FCNC and EFT interpretations in top quark events at CMS

ICHEP 2020

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on behalf of the CMS Collaboration

Motivation for new physics (NP)

- The usual suspects – compelling motivations for physics beyond Standard Model:
  1. Strong astrophysical evidence for **dark matter & dark energy**
  2. Aspects of SM are theoretically unsatisfying:
     - **Hierarchy problem:** why is there such a discrepancy between Higgs mass, $\mathcal{O}(10^2)$ GeV, and Planck mass $\mathcal{O}(10^{19})$ GeV?
     - **Matter–antimatter asymmetry:** the amount of CP violation observed in the weak interaction cannot account for the observed dominance of matter over antimatter in the universe.
     - **Strong CP problem:** the QCD Lagrangian permits CP-violating terms, but no observed evidence of CP violation in the strong interaction.

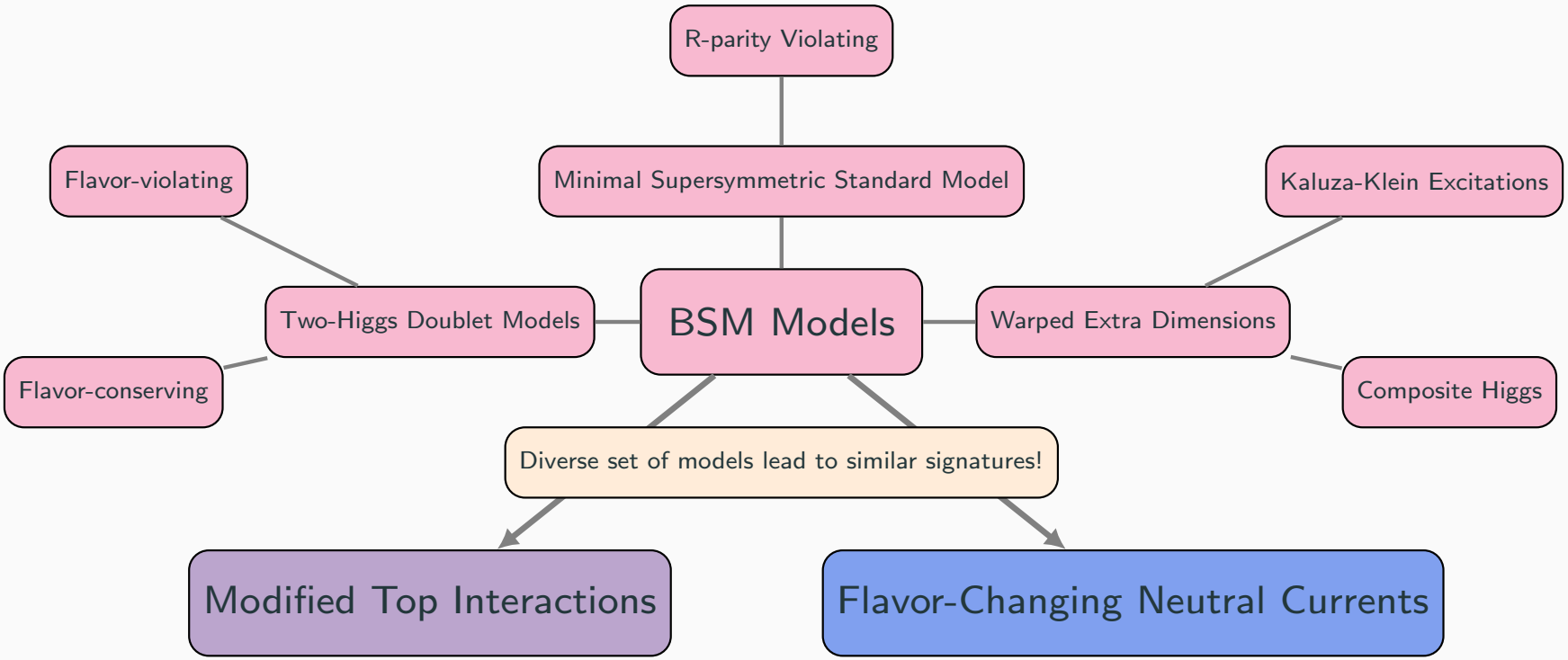
- So, why haven't we found NP at the LHC?

$\Lambda_{\text{NP}} > E_{\text{LHC}}$?

Perhaps the scale of NP is beyond the energies accessible at the LHC.

New physics at $\Lambda_{\text{NP}} > E_{\text{LHC}}$ through the top quark

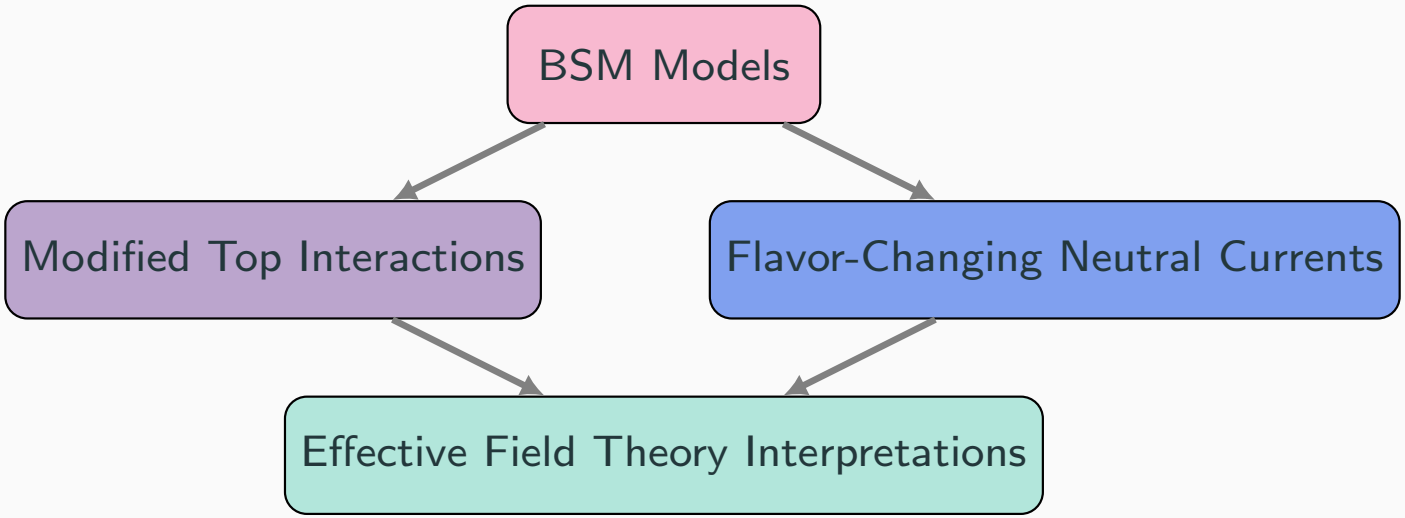
- How can we observe signatures of new physics models which live at energy scales beyond E_{LHC}? Through the top quark!
  - Many BSM theories result in **measurable** deviations of the top quark's couplings and/or allow for interactions forbidden in the SM at **rates accessible at the LHC**.



Effective Field Theory Interpretations

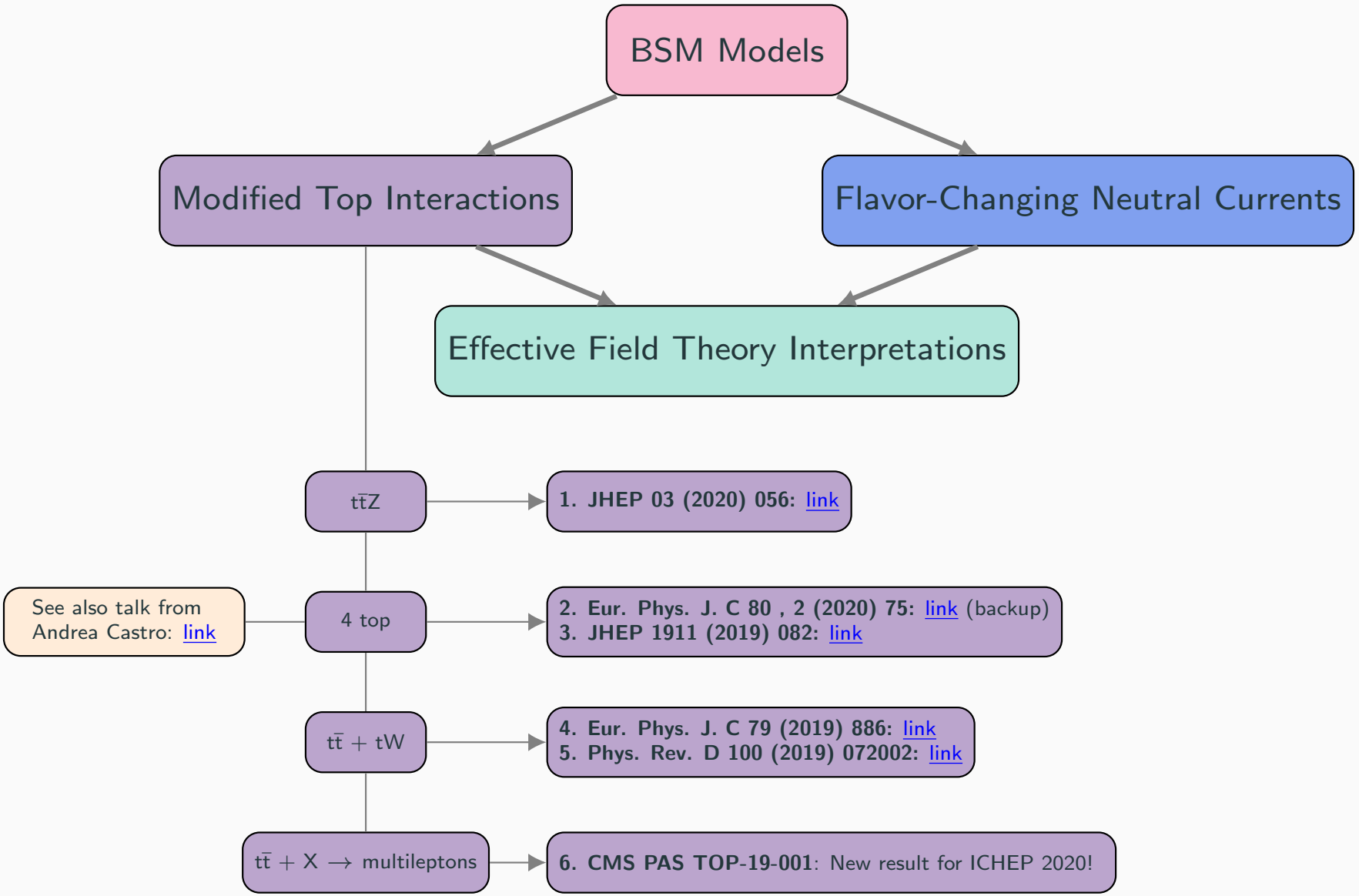
- Given plethora of BSM theories, how can we **interpret the results of top quark measurements in a unified, consistent way**?
  - **Effective Field Theory Interpretations:** express any deviations from SM in terms of coefficients on higher-dimensional operators.

