How large is a proton?

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A century ago Ernest Rutherford explained the structure of atoms: A tiny, but very heavy and positively charged nucleus is surrounded by negatively charged electrons. It was also Ernest Rutherford who, 101 years ago, discovered the proton as one of the building blocks of atomic nuclei. Today we know that protons as well as neutrons are compound objects, made from quarks and gluons, while electrons are point-like elementary particles.

The question "How large is a proton?" was first answered in 1954 by Robert Hofstadter at Standford using elastic electron scattering off a hydrogen target. He showed unambiguously that the proton's charge is not point-like, but rather distributed over a radius of about “0.7 x 10^{-13} cm”, or, in todays language, “0.7 fm”. Later, more precise measurements at Stanford, Orsay, Mainz and elsewhere yielded value of about 0.88 ± 0.01 fm.

Not only electron scattering, but also atomic physics, can be used to measure the size of a nucleus: The hydrogen atom is a single proton, orbited by a negative electron. The finite size of the proton affects the energy levels in atomic hydrogen only by an extremely tiny fraction: It enters enters at the tenth digit! But using ultra-precise laser spectroscopy and equally precise QED calculations has yielded a value in excellent agreement with the electron scattering result.

In 2010, we employed laser spectroscopy of the exotic “muonic hydrogen” atom. This is a proton where, instead of an electron, a heavy muon is orbiting. This “heavy brother” of the electron is 200 times heavier, and thus orbits the proton with a 200 times smaller distance. This enhances the effect of the finite proton size on the energy levels by a huge factor of 10 million, which enabled us to determine the proton charge radius with a tenfold higher precision.

To our (and everybody else’s) great astonishment, our result for the proton charge radius differs by as much as 4% from the canonical value obtained from electron scattering and regular hydrogen atoms! A similar discrepancy shows up in the charge radius of the deuteron, which is the heavier sister of the proton. Taken at face value, these two discrepancies are the biggest problem of the Standard Model, and several people have suggested New Physics as a solution to this so-called “proton radius puzzle”.

I will tell the story of the proton radius puzzle, and highlight a few ideas that could be responsible for this exciting discrepancy. Ultimately, we need new data, in particular also from elastic electron scattering at ultra-low momentum transfer such as envisaged by ProRad at PRAE, to find out what the muon wants to tell us.