The MUon Scattering Experiment (MUSE) at the Paul Scherrer Institute

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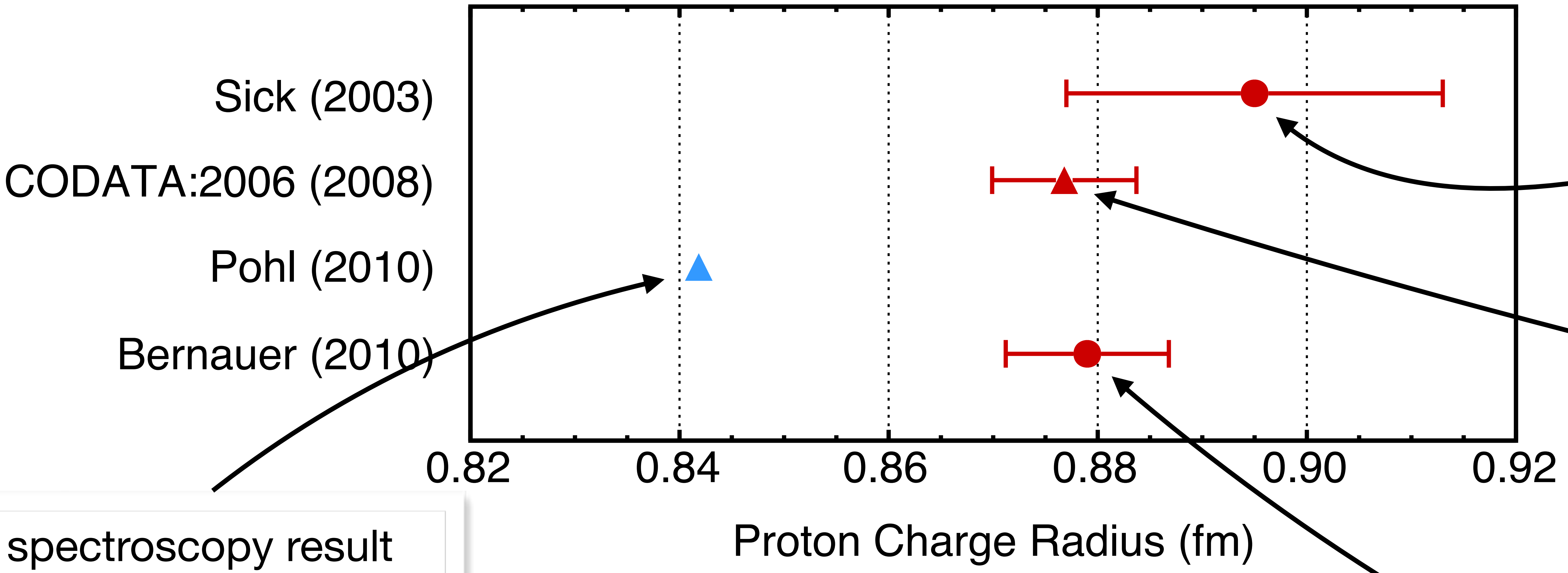
The proton radius puzzle (2010): Muonic and electronic measurements give different proton charge radii



Analysis of world electron-scattering data

Analysis of hydrogen spectroscopy data Committee on Data for Science and Technology (CODATA)

r_p = 0.8768(69) fm

Muonic-hydrogen spectroscopy result

Ten times more precise, but 4% smaller than previously accepted value

r_p = 0.84184(67) fm

Analysis of MAMI electron-scattering experiment

In 2010, the discrepancy between muonic and electronic measurements of the proton charge radius was a 5σ effect and grew to a 7σ effect in 2013.
Now? … **tension between experiments persist**.

I. Sick, PLB 576, 62 (2003); P.J. Mohr et al., Rev. Mod. Phys. 80, 633 (2008); J.C Bernauer et al., PRL 105, 242001 (2010); R. Pohl et al., Nature 466, 213 (2010)

MUon Scattering Experiment (MUSE) at PSI

Direct test of μp and ep interactions in a scattering experiment:

- higher precision than previously,
- low Q^2 region for sensitivity to the **proton charge radius**, $Q^2 = 0.002$ to $0.07\ \mathrm{GeV}^2$,
- with μ^+,μ^- and e^+,e^- to study possible **two-photon exchange mechanisms**,
- with μp and ep to have direct **μ/e comparison**

MUSE

$$e^- p \to e^- p$$
$$e^+ p \to e^+ p$$
$$\mu^- p \to \mu^- p$$
$$\mu^+ p \to \mu^+ p$$

The MUon Scattering Experiment at PSI (MUSE), MUSE Technical Design Report, arXiv:1709.09753 [physics.ins-det].

MUSE at the secondary beam line πM1

Beam

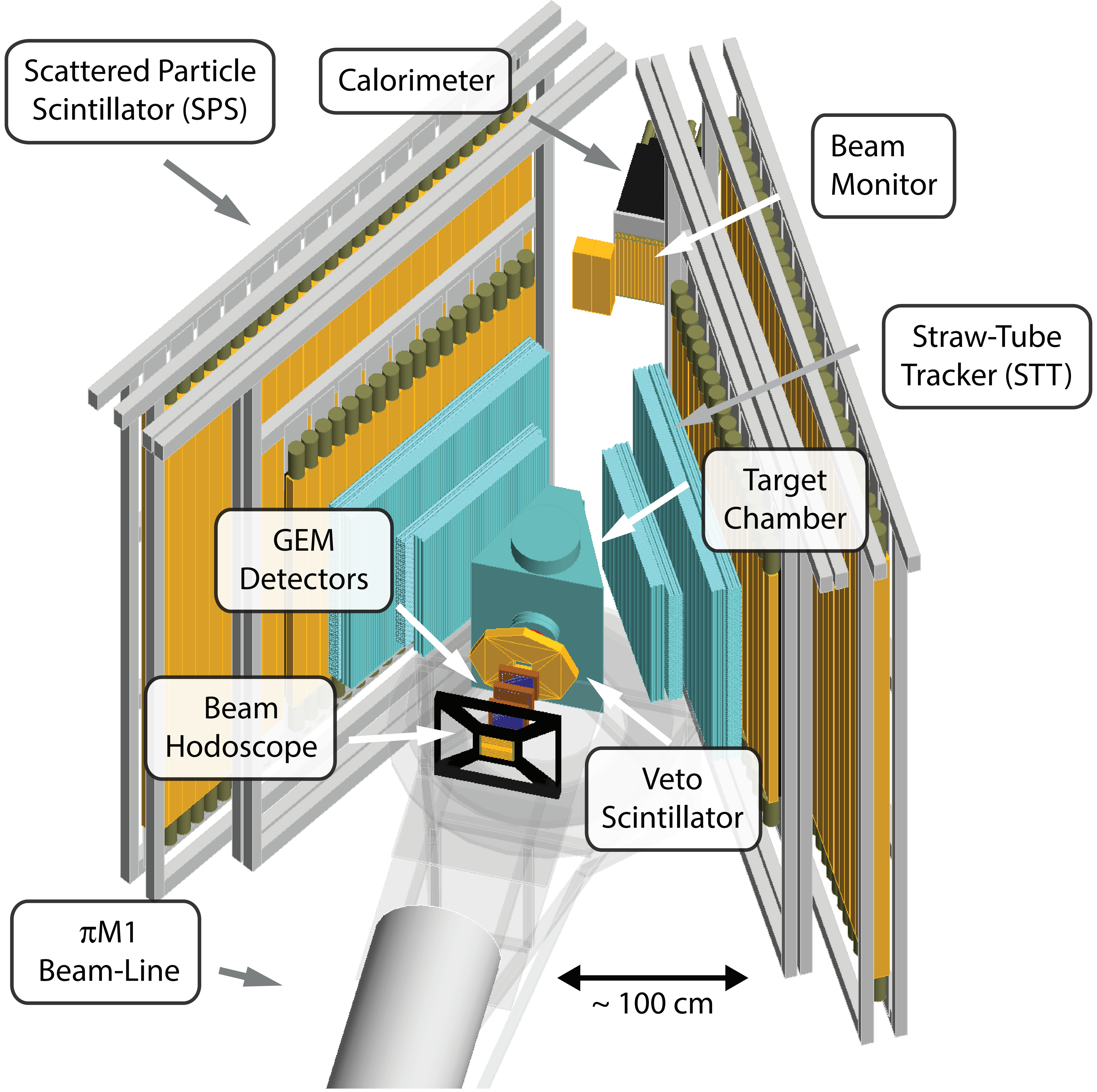
- 50 MHz RF (20 ns bunch separation)
- e, μ, π beams with large emittance
- Flux: 3.3 MHz
- Momentum: 115, 160, 210 MeV/c

Beam line detectors:

- Timing, identifying, and tracking of beam particles to the target and beyond

Scattered particle detectors:

