PROCEEDINGS OF SCIENCE

Top-quark properties at hadron colliders

Javier Fernández Menéndez[*][†]
Universidad de Oviedo
C/ Calvo Sotelo s/n, Oviedo, Spain
E-mail: `Javier.Fernández@cern.ch`

Recent results on top-quark properties and interactions are presented, obtained using data collected with the LHC ATLAS and CMS experiments during the years 2011 and 2012 at 7 and 8 TeV pp center-of-mass energies, and with the Tevatron's CDF and D0 experiments at 1.96 TeV $p\bar{p}$ center-of-mass energy. The mass of the top-quark is extracted using several methods, including indirect constraints from the measured cross section. Further results include measurements of top-quark properties, such as the top pair charge asymmetry, spin correlation and polarization, as well as the search for anomalous couplings and charge-parity violation in top-quark pair production. No deviations were found with respect to the predictions of the Standard Model.

Fourth Annual Large Hadron Collider Physics (LHCP2016)
13-18 June 2016
Lund, Sweden

[*] Speaker
[†] On behalf of the ATLAS, CDF, CMS and D0 collaborations

PoS(LHCP2016)038

1. Introduction

The top-quark is the heaviest known fundamental particle of the Standard Model (SM) with a mass of ≃ 173 GeV, close to the electroweak scale. Precise measurements of its mass allow for consistency checks of the SM. Besides, the top-quark has a very short lifetime and decays before it hadronizes. The bare quark properties are transferred to its decay products which allows for their precise measurements. New physics (NP) is likely to modify these properties of top-quark events from the SM expectations, either via underlying direct production modes or from interference effects from NP at higher mass scales. Measurements of the top-quark properties therefore provide an ideal laboratory to test perturbative QCD and probe for new physics.

During the Run II (2001-2011) of the Tevatron at $\sqrt{s}$ = 1.96 TeV and the Run I (2010-2012) of the LHC at $\sqrt{s}$ = 7 and 8 TeV, a large amount of $p\bar{p}$ and pp collisions have been recorded in the D0 [1] and CDF [2], and in the ATLAS [3] and CMS [4] experiments, respectively, allowing to precisely study the top-quark properties in $t\bar{t}$ processes. The results presented hereafter rely on the full dataset, approximately 10 fb^{-1} per experiment in the Tevatron case, and 5 and 20 fb^{-1} per experiment at 7 and 8 TeV, respectively, in the LHC case. Since ~85% of the $t\bar{t}$ production occurs via $q\bar{q}$ annihilation in $p\bar{p}$ collision, the Tevatron can be viewed as a $q\bar{q}$ collider, as opposed to the LHC which is rather a gg collider with ~84% of $t\bar{t}$ production coming from gluon fusion. Hence, measurements of top-quark production at the Tevatron are complementary to those at the LHC.

2. Top-quark polarization

The SM predicts that top-quark pairs are produced almost unpolarized at the Tevatron (only a small longitudinal polarization is generated by SM parity-violating weak interactions), while various models beyond the Standard Model (BSM) predict non-zero polarization of the top-quark pairs. The transverse polarization is allowed in strong interaction processes and is therefore predicted to be non-zero in the SM. The top-quark polarization $P_{\hat{n}}$ can be measured in the top-quark rest frame through the angular distribution of the top-quark decay products with respect to a chosen axis $\hat{n}$. D0 has performed [5] the first measurement of polarization along the transverse axis at a hadron collider using the lepton+jets channel. The polarization was measured for three different choices of spin quantization axis: the beam axis given by the direction of the proton beam, the helicity axis given by the direction of the parent top-quark, and the transverse axis defined as the direction perpendicular to the production plane given by the proton and parent top-quark directions. The results summarized in table 1 are consistent with zero polarization within uncertainties and in agreement with SM expectations.

Axis	Measured polarization $P_{\hat{n}}$	SM prediction
Beam	+0.070 ± 0.055	-0.002
Helicity	-0.102 ± 0.060	-0.004
Transverse	+0.040 ± 0.034	+0.011

Table 1. Preliminary measured top-quark polarization in beam, helicity, and transverse spin quantization bases by D0 [5]. The total uncertainties (statistical + systematic) are shown.

3. Spin correlations (SC)

The top-quark is the only quark that decays before hadronising, meaning the information about its spin is transferred to its decay products undiluted by non-perturbative effects. D0 [6] has measured the correlation between the spins of the top-quarks using a matrix element technique in dilepton and single-lepton+jets final states. Figure 1 shows the distribution of the measured distribution, compared to the predictions of correlated and uncorrelated scenarios. The measured value of the correlation coefficient in the off-diagonal basis, $O_{off} = 0.89 \pm 0.22$ (stat+syst), is in agreement with the SM prediction [7], and represents evidence for top-antitop-quark spin correlations at the level of 4.2 standard deviations.

