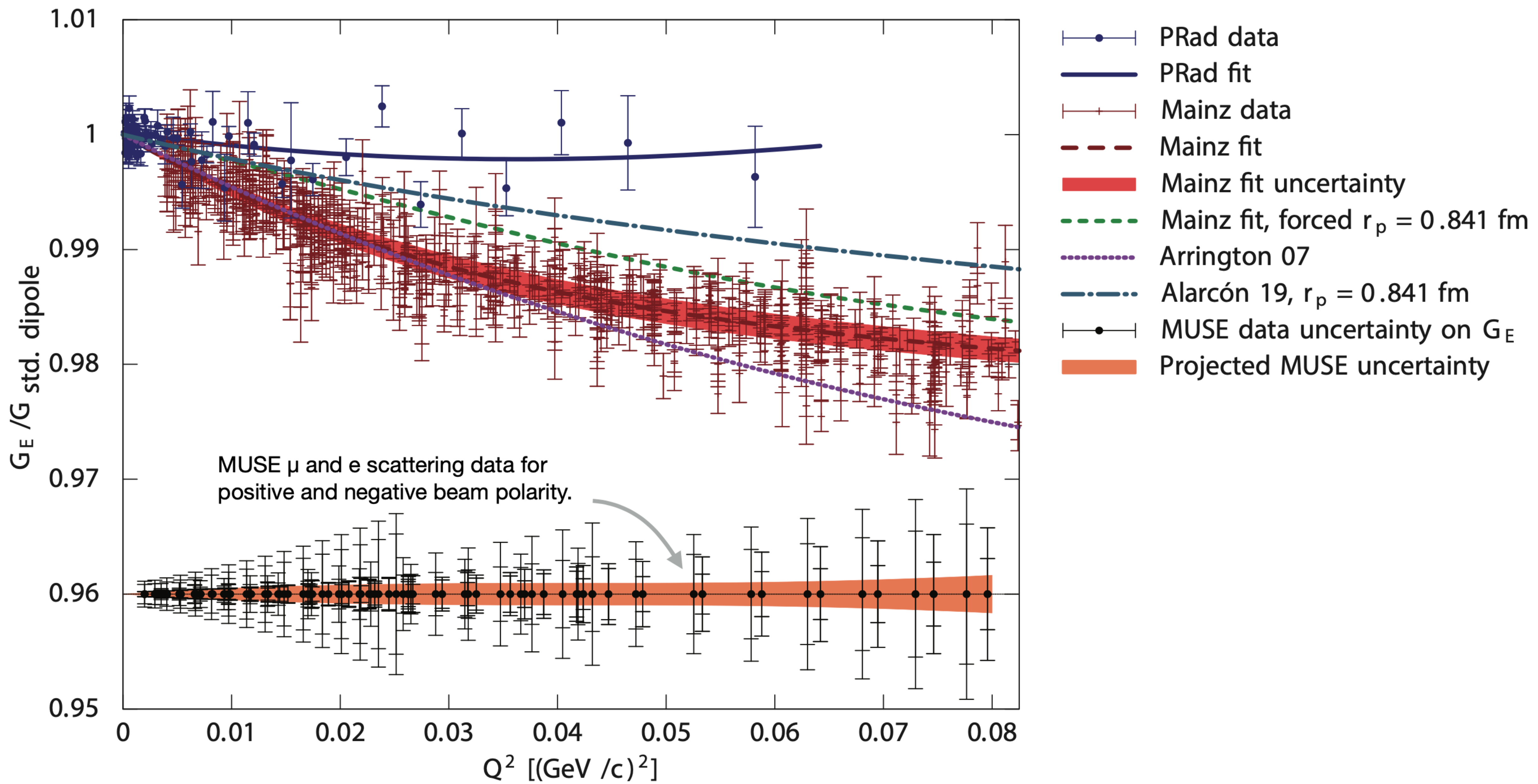
MUSE Projection on Proton Radius Extraction

- Sensitivity to the **absolute values** of extracted e/μ radii: $\sigma(r_e)$, $\sigma(r_\mu) \approx 0.008$ fm
- Sensitivity to **differences** in extracted e/μ radii: $\sigma(r_e - r_\mu) \approx 0.005$ fm



Systematic uncertainties are cancelled out in comparison of **e to μ** or **positive to negative** charges of leptons!

