Roadmap towards future combinations and Effective Field Theory interpretations of top+X processes

Jacob Kempster on behalf of the ATLAS Collaboration

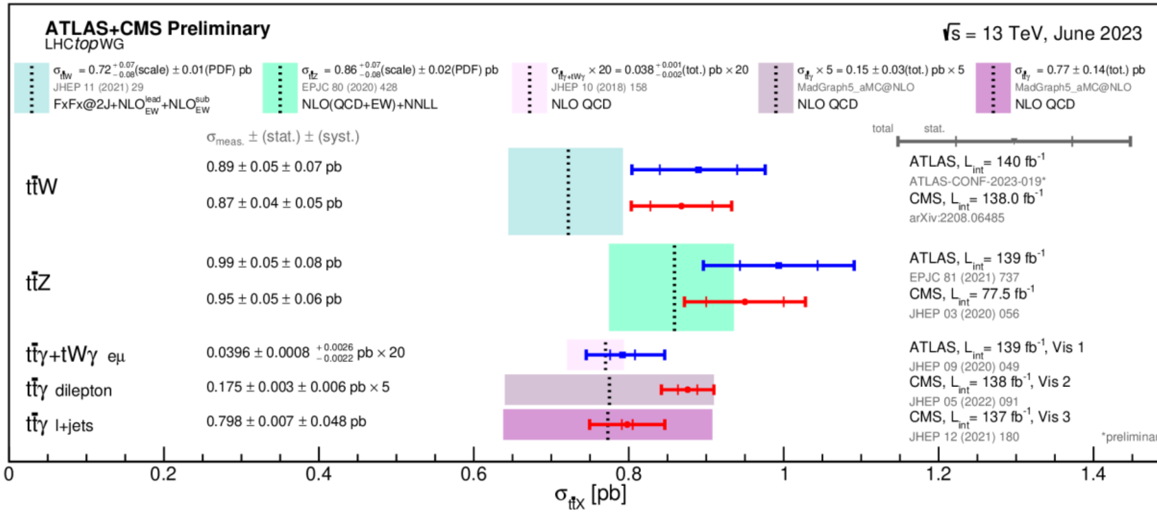
ATL-PHYS-PUB-2023-030

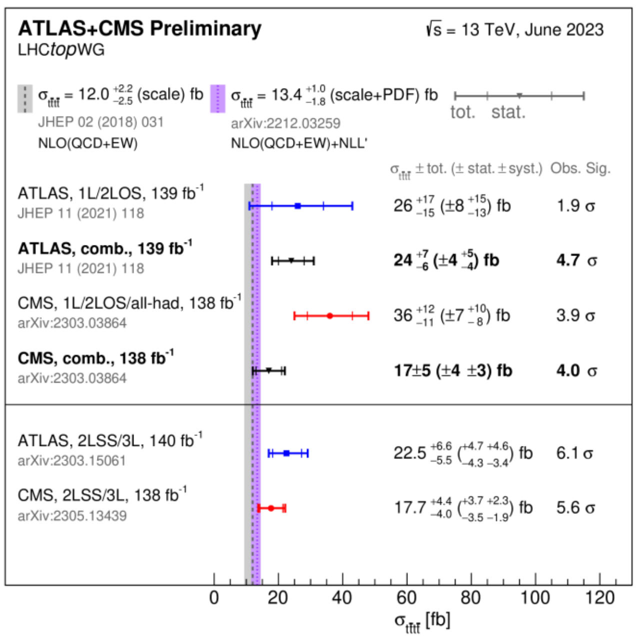
“A brief overview”

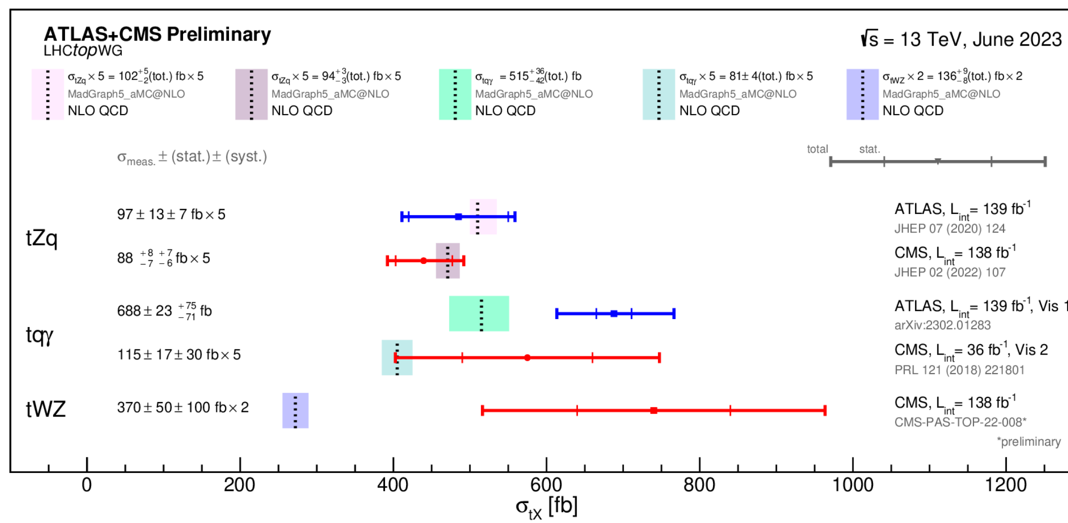
Top + X

ATL-PHYS-PUB-2023-013

There are a lot of individual high-precision SM Top+X measurements!







