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Applications of higher order QCD

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In this talk we summarize some recent developments in perturbative QCD and their application to particle physics phenomenology.

1. Introduction

With the discovery of a new boson at the Large Hadron Collider (LHC), particle physics has entered a new era. Since this discovery, the field has quickly moved towards precision measurements on the new particle. In order to further improve these measurements and to find possible small deviations that may hint towards new physics, improved theoretical predictions, including higher-order perturbative QCD corrections for production rates and kinematics are urgently needed. The same is true for other reactions of interest at the LHC, like top quark production and W/Z production. The toolkit used to this end ranges from fixed order calculations at the parton-level over resummation to parton showers and particle-level event generators. Tremendous progress has been made in the field during the past year. Some of the recent developments will be briefly summarized in this talk.

2. Higher-order calculations

Fixed-order calculations are available for a large variety of processes. At the tree level, they have long been performed completely automatically using programs like ALPGEN [1], Amegic++ [2], Comix [3], CompHEP [4], HELAC [5], MadGraph [6] and Whizard [7]. At the next-to-leading order (NLO), automation required two main ingredients: The implementation of known generic methods to perform the subtraction of infrared singularities [8–10], and the automated computation of one-loop amplitudes. As infrared subtraction terms consist of tree-level matrix elements joined by splitting operators, existing programs for leading order calculations are ideally suited to compute them. Correspondingly, Catani-Seymour dipole subtraction has been implemented in the existing generators Amegic++ [11], Comix, HELAC [12] and MadGraph [13, 14]. FKS subtraction is realized in MadGraph only [15].

The automated computation of virtual corrections has received a boost from generalized unitarity [18–20], which can be used to determine one-loop amplitudes

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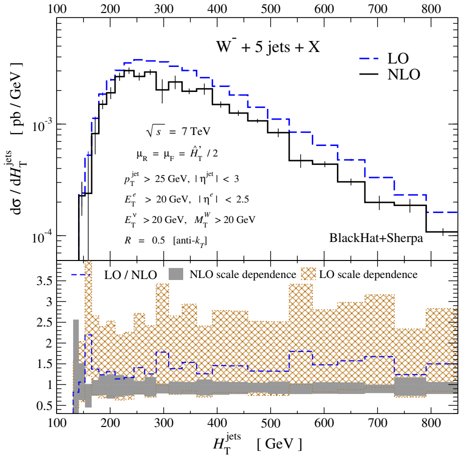

Fig. 1. Distribution of the visible energy in $W + 5$ jet events. Figure taken from [16].

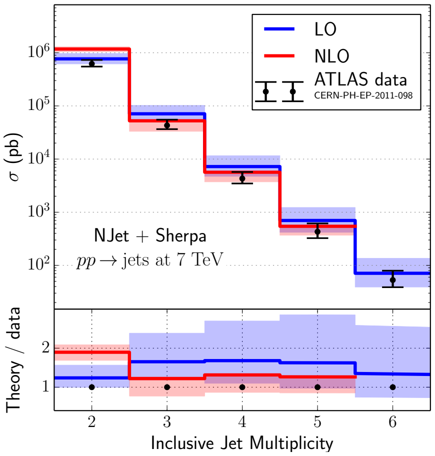

Fig. 2. Jet multiplicity distribution in pure jet events (right). Figure taken from [17].

by decomposing them into known scalar one-loop integrals and rational coefficients determined from tree amplitudes, plus a rational piece [21–25]. Programs like BlackHat [26], Gosam [27], HELACNLO [28], MadLoop [29], NJet [30], OpenLoops [31] and Rocket [32, 33] implement these techniques and supplement established programs like MCFM [34,35] and dedicated codes based on improved tensor reduction approaches [36, 37]. New techniques have also been proposed to accelerate the numerical calculation of the integrand of one-loop amplitudes, independent of the reduction scheme [31]. Figures 1 and 2 show examples from recent NLO calculations for W+5 jet production [16] and 5 jets production [17], both performed using unitarity based techniques. Other recently completed calculations include Higgs boson plus 3 jet production [38] and di-photon plus 2 jet production [39]. The rapid progress in this field is reflected by the fact that all calculations from the experimenter's wishlist for the LHC have now been tackled [40]. Most of the programs used to perform the calculations, or their results, are publicly available.

Driven by the need for higher precision in some selected Standard-Model reactions, the field of next-to-next-to leading order (NNLO) calculations has significantly advanced in the past years. One of the most challenging problems is the regularization of infrared divergences at NNLO. Sector decomposition [41–43] has been used in the past to perform several $2 \to 1$ calculations [44, 45]. Antenna subtraction [46, 47] was worked out and implemented for $e^+e^- \to 3$ jets [48, 49]. q_T subtraction [50] was employed in several calculations, including Higgs production [51], W/Z production [52], associated Higgs production [53] and di-photon production [54]. More recently sector-improved subtraction methods were introduced [55, 56]. They have been used to compute cross sections for $pp \to t\bar{t}$ [57,58] and $pp \to H$+jet [59]. At the same time, antenna subtraction was extended to initial states [60–63] and employed to compute $pp \to$ di-jets fully differentially at NNLO [64]. Figures 3 and 4 show

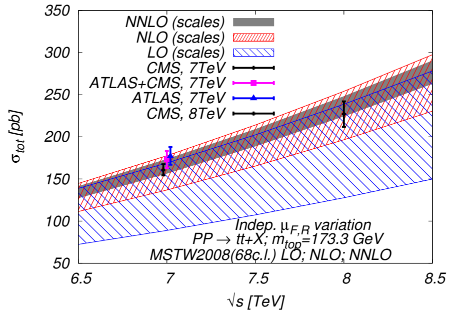

Fig. 3. Energy dependence of the $pp \to t\bar{t}$ total cross. Figure taken from [58].

