EFT interpretation in top-quark sector at ATLAS

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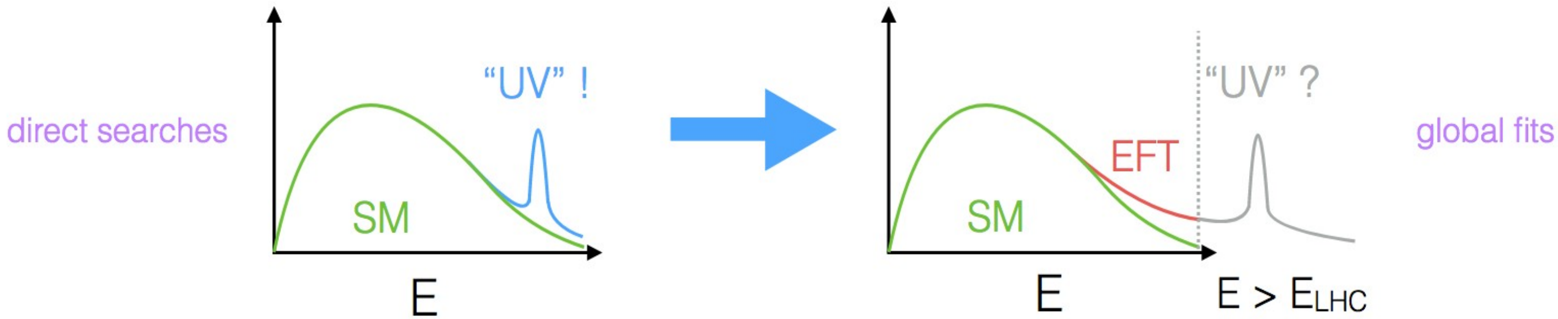
Why effective field theory (EFT) interpretations?

- At LHC, we haven't directly observed a physics beyond the Standard Model (BSM) yet
  → even if BSM is beyond the reach of LHC, it can reveal itself indirectly



- Top quark differs from other quarks/fermions mainly by it's large mass
  → if BSM reveals through EFT searches → high chance it will be in top processes
- The effect of BSM dynamics (characterized by energy scale Λ) can be parameterized at low energies E << Λ
  → effective field theory (EFT) model independent approach:

Wilson coefficients

$$\mathcal{L}_{\text{eff}} = \sum_i \frac{c_i \mathcal{O}_i^D}{\Lambda^{D-4}}$$

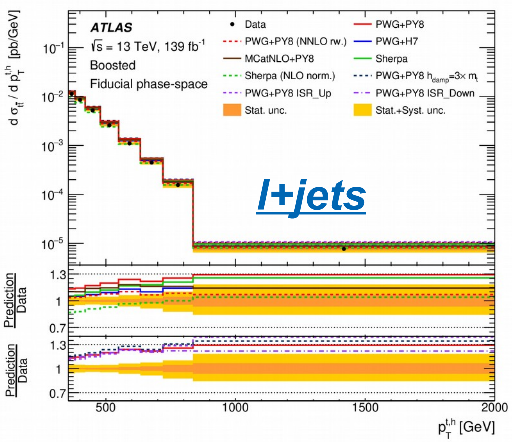
dim-D operators

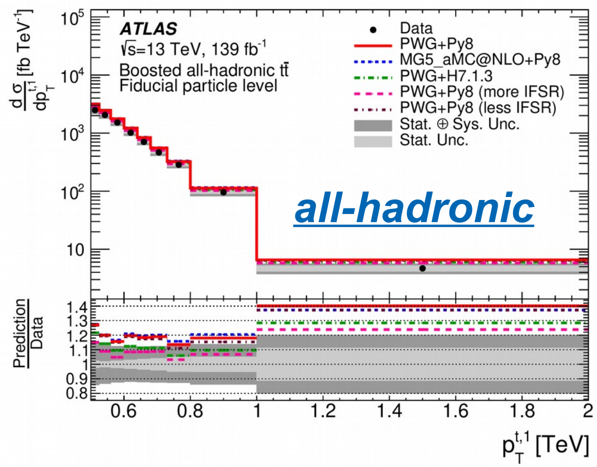
scale of dim-D interactions

O_i: higher-dimension operators build from SM fields and respecting SM symmetries

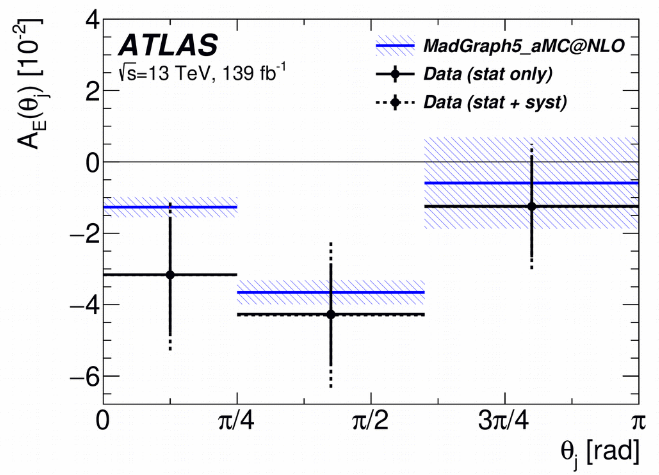
Top-quark analyses with EFT interpretation

Differential cross-sections:

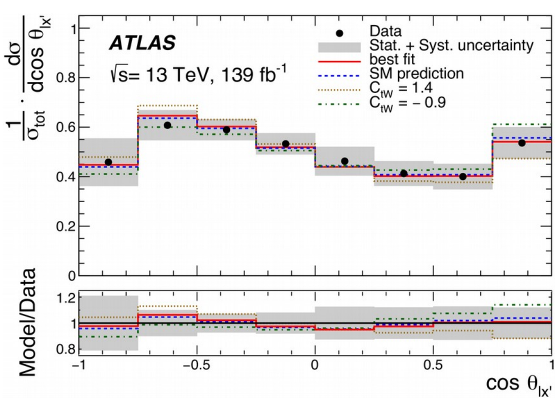




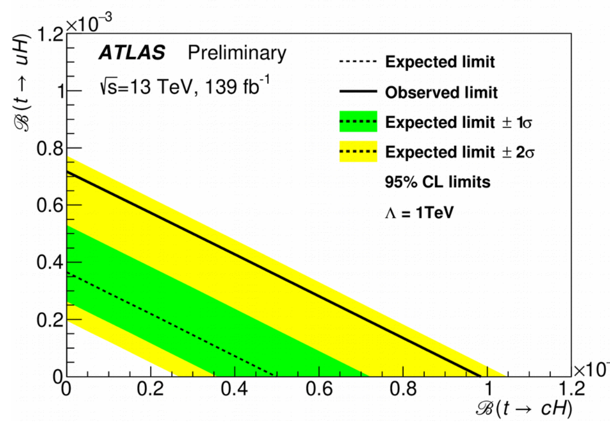
Charge / energy asymmetry:



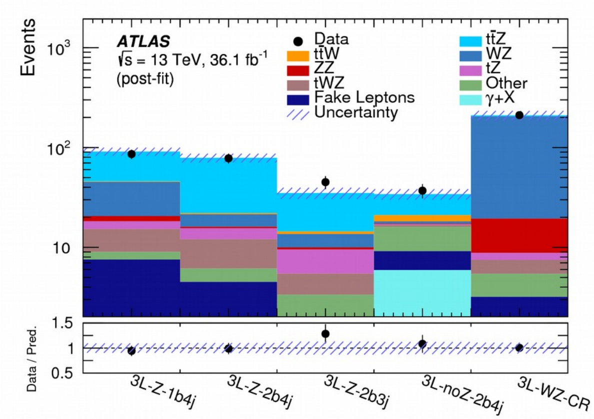
Top quark polarization



FCNC: tqH, tqγ, tqg, tqZ



tt + Z



Different measurements are sensitive to different EFT operators

EFT ingredients in ATLAS top-quark sector

$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \sum_i \frac{C_i}{\Lambda^2} O_i^{(6)} + \sum_j \frac{B_j}{\Lambda^4} O_j^{(8)} + \ldots$$

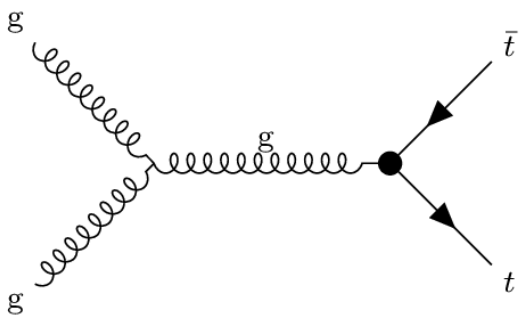
$$\begin{aligned}\sigma(C_i) &= \sigma_{\text{SM}} + \sigma_{\text{SM-EFT}} + \sigma_{\text{EFT-EFT}} \\ &= \sigma_{\text{SM}} + \frac{1}{\Lambda^2}\sum_i \alpha_i C_i + \frac{1}{\Lambda^4}\sum_i \beta_i C_i^2 + \frac{1}{\Lambda^4}\sum_{i,j,i<j} \tilde{\beta}_{ij} C_i C_j\end{aligned}$$

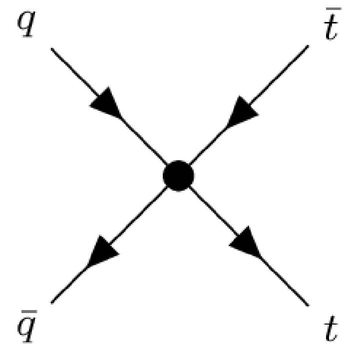
- We always consider only energy dimension six operators
  - compare results with linear-only ($1/\Lambda^2$) and linear+quadratic terms ($1/\Lambda^4$)
- EFT model:
  - MG5_aMC@NLO MC generator used to obtain parameters (α_i, β_i, β_{ij}) of the model
  - Warsaw basis used for the operators
  - different implementations of the SMEFT model are used: SMEFTatNLO, dim6top, TopFCNC
- We determine limits on Wilson coefficients (‘C_i’):
  - give a measure of strength of a given operator
  - 2499 coefficients for dimenstion six, 427 which affect top-quark in dim6top (various assumptions)
  - typically, only a few which affect a relevant vertex are measured in a given analysis

$t\bar{t}$ differential cross-sections

ATLAS-TOPQ-2018-11
ATLAS-TOPQ-2019-23

- Sensitive mainly to C_{tG} and 4-quark operators:



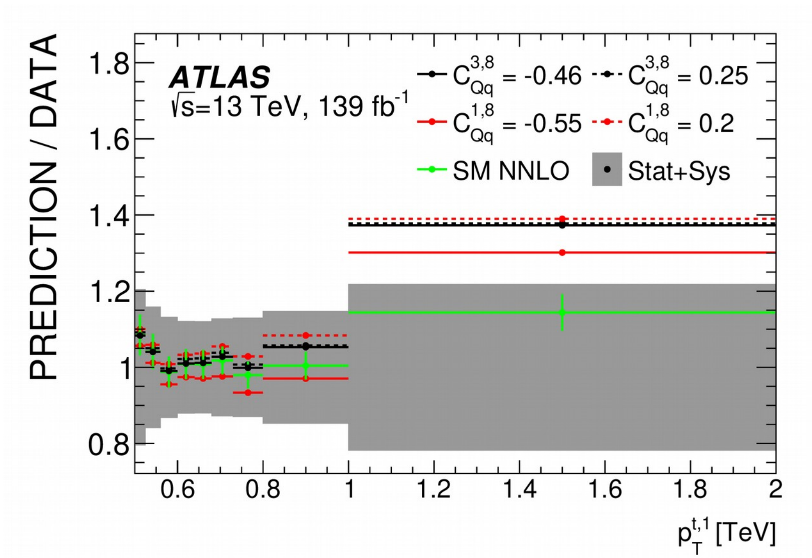


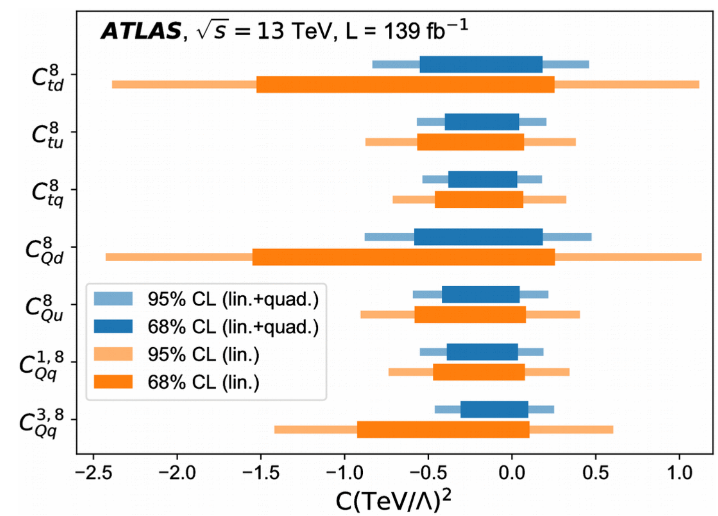
- Two measurements in boosted regime → better sensitivity at high p_T/m($t\bar{t}$)

	l+jets	all-hadronic
Observable	Hadronic top p_T (particle level)	Leading top p_T (parton level)
Uncertainty	Full covariance matrix (stat+syst)	Full covariance matrix (stat+syst)
LO EFT model	SMEFTatNLO	dim6top
SM prediction (σ_{SM})	NLO Powheg+Py8 reweighed to NNLO	NNLO fixed order (MATRIX)
Theory Uncertainty	NLO rew. to NNLO (scale, PDF, 6% incl.)	SM NNLO scale
Limits estimate	EFTfitter (arXiv:1605.05585)	EFTfitter

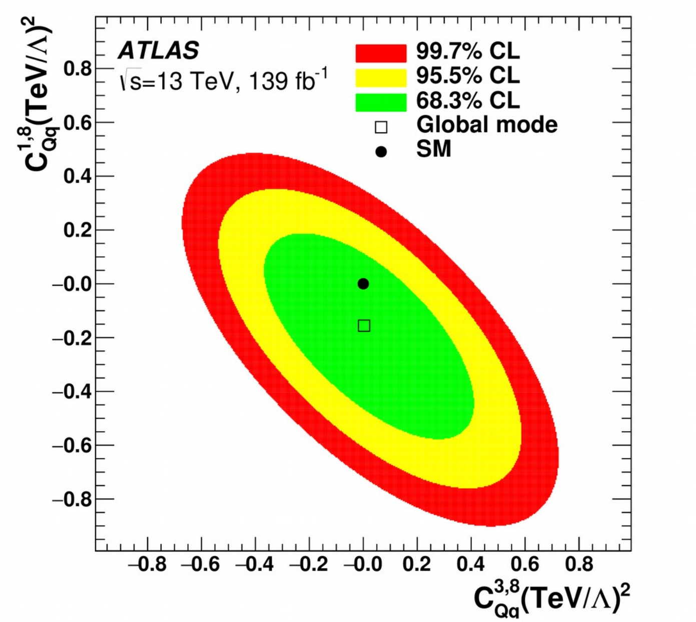
$t\bar{t}$ diff. cross-section in all-hadronic channel

ATLAS-TOPQ-2018-11



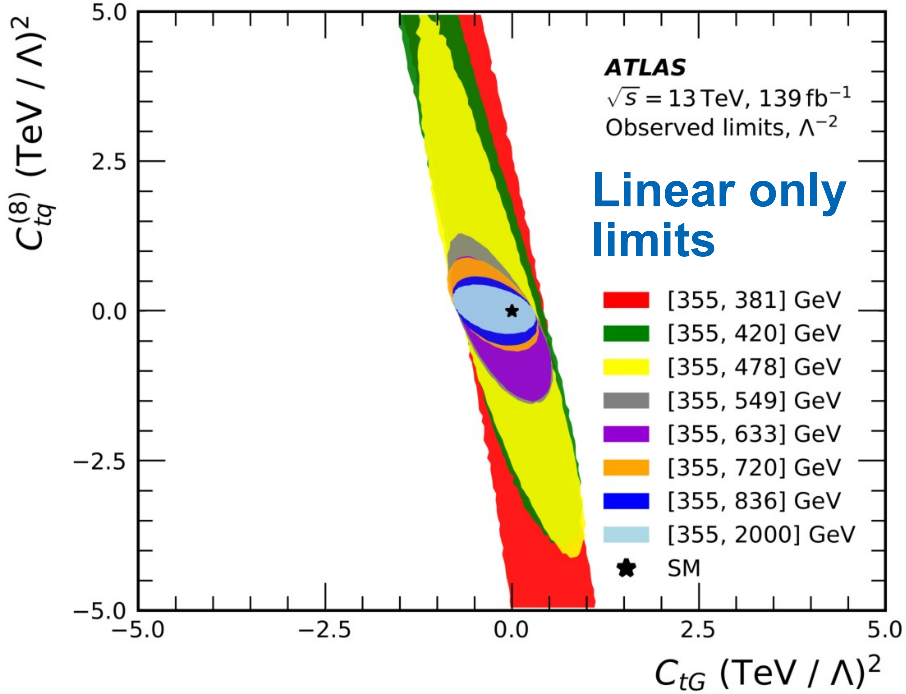


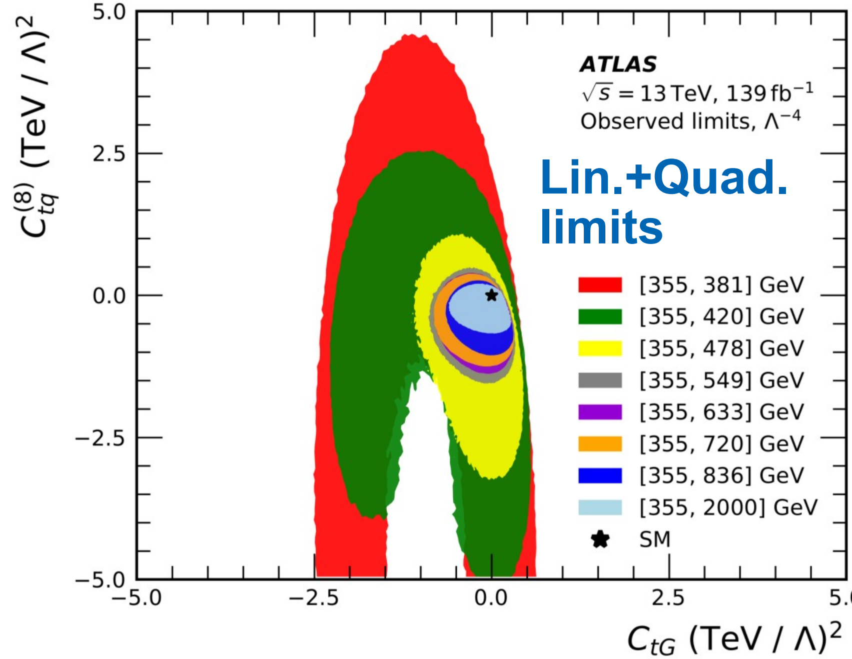
- EFT contribution affects mainly high-p_T bins
- Seven 4-quark operators constrained
  - explored all 4-quark and quark-boson C_i's
- Data a bit softer than NNLO prediction
  - limits shifted a little bit to negative values
- 3 examples of 2D limits performed



$t\bar{t}$ differential cross-section in l+jets

ATLAS-TOPQ-2019-23





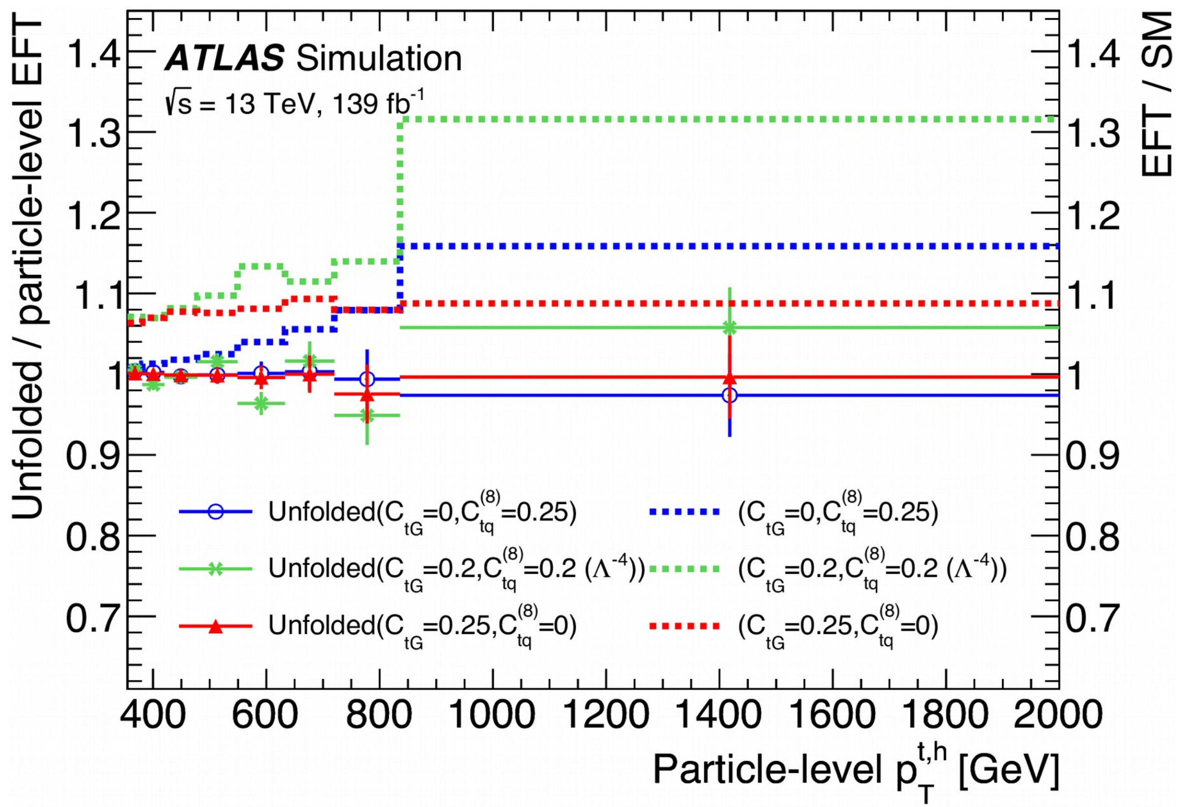
- high-p_T bins have the largest effect
- Quadratic terms important for 4-quark operator $C_{tq}^{(8)}$
- Both 1D (individual) and 2D (simultaneous) limits of two Wilson coefficients obtained:

Model	$C_i\ (\Lambda/\mathrm{TeV})^2$	Marginalised 95% intervals		Individual 95% intervals	
		Expected	Observed	Expected	Observed
Λ^{-4}	C_{tG}	[−0.44, 0.35]	[−0.53, 0.21]	[−0.44, 0.28]	[−0.52, 0.15]
	$C_{tq}^{(8)}$	[−0.57, 0.17]	[−0.60, 0.13]	[−0.57, 0.18]	[−0.64, 0.12]
Λ^{-2}	C_{tG}	[−0.44, 0.44]	[−0.68, 0.21]	[−0.41, 0.42]	[−0.63, 0.20]
	$C_{tq}^{(8)}$	[−0.35, 0.35]	[−0.30, 0.36]	[−0.35, 0.36]	[−0.34, 0.27]

