Results on top quark physics from CMS

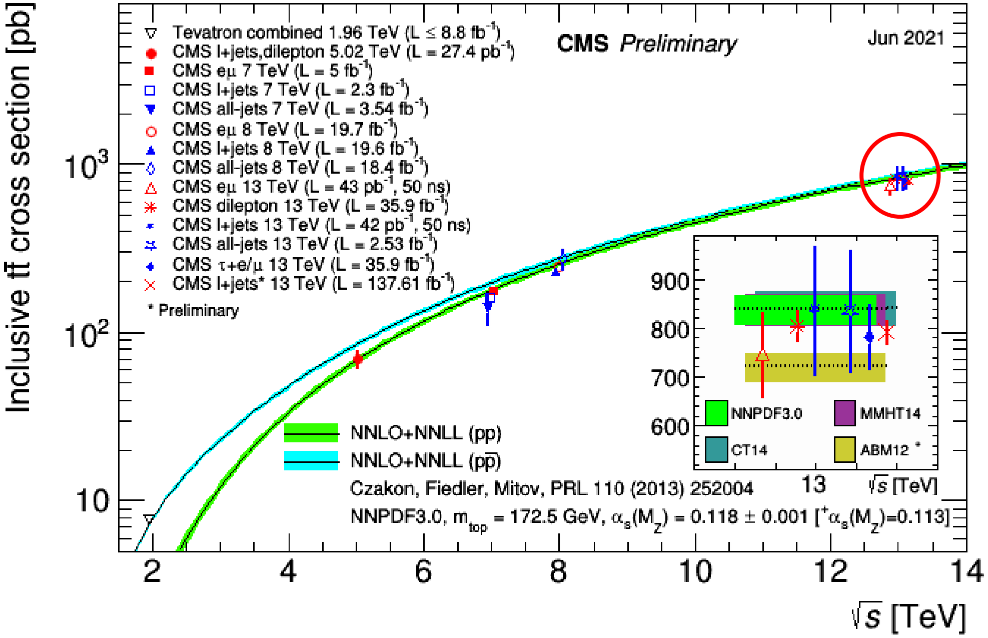
Mintu Kumar
On the behalf of CMS collaboration

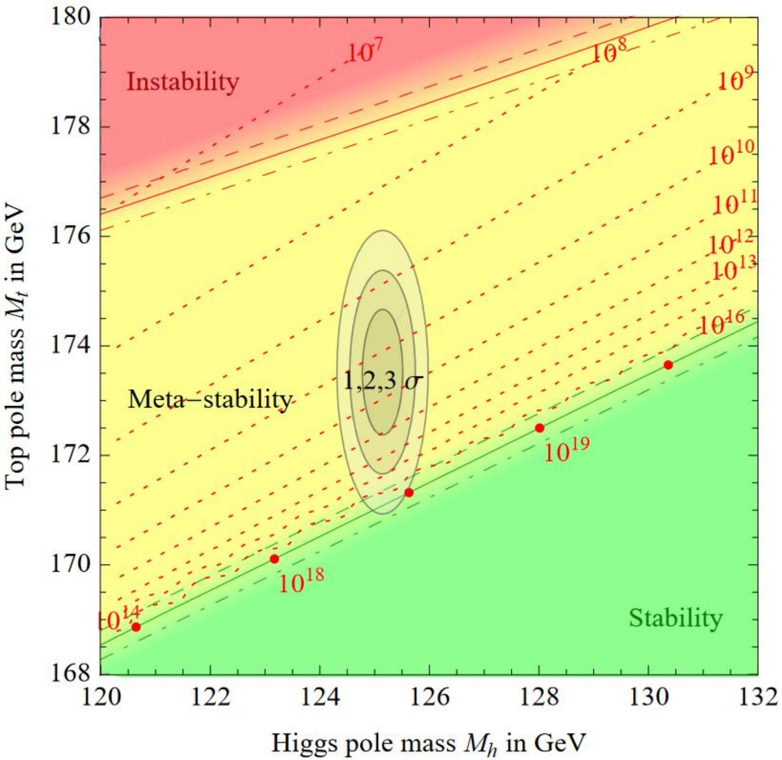
DISCRETE 2022

Kongresshaus Baden Baden, Germany
November 7-11, 2022

Motivation

- Top quark is the heaviest known elementary particle
- Crucial for electroweak vacuum stability ➛ maximum contribution in loop corrections to the masses of W, Z, and Higgs bosons

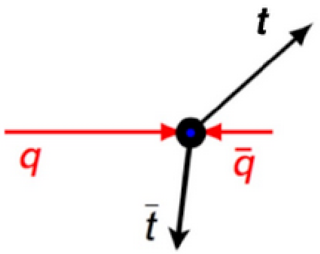




- LHC is a top quark factory ➛ production rates @ 13 TeV
  - Top pair ($t\bar{t}$) **~831 pb**
  - Single top:
    - *t*-channel **~217 pb**
    - tW-channel **~84 pb**

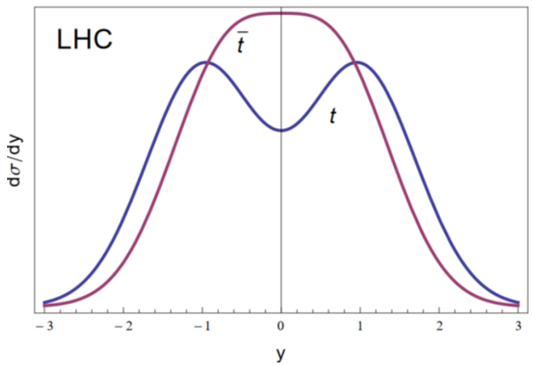
Symmetries and top quark

- Charge Asymmetry (A_C) and Forward-backward Asymmetry (A_{FB}) :
  - Qq $\rightarrow t\bar{t}$ expect a broader rapidity distribution for t than $\bar{t}$
  - At LO symmetry under charge conjugation
  - Charge Asymmetry arises at higher order [ref]



- CPT Invariance:
  - Particles & antiparticles have identical properties, e.g mass, lifetime
  - $\Delta m_t = m_t - m_{\bar{t}}$ measurement is a sensitive probe for CPT invariance

arXiv.1207.0331



- CP Violation (CPV):
  - CPV manifested due to an irreducible phase in the CKM matrix
  - CPV in SM is small to describe the matter-antimatter asymmetry [ref]
  - BSM interaction could be possible additional source of CPV which is manifested through finite chromo-electric dipole moment (CEDM)

- Charged Lepton Flavour Violation (CLFV):
  - CLFV is not allowed in the SM
  - Discovery of neutrino oscillations ➳ neutrinos have mass
  - CLFV is suppressed due to the smallness of neutrino masses
  - BSM effects ➳ CLFV in top quark decay

Charge asymmetry in $t\bar{t}$ with highly Lorentz-boosted top quarks

CMS-TOP-21-014

- Relative contribution of valence quarks increases at high momentum transfer ➳ more stringent probe of the QCD as well as sensitive to BSM physics

$$A_C = \frac{N(\Delta|y| > 0) - N(\Delta|y| < 0)}{N(\Delta|y| > 0) + N(\Delta|y| < 0)},$$

