Muon Scattering at PSI *

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~30 Muon scattering Experiment (MUSE) collaborators from 20 institutions:

Argonne National Lab, Christopher Newport University, Technical University of Darmstadt, Duke University, George Washington University, Hampton University, Hebrew University of Jerusalem, Jefferson Lab, Massachusetts Institute of Technology, Norfolk State University, Paul Scherrer Institute, Rutgers University, University of South Carolina, Seoul National University, St. Mary's University, Tel Aviv University, Temple University, University of Virginia, College of William & Mary, Old Dominion University

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Muon-proton scattering at PSI

- Motivation
- Proposed experiment
  - Muon beamline
  - Detector
  - Expected sensitivity
- Status & Schedule

NY Times, July 12, 2010
The proton radius puzzle

- 7σ discrepancy between muonic hydrogen Lamb shift and combined electronic Lamb shift and electron scattering
- High-profile articles in Nature, NYTimes, etc.
- Special feature at many conferences

<table>
<thead>
<tr>
<th>#</th>
<th>Extraction</th>
<th>$&lt;r_E&gt;^2$ (fm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Sick</td>
<td>0.895±0.018</td>
</tr>
<tr>
<td>2</td>
<td>Bernauer Mainz</td>
<td>0.879±0.008</td>
</tr>
<tr>
<td>3</td>
<td>Zhan JLab</td>
<td>0.870±0.010</td>
</tr>
<tr>
<td>4</td>
<td>CODATA</td>
<td>0.877±0.007</td>
</tr>
<tr>
<td>5</td>
<td>Combined 2-4</td>
<td>0.876±0.005</td>
</tr>
<tr>
<td>6</td>
<td>Muonic Hydrogen</td>
<td>0.842±0.001</td>
</tr>
</tbody>
</table>
PSI muonic hydrogen measurements

R. Pohl et al., Nature 466, 09259 (2010): 2S\rightarrow2P Lamb shift
ΔE (meV) = 209.9779(49) - 5.2262 \, r_p^2 + 0.0347 \, r_p^3
⇒ r_p = 0.842 ± 0.001.

Possible issues: atomic theory & proton structure
Proton radius from Mainz A1 data

- Low $Q^2$ – J. Bernauer et al., PRL105 (2010) 242001
- Left: world + Mainz fit; Middle: Mainz raw data; Right rebinned $G_E$
- Large difference in slope between $r = 0.84$ and 0.88 fm
- Floating normalization, higher-order $Q^2$ terms present
- Need yet higher precision

\[
G_E(Q^2) = 1 - Q^2 r^2/6 + \ldots
\]
The “PrimEx” proton radius proposal

- Low intensity beam in Hall B @ Jlab into windowless gas target.
- Scattered ep and Moller electrons into HYCAL at $0^\circ$.
- Lower $Q^2$ than Mainz. Very forward angle, insensitive to $2\gamma$, $G_M$.
- Conditionally approved by PAC38 (Aug 2011): “Testing of this result is among the most timely and important measurements in physics.”
- Approved by PAC39 (June 2012), graded “A”
Possible resolutions to the puzzle

- **The μp result is wrong**
  Discussion about theory and proton structure for extracting the proton radius from Lamb shift measurement

- **The ep (scattering) results are wrong**
  Fit procedures not good enough
  $Q^2$ not low enough, structures in the form factors

- **Proton structure issues in theory**
  Off-shell proton in two-photon exchange leading to enhanced effects differing between μ and e

- **Physics beyond Standard Model differentiating μ and e**
  Lepton universality violation
  Existing constraints on new physics

More insights from comparison of ep and μp scattering
Motivation for $\mu p$ scattering
Lepton scattering and charge radius

Lepton scattering from a nucleon:

\[ \gamma \mu^\pm, e^\pm \rightarrow N \]

Vertex currents:

\[ J^\mu_e = -\bar{e}u_e \gamma^\mu u_e \]

\[ J^\mu_N = \bar{\psi}_N \left[ F_1(Q^2)\gamma^\mu + F_2(Q^2) \frac{i\sigma^\mu\nu q_\nu}{2M_N} \right] \psi_N \]

