ATLAS-CMS comparison: Search for flavour-changing neutral-current couplings between the top quark and Higgs boson in multi-lepton final states

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LHC*top*WG Meeting April 2024, 25.04.2024

ATLAS Analysis: [arXiv:2404.02123] [Website]

CMS Analysis: [CMS-PAS-TOP-22-002] [Website]

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Introduction

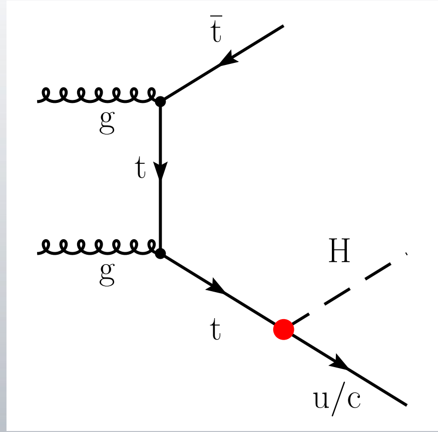
tHq FCNC couplings and multilepton final states

tHq FCNC Couplings

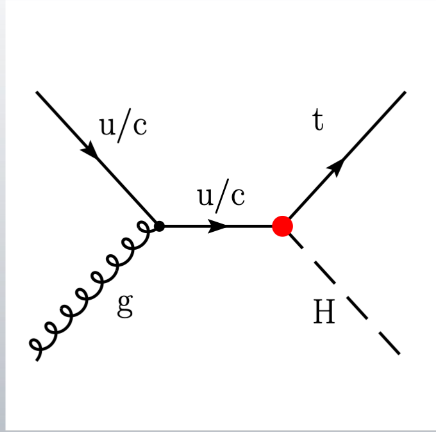
- FCNC processes **forbidden at tree-level** in the SM, higher orders suppressed by GIM mechanism
  → Any **observation** at the LHC indication of **new physics**
- **Model-independent** searches using an **Effective Field Theory** (EFT) with the full ATLAS/ CMS Run 2 datasets taken at $\sqrt{s} = 13$ TeV:

$$\mathcal{L}_{EFT} = \sum_{q=u,c} \frac{C_{u\phi}^{tq}}{\Lambda^2} \mathcal{O}_{u\phi}^{tq} + \frac{C_{u\phi}^{qt}}{\Lambda^2} \mathcal{O}_{u\phi}^{qt}; \qquad C_{u\phi}^{qt}, C_{u\phi}^{tq}\text{: Wilson coeff.}$$

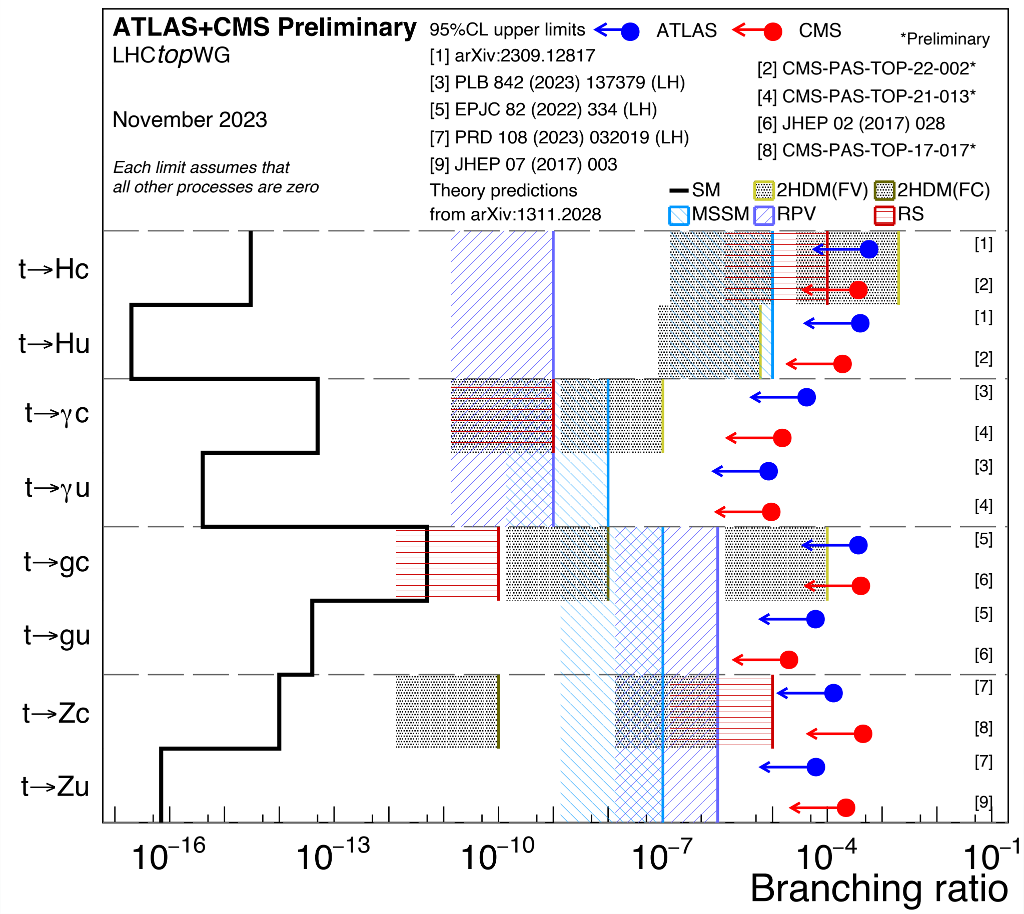
- Considering $t\bar{t}(t \to Hq)$ **decay process** and $gq \to Ht$ **production process**