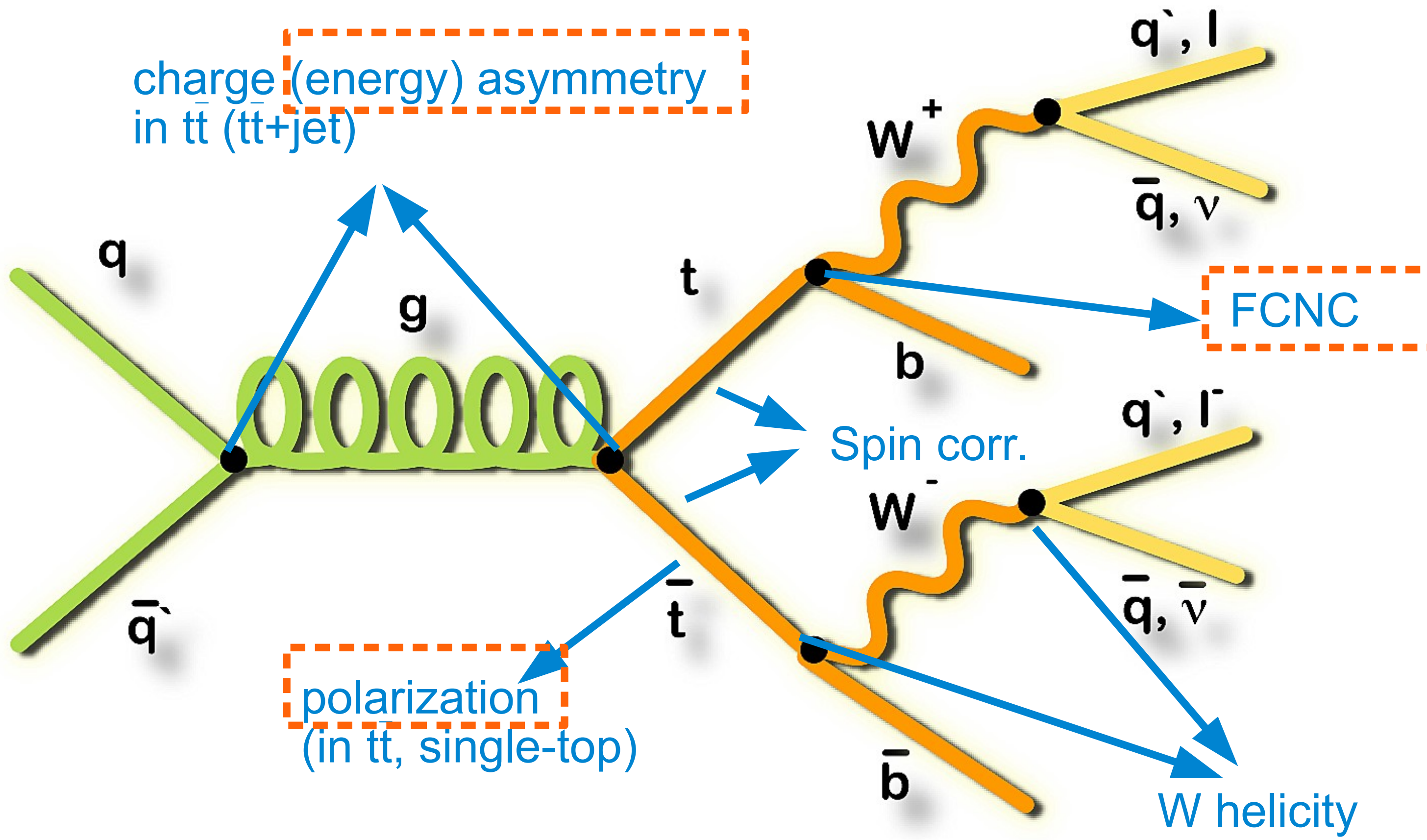
$t\bar{t}$ differential cross-sections

ATLAS-TOPQ-2019-23

- Robustness tests performed to show that:
  - the unfolding procedure is not affected by EFT contributions
  - the background dependence on EFT contributions have overall a small effect
- Performed in l+jets and all-hadronic analysis



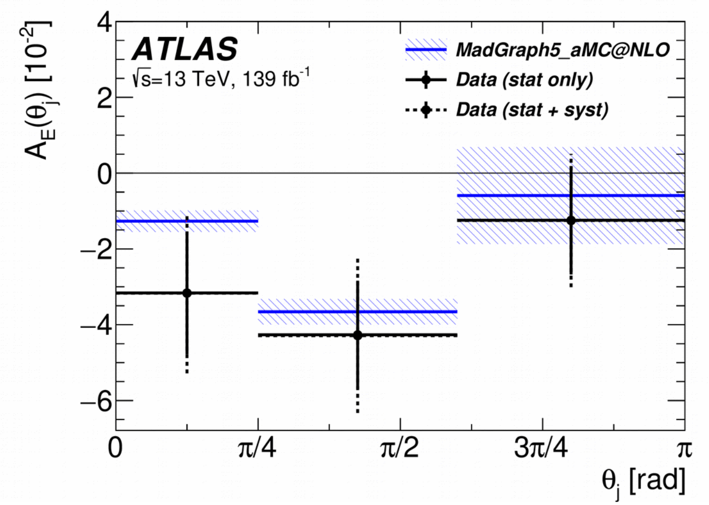
EFT interpretation with top-quark properties



sensitivity to various EFT operators highly depends on process, vertex, observable

Energy asymmetry in $t\bar{t}$+jet production

ATLAS-TOPQ-2019-28

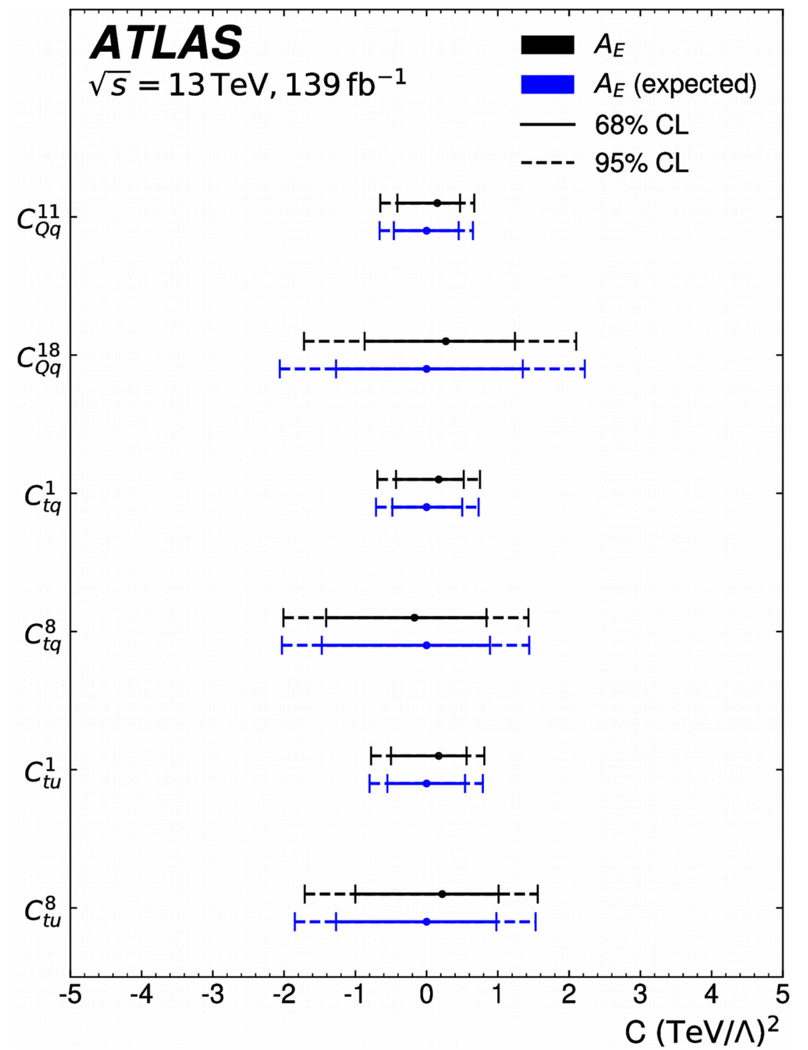


$$A_E(\theta_j) \equiv \frac{\sigma^{\rm opt}(\theta_j|\Delta E > 0) - \sigma^{\rm opt}(\theta_j|\Delta E < 0)}{\sigma^{\rm opt}(\theta_j|\Delta E > 0) + \sigma^{\rm opt}(\theta_j|\Delta E < 0)}$$

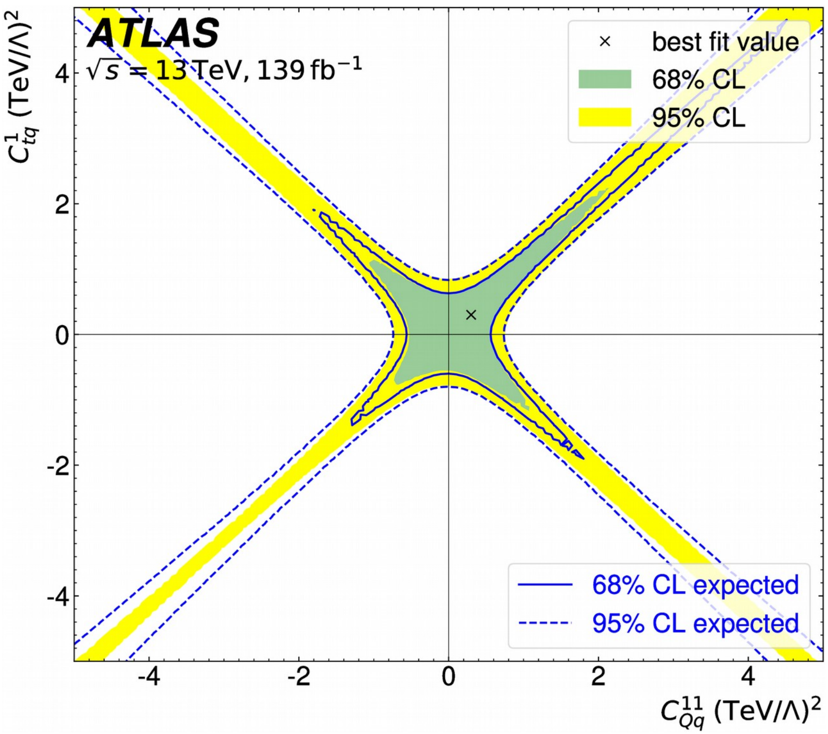
ΔE: difference between top and antitop energy

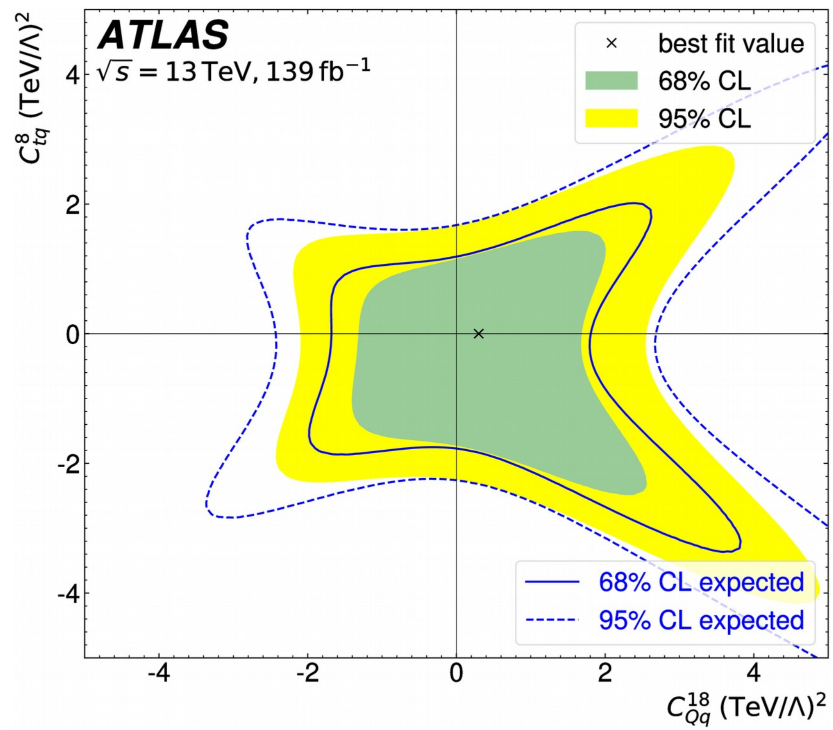
θ_j: jet angle w.r.t. initial parton direction in ttj rest frame

