Top Physics Results from CMS

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Titas Roy
University of Illinois Chicago

Introduction

Top quark - the **heaviest** elementary particle!

- At m_{top} ~ 173 GeV the top quark plays a special role in **SM and BSM processes**
  - close to the **EWK breaking scale** and **high Yukawa coupling** (~1) - many BSM theories predict massive particles interacting with the top quark
  - **decays before hadronizing** -> we can study the decay products
  - **t—>W(W-> lν or W-> qq̄)** boson and a **b** quark.
- LHC is a top quark producing factory - giving us the oppurtunity to study many interesting and rare processes associated with top quarks
  - these measurements are useful to verify SM predictions
  - deviations from these measurements would be a sign of **New Physics**!

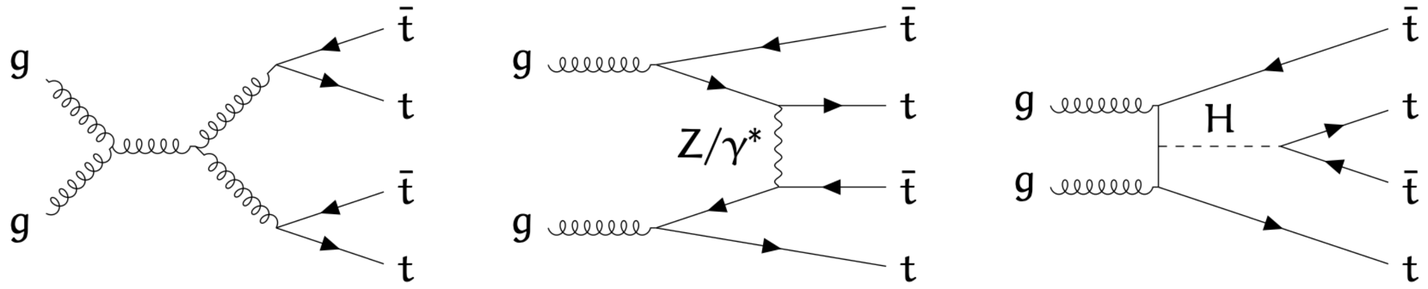
In today's talk …

In today's talk I will go over some latest results from **CMS** - covering measurements of SM processes using new techniques and some searches for new physics involving top quarks using 13 TeV and 13.6 TeV data

- $t\bar{t}t\bar{t}$ pair production
- $t\bar{t}b\bar{b}$ production
- tWZ production
- $t\bar{t}$ cross-section
- Search for Lorentz invariance in $t\bar{t}$
- Serach for new physics in $t\bar{t}$ using EFT
- Search for FCNC in top and Higgs interactions

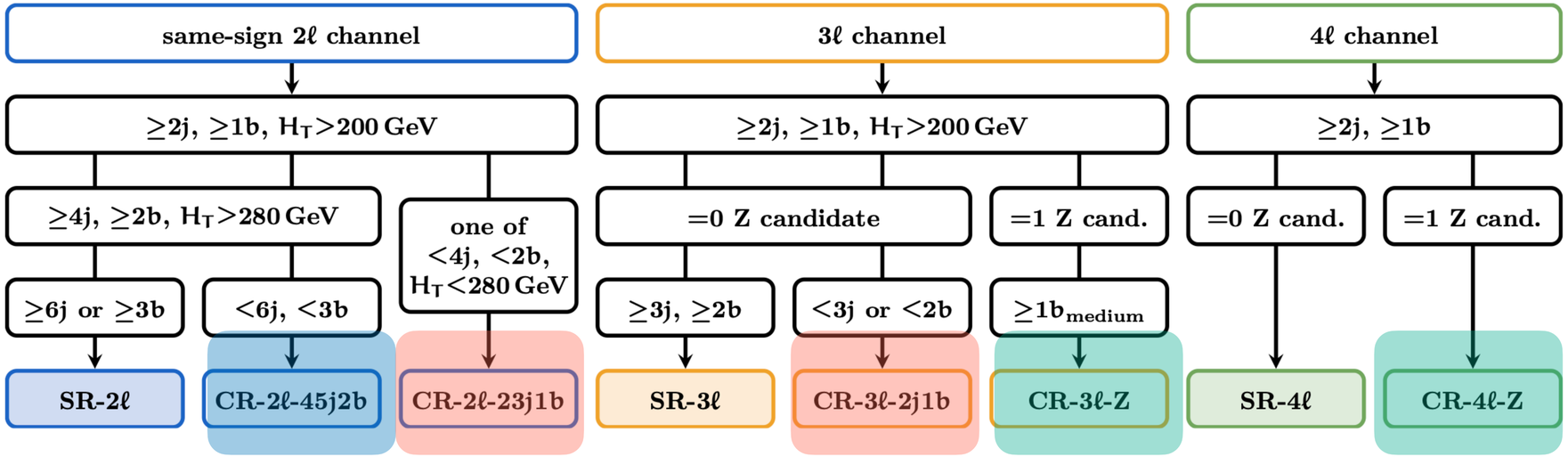
Observation of four top quark pair production in pp collisions at √s=13TeV

arXiv: 2305.13439



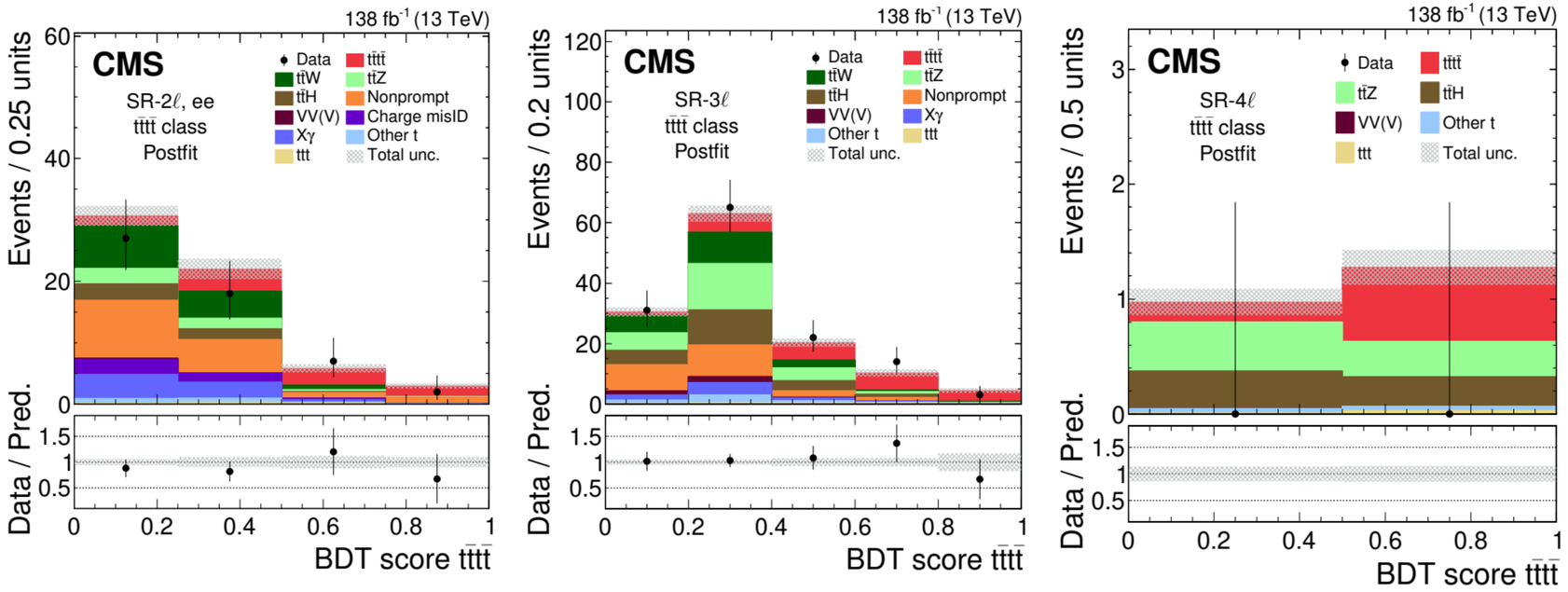
- Produced predominantly through strong interaction
- This can be used as a crosscheck for top Yukawa coupling measurement.
- Many BSM models may enhance the $t\bar{t}t\bar{t}$ production crosssection
- Events with two, three or 4 leptons are selected and at least 2 jets(1 bjet)

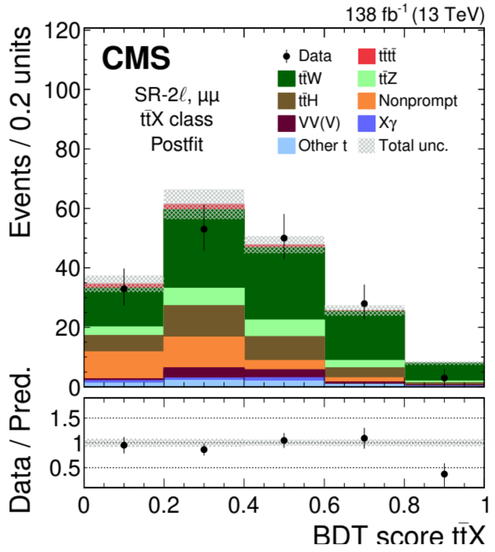
ttW
Nonprompt leptons
ttZ

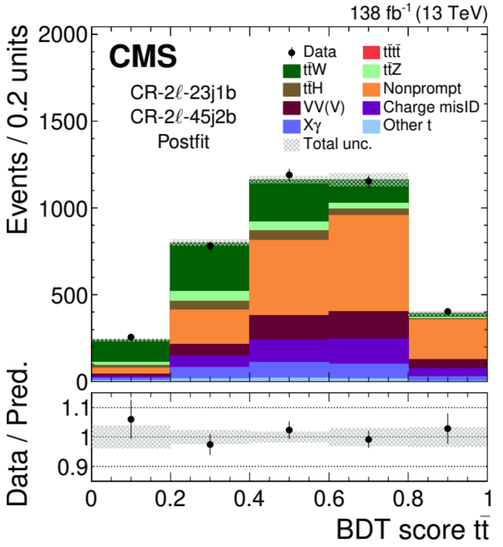


Observation of four top quark pair production in pp collisions at √s=13TeV

- Signal regions($t\bar{t}t\bar{t}$) are separated from backgrounds($t\bar{t}X$ and $t\bar{t}$) using multiclassification BDTs