$$\mathcal{L} = \mathcal{L}_{\text{SM}} + \underbrace{\frac{1}{\Lambda}\sum_k C_k^{(5)} O_k^{(5)}}_{\text{dim-5: neutrino masses, lepton number violation, don't couple to top quarks [1]}} + \underbrace{\frac{1}{\Lambda^2}\sum_k C_k^{(6)} O_k^{(6)}}_{\text{dim-6: CM/CE dipole moments, FCNC, etc}} + \mathcal{O}\left(\frac{1}{\Lambda^3}\right) \tag{1}$$



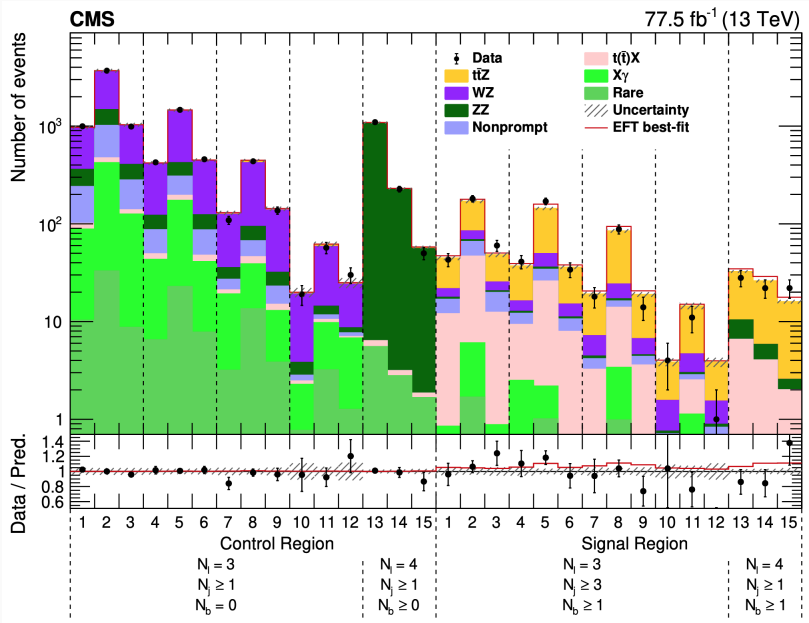
Results at CMS: Modified Top Interactions & EFT Interpretations

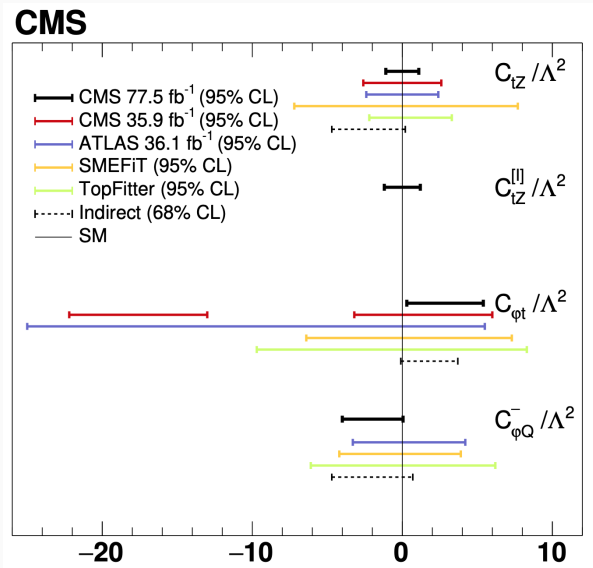
Modified Top Interactions & EFT Interpretations



EFT in top-Z Interactions

- **JHEP 03 (2020) 056:** link
- Inclusive and differential ($d\sigma/dp_T^Z$, $d\sigma/d\cos\theta_Z^*$) cross section measurements of $t\bar{t}Z$ production in $3l/4l$ final states with 77.5 fb^{-1}.
- **Core EFT strategy**: Simulation of LO samples in fine grid of WC parameter space $\Longrightarrow$ derive 2d reweighting of NLO $t\bar{t}Z$ sample in p_T^Z and $\cos\theta_Z^*$ to produce predictions parametrized by WC values.
  - Constraints on WC determined through fit to observed yields in data.
- Constraints on dim-6 Wilson coefficients:
  - **Electroweak dipole moments**: $C_{tZ}, C_{tZ}^{[I]}$
  - **Anomalous neutral current interactions**: $C_{\phi t}$, $C_{\phi Q}^-$

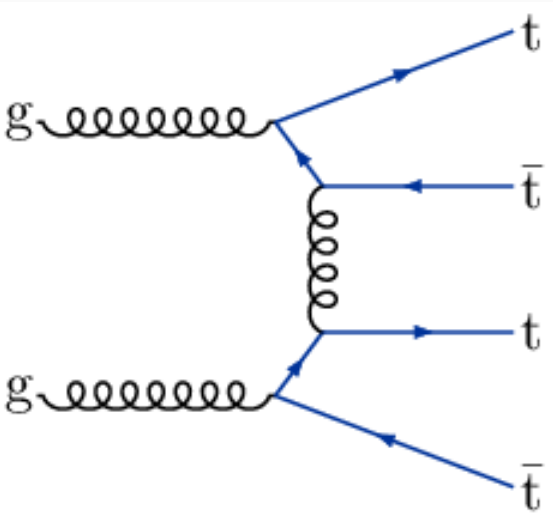


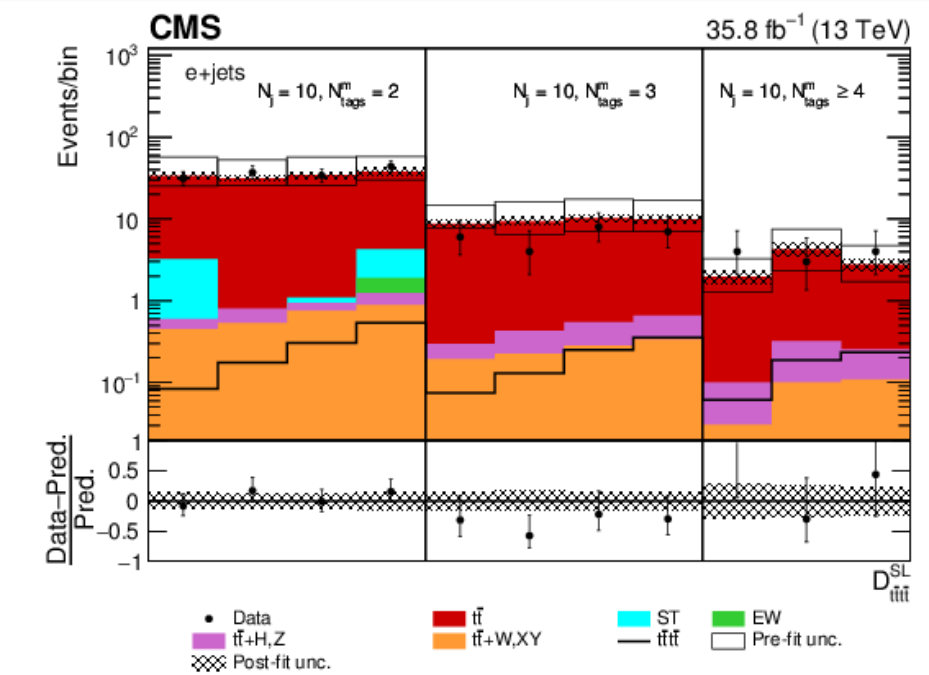


EFT + BSM interpretations of 4-top searches

- **JHEP 1911 (2019) 082:** link
- See also talk from Andrea Castro: link
- 35.8 fb^{-1}, $1l$ and $2l$ (OS) final states with additional jets.
- Selection based on additional BDTs trained on event-level kinematics (single lepton BDT shown on right).
- **Reinterpretation of cross section upper limit:** provide constraints on EFT operators contributing to 4-top production:

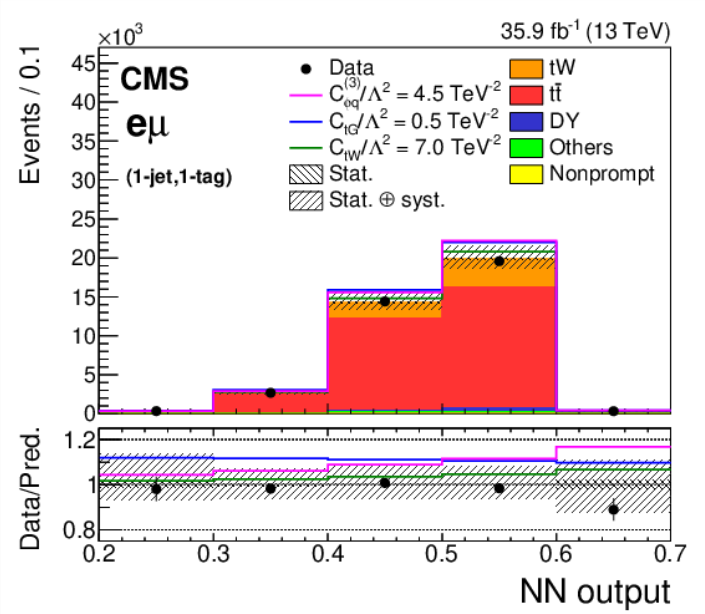
Operator	Expected C_k/Λ^2 (TeV^{-2})	Observed (TeV^{-2})
$\mathcal{O}^1_{tt}$	$[-1.5, 1.3]$	$[-2.1, 2.0]$
$\mathcal{O}^1_{QQ}$	$[-1.5, 1.3]$	$[-2.2, 2.0]$
$\mathcal{O}^1_{Qt}$	$[-2.4, 2.4]$	$[-3.5, 3.5]$
$\mathcal{O}^8_{Qt}$	$[-5.6, 4.3]$	$[-7.9, 6.6]$

