Search for $t\bar{t}H/A \rightarrow t\bar{t}t\bar{t}$ production in proton-proton collisions at $\sqrt{s} = 13TeV$ with the ATLAS detector

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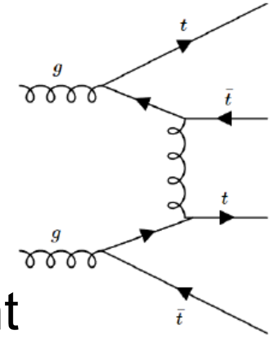
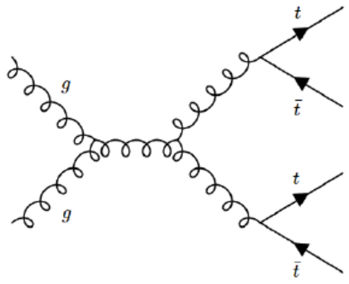
ATLAS EXPERIMENT

Motivation

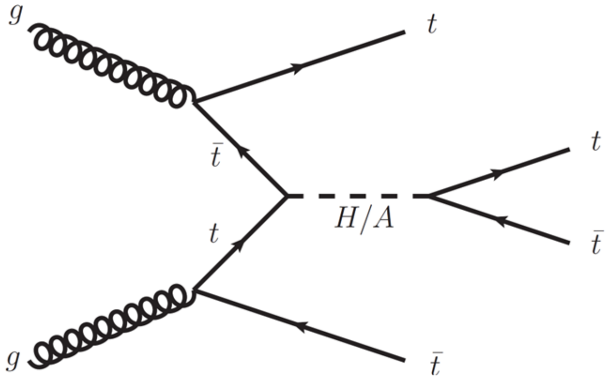
Experimental

- Standard model 4-tops process
  - SM cross section expectation: $\sigma_{t\bar{t}t\bar{t}} = 13.37^{+1.04}_{-1.78} fb$
  - Latest measurement in ATLAS: $\sigma_{t\bar{t}t\bar{t}} = 22.5^{+6.6}_{-5.5} fb$
  - Inconsistence arises between the theory and the experiment





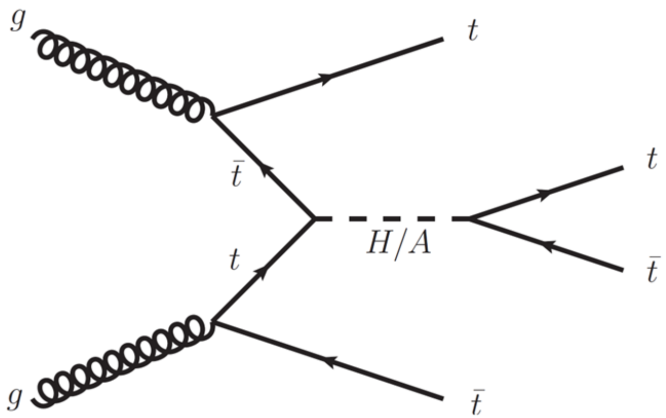
Aim

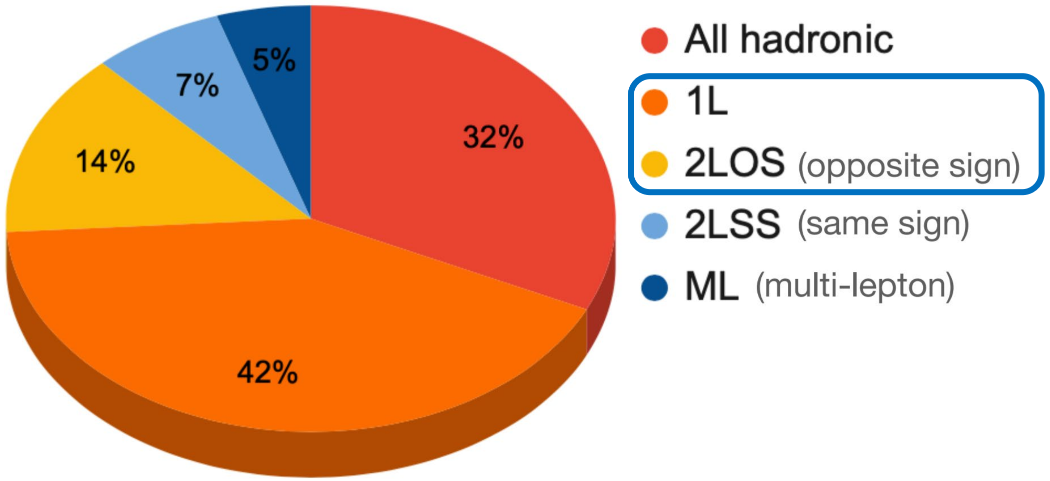


- Analysis targets:
  - Search for **Two-Higgs-Doublet-Model (2HDM) type-II** $t\bar{t}H/A \rightarrow t\bar{t}t\bar{t}$ signal
  - Interpretation on low tanβ region in the alignment limit sin(β-α)→1 where **h** couplings are similar to the SM Higgs boson
  - Reinterpretation of results in **sgluon** Model

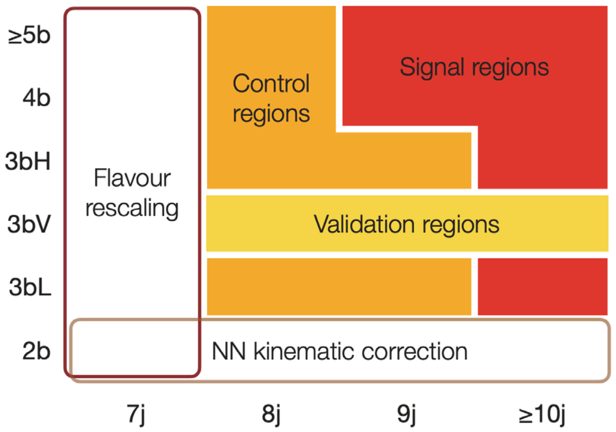
Introduction

- **Signal**: $t\bar{t}H/A \rightarrow t\bar{t}t\bar{t}$
  - **Higgs mass**: 0.4TeV to 1TeV with 0.1TeV granularity
  - **Decay channel:** one lepton (1L) + two opposite-sign lepton (2LOS)
    - Together constitute branching ratio of **56%**
  - **Main background:** $t\bar{t} + jets$
  - **Final state signature:** High jet & b-jet multiplicity
- Published for the same search in the di-lepton same-sign/multi-lepton channel (SSML channel) (link)

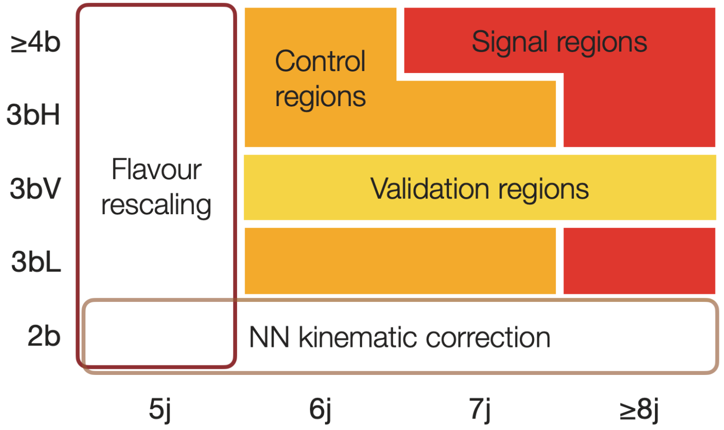




Analysis Strategy



(1L)



(2LOS)

Name	$N_b^{60\%}$	$N_b^{70\%}$	$N_b^{85\%}$
2b	-	= 2	-
3bL	≤ 2	= 3	-
3bH	= 3	= 3	> 3
3bV	= 3	= 3	= 3
≥4b (2LOS)	-	≥ 4	-
4b (1L)	-	= 4	-
≥5b (1L)	-	≥ 5	-

- Analysis regions categorized by lepton, jet and b-tagging multiplicity
- Two types of data-driven correction factors:
    - Jet flavor normalization factors
    - Neural network (NN)-based kinematic reweighting
- Trained H/A-mass-parameterized **GNN** to separate signals from background
- Profile likelihood fit in all CRs and SRs simultaneously, using $\mathbf{H_T}$ in CR and **GNN-score** in SR

Data & MC Samples and Event Selection

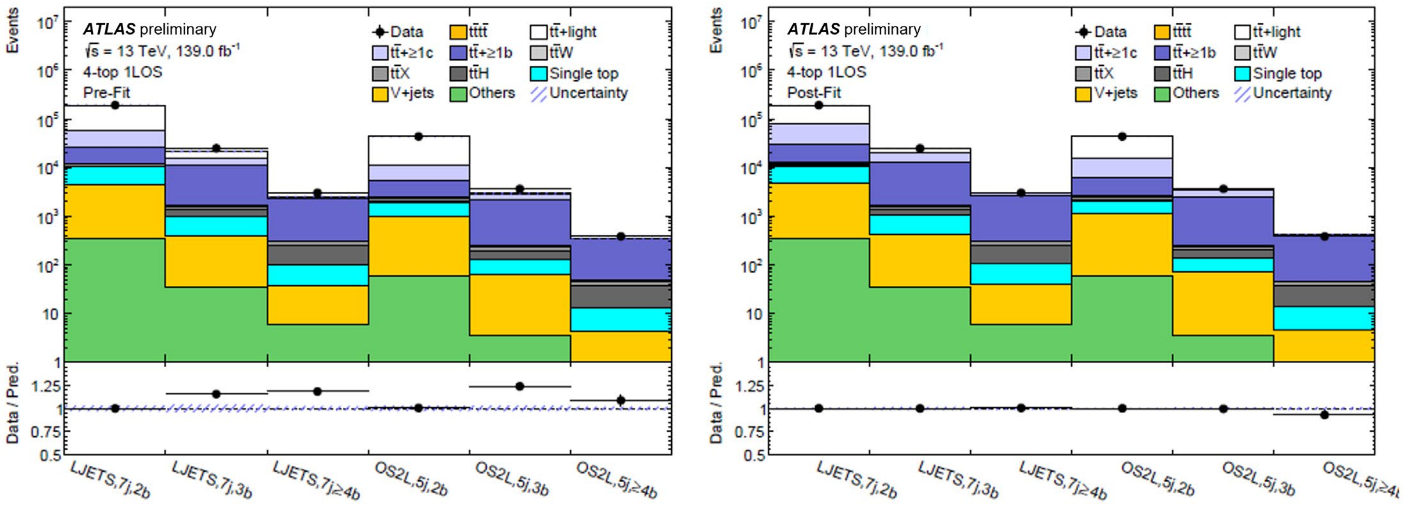
- Data: Full Run2 (2015-2018) ~ 139fb^{-1}, using single lepton triggers
- MC samples:
  - $t\bar{t}$ + jets, SM4t, ttW, ttZ, Single top, V + jets, ttt, Other top, VV, Signal
- Object definition & event selection:

Object	Baseline selection
Lepton	p_T>28GeV, |η|<1.37or1.52-2.47(e), |η|<2.5(μ) Identification: TightLH(e)/Medium(μ), Isolation: FCTight(e)/FCTightTrackOnly(μ) Impact parameter: z_0<0.5mm, σ_{d0}<5(3) for e(μ)
Jet	p_T>25GeV, |η|<2.5, JVT>0.5 for p_T < 60 GeV, |η|<2.4 Algorithm: Anti-k_T
b-jet	p_T>25GeV, |η|<2.5, JVT>0.5 for p_T < 60 GeV, |η|<2.4 Algorithm: DL1r
Event	Exactly one lepton (1L) / two opposite-charge leptons (2L) with ≥ 2 jets with b-tagging passing 70% OP

Background Modelling (flavor normalization)

