PROCEEDINGS OF SCIENCE

Top properties measurements with the CMS detector at the LHC

Jui-Fa Tsai[∗†]
National Taiwan University
E-mail: jui-fa.tsai@cern.ch

Measurement of top quark properties in top pair production at the LHC are presented. Spin correlations and asymmetries are studied using the angular distributions of the top quark decay products and the results are used to set constrains on new physics. Measurements of the associate production of top quark pairs with vector bosons (W and Z) are also presented. The results are compared with standard model predictions. The CP violation, helicity of W boson and studies of flavor-changing neutral currents are included in this report.

38th International Conference on High Energy Physics
3-10 August 2016
Chicago, USA

[∗]Speaker.
[†]Behalf of the CMS Collaboration

PoS(ICHEP2016)661

1. Introduction

The standard model (SM) of particle physics has provided precise predictions for experimentally measurable quantities for decades. The top quark is the heaviest elementary particle known and the measurement of its properties represent a test of the SM consistency. Due to its large mass, the top quark has a very short lifetime, and decays before hadronizing, behaving much like a bare quark. Therefore, certain properties of the top quark, such as spin or polarization, directly pass to its decay products. The very high production rate of top-antitop quark pairs ($\mathrm{t\bar{t}}$) in pp collisions, dominated by gluon-gluon fusion processes, allows for sufficient statistics for measuring some of these properties at the LHC.

In this report, results obtained using data of pp collisions collected by CMS are presented. Several properties of top quarks have been studied and categorized in two types. The first is properties related to $\mathrm{t\bar{t}}$ production, such spin correlations, charge asymmetry, and associated production with vector bosons. The second is related to the couplings in $\mathrm{t\bar{t}}$ production or decay, such that CP violation, helicity of W bosons (W) and flavor-changing neutral currents (FCNC) in top decays. results are compared with the SM predictions as probes for possible new physics.

2. Spin correlations

In the SM, the spin of heavy quarks is correlated at production [1]. Measuring the spin correlation of the quark pairs is difficult, since those quarks become hadronic bound-states rapidly, i.e. the information of the spin correlations may be lost. However, the life time of top quark is much smaller than the hadronization and spin decorrelation time, i.e. $\tau_{\mathrm{t}} < \tau(\text{hadronization}) < \tau(\text{spin decorrelation})$. Hence the behavior of top quark is as a bare quark, and the information of spin correlation is propagated to the final-state particles. The measurements of spin correlation of $\mathrm{t\bar{t}}$ can be directly done by studying the charge leptons with or without reconstructing the top system.

Several measurements focus on an asymmetry parameter (A_{spin}) which represents the strength of spin correlation. Each A_{spin} is depending on the kinematics observables. In order to compare with the SM prediction, an additional method-independent parameter is required. The parameter is the fraction of spin correlation of the SM (f_{SM}) and IS defined as $A_{\text{spin}}^{\text{obs.}} = A_{\text{spin}}^{\text{SM}} \times f_{\text{SM}}$, where $A_{\text{spin}}^{\text{obs.}}$ is the measured asymmetry parameter from the experiments, and $A_{\text{spin}}^{\text{SM}}$ is the prediction value of the SM for a particular observable. The fraction can give the degree of spin correlation relative to the SM.

