Top quark properties

Ziqing Hong

(On behalf of the ATLAS, CDF, CMS and D0 collaborations)

Mitchell Institute for Fundamental Physics and Astronomy, Texas A&M University,
College Station, Texas 77843, USA
zqhong@fnal.gov

The top quark physics has entered the precision era. The CDF and D0 collaborations are finalizing their legacy results of the properties of the top quark after the shutdown of the Fermilab Tevatron three years ago. The ATLAS and CMS collaborations have been publishing results from the LHC Run I with 7 TeV and 8 TeV proton-proton collisions, with many more forthcoming. We present a selection of recent results produced by the Tevatron and LHC experiments.

PRESENTED AT

XXXIV Physics in Collision Symposium
Bloomington, Indiana, September 16–20, 2014

1 Introduction

The top quark was first observed at the Fermilab Tevatron in 1995. Because the lifetime of the top quark is much shorter than the hadronization time, it provides a unique opportunity to study a "bare" quark. Due to its large mass, the top quark may play a special role in understanding electroweak supersymmetry breaking.

The top quarks can be produced via both strong interactions and electroweak interactions at the Tevatron and the LHC. The strong production of the top quarks is in the form of $t\bar{t}$ pair production, with the quark anti-quark annihilation process dominating at the Tevatron and the gluon-gluon fusion process dominating at the LHC. The electroweak production of the top quarks is in the form of single top production. The t-channel diagram dominates at both the Tevatron and the LHC, while the contributions from the s-channel at the LHC and the tW-channel at the Tevatron are expected to be small.

This report summarizes a selection of recent results of the top quark properties reported by the CDF [1] and D0 [2] collaborations at the Tevatron experiment and the ATLAS [3] and CMS [4] collaborations at the LHC experiment, including measurements of the top quark mass, the mass differences between the top quark and the top antiquark, the forward–backward asymmetry at the Tevatron and the charge asymmetry at the LHC, the top spin correlations, the extraction of $|\mathrm{V_{tb}}|$, and the top rare decays with flavor-changing neutral currents (FCNCs).

2 Top quark mass

The mass of the top quark is an important parameter of the standard model (SM). It is a critical input for electroweak physics, and strongly related to vacuum stability.

The first world combination of the top quark mass was published in March 2014 [5]. There are 17 measurements included in this combination, each of which are the most precise measurements in each channel in each experiment. All the included measurements are based on direct $t\bar{t}$ event reconstruction, and are all calibrated to the mass definition used in Monte-Carlo (MC) generators. The uncertainty on the translation from this MC mass definition to a theoretically well defined mass is estimated to be on the order of 1 GeV [6]. The combination yields a result of $m_{\mathrm{top}} = 173.34 \pm 0.76$ GeV, with a relative uncertainty of 0.44%, as shown in Fig. 1.

