Probing SMEFT at CMS

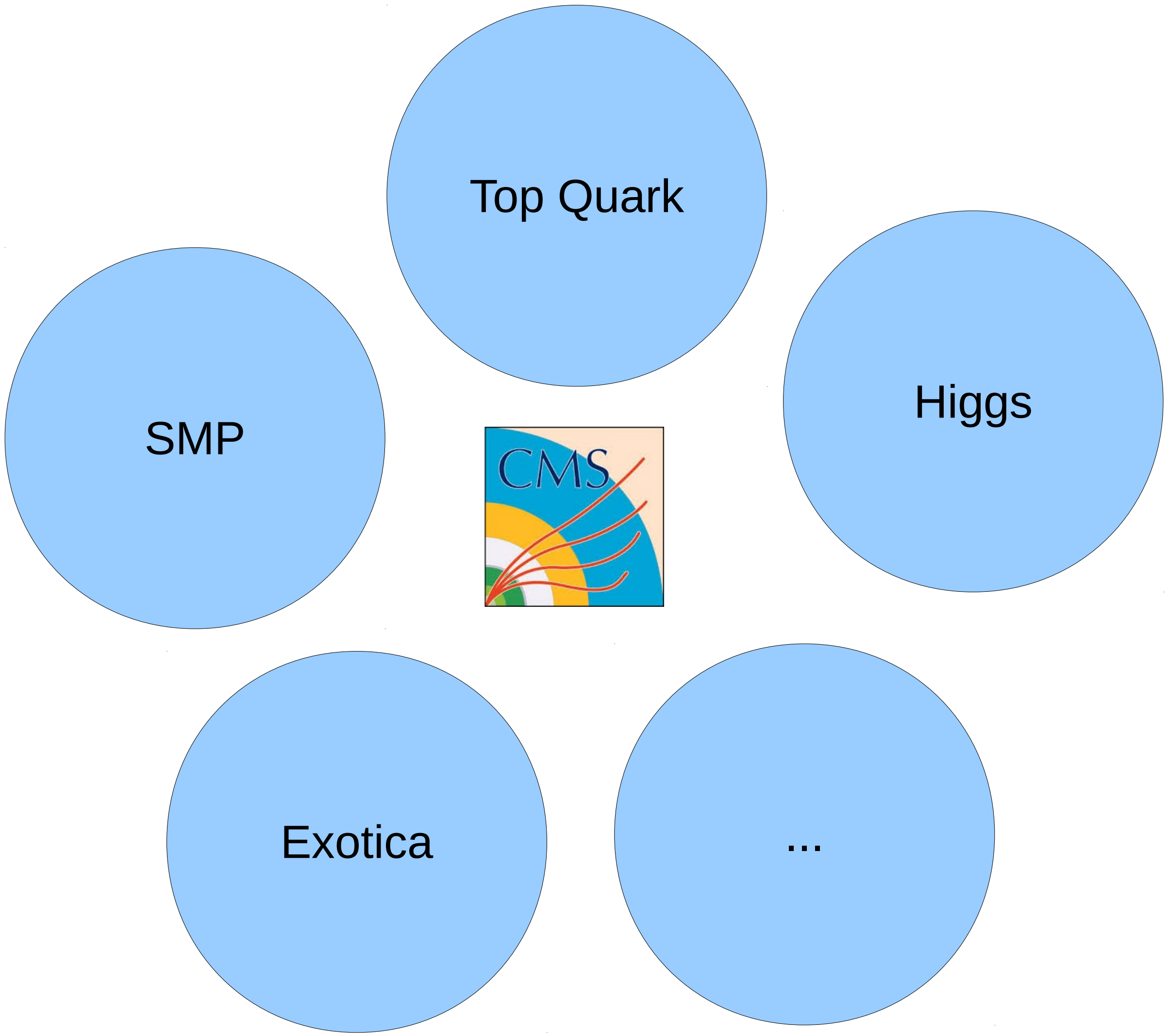
Alexander Grohsjean

Higgs Effective Field Theory 2020

15th - 17th April 2020

Global SMEFT interpretations in 2020

- several global analysis from theory community but neither ATLAS nor CMS



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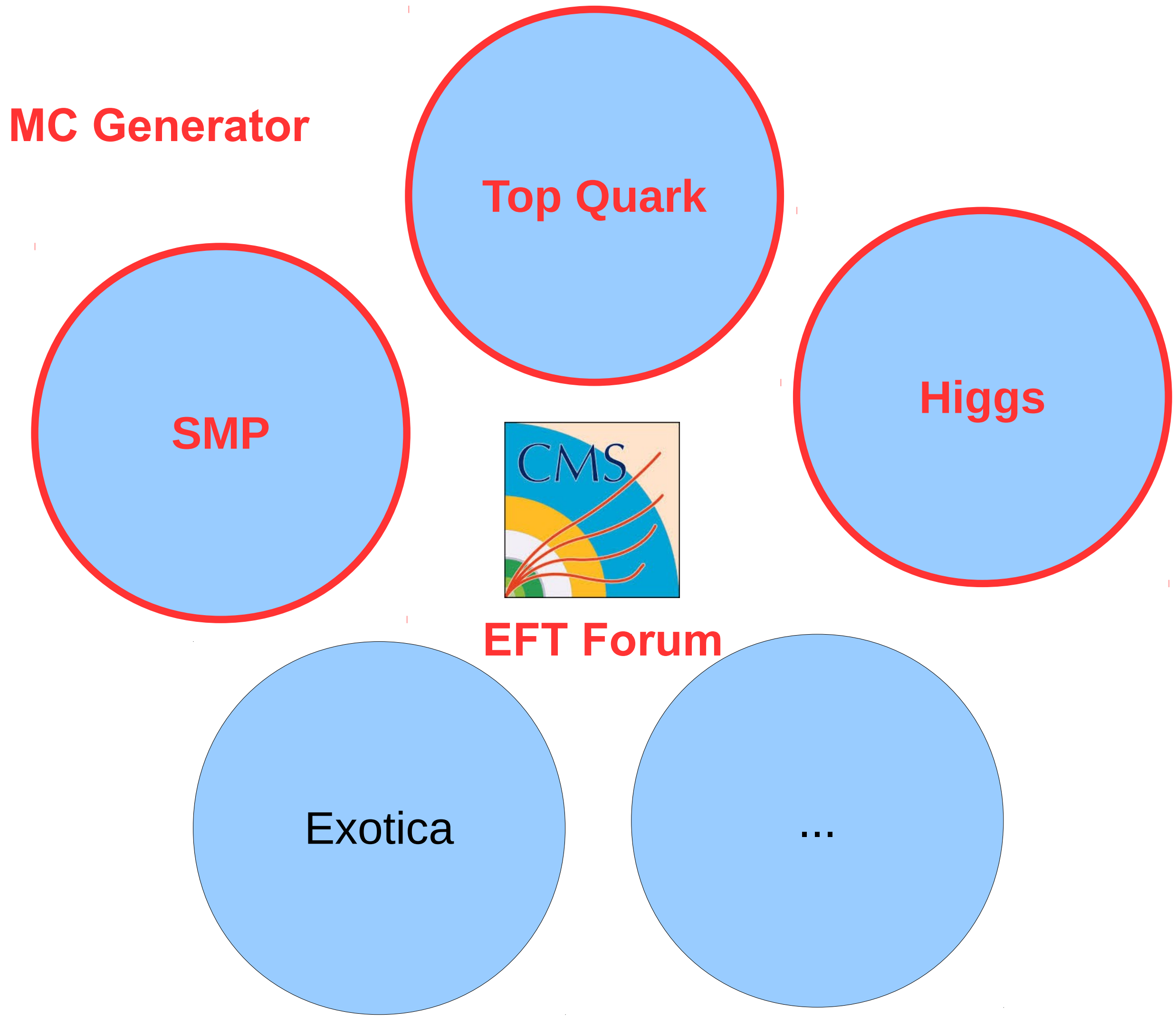
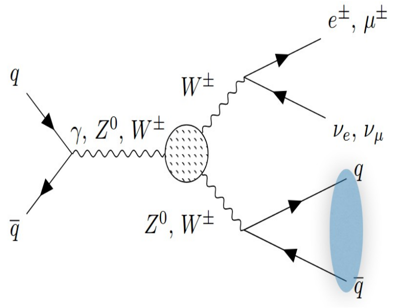
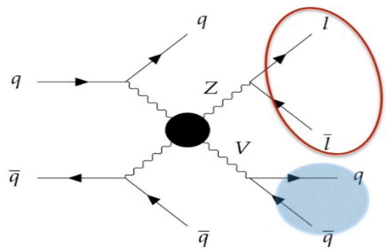
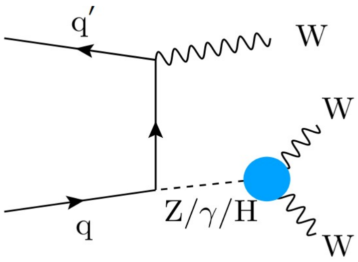


Large amount of individual EFT results

- SMP:
  - extensive collection of constraints on both dim.6 and dim.8

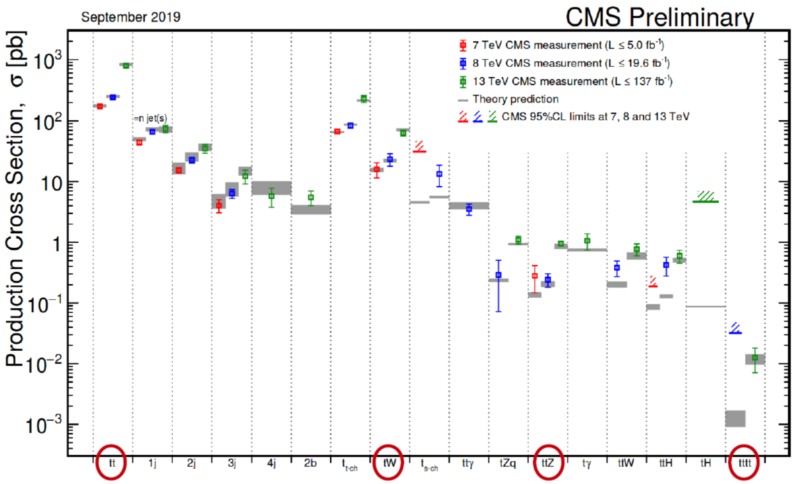






- Higgs:
  - first combined STXS results from CMS, CMS PAS HIG-19-005
  - ME analysis of HVV production and decay, PRD 99 (2019) 112003

- Top:
  - analysis of $t\bar{t}$ production in its spin space, PRD 100 (2019) 072002
  - differential studies of $t\bar{t}Z$ production, JHEP 03 (2020) 056



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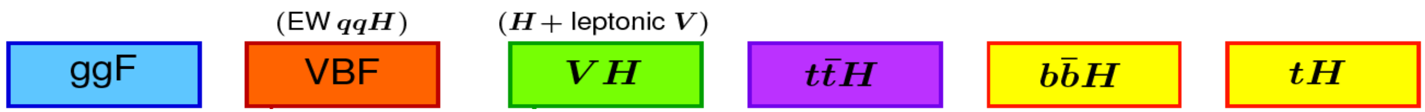
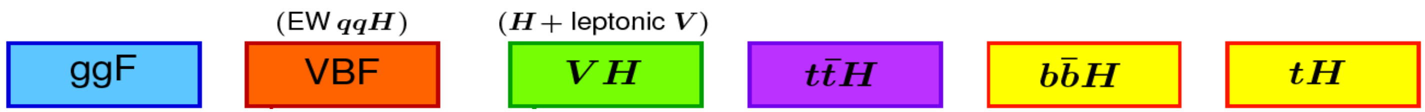
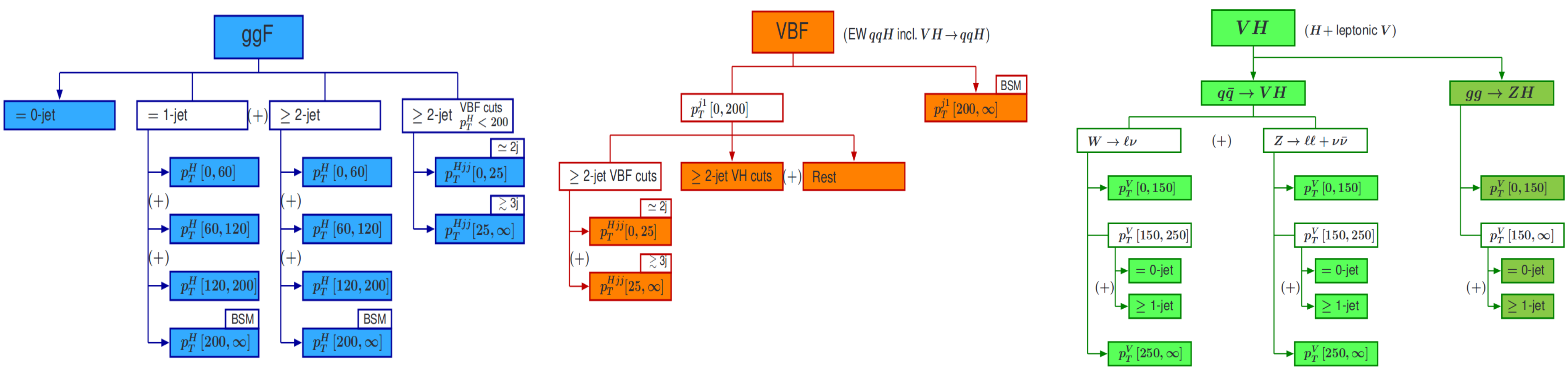
- evolution from inclusive cross section measurements



arXiv:1610.07922

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





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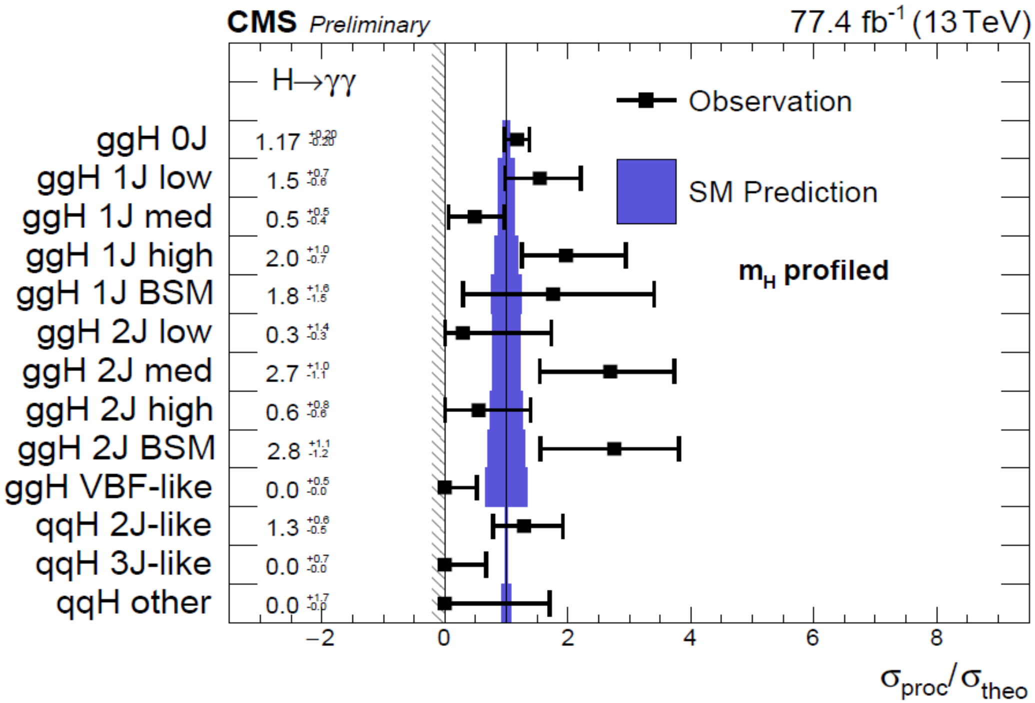
Connecting STXS with EFT

example: H → γγ, CMS PAS HIG-18-029



$$\mu_i(c_j) = \frac{\sigma_i^{\text{EFT}}}{\sigma_i^{\text{SM}}} = 1 + \sum_j A_j c_j + \sum_{jk} B_{jk} c_j c_k$$