There are two recent studies depending on the final-state particles of $\mathrm{t\bar{t}}$ with 8 TeV data. The first study [2] focus on events containing the dileptonic decay of $\mathrm{t\bar{t}}$, i.e. both W bosons of $\mathrm{t\bar{t}}$ decaying to lepton and neutrino. Three observables are used for the calculation of A_{spin} which formed by the angles between two leptons : $\Delta\phi$ is defined with the difference of azimuthal angle of the leptons in the laboratory frame; ϕ is defined as the open angle between the direction of the leptons with respect to the mother top quark; and $\cos\theta^*_+ \cos\theta^*_-$ is defined with the product of the cosines of the helicity angles (θ), where $+$ and $-$ are the sign of charge of the leptons. The distribution of the observables are obtained from the events after background subtraction and unfolded to parton level, allowing the comparison between data and theory. The final results show that the observed f_{SM} for each observables is consistent with 1 within uncertainties, i.e. the measurements agree with the SM. The second study [3] uses events containing the $\mathrm{t\bar{t}}$ decay to an isolated muon and jets, i.e. one of W bosons decay in leptonic, and one is in hadronic. The leading order matrix element method is applied in this study which uses the distribution of two hypotheses to calculate the sample likelihood and event probability, where two hypotheses are with and without spin correlation of $\mathrm{t\bar{t}}$. The final results show the f_{SM} of data agrees with spin correlated hypothesis in two standard deviation.

3. Charge asymmetry

The charge asymmetry of $\mathrm{t\bar{t}}$ events, i.e. the difference between top quark and antiquark production, is an interesting research. At the LHC, the large average momentum fraction of the valence quarks leads to an excess of top quarks produced in the forward and backward directions. Hence the distribution of rapidity y of top quark is boarder than antitop. An observable is defined as the difference of rapidity ($\Delta|y|$) between top and antitop as $\Delta|y| = |y_{\mathrm{t}}| - |y_{\bar{\mathrm{t}}}|$. The strength of charge asymmetry (A_{C}) is obtained from the difference of events between positive and negative of $\Delta|y|$. In the SM, the prediction of the A_{C} is relatively small. But the beyond standard model (BSM) scenarios can enhance the asymmetry [4].

Recent studies have been done in lepton + jets and dilepton decays of $\mathrm{t\bar{t}}$ events by CMS at 8 TeV. The lepton + jets studies are done with an unfolding [5] and a template fit [6] method. The unfolding method corrects the measurements to parton level and extracts A_{C} after background subtraction. The template fit method uses two different probability functions of symmetry and anti-asymmetry to extract A_{C} from the data. Both methods show good agreement with the SM expectations.

Another study is done in dileptonic events using the unfolding method [7]. In addition to use $\Delta|y|$, an extra observable is included by using only information of the leptons, i.e. free from the $\mathrm{t\bar{t}}$ reconstruction. The extra observable is defined as the difference of pseudorapidity (η) between two leptons $\Delta|\eta| = |\eta^{+}| - |\eta^{-}|$. The final results of both observables are also in the good agreement with the SM.

3.1 Associated production with vector bosons

After the discovery of the Higgs boson, the study of its properties becomes important. In order to study the top-Higgs coupling at the LHC, some inreducible background processes need to be understood. Some of these background processes are $\mathrm{t\bar{t}}$ production associated with the vector bosons (Z and W). The cross section measurement of both, i.e. $\mathrm{t\bar{t}+Z}$ and $\mathrm{t\bar{t}+W}$, was currently studied using the data collected by CMS in 2016 at 13 TeV.

The studies [8] are split in three different analysis depending on the event selections: same-sign two leptons (SS2L), three leptons (3L), and four leptons (4L). The SS2L is the category enriched in $\mathrm{t\bar{t}+W}$ events. The 3L and 4L categories are for the measurement of $\mathrm{t\bar{t}+Z}$ events, requiring two leptons with same flavor and opposite charges (SFOC). In the analysis, some of the background are obtained from data. A boosted decision tree (BTD) to extract $\mathrm{t\bar{t}+W}$ is used in SS2L. Fig. 1 shows the final results which are in good agreement with the SM.