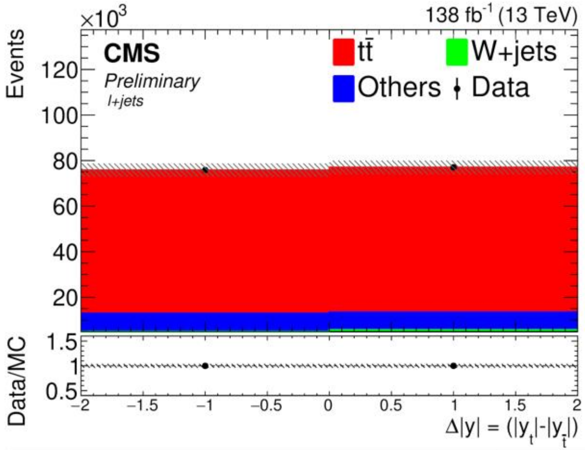
$\Delta|y| = |y_t| - |y_{\bar{t}}|$
y is the rapidity

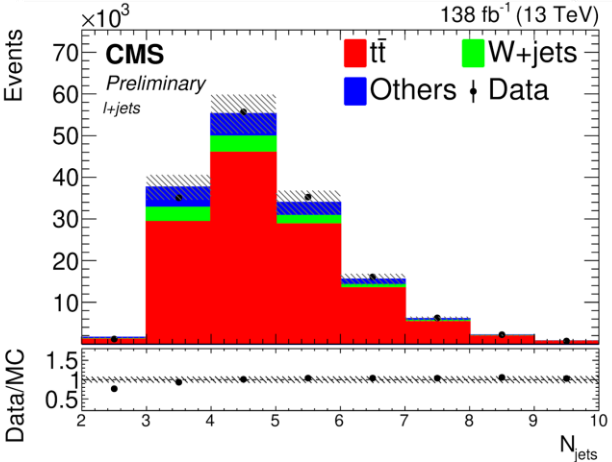
- **Lepton+jets:** 1 lepton, 2 AK4 jet, at least 1 b-tagged AK4 jet

- p_T^{miss}:
  - e ➳ $p_T^{miss} > 120\ GeV$
  - μ ➳ $p_T^{miss} > 50\ GeV$

- Three topological categories :
  1. Boosted ➳ one t-tag + no W tag
  2. Semiresolved ➳ W tag + no t-tag
  3. Resolved ➳ no t-tag + no W tag

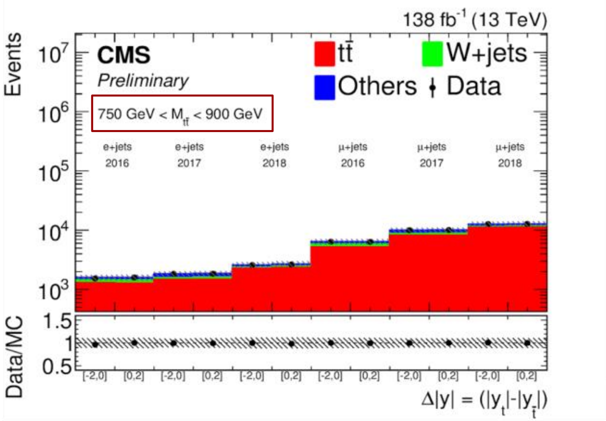
t and W tagging algo. applied to AK8 jet with p_T > 400 GeV

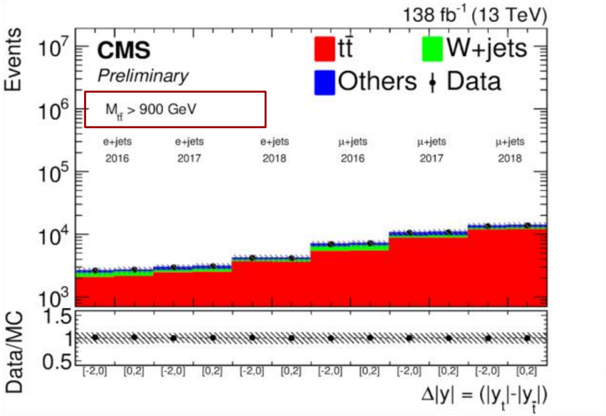




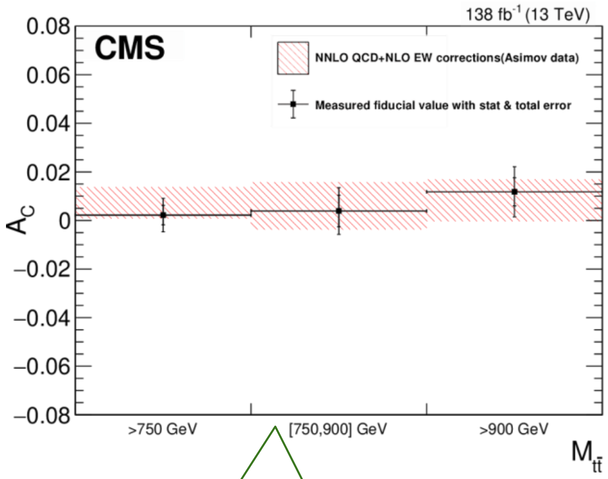
Charge asymmetry in $t\bar{t}$ with highly Lorentz-boosted top quarks

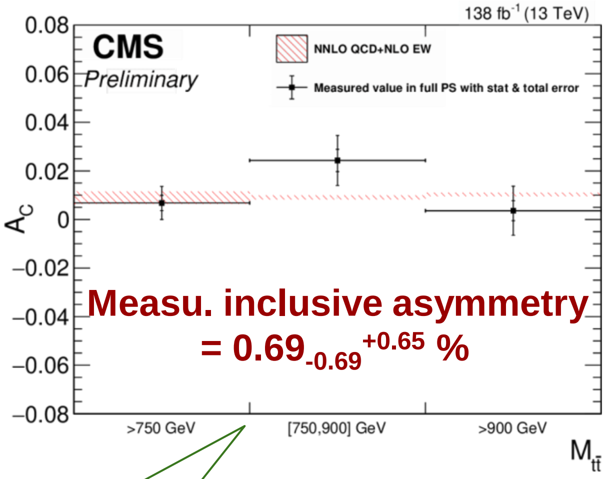
- Split into two invariant-mass categories, namely $750 < M_{tt} < 900$ GeV and $M_{tt} > 900$ GeV
- An ML fit performed ➳ bkg yield free parameter





Simultaneous fit 2×3×2 categories





Measu. inclusive asymmetry $= 0.69^{+0.65}_{-0.69}$ %

Fit has been done for Δ|y|>0 and Δ|y|<0 and then A_C fiducial is calculated

Fit has been done for Δ|y|<0 and A_C fiducial to ensure correct unct. estimation

A_c ~ 1% [ref] at LHC

Dominant systematic uncertainty: μ_F scale and PDF

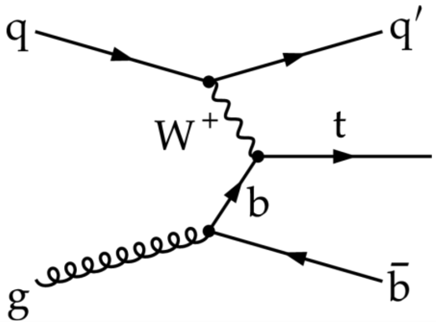
Mass ratio/diff. as a CPT probe in single top events

