ATLAS+CMS EFT combination

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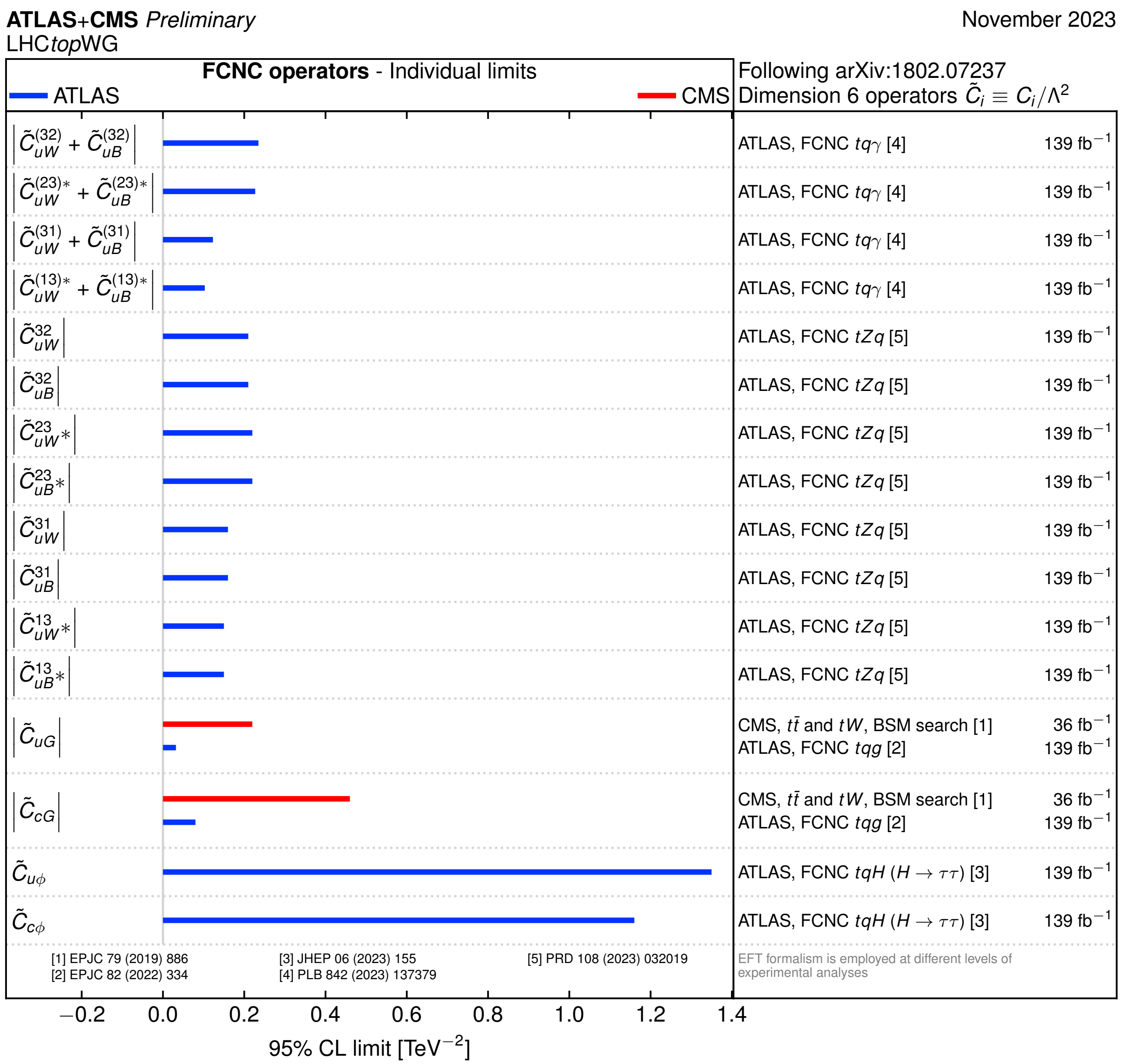
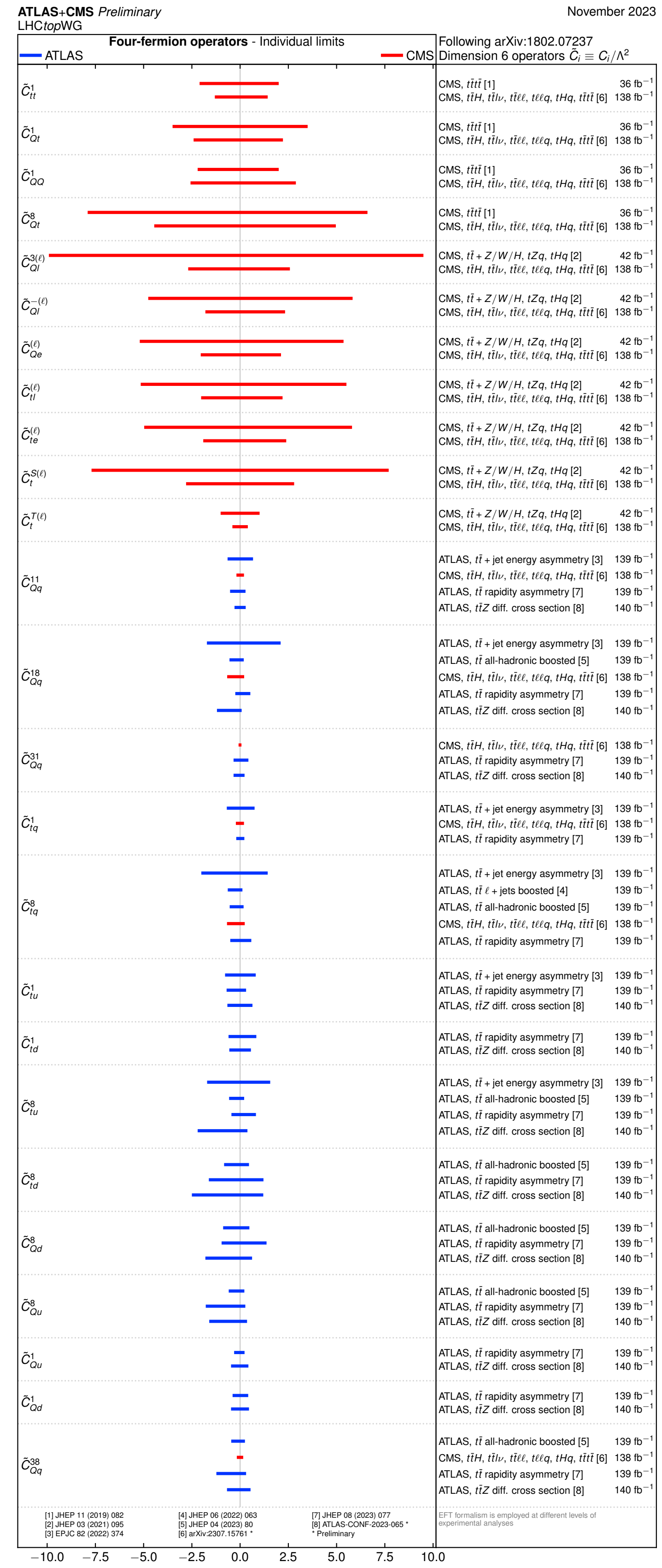
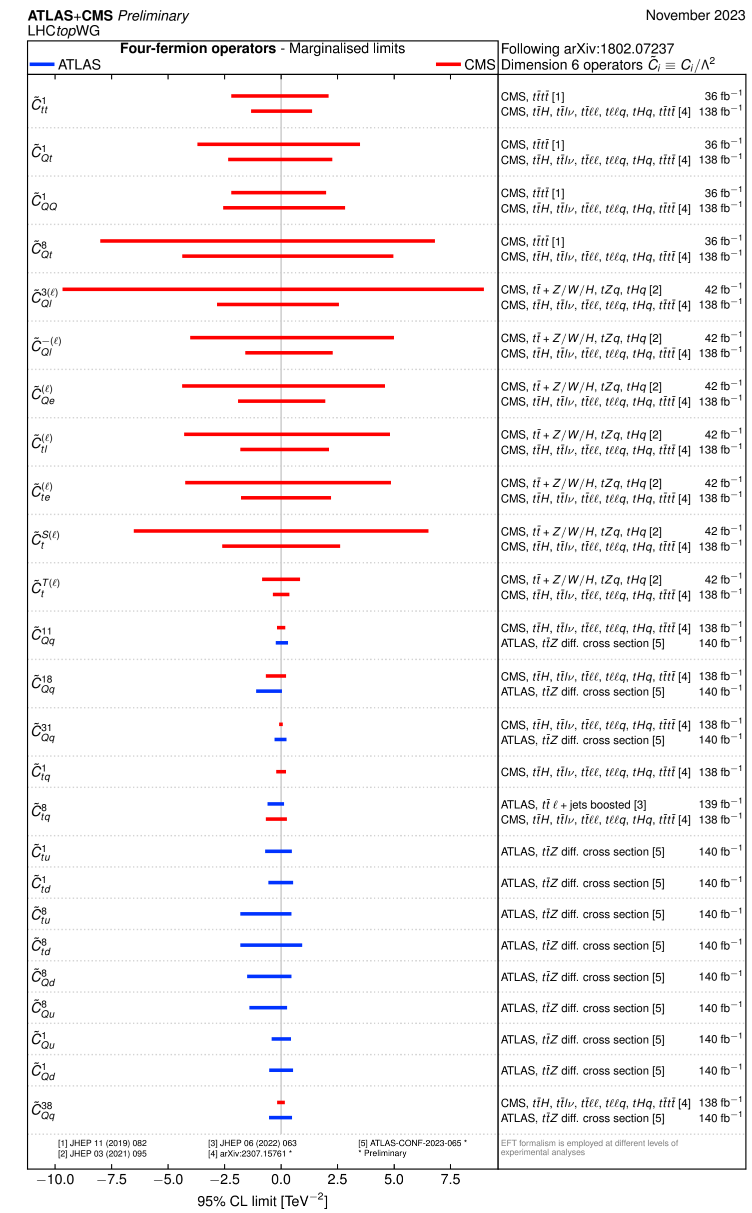
LHCtopWG meeting

Nov 29, 2023

LHC TOP EFT results

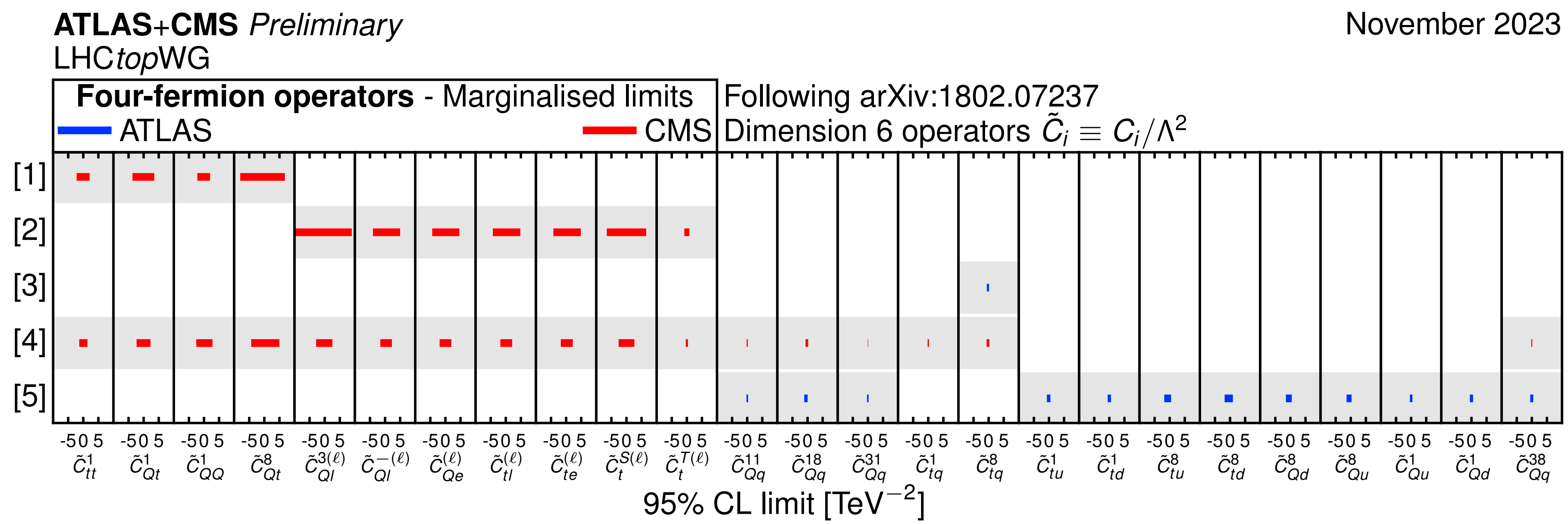




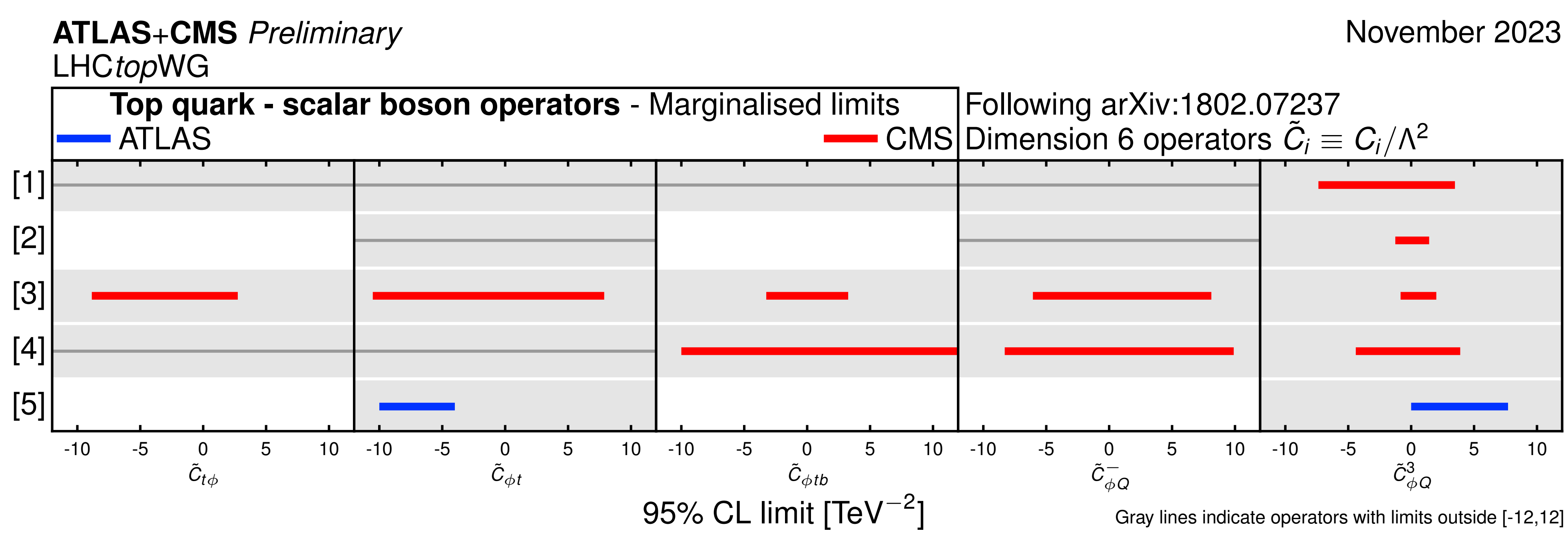


Fresh!

LHC TOP EFT results



[1] CMS, $t\bar{t}t\bar{t}$, JHEP 11 (2019) 082
[2] CMS, $t\bar{t}+Z/W/H$, tZq, tHq, JHEP 03 (2021) 095
[3] ATLAS, $t\bar{t}$ ℓ + jets boosted, JHEP 06 (2022) 063
[4] CMS, $t\bar{t}H$, $t\bar{t}l\nu$, $t\bar{t}\ell\ell$, $t\ell\ell q$, tHq, $t\bar{t}t\bar{t}$, arXiv:2307.15761 *
[5] ATLAS, $t\bar{t}Z$ diff. cross section, ATLAS-CONF-2023-065 *
* Preliminary



[1] CMS, $t\bar{t}+Z/W/H$, tZq, tHq, JHEP 03 (2021) 095
[2] CMS, tZq / $t\bar{t}Z$, JHEP 12 (2021) 083
[3] CMS, $t\bar{t}H$, $t\bar{t}l\nu$, $t\bar{t}\ell\ell$, $t\ell\ell q$, tHq, $t\bar{t}t\bar{t}$, arXiv:2307.15761 *
[4] CMS, $t\bar{t}$ + boosted Z/H, PRD 108 032008
[5] ATLAS, $t\bar{t}Z$ diff. cross section, ATLAS-CONF-2023-065 *
* Preliminary

Fresh!

How to combine?