- coefficients A,B from LO MC
  - Higgs effective Lagragian (SILH basis with flavor-universal couplings)
- parametrization includes deviations from SM Higgs branching ratios
- acceptance of event selection in each decay channel assumed to be SM-like
  - EFT can modify kinematics of decay products and change acceptance, particularly significant when intermediate decay states involved

Refs from CMS PAS HIG-19-005

Analysis	Decay tags	Production tags	Luminosity (fb^{-1})	References
$H \to \gamma\gamma$	$\gamma\gamma$	ggH, $p_T(H) \times$ N-jet bins VBF, $p_T(H\,jj)$ bins	77.4	[53]
		ttH	35.9, 41.5	[54], [55]
$H \to ZZ^{(*)} \to 4\ell$	4μ, $2e2\mu/2\mu2e$, 4e	ggH, $p_T(H) \times$ N-jet bins VBF, m_{jj} bins VH hadronic VH leptonic, $p_T(V)$ bins ttH	137	[56]
$H \to WW^{(*)} \to \ell\nu\ell\nu$	$e\mu/\mu e$	ggH $\leq$ 2-jets VBF	35.9	[57]
	$ee+\mu\mu$	ggH $\leq$ 1-jet		
	$e\mu$+jj	VH hadronic		
	3ℓ	WH leptonic		
	4ℓ	ZH leptonic		
$H \to \tau\tau$	$e\mu, e\tau_h, \mu\tau_h, \tau_h\tau_h$	ggH, $p_T(H) \times$ N-jet bins VH hadronic VBF	77.4	[58]
		VH, high-$p_T(V)$	35.9	[59]
$H \to bb$	$W(\ell\nu)H(bb)$ $Z(\nu\nu)H(bb)$, $Z(\ell\ell)H(bb)$	WH leptonic ZH leptonic	35.9, 41.5	[60], [61]
	bb	ttH, $t\bar{t} \to 0, 1, 2\ell$ + jets	77.4	[62]
		ggH, high-$p_T(H)$ bins	35.9	not considered
ttH production with $H \to$ leptons	2ℓss, 3ℓ, 4ℓ, $1\ell+2\tau_h$, 2ℓss$+1\tau_h$, $3\ell+1\tau_h$	ttH	35.9, 41.5	[64], [65]
$H \to \mu\mu$	$\mu\mu$	ggH VBF	35.9	not considered

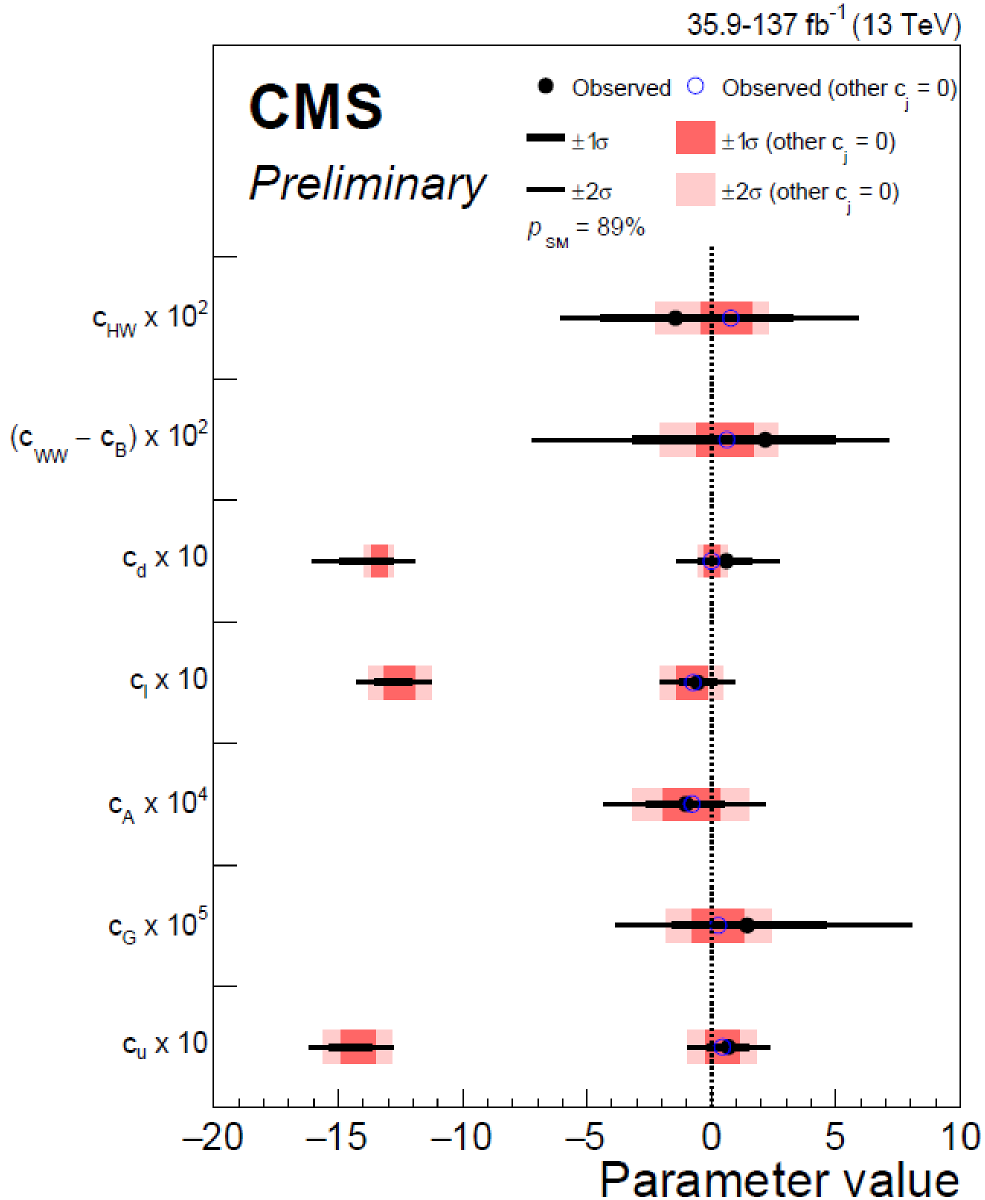
Selected EFT coefficients

- total of 15 dim-6 operators affecting Higgs physics
  - neglect CP-odd ones (-4)
  - neglect Higgs self-couplings (-1)
  - neglect Higgs field normalization as sensitivity not good enough for global change in rate (-1)
  - Cww + cB = 0 from precision electroweak parameter S: use only cWW−cB (-1)
  - drop CHB due to large degeneracies with cHW and cWW−cB

$$\mathcal{O}_g = |H|^2 G^A_{\mu\nu} G^{A\mu\nu}$$
$$\tilde{\mathcal{O}}_g = |H|^2 G^A_{\mu\nu} \tilde{G}^{A\mu\nu}$$
$$\mathcal{O}_\gamma = |H|^2 B_{\mu\nu} B^{\mu\nu}$$
$$\tilde{\mathcal{O}}_\gamma = |H|^2 B_{\mu\nu} \tilde{B}^{\mu\nu}$$
$$\mathcal{O}_u = y_u |H|^2 \bar{Q}_L H^\dagger u_R + \text{h.c.}$$
$$\mathcal{O}_d = y_d |H|^2 \bar{Q}_L H d_R + \text{h.c.}$$
$$\mathcal{O}_\ell = y_\ell |H|^2 \bar{L}_L H \ell_R + \text{h.c.}$$
$$\mathcal{O}_H = \left(\partial^\mu |H|^2\right)^2$$
$$\mathcal{O}_6 = \left(H^\dagger H\right)^3$$
$$\mathcal{O}_{HW} = i\,(D^\mu H)^\dagger \sigma^a (D^\nu H) W^a_{\mu\nu}$$
$$\tilde{\mathcal{O}}_{HW} = i\,(D^\mu H)^\dagger \sigma^a (D^\nu H) \tilde{W}^a_{\mu\nu}$$
$$\mathcal{O}_{HB} = i\,(D^\mu H)^\dagger (D^\nu H) B_{\mu\nu}$$
$$\tilde{\mathcal{O}}_{HB} = i\,(D^\mu H)^\dagger (D^\nu H) \tilde{B}_{\mu\nu}$$
$$\mathcal{O}_W = i \left(H^\dagger \sigma^a \overleftrightarrow{D}^\mu H\right) D^\nu W^a_{\mu\nu}$$
$$\mathcal{O}_B = i \left(H^\dagger \overleftrightarrow{D}^\mu H\right) \partial^\nu B_{\mu\nu}$$

probing 7 remaining operators

EFT constraints from combined STXS measurements

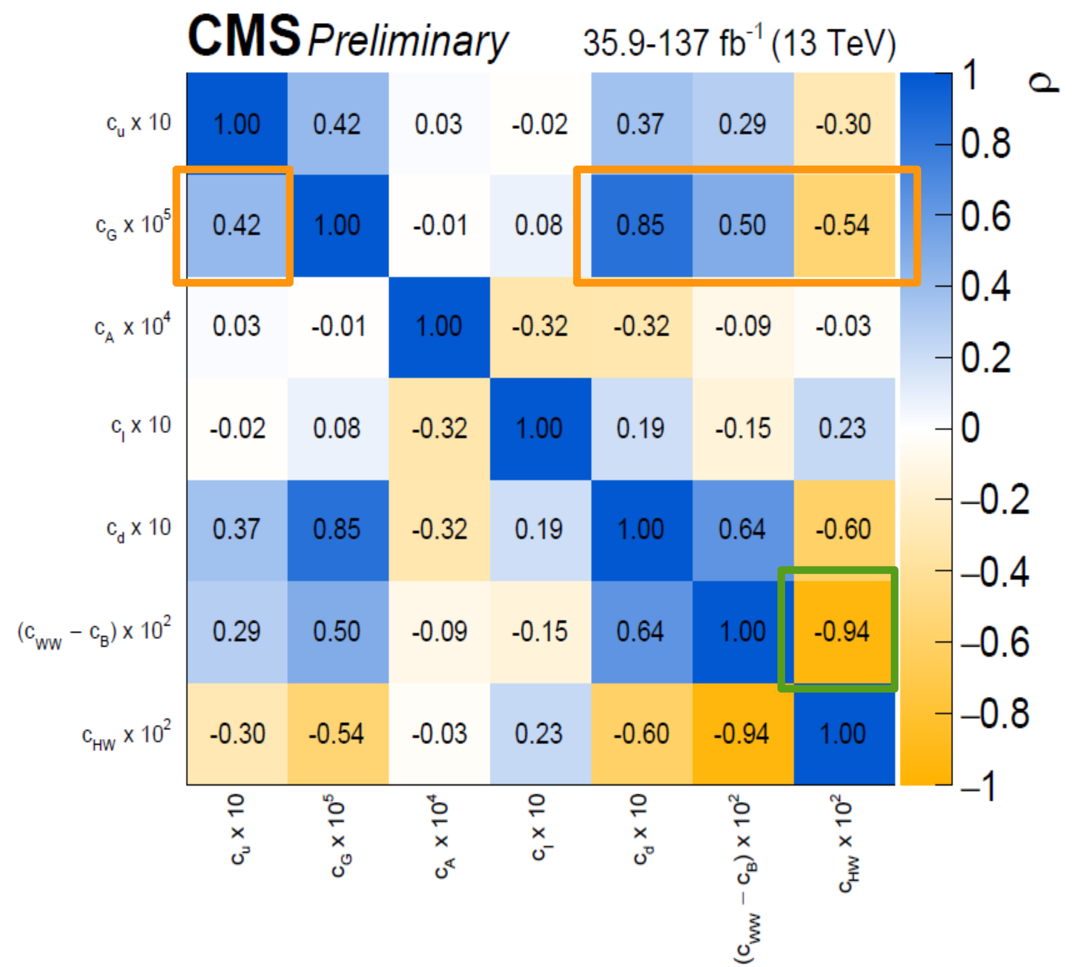


- analysis of up to 137 fb^{-1}
- new analyses specifically targeting $t\bar{t}H$ production
- inclusion of additional decay channels: $H \rightarrow WW$, $H \rightarrow b\bar{b}$ and $H \rightarrow \tau\tau$

significant improvements over previous results

Operator correlation

- large correlation of c_{HW} and $c_{WW}-c_B$: little differential info in VH analysis
- c_G leads to an increased cross section which cannot be differentiate from Γ_{tot} (where c_A and c_l contribute little)



correlations well understood

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ME based approaches for EFT

- matrix-element methods well established long before LHC in
  - high precision measurements
  - searches for rare, new physics
- measurement of anomalous HVV couplings at CMS benefits from both aspects
  - distinguish H production mechanism (VBF, VH, ggH), e.g. sig = VBF vs alt = ggH to categorize events
  - isolate signal from background
  - measure anomalous HVV (VV=ZZ / $Z\gamma^*/\gamma^*\gamma^*$) couplings

$$\mathcal{D}_{\text{alt}}(\mathbf{\Omega}) = \frac{\mathcal{P}_{\text{sig}}(\mathbf{\Omega})}{\mathcal{P}_{\text{sig}}(\mathbf{\Omega}) + \mathcal{P}_{\text{alt}}(\mathbf{\Omega})}$$