F_1, F_2 are the Dirac and Pauli form factors

Sachs form factors:

\[ G_E(Q^2) = F_1(Q^2) - \tau F_2(Q^2) \]

\[ G_M(Q^2) = F_1(Q^2) + F_2(Q^2) \]

Fourier transform (in the Breit frame) gives spatial charge and magnetization distributions

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

\[ \langle r_M^2 \rangle = -6 \frac{dG_M^p(Q^2)/\mu_p}{dQ^2} \bigg|_{Q^2 \rightarrow 0} \]

Expect identical result for ep and \( \mu p \) scattering
1960s-1970s: several experiments tested e-μ universality in scattering

Elastic μp scattering:
Ellsworth et al., Phys. Rev. 165 (1968)


\[ \frac{\sigma_{\mu p}}{\sigma_{e p}} \approx 1.0 \pm 0.04 \ (\pm 8.6\% \ \text{systematics}) \]

Data ~ 15% low

Constraints are not very good

  \[ \frac{\sigma_{\mu p}}{\sigma_{e p}} \approx 1.0 \pm 0.04 \ (\pm 8.6\% \ \text{systematics}) \]

- e-C, and μ-C are in agreement

\[ 1/\Lambda^2 = 0.006 \pm 0.016 \ \text{GeV}^{-2} \]
1960s-1970s: several experiments tested e-µ universality in scattering

Elastic µp scattering:
Ellsworth et al., Phys. Rev. 165 (1968)


\[ \frac{\sigma_{\mu p}}{\sigma_{ep}} \approx 1.0 \pm 0.04 (\pm 8.6\% \text{ systematics}) \]

Constraints are not very good
Lepton universality beyond SM

Batell, McKeen, Pospelov (arXiv:1103.0721):
- new e/µ differentiating force consistent with $g_\mu - 2$
- <100 MeV gauge boson V or dark photon
- resulting in large PV $\mu p$ scattering

Barger, Chiang, Keung, Marfatia (arXiv:1109.6652):
- constrained by $K \rightarrow \mu \nu$ decay
Lepton universality in $K_{12}$ decays

- **Highly precise SM value**
  
  \[ R_{K}^{SM} = (2.477 \pm 0.001) \times 10^{-5} \]

- **LFV beyond SM**
  
  \[ R_{K}^{LFV} = R_{K}^{SM} \left(1 + \frac{m_{K}^{4}}{M_{H^{+}}^{4}} \cdot \frac{m_{e}^{2}}{m_{\tau}^{2}} \Delta_{13}^{2} \tan^{6} \beta \right) \]

  e.g. MSSM with charged-Higgs SUSY-LFV

  \[ \Delta_{13} \sim \nu (Slepton) \]

  \[ \Delta_{13} \sim \nu (Sneutrino) \]

  \[ \Delta_{13} \sim \nu (Bino) \]

  \[ R_{K}^{LFV} \sim R_{K}^{SM} (1 \pm 0.013) \]

- **Current experimental precision (KLOE, NA62)**
  
  \[ R_{K} = (2.488 \pm 0.012) \times 10^{-5}, \quad \delta R_{K}/R_{K} = 0.48\% \]

TREK (P36) proposed at J-PARC for 0.25% precision
Proposal for $\mu^\pm p/e^\pm p$ scattering at PSI

Use the world’s most powerful low-energy separated $e/\pi/\mu$ beam for a direct test if $\mu p$ and $ep$ scattering are different:

- to higher precision than previously
- in the low $Q^2$ region (same as Mainz and latest JLab experiment just completed) for sensitivity to radius
- measure both $\mu^\pm p$ and $e^\pm p$ for direct comparison and a robust, convincing result

- depending on the results, 2nd generation experiments (lower $Q^2$, $\mu^\pm n$, higher $Q^2$, ...) might be desirable
Proposal for $\mu^\pm p/e^\pm p$ scattering at PSI

