# EFT Interpretations of Top and Higgs Measurements at LHC and First Steps Towards Global Analyses

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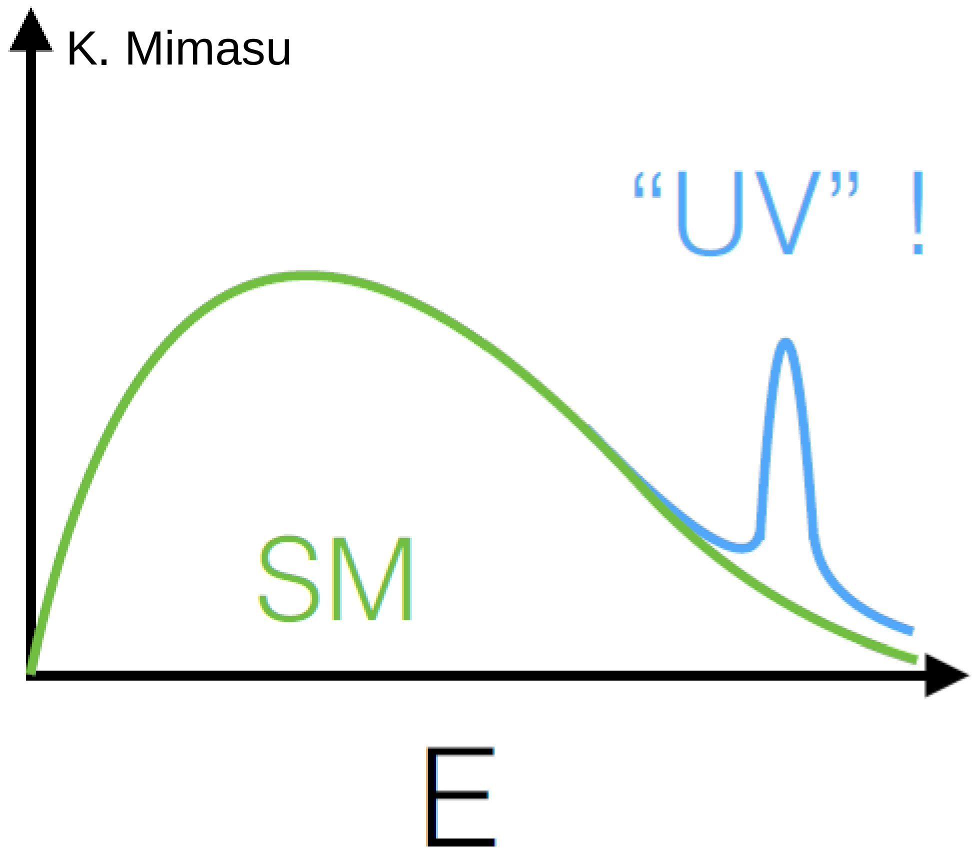
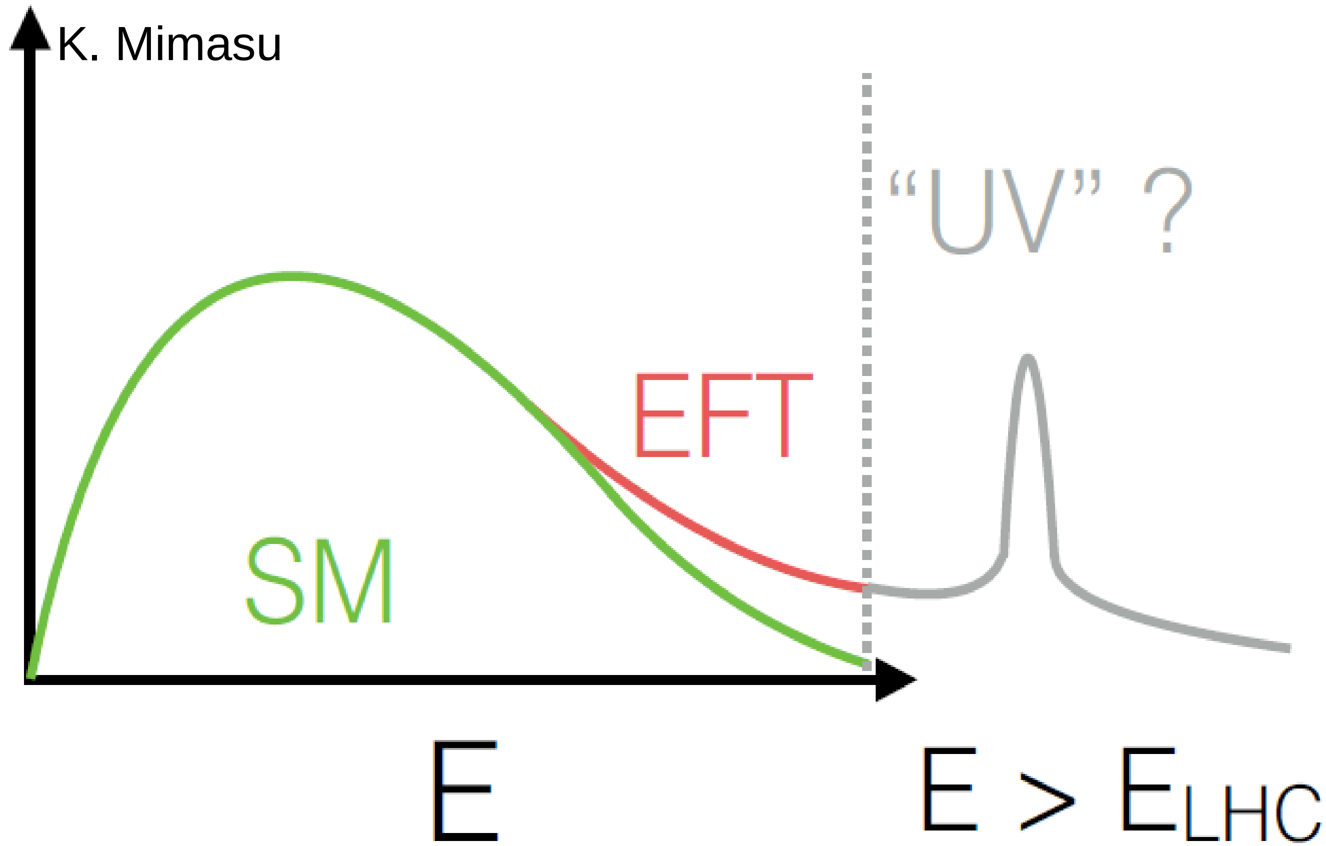
Top Quark Physics at the Precision Frontier 2019
Fermilab

# From Bumps ...



# ... to Tails




- new states might (just) exist beyond the LHC energy reach
  - indirect effects in kinematic tails, e.g., LEP limits on ~ TeV Z'
- small effects that require precise theoretical control on signal and background predictions

# SMEFT in a Nutshell

- SM effective field theory (SMEFT)

$$\boxed{L = L_{SM}^{(4)} + \sum_i \frac{c_i^{(5)}}{\Lambda_i} O_i^{(5)} + \sum_i \frac{c_i^{(6)}}{\Lambda_i^2} O_i^{(6)} + \ldots}$$

- operator expansion:
  - heavy BSM states are integrated out
  - only local operators from SM fields left
- truncated at dimension 6 (leading B & L preserving interactions)
- order-by-order: self-consistent, renormalizable QFT
- can be matched to UV theories of new physics

# Dimension-6 SMEFT Operators

| $X^3$ | | $\varphi^6$ and $\varphi^4 D^2$ | | $\psi^2\varphi^3$ | |
|---|---|---|---|---|---|
| $Q_G$ | $f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$ | $Q_\varphi$ | $(\varphi^\dagger\varphi)^3$ | $Q_{e\varphi}$ | $(\varphi^\dagger\varphi)(\bar l_p e_r \varphi)$ |
| $Q_{\widetilde G}$ | $f^{ABC} \widetilde G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$ | $Q_{\varphi\Box}$ | $(\varphi^\dagger\varphi)\Box(\varphi^\dagger\varphi)$ | $Q_{u\varphi}$ | $(\varphi^\dagger\varphi)(\bar q_p u_r \widetilde\varphi)$ |
| $Q_W$ | $\varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$ | $Q_{\varphi D}$ | $\left(\varphi^\dagger D^\mu\varphi\right)^\star \left(\varphi^\dagger D_\mu\varphi\right)$ | $Q_{d\varphi}$ | $(\varphi^\dagger\varphi)(\bar q_p d_r \varphi)$ |
| $Q_{\widetilde W}$ | $\varepsilon^{IJK} \widetilde W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$ | | | | |
| $X^2\varphi^2$ | | $\psi^2 X\varphi$ | | $\psi^2\varphi^2 D$ | |
| $Q_{\varphi G}$ | $\varphi^\dagger\varphi\, G_{\mu\nu}^A G^{A\mu\nu}$ | $Q_{eW}$ | $(\bar l_p \sigma^{\mu\nu} e_r)\tau^I\varphi W_{\mu\nu}^I$ | $Q_{\varphi l}^{(1)}$ | $(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar l_p\gamma^\mu l_r)$ |
| $Q_{\varphi\widetilde G}$ | $\varphi^\dagger\varphi\, \widetilde G_{\mu\nu}^A G^{A\mu\nu}$ | $Q_{eB}$ | $(\bar l_p \sigma^{\mu\nu} e_r)\varphi B_{\mu\nu}$ | $Q_{\varphi l}^{(3)}$ | $(\varphi^\dagger i\overleftrightarrow{D}_\mu^I\varphi)(\bar l_p\tau^I\gamma^\mu l_r)$ |
| $Q_{\varphi W}$ | $\varphi^\dagger\varphi\, W_{\mu\nu}^I W^{I\mu\nu}$ | $Q_{uG}$ | $(\bar q_p \sigma^{\mu\nu} T^A u_r)\widetilde\varphi\, G_{\mu\nu}^A$ | $Q_{\varphi e}$ | $(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar e_p\gamma^\mu e_r)$ |
| $Q_{\varphi\widetilde W}$ | $\varphi^\dagger\varphi\, \widetilde W_{\mu\nu}^I W^{I\mu\nu}$ | $Q_{uW}$ | $(\bar q_p \sigma^{\mu\nu} u_r)\tau^I\widetilde\varphi\, W_{\mu\nu}^I$ | $Q_{\varphi q}^{(1)}$ | $(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar q_p\gamma^\mu q_r)$ |
| $Q_{\varphi B}$ | $\varphi^\dagger\varphi\, B_{\mu\nu} B^{\mu\nu}$ | $Q_{uB}$ | $(\bar q_p \sigma^{\mu\nu} u_r)\widetilde\varphi\, B_{\mu\nu}$ | $Q_{\varphi q}^{(3)}$ | $(\varphi^\dagger i\overleftrightarrow{D}_\mu^I\varphi)(\bar q_p\tau^I\gamma^\mu q_r)$ |
| $Q_{\varphi\widetilde B}$ | $\varphi^\dagger\varphi\, \widetilde B_{\mu\nu} B^{\mu\nu}$ | $Q_{dG}$ | $(\bar q_p \sigma^{\mu\nu} T^A d_r)\varphi\, G_{\mu\nu}^A$ | $Q_{\varphi u}$ | $(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar u_p\gamma^\mu u_r)$ |
| $Q_{\varphi WB}$ | $\varphi^\dagger\tau^I\varphi\, W_{\mu\nu}^I B^{\mu\nu}$ | $Q_{dW}$ | $(\bar q_p \sigma^{\mu\nu} d_r)\tau^I\varphi\, W_{\mu\nu}^I$ | $Q_{\varphi d}$ | $(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar d_p\gamma^\mu d_r)$ |
| $Q_{\varphi\widetilde WB}$ | $\varphi^\dagger\tau^I\varphi\, \widetilde W_{\mu\nu}^I B^{\mu\nu}$ | $Q_{dB}$ | $(\bar q_p \sigma^{\mu\nu} d_r)\varphi\, B_{\mu\nu}$ | $Q_{\varphi ud}$ | $i(\widetilde\varphi^\dagger D_\mu\varphi)(\bar u_p\gamma^\mu d_r)$ |

Table 2: Dimension-six operators other than the four-fermion ones.

| $(\bar LL)(\bar LL)$ | | $(\bar RR)(\bar RR)$ | | $(\bar LL)(\bar RR)$ | |
|---|---|---|---|---|---|
| $Q_{ll}$ | $(\bar l_p\gamma_\mu l_r)(\bar l_s\gamma^\mu l_t)$ | $Q_{ee}$ | $(\bar e_p\gamma_\mu e_r)(\bar e_s\gamma^\mu e_t)$ | $Q_{le}$ | $(\bar l_p\gamma_\mu l_r)(\bar e_s\gamma^\mu e_t)$ |
| $Q_{qq}^{(1)}$ | $(\bar q_p\gamma_\mu q_r)(\bar q_s\gamma^\mu q_t)$ | $Q_{uu}$ | $(\bar u_p\gamma_\mu u_r)(\bar u_s\gamma^\mu u_t)$ | $Q_{lu}$ | $(\bar l_p\gamma_\mu l_r)(\bar u_s\gamma^\mu u_t)$ |
| $Q_{qq}^{(3)}$ | $(\bar q_p\gamma_\mu\tau^I q_r)(\bar q_s\gamma^\mu\tau^I q_t)$ | $Q_{dd}$ | $(\bar d_p\gamma_\mu d_r)(\bar d_s\gamma^\mu d_t)$ | $Q_{ld}$ | $(\bar l_p\gamma_\mu l_r)(\bar d_s\gamma^\mu d_t)$ |
| $Q_{lq}^{(1)}$ | $(\bar l_p\gamma_\mu l_r)(\bar q_s\gamma^\mu q_t)$ | $Q_{eu}$ | $(\bar e_p\gamma_\mu e_r)(\bar u_s\gamma^\mu u_t)$ | $Q_{qe}$ | $(\bar q_p\gamma_\mu q_r)(\bar e_s\gamma^\mu e_t)$ |
| $Q_{lq}^{(3)}$ | $(\bar l_p\gamma_\mu\tau^I l_r)(\bar q_s\gamma^\mu\tau^I q_t)$ | $Q_{ed}$ | $(\bar e_p\gamma_\mu e_r)(\bar d_s\gamma^\mu d_t)$ | $Q_{qu}^{(1)}$ | $(\bar q_p\gamma_\mu q_r)(\bar u_s\gamma^\mu u_t)$ |
| | | $Q_{ud}^{(1)}$ | $(\bar u_p\gamma_\mu u_r)(\bar d_s\gamma^\mu d_t)$ | $Q_{qu}^{(8)}$ | $(\bar q_p\gamma_\mu T^A q_r)(\bar u_s\gamma^\mu T^A u_t)$ |
| | | $Q_{ud}^{(8)}$ | $(\bar u_p\gamma_\mu T^A u_r)(\bar d_s\gamma^\mu T^A d_t)$ | $Q_{qd}^{(1)}$ | $(\bar q_p\gamma_\mu q_r)(\bar d_s\gamma^\mu d_t)$ |
| | | | | $Q_{qd}^{(8)}$ | $(\bar q_p\gamma_\mu T^A q_r)(\bar d_s\gamma^\mu T^A d_t)$ |

| $(\bar LR)(\bar RL)$ and $(\bar LR)(\bar LR)$ | | $B$-violating | |
|---|---|---|---|
| $Q_{ledq}$ | $(\bar l_p^j e_r)(\bar d_s q_t^j)$ | $Q_{duq}$ | $\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(q_s^{\gamma j})^T C l_t^k\right]$ |
| $Q_{quqd}^{(1)}$ | $(\bar q_p^j u_r)\varepsilon_{jk}(\bar q_s^k d_t)$ | $Q_{qqu}$ | $\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(u_s^\gamma)^T C e_t\right]$ |
| $Q_{quqd}^{(8)}$ | $(\bar q_p^j T^A u_r)\varepsilon_{jk}(\bar q_s^k T^A d_t)$ | $Q_{qqq}$ | $\varepsilon^{\alpha\beta\gamma}\varepsilon_{jn}\varepsilon_{km}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$ |
| $Q_{lequ}^{(1)}$ | $(\bar l_p^j e_r)\varepsilon_{jk}(\bar q_s^k u_t)$ | $Q_{duu}$ | $\varepsilon^{\alpha\beta\gamma}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(u_s^\gamma)^T C e_t\right]$ |
| $Q_{lequ}^{(3)}$ | $(\bar l_p^j \sigma_{\mu\nu} e_r)\varepsilon_{jk}(\bar q_s^k \sigma^{\mu\nu} u_t)$ | | |

Table 3: Four-fermion operators.

- complete, non-redundant set of operators:
  - dimension-6: 59 (76 real)
  - depending on CP/flavor assumptions