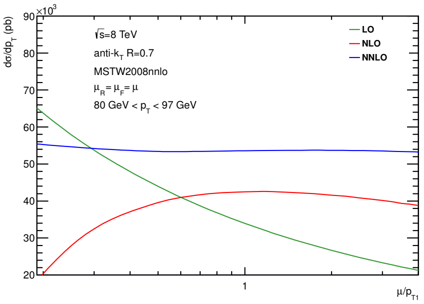

Fig. 4. Scale dependence of the pp →di-jet cross section. Figure taken from [64].

results from some of these calculations. The calculation of $pp \to t\bar{t}$ has also been combined with higher logarithmic resummation [65–67]. Its theoretical uncertainty is such that uncertainties from scale choices, PDF, strong coupling measurements and top-quark mass measurements are all of the same order [68].

3. Resummation of jet vetoes

The analysis of the Higgs-like particle discovered at the LHC places new demands on resummed calculations. Many of the Higgs analysis channels, most notably $H \to WW^* \to \ell^+\ell^-\nu\bar{\nu}$, veto on the transverse momentum of final state jets to distinguish different Standard Model backgrounds and separate them from the signal. The leading systematic uncertainty is the theoretical uncertainty on the signal cross section in the jet bins. This uncertainty can be reduced by a proper resummation of the logarithms associated with the jet veto. Various groups have investigated this problem, in most cases up to next-to-next-to leading logarithmic accuracy matched to NNLO fixed order, relying either on more traditional resummation methods [69, 70], or on Soft Collinear Effective Theory [71–75]. Higgs plus one jet production was studied at next-to-leading logarithmic order (NLL) and matched to NLO fixed order using SCET [76].

4. Parton showers and matching to NLO calculations

The interest in parton showers as a means to produce particle-level predictions fully differentially in the phase space of multi-jet events has increased significantly in recent years. New concepts for the construction of parton showers have been proposed, which are based on antenna subtraction [77, 78] and/or sectorizing the phase space [79, 80]. Efforts were made to include subleading color corrections into showers as a means to improve their logarithmic accuracy [81, 82]. However, the crucial development was the proposal of a method to match parton showers to NLO calculations [83], later extended to eliminate negative weights [84, 85]. This

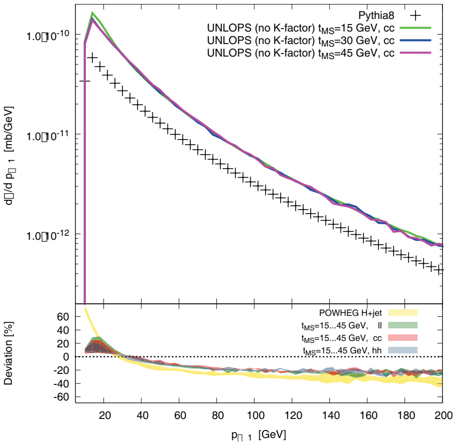

Fig. 5. Transverse momentum of first jet in Higgs plus jets events. Figure taken from [91].

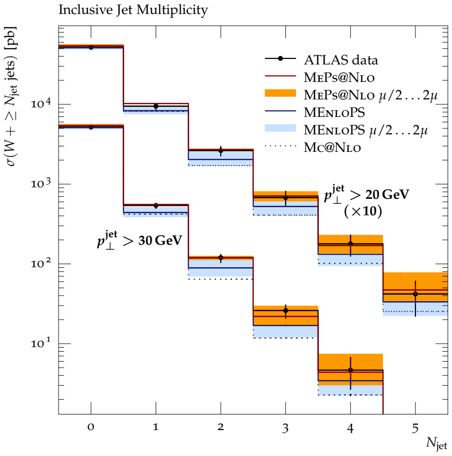

Fig. 6. Jet multiplicity distribution in W+jets events. Figure taken from [92].

matching has been partially or fully automated in several projects [86–90], such that particle-level predictions at NLO accuracy are now widely available.

The description of multi-jet final states with parton showers can be improved using so-called ME+PS merging methods [93–97], which, in contrast to matching methods, allow to correct the parton shower for an arbitrary number of emissions with higher-order tree-level calculations. These methods were recently refined and extended, leading to algorithms which can combine multiple NLO calculations of varying multiplicity (like $W + 0$ jet, $W + 1$ jet, $W + 2$ jet, etc.) into a single, inclusive simulation (e.g. of W+jets production) [91, 92, 98–100]. Figures 5 and 6 show examples for the application of ME+PS merging to Higgs boson plus jets production and to W+jets production. A particular scale choice is required for the evaluation of the strong coupling in ME+PS merging, which has also been adopted for the matching to higher-multiplicity NLO calculations on its own in the so-called MINLO approach [101].

The MINLO method accounts for Sudakov suppression effects in higher-multiplicity final states and allows to extrapolate NLO calculations to zero jet transverse momentum, thus offering the opportunity to match to NNLO calculations for a limited class of processes and observables [102]. A different proposal for a matching to NNLO parton-level calculations was made in [91, 98], which is based on a subtraction method similar to the one used in ME+PS merging at NLO. Both techniques are promising candidates to further increase the precision of event generators for collider physics.

5. Summary

We have presented some of the recent developments in perturbative QCD and applications to particle physics phenomenology. NLO parton-level calculations can nowadays often be provided by fully automated tools. New techniques in event generation allow to also use them for particle-level predictions. NNLO calculations and higher-logarithmic resummation techniques are at the forefront of current research.

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