We review selected recent theoretical activity in perturbative QCD. We focus on progress in the description of parton densities, including latest developments in neural network parton densities, on the description of high multiplicity final states at the LHC at leading and next-to-leading order, on progress in next-to-next-to-leading order, and on novel developments in jets physics.

1. Introduction

When this talk was presented, the LHC start-up was imminent. By the time this contribution is being written first beams successfully circulated in the LEP tunnel. After several years of planning, development and construction, an extremely exciting time awaits us. The unprecedented potential of the LHC, both in terms of energy and luminosity, will allow us to explore the region where electroweak symmetry breaking is expected to occur. For theorists the challenge is to provide theoretical predictions that match or exceed the accuracy of data, aiming at an early success in understanding this energy frontier. We give here a brief status report and a review of selected recent developments in perturbative QCD focusing on applications to the LHC.

The role of QCD as the theory of strong interactions is incontestable. We do not test QCD any longer, we use it. Despite this it is important to keep in mind that in the last years a naive application of well-established ideas to different contexts led sometimes to failures and mistakes at first, but subsequently resulted in new findings and developments. Examples are the discovery of non-global logarithms, which enter in observables sensitive only to radiation in a selected phase space region and of super-leading logarithms which point to a breakdown of coherence. Given this past experience and the fact that the LHC is unexplored ground with potential surprises ahead, one needs to proceed with care. Bearing this in mind, we want to use QCD to provide precise predictions of input parameters ($\alpha_s$, $m_t$, parton densities...) and of signal to background ratios.

The prerequisite when applying perturbative QCD techniques to high-energy scattering processes is factorization, which implies that hadronic cross sections (differential in some ensemble of variables called $X$ below) can be written as a convolution of partonic cross sections $\hat{\sigma}$ with parton distribution functions $f(x, \mu_F)$

$$\frac{d\sigma_{pp\rightarrow\text{hadrons}}}{dX} = \sum_{a,b} \int dx_1 dx_2 f_a(x_1, \mu_F) f_b(x_2, \mu_F) \times \frac{d\hat{\sigma}_{ab\rightarrow\text{partons}}(\alpha_s(\mu_R), \mu_R, \mu_F, x_1 x_2 Q^2)}{dX} + \mathcal{O}\left(\frac{\Lambda_{\text{QCD}}}{Q^n}\right). \tag{1}$$

The main feature of eq. (1) is that process specific partonic cross sections can be computed in perturbative QCD as an expansion in the coupling constant at leading order (LO), next-to-leading order (NLO), next-to-next-to-leading order (NNLO), etc., while parton distribution functions are extracted from data, but are universal and their evolution, that is the dependence on the factorization scale is fully calculable in perturbative QCD. Today factorization is widely accepted and we will assume it in the following, however one should keep in mind that despite its extensive use, with the exception of Drell-Yan production, there exists to date no rigorous proof of factorization at hadron colliders and recently factorization has been claimed to breakdown in dijet production at N^3LO. Assuming factorization, two ingredients are required to make predictions for the LHC: the parton distribution functions and the partonic scattering cross sections. In the following we will discuss recent progress in the description of both.

---

1 Unfortunately, also an incident occurred, delaying further operation by a few months.
2 Apologies for all the important work not covered here.
2. Parton distribution functions

The most accurate extractions of parton distribution functions (PDFs) today are from the HERA experiment. In Fig. 1 (left) we show the parton density coverage of HERA and LHC in terms of the energy fraction $x$ and the factorization scale $Q^2$ (the scale below which collinear emissions are included in parton densities). The figure illustrates that most of the LHC $x$-range is covered by the HERA experiments, but that one needs on average a $Q^2$ evolution of 2 or 3 orders of magnitude. One also sees that while total cross sections are mostly sensitive only to central $x$-values, rapidity distributions probe extreme (small and large) energy fractions. Also, while the production of states of mass of the order of $W, Z$ bosons is mostly sensitive to small-$x$ (sea) PDFs, potentially interesting TeV scale objects are sensitive to large $x$ values. Altogether it is important to keep in mind the key role of HERA in providing essential input to the LHC.

From a theoretical side recent major progress includes the NNLO evolution of parton densities, possible because of the pillar calculation of splitting functions at NNLO by Moch, Vermaseren, and Vogt in 2004 [6] and the related release of a number of tool-kits for the NNLO DGLAP evolution of PDFs [7]. In recent years a treatment of heavy flavour effects near quark masses has been accounted for, see e.g. [8][9]. It turns out that in some cases heavy flavour effects are large and not covered by the previous uncertainty estimates, which were purely statistical and did not intend to cover such effects. For example inclusion of heavy flavours has a (6-7)% effect on Drell-Yan cross sections at the LHC (while the effect is negligible at the Tevatron). The reason for these sizable corrections in this LHC standard candle process is that, due to momentum sum rules, the presence of heavy flavours in the initial state causes a suppression of light quarks at small $x$.