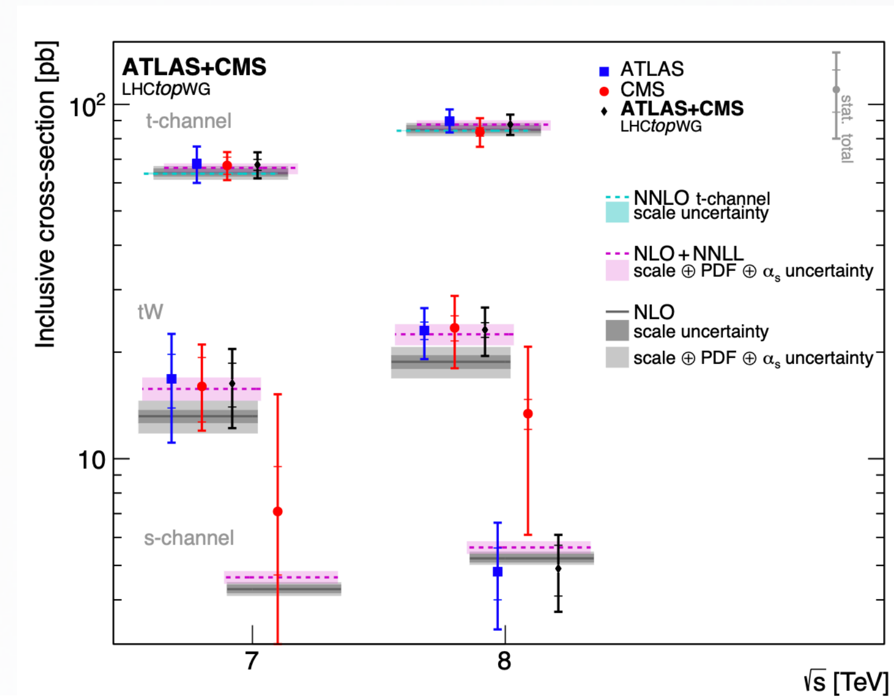
Combination story: Top

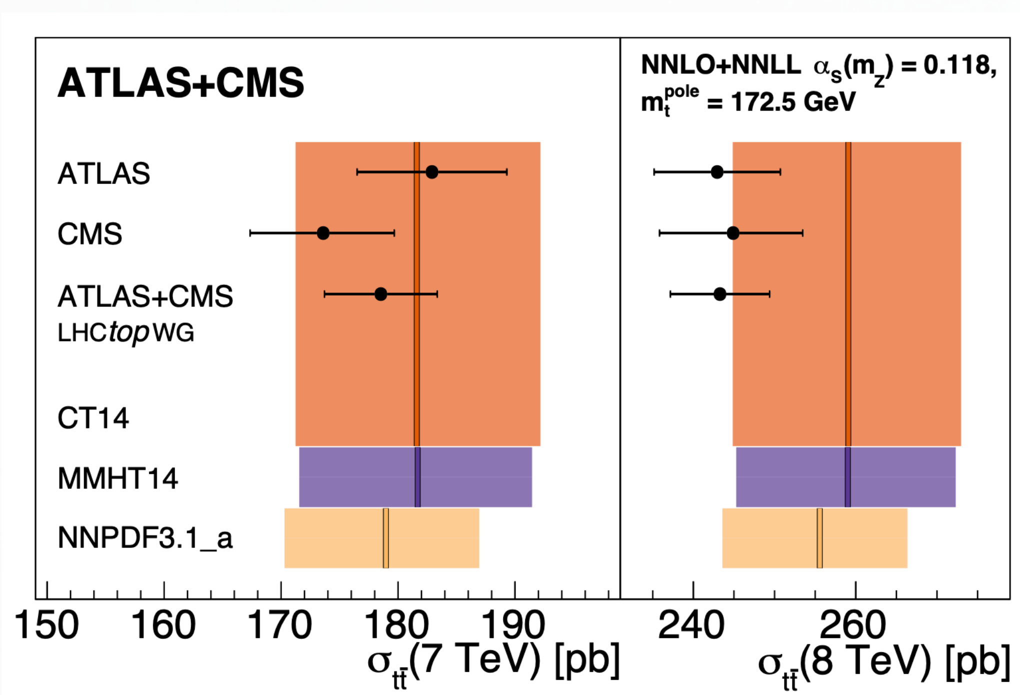
- Combinations of ATLAS and CMS results are steered by **LHCtopWG**
- Mainly based on best linear unbiased estimator (**BLUE**) and simplified-likelihood fits (**Convino**)
- **Many** dedicated efforts:
  - single top (Run I)
  - $t\bar{t}$ inclusive (Run I)
  - charge asymmetry (Run I)
  - W boson helicity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

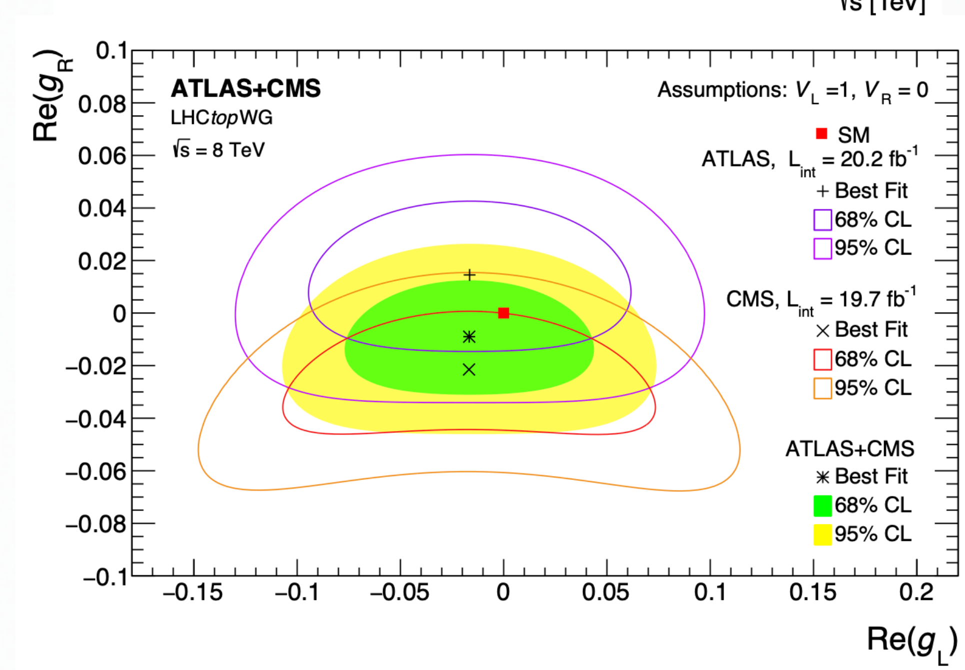
JHEP 05 (2019) 088

JHEP 07 (2023) 213

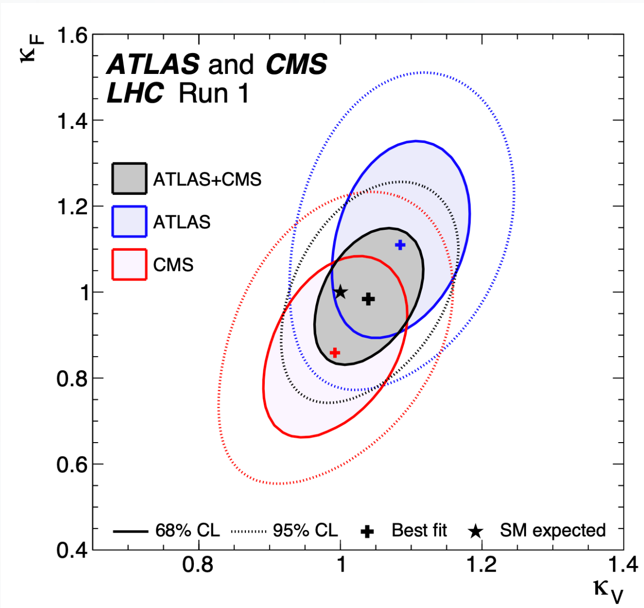
JHEP 08 (2020) 051

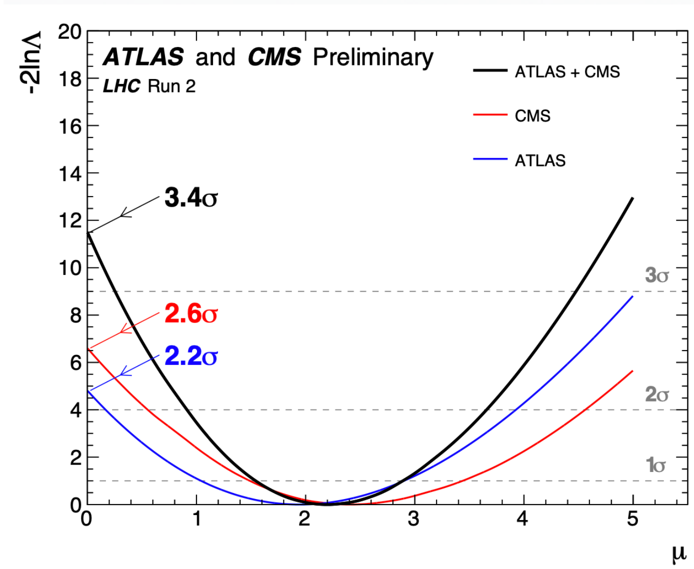


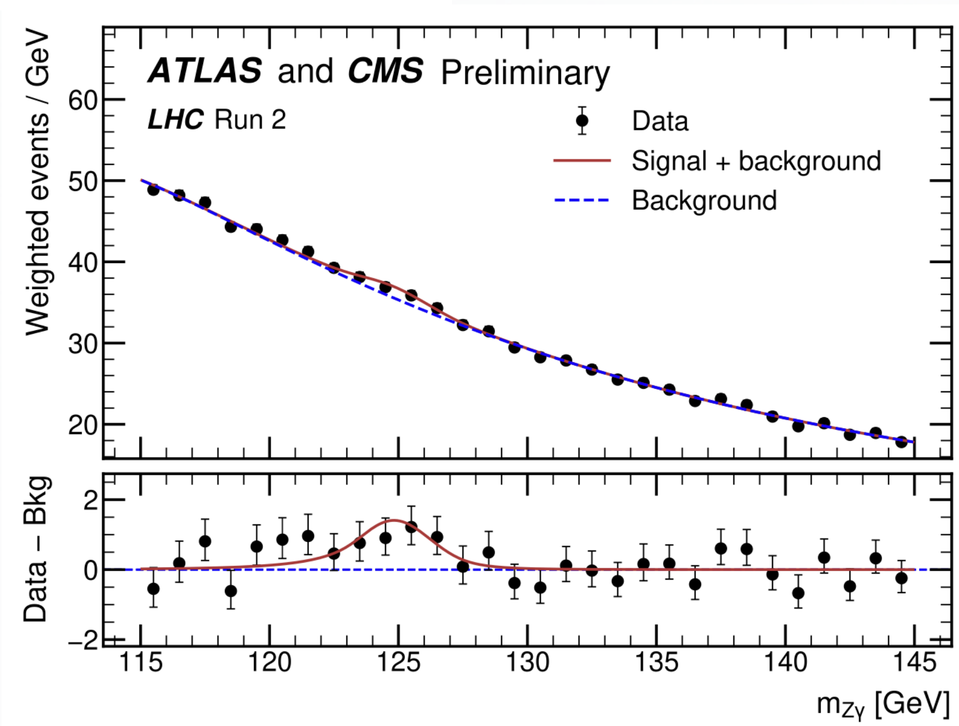




Combination story: Higgs







JHEP 08 (2016) 045

CMS-PAS-HIG-23-002

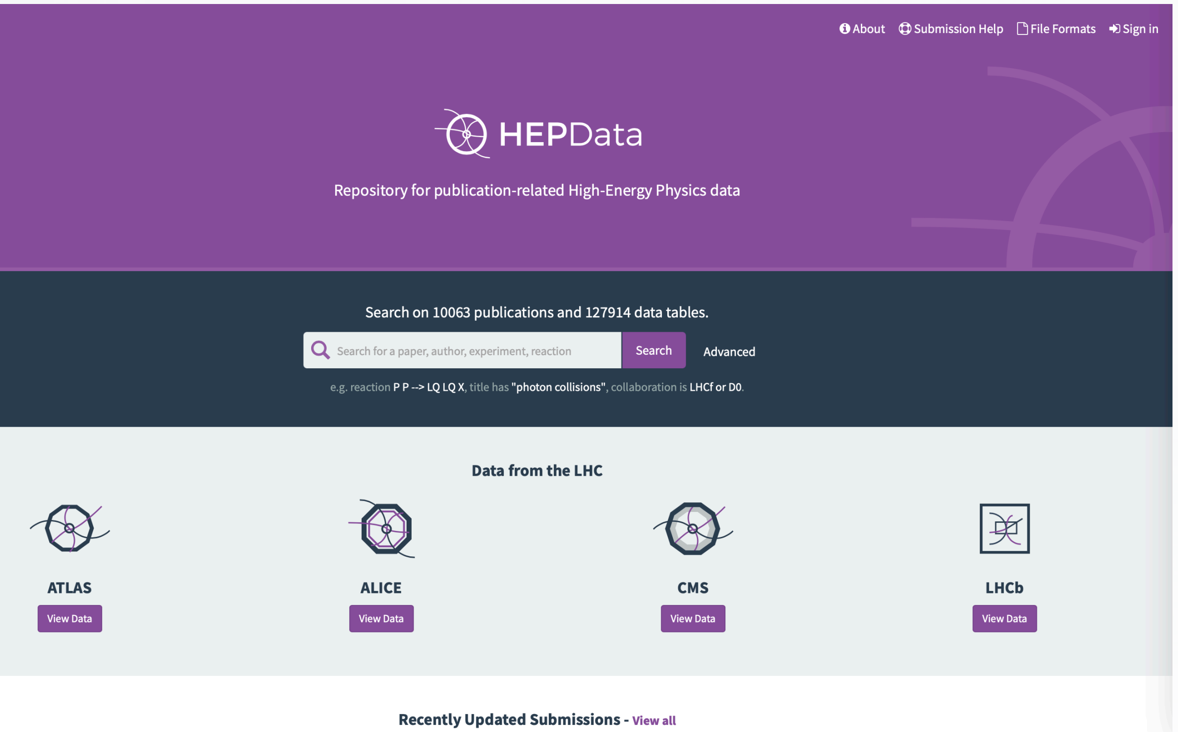
ATLAS-CONF-2023-025

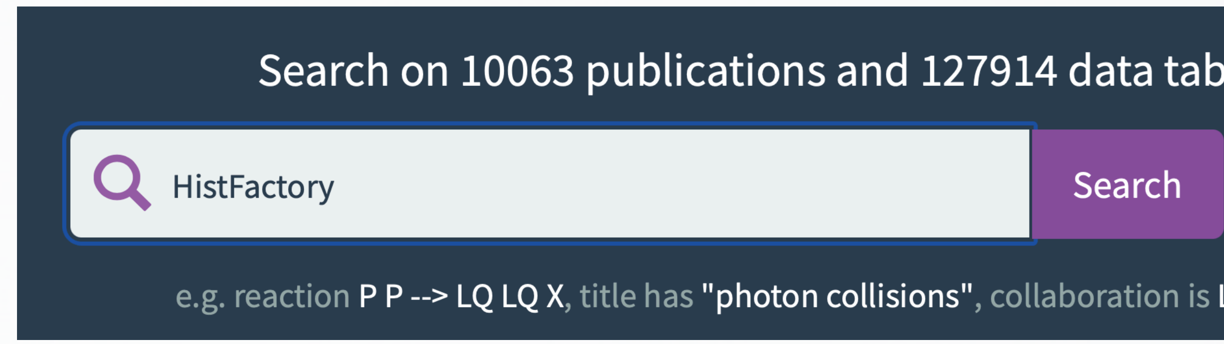
PRL 114 (2015) 191803

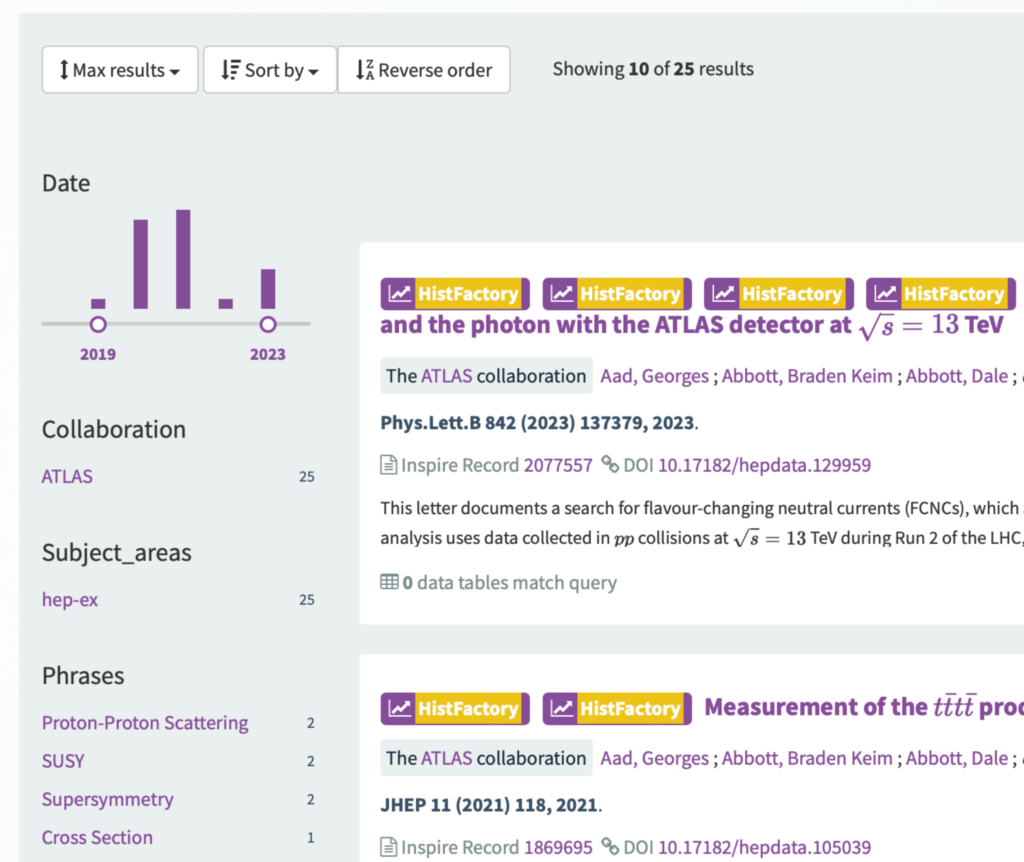
- Combinations of ATLAS and CMS results:
  - Higgs **mass** (Run I)
  - Higgs **couplings** (Run I)
  - $h \rightarrow Z\gamma$ (evidence in Run 2)
- Uses κ-framework formalism: ATLAS-PHYS-PUB-2011-11; CMS-NOTE-2011-005
- Built on **RooStats** workspaces with more than **4000** nuisance parameters (Higgs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

