Observation of Four-top-quark Production and Improving Top Quark Reconstruction Efficiency Using Machine Learning Method

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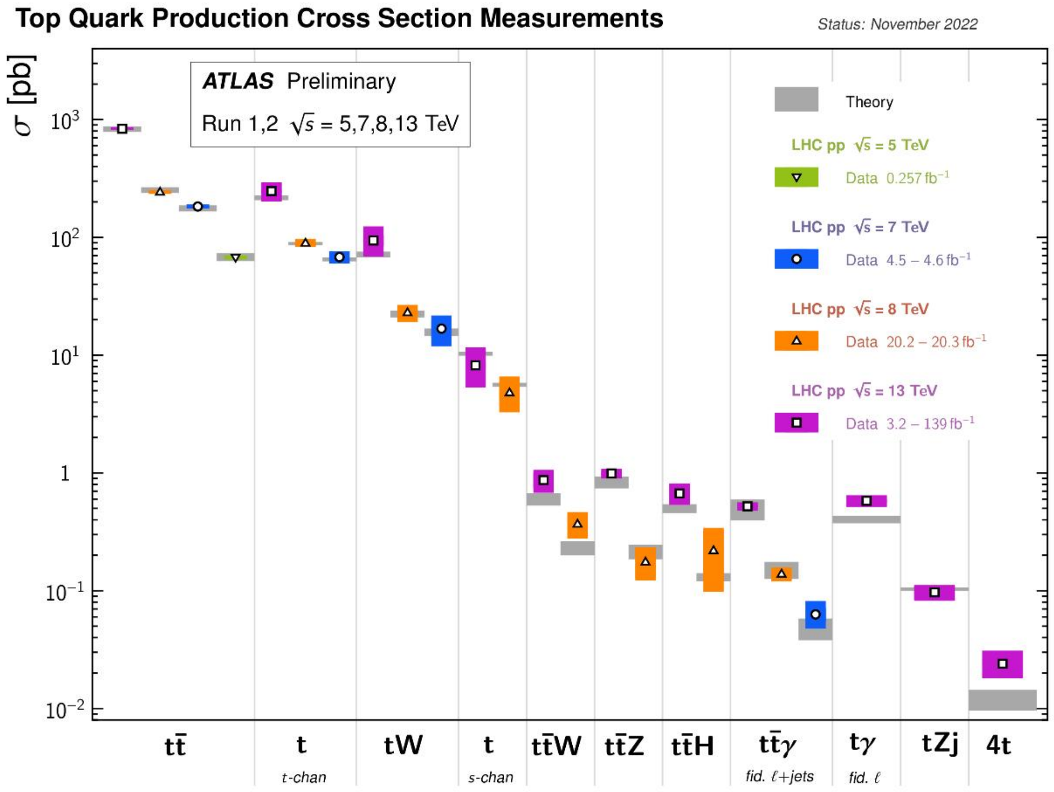
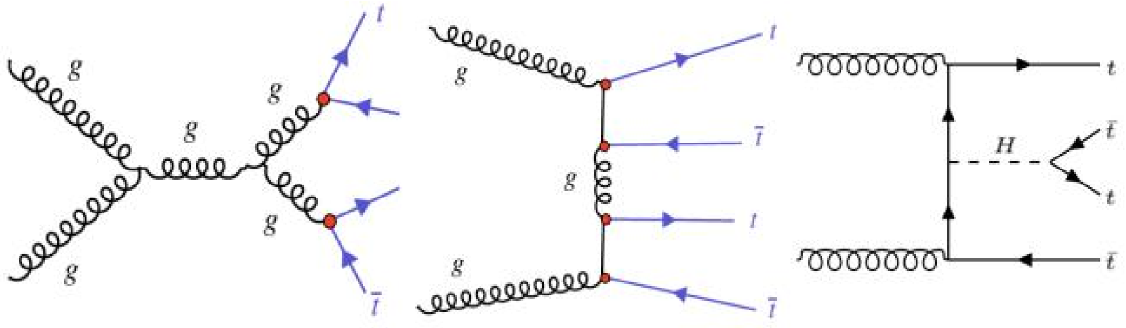
2024.08.14

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): $\sigma(t\bar{t}t\bar{t})$ = 12 fb ± 20% [JHEP 02 (2018) 031]
  - NLO+NLL: $\sigma(t\bar{t}t\bar{t})$ = 13.4 fb ± 11% [arXiv:2212.03259]

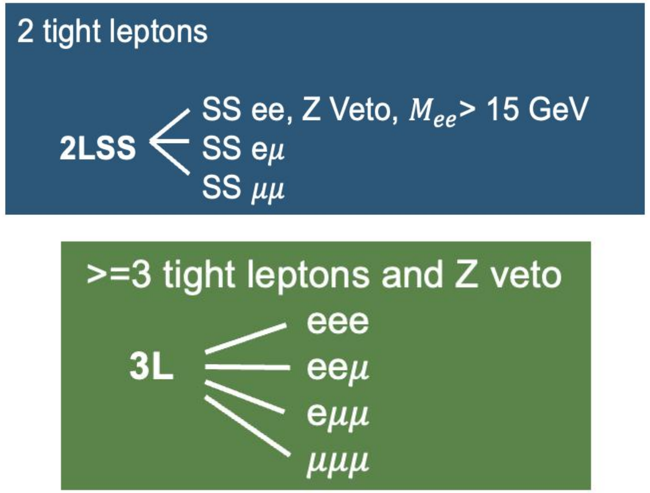
- $t\bar{t}t\bar{t}$ cross section is sensitive to anomalous top Yukawa coupling and Higgs CP properties
- Also it is sensitive probe for some new physics models such as EFT, 2HDM model

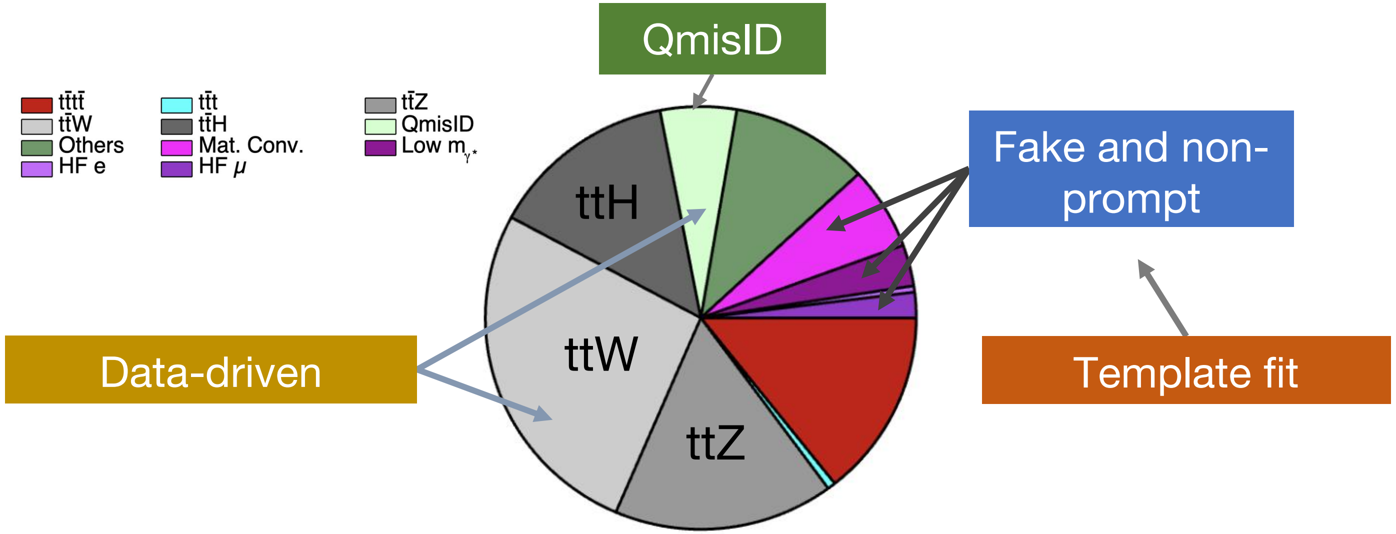
Four Top Process Signatures and Backgrounds

- **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





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Background Estimation

Fake/non-prompt backgrounds

- Heavy flavor electron and heavy flavor muon
- Material conversions and 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

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

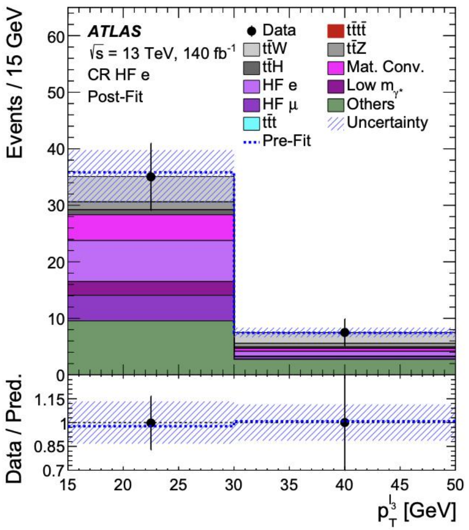
ttW background

- 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)