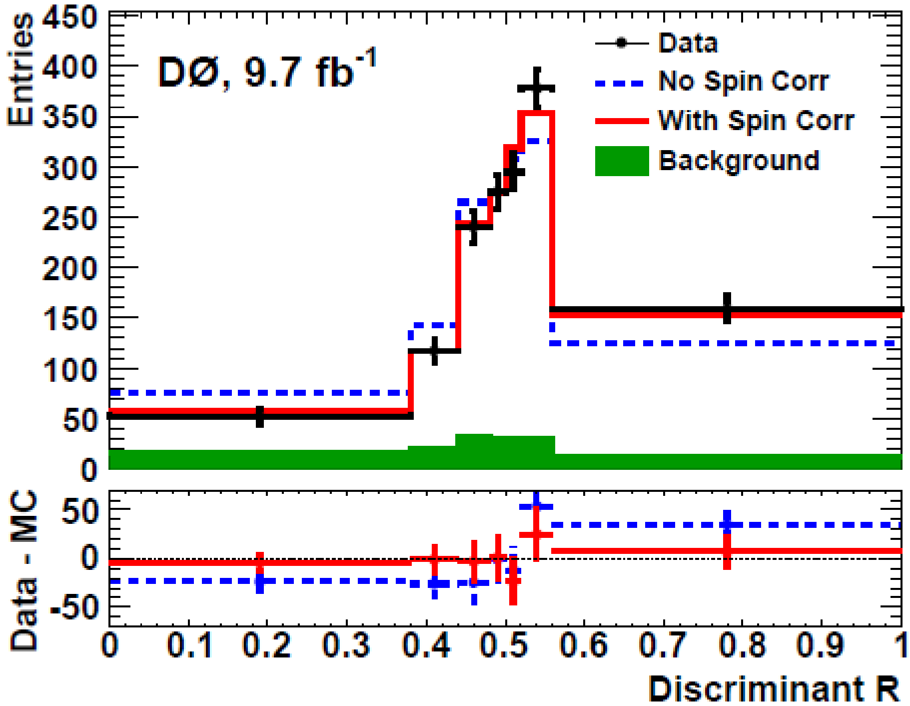

Figure 1. Distribution of the SC discriminant used in D0 [6] in data and for the mc@nlo $t\bar{t}$ prediction with background, showing the merged results from $\ell\ell$ and ℓ+jets events. The lower plot represents the difference between data and simulation with SM spin correlation and without spin correlation. The error bars correspond to statistical uncertainties.

At the LHC, the ATLAS [8, 10] and CMS [9] experiments have also measured the SC in the $t\bar{t}$ dilepton channel using both indirect measurements (looking at the azimuthal angle between leptons in the laboratory frame) and direct measurements (reconstructing the system and looking at the product of the cosines of the helicity angles of the two leptons). In the latter case, several observables have been used obtaining inclusive distributions unfolded at parton level. The leading uncertainties are the unfolding method, the $t\bar{t}$ modelling and the jet reconstruction. CMS [11] has also measured the correlation in the μ+jets channel with 4 or 5 jets using a Leading Order matrix element method with an event likelihood including the spin-correlated SM hypothesis and the spin-uncorrelated hypothesis. There is a previous measurement from ATLAS [12] in the lepton+jets channel too; both analysis gave results compatible with the spin-correlated hypothesis.

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In all cases the asymmetry variable has been defined in some basis using number of events with parallel (↓↓, ↑↑) or anti-parallel (↑↓, ↓↑) spins as: $A = \frac{(N_{\uparrow\uparrow}+N_{\downarrow\downarrow})-(N_{\uparrow\downarrow}+N_{\downarrow\uparrow})}{(N_{\uparrow\uparrow}+N_{\downarrow\downarrow})+(N_{\uparrow\downarrow}+N_{\downarrow\uparrow})}$. Actual values of A depend on the choice of the basis and on the production mechanism and energy.

Results are summarized in figure 2 in terms of the coefficient $f_{SM} = \frac{N_{SM}^{t\bar{t}}}{N_{SM}^{t\bar{t}}+N_{Uncorr}^{t\bar{t}}}$ which gives the degree of SC relative to the SM prediction: $A_{basis}^{meas} = A_{basis}^{SM} \cdot f_{SM}$. Results are consistent with the SM prediction, and some are already limited by systematic uncertainties.

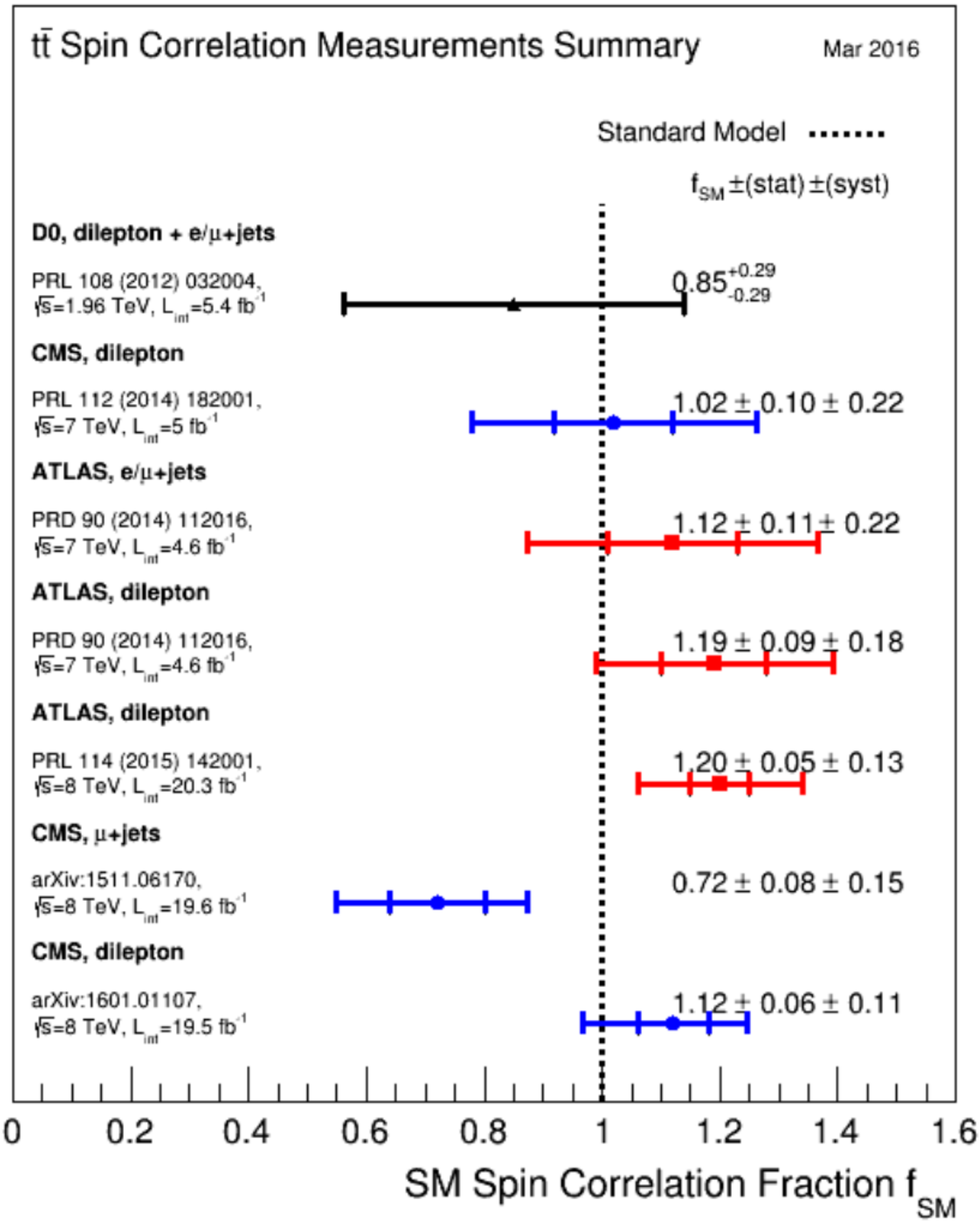

Figure 2. Summary by the LHCtopWG [32] of the $t\bar{t}$ SC measurements performed at the LHC with 7 and 8 TeV data.

