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

1. Motivation for a muon scattering experiment
2. Components of the MUSE experiment
3. Projected results

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NuFact2018, 20th workshop on neutrinos from accelerators
Virginia Tech, Blacksburg, August 13-18, 2018

Slope of proton form factor reveals radius

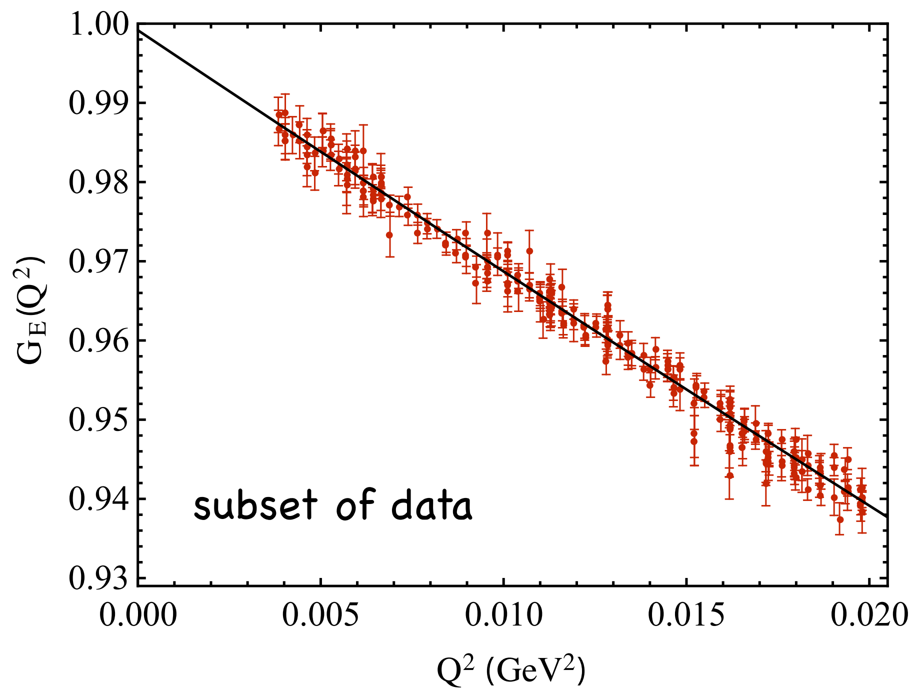
Cross section for ep scattering (one photon exchange)

$$\left(\frac{d\sigma}{d\Omega}\right) = \left(\frac{d\sigma}{d\Omega}\right)_{\text{Mott}} \frac{\tau}{\epsilon(1+\tau)} \underbrace{\left[G_M^2 + \frac{\epsilon}{\tau} G_E^2\right]}_{\text{reduced cross section}}$$

Definition of proton charge radius

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

(r_p is not related to integral over proton charge density) [G. Miller]



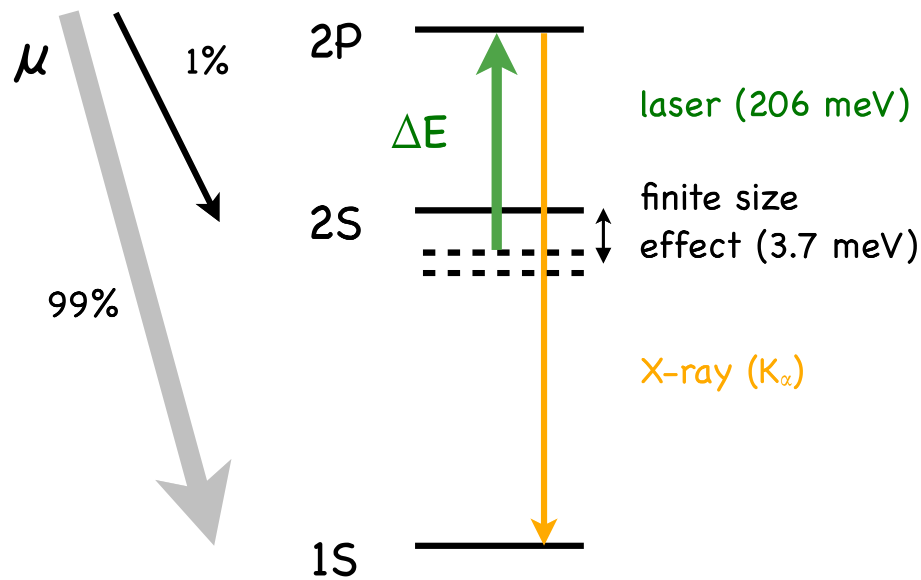
J. Bernauer et al., PRL 105, 242001 (2010),
J. Bernauer et al., PRC 93, 065207 (2016).

Determine r_p from the slope of $G_E(Q^2)$ at $Q^2 \to 0$.
Higher order terms come in early.

r_p = 0.879(8) fm (MAMI)

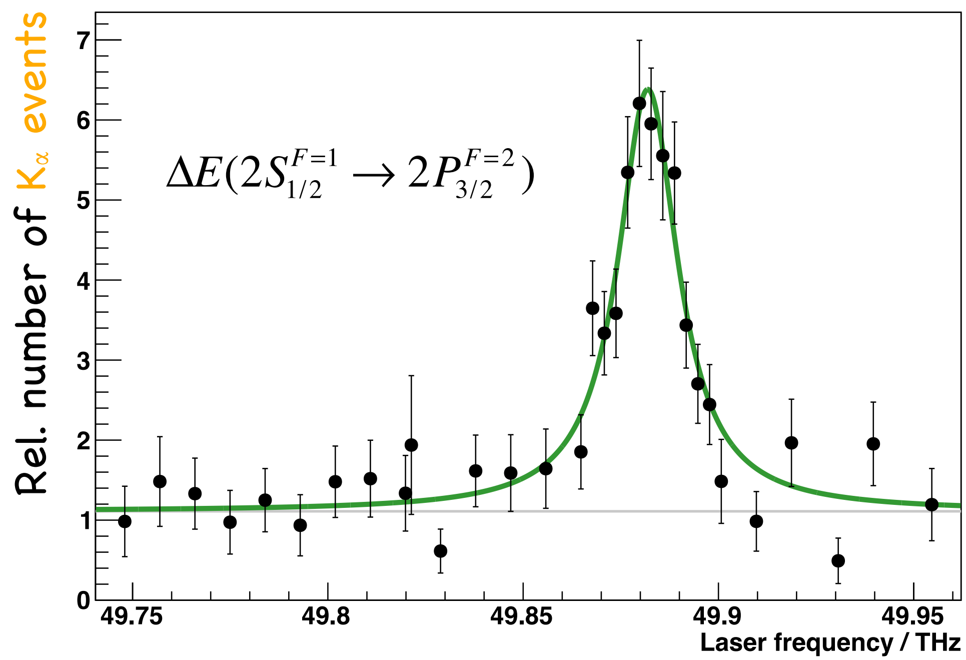
Spectroscopy of muonic hydrogen

μ beam stopped in H_2 gas



muonic hydrogen

2S-2P resonance curve



Lamb shift

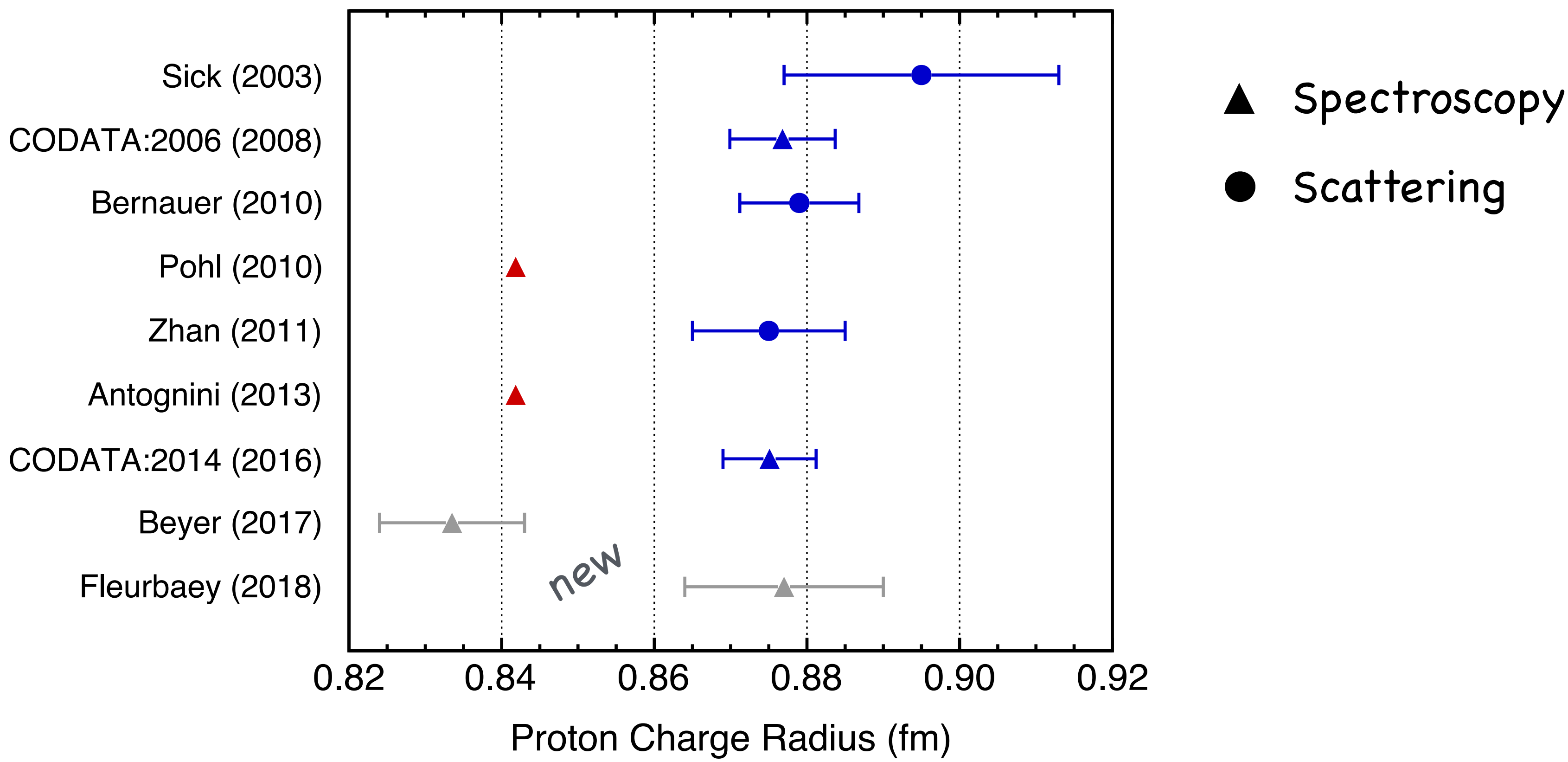
$$\boxed{\Delta E = 209.9779(49) - 5.2262 r_p^2 + 0.0347 r_p^3 \text{ meV}}$$

r_p = 0.84087(39) fm

Determine r_p from spectroscopic data and QED calculations

R. Pohl et al., Nature **466**, 213 (2010), A. Antognini et al., Science **339**, 417 (2013); Fig. adapted from Pohl, Miller, Gilman, Pachucki, arXiv:1301.0950v1

The proton radius puzzle: Muonic and electronic measurements give different proton radii



The discrepancy between muonic and previous electronic measurements of the proton charge radius is a **5.6σ effect (?).**

New atomic hydrogen spectroscopy data inconclusive.

