Observation of 4tops

Standard Model at the LHC 2023

Zhi Zheng on behalf of CMS and ATLAS Collaboration

July 10, 2023

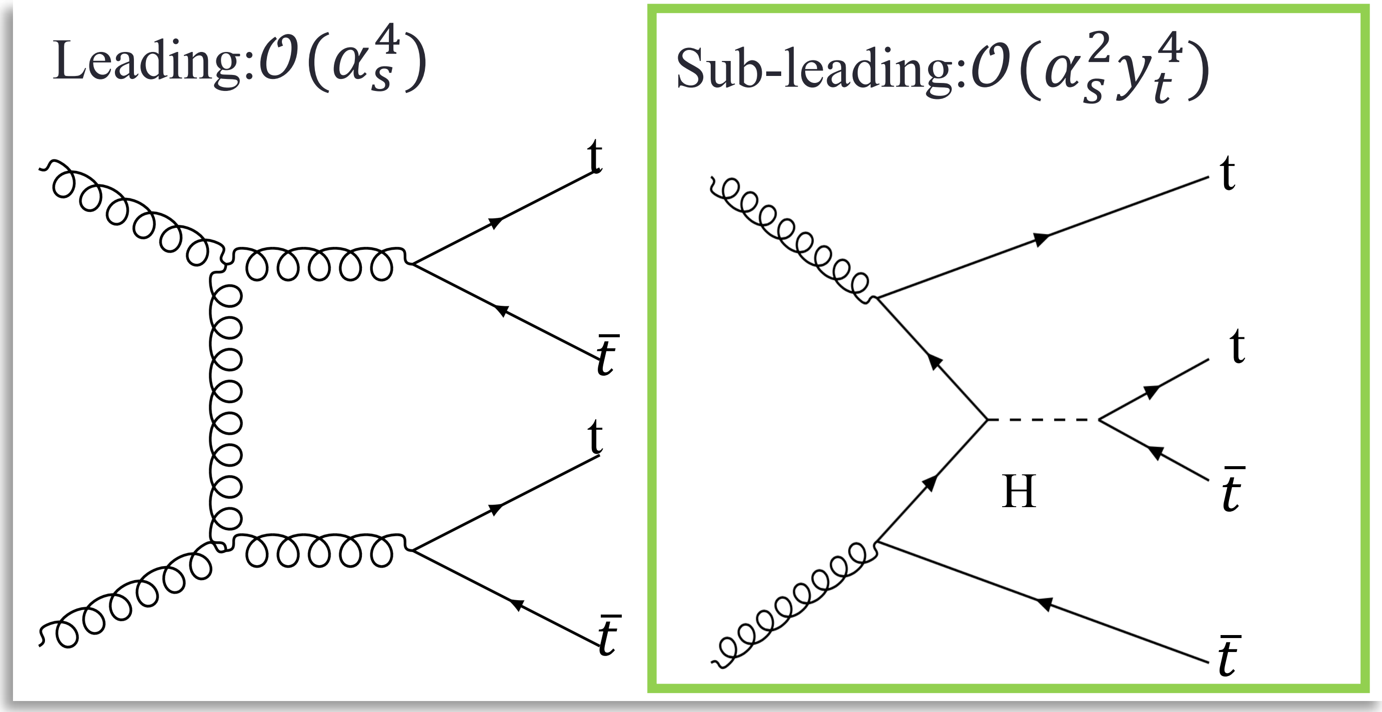
SLAC NATIONAL ACCELERATOR LABORATORY
ATLAS EXPERIMENT
CMS
Stanford University
U.S. DEPARTMENT OF ENERGY

Why 4tops is interesting?

4tops ($t\bar{t}t\bar{t}$) is a very rare process in the standard model (SM)

- $\sigma(t\bar{t}t\bar{t})_{NLO+NLL'} = 13.4^{+1.0}_{-1.8}$ fb [arXiv:2212.03259]

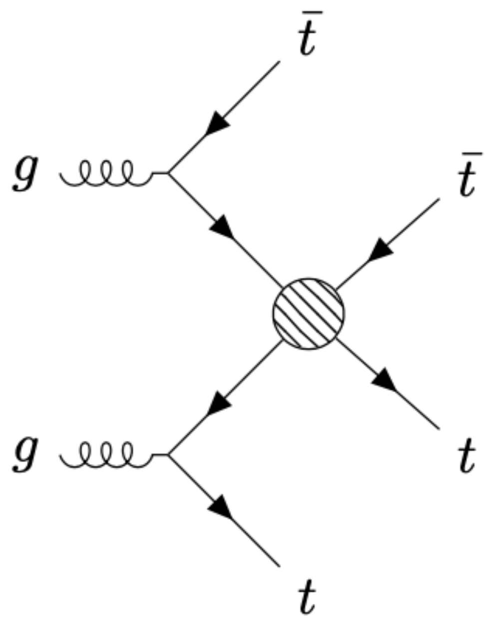
Probe top Higgs Yukawa coupling and top quark CP properties



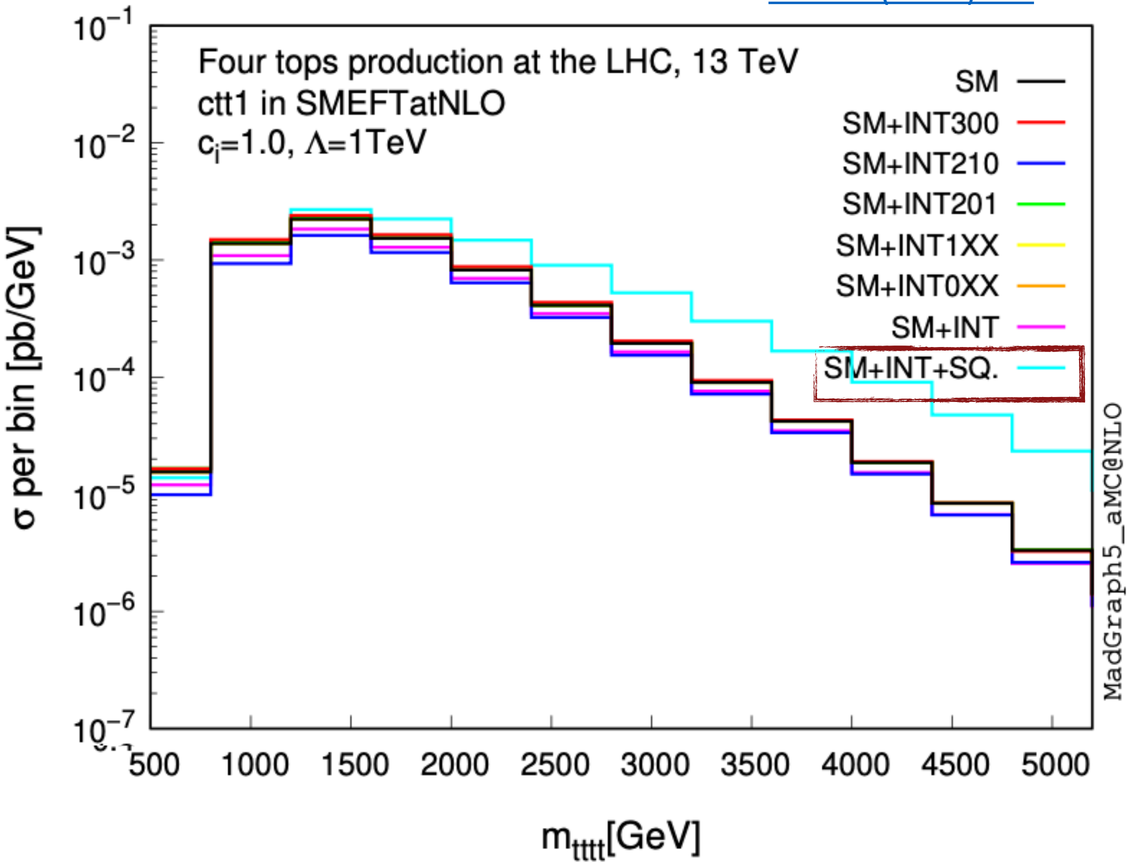
Why 4tops is interesting?

Very heavy final state with a total particle mass of almost 700 GeV – can be sensitive to many BSM models and EFT parameters

Access to four fermion operators



JHEP10(2022)163

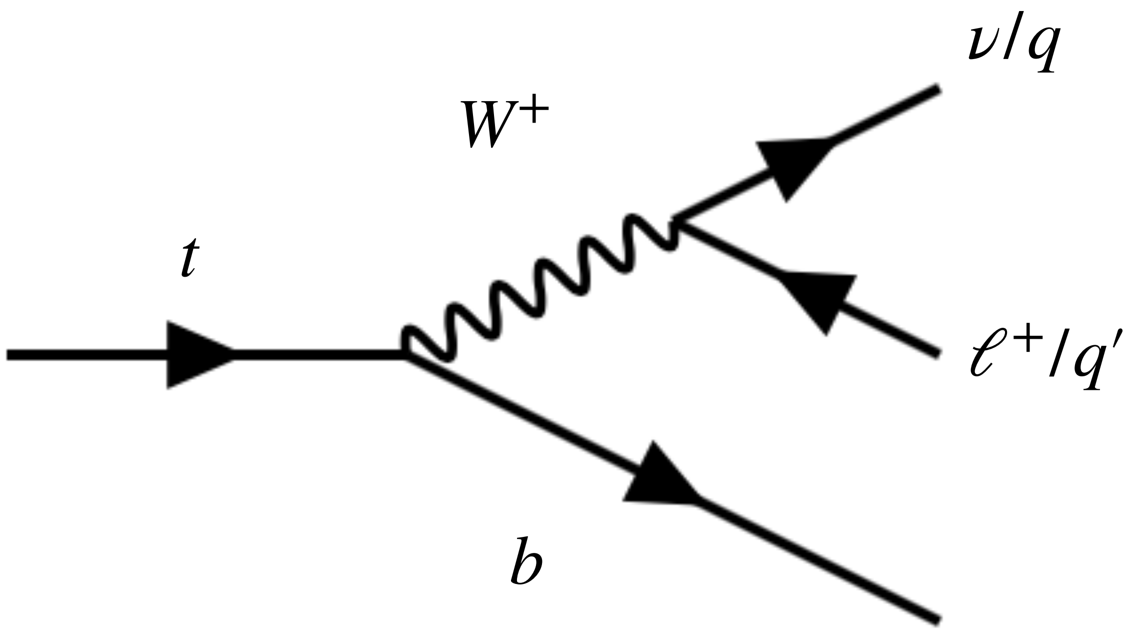


EFT predict increased four-top production rate

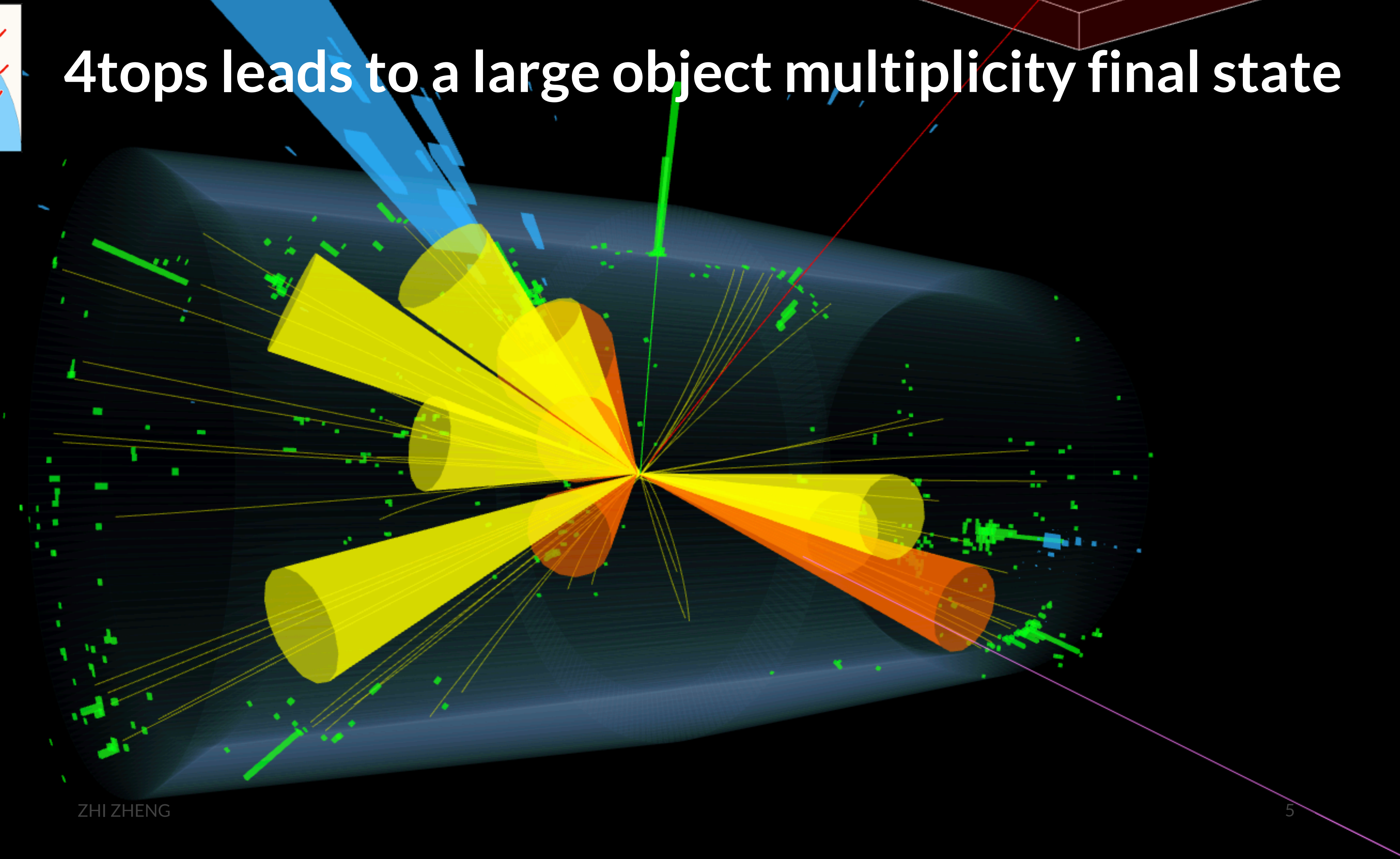
4tops: Signatures

Each top decays to Wb, so the detector signature is characterized by

- The presence of 4 b-quarks
- The decays of W bosons



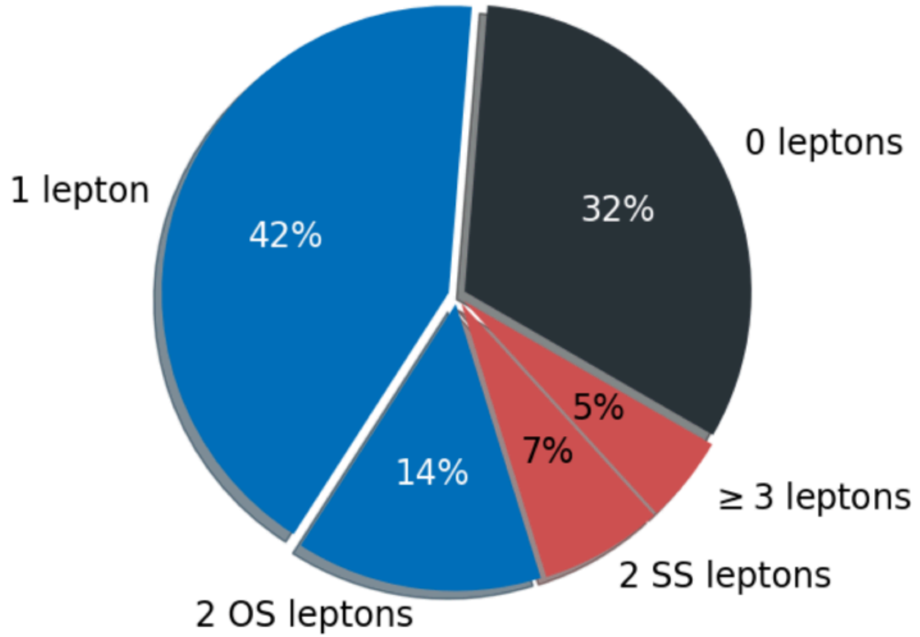
4tops leads to a large object multiplicity final state



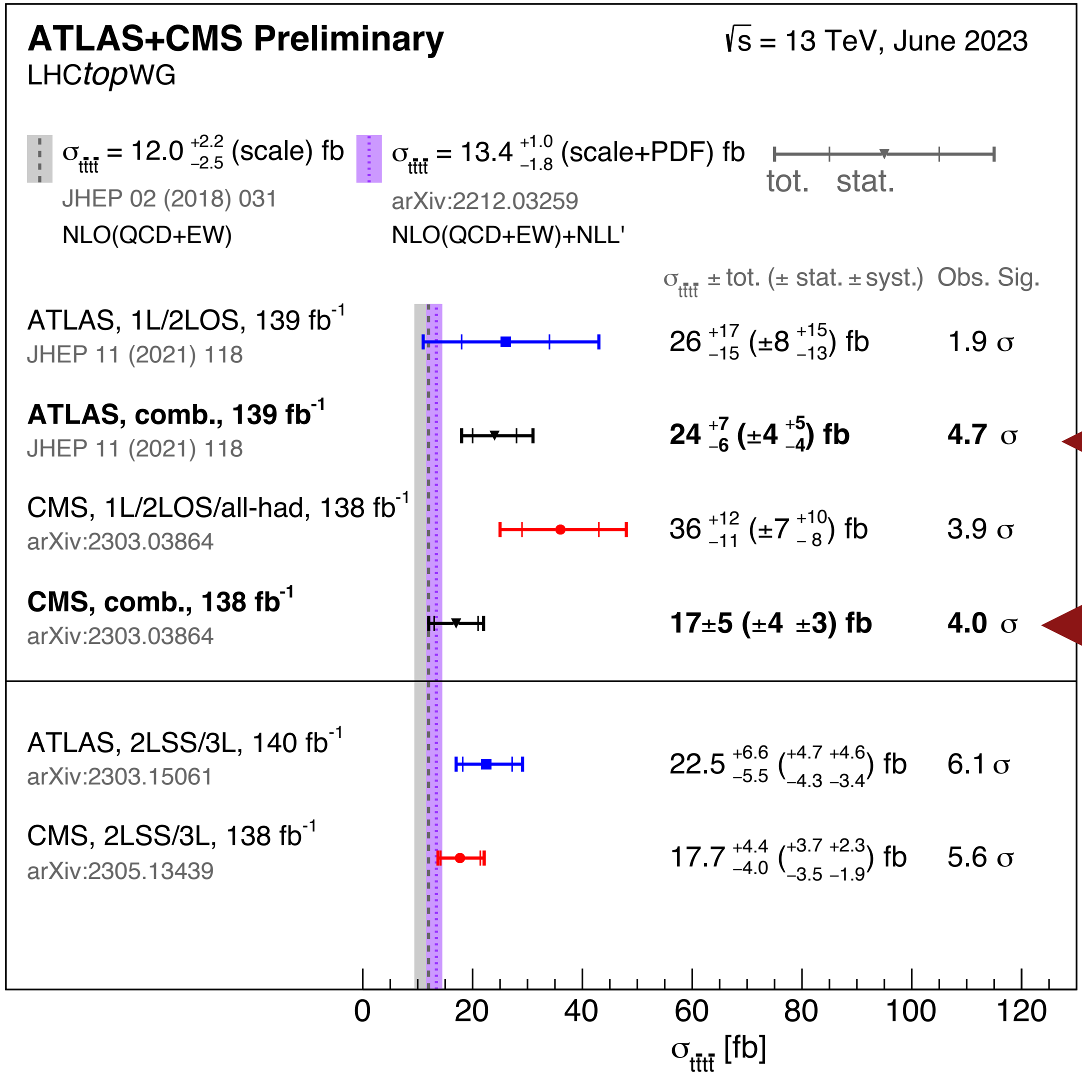
4tops final states @ LHC

3 channels are explored based on W decays:

- **All hadronic channel**
- **Single lepton and two opposite sign lepton (1LOS)**
  - Larger branching fraction and Larger irreducible background
- **Same-sign di-lepton and multi-lepton (SSML)**
  - Smaller branching fraction and higher purity