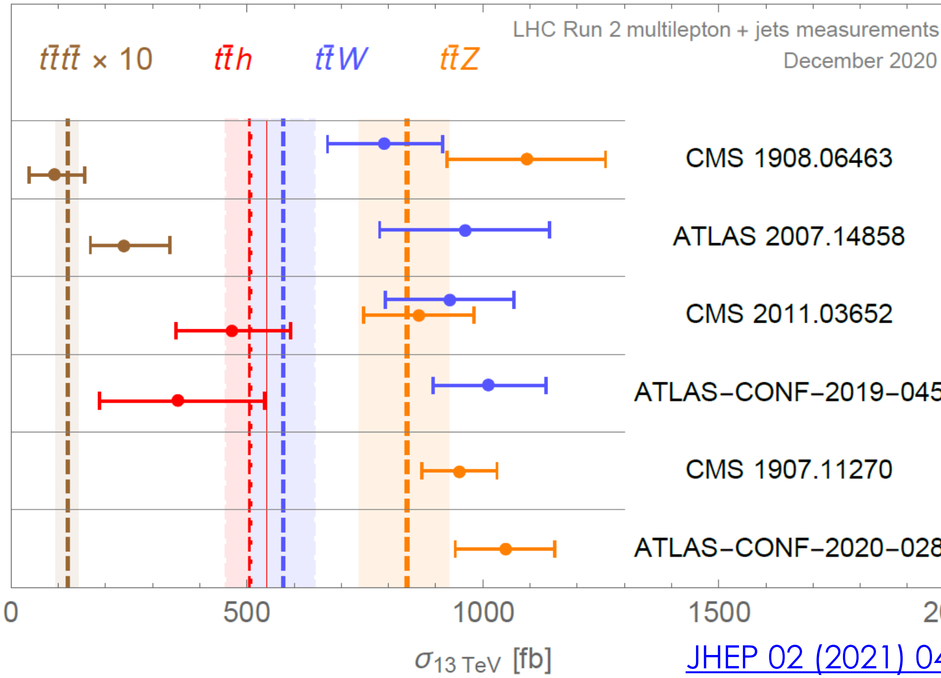
Top + X

There are also some hints of disagreement with SM predictions – especially in ttW and potentially 4tops

How to consider these effects in another way? (If they persist!)

- In a Top+X measurement, every other Top+X process is the main background
- Many Top+X processes are sensitive to the same EFT couplings
- Nearly impossible to disentangle them while measuring one at a time

(Plot not up to date, just exemplar)



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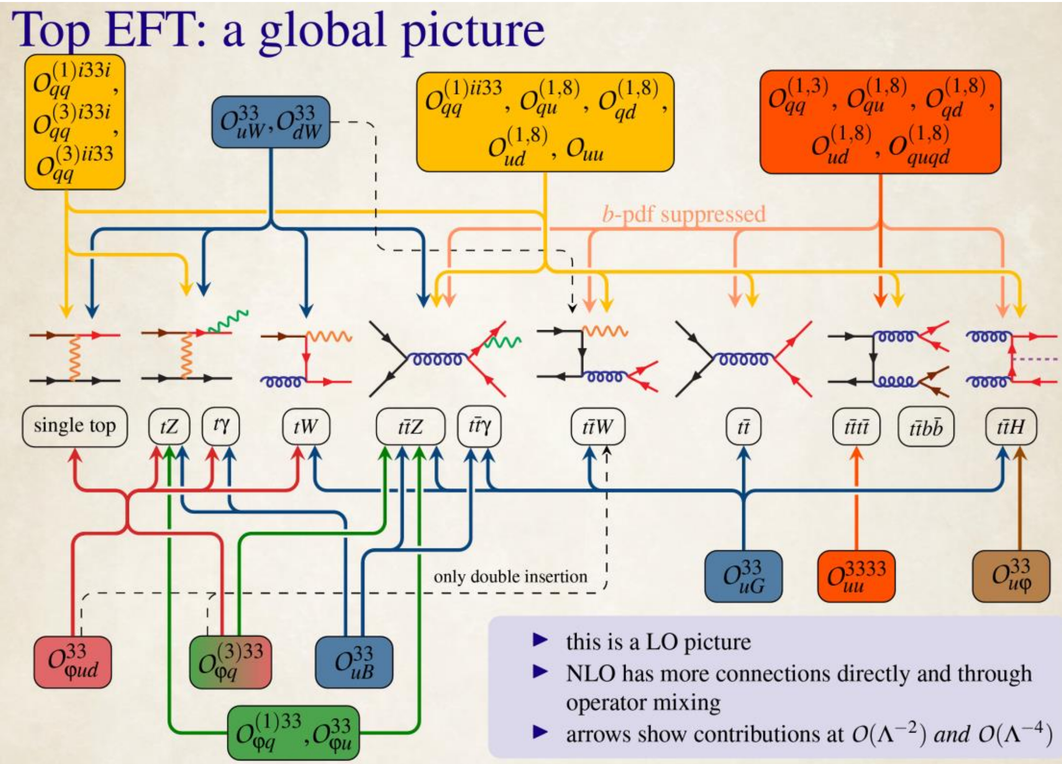
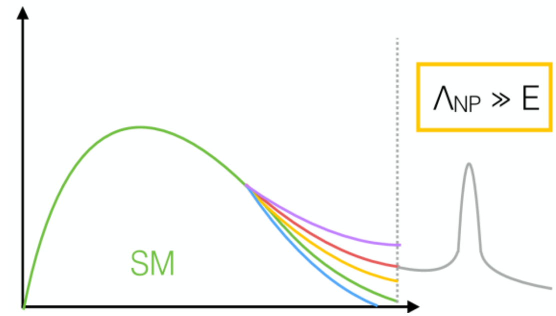
Top + X EFT Combinations

[K. Mimasu, EFTforTop](#)



[P. Galler, TopFitter, ICHEP 2020](#)