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); X. Zhan et al., PLB 705, 59 (2011); P.J. Mohr et al., Rev. Mod. Phys. 84, 1527 (2012); A. Antognini et al., Science 339, 417 (2013; A. Beyer, et al, Science 358 (2017) 79-85; H. Fleurbaey, et al., Phys. Rev. Lett. 120, 183001.

"This discrepancy has triggered a lively discussion..." Aldo Antognini et al., Science **339**, 417 (2013)

Possible explanations of the proton-radius puzzle

- Beyond Standard Model Physics:
  Violation of μ - e universality
- Novel Hadronic Physics:
  Strong-interaction effect entering in a loop diagram is important for μp but not for ep; e.g. proton polarizability (effect $\propto m_l^4$), off-shell corrections, two-photon proton-structure corrections.
- Electron scattering & atomic hydrogen data and radius extraction not as accurate as previously reported.

New experiments are planned or underway to address the issue

R. Pohl, R. Gilman, G.A. Miller, K. Pachucki, "Muonic hydrogen and the proton radius puzzle", arXiv:1301.0905 (2013).
G.A. Miller, Phys. Lett. B 718, 1078 (2013), G.A. Miller, A.W. Thomas, J.D. Carroll, J. Rafelski Phys. Rev. A **84**, 020101 (2011). C.E. Carlson, M. Vanderhaeghen, Phys. Rev. A **84**, 020102 (2011).

Important data to address the proton radius puzzle are missing ...

- Conflicting new atomic hydrogen spectroscopy data

  Beyer et al., Science **358**, 79 (2017), Fleurbaey et al,, PRL **120**, 183001 (2018)
- Conflicting results from various fits of electron scattering data

- Recent analysis of spectroscopy data gives 3.5σ <u>difference</u> between atomic and muonic D

  Pohl et al. arXiv:1607.03165v2 [atom-ph] Metrologia 54

r_p (fm)	ep	μp
spectroscopy	0.876(8)	0.8409(4)
scattering	0.877(6)	**?**

Ref.: CODATA2010 for H and D spectroscopy, Antognini et al. (2013) for muonic atom, average of Bernauer et al. (2010) and Zahn et al. (2011) for electron scattering.

- New and ongoing scattering experiments
  - Proton radius (PRad) experiment at JLab Hall B
  - Initial State Radiation (ISR) experiment at MAMI

- MUon Scattering Experiment (MUSE) at PSI

  MUSE Technical Design Report, arXiv:1709.09753 [physics.ins-det].

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 GeV^2,
- with μ^+,μ^- and e^+,e^- to study possible **2γ mechanisms**,
- with μp and ep to have direct ***μ/e* comparison**

MUSE

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

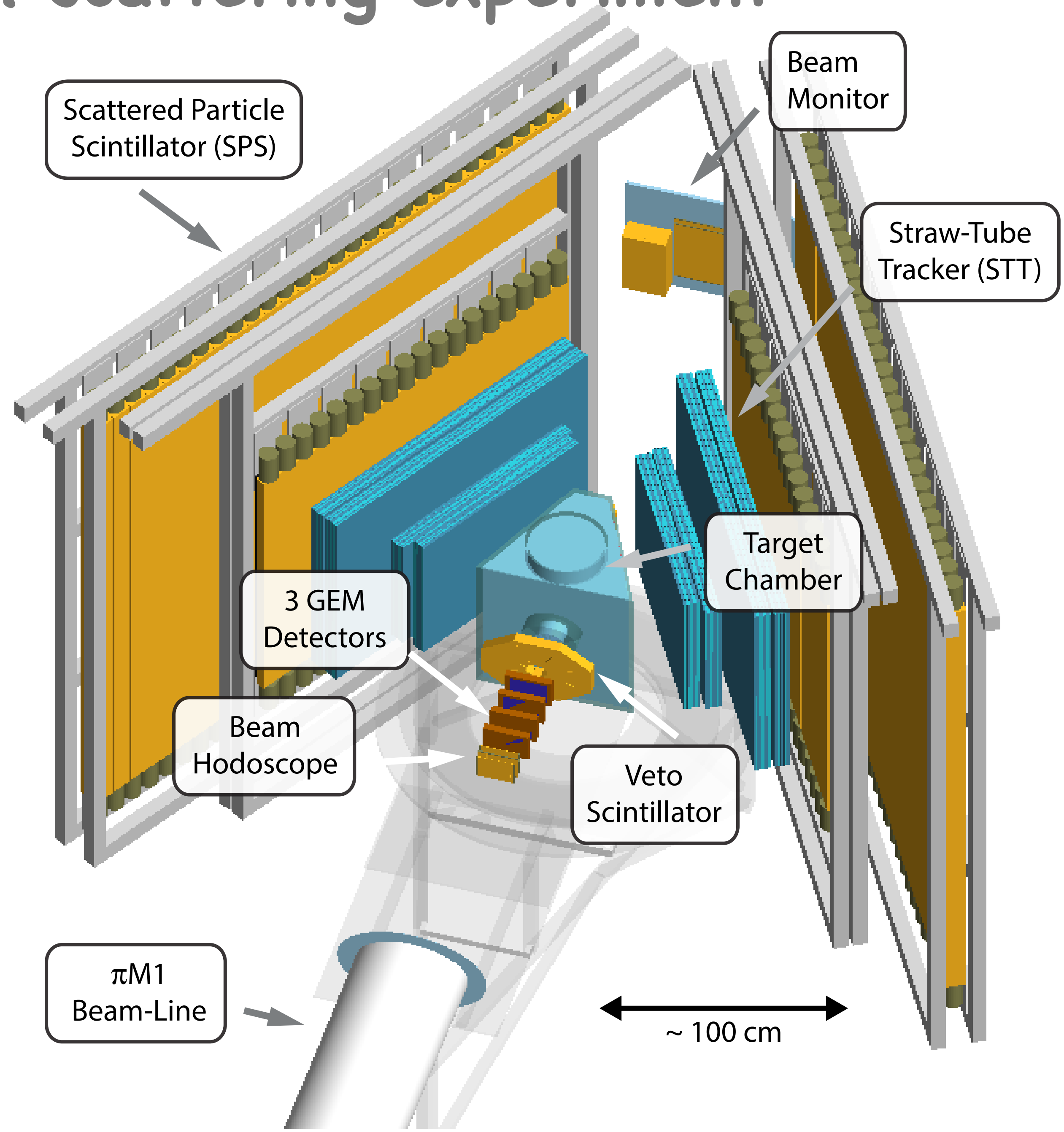
The MUon Scattering Experiment at PSI (MUSE), MUSE Technical Design Report, arXiv:1709.09753 [physics.ins-det].

MUSE is an unusual scattering experiment

Measure $e^{\pm}$ and $\mu^{\pm}$ elastic scattering off a liquid hydrogen target.

Challenges

- Secondary beam: identifying and tracking beam particles to target,
- Low beam flux: large angle, non-magnetic spectrometer,
- Background: e.g., Møller scattering and muon decay in flight.