$t\bar{t}(t \to Hq)$ decay



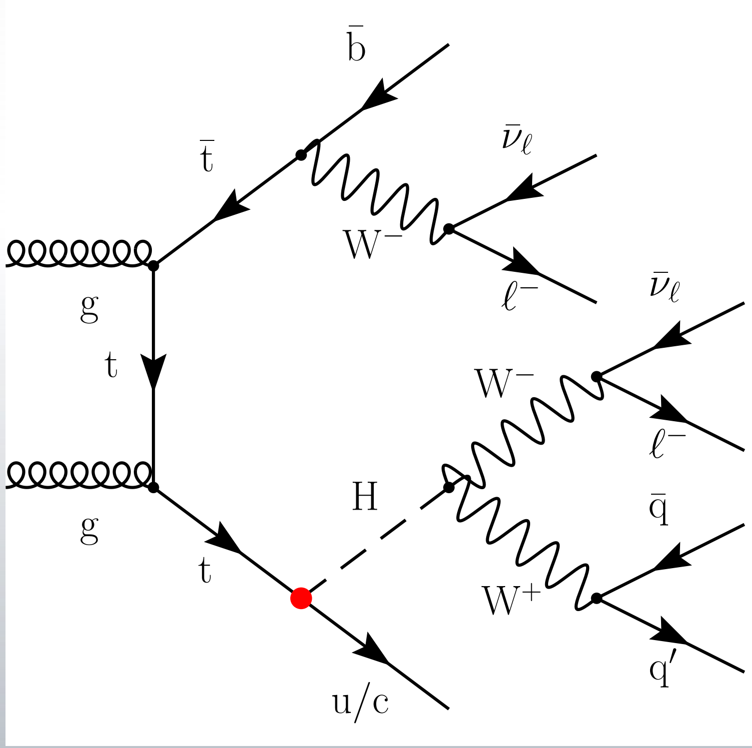
$gq \to Ht$ production



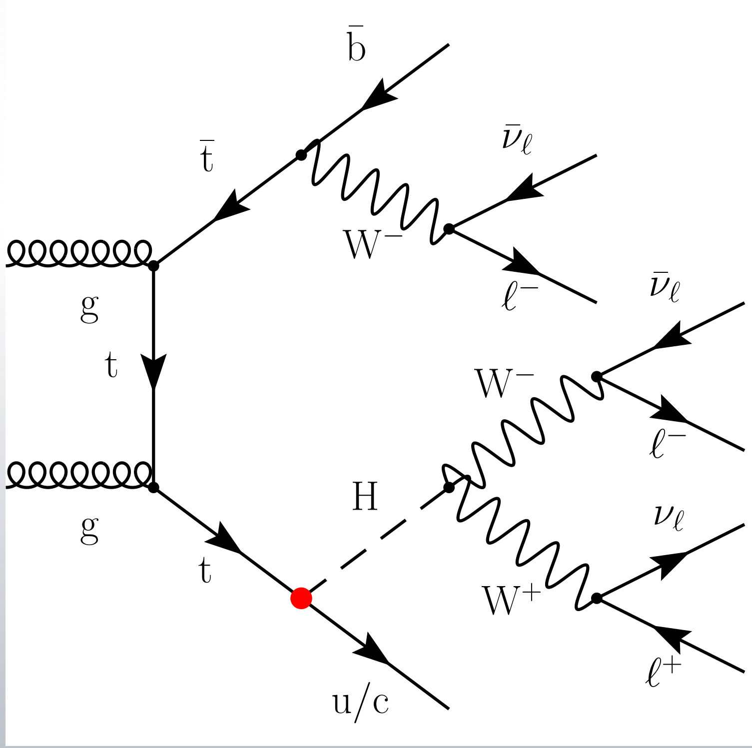
[LHCtopWG Summary Plots]

Multi-lepton final states

- Final states of two leptons with the same charge ($\mathbf{2\ell}$**SS**) or three leptons ($\mathbf{3\ell}$)
- Primary Higgs-boson decay mode: $\boldsymbol{H \rightarrow WW^*}$ ($\sim 75\ \%$ of events)
- Additional contributions from $H \rightarrow ZZ^*$ and leptonic $H \rightarrow \tau^+\tau^-$ decays



Exemplary 2ℓSS final state diagram



Exemplary 3ℓ final state diagram

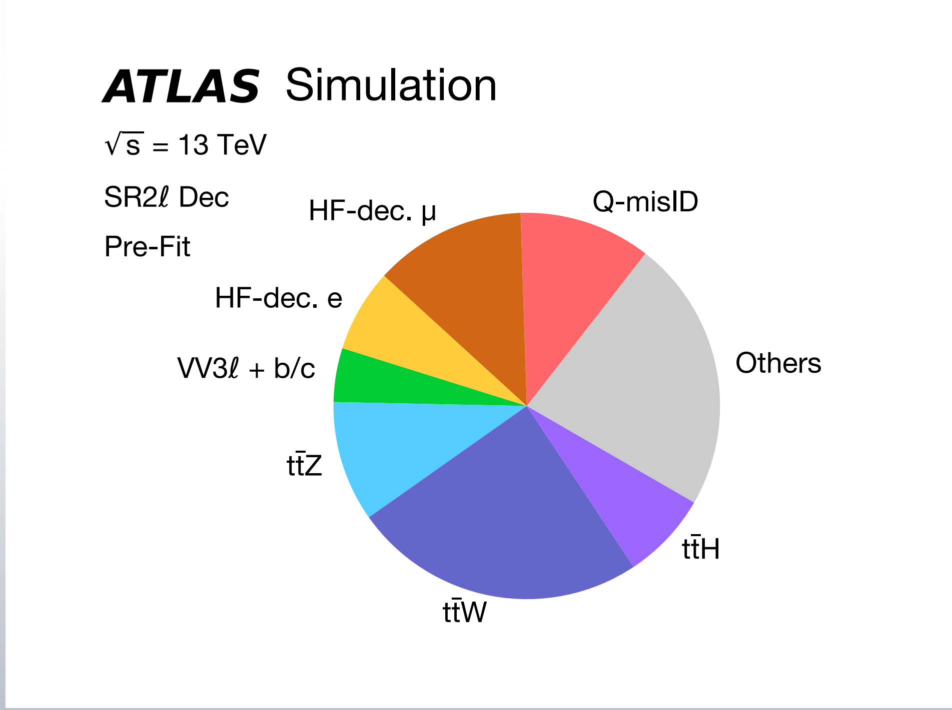
ATLAS Analysis Strategy

Background estimation, signal-background separation and fit results

[arXiv:2404.02123]

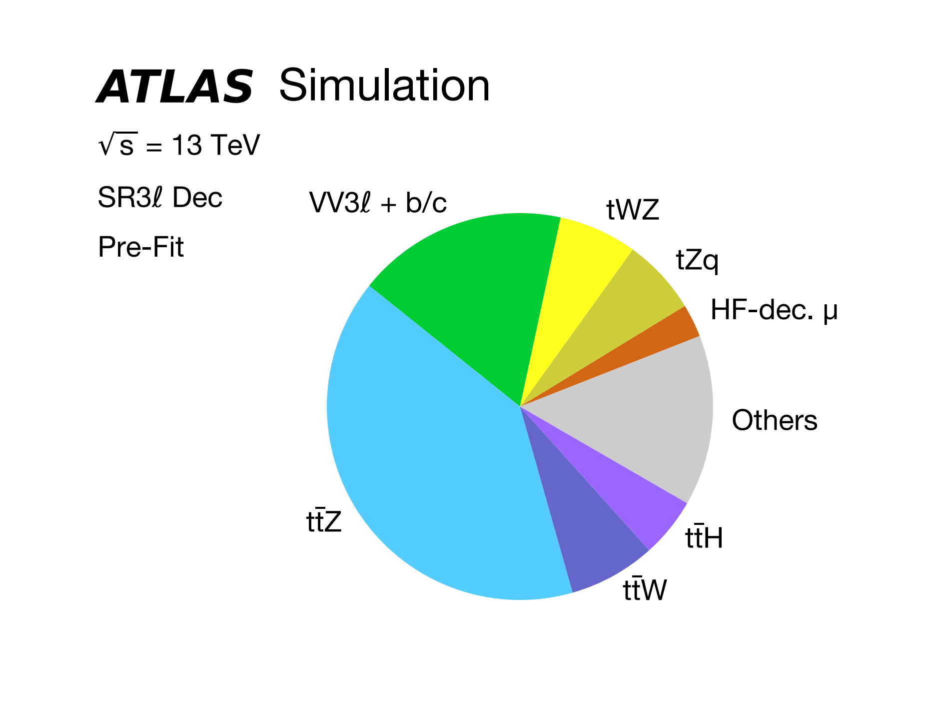
Signal Regions and background composition