- Timing and tracking of scattered particles with large solid-angle coverage

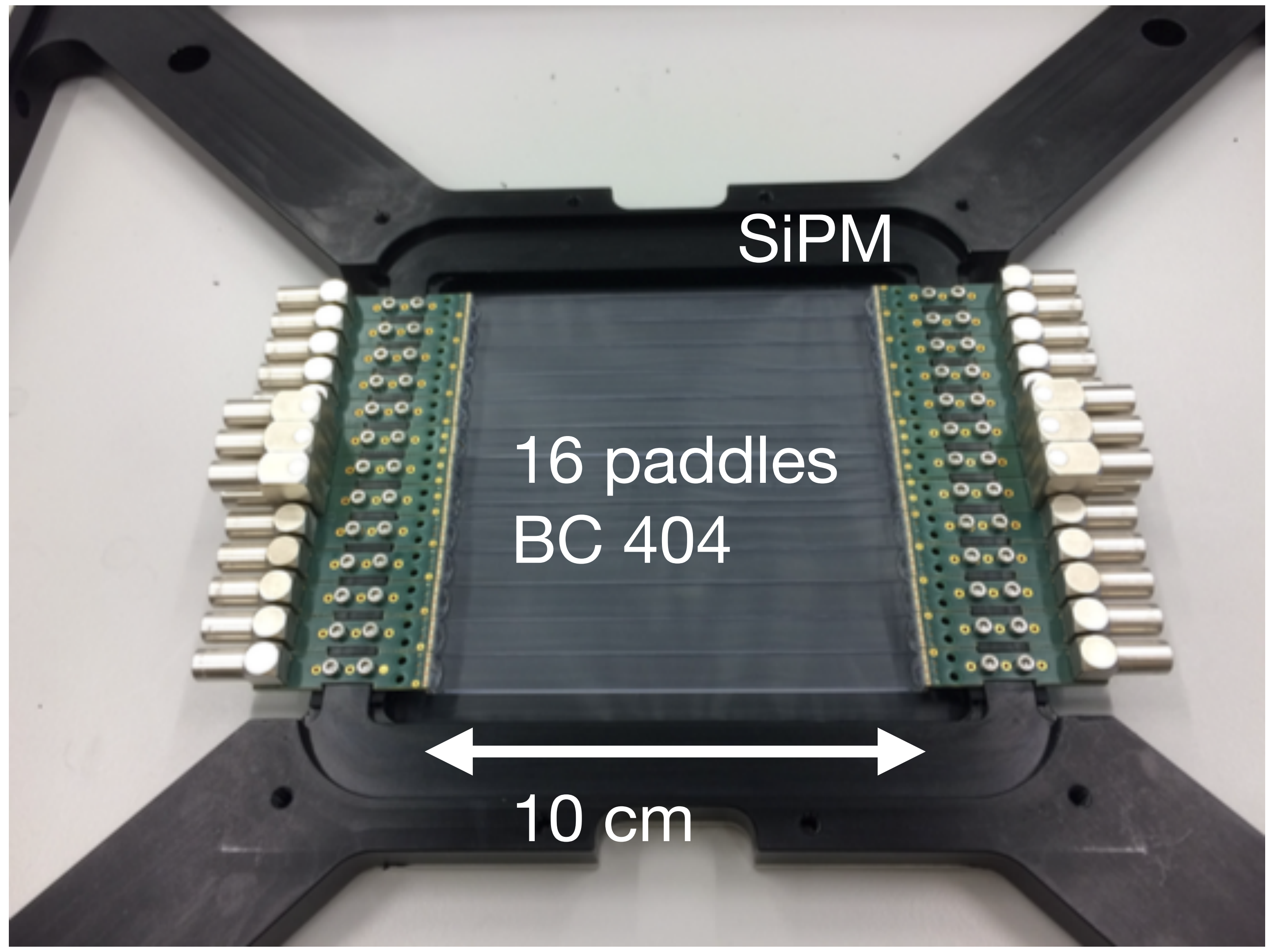


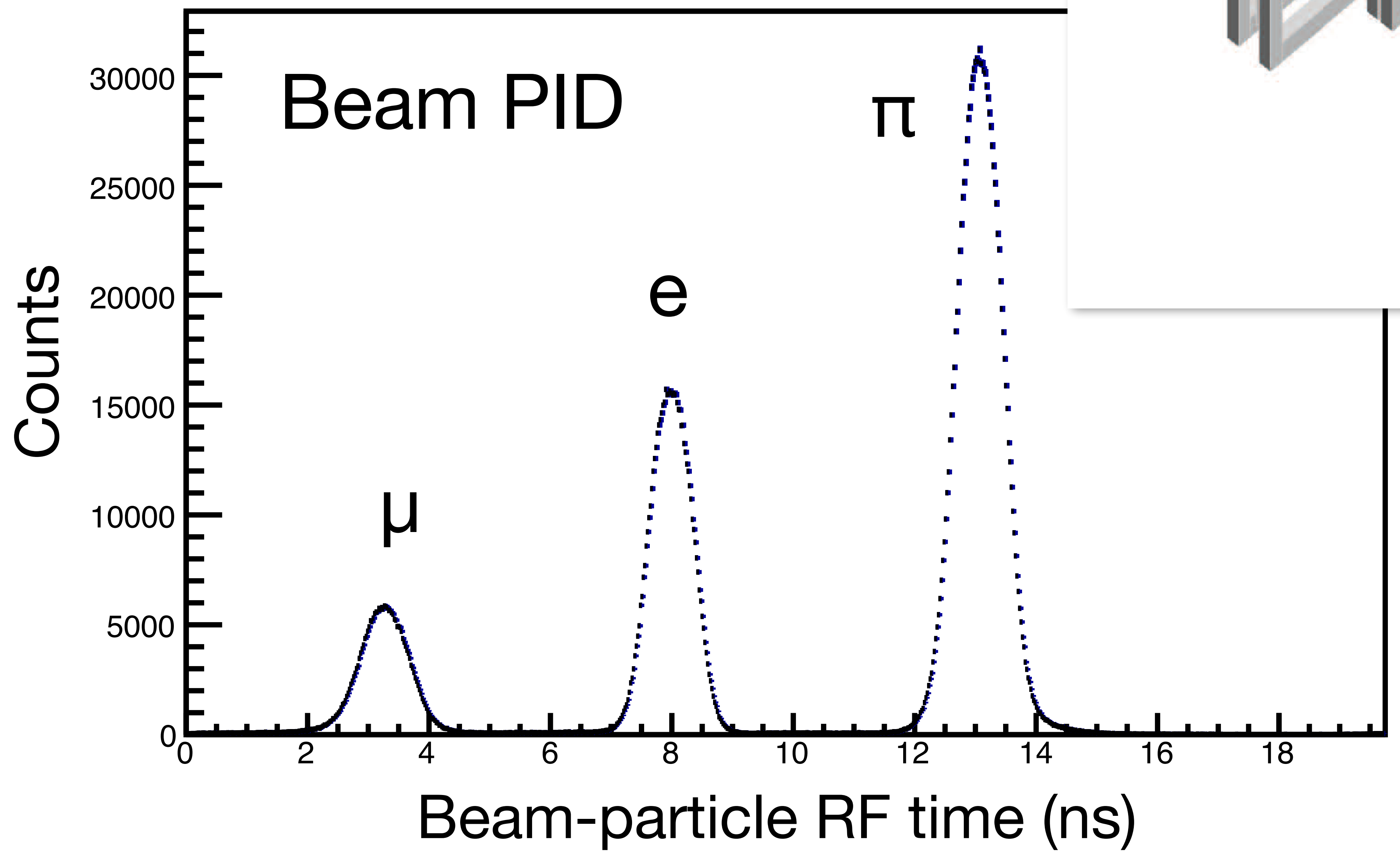
The MUon Scattering Experiment at PSI (MUSE), MUSE Technical Design Report, arXiv:1709.09753 [physics.ins-det].

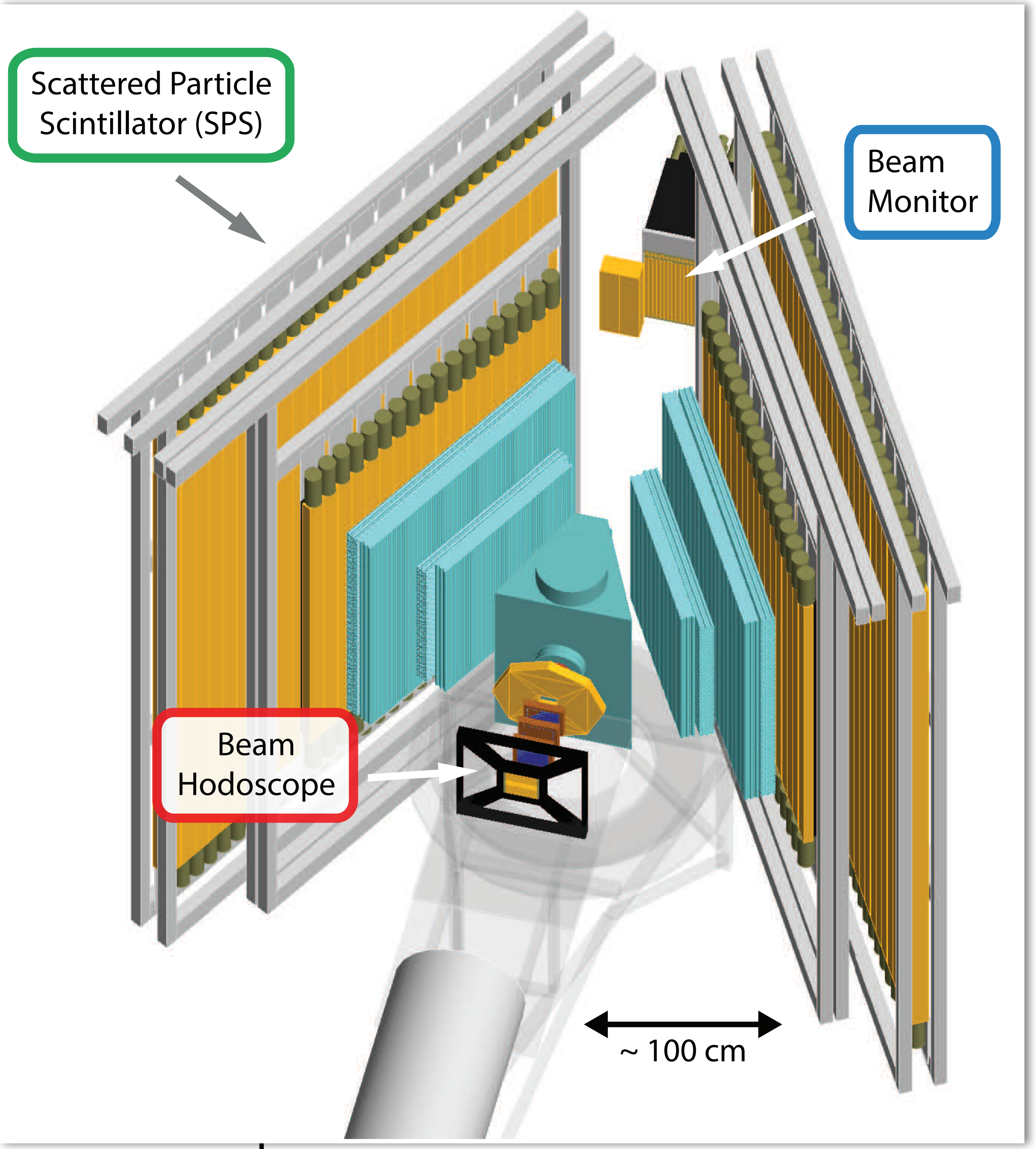
Beam Hodoscope

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

- RF time to hodoscope: beam-particle ID;
- Hodoscope to beam monitor: confirmation of beam-particle ID, background identification, muon and pion beam momenta;
- Hodoscope to scattered-particle scintillator: reaction type.