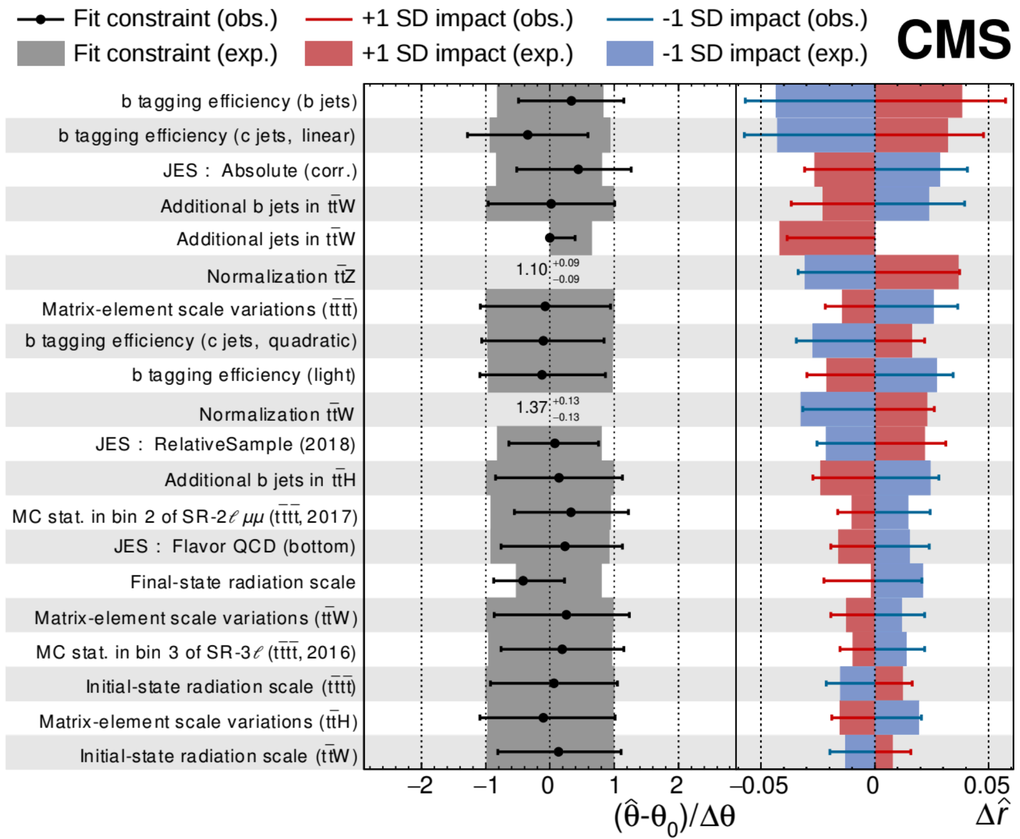


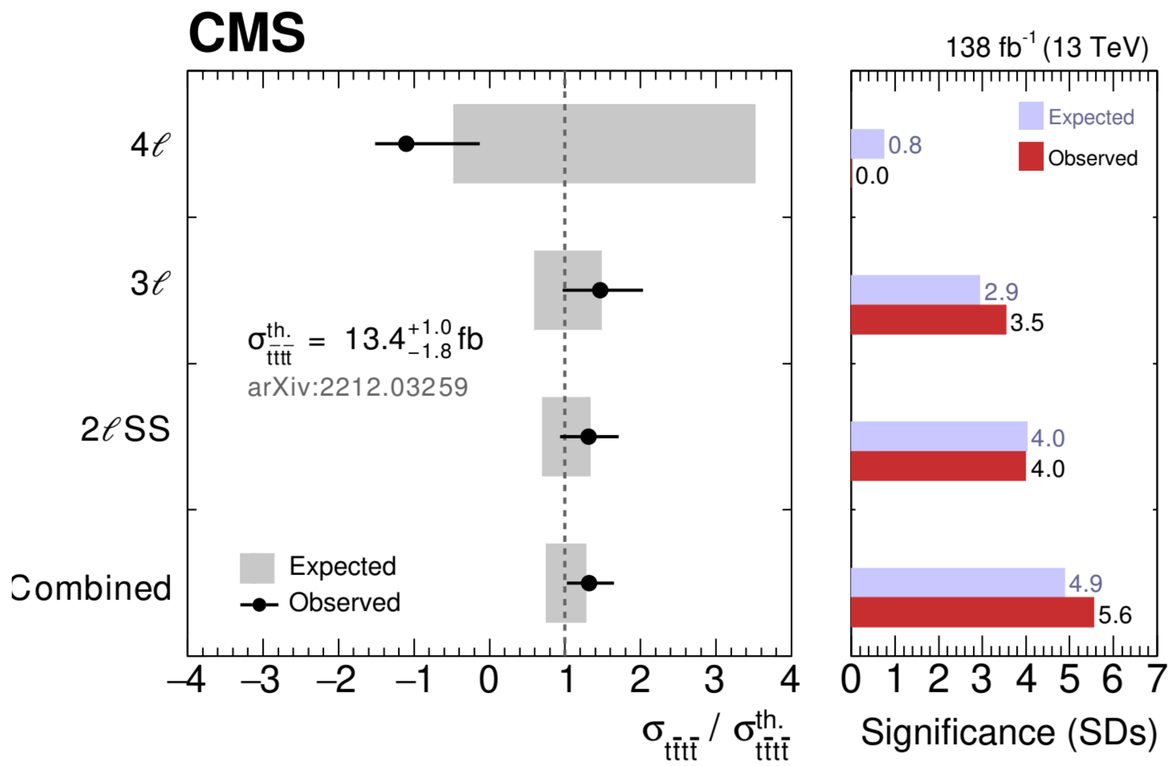
- Backgrounds to SR can be prompt and non prompt, additionally in the 2l region they can also come from charge misidentified sources.
  - Non prompt and charge misidentified backgrounds are estimated through sidebands in data

Observation of four top quark pair production in pp collisions at √s=13TeV

- A simultaneous binned profile likelihood fit to data is perfomed to extract the cross-sections of the $t\bar{t}t\bar{t}$, $t\bar{t}Z$ and $t\bar{t}W$ using the signal and control regions.

$$\sigma(t\bar{t}t\bar{t}) = 17.7^{+3.7}_{-3.5}(\text{stat})^{+2.3}_{-1.9}(\text{syst}) = 17.7^{+4.4}_{-4.0}\text{fb}$$

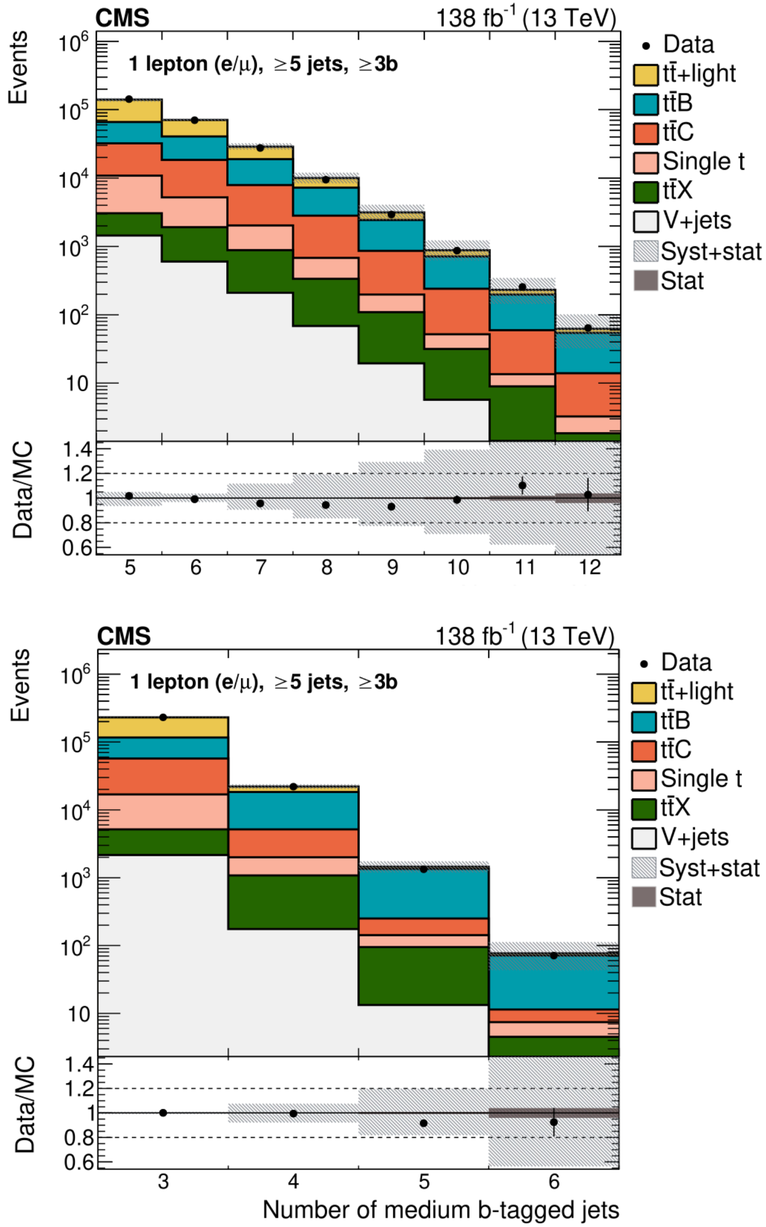




Inclusive and differential cross-section measurements of $t\bar{t}b\bar{b}$ production in the lepton+jets channel at $\sqrt{s}$=13TeV

arXiv: 2309.14442

- This process is an important background for many measurements like $t\bar{t}H$ (H-> $b\bar{b}$) which in turn can be used for top Yukawa coupling measurement.
- This measurement is an important test for perturbative QCD calculations
- Events are selected with one isolated electron/muon and leptons with a looser selection criteria are vetoed to reject events with >1 lepton.
- Four partially overlapping phase-spaces are considered:
  - **>=5 jets:>=3 b jets targetting $t\bar{t}b$; >=6 jets:>=4 b jets targetting $t\bar{t}b\bar{b}$**
  - **>=6 jets:>=3 b jets, >=3 light jets and >=7 jets:>=4 b jets, >=3 light jets targetting $t\bar{t}b\bar{b}j$ and $t\bar{t}\bar{b}j$**