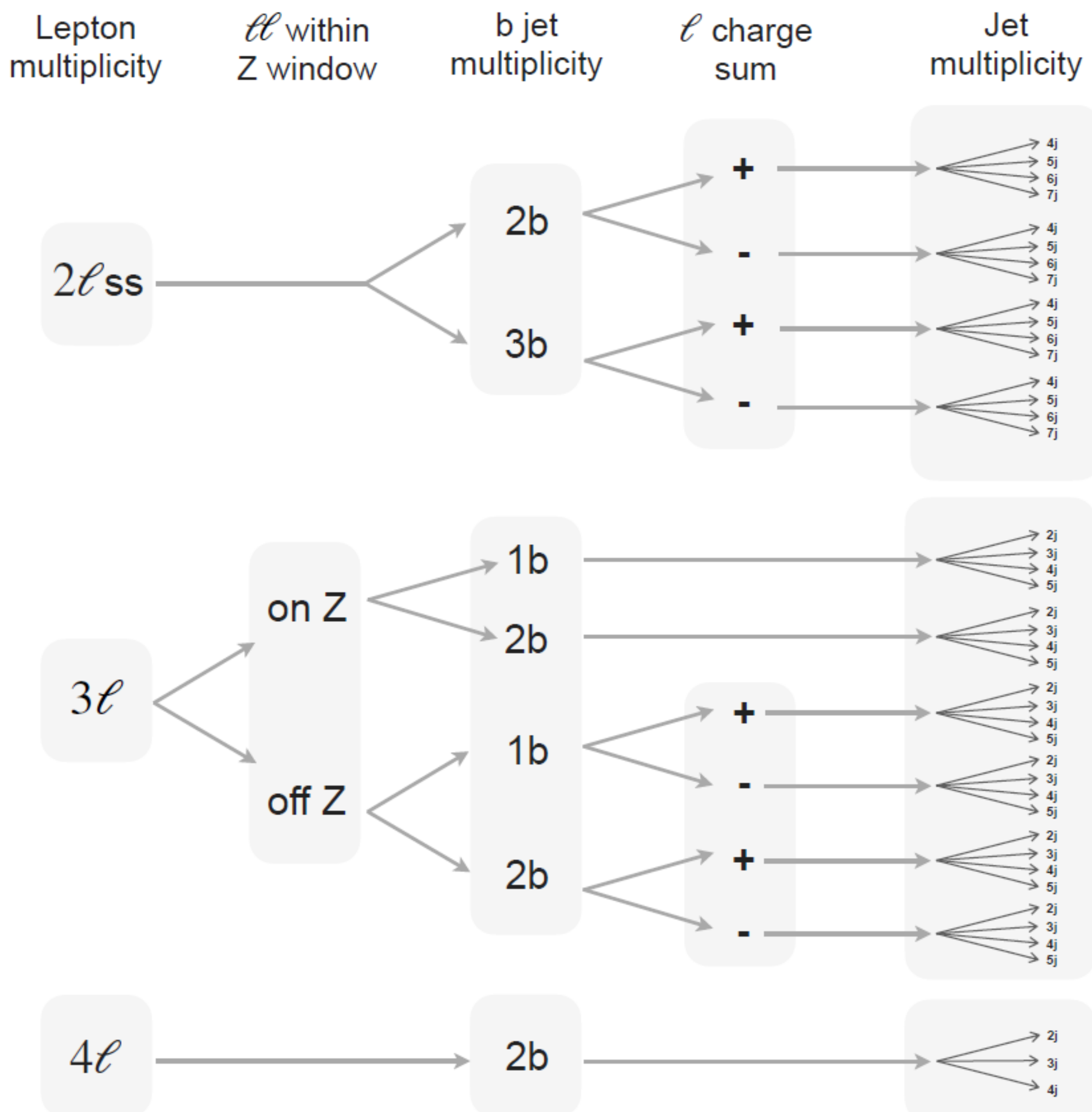


parameter	$t\bar{t}$	single t	tW	tZ	t decay	$t\bar{t}Z$	$t\bar{t}W$
$C_{Qq}^{1,8}$	Λ^{-2}	–	–	–	–	Λ^{-2}	Λ^{-2}
$C_{Qq}^{3,8}$	Λ^{-2}	Λ^{-4} [Λ^{-2}]	–	Λ^{-4} [Λ^{-2}]	Λ^{-4} [Λ^{-2}]	Λ^{-2}	Λ^{-2}
C_{tu}^{8}, C_{td}^{8}	Λ^{-2}	–	–	–	–	Λ^{-2}	–
$C_{Qq}^{1,1}$	Λ^{-4} [Λ^{-2}]	–	–	–	–	Λ^{-4} [Λ^{-2}]	Λ^{-4} [Λ^{-2}]
$C_{Qq}^{3,1}$	Λ^{-4} [Λ^{-2}]	Λ^{-2}	–	Λ^{-2}	Λ^{-2}	Λ^{-4} [Λ^{-2}]	Λ^{-4} [Λ^{-2}]
C_{tu}^{1}, C_{td}^{1}	Λ^{-4} [Λ^{-2}]	–	–	–	–	Λ^{-4} [Λ^{-2}]	–
C_{Qu}^{8}, C_{Qd}^{8}	Λ^{-2}	–	–	–	–	Λ^{-2}	–
C_{tq}^{8}	Λ^{-2}	–	–	–	–	Λ^{-2}	Λ^{-2}
C_{Qu}^{1}, C_{Qd}^{1}	Λ^{-4} [Λ^{-2}]	–	–	–	–	Λ^{-4} [Λ^{-2}]	–
C_{tq}^{1}	Λ^{-4} [Λ^{-2}]	–	–	–	–	Λ^{-4} [Λ^{-2}]	Λ^{-4} [Λ^{-2}]
$C_{\phi Q}^{-}$	–	–	–	Λ^{-2}	–	Λ^{-2}	–
$C_{\phi Q}^{3}$	–	Λ^{-2}	Λ^{-2}	Λ^{-2}	Λ^{-2}	–	–
$C_{\phi t}$	–	–	–	Λ^{-2}	–	Λ^{-2}	–
$C_{\phi tb}$	–	Λ^{-4}	Λ^{-4}	Λ^{-4}	Λ^{-4}	–	–
C_{tZ}	–	–	–	Λ^{-2}	–	Λ^{-2}	–
C_{tW}	–	Λ^{-2}	Λ^{-2}	Λ^{-2}	Λ^{-2}	–	–
C_{bW}	–	Λ^{-4}	Λ^{-4}	Λ^{-4}	Λ^{-4}	–	–
C_{tG}	Λ^{-2}	[Λ^{-2}]	Λ^{-2}	–	[Λ^{-2}]	Λ^{-2}	Λ^{-2}

