

Searching for new physics in the Higgs, Top and Electroweak sectors in EFT frameworks

ALPS 2018, Obergurgl

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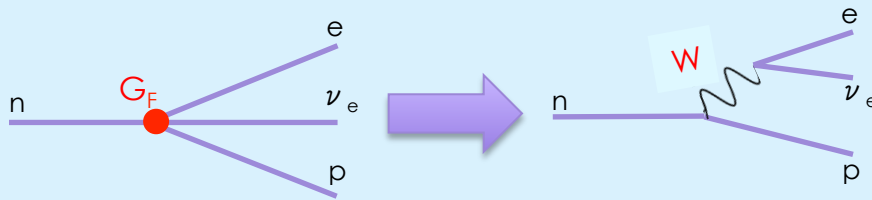
this talk

- **why EFT?**
 - the basic idea
 - general theoretical and experimental considerations
- **the status of efforts to constrain new physics in EFT**
 - a selection of **Higgs, Top and Electroweak** experimental results
 - focusing on 13 TeV measurements including EFT interpretation
- **outlook**

the search for new physics

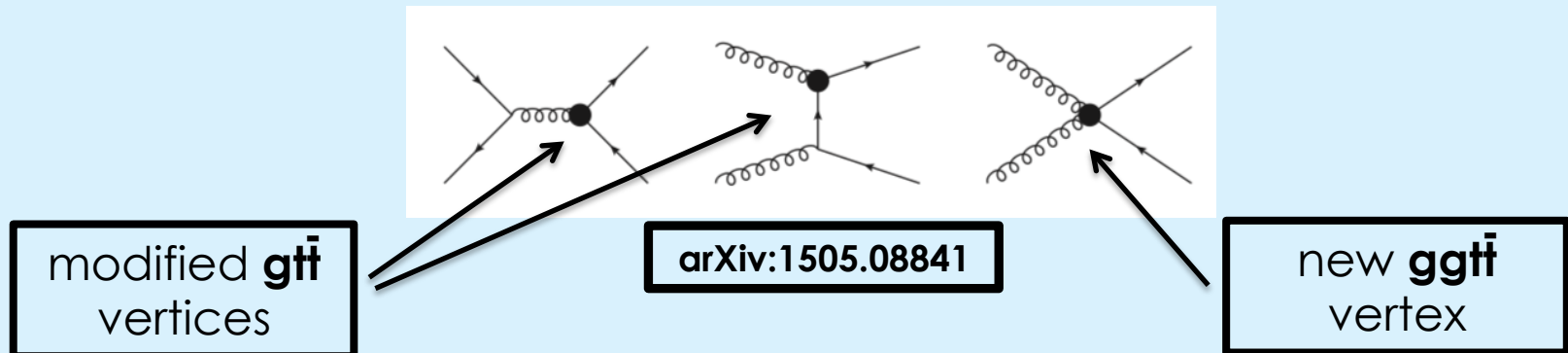
- no new BSM light particles observed at the LHC so far...
- **why?** is the NP scale (Λ_{NP}) far larger than the LHC scale?
- extend the SM Lagrangian with higher-order operators to model NP @ Λ_{NP}

famous example of Fermi theory of Beta decay



$$\mathcal{L}_{SM}^{(6)} = \mathcal{L}_{SM}^{(4)} + \sum_i \frac{c_i}{\Lambda^2} \mathcal{O}_i + \dots$$

LHC example - \mathcal{O}_{tG} affecting rate and kinematics of tt production

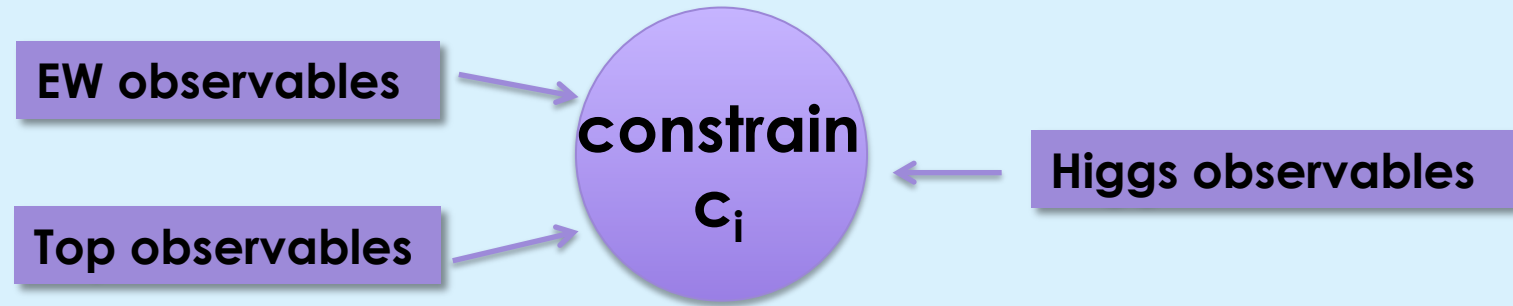


searching for new particles \rightarrow searching for new interactions

bump-hunting \rightarrow determining c_i

why EFT?

- well-defined parameterisation of array of new physics
- model-independent
- but for EFT to make sense, *all* operators must be considered together
- **long term goal:** (semi) global analyses to simultaneously constrain many c_i using multiple measurements



- **theory considerations**

- NLO vs LO
- what operators to consider?
- how to estimate theory uncertainties

**thoroughly discussed
in arXiv:1610.07922**

**sensitivity
detector level fit**

Vs.

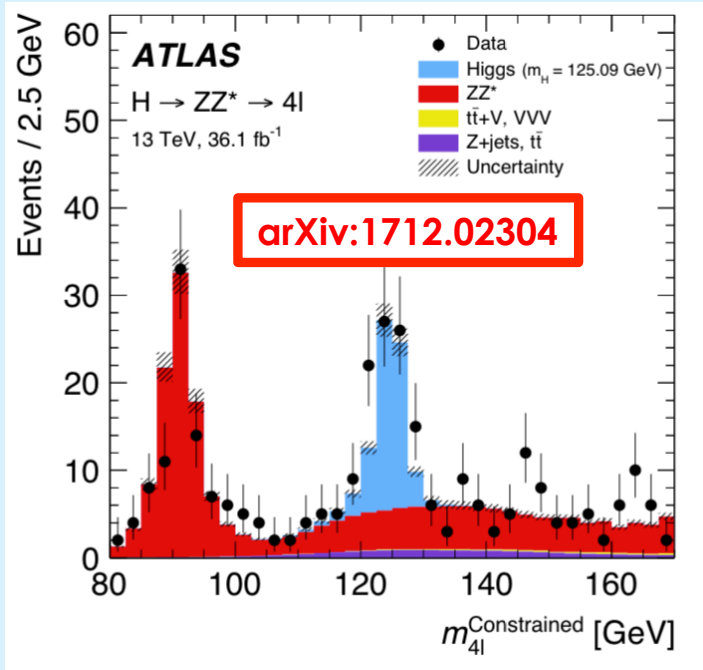
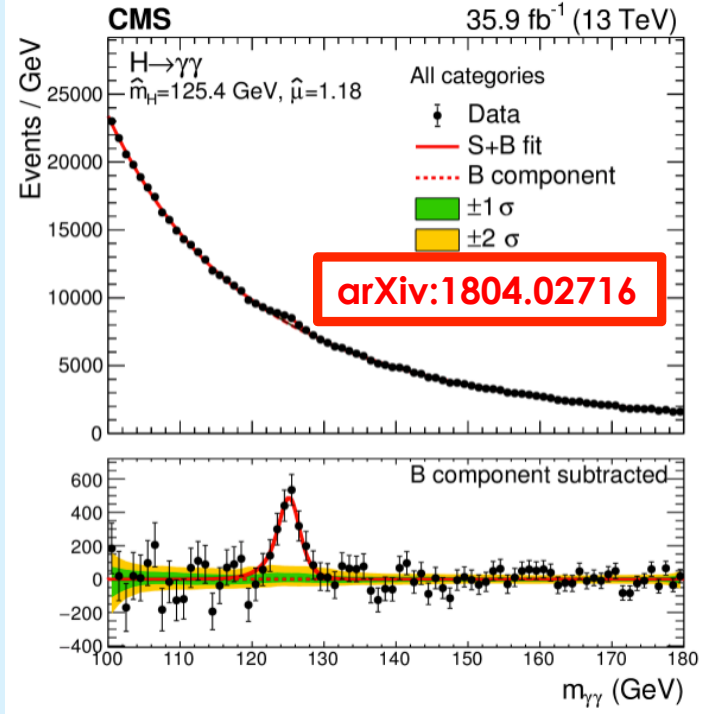
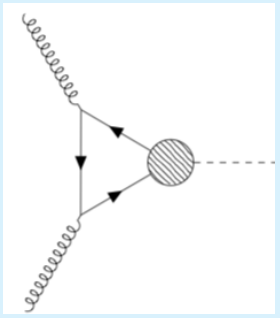
**scalability
unfold to particle-level**