- Manifestation of charge asymmetry in qg → ttq
- Sensitive to chirality of top/antitop
- SMEFTatNLO @ LO
- Six 4-quark operators with different chiral/color structures measured



Energy asymmetry in $t\bar{t}$+jet (2)

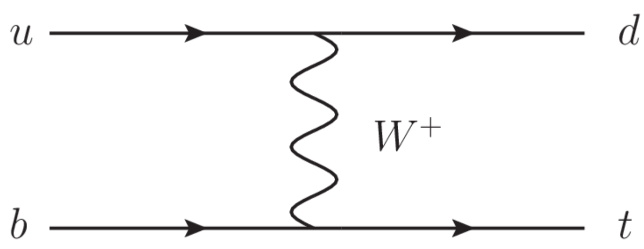


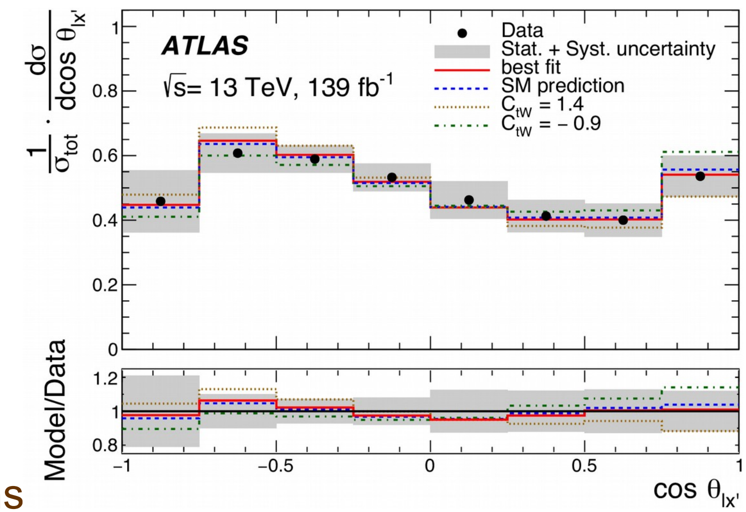


- Ability to resolve new directions in parameter space
  → combination with charge asymmetry would be useful

Top-quark polarization in single-top production

ATLAS-TOPQ-2018-10

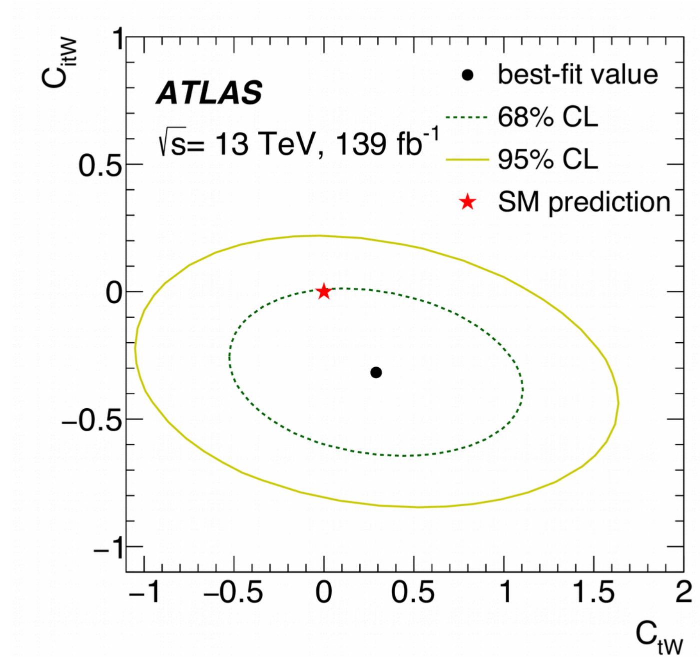




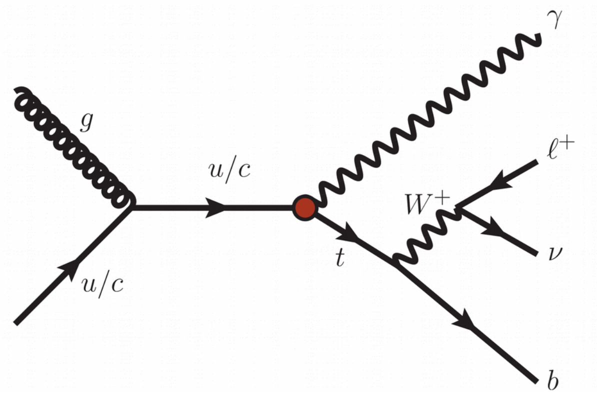
- Sensitive to operators affecting *Wtb* vertex
  - → bounds on complex coefficient of O_{tW}
- Measured lepton angles differential cross-sections
  - C_{tW} (C_{itW}) affects x-(y-) component
- SMEFT NLO model
  - EFT operators enter both production and decay
- 1D & 2D limits of both C_{tW} and C_{itW}
  - 1D results:

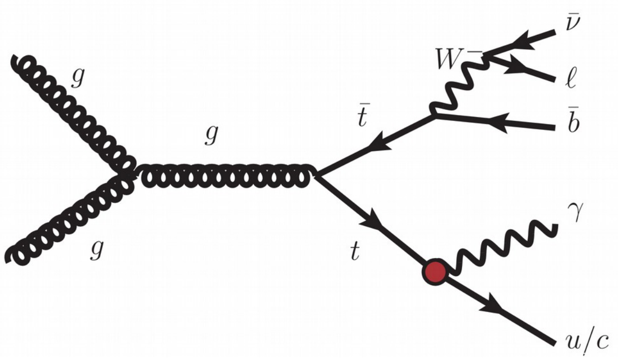
    C_{tW} = 0.1 ± 0.5

    C_{itW}= -0.3 ± 0.2



EFT interpretation with FCNC searches

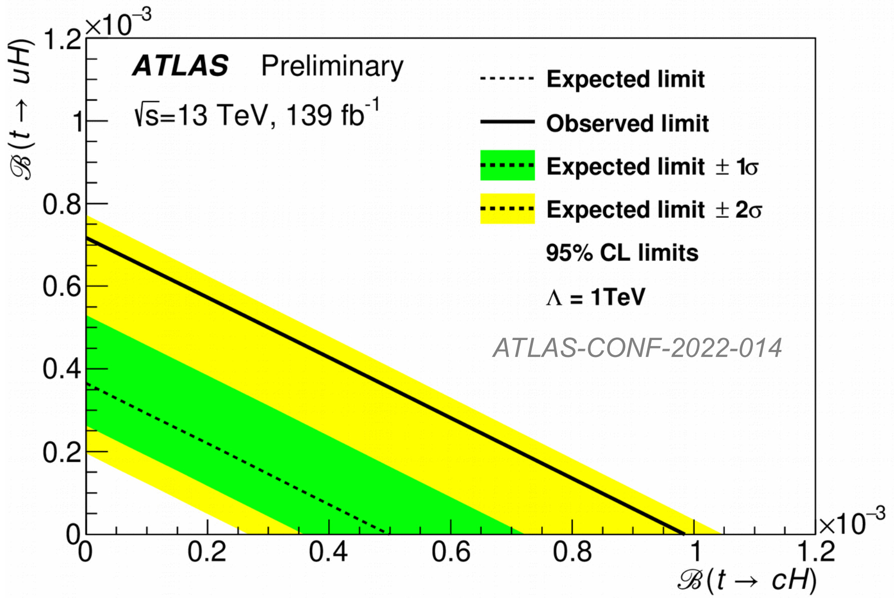




- Typically, FCNC in both production and decay of top-quark are considered
- EFT model ‘TopFCNC‘ @ NLO mostly used
- Multivariate discriminants used to set limits on cross-section

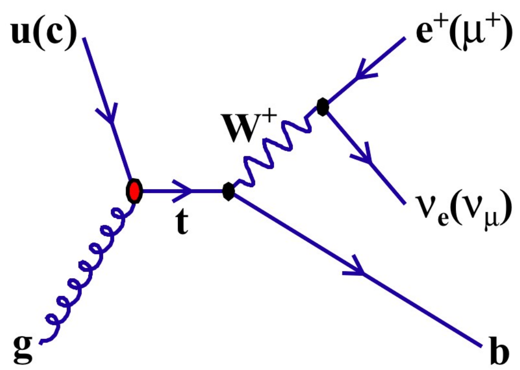
  → limits on Wilson Coefficients

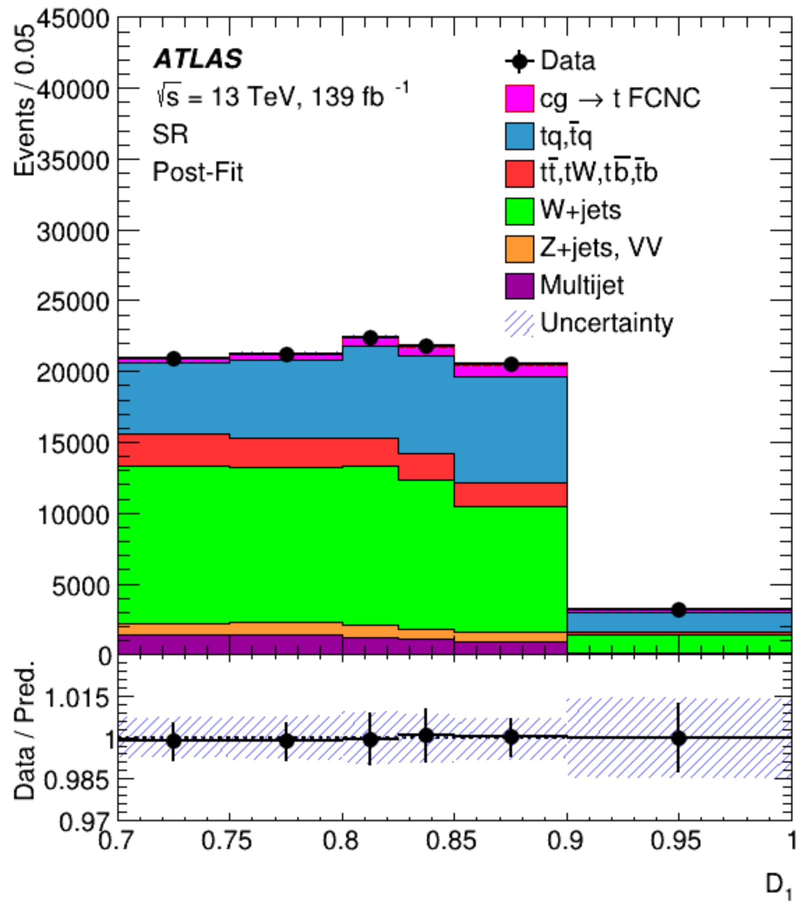
  → limits on branching ratios



FCNC: tqg vertex

ATLAS-TOPQ-2018-06





- Sensitivity to O^{ut}_{uG} and O^{ct}_{uG} operators
- FCNC cross-section dependence on EFT:
  - from MG5_aMC@NLO generator at NLO

$$\sigma(u+g\to t) = 2773\times\left(\frac{C^{ut}_{uG}}{\Lambda^2}\right)^2 \text{ pb TeV}^4$$

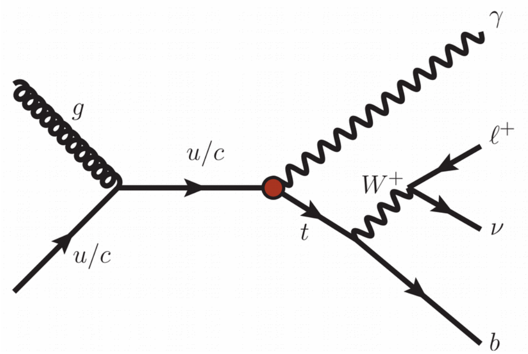
$$\sigma(c+g\to t) = 719\times\left(\frac{C^{ct}_{uG}}{\Lambda^2}\right)^2 \text{ pb TeV}^4.$$

