Save the EFT

Kirill Skovpen (Ghent University)

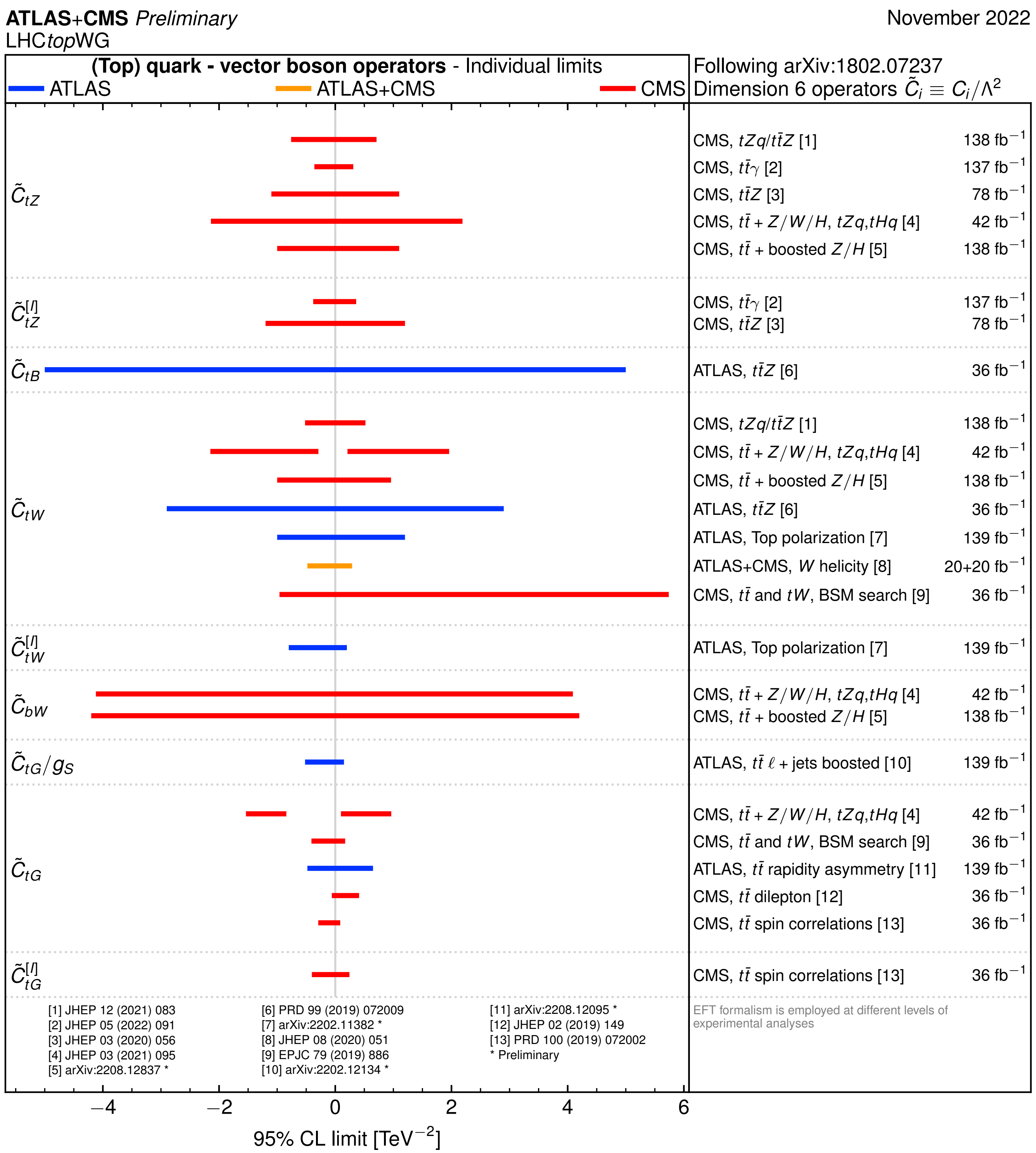
with special thanks to Combine and pyhf developers

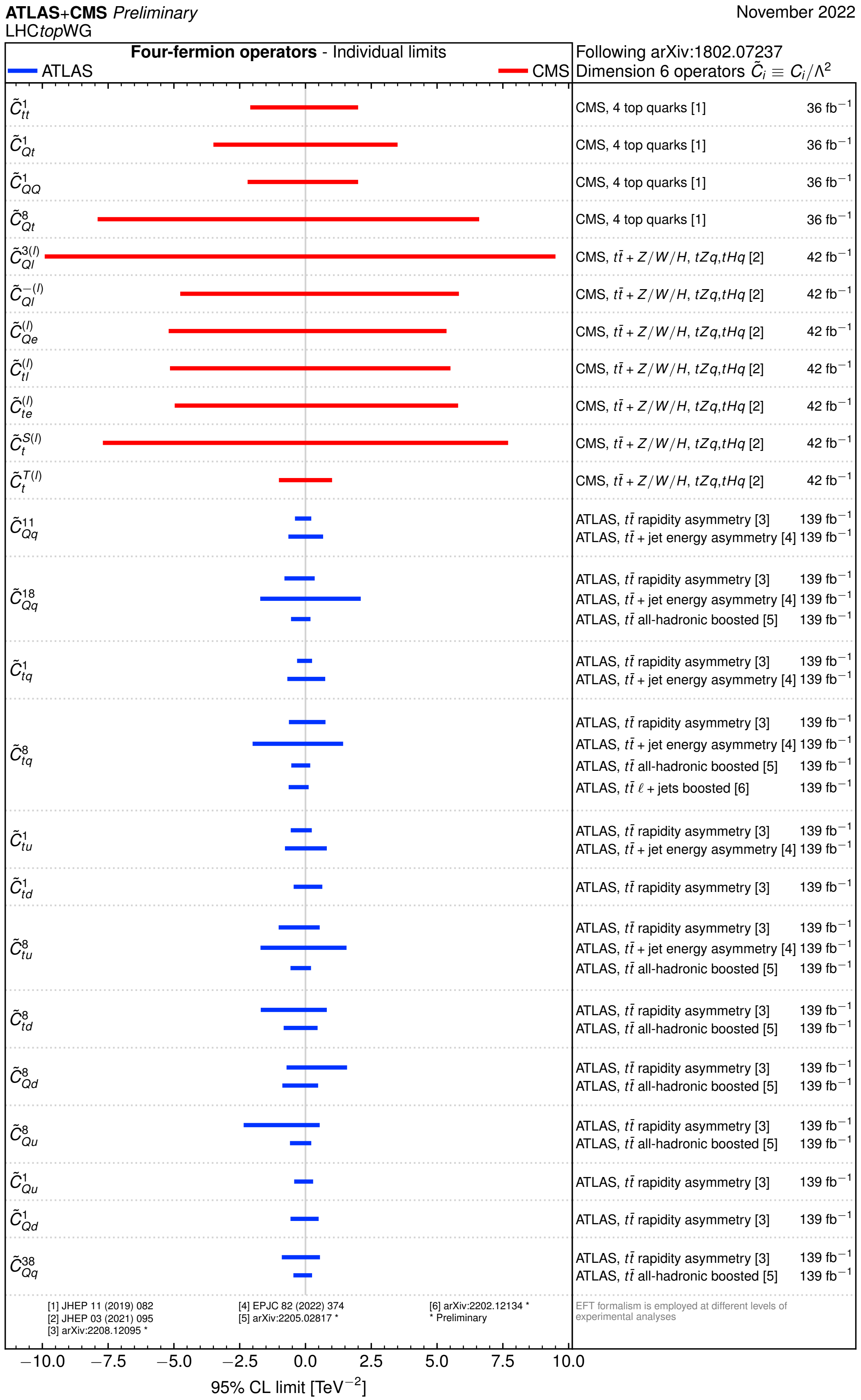
Forum on the interpretation of the LHC results for BSM studies

Durham, UK
Aug 29-Sep 1, 2023

Save the LHC EFT

LHC TOP EFT results





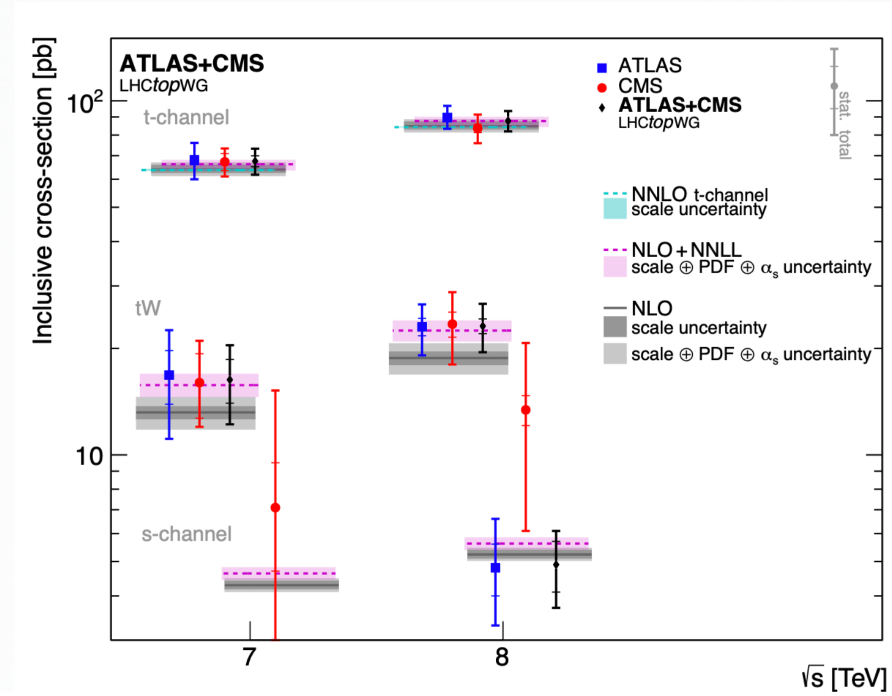
Combination story: Top

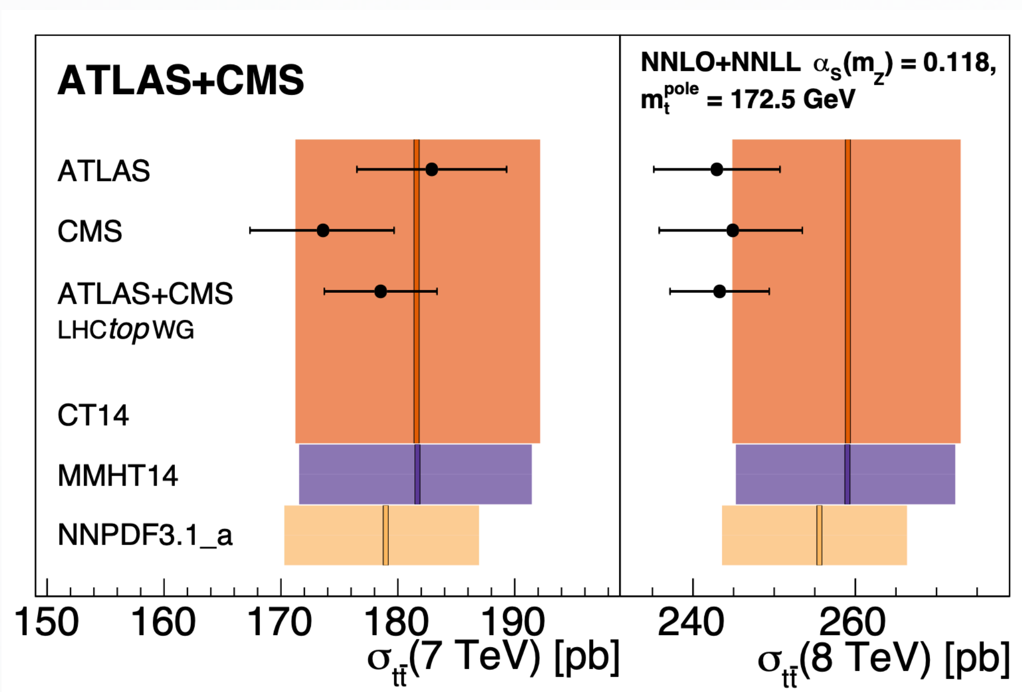
- Combinations of ATLAS and CMS results are steered by **LHCtopWG**
- Mainly based on best linear unbiased estimator (**BLUE**) and simplified-likelihood fits (**Convino**)
- **Many** dedicated efforts:
  - single top (Run I)
  - $t\bar{t}$ inclusive (Run I)
  - charge asymmetry (Run I)
  - W boson helicity (8 TeV)
  - Top mass and spin correlations (ongoing)
- **EFT interpretation** of the W boson helicity ATLAS+CMS result (**EFTfitter**)

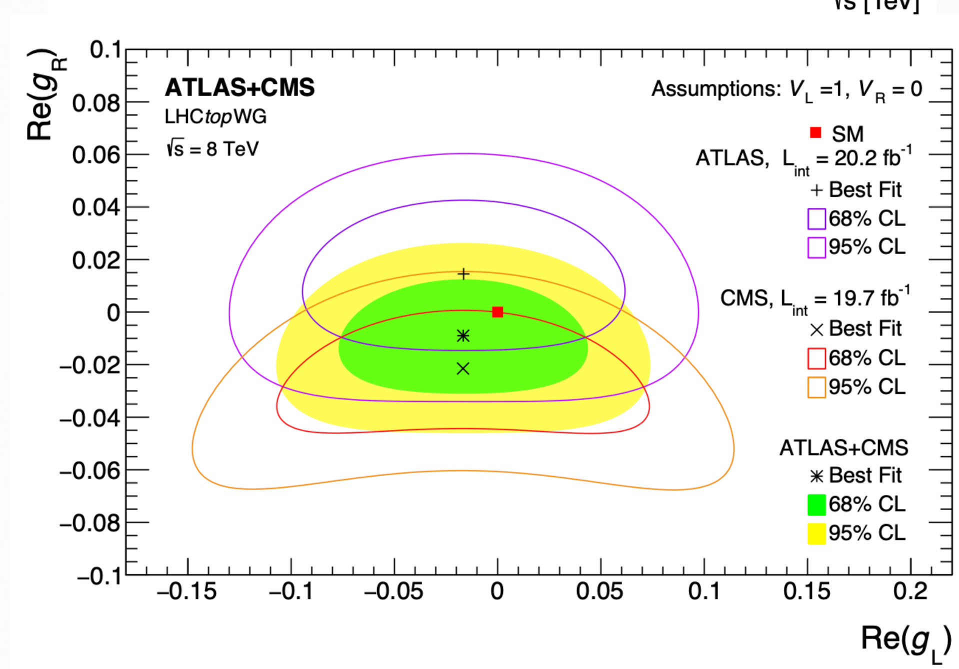
JHEP 05 (2019) 088

JHEP 07 (2023) 213

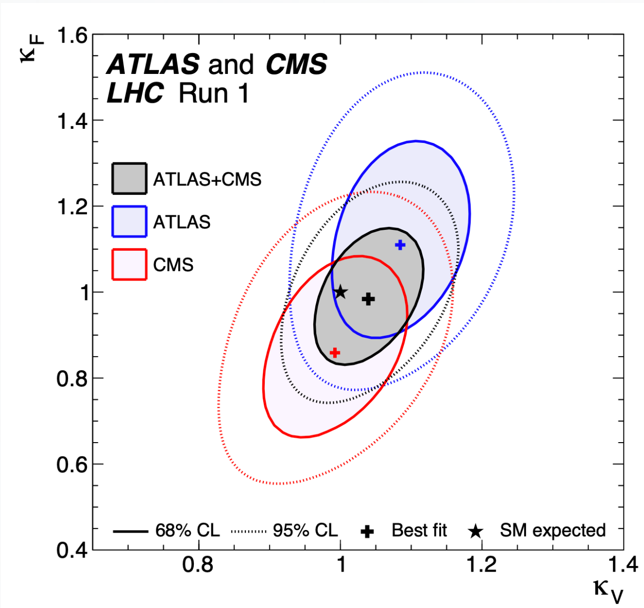
JHEP 08 (2020) 051

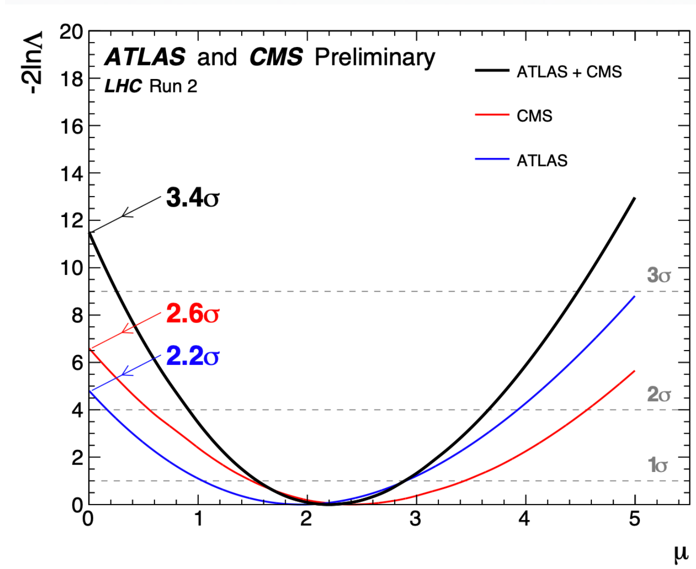


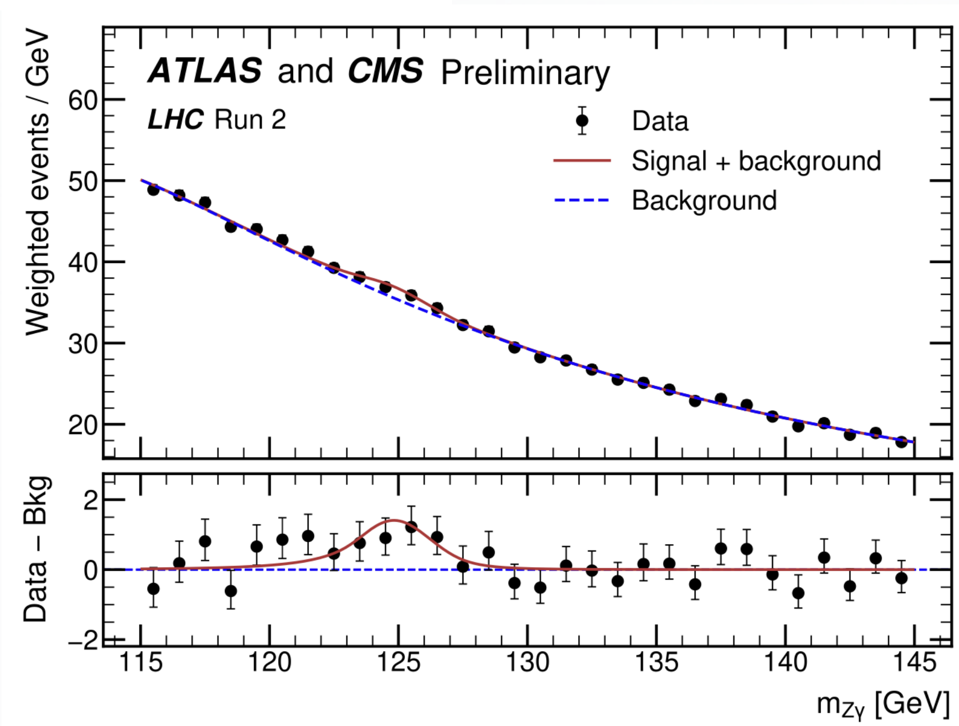




Combination story: Higgs







JHEP 08 (2016) 045

CMS-PAS-HIG-23-002

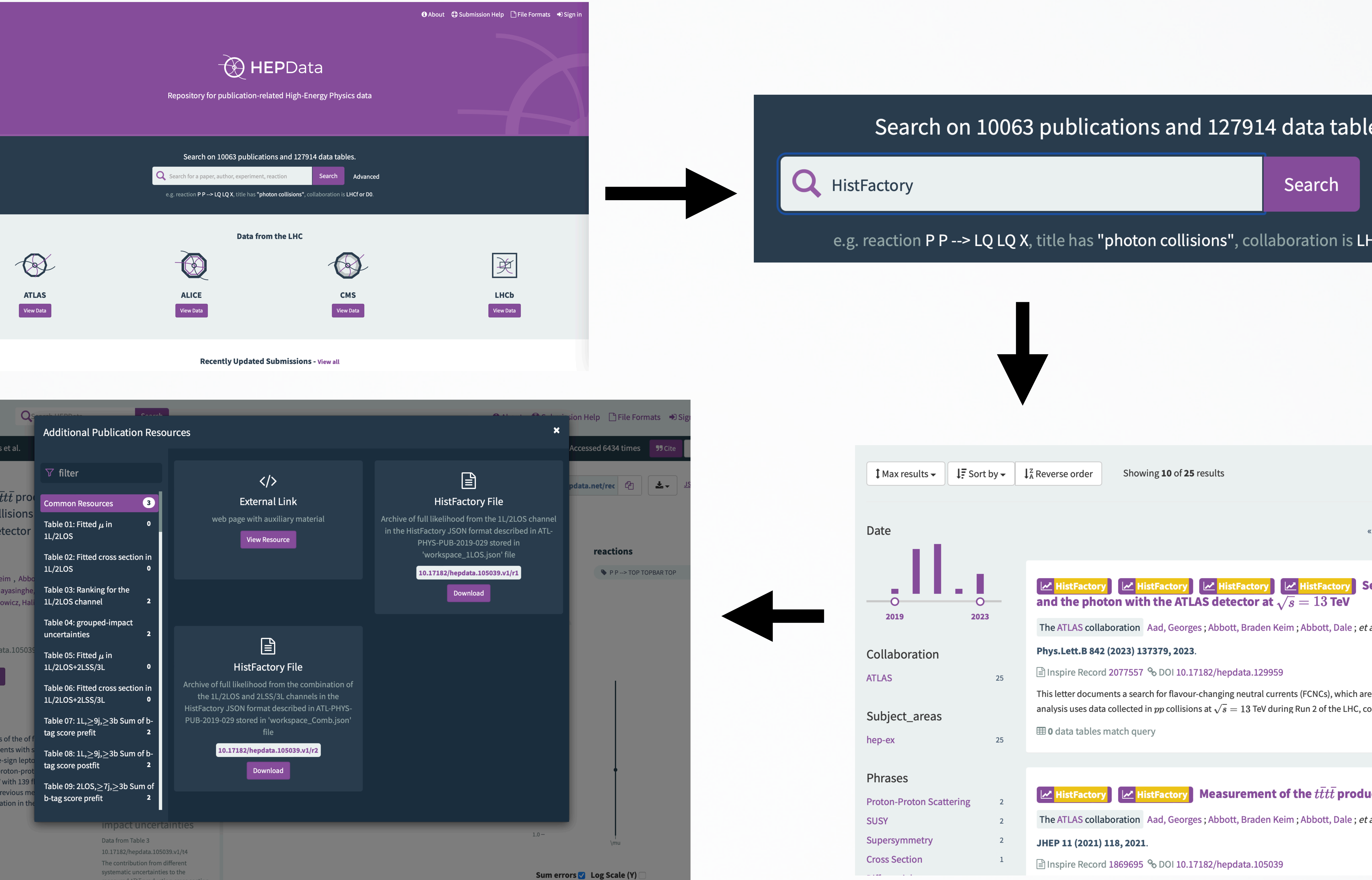
ATLAS-CONF-2023-025

PRL 114 (2015) 191803

- Combinations of ATLAS and CMS results:
  - Higgs **mass** (Run I)
  - Higgs **couplings** (Run I)
  - $h \rightarrow Z\gamma$ (evidence in Run 2)
- Uses κ-framework formalism: ATLAS-PHYS-PUB-2011-11; CMS-NOTE-2011-005
- Built on **RooStats** workspaces with more than **4000** nuisance parameters (Higgs couplings)
- Treat experimental uncertainties **uncorrelated** ($h \rightarrow Z\gamma$)
- Done by **experts** from both experiments directly involved in these studies

> These fits are rather challenging, involving many parameters of interest and a very large number of nuisance parameters. All the fit results were independently cross-checked to a very high level of precision by ATLAS and CMS, both for the combination and for the individual results. In particular, fine likelihood scans of all the parameters of interest were inspected to verify the convergence and stability of the fits.

