EPJ Web of Conferences **234**, 01001 (2020) https://doi.org/10.1051/epjconf/202023401001
FCCP2019

The proton radius puzzle – 9 years later

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Abstract. High-precision measurements of the proton radius via scattering, electric hydrogen spectroscopy and muonic hydrogen spectroscopy do not agree on the level of more than 5 σ. This proton radius puzzle persists now for almost a decade. This paper gives a short summary over the progress in the solution of the puzzle as well as an overview over the planned experiments to finally solve this puzzle at the interface of atomic and nuclear physics.

1 Introduction

The proton's elastic electric and magnetic form factors, which describe the distribution of charge and magnetization inside the proton, offer direct access to the proton's internal structure. Their accurate knowledge is a touchstone for QCD theory and lattice calculations.

However, even basic quantities like the charge root-mean-square radius, given by the slope of the electric form factor at zero four-momentum transfer ($Q^2 \to 0$), are not settled. The so-called proton radius puzzle (PRP) stems from a 4%, more than seven sigma difference between an analysis of a muonic hydrogen spectroscopy experiment [1] ($r_p = 0.84184(67)$ fm), and both the results of the Mainz high precision form factor experiment [2] ($r_p = 0.879(5)_{stat}(6)_{syst}$ fm) and the CODATA value [3] ($r_p = 0.8768(69)$ fm), based on a series of normal hydrogen spectroscopy measurements and radius extractions from earlier scattering data.

2 The origins of the puzzle

The proton radius can be extracted from different measurements in nuclear and atomic physics. The following is a very short overview over the used techniques.

2.1 Electron scattering

The perhaps most classical way to determine the proton radius is elastic electron-proton scattering, which delivers not only the charge radius, but full information about the distribution of charge and magnetization inside the proton.

The cross section for elastic electron-proton scattering is given to first order by the Rosenbluth formula,

$$\frac{d\sigma}{d\Omega} = \frac{d\sigma}{d\Omega}_{\text{Mott}} \frac{1}{\epsilon(1+\tau)} \left[\epsilon G_E^2(Q^2) + \tau G_M^2(Q^2)\right],$$

where $\tau = Q^2/(4m_p^2)$ is a unit-less quantity proportional to the (negative) four-momentum transfer squared, and ϵ is the polarization of the exchanged virtual photon. The Mott cross section $\frac{d\sigma}{d\Omega}_{\text{Mott}}$ encapsulates all of the kinematic terms, and the remaining structure with the two Sachs form factors G_E and G_M encodes the shape of the proton.

The root-mean-square charge and magnetic radius is now defined as the slope of the form factors at zero momentum transfer,

$$< r_{E/M}^2 >= -6\hbar^2 \frac{1}{G_{E/M}(0)} \left.\frac{dG_{E/M}}{dQ^2}\right|_{Q^2=0}.$$

It is important to note here that the Fourier transform of the form factors gives a space-like distribution, i.e. a distribution which depends on a space-like variable, however that space-like variable is not in the rest frame of the proton. Similarly, the root-mean-square radius is not the proton radius at rest.

Since scattering can not measure the slope, nor at $Q^2 = 0$, radii can only be extracted by fitting the measured data and extrapolating to zero. This extrapolation proved to be a point of contention in the community, see below.

At the time of the inception of the puzzle, the most precise measurement of the form factor at relevant Q^2 is the high-precision Mainz form factor experiment, [2, 4], which measured more than 1400 cross section points down to 0.0033 GeV$/c^2$.

Naively, one would expect that the extrapolation gets more precise with data at smaller Q^2. However, that is not necessarily true: The effect of the radius on the cross section scales with Q^2, the cross section itself however does not. Since statistical and systematical uncertainties typically scale with the cross section, i.e., do not get smaller for similar experimental setups, the sensitivity of the data at lower Q^2 to the radius actually drops. This effect has to be balanced with the systematic effects of the extrapolation, which get better at small Q^2.

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2.2 Electron spectroscopy

QED is the best tested theory, mainly through spectroscopy measurements, where energy levels can be measured and calculated to extraordinary precision. In the quest to test QED to higher and higher precision, the proton radius appears here as a nuisance, as it is outside of the purview of QED. The need for external input was indeed motivation for the muon spectroscopy below, as well as for an extension of the original Mainz measurement plan, which originally aimed only at mid-Q^2 to test higher-order shape parameters of the proton and search for the signature of a pion cloud.