# The Challenge

Top Quark

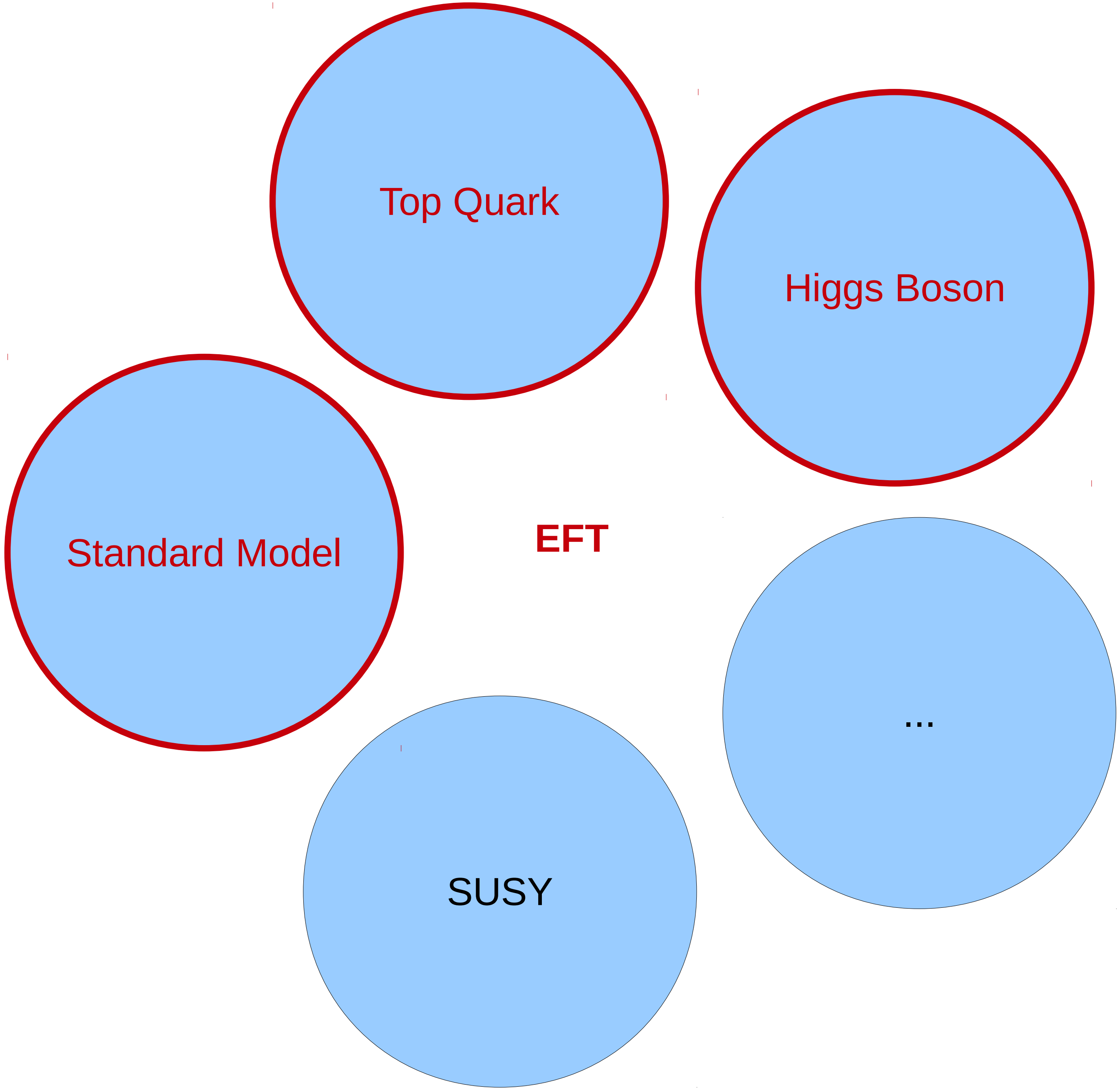
Higgs Boson

Standard Model

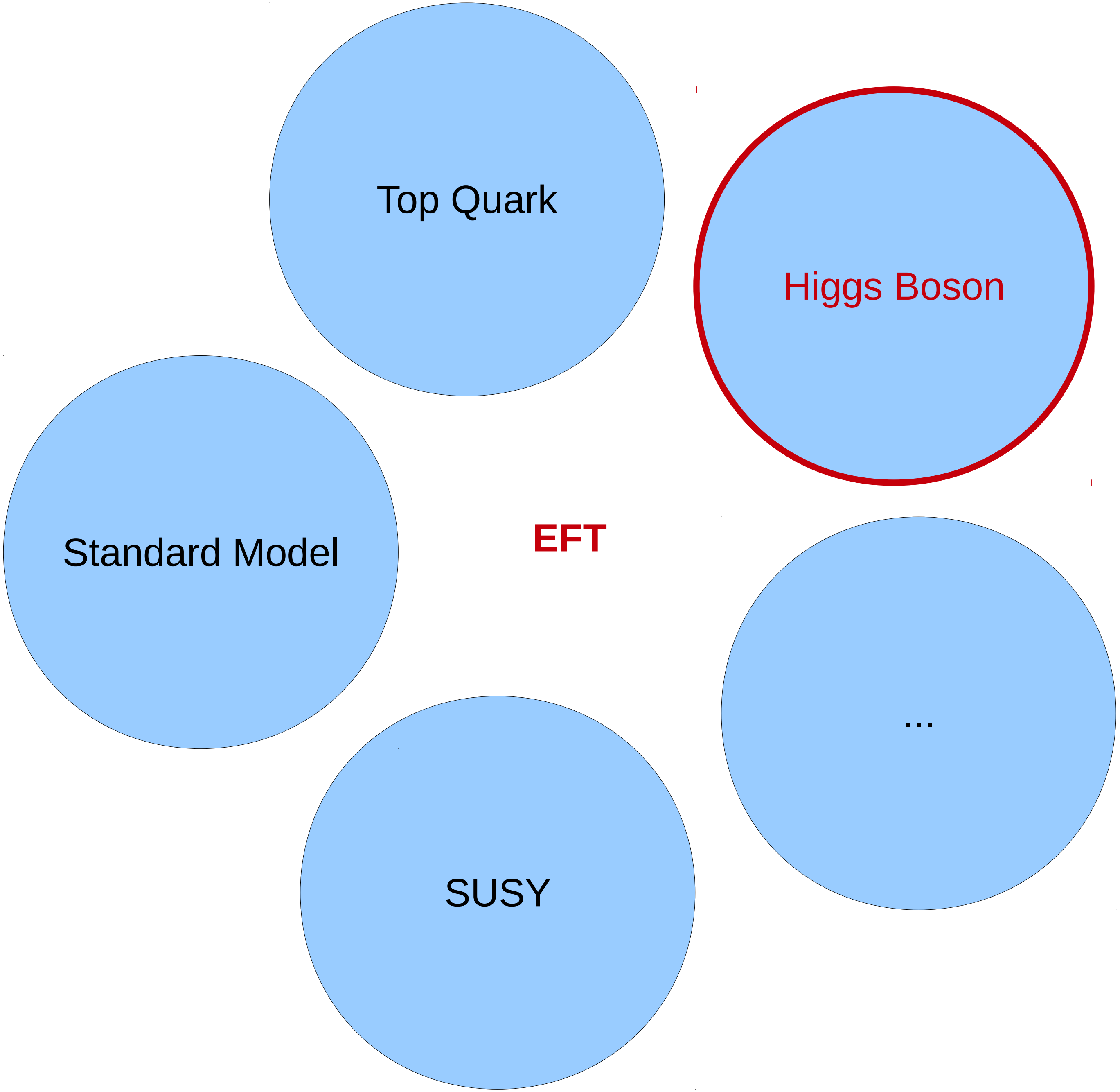
...

SUSY

# The Challenge

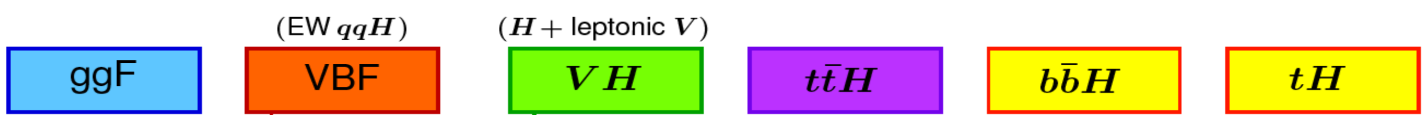


# The Challenge



# Simplified Template Cross Sections (STXS)

- evolution from inclusive cross section measurements

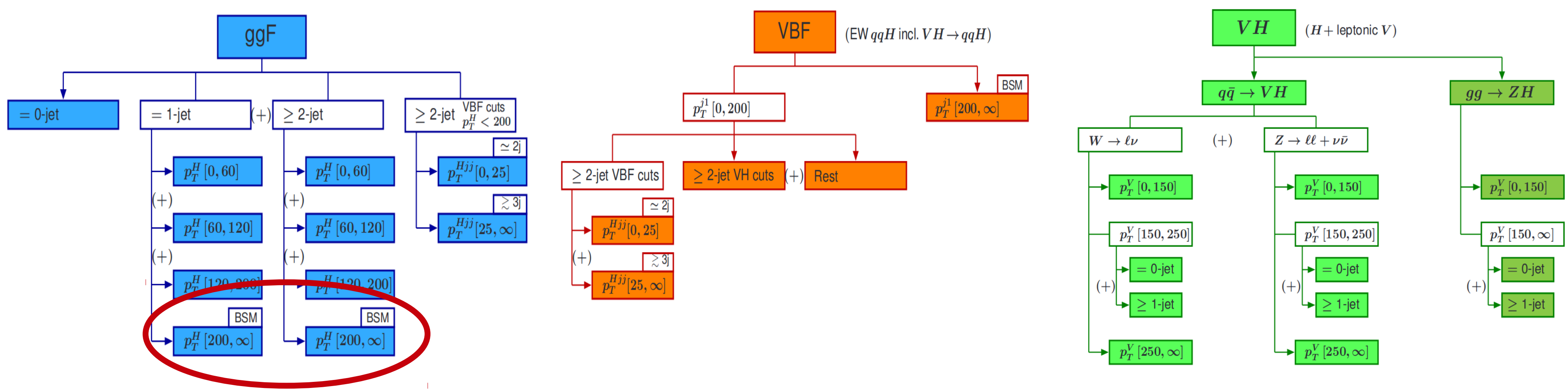



arXiv:1610.07922

# Simplified Template Cross Sections (STXS)

- evolution from inclusive cross section measurements
  - define several kinematic regions at generator level
  - maximize experimental sensitivity to e.g. BSM effects
  - minimize theory dependence

| ggF | VBF (EW $qqH$) | $VH$ ($H+$ leptonic $V$) | $t\bar{t}H$ | $b\bar{b}H$ | $tH$ |
|---|---|---|---|---|---|

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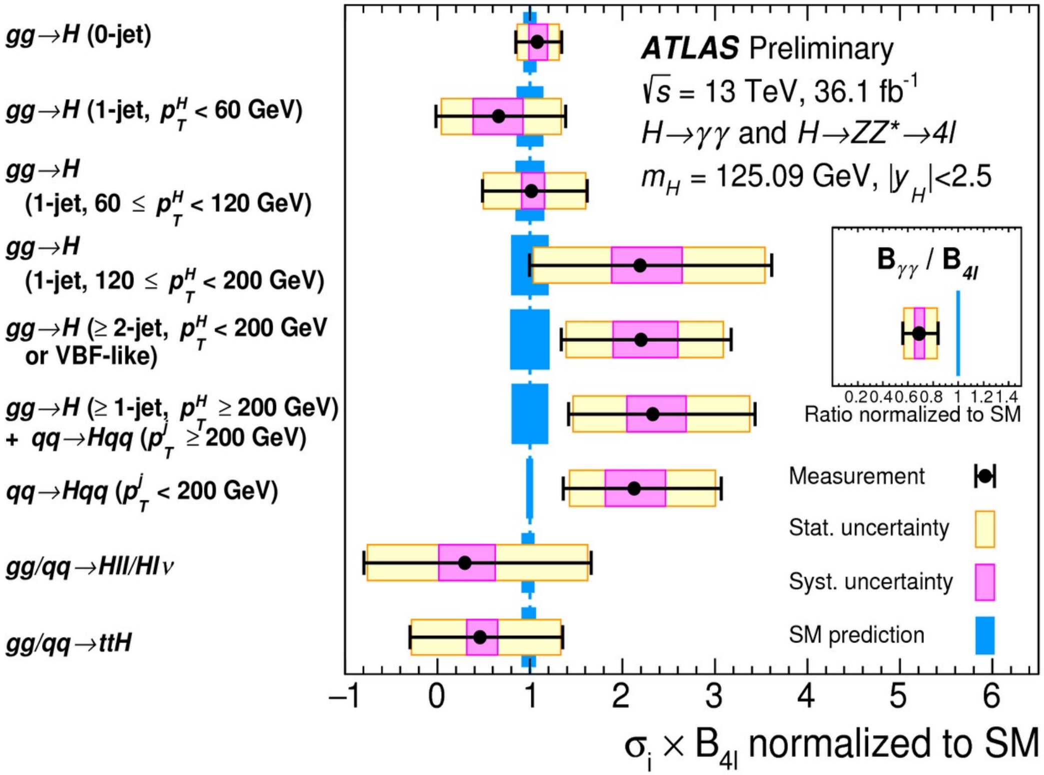
# Connecting STXS with EFT

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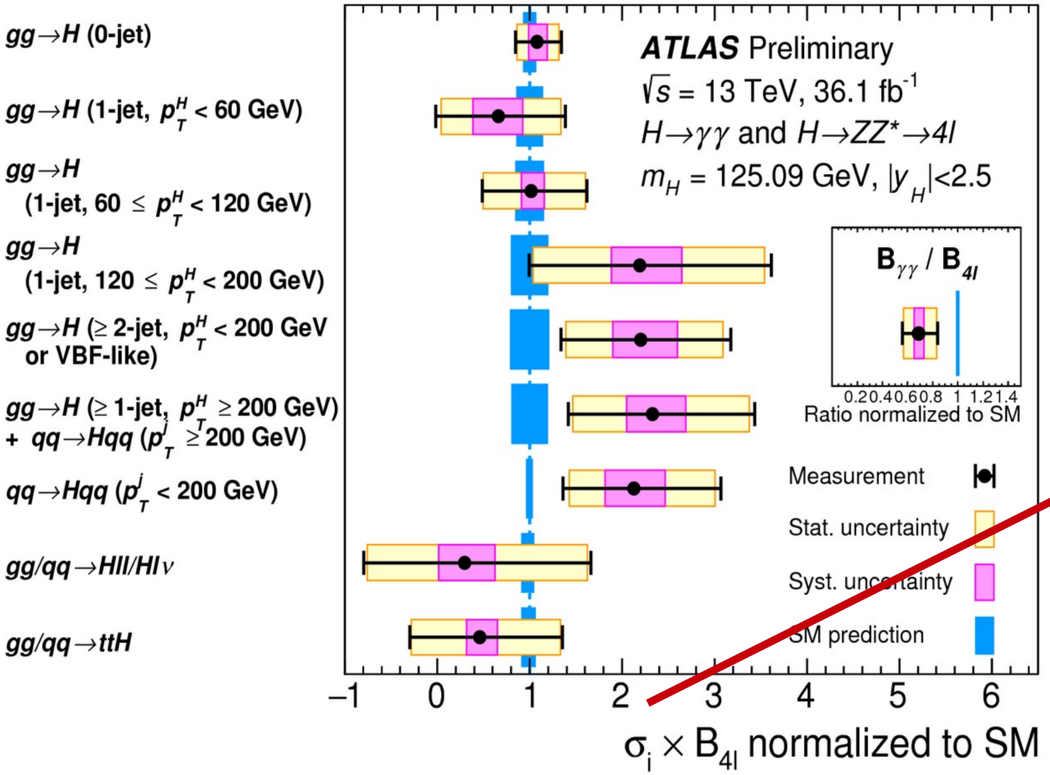
# Connecting STXS with EFT




$$\boxed{\sigma_{EFT}/\sigma_{SM} = 1 + \sum_i c_i A_i + \sum_{ij} c_i c_j B_{ij}}$$

- coefficients A,B from LO MC
  - HEL as effective Lagrangian (SILH basis with flavor-universal couplings)

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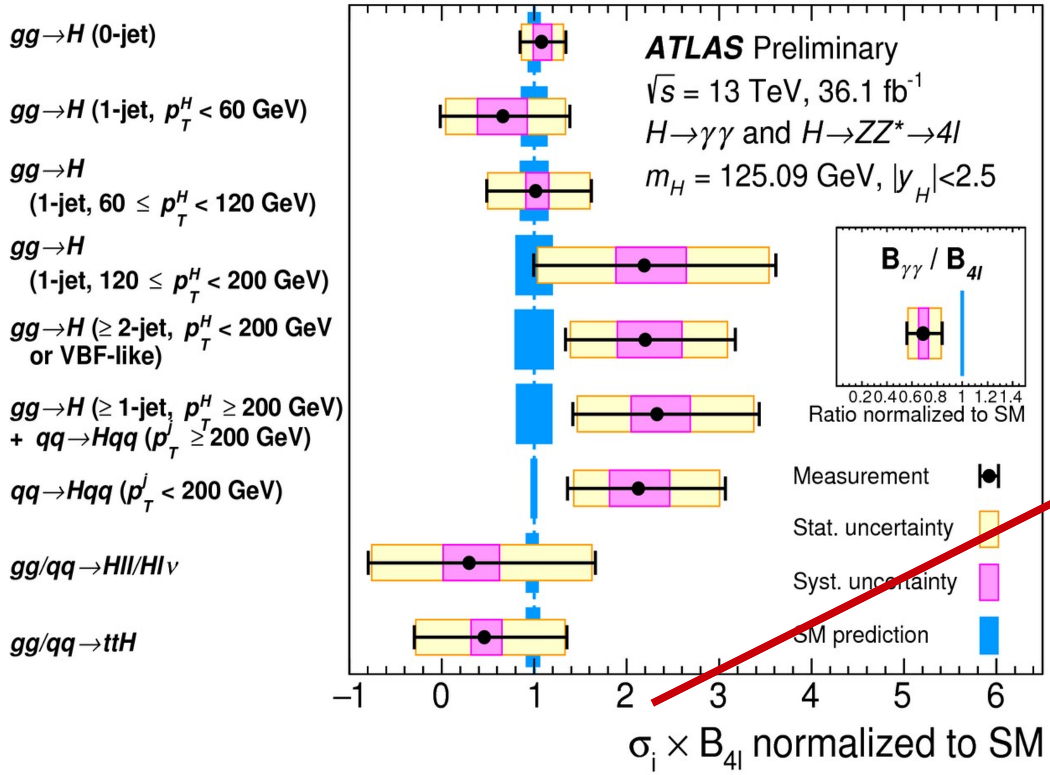
# Connecting STXS with EFT




$$\sigma_{EFT}/\sigma_{SM} = 1 + \sum_i c_i A_i + \sum_{ij} c_i c_j B_{ij}$$

$$\mathcal{B}_{4\ell} = \frac{\Gamma_{4\ell}}{\sum_f \Gamma_f} \approx \frac{\Gamma_{4\ell}^{SM}}{\sum_f \Gamma_f^{SM}} \left[ 1 + \sum_i A_i^{4\ell} c_i + \sum_{ij} B_{ij}^{4\ell} c_i c_j - \sum_f \left( \sum_i A_i^f c_i + \sum_{ij} B_{ij}^f c_i c_j \right) \right]$$

- coefficients A,B from LO MC
  - HEL as effective Lagrangian (SILH basis with flavor-universal couplings)

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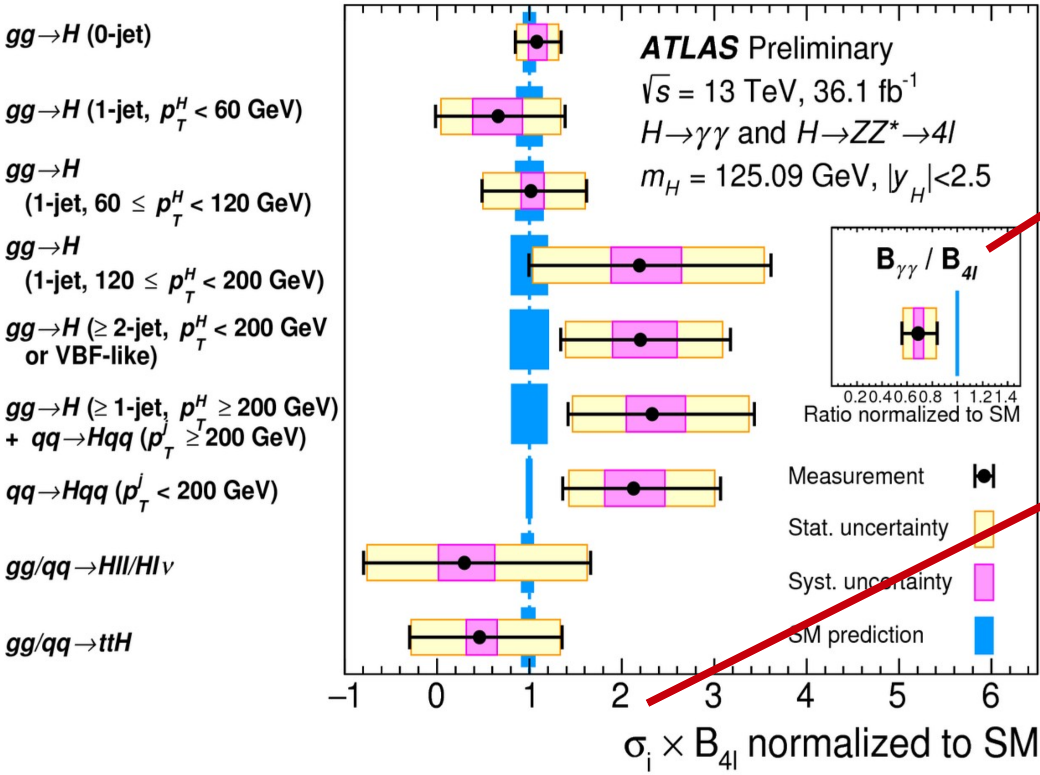
# Connecting STXS with EFT

$$\frac{\Gamma_f}{\Gamma_{4\ell}} \approx \frac{\Gamma_f^{SM}}{\Gamma_{4\ell}^{SM}}\left[1+\sum_i A_i^f c_i + \sum_{ij} B_{ij}^f c_i c_j - \left(\sum_i A_i^{4\ell} c_i + \sum_{ij} B_{ij}^{4\ell} c_i c_j\right)\right]$$




$$\sigma_{EFT}/\sigma_{SM} = 1 + \sum_i c_i A_i + \sum_{ij} c_i c_j B_{ij}$$

$$B_{4\ell} = \frac{\Gamma_{4\ell}}{\sum_f \Gamma_f} \approx \frac{\Gamma_{4\ell}^{SM}}{\sum_f \Gamma_f^{SM}}\left[1+\sum_i A_i^{4\ell} c_i + \sum_{ij} B_{ij}^{4\ell} c_i c_j - \sum_f\left(\sum_i A_i^f c_i + \sum_{ij} B_{ij}^f c_i c_j\right)\right]$$

- coefficients A,B from LO MC
  - HEL as effective Lagrangian (SILH basis with flavor-universal couplings)

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# Constraining Higgs EFT from $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ$