There are several updated measurements of the top quark mass after the first world combination, which are summarized in Fig. 2. The measurement in the lepton+jets channel from the D0 collaboration [7] features the most precise single measurement to date. The Tevatron combination [8] gives the smallest total uncertainty, with a result of $m_{\mathrm{top}} = 174.34 \pm 0.64$ GeV and relative uncertainty of 0.37%. The consistency among measurements is under study.
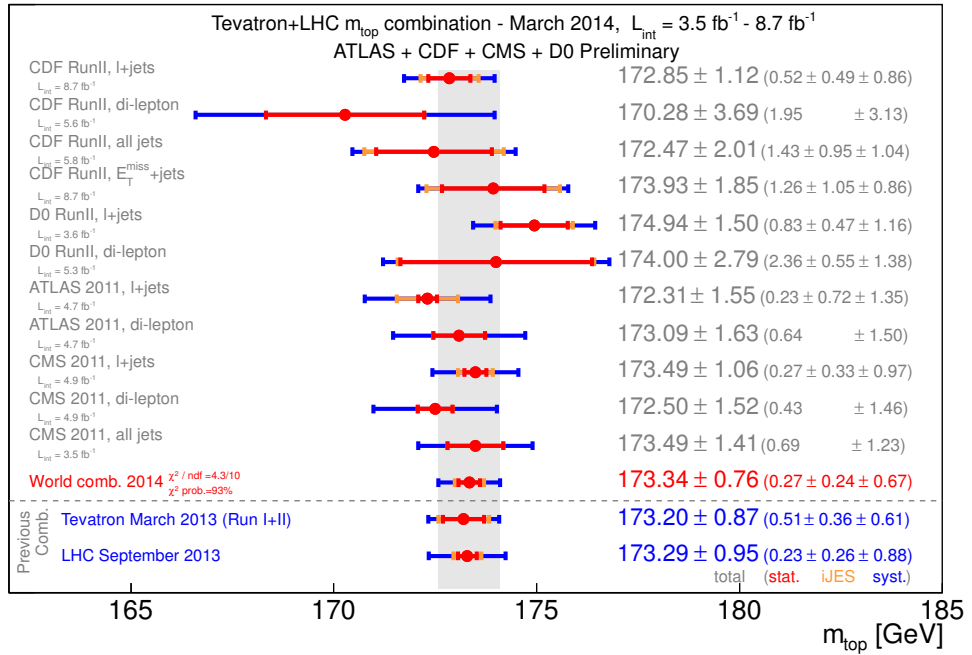
Figure 1: First world combination of the top quark mass measurements.

Alternative methods that do not involve direct $t\bar{t}$ event reconstruction have been developed at the Tevatron experiments and applied to measure the top quark mass by the LHC experiments with the results shown in Fig. 2. Since the lifetime of the B-hadrons is proportional to the top quark mass, the distance between the primary and the secondary vertices of a bottom jet has an approximately linear relation with the top quark mass [10], which allows for a measurement. Similarly, the m_{T2} variable, or the "stransverse mass" [9], can be defined in events with two undetected particles, and as this variable has the property of establishing a lower bound on the parent particle's mass, which is the top quark mass in this case, a measurement can be made with it [11]. The endpoint determinations in certain kinematic distributions are determined by the top quark mass, thus a measurement of the top quark can be based on these endpoints [12]. Finally, the top quark mass can be extracted from the results of the top quark pair production cross section ($\sigma_{t\bar{t}}$), where the mass extracted from these measurements is the pole mass, rather than the MC-defined top quark mass. Note that while the alternative methods have the advantage that the uncertainties are less correlated with the measurements based on full $t\bar{t}$ reconstruction, none are as precise as the direct measurements.
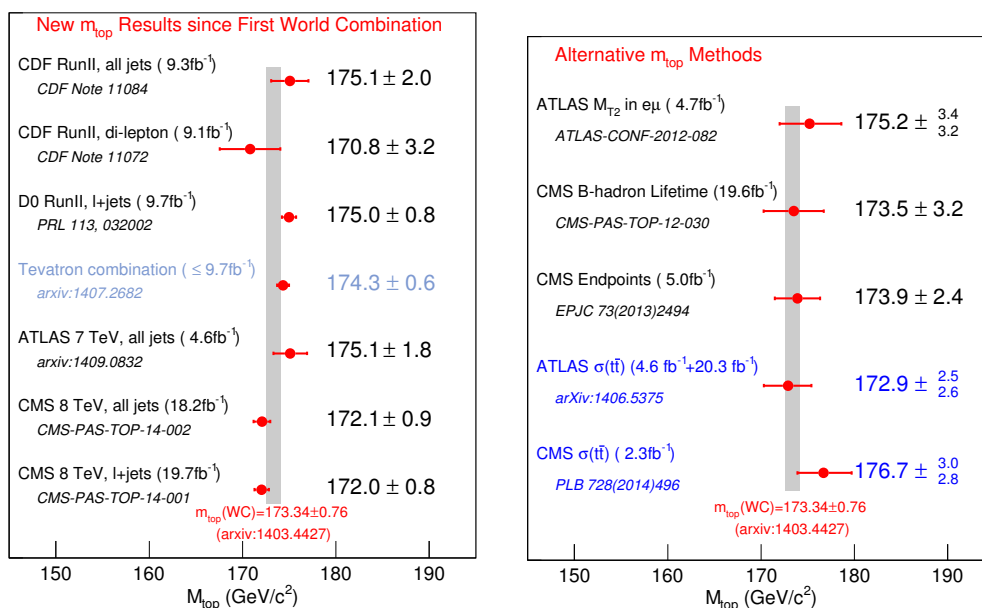
2

Figure 2: Updated top quark mass measurements after the first world combination (left) and top quark mass measurements with alternative methods from the LHC (right).

