Observation of Four Top Quark Production in the ATLAS Experiment

Top LHC France 2023

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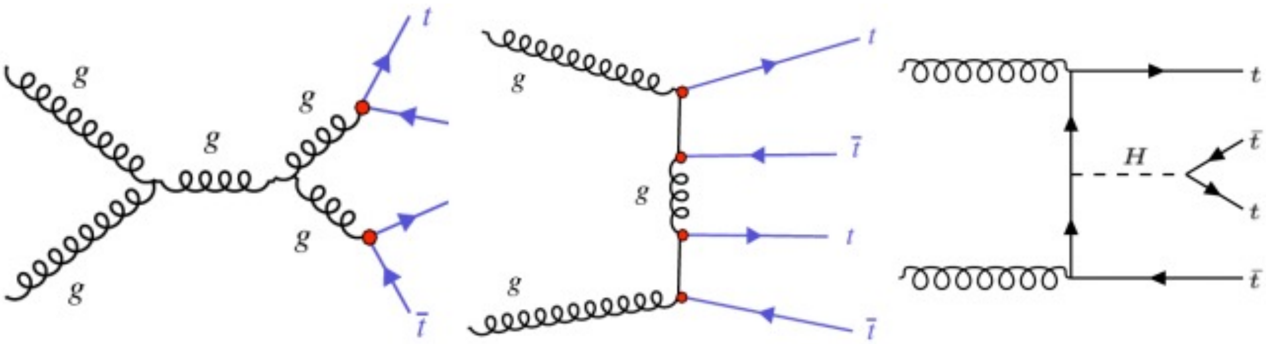
Four Top Quark Production

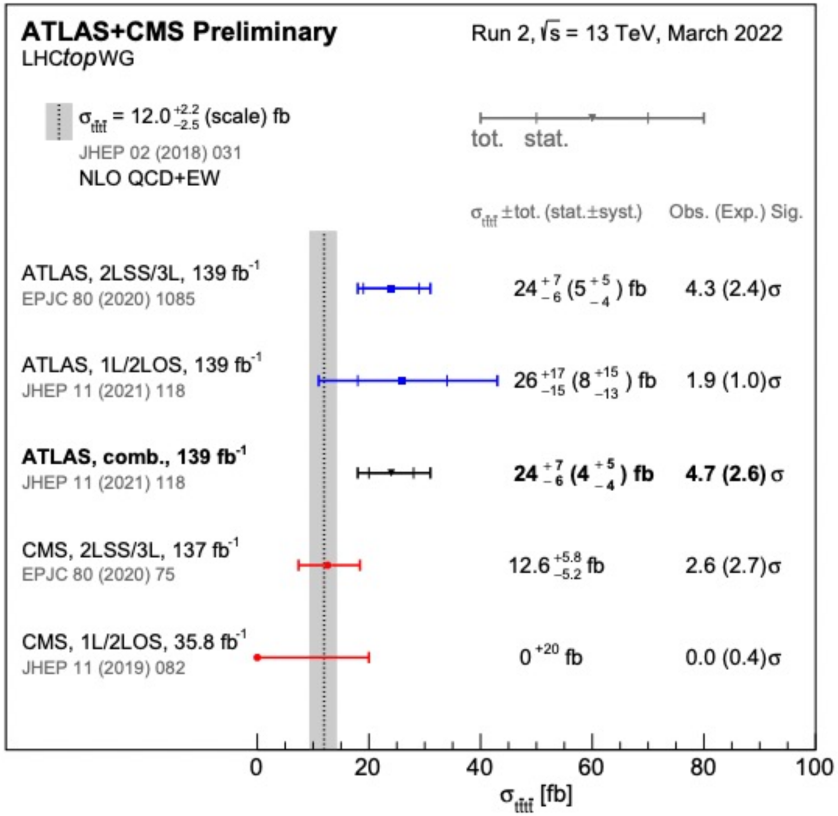
- $t\bar{t}t\bar{t}$ production is a rare top quark process predicted in the SM. It is one of the heaviest final state accessible at LHC
  - NLO (QCD+EW): σ($t\bar{t}t\bar{t}$) = 12 fb ±20% [JHEP 02 (2018) 031]
  - NLO+NLL: σ($t\bar{t}t\bar{t}$) = 13.4 fb ±11% [arXiv:2212.03259]

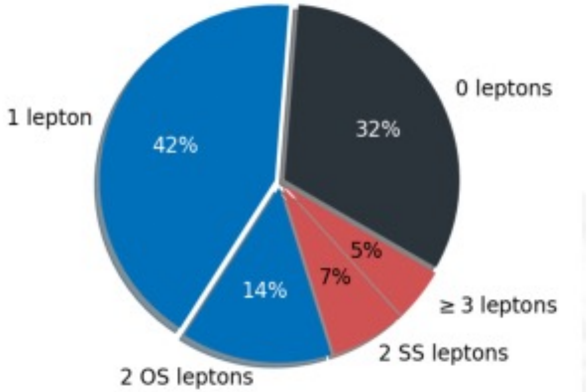


- $t\bar{t}t\bar{t}$ cross section is sensitive to anomalous top Yukawa coupling and Higgs CP properties
- A sensitive probe for new physics, such as EFT, 2HDM model

Four Top Quark Production Analysis

- $t\bar{t}t\bar{t}$ will decay into $W{+}W{-}W{+}W{-}b\bar{b}b\bar{b}$. Depending on the decay mode of the W bosons, it could lead to 2 channels
  - 2 lepton same-sign / 3 leptons (2LSS / 3L)
  - 1 lepton only / 2 lepton opposite sign (1L / 2LOS)





- This analysis is the refinement of the 2LSS/3L analysis which established evidence for the 4 top process for full Run 2 dataset

Evidence paper -- Eur. Phys. J. C 80 (2020) 1085

Outline Overview

- Analysis setup and strategy
- Background modeling
- Signal extraction and results
- BSM Interpretations

Four Top Process Signature

Multi-lepton channel: the most sensitive channel with small backgrounds

- High jet and b-jet multiplicity
- Small branching ratio (~12%)

