1 Theory of Elementary Particles

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The particle theory group at the Physik-Institut works on a broad spectrum of research projects dealing with the interpretation of data from high energy particle colliders. Our studies cover precision calculations of benchmark observables, simulation of full collider events, identification of optimal observables for searches and measurements, as well as developments of calculational techniques. We summarize some highlights of last year's research below.

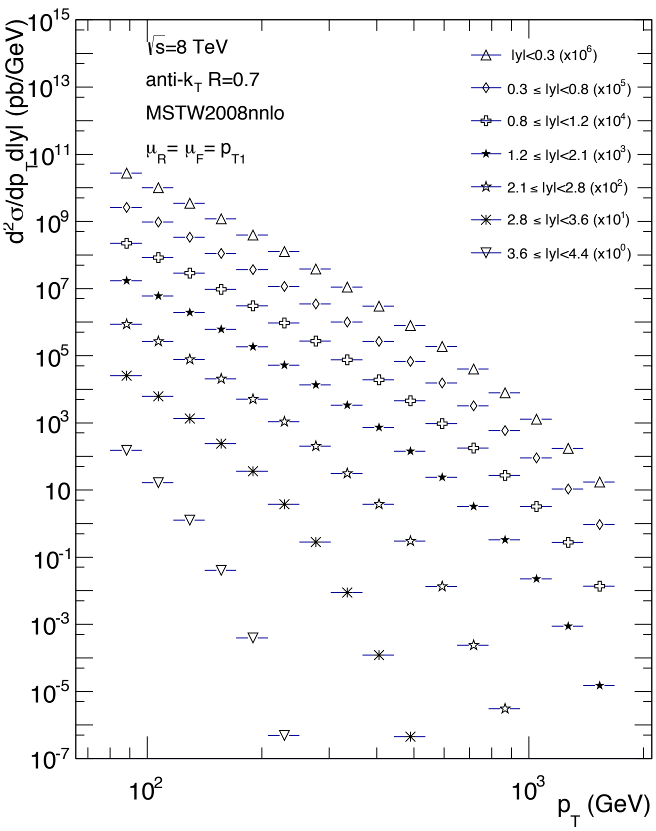

FIG. 1.1 – Doubly differential inclusive jet transverse energy distribution, $d^2\sigma/dp_T d|y|$, at $\sqrt{s} = 8$ TeV for the anti-k_T algorithm with $R = 0.7$ and for $p_T > 80$ GeV and various $|y|$ slices at NNLO.

1.1 NNLO corrections to jet production at hadron colliders

Single jet, inclusive jet and dijet observables are the most fundamental QCD quantities measured at hadron colliders. They describe the basic parton-parton scattering in $2 \to 2$ kinematics, and thus allow for a determination of the parton distribution functions in the proton and for a direct probe of the strong coupling constant α_s up to the highest energy scales that can be attained in collider experiments.

At present, these observables are calculated to next-to-leading order (NLO) precision in QCD, which is insufficient to fully exploit the highly accurate data now available from the LHC experiments. We are currently working towards the computation of the NNLO corrections to jet production at hadron colliders. The major challenge in these calculations is the handling of infrared singular configurations in different subprocesses, which cancel only once they are summed. To implement the different subprocesses in a numerical parton-level event generator program, we have developed the antenna subtraction method, which allows to shift infrared singular contributions between different processes to ensure all cancellations prior to implementation. We have applied this method in the calculation of NNLO corrections to gluon induced jet production [1, 2].

In Fig. 1.1 we present the inclusive jet cross section in double differential form at NNLO as it is measured at the LHC and Tevatron. The inclusive jet cross section is computed in jet p_T and rapidity bins over the range $0.0 - 4.4$ covering central and forward jets. To quantify the impact of the NNLO correction we present the double differential K-factors containing ratios of NNLO, NLO and LO cross sections in Fig. 1.2. We observe that the NNLO correction increases the cross section between 26% at low pT to 14% at high p_T with respect to the NLO calculation. This behaviour is similar for each of the three rapidity slices presented.

