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Accurate predictions for top-quark pair production at the LHC

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Summary. — The top quark is the heaviest elementary particle in the Standard Model. For this reason, a precise determination of its mass m_t is part of the LHC physics program. The most accurate determinations of m_t rely on the kinematic reconstruction of the top decay products and on the use of Monte Carlo event generators. In this contribution I discuss the impact of different theoretical descriptions for the process of top-pair production at the LHC on the extraction of m_t.

1. – Introduction

The phenomenology of the top-quark is driven by the large value of its mass m_t. It is the only quark that decays instead of hadronizing, giving us the opportunity to study the properties of a bare quark. Due to radiative corrections, the value of m_t has an impact on many parameters of the Standard Model (SM) like the Higgs self-couplings and the bosons masses.

The most accurate determinations of m_t are the so-called "direct measurements". Monte Carlo (MC) generators are used to simulate templates of kinematic distributions sensitive to the top-quark mass. These templates are produced varying the input mass m_t of the generator, in order to extract the parametric dependence of the distributions on m_t. The m_t value that fits the data the best is the extracted top-quark mass. This method has, however, an important drawback: the extracted m_t value strongly depends on the accuracy of the MC generator employed. This is a strong motivation for the theoretical community to improve the accuracy of the MC generators.

In this contribution I compare the predictions of two next-to-leading-order (NLO) event generators for $t\bar{t}$ production implemented in the POWHEG framework [1-4], namely the *hvq* [5] and the $b\bar{b}4\ell$ generators [6] for some observables that can be used to determine the top-quark mass. These NLO generators must be matched with a general purpose Shower Monte Carlo (SMC) program, like `Pythia8` [7] or `Herwig7` [8, 9]. I also show differences between distributions obtained with the two SMCs. The results presented here have first been published in ref. [10].

2. – Monte Carlo generators and simulated samples

NLO (QCD) events for $t\bar{t}$ production in pp collisions at a center-of-mass energy $\sqrt{s} = 8$ GeV have been produced using:

- The *hvq* [5] generator, which describes the process of $t\bar{t}$ production at NLO. The top decay is included at LO, using a re-weighting procedure that allows to partially take into account off-shell and spin-correlation effects between the t and the $\bar{t}$ decay products
- The $b\bar{b}4\ell$ generator [6], that implements the process $pp \to b\bar{b}e^+\nu_e\mu^-\bar{\nu}_\mu$ at NLO. Thus, as well as for top production, it describes its decay at NLO including off-shell and spin-correlations effects and the interference between radiation in production and in decay. Furthermore, all the processes which yield the same final state and their quantum interference are correctly included.

Selection cuts to suppress the Wt topology, which is present only in $b\bar{b}4\ell$, are adopted [10].

In order to implement the $b\bar{b}4\ell$ generator, a resonance-aware formalism has been developed, which is coded in the new `POWHEG BOX RES` framework [6]. By default, it generates multiple emissions, one from the production process and one from each decayed resonance. `Pythia8` [7] (or `Herwig7` [8, 9]) completes the NLO events, by adding subsequent emissions in the soft and collinear approximation (provided by the parton shower, PS) and translating the partonic final state into a hadronic one. In order not to spoil the NLO accuracy of the result, the PS must veto emissions that have a transverse momentum larger than the POWHEG radiation. This is done *per default* both by `Pythia8` and `Herwig7` if the emissions come from the production process. We extended this veto procedure also to the case of radiation from decayed top quarks. Since `Pythia8` implements a transverse momentum ordered PS, it is enough to require that the first emission has a transverse momentum smaller than the one of the corresponding POWHEG emission. `Herwig7` is an angular-ordered PS, thus all the emissions must be inspected.

3. – Comparison between the NLO generators showered with `Pythia8`

We choose simple observables O that can be directly related to the top-quark mass:

$$O = O_c + B(m_t - m_t^c), \tag{1}$$

where m_t^c is our reference mass $m_t^c = 172.5$ GeV and O_c and B are parameters that can be fitted using a MC generator. Neglecting the differences among the B coefficients between the generators, the differences in the extracted mass can be written as

$$\Delta m_t = -\frac{\Delta O_c}{B}. \tag{2}$$

The first observable we examine is the peak of the invariant mass of the reconstructed top quark (W and b-jet system), *i.e.*, $m_{Wb_j}^{\max}$. In this case $\Delta m_t \approx -\Delta m_{Wb_j}^{\max}$. Even if we apply a Gaussian smearing of 15 GeV to mimic experimental resolution effects, we find remarkable agreement between the peak position extracted using $b\bar{b}4\ell$ and *hvq*.

It is also intriguing to have a look at purely leptonic observables, as proposed by the authors of ref. [11]. There is an overall agreement between $b\bar{b}4\ell$ and *hvq* predictions, apart from observables sensitive to spin correlations, that are only approximatively described at LO by *hvq*. Two examples are given by $\langle m(e^+\mu^-)\rangle$, which yields to $\Delta m_t \approx 1.5$ GeV, and $\langle p_\perp(e^+\mu^-)\rangle$, which leads to $\Delta m_t \approx -2$ GeV.

4. – Comparison between Herwig7 and Pythia8 predictions

Quite large differences arise when we shower the events with `Herwig7` instead of `Pythia8`. If we look at the reconstructed-top mass peak, the `Herwig7` prediction is 1 GeV smaller than the `Pythia8` if $b\bar{b}4\ell$ is employed, 0.5 GeV in the case of *hvq*. A worse agreement is found when leptonic observables are considered: the m_t value extracted with `Herwig7` is roughly 2.5 GeV larger than the `Pythia8` one for both NLO generators.

This is not completely unexpected, given the different nature of the `Herwig7` PS with respect to the transverse-momentum shower implemented by `Pythia8`.

5. – Conclusions

When using `Pythia8`, the differences between *hvq* and $b\bar{b}4\ell$ are large enough to use the newest generator, but not large enough to completely overturn the current measurements that are based on *hvq*. When `Herwig7` is used, we do not have a nice and consistent picture, however we do believe that the option of dismissing `Herwig7` is not soundly motivated. The difference between the two PSs may be due to higher-order effects, that must be taken into account when estimating theoretical uncertainties. When a realistic analysis is performed, the parameters of a MC are tuned to reproduce the data fairly. This could improve the agreement between `Herwig7` and `Pythia8`.

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