4. Charge asymmetry

The charge asymmetry in top-quark pair production is an effect that occurs only in production processes involving quark-antiquark-annihilation. At the LHC, these processes have an asymmetry in the initial state due to the higher average momentum of the quarks as compared to the antiquarks, which do not occur as valence quarks. At the Tevatron, the proton-antiproton collisions result in a forward-backward asymmetry. The term charge asymmetry refers to effects that translate this initial-state asymmetry into a charge-dependent final-state asymmetry of the produced top-quarks and antiquarks; at the LHC, the higher quark momentum is predicted to result in a wider rapidity distribution for top-quarks when compared to top antiquarks, while at the Tevatron, the result is a forward (top-quark favored) backward (top antiquark favored) asymmetry. The typical asymmetries defined for the Tevatron and the LHC are (respectively):

$$A_{FB}^{t\bar{t}} = \frac{N\,(\Delta y > 0) - N(\Delta y < 0)}{N(\Delta y > 0) + N(\Delta y < 0)} \quad ; \quad A_{C}^{t\bar{t}} = \frac{N\,(\Delta|y| > 0) - N(\Delta|y| < 0)}{N(\Delta|y| > 0) + N(\Delta|y| < 0)}$$

with observables determined on an event-by-event basis using rapidity differences for the top-quark and antitop-quark: $\Delta y = y_t - y_{\bar{t}}$ and $\Delta|y| = |y_t| - |y_{\bar{t}}|$.

Measurements of the charge asymmetry have received significant attention because they are sensitive to some models introducing physics beyond the SM, and because initial measurements at CDF [13] have hinted at the existence of positive contributions of this kind. In recent times, however, the apparent discrepancy has become smaller since the theory predictions [14, 15] and last measurements have converged [16, 17]. The Tevatron results are summarized in Figure 3.

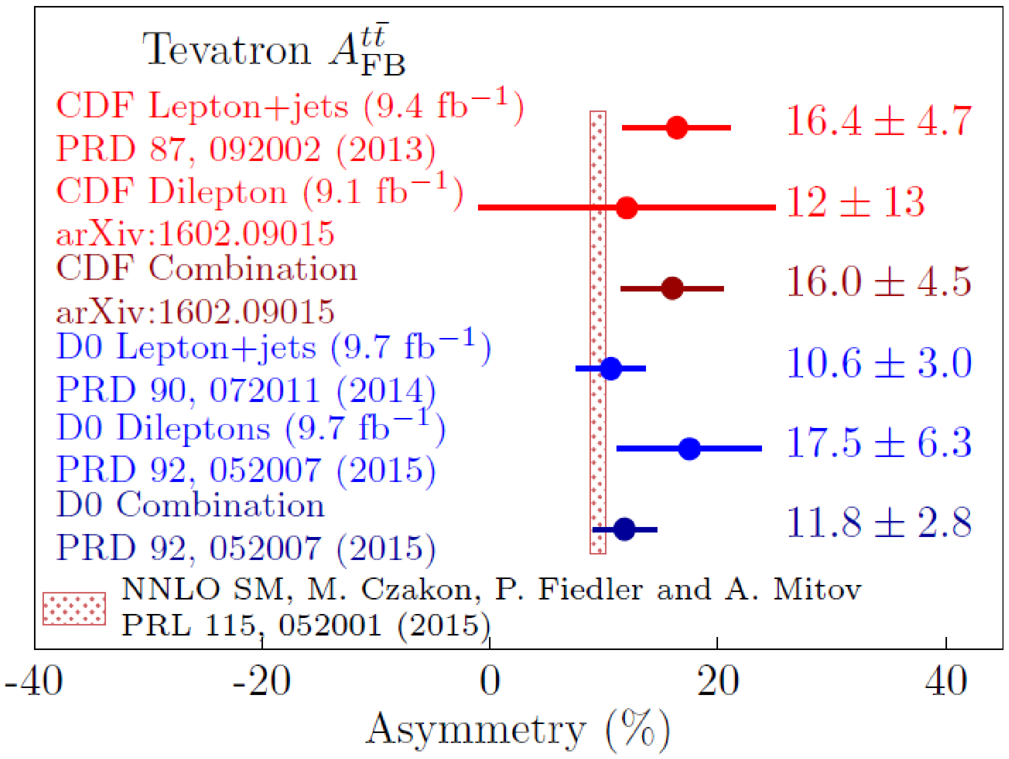

Figure 3. Summary of the forward-backward asymmetry measurements at the Tevatron [16].

At the LHC, ATLAS[18, 19] and CMS [20] have performed measurements of A_C in the dilepton channel using leptons from top-quark decays and reconstructed tops (complementary approaches) with differential distributions in $m(t\bar{t})$, $|y(t\bar{t})|$ and $p_T(t\bar{t})$, in the fiducial and full phase space in the case of ATLAS. Besides, both experiments have also used the lepton+jets channel to perform inclusive and differential measurements unfolded to the parton level. ATLAS has looked at differential distributions [21] of the $t\bar{t}$ invariant mass $m(t\bar{t})$, the $t\bar{t}$ velocity along the z-axis $\beta_z(t\bar{t})$ and the $t\bar{t}$ transverse momentum $p_T(t\bar{t})$ and in the boosted regime $m(t\bar{t})$>0.75 TeV [22], where the asymmetry is enhanced, while CMS has inspected $m(t\bar{t})$, $|y(t\bar{t})|$ and $p_T(t\bar{t})$ distributions [21] and has also used an alternative template method using the shape of the $\Delta|y|$ distribution [24].

Figure 4 summarizes the A_C measurements performed at the LHC. In general there is a good agreement between theory and experiment, hence results have been used in conjunction with the A_{FB} ones from the Tevatron to exclude several BSM models as shown in figure 5.