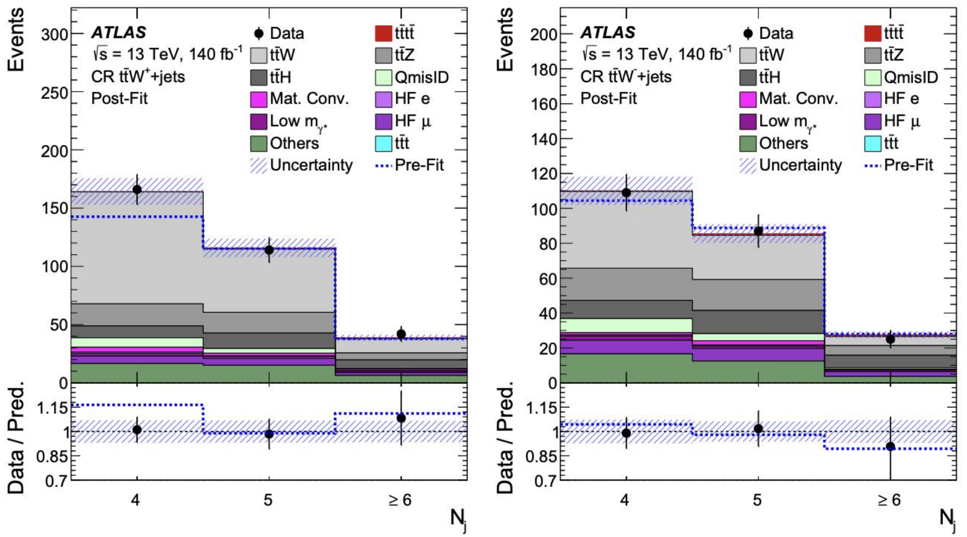
$$NF_{t\bar{t}W@nj} = NF_{t\bar{t}W^{+}@4j} \times \Pi_{n'=4}^{n'=n-1}\left[a_0 + \frac{a_1}{1+(n'-4)}\right] + NF_{t\bar{t}W^{-}@4j} \times \Pi_{n'=4}^{n'=n-1}\left[a_0 + \frac{a_1}{1+(n'-4)}\right].$$

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

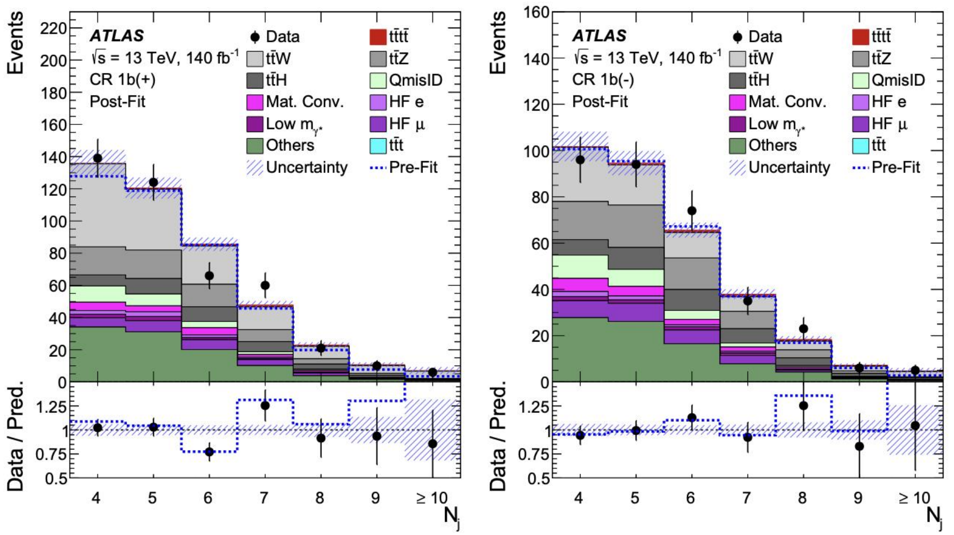
Heavy flavor e



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



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



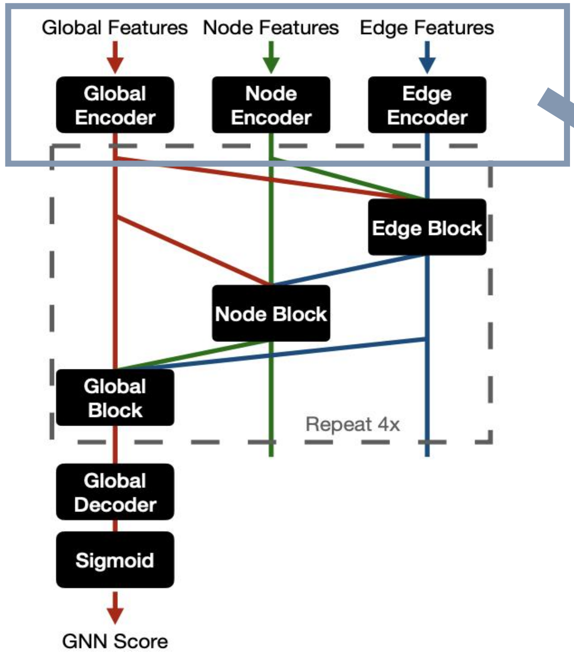
Four-Top-Quark Signal Discrimination with Machine Learning Method

- In order to improve the signal sensitivity, we tried different MVA methods,
  - Particle Flow Network (PFN)
  - Graph Neutral Network (GNN)

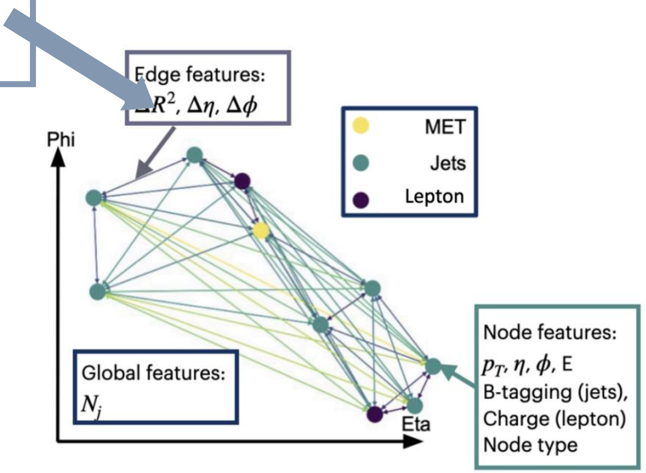
- GNN is constructed to combine the information about objects (jets, lepton, MET) in an event into graphs, with node, edge, and global properties.

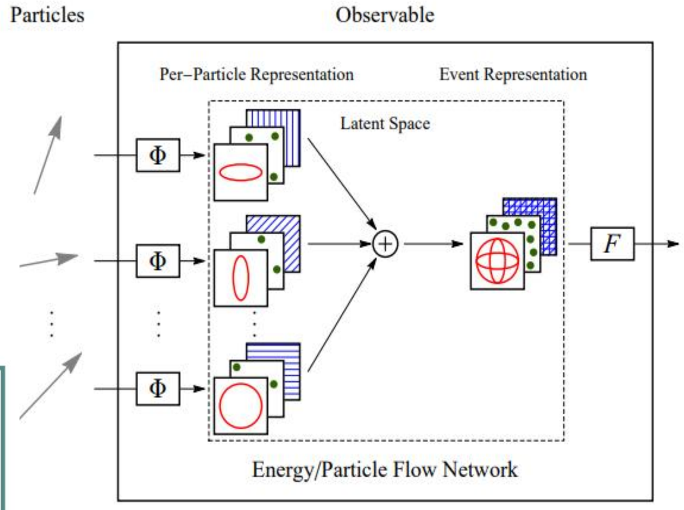
- PFN utlizes deep neutral network to extract the the character of each physics objects (lepton, jets) by the inputs and combines them with the event level informations (number of jets, MET).

