Elastic Electron and Muon Scattering Experiment Off the Proton at PSI

1. The proton-radius puzzle
2. The contribution of the **MUSE experiment** to a solution
3. Example simulation results addressing some challenges of the experiment

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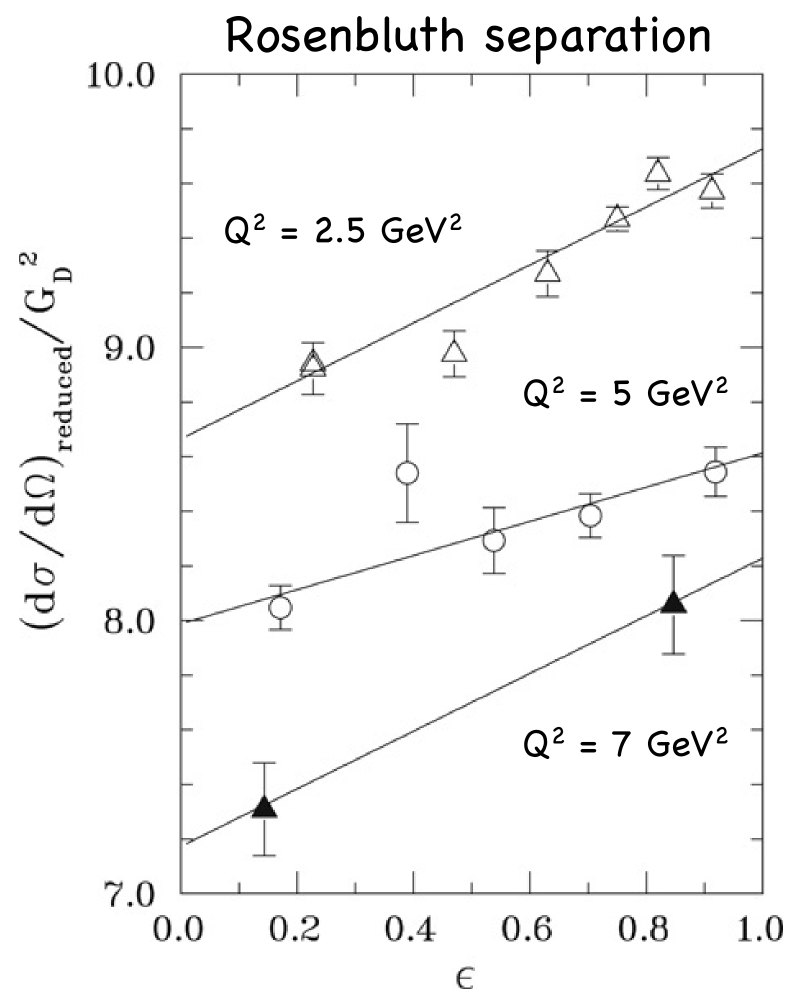
Supported in parts by the U.S. National Science Foundation: NSF PHY-1205782.

Particles and Nuclei International Conference (PANIC 14),
August 25-29, 2014, Hamburg, Germany

Nucleon form factors from ep cross sections

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

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

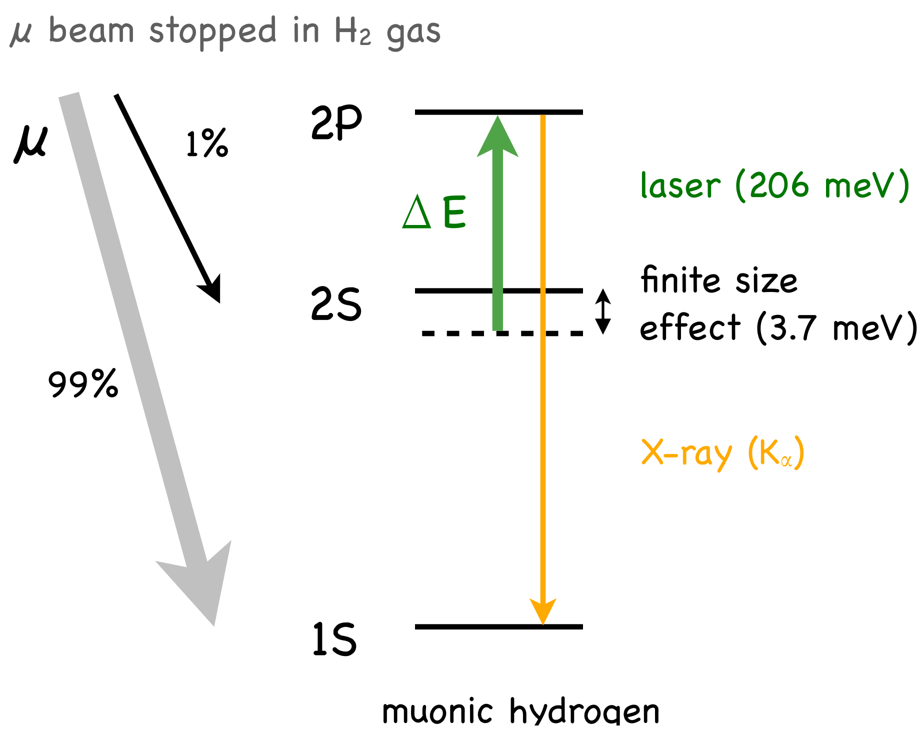
(r_p is not related to integral over proton charge density) [G. Miller]

