Search for EFT in associated top production

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57th Rencontres de Moriond (electroweak sesion)

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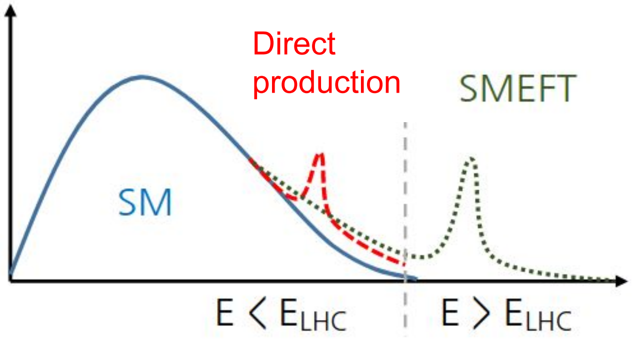
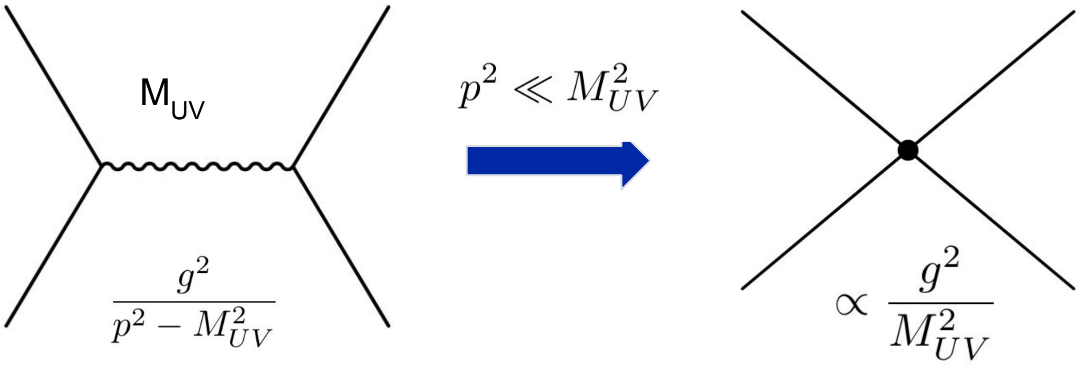
EFT introduction

- Lack of clear evidence of new physics at the LHC
- New physics may lie above the experimental energy scale
  - Indirect searches may provide hints!
- SMEFT extends the SM Lagrangian





Wilson coefficient

$$\mathcal{L} = \mathcal{L}_{SM} + \sum_i \frac{C_i}{\Lambda^2} O_i^{(6)}$$

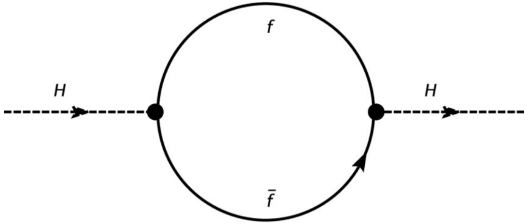
UV scale

EFT operator

The central role of the top quark

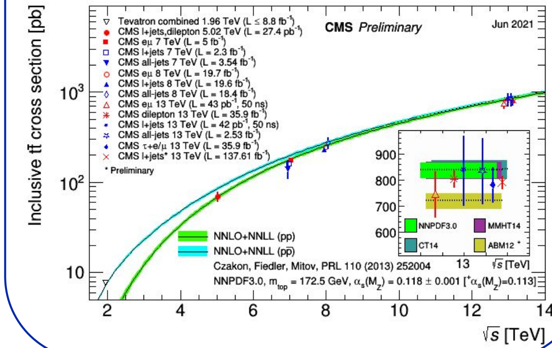
Large mass
Similar mass to a gold atom

SM naturalness



Natural coupling to the Higgs

Study of perturbative QCD



Proton pdfs

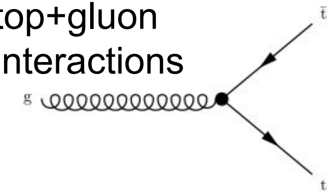
More precious than gold

1 top quark (HL-LHC prices) → O(5 CHF)
1 atom of gold → O(10^{-23} CHF)

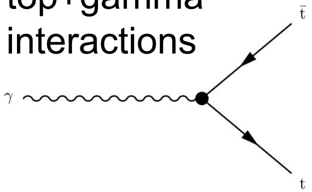
EFT in top physics

- EFT operators can contribute to many top quark production modes
- They affect differently each process
- The nature of the true UV theory is unknown
  - **Need to be comprehensive → consider all operators simultaneously**

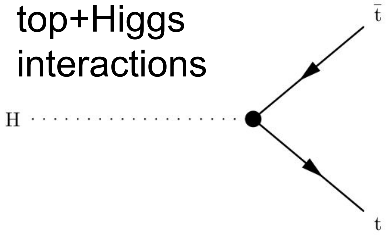
top+gluon interactions



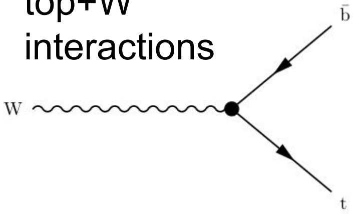
top+gamma interactions



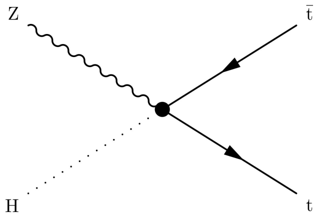
top+Higgs interactions



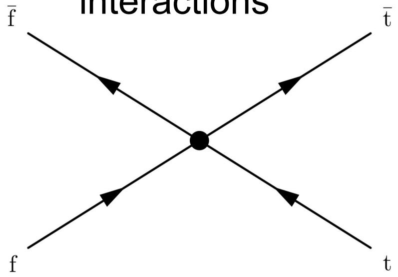
top+W interactions



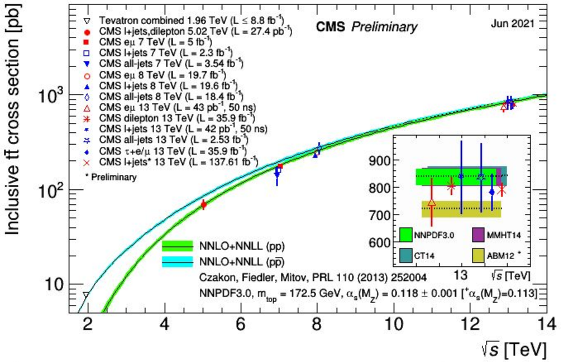
top+Z/H interactions

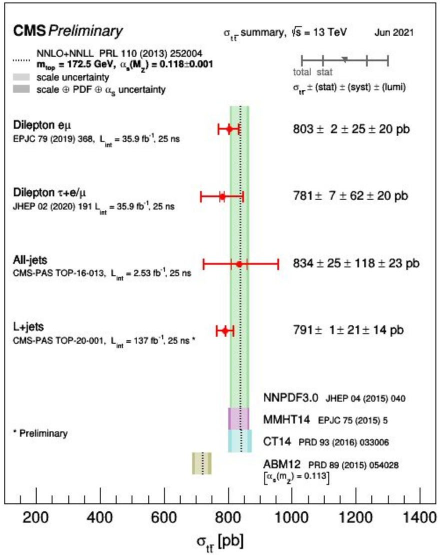


4-fermion interactions



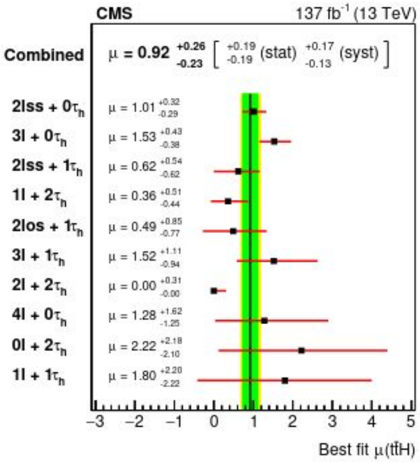
CMS top measurements





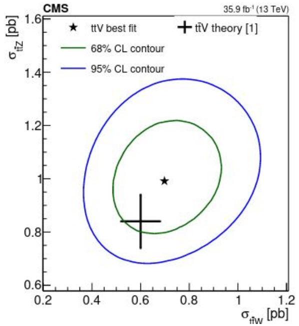
Top pair production

Associated top production

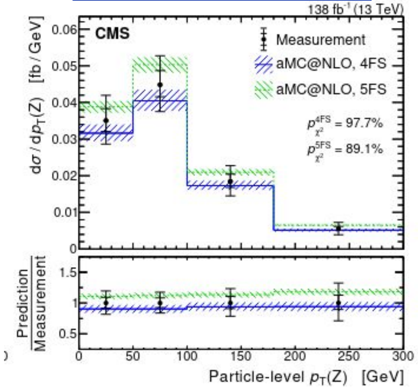


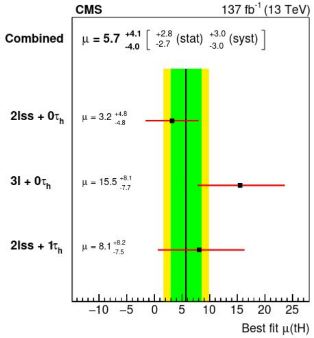
ttH production

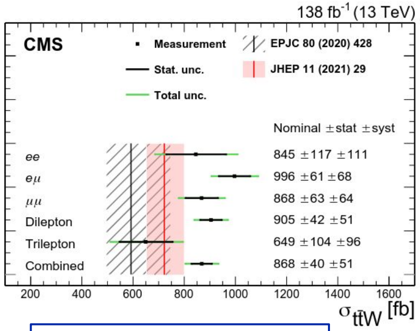
ttZ production



tZq production



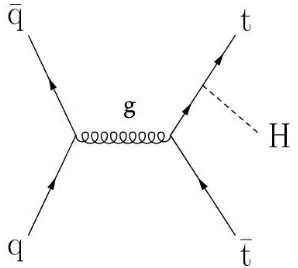




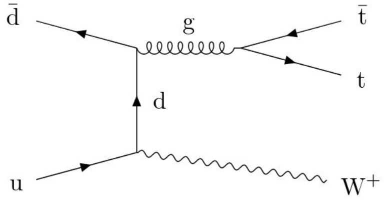
tHq production

ttW production

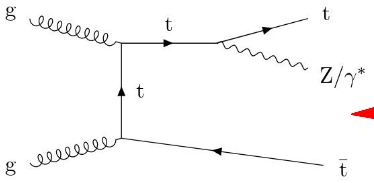
Exploring the top from all angles - associated top production



ttH

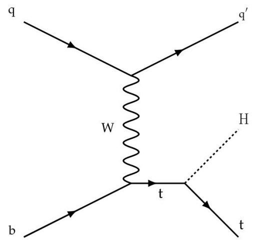


ttW

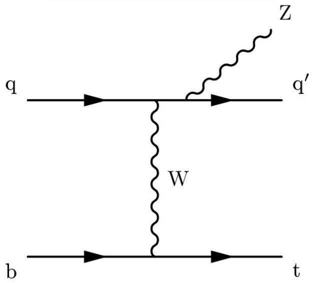


ttZ

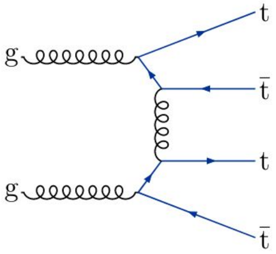
NEW result studying all these processes simultaneously
[CMS-PAS-TOP-22-006]