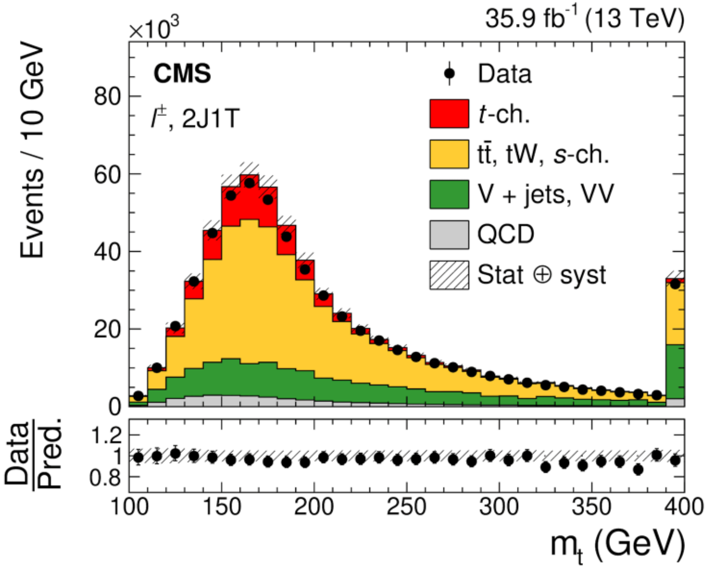
- t and $\bar{t}$ produced stat. independent events ➳ Mass of the top quark and antiquark measured separately
- The ratio and difference of t and $\bar{t}$ masses are measured in single top quark t-channel process
- 1 lepton + 2 jets (1 b-tagged jet)
- m_T (lepton, p_T^{miss}) > 50 GeV
- QCD bkg. is estimated by using the data-driven method
- Estimate $p_{z,\nu}$ using m_W constraint

$$m_{\mathrm{T}} = \sqrt{(p_{\mathrm{T},l} + p_{\mathrm{T}}^{\mathrm{miss}})^2 - (p_{x,l} + p_x^{\mathrm{miss}})^2 - (p_{y,l} + p_y^{\mathrm{miss}})^2}$$

- Top mass is reconstructed by adding the four momenta of final-state lepton, neutrino and the b-tagged jet

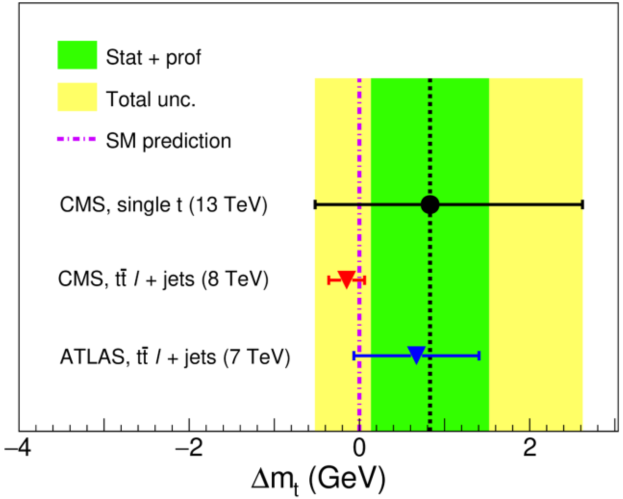
JHEP 12 (2021) 161

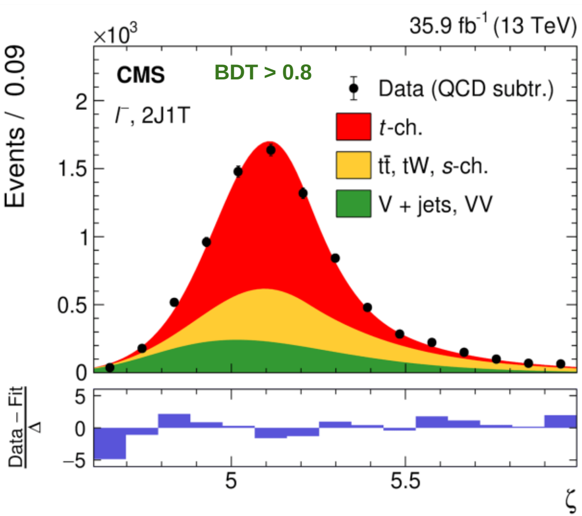


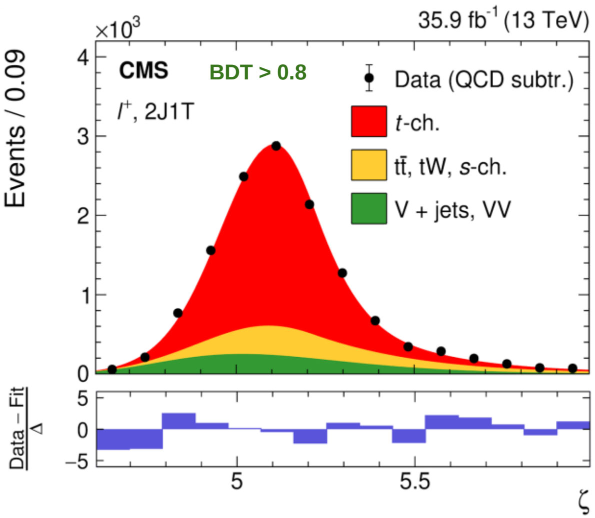


Mass ratio/diff. as a CPT probe in single top events

- 2 BDTs (e/μ) are used to extract signal
- ζ = ln(m_t/1 GeV) ➳ get symmetric distribution
- A simultaneous ML fit to ζ distributions in data in both lepton flavours