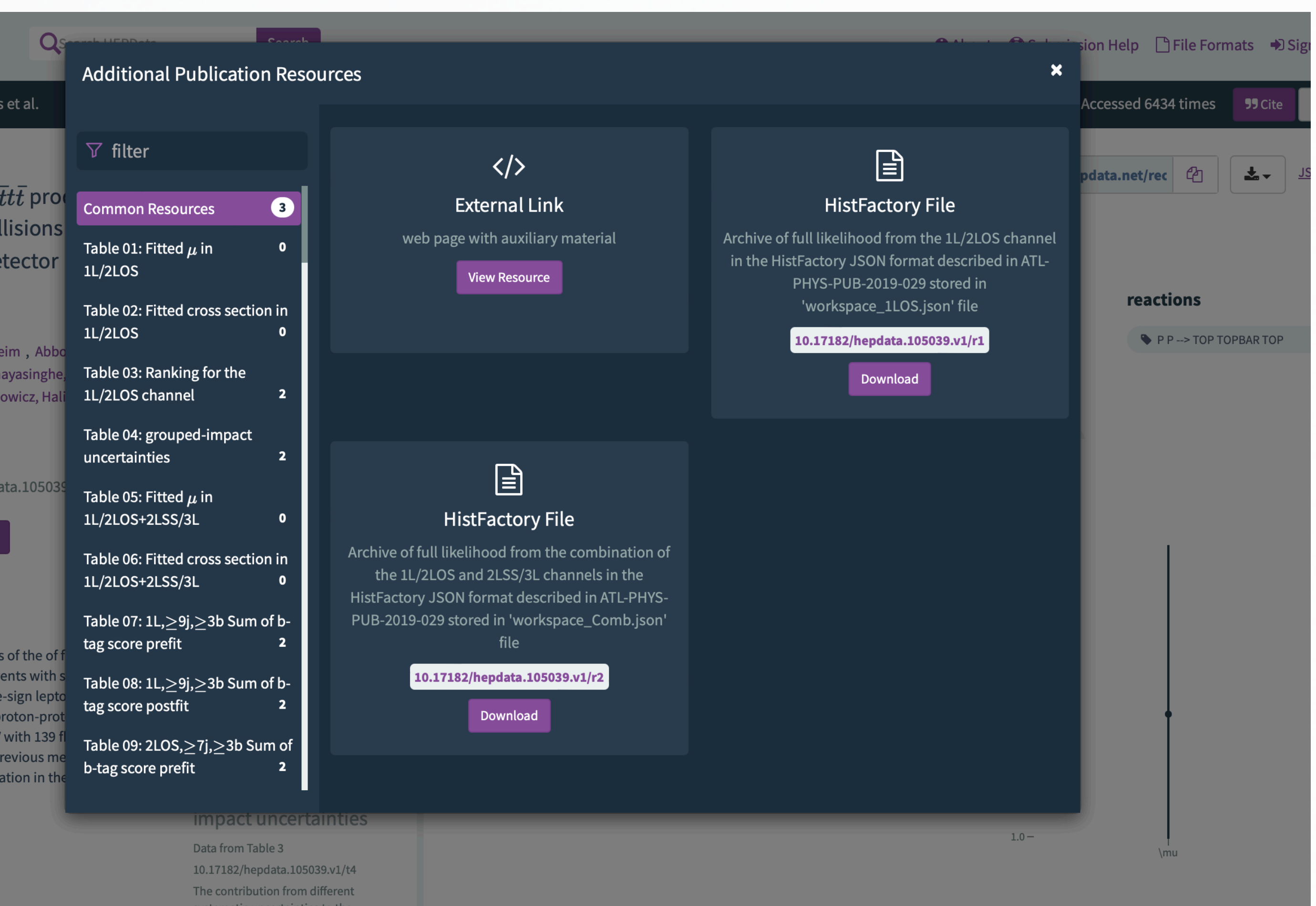
These fits are rather challenging, involving many parameters of interest and a very large number of nuisance parameters. All the fit results were independently cross-checked to a very high level of precision by ATLAS and CMS, both for the combination and for the individual results. In particular, fine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

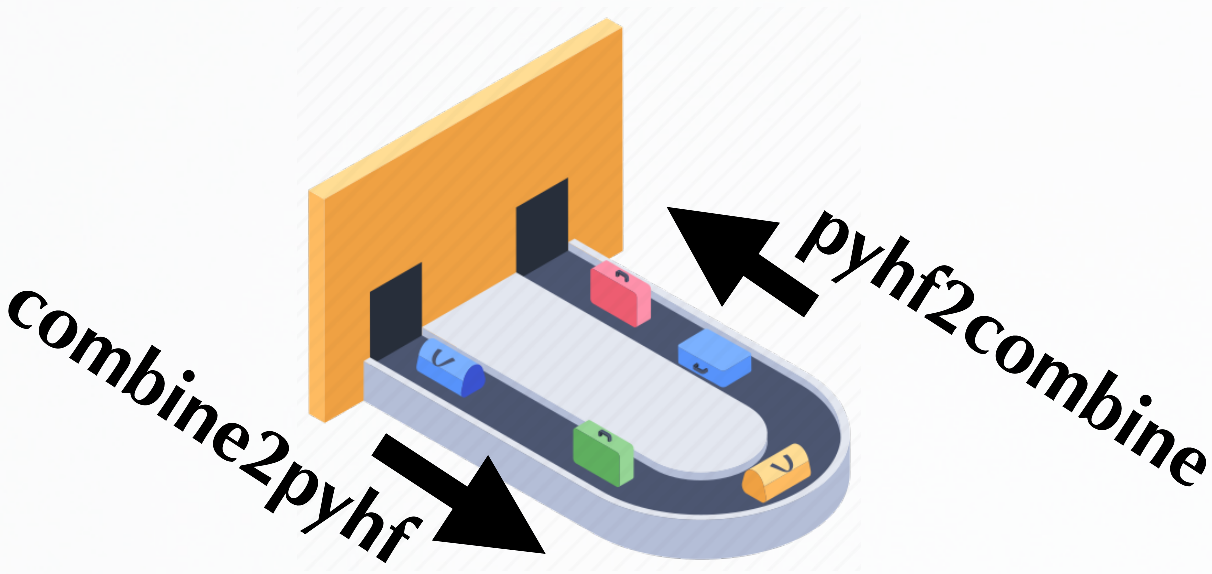
CMS Combine datacard: plain ASCII text + ROOT shape files