The proton radius appears as an ingredient in the calculation of the Lamb-shift L_{1S}. In the s-wave configuration, the electron has finite probability to be inside the proton, seeing an effective lowered charge. The electron is therefore slightly less strongly bound compared to a point charge. The energy of s-state in hydrogen are given by

$$E_{nS} \approx -\frac{R_\infty}{n^2} + \frac{L_1 S}{n^3}.$$

Dropping the original goal of testing QED and instead assuming QED and the calculations to be correct, measurements of the energy levels can be used to actually extract the radius.

Interestingly, the Rydberg constant R_∞ is actually determined to the required precision only by the same measurements, so that the measurement of an arbitrary transition is not enough. Two options remain: One can measure two transitions, typically 1s to 2s in combination with 2s to *n*p, to extract the Rydberg constant and the Lamb shift at the same time, or by a measurement of only 2s to 2p, in which the Rydberg constant cancels.

The energies of these transitions are quite different, and require different experimental techniques. Prior to the puzzle, extractions typically had large uncertainties, but the global fits by CODATA [3], using only spectroscopy data, found values in good agreement with the values extracted from scattering, with comparable errors.

2.3 Muon spectroscopy

In muonic hydrogen, where the electron is replaced by a muon, the finite-size effect of the proton is dramatically enlarged: The muon is roughly 200 times heavier, its distance from the proton is reduced by the same factor, and the probability to be inside the proton is boosted by a factor of 200^3. This makes the finite size effect one of the largest corrections of the spectrum.

However, the preparation of and a spectroscopic measurement on muonic hydrogen is not a trivial task. The CREMA collaboration finally succeeded after years of refinement and produced a measurement of two transitions [1, 5].

The experiment produced an more than an order of magnitude more precise value for the proton radius, which was about 0.04 fm, 4%, smaller. Depending on the way one averages the other measurements, this is a shift of 5.6 to more than 7 σ, and created the proton radius puzzle.

3 Solution attempts

Such a puzzle of course motivated many people in the field of scattering and spectroscopy to hunt for a solution. This tremendous work effort can be roughly organized into three directions

3.1 Theory

Originally the odd one out, a lot of theoretical work focused on the corrections required to convert the transition frequency measured in muonic spectroscopy into a value for the radius. All corrections have been checked by multiple groups, and while small improvements have been found, non of them was big enough to resolve the puzzle. Similarly, the corrections for normal hydrogen spectroscopy were checked.

On the scattering side, the influence of theory is somewhat smaller and mainly is found in the radiative corrections. Here, the Coulomb or Two-photon-exchange corrections were mainly discussed, and while better prescriptions change the extracted radii, nothing was found which can explain the discrepancy.

The question whether scattering and spectroscopy measures indeed the same quantity is often raised. It is maybe best answered by the paper of Miller [6], who finds that indeed all measurements determine the same quantity.

3.2 Fitting

On the electron scattering side, a series of papers [7–17] refit different subsets of the Mainz or world data set, with results generally either agreeing with the small or the large radius value. The small results typically stem from papers restricting the fitted Q^2-range to small Q^2. This has a natural allure, as the radius is given by the slope at $Q^2 = 0$, and a fit to a reduced Q^2 range can use a smaller number of parameters, which should make the extrapolation more robust.

On the other hand, [18–21] highlight problems with many of these approaches, and statistical tests like the F-test or AIC indicate that the functional choice in [2, 4] is adequate and should not lead to over-fitting.

Two approaches fitting a large Q^2 range indeed find a small radius [8, 17]. Both of them are based on dispersion relations. It has to be noted that the fit in [8] results in a considerably larger χ^2 than flexible fits, indicating that the data and the associated uncertainties are not compatible with the model.

The parametrization of the model in [17] is explicitly written as a function of the proton radius, and the value is found via a comparison of the parametrization evaluated with various radii to a descriptive fit to the world data with the radius forced to the same value. This approach does not produce a statistical statement about the compatibility of model and data easily.

In both cases, the fit function locks the radius and higher-order terms together, and the radius is effectively determined by the higher-Q^2 data, where the lever arm is bigger. In that sense, this approach is complementary to the low-Q^2 fits, but one has to trust the functional form, which does not seem to describe the data well simultaneously at all Q^2. While this discrepancy can be attributed to problems in the data, it is not clear why then data at higher Q^2 should be more trustworthy. In any case, the calculation of [17] can be used predict the form factor shape for any given radius, for example by using the precise value from muonic spectroscopy.