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

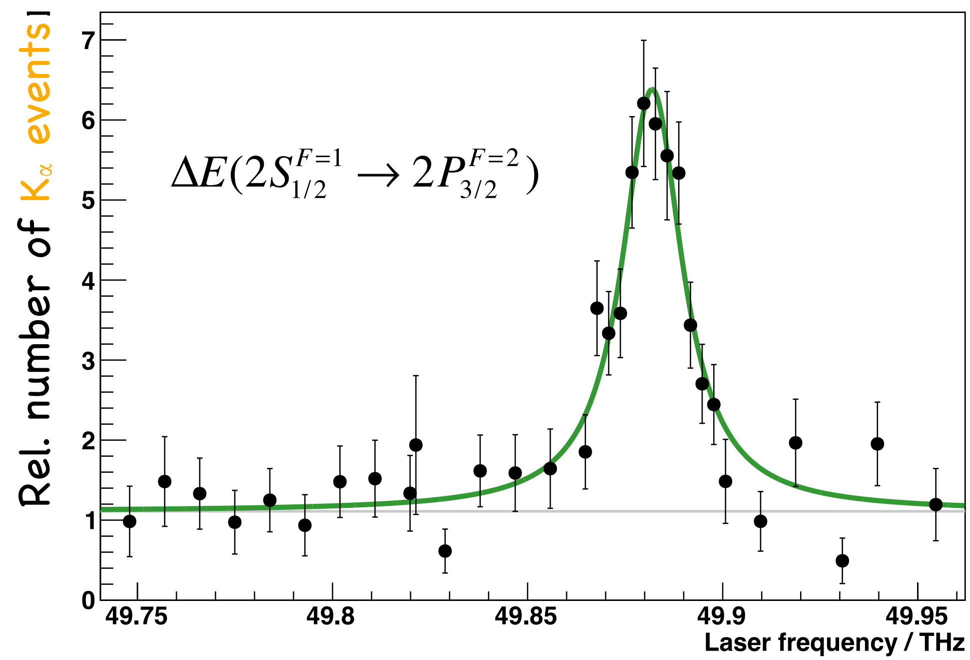
$$r_p=0.879(8)\text{ fm (MAMI)}$$

C.F. Perdrisat, V. Punjabi, M. Vanderhaeghen, Progress in Particle and Nuclear Physics **59** (2007) 694–764. Value of r_p from J. Bernauer et al. PRL **105**, 242001 (2010).

Spectroscopy of muonic hydrogen



2S-2P resonance curve



Lamb shift

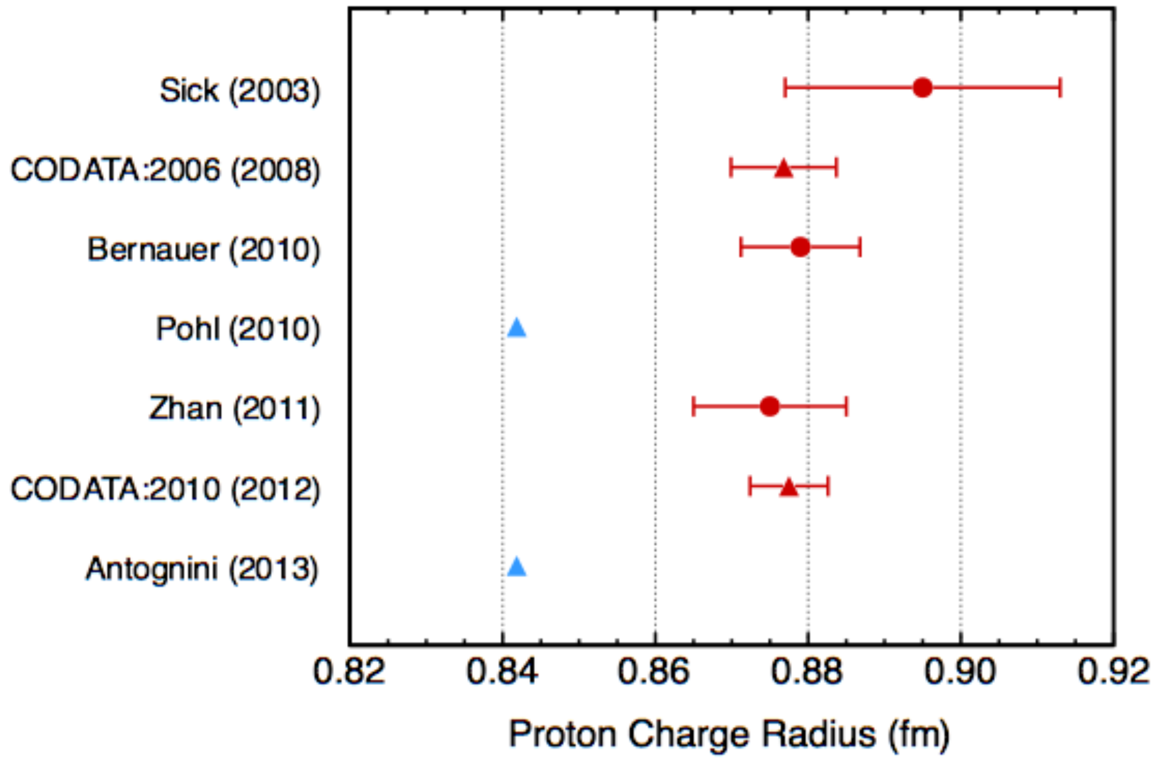
$$\boxed{\Delta E = 209.9779(49) - 5.2262 r_p^2 + 0.0347 r_p^3 \text{ meV}}$$

$$r_p = 0.84087(39)\ \text{fm}$$

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



▲ Spectroscopy

● Scattering

r_p = 0.84184(67) fm

r_p = 0.875(10) fm

r_p = 0.8768(69) fm

r_p = 0.84087(39) fm

The discrepancy between muonic and electronic measurements of the **proton** charge radius is a **7σ effect**; electronic and muonic measurements on D and He seem to agree.

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)

“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. Miler, 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).

MUon Scattering Experiment (MUSE) at PSI

Important data for proton radius puzzle missing ...

r	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.

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

- higher precision than previously,
- low Q^2 region for sensitivity to the proton 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), R. Gilman, E. Downie, G. Ron, spokespeople.
MUSE White Paper, arXiv 1303.2160 (2013).