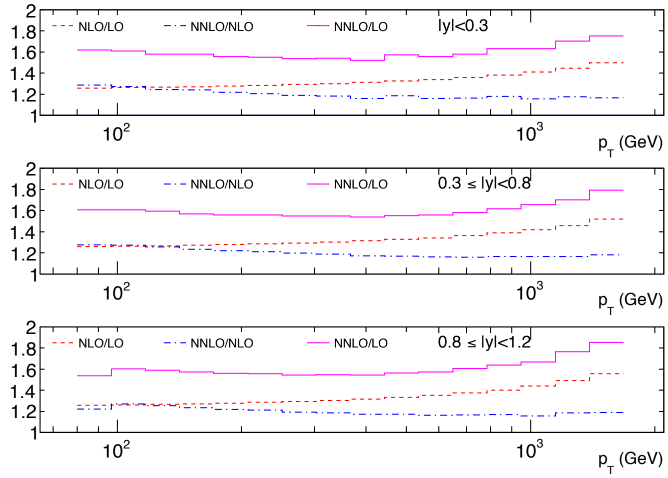

FIG. 1.2 – Ratios of NNLO, NLO and LO cross sections for three rapidity slices: $|y| < 0.3$, $0.3 < |y| < 0.8$ and $0.8 < |y| < 1.2$.

By studying the dependence of the theory prediction on unphysical renormalization and factorization scales, it is possible to estimate the potential magnitude of yet unknown higher order contributions. Going from NLO to NNLO accuracy, we observed a substantial reduction of this scale uncertainty, thus leading to a theoretical precision at the few per cent level. Work on the quark-initiated processes is well underway [3], such that full results on the NNLO corrections at hadron colliders can be expected in due course.

[1] A. Gehrmann-De Ridder, T. Gehrmann, E. W. N. Glover and J. Pires, Phys. Rev. Lett. **110** (2013) 16, 162003.

[2] J. Currie, A. Gehrmann-De Ridder, E. W. N. Glover and J. Pires, JHEP **1401** (2014) 110.

[3] J. Currie, E. W. N. Glover and S. Wells, JHEP **1304** (2013) 066.

1.2 Loop integrals for precision calculations

The calculation of higher order corrections in quantum field theory requires computation of multi-loop Feynman integrals. In particular, NNLO corrections to basic scattering processes require the derivation of two-loop four-point functions for the kinematical situation under consideration. In the framework of dimensional regularization, many powerful techniques have been developed in order to make the computation of two-loop corrections to three- and four-point functions feasible.

Using computer algebra methods, the large number of Feynman integrals appearing in the two-loop four-point function can be reduced to a limited set of so-called master integrals. To compute these master integrals, the differential equation technique has proven to be particularly powerful. Using this technique, we have computed the two-loop master integrals relevant for pair production of massive gauge bosons [1], and for fermionic corrections to top quark pair production [2], thereby enabling the calculation of NNLO corrections to these benchmark processes.

[1] T. Gehrmann, L. Tancredi and E. Weihs, JHEP **1308** (2013) 070.

[2] R. Bonciani, A. Ferroglia, T. Gehrmann, A. von Manteuffel and C. Studerus, JHEP **1312** (2013) 038.

1.3 Heavy quark mass effects in Higgs boson production at the LHC

In July 2012 ATLAS and CMS experiments at the LHC announced the observation of a new scalar resonance of mass $m_H \sim 125$ GeV. To establish to which extent the new resonance is consistent with the long sought Higgs boson predicted by the SM accurate theoretical predictions for the Higgs production cross section and the associated distributions are required. The dominant production channel for the Higgs boson at hadron colliders is gluon fusion, through a heavy-quark loop. For simplicity the calculations are usually performed in the large m_t limit, in which the top loop shrinks to a point. The effects of the finite quark masses are, however, known to significantly affect the shape of the distributions, especially at large transverse momenta of the Higgs boson and or its decay products. In Ref. [1] we have studied the effects of the finite top and bottom masses in the Higgs p_T spectrum.