It is quite interesting that the fit results are essentially bi-modal: either in agreement with the large, or the small radius, and rarely in between. It is unclear if this stems from an underlying feature of the data, or from an external effect like publication bias. This fitting conundrum can only be resolved with new, precise data at relevant Q^2, and fully blinded analysis. Different kinematics and different experimental setups lead to different systematic uncertainties. The combination in a world data set will inform model selection and identify problems present in individual data sets.

3.3 Beyond the Standard Model

Shortly after the proton radius puzzle has been established, different authors to suggested that the solution to the puzzle could lie in beyond the Standard Model physics. Light particles in the dark sector could in principle also solve the muon g-2 discrepancy [22] and/or explain the ^{8}Be signal [23]. While most of the earlier ideas, based on simple dark matter models, have been ruled out, new papers appear on a regular basis which can avoid all current limits. Papers on this topic include for example [24–27].

Other papers modify our current understanding of physics [28–39], spanning a wide gamut from extra dimensions to quantum gravity.

While some of these ideas are still viable, none of them have found widespread acceptance in the community.

4 New data

Since the inception of the puzzle nine years ago, multiple new experiments and analyses have presented their results, a selection is shown in Fig. 1.

4.1 Spectroscopy

In spectroscopy, two experiments using electronic hydrogen [40, 41] are in agreement with the small radius, while the new result from the Paris group [42], also on normal hydrogen, is in agreement with the large value. All three measurements have uncertainties comparable with the previous world average on electron spectroscopy and it is currently unclear why they disagree.

4.2 Scattering

The first new scattering data came from an experiment in Mainz [43, 44]. It made use of Initial State Radiation to reduce the effective beam energy, measuring a range of Q^2 with a fixed spectrometer position and only a small number of beam energies. Unfortunately, the results of this pilot experiment are not precise enough to distinguish between both radii. A successor experiment with improved systematics is planned.

New precise data comes from the recently released results of PRad [45], measuring the elastic cross section in a Q^2 range from $2.1 \cdot 10^{-4}$ (GeV/c)^2 to $6 \cdot 10^{-2}$ (GeV/c)^2 with good statistical and systematic precision. In contrast to other measurements, which measure at small beam energies and larger scattering angles, PRad measures at very forward angles and comparatively large beam energies of 1.1 and 2.2 GeV. The fit to the PRad data finds a radius of $0.831(7)_{stat}(12)_{syst}$ fm, in good agreement with the muon spectroscopy result.

The Q^2-range measured in PRad has overlap with precise data from earlier experiments from $3.8 \cdot 10^{-3}$ (GeV/c)^2 up, see Fig. 2. In that range, G_E extracted from fits to the Mainz and earlier data falls about 1.5% faster than the PRad data. This faster fall-off does not stem from the larger radius alone: a fit to the Mainz data with a radius forced to the muonic value falls by about 1% faster than PRad, and the dispersion relation based model of [17], with $r_p = 0.841$ fm, by about 0.8%. To give a scale for this difference in fall-off, in this Q^2 range, the form factor drops only by about 12%. The difference corresponds to a 3% shift in the cross section, larger than most systematic corrections in the Mainz experiment and PRad, and multiples of their uncertainties. This discrepancy cannot be explained by problems in the extrapolation to $Q^2 = 0$, or with an inadequate selection of fit models. The PRad data in this overlap region is mostly data taken with a 2.2 GeV beam. As can be seen in Fig. S16 of the supplementary information of [45], the radius fit is completely dominated by the 2.2 GeV data—the fit to the 1.1 GeV data alone cannot distinguish between the two radius values, while the fit to all data and to the 2.2 GeV data has essentially the same value and uncertainty. It is indeed strongly driven by only the 9 largest Q^2 points—the fit without these, i.e., for $Q^2 < 0.016$ (GeV/c)^2 gives a considerably smaller radius with much larger uncertainties.

5 Future scattering experiments

5.1 Mainz

At Mainz University, several experiments are gearing up to measure the electron-proton cross section in the interesting Q^2 region.

In the A2 hall, an experiment [49] will make use of a hydrogen Time-Projection-Chamber (TPC) to measure the recoiling proton for a Q^2 range from 0.001 to 0.04 (GeV/c)^2. This technique will have different systematic sensitivity than the more usual detection of the scattered electron. The experiment aims for 0.2% absolute and 0.1% relative errors.