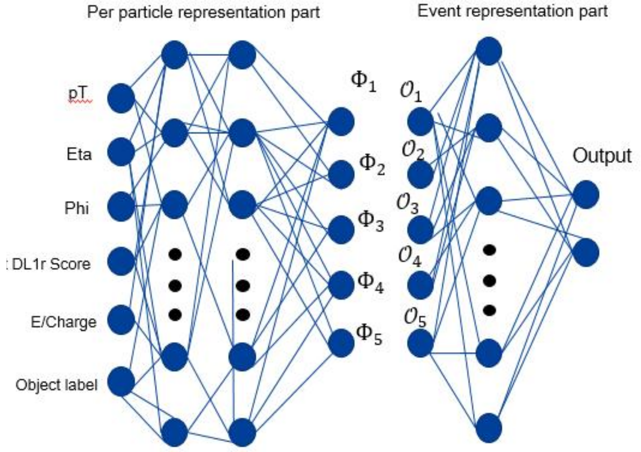
GNN network structure



GNN inputs



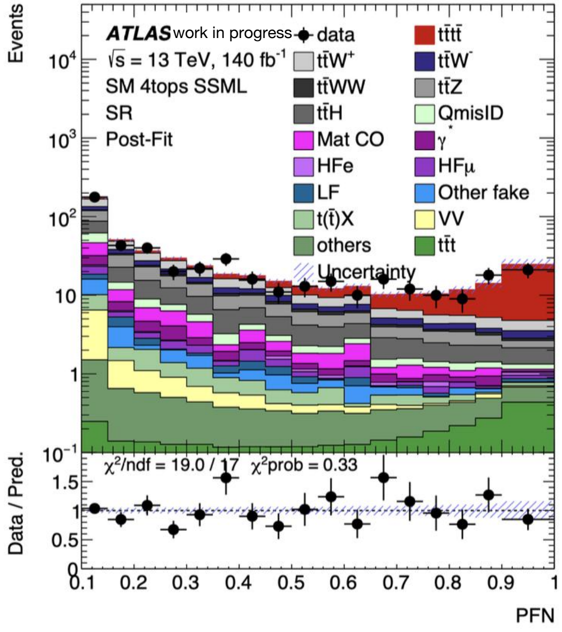




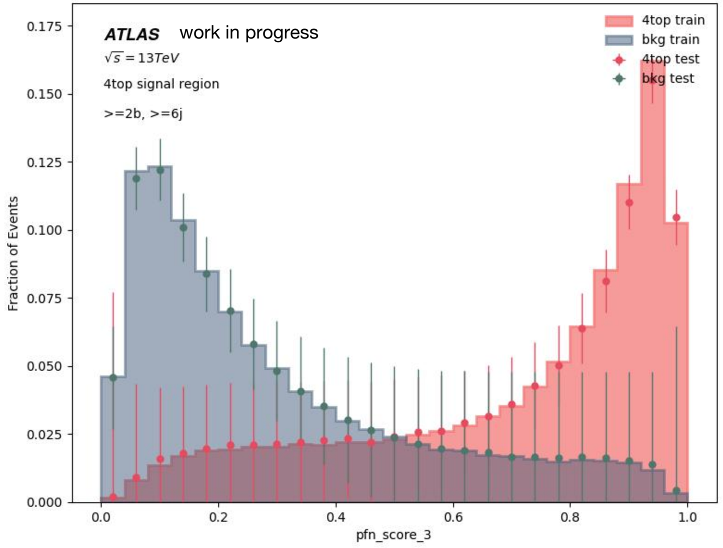
Four-Top-Quark Signal Discrimination with Machine Learning Method

- For all the machine learning method, their performance are checked to avoid mis-modelling
- k-Fold method is applied for optimization
- Good agreement in high MVA regions with data and MC
- GNN method was chosen to provide central value for cross section measurements

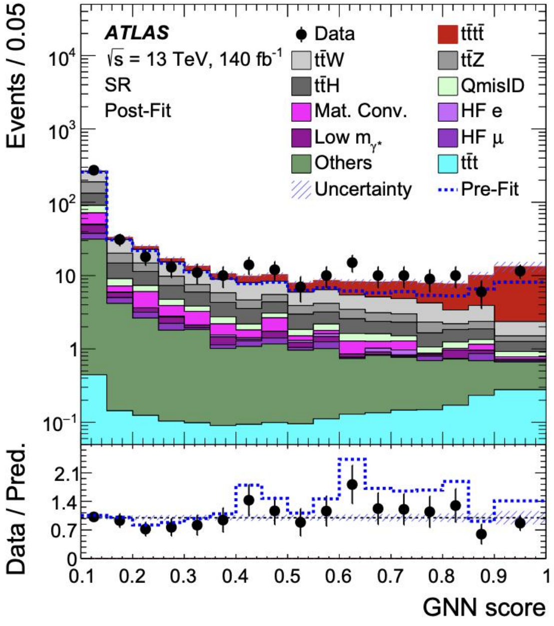
PFN SR



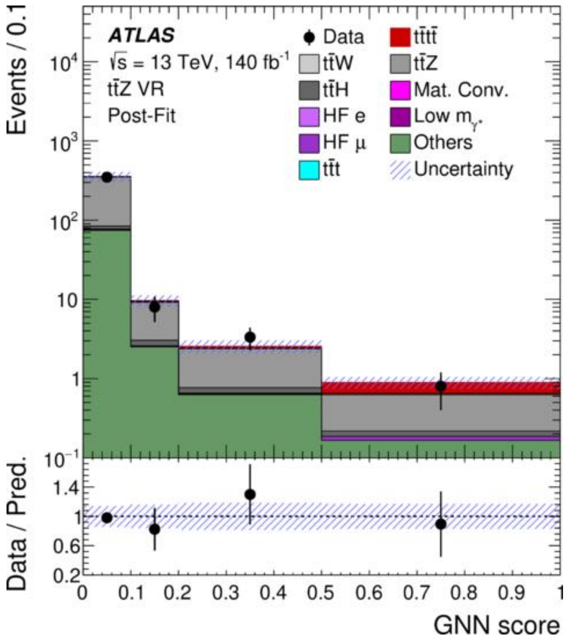
PFN Performance Check



GNN SR



ttZ VR GNN



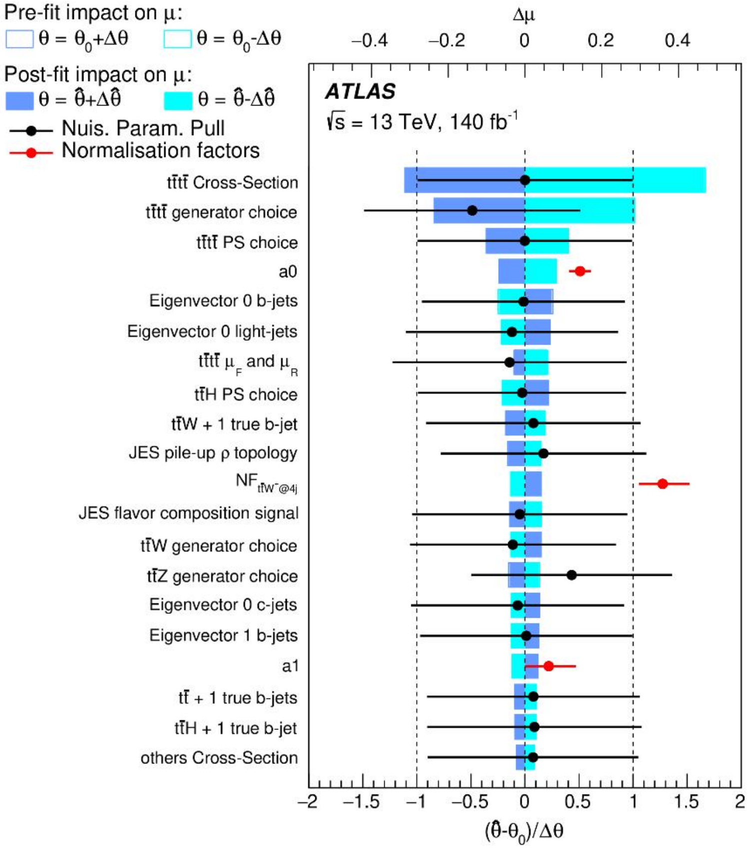
Four-Top-Quark Cross Section Results

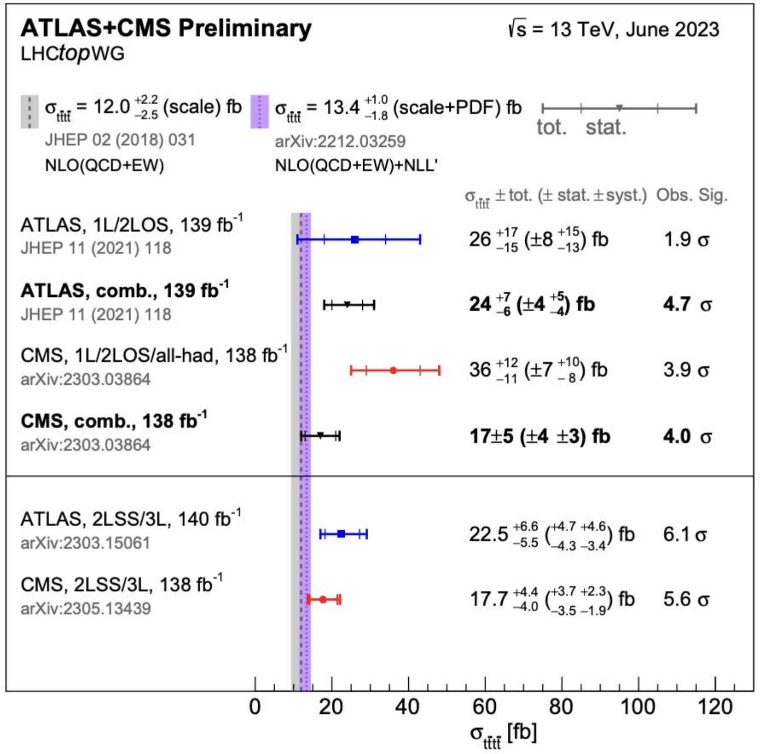
- The observed significance is **6.1** sigma: **first observation of four-top-quark production!**
- The largest uncertainties come from 4top modeling and the data-driven ttW parameters