Parametrization of anomalous couplings

- amplitude w./ three tensor structures with expansion of coefficients up to (q^2/Λ^2)

SM couplings

four-momenta

pole mass of massive gauge boson

scalar tensor $f^{(i)\mu\nu} = \epsilon_i^{\mu} q_i^{\nu} - \epsilon_i^{\nu} q_i^{\mu}$

$$A \sim \left[a_1^{VV} - \frac{\kappa_1^{VV} q_1^2 + \kappa_2^{VV} q_2^2}{\left(\Lambda_1^{VV}\right)^2} - \frac{\kappa_3^{VV} (q_1+q_2)^2}{\left(\Lambda_Q^{VV}\right)^2} \right] m_{V1}^2 \epsilon_{V1}^* \epsilon_{V2}^* + a_2^{VV} f_{\mu\nu}^{*(1)} f^{*(2)\,\mu\nu} + a_3^{VV} f_{\mu\nu}^{*(1)} \tilde{f}^{*(2)\,\mu\nu}$$

~mH2: no sensitivity

polarization vectors

pseudoscalar counterpart $\tilde{f}_{\mu\nu}^{(i)} = \frac{1}{2}\epsilon_{\mu\nu\rho\sigma} f^{(i)\,\rho\sigma}$

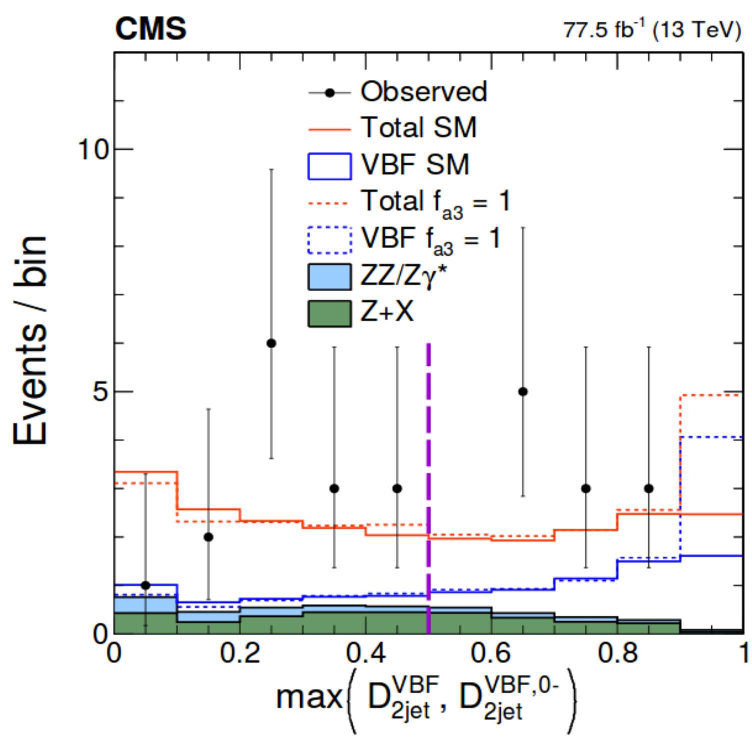
	κ^{VV}_1	κ^{VV}_2	a^{VV}_2	a^{VV}_3
ZZ	$-\exp(i\phi^{ZZ}_{\Lambda 1})$	$-\exp(i\phi^{ZZ}_{\Lambda 1})$	a^{ZZ}_2	a^{ZZ}_3
Zγ	$-\exp(i\phi^{Z\gamma}_{\Lambda 1})$	0	poor with respect to on-shell γ	
γγ	0	0		

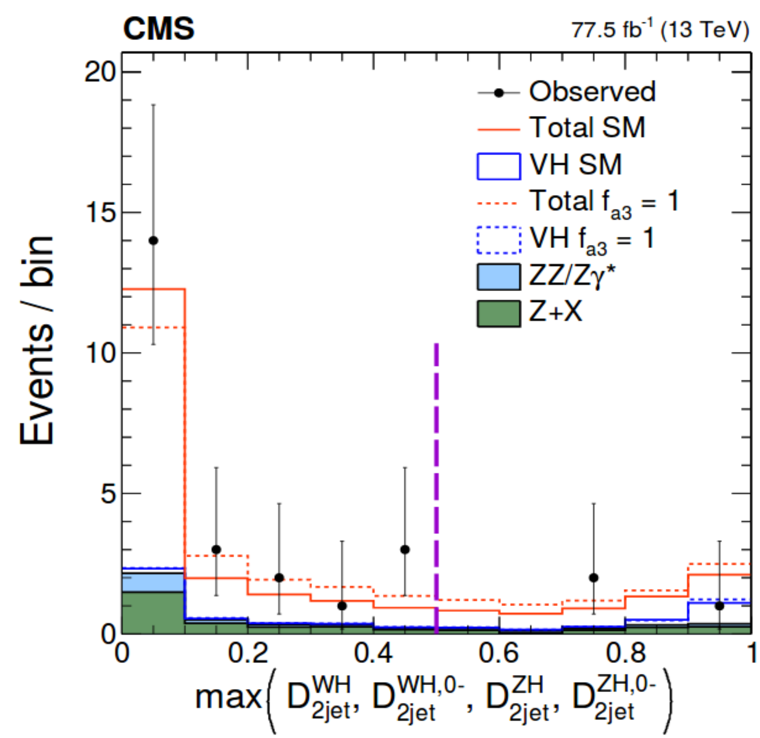
constraint 4 anomalous couplings

Event categorization

- lepton final state: $H \to 4e, 4\mu, 2e2\mu$
- on-shell ($104\ \text{GeV} < m_{4l} < 140\ \text{GeV}$) and off-shell region ($m_{4l} > 220\ \text{GeV}$)
- production mode

Category	VBF-tagged	VH-tagged	Untagged
Selection	$\mathcal{D}_{2jet}^{VBF}$ or $\mathcal{D}_{2jet}^{VBF,BSM} > 0.5$	$\mathcal{D}_{2jet}^{WH}$ or $\mathcal{D}_{2jet}^{WH,BSM}$, or $\mathcal{D}_{2jet}^{ZH}$ or $\mathcal{D}_{2jet}^{ZH,BSM} > 0.5$	Rest of events

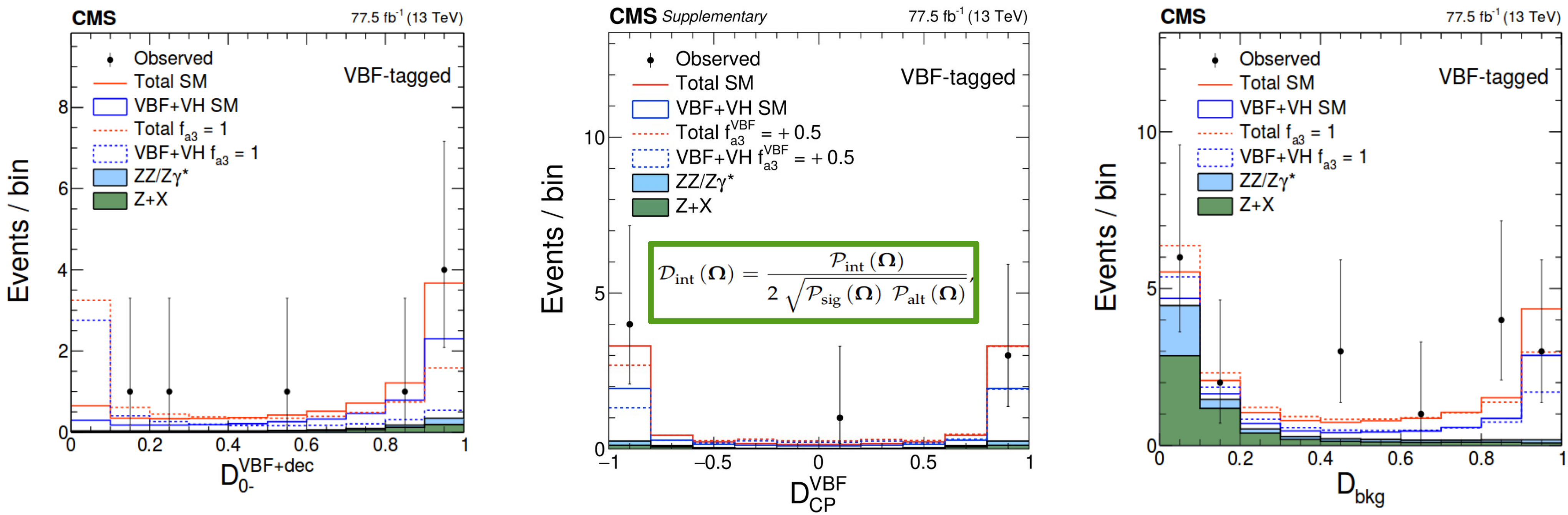




Coupling extraction

- constraint fraction f_{ai} of anomalous coupling as well as its complex sign $\cos(\phi_{ai})$ from maximum likehood fit of signal and background probabilities for process j in category k (M=4 for VBF/VH, M=2 for ggH)

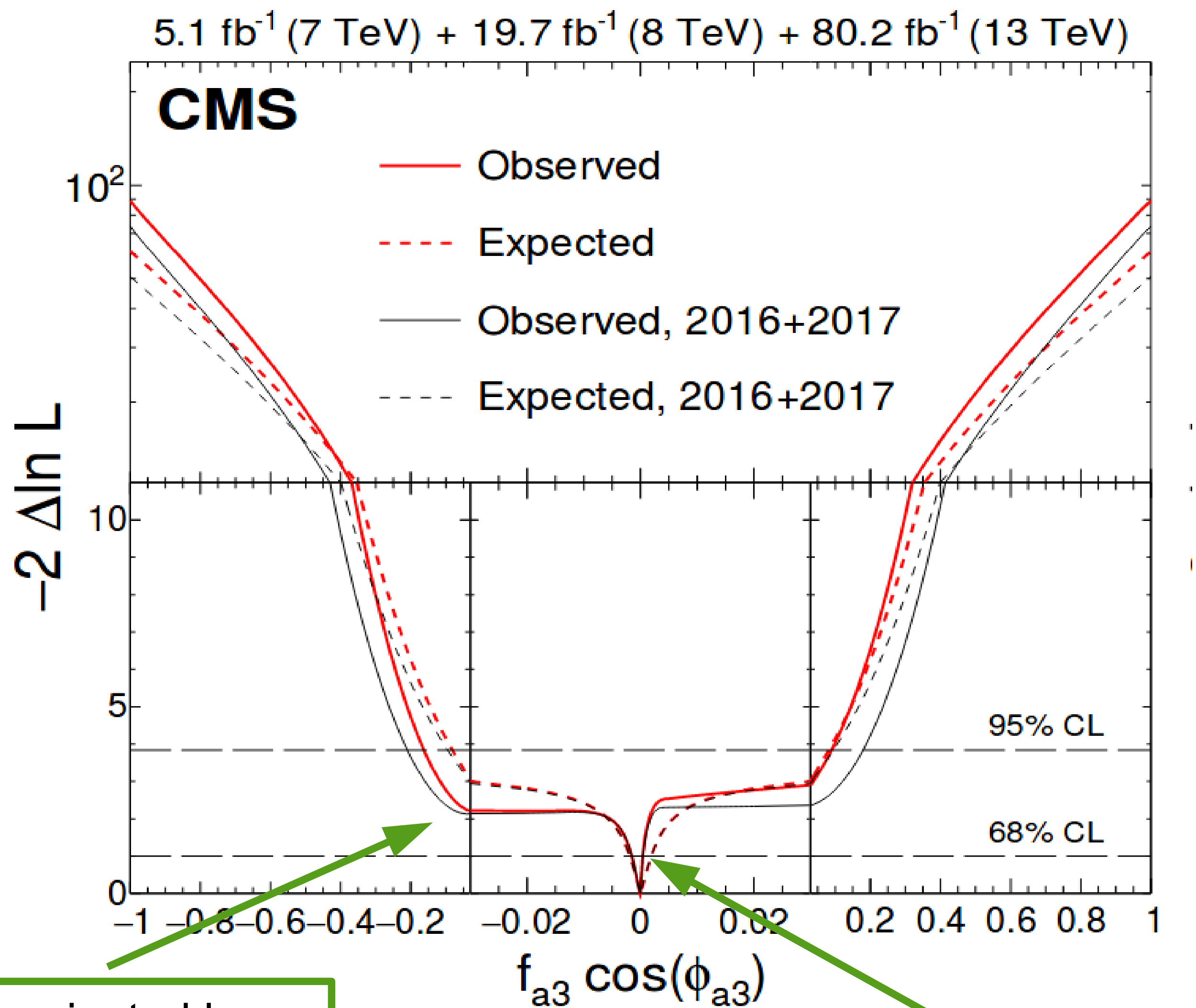
$$\sum_{m=0}^{M} \mathcal{P}^{\mathrm{sig/int}}_{jk,m}\left(\vec{x};\vec{\xi}_{jk}\right) f_{ai}^{\frac{m}{2}} \left(1-f_{ai}\right)^{\frac{M-m}{2}} \cos^{m}(\phi_{ai})$$



VBF signal/background PDFs:

a3 signal **a3 interference** **background**

Measured couplings



dominated by decay information

gain from production higher order polynomial in f_{ai}

Measured couplings

- combination of on-shell and off-shell region

$$\sigma^{\text{off-shell}}_{\text{vv}\to\text{H}\to 4\ell} \propto \mu_{\text{vvH}}\,\Gamma_{\text{H}}$$

Parameter	Scenario	Observed	Expected
$f_{a3}\cos(\phi_{a3})$	on-shell	$-0.0001^{+0.0004}_{-0.0015}$ $[-0.163, 0.090]$	$0.0000^{+0.0019}_{-0.0019}$ $[-0.082, 0.082]$
	any Γ_{H}	$0.0000^{+0.0003}_{-0.0010}$ $[-0.0165, 0.0087]$	$0.0000^{+0.0015}_{-0.0015}$ $[-0.038, 0.038]$
	$\Gamma_{\text{H}} = \Gamma_{\text{H}}^{\text{SM}}$	$0.0000^{+0.0003}_{-0.0009}$ $[-0.0067, 0.0050]$	$0.0000^{+0.0014}_{-0.0014}$ $[-0.0098, 0.0098]$
$f_{a2}\cos(\phi_{a2})$	on-shell	$0.0004^{+0.0026}_{-0.0006}$ $[-0.0055, 0.0234]$	$0.0000^{+0.0030}_{-0.0023}$ $[-0.021, 0.035]$
	any Γ_{H}	$0.0004^{+0.0026}_{-0.0006}$ $[-0.0035, 0.0147]$	$0.0000^{+0.0019}_{-0.0017}$ $[-0.015, 0.021]$
	$\Gamma_{\text{H}} = \Gamma_{\text{H}}^{\text{SM}}$	$0.0005^{+0.0025}_{-0.0006}$ $[-0.0029, 0.0129]$	$0.0000^{+0.0012}_{-0.0016}$ $[-0.010, 0.012]$
$f_{\Lambda 1}\cos(\phi_{\Lambda 1})$	on-shell	$0.0002^{+0.0030}_{-0.0009}$ $[-0.209, 0.089]$	$0.0000^{+0.0012}_{-0.0006}$ $[-0.059, 0.032]$
	any Γ_{H}	$0.0001^{+0.0015}_{-0.0006}$ $[-0.090, 0.059]$	$0.0000^{+0.0013}_{-0.0007}$ $[-0.017, 0.019]$
	$\Gamma_{\text{H}} = \Gamma_{\text{H}}^{\text{SM}}$	$0.0001^{+0.0015}_{-0.0005}$ $[-0.016, 0.068]$	$0.0000^{+0.0013}_{-0.0006}$ $[-0.015, 0.018]$
$f_{\Lambda 1}^{Z\gamma}\cos\left(\phi_{\Lambda 1}^{Z\gamma}\right)$	on-shell	$0.0000^{+0.3554}_{-0.0087}$ $[-0.17, 0.61]$	$0.0000^{+0.0091}_{-0.0100}$ $[-0.098, 0.343]$

