PROCEEDINGS OF SCIENCE

The MUon Scattering Experiment (MUSE) at the Paul Scherrer Institute

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In 2010, high-precision studies of muonic hydrogen found a notably smaller value for the charge radius than earlier results that have been extracted from elastic electron-scattering data and through the spectroscopy of atomic hydrogen. The MUon Scattering Experiment (MUSE) at the Paul Scherrer Institute (PSI) has been developed to address this so-called proton-radius puzzle. The experiment will measure elastic electron-proton and muon-proton scattering data with positively and negatively charged beams in a four-momentum-transfer range from 0.002 to 0.08 GeV^2. Each of the four sets of data will allow the extraction of the proton charge radius. In combination, the data test possible differences between the electron and muon interactions and two-photon exchange effects. The status of the experiment will be discussed.

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1. Introduction

The proton charge radius can be determined from the slope of the proton's electric form factor G_E at small four-momentum transfers Q^2: $r_p^2 = -6\hbar^2\, dG_E^p/dQ^2\big|_{Q^2=0}$. The form factor typically results from analyzing measured elastic electron-proton cross-sections that include corrections for radiative effects. The charge radius can alternatively be obtained from high-precision measurements of the Lamb shift in hydrogen as the finite size of the proton affects the energy of the s-states but not other states. About twelve years ago, an experiment at the Paul Scherrer Institute performed spectroscopy on muonic hydrogen and determined the charge radius with unprecedented precision [1, 2]. The experiment took advantage of the much larger overlap of the muon s-state wave function with the proton-nucleus compared to the overlap in ordinary hydrogen. They obtained with $r_p = 0.84087(39)$ fm a significantly smaller value of the proton charge radius compared to earlier values based on both electronic hydrogen spectroscopy and electron scattering [3]. Various review articles have discussed this so-called proton radius puzzle, e.g., Refs. [4–6], and explanations ranged from underestimated experimental uncertainties, over novel hadronic physics, to the violation of μ/e universally and a hint at physics beyond the standard model. Two new hydrogen-spectroscopy measurements [7, 8] have confirmed the small radius but one [9] finds a larger value. The result of the new electron-scattering experiment, PRad [10], agrees with the small radius value but is in tension with the earlier data from MAMI [11]. The recent initial-state-radiation experiment at MAMI [12] obtained a larger radius but has too large uncertainties to settle the issue.

The Muon Scattering Experiment (MUSE) [13] at the Paul Scherrer Institute (PSI) will measure $e^{\pm}p$ and $\mu^{\pm}p$ elastic-scattering cross-sections in a Q^2 range between 0.002 and 0.08 GeV$^2/c^2$ in overlapping kinematic settings with beam momenta of 115, 161, and 210 MeV/c [13]. It will directly compare ep and μp in an elastic scattering experiment and be the first experiment that allows the precise extraction of the proton charge radius from muon-proton scattering. Measurements with both charges for the lepton enable studies of possible two-photon exchange mechanisms. Using both e and μ beams provides for a direct test of lepton-type-dependent effects.

2. The MUSE Apparatus

MUSE is placed at the PiM1 beamline of the High-Intensity Proton Accelerator (HIPA) Facility [14] at PSI. The primary proton beam interacts with the carbon M target, and the secondary particles (electrons, muons, and pions) are momentum-selected and transported to the experimental setup. The MUSE collaboration has performed dedicated measurements to characterize the beamline for MUSE [15]. The incident mixed particles are identified and tracked to a liquid hydrogen target. The low luminosity requires large solid-angle detectors for the scattered particles. The experiment covers a range of scattering angles from 20° to 100°. The lepton scattering angle at a given beam momentum determines the kinematics of the reaction in the absence of inelastic reactions off the proton. A magnetic spectrometer to measure the scattered particle momentum is not needed. An overview of the MUSE detector system is shown in Fig. 1.