[JHEP 02 (2020) 131](#)

Combining multiple operators across multiple channels can help to improve constraints and reduce blind directions

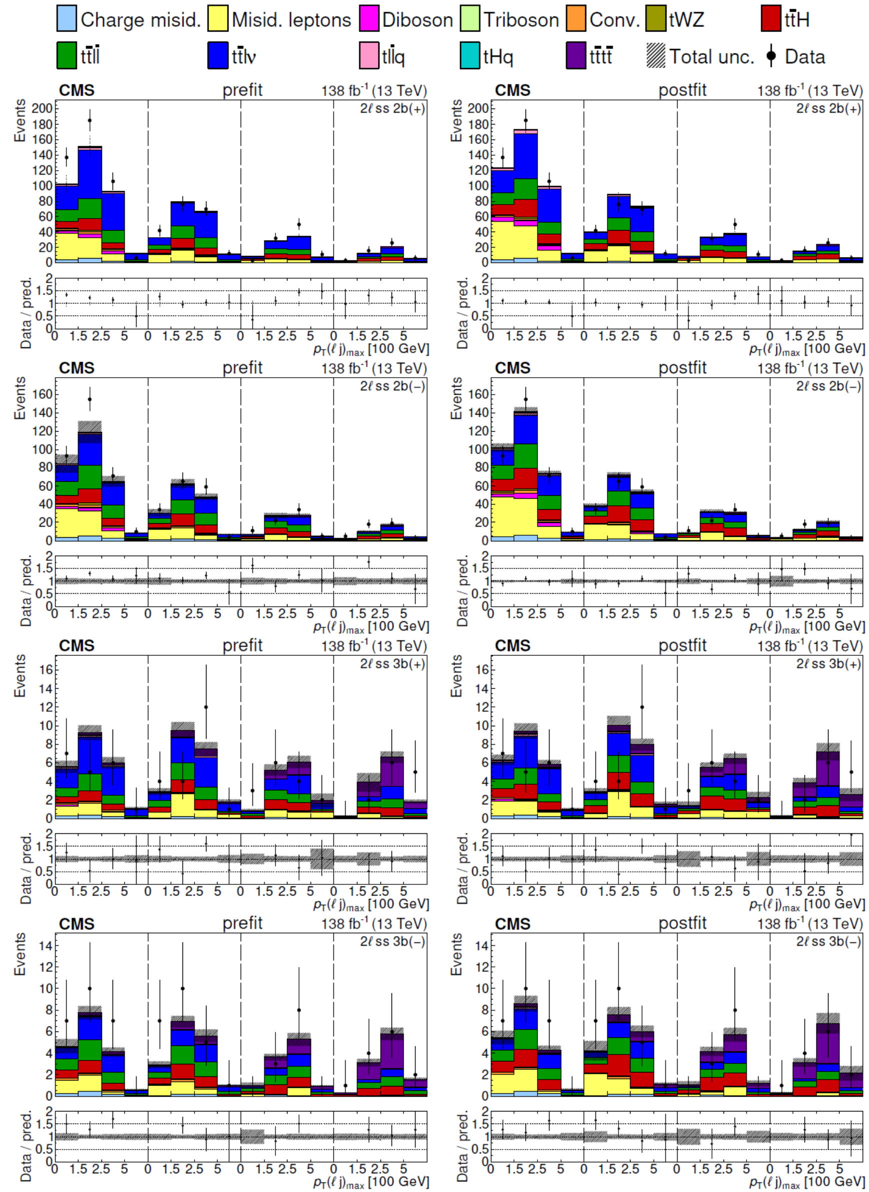
CMS Successes: JHEP03(2021)095 , arXiv:2307.15761



CMS Successes: JHEP03(2021)095 , arXiv:2307.15761

Event category	Leptons	$m_{\ell\ell}$	b tags	Lepton charge sum	Jets	Kinematical variable
2ℓss 2b	2	No requirement	2	$>0, <0$	$4, 5, 6, \geq 7$	$p_T(\ell j)_{max}$
2ℓss 3b	2	No requirement	≥ 3	$>0, <0$	$4, 5, 6, \geq 7$	$p_T(\ell j)_{max}$
3ℓ off-Z 1b	3	$\|m_Z - m_{\ell\ell}\| > 10\,\text{GeV}$	1	$>0, <0$	$2, 3, 4, \geq 5$	$p_T(\ell j)_{max}$
3ℓ off-Z 2b	3	$\|m_Z - m_{\ell\ell}\| > 10\,\text{GeV}$	≥ 2	$>0, <0$	$2, 3, 4, \geq 5$	$p_T(\ell j)_{max}$
3ℓ on-Z 1b	3	$\|m_Z - m_{\ell\ell}\| < 10\,\text{GeV}$	1	No requirement	$2, 3, 4, \geq 5$	$p_T(Z)$
3ℓ on-Z 2b	3	$\|m_Z - m_{\ell\ell}\| < 10\,\text{GeV}$	≥ 2	No requirement	$2, 3, 4, \geq 5$	$p_T(Z)$ or $p_T(\ell j)_{max}$
4ℓ	≥ 4	No requirement	≥ 2	No requirement	$2, 3, \geq 4$	$p_T(\ell j)_{max}$

Grouping of WCs	WCs	Lead categories
2hq2ℓ	$c_{Q\ell}^{3(\ell)}, c_{Q\ell}^{-(\ell)}, c_{Qe}^{(\ell)}, c_{t\ell}^{(\ell)}, c_{te}^{(\ell)}, c_{t}^{S(\ell)}, c_{t}^{T(\ell)}$	3ℓ off-Z
4hq	$c_{QQ}^{1}, c_{Qt}^{1}, c_{Qt}^{8}, c_{tt}^{1}$	2ℓss
2hq2lq "$t\bar{t}\ell\nu$-like"	$c_{Qq}^{11}, c_{Qq}^{18}, c_{tq}^{1}, c_{tq}^{8}$	2ℓss
2hq2lq "$t\ell\bar{\ell}$q-like"	c_{Qq}^{31}, c_{Qq}^{38}	3ℓ on-Z
2hqV "$t\bar{t}\ell\bar{\ell}$-like"	$c_{tZ}, c_{\varphi t}, c_{\varphi Q}^{-}$	3ℓ on-Z and 2ℓss
2hqV "tXq-like"	$c_{\varphi Q}^{3}, c_{\varphi tb}, c_{bW}$	3ℓ on-Z
2hqV (significant impacts on many processes)	$c_{tG}, c_{t\varphi}, c_{tW}$	3ℓ and 2ℓss