Full likelihoods



Input data

```
imax 1 number of bins
jmax 1 number of processes minus 1
kmax 1 number of nuisance parameters
-----------------------------------
shapes * ch1 one-bin-sys-histosys-corr.root ch1/$PROCESS ch1/$PROCESS_$SYSTEMATIC
-----------------------------------
bin          ch1
observation  -1
-----------------------------------
bin          ch1 ch1
process      sig bkg
process      0 1
rate         -1 -1
-----------------------------------
sys    shape    1.0 1.0
```

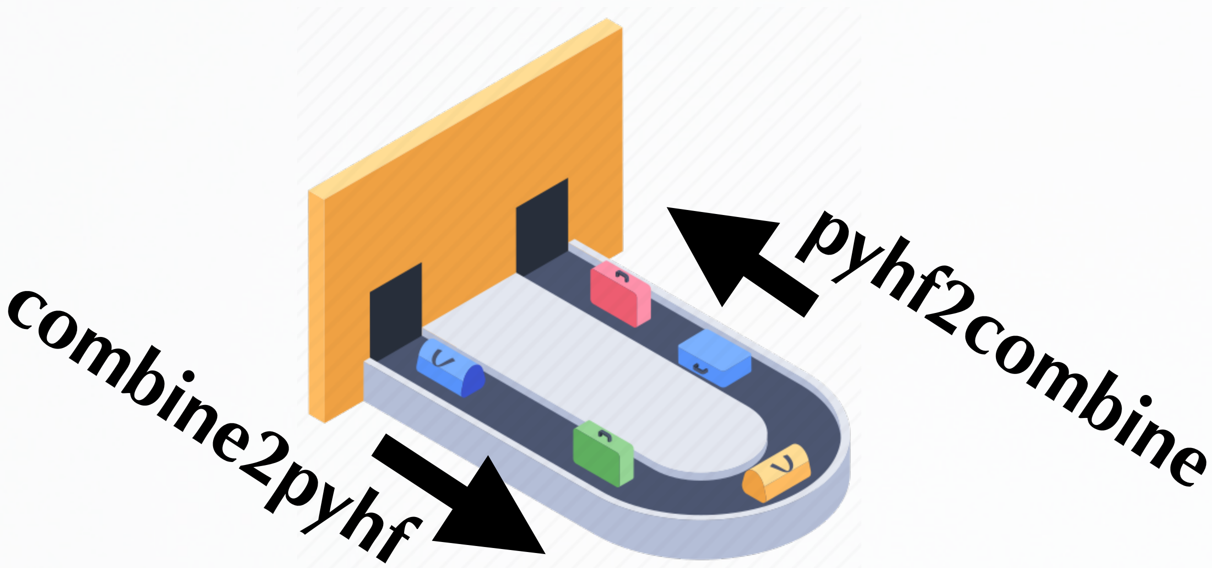
CMS Combine datacard: plain ASCII text + ROOT shape files

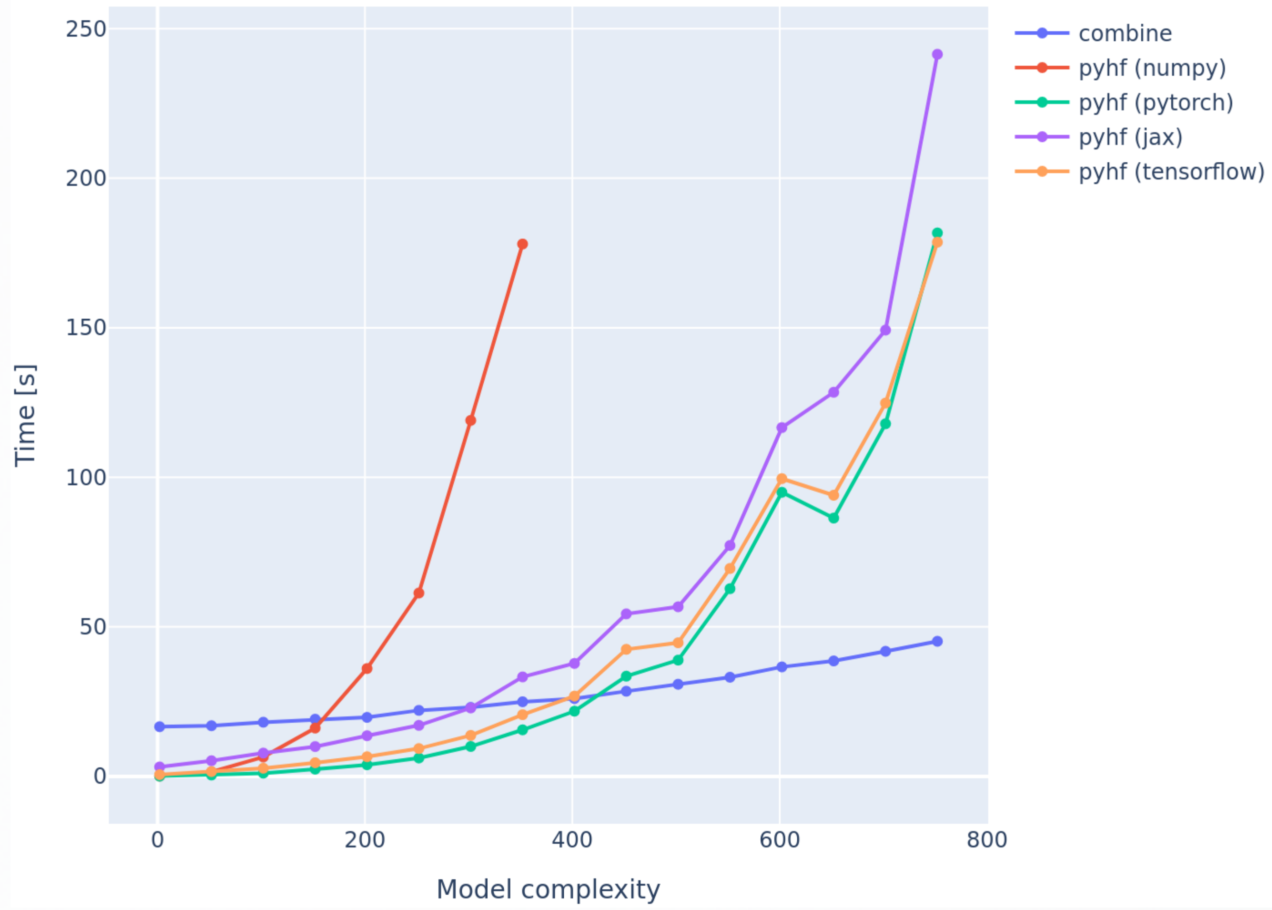
HistFactory JSON schema (**ATLAS** results)


```
{
    "channels": [
        {
            "name": "ch1",
            "samples": [
                {
                    "name": "sig",
                    "data": [
                        148.8058319091797
                    ],
                    "modifiers": [
                        {
                            "data": null,
                            "name": "r_sig",
                            "type": "normfactor"
                        },
                        {
                            "name": "sigsys",
                            "type": "histosys",
                            "data": {"hi_data": [163.68641510009767], "lo_data": [133.92524871826173]}
                        },
                        {
                            "name": "sigsys",
                            "type": "normsys",
                            "data": {"hi": 1.1, "lo": 0.9}
                        }
                    ]
                },
                {
                    "name": "bkg",
                    "data": [
                        43.84315872192383
                    ],
```

Full likelihood translation

- A tool for a carousel **model conversion** for Combine and pyhf inputs
- **Validate** translated inputs and physics results (likelihood scans, impacts, etc.)
- **Automated** fitting tests and performance comparisons
- **Helps** to understand the fitting procedure in ATLAS and CMS collaborations
- **Implemented** as combine2pyhf package

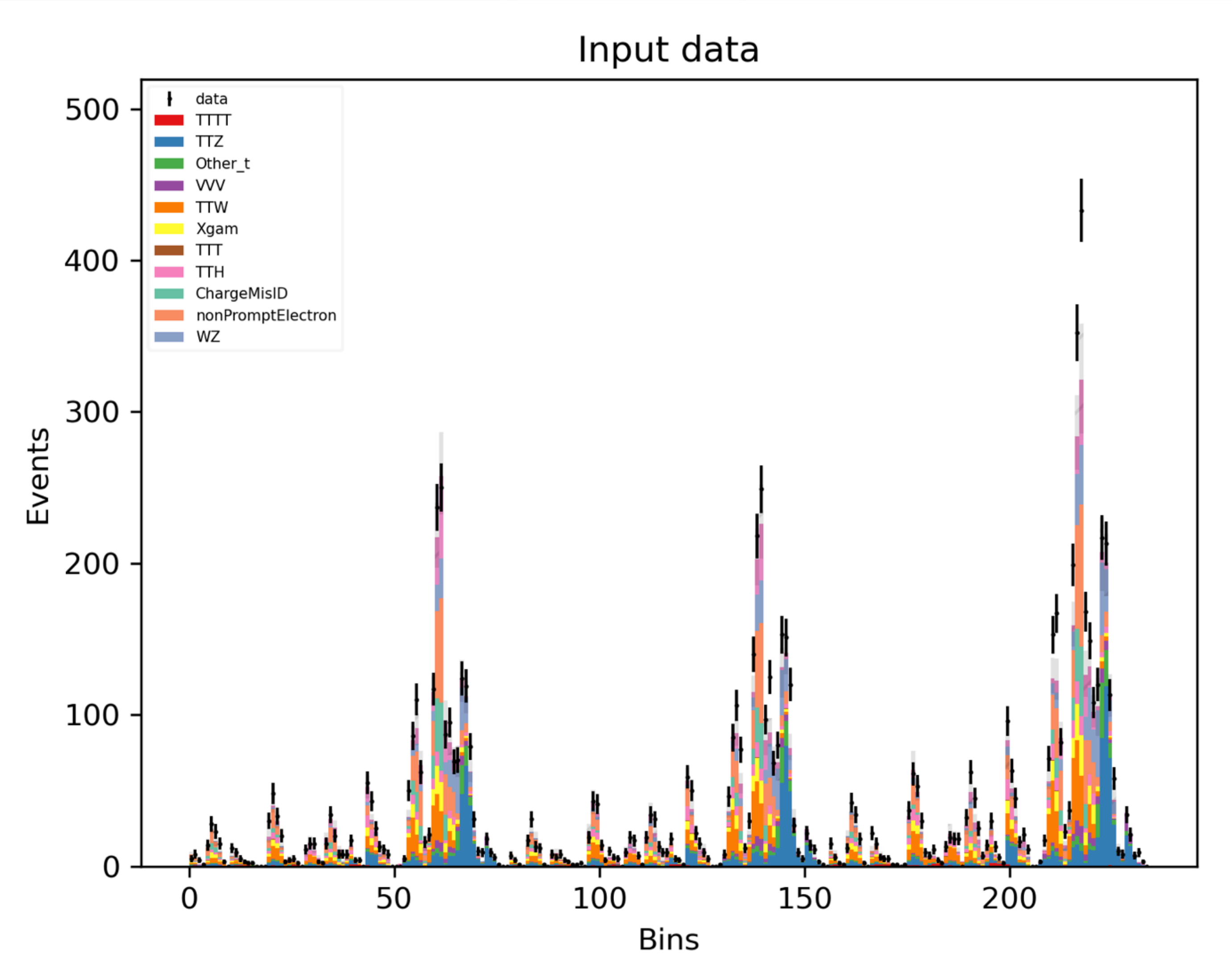


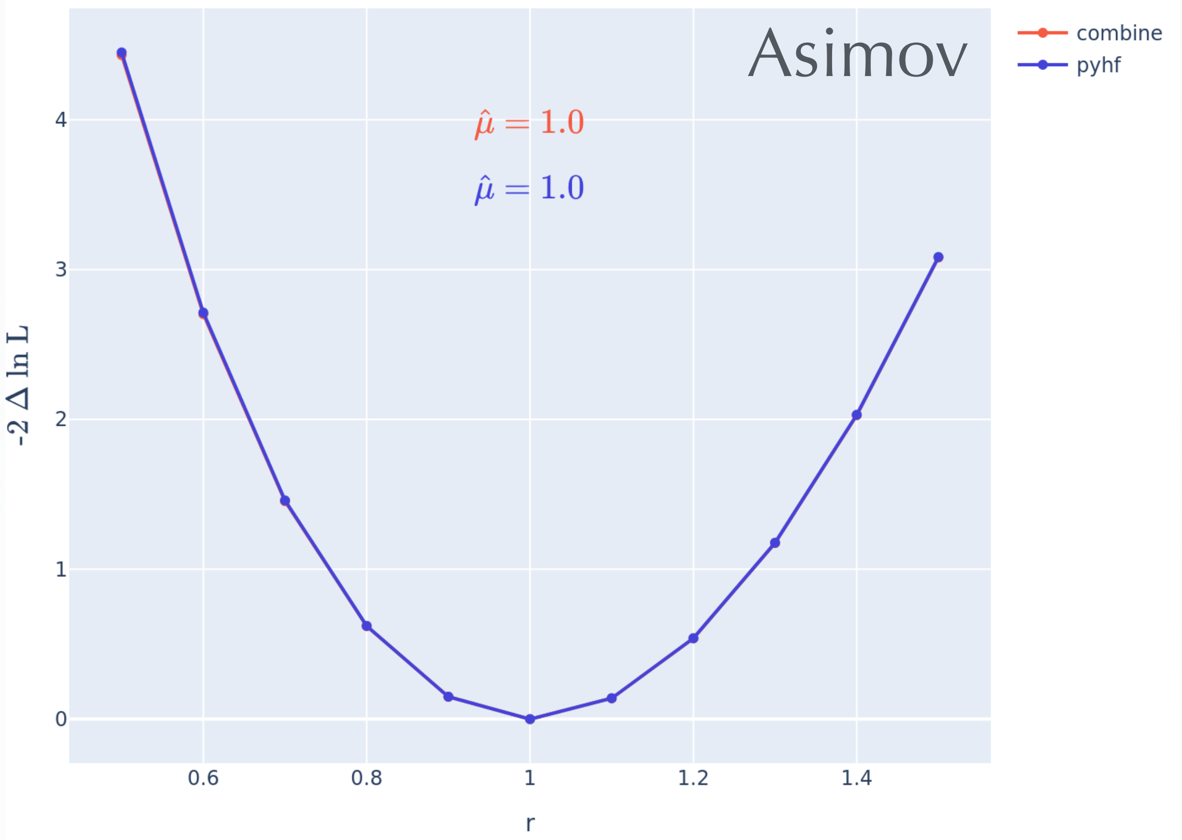


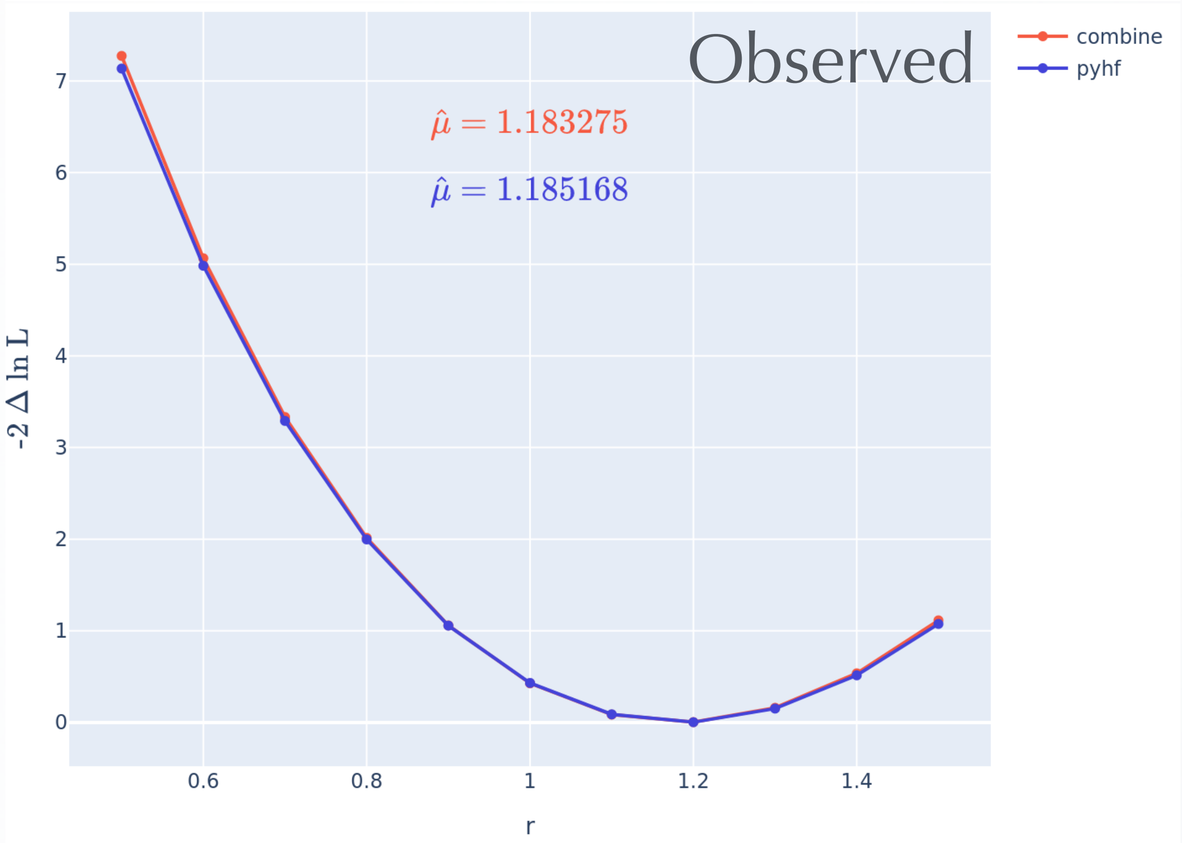
Looking forward to more inputs!

Full likelihood translation

- **Successful** validation
- **Able to reproduce** the full model results
- **Small** differences connected to the treatment of MC statistical uncertainties
- Automated **validation** process for any combine or pyhf inputs

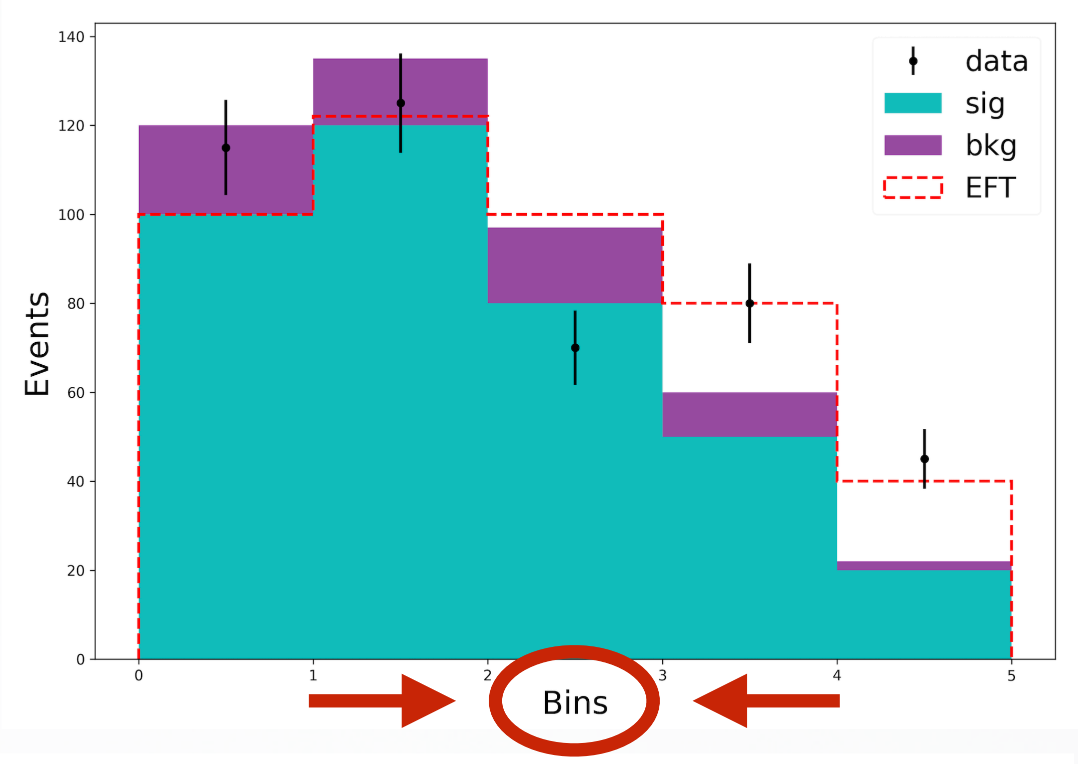


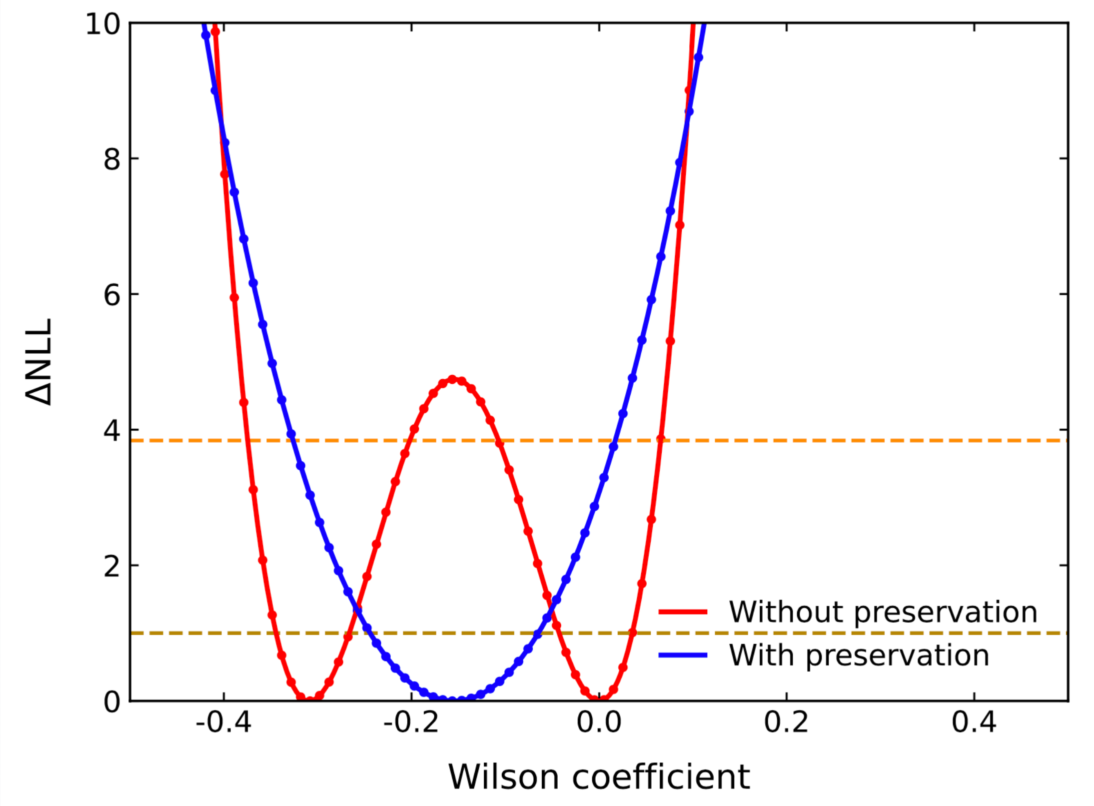




Observables and EFT

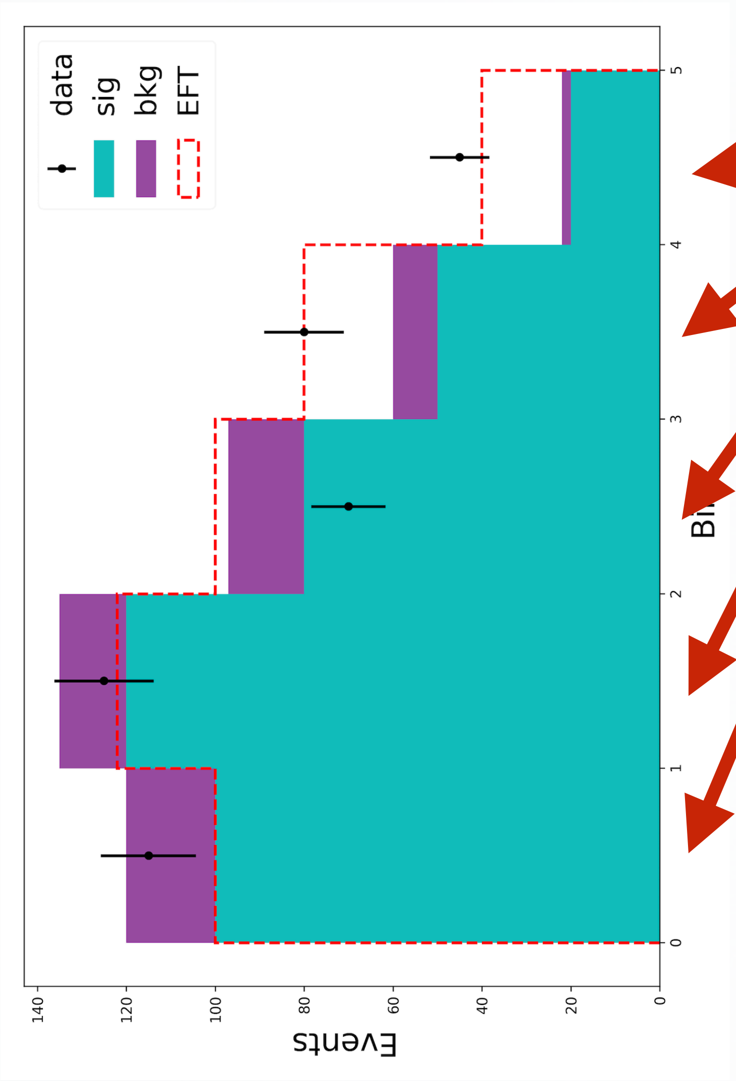
- Preservation of binned distributions with full experimental information **does not guarantee** its successful reinterpretation
- One needs to know **how** these bins were obtained
- Our studies have grown to become too complex - one simple kinematic observable is **not enough**
- Possible to describe the relevant MVA but **impossible** to reproduce
- Vital for **preserving** experimental EFT sensitivity
- EFT preservation = **publish** experimental observables





Preserving EFT

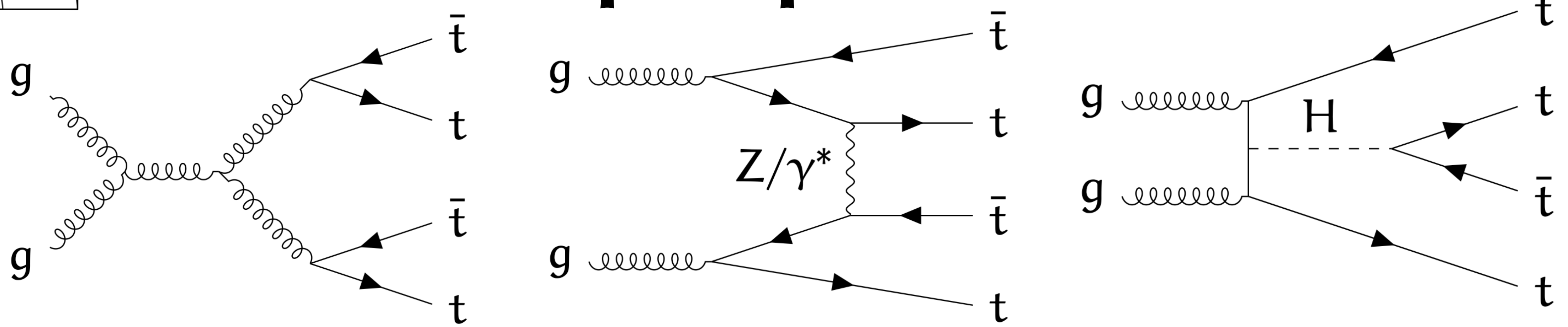
- **Parameterize EFT yield per bin** in the distribution of the fitted observable
- Dump the **coefficient matrix** as json, csv, etc.
- Remains **model-dependent** (as everything we do): can't modify any predictions when reinterpreting results



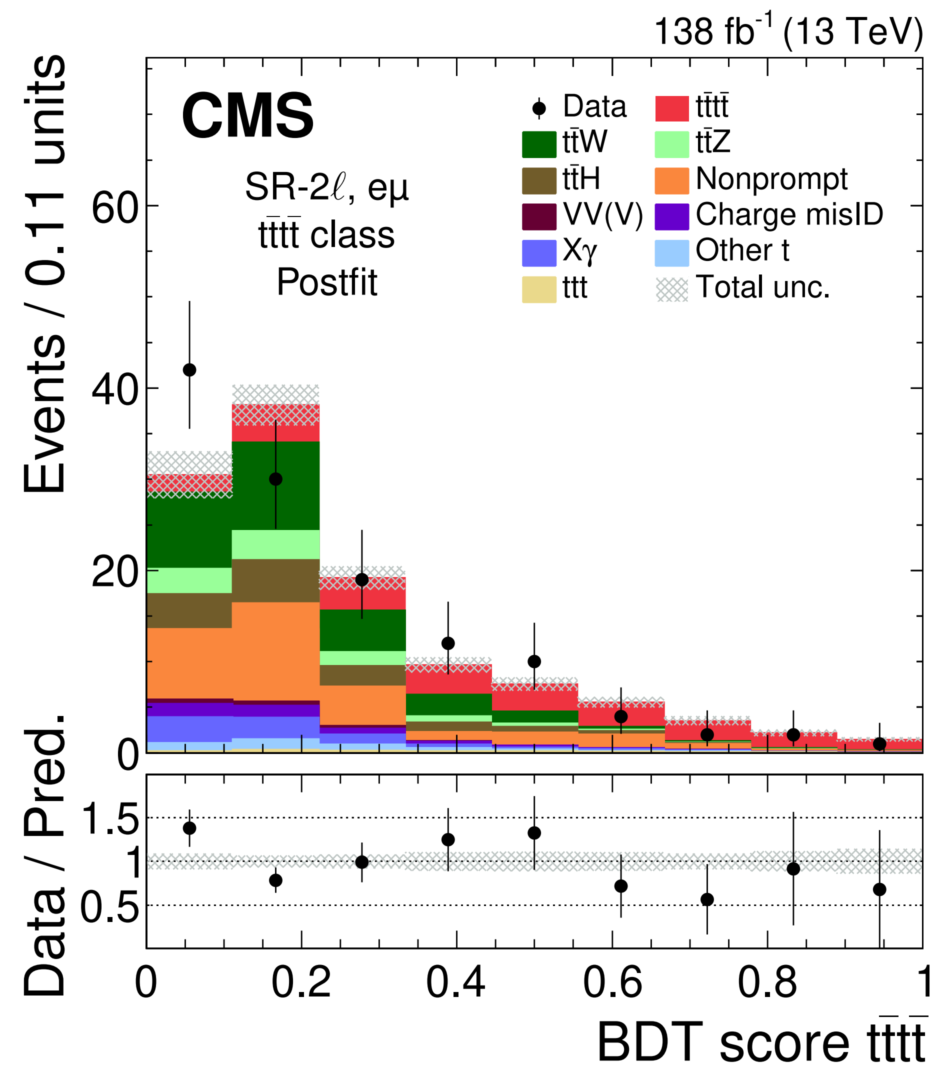
$$\sigma^i_{EFT} = c_0^2 + a^i_{10} c_0\, c_1 + a^i_{11} c_1^2 + a^i_{20} c_0\, c_2 + a^i_{22} c_2^2 + a^i_{12} c_1\, c_2 + \ldots$$

- Parametrization using **all relevant operators** is desirable
- Allows to reinterpret experimental result in a **given EFT model**
- Publish parametrization to **HEPData**?