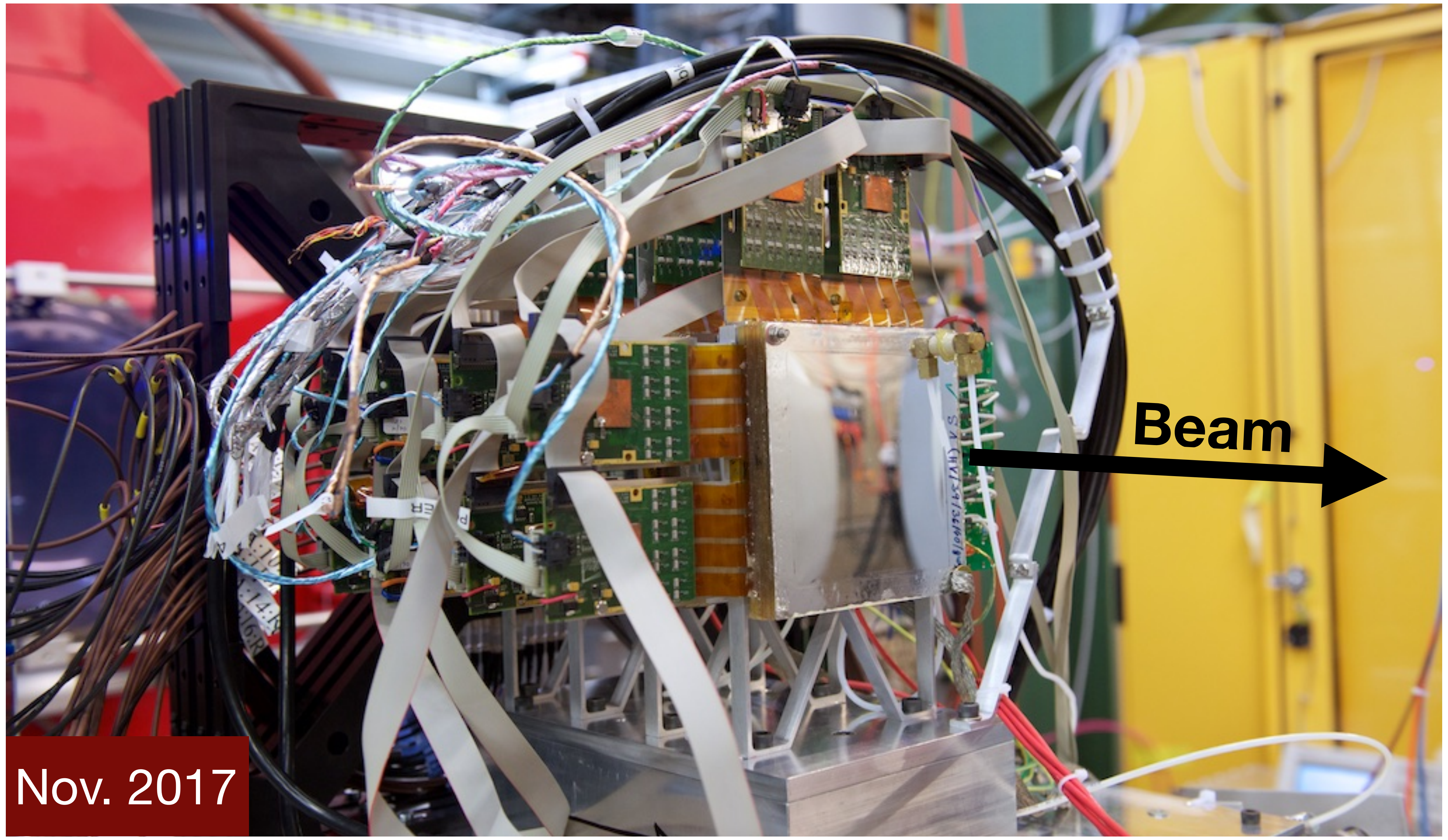


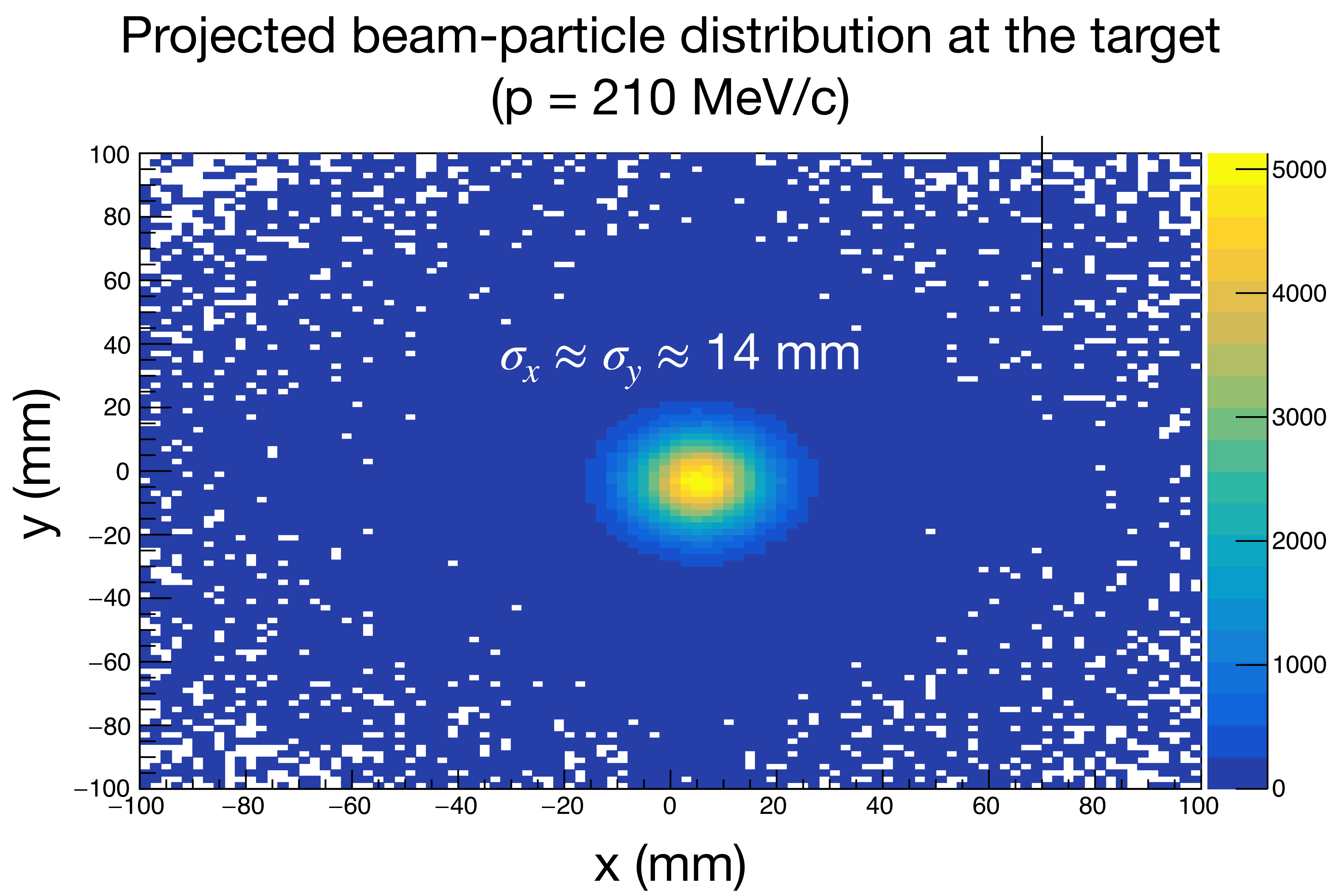


20 ns bunch separation

T. Rostomyan et al., NIM A 986, 164801 (2021)

GEM Detectors as incident-particle tracker

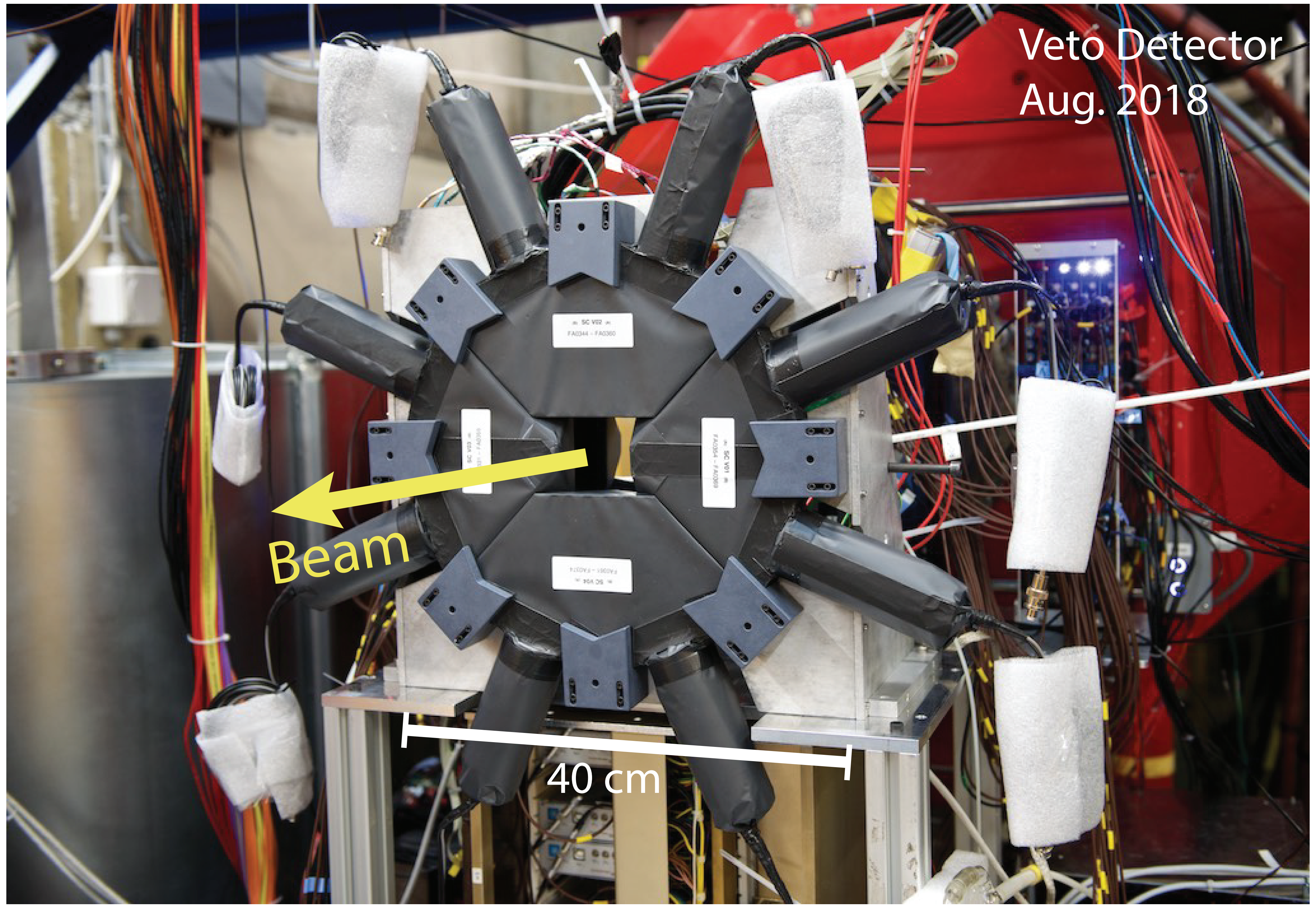


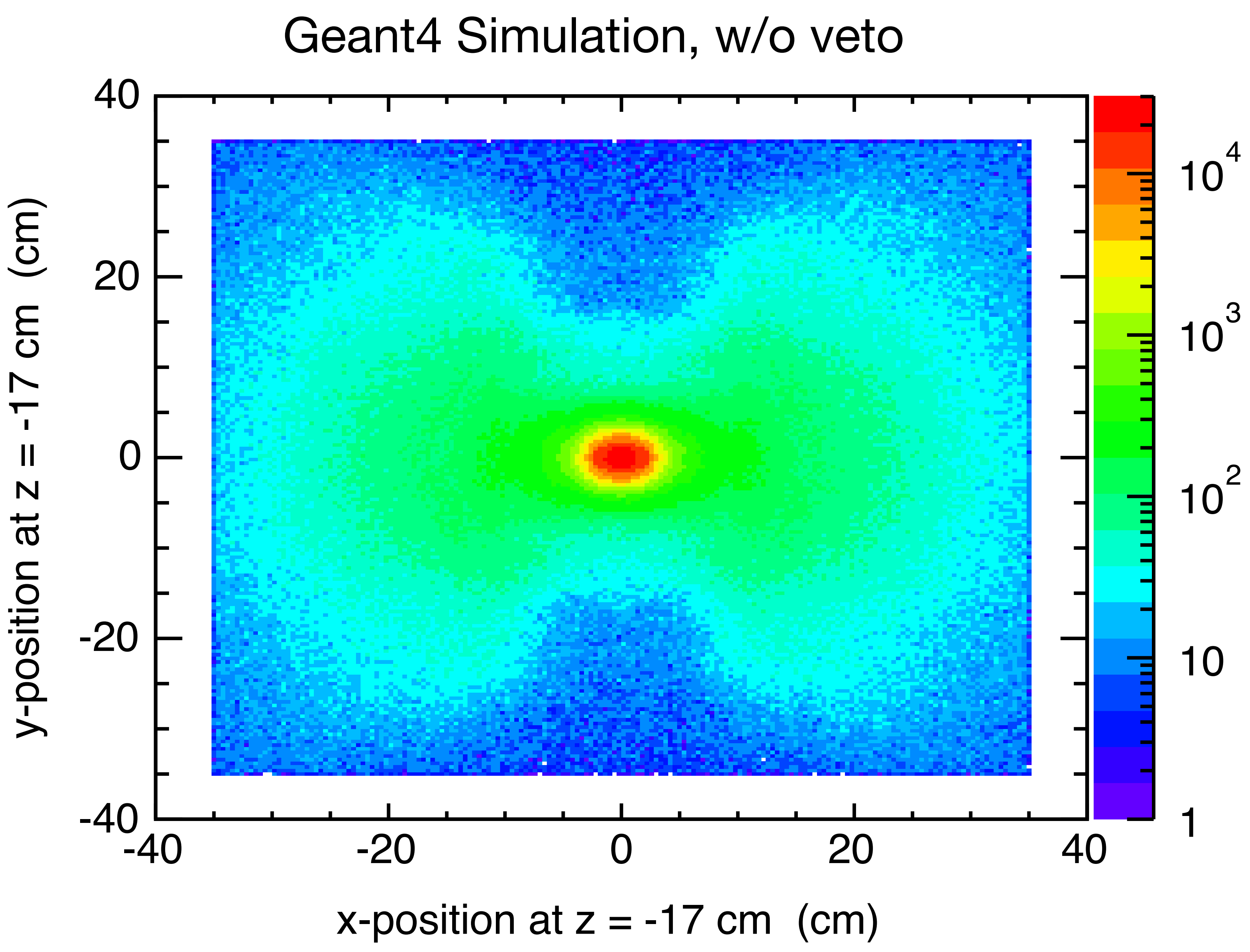


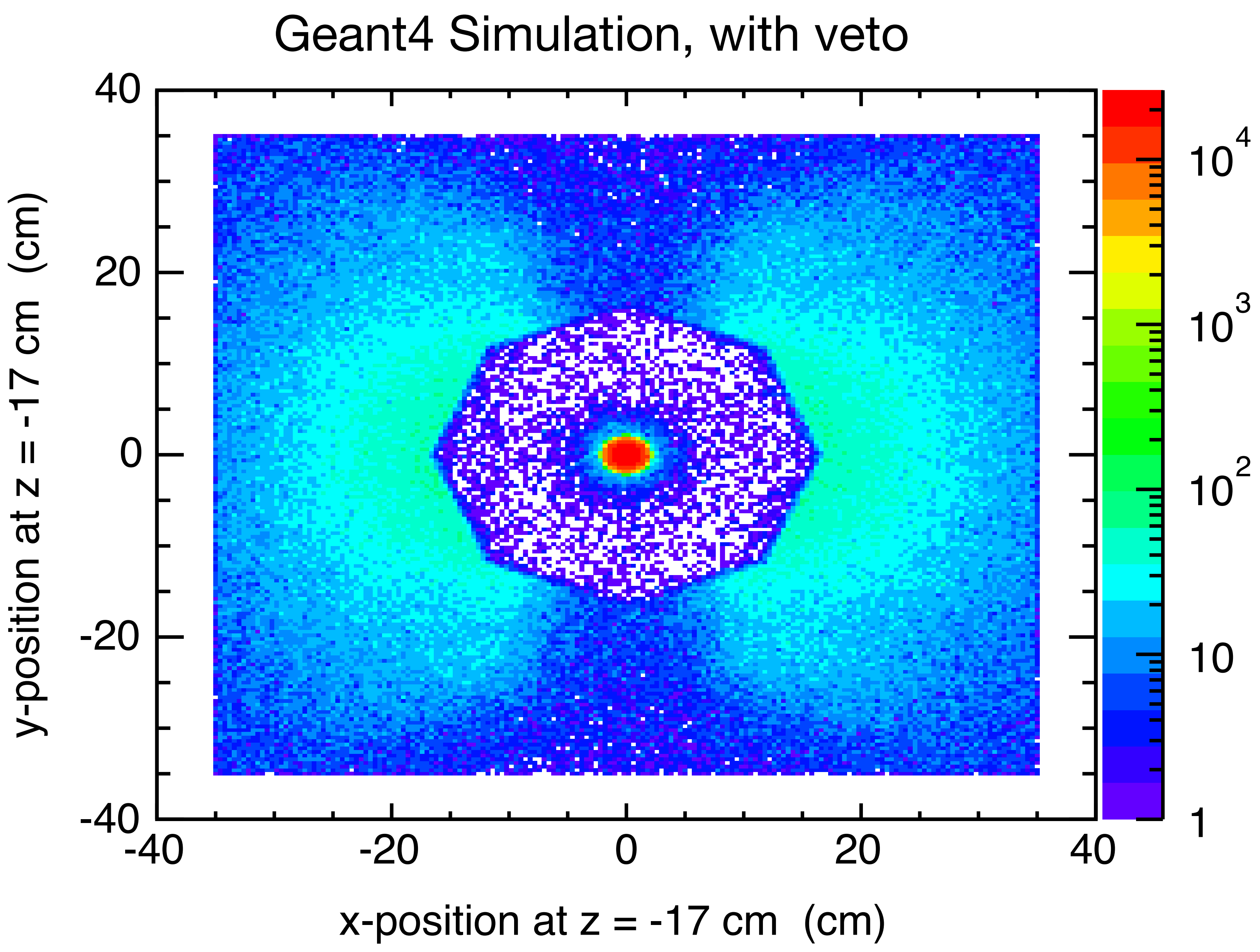
- Set of three 10 cm x 10 cm GEM detectors built for & run in OLYMPUS
- Measure trajectories into the target to reconstruct the scattering kinematics
- Achieved position resolution of 70 µm