- To correct the under-estimation of the $t\bar{t}$ + *jets* production rate in MC prediction
- $t\bar{t}$ + *jets* includes:
  - $t\bar{t}$ + ≥1b (TTB): $t\bar{t}$ + at least one jet matched with b-hadron(s)
  - $t\bar{t}$ + ≥1c (TTC): $t\bar{t}$ + at least one jet matched with c-hadron(s)
  - $t\bar{t}$ + light (TTL): $t\bar{t}$ + jets do not match with b or c-hadrons
- Data-driven fit to sum of pseudo-continuous b-tagging scores of 3rd and 4th jets
- Regions: 7j(5j) = 2b ,=3b, ≥4b for 1L(2LOS) channel
- Scale factor $\frac{t\bar{t}^{nominal}_{postfit}}{t\bar{t}^{nominal}_{prefit}}$ & $\frac{t\bar{t}^{nominal}_{postfit}}{t\bar{t}^{alternative}_{prefit}}$:

	TTL (1L)	TTL (OS)	TTC	TTB
Nominal	0.84 ± 0.04	0.87 ± 0.03	1.61 ± 0.13	1.18 ± 0.03
ttbb 4FS	0.83 ± 0.04	0.87 ± 0.04	1.60 ± 0.10	1.17 ± 0.02
aMcAtNloPy8	0.94 ± 0.04	0.96 ± 0.04	1.78 ± 0.11	1.27 ± 0.01
PhHerwig	0.66 ± 0.03	0.73 ± 0.03	2.21 ± 0.14	1.56 ± 0.02



Pre-fit & post-fit yields for HF normalization

Background Modelling (NN-reweighting)

- Kinematic reweighting based on Neural Network (NN)
  - NN output: a-posterior Bayesian probability

$$o(\boldsymbol{x}) \simeq P(data|\boldsymbol{x}) = \frac{\alpha_{data} P_{data}(\boldsymbol{x})}{\alpha_{data} P_{data}(\boldsymbol{x}) + \alpha_{MC} P_{MC}(\boldsymbol{x})}$$

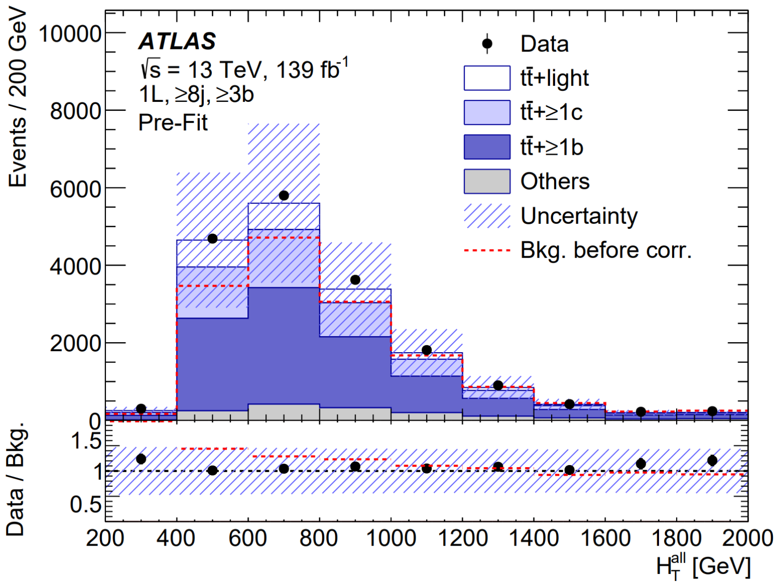
  - Input list: Njets, NRCjets, each jets & lep pT, missing ET
  - Training regions: ≥7j(5j), = 2b for 1L(2LOS)
- Using an exponential lose function:

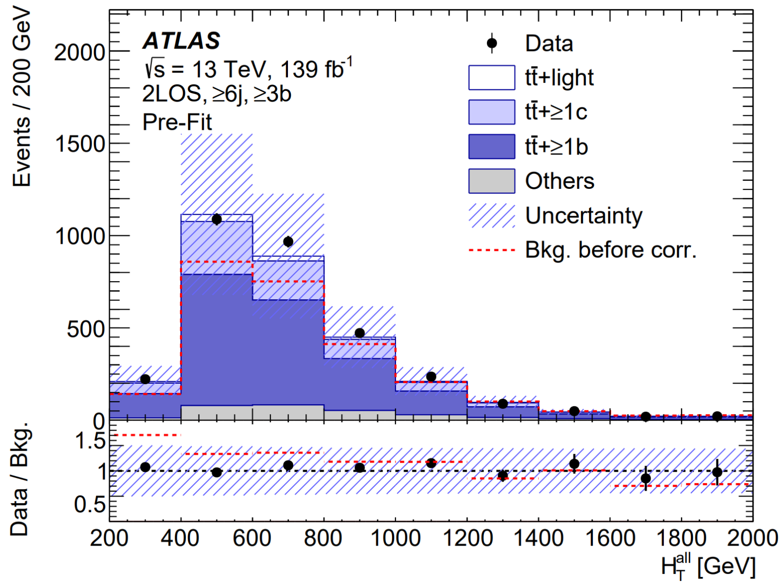
$$\mathcal{L} = P_{data} e^{-o(\boldsymbol{x})/2} + P_{MC} e^{o(\boldsymbol{x})/2}$$

$$\frac{d\mathcal{L}}{do(\boldsymbol{x})} = 0 \Rightarrow -\frac{P_{data}}{2} e^{-\frac{o(\boldsymbol{x})}{2}} + \frac{P_{MC}}{2} e^{\frac{o(\boldsymbol{x})}{2}} = 0$$

  - Reweighting factor can be derived as:

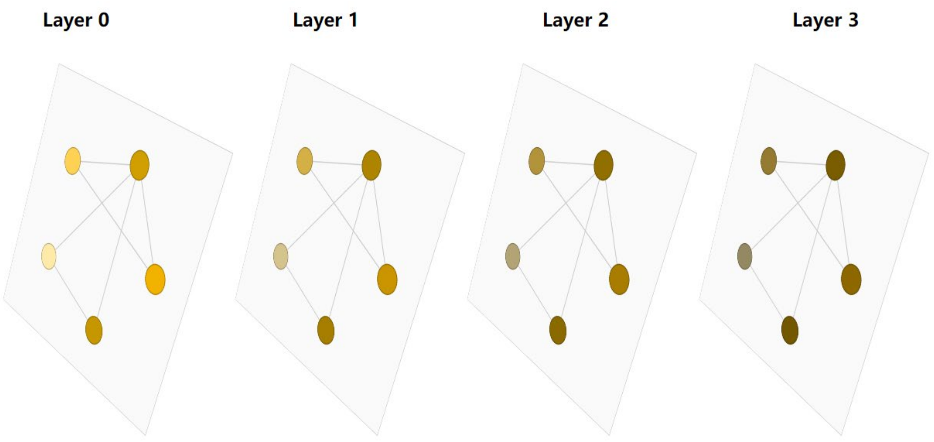
$$w(x) = \frac{P_{data}}{P_{MC}} = e^{o(\boldsymbol{x})}$$



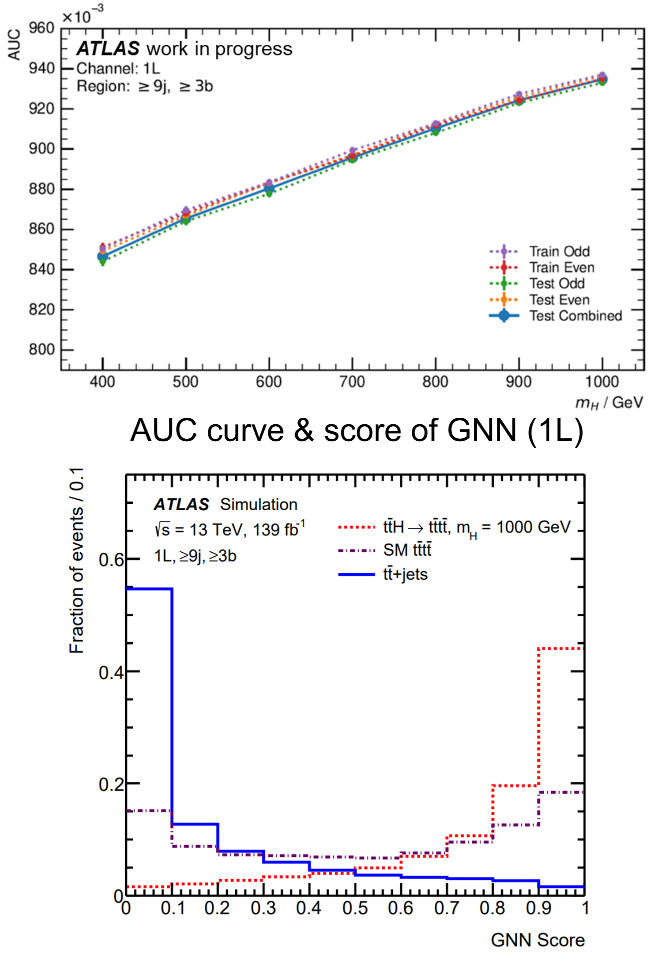


Signal Background Discrimination (GNN)

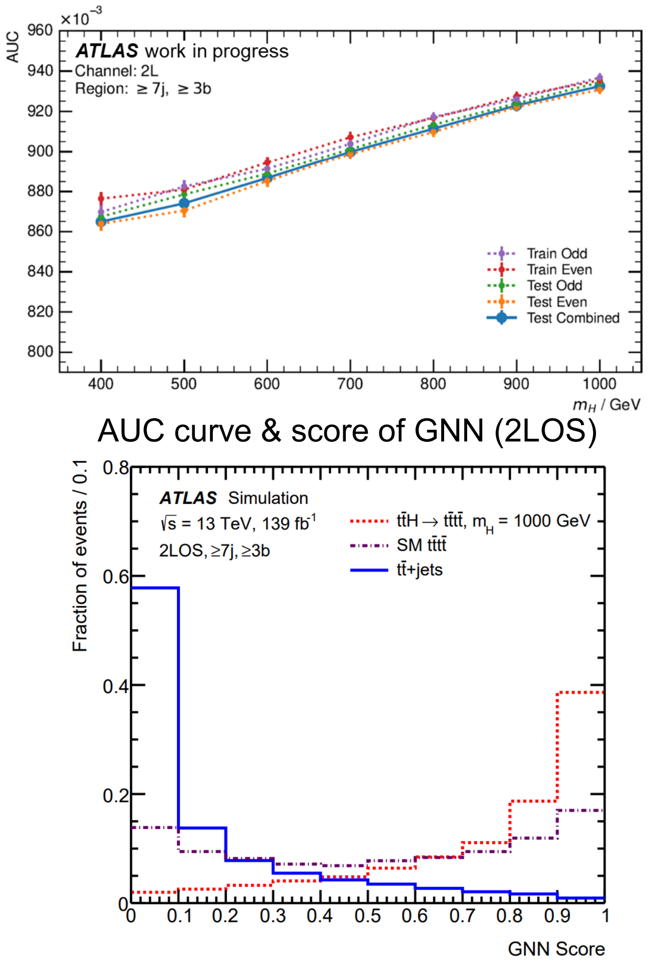
- For signal discrimination, GNN (graph neural network) has been used
  - GNN is agnostic to the number of nodes and are permutation invariant.
  - A relatively simple model can be used on events of varying multiplicity/topologies
  - Well suitable in our case with complex jet & b-jet multiplicity and structure



Simple sketch of node information accumulation through the network



AUC curve & score of GNN (1L)