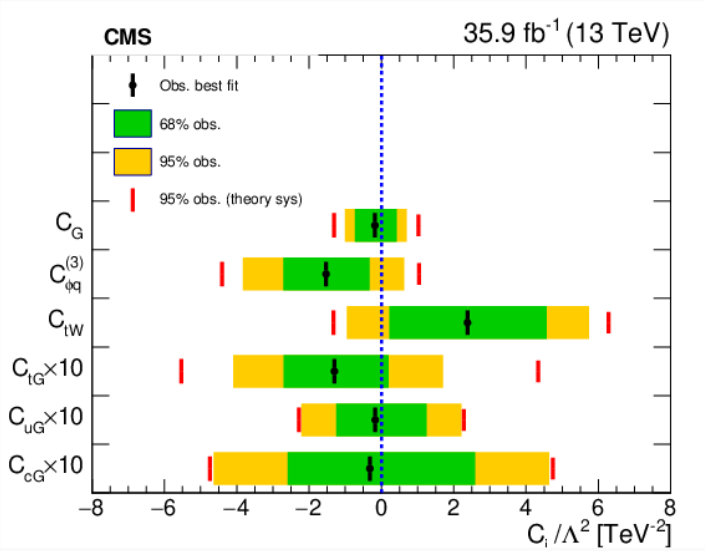




New interactions with $t\bar{t}$ & tW $\rightarrow ll$

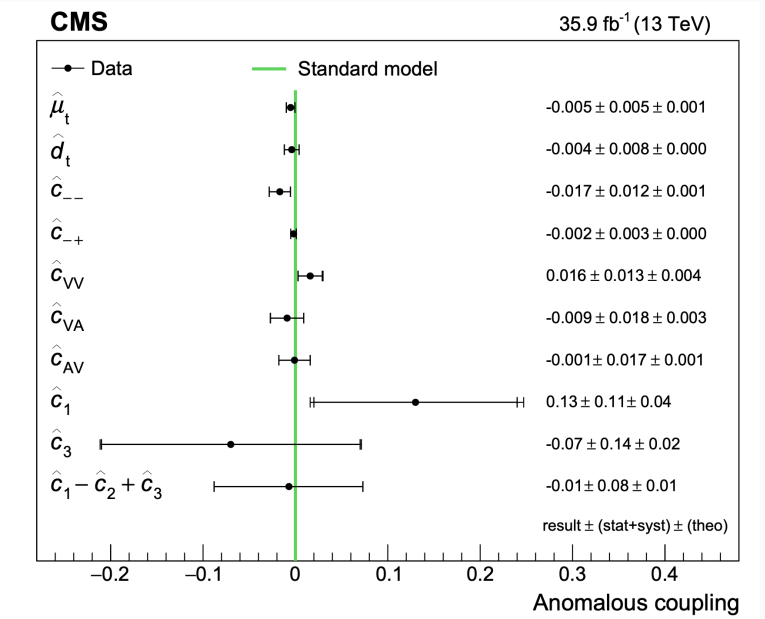
- **Eur. Phys. J. C 79 (2019) 886:** link
- 35.9 fb^{-1}, OS dilepton + b-jets.
- Neural network trained to separate $t\bar{t}$ and tW events $\implies$ exploits sensitivity of tW to NP (top right).
- **Core EFT approach:** $t\bar{t}$ & tW processes are simulated to detector level *under presence of new effective interactions*.
  - Fitted values, correlations, and uncertainties of WCs determined directly from data.
- Constraints on Wilson coefficients:
  - **Wtb coupling:** $C_{\phi q}^{(3)}$, C_{tW}
  - **Triple gluon strength operator:** C_{g}
  - **Chromomagnetic dipole moment:** C_{tg}
  - **FCNC:** C_{ug}, C_{cg}

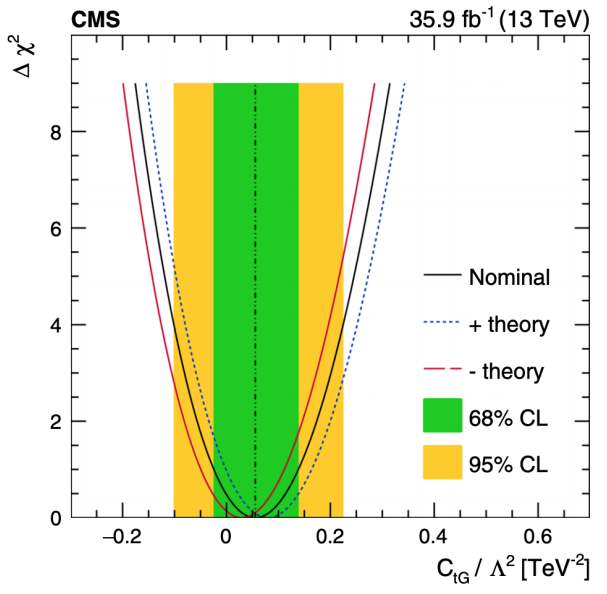




Top quark polarization and $t\bar{t}$ spin correlations

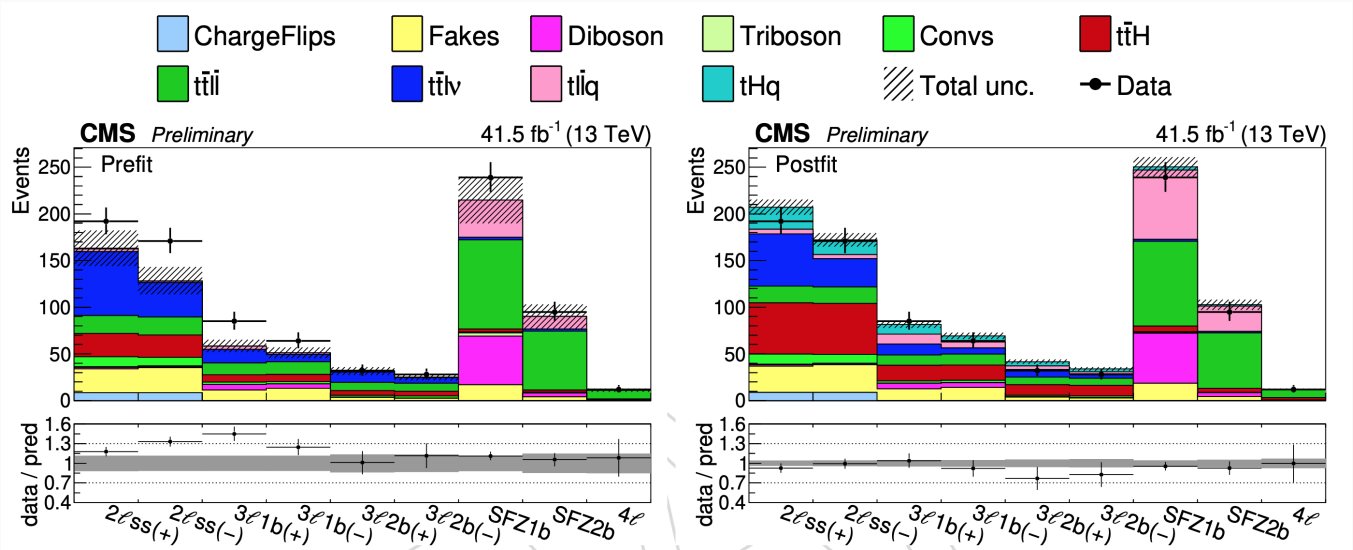
- **Phys. Rev. D 100 (2019) 072002:** link
- 35.9 fb^{-1}, OS dilepton + b-jets final states.
- Expand polarization vectors and spin-correlation matrix into orthonormal basis & probe through differential cross section measurements.
  - Deviations from SM prediction would be indications of BSM effects.
- **EFT Interpretation:** derive constraints on dim-6 operators involved in $t\bar{t}$ production, including $O_{tG} \implies$ anomalous chromomagnetic dipole moment (CMDM).
- Express corresponding WC, C_{tG}, in terms of polarization and spin correlation coefficients.
- Predicted yields parametrized as a function of C_{tG} and best-fit value and uncertainties are extracted from a χ^2 fit to data.





Novel EFT Approach with $t\bar{t} + X \rightarrow$ multilepton (1/3)

- **CMS PAS TOP-19-001:** new result!
- Analysis targets single top and $t\bar{t}$ production in association with W, Z, or H, requiring b-jets and multiple leptons: 2l (SS), 3l and 4l in final states.
- **Novel approach to EFT:** rather than search for specific processes, parametrize predicted event yields for *all* relevant processes in terms of *all* relevant WCs.
  - Examine event yields as a function of N_{leptons}, N_{jets}, and $N_{\text{b-jets}}$: different composition of underlying physics processes in each category $\implies$ sensitivity to a wide range of EFT operators!

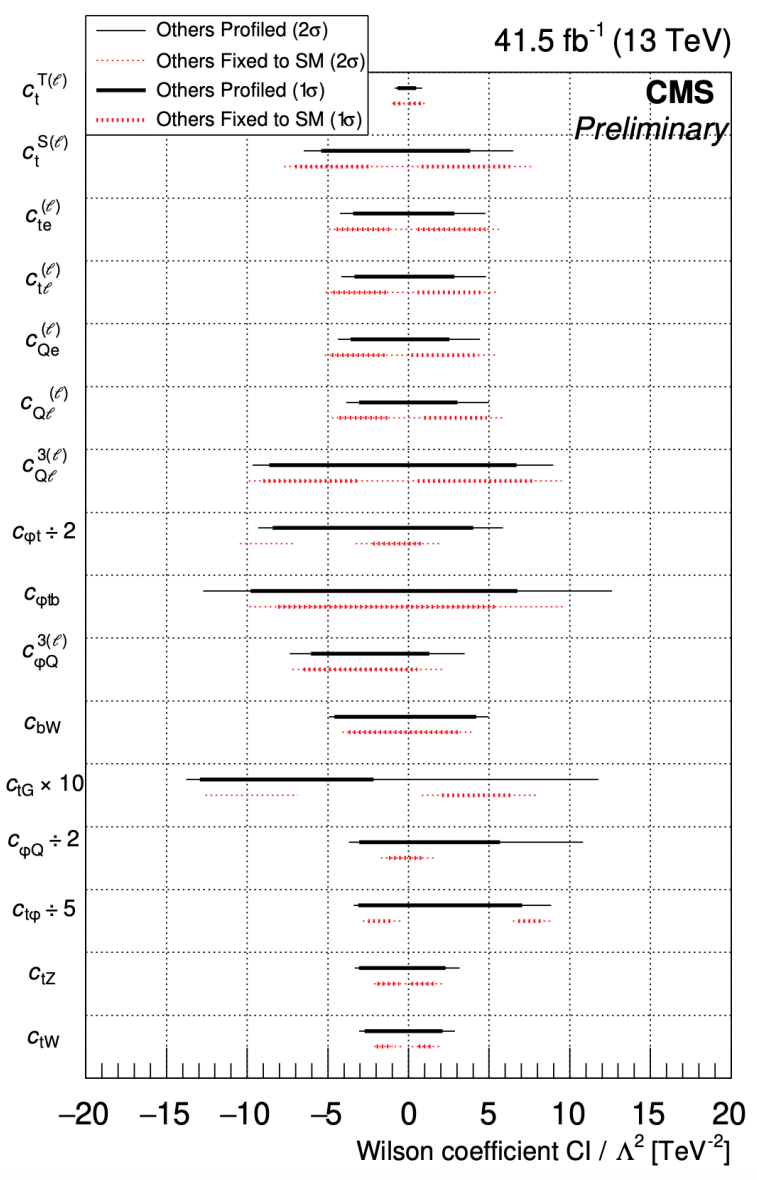


Novel EFT Approach with $t\bar{t} + X \rightarrow$ multilepton (2/3)