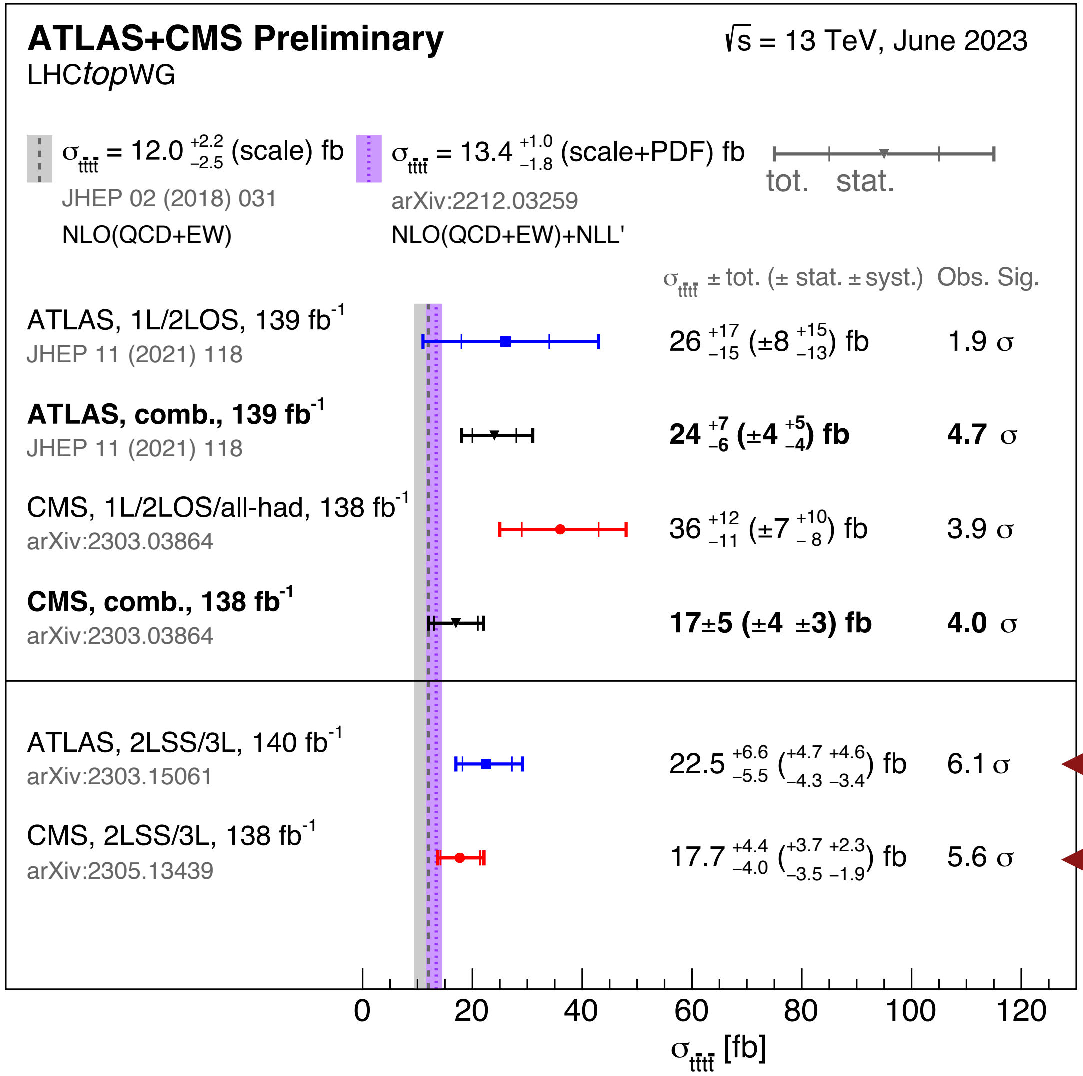


4tops @ LHC



Both **ATLAS** and **CMS** achieved **evidence** with combination of multiple channels

4tops @ LHC

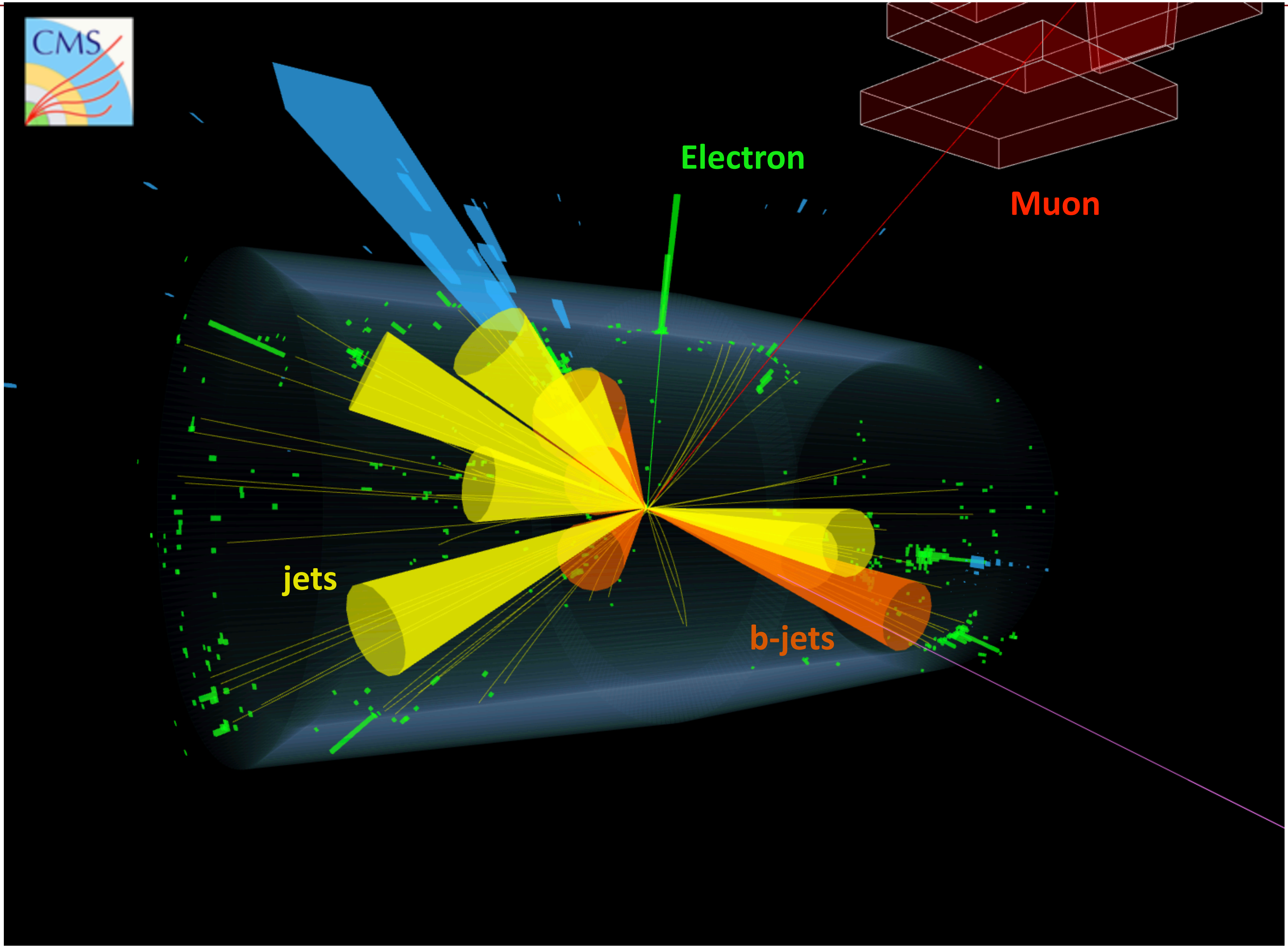


New ATLAS result:
[Eur. Phys. J. C 83, 496 (2023)]
New CMS result:
[Arxiv:2305.13439]

Both **ATLAS** and **CMS** improved analysis with Run 2 data in SSML channel

Path to “Observation of 4tops”

Path to improve: Objects

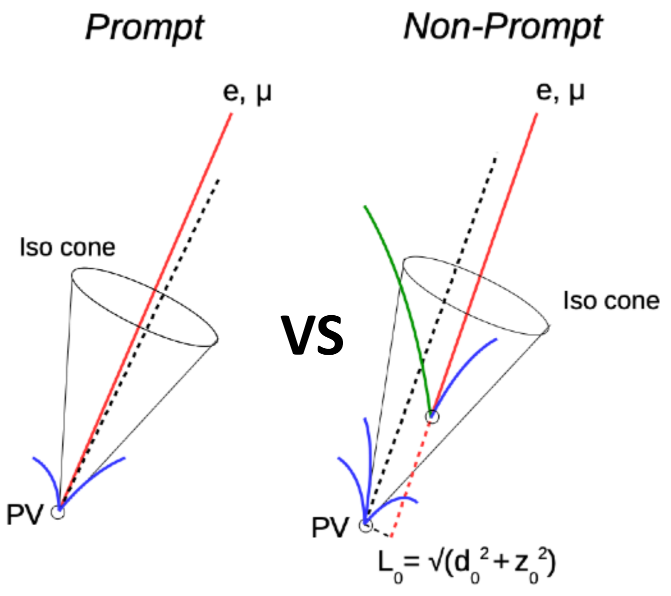


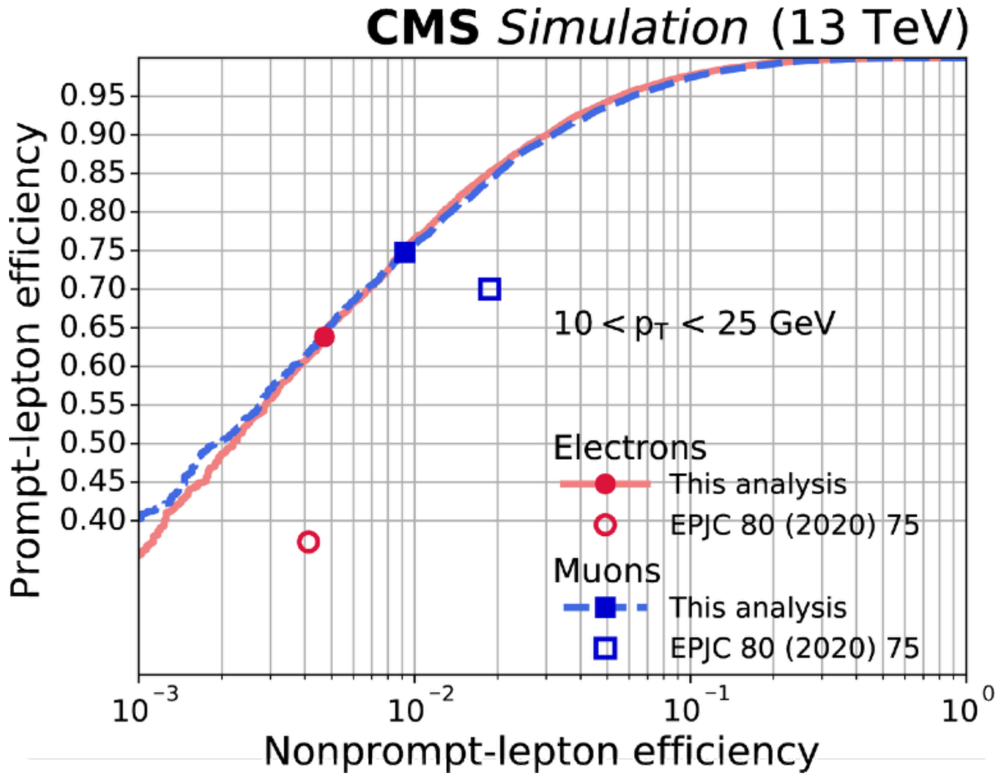
Path to improve: lepton (e/μ)

Both CMS and ATLAS **lower p_T for leptons to improve the 4tops acceptance**

Multivariate analysis (MVA) based lepton identification/isolation to suppress non-prompt lepton contribution

Non-prompt lepton is very crucial in SSML channel



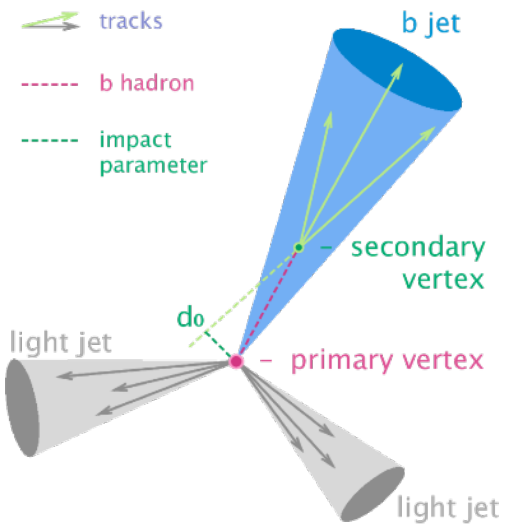


arXiv:2211.16345

Path to improve: Jets

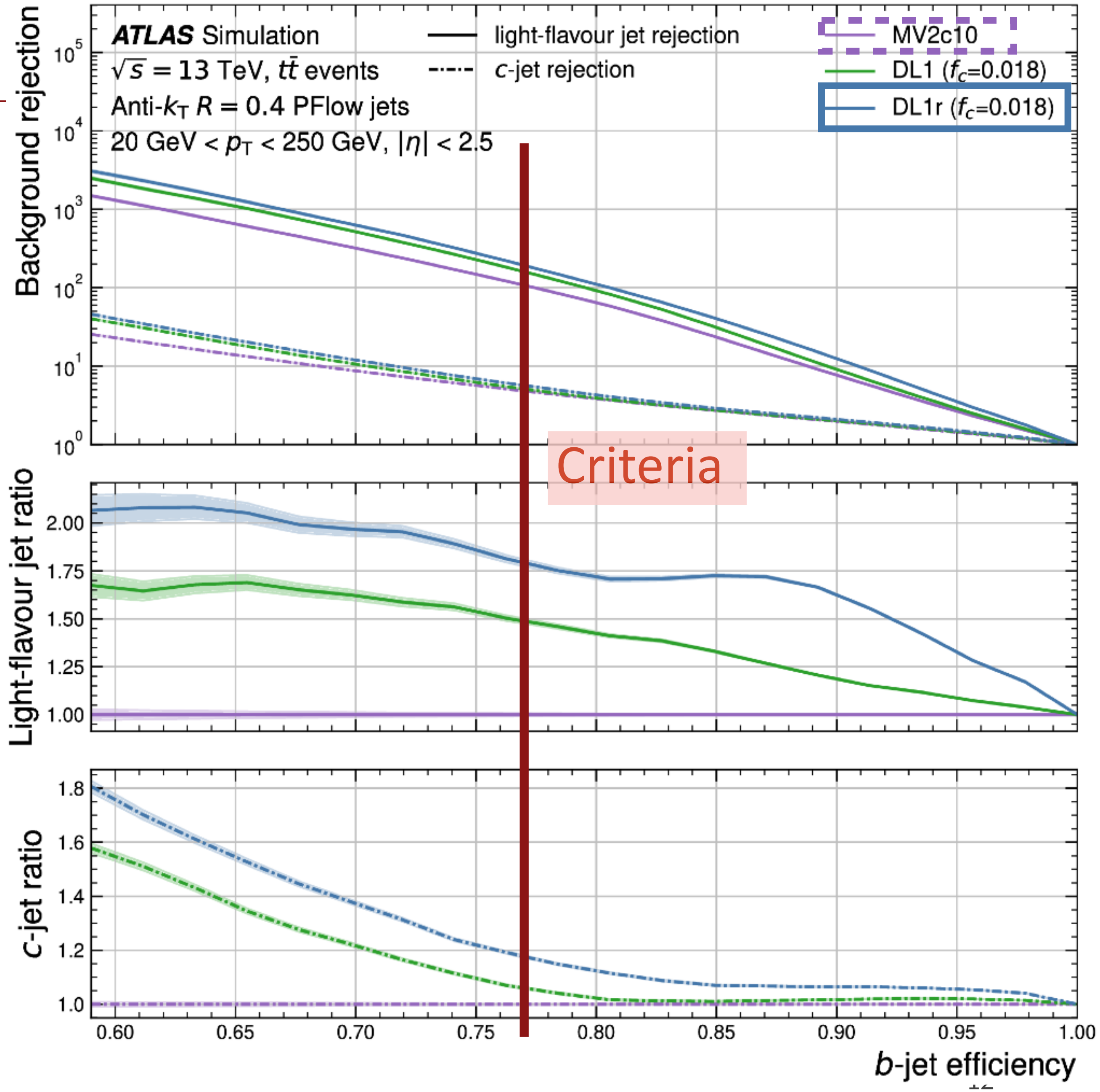
Both CMS and ATLAS **lower** p_T **for jets to improve the 4tops acceptance**

Using Improved B-tagging algorithm to reduce background



Reject **~1.76x** compared with **MV2c10**

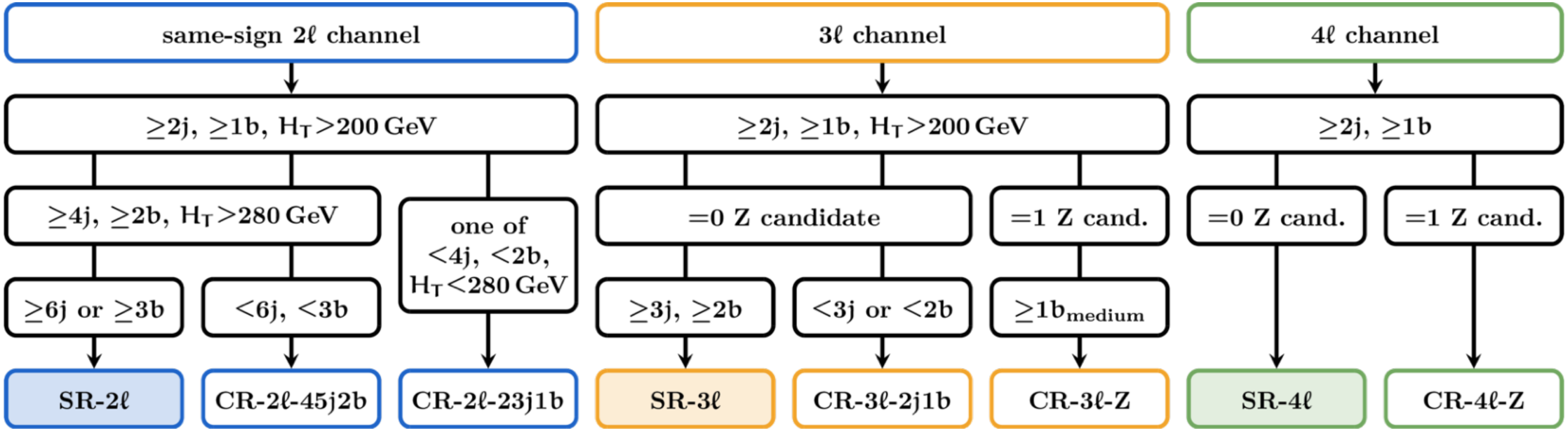
Reject **~1.15x** compared with **MV2c10**



Path to improve: Analysis strategy

ATLAS uses same selection over all channels, **CMS** uses different event selection for different channels

Signal Region (SR): >=2 bjets (77% WP) SSML with Zveto at 3ℓ, >= 6 jets, HT >= 500 GeV

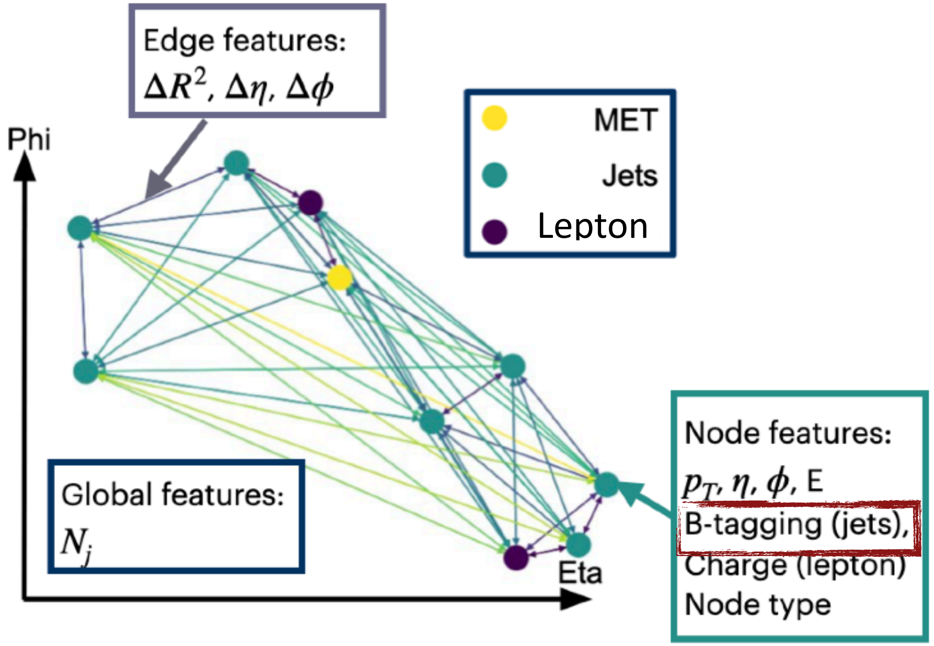


Path to improve: Analysis strategy

Advanced machine learning (ML) techniques are employed for better signal-background separation

