# MUSE
## Progress Report

Steffen Strauch
University of South Carolina
for the MUSE Collaboration

(Argonne National Laboratory, George Washington University, Hampton University, Hebrew University of Jerusalem, Montgomery College, MIT, New Mexico State University, Paul Scherrer Institute, Rutgers The State University of New Jersey, Stony Brook University, Tel Aviv University, Temple University University of South Carolina)

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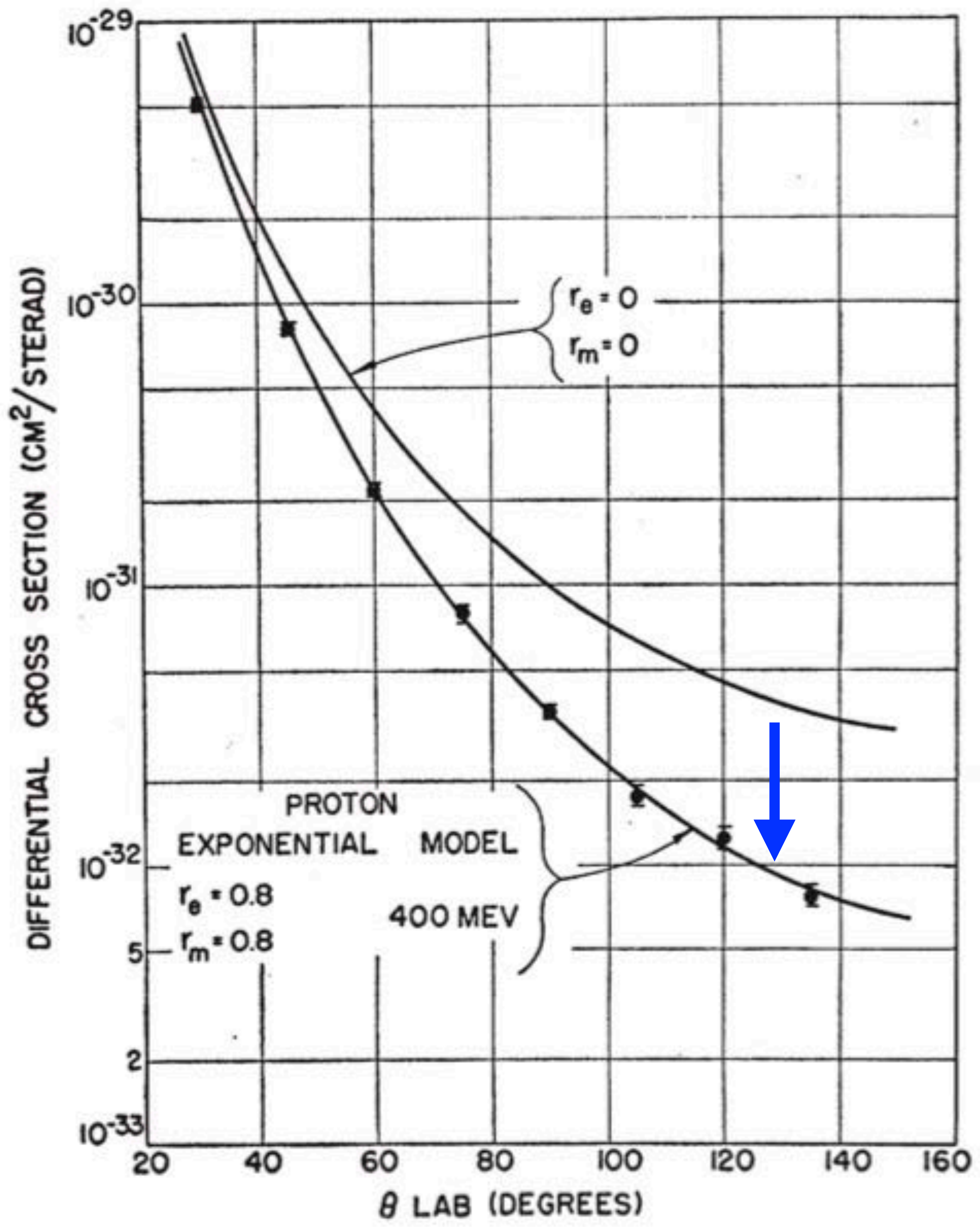
Open CHRISP Users Meeting BVR56, PSI, February 11, 2025

# Measuring the proton charge radius

**Lepton scattering experiments**

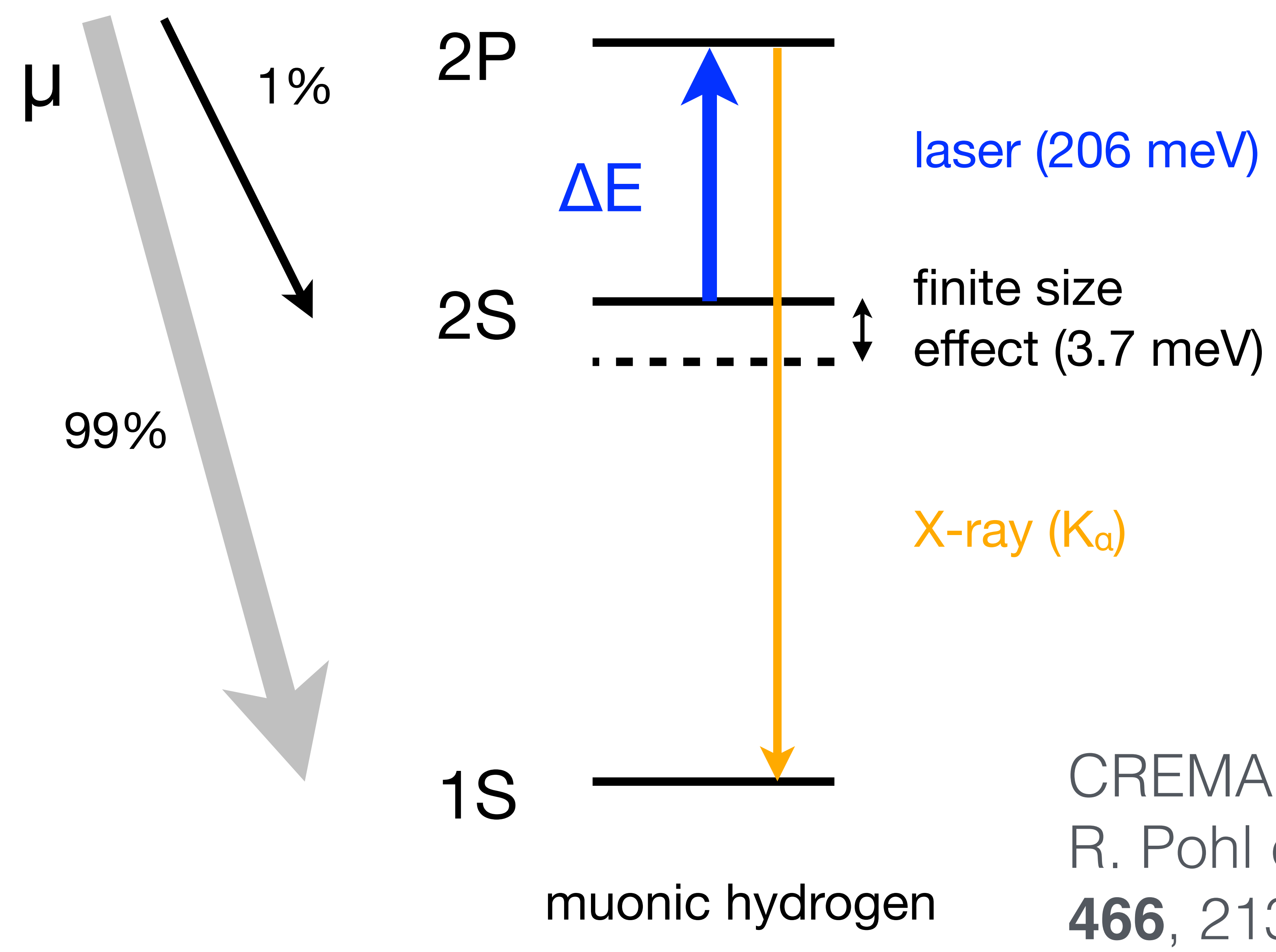
R. Hofstadter, Rev. Mod. Phys. **28**, 214 (1956)




$$\langle r^2 \rangle = -6\hbar^2 \frac{dG_E(Q^2)}{dQ^2}\Big|_{Q^2=0}$$

**Spectroscopy**

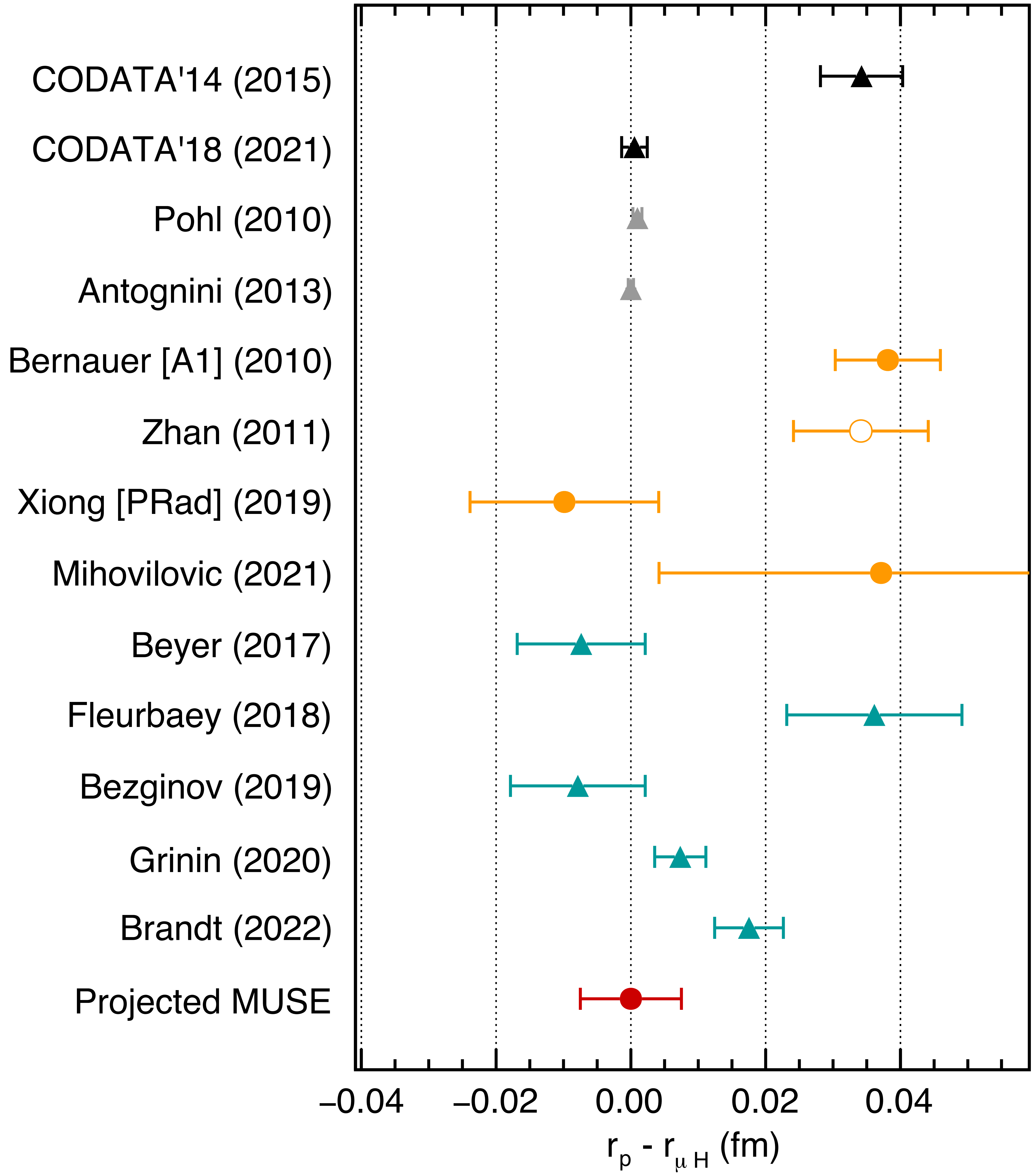
μ beam stopped in $H_2$ gas




CREMA collaboration:
R. Pohl et al., Nature **466**, 213 (2010),
A. Antognini et al., Science **339**, 417 (2013)

$$\Delta E = \Delta E(\langle r^2 \rangle)$$

# MUSE and The Proton-Radius Puzzle




Possible explanations of the proton charge-radius puzzle:

- Experimental issues
- Radiative Correction Effects
- Two Photon Exchange (TPE) / Polarizability
- Physics Beyond Standard Model (Violation of Lepton Universality)

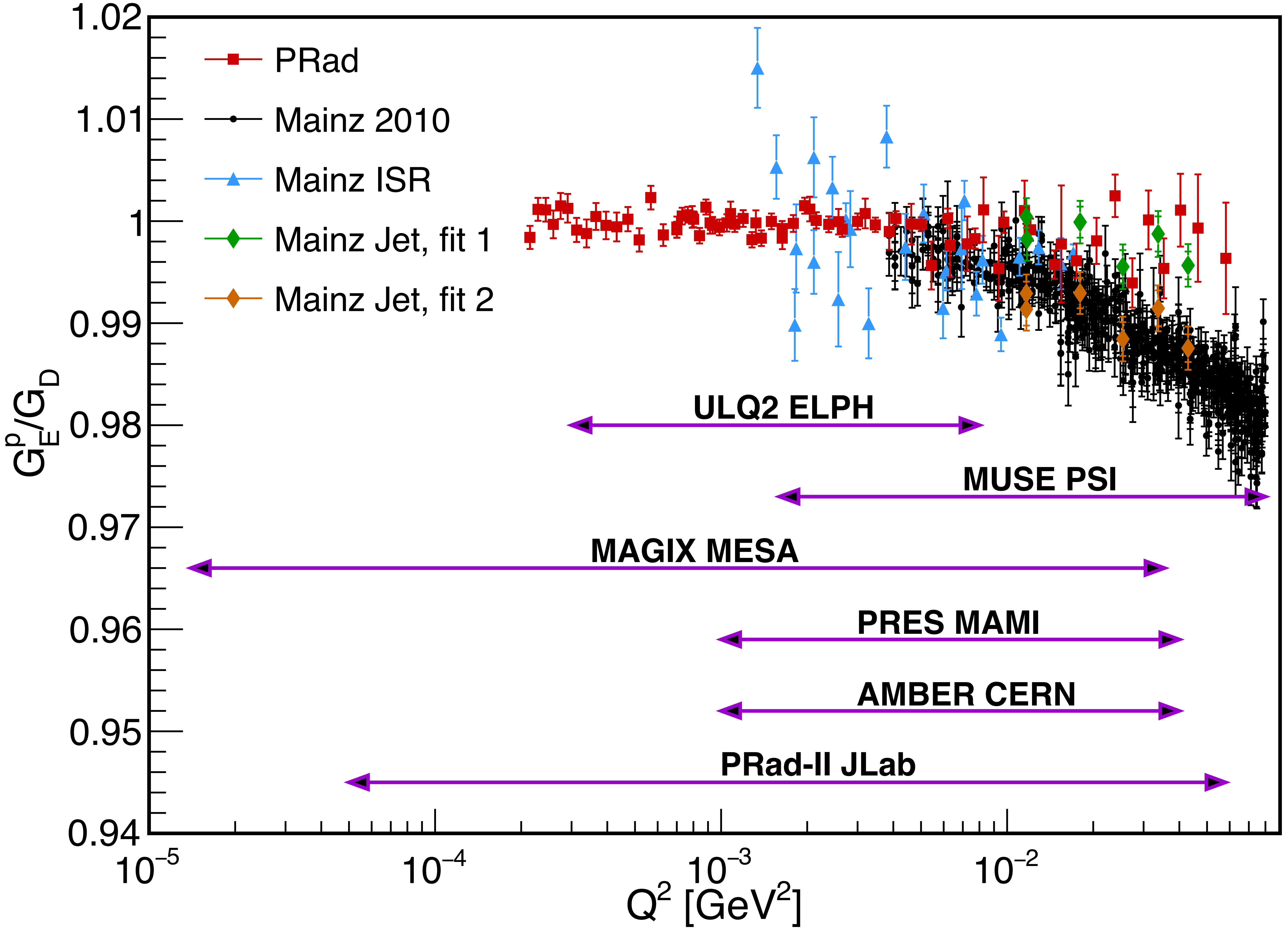
Inconsistent electron-scattering data

Inconsistent hydrogen-spectroscopy data

**MUSE**

$$e^{\pm}p \rightarrow e^{\pm}p$$
$$\mu^{\pm}p \rightarrow \mu^{\pm}p$$

# MUSE is only low-$Q^2$ scattering experiment using $e^\pm$ and $\mu^\pm$ beams




| Beam | $e^-$ | $e^+$ | $\mu^-$ | $\mu^+$ | |
|---|---|---|---|---|---|
| Mainz 2010 | ✓ | | | | completed |
| PRad | ✓ | | | | |
| Mainz ISR | ✓ | | | | |
| Mainz Jet | ✓ | | | | |
| **MUSE PSI** | ✓ | ✓ | ✓ | ✓ | ongoing |
| ULQ2 ELPH | ✓ | | | | |
| AMBER CERN | | | ✓ | ✓ | future |
| MAGIX MESA | ✓ | | | | |
| PRES MAMI | ✓ | | | | |
| PRad-II JLab | ✓ | | | | |

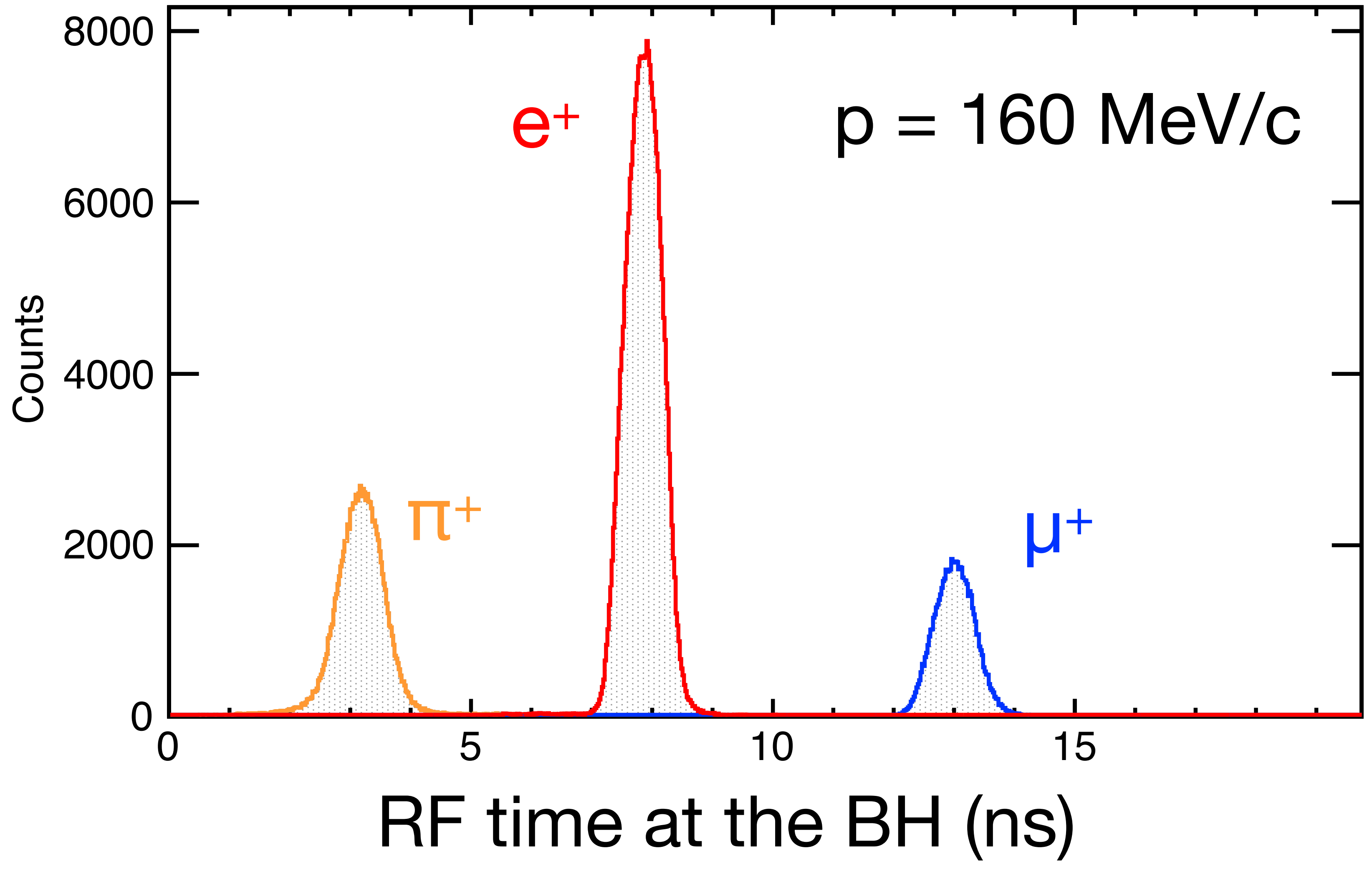
high-energy / small-angle experiments

Figure from 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 at the secondary beam line $\pi$M1 at PSI

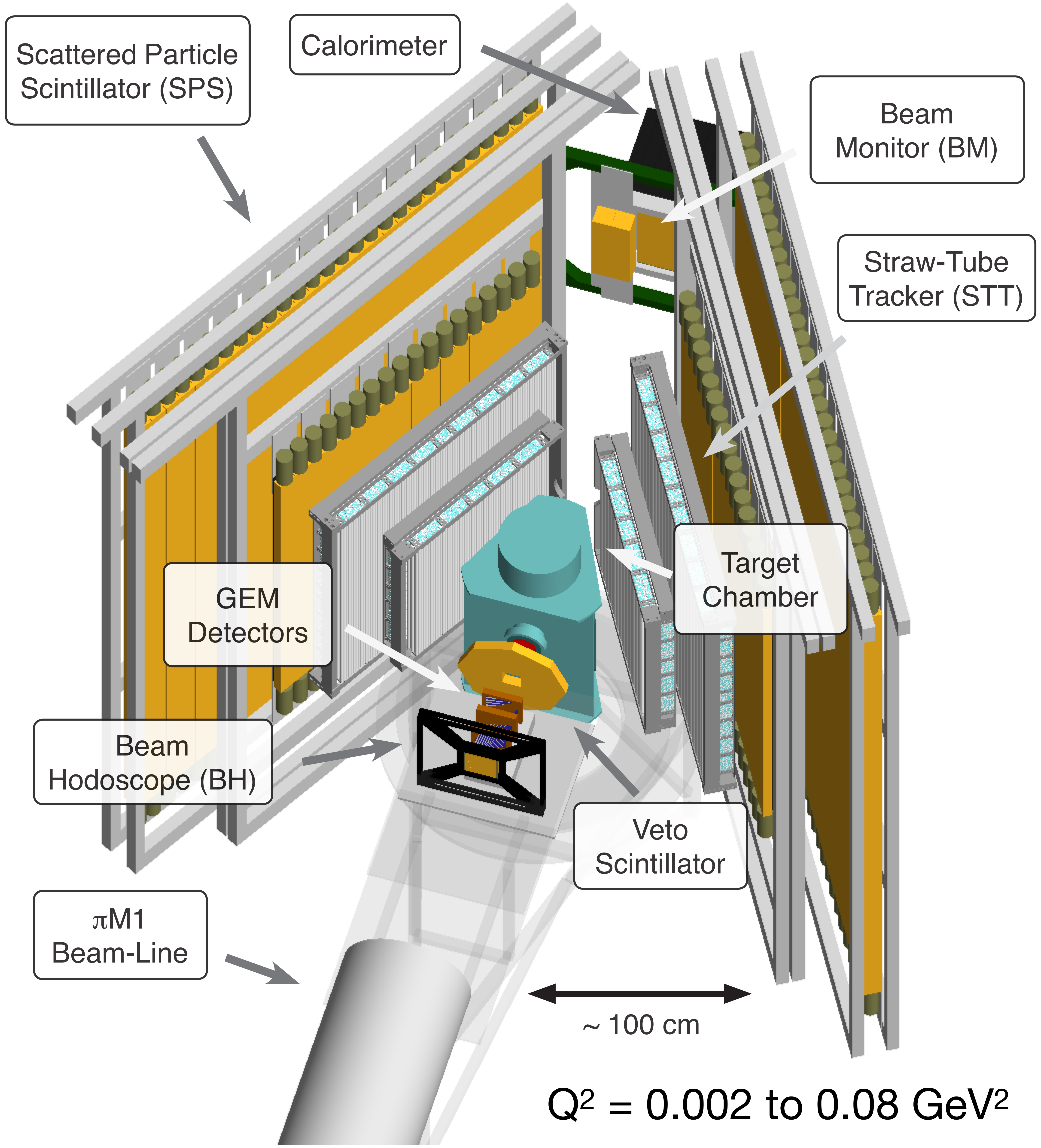
**Beam**

- 50 MHz RF (20 ns bunch separation)
- e, μ, π beams with large emittance
- Momenta: 115, 160, 210 MeV/c