- **CMS PAS TOP-19-001:** new result!
- EFT Parametrization: yields for processes with prompt leptons taken from simulation & parametrized as a function of WCs for all relevant EFT operators for that process. Processes with non-prompt leptons predicted with extrapolation from control regions.
- Can express matrix element as sum of SM and BSM contributions:

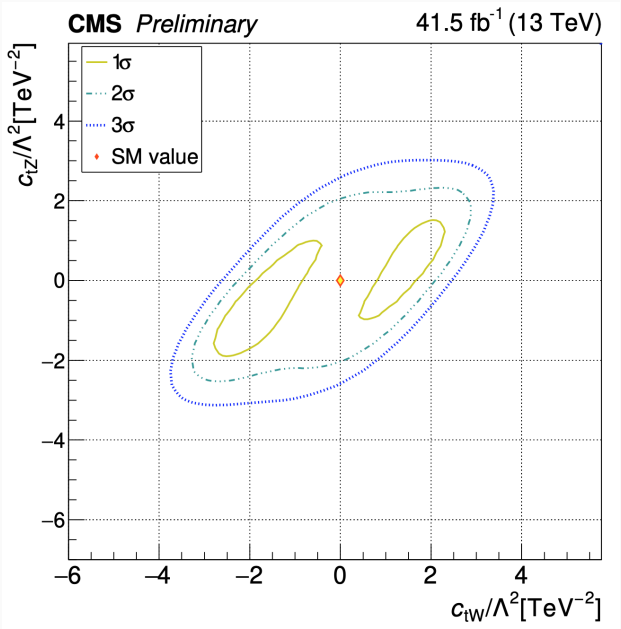
$$\mathcal{M} = \mathcal{M}_{\text{SM}} + \sum_i \frac{c_i}{\Lambda^2} \mathcal{M}, \qquad (2)$$

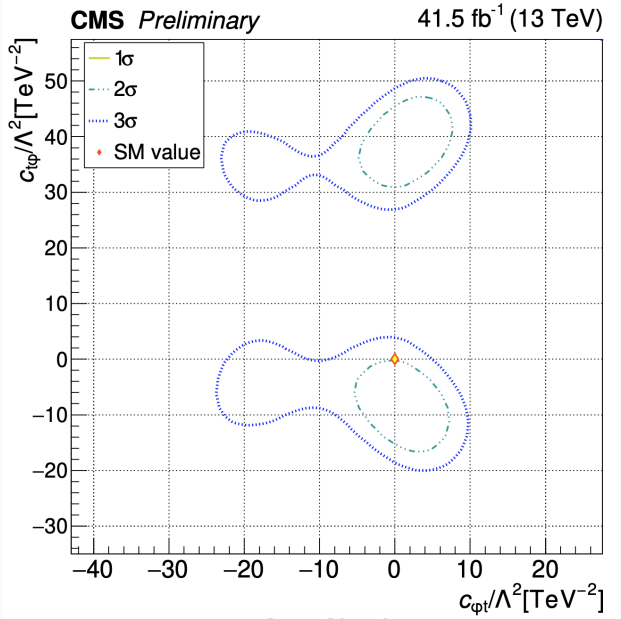
- and this can be translated to predicted event yields for each category which are a function of the 16 relevant WCs: $N = N(\vec{c}/\Lambda^2)$.



Novel EFT Approach with $t\bar{t} + X \rightarrow$ multilepton (3/3)

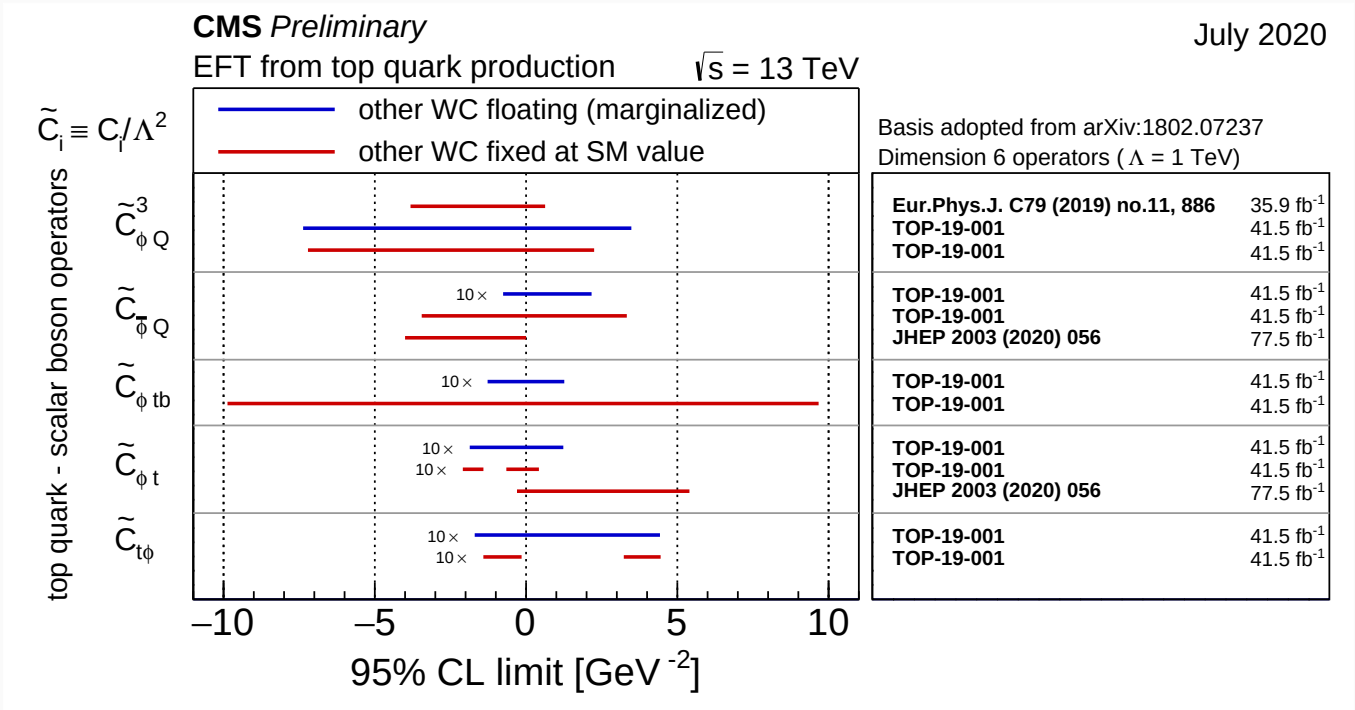
- **CMS PAS TOP-19-001:** new result!
- Two scenarios for fitting a given WC:
  1. All other WCs treated as unconstrained nuisance parameters (profiled).
  2. All other WCs set to SM values of 0.
- For some WCs, a 2σ interval is not clearly defined.
  - Some have multiple, nearly degenerate minima due to quadratic nature of WCs.
- In these cases, scans of pairs of WCs are performed (examples on right).
- **Takeaway:** novel approach to EFT pioneered through this analysis!
  - Multilepton final state serves as an illustration of its power, but is widely applicable to many other physics processes.





Summary of EFT Interpretations

- Wide variety of analyses sensitive to various WCs of EFT operators.
- Summary of constraints on WCs for top-scalar boson operators shown below:
  - Corresponding summary plot for top-fermion operators in backup.



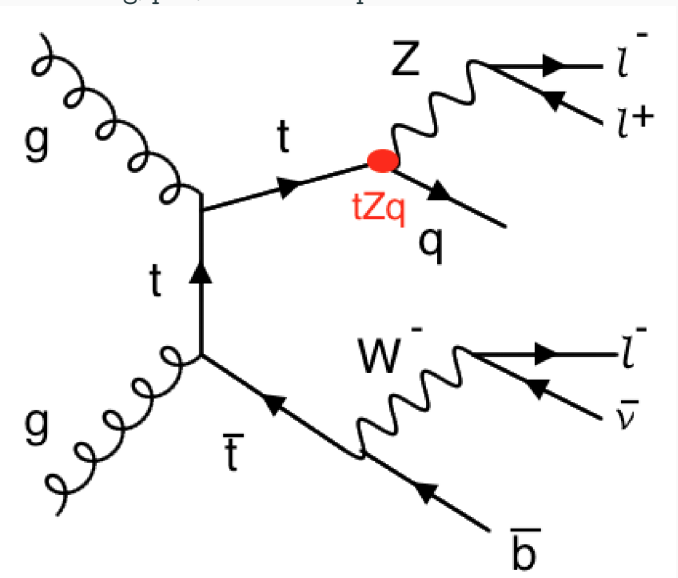
Results at CMS: Flavor-Changing Neutral Currents