In a combined experiment at A1@MAMI and the MAGIX@MESA, currently under construction, an updated version of the original Mainz measurement will be performed. Learning from the experiences of the earlier

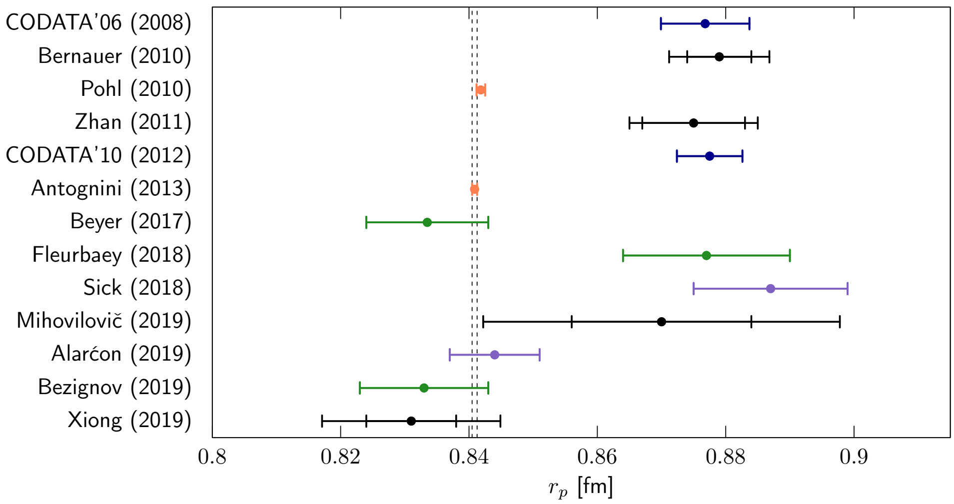

Figure 1. Collection of experimental results on the proton charge radius, and a (small) selection of fits by other authors. CODATA values (dark blue) [3, 46] are global fits, using electron spectroscopy and scattering data as input. Bernauer [2], Zhan [47], Mihovilovič [44] and Xiong [45] (black) are results from scattering experiments, sometimes including the world data set. Sick [21] and Alarćon [17] (purple) are refits of existing data, in the latter case based on dispersion relations. Beyer, Fleurbaey and Bezignov [40–42] (green) are electron spectroscopy results, Pohl and Antognini [1, 5] (orange) are the results from the muon spectroscopy experiment.

measurement, several systematics can be avoided or reduced. The main improvement is the new target system, which will exchange the cryogenic cell with a hydrogen cluster-jet target [50], which puts no extraneous material in the main beam trajectory. In combination with an upstream collimator and and active veto to suppress electrons in the beam halo, the experiment aims for a completely background-free measurement. Additionally, the point-like intersection of electron and hydrogen beam simplify track reconstruction, and the comparatively thin target reduces external radiation drastically.

With the smaller beam energies of MESA, the experiment will be able to measure not only cross section data relevant for the proton charge radius, but will also achieve an order of magnitude better precision on the magnetic form factor in the region most interesting for the determination of the magnetic radius (see Fig. 3), and from that, the Zemach radius, which is another connection point to atomic physics.

5.2 MUSE

MUSE [51], to take place at the Paul Scherrer Institute, CH, will measure $e^{\pm}$, $\mu\pm$ and $\pi^{\pm}$ scattering using a combined beam. Particle separation will be performed using Time-Of-Flight. Due to the simultaneous measurement of all three species, many systematic effects cancel, and MUSE can probe lepton universality. In combination with the charge-reversed beam, these data further allow to extract the two-photon exchange (TPE) contribution in the radiative corrections for comparison with theory, and to cancel this effect in the analysis without theory input.

The experiment will measure at three beam momenta (115, 153 and 210 MeV$/c$) with statistical uncertainties on the cross section of better than 1% for most of the data points, and few per mill systematic uncertainties.

5.3 COMPASS++/AMBER

As one of the planned measurements, COMPASS++/AMBER [52] will employ a similar hydrogen TPC to measure the muon-proton cross section in the Q^2 range of 0.001 to 0.037 (GeV$/c)^2$. The experiment aims to measure both outgoing lepton as well as the recoiling proton, and will use both muon charges. From the kinematics, it is very similar to PRad, with even more extreme forward scattering using a multiple tens of GeV$/c$ beam. The radiative corrections for muons are smaller, and, similar to MUSE, the measurement of both charges allows to extract and cancel TPE.

