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Differential top quark pair production cross section measurements at the LHC

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A status report on the measurements of differential top quark pair $\mathrm{t\bar{t}}$ production cross sections performed by the ATLAS and CMS experiments at the LHC is presented. A large number of results at different center of mass energies and in various top quark decay channels are available. This includes the first results at 13 TeV from CMS. The two definitions of the $\mathrm{t\bar{t}}$ system used in these measurements are discussed, namely the parton and the particle level approach. All measurements observe a softer $p_{\mathrm{T}}(\mathrm{t})$ spectrum than predicted by state of the art standard model calculations. This is also confirmed by measurements at very high $p_{\mathrm{T}}(\mathrm{t})$ where special techniques are used to reconstruct the boosted top quarks. However, there is a good agreement with the latest NNLO QCD calculation.

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1. Introduction

The high production rate of $t\bar{t}$ at the LHC allows for precise measurements of differential cross sections as a function of $t\bar{t}$ related variables. Extensive measurements were performed by the ATLAS [1] and CMS [2] experiments at different pp center of mass energies and in various $t\bar{t}$ decay channels, i.e, the dilepton, the lepton+jets, and the all-hadronic final states. These measurements provide an important test of the standard model and its ability to predict the observed distributions, which are sensitive to higher order perturbative QCD and electro-weak corrections.
A measurement of differential $t\bar{t}$ cross sections requires an unambiguous definition of the top quark and the related phase space. Two different approaches are used to present the measured results. The first approach is the extrapolation to the parton level where the top quark is defined as a top quark directly before the decay, but after radiation. Since in this definition the decay products are not considered, the results are often given without any kinematic restrictions. This requires a large extrapolation from experimentally accessible quantities like jets and leptons measured in a restricted phase space that is determined by the experimental acceptance. Such an extrapolation relies on theoretical models that imply additional systematic uncertainties. However, a parton level measurement is often the only way to compare the best theoretical calculations to measurements.
In the second approach the top quark is defined at particle level where in this context particles are theoretically defined objects that are directly experimentally accessible, e.g., jets of stable particles instead of partons and b jets are matched to intermediate b hadrons. These particles are selected in a phase space close to the experimental acceptances and further used to construct a proxy for the top quark, sometimes also referred to as pseudo-top. This is done using a dedicated algorithm that implements kinematic constraints to assign the particles to certain decay products of the top quark proxy. In general, it is desirable to define the top quark proxy as closely as possible to a top quark at parton level. The advantage of this approach is the minimization of dependencies on theoretical models in the measured results. This makes the results more persistent and allows for an easy comparison to updated future calculations. However, measurements at particle level can only be compared to theoretical predictions that incorporate a full parton shower and hadronization model.

2. Differential cross section measurements

Currently the most precise measurements are available at 8 TeV where both experiments have published results based on integrated luminosities of about 20 fb^{-1}. ATLAS performed the measurement in the e/μ+jets channels [3, 4]. A proxy of the $t\bar{t}$ system is reconstructed by applying the following algorithm on measured particles. Out of the two b jets with the highest p_{T} the one spatial closer to the lepton belongs to the leptonically decaying top quark, the other one to the hadronically decaying top quark. Two light jets whose invariant mass is most compatible with m_{W} form the hadronically decaying W boson. The m_{W} constraint together with the $E_{\mathrm{T}}^{\mathrm{miss}}$ and the lepton momentum is also used to obtain the longitudinal component of the neutrino momentum. The distributions of the so defined measured top quark proxies are unfolded to both the particle level and the parton level. The results are shown in Fig. 1.

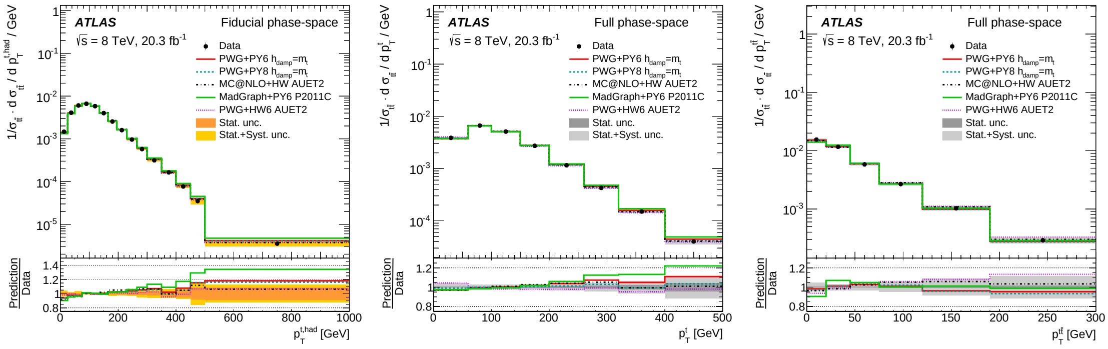

Figure 1: ATLAS measurement of the normalized differential cross sections [4]. Left: $p_{\mathrm{T}}(\mathrm{t})$ at particle level. Middle: $p_{\mathrm{T}}(\mathrm{t})$ at parton level. Right: $p_{\mathrm{T}}(\mathrm{t\bar{t}})$ at parton level.