Combined results

- on-shell results combined with $H \to \tau\tau$ analysis
- significantly increased sensitivity in the region around 0
  - driven by production information where $H \to \tau\tau$ dominates over $H \to 4l$

Parameter	Observed / (10^{-3}) 68% CL	Observed / (10^{-3}) 95% CL	Expected / (10^{-3}) 68% CL	Expected / (10^{-3}) 95% CL
$f_{a3}\cos(\phi_{a3})$	0.00 ± 0.27	$[-92, 14]$	0.00 ± 0.23	$[-1.2, 1.2]$
$f_{a2}\cos(\phi_{a2})$	$0.08^{+1.04}_{-0.21}$	$[-1.1, 3.4]$	$0.0^{+1.3}_{-1.1}$	$[-4.0, 4.2]$
$f_{\Lambda 1}\cos(\phi_{\Lambda 1})$	$0.00^{+0.53}_{-0.09}$	$[-0.4, 1.8]$	$0.00^{+0.48}_{-0.12}$	$[-0.5, 1.7]$
$f_{\Lambda 1}^{Z\gamma}\cos(\phi_{\Lambda 1}^{Z\gamma})$	$0.0^{+1.1}_{-1.3}$	$[-6.5, 5.7]$	$0.0^{+2.6}_{-3.6}$	$[-11, 8.0]$

PRD 100 (2019) 112002

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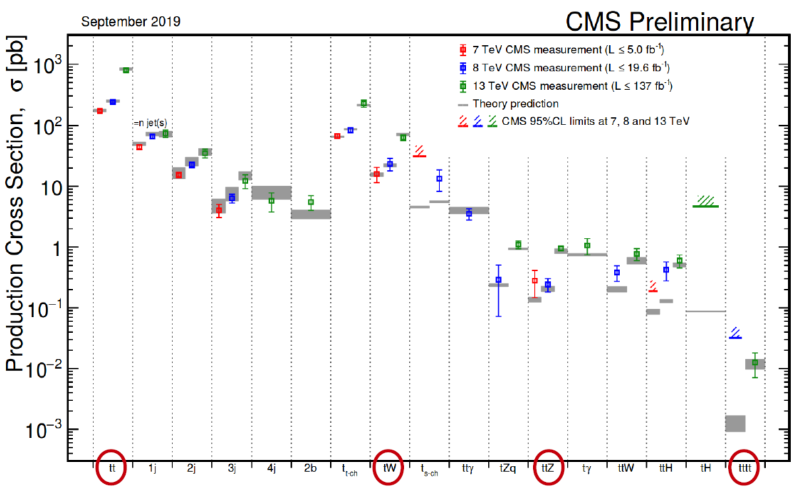
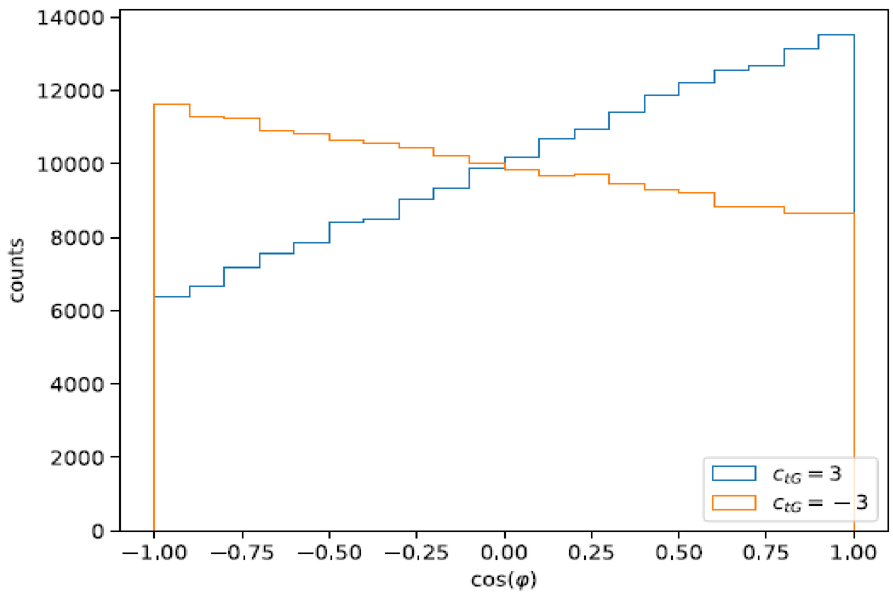


Probing EFT using $t\bar{t}$ spin density matrix

- orthogonal to pure rate changes or enhancements in particle momentum spectrum
- high sensitivity to EFT, e.g. chromomagnetic top dipole moment (CMDM): $c_{tG}\,O_{tG}$ with

$$O_{\mathrm{tG}} = y_{\mathrm{t}} g_{\mathrm{s}} (\overline{Q} \sigma^{\mu\nu} T^a t) \tilde{\phi} G^a_{\mu\nu}$$

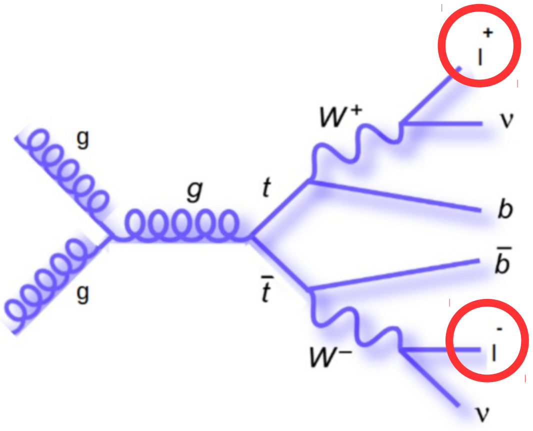


- 15 coefficients completely characterize spin dependence of $t\bar{t}$ production

$$\frac{1}{\sigma}\frac{\mathrm{d}^4\sigma}{\mathrm{d}\Omega_1 \mathrm{d}\Omega_2} = \frac{1}{(4\pi)^2}\left(1 + \vec{\mathrm{B}}_1 \cdot \hat{\ell}^1 + \vec{\mathrm{B}}_2 \cdot \hat{\ell}^2 - \hat{\ell}^1 \cdot \mathrm{C} \cdot \hat{\ell}^2\right)$$

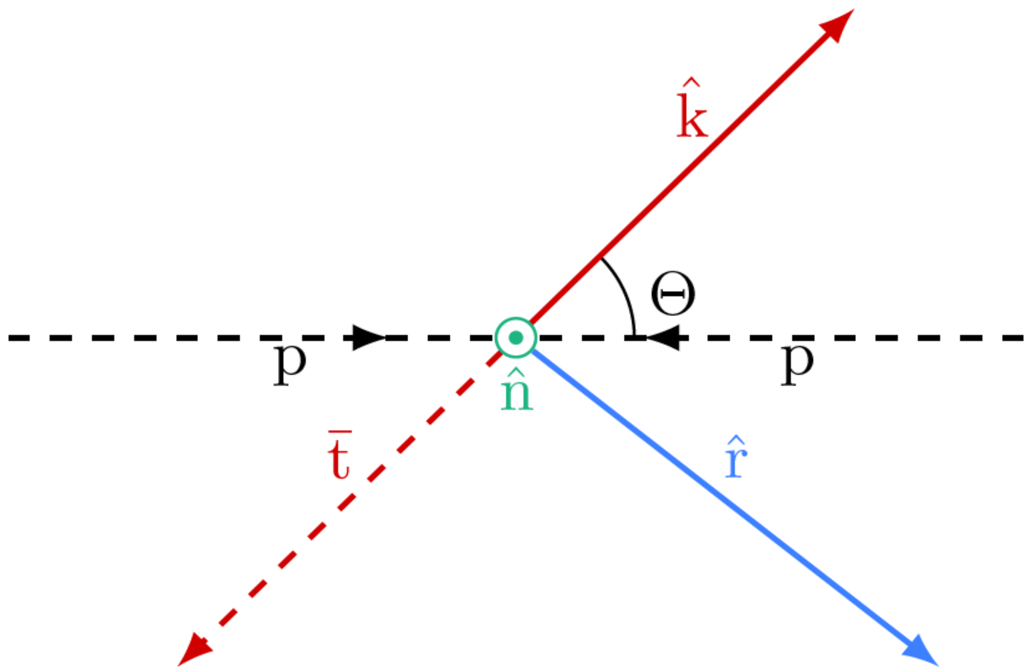
$$1 \qquad \vec{B}_{1/2} = \begin{pmatrix} x \\ x \\ x \end{pmatrix} \qquad C = \begin{pmatrix} x & x & x \\ x & x & x \\ x & x & x \end{pmatrix}$$

spin-independent — top polarization — spin correlation



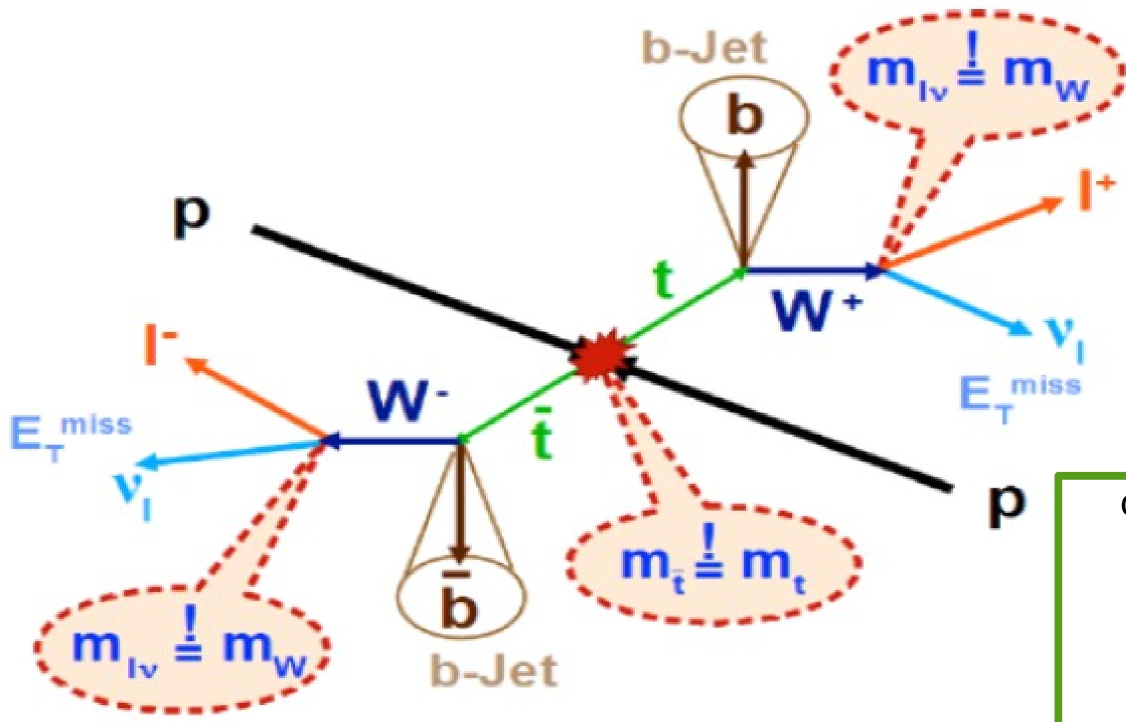
Analysis approach

- construct orthonormal basis



Analysis approach

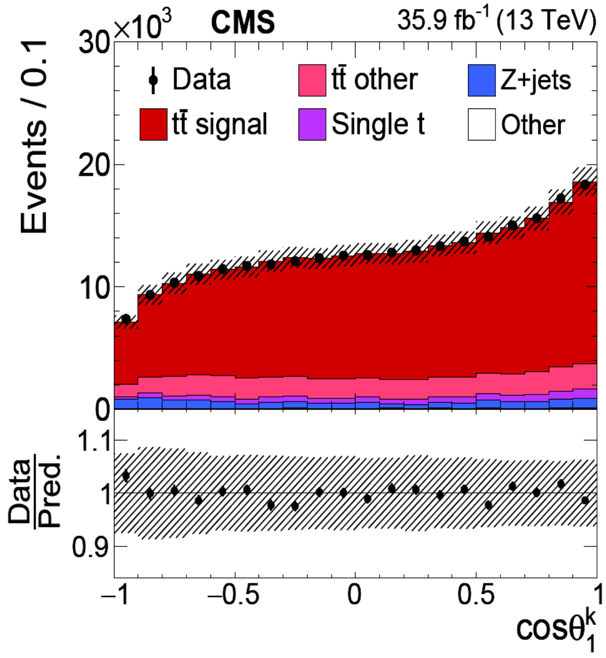
- construct orthonormal basis
- estimate angles in $t/\bar{t}$ rest frames → kinematic reconstruction



combination to pick

- solution with minimal $m_{t\bar{t}}$
- pair lepton and jet according to expected m_{lb}