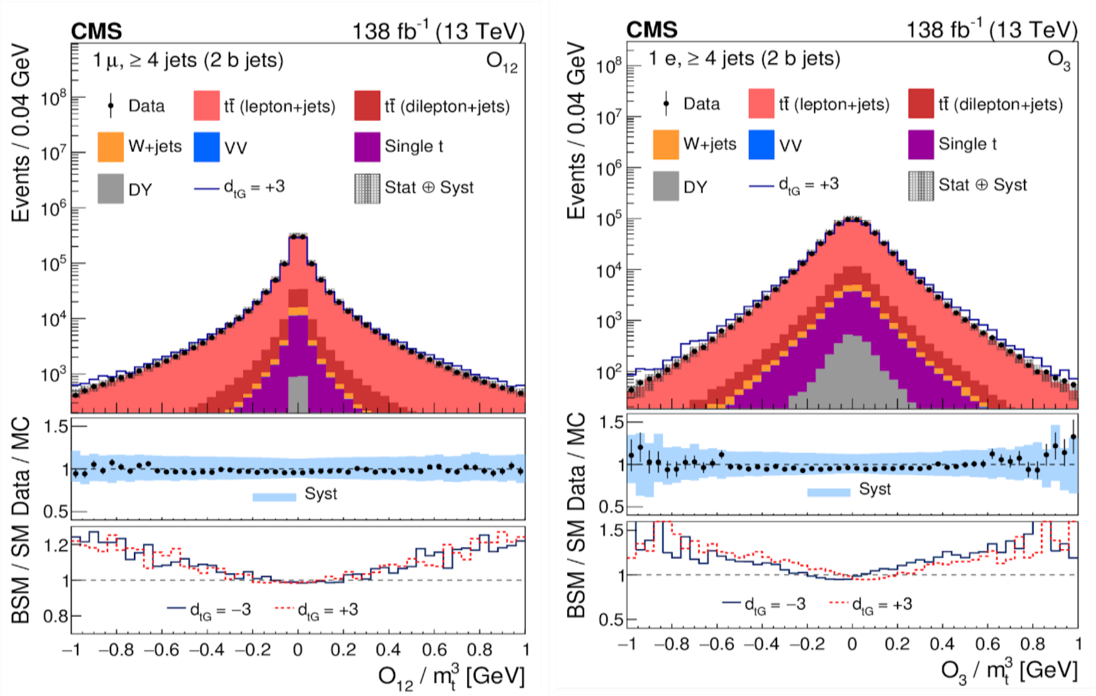


para	value	stat.	syst.	source
m_t	172.13	0.32	0.69	JES
Δm_t	0.83	0.69	1.65	JES
R_{mt}	0.9952	0.0040	0.0096	JES (Flavour)

Search for CP violation using $t\bar{t}$ events (lepton+jet)

- BSM interaction modifies *tg* coupling in the Lagrangian ➻ CEDM (d_{tG}) [ref] ➻ possible source of CPV
- 4 operators are observed

CMS-TOP-20-005



$$O_3 = Q_\ell \epsilon(p_b, p_{\bar{b}}, p_\ell, p_{j_1}) \propto Q_\ell \vec{p}^{\,*}_b \cdot (\vec{p}^{\,*}_\ell \times \vec{p}^{\,*}_{j_1}),$$
$$O_6 = Q_\ell \epsilon(P, p_b - p_{\bar{b}}, p_\ell, p_{j_1}) \propto Q_\ell (\vec{p}_b - \vec{p}_{\bar{b}}) \cdot (\vec{p}_\ell \times \vec{p}_{j_1}),$$
$$O_{12} = q \cdot (p_b - p_{\bar{b}}) \epsilon(P, q, p_b, p_{\bar{b}}) \propto (\vec{p}_b - \vec{p}_{\bar{b}})_z \cdot (\vec{p}_b \times \vec{p}_{\bar{b}})_z,$$
$$O_{14} = \epsilon(P, p_b + p_{\bar{b}}, p_\ell, p_{j_1}) \propto (\vec{p}_b + \vec{p}_{\bar{b}}) \cdot (\vec{p}_\ell \times \vec{p}_{j_1}).$$

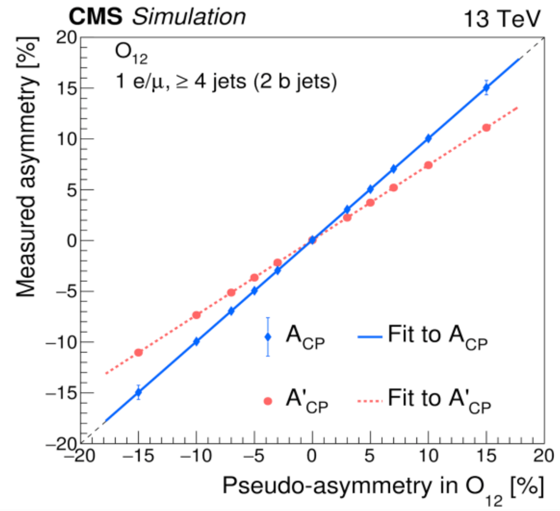
- **Lepton+jets:** 1 lepton, at least 4 jets (2 b-tagged jets)
- The combination of the jets selected which minimize the χ^2 :
- $\chi^2 < 20$ and $m_{lb} > 150$ GeV

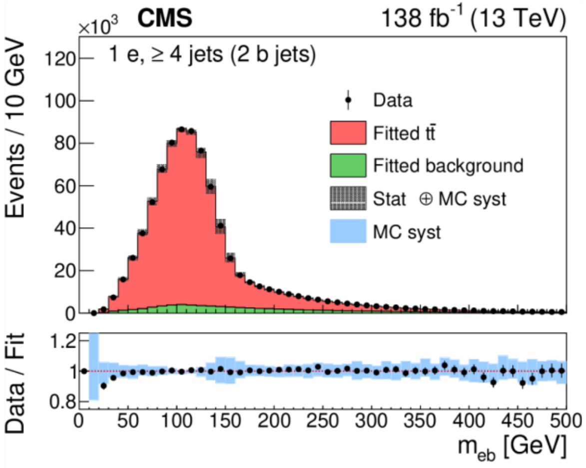
$$\chi^2 = \left(\frac{m_{jjb} - m_t}{\sigma_t}\right)^2 + \left(\frac{m_{jj} - m_W}{\sigma_W}\right)^2$$

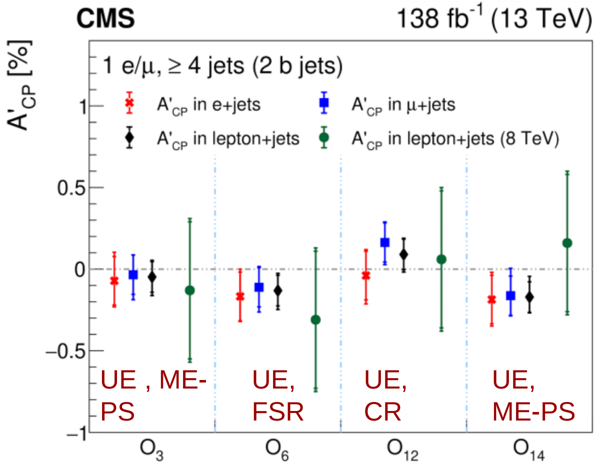
Search for CP violation using $t\bar{t}$ events (lepton+jet)

$$A_{\rm CP}(O_i) = \frac{N_{\rm events}(O_i > 0) - N_{\rm events}(O_i < 0)}{N_{\rm events}(O_i > 0) + N_{\rm events}(O_i < 0)}, \quad i = 3,\, 6,\, 12,\, 14.$$

- CEDM contribution can be as large as 8 and 0.4% for $A_{CP}(o_3)$ & $A_{CP}(o_{12})$ [ref]
- Data-driven bkg estimation has been done
- ML fit to data using the m_{lb} distribution
- A'_{CP} is calibrated using the A_{CP} value at the generator level







★ d_{tG} is determined from A_{CP}.

$$A_{\rm CP} = \frac{d_{tG} + a}{b d_{tG}^2 + c d_{tG} + d}$$

★ **d_{tG} = 0.04 ± 0.10 (stat) ± 0.07 (syst)**

Search for CP violation using $t\bar{t}$ events (leptonic)

