TRIUMF-2022 IOP Publishing
Journal of Physics: Conference Series **2391** (2022) 012015 doi:10.1088/1742-6596/2391/1/012015

Lepton Universality Test with MUSE at PSI

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Abstract. Lepton universality (LU) typically refers to the lepton coupling, which is considered to be the same for e, μ, and τ leptons, if the interaction is electroweak according to the Standard Model, and it is hence a compelling probe for New Physics. The same principle of universal electroweak lepton interaction leads to the expectation that lepton scattering yields are equal for e and μ beams under the same kinematic condition. The mere mass difference between e and μ affects kinematic quantities (such as the relation between scattering angle and Q^2), and the lepton mass dependence of elastic cross sections for leptons scattered from structured and pointlike objects are taken into account. By comparing e^+, e^-, μ^+, and μ^- scattering yields, two-photon exchange (TPE) effects, universal or not, can be separated from the general LU test of the e/μ yield ratio. With its separable mixed beams of e^+/μ^+ and e^-/μ^-, respectively, the MUSE experiment at PSI is not only designed to measure the proton charge radius with four lepton species, but is also uniquely suited to probe TPE and LU, while benefitting from partial cancellations of certain shared systematics. An overview will be given of the MUSE experiment, the sensitivity, and the present status.

1. Introduction

The Proton Radius Puzzle (PRP) began in 2010 with the then two most precise measurements of the proton charge radius [1, 2] contradicting each other at the 5-7 σ level [3, 4] or by 4% of the radius value. One measurement was based on a novel method using the Lamb shift in muonic hydrogen with enhanced sensitivity to the finite proton size effect on the 2S-2P transitions, resulting in a radius of about 0.84 fm, substantially smaller and more precise than the previous world average [1, 5]. The other measurement used a very large and comprehensive data set obtained with traditional electron scattering from hydrogen with high resolution spectrometers, resulting in a larger radius value of about 0.88 fm and consistent with the previous world average from decades of atomic hydrogen spectroscopy and electron scattering data [2, 6]. Several following experiments using scattering and spectroscopy methods, as well as a number of global analyses, obtained radius values covering the entire size of the puzzle, with the present situation remaining inconclusive [7]. If the discrepancy given by the two data sets from 2010 is true, it could hint to signals beyond the Standard Model in the muon-electron sector of lepton non-universality.

The MUSE experiment at Paul-Scherrer Institute (PSI) was conceived upon the fact that there have been precise radius determinations with spectroscopy both from regular and muonic hydrogen, while only electrons had been used for radius measurements from elastic scattering, and there has been no data from muon scattering with enough precision to discriminate between the contradicting data sets. Muon beams are necessarily generated as secondary beams with properties different from electron beams in electron accelerators. The secondary beam of the piM1 beamline at PSI includes besides muons also electrons and pions. A magnetic chicane is used to prepare the secondary beam with chosen charge polarity and selected momentum bite. The beam intensity is typically a few MHz with a 20 ns repetition rate for the primary proton beam in continuous wave mode. The e, π, and μ particles arriving at the MUSE experiment differ in their arrival time due to different average velocities of the three particle types. Three beam momenta of 115, 160, and 210 MeV/c are chosen for which the separation in arrival times between e, π, and μ is maximized to become several ns within the 20-ns repeating window. Secondary beams, like the one used at the piM1 beamline, are typically focussed to a finger-width beamspot and exhibit significant angular variation within the beam envelope, and thus require event-by-event beam particle tracking to provide the reference for an accurate scattering angle determination with the scattered particle detection system. The properties of the piM1 beamline at PSI used for the MUSE experiment have been fully characterized experimentally and matched with dedicated simulations [8].

2. MUSE setup

A schematic view of the MUSE setup is shown in Fig. 1, consisting of a mixed, collimated e/μ/π beam, scintillating-fiber beam hodoscopes (BH) for time-of-flight and position, Gas Electron Multiplier (GEM) tracking detectors for precise beam particle position and angle, a liquid hydrogen target, as well as drift tube chambers (STT) and scintillator walls (SPS) to detect scattered particles. Located downstream of the target is a beam monitor hodoscope (BM) for luminosity monitoring and quality control, and an electromagnetic calorimeter (CALO) to control radiative corrections.