Use the world’s most powerful low-energy separated $e/\pi/\mu$ beam for a direct test if $\mu p$ and $ep$ scattering are different:

- **Measure absolute cross section** for $\mu p$ scattering and cross section ratios to other species

- Simultaneously measure $ep$ scattering
  - $\mu/e$ ratio to cancel certain systematics
  - If radii differ by 4%, form factor slope differs by 8%, and cross section slope differs by 16%

- Measure $e^+$, $e^-$ and $\mu^+$, $\mu^-$ on target
  - Directly extract information on two-photon exchange (TPE) effect and compare for $e$, $\mu$

- Use multiple beam energies
  - separate $G_E$ and $G_M$ with the Rosenbluth method
PSI πM1 channel: 100-500 MeV/c μ/e/π

Beam spot (nominal): XY = 1.5x1 cm²; X’Y’ = 35x75 mr²

Momentum acceptance: 3%, resolution: 0.1%

Spots from 0.7x0.9 cm² up to 16x10 cm², and Δp/p from 0.1-3.0%, used previously
Separation of $e$, $\pi$, $\mu$ by RF time

Requirement: particle separation in time for PID
50 MHz RF $\rightarrow$ 20 ns between bunches

Timing of particles in target region wrt electron ($\beta = 1$)

Minimum time separation of particles in target region

$p = 115, 153, \text{ and } 210 \text{ MeV/c}$
Schematic layout

- **e/π/µ** separated in time
- Channel sci-fi array
- GEM chambers
- Wire chambers
- Trigger scintillators
- Beam Cerenkov
- Positive polarity

**Time of Flight (TOF) spectrum**
- Counts
- Positrons 56%
- Pions 29%
- Muons 15%

**Momentum acceptance:** 3%, **resolution:** 0.1%

**Beam spot (nominal):** 1.5 cm X x 1 cm Y, 35 mr X' x 75 mr Y'
Beamline instrumentation

**Beamline Elements:**
- Beam and target sci-fi arrays:
  - Flux, PID, TOF, momentum

Particles well separated at IFP:

GEM chambers:
- Determine incident angle to 0.5 mr
- Third GEM to reject ghost tracks
- Existing chambers from UVa and OLYMPUS (Hampton University)

COMPASS GEMs routinely operated to ≈2.5 MHz/cm²

Tested up to several 10s of MHz/cm²

PSI: 10 MHz/1.5 cm² = 6.7 MHz/cm² (average) rate
**Beamline instrumentation**

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

→ Limits acceptance to > 20°

→ Limits target thickness to 0.3 g/cm²

Beamline Cerenkov: provide redundant PID, and provide cross check for RF timing calibration

(designed under discussion)
Background considerations

Requirement: low backgrounds or background rejection

Scattering from electrons:

→ π, μ at forward angles
→ e-,e+ <10 MeV above 15°
→ Recoil e's low momentum

Muons from π decays

→ Will have π RF time (3 orders of magnitude suppression)
→ Track will not point back to the target

Suppression of μ → eνν background with offline time-of-flight (8-20 σ)
Recoil protons E loss so large that all except forward angle recoil protons stopped in target.

Large angle, very low energy Moller / Bhabha e’s lose large fraction of energy in target.

All the low-energy electron and proton backgrounds are ranged out in the first scintillator layer.

Scattered particle considerations
Detector: trigger scintillators

**Trigger Scintillators:** outermost element of detector stack, 70-100 cm from target

→ Based on 6 cm x 6 cm x 2 m long scintillators built for CLAS12
→ Thick enough to stop low energy e+, e-
→ Demonstrated ~50 ps resolution at analysis level (We will have ~1.4 m long bars → better timing)

Use for PID based on RF timing at analysis level to 70σ

Cover angular range of 20-100°
Detector: wire chambers, Cerenkov

Wire chambers: \(~400\, \text{kHz rate}\)
→ Position resolution \(~100\, \mu\text{m}\)
→ Angular resolution \(< 1\, \text{mr}\) (neglecting m.s.

