Top quark modelling and generators in CMS postprint

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Abstract

Recent top quark event modelling studies done using CMS proton-proton data collected at a centre of mass energies of 8 and 13 TeV and state-of-the-art theoretical predictions accurate to next-toleading order QCD interfaced with PYTHIA8 and HERWIG++ event generators are summarised. The particle-level top quark (pseudo-top), underlying event measurement in tt events and parton shower tuning using tt events are discussed.

Full Text

Top Quark Modelling and Generators in CMS

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Abstract: This document summarizes recent top quark event modelling studies performed using CMS proton-proton data collected at centre-of-mass energies of 8 and 13 TeV. These studies employ state-of-the-art theoretical predictions accurate to next-to-leading order QCD, interfaced with PYTHIA8 and HERWIG++ event generators. We discuss the particle-level top quark (pseudo-top), underlying event measurements in $t\bar{t}$ events, and parton shower tuning using $t\bar{t}$ events.

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1. Introduction

Top quark measurements provide crucial tests of QCD. Achieving the highest possible precision in the top quark mass, its interpretation, and other properties requires a better understanding of both perturbative and non-perturbative effects. Top quark measurements are also essential for improving the accuracy of predictions across different phase space regions in searches for physics beyond the Standard Model (SM). Precise top quark measurements are used in direct searches for new physics as well, for example through effective field theories that expand the SM Lagrangian. For these purposes, the uncertainties in both measurements and predictions must be reduced to a level where deviations from Monte Carlo (MC) code predictions or from new physics effects become visible.

State-of-the-art next-to-leading order (NLO) matrix element (ME) event generators interfaced with new parton shower (PS) codes used in LHC Run II may provide better modelling and eventually reduce the dominant theoretical uncertainties. These theory uncertainties can be partially tested and improved with datasets that enable differential measurements using well-defined top-quark objects.

In this note, we discuss a selection of recent top quark event modelling studies from CMS [**?**].

2. Particle-Level Top Quark

Simulations at NLO incorporate the finite width of the top quark, which is important for accurately modelling off-shell production and interference with backgrounds. In these calculations, however, the concept of a top quark as a particle is not well-defined and is MC-dependent. One can only unambiguously use the kinematics of final-state particles. A particle-level top quark (also called a pseudo-top quark) can be constructed from these final-state objects after hadronisation. Using particle-level top quarks yields smaller uncertainties from non-perturbative effects and from acceptance corrections, as the similar phase space definitions at particle and detector levels minimise MC dependence. Reference [**?**] discusses the details of particle-level top quark definitions and their implementation in the RIVET [**?**] framework within the official CMS reconstruction code. This work establishes a fundamental approach for current and future measurements of differential production cross sections in both $t\bar{t}$ and single-top quark production. The results reported in [**?**] indicate that the particle-level top quark definition needs to be optimised depending on the production mode, final state, variable, and phase space under investigation.

3. Underlying Event and Parton Shower Tuning in $t\bar{t}$ Events

The CMS Run I combination of direct top quark mass measurements at 7 and 8 TeV, performed in the lepton+jets, dilepton, and all-hadronic channels, achieves a precision of 0.3% [**?**]. In this result, the dominant uncertainties are related to event modelling. Therefore, dedicated measurements and theory studies are required to improve top quark mass measurements. The b quark from the top quark decay carries the colour flow. To become colourless, the b quark "connects" with beam remnants or other coloured final particles produced in the event. While a b jet can be constructed in the final state, uncertainty in the origin of all final states in the jet results in "odd clusters" (e.g., see [?]). Consequently, accurate descriptions of b quark fragmentation and hadronisation, as well as the underlying event (UE), are needed.

UE measurements typically use the highest p_T charged-particle jet, the highest E_T calorimeter jet, or the Z-boson direction as the leading object to define regions in η-ϕ space: the toward, away, and transverse regions. The transverse region is particularly sensitive to UE modelling. The PYTHIA8 tune CUETP8M1 and the HERWIG++ tune EE5C [?] are constructed by fitting UE data at several centre-of-mass energies, where the leading object is the highest p_T charged particle or charged-particle jet in the event. These tunes describe UE well as measured in Z-boson production. However, very little is known about UE in heavy quark production.

