Bernhard Mistlberger – Lecture 1 Questions

Questions marked in green were answered during the Q&A session. I haven't tried to correct grammar/spelling. Where a slide number was given it is shown.

Q1 (slide 8): Why is the Higgs width so much narrower than the W and Z widths?

The width is simply related to how easily a particle can decay. The Z and W can easily decay to light leptons (30 %) and quarks (60 %). For the Higgs it's a bit harder to find something to decay to. It's too light to decay to on-shell Z or W bosons. It couples to fermions proportional to their masses - which are very small for light quarks and leptons. And then it can decay through top quark loops to gluons. These complications make the difference. The Higgs decays in ~ 60% of all cases to bottom quarks (the heaviest of all light fermions) and in ~ 20% of all cases into off-shell W bosons.

Q2 (slide 19): Why is the expansion in mH^2 / (4 mt^2) and not mH^2 / mt^2? Factor of 4 would turn 0.13 to ~0.5.

The expansion parameter is really s/(4m_t^2) which is at LO equal to mH^2/(4mt^2). The reasoning is that you will run into problems if you have enough energy (s) available to actually excite the degrees of freedom of the top quark. Since you have to pair produce the top quarks this threshold is at E=2m_t or s= 4m_t^2.
Analytically, you'd find that there is a logarithmic singularity in the Born amplitude at this point. This means a series expansion around m_t=infinity of these functions is only valid up to this kinematic point.

Q3 (slide 23): When you couple the initial and final state particles in the Feynman diagram, does this break the factorization theorem where you can treat the production and decay modes separately?

I think I answered a different question in the talk, so let me try again here:
The fact that there are additional final state particles does not impact the factorisation of production and decay. You can have contributions that go beyond this factorisation if you connect for example decay products of the Higgs - like bottom quarks - with radiation that arises from the initial state partons. However, such corrections would take the Higgs boson slightly off its mass shell and move the virtuality away from the peak in the Breit-Wigner distribution. Consequently, such terms are suppressed and in particular for the Higgs boson this approximation works quite well.

Q4 (slide 32): How long do you think it will be before we have N4LO calculations?

Good question! Who wants to give it a try? Sounds like fun - call me!

Q5 (slide 33): what are the reasons for the uncertainties in predictions? And can we trust them? For example, LO with error bars are very far from the higher order results.

The uncertainties depicted in the plot are based on a variation of the perturbative scales by a factor of 2 or 0.5 around their chosen central value (mh/2). This is simply a prescription that gives you some estimates of how higher order corrections might behave.
For LO, this clearly is a terrible estimate. The gluon fusion Higgs boson production cross section is one of the worst examples in terms of perturbative convergence and this is a reason why we need to compute it

to such high order.
At higher orders, we complement uncertainty estimates with other tests: Threshold resummation, adding higher order terms, factorising the Wilson coefficient differently, inspecting the perturbative progression … Numerically this is very close to the result you see from scale variation. Since this is a very imperfect but accepted community wide standard, we stick with this prescription. Ideas are welcome ;)

Q6 (slide 33): Why this uncertainity in NLO is more than the LO ?

See also Q4. The gluon fusion cross section changes quite a bit at NLO. There is a large channel due to having a quark and a gluon in the initial state opening up, virtual corrections are large, initial state gluons get the possibility to radiate another gluon into the final state. Since all these components are large separately from each other and changing the scale in the cross section is changing the magnitude of the individual contributions with respect to each other and you observe larger effects at NLO.

Q7 (slide 39): What types of research developments let you do numerical calculations faster?

There are many steps forward to improve our numerical capabilities: Better ways to represent our scattering amplitudes, better techniques to evaluate numerical functions, smarter ways of sampling phase space - even AI techniques are used for that by now (check out https://arxiv.org/pdf/2001.10028.pdf). There are lots of improvements to be made by improving our algorithms and our fundamental understanding of scattering processes that will lead to a faster and more reliable prediction of cross sections.

Q8 (slide 40): Do you have to redo the numerical final state phase space integrals for every possible set of analysis level cuts ?

No, if you write clever code, you can set it up such that you are doing many observables or distributions at the same time. Most public numerical tools allow you to do just that.

Q9 (slide 40): what is fiducial, what is fiducial volume?

Q10 (slide 44): What exactly is fixed order calculation and how is low pT processes sensitive to low energy physics?