Top quartet



- Mainly **QCD**-driven
- Additional contributions from **EW** and **Higgs**
- Backgrounds from $t\bar{t}W$, $t\bar{t}Z$, non prompt, etc.
- Extensive number of **SRs** and **CRs** based on multi leptons and the number of (b-) jets
- **Multi-classification** of events ($t\bar{t}t\bar{t}$, $t\bar{t}V$, $t\bar{t}$)



$$\sigma_{t\bar{t}t\bar{t}} = 17.7\,^{+3.7}_{-3.5}\,(\text{stat})\,^{+2.3}_{-1.9}\,(\text{syst})\text{ fb}$$

$$\sigma_{\text{SM}} = 13.4\,^{+1.0}_{-1.8}\text{ fb}$$

S = 5.6σ (4.9σ)

arXiv:2305.13439 (Submitted to PLB)

arXiv:2212.03259

Top quartet

- **Previously** published combination of four top production channels by ATLAS
- **Using it**, because full likelihood is **available**!

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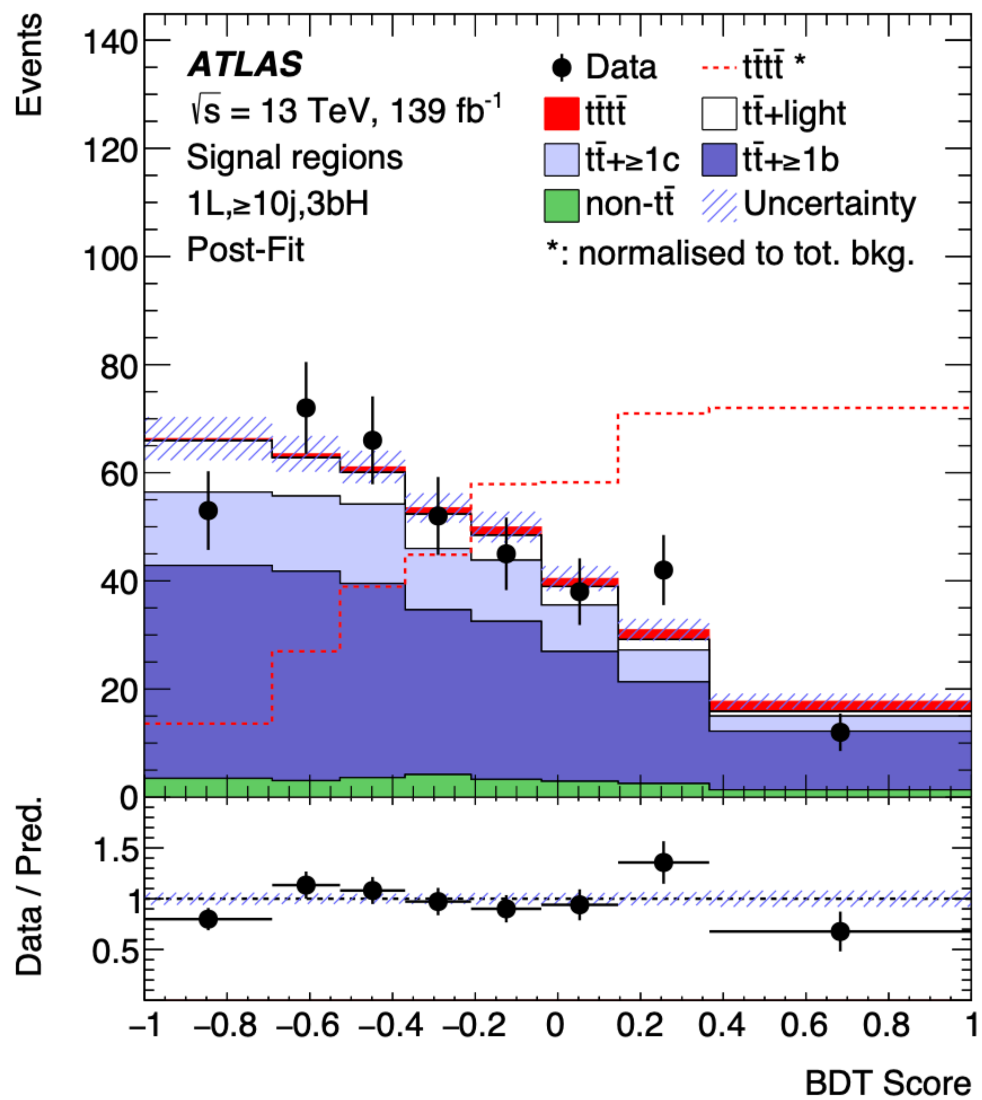
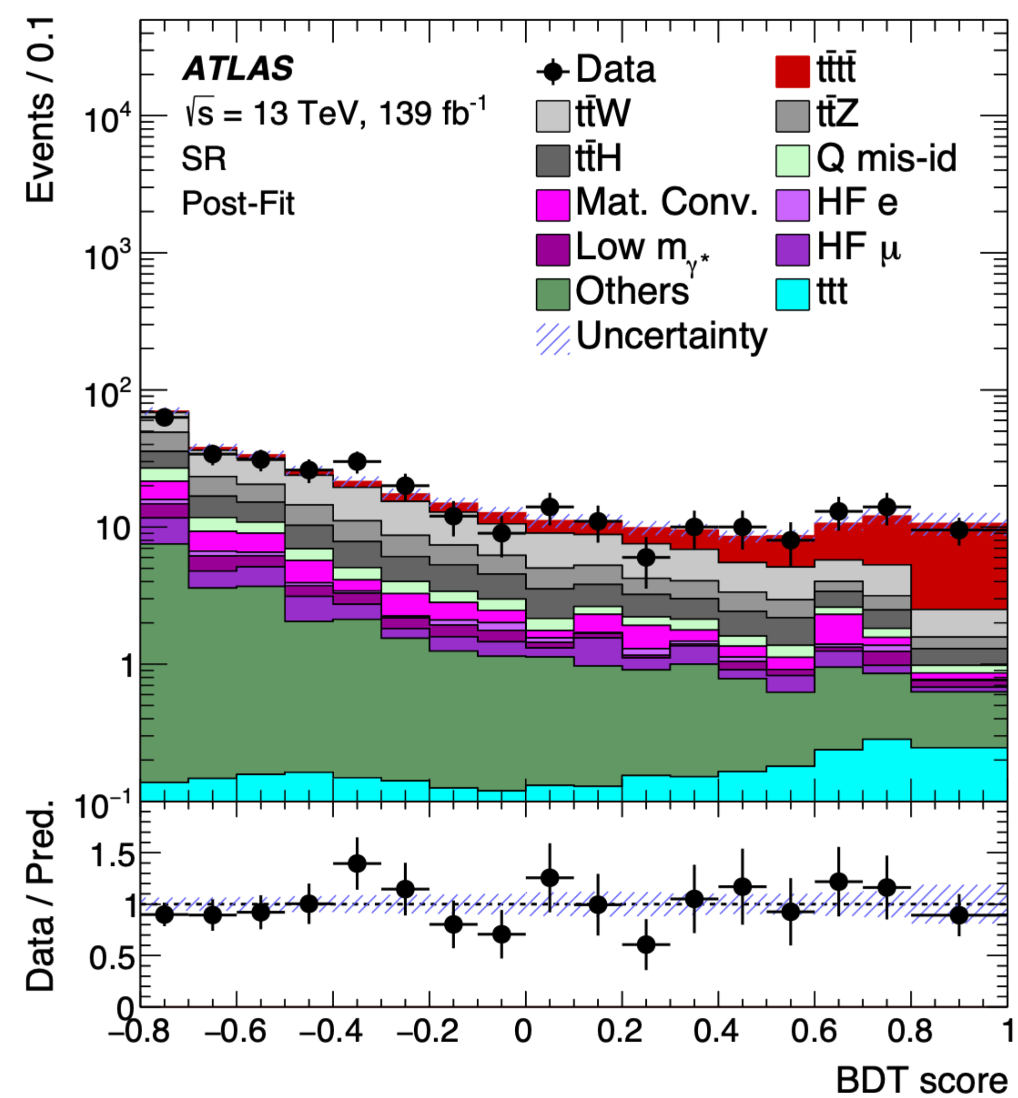




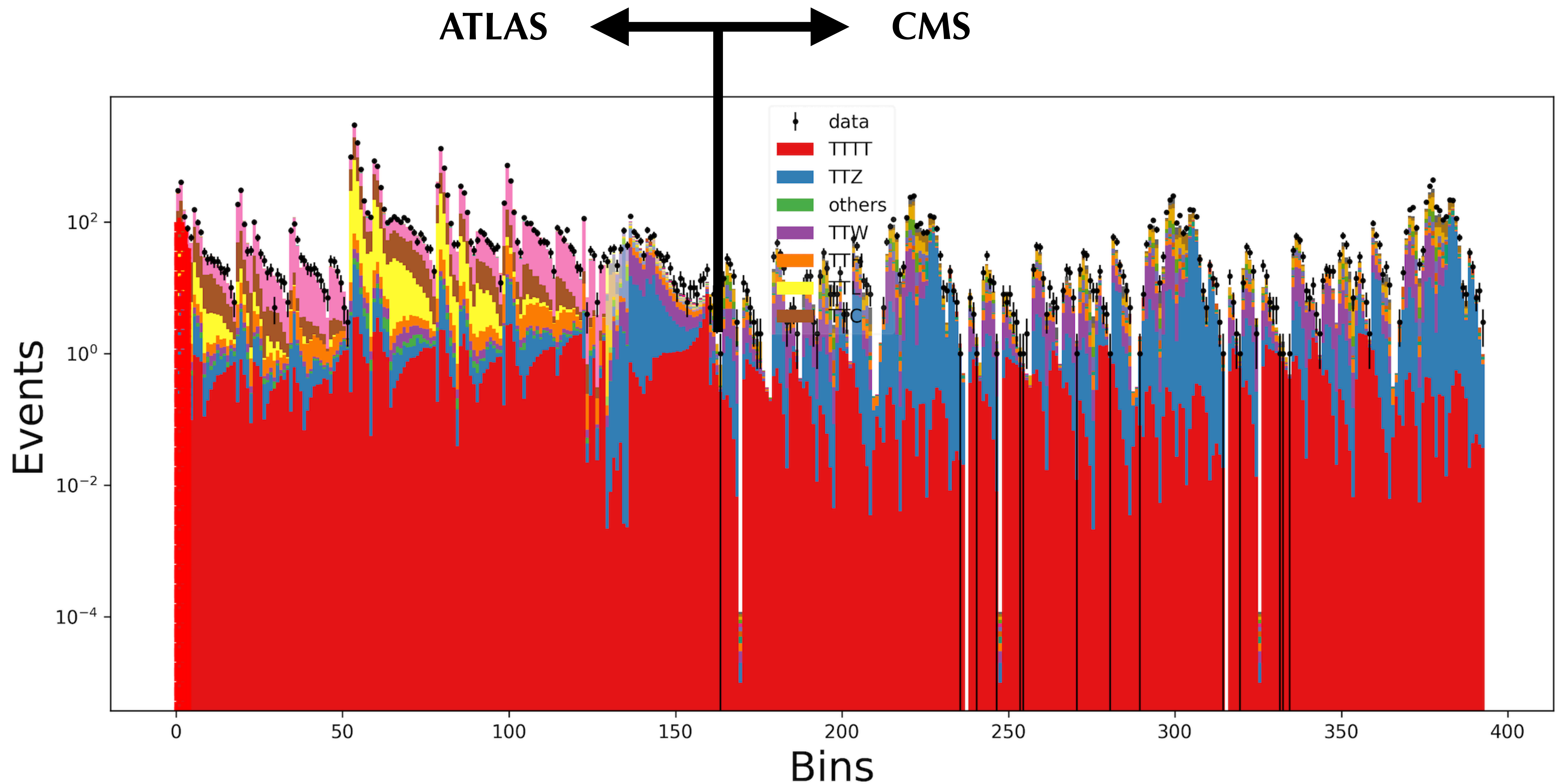
EPJC 80 (2020) 1085

$$\sigma_{t\bar{t}t\bar{t}} = 24 \ \pm 4\,(\text{stat})\,^{+5}_{-4}\,(\text{syst})\ \text{fb}$$

S = 4.7σ (2.6σ)

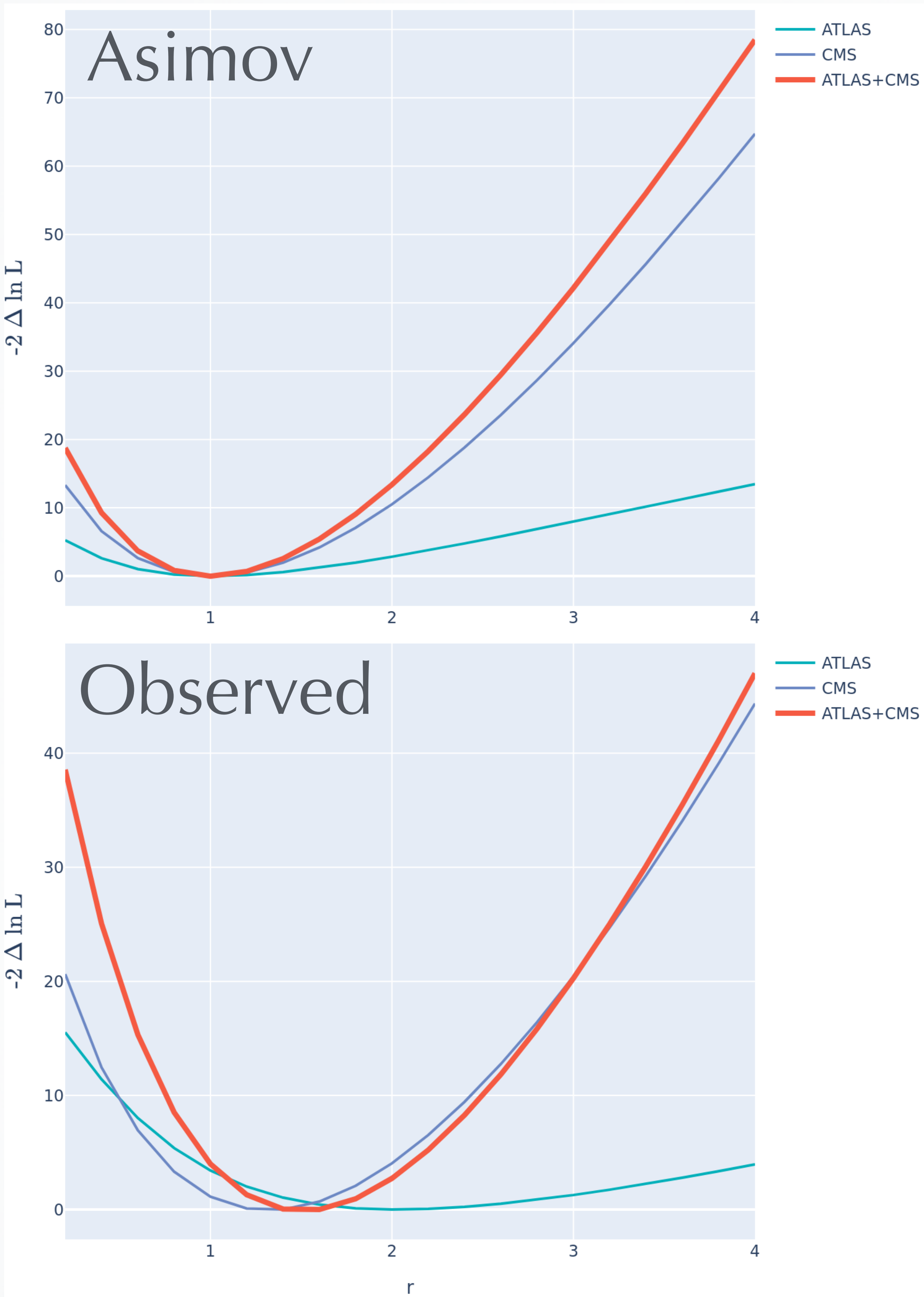
COMBINE !!

Fit model



- Number of **bins** ≈ 400
- Number of **processes** ≈ 20
- Number of **nuisances** ≈ 600

Four top re-observation

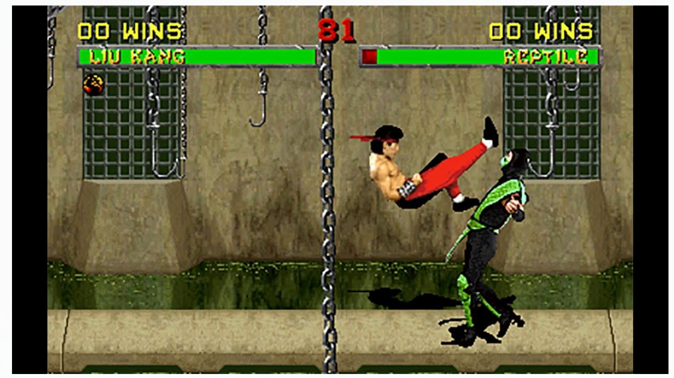


- **Still observing** four tops after combining CMS with ATLAS
- **But** now at $7.6\,\sigma$
- Will be even more σ's when combined with the **ATLAS observation** result
- Approach for **ATLAS+CMS combination**:
  - **Correlate** main physics processes: $t\bar{t}t\bar{t}$, $t\bar{t}W$, $t\bar{t}Z$, $t\bar{t}h$
  - Assume **no correlations** among systematic uncertainties

Correlating uncertainties

- Process modelling
- Leptons
- Jets
- E_T^{miss}
- Luminosity
- Pileup
- Data-driven

Correlating uncertainties



- Process modelling
- Leptons
- Jets
- E_T^{miss}
- Luminosity
- Pileup
- Data-driven

signal
background #1
background #2
electrons
muons
taus
light jets
b jets
c jets
corrections/filters
jet energy scale
year-by-year uncorr.
corr.
cross section
reweighting

Correlating uncertainties

We are here

- Process modelling
- Leptons
- Jets
- E_T^{miss}
- Luminosity
- Pileup
- Data-driven

signal
background #1
background #2

ISR
FSR
parton shower
normalization

electrons
muons
taus

ID efficiency
resolution
scale

light jets
b jets
c jets
corrections/filters
jet energy scale

source #1
source #2
source #3
…
source #100

year-by-year uncorr.
corr.

source #1
source #2
source #3
…
source #100

cross section
reweighting

***NB**: Process template definition can also differ, e.g. ttbar vs ttbar+j, ttbar+b, etc.*

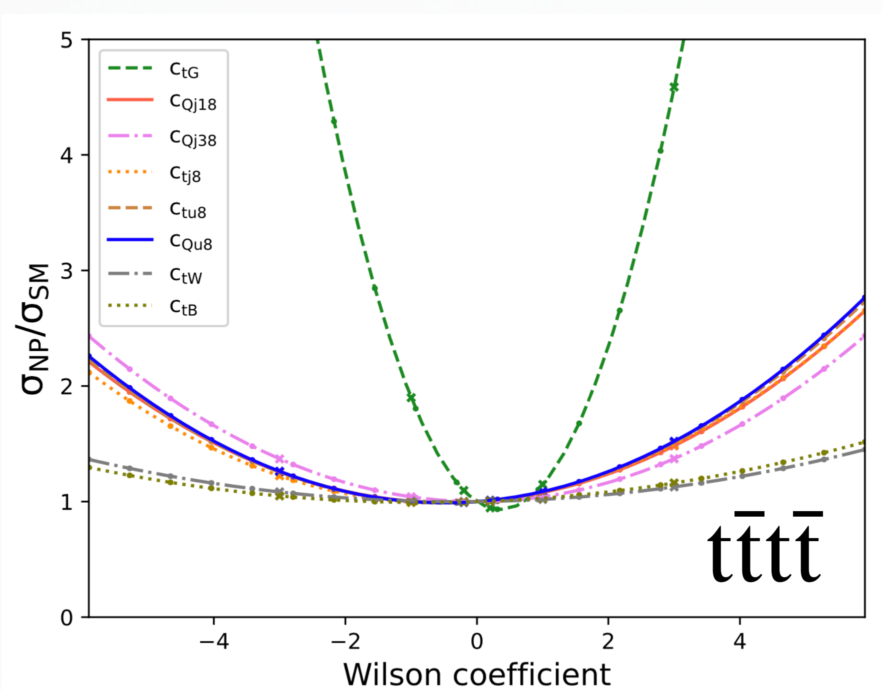
≈ 500 nuisance parameters per analysis

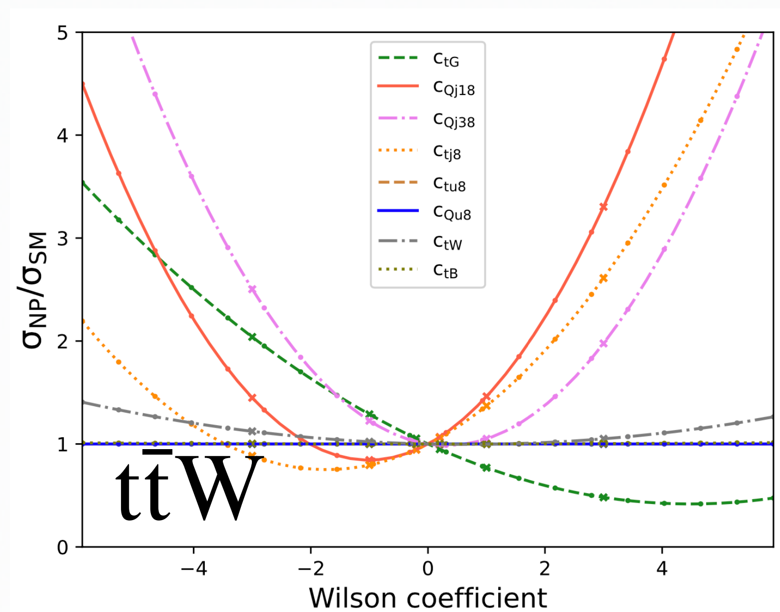
Correlating uncertainties

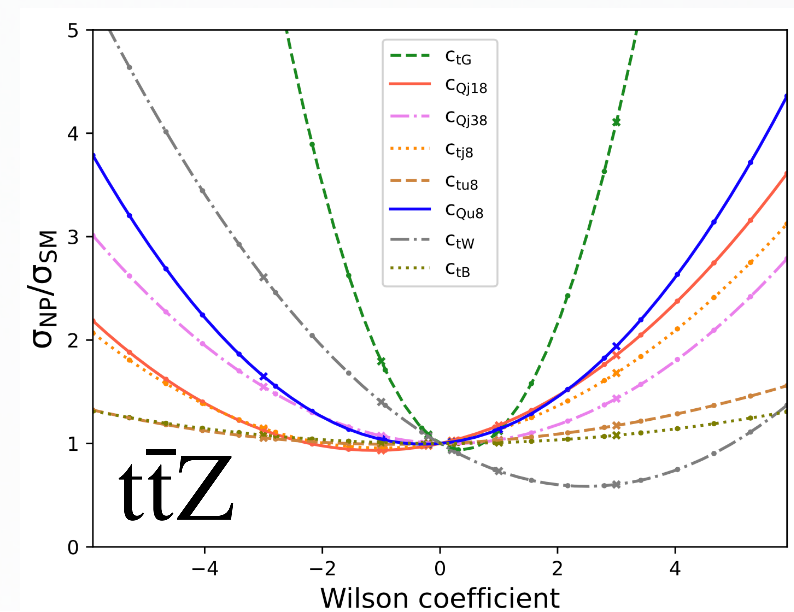
- It would be great to have a **common naming convention** for specifying nuisance parameters in a published result
- **Centralize** the description of the most common set of nuisances?
- Provide an **additional dictionary** to HEPData?
- Need to keep track of **evolution** of systematics with time

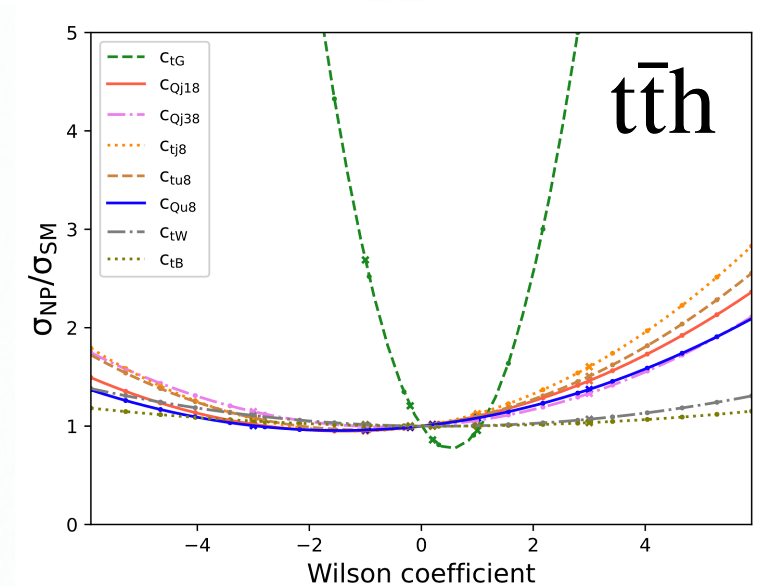
Parametrization

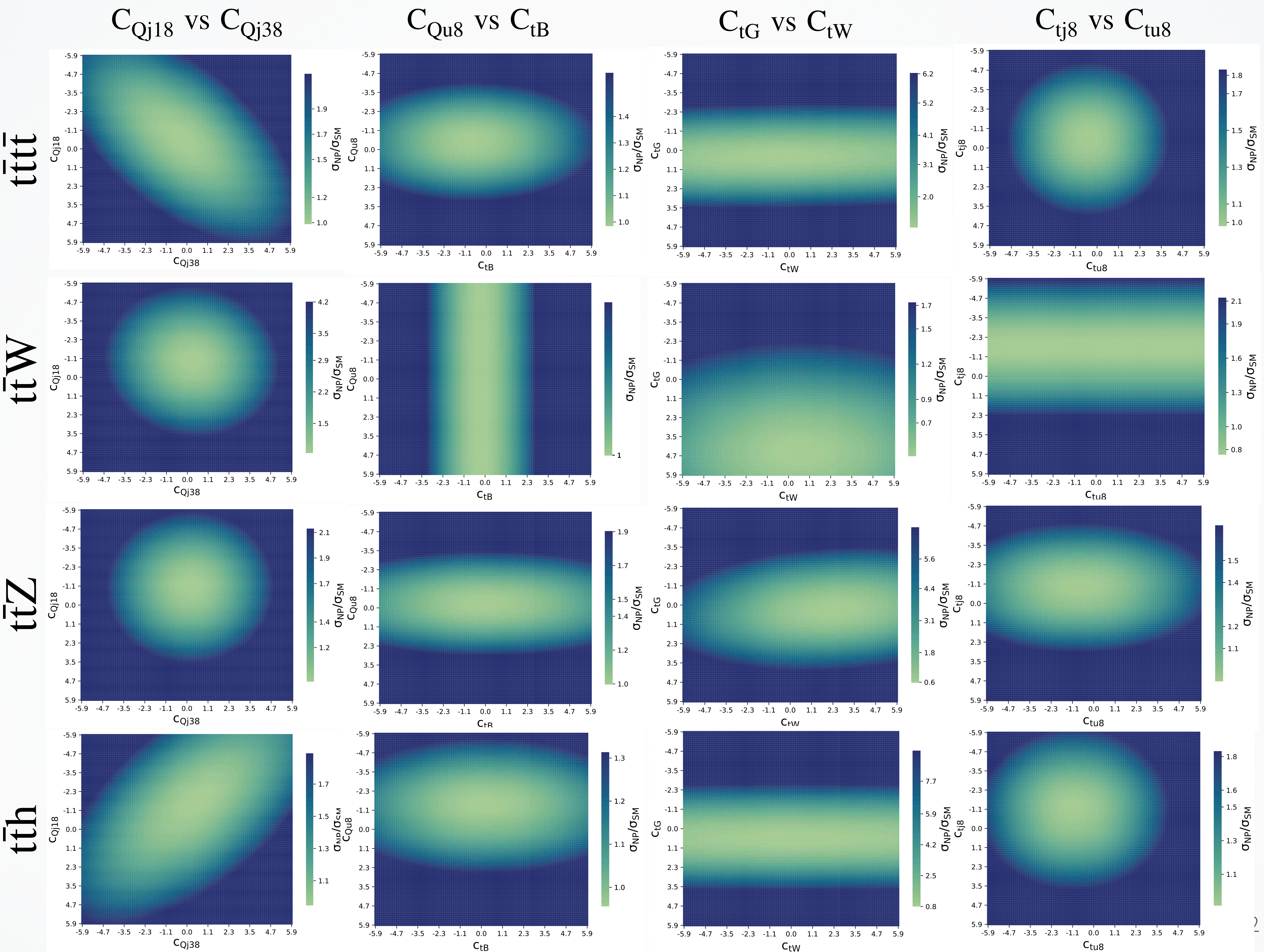
- **Proof-of-concept study**: focus on **8 EFT operators** affecting **signal** and **backgrounds**
- **Not yet including** four-fermion operators nor CP-violation
- Include **quadratic** and **linear** terms
- Experimental observables are not reproducible → modify signal and backgrounds by the **EFT-modified inclusive cross section**







