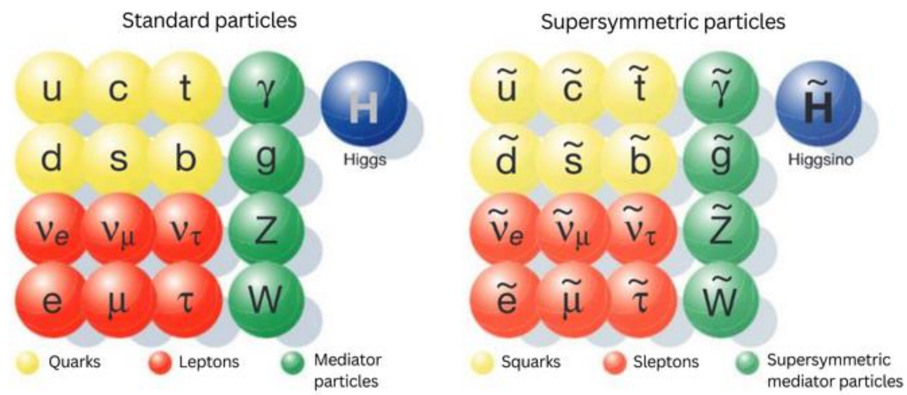
Beyond the Standard Model

The Standard Model represents a major achievement in our quantitative understanding of the infinitely small. The last stone in the edifice is thought to have been laid: the Higgs boson. Yet physicists already know that, for several reasons, this is not the end of the story.



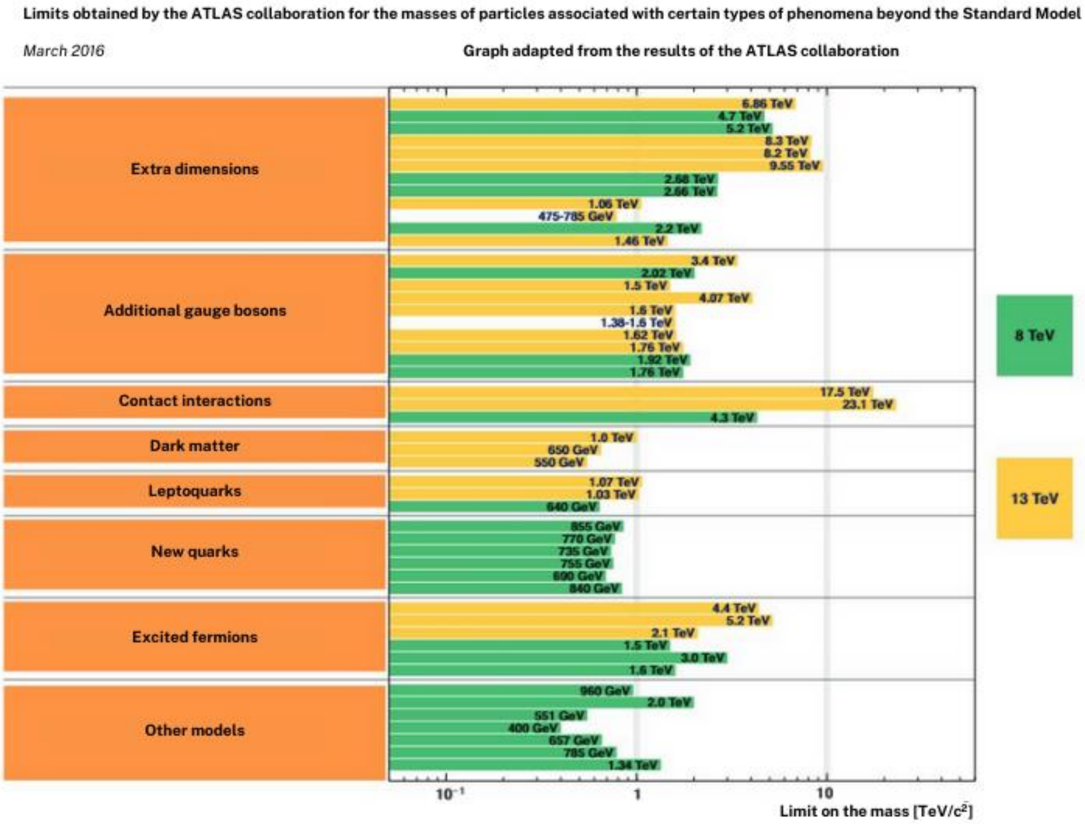
Credit: from University of Glasgow

Supersymmetric particles

In supersymmetric models beyond the Standard Model, each known particle is paired with a partner particle of a much greater mass that has therefore not yet been produced in colliders. This apparently artificial complexification (the number of elementary particles is doubled without any real experimental motivation) enables scientists to solve certain theoretical problems raised by the Standard Model. That is why the search for such new symmetry in Nature is a major stake for the LHC.

The Standard Model is certainly not an ‘theory of everything’, as it lacks the necessary ingredients to describe the first moments of the Universe, for instance. First of all, it only considers three of the four known fundamental interactions: gravity does not seem to fit easily in the same framework. But it cannot be left out altogether! The relative intensity of the four interactions varies with the energies involved. It is thought that on a very high scale (1,019 GeV, i.e. a million billion times higher than the energies reached at the LHC) gravity is no longer negligible compared with the other forces and must be taken into account. Then, the matter-antimatter asymmetry present in the Standard Model has proved to be clearly insufficient to explain the predominance of matter observed in the Universe. Finally, neutrinos are now known to have a very low mass, which goes against the Standard Model’s assumption that these particles have zero mass.

Even with these aspects aside, the Standard Model is characterised by a substantial number of parameters – 19! – whose values have been precisely determined; however, we cannot predict them nor explain



Credit: from ATLAS Collaboration

their orders of magnitude, which are sometimes very different (e.g. particles' masses). Nor can we yet understand why the strong, weak and electromagnetic interactions have such different ranges.

Physicists have tried to solve these problems by integrating the Standard Model into a broader theory. There are many alternatives, involving sometimes additional matter particles and interactions, sometimes extra space dimensions. Of course, these extensions have to match our experimental knowledge, and therefore be compatible with the Standard Model. We also need to be able to test them: these theories must be accompanied by new, unexpected but measurable phenomena. A particularly popular example is supersymmetry, which associates every known particle in the Standard Model with a new, much more massive supersymmetric particle.

In addition to studying the Higgs boson, the LHC experiments have been actively searching for such new particles – to no avail, so far. It is therefore to be assumed that these new phenomena are much rarer or occur at much higher energies than previously thought. Over the next 20 years, a series of upgrades to the LHC, its detectors and algorithms will significantly increase the amount of data collected and the sensitivity of the experiments. Meanwhile, the scientific community is also reflecting on the accelerators to build for the second half of the 21st century.

The ATLAS experiment seeks phenomena beyond the Standard Model

LHC experiments test all the theoretical models predicting the existence of new particles. In this image, each orange block represents a family of theories, and each line represents the search for a particle present in this type of theory. The colour of the bar indicates the energy of the collisions used for this ATLAS study: 8 TeV in green, 13 TeV in yellow. The longer the bar, the broader the range of masses explored. To date, none of these analyses has revealed the existence of a particle beyond the Standard Model. The increase in energy at the LHC and the large amounts of data to be accumulated in the future will enable us to take this research further and, perhaps, expand the very exclusive club of elementary particles.

Translated from 'Au-delà du Modèle Standard', Passeport pour les deux infinis, IN2P3/Dunod, https://pass2i.ijclab.in2p3.fr/ (French); updated with ICHEP2024 conference (https://ichep2024.org) for IPPOG