Studying the Proton "Radius" Puzzle with μp Elastic Scattering

The MUon proton Scattering Experiment (MUSE) Collaboration

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The Proton Radius Puzzle is the inconsistency between the proton radius determined from muonic hydrogen and the proton radius determined from atomic hydrogen level transitions and ep elastic scattering. No generally accepted resolution to the Puzzle has been found. Possible solutions generally fall into one of three categories: the two radii are different due to novel beyond-standard-model physics, the two radii are different due to novel aspects of nucleon structure, and the two radii are the same, but there are underestimated uncertainties or other issues in the ep experiments.

Here we discuss a simultaneous measurement of μ^+p and e^+p scattering, as well as μ^-p and e^-p scattering, which will allow a determination of the consistency of the μp and the ep interactions. The differences between $+$ and $-$ polarity scattering are sensitive to two-photon exchange effects, higher-order corrections to the scattering process. The slopes of the cross sections as $Q^2 \rightarrow 0$ determine the proton "radius". We plan to measure relative cross sections at a typical level of a few tenths of a percent, which should allow the proton radius to be determined at the level of ≈ 0.01 fm, similar to previous ep measurements. The measurements will test several possible explanations of the proton radius puzzle, including some models of beyond standard model physics, some models of novel hadronic physics, and some issues in the radius extraction from scattering data.

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I. PHYSICS MOTIVATION

A. Introduction

The *Proton Radius Puzzle* refers to the disagreement between the proton charge radius determined from muonic hydrogen and determined from electron-proton systems: atomic hydrogen and *ep* elastic scattering. Up until 2010, the accepted value for the proton radius was 0.8768±0.0069 fm, determined essentially from atomic hydrogen measurements in the 2006 CODATA analysis [1]. The best *ep* scattering result was probably 0.895 ± 0.018 fm, from the analysis of Sick [2]. The consistency of these two results made the muonic hydrogen determination of 0.84184 ± 0.00067 fm by Pohl *et al.* [3] quite surprising. The $\approx 5\sigma$ discrepancy, in terms of the order of magnitude less precise electron measurements, has attracted much attention. It has motivated numerous invited talks, dedicated sessions at several meetings, a Workshop on the Proton Radius Puzzle at the European Center of Theory in Trento, Italy [4], a review paper [5], some new experiments, and stories in the popular media. The paper by Pohl *et al.* has been cited about 200 times to date. Some of the numerous suggestions for how the Puzzle might be resolved are discussed below.

The Puzzle has been reinforced by three more recent experimental results and the 2010 CODATA analysis. First, a precise *ep* scattering cross section measurement [6] at Mainz determined ≈1400 cross sections in the range $Q^2 = 0.0038 \rightarrow 1$ GeV^2. The Mainz analysis of only their data with a wide range of functional forms led to a proton electric radius of 0.879 ± 0.008 fm. Second, an experiment [7] at Jefferson Lab measured $\vec{e}p \rightarrow e'\vec{p}$ to determine 1% form factor ratios in the range Q^2 = 0.3 → 0.8 GeV^2. An analysis of world data (excluding the Mainz data set but including the data analyzed in [2]) resulted in a radius of 0.870 ± 0.010 fm, consistent with the Mainz electric radius determination – although there were differences in the magnetic radius determination. Third, a new muonic hydrogen measurement by Antognini *et al.* [8] has recently reported a value for the proton radius, $r_p = 0.84087 \pm 0.00039$ fm, in agreement with the Pohl *et al.* measurement. Antognini *et al.* also report a magnetic radius consistent with electron scattering results, though in this case with uncertainties a few times larger. The 2010 CODATA analysis

[9] included the Mainz result – the JLab result appeared too late to be included – and adopted a proton radius value of $r_p = 0.8775 \pm 0.0051$ fm. The CODATA analysis concluded that: *“Although the uncertainty of the muonic hydrogen value is significantly smaller than the uncertainties of these other values, its negative impact on the internal consistency of the theoretically predicted and experimentally measured frequencies, as well as on the value of the Rydberg constant, was deemed so severe that the only recourse was to not include it in the final least-squares adjustment on which the 2010 recommended values are based.”* The Particle Data Group recently concluded that: *“Until the difference between the ep and μp values is understood, it does not make sense to average all the values together. For the present, we stick with the less precise (and provisionally suspect) CODATA 2012*[1] *value. It is up to workers in this field to solve this puzzle.”* Thus, the discrepancy between muonic and electronic measurements of the proton radius has increased from 5σ to 7σ in the past almost 3 years, and the inconsistency of the results is widely recognized. A partial summary of recent proton radius extractions is shown in Fig. 1.