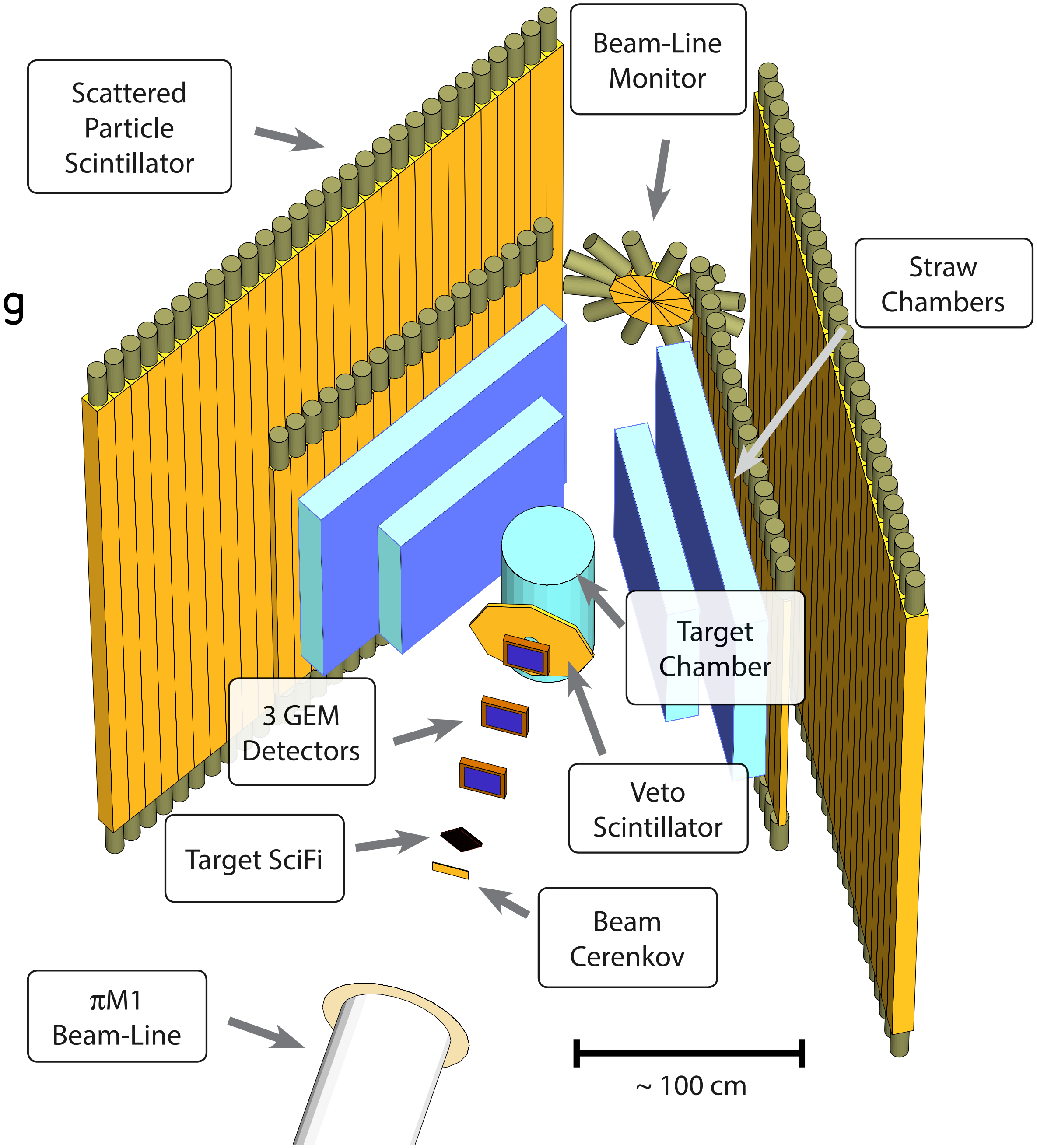
MUSE
Experimental setup

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

p = 115, 153, 210 MeV/c
θ = 20° to 100°
$Q^2 = 0.002 - 0.07\ GeV^2$
$\epsilon = 0.256 - 0.94$

Challenges:

- Secondary beam with π background,
- non-magnetic spectrometer,
- background from Møller scattering and muon decay in flight.



The MUon Scattering Experiment at PSI (MUSE), R. Gilman, E. Downie, G. Ron, spokespeople.
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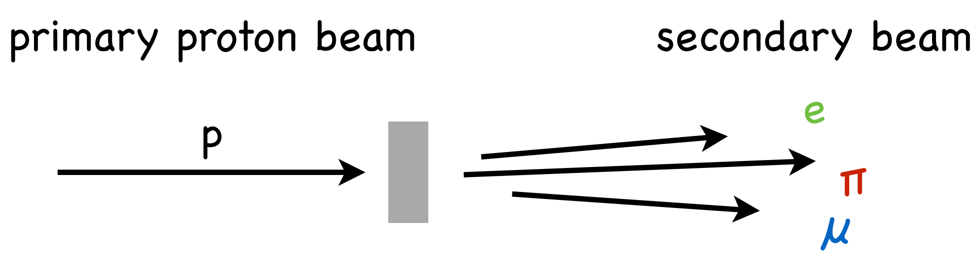
The challenges of a muon beam, particle ID