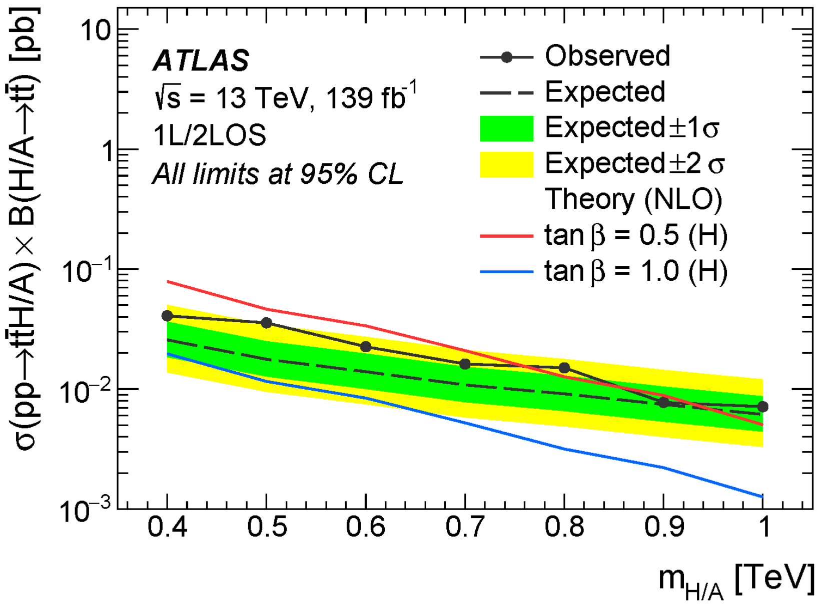
AUC curve & score of GNN (2LOS)

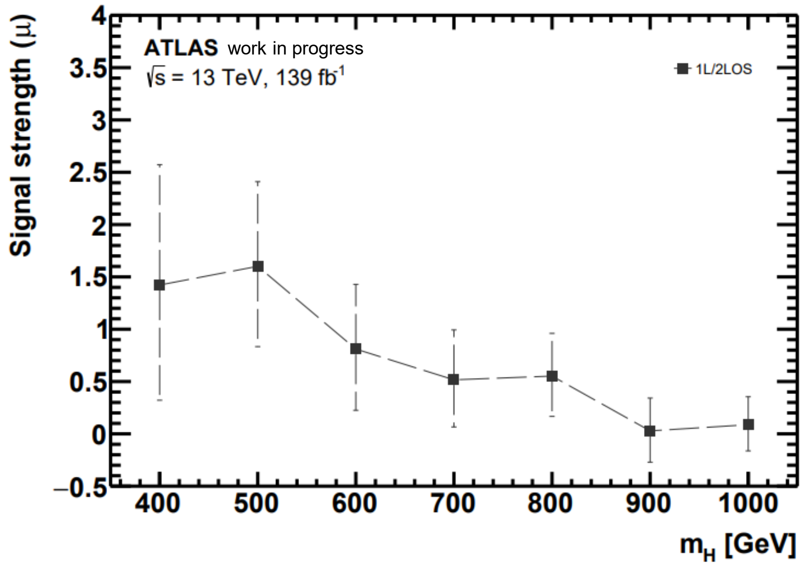
Systematics

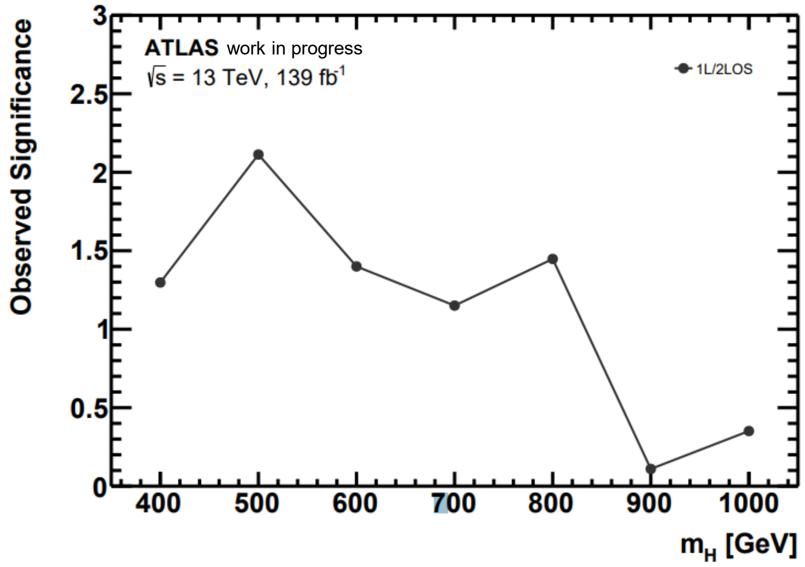
- Table of the grouped impact of nuisance parameters at mass point:
  - 400 GeV ($\sigma_{t\bar{t}H/A\to t\bar{t}t\bar{t}}$)=17fb)
  - 700 GeV ($\sigma_{t\bar{t}H/A\to t\bar{t}t\bar{t}}$)=6.1fb)
  - 1000 GeV ($\sigma_{t\bar{t}H/A\to t\bar{t}t\bar{t}}$)=1.0fb)
- ***$t\bar{t}$* + ≥1b modelling** has the highest impact for all mass points

Uncertainty source	$\Delta\sigma_{t\bar{t}H/A\to t\bar{t}t\bar{t}}$ [fb]					
	$m_{H/A}$=400 GeV		$m_{H/A}$=700 GeV		$m_{H/A}$=1000 GeV	
Signal Modelling						
BSM $t\bar{t}t\bar{t}$ modelling	< 1		+0.1	< 0.1	< 0.1	
Background Modelling						
$t\bar{t}$+≥1b modelling	+11	-10	+3.7	-3.4	+1.9	-1.7
SM $t\bar{t}t\bar{t}$ modelling	+3	-3	+2.1	-2.1	+0.9	-0.9
$t\bar{t}$+jets reweighting	+3	-3	+1.0	-1.0	+0.5	-0.5
$t\bar{t}$+≥1c modelling	+2	-2	+0.9	-0.8	+0.4	-0.4
$t\bar{t}$+light modelling	+1	-1	+0.2	-0.2	< 0.1	
Other background modelling	< 1		+0.4	-0.4	+0.2	-0.2
Experimental						
Jet energy scale and resolution	+4	-2	+1.3	-0.8	+0.5	-0.3
MC statistical uncertainties	+2	-3	+0.6	-0.7	+0.4	-0.4
b-tagging efficiency	+2	-1	+0.7	-0.4	+0.4	-0.4
Other uncertainties	< 1		+0.3	-0.5	+0.1	-0.2
Luminosity	< 1		+0.3	-0.1	< 0.1	
Total systematic uncertainty	+13	-12	+4.8	-4.6	+2.5	-2.4
Statistical uncertainty	+6	-6	+3.3	-3.2	+2.3	-2.2
Total uncertainty	+14	-13	+5.6	-5.4	+3.2	-3.0

2HDM interpretation



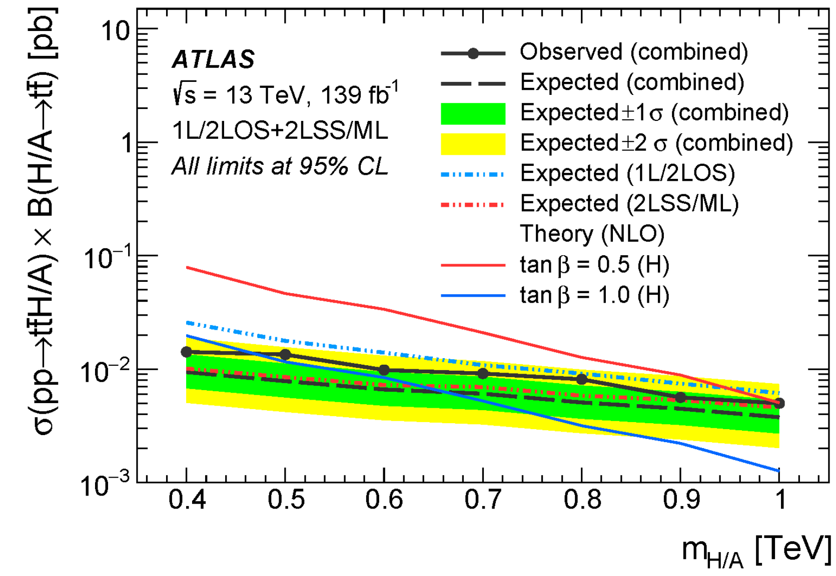


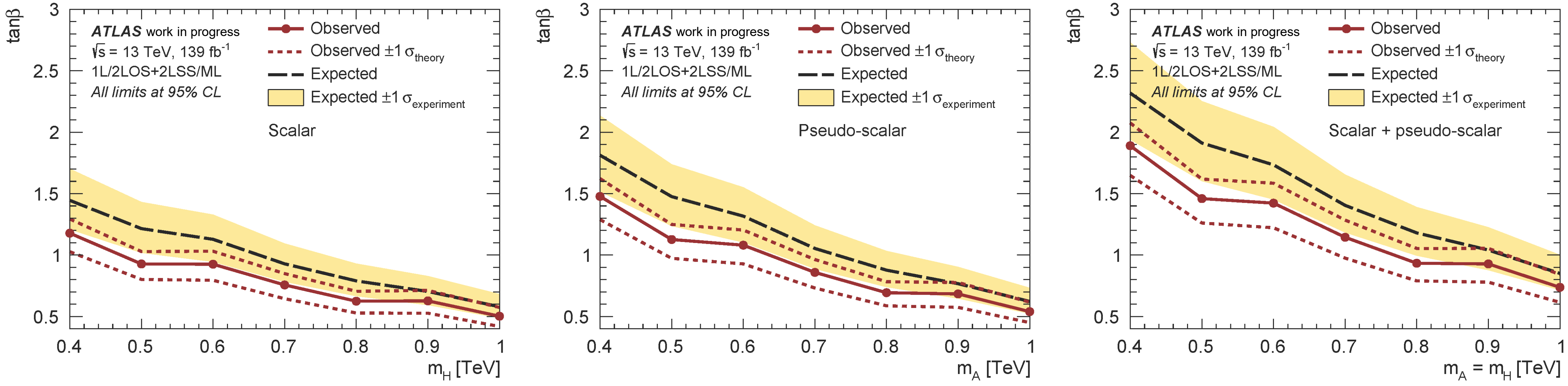


- 95% CLs upper limits on the cross section of the production estimated
- No significance evidence for the heavy Higgs production

2HDM: Combination with 2LSS/ML

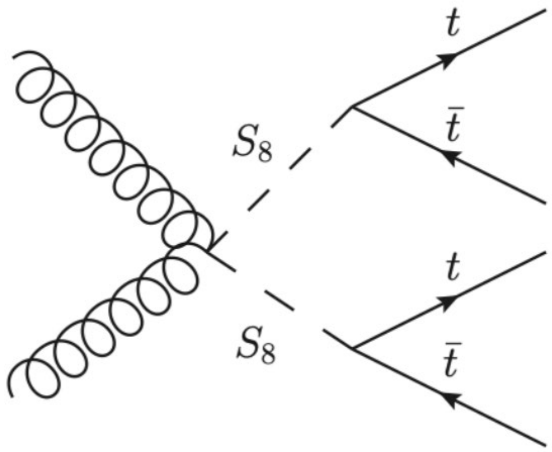
- Search in 1L/2LOS combined with Same-Sign-Multi-Lepton (2LSS/ML) channel (JHEP 07 (2023) 23) in the same phase space
  - Combination performed via a simultaneous profile likelihood fit including all SRs and CRs of both channels
- 95% CLs upper limits on the **cross section** estimated
  - ➢ 14.2 (5.0) fb for mass of H/A 400 (1000) GeV respectively
- 95% CLs lower limits on the **tanβ** estimated





