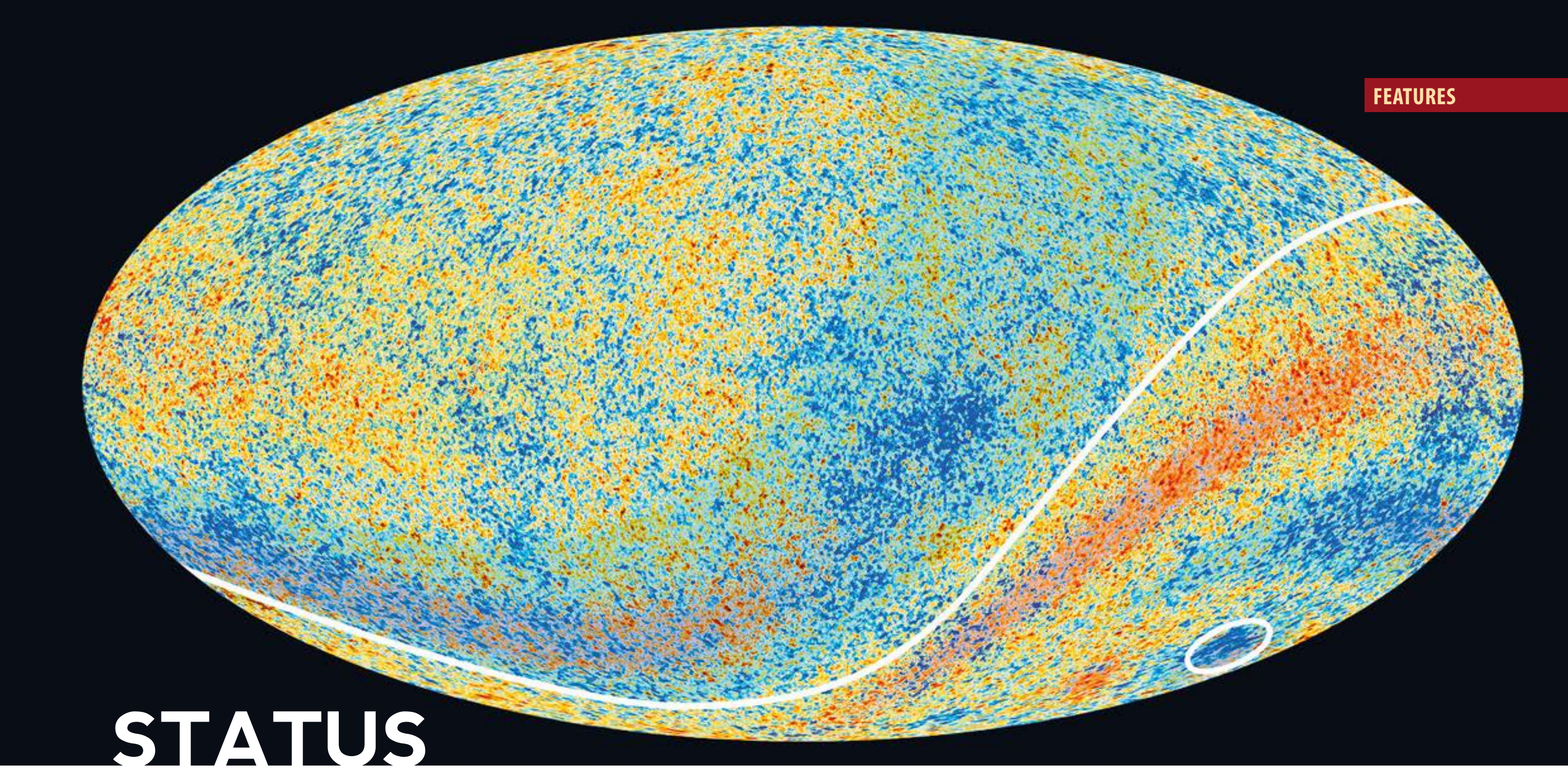


STATUS OF PARTICLE PHYSICS

Zoltán Trócsányi – ELTE Eötvös Loránd University, Budapest, Hungary – https://doi.org/10.1051/epn/2020204

While at CERN the upgrade of the Large Hadron Collider and the detectors is in full swing and the European strategy for particle physics research is being shaped we summarise the current status of particle physics, focusing on the established experimental observations at the energy, the intensity and the cosmological frontiers.