**Beam line detectors**

**Scattered particle detectors**

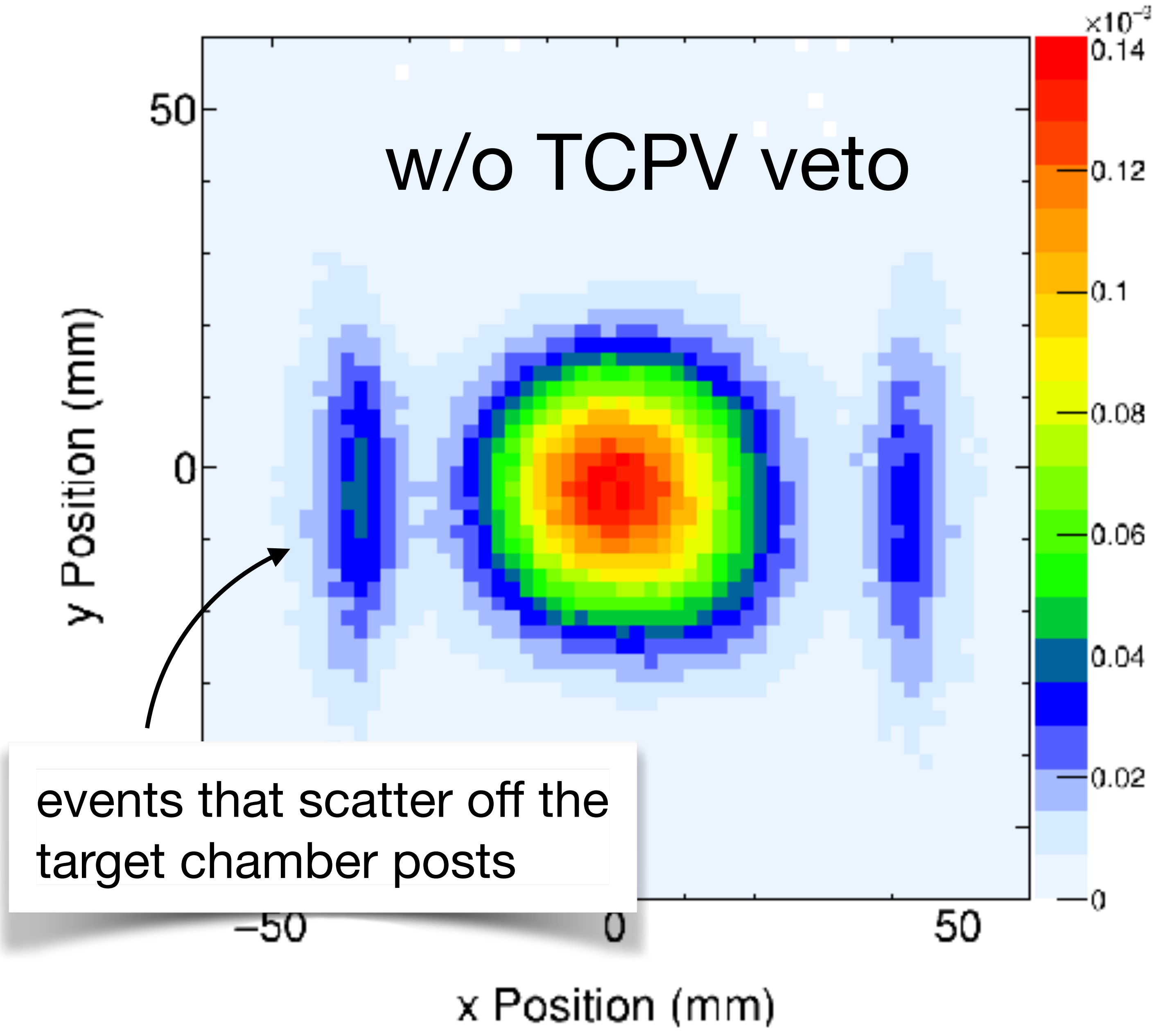


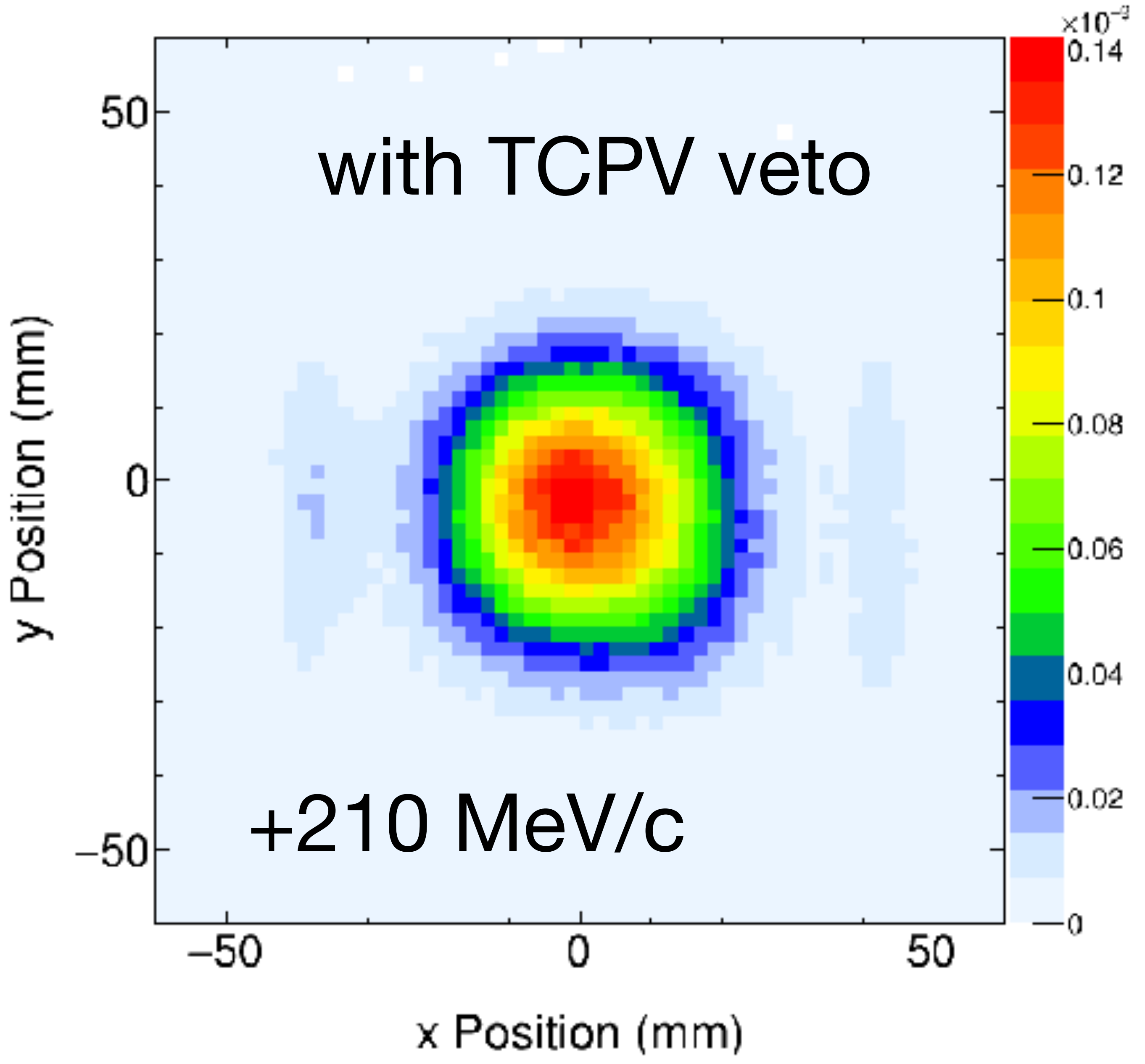

$Q^2$ = 0.002 to 0.08 $GeV^2$

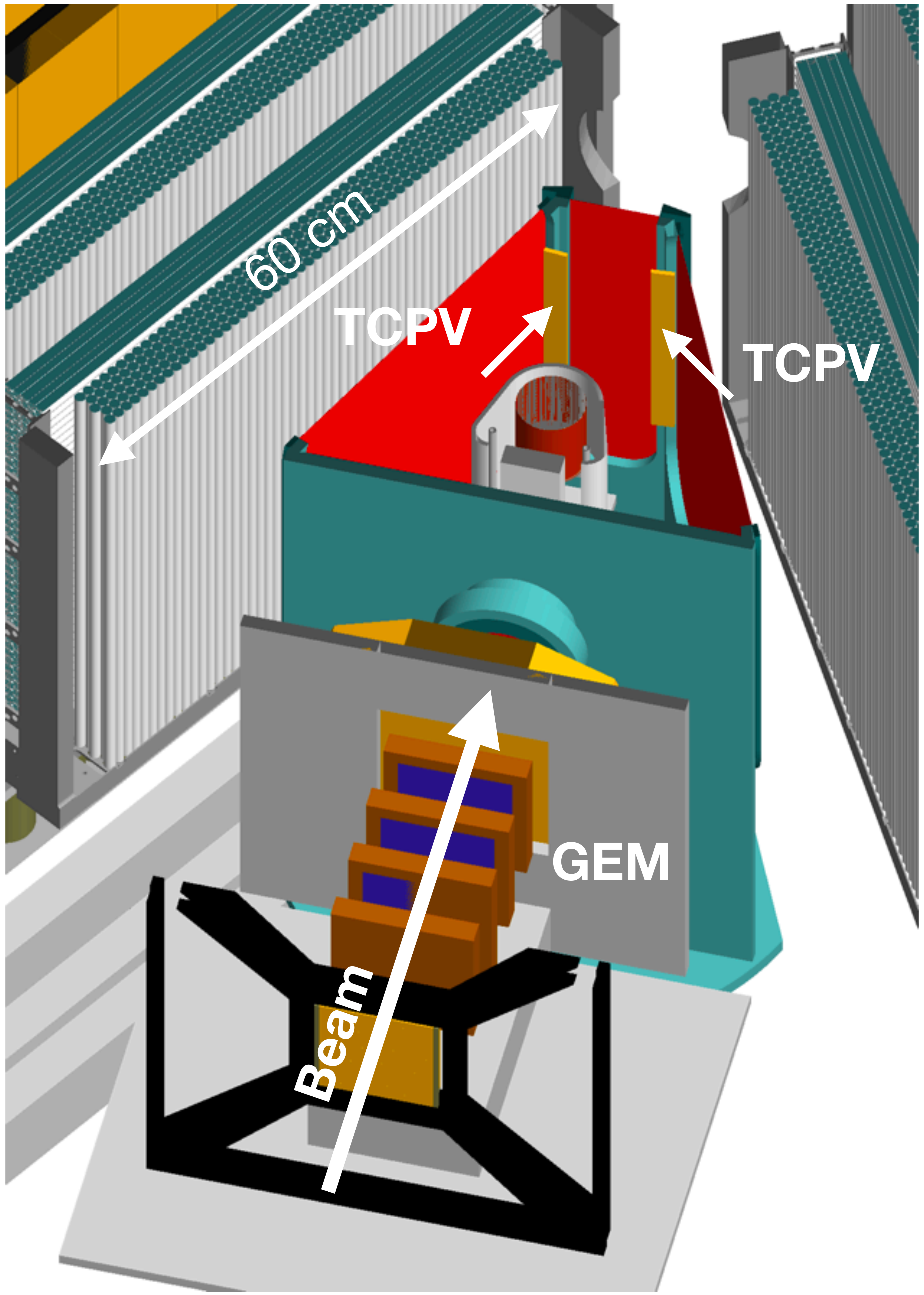
The MUon Scattering Experiment at PSI (MUSE), MUSE Technical Design Report, arXiv:1709.09753 [physics.ins-det]
E. Cline et al. (MUSE Collaboration), Phys. Rev. C 105 (2022) 5, 055201.