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

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

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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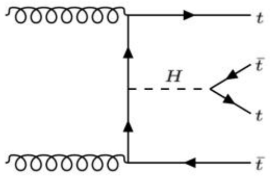
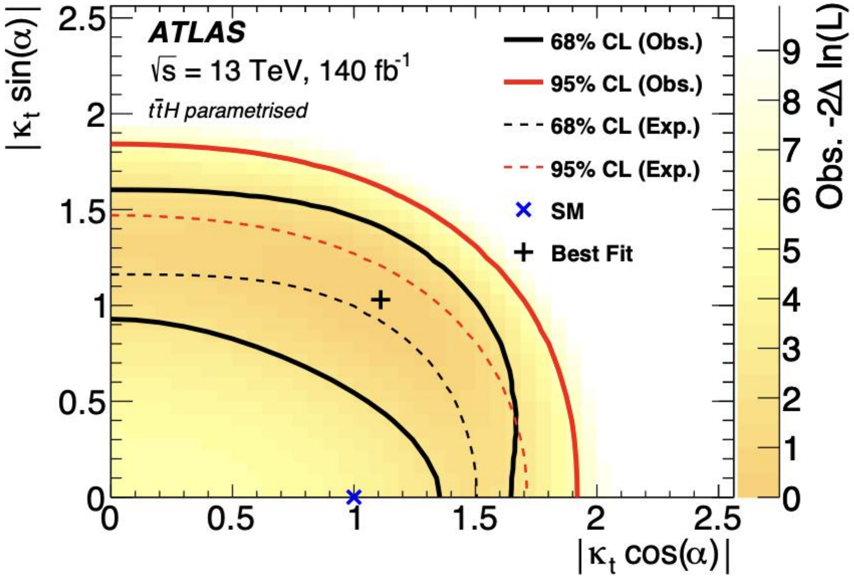
New Physics Interpretations

- **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)
- 

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

CP even CP odd

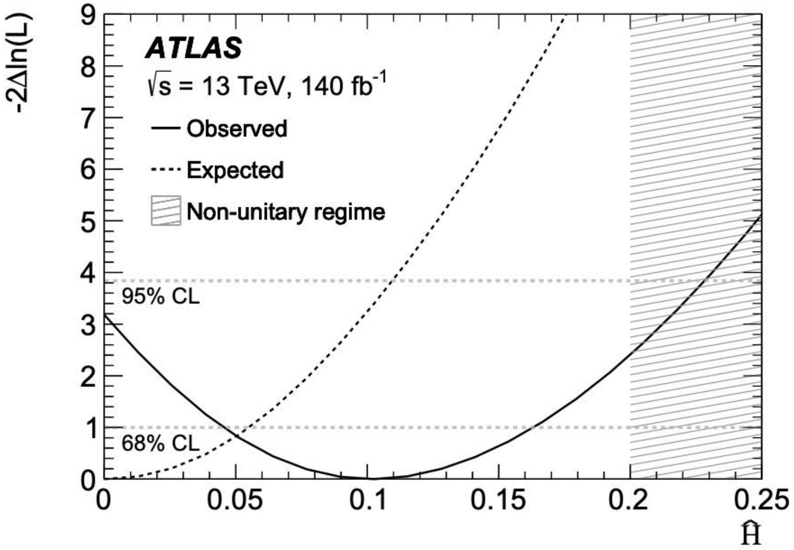


Higgs oblique paramter

- 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 Quark Reconstruction in Multi-lepton State

- 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
  - Large number of permutations and long running time
  - Hard to reconstruct leptonic top
  - Depending on b-tagging
- Generating 160k four top quark events. 38.5% top quarks have all reconstructed daughters

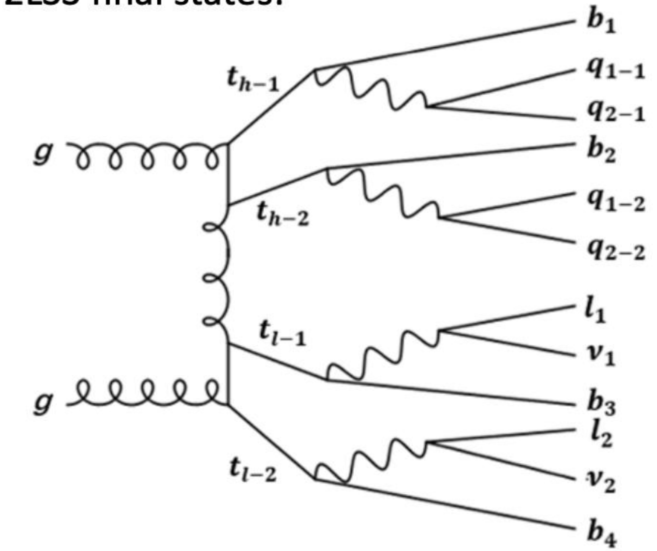
Event Type	N jet	Event fraction	Hadronic top chi2 efficiency
All Event	==6	7.9%	0.07
	==7	19.8%	0.130
	>=8	72.9%	0.1985
	inclusive	1	0.172

12 jets and 4 b jets: 2520 permutations
14 jets and 5 b jets: 113400 permutations

Find the best permutation with smallest chi2

$$\chi^2 = \frac{(m_{b_1 j_1 j_2} - m_{b_2 j_3 j_4})}{\sigma^2_{mbjj}} + \frac{(m_{j_1 j_2} - m_w)}{\sigma^2_{mw}} + \frac{(m_{j_3 j_4} - m_w)}{\sigma^2_{mw}}$$

2LSS final states:



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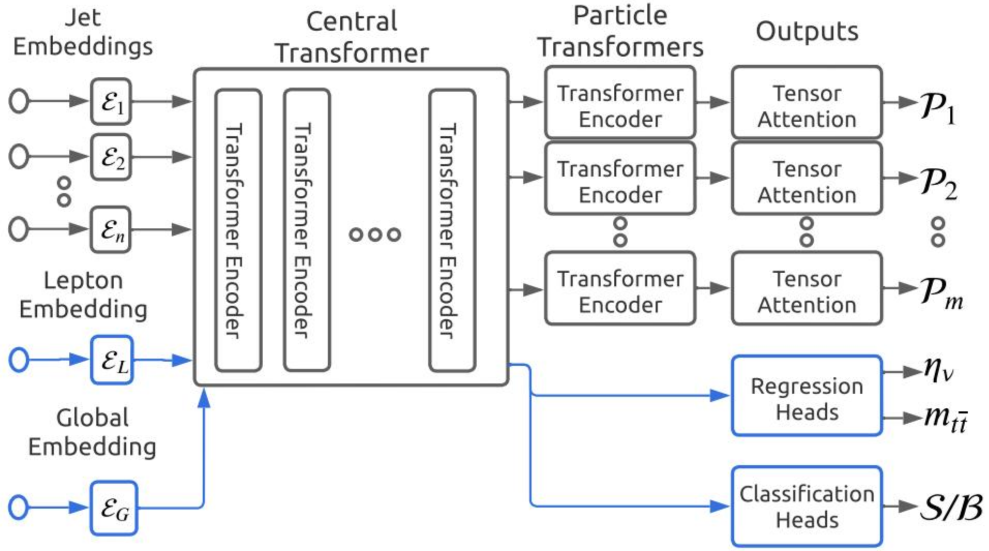
Machine Learning Method in Top Quark Reconstruction

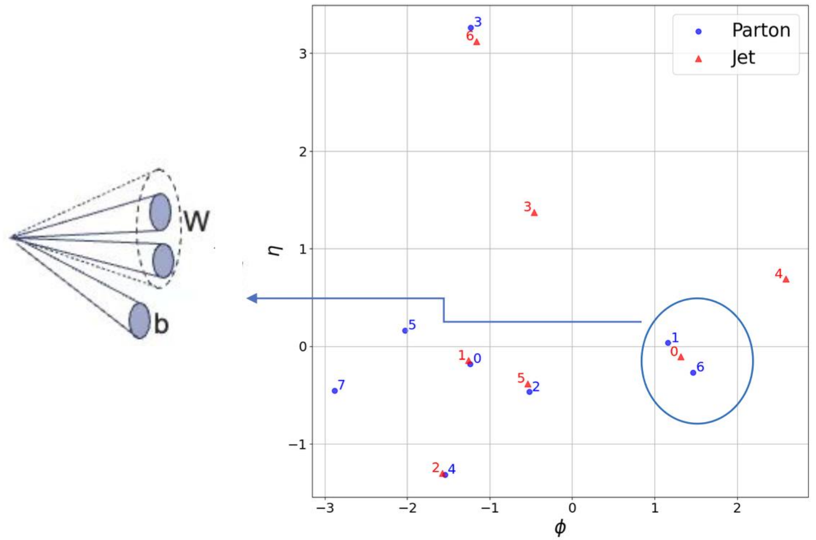
- Top reconstruction would be challenging in the 4top multi-lepton channel with missing momentum and extensive jet permutations.
  - Using SPA-Net based on the transformer network with fast simulation 4top process
  - Can handle partial events
  - Besides the top quark reconstruction, the network can also do the neutrino momentum regression
- Using 600k 4top same sign sample for training and validation. Events are filtered by the 4top SR selection mentioned previouly.

$$Loss = a_{reco}L_{reconstruction} + a_{det}L_{detection} + a_{reg}L_{regression}$$



SPANET

Truth labelling for supervised learning:
- Spatial matching based on truth-level partons in (eta, phi) plane
- The SPANET predicts the top candidate according to the combination possibility from network