- 15 dim-6 operators affecting Higgs physics
  - neglect CP-odd ones (-4)
  - neglect Higgs self-couplings/Yukawa couplings to down-type quarks and leptons (-3)
  - neglect Higgs field normalization as sensitivity not good enough for global change in rate (-1)
  - $C_{ww} + c_B = 0$ from precision electroweak parameter S (-1)

| Operator | Expression | HEL coefficient | Vertices |
|---|---|---|---|
| $O_g$ | $\lvert H\rvert^2 G^A_{\mu\nu} G^{A\mu\nu}$ | $\texttt{cG} = \frac{m_W^2}{g_s^2}\bar{c}_g$ | $Hgg$ |
| $O_\gamma$ | $\lvert H\rvert^2 B_{\mu\nu} B^{\mu\nu}$ | $\texttt{cA} = \frac{m_W^2}{g'^2}\bar{c}_\gamma$ | $H\gamma\gamma, HZZ$ |
| $O_u$ | $y_u \lvert H\rvert^2 \bar{u}_l H u_R + \text{h.c.}$ | $\texttt{cu} = v^2 \bar{c}_u$ | $Ht\bar{t}$ |
| $O_{HW}$ | $i\,(D^\mu H)^\dagger\,\sigma^a\,(D^\nu H)\,W^a_{\mu\nu}$ | $\texttt{cHW} = \frac{m_W^2}{g}\bar{c}_{HW}$ | $HWW, HZZ$ |
| $O_{HB}$ | $i\,(D^\mu H)^\dagger\,(D^\nu H)\,B_{\mu\nu}$ | $\texttt{cHB} = \frac{m_W^2}{g'}\bar{c}_{HB}$ | $HZZ$ |
| $O_W$ | $i\,(H^\dagger \sigma^a D^\mu H)\,D^\nu W^a_{\mu\nu}$ | $\texttt{cWW} = \frac{m_W^2}{g}\bar{c}_W$ | $HWW, HZZ$ |
| $O_B$ | $i\,(H^\dagger D^\mu H)\,\partial^\nu B_{\mu\nu}$ | $\texttt{cB} = \frac{m_W^2}{g'}\bar{c}_B$ | $HZZ$ |

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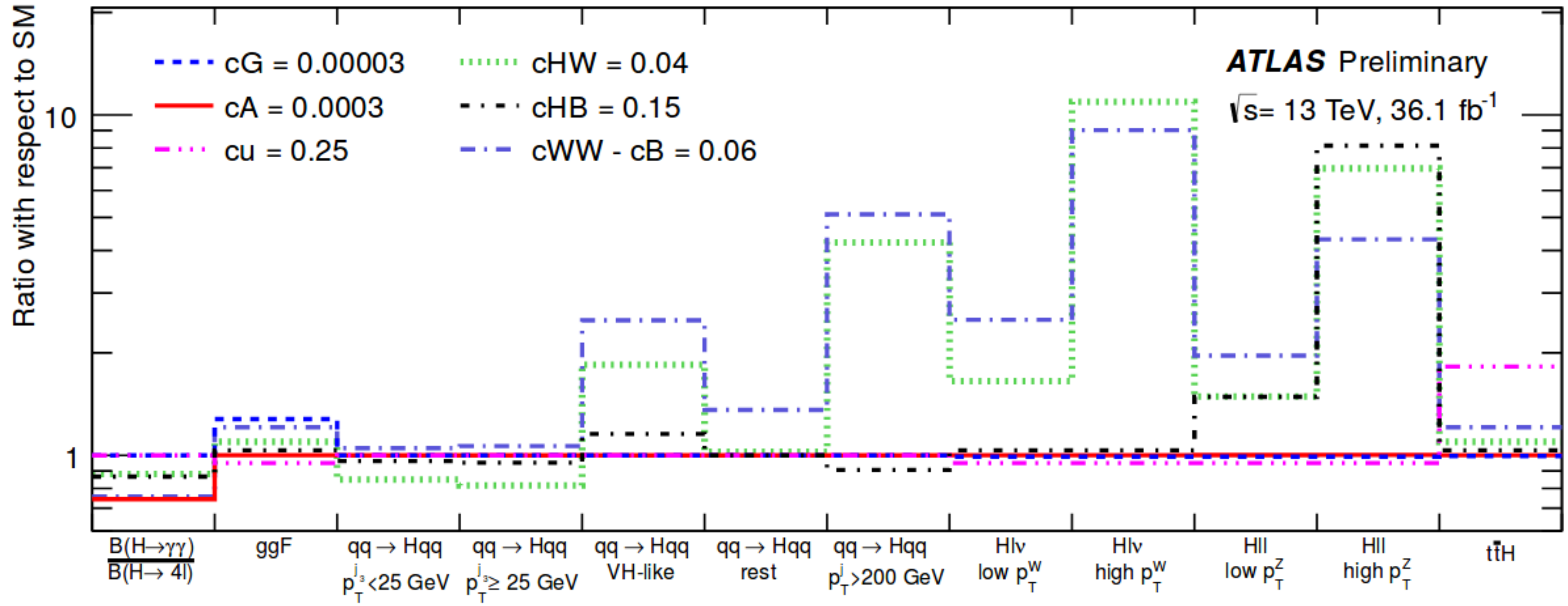
probe 6 remaining operators




| Operator | Expression | HEL coefficient | Vertices |
|---|---|---|---|
| $O_g$ | $\|H\|^2 G^A_{\mu\nu} G^{A\mu\nu}$ | $\mathtt{cG} = \frac{m_W^2}{g_s^2}\bar{c}_g$ | $Hgg$ |
| $O_\gamma$ | $\|H\|^2 B_{\mu\nu} B^{\mu\nu}$ | $\mathtt{cA} = \frac{m_W^2}{g'^2}\bar{c}_\gamma$ | $H\gamma\gamma, HZZ$ |
| $O_u$ | $y_u \|H\|^2 \bar{u}_l H u_R +$ h.c. | $\mathtt{cu} = v^2 \bar{c}_u$ | $Ht\bar{t}$ |
| $O_{HW}$ | $i\,(D^\mu H)^\dagger\, \sigma^a\, (D^\nu H)\, W^a_{\mu\nu}$ | $\mathtt{cHW} = \frac{m_W^2}{g}\bar{c}_{HW}$ | $HWW, HZZ$ |
| $O_{HB}$ | $i\,(D^\mu H)^\dagger\, (D^\nu H)\, B_{\mu\nu}$ | $\mathtt{cHB} = \frac{m_W^2}{g'}\bar{c}_{HB}$ | $HZZ$ |
| $O_W$ | $i\,(H^\dagger \sigma^a D^\mu H)\, D^\nu W^a_{\mu\nu}$ | $\mathtt{cWW} = \frac{m_W^2}{g}\bar{c}_W$ | $HWW, HZZ$ |
| $O_B$ | $i\,(H^\dagger D^\mu H)\, \partial^\nu B_{\mu\nu}$ | $\mathtt{cB} = \frac{m_W^2}{g'}\bar{c}_B$ | $HZZ$ |

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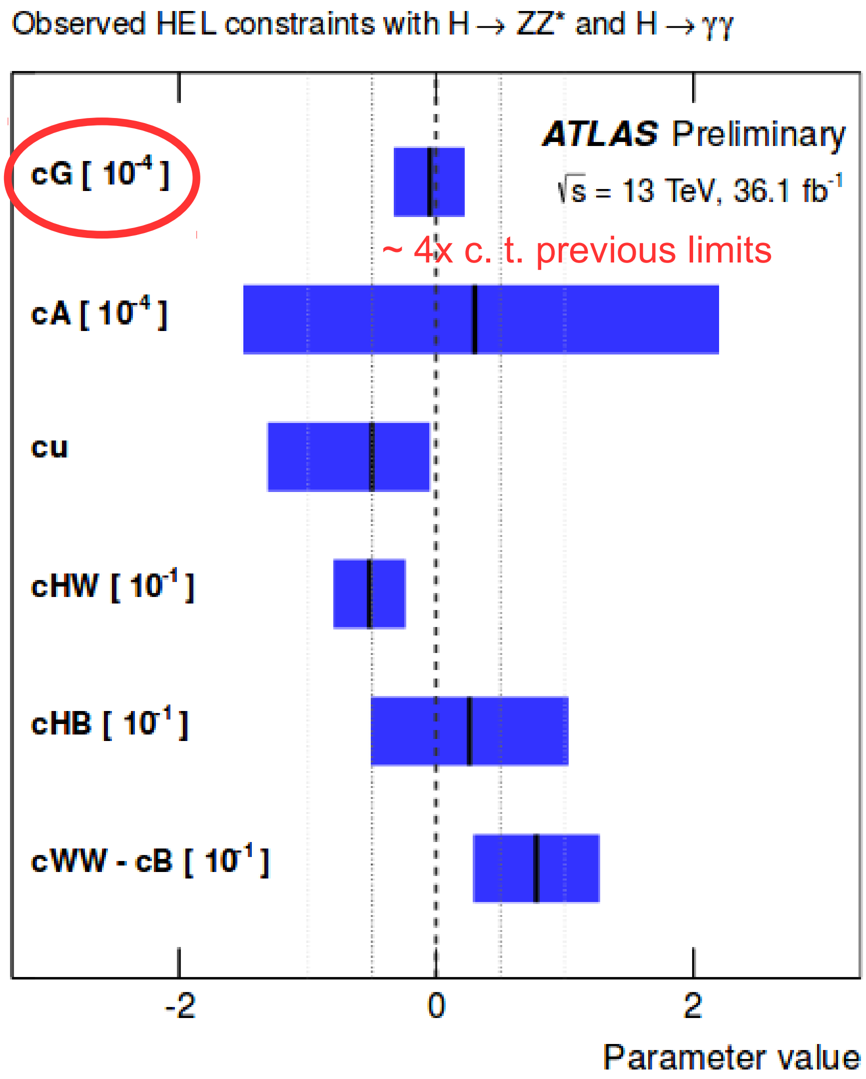
# Constraining Higgs EFT from $H \to \gamma\gamma$ and $H \to ZZ$

| Operator | Expression |
|---|---|
| $\mathcal{O}_g$ | $\lvert H\rvert^2 G^A_{\mu\nu} G^{A\mu\nu}$ |
| $\mathcal{O}_\gamma$ | $\lvert H\rvert^2 B_{\mu\nu} B^{\mu\nu}$ |
| $\mathcal{O}_u$ | $y_u \lvert H\rvert^2 \bar{u}_l H u_R +$ h.c. |
| $\mathcal{O}_{HW}$ | $i\,(D^\mu H)^\dagger\,\sigma^a\,(D^\nu H)\,W^a_{\mu\nu}$ |
| $\mathcal{O}_{HB}$ | $i\,(D^\mu H)^\dagger\,(D^\nu H)\,B_{\mu\nu}$ |
| $\mathcal{O}_W$ | $i\,(H^\dagger \sigma^a D^\mu H)\,D^\nu W^a_{\mu\nu}$ |
| $\mathcal{O}_B$ | $i\,(H^\dagger D^\mu H)\,\partial^\nu B_{\mu\nu}$ |

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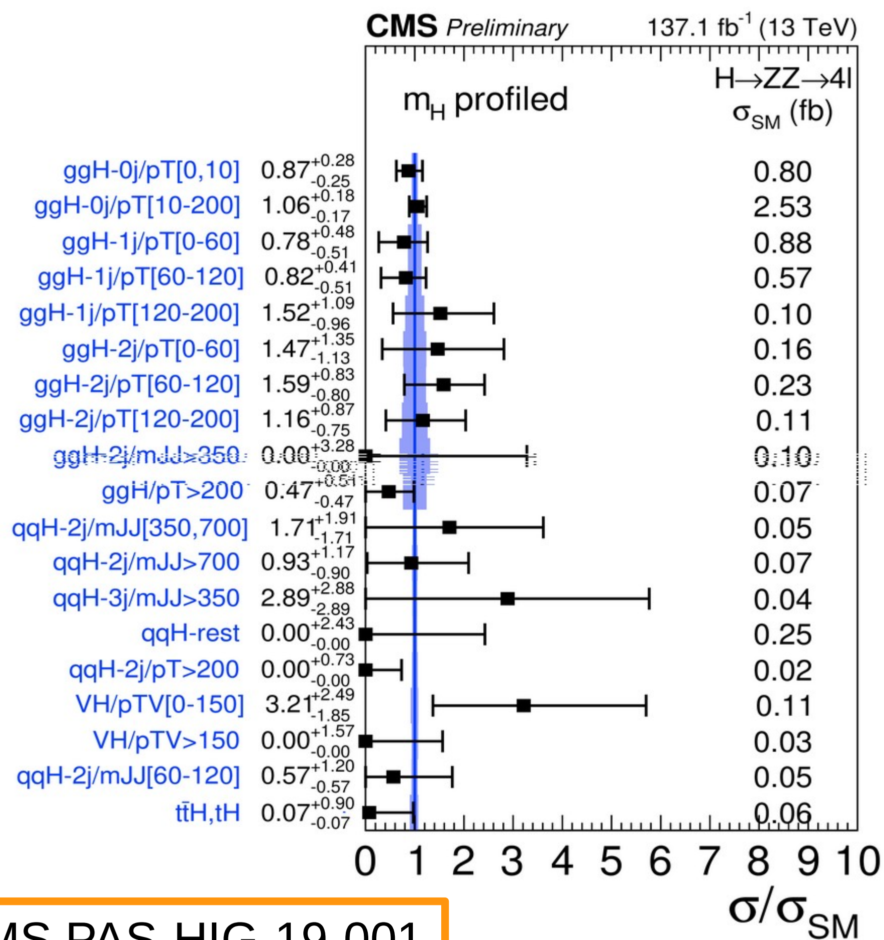
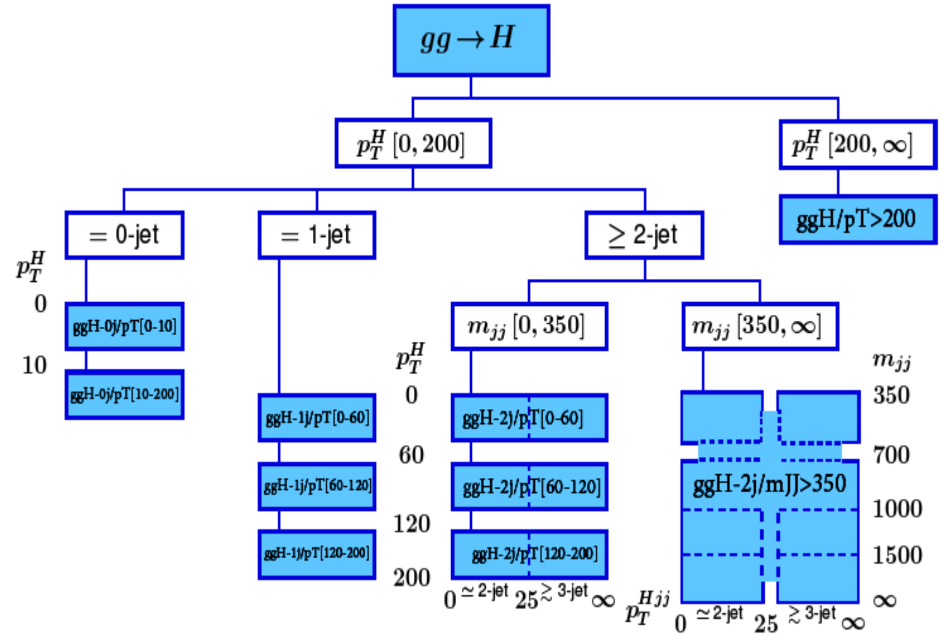
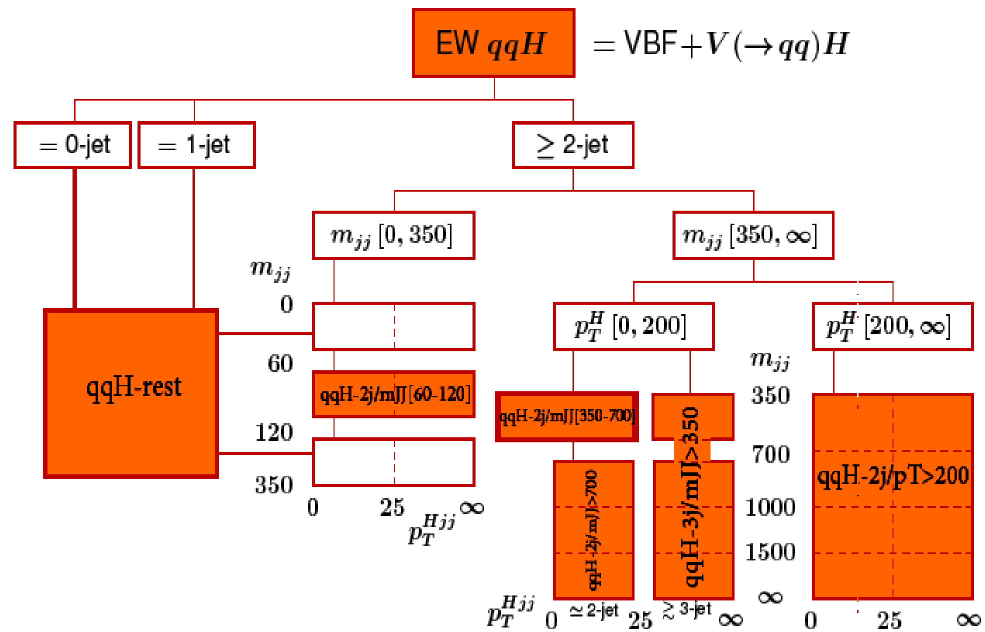
- targeting four production modes:
  ggH, VBF, VH, $t\bar{t}$H/tH
- first results with revised categorization (stage 1.1)