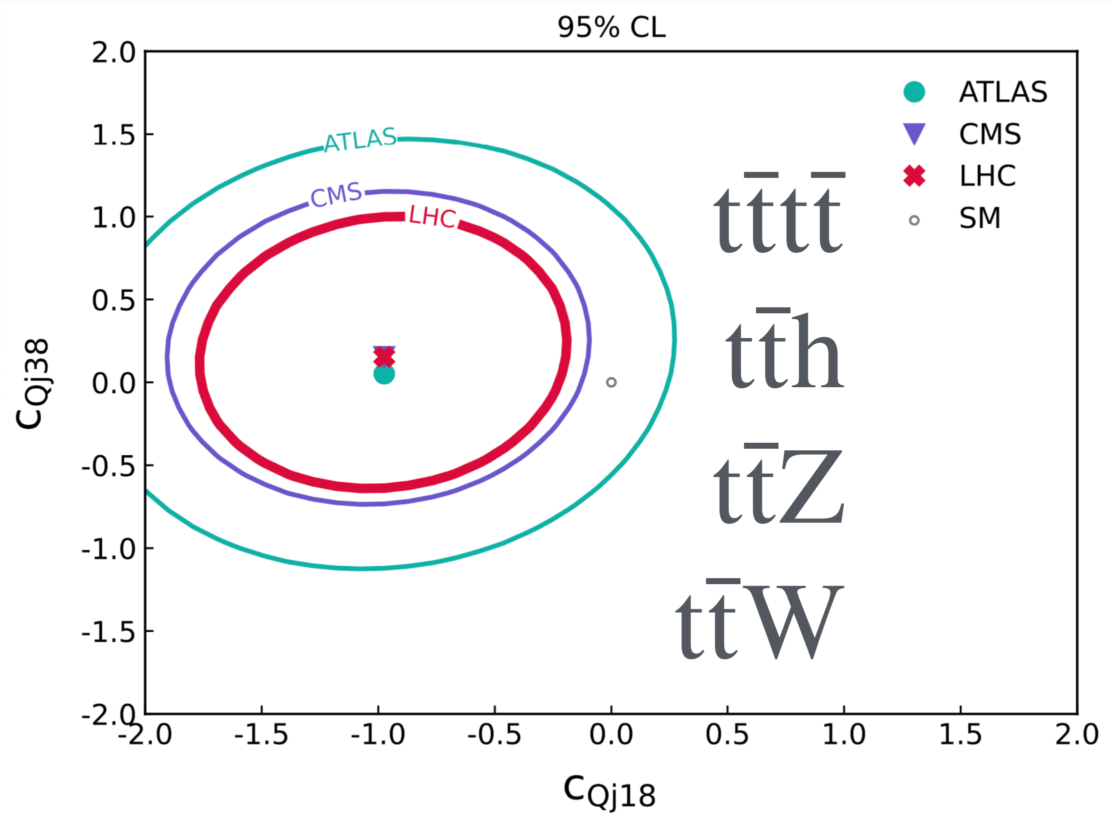


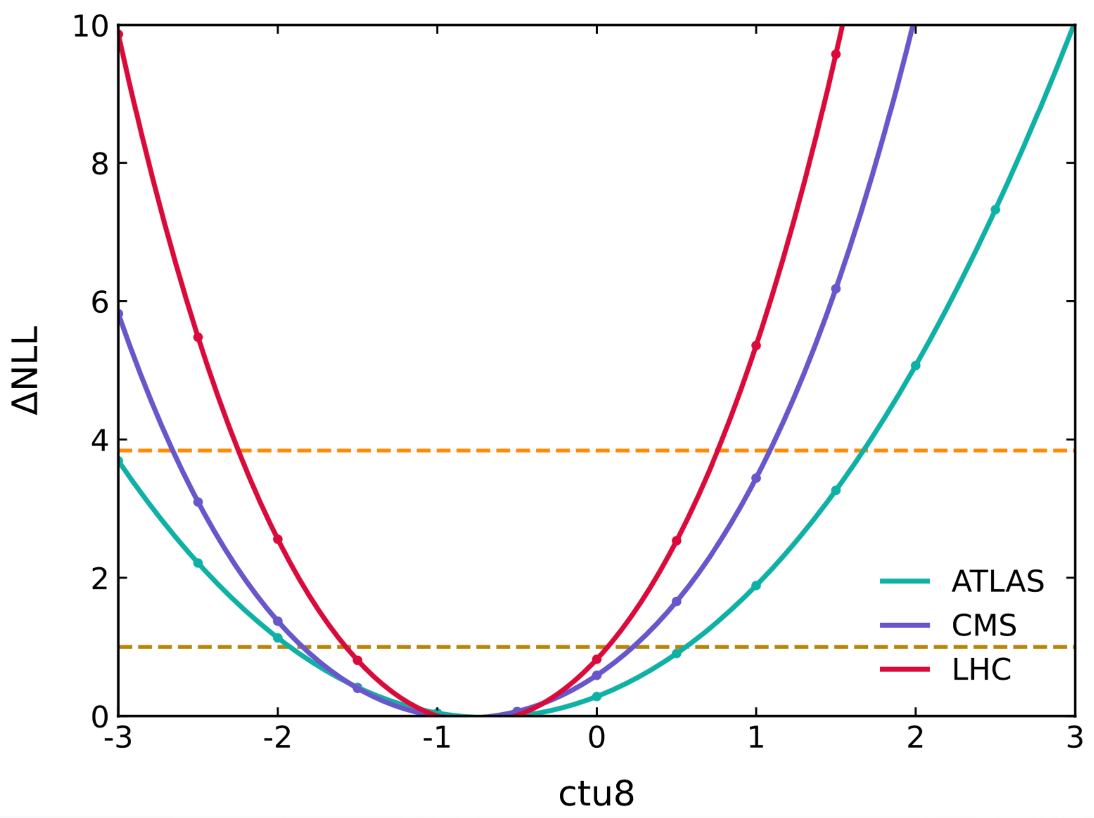


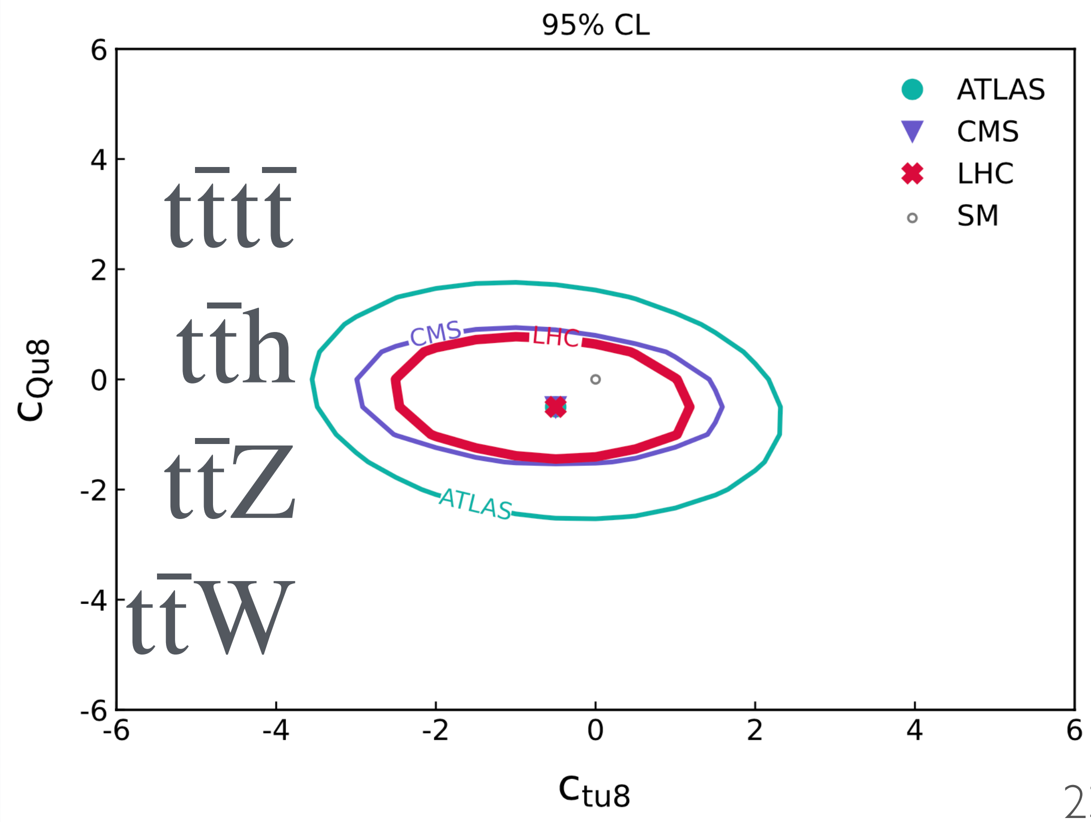
CQj18 vs CQj38
CQu8 vs CtB
CtG vs CtW
Ctj8 vs Ctu8
tt̄tt̄
tt̄W
tt̄Z
tt̄h
CQj18
CQj38
CQu8
CtB
CtG
CtW
Ctj8
Ctu8
σNP/σSM

Omnipresent EFT

- All dominant backgrounds are **as important as the signal process**
- Correct sensitivity only through a **comprehensive** EFT study
- **Do not artificially remove operators**, if well constrained by other processes
- These operators may be already constrained by **backgrounds**

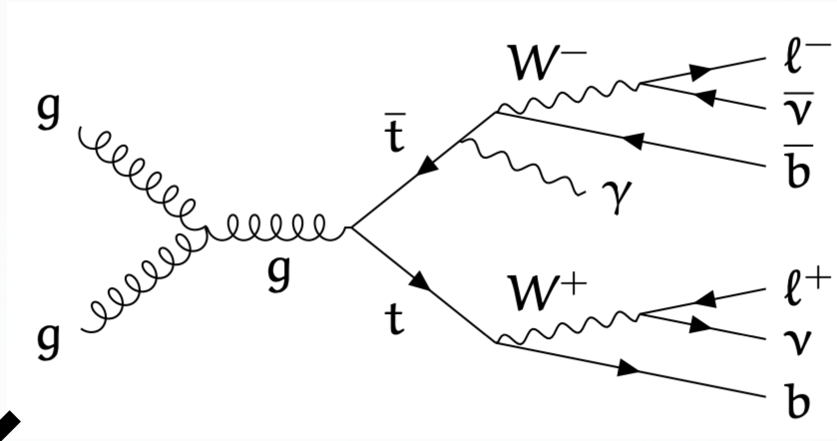


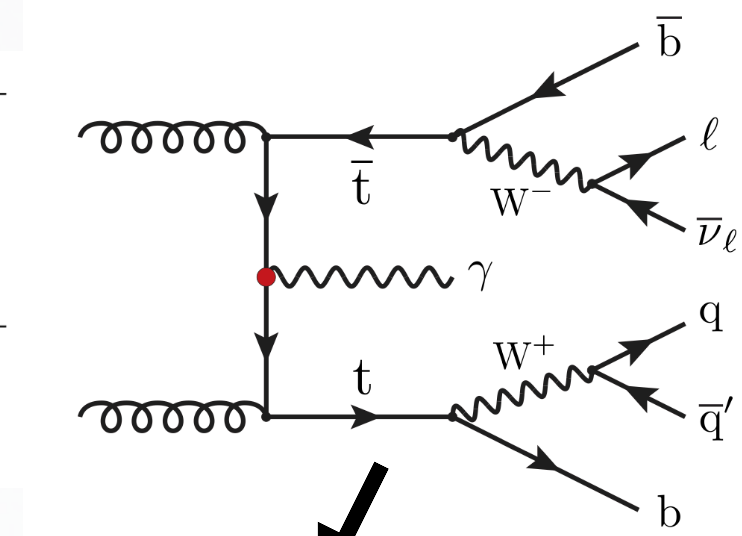


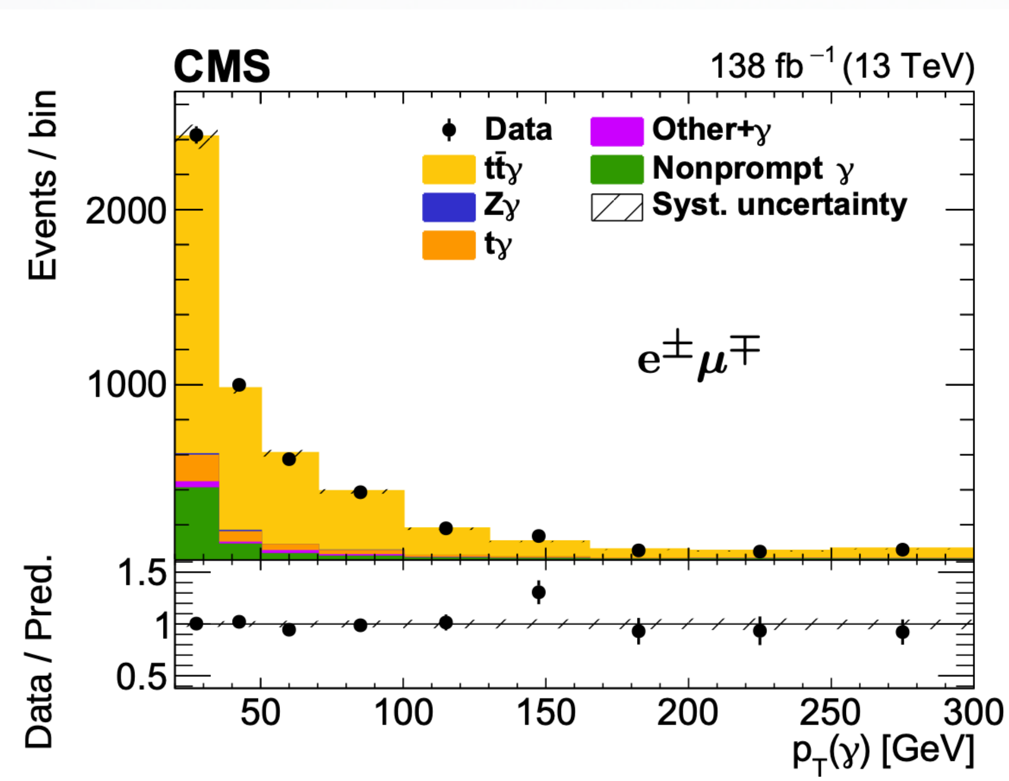


Top-photon

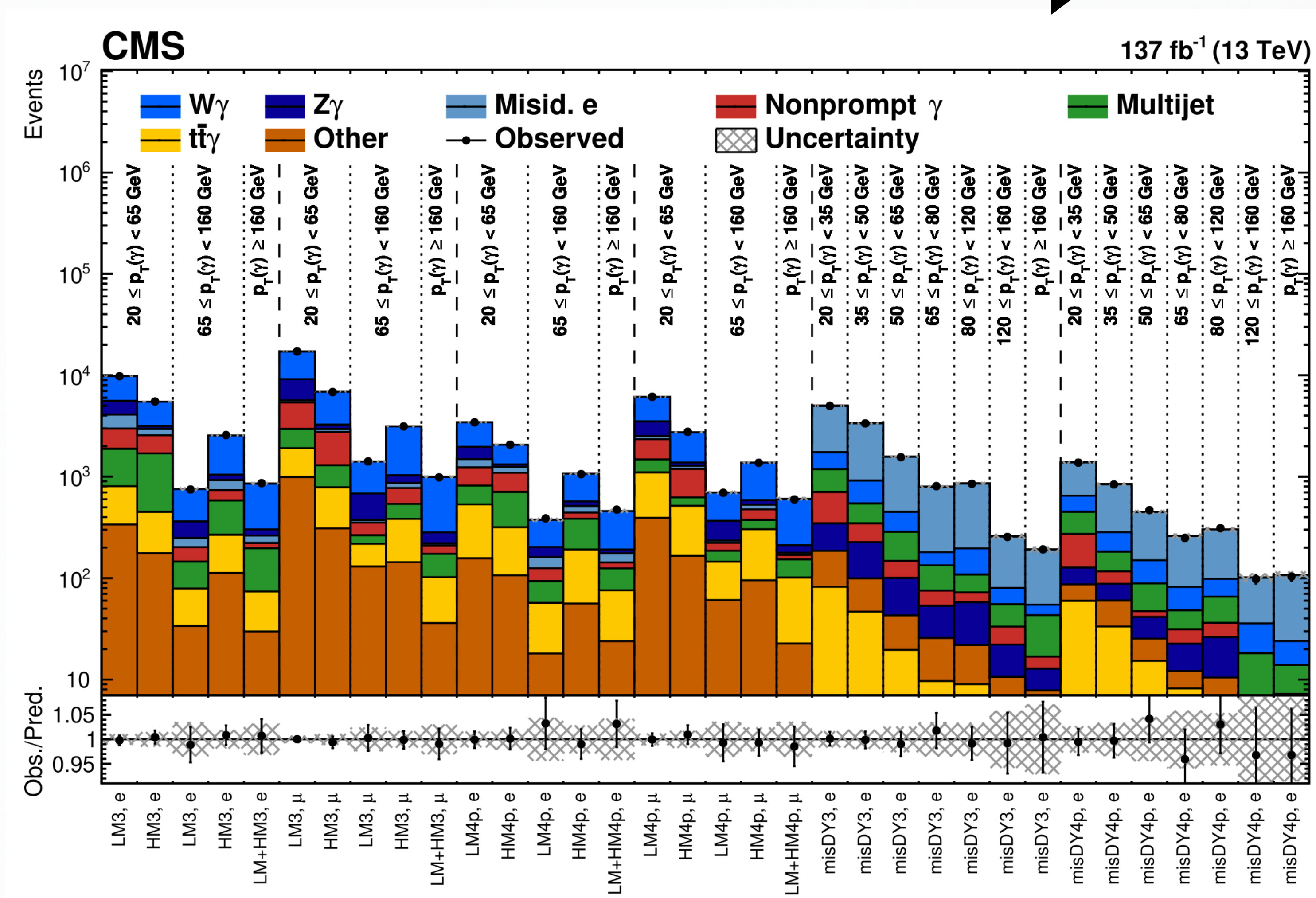
- Probe **top electroweak** EFT couplings
- **Single-lepton** (large sample) and **dilepton** (high purity) final states
- Categorize events based on **photon p_T**







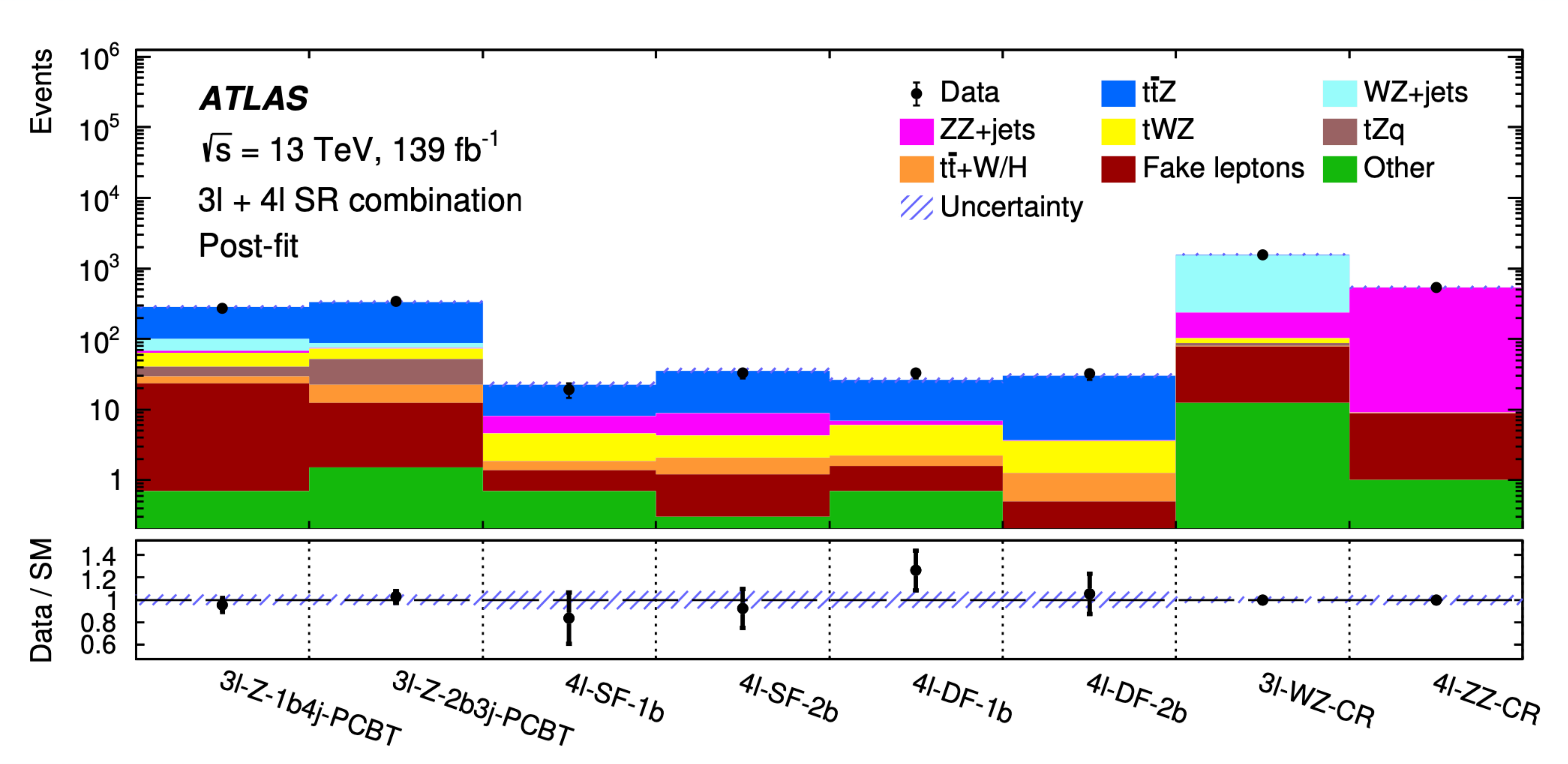
JHEP 05 (2022) 091



JHEP 12 (2021) 180

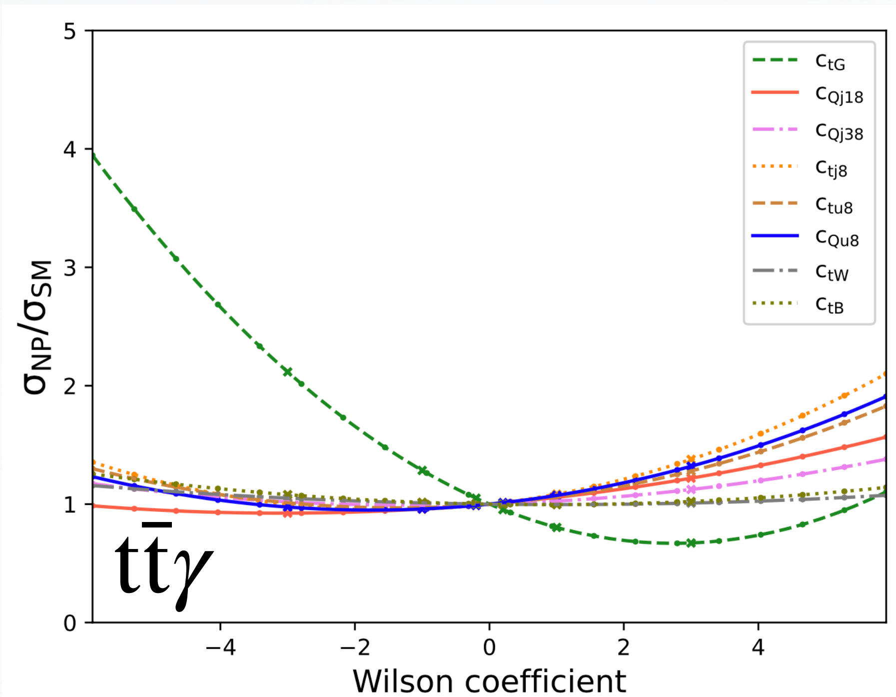
Top-Z

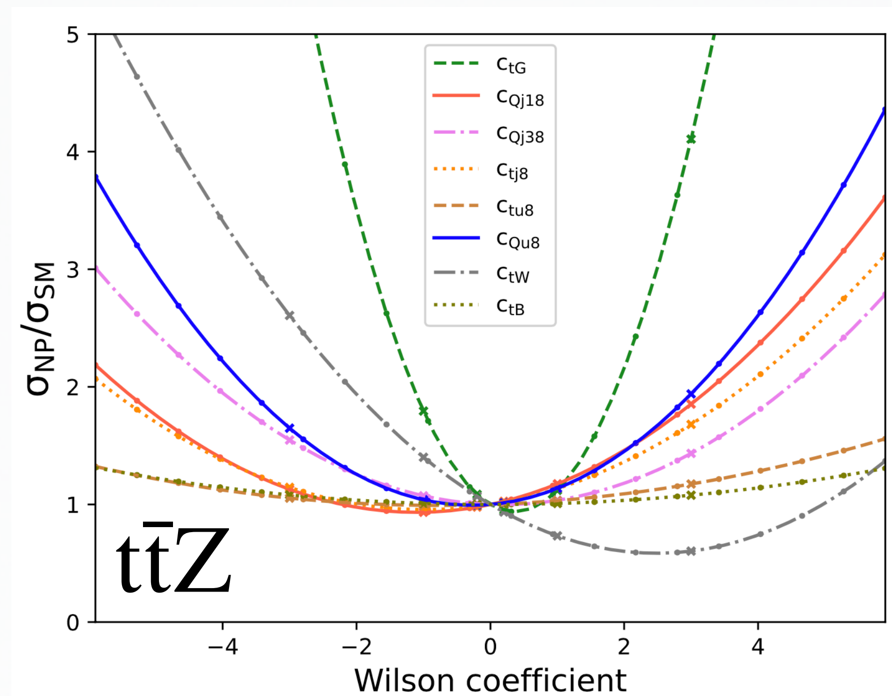
- Probe **top electroweak** EFT couplings
- Measure **inclusive** and **differential** $t\bar{t}Z$ cross sections in 3l and 4l final states
- **Full likelihood** available for the inclusive cross section measurement
- **No EFT** interpretation included in the analysis - **let's have it done now!**