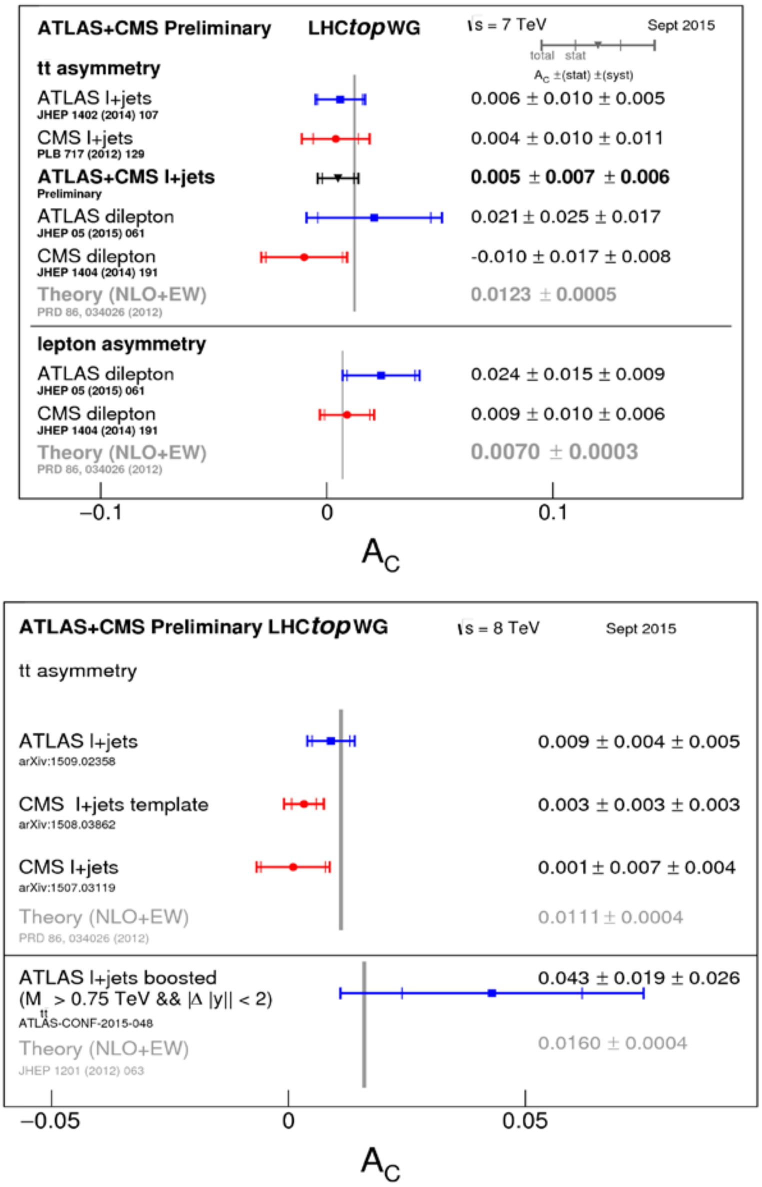

Figure 4. Summary by the LHCtopWG [32] of the charge asymmetry measurements performed in the LHC at 7 (top) and 8 (bottom) TeV.

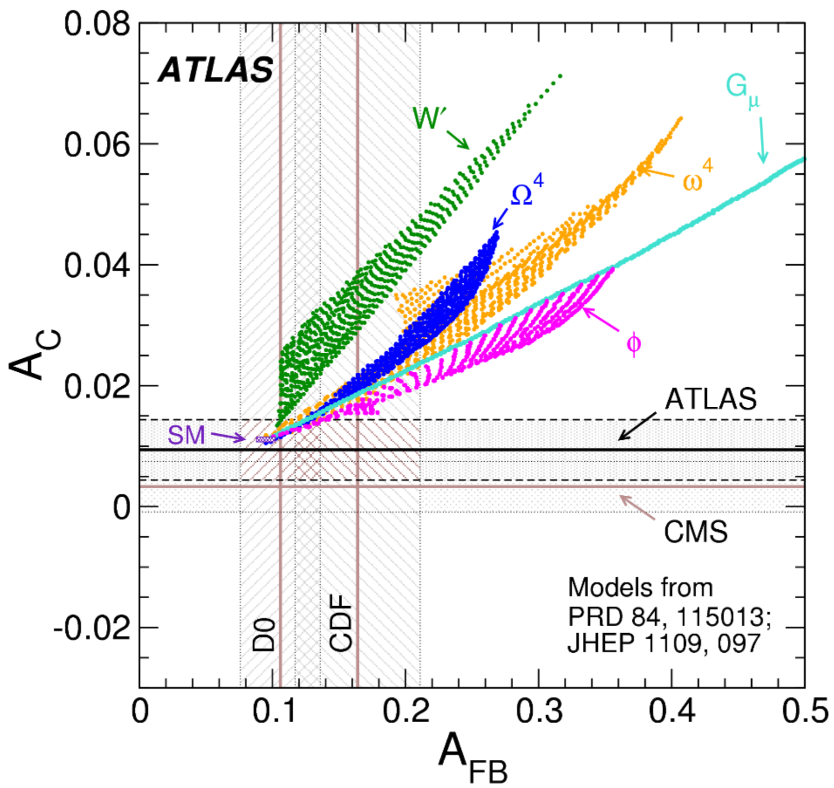

Figure 5. Measured inclusive charge asymmetries A_C at the LHC versus forward–backward asymmetries A_{FB} at Tevatron, compared with the SM predictions as well as predictions incorporating various potential BSM contributions: a W' boson, a heavy axigluon (G_μ), a scalar isodoublet (φ), a colour-triplet scalar (ω^4), and a colour-sextet scalar (Ω^4). The horizontal bands and lines correspond to the ATLAS and CMS measurements, while the vertical ones correspond to the CDF and D0 measurements. The uncertainty bands correspond to a 68% confidence level interval. Figure taken from the ATLAS [21] analysis.

5. Charge-Parity (CP) violation

Using 8 TeV data, CMS [25] has performed the first measurement at the LHC of CP-violation asymmetries in $t\bar{t}$ events in the lepton+jets channel based on the T-odd triple product correlations. Four T-odd observables are measured using the linearly independent four-momentum vectors associated with the top-quark production and decay. The presence of CP violation would be manifested by measuring a non-zero value of the asymmetry for an observable O_i:

$$A_{CP} = \frac{N_{events}(O_i>0) - N_{events}(O_i<0)}{N_{events}(O_i>0) + N_{events}(O_i<0)}.$$

The measured asymmetries show no evidence for CP-violation effects, in agreement with the SM prediction as shown in table 2. Using 7 TeV data, ATLAS [26] has seen no deviation from the SM prediction for top-quark polarization in either the CP conserving or CP violating scenario.