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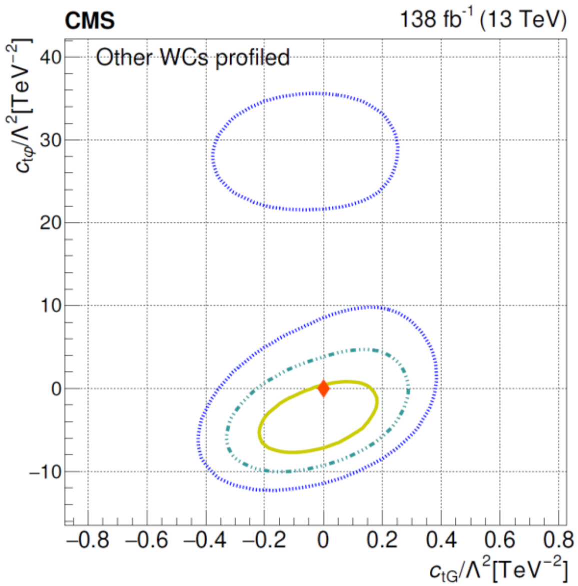
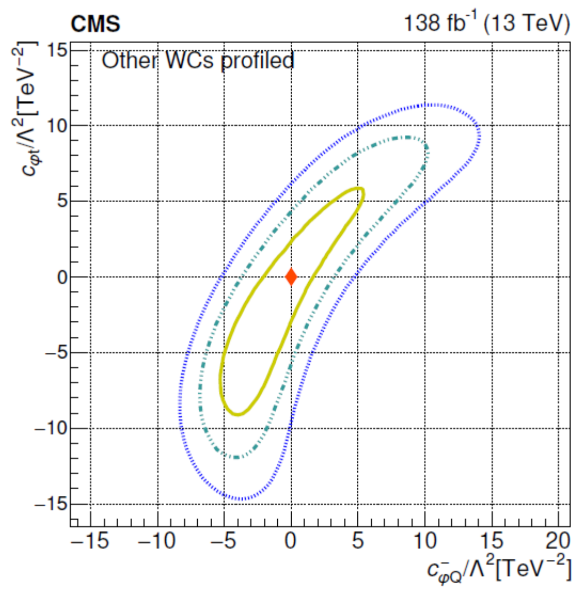
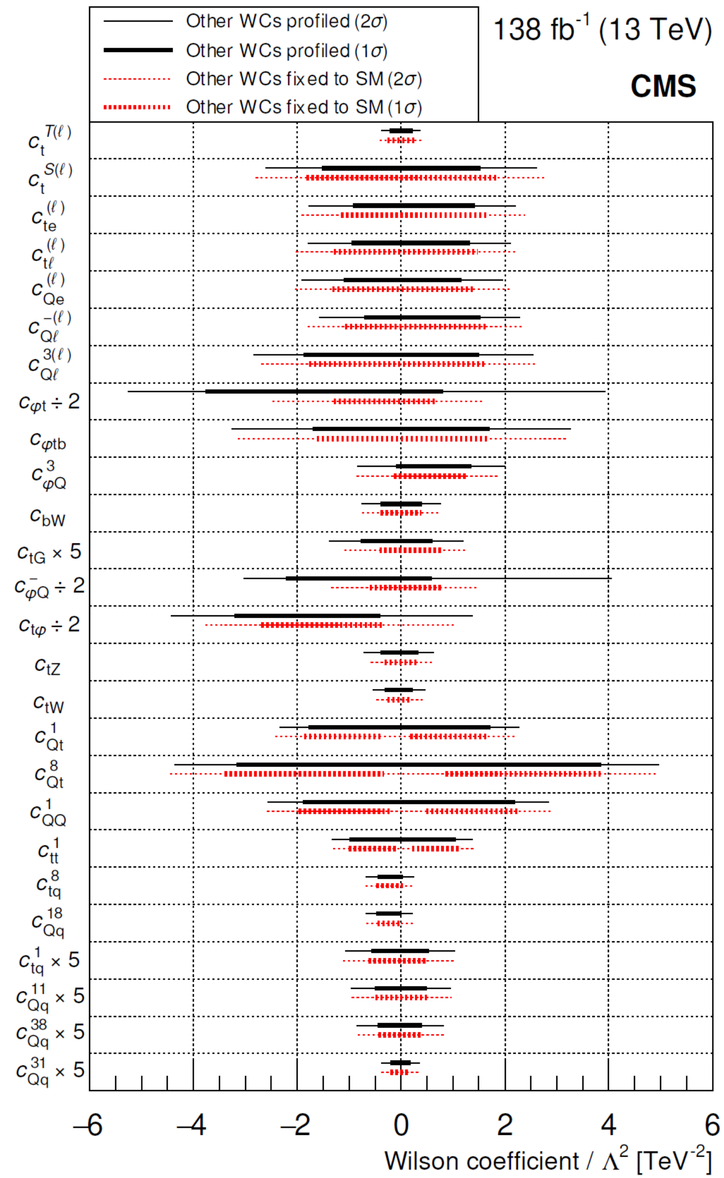
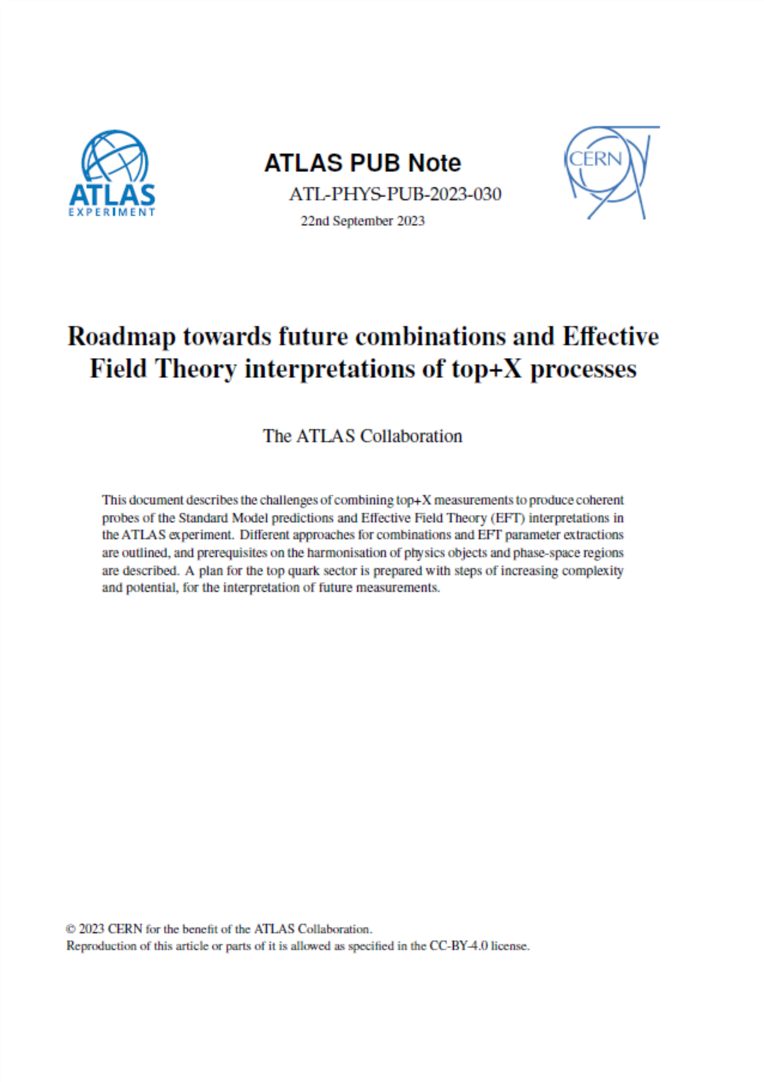