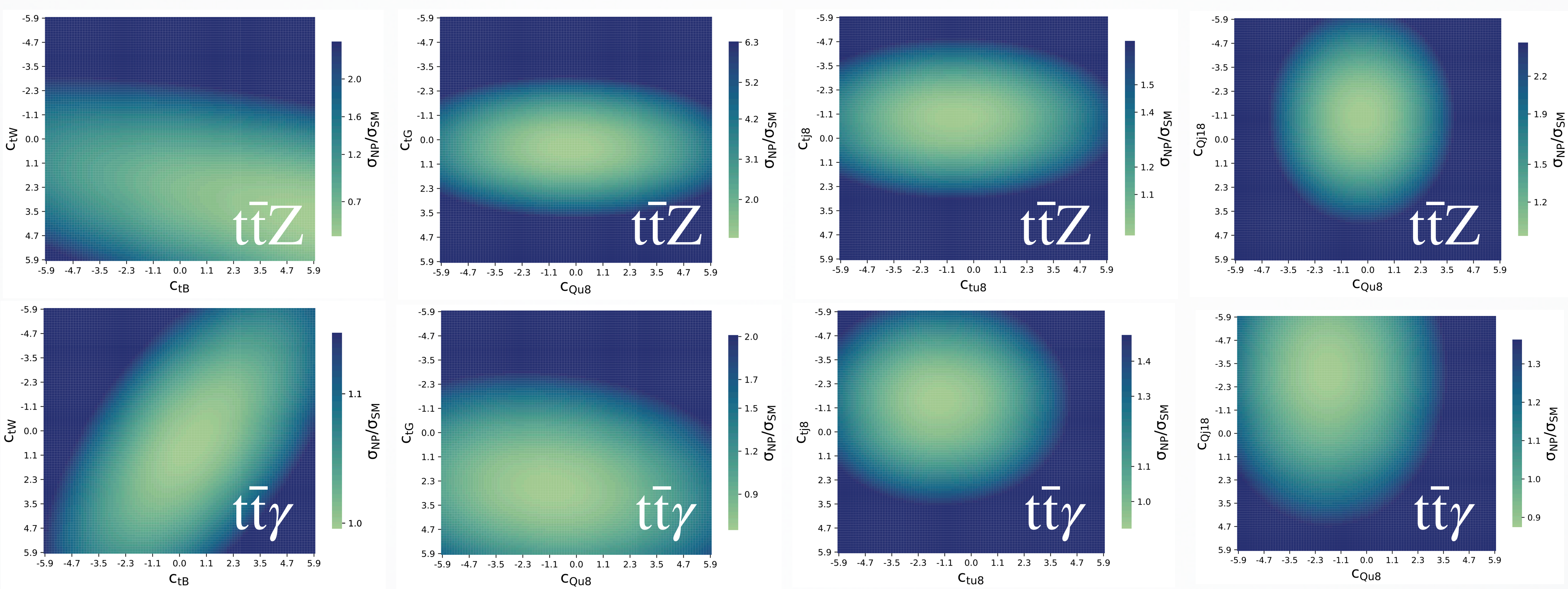
EPJC 81 (2021) 737

Top electroweak couplings

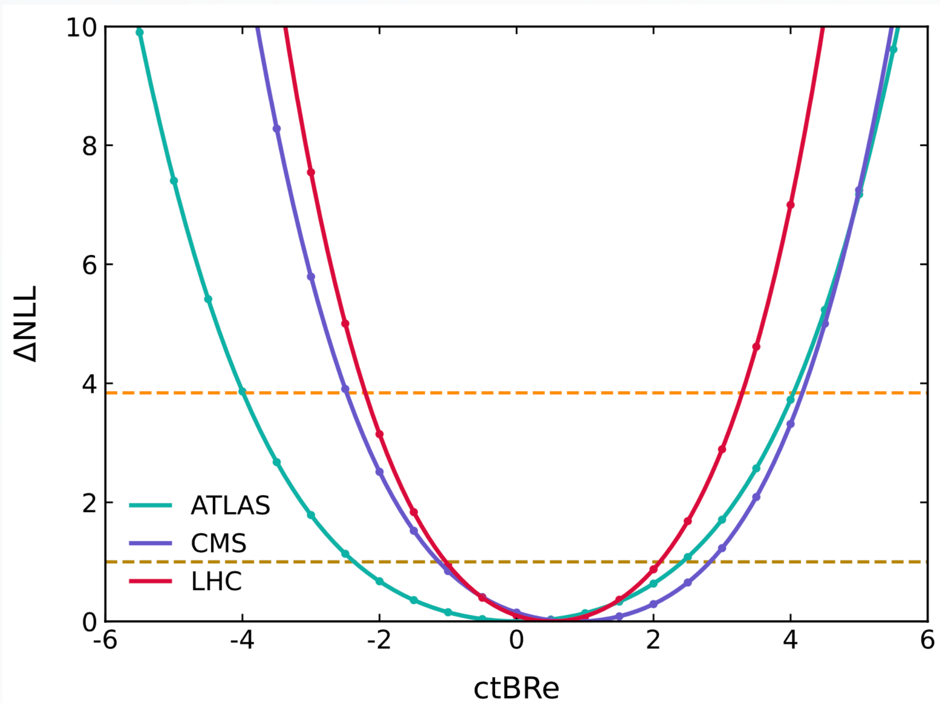


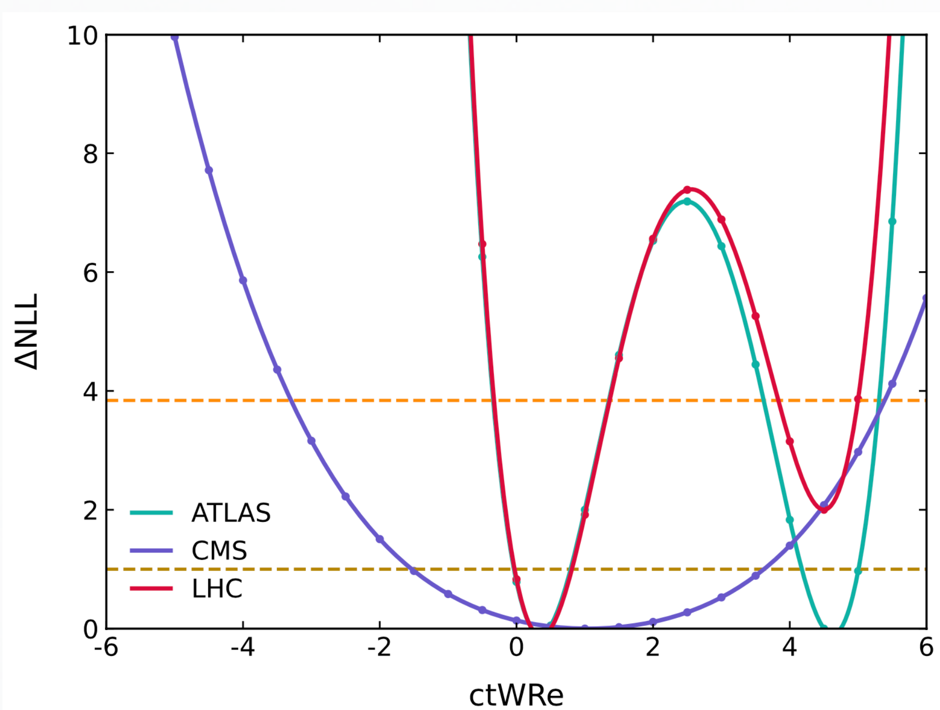


- **Strong interplay** for electroweak couplings in tt̄γ and tt̄Z
- Probe a **chosen set** of operators in the fit

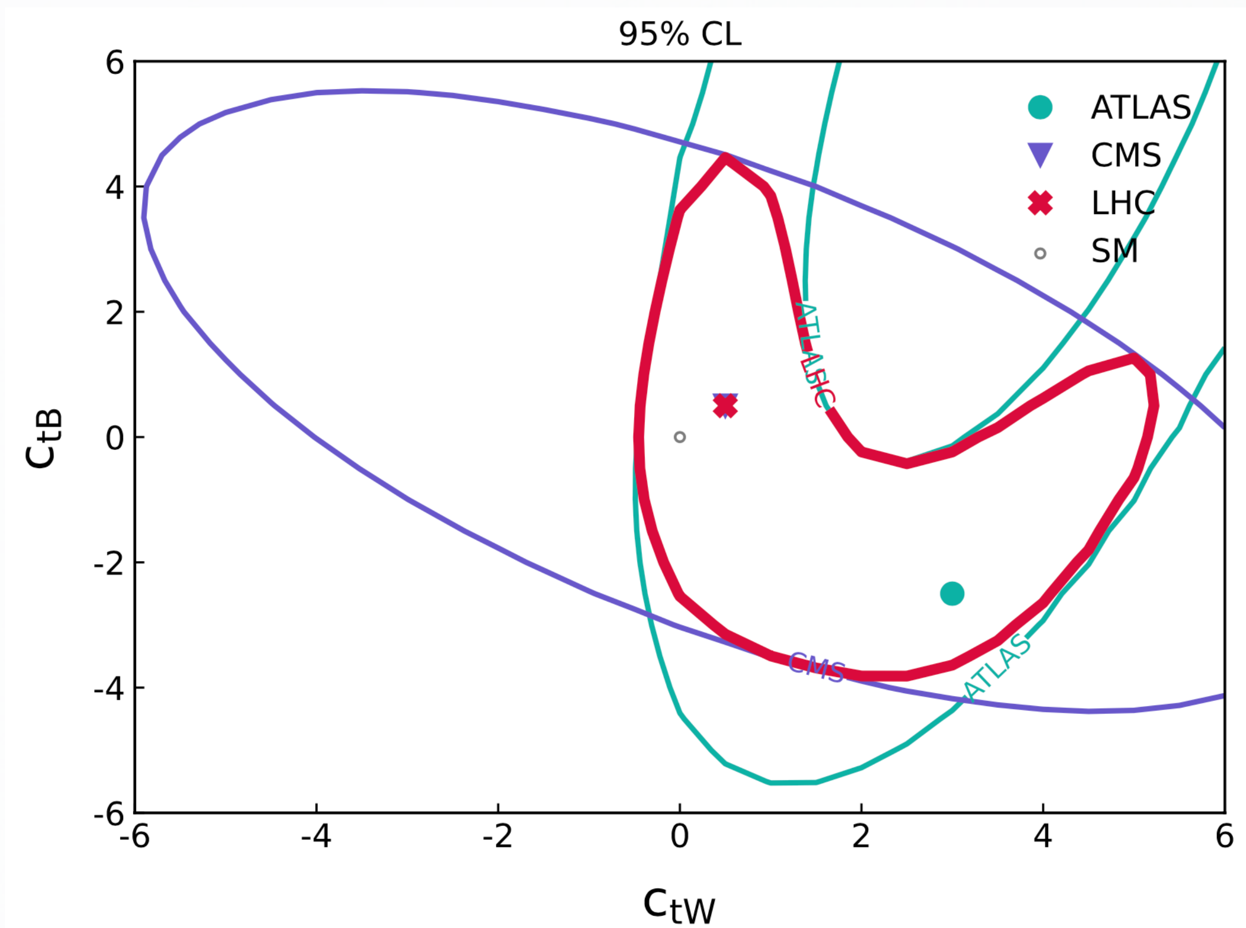


Top electroweak results



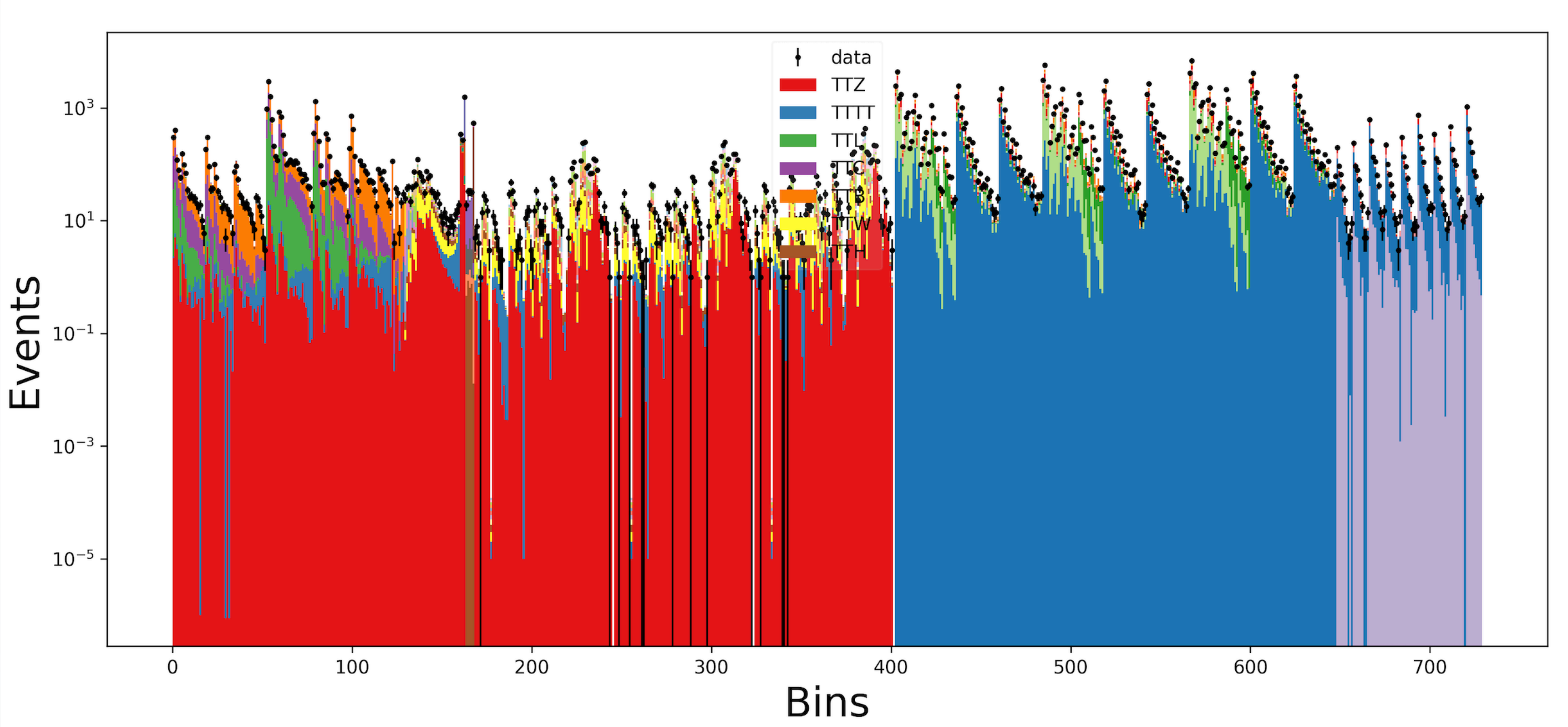


- Combine **full likelihoods** from:
  - $t\bar{t}\gamma$ (single lepton): **JHEP 12 (2021) 180**
  - $t\bar{t}\gamma$ (di-lepton): **JHEP 05 (2022) 091**
  - $t\bar{t}Z$ (multilepton): **EPJC 81 (2021) 737**
- **Very complementary** sensitivity

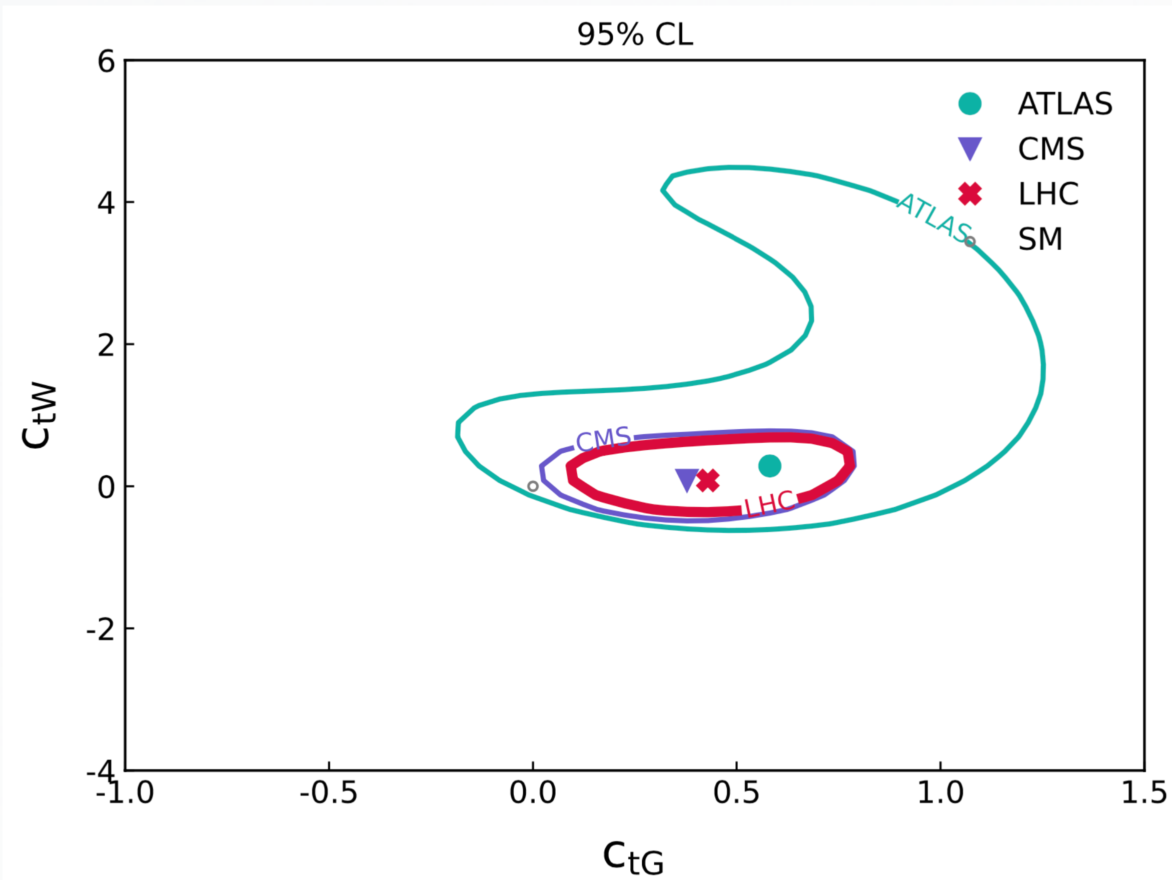


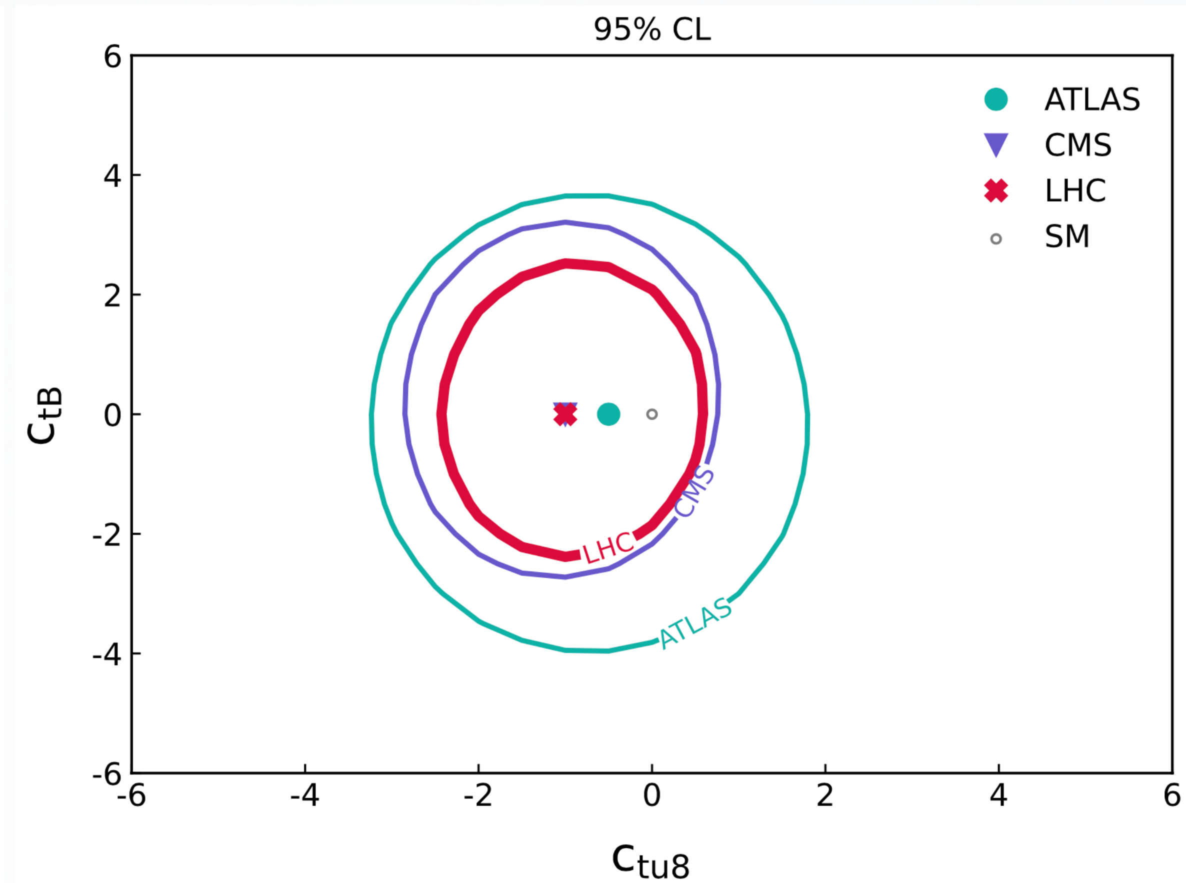
Let's combine everything

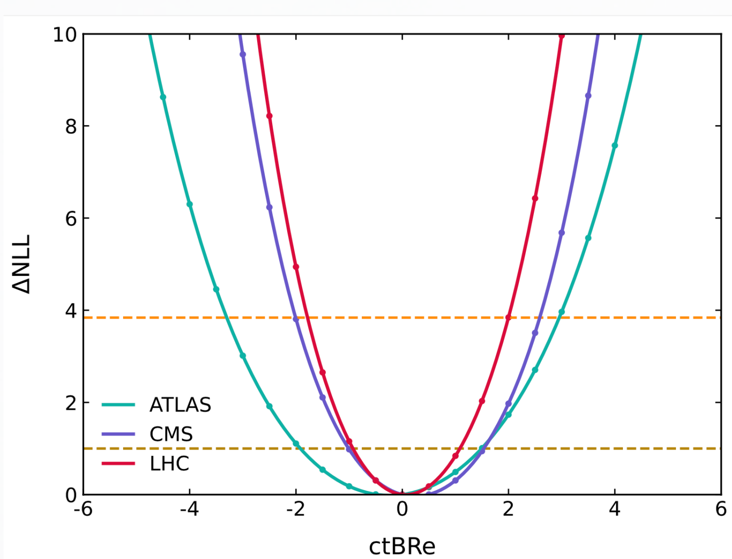
- Use **full likelihoods** from 5 published analyses:
  - $t\bar{t}t\bar{t}$ (multilepton): JHEP 11 (2021) 118, **arXiv:2305.13439**
  - $t\bar{t}\gamma$ (single lepton): **JHEP 12 (2021) 180**
  - $t\bar{t}\gamma$ (di-lepton): **JHEP 05 (2022) 091**
  - $t\bar{t}Z$ (multilepton): EPJC 81 (2021) 737
- Probe **EFT** through $t\bar{t}t\bar{t}$, $t\bar{t}\gamma$, $t\bar{t}Z$, $t\bar{t}W$, $t\bar{t}h$
- **More stringent** EFT constraints after ATLAS+CMS combination

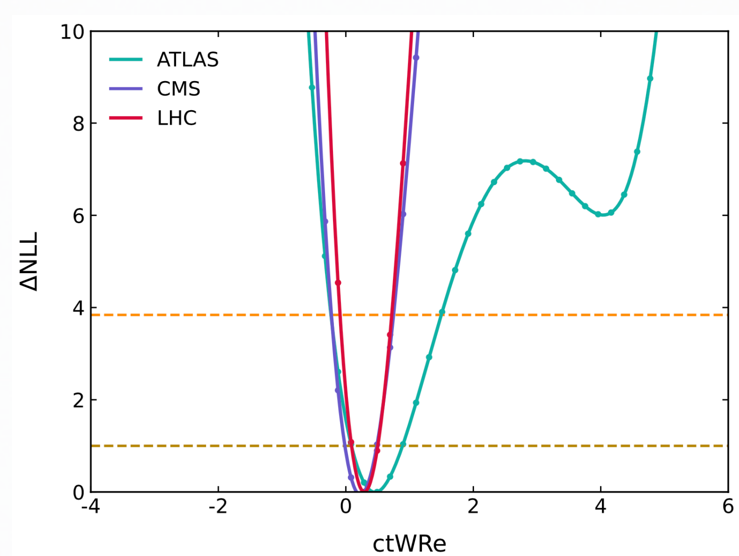


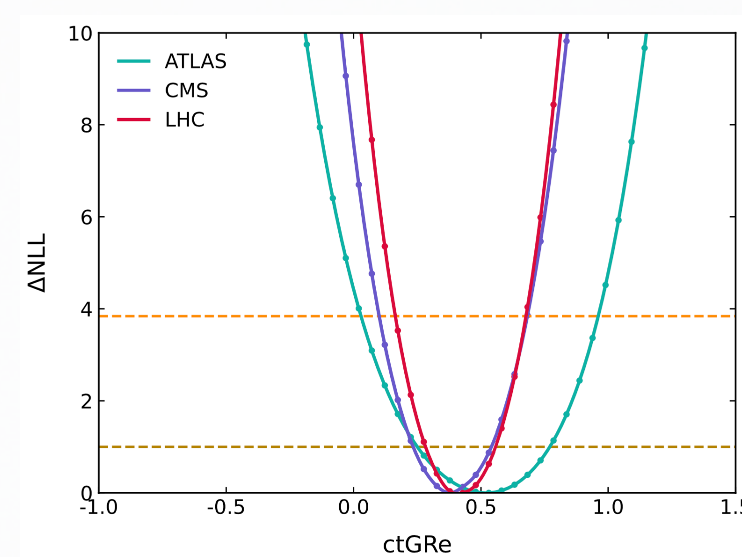
Grand combination results












01 WINS
63
FRIENDSHIP
CMS
ATLAS
EXPERIMENT

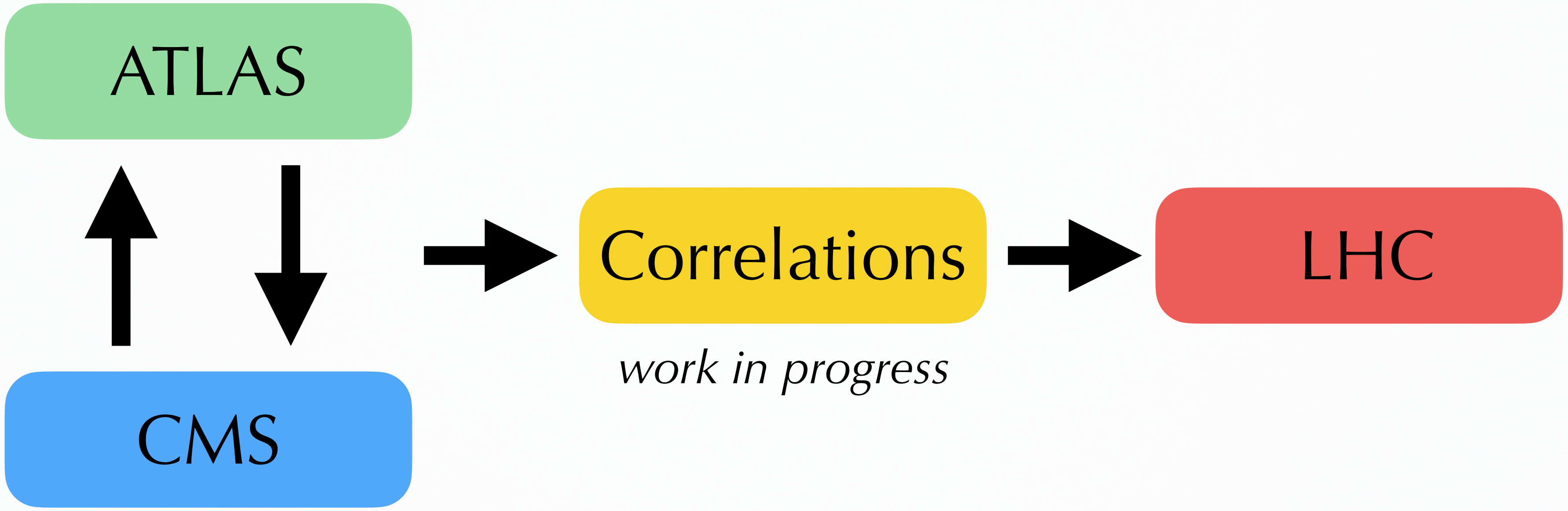
Summary

- **Translation** of the full detector-level information between ATLAS and CMS is working
- Need to move from the conservative treatment (i.e. all uncorrelated) of systematic uncertainties to a **proper correlation** model in a longer term
- Saving EFT means **preserving information about ML experimental observables** and/or the relevant **new physics bin-wise yield parametrization**