3 Mass difference between the top quark and the top antiquark

The mass difference between the top quark and the top antiquark ($\Delta m = m_t - m_{\bar{t}}$) is predicted to be consistent with zero in the scenario of CPT conservation. Table 1 summaries the recent Δm measurements from ATLAS, CDF, CMS and D0 collaborations. All results are consistent with zero.

Experiment	Δm (GeV)	Refs.
CMS@ 8 TeV	$0.27 \pm 0.20(\text{stat}) \pm 0.12(\text{syst})$	CMS-PAS-TOP-12-031
CMS@ 7 TeV	$0.44 \pm 0.46(\text{stat}) \pm 0.27(\text{syst})$	JHEP 06 (2012) 109
ATLAS@ 7 TeV	$0.67 \pm 0.61(\text{stat}) \pm 0.41(\text{syst})$	PLB 728, 363 (2014)
CDF RunII	$-1.95 \pm 1.11(\text{stat}) \pm 0.59(\text{syst})$	PRD 87 011101 (2013)
D0 RunII	$0.8 \pm 1.8(\text{stat}) \pm 0.5(\text{syst})$	PRD 84, 052005 (2011)

Table 1: Summary of the recent Δm measurements from ATLAS, CDF, CMS and D0. All results are consistent with zero.

4 Forward–backward asymmetry and charge asymmetry

The forward–backward asymmetry (A_{FB}) results at the Tevatron have shown potential anomalies for a number of years. Both the Tevatron and the LHC have been following up on them. The A_{FB} at the Tevatron and the charge asymmetry (A_C) at the LHC are both induced by the quark annihilation production mode. While there is no asymmetry arising from the leading order (LO) diagram, the next-to-leading order (NLO) QCD diagrams predicts that the top quark has a slightly larger probability of going in the direction of the quark in the initial state than the opposite direction. The Tevatron has a proton-antiproton initial state, where quarks dominantly come from the protons and antiquarks dominantly come from the antiprotons. As a result, the top quark rapidity distribution is expected to have a few percent shift towards the proton direction (forward) and the top antiquark rapidity distribution in the opposite direction, thus resulting in the A_{FB}.

Two more variables that are sensitive to the top quark A_{FB} at the Tevatron are the leptonic A_{FB} defined with the pseudorapidity (η) of the charged leptons from the cascade decays of the top quarks in scenarios where at least one W boson from the top quarks decays leptonically (A_{FB}^{ℓ}), and the A_{FB} of the difference between the pseudorapidities of the two charged leptons from the cascade decays of the top quarks in scenarios where both W bosons from the top quarks decay leptonically ($A_{\mathrm{FB}}^{\Delta\eta}$).

The results of $A_{\mathrm{FB}}^{t\bar{t}}$, A_{FB}^{ℓ} and $A_{\mathrm{FB}}^{\Delta\eta}$ from CDF and D0 collaborations [15–20] are summarized in Fig. 3, comparing with the NLO SM calculation in Ref. [14]. The results from the CDF collaboration show tension with the NLO SM prediction, with the results from D0 collaboration consistent with both the results from the CDF collaboration and the NLO SM calculations. Note that all results are higher than the NLO SM calculations quoted.

A preliminary calculation of QCD at the next-to-next-to-leading order (NNLO) with LO electroweak corrections suggests $A_{\mathrm{FB}}^{t\bar{t}} \sim 0.10$ [21]. If this holds up, it means that the tension between the results from the CDF experiment and the predictions is no longer significant, and suggests that the QCD calculation at NNLO is needed for predictions for the kinematic distributions of the top quarks.