The plastic-scintillator paddles of the beam hodoscope (BH) planes determine the arrival time of beam particles to better than 100 ps [16]. The beam hodoscope serves multiple purposes in the experiment. It is part of the event trigger and identifies the particle types by their arrival times

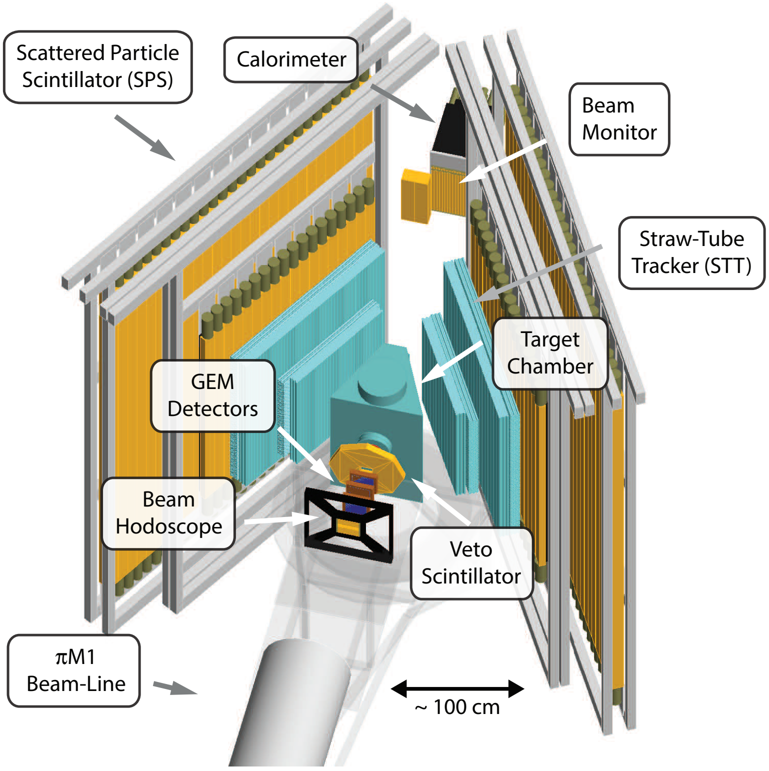

Figure 1: Geant4-based schematic view of the detector setup for the MUSE experiment at the πM1 beam-line at the Paul Scherrer Institute including beam-line instrumentation and scattered particle detectors.

relative to the accelerator's radio frequency (50 MHz). Together with the thick scintillators of the beam monitor, it determines in dedicated measurements the muon- and pion-momentum by time-of-flight. Together with the scattered-particle scintillators, it determines the reaction type of the event, particularly the discrimination between muon-proton scattering and muon decay-in-flight. The GEM detectors, downstream of the beam hodoscope, with an active area of 10 cm by 10 cm, track the incident beam particles into the target to reconstruct the scattering kinematics. The GEM detectors have achieved a position resolution of 70 μm. The veto detector is a scintillation detector with a small aperture on the beam axis in front of the target chamber. The detector vetos background events with off-axis particle tracks, e.g., after particle decay. The BH, GEM, and veto detectors are mounted on a sliding table that allows path-length variations for the time-of-flight measurements of up to 660 mm.

The primary MUSE target is liquid hydrogen in a cylindric 6-cm-diameter vessel inside the trapezoidal vacuum chamber [17]. The axis of the cell is perpendicular to the beamline. The LH_2 temperature has been observed to be stable, corresponding to a target-density stability of 0.02%. Other targets inside the chamber include an empty target, C and CH_2 targets, and empty space.

Small plastic scintillators, the beam focusing monitor, have been added to the target ladder to facilitate tracking calibrations [16].

The straw-tube trackers (STT) to the left and right of the beam direction provide high-resolution and high-efficiency tracking of the scattered particles from the target. Each STT consists of ten vertical and ten horizontal planes on each side with 60-cm and 90-cm long straw tubes. The high-resolution scattered-particle scintillators (SPS) serve in the event trigger and provide timing for the rejection of muon-decay background. The 18 short, 120-cm long, front-wall bars have a time resolution of better than 50 ps, the 28 220-cm long bars of each rear wall of better than 60 ps. MUSE does not measure the final-state particle momentum, and the experimental reaction yield will be integrated for each scattering angle from the lepton detection threshold to the momentum endpoint. The SPS detectors are energy calibrated close to the detection threshold with ^{22}Na, ^{88}Y, and ^{208}Tl gamma sources to precisely determine that threshold.

The beam monitor (BM) is located downstream of the target. It is segmented with 32 thin scintillators in the center flanked by two thick scintillators on each side of the beam. Those thick scintillators are with 30-ps resolution, the most precise timing detectors in MUSE. The BM helps to measure beam properties and to suppress background from Møller and Bhabha scattering. The BM is suspended on rails that accommodate a path-length variation from the BH of about 100 cm for the beam-momentum determination using the time-of-flight technique.

