PIC 2021, Aachen, Germany

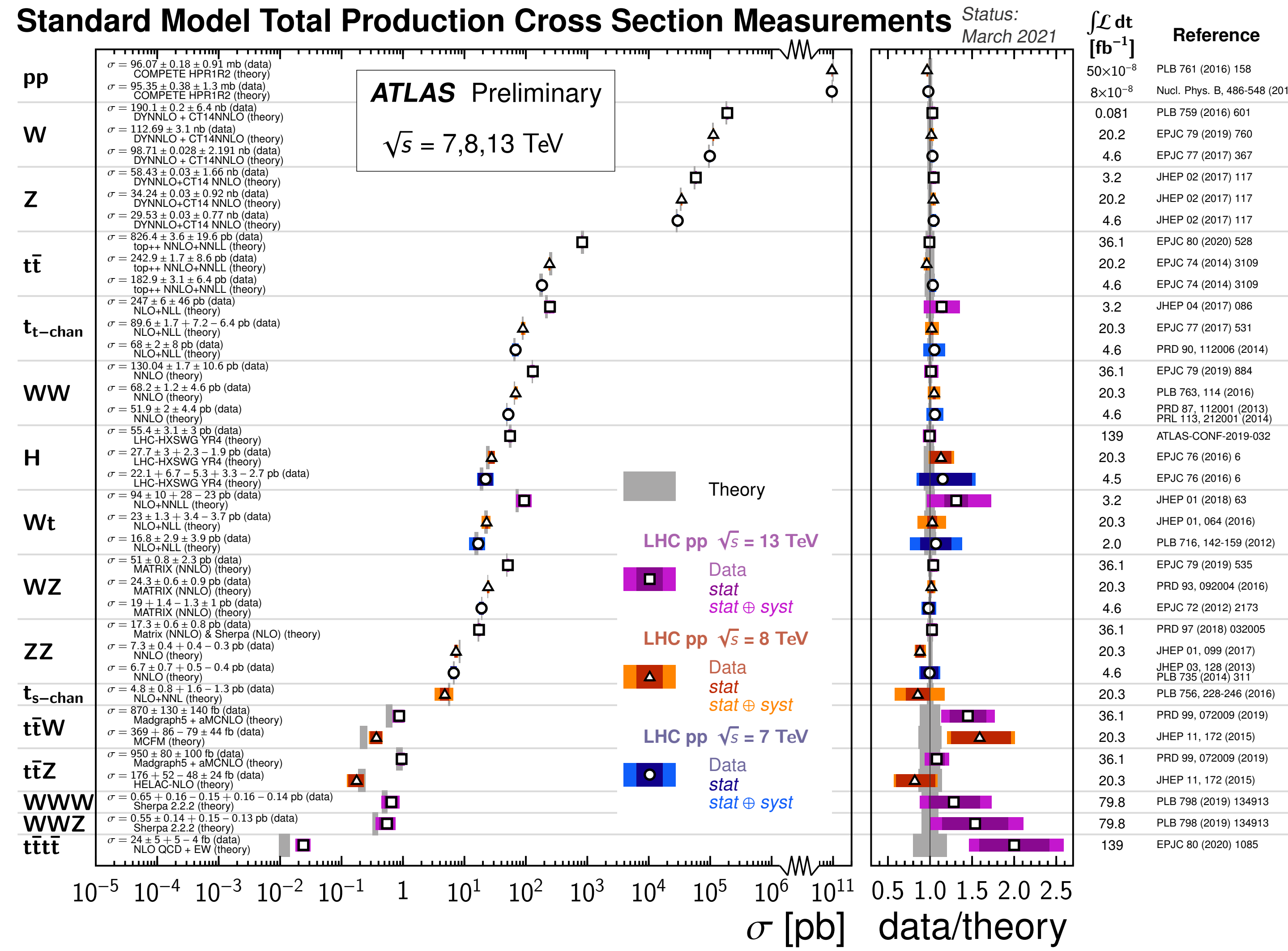
Model-independent searches at the LHC (with focus on EFT approaches)

Ana Cueto (CERN).
On behalf of the ATLAS and CMS Collaborations

Introduction

- Large success of the SM so far at the LHC and no clear evidence of BSM physics from direct searches

- Motivates model-independent searches for BSM effects



Generic searches

Phase-space not tailored to a specific model
Several final states can be explored

Effective Field Theory approach

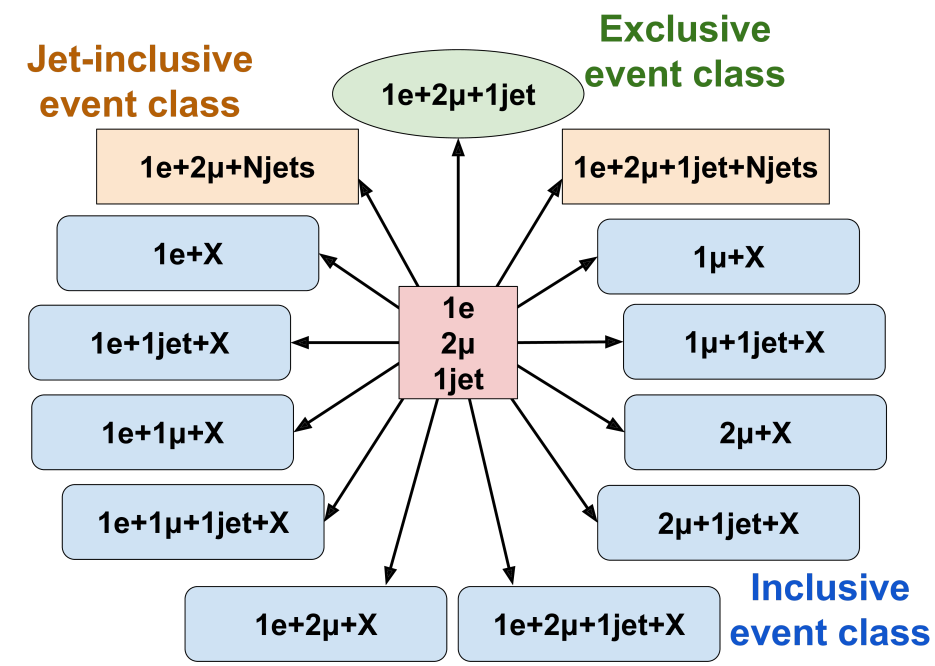
Allows to systematically interpret large datasets with the assumption that the new physics appears at larger scales.

FOCUS OF THIS TALK!

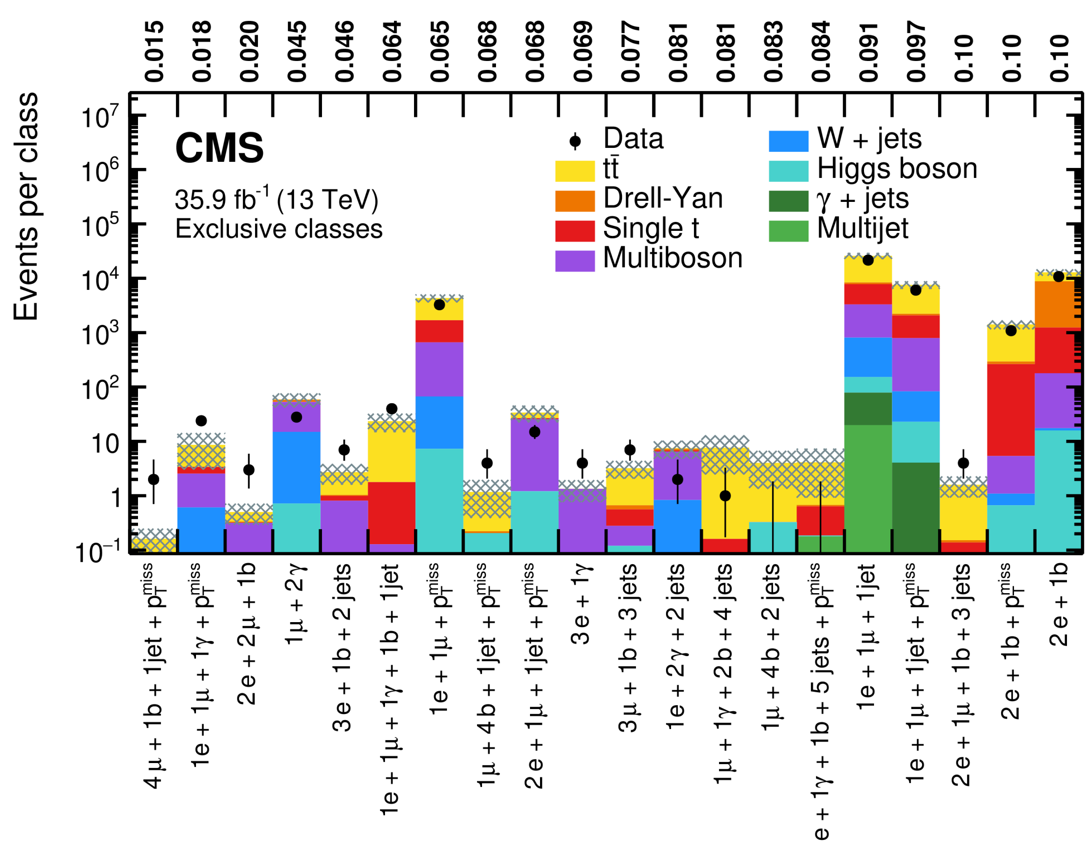
Generic searches

Generic searches: MUSiC in CMS [arXiv:2010.02984]

- Aims to identify discrepancies between CMS data with 35.1 / fb and SM predictions in hundreds of event classes
- Starts selecting events with one electron or muon and determine the class based on well reconstructed objects: electrons, muons, photons, jets, b-jets and missing transverse momentum.
  - Each event will fall in one exclusive category and one or more inclusive categories



- Scans for deviations are done on S_T, invariant mass and p_T^{miss}
  - RoI is the region with smallest p-value
  - Results corrected for Look-Elsewhere effect
- No significant deviations from SM found
- Also generic searches for individual signatures
  - See slides from Emma Torró



Most significant exclusive-event classes

Generic search by ATLAS: EXOT-2016-38

SM effective field theory

EFT introduction

- We assume that the SM is just an effective realisation of a higher-energy theory
- Take an energy cut-off $\Lambda >> \text{vev}$ and write down the most general Lagrangian preserving SM symmetries and particle content

$$\mathscr{L}_{SMEFT} = \mathscr{L}_{SM} + \sum_i \frac{c_i^{d=6}}{\Lambda^2}\mathcal{O}^{d=6} + \sum_i \frac{c_i^{d=8}}{\Lambda^4}\mathcal{O}^{d=8} + \dots$$

c_i are the so-called Wilson coefficients

- Only c_i / Λ^{d-4} is measurable
- Constrain EFT coefficients ➝ constrain large classes of UV theories
- SMEFT is a complete QFT compatible with NLO calculations, in contradistinction to kappa framework or anomalous couplings interpretations

Some operators in the Warsaw basis

Z,W couplings

$$\mathcal{Q}_{Hl}^{(1)} = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{l}\gamma^\mu l)$$
$$\mathcal{Q}_{He} = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{e}\gamma^\mu e)$$
$$\mathcal{Q}_{Hq}^{(1)} = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{q}\gamma^\mu q)$$
$$\mathcal{Q}_{Hq}^{(3)} = (iH^\dagger \overleftrightarrow{D}^i_\mu H)(\bar{q}\sigma^i\gamma^\mu q)$$
$$\mathcal{Q}_{Hu} = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{u}\gamma^\mu u)$$
$$\mathcal{Q}_{Hd} = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{d}\gamma^\mu d)$$

Bhabha scattering

$$\mathcal{Q}_{ee} = (\bar{e}\gamma^\mu e)(\bar{e}\gamma^\mu e)$$
$$\mathcal{Q}_{le} = (\bar{l}\gamma^\mu l)(\bar{e}\gamma^\mu e)$$
$$\mathcal{Q}_{ll} = (\bar{l}_p\gamma^\mu l_p)(\bar{l}_r\gamma^\mu l_r)$$

$$\mathcal{Q}_{HD} = (D_\mu H^\dagger H)(H^\dagger D^\mu H)$$
$$\mathcal{Q}_{HWB} = (H^\dagger \sigma^i H) W^i_{\mu\nu} B^{\mu\nu}$$
$$\mathcal{Q}_{Hl}^{(3)} = (iH^\dagger \overleftrightarrow{D}^i_\mu H)(\bar{l}\sigma^i\gamma^\mu l)$$
$$\mathcal{Q}'_{ll} = (\bar{l}_p\gamma^\mu l_r)(\bar{l}_r\gamma^\mu l_p)$$

input quantities

$$\mathcal{Q}_{Hbox} = (H^\dagger H) \Box (H^\dagger H)$$
$$\mathcal{Q}_{HG} = (H^\dagger H) G^a_{\mu\nu} G^{a\mu\nu}$$
$$\mathcal{Q}_{HB} = (H^\dagger H) B_{\mu\nu} B^{\mu\nu}$$
$$\mathcal{Q}_{HW} = (H^\dagger H) W^i_{\mu\nu} W^{i\mu\nu}$$
$$\mathcal{Q}_{uH} = (H^\dagger H)(\bar{q}\tilde{H}u)$$
$$\mathcal{Q}_{dH} = (H^\dagger H)(\bar{q}Hd)$$
$$\mathcal{Q}_{eH} = (H^\dagger H)(\bar{q}He)$$
$$\mathcal{Q}_{G} = \varepsilon_{abc} G^{a\nu}_\mu G^{b\rho}_\nu G^{c\mu}_\rho$$
$$\mathcal{Q}_{uG} = (\bar{q}\sigma^{\mu\nu} T^a \tilde{H} u) G^a_{\mu\nu}$$

H processes

$$\mathcal{Q}_{W} = \varepsilon_{ijk} W^{i\nu}_\mu W^{j\rho}_\nu W^{k\mu}_\rho$$

TGC

Common input schemes:

→ (mW,mZ,GF)

→ (α, mZ, GF)

Ilaria Brivio

Top-philic operators in backup

Implementation of EFT analyses

Dedicated measurements → Measurements directly in terms of EFT coefficients, c_i

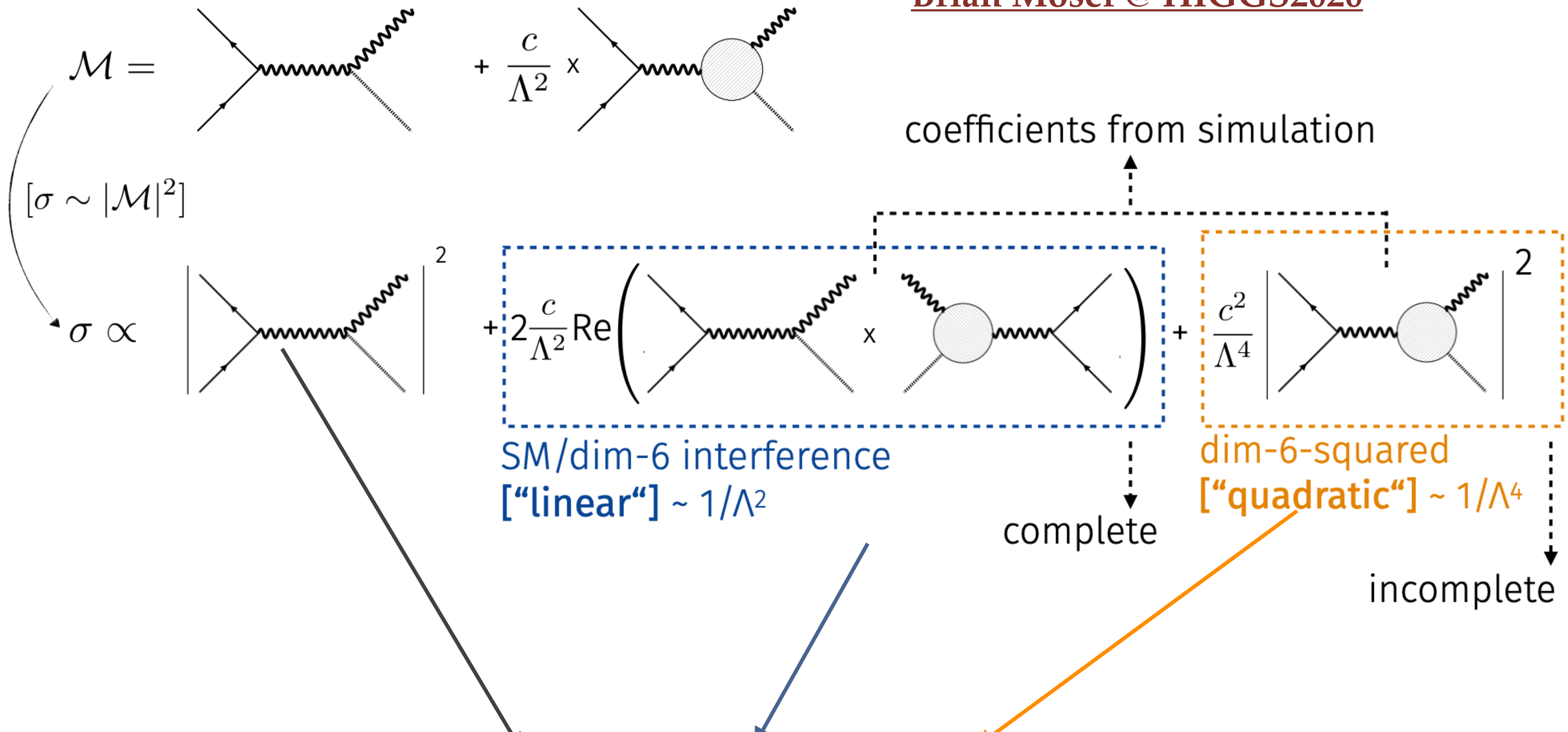
Reparametrisations →
- Parametrise measured observables (usually cross-sections) in terms of EFT coefficients.
- Measure c_i using the reparametrised likelihood

Reinterpretations → As reparametrisations but using gaussian assumptions

More assumptions means also less sensitivity but also easier implementation

EFT simulation

Brian Moser @ HIGGS2020



$$|\mathcal{A}_{\mathrm{EFT}}|^2 = |\mathcal{A}_{\mathrm{SM}}|^2 + \bar{g}\,|\mathcal{A}_{\mathrm{SM}} \cdot \mathcal{A}_6^{(1,1)}| + \bar{g}^2\,|\mathcal{A}_6^{(1,1)}|^2 + \bar{g}^2\,|\mathcal{A}_{\mathrm{SM}} \cdot \mathcal{A}_6^{(1,2)}| + \frac{\bar{g}}{\Lambda^2}\,|\mathcal{A}_{\mathrm{SM}} \cdot \mathcal{A}_8^{(1,1)}| + \ldots$$

EW and Higgs interpretations

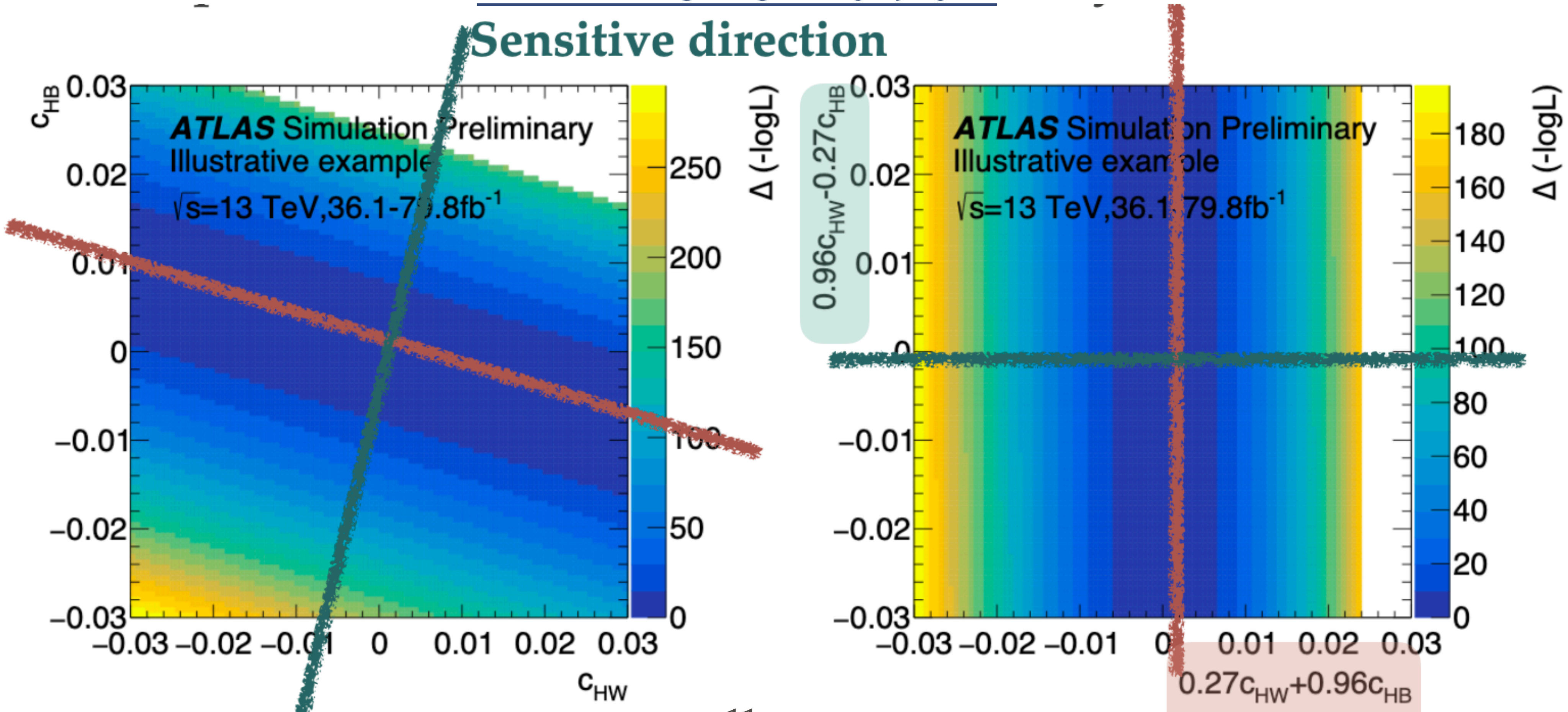
Anomalous gauge couplings covered by Ricardo Bellan

