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

Steffen Strauch for the MUSE Collaboration
University of South Carolina
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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)

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

reduced cross section

Definition of proton charge radius

\[
\langle r_p^2 \rangle = -6 \hbar^2 \frac{dG_E(Q^2)}{dQ^2} \bigg|_{Q^2=0}
\]

(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.

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

\[ r_p = 0.879(8) \text{ fm (MAMI)} \]
Determine $r_p$ from spectroscopic data and QED calculations

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

\[ r_p = 0.84087(39) \text{ fm} \]
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 $5.6\sigma$ effect (¿).

New atomic hydrogen spectroscopy data inconclusive.

“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 $\mu - e$ universality

- **Novel Hadronic Physics:**
  Strong-interaction effect entering in a loop diagram is important for $\mu p$ 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


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

- Conflicting new atomic hydrogen spectroscopy data
- Conflicting results from various fits of electron scattering data
- Recent analysis of spectroscopy data gives 3.5σ difference between atomic and muonic D

<table>
<thead>
<tr>
<th>( r_p ) (fm)</th>
<th>ep</th>
<th>( \mu p )</th>
</tr>
</thead>
<tbody>
<tr>
<td>spectroscopy</td>
<td>0.876(8)</td>
<td>0.8409(4)</td>
</tr>
<tr>
<td>scattering</td>
<td>0.877(6)</td>
<td>?</td>
</tr>
</tbody>
</table>

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
Direct test of $\mu p$ and $e p$ 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 $0.07 \text{ GeV}^2$,
- with $\mu^+,\mu^-$ and $e^+,e^-$ to study possible $2\gamma$ mechanisms,
- with $\mu p$ and $e p$ to have direct $\mu/e$ comparison

\[ e^- p \rightarrow e^- p \]
\[ e^+ p \rightarrow e^+ p \]
\[ \mu^- p \rightarrow \mu^- p \]
\[ \mu^+ p \rightarrow \mu^+ p \]
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.

SiPM
16 paddles
BC 404

~ 100 cm
Beam-particle identification with beam hodoscope

**PSI πM1 beam line**

- primary proton beam
- secondary beam

- p
- e
- π
- µ

50 MHz RF (20 ns bunch separation)
Flux ≈ 3.3 MHz

e, µ, π beams with large emittance

p = 119, 165, 210 MeV/c

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

Beam hodoscope determines time of flight for particle ID
Consistent beam momenta were extracted from muon and pion time-of-flight data.

![Graph showing 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.
Beam Hodoscope mounted at PSI

Nov. 2017
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

Nov. 2017
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

LH$_2$ cell

6 cm

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.

![Diagram of the beam monitor with beam passage and 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 $\mu$m.
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:

\[ \sigma_{\text{Front}} < 50 \text{ ps}, \quad \sigma_{\text{Rear}} < 60 \text{ ps} \]
MUSE directly compares $\mu p$ to $ep$ cross sections

Projected relative statistical uncertainties in the ratio of $\mu p$ to $ep$ elastic cross sections. Systematics $\approx 0.5\%$.

The relative statistical uncertainties in the form factors are half as large.
MUSE allows to study two-photon exchange

\[ \sigma = \left[ \frac{e^-}{p} + \text{...} \right] \left[ e^+ / p' \right] \]

\[ \sigma_{e^\pm p} = |M_{1\gamma}|^2 \pm 2 \Re \{M_{1\gamma}^\dagger M_{2\gamma}\} + \cdots \]

\[ \frac{\sigma_{e^+ p}}{\sigma_{e^- p}} = 1 + 4 \left| \frac{\Re \{M_{1\gamma}^\dagger M_{2\gamma}\}}{|M_{1\gamma}|^2} \right| \]

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

\[ \sigma(r_e-r_\mu) \approx 0.005 \text{ fm} \]

What is the radius?
Absolute values of extracted e/µ radii
(assuming no +/- difference seen):

\[ \sigma(r_e), \sigma(r_\mu) \approx 0.008 \text{ fm} \]

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

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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 $\mu p$ and $ep$ interactions different? If so, does it arise from $2\gamma$ 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.