Constraining top-sector EFT effects with combined associated top-quark production measurements at ATLAS

Betsy Cunnett

IOP APP/HEPP Annual Conference 2026, Edinburgh, UK

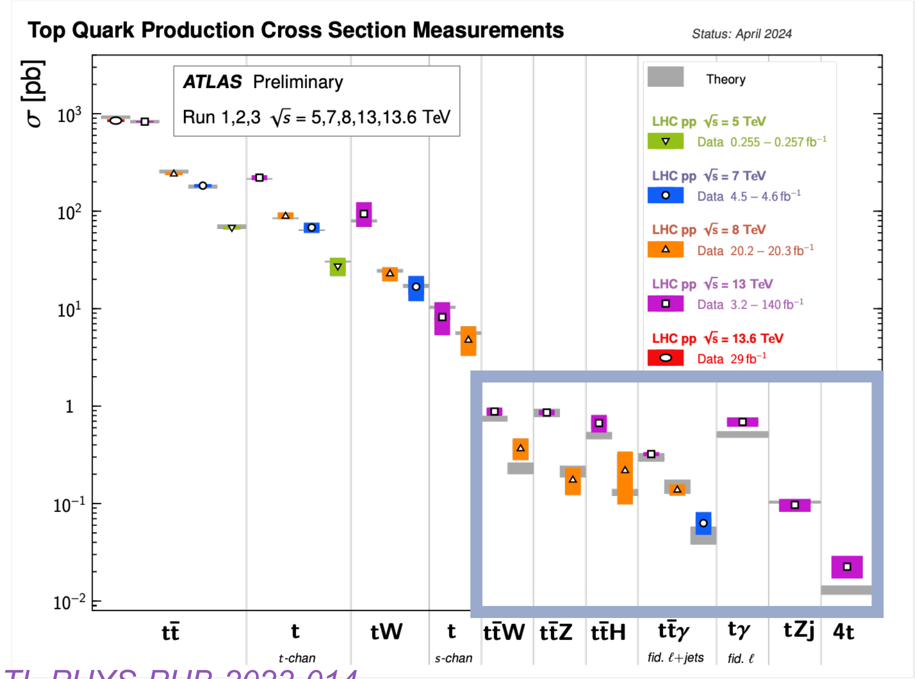
UNIVERSITY OF SUSSEX

ATLAS EXPERIMENT

Top quarks as a probe for new physics

Why care about the top quark?

- Heavy - feels BSM effects more strongly?
- Couplings - Able to probe effects in gauge, Higgs, and flavour sectors → crucial component of global fits
- No hadronisation - spin and decay information accessible
- Many different processes:



ATL-PHYS-PUB-2023-014

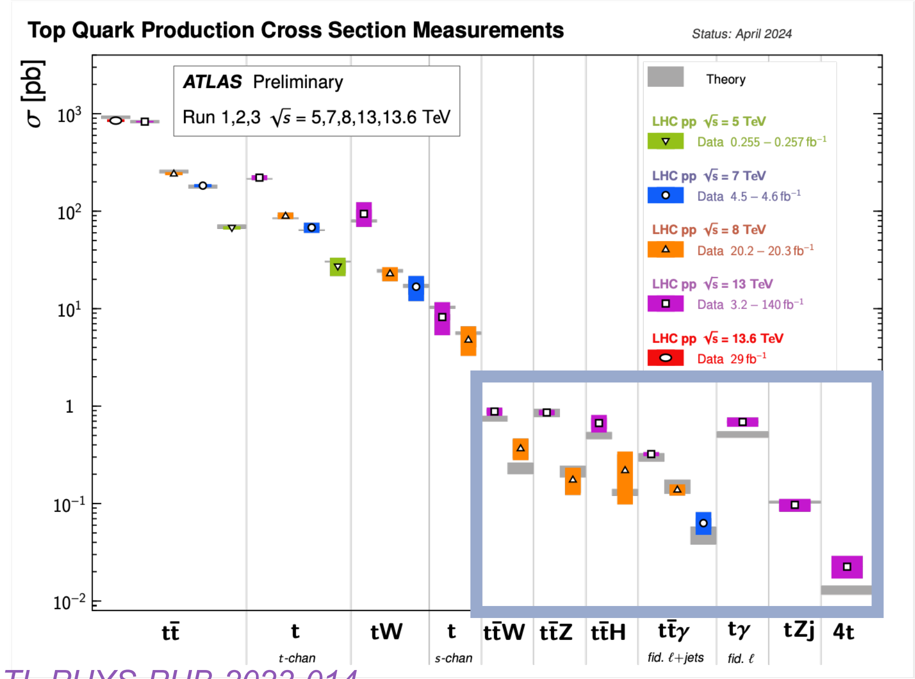
- Tops + other particles
- Rare
- Sensitive to new physics

'Top+X'

Top quarks as a probe for new physics

Why care about the top quark?

- Heavy - feels BSM effects more strongly?
- Couplings - Able to probe effects in gauge, Higgs, and flavour sectors → crucial component of global fits
- No hadronisation - spin and decay information accessible
- Many different processes:



ATL-PHYS-PUB-2023-014

- Tops + other particles
- Rare
- Sensitive to new physics

'Top+X'

Search for heavy new physics in a generic way with Standard Model Effective Field Theory (SMEFT):

$$\mathcal{L}_{\mathrm{SMEFT}} = \mathcal{L}_{4,\mathrm{SM}} + \mathcal{L}_5 + \mathcal{L}_6 + \cdots$$

$$\mathcal{L}_6 = \sum_i \frac{c_i^6}{\Lambda^{6-4}} \mathcal{O}_i^6 + \ \ldots$$

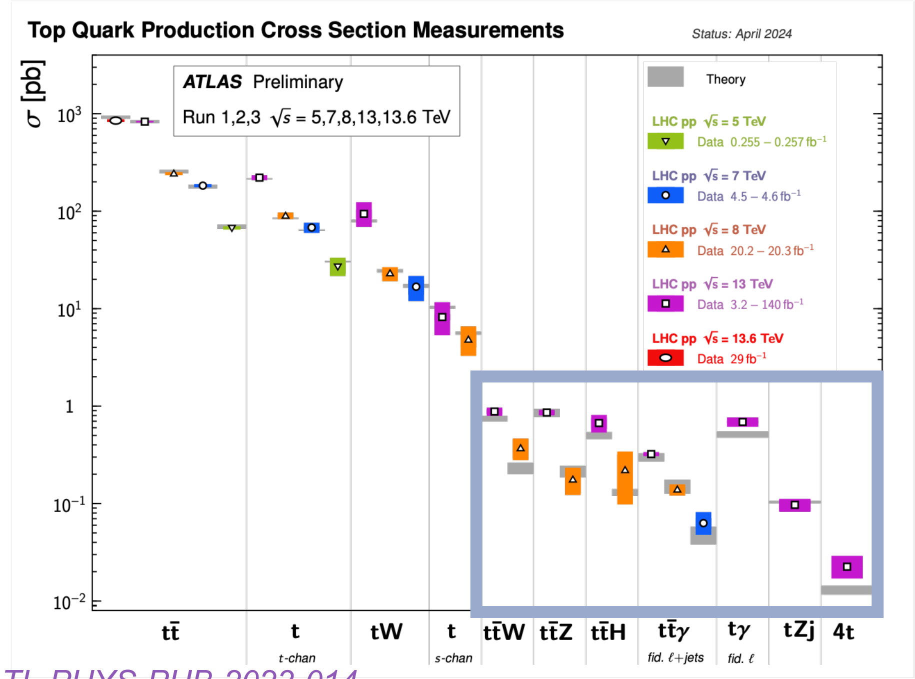
Set limits on Wilson Coefficients, c_i

Set of 59 operators at dimension 6 (combinations of SM fields)

Top quarks as a probe for new physics

Why care about the top quark?