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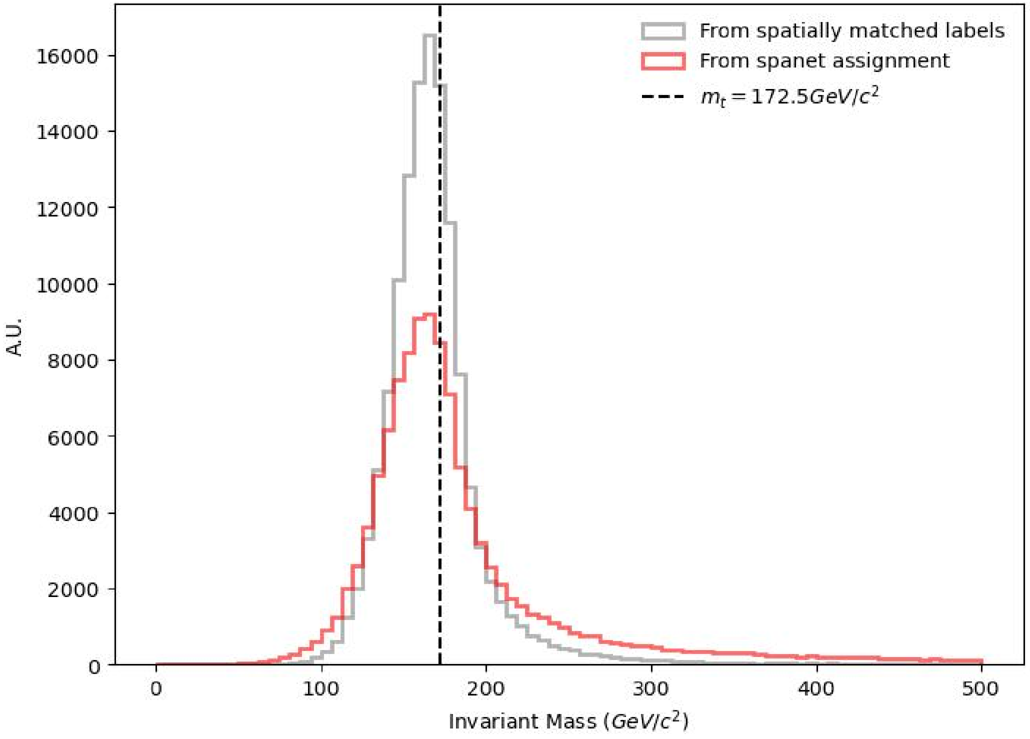
Preliminary Results for Four-Top-Quark Reconstruction with SPANET

- Evaluating the perfromance using the top quarks which decay products are spatially matched to partons
- The machine learning method outperforms the traditional method in accuracy and speed:
  - Speed: SPANET improves about **3 times** faster in running time(both in CPU)
  - Accuracy: SPANET achieves **~38%** in hadronic top efficiency, **~70%** for leptonic top efficiency

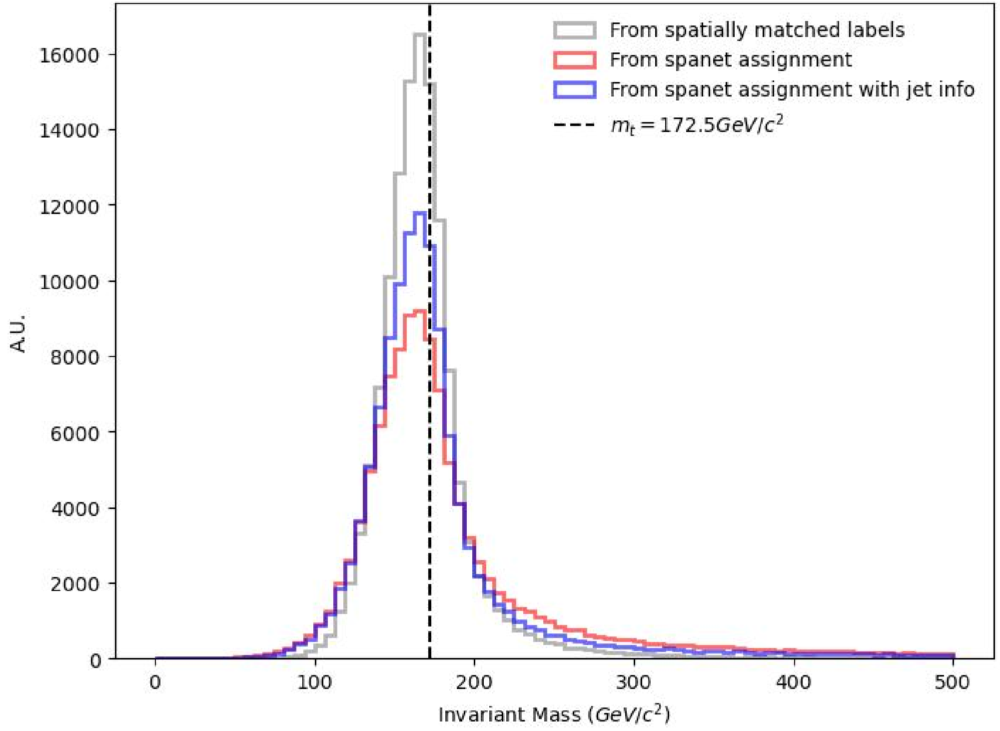


SPANET result

Event Type	N jet	Event fraction	Hadronic top	Leptonic top
All Event	==6	7.9%	0.326	0.752
	==7	19.8%	0.375	0.727
	>=8	72.9%	0.387	0.692
	inclusive	1	0.383	0.703

Further Improvement in Four-Top-Quark Reconstruction

- In order to improve the performance, we try to add some jet substructures in the training
  - Adding $\tau_1, \tau_2, \tau_3, \tau_4, \tau_5$ and ratio of charge particles over neutral particles
- The improvement coming from jet substructures is ~5% for hadronic top quark
- Would investigate more about the b-jet tagging variables in the future

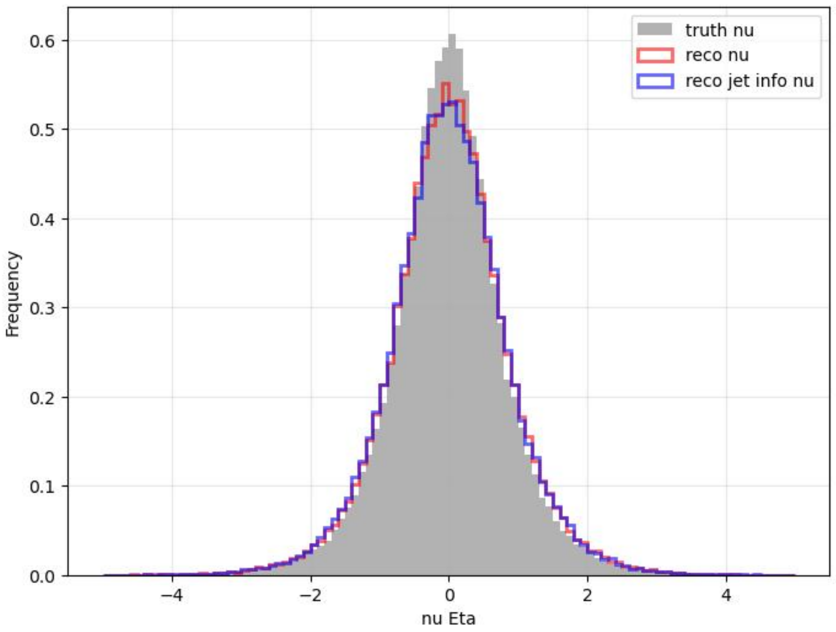


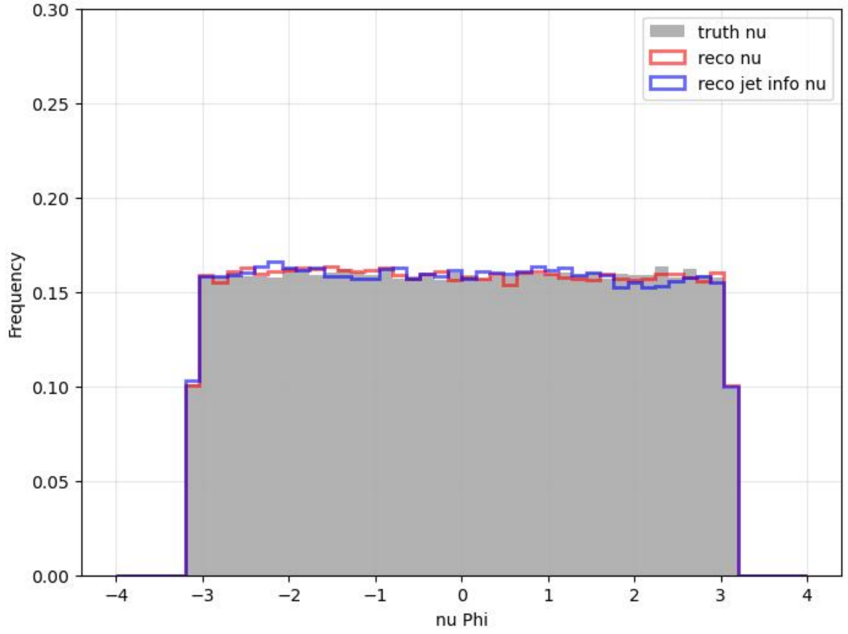
SPANET result with substructures

Event Type	N jet	Event fraction	Hadronic top	Leptonic top
All Event	==6	7.9%	0.332	0.766
	==7	19.8%	0.386	0.735
	>=8	72.9%	0.402	0.700
	inclusive	1	0.397	0.711