Arguably, the Proton Radius Puzzle is more puzzling today than when it first appeared. Not

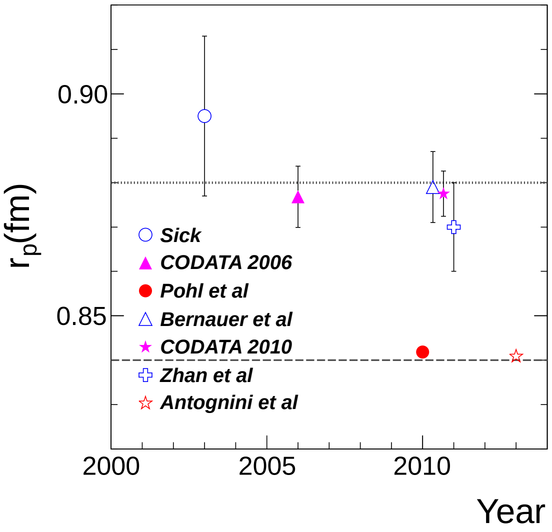

FIG. 1. A summary of some recent proton charge radius determinations: Sick [2], CODATA 2006 [1], Pohl *et al.* [3], Bernauer *el al.* [6], CODATA 2010 [9], Zhan *et al.* [7], and Antognini *el al.* [8].

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[1] Note that the CODATA 2010 result appeared in 2012.

only has the discrepancy increased, but numerous possible explanations of the Puzzle have been shown to not work. There have been suggestions of issues in the μp radius determination, issues in the *ep* radius determination, novel hadronic physics, and novel beyond standard model (BSM) physics. We briefly review the suggested explanations here. More detail can be found in talks at the Trento Workshop [4], and in the review paper by Pohl, Gilman, Miller and Pachucki [5].

The finite size of the proton causes a small perturbation to the Coulomb potential that basically shifts the energies of only *s* states. The effect can be determined through Lamb shift measurements, given a sufficiently accurate relativistic theory that accounts for recoil corrections, vacuum polarization, etc., as the finite size effect is rather small. The atomic physics calculations have now all been repeated and verified by independent groups, and it is believed that at the level of the muonic hydrogen experiment there is no significant missing or uncalculated higher order physics. The extraction of the radius from muonic hydrogen also requires some knowledge of additional details of the proton's structure – e.g., the third Zemach moment – but it is generally believed that there are no significant issues here; we will return to this point below. Experimentally, once the laser system exists, the muonic hydrogen measurement is 8,000,000 times more sensitive to the proton radius than an electronic hydrogen measurement, as $\psi(r = 0) \propto m_l^3$, so the muonic hydrogen experiment appears to be the most solid of all the experimental results.

Issues in the *ep* experiments would appear to be unlikely. It would be odd if two independent techniques, atomic hydrogen and *ep* scattering, gave the same wrong result, especially as there are two independent *ep* analyses from different data sets. However, the CODATA analyses neglect that the atomic hydrogen measurements were done by only a few groups, and thus likely there are some correlations between the results; they are not entirely independent. Also, nearly all the atomic hydrogen results are individually within 1σ of the muonic hydrogen result. Only one is 3σ away. Only when all the atomic hydrogen results are averaged does the discrepancy become so impressive. Thus, the uncertainty in the atomic hydrogen result is probably underestimated.

Numerous mistakes have been made over the years in determining the radius from *ep* scattering analyses, and there continues to be a range of results. The analysis of Sick [2] was arguably the first to include all necessary ingredients to get a reliable answer, and more recent analyses tend to as well, although typically insufficient attention is paid to the issue of model dependence. In addition to the results reported by the experimenters above, we can consider the dispersion relation analysis of [10] ($r_p = 0.84 \pm 0.01$ fm with χ^2/d.o.f ≈ 2.2), the z expansion of [11] ($r_p = 0.871$ fm $\pm$ 0.009 fm $\pm$ 0.002 fm $\pm$ 0.002 fm), the sum-of-Gaussians fit of [12, 13] ($r_p = 0.886$ fm $\pm$ 0.008 fm), and unpublished Taylor expansion fits to the low Q^2 data by C.E. Carlson and K. Griffioen ($r_p \approx$ 0.84 fm). Of these recent analyses, there are reasons to favor the two analyses yielding larger radii – see [5] – but the variation in results does suggest that the uncertainty arising out of the fits is underestimated.

There have been a number of suggestions of novel hadronic physics, but almost none of them are accepted by experts as reasonable. It is hard to see how narrow structures in the form factors or anomalously large third Zemach moments arise out of conventional hadronic physics. The one existing viable idea [14] is that the uncertainty in the two-photon exchange term coming from the proton polarizibility is underestimated; changes in this term affect the radius extracted from muonic hydrogen. Technically, evaluating the polarizibility requires elastic, inelastic, and subtraction terms, where the subtraction term is needed for convergence. The subtraction term diverges without the introduction of a form factor, which has known behavior at small and large Q^2, but at present does not appear constrained at intermediate Q^2. Typical assumptions lead to the subtraction term contribution and uncertainty having an effect that is only a few percent of the Puzzle, but at present it appears that there is no constraint from data – only theoretical bias – that prevents it from being much larger. We note that this explanation of the puzzle affects mainly the muon, as the effect is proportional to the m^4_{lepton}, and that this effect predicts enhanced two-photon exchange effects in muon scattering from the proton.