$A'_{CP}(O_i)$	e+jets	μ+jets	ℓ+jets
O_2	$-0.01 \pm 0.61 \pm 0.01$	$+0.50 \pm 0.56 \pm 0.02$	$+0.27 \pm 0.41 \pm 0.01$
O_3	$-0.34 \pm 0.61 \pm 0.02$	$-1.03 \pm 0.56 \pm 0.04$	$-0.71 \pm 0.41 \pm 0.03$
O_4	$-0.24 \pm 0.61 \pm 0.02$	$-0.49 \pm 0.56 \pm 0.04$	$-0.38 \pm 0.41 \pm 0.03$
O_7	$-0.42 \pm 0.61 \pm 0.00$	$+0.46 \pm 0.56 \pm 0.01$	$-0.06 \pm 0.41 \pm 0.01$

Table 2. Measured A_{CP} (in %) for the signal region for different observables in CMS [25].

6. Flavour-changing neutral currents (FCNC)

Searches for flavour-changing neutral current decays of a top-quark to an up-type quark (q=u,c) and the Standard Model Higgs boson have been carried out by ATLAS and CMS. The analyses search for top-quark pair events in which one top-quark decays to Wb, with the W boson decaying leptonically, and the other top-quark decays to Hq. Analyses assume all anomalous couplings are zero, but one.

In particular ATLAS [27] has looked for decays where the Higgs boson decays to $b\bar{b}$, where no significant excess of events above the background expectation is found, and observed (expected) 95% CL upper limits of 0.56% (0.42%) and 0.61% (0.64%) are derived for the $t\rightarrow Hc$ and $t\rightarrow Hu$ branching ratios respectively. The combination of this search with other ATLAS searches in the $H\rightarrow\gamma\gamma$, $H\rightarrow WW^*$ and $H\rightarrow\tau\tau$ decay modes significantly improves the sensitivity, yielding observed (expected) 95% CL upper limits on the $t\rightarrow Hc$ and $t\rightarrow Hu$ branching ratios of 0.46% (0.25%) and 0.45% (0.29%) respectively.

CMS has performed similar searches where the $t\rightarrow Hq\rightarrow b\bar{b}q$ (q=u,c) [28], searches where $t\rightarrow Hq\rightarrow\gamma\gamma q$ (q=u,c) [29] and searches where $t\rightarrow Hc\rightarrow$ $\tau^+\tau^-c$, ZZ^*c and $WW^{*-}c$ [30]. A best observed upper limit on the branching fraction of $t\rightarrow c(u)H$ is determined from the $\gamma\gamma q$ channel only to be 0.47(0.42)% at the 95% confidence level while the expected upper limit on the branching fraction of $t\rightarrow c(u)H$ is 0.71(0.65)% at the 95% confidence level.

Figures 6 and 7 summarize the current exclusion limits which are still above SM predictions, but sensitivity to certain BSM models is getting closer or even already reached. Experiments at LEP, HERA, and the Tevatron, give complementary results that start to be superseded by the LHC.

7. Top-quark mass

Since its discovery, the determination of the top-quark mass m_t, a fundamental parameter of the SM, has been one of the main goals of the LHC and of the Tevatron Colliders. Indeed, m_{top} and the masses of the W and Higgs bosons are related through radiative corrections providing thus an internal consistency check of the SM. Furthermore, m_{top} dominantly affects the stability of the SM Higgs potential. However, not being a direct observable, its value is scheme-dependent.

Direct reconstruction methods measure the m_t parameter as implemented in MC generators doing a full reconstruction by resolving the pairing ambiguities with either a kinematic fit to improve the mass resolution or fitting the mass with MC templates. Figures 8 and 9 summarize the current measurements from the LHC and Tevatron [33] respectively, which result in a world-average value of m_{top} = 173.34±0.76 GeV, with a combined precision of about 0.5% [31].

On the other hand, indirect methods use the dependence on the top (pole) mass for other variables like top pair production cross section mainly. The main issue of these methods is the need for high statistics samples. Results are summarized in figure 10 where precisions below 2 GeV are reached, compatible with direct measurements.