Dedicated Higgs analyses looking for CP violations covered by Ximo Poveda

Reparametrisations in ATLAS

- Latest ATLAS combinations typically use a common strategy:
  - Usage of Warsaw basis
  - Present the results as a simultaneous fit to several directions determined from a principal component analysis (PCA) starting from the covariance matrix of the measurement
  - A second PCA is done after grouping operators by physics meaning
    - Only directions with small impact ("blind" directions) are fixed to 0

ATL-PHYS-PUB-2019-042

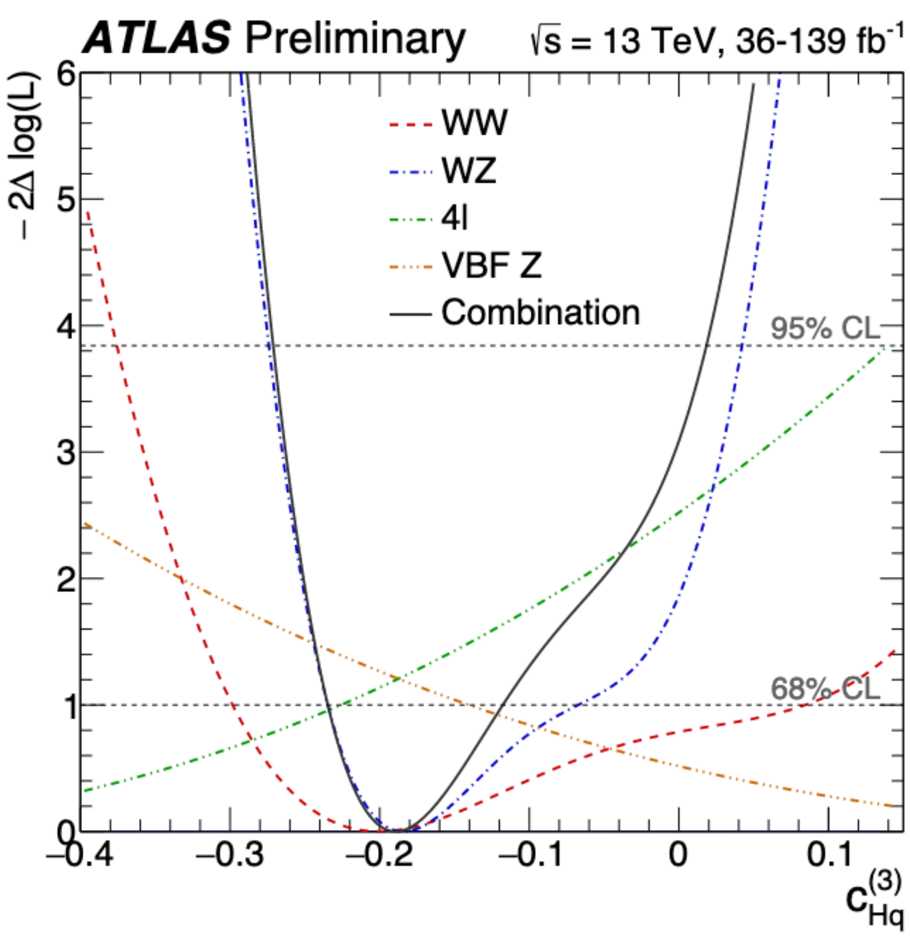


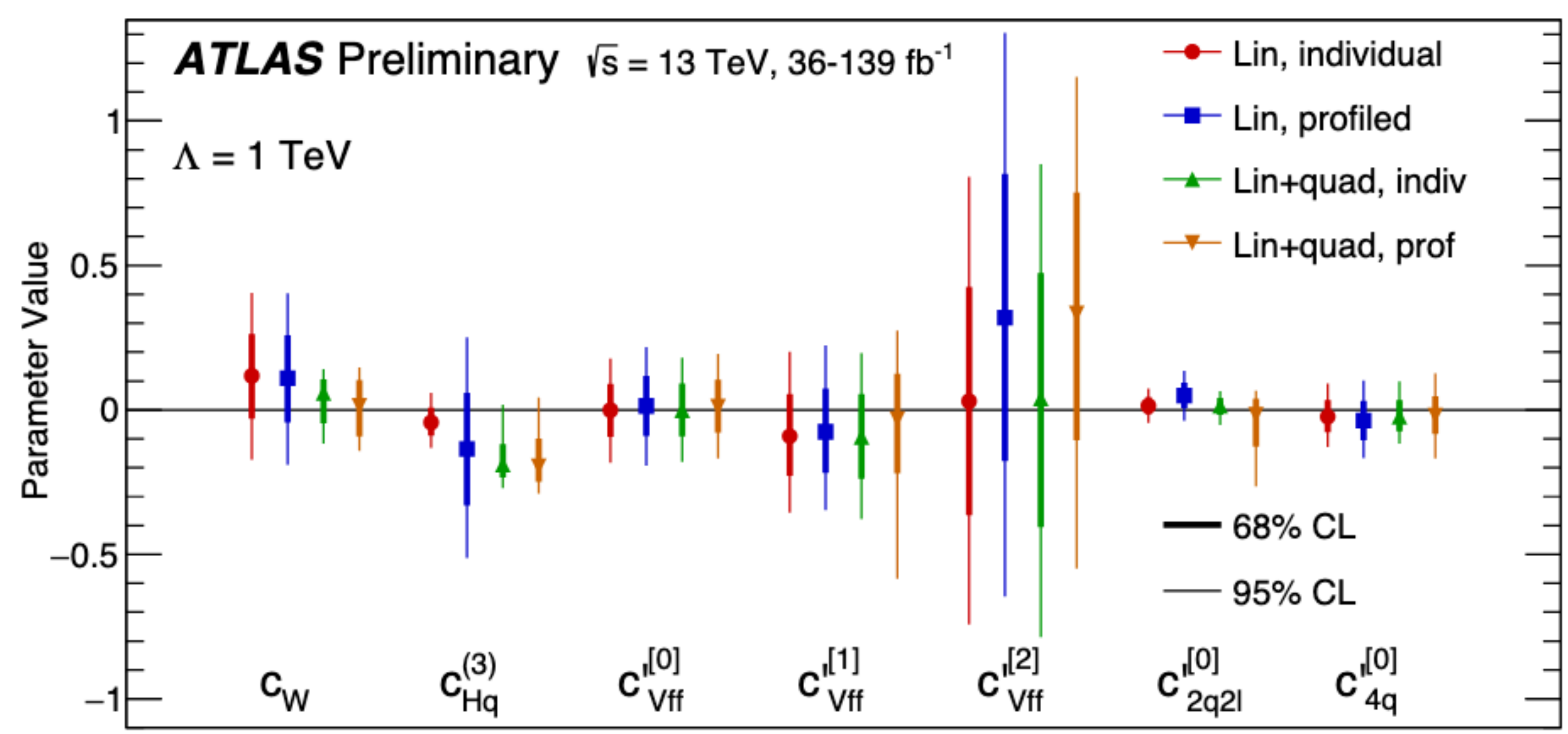
WW, WZ, 4l and VBF Z combination

ATL-PHYS-PUB-2021-022

- First interpretation of EW measurements (36-139 / fb) combination taking into account their correlations
- Re-interpretation of differential cross section measurements
- Clear improvement in the constraints over single measurements
- In WW analysis phase-space, cW contribution is suppressed

15 directions measured in the linear or linear+quadratic terms





$$c'^{[0]}_{Vff} \approx 0.81c_{HWB} + 0.38c_{HD} + 0.13c^{(1)}_{Hl} + 0.37c^{(3)}_{Hl} - 0.14c^{(1)}_{ll} + 0.12c^{(1)}_{Hq}$$

$$c'^{[1]}_{Vff} \approx 0.73c^{(1)}_{Hl} - 0.28c^{(3)}_{Hl} - 0.48c_{He} + 0.38c^{(1)}_{ll} + 0.13c^{(1)}_{Hq}$$

$$c'^{[2]}_{Vff} \approx 0.37c_{HWB} + 0.17c_{HD} - 0.31c^{(1)}_{Hl} - 0.53c^{(3)}_{Hl} + 0.25c_{He} + 0.59c^{(1)}_{ll} - 0.21c^{(1)}_{Hq}$$

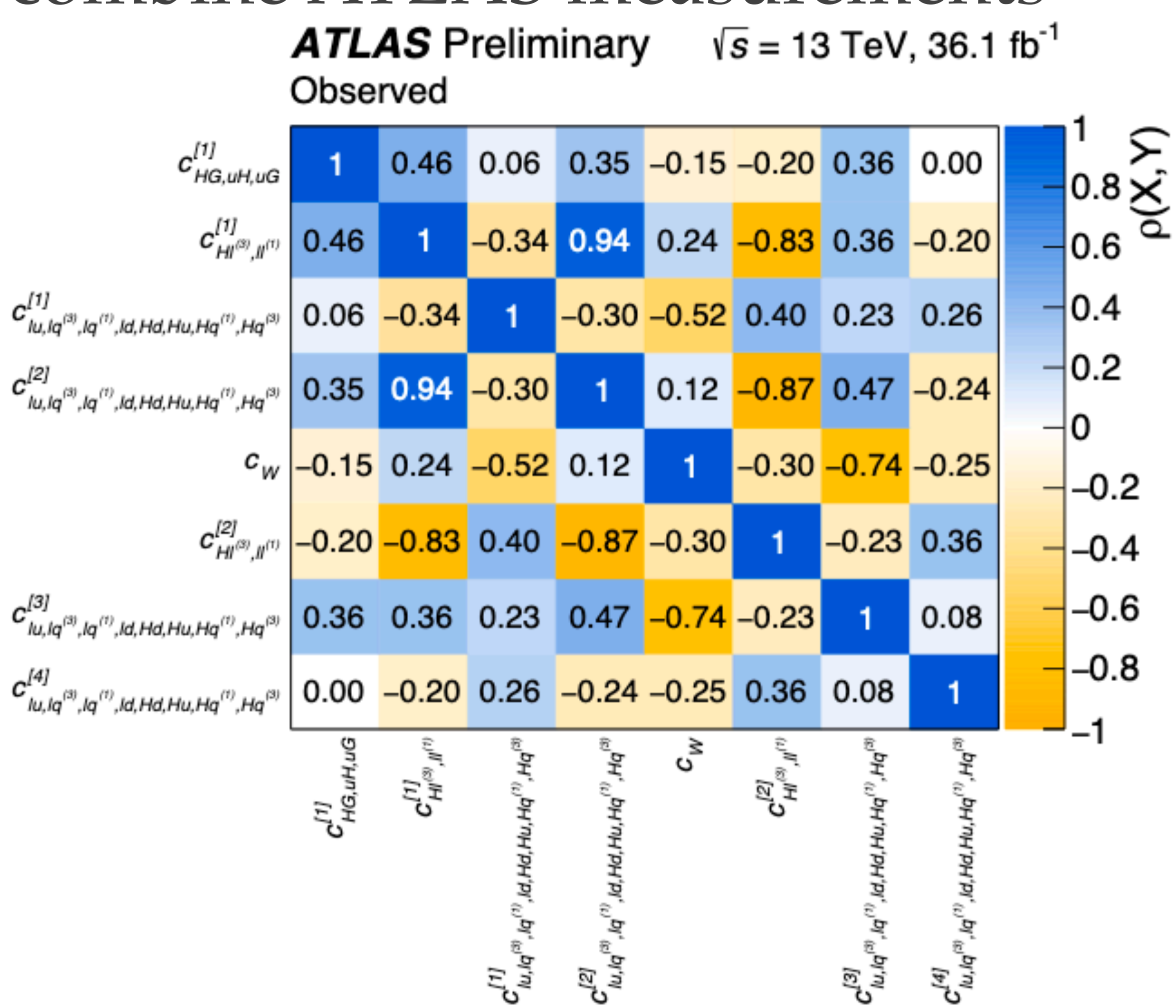
$$c'^{[0]}_{2q2l} \approx -0.37c^{(1)}_{lq} + 0.89c^{(3)}_{lq} - 0.11c_{lu} - 0.21c_{eu} - 0.13c_{qe}$$

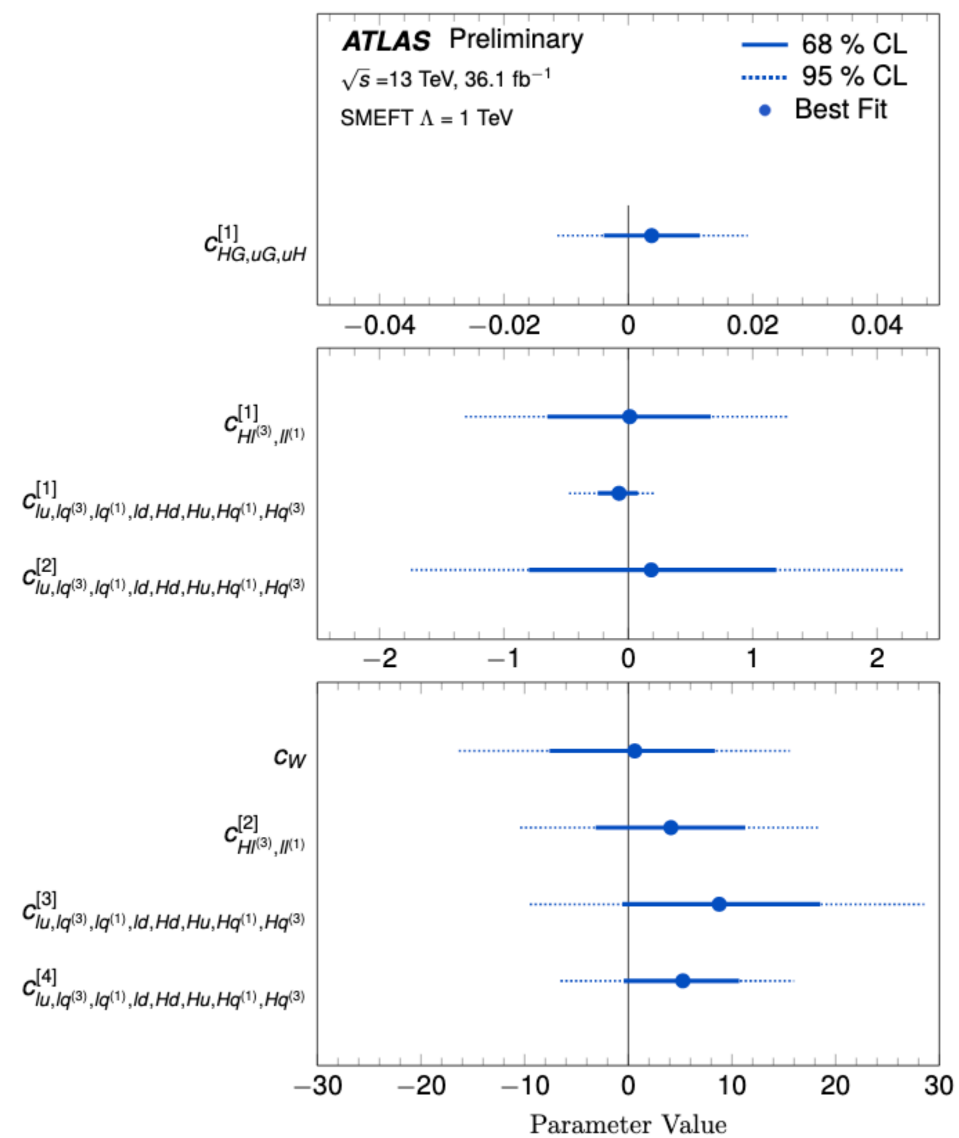
$$c'^{[0]}_{4q} \approx 0.11c^{(11)}_{qq} + 0.22c^{(18)}_{qq} + 0.95c^{(31)}_{qq} - 0.2c^{(38)}_{qq}$$

WW combination

ATL-PHYS-PUB-2021-010

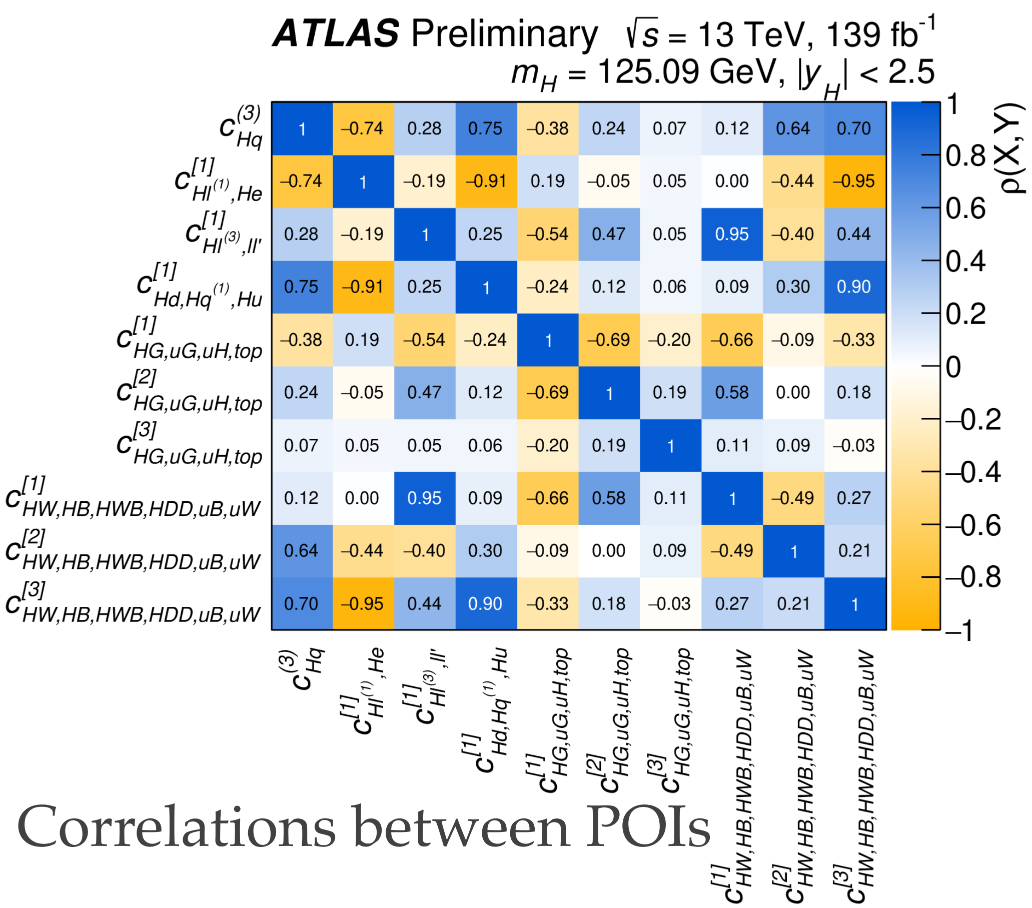
- Combination of H->WW* production mode signal strengths in the VBF and ggH channel with differential WW cross sections.
- Measured in orthogonal regions and uncertainties correlated appropriately
- Differences in acceptance between EFT and SM are taken into account:
  - In SM WW (as it is a fiducial measurement)
  - The difference due to modified Higgs decay kinematics for cHW(+10% wrt. SM) and cHl3 (-1.8% wrt. SM)
- Technical study of how we can properly combine ATLAS measurements