# The Target Chamber Post Veto detectors help reducing the trigger rate from background events

GEM tracked 210 MeV/c beam particles that trigger the DAQ readout

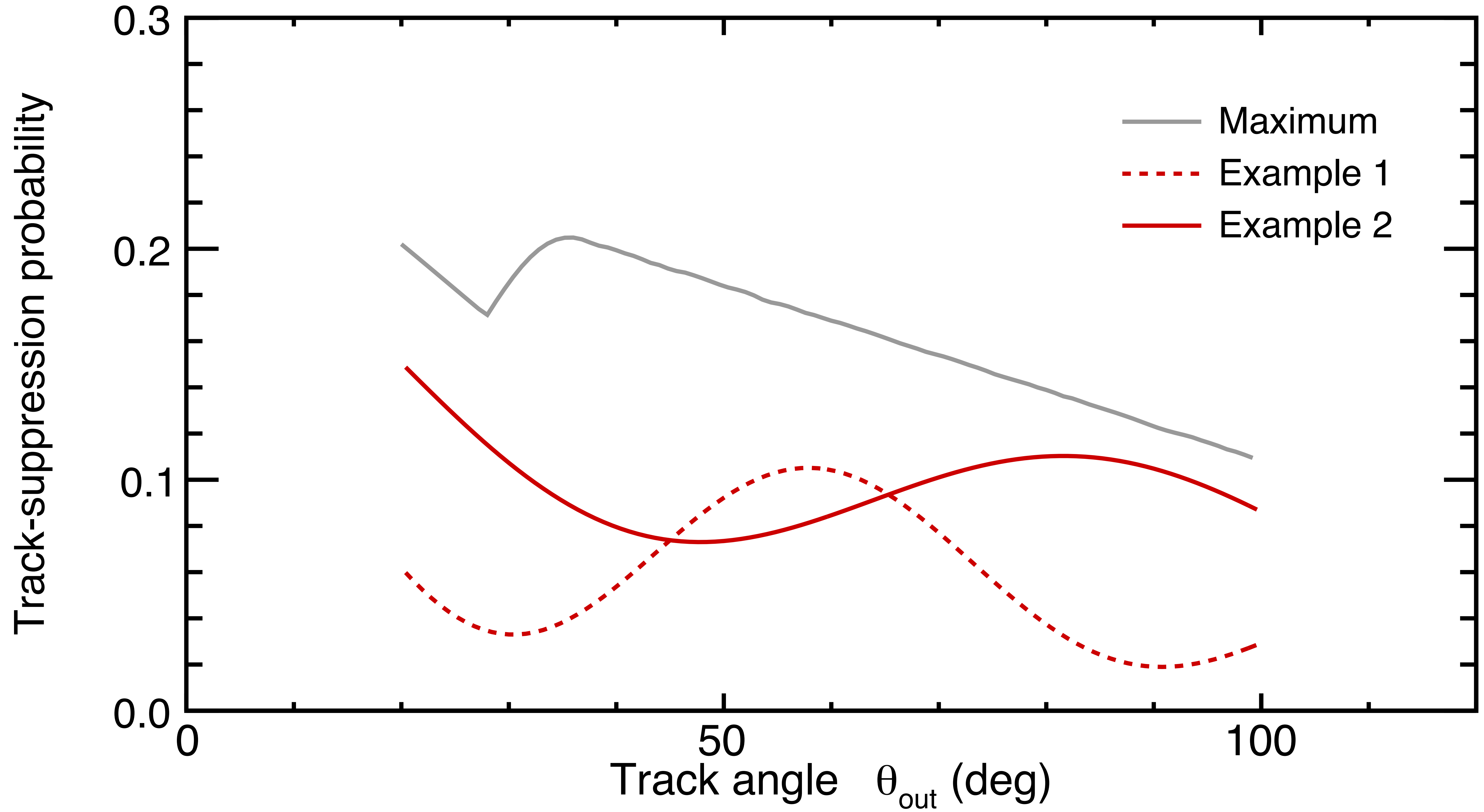



The **in-chamber** readout of the SiPM detectors was first employed during the 2024 beam time and resulted in superior data quality compared to the optical fibers readout.

# MUSE data analysis is blinded: Tracked particles are suppressed in the analysis chain




Suppress track with track angle $\theta_{out}$ if

$$20\ \%\ (A_i + 0.3 \cos B_i \theta_{out}) \left(1 - \frac{1}{3}\theta_{out}\right) > R,$$

where $0 \leq R \leq 1$ is a uniformly distributed variable chosen pseudorandomly for each event, and $0.25 \leq A_i \leq 1$, $3 \leq B_i \leq 10$, i = 1, …, 36.

⇒ minimally biased analysis

Differently encrypted for data 36 groups

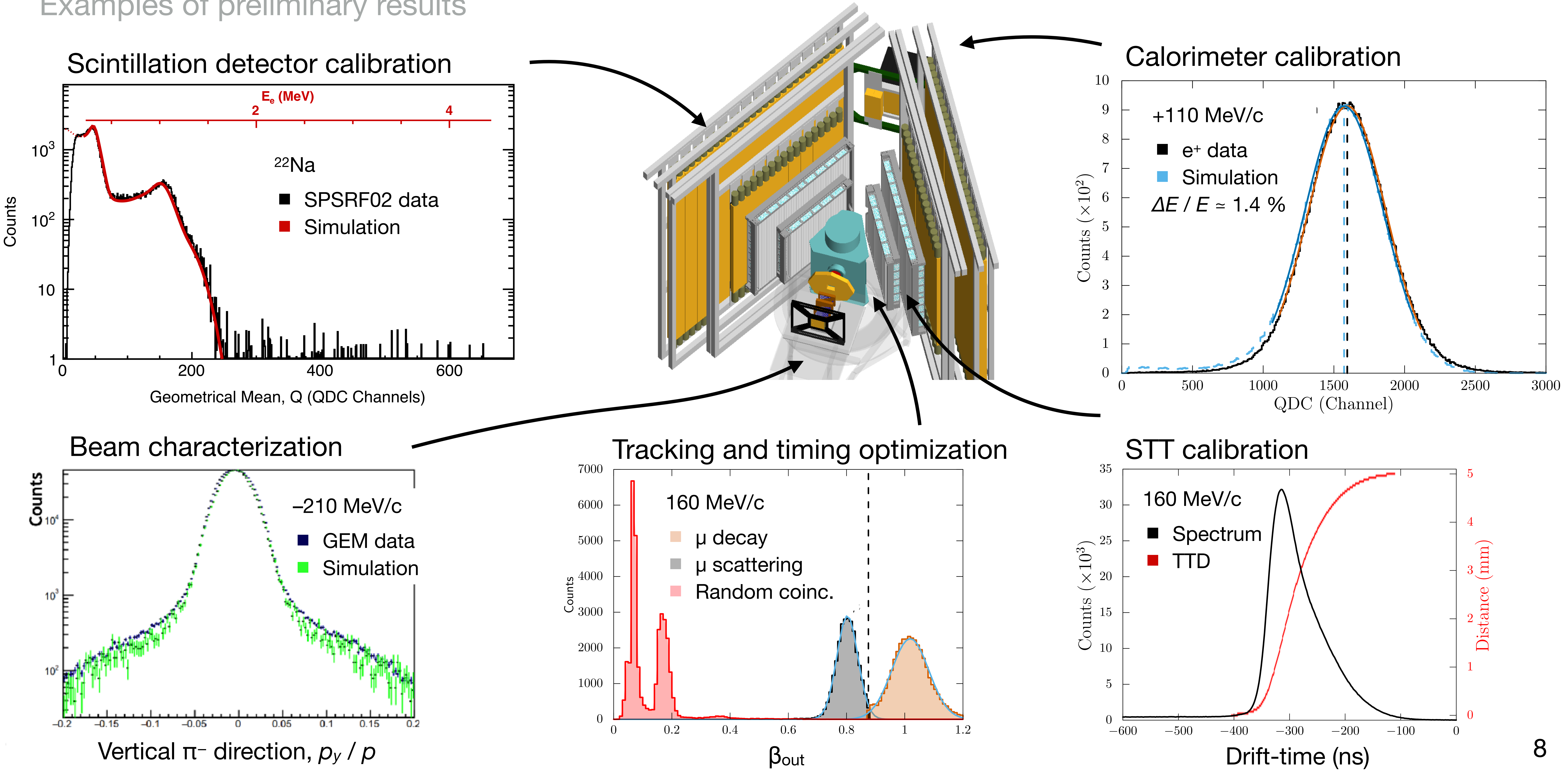
(e, μ, π) × (+, –) × (115, 160, 210 MeV/c) × (data, MC)

Effect of blinding can be larger or smaller than one for ratios, e.g., x(data) / x(MC)

