Top Quark property measurements and searches for BSM signatures

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On behalf of ATLAS and CMS collaboration

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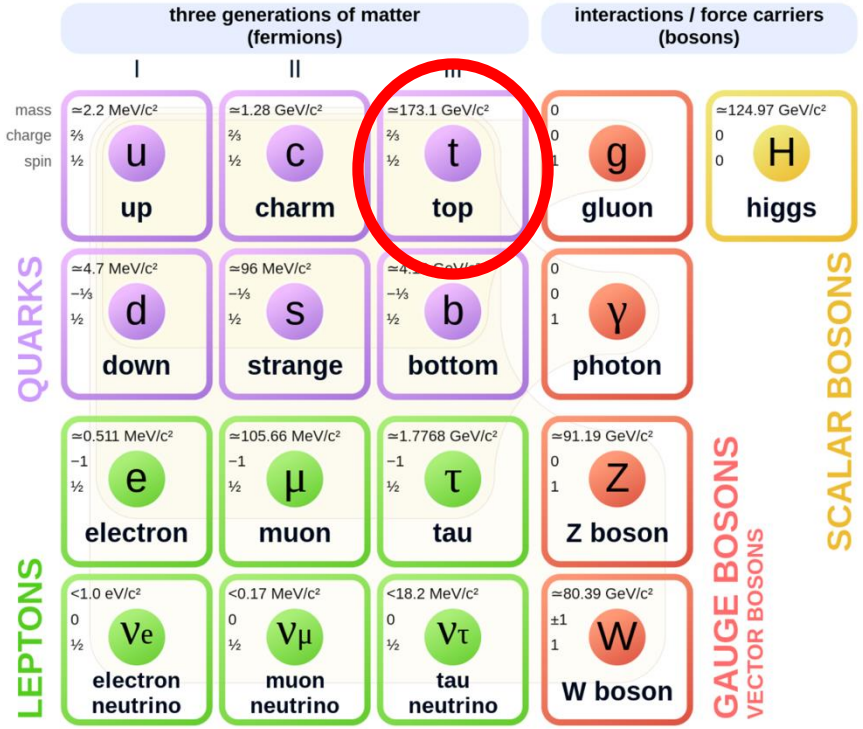
Outline

- Introduction
- Top quark properties:
  - Will present: Spin/polarization/Vtb/H-t/CP
  - Covered by others: entanglement, mass/productions
- Top quark in searches for BSM signatures
  - BSM signal in top production/decay
  - EFT search interpretations
  - Heavy resonance decay to top quark signature
- Summary

Top quark resume



Electric charge	$+\frac{2}{3}\,e$
Color charge	Yes
Spin	$\frac{1}{2}$
Topness	1
Weak isospin	LH: $+\frac{1}{2}$, RH: 0
Weak hypercharge	LH: $+\frac{1}{3}$, RH: $+\frac{4}{3}$

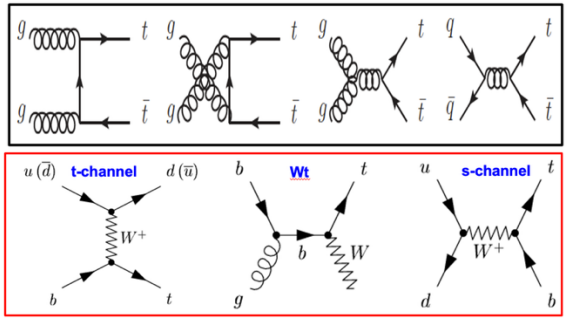
- Mass: ~173 GeV
  - The heaviest known elementary particle
- Lifetime: ~$4*10^{-25}$ Sec.
  - Decay before hadronization
- Large Yukawa Couplings
  - With Higgs: $Yt=\sqrt{2}Mt/vev \sim 1$
- Produced with strong or electroweak interaction
- Decay CKM mechanism
- Precision test of SM
  - $\alpha_s(Mt) \sim 0.1$
  - pQCD calculation accurate

30-year anniversary

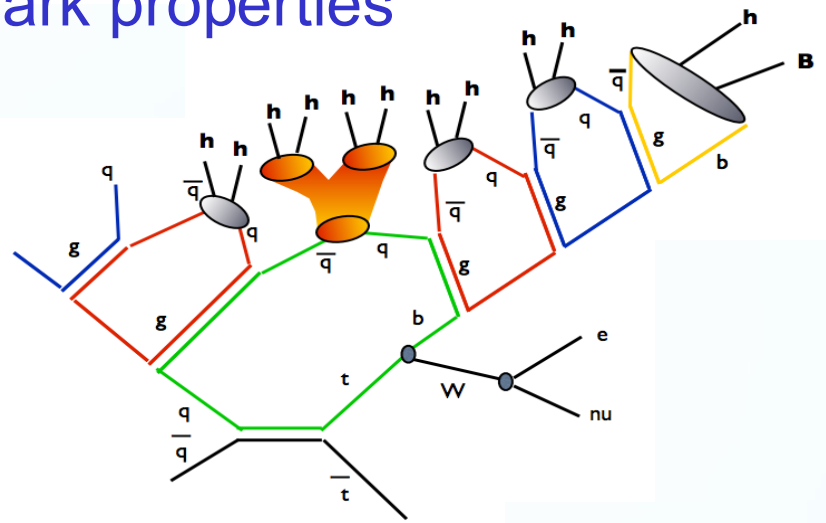
Top quark: the only “naked” quark

- Lifetime: ~4*10^{-25} Sec:

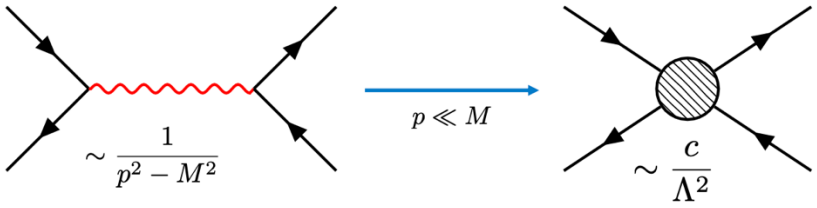
$$\underbrace{\frac{1}{m_t}}_{\text{production}\ 10^{-27}\ \text{s}} < \underbrace{\frac{1}{\Gamma_t}}_{\text{lifetime}\ 10^{-25}\ \text{s}} < \underbrace{\frac{1}{\Lambda_{QCD}}}_{\text{hadronization}\ 10^{-24}\ \text{s}} < \underbrace{\frac{m_t}{\Lambda^2}}_{\text{spin-flip}\ 10^{-21}\ \text{s}}$$



- Only place to study a “naked” quark properties
  - Mass (see Haifeng’s talk)
  - Spin
  - Polarization
  - Vtb
  - Charge

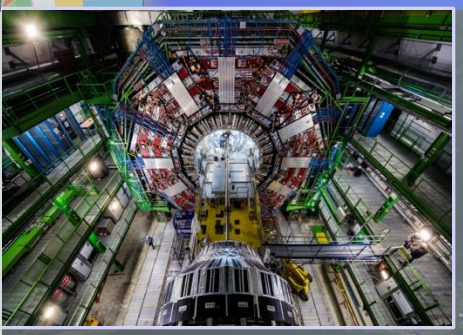


- Portal to new physics



Top quark is a laboratory to precise test SM and search for BSM

ATLAS and CMS experiments

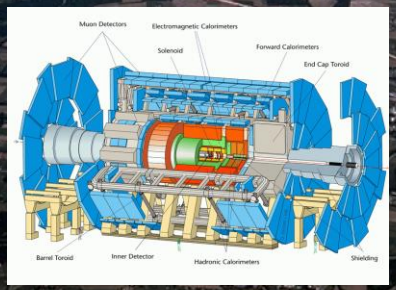


CMS

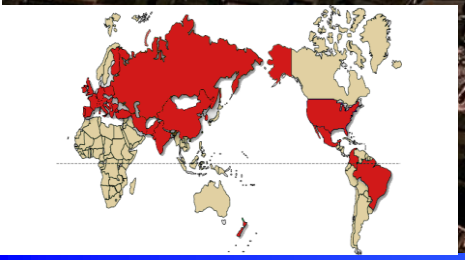
Energy frontier: Ecm up to 13.6 TeV

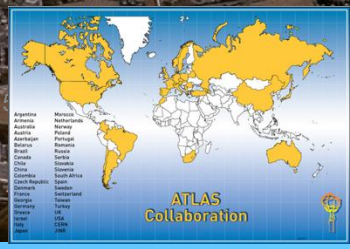
Physics: Higgs, precision SM, new physics

~4000 Collaborators from ~50 countries of each



ATLAS

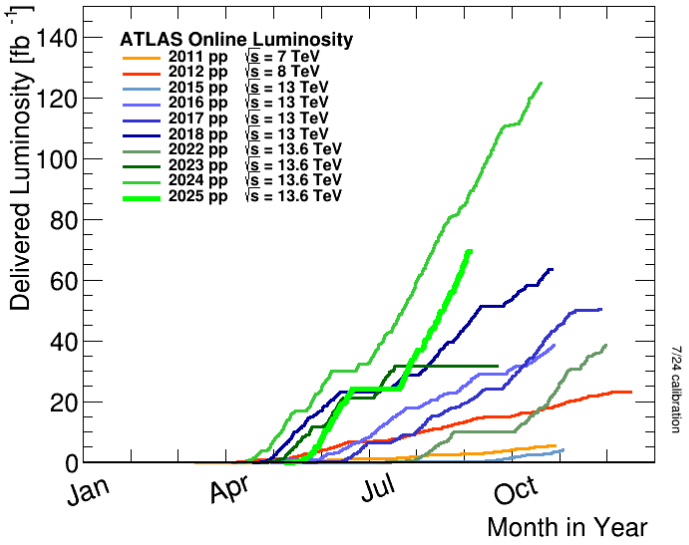




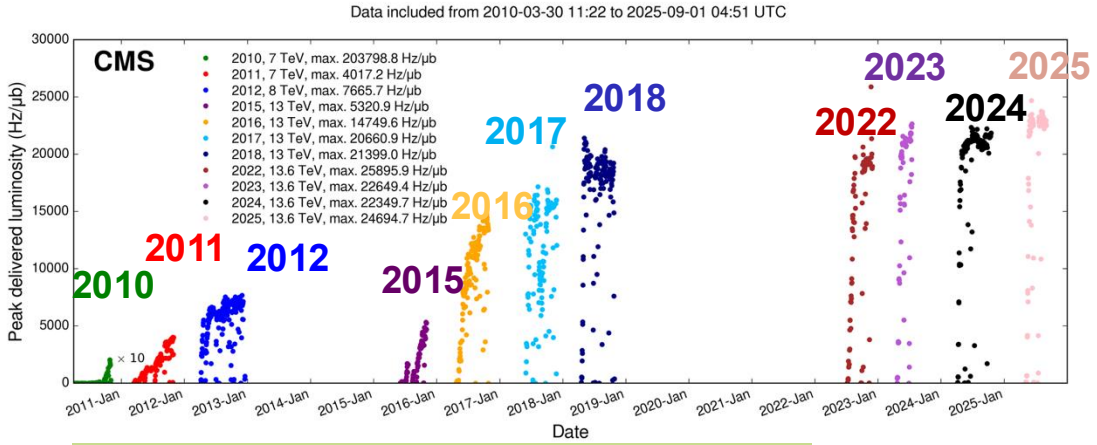
Data taking status: Big Success

- Data taken from 2010-2025
  - 7TeV → 8 TeV → 13 TeV → 13.6 TeV
- Integrated Luminosity (Delivered)