PoS(ICHEP2016)661

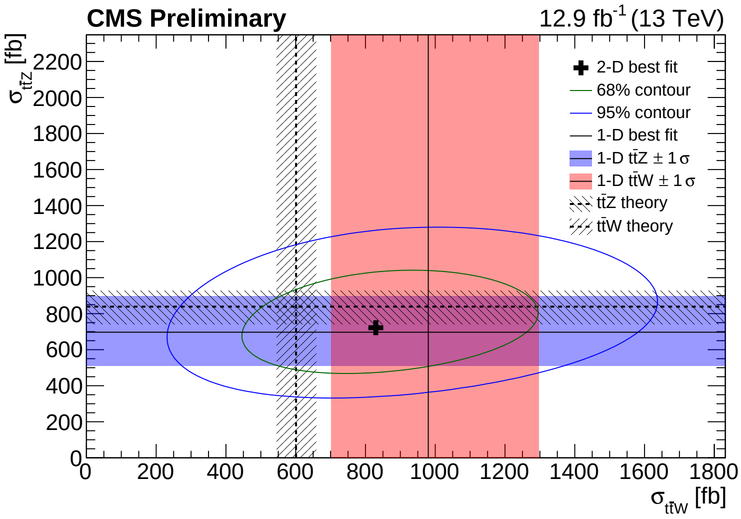

Figure 1: Measured and expected cross sections for $t\bar{t}+Z$ and $t\bar{t}+W$.

4. CP violation

The matter-antimatter asymmetry in the universe is an important open question in the particle physics. CP violation (CPV) can produce this asymmetry, and it can be experimentally investigated in strange and bottom quark sectors. But the results are too small to be compared with observation in the universe. In the SM, the CPV of $t\bar{t}$ is expected to be negligible. But if new physics are involved in the production and decay of $t\bar{t}$, CPV can be enhanced, such anomalous couplings. Thus, any asymmetric distribution found in the measurements may shed the light to explain the matter-antimatter asymmetry.

Certain BSM models, such as [9], add the anomalous coupling in the production and decay of $t\bar{t}$ to enhance CPV. This can affect kinematics of the final-state particles of $t\bar{t}$. The behavior can be observed from the distribution of T-odd, triple-produce observables, which is formed by the three momenta or spins of final-state particles of $t\bar{t}$. Given the CPT conservation, the CP-odd observable is assumed to be equivalent to T-odd. The distribution of observables is expected to be symmetric with the center value of 0, i.e. having same event yields of $t\bar{t}$ in positive- and negative-sign regions, while the asymmetric distribution happens if any new physics is involved. Thus, the measurement of CPV can be parametrized by an asymmetry parameter, so called A_{CP}. It is calculated by the difference rate between positive or negative sign of observable. The expected A_{CP} in the SM is zero for each observable, while the BSM can have nonzero A_{CP}. The current experimental study [10] with data collected by CMS is done in the lepton + jets decay of $t\bar{t}$ events at 8 TeV. The background is obtained from a control region in data and without asymmetric bias. The result of the measurement A_{CP} after background subtraction is zero, consistent with the SM.

5. W boson helicity fractions

The measurements of helicity fractions in W boson are related to the vertex structure in the decay of top quarks [11], i.e. $t(\bar{t}) \rightarrow bW(\bar{b}W)$. The three helicity components of the W boson: longitudied (F_0), right-handed (F_R) and left-handed (F_L) are interesting observables independent of the production rate. F_R is predicted to be zero in the SM, and the three fractions are constrained by $F_0 + F_R + F_L = 1$. However, new physics can alter these values, e.g. anomalous coupling in decay. The study [12] presented here focus on events containing a lepton and at least four jets, including two b-tagged jets, using the data collected by CMS at 8 TeV. The analysis uses a template fit to the angular distribution between down-style fermion and top boost in the W rest-frame, from where the fractions are extracted. The results are in good agreement with the SM as shown in Fig. 2.