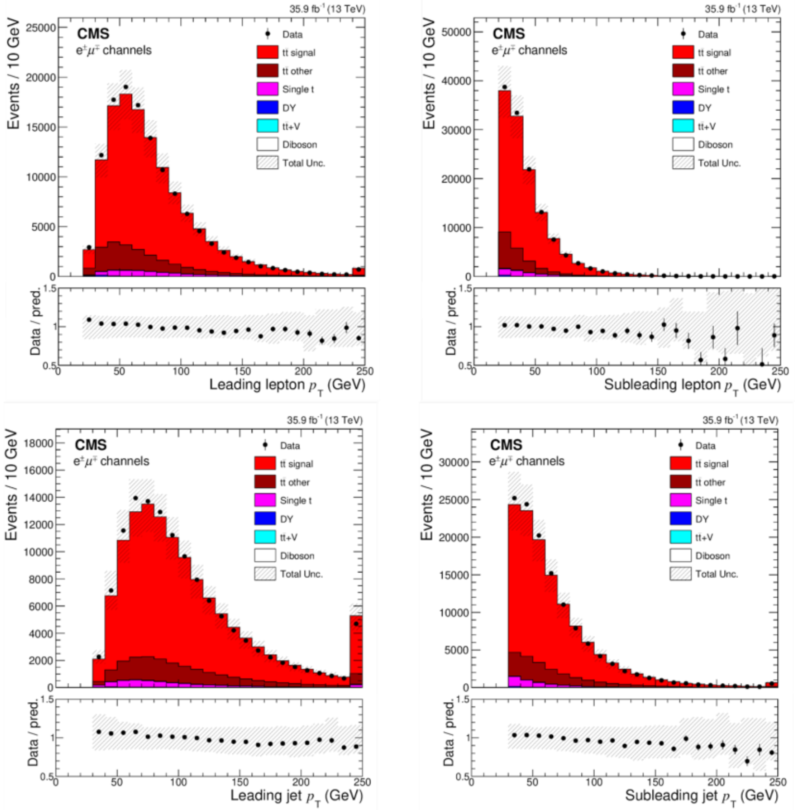
- Two CP-odd observables are explored, namely O_1 and O_3, which are scalar under the Lorentz transformation

$$\mathcal{O}_1 = \epsilon(p_{\mathrm{t}}, p_{\bar{\mathrm{t}}}, p_{\ell+}, p_{\ell-}) = \begin{vmatrix} E_{\mathrm{t}} & p_{\mathrm{t},x} & p_{\mathrm{t},y} & p_{\mathrm{t},z} \\ E_{\bar{\mathrm{t}}} & p_{\bar{\mathrm{t}},x} & p_{\bar{\mathrm{t}},y} & p_{\bar{\mathrm{t}},z} \\ E_{\ell+} & p_{\ell+,x} & p_{\ell+,y} & p_{\ell+,z} \\ E_{\ell-} & p_{\ell-,x} & p_{\ell-,y} & p_{\ell-,z} \end{vmatrix}$$

$$\mathcal{O}_3 = \epsilon(p_{\mathrm{b}}, p_{\bar{\mathrm{b}}}, p_{\ell+}, p_{\ell-}) = \begin{vmatrix} E_{\mathrm{b}} & p_{\mathrm{b},x} & p_{\mathrm{b},y} & p_{\mathrm{b},z} \\ E_{\bar{\mathrm{b}}} & p_{\bar{\mathrm{b}},x} & p_{\bar{\mathrm{b}},y} & p_{\bar{\mathrm{b}},z} \\ E_{\ell+} & p_{\ell+,x} & p_{\ell+,y} & p_{\ell+,z} \\ E_{\ell-} & p_{\ell-,x} & p_{\ell-,y} & p_{\ell-,z} \end{vmatrix}$$

- 2 leptons with opposite charge, at least 2 jets (1 b-tagged jet)
- Three di-leptonic channels (e^+e^-, $\mu^+\mu^-$, $e^\pm\mu^\mp$)
- $m_{\ell\ell} > 20\ GeV$
- exclude Z mass window for same flavour leptons (76 to106 GeV)

CMS-TOP-18-007



Search for CP violation using $t\bar{t}$ events (leptonic)

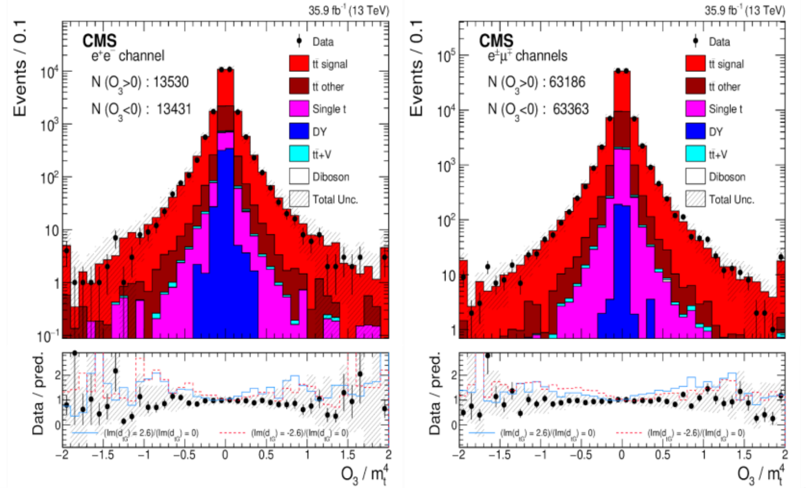
- ML fit to data using O_1 and O_3 ➳ extract the $t\bar{t}$ x-sec.
- O_1 and O_3 are stat. correlated (~46%) ➳ measured A_{CP} combined using the best linear unbiased estimator method

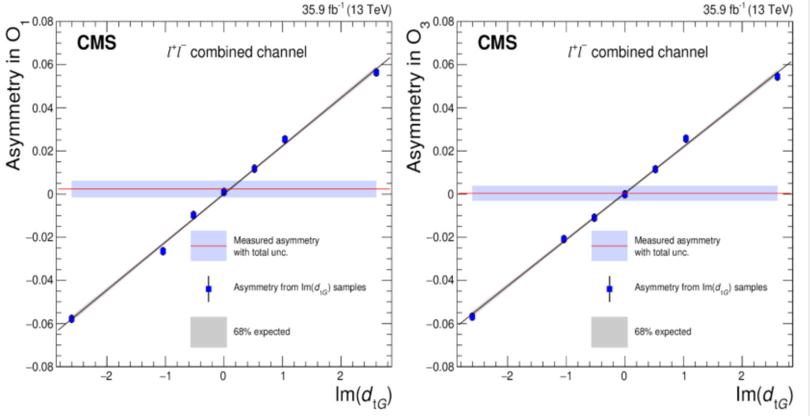
Observable	Asymmetry and uncertainty ($\times 10^{-3}$) e^+e^-	$e^\pm\mu^\mp$	$\mu^+\mu^-$	Combined
$A_{\mathcal{O}_1}$	8.8 ± 7.5	0.6 ± 3.4	6.9 ± 5.3	2.4 ± 2.8
$A_{\mathcal{O}_3}$	4.1 ± 7.5	-1.7 ± 3.4	6.1 ± 5.3	0.4 ± 2.8

- CEDM par. img(d_{tG}) is parametrize with the Asymmetry

$$A = a\,\mathrm{Im}(d_{tG}) + b$$

oper.	d_{tG}	stat.	syst.	Source (Domi.)
O_1	0.10	0.12	0.12	CR, UE
O_3	0.00	0.12	0.10	CR, UE