Both the CDF and D0 collaborations reported the differential $A_{\mathrm{FB}}^{t\bar{t}}$ as a function of $m_{t\bar{t}}$ and $|\Delta y|$ as well as the differential A_{FB}^{ℓ} as a function of $|y_l|$, shown in Fig. 4. The D0 collaboration also reported the differential A_{FB}^{ℓ} as a function of $p_{T,\ell}$. The results from both collaborations show mostly good agreement with each other, with the regions with high $m_{t\bar{t}}$ and high $|\Delta y|$ under study.

The LHC experiment has followed up on this issue by measuring A_C. At the LHC, due to the proton-proton initial state, there is no predefined forward direction. Since there are both valance and sea quarks and only sea antiquarks in protons, the top
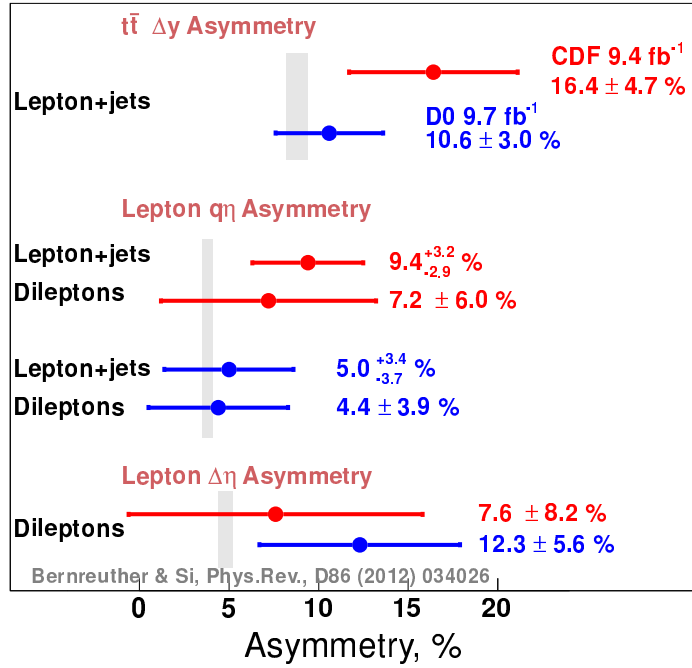
Figure 3: The results of A_{FB} from the CDF and D0 collaborations, comparing with the NLO SM calculations.
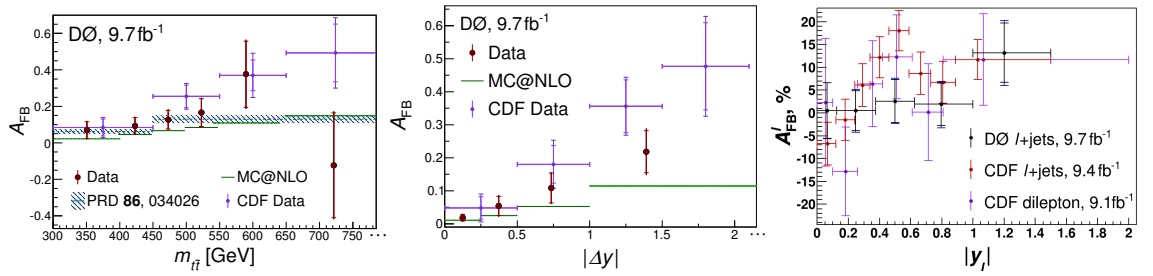

Figure 4: The result of $A_{\mathrm{FB}}^{t\bar{t}}$ as a function of $m_{t\bar{t}}$ and $|\Delta y|$ and A_{FB}^{ℓ} as a function of $|y_l|$.