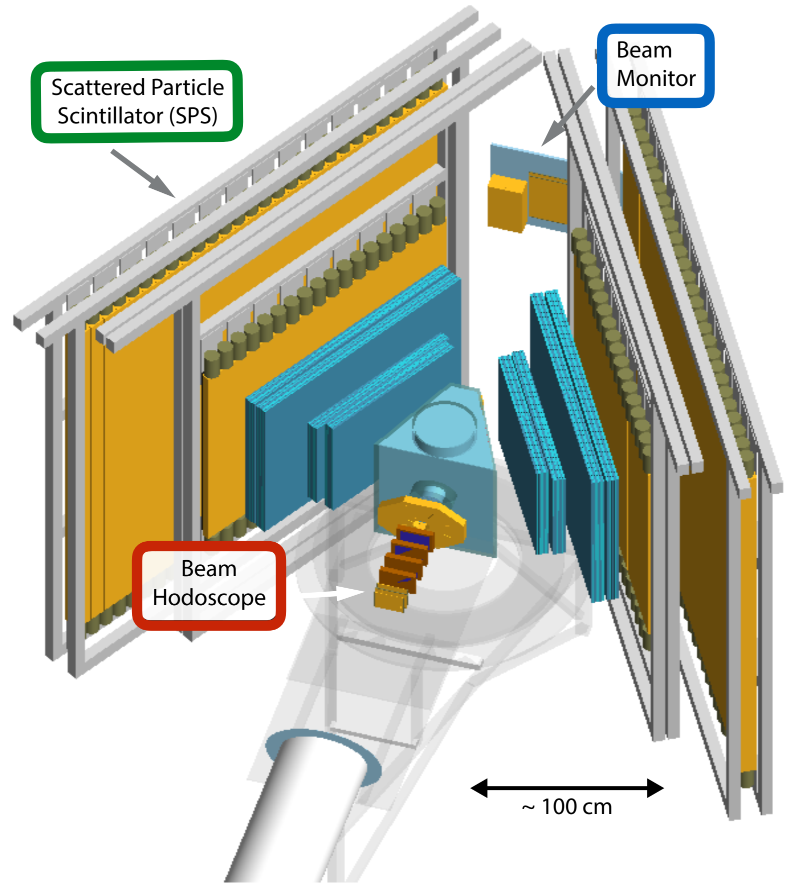


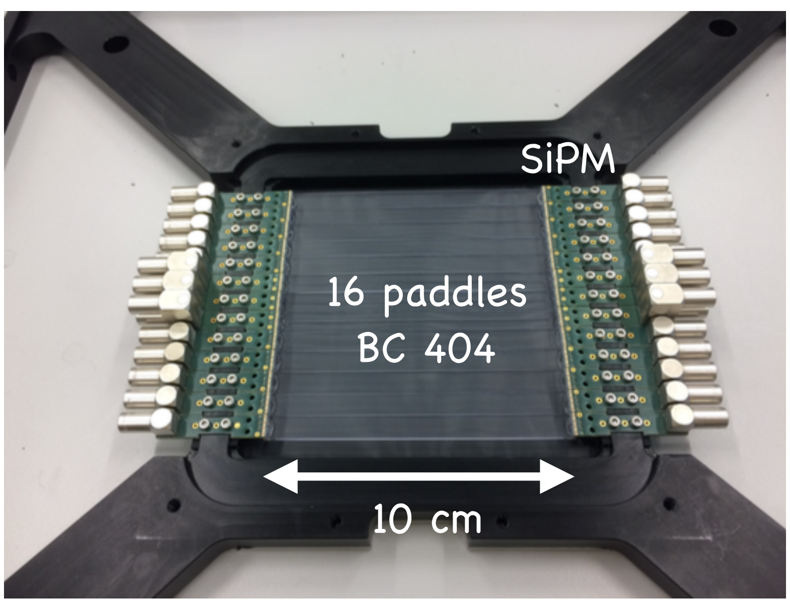
The MUon Scattering Experiment at PSI (MUSE), MUSE Technical Design Report, arXiv:1709.09753 [physics.ins-det].

Beam Hodoscope (TAU, Rutgers, PSI)

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.



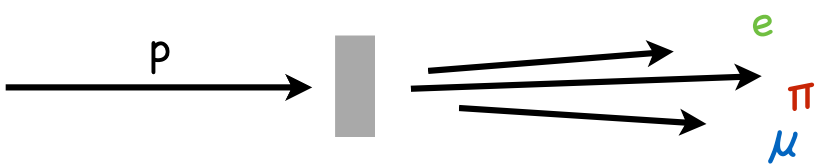


- Two to four planes for beam hodoscope
- Achieved 80 ps time resolution and 99.8% efficiency.

Beam-particle identification with beam hodoscope

PSI πM1 beam line

primary proton beam secondary beam

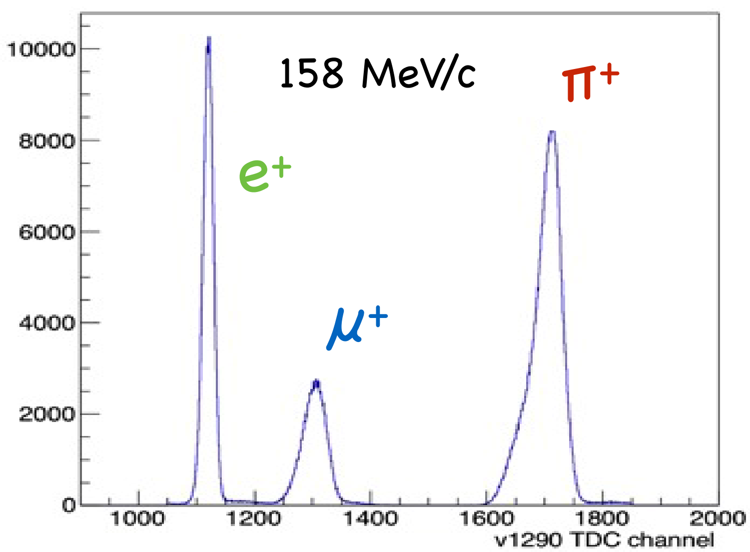


50 MHz RF (20 ns bunch separation)

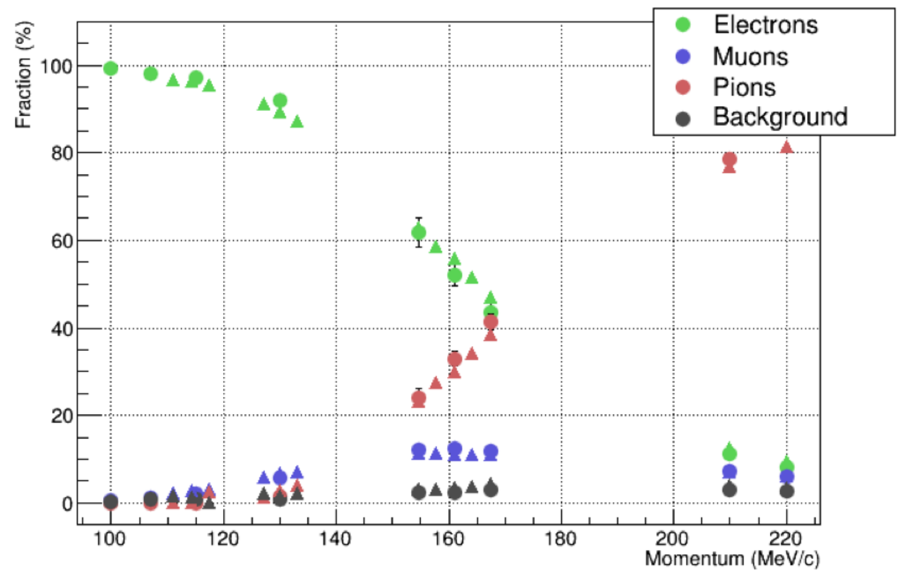
Flux ≈ 3.3 MHz

e, μ, π beams with large emittance

p = 119, 165, 210 MeV/c

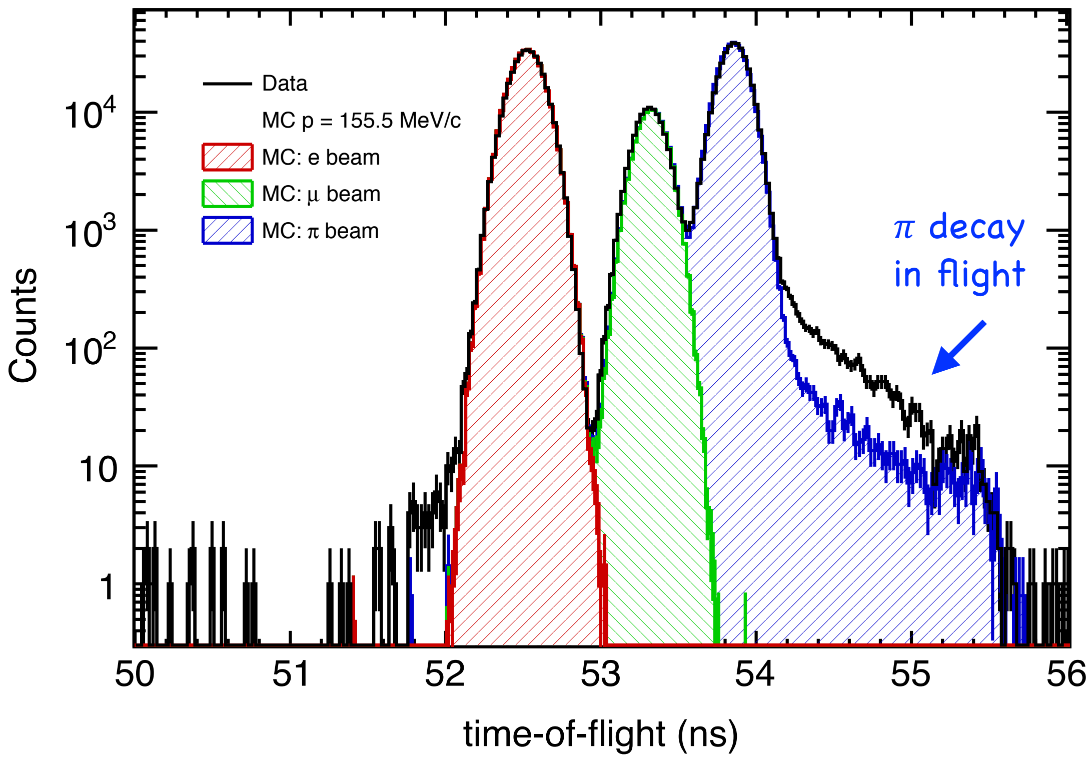


Beam hodoscope determines time of flight for particle ID



Positive polarity particle fractions determined in June 2013 beam test (K. Mesick)