2 tight leptons

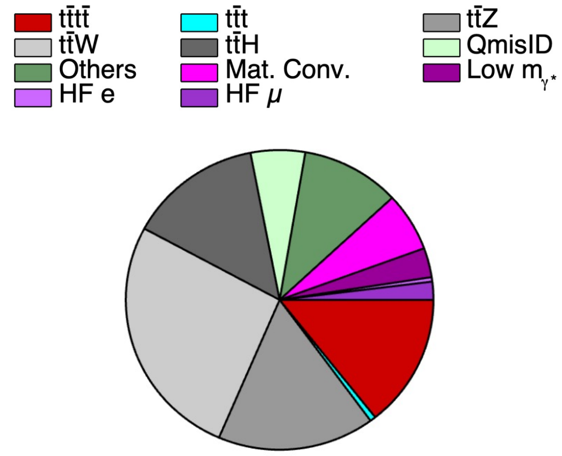
2LSS
- SS ee, Z Veto, M_{ee}> 15 GeV
- SS eμ
- SS $\mu\mu$

>=3 tight leptons and Z veto

3L
- eee
- eeμ
- e$\mu\mu$
- $\mu\mu\mu$

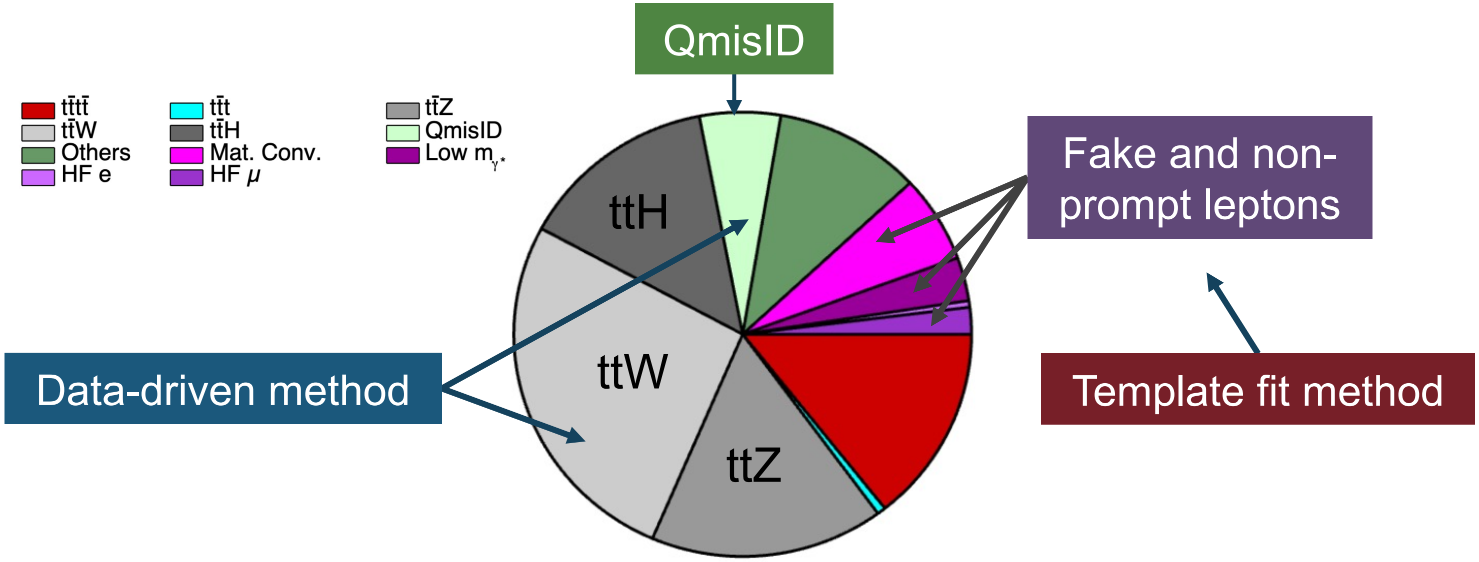
Signal region selection:

- ≥ 6 jets ≥ 2 b-jets
- HT = ∑pT(lepton) + ∑pT(jets) ≥ 500 GeV



Background Estimation

- SM model physics process (~85%):
  - ttZ + jets, ttH + jets, ttW+jets
- Fake/non-prompt leptons: coming from reconstruction fakes or charge mis-identified electrons (~15%):
  - Processes with electron charge misidentified
  - Events with non-prompt or fake leptons