Goals of the roadmap document


ATLAS PUB Note

ATL-PHYS-PUB-2023-030

22nd September 2023

Roadmap towards future combinations and Effective Field Theory interpretations of top+X processes

The ATLAS Collaboration

This document describes the challenges of combining top+X measurements to produce coherent probes of the Standard Model predictions and Effective Field Theory (EFT) interpretations in the ATLAS experiment. Different approaches for combinations and EFT parameter extractions are outlined, and prerequisites on the harmonisation of physics objects and phase-space regions are described. A plan for the top quark sector is prepared with steps of increasing complexity and potential, for the interpretation of future measurements.

- **Describe:**
  - Challenges of combining top+X measurements to coherently probe SM + EFTs
  - Available MC generators and UFOs
- **Discuss:**
  - Harmonisation of physics objects
  - Harmonisation of phase-space regions
- **Deliberate:**
  - Options for optimal observables
- **Develop:**
  - Incremental roadmap with increasing complexity, towards maximising the potential of Run-3 ATLAS data

ATL-PHYS-PUB-2023-030

Brief summaries

EFT for Monte Carlo

Generators:

- Madgraph
  - Predominant recommendation
  - Highly compatible with UFO models
  - 'Simple' user interface
  - Extension enabling computation of NLO in QCD and NLO EW corrections
  - (NLO generators often introduce more negative weights which can be difficult to deal with experimentally)

- Powheg:
  - Better modelling of SM ttbar process at NLO in QCD
  - Still requires reweighting according to MG5 EFT predictions
  - Resulting approximations would require extensive validation studies

- Pythia
  - Does not retain spin correlations
  - Problems associated to EFT operators which generate gluons and interaction with the parton shower

Brief summaries

EFT for Monte Carlo

UFO models:

- SMEFTSim3.0
  - Current recommendation used widely in ATLAS
  - ‘top’ flavour assumption – treats operators with lepton-flavour indices as individual entities
  - LO accuracy only
  - Distinguishes between EFT insertions in vertices or in corrections to widths of propagators

- SMEFTatNLO
  - Both LO and NLO QCD precision
  - No implementation of CP violating operators, or operators with b-quarks in the initial state, or FCNC interactions
  - Extensive upgrades planned over the next ~5 years

Brief summaries

EFT for Monte Carlo

Other topics discussed:

- Coupling orders
- Decomposition of EFT contributions
- Internal reweighting vs dedicated generation
- Higher-order corrections
- EFT effects in top decay

Brief summaries

Harmonisation

Object definitions proposals:

- Harmonise object definitions between all combinable analyses apriori
- Design lepton working points which support (pseudo)-continuous calibrations
- Adopt common-denominator systematic reduction schemes for different processes, according to the sensitivity of each

Phase-space regions proposals:

- Harmonise region definitions between all combinable analyses apriori
- Design common ML algorithms to separate heavily overlapping processes (ttH, ttW, tttt)
- Adopt common fakes control regions between analyses

