International Particle
Physics Outreach Group

Working group
EXPLAINING PARTICLE PHYSICS to the PUBLIC
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Precision counts

Each view of our world is only as good as it is confirmed by observation.

Often precise observations trigger breakthroughs in science and radically change our view of the world:

The use and improvements of the newly discovered telescope let Galileo remove our Earth from the centre of the Universe and initiate modern science. Tycho Brahe’s precise astronomical measurements allowed Kepler to postulate that planets do not move on circles but on ellipses which paved the way to Newton’s theory of gravitation. Microscopes allowed us to study life much more precisely, to discover cells and bacteria and to fight diseases.

In the early 19th century the orbit of Uranus was precisely measured. Tiny irregularities were recorded. Based on Newton’s theory of gravity and these measurements the French astronomer Le Verrier predicted a new planet to explain these deviations. One night after this prediction reached Berlin its Observatory discovered the predicted planet - Neptune. This brilliantly confirmed both Newton’s theory and the scientific method going from precise theoretical prediction to experimental observation.

To decide whether the Earth is flat or a sphere also requires precision. Sailors always doubted that it is flat and suspected that it might be a sphere: new objects show up behind the horizon as you sail on. In the 3rd century BC, the Greek scientist Eratosthenes assumed that Earth is a sphere and even measured its diameter.

Civil engineers can normally assume that Earth is flat. However, in CERN’s 27 km long circular accelerator it had to be taken into account that at opposite points vertical plumb lines are not anymore parallel: they follow Earth's curvature.

Fig 1) Picture from a 1550 edition of On the sphere of the World, the most influential astronomy textbook of 13th-century Europe. Wikipedia

At the end of the 19th century Michelson measured the speed of light with high precision and found to everybody's surprise that it does not depend on whether it is emitted in or against the movement of Earth around the Sun. This allowed Einstein to revolutionize our ideas of electromagnetism, space and time - and to develop his Special Theory of Relativity.

Precise measurements of the precession of Mercury's orbit around the Sun confirmed predictions made by Einstein's General Theory of Relativity, providing evidence for the validity of his groundbreaking theory. A century later, gravitational wave detectors were able to detect distance variations of less than a per mille of a proton radius or 10^{-22} of the detector size. This incredible precision allowed us to discover the tiny ripples of space-time caused by the mergers of heavy celestial bodies like black holes, also predicted by Einstein's theory.

GPS requires a delicate balance between effects of both Einstein's Special and General Theories of Relativity. (The satellite clocks run faster than on ground due to the smaller gravity in their orbit but slower due to their speed.) If these relativistic effects are not precisely taken into account GPS becomes wrong by several meters per minute and hence unusable.

The Standard Model of particle physics describes most phenomena of microcosm to a precision of better than a per mille:

This is a great success of decades of research. The Higgs field is a cornerstone of this model: It gives masses to the building blocks of matter. If this is true, its couplings should be proportional to the particle masses which it generates. This mechanism has to be observed at work and verified precisely. To achieve this the Higgs couplings to matter have to be measured over a large range of particle masses better than with the present precision of about ten percent. Finally, to determine the potential of the Higgs field filling the Universe and in order to test models beyond the standard model we have to measure the coupling of Higgs particles among themselves. This is an ambitious experimental effort.

The Standard Model leaves, however, many important questions open:

What is the nature of Dark Matter and Dark Energy? Why is there more matter than antimatter in the Universe? What determines the masses (and mixings) of the elementary particles? Why are the neutrino masses so incredibly small? To unravel the unknown physics beyond the Standard Model, colliding particles at higher and higher energies and requiring ever larger and more expensive machines is not the only strategy. As we have seen, higher precision is another way to go beyond the limits of known physics and to reveal the mysteries of Nature.

In this spirit, new projects of electron-positron colliders and Higgs factories like the circular FCC-ee and CEPC or the linear accelerators ILC and CLIC first of all aim to precisely test the Standard Model and find hints for new physics beyond its limits. In such machines, the couplings of the Higgs field to matter can for example be measured about ten times better than now. Later, higher energy proton-proton colliders may lead us to discoveries beyond the Standard Model. In a more subtle and less expensive way, measurements of the electric dipole moments of particles or of decays of the heavy electron, the muon, to the normal electron may also lead us to new physics.

Author: Thomas Naumann (DESY), member of the IPPOG Working Group “Explaining Particle Physics to the Public”