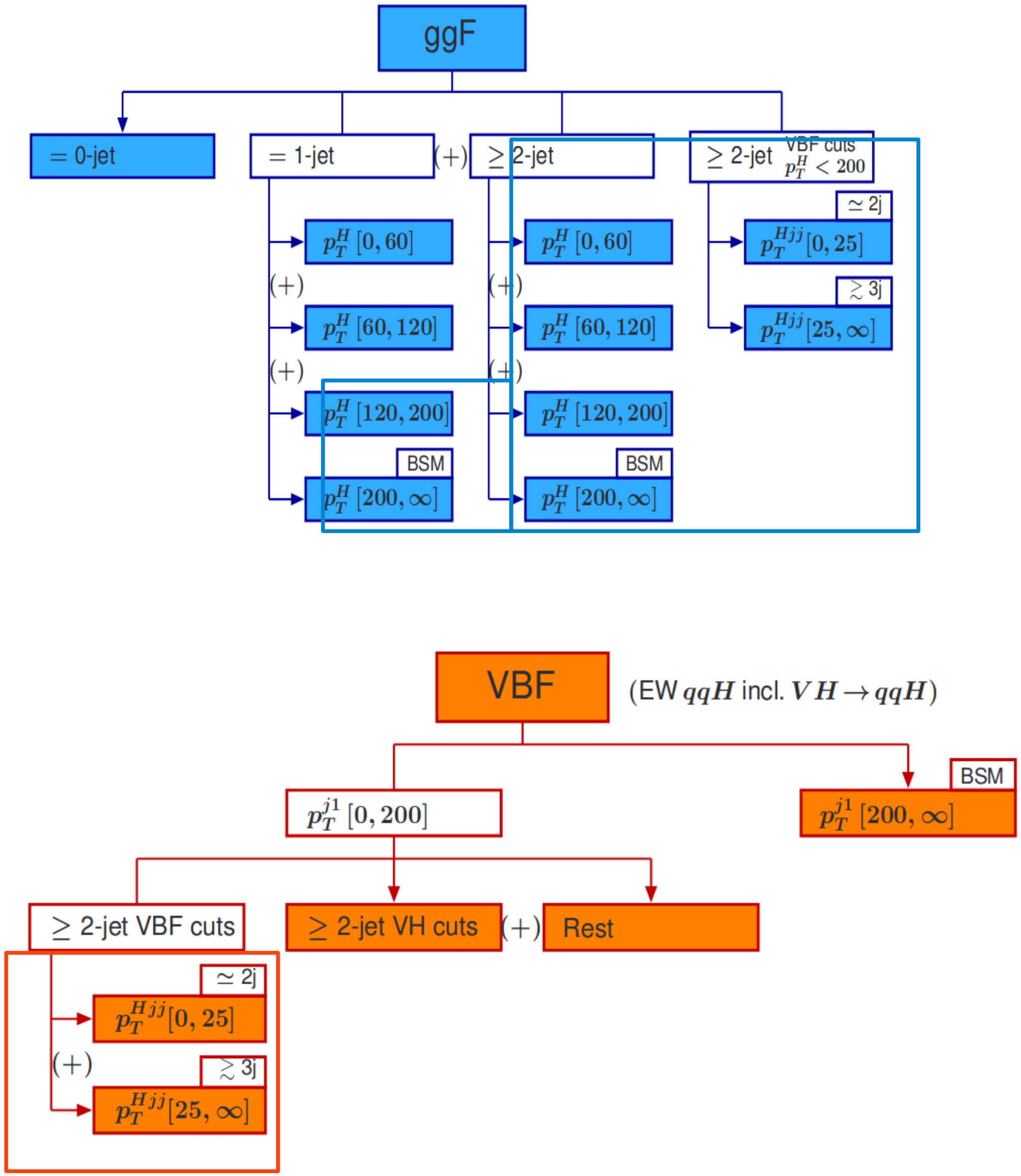


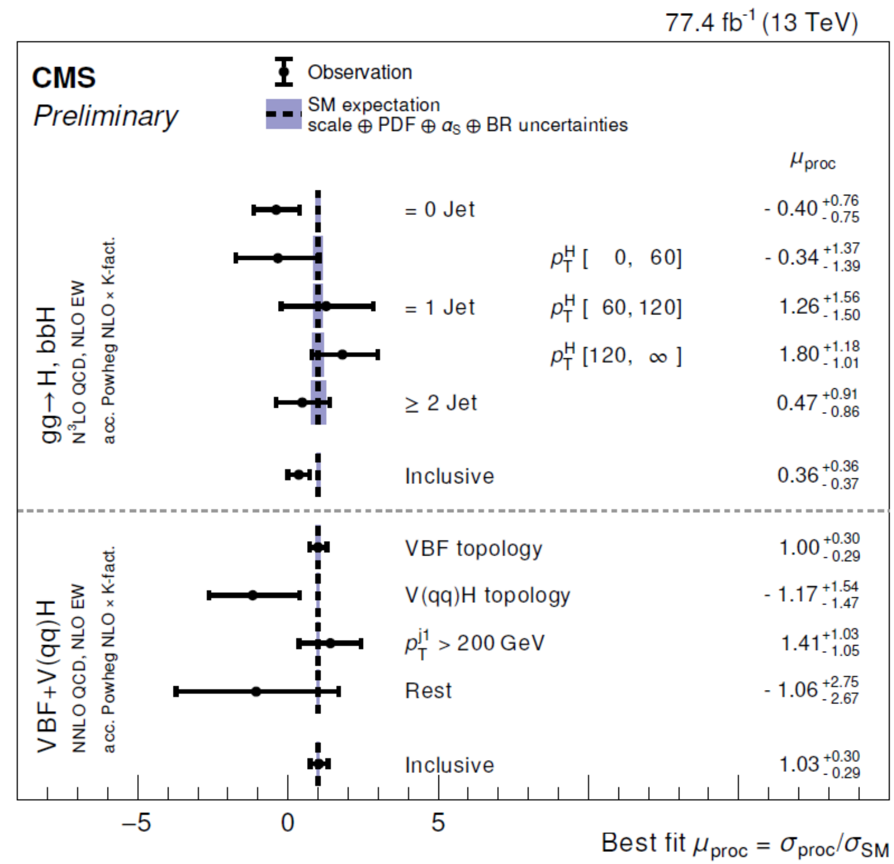




CMS PAS-HIG-19-001

# STXS Examples from CMS: H$\rightarrow \tau\tau$ (2016-2017)

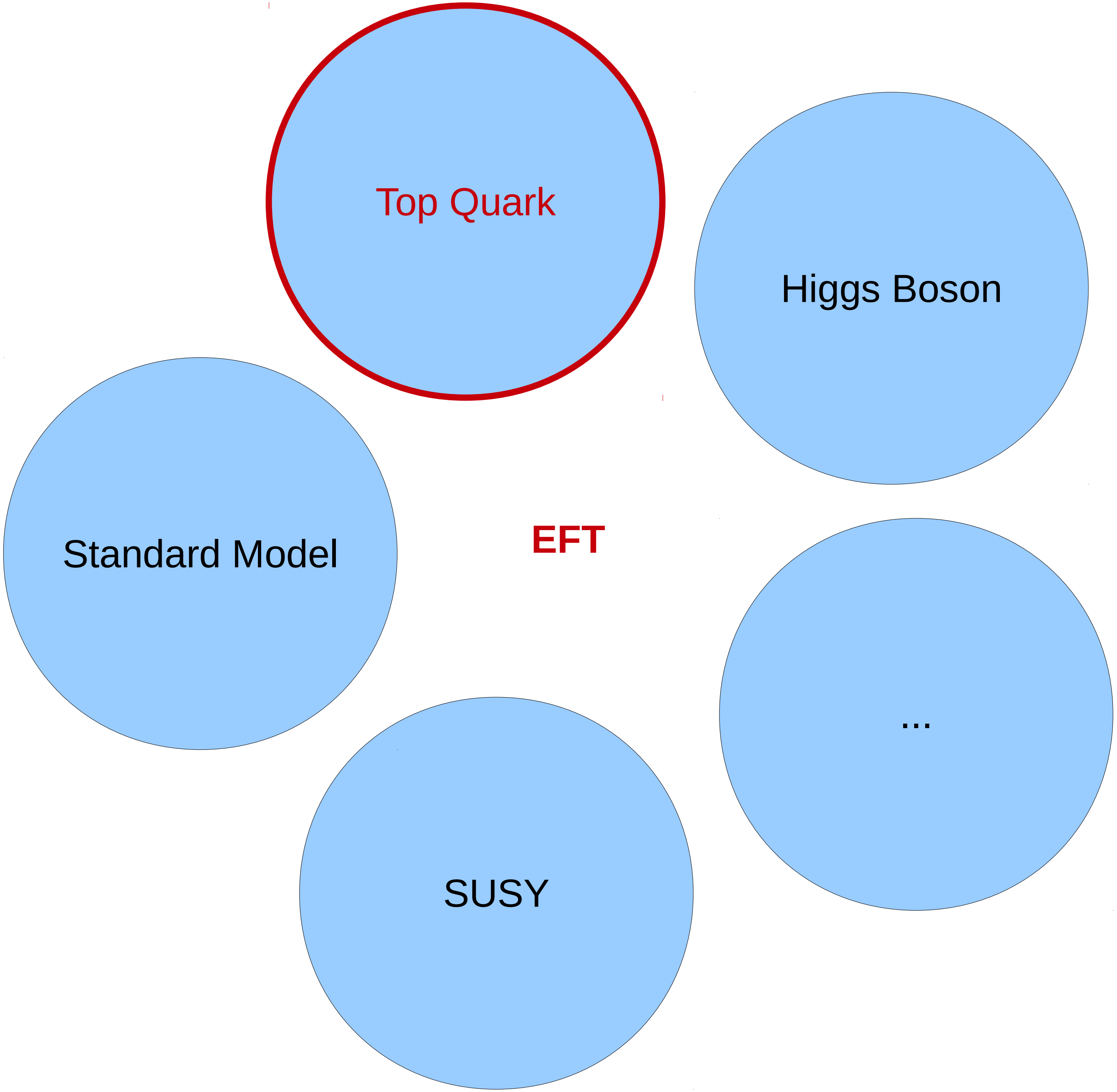



- first $\tau\tau$ stage 1 measurement in multiple ggF & VBF bins

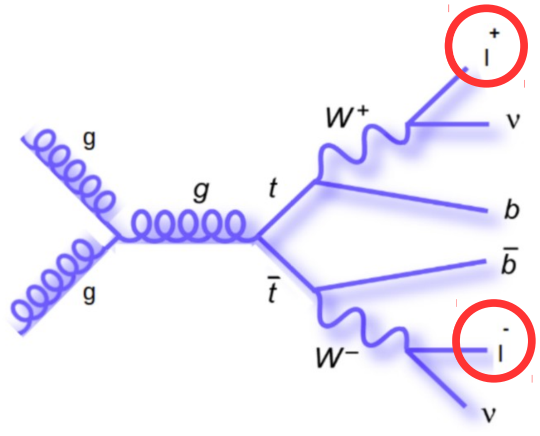



CMS PAS-HIG-18-032

# The Challenge



- top ideal quark for spin measurements
  - decays before forming bound states
  - spin transferred to daughter particles
  - leptons represent an ideal probe of top spin



- top ideal quark for spin measurements
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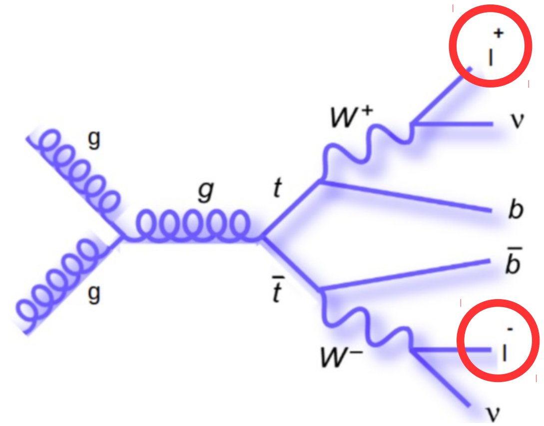
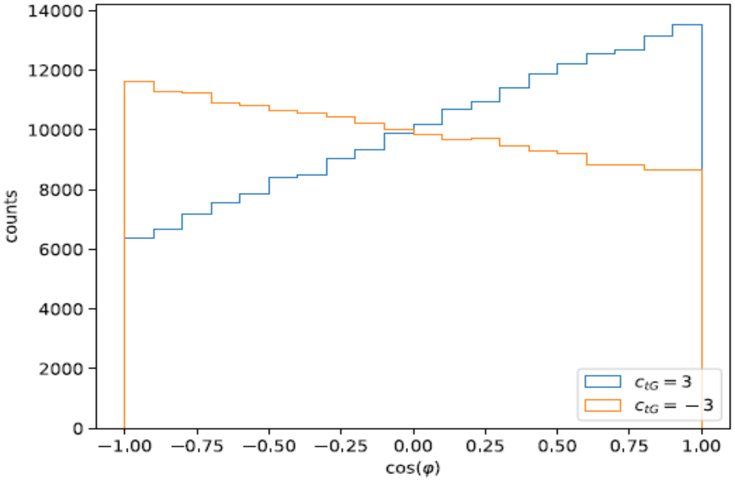
- powerful probe of BSM physics

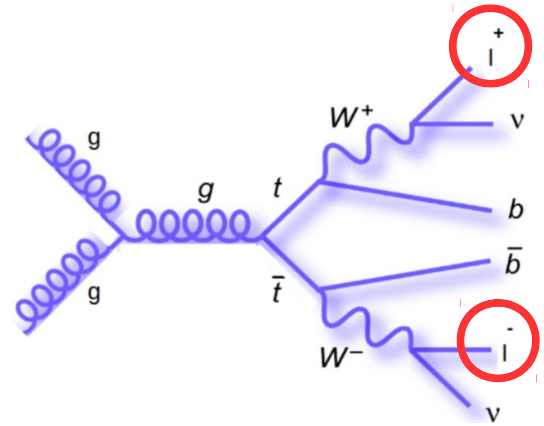
  → high sensitivity to EFT, e.g. chromomagnetic dipole moment (CMDM)

$$O_{tG} = y_t g_s (\overline{Q}\sigma^{\mu\nu} T^a t)\tilde{\phi} G^a_{\mu\nu}$$



# Direct Measurement of $t\bar{t}$ Spin Density Matrix

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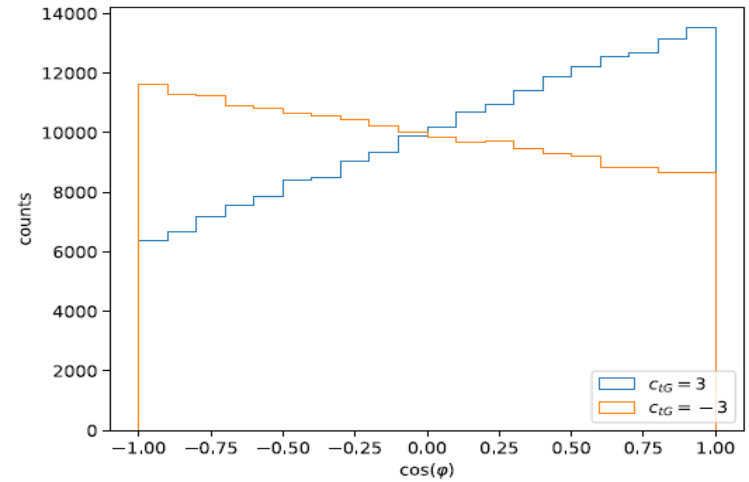
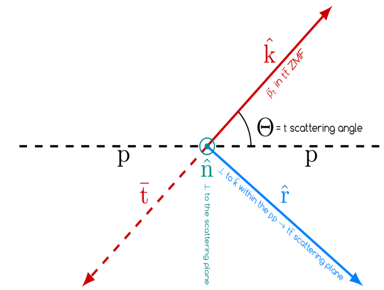
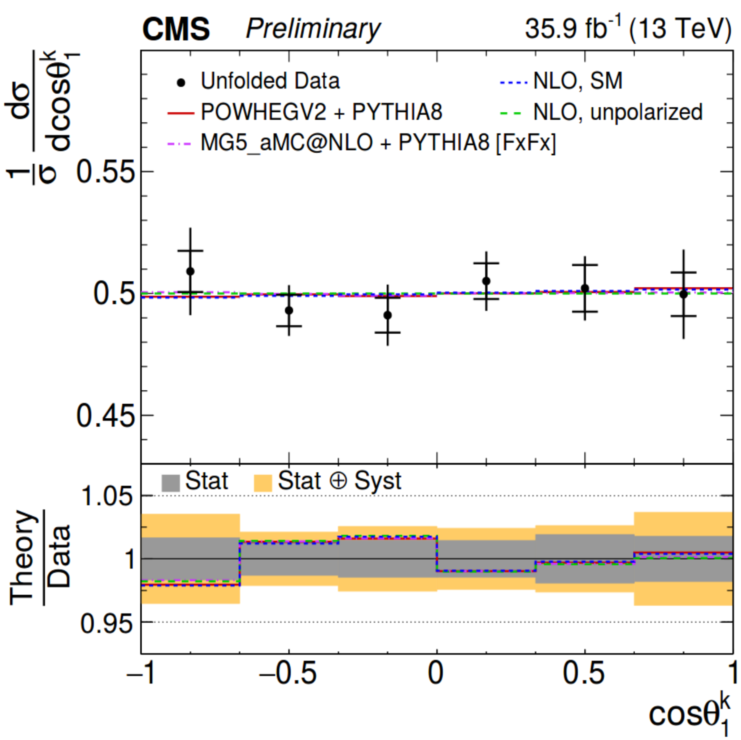


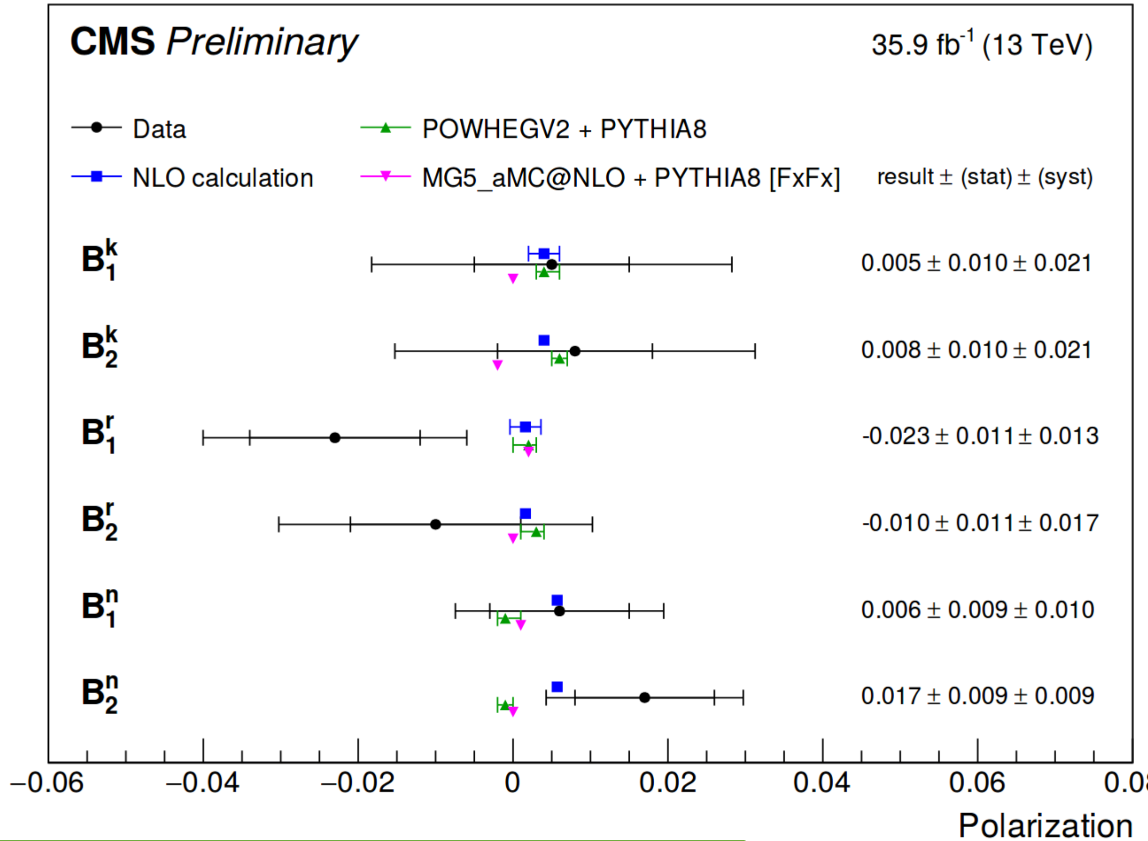

- 15 coefficients completely characterize spin dependence of $t\bar{t}$ production
  - probe by measuring unfolded 1D angular distributions

$$\frac{1}{\sigma}\frac{d\sigma}{d\Omega_+ d\Omega_-} = \frac{1}{(4\pi)^2}\left(1 + \mathbf{B}^+ \cdot \hat{\ell}^+ + \mathbf{B}^- \cdot \hat{\ell}^- - \hat{\ell}^+ \cdot \mathbb{C} \cdot \hat{\ell}^-\right)$$

- polarization consistent with zero for each axis
  - not yet sensitive to small level of polarization in the SM



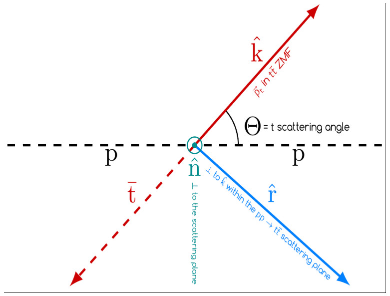



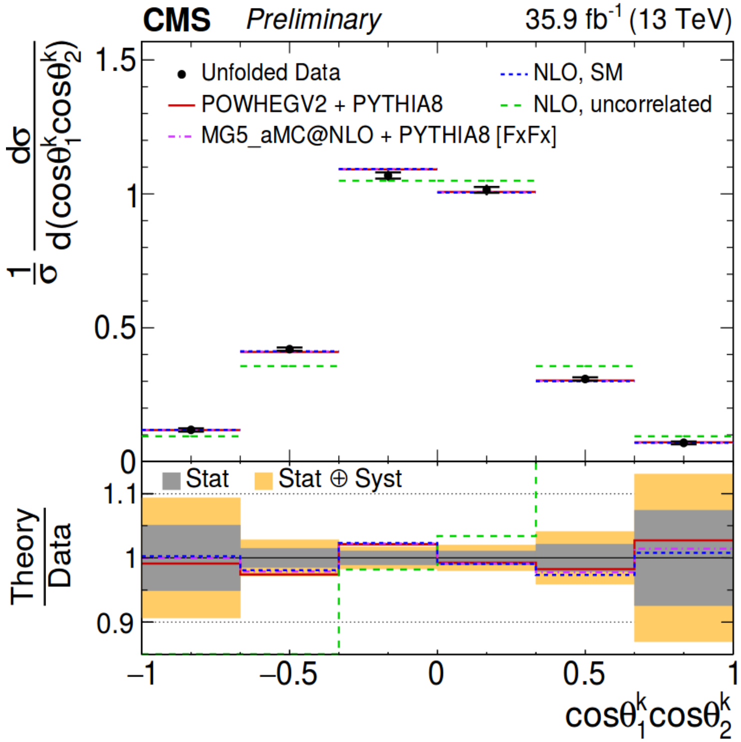

$$\frac{1}{\sigma}\frac{d\sigma}{d\Omega_+ d\Omega_-} = \frac{1}{(4\pi)^2}\left(1 + \mathbf{B}^+\cdot\hat{\ell}^+ + \mathbf{B}^-\cdot\hat{\ell}^- - \hat{\ell}^+\cdot\mathbb{C}\cdot\hat{\ell}^-\right)$$