Analysis approach



- construct orthonormal basis
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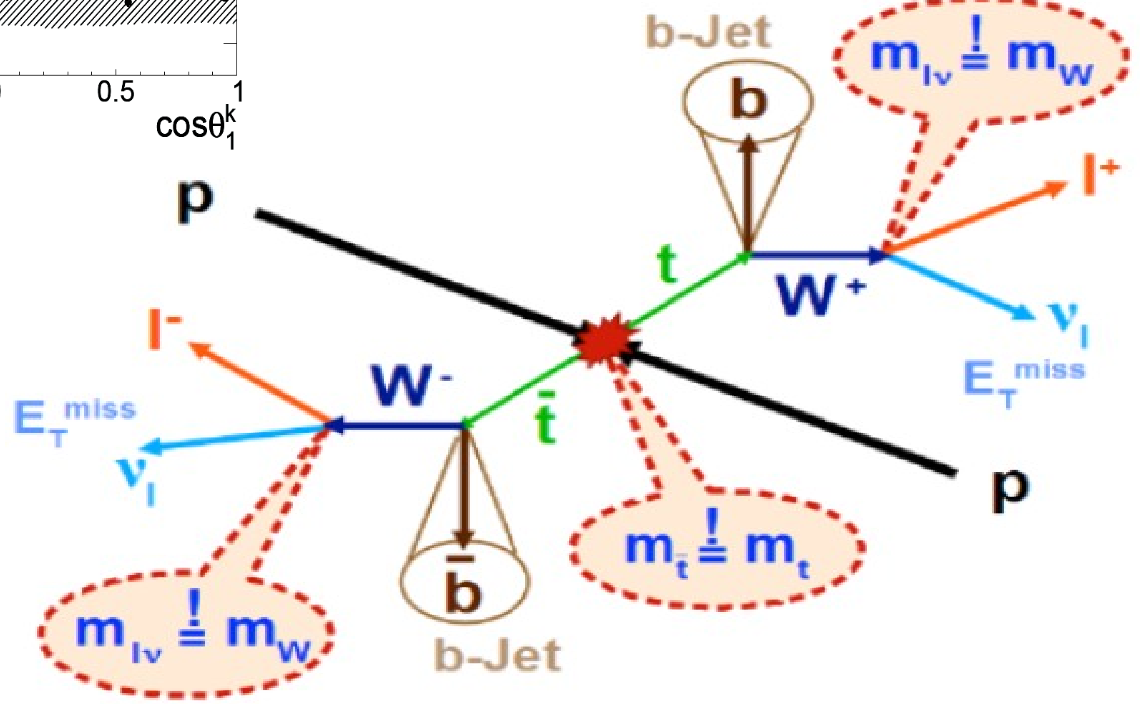

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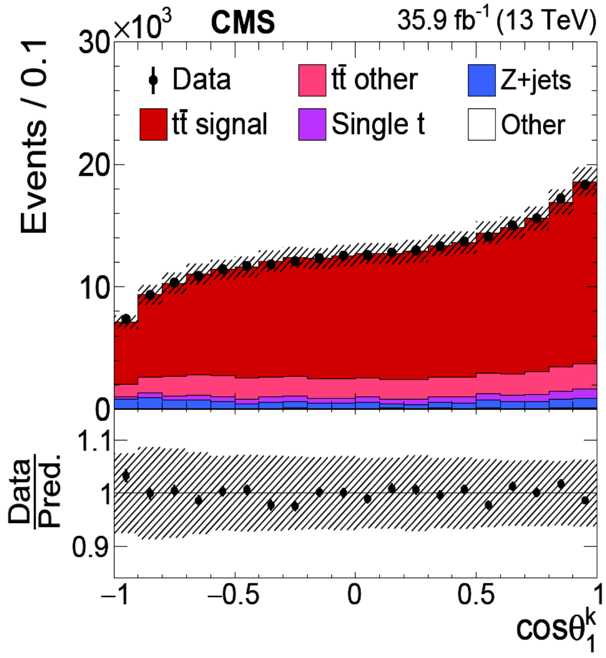
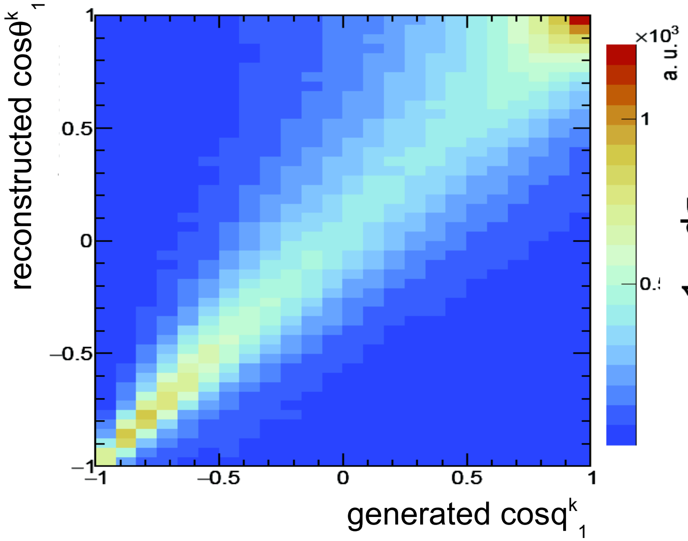
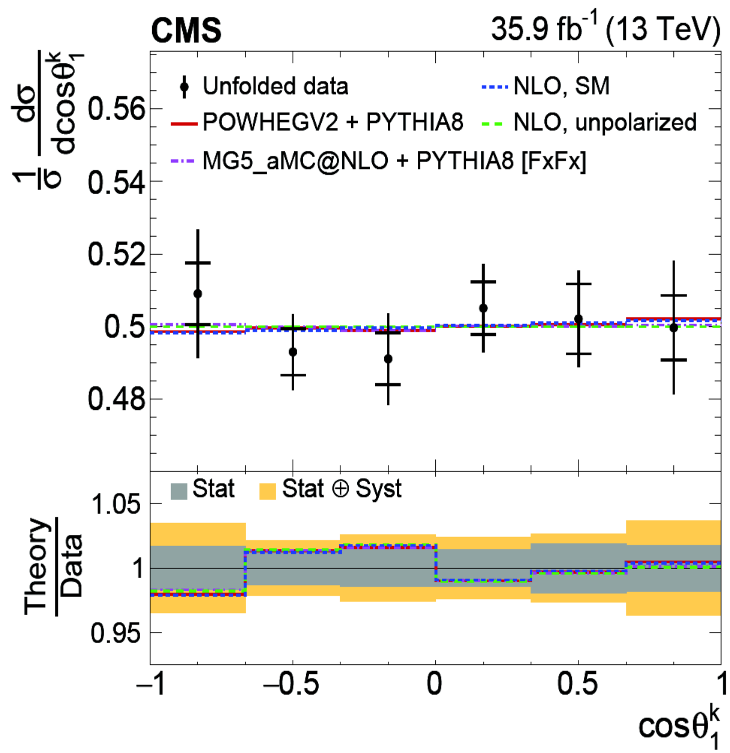


- construct orthonormal basis
- estimate angles in t/t̄ rest frames → kinematic reconstruction
- correct acceptance and detector effects (parton-level unfolding)

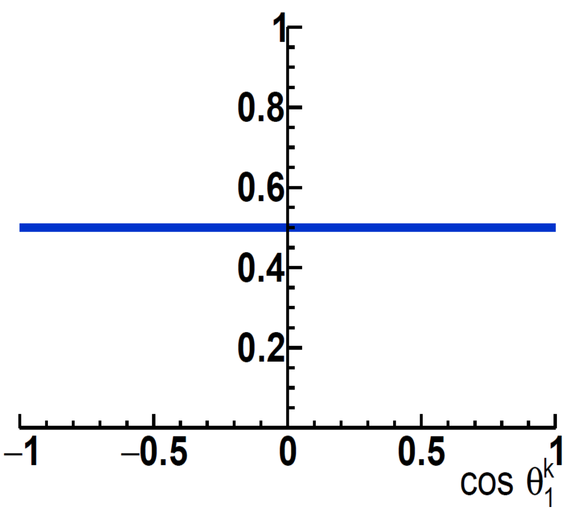


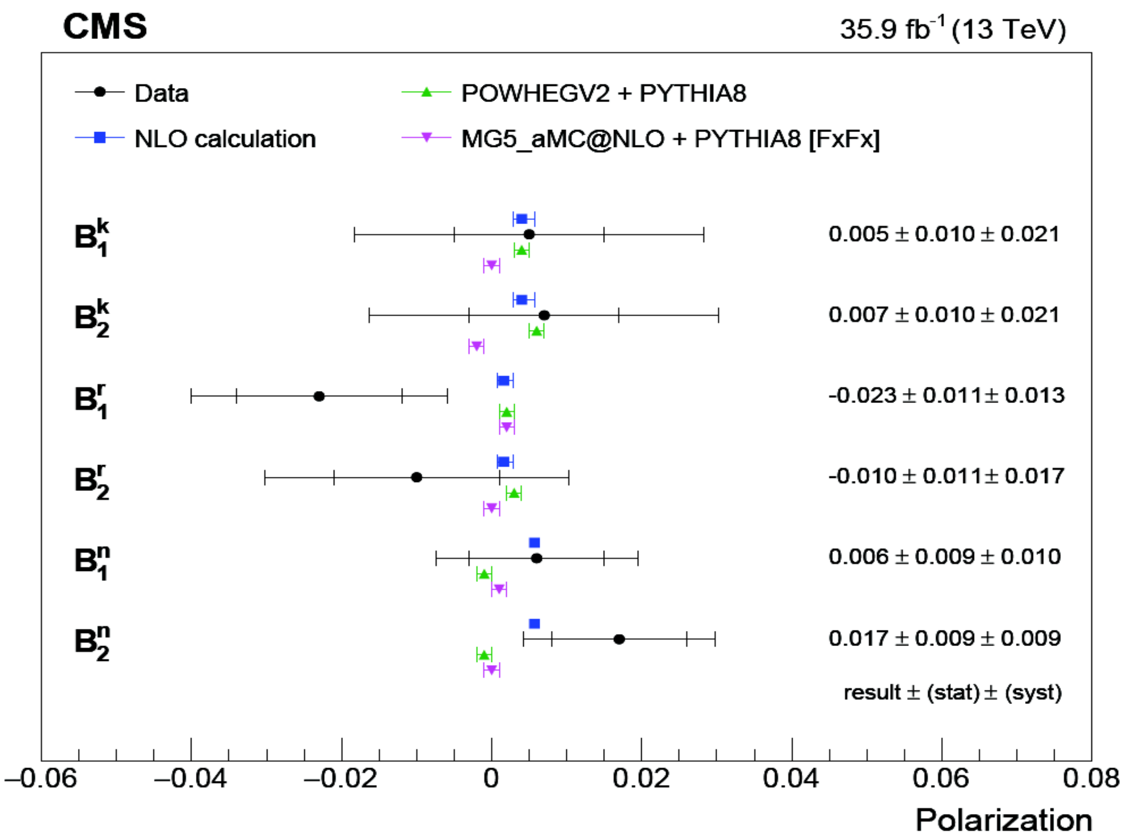


Results: polarization vector

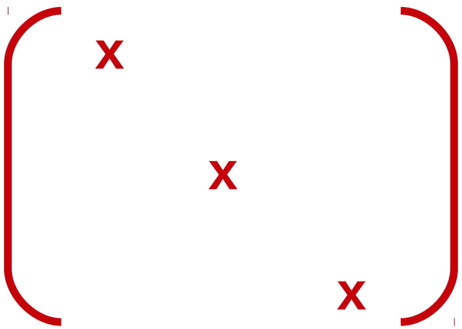
- consistent with zero for each axis
- not yet sensitive to small polarization in the SM
- dominant uncertainty from JES (top rest frame reconstruction)

$$\frac{1}{\sigma}\frac{d^4\sigma}{d\Omega_1 d\Omega_2} = \frac{1}{(4\pi)^2}\left(1 + \boxed{\vec{B}_1}\cdot\hat{\ell}^1 + \boxed{\vec{B}_2}\cdot\hat{\ell}^2 - \hat{\ell}^1 \cdot \mathrm{C} \cdot \hat{\ell}^2\right)$$

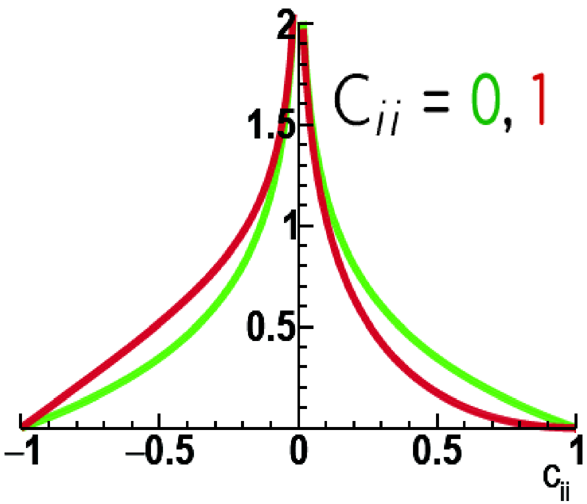


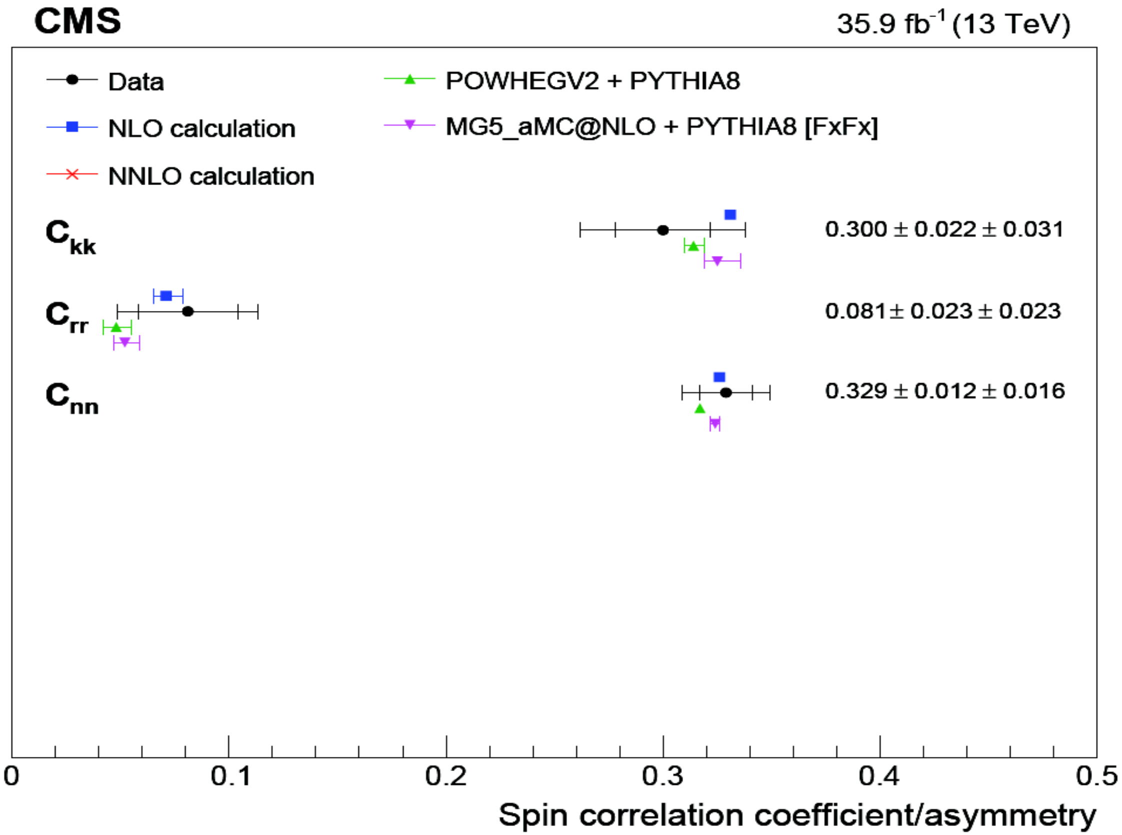


- correlations along each axis consistent with SM expectations
- dominant uncertainties from background and top p_T modeling



$$\frac{1}{\sigma}\frac{d^4\sigma}{d\Omega_1 d\Omega_2} = \frac{1}{(4\pi)^2}\left(1 + \vec{B}_1\cdot\hat{\ell}^1 + \vec{B}_2\cdot\hat{\ell}^2 - \hat{\ell}^1\cdot C\cdot\hat{\ell}^2\right)$$