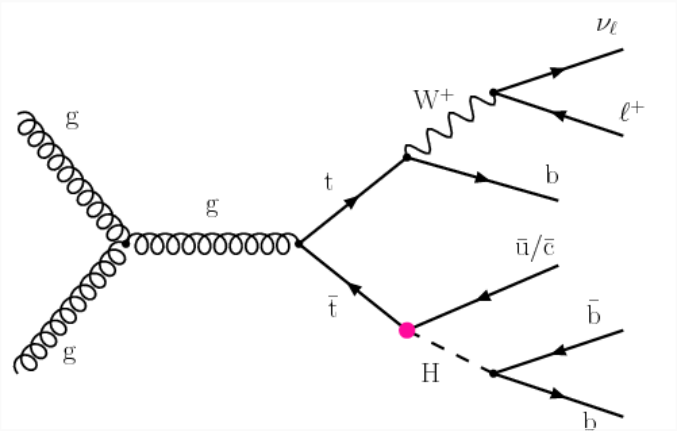
Flavor-Changing Neutral Currents

A potential "discovery story" with FCNC at the LHC [1]:

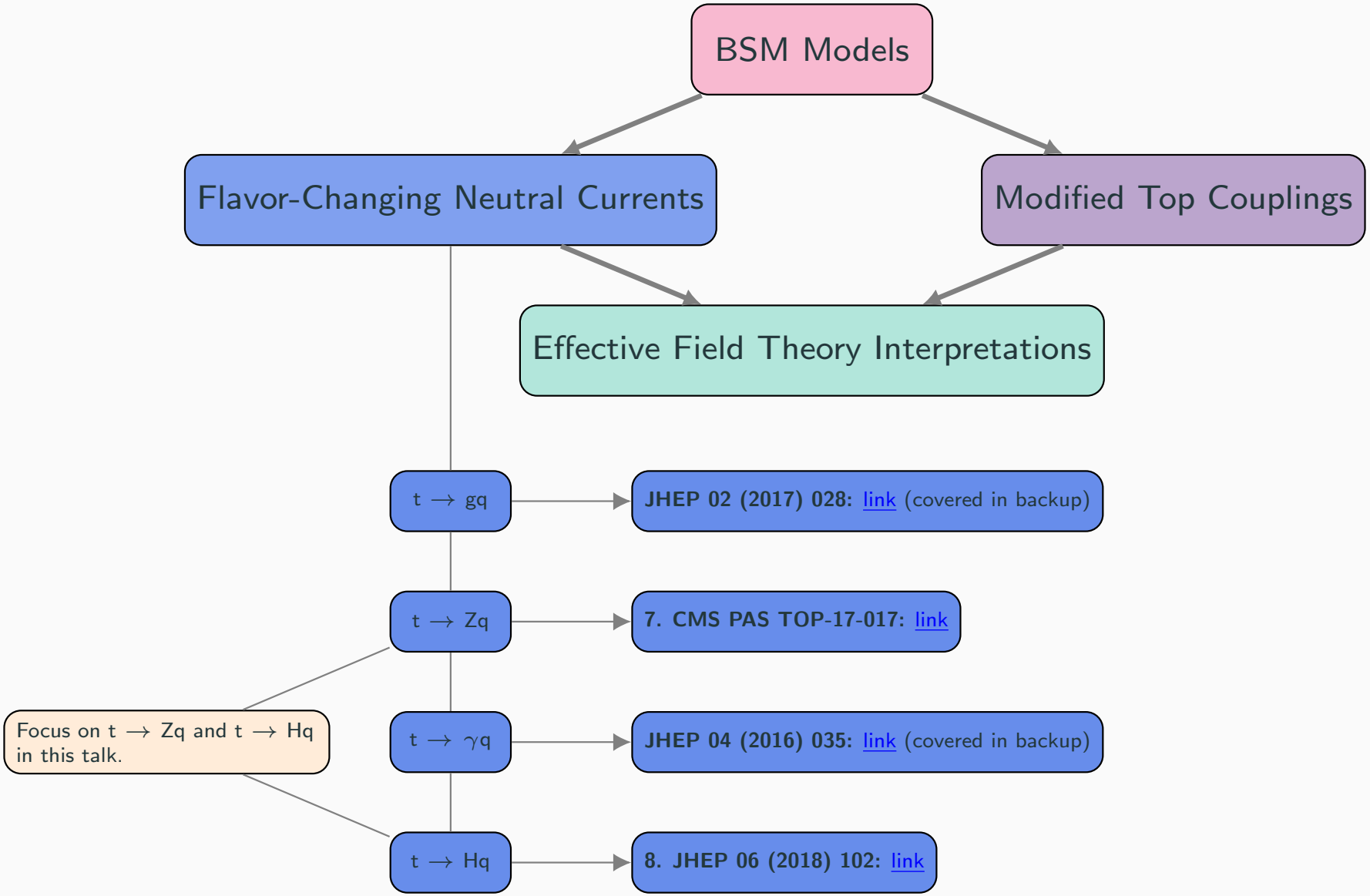
- FCNC forbidden at tree-level and heavily suppressed in loop diagrams due to GIM mechanism: $\mathcal{O}(10^{-15})$
- t $\rightarrow$ Zq and t $\rightarrow$ Hq FCNC well-motivated by multiple BSM theories, including warped extra dimensions, composite Higgs scenarios, and flavor-violating 2HDM models.
- Branching ratios for t $\rightarrow$ Zc (Hc) could be on the order of 10^{-5} (10^{-4}).
  - Some models may even result in rates for other FCNC below LHC sensitivity, making t $\rightarrow$ Zc and $\rightarrow$ Hc important channels to study.

[1] https://arxiv.org/pdf/1311.2028.pdf



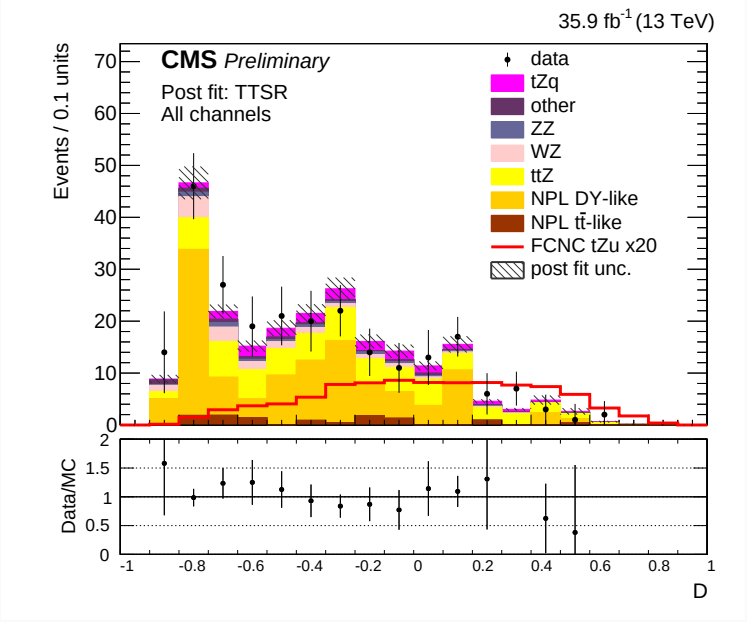


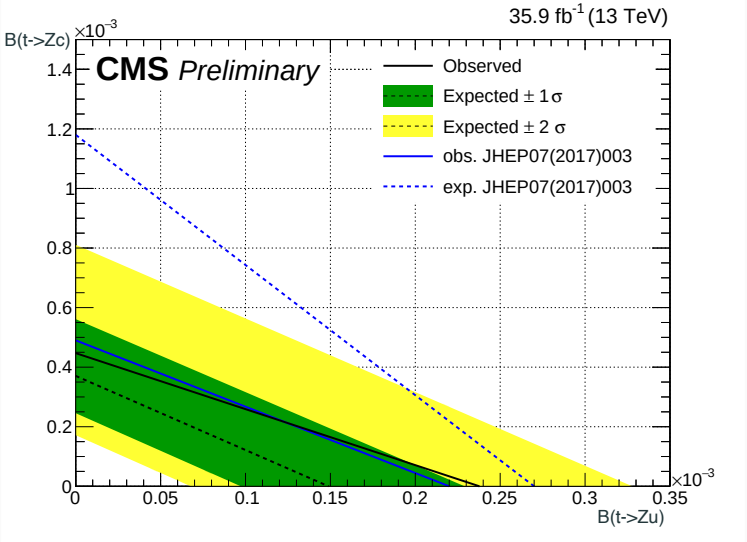
Flavor-Changing Neutral Currents



$t \to Zq$ FCNC

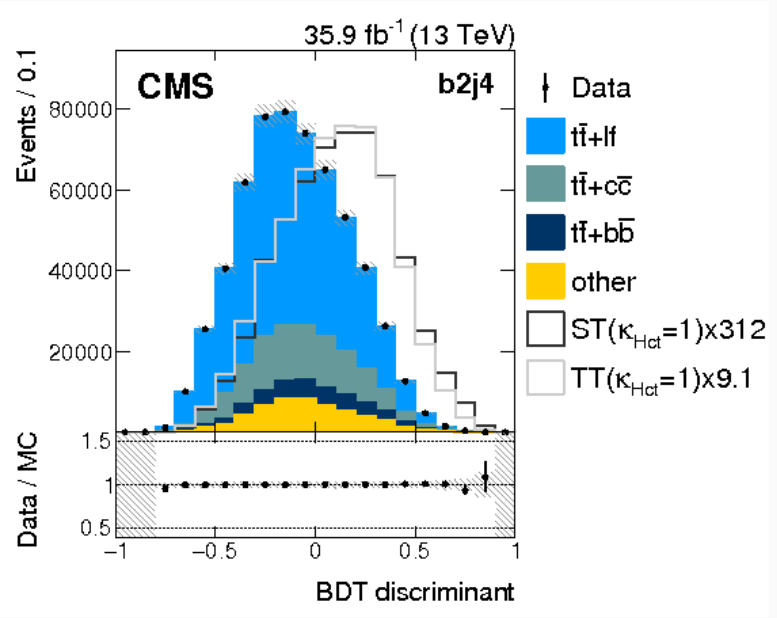
- **CMS PAS TOP-17-017:** link
- 35.9 fb^{-1}, require final states with exactly 3 leptons (one OSSF pair) and 1–3 jets.
- Search for $t \to Zq$ decays in single top and $t\bar{t}$ events, with separate BDTs targeting each production mode.
- Control region targeting WZ and non-prompt lepton events (dominant backgrounds) to constrain background prediction.
- Observed (expected) exclusion limits:
  - $\mathcal{B}$ ($t \to Zc$): 0.045% (0.037%)
  - $\mathcal{B}$ ($t \to Zu$): 0.024% (0.015%)