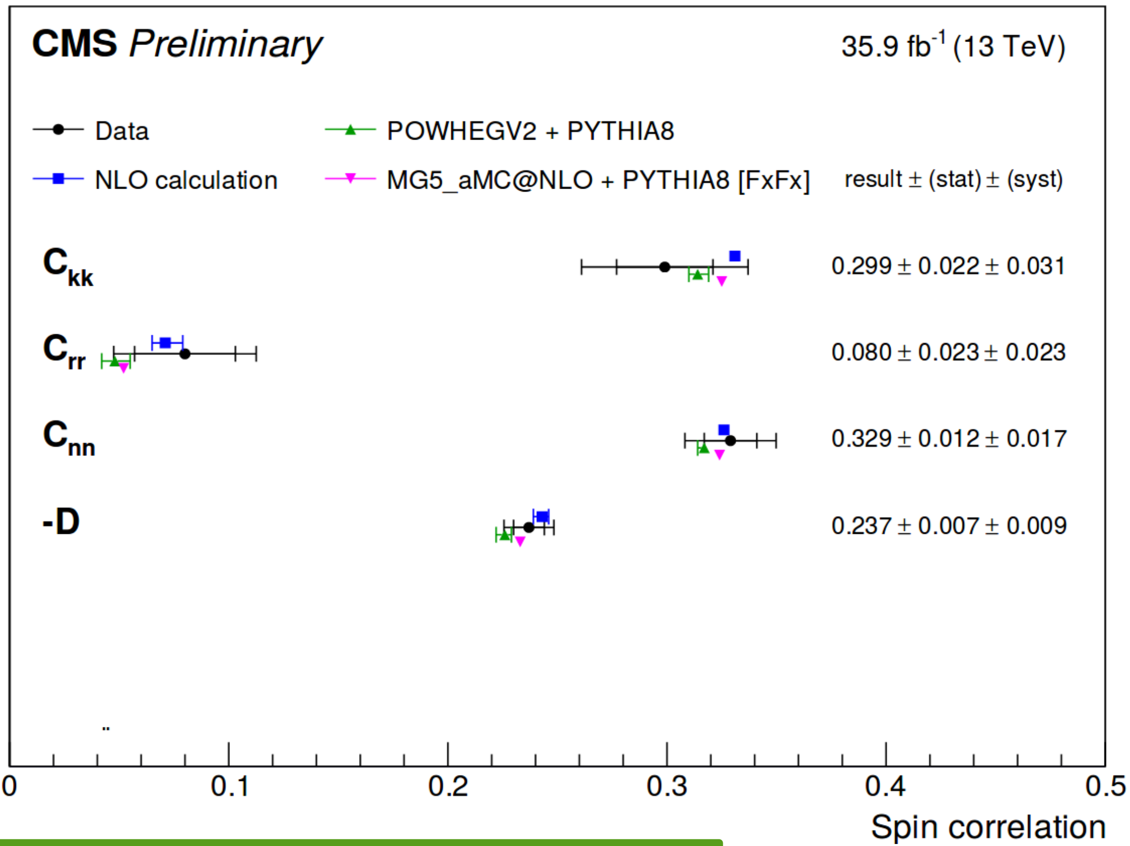
# Top Quark Spin Correlation - Diagonal Elements



- spin correlations consistent with SM along each axis



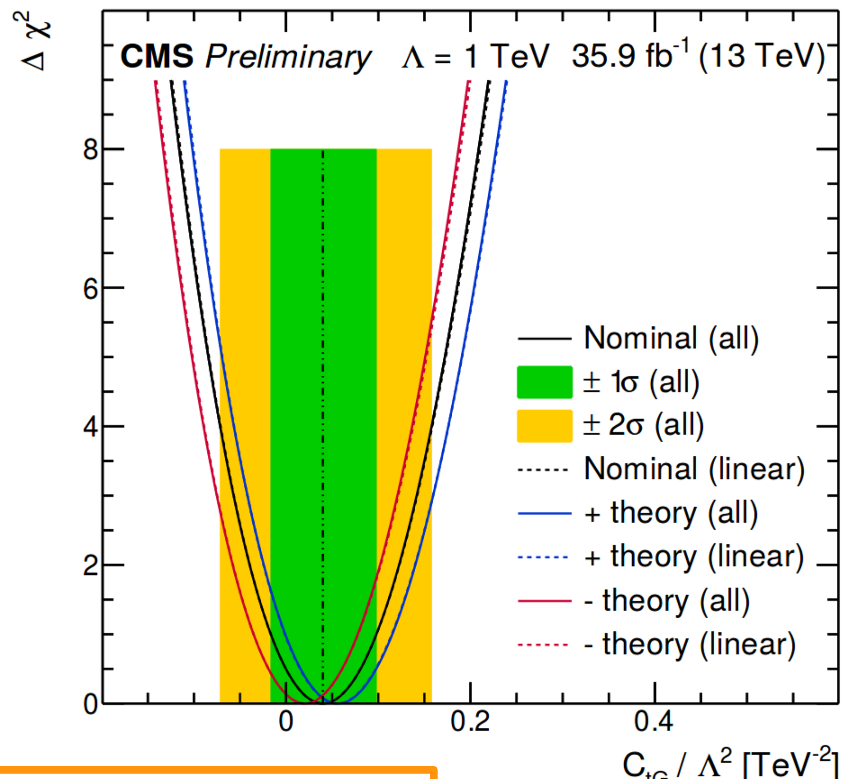



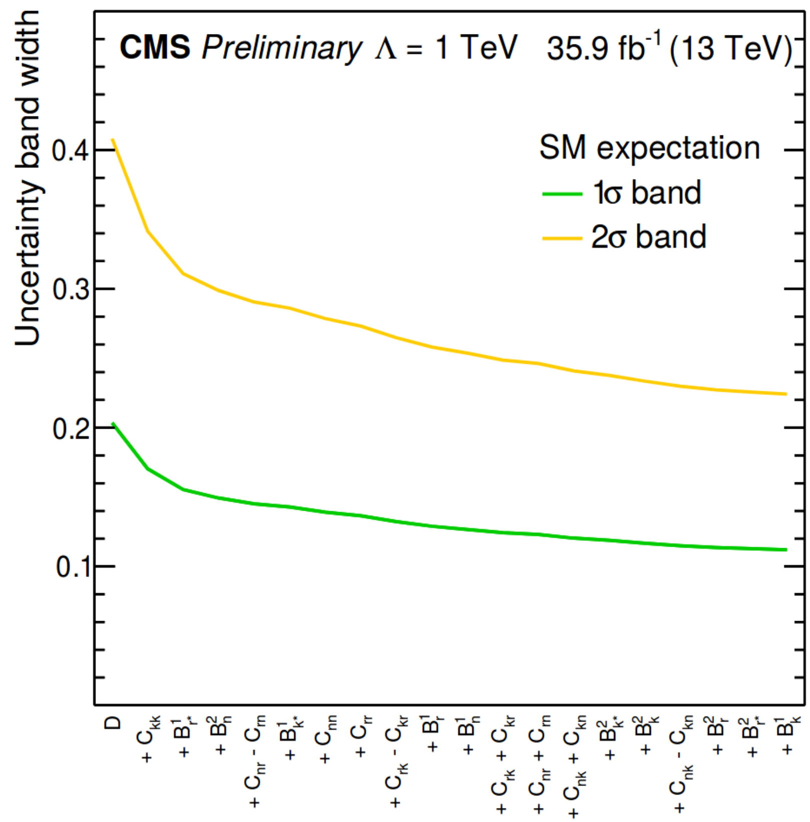

$$\frac{1}{\sigma}\frac{d\sigma}{d\Omega_+ d\Omega_-} = \frac{1}{(4\pi)^2}\left(1 + \mathbf{B}^+ \cdot \hat{\ell}^+ + \mathbf{B}^- \cdot \hat{\ell}^- - \hat{\ell}^+ \cdot \mathbb{C} \cdot \hat{\ell}^-\right)$$

- 95% CL limits on CMDM operator from simultaneous fit to all measured differential cross sections to constrain systematics

$$\boxed{-0.07 < C_{tG}/\Lambda^2 < 0.16\ \mathrm{TeV}^{-2}}$$

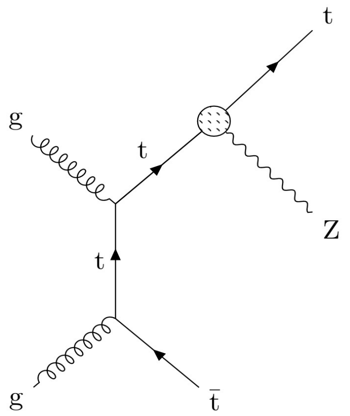
- strongest direct limits to date, additional operator constraints in preparation

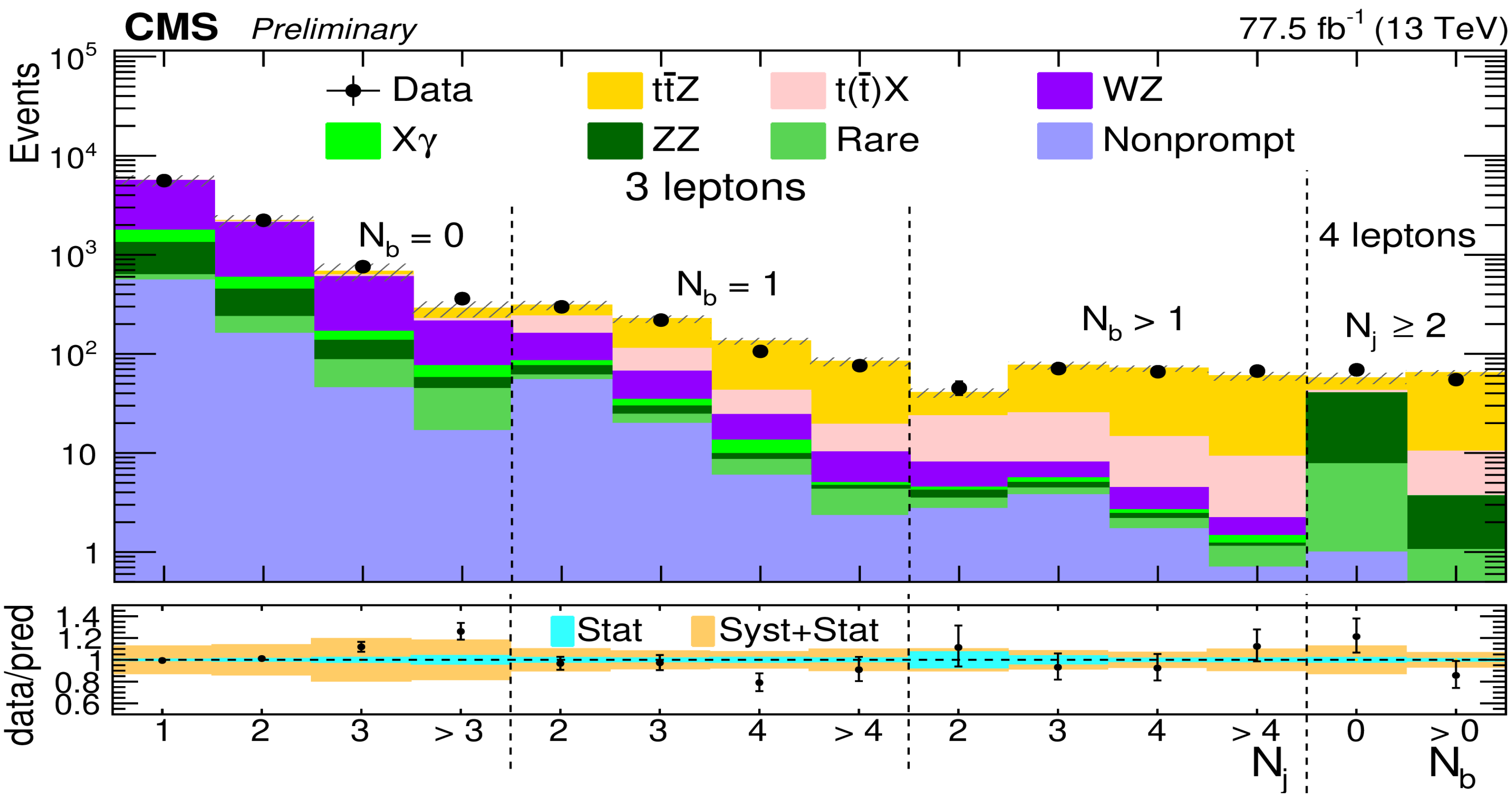



CMS PAS-TOP-18-006

- electroweak-top interactions from $t\bar{t}Z$ production
  - split events with 3/4 leptons into jet/b-jet multiplicity bins



# Measuring Top-EWK Couplings



- electroweak-top interactions from $t\bar{t}Z$ production
- translate cross-section measurements into limits of
  - 4 independent EFT operators

$$
\begin{aligned}
c_{tZ} &= \mathrm{Re}\left(-\sin\theta_W C_{uB}^{(33)} + \cos\theta_W C_{uW}^{(33)}\right) \\
c_{tZ}^{[I]} &= \mathrm{Im}\left(-\sin\theta_W C_{uB}^{(33)} + \cos\theta_W C_{uW}^{(33)}\right) \\
c_{\phi t} &= C_{\phi t} = C_{\phi u}^{(33)} \\
c_{\phi Q}^{-} &= C_{\phi Q} = C_{\phi q}^{1(33)} - C_{\phi q}^{3(33)},
\end{aligned}
$$

tensor couplings (quad.): $C_{tZ}/C_{tZ}^{[I]}$

$$
\begin{aligned}
O_{uB}^{(ij)} &= (\bar{q}_i \sigma^{\mu\nu} u_j) \quad \tilde{\varphi} B_{\mu\nu} \\
O_{uW}^{(ij)} &= (\bar{q}_i \sigma^{\mu\nu} \tau^I u_j)\, \tilde{\varphi} W_{\mu\nu}^I
\end{aligned}
$$

vector couplings (lin.): $C_{\Phi t}/C^{-}_{\Phi Q}$

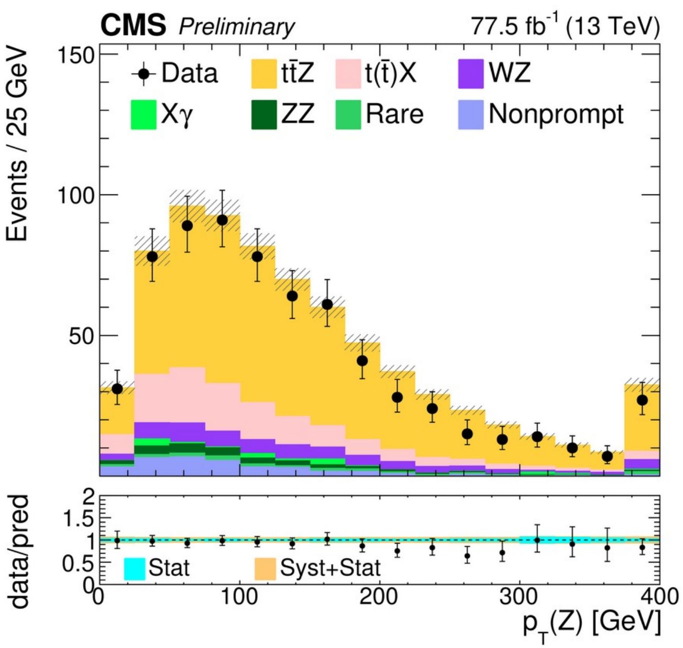
$$
\begin{aligned}
O_{\varphi u}^{(ij)} &= (\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar{u}_i \gamma^\mu u_j) \\
O_{\varphi q}^{1(ij)} &= (\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar{q}_i \gamma^\mu q_j) \\
O_{\varphi q}^{3(ij)} &= (\varphi^\dagger i\overleftrightarrow{D}_\mu^I \varphi)(\bar{q}_i \gamma^\mu \tau^I q_j)
\end{aligned}
$$

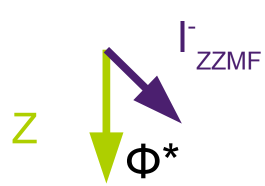
# Measuring Top-EWK Couplings

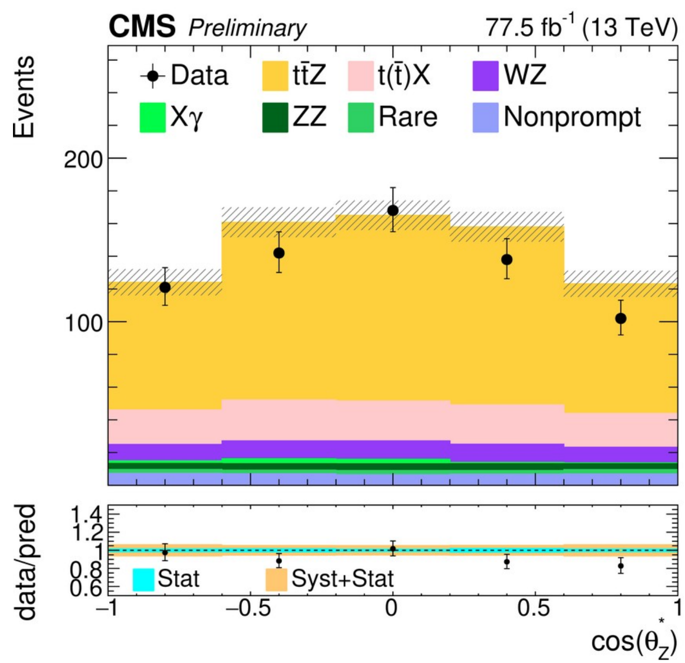


- electroweak-top interactions from $t\bar{t}Z$ production
- translate cross-section measurements into limits of
  - 4 independent EFT operators
  - main impact on $p_T^Z$ and $\cos(\Phi_Z^*)$ → use to reweight NLO SM simulations

$$
\begin{aligned}
c_{tZ} &= \mathrm{Re}\left(-\sin\theta_W C_{uB}^{(33)} + \cos\theta_W C_{uW}^{(33)}\right)\\
c_{tZ}^{[I]} &= \mathrm{Im}\left(-\sin\theta_W C_{uB}^{(33)} + \cos\theta_W C_{uW}^{(33)}\right)\\
c_{\phi t} &= C_{\phi t} = C_{\phi u}^{(33)}\\
c_{\phi Q}^{-} &= C_{\phi Q} = C_{\phi q}^{1(33)} - C_{\phi q}^{3(33)},
\end{aligned}
$$