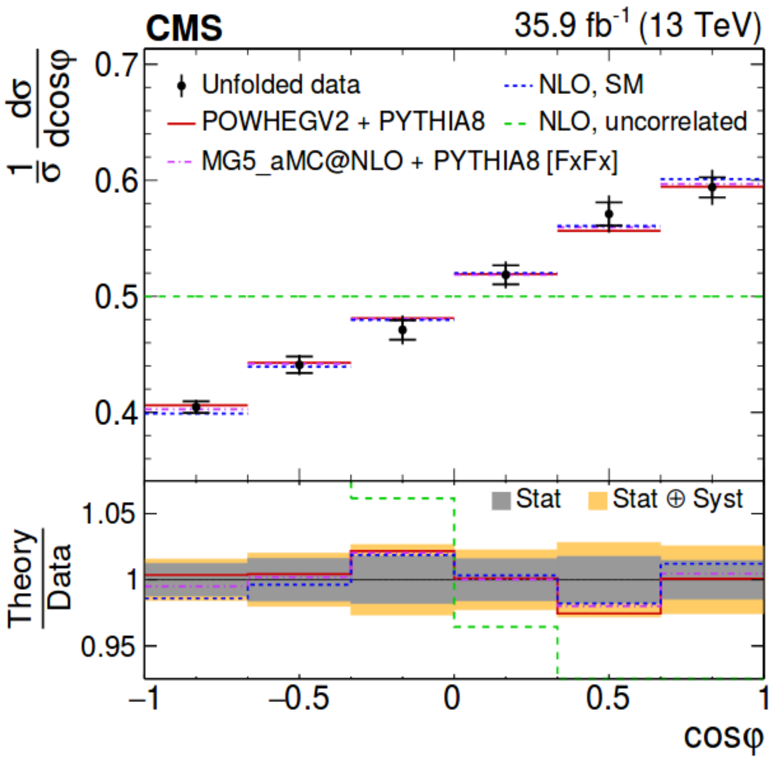


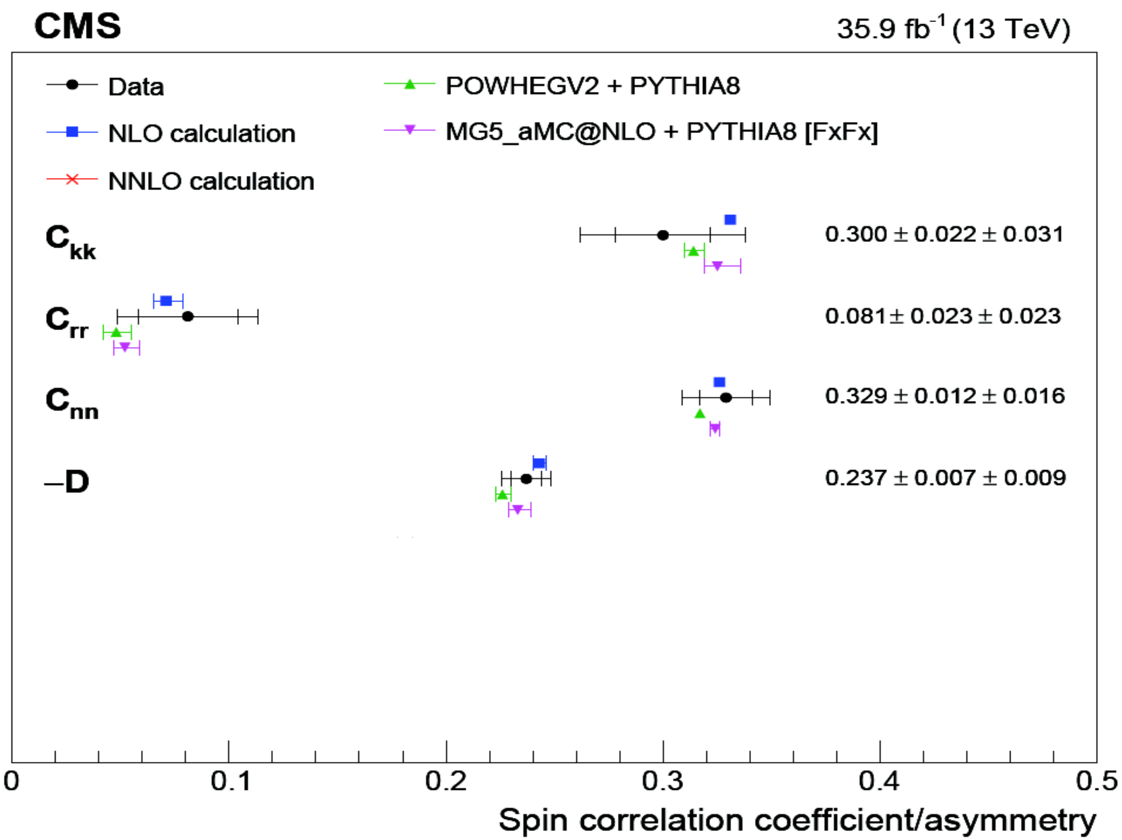
Maximal sensitivity to spin correlation

- provided by full lepton (in top parent rest frame) opening angle
- most precise measurement to date (5% uncertainty)

$$\mathrm{Tr}\begin{pmatrix} x & & \\ & x & \\ & & x \end{pmatrix}$$

$$\frac{1}{\sigma}\frac{d^4\sigma}{d\Omega_1 d\Omega_2} = \frac{1}{(4\pi)^2}\left(1 + \vec{B}_1 \cdot \hat{\ell}^1 + \vec{B}_2 \cdot \hat{\ell}^2 - \hat{\ell}^1 \cdot \boxed{C} \cdot \hat{\ell}^2\right)$$





Constraining top chromomagnetic dipole moment

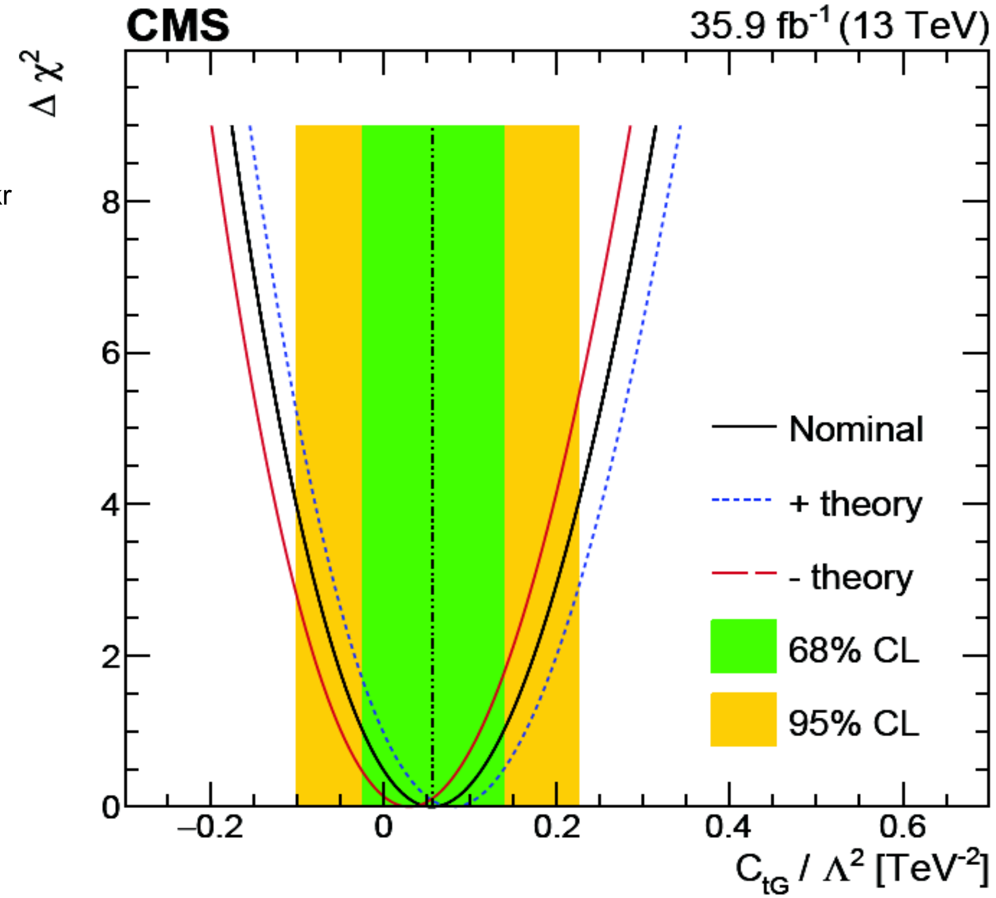
$$O_{tG} = y_t g_s (\bar{Q}\sigma^{\mu\nu} T^a t)\tilde{\phi} G^a_{\mu\nu}$$

- EFT predictions based on NLO MC simulation
  - apply NNLO/NLO k-factor of 1.22 from SM calculation
- 95% CL limits from simultaneous χ^2 fit
  - to normalized cos(φ), C_{kk}, C_{nn}, $C_{rk} + C_{kr}$
  - including full covariance matrix V_{ij}

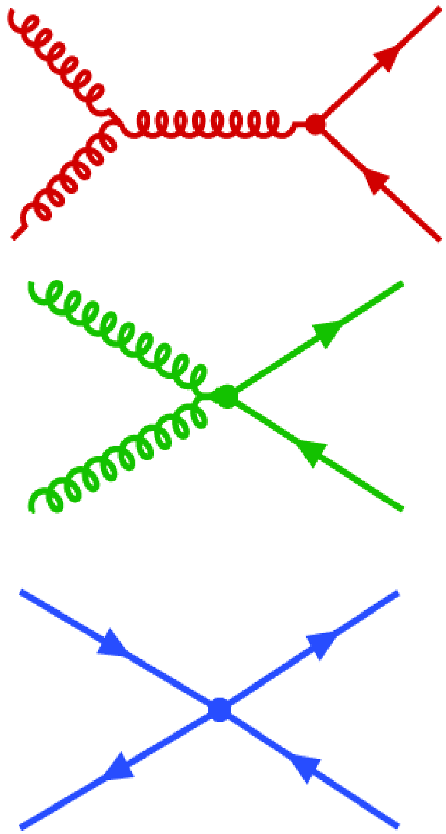
$$\chi^2 = \sum_i^N \sum_j^N \left(\mathrm{data}_i - \mathrm{pred}_i\right) \cdot \left(\mathrm{data}_j - \mathrm{pred}_j\right) \cdot V_{ij}^{-1}$$

- strongest direct limits to date on top quark CMDM

$$-0.10 < C_{tG}/\Lambda^2 < 0.22\ \mathrm{TeV}^{-2}$$



- total of 11 EFT operators affecting hadronic $t\bar{t}$ production
  - 10 of them impact spin density matrix (LO prediction from JHEP 12 (2015) 026)
  - choose 4 best observables to constraint each operator