If the experiments are not wrong, and there is no novel hadronic physics, novel BSM physics has to be considered. Previous measurements of lepton universality and numerous other data, such as the muon $(g-2)$ measurements, constrain possible models of new physics. Nevertheless, several models have been created. Tucker-Smith and Yavin [15] found that a new scaler force carrier in the

MeV mass range is not ruled out by other data and could account for the Proton Radius Puzzle. The main constraint is that the scaler needs to have smaller coupling to the neutron than to the proton. Batell, McKeen, and Pospelov [16] indicate that there are a number of ways new forces can evade existing constraints but lead to the Proton Radius Puzzle. In particular, they consider a combination of new vector and scaler particles with masses of 10's of MeV. The combination of two new particles allows the Puzzle to be explained while evading other constraints. This model leads to enhanced parity violation in muon scattering and in muonic atom radiative capture. Rislow and Carlson [17] show that one can explain the Puzzle while evading other constraints by a combination of new scaler and pseudoscalar, or new vector and pseudovector, particles. The allowed coupling constants are constrained by the Puzzle and muon $(g-2)$, and the mass ranges are constrained by K decays, but not too much if the new forces couple much more strongly to muons than to electrons. Thus there are a variety of possible BSM explanations of the Puzzle, with parameters constrained by existing data, and with potentially observable consequences in several experiments.

The various explanations of the Puzzle were reviewed during the Proton Radius Puzzle Workshop [4] in Trento, Italy from Oct 29 - Nov 2, 2012. The workshop, organized by R. Pohl, G. A. Miller, and R. Gilman, included nearly 50 experts in atomic and nuclear theory and experiment, as well as BSM theory. At the end of the workshop, a vote was held the likely resolution of the Puzzle. The about equally favored alternatives were BSM physics and issues in the *ep* experiments. There was also support for the proton polarizibility explanation described above, and a significant fraction of the community that was uncertain about the most likely explanation.

A number of experiments that might help resolve the Puzzle were discussed at the Workshop. Efforts to perform new atomic hydrogen experiments in the next 5 - 10 years could help confirm the Puzzle exists, or instead indicate consistency in the muonic and electronic atomic physics measurements. A new muonic deuterium experiment can be compared with the electron-deuteron radius measurements to check for consistency. A new Jefferson Lab experiment [18] approved by PAC39 plans to measure very low Q^2 electron scattering, from $\approx 10^{-4}$ GeV^2 to 10^{-2} GeV^2, perhaps as early as 2015. We quote from Jefferson Lab PAC38: "*Testing of this result is among* *the most timely and important measurements in physics.*" The efforts of the MUSE collaboration – the focus of this White Paper – to compare $\mu^{\pm}p$ and $e^{\pm}p$ elastic scattering were also discussed. The Workshop conferees strongly supported all of the experimental efforts; since the origin of the Puzzle is uncertain, it is not clear which of the possible experiments will give us the data that resolves the Puzzle.

To summarize, in the nearly 3 years since it appeared, the Proton Radius Puzzle has become more puzzling, not less. New experimental results confirm the puzzle. Theoretical studies have ruled out many possible explanations, leaving only a few possible. The Puzzle has attracted wide interest, not just in the atomic, nuclear, and particle physics communities, but in the popular science media as well, demonstrating the timeliness of resolving this issue.

B. Muon-Proton Scattering Experiments

The MUSE experiment was created on recognizing that the proton radius has been measured in muonic and electronic atomic systems, and in electron-proton elastic scattering, but not in muon-proton elastic scattering. Here we describe some previous tests of lepton universality, the equivalence of muons and electrons, that were largely done about 30 years ago. We will focus on μp and ep scattering.

One of the better early μp elastic scattering experiments was Ellsworth *et al.* [19], which found that cross sections in the range $Q^2 \approx 0.5$ - 1 GeV^2 were about 15% below the standard dipole parameterization, $G_E = G_M/\mu_p = (1 + Q^2/0.71)^{-2}$ with Q^2 in GeV^2, and a similar percentage below modern form factor fits, as shown in Fig. 2. While this suggests an ep vs. μp interaction difference, Ellsworth *et al.* interpreted the difference as an upper limit on any difference in μp and ep interactions. These data are too high in Q^2 to make any inferences about the proton radius. A subsequent experiment [21] covering $0.15 < Q^2 < 0.85$ GeV^2 found μp cross sections about 8% smaller than the electron scattering results, similar to [19], and considered the μp and ep scattering results consistent within uncertainties. A final elastic scattering experiment [22] analyzed the ratio of proton elastic form factors determined in μp and ep scattering as $G^2_{\mu p}/G^2_{ep} =$

