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Precision measurements at CMS

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Abstract

An overview of a few of the most recent precision measurements performed at the CMS experiment is presented, focusing on top quark measurements. High precision measurements of top quarks are important because they allow us to better understand the properties of the top quark, crucial to test the internal consistency of the Standard Model, and to better constrain new physics. Measurements of the Lund jet plane density and of the luminosity via Z bosons are also presented.

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Precision measurements at CMS

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An overview of a few of the most recent precision measurements performed at the CMS experiment is presented, focusing on top quark measurements. High precision measurements of top quarks are important because they allow us to better understand the properties of the top quark, crucial to test the internal consistency of the Standard Model, and to better constrain new physics. Measurements of the Lund jet plane density and of the luminosity via Z bosons are also presented.

1 Top quark measurements

The top quark physics at the LHC has reached the precision era thanks to the huge number of produced top quark events: $\sim$ 200M top quark pairs collected in Run 2. The top quark pair production cross-sections, used to constrain fundamental parameters of the Standard Model (SM), are established at a level of $\sim 5 - 10\%$, reaching the precision of the theory predictions ($\sim 5\%$). The single top quark production in association with weak bosons, which constrains the electro-weak sector of SM, has a precision of $\sim 10\%$.

1.1 Differential cross-section for $t\bar{t}$+jets

The analysis of the $t\bar{t}$+jets differential cross-section[1], performed by the CMS experiment[2] using full Run 2 data in dilepton events with additional jets, shows multi-differential measurements at both parton and particle level, studying the $t\bar{t}$ cross-section as a function of kinematics of top/anti-top quarks, $t\bar{t}$, decay products, and additional jets.
In this analysis, the first comparisons to predictions beyond the next-to-leading-order (NLO) accuracy have been performed. The next-to-next-to-leading-order (NNLO) models provide a similar or better description of data than NLO: e.g. for $p_{\mathrm{T}}(t)$ the trend towards harder distribution predicted by NLO models decreases at NNLO, as shown in Fig. 1 (top left). Several measured cross-sections are not described well by the nominal predictions and deviations from models are larger for multi-differential cross-sections, indicating that we need more accurate predictions.
Thanks to a better estimate of the jet energy scale (JES), b-tagging and backgrounds, the total uncertainty is reduced by a factor ~ 2 with respect to the previous analysis.

1.2 Inclusive cross-section for $t\bar{t}W$

The measurement of the inclusive cross-section of $t\bar{t}$ production in association with a W boson[3] is performed using full Run 2 data with two same-sign lepton (2LSS) or three lepton (3L) events.

For 2LSS events a deep neural network (DNN) discriminant is used to separate the $t\bar{t}$W signal from the backgrounds, while for 3L events the variable with the best signal over background separation, $m(3l)$, is chosen. The cross-section is then extracted from a simultaneous profile likelihood fit to the DNN output distributions and to the $m(3l)$ distributions in 12 different regions defined by the jet/b-jet multiplicity and lepton charge. It has a precision of $\sim 10\%$: $\sigma(t\bar{t}\mathrm{W}) = 868 \pm 40$ (stat) $^{+52}_{-50}$ (syst) fb. Thanks to the new DNN approach and a better background estimation in the large number of regions employed in the fit, there is a $\sim 50\%$ improvement of the systematic uncertainties with respect to an earlier measurement with data from only 2016.
The cross-sections of $t\bar{t}W^+$ and $t\bar{t}W^-$, shown in Fig. 1 (top right), are separately measured in order to extract their production ratio: $R_{t\bar{t}W^+/t\bar{t}W^-} = 1.61^{+0.15}_{-0.14}$ (stat) $^{+0.07}_{-0.05}$ (syst).
All the measurements show a trend to higher values than predictions but they are still in agreement with SM.

1.3 Inclusive and differential cross-section for tW

The first full Run 2 measurement of inclusive and differential tW cross-section[4] is performed using dilepton events. For the inclusive cross-section, three regions defined by jet/b-jet multiplicity are considered: two regions are sensitive to tW and are used to separately train two Boosted-Decision-Trees (BDTs) to separate signal from background events, while in the third region, used to control the $t\bar{t}$ background, a well modeled variable, p_{T}(sub-leading jet), is chosen. The cross-section is then extracted by a simultaneous maximum likelihood fit to BDT responses and p_{T}(sub-leading jet). It has a total uncertainty of $\sim 10\%$ and is in good agreement with SM predictions beyond NLO: $\sigma(tW) = 79.2 \pm 0.8$ (stat) $^{+7.0}_{-7.2}$ (syst) ± 1.1 (lumi) pb.
For the differential cross-section, a maximum-likelihood fit is performed in a signal-enriched region in order to extract the signal from six kinematic distributions unfolded to particle level. The agreement with expectations from different generators is overall good and the total uncertainty is $\sim 10 - 50\%$.