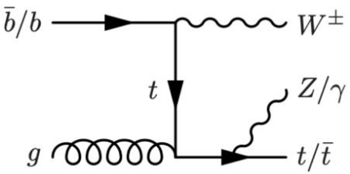
tHq



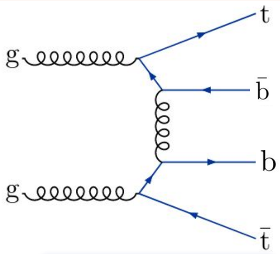
tZq



tttt



tWZ

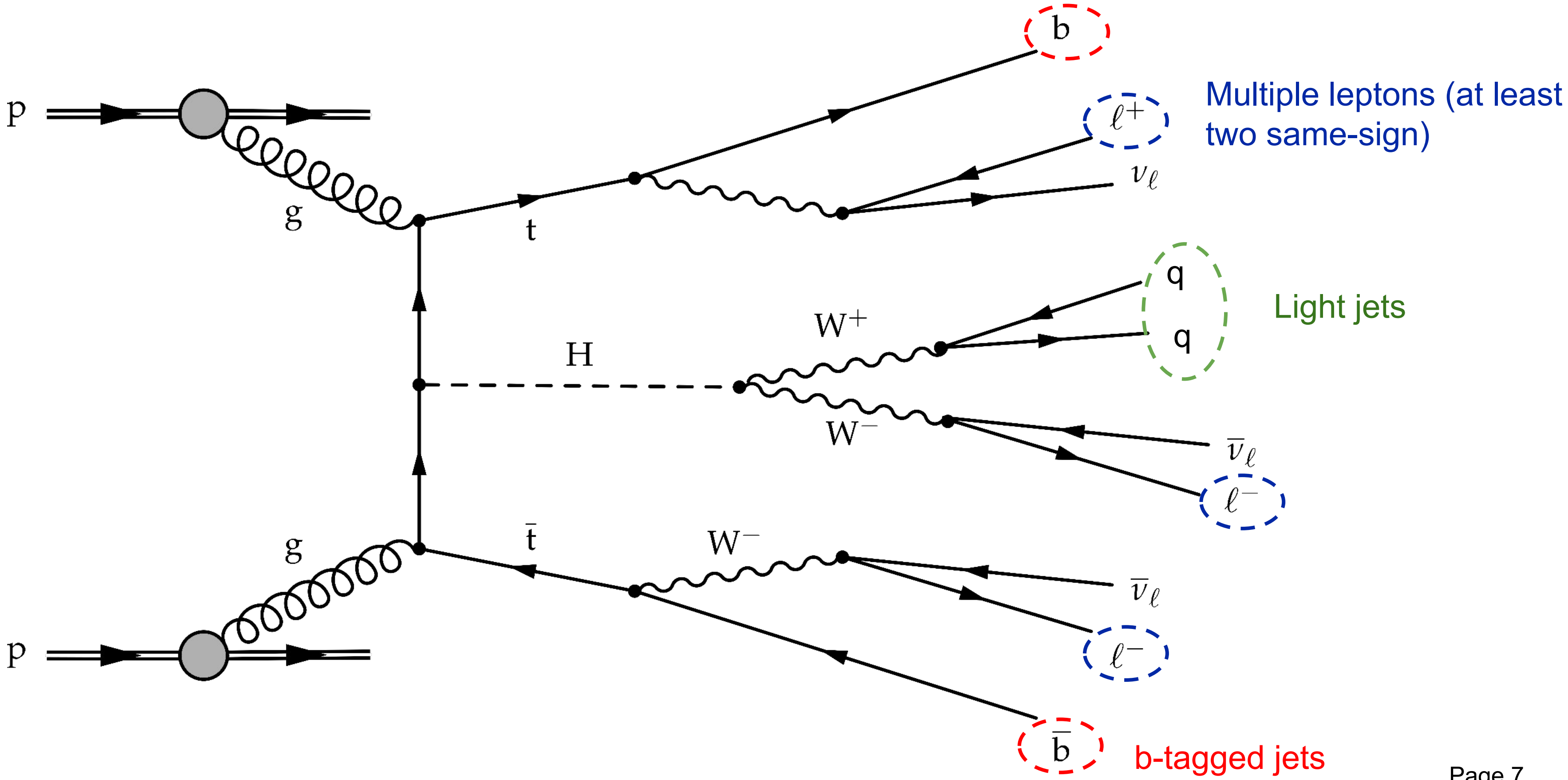


ttbb

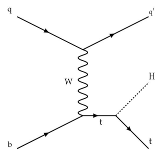
See Soureek's talk for many dedicated measurements

See Jack's talk for more exotic interactions with LFV

Experimental signatures



The multilepton final state



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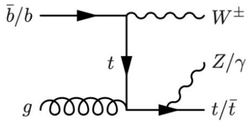

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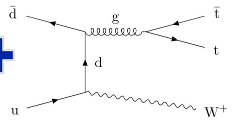

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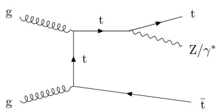

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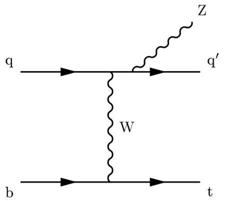

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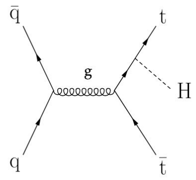
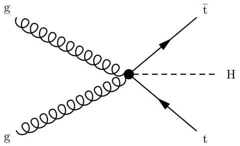


+ (perhaps EFT diagrams)



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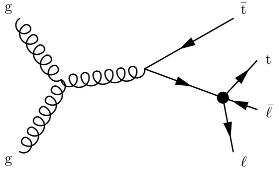

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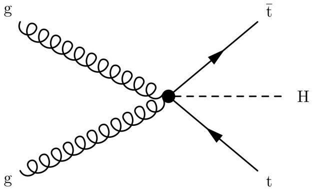

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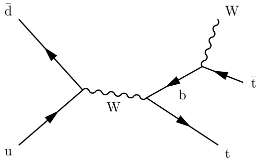

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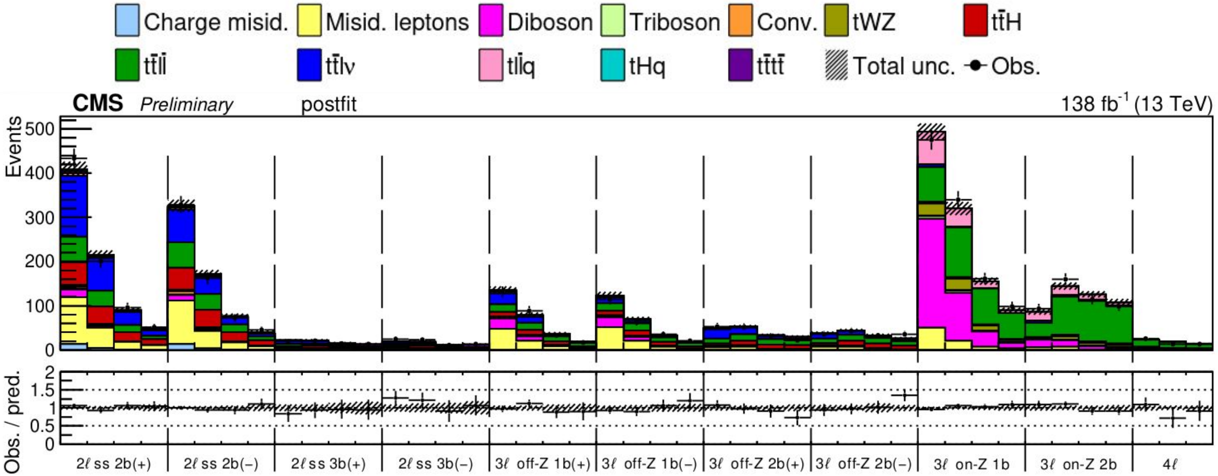
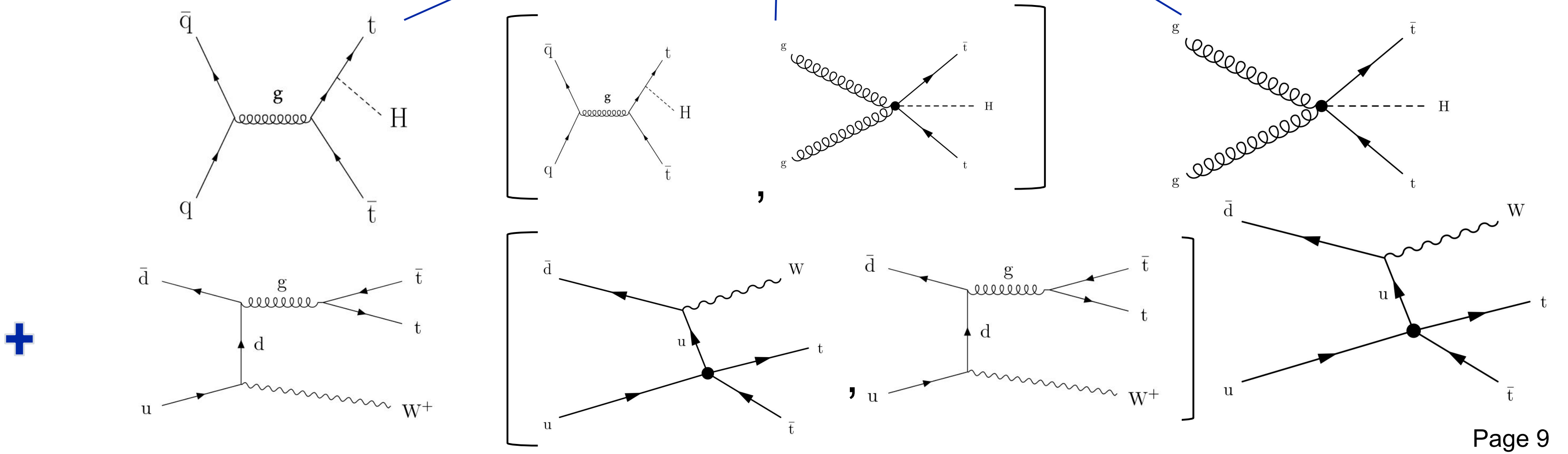