$N(1+Q^2/\Lambda^2)^{-2}$, with the result that the normalizations are consistent with unity at the level of 10%, and the combined world μp data give $1/\Lambda^2 = 0.051 \pm 0.024$ GeV^{-2}, about 2.1σ from the electron-muon universality expectation of 0. For deep-inelastic scattering [23], a similar analysis yields a normalization consistent with unity at the level of 4% and $1/\Lambda^2 = 0.006 \pm 0.016$ GeV^{-2}. In summary, old comparisons of ep and μp elastic scattering were interpreted as indicating no differences between μp and ep scattering, within the 5% – 10% uncertainties of the experiments. In light of the Proton Radius Puzzle, it seems that the directly measured constraints on differing μp and ep interactions are insufficient. While ep studies have advanced significantly in the past decades, the μp work has not.

Two-photon exchange effects have also been tested in μp scattering. In [24], no evidence was found for 2γ effects, as $\mu^+ p$ vs. $\mu^- p$ elastic scattering cross section asymmetries were consistent with 0, with uncertainties from 4 → 30%, and with no visible nonlinearities in Rosenbluth separations at $Q^2 \approx 0.3$ GeV^2. The Rosenbluth cross sections were determined to about 4%. Tests in ep scattering [25] have found no nonlinearities even with ≈1% cross sections; improved exper-

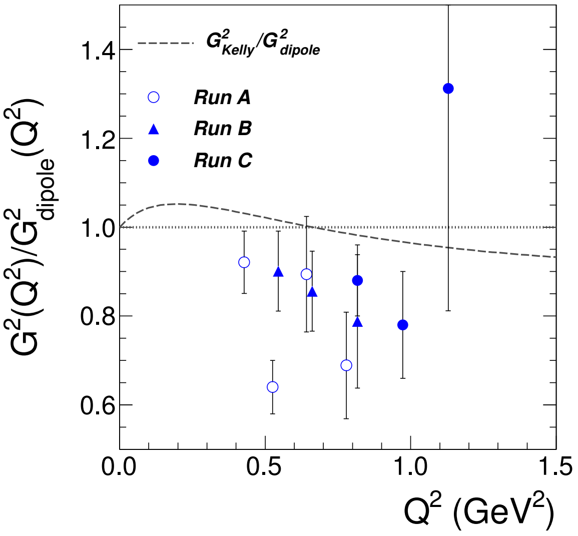

FIG. 2. Reduced cross sections, $d\sigma/d\Omega/d\sigma/d\Omega_{Mott}$, for μp elastic scattering, from Ellsworth *et al.* [19]. The data are somewhat below expectations from the dipole form factor parameterization. Use of the more modern Kelly parameterization [20] does not qualitatively change the result.

iments are underway [26]. Current best estimates of the size of the nonlinearities in Rosenbluth separations for *ep* scattering are typically at the percent level. Thus, it seems again in light of current knowledge that two-photon exchange has not been precisely enough studied in the case of μp scattering.

The radius of ^{12}C is one of the most precisely determined radii from electron scattering. The electron scattering result [27] is $\langle r^2 \rangle^{1/2} = 2.472 \pm 0.015$ fm, based on scattering of 25 – 115 MeV electrons at momentum transfers from 0.1 – 1.0 fm^{-1}, or $Q^2 \approx 0.0004$ - 0.04 GeV^2. A subsequent analysis of world data [28] found that dispersive corrections increase the extracted radius to 2.478 ± 0.009 fm. The charge radius was also measured by determining the ≈90 keV X-ray energies in muonic carbon atoms to several eV [29]. Assuming a harmonic oscillator nuclear charge distribution led to a ^{12}C radius of $\langle r^2 \rangle^{1/2} = 2.4715 \pm 0.016$ fm. A subsequent muonic atom experiment[30] found $\langle r^2 \rangle^{1/2} = 2.483 \pm 0.002$ fm. There is a consistent result for the carbon radius from a μC scattering experiment [31], but with uncertainties an order of magnitude worse. There is evidently no μp vs. *ep* issue in the carbon radius determination. There are several possible reasons why there might be a μ / e difference in the proton but not in carbon. Examples include opposite effects in the case of μn vs. μp interactions, and the charge distribution in carbon resulting largely from orbital motion of the nucleons, in which there is no effect, vs. charge distributions of the nucleons, in which there is an effect.

To summarize, direct comparisons of μp and *ep* scattering were done, but with poor overall precision. The comparisons were also at sufficiently large Q^2 that they would not be sensitive to the proton radius. Measurements sensitive to 2γ exchange were also performed, but at a level that we now believe is not sufficiently precise to provide significant results. While the carbon radius is much better determined, and is consistent for muon and electron measurements, the implications of this for the Proton Radius Puzzle are not clear.

