Observation of Four-Top-Quark Production in the Multi-lepton Final State with the ATLAS Experiment

Xiang Chen
Shanghai Jiao Tong University
IRFU, CEA Saclay

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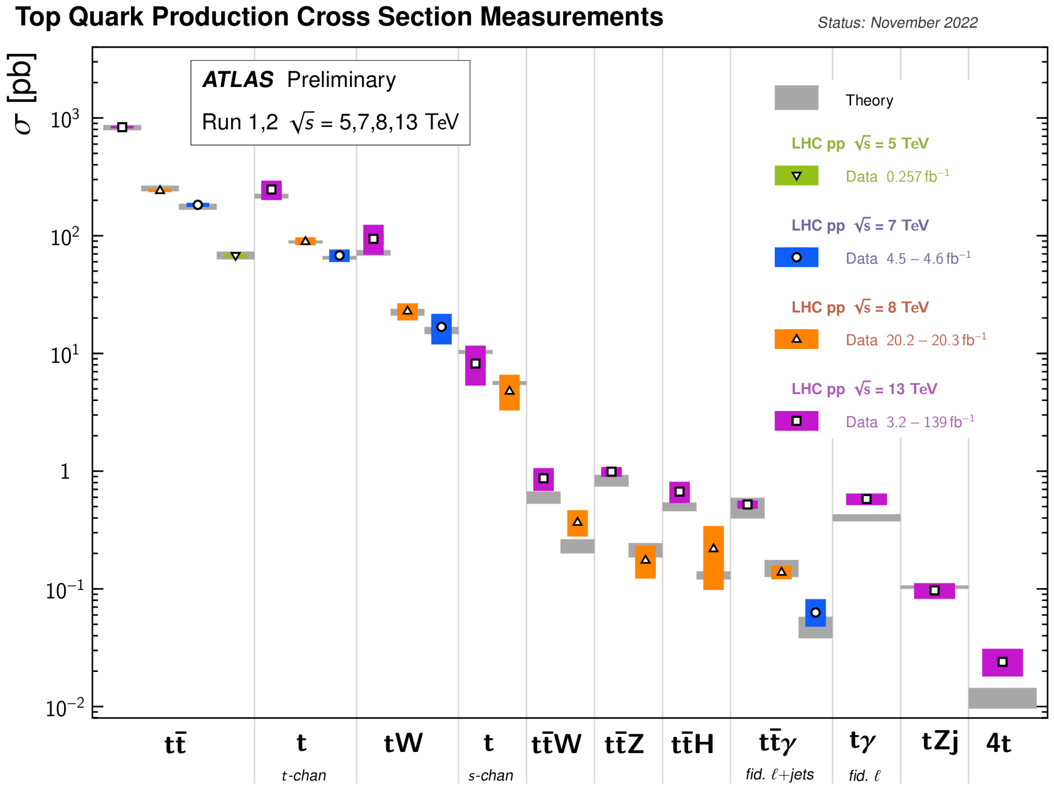
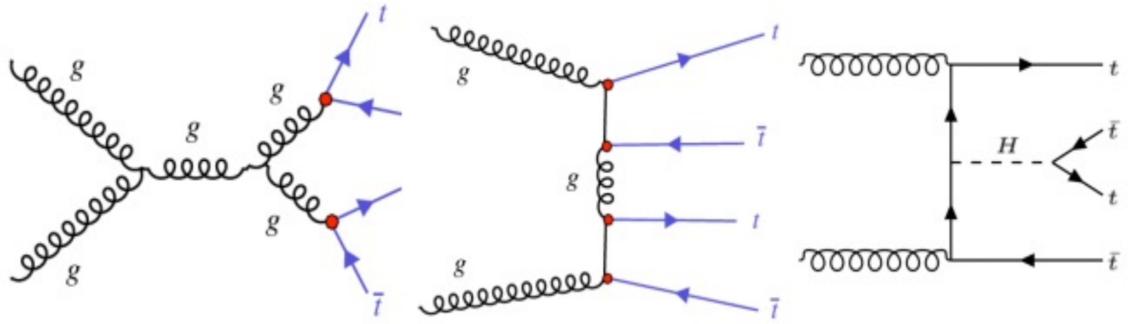
Rare Top Quark Production Process

- Precision measurement with a rare top quark production process is a good approach to searching for new physics.



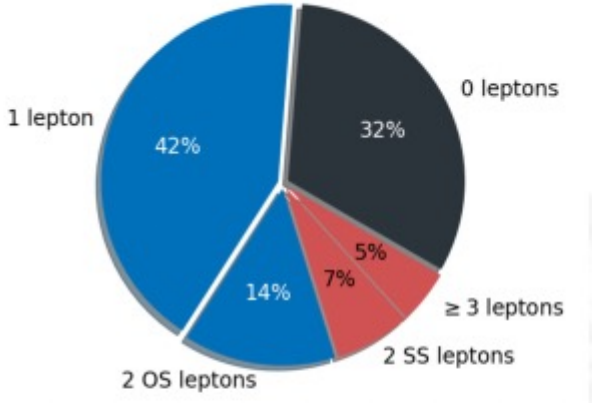


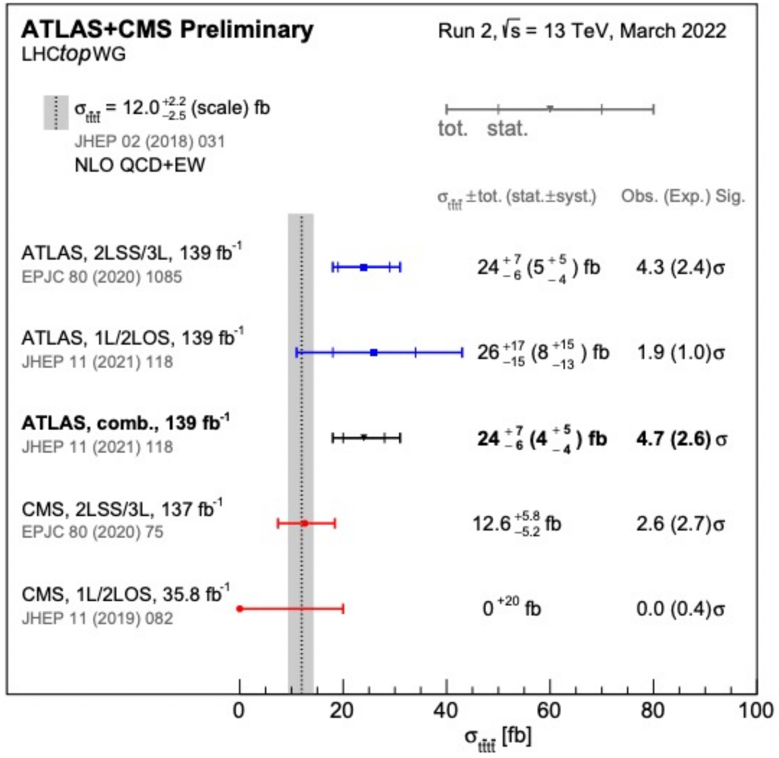
- $t\bar{t}t\bar{t}$ production is a rare top quark process predicted in the SM
  It is one of the heaviest final states accessible at LHC
  - NLO (QCD+EWK): σ($t\bar{t}t\bar{t}$) = 12 fb ±20% [JHEP 02 (2018) 031]
  - NLO+NLL: σ($t\bar{t}t\bar{t}$) = 13.4 fb ±11% [arXiv:2212.03259]

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

Four-Top-Quark Production

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





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

- ATLAS and CMS made several measurements with four tops, ATLAS found evidence in 2020 using full Run2 dataset with 2LSS/3L analysis and also the combination analysis.
- This analysis is the refinement of the 2LSS/3L analysis with improved object reconstruction and analysis techniques as well as new BSM interpretations.

Outline:

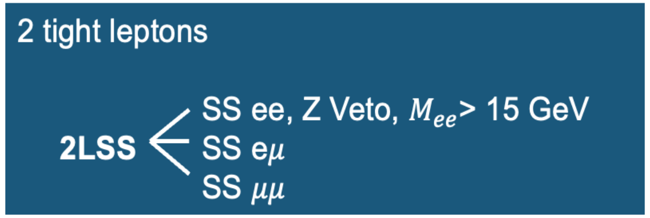
1. Analysis strategy
2. Background modeling
3. Signal extraction and results
4. BSM Interpretations
5. Top reconstruction in 4top

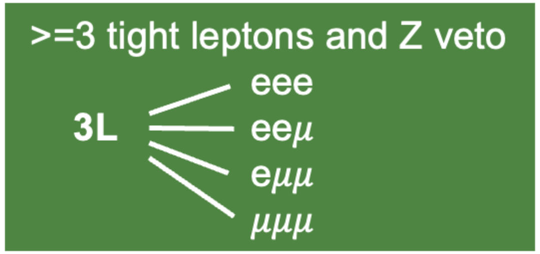
Main updates:

1. Improved object definition
2. Better background modeling
3. New MVA method

Signal and Backgrounds

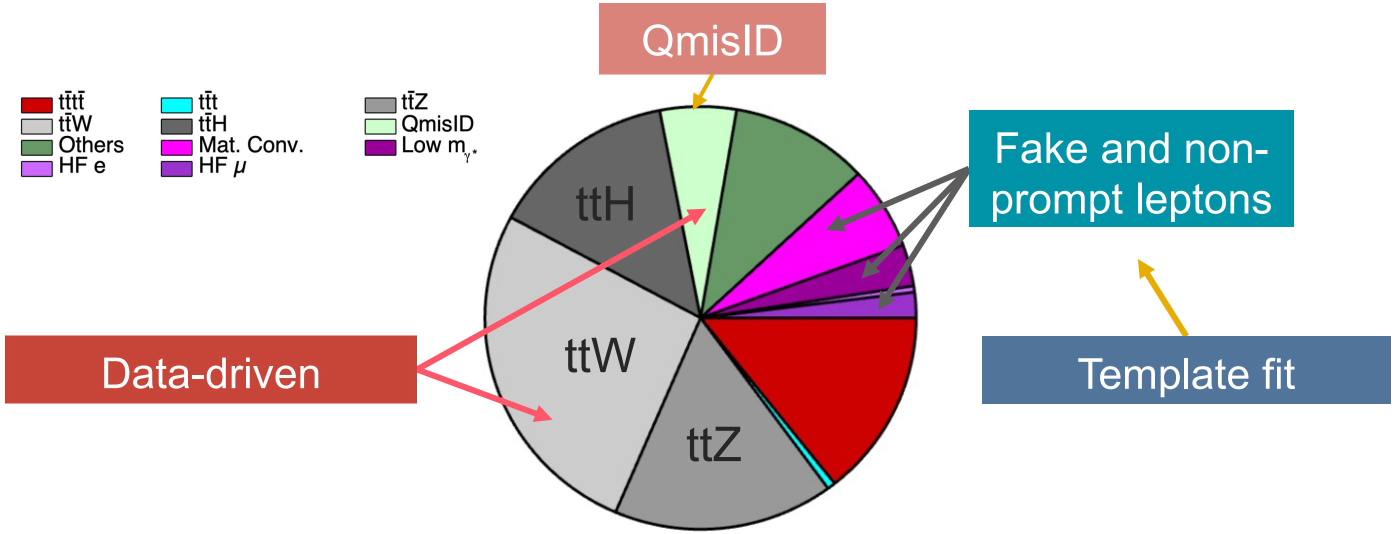
- **Multi-lepton channel: the most sensitive channel with small backgrounds**
  - High jet and b-jet multiplicity
  - Small branching ratio (~12%)
- **Signal region selection:**
  - ≥ 6 jets, ≥ 2 b-jets
  - HT = ∑pT(lepton) + ∑pT(jets) ≥ 500 GeV





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



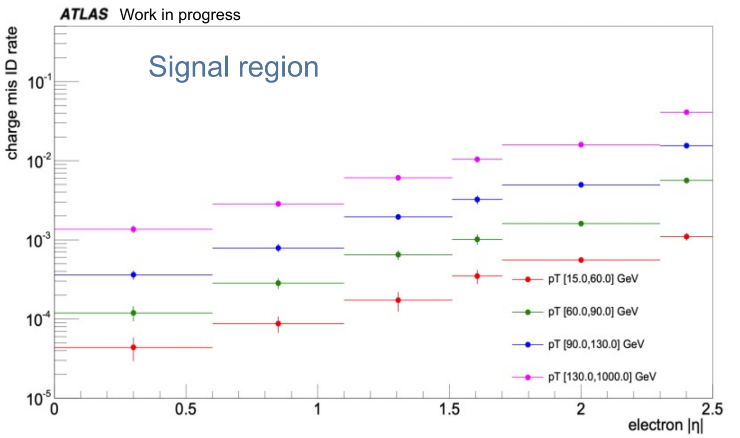
Fake/non-prompt and QmisID Backgrounds

Fake/non-prompt backgrounds

- Define regions enriched in the following background processes to estimate normalization factors
  - Heavy flavor electron and heavy flavor muon
  - Material conversions
  - Virtual photon conversion

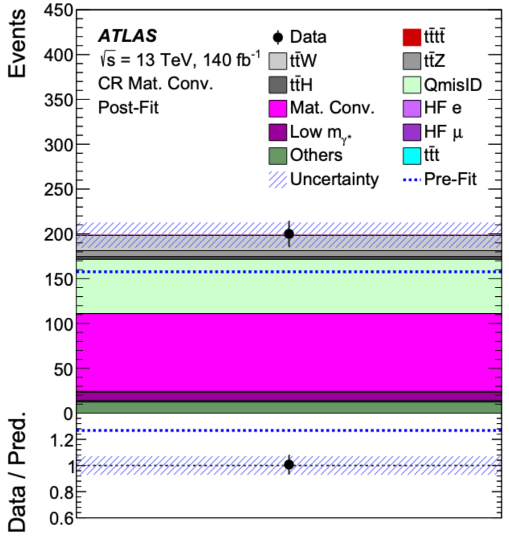
Charge misidentification backgrounds

- Applying charge flip rate deriving from Z->ee data as 2D bins of pT and eta in all control regions and the signal region
- The rate is estimated by minimizing the negative log poisson likelihood fit

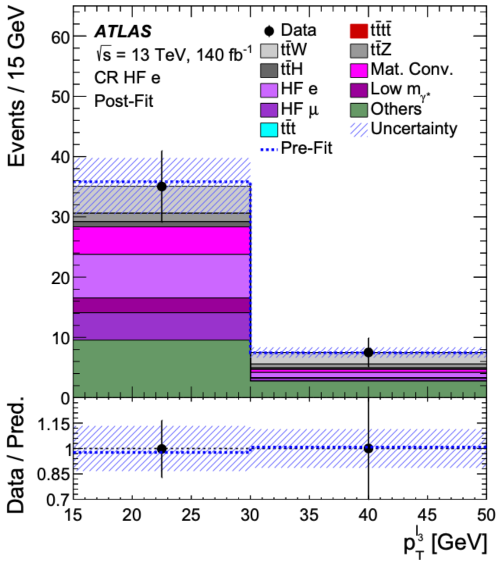


$NF_{\text{Mat. Conv.}}$	$NF_{\text{Low } m_{\gamma^*}}$	$NF_{\text{HF } e}$	$NF_{\text{HF } \mu}$
$1.80^{+0.47}_{-0.41}$	$1.08^{+0.37}_{-0.31}$	$0.66^{+0.75}_{-0.46}$	$1.27^{+0.53}_{-0.46}$

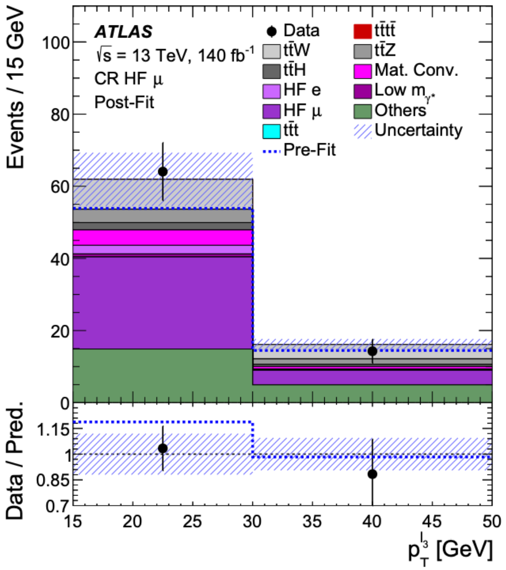
Material conversions



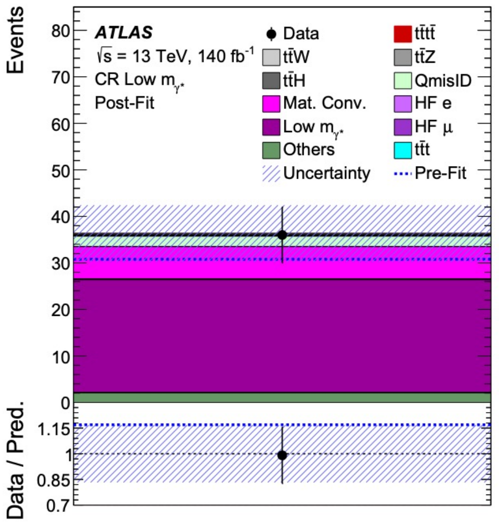
Heavy flavor e



Heavy flavor mu



Virtual photon conversion

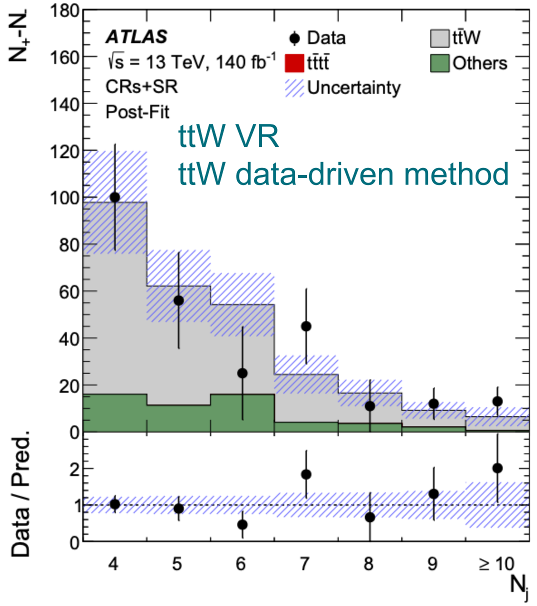


ttW background: Data-Driven Method

- ttW+jets systematics was one of the leading systematic uncertainties in the previous analysis
- To get rid of it, the data-driven method is applied to derive the free parameters from ttW and 1b control regions with charge split (4 control regions)

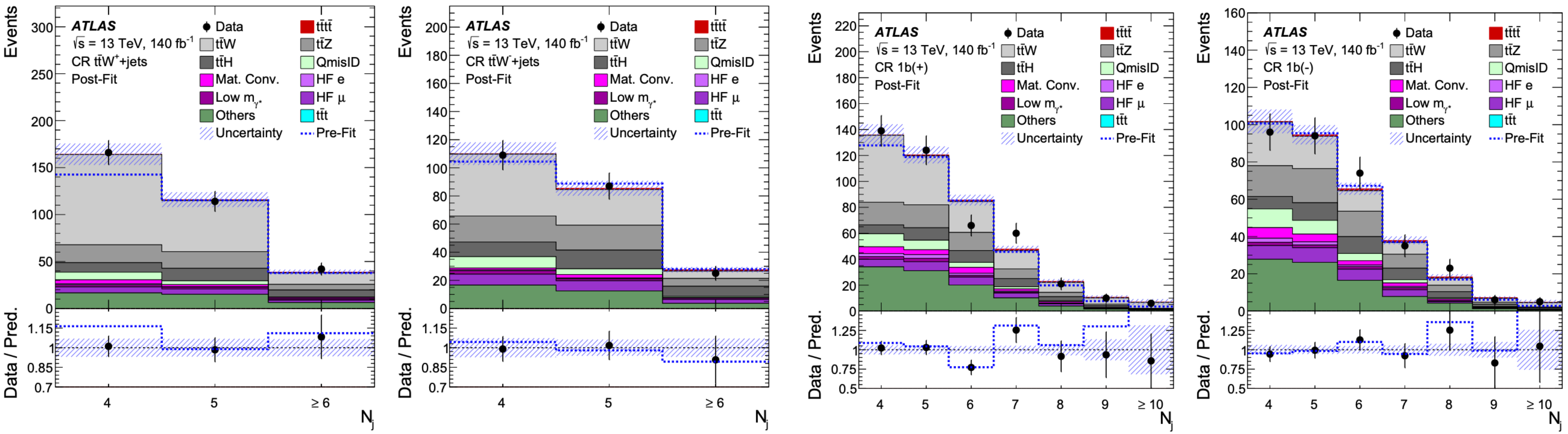
$$\mathrm{NF}_{t\bar{t}W@nj} = \mathrm{NF}_{t\bar{t}W^+@4j} \times \Pi_{n'=4}^{n'=n-1}\left[a_0 + \frac{a_1}{1+(n'-4)}\right] + \mathrm{NF}_{t\bar{t}W^-@4j} \times \Pi_{n'=4}^{n'=n-1}\left[a_0 + \frac{a_1}{1+(n'-4)}\right].$$