Standard model of particle interactions

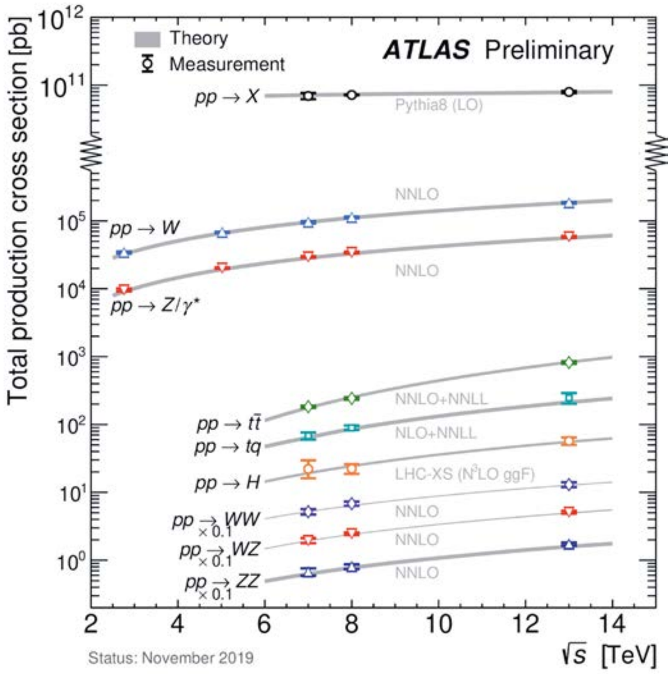
The standard model (SM) of particle physics describes the decays and collisions of elementary particles with extraordinary precision. It builds on three fermion families, each containing two electrically charged quarks, a charged and a neutral lepton. The neutral leptons are the neutrinos that are distinguished only by their *flavours*. The flavour of a neutrino means which charged lepton (electron, muon or tau) appears with it in the decay of a charged $W^{\pm}$ boson – the massive, electrically charged akin of the photon. Apart from particle flavour, the only difference between the families is the mass of the particles. The three forces (the strong, electromagnetic and weak interactions) are mediated by bosons, whose existence follows automatically from symmetry principles. We require that the Lagrangian of the model, is invariant under local SU(3)⊗SU(2)⊗U(1) gauge transformations.

The standard model became complete in 2012 when the Higgs particle was discovered by the ATLAS and CMS experiments at the Large Hadron Collider (LHC) [1,2]. To date this is the only known scalar elementary particle in the standard model. The correct design of the accelerator and detectors needed for the discovery would not have been possible without the detailed and precise predictions of the SM theory.

Experimental status of the standard model

The standard model has 19 free parameters (considering the neutrinos exactly massless). These parameters were determined from fitting a plethora of measurements with SM predictions. Most of the parameters were also measured directly at the Large Electron-Positron collider. The fitted and the measured values were found in excellent agreement, suggesting a consistent and precise experimental support for the validity of the model. Such a support has also been confirmed by the measurements performed at the TEVATRON and LHC hadron colliders. Fig. 1 shows the results of ATLAS measurements of eight benchmark processes for which the theoretical predictions are the most precise [3]. It is a great triumph for the

Invariance under local gauge transformations means that the equations do not change if we transform the ψ fermion fields by multiplying it with a matrix $U = \exp(i\,\boldsymbol{\alpha}(x)\cdot \boldsymbol{T}) \in SU(N)$. The vector $\boldsymbol{\alpha}$ has N elements that are space-time dependent arbitrary real numbers. The vector $\boldsymbol{T}$ has also N elements, each being a matrix, and are called generators of the SU(N) group.



▲ **FIG. 1:** Total cross sections of benchmark processes at the LHC as a function of the centre-of-mass energy of the colliding particles [3]. Experimental uncertainties are shown by error bars, and the theoretical ones are presented as very narrow bands. The largest theoretical uncertainty stems from the neglected higher-order radiative corrections in Quantum Chromodynamics in the perturbation series of the cross sections. The label 'NNLO' represents the first three terms in the expansion. The 'NNLL' label means that the three largest powers of logarithmic contributions are summed up.

standard model that the predictions and measurements agree very well. Fig. 2 shows the comparisons of standard model predictions and data measured by the CMS experiment [4]. In total there are 37 final states, out of which only in two instances the deviation between theory and experiment exceeds 1-σ uncertainty, meaning a confidence of 62%. These are the s-channel single t-quark and W+H productions. In both cases the measured value is larger than the predicted one. However, the probabilities of these final states are very small, so the excesses may be simple statistical fluctuations.