PSI πM1 beam line

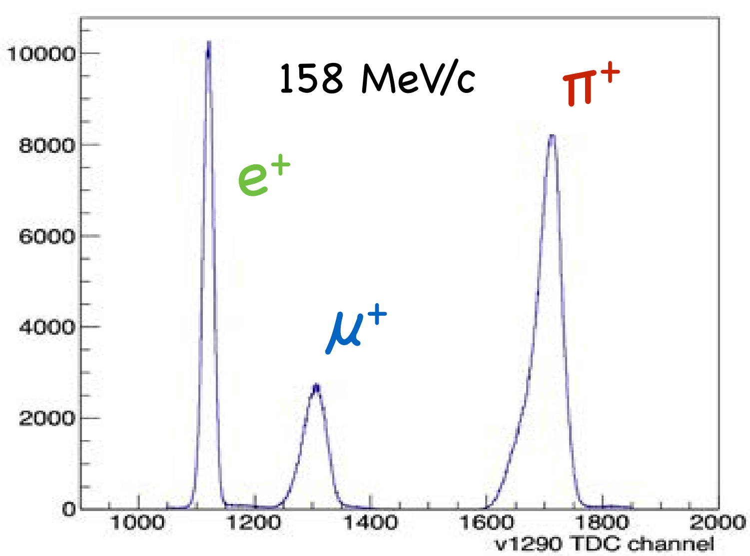


50 MHz RF (20 ns bunch separation)

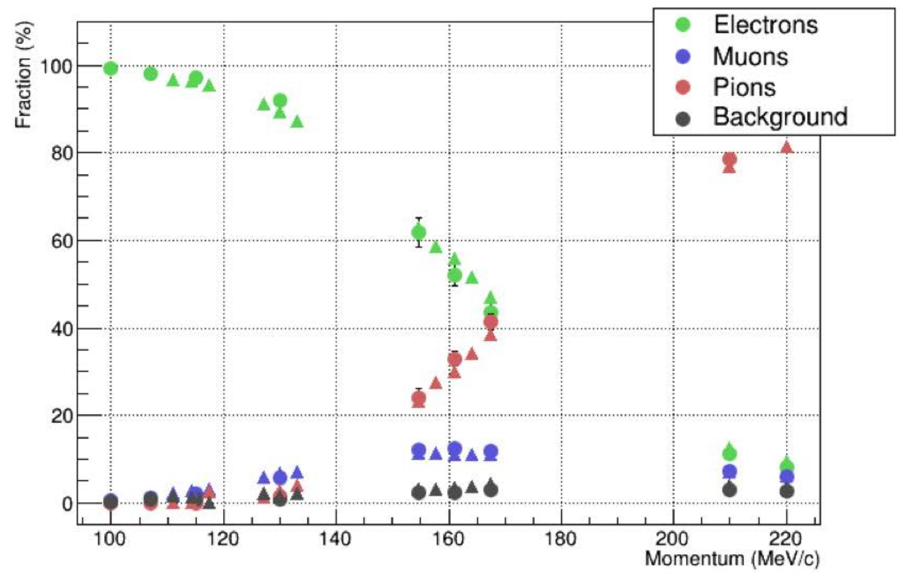
Flux ≈ 5 MHz,

e, μ, π beams with large emittance

p = 115, 158, 210 MeV/c

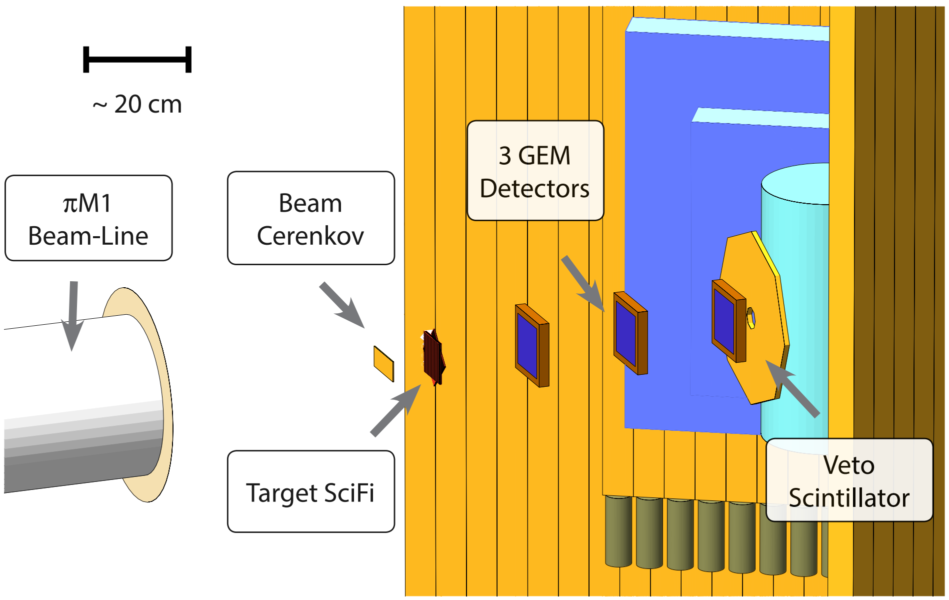


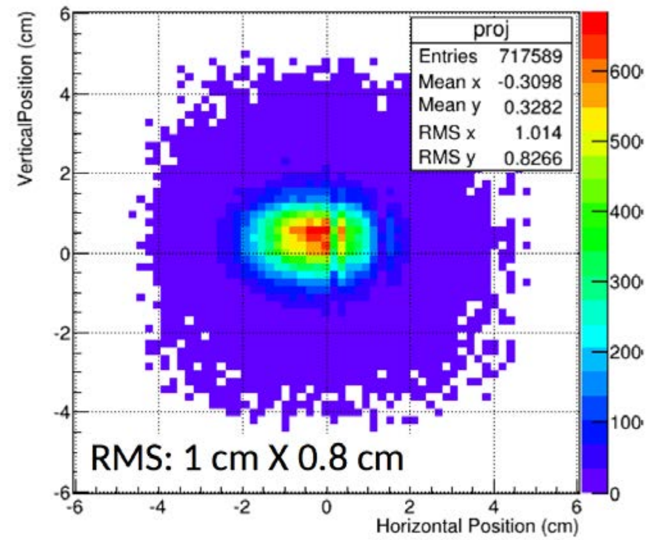
Scintillating Fiber arrays determine time of flight for particle ID



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

Measuring the incident particle trajectory

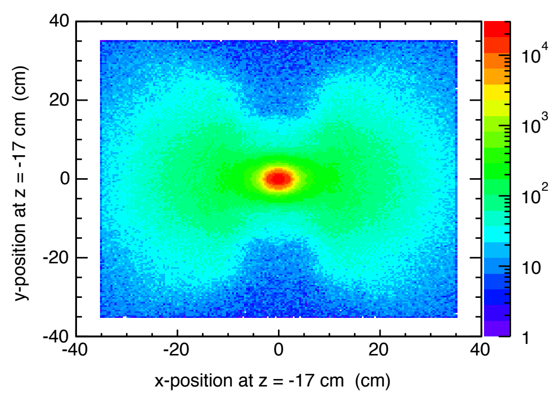




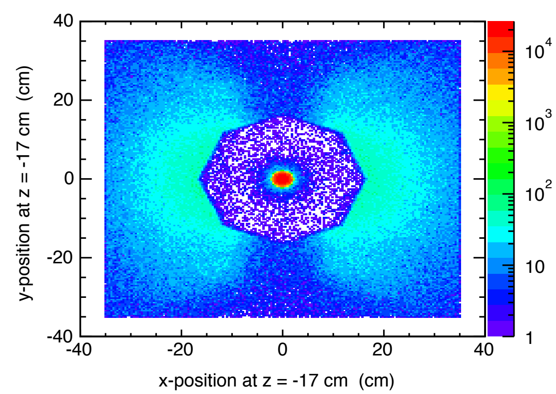
Beam spot measurement, June 2014 (K. Meyers)

GEM chambers (Hampton) and **scintillating fiber arrays** (Tel Aviv) to track individual beam particles into the target.