Further Improvement in Four-Top-Quark Reconstruction

- Neutrino kinematics information can be extracted using SPA-NET as well

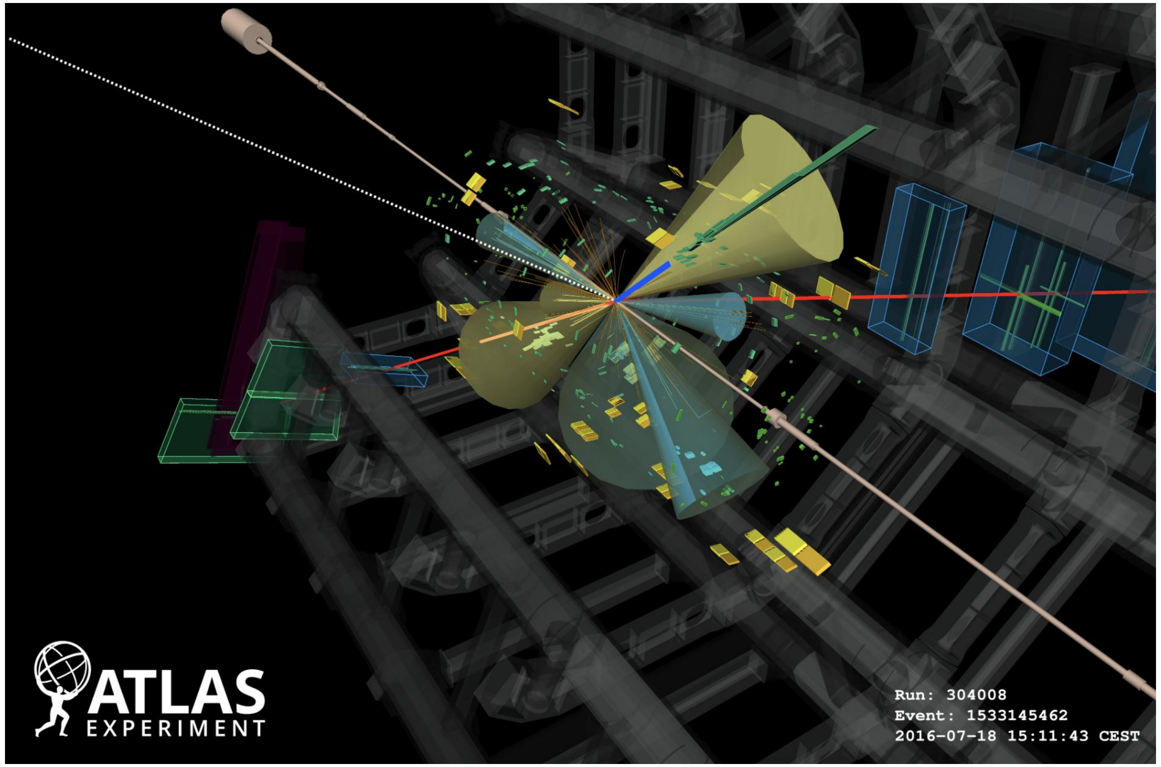




- Further optimizations underway:
- Model optimization: signal and background separation with the assignment probabilities from SPA-Net
- Further application:
  - Try to test with real data from ATLAS to improve 4top signal efficiency and measurement precision
  - Use SPA-Net to reconstruct other sophisticated 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
  - Using SPANET for top reconstrution: 3 times faster and hadronic top efficiency doubled to be ~40%, leptonic top efficiency reaches 70%
  - Futher optimizations such as neutrino reconstruction and jet substructures



Backups

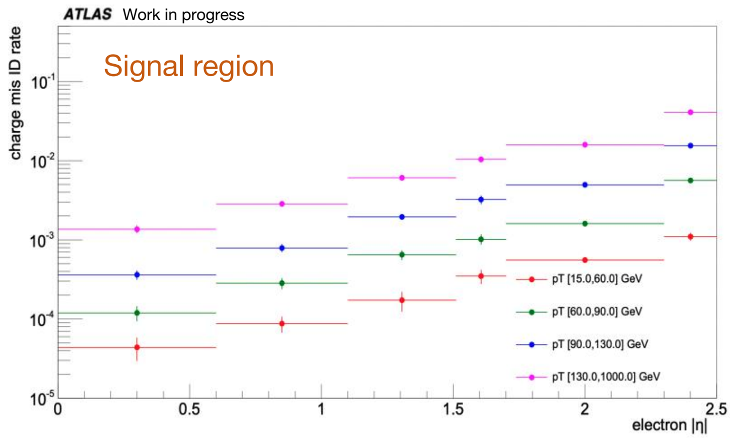
Fake/non-prompt and QmisID Backgrounds

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



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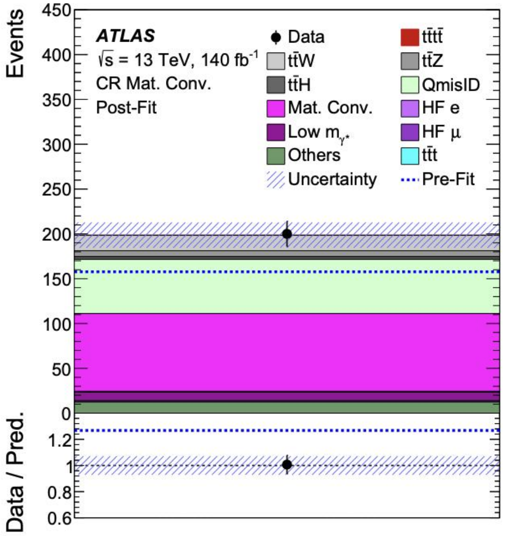
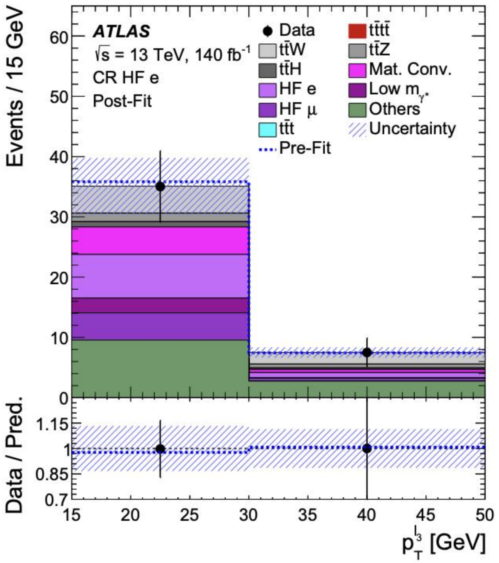
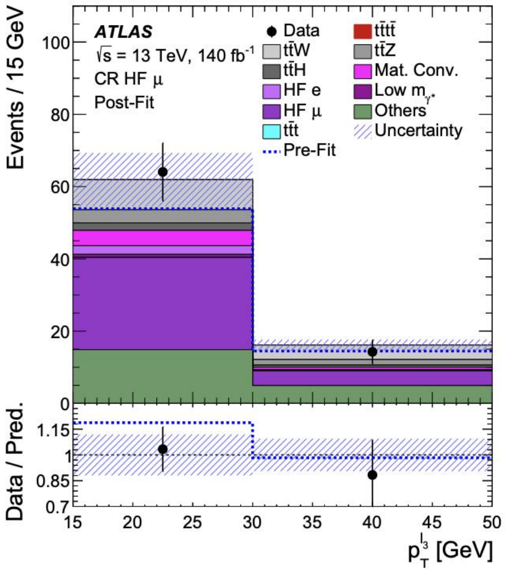


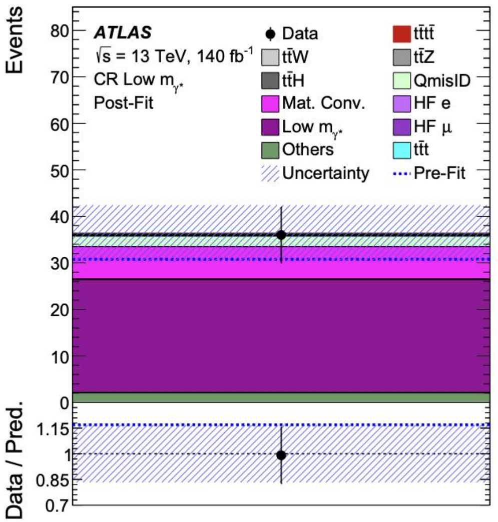
Heavy flavor e



Heavy flavor mu



Virtual photon conversion



ttW background: Data-Driven Method

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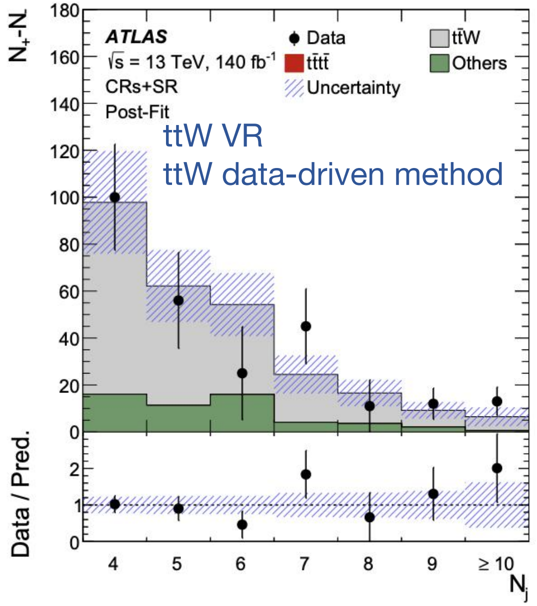
$t\bar{t}W$ background	a_0	a_1	$\mathrm{NF}_{t\bar{t}W^{+}(4\mathrm{jet})}$	$\mathrm{NF}_{t\bar{t}W^{-}(4\mathrm{jet})}$
Value	0.51 ± 0.10	$0.22^{+0.25}_{-0.22}$	$1.27^{+0.25}_{-0.22}$	$1.11^{+0.31}_{-0.28}$