J. C. Bernauer, et al. (MUSE Collaboration), submitted to PRC, arXiv:2310.11469 [physics.data-an] (2023)

# Detector calibrations are unaffected by blinding

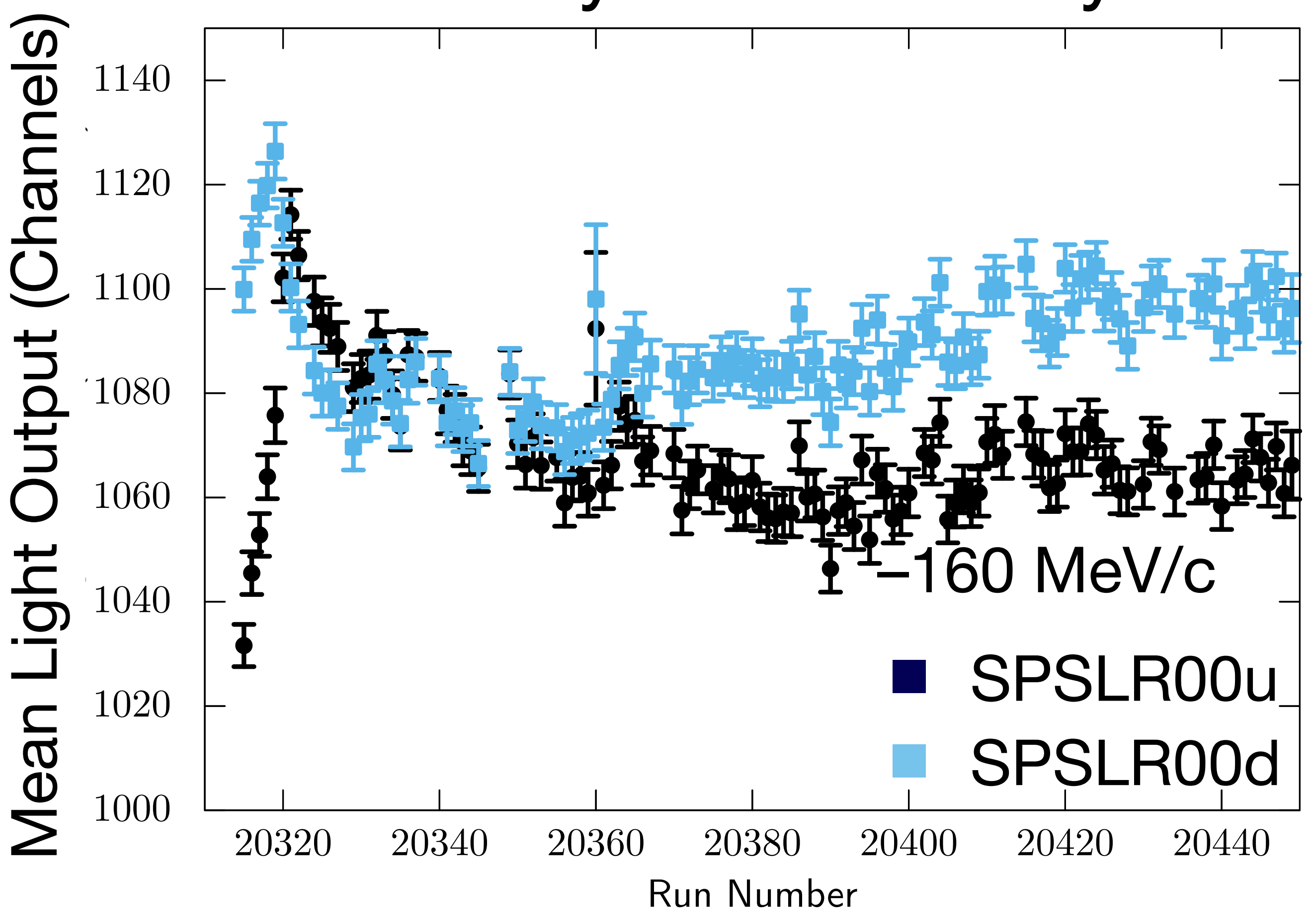
Examples of preliminary results

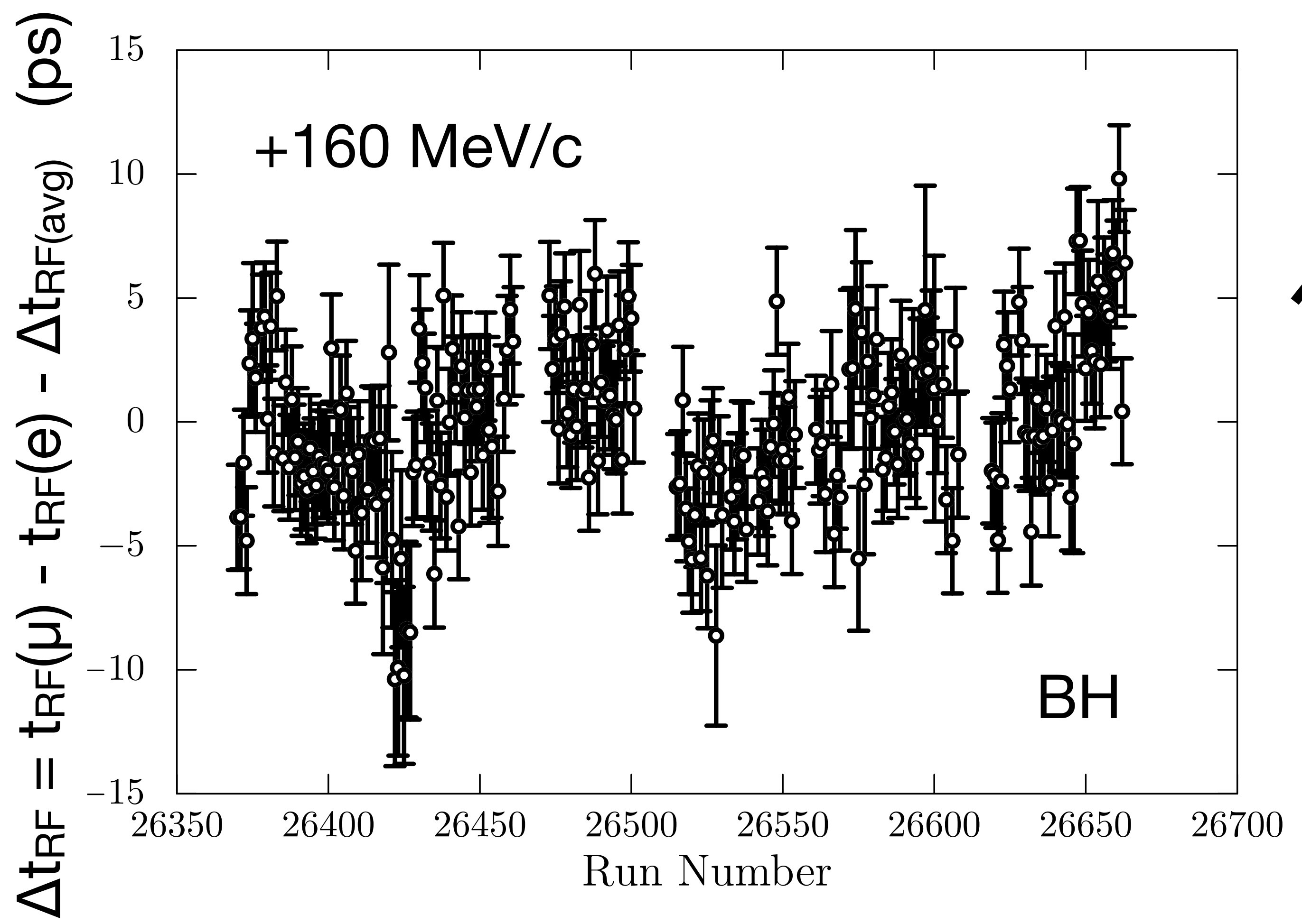


# Quality tests are unaffected by blinding

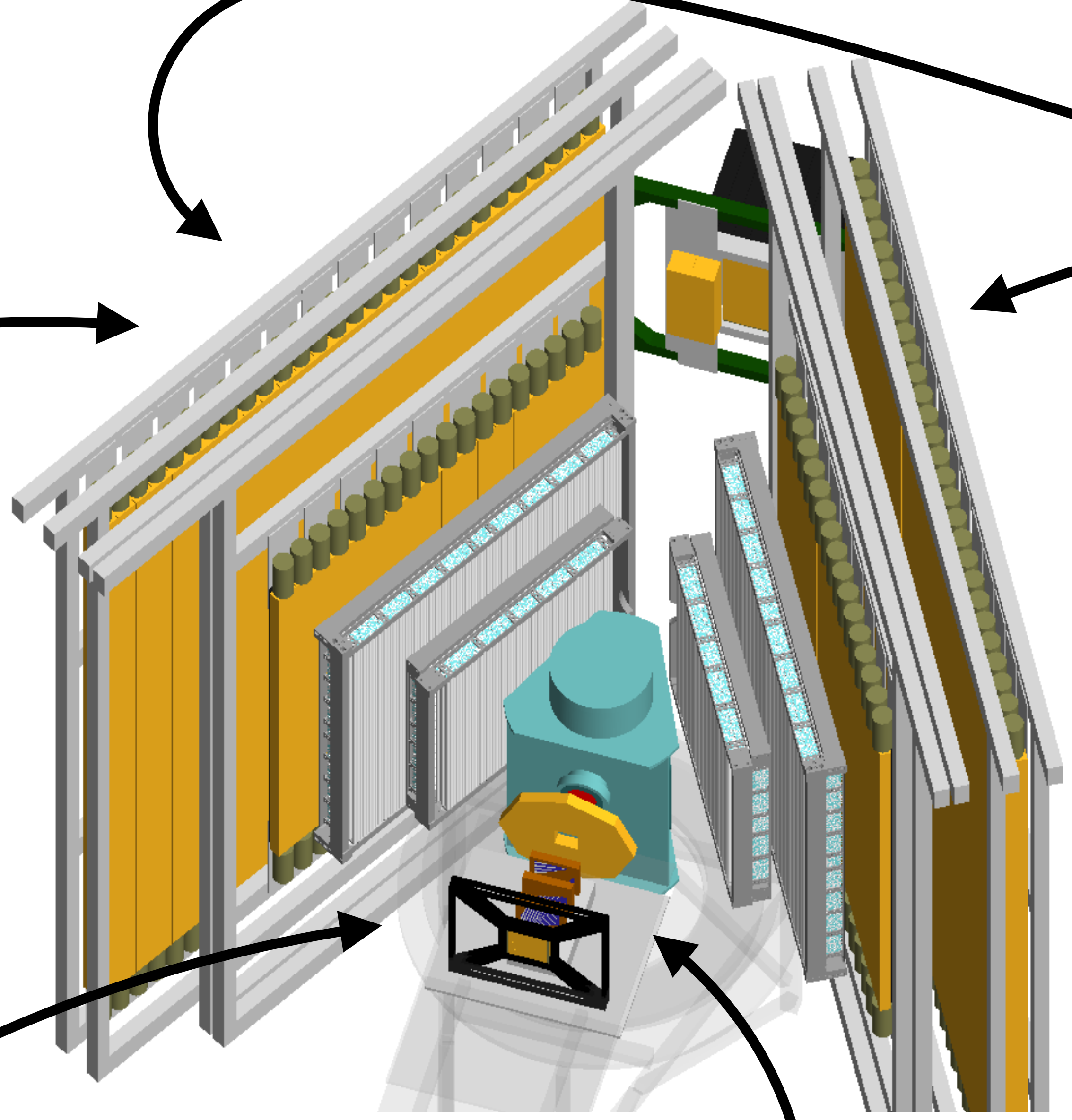
Examples of preliminary results