Veto detector (UofSC) reduces trigger rate from background events.



Geant4 Simulation, w/o veto



Geant4 Simulation, with veto

Scattered particle detectors

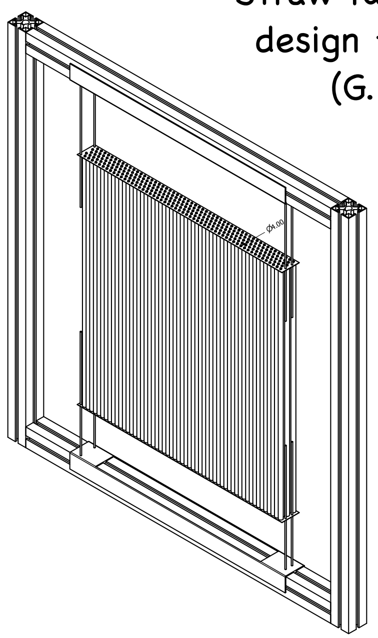
Each side of the beam line symmetrically equipped.

Straw Tube Tracker (HUJI + Temple)

Two chambers; 3000 straws total

PANDA design

Determine scattered particle trajectory to 140 μm



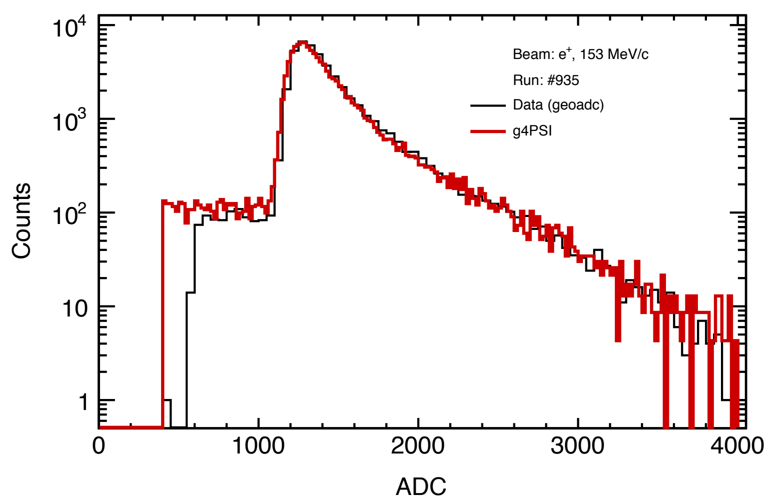
Straw Tube Tracker design for MUSE (G. Ron)

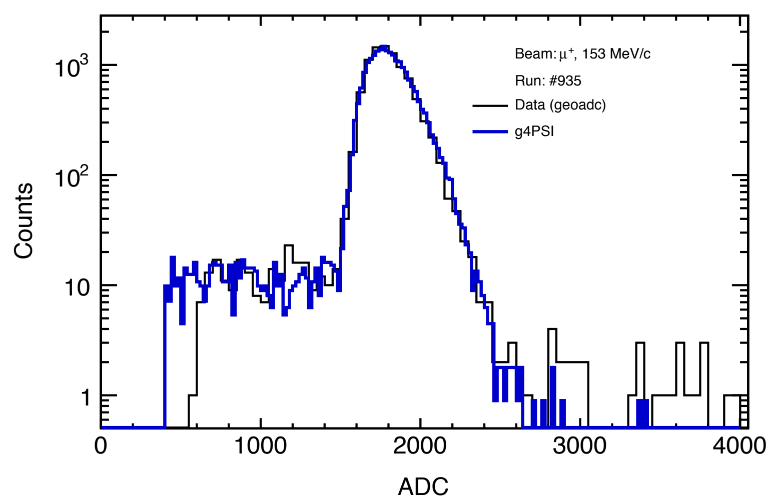
Time-of-Flight Scintillators (UofSC)