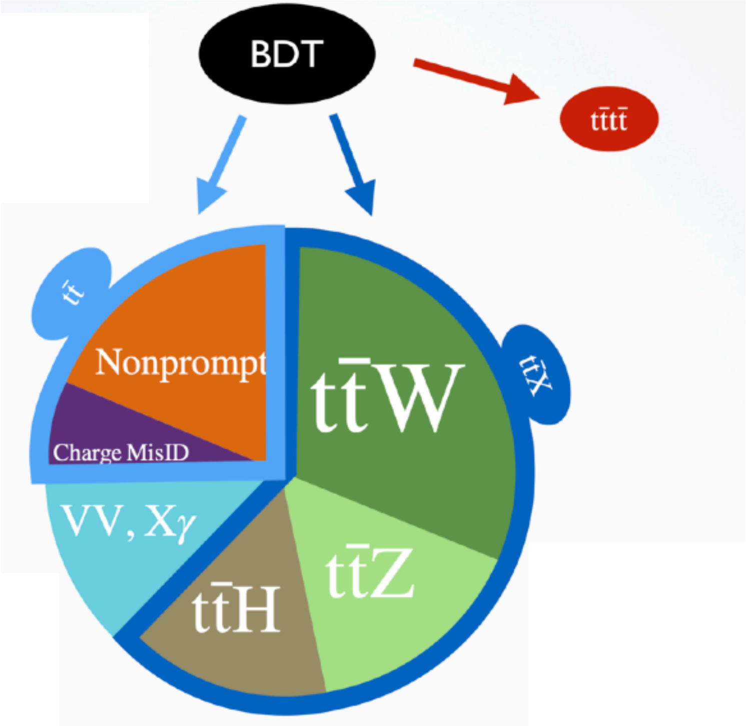
ATLAS EXPERIMENT

- Graph Neural Network (GNN)
- Trained on 4tops vs others in SR

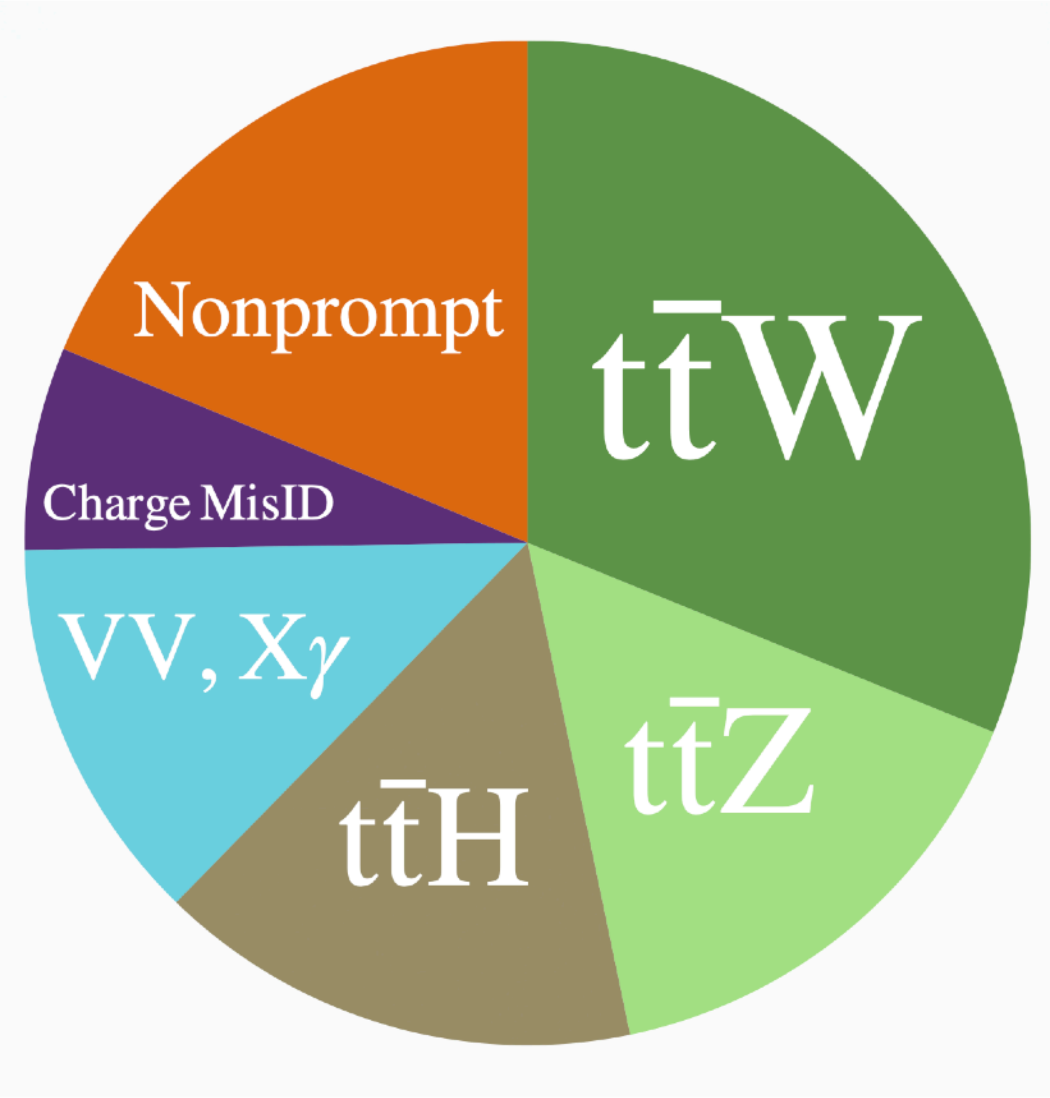


CMS

- Train multiclass BDTs
- Use 30 (24) input variables in 2LSS (3L+4L)



Background



Background

		ATLAS	CMS
$t\bar{t}X$	$t\bar{t}W$:	Correcting N_j distribution to data	Free-floating in the Fit
	$t\bar{t}Z$:	Validate modeling in 3ℓ-Zpeak region	Free-floating in the Fit
	$t\bar{t}X + b(b)$:	50% uncertainty	40% uncertainty
Instrumental background	Non-prompt lepton:	Template method	Tight-to-loose ratio method
	Charge mis-identification:	Apply the measured charge misidentified rates to OS data	

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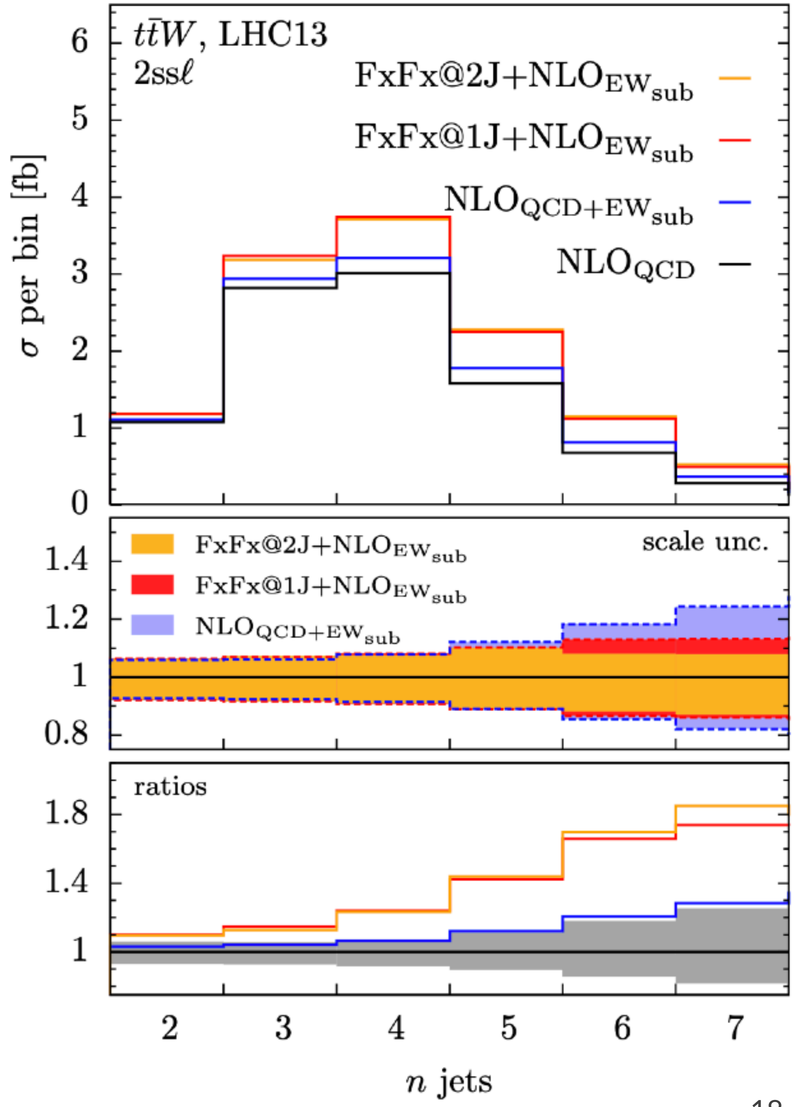
Background: $t\bar{t}W$ process

JHEP11(2021)029



<u>$t\bar{t}W$ is difficult to model</u>

Theoretically challenging: Sizable contribution from NLO EW

- σ(FxFx@2J+$\mathrm{NLO_{EW}^{lead}}$+$\mathrm{NLO_{EW}^{sub}}$) = 722 fb (JHEP11(2021)029)

Large EW corrections at high jet multiplicity

JHEP02(2018)031

$\delta[\%]$	$\mu = H_T/2$
LO_2	-
LO_3	0.9
NLO_1	50.0 (25.7)
NLO_2	−4.2 (−4.6)
NLO_3	12.2 (9.1)
NLO_4	0.04 (−0.02)

Background: $t\bar{t}W$ process @ CMS

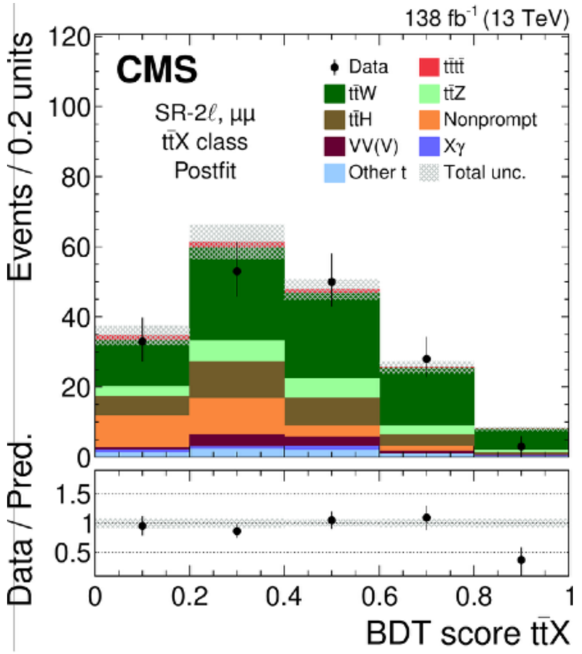
JHEP11(2021)029

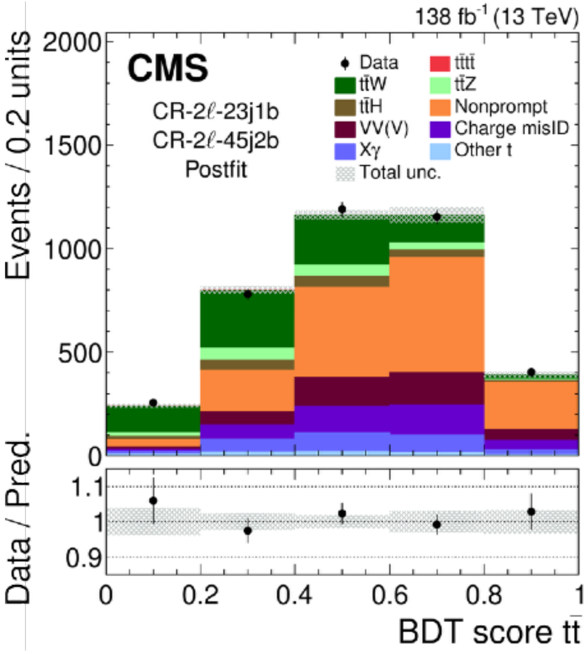
Sample: NLO QCD MG sample with FxFx merging

Conservative uncertainty as function of N_j

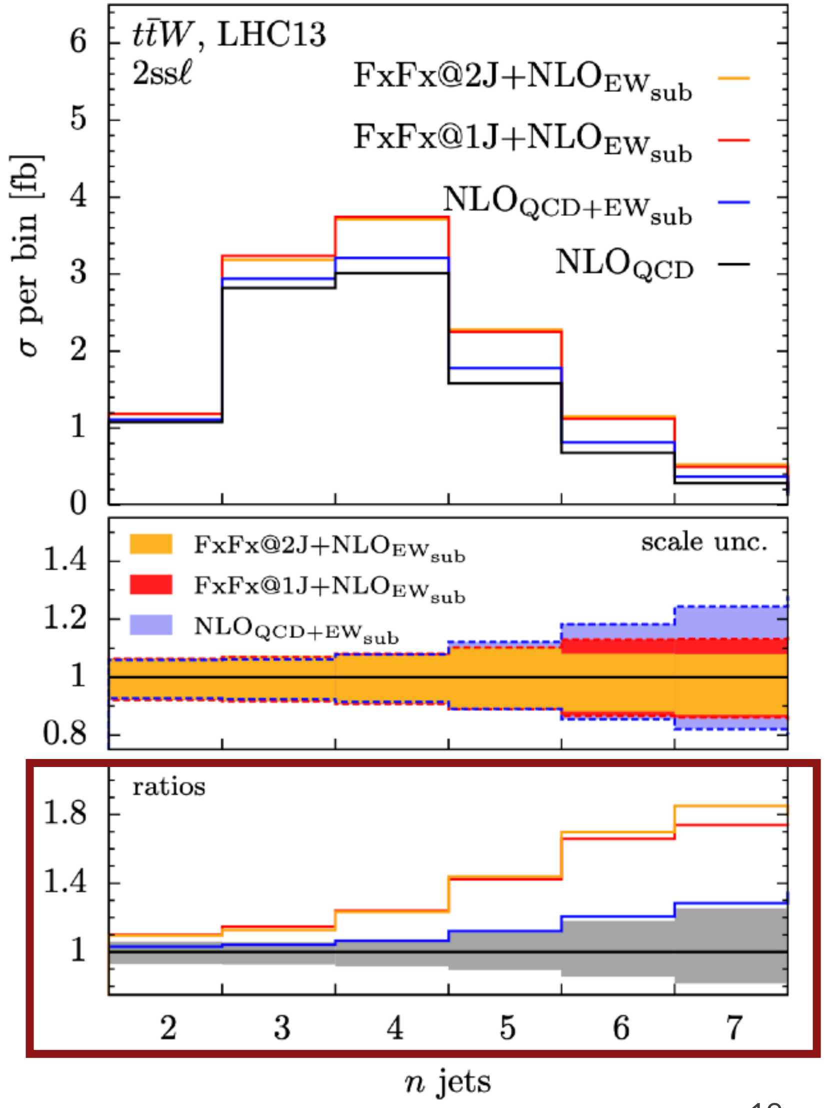
Free-floating in the fit: $\sigma_{t\bar{t}W}$ = 990±98 fb

- Dedicated control regions (CRs) from multiclass BDT





Variations up to 55% in events for Nj ≥ 7



Background: $t\bar{t}W$ process @ ATLAS

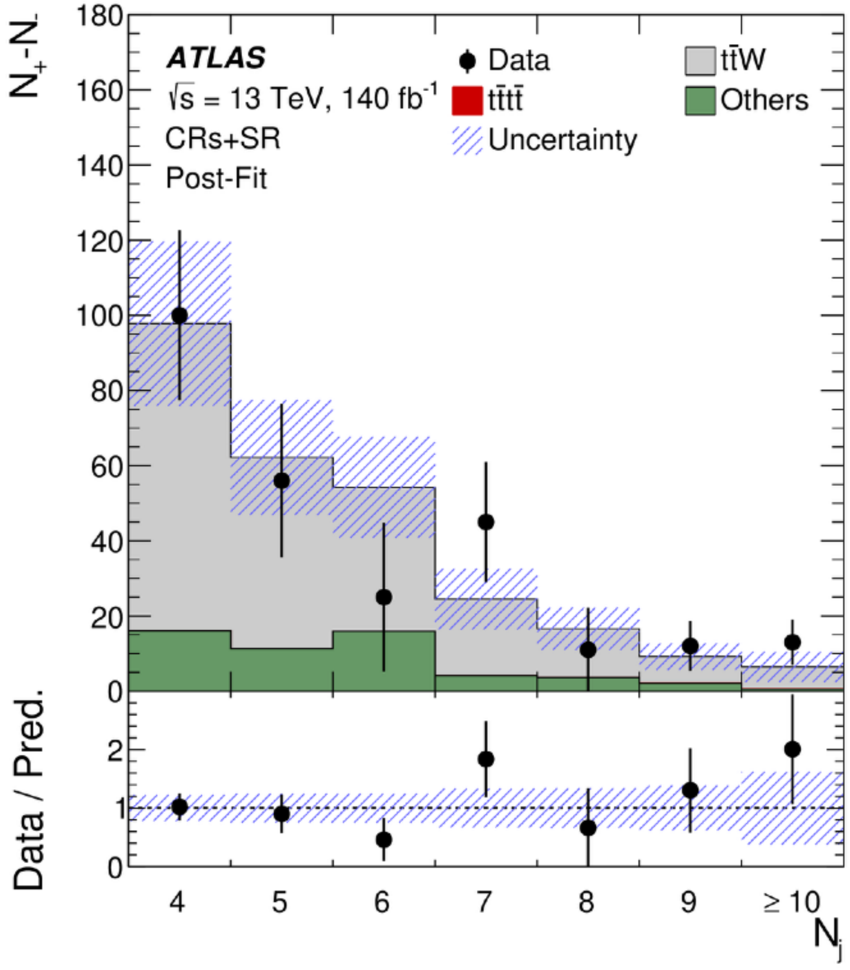
Sample: Sherpa multileg sample with additional ttW EW sample consider ttW+1 jets for NLO3 contribution

Correcting N_j distribution to data with parameterized function

N_{jet} distribution is parametrized making use of known jet scaling regimes $--R(j) = N(j+1)/N(j)$, j is the jet multiplicity

- $R(j) = a_0$ for very high jet multiplicities
- $R(j) = a_1/(1+n)$, n is the number of extra jets

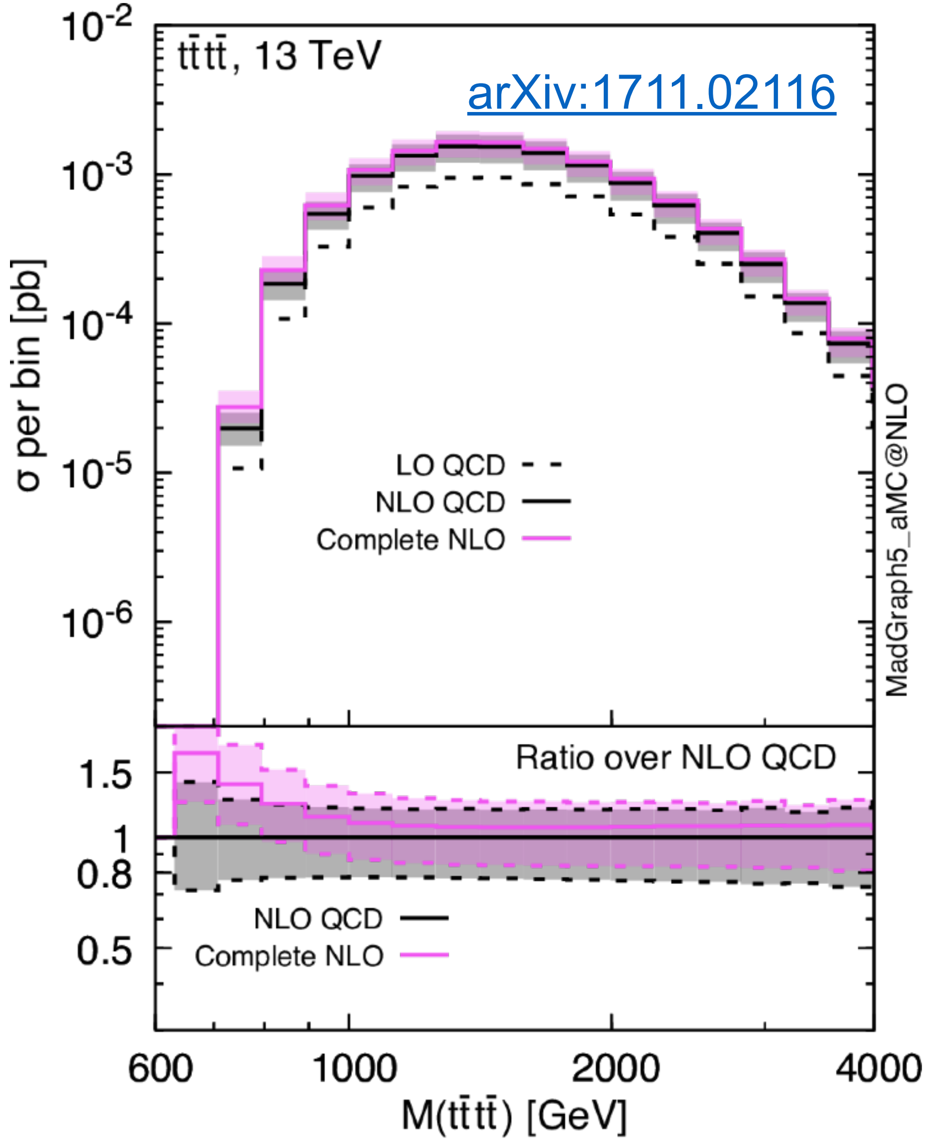
Separate normalizations (NFs) for $t\bar{t}W^+$ and $t\bar{t}W^-$: $\text{NF}_{t\bar{t}W^+(4\text{jet})}$, $\text{NF}_{t\bar{t}W^-(4\text{jet})}$



