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Deciphering the Origin of Quark and Lepton Mass

Viewpoint on *"Evidence for the dimuon decay of the Higgs boson in pp collisions with the ATLAS detector"*

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The most basic bits of matter that we have found are quarks and leptons, which we idealize as pointlike—objects with no internal structure and no measurable size (experiments constrain their sizes to below an attometer—a billionth of a billionth of a meter). The quarks, which experience strong, weak, and electromagnetic interactions, come in six flavors: up and down (the constituents of the proton and neutron), charm and strange, top and bottom. The charged leptons—electron, muon, and tau—experience weak and electromagnetic interactions, while the neutral leptons—the three neutrinos—feel only the weak interactions. The masses of the quarks and charged leptons span more than five orders of magnitude: the top-quark mass is nearly 340,000 times that of the electron. How might such a hierarchy arise? New results from CERN's ATLAS collaboration[1], which confirm 2021 observations from the CMS collaboration[2], support the idea that the quark and charged-lepton masses are the work of the Higgs field, which hides electroweak symmetry and gives masses to the weak bosons $W^{\pm}$ and Z^0. The new evidence comes from measurements showing that the Higgs boson decays—rarely—into a muon and antimuon, with a decay rate consistent with theoretical expectations.

In a world governed only by strong and electromagnetic interactions, one would expect that the masses of the quarks and charged leptons are fixed by nature. Left-handed and right-handed fermions respect the same symmetries—they have the same electric and color charges. They can thus pair up to form massive particles (left–right combinations) without violating fundamental symmetries. At first sight, mass appears to be incompatible with the weak symmetry, because charged-current transitions (those involved in beta decay) involve only the left-handed quarks and leptons. When theorist Steven Weinberg formulated his model of leptons,[3] he observed that a gauge symmetry hidden by the action of the Higgs field could give rise to fermion masses that do not clash with the symmetry. For this picture to be the whole story, the strength of the Higgs–fermion–antifermion coupling must be proportional to the fermion mass. That has been verified in earlier studies at the Large Hadron Collider by the ATLAS[4] and CMS[5] Collaborations for the heaviest fermions: the top quark (173 GeV), the bottom quark (4.2 GeV), and the tau lepton (1.8 GeV) .

In gauge theories such as the electroweak theory, symmetries dictate interactions: the coupling of the spin-one gauge fields with a particle depends on symmetry properties, not on the particle's identity. By Weinberg's hypothesis, that is not the case for interactions of the Higgs field with the charged

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[1] ATLAS Collaboration, *"Evidence for the dimuon decay of the Higgs boson in pp collisions with the ATLAS detector,"* Phys. Rev. Lett. **135**, 231802 (2025).

[2] *A.M. Sirunyan et al. (CMS Collaboration), Evidence for Higgs boson decay to a pair of muons, JHEP 01 (2021) 148, arXiv: 2009.04363 [hep-ex].*

[3] S. Weinberg, *"A Model of Leptons,"* Phys. Rev. Lett. **19**, 1264-1266 (1967). See also *A. Salam, in Elementary Particle Theory: Relativistic Groups and Analyticity (8th Nobel Symposium), ed. N. Svartholm, Almqvist and Wiksell International, Stockholm, 1968, p. 367.*

[4] ATLAS Collaboration*, "A detailed map of Higgs boson interactions by the ATLAS experiment ten years after the discovery,"* Nature **607**, no.7917, 52-59 (2022) [erratum: Nature **612**, no.7941, E24 (2022)].

[5] A. Tumasyan et al. [CMS Collaboration], *"A portrait of the Higgs boson by the CMS experiment ten years after the discovery.,"* Nature **607**, no.7917, 60-68 (2022) [erratum: Nature **623**, no.7985, E4 (2023)].

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leptons. A subsequent generalization[6] extended this conclusion to interactions with quarks. As theorist Martinus Veltman was fond of saying, "the Higgs boson knows something we don't know."

Does the same mechanism apply to fermions lighter than the top and bottom quarks and the tau lepton? The muon (0.106 GeV) offers the most promising target, but even here the challenge is formidable. Only about one Higgs boson in 5000 should decay to a muon-antimuon pair. In 2021, the CMS Collaboration provided the first significant indication that the Higgs field interacts with the muon at the expected rate. Their analysis, based on 13-TeV proton–proton collisions, showed an excess signal over background of approximately 3 standard deviations, and a decay rate consistent with (1.2 ± 0.4 times) the theoretical expectation.

The new evidence comes from ATLAS, the second general-purpose detector at the Large Hadron Collider. There, information from a hundred million electronic channels sifts a billion collisions per second for interesting events. The new analysis draws on more than a decade refining knowledge of the detector, signals, and backgrounds. The ATLAS search for the dimuon decay of the 125-GeV Higgs boson in 13 and 13.6-TeV *pp* collisions yielded an excess signal of 3.4 standard deviations over background. The inferred Higgs-boson to muon-antimuon decay rate is in line with (1.4 ± 0.4 times) theoretical expectations.

The ATLAS and CMS results are thus consistent with the idea that the Higgs field endows the muon with mass, just as it does for the heavier fermions. Particle physicists, however, will demand more compelling evidence. Whereas the current signal has only a one-in-3000 chance to arise from statistical fluctuations, the goal is to reach the threshold for discovery: a statistical significance of five standard deviations. At that point, researchers will be able to compare expectation with observation as precisely as possible, to ask whether the Higgs interaction is the sole source of fermion mass. Even at the present stage, the inferred muon coupling to the Higgs boson suggests a mesmerizing experimental possibility: a future muon-antimuon collider could be turned into a "Higgs factory" by tuning its energy to the Higgs-boson mass. Experiments with such an instrument could map out with unprecedented detail the Higgs-boson line shape—which would be sensitive to all decays of the Higgs boson, potentially including non-standard-model particles.

Much remains to be done. Measuring the Higgs field's interaction rates with the strange, down, and up quarks will be extremely challenging. An ambitious goal for a more distant future would be to establish the Higgs boson decay into an electron and a positron, an event expected in only one out of 200 million decays. Doing so would amount to uncovering the origin of the electron mass, and by implication the origin of the Bohr radius that sets the size of atoms. That achievement would be spectacular.

Should we establish that interactions with the Higgs field set the fermion masses, what sets the individual values of the masses? Is the top quark, so much more massive than the others, an outlier, or the only "normal" quark? (In appropriate units, its coupling to the Higgs field is about unity.) Many experimental studies tackling such questions lie ahead, and many other gaps in our understanding persist. For one, the tiny masses of the neutrinos pose an unresolved puzzle, hinting that the story of how matter particles acquire masses is far from complete.

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[6] S. L. Glashow, J. Iliopoulos and L. Maiani, *"Weak Interactions with Lepton-Hadron Symmetry,"* Phys. Rev. D**2**, 1285-1292 (1970).