C. Motivation Summary

The Proton Radius Puzzle has attracted wide interest, but the resolution to the Puzzle is unclear. It might arise from beyond standard model physics, novel hadronic physics, or issues and / or underestimated uncertainties in the determination of the radius from the actual experimental data. There is strong support in the community for a number of experiments that test different explanations for the Puzzle. New ep atomic physics and scattering experiments are planned, as are additional muonic atom experiments.

The MUSE experiment presented here is the only proposed μp elastic scattering experiment. MUSE intends to

- measure both μp and ep scattering in the low Q^2 region,
- measure both charge signs,
- extract form factors and proton radii,
- compare ep and μp scattering, form factors, and radii as a test of lepton (non-)universality,
- study the possibility of unexpected structures and/or extrapolation errors affecting the radius extraction, and
- determine two-photon exchange effects, to test their effect on the radius extraction and to test possible hadronic physics explanations of the Puzzle.

Thus the MUSE experiment looks at several possible explanations of the Proton Radius Puzzle.

II. MEASUREMENT OVERVIEW

The MUSE measurement is planned for the πM1 beam line at the Paul Scherrer Institut (PSI), in Villigen Switzerland. The MUSE approach to resolving the Proton Radius Puzzle is to measure simultaneously elastic $\mu^{\pm}p$ scattering and $e^{\pm}p$ scattering. The μp scattering will be compared to ep scattering at the cross section level, with extracted form factors, and ultimately with an extracted radius. Measurements with the two beam polarities will be compared to determine the (real part of the) two-photon exchange. The basic idea is to provide a higher precision comparison of μp and ep interactions in a region sensitive to the proton radius, and to check that the two-photon exchange is under control, and does not distort the extraction of the radius. At the same time, these data can check predictions of enhanced two-photon exchange from novel hadronic physics, and certain BSM physics models that affect the form factors in μp vs. ep determinations.

In electron scattering, high precision experiments have typically used an intense, low-emittance beam incident on a cryotarget, with scattered particles detected by a high-resolution, small solid angle spectrometer. A muon scattering experiment must be different because the intense low-emittance primary electron beam is replaced by an $8-9$ orders of magnitude less intense, much larger emittance, secondary muon beam, which is also contaminated with electrons and pions. To run a high precision experiment in these conditions requires several adjustments. The low intensity necessitates a large acceptance spectrometer and long run times. The large emittance necessitates measuring the individual beam particle incident trajectories. The presence of several different particle species in the beam requires identifying each individual beam particle type.

The difficulties of muon scattering are in part compensated by several advantages. Since the muon beam is a secondary beam, one can easily obtain essentially identical beams of both charge signs, which allows a precise determination of two-photon exchange effects. Conventional two-photon effects are expected to be of order 1% – though they have not been measured that precisely – and have the potential to affect the extracted radius; there is also the possibility that the proton polarizibility in the underlying cause of the Puzzle, and it will lead to enhanced two-photon exchange. Here the effects of two-photon exchange can be determined and the average of $\mu^{\pm}p$ cross sections removes the two-photon exchange contributions from the cross sections and the form factors. The low muon intensity eliminates target density fluctuations from beam heating. The electron contamination in the beam allows a simultaneous measurement of ep scattering for comparison with the muon scattering. The use of a non-magnetic spectrometer allows the solid angle to be determined more precisely than is typically possible with a magnetic spectrometer.

A precise measurement also requires an amount of kinematic overlap, measuring cross sections multiple times to ensure that the experimental systematics are well understood. In electron scattering experiments this can be done with multiple beam energies and overlapping spectrometer settings, using a monitor spectrometer to confirm the relative luminosity for each setting at a fixed beam energy. In MUSE the overlap is provided by using 3 beam momenta and two independent large solid angle spectrometer systems. A run with the spectrometer wire chambers rotated by a small angle is also planned as a cross check.

MUSE runs in several stages. Initial beam tests in Fall 2012 verified the basic properties of the muon beam in the πM1 beam line at PSI. A second round of beam tests will run in summer 2013; these tests will study beam properties in more detail using GEM chambers, prototype a quartz Cerenkov detector, and do a simplified scattering experiment to verify simulated backgrounds. As equipment is constructed, we expect additional beam tests of various experiment components, described in more detail below, leading up to a two-month "dress rehearsal" measurement with beam line detectors and at least one spectrometer, perhaps in late 2015. The dress rehearsal is intended to be a high statistics study to investigate any potential issues with the equipment as built or with backgrounds. Assuming analysis of this initial high statistics measurement confirms the experiment functionality, MUSE is ready to commence a two year production run.

III. EXPERIMENTAL DETAILS

A. Muon Beam Line

The PSI πM1 beam line provides a mixed muon / pion / electron beam with a $\approx$50 MHz time structure. The three beam momenta selected, $p_{in} \approx 115$ MeV/c, 153 MeV/c, and 210 MeV/c, are chosen both to cover a kinematic range and provide overlaps, and because at these three momenta, with the expected detector geometry, the different beam particle types can be efficiently separated using RF time measurements. Magnet polarities can be reversed to allow the channel to transport either positive or negative polarity particles.

