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Vector Boson Pair Production in NNLO QCD
by
Dirk Rathlev

It is a real pleasure to review the doctoral dissertation submitted by Dirk Rathlev. The thesis tackles one of the outstanding problems of LHC phenomenology, namely the precise description of events produced in high energy proton-proton collisions that contain pairs of vector bosons. These processes often form backgrounds to searches for new physics and, together with the anticipated high integrated luminosity expected to be achieved by the LHC, require as precise a theoretical description as possible. In many cases, the new results presented here are able to mimic the experimental cuts very closely so that the fiducial cross sections can be directly compared with data. This is extremely valuable, and imposes new challenges on the calculations since restrictions on the phase space can produce up new effects that need resummation. This well written thesis describes a series of cutting edge calculations at next-to-next-to-leading order (NNLO) in the strong coupling constant. These computations are an important improvement over the previous state of the art which was next-to-leading order (NLO).

The thesis itself is both well organised and well written. The main new results are given in Chapters 4 and 5. Chapter 4 describes the implementation of the calculation though a numerical program MATRIX, which combines the general purpose NLO generator Munich with the qT subtraction method employed to isolate the infrared divergences present in the NNLO computation and the one-loop amplitude provider OpenLoops (that was also developed at UZH). MATRIX is able to perform NNLO computations for various important processes at hadron colliders once the relevant two-loop amplitudes are available – many of which have been provided by other groups at UZH. The phenomenological results of the thesis are presented in Chapter 5. This work has mostly appeared in a number of research papers co-authored by Rathlev:

1. "Zγ production at hadron colliders in NNLO QCD," M.Grazzini, S.Kallweit, D.Rathlev and A.Torre, Phys.Lett.B 731 (2014) 204

2. "ZZ production at hadron colliders in NNLO QCD," F.Cascioli et al, Phys.Lett.B 735 (2014) 311

3. “W+W- Production at Hadron Colliders in Next to Next to Leading Order QCD," T.Gehrmann, M.Grazzini, S.Kallweit, P.Maierhöfer, A.von Manteuffel, S.Pozzorini, D.Rathlev and L.Tancredi, Phys.Rev.Lett. 113 (2014) 21, 212001

4. “Wγ and Zγ production at the LHC in NNLO QCD," M.Grazzini, S.Kallweit and D.Rathlev, JHEP 1507 (2015) 085

5. “Transverse-momentum resummation for vector-boson pair production at NNLL+NNLO," M.Grazzini, S.Kallweit, D.Rathlev and M.Wiesemann, arXiv:1507.02565 [hep-ph].

6. “ZZ production at the LHC: fiducial cross sections and distributions in NNLO QCD," M.Grazzini, S.Kallweit and D.Rathlev, arXiv:1507.06257 [hep-ph].

Four of these papers have already appeared in top quality peer-reviewed journals and I have no doubt that the last two papers will swiftly be published. They are already well cited (more than 150 citations so far) and they will continue to attract citations.

Let me summarize the thesis in a little more detail. After a brief introduction, Chapter 2 gives a brief overview of some of the aspects of QCD that will be relevant for the later chapters – regularisation, renormalisation, running couplings, factorization and the structure of infrared singularities. More detail about perturbative calculations are given in chapter 3, including a detailed description of how to assemble NLO computations, and a nice description of the additional complexity of NNLO computations. Various methods for solving the infrared problem are summarized before the qT subtraction method (that forms the basis of the later work) is introduced. I appreciated very much the description of the origins of the qT subtraction from the qT resummation procedure, particularly as the implementation described in chapter 4 enabled the qT resummation to be swiftly implemented in a qT subtracted NNLO calculation. One point that was very welcome was the clear description of qT subtraction as a pure slicing method together with the comments on how to make the subtraction more local.

Chapter 4 describes the numerical implementation of the qT subtraction scheme. qT subtraction explicitly exploits the fact that a significant part of a NNLO cross section computation consists of computations which are only of NLO complexity. It is therefore crucial that the recent developments in NLO automation can be exploited to provide a significant part of the NNLO calculation. There are however subtle details – both the virtual and real contributions of a NLO calculation (the real-virtual and double-real parts of a NNLO computation) are driven to regions of phase space which cannot be accessed by a NLO calculation (the experimental cuts and jet algorithms ensure that the unresolved regions are not explored). The way that the phase space is sampled, and how the NLO generator handles the unresolved regions are crucial. There is a nice description of the mixed multichannel/importance sampling of the phase space and rescue system for unstable phase space points. When a slicing scheme such as qT subtraction is successfully implemented, there should be no dependence on the slicing parameter. This is discussed in depth and we are left in no doubt that there are strong checks on the correctness of both the real-virtual and the double-real emission contributions. MATRIX combines sophisticated NLO technology, both on the amplitude and on the phase-space integration side, with the NNLO qT subtraction scheme. It therefore significantly reduces the manual work required to obtain a numerical

NNLO code for a given process. On top of that, MATRIX is also able to automatically perform NNLL+NNLO resummation of the large logarithms in the low transverse-momentum region.

The main phenomenological results are all contained in chapter 5. This is an impressive body of work that contains many new and important results. Not only are new NNLO calculations derived, but clearly a significant amount of effort has been made to make the connection with the experiment – the decays of the final state particles are included so that one can actually apply experimental selection cuts. This provides additional complications, for example in isolating the top and Higgs contributions to WW production. All are dealt with in a very satisfactory manner. New results for $Z\gamma$, $W\gamma$, ZZ and WW production at NNLO are summarized, together with NNLL+NNLO results for ZZ and WW production. To illustrate the quality and impact of the results, let me just pick out one or two. For $W\gamma$ production, the NNLO corrections are large (order 20%). The reason for this is identified as the LO results being smaller than expected because of the well known radiation zero. The impact is that the apparent excess measured by the ATLAS collaboration can be explained by the NNLO corrections. Similarly, the NNLO corrections to the production of an on-shell W^+W^- pair presented here went some way to reducing the tension with the experimental measurements reported by ATLAS and CMS, and leading to a more careful comparison between theory and experiment.

The thesis is nicely summarized in chapter 6 which also contains a number of pointers to future (and most likely ongoing) work.

It should be clear that both the work described in the thesis and the way that the work is described in the thesis is of the **very highest quality**. It is without doubt one of the better PhD theses that I have had the privilege to read. In view of this, I have no hesitation in recommending that Rathlev is awarded his PhD. In some countries there is the possibility of awarding a distinction or similar for the dissertation – not in the UK, but definitely in Germany and the US. If this is possible at the University of Zurich, then I am very much in favour of recommending the highest possible classification of degree.

Yours sincerely,

Professor E.W.N. Glover FRS
Institute for Particle Physics Phenomenology
Durham University

Institute for Particle Physics Phenomenology Ogden Centre for Fundamental Physics
Science Laboratories South Road Durham DH1 3LE

Telephone +44 191 3343811 Fax +44 191 3343658
www.ippp.dur.ac.uk