5

Experiment	$A_C^{t\bar{t}}$	Refs.
CMS	$0.004 \pm 0.010(\text{stat}) \pm 0.011(\text{syst})$	PLB 717, 129 (2012)
ATLAS	$0.006 \pm 0.010(\text{stat}) \pm 0.005(\text{syst})$	JHEP 1402 (2014) 107
ATLAS+CMS	$0.005 \pm 0.007(\text{stat}) \pm 0.006(\text{syst})$	ATLAS-CONF-2014-012/CMS-PAS-TOP-14-006
Theory (NLO+EW)	0.0115 ± 0.0006	JHEP 1201 (2012) 063

Table 2: The results of the inclusive $A_C^{t\bar{t}}$ comparing with the SM prediction.

quark rapidity distribution is expected to be broader than the top antiquark rapidity distribution, causing an effect characterized as A_C. Since the gluon fusion production mode dominates at the LHC, the A_C is predicted to be even smaller. Measurements of both the inclusive [22] (Table 2) and differential [23–25] asymmetries are made at the LHC with both 7 TeV and 8 TeV data. All results show agreement with the standard model predictions. We note that A_{FB} at the Tevatron and A_C at the LHC can be related only in a model-dependent way.

5 Spin correlation

The spins of the top quark and the top antiquark in the top pair production are predicted to be correlated in the standard model, while it can be altered in new physics scenarios. Measurements have been done both at the Tevatron and at the LHC for the spin correlation of the top quark pairs. Three measurement methodologies can be applied in determining the spin correlation coefficients. One methodology is based on the azimuthal angles of the charged leptons from top quark decays [30]. The second methodology can be applied with the reconstruction of the top quark and antiquark momenta, with templates of the cosine of the lepton and bottom quark production angles in different spin correlation scenarios [27]. The third methodology is based on matrix element technique [28].

The recent results of the top spin correlation measurements [27, 28] from the Tevatron experiment are summarized in Table 3, together with the SM prediction [29]. Different methodologies were applied in measurements at the LHC [30, 31] and are summarized in Fig. 5. All results are consistent with the SM predictions.

Experiment	Spin correlation coefficient	Refs.
CDF	$0.042^{+0.563}_{-0.562}$	CDF Note 10719 (2011)
D0	0.85 ± 0.29	PRL 108, 032004 (2012)
NLO SM	$0.78^{+0.03}_{-0.04}$	NPB 690, 81 (2004)

Table 3: Summary of the recent top quark spin correlation results from the Tevatron experiments. All results are consistent with the SM predictions.
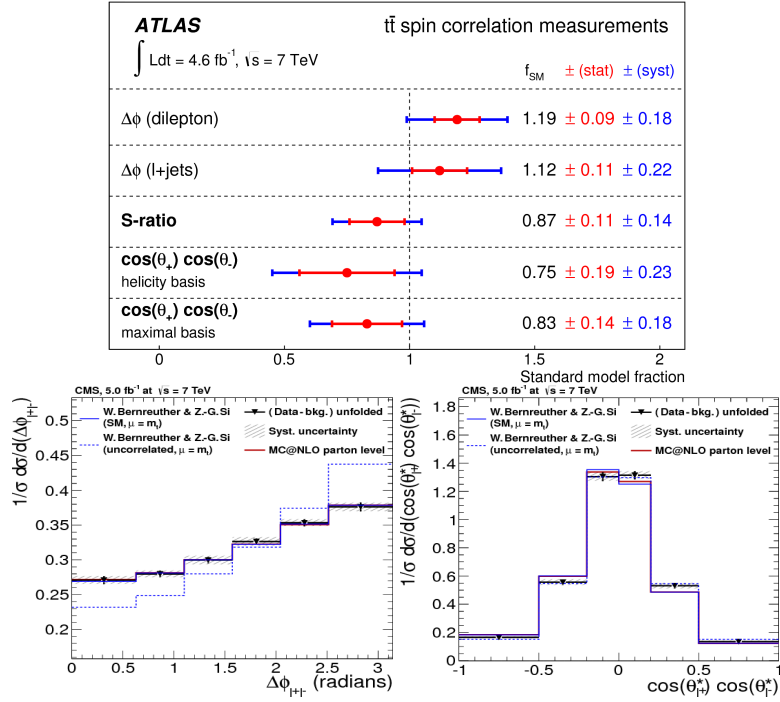
Figure 5: Results of the top spin correlation measurements at the LHC experiment. All results are consistent with the SM predictions.