B. Detector Overview

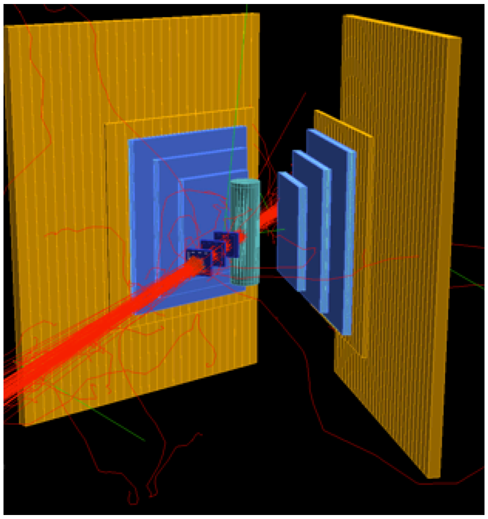

FIG. 3. A Geant4 simulation showing part of the MUSE experimental system. Here one sees the beam going through the GEM chambers and the scattering chamber, along with the spectrometer wire chambers and scintillator hodoscopes. The beam SciFi's, quartz Cerenkov, and beam monitor scintillators are missing from this view.

The πM1 channel features a momentum dispersed ($\approx$7 cm/%) intermediate focal point (IFP) and a small beam spot ($\sigma_{x,y} < 1$ cm) at the scattering target. The base line design for the MUSE beam detectors has a collimator and a scintillating fiber detector (SciFi) at the intermediate focus. Some of the detectors in the target region are shown in Fig. 3. After the channel and immediately before the target there are a SciFi detector, a quartz Cerenkov detector, and a set of GEM chambers. A high precision beam line monitor scintillator hodoscope is downstream of the target.

The IFP collimator serves to cut the πM1 channel acceptance to reduce the beam flux to manageable levels. The IFP SciFi measures the RF time, for use in determining particle type, and measures beam particle position, to determine the particle momentum and thus the beam momentum spectrum.

The target SciFi measures the RF time, for use in determining particle type. The quartz Cerenkov provides higher resolution timing which will be used at the analysis level to reject muon decay events. The GEM chambers determine the trajectory of particles incident upon the target. The time at the target, in conjunction with the time at the IFP, provides a time of flight measurement of the beam particles over a path length of about 9 m, providing additional identification capability at the analysis level.

The beam line monitor hodoscope is intended to provide a high resolution determination of the RF time for randomly coincident unscattered beam particles. This monitors the stability of the channel and timing with the accelerator RF signals.

The base line design for the scattered particle spectrometers is a set of three wire chambers followed by two scintillator hodoscopes. The wire chambers provide outgoing trajectories, that are used in combination with the tracks found by the GEM chambers to determine scattering angles and interaction positions. The two scintillator hodoscopes provide high resolution timing, high efficiency triggering, and limited position information.

The detector systems operate in a triggered mode with VME-based readout. The much larger pion scattering cross section necessitates using custom field programmable gate array (FPGA) units to determine beam particle type from the SciFi signals at the hardware level. The trigger is based on this hardware determination of beam particle type along with a trigger matrix (also implemented in an FPGA) for the scattered particle scintillator hodoscopes to limit triggers to events with trajectories pointing approximately to the target. VME modules are a mix of mostly time and charge to digital converters (TDCs and QDCs). The MIDAS data acquisition system developed at PSI by Stefan Ritt was used in the initial test run and is planned to be used in MUSE.

The hardware components of MUSE are largely established technology. SciFi detectors are now common. The use of a quartz Cerenkov detector to provide ≈10 ps timing has been prototyped by a group at Fermilab [32]. The GEM chambers exist already, having been used in the OLYMPUS experiment at DESY. The high precision scintillators, used both in the spectrometer and for beam line monitoring, copy a design already constructed and tested for the Jefferson Lab CLAS 12 upgrade. The wire chamber designs are based upon the chambers built at University of Virginia for the Hall A Bigbite Spectrometer.

For the trigger and readout electronics, a mixture of existing commercial equipment and custom or recently prototyped boards is planned. The beam particle identification system will be implemented in commercial FPGAs, but the FPGAs will be installed in custom designed boards. The trigger uses a CAEN FPGA. We note here that the use of FPGAs in subatomic physics experiments has become fairly commonplace. To contain costs, time measurements will be done with the recently prototyped TRB3 TDC, developed GSI in Darmstadt, Germany.

C. Cryotarget

Liquid hydrogen targets in vacuum systems are a mature technology. The design will follow standard, well known and tested cryogenic cell designs. The MUSE target is a relatively easy target, as the beam power deposited in the target is a few μW. The main concerns then are residual air in the vacuum system freezing to the target, and radiative heating of the target by the vacuum system; both issues can be ameliorated through liquid nitrogen baffles in the scattering chamber. The base line design is for the cryotarget system to have a target ladder containing the cryogenic cell, constructed from thin kapton, a dummy target for wall backgrounds, a carbon target for positioning, and an empty target position.