Brief summaries

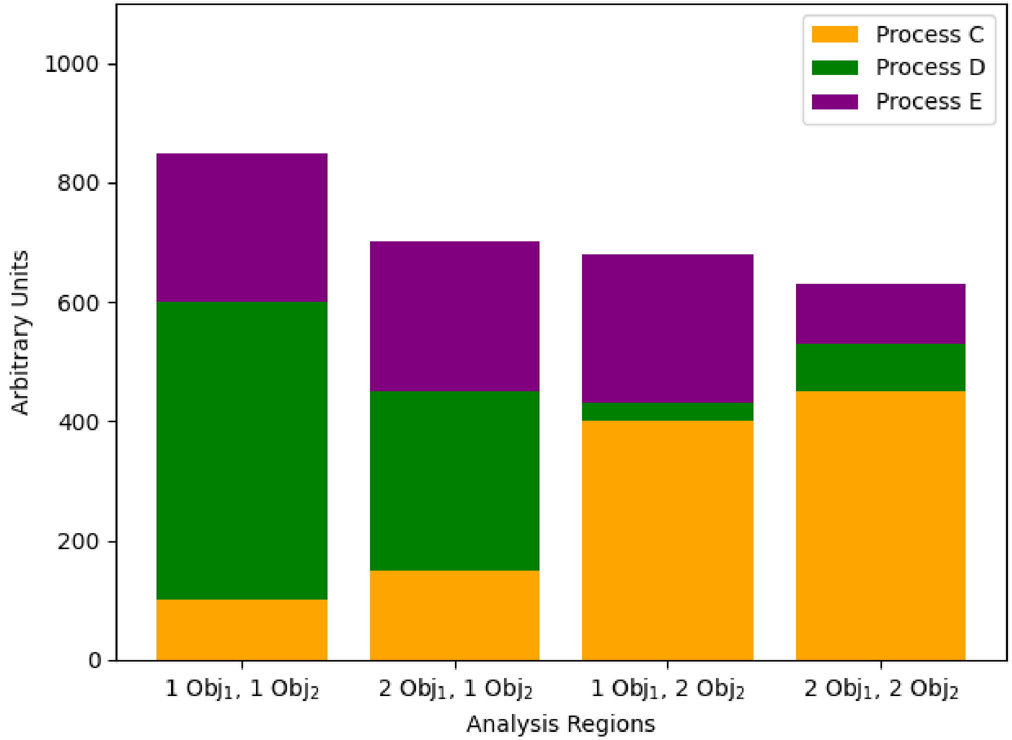
Region definitions and fitting tactics:

1. **Object-based (OB) fit:** The regions are broken down by lepton/jet/b-tag multiplicity, lepton charge etc. (à la CMS!)
    - Clean and simple to implement
    - Object + region harmonisation are automatic
    - Fakes treatment is coherent

- Some processes easy to distinguish – e.g. $t\bar{t}\gamma$
- Other processes difficult to separate this way – e.g. $t\bar{t}W, t\bar{t}H, t\bar{t}t\bar{t}$

- Principal Component Analysis will identify sensitive directions

- **Need to be clear what you are optimising for!**



Brief summaries

2. Process-based (PB) fit: The regions are defined with specific Top+X processes individually targeted in each.

- Potential to re-use dedicated cross section analyses to minimise work duplication
- Object + Region harmonisation and fakes treatment all require careful consideration if starting from separate analyses

- Some processes 'easy' to distinguish – e.g. $t\bar{t}Z$, tZq, $t\bar{t}\gamma$, $t\bar{t}H$
- Other processes remain difficult to separate this way – e.g. $t\bar{t}W, t\bar{t}H, t\bar{t}t\bar{t}$

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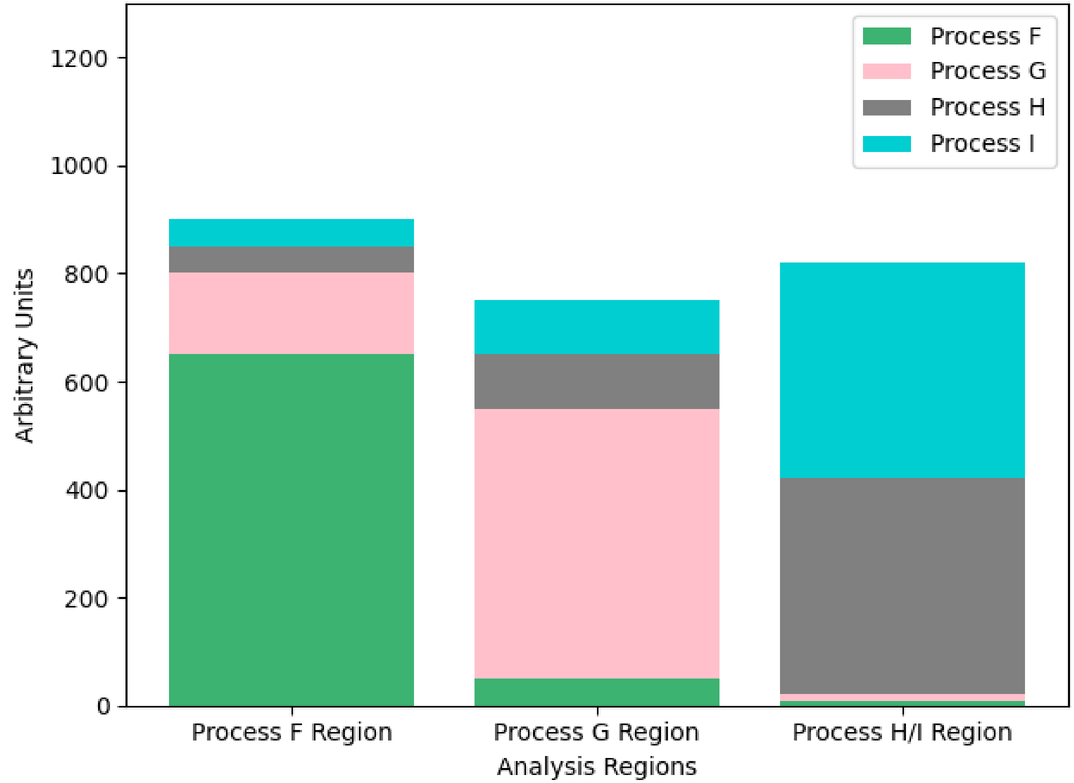
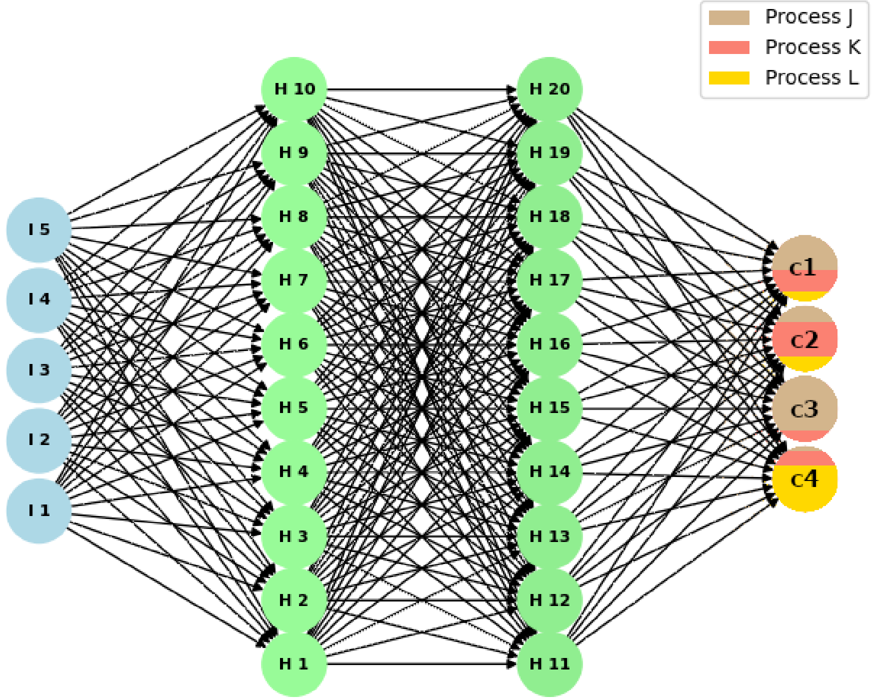


Brief summaries

3. **EFT-optimised (EO) fit:** The regions are defined by ML algorithms to select events with the highest sensitivity to particular EFT operators. [Lots of freedom here to define your targets, but lots of complications too].
    - Object + region harmonisation are automatic
    - Fakes treatment is coherent
    - Higher dependency on EFT model
    - Is it easily reinterpretable? How about surrogate networks?

- This methodology may provide the opportunities to separate $t\bar{t}W, t\bar{t}H, t\bar{t}t\bar{t}$
    - (Or can determine whether it is even necessary)
- Principal Component Analysis will identify sensitive directions
- **Need to be clear what you are optimising for!**

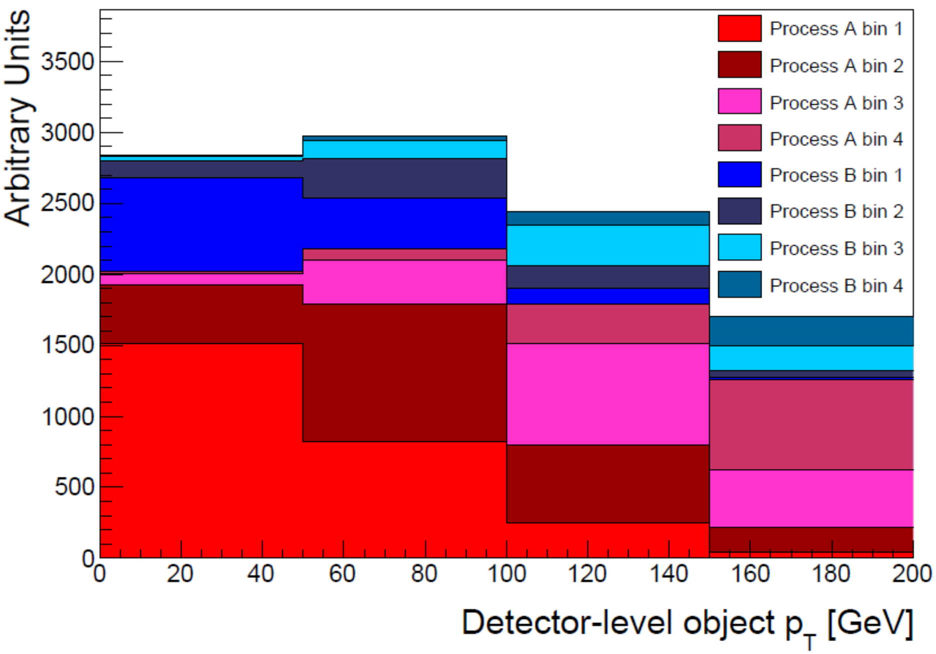


Brief summaries

4. **Fully differential multi-process unfolding:**
   - An extension of **(1)** or **(2)** (or technically **(3)**, with adjustments)
   - Best reinterpretations and reusability
     - Unbiased unfolding retains reliable results even under updated SM or EFT predictions
     - Simple to compare to new theories
   - Profile-likelihood unfolding with multiple signals reduces assumptions about EFT contributions compared to methods subtracting fixed SM backgrounds

- Truth-level binning optimisation required for EFT sensitivity

- Multi-signal unfolding is useful when dealing with largely inseparable processes



Brief summaries

Intermediate milestones:

1. Combination of two processes with small or zero statistical overlap and largely independent analyses but with some overlap of EFT sensitivity e.g. $t\bar{t}Z$ and $t\bar{t}\gamma$

2. Combination of processes with overlapping analyses (e.g. a control region in one is signal region in another), but without strong statistical overlap, where there is also overlap of EFT sensitivity, e.g. $t\bar{t}Z$ and $t\bar{t}WjEW$

3. Combination of similar processes with a large statistical overlap and overlap of EFT sensitivity e.g. $t\bar{t}Z$ and tZq

4. Combination of similar processes with a large statistical overlap and some overlap of EFT sensitivity but also individual sensitivity, e.g. $t\bar{t}W, t\bar{t}H, t\bar{t}t\bar{t}$

5. Combination of as many top+X processes as available, including all those previously described.

6. Combination of as many top processes as available, i.e. top+X and differential $t\bar{t}$ measurements and measurements of single top quark production.

Summary

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BACKUP