Recently Neural Network (NN) PDFs have been introduced [5]. These exploit standard NN techniques to provide density fits which do not assume a specific parton density parametrization form, as is the case for all other currently available PDFs and use replica data to treat errors. To understand the importance of NN PDFs it is useful to examine the errors quoted by different groups when performing global fits. As can be seen for example in fig. 1 (right), while various PDFs tend to agree in the central $x$ region covered by data, they disagree in the extrapolation regions, both at very small and at very large $x$ where different parametrization bias the distributions in different directions. In particular, various PDFs do not agree within the quoted uncertainties, which represent statistical errors only. This suggests that the dominant uncertainty is due to the specific choice of the PDF parametrization.
used in the fits. This uncertainty is difficult to estimate with standard techniques, NN PDFs on the other hand are free of this parametrization bias. Additionally with standard PDFs it is sometimes not clear whether it is better to focus on selected, very clean data, or whether it is advantageous to include more and more data in the fits, even if different data sets taken separately would give inconsistent PDFs. With NN PDFs one naturally just includes all available data so as to make the best out of all experimental input. Altogether, the description of PDFs is reaching precision, but still some work ahead is required and more progress is to be expected soon.

3. Multiparticle final states

The LHC will operate in a new regime with the highest energy and luminosity ever reached. This implies that we expect to produce a very large number of high-multiplicity events, both because typical Standard Model (SM) processes can be accompanied by the radiation of many jets and because most Beyond the Standard Model (BSM) signals involve pair production and subsequent decay chains. This means that at the LHC it will be more important to describe high-multiplicity final states than ever before.

A. Leading order

The simplest description in exact perturbative calculations is at leading order. Here partons (or particles) should be well-separated and hard so as to avoid large soft-collinear corrections. Leading order calculations are today fully automated, and can have up to 8 particles in the final state, depending on the process under consideration [10]. This is a remarkable progress compared to few years ago when the best approximation for multi-particle production was often based on a hard $2 \rightarrow 2$ scattering followed by the emission of the remaining particles in the soft-collinear approximation, as implemented in Herwig or Pythia. The drawback of leading order calculations is that they have very large scale dependencies, enhanced sensitivities to kinematical cuts and a poor modeling of the jet structure (each parton corresponding to a jet). For example, in the simple case of the $W+4$ jets cross section (a process relevant for many BSM searches because of the presence of 4 jets, a lepton and missing transverse energy), the LO cross section is proportional to $\alpha_s^4(Q)$. Here $Q$ denotes an arbitrary scale, which should be chosen to be of the order of the hard scale of the process, but is otherwise unspecified. The residual scale dependence of the cross section can be used to gauge the uncertainty of the result. If one varies this scale in such a way that the coupling varies by $\pm 10\%$, the cross section for $W+4$ jets will vary by $\pm 40\%$. This illustrates the large uncertainties of LO calculations. In many cases, where NLO corrections are known, the LO result turns out to be off by $O(100\%)$. One might therefore wonder why we care about LO calculations at all. LO is always the fastest option and often the only one. Today LO can be matched to parton showers, providing a framework to test quickly new ideas in a fully exclusive description. Also, currently there are various working and very well-tested LO generators. Given the complexity of the processes and observables studied at the LHC, the importance of this should not be underestimated. To summarize, LO is highly automated, crucial to explore new ground, but lacks precision. It is interesting to mention which techniques beyond standard Feynman diagrams are available at LO. One powerful method developed by Berends and Giele (BG) 20 years ago uses off-shell currents to construct amplitudes recursively using the building blocks given by the vertices present in the Lagrangian [11]. Britto-Cachazo-Feng (BCF) relations allow one to compute any helicity amplitude via on-shell recursions using complex momentum shifts [12]. Finally with Cachazo-Svrcek-Witten (CSW) relations one can compute any helicity amplitude by sewing together MHV amplitudes [13]. It is interesting to compare the numerical performance of those methods. A study is shown in Tab. 1 which shows the time in seconds to compute $10^4$ amplitudes for $2 \rightarrow n$ gluon production. The numerical superiority of BG relations can be seen clearly here.