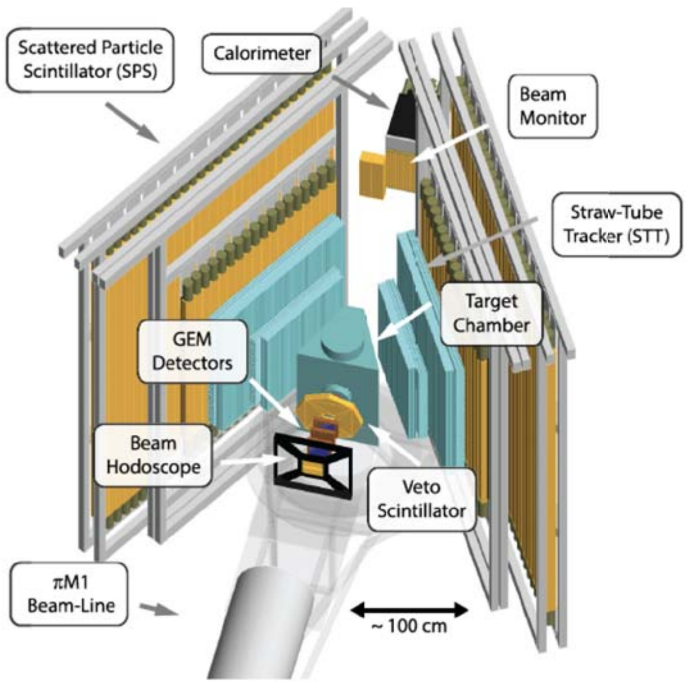

Figure 1. Schematic view of the MUSE setup.

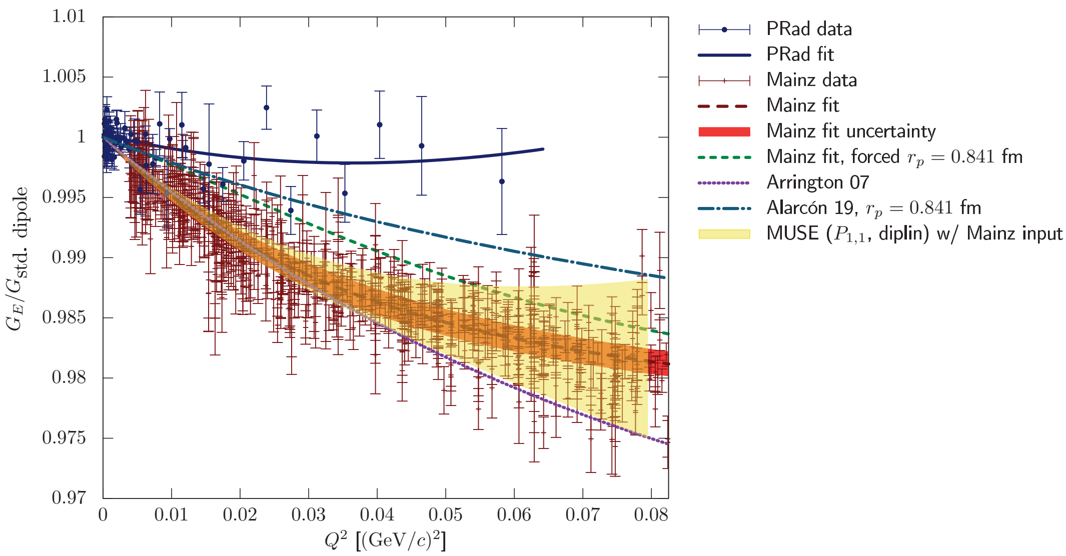

Figure 2. Figure courtesy of J.C. Bernauer. The plot shows the proton electric form factor G_E normalized by the standard dipole $G_{\text{std. dipole}} = (1 + Q^2/0.71)^{-2}$ as a function of Q^2, with data from Mainz [6] and Jefferson Lab [9], and several curves representing a variety of analyses. The projected error band for MUSE is overlaid in yellow.

3. Sensitivity

The MUSE experiment will measure elastic cross sections, extract the electric form factor over a wide range of four-momentum transfer, $Q^2 = 0.002 - 0.07$ (GeV/c)^2, and determine the proton charge radius with four different lepton probes. Figure 2 shows the distribution of the electric form factor G_E, normalized to the dipole form factor, at low Q^2, with data from Mainz [6] and Jefferson Lab [9], and several curves that represent a variety of analyses. Overlaid in yellow is the expected uncertainty band for a future extraction with MUSE data. The precision will be high enough to distinguish between the discrepant data sets from Mainz and Jefferson Lab.

The TPE effects are studied by comparing the yields between the charge polarity of a given lepton family e^+ vs. e^-, and μ^+ vs. μ^-, respectively, shown for muons in Fig. 3, for the planned three values of beam momentum settings [10].