- Definition of **4 signal regions** (SRs): 2 per final state, each focuses either on decay or production signal ($N_{b-\text{tags}} = 1$ in all of them)
- Contribution of **prompt-lepton background** processes (with leptons originating from on-shell $W/H/Z$-boson decay) and **non-prompt lepton background** processes



Background composition in the SR2ℓ Dec

[arXiv:2404.02123]

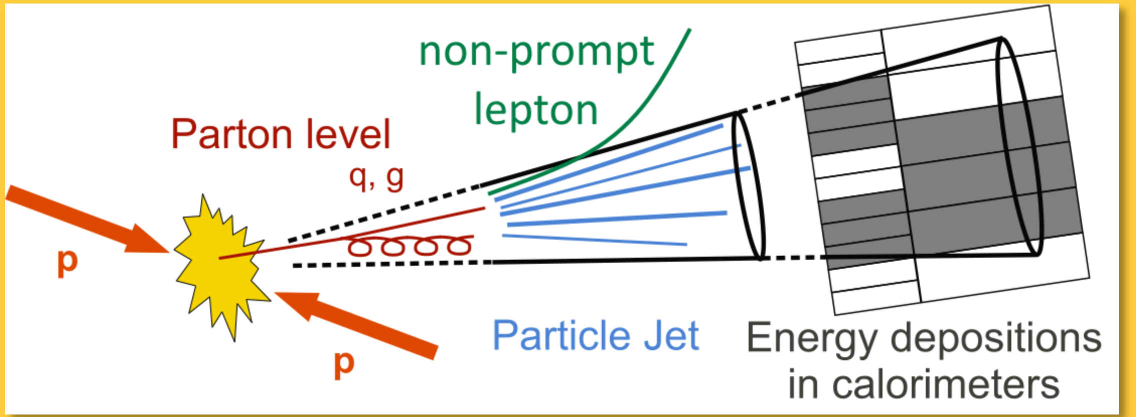


Background composition in the SR3ℓ Dec

B-hadron decay and Q-misID background

Leptons from B-hadron decay (HF-decay e/μ)

- Assumption: **Shape** of kinematic distributions **accurately modelled** by Monte-Carlo (MC) simulations
- **Free normalisation** in final fit
- **4 control regions** (CRs) defined to constrain normalisation (2 CRs per final state)



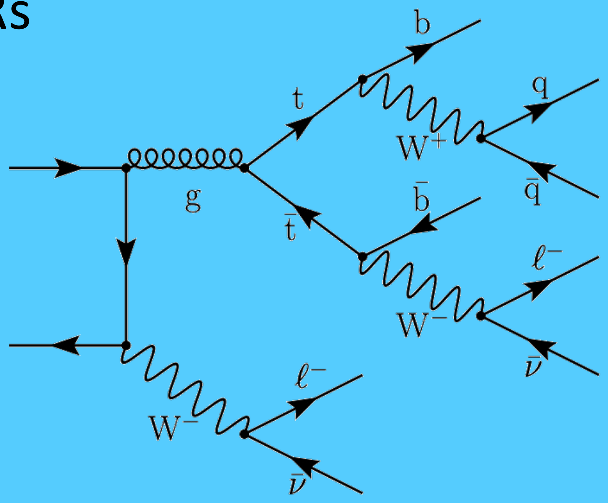
Q-misID electrons (only 2ℓSS final state)

- Leptons **reconstructed with inverted charge** due to
  A. false track reconstruction
  B. Bremsstrahlung + material conversion
- **Data-driven estimate** using same-charge and opposite-charge events around the $Z \to ee$ mass peak
- Results in **p_{T}- and η-dependent** efficiencies to be applied to opposite-charge data events

$t\bar{t}V$ and VV background

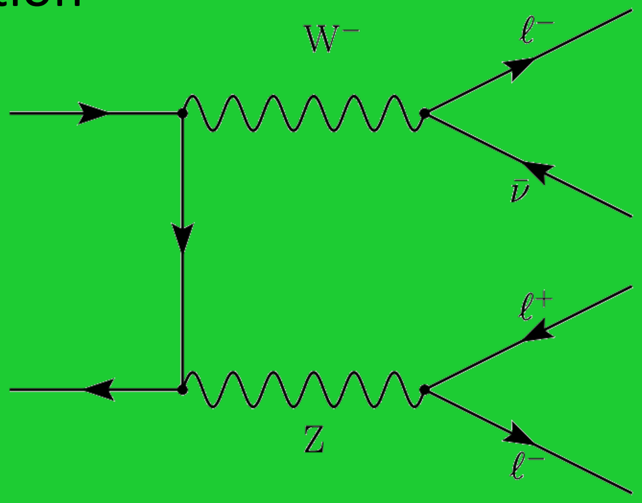
$t\bar{t}W$ and $t\bar{t}Z$ production

- $t\bar{t}W$ cross-section measured **$1.4\ \sigma$ above prediction** [arXiv:2401.05299]
- $t\bar{t}Z$ only **measured for high N_{jets}** while this analysis considers $N_{\text{jets}} \geq 1$ [arXiv:2312.04450]
- **Free-floating normalisation** for both processes with 3 CRs