Fake/non-prompt and QmisID Backgrounds

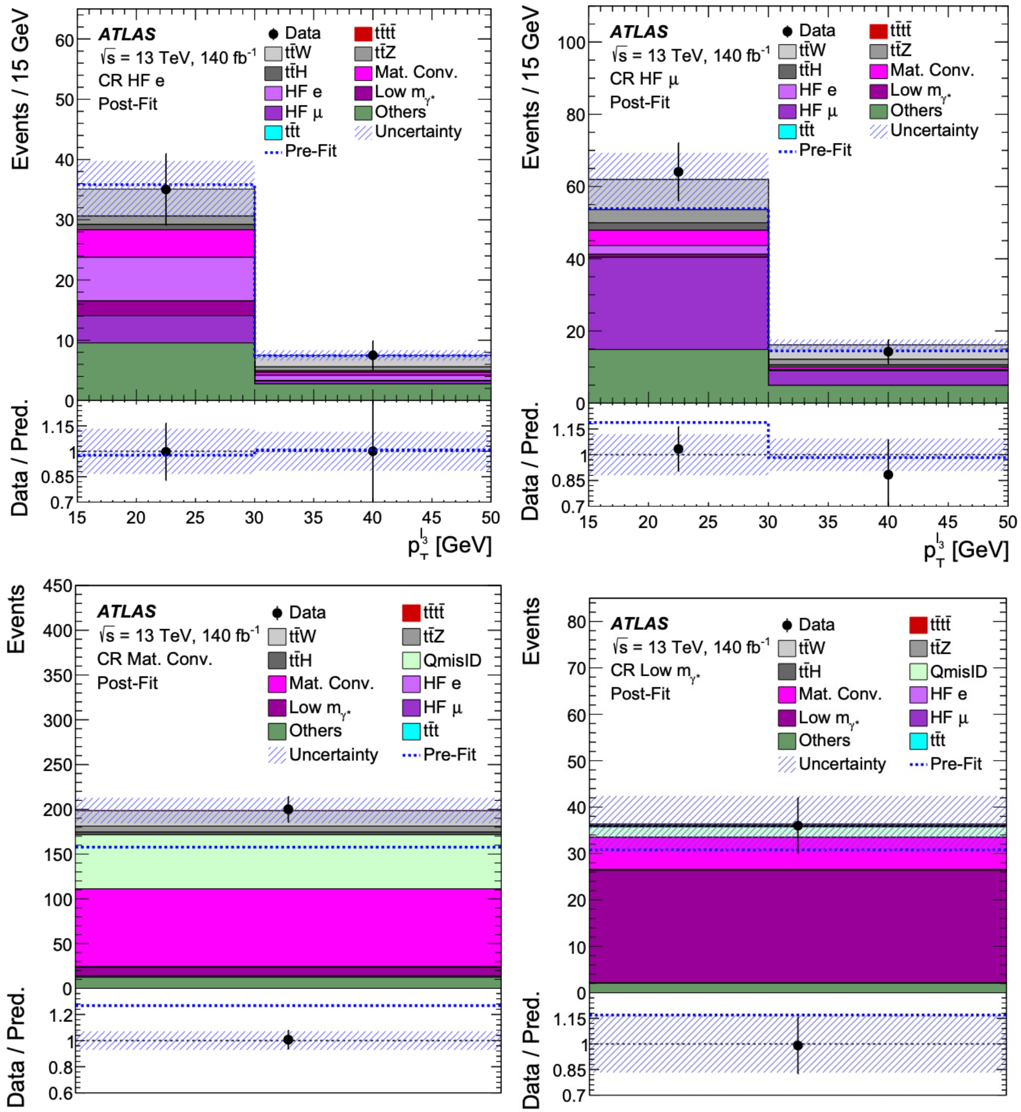
Fake/non-prompt backgrounds

- Define regions enriched in backgrounds to estimate normalization factors from data
- Heavy flavor electron and heavy flavor muon
- Material conversions
- Virtual photon conversion

$NF_{\text{Mat. Conv.}}$	$NF_{\text{Low } m_{\gamma^*}}$	$NF_{\text{HF } e}$	$NF_{\text{HF } \mu}$
$1.80^{+0.47}_{-0.41}$	$1.08^{+0.37}_{-0.31}$	$0.66^{+0.75}_{-0.46}$	$1.27^{+0.53}_{-0.46}$

Charge misidentification backgrounds

- Applying charge flip rate from data



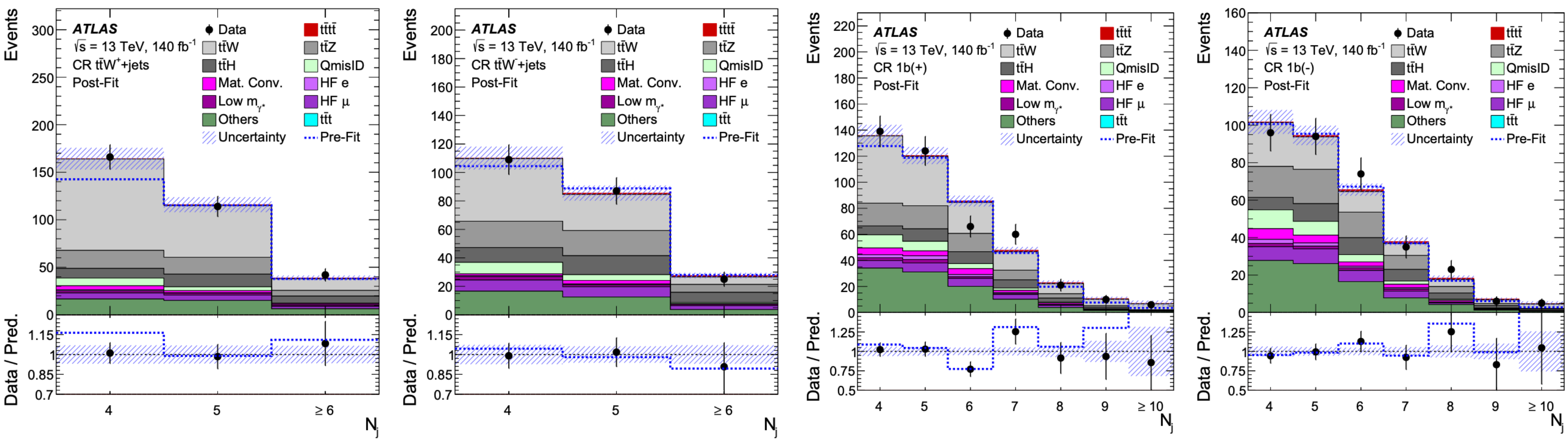
Data-driven Method for ttW Background

- Define 4 parameters to estimate ttW per jet bin:

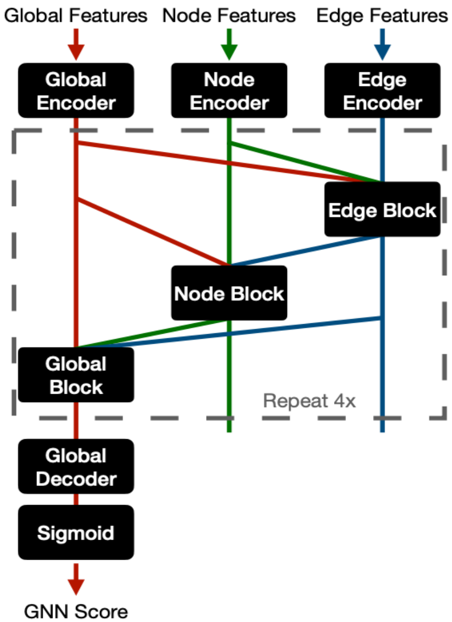
$$\mathrm{NF}_{t\bar{t}W@nj} = \mathrm{NF}_{t\bar{t}W^{+}@4j} \times \Pi_{n'=4}^{n'=n-1}[a_0 + \frac{a_1}{1+(n'-4)}] + \mathrm{NF}_{t\bar{t}W^{-}@4j} \times \Pi_{n'=4}^{n'=n-1}[a_0 + \frac{a_1}{1+(n'-4)}].$$