B. Next-to-leading order

While LO is a tool to explore new ground, for precision studies NLO is mandatory, simply because the QCD coupling is not very small, so that NLO corrections can be numerically large. Benefits of NLO include a reduced
Table I: Time in seconds to evaluate $2 \rightarrow n$ gluon amplitudes for $10^4$ points (numbers taken from [14], see also [15]).

| Final state | 2g | 3g | 4g | 5g | 6g | 7g | 8g | 9g | 10g |
|-------------|----|----|----|----|----|----|----|----|-----|
| BG          | 0.28 | 0.48 | 1.04 | 2.69 | 7.19 | 23.7 | 82.1 | 270 | 864 |
| BCF         | 0.33 | 0.51 | 1.32 | 7.26 | 59.1 | 646 | 8690 | -  | -   |
| CSW         | 0.26 | 0.55 | 1.75 | 5.96 | 30.6 | 195 | 1890 | 29700 | -   |

dependence on unphysical scales, a better modelling of jets, and a more reliable control of the normalization and shape of cross sections. The status of NLO corrections can be summarized as follows (see also [16])

- all $2 \rightarrow 2$ scatterings are known (or easy to compute) in the SM and beyond;
- very few $2 \rightarrow 3$ scattering processes in the SM are still not known; \(^3\)
- $2 \rightarrow 4$ is a hardly explored ground [17] and today no $2 \rightarrow 4$ LHC scattering process is fully known at NLO.

Three ingredients are needed to compute a $2 \rightarrow N$ process at NLO

- the real radiation of one parton from the $2 + N$ parton system (tree-level $2 + N + 1$ processes);
- one-loop virtual corrections to the $2 \rightarrow N$ process;
- a method to cancel the divergences of real and virtual corrections before numerical integration.

As discussed before, the calculation of tree level amplitudes has been automated and also the cancellation of divergences is well understood [18] and various automated subtraction methods based on the Catani-Seymour dipole approach have been formulated [19]. Therefore at NLO the bottleneck has been the calculation of virtual, loop amplitudes. Because of the importance of these calculations there has been a community effort in the last years following two main streamlines. The first one uses traditional Feynman diagram methods supplemented by robust numerical techniques (integration by parts, Passarino-Veltman and Davydychev reduction, expansions or interpolations close to numerically unstable points etc.). Despite being very advanced [20, 21, 22, 23, 24, 25, 26], these computational tools are plagued by a factorial growth, both in the number of Feynman diagrams to be considered and in the number of terms generated by the tensor reduction. While these methods have been successfully applied to some $2 \rightarrow 3$ processes (see e.g [16]), it turns out to be very difficult to go beyond that [27]. Alternatively, one can exploit analytical methods, which allow one to compute loop amplitudes without doing any loop integration. Unfortunately, with most analytical techniques it was possible to obtain only partial results. For instance using a supersymmetric decomposition of QCD amplitudes one could compute “easily” the $\mathcal{N} = 4$ and $\mathcal{N} = 1$ contributions to the amplitude, but a full QCD calculation requires also the non-supersymmetric scalar contribution. Also, one was able to compute one-loop gluon amplitudes with any number of gluons in the final state, but only for specific helicity configurations, see e.g. [28]. Cross sections on the other hand require a sum/average over all possible allowed helicity states. So despite their remarkable interest, only very few analytical results ended in having a phenomenological application (important examples are [29, 30]). Because of the high complexity of LHC final states, it is clear that for a modern method to be competitive, it should allow one to compute full amplitudes and it should be systematic, making it possible to automate the calculation of the virtual correction, as is currently done for tree-level and for subtraction terms.

Before sketching modern techniques for calculating one-loop amplitudes, we present one NLO example: the recent calculation of $t\bar{t}+1$ jet at the LHC [31]. Fig. 2 shows the improved stability of the NLO result (left panel) and the large effect of the NLO correction on the forward-backward top asymmetry measured at the Tevatron, which is

\(^3\)There is however the important caveat that many recent calculations do not include decays and newest codes are mostly private, limiting the possibility to perform realistic experimental studies.
compatible with zero at NLO (right panel). It is also remarkable that the scale variation at LO is very flat and not a good measure of the size of the NLO correction (essentially because of cancellations between terms in the numerator and denominator in the asymmetry). Finally we note that this calculation constitutes an essential ingredient for the NNLO $t\bar{t}$ production cross section (though an expansion to higher orders in $\epsilon$ is needed and has recently been calculated in the case of gluons in the initial state [32]). Other recently computed calculations include Higgs+dijet production, three vector boson production, $WW+1$jet, $ttZ$, $Wbb$, etc. All those calculations have been done using traditional, Feynman diagram based methods. For a recent review we refer the reader to [16].

In recent years we saw a large number of novel analytical ideas, in the following we will mention only two breakthrough ones. The first one is the formulation of generalized unitarity "...we show how to use generalized unitarity to read off the (box) coefficients. The generalized cuts we use are quadrupole cuts..." [33]. Generalized (quadrupole) cuts in four dimensions completely freeze the loop integration and allow one to compute the box coefficients as products of tree-level amplitudes. The important observation is that because the solution to the on-shell conditions correspond to complex momenta, tree-level amplitudes with 3 on-shell gluons are non-zero (while they would vanish if all momenta were real). The second breakthrough idea goes now under the name of the Ossola-Papadopoulos-Pittau (OPP) method "We show how to extract the coefficients of 4-, 3-, 2-, 1-point one-loop scalar integrals..." [34]. The idea here is to just set up a system of equations in the loop-momentum and reduce the problem to an algebraic problem of finding solutions to those equations.