EFT parametrization

- SM and BSM contribution to the total yield is estimated with simulations
  - Observed events depend quadratically on the Wilson coefficients (WCs)
- The effect of all operators is taken into account for all processes simultaneously

$$\mathcal{M} = \mathcal{M}_{\rm SM} + \sum \frac{c_i}{\Lambda^2}\mathcal{M}_i$$

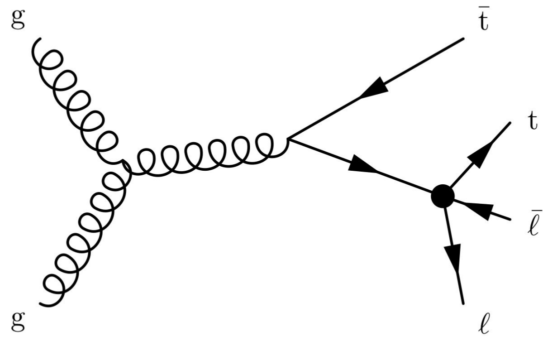
$$\mathrm{n} = \mathrm{n}_{\rm SM} + \sum_i L_i \frac{c_i}{\Lambda^2} + \sum_i Q_{ij} \frac{c_i c_j}{\Lambda^4}$$



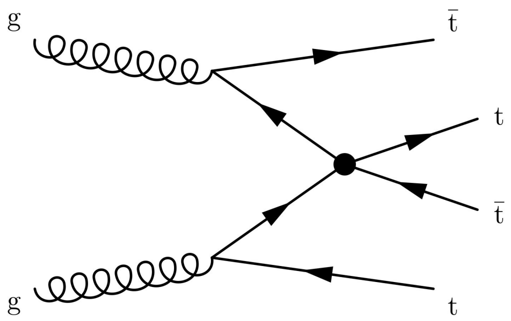
EFT operators of interest

We consider a total of **26 independent operators**

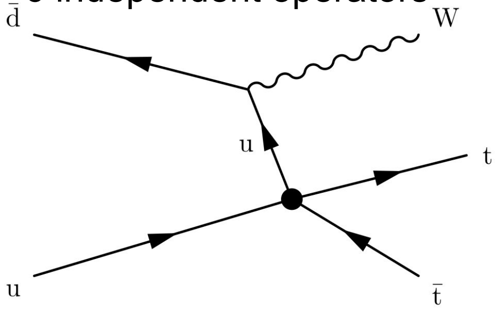
2-top-2-lepton operators
7 independent operators



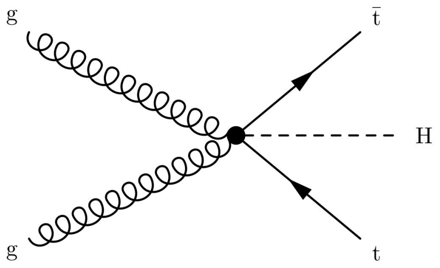
4-heavy-quark operators
4 independent operators

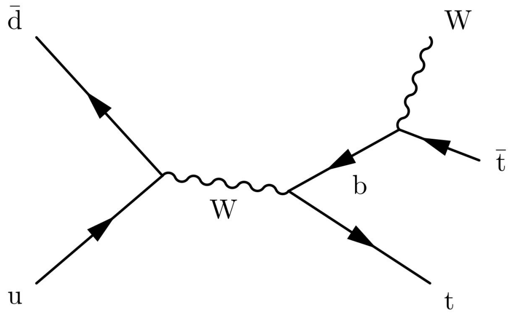


2-heavy-2-light-quark operators
6 independent operators



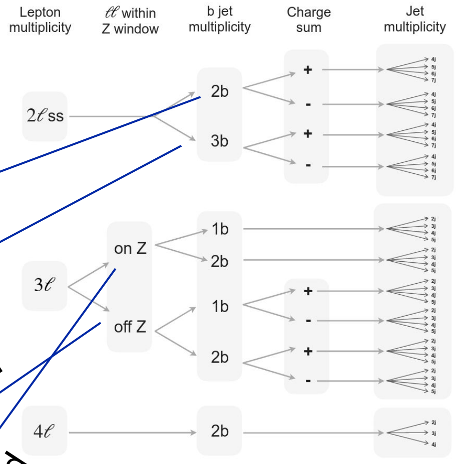
top+boson operators
9 operators





Observables considered

- We consider the number of observed events in a set of signal regions
- Regions are defined based on lepton/jet multiplicity and event kinematics to separate different processes

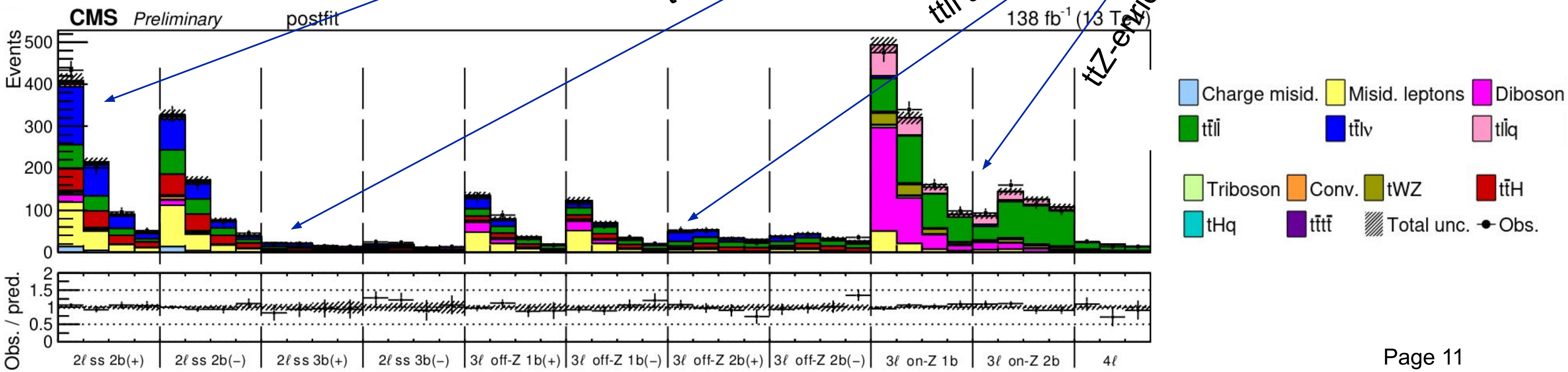


ttW and ttH-enriched

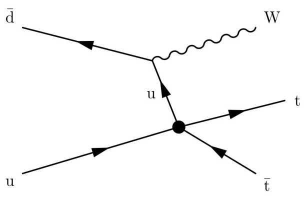
tttt-enriched

ttll and ttW-enriched

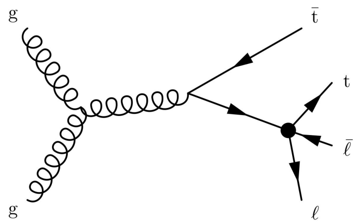
ttZ-enriched



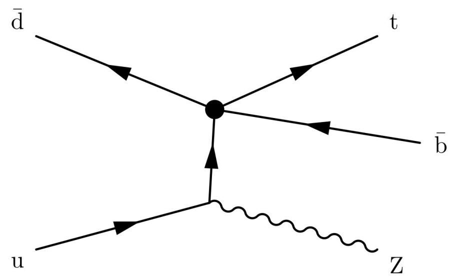
Observables considered



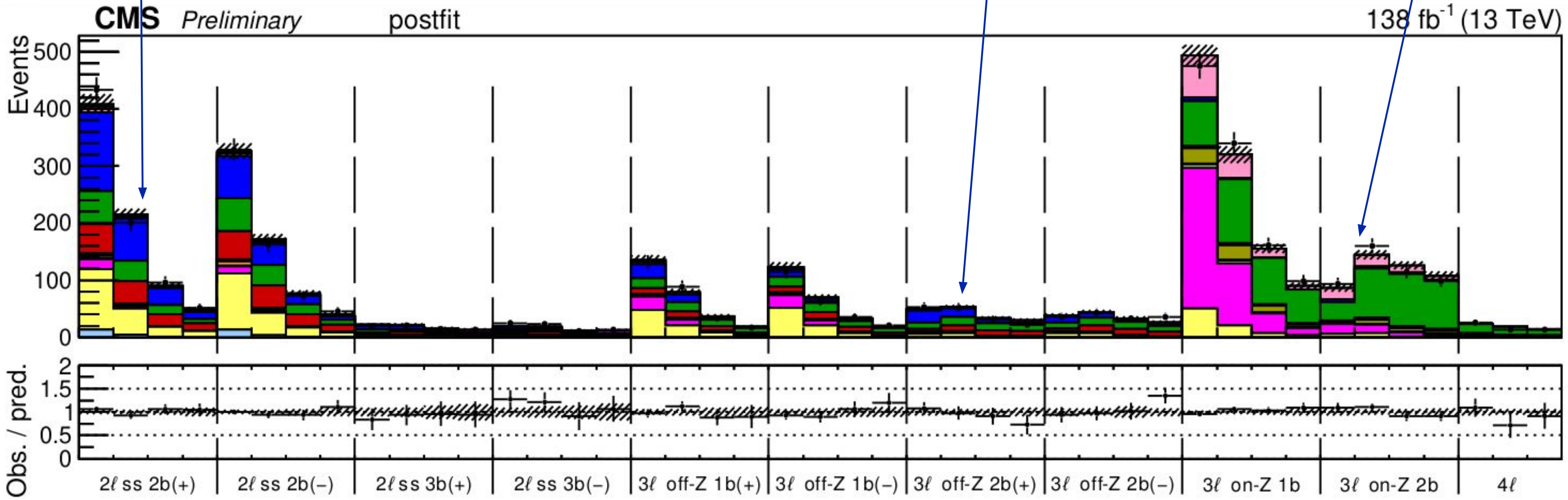
2-heavy-2-light quarks op.