## Tests of system stability

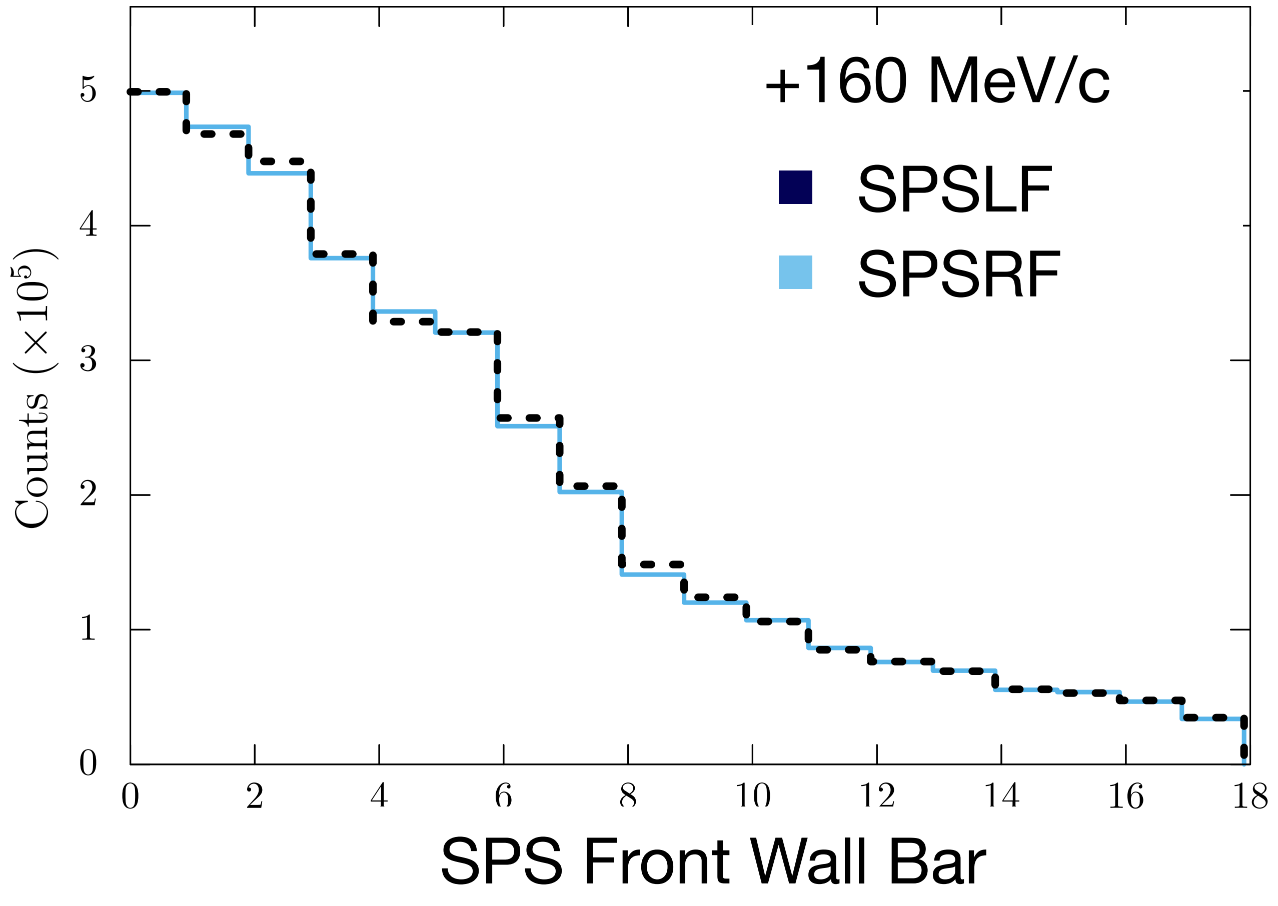


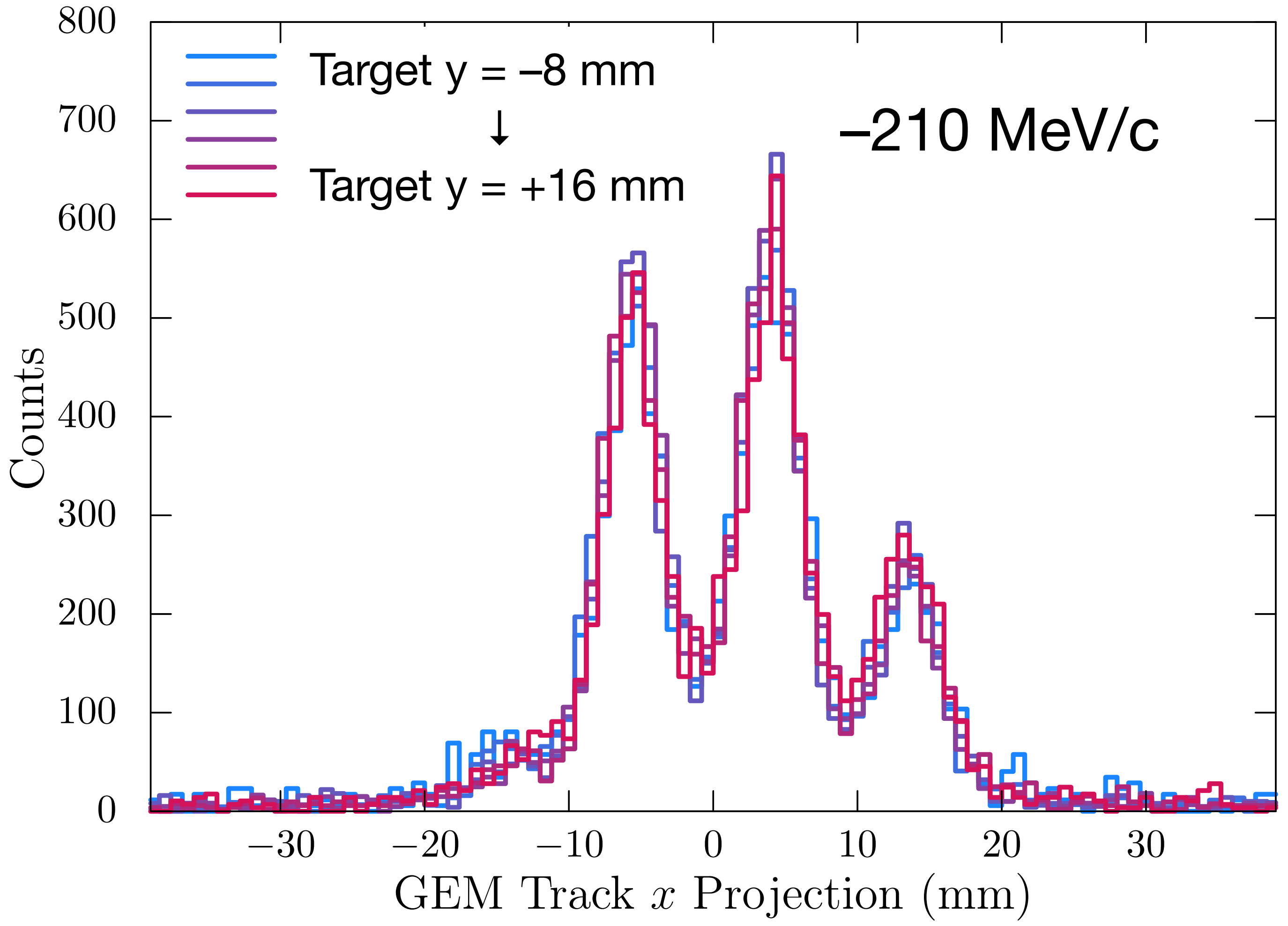

Time (run number)

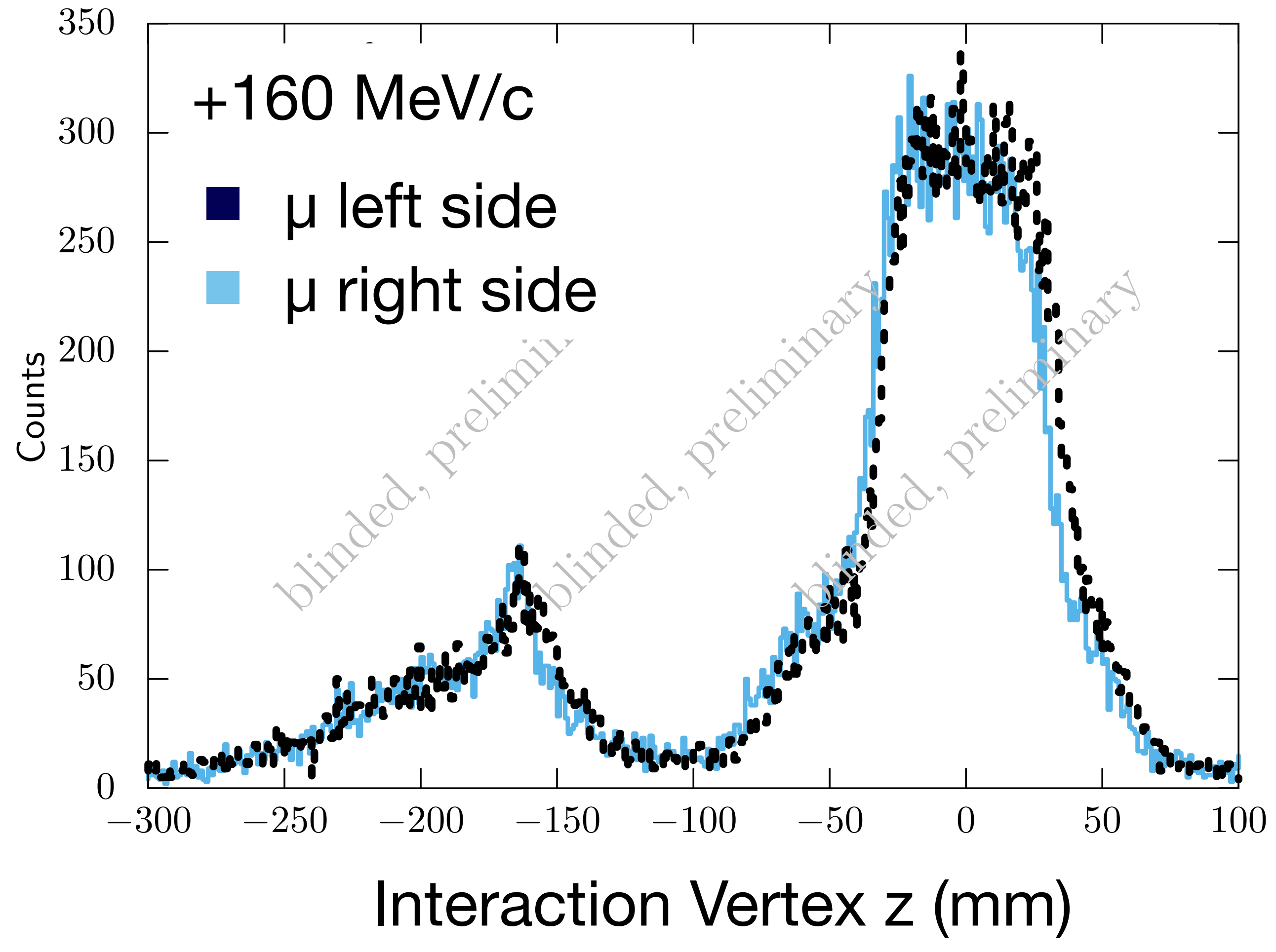


## Left/Right asymmetry




## Tracking and geometry tests



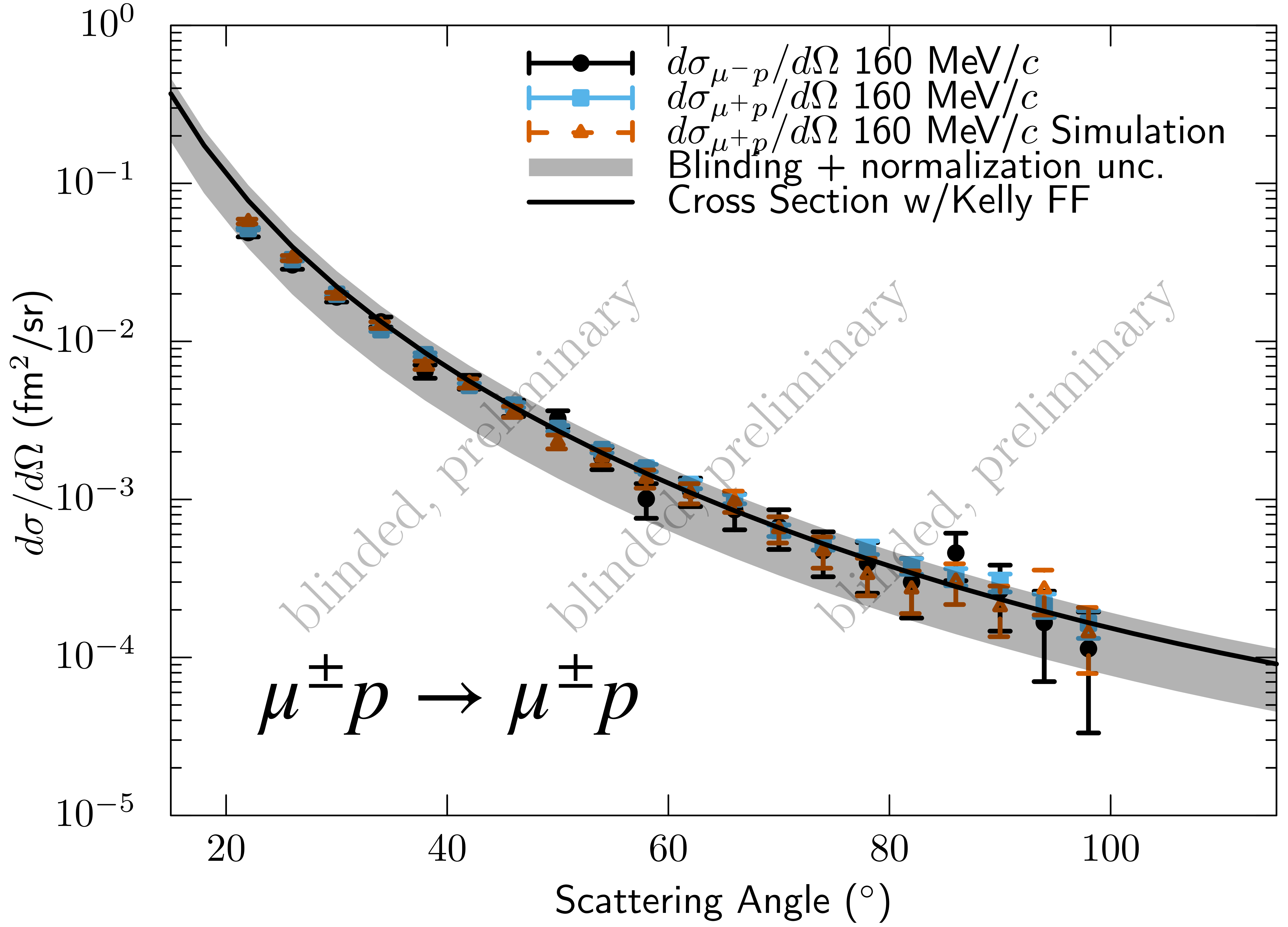

Surveyed detector positions are not yet fully included in the analysis and lead to offsets in the reconstructed tracks.