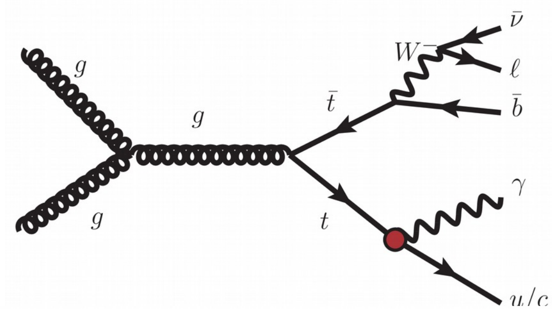
EFT 1D limits:

$$\frac{|C^{ut}_{uG}|}{\Lambda^2} < 0.057\text{ TeV}^{-2} \quad\text{and}\quad \frac{|C^{ct}_{uG}|}{\Lambda^2} < 0.14\text{ TeV}^{-2}$$

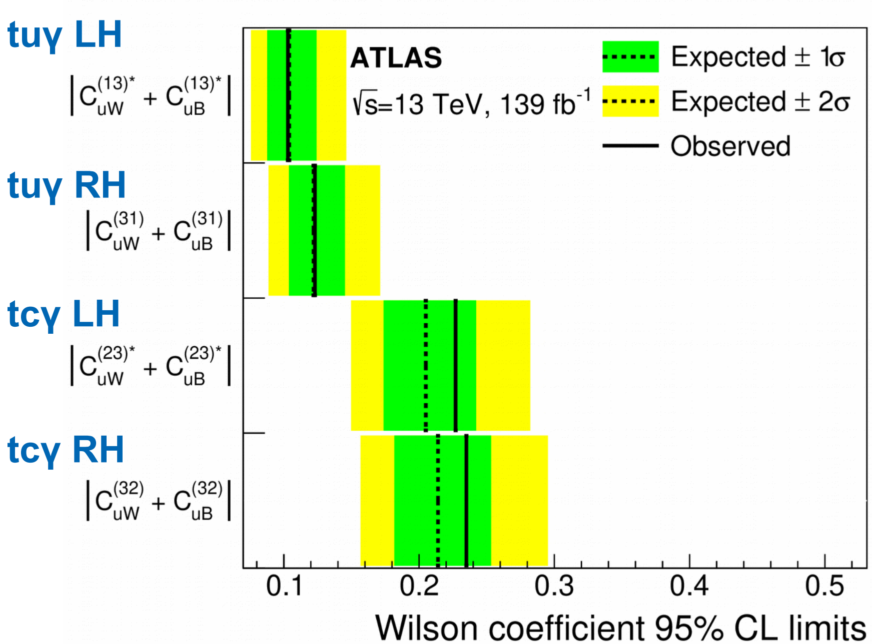
FCNC: tqγ vertex

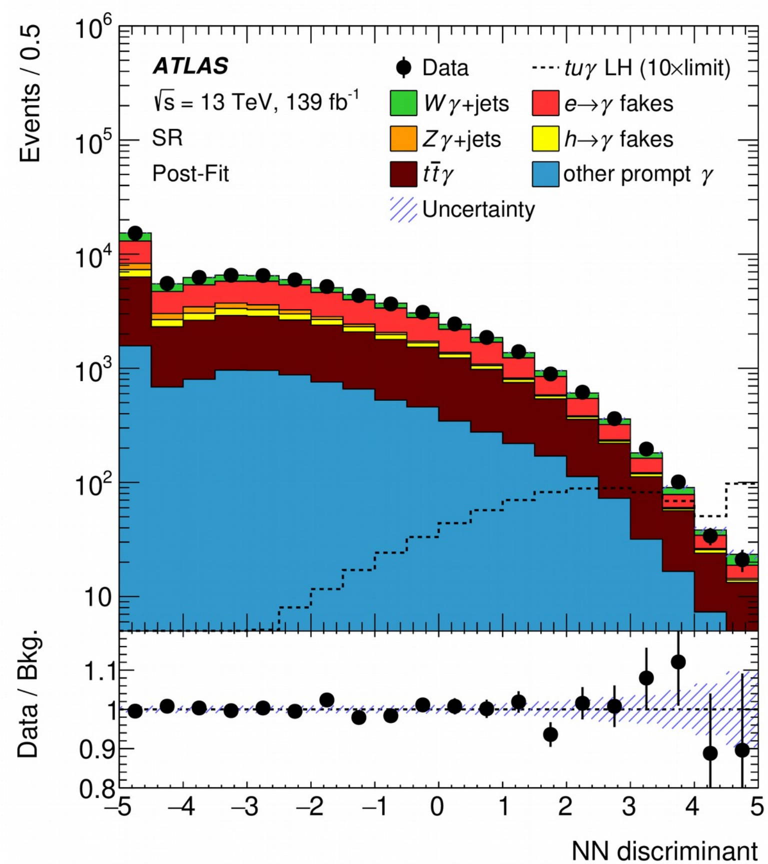
ATLAS-TOPQ-2019-19





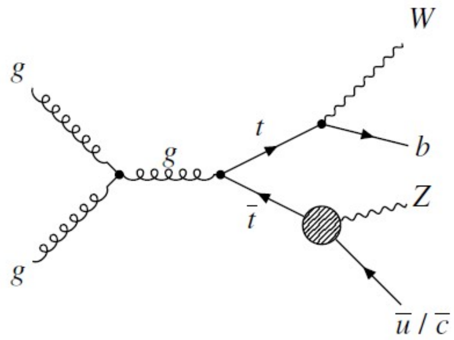
- Sensitivity to O_{uB} and O_{uW} operators
  - Different for LH and RH production
  - Different for ‘u’- and ‘c’-quarks

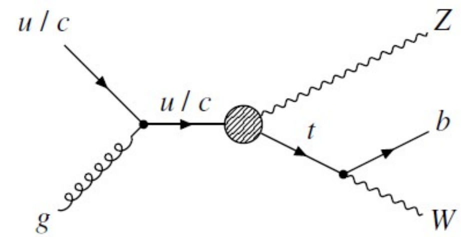




FCNC: tqZ vertex

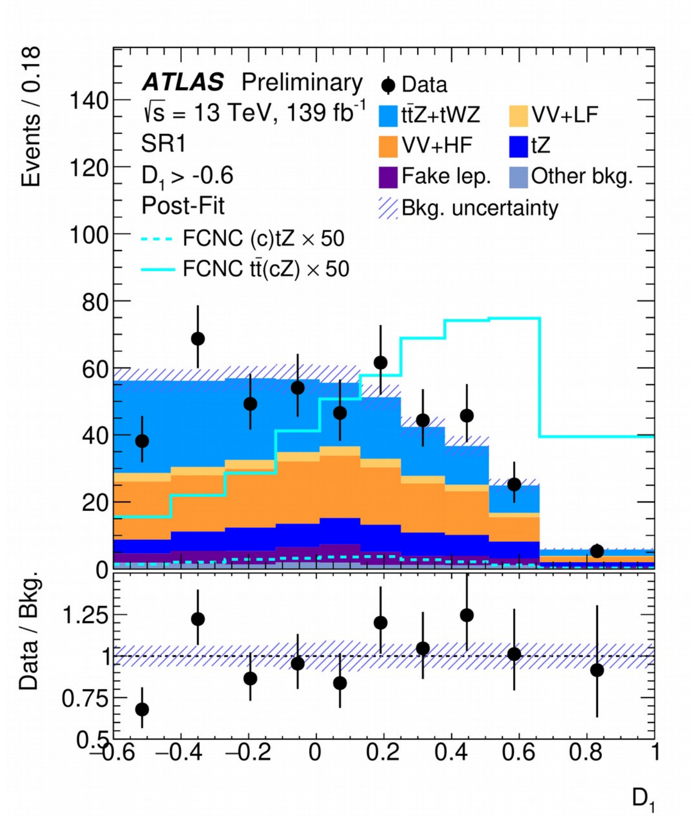
ATLAS-CONF-2021-049





- Sensitivity to O_{uB} and O_{uW} operators
  - Different for LH and RH production
  - Different for ‘u’- and ‘c’-quark

Observable	Vertex	Coupling	Observed	Expected
$\lvert C_{uW}^{(13)*}\rvert$ and $\lvert C_{uB}^{(13)*}\rvert$	tZu	LH	0.15	$0.13^{+0.03}_{-0.02}$
$\lvert C_{uW}^{(31)}\rvert$ and $\lvert C_{uB}^{(31)}\rvert$	tZu	RH	0.16	$0.14^{+0.03}_{-0.02}$
$\lvert C_{uW}^{(23)*}\rvert$ and $\lvert C_{uB}^{(23)*}\rvert$	tZc	LH	0.22	$0.20^{+0.04}_{-0.03}$
$\lvert C_{uW}^{(32)}\rvert$ and $\lvert C_{uB}^{(32)}\rvert$	tZc	RH	0.21	$0.19^{+0.04}_{-0.03}$



FCNC: tqH vertex

ATLAS-CONF-2022-014

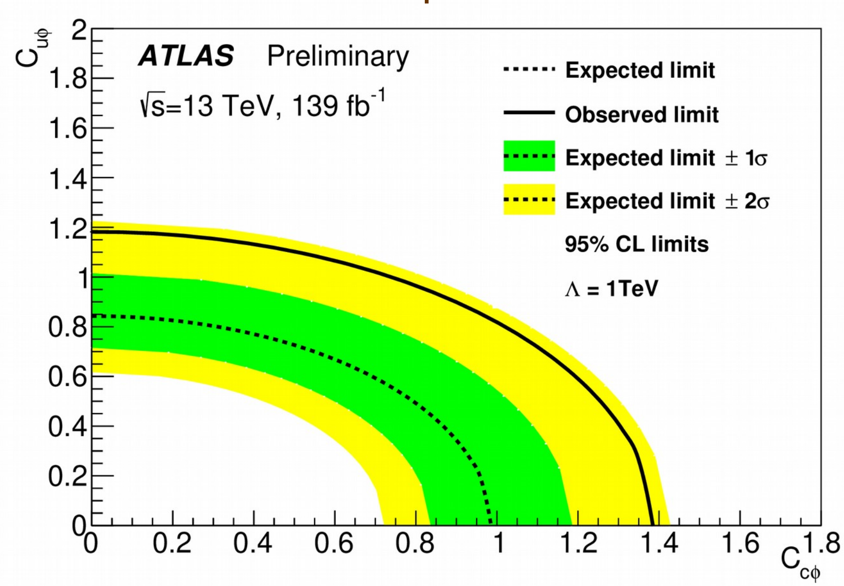
- Sensitivity to $C_{c\varphi}$ and $C_{u\varphi}$ coefficients
- Limits on BR(t → qH) translated to EFT limits:
  - BR(t → qH) = Γ(t→qH) / Γ(t→Wb) →