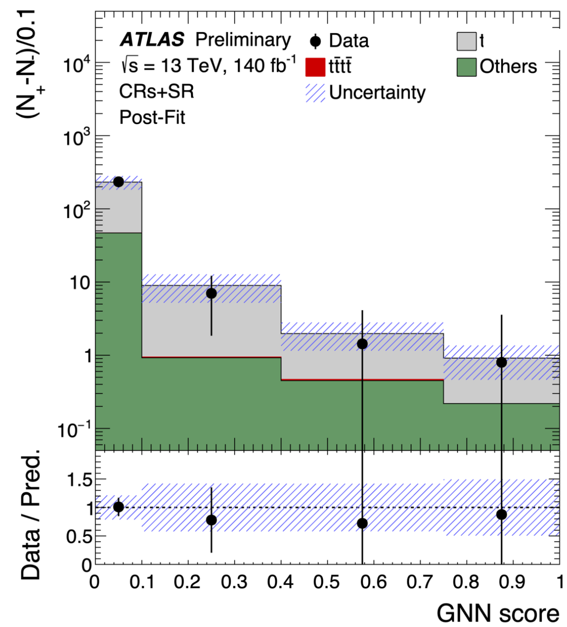
- Derive the parameters from ttW and 1b control regions, with charge split

$t\bar{t}W$ background	a_0	a_1	$\mathrm{NF}_{t\bar{t}W^{+}(4\mathrm{jet})}$	$\mathrm{NF}_{t\bar{t}W^{-}(4\mathrm{jet})}$
Value	0.51 ± 0.10	$0.22^{+0.25}_{-0.22}$	$1.27^{+0.25}_{-0.22}$	$1.11^{+0.31}_{-0.28}$



Signal Extration - GNN

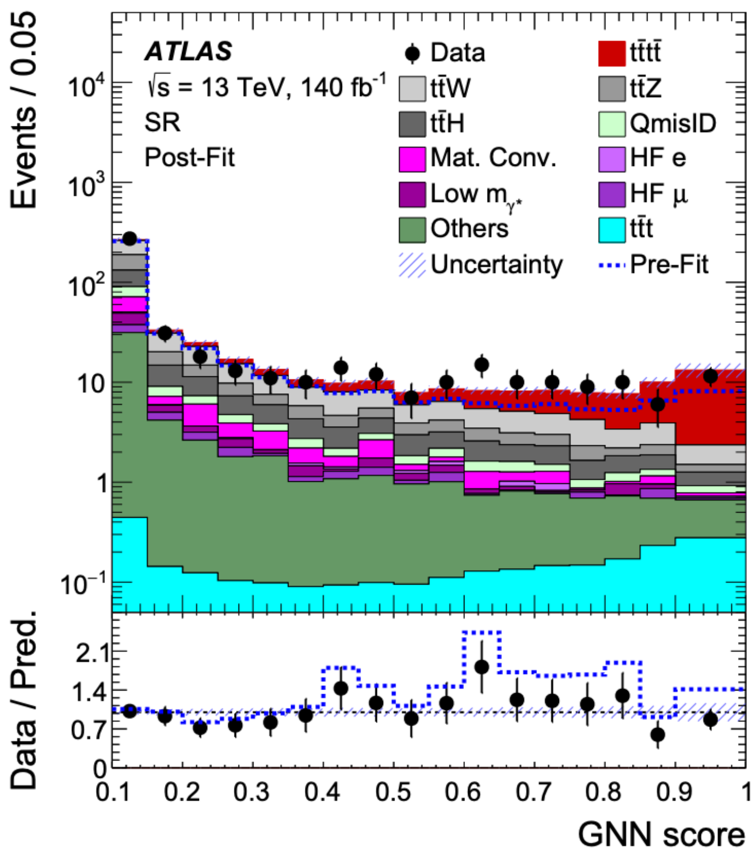




- In order to improve the signal sensitivity, we tried different MVA methods and **Graph Neutral Network (GNN)** is the final choice
- GNN is constructed to combine the information about objects (jets, lepton, MET) in an event into graphs, with node, edge, and global properties.
    - Trained with the un-weighted 4top LO, nominal backgrounds MC and up-weighted ttW sample
    - GNN modeling checked in the 1LOS channel and ttW VR

Four Top Cross Section Results

- Perform a maximum-likelihood fit to the GNN score distribution in SR and distributions in 8 CRs
- The observed significance is 6.1 sigma: the first observation of 4top production!



$$\mu = 1.9 \pm 0.4(\text{stat})\,^{+0.7}_{-0.4}(\text{syst}) = 1.9\,^{+0.8}_{-0.5}$$

$$\sigma_{t\bar{t}t\bar{t}} = 22.5^{+4.7}_{-4.3}(\text{stat})\,^{+4.6}_{-3.4}(\text{syst})\text{ fb} = 22.5\,^{+6.6}_{-5.5}\text{ fb}$$

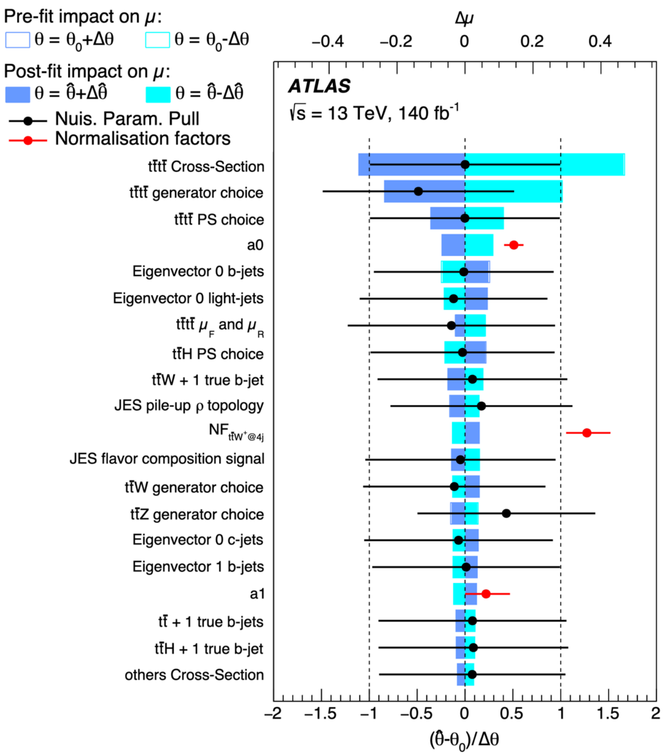
Setups	Significance(σ)
Realistic	4.3 (12fb)/ 4.7(13fb)
Observed	6.1
Realistic (evidence)	2.69
Data obs (evidence)	4.3

