Questions and answers - Marius Wiesemann Lecture 1

The following questions were submitted through Google Form. Some / all may have been answered in the Q&A session already. Nevertheless, we request our lecturers to provide written answers here for the benefit of those who could not attend that session. Thank you!

Slide 46. The picture shows underlying event disconnected from the hard process. How well can this process be factorized out?

—> As indicated in the factorization theorem for the LHC the underlying event contributes as a power correction in Lambda^2/Q^2 and therefore it's contribution for a high-energy LHC process is expected to sufficiently small. Whether there can be linear power corrections is still an open problem, but all studies so far suggest that the dependence is quadratic (see for instance recent work by Paolo Nason). The underlying event can be modeled through multi-parton interactions in Monte Carlo generators. However, since these interactions are typically at much lower energy, phenomenological non-perturbative models are used to model them. On top of that, indeed the underlying event cannot be fully factorized from the hard interaction due to colour connections between them, which in principle is included in the non-perturbative models. Furthermore, in principle a consistent definition of an LHC observable requires a fully inclusive definition over multiple parton interactions.

Slide 117. It appears that some techniques like N-jettiness is used for some time but not any more. Is this really the case? If so, why?

—> N-jettiness is still used, especially in context of the MCFM generator (both 0-jettiness and 1-jettiness). However, for colour-singlet processes 0-jettiness has the disadvantage over qT slicing that the power corrections are linear (times a logarithm) and not quadratic (like for qT). An example, where N-jettiness was used more recently, is the N3LO for W production, where it was used in the W+jet NNLO part (see the example #7 on slide 134). The timeline only shows the first calculations at NNLO for a given process (for W+jet that already around 2017), and a few never calculations might have been done in the recent past that are missing here in the diagram.

Slide 29. When can one "feel" safe that there is or isn't NP? It seems that the reasoning could lead to an almost endless race between the precision in data and theory. For example, what if the left picture is valid up to some 10^(-absurd) precision and only then the right picture emerges? In that case, how do we even know where to look for NP? In some sense, an answer to the final part could be "we look where we are capable of looking", but maybe there are some other considerations?

—> We can probe NP in indirect searches as small deviation from the SM only up to the precision that we can achieve in both experimental measurement and theory predictions. If NP induces an effect that is smaller than that, we will not be able to access it at the LHC, and we need either more energy (new collider) or more statistics (more luminosity). There is at the moment not really a fundamental concept that tells us where NP will appear and it what form (only that it has to do before the Planck scale, which is very large). Surely, certain models favour lighter NP, but this is a case-by-case consideration. Hints where to look for NP typically come from theoretical ideas and explicit models. In SMEFT searches, you can (essentially) only ask in which observable can we constrain an OP that has not been constrained so far. Putting this together with achieving the best possible precision allows us to maximize our chances to find NP or to rule it out with the best of our capabilities at the LHC to certain energy scales. Completely ruling it out will not be possible, unless we can probe NP to arbitrary high scales (which is impossible).

Unspecified slide. Can you explain the interpretation or meaning of the factorization scale at which we renormalize the PDFs?

—> The bare PDFs and the partonic cross section are actually separately divergent and only their product is finite. This is due to singular collinear initial state emissions. Through so-called massfactorization procedure, we can essentially move a term (collinear counterterm) between the bare PDFs and the partonic cross section to turn them both separately finite. This procedure to factorize into finite PDFs and partonic cross section creates a scale dependence that connects the two and that is the factorization scale.

Unspecified slide. Nearly all higher order calculations are with massless quarks, even LO calculatio
ns with finite quark mass is hard to find. What's the complication with finite quark mass and prospects for more calculations with massive quarks ?

—> Most LHC calculations use massless quarks apart from the top quark, because the calculations are simpler and treating the quark as massless is typically a good approximation (resumming logarithms into the quark PDFs). In certain cases, especially for bottom quarks, also calculations with massive bottom quarks exist. Generally speaking, are LO and NLO calculations not problem anymore today (fully automated). For NNLO calculations, mass effects can be indeed difficult to compute in the two-loop amplitude, as the additional mass scale (over using a massless quark) substantially complicates the calculation of the loop integrals, and often involves a much more complicated functional form of the amplitude.

no specific slide: Isn’t the limited accuracy of PDFs a problem that dominates the uncertainties of higher-order predictions (order of calculation vs. "order" of PDFs)?

—> This problem has been there in the past, when there were no NNLO PDFs to be used for NNLO calculations. This is solved now since several years, as we have NNLO PDFs in all PDF groups. Also there are so many NNLO computations that meaningful PDF fits with NNLO calculations as input can be made. The problem has now shifted to N3LO, where we only have approximate N3LO PDFs and very few processes are known at N3LO that are useful for PDF fits. NNLO PDFs are very accurate already, so the problem is not that drastic, but indeed the PDF uncertainties are an important uncertainty, especially in the few of upcoming N3LO calculations, where the PDFs (with few-percent uncertainties) are becoming one of the limiting precision factors (to go below 1-few % theory uncertainties).

no specific slide: Why are QCD corrections so large in certain cases? How do I know if the next order doesn’t still have a large correction?

—> That is very process dependent. In most cases there are reasons why higher-order corrections are large, in other cases it is less clear and coincidental. A few examples: Wgamma and WZ have kinematical effect at the amplitude level, called radiation zero, where the leading helicity amplitude vanishes. This region is in the bulk of the cross section and gets filled only upon inclusion of higher-order effects. In charge-neutral qq->VV production there is a contribution/process appearing at NNLO that is loop-induced and goes as gg->VV. This process is enhanced by the gluon luminosities and ass a large contribution to the NNLO correction. In many processes, like gg->H, HH, VV, but also qq->2gamma, 3gamma, the corrections are huge. In many cases the reason is that soft effects are very important. If soft-gluon resummation is included, the series stabilizes. On top of that, new channels appear at NLO (in particular a gq channels) and NNLO (depending on the process) rendering the corrections large as such contributions were not included before. In general, one can expect that at NNLO all contributions/relevant processes are included, and that the perturbative series should become more stable beyond NNLO, but without actually computing the corrections (at least for a number of representative processes) it can not be said with certainty. One possible approach is to consider the corrections at lower orders, and try to assign a conservative uncertainty based on that on top of the scale variations.