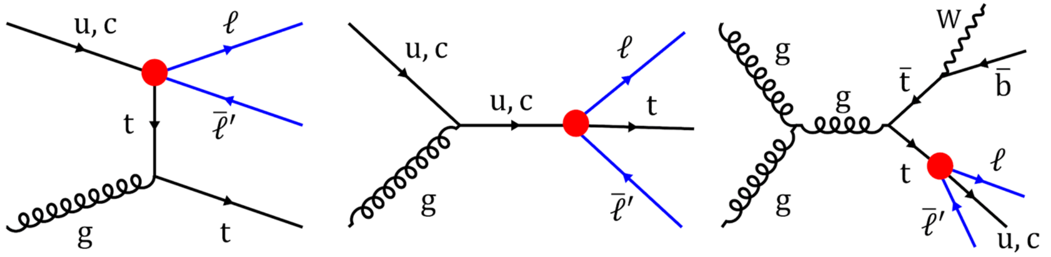
Charged lepton flavour violation in top quark production

- Effective Lagrangian consisting Wilson coefficient of dim-6 ➸ CLFV interaction of the top quark

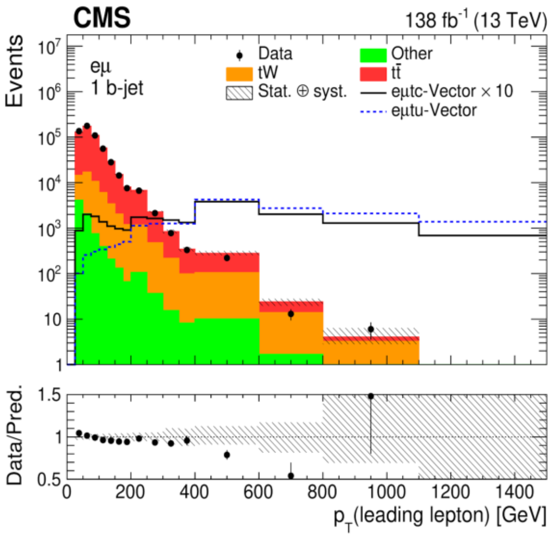
JHEP 06 (2022) 082

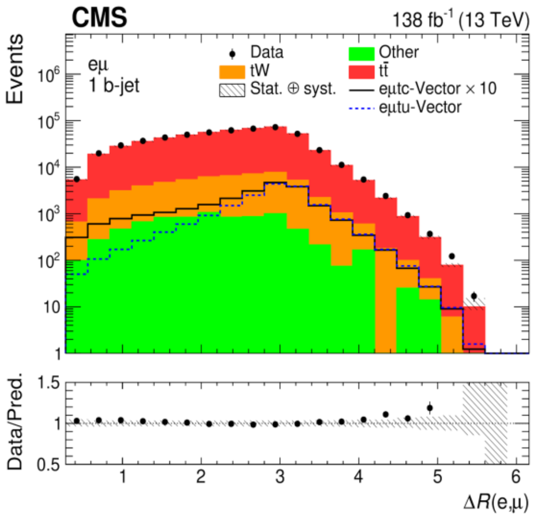
$$\mathcal{L} = \mathcal{L}_{SM} + \mathcal{L}_{eff} = \mathcal{L}_{SM} + \sum_x \frac{C_x}{\Lambda^2} O_x + \cdots$$

Λ = 1 TeV; $C_x^{e\mu tq}$ = 1 for Simulation



Analysis combines the search for "eμtu" and "eμtc" (generated separately) CLFV interaction in top quark production





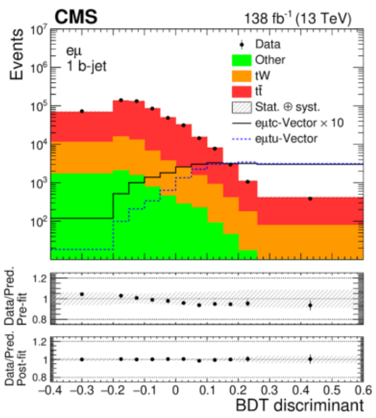
- Oppositely charged eμ lepton pair, at least 1 AK4 b-tagged jets

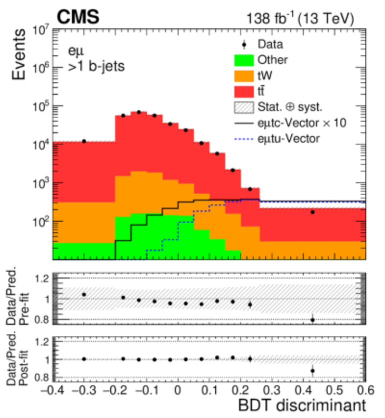
- Leading lepton p_T > 20 GeV, m(eμ) > 20 GeV

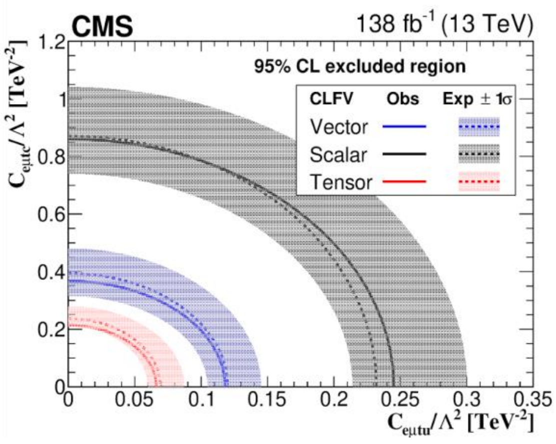
Charged lepton flavour violation in top quark production

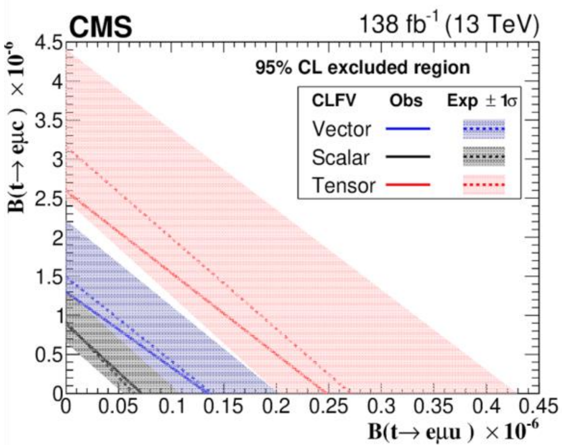
- ML fit has been performed to the BDT discriminants in data simultaneously in signal and control regions ➳ extract signal cross-section

- Upper limit on the WC ➳ 95% (CL_s) ➳ limit on the top quark CLFV BRs.