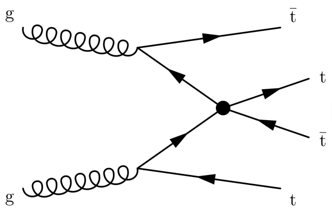
2-top-2-lepton op.



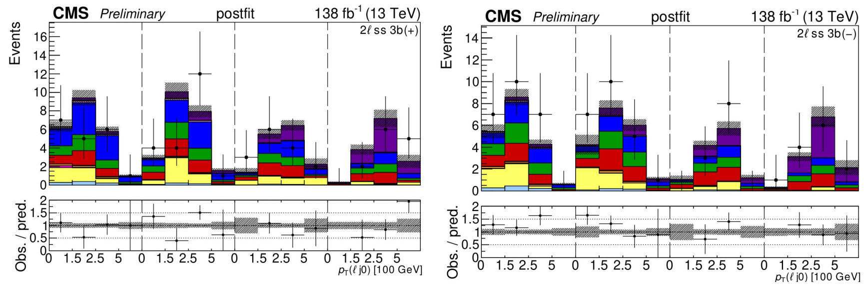
2-heavy-2-light quarks op.



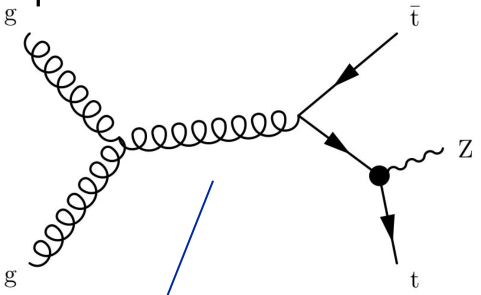
Observables considered

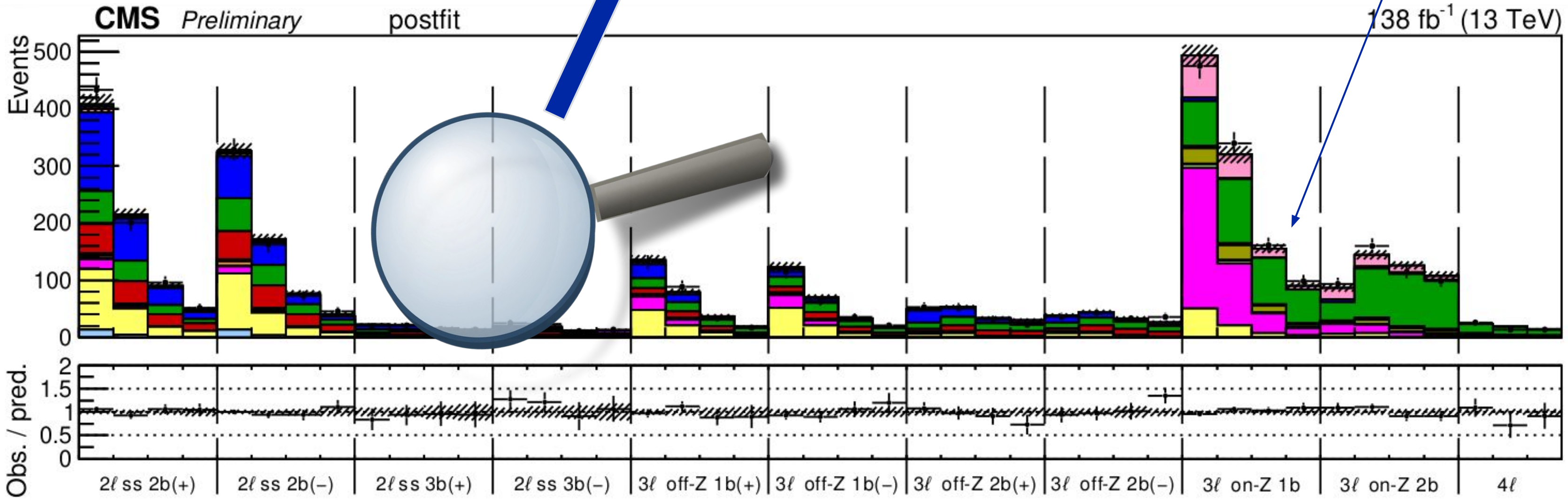


4-heavy-quarks op.



ttZ top+boson operators



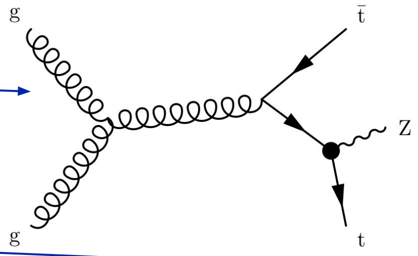


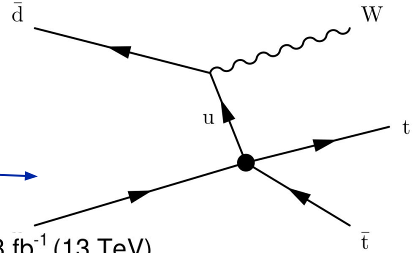
EFT kinematic dependence

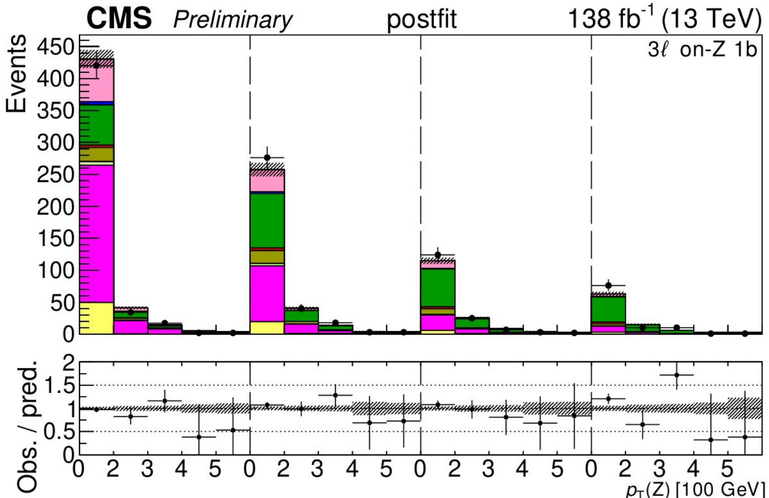
- Sensitivity is enhanced by exploiting the kinematic dependence of EFT vertices
- Different variable used in each category depending on the targeted operators

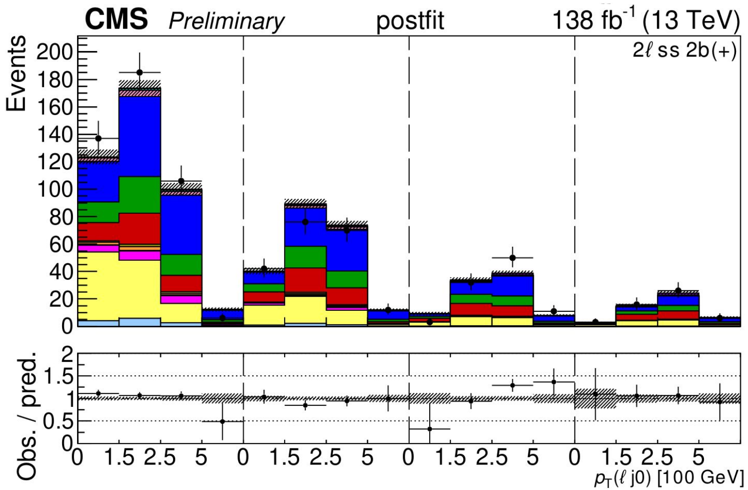
Regions sensitive to ttZ (most of 3l on-Z)
Using the p_T of the Z boson candidate