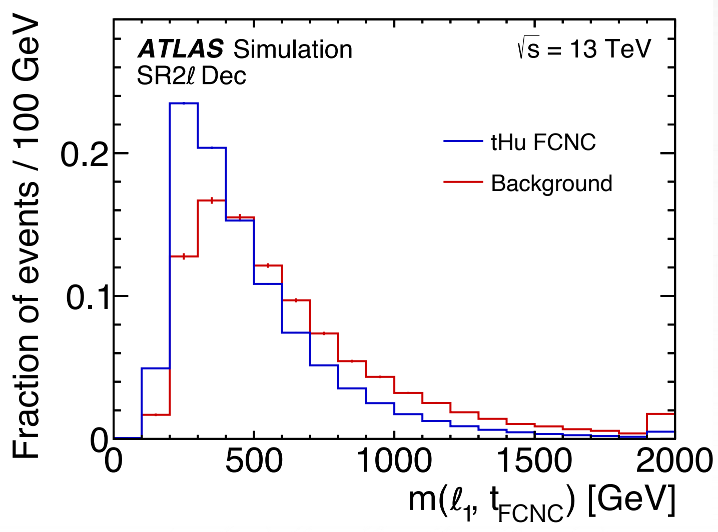
VV+HF production

- VV samples produced without additional b-quark → poor modelling in regions with $N_{b\text{-tags}} \geq 1$
- **Splitting VV samples** by number of leptons and jet flavour
- Largest template $\boldsymbol{VV3\ell + b/c}$ with **free-floating** normalisation

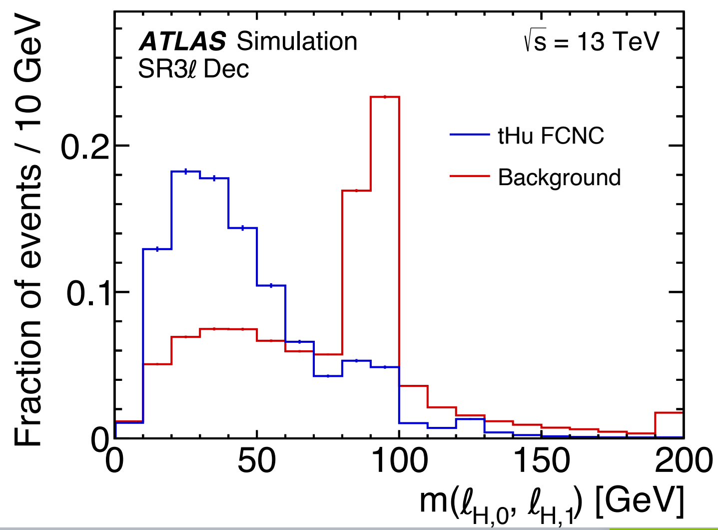


Reconstruction Algorithms in the Signal Regions

- Extensive **event reconstruction** to optimise signal-background separation in SRs
- Focusing on $\boldsymbol{H \to WW^*}$ decay mode
- **Recursive Jigsaw Reconstruction (RJR)**
  - Aims to reconstruct particles in the decay tree
  - Uses recursively defined jigsaw rules to match final-state objects and decay-tree particles, maximising a global likelihood
- **Neutrino-independent combinatorics estimator (NICE) Reconstruction**
  - Identification of leptons from Higgs-boson decay using angular and charge information
  - No direct dependence on $H \to WW^*$ decay mode
    → Good performance also for $H \to ZZ^*$ and $H \to \tau^+\tau^-$

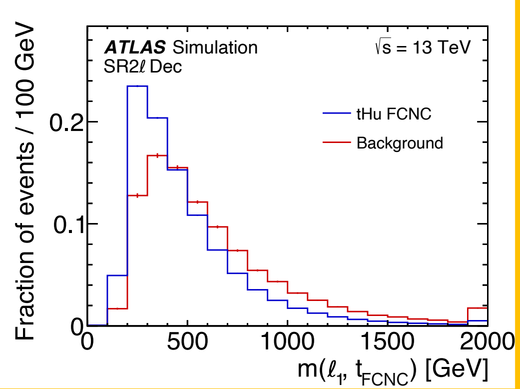


[arXiv:2404.02123]



Neural Networks in the Signal Regions

Reconstruction Algorithms



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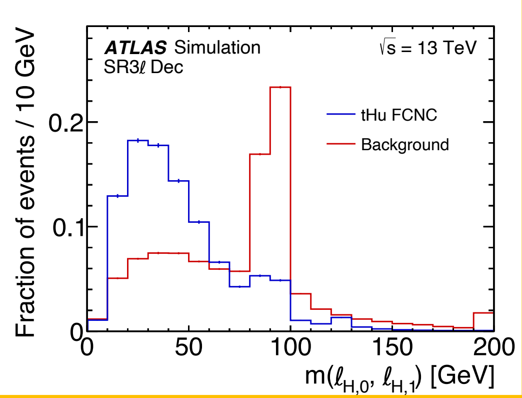

[arXiv:2404.02123]

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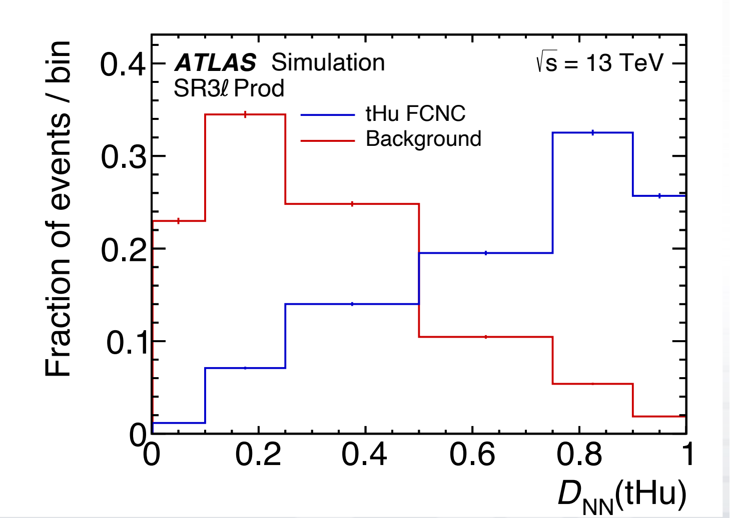
Variable pre-processing and Neural Network (NN) training