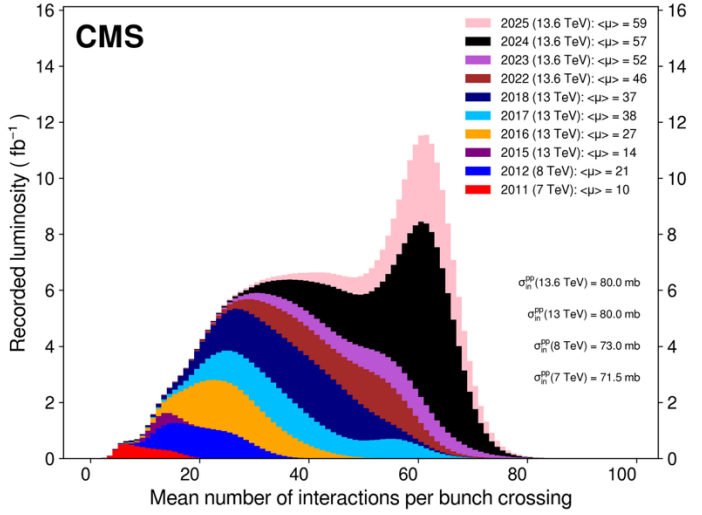
	7TeV	8TeV	13TeV	13.6TeV
ATLAS	5.5 fb^{-1}	22.8fb^{-1}	158fb^{-1}	249fb^{-1}
CMS	6.1 fb^{-1}	23.3fb^{-1}	163fb^{-1}	244fb^{-1}



> 1.7 B top quarks produced



* >94% of detector channels active



top quark properties

Full Spin density matrix measurement in l+jet(1)

- Double differential cross-section

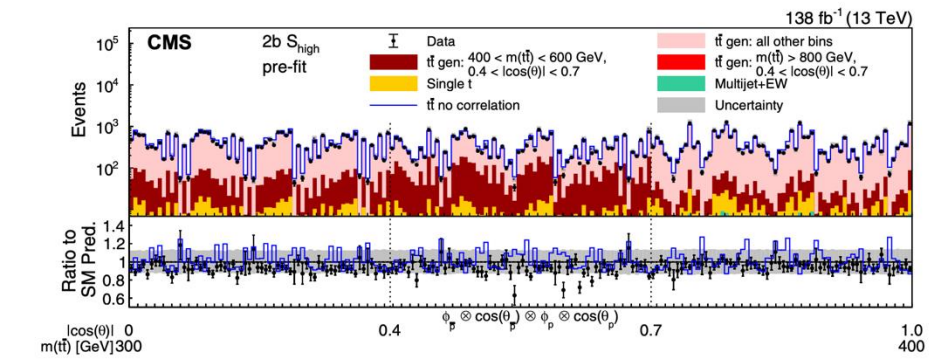
Phys. Rev. D 110, 112016 (2024)

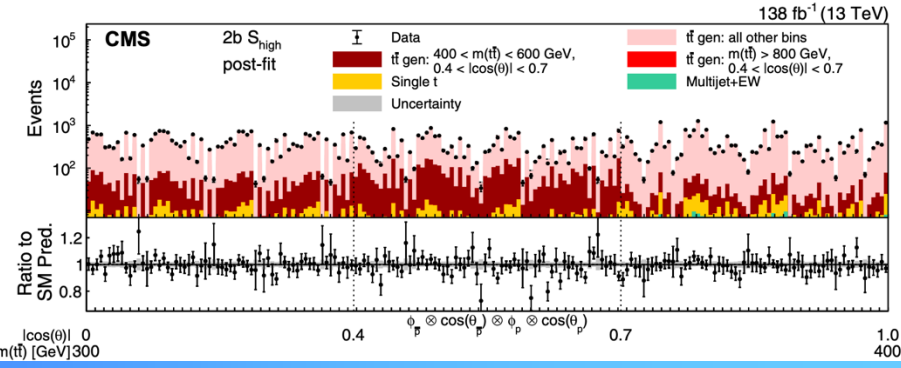
$$\frac{1}{\sigma}\frac{\mathrm{d}^2\sigma}{\mathrm{d}\cos\theta_+^a\,\mathrm{d}\cos\theta_-^b} = \frac{1}{4}(1 + B_+^a\cos\theta_+^a + B_-^b\cos\theta_-^b - C(a,b)\cos\theta_+^a\cos\theta_-^b)$$

- Top-antitop spin dependence completely described by 15 coef.

$$\frac{1}{\sigma}\frac{d\sigma}{dx} = \frac{1}{2}(1 + [\mathrm{Coef.}]\,x)\,f(x)$$

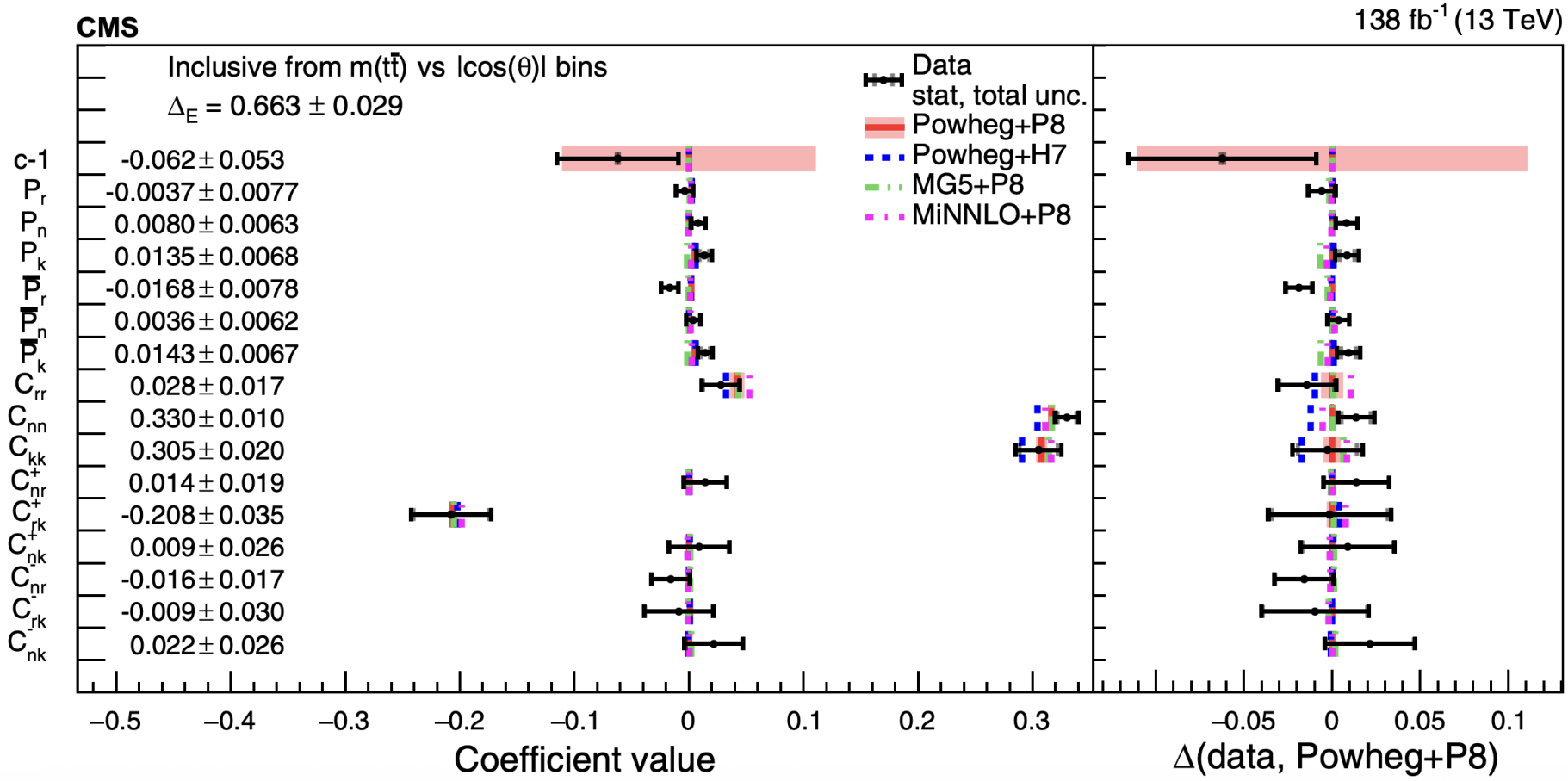
- Polarization vector P(0 in SM) and spin correlation probed by angular distributions:
  - Simultaneously fitting data in 16 cat.: (2*b*,1*b*) × (2 *NN bin*) x 4 periods.





Full Spin density matrix measurement in l+jet(2)

- Spin density matrix coefficients measured inclusively & differentially in bins of $m(tt)$, $|\cos(\theta)|$, $p_T(t)$



In agreement with SM

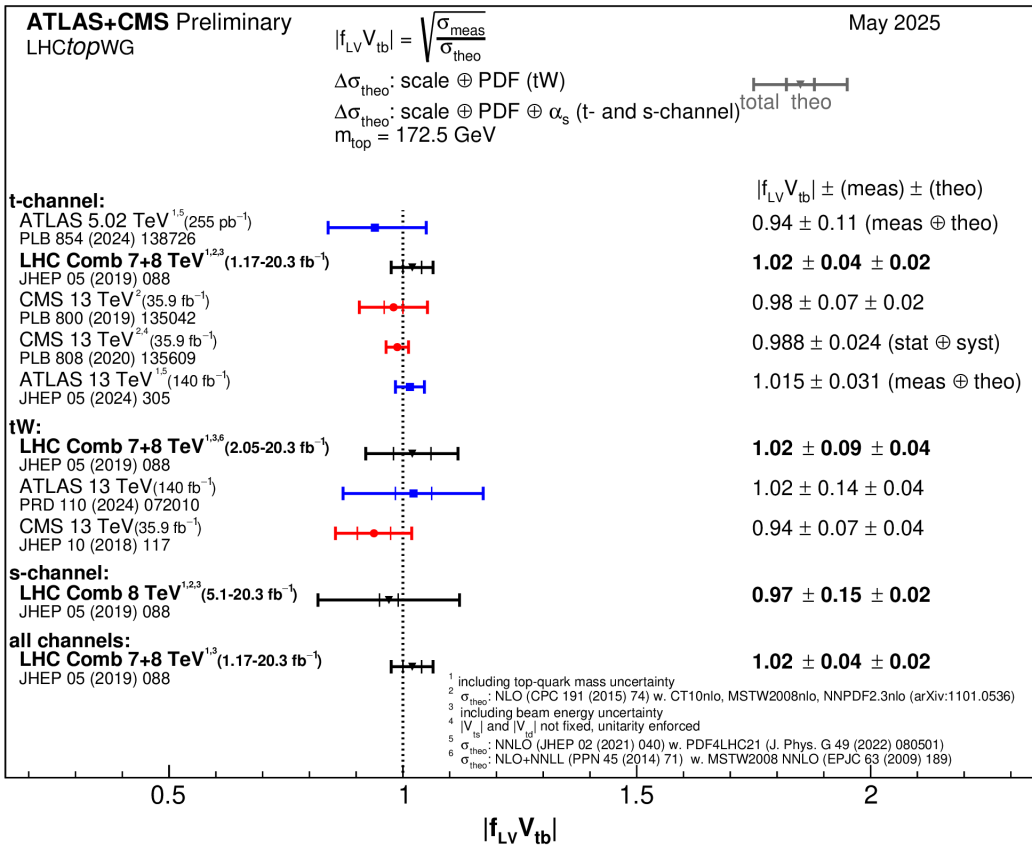
Phys. Rev. D 110, 112016 (2024)