The implementation of the top-mass dependence does not lead to substantial complications. By contrast, since $m_b \ll m_H$, the inclusion of the exact bottom-mass dependence in the resummed p_T spectrum implies the solution of a non-trivial three-scale problem. We have studied the analytical behaviour of the relevant QCD matrix elements, showing that, when the bottom-quark contribution is considered, naive factorization is valid only in a limited region of the phase space, i.e. when $p_T \lesssim 2m_b$. We have provided a simple solution to this issue by controlling the resummed bottom-quark contribution through an additional resummation scale Q_2, which was chosen of the order of the bottom mass m_b. We have shown that this solution has a clear advantage: it limits the impact of the resummation to the region where it is really needed, i.e. $p_T \lesssim 2m_b$, and our resummed result for the bottom quark contributions smoothly merges with the fixed order NLO result at $p_T \gtrsim 2m_b$, where the resummation is not anymore justified.

We have studied the impact of mass effects on the NLL+NLO calculation, by showing that the effect of heavy-quark masses is significant, although at this order large uncertainties affect the resummed p_T spectrum.

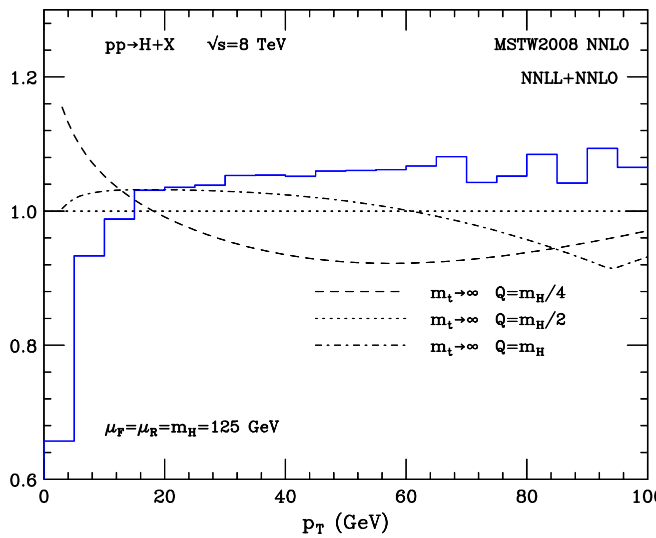

FIG. 1.3 – Transverse momentum spectrum at NNLL+NNLO with full dependence on heavy quark masses ($Q_2 = m_b$) normalized to the result in the large-m_t limit (solid histogram). The result is compared to the NNLL+NNLO results in the large-m_t limit obtained with $Q = m_H, m_H/4$.

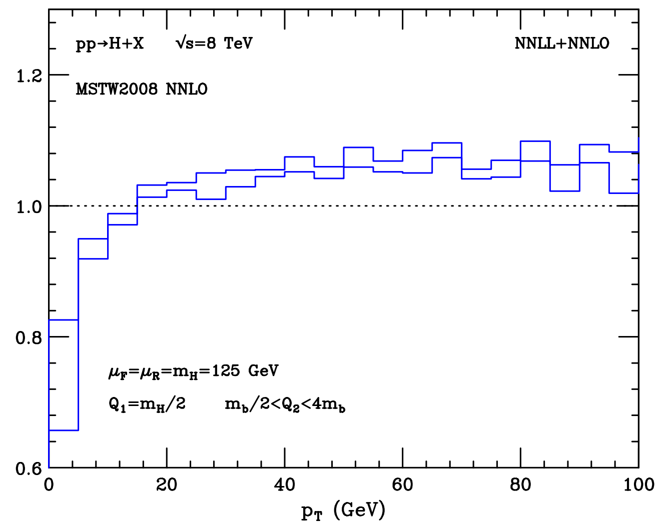

FIG. 1.4 – Transverse momentum spectra at NNLL+NNLO for $m_b/2 < Q_2 < 4m_b$ normalized to the result in the large-m_t limit.

When going to NNLL+NNLO, where the perturbative uncertainties are much smaller, the impact of heavy-quark masses still distorts the spectrum in the low-p_T region (see Figures 1.3 and 1.4). The calculations are implemented in updated versions of the HNNLO and HRes numerical programs.

[1] M. Grazzini and H. Sargsyan, JHEP **1309** (2013) 129.

1.4 $Z\gamma$ production in NNLO QCD

Vector-boson pair production is crucial in physics studies within and beyond the Standard Model (SM). In particular, the production of neutral vector-boson pairs, like $Z\gamma$, is well suited to search for anomalous couplings.