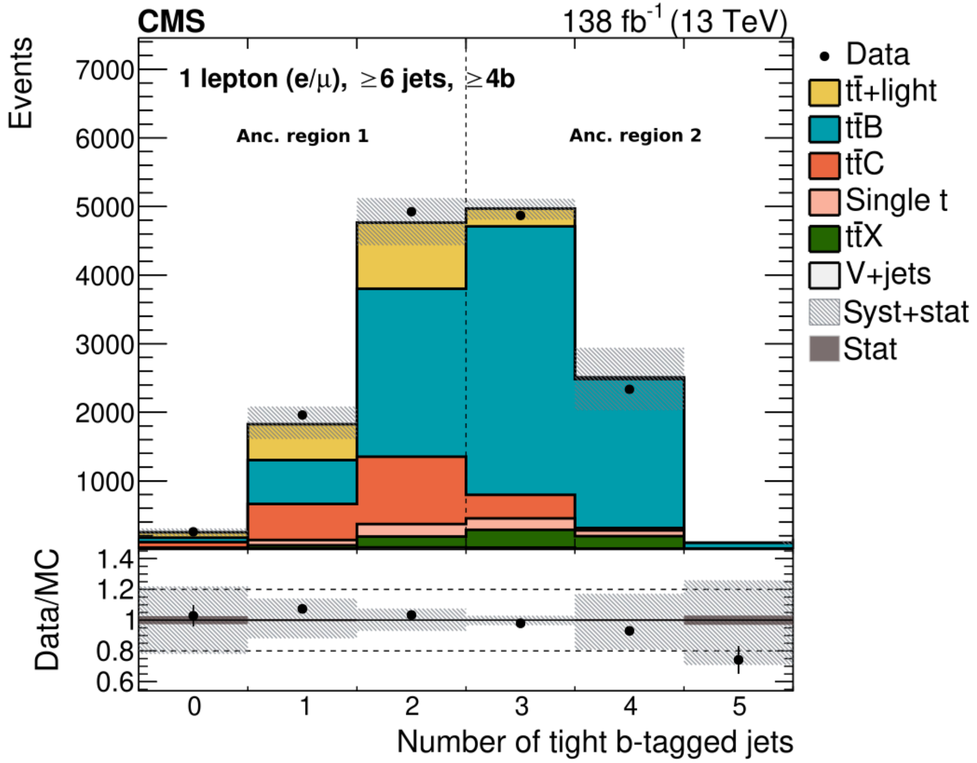


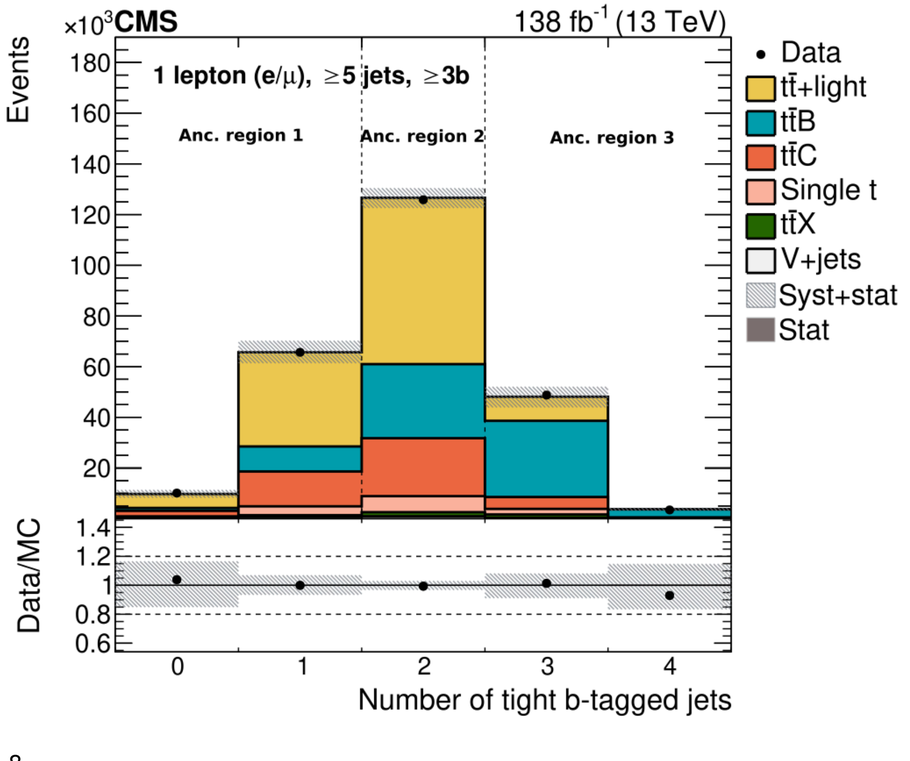
Inclusive and differential cross-section measurements of $t\bar{t}b\bar{b}$ production in the lepton+jets channel at $\sqrt{s}$=13TeV

- Signal and background processes are distinguished using the number of tight btagged jets in 5j3b and 6j4b categories.

- A DNN is used to identify additional b jets (not decaying from top) in 6j4b phase space to

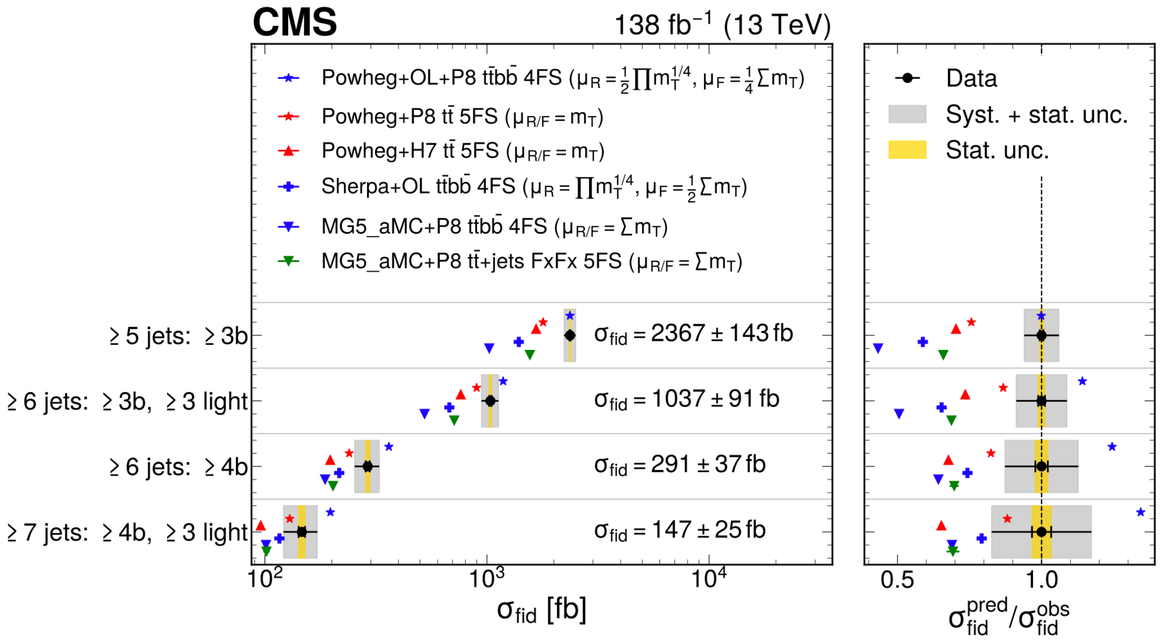
$p_T(b_1^{add.})$	p_T of leading additional b jet
$\lvert\eta(b_1^{add.})\rvert$	$\lvert\eta\rvert$ of leading additional b jet
$p_T(b_2^{add.})$	p_T of subleading additional b jet
$\lvert\eta(b_2^{add.})\rvert$	$\lvert\eta\rvert$ of subleading additional b jet
$\Delta R(bb^{add.})$	ΔR of $bb^{add.}$ pair
$\lvert\eta(bb^{add.})\rvert$	$\lvert\eta\rvert$ of $bb^{add.}$ pair
$m(bb^{add.})$	invariant mass of $bb^{add.}$ pair
$p_T(bb^{add.})$	p_T of $bb^{add.}$ pair

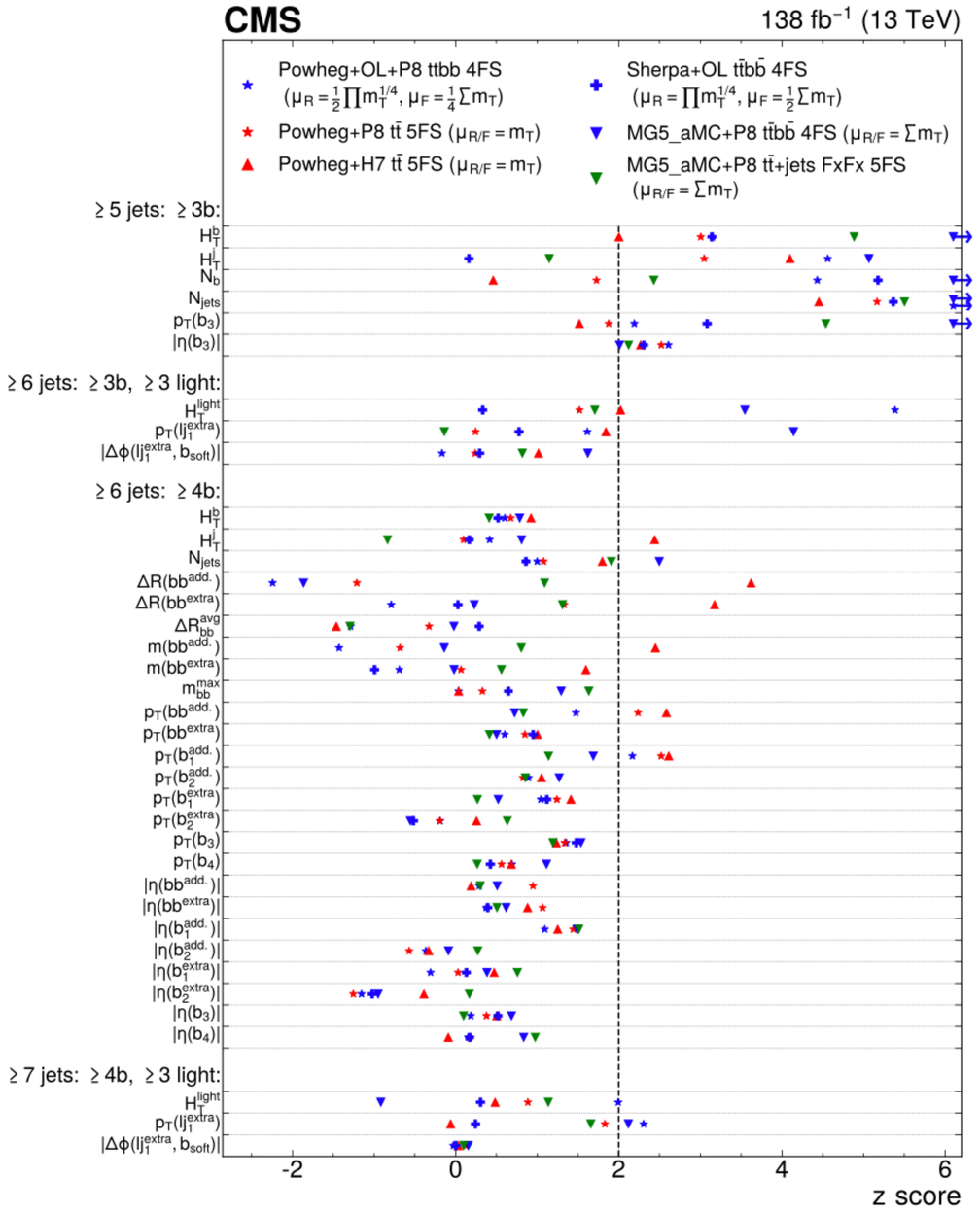




Inclusive and differential cross-section measurements of $t\bar{t}b\bar{b}$ production in the lepton+jets channel at $\sqrt{s}$=13TeV

- A dedicated binned maximum likelihood fit is performed to extract the cross-section in the fiducial and unfolded phase space.