Search for physics beyond the standard model

In the high-energy literature, a lot of models have been proposed that predict new particles. Apart from the stringent tests of the SM, the ATLAS and CMS experiments focus mainly on searches for new particles. The most important message of such searches is presented in exclusion limits for the masses of the predicted particles. Many hypothetical particles have been excluded below 1 TeV/c^2 mass, which corresponds to about a thousand proton masses. We can draw similar conclusions from the searches for weakly interacting massive particles (WIMPs) that may constitute the dark matter in the Universe. These results are often called "negative", although one may also consider them "positive" in the sense that the high-energy experiments do not seem to favour rich physics beyond the SM. Thus, we can state that high-energy particle collisions provide firm basis for the validity of the standard model and show no sign of new physics. Nevertheless, there are several discoveries that cannot be explained by the SM, and call for its extension. We turn to their descriptions.

Observations that do not fit into the standard model

Neutrinos have masses

An important discovery was the observation of *neutrino oscillations* [5]. It is a quantum mechanical interference effect, which can be interpreted by the existence of neutrino masses. If the flavour and mass eigenstates of the neutrinos differ, then the flavour-eigenstate neutrinos produced in a decay (say of a pion) are mixtures of mass eigenstates that will have an increasing phase difference as they propagate. As a result, an interference in the flavour space of neutrinos occurs [6].

Dark matter fills the Universe

Another key observation is that the measured energy density of matter in the Universe is about five times more than that of baryonic matter that we are made of (mostly hydrogen and helium, but includes radiation and neutrinos as well). The difference of matter and baryonic matter is called *dark matter* that we do not know. Dark matter feels gravity like ordinary matter, but otherwise it has very weak interaction with matter. The most precise measurements that support this observation is provided by the Planck satellite [7] that measures the intensity of the cosmic microwave background radiation (CMBR). This intensity can be transformed into temperature by Planck's formula of blackbody radiation. The temperature of CMBR is found to be (2.7260±0.0013)K almost independently of direction of observation, but there are fluctuations at the 100μK scale. Those temperature fluctuations can be explained by the cosmological standard model containing six parameters that can be fitted to the measured data. These fits show that the energy density of matter (in units of critical density belonging to eternal expansion) is 0.306±0.007, while that of baryonic matter is 0.0484±0.0005. The difference clearly does not vanish, signalling that some unknown material has a significant contribution to the energy content of the Universe. In the absence of any credible astrophysical explanation it is natural to assume that dark matter consists of particles. Particle physicists exert immense effort to find those.

Baryon-antibaryon asymmetry

The third firm observation is our *existence*. According to the cosmological standard model, at some time in the past the Universe was filled with a hot and dense plasma, in which matter and antimatter particles were present in equal amounts. Our existence proves that this symmetry was broken because today we find only matter in the Universe, but no antimatter. We can create antimatter in the laboratory in small amounts. The CP-violation phase (implying that the equations *change* if we perform simultaneous charge conjugation and space reflection) is present in the Lagrangian of the SM, but it is not sufficiently large to explain the cosmological observations. Among about $4{\cdot}10^{10}$ protons and antiprotons there was one more proton than antiproton after the Big Bang. At present we do not have a proven model of particle interactions that could explain the matter-antimatter asymmetry. The neutrino oscillations may also imply a CP-violation phase that can be large enough to explain sufficiently large lepton-antilepton asymmetry. If so, there is a mechanism proposed theoretically, called sphaleron process, that could lead to baryon-antibaryon asymmetry.

Accelerated expansions of the Universe

The fourth observation is the *accelerated expansion* of the Universe at *present* [8], observed by studying the recession speed of type Ia supernovae [9]. This accelerated expansion is attributed to dark energy, which refers to the existence of energy density ε. Dark energy is characterised by an equation of state $p = w\,\varepsilon$, with $w < -1/3$, implying negative pressure. According to the measurements of the Planck satellite, about 70% of the energy density in the Universe comes with $w = -1.028 \pm 0.032$. We do not have experimental proof for the rapid expansion in the early universe, called inflation. Nevertheless, it is generally accepted that several firm observations can be explained by this assumption. As the early Universe was hot and dense, particle interactions were dominant over gravity. Hence it is natural to search for particle physics origin of inflation.