CKM element Vtb measurement

- CKM matrix

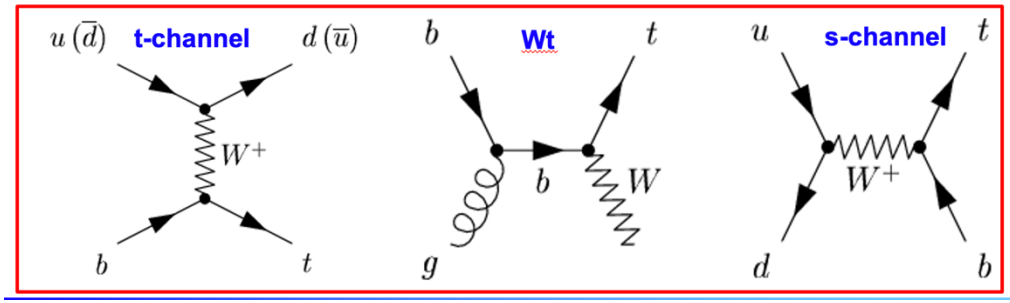
$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

$$\begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix}$$

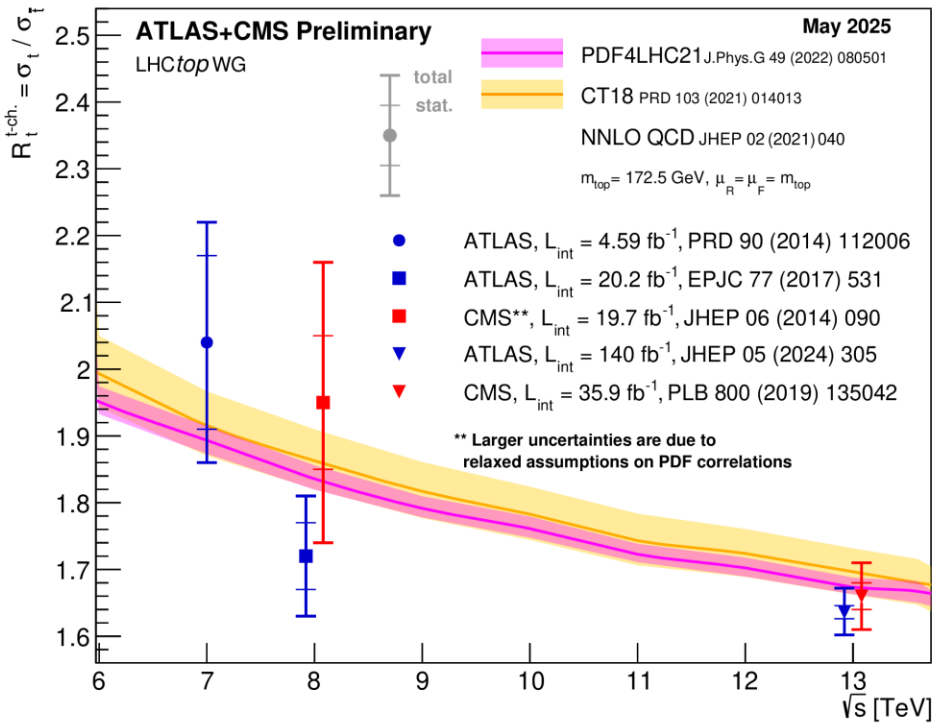


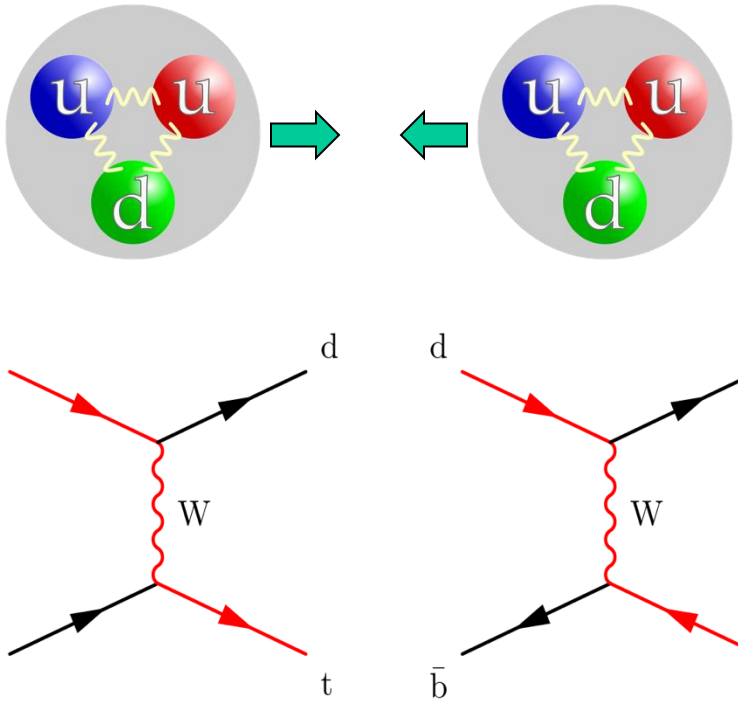
Origin of CP violation:
mater antimatter asymmetry

No significant deviation of Vtb



top and anti-top ratio in single top t-channel

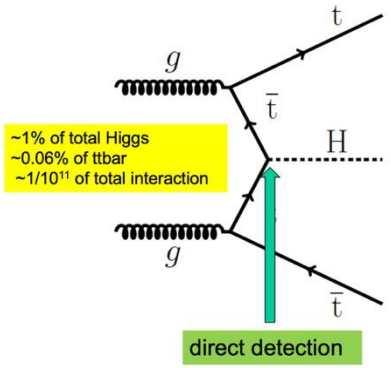


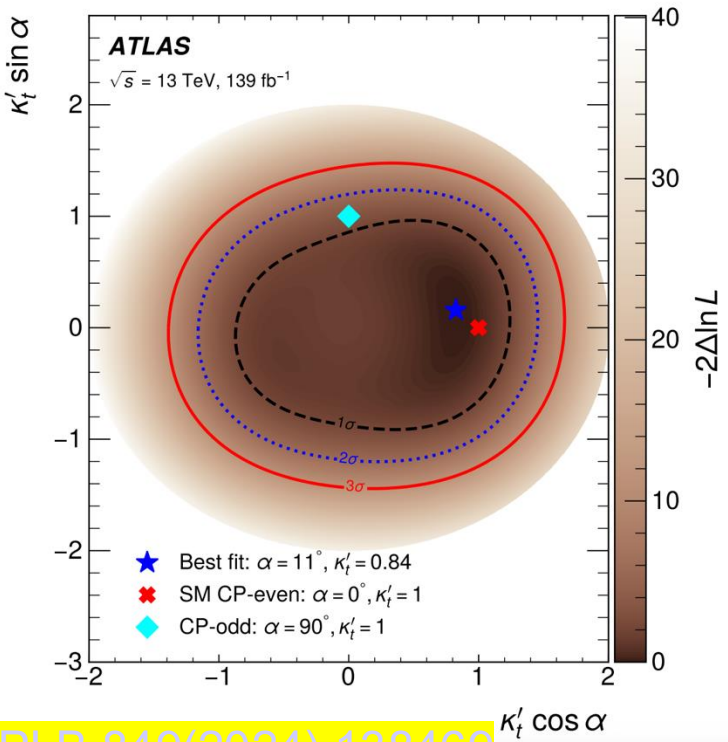


- Measure the ratio of top and anti-top t-channel production cross-section
  - Ratio of integrated u/d quark PDF
  - Compared to NNLO QCD calculations using the PDF4LHC21 and CT18 PDF sets. Uncertainties on the theoretical predictions (scale and PDF).

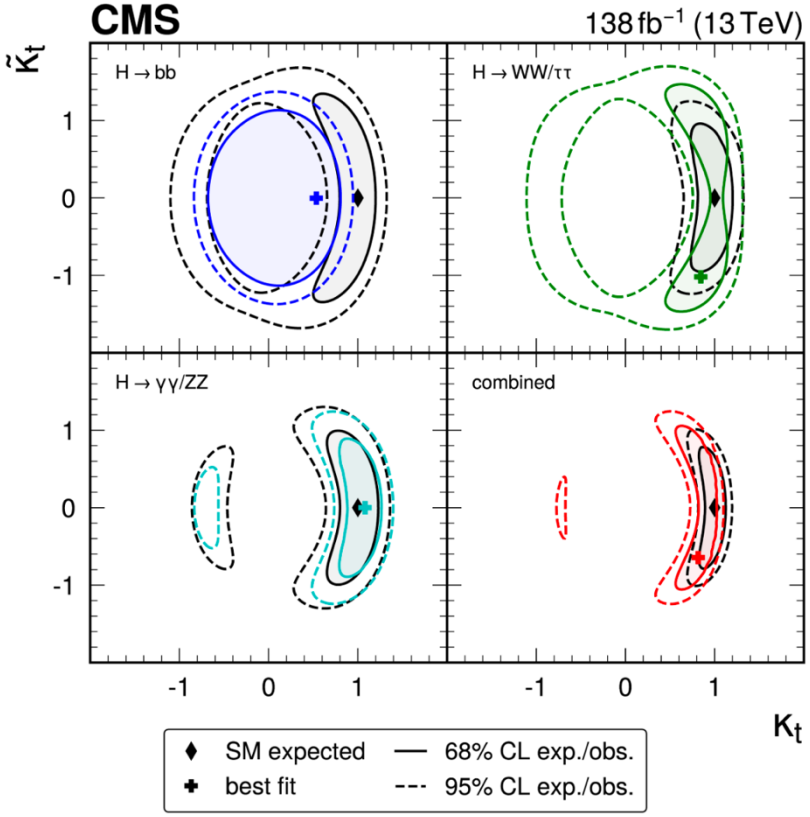
H-tt coupling and CP measurement

- Mainly via ttH, H→WW/$\tau\tau$/ ZZ/$\gamma\gamma$/bb; + tH
- Full run 2 data used
- Coupling consistent with SM:
  - Best 95% CL: $|f_{CP}|<0.85$, $\cos\alpha>0.39$





PLB 849(2024) 138469

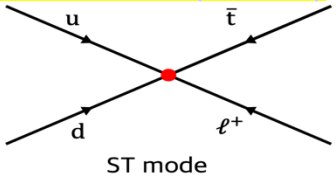


Searches for BSM signature

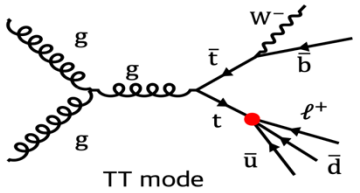
Search for baryon number violation in top decay

PRL 132, 241802 (2024)

- General effective Lagarangian for BNV
  - $$\mathcal{L}_{\text{eff}} = \frac{C_s}{\Lambda^2}\epsilon^{\alpha\beta\gamma}[\overline{t^c_\alpha} d_\gamma][\overline{u^c_\beta}\ell] + \frac{C_t}{\Lambda^2}\epsilon^{\alpha\beta\gamma}[\overline{t^c_\alpha}\ell][\overline{u^c_\beta} d_\gamma] + \text{H.c.}$$
  - Total 24 couplings(2*6*2):
    - s/t channel(2), quarks(6:u/cⓍd/s/b), leptons(2:e,μ)