IV. COLLABORATION RESPONSIBILITIES AND COMMITMENTS FROM PSI

The MUSE collaboration is comprised of a combination people with experience in electron scattering experiments and in experiments with secondary meson beam lines. Many members of the collaboration have worked together for periods exceeding a decade. Many of the younger members of the collaboration have previously worked with older members of the collaboration during their time in graduate school or as postdocs. Working on an experiment that lasts several years and requires a significant amount of new equipment construction is a familiar situation for nearly all collaborators.

The core of the collaboration is the institutions making a commitment to develop major parts of the experiment and/or have Ph.D. students and postdocs essentially fully committed to the experiment. A summary of commitments to the basic equipment development and some other tasks is shown in Table I. Several of the institutions – GW, Hebrew University, MIT, Rutgers, and Tel Aviv – have committed to having Ph.D. students and / or postdocs spend significant fractions of their time at PSI for the experiment.

TABLE I. MUSE equipment responsibilities.

Device	**Institution**	**Person**
πM1 Channel	PSI	K. Dieters
Scintillating Fibers	Tel Aviv	E. Piasetzky
Scintillating Fibers	St. Mary's	A. Sarty
GEM chambers (existing)	Hampton	M. Kohl
Beam Quartz Cerenkov	Hebrew University	G. Ron (Co-Spokesperson)
Cryogenic Target System	Hebrew University	G. Ron (Co-Spokesperson)
Wire Chambers	M.I.T.	S. Gilad
Scintillators	South Carolina	S. Strauch
Electronics and Trigger	Rutgers	R. Gilman (Spokesperson)
Readout Electronics and DAQ System	George Washington	E. J. Downie (Co-Spokesperson)
Data Acquisition Software	MIT & Rutgers	V. Sulkosky & K. Myers
Radiative Corrections	George Washington	A. Afanasev
Analysis and Radius Extraction	Argonne	J. Arrington

A. Schedule

MUSE was approved by the PSI PAC in Jan 2013. A second test run is planned for summer 2013. It is the intent of the collaboration to seek funding during 2013, so that equipment construction can start in 2014.

Construction of the experiment requires about two years. To a large degree, the beam detectors are all small and can be constructed in several months. The time needed for procurement and testing will result in these detectors being available in about 9 - 12 months after funds are available.

The cryotarget, high precision scintillators, trigger, and wire chambers require more time.

The cryotarget requires about 2 years to construct. Designing the target, purchasing components, and assembling the basic system requires about 12 months. Installing and commissioning the control system will require an additional 9 months. At this point the target can be cooled and tested, which requires an additional 3 months.

The high-precision scintillators are similar to those constructed at South Carolina for the CLAS 12 GeV upgrade. The exact construction rate depends on the number and expertise of students involved in building and testing the scintillators; we expect the average production rate to be about two scintillator paddles per week. Production will come up to speed faster if experienced students from the CLAS 12 project are still available. In addition to the 1 year needed to build the scintillators, an additional 6 months will be needed for procurement, testing, and shipping. Thus, the entire scintillator project will require about 18 months. It should be possible to start the initial procurement activities, such as obtaining bids, before funds arrive. As a result, it should be possible to have all the scintillators needed for one spectrometer for a dress rehearsal run in late 2015, and the full complement of scintillators for production running in 2016.

Constructing the beam PID requires design work, prototyping, extensive programming, and design and construction of the final system. FPGAs often exhibit quirky and interesting behavior. Thus, even when the FPGA selected for the project is chosen appropriately, and even though the estimate of the time for the project comes from an experienced FPGAs programmer, the project time can exceed estimates. The Rutgers electronics shop also has LHC projects that will compete for programmer time. An initial system should be ready for the dress rehearsal, in just over a year, and the experience gained should allow the full system to be deployed within 2 years, in time for the production data. The trigger FPGA system can be developed in parallel with the beam PID FPGA system; it is a simpler programming challenge that uses commercial equipment, so it should be ready sooner. This part of the system can be developed by students and postdocs.

The wire chambers are the most time-consuming construction project. It requires about 6 months of design, procurement, and preparation before wire chamber construction can begin. We assume here that clean room space can be found, so that a new clean room does not need to be constructed. Initially, as the chamber workers are trained, it will take about 3 months to produce the first wire chamber, and an additional month to test it. Each subsequent chamber can be produced in slightly less time, but it will require about two years to produce all the chambers. Within a year it should be possible to have available at least two chambers for one of the spectrometers for a dress rehearsal run. With sufficient space and personnel, it might be possible to produce two chambers in parallel and shorten the production time.

The equipment, on being brought to PSI, has to be installed, hooked up to electronics, etc., and commissioned. Doing this for the entire set of experimental apparatus will take about 6 months, but as indicated above the equipment is expected to arrive over a period of about 1 year.