Other regions
Using the p_T of the most energetic pair of lepton and jet



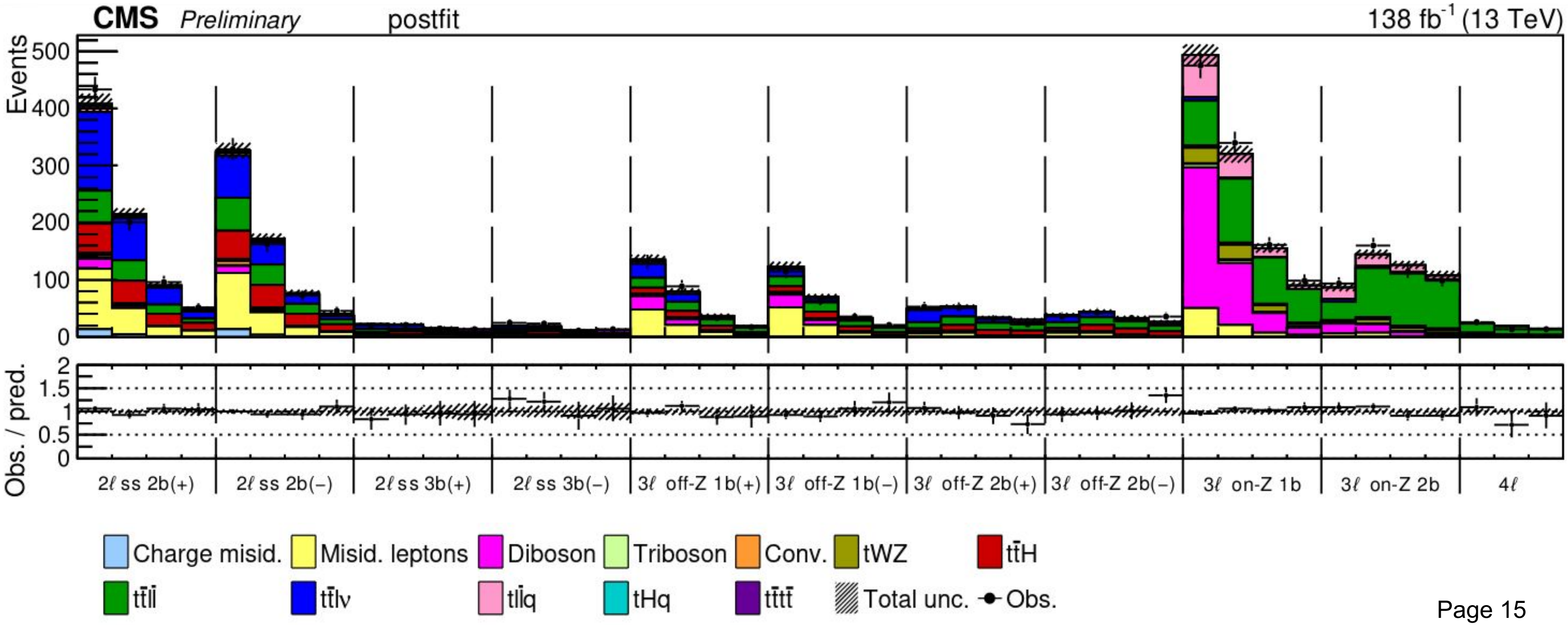






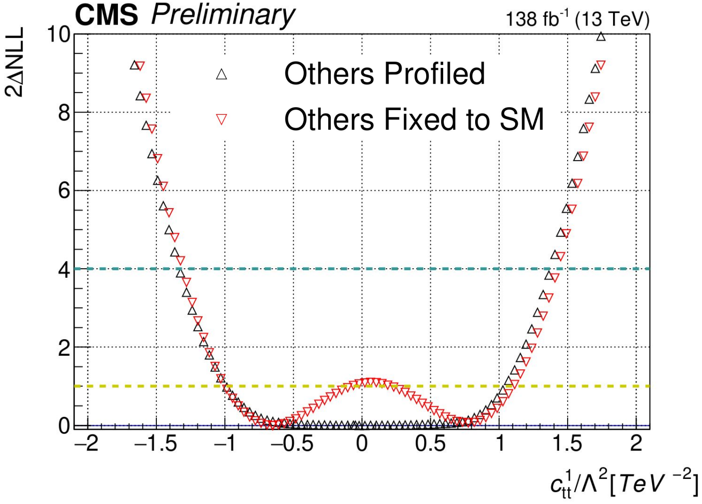
Background estimation

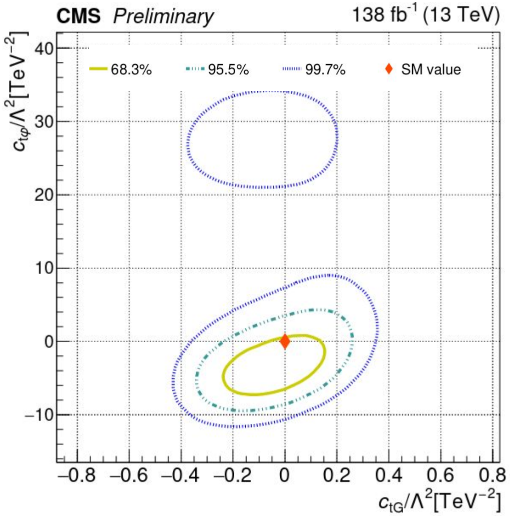
- Background dominated by WZ production → estimated with simulations and validated in control regions
- Nonprompt leptons have also a sizable contribution → estimated using data driven methods

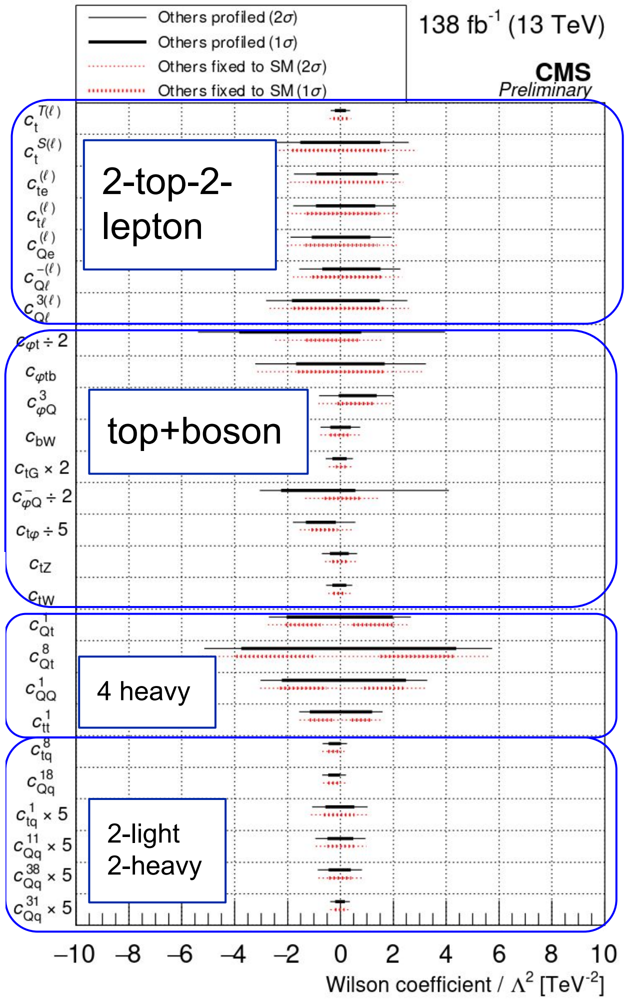


Results

- No significant deviations from SM observed
- Setting constraints on Wilson coefficients
  - Measuring a single coefficient at a time
  - Measuring all of them simultaneously

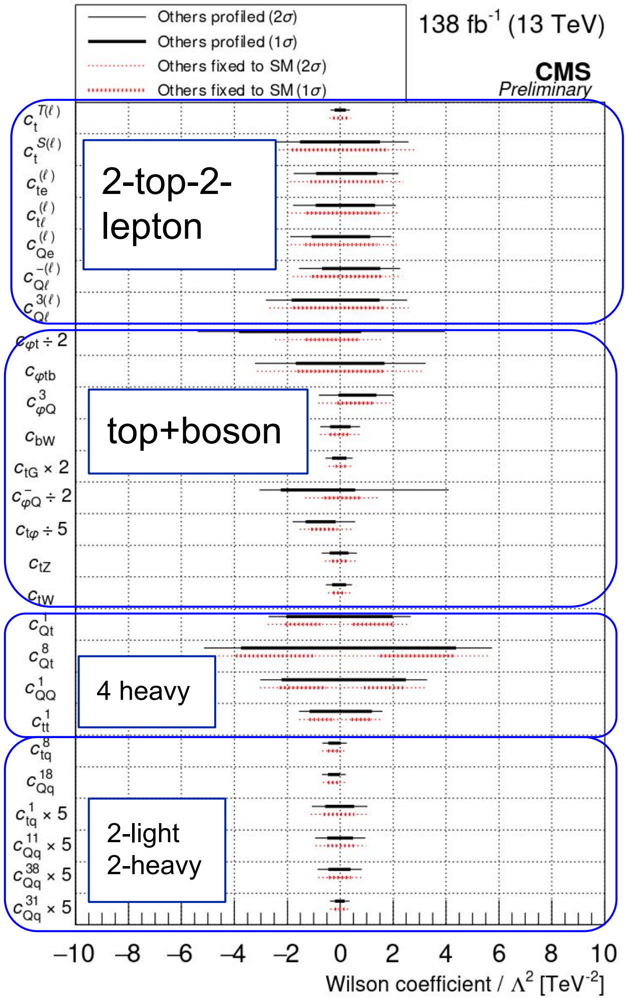






Results

- Limits on WC are obtained assuming Λ = 1 TeV
- Assuming WCs~1, we can set limits on the scale of the UV theory
  - 2-top-2-lepton operators: Λ > O(800 GeV) - O(1 TeV)
  - top+boson operators: Λ > O(300 GeV) - O(1 TeV)
  - 4-heavy-quark-operators: Λ > O(700 GeV) - O(1 TeV)
  - 2-light-2-heavy operators: Λ > O(1 - 3 TeV)

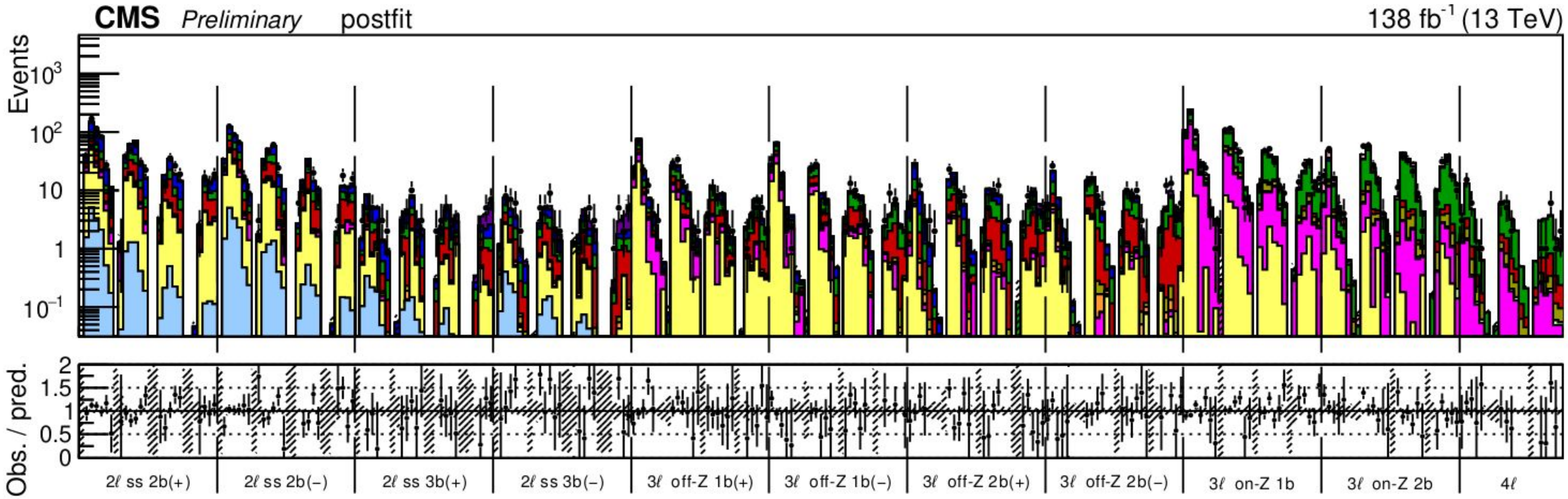


Summary and outlook

- CMS is developing a comprehensive program of measurements and searches involving top production
- We have searched for new physics in selections enriched in tt+X, t+X and tttt production
  - Interesting set of processes, sensitive to interactions of the top with other particles
  - We have set limits on 26 different operators
- Long (and interesting) future ahead for EFT searches:
  - Considering more top quark-related processes and more operators
  - Improving EFT modeling
  - More data will allow us to probe rarer processes