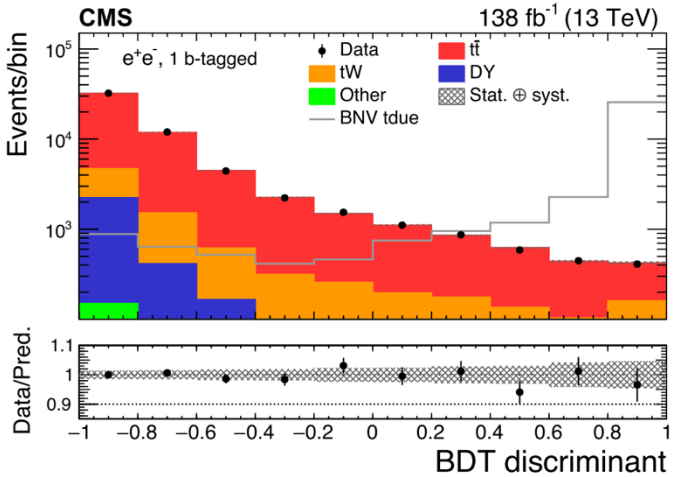


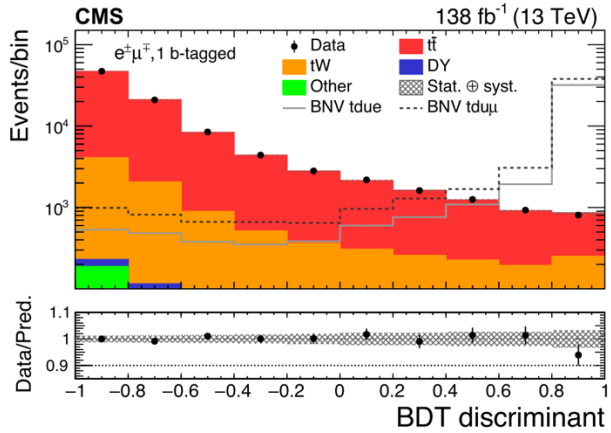
ST mode

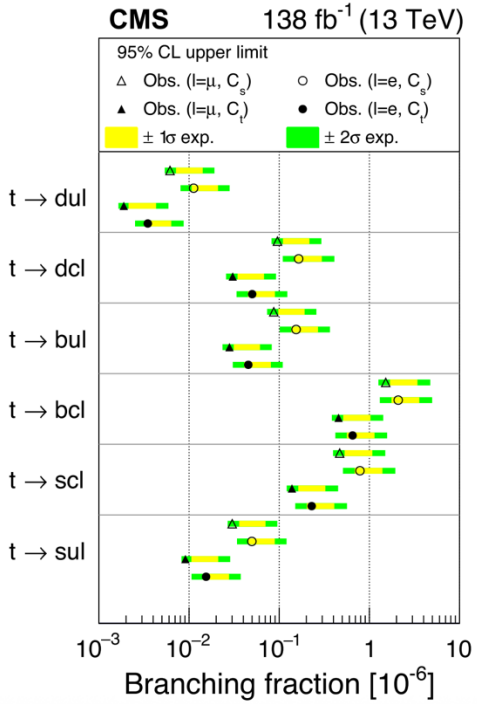


TT mode

- Full run 2 data analyzed
  - Final states with opposite sign lepton pair(ee,$\mu\mu$,eμ)
  - BDT used to separate BNV signal
  - Limits on Br: ~ 10^{-6} to 10^{-8}

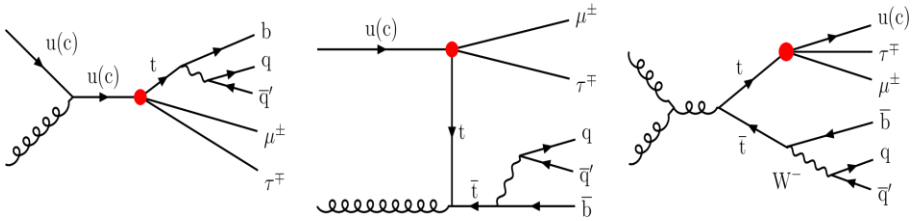




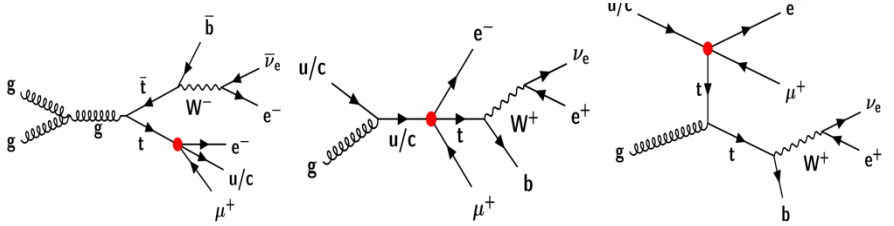


Charged lepton flavour violation in top quark decays

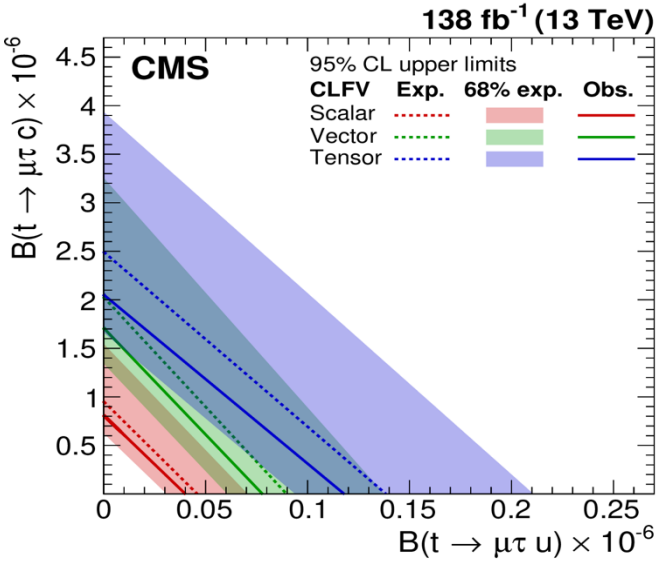
- Inspired by excessive τ decays observed in B physics
  - Can be explained by CLFV with τ lepton
  - Might be visible in top quark interactions
- Performed in trilepton final state and up quark + muon, τ lepton

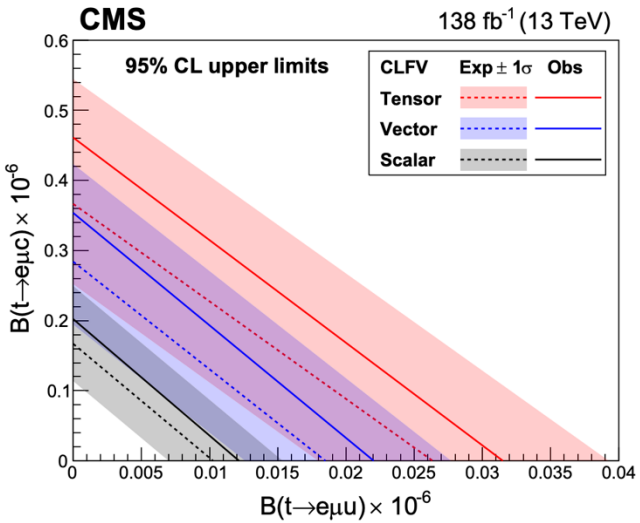


arXiv:2504.08532



PRD 111 (2025) 012009

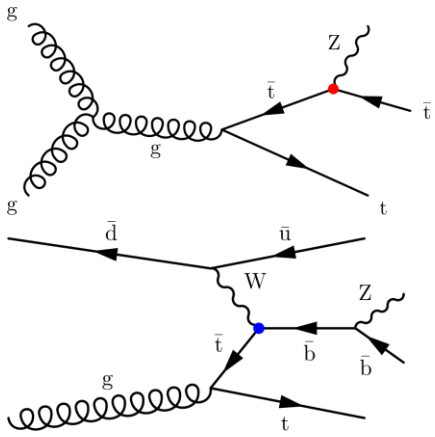


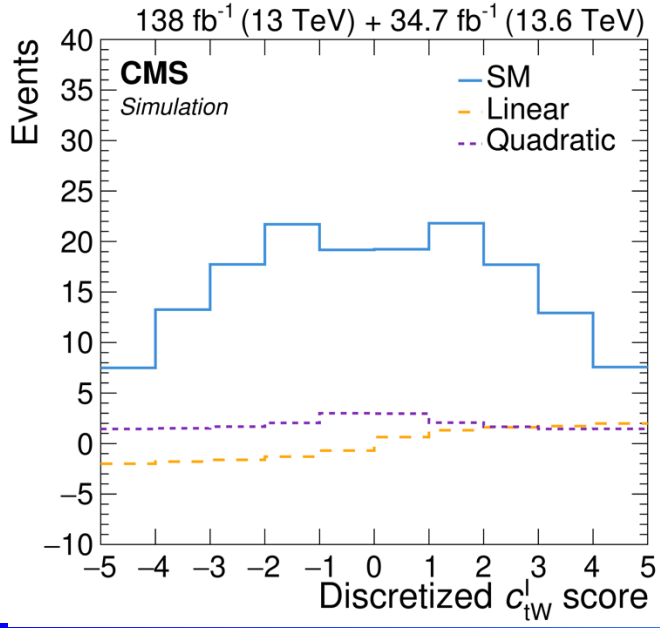


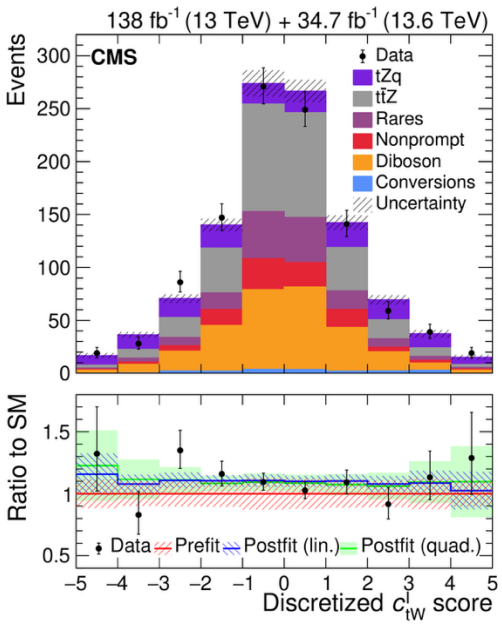
CP violation with top quarks and Z

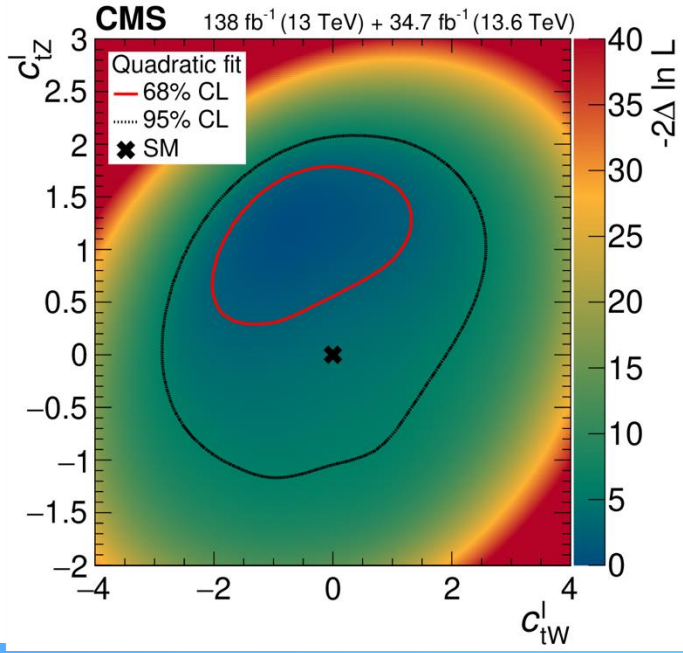
- CP violation in EFT operators (mostly CP-even observables)
  - Constructs CP-odd observables in ttZ and tZq
  - ttZ probes C^{I}_{tZ}; tZq probes C^{I}_{tW}
- Combine Run2 and Run3 173 fb^{-1} data
  - Physics-informed ML used, linear/quadratic term
- 95% CL limits
  - $-2.7 < C^{I}_{tW} < 2.5$; $-0.2 < C^{I}_{tZ} < 2.0$;