MUSE Projection on G_E Extraction



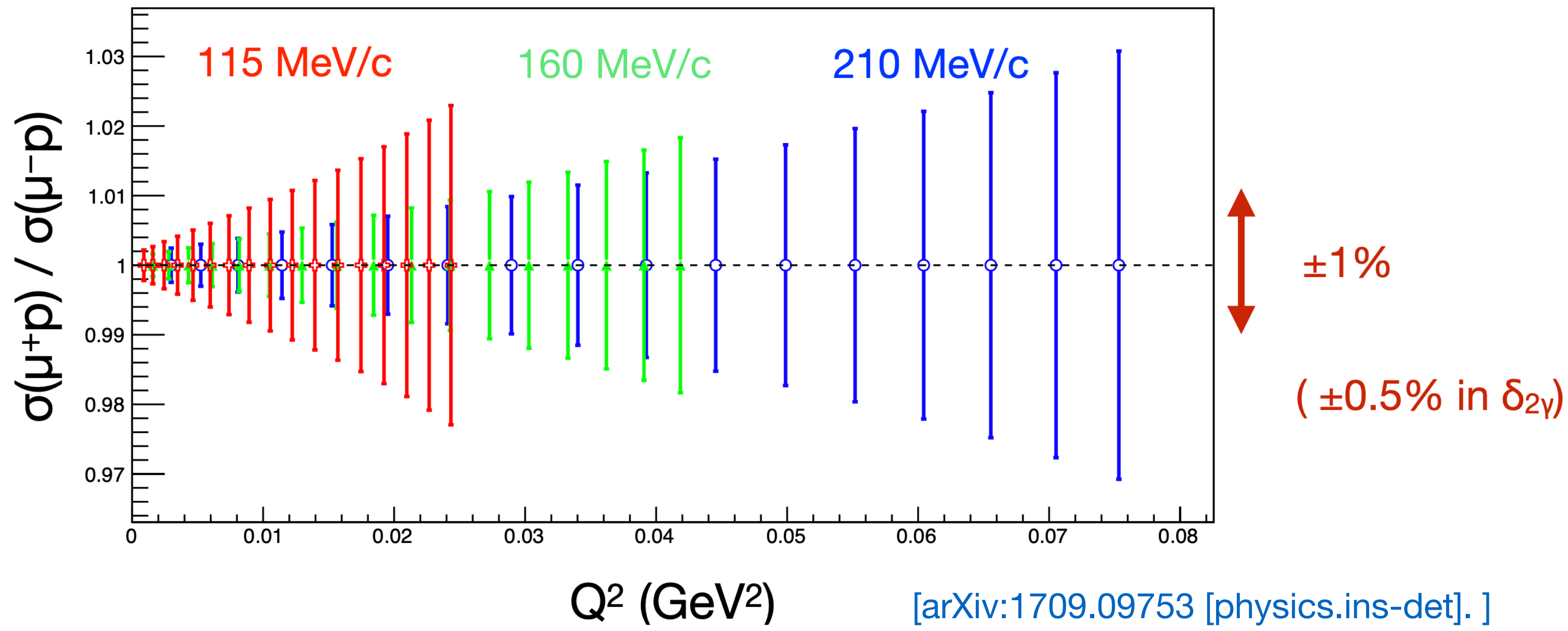
MUSE can help clarify the tension between the Mainz and PRad data!

MUSE Projection on TPE

Projected relative uncertainty in the ratio of μ^+p to μ^-p elastic cross sections.

Systematics:

- 0.2% in the cross section ratio;
- 0.1% in $\delta_{2\gamma}$.