$t\bar{t}W$ 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	$0.22^{+0.25}_{-0.22}$	$1.27^{+0.25}_{-0.22}$	$1.11^{+0.31}_{-0.28}$



ttW control regions: 2L, $N_b \geq 2$, $N_{jet} \geq 4$

1b control regions: SS/3L, $N_b = 1$, $N_{jet} \geq 4$

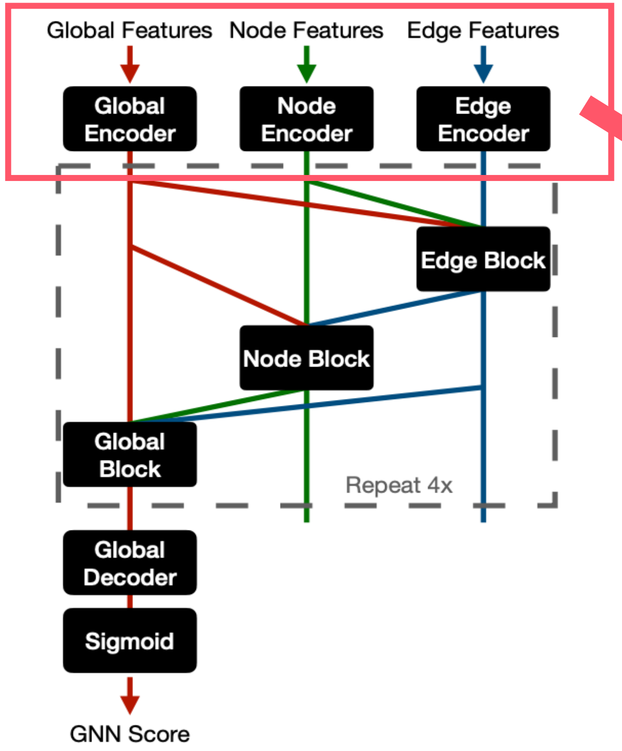


MVA Method: GNN

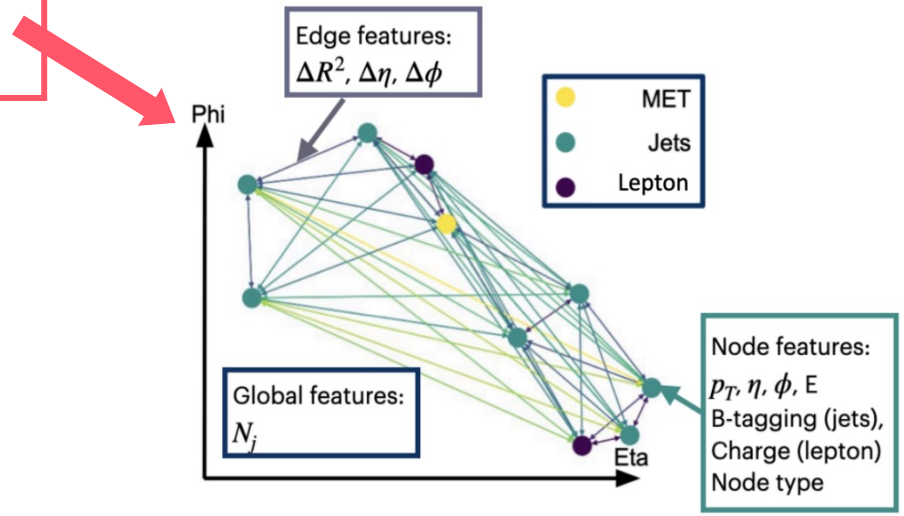
- In order to improve the signal sensitivity, we tried different MVA methods and **Graph Neutral Network (GNN)** was the final choice
- GNN is constructed to combine the information about objects (jets, lepton, MET) in an event into graphs, with node, edge, and global properties.

- Trained with the un-weighted 4top LO, nominal backgrounds MC, and up-weighted ttW sample
- The k-fold method (k=6) is applied for optimization
- AUC is used for estimating the performance: GNN outperforms XGBoost

GNN network structure



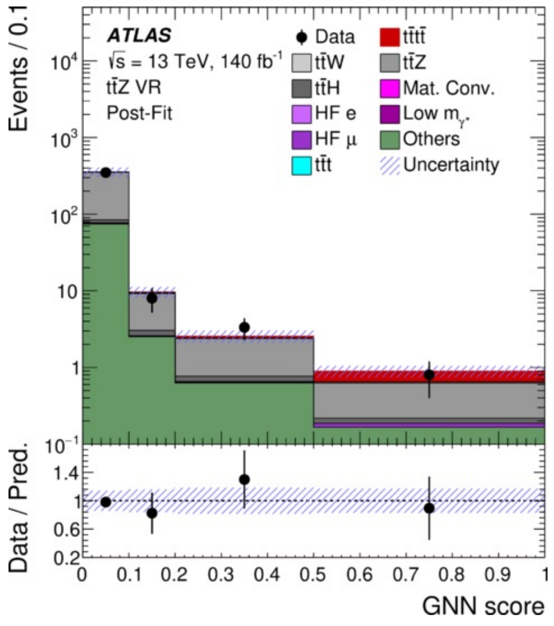
GNN inputs



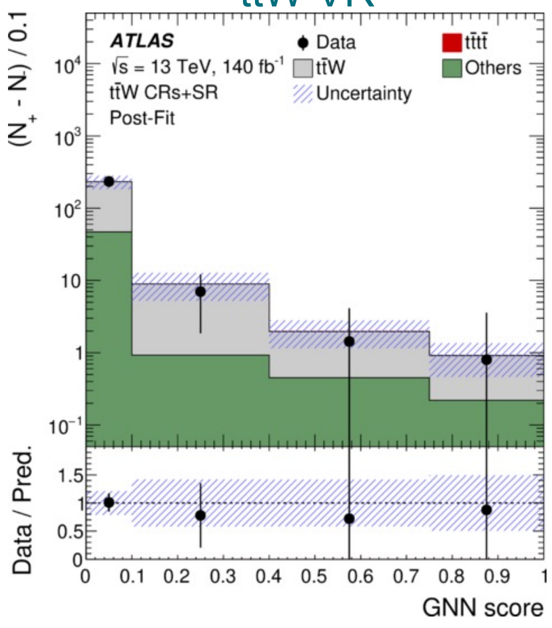
GNN Fitting Results

- Perform a maximum-likelihood fit to the GNN score distribution in SR and distributions in 8 CRs
- GNN modeling is checked in the 1LOS channel and validation regions
- Good agreement in high GNN regions with data and MC