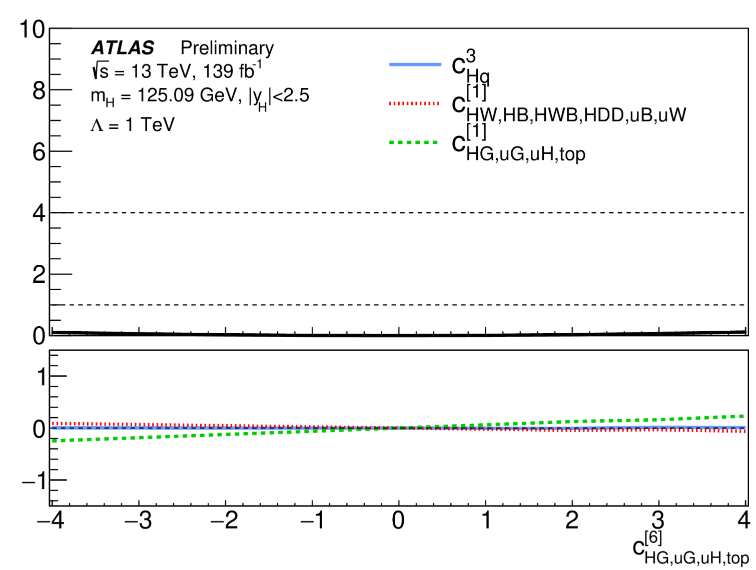
Higgs combination ATLAS

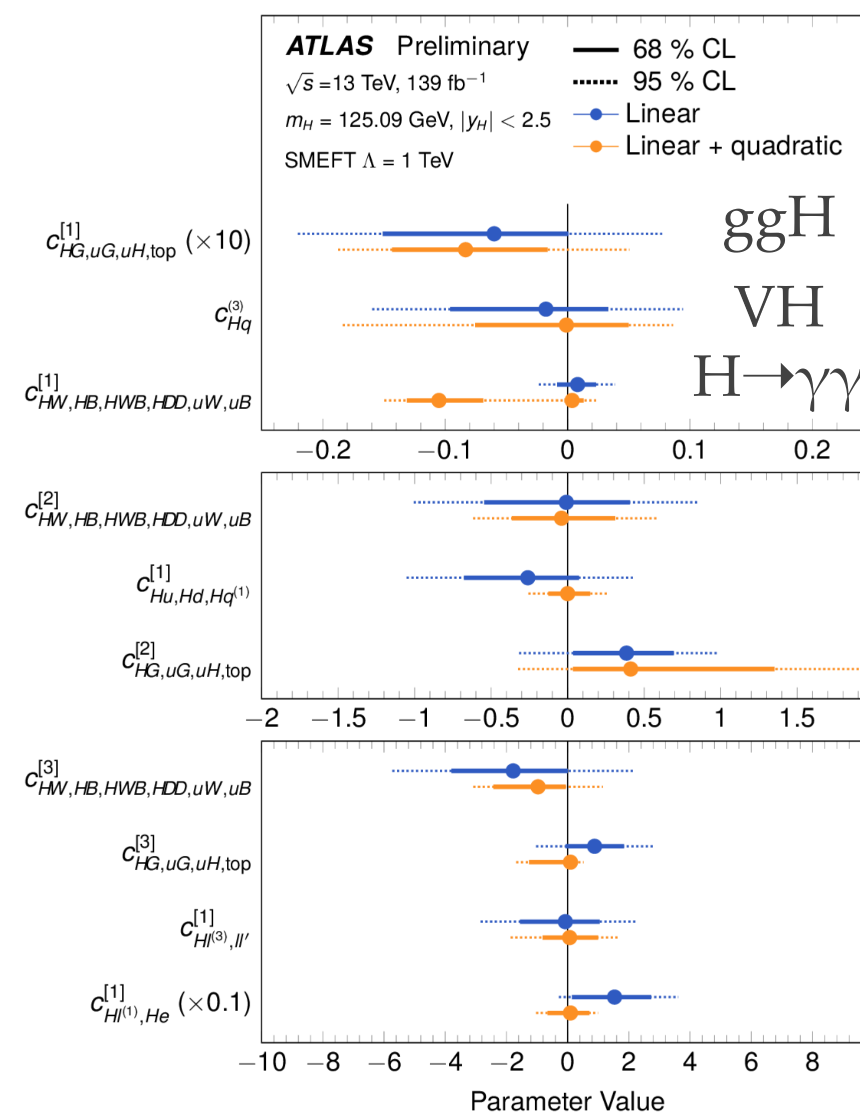
- Stage 1.2 STXS combination of H→γγ, VH(H→bb) and H→ZZ*→4l for full Run2. Based on $\sigma_{STXSi} \times BR_{H\to X}$ signal strength measurement
  - Lowest order of each production mode or decay channel: NLO QCD for ggH and ggZH from SMEFT@NLO, NLO EW for H→γγ, LO for the rest from SMEFTsim
  - Only CP-even operators (no linear contribution from CP-odd ones and not available in SMEFT@NLO)
  - Include the acceptance effects in H→ZZ*→4l for cHW, cHB and cHWB



Correlations between POIs

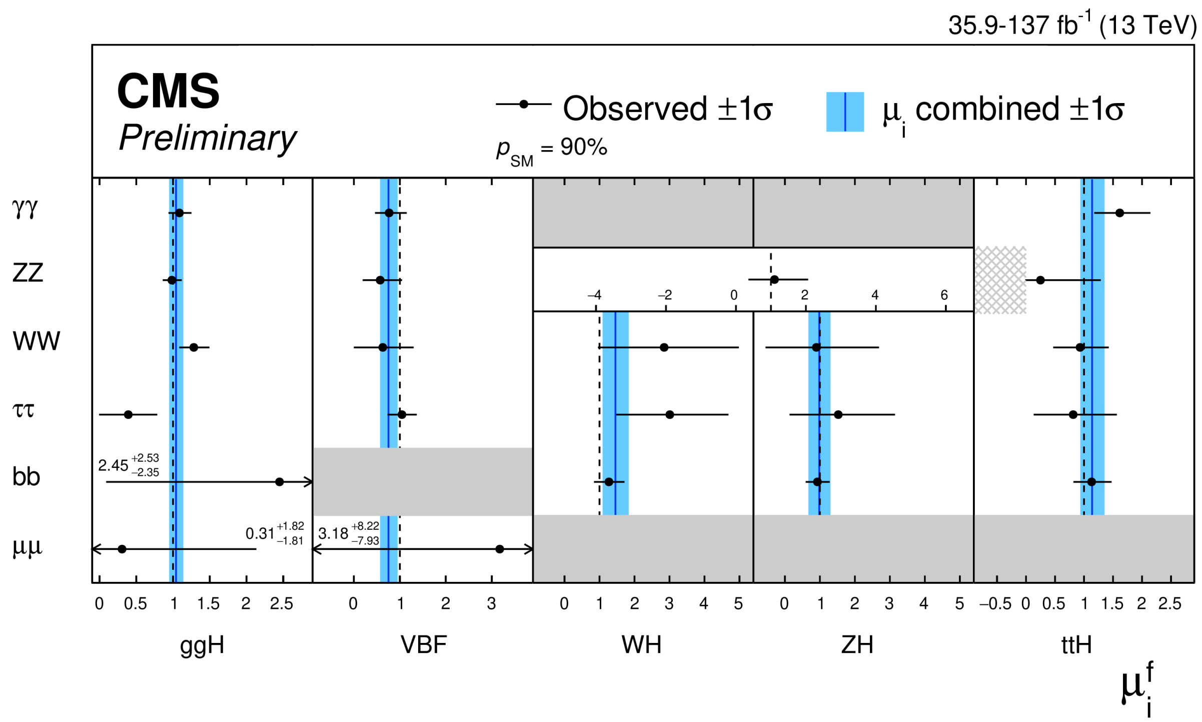
Neglected direction





Good sensitivity to the 10 fitted POIs

Higgs Combination CMS



HEL Parameters	Definition	Others profiled	Fix others to SM
$c_A \times 10^4$	$c_A = \frac{m_W^2}{g'^2}\frac{f_A}{\Lambda^2}$	$-1.03^{+1.53}_{-1.59}$ $\binom{+1.59}{-1.56}$	$-0.78^{+1.11}_{-1.16}$ $\binom{+1.10}{-1.11}$
$c_G \times 10^5$	$c_G = \frac{m_W^2}{g_s^2}\frac{f_G}{\Lambda^2}$	$1.43^{+3.20}_{-3.00}$ $\binom{+3.13}{-2.74}$	$0.27^{+1.05}_{-1.05}$ $\binom{+1.03}{-1.01}$
$c_u \times 10$	$c_u = -v^2\frac{f_u}{\Lambda^2}$	$0.68^{+0.82}_{-0.83}$ $\binom{+0.83}{-0.79}$	$0.43^{+0.69}_{-0.69}$ $\binom{+0.68}{-0.67}$
$c_d \times 10$	$c_d = -v^2\frac{f_d}{\Lambda^2}$	$0.59^{+1.03}_{-1.13}$ $\binom{+1.08}{-1.05}$	$-0.01^{+0.31}_{-0.28}$ $\binom{+0.30}{-0.28}$
$c_\ell \times 10$	$c_\ell = -v^2\frac{f_\ell}{\Lambda^2}$	$-0.57^{+0.74}_{-0.73}$ $\binom{+0.72}{-0.77}$	$-0.75^{+0.60}_{-0.64}$ $\binom{+0.58}{-0.60}$
$c_{HW} \times 10^2$	$c_{HW} = \frac{m_W^2}{2g}\frac{f_{HW}}{\Lambda^2}$	$-1.45^{+4.72}_{-3.03}$ $\binom{+3.93}{-3.27}$	$0.77^{+0.84}_{-1.20}$ $\binom{+1.04}{-1.38}$
$(c_{WW} - c_B) \times 10^2$	$c_{WW} = \frac{m_W^2}{g}\frac{f_{WW}}{\Lambda^2}$, $c_B = \frac{2m_W^2}{g'}\frac{f_B}{\Lambda^2}$	$2.16^{+2.84}_{-5.35}$ $\binom{+3.46}{-5.00}$	$0.62^{+1.06}_{-1.22}$ $\binom{+1.09}{-1.23}$

- Combined measurements of the production and decay rates of the Higgs boson and its couplings to vector bosons and fermions
- Interpretation in the HEL Lagrangian
  - SILH basis with flavour universality
- Signal strength values reparametrized in terms of EFT coefficients.
- Only interference term considered
  - CP-even terms not tightly constrained by other data
- Acceptance effects not taken into account
- Limits from simultaneous likelihood fits in the chosen parameters.
  - Significant differences in the constraints compared to 1-D fits

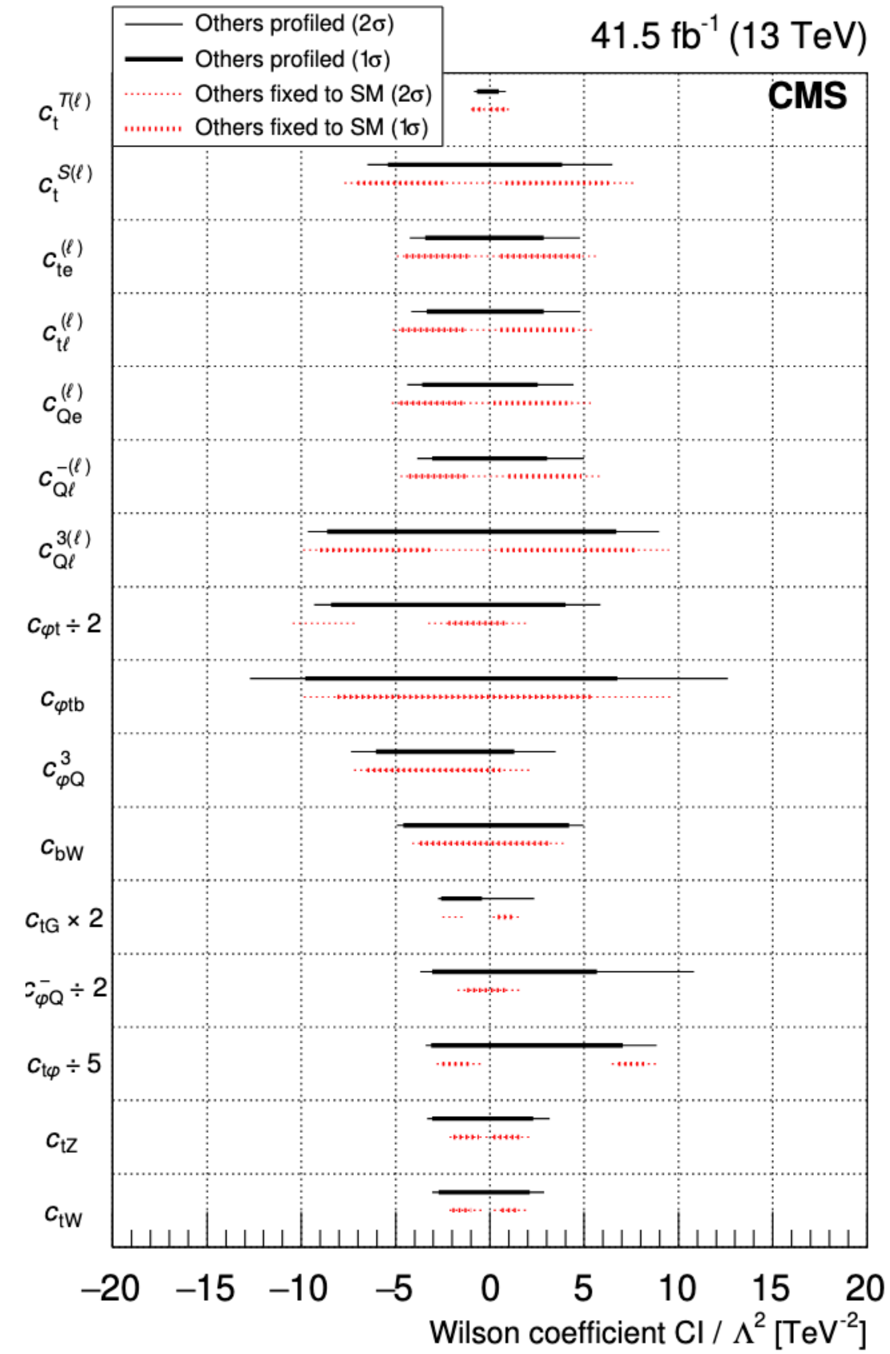
Top interpretations

EFT fit in differential cross-section tt measurements in M. Narain's talk

Top with additional leptons

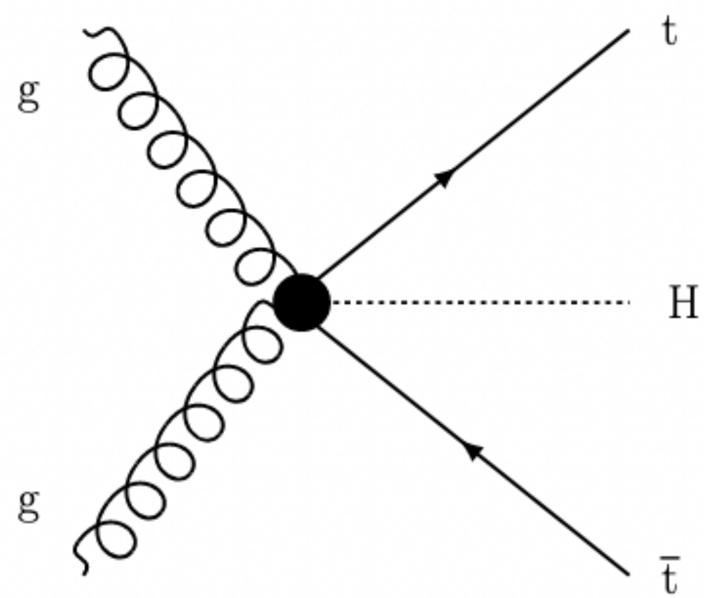
- Simultaneous fit to 16 EFT parameters affecting two quarks + boson(s) or two quarks and two leptons
- Yields parametrised in terms of the c_i. Exploits reweighing capabilities of MC generators
- 35 signal regions
  - 2l (same-sign): ttW and ttH
  - 3l: ttW (tt leptonic), tZq
  - 4l : ttZ, ttH

Subdivided by numbers of b-jets



linear+quadratic

[CMS-TOP-19-001](#)



Top EFT approach described in [arXiv: 1802.07237](#)

- Also obtained 1D and 2D limits from likelihood fit
- Largest uncertainties on EFT coming from additional radiation

tZ and ttZ

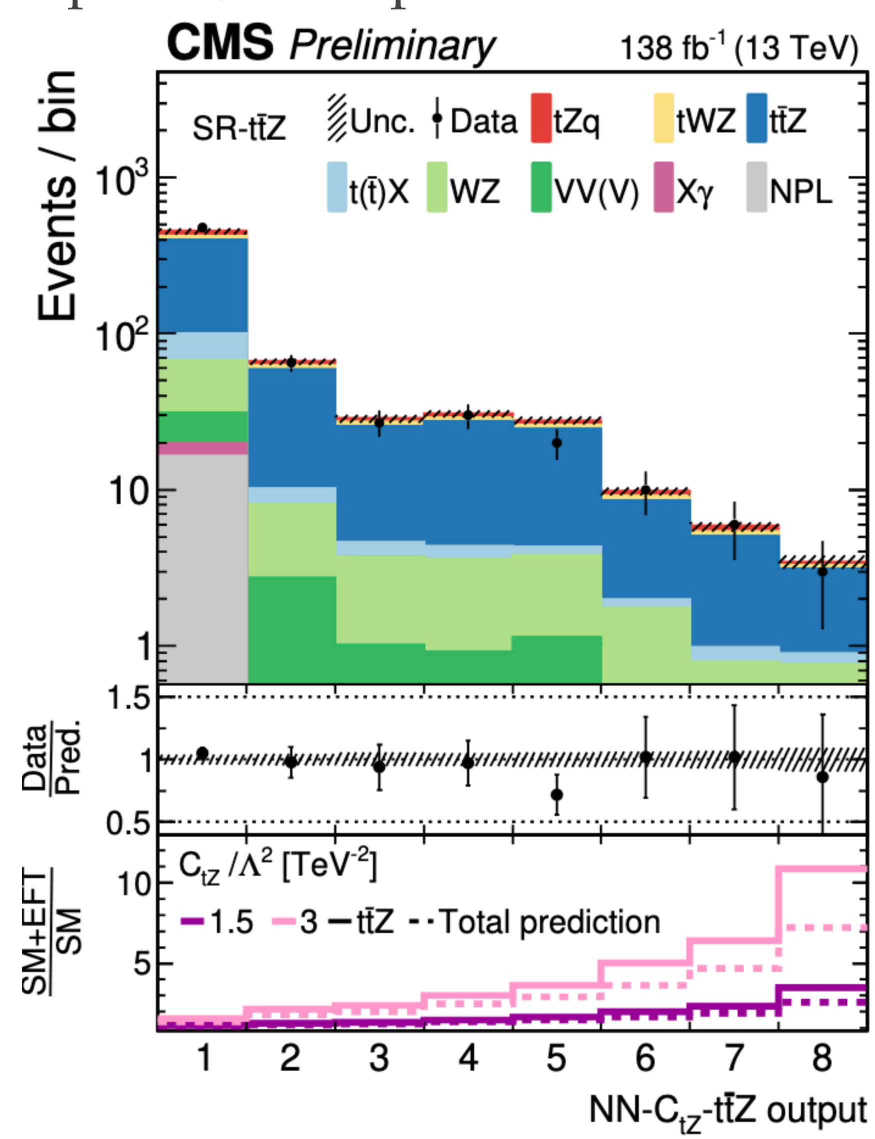
CMS-TOP-20-010

- Subset of 5 operators chosen in the Warsaw basis and combining them.
- Extensive use of MVA techniques
- Good sensitivity from SR-3l
- Signal extraction with 1D, 2D and 5D likelihood fit
- Better limits than earlier results from the ttZ cross section measurement