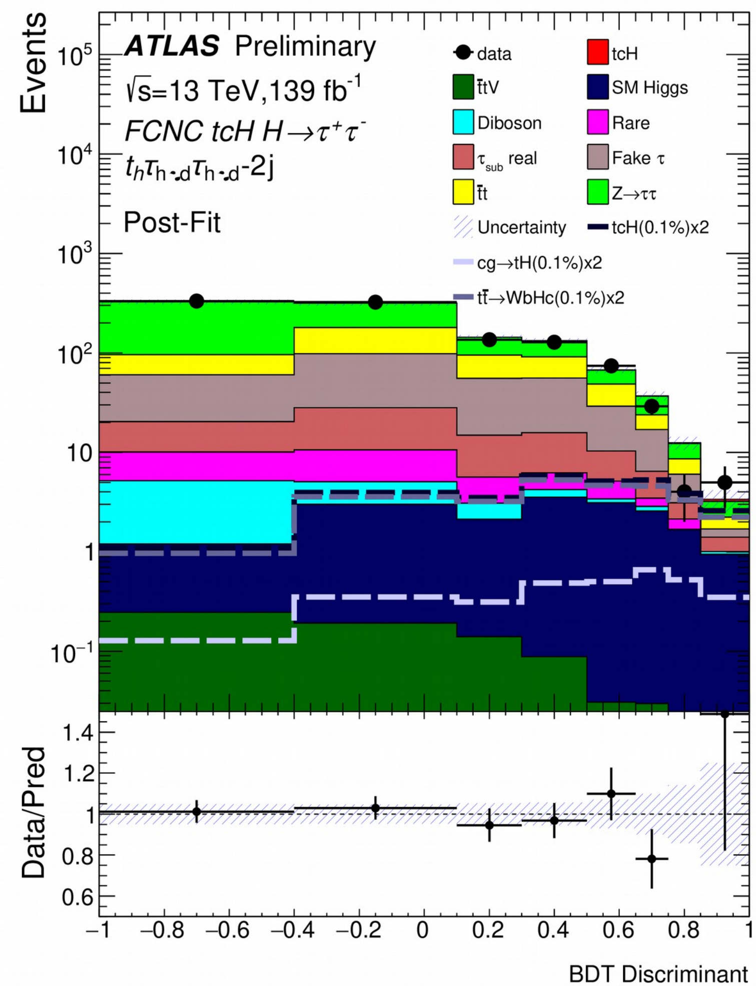
$$C_{q\phi} = \sqrt{1946.6\,\mathscr{B}(t \to qH)}$$

$$C_{q\phi} = \sqrt{(C^{i3}_{q\phi})^2 + (C^{3i}_{q\phi})^2}$$

- Combines LH (i3) and RH (3i) combinations
- i=1(2) for u- (c-) quark

Both 1D and 2D limits provided:





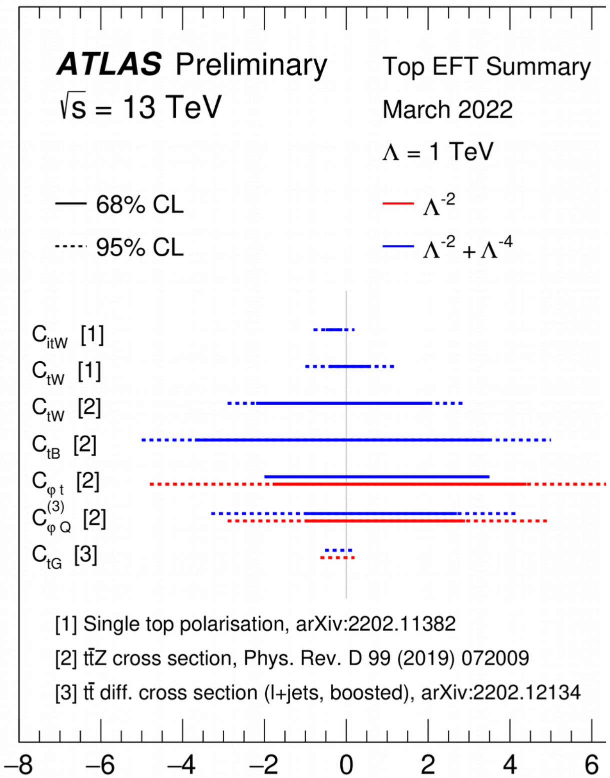
1D limits:

$$C_{c\phi} < 1.38 \quad C_{u\phi} < 1.18$$

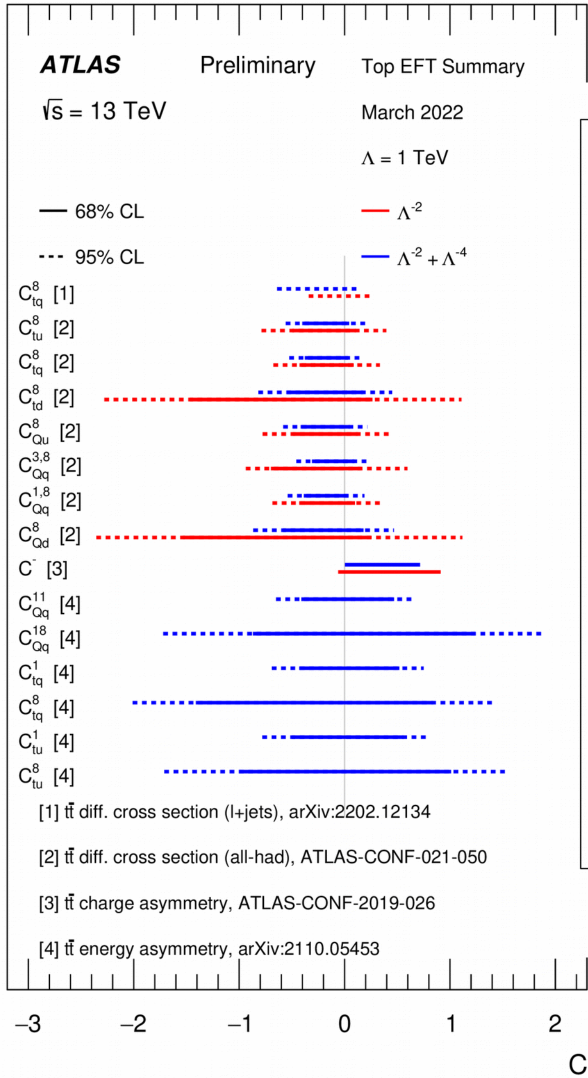
ATLAS EFT Summary

ATL-PHYS-PUB-2022-014

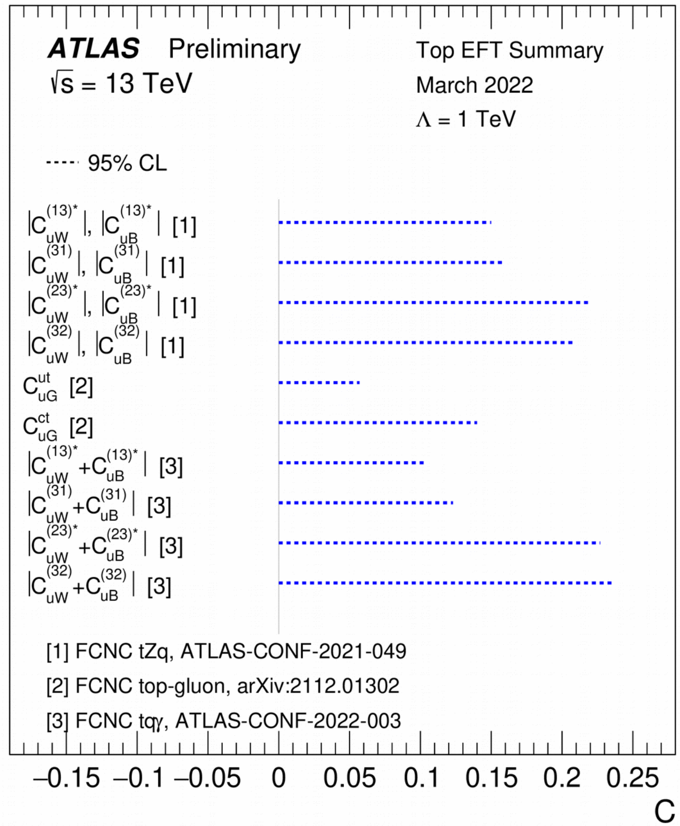
Top-boson coefficients



4-quark coefficients



FCNC coefficients



- Typically, limits are about the same or better than from existing global fits
- Papers which superseded CONF notes are already available:
  - ATLAS-CONF-2021-050 → ATLAS-TOPQ-2018-11, ATLAS-CONF-2022-003 → ATLAS-TOPQ-2019-19

Conclusions

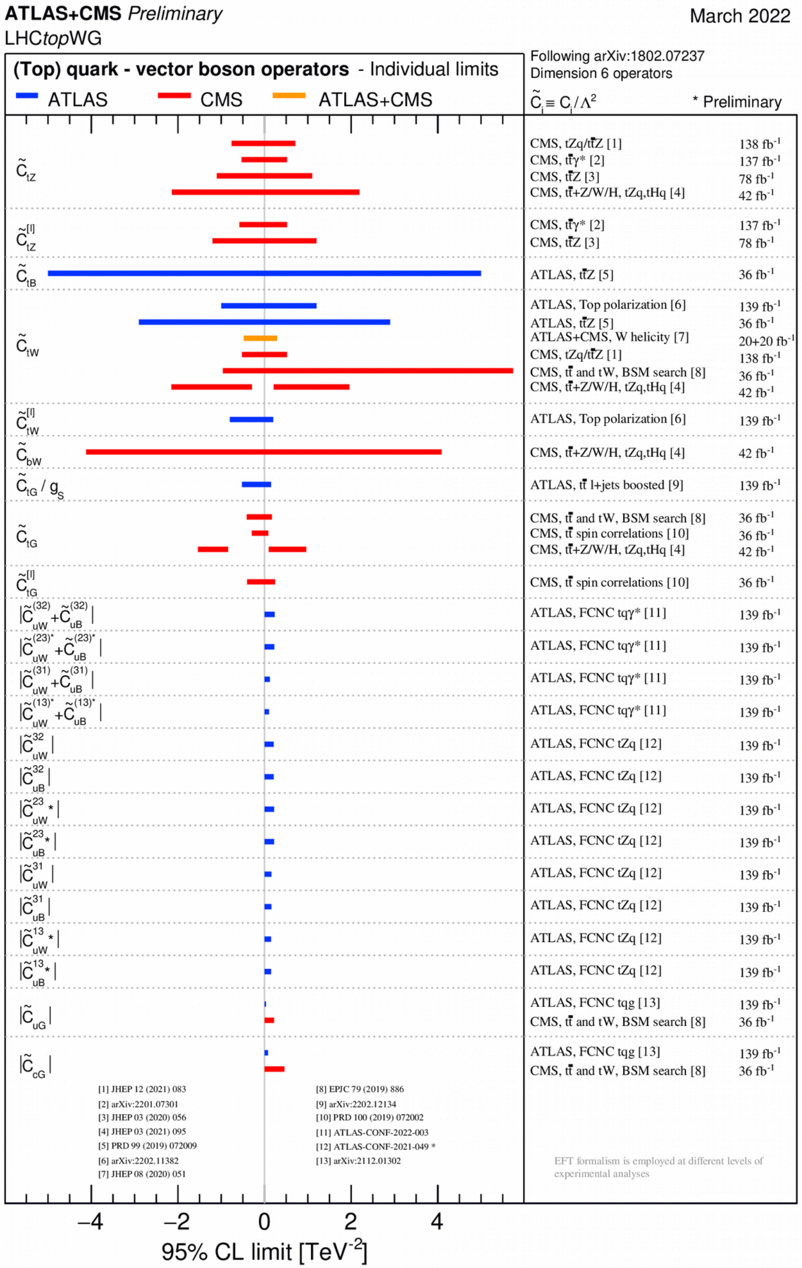
- Effective field theory interpretation a powerful tool to look for BSM physics
  - Becomes a standard in top-quark sector at ATLAS
  - Plan to harmonize various aspects of interpretation
- Different analyses constraining various single or pairs of Wilson coefficients
- Combining EFT interpretations in top-quark sector should be a future goal
  - Will allow simultaneous determination of Wilson coefficients (‘global fit’)
  - Will remove blind directions
  - Eventually, should do a global EFT ATLAS and LHC fit