Two planes; 90 bars total

FTOF12 for CLAS12 design

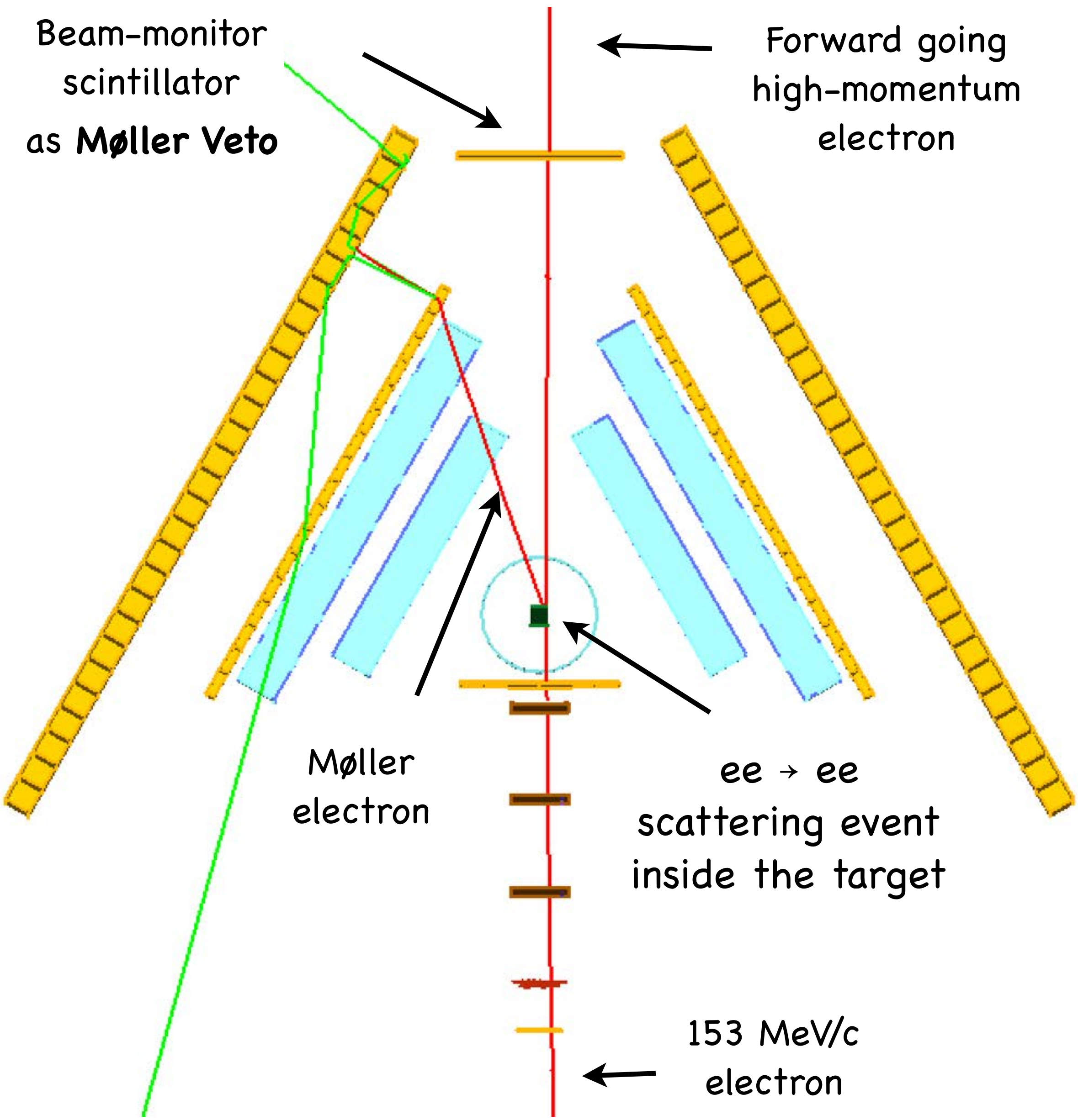
Time resolution better than 60 ps





Beam test and simulated pulse-height data

Møller scattering background



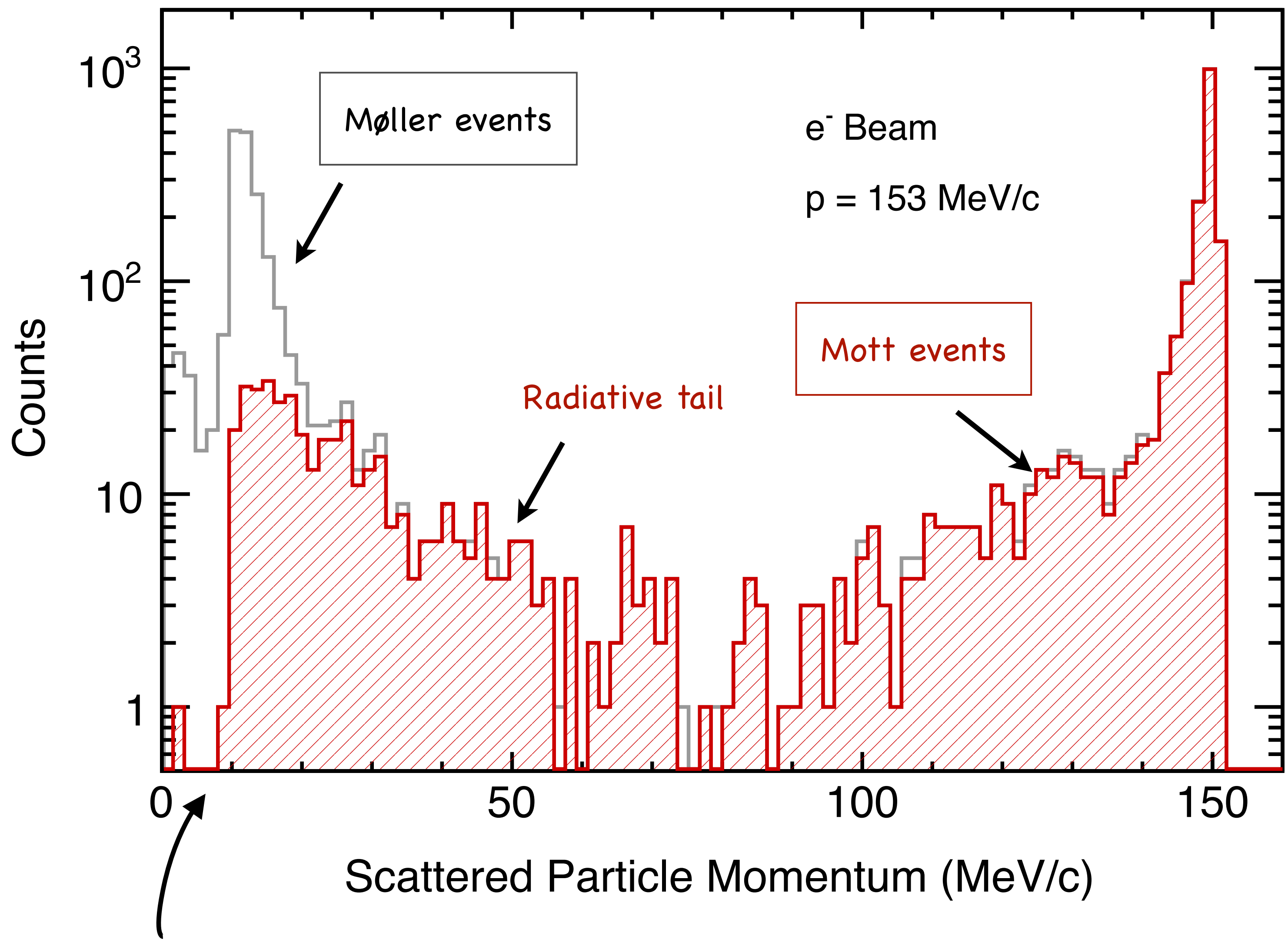
Signatures

- Scattered Møller electron forward peaked
- Scattered electron has low momentum
- Forward going high-momentum beam electron

Suppression

- Directional cut on **scintillator wall** bar combination
- Beam-monitor scintillator as **Møller veto**