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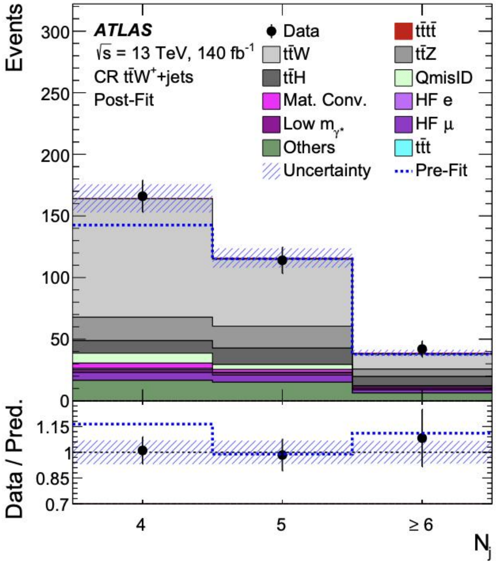
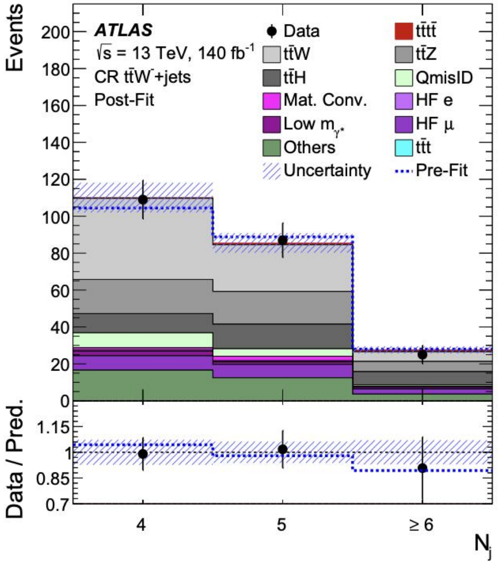
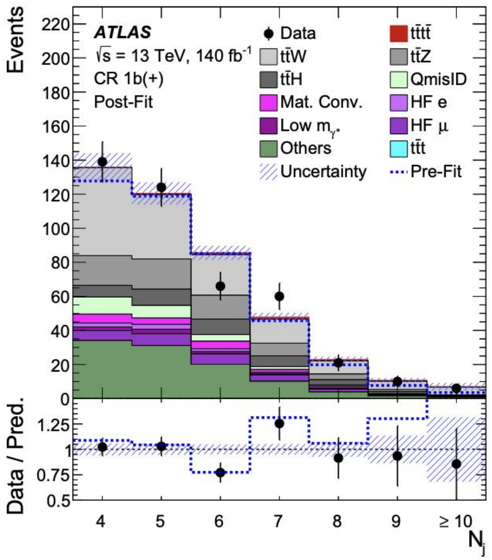
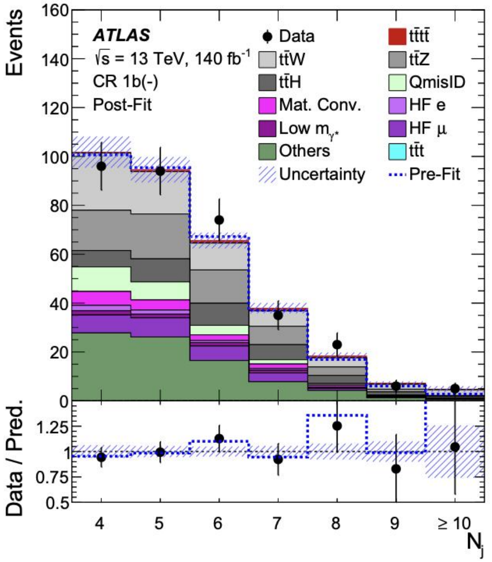




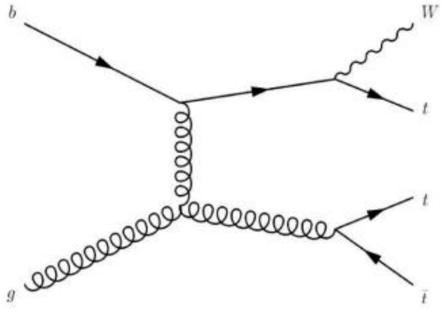
1b control regions: SS/3L, $N_b = 1$, $N_{jet} \geq 4$



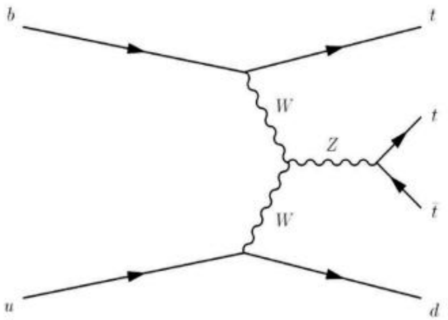


Interpretations - Three Top Cross Section

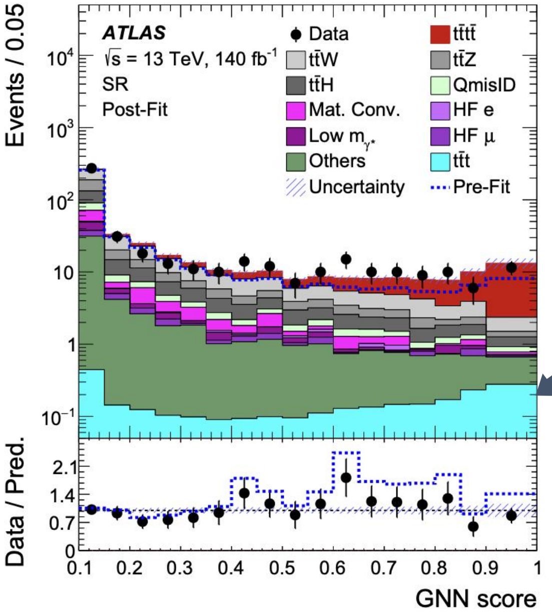
- SM three top production is even rarer than 4 top and has yet to be discovered.
- The three top final state is very similar to the four top: large contribution in high GNN region
- We also tried to constrain the 3top production
- The correlation between 4top and 3top is very large (-93%) after free-floating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

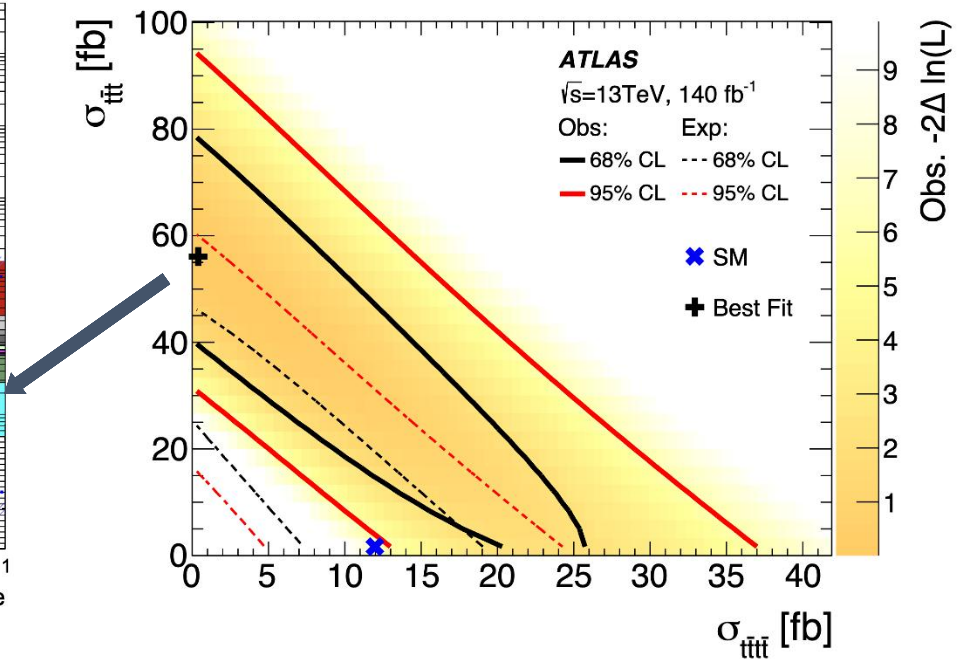


σ(tt̄t W) ~ 1 fb



σ(tt̄t 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]