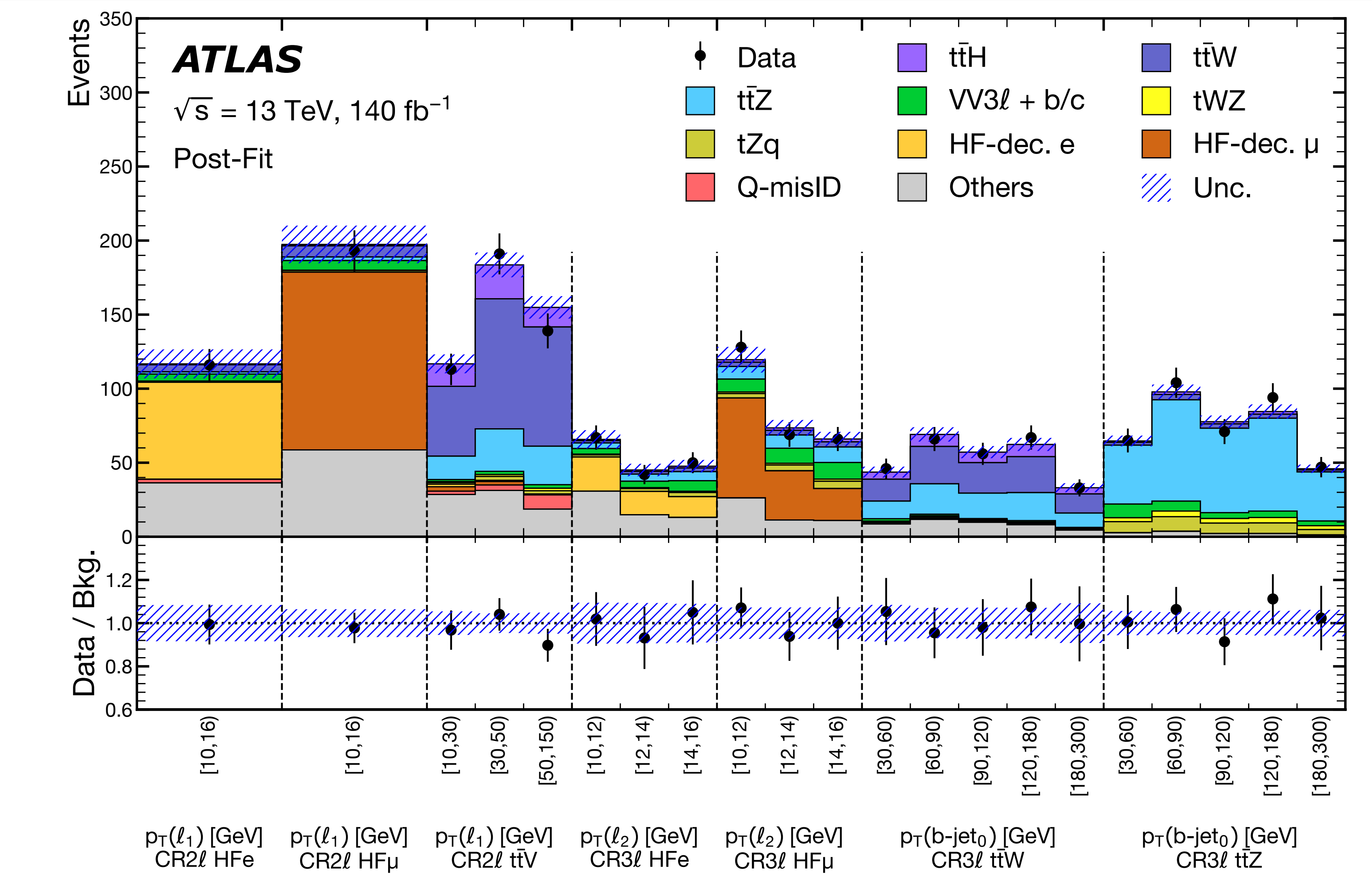
- Separation power of all variables combined using NNs
- Training one NN per signal process (tHu/tHc) and per SR$2\ell/3\ell$ Dec/Prod
- Extensive **pre-processing**
  - *Variable selection* based on added significance
  - *Normalisation* ($\mu = 0, \sigma = 1$) and *decorrelation* of input variables
  - Transformation to *signal purity* S/B with *spline fit* to reduce statistical fluctuations

→ Allows for **NNs of very small size** (1 hidden layer)



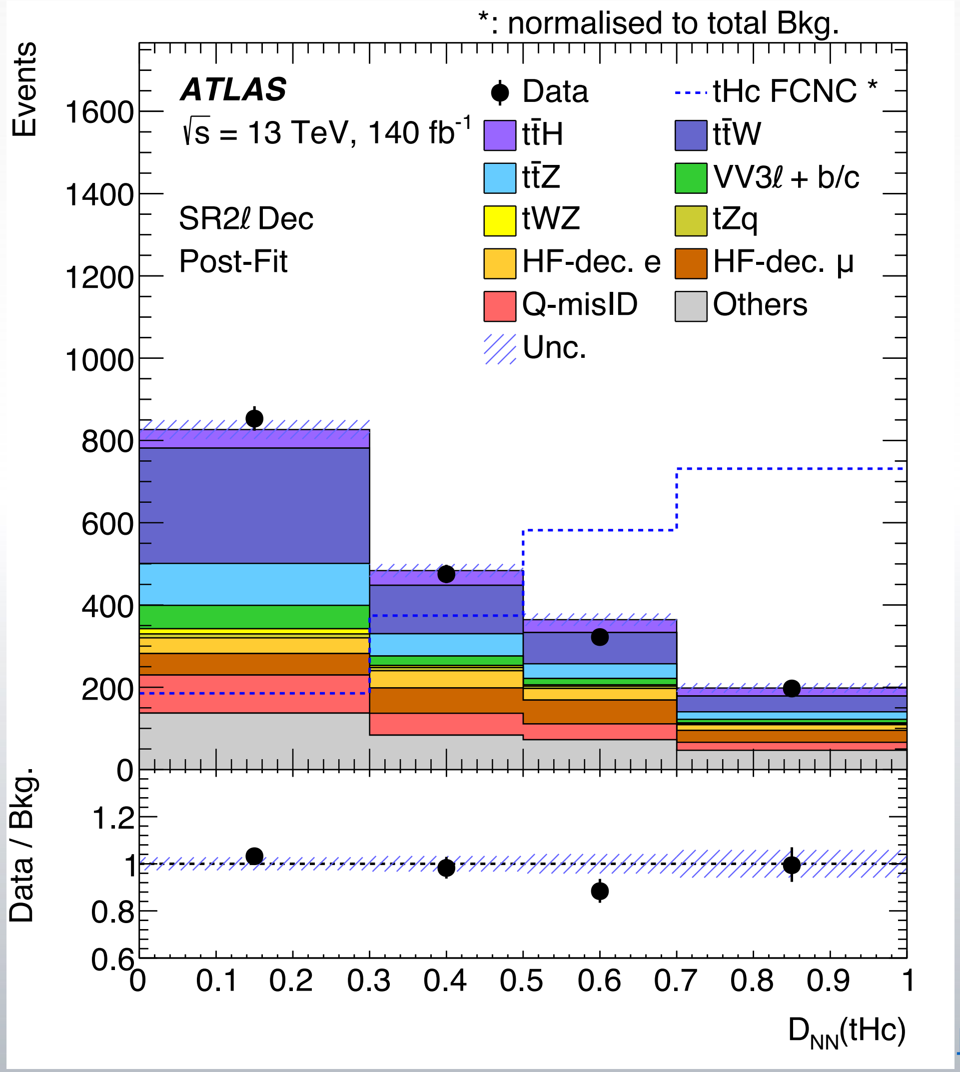
[arXiv:2404.02123]