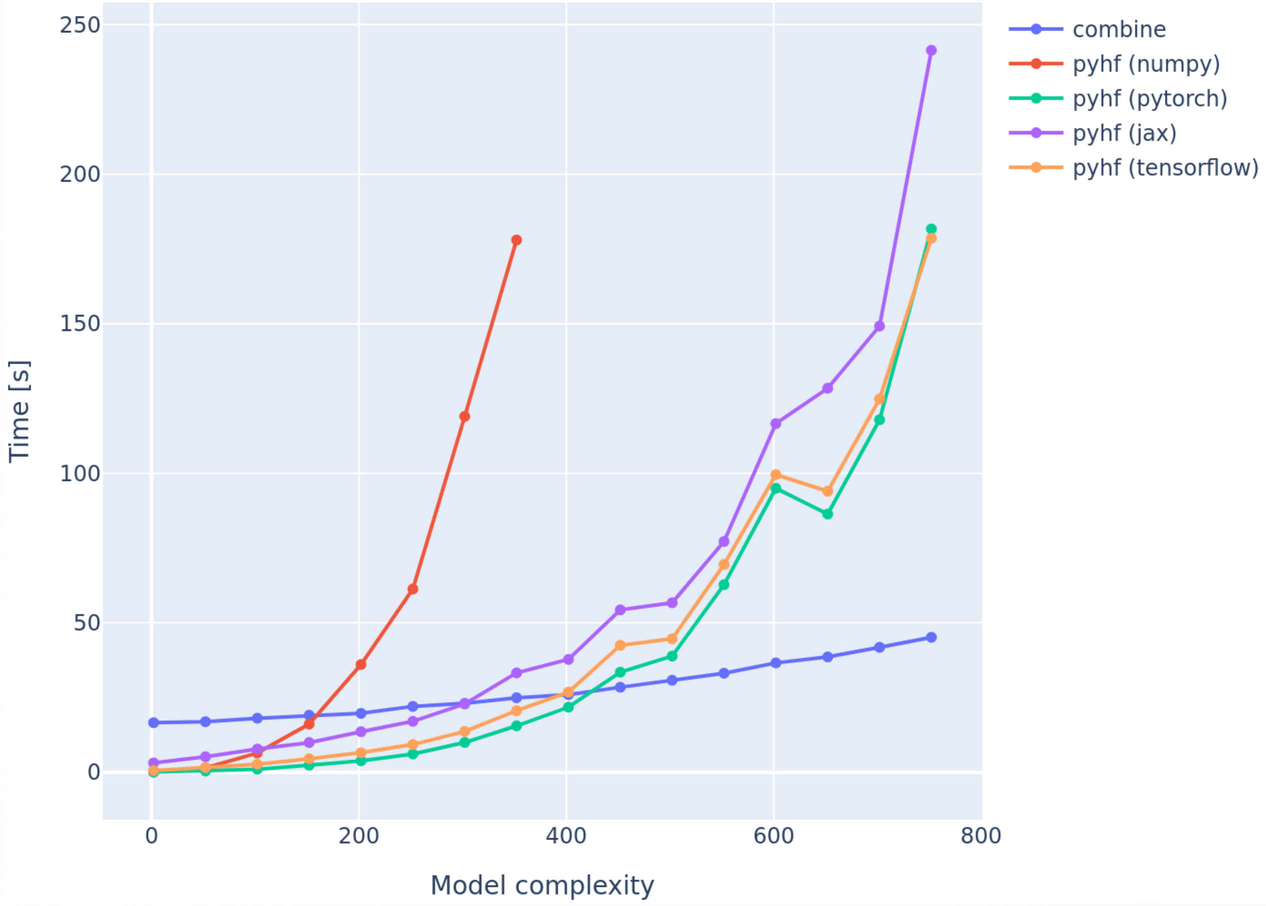
HistFactory JSON schema (**ATLAS** results)

```
{
    "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

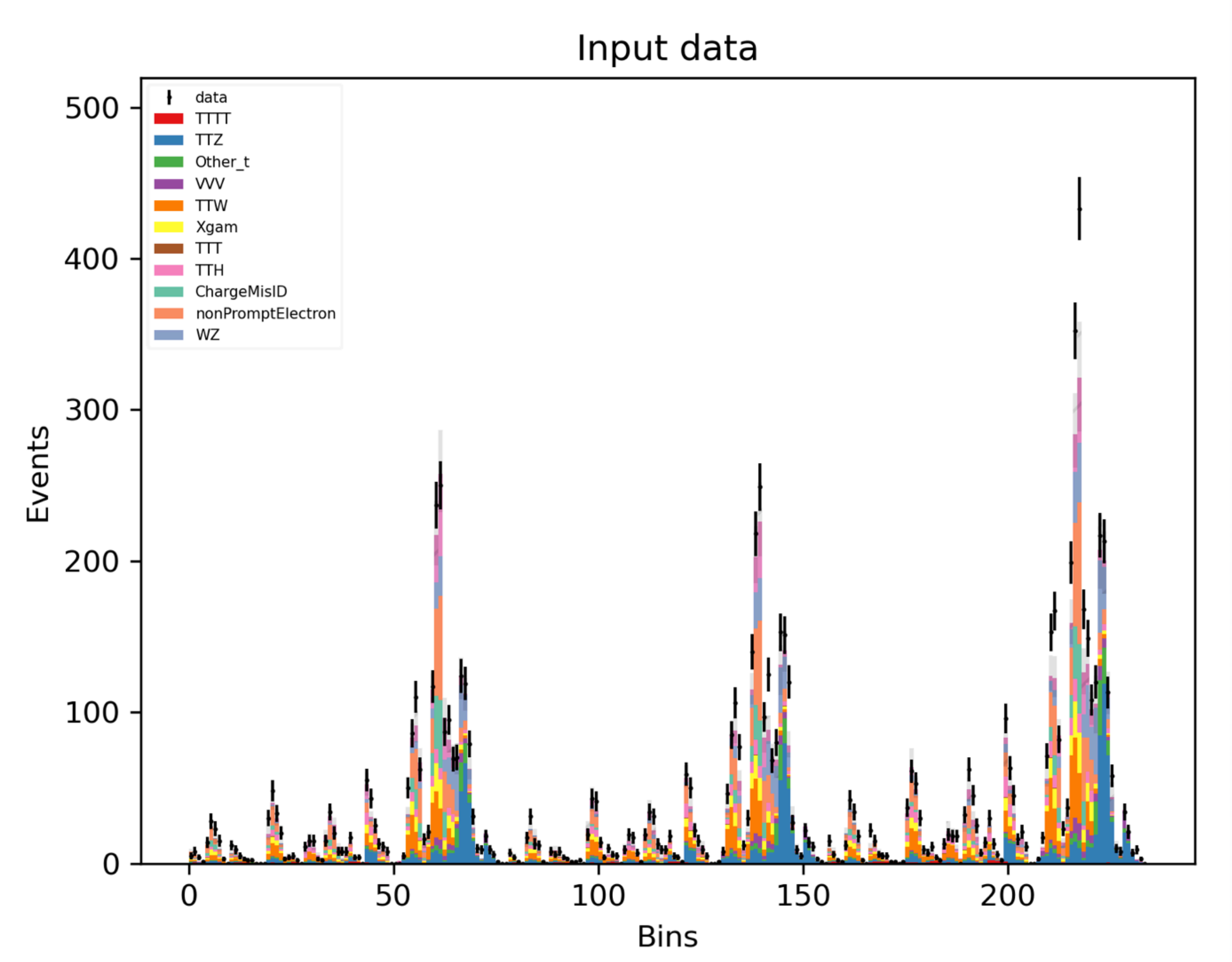


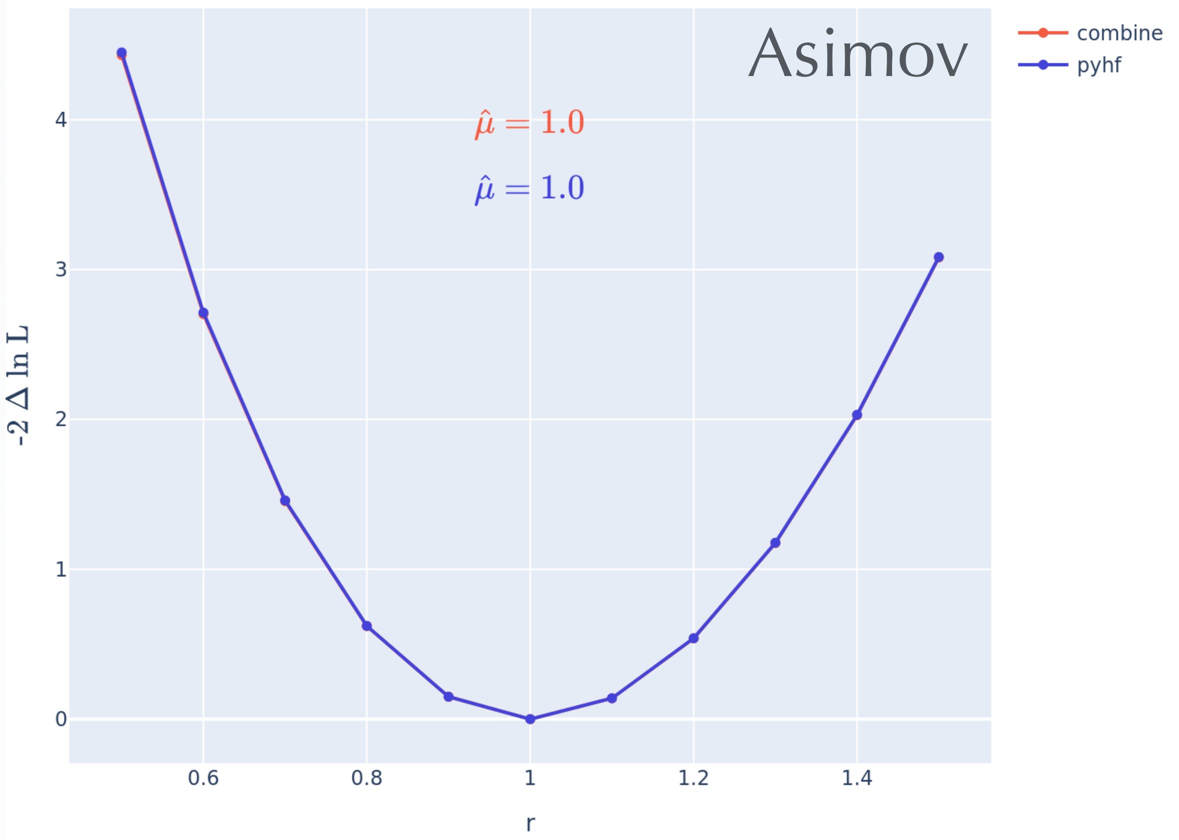


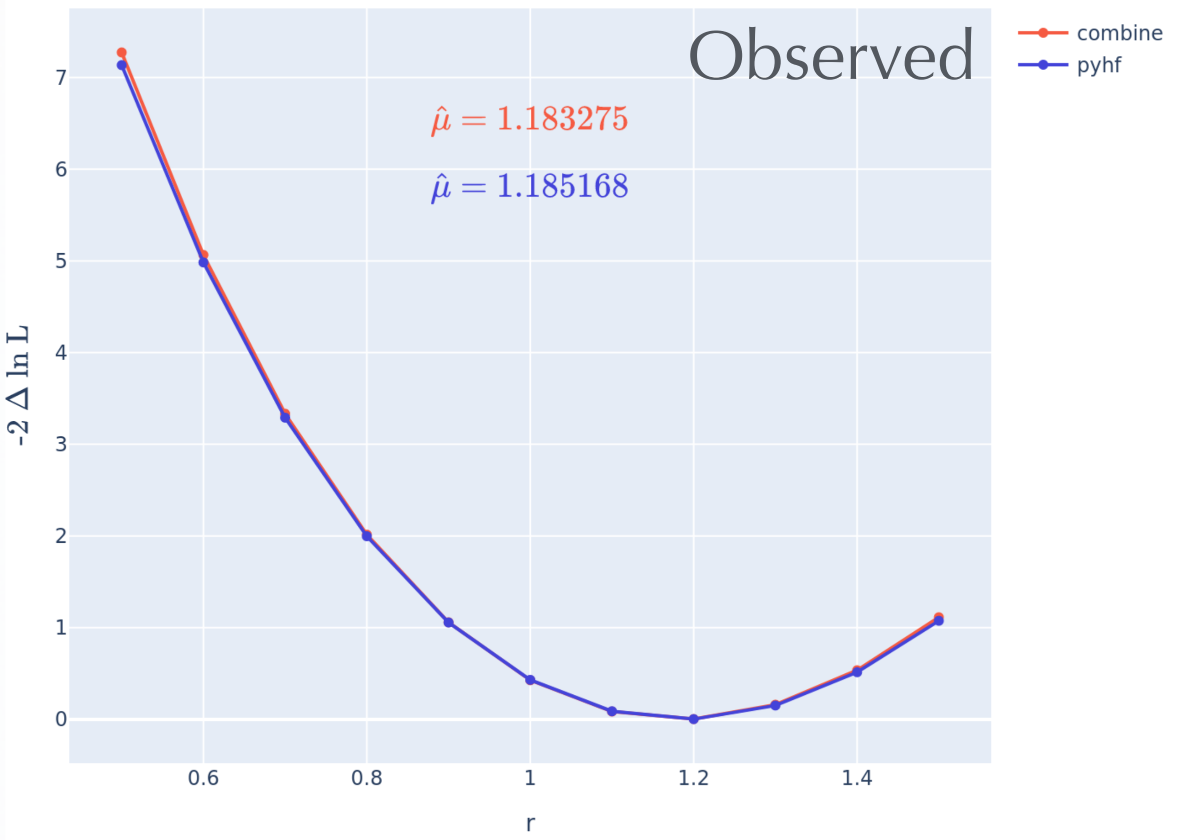
Looking forward to more inputs!

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

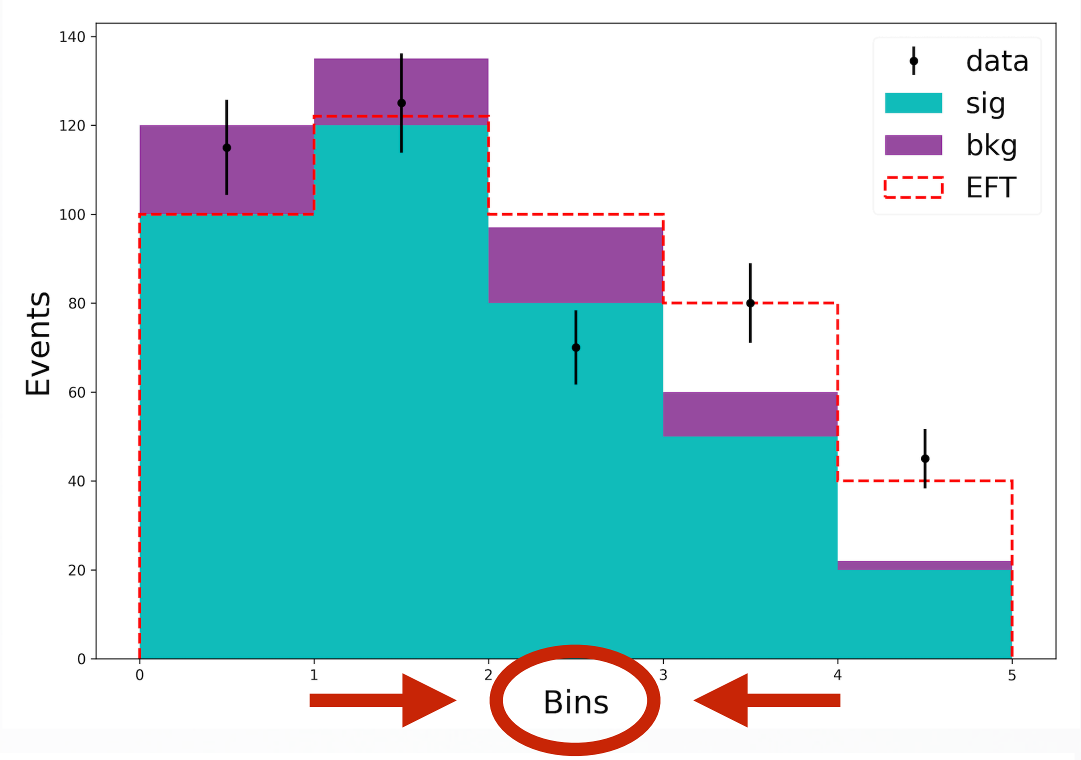


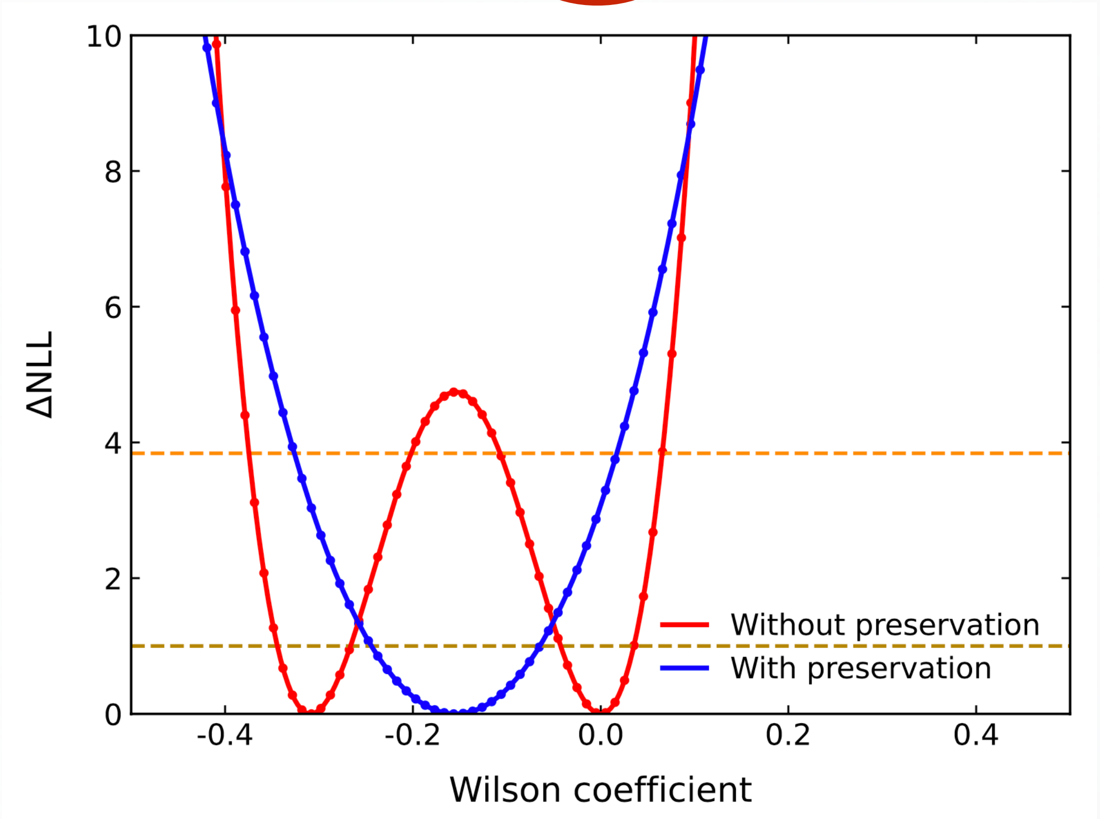




Observables and EFT

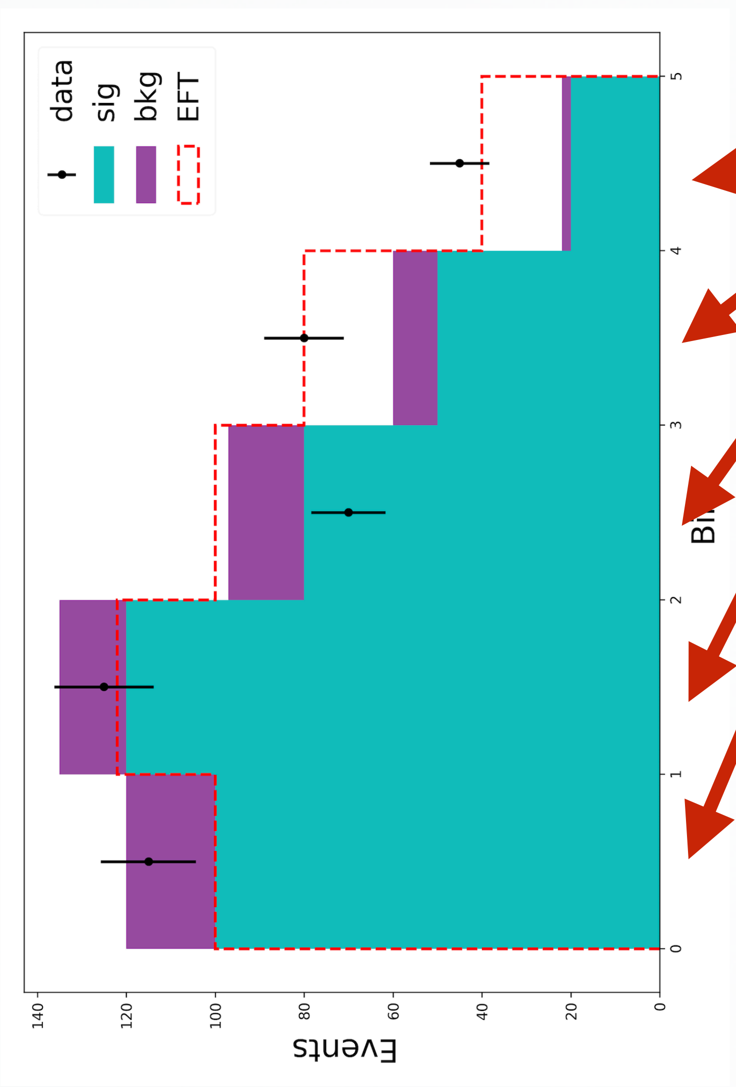
- Preservation of binned distributions with full experimental information **does not guarantee** its successful reinterpretation
- One needs to know **how** these bins were obtained
- Our studies have grown to become too complex - one simple kinematic observable is **not enough**
- Possible to describe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





Preserving EFT

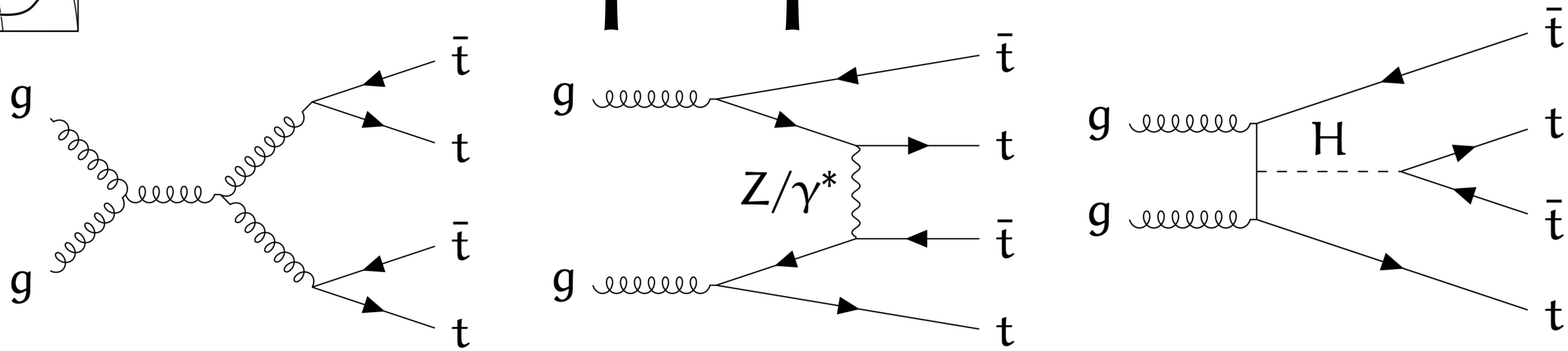
- **Parameterize EFT yield per bin** in the distribution of the fitted observable
- Dump the **coefficient matrix** as json, csv, etc.
- Remains **model-dependent** (as everything we do): can't modify any predictions when reinterpreting results



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

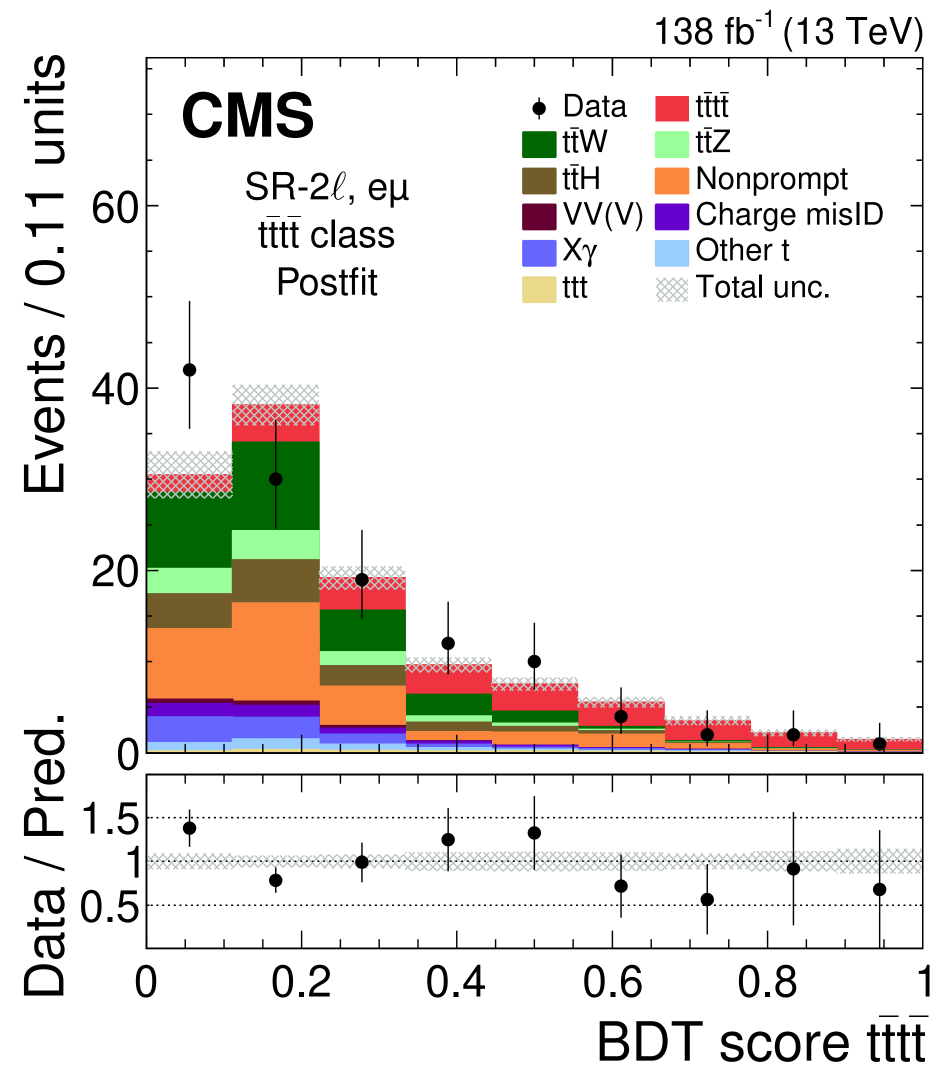
- Parametrization using **all relevant operators** is desirable
- Allows to reinterpret experimental result in a **given EFT model**
- Publish parametrization to **HEPData**?

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 ($t\bar{t}t\bar{t}$, $t\bar{t}V$, $t\bar{t}$)