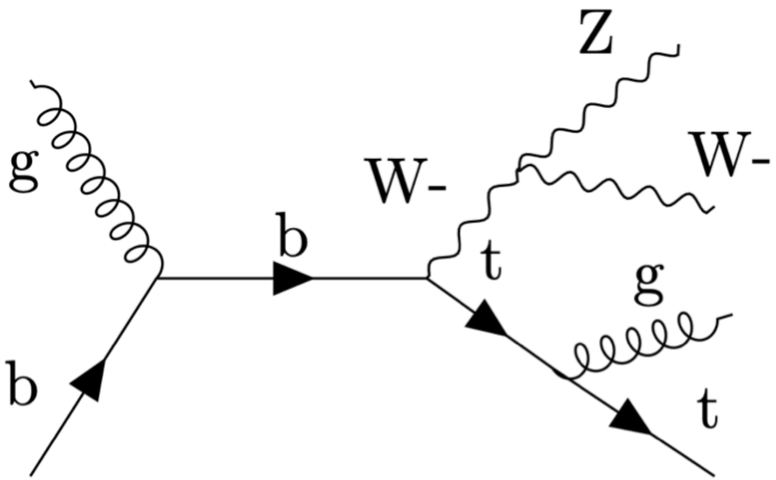




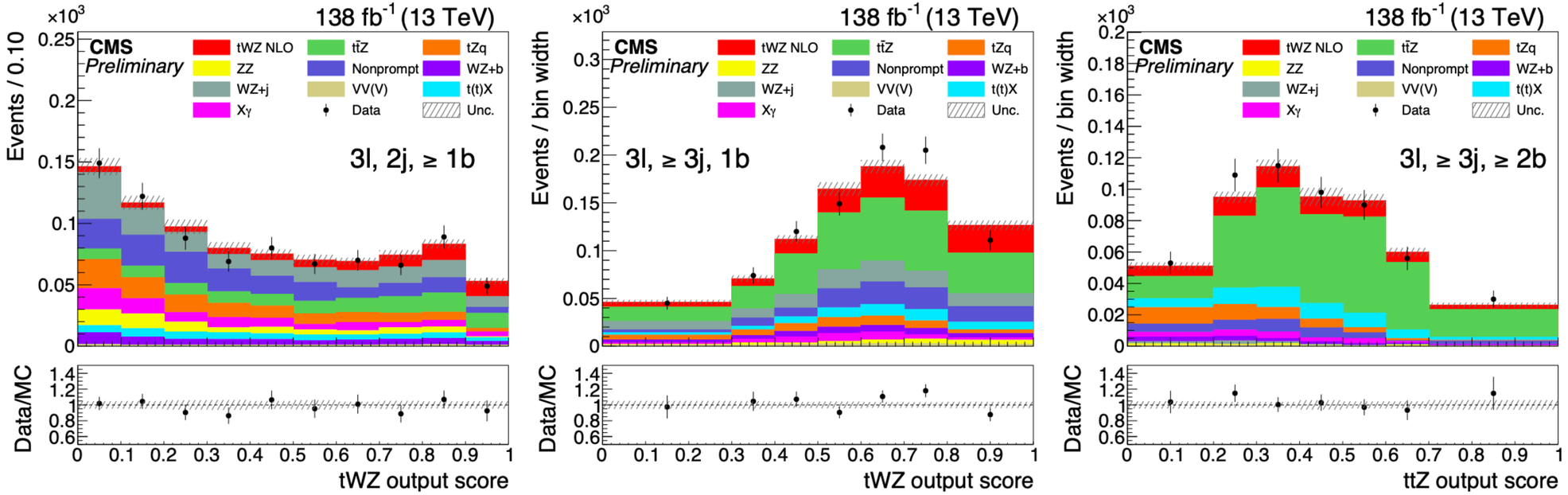
Evidence of tWZ production in pp collisions at √s=13TeV in multilepton final states

CDS

- This process is suitable for probing several SM interactions
- The main background to this process in $t\bar{t}Z$ which is signifacantly higher cross-section
- A deep neural network is used to discriminate signal from backgrounds
- Low p_T and high p_T regions of the top quark are included to be sensitive to SM and beyond new physics



Evidence of tWZ production in pp collisions at √s=13TeV in multilepton final states



- A binned maximum likelihood fit is performed to extract the cross-section

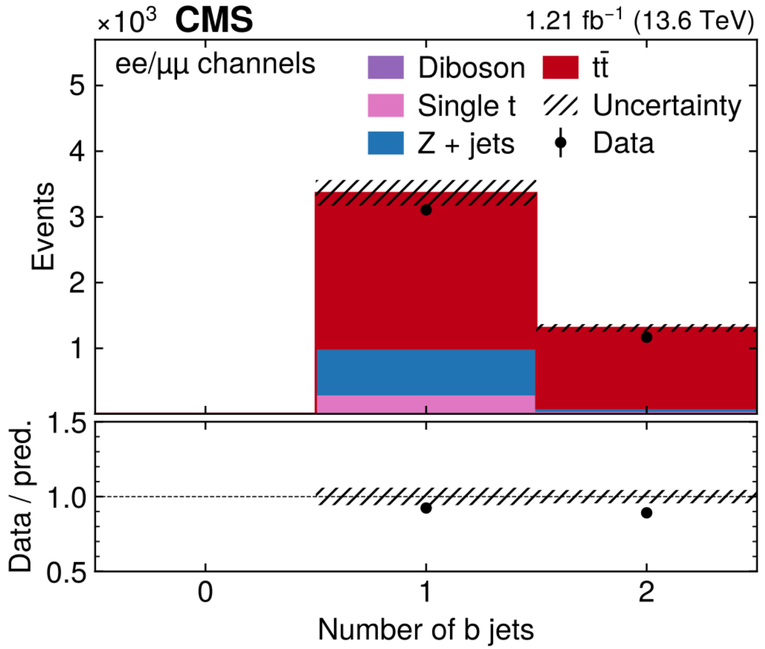
$$\sigma(tWZ) = 0.37 \pm 0.05(\text{stat}) \pm 0.10(\text{syst})$$ **2.1 SD from SM expectations**

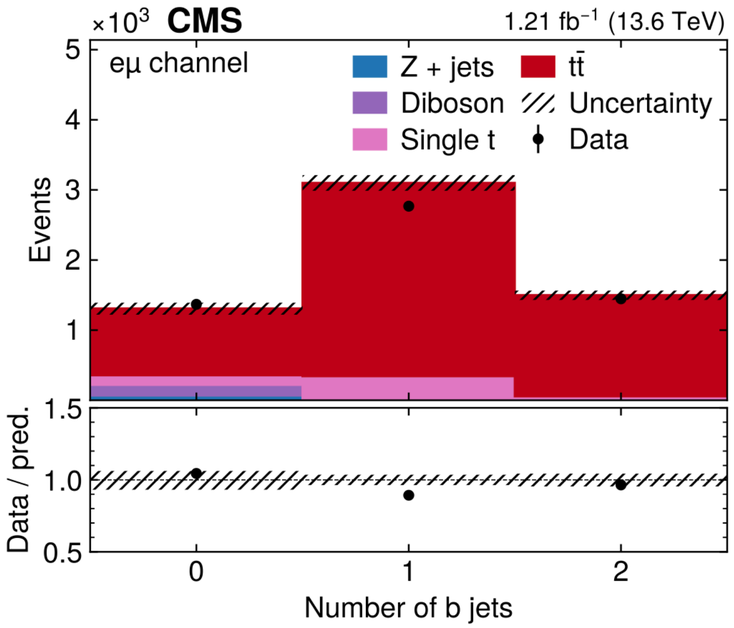
- the uncertainty associated with ttZ normalization has a dominant effect on the systematic uncertainty

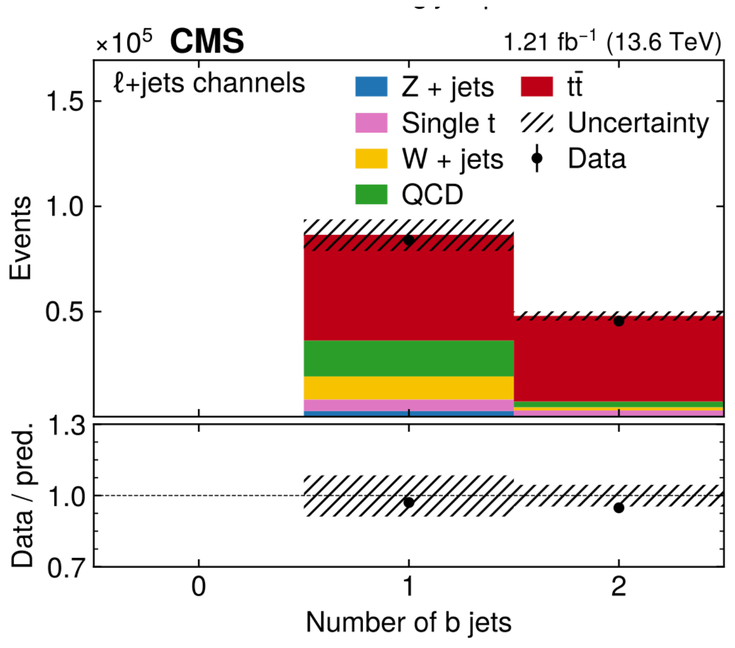
Frist measurement of top quark pair cross-section in pp collisions at $\sqrt{s}$=13.6 TeV

arXiv: 2303.10680

- First measurement to verify if the $\sigma_{t\bar{t}}$ increases with the increase in center of mass energy
- Events are selected with either two opposite charged leptons or a single lepton.
  - At least 3 jets with 1 or 2 jets passing b tagging criteria in semileptonic decay channel
  - At least 1 jet is require in the dileptonic channel with $m_{ll} > 20$ GeV

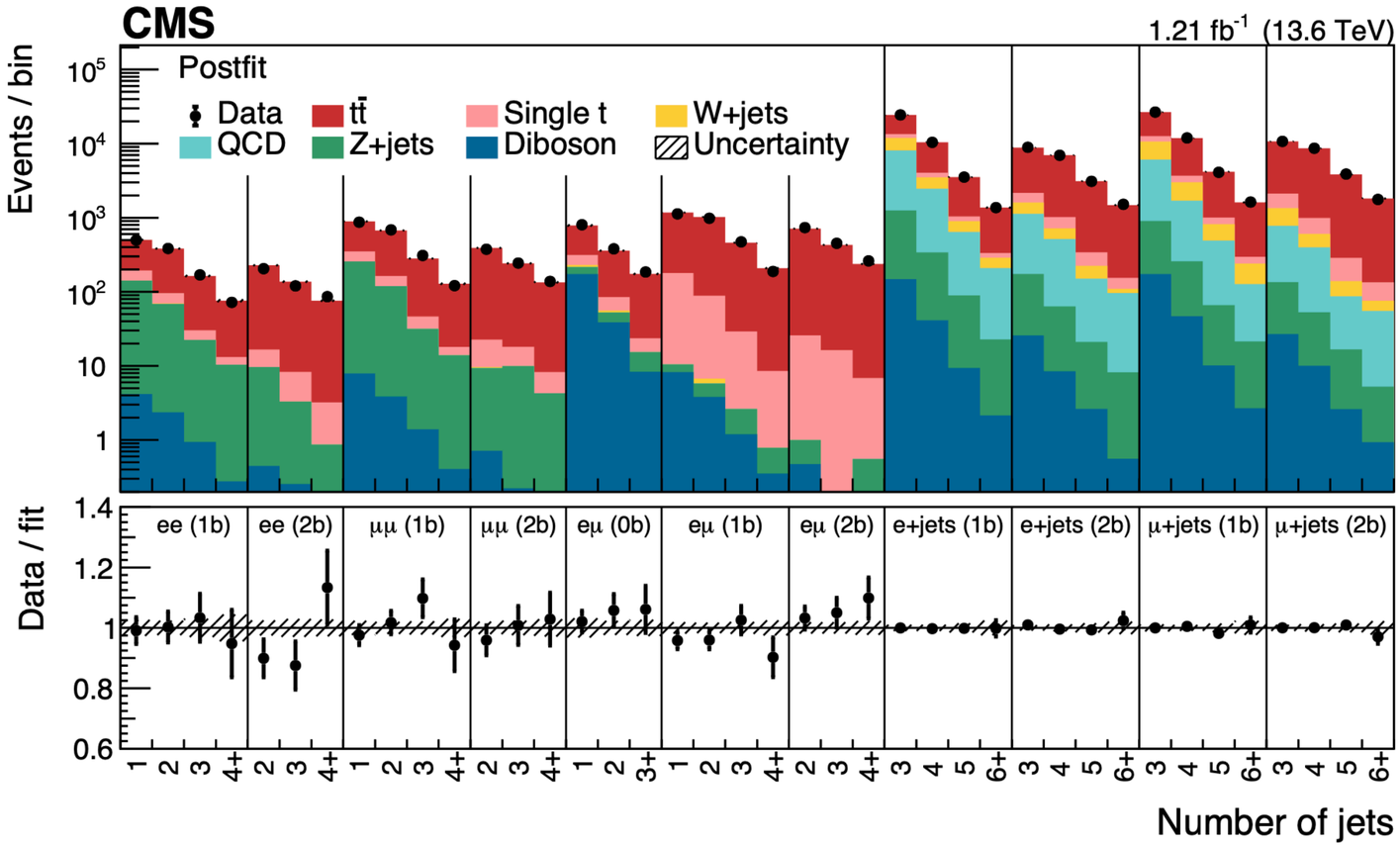






Frist measurement of top quark pair cross-section in pp collisions at √s=13.6 TeV