A unified approach suggests merging partial fractioning via OPP with generalized unitarity in integer higher dimensions so as to get the cut-constructable as well as the rational part [35]. This method allows one to get full one-loop amplitudes from tree-level amplitudes, computed e.g. with Berends-Giele recursion relations. When such an approach is formulated two issues arise: the one of practicality (speed and stability) and the one of generality, i.e. whether the method can be used for realistic LHC processes which involve light and heavy fermions, gluons and vector bosons. As far as practicality is concerned, an excellent performance of the method has been demonstrated in the case of pure gluonic amplitudes [36]. This is illustrated in fig. 3 (left) which shows the time needed to evaluate the most difficult alternating sign helicity amplitudes as a function of the number of gluons ranging between 4 and 20. Also stability of the results is not an issue as long as one evaluates a few unstable points in quadruple precision. Similar results for pure gluonic amplitudes have been obtained using the unitary method and on-shell recursions [37]. As far as applying the method to realistic LHC processes, beyond pure gluonic amplitudes two cases have been considered now: $gg \rightarrow ttg$ [38] amplitudes and all leading and sub-leading $0 \rightarrow q\bar{q}Wggg$ and $0 \rightarrow q\bar{q}WQQg$ amplitudes [39] relevant for $W+3jet$ production. Within a similar approach based on on-shell methods, leading color $0 \rightarrow q\bar{q}Wggg$ amplitudes have also been computed [40].

To conclude, while at the QCD plenary talk at ICHEP04 the statement was made that no automation was in sight for loop amplitudes, today automation for loop amplitudes is on the horizon and the focus in the upcoming years will be finally on computing full cross sections.
After discussing recent progress at NLO, the natural question which arises is: how do we know if NLO is good enough or not? Usually NLO is insufficient when NLO corrections are very large, i.e. when the NLO correction is comparable to, or larger than, the LO result. This may happen when a process involves very different scales, so that large logarithms of the ratio of the two scales arise which need to be resummed. This may also happen when new channels open up (at NLO those channels are effectively LO), this is the case for instance for $b$-jet production, where gluon splitting and flavour excitation processes enter at NLO and are enhanced by large logarithms. Also, gluon dominated processes are often characterized by large corrections, both because gluons radiate on average more than quarks and because of the steeply falling PDFs at small $x$. NLO might also not be sufficient if very high precision is useful, this is occasionally the case, for instance for Drell-Yan, top pair production, and 3-jet production in $e^+e^-$. Finally, since NLO provides a first reliable estimate of cross sections, only NNLO can in principle provide a reliable error estimate of those cross sections. The bottleneck at NNLO is not the calculation of virtual matrix elements, as is the case at NLO, but rather the cancellation of divergences before numerical evaluation.

Today Drell-Yan is the best known process at a hadron collider and constitutes the most important and most precise test of the SM at the LHC. Indeed Drell-Yan is known at NNLO including spin-correlation effects, finite-width effects, $\gamma - Z$ interference and the calculation is fully differential in the lepton momenta [41, 42]. Sample results are shown in fig. 3 which demonstrate the improved scale stability at higher orders.

Inclusive Higgs production at NNLO has also been known for a few years now [43, 44, 45]. Recently, the decays of the Higgs into 4 charged leptons or into 2 charged leptons and two neutrinos have been included [46, 47, 48]. This gives one the possibility to study cross sections with realistic cuts on the jets and on the lepton momenta. It turns out that a veto on jets with large transverse momentum dramatically decreases the size of the NNLO corrections and improves the convergence of the perturbative expansion. Very recently, a study suggests that the large perturbative corrections to Higgs production stem from $(C_A\pi\alpha_s)^n$ enhanced terms, which arise in the analytic continuation of the gluon form factor to time-like region [49].

Another NNLO calculation completed after several years in 2007 is the one of 3-jet production in $e^+e^-$ [50]. The main motivation for this calculation was that the error on $\alpha_s$ from jet-observables was dominated by the theoretical uncertainty, $\alpha_s(M_Z) = 0.121 \pm 0.001(\text{exp}) \pm 0.005(\text{th})$. Higher orders were therefore mandatory to reduce this error.

For this calculation a new method based on antenna subtraction at NNLO was developed. The first application was a NNLO fit of $\alpha_s$ from event-shapes. As illustrated in fig. 4, the scale variation effect is reduced at NNLO by a factor of 2, the scatter between $\alpha_s$ from different event shapes is also reduced, and the fit gives a central value closer to the world average with a better $\chi^2$ value.