EFT in the Higgs sector

- rich Higgs phenomenology at the LHC
 - multiple production and decay modes
 - diverse experimental signatures
- many observables to measure
 - inclusive cross sections, fiducial rates,
 - rates by production mode, decay mode
- large statistics → detailed studies
 - (double) differential cross sections
 - rare production modes accessible – ttH
- observables affected by EFT operators
 - rescaling of rates
 - deformations of distribution shapes

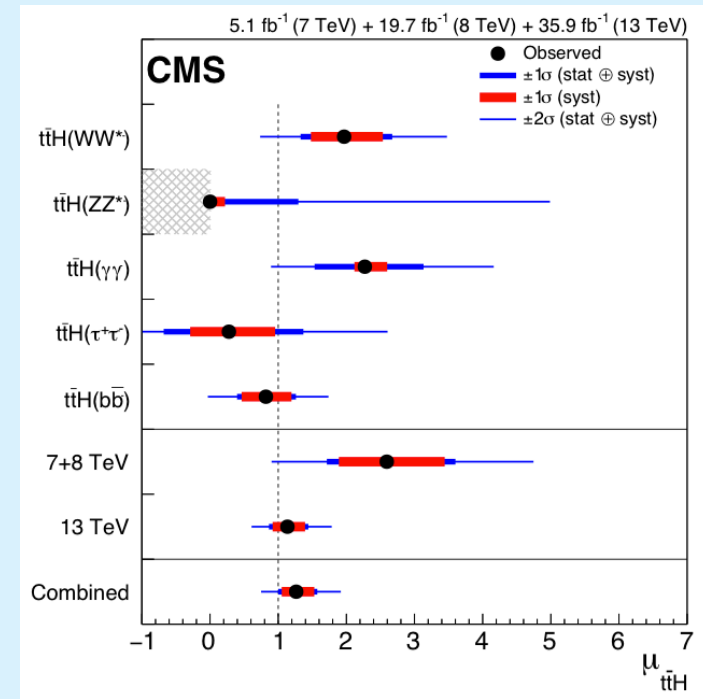
example

– operator modifies the top loop in gg Higgs production mode



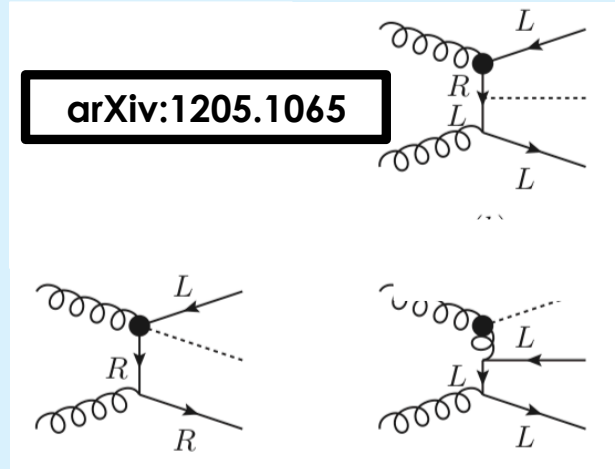
ttH observation

- **observation of ttH @ 7 + 8 + 13 TeV**
- significance across H decay channels and COM energies:
 - **5.2σ (obs.) , 4.2σ (exp.)**
- signal strength (relative to SM) $\mu = 1.26^{+0.31}_{-0.26}$
- signal strength in all decay channels consistent with SM
- important milestone – paves the way for more detailed measurements



consequences for EFT

- dim-6 operators $O_{hg}, O_{HG}, O_H, O_{Hy}$ contribute to ttH production at tree-level
- O_H, O_{Hy} affect ttH rate,
 - can already be constrained
- O_{hg}, O_{HG} alter distribution shapes
 - can be constrained with more detailed future measurements

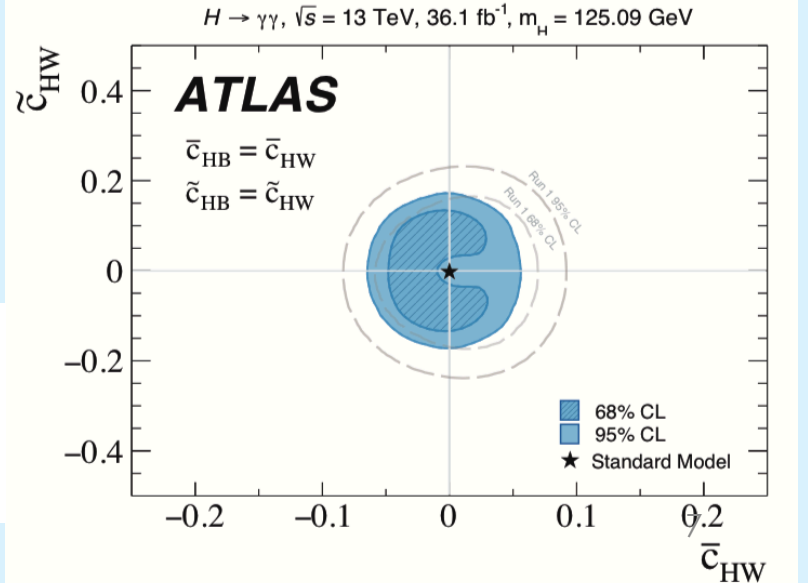
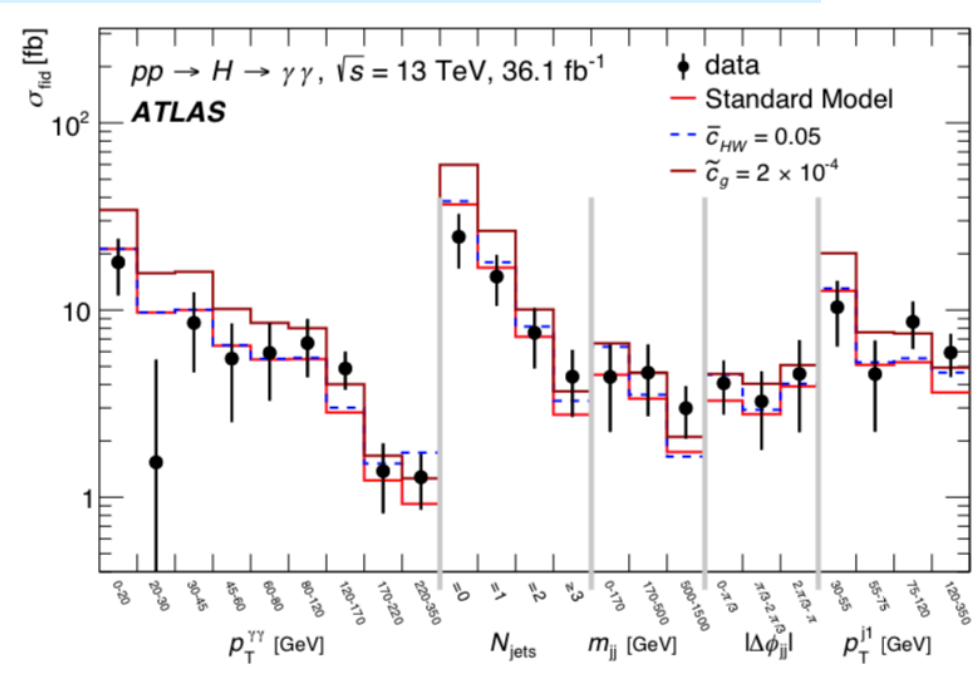