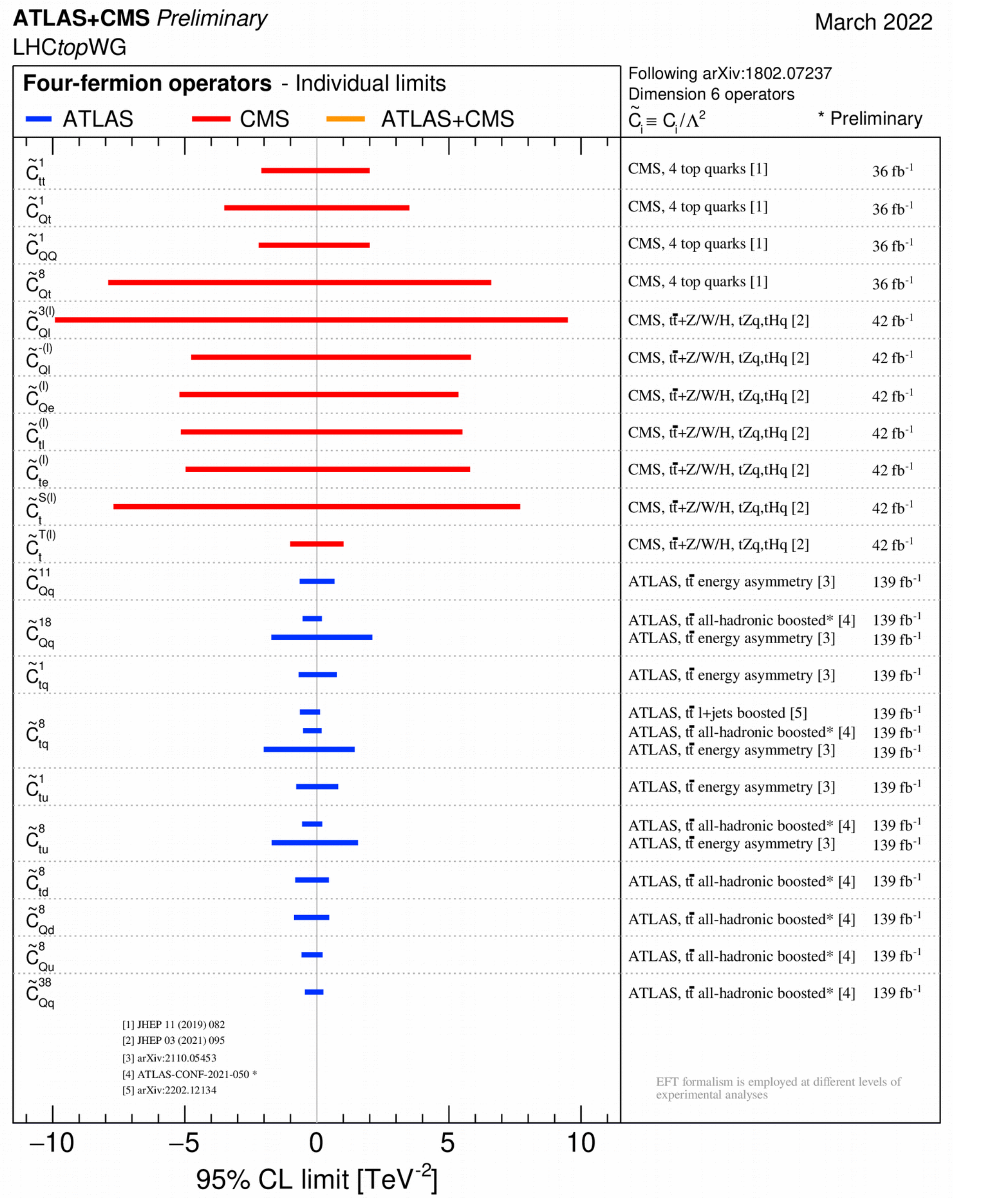
All results available on public web page:
https://twiki.cern.ch/twiki/bin/view/AtlasPublic/TopPublicResults

BACKUP

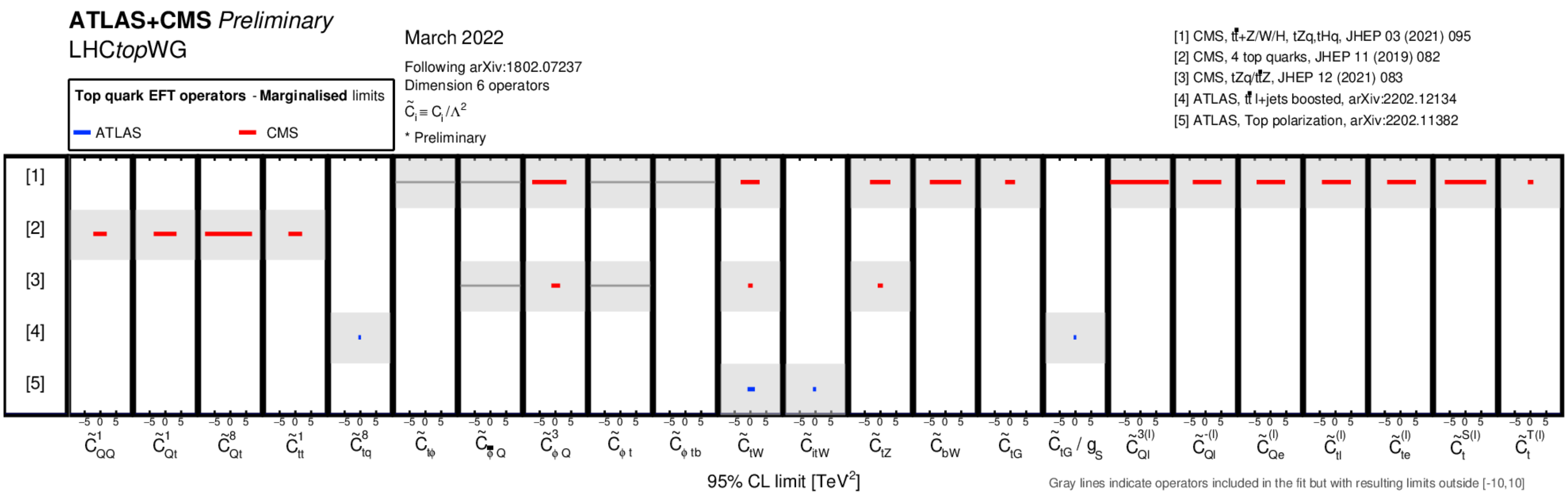
ATLAS+CMS EFT summary

ATL-PHYS-PUB-2022-014





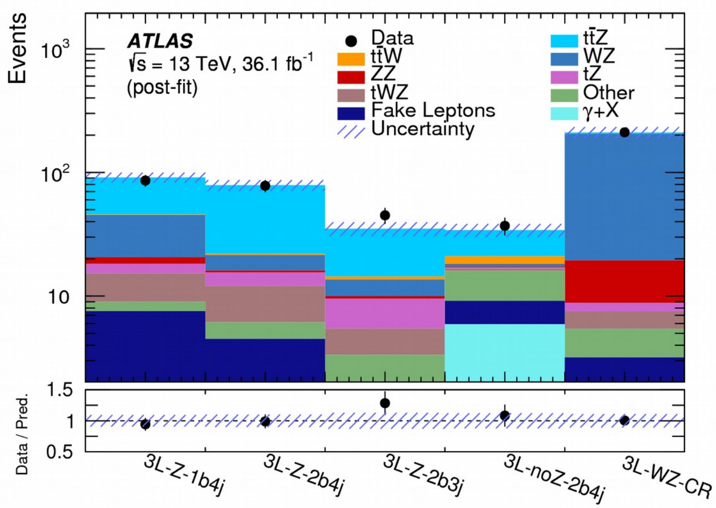
ATLAS+CMS EFT summary (2)

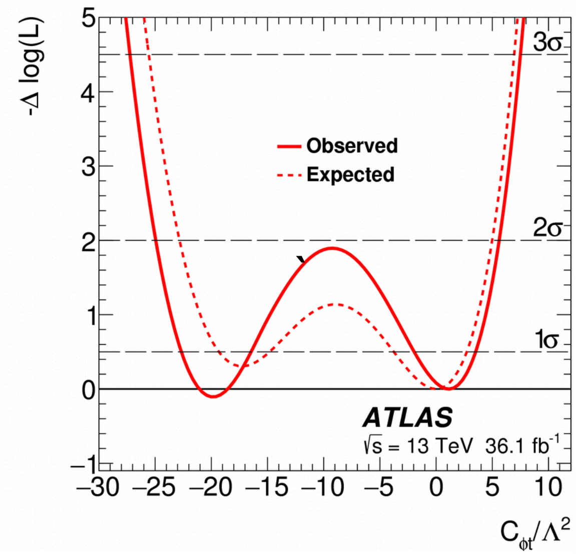


EFT limits from $t\bar{t}$+Z cross-section

ATLAS-TOPQ-2016-11

- Used cross-sections in 4 trilepton and 4 tetralepton signal regions targeting ttZ
- 5 C_i's considered which affect ttZ vertex (sensitive to $C_{\Phi Q}^{(3)}$-$C_{\Phi Q}^{(1)}$, assuming $C_{\Phi Q}^{(1)}$=0)
- EFT model at NLO, 1D limits only

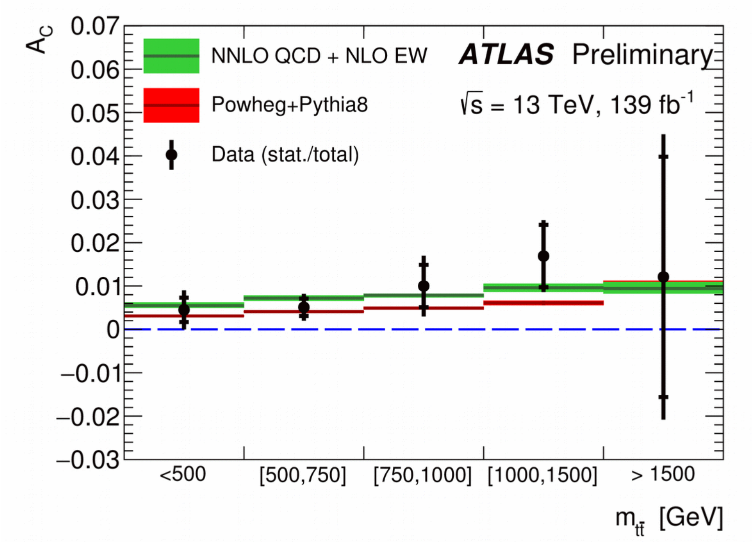




Coefficients	$\mathcal{C}_{\phi Q}^{(3)}/\Lambda^2$	$\mathcal{C}_{\phi t}/\Lambda^2$	$\mathcal{C}_{tB}/\Lambda^2$	$\mathcal{C}_{tW}/\Lambda^2$
Previous indirect constraints at 68% CL	[−4.7, 0.7]	[−0.1, 3.7]	[−0.5, 10]	[−1.6, 0.8]
Previous direct constraints at 95% CL	[−1.3, 1.3]	[−9.7, 8.3]	[−6.9, 4.6]	[−0.2, 0.7]
Expected limit at 68% CL	[−2.1, 1.9]	[−3.8, 2.7]	[−2.9, 3.0]	[−1.8, 1.9]
Expected limit at 95% CL	[−4.5, 3.6]	[−23, 4.9]	[−4.2, 4.3]	[−2.6, 2.6]
Observed limit at 68% CL	[−1.0, 2.7]	[−2.0, 3.5]	[−3.7, 3.5]	[−2.2, 2.1]
Observed limit at 95% CL	[−3.3, 4.2]	[−25, 5.5]	[−5.0, 5.0]	[−2.9, 2.9]
Expected limit at 68% CL (linear)	[−1.9, 2.0]	[−3.0, 3.2]	–	–
Expected limit at 95% CL (linear)	[−3.7, 4.0]	[−5.8, 6.3]	–	–
Observed limit at 68% CL (linear)	[−1.0, 2.9]	[−1.8, 4.4]	–	–
Observed limit at 95% CL (linear)	[−2.9, 4.9]	[−4.8, 7.5]	–	–