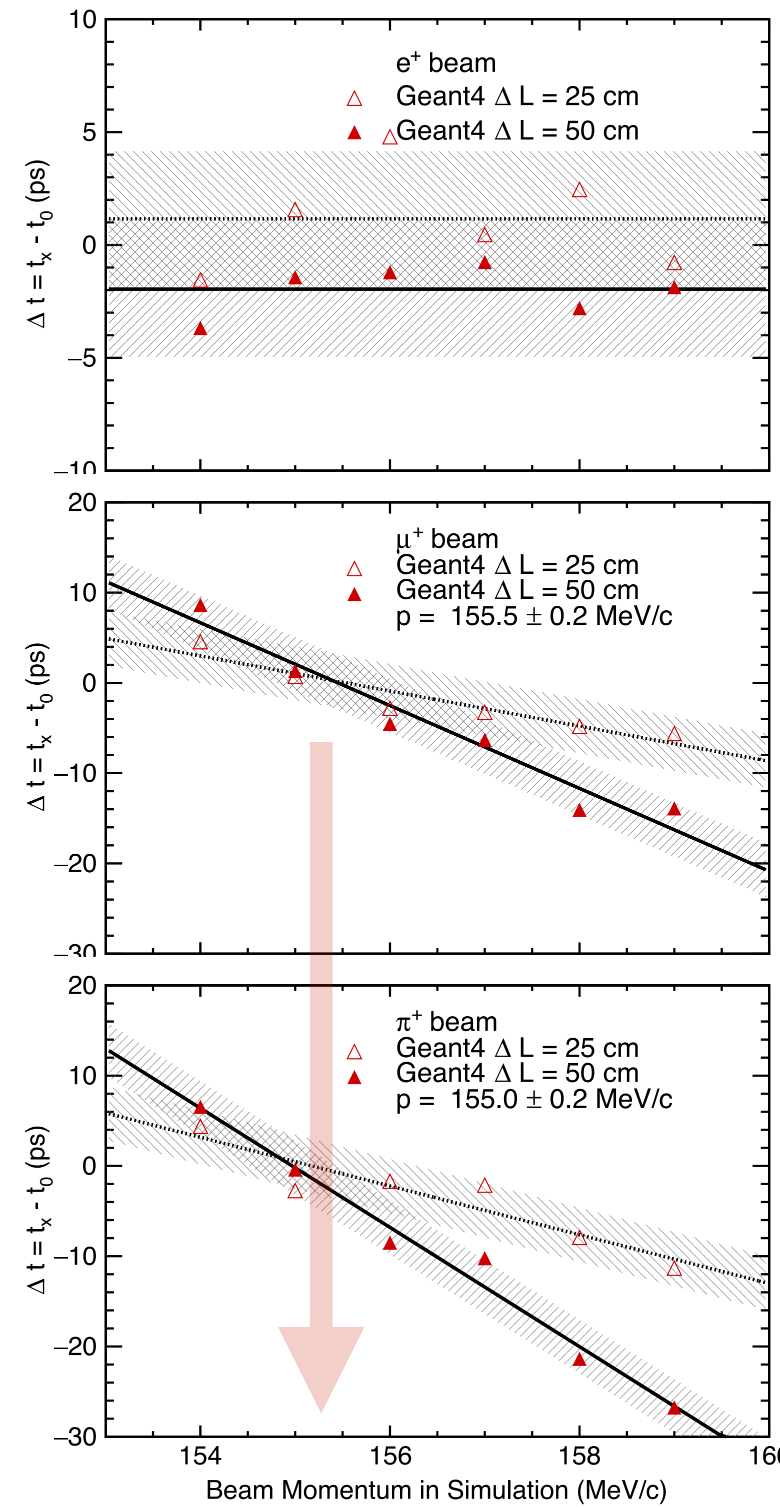
Consistent beam momenta were extracted from muon and pion time-of-flight data



Good agreement between simulation and data, no evidence of beam tail from collimation.

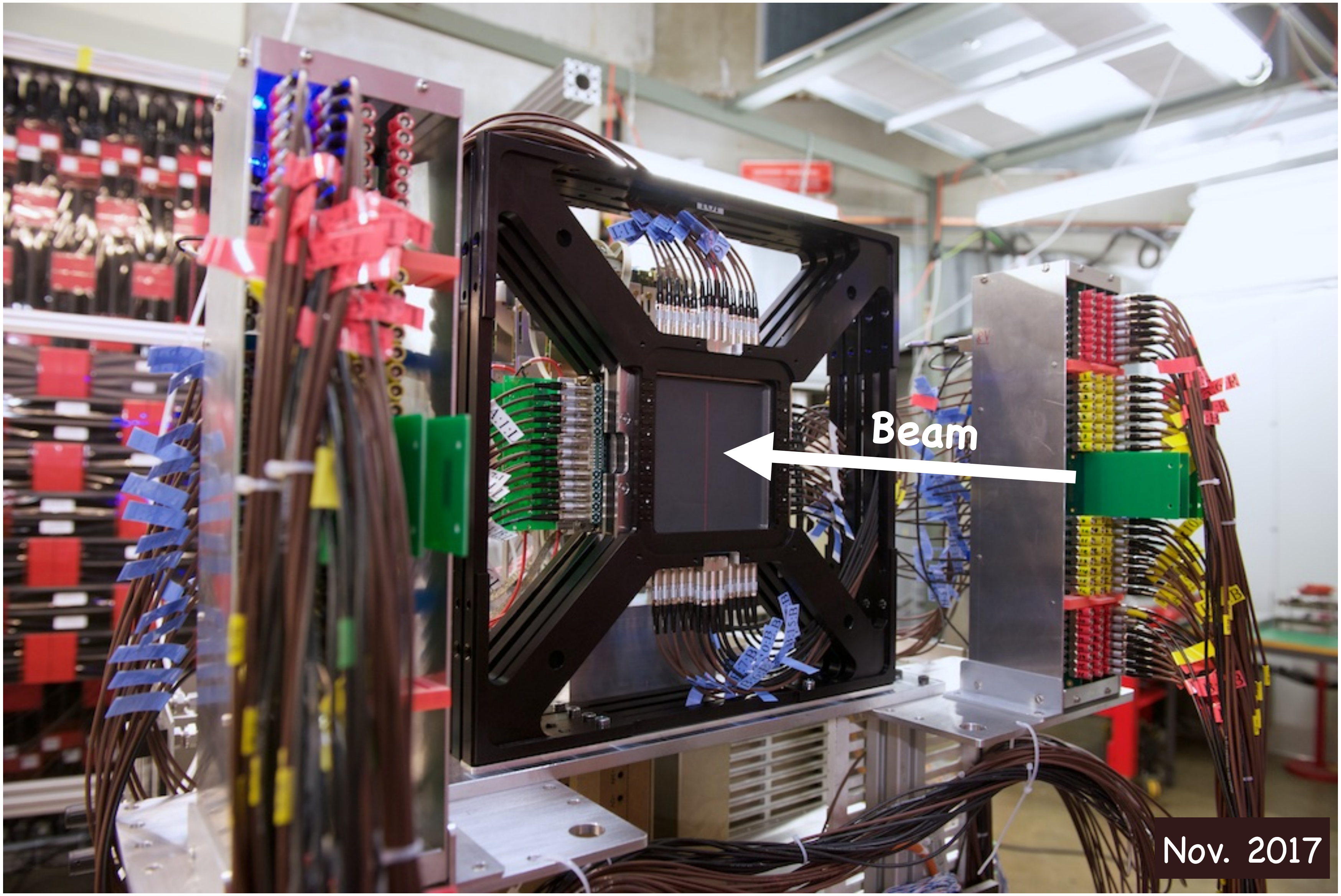
$$p(\pi) \approx p(\mu), \quad \text{with} \quad dp\,/\,p < 0.3\%$$

Preliminary results meet specifications.

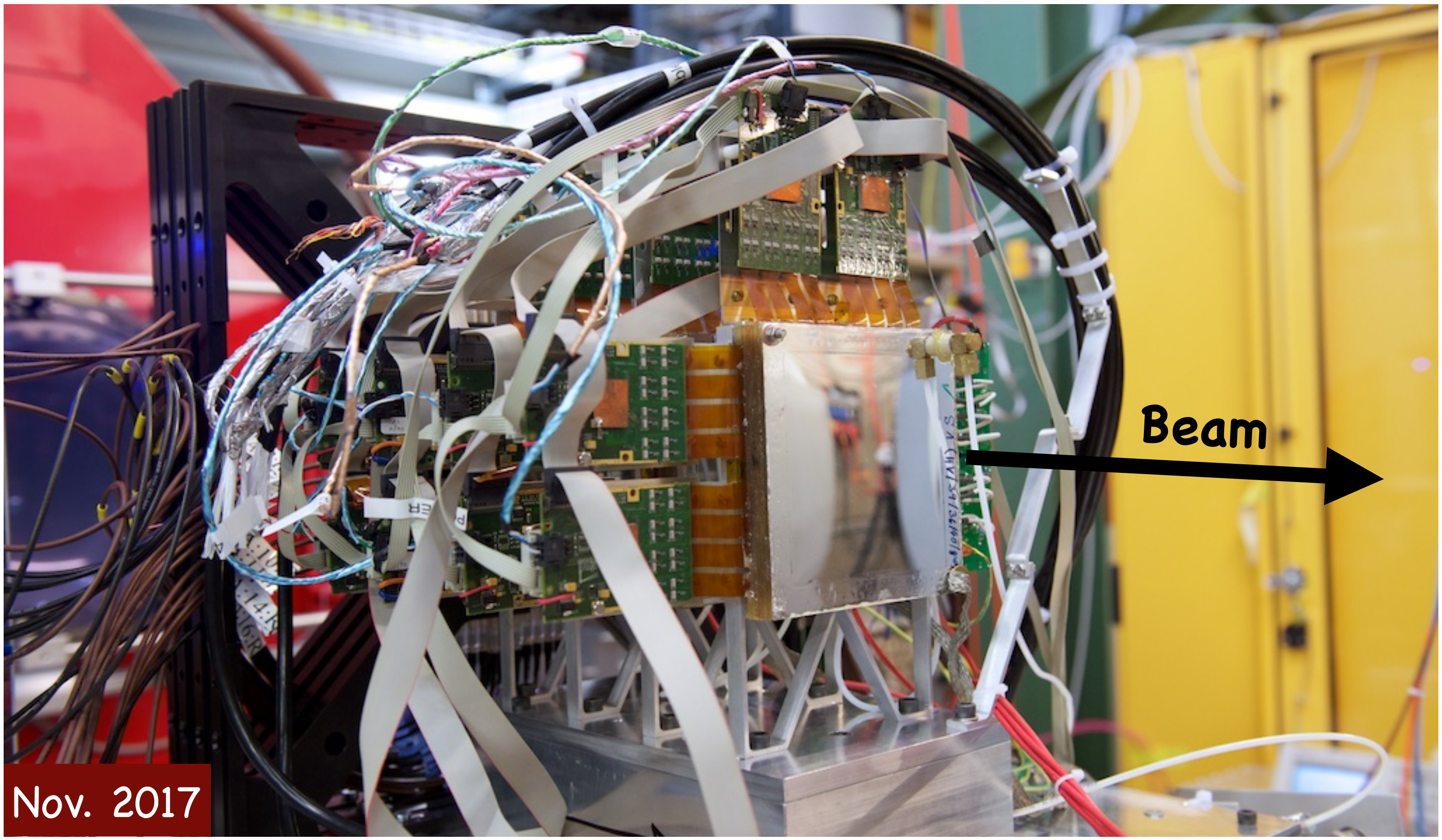


2015 test measurement

Beam Hodoscope mounted at PSI



GEM Detectors as incident-particle tracker (Hampton Univ.)

