Theoretical developments in jet physics at hadron colliders

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We review the calculation of next-to-next-to-leading order (NNLO) QCD corrections to dijet production and related observables at hadron colliders in the purely gluonic channel. Our results show that the NNLO correction significantly reduces the scale uncertainties and we present the NNLO double-differential single jet inclusive and dijet cross sections. Jets are reconstructed using the anti-k_T jet algorithm and the jet resolution parameter R dependence of the inclusive cross section is given to NNLO.

1 Introduction

Single jet inclusive jet and dijet observables are the most fundamental QCD processes measured at hadron colliders. They probe 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.

In the single jet inclusive cross section, each identified jet in an event contributes individually. The exclusive dijet cross section consists of all events with exactly two identified jets. These cross sections have been studied as functions of different kinematical variables: the transverse momentum and rapidity of the jets (of any jet for the single jet inclusive distribution, or of the two largest transverse momentum jets for the dijet distributions). Precision measurements of single jet and dijet cross sections have been performed by CDF [1] and D0 [2] at the Tevatron and by ATLAS [3] and CMS [4] at the LHC. The latest experimental results with jets as well as extractions of α_s using hadron collider jet data are reported in [5,6].

The state of the art of the theoretical predictions for these observables are accurate to next-to-leading order (NLO) in QCD [7] (with the inclusion of shower effects in [8]) and in the electroweak theory [9]. Reference [10] computed higher order logarithmic corrections in the threshold region. In this talk we present our results for the jet cross sections at NNLO accuracy in QCD in double differential form [11]

$$\frac{\mathrm{d}^2\sigma}{\mathrm{d}p_T \mathrm{d}|y|} \quad ; \quad \frac{\mathrm{d}^2\sigma}{\mathrm{d}m_{jj}\mathrm{d}y^*}$$

in the gluons-only channel at leading colour.

2 Results at NNLO

To perform our calculation we have employed the antenna subtraction scheme [12] for the analytic cancellation of infra-red (IR) singularities at NNLO extended to the case of processes with coloured particles in the initial state [13]. As demonstrated in [14], using the antenna subtraction

scheme the explicit ϵ-poles in the dimension regularization parameter of one- and two-loop matrix elements entering this calculation are cancelled in analytic and local form against the ϵ-poles of the integrated antenna subtraction terms thereby enabling the computation of jet cross sections at hadrons colliders at NNLO accuracy. This allows the combination of the two-loop virtual corrections to the basic $2 \to 2$ process [15] together with the one-loop virtual corrections to the single real radiation $2 \to 3$ process [16] and the double real radiation $2 \to 4$ process at tree-level [17] in a parton-level event generator NNLOJET.