Back-up

Fitted variable



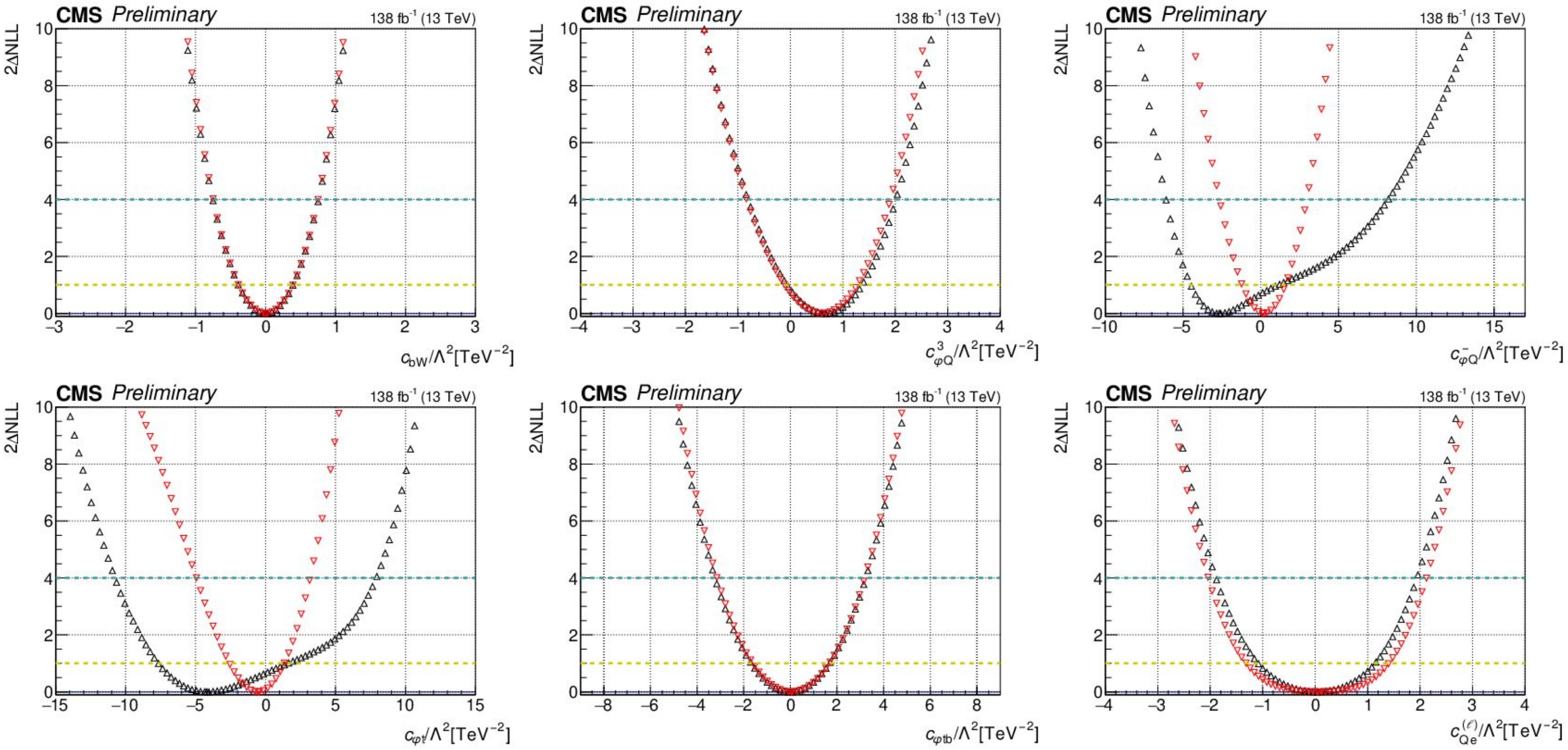
Operators considered

Operators involving two quarks and one or more bosons			
Operator	Definition	WC	Lead processes affected
$^{\ddagger}O_{u\varphi}^{(ij)}$	$\bar{q}_i u_j \tilde{\varphi}\,(\varphi^{\dagger}\varphi)$	$c_{t\varphi} + ic^{I}_{t\varphi}$	$t\bar{t}H$, tHq
$O_{\varphi q}^{1(ij)}$	$(\varphi^{\dagger} i\overleftrightarrow{D}_{\mu}\varphi)(\bar{q}_i\gamma^{\mu}q_j)$	$c^{-}_{\varphi Q} + c^{3}_{\varphi Q}$	$t\bar{t}H$, $t\bar{t}l\nu$, $t\bar{t}l\bar{l}$, tHq, $tl\bar{l}q$
$O_{\varphi q}^{3(ij)}$	$(\varphi^{\dagger} i\overleftrightarrow{D}^{I}_{\mu}\varphi)(\bar{q}_i\gamma^{\mu}\tau^{I}q_j)$	$c^{3}_{\varphi Q}$	$t\bar{t}H$, $t\bar{t}l\nu$, $t\bar{t}l\bar{l}$, tHq, $tl\bar{l}q$
$O_{\varphi u}^{(ij)}$	$(\varphi^{\dagger} i\overleftrightarrow{D}_{\mu}\varphi)(\bar{u}_i\gamma^{\mu}u_j)$	$c_{\varphi t}$	$t\bar{t}H$, $t\bar{t}l\nu$, $t\bar{t}l\bar{l}$, $tl\bar{l}q$
$^{\ddagger}O_{\varphi ud}^{(ij)}$	$(\tilde{\varphi}^{\dagger} iD_{\mu}\varphi)(\bar{u}_i\gamma^{\mu}d_j)$	$c_{\varphi tb} + ic^{I}_{\varphi tb}$	$t\bar{t}H$, $tl\bar{l}q$, tHq
$^{\ddagger}O_{uW}^{(ij)}$	$(\bar{q}_i\sigma^{\mu\nu}\tau^{I}u_j)\,\tilde{\varphi}W^{I}_{\mu\nu}$	$c_{tW} + ic^{I}_{tW}$	$t\bar{t}H$, $t\bar{t}l\nu$, $t\bar{t}l\bar{l}$, tHq, $tl\bar{l}q$
$^{\ddagger}O_{dW}^{(ij)}$	$(\bar{q}_i\sigma^{\mu\nu}\tau^{I}d_j)\,\varphi W^{I}_{\mu\nu}$	$c_{bW} + ic^{I}_{bW}$	$t\bar{t}H$, $t\bar{t}l\bar{l}$, tHq, $tl\bar{l}q$
$^{\ddagger}O_{uB}^{(ij)}$	$(\bar{q}_i\sigma^{\mu\nu}u_j)\,\tilde{\varphi}B_{\mu\nu}$	$(c_W c_{tW} - c_{tZ})/s_W +$ $i(c_W c^{I}_{tW} - c^{I}_{tZ})/s_W$	$t\bar{t}H$, $t\bar{t}l\nu$, $t\bar{t}l\bar{l}$, tHq, $tl\bar{l}q$
$^{\ddagger}O_{uG}^{(ij)}$	$(\bar{q}_i\sigma^{\mu\nu}T^{A}u_j)\,\tilde{\varphi}G^{A}_{\mu\nu}$	$g_s(c_{tG} + ic^{I}_{tG})$	$t\bar{t}H$, $t\bar{t}l\nu$, $t\bar{t}l\bar{l}$, tHq, $tl\bar{l}q$