In Ref. [1] the first complete computation of $pp \to Z\gamma + X$ in NNLO QCD has been reported. We note that the notation "$Z\gamma$" is misleading, as it suggests the production of an on-shell Z boson plus a photon, followed by a factorized decay of the Z boson. Instead, the calculation of Ref. [1] regards the process $pp \to l^+l^-\gamma + X$, where the lepton pair l^+l^- is produced either by a Z boson or a virtual photon, and the contributions in which the final-state photon is radiated from the leptons is consistently included. The NNLO calculation, which relies on the method of Ref. [2] and the results of Ref. [3], is implemented in a numerical program which allows arbitrary cuts on the final state leptons, the photon and the associated jet activity.

The impact of the NNLO corrections strongly depends on the selection cuts. In the ATLAS results the photon is required to have a transverse momentum $p_T^\gamma > 15$ GeV and pseudorapidity $|\eta^\gamma| < 2.37$. The charged leptons are required to have $p_T^l > 25$ GeV and $|\eta^l| < 2.47$, and their invariant mass m_{ll} must fulfil $m_{ll} > 40$ GeV. The separation in rapidity and azimuth ΔR between the leptons and the photon must be $\Delta R(l,\gamma) > 0.7$. Jets are reconstructed with the anti-k_T algorithm with radius parameter $D = 0.4$. A jet must have $E_T^{\text{jet}} > 30$ GeV and $|\eta^{\text{jet}}| < 4.4$. The separation ΔR between the leptons (photon) and the jets must be $\Delta R(l/\gamma, \text{jet}) > 0.3$. With these cuts the NNLO corrections are found to increase the NLO result by 6%. The loop-induced gg contribution amounts to 8% of the $\mathcal{O}(\alpha_S^2)$ correction and thus to less than 1% of σ_{NNLO}.

In Fig. 1.5 a comparison of the NLO and NNLO theoretical predictions with the ATLAS data is presented. We see that the data agree with the NLO and NNLO theoretical predictions within the uncertainties, and that the NNLO corrections slightly improve this agreement.

ATLAS also considers an additional set up with $p_T^\gamma > 40$ GeV. In this case the NNLO corrections are more significant, and increase the NLO result by 15%.

[1] M. Grazzini, S. Kallweit, D. Rathlev and A. Torre, Phys. Lett. B **731** (2014) 204.
[2] S. Catani and M. Grazzini, Phys. Rev. Lett. **98** (2007) 222002.
[3] S. Catani, L. Cieri, D. de Florian, G. Ferrera and M. Grazzini, Nucl. Phys. B **881** (2014) 414.

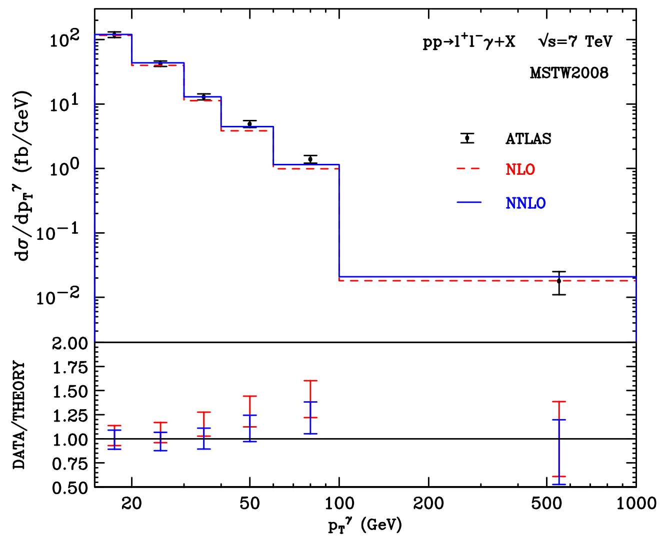

FIG. 1.5 – Transverse momentum spectrum of the photon at NLO and NNLO compared with ATLAS data. The lower panel shows the ratio data/theory.