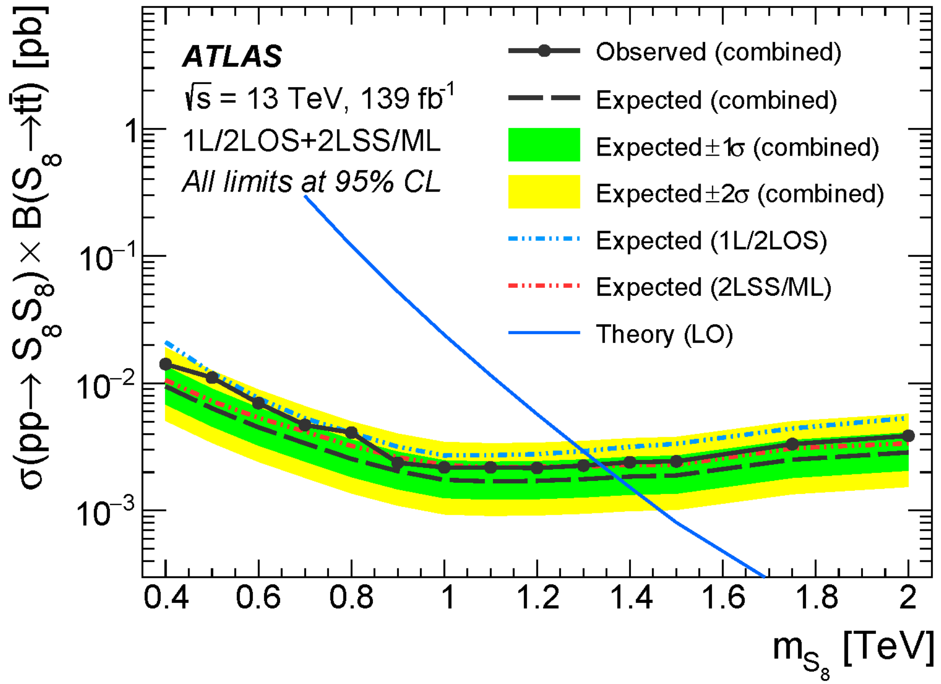
Sgluon interpretation

- **Signal**: $S_8 S_8 \rightarrow t\bar{t}t\bar{t}$ (link)
  - $m_{S_8} \in [0.4, 1.5]$ TeV with 0.1TeV granularity
  - $m_{S_8} \in [1.75, 2.0]$ TeV with 0.25TeV granularity



- Combination using **the same** binning, MC background systematics correlation strategy as in H/A fit

- 95% CLs upper limits on the cross section of the production estimated
  - Sgluon masses $\boldsymbol{m_{S_8} \leq 1.3}$ **TeV** are excluded



Summary

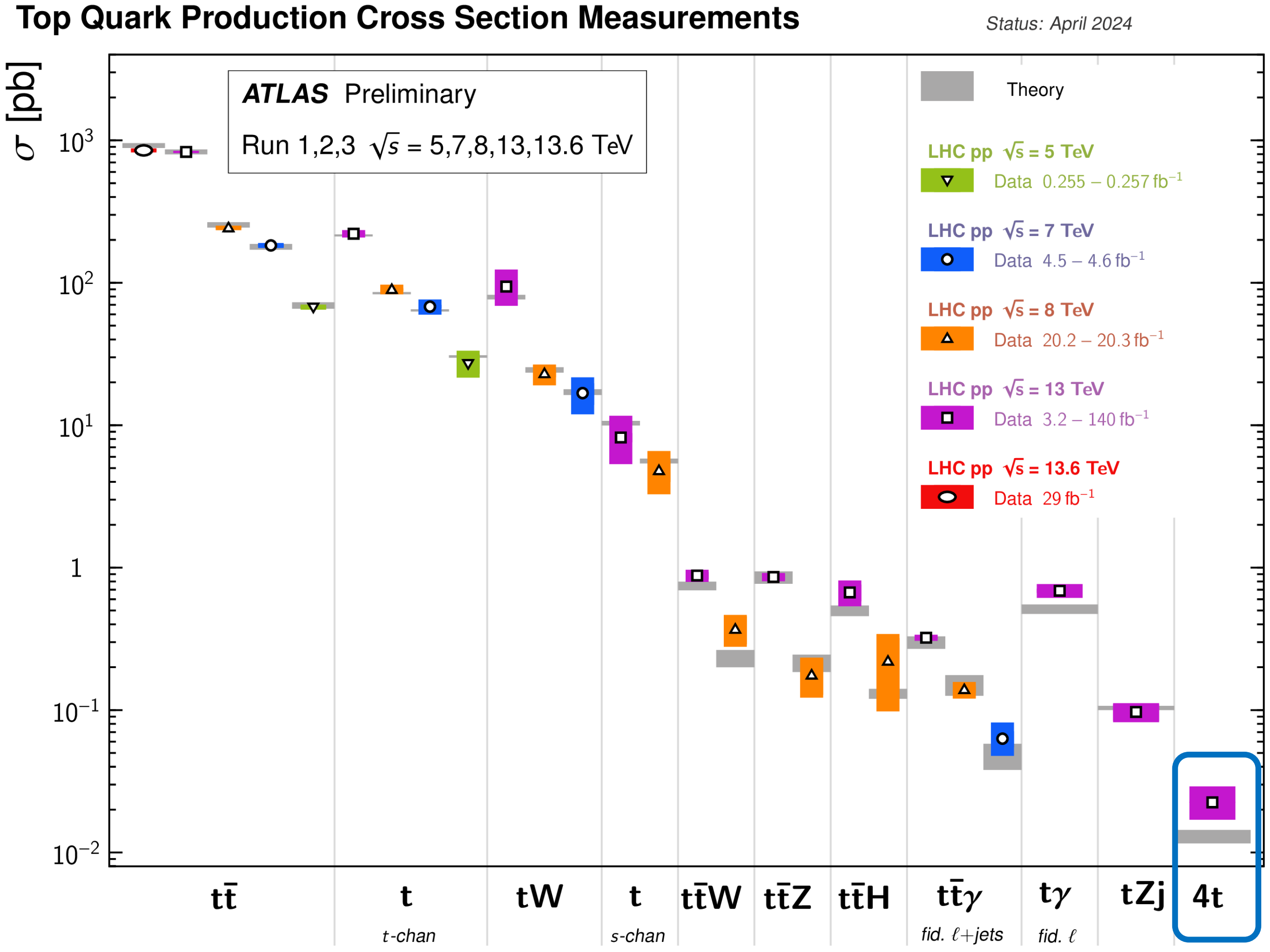
- Heavy Higgs production in the 4-top process has been searched using ATLAS full run-2 data
- Background correction with 2 data-driven factors
  - Flavor normalization
  - NN-reweighting
- Signal-background discriminated by GNN
- Limits of the 2HDM search in $t\bar{t}t\bar{t}$:

	400 GeV	1000 GeV
Upper limits on xsec of $t\bar{t}H/A \rightarrow t\bar{t}t\bar{t}$	14fb	5.0fb
Lower limits on tanβ	1.9	0.7

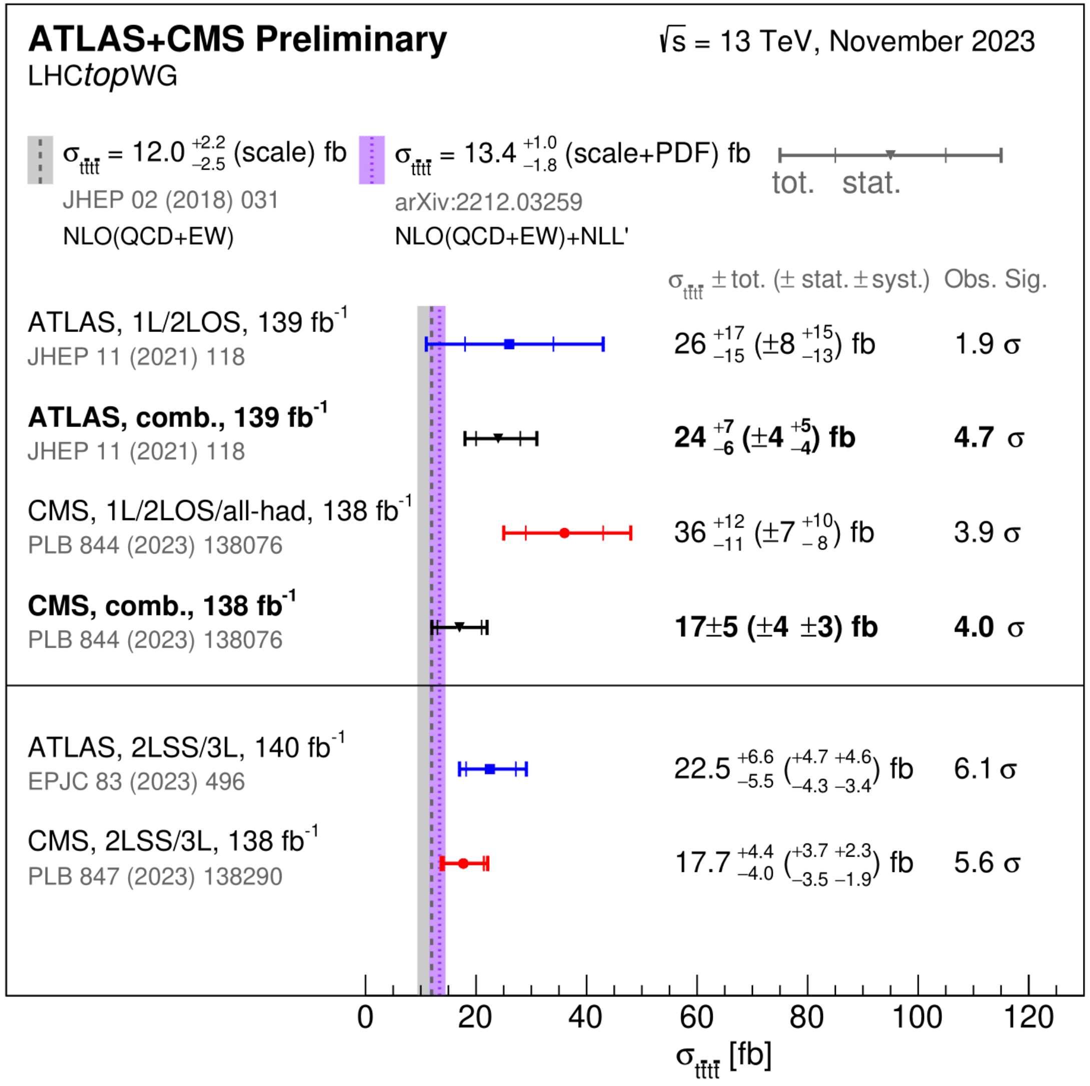
- Sgluon masses $m_{S_8} \leq 1.3$ TeV are excluded
- Submitted to EPJC (arXiv:2408.17164)

BACKUP

4tops in LHC



Top Quark Production Cross Section Measurements
Status: April 2024
ATLAS Preliminary
Run 1,2,3 √s = 5,7,8,13,13.6 TeV
σ [pb]
Theory
LHC pp √s = 5 TeV
Data 0.255 – 0.257 fb⁻¹
LHC pp √s = 7 TeV
Data 4.5 – 4.6 fb⁻¹
LHC pp √s = 8 TeV
Data 20.2 – 20.3 fb⁻¹
LHC pp √s = 13 TeV
Data 3.2 – 140 fb⁻¹
LHC pp √s = 13.6 TeV
Data 29 fb⁻¹
tt̄
t
t-chan
tW
t
s-chan
tt̄W
tt̄Z
tt̄H
tt̄γ
fid. ℓ+jets
tγ
fid. ℓ
tZj
4t