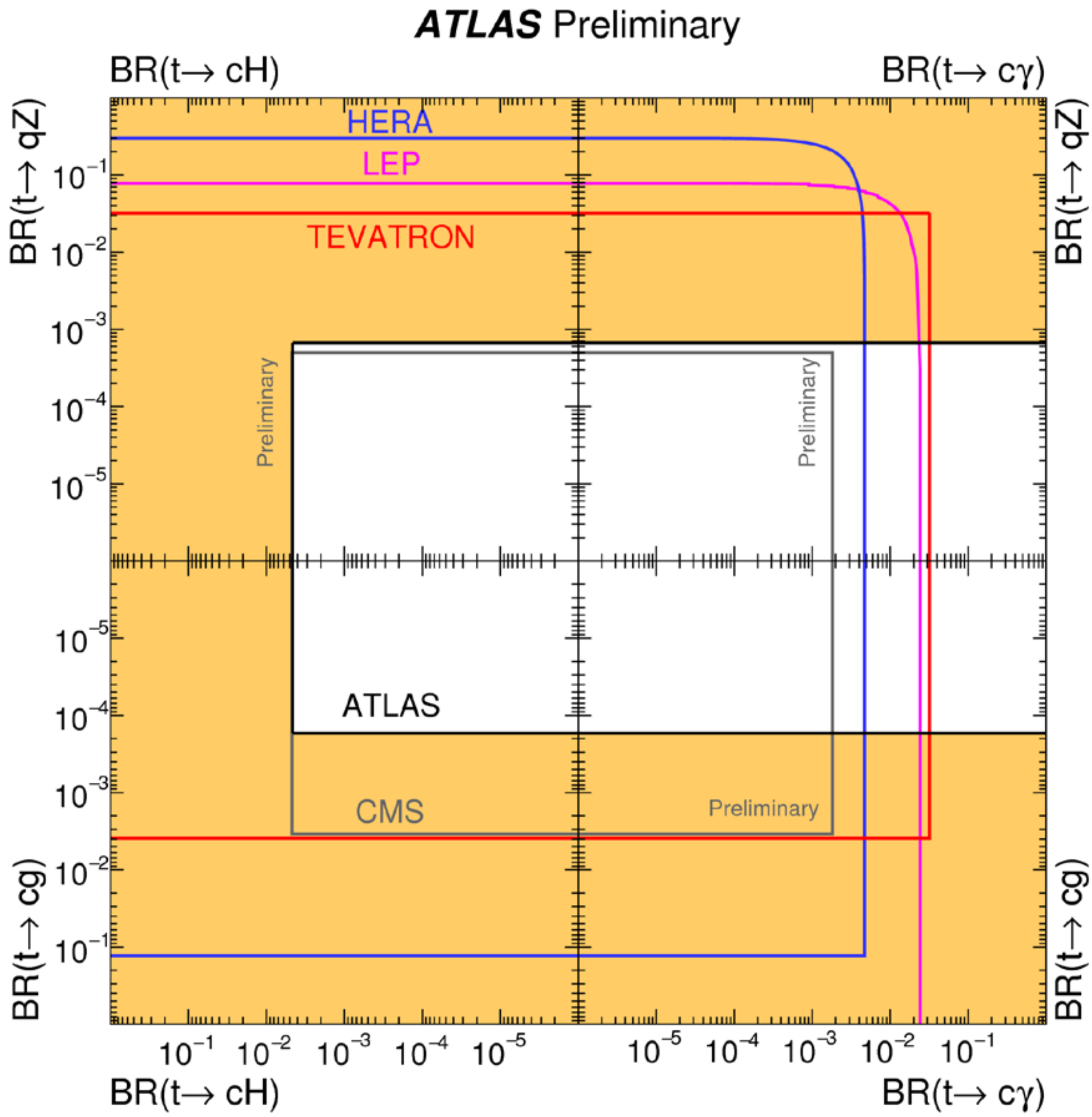

Figure 6. Summary of the current 95% confidence level observed limits on the branching ratios of the top-quark decays via flavour changing neutral currents to a charm quark and a neutral boson t→cX (X=g, Z, γ or H). The coloured lines represent the results from HERA (the most stringent limits between the ones obtained by the H1 and ZEUS collaborations, in blue), LEP (combined ALEPH, DELPHI, L3 and OPAL collaborations result, in magenta), TEVATRON (the most stringent limits between the ones obtained by the CDF and D0 collaborations, in red) and the CMS Collaboration (in grey). The yellow area represents the region excluded by the ATLAS Collaboration. Figure taken from the ATLAS [26] publication.

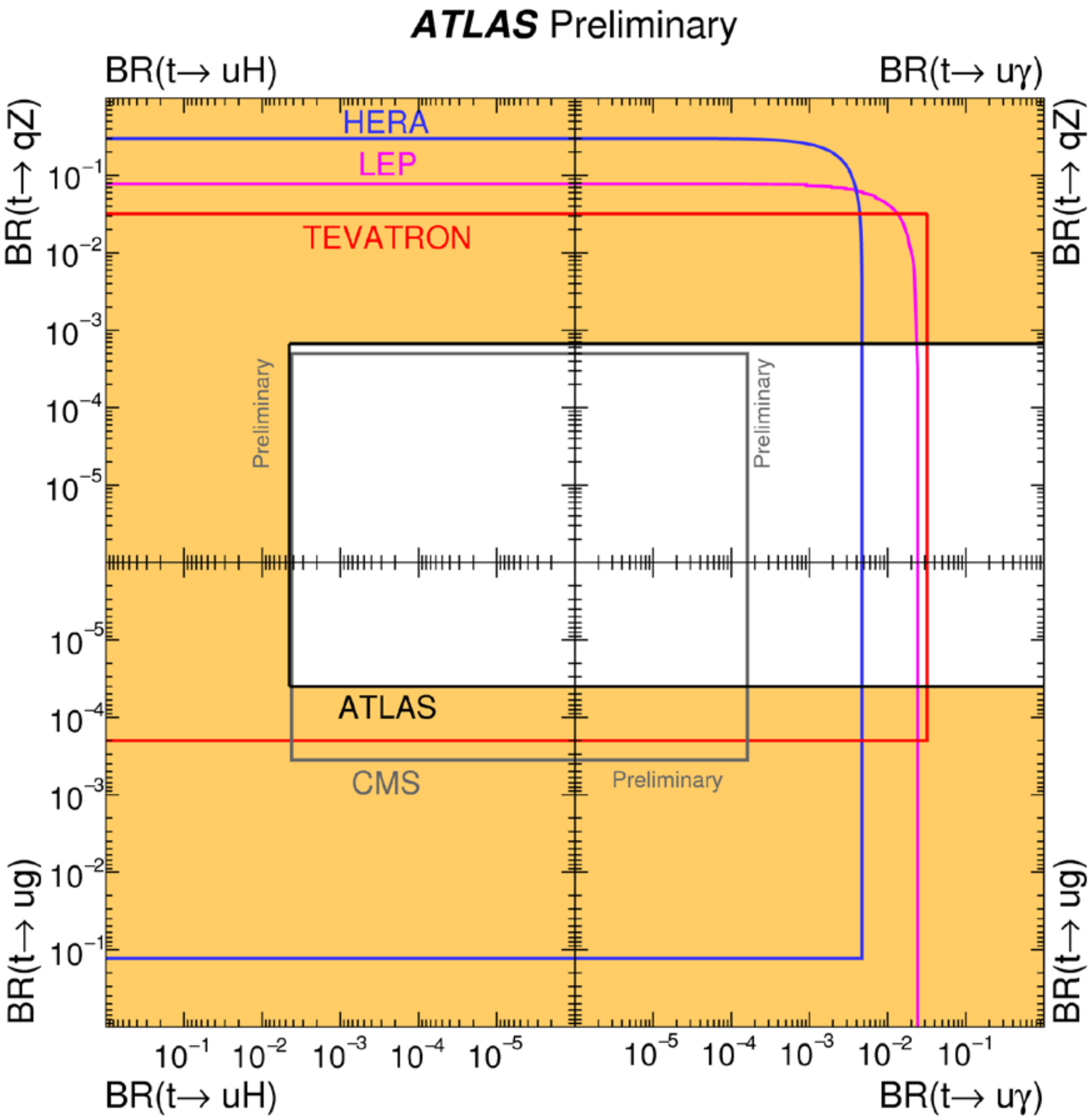

Figure 7. Summary of the current 95% confidence level observed limits on the branching ratios of the top-quark decays via flavour changing neutral currents to an up quark and a neutral boson t→uX (X=g, Z, γ or H). The coloured lines represent the results from HERA (the most stringent limits between the ones obtained by the H1 and ZEUS collaborations, in blue), LEP (combined ALEPH, DELPHI, L3 and OPAL collaborations result, in magenta), TEVATRON (the most stringent limits between the ones obtained by the CDF and D0 collaborations, in red) and the CMS Collaboration (in grey). The yellow area represents the region excluded by the ATLAS Collaboration. Figure taken from the ATLAS [26] publication.