By fixed order calculation, we refer to a computation of a cross section up to a given (fixed) order in the perturbative expansion. If you computed all terms up to alpha_S^2 with respect to the Born level cross section, you computed a fixed order NNLO cross section.

Fixed order computations include as many final state particles on top of the state you are interested in the computation as the order you are computing at.
We speak of an infrared / low energy sensitive observable if the computed cross section is changing a lot with how many low energy degrees of freedom we are including. If we try to measure how many Higgs bosons are produced at very low transverse momenta, we are entering this regime.

For example, in our calculations we see that our numerical results are changing drastically as we add one more very low energetic parton to the scattering amplitudes. This additional parton may be so low energetic that we cannot even observe it in our detectors. Our intuition clearly tells us that an unobservable change to our description should not change the numerical consequences of our calculations.
Nevertheless, we see exactly that when we stick to fixed order perturbation theory and only include a

finite number of this very low energetic partons. Consequently, we speak about a breakdown of fixed order perturbation theory. If we think about the problem differently and find ways of computing the effects of infinitely many low energetic particles, then we can cure the mathematical deficiencies we found. This is realised by so-called resummed cross sections that re-order perturbative expansion exactly in such a way, that this infrared sensitivity is cured. (Maybe check out https://arxiv.org/pdf/1410.1892.pdf ?)

Q11 (slide 44): Are there 2 different expansions in the N^3LO and N^3LL result? Does this mean you need to stitch together 2 different calculations?

Yes, that's correct.
By N3LO (next-to-next-to-next-to leading order) we refer to the power in the strong coupling to which the displayed distribution is accurate.
By N3LL (next-to-next-to-next-to leading logarithm) we refer to how many powers of logarithms are computed correctly to **all** orders in QCD perturbation theory. This expansion is however only valid in the limit of pT ->0, i.e. there are power suppressed terms with the same logarithmic counting of O(pt^2) that are not controlled at all orders.
At leading logarithmic order, you would be computing correctly the terms that behave as

~ alpha_S^n Log^(2n-1)(pT^2)

Further, "sub-lead" logarithms are characterised by reducing the power of the logarithm that you are predicting correctly:

~ alpha_S^n Log^(2n-2)(pT^2)

~ alpha_S^n Log^(2n-3)(pT^2)

…

There are unfortunately a couple of different counting methods to what exactly N3LL means. In the distribution I showed it essentially means that you are collecting all logarithmically enhanced terms in the N3LO fixed order cross section. (https://arxiv.org/pdf/1410.1892.pdf)

Q12 (slide 41): what does POWHEG refer to ?

Powheg - https://arxiv.org/abs/1007.3893 - is a method and framework for the interface of NLO calculations and parton showers. It appears in this plot as it is always interesting to see how well NLO computations + parton showers fare compared to more accurate fixed order computations. Frameworks like Powheg are easy to use and give you realistic particle events simulated for LHC processes. As a consequence they are widely used and it is important to figure out if and when they fail us.

Q13: Is the focus on this research field in improving PDFs or in improving the hard scattering cross-section calculations?

The two really are very intertwined. The more precise measurements and predictions we can make, the better we can determine the parton content of the proton. On the other hand, if we have more precise PDFs, we can make better predictions. This may seem a bit circular, but in the end you can think about this program as simultaneous extraction of many parameters over a large set of observables and measurements.

Q14 (slide 33): why does the magenta error bar (for NLO) prediction is even bigger than the LO?

See Q5 + Q6

Q15 (slide 37): why Pt cut for two photons are different?

Cuts are designed to ensure predictability, good detection efficiency and clean observables. A larger pT cut reduces the rate. Choosing a pT cut too small will make a photon harder to identify in the very busy environment of a Hadron collider. In the end choosing cuts is an artform and often assisted by optimisation procedures or artificial intelligence. There may actually be better choices than what is currently used: Check out https://arxiv.org/pdf/2106.08329.pdf

Q16 (slide 41): What is the difference between POWHEG prediction and the NNLO? Why does it have lower uncertainties and lower cross section at the same time

See also Q12. Parton showers sometimes reduce the dependence on perturbative scales based on the way they are set up. This is not too surprising but given the fact we see a non-overlap of uncertainty bands, this teaches us to use events generated with Powheg for this observable with a slight grain of salt - we might have to find other ways to estimate uncertainties or improve our simulation depending on the required precision.