An exciting future

In summary, we can say that the standard model is firmly established experimentally, yet there are several observations that predict the existence of physics beyond the SM. The SM – in addition to explaining the results of measurements – is highly economical. The underlying symmetry principle – *the Lagrangian has to be invariant under local transformations of the symmetry group, which can be broken only spontaneously by the vacuum* – is simple, suggesting that its extension should also be economical. Any extension is tightly constrained by data. The new model has to respect the precision measurements and at the same time provide explanation for the few observations not fitting into the SM. The status is similar to that 120 years ago at the dawn of the quantum revolution when "almost everything was known about physics, only the spectrum of blackbody radiation required understanding".

About the author

Zoltán Trócsányi is a professor at Eötvös Loránd University in Budapest, an expert of the theory of strong interactions. He was awarded many prizes for his contributions to the advancement of particle physics in Hungary.

References

[1] ATLAS Collaboration, *Phys.Lett. B* **716**, 1 (2012).

[2] CMS Collaboration, *Phys.Lett. B* **716**, 30 (2012).

[3] https://twiki.cern.ch/twiki/bin/view/AtlasPublic/StandardModelPublicResults

[4] https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsCombined

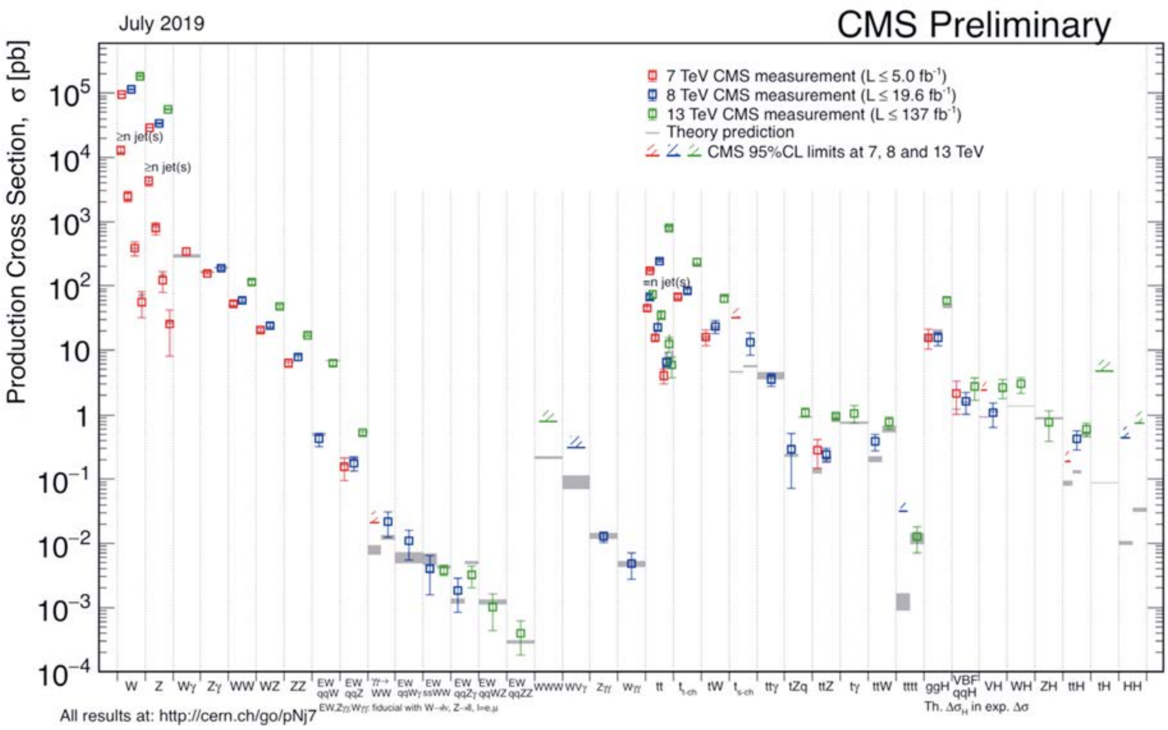
[5] Y. Sirois and M. Mezzetto, *Europhysics News* **46 (5-6)**, 6 (2015).

[6] G. Tammann, F. Thielemann and D. Trautmann, *Europhysics News* **34 (2)**, 68 (2003).

[7] https://www.cosmos.esa.int/web/planck/home

[8] R. van de Weygaert, *Europhysics News* **42 (6)**, 20 (2011).

[9] B. Leibundgut and J. Sollerman, *Europhysics News* **32 (4)**, 121 (2001)



◄ **FIG. 2:** Total production cross sections of the final states [on x-axis] observed by the CMS detector and predictions (grey bands, whose thickness represents the theoretical uncertainty) [4].