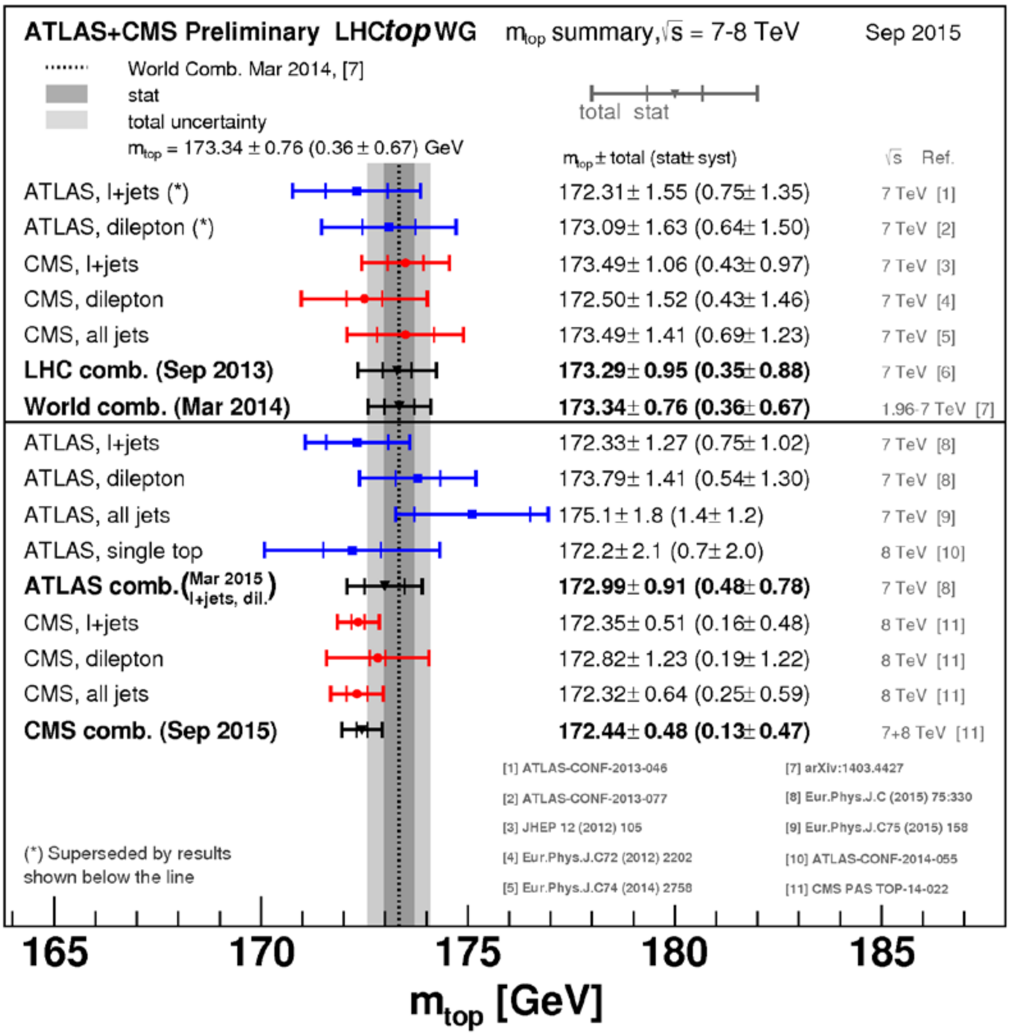

Figure 8. Summary of the ATLAS and CMS direct m_{top} measurements by the LHCtopWG [32]. The results are compared with the LHC and Tevatron+LHC m_{top} combinations. For each measurement, the statistical uncertainty includes the jet scale factor (JSF) and b-jet scale factor (bJSF) contributions (when applicable), while the sum of the remaining systematic uncertainties is reported separately. The JSF and bJSF contributions are statistical in nature and apply to analyses performing in-situ (top-quark pair based) jet energy calibration procedures. The results below the line are results produced after the LHC and Tevatron+LHC combinations were performed.