5.4 ULQ2

The ULQ2 project at Tohoku University, Sendai, Japan, aims to measure the electron proton cross section in the Q^2 range of 0.0003 to 0.008 (GeV$/c)^2$ using beam energies between 20 and 60 MeV. The experimenters plan to use a CH_2 target to achieve an absolute measurement on the 3 per mill level, by measuring relative to the well known carbon cross section. This unique approach will produce different systematic errors than those employed by the other experiments.

An overview of the Q^2 ranges and projected errors is given in Fig. 4.

6 Conclusion

After almost a full decade, the proton radius puzzle is still not resolved, but it has motivated uncounted work

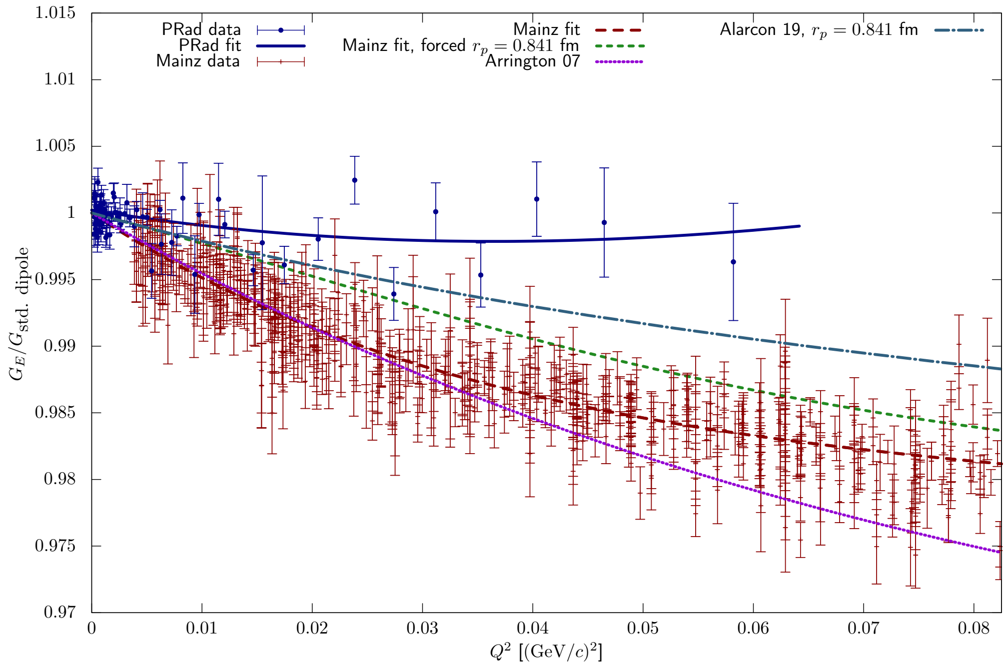

Figure 2. Extracted data and fits for G_E, as the ratio to $G_{\text{std. dipole}} = (1 + Q^2/0.71(\text{GeV}/c)^2)^{-2}$ to compress the range. Shown are the PRad data and fit [45], the Mainz data, polynomial fit and experimental uncertainty [2], a fit to the Mainz data with a radius forced to the muonic spectroscopy value, an fit to pre-Mainz data [48], the theoretical calculation by Alarćon [17]. Data are normalized according to their respective fits.