# Order and time-frame of tests prior to unblinding our primary lepton scattering physics

| Order | Tests of data quality, MC, and analysis techniques | Blinding | Year |
|---|---|---|---|
| **1.1** | Stability and direct comparison of basic **scintillator** and **calorimeter** responses with MC simulations | blinded | 2026 |
| **1.2** | Efficient and precise **track reconstruction** (GEM-STT straight through tracks, and scattering vertices using rod and production targets) | blinded | 2026 |
| **1.3** | Verification of physics model, geometry, beam characteristics, and trigger digitization in the **MC** | blinded | 2026 |
| **2** | Verify $\varphi$ independence: direct comparison of quantities using<br>• **left** and **right** sides of the experiment<br>• **up** and **down** halves of the experiment | blinded | 2027 |
| **3** | Verify results indepent of analysis procedures and cuts | blinded | 2027 |
| **4** | Determination of **pion**-scattering cross sections | $\pi$-data unblinded | 2027+ |
| **5** | Determination of **muon**-decay distributions | $\mu$-data unblinded | 2027+ |

# Expected uncertainties of MUSE proton charge-radius extraction

Blinded, preliminary analysis of 2023 μ±p scattering data




**What is the radius?**

Absolute values of extracted e/μ radii (assuming no +/– difference seen):

$\sigma(r_e)$, $\sigma(r_\mu) \approx 0.008$ fm

**Are the $r_e$ and $r_\mu$ radii different?**

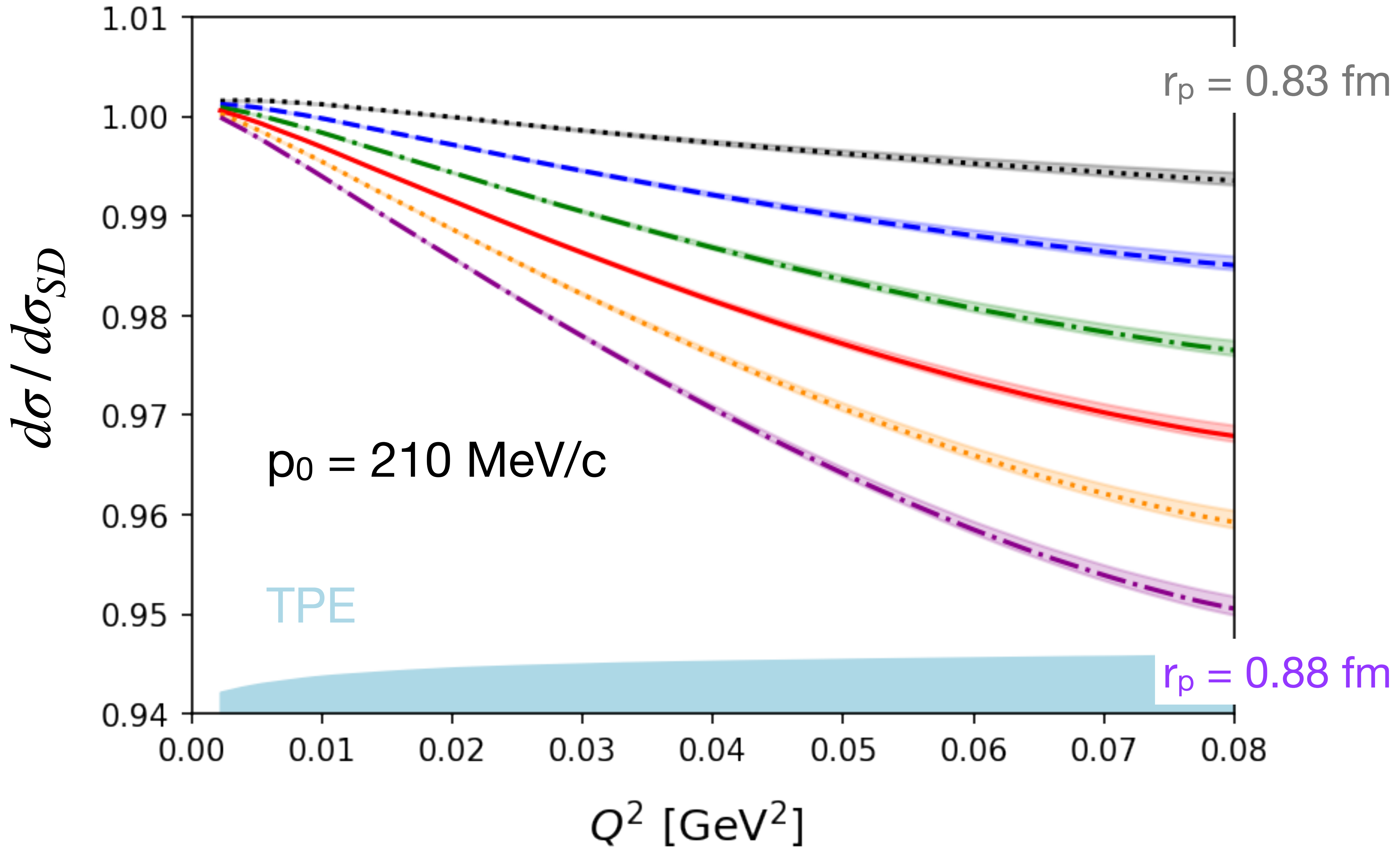
The most sensitive test is a direct comparison of $G_E(Q^2)$ from ep and μp scattering.

Comparisons of **e to μ** or of **positive to negative** data are insensitive to many of the systematics.

# Dispersively improved chiral effective field theory shows sensitivity of the μp cross section to the proton charge radius

- A 0.01 fm change in radius corresponds to about 0.9 % change in cross section.
- Good control of systematic uncertainties is required to achieve the goal of the experiment.
- Radiative corrections are the largest contributor to systematic uncertainties in MUSE.

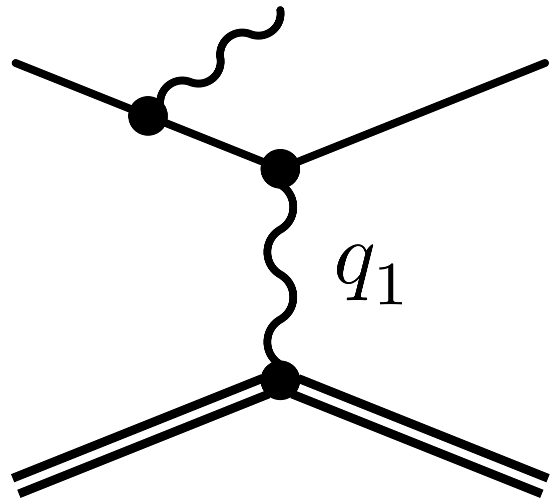
$\mu p \to \mu p$

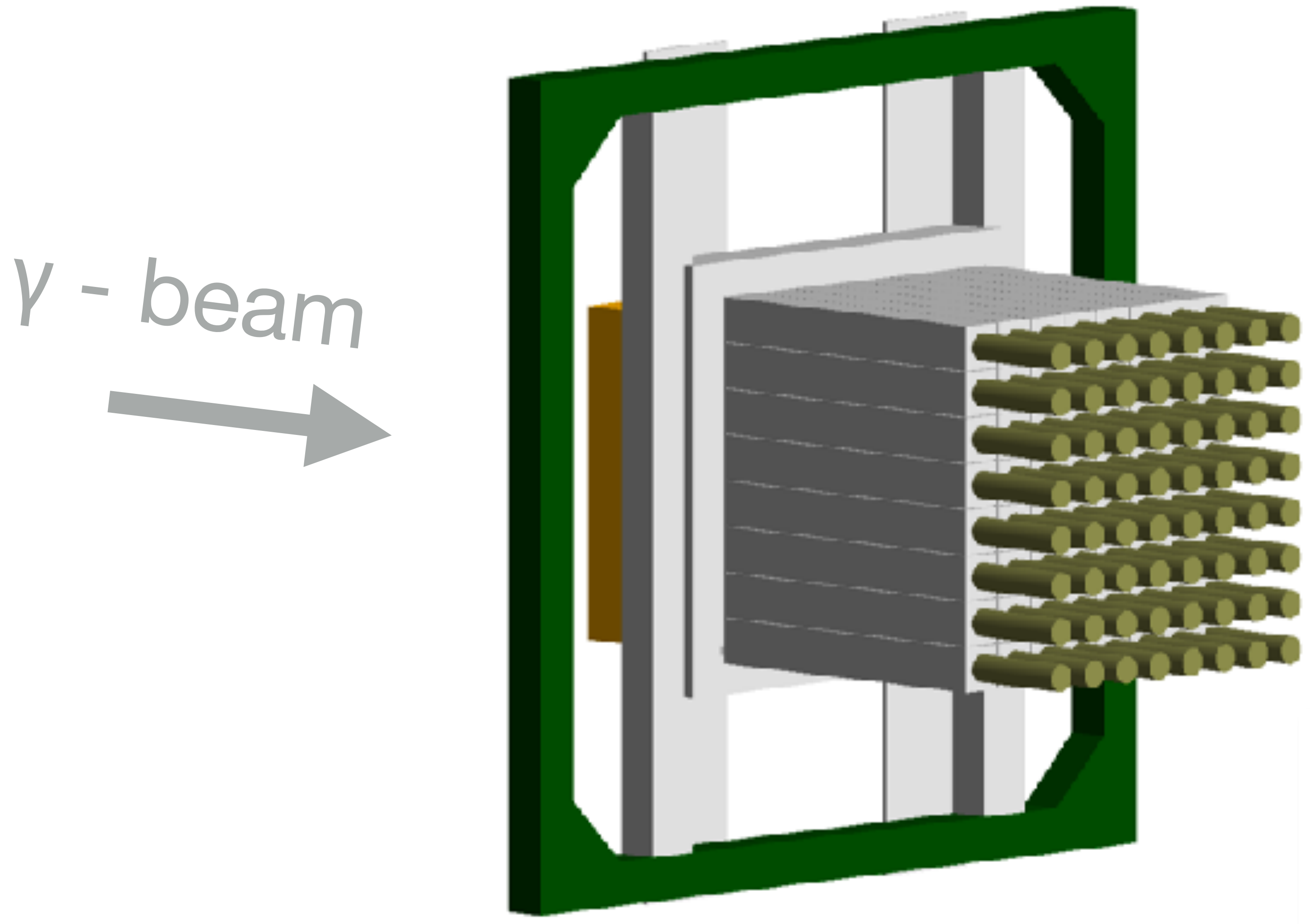



Dispersively improved chiral effective field theory:
F. Gil-DomÍnguez, J.M. Alarcón and C. Weiss, Phys. Rev. D 108, no.7, 074026 (2023)