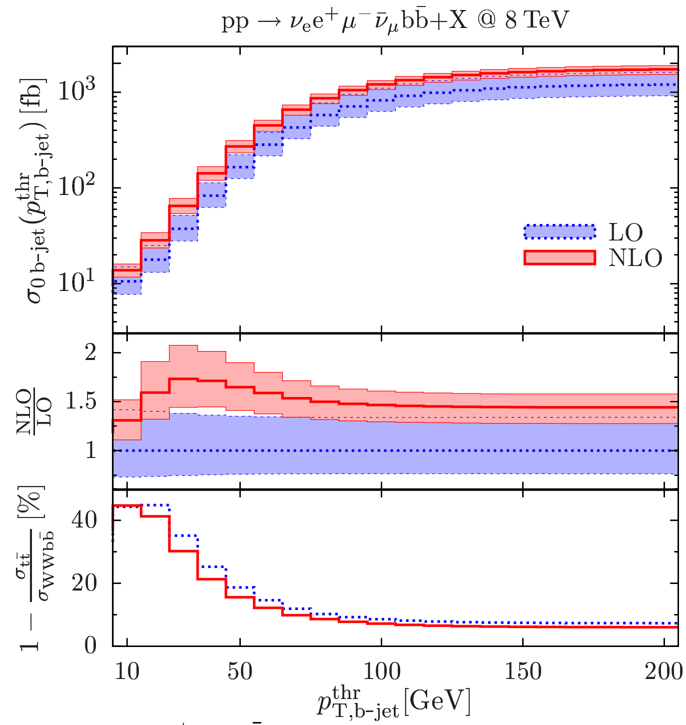

FIG. 1.6 – $W^+W^-b\bar{b}$ cross section as a function of a b-jet veto, $p_{\mathrm{T},b} < p_{\mathrm{T}}^{\mathrm{thr}}$ [2]. The middle and lower frames show the NLO corrections and the corrections with respect to zero-width approximation, respectively.

1.5 A unified description of top-pair and single-top production at the LHC

Top quarks are the heaviest fundamental particles known, and the precise theoretical understanding of their production and decay mechanism, within or beyond the Standard Model, has deep implications on many aspects of the LHC physics program.

At the LHC, top quarks can be produced as top-antitop ($t\bar{t}$) pairs or in single-top production modes, where the top quark (or anti-quark) is accompanied either by a light jet or by a W boson. The single-top production modes play an important role as direct probes of top-quark weak interactions and of their flavour structure.

The importance of precise theoretical simulations for the various top-production modes is reflected in a rich and continuously growing literature of higher-order perturbative calculations. In order to keep the complexity of the computations at a manageable level, the production of top pairs, $pp \to t\bar{t}$, and the subsequent top-decays, $t \to W^+b$ and $\bar{t} \to W^-\bar{b}$, are typically handled as separate processes which corresponds to the limit $\Gamma_t \to 0$. An exact treatment requires simulations of the full six-particle processes $pp \to W^+W^-b\bar{b}$, including contributions from off-shell intermediate top quarks pairs as well as intermediate states without or with only one top.

NLO calculations of $pp \to W^+W^-b\bar{b}$ production with finite b-quark masses [2] became possible very recently with the advent of a new generation of NLO algorithms which are based on the OpenLoops method [1], a fast and fully general technique for multi-particle NLO calculations that has been developed by our group. The inclusion of a finite b-quark mass permits, for the first time, to describe regions of the $W^+W^-b\bar{b}$ phase space where one or both b-quarks remain unresolved, and where the massless approximation would give rise to collinear singularities. In particular, the method gives access to final states that are dominated by Wt single-top production. These calculations provide the first unified NLO treatment of top-pair and Wt production, including the quantum interference between these two channels and overcome serious limitations inherent in previous heuristic attempts to treat $t\bar{t}$ and Wt production separately.