arXiv:2305.13439 (Submitted to PLB)



arXiv:2212.03259

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

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

S = 5.6σ (4.9σ)

Top quartet

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

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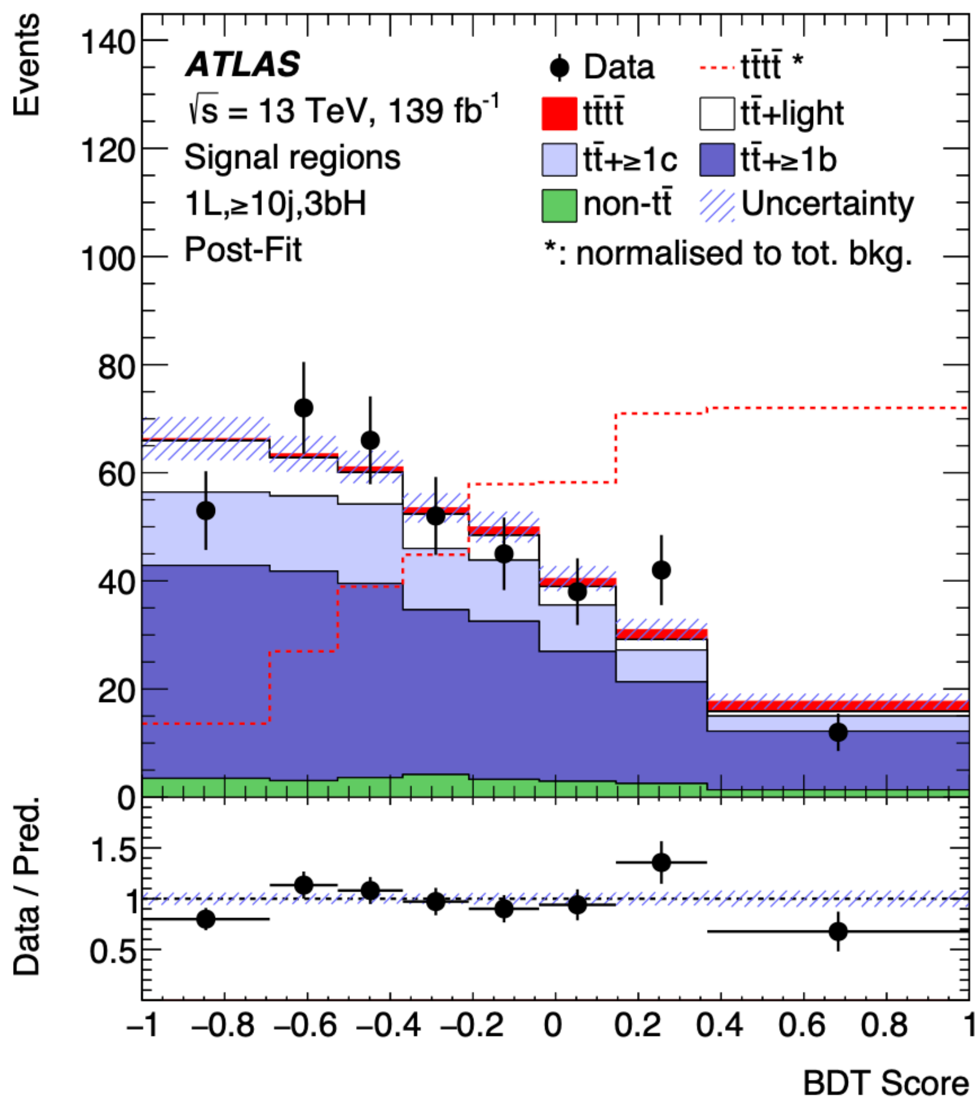

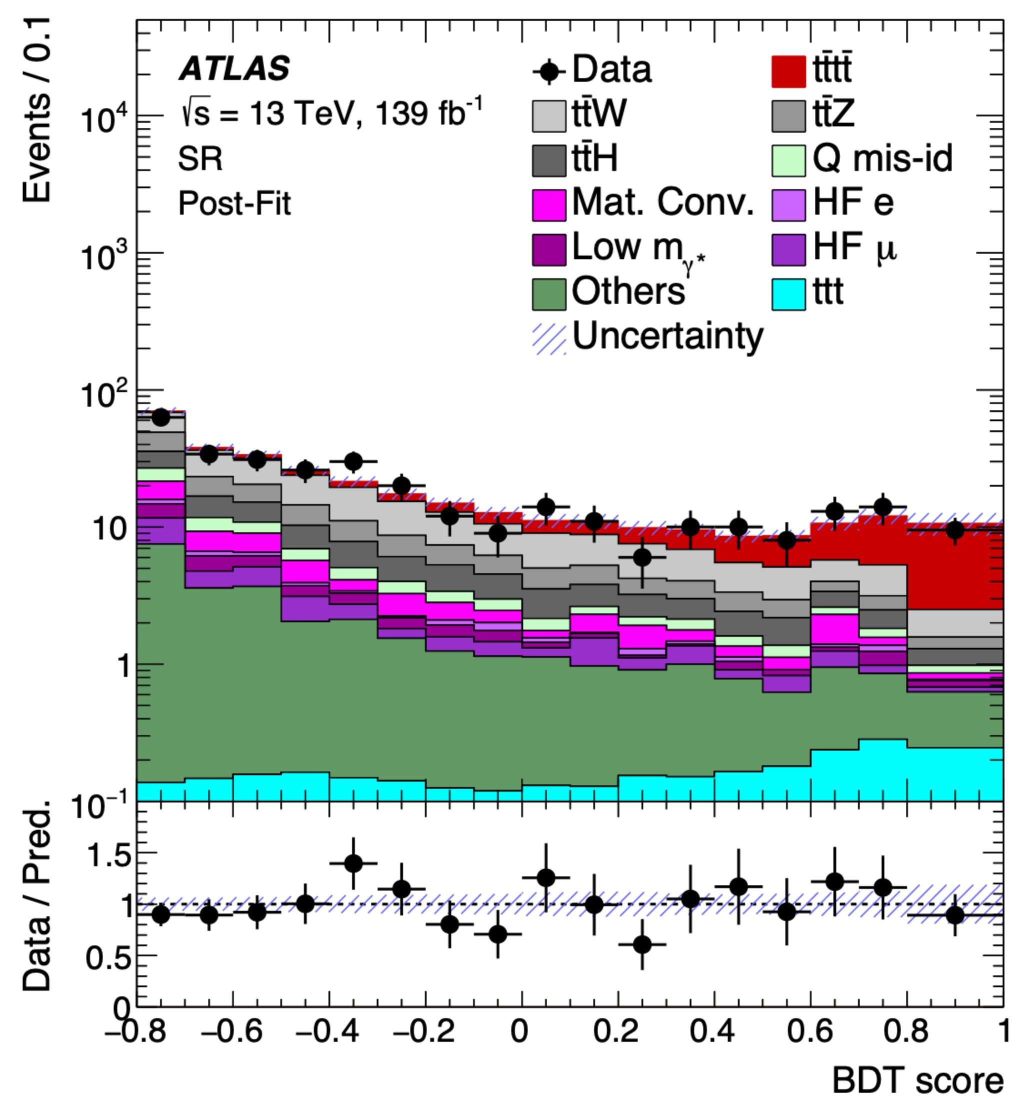

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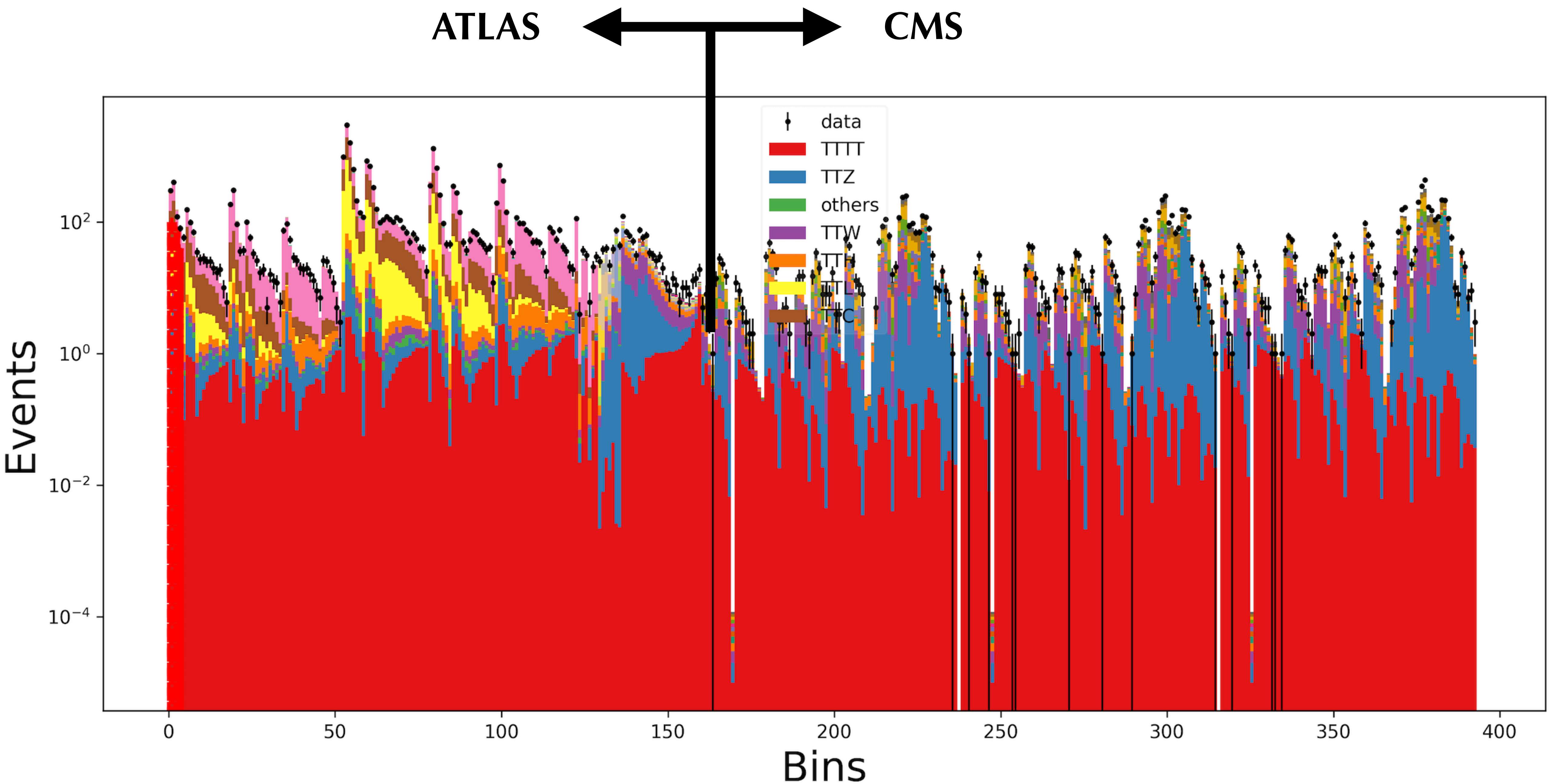
$$\sigma_{t\bar{t}t\bar{t}} = 24\ \pm 4\,(\text{stat})\,^{+5}_{-4}\,(\text{syst})\ \text{fb}$$

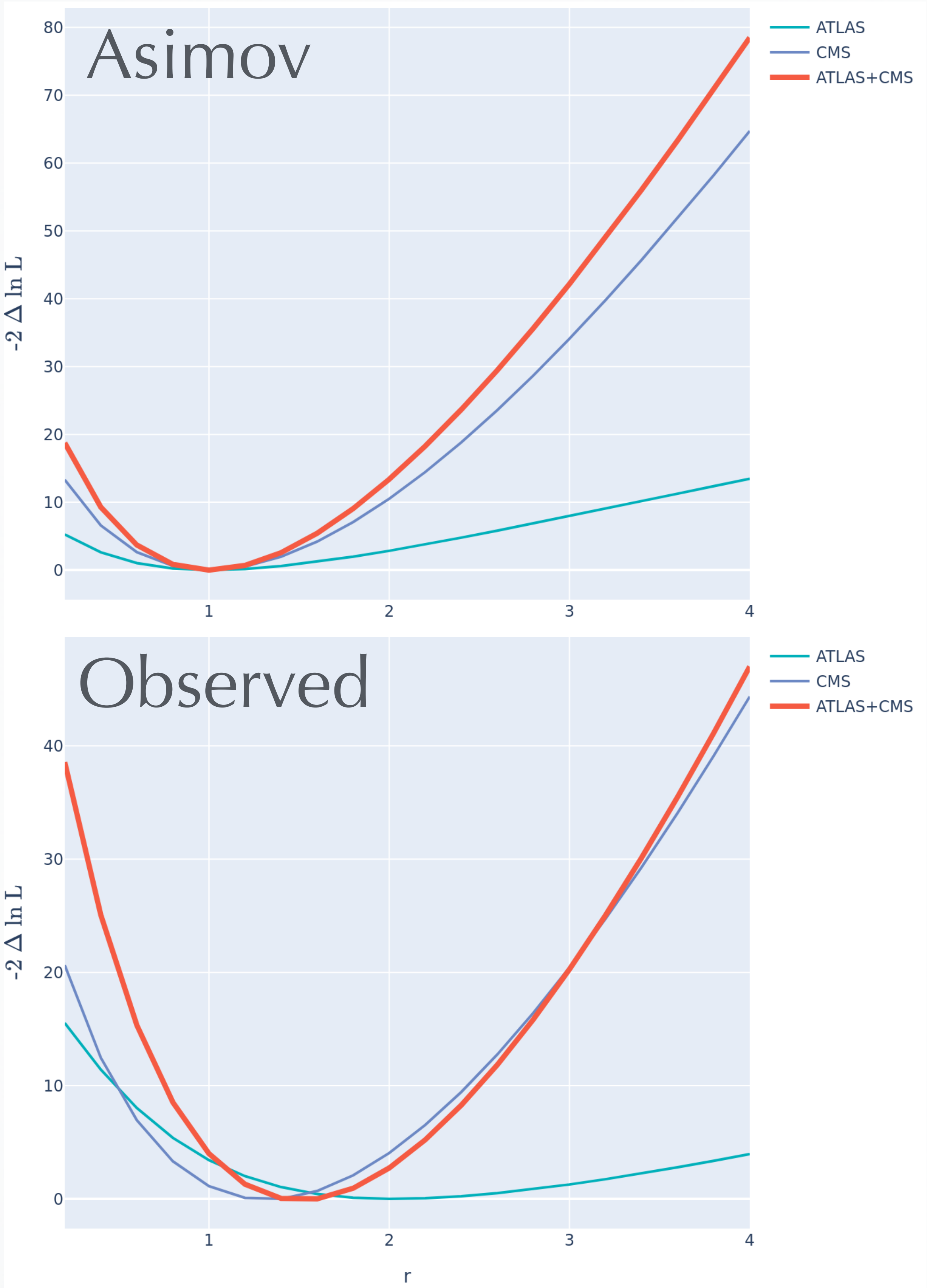
S = 4.7σ (2.6σ)

ATLAS+CMS: Four tops



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

Four top re-observation

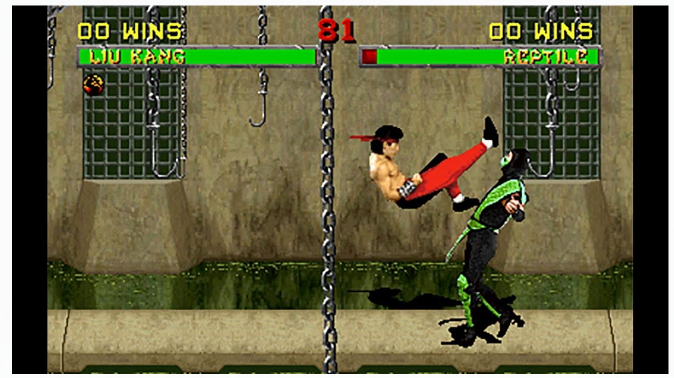


- **Still observing** four tops after combining CMS with ATLAS
- **But** now at $7.6\,\sigma$
- Will be even more σ's when combined with the **ATLAS observation** result
- Approach for **ATLAS+CMS combination**:
  - **Correlate** main physics processes: $t\bar{t}t\bar{t}$, $t\bar{t}W$, $t\bar{t}Z$, $t\bar{t}h$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

Correlating uncertainties

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

Correlating uncertainties



- Process modelling
  - signal
  - background #1
  - background #2
- Leptons
  - electrons
  - muons
  - taus
- Jets
  - light jets
  - b jets
  - c jets
- E_T^{miss}
  - corrections/filters
  - jet energy scale
- Luminosity
  - year-by-year uncorr.
  - corr.
- Pileup
  - cross section
  - reweighting
- Data-driven

Correlating uncertainties