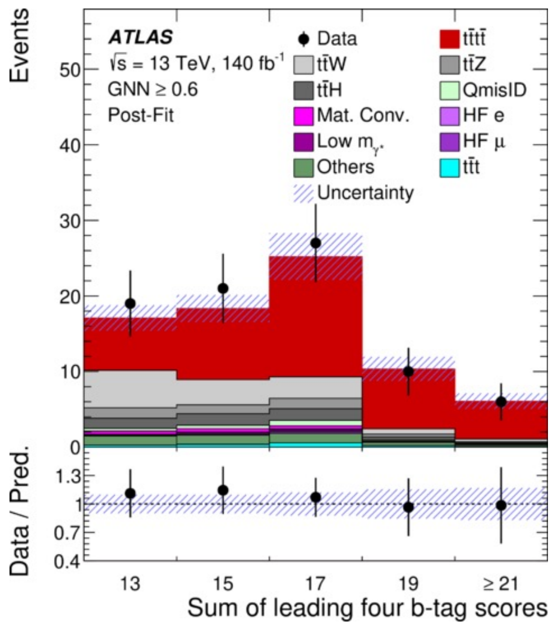
ttZ VR



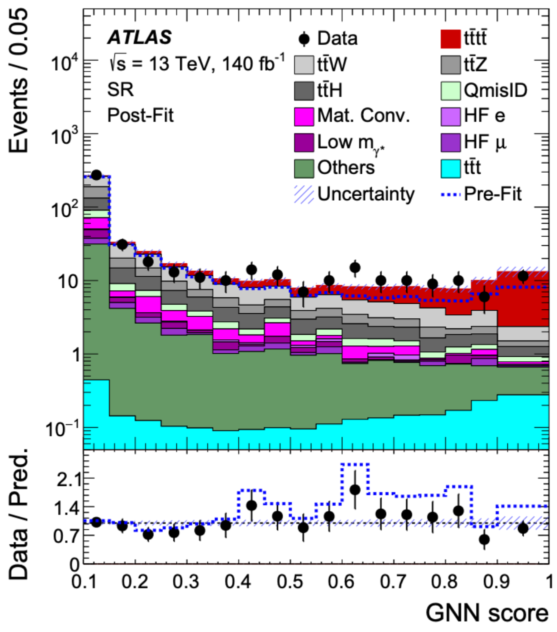
ttW VR



SR, high GNN



SR



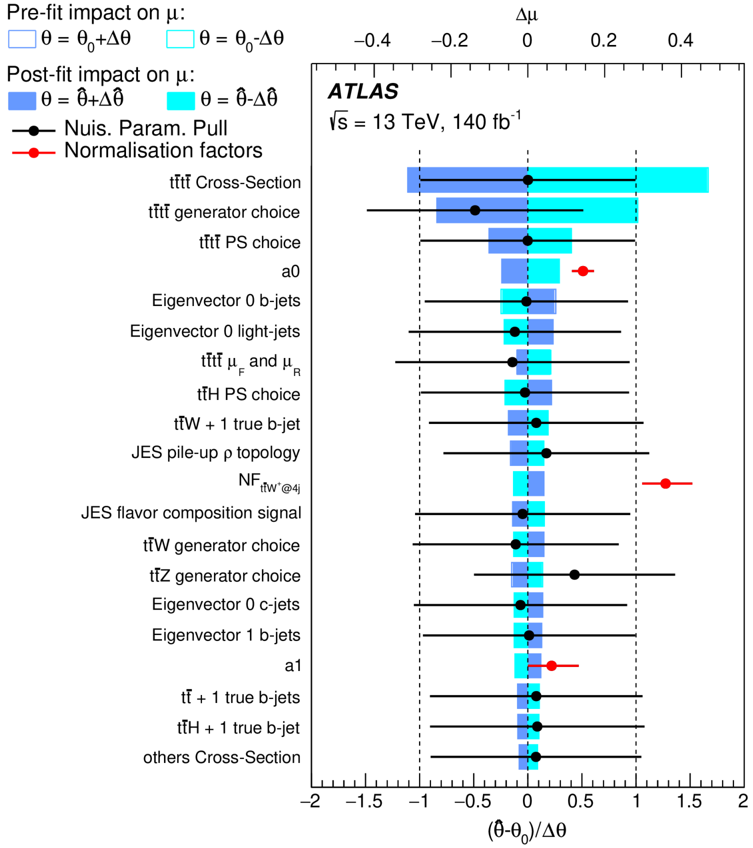
Four-Top-Quark Cross Section Results

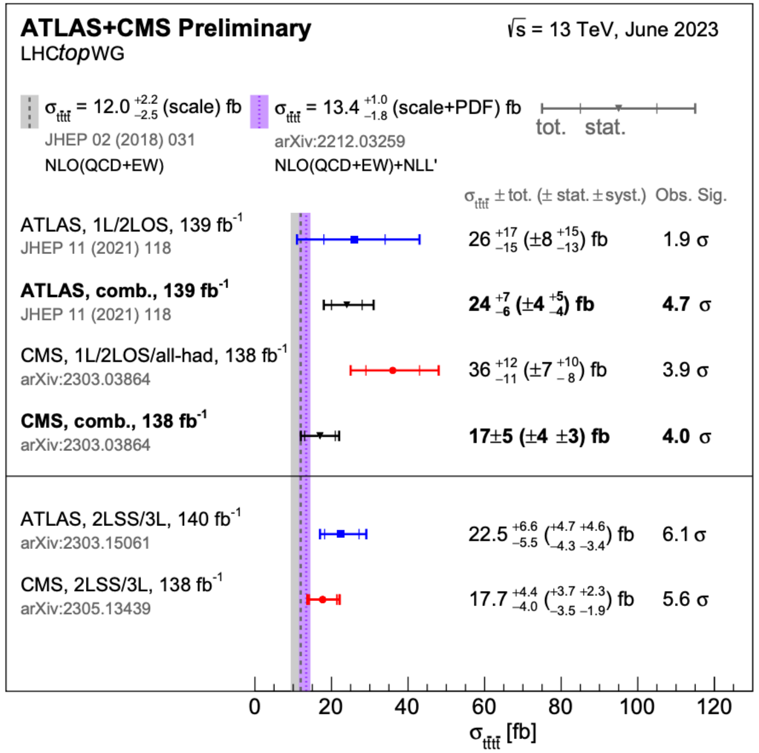
- The observed significance is **6.1** sigma: **first observation of four-top-quark production!**
- The largest uncertainties come from 4top modeling and the data-driven ttW parameters

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

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

Significance	Observation	Evidence paper
Expected (σ)	**4.3**	2.7
Observed (σ)	**6.1**	4.3





The improvements (from 4.7σ to 6.1 σ) come from:

- Updated lepton and jet selections + b-tagging
- Use of the GNN discriminant
- Better modeling of the ttt and ttW backgrounds

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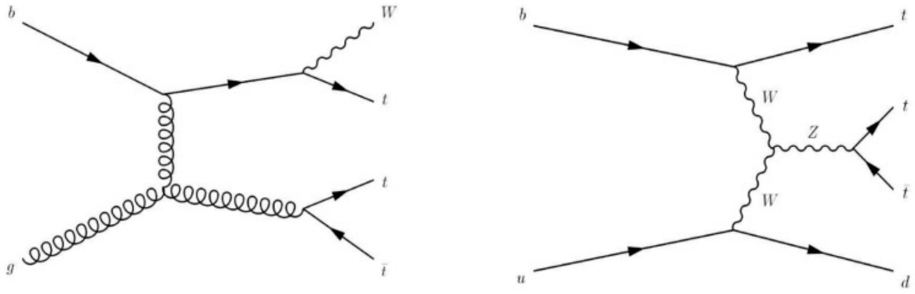
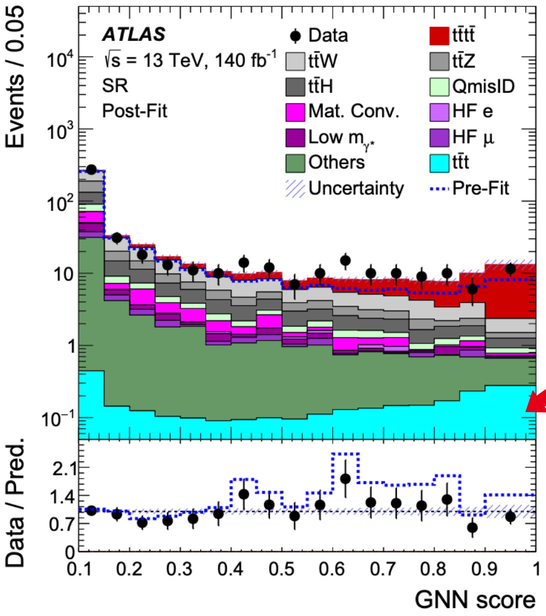
Interpretations - Three Top Cross Section

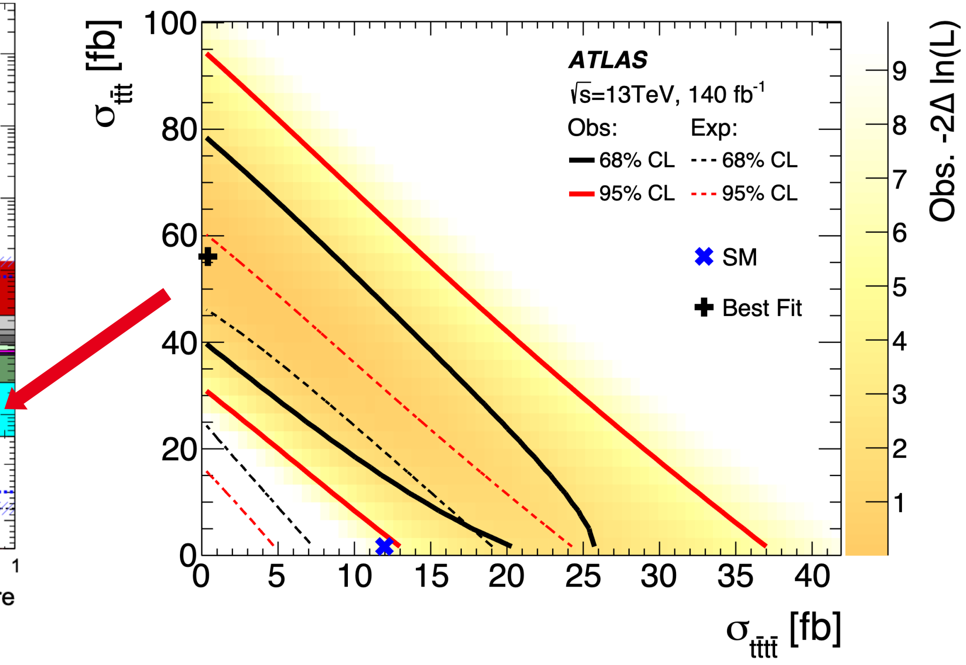
- SM three top production is even rarer than 4 top and has yet to be discovered.
- The three top final state is very similar to the four top: large contribution in high GNN region
- We also tried to constrain the 3top production
- The correlation between 4top and 3top is very large (-93%) after free-floating both cross sections



σ(t̄tt W) ~ 1 fb

σ(t̄tt q) ~ 0.6 fb





Limit on 3top 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]

New Physics Interpretations - EFT

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

EFT parameters:

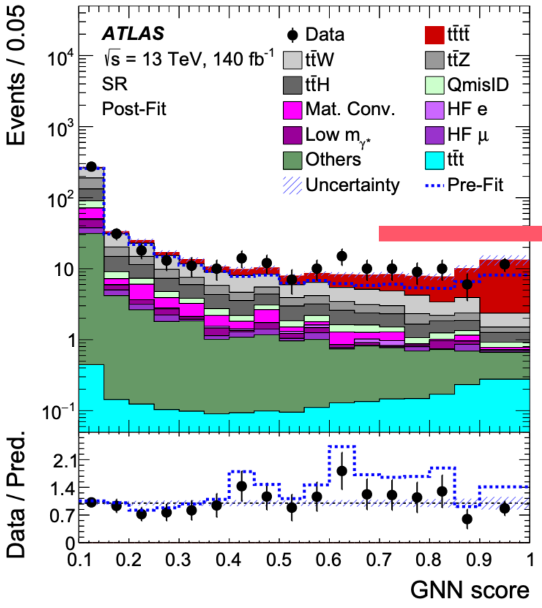
- Four-top-quark production is sensitive to some heavy flavor fermion operators in EFT framework
- The four heavy flavour fermion operators expecting to affect the amplitude of 4top production are cQQ1, cQt1, ctt1, cQt8
- The function of the cross section enhancement with EFT parameters is fitted in each SR bin. Then it is applied to the reference SM 4top sample as the normalization factor in the profile-likelihood fit