H -> $\gamma \gamma$

- H-> $\gamma \gamma$ @ 13 TeV with 36.1 fb⁻¹
- large stats allow detailed measurements
- **signal strength** $\mu = 0.99^{+0.15}_{-0.14}$
- diff. results agree with SM

EFT reinterpretation

- dim-6 operators
 - $\mathcal{O}_g, \tilde{\mathcal{O}}_g \rightarrow$ ggH interactions
 - $\mathcal{O}_{HW}, \tilde{\mathcal{O}}_{HW} \rightarrow$ HWW, HZZ, HZ γ interactions
 - shape + rate changes
 - $\mathcal{O}_{HB}, \tilde{\mathcal{O}}_{HB} \rightarrow$ HZZ, HZ γ interactions
- diff. distributions constrain associated c_i



Coefficient	Observed 95% CL limit	Expected 95% CL limit
\tilde{c}_g	$[-0.8, 0.1] \times 10^{-4} \cup [-4.6, -3.8] \times 10^{-4}$	$[-0.4, 0.5] \times 10^{-4} \cup [-4.9, -4.1] \times 10^{-4}$
\tilde{c}_g	$[-1.0, 0.9] \times 10^{-4}$	$[-1.4, 1.3] \times 10^{-4}$
\tilde{c}_{HW}	$[-5.7, 5.1] \times 10^{-2}$	$[-5.0, 5.0] \times 10^{-2}$
\tilde{c}_{HW}	$[-0.16, 0.16]$	$[-0.14, 0.14]$

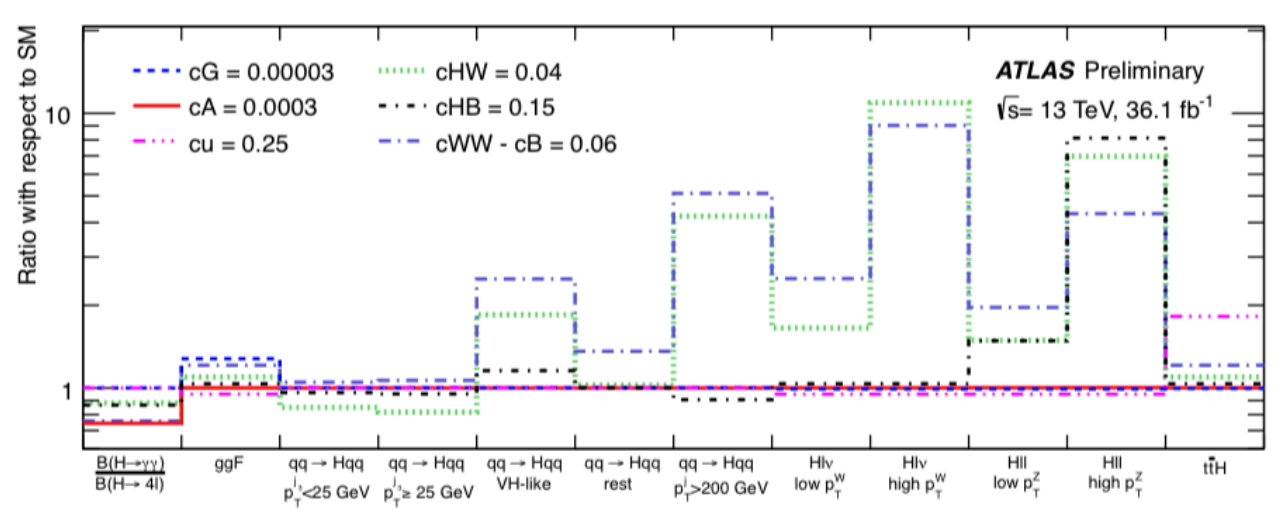
6 operator fit to $H \rightarrow ZZ, H \rightarrow \gamma\gamma$

- constrain 7 dim-6 operators with $H \rightarrow \gamma\gamma, H \rightarrow ZZ$ results @ 13 TeV
- utilising STXS observables to separate by production mode

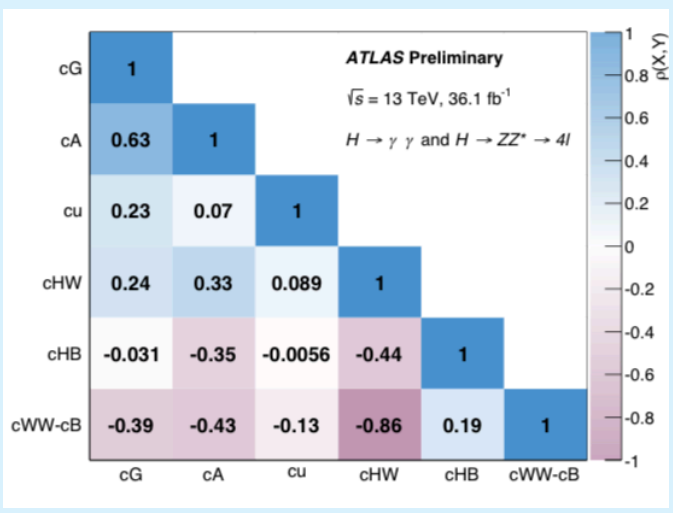
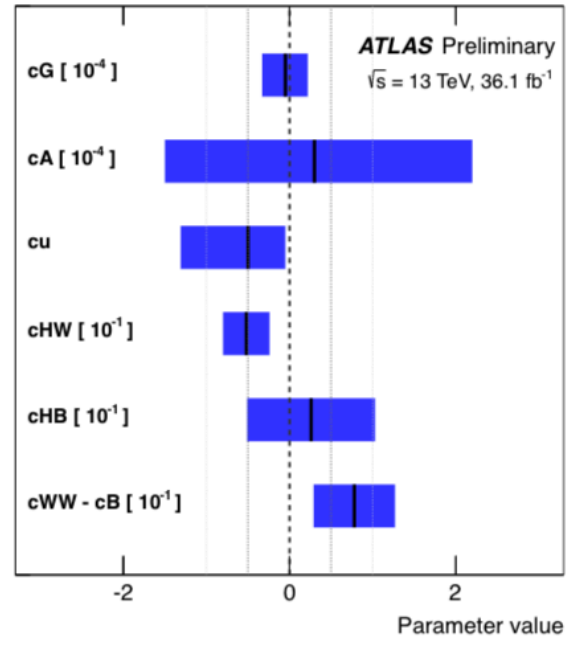
ATL-PHYS-PUB-2017-018

dim-6 operators

- \bigcirc_g
- \bigcirc_γ
- \bigcirc_u
- \bigcirc_{HW}
- \bigcirc_{HB}
- \bigcirc_W
- \bigcirc_B



Observed HEL constraints with $H \rightarrow ZZ^*$ and $H \rightarrow \gamma\gamma$