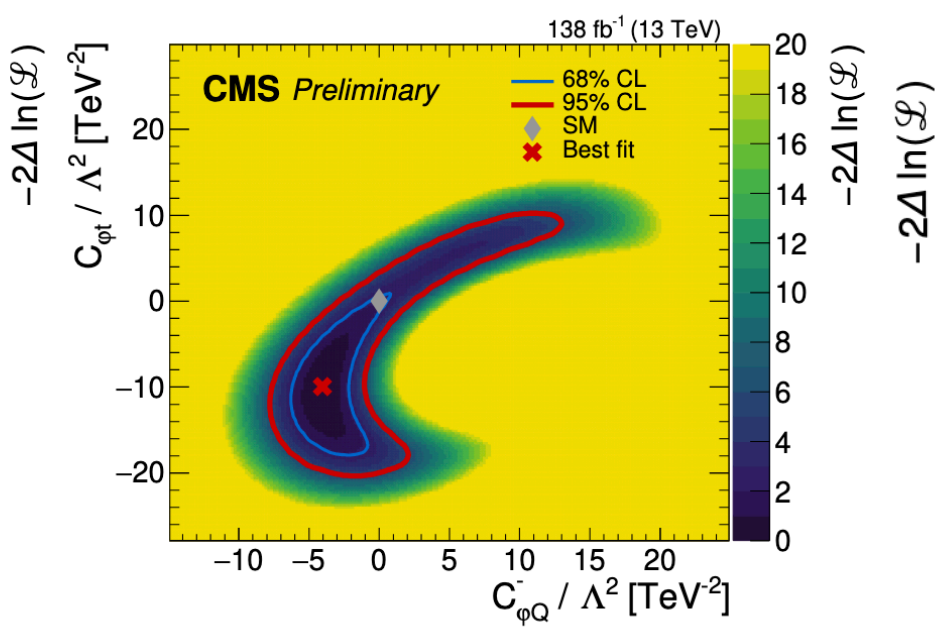
Operator	WC	Mapping to Warsaw-basis coefficients
$\mathcal{O}_{tZ}$	c_{tZ}	$\mathrm{Re}\{-s_W c_{uB}^{(33)} + c_W c_{uW}^{(33)}\}$
$\mathcal{O}_{tW}$	c_{tW}	$\mathrm{Re}\{c_{uW}^{(33)}\}$
$\mathcal{O}_{\varphi Q}^{3}$	$c_{\varphi Q}^{3}$	$c_{\varphi q}^{3(33)}$
$\mathcal{O}_{\varphi Q}^{-}$	$c_{\varphi Q}^{-}$	$c_{\varphi q}^{1(33)} - c_{\varphi q}^{3(33)}$
$\mathcal{O}_{\varphi t}$	$c_{\varphi t}$	$c_{\varphi u}^{(33)}$

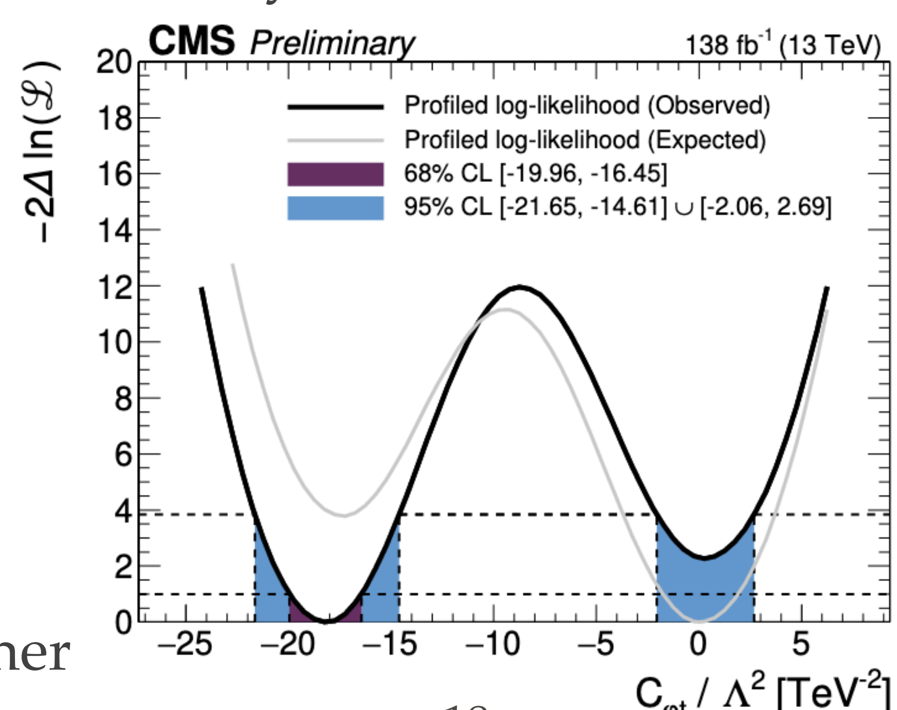
Only CP-even c_i involving gauge bosons and 3rd generation quarks

Using terms with up to $1/\Lambda^4$ dependence



Negative minima favoured 20% of the times (based on toys) due to fluctuations

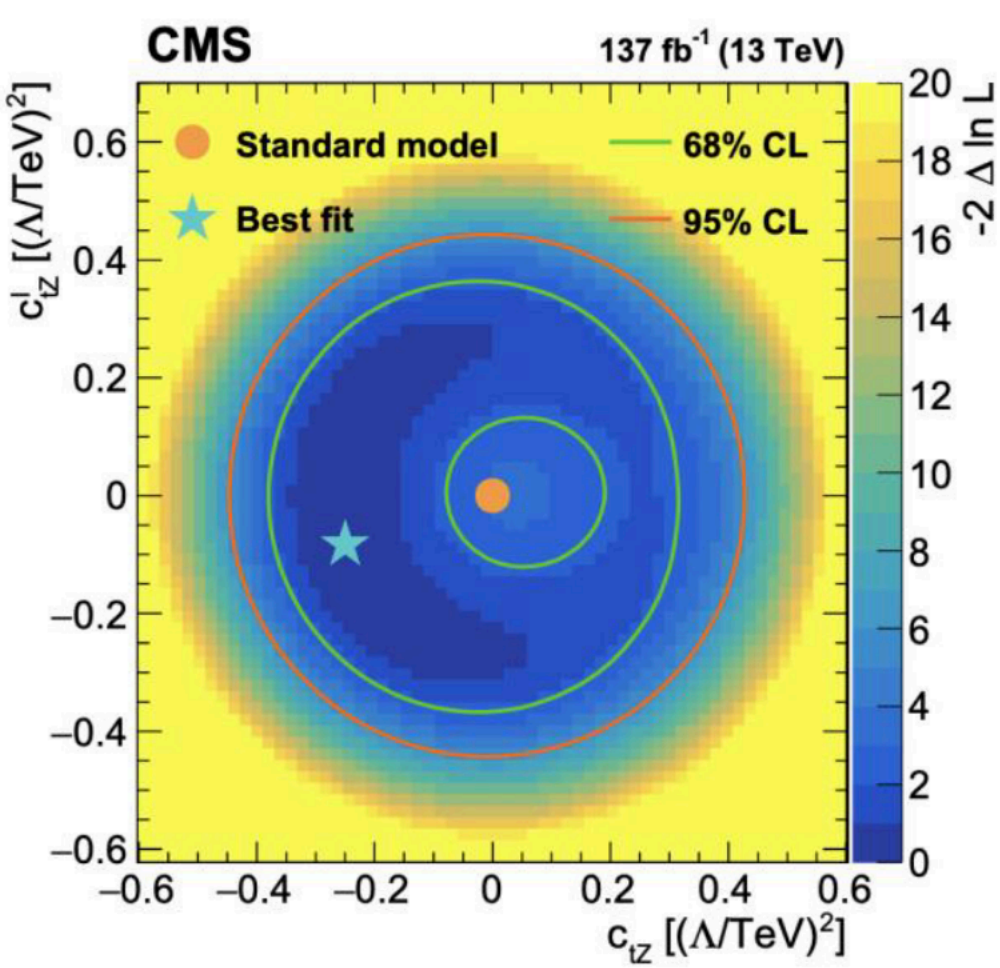




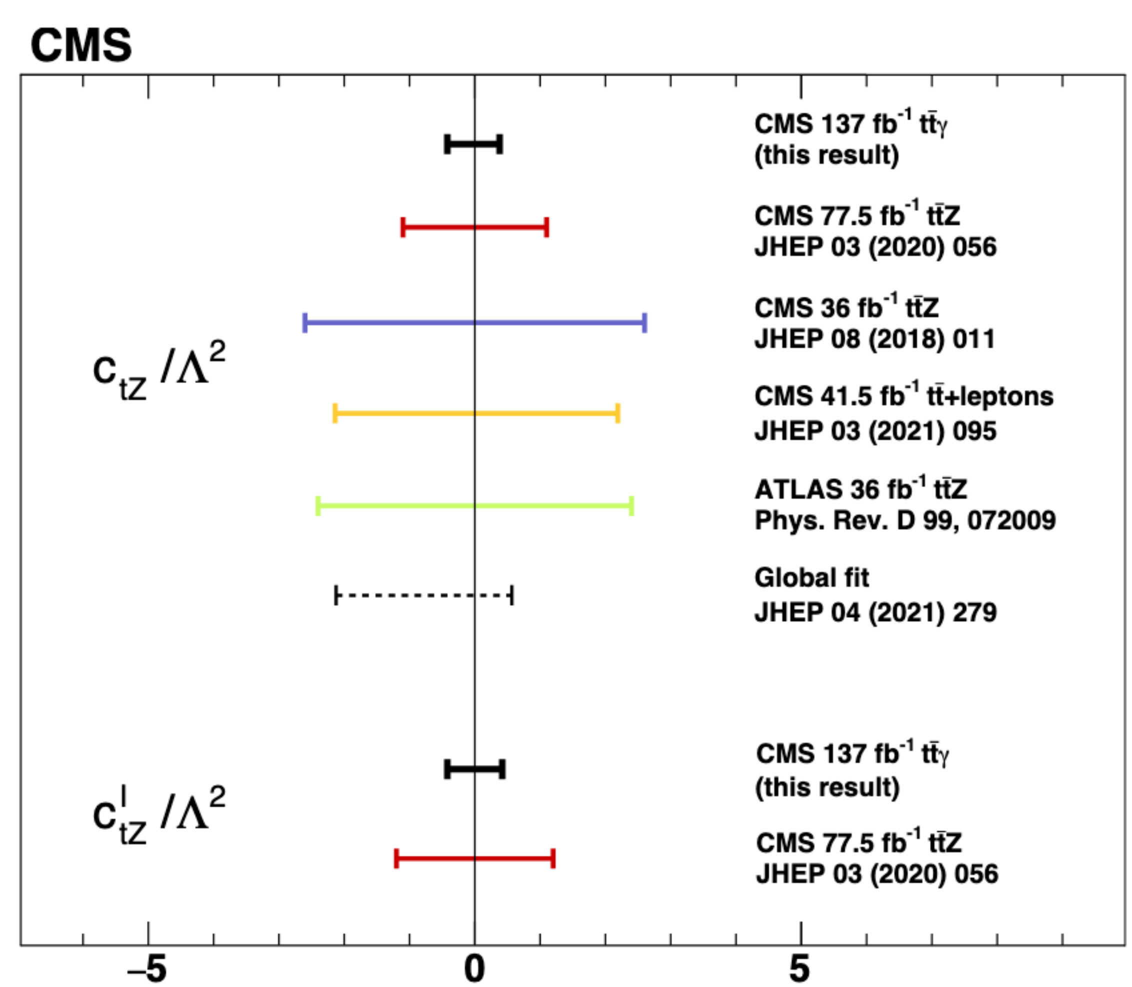
1D and 2D constraints with other parameters fixed to SM

- First CMS ttγ differential cross section measurement in the 1l channel
  - Exactly one lepton, one photon, at least 3 jets one b-tagged. Classified in Nj=3, Nj≥4 (for e- and μ- channels)
- Interpretation of linear and imaginary part of ctZ (EW dipole moment)
- Best current limits: operators inducing an EW dipole moment affects ttγ stronger than ttZ (provided that ctW is small)

Using terms with up to $1/\Lambda^4$ dependence



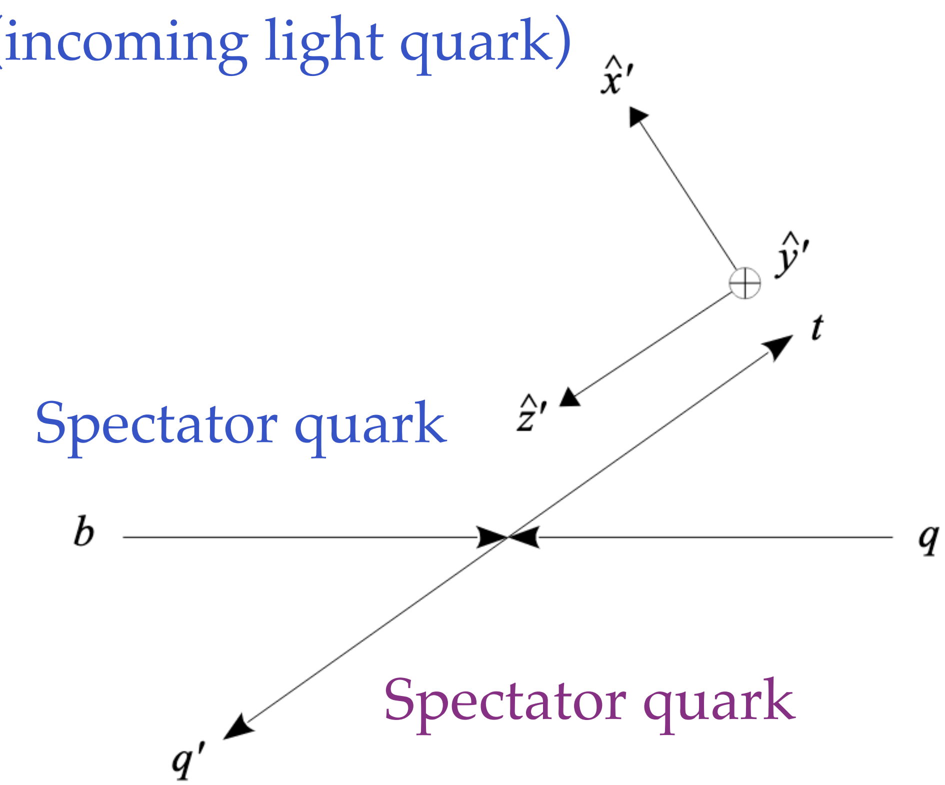
Limits extracted from pTγ distribution

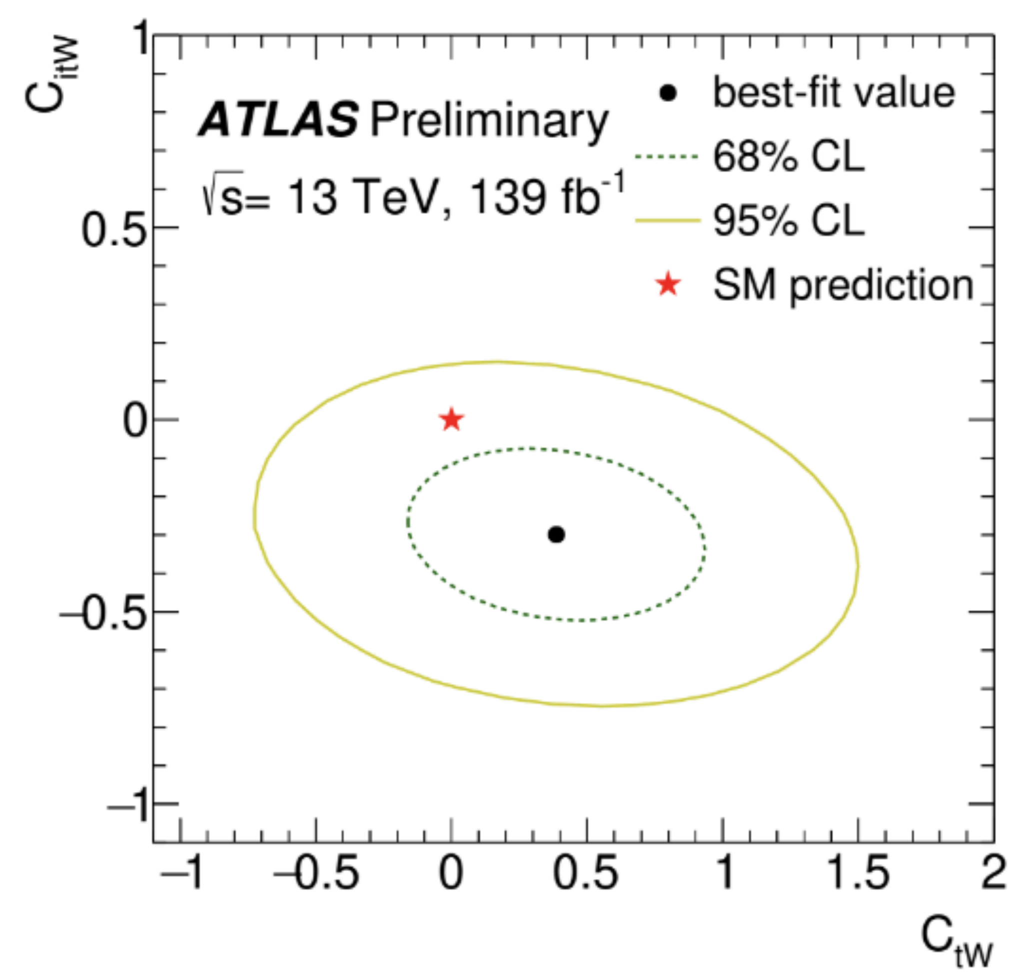


Top quark polarisation

ATLAS-CONF-2021-027

- Simultaneous measurement of the three components of the top polarisation vectors in t-channel tWq
- At LO top spins aligned along the direction of the spectator quark.
  - Spin information transmitted to decay products
- Polarisation vector extracted from angular distributions
  - Unfolded to particle level
- Obtain real and imaginary parts of ctW (affects Px and Py respectively)
- Better constraints of ctW in W-helicity measurement tt decays combination but imaginary part ignored there.
- Similar constraints for interference or quadratic terms



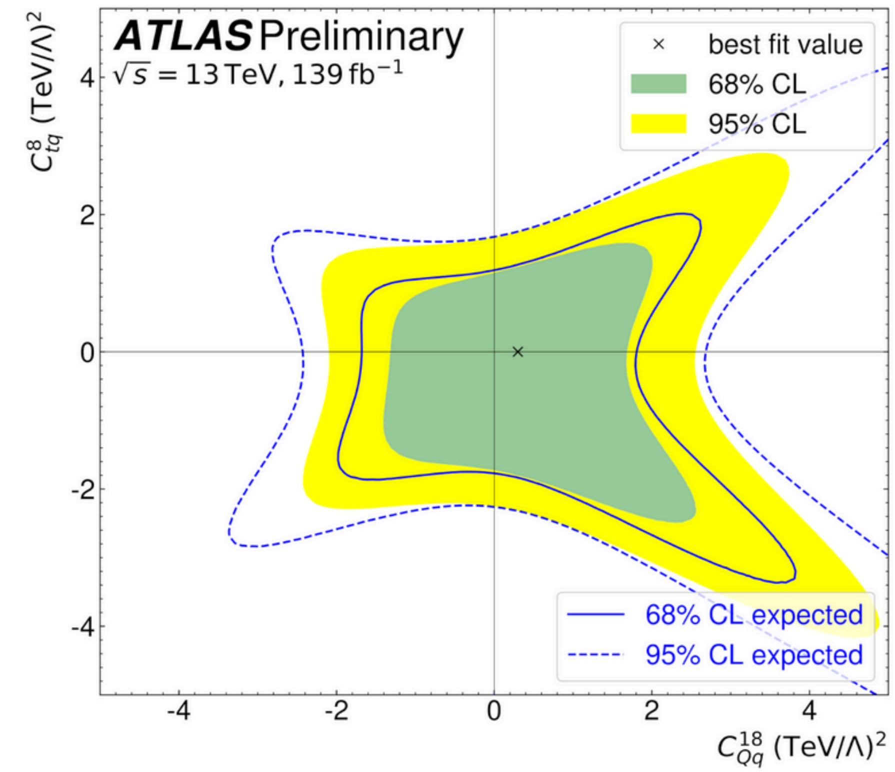


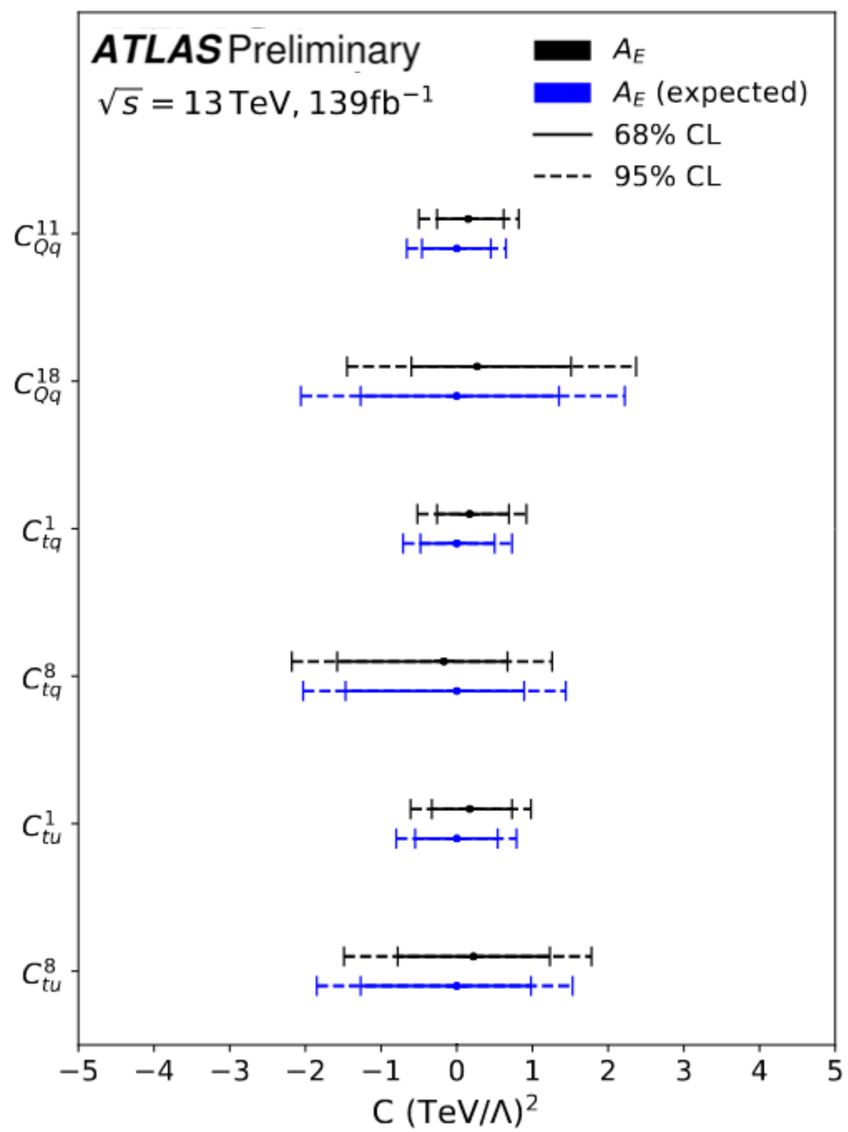
Energy asymmetry in tt+jets

- Measures the difference of top and antitop energies as a function of jet scattering angle with respect to beam axis:

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

$$\sigma^{\text{opt}}(\theta_j) = \sigma(\theta_j|y_{t\bar{t}j} > 0) + \sigma(\pi - \theta_j|y_{t\bar{t}j} < 0)$$





Link to come
[TOPQ-2019-28-002]

- In ttj events, asymmetries occur at tree level (at NLO in tt)
- SMEFT analysis in the boosted regime (600 GeV< mtt <1200 GeV)
- Particularly sensitive to the chirality and the color charges of the involved quark fields SMEFT fit to 6 selected operators in Warsaw basis

Summary

- Model-independent searches (no EFT) can help to explore phase-spaces that have not been checked before
- Large plethora of measurements including EFT interpretations of their results
  - Global fits are quite challenging but will improve the constraints
  - Evolving to common strategies (LHC EFT WG formed last year)
- Also several dedicated analysis built to be able to constrain EFT parameters looking at different regions of the phase-space
- No significant deviation from the SM found.