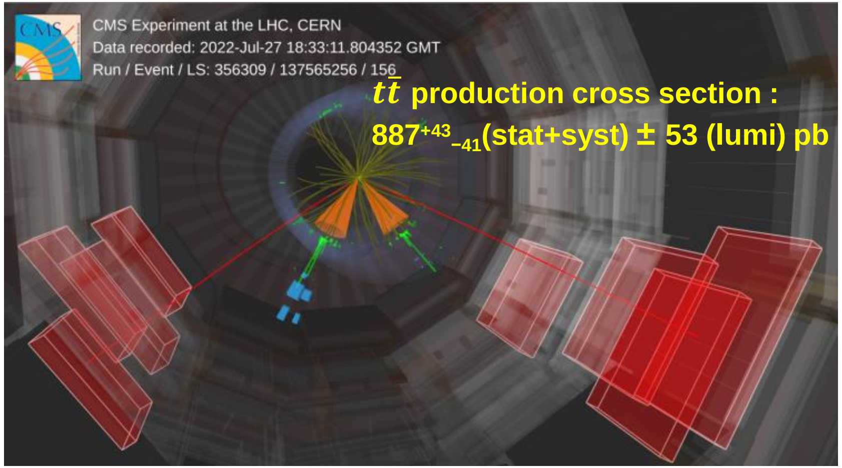


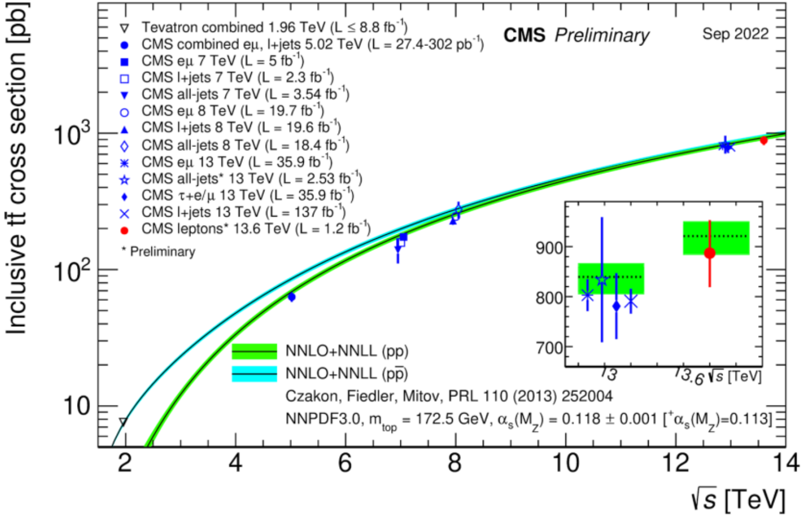
★ No significant excess is observed over the SM expectation

B(t->eμq) < 0.13 (1.31), 0.07(0.89), 0.25(2.59) O(10^{-6}) , q=u(c)

Summary

- Latest results from CMS on tests of various asymmetries related to the top quark sector are summarised
- No significant excess is observed over the SM expectation
- More results are still to come from legacy Run-2 of LHC data in the near future
- The top qualk factory is back on production for LHC Run 3 of data taking
- From cms Run3 results already shown up:





BackUp

Charge asymmetry in $t\bar{t}$ with highly Lorentz-boosted top quarks

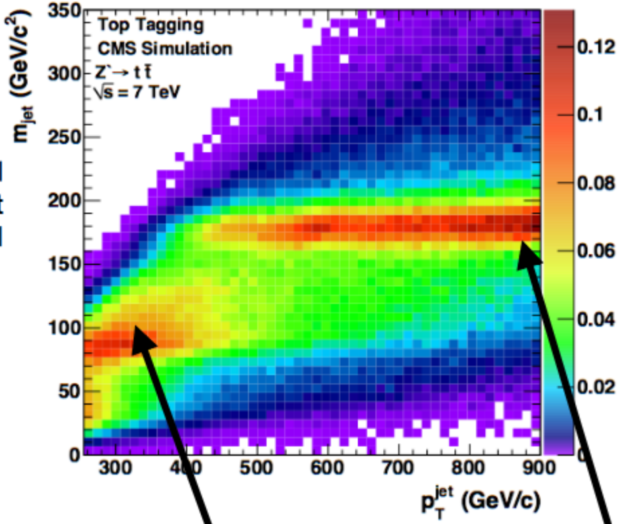
AK8 Top/W tagging

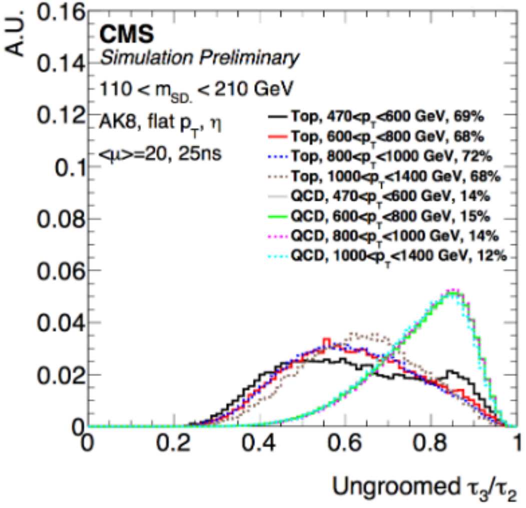
- Jets from a hadronic boosted top quark (W boson), will have three (two) groups of clusters where the jet energy is concentrated. These structures correspond to the quarks from the decay.
- Sub-structure techniques are applied to large footprint jets to identify top quarks:
  - Jet mass near to the top (W) mass
  - Compatibility of a large radius jet having 3 (2 subjets)

Currently using these working points

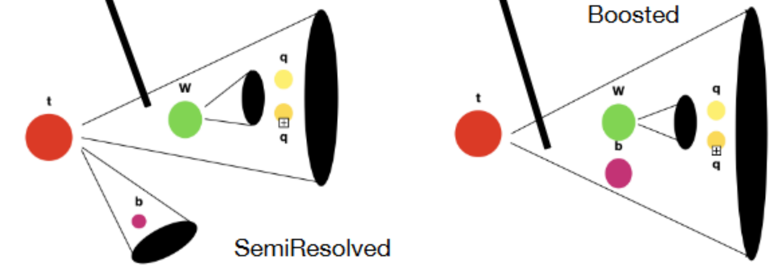
	mSD	$\tau_{32} = \tau_3/\tau_2$
Toptagging	105 < m_jet < 220	< 0.65
	mSD	$\tau_{21} = \tau_2/\tau_1$
W tagging	65 < m_jet < 105	< 0.45