arXiv:2505.21206



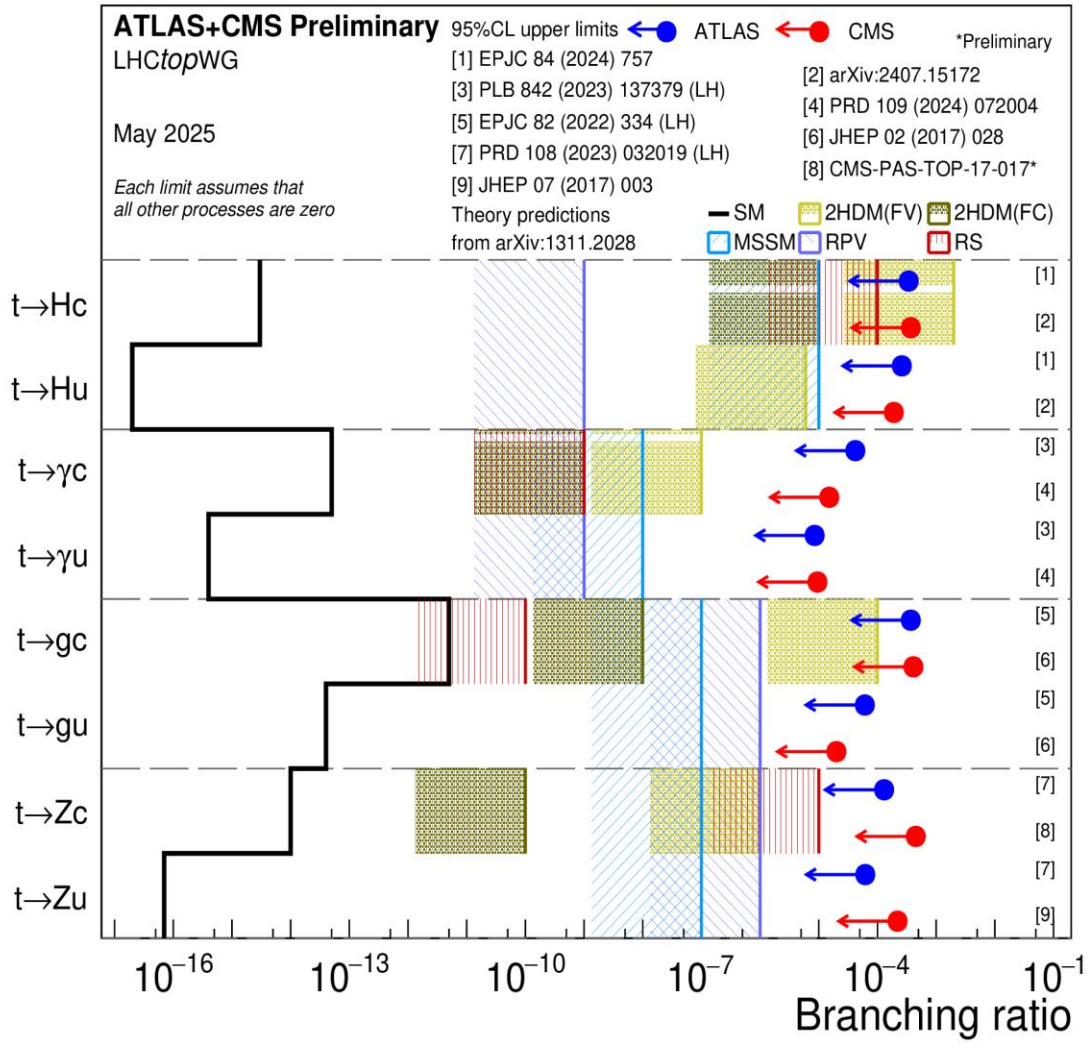






FCNC searches in top quark decays

- FCNC: ~10^{-14} @ SM
  - Forbidden at tree level
  - Strongly suppressed at higher orders via the GIM
- BSM allows FCNC
  - RPV SUSY
  - Two higgs doublets
- Various FCNC processes continiously tested
- No FCNC found so far
- Still room for BSM

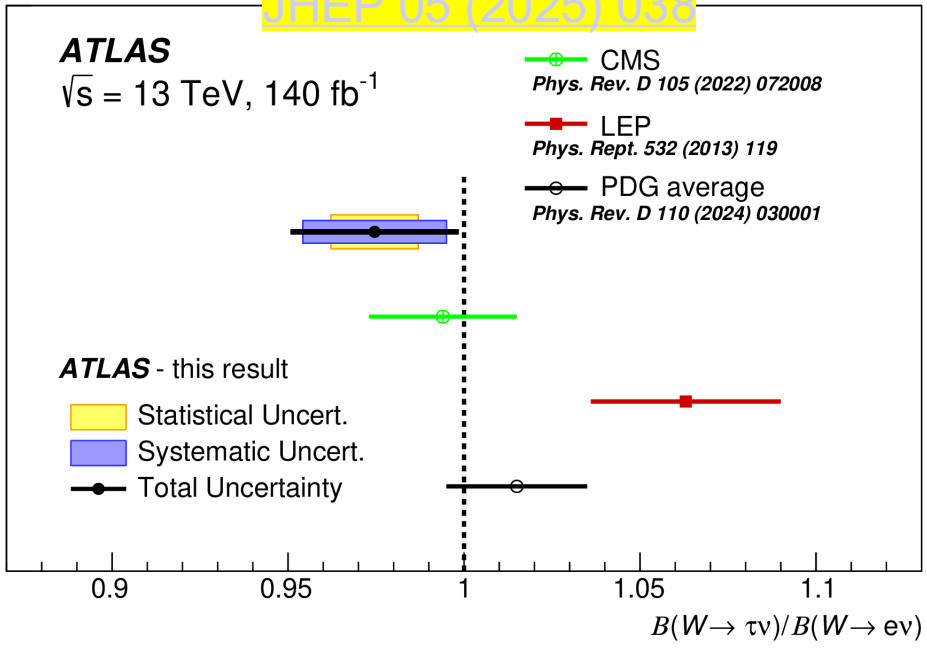


Test of lepton universality in top-decayed W

- SM assumes equal coupling of e/m/tau to W
- Top quark sample provide substantial W dataset
- Measure the ratio of $B(W \to \tau\nu)/B(W \to e\nu)$ and $B(W \to \mu\nu)/B(W \to e\nu)$
- No deviation from SM observed

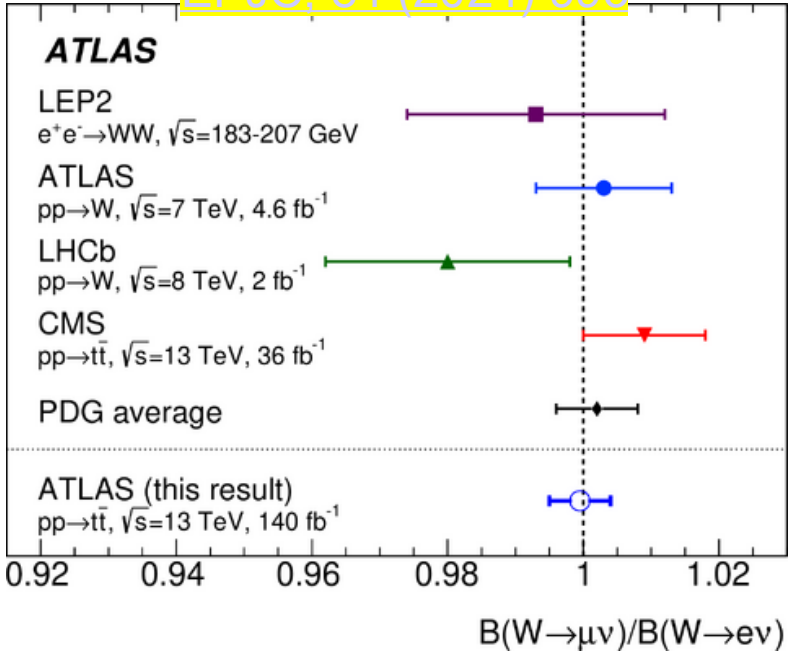
$$R^W_{\tau/e} = 0.975 \pm 0.012_{\text{stat.}} \pm 0.020_{\text{syst.}}$$

JHEP 05 (2025) 038



$$R^W_{\mu/e} = 0.9995 \pm 0.0044$$

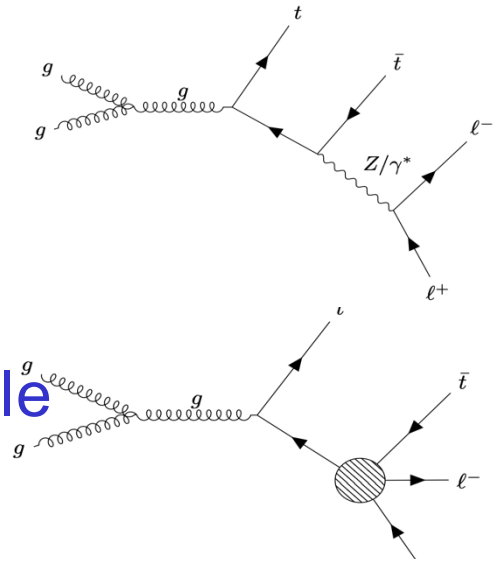
EPJC, 84 (2024) 993

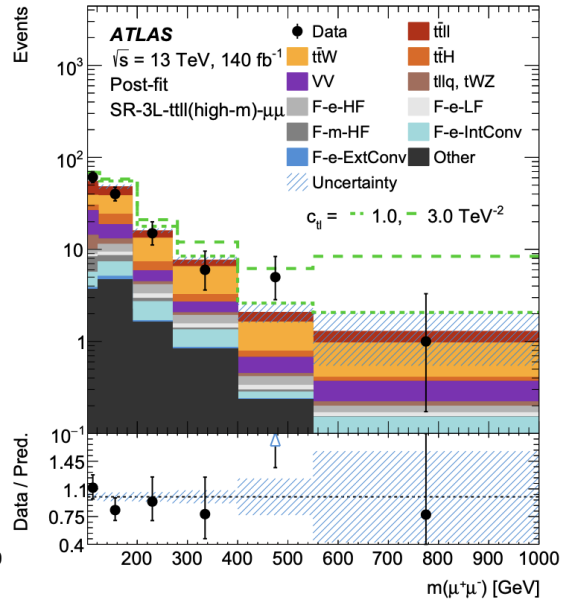


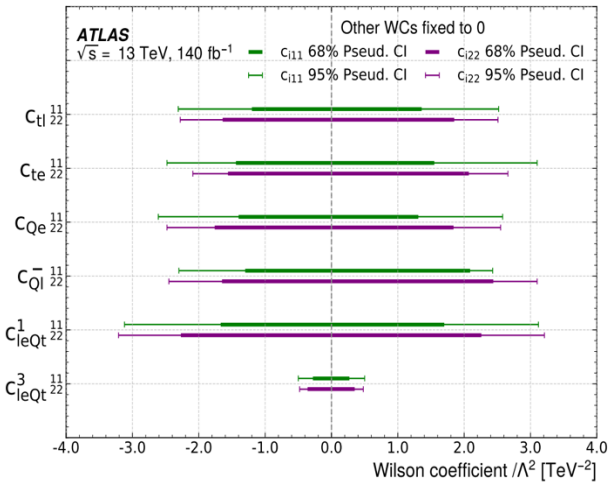
EFT interpretation on ttll

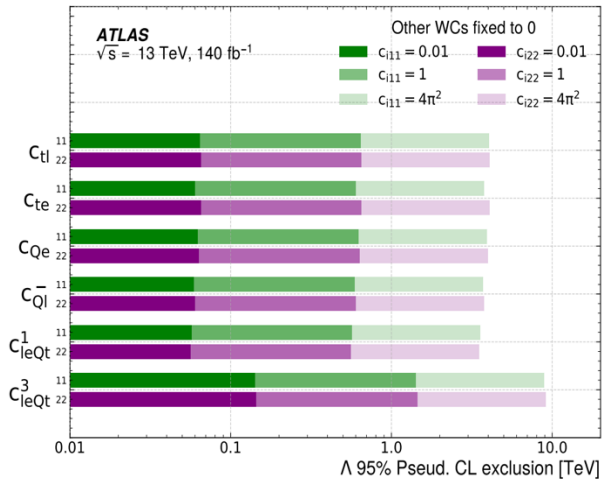
arXiv:2504.05919

- Differential measurement with Run2 data
  - EFT focus on four fermion operators
  - Focus on trip-lepton final states
  - Tagerting high mass region(m_{ll}>100GeV)
  - Separate measurement of ee/mumu for LFV
- Wilson coefficient measured, Limits on NP scale