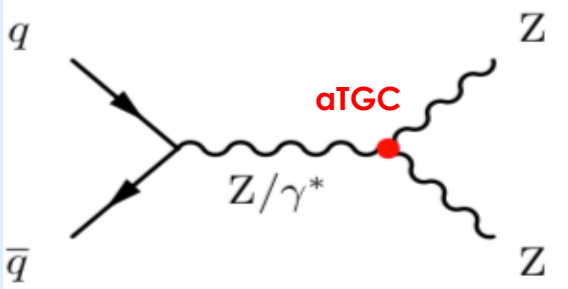
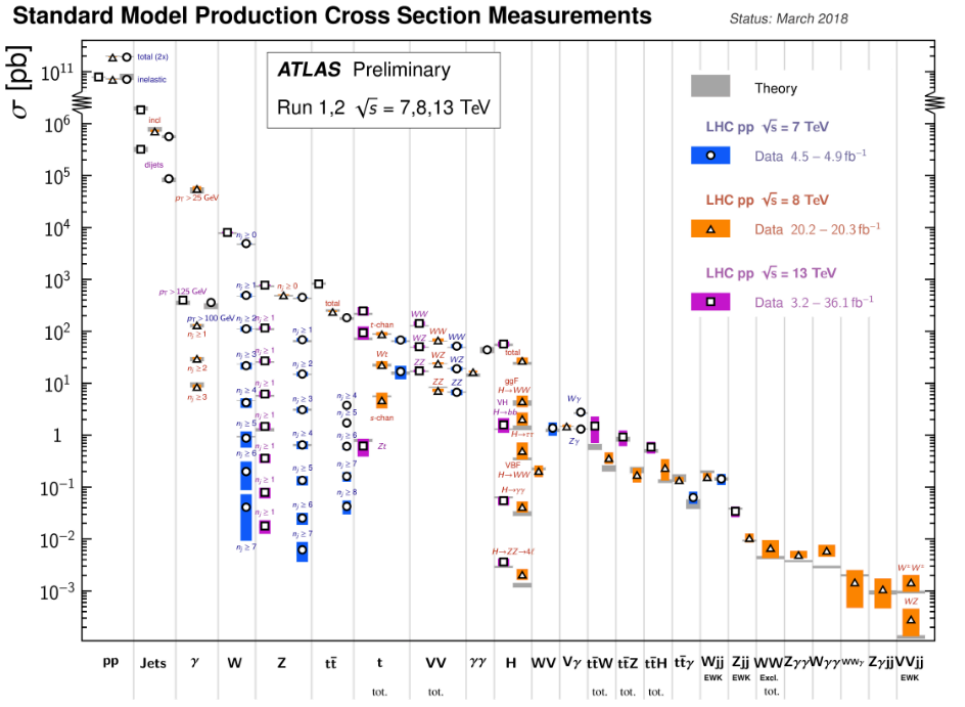
- correlation between EFT coefficients highlight important of multi-operator fits

EFT in the electroweak sector

- large stats. @ LHC allow EW studies in great detail
- rare EW processes measured e.g. EW V+jets, EW ZZ, same sign WW
- sufficient stats for differential measurements in some cases
- subtle effects of NP in multiboson events

Triple-Gauge-Couplings (TGC)

- fixed in SM
- α TGC in EFT increases cross section especially at large energy scales
- diboson and Higgs production are related in EFT

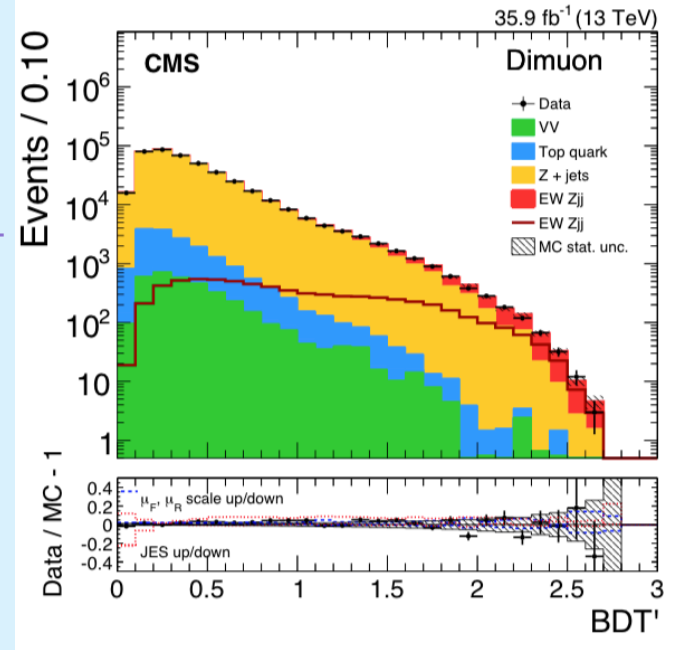


EW Z+2jet

arXiv:1712.09814

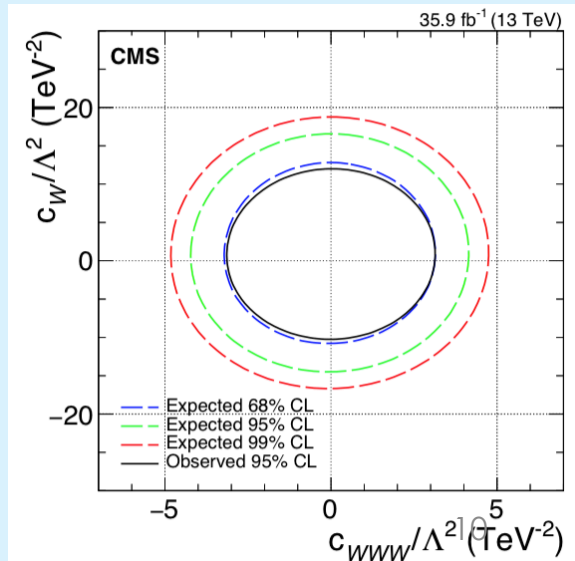
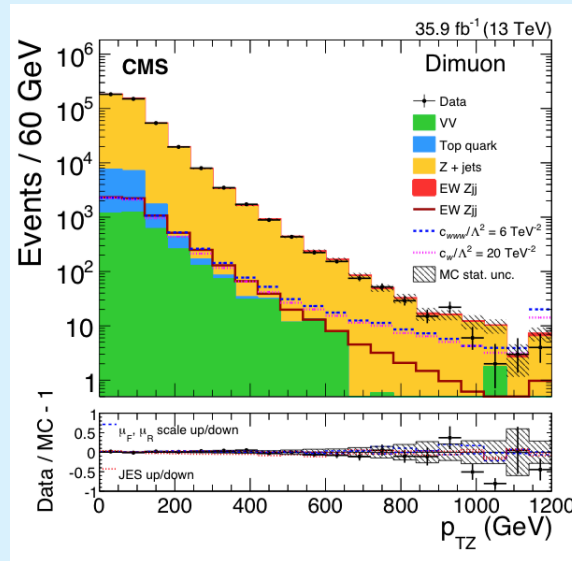


- EW Z+2jet @ 13 TeV with 35.9fb⁻¹
 - 2 lepton + 2 jet final state
 - cross section extracted from fit to BDT discriminant
 - **result consistent with SM**



EFT reinterpretation

- P_{TZ} distribution used to constrain EFT parameters c_{WWW}/Λ^2 , c_W/Λ^2
- results consistent with SM
- parameters constrained individually and in pair