- Main background in this measurement comes from single top processes, followed by Z/W+jets, Diboson and are estimated from simulation.
- QCD multijet events contribution are estimated using data driven control regions.
- A maximum likelihood fit is performed to extract the cross-section



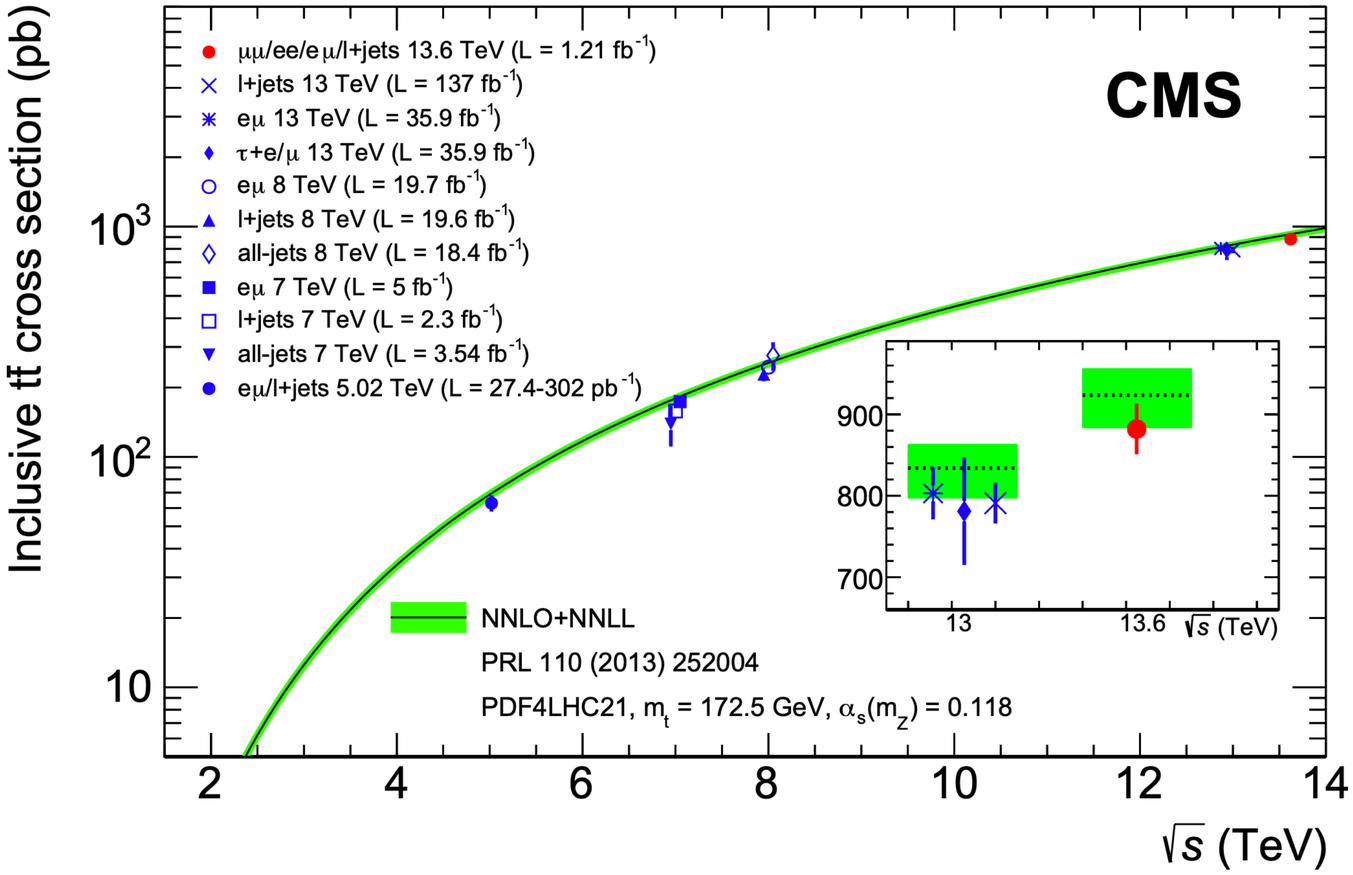
Frist measurement of top quark pair cross-section in pp collisions at √s=13.6 TeV

The measured value

$\sigma(t\bar{t}) = 881 \pm 23\text{(stat+syst)} \pm 20\text{(lumi)pb}$

is in agreement with SM prediction of
$\sigma(t\bar{t}_{SM}) = 924^{+32}_{-40}$pb

- The measurement is done using data from summer 2022 corresponding to an integrated luminosity of 1.21 fb^{-1}
  - $t\bar{t}$ samples simulated with a m_{top}=172.5 GeV



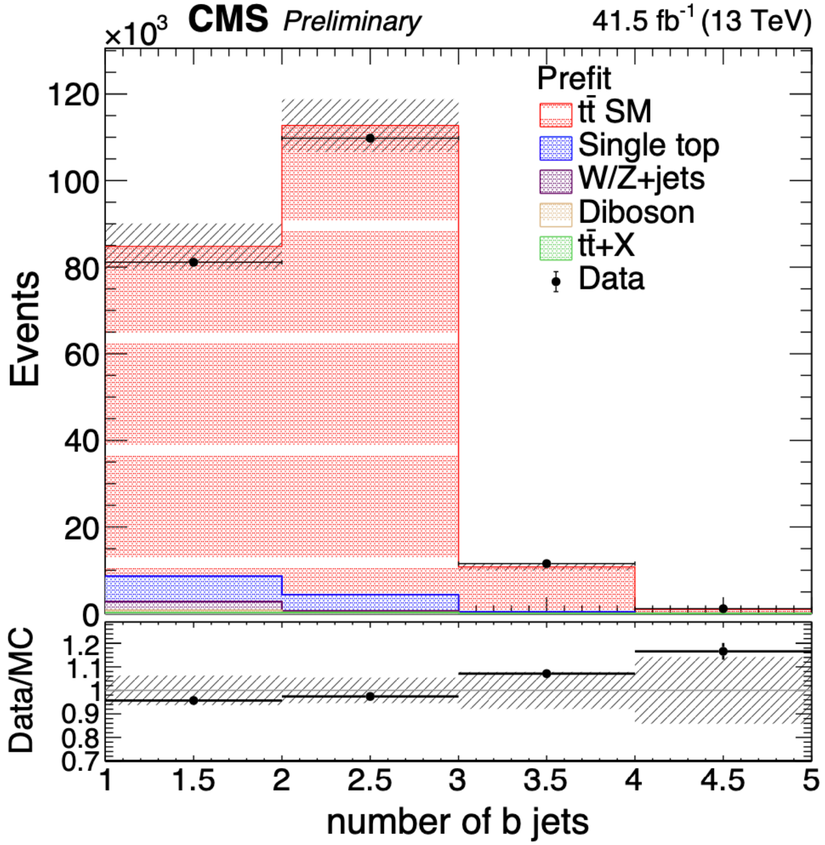
Searches for violations of Lorentz invariance in $t\bar{t}$ production using dilepton events using pp collisions at $\sqrt{s}$=13.6 TeV

CDS link

- In SM we have Lorentz invariance. String theory and quantum loop gravity models predict violations in Lorentz invariance that may be visible in the TeV scale.

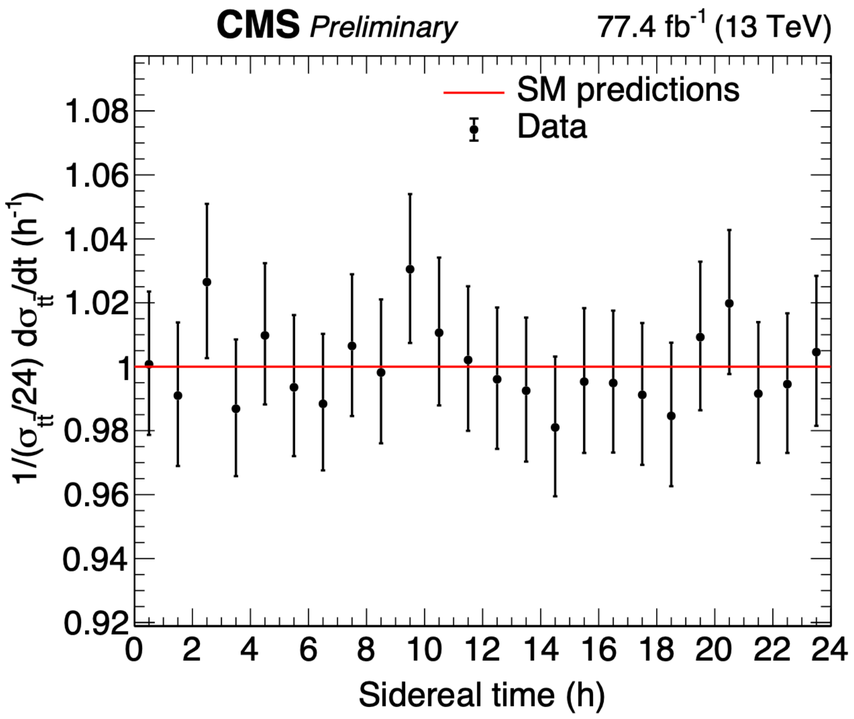
$$L_{\mathrm{SME}} = \frac{1}{2} i\bar{\psi}(\gamma^{\nu} + c^{\mu\nu}\gamma_{\mu} + d^{\mu\nu}\gamma_5\gamma_{\mu}) \overleftrightarrow{\partial_{\nu}} \psi - m_t\bar{\psi}\psi$$