6 $|V_{tb}|$ extractions

The element $|V_{tb}|$ of the Cabibbo-Kobayashi-Maskawa (CKM) matrix is an important parameter of the SM. The value of $|V_{tb}|$ can be extracted both from measurements of the single top production cross section, assuming $|V_{tb}| \gg |V_{td}|$ and $|V_{ts}|$, and from measurements of the branching ratio of $t \rightarrow Wb$, assuming in addition that the CKM matrix is a 3x3 unitary matrix. Table 4 [32–46] summarizes the results of $|V_{tb}|$ measurements from both the Tevatron and the LHC. All measurements lead to compatible results.

7   Search for flavor-changing neutral currents

Processes involving flavor-changing neutral currents (FCNC) are heavily suppressed in the SM and result in the small branching ratios of the top rare decay modes. Potential enhancements of FCNC processes are possible in the presence of physics beyond the standard model [53]. The limits on branching ratios of the top rare decay modes can

7

Experiment	Channel	$|V_{tb}|$	$|V_{tb}|$ lower limit @ 95% C.L.	Refs.
CDF	Single top (s+t) ℓ+jets	0.95 ± 0.10	0.78	arXiv:1407.4031
CDF	Single top $\not{E}_T$+jets	-	0.63	CDF Note 11033 (2014)
CDF	Single top (s+t) combo	-	0.84	CDF Note 11033 (2014)
D0	Single top (s+t)	$1.12^{+0.09}_{-0.08}$	0.92	PLB 726, 656 (2013)
CDF	$t\bar{t}$ ℓ+jets	0.97 ± 0.05	0.89	PRD 87, 111101 (2013)
CDF	$t\bar{t}$ $\ell\ell$	0.93 ± 0.04	0.85	PRL 112, 221801 (2014)
D0	$t\bar{t}$ ℓ+jets/$\ell\ell$	0.95 ± 0.02	0.96	PRL 107, 121802 (2011)
ATLAS	t-ch, 7 TeV	$1.13^{+0.14}_{-0.13}$	0.75	PLB 717, 330 (2012)
ATLAS	t-ch, 8 TeV	$0.97^{+0.09}_{-0.10}$	0.78	ATLAS-CONF-2014-007
ATLAS	tW-ch, 8 TeV	1.10 ± 0.12	0.72	ATLAS-CONF-2013-100
CMS	tW-ch, 7 TeV	$1.010^{+0.163}_{-0.136}$	-	PRL 110, 02203 (2013)
CMS	tW-ch, 8 TeV	1.030 ± 0.126	-	PRL 112, 231802 (2014)
CMS	t-ch, 7 TeV	1.029 ± 0.049	-	JHEP 12(2013)035
CMS	t-ch, 8 TeV	0.979 ± 0.048	-	JHEP 06(2014)090
CMS	t-ch, 7 & 8 TeV comb.	0.998 ± 0.041	-	JHEP 06(2014)090
CMS	$t\bar{t}$ R_b, 8 TeV	1.007 ± 0.016	-	PLB 736, 33 (2014)

Table 4: Results of $|V_{tb}|$ measurements at the Tevatron and the LHC.

be directly measured in $t\bar{t}$ channels as well as extracted from FCNC couplings at the production vertex involving single top production. Table 5 summarizes the recent limits on the branching ratios of top rare decays [47–52], comparing with the SM predictions and benchmark predictions from physics beyond the SM. The results are approaching the sensitivity to some plausible new physics models.