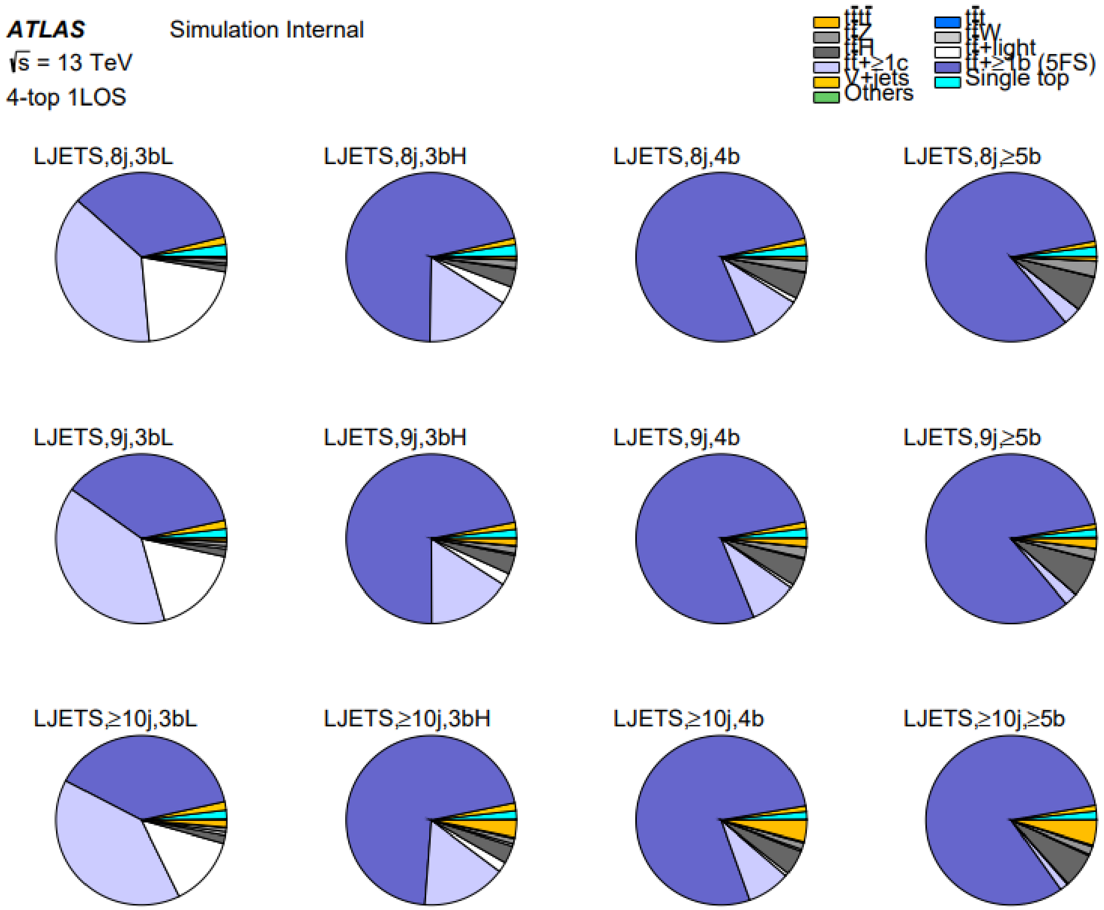
ATLAS+CMS Preliminary
LHCtopWG
√s = 13 TeV, November 2023
σ_tttt = 12.0 +2.2 −2.5 (scale) fb
JHEP 02 (2018) 031
NLO(QCD+EW)
σ_tttt = 13.4 +1.0 −1.8 (scale+PDF) fb
arXiv:2212.03259
NLO(QCD+EW)+NLL'
tot. stat.
σ_tttt ± tot. (± stat. ± syst.) Obs. Sig.
ATLAS, 1L/2LOS, 139 fb⁻¹
JHEP 11 (2021) 118
26 +17 −15 (±8 +15 −13) fb 1.9 σ
ATLAS, comb., 139 fb⁻¹
JHEP 11 (2021) 118
24 +7 −6 (±4 +5 −4) fb 4.7 σ
CMS, 1L/2LOS/all-had, 138 fb⁻¹
PLB 844 (2023) 138076
36 +12 −11 (±7 +10 −8) fb 3.9 σ
CMS, comb., 138 fb⁻¹
PLB 844 (2023) 138076
17±5 (±4 ±3) fb 4.0 σ
ATLAS, 2LSS/3L, 140 fb⁻¹
EPJC 83 (2023) 496
22.5 +6.6 −5.5 (+4.7 −4.3 +4.6 −3.4) fb 6.1 σ
CMS, 2LSS/3L, 138 fb⁻¹
PLB 847 (2023) 138290
17.7 +4.4 −4.0 (+3.7 −3.5 +2.3 −1.9) fb 5.6 σ
σ_tttt [fb]

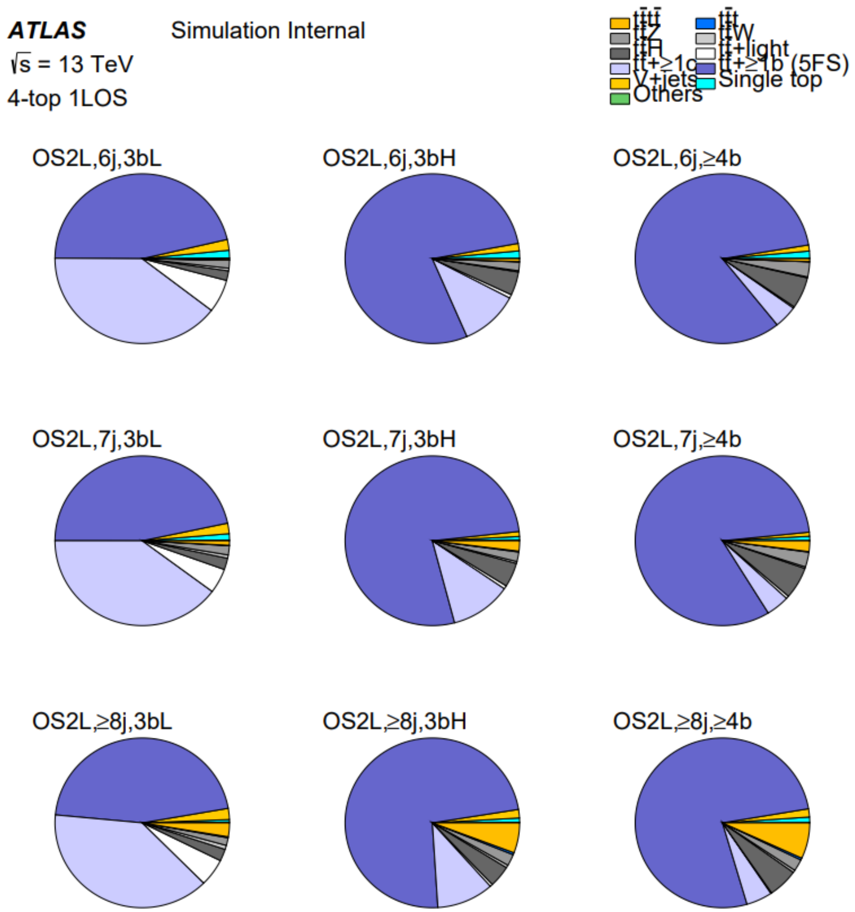
Samples

- Recent p-tag from the TOPQ1 has been used for over all MC/Data samples.
- AnalysisBase 21.2.169.
- Framework: TTHbb analysis (Link).
- Only prompt SM processes modelled with MC for background:

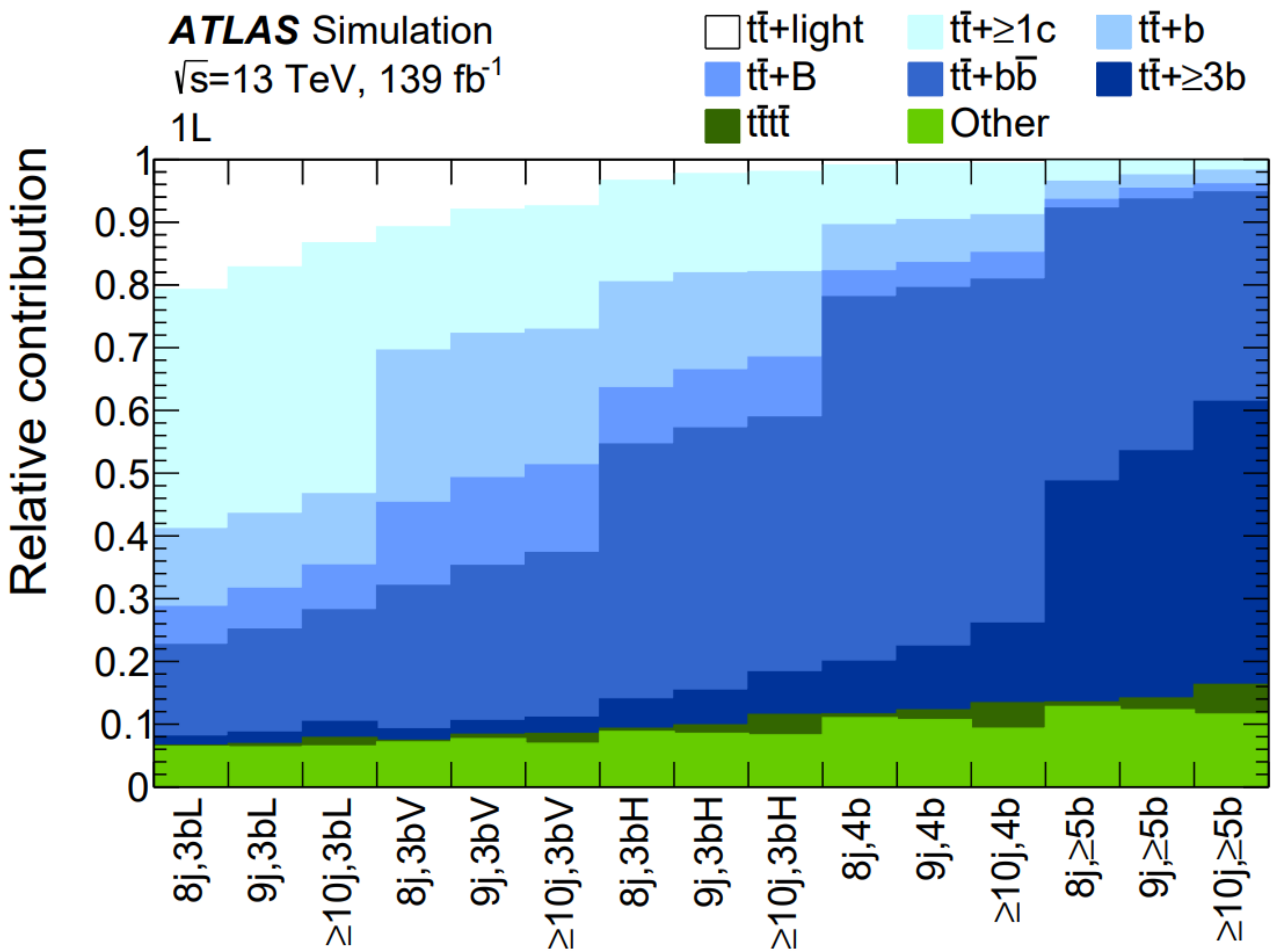
	Nominal	Alternative
$t\bar{t}$ + jets	PhPy8 (5FS ttbb, inclusive + HF filtered +HT sliced)	Mg5Py8, PhHw, PhPy8 (4FS ttbb)
SM4t	aMcAtNloPy8	aMcAtNloHerwig7, Sherpa
ttW	Sherpa	aMcAtNloPy8
ttZ	aMcAtNloPy8	Sherpa
Single top	PhPy8	PhH7, aMcAtNloPy8
V + jets	Sherpa	-
ttt	Mg5Py8	-
Other top, VV	MgPy8, aMcAtNloPy9	-
Signal	Mg5Py8	-