➡ **Publish** more full likelihoods

➡ **Combine**

➡ Together, we will **save the EFT**



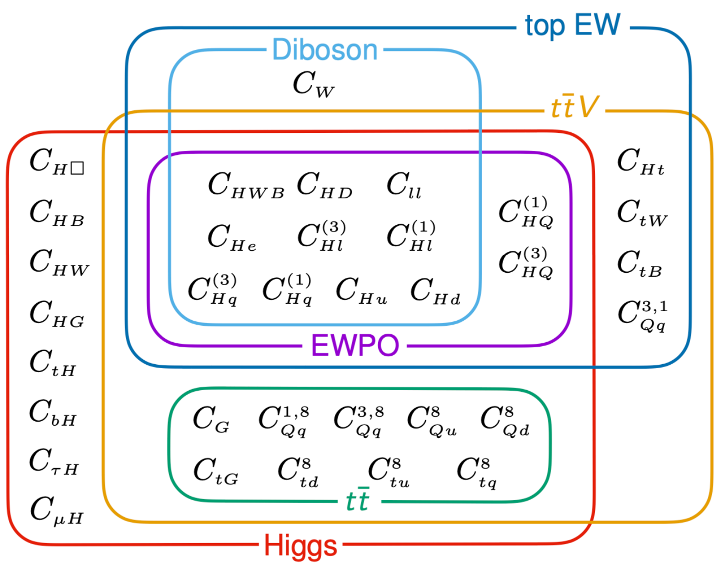
theory

$$\mathcal{L}_{eff} = \mathcal{L}_0 + \frac{1}{\Lambda}\mathcal{L}_1 + \frac{1}{\Lambda^2}\mathcal{L}_2 + \dots$$

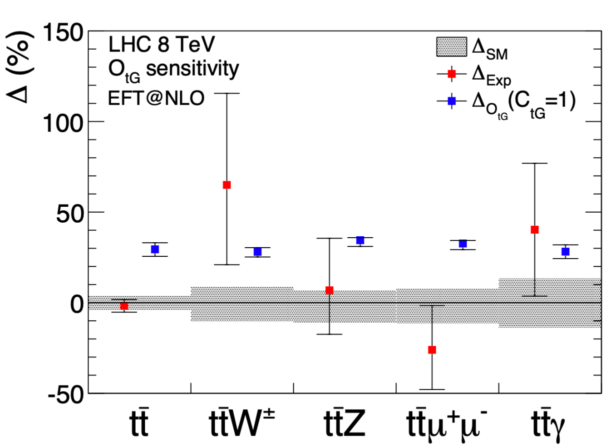
SMEFT@NLO

PRD 103 (2021) 096024

c_i	$\mathcal{O}(\Lambda^{-2})$ LO	NLO		$\mathcal{O}(\Lambda^{-4})$ LO	NLO
c^8_{tu}	$4.27^{+11\%}_{-9\%}$	$4.06^{+1\%}_{-3\%}$		$1.04^{+6\%}_{-5\%}$	$1.03^{+2\%}_{-2\%}$
c^8_{td}	$2.79^{+11\%}_{-9\%}$	$2.77^{+1\%}_{-3\%}$		$0.577^{+6\%}_{-5\%}$	$0.611^{+3\%}_{-2\%}$
c^8_{tq}	$6.99^{+11\%}_{-9\%}$	$6.67^{+1\%}_{-3\%}$		$1.61^{+6\%}_{-5\%}$	$1.29^{+3\%}_{-2\%}$
c^8_{Qu}	$4.26^{+11\%}_{-9\%}$	$3.93^{+1\%}_{-4\%}$		$1.04^{+6\%}_{-5\%}$	$0.798^{+3\%}_{-3\%}$
c^8_{Qd}	$2.79^{+11\%}_{-9\%}$	$2.93^{+0\%}_{-1\%}$		$0.58^{+6\%}_{-5\%}$	$0.485^{+2\%}_{-2\%}$
$c^{8,1}_{Qq}$	$6.99^{+11\%}_{-9\%}$	$6.82^{+1\%}_{-3\%}$		$1.61^{+6\%}_{-5\%}$	$1.69^{+3\%}_{-3\%}$
$c^{8,3}_{Qq}$	$1.50^{+10\%}_{-9\%}$	$1.32^{+1\%}_{-3\%}$		$1.61^{+6\%}_{-5\%}$	$1.57^{+2\%}_{-2\%}$
c^1_{tu}	$[0.67^{+1\%}_{-1\%}]$	$-0.078(7)^{+31\%}_{-23\%}$	$[0.41^{+13\%}_{-17\%}]$	$4.66^{+6\%}_{-5\%}$	$5.92^{+6\%}_{-5\%}$
c^1_{td}	$[-0.21^{+1\%}_{-2\%}]$	$-0.306^{+30\%}_{-22\%}$	$[-0.15^{+10\%}_{-13\%}]$	$2.62^{+6\%}_{-5\%}$	$3.46^{+5\%}_{-5\%}$
c^1_{tq}	$[0.39^{+0\%}_{-1\%}]$	$-0.47^{+24\%}_{-18\%}$	$[0.50^{+3\%}_{-2\%}]$	$7.25^{+6\%}_{-5\%}$	$9.36^{+6\%}_{-5\%}$
c^1_{Qu}	$[0.33^{+0\%}_{-0\%}]$	$-0.359^{+23\%}_{-17\%}$	$[0.57^{+6\%}_{-5\%}]$	$4.68^{+6\%}_{-5\%}$	$5.96^{+6\%}_{-5\%}$
c^1_{Qd}	$[-0.11^{+0\%}_{-1\%}]$	$0.023(6)^{+114\%}_{-75\%}$	$[-0.19^{+6\%}_{-5\%}]$	$2.61^{+6\%}_{-5\%}$	$3.46^{+5\%}_{-5\%}$
$c^{1,1}_{Qq}$	$[0.57^{+0\%}_{-1\%}]$	$-0.24^{+30\%}_{-22\%}$	$[0.39^{+9\%}_{-12\%}]$	$7.25^{+6\%}_{-5\%}$	$9.34^{+5\%}_{-5\%}$
$c^{1,3}_{Qq}$	$[1.92^{+1\%}_{-1\%}]$	$0.088(7)^{+28\%}_{-20\%}$	$[1.05^{+17\%}_{-22\%}]$	$7.25^{+6\%}_{-5\%}$	$9.32^{+5\%}_{-5\%}$
c^8_{QQ}	$0.0586^{+27\%}_{-25\%}$	$0.125^{+10\%}_{-11\%}$		$0.00628^{+13\%}_{-16\%}$	$0.0133^{+7\%}_{-5\%}$
c^8_{Qt}	$0.0583^{+27\%}_{-25\%}$	$-0.107(6)^{+40\%}_{-33\%}$		$0.00619^{+13\%}_{-16\%}$	$0.0118^{+8\%}_{-5\%}$
c^1_{QQ}	$[-0.11^{+15\%}_{-18\%}]$	$-0.039(4)^{+51\%}_{-33\%}$	$[-0.12^{+7\%}_{-5\%}]$	$0.0282^{+13\%}_{-16\%}$	$0.0651^{+5\%}_{-6\%}$
c^1_{Qt}	$[-0.068^{+16\%}_{-18\%}]$	$-2.51^{+29\%}_{-21\%}$	$[-0.12^{+3\%}_{-6\%}]$	$0.0283^{+13\%}_{-16\%}$	$0.066^{+5\%}_{-6\%}$
c^1_{tt}	×	$0.215^{+23\%}_{-18\%}$		×	×

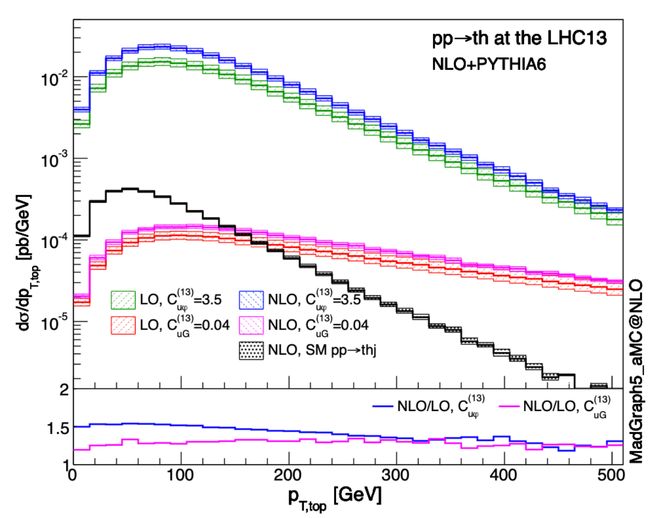


JHEP 04 (2021) 279



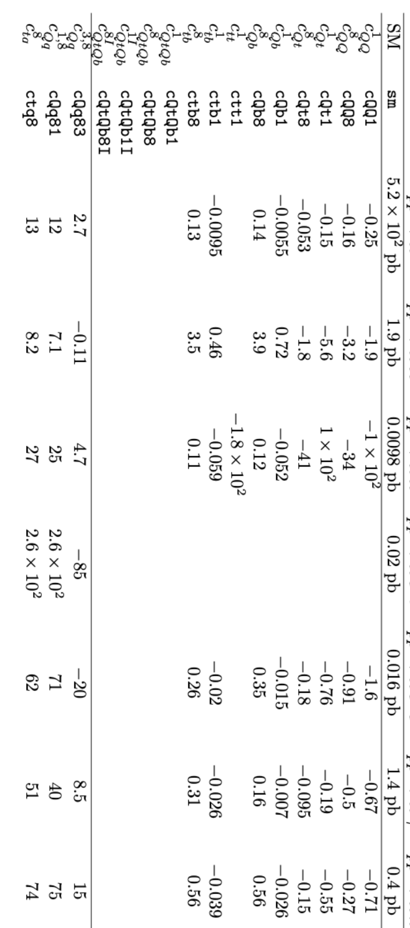
JHEP 05 (2016) 052

TopFCNC



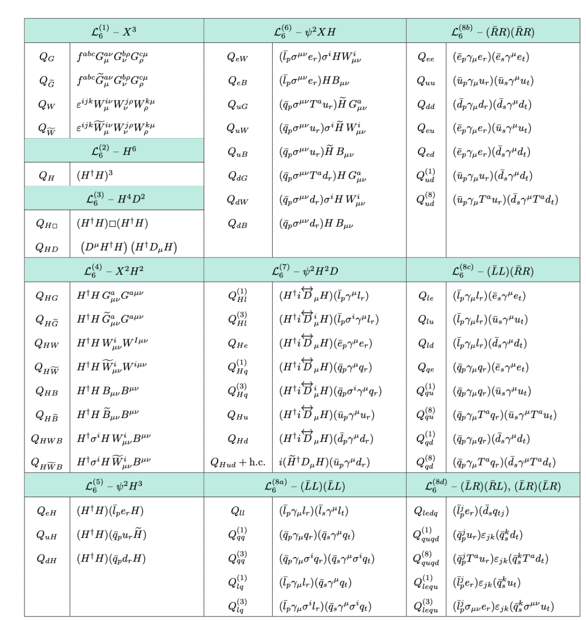
PRD 91 (2015) 034024

dim6top



arXiv:1802.07237

SMEFTsim



JHEP 12 (2017) 070

Conventions ≈ agreed by experimentalists:

- Warsaw basis
- topU3l
- (m_W, m_Z, G_F)
- SMEFTsim / SMEFT@NLO

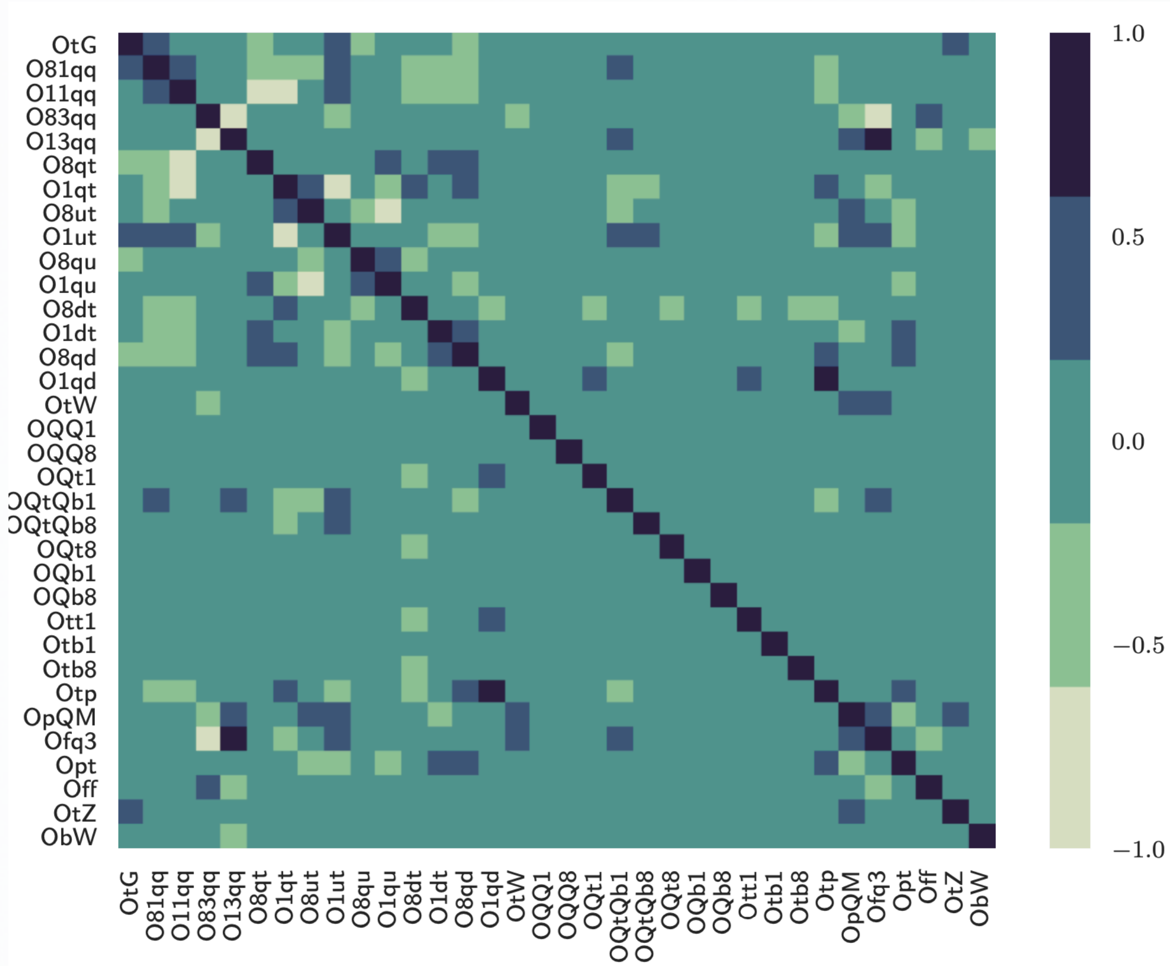
Recommendations are provided by LHC EFT WG via notes

Operators

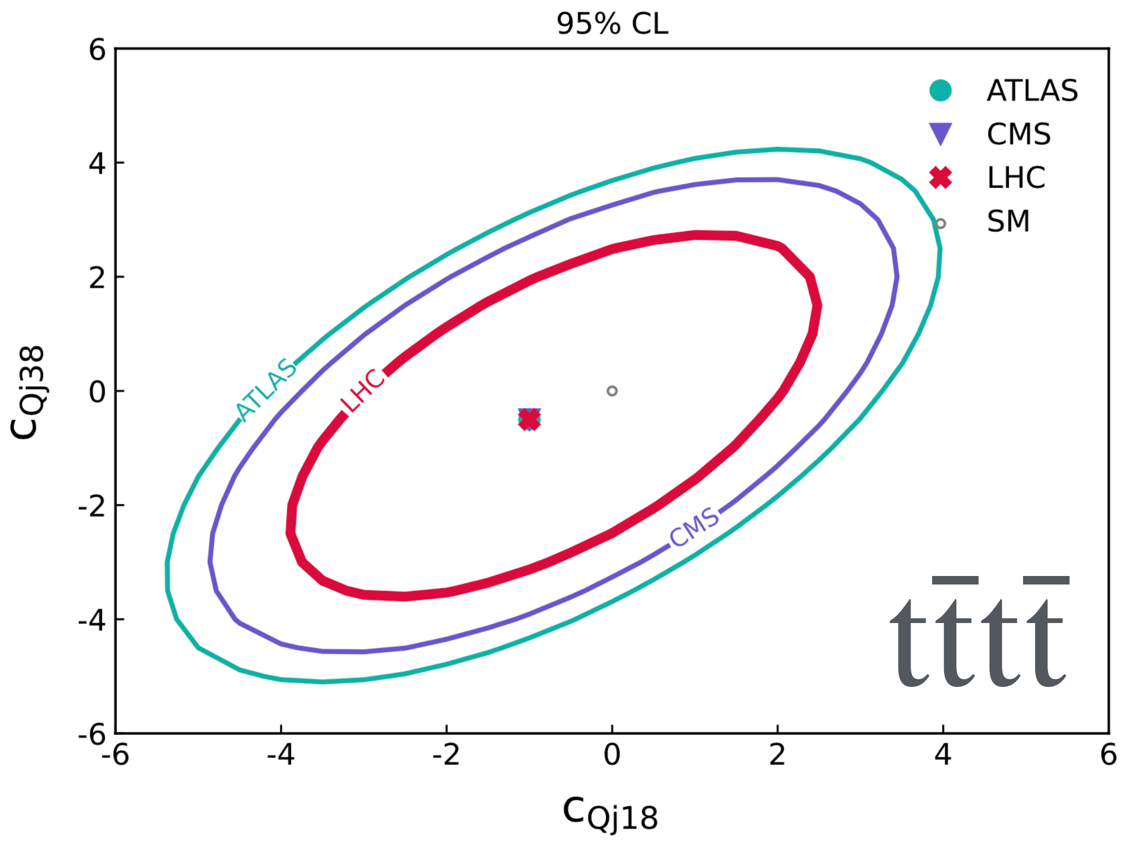
JHEP 04 (2019) 100

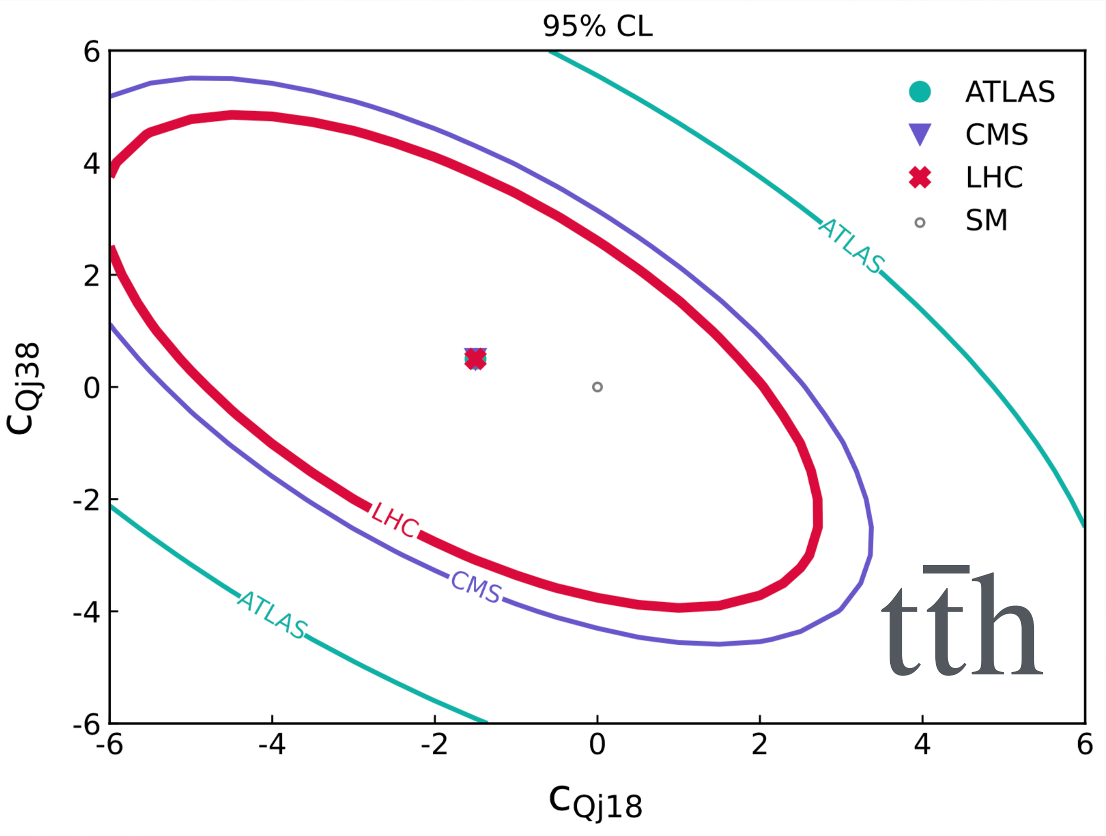
Notation	Sensitivity at $\mathcal{O}(\Lambda^{-2})$ $(\mathcal{O}(\Lambda^{-4}))$								
	$t\bar{t}$	single-top	tW	tZ	$t\bar{t}W$	$t\bar{t}Z$	$t\bar{t}H$	$t\bar{t}t\bar{t}$	$t\bar{t}b\bar{b}$
OQQ1								✓	✓
OQQ8								✓	✓
OQt1								✓	✓
OQt8								✓	✓
OQb1									✓
OQb8									✓
Ott1								✓	
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							✓		

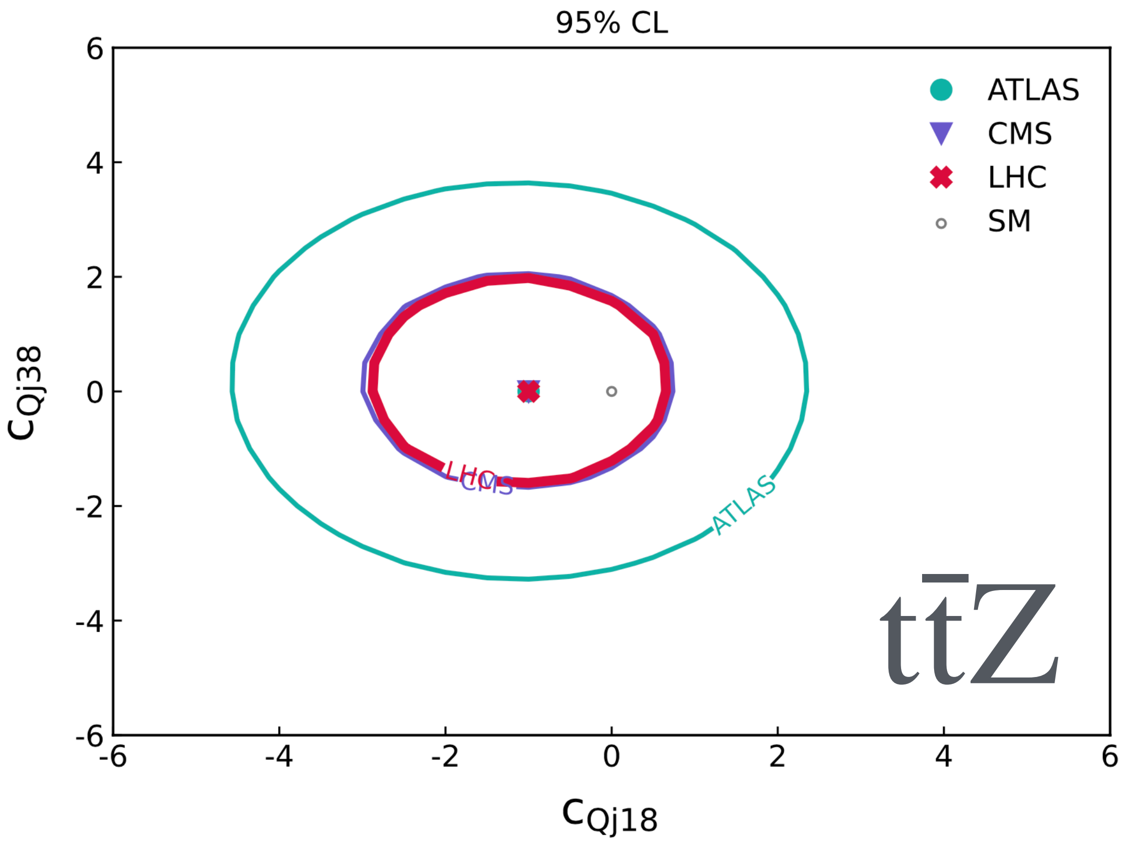
- Use ATLAS+CMS four-top quark combination to **probe EFT**
- Many **common operators** for processes giving multilepton final states
- Important to include **interference** terms

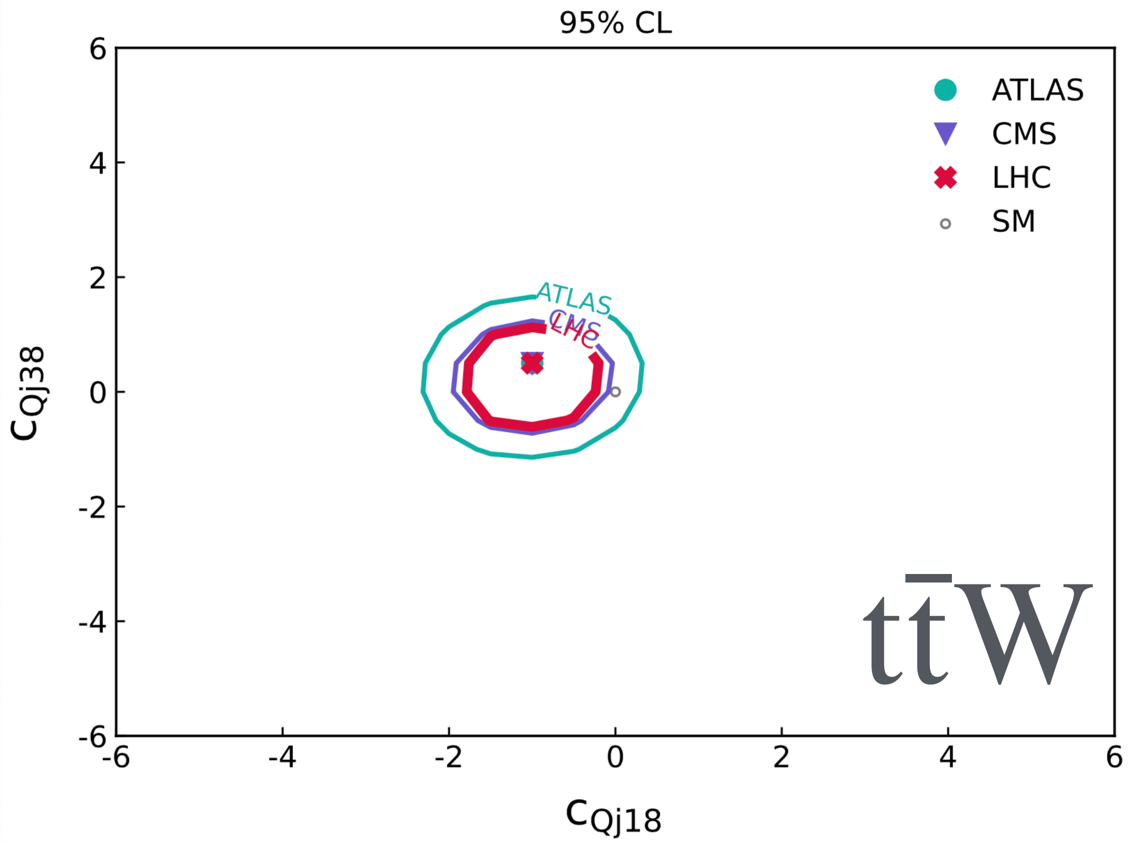


Omnipresent EFT









Correlating uncertainties

Theory systematics

- ↓ Signal (ttbar and single top) TH systematics
- ↓ Background TH systematics
- ↓ Other to-dos/proposals
- ↓ Papers and notes with ATLAS and CMS theory modelling info
  - ↓ Descriptions and comparisons of generator setups used by ATLAS and CMS:

2019-01-18

Signal (ttbar and single top) TH systematics

Note that this page is outdated as of January 2019. Information on currently used TH systematics can be found in the ATLAS and CMS papers.