Threshold Cerenkov: (discussed)
→ provide alternate method of PID at the trigger level
→ additional suppression of pion triggers
→ medium different for each momentum

<table>
<thead>
<tr>
<th>Beam (MeV/c)</th>
<th>(n_{\text{threshold}})</th>
<th>Material</th>
</tr>
</thead>
<tbody>
<tr>
<td>210</td>
<td>1.19-1.20</td>
<td>Pinhole dried Aerogel</td>
</tr>
<tr>
<td>154</td>
<td>1.32-1.36</td>
<td>Water/teflon</td>
</tr>
<tr>
<td>115</td>
<td>1.50-1.58</td>
<td>Quartz/lucite</td>
</tr>
</tbody>
</table>
Rate considerations

- 10 MHz beam rate / 50 MHz RF
  - 82% chance clean
  - 16% chance 2 particles
  - 2% chance >2 particles in RF bucket
- Reduce acceptance to limit rates for +210, +153 MeV/c
- 250 ns chamber time scale ➩ 2.5 background tracks per event
- Eventually handle 2\textsuperscript{nd} particle in same RF bucket as µ trigger
Rate considerations

- Trigger rates in Hz for total beam flux of 10 MHz – always < 1kHz
- Singles rates can exceed 1 MHz
- Up to ~15% accidental triggers from pion induced processes at high momentum

<table>
<thead>
<tr>
<th>Rate Considerations</th>
<th>Positive beam charge</th>
<th>Negative beam charge</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Momentum (MeV/c)</strong></td>
<td>+115</td>
<td>+153</td>
</tr>
<tr>
<td>$\mu p$ elastic scattering</td>
<td>6.4</td>
<td>5.5</td>
</tr>
<tr>
<td>$\mu$Al elastic scattering</td>
<td>7.7</td>
<td>6.6</td>
</tr>
<tr>
<td>$\mu$ decays in flight $\rightarrow e$’s in detector</td>
<td>460</td>
<td>440</td>
</tr>
<tr>
<td>$\mu$ knockout of $\delta$’s</td>
<td>$\approx$0</td>
<td>$\approx$0</td>
</tr>
<tr>
<td>$ep$ elastic scattering</td>
<td>67</td>
<td>27</td>
</tr>
<tr>
<td>$e$Al elastic scattering</td>
<td>81</td>
<td>33</td>
</tr>
<tr>
<td>$ee$ Bhabha / Moller scattering</td>
<td>7200 $\rightarrow$ $\approx$0</td>
<td>5300 $\rightarrow$ $\approx$0</td>
</tr>
<tr>
<td>$\pi^\pm p$ elastic scattering</td>
<td>62 $\rightarrow$ 8</td>
<td>5500 $\rightarrow$ $\approx$0</td>
</tr>
<tr>
<td>$\pi$ decays in flight $\rightarrow \mu$’s in detector</td>
<td>3600 $\rightarrow$ 480</td>
<td>660k $\rightarrow$ 0.9</td>
</tr>
<tr>
<td>$\pi$ knockout of $\delta$’s</td>
<td>$\approx$0</td>
<td>$\approx$0</td>
</tr>
</tbody>
</table>
Systematics to be controlled

Left:
need to know central momentum to tenths of a percent, but can average over a few percent bin. Can “fit this out”.

Right:
need to know central angle to mr level, but can average over several mr. Can “fit out” offset and correct cross sections for resolution.
Projected sensitivity

\[ G_E(Q^2) = 1 - Q^2 r^2/6 + \ldots \]

- \(\pi\)M1 channel, with \(p_{\text{in}} = 115, 153,\) and 210 MeV/c: PID reasons
- Choose \(\theta = 20 - 100^\circ\): rates, backgrounds, systematics
- Statistics for 30 days/setting at 10 MHz on 0.3 g/cm\(^2\) liq. H\(_2\)
- Statistics plus estimated systematics lead to \(\delta R \approx 0.01\) fm for \(\mu^+, e^\pm,\) and 0.015 fm for \(\mu^-\)
- \(\Delta R = 4\% \Rightarrow \text{slopes } \Delta G' = 8\% \Rightarrow \Delta \sigma' = 16\%\)
- If radius difference is real, are the slope differences that large?
Projected sensitivity