Thanks!

Back up

Outline

- Introduction
- Generic searches
- EFT interpretations - EW and Higgs
- EFT interpretations - Top
- Summary

CAVEAT: Large number of EFT analyses or measurements including EFT interpretation. Only most recent or relevant covered

Bases

- At each dimension, several bases can be worked out

Basis: Complete set of not-redundant operators. Takes into account:
  - Group identities (Fierz)
  - Equations of motion
  - Integration by parts

- Some examples for **dimension 6**:

Basis	Underlying gauge symmetry	Fields used in the Lagrangian
Warsaw, SILH	$SU(3)_C \times SU(2)_L \times U(1)_Y$	Gauge-eigenstates
BSM primaries, Higgs	$SU(3)_C \times SU(2)_L \times U(1)_Y$	Mass-eigenstates
Higgs/BSM characterisation	$SU(3)_C \times U(1)_{EM}$	Mass-eigenstates

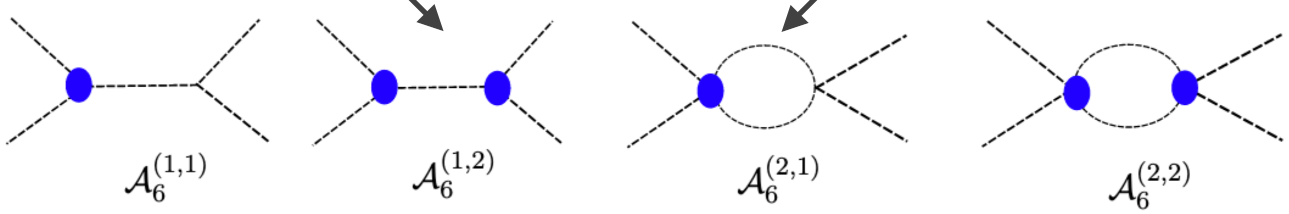
From Eur. Phys. J. C (205) 75:583

- Full RGE for **Warsaw** basis (being standardised in experiments but translation is always possible)

- Number of operators depends on flavour assumptions
  - 2499 in d=6 for Nf=3; 76 for Nf=1

Higher orders in SMEFT and other concepts

More insertions More loops



And higher dimensional operators

Interference Quadratic

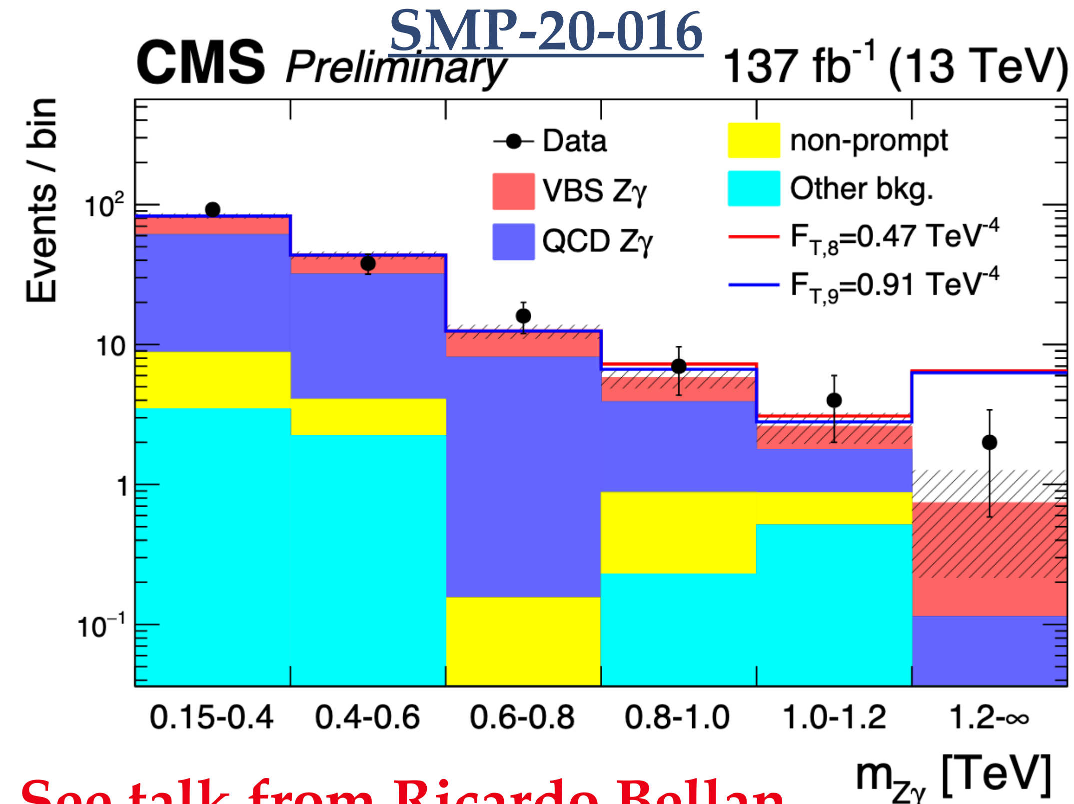
$$|\mathcal{A}_{\text{EFT}}|^2 = |\mathcal{A}_{\text{SM}}|^2 + \bar{g}\,|\mathcal{A}_{\text{SM}} \cdot \mathcal{A}_6^{(1,1)}| + \bar{g}^2\,|\mathcal{A}_6^{(1,1)}|^2 + \bar{g}^2\,|\mathcal{A}_{\text{SM}} \cdot \mathcal{A}_6^{(1,2)}| + \frac{\bar{g}}{\Lambda^2}\,|\mathcal{A}_{\text{SM}} \cdot \mathcal{A}_8^{(1,1)}| + \ldots$$

From 1809.04189

- Naive expectation: dim-6-interf > dim-6 quadratic ~ dim-8 interference
  - Not always true (e.g. if interference is suppressed)
  - Studies of quadratic terms can be a test of the EFT convergence
- Typically, a LO SMEFT is used
  - But SMEFT compatible with NLO corrections, unlike kappa-framework or anomalous couplings.
- No clear recommendations on uncertainties for EFT predictions.
- In differential measurements, effect of operators usually growing with $(E/\Lambda)^{d-4}$
  - Measure in tails of distributions
- Growth of amplitude with energy can violate unitarity → EFT no longer valid

CMS anomalous couplings

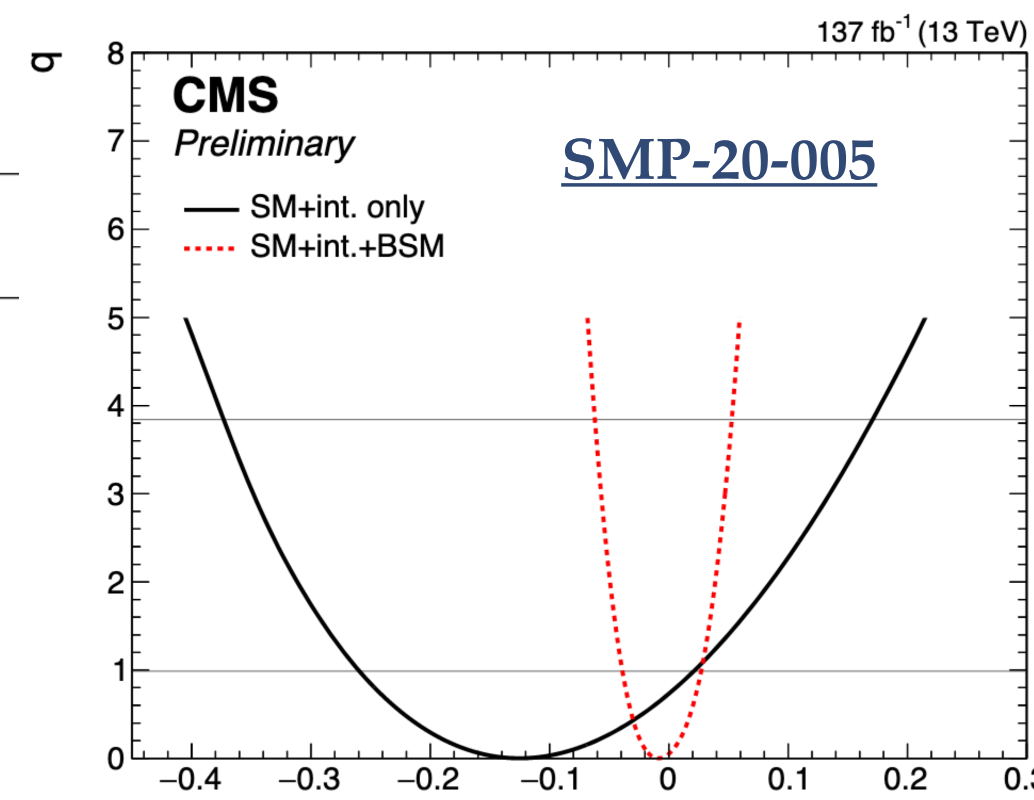
- Several new results from the CMS collaboration searching for anomalous triple and quartic gauge coupling: Zγ, Wγ, W$\gamma\gamma$ and Z$\gamma\gamma$
  - Using EFT: Éboli basis for dim 8
  - Limits extracted from mZγ, pTγ and $|\phi_f|$ or pT$\gamma\gamma$ unfolded distributions
  - Most stringent limits to date to fT,9 from Zγ (± 0.91)



See talk from Ricardo Bellan

Parameter	W$\gamma\gamma$ (TeV^{-4}) Expected	W$\gamma\gamma$ (TeV^{-4}) Observed	Z$\gamma\gamma$ (TeV^{-4}) Expected	Z$\gamma\gamma$ (TeV^{-4}) Observed
$f_{M,2}/\Lambda^4$	[−57.3, 57.1]	[−39.9, 39.5]	-	-
$f_{M,3}/\Lambda^4$	[−91.8, 92.6]	[−63.8, 65.0]	-	-
$f_{T,0}/\Lambda^4$	[−1.86, 1.86]	[−1.30, 1.30]	[−4.86, 4.66]	[−5.70, 5.46]
$f_{T,1}/\Lambda^4$	[−2.38, 2.38]	[−1.70, 1.66]	[−4.86, 4.66]	[−5.70, 5.46]
$f_{T,2}/\Lambda^4$	[−5.16, 5.16]	[−3.64, 3.64]	[−9.72, 9.32]	[−11.4, 10.9]
$f_{T,5}/\Lambda^4$	[−0.76, 0.84]	[−0.52, 0.60]	[−2.44, 2.52]	[−2.92, 2.92]
$f_{T,6}/\Lambda^4$	[−0.92, 1.00]	[−0.60, 0.68]	[−3.24, 3.24]	[−3.80, 3.88]
$f_{T,7}/\Lambda^4$	[−1.64, 1.72]	[−1.16, 1.16]	[−6.68, 6.60]	[−7.88, 7.72]
$f_{T,8}/\Lambda^4$	-	-	[−0.90, 0.94]	[−1.06, 1.10]
$f_{T,9}/\Lambda^4$	-	-	[−1.54, 1.54]	[−1.82, 1.82]

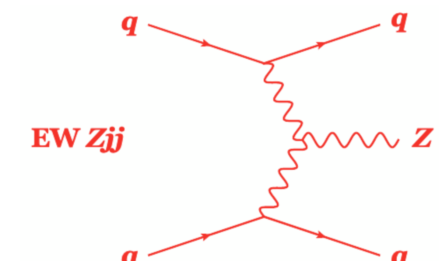
SMP-19-039



$$\sigma_j^{tot} = \sigma_j^{SM} + C_{3W}\sigma_j^{int} + C_{3W}^2\sigma_j^{BSM}$$

Limits extracted for different pTγ cutoffs

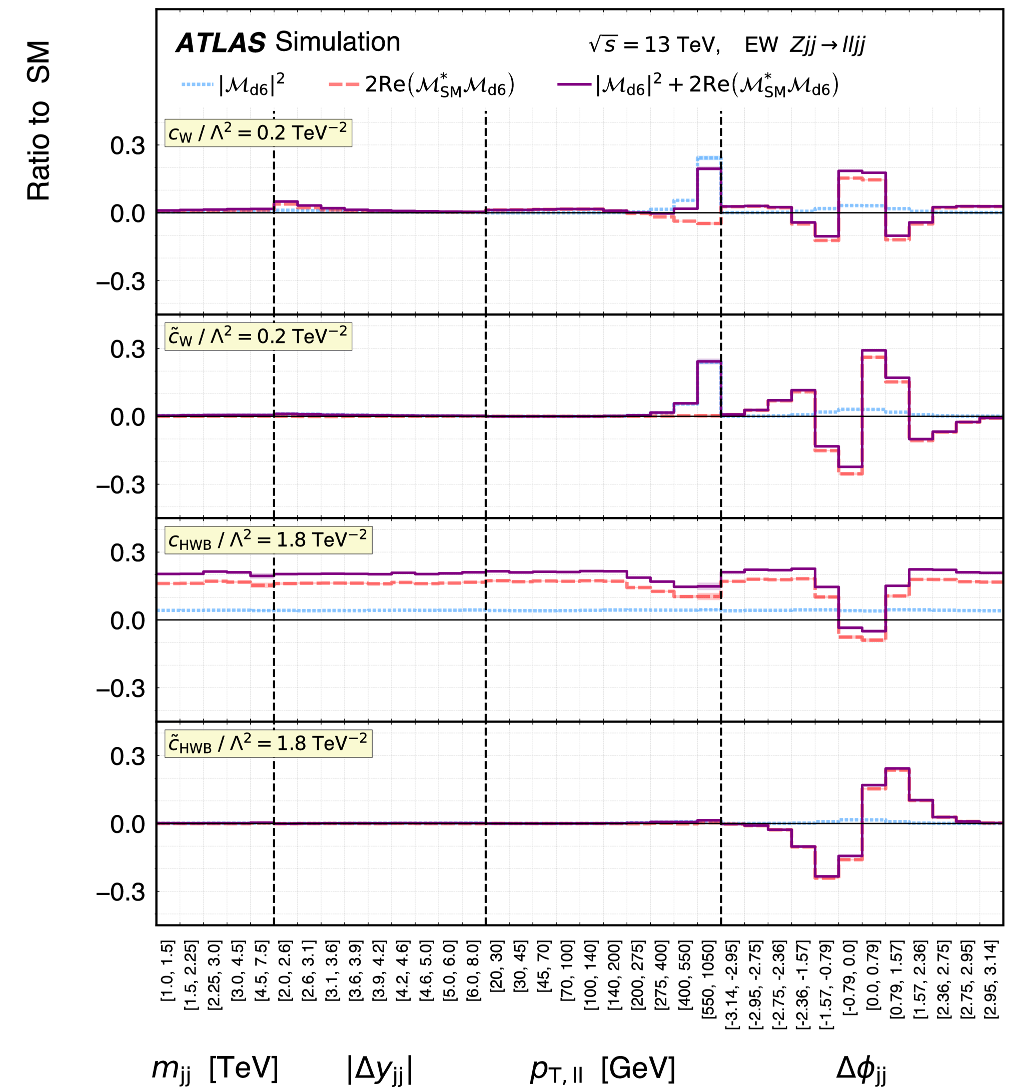
ATLAS: EW Zjj



(a)

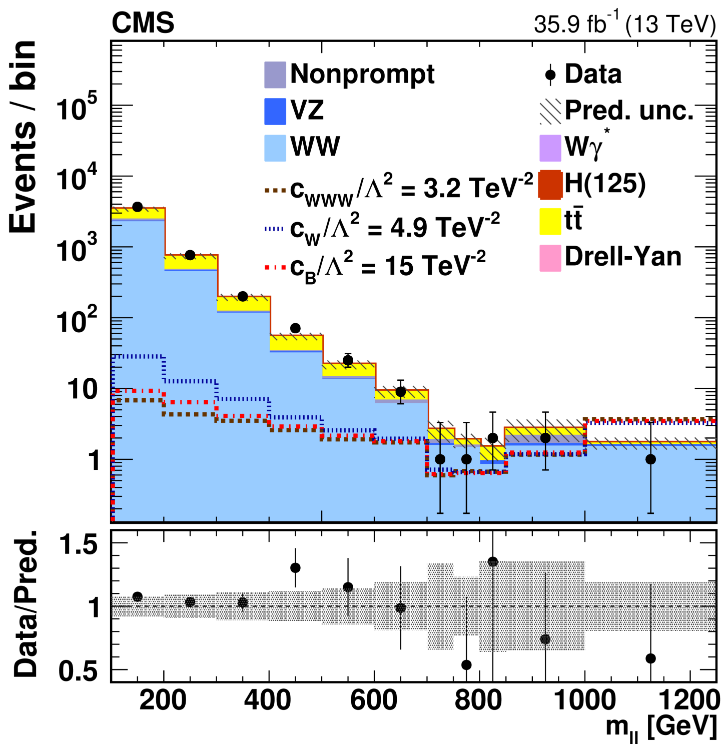
- Differential cross sections for EW Zjj production (Z to ee or μμ) for the first time. Full Run 2 analysis
- Shape and normalisation of strong Zjj from data-driven method (significant modelling unc. in the predictions)
- Using Warsaw basis as implemented in SMEFTsim package
- Also exploits parity odd observables, $\Delta\phi_{jj}$, for the constraint of CP-even and CP-odd operators
- Checked importance of quadratic terms
  - Constraints mainly from interference (test of EFT convergence), no unitarity violation issues.