The analysis strategy of CMS [6, 7] is different. Here algorithms are used to identify a reconstructed top quark as close as possible to the parton level top quark. In the e/μ+jets channel a kinematic fit that puts constraints on m_{W} and m_{t} is used to optimize the association of jets and parton level top quark decay products. The result of the algorithm can be improved taking into account the momentum resolution of the measured objects. Therefore, the kinematic fit is repeated many times with object momenta randomly smeared according to their resolution. After a final cut on the likelihood of the fit a sample with a fraction of 87% correctly reconstructed $\mathrm{t\bar{t}}$ pairs is obtained and the measured distributions are unfolded to the parton level. A similar reconstruction method is used in the all-hadronic channel [8], but instead of the m_{t} constraint it is only required that m_{t} is equal for both top quarks. Afterwards a template fit of the m_{t} distribution is used to subtract the large QCD multi-jet background. In the dilepton channel an algebraic reconstruction is used to calculate the neutrino momenta and the correct b jet association where constraints on the p_{T} balance, m_{W}, and m_{t} are used. Again the momenta of reconstructed objects are smeared to increase the number of solvable events.
The results are shown in Fig. 2. In general, a good agreement between most of the predictions and the measured spectra is observed. Only the spectrum of $p_{\mathrm{T}}(\mathrm{t})$ is measured to be softer in all channels. A similar effect is also observable in the ATLAS results. Even the distribution of the lepton p_{T} that is measured at particle level in the fiducial phase space shows a consistent behavior. A new NNLO QCD calculation predicts exactly such a trend [12, 13].

3. Measurements of boosted top quarks

The observed behavior of a softer $p_{\mathrm{T}}(\mathrm{t})$ spectrum raises interest in $p_{\mathrm{T}}(\mathrm{t})$ at high values. These are not accessible with the standard reconstruction methods since due to the large boost of the top quark the decay products are spatial close and can often not be reconstructed as separated objects. ATLAS and CMS performed measurements [5, 9] in the e/μ+jets channels. The common strategy is to identify a fat jet with a larger cone size than usual jets. This jet is supposed to contain all decay products of the hadronically decaying top quark. Therefore, the jet mass is selected to be compatible with the top quark mass. In addition the substructure of the fat jet is tested for its compatibility with the typical substructure of a fat jet from boosted top quarks. In the opposite hemisphere a b