Pseudo-random data with errors:

→ 30 days of running at each energy
→ sub 1% statistical uncertainty ($\mu^+ p$)
→ slightly worse for $\mu^- p$, but sufficient for comparison of TPE

Estimate of systematic uncertainties for $\mu^+ p$:

<table>
<thead>
<tr>
<th>Systematic Uncertainty</th>
<th>Absolute (%)</th>
<th>Point-to-point (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$x\rho_{\text{target}}$</td>
<td>1.0</td>
<td>-</td>
</tr>
<tr>
<td>Beam flux ($\pi / \mu / e$ misidentification)</td>
<td>small</td>
<td>-</td>
</tr>
<tr>
<td>Radiative correction</td>
<td>0.3</td>
<td>0.1</td>
</tr>
<tr>
<td>Solid angle</td>
<td>0.2</td>
<td>0.2</td>
</tr>
<tr>
<td>Efficiencies - triggering, analysis, etc.</td>
<td>0.5</td>
<td>0.1</td>
</tr>
<tr>
<td>Beam energy</td>
<td>0.2</td>
<td>0.1</td>
</tr>
<tr>
<td>Averaging over beam energies</td>
<td>small</td>
<td>small</td>
</tr>
<tr>
<td>Knowledge of angle</td>
<td>0.45</td>
<td>0.3</td>
</tr>
<tr>
<td>Averaging over angles / multiple scattering</td>
<td>0.2</td>
<td>0.2</td>
</tr>
<tr>
<td>Cell wall subtraction</td>
<td>small</td>
<td>small</td>
</tr>
<tr>
<td>Cosmic ray subtraction</td>
<td>small</td>
<td>small</td>
</tr>
<tr>
<td>$\pi / \mu$ decay corrections</td>
<td>small</td>
<td>small</td>
</tr>
<tr>
<td>TOTAL</td>
<td>1.3</td>
<td>0.5</td>
</tr>
</tbody>
</table>

$\Delta r \approx 0.01$ fm for $\mu^+$, $e^\pm$, but about 0.015 fm for $\mu^-$

Systematics: ~1.3% absolute precision, 0.5% pt-to-pt
Charge radius extraction limited by systematics, fit uncertainties

Comparable to existing e-p extractions, but not better

Many uncertainties are common to all extractions in the experiments: Cancel in e+/e-, μ+/μ-, and μ/e comparisons
Projected sensitivity

Charge radius extraction limited by systematics, fit uncertainties

Comparable to existing e-p extractions, but not better

Many uncertainties are common to all extractions in the experiments: Cancel in e+/e-, µ+/µ-, and µ/e comparisons

Relative comparison reduces errors by factor of 2
Summary

- **Proton Radius Puzzle** – a $7\sigma$ discrepancy between ep and muonic Lamb shift measurements
- **Still unresolved ~2 years later**
- **PSI Experiment**
  - Measure $\mu p$ and ep scattering and compare directly
  - Measure $e^+/e^-$ and $\mu^+/$ to study/constrain TPE effects
- **Technical Challenges** – particle ID, timing resolution, background rejection, momentum and flux determination
- **MUSE timeline**
  - Initial proposal February 2012
  - Technical Review July 2012
  - Engineering test run – Fall 2012
  - Production run 2014-2015 (6 months)
Backup slides
μ decay background

Distribution of electrons from 153 MeV/c μ decay.

μ⁺ → e⁺ν_μν gives several kHz track rate and ≈400 Hz e⁺ background trigger rate. Rejected at analysis level by requiring tracks from the target, and μ RF time from the detector - the decay electrons will be ≈ 0.8 ns faster than μ scattering events. Rate can be directly measured with empty target.
πp scattering rates calculated with cross sections from SAID and expected luminosities, assuming $2\pi$ azimuthal acceptance. Up to a few tens of kHz chamber rates, plus a DAQ rate issue for some kinematics, if not suppressed at the trigger level.