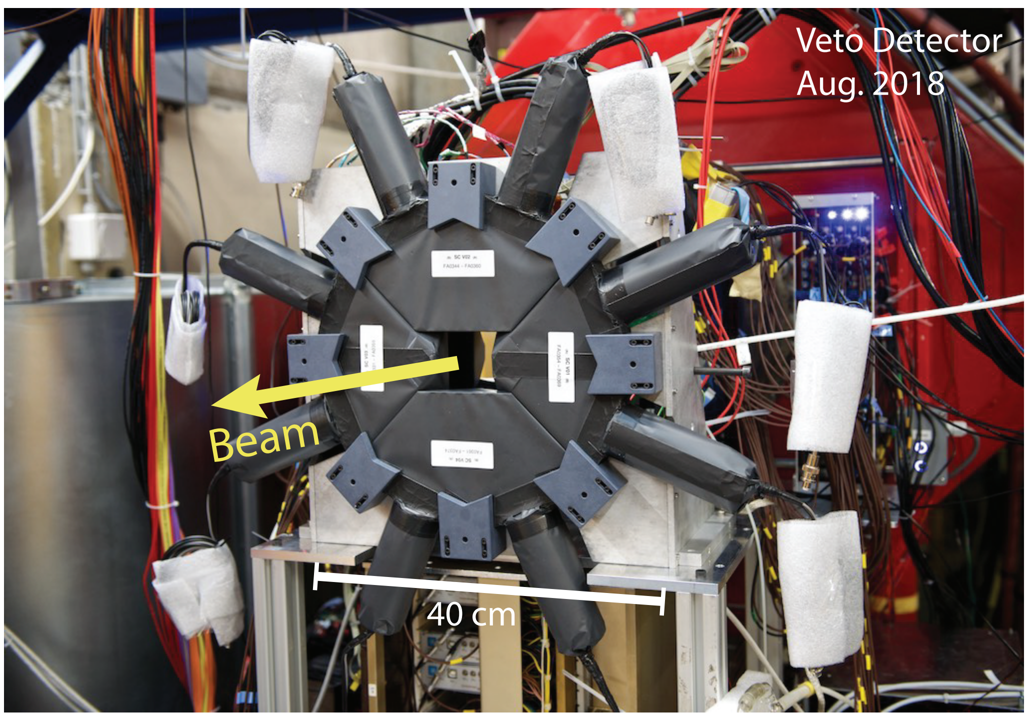


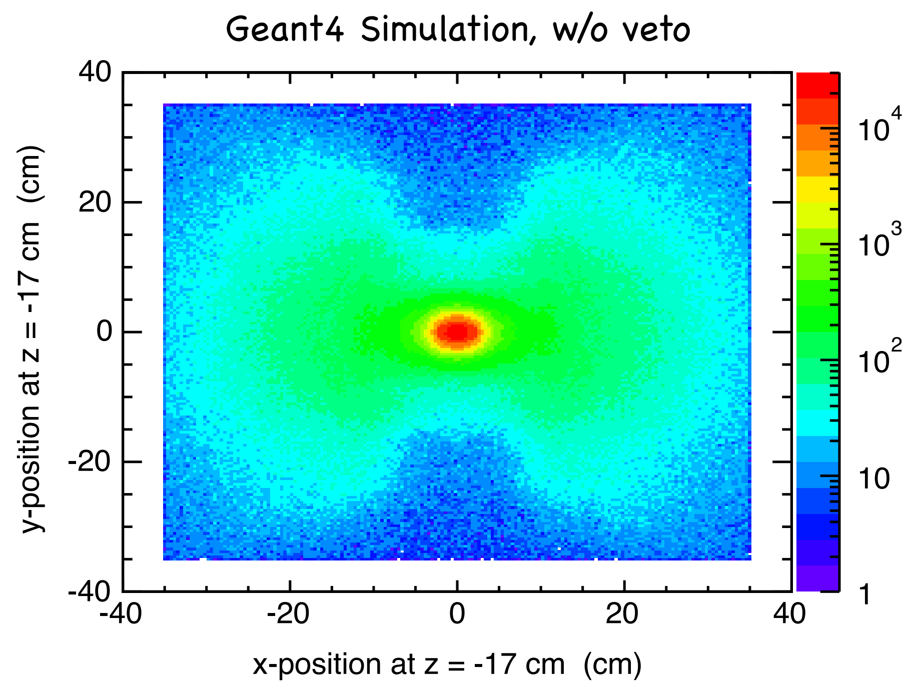
- Set of three 10 cm x 10 cm GEM detectors built for & run in OLYMPUS
- Measure trajectories into the target to reconstruct the scattering kinematics
- Achieved position resolution of 70 μm

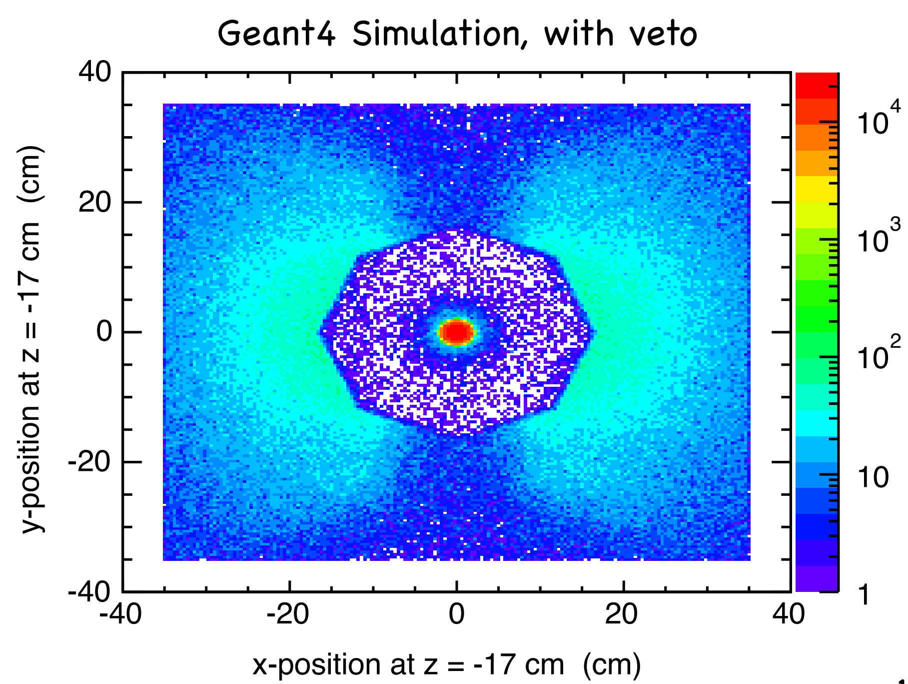
Veto detector (USC)

The veto detector expected to reduce trigger rate from background events

(Simulation of veto prototype with slightly different geometry.)