More recently, this NNLO calculation has been used in conjunction with a $N^3LL$ resummation for the thrust
distribution using soft collinear effective theory (SCET) methods \[52\]. This impressive calculation gives an $\alpha_s$ which lies on top of the world average with an error comparable to that of the world average. However, SCET resummation points to potential problems in some (2 or 3) color structures in the low thrust region. After that, an independent NNLO calculation confirmed the disagreements on those color structures \[53\]. Whether the value of $\alpha_s$ from NNLO fits will remain largely unaffected is something we will know soon.

Other very accurate recent determinations of the strong coupling come from $Z$ and $\tau$ decays. These calculations use cutting-edge five-loop results for massless propagator integrals, fixed order versus contour-improved perturbation theory and sum rules \[54\]. As a general feature, higher order terms lead to a stabilization of the perturbative series, to a reduction of the theoretical uncertainty and to a small shift in the central value. A good agreement between the values of $\alpha_s$ from $Z$ and $\tau$ decays occurring at very different energies is found, however comparing with lattice simulations, partially conflicting results emerge.

4. Jets

Two years ago when discussing or reading about jets, one encountered various qualitative statements whose origin and level of correctness was largely unclear. Since then a tremendous progress in the description of jets has been achieved. This includes a fast implementation of the $k_t$ algorithm (FastJet) \[55\], an infrared safe definition of jet flavour and related accurate predictions for $b$-jets \[56\], an infrared safe cone algorithm (SISCone) \[57\], a new anti-$k_t$ algorithm \[58\], new concepts of jet-areas and related techniques for pile-up subtraction \[59\], quality measures to quantify systematically the performance of jet-algorithms \[60\], analytical and Monte Carlo based studies of non-perturbative effects in jets \[61\] and studies of the jet-substructure as a way to enhance important search channels \[62\].

In the following we will illustrate just two recent developments, for a recent review on the subject see \[9\].

The first one relates to the issue of infrared unsafety of standard, seeded cone algorithms. To understand what the problem is it is useful to examine fig. 5 (left), which shows schematically a simple event with 3 hard emissions. By running, for instance, a midpoint algorithm with a given $R$ one would identify two stable cones. When an additional very soft emission is added to the event fig. 5 (right), the same algorithm finds 3 stable cones. This is because the additional emission provides an additional seeds (i.e. trial direction). So the stable cone which was missed before is now found. Because a soft emission can change the structure of the final state hard jets the algorithm is infrared unsafe. The solution is to use SISCone \[57\], a seedless, fast ($N^2 \ln N$) algorithm which finds all stable cones. Similarly one can show that the iterative cone is collinear unsafe and can be replaced by the anti-$k_t$ algorithm (which, just like the iterative cone, has the property that very soft emissions are recombined together only later on, while hard emissions eat up efficiently everything which lies close by, hence the nice circular shape of the jets).

![Figure 4: Scatter in the extraction of $\alpha_s(M_Z)$ from six event shapes when using NNLO, NLO and NLO+NLL approximations (figure taken from \[51\]).](image-url)
One might wonder whether infrared unsafety is just an aesthetic, formal issue with negligible practical consequences or whether it can have a physical impact at the LHC. Some studies at the Tevatron suggested that the difference between running an infrared safe or unsafe algorithm on inclusive jet cross sections is less than 1%. For more exclusive quantities on the other hand larger differences can occur. For instance one can find up to 40% differences between SISCone and midpoint when looking at the mass-spectrum of the second hardest jet. In general the more particles are present in the hard event, the earlier in the perturbative expansion one will start missing stable cones. For instance in the case of W/V/H + 2-jet cross section, cones are missed at NLO, therefore the last meaningful order is LO (while a NLO calculation is available in MCFM). Similarly, for jet masses in 3 jet events, cones are already missed at leading order, so that no perturbative order is meaningful. Therefore, if one does not want theoretical efforts to be wasted one should stick to infrared safe algorithms.