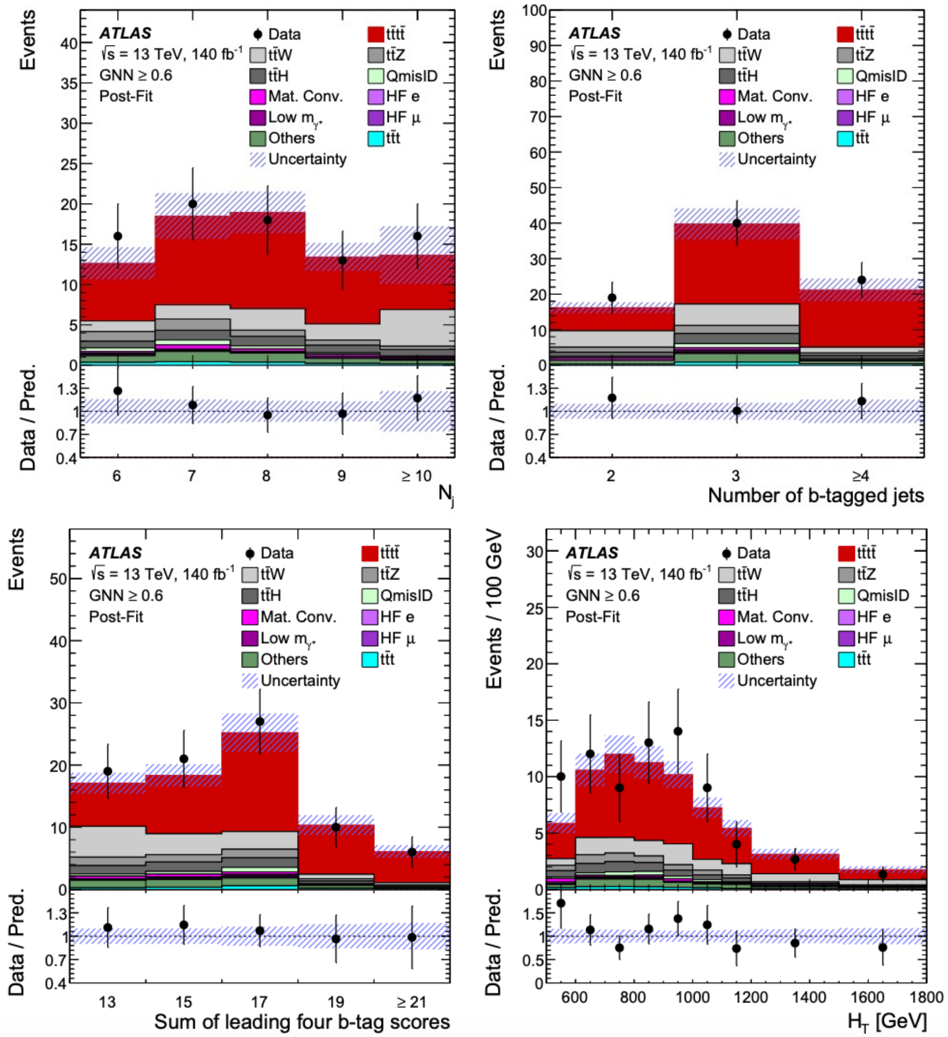
Four Top Production Results

- The largest uncertainties come from 4top modeling and the data-driven ttW parameters
- Good agreement in high GNN regions with data and MC

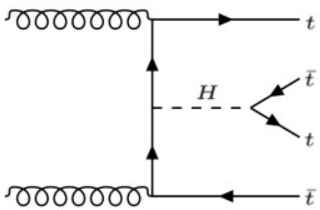
The improvements come from:

- Updated lepton and jet selections
- Use of the GNN discriminant
- Better modeling of the ttt backgrounds





Interpretations- top Yukawa coupling



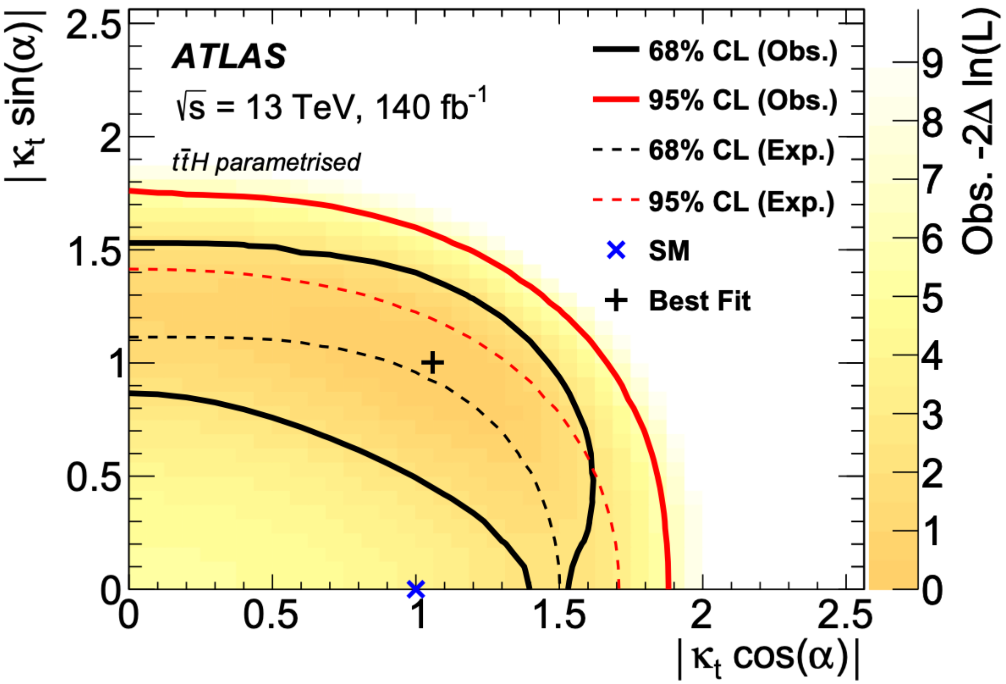
- Four top production with off-shell Higgs leads to the possibility to measure the top-Higgs Yukawa coupling
- The four top cross-section can be enhanced by the CP-odd coupling parameters

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

CP even CP odd

When alpha = 0

- CP even: obs (exp) |kt| < 1.8(1.6) (with ttH parameterised with kt)
- CP even: obs (exp) |kt| < 2.2(1.8) (with ttH free floated)