Veto detector

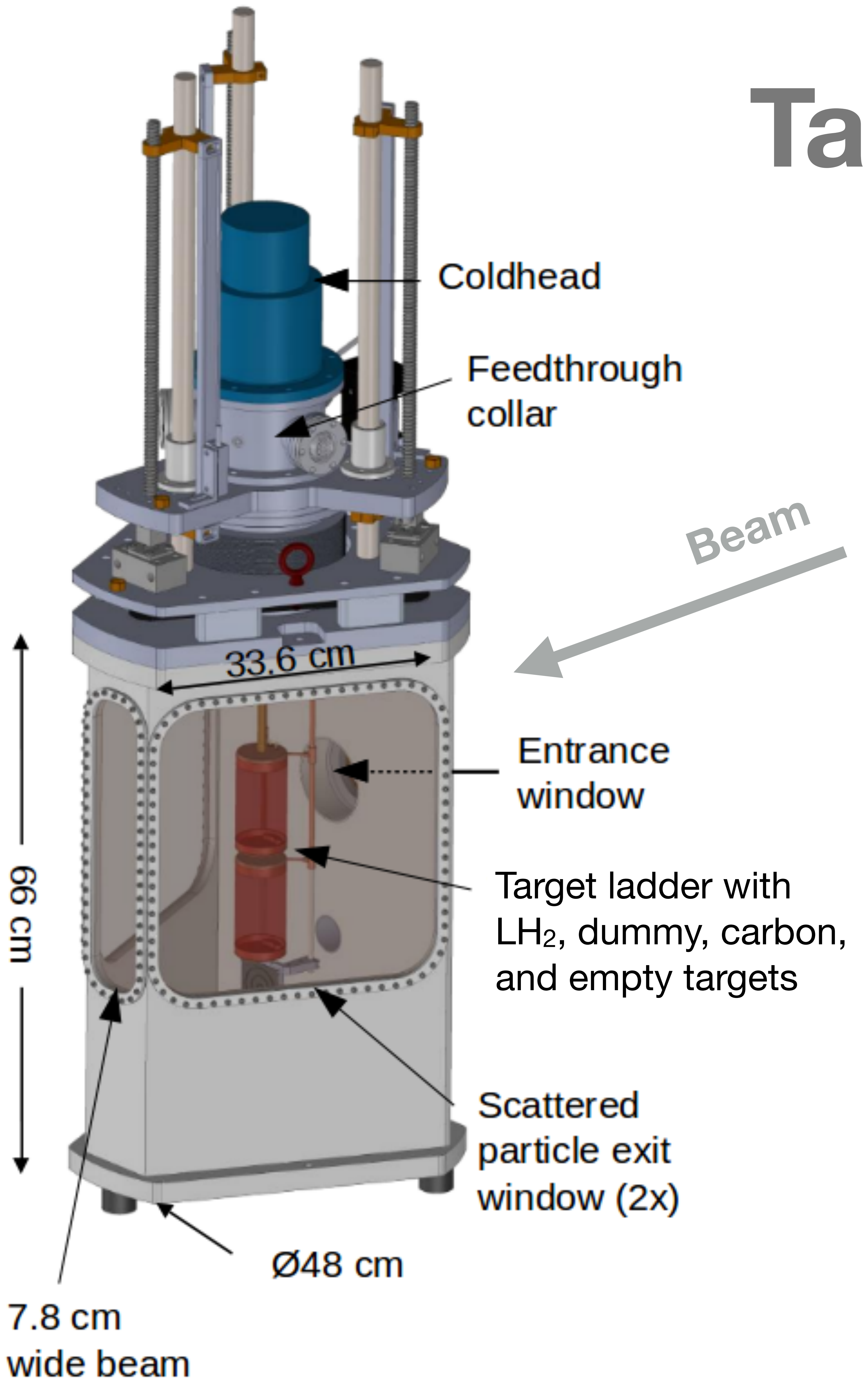
The veto detector reduces trigger rate from background events by about 25%. (Preliminary Fall 2021 test at 115 MeV/c)



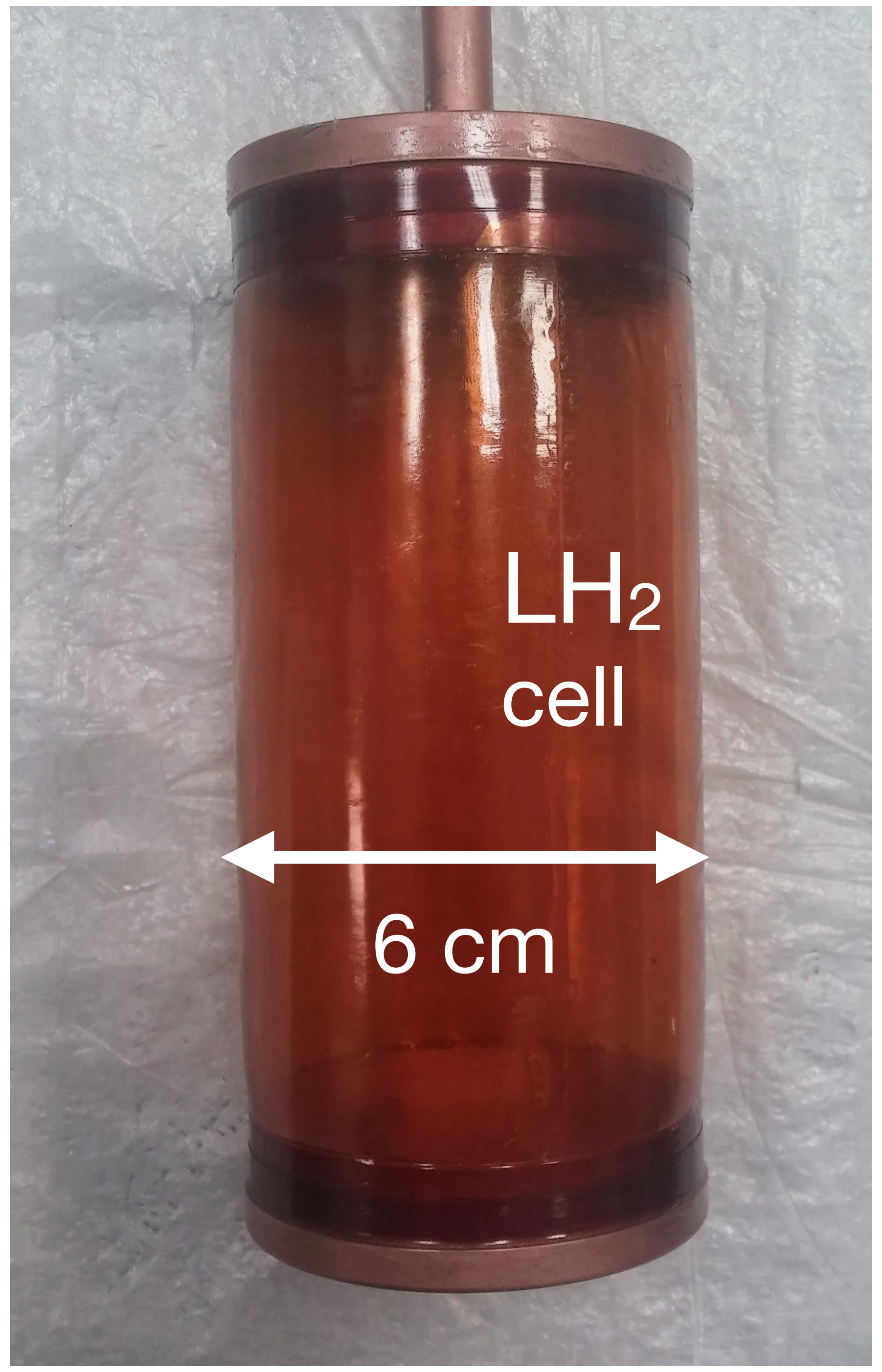




Target and Scattering Chamber



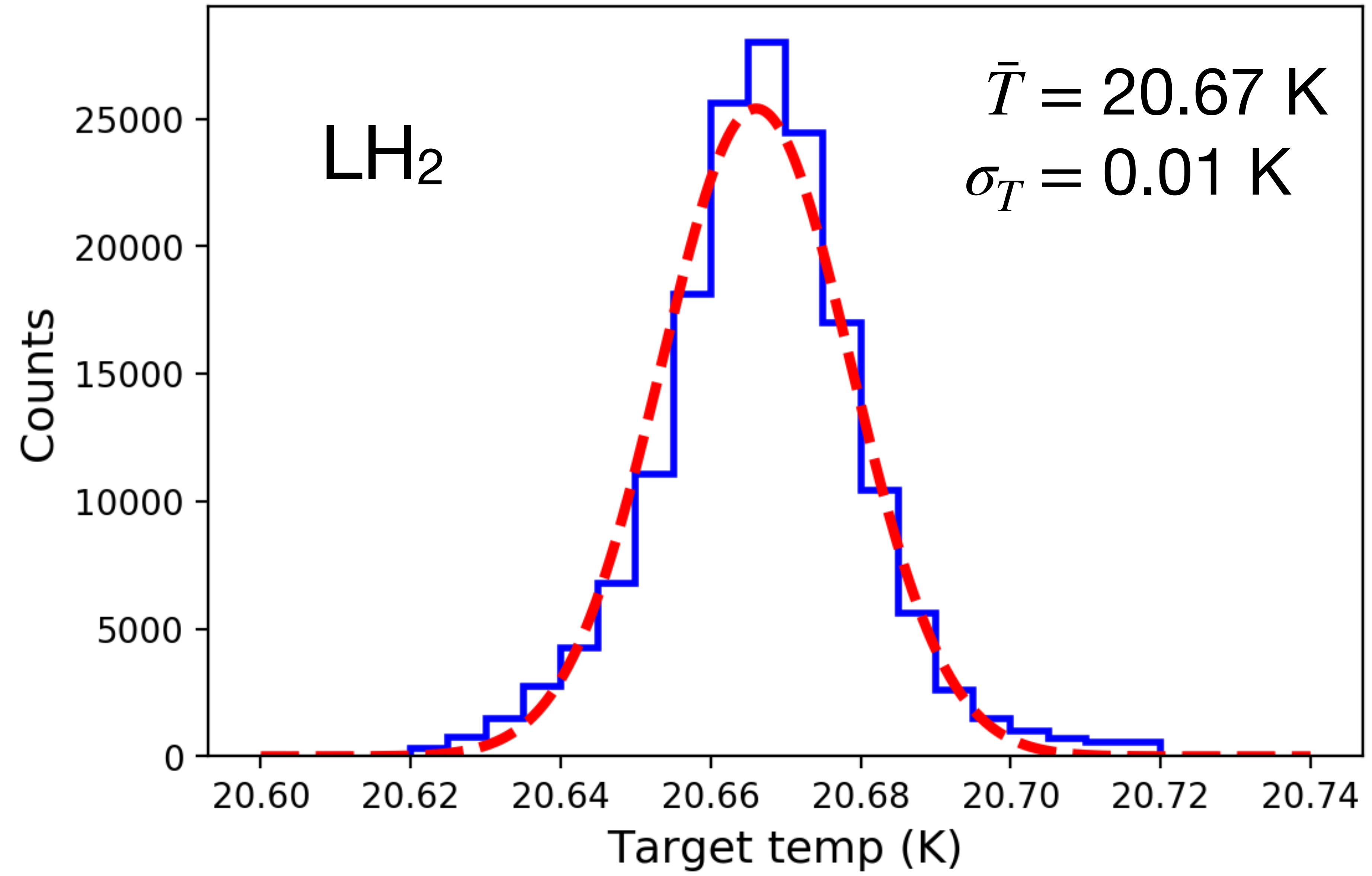
Roy et al., NIM A949, 162874 (2020)