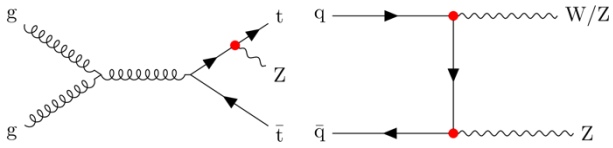


EFT interpretation on ttZ/WZ/ZZ

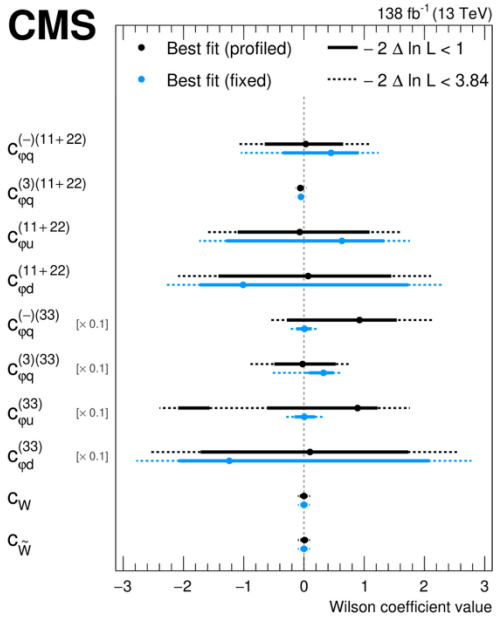
- Run 2 differential measurement with >=3l final states
  - ttZ(3l jet enriched); WZ(3l jet depleted); ZZ (4l)

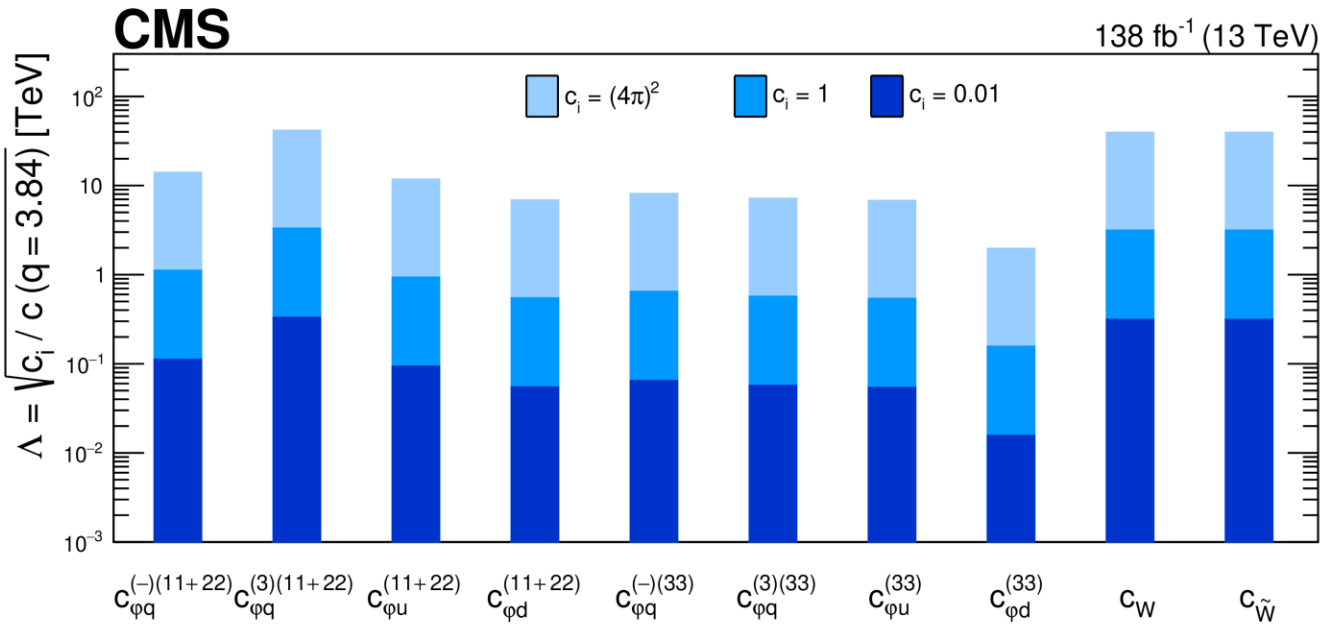
arXiv:2507.17498

- Simultaneous fit Wilson coefficient in different kinematic regions
  - Focus on quark-flavor structure
  - Distinguish with 1/2/3rd quark generations



- limits are set on the selected Wilson coefficient

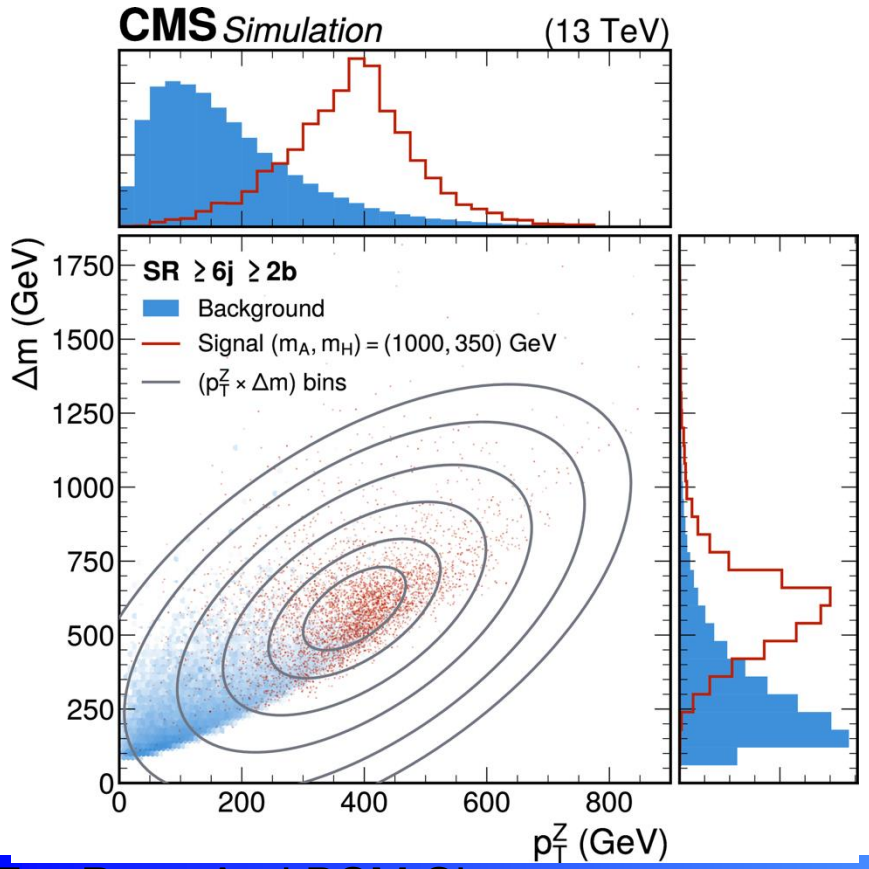


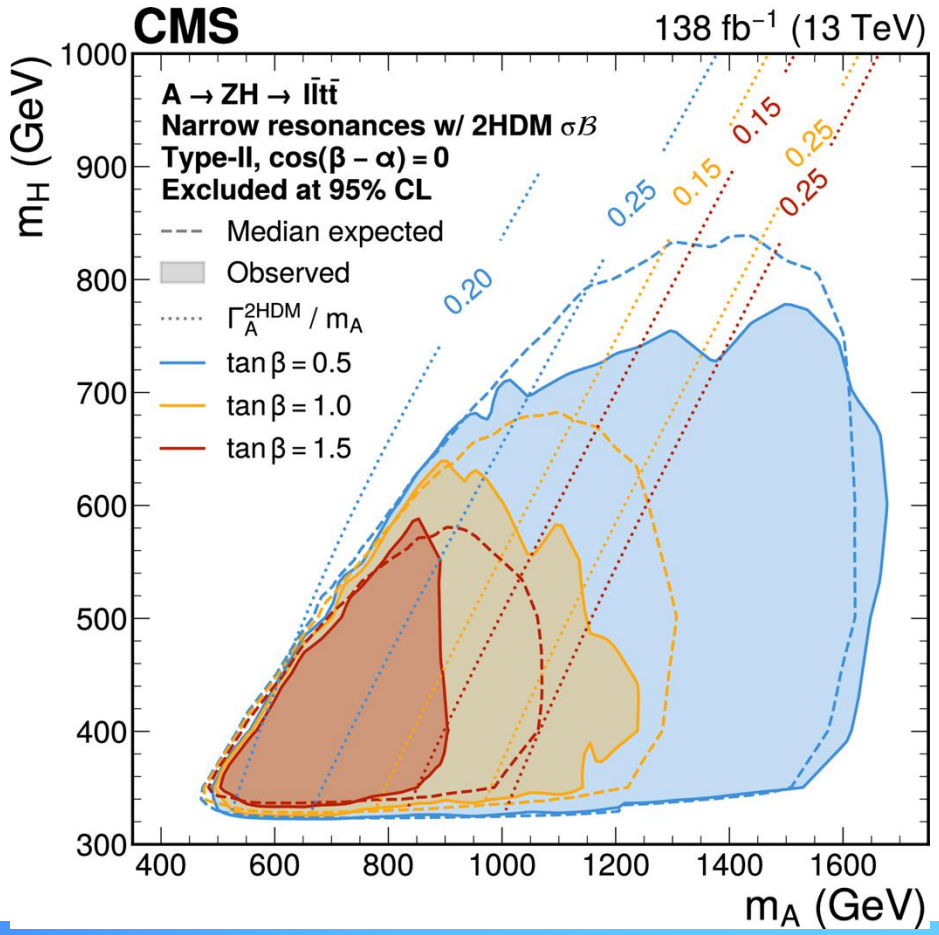


Search for heavy Higgs A and H in the ttZ channel

PLB 866 (2025) 139568

- Searching for pp→ZH(H→tt)→Ztt
- 2D simultaneous fit on (p^Z_T,Δm) for each (m_A, m_H)
  - $\Delta m = m_{t\bar{t}Z} - m_{t\bar{t}} \approx m_A - m_H$

