

The ‘Standard Model’ of particle physics, describing the fundamental particles making up the universe and the forces between them, is one of the most successful scientific theories in history. Since it predicted the existence of the Higgs boson, confirmed experimentally in 2012, it has been further stress-tested by the measurements conducted at the Large Hadron Collider (LHC) at CERN. Despite this success, the Standard Model is known to be incomplete. Unmodified, it cannot account for neutrino oscillations or masses, or explain the nature of ‘dark matter’, which we believe must exist in order to explain galaxy-scale observations. To resolve these questions, and identify any new particles or forces, requires us to stress-test the Standard Model at even greater precision.

On the experimental side, the LHC has recently started its Run 3, and in the 2030s will be upgraded to collide even more particles per second (from 1 billion now, to 6 billion). Theoretical particle physics must keep pace if we are to make the most of these advances. The first traces of new particles or forces will come from small deviations between the theoretical predictions of the Standard Model, and experimental measurements. To detect them, our methods for making theoretical predictions must be refined, to increase their precision. Standard Model predictions cannot be calculated exactly. Instead we make a series of approximations, in a framework called ‘perturbation theory’, in which successive ‘fixed-order’ approximations become increasingly accurate at higher orders, but also increasingly difficult to calculate. Since the 1980s, for the most common processes, the development of more advanced methods has allowed the state-of-the-art to improve from ‘leading-order’ (‘LO’, the simplest approximation) to ‘next-to-next-to-leading-order’ (‘NNLO’), reducing the theoretical uncertainty from 50-100% to the percent-level.

Protons, the particles undergoing collisions at the LHC, are composite particles: they are made up of quarks and gluons, which, within the Standard Model, are governed by the theory of ‘Quantum Chromodynamics’ (QCD). While the high-energy interactions between quarks and gluons are calculable within perturbation theory, their ‘confinement’ within the proton is not. To make predictions for proton-proton collisions, we rely on ‘factorisation’, in which the perturbative high-energy calculation is augmented by ‘Parton Distribution Functions’ (‘PDFs’) which describe the partons within the proton. This factorisation is not unique, which leaves an ambiguity in the division of contributions between the process-specific perturbative calculation, and the universal PDFs. The choice made for this division is called a ‘factorisation scheme’. Traditionally, a very simple choice has been made, for theoretical elegance and calculational simplicity. However, recent research has suggested that alternative schemes may lead to PDFs with certain desirable properties, such as positivity. Whichever scheme is favoured, all schemes give predictions of the same formal accuracy, and so comparing the predictions made with alternative schemes gives a sense of the theoretical uncertainty arising from this ambiguity. In the quest for higher-and-higher precision to match the experimental advances, understanding this uncertainty is likely to prove indispensable.

To make progress in this direction, we intend to build on our recent work surveying the landscape of factorisation schemes that have been proposed in the past, and assessing their similarities and differences both mathematically and numerically. We will compute PDFs in the different schemes, both by modifying existing PDFs, and by performing independent fits to experimental data to obtain PDFs directly in each scheme. When combined with a modification of NLO calculations to work with PDFs in the other schemes, we will have the first systematic estimate of factorisation-scheme uncertainty at NLO and, potentially, NNLO. As part of this programme of work we will investigate the theoretical properties of the alternative schemes, including positivity and perturbative convergence, potentially arriving at a recommendation for a new ‘default’ scheme to be adopted in future.