LH_2 target cell

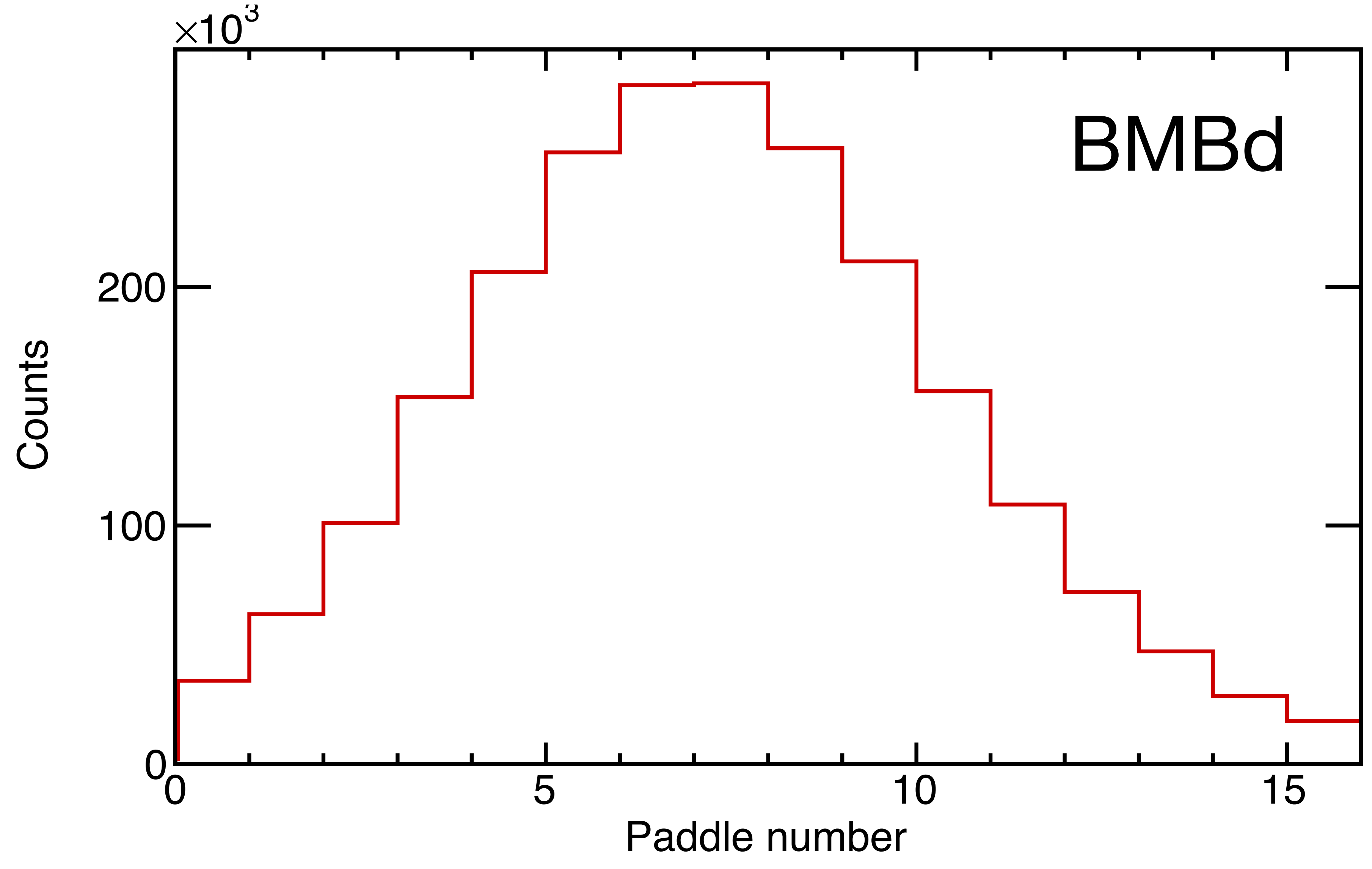
Target performance over 72 h

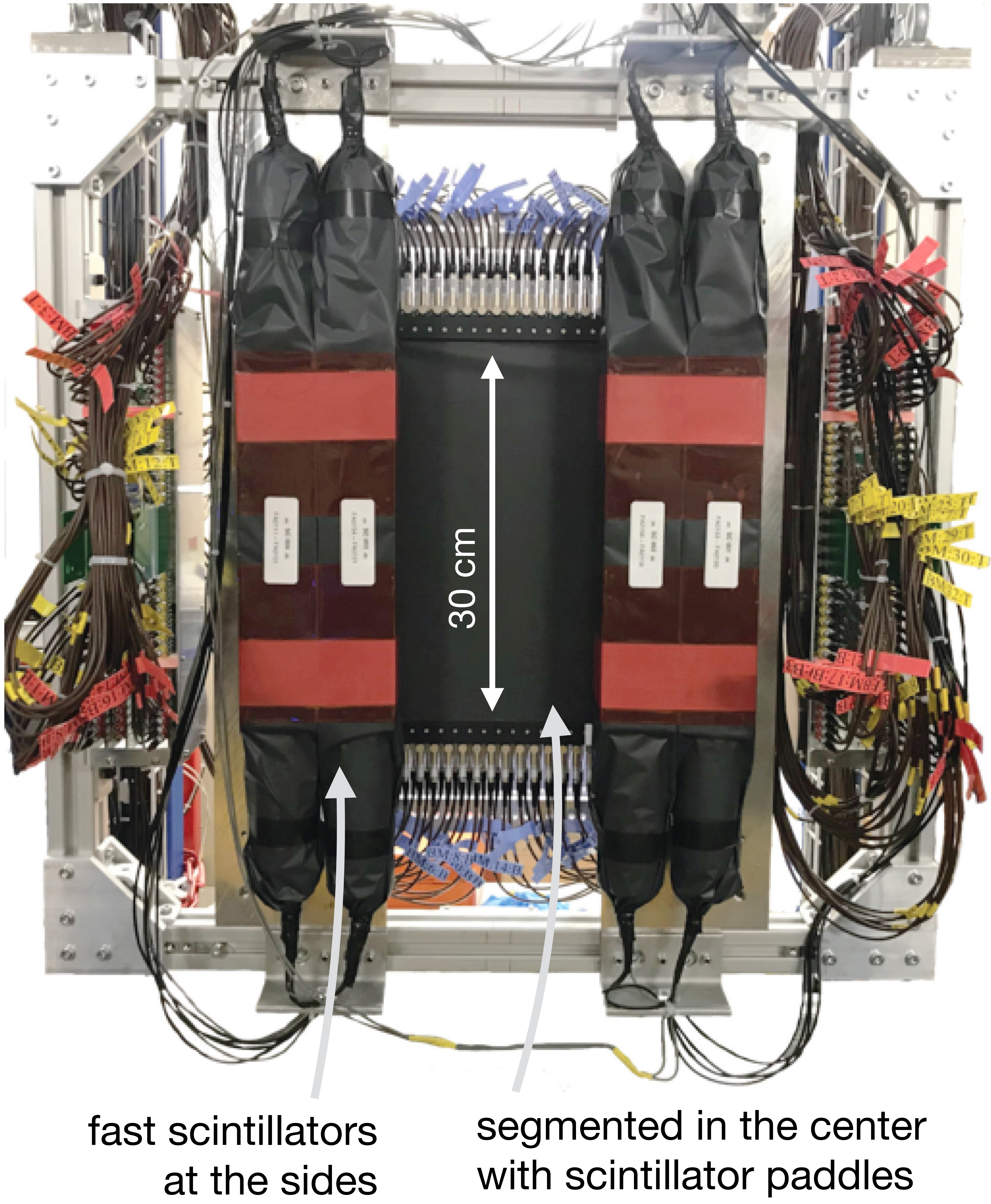
- LH_2 temperature: 20.67 ± 0.01 K
- LH_2 density: 0.070 g/cm^3 stable to 0.02%



Beam Monitor

- Determination of **particle flux** downstream of the target
- Monitor beam **stability**
- RF-time independent determination of **particle type**
- Veto for **Møller / Bhabha scattering background**
- Determination of muon and pion **momenta**



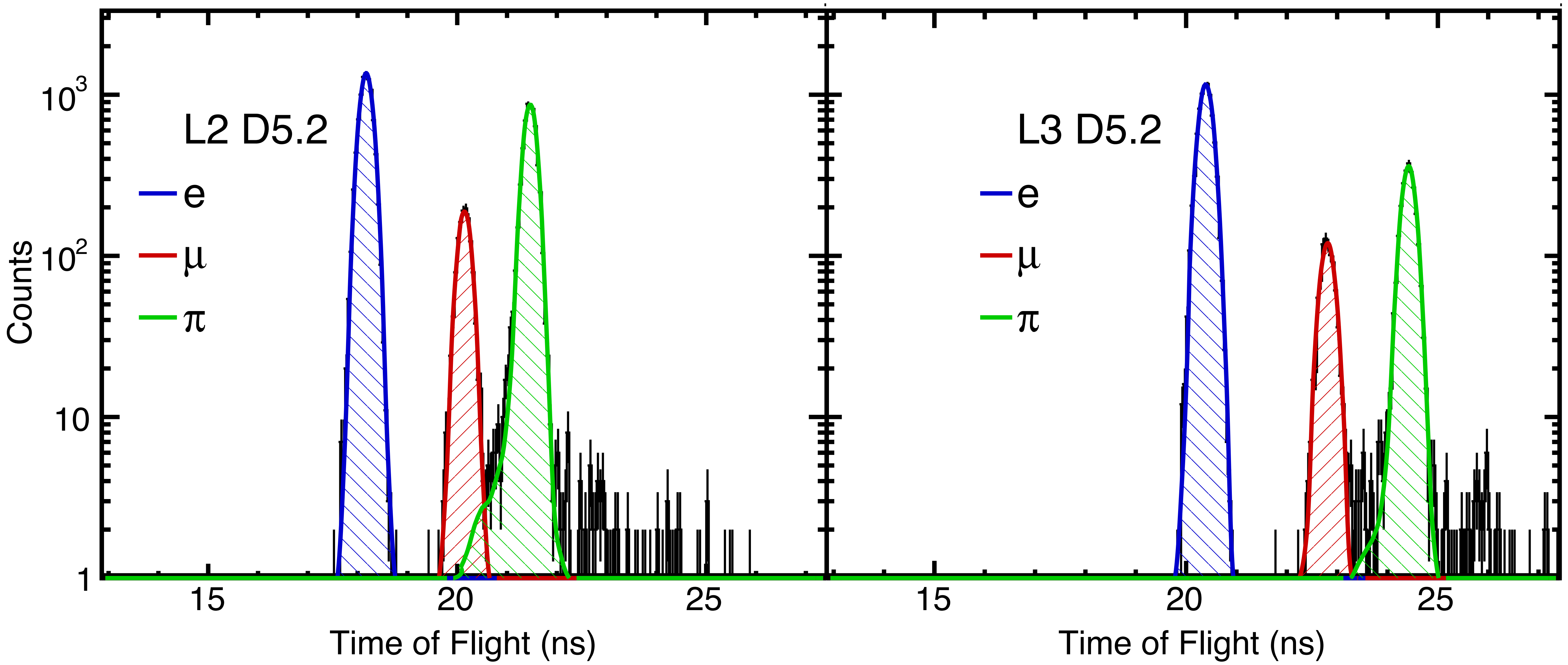


Beam Monitor

Carriages on rails allow for precise variation of beam-monitor position: 100-cm travel