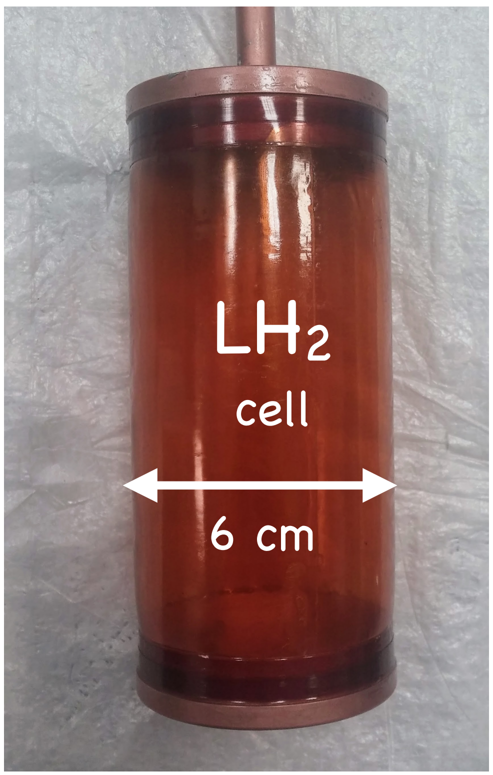






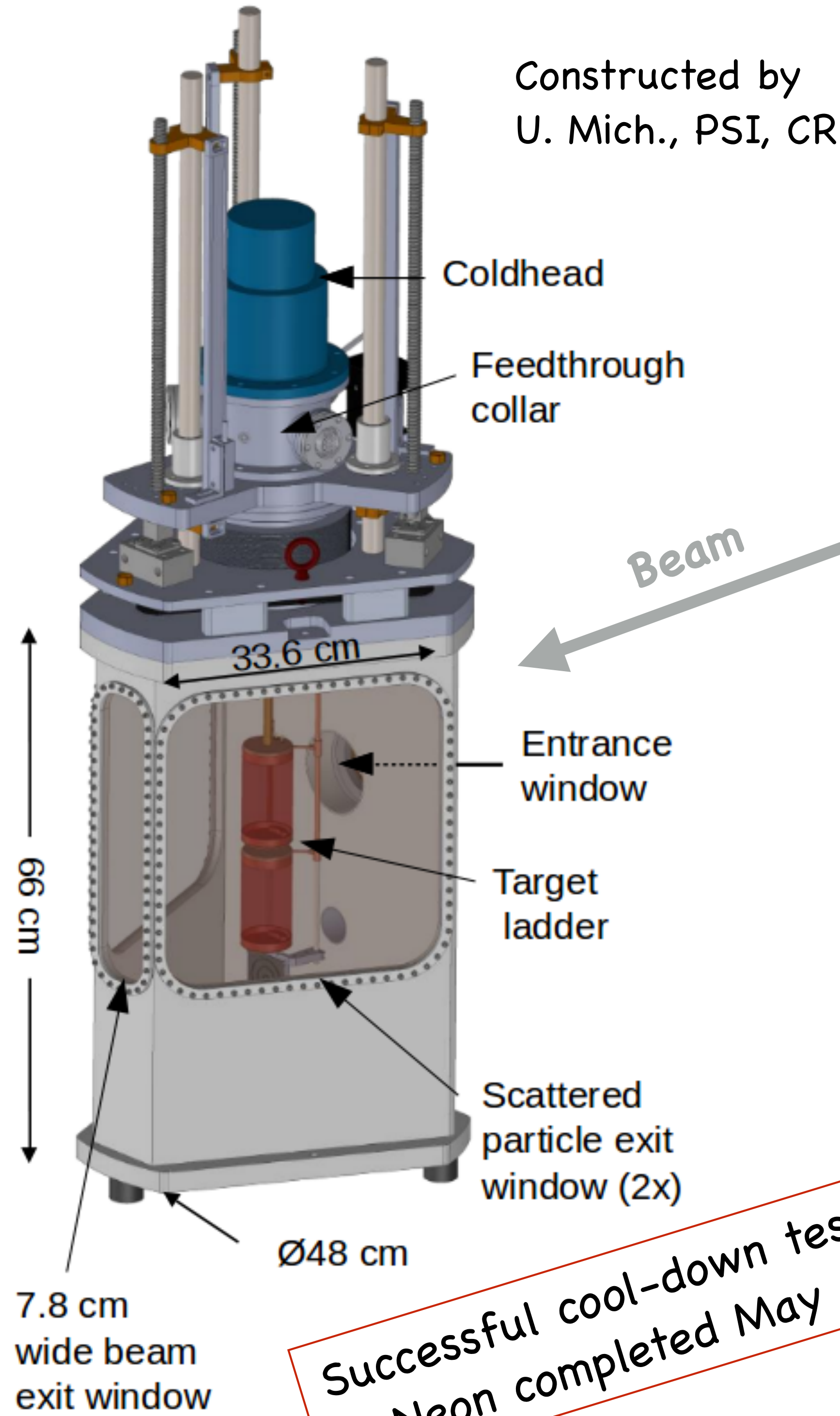
Target and Scattering Chamber (U. of Mich.)

Target ladder with
LH_2, dummy, carbon, and empty targets



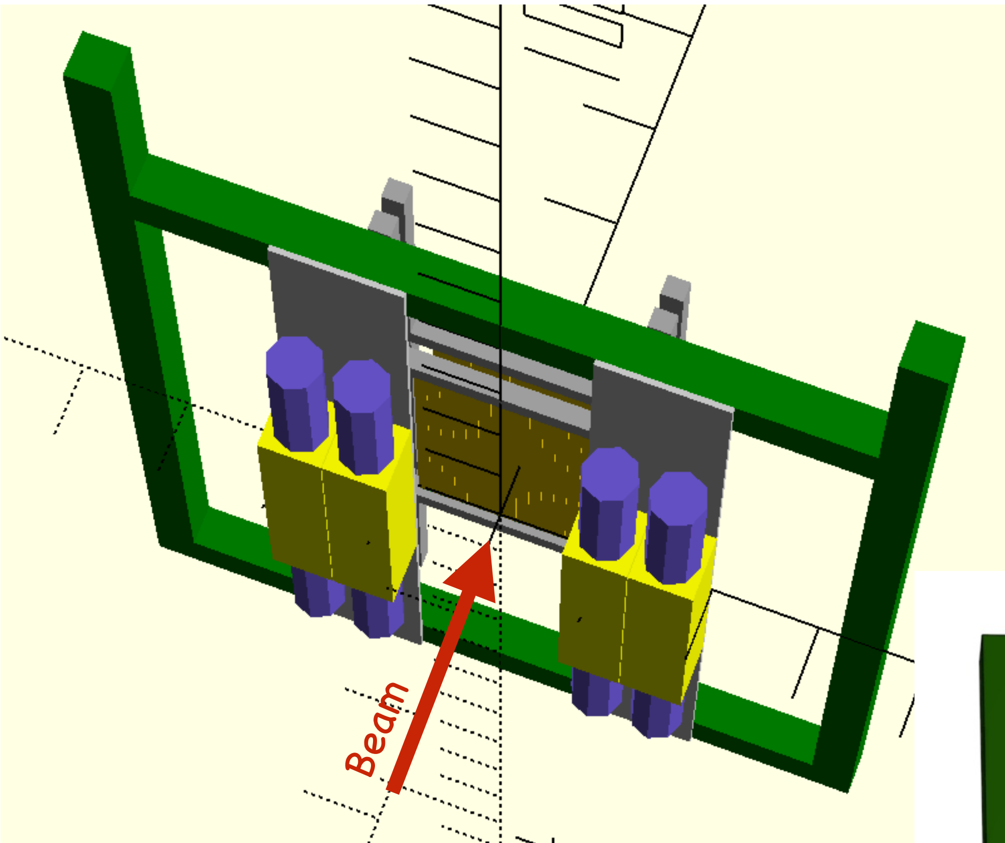
target cell prototype

Constructed by
U. Mich., PSI, CREARE

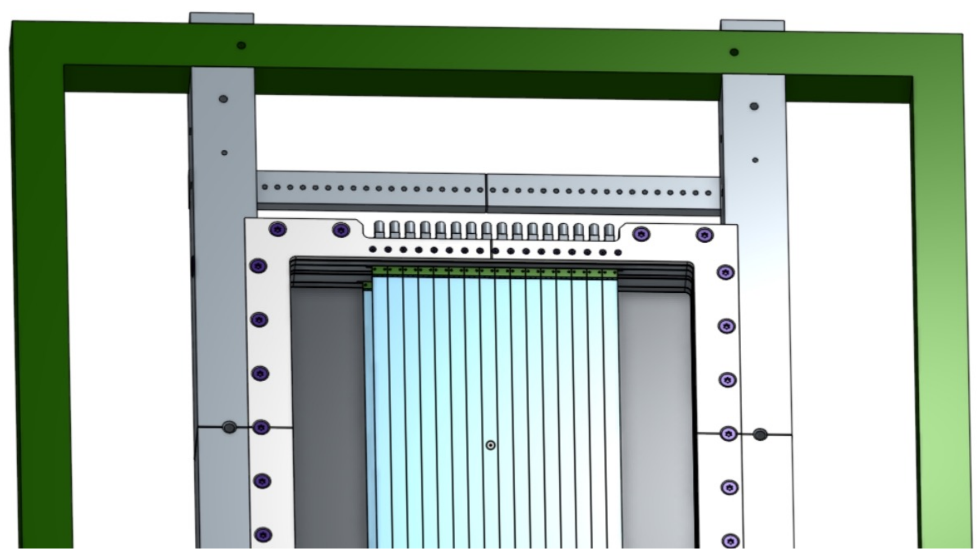


Successful cool-down test with
Neon completed May 2018

Beam Monitor (TAU, Rutgers, USC)



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



fast scintillators at the sides

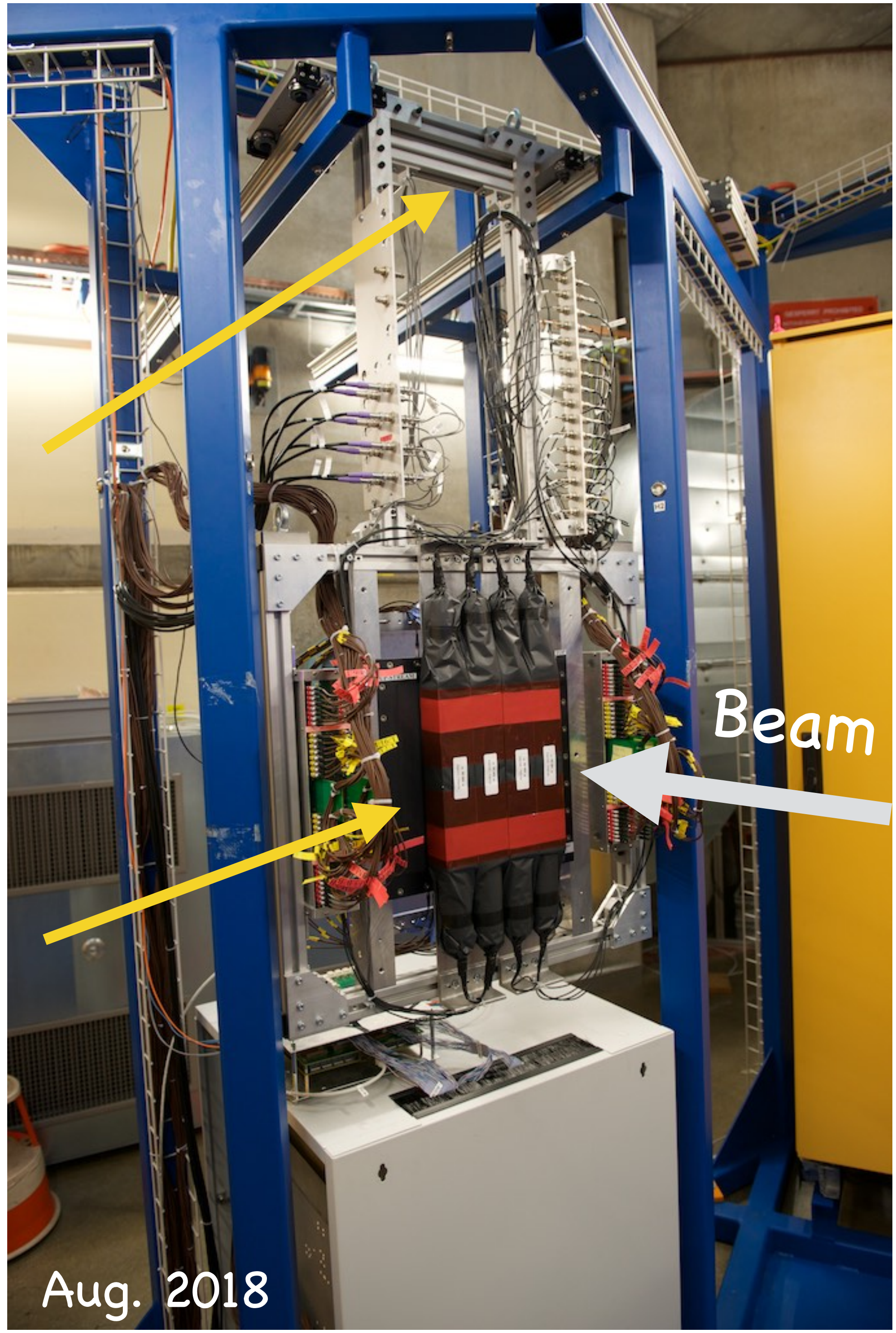
segmented in the center with scintillator paddles