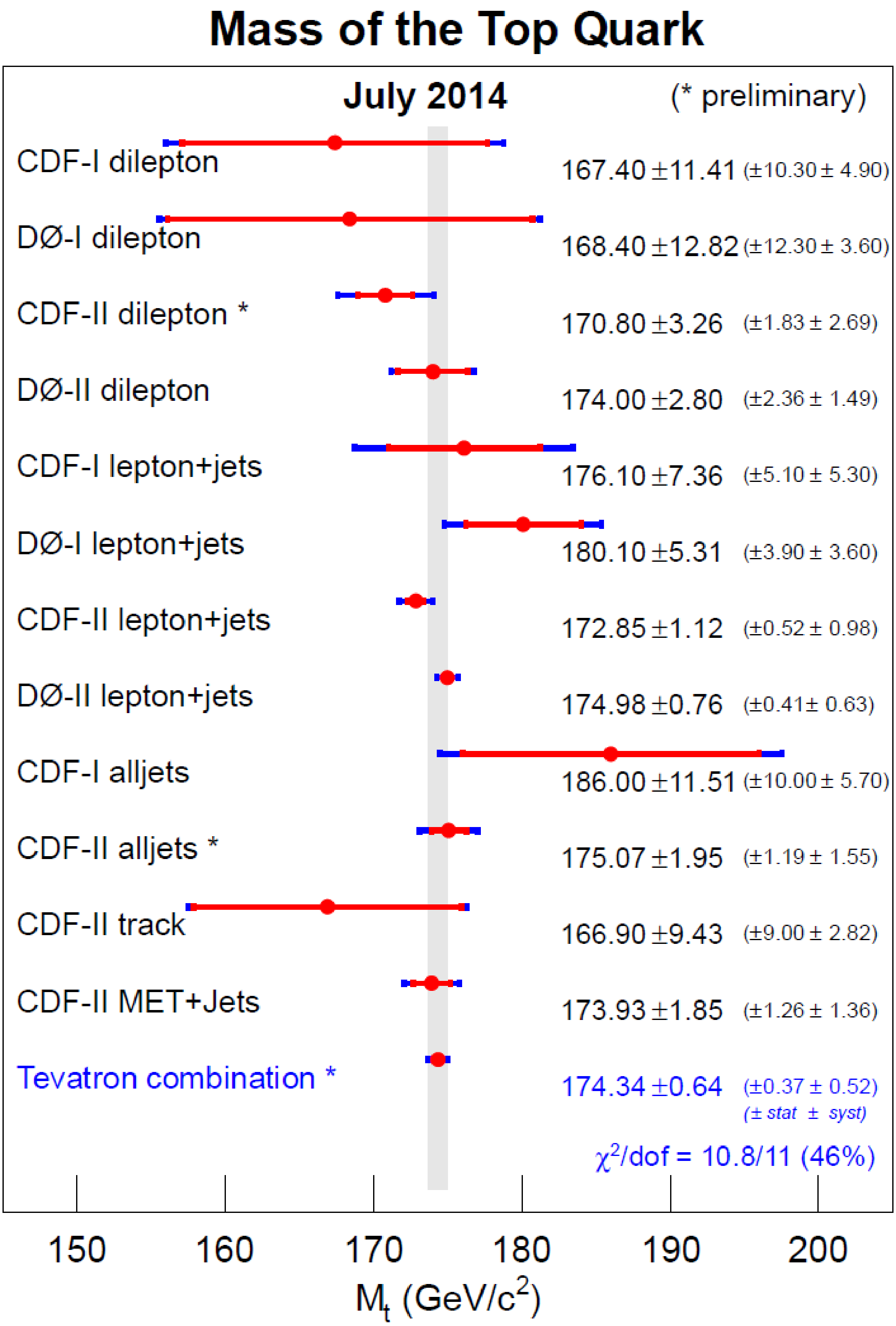

Figure 9. Summary of the CDF and D0 direct m_{top} measurements by the Tevatron Electroweak Working Group [33].

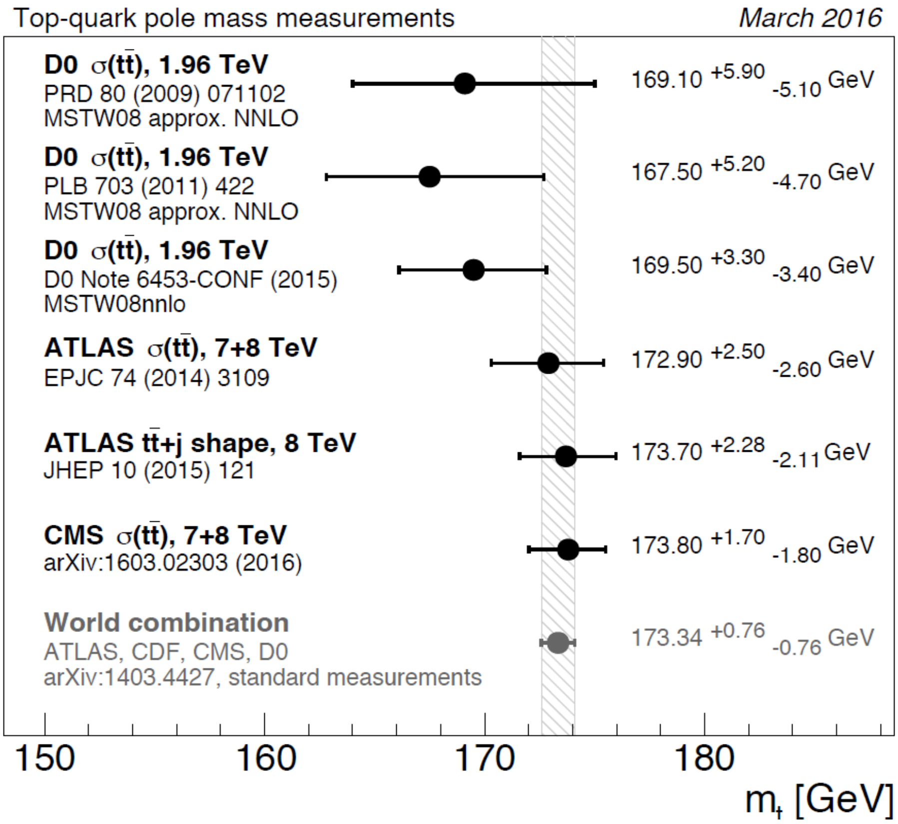

Figure 10. Summary of the ATLAS, CMS and D0 indirect m_{top} measurements. The results are compared with the direct Tevatron+LHC m_{top} combinations. Figure taken from the LHCtopWG [32]. The third D0 result for Note 6453-CONF has been superseded with [34] in which the value m_t^{pole} = 172.8 +3.2 -3.4 GeV, reducing tension with the LHC measurements.

8. Conclusions

Top-quark physics is a pillar of the current research program in HEP and provides stringent tests of perturbative QCD. Both the CMS and ATLAS collaborations cover a wide range of top-related topics, as previously D0 and CDF did. All measurements are an ideal probe for constraining (directly and indirectly) the symmetry breaking of the SM. Given its mass, the top has the largest Yukawa coupling to the SM Higgs boson. As such, top-quark-related precision measurements are an ideal playground to look for NP beyond the SM.

The most recent results from Tevatron and LHC related to top-quark properties in $t\bar{t}$ events have been presented in this document. Results are in agreement with SM predictions for SC and charge asymmetry, while no signs of CP violation and FCNC have been found so far.

Concerning the top-quark mass, a summary of both direct and indirect measurements has been presented, the former giving excellent precision below 0.5 GeV while for indirect measurements (pole mass) the precision achieved is below 2 GeV, compatible with that of direct measurements.

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