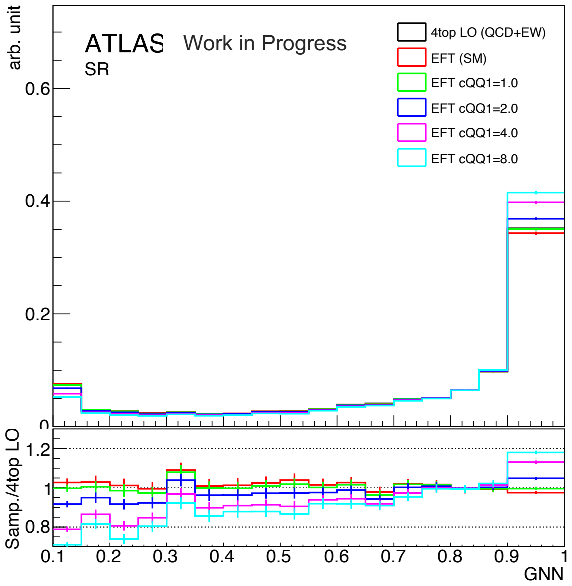
$$O^1_{tt} = (\bar{t}_R\gamma^\mu t_R)(t_R\gamma_\mu\bar{t}_R)$$

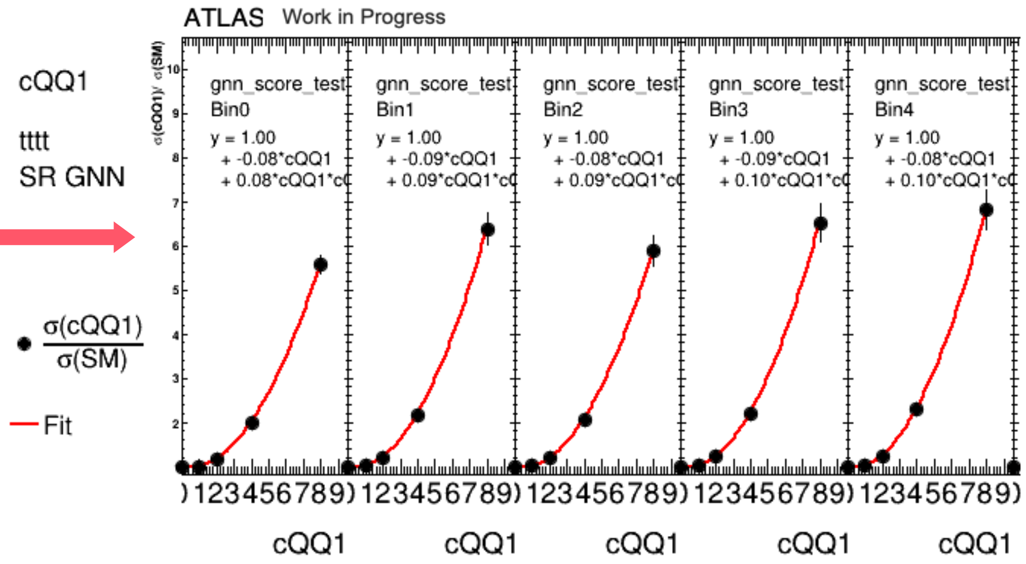
$$O^1_{QQ} = (\bar{Q}_L\gamma^\mu Q_L)(Q_L\gamma_\mu\bar{Q}_L)$$

$$O^1_{Qt} = (\bar{Q}_L\gamma^\mu Q_L)(t_R\gamma_\mu\bar{t}_R)$$

$$O^8_{Qt} = (\bar{Q}_L\gamma^\mu T^A Q_L)(t_R\gamma_\mu T^A\bar{t}_R).$$







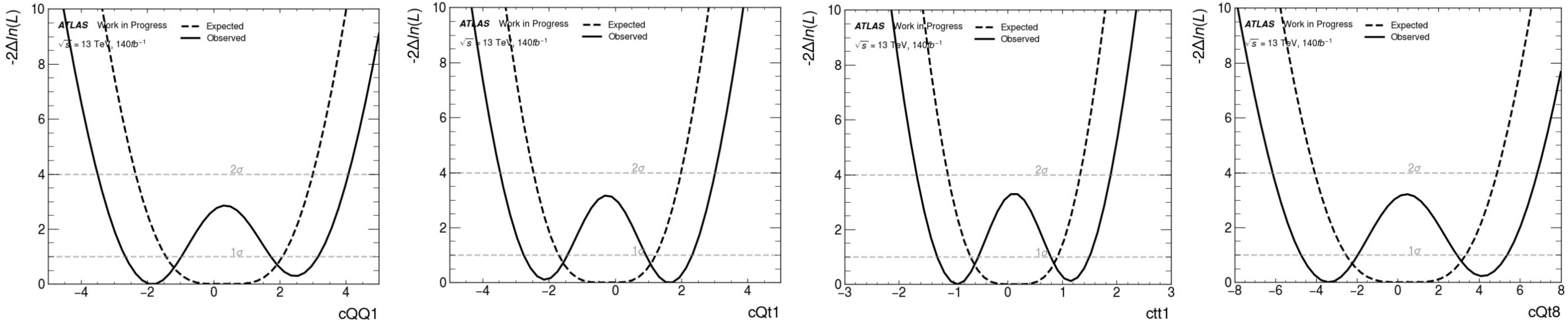
New Physics Interpretations - EFT

EFT Quadratic parameterization:

- Derive bin-by-bin quadratic interpolation in GNN bins and get the 95% CL intervals of the coefficient shown in the likelihood scan
- Assume only one operator contributes to the enhancement of the cross section and others are fixed to zero
- The sensitivity is improved by the GNN discriminant

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

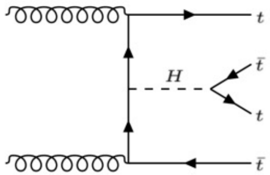
Operators	Expected C_i/Λ^2 [TeV $^{-2}$]	Observed C_i/Λ^2 [TeV $^{-2}$]
O^1_{QQ}	[-2.5, 3.2]	[-4.0, 4.5]
O^1_{Qt}	[-2.6, 2.1]	[-3.8, 3.4]
O^1_{tt}	[-1.2, 1.4]	[-1.9, 2.1]
O^8_{Qt}	[-4.3, 5.1]	[-6.9, 7.6]



New Physics Interpretations

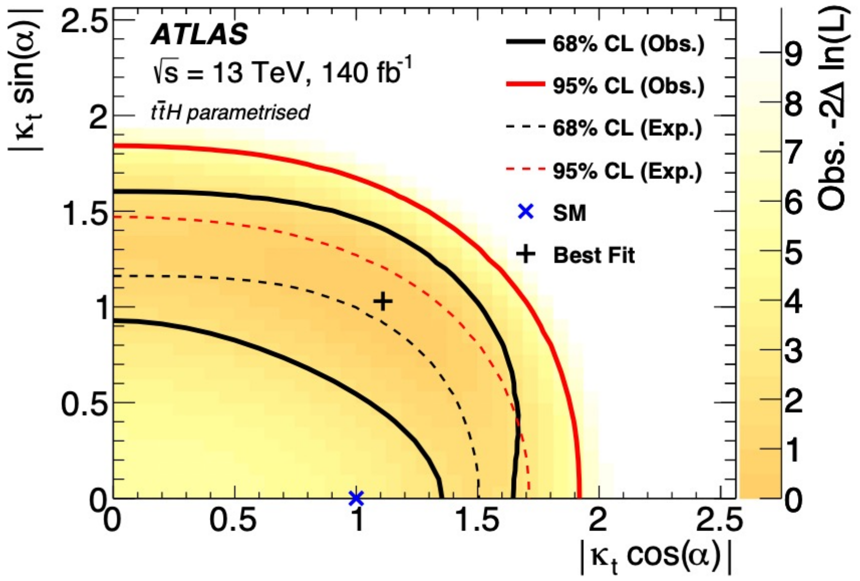
Top Yukawa Coupling

- Four top production is sensitive to measure the top-Higgs Yukawa coupling and its XS can be enhanced by the CP-odd coupling parameters
- CP even: obs (exp) |kt| < 1.9(1.6) (ttH parameterised with kt)
- CP even: obs (exp) |kt| < 2.3(1.9) (ttH free floated)



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

CP even CP odd

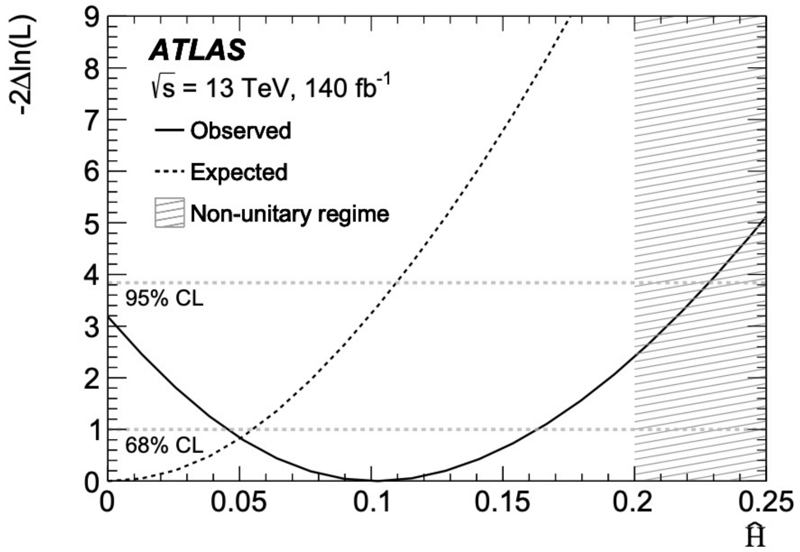


Higgs oblique paramter

- Four top productions also is sensitive to self-energy correction of the Higgs boson Ĥ that affects off-shell Higgs interaction
- The observed (expected) upper limit on the Ĥ value is 0.23 (0.11) at 95% CL

$$\delta\sigma_{t\bar{t}t\bar{t}} \equiv \frac{\sigma_{\hat{H}}}{\sigma_{SM}} \approx 0.03\left(\frac{\hat{H}}{0.04}\right) + 0.15\left(\frac{\hat{H}}{0.04}\right)^2$$