Interpretations-EFT

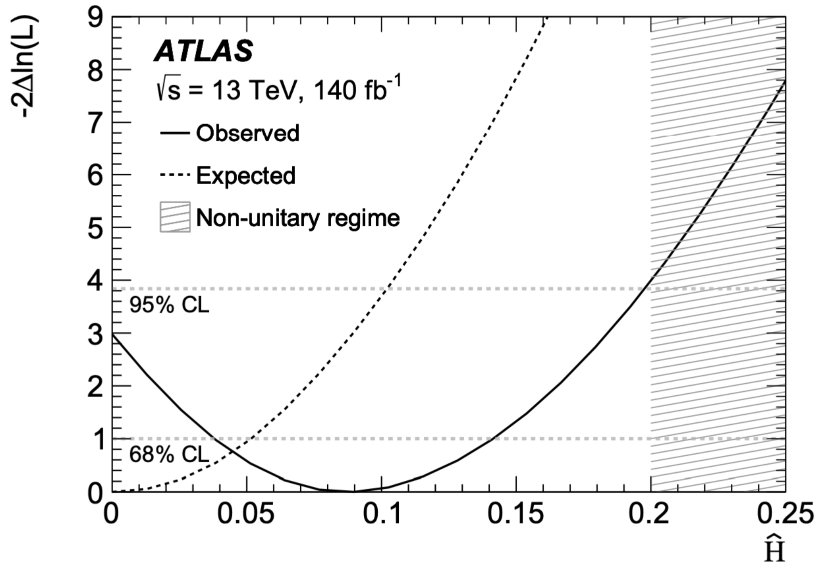
$$\sigma_{t\bar{t}t\bar{t}} = \sigma^{SM}_{t\bar{t}t\bar{t}} + \frac{1}{\Lambda^2}\sum_i C_i \sigma_i^{(1)} + \frac{1}{\Lambda^4}\sum_{i\le j} C_i C_j \sigma_{i,j}^{(2)}$$

- Four top productions is sensitive to heavy flavor fermion operators in EFT framework
- It also is sensitive to self-energy correction of the Higgs boson Ĥ that affects off-shell Higgs interaction (Ĥ=0 in the SM)

Limits on EFT operators sensitive to four top production (one operator at a time)

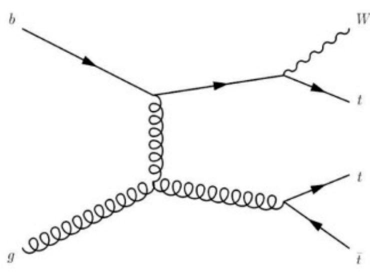
Operators	Expected C_i/Λ^2 [TeV $^{-2}$]	Observed C_i/Λ^2 [TeV $^{-2}$]
O^1_{QQ}	[-2.4, 3.0]	[-3.5, 4.1]
O^1_{Qt}	[-2.5, 2.0]	[-3.5, 3.0]
O^1_{tt}	[-1.1, 1.3]	[-1.7, 1.9]
O^8_{Qt}	[-4.2, 4.8]	[-6.2, 6.9]

Limit on Higgs oblique parameter Ĥ

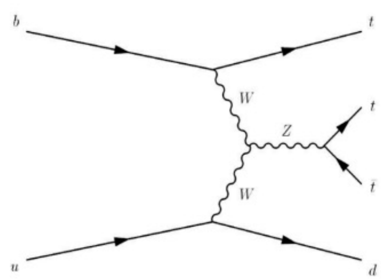


Interpretations-Three Top Cross Section

- SM three top production is even rarer than 4 top and is not discovered yet.
- Three top final state is very similar to four top: polluted in high GNN region