Reference [?] compared detector-level top-quark production data at 13 TeV with the PYTHIA8 CUETP8M1 tune and the HERWIG++ EE5C tune after detector simulation in $t\bar{t}$-enriched events in the lepton+jets channel. Both parton shower models are interfaced with POWHEG V2. Fair agreement is observed between POWHEG V2+PYTHIA8 CUETP8M1 tune predictions and data. UE is also observed to be sensitive to QCD scales. Fig. 1a [Figure 1: see original paper] displays the charged-particle multiplicity when the PS scale is increased from its default value. A complete particle-level measurement of UE in $t\bar{t}$ events may lead to more precise top quark mass measurements with better-understood systematic uncertainties.

It is observed that predictions from NLO MC ME generators + PYTHIA8 CUETP8M1 tune [?] overshoot the $\sqrt{s} = 8$ TeV [?, ?] and 13 TeV [?, ?] data for large jet multiplicities when using out-of-the-box parameters, while all other distributions are modelled well (except for top quark p_T). The CUETP8M1 tune is based on the Monash tune [?]. Accurate predictions of this observable are particularly important for Higgs boson measurements and many new physics search analyses.

To improve the description of high jet multiplicities in $t\bar{t}$ events, several parameters have been studied, and the ones most sensitive to jet kinematics in $t\bar{t}$ events have been selected and optimised. The strong coupling parameter at m_Z for initial-state radiation in the PS, α_S^{ISR}, and the h_{damp} parameter that controls jet matching in the POWHEG V2+PYTHIA8 [?, ?, ?] setup are tuned using Run 1 data on jet activity in $t\bar{t}$ events. The Monash tune' s α_S^{ISR} value was tuned to LEP event shapes, which is found to be the main cause of jet overproduction in the MC.

We tuned the values of α_S^{ISR} and h_{damp} using the jet multiplicity and leading additional jet p_T distributions in the dilepton final state measured at $\sqrt{s} = 8$ TeV, employing the PROFESSOR tool [?]. In this procedure, all other PYTHIA8 parameters are kept fixed to those in the CUETP8M1 tune. It is observed that α_S^{ISR} primarily impacts $N_{\mathrm{jets}} > 3$, while h_{damp} affects the ratio of 2-to-3-jet events and the leading additional jet p_T. This agrees with the fact that, in the POWHEG V2+PYTHIA8 configuration, the leading additional jet stems from real radiation calculated by the POWHEG V2 generator. The tuning procedure yields $h_{\rm damp} = 1.581^{+0.658}_{-0.1108}$ and $\alpha_S^{ISR} = 0.0011^{+0.0145}_{-0.0011}$ [?], well within uncertainties. Fixing $h_{\rm damp}$ to its default value of m_t and re-tuning α_S^{ISR} alone to the same data yields $\alpha_S^{ISR} = 0.115^{+0.021}_{-0.019}$ [?], again in agreement with the PDG value. POWHEG V2+PYTHIA8 with these optimised parameters cures the overshoot of CUETP8M1 at high jet multiplicities. This value agrees with the PDG value of $\alpha_s(M_Z) = 0.1181$.

The jet activity mainly constrains parameters that control the probability for parton emission and the interplay between hard and soft parton emission. However, jet activity does not strongly constrain the global production of hadrons known as the underlying event (UE). Therefore, α_S^{ISR} as determined from $t\bar{t}$ jet kinematics can be used as a fixed parameter to tune the UE. See ref. [?] for details of the CUETP8M2T4 tune derived by fixing α_S^{ISR} to 0.1108.

The performance of the CUETP8M2T4 PYTHIA8 tune is evaluated in different configurations. Both POWHEG V2+PYTHIA8 and MG5_aMC@NLO + PYTHIA8 with FxFx merging [?] describe the top quark data well (except for top quark p_T, which is independent of the tune), while MG5_aMC@NLO + PYTHIA8 with MLM matching [?] and inclusive aMC@NLO + PYTHIA8 do not describe the data in general (e.g., see Fig. 1b). It is also observed that global event variables such as H_T or S_T are not modified significantly with changes to α_S^{ISR} (except for MG5_aMC@NLO + PYTHIA8 [MLM] and aMC@NLO + PYTHIA8, which are independent of the tune for some variables such as jet multiplicity) [?]. Comparisons of POWHEG V2+PYTHIA8 predictions with the CUETP8M2T4 tune to six different differential cross-sections measured with 35.9 fb^{-1} of data at $\sqrt{s} = 13$ TeV yield an overall p-value from < 0.01 when theory uncertainties are ignored to 0.91 when theory uncertainties are included [?].

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Note: Figure translations are in progress. See original paper for figures.