EFT limits from $t\bar{t}$ charge asymmetry

ATLAS-CONF-2019-026

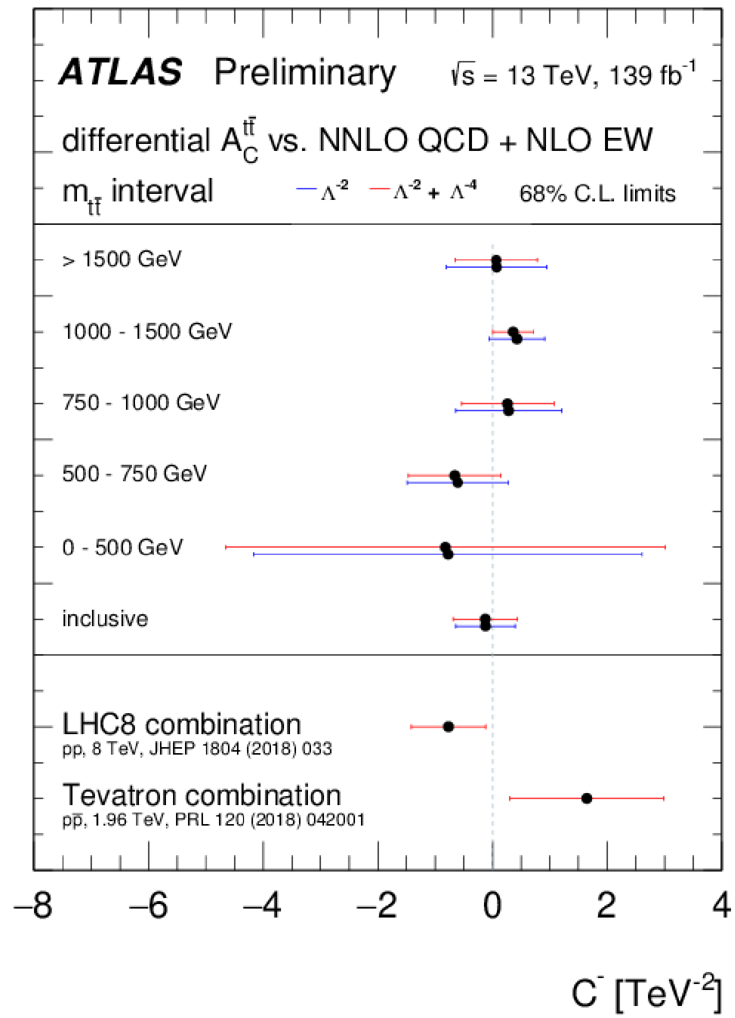


- sensitive to seven 4-fermion operators in Warsav basis
  - reduced to 4 operators by using a flavour-specific linear combination:

$$C_u^1 = C_{qq}^{(8,1)} + C_{qq}^{(8,3)} + C_{ut}^{(8)}$$
$$C_u^2 = C_{qu}^{(1)} + C_{qt}^{(1)}$$
$$C_d^1 = C_{qq}^{(8,1)} - C_{qq}^{(8,3)} + C_{dt}^{(8)}$$
$$C_d^2 = C_{qd}^{(1)} + C_{qt}^{(1)}$$

  - reduced further by assumption of equal couplings to up- and down-type quarks:

$$C_u^1 = C_d^1 = C^1 \qquad C_u^2 = C_d^2 = C^2$$

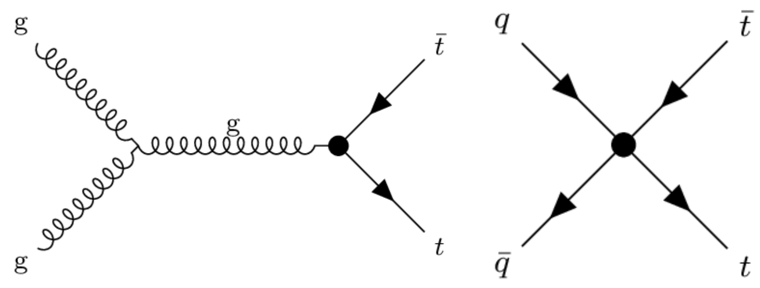


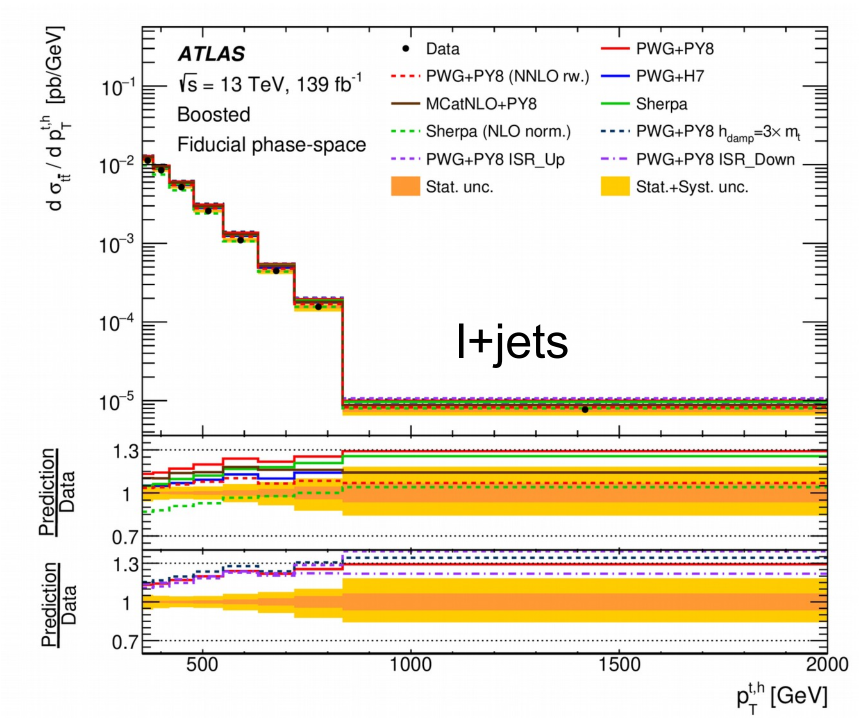
- charge asymmetry is affected by the difference: $C^- = C^1 - C^2$
- SM prediction used: NNLO QCD + NLO EW

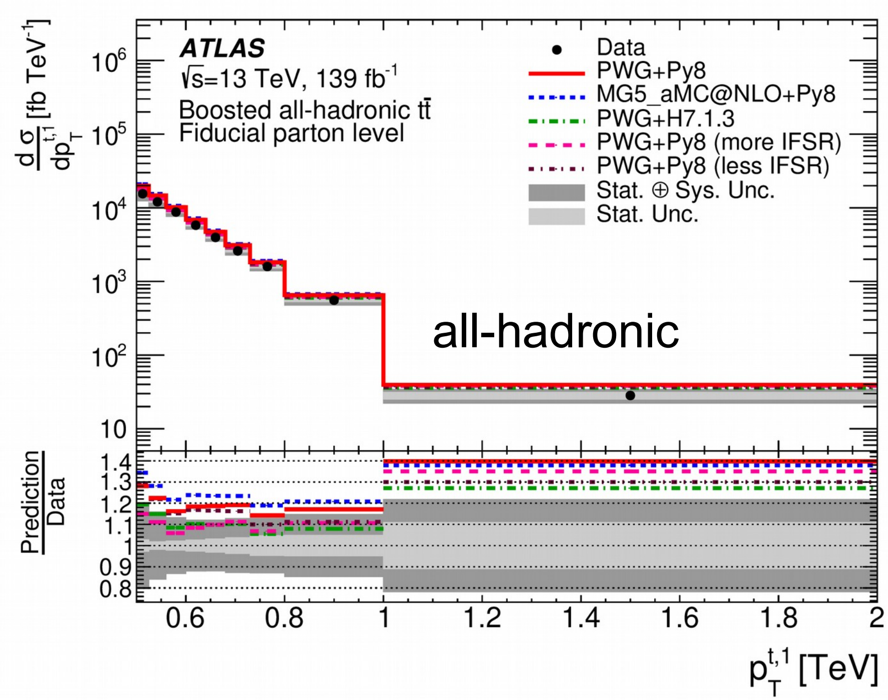
$t\bar{t}$ differential cross-sections

check performed in all-hadronic channel:

- Unfolding recovers truth distribution within 1% even when EFT effects included on both signal and background







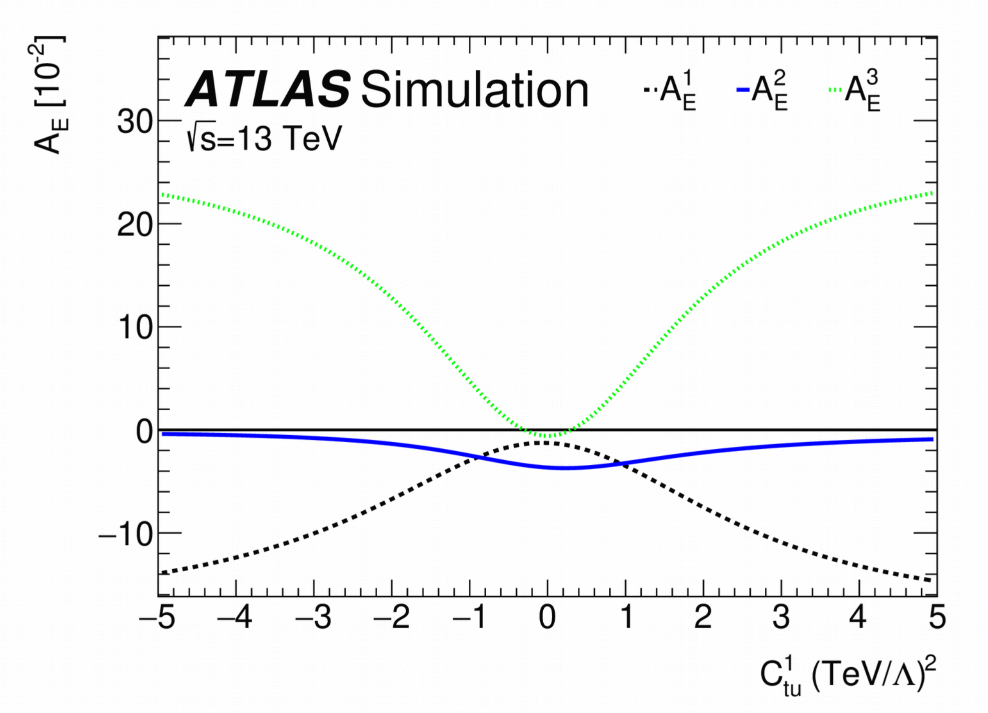
EFT from top-quark properties

	Top polarization	Energy asymmetry
Observable	Unfolded lepton angles (normalized)	Unfolded differential energy asymmetry as a function of jet angle
Uncertainty	Full covariance matrix	Full covariance matrix (stat+syst)
EFT model	SMEFT at NLO	SMEFTatNLO @ LO
SM prediction (σ_{SM})	NLO MG5+Py8	NLO SM (tt+j)
Theory Uncertainty	stat. uncert. of the parametrisation	SM NLO+ LO EFT scale uncertainties + MC sample size
Limits estimate	Likelihood	Chi2 fit

Sensitivity of energy asym. to EFT coefficients

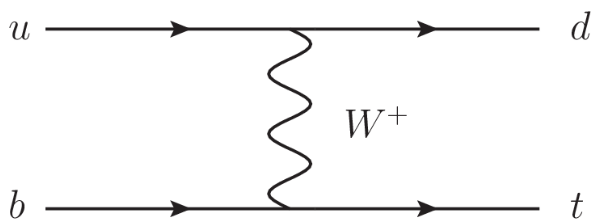
ATLAS-TOPQ-2019-28

- Both linear and linear+quadratic limits provided
  - Limits dominated by quadratic terms



Top-quark polarization in single-top production

ATLAS-TOPQ-2018-10



- Sensitive (affect Wtb vertex) to $O_{\varphi q}$, O_{qq}, O_{tW} at tree level
  - $O_{\varphi q}$ affects just a cross-section, no effect on shape
  - O_{qq}: negligible effect on angular distributions

    → placing limit only on O_{tW}
- Tests: unfolding recovers non-zero EFT coefficients, effects on background negligible
- Morphing technique used to interpolate MC EFT samples in order to describe angular distribution
- C_{itW}: non-zero value could be hint of non-SM CP violation in Wtb vertex

Top quark FCNC summary plot