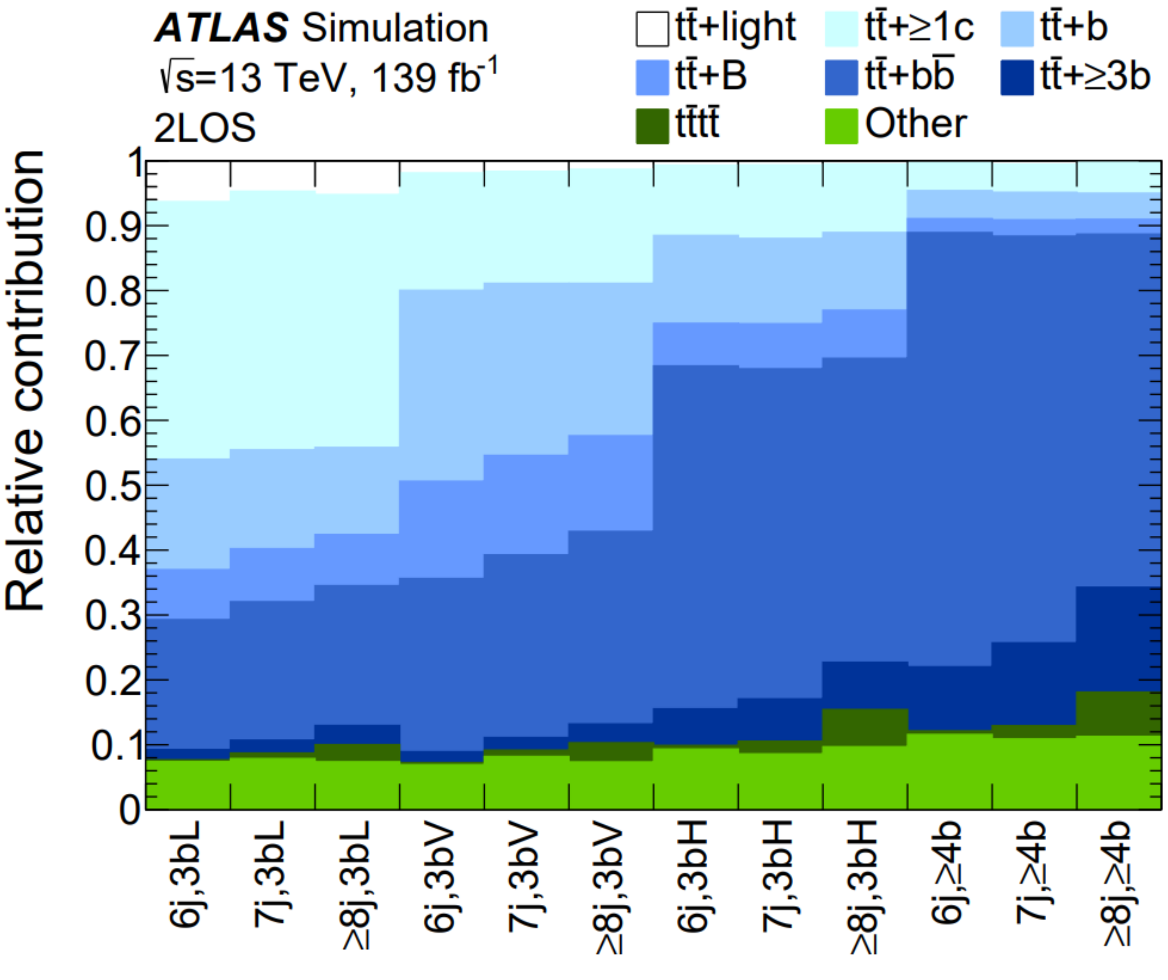
Background Composition





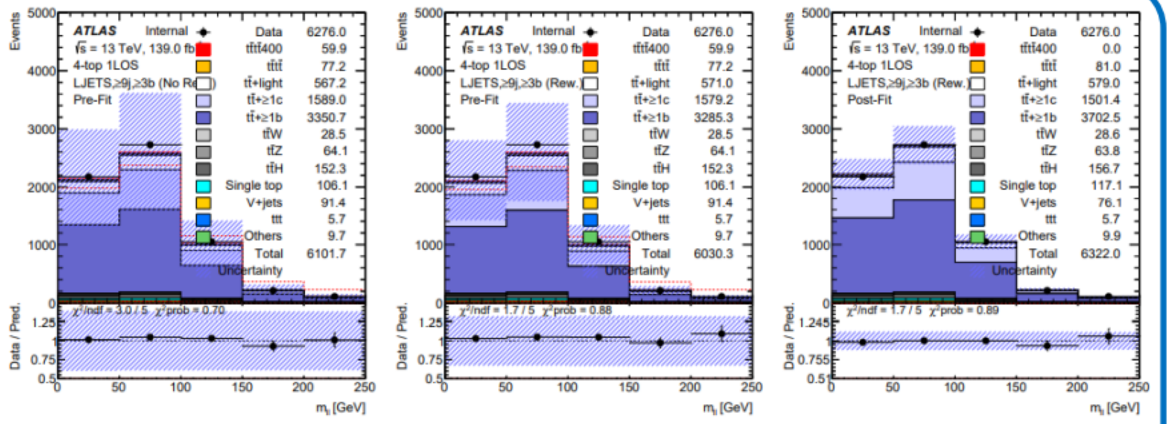
Background Composition



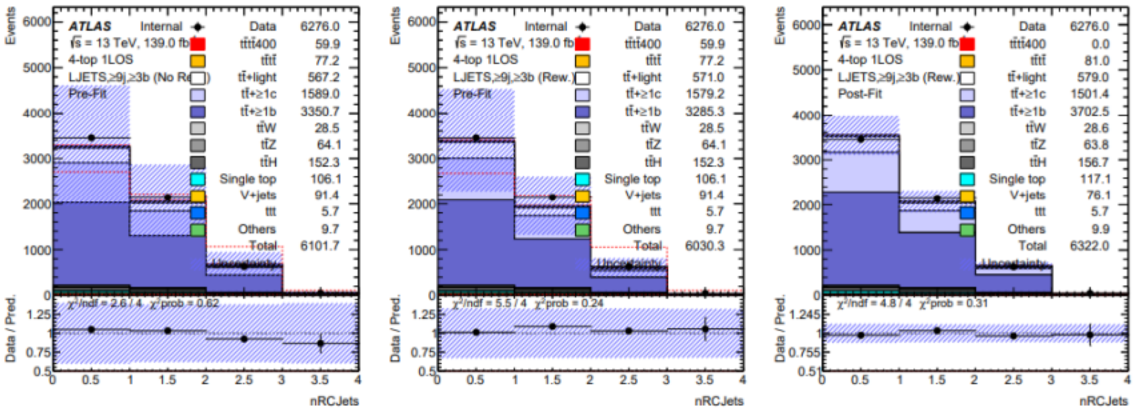


Performance of NN-reweighting

- Added several Data/MC comparison plots for the variables used in the MVA training (Appendix K.2)
  - Pre-fit plots without reweighting (left), pre-fit plots with reweighting (middle), post-fit plots (right)



(a) mtw



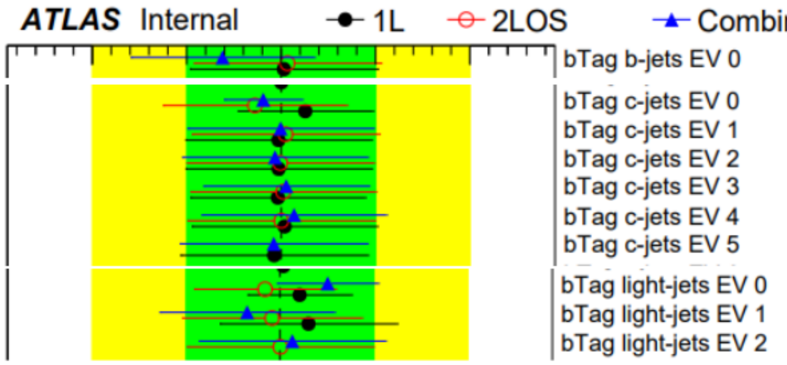
(a) nRCJets

Example plots

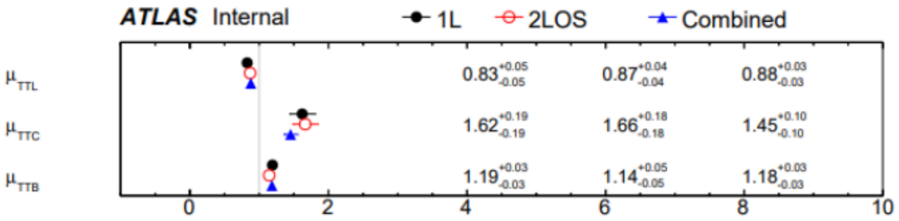
- Shows good modelling after NN-reweighting and fitting

Heavy Flavor Correction Factor

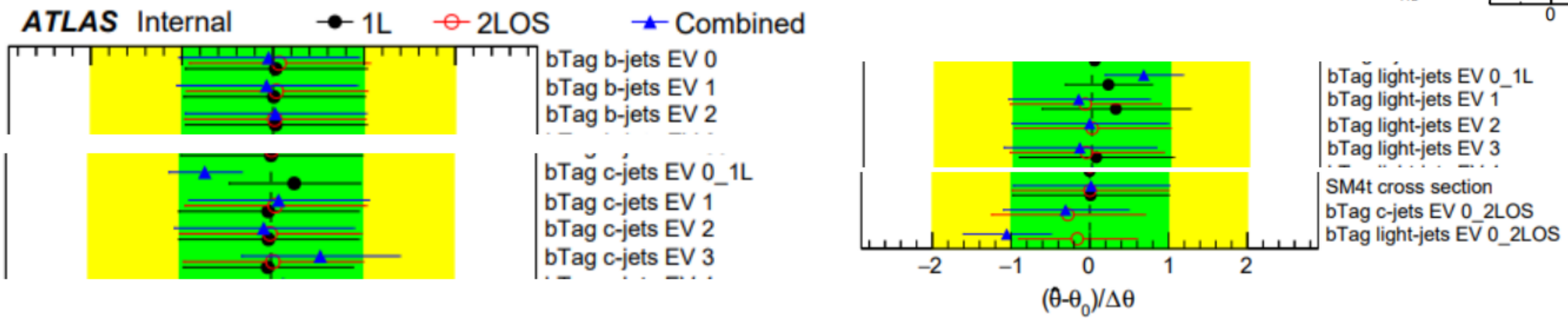
- Regions: 7j (5j) for 1L (2LOS) with 2b, 3b, ≥4b



- Combined Fit with Nuisance Parameters Correlated among Channels
  - Unstable pulls is come from the performance differences among the two channels.
  - major differences can be found in NP bTag c-jets EV0 (C0) and bTag light-jets EV0 (L0)



- Combined Fit with C0 and L0 Decorrelated among Channels
  - Do not entirely resolve the issue



Heavy Flavor Correction Factor

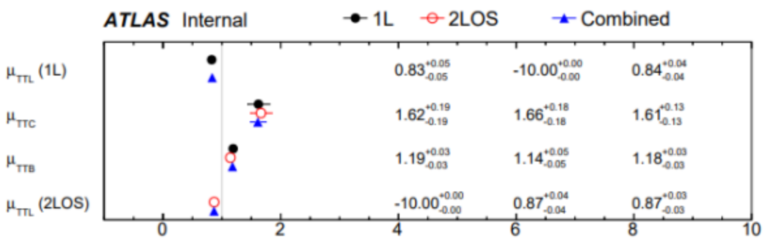
- Combined Fit with Different Correction Factors Decorrelation among Channels:

✓**Decorrelated TTL**:

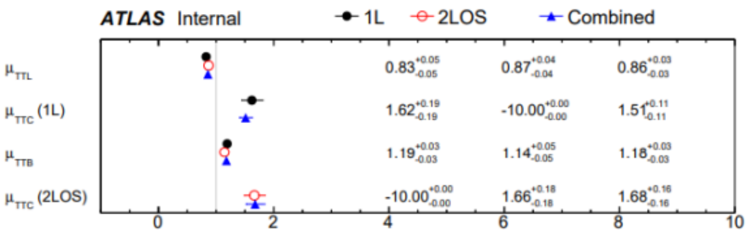
  - The correction factors derived from the combined fit are closed to and in between the results derived from 1L and 2LOS separated fits.