ZZ production

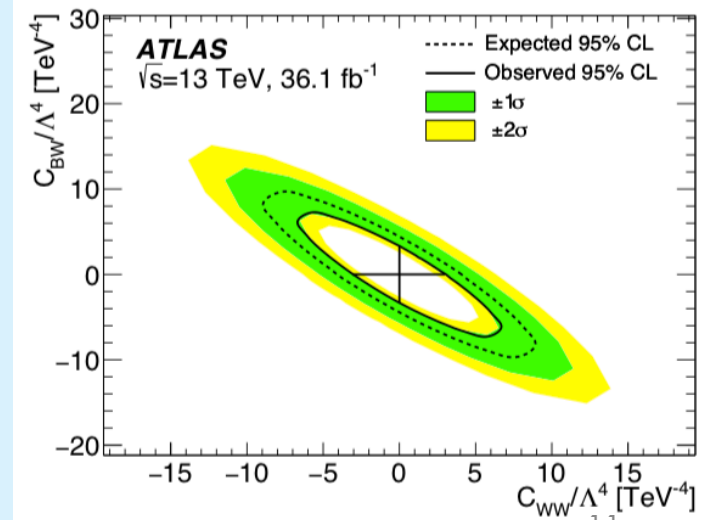
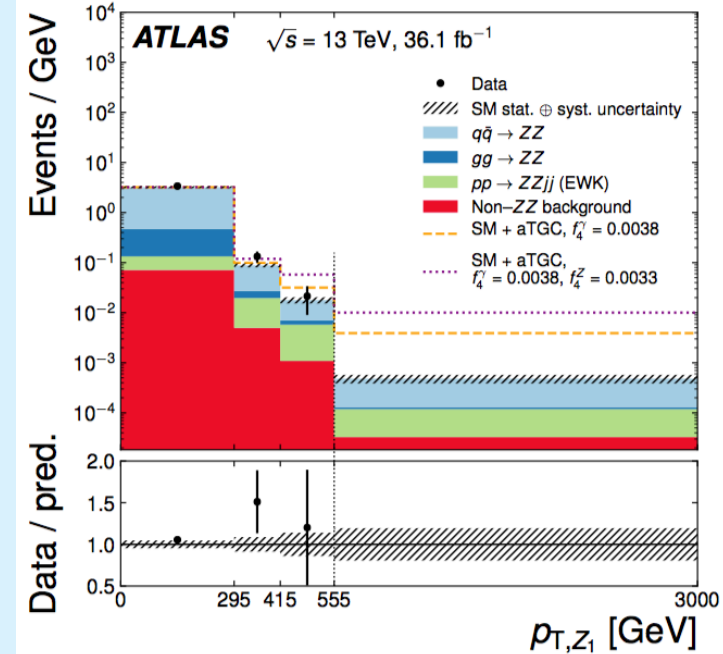
arXiv:1709.07703



- inclusive and differential ZZ cross sections at 13 TeV with 36.1 fb⁻¹
- 4l final state
- differential cross sections for a range of observables

EFT reinterpretation

- aTGC vertex forbidden in SM
 - enhanced in BSM @ large energy scales
- **leading Z P_T** distribution constrains aTGC
- data consistent with no aTGC



EFT parameter	Expected 95% CL [TeV^{-4}]	Observed 95% CL [TeV^{-4}]
$C_{\bar{B}W}/\Lambda^4$	-8.1, 8.1	-5.9, 5.9
C_{WW}/Λ^4	-4.0, 4.0	-3.0, 3.0
C_{BW}/Λ^4	-4.4, 4.4	-3.3, 3.3
C_{BB}/Λ^4	-3.7, 3.7	-2.7, 2.8

EFT coefficients constrained individually

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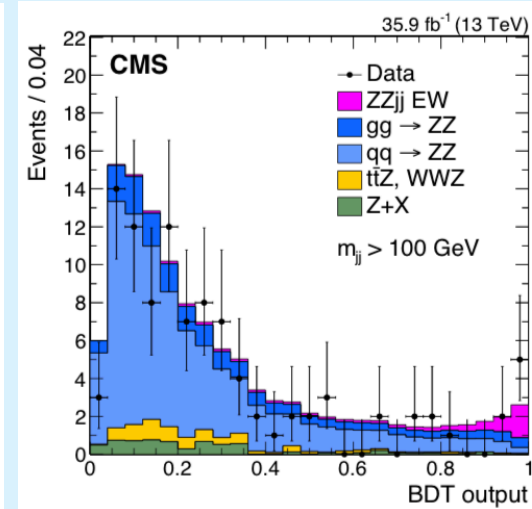
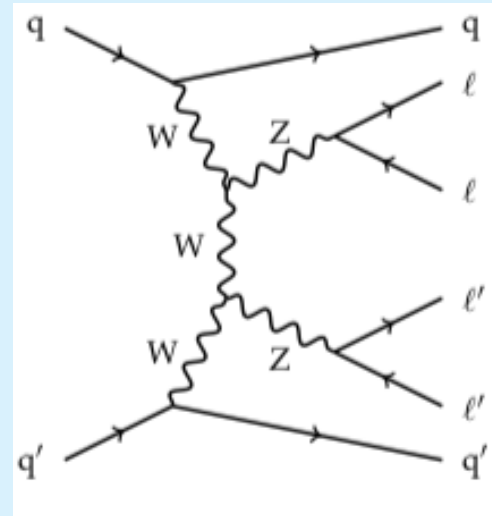
EFT coefficients constrained in pairs

EW ZZ production

arXiv:1708.02812

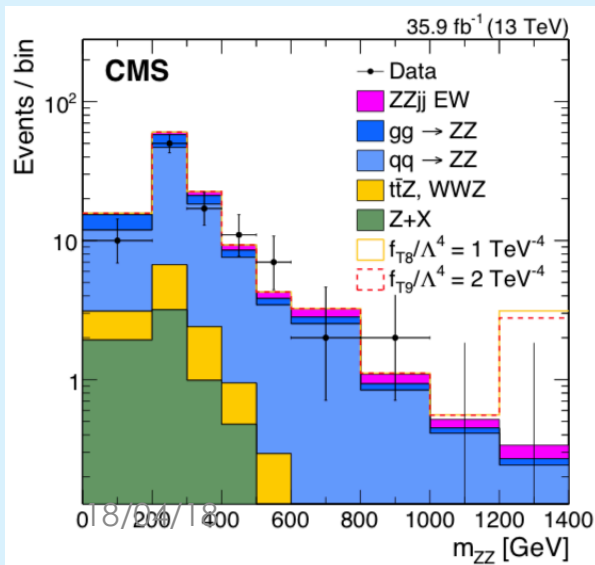


- measurement of EW production of ZZ+2jets @ 13 TeV with 35.9fb⁻¹
 - four lepton + 2jet final state
 - BDT discriminant distinguishes QCD and EW processes
 - signal extracted with 2.7 σ significance
 - fiducial cross section result consistent with SM



EFT reinterpretation

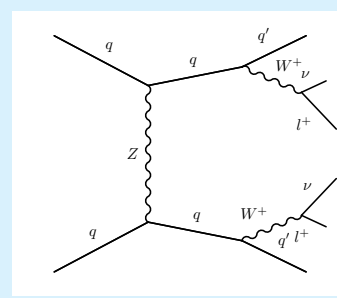
- m_{ZZ} distribution used to constrain EFT parameters f_{Ti}/Λ^4 describing aQGC



Coupling	Exp. lower	Exp. upper	Obs. lower	Obs. upper	Unitarity bound
f_{T0}/Λ^4	-0.53	0.51	-0.46	0.44	2.5
f_{T1}/Λ^4	-0.72	0.71	-0.61	0.61	2.3
f_{T2}/Λ^4	-1.4	1.4	-1.2	1.2	2.4
f_{T8}/Λ^4	-0.99	0.99	-0.84	0.84	2.8
f_{T9}/Λ^4	-2.1	2.1	-1.8	1.8	2.9