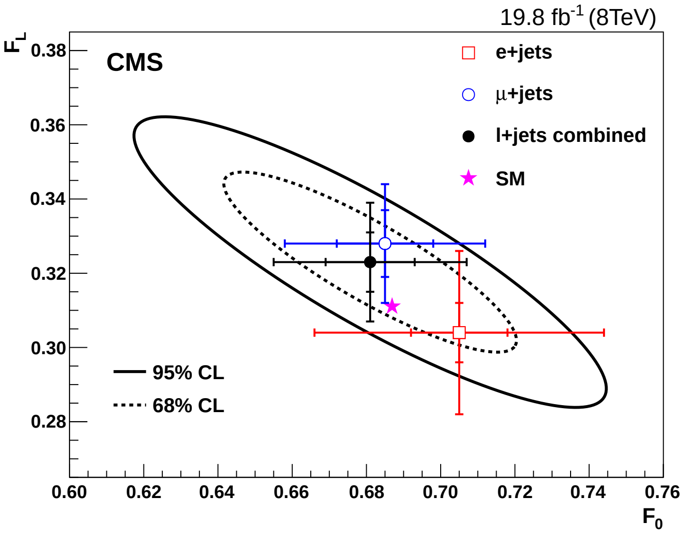

Figure 2: W boson helicity fraction measurements in $t\bar{t}$ events.

6. FCNC

Within the SM, FCNC decays of the top quark to a Z/H/γ and a light up-type quark (u or c), are suppressed by the GIM mechanism. The detection of FCNC top decays at a higher rate than the expected would therefore be clear evidence for physics beyond the SM. Several researches have been done in CMS as Refs. [13, 14]. The current observed and expected limits for the different FCNC studies of top quark in CMS are reported in Fig. 3 including measurements done in $t\bar{t}$ and single top events.

7. Conclusion

Several measurements of top quark properties are reported. All the results so far are consistent with the SM predictions.

References

[1] G. Mahlon and S. J. Parke, *Spin Correlation Effects in Top Quark Pair Production at the LHC*, Phys. Rev. D **81** (2010) 074024 doi:10.1103/PhysRevD.81.074024 [arXiv:1001.3422 [hep-ph]].

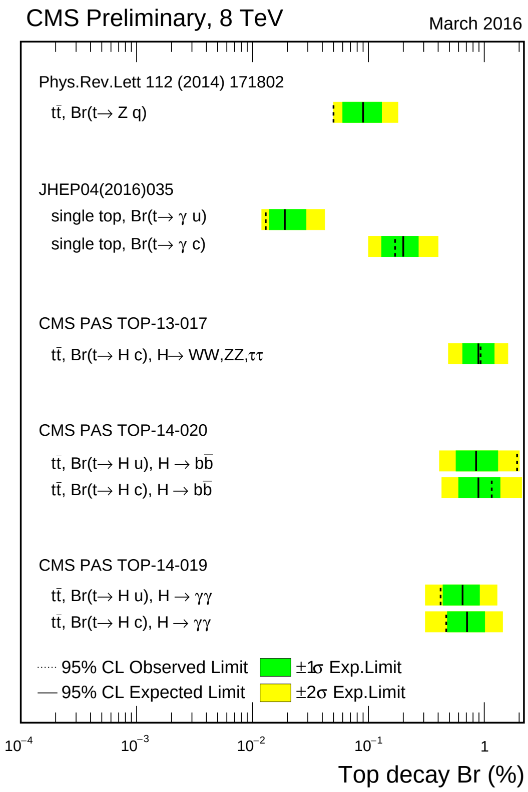

Figure 3: Summary of the limits of FCNC search in CMS with the branch ratio (Br) of rare top decay.

[2] V. Khachatryan *et al.* [CMS Collaboration], *Measurements of* $\mathrm{t\bar{t}}$ *spin correlations and top quark polarization using dilepton final states in* pp *collisions at* $\sqrt{s} = 8\,\mathrm{TeV}$, Phys. Rev. D **93** (2016) no.5, 052007 doi:10.1103/PhysRevD.93.052007 [arXiv:1601.01107 [hep-ex]].