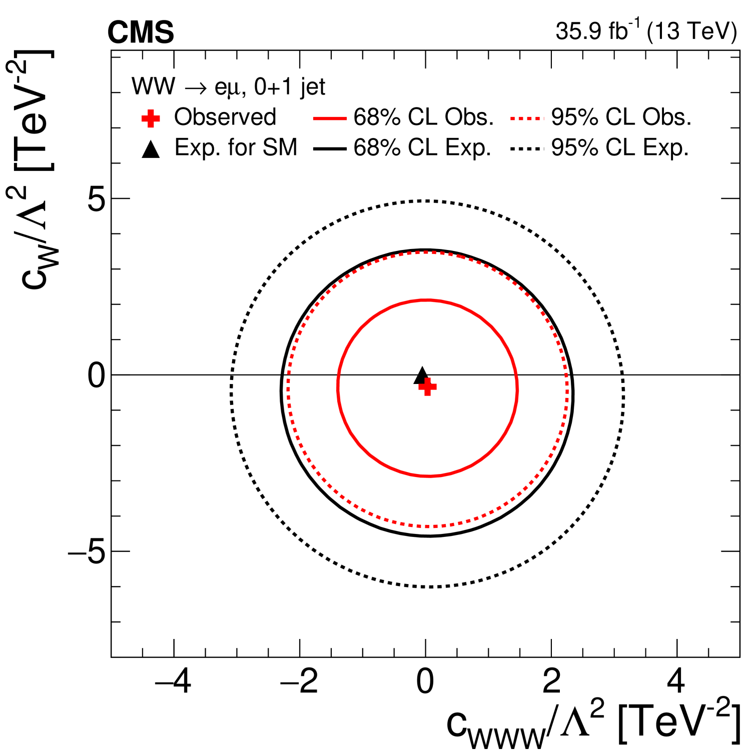
Wilson coefficient	Includes $\lvert\mathcal{M}_{d6}\rvert^2$	95% confidence interval [TeV^{-2}] Expected	Observed	p-value (SM)
c_W/Λ^2	no	$[-0.30,\ 0.30]$	$[-0.19,\ 0.41]$	45.9%
	yes	$[-0.31,\ 0.29]$	$[-0.19,\ 0.41]$	43.2%
$\tilde{c}_W/\Lambda^2$	no	$[-0.12,\ 0.12]$	$[-0.11,\ 0.14]$	82.0%
	yes	$[-0.12,\ 0.12]$	$[-0.11,\ 0.14]$	81.8%
c_{HWB}/Λ^2	no	$[-2.45,\ 2.45]$	$[-3.78,\ 1.13]$	29.0%
	yes	$[-3.11,\ 2.10]$	$[-6.31,\ 1.01]$	25.0%
$\tilde{c}_{HWB}/\Lambda^2$	no	$[-1.06,\ 1.06]$	$[0.23,\ 2.34]$	1.7%
	yes	$[-1.06,\ 1.06]$	$[0.23,\ 2.35]$	1.6%



$\Delta\phi_{jj}=y_f-y_b$ with $y_f>y_b$

CMS: WW

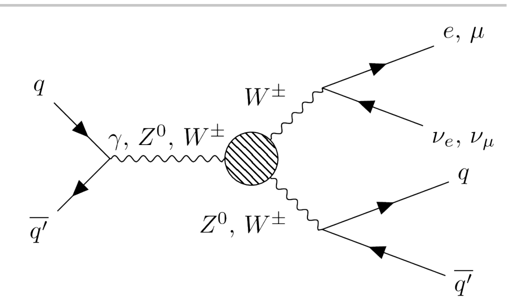




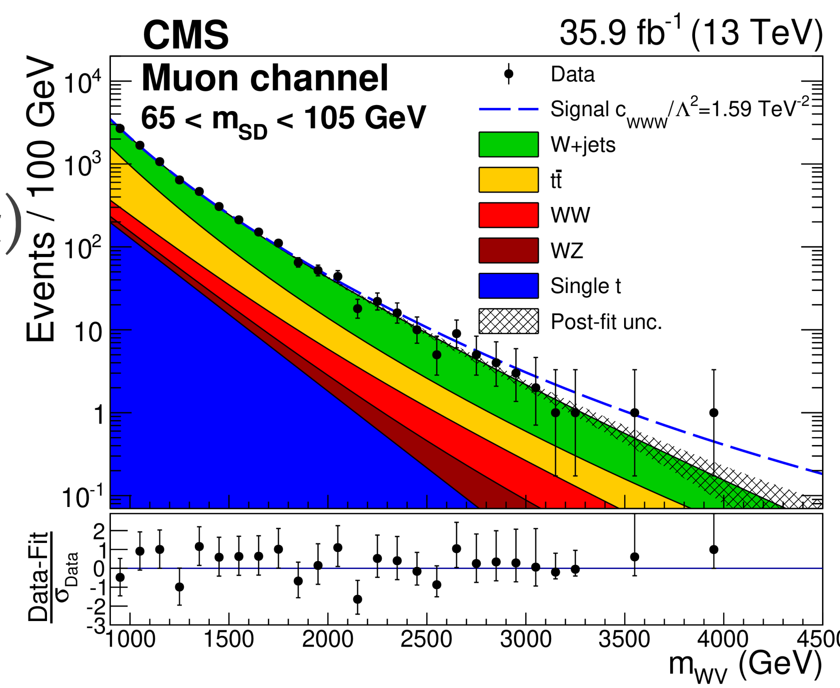
- Two methodologies (sequential cuts and random forests) studied for background estimation.
- $WW \to l^+\nu l^-\nu$ with 0 or 1-jet
- Limits from $m_{e\mu}$ templates (not sensitive to higher-order QCD effects or jet energy scale). BSM terms behave as SM in the unfolding
- Only different flavour event sample
  - Same flavour has larger contamination from DY
  - $m_{e\mu}$>100 GeV to reduce Higgs contribution
- Almost a factor 2 better more stringent than ATLAS
  - Due to the usage of 1-jet measurement

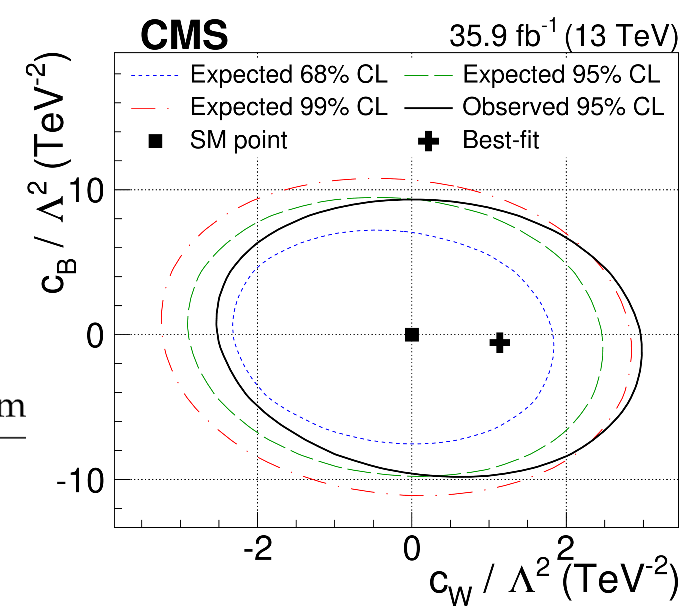
Coefficients (TeV^{-2})	68% confidence interval expected	68% confidence interval observed	95% confidence interval expected	95% confidence interval observed
c_{WWW}/Λ^2	$[-1.8, 1.8]$	$[-0.93, 0.99]$	$[-2.7, 2.7]$	$[-1.8, 1.8]$
c_W/Λ^2	$[-3.7, 2.7]$	$[-2.0, 1.3]$	$[-5.3, 4.2]$	$[-3.6, 2.8]$
c_B/Λ^2	$[-9.4, 8.4]$	$[-5.1, 4.3]$	$[-14, 13]$	$[-9.4, 8.5]$

CMS: WW and WZ



- Dedicated measurement for constraining anomalous $WW\gamma$ and WWZ couplings
- W decaying leptonically and Z or W hadronically (fat jet)
  - Semi-leptonic channels offer a good balance between purity and efficiency
  - Reduction of W+jets with jet substructure techniques
- Limits from 2D unbinned LH fits to (m_{SD},m_{WV})
- c_{WWW} and c_W similar impact in WW and WZ, c_B much greater in WW region.
  - Little separation power between c_{WWW} and c_W
- Improvement wrt. 8 TeV results

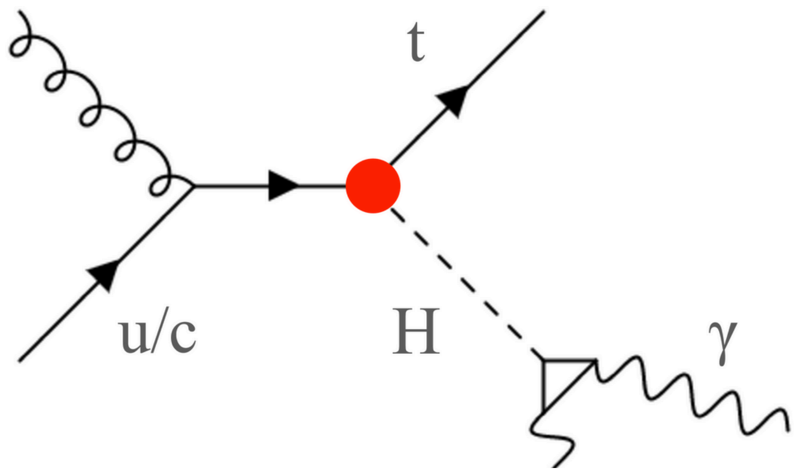




Parametrization	aTGC	Expected limit	Observed limit	Observed best-fit	8 TeV observed lim
EFT	c_{WWW}/Λ^2 (TeV^{-2})	[-1.44, 1.47]	[-1.58, 1.59]	-0.26	[-2.7, 2.7]
	c_W/Λ^2 (TeV^{-2})	[-2.45, 2.08]	[-2.00, 2.65]	1.21	[-2.0, 5.7]
	c_B/Λ^2 (TeV^{-2})	[-8.38, 8.06]	[-8.78, 8.54]	1.07	[-14, 17]
LEP	λ_Z	[-0.0060, 0.0061]	[-0.0065, 0.0066]	-0.0010	[-0.011, 0.011]
	Δg_1^Z	[-0.0070, 0.0061]	[-0.0061, 0.0074]	0.0027	[-0.009, 0.024]
	$\Delta\kappa_Z$	[-0.0074, 0.0078]	[-0.0079, 0.0082]	-0.0010	[-0.018, 0.013]

Top dedicated analysis: FCNC

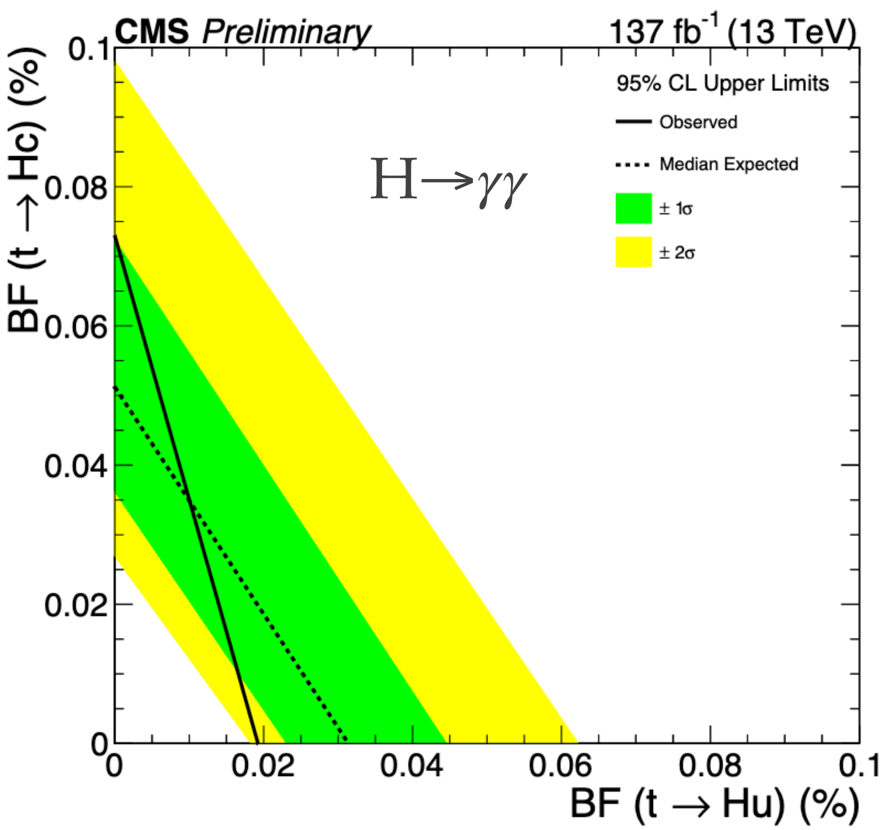
Example diagram of FCNF in tH($\gamma\gamma$) production

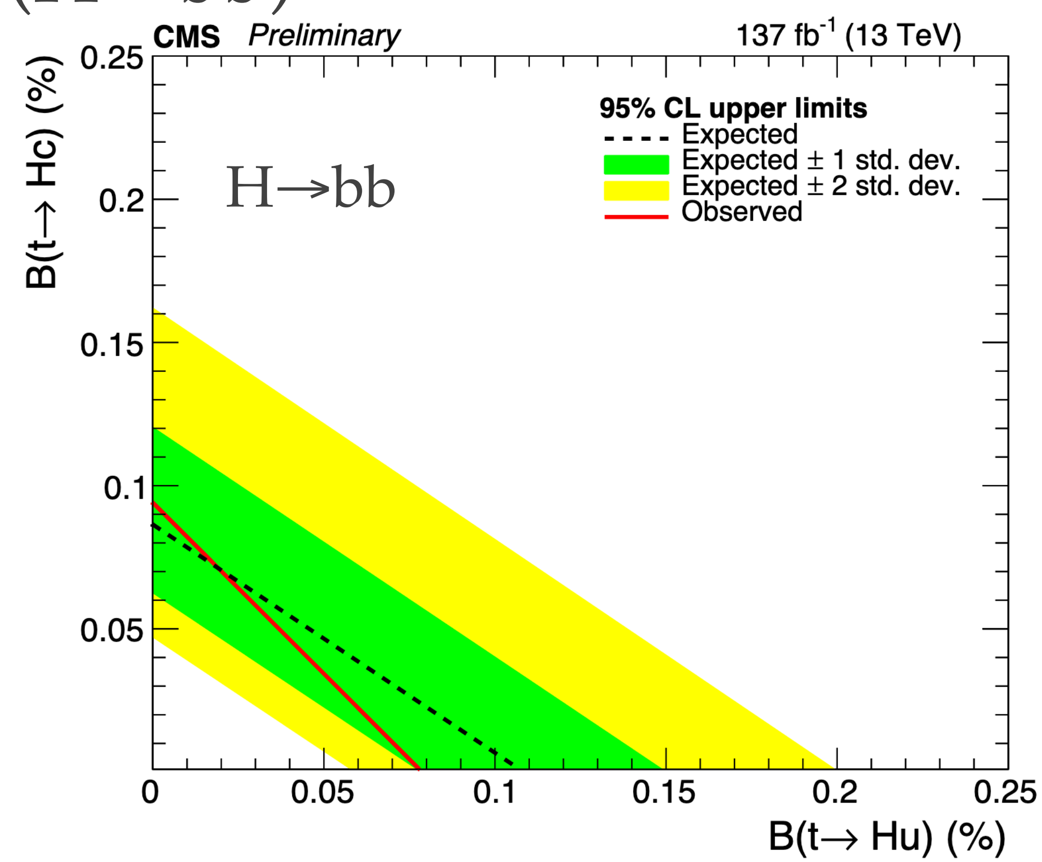


$$\mathcal{L} = \sum_{q=u,c} \frac{g}{\sqrt{2}} \bar{t}\kappa_{Hqt}\left(F^{L}_{Hq}P_{L} + F^{R}_{Hq}P_{R}\right)qH + \text{h.c.},$$

$$\kappa^2_{Hqt} = \mathcal{B}(t \to Hq)\frac{\Gamma_t}{\Gamma_{Hqt}}$$

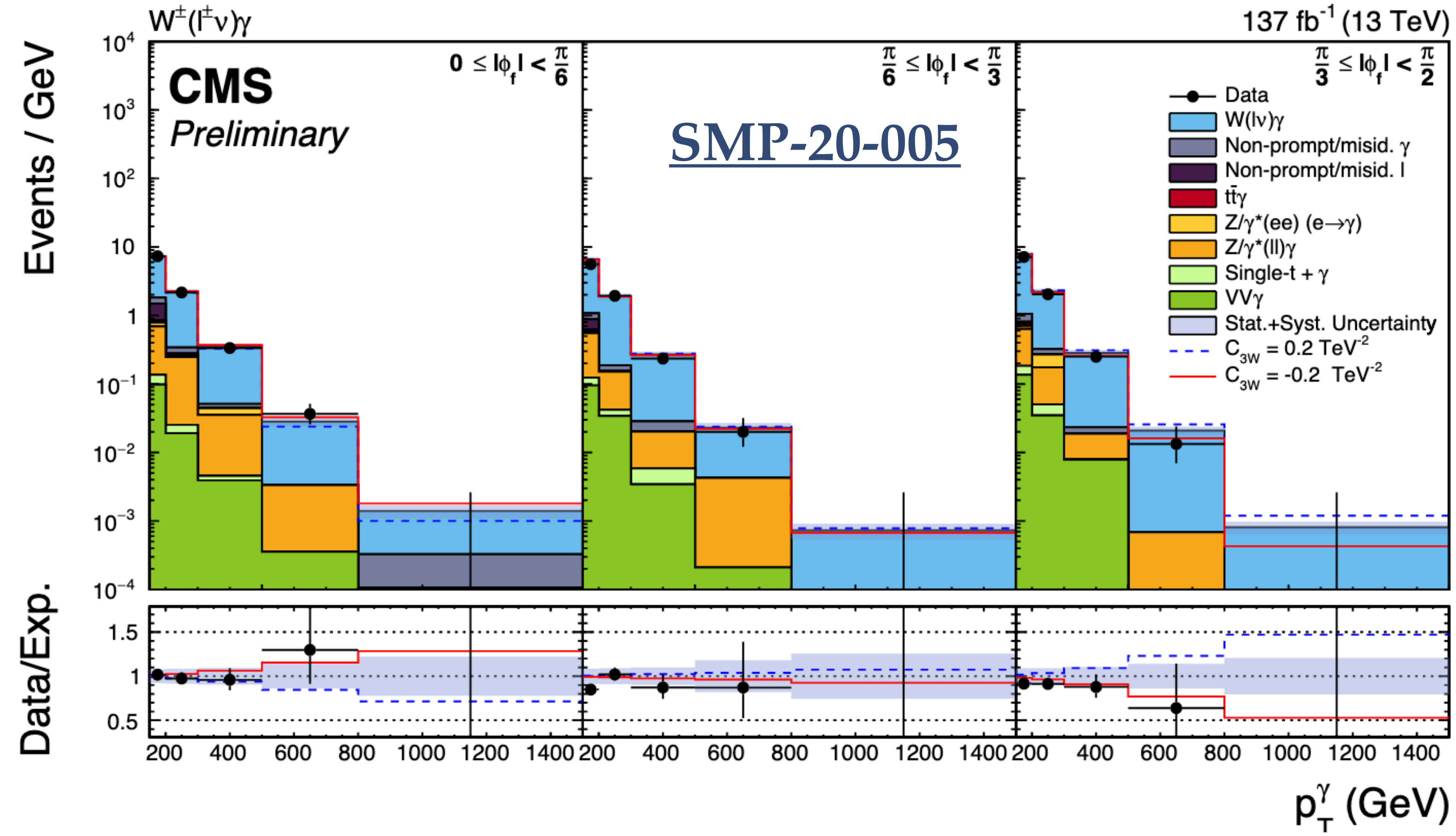
- Forbidden at tree level: Sensitive to new physics!
- FCNC in single top and tt production and in H→$\gamma\gamma$ and H→bb
- Improvement of the t →Hu and t →Hc BF
- Using a extension of the Lagrangian to allow for FCNC
- BR from m$\gamma\gamma$ fit in each category (H→$\gamma\gamma$) or BDT scores (H→bb)

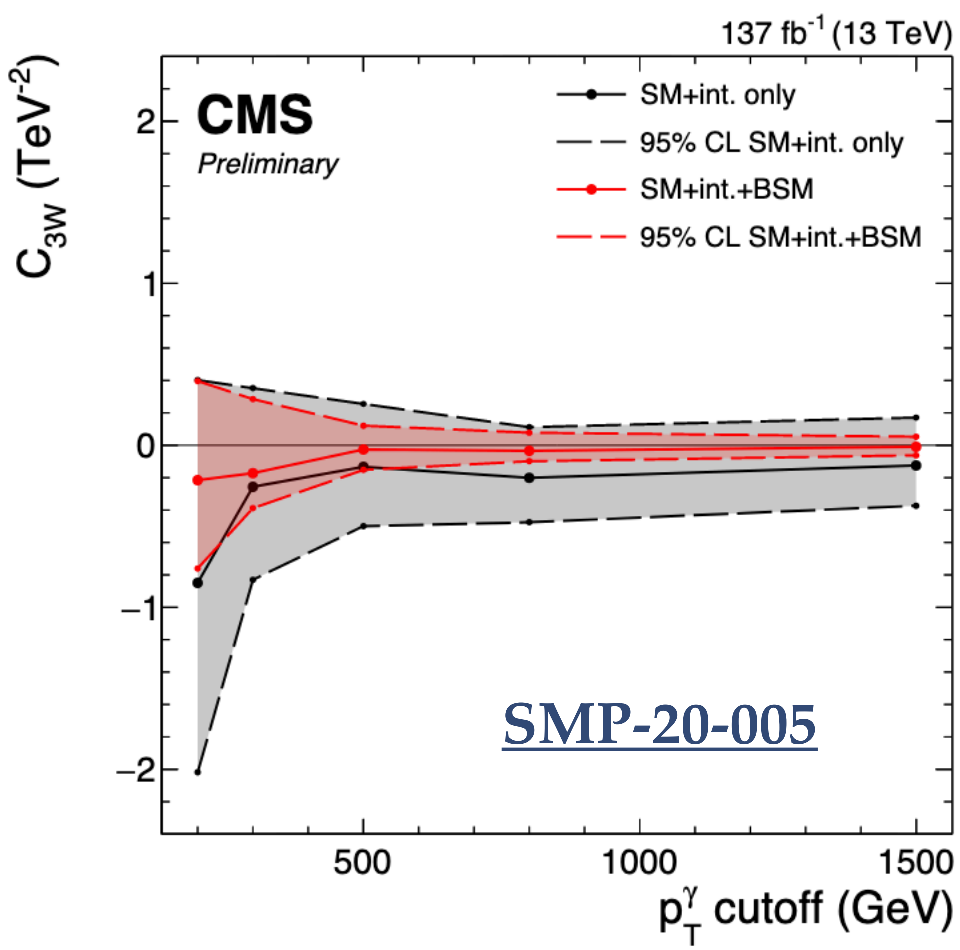




CMS anomalous couplings

- Usage of $|\phi_f|$ in the Wγ analysis helped to restore the sensitivity to the c_{3W} interference terms (suppressed when looking inclusively in the decay angles of the final-state fermions)





- Dimension-6 operators can violate unitarity at high values of pTγ
  - Limits to the c3W operator were obtained for different cutoff values corresponding to the upper edge of the last bin used in the EFT fit.