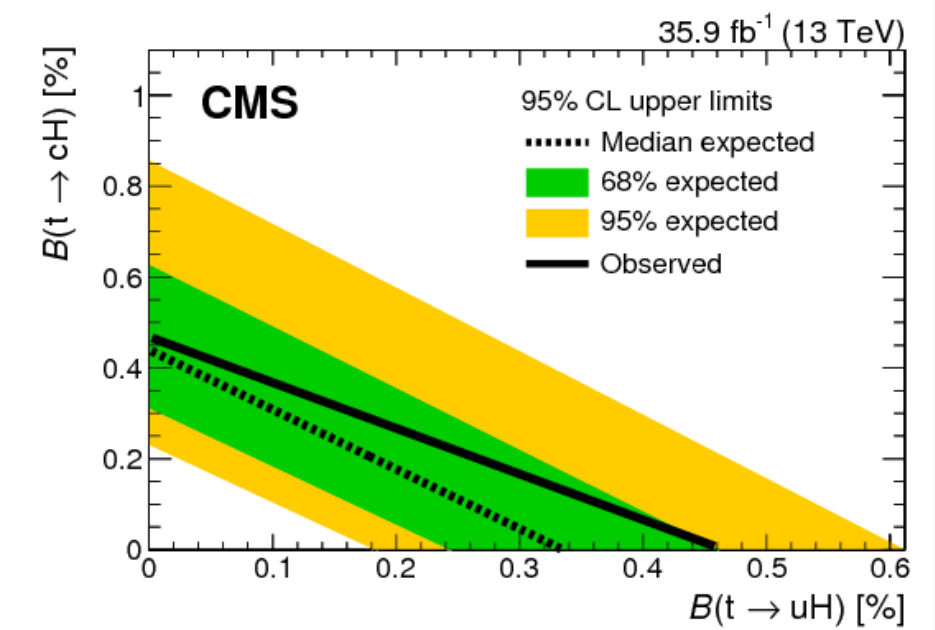




t → Hq FCNC

- **JHEP 06 (2018) 102:** link
- 35.9 fb^{-1}, search in H → bb decay mode.
  - Dominant systematic uncertainties due to b-tagging – up to 30%.
- Search for t → Hq decays in single top and $t\bar{t}$ events, with BDT-based approach.
  - Signal regions binned in N_{jets} and $N_{\text{b-jets}}$
- Observed/expected exclusion limits on $\mathcal{B}$ (t → Hq):
  - $\mathcal{B}$ (t → Hc): 0.047% (0.044%)
  - $\mathcal{B}$ (t → Hu): 0.047% (0.034%)

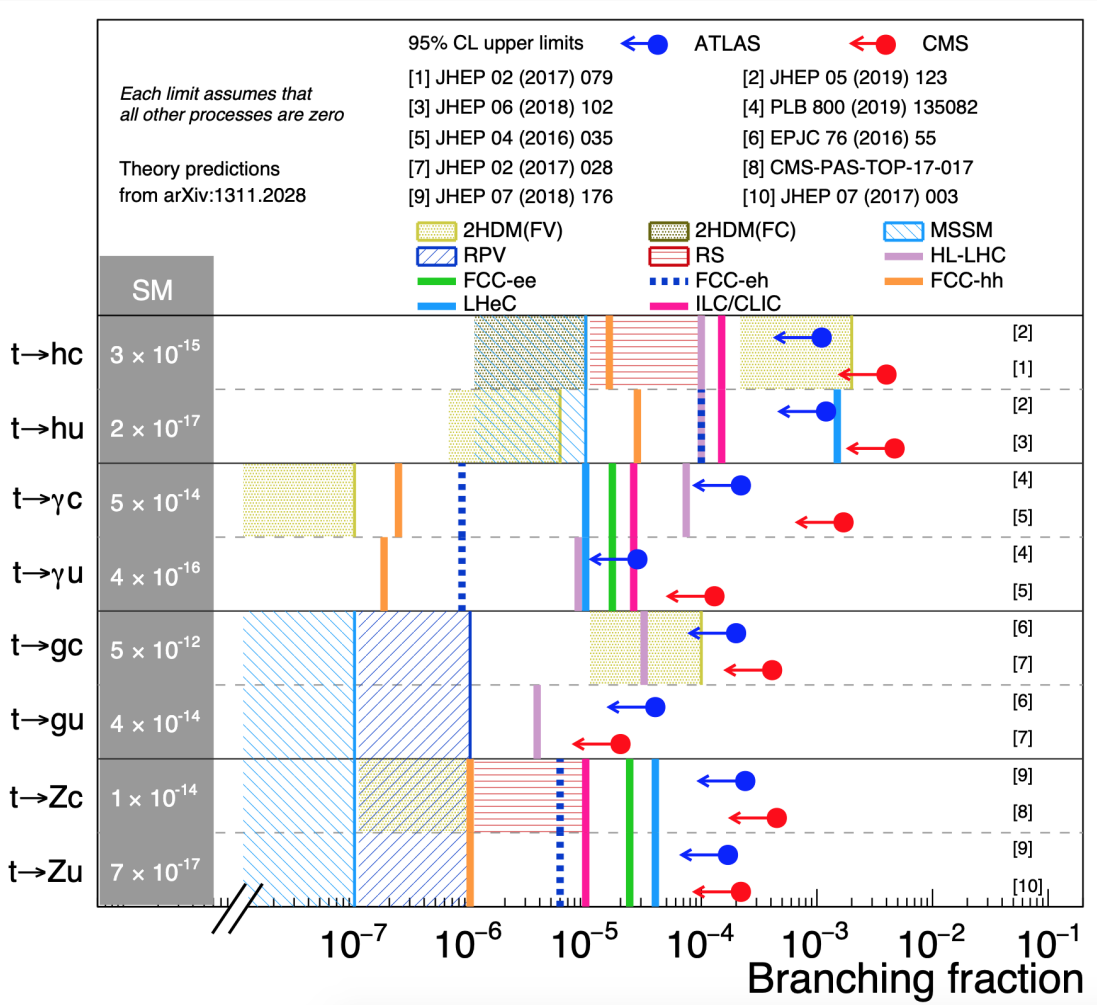




Landscape of FCNC Limits

- The "discovery story" mentioned earlier [1] not yet ruled out by current LHC limits.
- Results with the full Run 2 dataset will shed more light on the situation.
  - Analyses for t $\rightarrow$ Hq FCNC in the multilepton, bb, and $\gamma\gamma$ decay channels of the H should provide very competitive limits.

[1] https://arxiv.org/pdf/1311.2028.pdf



Note: updated version of Fig 6.4 in FCC CDR: link.

Conclusions & Future Prospects

Conclusions & Future Prospects

- Despite well-founded motivations for the presence of physics beyond the SM, has not yet been found at the LHC.
  - Perhaps the scale of new physics is beyond LHC's energy reach: $\Lambda_{\text{NP}} > E_{\text{LHC}}$?
- Motivates searching for subtle signatures of NP that may still be accessible at LHC:
  1. **Modified top couplings:** search for small deviations from SM predictions in differential cross-section measurements, searches for SM processes.
  2. **Flavor-changing neutral currents:** only allowed in SM through heavily suppressed loop diagrams with rates of $\mathcal{O}(10^{-15}) \implies$ any evidence of FCNC would be a clear indication of NP.
- **Effective field theory interpretations** cast results in model-independent way.
- Results from CMS are in agreement with SM $\implies$ no hints of NP yet.
- Despite no sign of NP, we are confident there must be physics beyond the Standard Model:
  - Motivates need to continue searching for NP in **modified top couplings** and **flavor-changing neutral currents** with full Run 2 dataset and beyond.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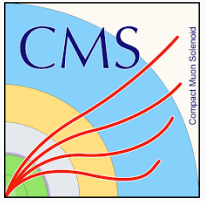
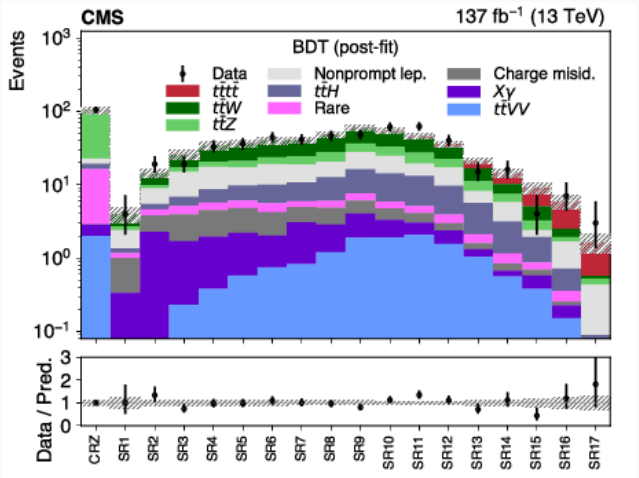
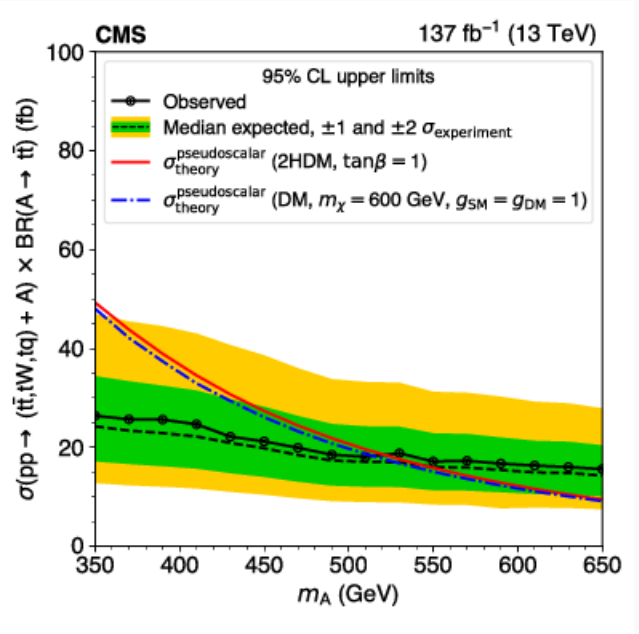

CMS
Compact Muon Solenoid

Backup

EFT + BSM interpretations of 4-top searches

- **Eur. Phys. J. C 80 , 2 (2020) 75:** link
- 137 fb^{-1}, targeting $2l$ (SS) and $3l$ final states.
- Both cut-based and BDT-based analyses are performed.
- See also talk from Andrea Castro: link