Beam Monitor

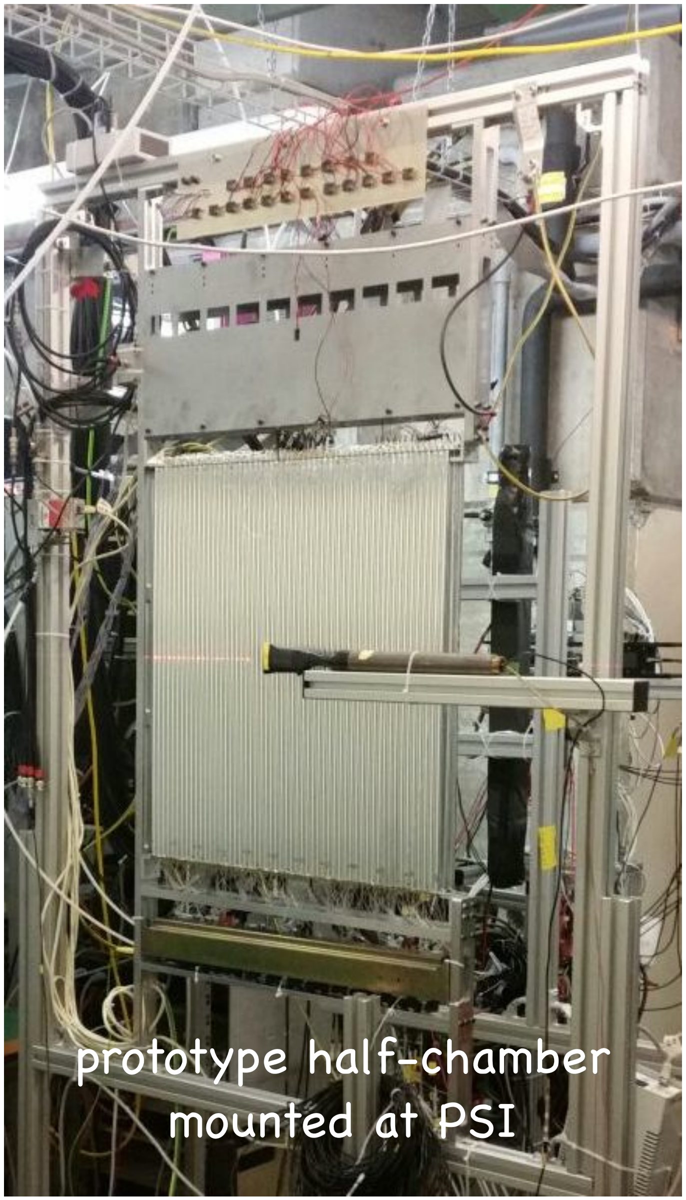
Carriages on rails allow for precise variation of beam-monitor position

100-cm travel

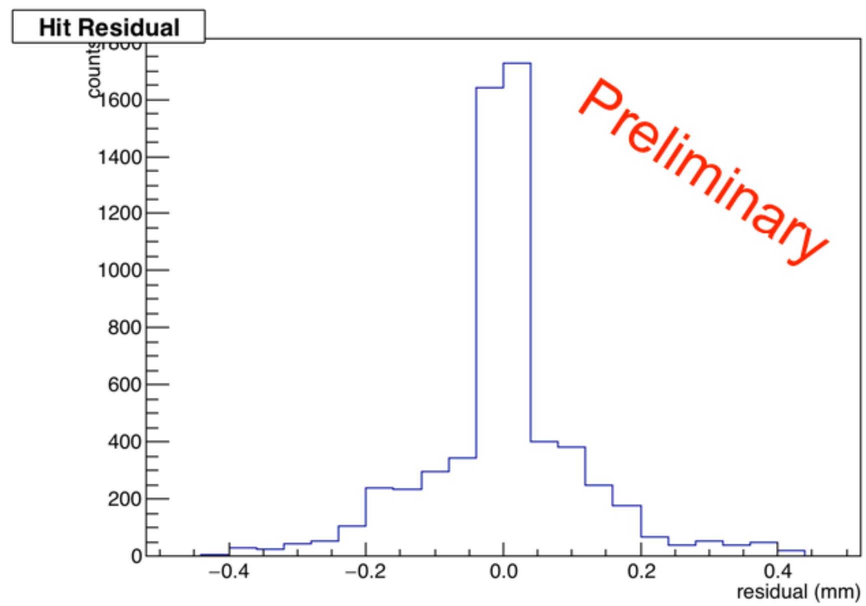
High-resolution scintillators moved into the beam for time-of-flight measurements



Straw-tube tracker (HUJI + Temple)



- The Straw Tube Tracker provides high-resolution and high-efficiency tracking of the scattered particles from the target.
- Two chambers with 5 vertical and 5 horizontal planes each (3000 straws total).
- Based on PANDA design.

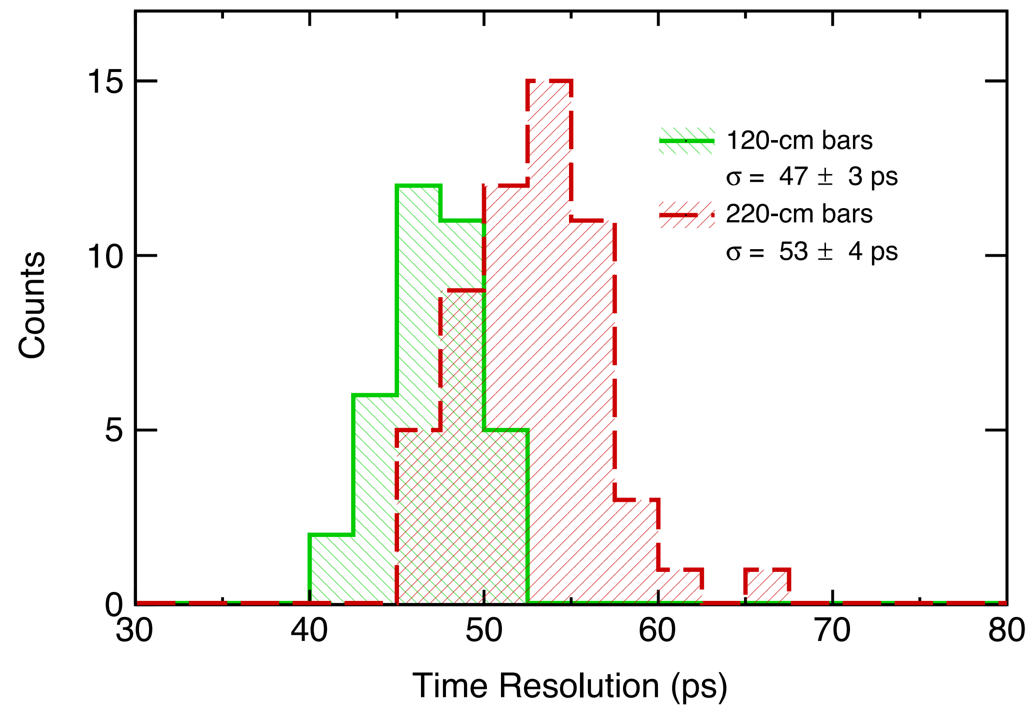


A preliminary analysis of the chamber resolution using a small calibration dataset shows a position resolution of approximately 115 μm.

Scattered-particle scintillators (USC)

SPS provides event trigger and particle 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)

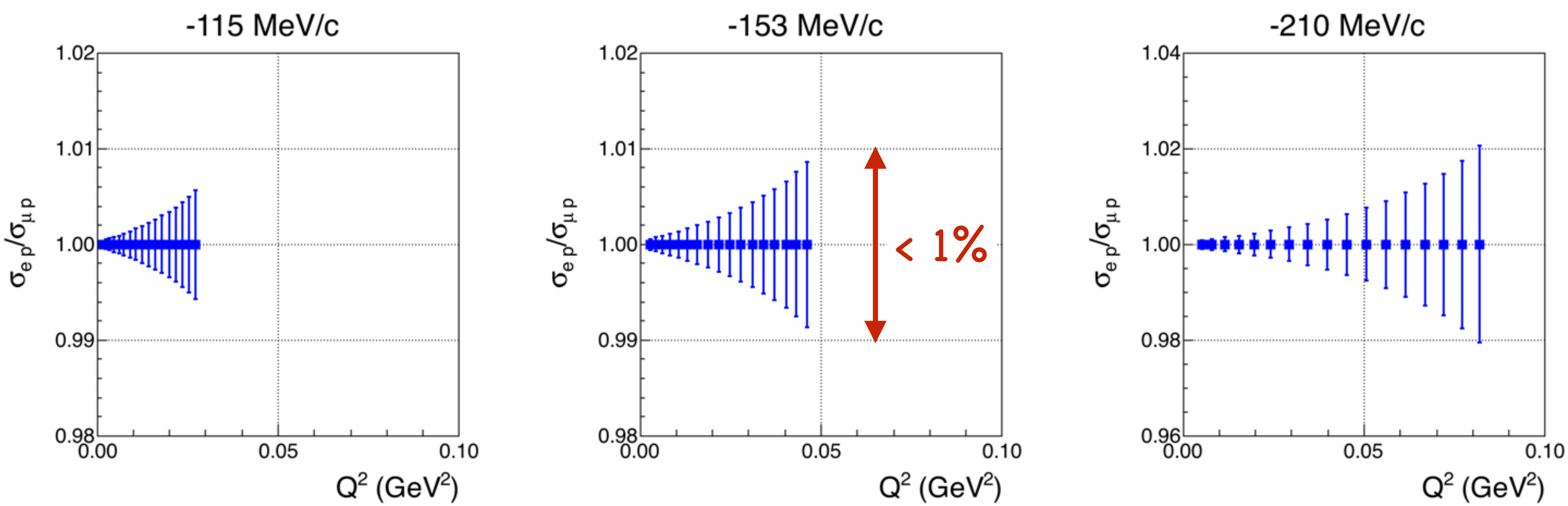


Scattered-particle scintillators exceed required time resolution:

σ(Front) < 50 ps, σ(Rear) < 60 ps

MUSE directly compares μp to ep cross sections

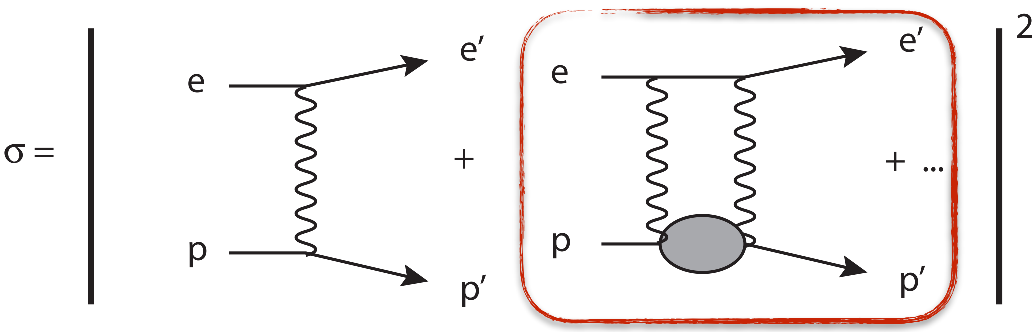
Projected relative statistical uncertainties in the ratio of μp to ep elastic **cross sections**. Systematics ≈ 0.5%.



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

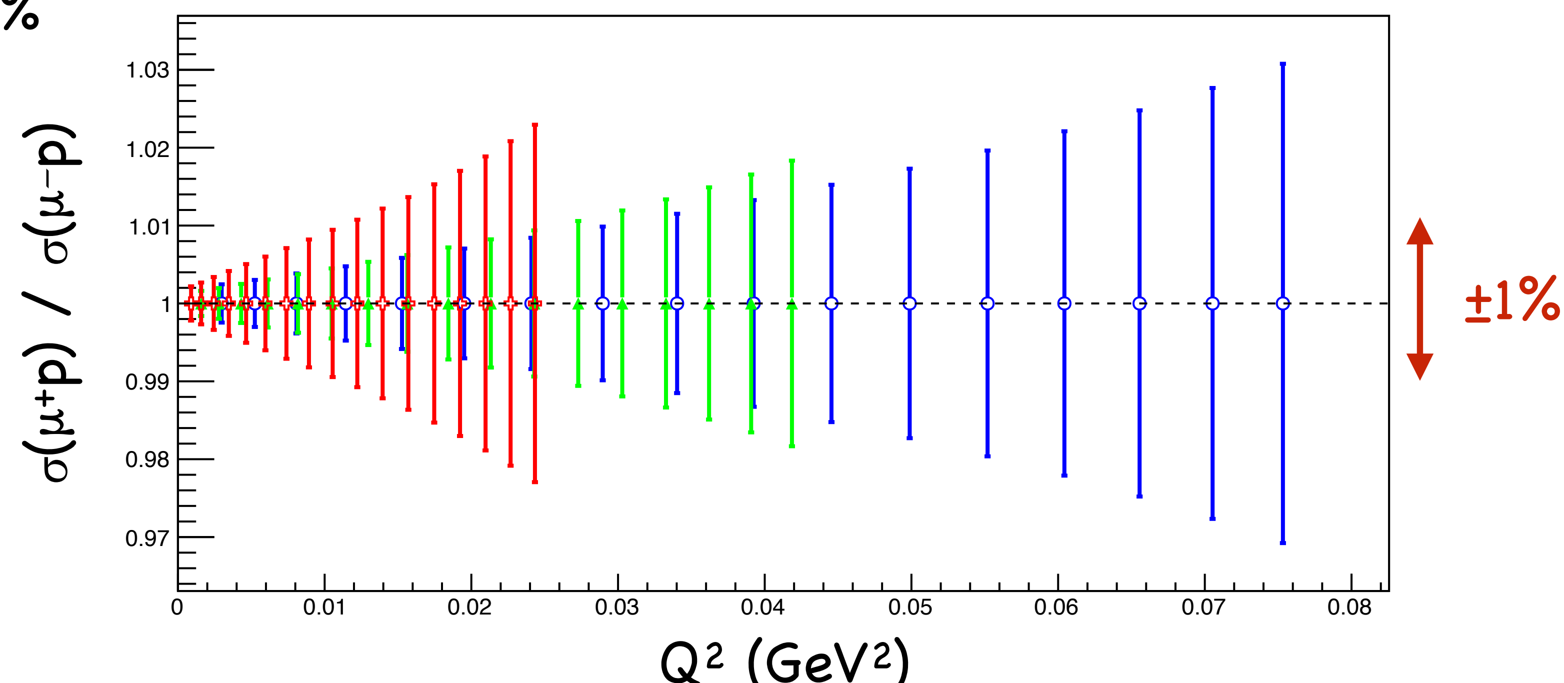


$$\sigma_{e^{\pm}p} = |\mathscr{M}_{1\gamma}|^2 \pm 2\Re\{\mathscr{M}^{\dagger}{}_{1\gamma}\mathscr{M}_{2\gamma}\} + \cdots$$

$$\frac{\sigma_{e^{+}p}}{\sigma_{e^{-}p}} = 1 + 4\frac{\Re\{\mathscr{M}^{\dagger}{}_{1\gamma}\mathscr{M}_{2\gamma}\}}{|\mathscr{M}_{1\gamma}|^2}$$

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

Systematics: 0.2%



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

Projected MUSE proton charge-radius results

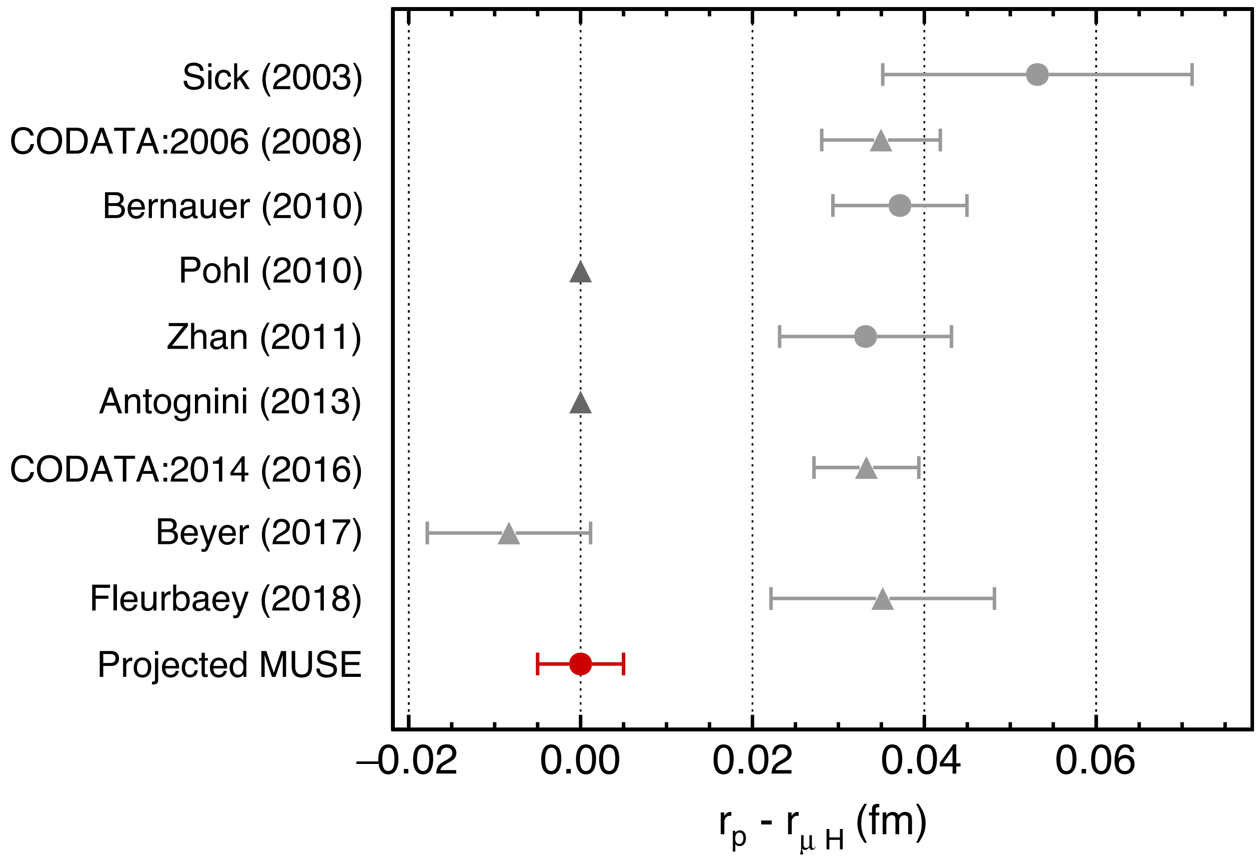
How different are the e/μ radii?
(truncation error largely cancels)
Sensitivity to differences in extracted e/μ radii:

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

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

Current discrepancy: $r_e - r_\mu \approx 0.034$ fm



Comparisons of, e.g., **e to *μ*** or of ***μ*⁺ to *μ*⁻** are insensitive to many of the systematics

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

Summary

- Proton radius puzzle: The discrepancy between muonic and electronic measurements of the proton radius is a 5.6σ effect.
- MUSE scattering experiments off the proton address the puzzle:
  - $\mu^{\pm}p$ and $e^{\pm}p$ scattering directly tests interesting possibilities:

    Are μp and ep interactions different? If so, does it arise from 2γ exchange effects ($\mu^+ \neq \mu^-$) or beyond the standard model physics ($\mu^+ \approx \mu^- \neq e^-$)?
  - Experiment setup and dress-rehearsal run ongoing at PSI.
  - Planning for production running in 2019-2020.