$\sigma(t\bar{t}t\ W) \sim 1$ fb

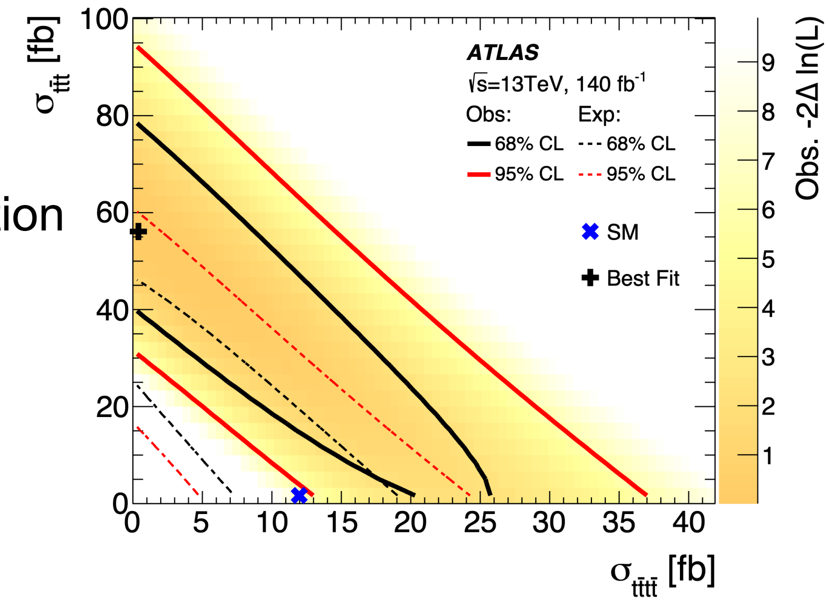


$\sigma(t\bar{t}t\ q) \sim 0.6$ fb

Limit on 3top production

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

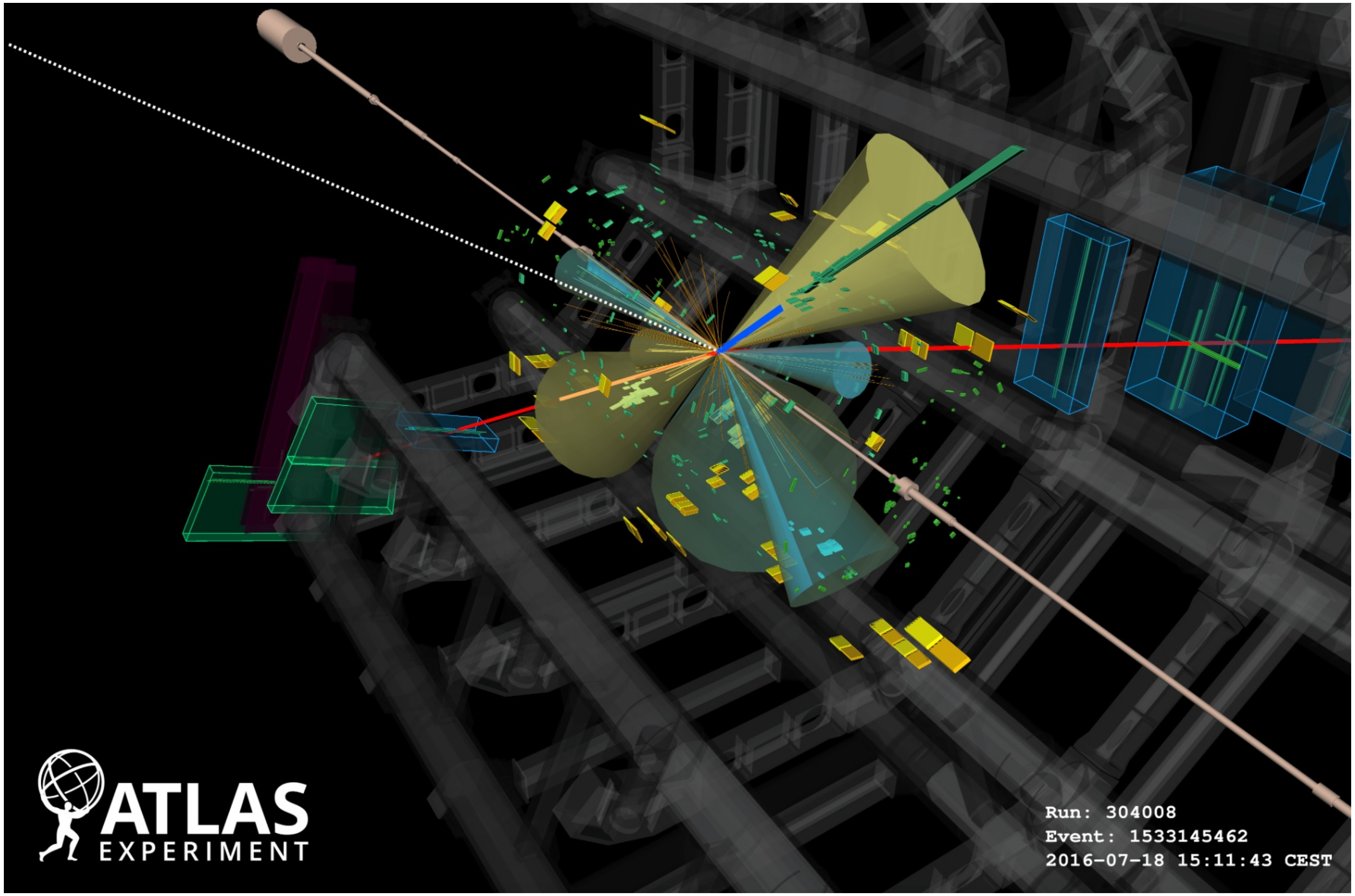
- We tried also to constrain the 3top production
- The correlation between 4top and 3top is very large (-93%) after free-floating both cross sections



Summary

- Re-analyzing the full Run2 dataset in the multilepton channel in ATLAS:
  - **The first observation of 4top**: the observed (expected) significance of 4top reaches 6.1 (4.3) σ
  - Many interpretations also included: top-Higgs Yukawa coupling, EFT, Higgs oblique, 3 top cross-section
  - Accepted by EPJC – arXiv 2303.15061

- Many improvements in this analysis:
  - Objection definitions: PLIV isolations, loose lepton/jet pT cuts
  - New MVA: the GNN method
  - Background modeling: ttW data-driven method, 3top treatments


ATLAS
EXPERIMENT
Run: 304008
Event: 1533145462
2016-07-18 15:11:43 CEST

Thank You

Backups

Object Definations

Generally, the objection definations is similar to the evidence paper

Main changes coming from:

- b-tagging changed from mv2c10 to DL1r
- Loosing the pT selection for lepton (jets) from 28 (25) GeV to 15 (20) GeV
- Lepton isolations changed to PLIV to suppress fake leptons

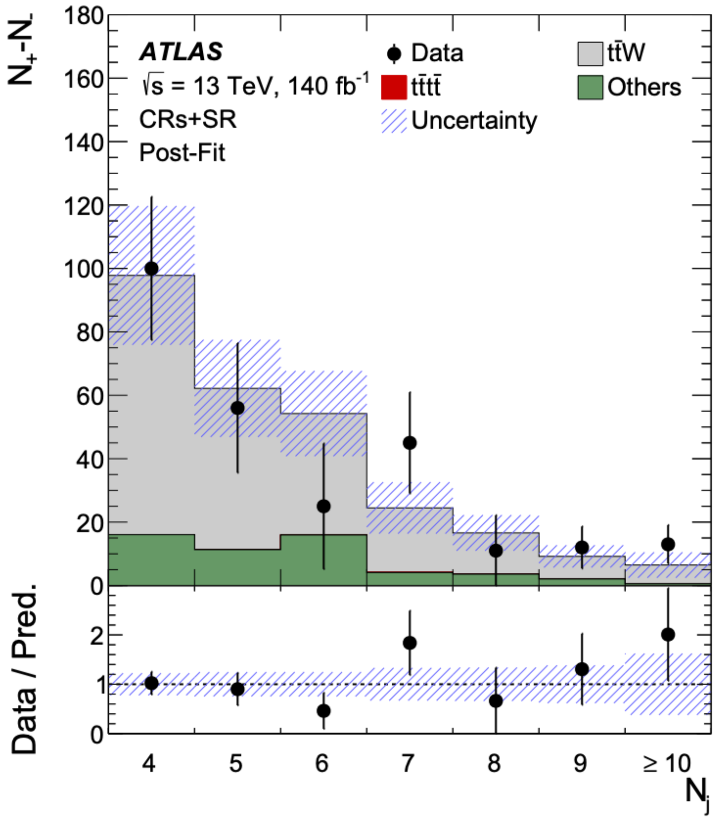
	Electrons		Muons		Jets	b-jets
	loose	tight	loose	tight		
p_T [GeV]	> 15		> 15		> 20	> 20
$\|\eta\|$	< 1.37 or $1.52 - 2.47$		< 2.5		< 2.5	< 2.5
ID quality	mediumLH ECIDS ($ee, e\mu$)	tightLH ECIDS ($ee, e\mu$)	medium		cleaning + JVT	DL1r 77%
Isolation	Loose_VarRad	PLImprovedTight	PflowLoose_FixedRad	PLImprovedTight		
Track vertex :						
– $\|d_0/\sigma_{d_0}\|$	< 5		< 3			
– $\|z_0 \sin\theta\|$ [mm]	< 0.5		< 0.5			