- **Decorrelated TTC**:
  - C0 pulls in the combined fit are opposite to the separated fits
  - μTTC (1L) derived in the combined fit is deviated from the result derived in the 1L separate fit

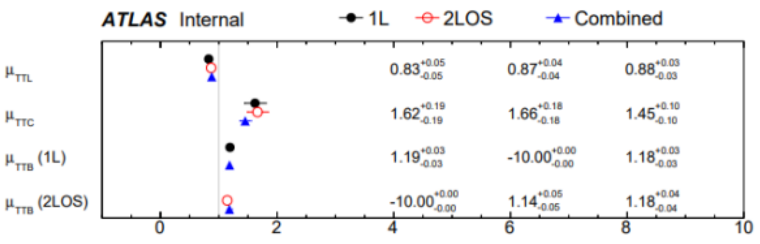
- **Decorrelated TTB**:
  - The NP pulls and the HF correction factors are nearly the same as the case of without decorrelating the correction factors.



Decorrelated TTL



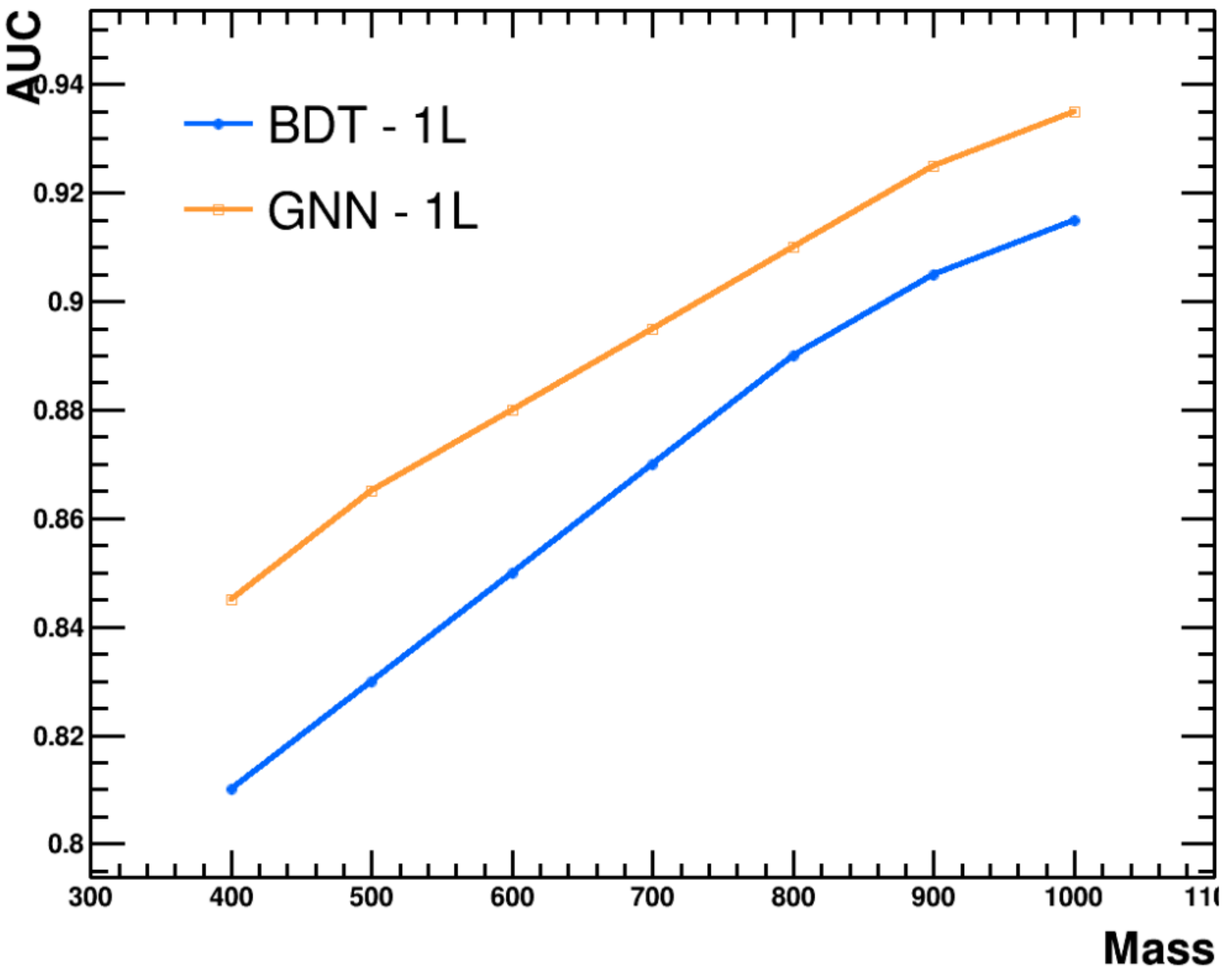
Decorrelated TTC



Decorrelated TTB

GNN VS BDT

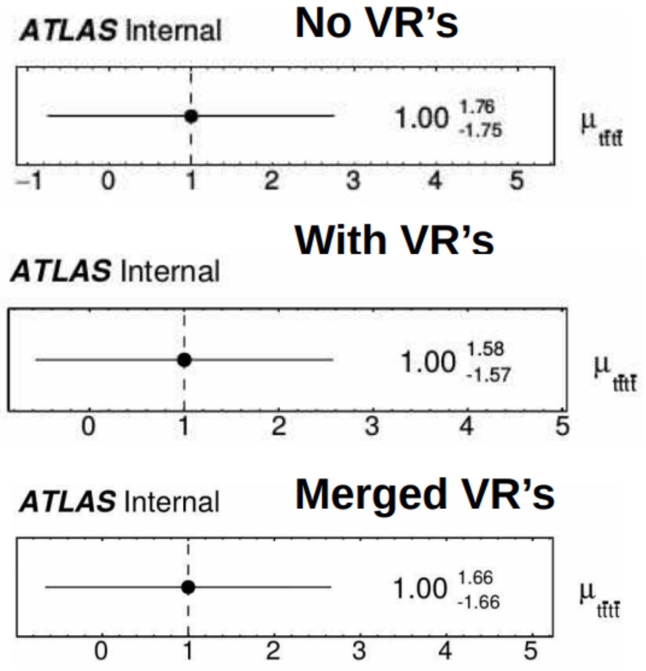
- SM4top like BDT has been also studies with the same input list used as global feature in GNN
- Purposed as a benchmark, and used only for control
- GNN shows significant improvement comparing to BDT
- GNN and BDT shows same level agreement over the data/MC in SR
- Observed same level of pulls/constrains in fits using BDT or GNN
- GNN found to be more sensitive

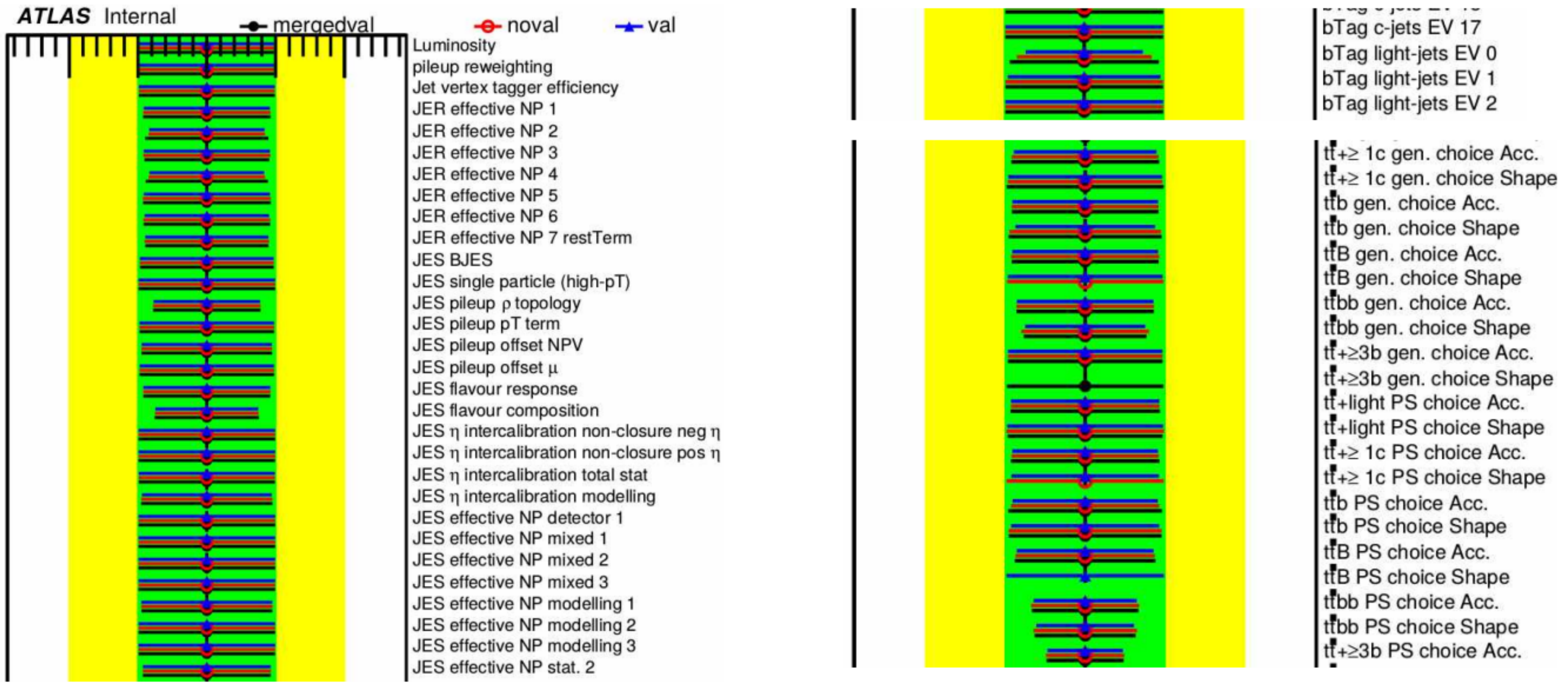


Validation Regions

- Validation region defined in SM 4-top is studied 3bV(SM 4-top)
  - In our analysis this region found to be more sensitive than 3bH
  - Simply this two region definition swapped in our analysis
    - 3bV (SM 4-top) = 3bH & 3bH(SM 4-top) = 3bV

Name	$N_b^{60\%}$	$N_b^{70\%}$	$N_b^{85\%}$
2b	-	= 2	-
3bL	≤ 2	= 3	-
3bH	= 3	= 3	= 3
3bV	= 3	= 3	≥ 4
≥4b (2LOS)	-	≥ 4	-
4b (1L)	-	= 4	-
≥5b (1L)	-	≥ 5	-



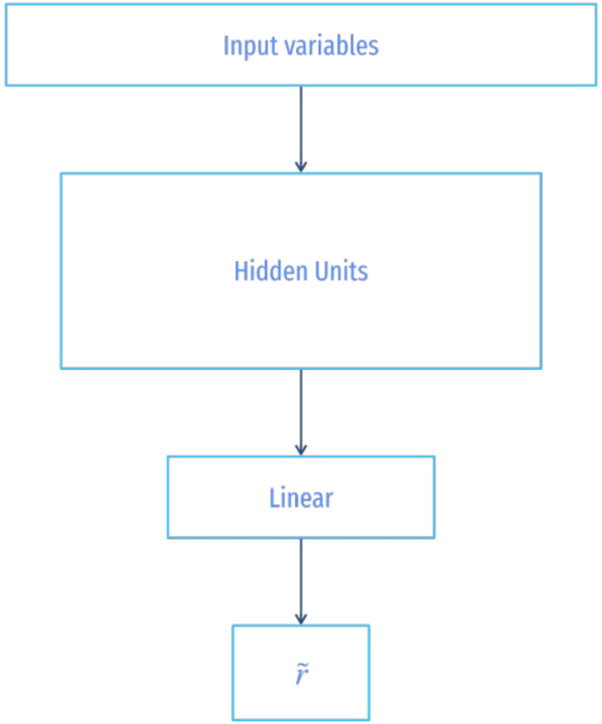


NN-reweighting (loss function)