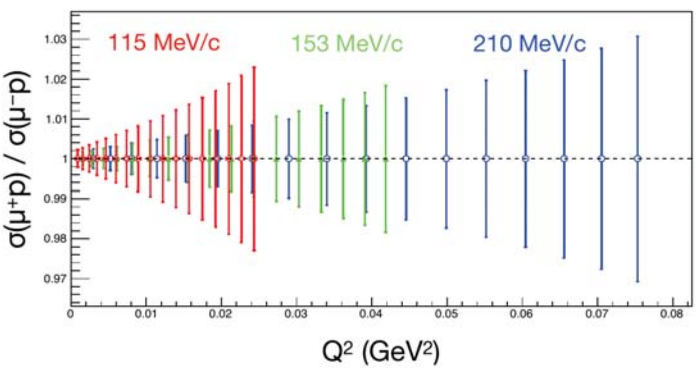

Figure 3. Relative uncertainties in the ratio of μ^+p to μ^-p elastic cross sections, also referred to as muon two-photon exchange (TPE) ratio.

The TPE effect is canceled in the charge average, i.e. precise cross sections, electric form factor distributions, and charge radii are extracted for both lepton species, e and μ. The differences of cross sections, form factors, and charge radii between the e and μ probes are sensitive to lepton non-universality, and are measured with even higher precision than the individual quantitities, since some of the systematic uncertainties are common to both species present in the same beam under the same experimental and kinematic conditions, and partially cancel. The projected uncertainties for lepton universality tests for the three beam momenta are shown in Fig. 4 [10].

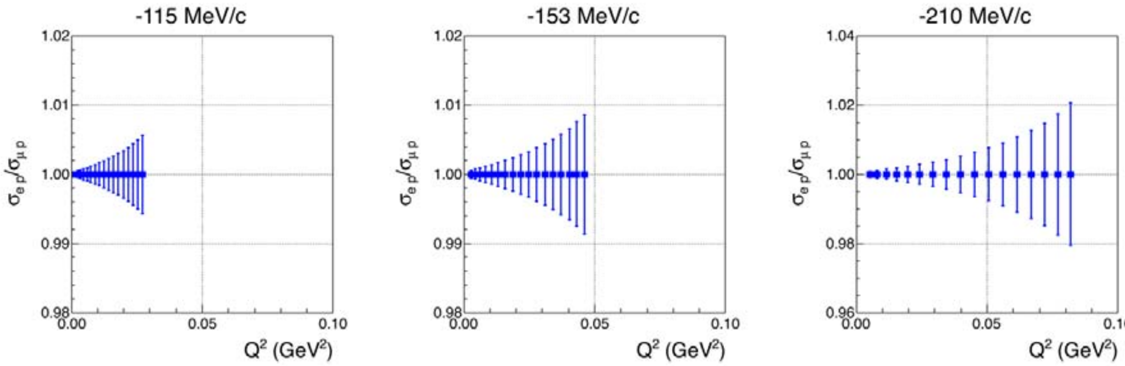

Figure 4. Relative uncertainties in the ratio of μp to ep elastic cross sections, also referred to as lepton universality (LU) ratio.

4. Status and Timeline

The MUSE experiment was first conceived at a workshop in Morocco in discussions between Ron Gilman, Gerald Miller, and M.K. [11] - it was first proposed to the Program Advisory Committee at PSI in 2012 [12] and conditionally approved in 2013 [13]; from 2013-2016 beamline and detectors tests were performed at the piM1 beamline to identify the best design of the MUSE experiment. Funding to construct the apparatus began in 2016 following the approved baseline design documented in the Technical Design Report [10]. Initial construction was completed in 2019 [14, 15]. Commissioning of the full apparatus began in 2019 and has been reiterated through 2022, including a full characterization of the piM1 beamline [8]. In 2021 a first scattering data set was collected. In 2022 the apparatus was further improved by adding an enlarged electromagnetic calorimeter in the downstream region to control radiative corrections, and by adding active veto counters inside the scattering chamber to suppress reading out events originating from chamber-post scattering. Further scattering data taking is beginning in Fall 2022, for a total of 12 beam months over the next two years to acquire the required statistics.

Acknowledgments

This material is based upon work supported by the National Science Foundation under NSF grants PHY-1812402 and PHY-2113436. The MUSE experiment is supported by the Department of Energy, NSF, PSI, and the US-Israel Binational Science Foundation.

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