4tops modeling

Modeling: NLO QCD madgraph (MG) + Phythia 8

- CMS: μ_R, μ_F and PDF variations, initial/ final state radiation (ISR/FSR)
- ATLAS: μ_R, μ_F and PDF variations, generator (MG vs sherpa) and parton shower (Pythia 8 vs Herwig 7) variations



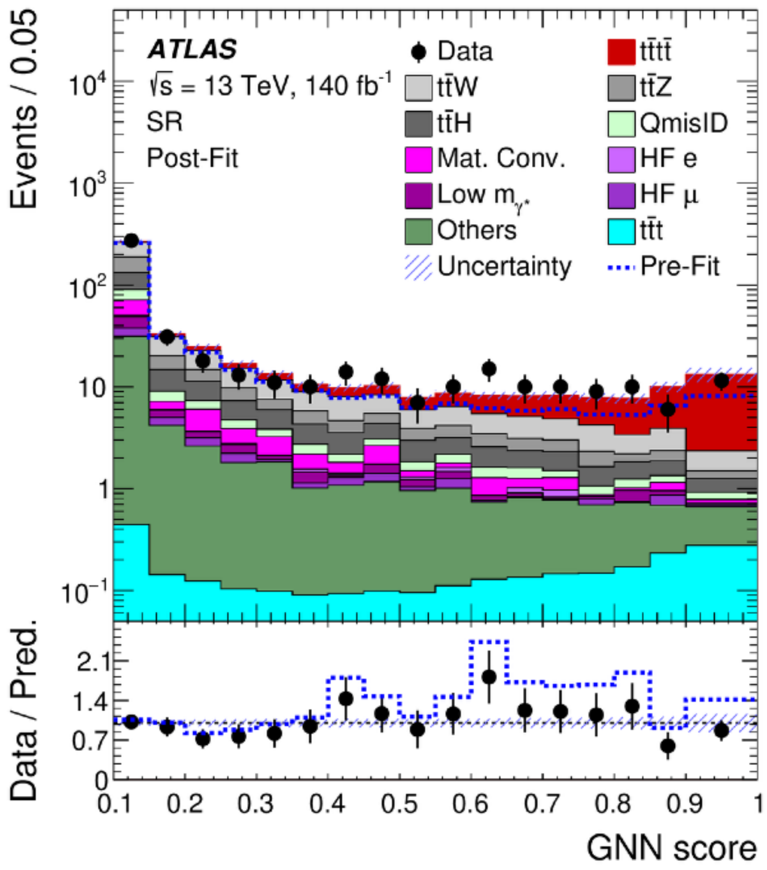
Results

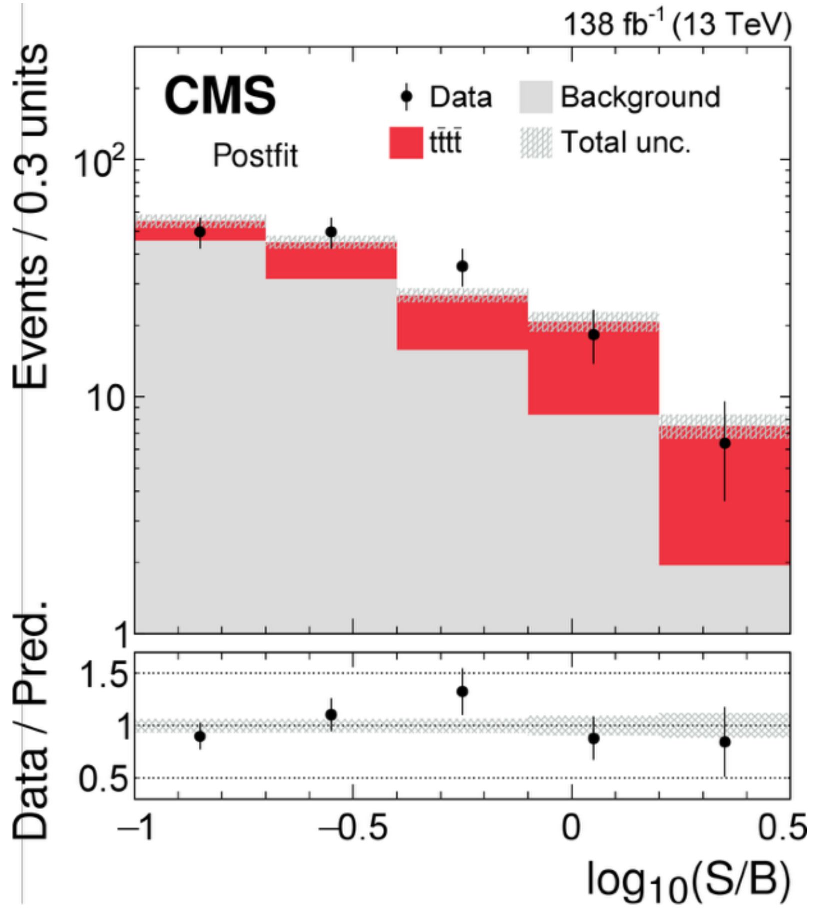
$\sigma_{t\bar{t}t\bar{t}} = 22.5^{+4.7}_{-4.3}(\text{stat})^{+4.7}_{3.4}(\text{syst})\ \text{fb} = 22.5^{+6.6}_{-5.6}\ \text{fb}$

Obs. (exp.) significance: (@ 13.4 fb - NLO+NLL'): **6.1** (4.7) σ

$\sigma_{t\bar{t}t\bar{t}} = 17.7^{+3.7}_{-3.5}(\text{stat})^{+2.3}_{1.9}(\text{syst})\ \text{fb} = 17.7^{+4.4}_{-4.0}\ \text{fb}$

Obs. (exp.) significance: (@ 13.4 fb - NLO+NLL'): **5.6** (4.9) σ

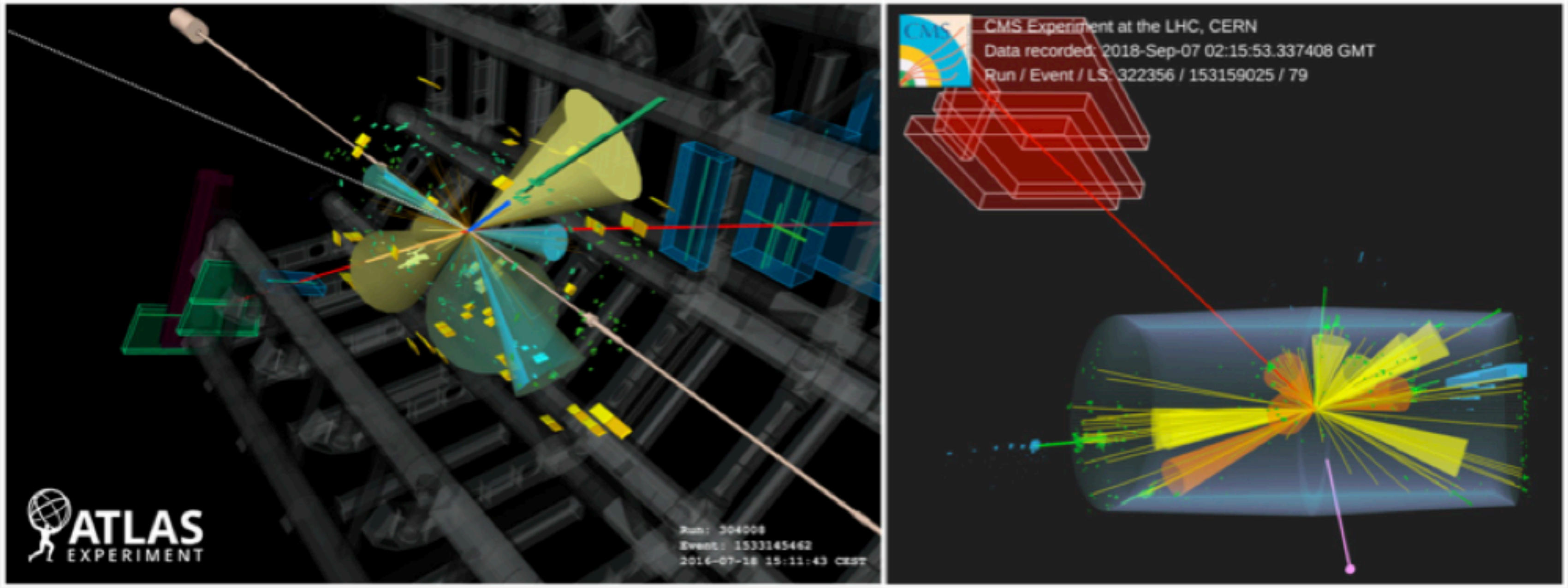




ATLAS and CMS observe simultaneous production of four top quarks

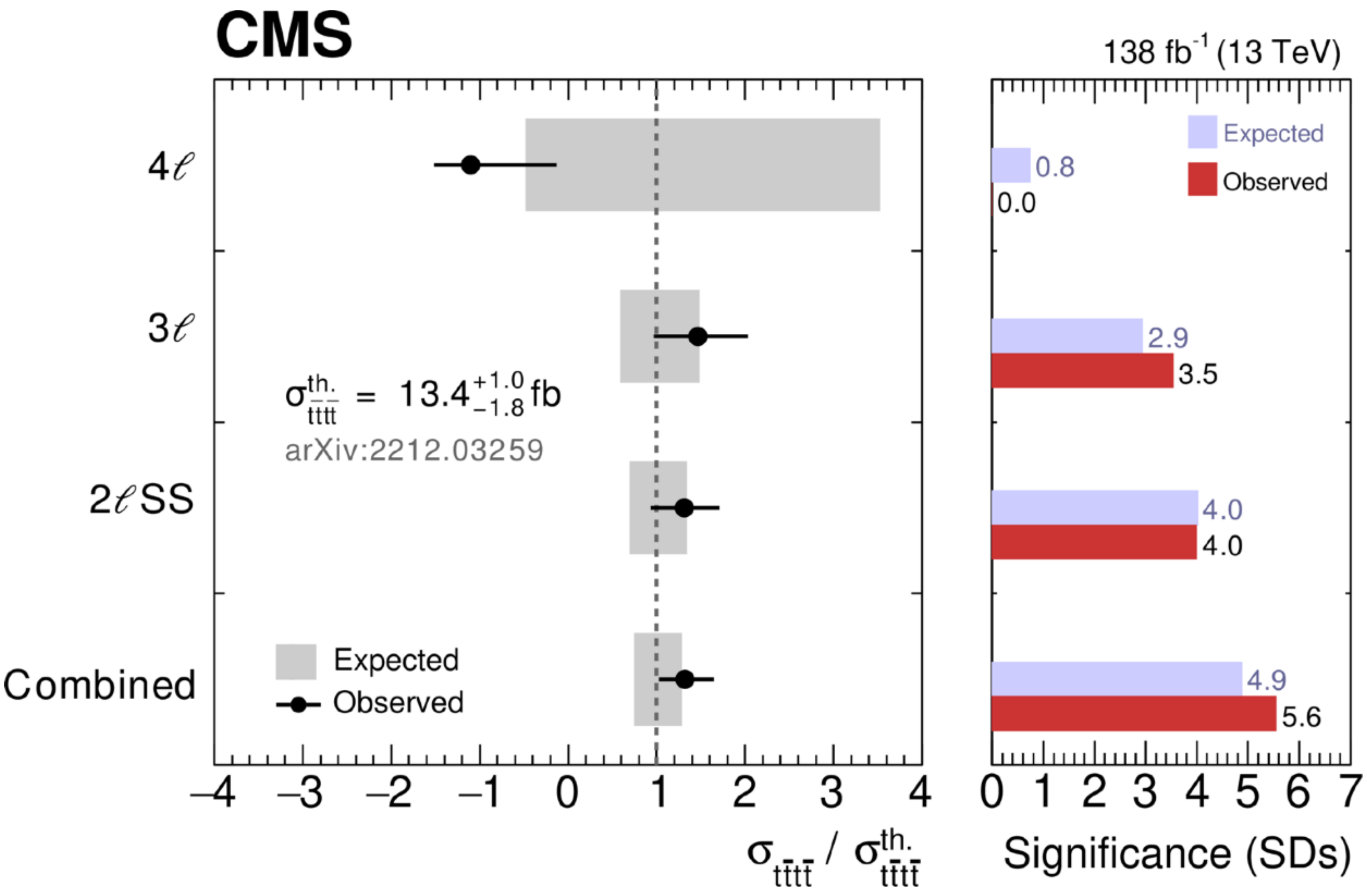
The ATLAS and CMS collaborations have both observed the simultaneous production of four top quarks, a rare phenomenon that could hold the key to physics beyond the Standard Model

24 MARCH, 2023 | By Naomi Dinmore



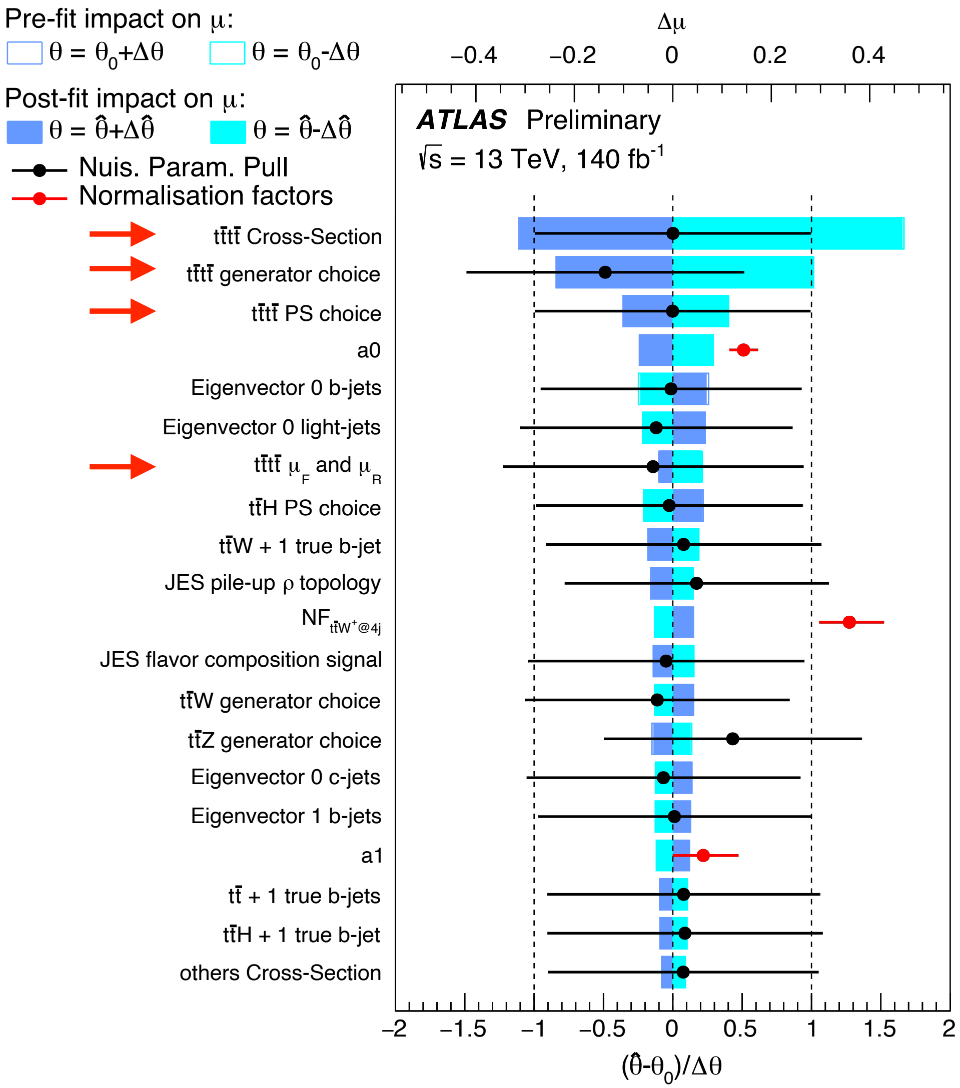
Event displays of four-top-quark production from ATLAS (left) and CMS (right).

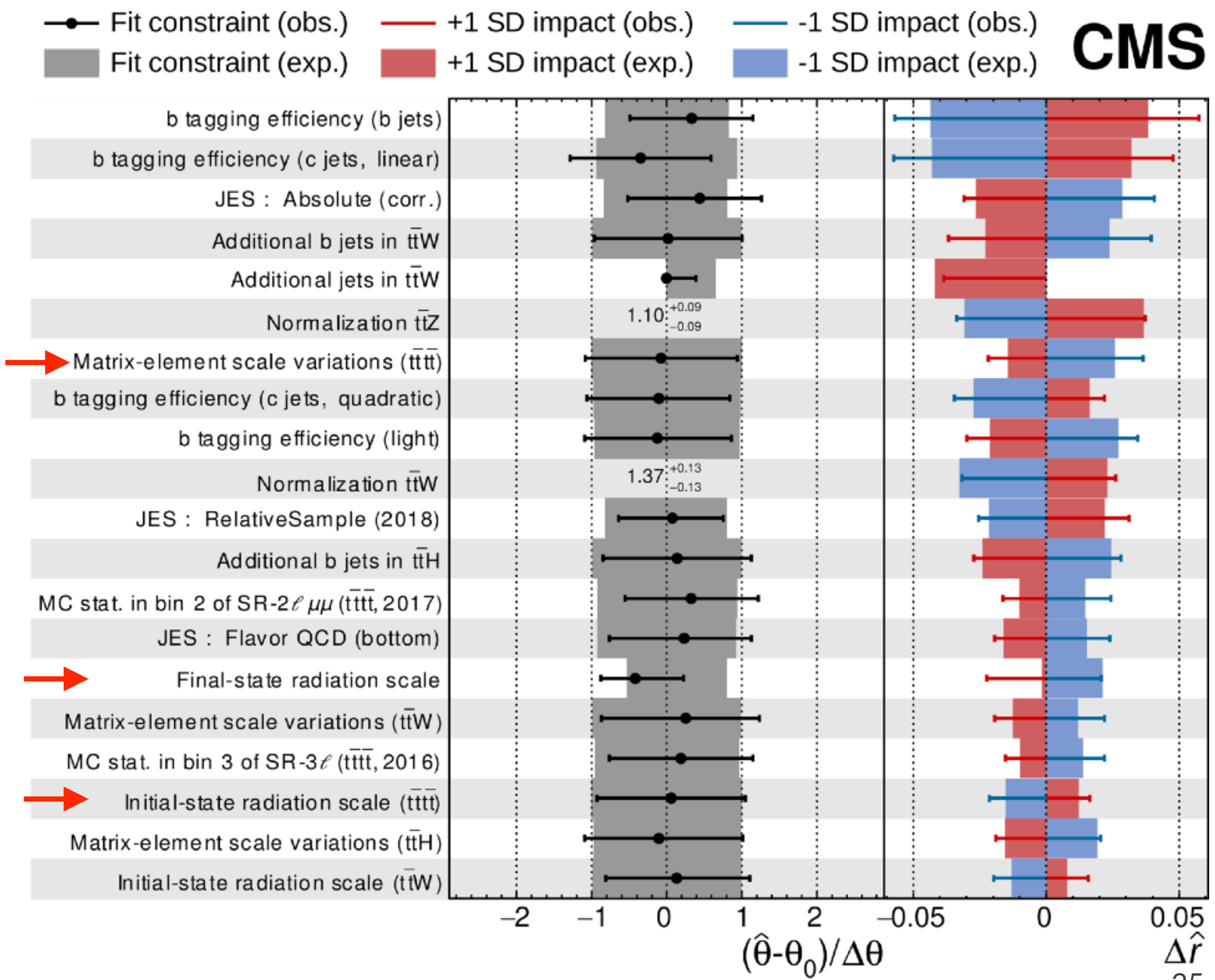
Best-fit values and significance per channel @ CMS