	7 TeV Single top CMS CMS-PAS -TOP-14-007	8 TeV Single top ATLAS ATLAS-CONF -2013-063	7+8 TeV $t\bar{t}$ CMS PRL 112 171802 (2014)	8 TeV Single top+γ CMS CMS-PAS -TOP-14-003	7+8 TeV $t\bar{t}$ ATLAS JHEP 06 (2014) 008	8 TeV $t\bar{t}$ CMS CMS-PAS -HIG-13-034	7 TeV Single top + Z CMS CMS-PAS TOP-12-021	SM hep-ph/0409342 (2004)	BSM (MSSM)
BR(t→gu)	$< 3.6 \cdot 10^{-4}$	$< 3.1 \cdot 10^{-5}$					$< 5.6 \cdot 10^{-3}$	$4 \cdot 10^{-14}$	$2 \cdot 10^{-6}$
BR(t→gc)	$< 3.4 \cdot 10^{-3}$	$< 1.6 \cdot 10^{-4}$					$< 7.1 \cdot 10^{-3}$	$5 \cdot 10^{-12}$	$8 \cdot 10^{-5}$
BR(t→Zq)			$< 5.0 \cdot 10^{-4}$				$< 5.1 \cdot 10^{-3}(Zu)/0.11(Zc)$	$1 \cdot 10^{-14}$	$2 \cdot 10^{-6}$
BR(t→uγ)				$< 1.6 \cdot 10^{-4}$				$4 \cdot 10^{-16}$	$2 \cdot 10^{-6}$
BR(t→cγ)				$< 1.8 \cdot 10^{-3}$				$5 \cdot 10^{-14}$	$2 \cdot 10^{-6}$
BR(t→ch)					$< 7.9 \cdot 10^{-3}$	$< 5.6 \cdot 10^{-3}$		$3 \cdot 10^{-15}$	$1 \cdot 10^{-5}$

Table 5: Summary of recent limits on the branching ratios of top rare decays, compared with the SM predictions and benchmark predictions from physics beyond the SM.

8 Conclusions

The large mass and the short lifetime of the top quark makes it a fascinating particle with properties need to be further understood. A lot of measurements of the top quark production and properties have been done at both the Tevatron and the LHC. Top physics has entered the precision era, with some analyses already reaching the point where more precise QCD calculations are essential. Both CDF and D0 are finalizing their legacy results on top physics. More results are expected from LHC Run I data, with LHC Run II right around the corner.

References

[1] D. Acosta *et al.* (CDF Collaboration), Phys. Rev. D 71, 032001 (2005).

[2] V. M. Abazov *et al.* (D0 Collaboration), Nucl. Instrum. Methods Phys. Res., Sect. A 565, 463 (2006).

[3] ATLAS Collaboration, JINST **3**, S08003 (2008).

[4] S. Chatrchyan *et al.* (CMS Collaboration), JINST **3**, S08004 (2008).

[5] Tevatron Electroweak and Top Physics LHC Working Groups (ATLAS and CDF and CMS and D0 Collaborations), arXiv:1403.4427.

[6] S. Moch *et al.*, arXiv:1405.4781.

[7] V. M. Abazov *et al.* (D0 Collaboration), Phys. Rev. Lett. **113**, 032002 (2014).

[8] Tevatron Electroweak Working Group (CDF and D0 Collaborations), arXiv:1407.2682.

[9] C. G. Lester and D. J. Summers, Phys. Lett. B **463**, 99 (1999).

[10] S. Chatrchyan *et al.* (CMS Collaboration), CMS-PAS-TOP-12-030.

[11] ATLAS Collaboration, ATLAS-CONF-2012-082.

[12] S. Chatrchyan *et al.* (CMS Collaboration), Eur. Phys. J. C **73**, 2494 (2013).

[13] J. A. Aguilar-Saavedra, D. Amidei, A. Juste and M. Perez-Victoria, arXiv:1406.1798.

[14] W. Bernreuther and Z. G. Si, Phys. Rev. D **86**, 034026 (2012).

[15] T. Aaltonen *et al.* (CDF Collaboration), Phys. Rev. D **87**, 092002 (2013).

[16] V. M. Abazov *et al.* (D0 Collaboration), arXiv:1405.0421.

[17] T. Aaltonen *et al.* (CDF Collaboration), Phys. Rev. D **88**, 072003 (2013).