**tensor couplings (quad.): $C_{tZ}/C_{tZ}^{[I]}$**

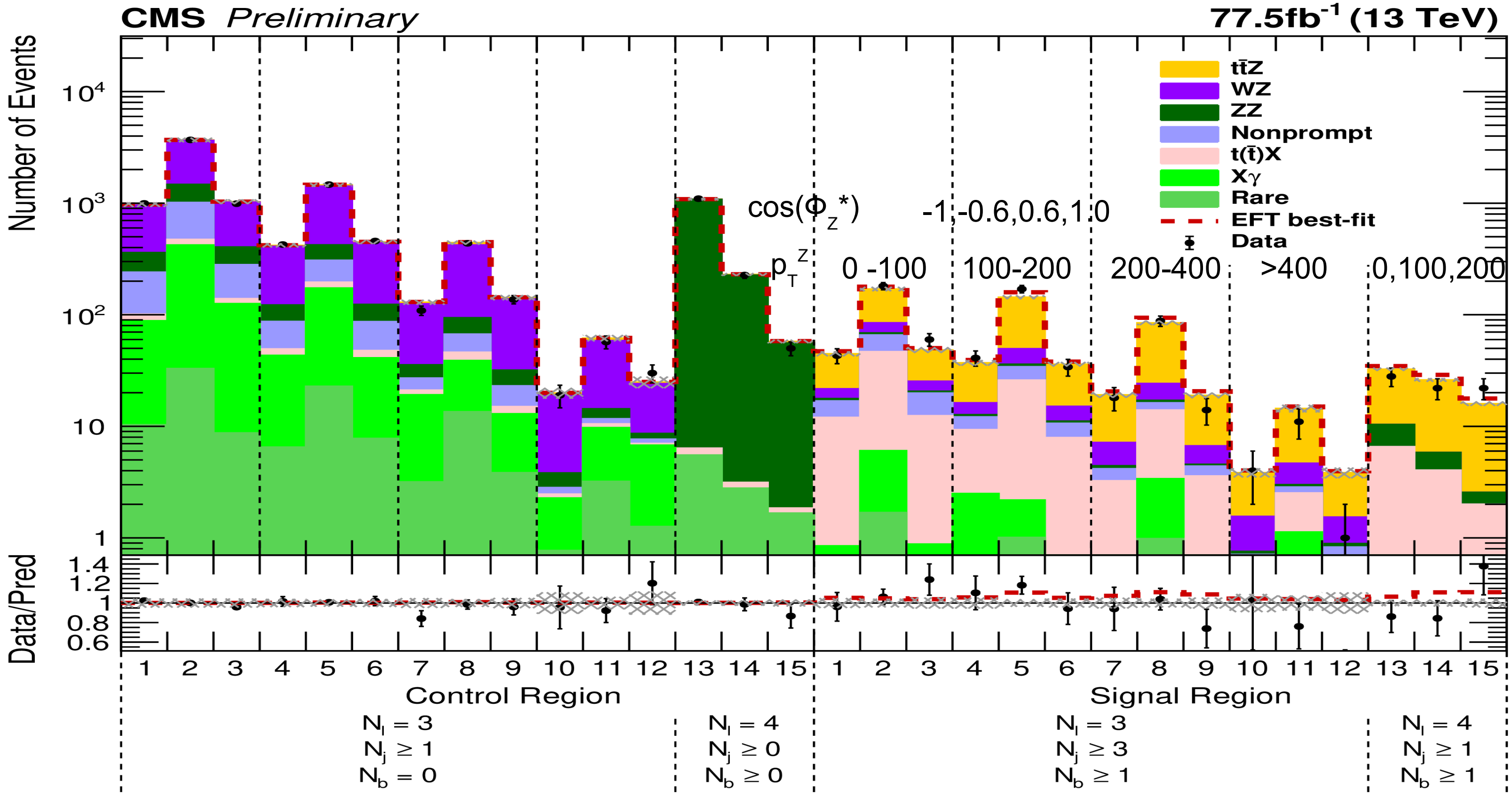
$$
O_{uB}^{(ij)} = (\bar{q}_i\sigma^{\mu\nu}u_j)\quad\tilde{\varphi}B_{\mu\nu}
$$
$$
O_{uW}^{(ij)} = (\bar{q}_i\sigma^{\mu\nu}\tau^I u_j)\,\tilde{\varphi}W_{\mu\nu}^I
$$

**vector couplings (lin.): $C_{\phi t}/C_{\phi Q}^{-}$**

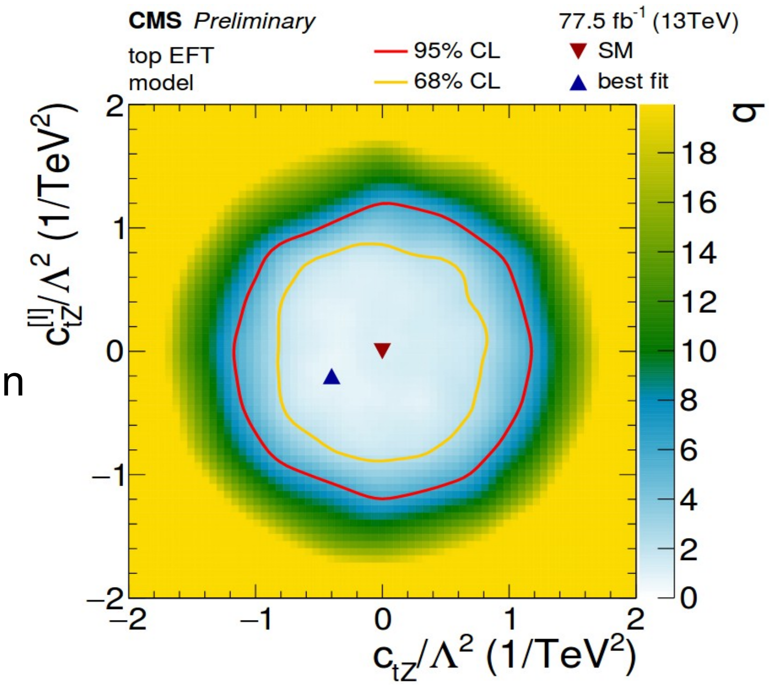
$$
O_{\varphi u}^{(ij)} = (\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{u}_i\gamma^\mu u_j)
$$
$$
O_{\varphi q}^{1(ij)} = (\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{q}_i\gamma^\mu q_j)
$$
$$
O_{\varphi q}^{3(ij)} = (\varphi^\dagger i\overleftrightarrow{D}_\mu^I\varphi)(\bar{q}_i\gamma^\mu\tau^I q_j)
$$

- electroweak-top interactions from $t\bar{t}Z$ production
- translate cross-section measurements into limits of
- additional bins of $p_T^Z$ and $\cos(\Phi_Z^*)$ for enhanced sensitivity

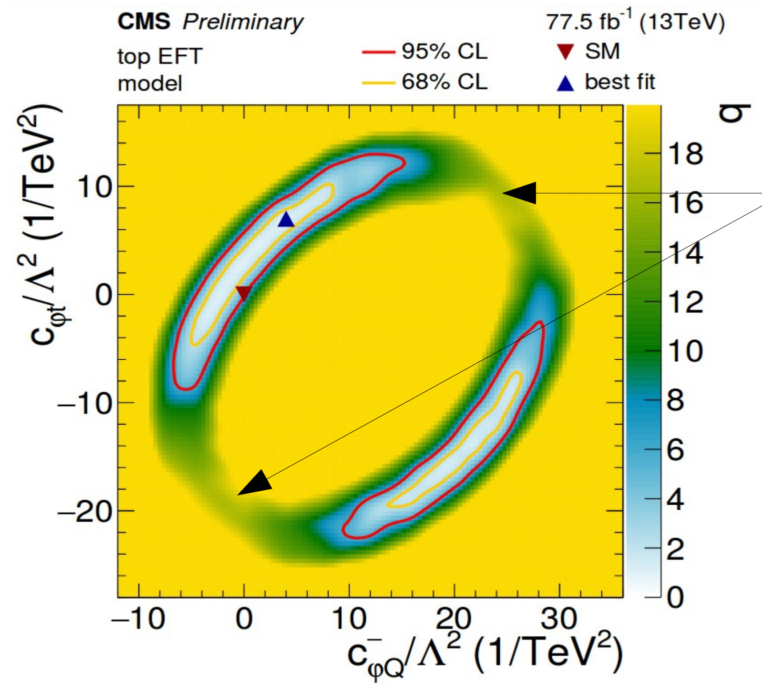
$$
\begin{aligned}
c_{tZ} &= \mathrm{Re}\left(-\sin\theta_W C_{uB}^{(33)} + \cos\theta_W C_{uW}^{(33)}\right) \\
c_{tZ}^{[I]} &= \mathrm{Im}\left(-\sin\theta_W C_{uB}^{(33)} + \cos\theta_W C_{uW}^{(33)}\right) \\
c_{\phi t} &= C_{\phi t} = C_{\phi u}^{(33)} \\
c_{\phi Q}^{-} &= C_{\phi Q} = C_{\phi q}^{1(33)} - C_{\phi q}^{3(33)},
\end{aligned}
$$



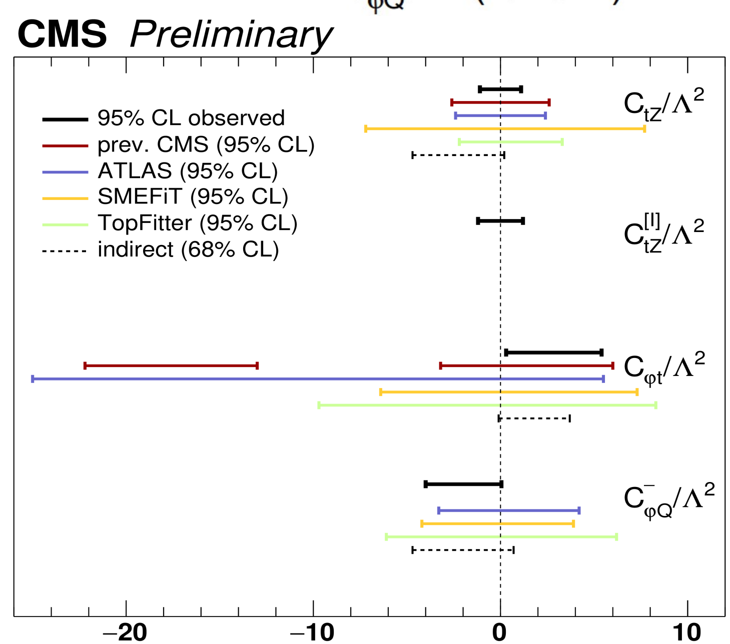
# Limits on Anomalous Top-EWK Couplings




20% reduction from $p_T^Z/\cos(\Phi_Z^*)$




benefit from $p_T^Z/\cos(\Phi_Z^*)$ information



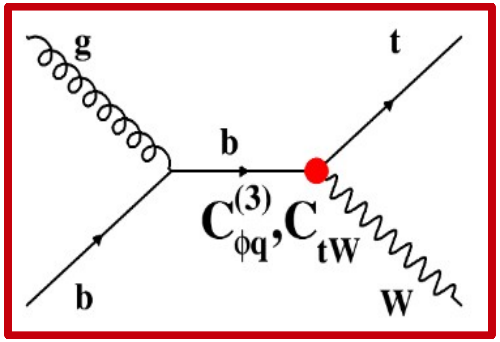

- most stringent direct constraints on electroweak dipole moments and top-Z vector couplings (individual limits)

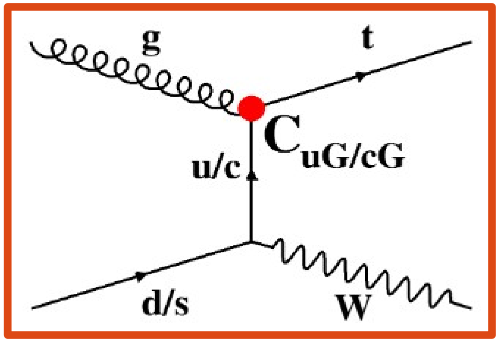
CMS PAS-TOP-18-009

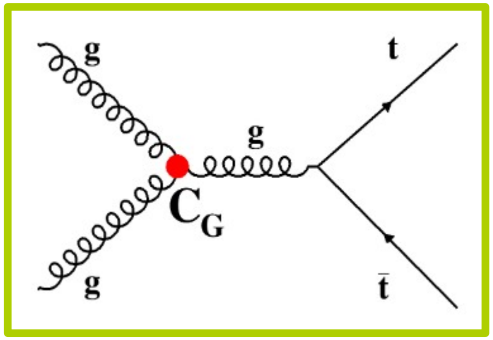
# Probing Simultaneously $t\bar{t}$ and tW Production

- constraint separately 6 EFT couplings in dilepton final states

single top tW | $t\bar{t}$ | $t\bar{t}$ + single top tW



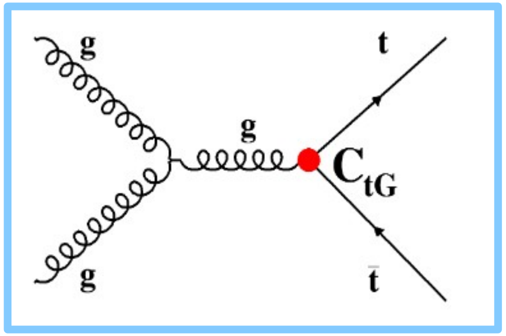




$$O_{tW} = (\bar{q}\sigma^{\mu\nu}\tau^i t)\tilde{\phi}W^i_{\mu\nu}$$

$$O^{(3)}_{\phi q} = (\phi^+ \tau^i D_\mu \phi)(\bar{q}\gamma^\mu \tau^i q)$$

$$O_{u(c)G} = (\bar{q}\sigma^{\mu\nu}\lambda^a t)\tilde{\phi}G^a_{\mu\nu}$$

$$O_G = f_{abc}G^{a\nu}_{\mu}G^{b\rho}_{\nu}G^{c\mu}_{\rho}$$



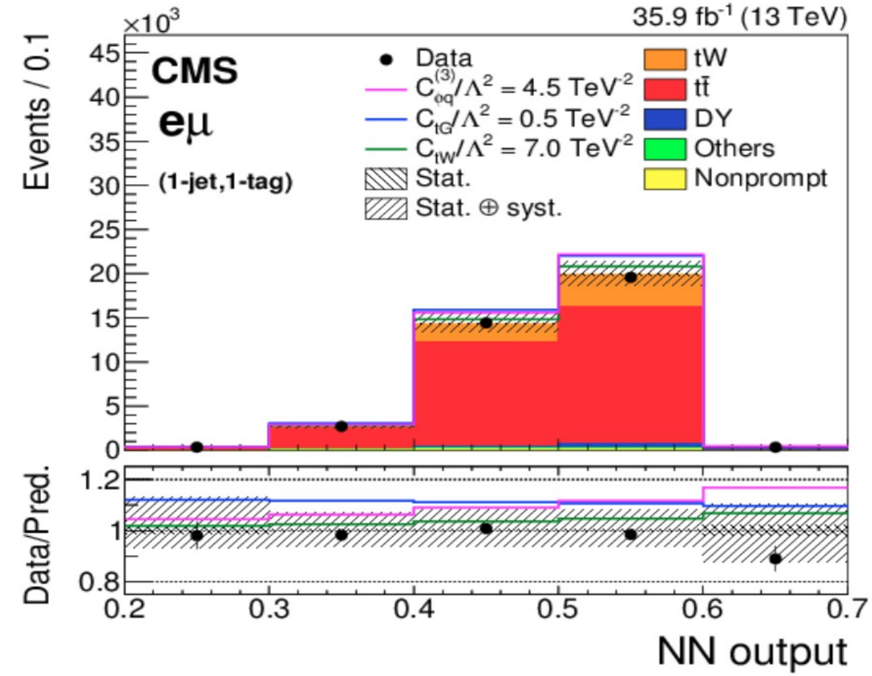

$$O_{tG} = (\bar{q}\sigma^{\mu\nu}\lambda^a t)\tilde{\phi}G^a_{\mu\nu}$$

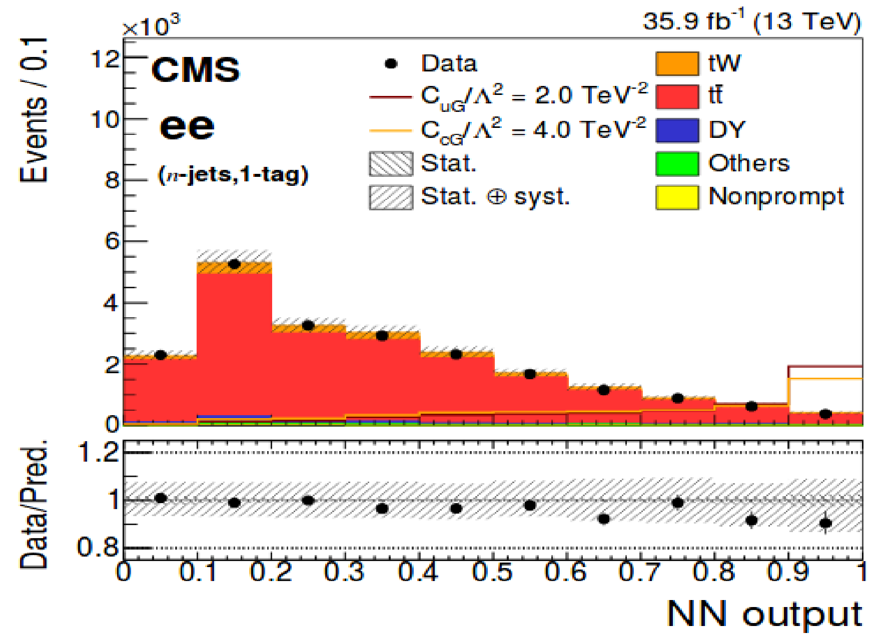
# Analysis Strategy

- different categories of jet and b-jet multiplicities

| Eff. coupling | Channel | Categories 1-jet ,0-tag | 1-jet ,1-tag | 2-jets,1-tag | >2-jets ,1-tag | ≥2-jets,2-tags |
|---|---|---|---|---|---|---|
| $C_G$ | ee | — | Yield | Yield | — | Yield |
| | $e\mu$ | Yield | Yield | Yield | — | Yield |
| | $\mu\mu$ | — | Yield | Yield | — | Yield |
| $C^{(3)}_{\phi q}$, $C_{tW}$, $C_{tG}$ | ee | — | $NN_{11}$ | $NN_{21}$ | — | Yield |
| | $e\mu$ | $NN_{10}$ | $NN_{11}$ | $NN_{21}$ | — | Yield |
| | $\mu\mu$ | — | $NN_{11}$ | $NN_{21}$ | — | Yield |
| $C_{uG}$, $C_{cG}$ | ee | — | | $NN_{FCNC}$ | | — |
| | $e\mu$ | — | | $NN_{FCNC}$ | | — |
| | $\mu\mu$ | — | | $NN_{FCNC}$ | | — |

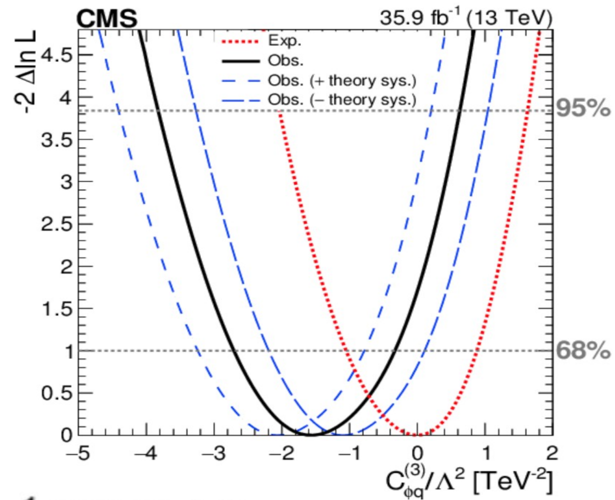
- dedicated NNs
  - to distinguish tW from $t\bar{t}$ topologies
  - to split FCNC from SM backgrounds

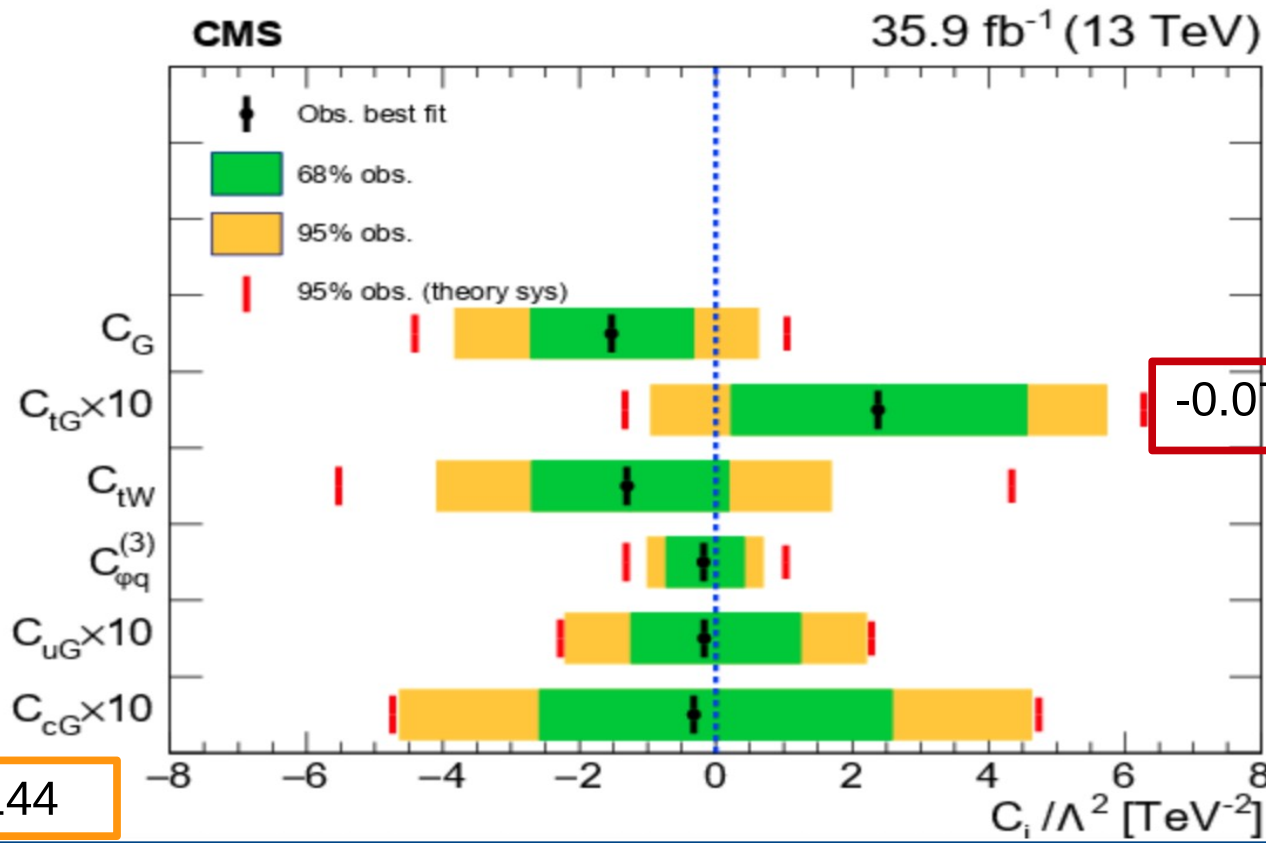


# EFT Limits from Combined $t\bar{t}$ and tW Production

- limits on one operator at a time
- sensitivity not yet at the level of more dedicated approaches (e.g. CMS PAS-TOP-18-006)
- first step towards more global approaches