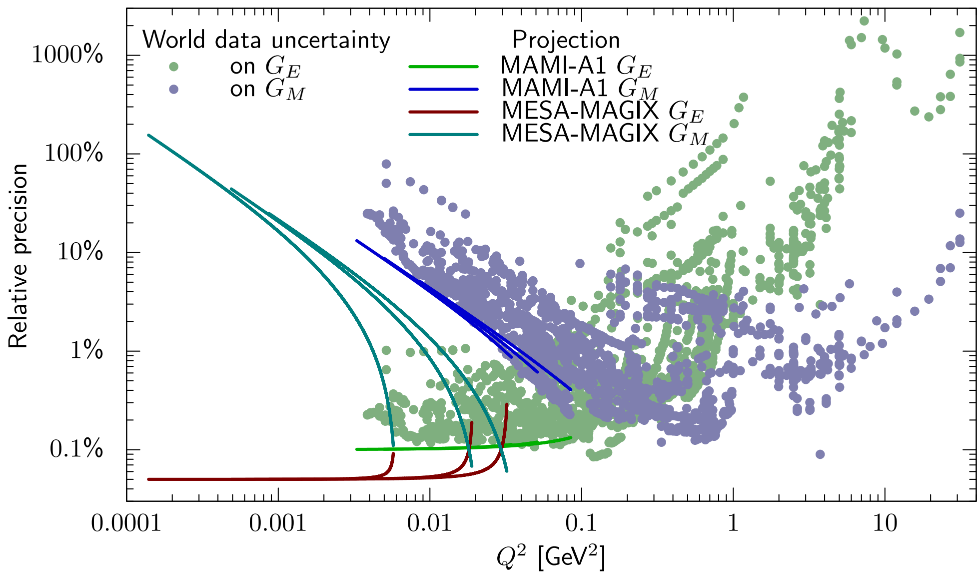

Figure 3. Effective uncertainty on the form factors of existing cross section data (points), and projections for the A1@MAMI and MAGIX@MESA experiment (lines). At small Q^2, the cross section is fully dominated by G_E except for extreme backward scattering.

in theory and experiment. On the spectroscopy side, recent results seem to converge on the smaller radius, however, without a good explanation why earlier measurements found a different value.

On the scattering side, while the PRad result points to a resolution of the puzzle, without an explanation of the discrepancy in the overlap region, it would call into question all previous form factor measurements at these and higher Q^2. This discrepancy cannot be resolved with alternative fit functions or ranges. It is evident that the PRad data needs verification from at least one independent experiment, and that a full resolution of the puzzle needs to explain the discrepancy with older measurements. In essence, there are three possible scenarios how the puzzle develops: 1) Experiments with similar kinematics as the earlier measurements, i.e. small beam energies and larger

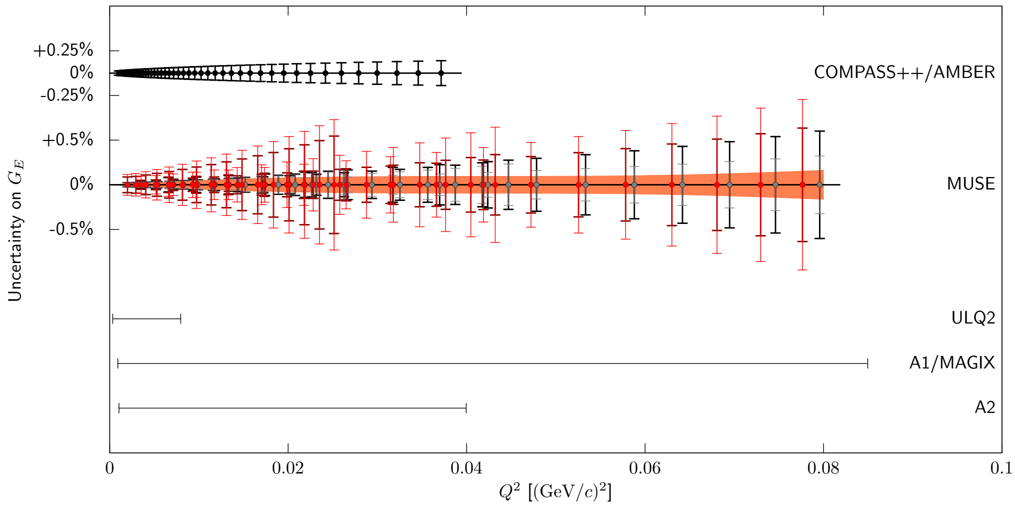

Figure 4. Q^2 ranges and, when available, the expected uncertainties on G_E of future planned experiments. COMPASS++/AMBER from [53]. MUSE: Projected uncertainty for e^+ (black), e^- (grey), μ^+ (dark red) and μ^- (bright red), from [51]. The fit uncertainty (orange) has been determined by the author.

angles, find agreement with PRad. Then, the puzzle is resolved, and the only remaining issue is to identify the source of the error in earlier experiments, if possible. If, however, those experiments agree with the earlier measurements, then either 2) the PRad data has an unknown experimental systematic, and instead of a muon vs. electron puzzle, the puzzle would be between spectroscopy and scattering. Or 3), our understanding of the underlying physical processes are lacking. Besides Beyond the Standard Model physics, radiative corrections appear as a likely candidate, as they depend on the kinematics, a main difference between PRad and the other experiments – if this is the case, the final radius value from scattering is undetermined.

Further experiments are gearing up, and, if all can be realized, should be able to illuminate the puzzle from enough sides that it can be resolved in a satisfactory way. At the same time, these experiments, at the cutting edge of precision cross section measurements, will deliver unique data interesting beyond the proton radius puzzle.

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