[18] T. Aaltonen *et al.* (CDF Collaboration), Phys. Rev. Lett. **113**, 042001 (2014).

[19] V. M. Abazov *et al.* (D0 Collaboration), arXiv:1403.1294.

[20] V. M. Abazov *et al.* (D0 Collaboration), Phys. Rev. D **88**, 112002 (2013).

[21] A. Mitov, *Top quark pair cross section*, to appear in *Proceedings of the 8th International Workshop on the CKM Unitarity Triangle (CKM 2014), Vienna, Austria, September 8-12, 2014*

[22] Top Physics LHC Working Group (ATLAS and CMS Collaborations), ATLAS-CONF-2014-012, CMS-PAS-TOP-14-006.

[23] ATLAS Collaboration, JHEP 02(2014)107.

[24] S. Chatrchyan *et al.* (CMS Collaboration), CMS-PAS-TOP-12-033.

[25] S. Chatrchyan *et al.* (CMS Collaboration), JHEP 04(2014)191.

[26] ATLAS Collaboration, arXiv:1407.4314.

[27] T. Aaltonen *et al.* (CDF Collaboration), CDF Note 10719 (2011).

[28] V. M. Abazov *et al.* (D0 Collaboration), Phys. Rev. Lett. **108**, 032004 (2012).

[29] W. Bernreuther, A. Brandenburg, Z. G. Si and P. Uwer, Nucl. Phys. B **690**, 81 (2004).

[30] ATLAS Collaboration, arXiv:1407.4314.

[31] S. Chatrchyan *et al.* (CMS Collaboration), Phys. Rev. Lett. **112**, 182001 (2014).

[32] T. Aaltonen *et al.* (CDF Collaboration), arXiv:1407.4031.

[33] T. Aaltonen *et al.* (CDF Collaboration), CDF Note 11033 (2014).

[34] V. M. Abazov *et al.* (D0 Collaboration), Phys. Lett. B **726**, 656 (2013).

[35] T. Aaltonen *et al.* (CDF and D0 Collaborations), Phys. Rev. Lett. **112**, 231803 (2014).

[36] T. Aaltonen *et al.* (CDF Collaboration), Phys. Rev. D **87**, 111101 (2013).

[37] T. Aaltonen *et al.* (CDF Collaboration), Phys. Rev. Lett. **112**, 221801 (2014).

[38] V. M. Abazov *et al.* (D0 Collaboration), Phys. Rev. Lett. **107**, 121802 (2011).

[39] S. Chatrchyan *et al.* (CMS Collaboration), Phys. Rev. Lett. **110**, 022003 (2013).

[40] S. Chatrchyan *et al.* (CMS Collaboration), Phys. Rev. Lett. **112**, 231802 (2014).

[41] S. Chatrchyan *et al.* (CMS Collaboration), JHEP 12(2012)035.

[42] V. Khachatryan *et al.* (CMS Collaboration), JHEP 06(2014)090.

[43] V. Khachatryan *et al.* (CMS Collaboration), Phys. Lett. B **736**, 33 (2014).

[44] ATLAS Collaboration, Phys. Lett. B **717**, 330 (2012).

[45] ATLAS Collaboration, ATLAS-CONF-2014-007.

[46] ATLAS Collaboration, ATLAS-CONF-2013-100.

[47] S. Chatrchyan *et al.* (CMS Collaboration), CMS-PAS-TOP-14-007.

[48] ATLAS Collaboration, ATLAS-CONF-2013-063.

[49] S. Chatrchyan *et al.* (CMS Collaboration), Phys. Rev. Lett. **112**, 171802 (2014).

[50] S. Chatrchyan *et al.* (CMS Collaboration), CMS-PAS-TOP-14-003.

[51] ATLAS Collaboration, JHEP 06(2014)008.

[52] S. Chatrchyan *et al.* (CMS Collaboration), CMS-PAS-HIG-13-034.

[53] J. A. Aguilar-Saavedra, Acta Phys. Polon. B **35**, 2695 (2004).