We are here

- Process modelling
  - signal
    - ISR
    - FSR
    - parton shower
    - normalization
  - background #1
  - background #2
- Leptons
  - electrons
    - ID efficiency
    - resolution
    - scale
  - muons
  - taus
- Jets
  - light jets
    - source #1
    - source #2
    - source #3
    - …
    - source #100
  - b jets
  - c jets
  - corrections/filters
- E_T^{miss}
  - jet energy scale
- Luminosity
  - year-by-year uncorr.
    - source #1
    - source #2
    - source #3
    - …
    - source #100
  - corr.
- Pileup
- Data-driven
  - cross section
  - reweighting

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

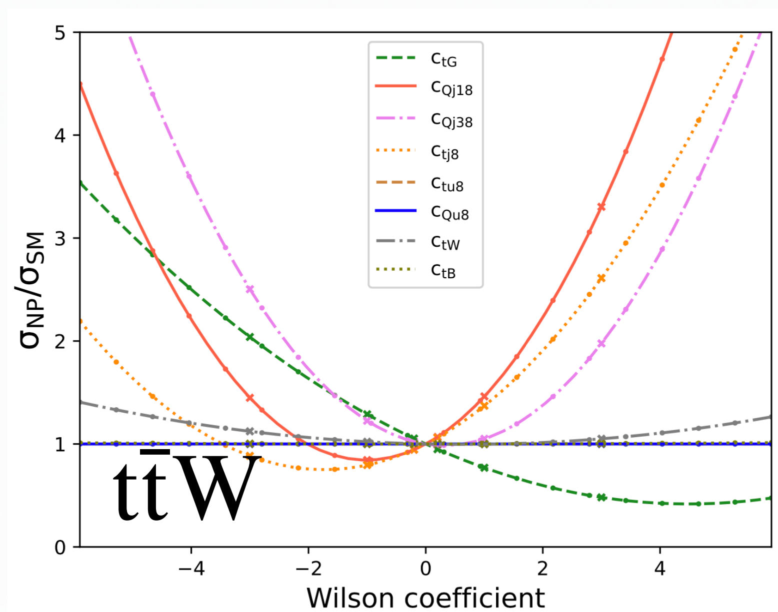
≈ 500 nuisance parameters per analysis

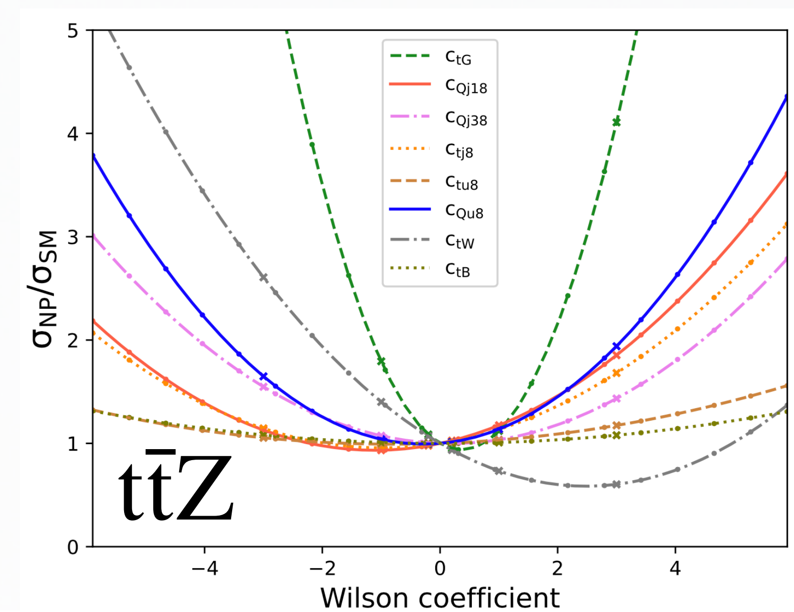
Correlating uncertainties

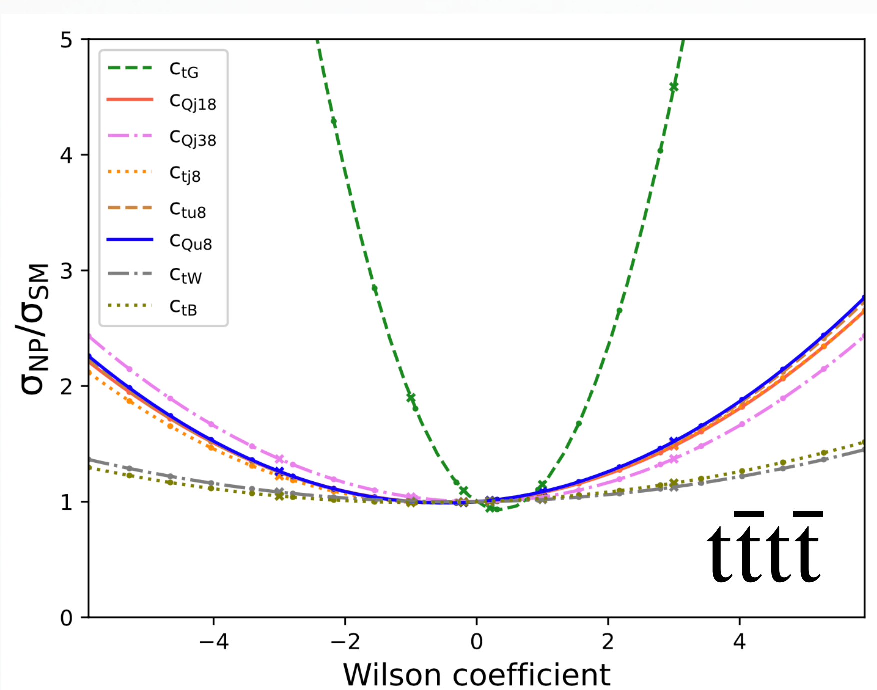
- It would be great to have a **common naming convention** for specifying nuisance parameters in a published result
- **Centralize** the description of the most common set of nuisances?
- Provide an **additional dictionary** to HEPData?
- Need to keep track of **evolution** of systematics with time

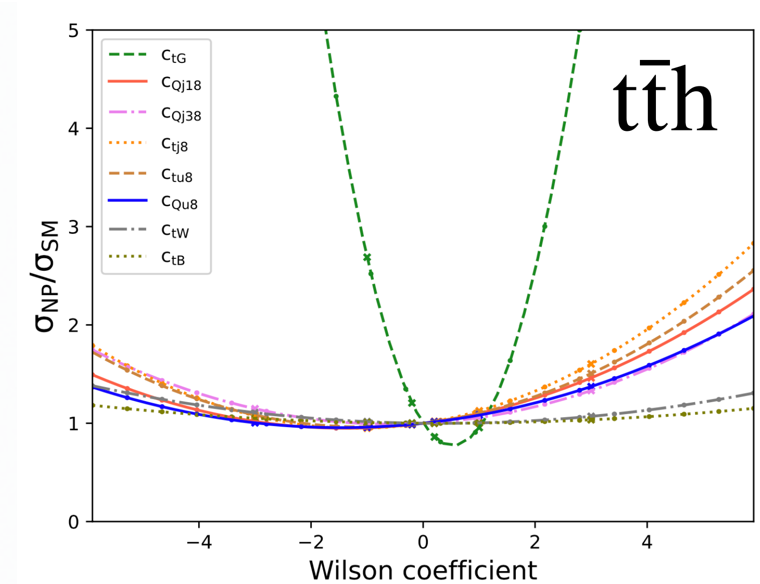
Parametrization

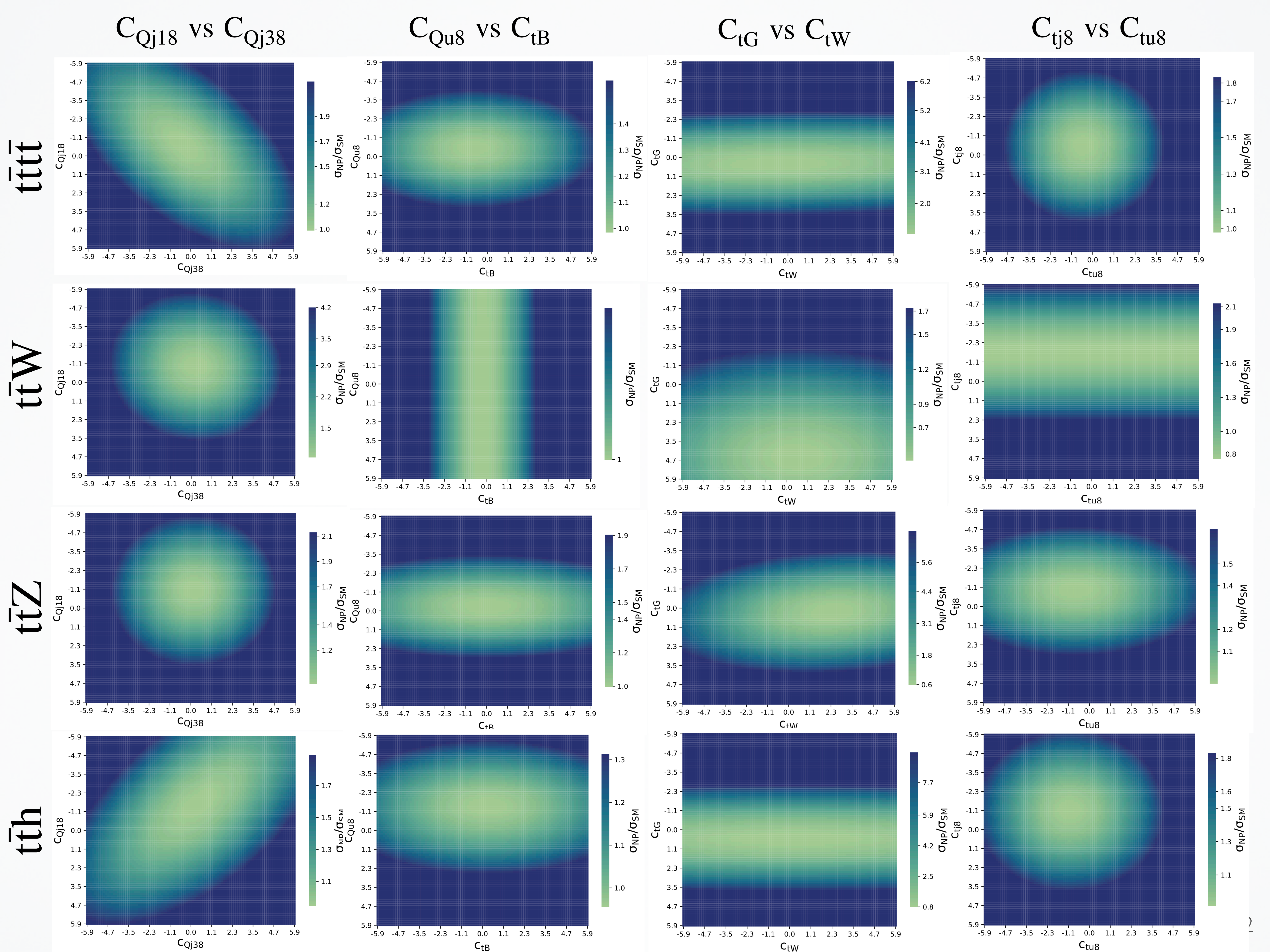
- **Proof-of-concept study**: focus on **8 EFT operators** affecting **signal** and **backgrounds**
- **Not yet including** four-fermion operators nor CP-violation
- Include **quadratic** and **linear** terms
- Experimental observables are not reproducible → modify signal and backgrounds by the **EFT-modified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