A photon calorimeter with 64 lead-glass crystals is mounted downstream of the beam monitor. The calorimeter will reduce the experimental ep yield close to the lepton detection threshold by vetoing events with hard initial-state radiation. It thus helps control radiative corrections for the elastic ep scattering reaction [18]. The radiative corrections for μp scattering are much smaller than ep ones due to the larger muon mass.

3. Anticipated results from MUSE

The experiment aims for systematic uncertainties of the elastic cross sections below 0.5%. Anticipated uncertainties for the electric form factor are shown in Fig. 2 along with experimental results of the PRad and Mainz experiments. The very competitive uncertainties of MUSE will help address the tension between the two experiments. The proton charge radius will be separately extracted from the electric form factors of the μp and ep data for both charges. However, MUSE will be most sensitive in the determination of potential *differences* between the extracted μ and e radii with $\sigma(r_e - r_\mu) \approx 0.005$ fm. Any observed differences in the μp and ep cross-sections may hint at issues with the radiative corrections or new physics [15].

Using lepton beams with positive and negative charges in the same setup allows MUSE to study the effects of two-photon exchange (TPE). At leading order, two-photon corrections, $\delta_{2\gamma}$ cause deviations from unity of the cross-section ration $\sigma^+/\sigma^- \approx 1 + 2\delta_{2\gamma}$. Anticipated systematic uncertainties in the cross-section ratio are 0.2%. Although the effect is expected to be small, MUSE might be able to study the predicted differences in μp and ep TPE, e.g., Refs. [19, 20].

The commissioning of MUSE is mainly completed. Initial production data were taken in Fall 2021 at 115 MeV/c beam momentum, and additional beam time is expected for the second half of 2022 and beyond.

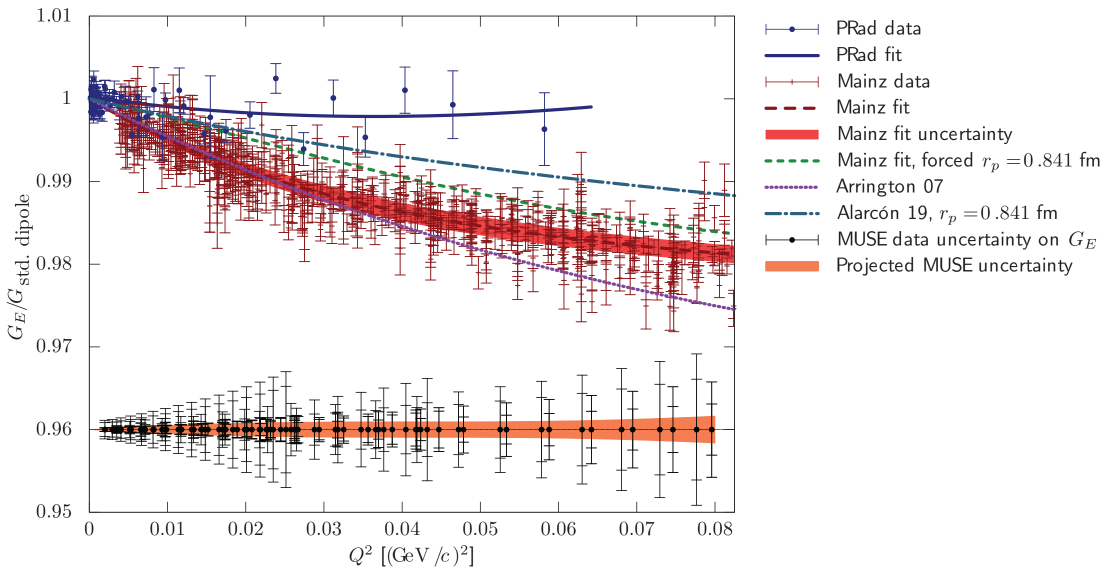

Figure 2: Experimental results for G_E relative to the dipole form factor from the PRad [10] and Mainz [11] experiments along with various parameterizations. The expected results from μp and ep of MUSE, arbitrarily placed at 0.96, are shown with inner and outer error bars for positive and negative lepton charges, respectively. The figure is from [21].

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