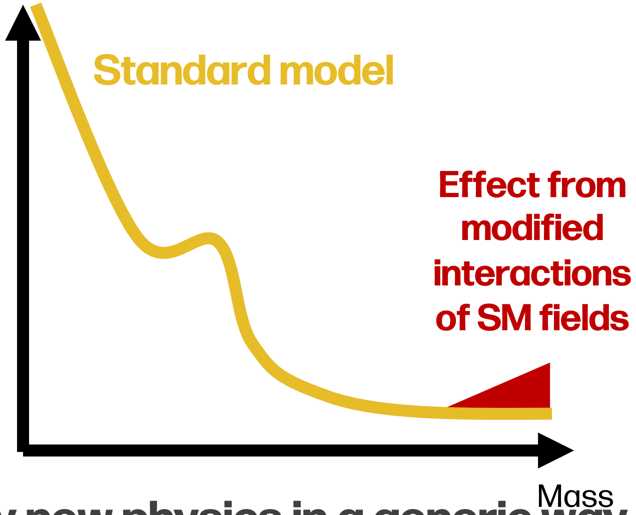
- Heavy - feels BSM effects more strongly?
- Couplings - Able to probe effects in gauge, Higgs, and flavour sectors → crucial component of global fits
- No hadronisation - spin and decay information accessible
- Many different processes:



ATL-PHYS-PUB-2023-014

- Tops + other particles
- Rare
- Sensitive to new physics

'Top+X'



Search for heavy new physics in a generic way with Standard Model Effective Field Theory (SMEFT):

$$\mathcal{L}_{\mathrm{SMEFT}} = \mathcal{L}_{4,\mathrm{SM}} + \mathcal{L}_5 + \mathcal{L}_6 + \cdots$$

Set limits on Wilson Coefficients, c_i

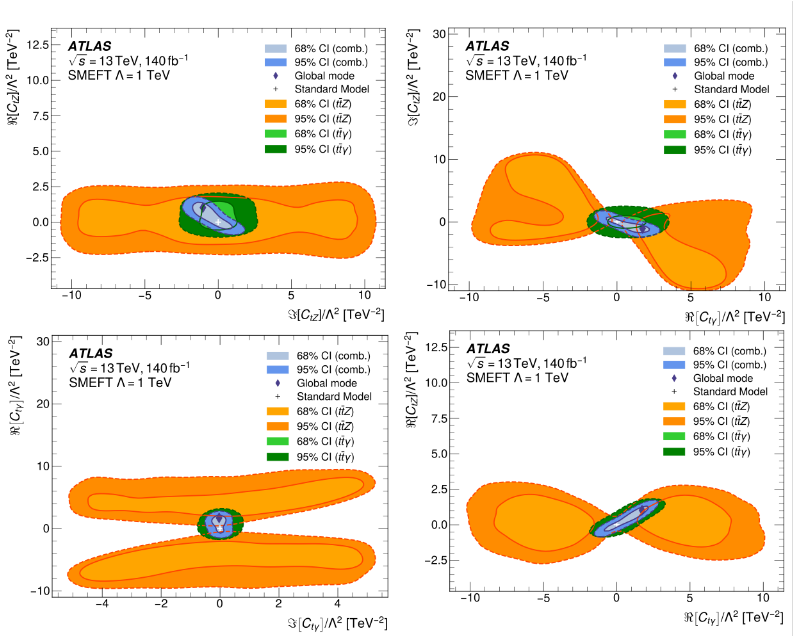
$$\mathcal{L}_6 = \sum_i \frac{c_i^6}{\Lambda^{6-4}} \mathcal{O}_i^6 + \ \ldots$$

Set of 59 operators at dimension 6 (combinations of SM fields)

Current 'Top+X' landscape in ATLAS:

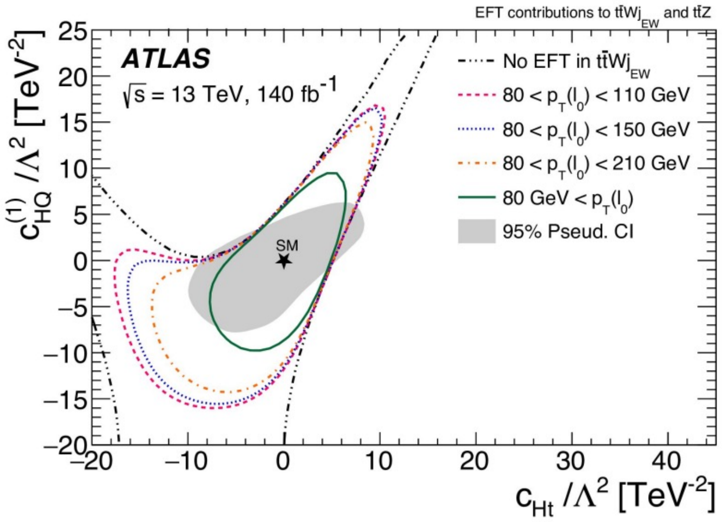
- Many Run 2 analyses with EFT interpretations within dedicated top+X measurements e.g:

ttZ/tty

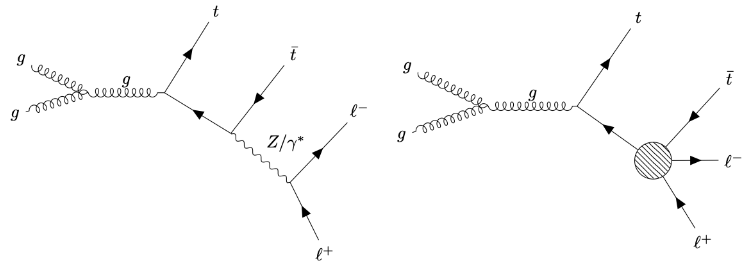


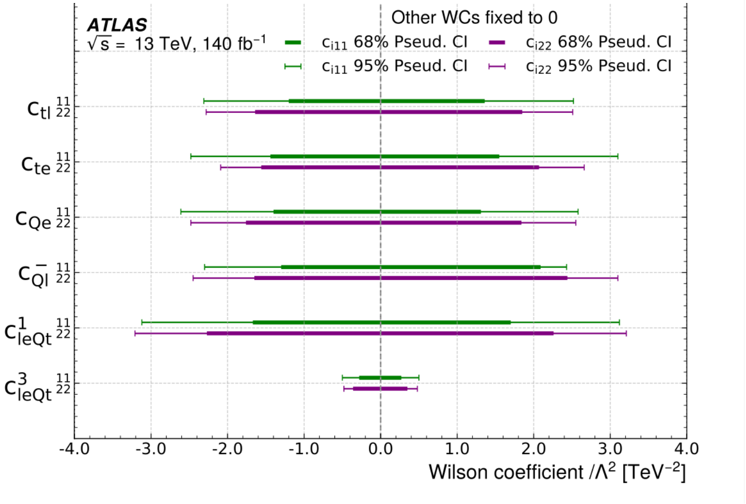
Combinations that break degeneracies

ttWj



Focusing in on processes with unique sensitivity to blind directions



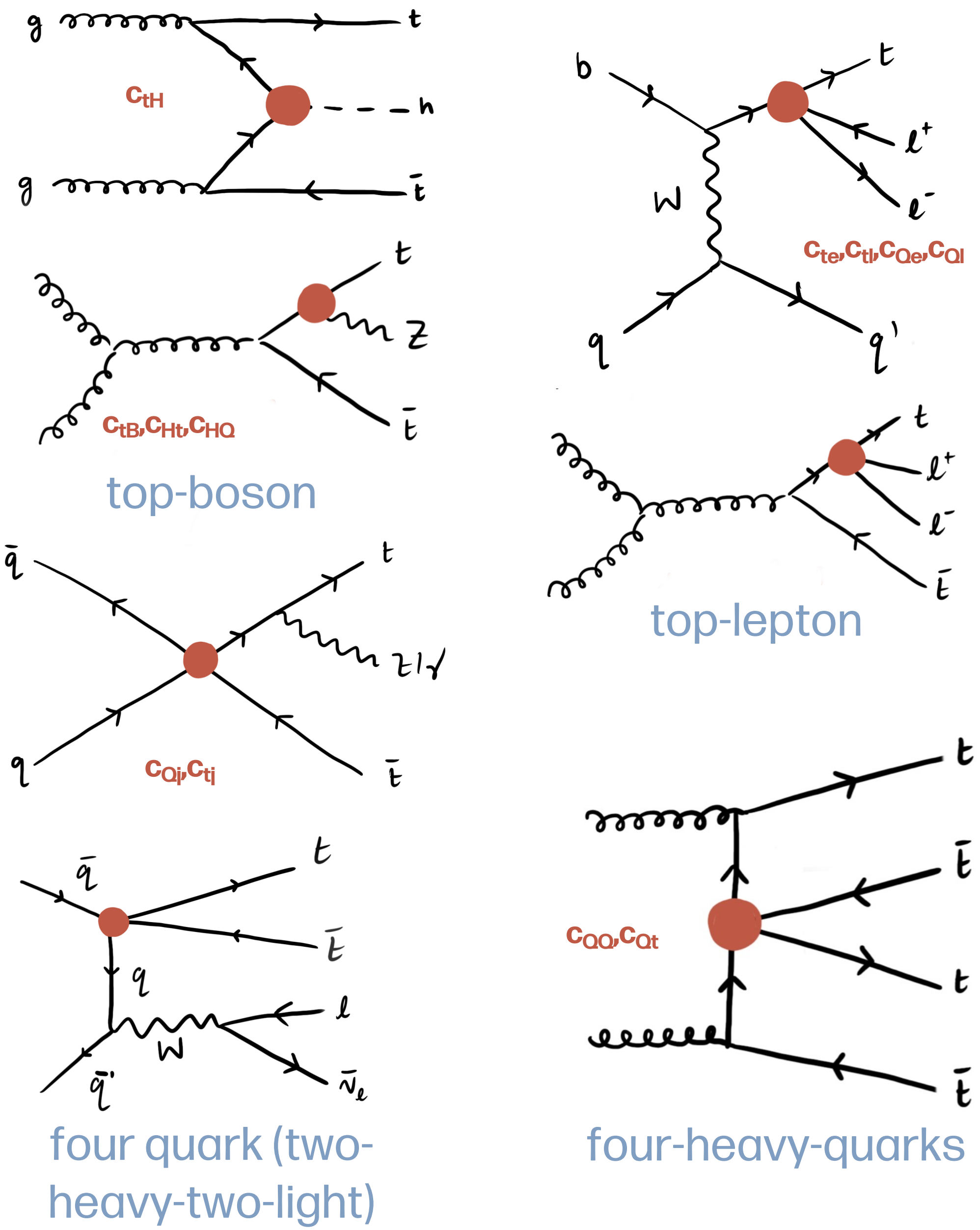


High-mass ttll

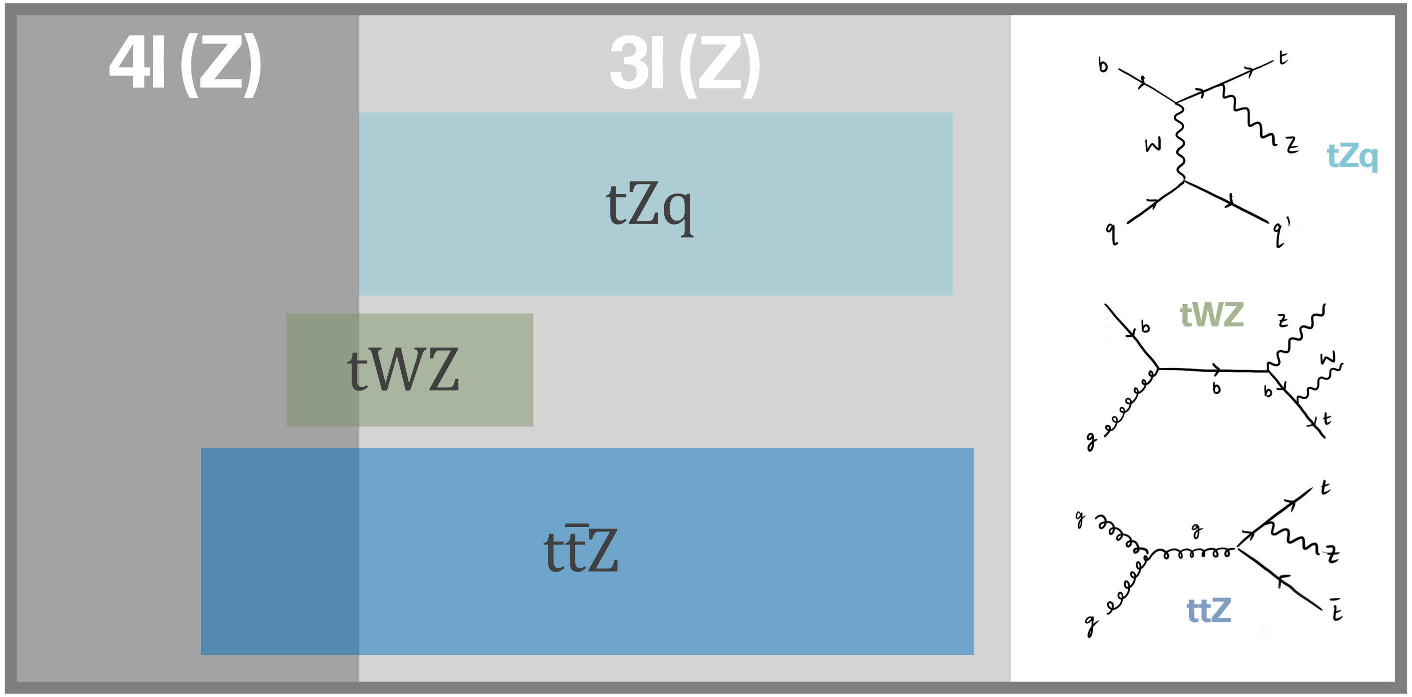
Extreme phase space with singular sensitivity to groups of operators and flavour differences

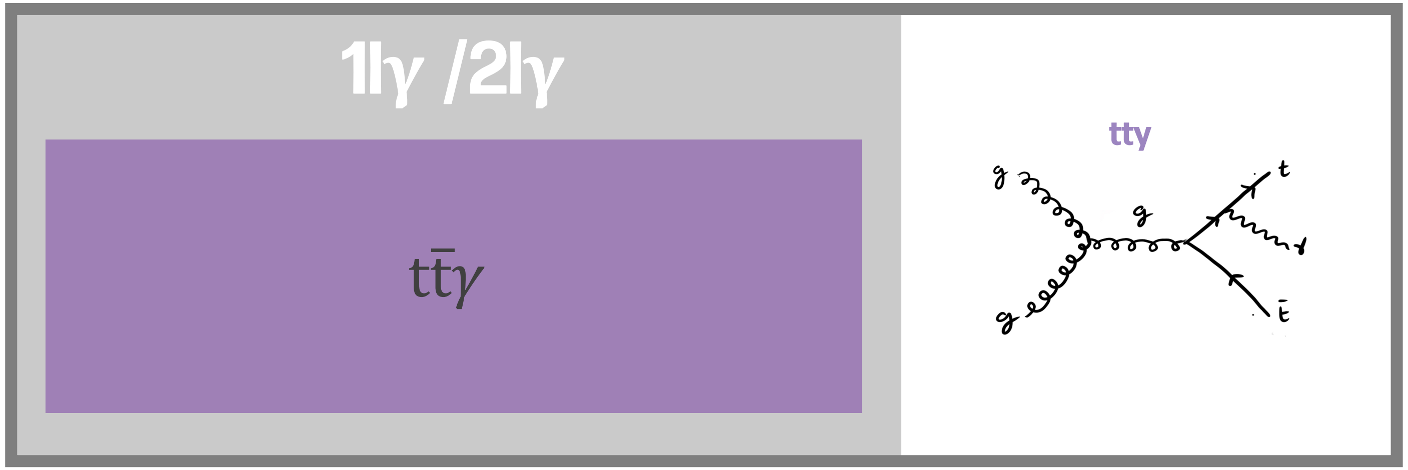
This talk: ATLAS Top+X EFT Combination

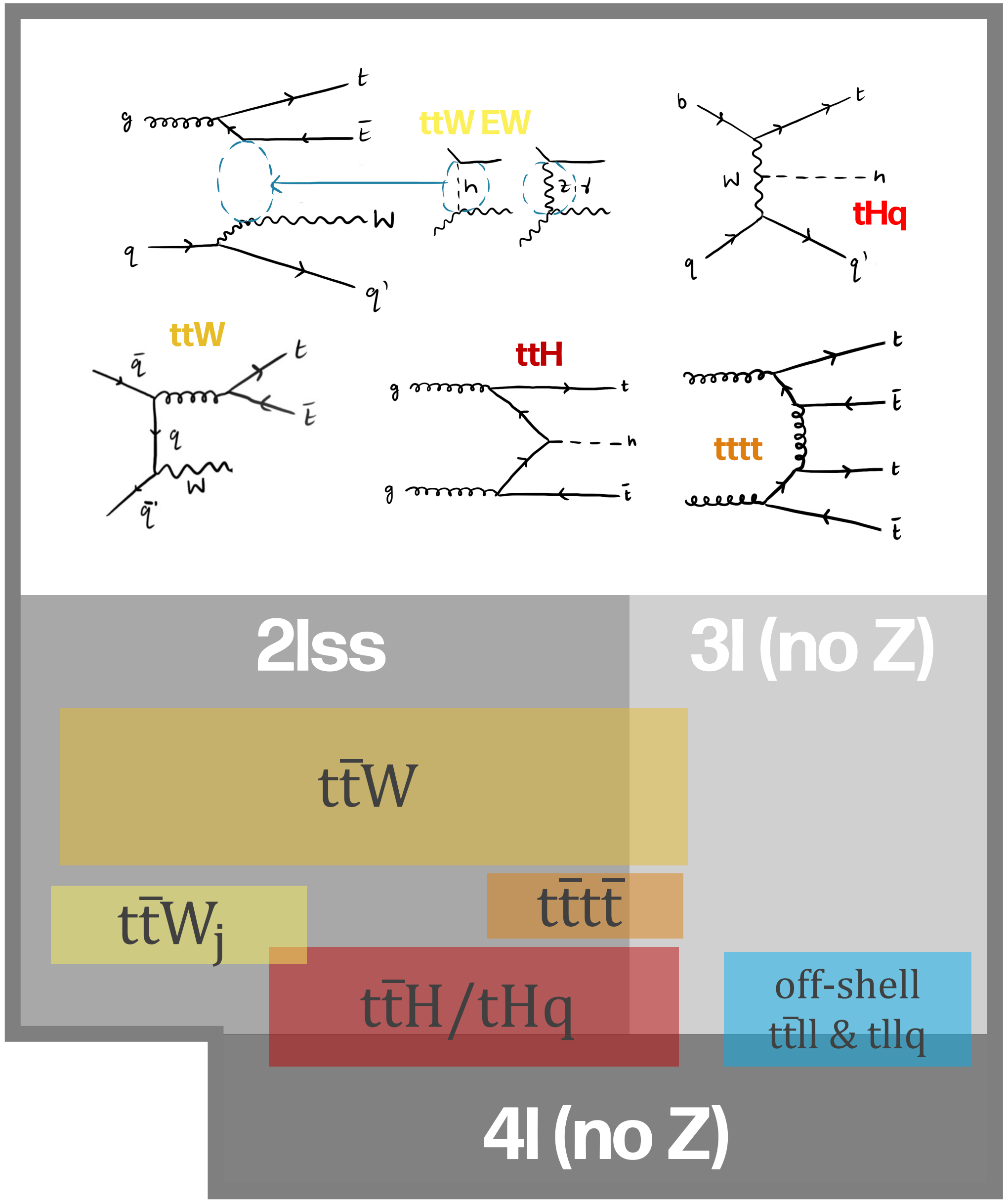
- Detector-level combined fit to measure top-sector EFT effects on ttZ, tZq, ttH, ttW, ttγ, tttt, ttW$_{EW}$, tWZ, tHq
- Many EFT operators affect multiple TPX processes
  - Combining Processes: break degeneracies or flat directions
  - Combining EFT Effects: include correlations and cancelations between operators
- Most complete probe of top-sector EFT
- Crucial input for global combinations



Phase space harmonisation







Regions designed to separate individual processes using cuts and dedicated NNs/BDTs:

- MVAs designed for ATLAS dedicated measurements of ttH, ttZ, tttt, tZq re-purposed
- Requires careful harmonization of region and object definitions to gain wide sensitivity
- Backgrounds constrained with mix of template MC and data-driven methods

2l(same-sign)&3l(off-shell Z)

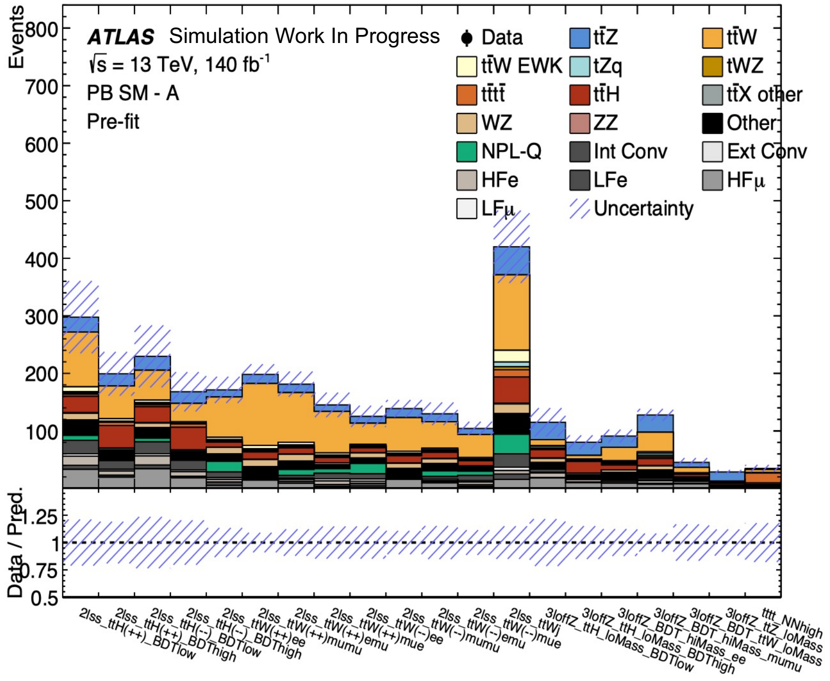
NNs/BDTs to split ttH, tttt, ttW, tZq, tHq
Cut-based for ttW EW, high-mass ttll/tllq

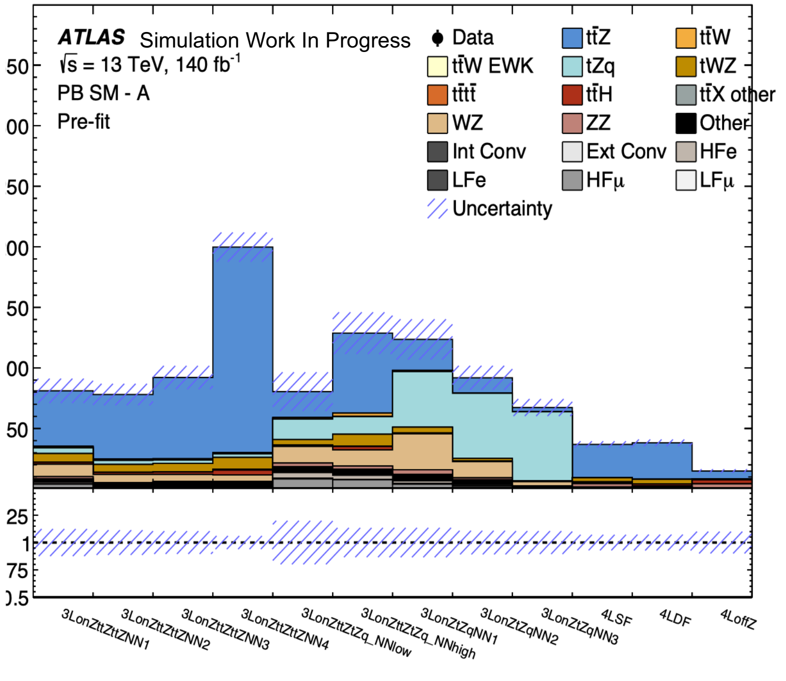
3l/4l (on-shell Z)

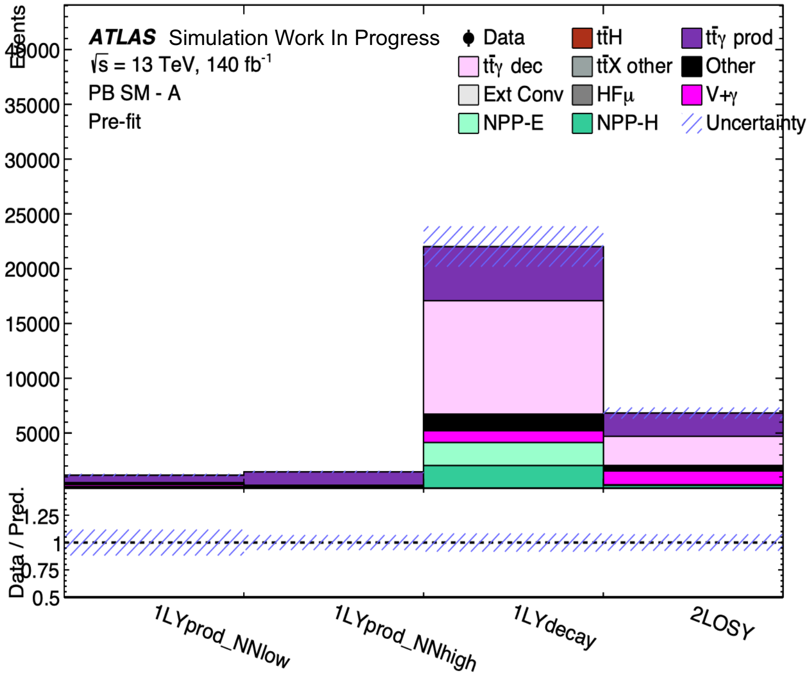
MVAs to split ttZ, tZq

1ly,2ly

MVAs to split ttY production, decay







Inclusion of EFT effects

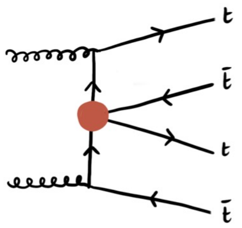
- Over 30 top-sector EFT operators included in 9 processes simultaneously in a profile-likelihood fit

- **Generator-level EFT parameterisation**
  Events generated with MadGraph5_aMC@NLO + SMEFTsim 3.0, storing weights for different Wilson coefficients → polynomial (linear + quadratic) dependence per event via reweighting
- **Bin-by-bin interpolation:**
  Event weights combined to build yield and shape dependence on Wilson coefficients in each bin
- **Fit implementation**
  Parameterisations enter the likelihood model as continuous parameters of interest constrained via a global profile likelihood fit to data.

	Operator	Codename	$t\bar{t}Z$	tZq	$t\bar{t}H$	$t\bar{t}W$	$t\bar{t}Wj$	$t\bar{t}\gamma$	$t\bar{t}t\bar{t}$	tWZ	tHq
top-boson	Q_{tW} (Re+Im)	ctWRe, ctWIm	X	X		X	X	X	X	X	X
	Q_{tB} (Re+Im)	ctBRe, ctBIm	X	X			X	X	X	X	
	Q_{tG} (Re+Im)	ctGRe, ctGIm	X		X	X	X	X	X	X	
	$Q_{HQ}^{(1)}$	cHQ1	X	X			X	X	X	X	
	$Q_{HQ}^{(3)}$	cHQ3	X	X			X	X	X	X	X
	Q_{Ht}	cHt	X	X			X	X	X	X	
	Q_{tH} (Re+Im)	ctHRe, ctHIm			X		X		X		X
four-quark	$Q_{tu}^{(1)}$	ctu1	X		X			X	X		
	$Q_{tu}^{(8)}$	ctu8	X		X			X	X		
	$Q_{td}^{(1)}$	ctd1	X		X			X	X		
	$Q_{td}^{(8)}$	ctd8	X		X			X	X		
	$Q_{qt}^{(1)}$	ctj1	X		X	X		X	X		
	$Q_{qt}^{(8)}$	ctj8	X		X	X		X	X		
	$Q_{Qt}^{(1)}$	cQt1	X		X			X	X		
	$Q_{Qt}^{(8)}$	cQt8	X		X			X	X		
	$Q_{Qu}^{(1)}$	cQu1	X		X			X	X		
	$Q_{Qu}^{(8)}$	cQu8	X		X			X	X		
	$Q_{Qd}^{(1)}$	cQd1	X		X			X	X		
	$Q_{Qd}^{(8)}$	cQd8	X		X			X	X		
	$Q_{QQ}^{(1)}$	cQQ1	X		X			X	X		
	$Q_{QQ}^{(8)}$	cQQ8	X		X			X	X		
	$Q_{Qq}^{(1,1)}$	cQj11	X		X	X		X	X		
	$Q_{Qq}^{(3,1)}$	cQj31	X	X	X	X		X	X		
	$Q_{Qq}^{(1,8)}$	cQj18	X		X	X		X	X		
	$Q_{Qq}^{(3,8)}$	cQj38	X	X	X	X		X	X		
top-lepton	Q_{et} (11,22)	cte11, cte22	X							X	
	Q_{Qe} (11,22)	cQe11, cQe22	X							X	
	Q_{lt} (11,22)	ctl11, ctl22	X							X	
	$Q_{lQ}^{(1)}$ (11,22)	clQ111, clQ122	X	X						X	
	$Q_{lQ}^{(3)}$ (11,22)	clQ311, clQ322	X	X						X	
	$Q_{leQt}^{(1)}$ (Re) (11,22)	cleQt111, cleQt122	X	X						X	
	$Q_{leQt}^{(3)}$ (Re) (11,22)	cleQt311, cleQt322	X	X						X	

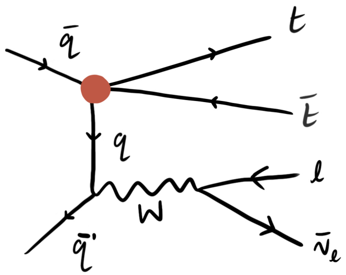
Full Run 2 Top+X EFT Analysis: Optimising for EFT sensitivity

Signal regions: optimised binning in energy variables that give sensitivity to EFT effects that grow with energy:



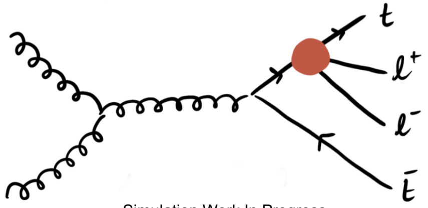
tttt

cQt1



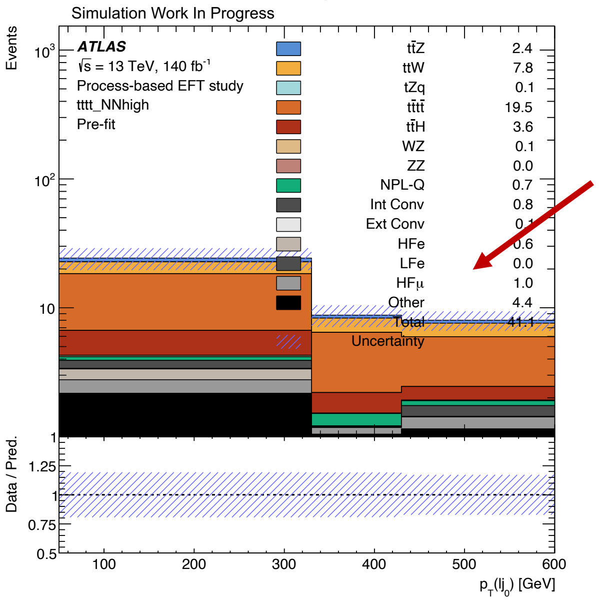
ttW

cQj1

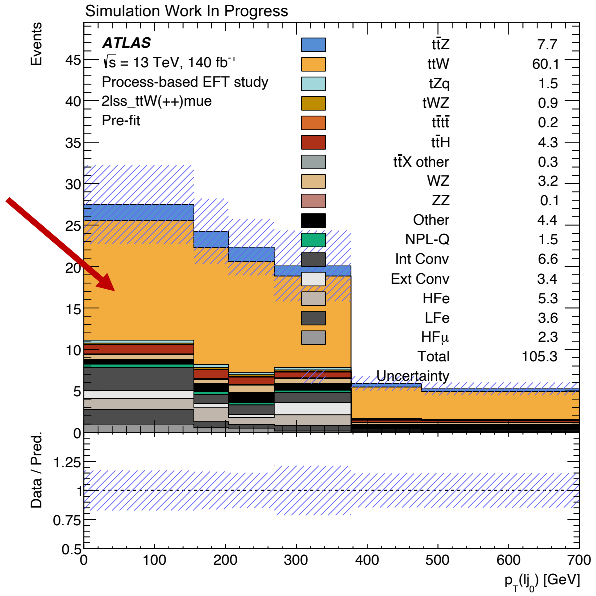


high-mass ttll

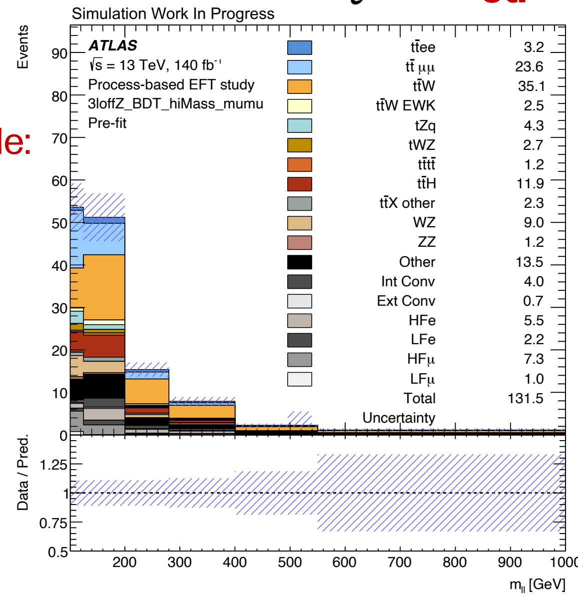
ctl

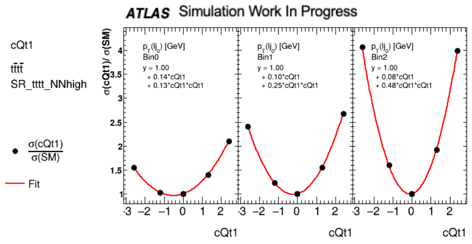


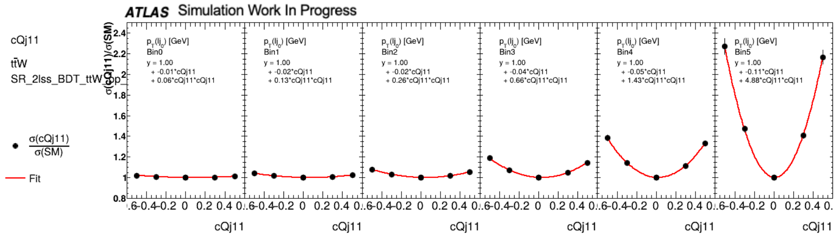
Variable: largest pT combination of any $\ell\ell, jj, \ell j$ pair→ widely EFT sensitive

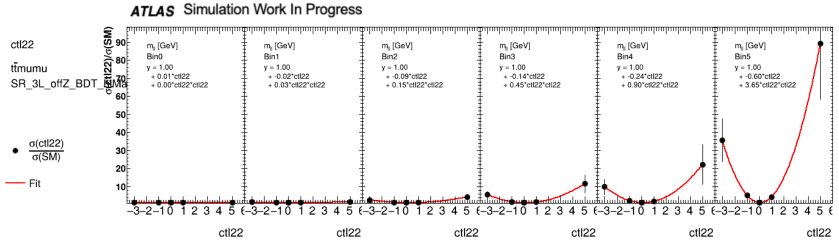


Variable: $m_{\ell\ell}$





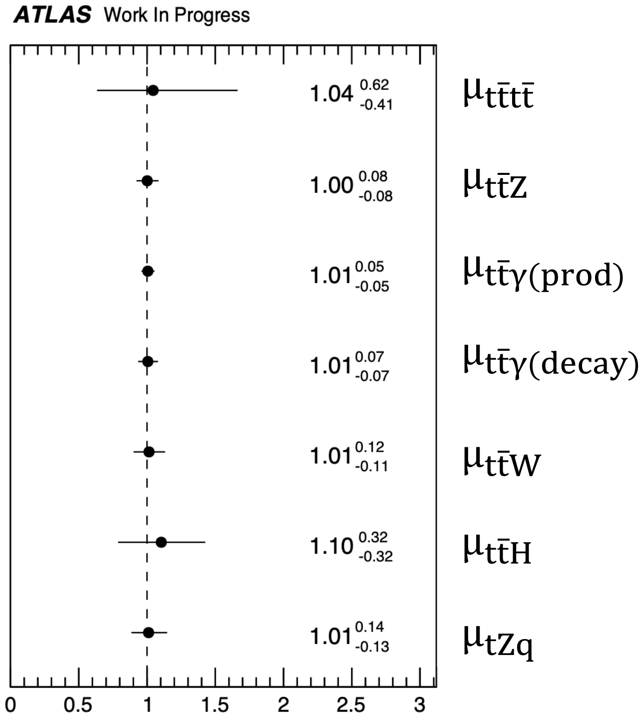




Work in progress Hybrid Asimov results (signal regions blinded)

Cross-check

Norm-factors (μ) for top+X processes are measured with similar sensitivity to dedicated ATLAS measurements:



Initial EFT results

- Linear+quadratic EFT terms
- Profile likelihood fit of all EFT coefficients simultaneously and one-at-a-time using
- Gain competitive predicted limits across the most comprehensive range of top-sector effects simultaneously constrained at detector level

EFTRExFitter

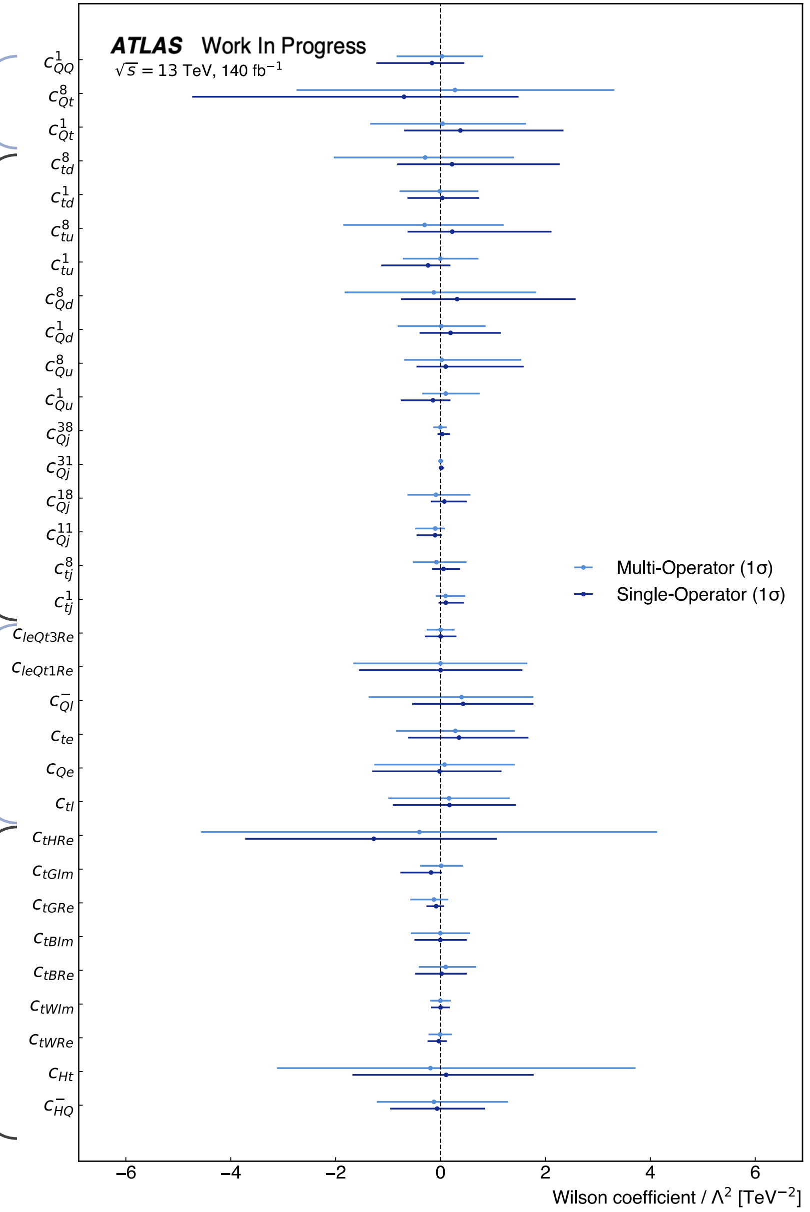
COUPLING TYPE:

4 heavy quarks

2 heavy 2 light quarks

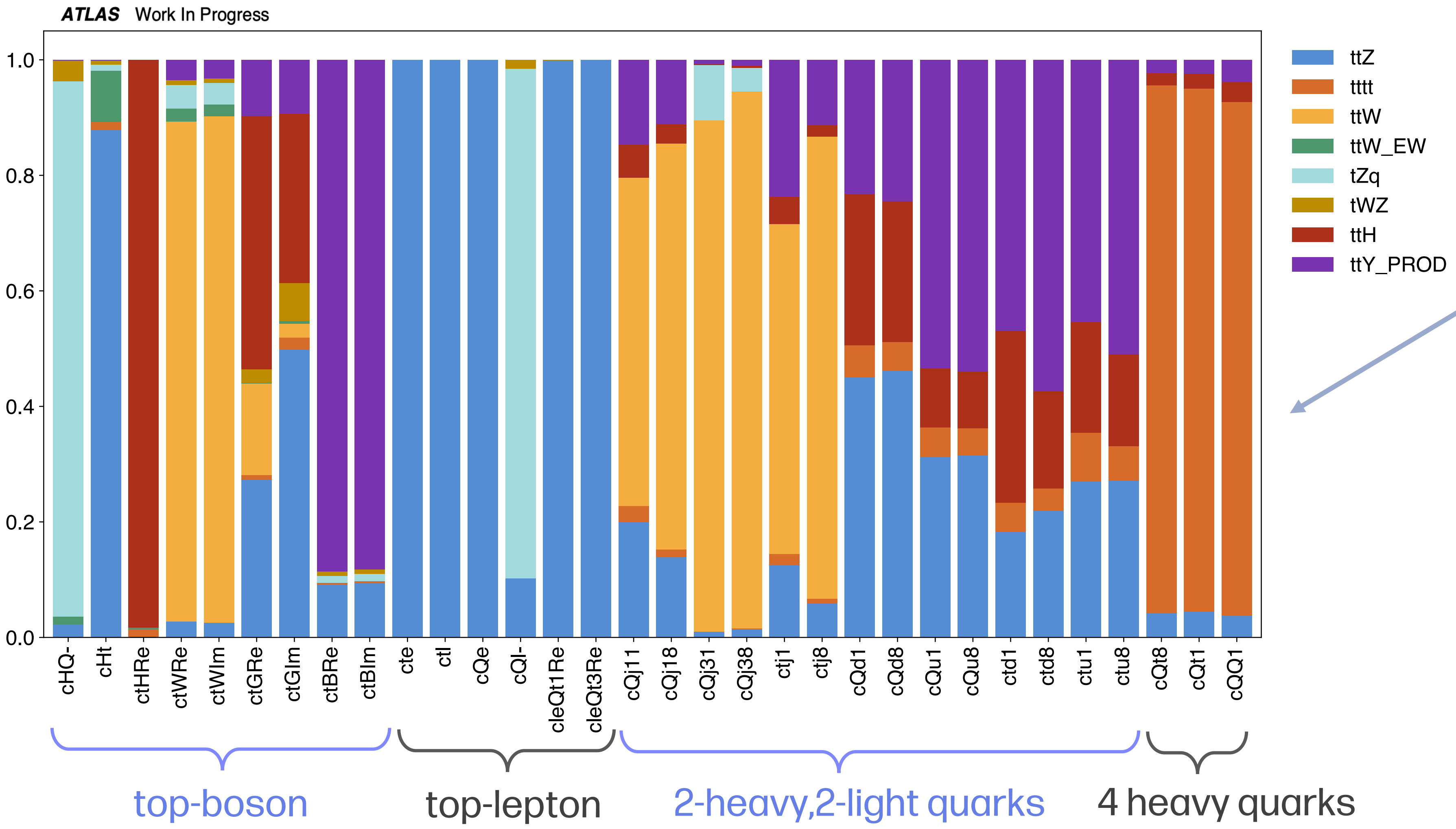
top quark, lepton

top quark, boson



The case for combining

- Many processes can contribute sensitivity to individual EFT Wilson coefficients
- Crucial to include all at the same time to set global limits:



How much sensitivity each Wilson coefficient gains from each Top+X process

limit including only process i

$$z_i(c) = \frac{\frac{1}{\sigma_i(c)^2}}{\sum_j \frac{1}{\sigma_j(c)^2}}$$

Summary and forward steps:

- Combined measurement of ‘top+ using Run 2 dataset collected by the ATLAS experiment at the LHC
- Results interpreted within the framework of the Standard Model Effective Field Theory (SMEFT), allowing constraints to be placed on 30+ dimension-six, top-sector operators
- Able to **exploit correlations and interplays between processes and SMEFT effects** for a consistent and comprehensive interpretation of the data.
- Analysis in final stages, aiming to set competitive limits on the most comprehensive range of top-sector SMEFT coefficients

Thanks for listening!

Backups

Object Definitions

Leptons

	Pre-selected Electron	Pre-selected Muon
Acceptance	$p_T > 7$ GeV, $\lvert\eta^{clust}\rvert < 2.47$ except $1.37 < \lvert\eta^{clust}\rvert < 1.52$	$p_T > 7$ GeV, $\lvert\eta\rvert < 2.5$
Quality	`LooseAndBLayerLH`	`Medium`
Overlap removal	see Section 4.6	
Impact parameter	$\lvert d_0/\sigma(d_0)\rvert < 5.0$ $\lvert z_0 \cdot \sin(\theta)\rvert < 0.5$ mm	$\lvert d_0/\sigma(d_0)\rvert < 3.0$ $\lvert z_0 \cdot \sin(\theta)\rvert < 0.5$ mm
	Signal Electron	**Signal Muon**
Quality	`TightLH`	`Medium`
Isolation	`PLVTight`	`PLVTight`

Jets

Selected jet	
Collection	`AntiKt4EMPFlow`
Acceptance	$p_T > 20$ GeV, $\lvert\eta\rvert < 4.5$
Overlap removal	see Section 4.6
Jet Vertex Tagger	reject jets with $p_T < 60$ GeV, $\lvert\eta\rvert < 2.4$ and JVT < 0.5 after overlap removal
Forward Jet Vertex Tagger	reject jets with $p_T < 60$ GeV, $2.5 < \lvert\eta\rvert < 4.5$, fJVT > 0.4 and $\lvert$timing$\rvert > 10$ ns
***b*-tagged jet**	
Acceptance	$p_T > 20$ GeV, $\lvert\eta\rvert < 2.5$
b-tagging	85% efficiency

Photons:
Quality: Tight
Isolation: FixedCutTight
pT > 20 GeV, $|\eta| < 2.37$

Harmonisation: definitions compared to dedicated analyses

	TPX	$t\bar{t}Z$	$t\bar{t}\ell^+\ell^-$	$t\bar{t}t\bar{t}$	$t\bar{t}W/t\bar{t}H$	$t\bar{t}Wj$	tZq	$t\bar{t}\gamma$
Electron Quality	TightLH	MediumLH	TightLH	TightLH	TightLH	TightLH	MediumLH	MediumLH
Electron Isolation	PLVTight	PLVLoose	PLVTight	PLIVTight	PLIVVeryTight	PLVTight	PLVLoose	PLVLoose
ECIDS	✓	✗	✓	✓	✓	✓	✗	✗
Muon Quality	Medium	Medium	Medium	Medium	Medium	Medium	Medium	Medium
Muon Isolation	PLVTight	PLVLoose	PLVTight	PLIVTight	PLIVVeryTight	PLVTight	PLVLoose	PLVLoose
Photon Quality	Tight	—	—	—	—	—	—	Tight
Photon Isolation	FixedCutTight	—	—	—	—	—	—	FixedCutTight
Jet p_T [GeV]	≥ 20	≥ 25	≥ 25	≥ 20	≥ 25	≥ 25	≥ 25	≥ 25
Jet $\lvert\eta\rvert$	< 4.5	< 2.5	< 2.5	< 2.5	< 2.5	< 4.5	< 4.5	< 2.5

Common Control Regions: Non-Prompt Leptons (Fakes)

9 Common control regions in total

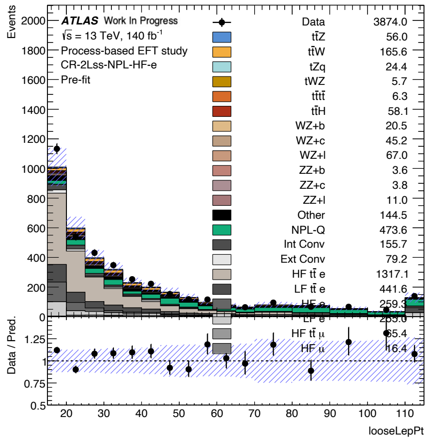
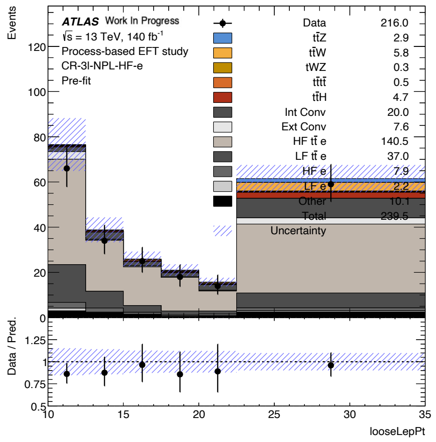
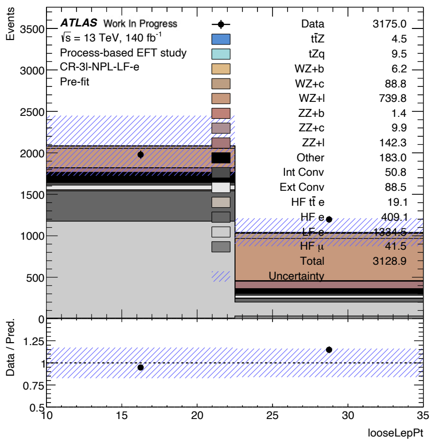
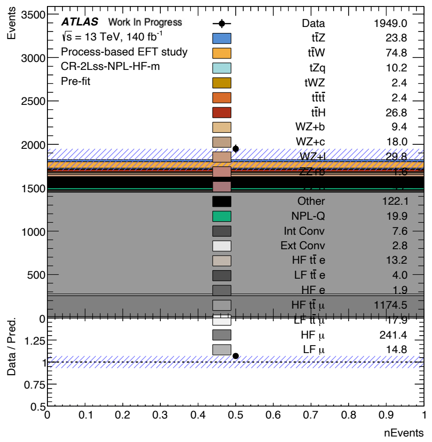
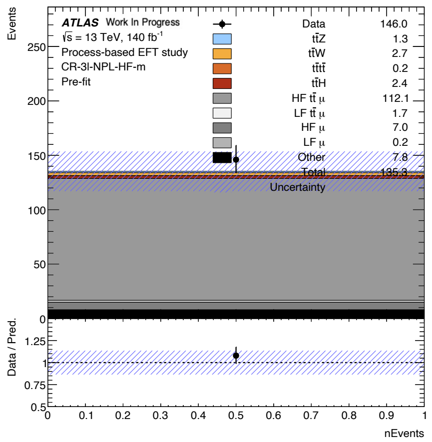
Fake control regions:

- Exactly one Loose (not tight) lepton (used to define e/mu definition)
- LF: no b-jets
- HF: ≥ 1 b-jet 85%
- Additional cuts on pT and m_{ll}
- Fakes defined using MC truth

Used to constrain background normfactors on:

- HF e-fakes
- HF mu-fakes
- LF e-fakes

Non-prompt-leptons (NPL) fakes:

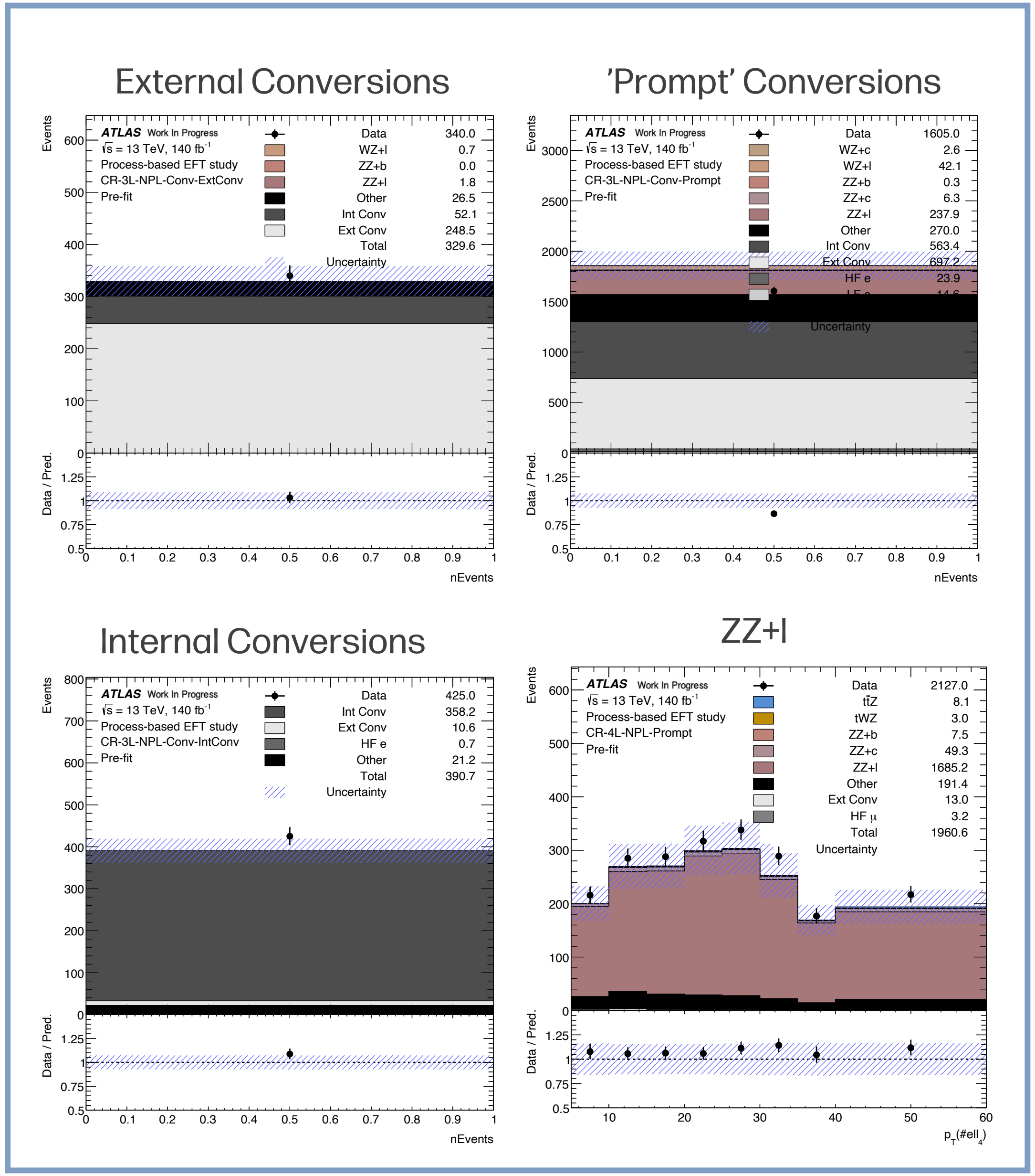
	2lss HF	3l HF	3l LF
Electron			
Muon			

Same approach as in many top+X analyses:

Targeting Z(→ μμ)γ, with a γ conversion to electrons

- 0 b-jets @85%
- $\mu^{-}\mu^{+}e$ required, all passing tight criteria
- M_{lll} within Z peak
- Internal: within conversion radius (20mm)
- External: outside conversion radius (20mm)
- 'Prompt': no conversion vertex

Included an additional 4l0b region to control ZZ+l contamination in the prompt conversion region



Charge flip estimation

- Significant background in 2lss regions
- Uses standard workflow (and same code as as ttll high-mass/ttWj)
- Use data Z→ee regions (OS and SS) - subtract side bands from peak region
- Likelihood minimization to derive charge flip factors
- Additional systematics for
  - Extrapolation, Sideband, Binning, Statistics
- Only applied in 2lss SRs: MC Charge flips used in 3l regions and common CR

Non-prompt photon estimation:

Significant backgrounds in photon regions

DD methods used in dedicated ttγ analysis updated to object definitions used here (tighter lepton requirements)

Derive fake-rate scale factors in pt/eta bins for:

e-fakes: photons which are mis-reconstructed or mismatched true electrons or caused by non-prompt QED processes with nearby electrons.

- Tag and probe method is used to derive FRSFs in (pT, eta) bins separately for converted and unconverted photons.

H-fakes: photons from hadronic processes or deposits in the hadronic calorimeter

- MC Scale-factors estimated using 2-D sideband (ABCD) method