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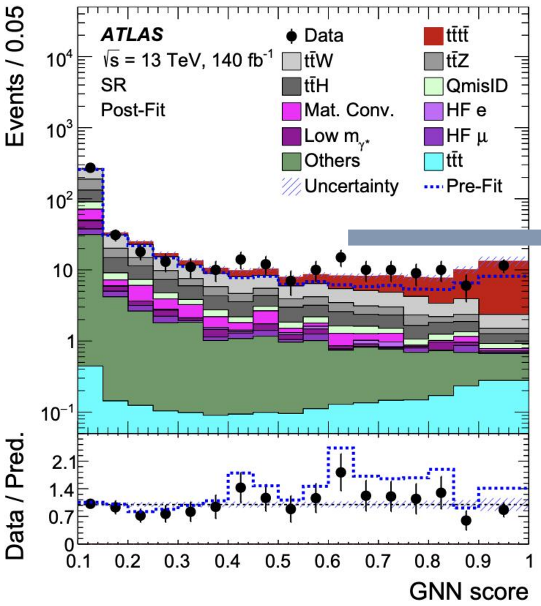
New Physics Interpretations - EFT

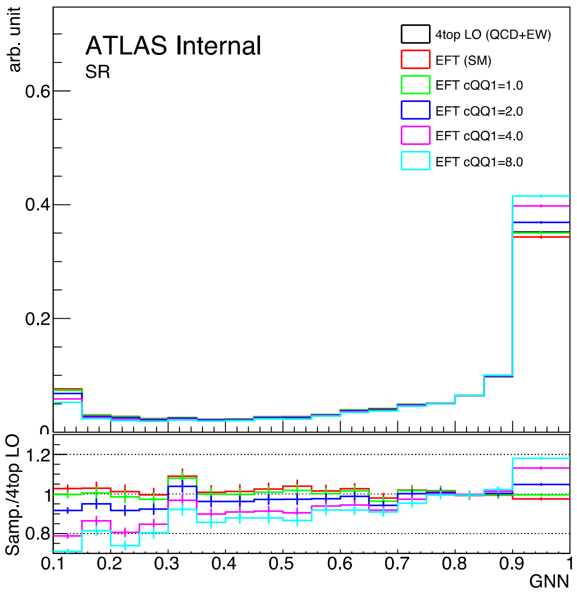
$$\sigma_{t\bar{t}t\bar{t}} = \sigma^{SM}_{t\bar{t}t\bar{t}} + \frac{1}{\Lambda^2}\sum_i C_i \sigma_i^{(1)} + \frac{1}{\Lambda^4}\sum_{i\leq j} C_i C_j \sigma_{i,j}^{(2)}$$

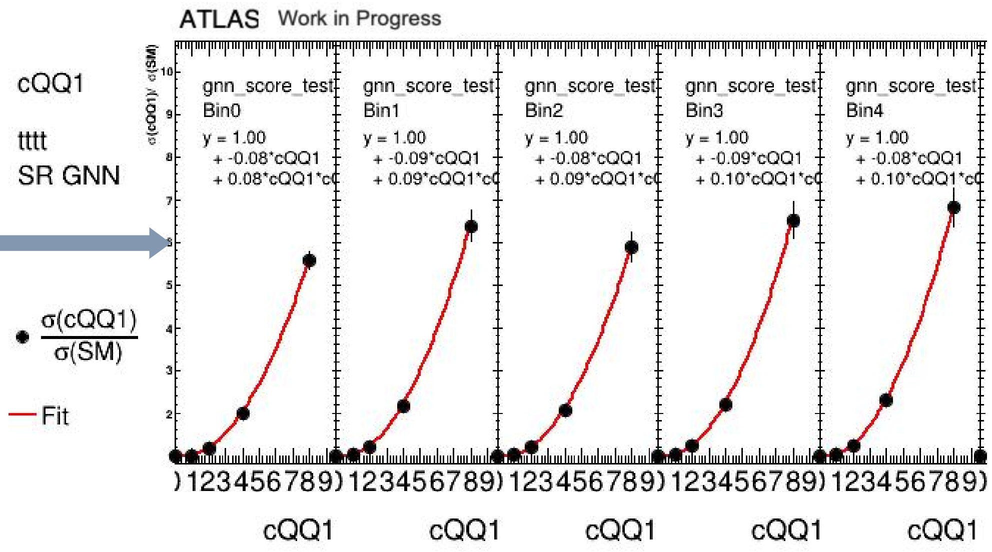
EFT parameters:

- 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

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]





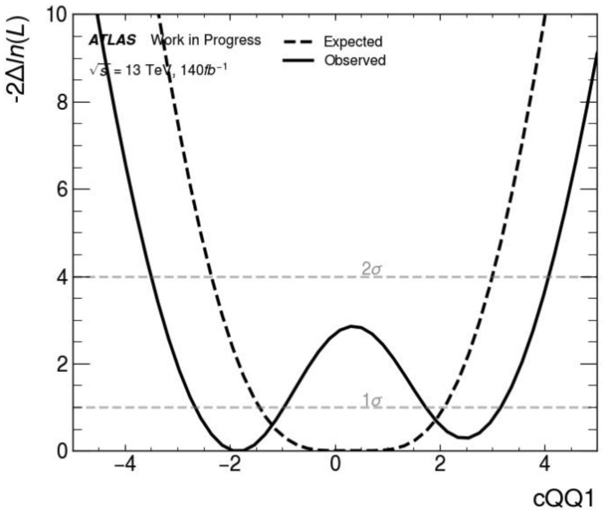


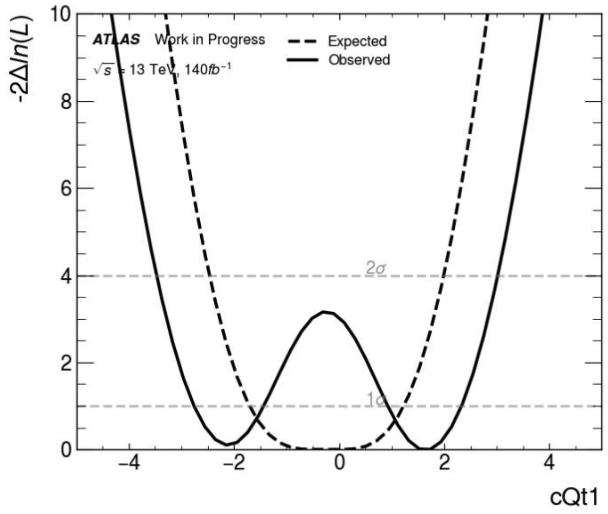
New Physics Interpretations - EFT

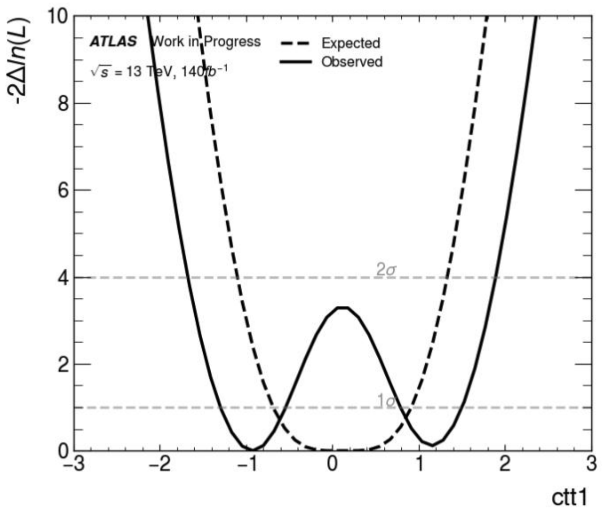
- **EFT Quadratic parameterization:**
- Derive bin-by-bin quadratic interpolation in GNN bins and get the 95% CL intervals of the coefficient shown in the likelihood scan
- Assume only one operator contributes to the enhancement of the cross section and others are fixed to zero
- The sensitivity is improved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

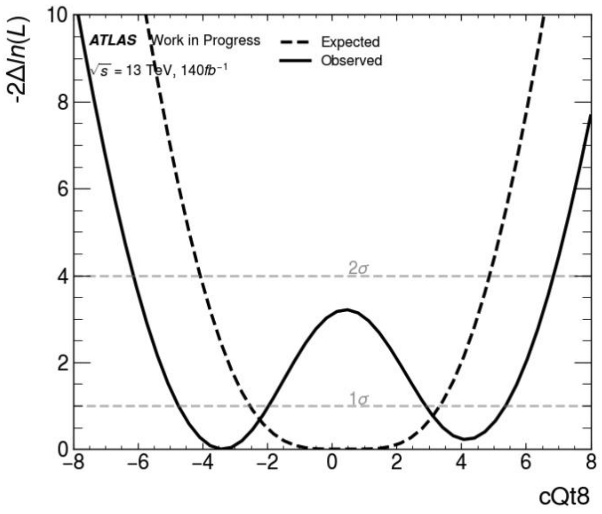
Limits on EFT operators sensitive to four top production (one operator at a time)

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]









Neutrino Reconstruction

- Check the nuetrino reconstruction result, the input variable is different with the default sample, maybe it is better to change to px py pz E, other than E, phi, eta, pt, expeally for phi