Studying the Proton Radius Puzzle with $\mu p$ Elastic Scattering

Katherine Myers
Rutgers University

This work support in part by NSF grant PHY 09-69239

~50 Muon proton Scattering Experiment (MUSE) collaborators from:

R. Gilman (Contact person) rgilman@physics.rutgers.edu
E.J. Downie, G. Ruy - Spokespersons

Argonne National Lab, Christopher Newport University, College of William & Mary, Duke University, Duquesne University, George Washington University, Hampton University, Hebrew University of Jerusalem, Institut für Kernphysik, Jefferson Lab, Massachusetts Institute of Technology, Norfolk State University, Old Dominion University, Paul Scherrer Institut, Rutgers University, University of South Carolina, Seoul National University, Soreq Nuclear Research Center, St. Mary's University, Technical University of Darmstadt, Tel Aviv University, Temple University, University of Virginia, Weizmann Institute
FF's and the Proton Radius

Lowest order \( ep \) scattering cross section:

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

Sach's form factors: \( G_E \) and \( G_M \)

Proton “radius” determined from slope of \( G_E \) in the low \( Q^2 \) limit

Low \( Q^2 \) data example:

Mainz A1 (2010) \( \sim 1400 \) points covering \( Q^2 \sim 0.01 - 1 \text{ GeV}^2 \)

Global fit of \( G_E, G_M \) with several different models

Their result: \( r_{Ep} = 0.879(8) \text{ fm} \)
The Proton Radius "Puzzle"

Measurements of the proton radius:

- ● Scattering
- ▲ Spectroscopy

Puzzle

There exists a 7.9σ discrepancy between electronic (ep atomic and ep scattering) and muonic extractions of the proton radius.
Possible Resolutions to the Puzzle

Error in the $ep$ scattering & atomic extractions:
  problem with fits, lack of data, underestimated uncertainties

Proton structure issues in theory (TPE):
  enhanced effects differing between $e$ and $\mu$

Novel beyond Standard Model physics:
  lepton non-universality, new $e/\mu$ differentiating force, parameters constrained by existing data

New data is needed
  new low $Q^2$ $ep$ scattering measurement (JLab 12 GeV)
  $\mu p$ scattering measurement (this talk)
1970s-1980s: several scattering experiments directly tested e-μ universality to ~10%

Ellsworth et al, Phys. Rev. 165 (1968):
Elastic μp data with ep dipole FF fit

Parameterization of μp versus ep

DIS measurement \[ \frac{1}{\Lambda^2} = 0.006 \pm 0.016 \text{ GeV}^{-2} \]
\[ \sigma_{\mu p}/\sigma_{ep} \approx 1.0 \pm 0.04 (\pm 8.6\% \text{ systematics}) \]
e-C, μ-C scattering are in agreement, but constraints are not very good
The MUSE Experiment

μp scattering at the Paul Scherrer Institut

<table>
<thead>
<tr>
<th>$r_p$ (fm)</th>
<th>ep</th>
<th>μp</th>
</tr>
</thead>
<tbody>
<tr>
<td>atom</td>
<td>0.877 ± 0.007</td>
<td>0.841 ± 0.001</td>
</tr>
<tr>
<td>scattering</td>
<td>0.875 ± 0.006</td>
<td>?</td>
</tr>
</tbody>
</table>

→ Low $Q^2$ range (0.002 – 0.07 GeV$^2$) to have sensitivity to radius

→ Directly test if μ and e are different to a higher precision

→ Simultaneously measure $ep$ and $μp$ for a direct comparison

→ Measure e+, e- and μ+, μ- to extract TPE effects
The MUSE Experiment

Experimental Considerations and Components:

Mixed beam of e, μ, and π
→ select beam momenta with good RF separation at target

\[ p = 115, 153, \text{ and } 210 \text{ MeV/c} \]

RF time spectrum measured in Fall 2012 Test Run at 158 MeV/c

RF timing determined by scintillating fiber arrays in the target region:
→ 1 ns resolution
→ reject pion events

Limit total channel flux to 5 MHz

GEM chambers:
→ Determine incident angle to 0.5 mr
→ project track to target
→ Existing chambers from OLYMPUS
The MUSE Experiment

Target:

→ 4 cm LH2, thickness constrained by effects of multiple scattering

Quartz Cerenkov in target region

→ 50 ps resolution
→ better RF time at analysis level for PID
→ muon decay rejection

Scattering measured for $\theta = 20-100$ degrees

Wire Chambers

→ 3 UU'VV'XX'
→ mimic Hall A BigBite design
→ 98% plane efficiency
→ 100 $\mu$m resol.

Scintillators

→ 2 planes with $\leq 50$ ps resol.
→ PID and muon decay rejection
→ Adopt South Carolina design for CLAS12

Albrow et al (FNAL)
Projected Impact

Point-to-point systematics: 0.7%, dominated by radiative corrections

Uncertainty in radius extractions: Independent measurements: 0.01 fm
Relative comparison: 0.006 fm
Current discrepancy: 0.035 fm
Summary

→ Proton Radius “Puzzle” challenging and unresolved
  - $7\sigma$ discrepancy between muonic and electronic measurements

→ MUSE will do a direct comparison of ep and $\mu p$ scattering to:
  - Compare proton charge radius, extract form factors
  - Test beyond SM physics: difference between e's and $\mu$'s
  - Measure two-photon exchange effects

→ Timeline for MUSE:
  - Experiment approved by PSI PAC January 2013
  - Successful beam test run Fall 2012
  - Another test run planned June 2013
  - Plan few month “dry run” in late 2015
  - Two 6 month production runs 2016-2017
Summary

→ Proton Radius “Puzzle” challenging and unresolved
  • $7\sigma$ discrepancy between muonic and electronic measurements

→ MUSE will do a direct comparison of ep and $\mu p$ scattering to:
  • Compare proton charge radius, extract form factors
  • Test beyond SM physics: difference between e's and $\mu$'s
  • Measure two-photon exchange effects

→ Timeline for MUSE:
  • Experiment approved by PSI PAC January 2013
  • Successful beam test run Fall 2012
  • Another test run planned June 2013
  • Plan few month “dry run” in late 2015
  • Two 6 month production runs 2016-2017

Thank You!