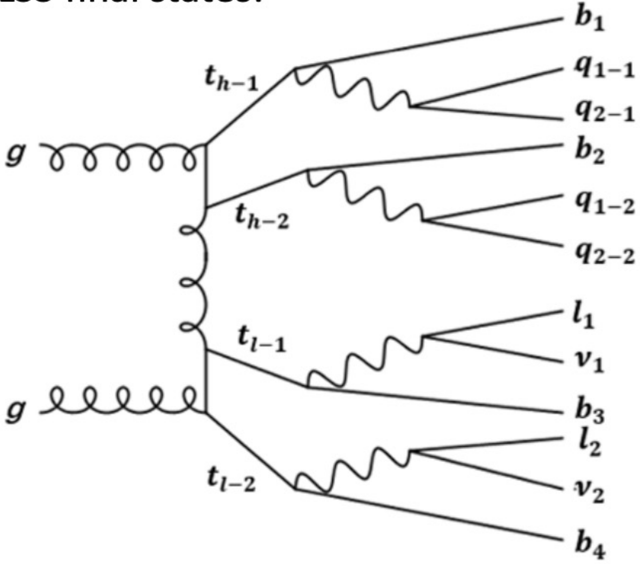
Limit on Higgs oblique parameter Ĥ



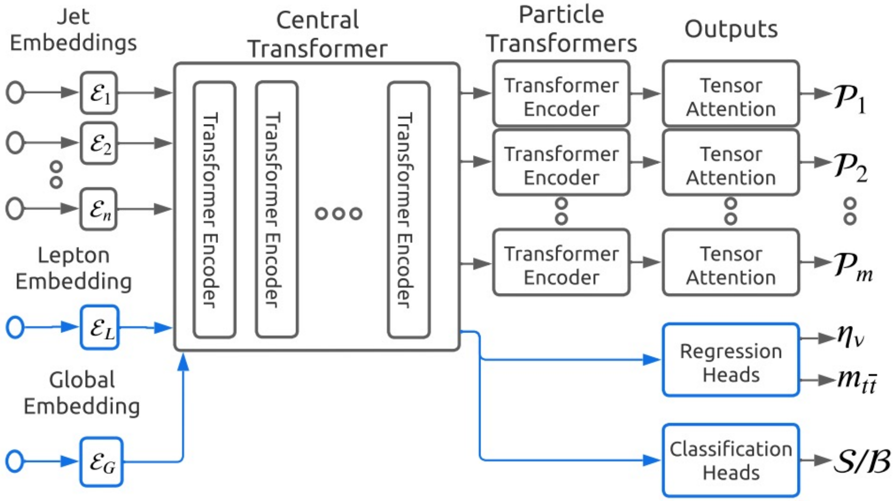
Top Reconstruction in the 4top Multi-lepton Channel

- Top quark reconstruction relies on the measurement of final states and jet-parton assignment is important in heavy particle reconstruction.
- Traditionally we use the chi2 method to build each possible permutation of the event to find the best solution
- Top reconstruction would be challenging in the 4top multi-lepton channel with missing momentum and extensive jet permutations.
  - Using SPA-Net based on the transformer network with fast simulation 4top same sign samples

2LSS final states:



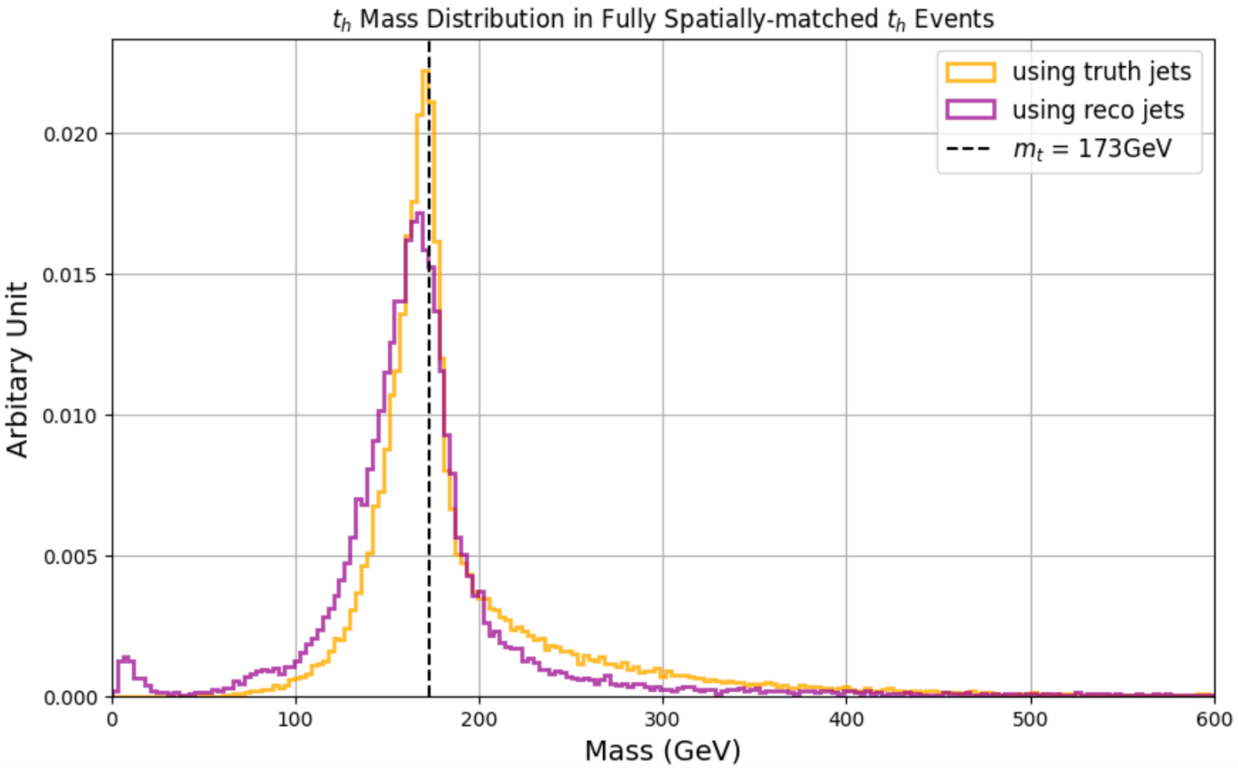
$$\chi^2 = \frac{(m_{b_1 j_1 j_2} - m_{b_2 j_3 j_4})^2}{\sigma^2_{m_{bjj}}} + \frac{(m_{j_1 j_2} - m_W^{MC})^2}{\sigma^2_{m_W^{MC}}} + \frac{(m_{j_3 j_4} - m_W^{MC})^2}{\sigma^2_{m_W^{MC}}}$$



Preliminary Results for Top Reconstruction in 4tops

- The machine learning method can outperform the traditional method in accuracy and speed
- To evaluate the performance of the reconstruction using the machine method, we try to derive the top quark mass distribution predicted from the SPA-Net
  - The top quark mass peak would be 'sharper' with the truth level jet due to better resolution

Event Type	N_{jets}	Event Fraction	SPA-NET Efficiency		χ^2 Efficiency
			t_h	t_l	t_h Only
All Events	≤8	65.4%	**0.135**	**0.568**	0.081
	=9	18.9%	**0.214**	**0.591**	0.139
	≥10	15.7%	**0.226**	**0.593**	0.143
	Inclusive	100%	**0.164**	**0.576**	0.101
Fully Spatially-matched Events	=8	1.16%	**0.703**	**0.819**	0.405
	=9	1.75%	**0.628**	**0.774**	0.378
	≥10	2.51%	**0.524**	**0.741**	0.313
	Inclusive	5.42%	**0.596**	**0.768**	0.354

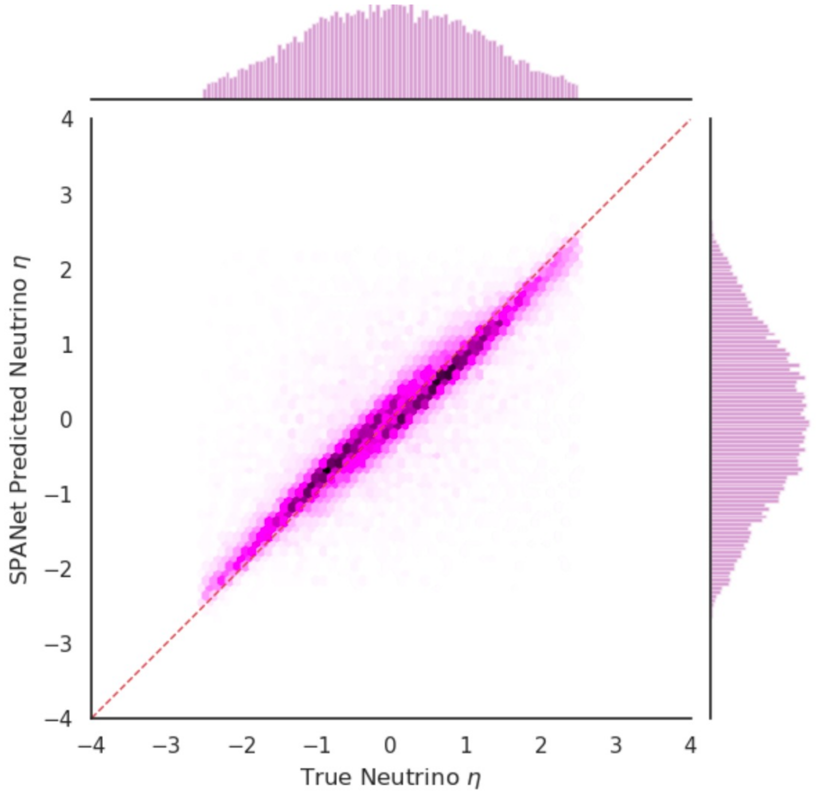


Future Improvements for Top Reconstruction

- We try to regress the neutrino four-momentum distribution using SPA-Net in the dilepton channel