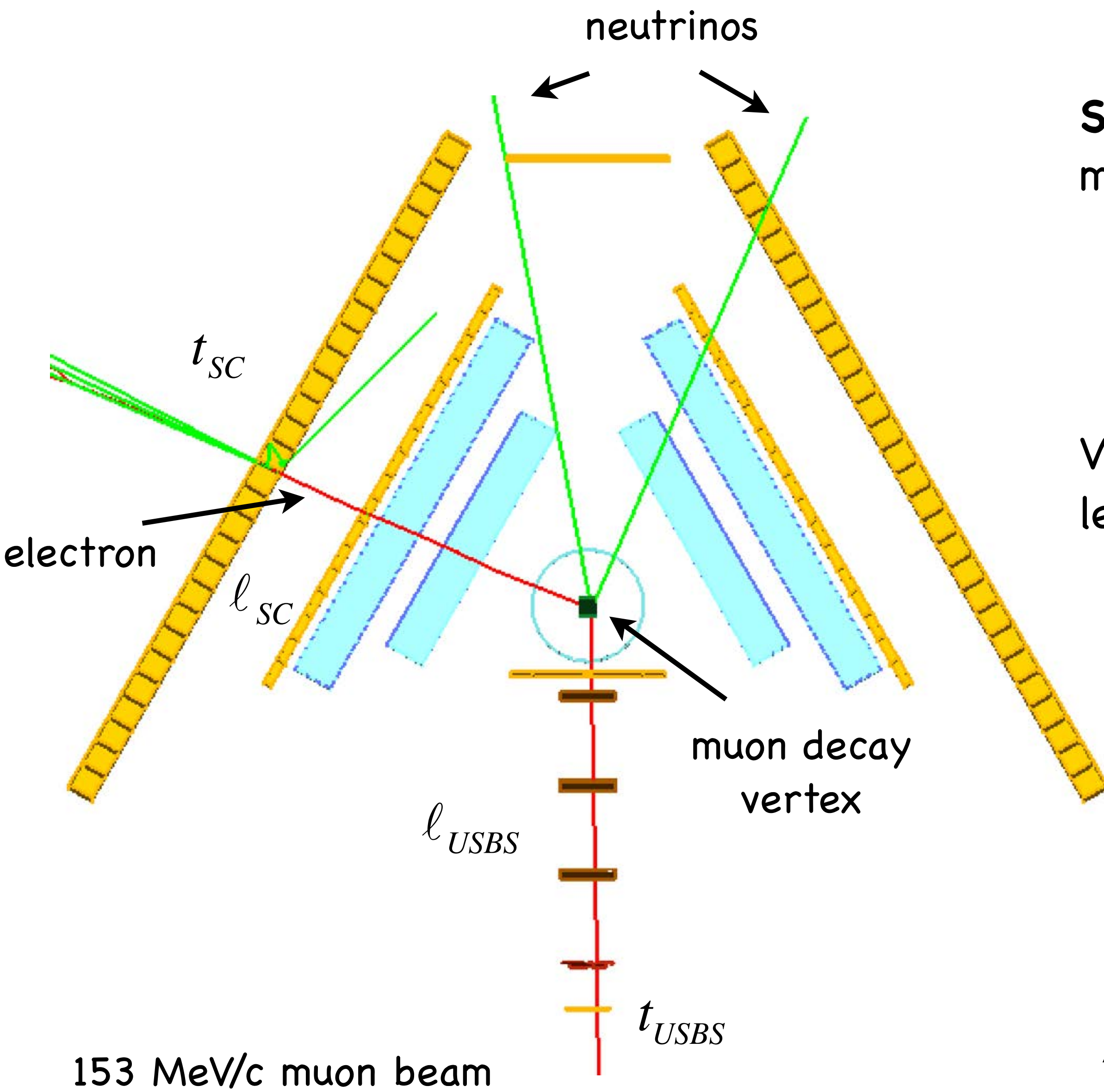
Møller scattering background efficiently suppressed with veto from beam-line monitor



simulation determines detection threshold, which is an input to the calculations of radiative corrections

Muon decay in flight

$$\mu^- \to e^- + \bar{\nu}_e + \nu_\mu$$



Suppression of background from muon decay

- Target vertex cut
- Time of flight

Vertex-time difference from path lengths and measured times

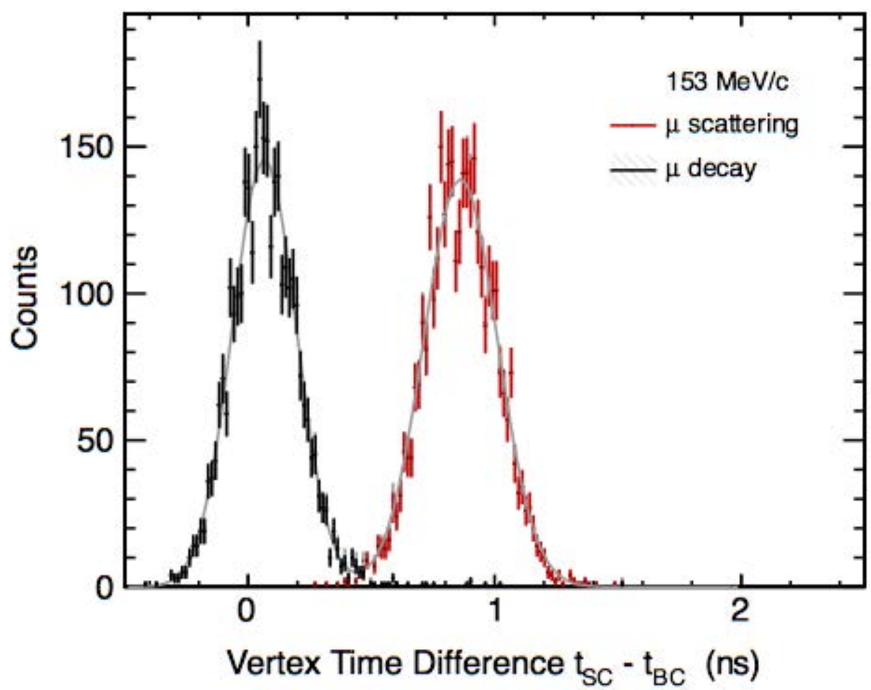
$$\Delta t = \left(t_{SC} - \frac{\ell_{SC}}{c} \right) - \left(t_{USBS} - \frac{\ell_{USBS}}{\beta_\mu c} \right)$$