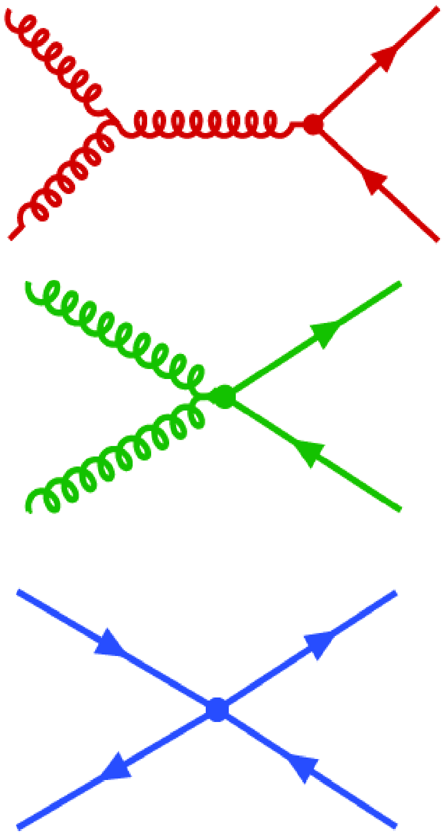


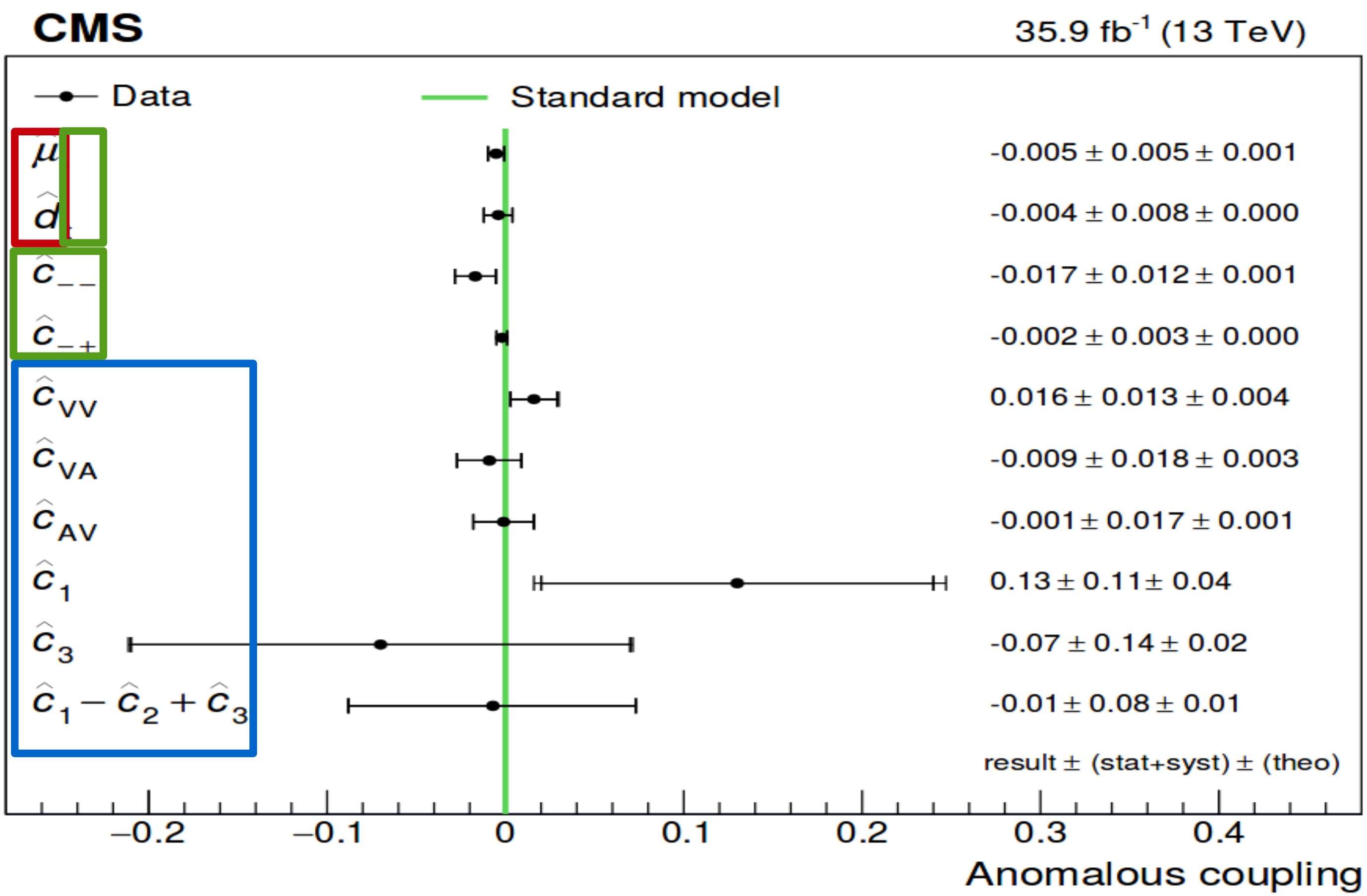
Operator	Lagrangian	Vertex	Direct effects
$\hat{\mu}_t$	$g_1\left[\bar{t}\sigma^{\mu\nu}T^a t G^a_{\mu\nu}\right]$	$gt\bar{t}$ $ggt\bar{t}$	C_{ii}, $C_{rk}+C_{kr}$, C_{hel}
$\hat{d}_t$	$g_1\left[\bar{t}i\sigma^{\mu\nu}\gamma_5 T^a t G^a_{\mu\nu}\right]$	$gt\bar{t}$ $ggt\bar{t}$	$C_{nr}-C_{rn}$, $C_{nk}-C_{kn}$
$\hat{c}_{--}$	$g_2\left[\mathcal{O}_- + \mathcal{O}_-^\dagger\right]$, $\mathcal{O}_- = i[\bar{t}\gamma^\mu\gamma_5 T^a D^\nu t]G^a_{\mu\nu}$	$ggt\bar{t}$	$C_{nr}-C_{rn}$, $C_{nk}-C_{kn}$
$\hat{c}_{-+}$	$g_2 i\left[\mathcal{O}_+ - \mathcal{O}_+^\dagger\right]$, $\mathcal{O}_+ = [\bar{t}\gamma^\mu T^a D^\nu t]G^a_{\mu\nu}$	$ggt\bar{t}$	b^a_n
$\hat{c}_{VV}$	$g_3 q_V t_V$	$q\bar{q}t\bar{t}$	C_{ii}, $C_{rk}+C_{kr}$, C_{hel}
$\hat{c}_{VA}$	$g_3 q_V t_A$ weak isospin 0	$q\bar{q}t\bar{t}$	b^a_k, b^a_r
$\hat{c}_{AV}$	$g_3 q_A t_V$	$q\bar{q}t\bar{t}$	$b^a_{k^*}$, $b^a_{r^*}$
$\hat{c}_{AA}$	$g_3 q_A t_A$	$q\bar{q}t\bar{t}$	-
$\hat{c}_1$	$g_4\left[q'_V t_V + q'_A t_V\right]$	$q\bar{q}t\bar{t}$	C_{ii}, $C_{rk}+C_{kr}$, C_{hel}
$\hat{c}_3$	$g_4\left[q'_V t_A + q'_A t_V\right]$ weak isospin 1	$q\bar{q}t\bar{t}$	b^a_k, b^a_r
$\hat{c}_1 - \hat{c}_2 + \hat{c}_3$	$\hat{c}_2 = g_4\left[q'_A t_A - q'_A t_V\right]$	$q\bar{q}t\bar{t}$	$b^a_{k^*}$, $b^a_{r^*}$

definition following JHEP 12 (2015) 026
table by A. Anuar

Beyond top CMDM

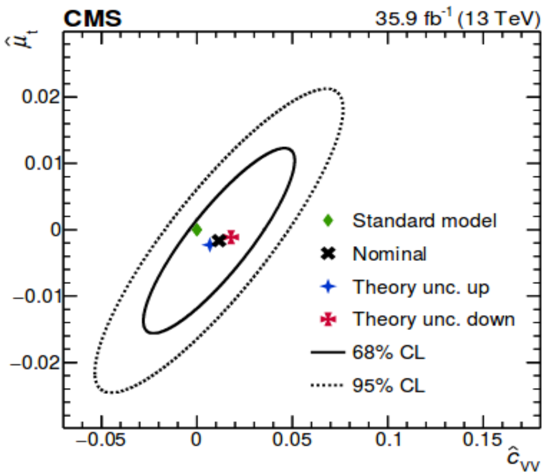
- total of 11 EFT operators affecting hadronic $t\bar{t}$ production
  - 10 of them impact spin density matrix (LO prediction from JHEP 12 (2015) 026)
  - choose 4 best observables to constraint each operator

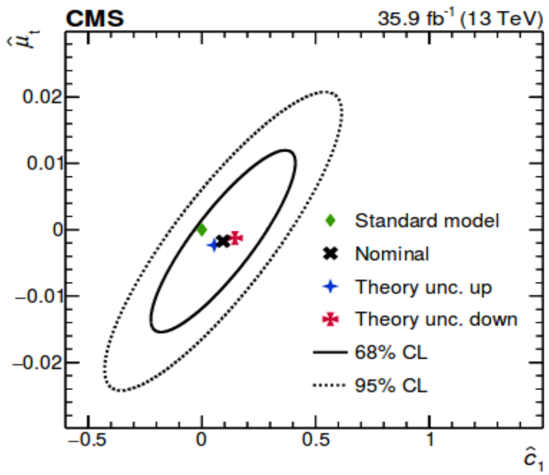


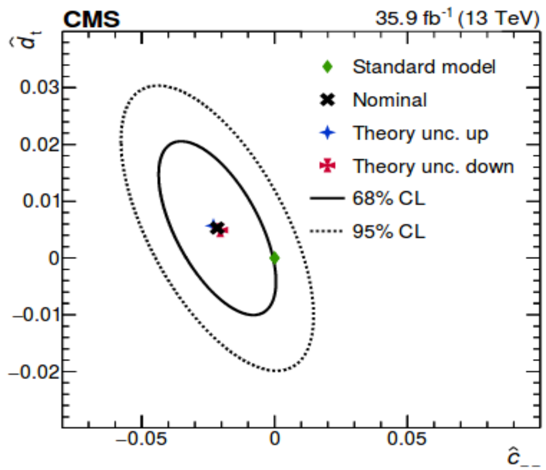


Beyond top CMDM

- total of 11 EFT operators affecting hadronic $t\bar{t}$ production
  - 10 of them impact spin density matrix (LO prediction from JHEP 12 (2015) 026)
  - choose 4 best observables to constraint each operator
  - 2 dimensional contours provided where needed





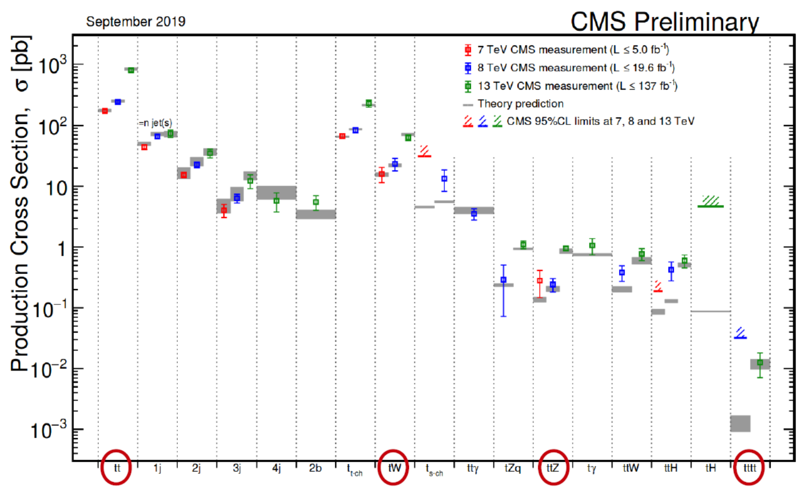


Large amount of individual EFT results

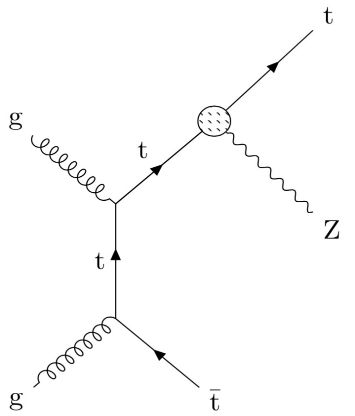
- SMP:
  - extensive collection of constraints on both dim.6 and dim.8

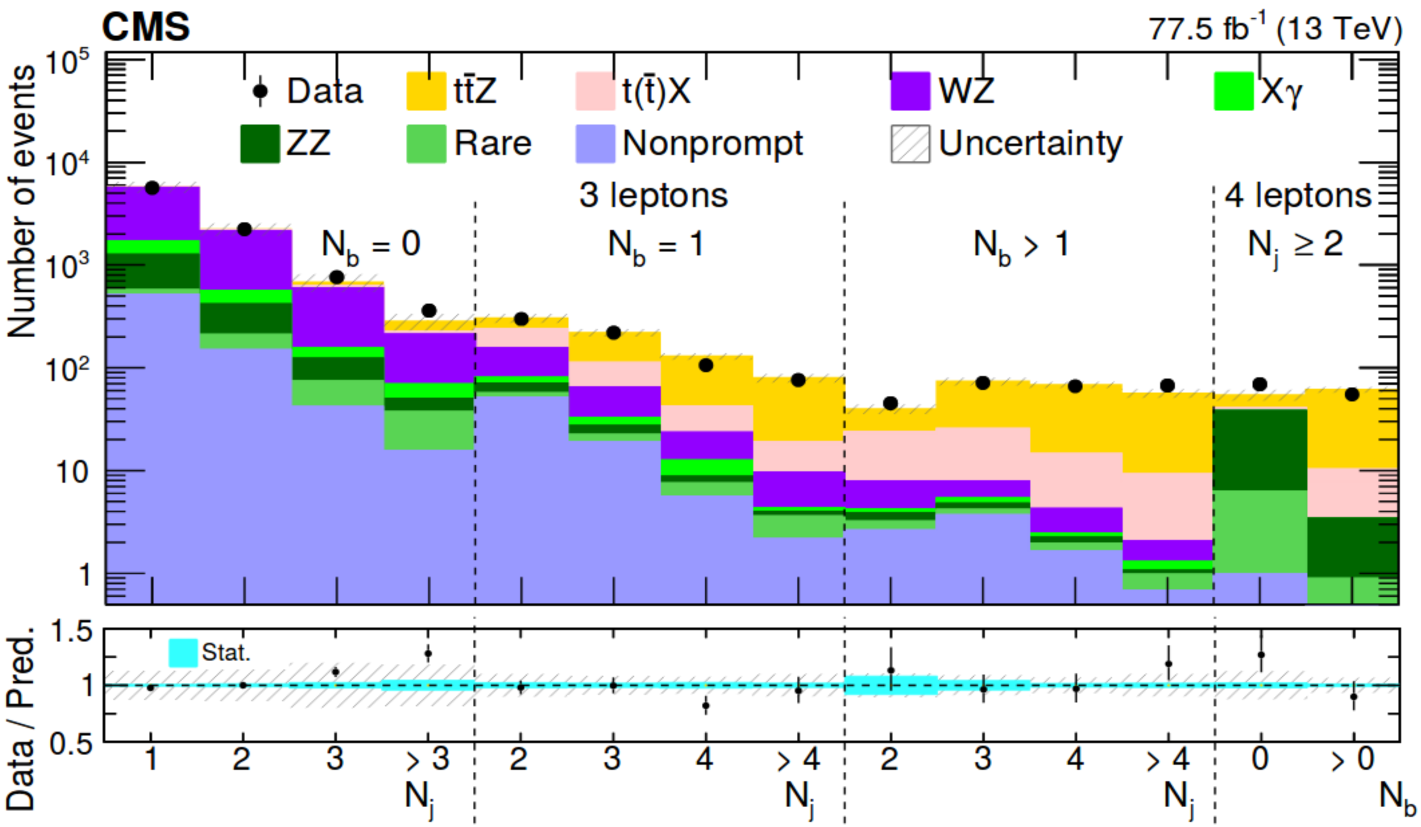
- Higgs:
  - first combined STXS results from CMS, CMS PAS HIG-19-005
  - ME analysis of HVV production and decay, PRD 99 (2019) 112003

- Top:
  - analysis of $t\bar{t}$ production in its spin space, PRD 100 (2019) 072002
  - differential studies of $t\bar{t}Z$ production, JHEP 03 (2020) 056