Assuming that PSI continues to run during the second half of each calendar year, and assuming that funding for equipment construction is received in early - mid 2014, it should be possible to have a significant fraction of the MUSE equipment on hand for a significant test of the system in late 2015. The beam line detectors, scintillators, some of the wire chambers, and a simplified version of the trigger should all be available. The cryotarget will not be ready, but solid targets can be used for initial testing.

B. PSI Commitments

We quote from the verbal close out of the January 2013 PSI PAC by the chair, Cy Hoffman, on MUSE: “We are certainly convinced that the proton radius puzzle is an important physics puzzle, largely this lab is responsible for that, and therefore it is totally fitting to finding a solution to it. So we approve the experiment, we want to see it done. We are very pleased by the progress made last year in the beam test, a lot of lessons were learned, a few things were not quite as optimistic as hoped, on the other hand there is nothing there which was a major problem.”

PSI was an excellent host for our test beam time in 2012. We were provided with access to πM1, beam time, installation assistance, office space, access to infrastructure such as computer networking, and the use of large amounts of existing experimental equipment, such as electronics.

PSI will be providing us with additional beam time in 2013, along with similar access to that which we had in 2012. The laboratory is making minor adjustments to the πM1 channel for our tests: installation of an NMR to monitor dipole stability, installation of a collimator at the intermediate focus, and adjustments to quadrupoles to fine tune the positioning of the beam focus. Also planned for the future are minor adjustments to vacuum pipes in the downstream half of the beam line, and the possible addition of a concrete shielding wall just before the detectors.

C. Cost Estimates

Estimated equipment costs in Table II include the cost of hiring students to be involved in the construction effort, plus one postdoc based at GW to work on the DAQ. The estimates do not cover certain costs related to the channel which we expect to be covered by PSI, and do not include contingency or inflation estimates. There is no entry for the GEM chambers as the chambers already exist; the GEM chambers were funded by NSF MRI 0959521.

TABLE II. Estimated cost of capital equipment.

Device	**Cost** (kUSD)	**Institution**
Scintillating Fibers	300	Tel Aviv & St. Mary's
Quartz Cerenkov	100	Rutgers
Wire Chambers	450	MIT
Scintillators	320	South Carolina
Beam PID & Trigger	198	Rutgers
DAQ & Electronics	500	GW
Target	550	Hebrew University
Mechanical Frames	40	Hebrew University
Total	**2458**	

V. FUTURE PLANS

The equipment to be constructed for this experiment is versatile enough to be used as part of several measurements at PSI, as well as potential future measurements at US and other worldwide facilities.

Depending on the results of MUSE and other Proton Radius Puzzle experiments, there are natural follow up μp scattering measurements to be performed. One is a measurement of enhanced parity violation as predicted by certain BSM models. A second would be a higher precision measurement focused on the two-photon exchange contributions at large angles. A third would be to move the apparatus to a different PSI muon beam line to obtain lower momentum surface muons, to reach even lower beam momenta and momentum transfer.

Another direction is determining the radii of light nuclei with muon scattering. The PSI CREMA collaboration, responsible for the muonic hydrogen measurements, intends to measure nuclei such as ^{3}He, ^{4}He, ^{6}Li, and ^{11}B. Some have recently been measured at JLab to high precision. Muon scattering can determine the radii of these nuclei or others, such as ^{12}C, which was already measured, but with low precision. Of particular interest is a measurement on deuterium, which will also allow the only extraction of the muonic neutron radius. Additionally, some US groups have expressed interest in extending the measurements to include ^{3}H charge radii.

VI. SUMMARY

The Proton Radius Puzzle is arguably the most pertinent, controversial and timely issue in the Hadron Physics community at this present time. The discrepancy between the proton charge radius as measured with muons and that measured in electron experiments, in both scattering and excitation spectra-based extractions, is widely recognized and needs to be explained, as stated in the CODATA analysis and the Particle Data Group review, and reiterated by the JLab and PSI PACs. No resolution to the Puzzle has been found, and it has attracted widespread interest.

The MUSE experiment measures muon- and electon-proton elastic scattering, at the same time with the same equipment, which will allow:

- The highest precision scattering experiment determination of the consistency of the μp interaction with the ep interaction, through cross sections and extracted form factors and radii.
- A test of the importance of 2γ exchange effects.
- Checks of possible explanations of the puzzle including structures in the form factors, extrapolation errors in the radius extraction from scattering measurements, anomalously large two-photon effects leading to issues in extracting the radius, including possible effects from proton polarizibility, and possible electron-muon differences.

MUSE provides the missing measurement of the four possible radius determinations using scattering or atomic energy levels of μp and ep systems, and tests several possible explanations of the Proton Radius Puzzle. The experiment is technically feasible on a time scale of about 4 years. It requires about \$2.5M in equipment funding.

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