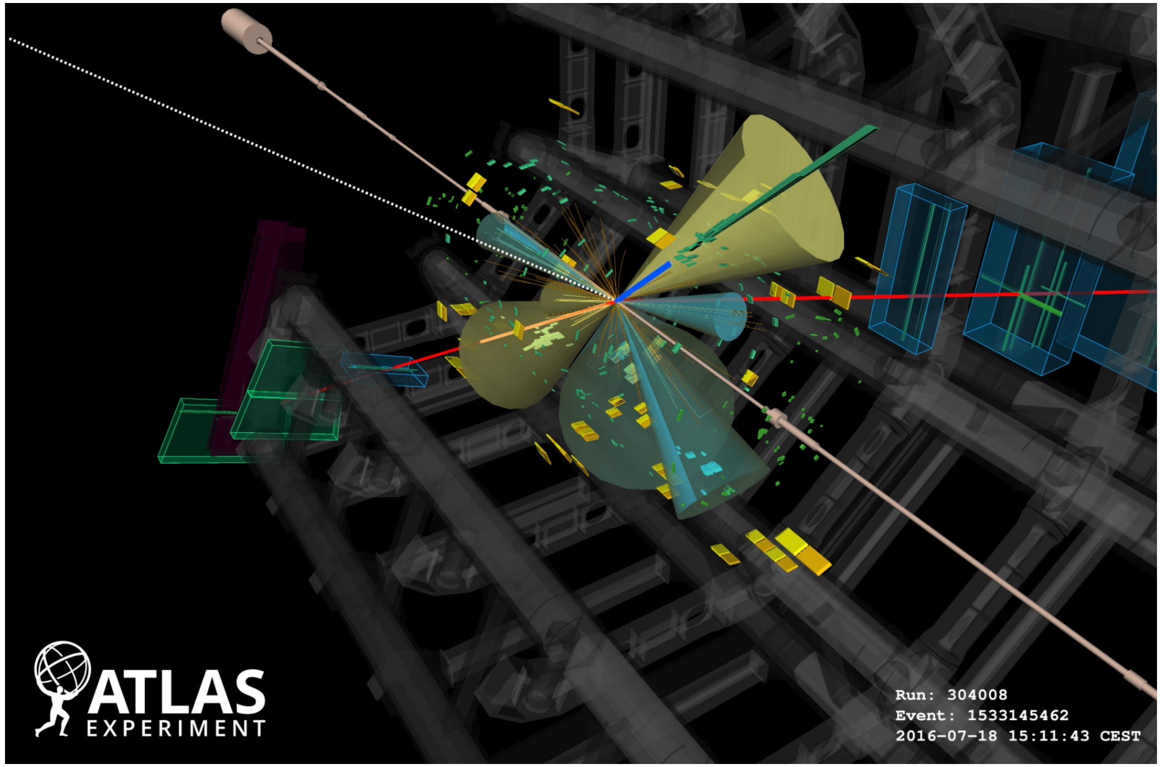
Currently, the top reconstruction with SPA-Net in 4top still needs optimizations

- Model optimization:
  - Model fine-tuning and increasing training statistics for better performance
  - Signal and background separation with the assignment probabilities from SPA-Net
- Further application:
  - Try to test with real data from ATLAS to improve 4top signal efficiency and measurement precision
  - Use SPA-Net to reconstruct other sophisticated final states, such as ttW, ttt, etc.



Summary

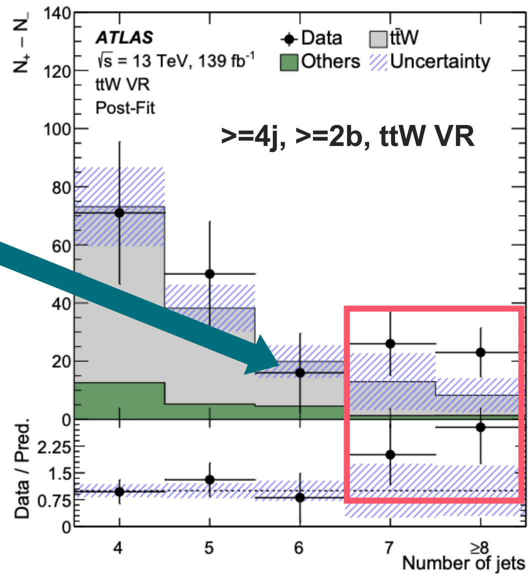
- Observation of tttt with full Run2 data in the multilepton channel with the ATLAS experiment
  - **The first observation of 4-top**: the observed (expected) significance of 4-top reaches 6.1 (4.3) σ
  - Many new physics interpretations also included: top-Higgs Yukawa coupling, EFT, Higgs oblique
  - Paper link: Eur. Phys. J. C 83 (2023) 496
  - 4top Run3 analysis is also on-going
- The machine learning method is also applied for the further top reconstruction in the 4top multi-lepton final state

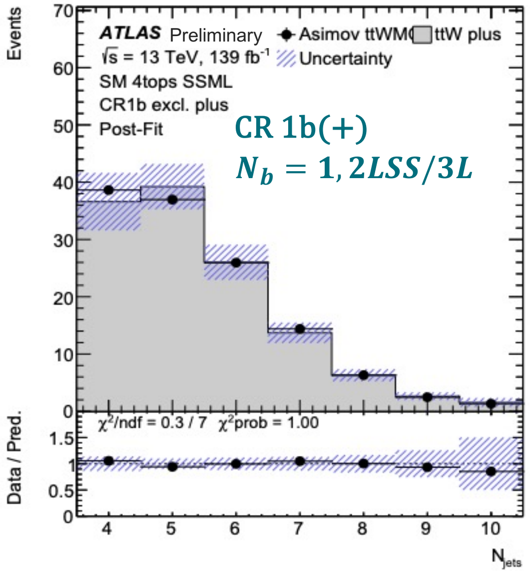


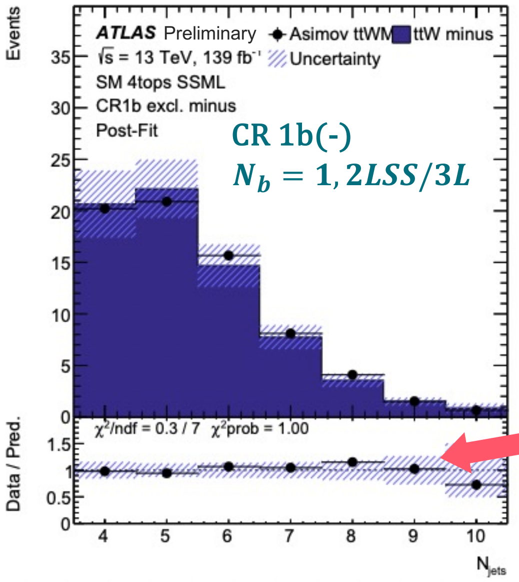
Backups

ttW background

- In the evidence paper, large uncertainties were assigned to ttW+jets coming from template fit. Based on ttW+/- charge asymmetry, data/MC difference reached 125%(300%) with 7jets (>=8jets)
- The impact of μ_{tttt} from the ttW+jets systematics was 10% (one of the leading systematic uncertainties)
- A **data-driven method** is developed to get rid of these ad-hoc uncertainties







- Use kinematics from MC but the dependency is corrected to data by a parameterized model based on a staircase and Poisson scaling
- ttW contribution per jet bin parameterized as:

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

- Many checks were done to validate the parameterized function
- A stat-only fit to ttW Asimov MC (with different choice or generators) to test stability: the good agreement between the post-fit ttW estimation and the Asimov ttW MC

Objection Definition Details

Generally, the objection definitions 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

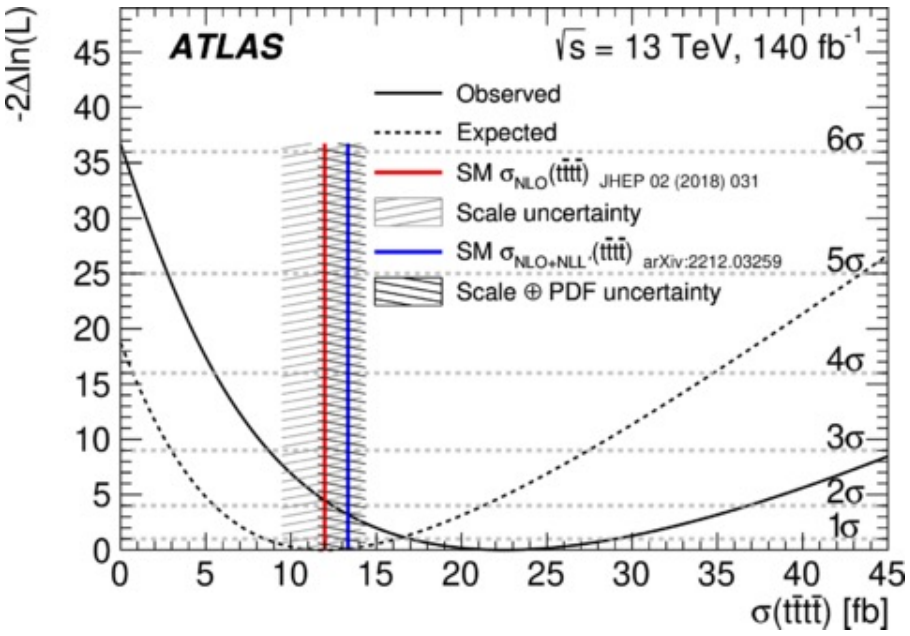
	Electrons		Muons		Jets	b-jets
	loose	tight	loose	tight		
p_T [GeV]	> 15		> 15		> 20	> 20
$\|\eta\|$	< 1.37 or 1.52 – 2.47		< 2.5		< 2.5	< 2.5
ID quality	mediumLH ECIDS (ee, $e\mu$)	tightLH ECIDS (ee, $e\mu$)	medium		cleaning + JVT	DL1r 77%
Isolation	Loose_VarRad	PLImprovedTight	PflowLoose_FixedRad	PLImprovedTight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