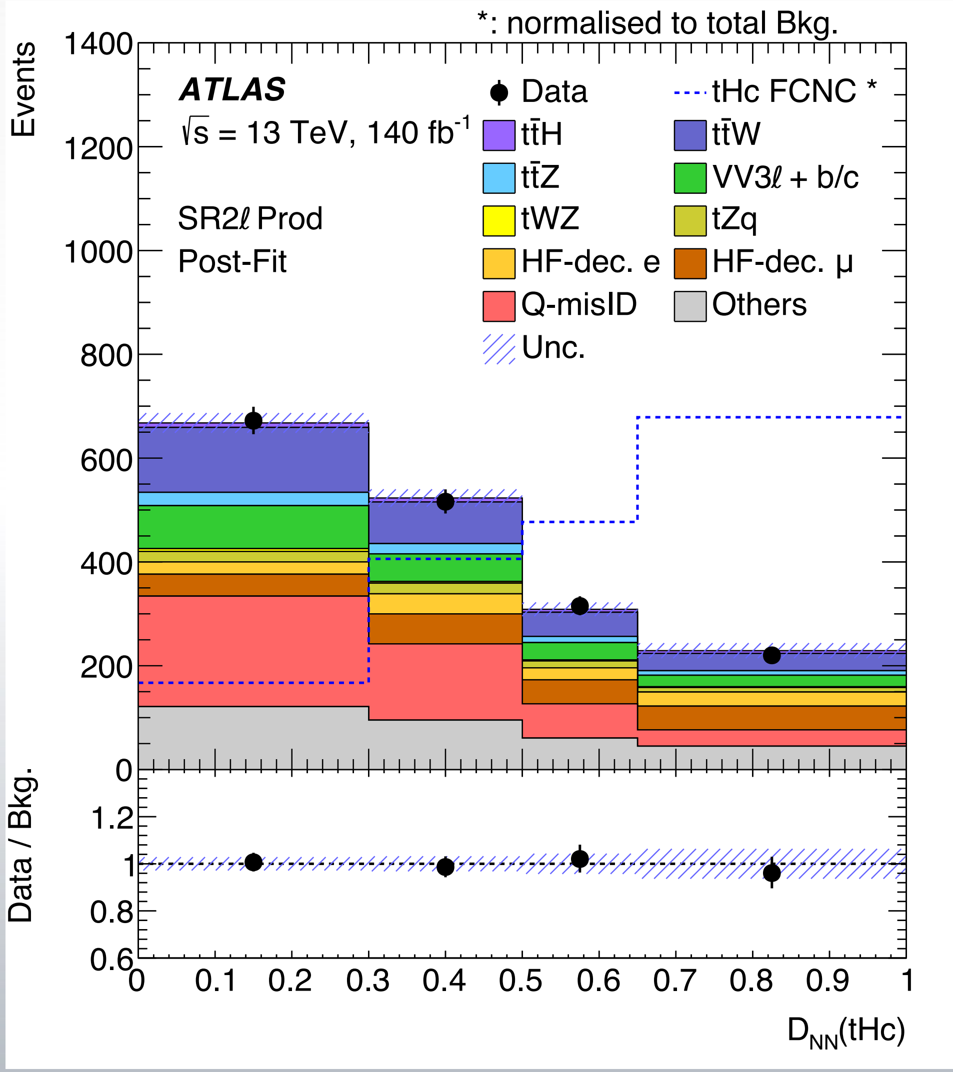
Profile-Likelihood Fit – Control Regions



[arXiv:2404.02123]

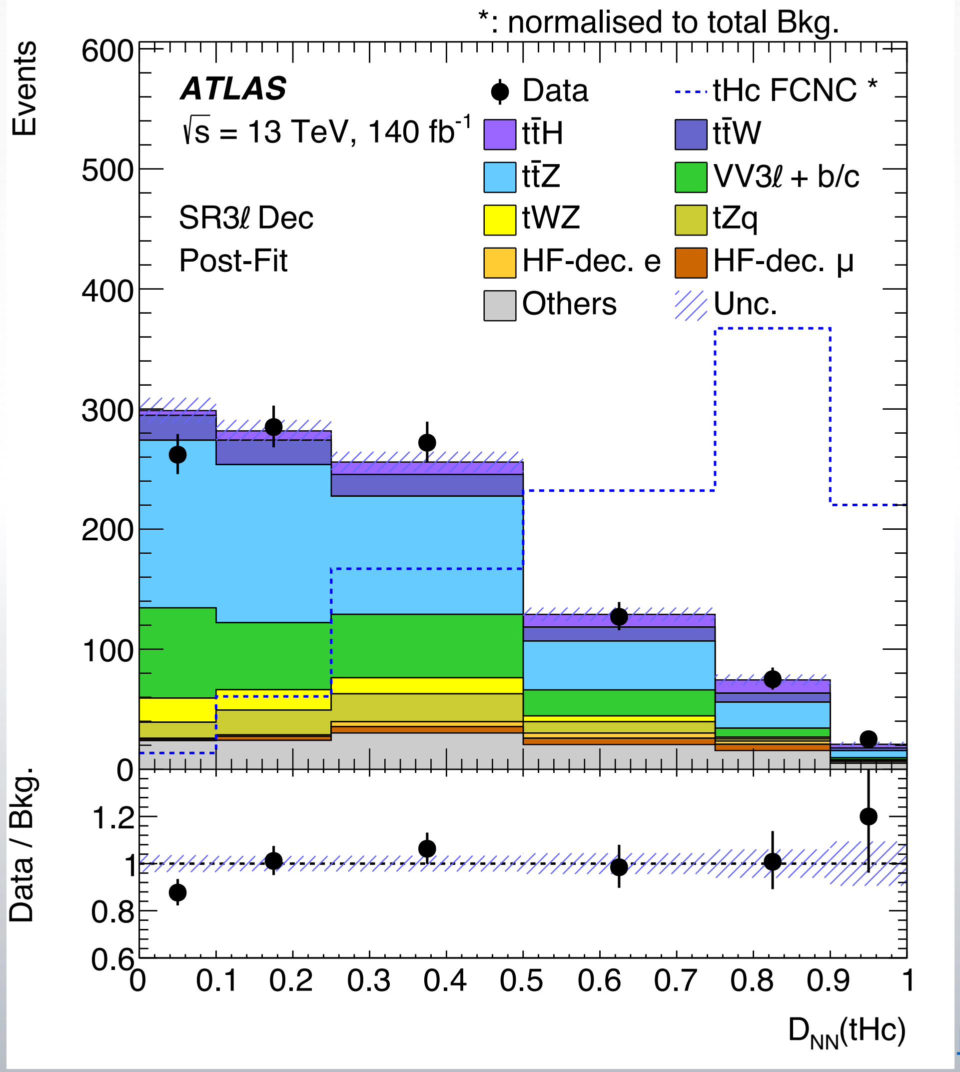
Profile-Likelihood fit – 2ℓSS Signal Regions