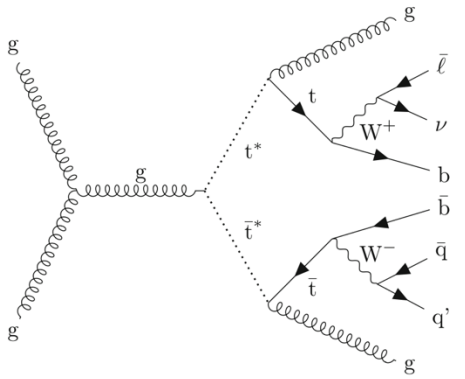


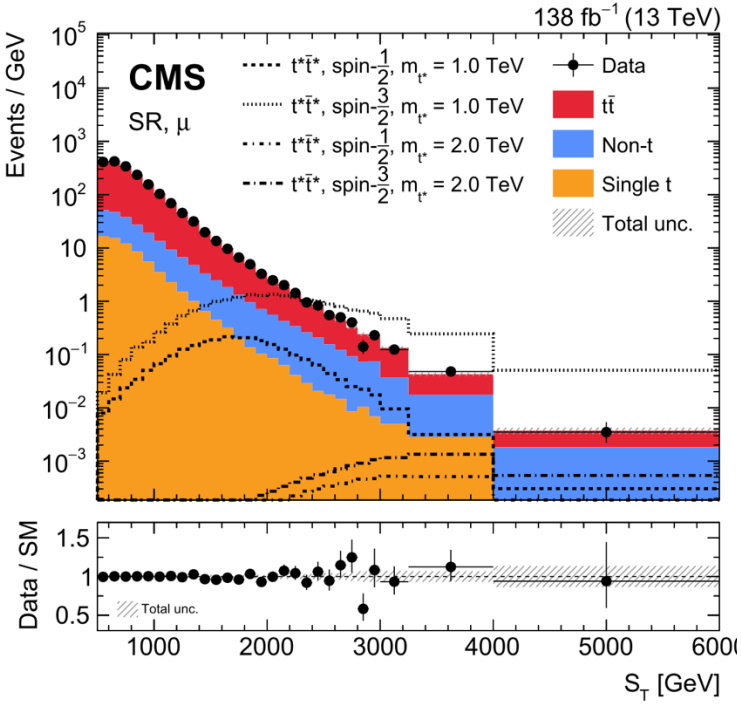


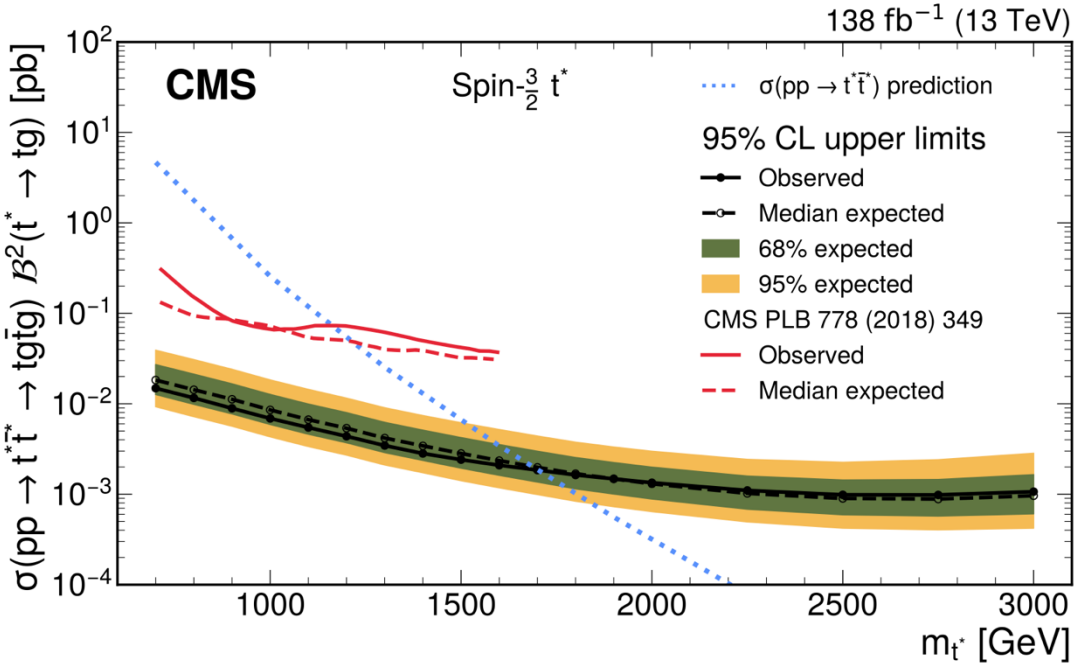
Heavy particles decaying to a top quark and a gluon

EPJC 85, 342(2025)

- Pair produced t* decay to tg
  - Spin 1/2 and 3/2 t* considered
  - Search excess on S_T distributions
    - $S_T = p_T^{\ell} + p_T^{miss} + \sum_i p_{T,i}^{jet}$
  - Exclusion @ 95 CL: <1050(1700)GeV for spin ½(3/2)



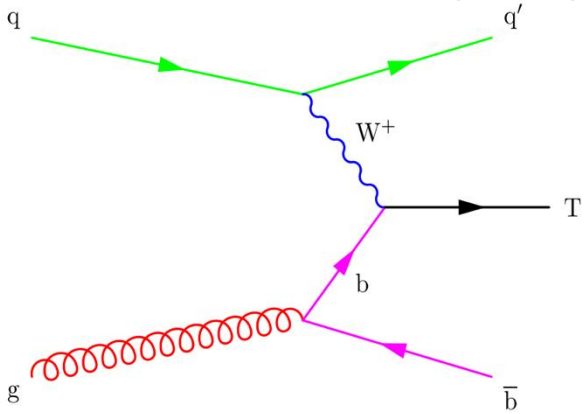


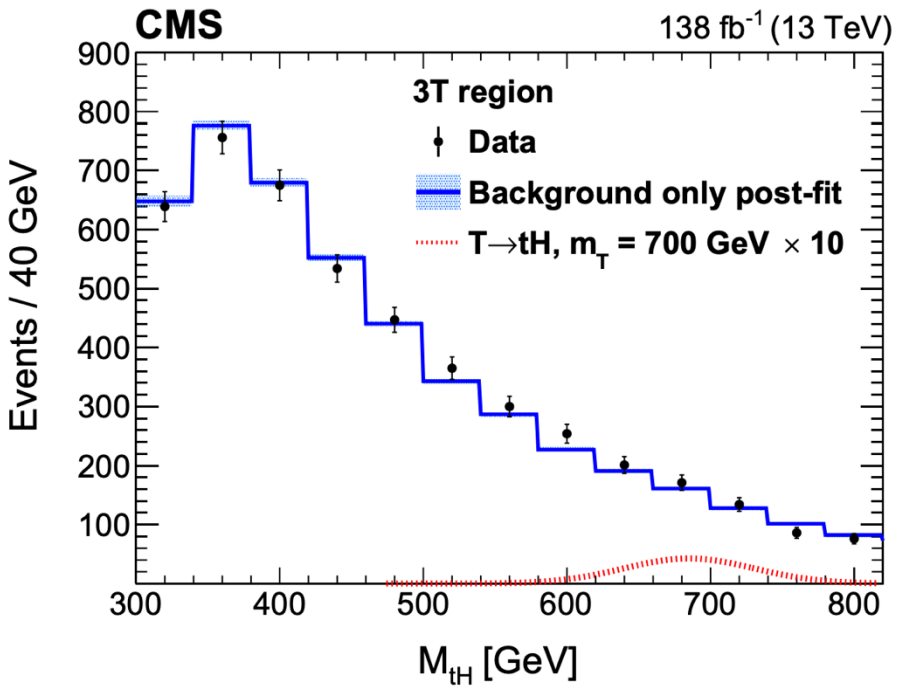


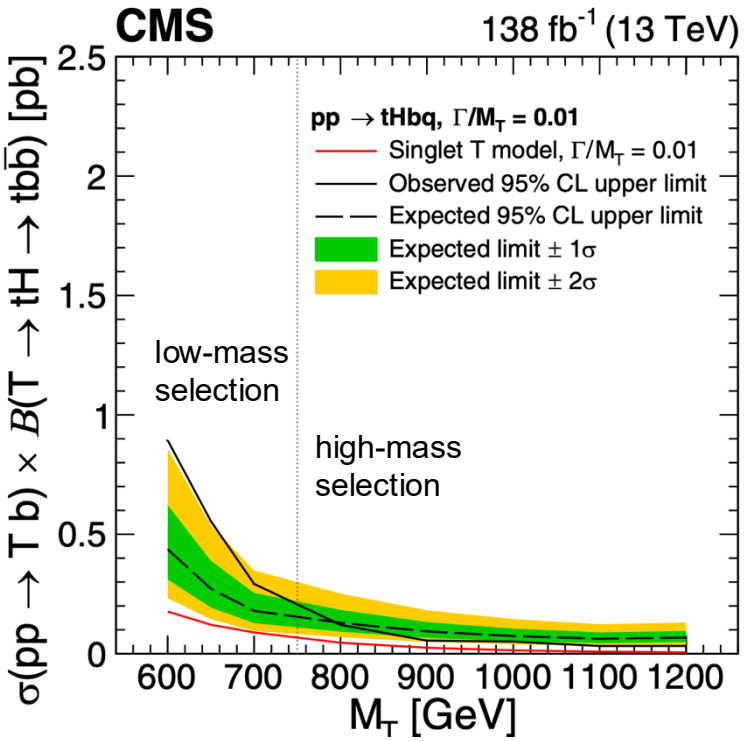
Single produced VLQ decaying to tH or tZ

PRD 110, 072012 (2024)

- VLQ T produce singly via EW process
  - T decay to tH or tZ
- All hadronic channel analyzed
- Set 95% CL limits on T production:
  - [1200-68] fb for m_T [600-1200] GeV





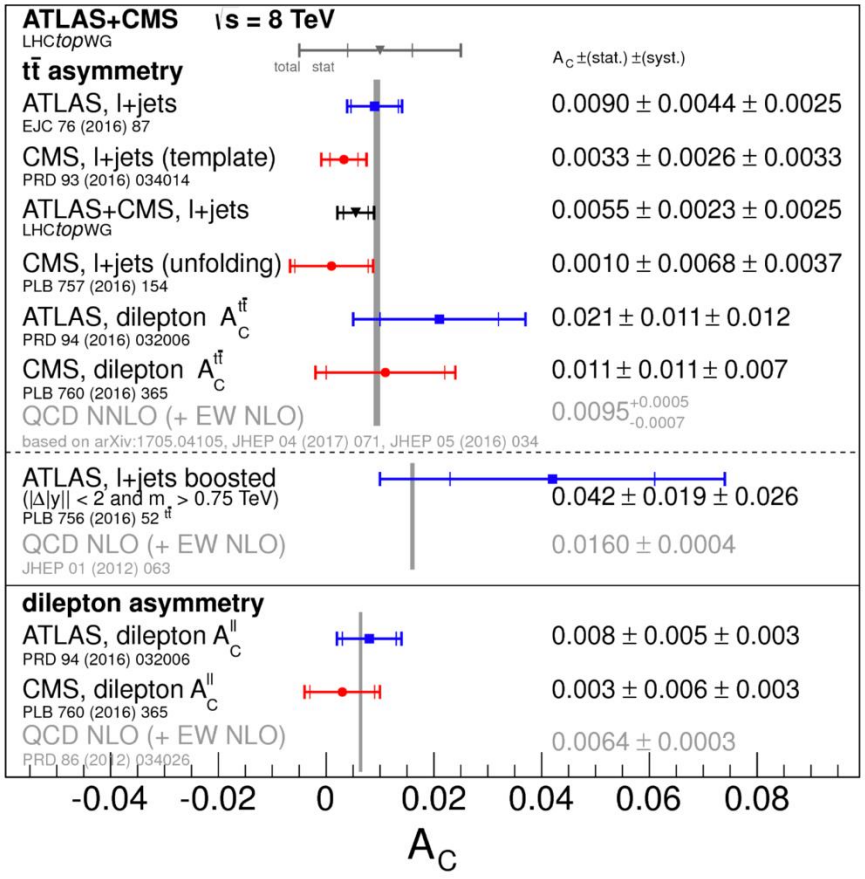


Summary

- Top quark properties measured @ LHC agrees with predictions
  - Spin density matrix coefficients measured inclusively: agree with SM
  - Coupling and CP structure with W,H boson tested: agree with SM
- BSM searches with top quark
  - Extensively checked in decays, EFT, and decay to top quark
  - No deviation observed yet
- LHC keep having largest top quark sample for next decades
  - Golden age for top quark physics at LHC
- More results come with 13.6 TeV data (mostly run2 in this talk)
  - Stay tuned

Lastes details:
https://twiki.cern.ch/twiki/bin/view/AtlasPublic/TopPublicResults
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsTOP
https://cms-results.web.cern.ch/cms-results/public-results/publications/B2G/index.html

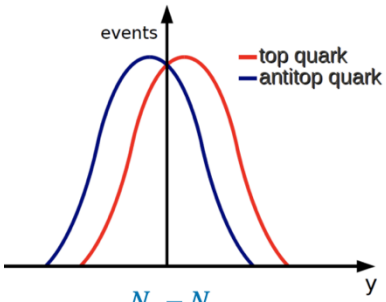
Charge asymetry in top-antitop system



$$A_C = \frac{N^{\Delta|y|>0} - N^{\Delta|y|<0}}{N^{\Delta|y|>0} + N^{\Delta|y|<0}} \qquad \Delta|y| = |y_t| - |y_{\bar{t}}|$$