- coefficients constrained individually
 - most precise constraints to date
- first results on EW ZZ production

same sign WW

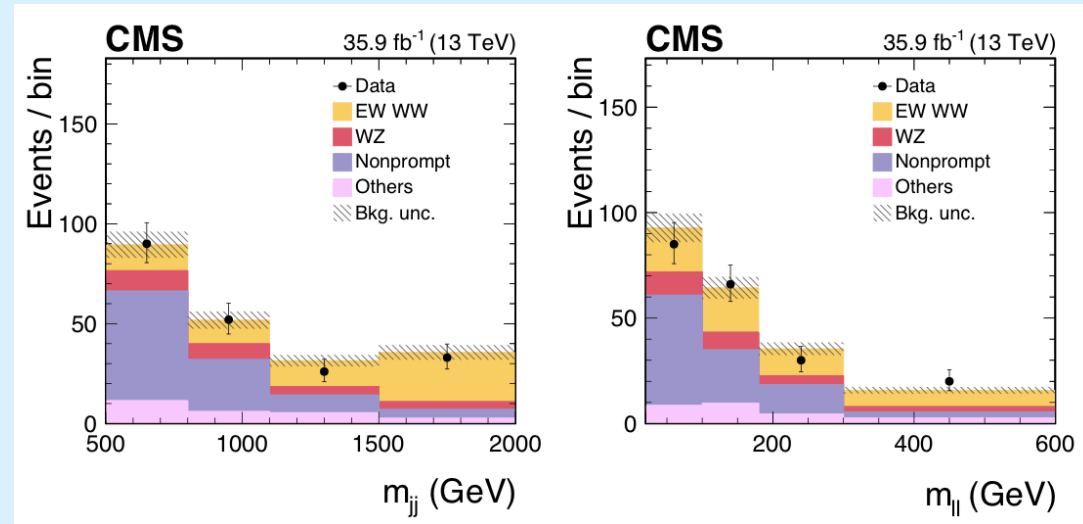


arXiv:1709.05822



- measurement of same-sign WW @ 13 TeV with 35.9fb⁻¹

- 2 SS lepton + 2 jet + MET
- signal extracted with 5.5 σ
- **result consistent with SM**
- **first observation of SS WW**

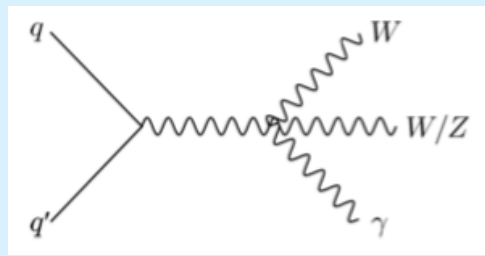


EFT reinterpretation

- m_{ll} distribution used to constrain dim-8 EFT operators
- independently constrain 9 c_i
- bounds improved by up to factor of 6 on previous results

	Observed limits (TeV ⁻⁴)	Expected limits (TeV ⁻⁴)	Previously observed limits (TeV ⁻⁴)
f_{S0}/Λ^4	[-7.7, 7.7]	[-7.0, 7.2]	[-38, 40] , [11]
f_{S1}/Λ^4	[-21.6, 21.8]	[-19.9, 20.2]	[-118, 120] , [11]
f_{M0}/Λ^4	[-6.0, 5.9]	[-5.6, 5.5]	[-4.6, 4.6] , [36]
f_{M1}/Λ^4	[-8.7, 9.1]	[-7.9, 8.5]	[-17, 17] , [36]
f_{M6}/Λ^4	[-11.9, 11.8]	[-11.1, 11.0]	[-65, 63] , [11]
f_{M7}/Λ^4	[-13.3, 12.9]	[-12.4, 11.8]	[-70, 66] , [11]
f_{T0}/Λ^4	[-0.62, 0.65]	[-0.58, 0.61]	[-0.46, 0.44] , [37]
f_{T1}/Λ^4	[-0.28, 0.31]	[-0.26, 0.29]	[-0.61, 0.61] , [37]
f_{T2}/Λ^4	[-0.89, 1.02]	[-0.80, 0.95]	[-1.2, 1.2] , [37]

WW γ , WZ γ

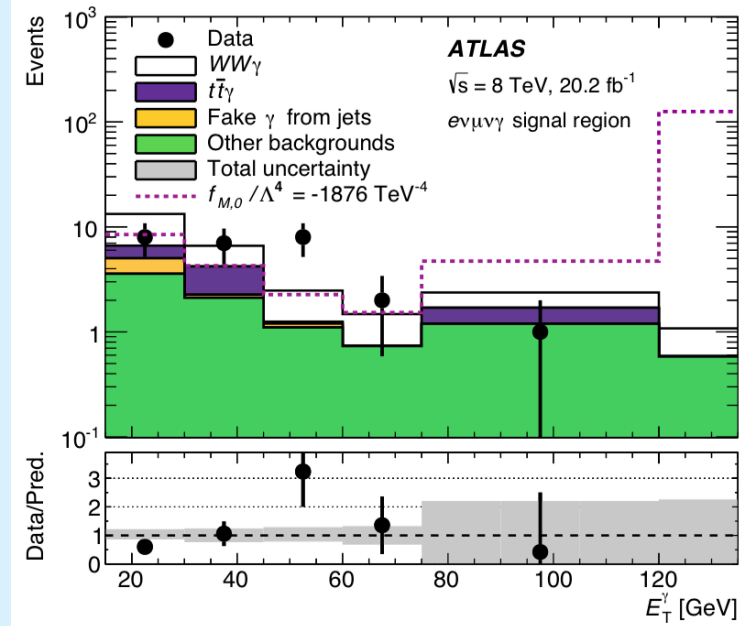


arXiv:1707.05597



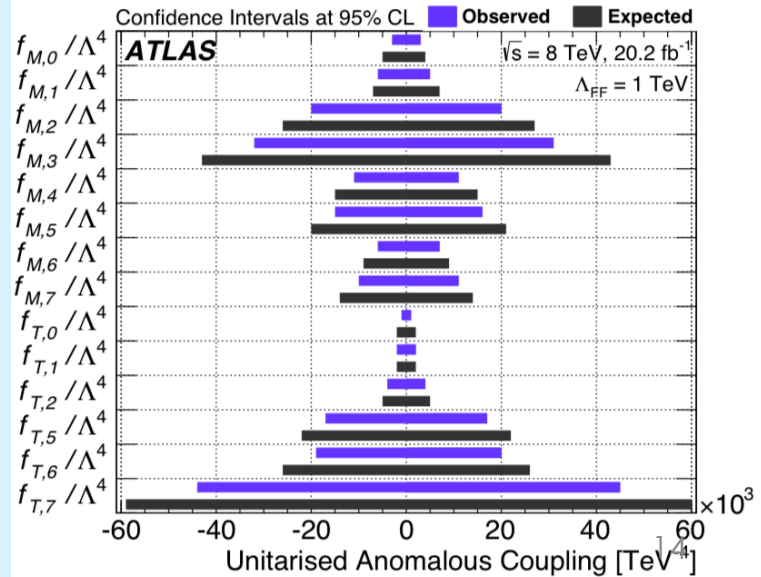
search for WW γ WZ γ production @ 8TeV with 20.2fb⁻¹

- e, mu, γ , 2 jet, MET
- fiducial region defined to be optimal wrt aQGC effects
- backgrounds determined from control regions
- upper limit placed on cross sections in optimal fiducial region for BSM



EFT reinterpretation

- upper limit used to constrain dim-8 EFT
- aQGC affect fiducial rates
- independently constrain 14 c_i describing anomalous WWZ γ and WW $\gamma\gamma$
- results consistent with SM