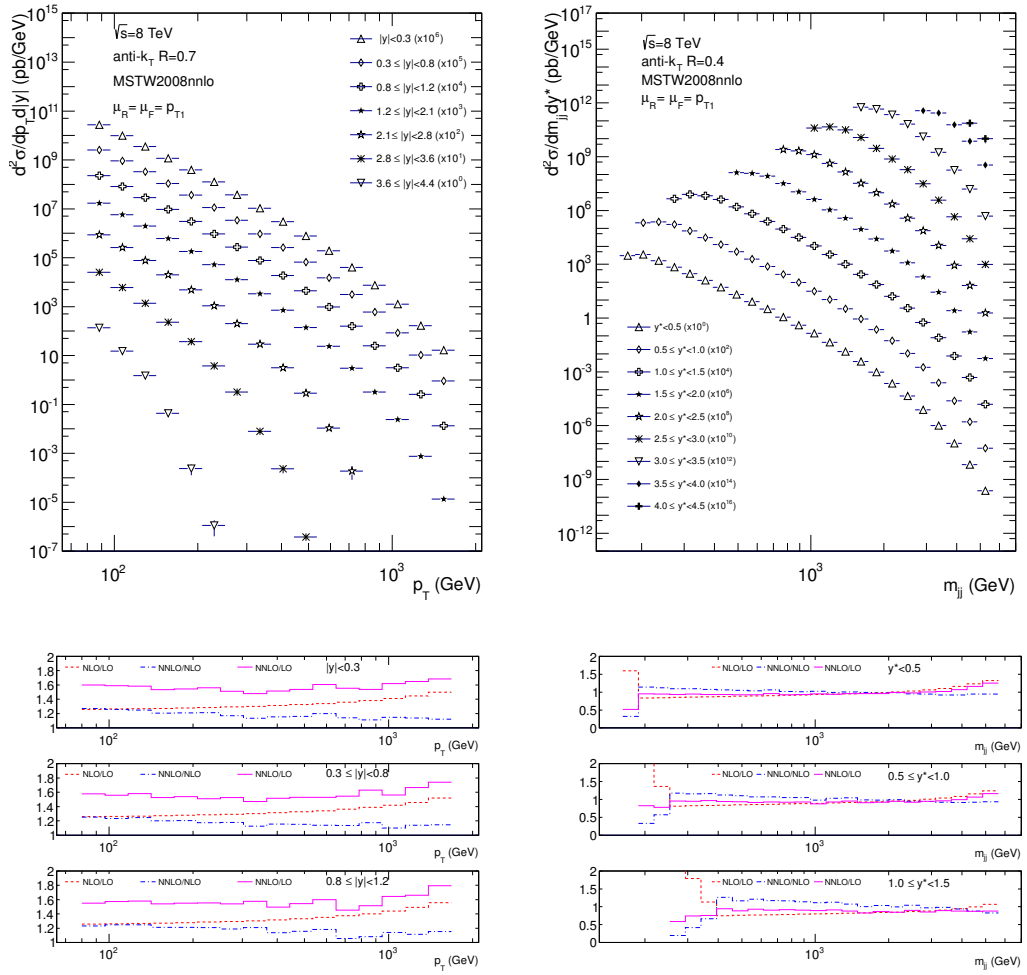

Figure 1: (Left plot) The NNLO doubly differential single jet inclusive transverse momentum distribution, $d^2\sigma/dp_T d|y|$, at $\sqrt{s} = 8$ TeV for the anti-k_T algorithm with $R = 0.7$ and for $p_T > 80$ GeV and various $|y|$ slices. (Right plot) The NNLO doubly differential dijet mass distribution, $d^2\sigma/dm_{jj}dy^*$, at $\sqrt{s} = 8$ TeV for the anti-k_T algorithm with $R = 0.4$ and for $p_{T1} > 80$ GeV, $p_{T2} > 60$ GeV and various $y^* = 1/2|y_1 - y_2|$ slices. The double differential k-factors are presented in the lower panels.

Our numerical studies for proton-proton collisions at centre-of-mass energy $\sqrt{s} = 8$ TeV concern the single jet inclusive cross section and the two-jet exclusive cross section. Jets are identified using the anti-k_T algorithm. Jets are accepted at central rapidity $|y| < 4.4$, and ordered in transverse momentum. An event is retained if the leading jet has $p_{T1} > 80$ GeV. For the dijet invariant mass distribution, a second jet must be observed with $p_{T2} > 60$ GeV. All calculations are carried out with the MSTW08NNLO gluon distribution function [18], including the evaluation of the LO and NLO contributions[a]. This choice of parameters allows us to quantify the size of the

[a]Note that the evolution of the gluon distribution within the PDF set together with the value of α_s intrinsically includes contributions from the light quarks. The NNLO calculation presented here is "gluons-only" in the sense

genuine NNLO contributions to the parton-level subprocess. Factorization and renormalization scales (μ_F and μ_R) are chosen dynamically on an event-by-event basis. As default value, we set $\mu_F = \mu_R \equiv \mu$ and set μ equal to the transverse momentum of the leading jet so that $\mu = p_{T1}$.

In Fig. 1 we present the double-differential jet cross sections at NNLO for the central scale choice. The NNLO/NLO k-factor shows the size of the higher order NNLO effect in each bin of the distribution with respect to the NLO cross section. For the single jet inclusive cross section we see that the NNLO/NLO k-factor increases the cross section between 25% at low p_T to 12% at high p_T and this behaviour is similar for the three rapidity slices $|y| < 0.3$, $0.3 < |y| < 0.8$ and $0.8 < |y| < 1.2$. For the exclusive dijet mass distribution the NNLO corrections are up to 20% with respect to the NLO cross section and increase slightly for large y^*.