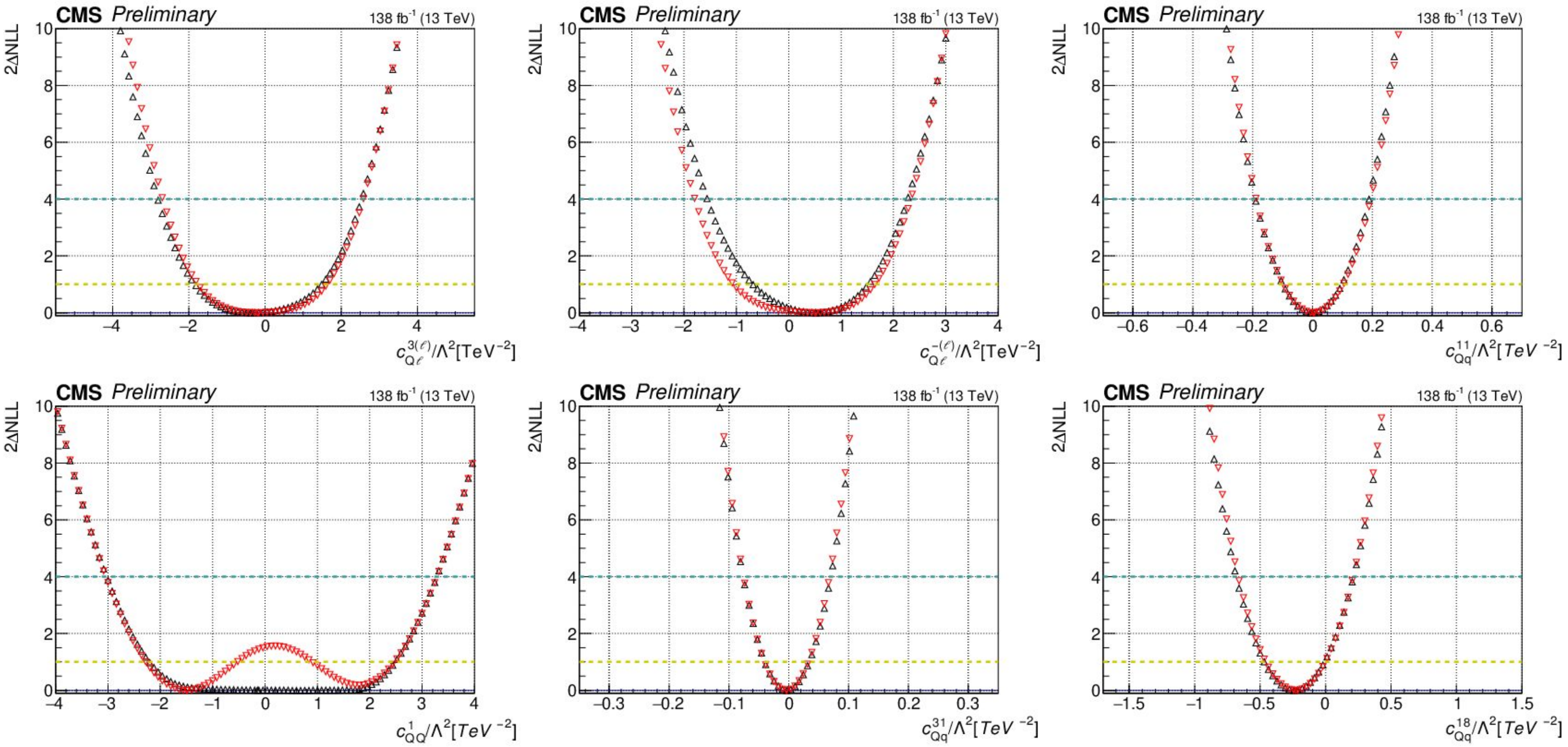
Operators involving two quarks and two leptons			
Operator	Definition	WC	Lead processes affected
$O_{\ell q}^{1(ijkl)}$	$(\bar{\ell}_i\gamma^{\mu}\ell_j)(\bar{q}_k\gamma^{\mu}q_{\ell})$	$c^{-(\ell)}_{Q\ell} + c^{3(\ell)}_{Q\ell}$	$t\bar{t}l\nu$, $t\bar{t}l\bar{l}$, $tl\bar{l}q$
$O_{\ell q}^{3(ijkl)}$	$(\bar{\ell}_i\gamma^{\mu}\tau^{I}\ell_j)(\bar{q}_k\gamma^{\mu}\tau^{I}q_{\ell})$	$c^{3(\ell)}_{Q\ell}$	$t\bar{t}l\nu$, $t\bar{t}l\bar{l}$, $tl\bar{l}q$
$O_{\ell u}^{(ijkl)}$	$(\bar{\ell}_i\gamma^{\mu}\ell_j)(\bar{u}_k\gamma^{\mu}u_{\ell})$	$c^{(\ell)}_{t\ell}$	$t\bar{t}l\bar{l}$
$O_{eq}^{(ijkl)}$	$(\bar{e}_i\gamma^{\mu}e_j)(\bar{q}_k\gamma^{\mu}q_{\ell})$	$c^{(\ell)}_{Qe}$	$t\bar{t}l\bar{l}$, $tl\bar{l}q$
$O_{eu}^{(ijkl)}$	$(\bar{e}_i\gamma^{\mu}e_j)(\bar{u}_k\gamma^{\mu}u_{\ell})$	$c^{(\ell)}_{te}$	$t\bar{t}l\bar{l}$
$^{\ddagger}O_{\ell equ}^{1(ijkl)}$	$(\bar{\ell}_i e_j)\,\varepsilon\,(\bar{q}_k u_{\ell})$	$c^{S(\ell)}_{t} + ic^{SI(\ell)}_{t}$	$t\bar{t}l\bar{l}$, $tl\bar{l}q$
$^{\ddagger}O_{\ell equ}^{3(ijkl)}$	$(\bar{\ell}_i\sigma^{\mu\nu}e_j)\,\varepsilon\,(\bar{q}_k\sigma_{\mu\nu}u_{\ell})$	$c^{T(\ell)}_{t} + ic^{TI(\ell)}_{t}$	$t\bar{t}l\nu$, $t\bar{t}l\bar{l}$, $tl\bar{l}q$

Operator category	WCs
Two heavy quarks	$c_{t\varphi}$, $c^{-}_{\varphi Q}$, $c^{3}_{\varphi Q}$, $c_{\varphi t}$, $c_{\varphi tb}$, c_{tW}, c_{tZ}, c_{bW}, c_{tG}
Two heavy quarks two leptons	$c^{3(\ell)}_{Q\ell}$, $c^{-(\ell)}_{Q\ell}$, $c^{(\ell)}_{Qe}$, $c^{(\ell)}_{t\ell}$, $c^{(\ell)}_{te}$, $c^{S(\ell)}_{t}$, $c^{T(\ell)}_{t}$
Two light quarks two heavy quarks	c^{31}_{Qq}, c^{38}_{Qq}, c^{11}_{Qq}, c^{18}_{Qq}, c^{1}_{tq}, c^{8}_{tq}
Four heavy quarks	c^{1}_{QQ}, c^{1}_{Qt}, c^{8}_{Qt}, c^{1}_{tt}

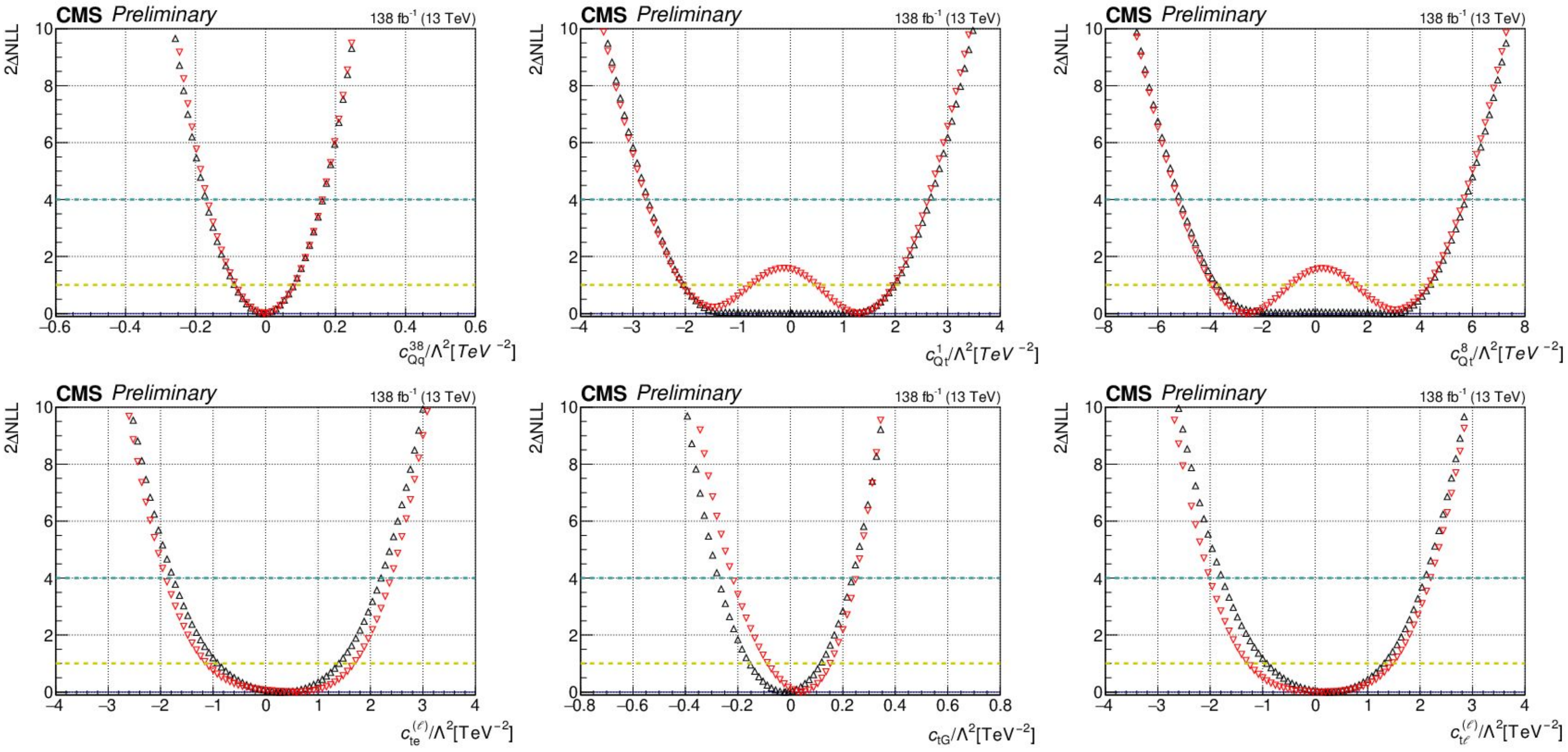
Results per operator (I)



