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Top physic results from ATLAS and CMS

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Summary. — In this paper a summary of some of the latest and most precise measurements in the top quark physics field performed by the ATLAS and CMS experiments are presented. These include the most precise measurements for $t\bar{t}$ and single top cross-section as well as for the top mass, but also various measurements of top production and decay. Higgs and New Physics searches in the top quark sector are not reported here.

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1. – Introduction

The top quark, discovered by the CDF and D0 experiments at the Tevatron 1.8 TeV $p\bar{p}$ collisions in 1995 [1], has been observed at CERN by the ATLAS [2] and CMS experiments [3] in 2010, in pp collisions at $\sqrt{s} = 7\,\text{TeV}$. Thanks to the excellent performance of the Large Hadron Collider (LHC) and of the two detectors, millions of top quarks have been produced in 7 and 8 TeV collisions in 2010-2011 and 2012 respectively and collected by ATLAS and CMS. With this large dataset, top quark production mechanisms and properties have been measured with high precision, approaching or even beating Teavtron precision.

2. – Top pair production

At the LHC the top quark is produced predominantly as $t\bar{t}$ pairs via strong interaction. NNLO calculations are currently available, predicting a $t\bar{t}$ cross section of $\sigma_{t\bar{t}} = 172.0^{+4.4}_{-5.8}(\text{scales})^{+4.7}_{-4.8}(\text{pdf})$ pb at 7 TeV and $\sigma_{t\bar{t}} = 245.8^{+6.2}_{-8.4}(\text{scales})^{+6.2}_{-6.4}(\text{pdf})$ pb at 8 TeV [4]. Once produced, the top quark decays to a W boson and a b quark about 100% of the times, according to the Standard Model (SM). Thus, top-quark pairs present three different final state topologies depending on the decays of the two W boson. The most studied final states are the semi-leptonic and the dileptonic ones, where at least one electron or muon is present in the final state, allowing a cleaner signature than a fully hadronic one. The most precise measurements for the inclusive $\sigma_{t\bar{t}}$ are performed in these channels, and rely on the first fraction of the 7 TeV dataset, which is at present better understood and less affected by systematics (*e.g.* the ones related to the pile-up).

The best measurement by CMS [5] is performed in the dilepton channel, using $2.3\,\mathrm{fb}^{-1}$ of integrated luminosity at 7 TeV, selecting events with two opposite-signed, high-p_T, central and isolated electrons or muons and two or more reconstructed jets. A profile likelihood ratio fit is then performed on the two-dimensional distribution of number of jets and number of b-tagged jets, resulting in $\sigma_{t\bar{t}} = 162 \pm 2(\mathrm{stat}) \pm 5(\mathrm{syst}) \pm 4(\mathrm{lumi})$ pb.

The most precise measurement by ATLAS [6] is instead performed in the single lepton channel, requiring only one electron or muon and at least three jets in the final state. A Likelihood discriminant is then built combining four different kinematical variables to discriminate the $t\bar{t}$ signal from the main background coming from W+jets events. Like for CMS analysis, a profile likelihood ratio fit is performed to extract the final measurement, fitting symultaneously the Likelihood discriminant in three jet multiplicity regions per lepton flavour, and giving $\sigma_{t\bar{t}} = 179 \pm 4(\mathrm{stat}) \pm 9(\mathrm{syst}) \pm 7(\mathrm{lumi})$ pb.

Other measurements at 7 TeV have been performed by the two experiments considering different final states, and a combination of the complementary results has been produced [7]. This combination, even if not including the most precise more recent results, provides a good example for an efficient cooperation between the two experiments. The final result, $\sigma_{t\bar{t}} = 173.3 \pm 2.3(\mathrm{stat}) \pm 9.8(\mathrm{syst})$ pb, shows a 7% gain in the experimental precision with respect to the most precise single measurement included there.