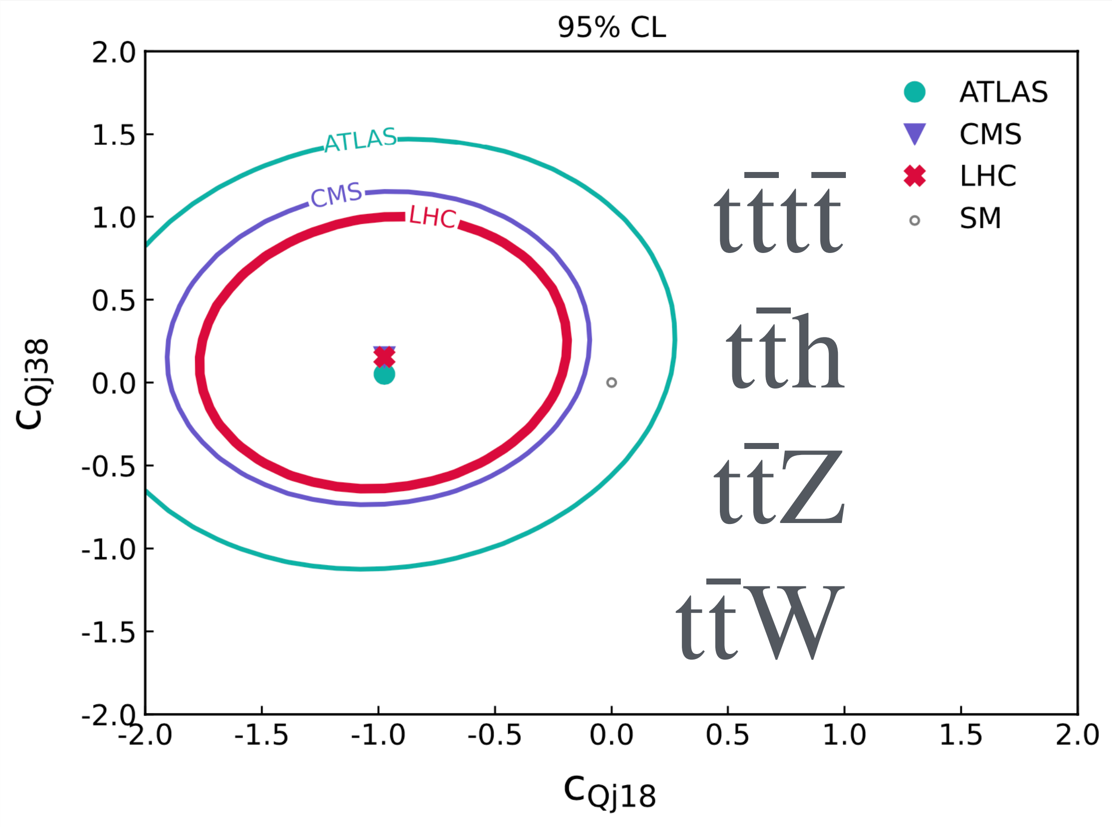


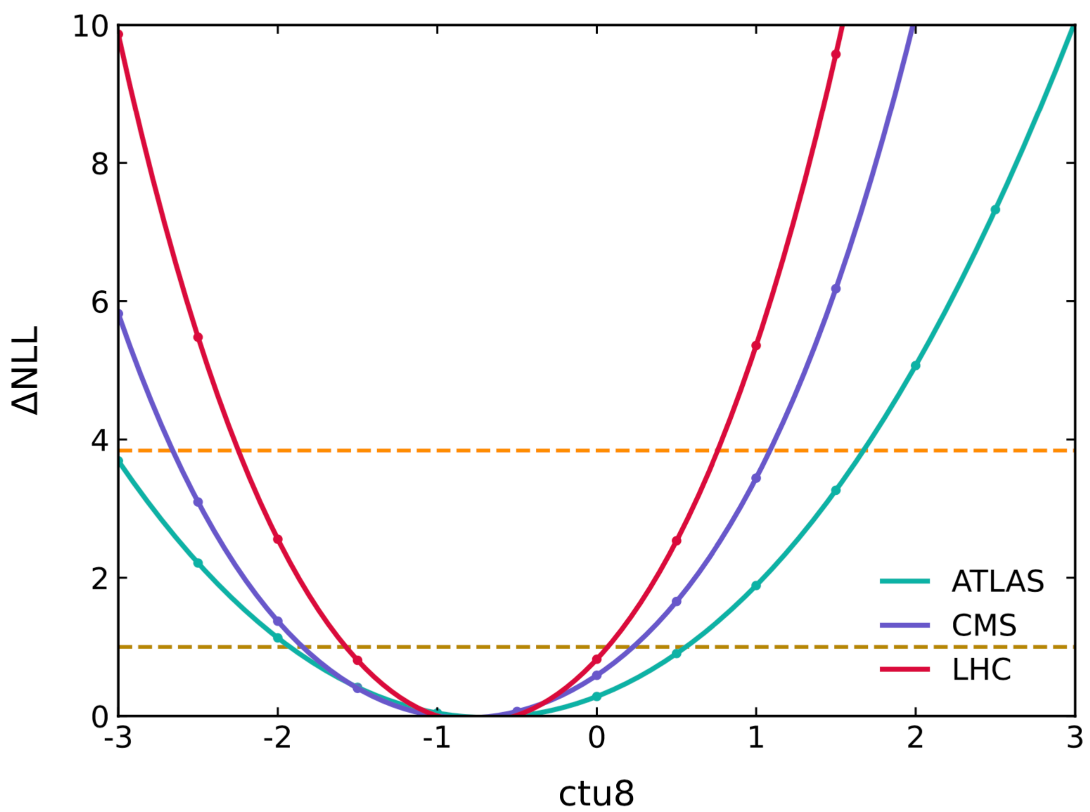


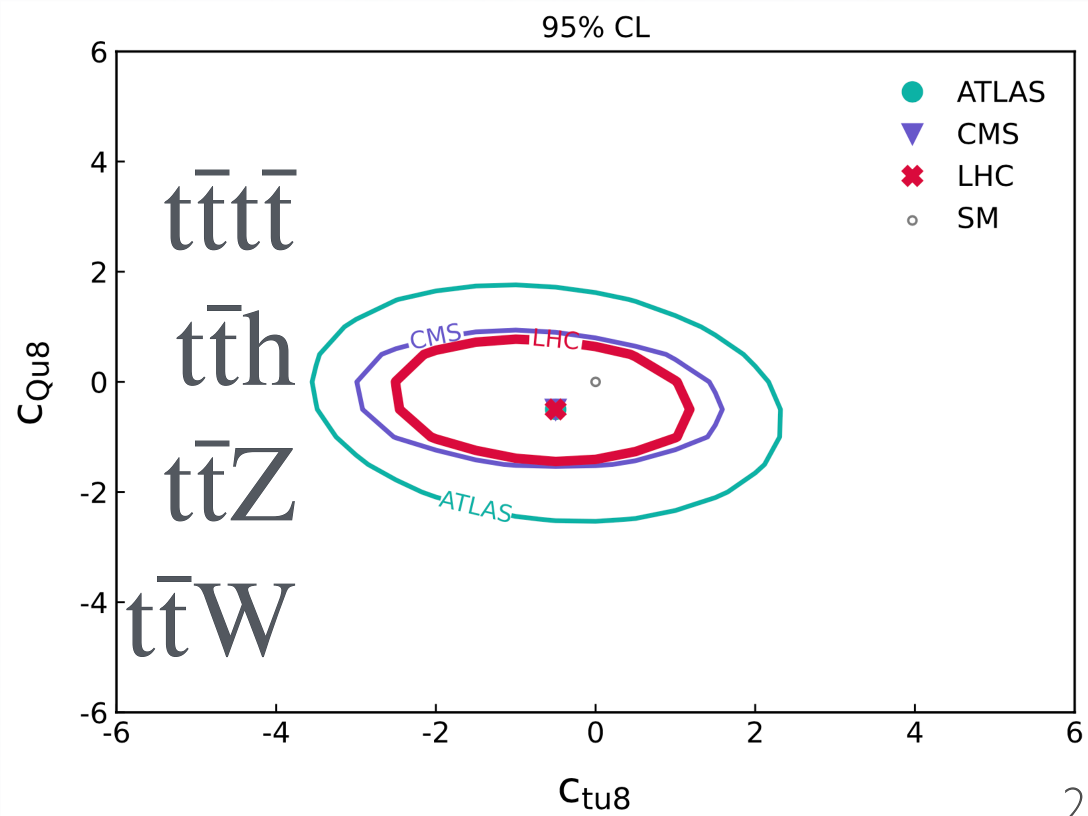
C_{Qj18} vs C_{Qj38}
C_{Qu8} vs C_{tB}
C_{tG} vs C_{tW}
C_{tj8} vs C_{tu8}
$t\bar{t}t\bar{t}$
$t\bar{t}W$
$t\bar{t}Z$
$t\bar{t}h$
σ_{NP}/σ_{SM}

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**

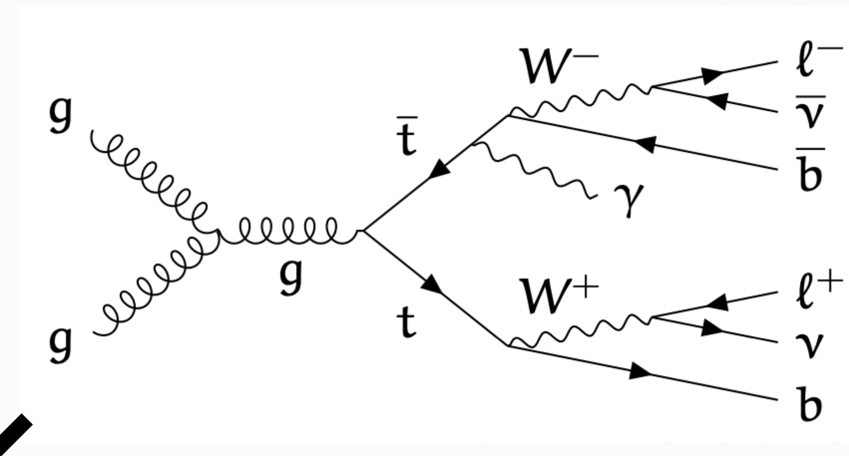


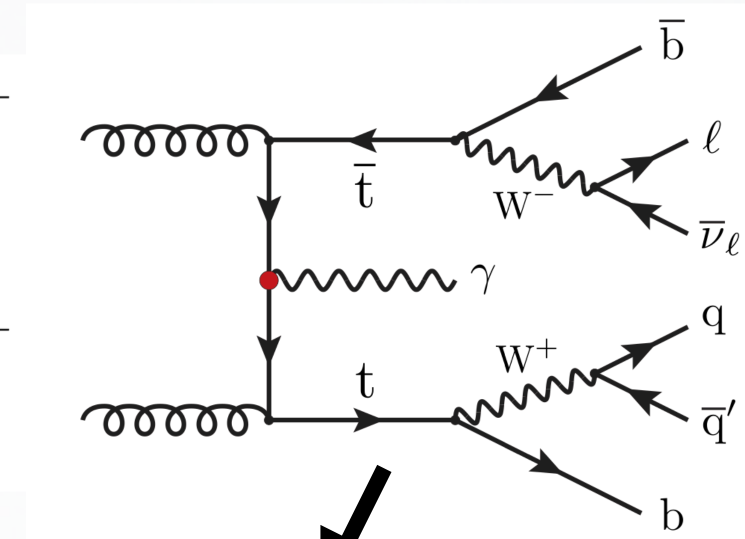


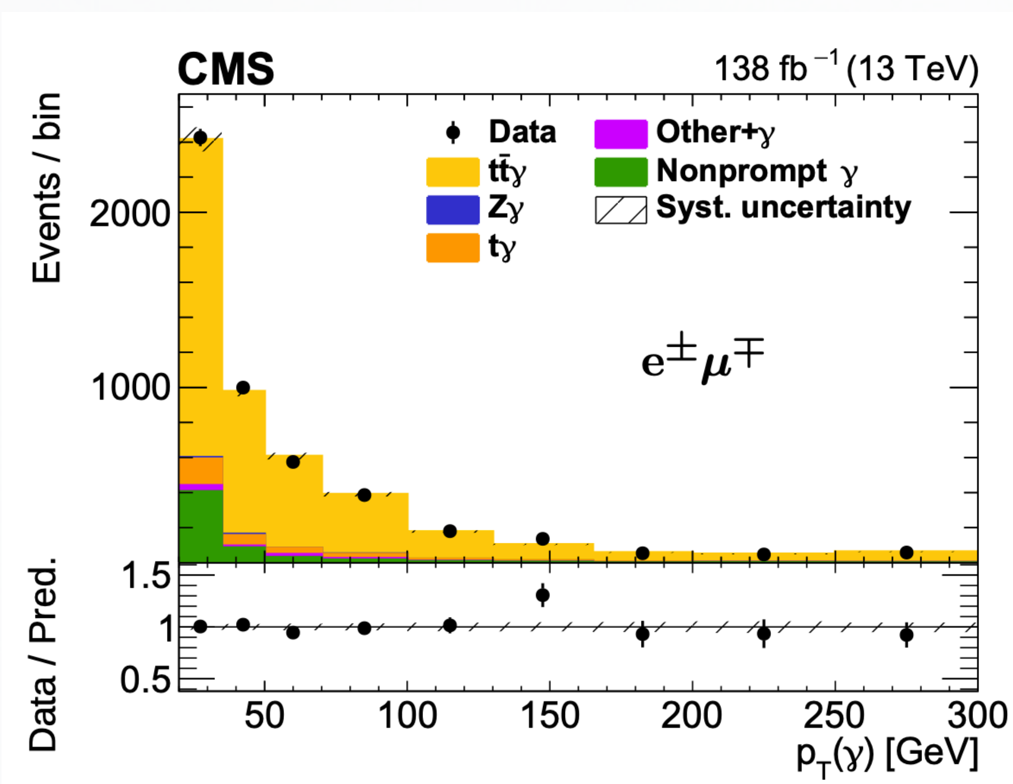


Top-photon

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







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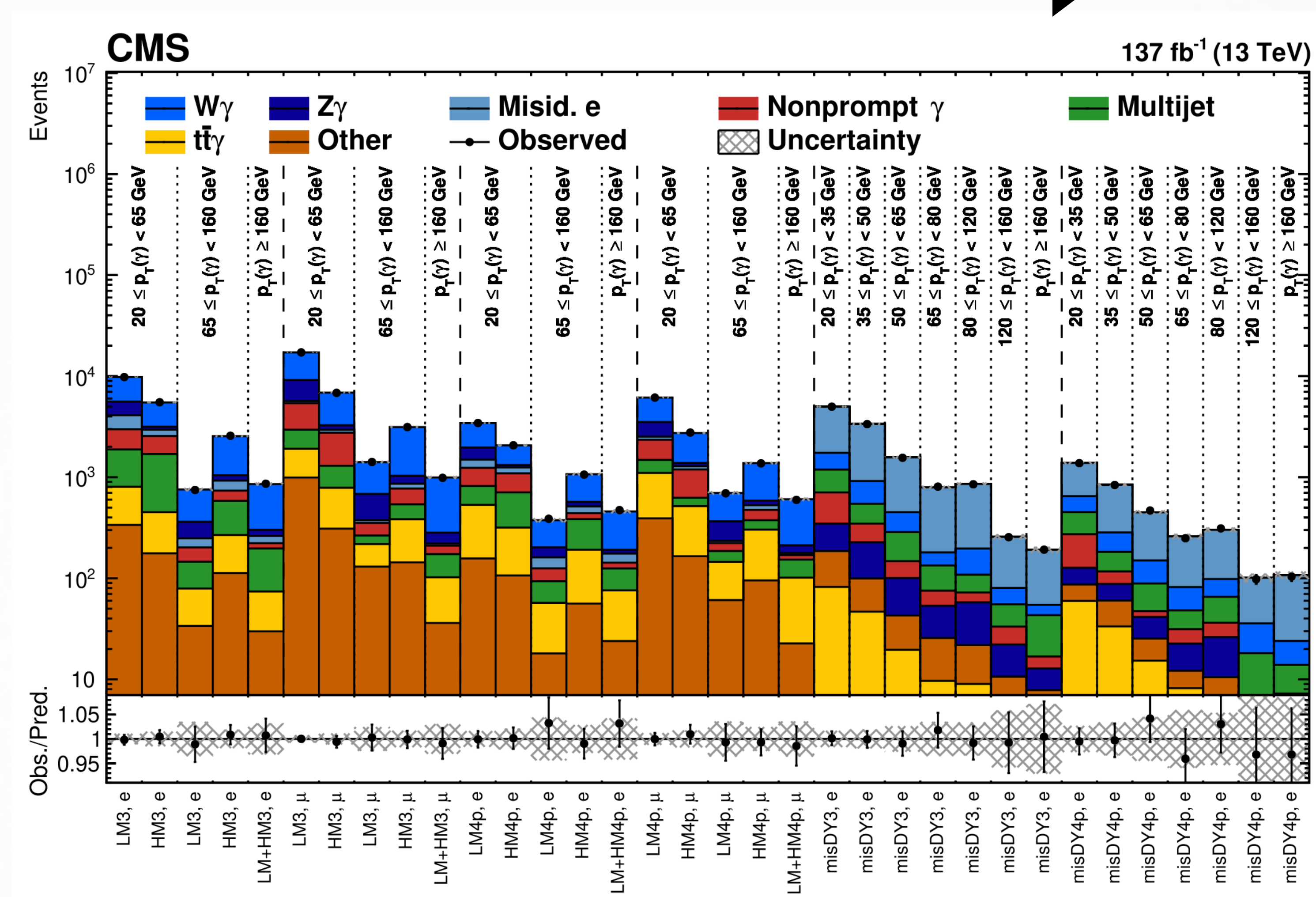

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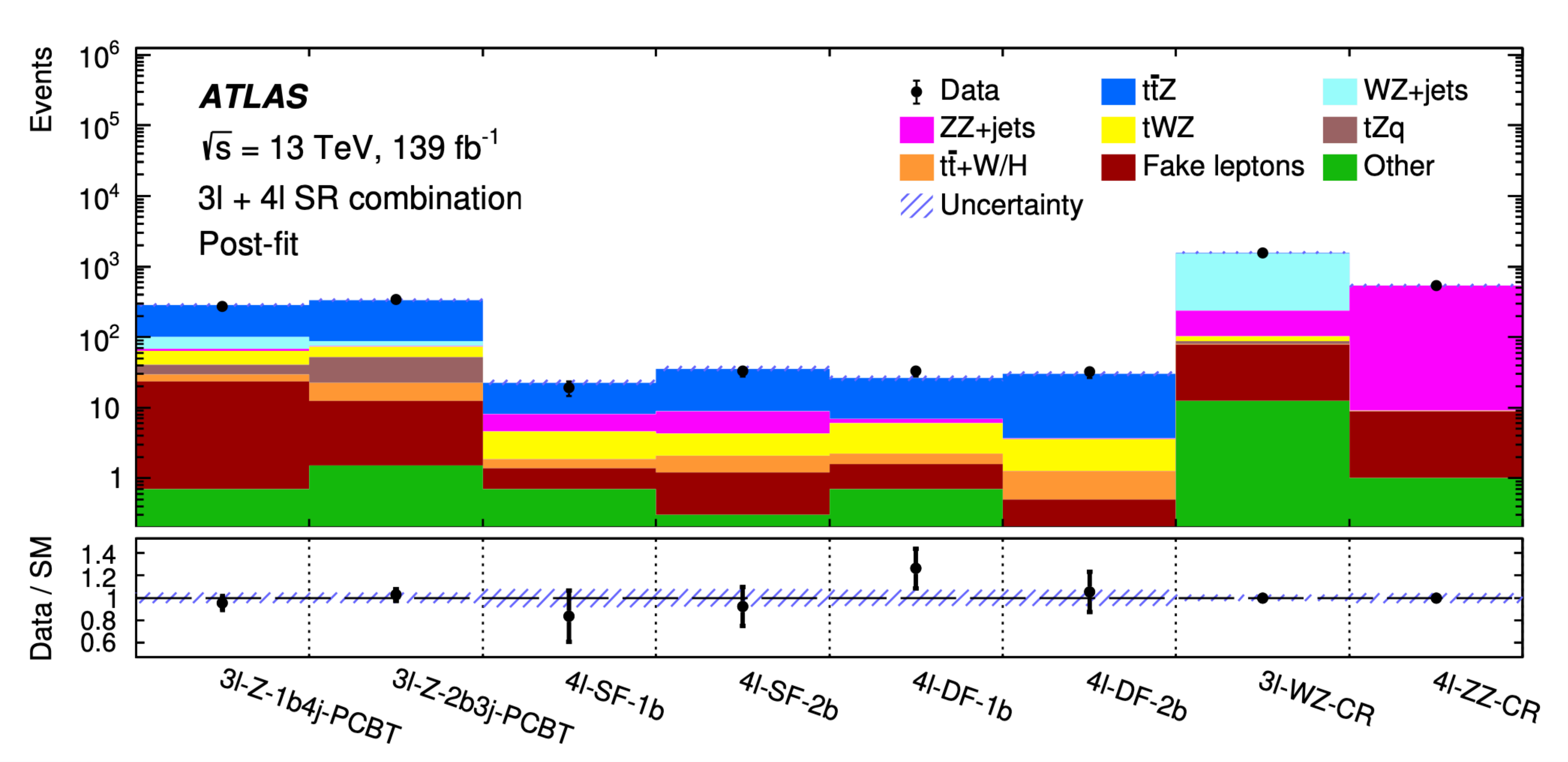
Top-Z

- 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!**



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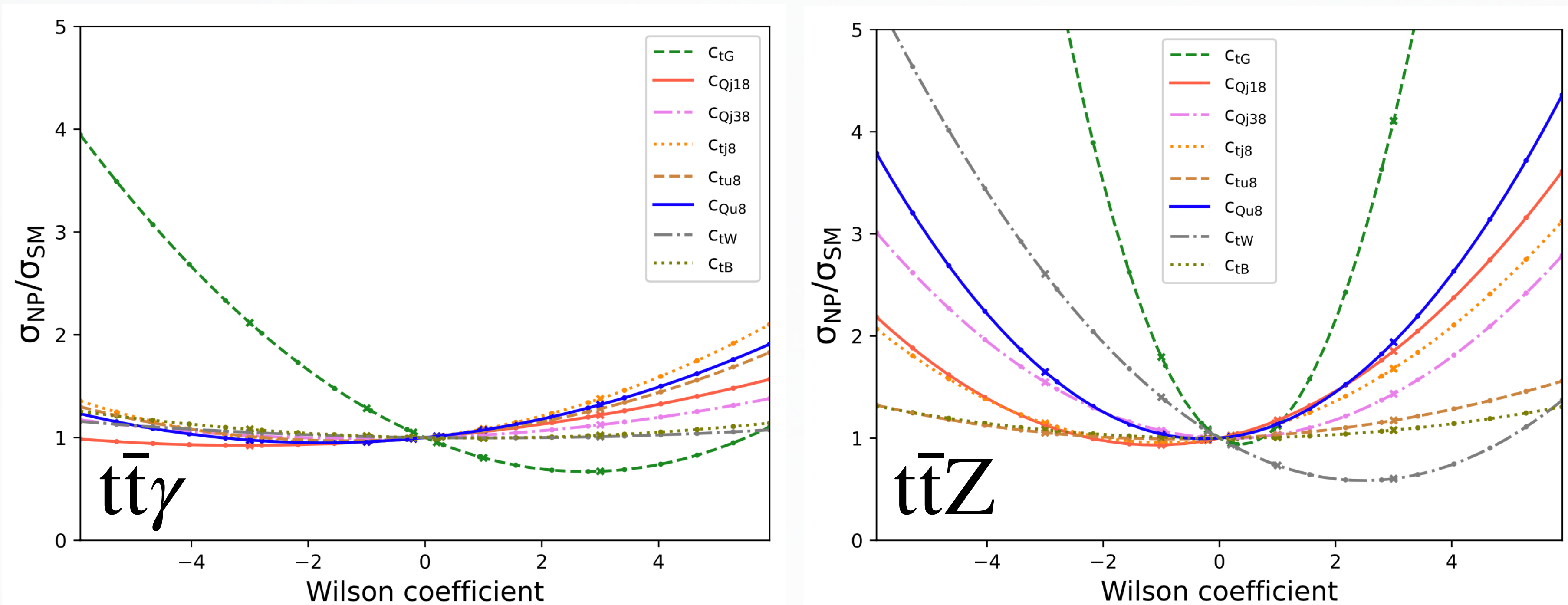
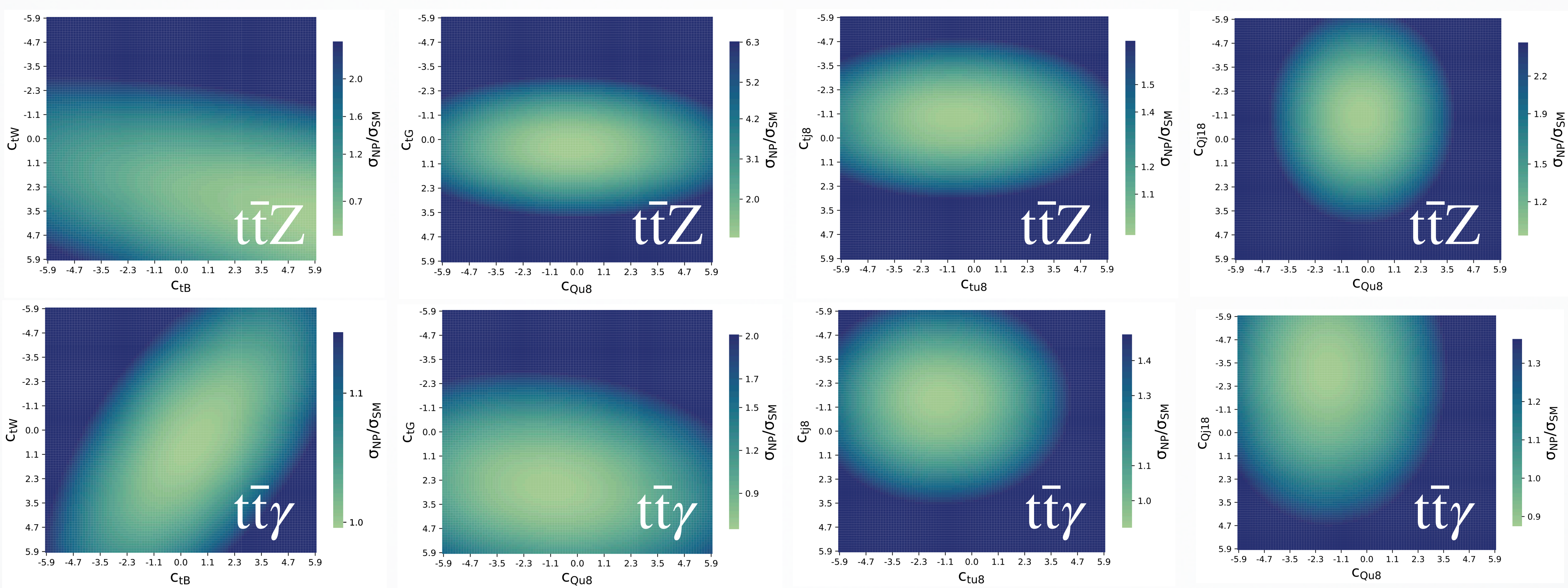
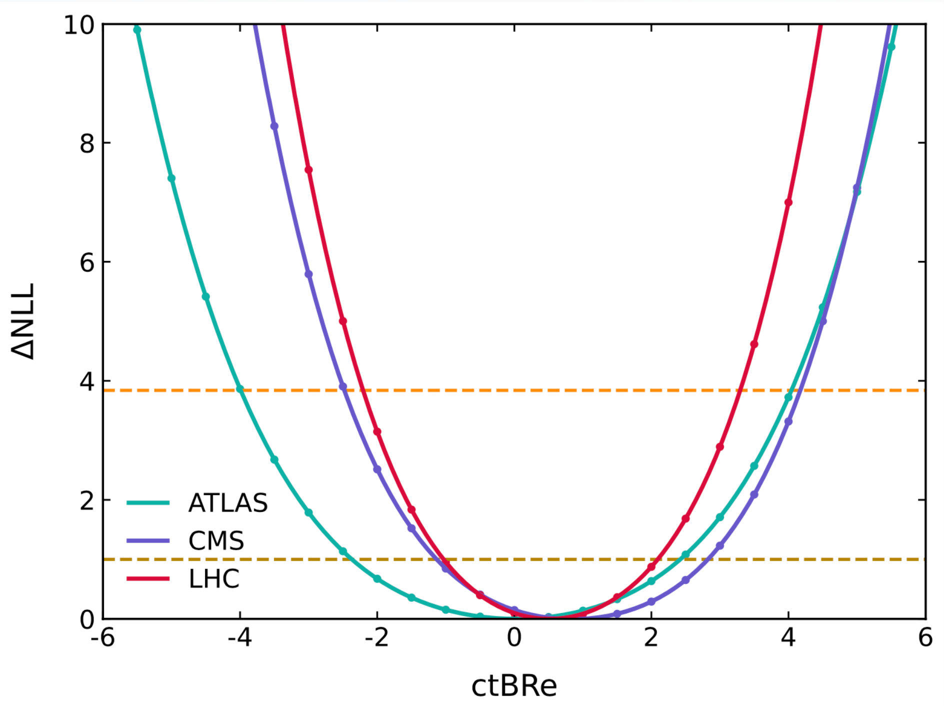
Top electroweak couplings

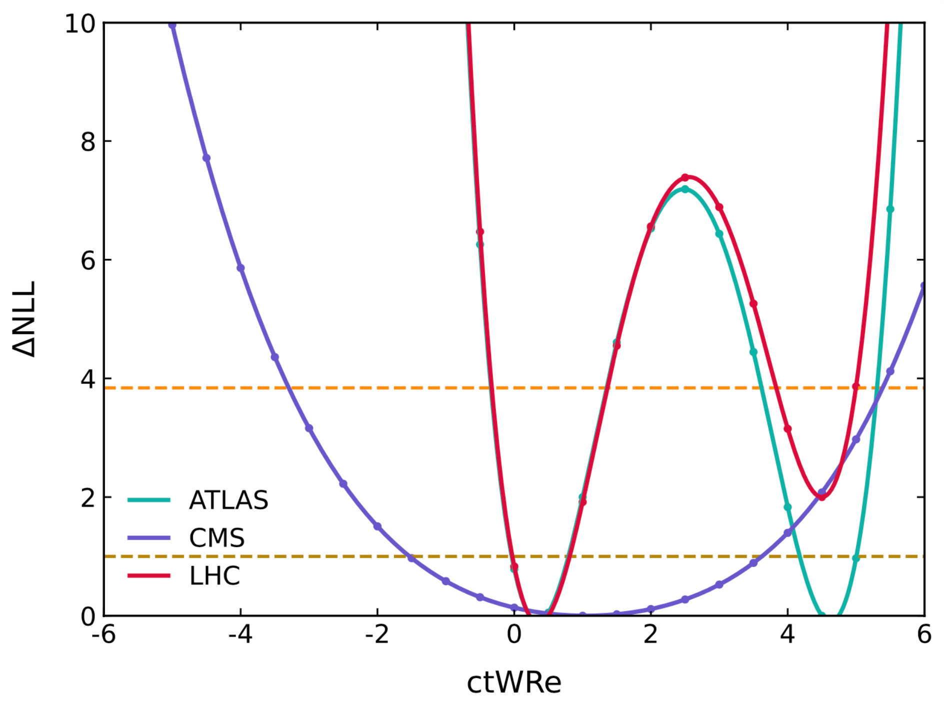


- **Strong interplay** for electroweak couplings in $t\bar{t}\gamma$ and $t\bar{t}Z$
- Probe a **chosen set** of operators in the fit

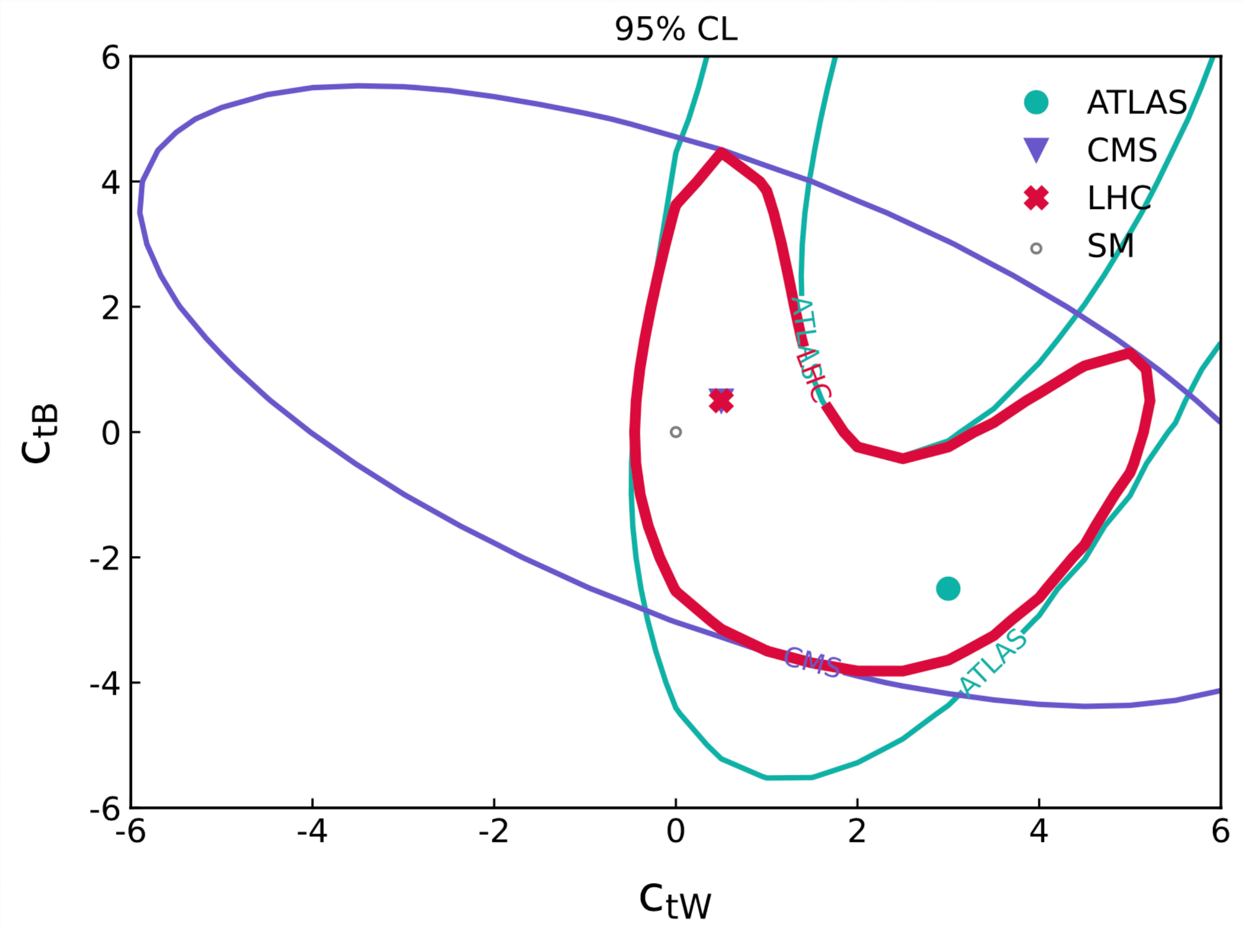


Top electroweak results



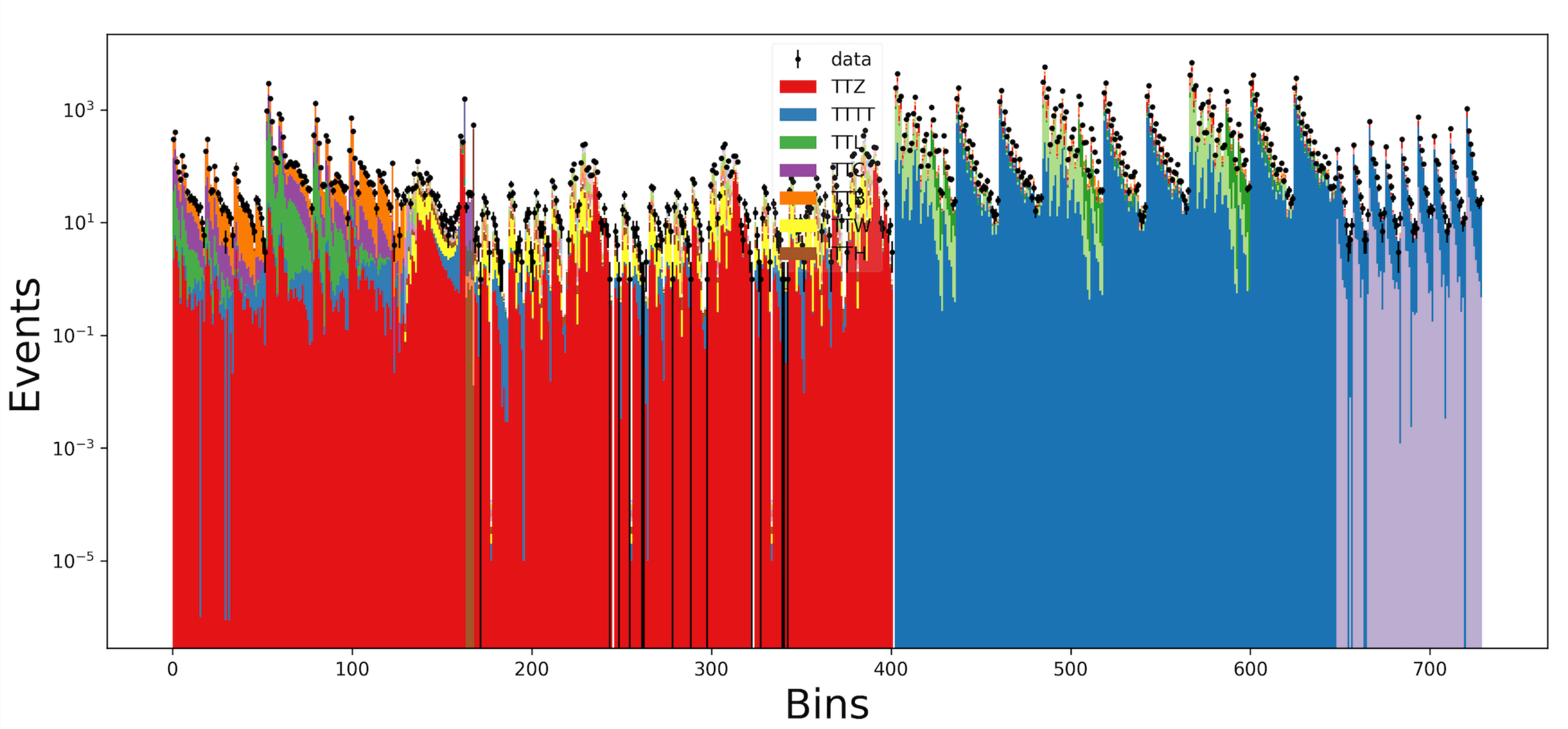


- Combine **full likelihoods** from:
  - $t\bar{t}\gamma$ (single lepton): JHEP 12 (2021) 180
  - $t\bar{t}\gamma$ (di-lepton): JHEP 05 (2022) 091
  - $t\bar{t}Z$ (multilepton): EPJC 81 (2021) 737
- **Very complementary** sensitivity