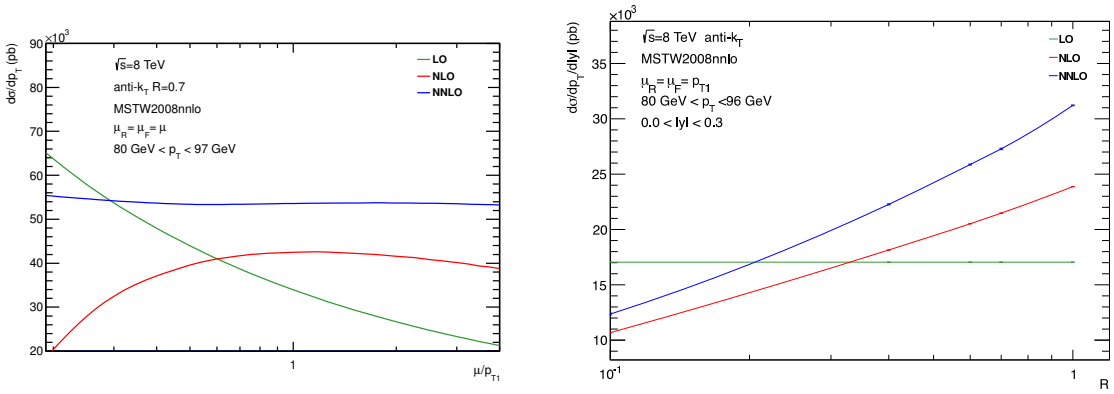

Figure 2: (Left plot) Scale dependence of the single jet inclusive cross section for pp collisions at $\sqrt{s} = 8$ TeV for the anti-k_T algorithm with R=0.7 and with $|y| < 4.4$ and 80 GeV $< p_T <$ 97 GeV at NNLO (blue), NLO (red) and LO (green). (Right plot) Single jet inclusive cross section versus resolution parameter R of the anti-k_T jet algorithm at $\sqrt{s} = 8$ TeV, 80 GeV $< p_T <$ 96 GeV and $|y| < 0.3$ at NNLO (blue), NLO (red) and LO (green).

In Fig. 2 we plot the dependence of the single jet inclusive cross section as a function of the scale choice and of the resolution parameter R of the anti-k_T jet algorithm, at each order in perturbation theory. We observe that the computation of higher order corrections to the cross section has the effect of reducing the scale uncertainties on the theory prediction. In particular for this observable we obtain a scale variation at the percent level at NNLO.

The R dependence shows that the cross section increases as the value of R increases. This is observed first at NLO where for the first time additional parton radiation can be inside or outside the jet. At NNLO up to three partons can form a jet and this should lead to a better matching of the jet algorithm between theory and experiment. We observe that the size of the NNLO correction decreases for small R.

3 Conclusions and outlook

We presented the NNLO QCD calculation in the purely gluonic channel at leading colour to the fully differential inclusive jet and dijet cross section at hadron colliders opening the path towards precision QCD phenomenology with the LHC. For all of the observables considered here, we observed a dramatic reduction of the respective uncertainties in the theory prediction due to variations of the factorization and renormalization scales. We expect similar conclusions when including the processes involving quarks.

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that only gluonic matrix elements are involved.