$-0.07 < C_{tG}/\Lambda^2 < 0.16$ TeV$^{-2}$

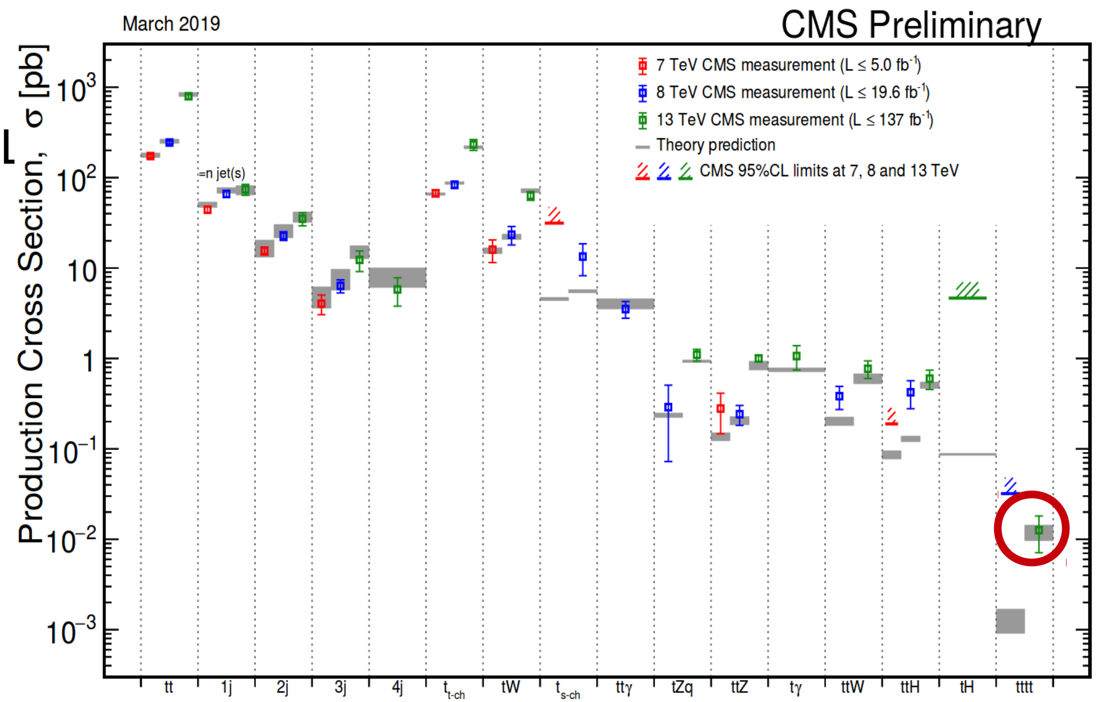
BR(t→ug)<0.1%

BR(t→cg) < 0.53 %

arXiv:1903.11144

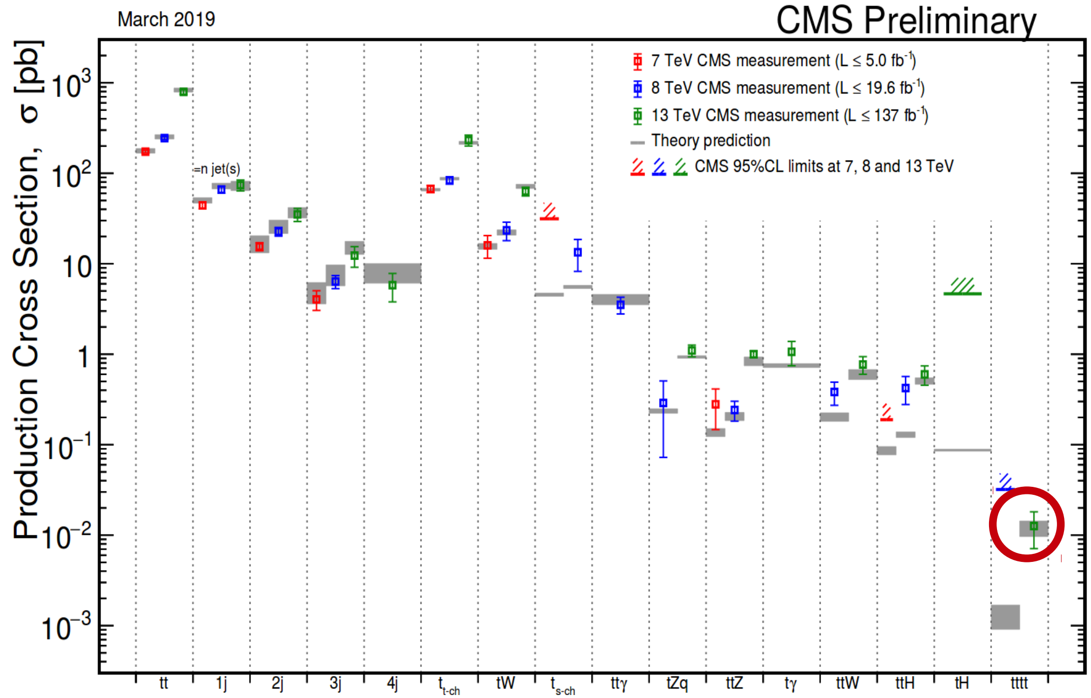
# Probing $t\bar{t}t\bar{t}$ Production

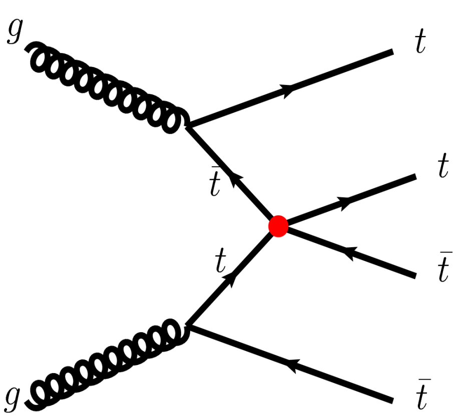
- not yet observed ($\sigma_{SM}$ ~ 9fb @ NLO) at L
  - O($10^5$) smaller than $t\bar{t}$



# Probing $t\bar{t}t\bar{t}$ Production

- not yet observed ($\sigma_{SM}$ ~ 9fb @ NLO) at LHC
  - O($10^5$) smaller than $t\bar{t}$
- high sensitivity to four heavy-quark operators
  - quadratic cross section contributions up to ~6 fb for coefficient strengths of 1




| Operator | $\mathcal{O}^1_{tt}$ | $\mathcal{O}^1_{QQ}$ | $\mathcal{O}^1_{Qt}$ | $\mathcal{O}^8_{Qt}$ |
|---|---|---|---|---|
| $\mathcal{O}^1_{tt}$ | 5.59 | 0.36 | −0.39 | 0.3 |
| $\mathcal{O}^1_{QQ}$ | | 5.49 | −0.45 | 0.13 |
| $\mathcal{O}^1_{Qt}$ | | | 1.9 | −0.08 |
| $\mathcal{O}^8_{Qt}$ | | | | 0.45 |

$$\boxed{\mathcal{O}^1_{tt} = (\bar{t}_R\gamma^\mu t_R)(\bar{t}_R\gamma_\mu t_R)}$$

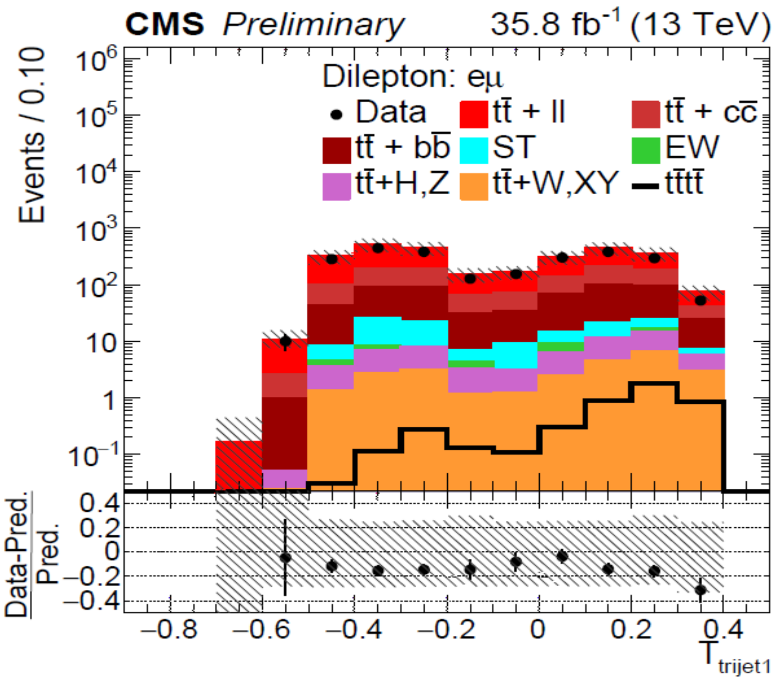
$$\boxed{\mathcal{O}^1_{QQ} = (\bar{Q}_L\gamma^\mu Q_L)(\bar{Q}_L\gamma_\mu Q_L)}$$

$$\boxed{\mathcal{O}^1_{Qt} = (\bar{Q}_L\gamma^\mu Q_L)(\bar{t}_R\gamma_\mu t_R)}$$

$$\boxed{\mathcal{O}^8_{Qt} = \left(\bar{Q}_L\gamma^\mu T^A Q_L\right)\left(\bar{t}_R\gamma_\mu T^A t_R\right)}$$

# EFT Sensitivity of $t\bar{t}t\bar{t}$

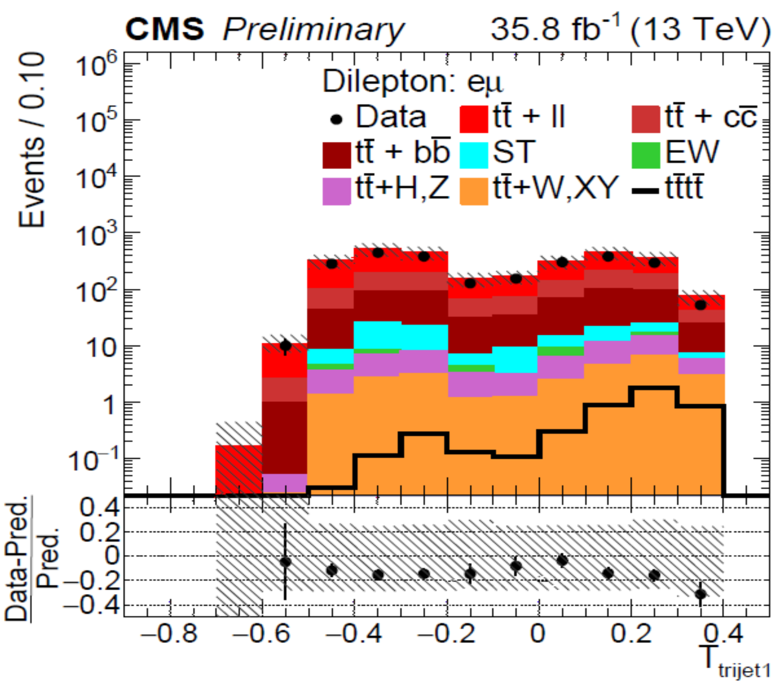
- single lepton and opposite-sign dilepton final states
- two dedicated boosted decision trees:
  - identify 3 jet combinations from all-hadronic top decays rather than ISR/FSR (dijet/trijet masses, b-tagging, jet angles, … )

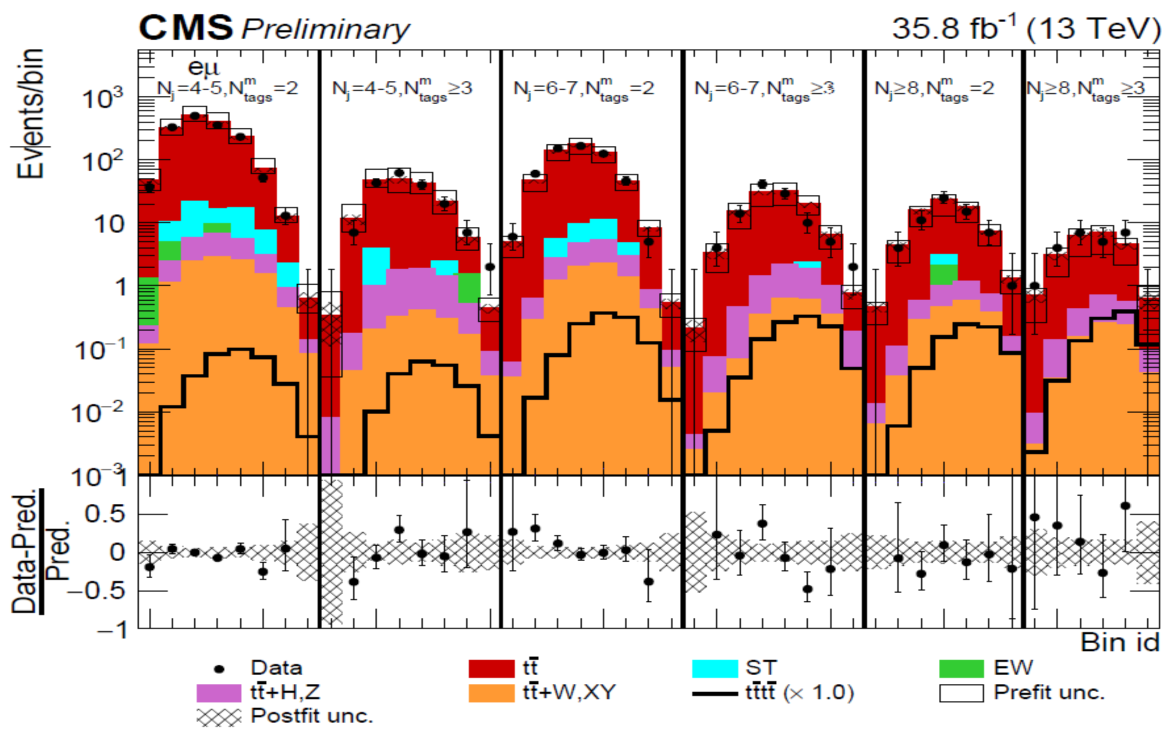


# EFT Sensitivity of $t\bar{t}t\bar{t}$

- single lepton and opposite-sign dilepton final states

- two dedicated boosted decision trees:
  - identify 3 jet combinations from all-hadronic top decays rather than ISR/FSR (dijet/trijet masses, b-tagging, jet angles, … )
  - distinguish $t\bar{t}t\bar{t}$ from dominant $t\bar{t}$ background with separate BDTs per final state



# $t\bar{t}t\bar{t}$ Cross Sections and EFT Limit

- combine results with same sign dilepton and trilepton analysis (EPJC 78 (2017) 140)
  - observed limit of 3.6 $\sigma_{SM}$, significance of 1.4 S.D.

| Channel | Expected limit ($\times\sigma^{SM}_{t\bar{t}t\bar{t}}$) | Observed limit ($\times\sigma^{SM}_{t\bar{t}t\bar{t}}$) | Expected limit (fb) | Observed limit (fb) |
|---|---|---|---|---|
| Single lepton | $9.4^{+4.4}_{-2.9}$ | 10.6 | $86^{+40}_{-26}$ | 97 |
| Dilepton | $7.3^{+4.5}_{-2.5}$ | 6.9 | $67^{+41}_{-23}$ | 64 |
| Combined (this analysis) | $5.7^{+2.9}_{-1.8}$ | 5.2 | $52^{+26}_{-17}$ | 48 |
| Multilepton [25] | $2.5^{+1.4}_{-0.8}$ | 4.6 | $23^{+12}_{-8}$ | 42 |
| Combined (this analysis + multilepton) | $2.2^{+1.1}_{-0.7}$ | 3.6 | $20^{+10}_{-6}$ | 33 |

- constraint heavy-fermion EFT coefficients (inserting at most one additional EFT vertex)
  - 95% C.L. intervals (contribution of other operators marginalized)

| Operator | Expected $C_k/\Lambda^2$ (TeV $^{-2}$) | Observed (TeV $^{-2}$) | Chin. Phys. C42 (2018) 023104 |
|---|---|---|---|
| $\mathcal{O}^1_{tt}$ | $[-1.5, 1.4]$ | $[-2.2, 2.1]$ | [-2.92,2.80] |
| $\mathcal{O}^1_{QQ}$ | $[-1.5, 1.4]$ | $[-2.2, 2.0]$ | |
| $\mathcal{O}^1_{Qt}$ | $[-2.5, 2.4]$ | $[-3.7, 3.5]$ | [-4.97,4.90] |
| $\mathcal{O}^8_{Qt}$ | $[-5.7, 4.5]$ | $[-8.0, 6.8]$ | [-10.3,9.33] |

  - increased sensitivity compared to previous results

CMS PAS-TOP-17-019

# A Global Analysis within the LHC WGs

- individual measurements of top, Higgs and electroweak processes not easily lend themselves to EFT interpretation
  - e.g. “backgrounds” of $t\bar{t}Z$ cross sections like $t\bar{t}W$, $t\bar{t}H$, tqZ, tHq,… also affected by EFT
  - considerable statistical overlap between different measurements

- consistent treatment crucial
  - theory model
  - systematic uncertainties
  - correlations across measurements

- intrinsically small effects
  - precise theoretical control
  - excellent experimental precision

→ a global effort including the experimental and theoretical LHC communities desirable

# Towards Global Analysis

- LHC Higgs working group (STXS framework):
  - excellent scalability → easy to add new results
  - benefit from new theory developments
  - sensitivity driven by categorization

- LHC Top working group:
  - common EFT model: dim6top (arXiv 1802.07237)
  - re-interpretation of unfolded results
    - good scalability, easy combinable beyond LHC
    - treat background SM-like
    - full phase space results sensitive to efficiency/acceptance differences → fiducial, particle level
  - measurements at detector level
    - good sensitivity
    - probe EFT in all contributing processes
    - so far relying on MC reweighing → further developments crucial
    - several options for later combinations

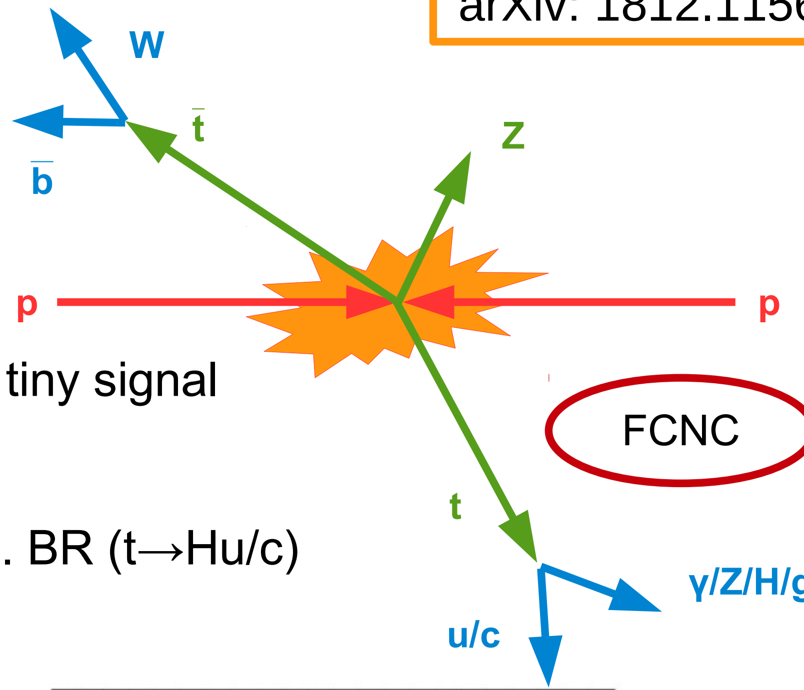
# Summary

- precision SMEFT measurements will be an essential part of the LHC heritage
- the LHC has entered an EFT era
  - large variety of 13 TeV results already available
- first strategies for more global LHC SMEFT measurements established
- need to combine efforts across existing research groups
- right time to re-think and improve research strategies
- still many unexplored processes