The second recent jet development we will illustrate here is the use of jet substructure in the case of Higgs production. As is well-known a light Higgs is difficult to find experimentally at the LHC and several channels with individually low significance have to be combined to achieve an acceptable total sensitivity. If the Higgs is light it decays predominantly in $b\bar{b}$. The associated $Z/W+H$ production with $H \rightarrow b\bar{b}$ could seem at first sight a good channel, however, because of very large QCD backgrounds, the ATLAS Technical Design Report concluded that “The extraction of a signal from $H \rightarrow b\bar{b}$ decays in the $WH$ channel will be very difficult at the LHC even under the most optimistic assumptions…” [63]. Since then this channel has been largely neglected. Recently on the other hand, it has been recognized that despite the loss in statistics, there are important benefits in considering highly boosted, high $p_t$ Higgs bosons: their central decay products give rise to a single massive jet [62]. One can then use a jet-finding geared to identify the characteristic structure of the fast-moving Higgs that decays into a $b\bar{b}$ pair close in angle. Concretely, one can use a Cambridge/Aachen algorithm with a quite large radius $R$, one can then undo the last recombination step and require that this gives rise to a large mass drop and to a symmetric event with two $b$-tags. Finally one can filter away the underlying event by taking only the 3 hardest sub-jets in the event. The invariant mass of those is plotted in fig. 5 for $m_H = 115$ GeV when imposing standard search cuts, combining the three channels $W \rightarrow l\nu, Z \rightarrow t^+t^-$ and $Z \rightarrow \nu\bar{\nu}$ and assuming a real and fake $b$-tag rates of 0.6 and 0.02. One can clearly see the Higgs peak at 115 GeV. Additionally, one can see a very neat peak at the $Z$ mass due to $WZ (Z \rightarrow b\bar{b})$ which is important for calibration. A preliminary study indicates that a $4.5\sigma$ sensitivity can be obtained with 30 fb$^{-1}$. This would mean that $VH$ with $H \rightarrow b\bar{b}$ is recovered as one of the best discovery channels for a light Higgs. Of course more experimental studies are to come.

5. Conclusions

In the last years we have seen an impressive amount of progress in perturbative QCD in the description of parton densities, in higher order calculations (LO, NLO, NNLO and resummations) and in the description of jets, where an amazing level of sophistication has been reached. Progress was mainly driven by automation, flexibility, release of public codes, many new ideas and very good communication with experimentalists, leading to several common
Figure 6: Signal and background for a 115 GeV SM Higgs simulated using Herwig. The jet-clustering is C/A MD-F with $R = 1.2$ and $p_T > 200$ GeV. A $b$-tagging efficiency of 60% and a mistag of 2% is used. $q\bar{q}$ denotes both heavy and light dijets. The errors reflect the statistical uncertainty on 30 fb$^{-1}$ (figure kindly provided by Adam Davison).

papers. Of course there are still many challenges ahead and we don’t know yet what we might discover at the LHC, but QCD theory will provide solid basis for a successful physics programme at the LHC.

Acknowledgments

Many thanks to Babis Anastasiou, Andrea Banfi, Matteo Cacciari, Keith Ellis, Fabio Maltoni, Kirill Melnikov, Juan Rojo, Gavin Salam and Gregory Soyez for valuable discussions and to the organizers for the making ICHEP08 such an enjoyable and stimulating meeting. The author is supported by the British Science and Technology Facilities Council (STFC).