EFT in the top sector

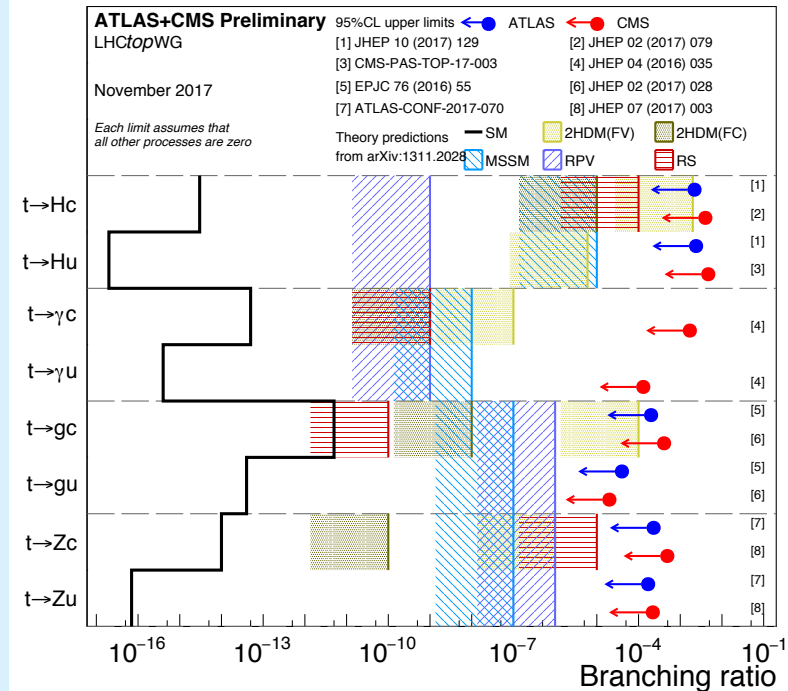
- top observables at the LHC**

- $t\bar{t}$ -> precision regime: percent level incl. cross section, multi-differential, jet spectra, charge asymmetries, spin correlations
- single-top** -> detailed diff measurements: t-channel, tW, tZq channels,
- $t\bar{t}V$ -> observed, first inclusive measurements
- $t\bar{t}t$ -> approaching observation
- FCNC** -> upper limits at the 10^{-5} level

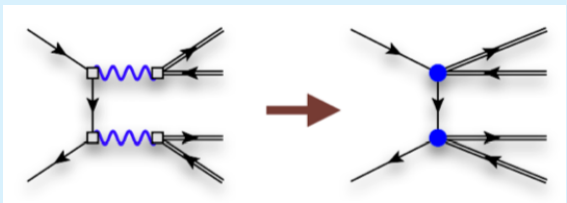
- EFT in top**

- many top observables modified in EFT
- both rate increase and shape deformations
- interplay with Higgs sector in $t\bar{t}H$, $t\bar{t}t$ and FCNC
- NLO QCD EFT predictions for many observables already available
- suggested “common standards” from theory experts

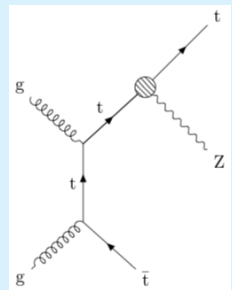
arXiv:1802.07237



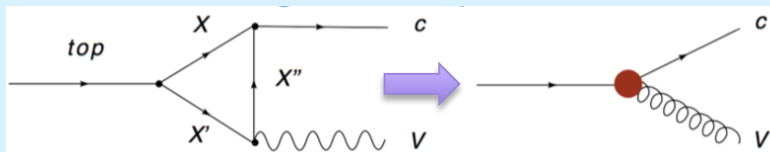
limits on FCNC branching ratios



BSM alters $t\bar{t}t$ rate in EFT

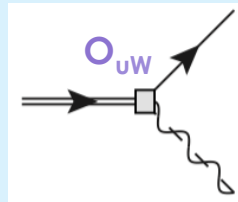


dim-6 operator in $t\bar{t}Z$ production



BSM loop modifying $Br(FCNC)$ in EFT

top FCNC decays



NEW arXiv:1803.09923

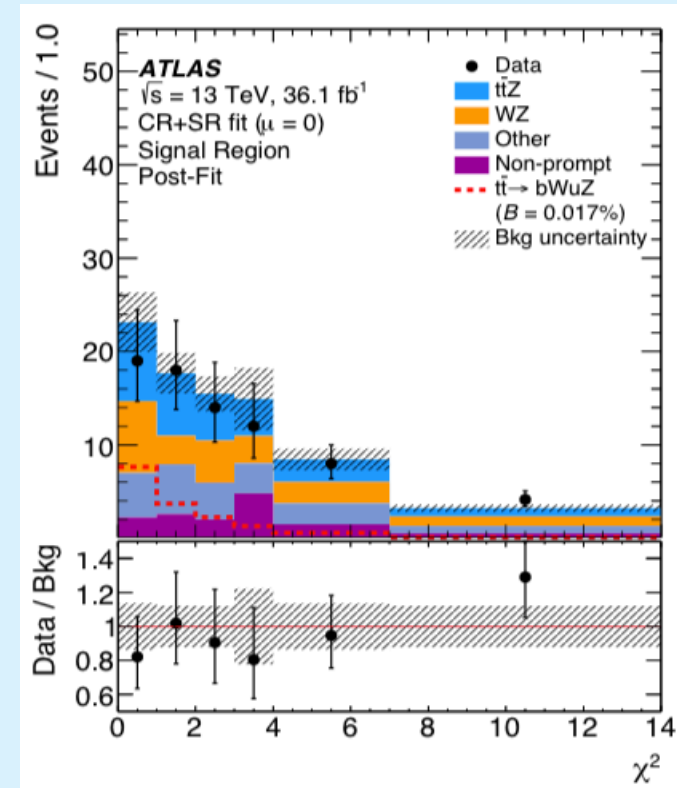
- $t \rightarrow uZ, t \rightarrow cZ$ decays @ 13 TeV with 36.1 fb^{-1}
- anomalous $t \rightarrow uZ, t \rightarrow cZ$ branching ratios is a feature of BSM scenarios
- **strategy**
 - $t\bar{t}$ events where one top decays to uZ , or cZ
 - require 3 leptons, 2 jets, 1 b-tag and MET
 - kin. reco. to find $t \rightarrow uZ$ or $t \rightarrow cZ$ decays
 - binned likelihood fit to kinematic distributions

result- no evidence of $t \rightarrow uZ, t \rightarrow cZ$ decays

- upper limits on branching ratios @ 95% CL

$$\text{Br}(t \rightarrow uZ) < 1.7 \times 10^{-4}$$

$$\text{Br}(t \rightarrow cZ) < 2.4 \times 10^{-4}$$



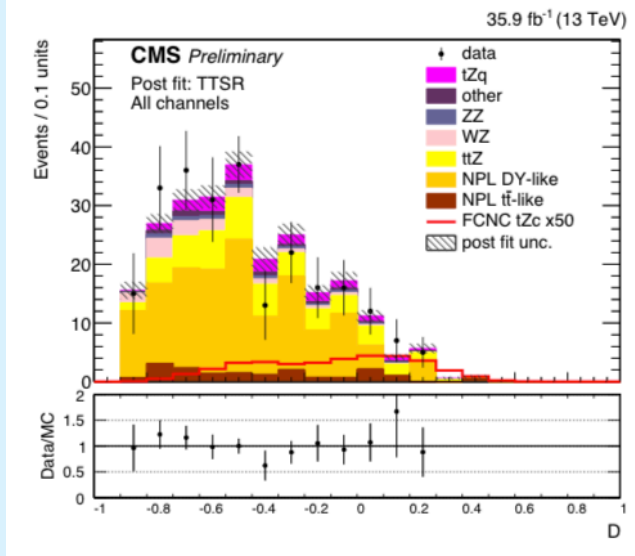
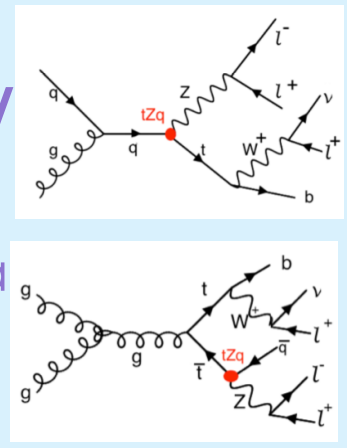
interpretation in TopFCNC EFT model arXiv:1412.5594