mSD cut keeps Top tagging and W tagging exclusive





CMS-TOP-21-014



Veto on events with more than one Top/W tagged jet

Charge asymmetry in $t\bar{t}$ with highly Lorentz-boosted top quarks

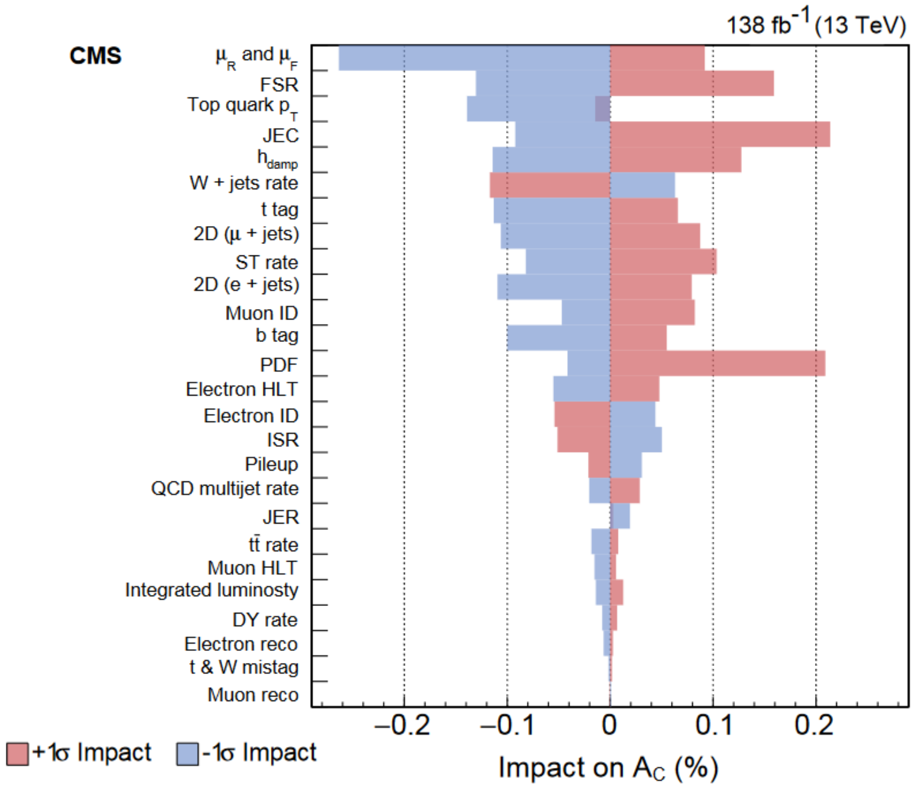


Figure 4: The ±1 standard deviation (σ) impacts of the nuisance parameters corresponding to the systematic uncertainties in the full phase space A_C measurement for $M_{t\bar{t}} > 750$ GeV. The red and blue bars show the effect on the unfolded A_C values for up and down variations of the systematic uncertainty. The MC statistical uncertainties are omitted here.

Table 2: Measured unfolded charge asymmetry in the fiducial phase space (upper rows) and the full phase space (lower rows) shown for individual channels compared with the theoretical prediction from MC. Results are shown for events with $M_{t\bar{t}} > 750$ GeV and for two invariant mass ranges, 750–900 and >900 GeV. The statistical (stat) and systematic (syst) uncertainties in the data, the MC statistical uncertainty (MC stat), and the total uncertainty in the measured values (Total) are also shown. All values are in percent.

$M_{t\bar{t}}$ (GeV)	A_C (%)					
	Measured	Stat	Syst	MC stat	Total	Theory
	Fiducial phase space (A_C^{fid})					
> 750	0.22	± 0.44	$^{+0.34}_{-0.43}$	± 0.32	$^{+0.64}_{-0.69}$	$0.72\ ^{+0.64}_{-0.61}$
$750 - 900$	0.39	$^{+0.66}_{-0.65}$	$^{+0.39}_{-0.56}$	$^{+0.43}_{-0.44}$	$^{+0.88}_{-0.96}$	$0.60\ ^{+0.97}_{-0.91}$
> 900	1.18	± 0.58	$^{+0.55}_{-0.75}$	± 0.41	$^{+0.90}_{-1.03}$	$0.83\ ^{+0.85}_{-0.82}$
	Full phase space (A_C)					
> 750	0.69	± 0.44	$^{+0.34}_{-0.42}$	± 0.32	$^{+0.65}_{-0.69}$	$0.94\ ^{+0.05}_{-0.07}$
$750 - 900$	2.43	± 0.65	$^{+0.29}_{-0.64}$	$^{+0.45}_{-0.43}$	$^{+0.84}_{-1.01}$	$0.87\ ^{+0.06}_{-0.08}$
> 900	0.37	± 0.58	$^{+0.55}_{-0.72}$	$^{+0.41}_{-0.40}$	$^{+0.90}_{-1.01}$	$1.01\ ^{+0.06}_{-0.07}$

Search for CP violation using $t\bar{t}$ events (lepton+jet)

Table 5: The sources and values of the systematic uncertainties in A'_{CP} for each of the CP observables in percent, averaged over the two lepton-flavor channels. The experimental sources are listed first and then the theoretical ones.

Systematic sources	A'_{CP} (%)			
	O_3	O_6	O_{12}	O_{14}
Pileup	−0.0008 +0.0010	−0.0003 +0.0007	+0.0023 −0.0017	+0.0040 −0.0044
b tagging scale factor (b and c quarks)	+0.0002 −0.0002	+0.0001 −0.0003	<0.0001 <0.0001	<0.0001 −0.0002
b tagging scale factor (light-flavor quarks and gluons)	−0.0003 +0.0004	−0.0003 <0.0001	−0.0009 +0.0007	−0.0007 +0.0005
Lepton efficiencies	−0.0002 +0.0002	−0.0001 −0.0001	−0.0001 <0.0001	−0.0004 +0.0001
Jet energy resolution	−0.0028 −0.0029	−0.0069 +0.0032	−0.0024 −0.0021	−0.0070 +0.0026
Jet energy scale	−0.0051 −0.0018	−0.0046 +0.0065	−0.0046 +0.0011	−0.0062 +0.0041
Background template	+0.0061	+0.0050	+0.0139	+0.0016
PDF	+0.0008 −0.0008	−0.0008 +0.0006	+0.0003 −0.0004	+0.0003 −0.0006
QCD renormalization and factorization	+0.0008 +0.0012	+0.0008 −0.0002	+0.0013 −0.0033	+0.0007 −0.0004
Initial-state QCD radiation	+0.0006 −0.0004	−0.0005 +0.0004	+0.0017 −0.0015	+0.0024 −0.0021
Final-state QCD radiation	−0.0001 −0.0008	−0.0215 +0.0122	+0.0053 −0.0017	−0.0129 +0.0060
Color reconnection	−0.0162 <0.0001	+0.0186 −0.0206	+0.0091 −0.0464	+0.0384 +0.0304
ME-PS matching	−0.0235 +0.0399	−0.0043 +0.0177	−0.0185 +0.0139	+0.0352 +0.0376
Underlying event	−0.0515 −0.0099	−0.0576 +0.0355	−0.0082 +0.0218	+0.0116 +0.0424
Flavor response	−0.0017 −0.0024	−0.0007 +0.0024	−0.0033 −0.0004	−0.0105 +0.0070
Top quark mass variation	+0.0049 −0.0179	+0.0152 −0.0118	+0.0119 −0.0097	+0.0082 −0.0046
Per-event resolution	−0.0027 −0.0004	−0.0022 +0.0040	+0.0023 +0.0014	−0.0005 +0.0048
W+HF fraction	−0.0174	−0.0132	−0.0102	−0.0098
No top quark p_T reweighting	−0.0008	−0.0005	<0.0001	<0.0001

Table 7: The measured A_{CP} and corresponding d_{tG} values for each of the CP observables using the SM simulation predictions for the dilution factor D in the combined lepton+jets channel. The first uncertainty is statistical and the second is systematic.

CP observable	A_{CP} (%)	d_{tG}
O_3	$-0.10 \pm 0.20 \pm 0.14$	$+0.04 \pm 0.11 \pm 0.07$
O_6	$-0.30 \pm 0.21 \pm 0.16$	$+0.25 \pm 0.20 \pm 0.15$
O_{12}	$+0.12 \pm 0.13 \pm 0.07$	$+0.45 \pm 0.47 \pm 0.27$
O_{14}	$-0.29 \pm 0.16 \pm 0.14$	$-0.81 \pm 0.48 \pm 0.44$