[3] V. Khachatryan *et al.* [CMS Collaboration], *Measurement of spin correlations in* $\mathrm{t\bar{t}}$ *production using the matrix element method in the muon+jets final state in* pp *collisions at* $\sqrt{s} = 8\,\mathrm{TeV}$, Phys. Lett. B **758** (2016) 321 doi:10.1016/j.physletb.2016.05.005 [arXiv:1511.06170 [hep-ex]].

[4] J. H. Kuhn and G. Rodrigo, *Charge asymmetries of top quarks at hadron colliders revisited*, JHEP **1201** (2012) 063 doi:10.1007/JHEP01(2012)063 [arXiv:1109.6830 [hep-ph]].

[5] V. Khachatryan *et al.* [CMS Collaboration], *Inclusive and differential measurements of the* $\mathrm{t\bar{t}}$ *charge asymmetry in* pp *collisions at* $\sqrt{s} = 8\,\mathrm{TeV}$, Phys. Lett. B **757** (2016) 154 doi:10.1016/j.physletb.2016.03.060 [arXiv:1507.03119 [hep-ex]].

[6] V. Khachatryan *et al.* [CMS Collaboration], *Measurement of the charge asymmetry in top quark pair production in* pp *collisions at* $\sqrt{s} = 8\,\mathrm{TeV}$ *using a template method*, Phys. Rev. D **93** (2016) no.3, 034014 doi:10.1103/PhysRevD.93.034014 [arXiv:1508.03862 [hep-ex]].

[7] V. Khachatryan *et al.* [CMS Collaboration], *Measurements of* $\mathrm{t\bar{t}}$ *charge asymmetry using dilepton final states in pp collisions at* $\sqrt{s} = 8\,\mathrm{TeV}$, Phys. Lett. B **760** (2016) 365 doi:10.1016/j.physletb.2016.07.006 [arXiv:1603.06221 [hep-ex]].

[8] CMS Collaboration, *Measurement of the top pair-production in association with a* W *or* Z *boson in* pp *collisions at* 13 TeV, CMS-PAS-TOP-16-017 (2016)

[9] A. Hayreter and G. Valencia, *T-odd correlations from the top-quark chromoelectric dipole moment in lepton plus jets top-pair events*, Phys. Rev. D **93** (2016) no.1, 014020 doi:10.1103/PhysRevD.93.014020 [arXiv:1511.01464 [hep-ph]].

[10] CMS Collaboration, *Search for CP violation in top-pair events with lepton+jets channel at* $\sqrt{s} = 8$ TeV, CMS-PAS-TOP-16-001 (2016)

[11] A. Czarnecki, J. G. Korner and J. H. Piclum, *Helicity fractions of W bosons from top quark decays at NNLO in QCD*, Phys. Rev. D **81** (2010) 111503 doi:10.1103/PhysRevD.81.111503 [arXiv:1005.2625 [hep-ph]].

[12] V. Khachatryan *et al.* [CMS Collaboration], *Measurement of the* W *boson helicity fractions in the decays of top quark pairs to lepton + jets final states produced in* pp *collisions at* $\sqrt{s} = 8$ TeV, Phys. Lett. B **762** (2016) 512 doi:10.1016/j.physletb.2016.10.007 [arXiv:1605.09047 [hep-ex]].

[13] S. Chatrchyan *et al.* [CMS Collaboration], *Search for Flavor-Changing Neutral Currents in Top-Quark Decays* $\mathrm{t} \to \mathrm{Zq}$ *in* pp *Collisions at* $\sqrt{s} = 8$ TeV, Phys. Rev. Lett. **112** (2014) no.17, 171802 doi:10.1103/PhysRevLett.112.171802 [arXiv:1312.4194 [hep-ex]].

[14] V. Khachatryan *et al.* [CMS Collaboration], *Search for anomalous single top quark production in association with a photon in* pp *collisions at* $\sqrt{s} = 8$ TeV, JHEP **1604** (2016) 035 doi:10.1007/JHEP04(2016)035 [arXiv:1511.03951 [hep-ex]].