- **Generator modeling**: comparison of central predictions from generators. Other sources not ending in one of the following categories and specific to a c here (example: DR vs DS scheme for ttbar subtraction in Wt). General guidelines suggest to use for the ttbar signal at least one multileg generator and generator, and for single top at least two different models (one of which NLO). Differences coming from the use of different (tuned) PS models can also whenever it is clear this is not already covered by the explicit systematic error on the description of radiation (and hadronisation).
  - to be discussed: do we want to leave this error optional, only for when the difference between the two predictions goes outside the band from the hadronisation)?
  - some authors advice, for observables at NLO precision, to also quote the uncertainty from interfacing the prediction to two different parton showe conservative approach, it is under discussion how to quantify the amount of double counting of the uncertainty coming from hadronization effects.
  - other authors claim that different NLO-PS matching scheme should be compared (e.g. MC@NLO vs Powheg). It is uncertain whether the differen extra systematic uncertainty on top of the rest.
- **Radiation description**: Q^2 and I/FSR independent variations (to be agreed for NLO generators) or Q^2+PS consistent variations (for matched generator in some cases use LO generators not using multi-leg processes/matching. With Q^2 we indicate both renormalization and factorization scales, ideally changed in an independent way. The suggested variations are conservative and correspond to a factor 0.25 and 4 (1/2 and 2 on Q) or constraints on the variations from the data when available. While the procedure for estimating this error is conceptually the same whether an NLO tool or a matched generator are used for describing the signal, procedural differences from the guidelines
  - Bot
  - the in N

Used by combination efforts within LHCtopWG

Jet energy scale uncertainty correlations between ATLAS and CMS at 8 TeV

2015/11/19

The ATLAS and CMS Collaborations

Treatment of the Correlations in b-Tagging Systematics in ATLAS and CMS

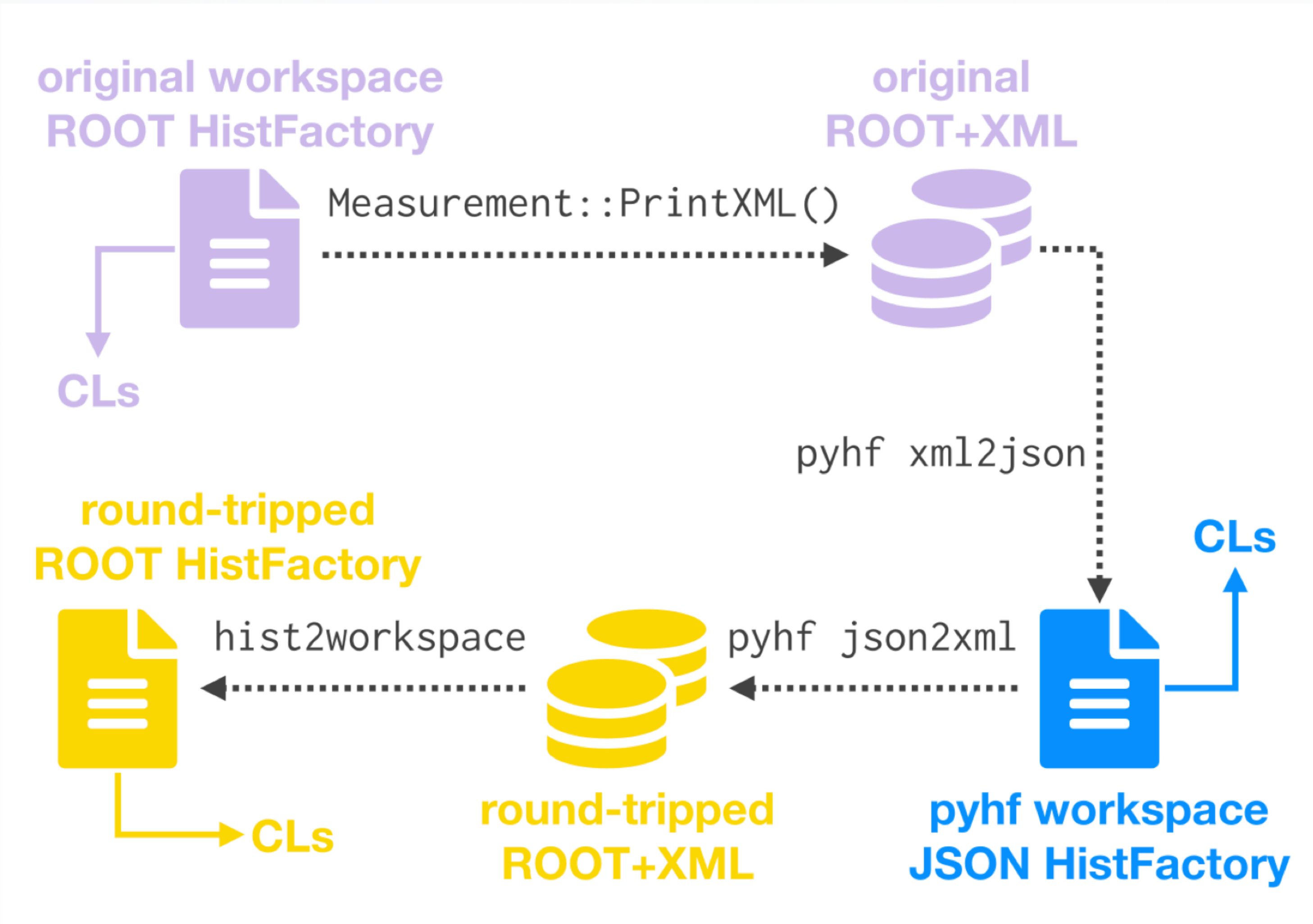
Introduction

2015-11-12

- Top physics at LHC has entered the realm of precision physics for both experiments ATLAS and CMS
  - gain in precision by combining the results of both experiments
- Correct treatment of the uncertainties important
- Flavor tagging is one of the dominant systematics uncertainties, therefore compare for ATLAS and CMS
  - the correlations between flavor tagging algorithms and calibration techniques,
  - the sources of uncertainty and provide procedures for the combination
- b-jet identification (tagging) is a key ingredient of many analyses
  - so far no correlation has been considered
- the two collaborations use different approaches regarding every aspect of b-jet identification:
  - b-tagging algorithms and working point definition
  - calibrations samples and methods
  - combination strategy
  - source of systematics considered and their treatment
- we compared the different approaches, and identified a list of common sources of uncertainty:
  - treatments of each uncertainty compared to understand how it's effect is correlated in the flavour tagging
  - size of the uncertainties has been found to be in reasonable agreement across the whole pT spectrum of jets from top decays
- a proposal is advanced for the treatment of b-tagging correlations for future top physics combinations at LHC

- Understanding and detailing systematic correlations among experiments is a **tedious** effort
- Nevertheless, **it has to be done**
- Performing detector-level combinations can further **steer discussions** on systematics treatment

Likelihood preservation: pyhf



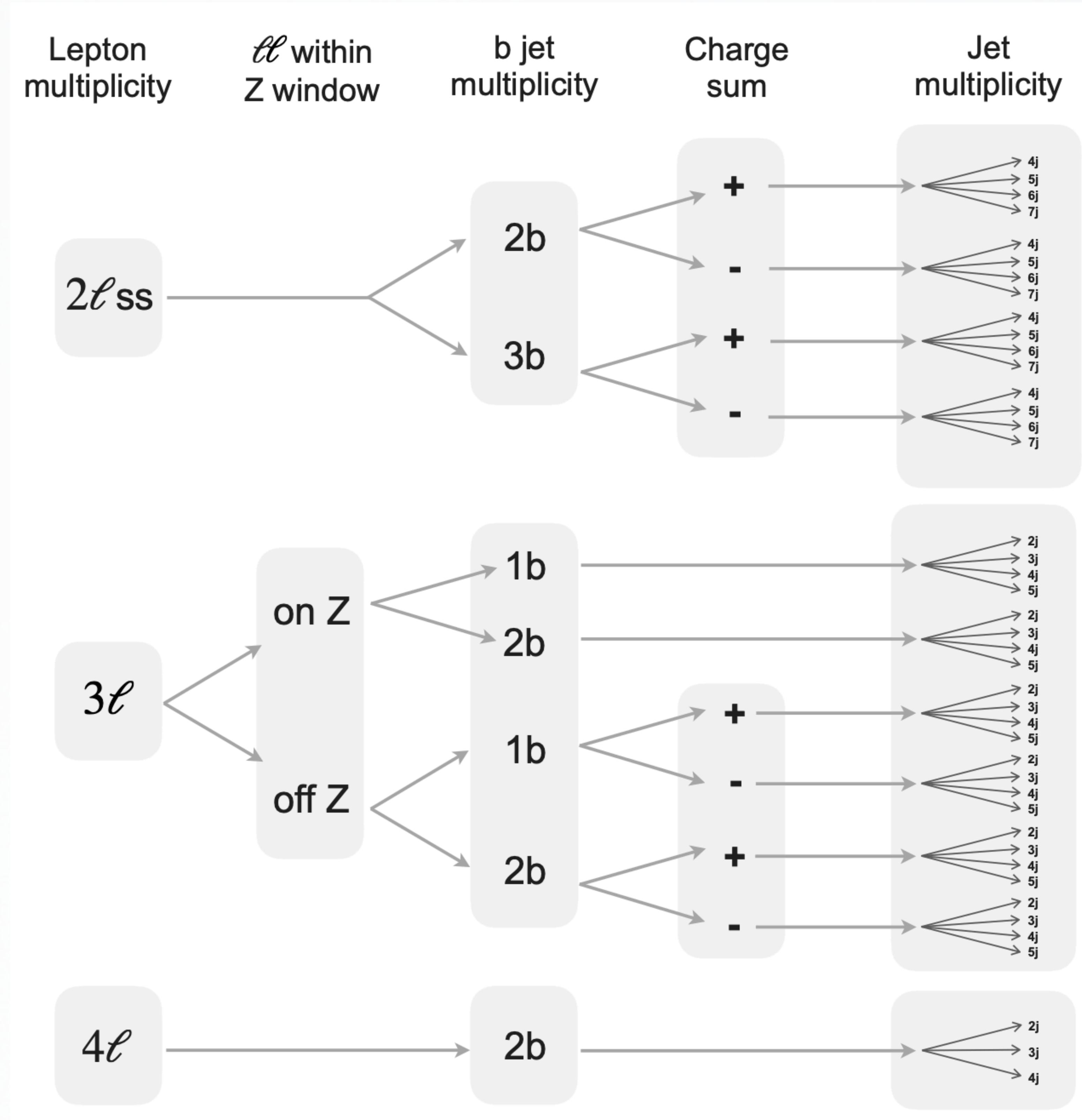
- The **methodology** described in ATL-PHYS-PUB-2019-029
- Introduces a **JSON** schema for the **HistFactory** statistical model
- Input data model and fitting procedure implemented in **pyhf**
- ATLAS uses this approach to publish likelihoods in **HEPData**

	Description	Modification	Constraint Term c_χ	Input
constrained	Uncorrelated Shape	$\kappa_{scb}(\gamma_b) = \gamma_b$	$\prod_b \mathrm{Pois}\left(r_b = \sigma_b^{-2} \middle\vert \rho_b = \sigma_b^{-2}\gamma_b\right)$	σ_b
	Correlated Shape	$\Delta_{scb}(\alpha) = f_p\left(\alpha \middle\vert \Delta_{scb,\alpha=-1}, \Delta_{scb,\alpha=1}\right)$	$\mathrm{Gaus}\left(a = 0 \vert \alpha, \sigma = 1\right)$	$\Delta_{scb,\alpha=\pm1}$
	Normalisation Unc.	$\kappa_{scb}(\alpha) = g_p\left(\alpha \middle\vert \kappa_{scb,\alpha=-1}, \kappa_{scb,\alpha=1}\right)$	$\mathrm{Gaus}\left(a = 0 \vert \alpha, \sigma = 1\right)$	$\kappa_{scb,\alpha=\pm1}$
	MC Stat. Uncertainty	$\kappa_{scb}(\gamma_b) = \gamma_b$	$\prod_b \mathrm{Gaus}\left(a_{\gamma_b} = 1 \middle\vert \gamma_b, \delta_b\right)$	$\delta_b^2 = \sum_s \delta_{sb}^2$
	Luminosity	$\kappa_{scb}(\lambda) = \lambda$	$\mathrm{Gaus}\left(l = \lambda_0 \vert \lambda, \sigma_\lambda\right)$	$\lambda_0, \sigma_\lambda$
free	Normalisation	$\kappa_{scb}(\mu_b) = \mu_b$		
	Data-driven Shape	$\kappa_{scb}(\gamma_b) = \gamma_b$		

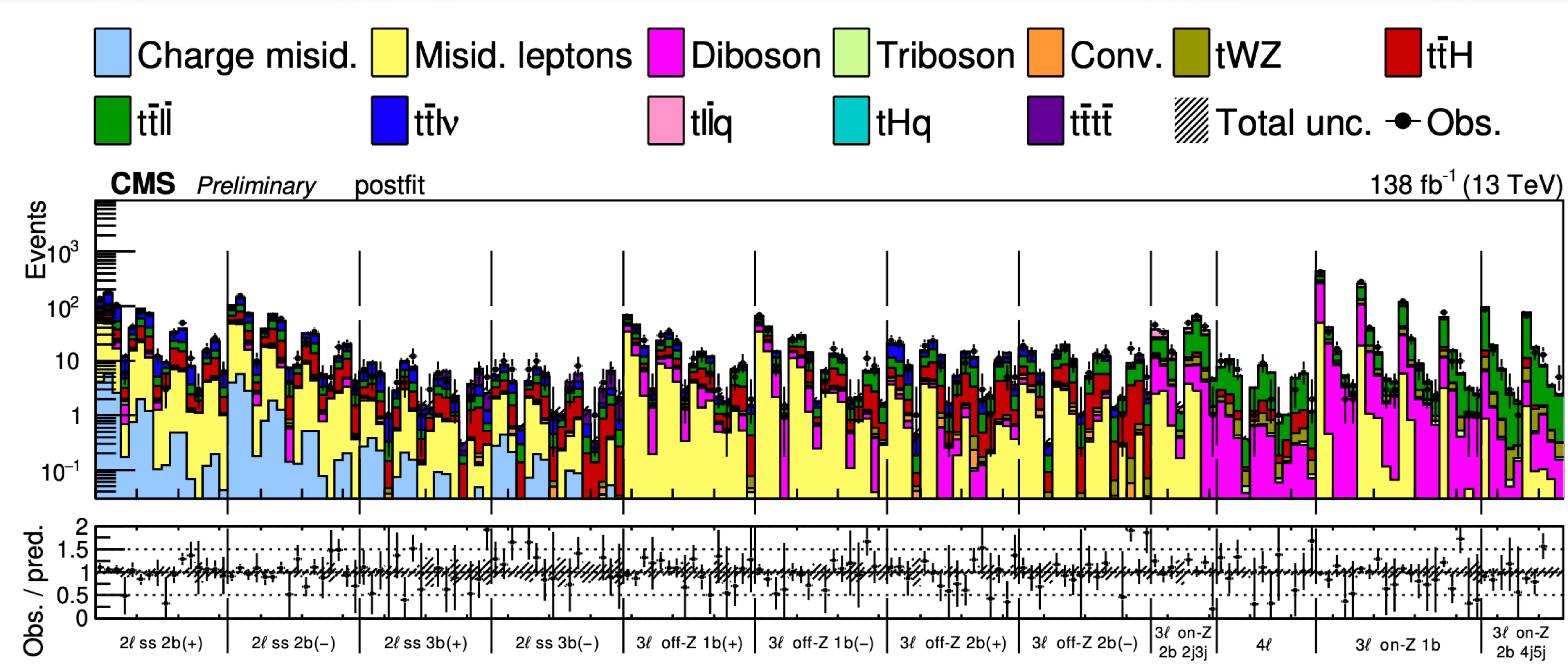
Global fit for t(t)X

- Simultaneously probe EFT effects in **multiple** t(t)X processes using multileptons
- Study **26** operators (four-fermion, two quark-two boson)
- **Categorize** events based on the lepton and jet multiplicities, as well as p_T

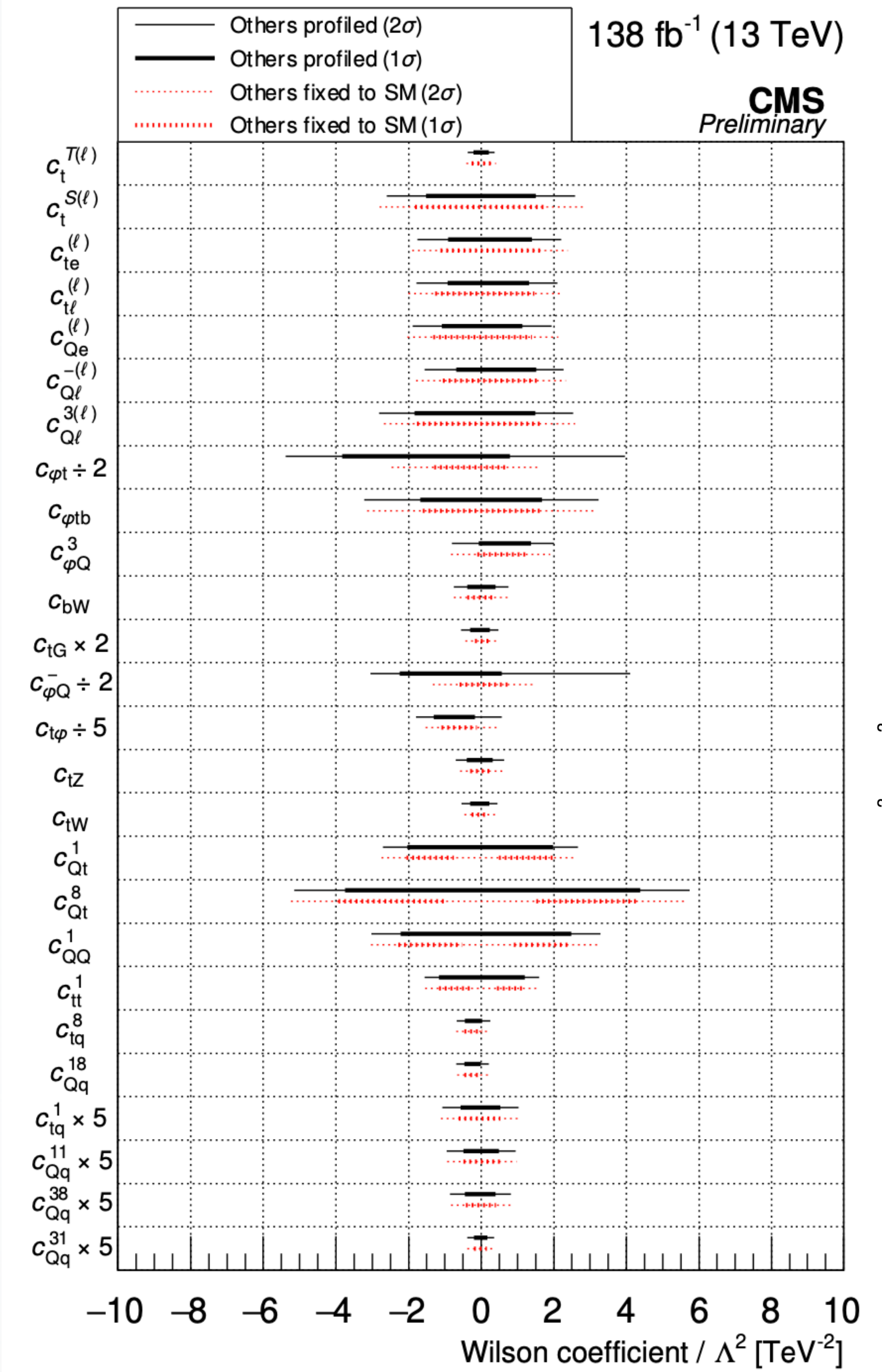
CMS-PAS-TOP-22-006



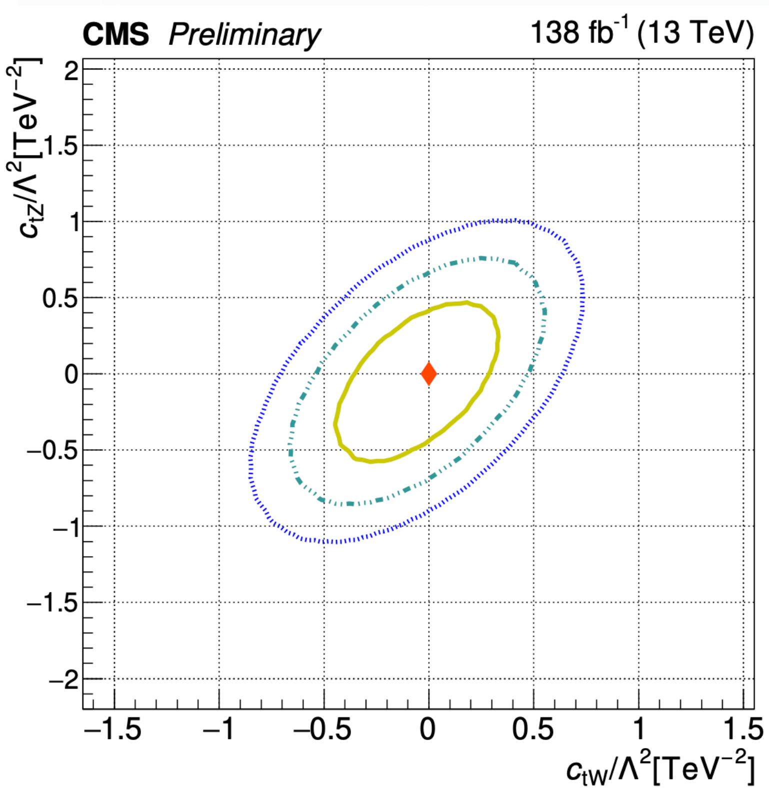
Global fit for t(t)X

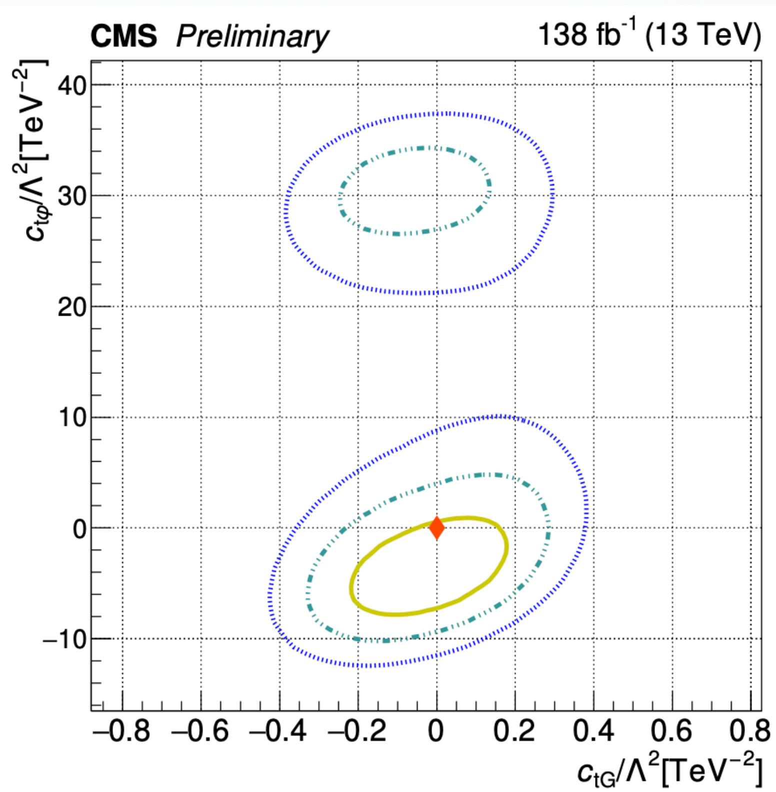


Global fit for t(t)X

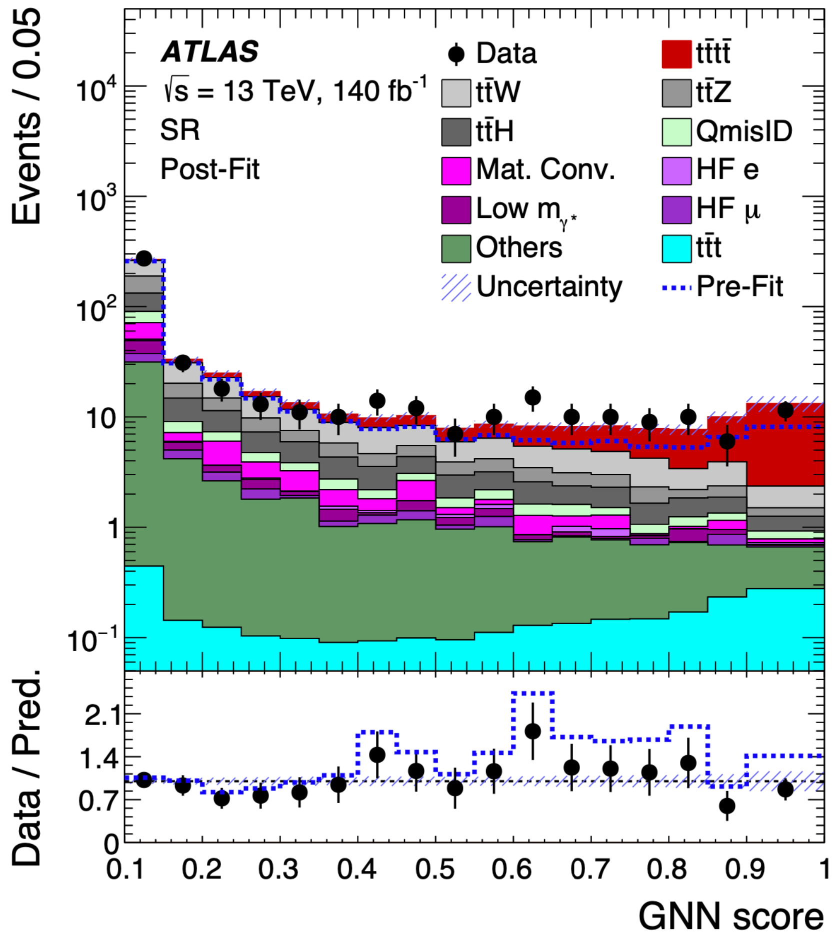


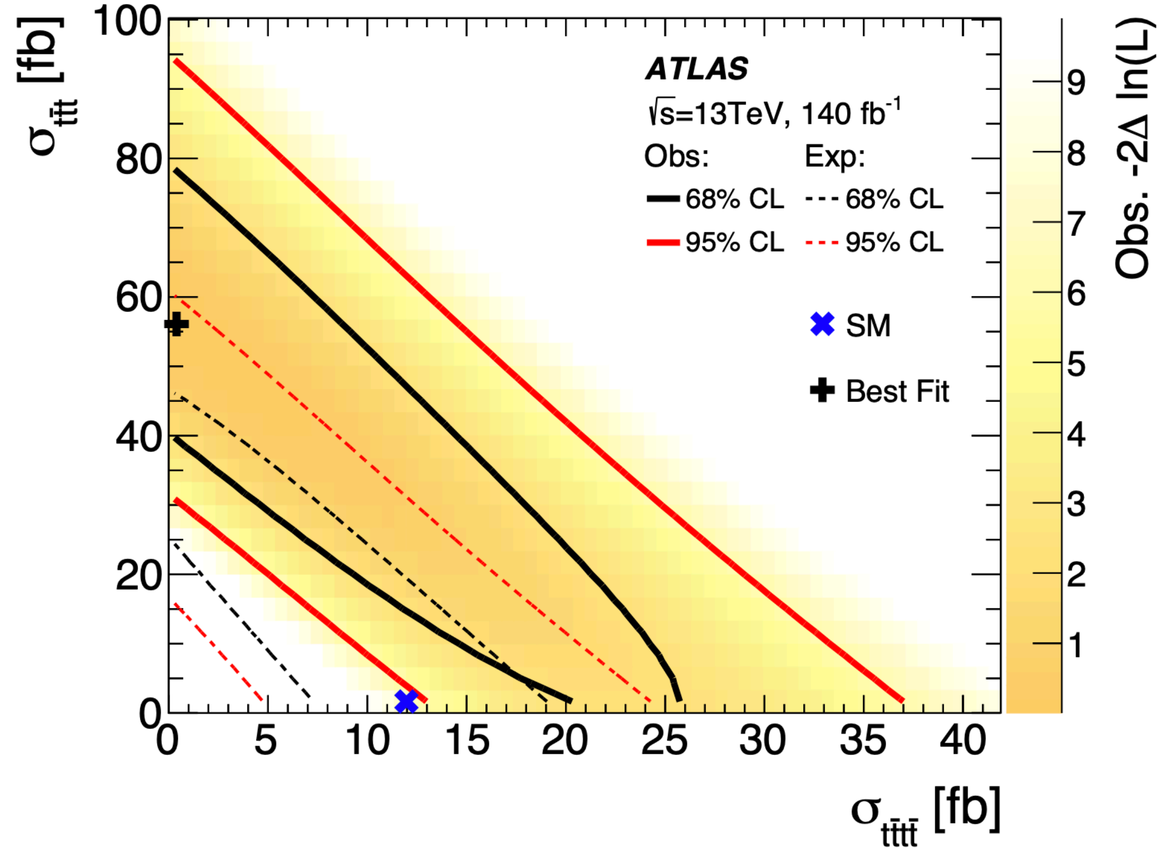
Grouping of WCs	WCs	Lead categories
Two heavy two leptons	$c_{Q\ell}^{3(\ell)}$, $c_{Q\ell}^{-(\ell)}$, $c_{Qe}^{(\ell)}$, $c_{t\ell}^{(\ell)}$, $c_{te}^{(\ell)}$, $c_{t}^{S(\ell)}$, $c_{t}^{T(\ell)}$	3ℓ off-Z
Four heavy	c_{QQ}^{1}, c_{Qt}^{1}, c_{Qt}^{8}, c_{tt}^{1}	2ℓss
Two heavy two light "$t\bar{t}l\nu$-like"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