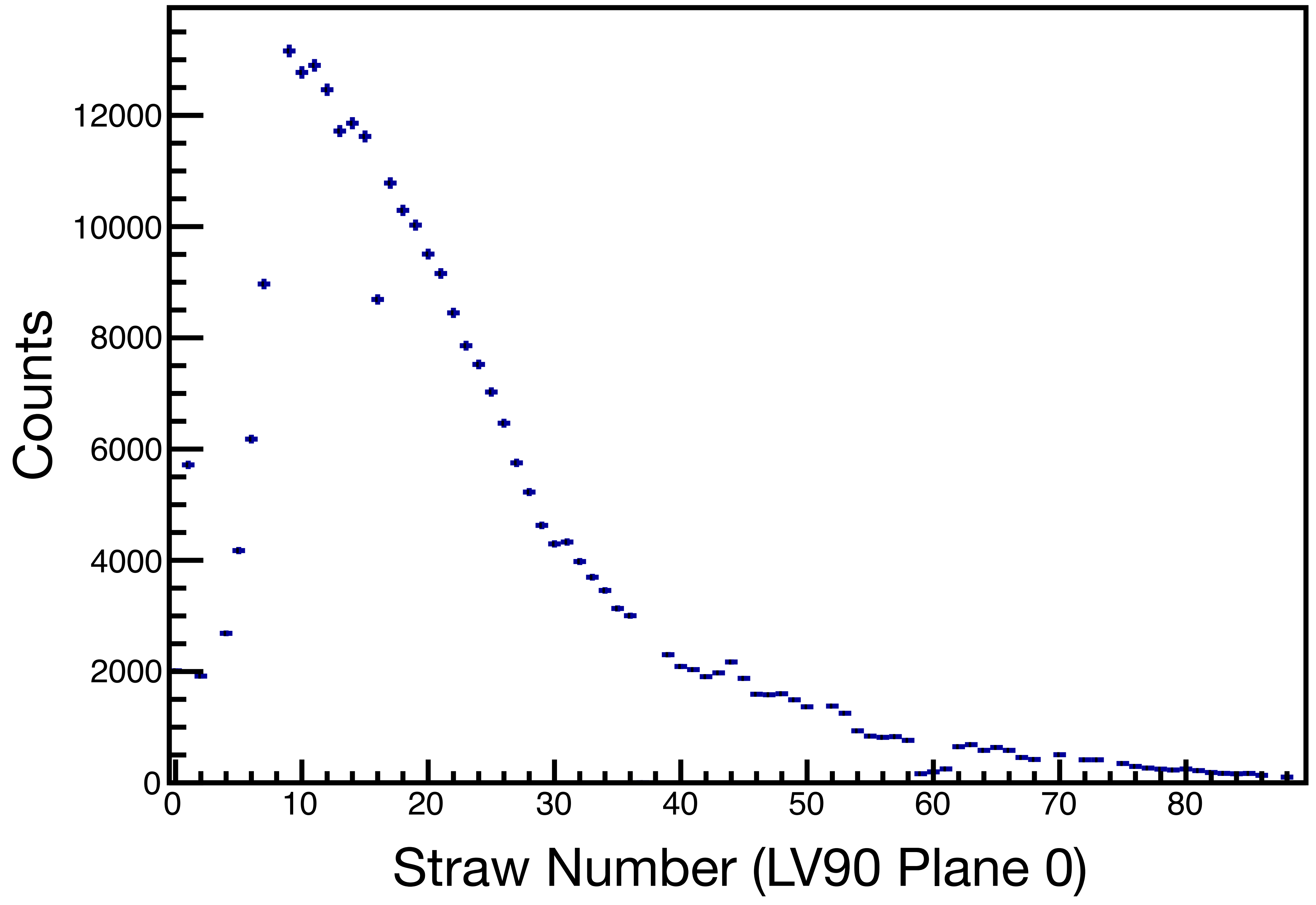
High-resolution scintillators ($\sigma_t \approx 30$ ps) moved into the beam for time-of-flight measurements

Example Time-of-Flight fit at 161(-) MeV/c



Straw-tube tracker

- The Straw Tube Tracker provides high-resolution and high-efficiency tracking of the scattered particles from the target.
- 10 vertical and 10 horizontal planes on each side of the beam.
- Based on PANDA design.

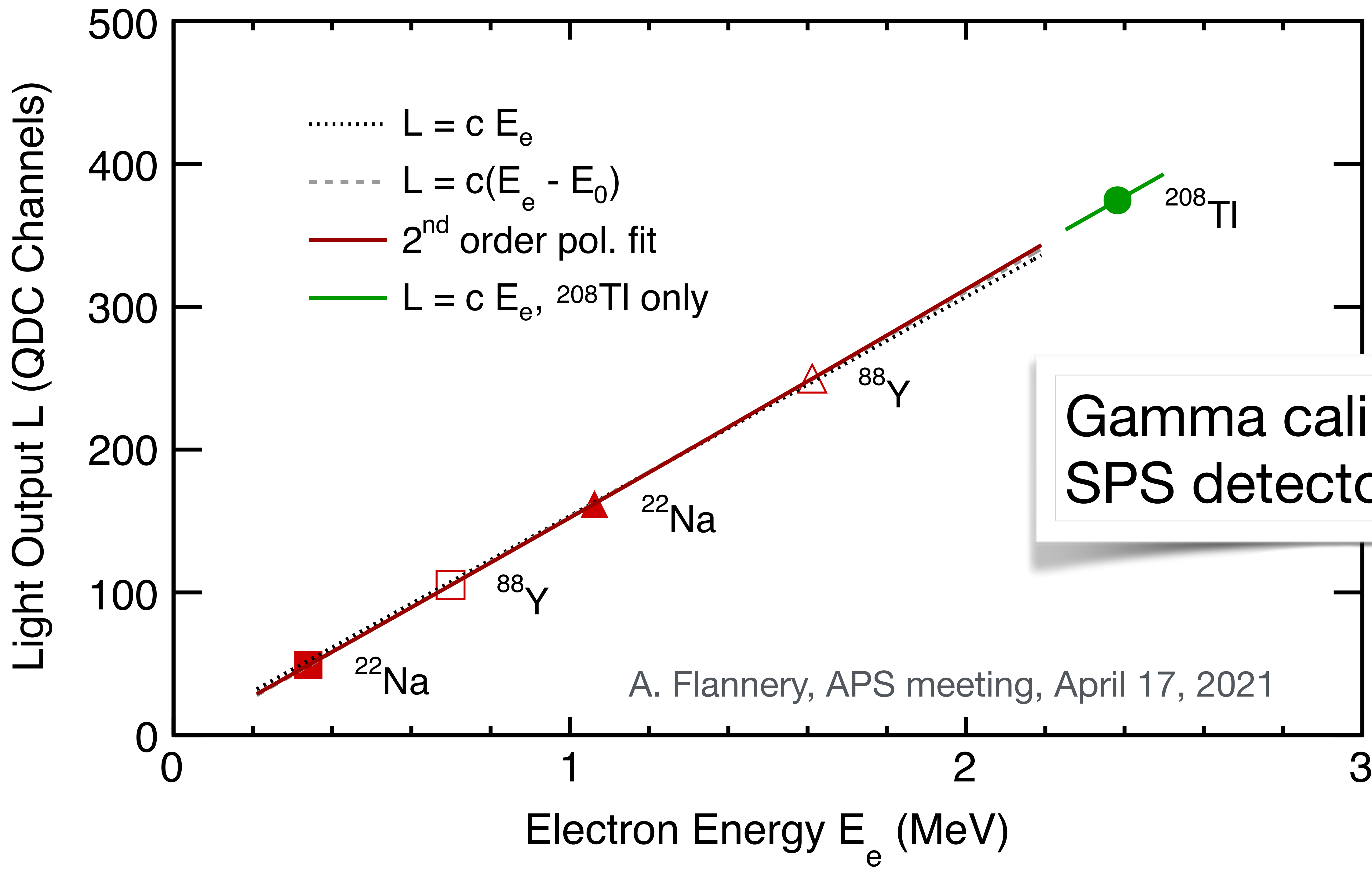


Scattered-particle scintillators as event trigger and for reaction ID

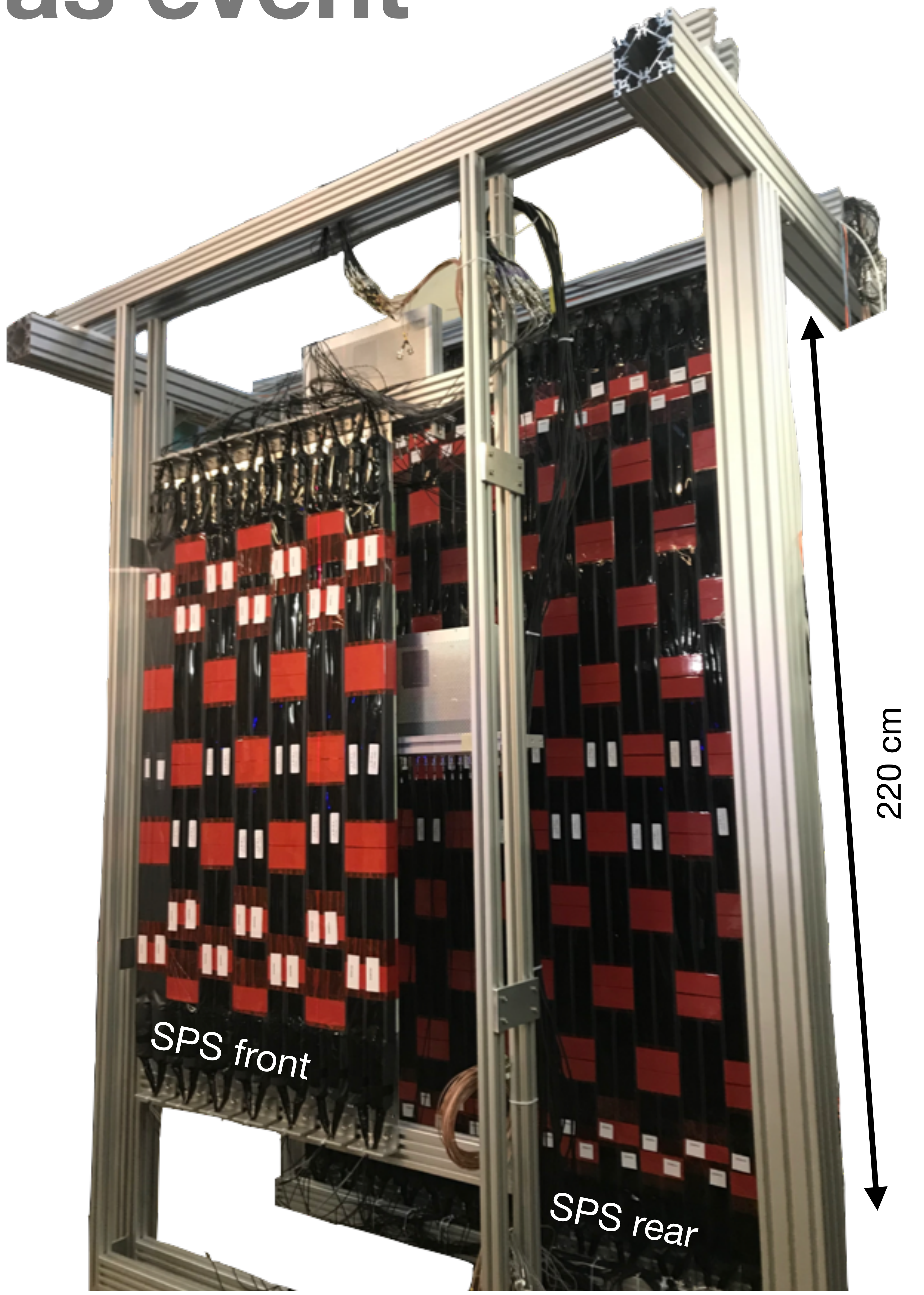
Front wall: 18 bars (6 cm x 3 cm x 120 cm)
Rear wall: 28 bars (6 cm x 6 cm x 220 cm)

Scattered-particle scintillators exceed required time resolution:

σ(Front) < 50 ps, σ(Rear) < 60 ps

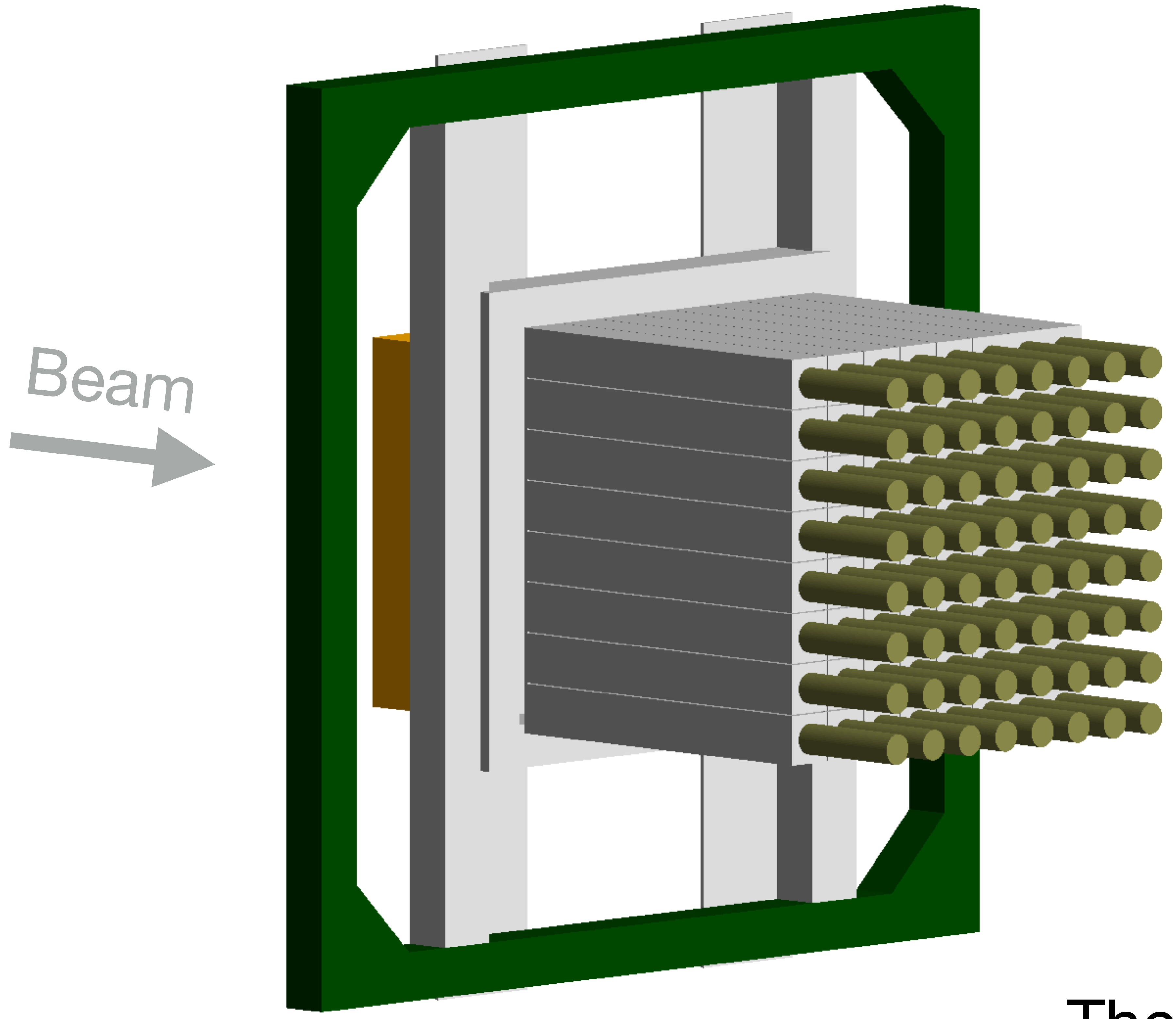


Gamma calibration of SPS detectors

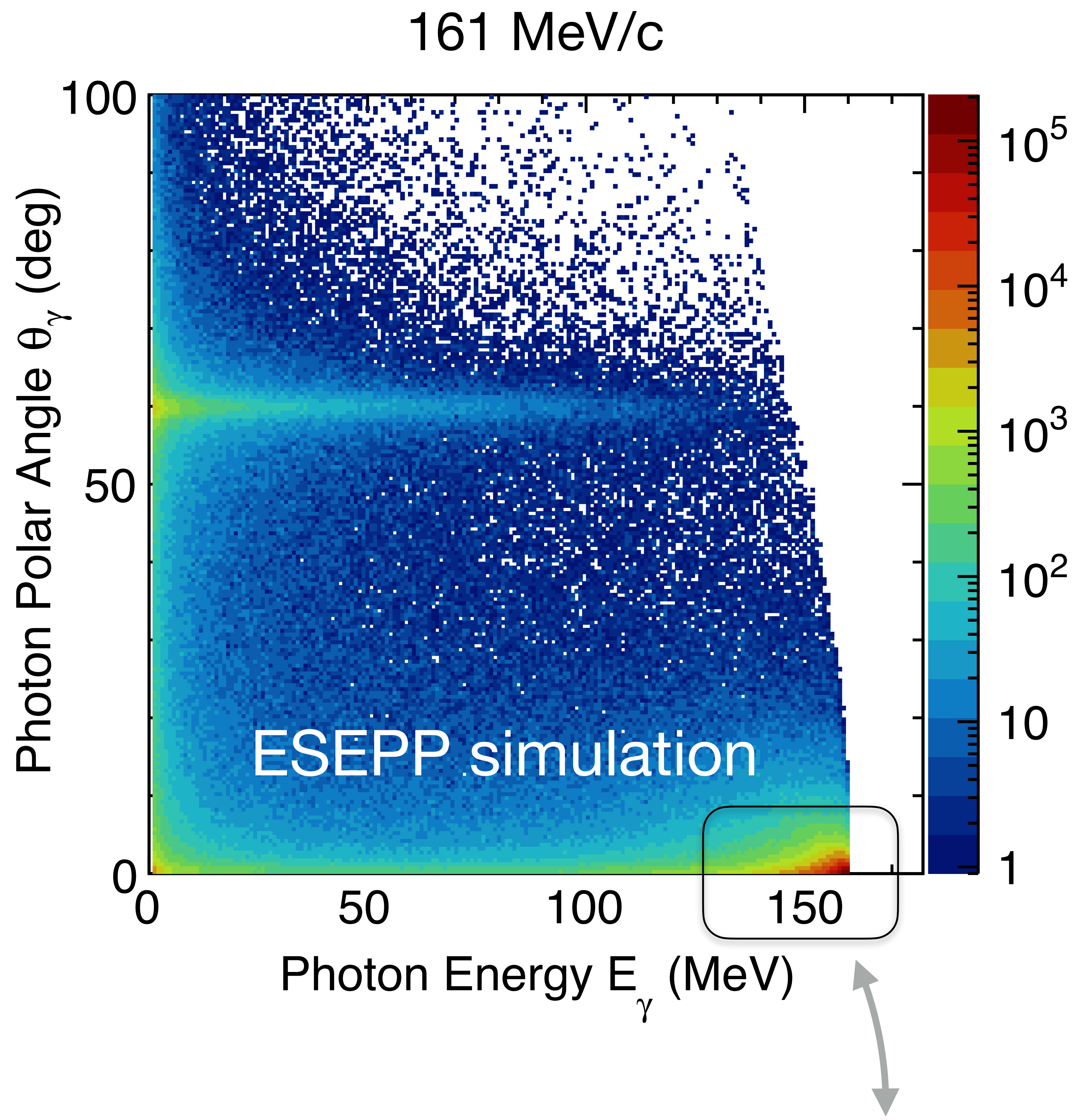


SPS detector in test stand

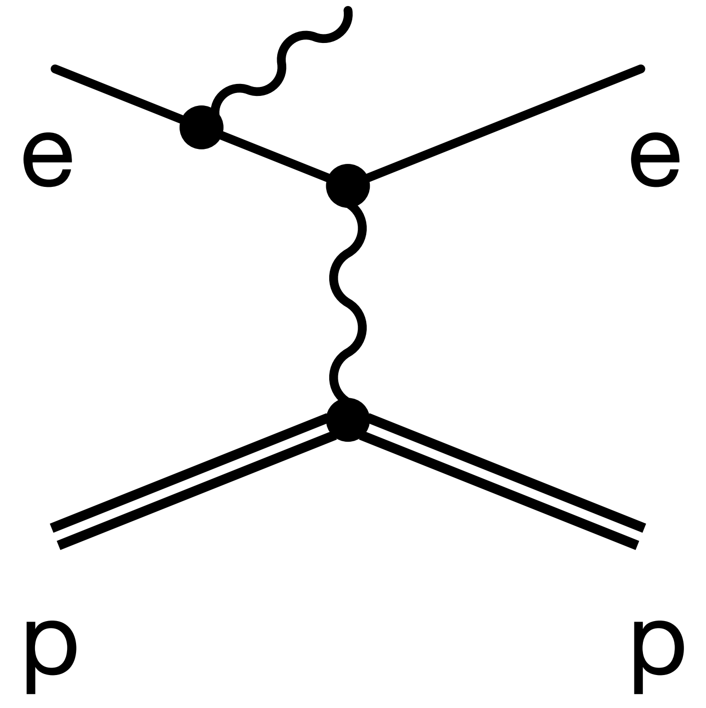
Photon Calorimeter



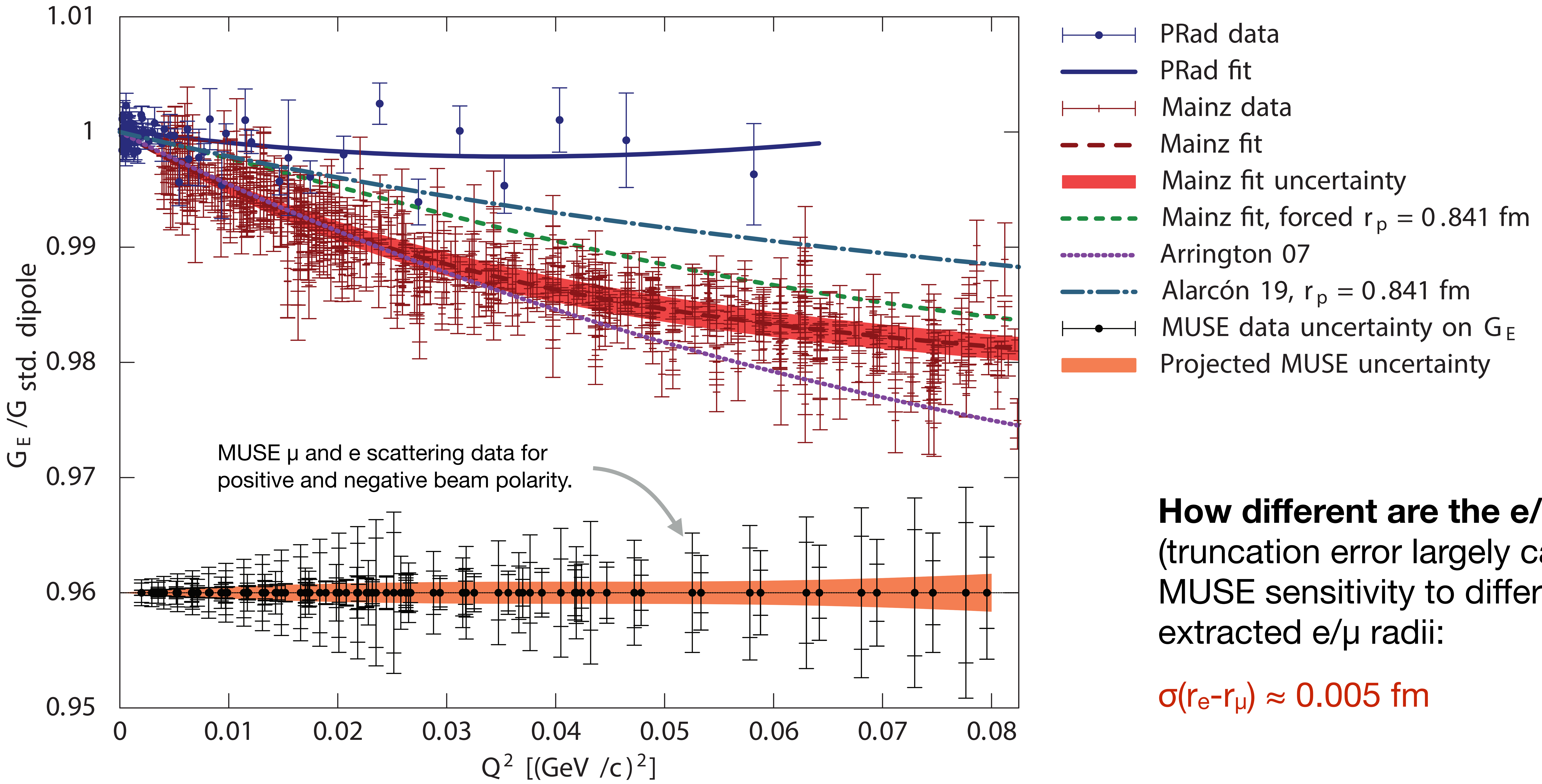
64 lead-glass crystals
(4 cm x 4 cm x 30 cm)



The downstream photon calorimeter will veto events with hard initial-state radiation and help control radiative corrections for ep → ep.