ATLAS anomalous couplings

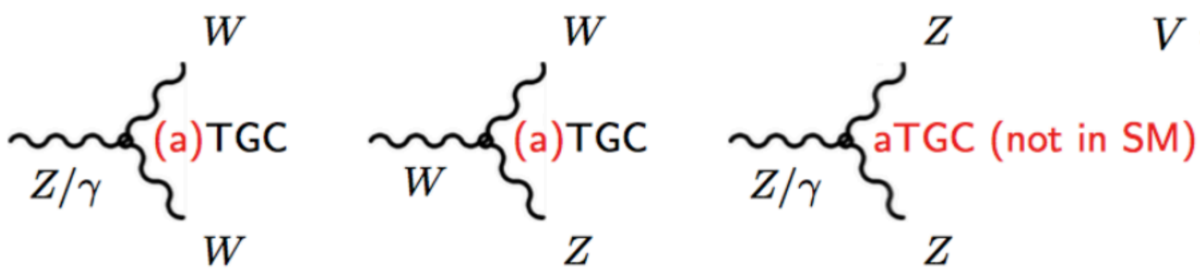
STDM-2018-34

- Many ATLAS analysis being combined (covered later)
- New results covering specific phase-space regions like WW+jets
Using EFT:
  - The requirement of an extra hard jet also reduces the suppression of the interference of SM and anomalous amplitudes
- Limits to c_W based on the unfolded $m_{e\mu}$ cross section for $pT_{jet} > 30$ GeV and $pT_{jet} > 200$ GeV

Jet p_T	Linear only	68% CI obs.	95% CI obs.	68% CI exp.	95% CI exp.
> 30 GeV	yes	[–1.64, 2.86]	[–3.85, 4.97]	[–2.30, 2.27]	[–4.53, 4.41]
> 30 GeV	no	[–0.20, 0.20]	[–0.33, 0.33]	[–0.28, 0.27]	[–0.39, 0.38]
> 200 GeV	yes	[–0.29, 1.84]	[–1.37, 2.81]	[–1.12, 1.09]	[–2.24, 2.10]
> 200 GeV	no	[–0.43, 0.46]	[–0.60, 0.58]	[–0.38, 0.33]	[–0.53, 0.48]

- The linear fit constraints improve previous WW results but still weaker than in Zjj EW production
- Exploration of different variables to increase the sensitivity to EFT also done in Zjj EW production (STDM-2017-27)

From aTGCs to EFTs



$V = Z, \gamma$

- aTGCs controlled by 3 CP-conserving parameters $\{\delta_1^V, \kappa_V, \lambda_V\}$. Additional terms needed for neutral gauge couplings and aQGCs. Lagrangian approach

$$-ig_{WWV}[g_1^V(W^+_{\mu\nu}W^{-\mu}V^\nu - W^-_{\mu\nu}W^{+\mu}V^\nu) + \kappa_V W^+_\mu W^-_\nu V^{\mu\nu}] - i\frac{\lambda_V}{m_W^2}V^{\mu\nu}W^{+\rho}_\nu W^-_{\rho\mu}$$

- Can add more terms adding derivatives (with additional 1/Mw scaling).
- Not necessarily gauge invariant
- Leads to unitarity violation → Use e.g. form factors
- EFT operators in dimension-6 for TGCs

$$g_1^Z = 1 + c_W\frac{m_Z^2}{\Lambda^2}$$

$$\kappa_\gamma = 1 + (c_w + c_B)\frac{m_W^2}{2\Lambda^2}$$

$$\mathcal{O}_B = (D_\mu H^\dagger)B^{\mu\nu}D_\nu H$$

Others in Backup

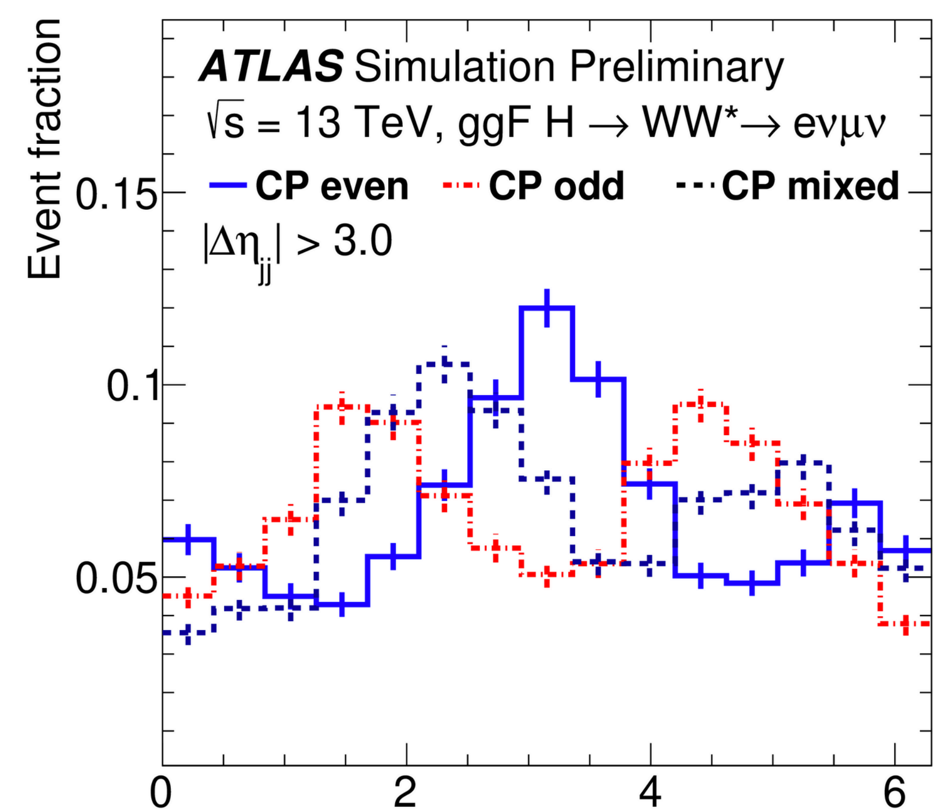
$$\mathcal{O}_W = (D_\mu H)^\dagger W^{\mu\nu}D_\nu H \qquad \mathcal{O}_{\tilde{W}} = (D_\mu H)^\dagger \tilde{W}^{\mu\nu}D_\nu H$$

$$\mathcal{O}_{WWW} = \mathrm{Tr}[W_{\mu\nu}W^\nu_\rho W^{\rho\nu}] \qquad \mathcal{O}_{W\tilde{W}W} = \mathrm{Tr}[W_{\mu\nu}W^\nu_\rho \tilde{W}^{\rho\nu}]$$

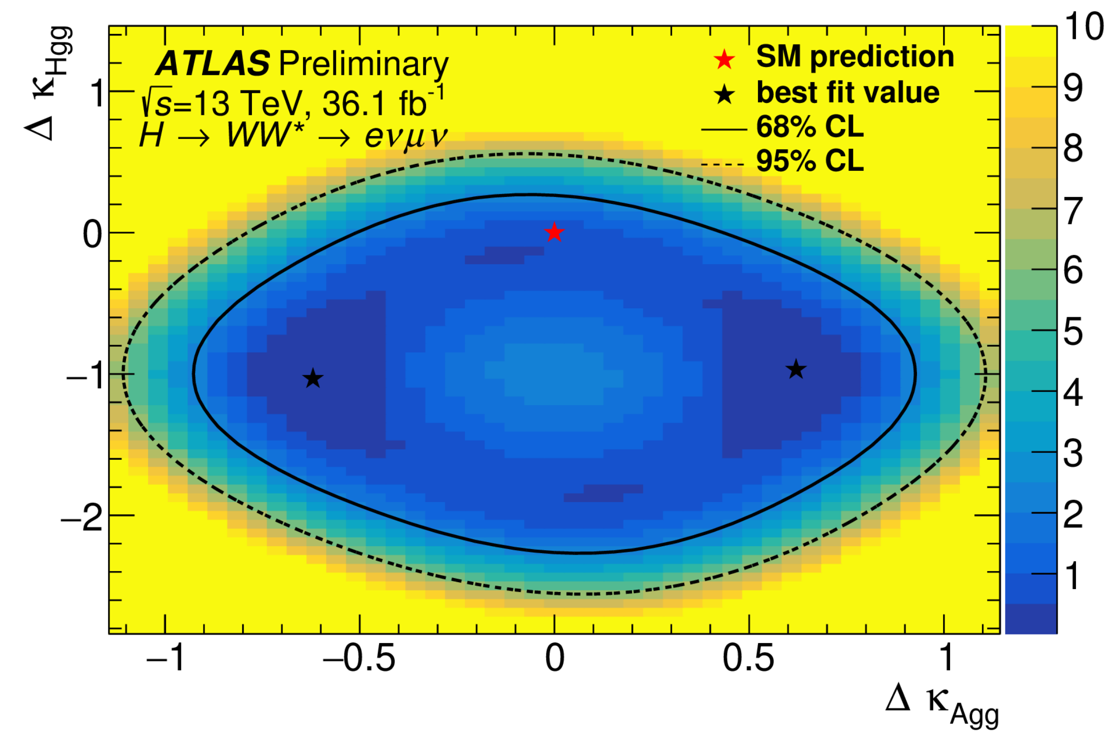
- In EFT many other operators affect vector-boson measurements, usually not considered since they were well constrained at LEP (this is basis dependent)

Dedicated Higgs analyses in ATLAS

- Measuring CP properties of HVV, Hff, Hgg vertices
- Example from a H->WW* +jj analyses measuring the CP properties of the Higgs couplings in the ggH+jj and VBF from signed $\Delta\phi_{jj}$
  - Other ATLAS Higgs CP analyses: ttH($\gamma\,\gamma$), VBF H→ττ
- Estimate c_i-dependence of reco-level observables
  - Using morphing: interpolate between yields from multiple samples produced for various couplings points
- Usage of optimal observable approach in VBF analyses
- $m\gamma\gamma$ fit to several regions defined through BDT discriminant in ttH($\gamma\gamma$)



ATLAS-CONF-2020-055



Dedicated H→4l analysis CMS

HIG-19-005

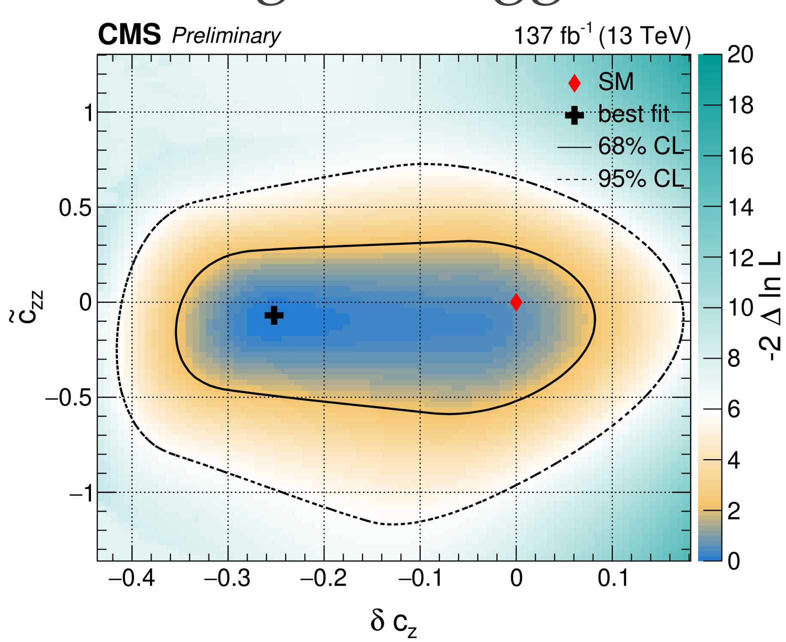
- Dedicated search for Higgs anomalous coupling
  - 2 in Htt couplings (magnitude and the phase, ttH and ggH combined)
  - 2 in ggH couplings: c_{gg} and its CP-odd counterpart
  - 5 anomalous couplings for HVV, simplifications to conserve custodial sym.

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

  - EFT interpretation using the Higgs basis

Channels	Coupling	Observed	Expected	Observed correlation			
ggH	c_{gg}	$0.0056^{+0.0025}_{-0.0039}$	$0.0084^{+0.0007}_{-0.0084}$		1		
	$\tilde{c}_{gg}$	$-0.0058^{+0.0037}_{-0.0024}$	$0.0000^{+0.0085}_{-0.0085}$		$+0.980$	1	
$\mathrm{t\bar{t}H}$	κ_{t}	$1.06^{+0.14}_{-0.18}$	$1.00^{+0.15}_{-0.23}$		1		
	$\tilde{\kappa}_{\mathrm{t}}$	$0.00^{+0.76}_{-0.72}$	$0.00^{+0.80}_{-0.80}$		0.000	1	
$\mathrm{t\bar{t}H + ggH}$	κ_{f}	$0.76^{+0.23}_{-0.21}$	$1.00^{+0.26}_{-0.39}$		1		
	$\tilde{\kappa}_{\mathrm{f}}$	$-0.21^{+0.28}_{-0.12}$	0.00 ± 0.37		$+0.745$	1	
$\mathrm{VBF + VH + H \to 4\ell}$	δc_z	$-0.25^{+0.27}_{-0.07}$	$0.00^{+0.10}_{-0.28}$	1			
	c_{zz}	$0.03^{+0.10}_{-0.10}$	$0.00^{+0.22}_{-0.16}$	$+0.144$	1		
	$c_{z\Box}$	$-0.03^{+0.04}_{-0.04}$	$0.00^{+0.06}_{-0.09}$	-0.186	-0.847	1	
	$\tilde{c}_{zz}$	$-0.11^{+0.30}_{-0.31}$	$0.00^{+0.63}_{-0.63}$	$+0.077$	-0.016	$+0.009$	1

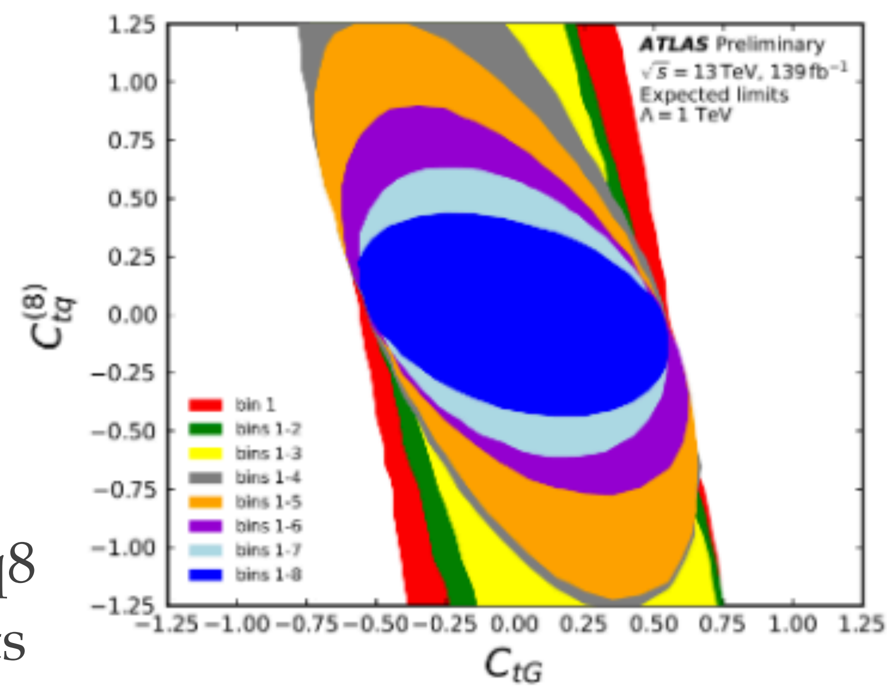
- Matrix element techniques to identify the production mechanism

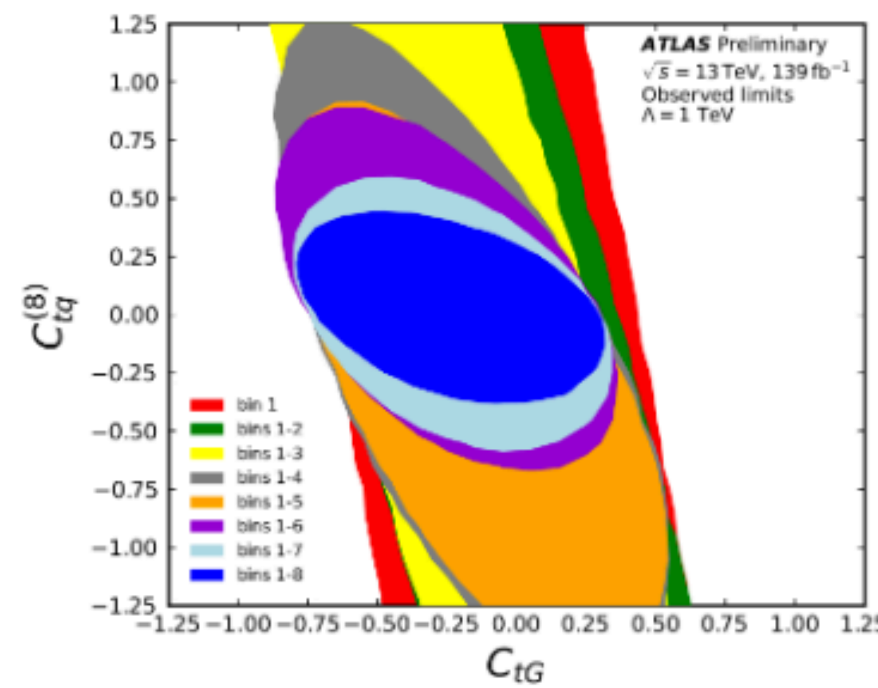


Boosted tt cross sections in l+jets

- Hadronically decaying top quark with pT>355 GeV
- Reinterpretation of cross section measurements focussing in two parameters
  - ctG and ctq8. EFT predictions generated with SMEFT@NLO at LO
- Only linear terms considered
- Using EFTFitter package to set constraints

More stringent constraints to ctq8 than in global fits





Global fit from: arXiv:2105.00006

Wilson coefficient	Marginalised 95% intervals		Individual 95% intervals		
	Expected	Observed	Expected	Observed	Global fit [99]
C_{tG}	[-0.44, 0.44]	[-0.68, 0.21]	[-0.41, 0.42]	[-0.63, 0.20]	[0.007, 0.111]
$C_{tq}^{(8)}$	[-0.35, 0.35]	[-0.30, 0.36]	[-0.35, 0.36]	[-0.34, 0.27]	[-0.40, 0.61]