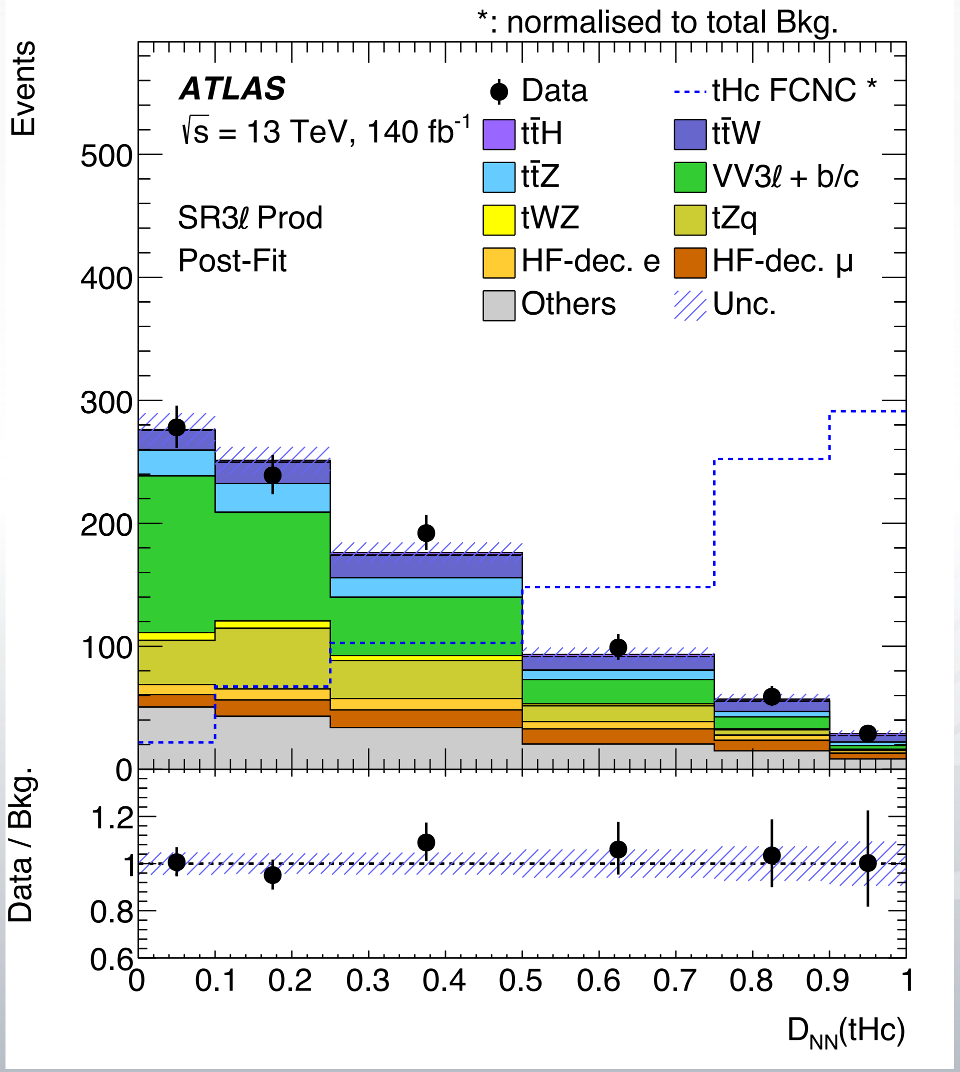




[arXiv:2404.02123]

Profile-Likelihood Fit – 3ℓ Signal Regions



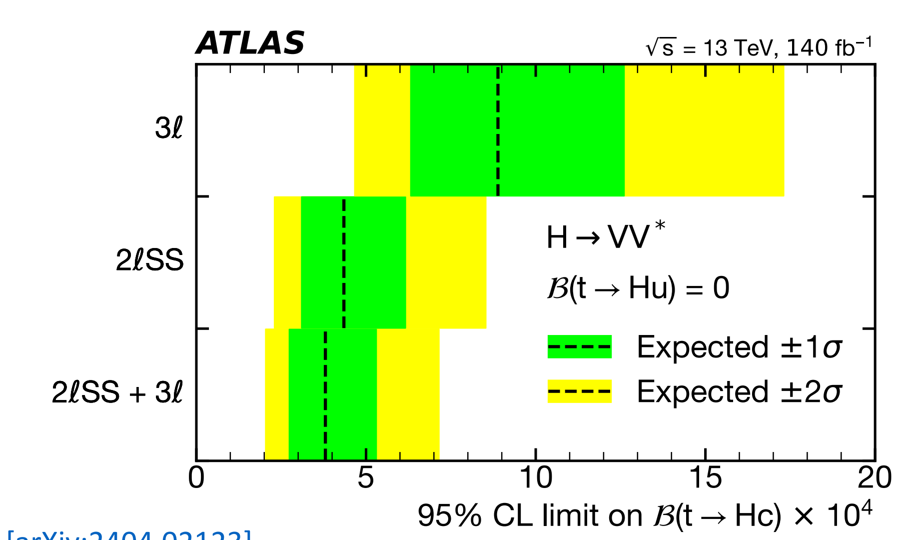


[arXiv:2404.02123]

Expected Upper Limits on $\mathcal{B}(t \to Hq)$

- Results compatible with background-only hypothesis → Determination of **upper exclusion limits**
- Comparison of final states: 2ℓSS more important, but $\sim$ **20 % improvement due to** 3ℓ
- Increase of expected upper limits due to systematic uncertainties: $\sim 20\ \%$ → **Analysis statistically limited**

Fit configuration	Expected 95% CL upper limits / 10^{-4} $\mathcal{B}(t \to Hu)$	$\mathcal{B}(t \to Hc)$
Nominal fit	$3.0^{+1.2}_{-0.8}$	$3.8^{+1.5}_{-1.1}$
Statistical uncertainties only	$2.6^{+1.1}_{-0.7}$	$3.3^{+1.2}_{-1.0}$ (+20 %)
2ℓSS final state only	$3.6^{+1.5}_{-1.0}$	$4.3^{+1.9}_{-1.2}$
3ℓ final state only	$6.5^{+2.7}_{-1.9}$	$8.9^{+3.7}_{-2.6}$