Anticipated *e* and μ data for G_E from MUSE



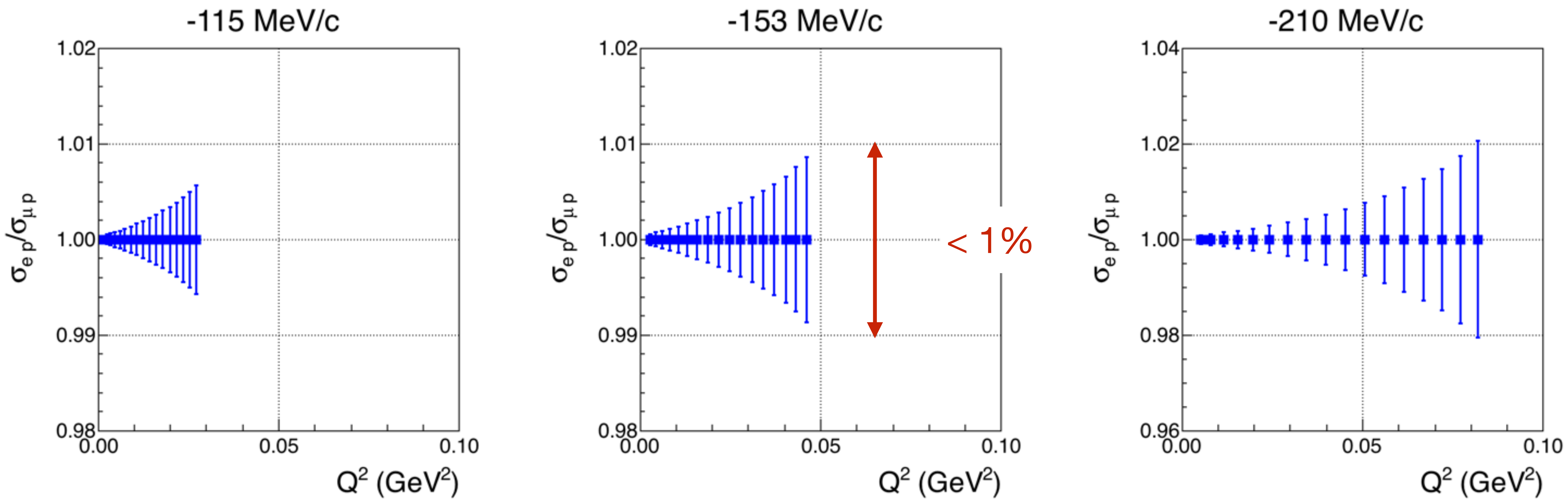
How different are the e/μ radii?
(truncation error largely cancels)
MUSE sensitivity to differences in extracted e/μ radii:

$\sigma(r_e - r_\mu) \approx 0.005$ fm

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

MUSE directly compares μp to ep cross sections

Projected relative statistical uncertainties in the ratio of μp to ep elastic **cross sections**.
Systematics ≈ 0.5%.



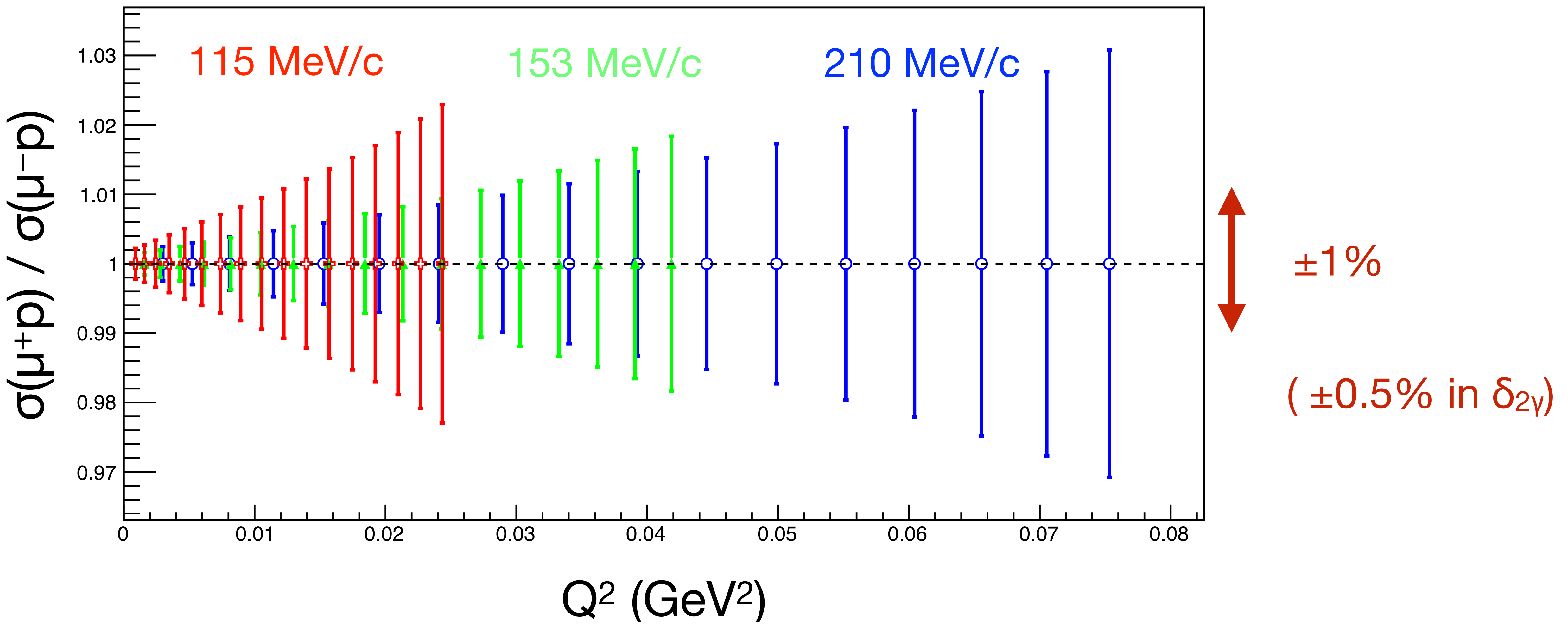
The relative statistical uncertainties in the **form factors** are half as large.

The MUon Scattering Experiment at PSI (MUSE), MUSE Technical Design Report, arXiv:1709.09753 [physics.ins-det].

MUSE allows to study two-photon exchange

Projected relative uncertainty in the ratio of μ^+p to μ^-p elastic cross sections.
Systematics: 0.2% in the cross section ratio.

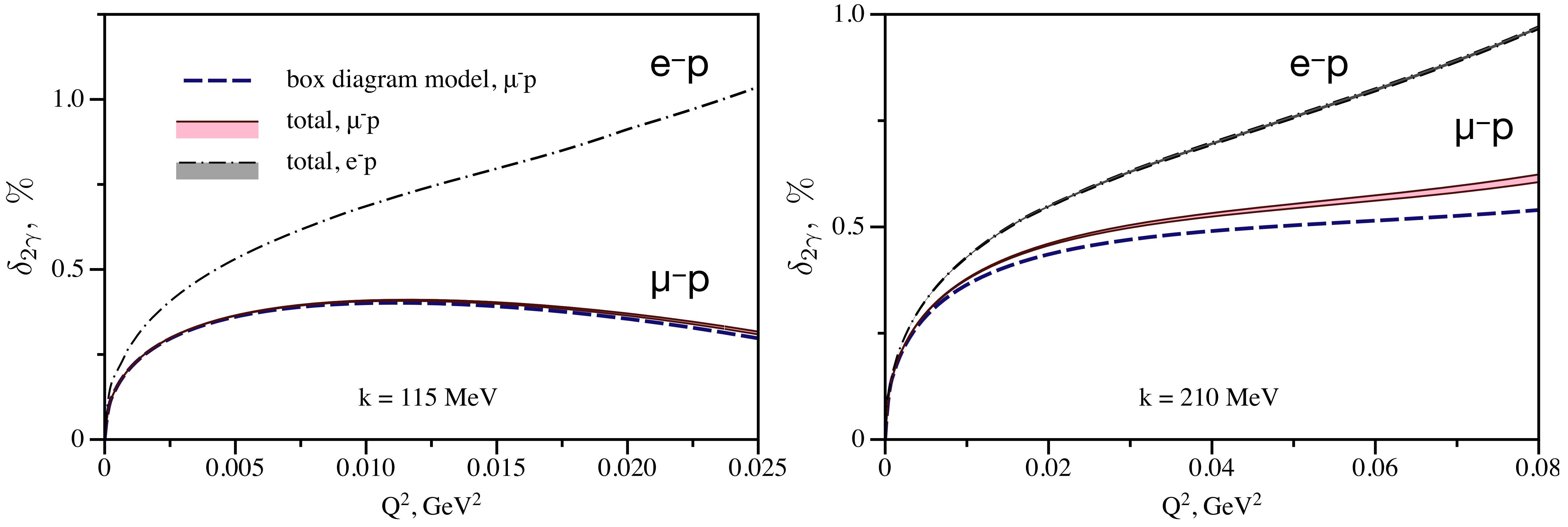
The MUon Scattering Experiment at PSI (MUSE), MUSE Technical Design Report, arXiv:1709.09753 [physics.ins-det].



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

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

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



Prediction: Due to the cancellation of the helicity-flip and non-flip contributions, TPE in μp smaller than in ep.

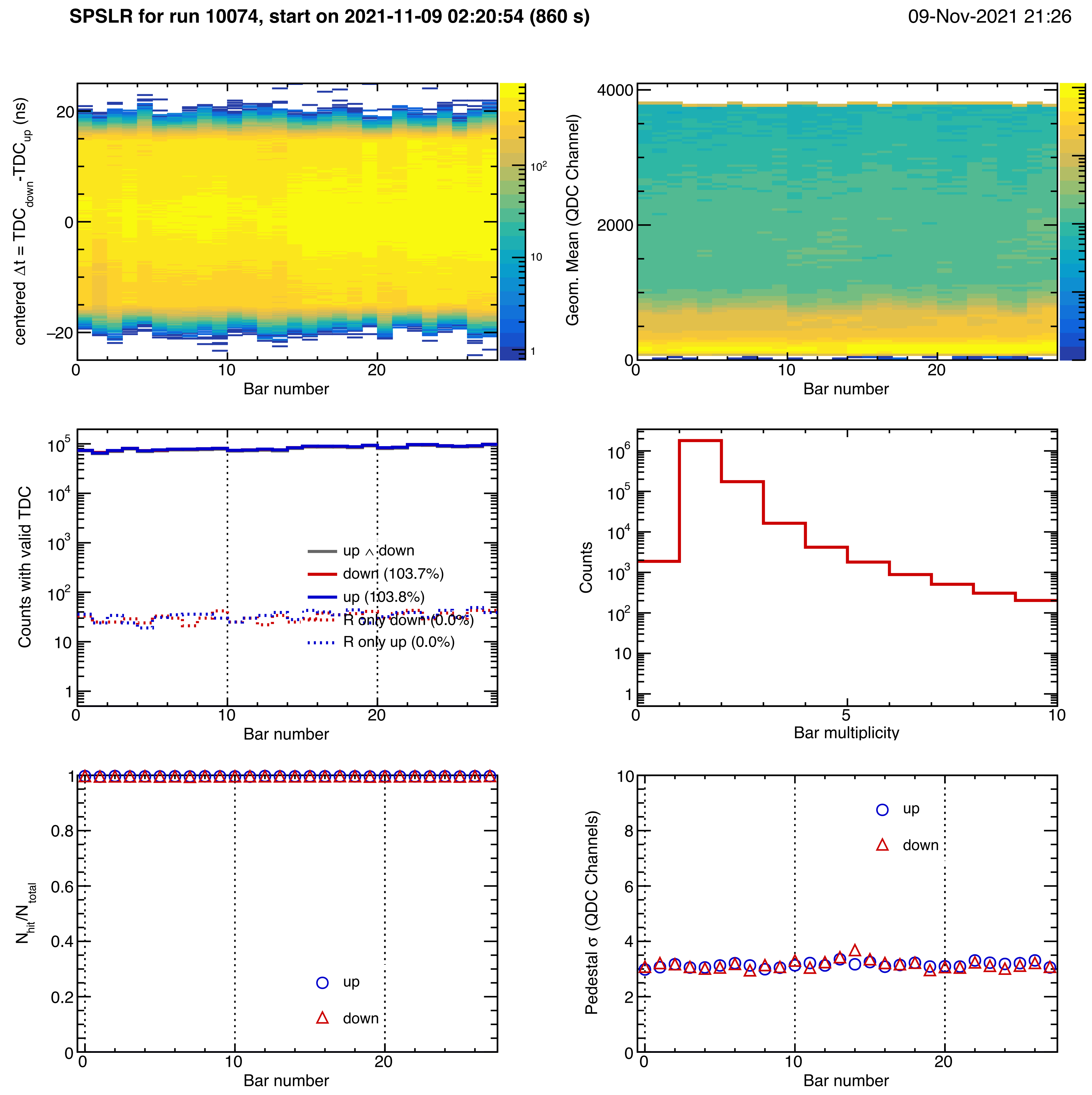
Oleksandr Tomalak, Few-Body Systems, **59**, 87 (2018)

Summary

MUSE will measure $\mu^{\pm}p$ **and** $e^{\pm}p$ simultaneously in an elastic scattering experiment.

- Each of the four sets of data will allow the extraction of the proton charge radius
- The data will allow for a direct μ/e comparison of the cross-section
- With two polarities will enable the study of two-photon exchange effects

Fall 2021 online monitoring:
Calibration run for SPS detector



Beamtime

- We are completing detector commissioning and will begin production running in Fall 2021
- Planning for further production running in 2022 - 2023