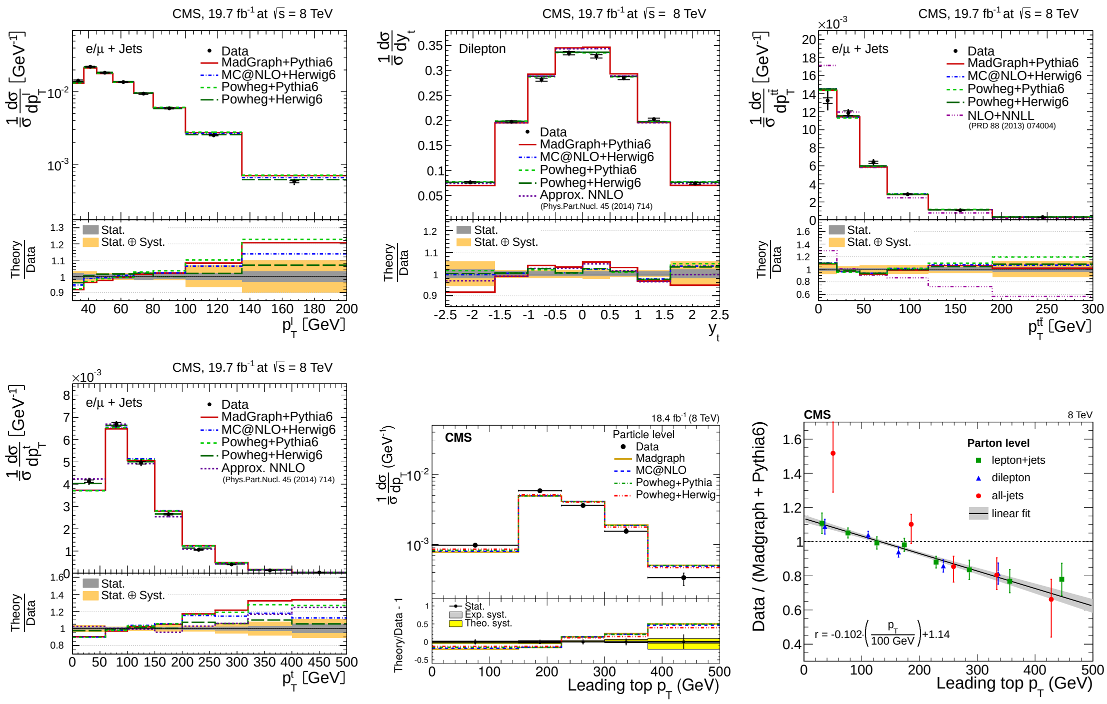

Figure 2: Measurements of normalized differential cross sections from CMS in various channels [7]. The bottom line plots show the observation of a softer $p_{\rm T}(\rm t)$ spectrum consistent among the various channels (bottom middle: all-hadronic result [8]).

jet accompanied by a lepton is expected. The measured results are shown in Fig. 3. The observed deficit at low $p_{\rm T}(\rm t)$ persists at higher $p_{\rm T}(\rm t)$.

4. First results at 13 TeV

The first differential cross section measurements at 13 TeV from CMS based on 42 pb^{-1} are shown in Fig. 4. The used techniques are similar to those at 8 TeV and the results are presented at parton level in the full phase space for the e/μ+jets [10] and the dilepton [11] channels. The measurements are widely dominated by statistical uncertainties, but show a good agreement with the standard model predictions.

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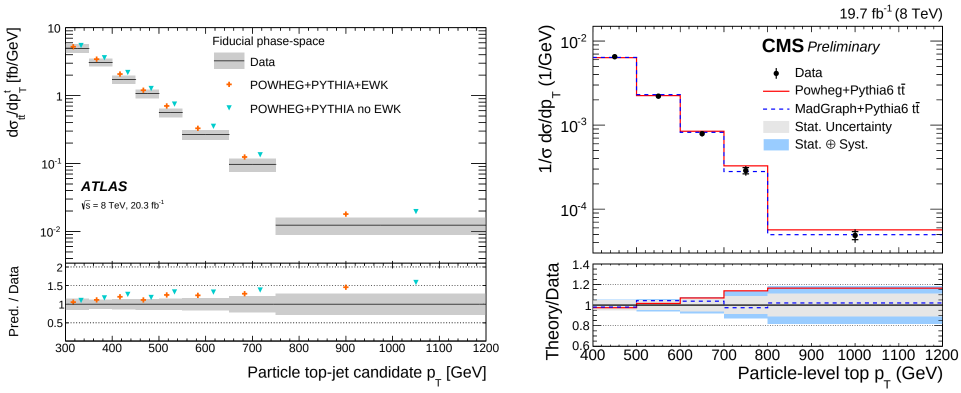

Figure 3: Left: absolute differential cross section measurement of boosted top p_{T} from ATLAS [5]. Right: normalized differential cross section measurement of boosted top p_{T} from CMS [9]. The absolute normalization undershoots the expectation by about 15%.

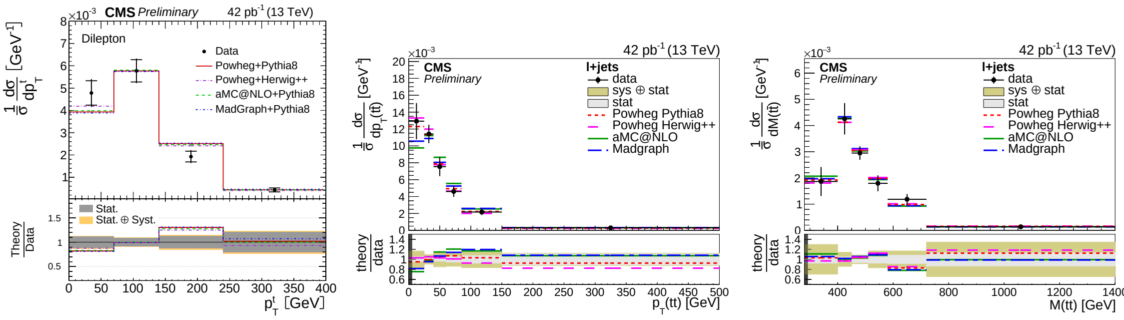

Figure 4: First measurements of differential cross sections at 13 TeV from CMS. From left to right as a function of $p_{\mathrm{T}}(\mathrm{t})$ in the dilepton channel [11], and of $p_{\mathrm{T}}(\mathrm{t\bar{t}})$ and $\mathrm{M}(\mathrm{t\bar{t}})$ in the e/μ+jets channels [10].

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