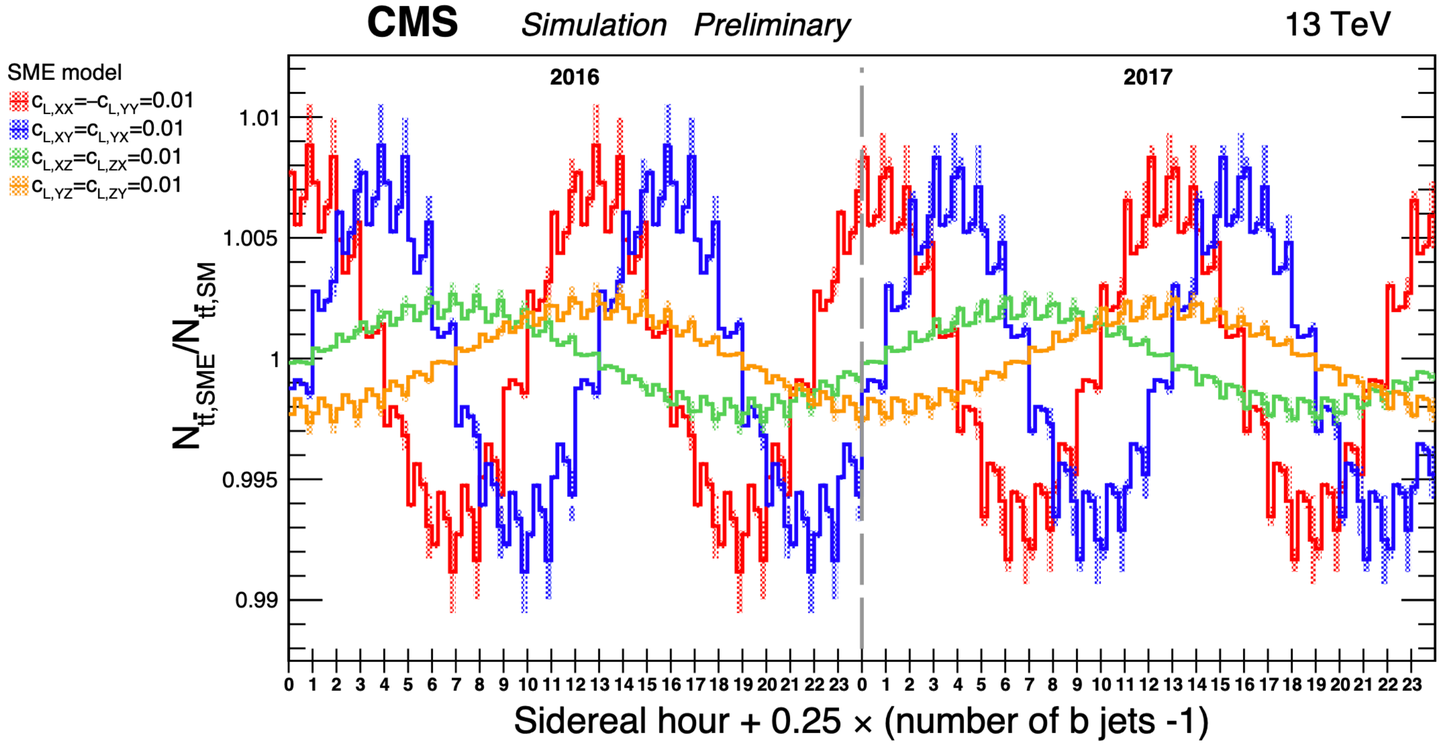
- $c^{\mu\nu}$ and $d^{\mu\nu}$ are SME Wilson coefficients - SME predicts modulation of $t\bar{t}$ cross-section in sidereal time
  - they show preferential direction in space time from the top quarks frame of reference
  - Lorentz invariance preserved when they are 0.
- Dilepton events with opposite sign, opposite flavours and $m_{e\mu} > 20$ GeV are selected for this search.
  - Additionally events must have >=2 jets, with >=1 b jet



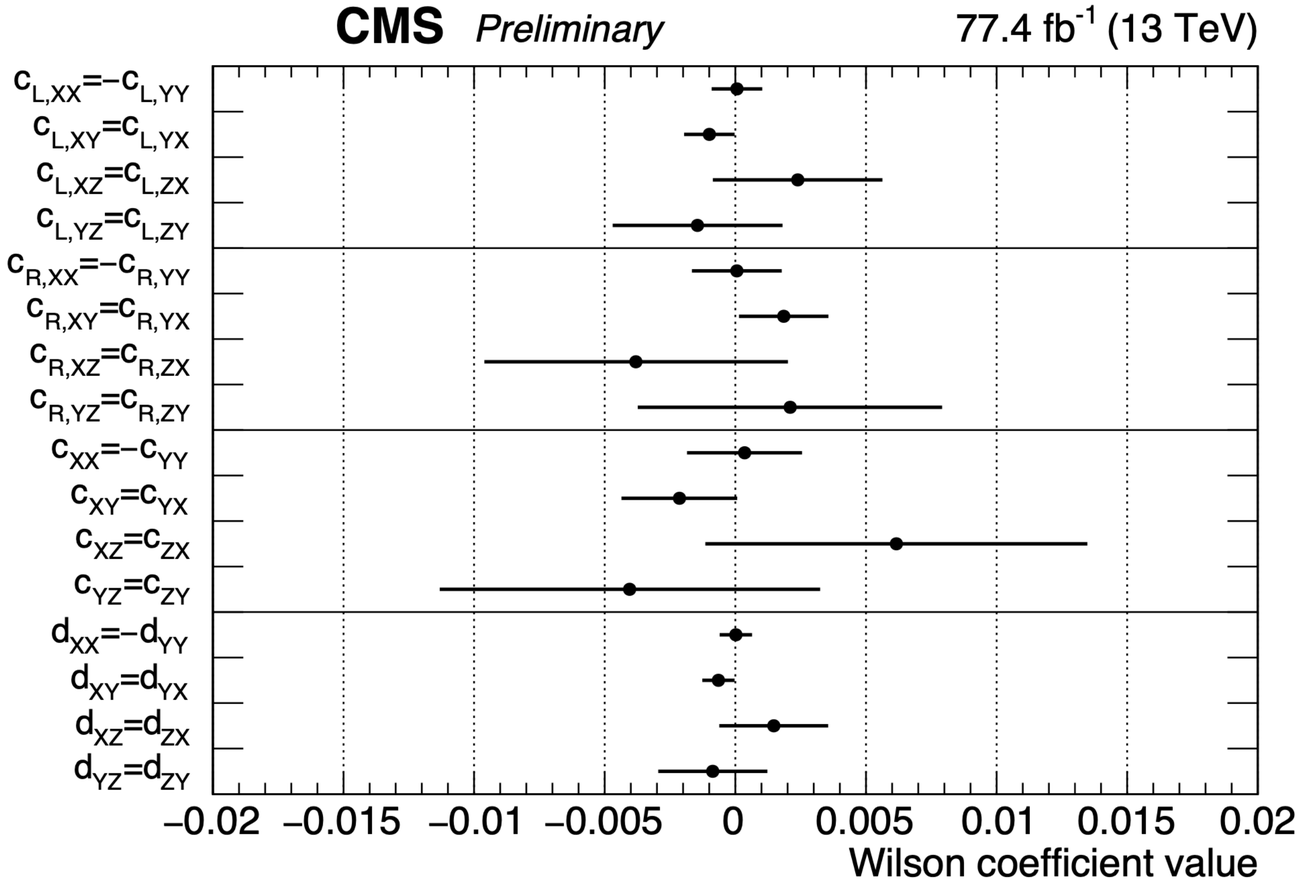
Searches for violations of Lorentz invariance in $t\bar{t}$ production using dilepton events using pp collisions at $\sqrt{s}$=13.6 TeV

- The differential cross-section of $t\bar{t}$ is measured in all sidereal bins
- SME coefficients are extracted to study the Lorentz invariance effects





Searches for violations of Lorentz invariance in $t\bar{t}$ production using dilepton events using pp collisions at $\sqrt{s}$=13.6 TeV



Fitted value for each coefficient while the other three are floated

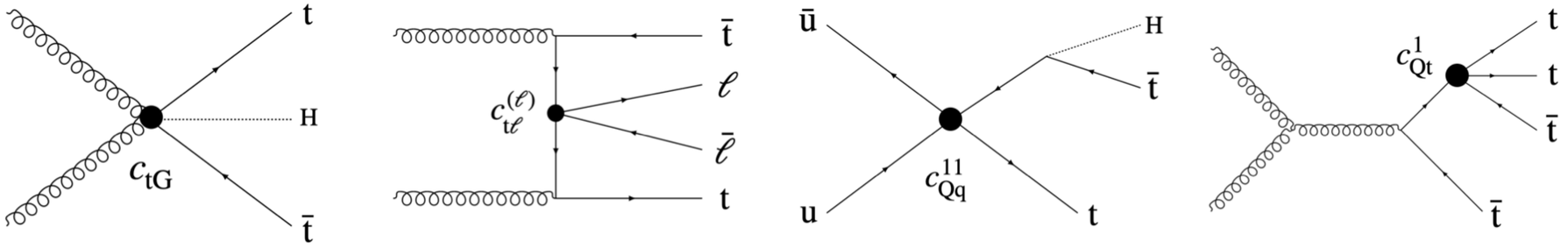
- Measurements are found to be compatible with SM
- Most precise measurement so far- ranging between 10^{-3} to 8×10^{-3}

Searches for physics beyond the SM in top quark production with additional leptons in the context of EFT

arXiv: 2307.15761

$$\mathcal{L}_{\mathrm{EFT}} = \mathcal{L}_{\mathrm{SM}} + \sum_{d,i} \frac{c_i^d}{\Lambda^{d-4}} \mathcal{O}_i^d$$

- Effective Field theory is used to probe high energy scales in search of new physics
  - d=6 operators are considered here. Specifically operators that couple the top to heavy quarks, leptons and bosons; a total of 26 operators are studied.
- The effects of EFT are implemented as weights in the simulated samples at detector level



Searches for physics beyond the SM in top quark production with additional leptons in the context of EFT

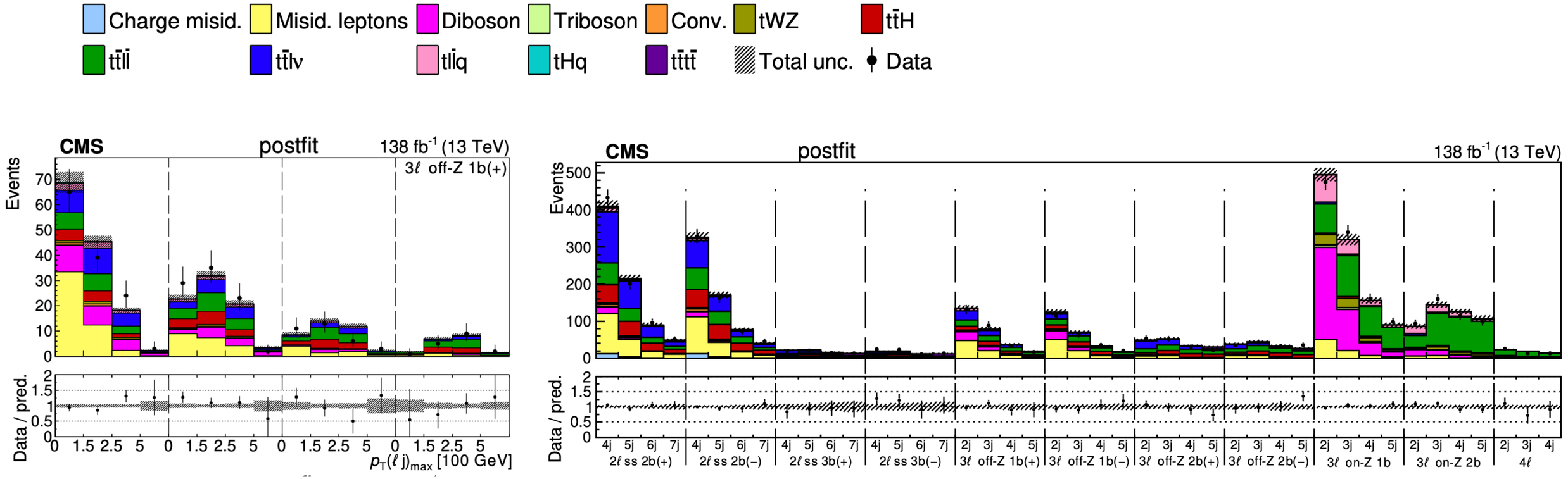
- Events are categorized on the basis of number of leptons, jets and b jets - resulting in 43 categories