- assume only one operator has non-zero value

Operator	Observed	Expected
$ C_{uB}^{(31)} $	0.25	0.30
$ C_{uW}^{(31)} $	0.25	0.30
$ C_{uB}^{(32)} $	0.30	0.34
$ C_{uW}^{(32)} $	0.30	0.34

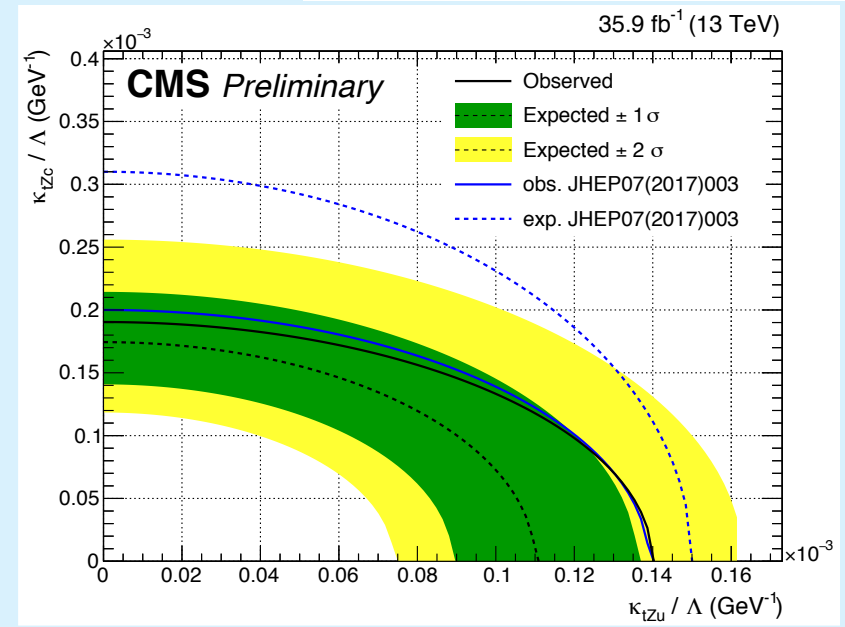


- search for top FCNC in production and decay @ 13 TeV with 36.1 fb^{-1}
- anomalous top FCNC interactions branching ratios is a feature of BSM scenarios
- strategy
 - $t\bar{t}$ or single top events
 - require 3 leptons
 - binned likelihood fit to kinematic distributions



interpretation in EFT model

- include trilinear quark-top couplings only
- significant improvement w.r.t. 8 TeV

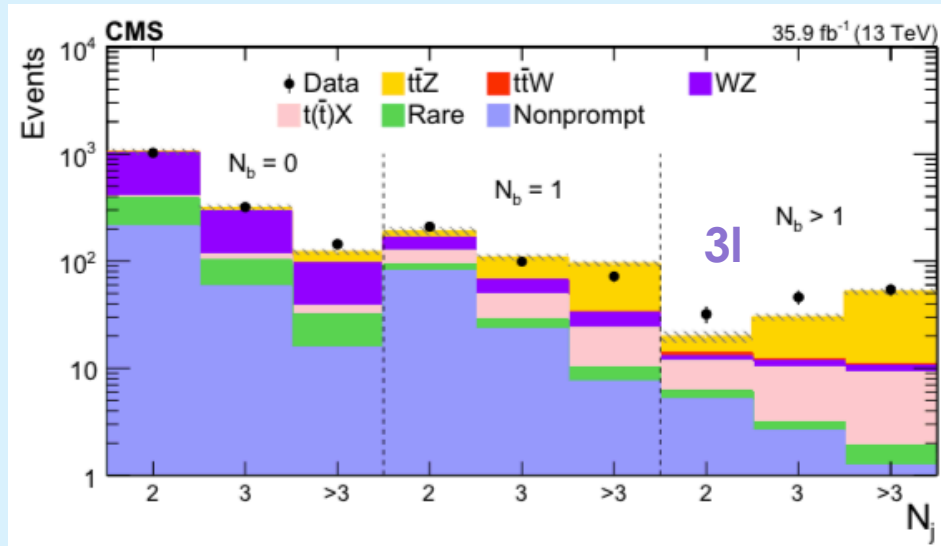


tt + V

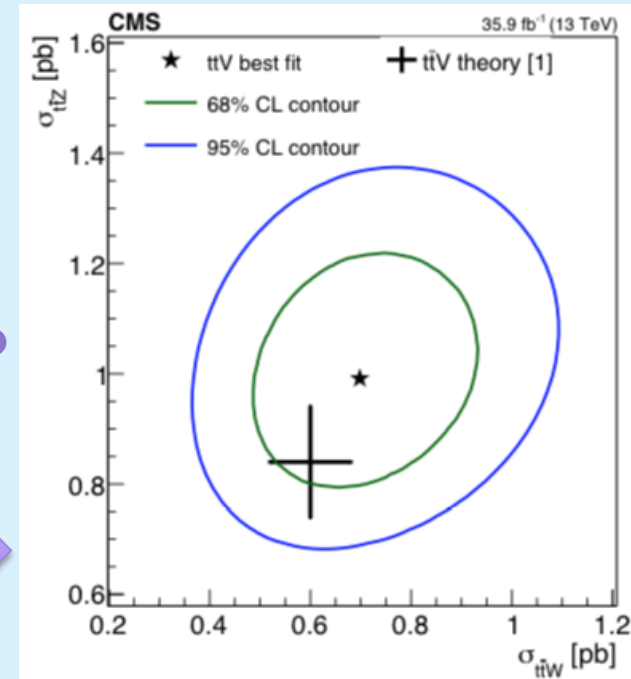
arXiv:1711.02547



- measurement of tt+Z and tt+W cross sections at 13 TeV with 35.9 fb⁻¹
- tt̄ + V rates increased in NP scenarios
 - same-sign dileptons -> optimal for tt̄+W
 - 3, 4 leptons -> optimal for tt̄+Z
 - BDT discriminator in same-sign dilepton



fit across categories to extract σ_{ttW} and σ_{ttZ}



- 8 c_i independently constrained
- results consistent with SM

Wilson coefficient	68% CL [TeV ⁻²]	95% CL [TeV ⁻²]
\bar{c}_{uW}/Λ^2	[-1.6, 1.5]	[-2.2, 2.2]
$ \bar{c}_H/\Lambda^2 - 16.8 \text{ TeV}^{-2} $	[3.7, 23.4]	[0, 28.7]
\bar{c}_{3G}/Λ^2	[-0.5, 0.5]	[-0.7, 0.7]
\tilde{c}_{3G}/Λ^2	[-0.3, 0.7]	[-0.5, 0.9]
\bar{c}_{uG}/Λ^2	[-0.9, -0.8] and [-0.3, 0.2]	[-1.1, 0.3]
$ \bar{c}_{uB}/\Lambda^2 $	[0, 1.5]	[0, 2.1]
\bar{c}_{Hu}/Λ^2	[-9.2, -6.5] and [-1.6, 1.1]	[-10.1, 2.0]
\bar{c}_{2G}/Λ^2	[-0.7, 0.4]	[-0.9, 0.6]

summary and outlook

- EFT provides a model-independent framework in which to search for subtle hints of new physics at the LHC
- “global” analysis becoming more feasible with wealth of Higgs, EW and Top measurements
 - long way to go to incorporate large numbers of operators
- many analyses from ATLAS and CMS appearing with *stand-alone* EFT reinterpretations
 - **so far no hints of new physics**