Ranking and pulls

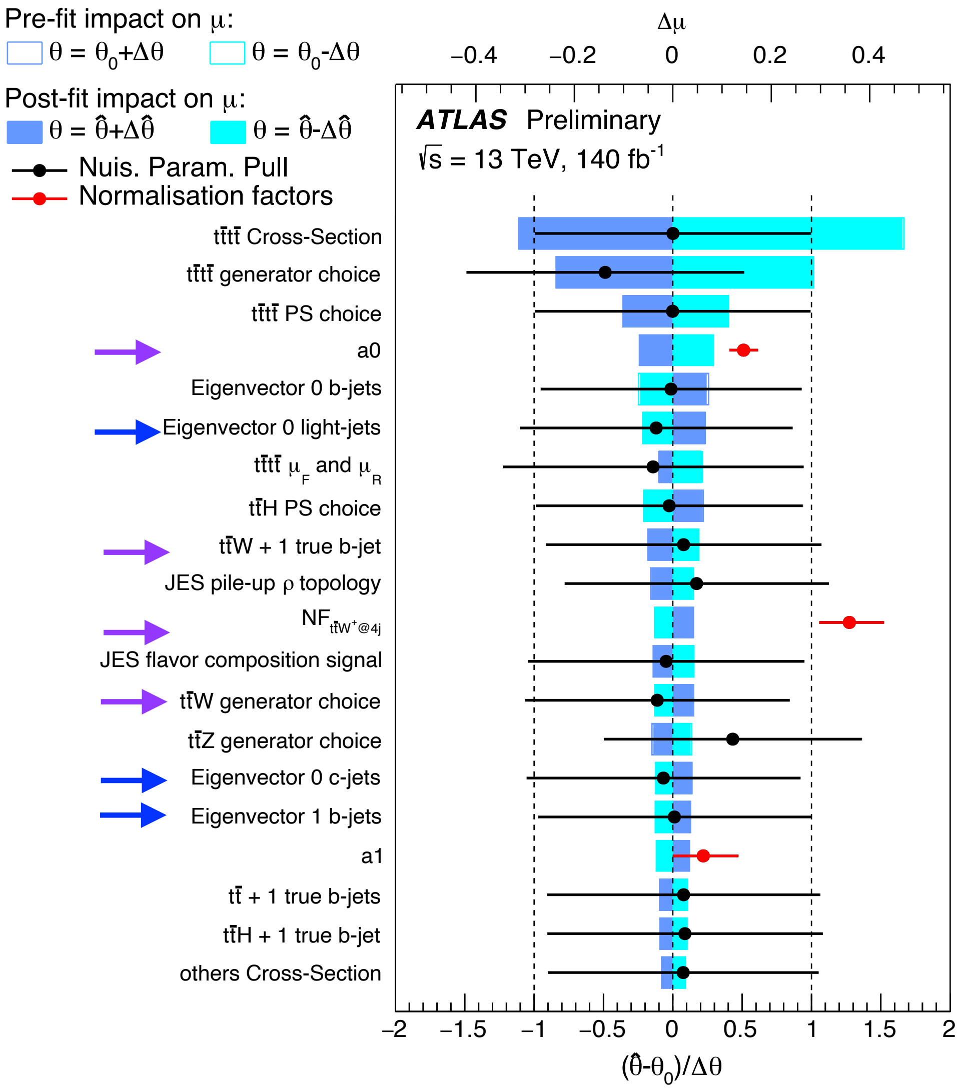
In ATLAS, signal modeling has large impact in the cross section measurement compared with CMS

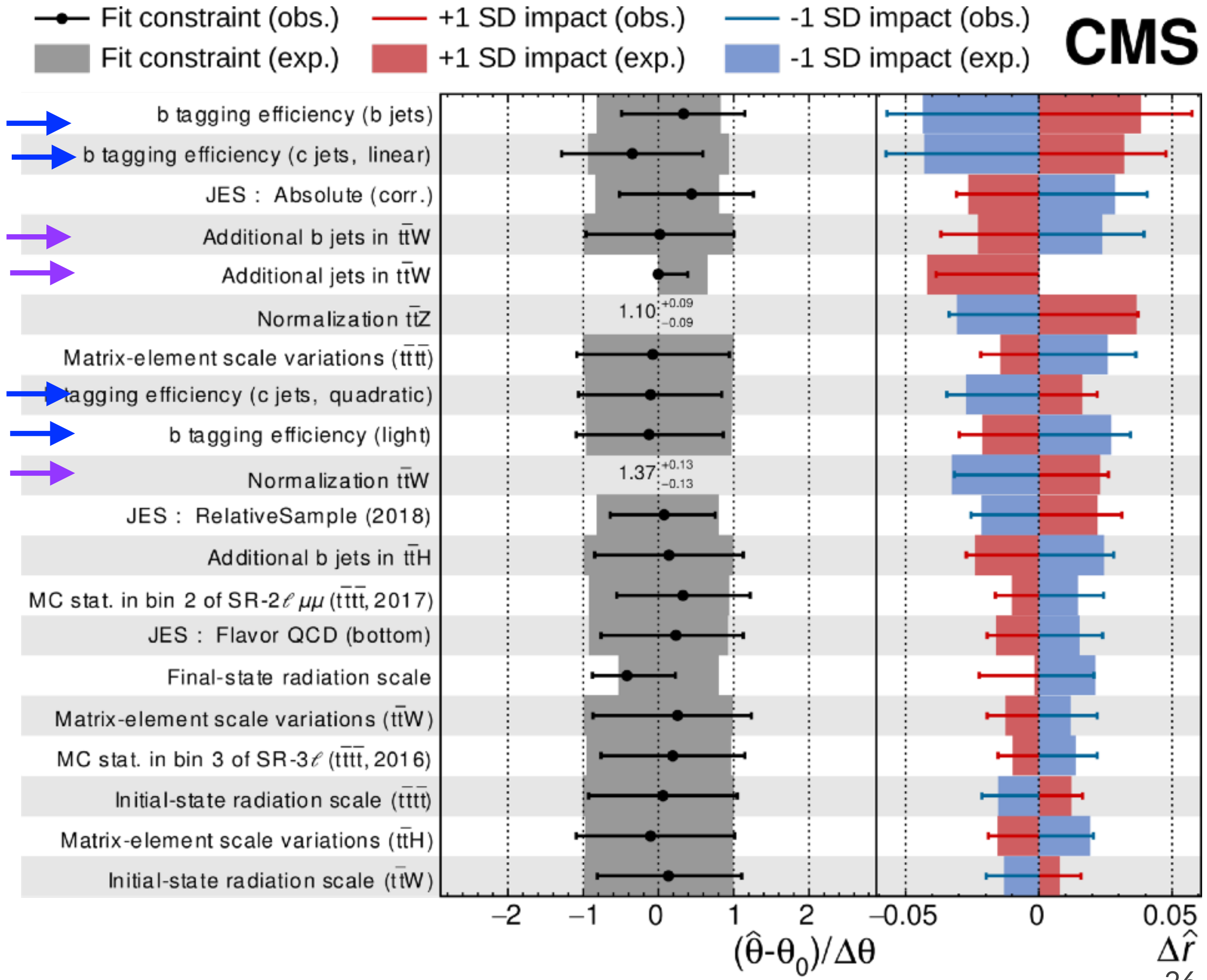




Ranking and pulls

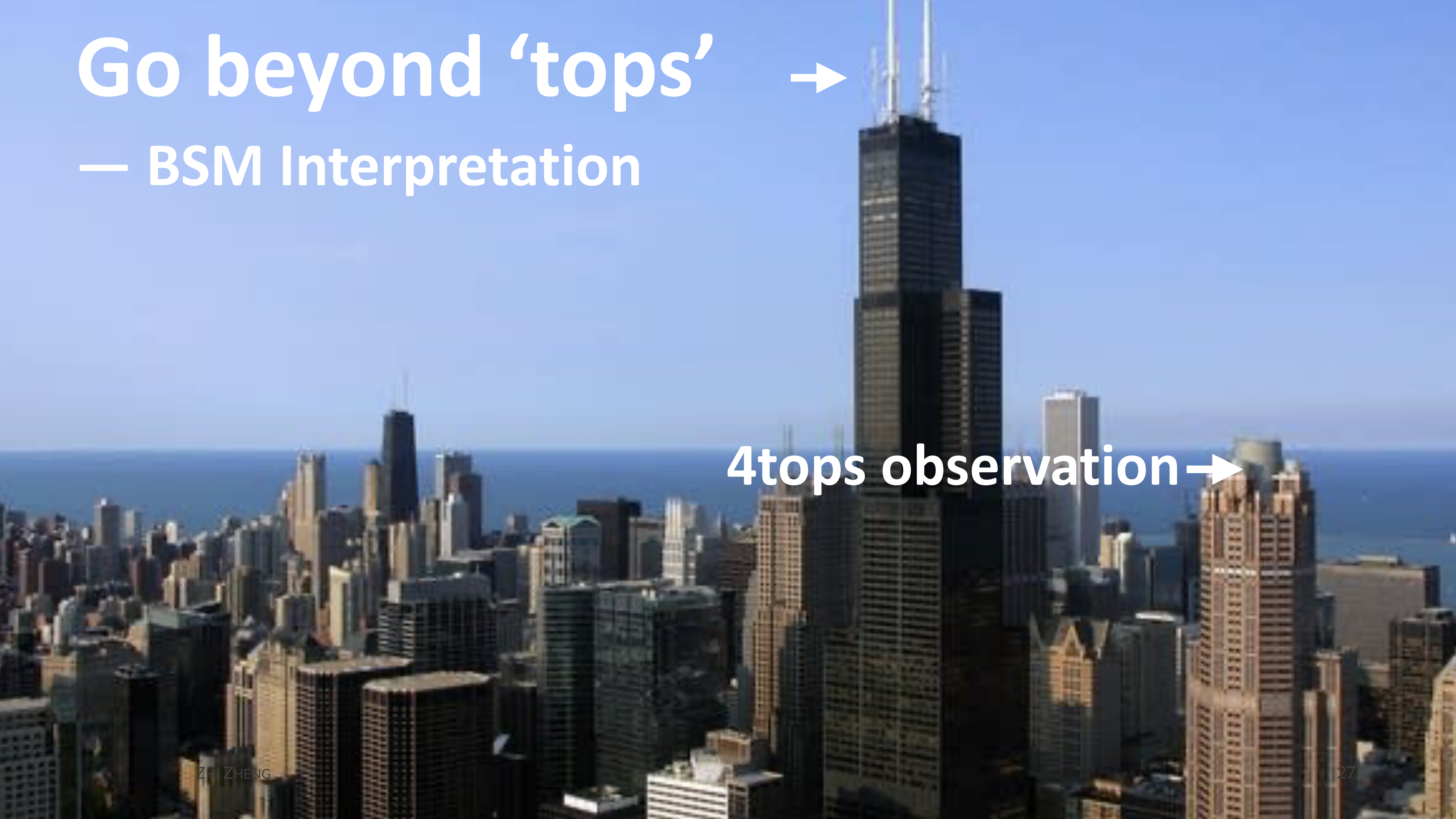
Leading impacts come from b-jets and $t\bar{t}W$ modeling in both CMS and ATLAS





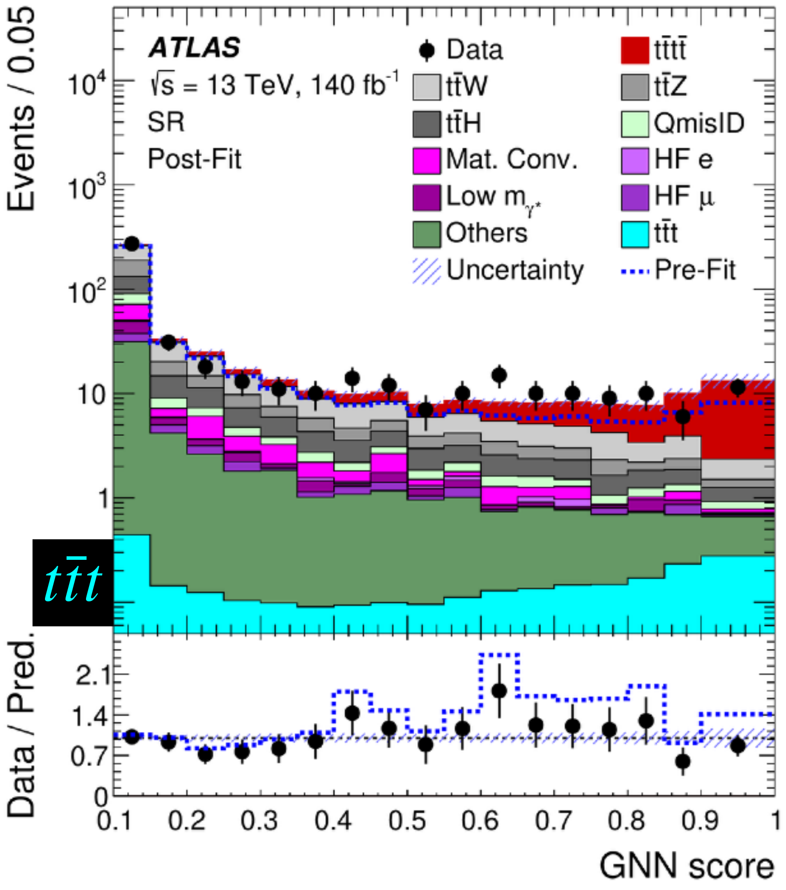
Go beyond 'tops' →

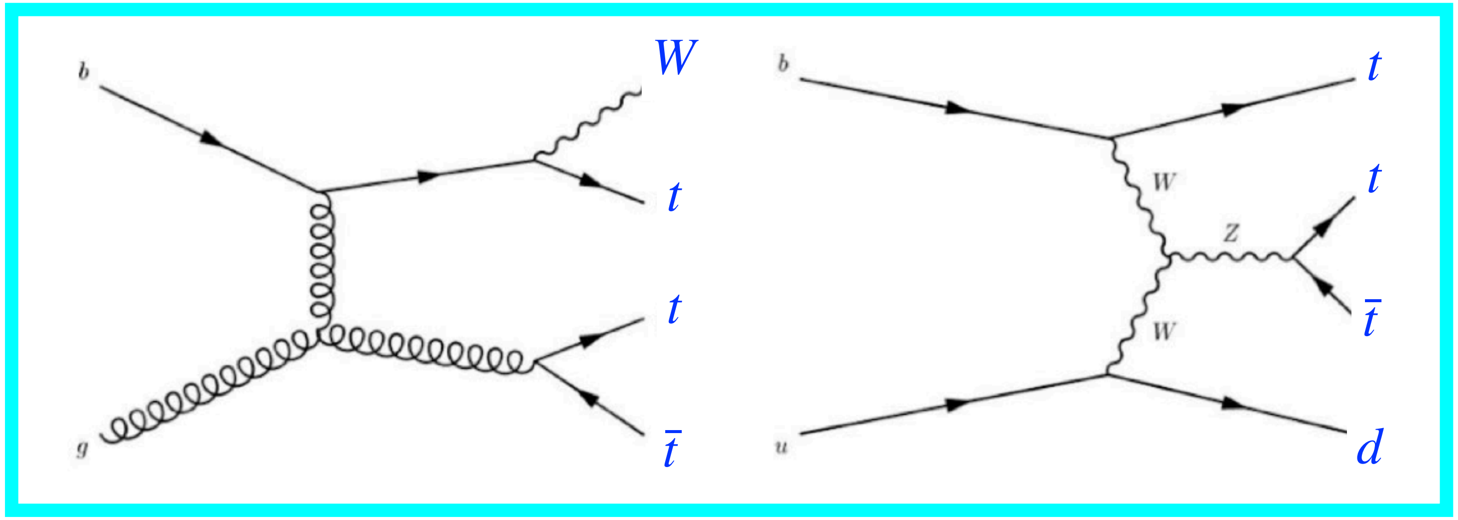
— BSM Interpretation



Result: $t\bar{t}t$ @ ATLAS

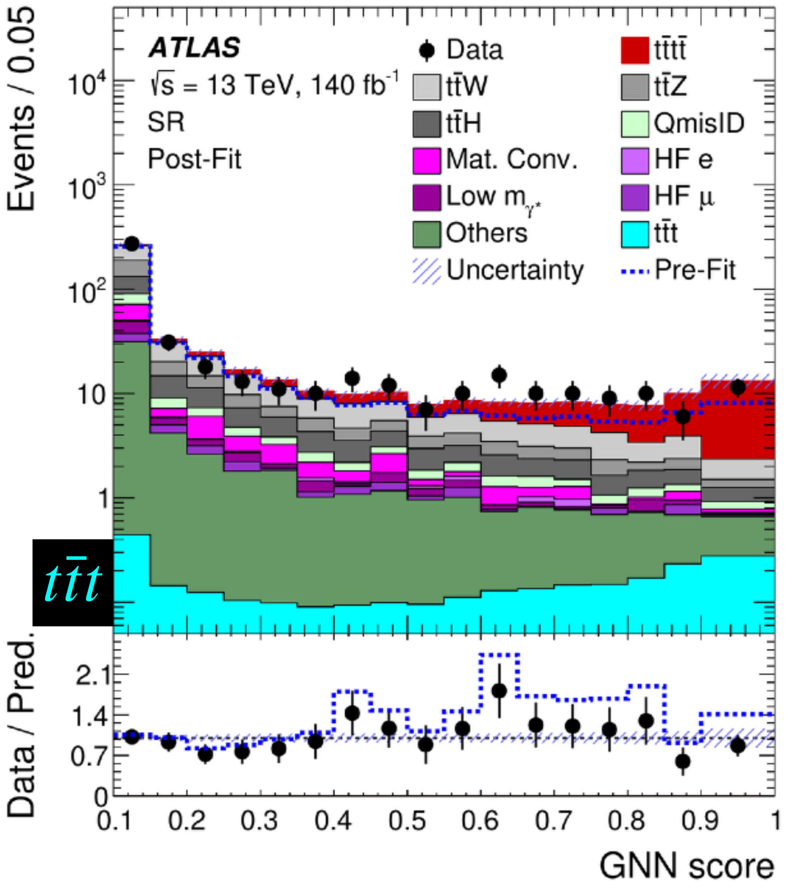
$t\bar{t}t$: final state similar as $t\bar{t}t\bar{t}$ and populates in region of high MVA score





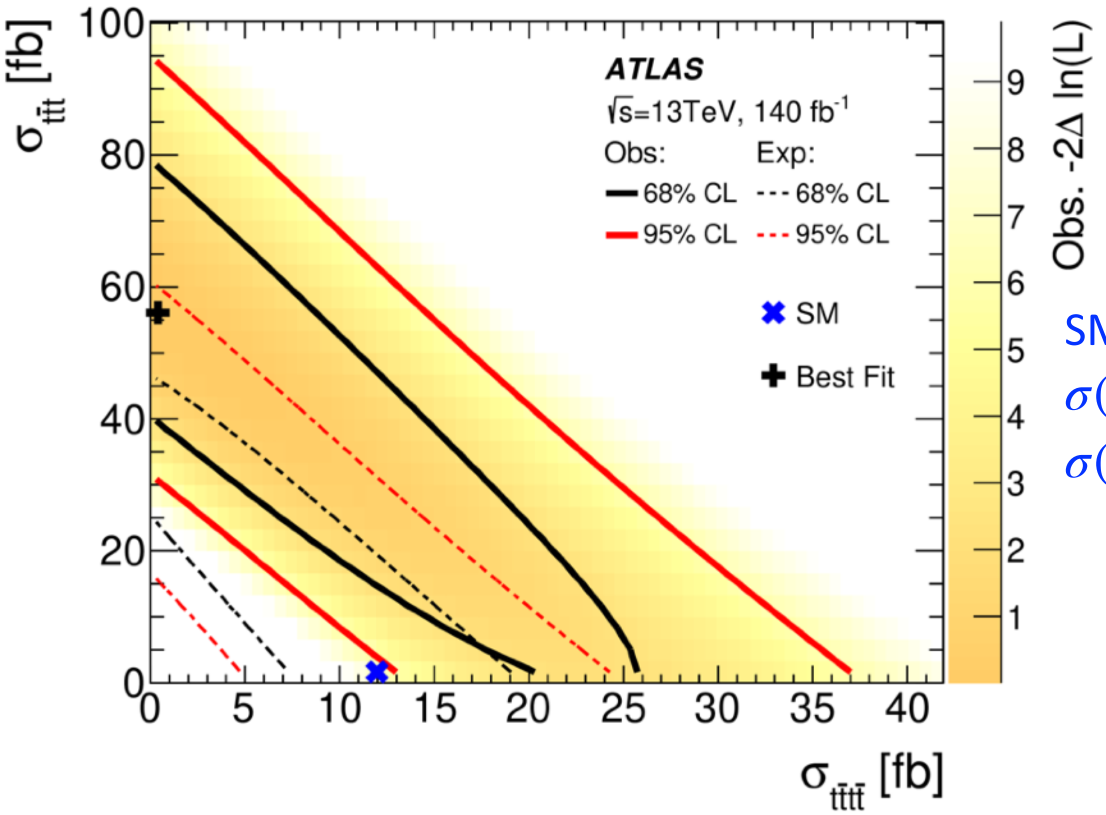
ATLAS: NLO QCD $\sigma(t\bar{t}tW) = 1.02$ fb $\sigma(t\bar{t}tq) = 0.65$ fb

Result: $t\bar{t}t$ @ ATLAS



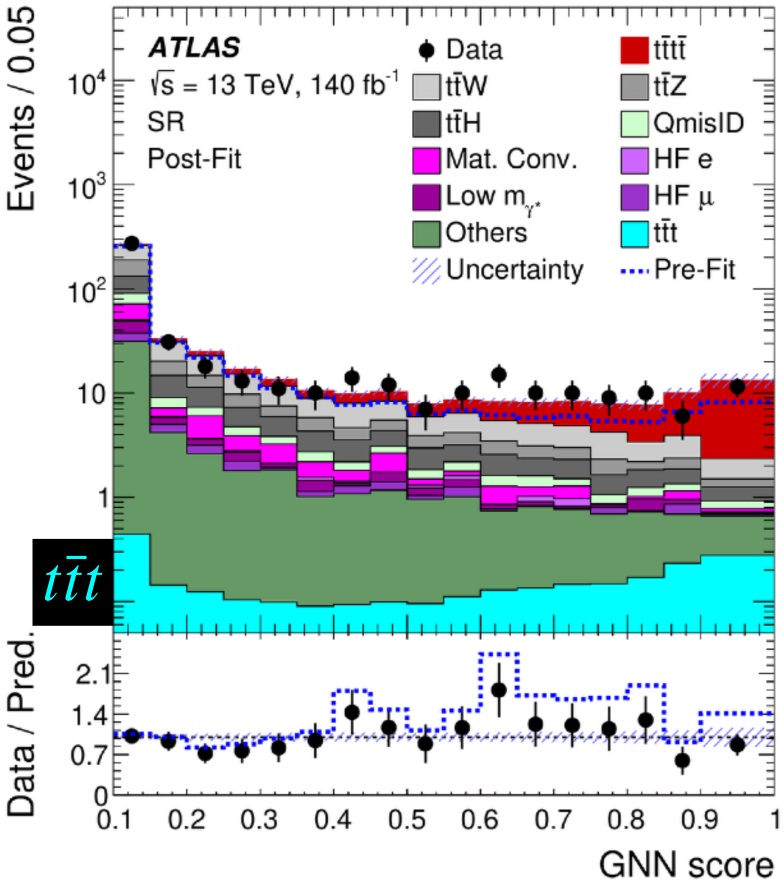
$t\bar{t}t$: final state similar as $t\bar{t}t\bar{t}$ and populates in region of high MVA score

If both $t\bar{t}t$ and $t\bar{t}t\bar{t}$ cross section are free parameters of the fit, anti correlation is -93%



SM:
$\sigma(t\bar{t}t\bar{t})$ =13.4 fb
$\sigma(t\bar{t}t)$ = 1.7 fb

Result: $t\bar{t}t$ @ ATLAS



$t\bar{t}t$: final state similar as $t\bar{t}t\bar{t}$ and populates in region of high MVA score

If both $t\bar{t}t$ and $t\bar{t}t\bar{t}$ cross section are free parameters of the fit, anti correlation is -93%

First limits on $t\bar{t}t$ production!