Event category	Leptons	$m_{\ell\ell}$	b tags	Lepton charge sum	Jets	Kinematical variable
2ℓss 2b	2	No requirement	2	>0, <0	4, 5, 6, ≥7	$p_{\mathrm{T}}(\ell\mathrm{j})_{\mathrm{max}}$
2ℓss 3b	2	No requirement	≥3	>0, <0	4, 5, 6, ≥7	$p_{\mathrm{T}}(\ell\mathrm{j})_{\mathrm{max}}$
3ℓ off-Z 1b	3	$\lvert m_{\mathrm{Z}} - m_{\ell\ell}\rvert > 10\,\mathrm{GeV}$	1	>0, <0	2, 3, 4, ≥5	$p_{\mathrm{T}}(\ell\mathrm{j})_{\mathrm{max}}$
3ℓ off-Z 2b	3	$\lvert m_{\mathrm{Z}} - m_{\ell\ell}\rvert > 10\,\mathrm{GeV}$	≥2	>0, <0	2, 3, 4, ≥5	$p_{\mathrm{T}}(\ell\mathrm{j})_{\mathrm{max}}$
3ℓ on-Z 1b	3	$\lvert m_{\mathrm{Z}} - m_{\ell\ell}\rvert < 10\,\mathrm{GeV}$	1	No requirement	2, 3, 4, ≥5	$p_{\mathrm{T}}(\mathrm{Z})$
3ℓ on-Z 2b	3	$\lvert m_{\mathrm{Z}} - m_{\ell\ell}\rvert < 10\,\mathrm{GeV}$	≥2	No requirement	2, 3, 4, ≥5	$p_{\mathrm{T}}(\mathrm{Z})$ or $p_{\mathrm{T}}(\ell\mathrm{j})_{\mathrm{max}}$
4ℓ	≥4	No requirement	≥2	No requirement	2, 3, ≥4	$p_{\mathrm{T}}(\ell\mathrm{j})_{\mathrm{max}}$

- Backgrounds come from irreducible (dominated by WZ & ZZ) and reducible sources

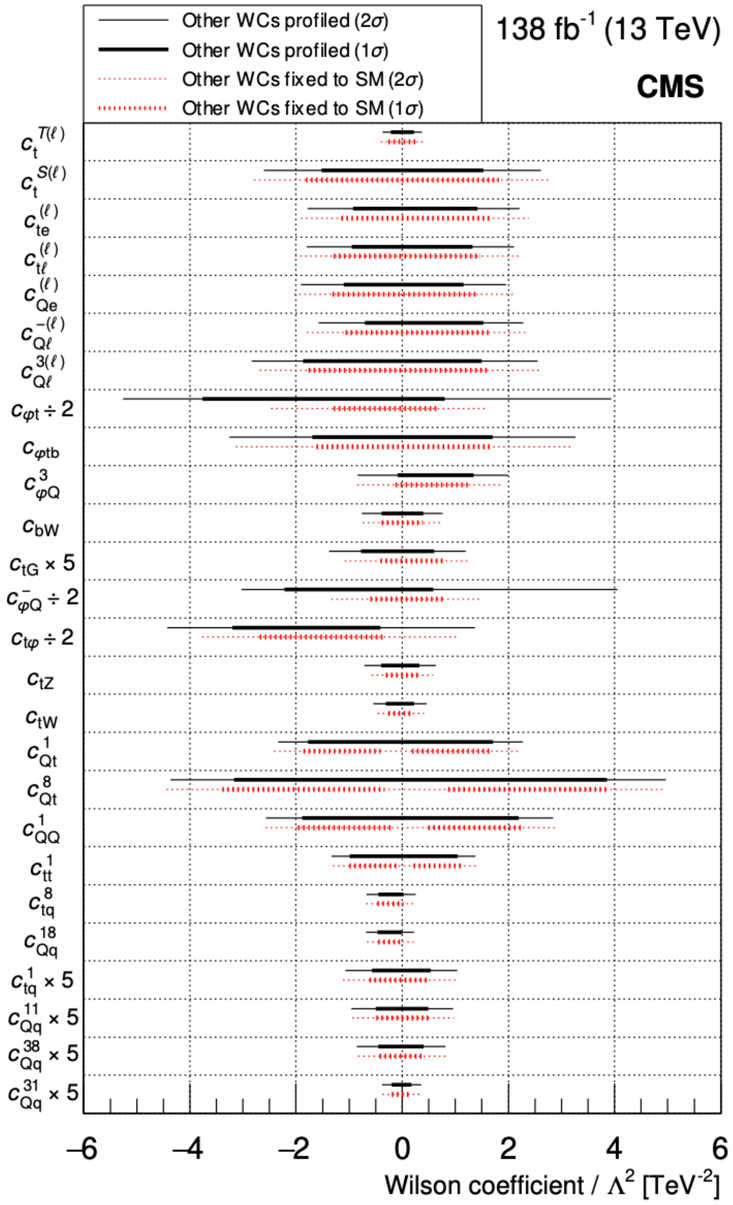
- A maximum likelihood fit is performed across all categories

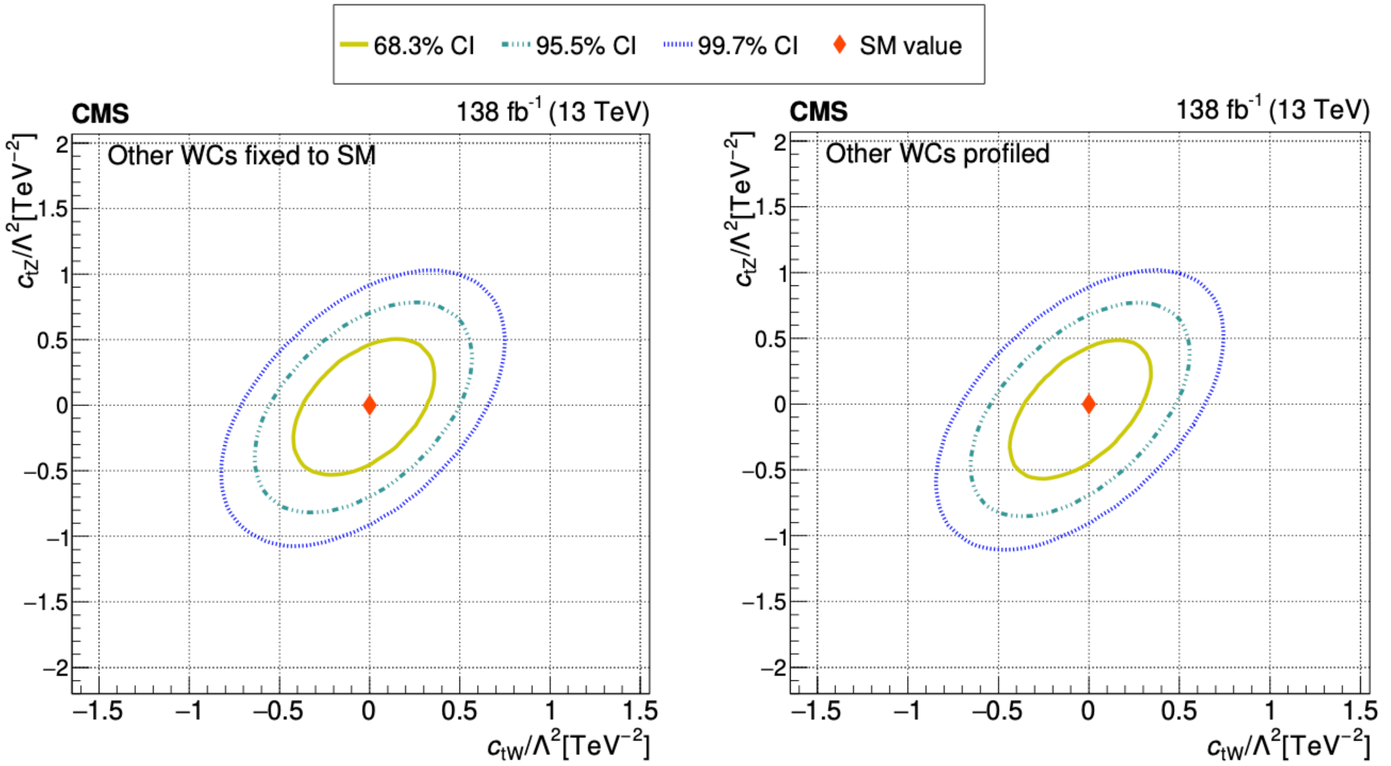
Searches for physics beyond the SM in top quark production with additional leptons in the context of EFT



All 26 WCs are varied in the fit and the nuisance parameters and correlations are taken into account in the different categories

Searches for physics beyond the SM in top quark production with additional leptons in the context of EFT





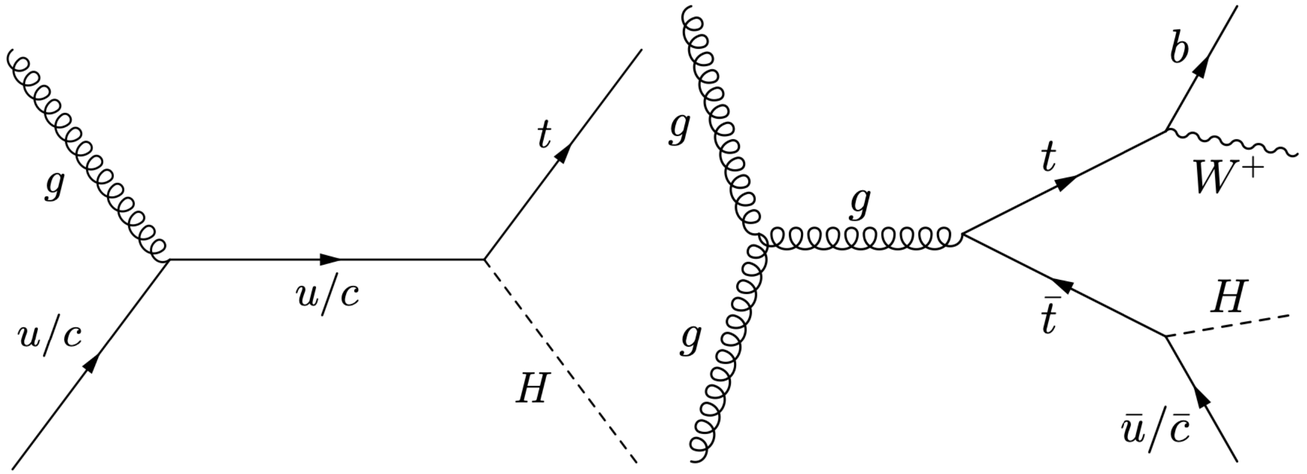
- CL are extracted for all Wilson coefficients individually or in pairs by scanning likelihoods where other WCs are fixed or profiled.
- Results are found to be consistent with SM

Searches for flavor changing neutral current interactions of the top quark and Higgs boson in pp collisions at √s=13 TeV

CDS

- SM forbids quarks decaying by FCNCs at the tree level and are suppressed at higher orders

- Many theories (warped extra dimensions, composite Higgs boson, SUSY with R-parity violation) predicts new physics that may enhance these processes. Particulary t->Hc may be enhanced in 2HDMs



Searches for flavor changing neutral current interactions of the top quark and Higgs boson in pp collisions at √s=13 TeV