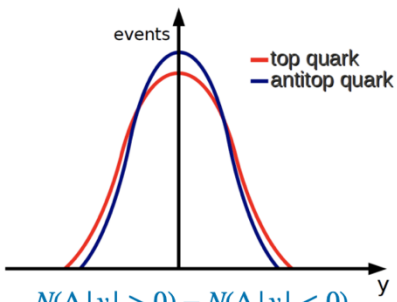
$$A_{FB}^{t\bar{t}} = \frac{N(\Delta y_{t\bar{t}} > 0) - N(\Delta y_{t\bar{t}} < 0)}{N(\Delta y_{t\bar{t}} > 0) + N(\Delta y_{t\bar{t}} < 0)} \qquad \Delta y_{t\bar{t}} = y_t - y_{\bar{t}}$$

qq anihilation

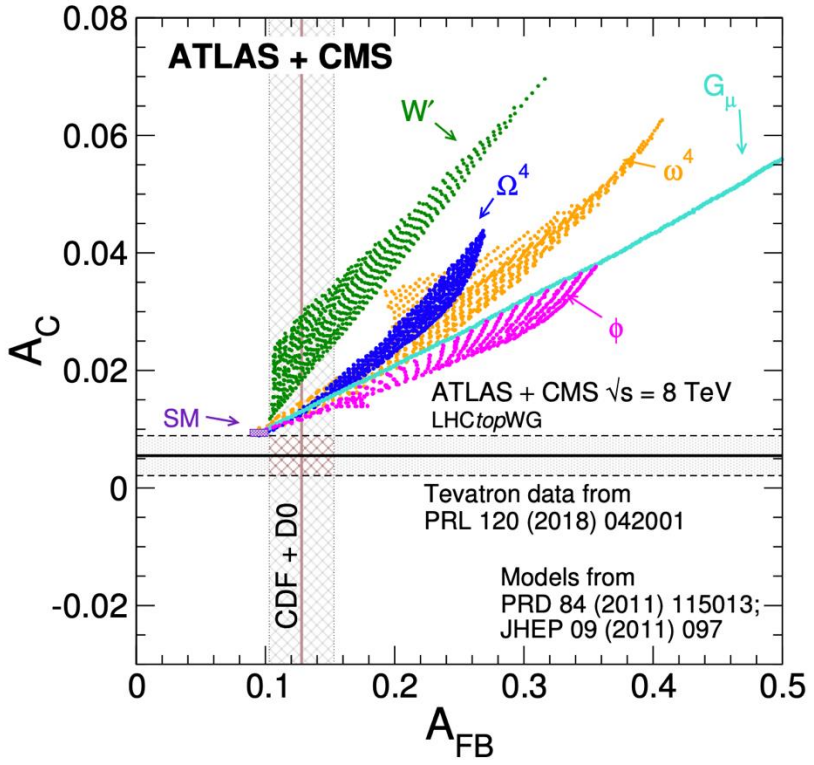


$$A_C = \frac{N_F - N_B}{N_F + N_B}$$

gg fusion

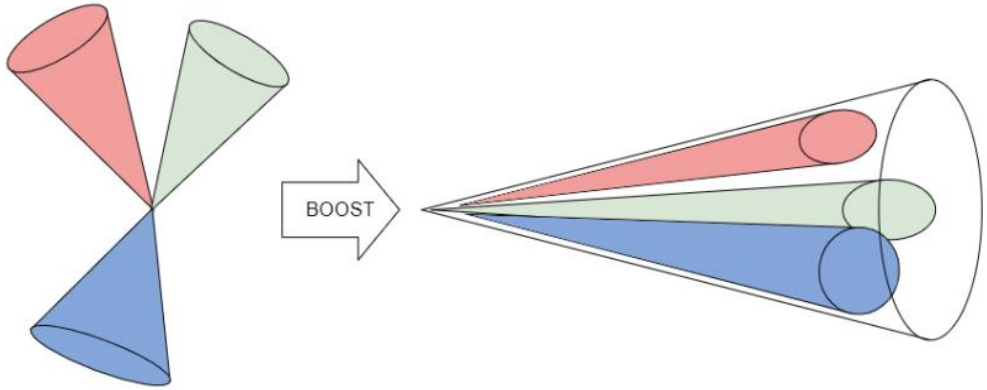


$$A_C = \frac{N(\Delta|y|>0) - N(\Delta|y|<0)}{N(\Delta|y|>0) + N(\Delta|y|<0)}$$



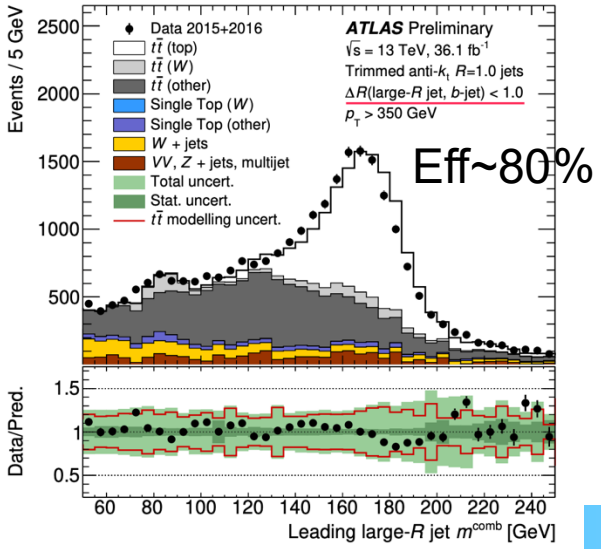
Top tagger / boost top

- Super heavy particle decay to top quark: boosted top

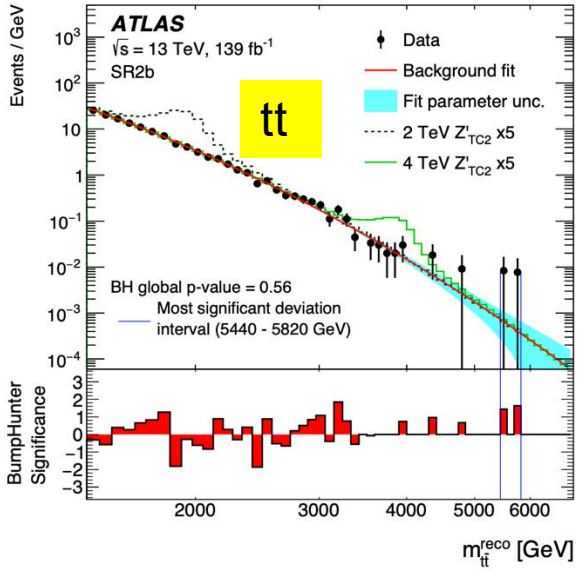


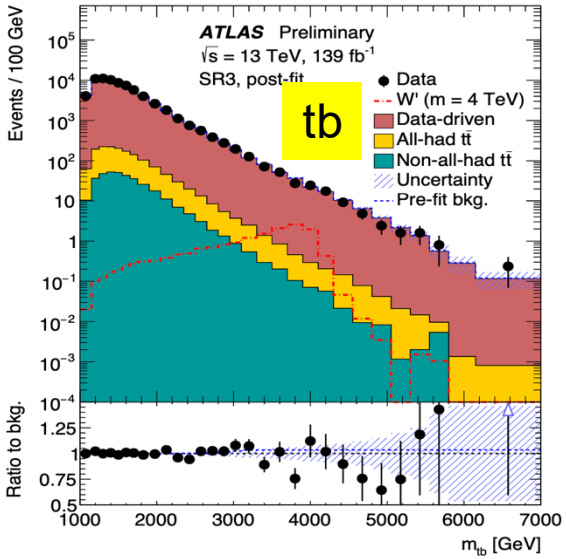
Top jets

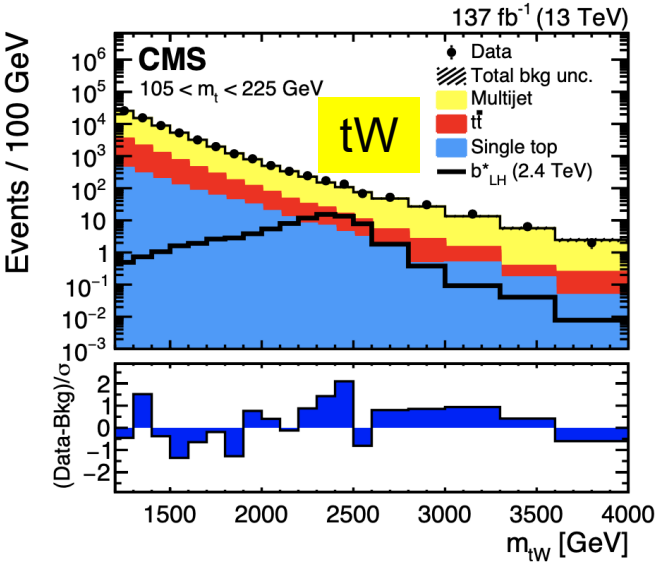
Algorithm	Subsection	jet p_T [GeV]	t quark	W boson	Z boson	H boson
$m_{SD} + \tau_{32}$	6.1	400	✓			
$m_{SD} + \tau_{32} + b$	6.1	400	✓			
$m_{SD} + \tau_{21}$	6.1	200	✓	✓		
HOTVR	6.2	200	✓			
N_3-BDT (CA15)	6.3	200	✓			
$m_{SD} + N_2$	6.3	200		✓	✓	✓
BEST	6.5	500	✓	✓	✓	✓
ImageTop	6.6	600	✓			
DeepAK8(*)	6.7	200	✓	✓	✓	✓
ParticleNet [1]		200	✓	✓	✓	✓

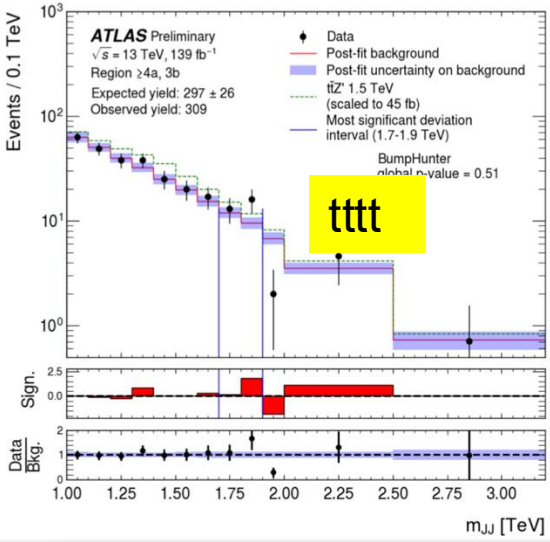


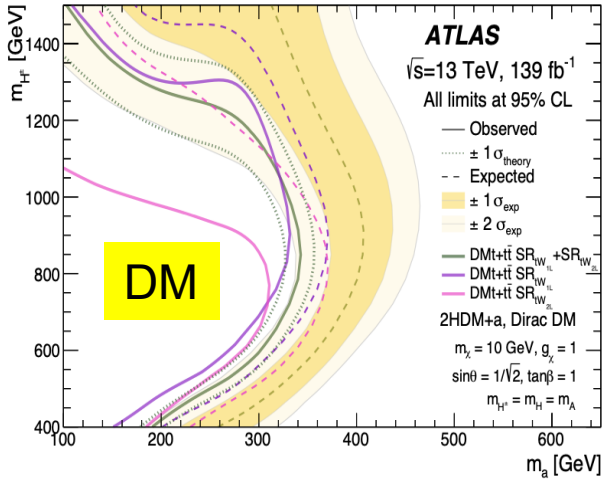
Selected New physics with boosted top quarks

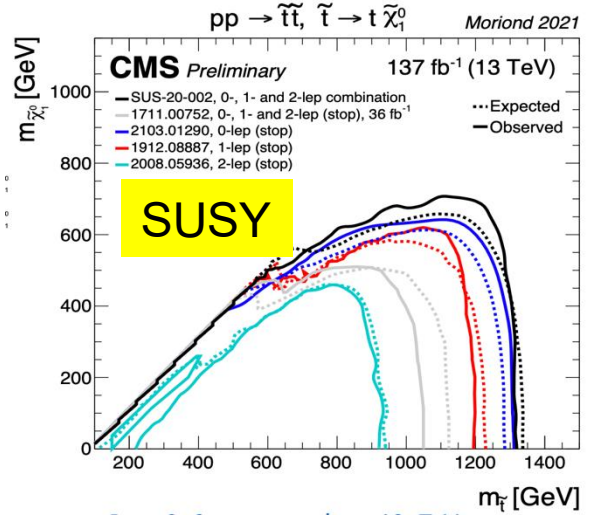












- New heavy resonance couples to top quark
  - Decay to top quark or associate produced with top quark