References

[1] M. Dasgupta and G. P. Salam, Phys. Lett. B 512 (2001) 323 [arXiv:hep-ph/0104277].
[2] J. R. Forshaw, A. Kyrieleis and M. H. Seymour, JHEP 0608 (2006) 059 [arXiv:hep-ph/0604094].
[3] J. Collins and J. W. Qiu, Phys. Rev. D 75 (2007) 114014 [arXiv:0705.2141 [hep-ph]].
[4] M. Dittmar et al., arXiv:hep-ph/0511119.
[5] L. Del Debbio, S. Forte, J. I. Latorre, A. Piccione and J. Rojo [NNPDF Collaboration], JHEP 0703, 039 (2007) [arXiv:hep-ph/0701127]; R. D. Ball et al., arXiv:0808.1231 [hep-ph].
[6] A. Vogt, S. Moch and J. A. M. Vermaseren, Nucl. Phys. B 691, 129 (2004) [arXiv:hep-ph/0404111]; S. Moch, J. A. M. Vermaseren and A. Vogt, Nucl. Phys. B 688, 101 (2004) [arXiv:hep-ph/0403192].
[7] A. Vogt, Comput. Phys. Commun. 170, 65 (2005) [arXiv:hep-ph/0408244]; M. Botje, QCDNUM, http://www.nikhef.nl/~h24/qcdnum/; A. Cafarella, C. Coriano and M. Guzzi, arXiv:0803.0462 [hep-ph]; G. P. Salam and J. Rojo, arXiv:0804.3755 [hep-ph].
[8] R. S. Thorne and W. K. Tung, arXiv:0809.0714 [hep-ph]; P. M. Nadolsky et al., Phys. Rev. D 78 (2008) 013004 [arXiv:0802.0007 [hep-ph]].
[9] C. Buttar et al., arXiv:0803.0678 [hep-ph].
[10] M. L. Mangano, M. Moretti, F. Piccinini, R. Pittau and A. D. Polosa, JHEP 0307 (2003) 001 [arXiv:hep-ph/0206293]; F. Maltoni and T. Stelzer, JHEP 0302 (2003) 027 [arXiv:hep-ph/0208156]; T. Gleisberg, S. Hoche, F. Krauss, A. Schalicke, S. Schumann and J. C. Winter, JHEP 0402 (2004) 056 [arXiv:hep-ph/0311263]; W. Kilian, T. Ohl and J. Reuter, arXiv:0708.4233 [hep-ph].
[11] F. A. Berends and W. T. Giele, Nucl. Phys. B 306 (1988) 759.
[12] R. Britto, F. Cachazo and B. Feng, Nucl. Phys. B 715 (2005) 499 [arXiv:hep-th/0412308].
[13] F. Cachazo, P. Svrcek and E. Witten, JHEP 0409 (2004) 006 [arXiv:hep-th/0403047].
[14] C. Duhr, S. Hoche and F. Maltoni, JHEP 0608 (2006) 062 [arXiv:hep-ph/0607057].
[15] M. Dinsdale, M. Ternick and S. Weinzierl, JHEP 0603 (2006) 056 [arXiv:hep-ph/0602204].
[16] Z. Bern et al. [NLO Multileg Working Group], arXiv:0803.0494 [hep-ph].
[17] A. Bredenstein, A. Denner, S. Dittmaier and S. Pozzorini, JHEP 0808 (2008) 108 [arXiv:0807.1248 [hep-ph]].
[18] R. K. Ellis, D. A. Ross and A. E. Terrano, Nucl. Phys. B 178, 421 (1981);
S. Catani and M. H. Seymour, Nucl. Phys. B 485 (1997) 291 [Erratum-ibid. B 510 (1998) 503] [arXiv:hep-ph/9605323];
S. Frixione, Z. Kunszt and A. Signer, Nucl. Phys. B 467 (1996) 399 [arXiv:hep-ph/9512328].
[19] M. Dinsdale, M. Ternick and S. Weinzierl, JHEP 0603 (2006) 056 [arXiv:hep-ph/0602204].
[20] A. I. Davydychev, Phys. Lett. B 263 (1991) 107.
[21] G. Duplancic and B. Nizic, Eur. Phys. J. C 35 (2004) 105 [arXiv:hep-ph/0303184].
[22] W. T. Giele and E. W. N. Glover, JHEP 0404 (2004) 029 [arXiv:hep-ph/0402152].
[23] R. K. Ellis, W. T. Giele and G. Zanderighi, Phys. Rev. D 73 (2006) 014027 [arXiv:hep-ph/0508308].
[24] A. Denner and S. Dittmaier, Nucl. Phys. B 734, 62 (2006) [arXiv:hep-ph/0509141].
[25] A. van Hameren, J. Vollinga and S. Weinzierl, Eur. Phys. J. C 41 (2005) 361 [arXiv:hep-ph/0502165].
[26] Z. Bern, L. J. Dixon and D. A. Kosower, Nucl. Phys. B 513 (1998) 3 [arXiv:hep-ph/9708239].
[27] M. H. Seymour and C. Tevlin, arXiv:0803.2231 [hep-ph];
T. Gleisberg and F. Krauss, Eur. Phys. J. C 53 (2008) 501 [arXiv:0709.2881 [hep-ph]]; K. Hasegawa, S. Moch and P. Uwer, arXiv:0807.3701 [hep-ph].
[28] Z. Bern, L. J. Dixon and D. A. Kosower, Phys. Rev. Lett. 70 (1993) 2677 [arXiv:hep-ph/9302280].
[29] Z. Bern, L. J. Dixon and D. A. Kosower, Nucl. Phys. B 734, 275 (2005) [arXiv:hep-th/0412103].
[30] A. Denner and S. Dittmaier, Nucl. Phys. B 734, 62 (2006) [arXiv:hep-ph/0509141].
[31] R. K. Ellis, W. T. Giele and G. Zanderighi, JHEP 0605 (2006) 027 [arXiv:hep-ph/0602185].
[32] S. Catani and M. H. Seymour, Nucl. Phys. B 485 (1997) 291 [Erratum-ibid. B 510 (1998) 503] [arXiv:hep-ph/9605323];
S. Frixione, Z. Kunszt and A. Signer, Nucl. Phys. B 467 (1996) 399 [arXiv:hep-ph/9512328].
[33] W. T. Giele, Z. Kunszt and K. Melnikov, JHEP 0804 (2008) 049 [arXiv:0801.2237 [hep-ph]].
[34] W. T. Giele and G. Zanderighi, JHEP 0804 (2008) 049 [arXiv:0801.2237 [hep-ph]].
[35] W. T. Giele, Z. Kunszt and K. Melnikov, JHEP 0804 (2008) 049 [arXiv:0801.2237 [hep-ph]].
[36] W. T. Giele and G. Zanderighi, JHEP 0804 (2008) 049 [arXiv:0801.2237 [hep-ph]].
[37] C. Anastasiou, L. J. Dixon, K. Melnikov and F. Petriello, Phys. Rev. D 69 (2004) 094008 [arXiv:hep-ph/0312260].
[38] K. Melnikov and F. Petriello, Phys. Rev. Lett. 96 (2006) 231803 [arXiv:hep-ph/0603182].
[39] R. V. Harlander and W. B. Kilgore, Phys. Rev. Lett. 88 (2002) 201801 [arXiv:hep-ph/0201206].
[40] V. Ravindran, J. Smith and W. L. van Neerven, Nucl. Phys. B 665, 325 (2003) [arXiv:hep-ph/0302153].
[41] C. Anastasiou, G. Dissertori and F. Stockli, JHEP 0709 (2007) 018 [arXiv:0707.2373 [hep-ph]].
[42] C. Anastasiou, G. Dissertori, F. Stockli and B. R. Webber, JHEP 0803 (2008) 017 [arXiv:0801.2682 [hep-ph]].
[43] M. Grazzini, JHEP 0802 (2008) 043 [arXiv:0801.3232 [hep-ph]].
[44] V. Ahrens, T. Becher, M. Neubert and L. L. Yang, arXiv:0808.3008 [hep-ph].
[45] A. Gehrmann-De Ridder, T. Gehrmann, E. W. N. Glover and G. Heinrich, Phys. Rev. Lett. 99 (2007) 132002 [arXiv:0707.1285 [hep-ph]].
[46] C. Anastasiou, G. Dissertori, F. Stockli and B. R. Webber, JHEP 0803 (2008) 017 [arXiv:0801.2682 [hep-ph]].
[47] M. Grazzini, JHEP 0802 (2008) 043 [arXiv:0801.3232 [hep-ph]].
[48] V. Ahrens, T. Becher, M. Neubert and L. L. Yang, arXiv:0808.3008 [hep-ph].
[49] A. Gehrmann-De Ridder, T. Gehrmann, E. W. N. Glover and G. Heinrich, Phys. Rev. Lett. 99 (2007) 132002 [arXiv:0707.1285 [hep-ph]].
[50] G. Dissertori, A. Gehrmann-De Ridder, T. Gehrmann, E. W. N. Glover, G. Heinrich and H. Stenzel, JHEP 0802 (2008) 040 [arXiv:0712.0327 [hep-ph]]; T. Gehrmann, G. Luisoni and H. Stenzel, Phys. Lett. B 664 (2008) 265 [arXiv:0803.0695 [hep-ph]].
[51] T. Becher and M. D. Schwartz, JHEP 0807 (2008) 034 [arXiv:0803.0342 [hep-ph]].
[53] S. Weinzierl, arXiv:0807.3241 [hep-ph].