Measurements at 8 TeV are also available [8, 9], but despite the larger considered dataset and the higher expected cross section, the experimental measurements suffer from a higher systematic uncertainty coming form the higher amount of pile-up activity. The results, $\sigma_{t\bar{t}} = 241 \pm 2(\mathrm{stat}) \pm 31(\mathrm{syst}) \pm 9(\mathrm{lumi})$ pb from ATLAS and $\sigma_{t\bar{t}} = 227 \pm 3(\mathrm{stat}) \pm 11(\mathrm{syst}) \pm 10(\mathrm{lumi})$ pb from CMS, obtained with a limited fraction of the 8 TeV dataset, are anyway useful to test QCD calculations at different center of mass energies.

Thanks to the large accumulated statistics, differential $\sigma_{t\bar{t}}$ measurements were made possible. The dependency of $\sigma_{t\bar{t}}$ on various kinematical properties of the $t\bar{t}$ system, of individual tops or their decay products are measured at 7 TeV by both ATLAS [10] and CMS [11] and at 8 TeV by CMS [12]. They provide useful tests for perturbative QCD calculations and can be used to constrain new physics models. In addition, the dependency of the $\sigma_{t\bar{t}}$ on the number of additional jets is obtained [13,14], providing tests for Monte Carlo (MC) predictions for non-perturbative QCD including the emission of initial and final state radiation. No significant deviation from the shapes predicted by the SM-based MC simulations are found in any of the considered distributions.

The isolation of associated production of a $t\bar{t}$ pair with either a vector boson or a pair of b-jets, useful to control important backgrounds in the searches for the top-associated Higgs production, has also been made possible by the large available statistics. By selecting events with at least three (or two same-sign) leptons in the final state, $t\bar{t}+Z$ is measured to be $\sigma_{t\bar{t}Z} = 0.30^{+0.14}_{-0.11}(\mathrm{stat})^{+0.04}_{-0.02}(\mathrm{syst})$ pb by CMS [15] and $\sigma_{t\bar{t}Z} = 0.28^{+1.57}_{-0.14}$ pb by ATLAS [16], with a NLO theoretical prediction of $\sigma_{t\bar{t}Z} = 0.14\,\mathrm{pb}$ [17] (no theoretical uncertainty was available at the time this report was written). CMS also measures a $t\bar{t}+W$ and an inclusive $t\bar{t}+W/Z$ cross sections, $\sigma_{t\bar{t}W} = 0.28^{+0.14}_{-0.12}(\mathrm{stat}) \pm 0.04(\mathrm{syst})$ pb and $\sigma_{t\bar{t}V} = 0.45^{+0.17}_{-0.15}(\mathrm{stat})^{+0.06}_{-0.05}(\mathrm{syst})$ pb respectively, to be compared with the theoretical predictions at NLO [18] of $\sigma_{t\bar{t}W} = 0.17^{+0.03}_{-0.05}$ pb and $\sigma_{t\bar{t}V} = 0.308\,\mathrm{pb}$. ATLAS reports a measured $t\bar{t}+\gamma$ cross section of $\sigma_{t\bar{t}\gamma} = 2.0 \pm 0.5(\mathrm{stat}) \pm 0.7(\mathrm{syst}) \pm 0.8(\mathrm{lumi})$ pb [19], with a theoretical prediction of $\sigma_{t\bar{t}\gamma} = 2.1 \pm 0.4\,\mathrm{pb}$ [20]. The $t\bar{t}+b\bar{b}$ cross section is measured by CMS [21] with the result, $\frac{\sigma_{t\bar{t}b\bar{b}}}{\sigma_{t\bar{t}jj}} = 3.6 \pm 1.1(\text{stat}) \pm 0.9(\text{syst})\%$, being somehow higher than the fractions predicted by various LO and NLO MC generators.

Another important measurement in the context of the $t\bar{t}$ production is the so called $t\bar{t}$ Charge Asymmetry, defined as $A_C = \frac{N(\Delta|y|>0)-N(\Delta|y|<0)}{N(\Delta|y|>0)+N(\Delta|y|<0)}$, where $\Delta|y| = |y_t| - |y_{\bar{t}}|$. This quantity is predicted to be very close to 0 in the SM ($A_C = 0.0115 \pm 0.0006$) [22], but many models which are able to explain the anomalous $t\bar{t}$ Forward-Backward asymmetry measured at the Tevatron [23] also predict higher values for A_C. Both ATLAS and CMS measured A_C considering single lepton and dilepton $t\bar{t}$ final states, finding no significant deviation from the SM prediction. ATLAS single lepton and dilepton results combined give $A_C = 0.029 \pm 0.018(\text{stat}) \pm 0.014(\text{syst})$ [24], while CMS best measurement (in single lepton channel) is $A_C = 0.004 \pm 0.010(\text{stat}) \pm 0.011(\text{syst})$ [25]. Both experiments also reported differential measurements of A_C as a function of the invariant mass (ATLAS and CMS), p_T and y (CMS only) of the $t\bar{t}$ system.

3. – Single top production

Beside the $t\bar{t}$ production, top quarks can be produced singly, via weak interaction. The main single top production mode at the LHC is the t-channel, with the associated Wt and the s-channel production having lower cross section. Precise measurements of the single top production cross section in the different production modes are important to extract direct $|V_{tb}|$ measurements and to constrain new physics anomalous couplings. For the t-channel, at 7 TeV ATLAS measures $\sigma_t = 83 \pm 4(\text{stat}) \pm 20(\text{syst})$ pb [26], while CMS measures $\sigma_t = 67 \pm 4(\text{stat}) \pm 5(\text{syst}) \pm 1(\text{lumi})$ pb [27]. At 8 TeV ATLAS measures $\sigma_t = 95 \pm 2(\text{stat}) \pm 18(\text{syst})$ pb [28], while CMS measures $\sigma_t = 80 \pm 6(\text{stat}) \pm 11(\text{syst}) \pm 4(\text{lumi})$ pb [29]. All these values agree with the approximated NNLO predictions [30] of $\sigma_t = 64.6 \pm 2.4$ pb and $\sigma_t = 87.8 \pm 2.4$ pb at 7 and 8 TeV respectively, and are used to derive the limit $|V_{tb}| > 0.92$ at 95% confidence level.

Being the LHC a pp collider, the t-channel production is expected to be charge asymmetric, with the number of tops being approximately twice the number of anti-tops. The measurements of the ratio $R_t = \sigma_t/\sigma_{\bar{t}}$ by ATLAS [31] and CMS [32] agree with the SM prediction within the experimental error. Once sufficient precision is reached, this measurement could be used to constrain proton PDF's at the LHC energies.

First results are available for Wt and s-channels as well. With a dilepton event selection and a dedicated multi-variate discriminant against $t\bar{t}$ events, both ATLAS and CMS measure the Wt cross section with a $\sim 30\%$ precision: ATLAS measures $\sigma_{Wt} = 16.8 \pm 2.9(\text{stat}) \pm 4.9(\text{syst})$ pb [33], while CMS measures $\sigma_{Wt} = 16^{+5}_{-4}$ pb [34], both measurements agreeing with the SM prediction. For s-channel, suffering from a lower cross section and being characterized by final states very close to the t-channel ones, no observation is obtained yet, even if ATLAS set an upper limit of 5.8 times the SM prediction [35].

4. – Top quark mass

Due to its large mass, the top quark gives large contributions to electroweak radiative corrections. Together with precision electroweak measurements, the top quark mass can be used to derive constraints on the masses of the Higgs boson and new Physics particles.

The best top mass measurements at the LHC are performed focusing on $t\bar{t}$ events with single lepton final states, being the best compromise between having a clean signal and being able to fully reconstruct at least one of the two top quarks trough its hadronic decay. As in the case of the $t\bar{t}$ total cross section, the best precision is obtained by both ATLAS [36] and CMS [37] by considering only 7 TeV data, where systematic uncertainties are more under control. In ATLAS analysis, a so called 2D Template Method is used. An event-by-event kinematical likelihood fit is performed to reconstruct the $t\bar{t}$ system by solving the combinatorial issue of assigning jets and b-jets to the hadronically decaying W and the two tops. A two-dimensional histogram is then filled with the reconstructed values for top and W masses and a template fit is applied on it, by using different MC templates for different top mass hypotheses. While the W mass is fixed in the fit, both the top mass (m_t) and a jet energy scale (JES) overall factor are fitted simultaneously, performing a sort of *in situ* JES calibration thanks to the W mass constraint. The result is $m_t = 174.5 \pm 0.6(\text{stat}) \pm 2.3(\text{syst})$ GeV. CMS analysis applies the same principle of a simultaneous m_t and JES fit, but uses the so called Ideogram Method. Each jet permutation in each event in data is weighted according to its probability of having reconstructed the $t\bar{t}$ decay correctly. An analytical expression for a global Likelihood function is then maximized, providing a pair of best fit values for m_t and JES. The result is $m_t = 173.5 \pm 0.4(\text{stat} + \text{jes}) \pm 1.0(\text{syst})$ GeV.

Also for top mass measurement ATLAS and CMS exercised a combination of some of their early results [38], resulting in $m_t = 173.3 \pm 0.5(\text{stat}) \pm 1.3(\text{syst})$ GeV. A more recent CMS combination [39], including dilepton and all-hadronic final states in addition to the measurement in single lepton channel reported above, gives $m_t = 173.4 \pm 0.4(\text{stat}) \pm 0.9(\text{syst})$ GeV, reaching Tevatron experiment precision ($m_t = 173.2 \pm 0.6(\text{stat}) \pm 0.8(\text{syst})$ GeV [40]).

CMS experiment also reported a differential top mass measurement [41], testing the MC description of the dependence of the top mass measurement in $t\bar{t}$ single lepton events on various kinematical properties of the final state.

5. – Top decay

Concerning top quark decay, two recent results from ATLAS and CMS are presented. CMS measured the top quark relative branching ratio $R = BR(Wb)/BR(Wq)$ (with $q = d, s, b$) [42], which can be used to extract an indirect constrain on $|V_{tb}|$ (under the assumption of unitary CKM matrix) or probe new physics scenarios like fourth generation quarks or charged Higgs boson from top decay. The measurement is focused on a $t\bar{t}$ dilepton event selection, but takes into account also the fraction of single top events entering the selection. A maximum likelihood fit is applied on the distribution of b-tagged jet multiplicity resulting in $R = 1.023^{+0.036}_{-0.034}$, corresponding to a 95% confidence level limit $|V_{tb}| > 0.972$ (the most stringent experimental constrain on V_{tb} at present).

An important measurement to probe the V-A coupling of the weak charge is the W polarization measurement in top decay. By looking at the $t \to W(\to \ell\nu)b$ decay in $t\bar{t}$ events in 7 TeV data, ATLAS and CMS Collaborations measure the angle between the b-jet from top and the lepton from W in the top rest frame. From this distribution, the fraction of right-handed, left-handed and non-polarized W are extracted. The results from ATLAS with single lepton and dilepton final states were combined with the CMS single muon measurement [43], finding a result in good agreement with SM predictions. CMS also measured the same quantity selection single top final states [44], again in agreement with theoretical predictions, even if with larger uncertainty.

6. – Summary

After 18 years from top quark discovery, top physics is still a fascinating topic in experimental high energy physics. Many measurements, like the total $t\bar{t}$ cross section and the top mass, are now precision measurements, reaching and even exceeding Teavtron precision, while single top and differential measurements are on the way too, benefiting from the recent large increase in statistics. Many of the presented measurements are not yet fully exploiting the potential of the LHC: they use only a fraction of the available statistics and are already dominated by systematics mainly related to detector performances and MC simulation, uncertainties which are expected to become smaller with the increasing understanding of the relatively young multi-TeV-energy physics.

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