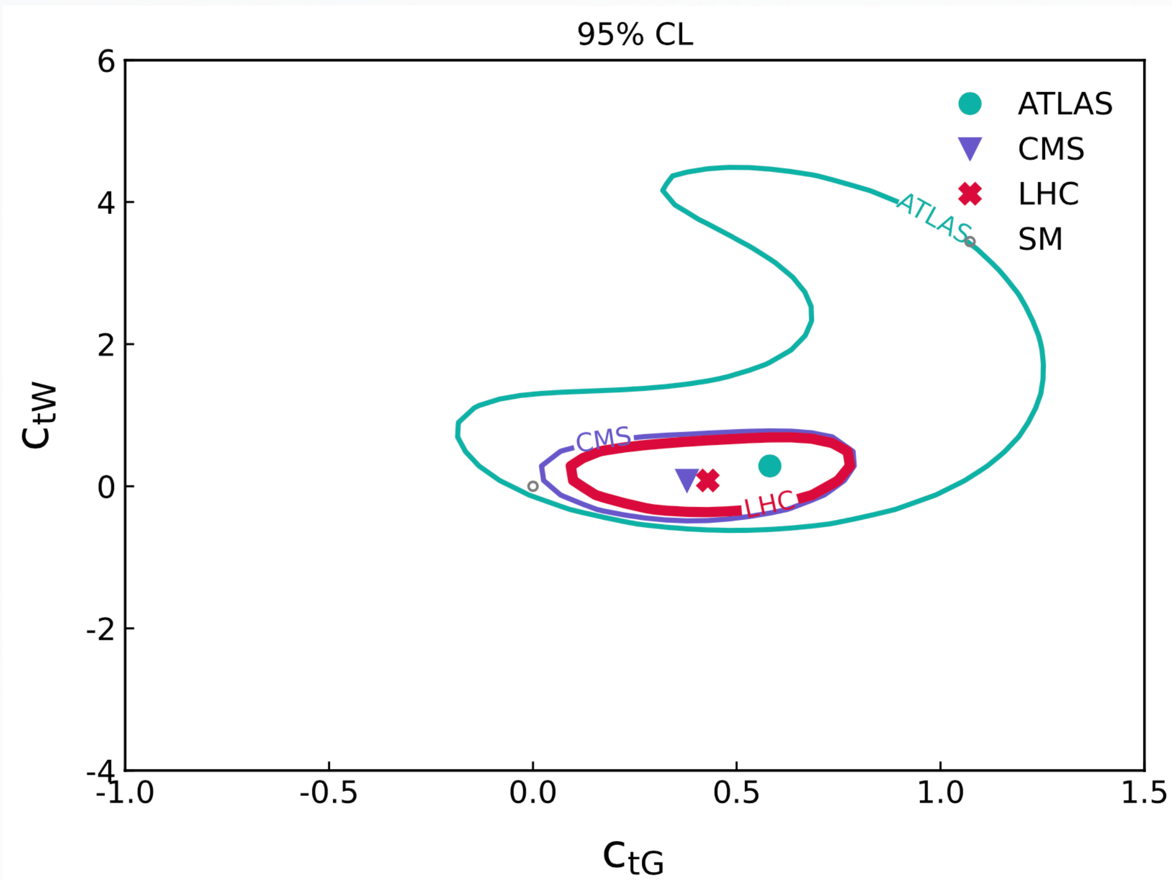


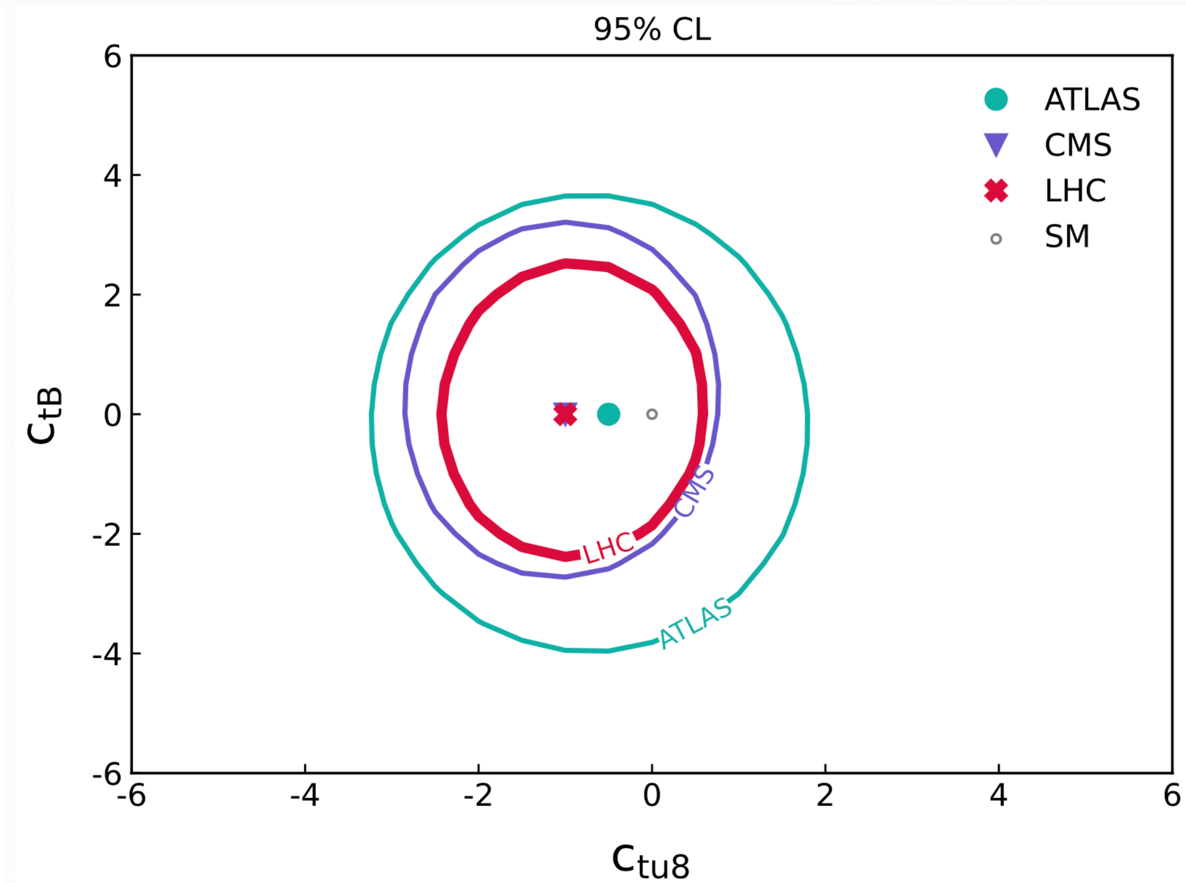
Let's combine everything

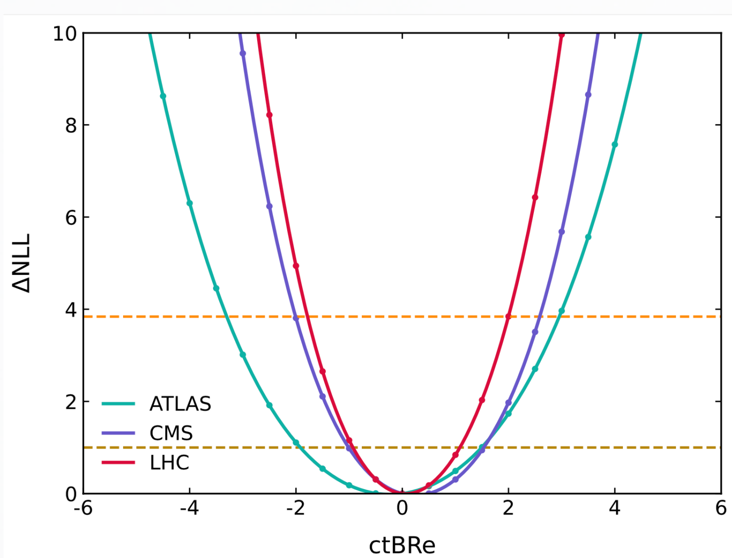
- Use **full likelihoods** from 5 published analyses:
  - $t\bar{t}t\bar{t}$ (multilepton): JHEP 11 (2021) 118, arXiv:2305.13439
  - $t\bar{t}\gamma$ (single lepton): JHEP 12 (2021) 180
  - $t\bar{t}\gamma$ (di-lepton): JHEP 05 (2022) 091
  - $t\bar{t}Z$ (multilepton): EPJC 81 (2021) 737
- Probe **EFT** 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

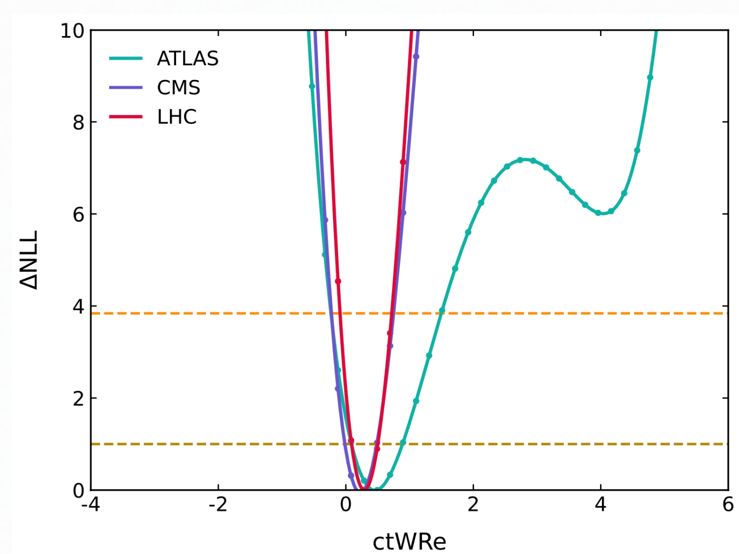


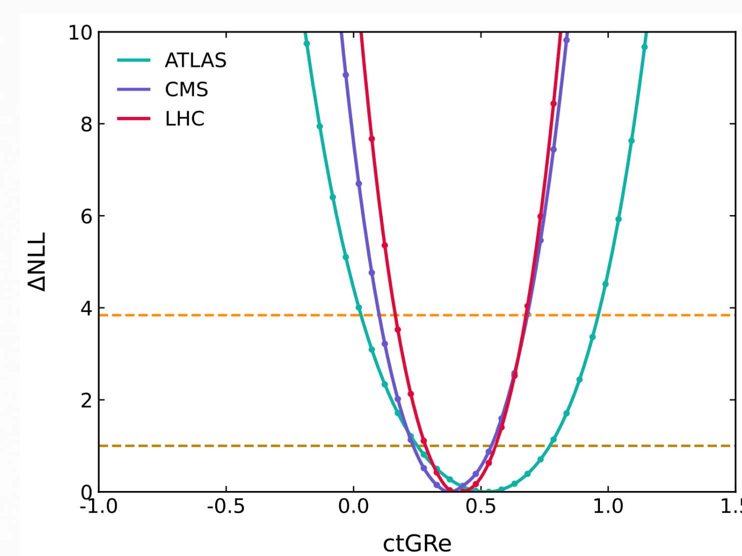
Grand combination results











Summary

- **Translation** between ATLAS and CMS full statistical models is available
- Allows for a **proper combination** of the results between the experiments
- **Direct measurement**:
  - **Combine** our measurements using either of the statistical tools
  - Include EFT in **all relevant processes**
  - **Harmonizing** uncertainty correlations can be a challenge
- **Reinterpretation**:
  - Almost any published LHC result can be reinterpreted in terms of EFT sensitivity, however in most cases can only introduce EFT parametrization on the **total cross section**
  - For EFT-specific experimental studies need to **publish EFT-specific information** (e.g. parameterization, selected event samples, etc.)
- **What's next**:
  - Try to publish?
    - a full-likelihood combination for a selected process (latest four top results?)
    - also may include an EFT reinterpretation
  - EFT combination based on unfolded differential measurements coming soon