Processes	95% CL cross section interval [fb] $\mu_{t\bar{t}t\bar{t}} = 1$	$\mu_{t\bar{t}t\bar{t}} = 1.9$
$t\bar{t}t$	[4.7, 60]	[0, 41]
$t\bar{t}tW$	[3.1, 43]	[0, 30]
$t\bar{t}tq$	[0, 144]	[0, 100]

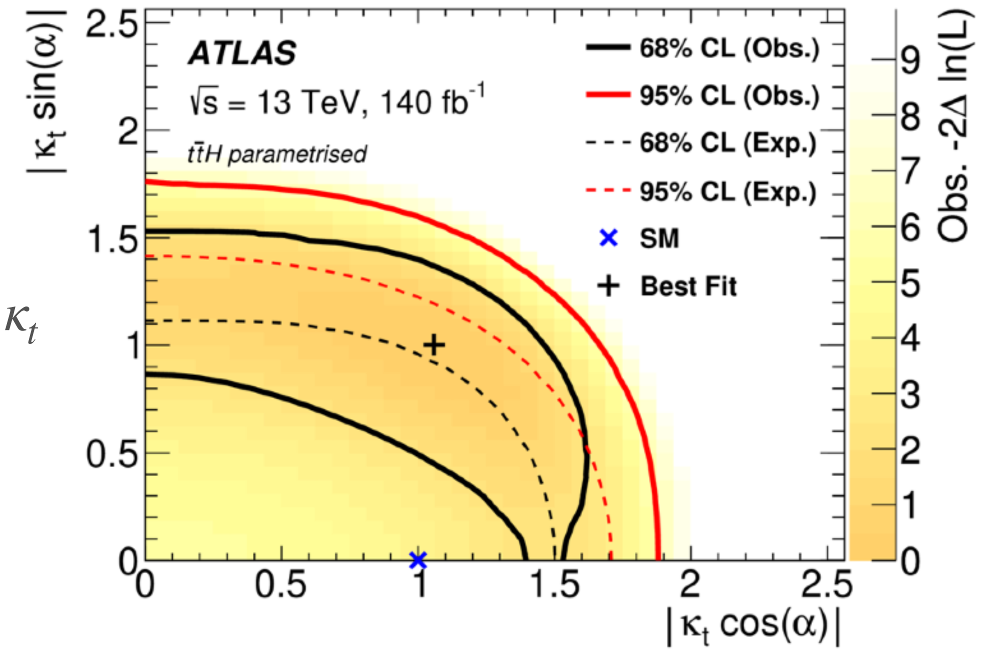
Interpretations @ ATLAS

Top yukawa coupling:

$$L = -\frac{1}{\sqrt{2}}\kappa_t \bar{t}(\cos(\alpha) + i\sin(\alpha)\gamma_5)th$$

CP even CP odd

CP even: Obs (exp.): $|\kappa_t| < 1.8$ (1.6) $t\bar{t}H$ parametrized in κ_t



Higgs oblique parameter $\hat{H}$ modifies propagator of SM Higgs in dim-6 EFT : $\hat{H} < 0.2$

Limits on heavy flavor fermion operators in EFT (one parameter variation)

* with improved limits highlighted

$$\sigma_{t\bar{t}t\bar{t}} = \sigma^{SM}_{t\bar{t}t\bar{t}} + \frac{1}{\Lambda^2}\sum_i C_i\sigma_i^{(1)} + \frac{1}{\Lambda^4}\sum_{i\leq j} C_iC_j\sigma_{i,j}^{(2)}$$

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

New ATLAS result
[Eur. Phys. J. C 83, 496 (2023)]
New CMS result:
[Arxiv:2305.13439]

Now and Future for four-tops

Observation of four-top-production achieved with Run 2 dataset in both CMS and ATLAS

- Improving objects
- Using advanced ML techniques

What is limiting:

- $t\bar{t}t\bar{t}$ and $t\bar{t}W$ and $t\bar{t}$ modeling
- Performance side: b-tagging has the largest instrumental impacts

Moving to Run 3:

- Better signal over background ratio
  ➡ ~20% increase in $t\bar{t}t\bar{t}$ cross section vs only 11% for $t\bar{t}$, ~15% for $t\bar{t}X$ backgrounds
- Improvements in objects (etc. b-tagging) and analysis techniques
- Exploring beyond-the-SM interpretations with $t\bar{t}t\bar{t}$ phase space

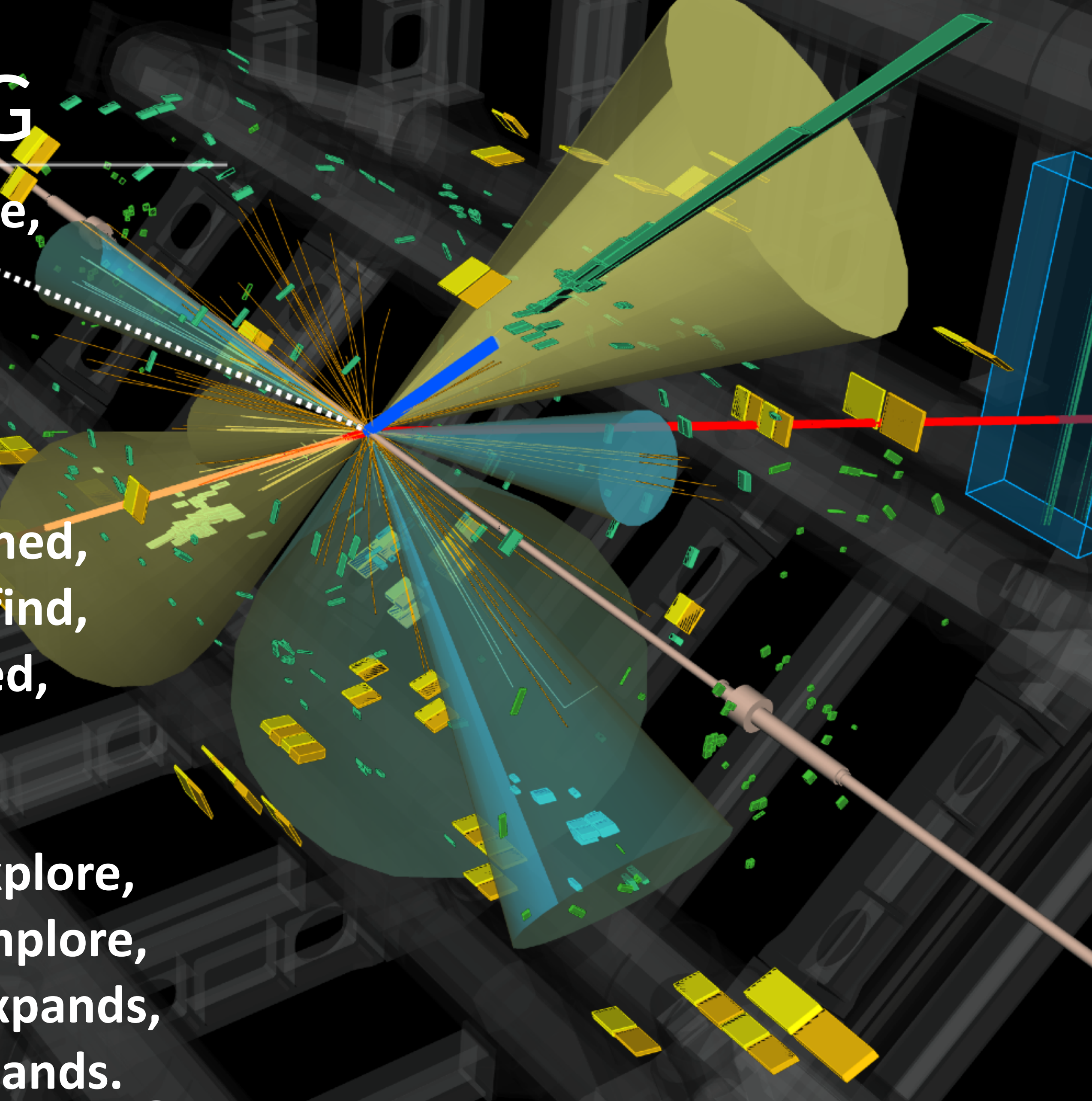
THANKS FOR LISTENING

In the LHC's depths, where particles dance,
4tops quarks emerge, a rare chance,
Heaviest of all, the secrets they hold,
The universe's mysteries, soon to unfold.

Advancements in techniques, signals refined,
With Graph Neural Networks, clarity we find,
Six point one standard deviations amassed,
A threshold surpassed, discovery at last.

New doors now opened, as we further explore,
The cosmic labyrinth, seeking truths to implore,
With future endeavors, our knowledge expands,
Unveiling the secrets, the universe commands.

—— ChatGPT-4



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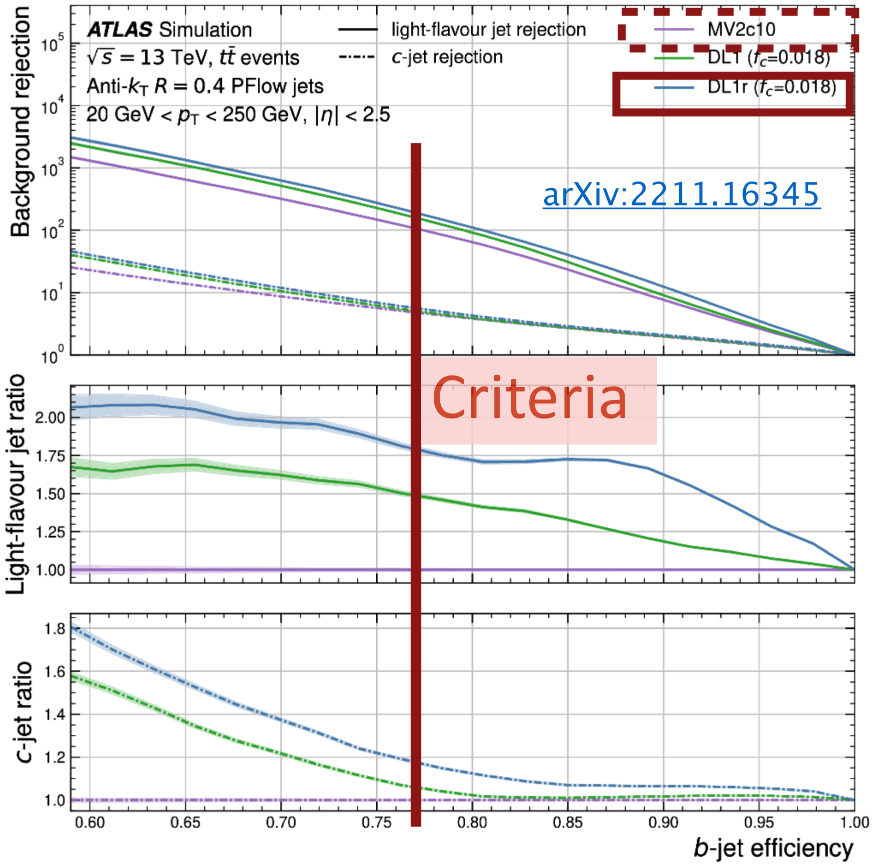
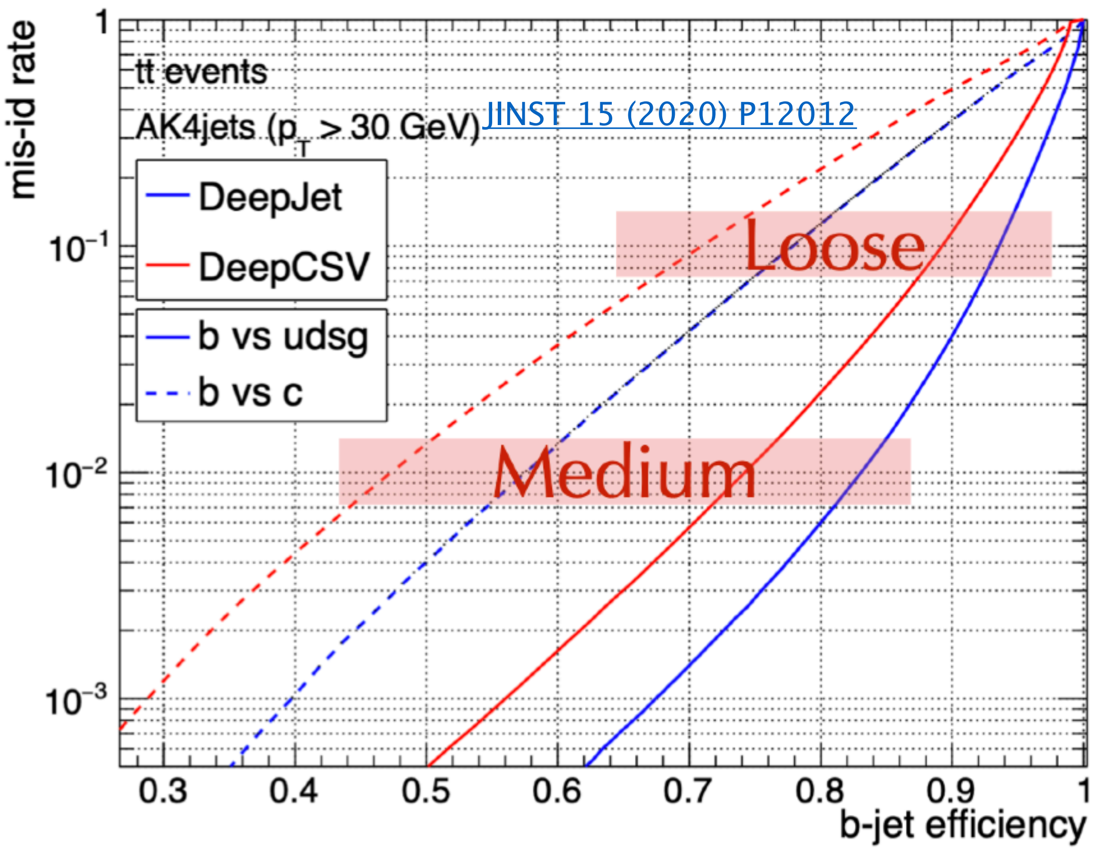
Path to improve: Jets

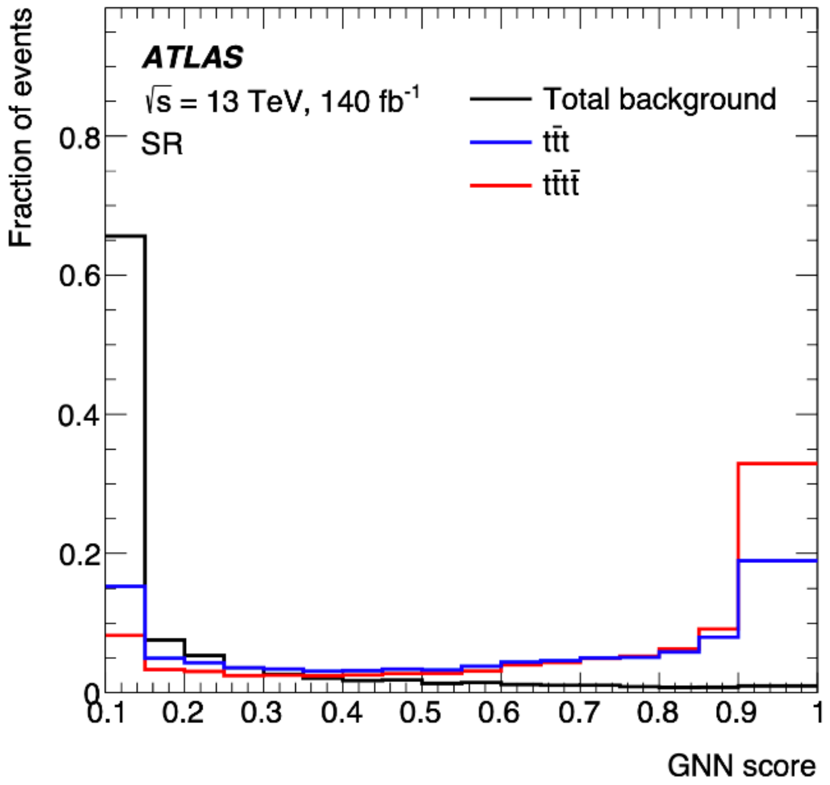
Both CMS and ATLAS **lower p_T jets to improve the 4tops acceptance**

Using Improved B-tagging algorithm to reduce background



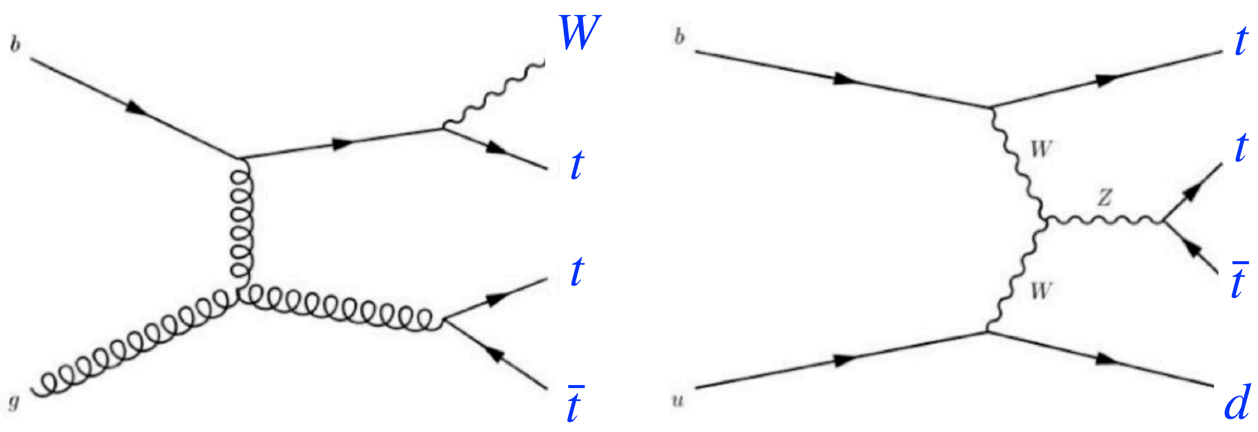


Results: $t\bar{t}t$



$t\bar{t}t$: final state similar as $t\bar{t}t\bar{t}$ and populates in region high MVA scores