Control Regions and Signal Regions

Region	Channel	N_j	N_b	Other selection	Fitted variable
CR Low m_{γ^*}	SS, ee or eμ	$4 \leq N_j < 6$	≥ 1	ℓ_1 or ℓ_2 is from virtual photon (γ^*) decay ℓ_1 and ℓ_2 are not from photon conversion	counting
CR Mat. Conv.	SS, ee or eμ	$4 \leq N_j < 6$	≥ 1	ℓ_1 or ℓ_2 is from photon conversion	counting
CR HF μ	e$\mu\mu$ or $\mu\mu\mu$	≥ 1	$= 1$	$100 < H_T < 300$ GeV $E_T^{miss} > 50$ GeV total charge $= \pm 1$	$p_T^{\ell_3}$
CR HF e	eee or eeμ	≥ 1	$= 1$	$100 < H_T < 275$ GeV $E_T^{miss} > 35$ GeV total charge $= \pm 1$	$p_T^{\ell_3}$
CR $t\bar{t}W^+$+jets	SS, eμ or $\mu\mu$	≥ 4	≥ 2	$\lvert\eta(e)\rvert < 1.5$ when $N_b = 2$: $H_T < 500$ GeV or $N_j < 6$ when $N_b \geq 3$: $H_T < 500$ GeV total charge > 0	N_j
CR $t\bar{t}W^-$+jets	SS, eμ or $\mu\mu$	≥ 4	≥ 2	$\lvert\eta(e)\rvert < 1.5$ when $N_b = 2$: $H_T < 500$ GeV or $N_j < 6$ when $N_b \geq 3$: $H_T < 500$ GeV total charge < 0	N_j
CR 1b(+)	2LSS+3L	≥ 4	$= 1$	ℓ_1 and ℓ_2 are not from photon conversion $H_T > 500$ GeV total charge > 0	N_j
CR 1b(-)	2LSS+3L	≥ 4	$= 1$	ℓ_1 and ℓ_2 are not from photon conversion $H_T > 500$ GeV total charge < 0	N_j
SR	2LSS+3L	≥ 6	≥ 2	$H_T > 500$ GeV	GNN score

ttW Data-Driven Check

- Validation of ttW data-driven method
- Difference between the number of positive events and the number of negative events ($N+ - N-$) as a function of the number of jets (Nj) in the sum of four ttW CRs and the SR



Systematics Models

Theory/modeling uncertainties:

1. **SM tttt**: x-sec (20%), PDF (1%), generator (MG vs Sherpa 2210 QCD), μR/F variations (QCD scale), PS (Pythia vs Herwig)
2. **ttt / ttZ / ttH / ttW QCD+EW**:
   - QCD scale μR/F
   - Generator:
     ttZ: MG vs. Sherpa2211
     ttH: PH vs. MG
     ttW: Sherpa 2210 vs. Old MG FxFx
     Heavy flavor content: 50% on ttX+1b, 50% on ttX+ ≥ 2b
   - x-sec: 12% on ttZ, 10% on ttH, 30% on ttt; PDF on ttZ/ttH (1%)
3. **x-sec for others**:
   - VVV+VH(other) / ttWW / rare ttVV: 50%
   - VV: 40%; tt LF: 100% tZ+tWZ: 30%
4. **>3 / >= 3 truth b-jets**:
   - VV / VVV+VH(other) / ttWW / rare ttVV / tZ+tWZ - 50% / 50% for events with =3 / > 3 true b-jets,
   - ttt - 50% for events with > 3 true b-jets, tt+jets Heavy flavor content - 30% / 30% for events with =3 / >3 true b-jets

Experimental uncertainties

Systematic uncertainty	Short description
Event	
Luminosity	uncertainty on the total integrated luminosity
Pileup reweighting	uncertainty on data SF used for the computation of pileup reweighting
Electrons	
ATLAS_EL_SF_TRIGGER	trigger efficiency uncertainty
ATLAS_EL_SF_RECO	reconstruction efficiency uncertainty
ATLAS_EL_SF_ID	ID efficiency uncertainty
ATLAS_EL_SF_ISO	isolation efficiency uncertainty
EG_SCALE_ALL	energy scale uncertainty
EG_RESOLUTION_ALL	energy resolution uncertainty
ATLAS_EL_SF_ChargeID_Stat	uncertainties associated to the efficiencies of the ECIDS
Muons	
ATLAS_MU_SF_TRIG_Stat ATLAS_MU_SF_TRIG_Syst	trigger efficiency uncertainty
ATLAS_MU_SF_ID_Stat ATLAS_MU_SF_ID_Syst	identification/reconstruction efficiency uncertainty for p_T > 15 GeV
ATLAS_MU_SF_ISO_Stat ATLAS_MU_SF_ISO_Syst	isolation efficiency uncertainty
ATLAS_MU_SF_TTVA_Stat ATLAS_MU_SF_TTVA_Syst	track-to-vertex association efficiency uncertainty
MUONS_SCALE	energy scale uncertainty
MUON_SAGITTA_DATASTAT	variations in the scale of the momentum (charge dependent)
MUONS_SAGITTA_RESBIAS	variations in the scale of the momentum (charge dependent)
MUONS_CB	energy resolution uncertainty from muon system
Small-R Jets	
JES_EffectiveNP (15 terms) JES_EtaIntercalibration (6 terms) JES_Flavour (2 terms) JES_Pileup (4 terms) JES_PunchThrough (FS,AFII 2 terms) JES_RelativeNonClosure_MC16_AFII JES_SingleParticle_HightPt (1 terms) BJETS_Response (1 terms)	jet energy scale uncertainties
JER_EffectiveNP (12 terms) JER_DataVsMC (FS,AFII 2 terms)	jet energy resolution uncertainties
JvtEfficiency	JVT efficiency uncertainty
b-tagging DL1r B[0-44] b-tagging DL1r C[0-19] b-tagging DL1r Light[0-19]	b-tagging efficiency uncertainties: 45 components for b-jets, 20 for c-jets and 20 for light jets
Jet PCBT high p_T	b-tagging efficiency uncertainty on the extrapolation on high p_T-jets
E_T^{miss}-Terms	
MET_SoftTrk_ResoPerp	track-based soft term related to transversal resolution uncertainty
MET_SoftTrk_ResoPara	track-based soft term related to longitudinal resolution uncertainty
MET_SoftTrk_Scale	track-based soft term related to longitudinal scale uncertainty