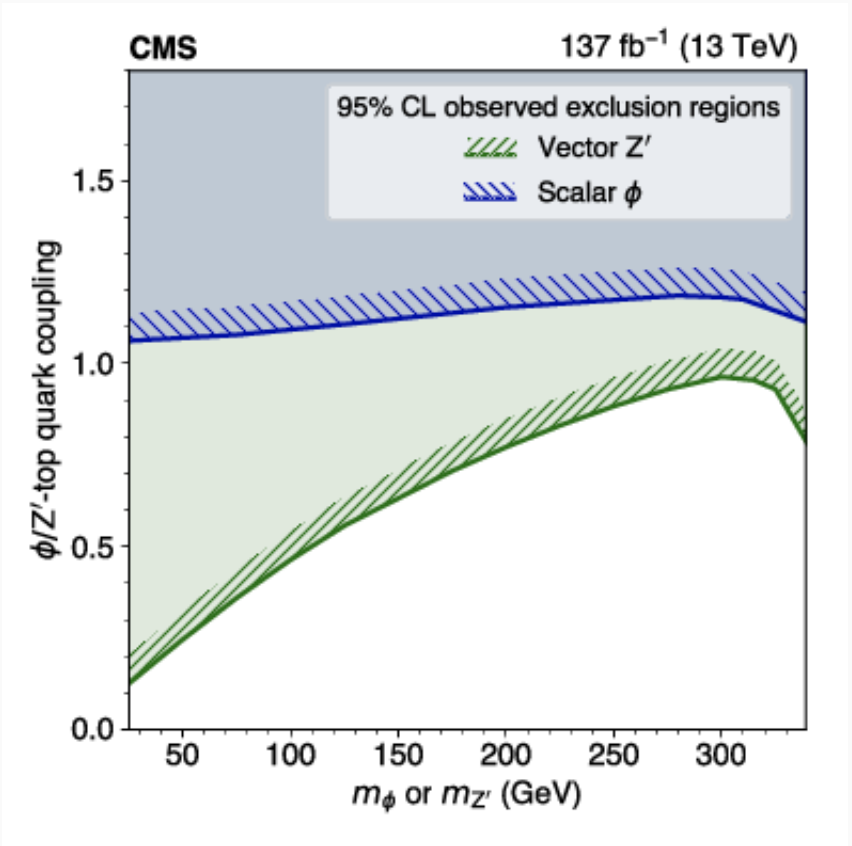


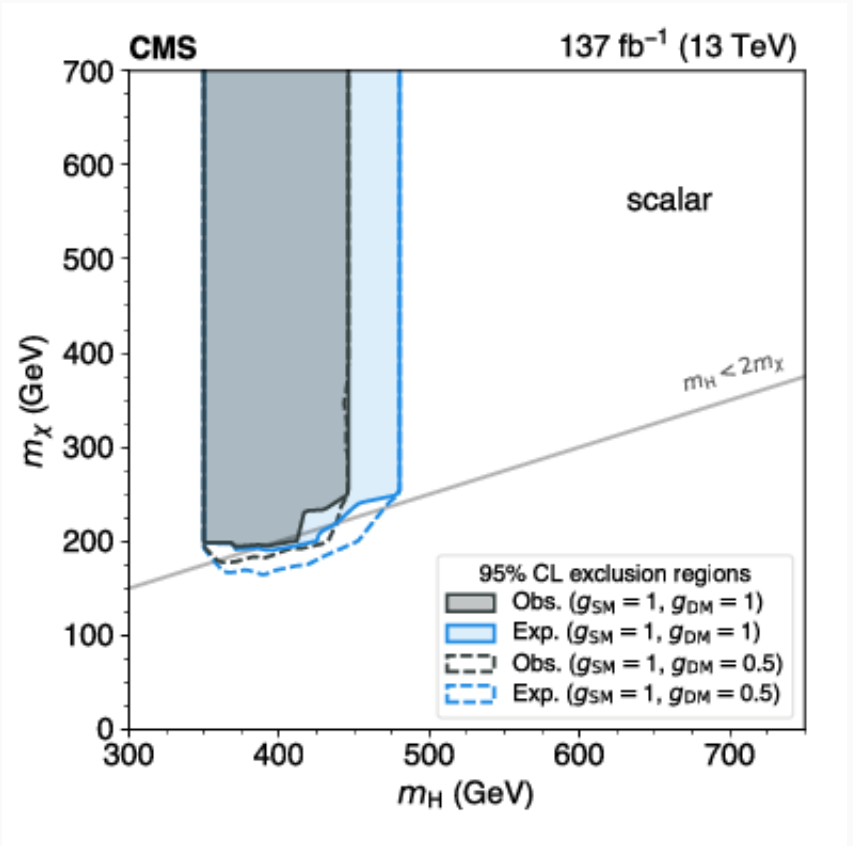


- BSM Interpretations: scenarios in which a new heavy particle decays to a $t\bar{t}$ pair
  1. Limits on the top quark coupling to new scalar (ϕ) and vector (Z') particles as a function of mass (backup).
  2. Limits on cross section for models of a heavy scalar/pseudoscalar, in the context of Two-Higgs Doublet Models and simplified dark matter scenarios.