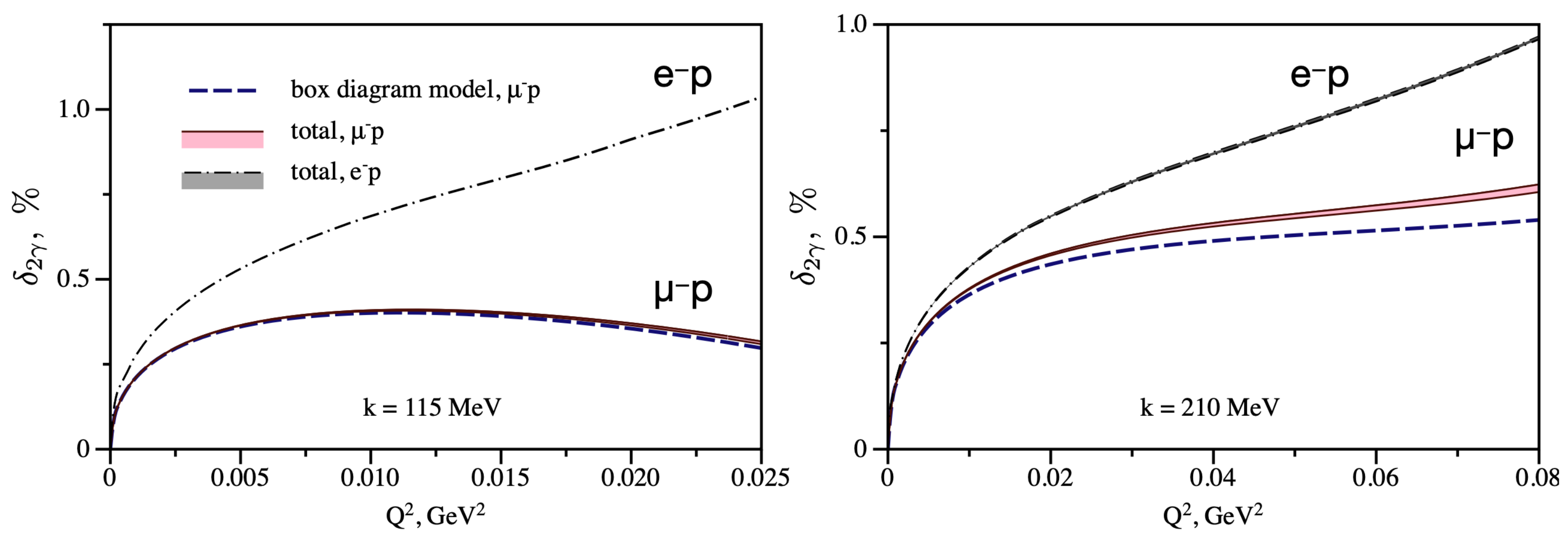
[arXiv:1709.09753 [physics.ins-det].]

TPE correction ($\delta_{2\gamma}$) at leading order:

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

$$\frac{\sigma^+}{\sigma^-} \approx 1 + 2\delta_{2\gamma}$$

TPE Calculations for MUSE kinematics:



[O. Tomalak, Few-Body Systems, **59**, 87 (2018)]

MUSE Progress and Plans

- 2011: Ron Gilman & Michael Kohl proposed MUSE
- 2012-2017: MUSE experiment was built up
- 2018-2020: Beam studies, technical refinements, fine tuning
- 2020-2021: COVID-19 delay
- 2021: Obtained **first** high statistics scattering data set at ±115 MeV/c.
- 2022: One month of scattering data taken.
- 2023: MUSE has been approved for 5 month of beam time.
- 2024-2025: Plan to continue production data taking: 6 months/year
- 2023-2026: Data analysis and physics publications.

We are here!

MUSE Publications

- 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”, arXiv:1709.09753v1 [https://arxiv.org/abs/1709.09753]
- P. Roy *et al.*, *A Liquid Hydrogen Target for the MUSE Experiment at PSI*, NIM A [https://doi.org/10.1016/j.nima.2020.164801]
- T. Rostomyan *et al.*, *Timing Detectors with SiPM read-out for the MUSE Experiment at PSI*, NIM A [https://doi.org/10.1016/j.nima.2019.162874]
- E.Cline, J. Bernauer, E.J. Downie, R. Gilman, *MUSE: The MUon Scattering Experiment,* Review of Particle Physics at PSI [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]
- More is coming soon….

Thank you!