1.4 Top quark mass with profile likelihood approach

The top quark mass measured with a profile likelihood approach[5] is performed using 2016 data in the lepton+jets channel. The top quark mass is first reconstructed from a kinematic fit of the decay products to a top quark pair hypothesis and then extracted from a simultaneous fit on up to five variables: m_{t} as baseline and four additional variables sensitive to m_{t} or constraining JES. The result is the most precise measurement to date: $m_{\mathrm{t}} = 171.77 \pm 0.37$ GeV. The total uncertainty is reduced by $\sim 40\%$ with respect to the 2016 analysis, thanks in particular to the inclusion of additional observables in the fit, and also to a better $t\bar{t}$ modelling and b-tagging.

1.5 Boosted top quark mass

The top quark mass is measured from the jet mass in boosted top quark decays[6] using full Run 2 data in the lepton+jets channel. Decay products are merged into one single jet with a 2-step jet reconstruction algorithm called *XCone*, which has an excellent m_{jet} resolution.
The $t\bar{t}$ cross-section as a function of m_{jet} is unfolded to particle level and the top quark mass is extracted from the normalized distributions and compared to various mass hypotheses, shown in Fig. 1 (middle left). The measured top quark mass is $m_{\mathrm{t}} = 172.76 \pm 0.81$ GeV, with a precision ~ 3 times better than the 2016 analysis. Its uncertainties are significantly reduced thanks to a dedicated jet mass calibration and a dedicated final state radiation calibration.

2 Lund jet plane density

The Lund jet plane is a 2D representation of the phase space of $1 \to 2$ jets splittings. An iterative jet reclustering is considered and the emission of jets at each step is characterized by the angle of emission relative to the jet core, ΔR, and the relative transverse momentum of emission with respect to the jet core, $k_{\mathrm{T}} = p_{\mathrm{T}}\Delta R$. The jet-averaged density of emissions, $\frac{1}{N^{\mathrm{jets}}}\frac{d^2 N_{\mathrm{emissions}}}{dln(k_{\mathrm{T}})dln(R/\Delta R)}$ is measured using inclusive jets with full Run 2 data[7] and is shown in Fig. 1 (middle right). The total uncertainty is $\sim 2-7\%$ on the Lund jet plane and reaches $\sim 20\%$ at the kinematical edge of the plane.
The Lund jet plane density measurement is used for parton shower calculations and jet substructure technique developments. Comparisons to different Pythia8 tunes and parton-shower and hadronization setups, important to test the accuracy and better tune MC generators, are performed projecting the Lund jet plane in slices of k_{T} and ΔR.

3 Luminosity via Z bosons

The luminosity at LHC can be determined from proton-proton collision products in the fiducial phase space, e.g. using $Z \to \mu\mu$ events measured with high precision. However, the fiducial cross-section is only known to $\sim 2-3\%$ precision so special runs are needed to calibrate the measurement. A new method proposes to calibrate the Z bosons rate with a reference run, using the 2017 low pile-up (PU) fills: $L_{\mathrm{highPU}} = \frac{N^{\mathrm{Z}}_{\mathrm{highPU}}}{N^{\mathrm{Z}}_{\mathrm{lowPU}}} L_{\mathrm{lowPU}}$. The advantages are that the luminosity is measured with very good precision at low PU and the PU-independent systematic uncertainties cancel out.
The first quantitative uncertainty analysis of the use of the Z boson rate for luminosity estimation[8] is performed using Z boson decays in two muons events with 2017 data. A fit to the Z boson invariant mass distribution is performed to simultaneously extract efficiencies and number of Z bosons in data. The Z boson rate calibrated with the new method and compared to the reference luminosity shows a good stability for the full 2017. The agreement between the Z boson rate for a single fill and the reference luminosity is shown in Fig. 1 (bottom). The uncertainty on the high PU luminosity results in 1.73%, which is a big improvement with respect to the current precision of 2.4%.

4 Conclusions

The CMS Collaboration has provided a lot of precision results in Run 2, in particular in the top quark sector, with an improved precision in cross-section measurements and boosted jet mass measurement, and with the most precise direct measurement of top quark mass.
The precision of the measurements is now competing with theory predictions and in many cases an improved modelling is required.
So far the results are compatible with the SM but Run 3 will provide even higher precision.