[54] P. A. Baikov, K. G. Chetyrkin and J. H. Kuhn, Phys. Rev. Lett. 101 (2008) 012002 arXiv:0801.1821 [hep-ph]; M. Davier, S. Descotes-Genon, A. Hocker, B. Malaescu and Z. Zhang, Eur. Phys. J. C 56 (2008) 305 arXiv:0803.0979 [hep-ph]; M. Beneke and M. Jamin, JHEP 0809 (2008) 044 arXiv:0806.3156 [hep-ph]; K. Maltman and T. Yavin, arXiv:0807.0650 [hep-ph].

[55] M. Cacciari and G. P. Salam, Phys. Lett. B 641 (2006) 57 arXiv:hep-ph/0512210.

[56] A. Banfi, G. P. Salam and G. Zanderighi, Eur. Phys. J. C 47 (2006) 113 arXiv:hep-ph/0601139; A. Banfi, G. P. Salam and G. Zanderighi, JHEP 0707 (2007) 026 arXiv:0704.2999 [hep-ph].

[57] G. P. Salam and G. Soyez, JHEP 0705 (2007) 086 arXiv:0704.0292 [hep-ph].

[58] M. Cacciari, G. P. Salam and G. Soyez, JHEP 0804 (2008) 063 arXiv:0802.1189 [hep-ph].

[59] M. Cacciari, G. P. Salam and G. Soyez, JHEP 0804 (2008) 005 arXiv:0802.1188 [hep-ph]; M. Cacciari and G. P. Salam, Phys. Lett. B 659 (2008) 119 arXiv:0707.1378 [hep-ph].

[60] M. Cacciari, J. Rojo, G. P. Salam and G. Soyez, arXiv:0810.1304 [hep-ph].

[61] M. Dasgupta, L. Magnea and G. P. Salam, JHEP 0802 (2008) 055 arXiv:0712.3014 [hep-ph].

[62] J. M. Butterworth, A. R. Davison, M. Rubin and G. P. Salam, Phys. Rev. Lett. 100 (2008) 242001 arXiv:0802.2470 [hep-ph].

[63] ATLAS, Detector physics performance technical design report, CERN/LHCC/99-14/15(1999).