Exponential Loss

$$\mathcal{L} = p_A e^{-r'/2} + p_B e^{r'/2}$$

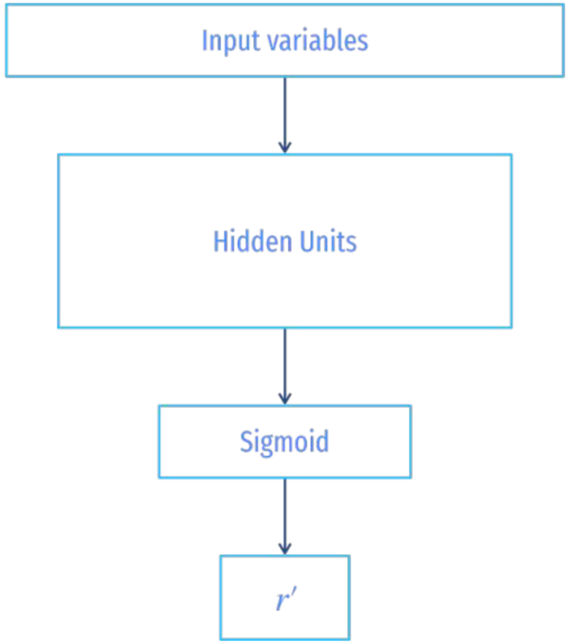
$$\frac{\partial \mathcal{L}}{\partial r'} = -\frac{p_A}{2} e^{-r'/2} + \frac{p_B}{2} e^{r'/2} = 0 \rightarrow e^{r'} = \frac{p_A}{p_B} = r$$



Binary Cross Entropy

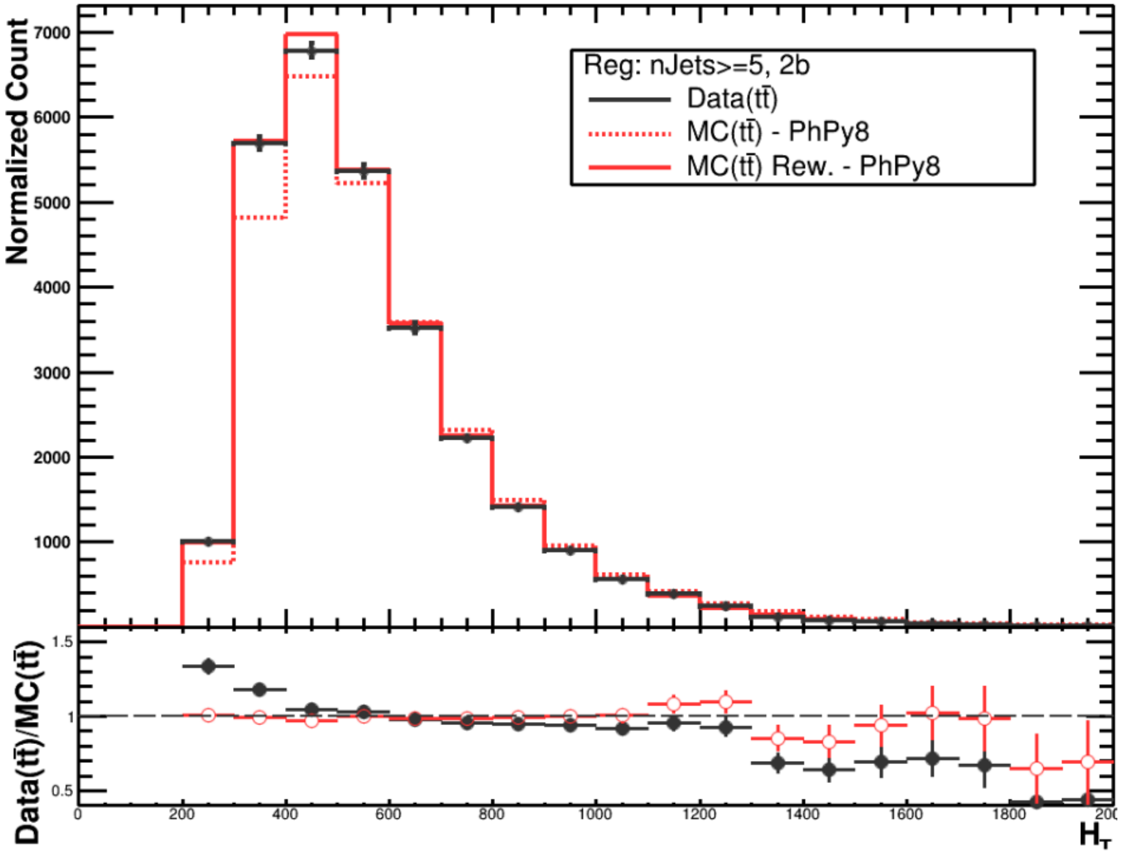
$$\mathcal{L} = -p_A \log r' - p_B \log(1 - r')$$

$$\frac{\partial \mathcal{L}}{\partial r'} = -\frac{p_A}{r'} + \frac{p_B}{1 - r'} = 0 \rightarrow r' = \frac{p_A}{p_A + p_B} \rightarrow r = \frac{r'}{1 - r'}$$

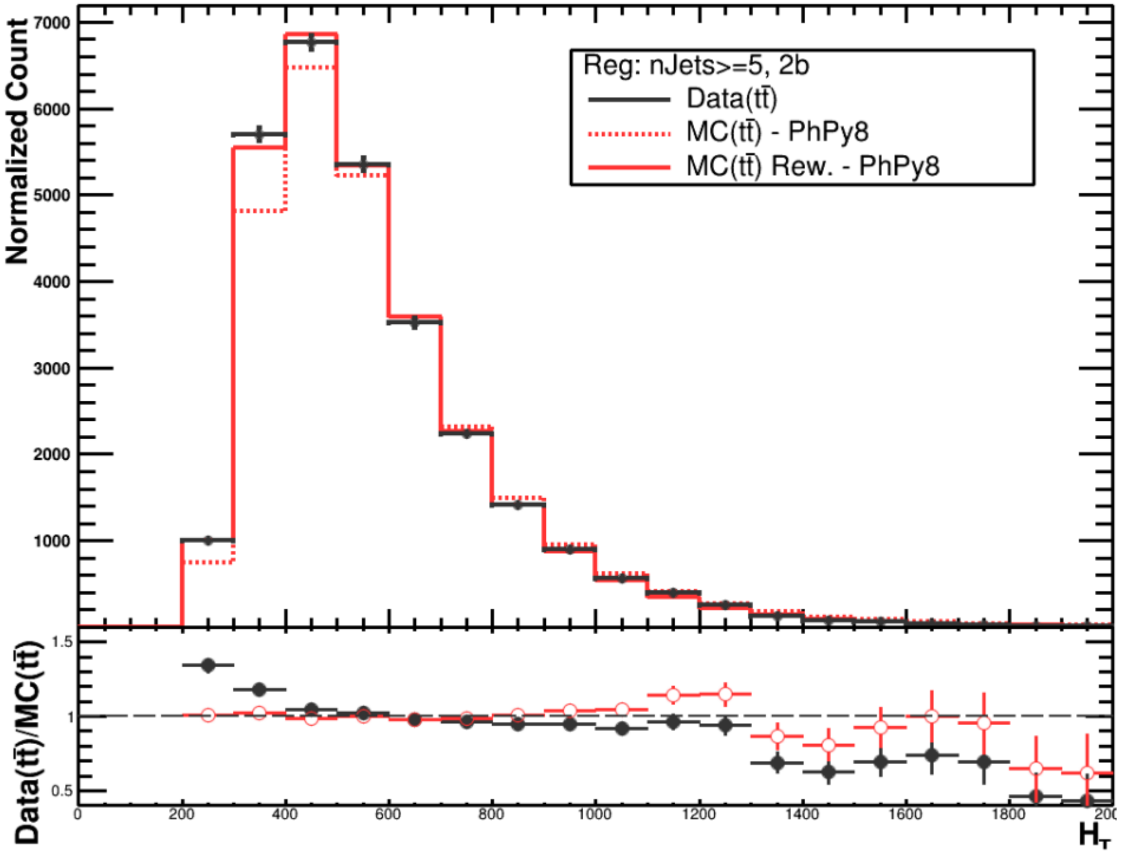


NN-reweighting (loss function)

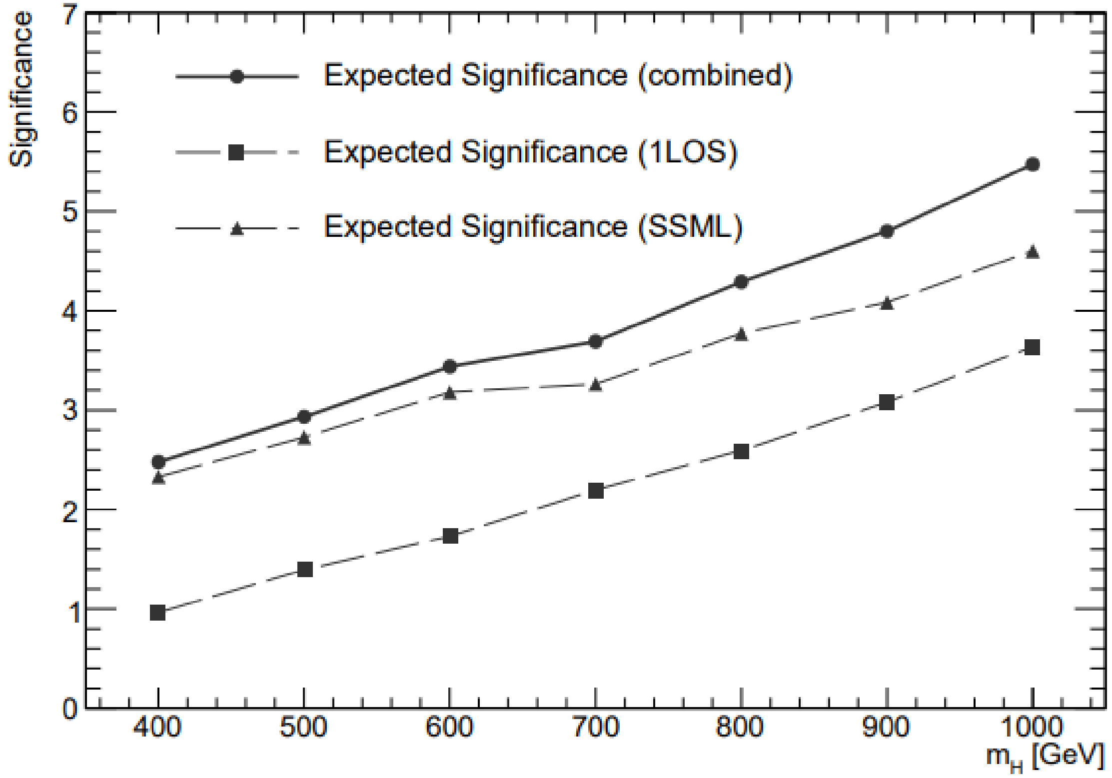
Exponential Loss



Binary Cross Entropy



Expected significance



SSML search

- ATLAS 2LSS/ML channel: similar strategy as the observation analysis
- Additional BDT to separate BSM vs SM $t\bar{t}t\bar{t}$