assuming electron after muon decay, $\beta_e = 1$

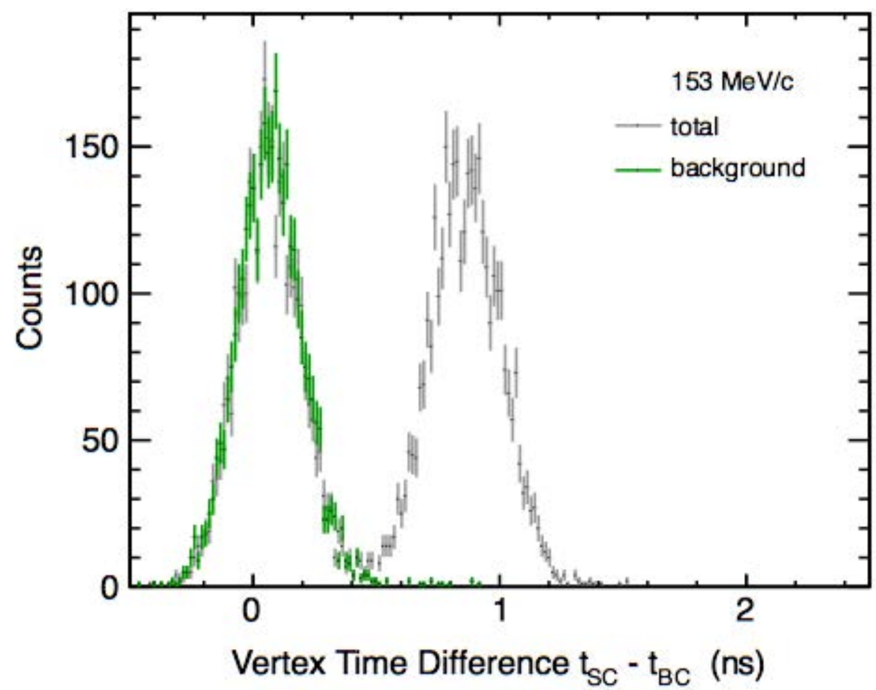
$\Delta t \approx 0$, for muon decay in target

Direct measurement of the muon decay in flight background

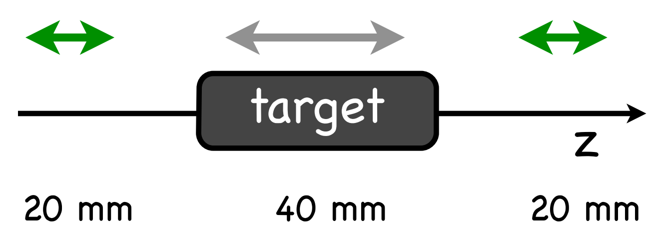
Muon decay flagged in simulation



Muon decay distribution measured



In situ measurement of muon decay-in-flight background from events upstream & downstream of the target.



Projected MUSE results (preliminary)

Total relative uncertainty in the cross section

$$\Delta\sigma(\mu)/\sigma = 0.4\%$$

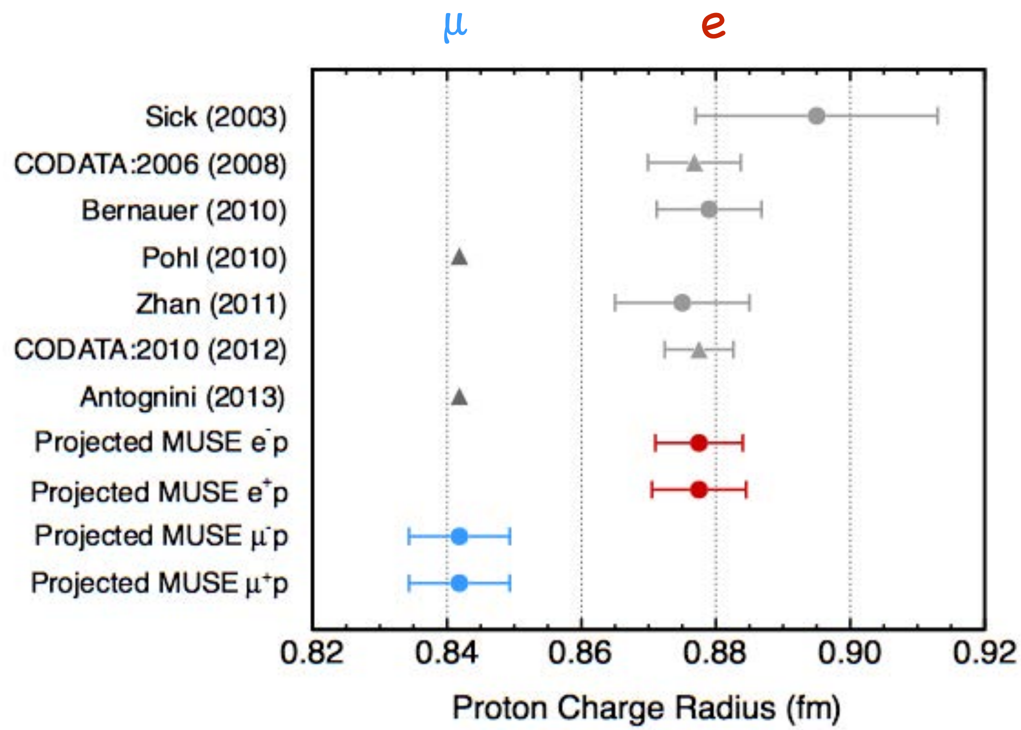
$$\Delta\sigma(e)/\sigma = 0.6\%$$

Sensitivity to differences in extracted e/μ radii:

$$\sigma^{\text{MUSE}}(r_e - r_\mu) \approx 0.009 \text{ fm}$$

Current discrepancy:

$$r_e - r_\mu \approx 0.035 \text{ fm}$$



Projected radius results including only **relative** uncertainties

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), R. Gilman, E. Downie, G. Ron, spokespeople.
MUSE White Paper, arXiv 1303.2160 (2013). Radius extraction from expected data by John Arrington.

Summary

- Proton radius puzzle: The discrepancy between muonic and electronic measurements of the proton radius is a 7σ effect.
- MUSE scattering experiments off the proton try to solve 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 ($\mu^+ \approx \mu^- \neq e^-$)?
  - Detailed simulations underway to help optimize the detector setup and to study the feasibility of the experiment.
  - R&D work underway, funded by the U.S. NSF & DOE; planning for production running in 2017-2018.