Fig. 1.6 shows the $W^+W^-b\bar{b}$ cross section as a function of a b-jet veto, $p_{\mathrm{T},b} < p_{\mathrm{T}}^{\mathrm{thr}}$. The benefit of NLO predictions is evident from the reduced uncertainty band as compared to leading order (LO). In the limit of large jet vetoes, corresponding to the total cross section, deviations from the zero-width approximation are just below 10% (see lower frame). These effects are mainly due to Wt single-top production, and their impact is strongly enhanced by the jet veto, reaching up to 50% of the vetoed cross section. These results demonstrate the relevance of a $W^+W^-b\bar{b}$ calculation for a consistent simulation of top-pair and single-top contributions in presence of jet vetoes or jet bins. This is of great importance for Higgs-boson studies in the $H \to W^+W^-$ decay channel and for any other analysis involving large top backgrounds at the LHC. This calculation is also an ideal theoretical tool for the rich program of top-mass precision measurements at the LHC.

[1] F. Cascioli, P. Maierhöfer and S. Pozzorini, Phys. Rev. Lett. **108** (2012) 111601.

[2] F. Cascioli, S. Kallweit, P. Maierhöfer and S. Pozzorini, Eur. Phys. J. C **74** (2014) 2783.

1.6 Impact of off-shell effects and scheme dependence on the determination of the top quark mass

The top quark mass, m_t, is presently known with an accuracy of $\pm 0.5\%$. To match this precision on the theory side, the process $h_1\, h_2 \to t\bar{t} \to W^+\, J_b\, W^-\, J_{\bar{b}}$, where J_b denotes a b-jet and $h_i \in \{p, \bar{p}\}$, has to be studied very carefully, controlling off-shell effects and sub-leading effects due to interference with so-called background processes.

We have developed an efficient method [1] to take into account these effects near the resonance region. In the single-top case $p\, p \to t\, J \to W^+\, J_b\, J$ this method has been compared to a full calculation [2] and excellent agreement has been found in the resonance region.

As an application of this method we have studied [3] the impact of these corrections on observables that are very sensitive to m_t. An example is the transverse mass $M_T(J_b\, W^+)$ of the reconstructed top. At tree level $M_T \leq m_t$ and, therefore, the distribution has a sharp edge, a feature that potentially can be used to measure m_t. As shown in Fig. 1.7, the off-shell and subleading corrections are small except near the edge so these effects need to be taken into account for an accurate determination of m_t.

We have also studied the use of different mass schemes and found scheme ambiguities of the order of 500 MeV for m_t [3]. Usually m_t is identified with the pole mass. However, the pole mass is known to suffer from renormalisation ambiguities. Thus other schemes might be preferable and should be studied carefully.

[1] P. Falgari, F. Giannuzzi, P. Mellor and A. Signer, Phys. Rev. D **83** (2011) 094013.

[2] A. S. Papanastasiou *et al.*, Phys. Lett. B **726** (2013) 223.

[3] P. Falgari, A. S. Papanastasiou and A. Signer, JHEP **1305** (2013) 156.

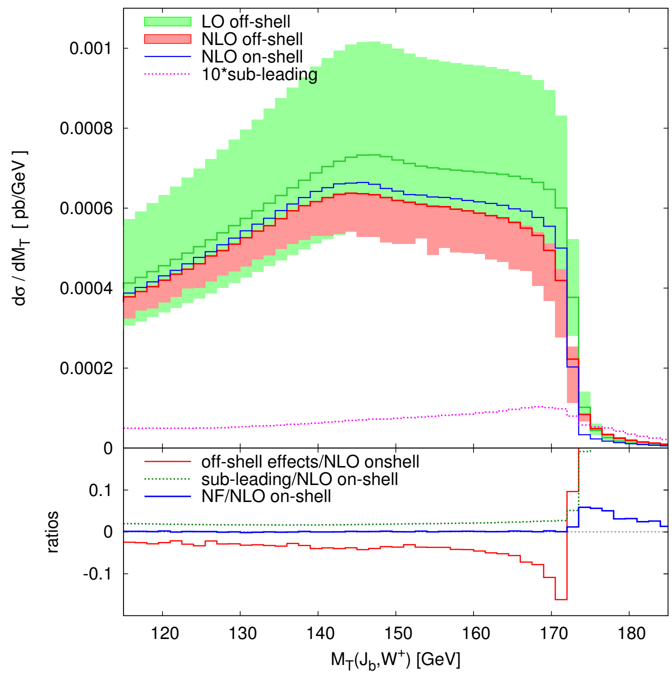

FIG. 1.7 – Transverse mass distribution at the Tevatron for the reconstructed top quark.