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





Measuring top-Z couplings

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

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

≡ 0 : assume SM Wtb vertex

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

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

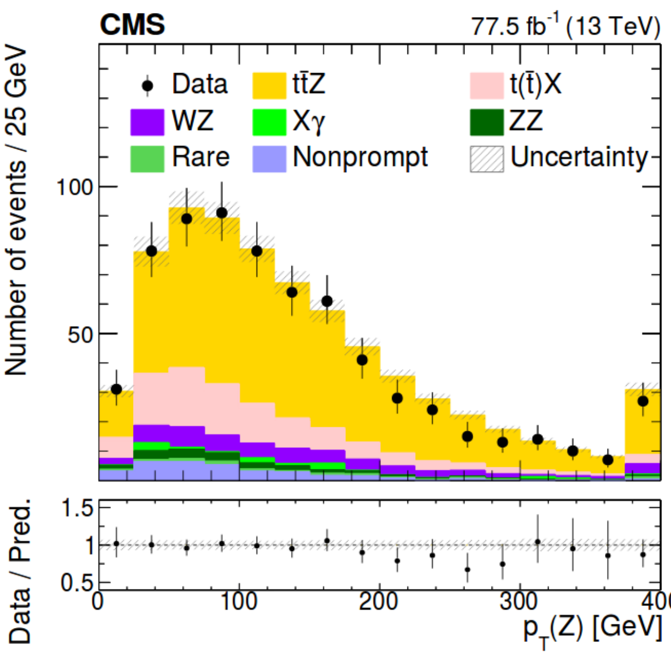
vector couplings (lin.): $C_{\Phi t}/C^{-}_{\Phi Q}$

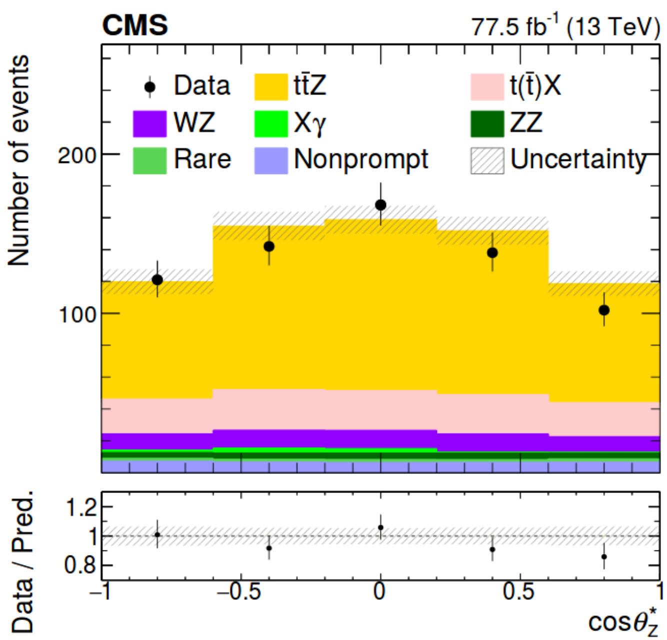
$$
\begin{aligned}
O_{\varphi u}^{(ij)} &= (\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar{u}_i \gamma^\mu u_j) \\
O_{\varphi q}^{1(ij)} &= (\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar{q}_i \gamma^\mu q_j) \\
O_{\varphi q}^{3(ij)} &= (\varphi^\dagger i\overleftrightarrow{D}_\mu^I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

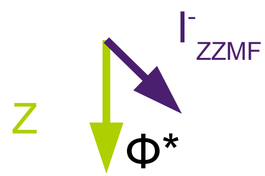
Measuring top-Z couplings

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

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







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

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

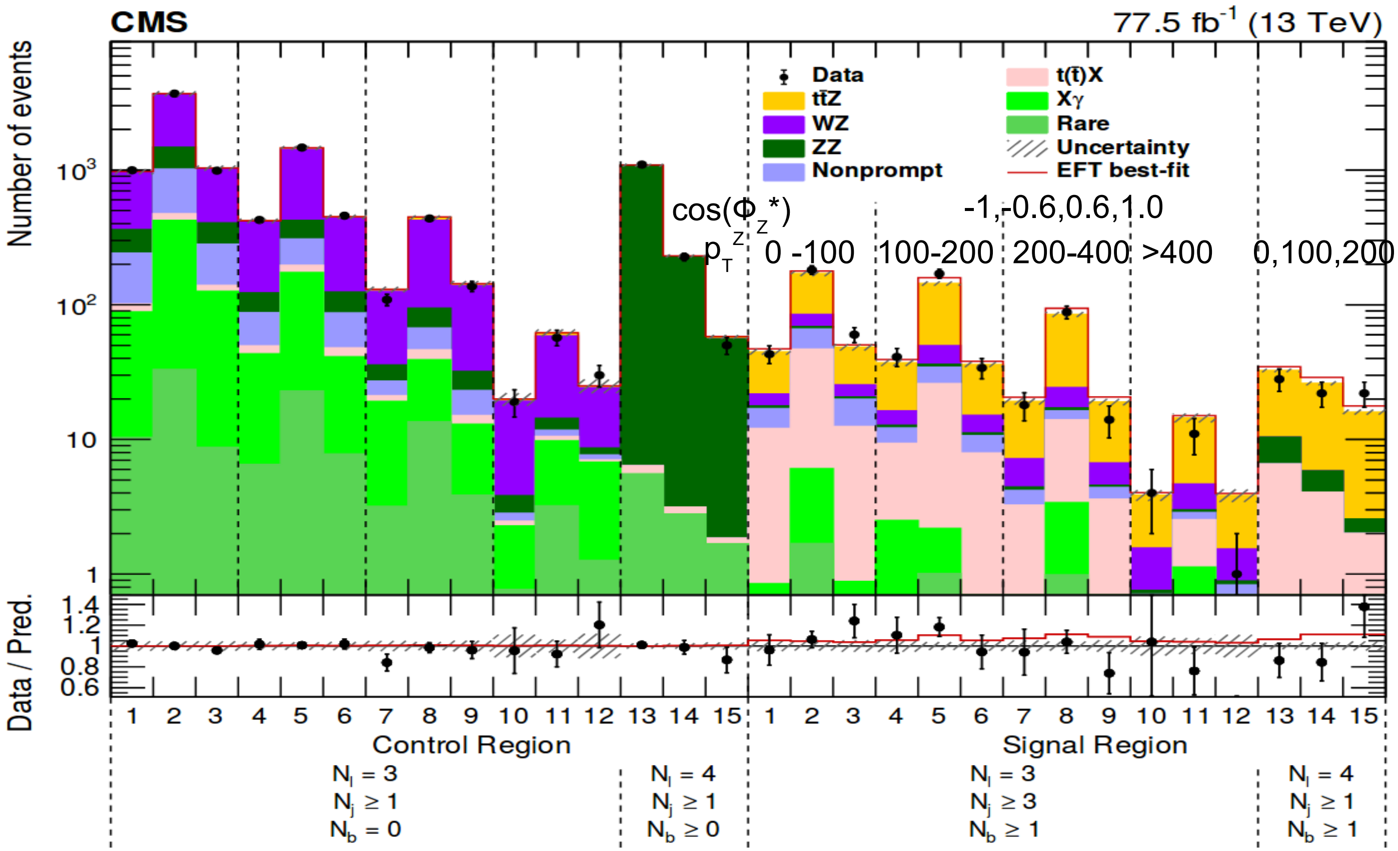
vector couplings (lin.): $C_{\phi t}/C_{\phi Q}^{-}$

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

Measuring top-Z couplings

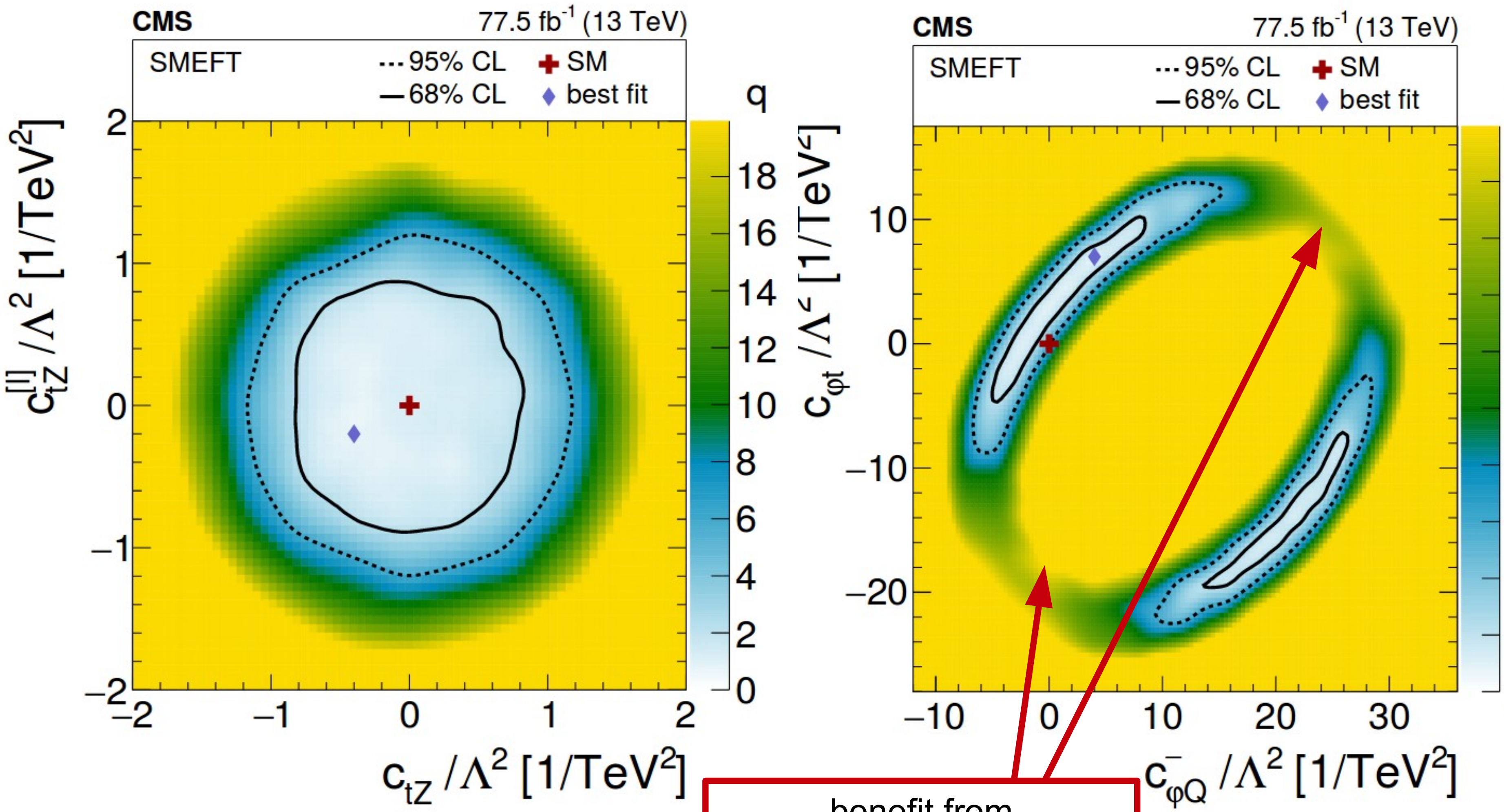
- electroweak-top interactions from $t\bar{t}Z$ production
- translate cross-section measurements into limits
- additional bins of p_T^Z and $\cos(\Phi_Z^*)$ for enhanced sensitivity

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



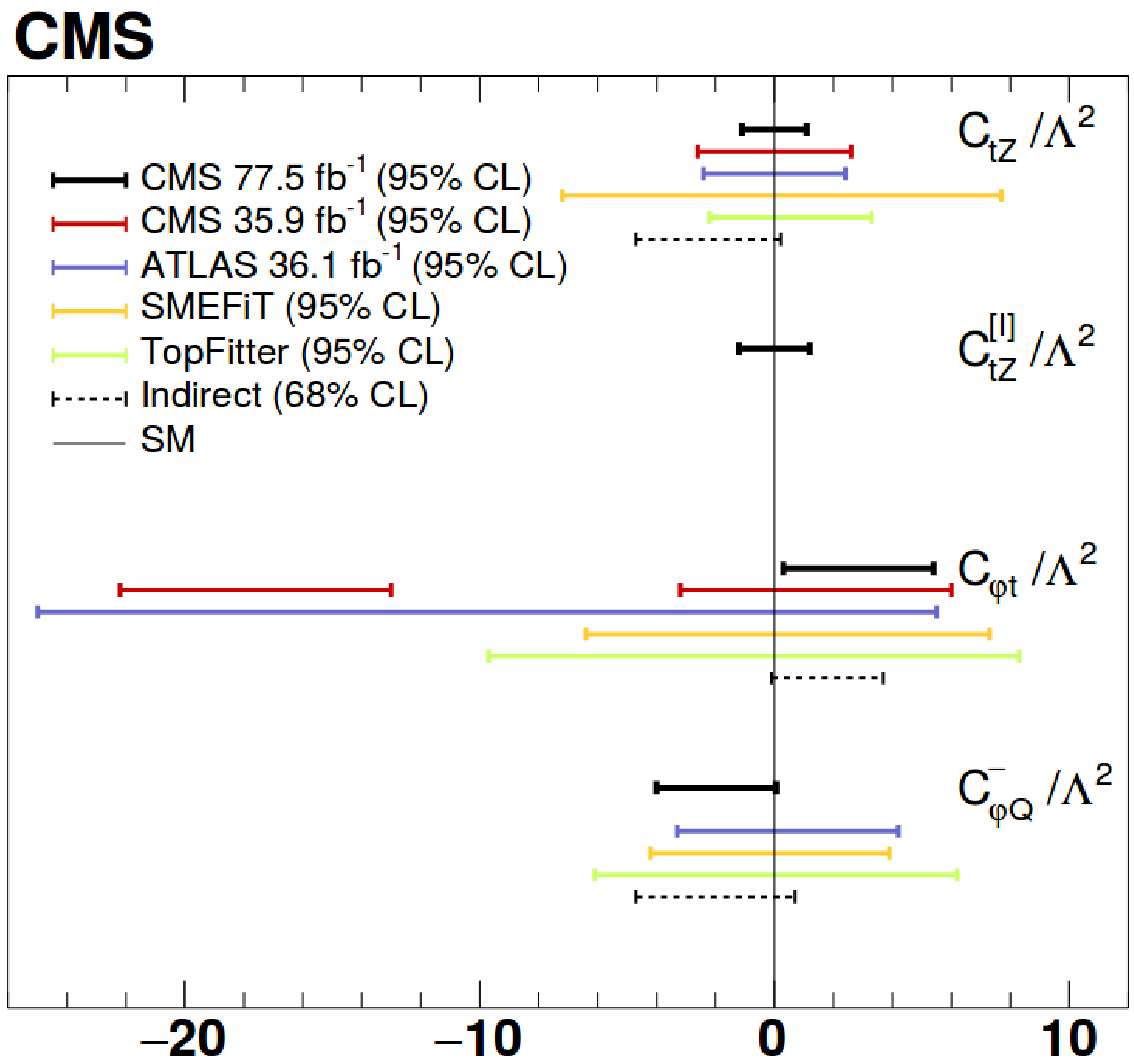
Limits on anomalous top-Z couplings

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



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

Limits on anomalous top-Z couplings



most stringent direct constraints on tZ couplings

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 initiatives for 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
- expect first global CMS results for HEFT 2021