In SM $t\bar{t}t$ produced always with other particles

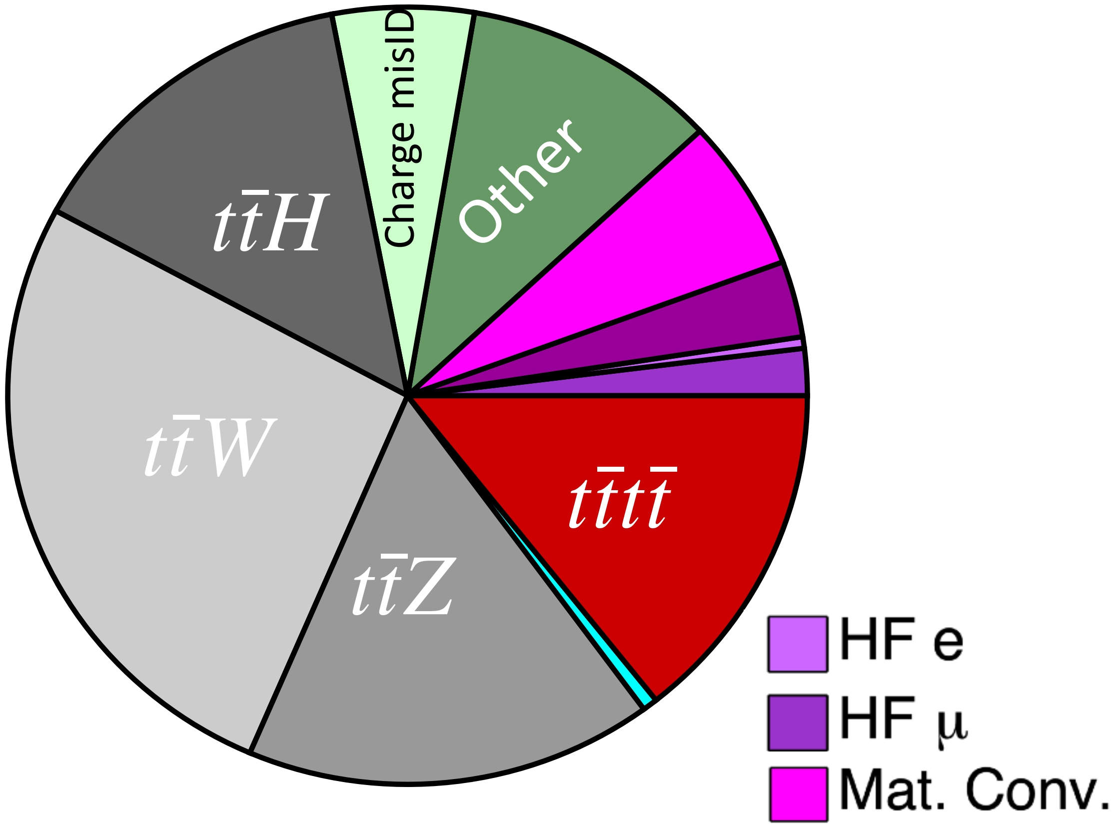


ATLAS: NLO QCD $\sigma(t\bar{t}tW) = 1.02$ fb $\sigma(t\bar{t}tq) = 0.65$ fb

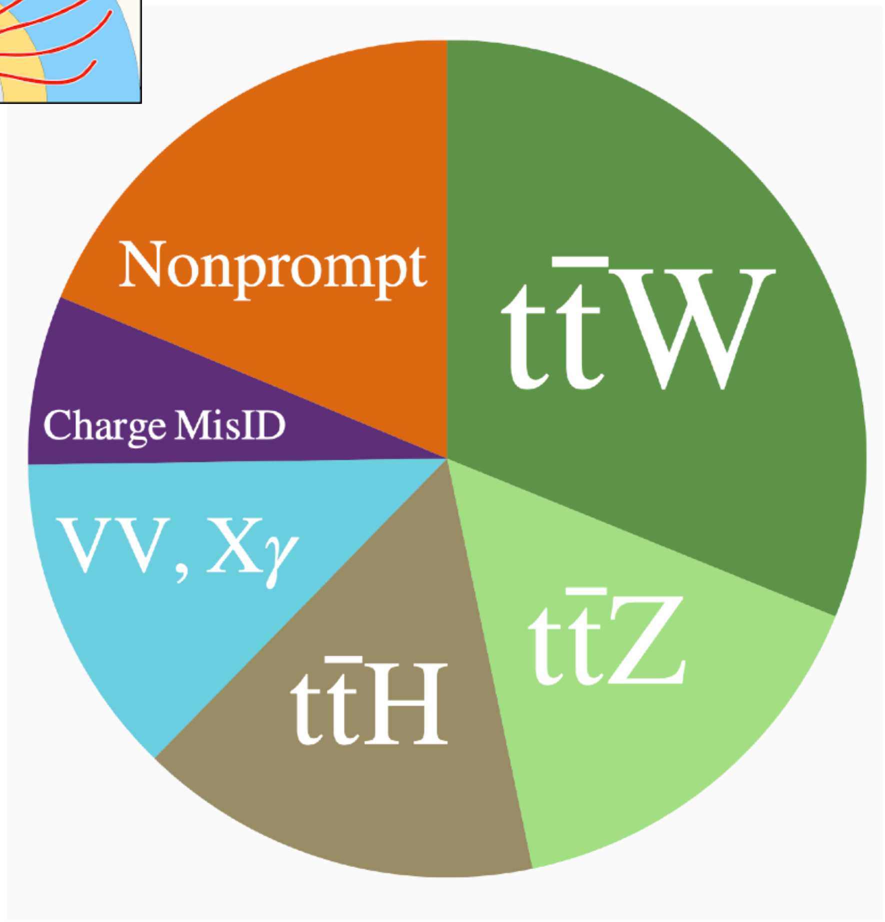
CMS: NLO QCD+LO EW $\sigma(t\bar{t}tW) = 1.3$ fb $\sigma(t\bar{t}tq) = 0.7$ fb

Uncertainty: ATLAS 35%, CMS 20%

Background



$t\bar{t}H$
Charge misID
Other
$t\bar{t}W$
$t\bar{t}Z$
$t\bar{t}t\bar{t}$
HF e
HF μ
Mat. Conv.



Nonprompt
$t\bar{t}W$
Charge MisID
VV, Xγ
$t\bar{t}H$
$t\bar{t}Z$

ATLAS EXPERIMENT

$p_T > 28$ GeV, $|\eta|<2.5$

$p_T > 25$ GeV, $|\eta|<2.5$
b-jet identification with MV2c10

$p_T > 15$ GeV, $|\eta|<2.5$
$p_T(l1) > 28$ GeV for trigger requirement
Using improved isolation from BDT

$p_T > 20$ GeV, $|\eta|<2.5$
b-jet identification with DL1r; efficiency 77% WP for b-jets, only ~17% for c-jets

Change

Old selection:

Lepton

Jet

New selection

Lepton

Jet

CMS

$p_T > 20$ GeV, $|\eta|<2.5$

$p_T > 40$ GeV
b-jets: $p_T > 25$ GeV (DeepCSV)

$p_T > 10$ GeV, $|\eta|<2.5$
$p_T(l1) > 25$ GeV, $p_T(l2) > 20$ GeV for triggers
Using improved isolation

$p_T > 25$ GeV, $|\eta|<2.4$
b-jet identification with RNN (DeepJet)

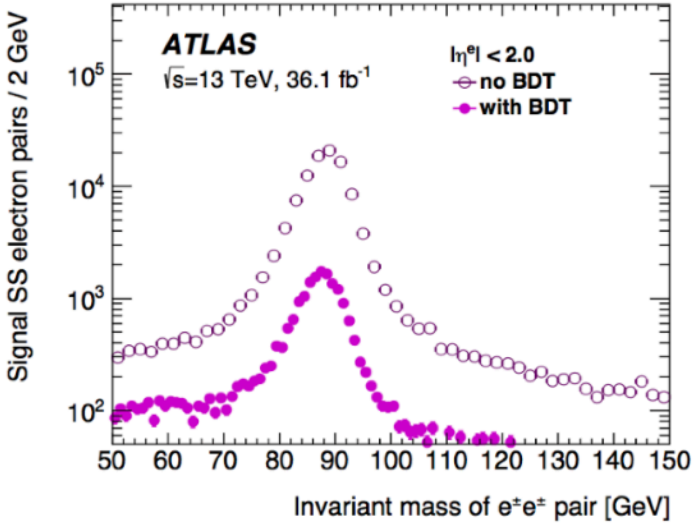
Lepton selection

ATLAS

pT> 15 GeV, |η|<2.5

pT(l1) > 28 GeV for trigger requirement

BDT to reduce mis-identification rate with calo/track quantities



Base cuts

Trigger thresholds

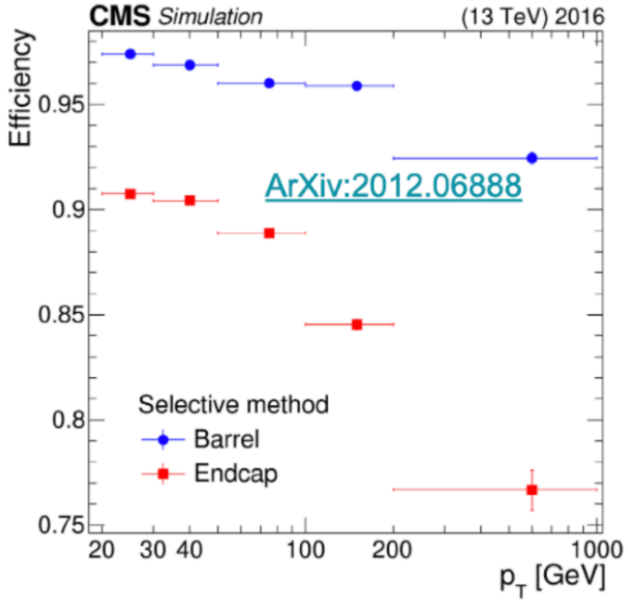
Charge mis-identification

CMS

pT> 10 GeV, |η|<2.5

pT(l1) > 25 GeV, pT(l2) > 20 GeV for triggers

- Three charge measurements are performed for any electron in CMS
- Usually majority vote for charge assignment
- In this analysis require all to be consistent



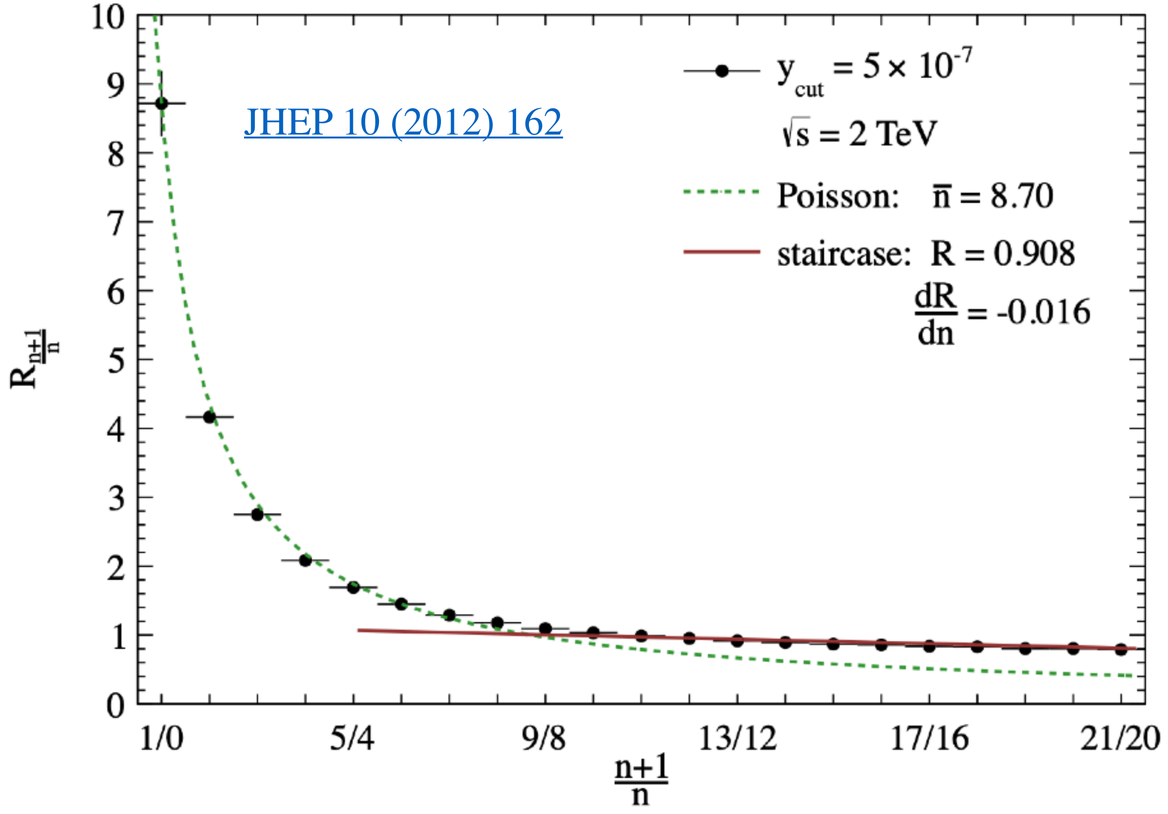
$t\bar{t}W$ data driven method @ ATLAS

N_{jet} distribution is parametrized making use of known jet scaling regimes

- $R(j) = N(j+1)/N(j)$, j is the jet multiplicity
- $R(j) = a_0$ for very high jet multiplicities
- $R(j) = a_1/(1+n)$, n is the number of extra jets

Separate normalizations (NFs) for $t\bar{t}W^+$ and $t\bar{t}W^-$: $\text{NF}_{t\bar{t}W^+(4\text{jet})}$, $\text{NF}_{t\bar{t}W^-(4\text{jet})}$

Scaling patterns for QCD jets



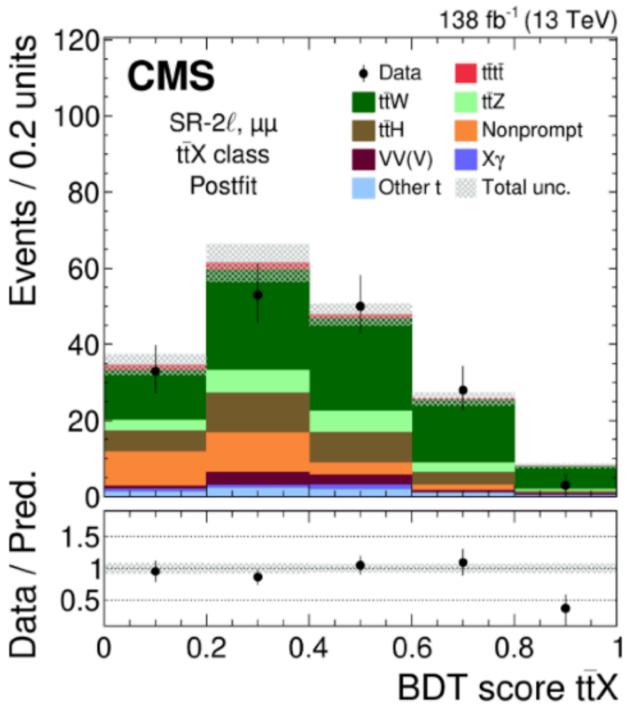
ttW comparison

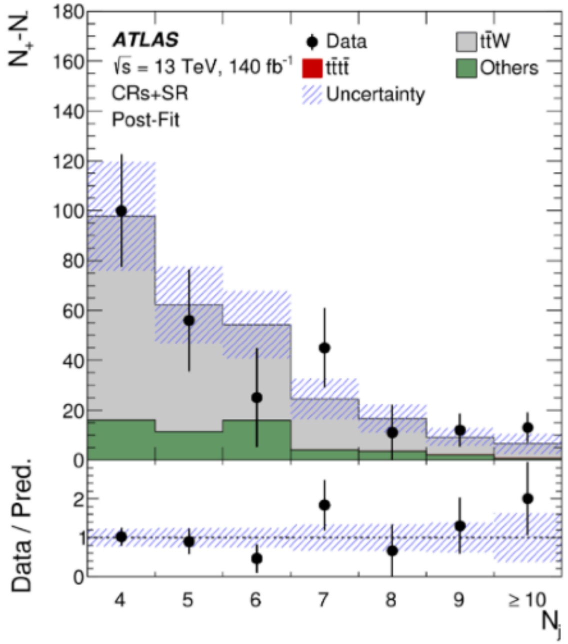
Similarities:

- Same central cross section of 722 fb
- Additional uncertainty on **ttW+b(b)**
  - 40% in CMS, 50% in ATLAS
- Modelling problems at **high NJets**
  - Additional uncertainty in CMS result
  - Using Njets parameterization in ATLAS

Differences:

- Samples:
  - **Sherpa** multileg sample + **EW contribution** in ATLAS
    - MG FxFx+ EW contribution as alternative sample used in systematics
  - **MG FxFx** sample in CMS
- Normalization free floating vs NJets parameterization
  - Additional uncertainty in CMS result from EW corrections
  - SF in CMS: 1.37 vs SF (=post-fit/pre-fit in SR) in ATLAS: 0.98
    - Samples are different, derived regions are different





Triple top treatment

Cross sections and uncertainty

Samples

ATLAS EXPERIMENT

Central value: 1.67 fb (NLO QCD)

- Normalization uncertainty of **35%**
  - 4FS vs 5 FS, EW contribution, scale variation
- Scale variations (shape)

σ(tttq) = 0.65 fb
σ(tttW) = 1.02 fb

MG LO sample with 5FS

CMS

Higher central value: 2 fb (NLO QCD + **LO EW**)

- Normalization uncertainty of **20%**
- Scale/PDF variations (shape)

σ(tttq) = 0.7 fb
σ(tttW) = 1.3 fb

MG LO sample with 5 FS

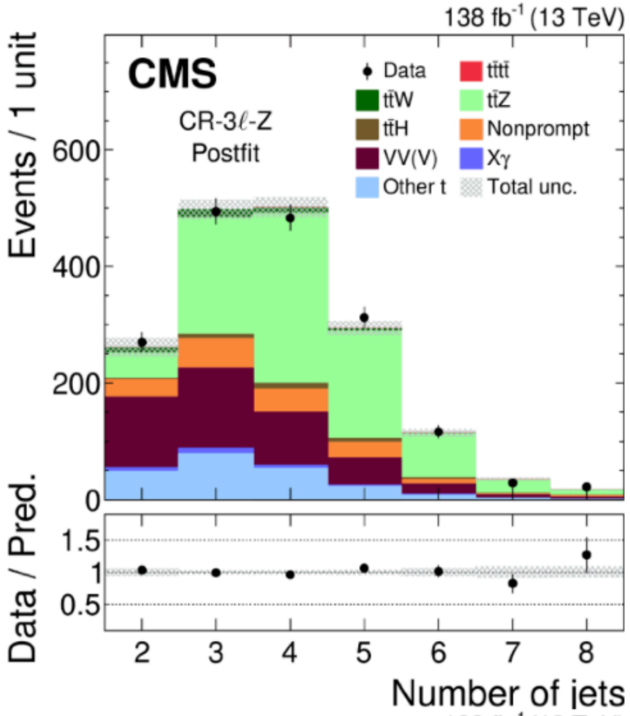
ttZ in CMS

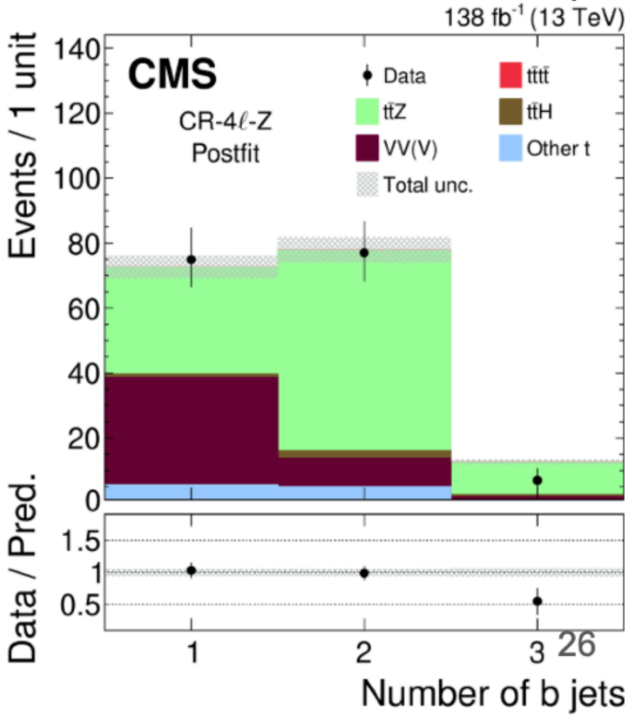
Two **on-Z control regions** (in 3 and 4 lepton channels):

- Allows for **free-floating ttZ** normalization in fit
  - Postfit normalization: 945 ± 81 fb
  - Compatible and competitive with 2016+2017 CMS measurement
  - Signal strength of **1.10 (w.r.t. SM prediction)**
- Allows for better constraints on **WZ & ZZ with additional (b)-jets**
  - Scale factor as a function of NJets applied and can be constrained
- Additional contributions from rare top backgrounds can be constrained (tZq, tWZ)

Modelling and additional uncertainties:

- Sample: NLO QCD (MG) + P8 (mll > 10 GeV)
- 40% uncertainty on **ttZ+b(b)**





ttZ in ATLAS

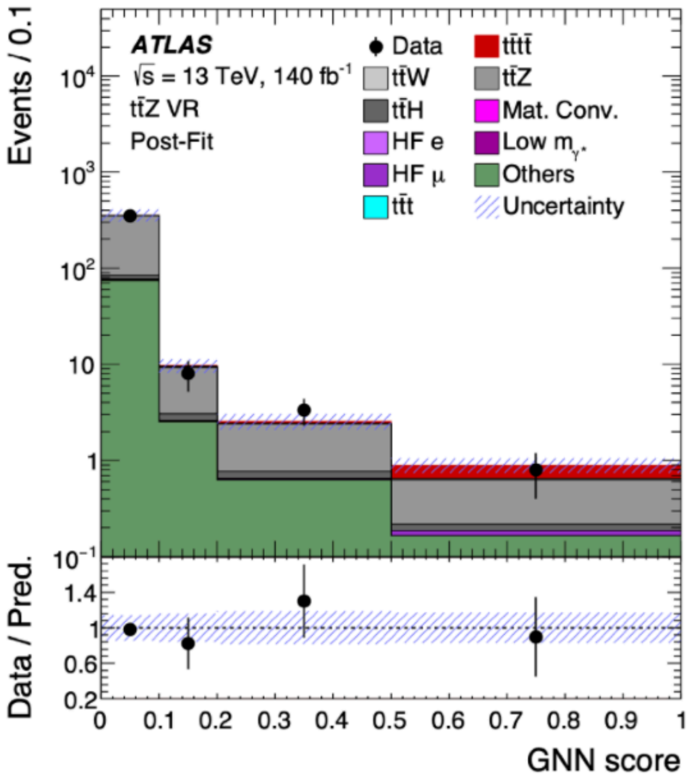
Sample: NLO MG+P8 (m(ll)>1GeV modelled in ME)

Normalization fixed in analysis: checked in ttZ Validation Region

Uncertainties:

- 12% on **normalization**
- Scale/PDF variations
- Generator comparison: Sherpa vs MG
- 50% for **ttZ+b/bb**

3L with on-Z requirement
Nj>= 6
Nb-j >= 2

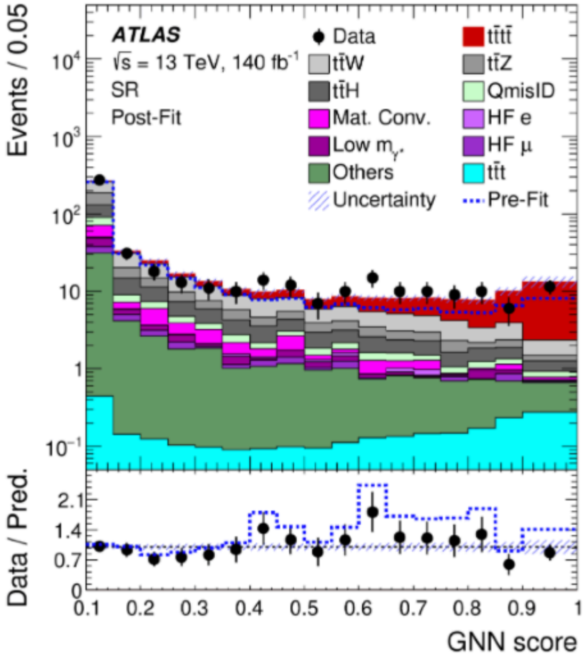


ATLAS EXPERIMENT

$$\sigma_{t\bar{t}t\bar{t}} = 22.5^{+4.7}_{-4.3}(\text{stat})^{+4.7}_{3.4}(\text{syst})\ \text{fb} = 22.5^{+6.6}_{-5.6}\ \text{fb}$$

Total uncertainty: +29%, -25%
Systematic: +21%, -15%
Statistical: +21%, -19%

6.1 (4.7)σ



Results: overview

Central result

Relative uncertainty

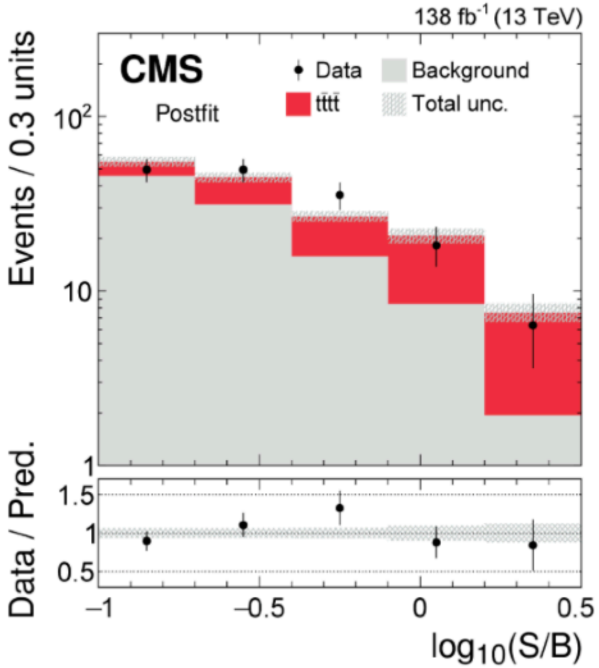
Obs. (exp.) significance (@ 13.4 fb - NLO+NLL')

CMS

$$\sigma(t\bar{t}t\bar{t}) = 17.7^{+3.7}_{-3.5}(\text{stat})^{+2.3}_{-1.9}(\text{syst})\,\text{fb} = 17.7^{+4.4}_{-4.0}\,\text{fb}$$

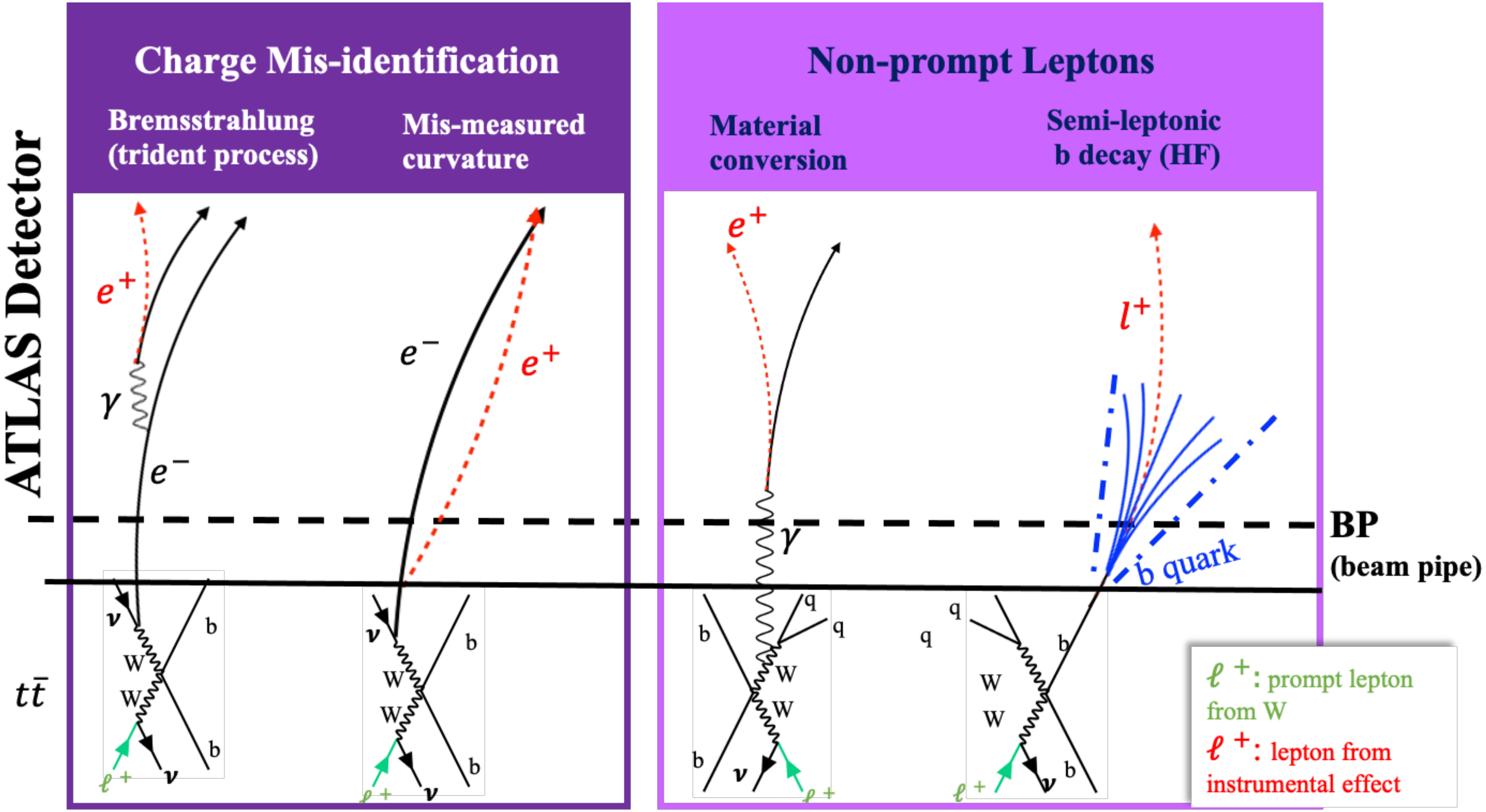
Total uncertainty: +25%, -23%
Systematic: +13%, -11%
Statistical: +21%, -20%

5.6 (4.9)σ



Instrumental background

Mainly arise from $t\bar{t}$

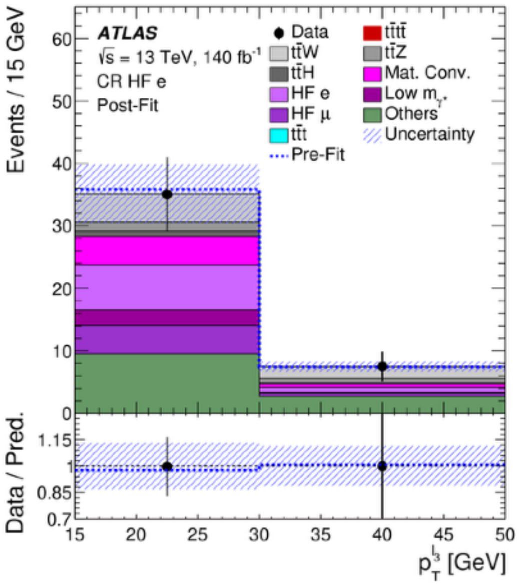


Background: Non-prompt leptons @ ATLAS

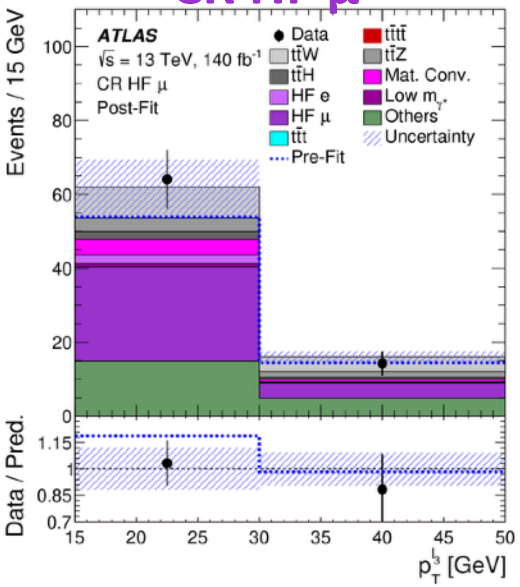
General Ideas: Fit to data in CRs to estimate the normalization of backgrounds

- Rely on Monte Carlo simulation for shapes for different components
- 4 normalization factors are allowed to float in the fit:
  - **HF e, HF μ, Mat. Conv., virtual photon conversion (low $m_{\gamma*}$)**
- 4 Dedicated CRs are defined to constrain normalization factors

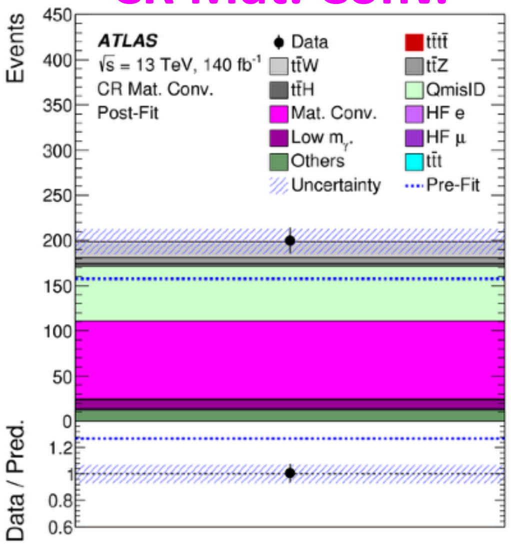
CR HF e



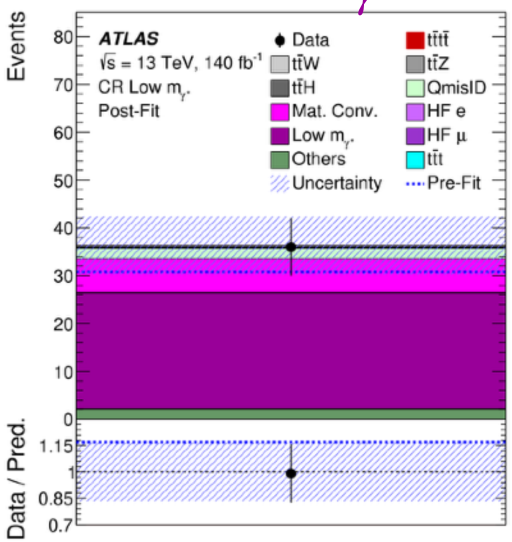
CR HF μ



CR Mat. Conv.



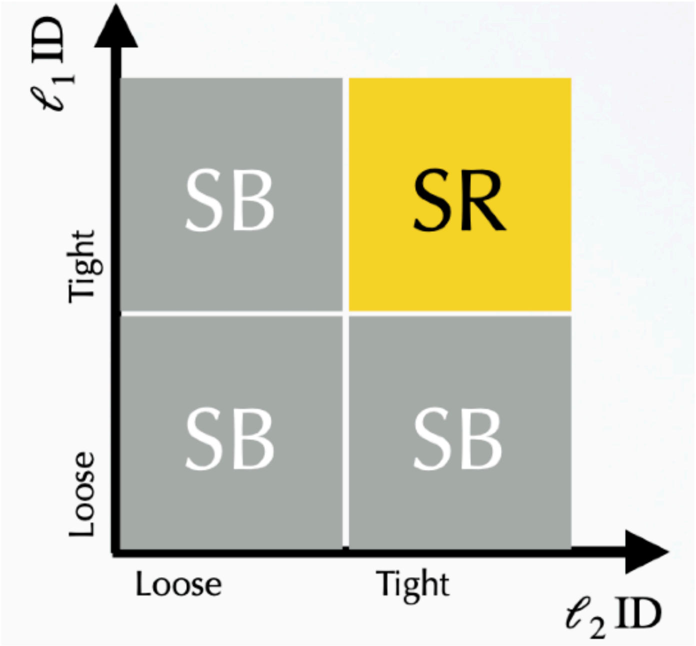
CR low $m_{\gamma*}$

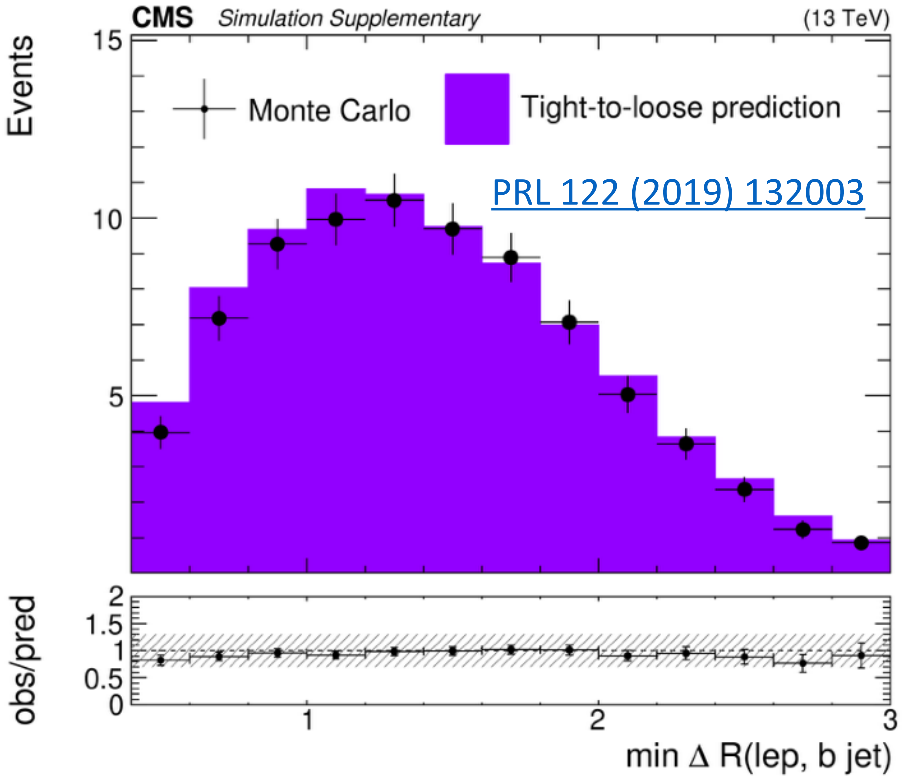


Background: Non-prompt leptons @ CMS

Use tight-to-loose ratio method

- Fake rates (FRs) measured in QCD multijet events in data
- **Validate FRs** (from QCD MC) in $t\bar{t}$ and DY (Drell Yan) MC
- Apply measured fake rates in **application region** using looser lepton ID





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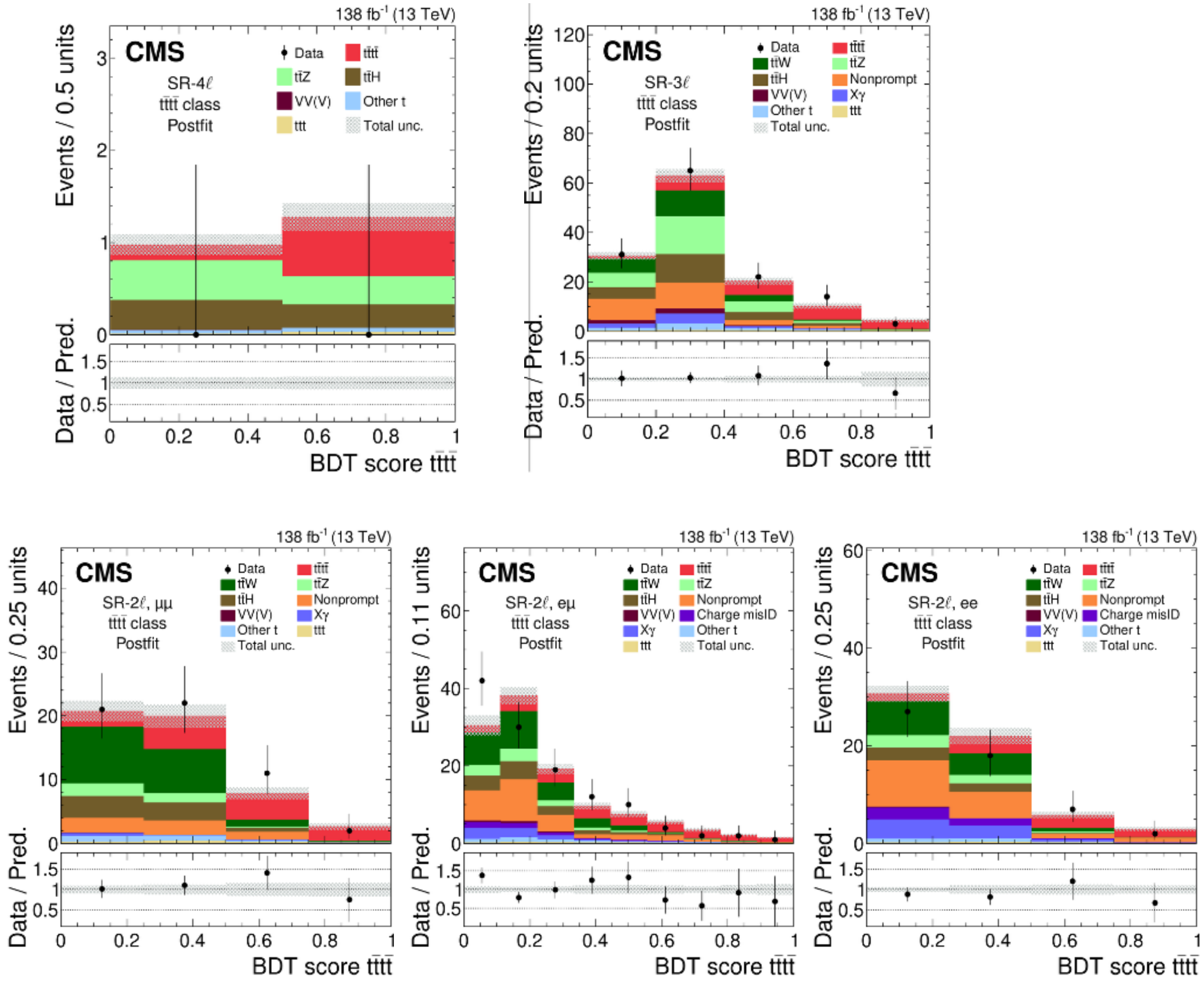
Signal Regions @ CMS



Result: interpretation

Top Higgs Yukawa coupling

ATLAS Higgs coupling comb.: kappa_t 95% CL limit of 0.81-1.25 (0.85-1.42 exp)
This analysis: <1.8 (<1.6 exp) for ttH+tttt, and **<2.2 (<1.8) for tttt only**
Top Higgs CP: