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Top Quark Physics at the LHC

R. Di Sipio
Università di Bologna e INFN
E-mail: disipio@bo.infn.it

A. O. M. Iorio[*]
Università di Napoli e INFN
E-mail: iorio@na.infn.it

In this talk we review the measurements performed by the ATLAS and CMS experiments at the LHC concerning the physics of the top quark. We classify the various measurements in three large categories: production, properties and searches for new phenomena beyond the Standard Model. Finally, we discuss possible developments is this field in preparation for the $\sqrt{s} = 13$ TeV LHC data taking.

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[*] Speaker.

1. Introduction

The top quark, first observed[1] by the CDF experiments in 1995, has been "rediscovered" at CERN by the ATLAS[2] and CMS experiments[3] and now is being studied with large data samples. Thanks to the high performance of the Large Hadron Collider (LHC) and of the two detectors, several thousands top quarks have been collected. In fact, as we shall discuss in the following sections, most of the measurements are dominated by systematic uncertainties. We believe that it will be of great importance to pay a lot of effort into trying to understand and reduce these uncertainties, both of theoretical and experimental nature, before the start of the LHC data taking at $\sqrt{s} = 13$ TeV that is scheduled to start in 2015.

2. Production Mechanisms

Top quarks at the hadron colliders can be produced in pairs via strong interactions or singly via electroweak interactions. At the LHC the top pair production has a higher cross-section of 172.0 ± 4.8 pb at $\sqrt{s} = 7$ TeV and 245.8 ± 9.6 at $\sqrt{s} = 8$ TeV as calculated at next-to-next to leading order (NNLO) precision[4]. This happens in about 85% of the times via gluon-gluon fusion, the remaining part via quark-antiquark annihilation. Single top quarks can be produced mainly in the t channel in association with a jet originated from a light quark and a b-jet from gluon splitting with a cross-section of 64.6 ± 2.1 pb at $\sqrt{s} = 7$ TeV and 87.1 ± 2.8 at $\sqrt{s} = 8$ TeV with approximate NNLO precision[5] . Less frequently, single tops can be produced in association with a W boson via flavor excitation (tW-channel) and in association with a b jet (s-channel).

Once produced, top quarks decay 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 according to the combination of the decays of the W boson.

Both ATLAS and CMS measured the inclusive $t\bar{t}$ production cross section in semileptonic, dileptonic and fully-hadronic channels. The combined measurements are compatible with the Standard Model predictions with precisions less that 10% that are in the same order of the theoretical uncertainties, the latter being mostly due to parton distribution functions and scale uncertainty. ATLAS measured $\sigma_{t\bar{t}} = 177^{+11}_{10}$[6] at $\sqrt{s} = 7$ TeV and $\sigma_{t\bar{t}} = 241 \pm 32$[8] at $\sqrt{s} = 8$ TeV, while CMS measured $\sigma_{t\bar{t}} = 166 \pm 13$ at $\sqrt{s} = 7$ TeV[7] and $\sigma_{t\bar{t}} = 227 \pm 15$[9] at $\sqrt{s} = 8$ TeV.

The value of the inclusive $t\bar{t}$ cross section depends on a number of parameters. Thus, inverting these relationships, it both ATLAS and CMS extracted the top-quark pole mass obtaining of $m_t = 166.4^{+7.8}_{-7.3}$ GeV[10] and $m_t = 166.4^{+7.8}_{-7.3}$ GeV[11] respectively. CMS also extracted the value of the strong coupling constant $\alpha_S(m_Z) = 0.1178^{+0.0046}_{-0.0040}$[12]. Such results are in good agreement with the current world average.

Apart from the inclusive measurement, it is of great interest to study the differential distributions of top-quark pairs to constrain Monte Carlo models, gluon PDF and other theoretical assumptions. The measurements performed by ATLAS at $\sqrt{s} = 7$ TeV[13] and by CMS at $\sqrt{s} = 7$ TeV[14] and $\sqrt{s} = 8$ TeV[15, 16] are in good agreement with several Monte Carlo models for the $t\bar{t}$ invariant mass, transverse momentum and rapidity distributions.

To further constrain the perturbative QCD models, the $t\bar{t}$+jets production has been studied by both experiments[17][18]. The measured distribution showed a disagreement in the jet transverse-momentum predicted by MC@NLO[19], and constrained the tuning of PYTHIA[20].

The perturbative QCD theory predicts a small asymmetry in the production of $t\bar{t}$ pairs due to interference among quark-antiquark annihilation diagrams between LO and NLO. Recently, the Tevatron experiments reported[21] a measurement of the forward-backward asymmetry (A_{FB}) in disagreement with the theoretical calculation, especially evident for high invariant mass, hinting towards effects of new physics. However, the charge asymmetry (A_C), which is correlated with A_{FB}, as measured by ATLAS[22] and CMS[23] does not show any significant deviation from the Standard Model prediction. These measurements put some constraints to models that could explain the Tevatron anomaly.

As for the single-top production, the t channel cross-section measured by ATLAS $\sigma_{t-ch} = 80 \pm 20$ pb[24] at $\sqrt{s} = 7$ TeV and $\sigma_{t-ch} = 95 \pm 18$ pb[25] at $\sqrt{s} = 8$ TeV and by CMS $\sigma_{t-ch} = 67.2 \pm 6.1$ pb[26] at $\sqrt{s} = 7$ TeVand $\sigma_{t-ch} = 80 \pm 13$ pb[27] at $\sqrt{s} = 8$ TeV are in good agreement with the Standard Model prediction. The tW channel production cross-section has been measured at $\sqrt{s} = 7$ TeV by ATLAS to be $\sigma_{tW} = 17 \pm 6$ pb[24] and by CMS to be $\sigma_{tW} = 16 \pm 5$ pb[26]. ATLAS also set an upper limit to the s channel cross section at $\sqrt{s} = 7$ TeV: $\sigma_{s-ch} < 26.5$ pb.[30]

Finally, ATLAS and CMS also measured the ratio between the production cross section of single top and single antitop in the t channel[31][32]. This quantity is sensitive to the gluon and bottom parton distribution functions.

3. Properties and Decays

Once the production cross sections have been established and mostly found to be in good agreement with the theory, many other properties are worth measuring as they can both allow us to precisely measure correlated observables in the Standard Model and provide constraints to a broad variety of BSM models. Usually, a fitting procedures is deployed to extract the parameter of interest (PoI). In the case of the mass of the top quark, a combined fit of the PoI and the jet energy scale (JES) gives the most precise measurement. Furthermore, the two experiments comvined the earlier measurements of the PoI, obtaining the value of $m_t = 173.3 \pm 0.5(stat) \pm 1.3(syst)$ GeV[33]. It is also to note that the most recent results from CMS have been included in a new combination yielding a slightly more precise value of $m_t = 173.36 \pm 0.38(stat) \pm 0.91(syst)$ GeV[35], yielding a precision which is very close to the one of Tevatron's measurement [36]. CMS measured also the stability of m_t as a function of some observables that are expected to affect its measurement due to ISR/FSR and color reconnection effects. No significant deviation is observed[34].

The other defining characteristic of the top quark is its electric charge. The Standard Model prediction of +2/3e is tested against the exotic quark hypothesis -4/3e. By measuring the charge of muons in the b-jet with various methods ATLAS[37] and CMS[38] excluded the exotic model with more than 5 standard deviations. The coupling with photons is also consistent with the SM calculation[44].

The Standard Model predicts the value of the polarization of $t\bar{t}$ pairs, of the W bosons from top quark decays and spin correlation effects in $t\bar{t}$ events. All these quantities have been measured by ATLAS [39][41] and CMS [40][42], and combined in a single measurement in the case of the helicity fractions in the W polarization. No significant deviation is observed.

The branching fraction of $t \to bW = 1.023^{+0.036}_{-0.034}$ was measured by CMS[45] and is found to be compatible with the SM prediction. This value can be reinterpreted as a measurement on the V_{tb} element. However, the determination of the same quantity by the unitary limit is about two order of magnitudes more precise.

4. Beyond the Standard Model

Massive particles decaying to top quarks are searched as resonances in the $t\bar{t}$ invariant mass spectrum. A leptophobic vector boson Z' is used to represent a narrow resonance, while Kaluza–Klein gluons g_{KK} are used to represent wide resonances. With the $\sqrt{s} = 8$ TeV data CMS excluded a Z' boson with mass < 2.5 TeV with a cross-section $\sigma_{Z'} > 33$ fb[46], while ATLAS excluded a g_{KK} with mass less than 1.9 TeV with a cross-section $\sigma_{g_{KK}} > 0.11$ pb[47]

New particles could also affect a number of electroweak vertices enhancing the rate of flavour-changing neutral currents (FCNC). ATLAS and CMS searched for such effects in events containing three charged leptons, looking for $t\bar{t}$ topologies in which one of the top decays to a b quark and a $Z \to l^+l^-$ boson. If present, the branching fraction of such decay must be less than 0.21% at 95% CL[48][49]. ATLAS excluded also a $qg \to t$ production with a cross-section larger than 3.9 pb, and set upper limits to the branching ratios $BR(t \to ug) < 5.7\ 10^{-5}$ and $BR(t \to cg) < 2.7\ 10^{-4}$ at 95% CL[50].

5. Prospects Before the Next LHC Data Taking

The top quark can be seen as an important tool in searches for phenomena not accounted by the Standard Model, but also to constrain uncertainties related to well-known processes. In particular, we believe that it could be used to reduce the gluon PDF uncertainty in high-x region, thanks to inclusive cross section at NNLO precision. As soon as this calculation will be available for differential distributions, its comparison against data will help improve our knowledge about the structure of the proton, in turn lowering the uncertainty on the Higgs-boson production cross section in gluon-gluon fusion events. With higher center-of-mass energy and luminosity, it will be possible to study new classes of events such as the associated production of a Higgs boson with top quarks. This will provide a unique opportunity to measure the Yukawa coupling y_t. Boosted objects taggers are being tuned with the 2011 and 2012 data, and will let us extend the experimental reach in the high-mass region above 1 TeV. Last but not least, it is important to point out the effort to combine the measurements between ATLAS and CMS: in the case of the top mass, the combined value is about 9% more precise than the most precise of the two separate measurements. Tevatron's combined m_t has still an overall uncertainly that is lower, but not much lower than the LHC one. Hopefully, the same precision will be reached after few iterations. Extending this expertise to other measurements will be of extreme importance for the future.

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