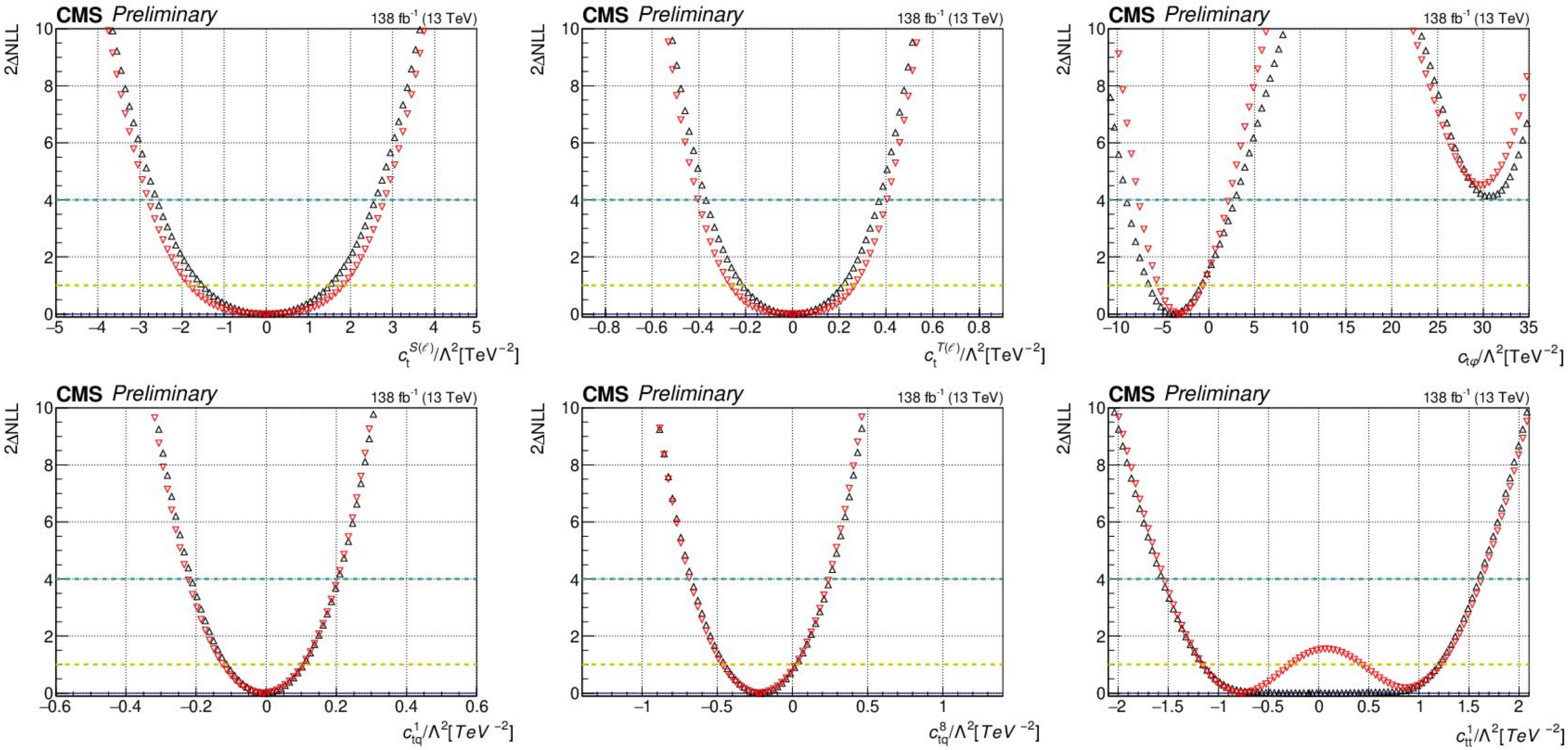
Results per operator (II)



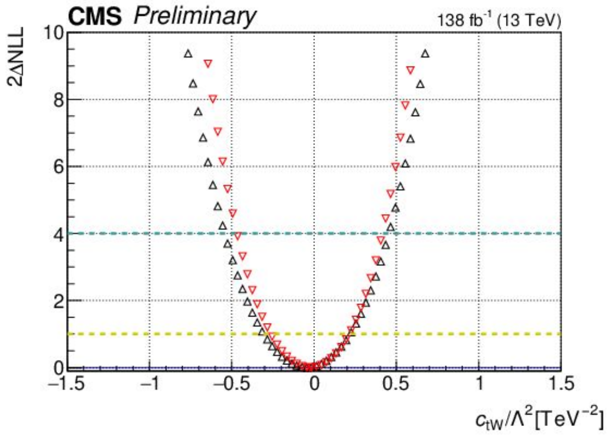
Results per operator (III)

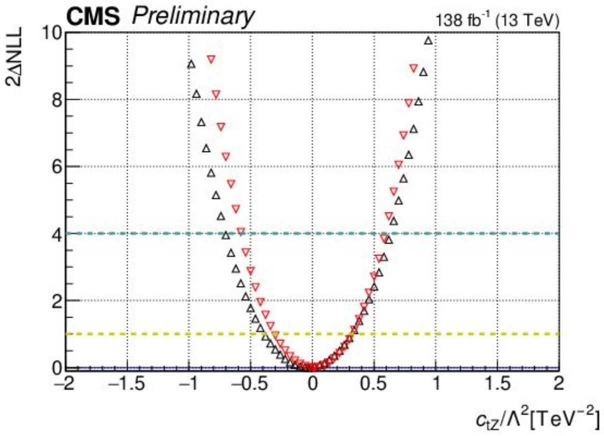


Results per operator (IV)

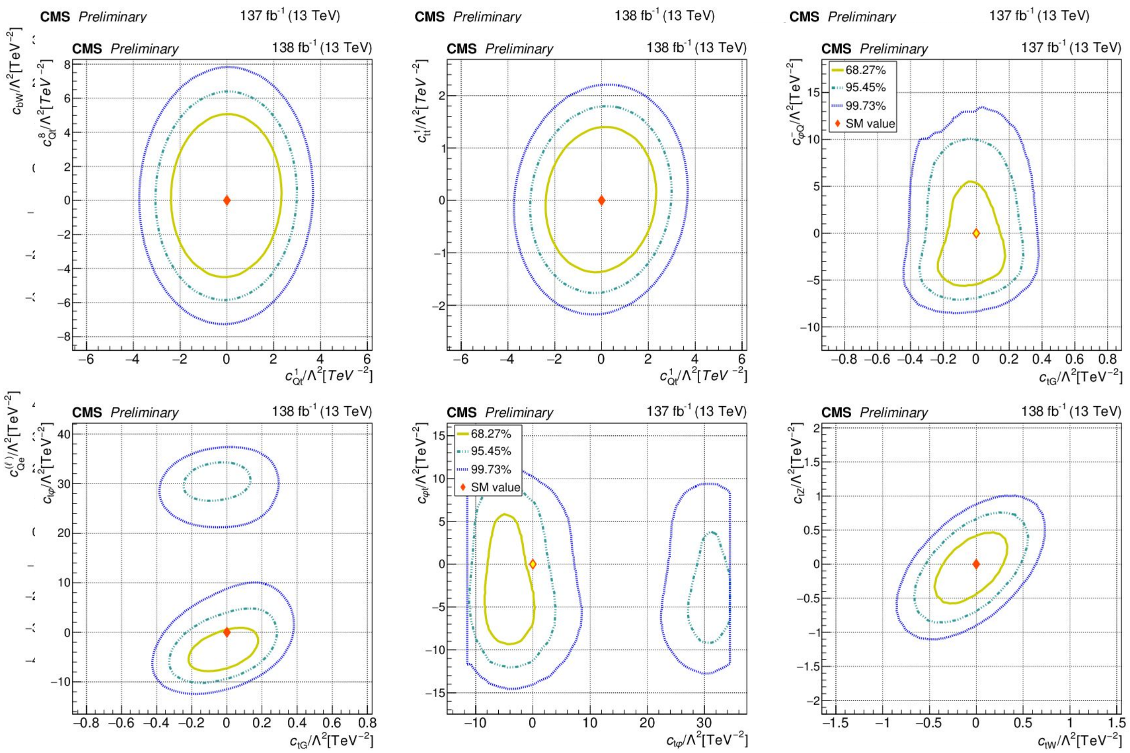


Results per operator (V)

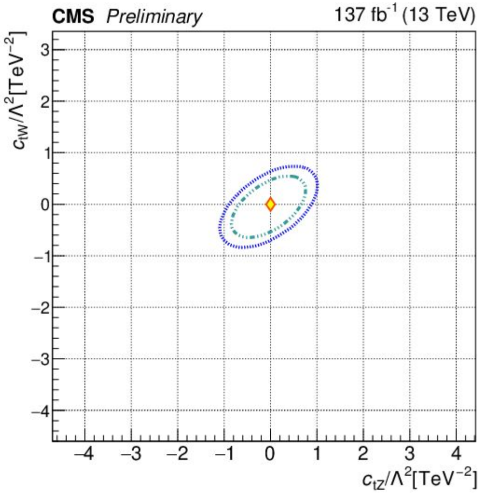




Results per pairs (I)

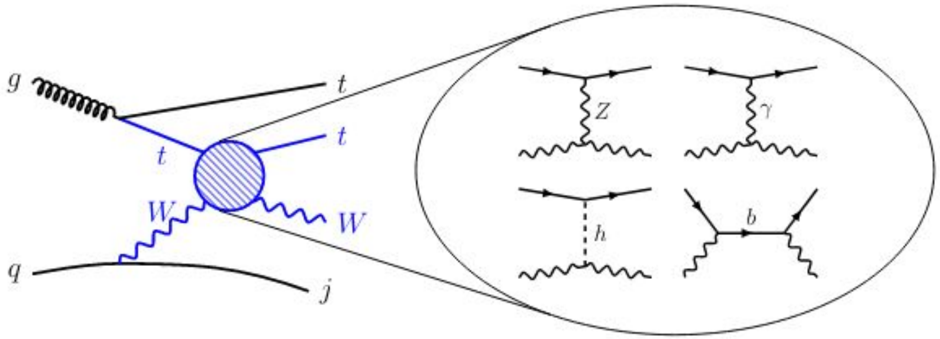


Results per pairs (II)



ttW modeling

- ttW is modeled using LO samples with an extra parton
- We assume a cross section of
- We have observed a good agreement between LO and NLO samples
- LO ttW+1jet samples include
- ttW receives contribution from
  - Two-light-two-heavy-quark operators
  - Top+lepton operators inducing charged currents
  - Top+boson operators



Detailed event selection

Event category	Leptons	$m_{\ell\ell}$	b-tags	Lepton charge sum	Jets	Differential variable
2ℓss 2b	2	No requirement	2	>0, <0	4,5,6,$\geq$7	$p_T(\ell j0)$
2ℓss 3b	2	No requirement	≥ 3	>0, <0	4,5,6,$\geq$7	$p_T(\ell j0)$
3ℓ off-Z 1b	3	$\|m_Z - m_{\ell\ell}\| > 10\,GeV$	1	>0, <0	2,3,4,$\geq$5	$p_T(\ell j0)$
3ℓ off-Z 2b	3	$\|m_Z - m_{\ell\ell}\| > 10\,GeV$	≥ 2	>0, <0	2,3,4,$\geq$5	$p_T(\ell j0)$
3ℓ on-Z 1b	3	$\|m_Z - m_{\ell\ell}\| \leq 10\,GeV$	1	No requirement	2,3,4,$\geq$5	$p_T(Z)$
3ℓ on-Z 2b	3	$\|m_Z - m_{\ell\ell}\| \leq 10\,GeV$	≥ 2	No requirement	2,3,4,$\geq$5	$p_T(Z)$ or $p_T(\ell j0)$
4ℓ	$\geq$4	No requirement	≥ 2	No requirement	2,3,$\geq$4	$p_T(\ell j0)$

Flavor assumptions

- Using flavor assumptions from arXiv:1802.07237
- Lepton sector: $[SU(3)]^3$
  - Further restricted: top+lepton couplings assumed to be the same in three generations
- Quark sector: $U(2)_q x U(2)_u x U(2)_d$ among the first and second generations
  -