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References

1. T. Aaltonen *et al.* [CDF Collaboration], Phys. Rev. D **78** (2008) 052006 [Erratum-ibid. D **79** (2009) 119902] [arXiv:0807.2204 [hep-ex]].
2. V. M. Abazov *et al.* [D0 Collaboration], Phys. Rev. Lett. **101** (2008) 062001 [arXiv:0802.2400 [hep-ex]].
3. G. Aad *et al.* [Atlas Collaboration], Eur. Phys. J. C **71** (2011) 1512 [arXiv:1009.5908 [hep-ex]]. G. Aad *et al.* [ATLAS Collaboration], Phys. Rev. D **86** (2012) 014022 [arXiv:1112.6297 [hep-ex]].
4. S. Chatrchyan *et al.* [CMS Collaboration], Phys. Lett. B **700** (2011) 187 [arXiv:1104.1693 [hep-ex]]. S. Chatrchyan *et al.* [CMS Collaboration], Phys. Rev. Lett. **107** (2011) 132001 [arXiv:1106.0208 [hep-ex]]. S. Chatrchyan *et al.* [CMS Collaboration], JHEP **1206** (2012) 036 [arXiv:1202.0704 [hep-ex]]. S. Chatrchyan *et al.* [CMS Collaboration], arXiv:1212.6660 [hep-ex].
5. K. Rabbertz 48th Recontres de Moriond conference proceedings
6. M. Wobbisch 48th Recontres de Moriond conference proceedings
7. S. D. Ellis, Z. Kunszt and D. E. Soper, Phys. Rev. Lett. **69** (1992) 1496. W. T. Giele, E. W. N. Glover and D. A. Kosower, Phys. Rev. Lett. **73** (1994) 2019 [hep-ph/9403347]. Z. Nagy, Phys. Rev. Lett. **88** (2002) 122003 [hep-ph/0110315]; Phys. Rev. **D68** (2003) 094002 [hep-ph/0307268]. J. Gao *et. al.*, 1207.0513.
8. S. Alioli, K. Hamilton, P. Nason, C. Oleari and E. Re, JHEP **1104** (2011) 081 [1012.3380].
9. S. Dittmaier, A. Huss and C. Speckner, JHEP **1211** (2012) 095 [1210.0438].
10. N. Kidonakis and J. F. Owens, Phys. Rev. D **63** (2001) 054019 [hep-ph/0007268].
11. A. Gehrmann-De Ridder, T. Gehrmann, E. W. N. Glover and J. Pires, Phys. Rev. Lett. **110** (2013) 162013 arXiv:1301.7310 [hep-ph].
12. A. Gehrmann-De Ridder, T. Gehrmann and E. W. N. Glover, JHEP **09** (2005) 056 [hep-ph/0505111].
13. A. Daleo, T. Gehrmann and D. Maitre, JHEP **0704** (2007) 016 [hep-ph/0612257]. A. Daleo, A. Gehrmann-De Ridder, T. Gehrmann and G. Luisoni, JHEP **1001** (2010) 118 [0912.0374]. R. Boughezal, A. Gehrmann-De Ridder and M. Ritzmann, JHEP **1102** (2011) 098 [1011.6631]; A. Gehrmann-De Ridder, T. Gehrmann and M. Ritzmann, JHEP **1210** (2012) 047 [1207.5779]. T. Gehrmann and P. F. Monni, JHEP **1112** (2011) 049 [1107.4037]. E. W. N. Glover and J. Pires, JHEP **1006** (2010) 096 [1003.2824]. J. Currie, E. W. N. Glover and S. Wells, JHEP **1304** (2013) 066 [arXiv:1301.4693 [hep-ph]].
14. A. Gehrmann-De Ridder, E. W. N. Glover and J. Pires, JHEP **1202** (2012) 141 [1112.3613]. A. Gehrmann-De Ridder, T. Gehrmann, E. W. N. Glover and J. Pires, JHEP **1302** (2013) 026 [arXiv:1211.2710 [hep-ph]].
15. E. W. N. Glover, C. Oleari and M. E. Tejeda-Yeomans, Nucl. Phys. **B605** (2001) 467 [hep-ph/0102201]; E. W. N. Glover and M. Tejeda-Yeomans, JHEP **0105** (2001) 010 [hep-ph/0104178]; Z. Bern, A. De Freitas and L. J. Dixon, JHEP **0203** (2002) 018 [hep-ph/0201161].
16. Z. Bern, L. J. Dixon, D. C. Dunbar and D. A. Kosower, Nucl. Phys. **B425** (1994) 217 [hep-ph/9403226].
17. M. L. Mangano and S. J. Parke, Phys. Rept. **200** (1991) 301 [hep-th/0509223].
18. A. D. Martin, W. J. Stirling, R. S. Thorne and G. Watt, Eur. Phys. J. **C63** (2009) 189 [0901.0002].