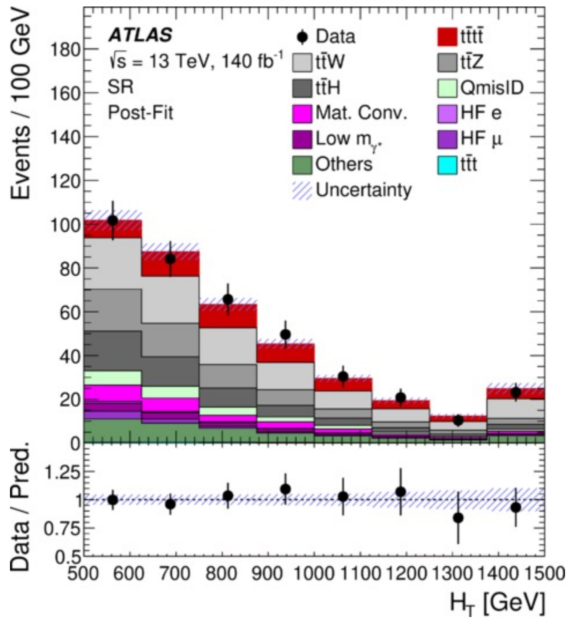
Regions Four Top

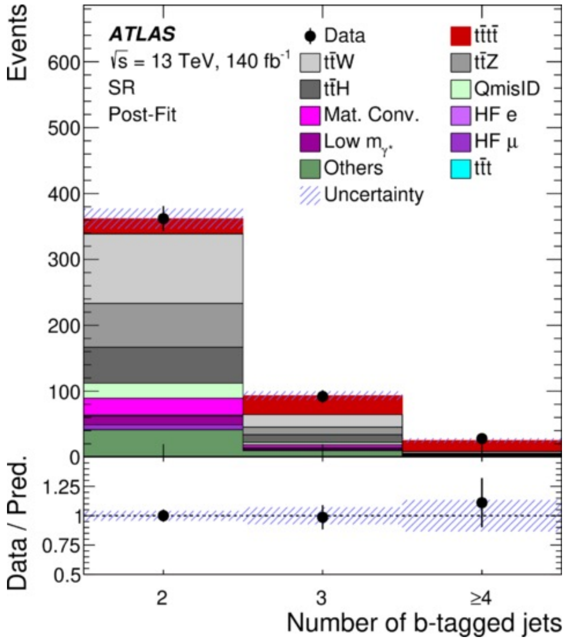
Region	Channel	N_j	N_b	Other selection	Fitted variable
CR Low m_{γ^*}	SS, ee or eμ	$4 \leq N_j < 6$	≥ 1	ℓ_1 or ℓ_2 is from virtual photon (γ^*) decay ℓ_1 and ℓ_2 are not from photon conversion	event yield
CR Mat. Conv.	SS, ee or eμ	$4 \leq N_j < 6$	≥ 1	ℓ_1 or ℓ_2 is from photon conversion	event yield
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

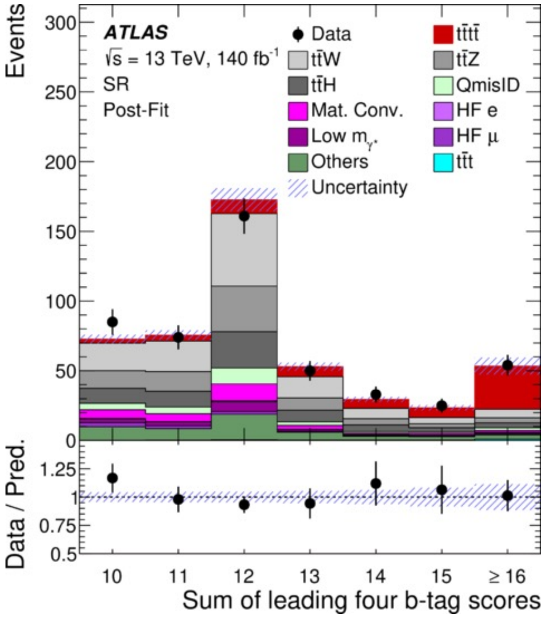
Fitting Results

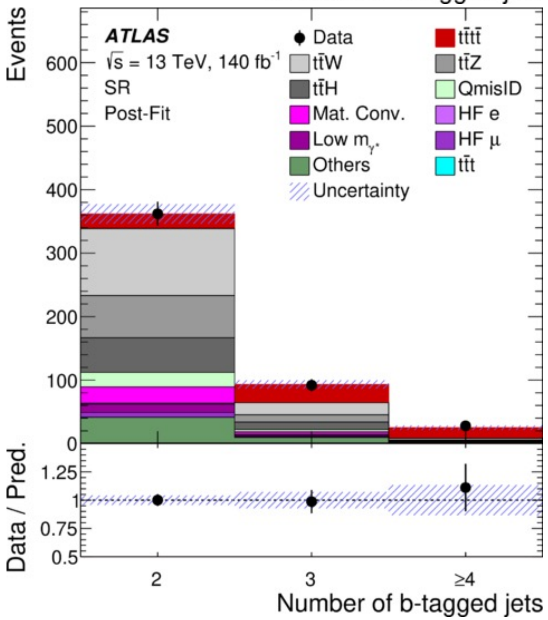
- The fitting result of the signal region
- The negative log-likelihood values as a function of the $t\bar{t}t\bar{t}$ signal cross section. The continuous line represents the observed likelihood while the dashed line corresponds to the expected one.











Detailed Uncertainties - tttt

Uncertainty source	$\Delta\sigma$ [fb]		$\Delta\sigma/\sigma$[%]	
Signal modelling				
$t\bar{t}t\bar{t}$ generator choice	+3.7	−2.7	+17	−12
$t\bar{t}t\bar{t}$ parton shower model	+1.6	−1.0	+7	−4
Other $t\bar{t}t\bar{t}$ modelling	+0.8	−0.5	+4	−2
Background modelling				
$t\bar{t}H$+jets modelling	+0.9	−0.7	+4	−3
$t\bar{t}W$+jets modelling	+0.8	−0.8	+4	−3
$t\bar{t}Z$+jets modelling	+0.5	−0.4	+2	−2
Other background modelling	+0.5	−0.4	+2	−2
Non-prompt leptons modelling	+0.4	−0.3	+2	−2
$t\bar{t}t$ modelling	+0.3	−0.2	+1	−1
Charge misassignment	+0.1	−0.1	+0	−0
Instrumental				
Jet flavour tagging (b-jets)	+1.1	−0.8	+5	−4
Jet uncertainties	+1.1	−0.7	+5	−3
Jet flavour tagging (light-flavour jets)	+0.9	−0.6	+4	−3
Jet flavour tagging (c-jets)	+0.5	−0.4	+2	−2
Simulation sample size	+0.4	−0.3	+2	−1
Other experimental uncertainties	+0.4	−0.3	+2	−1
Luminosity	+0.2	−0.2	+1	−1
Total systematic uncertainty	+4.6	−3.4	+20	−16
Statistical				
Intrinsic statistical uncertainty	+4.2	−3.9	+19	−17
$t\bar{t}W$+jets normalisation and scaling factors	+1.2	−1.1	+6	−5
Non-prompt leptons normalisation (HF, Mat. Conv., Low m_{γ^*})	+0.4	−0.3	+2	−1
Total statistical uncertainty	+4.7	−4.3	+21	−19
Total uncertainty	+6.6	−5.5	+29	−25

New Physics Interpretations - EFT

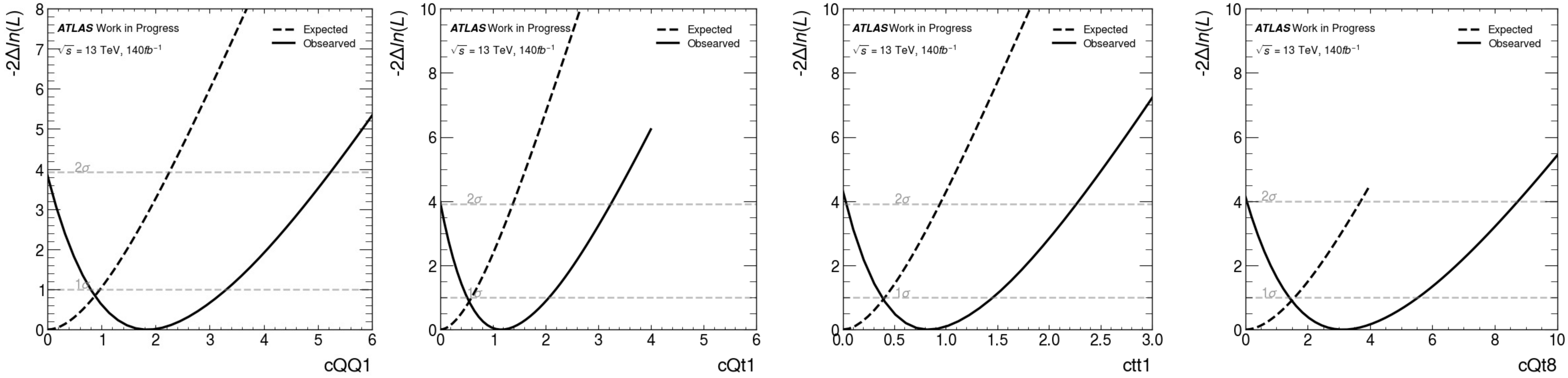
EFT Linear parameterzation:

- Get the upper limit of the EFT coefficient at 95% CL, assuming linear term only
- The wider limit compared to the quadratic interpolation shows the importance of the quadratic terms

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

Limits on EFT operators sensitive to four top production (linear interpolation)

Operators	Expected C_i/Λ^2 [TeV $^{-2}$]	Observed C_i/Λ^2 [TeV $^{-2}$]
$\mathcal{O}^1_{QQ}$	2.3	5.3
$\mathcal{O}^1_{Qt}$	1.4	3.4
$\mathcal{O}^1_{tt}$	1.0	2.4
$\mathcal{O}^8_{Qt}$	3.6	8.8



HT Fitting Results

HT fit in this analysis also get the significance over 5 sigma

Significance	GNN	HT
Expected (σ)	**4.3**	2.7
Observed (σ)	**6.1**	5.0

Channel	Selection criteria
Common	$N_j \geq 6$, $N_b \geq 2$ and $H_T > 500$GeV
SR2b2l	SS events with $N_b = 2$
SR2b3l	multilepton events with $N_b = 2$
SR3b2l	SS events with $N_b = 3$
SR3b3l	multilepton events with $N_b = 3$
SR4b	events with $N_b \geq 4$