Top quartet





- Sensitive to **four-fermion** operators and **Higgs oblique** parameter
- Probe **CP** of **top Yukawa**
- Important sensitivity to **triple-top** production ($t\bar{t}tW$, $t\bar{t}tq$)

$$\sigma_{t\bar{t}t\bar{t}} = 22.5\,^{+4.7}_{-4.3}\,(\text{stat})\,^{+4.6}_{-3.4}\,(\text{syst})\ \text{fb}$$

S = 6.1σ (4.3σ)

arXiv:2303.15061 (Submitted to EPJC)

JHEP 10 (2022) 163

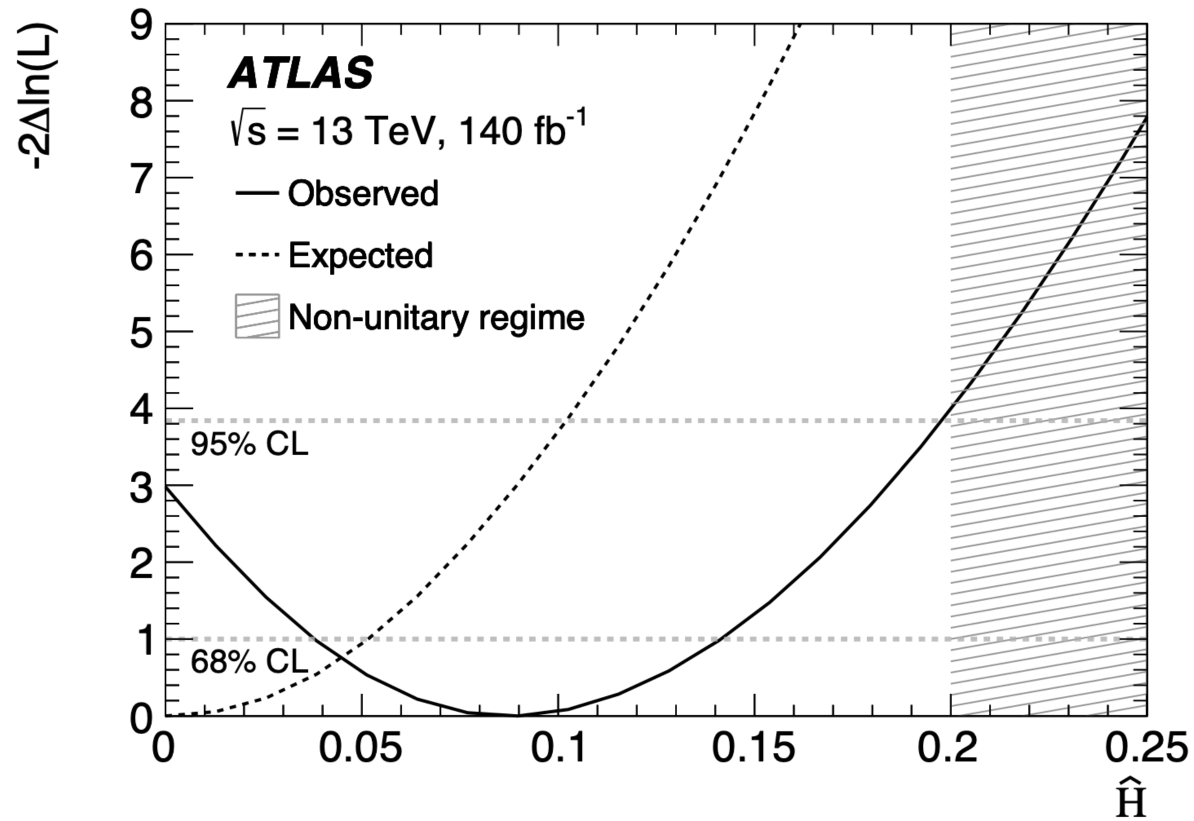
IJMPA 05 (2022) 225023

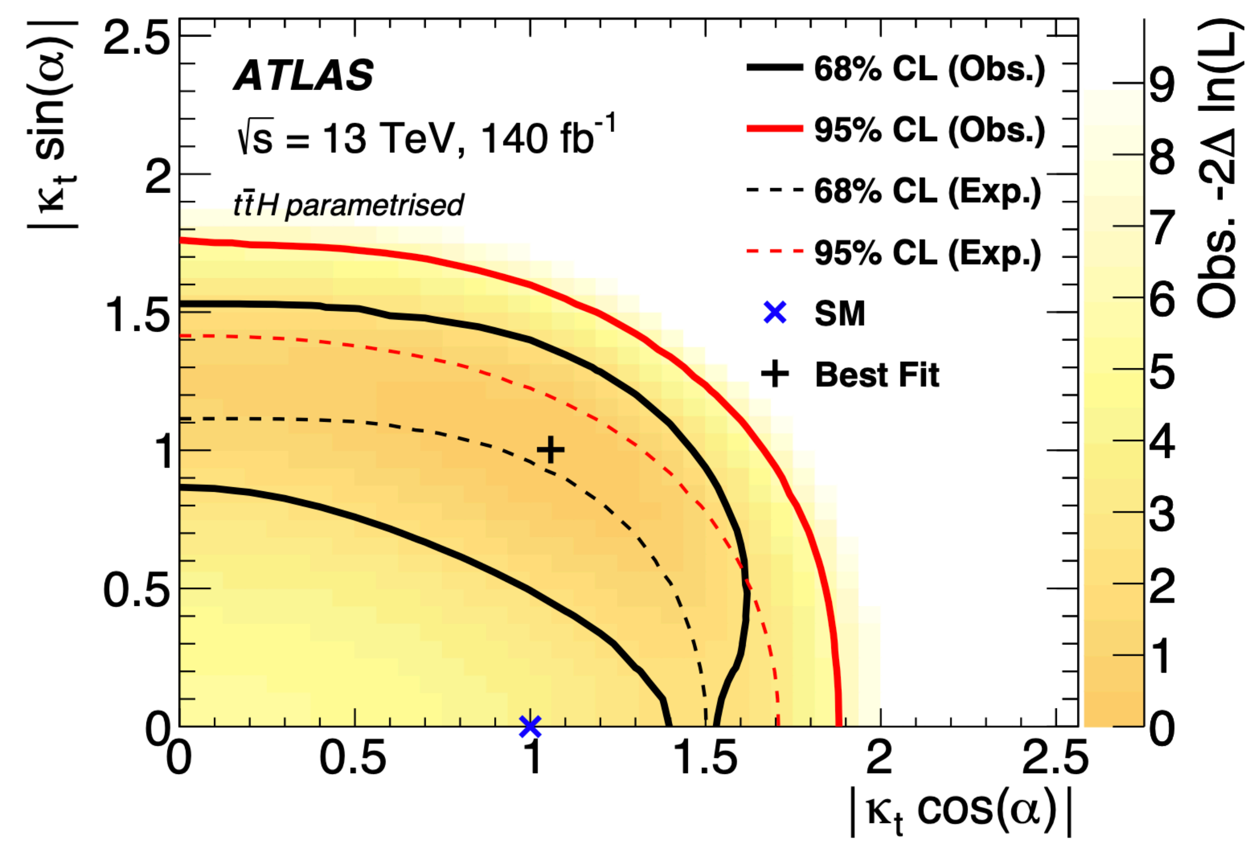
JHEP 09 (2019) 041

Top quartet

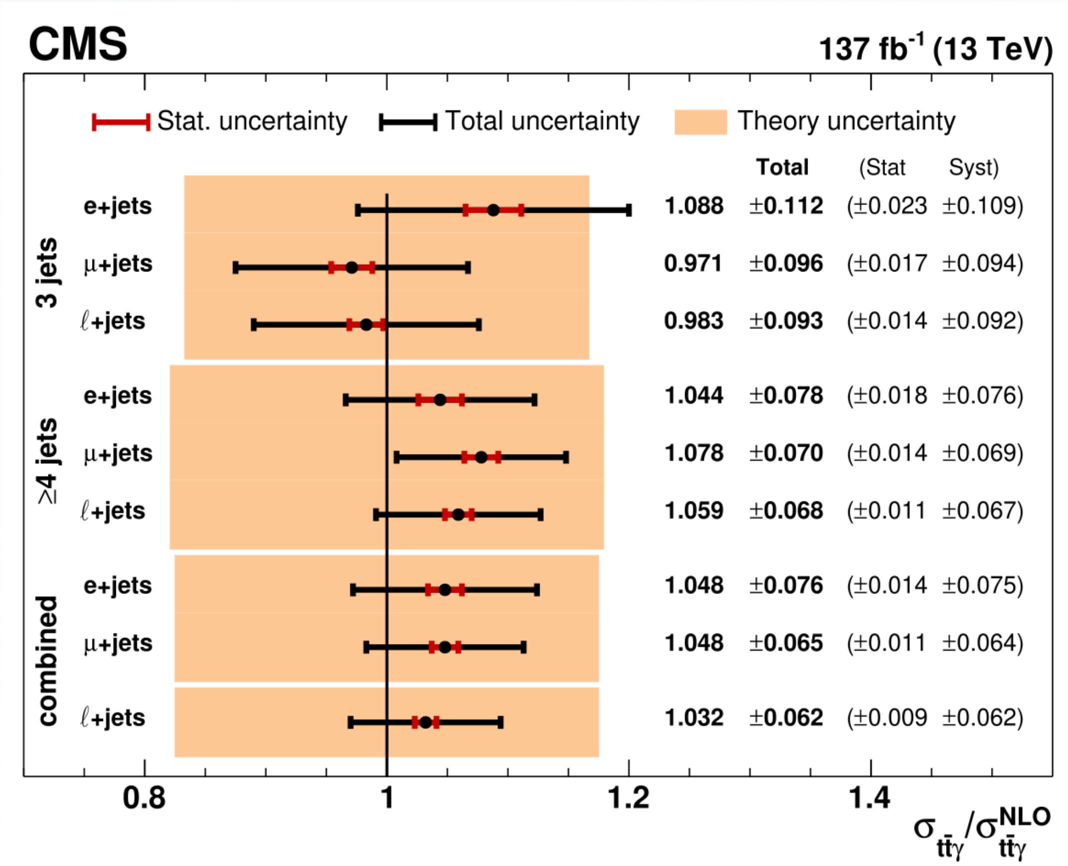
Operators	Expected C_i/Λ^2 [TeV $^{-2}$]	Observed C_i/Λ^2 [TeV $^{-2}$]
$\mathcal{O}^1_{QQ}$	[-2.4, 3.0]	[-3.5, 4.1]
$\mathcal{O}^1_{Qt}$	[-2.5, 2.0]	[-3.5, 3.0]
$\mathcal{O}^1_{tt}$	[-1.1, 1.3]	[-1.7, 1.9]
$\mathcal{O}^8_{Qt}$	[-4.2, 4.8]	[-6.2, 6.9]

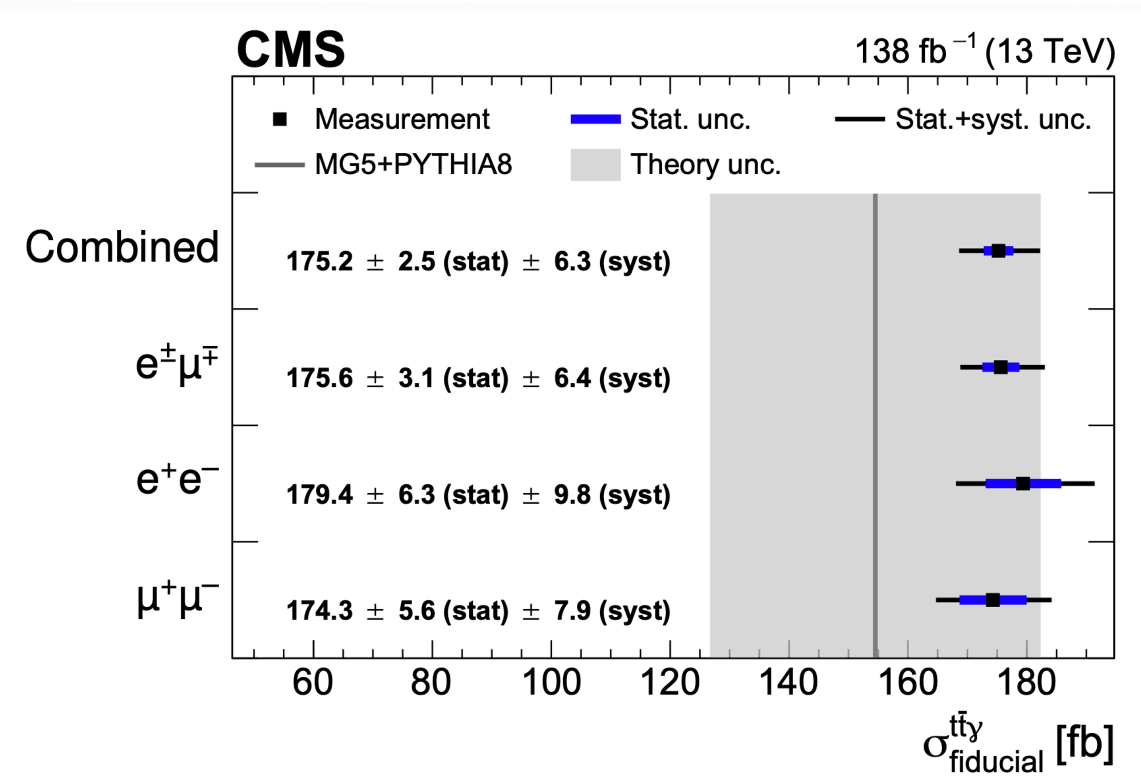
arXiv:2303.15061 (Submitted to EPJC)

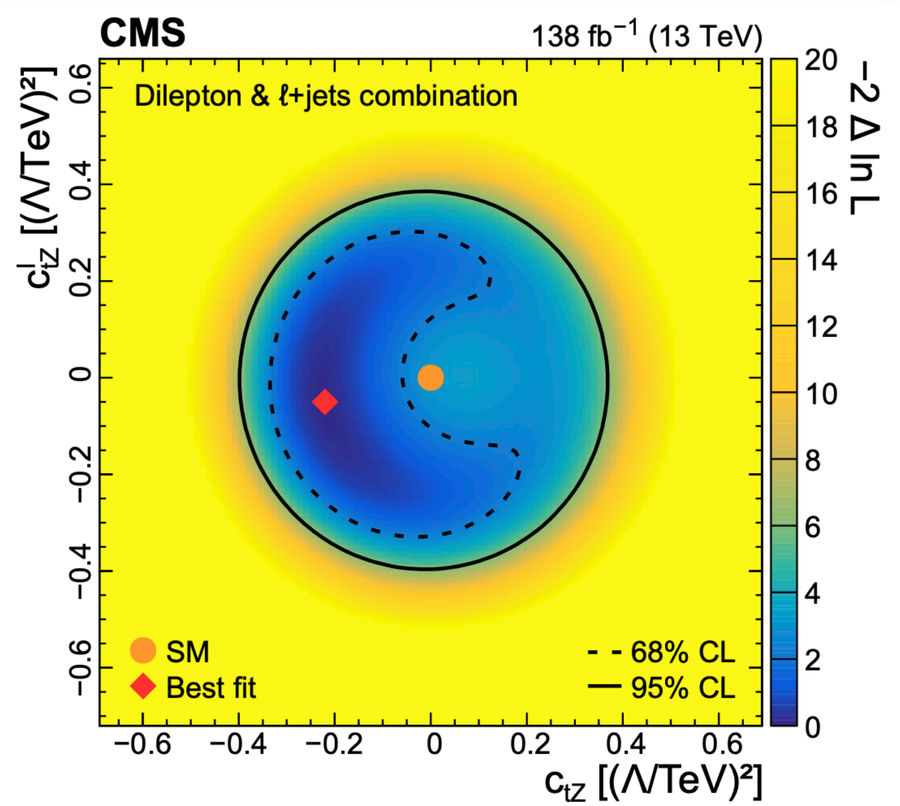


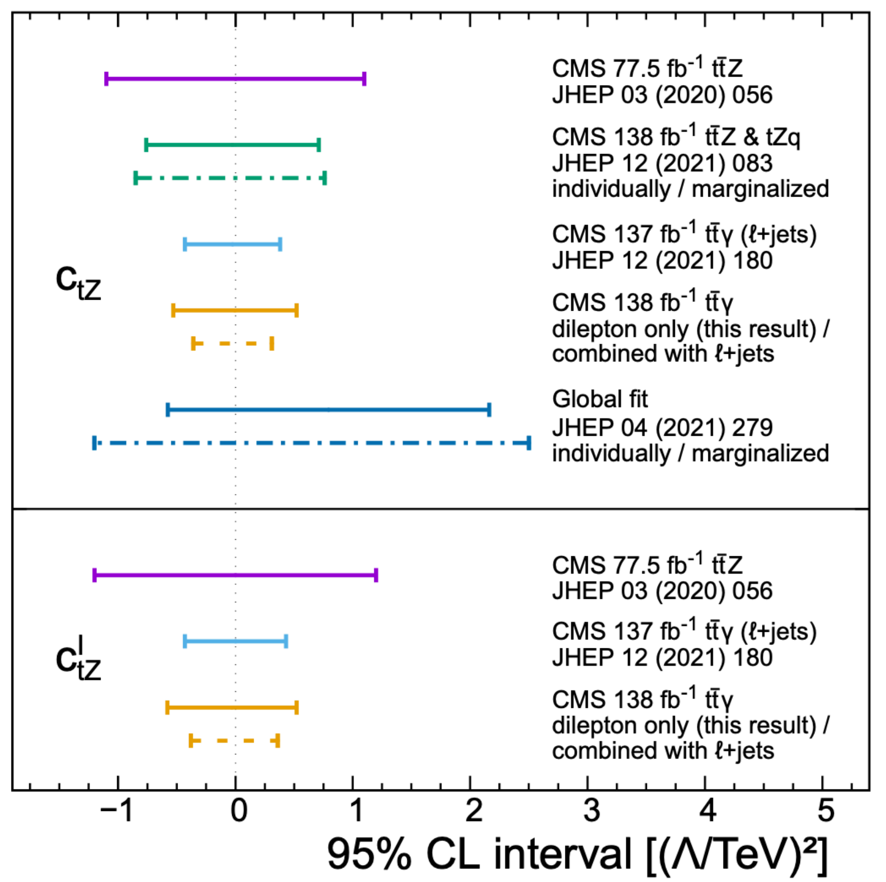


Top-photon







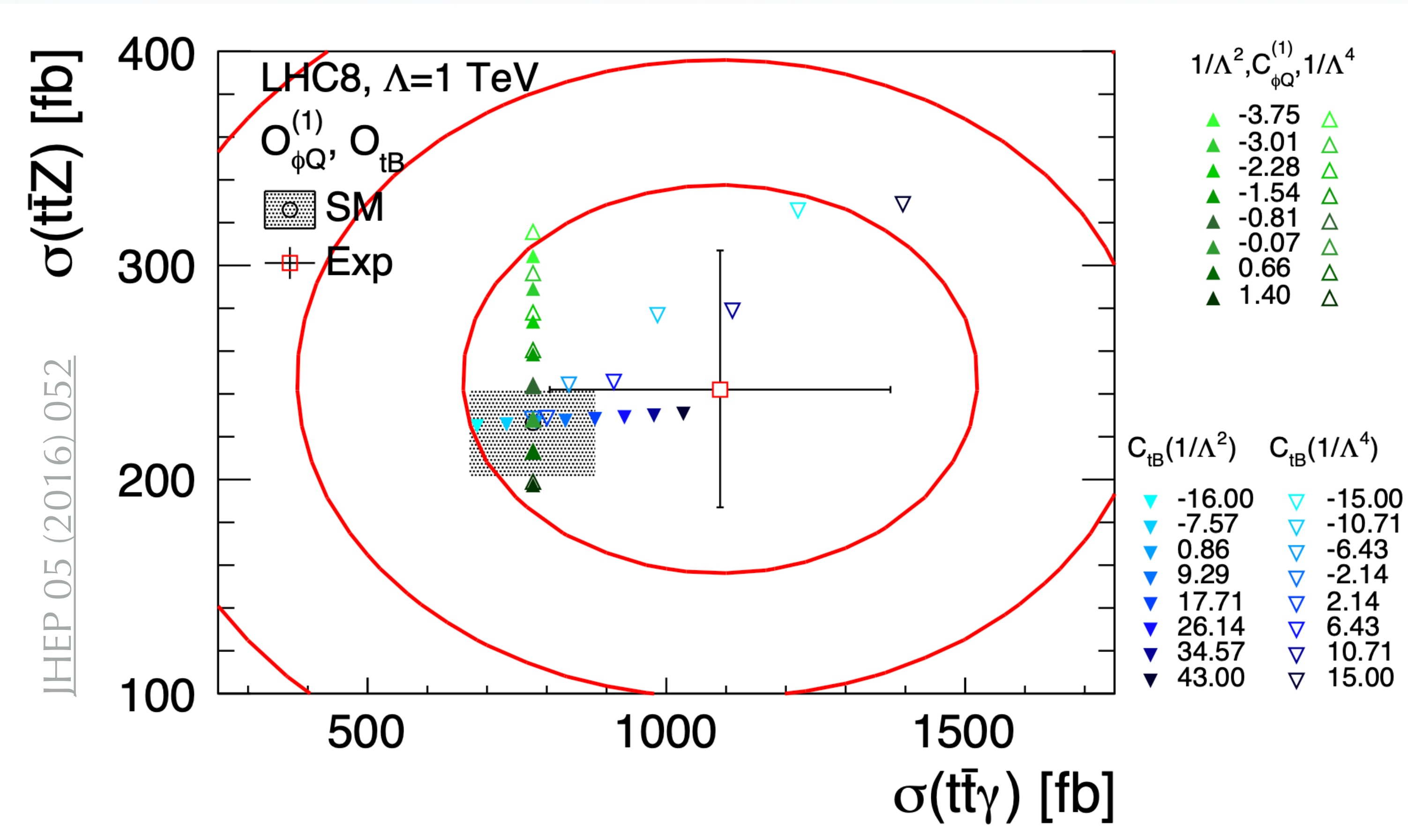


JHEP 05 (2022) 091

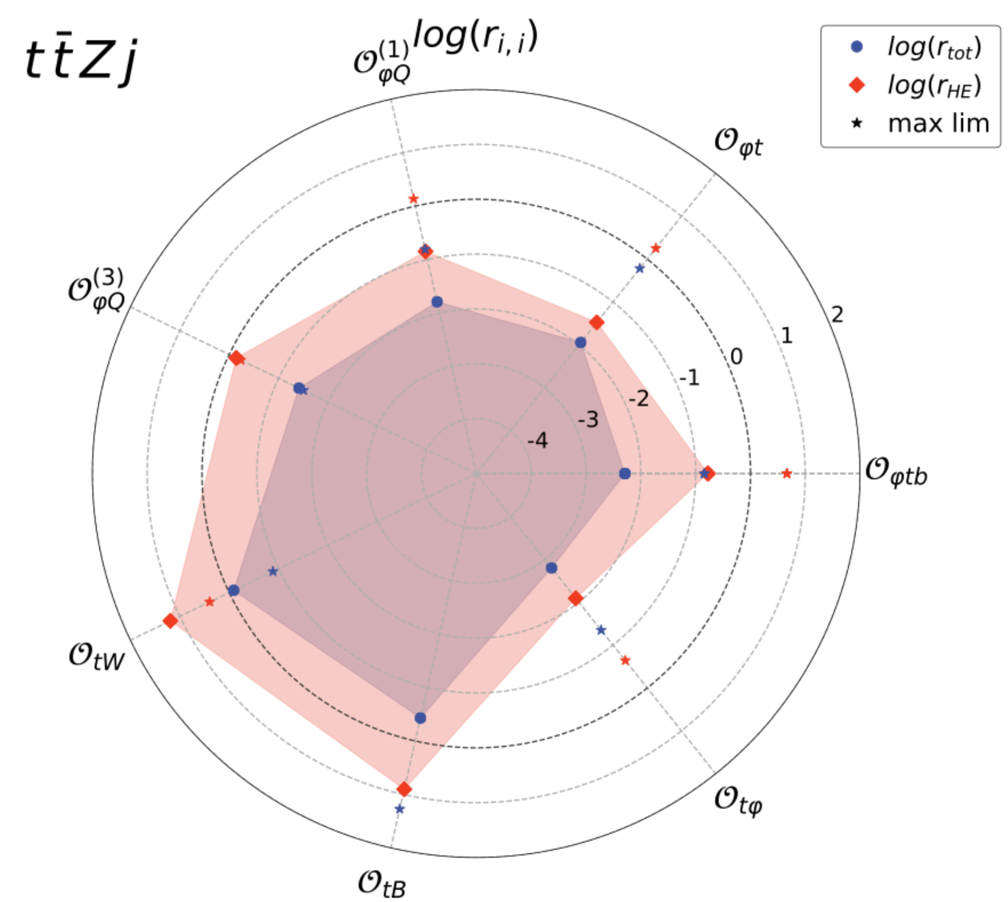
JHEP 12 (2021) 180

$$C_{tA} \equiv c_w C_{tB} + s_w C_{tW} = \frac{1}{s_w}\left(C_{tW} - c_w C_{tZ}\right)$$

Top electroweak couplings



JHEP 05 (2016) 052



JHEP 10 (2019) 004

ATLAS+CMS combination