# $ep \to e'p\gamma$ and $\mu p \to \mu' p\gamma$ cross sections in MUSE kinematics—study of radiative corrections

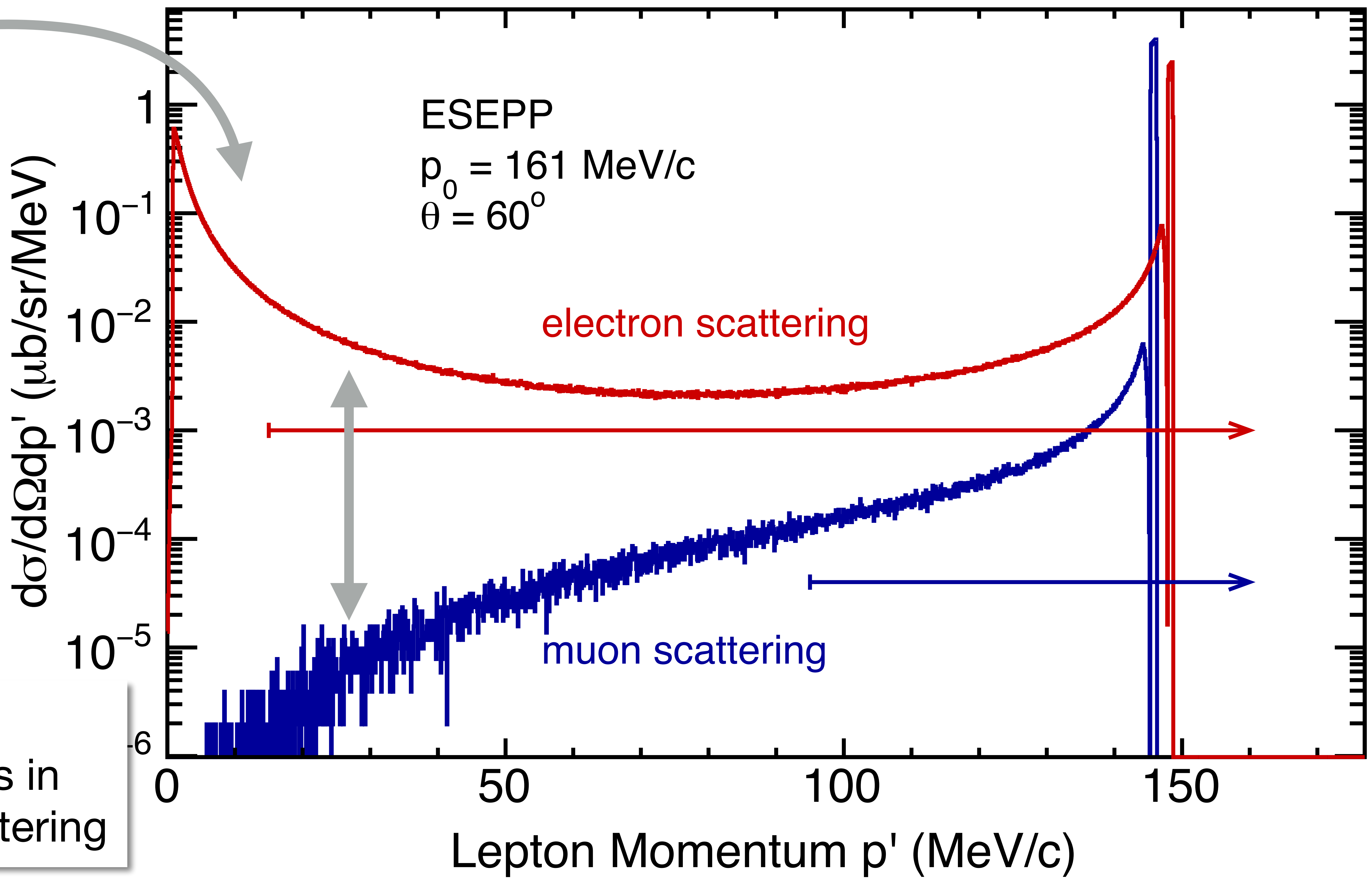
Initial-state radiation detectable by the downstream calorimeter




64 lead-glass crystals (4 cm x 4 cm x 30 cm)

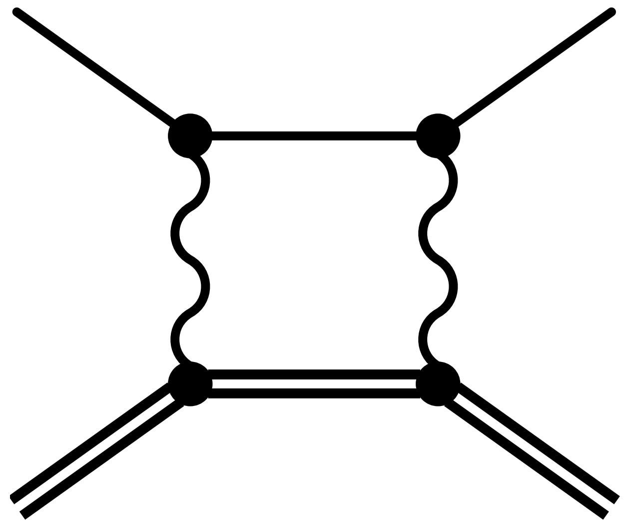
MUSE will integrate over a large momentum range.




Very different radiative effects in ep and μp scattering

L. Li et al. (MUSE Collaboration), Eur. Phys. J. A 60:8 (2024)

# MUSE allows the study of two-photon exchange



MUSE covers wide ε range, at small values of $Q^2$
Projected systematic uncertainties: 0.1% in $\delta_{2\gamma}$.

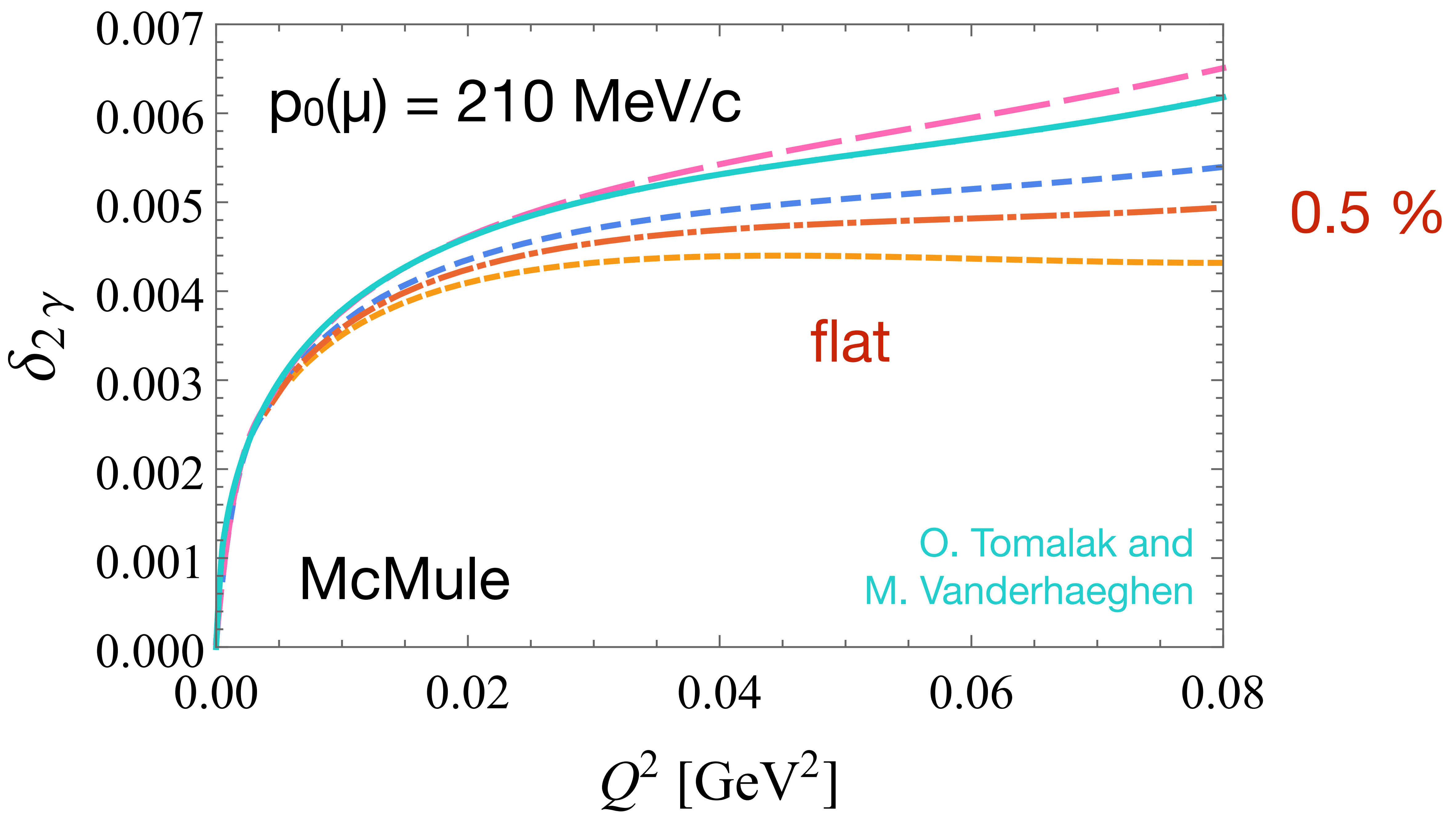
MUSE TDR, arXiv:1709.09753 [physics.ins-det].

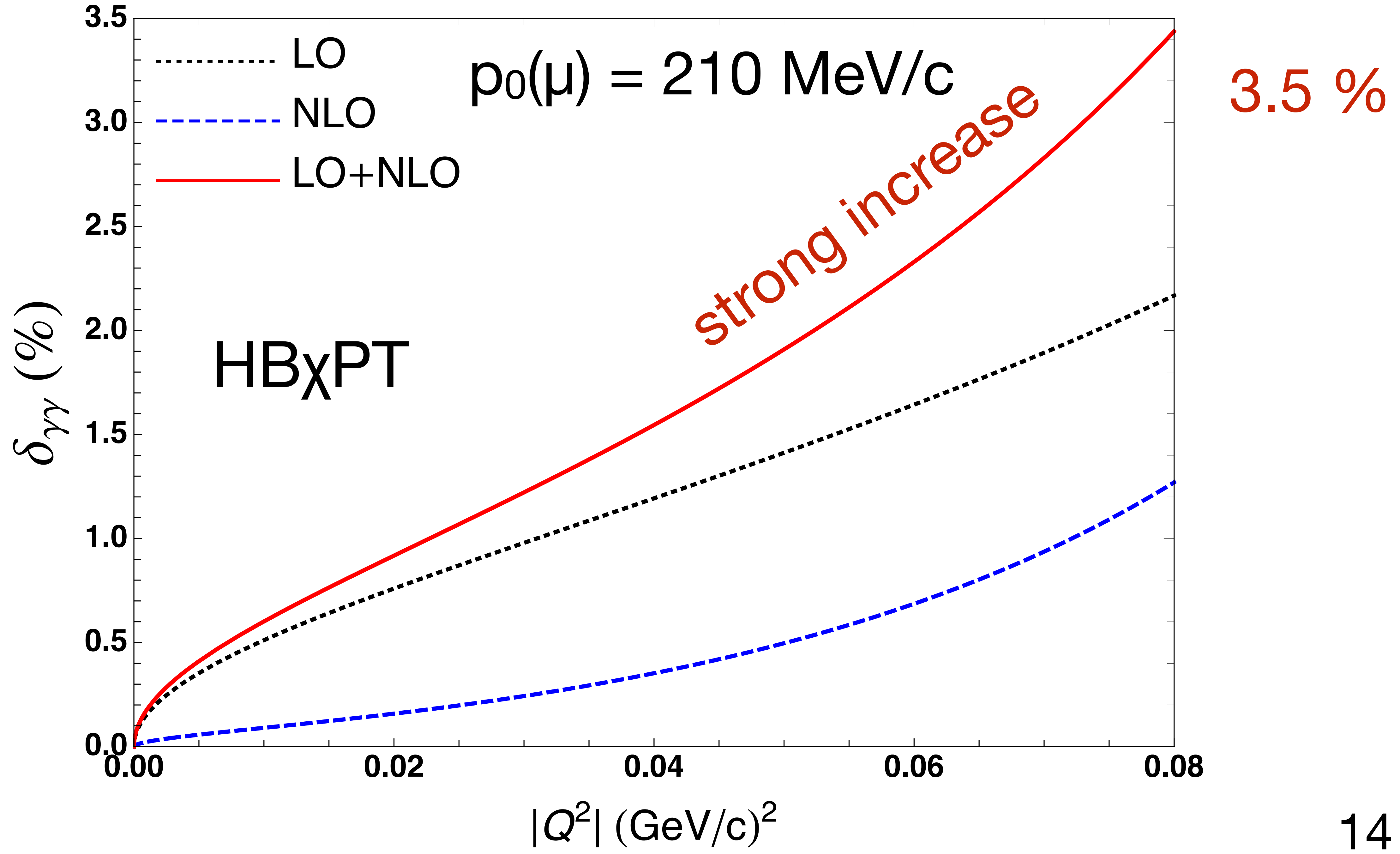
TPE correction at leading order, $\delta_{2\gamma}$

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

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

Oleksandr Tomalak, Few-Body Systems, 59, 87 (2018)
T. Engel, et al., Eur. Phys. J. A 59, 253 (2023) - McMule
P. Choudhary, et al., Eur. Phys. J. A 60, 69 (2024) - HBχPT



# Beam-time Request and Outlook

MUSE requests 6 months of beam time in 2025 at PiM1.

With the 2025 beam time, MUSE will achieve its statistics goals to provide valuable insights into the proton charge radius puzzle:

- the comparison between ep and μp (cross section, form factor, radius) will be a direct test for lepton-universality violation and any related new physics;
- ep and μp comparison and the photon calorimeter can test radiative corrections;
- the use of both positive and negative polarities allows the study of two-photon exchange mechanisms.

| Year | Events |
|---|---|
| 2023 | $3 \times 10^9$ |
| 2024 | $6 \times 10^9$ |
| 2025 anticipated | $6 \times 10^9$ |
| Goal | $15 \times 10^9$ |