- Events are selected with >=1 same sign isolated leptons, >=1 jet

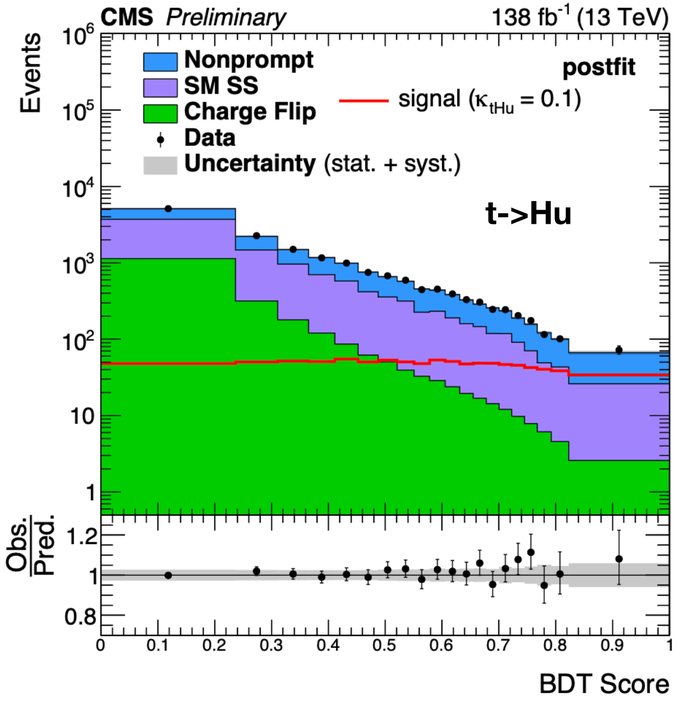
Physics Object	Selection Criteria
Lepton	Pair of isolated SS leptons (e or μ), lead $p_{\mathrm{T}} > 25$ GeV, else $p_{\mathrm{T}} > 20$ GeV, $\lvert\eta_{\mathrm{e}}\rvert < 2.4$, $\lvert\eta_{\mu}\rvert < 2.5$
Jet	≥ 2 in SS events or ≥ 1 in multilepton events, $p_{\mathrm{T}} > 30$ GeV, $\lvert\eta\rvert < 2.4$
b-tagged jet	$p_{\mathrm{T}} > 25$ GeV, $\lvert\eta\rvert < 2.4$
$m_{\ell\ell}$(SF)	> 12 GeV
$m_{\ell\ell}$(any flavor, any charge)	> 8 GeV
m_{ee}(SS,SF)	< 75 GeV or > 105 GeV

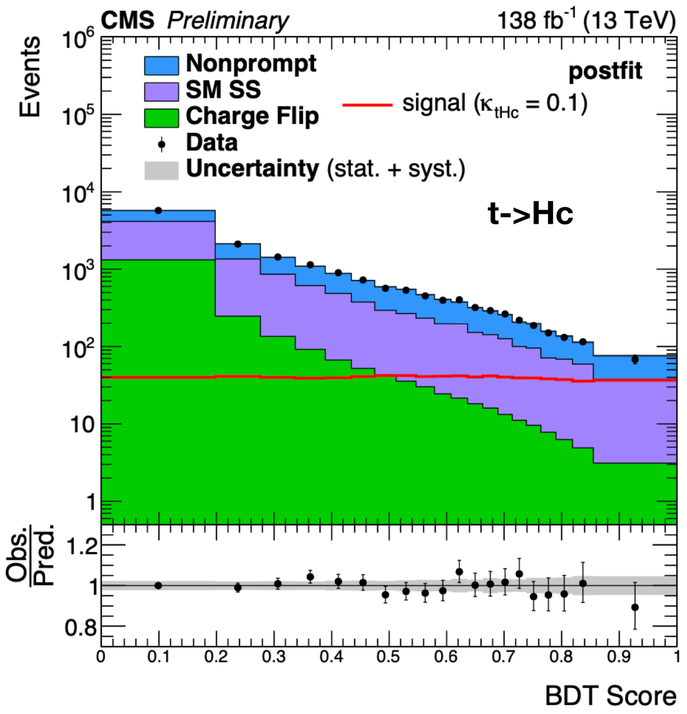
- Two boosted decision trees (BDT) are trained to identify tuH signal and tcH signal using input variables like $N_{jets,}$ p_T^{miss}, m_{ll}

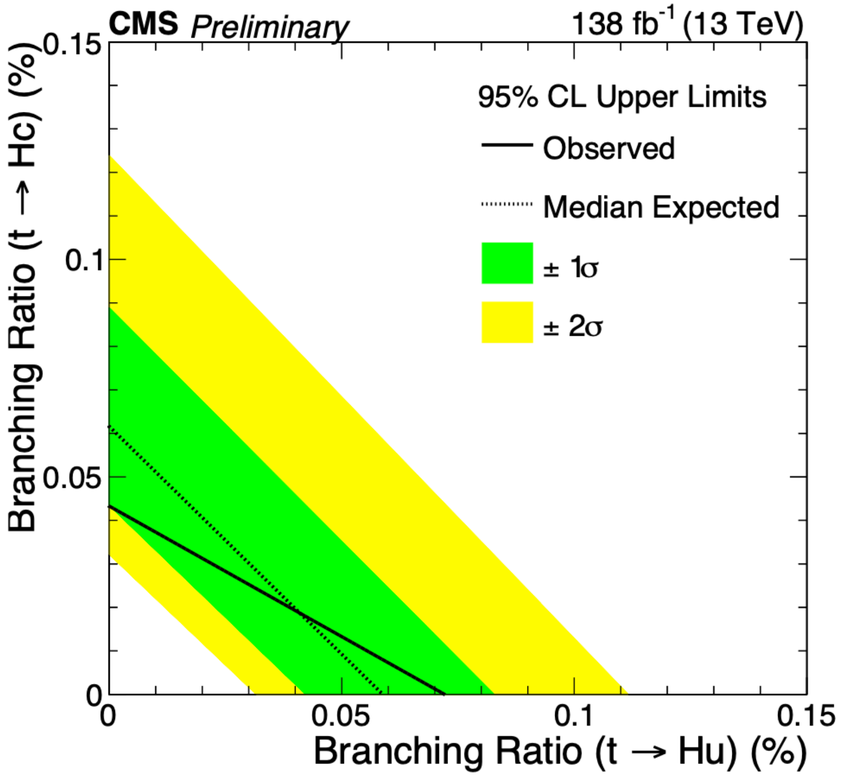
- Backgrounds can come from events having nonprompt(decay of heavy flavor hadron) and prompt leptons (diboson, triboson)

Searches for flavor changing neutral current interactions of the top quark and Higgs boson in pp collisions at √s=13 TeV

- ***B*** (t->Hu) and ***B*** (t->Hc) is measured to be 0.072% and 0.043% at 95% CL and
- No excess above estimated background in SM are observed







Summary

- Top Physics continues to be exciting in terms of more precise measurements and as a tool for probing for new physics as the LHC goes higher up in center of mass energy
- Today we went over some recent results from CMS
  - $t\bar{t}t\bar{t}$ production crosssection measurement
  - cross-section measurements of $t\bar{t}b\bar{b}$ production
  - tWZ production
  - $\sigma_{t\bar{t}}$ at $\sqrt{s}$=13.6 TeV
  - Searches of violations of Lorentz invariance in $t\bar{t}$ production at $\sqrt{s}$=13.6 TeV
  - Searches for new physics in EFT
  - Searches for FCNC in top and Higgs interaction
- Stay tuned for more interesting results from Run 2 and the ongoing Run3 from CMS!

Backup

Searches for violations of Lorentz invariance in tt production using dilepton events using pp collisions at √s=13.6 TeV

$$\Omega_{\text{sidereal}} t_{\text{sidereal}} = \Omega_{\text{UTC}} (t_{\text{UNIX}} - t_0) + \phi_{\text{UNIX}} + \phi_{\text{longitude}}$$

Ω =angular velocity of earth's roation ; ϕ_{UNIX}= phase between UNIX epoch and sidereal time count

Symbol	Definition	2ℓ	3ℓ+4ℓ
$\max_2$ DJ	Second-highest DEEPJET score of any jet	1	1
$\max_3$ DJ	Third-highest DEEPJET score of any jet	8	15
$\max_4$ DJ	Fourth-highest DEEPJET score of any jet	29	—
DJ(j_1)	DEEPJET score of leading jet	9	7
DJ(j_2)	DEEPJET score of subleading jet	12	11
DJ(j_3)	DEEPJET score of jet with third-highest p_T	16	18
DJ(j_4)	DEEPJET score of jet with fourth-highest p_T	—	22
$\Delta R(\ell_1, \ell_2)$	ΔR between leading and subleading lepton	2	4
$\Delta\phi(\ell_1, \ell_2)$	$\Delta\phi$ between leading and subleading lepton	5	—
$\min \Delta R(\mathrm{b}, \mathrm{b})$	Smallest ΔR between any two b jets	3	3
$\min \Delta R(\ell, \mathrm{b})$	Smallest ΔR between any lepton and b jet	6	—
$\min_2 \Delta R(\ell, \mathrm{b})$	Second-smallest ΔR between any lepton and b jet	4	6
$m(\mathrm{t}_1)$	Invariant mass of any three jets, of which one is identified as b jet, that is closest to the top quark mass	7	2
$m(\mathrm{W}_1)$	Invariant mass of any two jets used for $m(\mathrm{t}_1)$ that is closest to the W boson mass	10	5
$m(\mathrm{t}_2)$	Invariant mass of any three jets, of which one is identified as b jet and none of which is used for $m(\mathrm{t}_1)$, that is closest to the top quark mass	23	—
$m(\mathrm{W}_2)$	Invariant mass of any two jets used for $m(\mathrm{t}_2)$ that is closest to the W boson mass	28	—
H_T	Scalar p_T sum of all jets	14	8
$p_\mathrm{T}^\mathrm{miss}$	Missing transverse momentum	20	13
N_j	Number of jets	24	23
$N_\mathrm{b}^\mathrm{tight}$	Number of jets passing the tight DEEPJET WP	27	24
$N_\mathrm{b}^\mathrm{medium}$	Number of jets passing the medium DEEPJET WP	30	—
$p_\mathrm{T}(\ell_1)$	Highest p_T of any lepton	19	14
$p_\mathrm{T}(\ell_2)$	Second-highest p_T of any lepton	15	17
$p_\mathrm{T}(\ell_3)$	Third-highest p_T of any lepton	—	9
$p_\mathrm{T}(\mathrm{j}_1)$	Highest p_T of any jet	18	12
$p_\mathrm{T}(\mathrm{j}_2)$	Second-highest p_T of any jet	22	—
$p_\mathrm{T}(\mathrm{j}_3)$	Third-highest p_T of any jet	—	10
$p_\mathrm{T}(\mathrm{j}_4)$	Fourth-highest p_T of any jet	11	—
$p_\mathrm{T}(\mathrm{j}_5)$	Fifth-highest p_T of any jet	13	21
$m_\mathrm{T}(\ell_1)$	Transverse mass of leading lepton and $p_\mathrm{T}^\mathrm{miss}$	17	19
$m_\mathrm{T}(\ell_2)$	Transverse mass of subleading lepton and $p_\mathrm{T}^\mathrm{miss}$	21	16
$m_\mathrm{T2}(\ell)$	m_T2 variable constructed from leading and subleading leptons	—	20
$m_\mathrm{T2}(\mathrm{b})$	m_T2 variable constructed from leading and subleading b jets	25	—
$m_\mathrm{T2}(\ell$+$\mathrm{b})$	m_T2 variable constructed from two lepton+jet systems built with leading two leptons and leading two b jets	26	—

- Input variables for BDT in 4 top production