Eboli basis

a. Operators containing just $D_\mu\Phi$

The two independent operators in this class are

$$\mathcal{L}_{S,0} = \left[(D_\mu\Phi)^\dagger D_\nu\Phi\right] \times \left[(D^\mu\Phi)^\dagger D^\nu\Phi\right] \tag{A5}$$
$$\mathcal{L}_{S,1} = \left[(D_\mu\Phi)^\dagger D^\mu\Phi\right] \times \left[(D_\nu\Phi)^\dagger D^\nu\Phi\right] \tag{A6}$$

b. Operators containing $D_\mu\Phi$ and field strength

The operators in this class are:

$$\mathcal{L}_{M,0} = \mathrm{Tr}\left[\hat{W}_{\mu\nu}\hat{W}^{\mu\nu}\right] \times \left[(D_\beta\Phi)^\dagger D^\beta\Phi\right] \tag{A7}$$
$$\mathcal{L}_{M,1} = \mathrm{Tr}\left[\hat{W}_{\mu\nu}\hat{W}^{\nu\beta}\right] \times \left[(D_\beta\Phi)^\dagger D^\mu\Phi\right] \tag{A8}$$
$$\mathcal{L}_{M,2} = \left[B_{\mu\nu}B^{\mu\nu}\right] \times \left[(D_\beta\Phi)^\dagger D^\beta\Phi\right] \tag{A9}$$
$$\mathcal{L}_{M,3} = \left[B_{\mu\nu}B^{\nu\beta}\right] \times \left[(D_\beta\Phi)^\dagger D^\mu\Phi\right] \tag{A10}$$
$$\mathcal{L}_{M,4} = \left[(D_\mu\Phi)^\dagger \hat{W}_{\beta\nu} D^\mu\Phi\right] \times B^{\beta\nu} \tag{A11}$$
$$\mathcal{L}_{M,5} = \left[(D_\mu\Phi)^\dagger \hat{W}_{\beta\nu} D^\nu\Phi\right] \times B^{\beta\mu} \tag{A12}$$
$$\mathcal{L}_{M,6} = \left[(D_\mu\Phi)^\dagger \hat{W}_{\beta\nu}\hat{W}^{\beta\nu} D^\mu\Phi\right] \tag{A13}$$
$$\mathcal{L}_{M,7} = \left[(D_\mu\Phi)^\dagger \hat{W}_{\beta\nu}\hat{W}^{\beta\mu} D^\nu\Phi\right] \tag{A14}$$

Eboli basis

$$\mathcal{L}_{T,0} = \mathrm{Tr}\left[\hat{W}_{\mu\nu}\hat{W}^{\mu\nu}\right] \times \mathrm{Tr}\left[\hat{W}_{\alpha\beta}\hat{W}^{\alpha\beta}\right] \quad \text{(A15)}$$

$$\mathcal{L}_{T,1} = \mathrm{Tr}\left[\hat{W}_{\alpha\nu}\hat{W}^{\mu\beta}\right] \times \mathrm{Tr}\left[\hat{W}_{\mu\beta}\hat{W}^{\alpha\nu}\right] \quad \text{(A16)}$$

$$\mathcal{L}_{T,2} = \mathrm{Tr}\left[\hat{W}_{\alpha\mu}\hat{W}^{\mu\beta}\right] \times \mathrm{Tr}\left[\hat{W}_{\beta\nu}\hat{W}^{\nu\alpha}\right] \quad \text{(A17)}$$

$$\mathcal{L}_{T,3} = \mathrm{Tr}\left[\hat{W}_{\alpha\mu}\hat{W}^{\mu\beta}\hat{W}^{\nu\alpha}\right] \times B_{\beta\nu} \quad \text{(A18)}$$

$$\mathcal{L}_{T,4} = \mathrm{Tr}\left[\hat{W}_{\alpha\mu}\hat{W}^{\alpha\mu}\hat{W}^{\beta\nu}\right] \times B_{\beta\nu} \quad \text{(A19)}$$

$$\mathcal{L}_{T,5} = \mathrm{Tr}\left[\hat{W}_{\mu\nu}\hat{W}^{\mu\nu}\right] \times B_{\alpha\beta}B^{\alpha\beta} \quad \text{(A20)}$$

$$\mathcal{L}_{T,6} = \mathrm{Tr}\left[\hat{W}_{\alpha\nu}\hat{W}^{\mu\beta}\right] \times B_{\mu\beta}B^{\alpha\nu} \quad \text{(A21)}$$

$$\mathcal{L}_{T,7} = \mathrm{Tr}\left[\hat{W}_{\alpha\mu}\hat{W}^{\mu\beta}\right] \times B_{\beta\nu}B^{\nu\alpha} \quad \text{(A22)}$$

$$\mathcal{L}_{T,8} = B_{\mu\nu}B^{\mu\nu}B_{\alpha\beta}B^{\alpha\beta} \quad \text{(A23)}$$

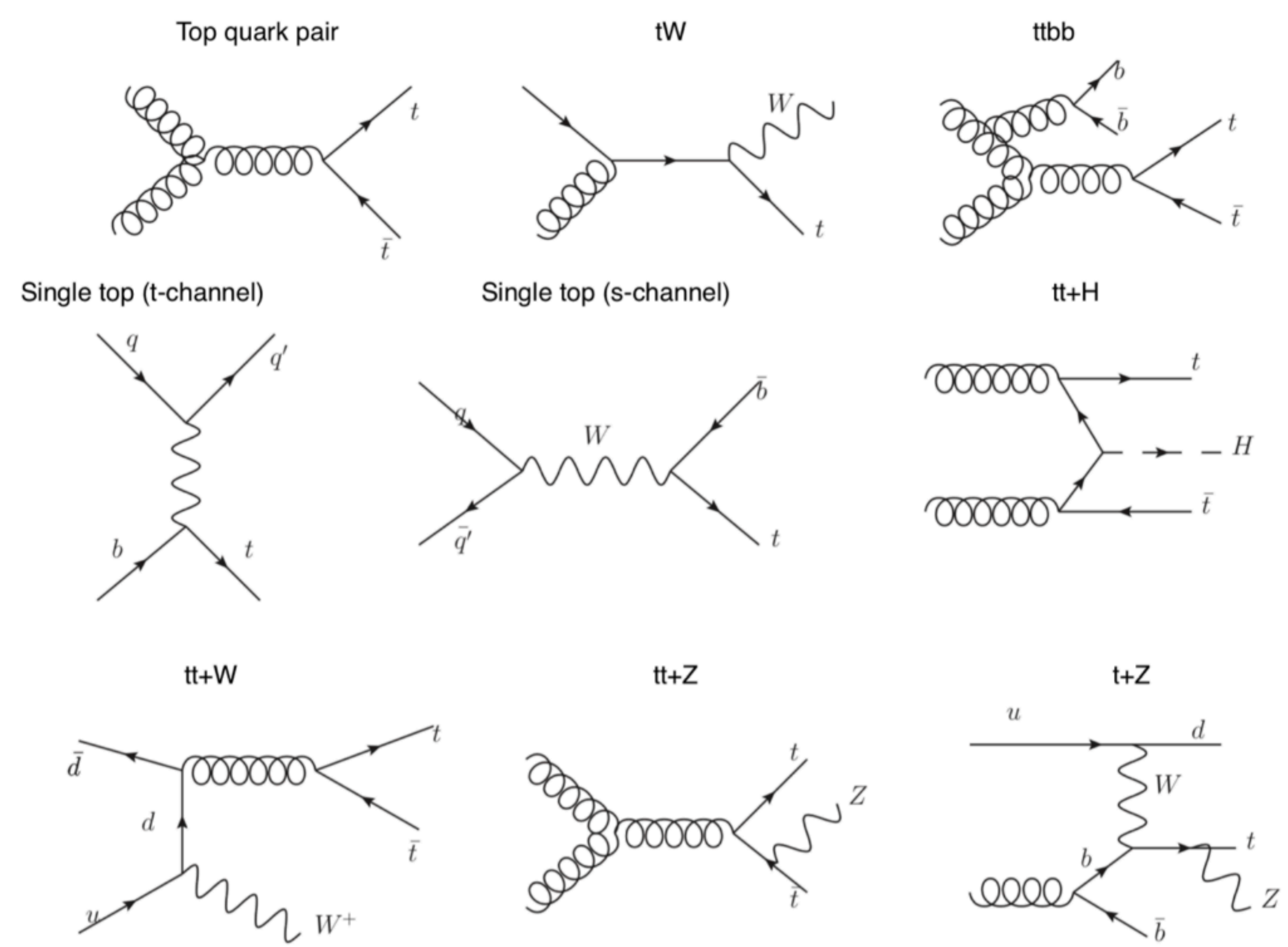
$$\mathcal{L}_{T,9} = B_{\alpha\mu}B^{\mu\beta}B_{\beta\nu}B^{\nu\alpha} \quad \text{(A24)}$$

The top quark sector of the SMEFT

Notation	Sensitivity at $\mathcal{O}(\Lambda^{-2})$ ($\mathcal{O}(\Lambda^{-4})$)								
	$t\bar{t}$	single-top	tW	tZ	$t\bar{t}W$	$t\bar{t}Z$	$t\bar{t}H$	$t\bar{t}t\bar{t}$	$t\bar{t}b\bar{b}$
OQQ1								✓	✓
OQQ8								✓	✓
OQt1								✓	✓
OQt8								✓	✓
OQb1								(✓)	✓
OQb8								(✓)	✓
Ott1								✓	✓
Otb1								(✓)	✓
Otb8								✓	✓
OQtQb1									
OQtQb8									
O81qq	✓				✓	✓	✓	✓	✓
O11qq	✓				(✓)	(✓)	(✓)	✓	✓
O83qq	✓	✓		(✓)	✓	✓	✓	✓	✓
O13qq	✓	✓		✓	(✓)	(✓)	(✓)	✓	✓
O8qt	✓				✓	✓	✓	✓	✓
O1qt	✓				(✓)	(✓)	(✓)	✓	✓
O8ut	✓					✓	✓	✓	✓
O1ut	✓					(✓)	(✓)	✓	✓
O8qu	✓					✓	✓	✓	✓
O1qu	✓					(✓)	(✓)	✓	✓
O8dt	✓					✓	✓	✓	✓
O1dt	✓					(✓)	(✓)	✓	✓
O8qd	✓					✓	✓	✓	✓
O1qd	✓					(✓)	(✓)	✓	✓
OtG	✓				✓	✓	✓	✓	✓
OtW		✓	✓	✓					
ObW		(✓)	(✓)						
OtZ				✓		✓			
Off		(✓)	(✓)	(✓)					
Ofq3		✓	✓	✓		✓			
OpQM				✓		✓			
Opt				✓		✓	✓		
Otp							✓		

A large number of different dimension-6 SMEFT operators modify **top production at LHC**

$$\sigma_i^{\rm th}\left(\{c_n\}\right) = \sigma_{{\rm SM},i} + \sum_{n=1}^{N_{\rm op}} \widetilde{\sigma}_{i,n}\frac{c_n}{\Lambda^2} + \sum_{n,m=1}^{N_{\rm op}} \widetilde{\sigma}_{i,nm}\frac{c_n c_m}{\Lambda^4}$$



Juan Rojo

Top with additional leptons

Operators involving two quarks and one or more bosons

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

Operators involving two quarks and two leptons

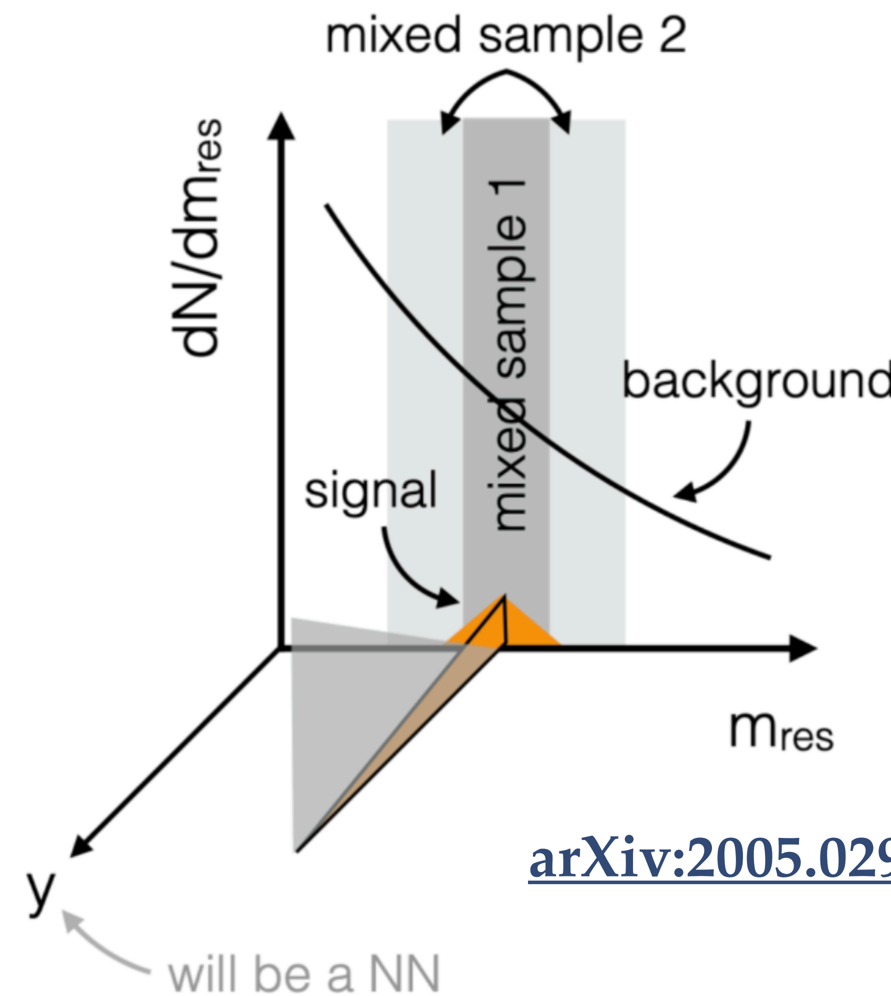
Operator	Definition	WC	Lead processes affected
$O_{\ell q}^{1(ijkl)}$	$(\bar{\ell}_i \gamma^\mu \ell_j)(\bar{q}_k \gamma^\mu q_\ell)$	$c_{Q\ell}^{-(\ell)} + c_{Q\ell}^{3(\ell)}$	$t\bar{t}l\nu$, $t\bar{t}l\bar{l}$, $tl\bar{l}q$
$O_{\ell q}^{3(ijkl)}$	$(\bar{\ell}_i \gamma^\mu \tau^I \ell_j)(\bar{q}_k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

Generic searches: CWoLA in ATLAS

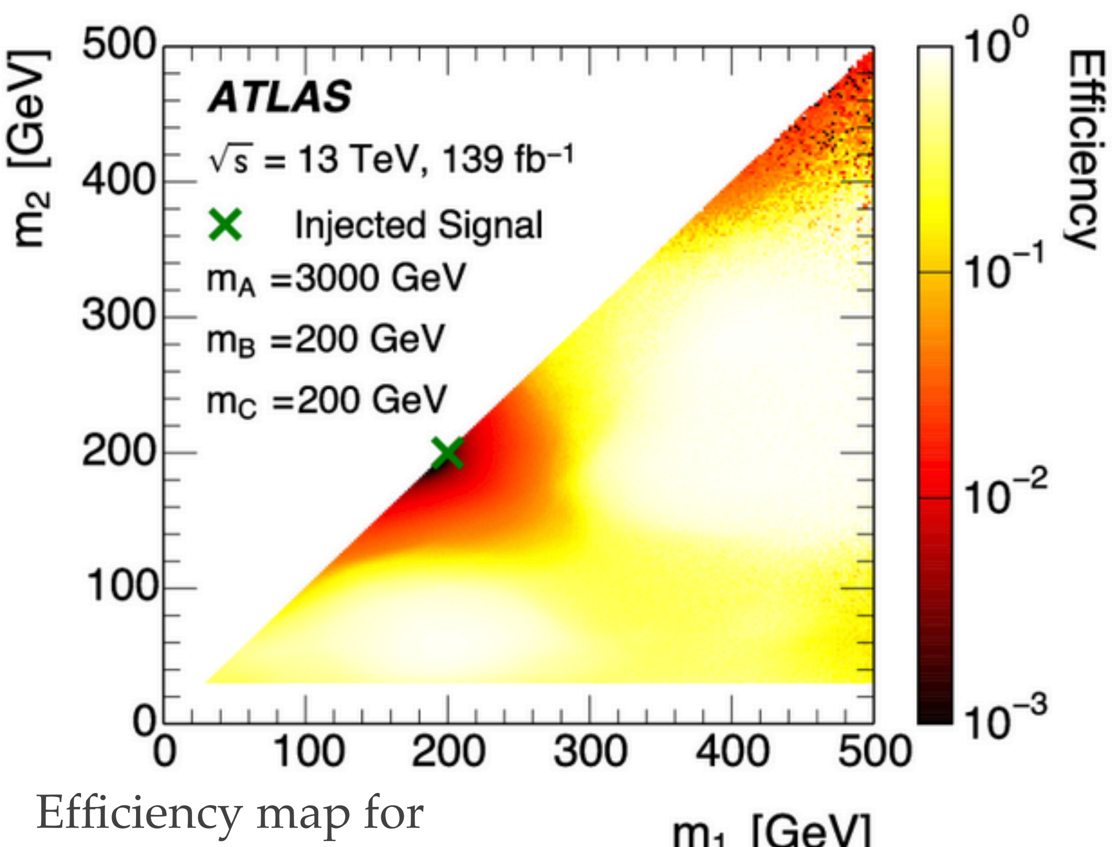
- CwoLA (Classification without labels) used in dijet resonances

3-D search : A→BC

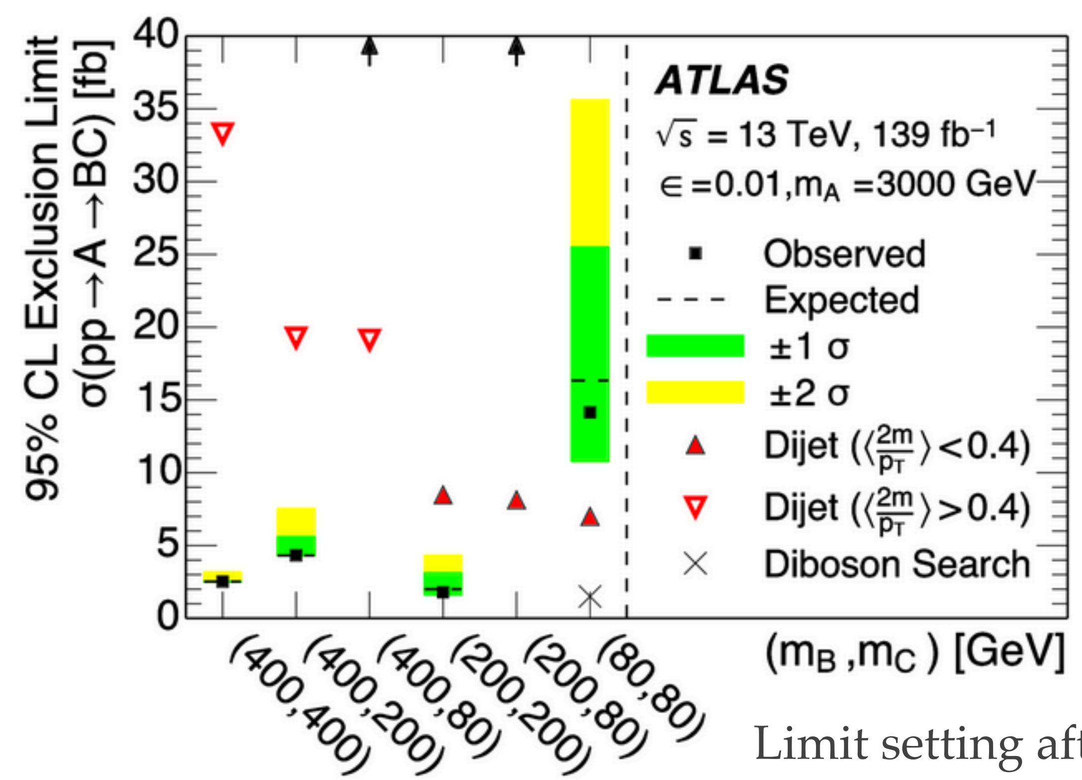
- Neural networks are trained directly on data
    - Construct two datasets with background and potentially signal being the only difference the proportion of signal
    - Combined with a bump-hunt search. Distinguish one mJJ from their neighbours. If there is not signal mJJ will continue to be smooth after the labelling of the classifier



arXiv:2005.02983



Efficiency map for injected signal



Limit setting after re-training for particular signals