EFT + BSM interpretations of 4-top searches

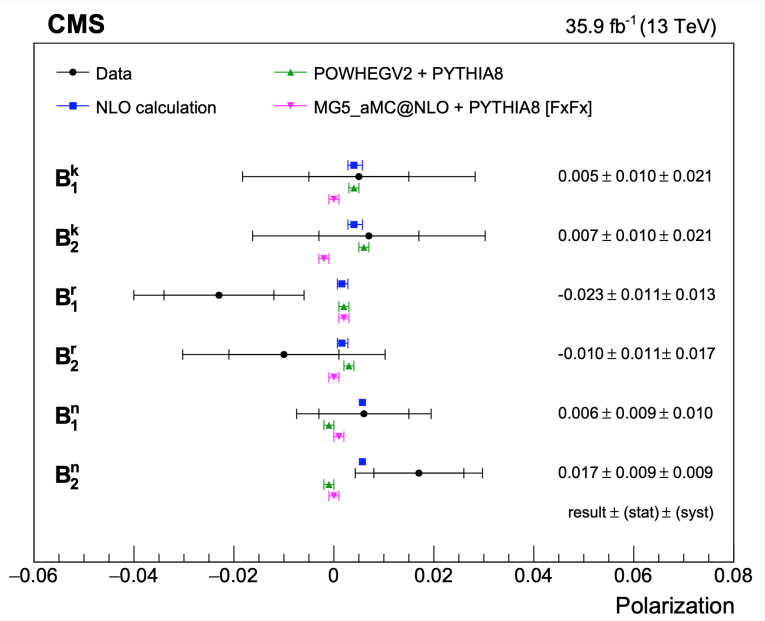
JHEP 1911 (2019) 082: link

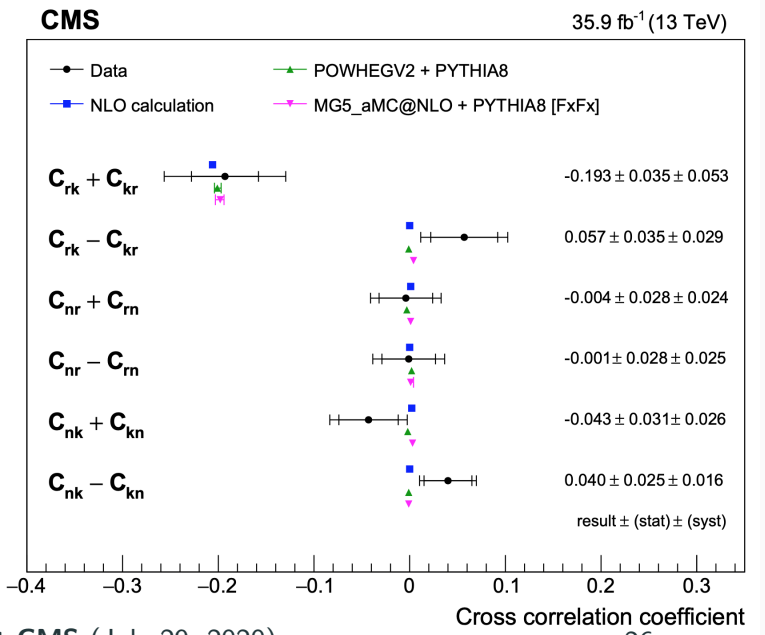




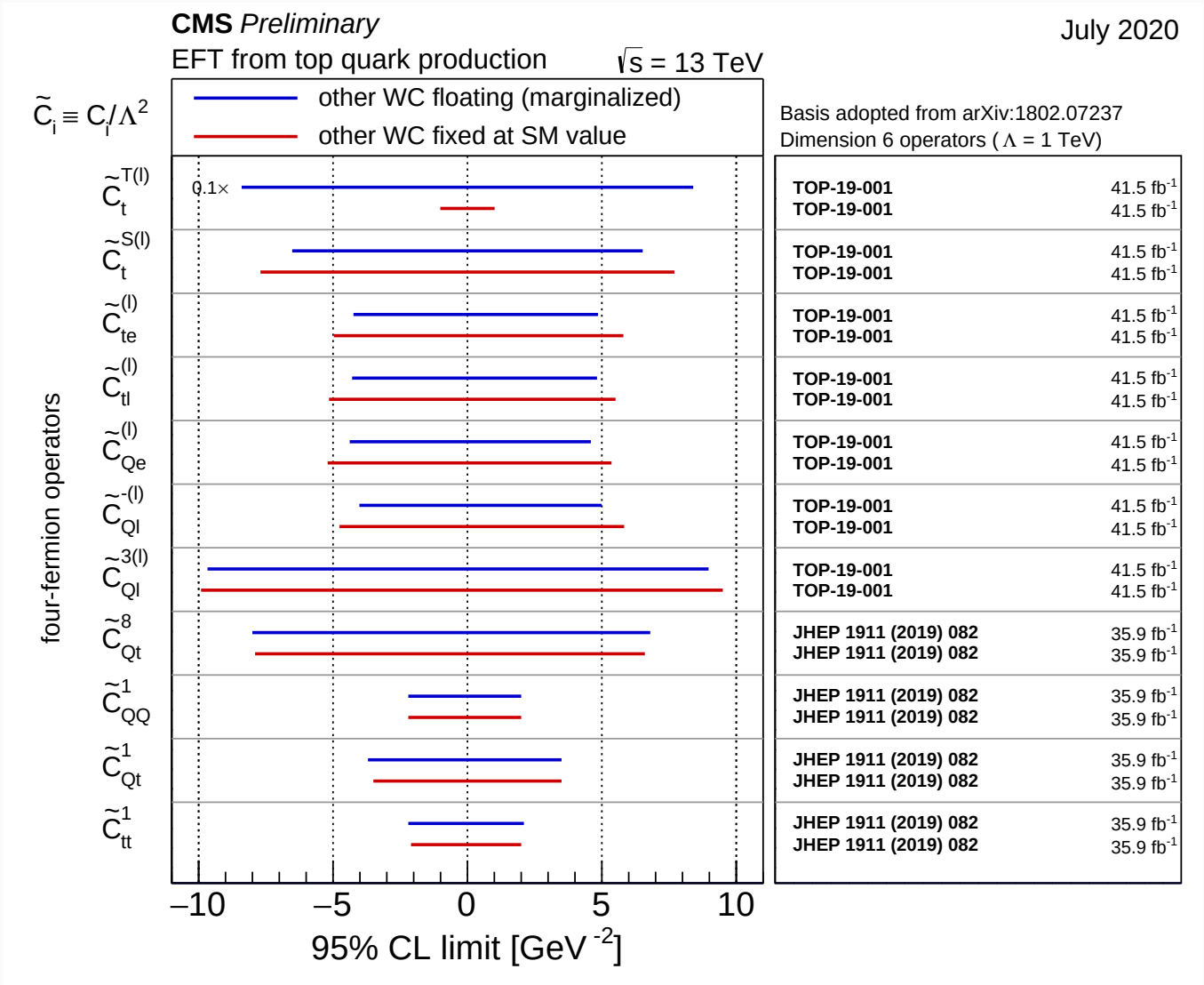
Top quark polarization and $t\bar{t}$ spin correlations

- **Phys. Rev. D 100 (2019) 072002:** link
- 35.9 fb^{-1}, OS dilepton + b-jets final states.
- Top quark lifetime ($\sim 10^{-25}$s) is four orders of magnitude smaller than top quark spin decorrelation timescale ($\sim 10^{-21}$s) $\implies$ spin information preserved in angular distributions of decay products.
- Expand polarization vectors and spin-correlation matrix into orthonormal basis & probe through differential cross section measurements.
  - Deviations from SM prediction would be indications of BSM effects!
- Also sensitive to dim-6 operators involved in $t\bar{t}$ production (see backup).
  - Look for anomalous couplings!

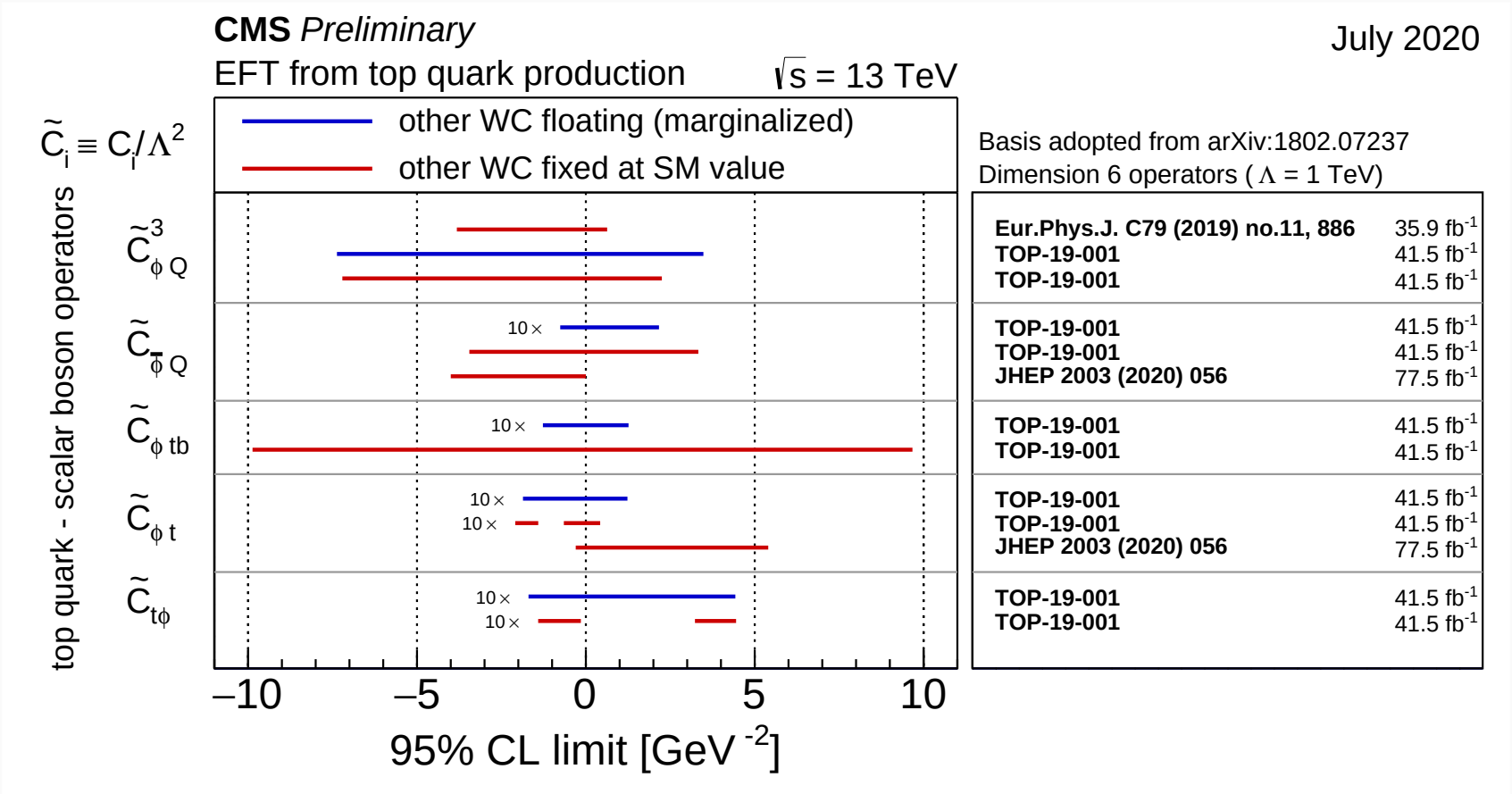




Summary of EFT Interpretations: Fermions

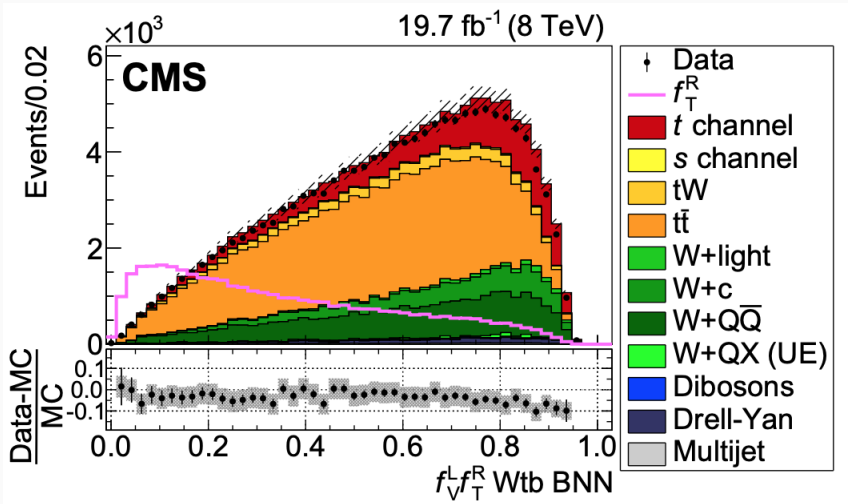


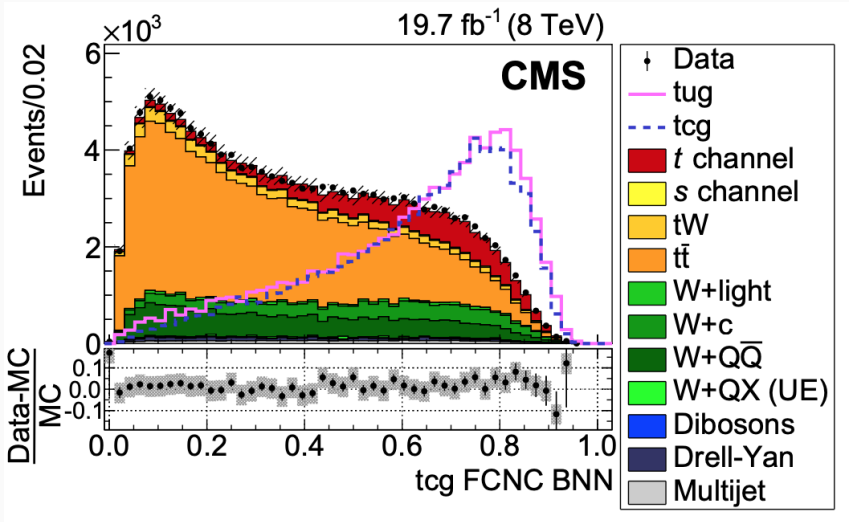
Summary of EFT Interpretations: Scalar Bosons



t → gq FCNC

- **JHEP 02 (2017) 028:** link
- 25 fb^{-1} data from $\sqrt{s} = 7, 8$ TeV
- Search for anomalous Wtb coupling and t → gq FCNC using NN approach.
- Observed (expected) limits on t → gq:
  - t → gu: $2.0(2.8) \times 10^{-5}$
  - t → gc: $4.1(2.8) \times 10^{-4}$





$t \to \gamma q$ FCNC

- **JHEP 06 (2018) 102:** link
- 20 fb^{-1} data from $\sqrt{s} = 7, 8$ TeV
- Dominant W + (γ) + jets backgrounds estimated with data-driven procedure, using a NN to separate the W + jets and W + γ + jets processes.
- BDTs (below) trained to separate $t \to \gamma q$ FCNC from backgrounds.
- Observed (expected) limits on $t \to \gamma q$:
  - $t \to \gamma u$: $1.9(1.3) \times 10^{-4}$
  - $t \to \gamma c$: $2.0(1.7) \times 10^{-3}$