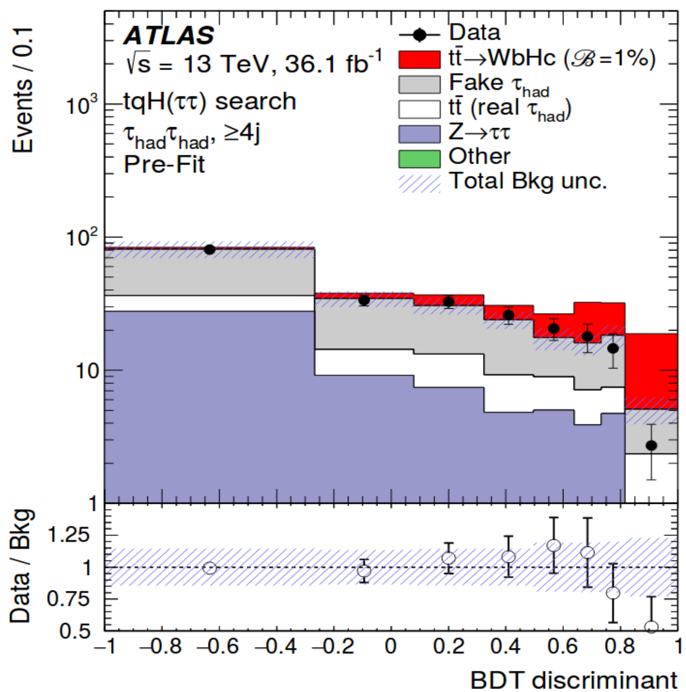
# Back-Up

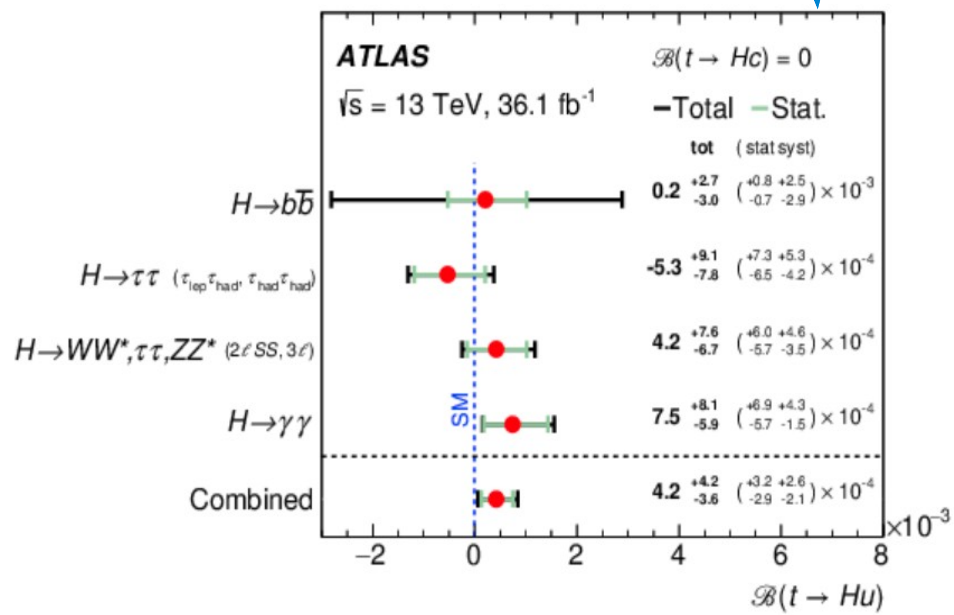
arXiv: 1812.11568

- large variety of analysis searching for FCNC through Higgs/Z/photon/gluon
  - $t\bar{t}$ decay and single top production

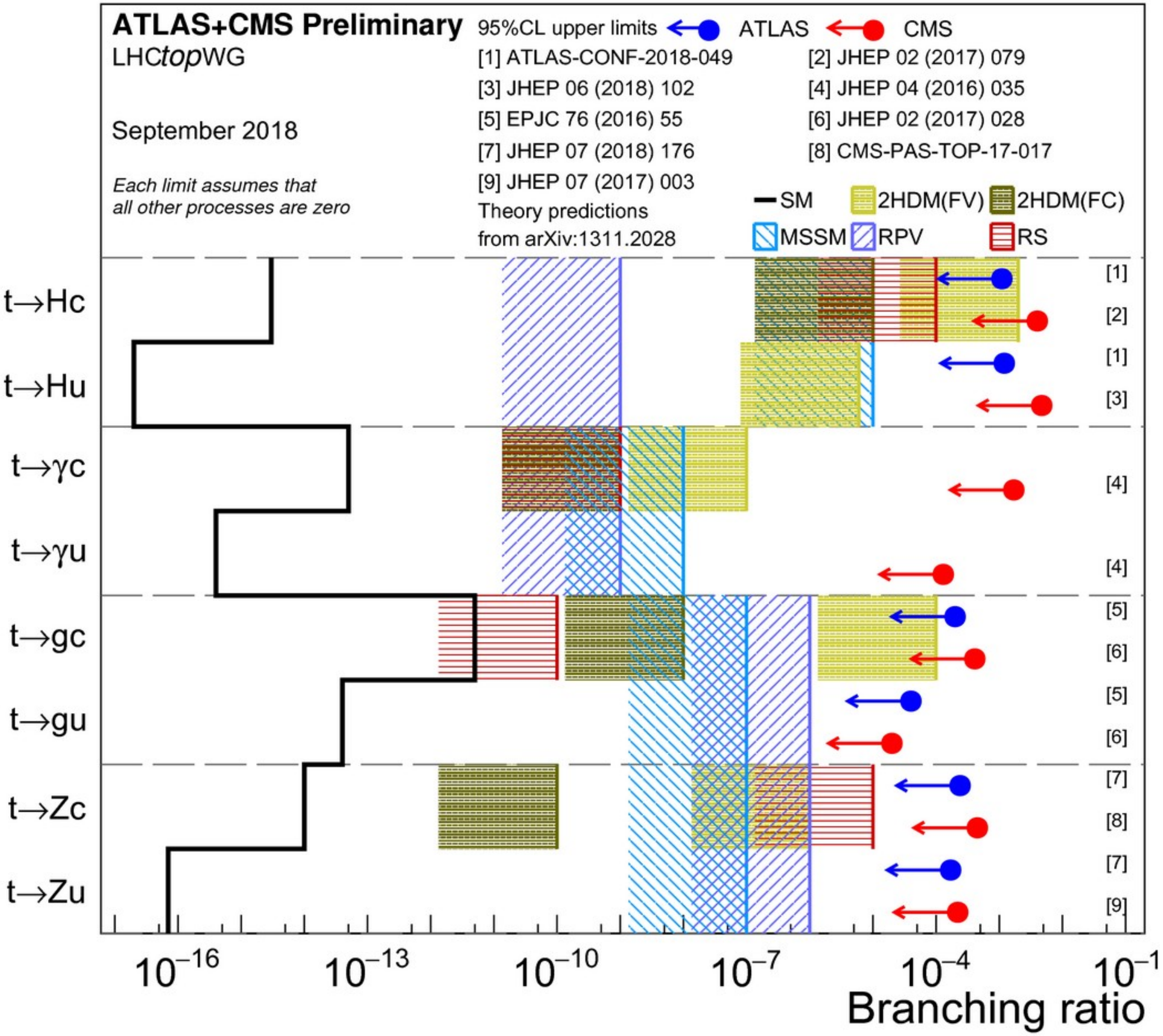



- multivariate analysis techniques standard to probe tiny signal
- combine all possible final states to set limits on e.g. BR (t→Hu/c)



# Limits on BSM Models of FCNC



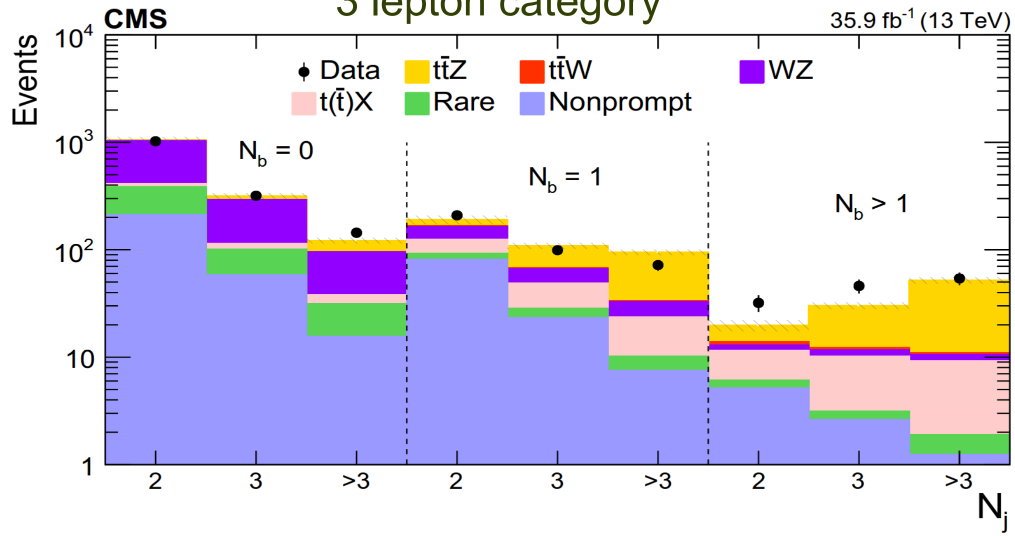

start probing models predicting highest branching fractions

# Rare Process: $t\bar{t}Z/t\bar{t}W$

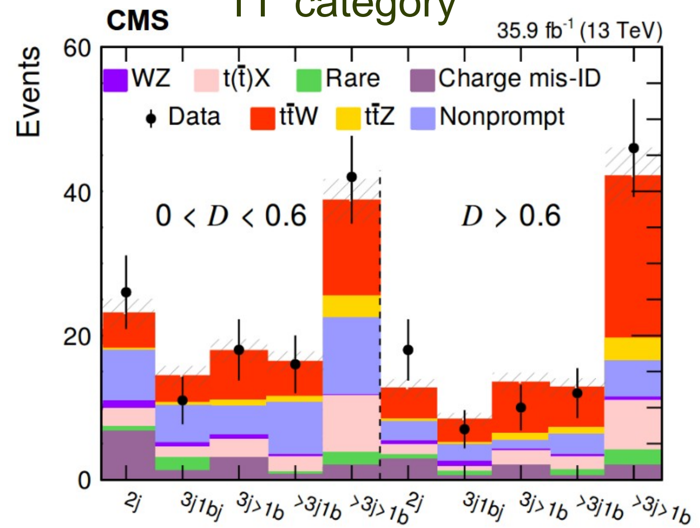
arXiv:1711.02547

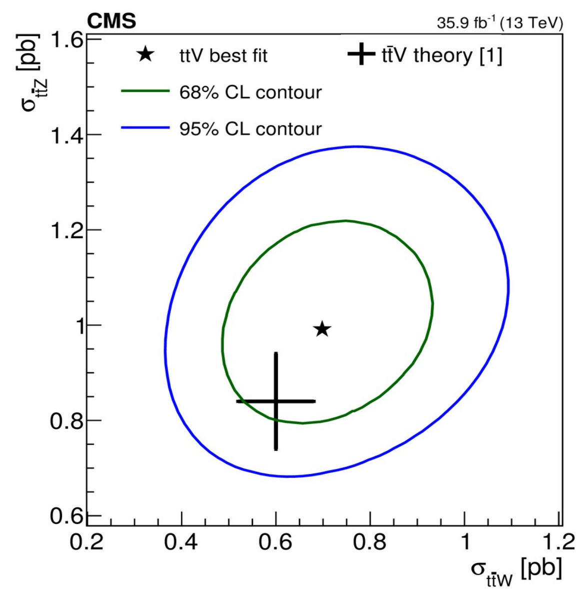
- measurement of $t\bar{t}X$ cross sections at 13 TeV using 35.9 fb$^{-1}$
  - $t\bar{t}W$ from same-sign dilepton events
  - $t\bar{t}Z$ from final states with 3 and 4 leptons
- split events according to number of jets and b-tagged jets
- train BDT for same-sign dilepton events (“D”) to separate $t\bar{t}W$ from non-prompt leptons
- fit across categories to extract $\sigma_{t\bar{t}W}$ vs $\sigma_{t\bar{t}Z}$

3 lepton category




l+l+ category



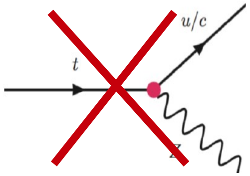
# ttZ 2016 + 2017

- improved analysis strategy:
  - more inclusive trigger
  - multivariate lepton identification (x2 syst. red.)
  - better lepton and efficiency measurements
  - (~15% higher prompt-lepton efficiency)

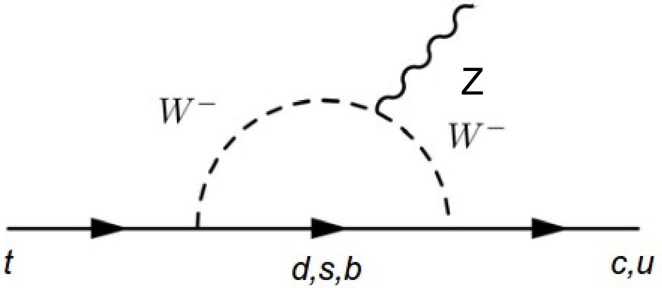
| Source | Uncertainty range (%) | Correlated in 2016 and 2017 | Impact on the $t\bar{t}Z$ cross section (%) |
|---|---|---|---|
| Integrated luminosity | 2.5 | × | 2 |
| PU modeling | 1–2 | ✓ | 1 |
| Trigger | 2 | × | 2 |
| Lepton ID efficiency | 4.5–6 | ✓ | 4 |
| Jet energy scale | 1–9 | ✓ | 2 |
| Jet energy resolution | 0–1 | ✓ | 1 |
| B tagging light flavor | 0–4 | × | 1 |
| B tagging heavy flavor | 1–4 | × | 2 |
| Choice in $\mu_R$ and $\mu_F$ | 1–4 | ✓ | 1 |
| PDF choice | 1–2 | ✓ | 1 |
| Color reconnection | 1.5 | ✓ | $< 1$ |
| Parton shower | 1–8 | ✓ | 1 |
| WZ cross section | 10–20 | ✓ | 3 |
| WZ + heavy flavor | 8 | ✓ | 1 |
| ZZ cross section | 10 | ✓ | 1 |
| $t(\bar{t})X$ bg. | 10–15 | ✓ | 3 |
| $X\gamma$ background | 20 | ✓ | 1 |
| Nonprompt background | 30 | ✓ | $< 1$ |
| Rare SM background | 50 | ✓ | 2 |
| Stat. unc. in nonprompt bg. | 5–50 | × | $< 1$ |
| Stat. unc. in rare SM bg. | 5–100 | × | $< 1$ |
| Total uncertainty | | | 7 |

# Flavor Changing Neutral Currents

- forbidden at tree level in SM




- suppressed by GIM mechanism at higher orders




- many BSM models predict sizable FCNC branching fraction

| | SM | 2HDM FC / FV | MSSM / w. RPV | RS |
|---|---|---|---|---|
| BR(t → cg) | $10^{-12}$ | $10^{-8}$ / $10^{-4}$ | $10^{-7}$ / $10^{-6}$ | $10^{-10}$ |
| BR(t → cZ) | $10^{-14}$ | $10^{-10}$ / $10^{-6}$ | $10^{-7}$ / $10^{-6}$ | $10^{-5}$ |
| BR(t → cγ) | $10^{-14}$ | $10^{-9}$ / $10^{-7}$ | $10^{-8}$ / $10^{-9}$ | $10^{-9}$ |
| BR(t → cH) | $10^{-15}$ | $10^{-5}$ / $10^{-3}$ | $10^{-5}$ / $10^{-9}$ | $10^{-4}$ |

arXiv:1311.2028

- large variety of searches for enhanced couplings of top quarks to u/c quarks via g, Z, γ, H in top production and decay

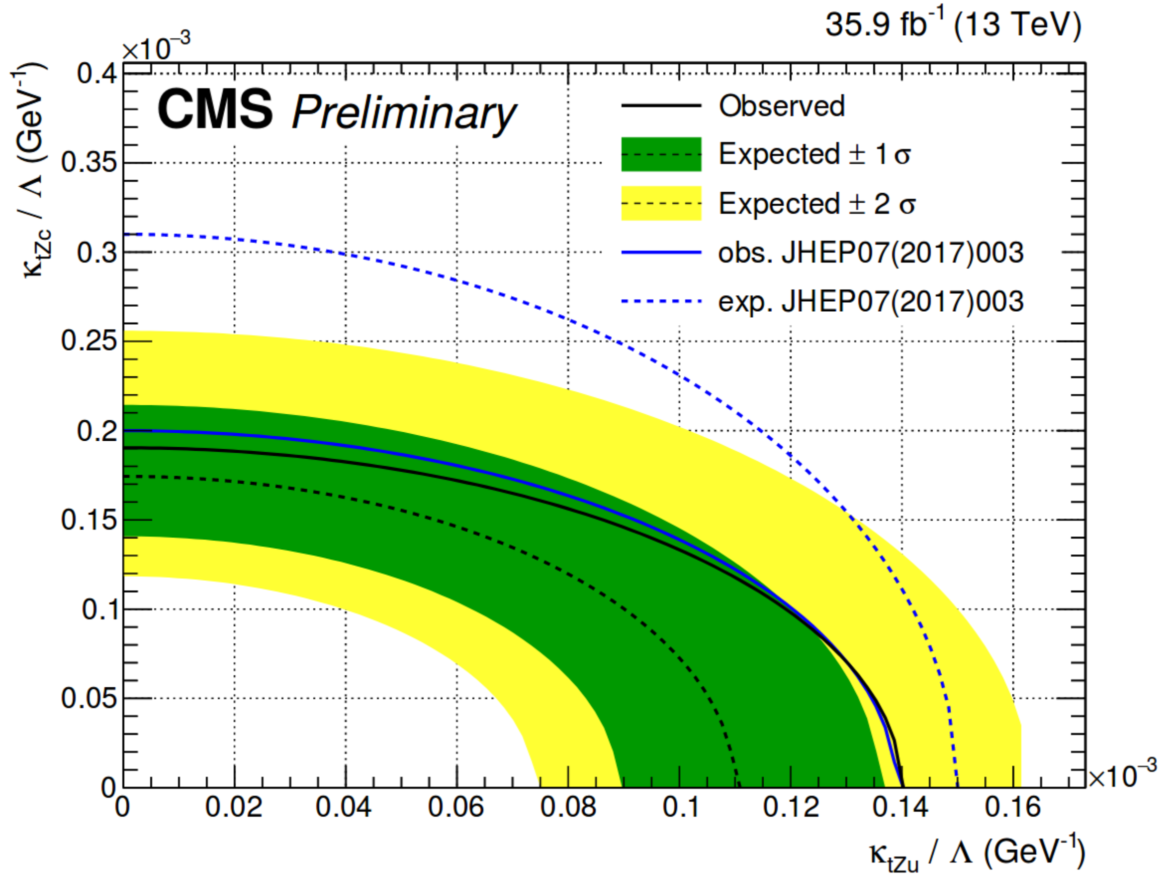
# FCNC Interpretation in Terms of EFT

CMS-PAS-TOP-17-017

- set limits on trilinear top-quark-boson couplings

$$L = \sum_{q=u,c} \frac{g}{\sqrt{2}c_W} \frac{\kappa_{tZq}}{\Lambda} \bar{t}\sigma^{\mu\nu}(f^L_{Zq}P_L + f^R_{Zq}P_R)qZ_{\mu\nu}$$

arXiv:1812.11568




significant improvement compared to 8 TeV result