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Theoretical physicists present significantly improved calculation of the proton radius

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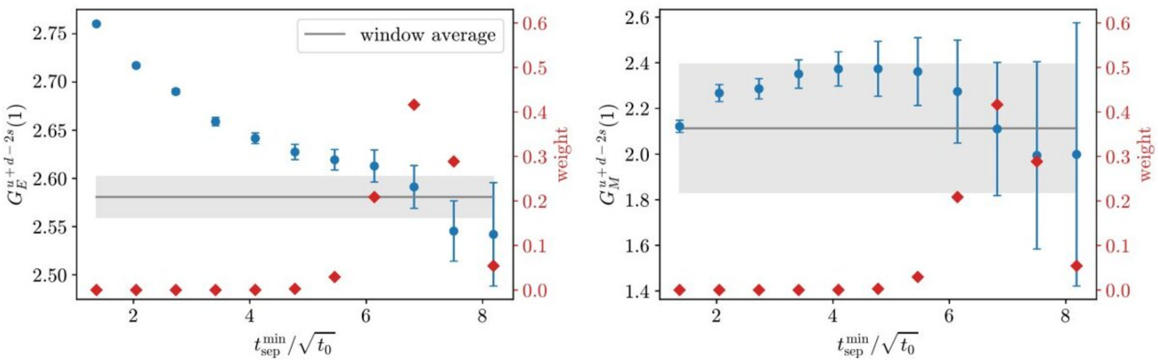

Isoscalar electromagnetic form factors at the lowest non-vanishing momentum ($Q^2 \approx 0.067\ GeV^2$) on ensemble E300 as a function of the minimal source-sink separation entering the summation fit. Each blue point corresponds to a single fit starting at the value given on the horizontal axis. The associated weights in the average are represented by the red diamonds, with the gray curves and bands depicting the averaged results. Credit: *arXiv* (2023). DOI: 10.48550/arxiv.2309.07491

A group of theoretical physicists at Johannes Gutenberg University Mainz (JGU) has once again succeeded in significantly improving their calculations of the electric charge radius of the proton published in 2021. For the first time they obtained a sufficiently precise result completely without the use of experimental data.

With respect to the size of the proton, these new calculations also favor the smaller value. Concurrently, the physicists for the first time have published a stable theory prediction for the magnetic charge radius of the proton. All new findings can be found in three preprints published on the *arXiv* server.

All known atomic nuclei consist of protons and neutrons, yet many of the characteristics of these ubiquitous nucleons remain to be understood. Specifically, despite several years of effort, scientists have been unable to pin down the radius of the proton. In 2010, the result of a new proton radius measurement technique involving laser spectroscopy of muonic hydrogen caused a stir—in this 'special' kind of hydrogen, the electron in the shell of the atom was replaced by its heavier relative, the muon, which is a much more sensitive probe for the proton's size.

The experimentalists came up with a significantly smaller value than that found following corresponding measurements of 'normal' hydrogen as well as the traditional method of determining the proton radius using electron-proton scattering. The big question that physicists have been asking ever since is whether this deviation could be evidence for new physics beyond the Standard Model or 'simply' reflects systematic uncertainties inherent to the different measuring methods.

Has the proton radius puzzle been solved?

In recent years, there has been increasing evidence that the smaller experimental value is the correct one, i.e. that there is no new physics behind the proton radius puzzle. Theoretical calculations make a significant contribution to answering this question definitively. Already in 2021, researchers led by Prof. Dr. Hartmut Wittig of the Mainz Cluster of Excellence PRISMA+ succeeded in performing so-called lattice calculations with sufficient precision to provide another reliable clue to the smaller proton radius.

"In the meantime, we have made another big step forward," explains Hartmut Wittig. "For example, Miguel Salg, a doctoral student in my research group, has achieved very nice results that again significantly improve and extend our earlier calculation."

Two years ago, the Mainz research group had "only" calculated the so-called isovector radius, which is not the same as the proton radius. They determined the value published at that time for the proton radius by adding experimental data for the neutron radius. "In the meantime, we have also calculated the fractions that were missing at that time, increased our statistics and better constrained the systematic errors, so that we can now completely dispense with experimental data for the first time," Miguel Salg says.

"In addition, we were able to check the extent to which our 2021 result stands up to complete direct calculation—with the result that we were also correct with the 2021 value." "With regard to the proton radius puzzle, we can safely say that even with the new calculations, the evidence continues to grow that the proton radius is correctly described by the smaller value," Hartmut Wittig says.

The calculations of the Mainz physicists are based on the theory of quantum chromodynamics (QCD). It describes the interplay of forces in the atomic nucleus: The strong interaction binds the quarks, the elementary building blocks of matter, to form protons and neutrons and is mediated by gluons which act as exchange particles. In order to be able to treat these processes mathematically, the scientists at Mainz draw on what is called lattice field theory.

In this case, as if in a crystal, the quarks are distributed over the points of a discrete space-time lattice. Special simulation methods can then be used to calculate the properties of the nucleons using supercomputers: in a first step, the so-called electromagnetic form factors. These describe the distribution of electric charge and magnetization within the proton. From these, in turn, the proton radius can be determined.

First stable theory prediction for the magnetic charge radius

In addition to the electric charge radius, which has been discussed so far, the proton also has a magnetic charge radius, which also poses a puzzle. The Mainz theorists have also calculated this property on the basis of QCD. "One could illustrate the different radii in a very simplified way by the expansion of an accumulation of electric or magnetic charge given by the proton, which an incoming electron 'sees' in the scattering process," Hartmut Wittig explains.

The Mainz group also obtained a stable prediction for the magnetic charge radius for the first time, based purely on theoretical calculations. "Furthermore, from the precise knowledge of the electric and magnetic form factors, we were able to derive for the first time the so-called Zemach radius of the proton purely from QCD, which is an important input quantity for the experimental measurements on muonic hydrogen. This shows once again how far the quality of lattice QCD calculations has advanced in the meantime," Hartmut Wittig concludes.

More information: Dalibor Djukanovic et al, Electromagnetic form factors of the nucleon from Nf=2+1 lattice QCD, *arXiv* (2023). DOI: 10.48550/arxiv.2309.06590

Dalibor Djukanovic et al, Precision calculation of the electromagnetic radii of the proton and neutron from lattice QCD, *arXiv* (2023). DOI: 10.48550/arxiv.2309.07491

Dalibor Djukanovic et al, Zemach radius of the proton from lattice

QCD, *arXiv* (2023). DOI: 10.48550/arxiv.2309.17232

Provided by Johannes Gutenberg University Mainz

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