MUon-proton Scattering Experiment at PSI

workshop on Physics of fundamental Symmetries and Interactions - PSI2019

Paul Scherrer Institute, Switzerland
October 22 2019
μ-p Scattering – The missing Piece

Electronic hydrogen
2010 0.8758(77)
... 

CODATA 2010: 0.8775(51)

Muonic hydrogen
2010 0.84184(67)
2013 0.84087(39)
...

Muon scattering ???
with similar precision

Spectroscopy

Discrepancies not explained

2014: 0.8751(61) 2018: (released May 20, 2019): 0.8414(19)

Electron scattering
2010 0.8790(80)
2017 0.8770(60)
...

Scattering
μ-p Scattering?

How about μ and e scattering ... in the same experiment μ+ e- μ- and e+?

cross sections  form factors  two photon exchange charged lepton universality

Good idea!

Ronald Gilman  Michael Kohl  Gerry Miller  Zein-Eddine Meziani
Measure cross sections, form factors, and radius

\[
\frac{d\sigma}{d\Omega} = \left( \frac{d\sigma}{d\Omega} \right)_{M} \times \left[ G_{E}^{2} + \frac{\tau}{\epsilon} G_{M}^{2} \right] \frac{1}{(1 + \tau)}
\]

\[
\epsilon = \left[ 1 + 2(1 + \tau) \tan^{2} \frac{\theta_{e}}{2} \right]^{-1}
\]

\[
\tau = \frac{Q^{2}}{4M^{2}}
\]

\[
\tau \propto Q^{2} \quad Q^{2} \rightarrow 0 \quad \Rightarrow \quad \left( \frac{d\sigma}{d\Omega} \right)_{\text{exp}} / \left( \frac{d\sigma}{d\Omega} \right)_{M} \propto G_{E}^{2}
\]

\[
r_{p} \equiv \left( -6 \frac{dG_{E}(Q^{2})}{dQ^{2}} \bigg|_{Q^{2}=0} \right)^{1/2}
\]

This definition is consistent with radius extracted from spectroscopy data
Where to find beam with muons and electrons

- **Sep 2011**: original idea
- **2012 - 2014**: MUSE proposal, R&D funding from NSF & DOE, PSI physics approval
- **Sep 15th 2016**: full construction funding from NSF
- **2017**: start building MUSE, beam tests, reviews
- **2018-2019**: assembly, commissioning, beam tests, start taking production data
πM1 / MUSE beamline

- πM1: 100-500 MeV/c RF+TOF sep. π, μ, e

Intermediate Focus Dispersion 7cm/%

πM1

LH₂ target

π, μ, e

protons

π, μ, e

ρ, μ, e

ρ-target
MUSE setup

Non-magnetic spectrometer

Secondary beam

Liquid hydrogen target

Beam $p = 115, 153, 210 \text{ MeV/c}$

$\theta = 20^\circ - 100^\circ$

$Q^2 = 0.002 - 0.07 \text{ (GeV/c)}^2$

$\varepsilon = 0.256 - 0.94$

Particle ID and trajectory determined event by event

Momentum distribution determined by calibration
Beam Hodoscope

Counts and times incoming beam particles

Achieved 80 ps time resolution and 99.8% efficiency.

Observed slight activation from $^{11}$C production, when beam turns off
GEM Telescope

Measures incoming trajectories

Achieved position resolution of 70 μm
Beam Veto

reduces trigger rate from background events
Liquid Hydrogen Target

- Condenser
- Supply/vent tubes
- Alignment tubes (2x)
- Fill/return tube with VCR connection
- Precision stainless steel support tubes (2x)
- LH₂ target cell
- Empty target cell
- CH₂ target
- C target
- Beam focusing detector
- Bull's-eye
- Empty space
Stable cryo-target operation

Temperature $20.67 \pm 0.01$ K

- pressure of $\sim 1.1$ bar

Density $70 \text{ mg/cm}^3$ (stable to 0.02%)

- once equilibrium concentration of para (>99%) and ortho (<1%) hydrogen has been reached

beam does not affect temperature
Straw-Tube Tracker

tracks particles scattered from target with high resolution and high efficiency

consists of four chambers with 5 vertical and 5 horizontal planes each (2864 straws total)

Preliminary analysis of chamber resolution using a small calibration dataset shows position resolution of approximately 120 μm
Beam Monitor

counts and times outgoing beam particles

monitors beam stability

determines particle type independent of RF-time

determines muon and pion momenta based on TOF

vetos Møller / Bhabha scattering background

30 cm
Scattered-particle scintillators

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:

\[ \sigma(\text{Front}) < 50 \text{ ps}, \quad \sigma(\text{Rear}) < 60 \text{ ps} \]
Two-photon exchange at low $Q^2$

- High precision test of TPE for electron and muons at low $Q^2$
- TPE largest theoretical uncertainty in low-energy proton structure
- Expect sign change for $e^+$ and $e^-$ (same applies to muons)
- Projected relative uncertainty in $\mu^+p$ to $\mu^-p$ elastic cross sections
- Systematics: 0.2%

![Diagram of two-photon exchange](image)

![Graph showing $\sigma(\mu^+p)/\sigma(\mu^-p)$ vs. $Q^2$](image)
Radiative corrections for muons

- Recent calculation by Afansev et al. to be published soon
- Integrate from maximum energy down to varying minimum
- Not very sensitive to them
Compare e-p and μ-p elastic cross sections

- projected relative statistical uncertainties in the ratio of e-p to μ-p elastic cross sections
- systematics: 0.5%

- relative statistical uncertainties in the form factors are half as large
Projected sensitivity for MUSE

- **absolute radius** extraction uncertainty similar to current experiments
  \[ \sigma(r_e), \sigma(r_m) \approx 0.009 \text{ fm} \]

- **radius difference**: common uncertainties cancel
  - comparison of \( \mu \) to \( e \), or \( \mu^+ \) to \( \mu^- \)
    insensitive to many syst. errors
  \[ \sigma(r_e - r_m) \approx 0.005 \text{ fm} \]

  \( \rightarrow \) **almost factor two more sensitive** than absolute radius extraction
Many worked on MUSE including dozens of PSI staff

70 MUSE collaborators from 25 institutions in 5 countries:


George Washington University, Montgomery College, Argonne National Lab, Temple University, Duquesne University, Stony Brook University, Rutgers University, Hebrew University of Jerusalem, Tel Aviv University, University of Basel, Paul Scherrer Institute, Johannes Gutenberg-Universität, Hampton University, University of Michigan, University of South Carolina, Jefferson Lab, Massachusetts Institute of Technology, Technical University of Darmstadt, St. Mary’s University, Soreq Nuclear Research Center, Leizmann Institute, Old Dominion University
first precision measurement of proton charge radius with simultaneous low-momentum muon, electron and positron scattering

STATUS
- construction completed
- engaged in commissioning

PLAN
- complete commissioning
- take data for total of 12 months in 2019-2021

EXPECT
- shapes of e- e+ μ- μ+ form factors
- test of existing values for proton radius
- test of two-photon exchange and lepton universality