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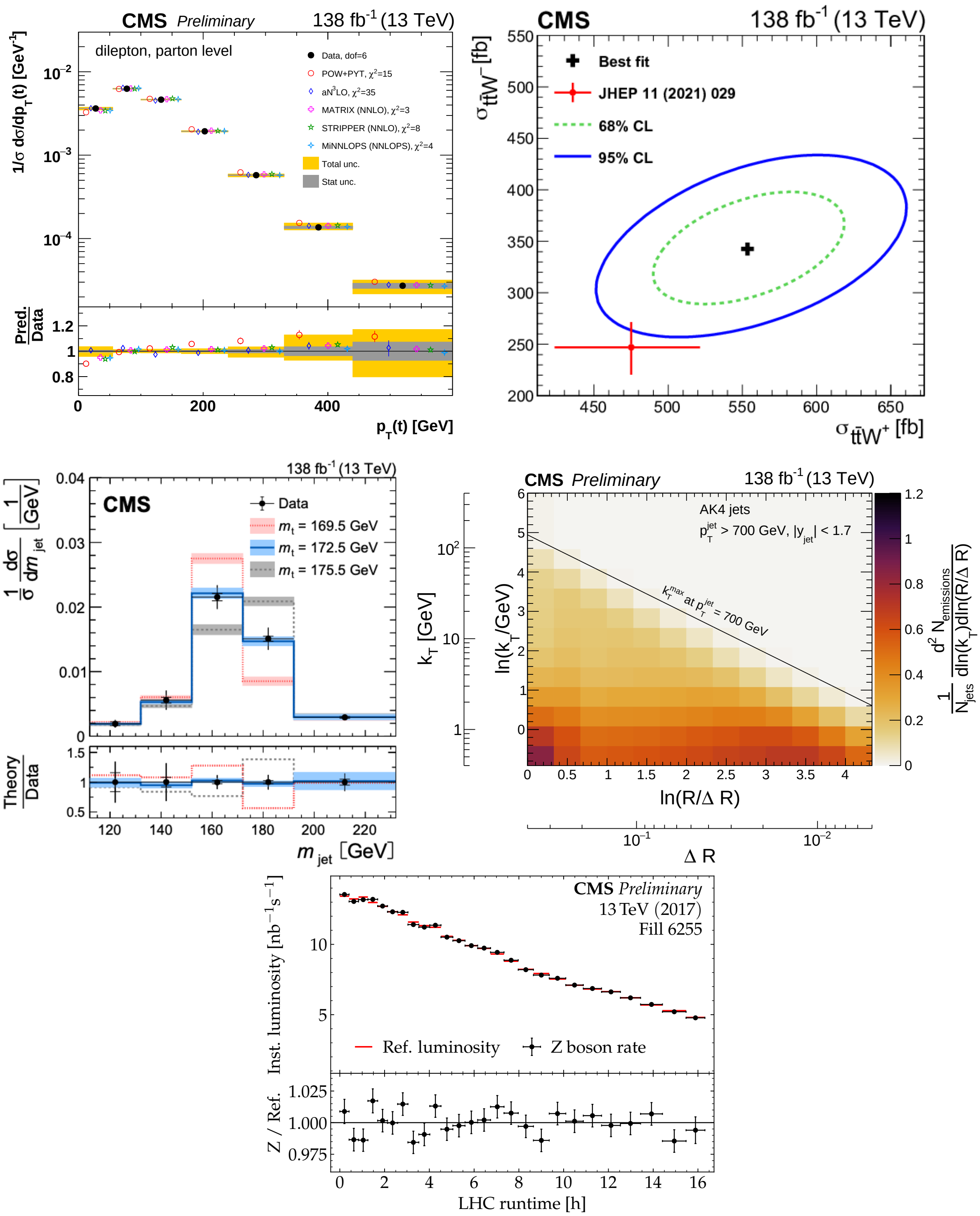

Figure 1 – Top left: Normalized differential $t\bar{t}$ production cross section as a function of $p_{\rm T}(t)$ measured at the parton level and compared to NNLO predictions.[1] Top right: $t\bar{t}W^{+}$ and $t\bar{t}W^{-}$ cross sections compared to SM prediction.[3] Middle left: Normalised differential $t\bar{t}$ production cross section as a function of $m_{\rm jet}$ compared to predictions with different $m_{\rm t}$.[6] Middle right: Two-dimensional distributions of the primary Lund jet plane densities.[7] Bottom: The Z boson rate in 2017 LHC Fill 6255, compared to the reference luminosity measurement.[8]