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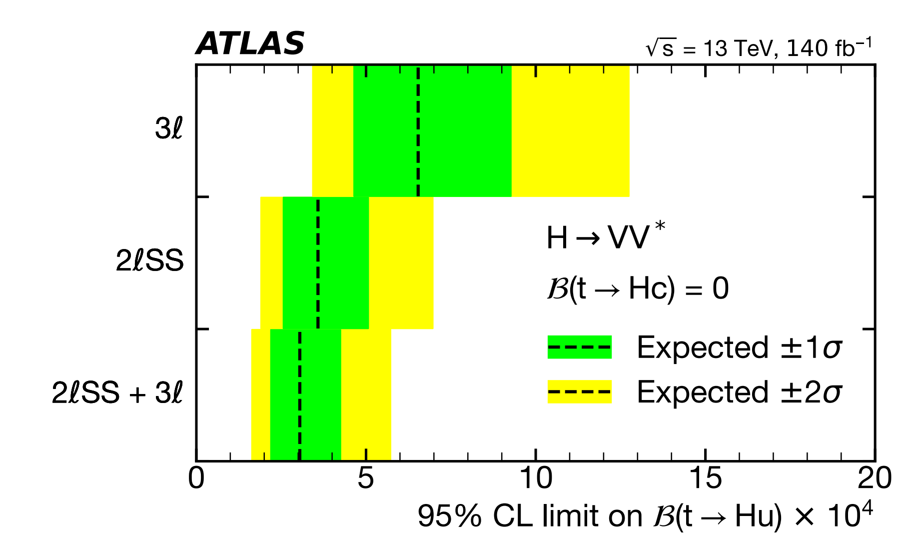
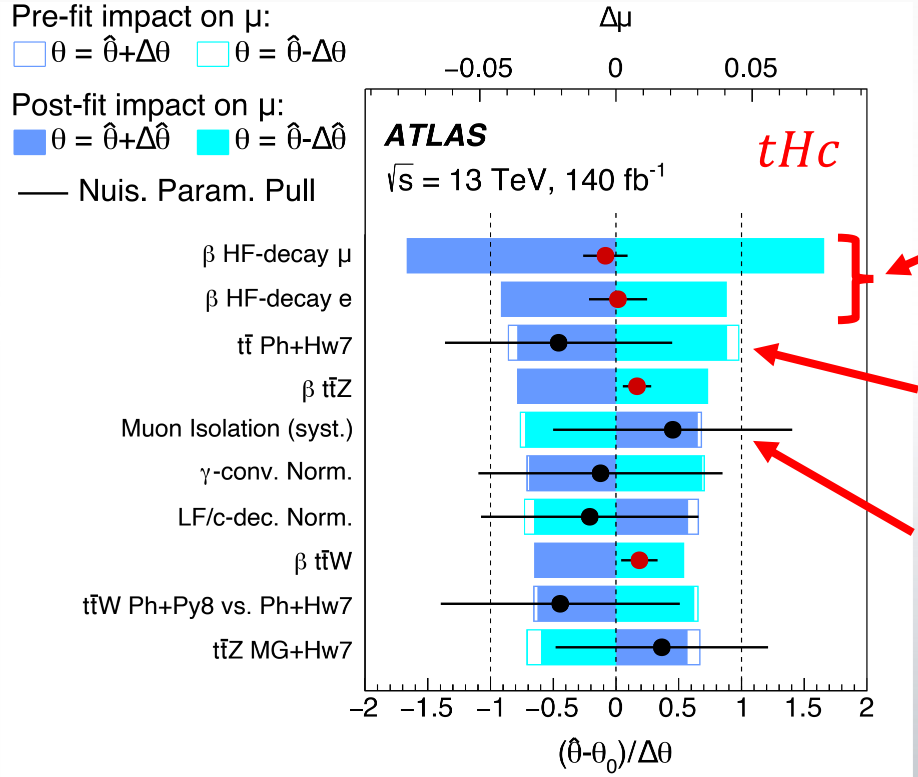


Impact of Systematic Uncertainties

- Impact of individual systematic uncertainties determined by fixing related nuisance parameters to $\pm 1\,\sigma$ and comparing the differences in the signal normalisation μ

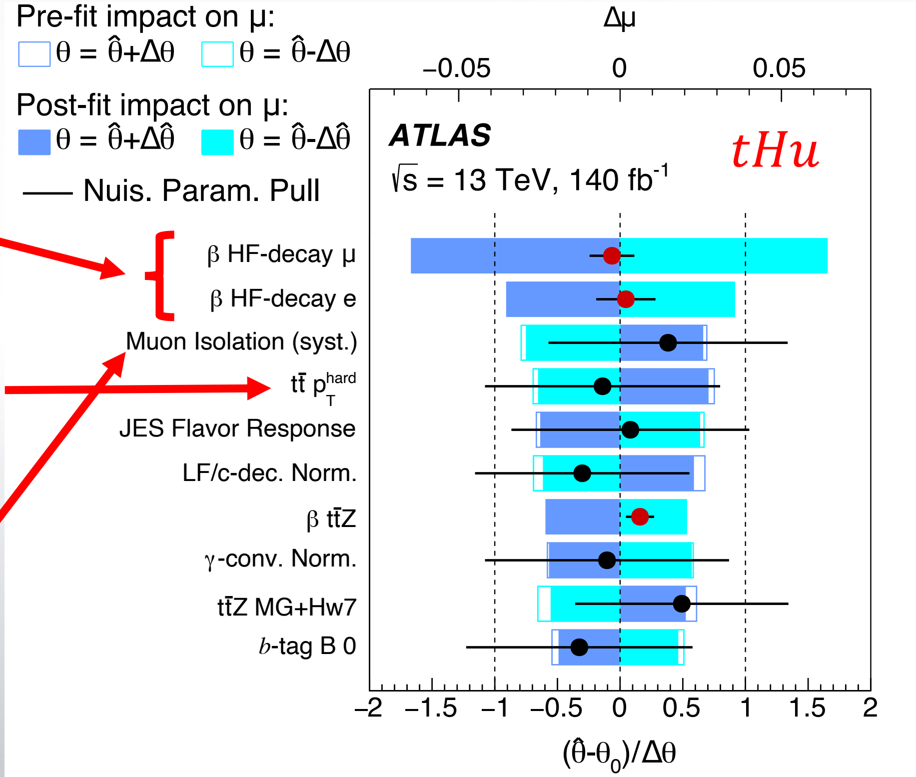
[arXiv:2404.02123]



Normalisation factors (HF-decay)

$t\bar{t}$ modelling (mainly HF-decay background)

Muon isolation sensitive to HF-decay μ



Mainly related to **HF-decay background**

→ Difficult to separate against in NN training, largest background in high-D_{NN} bins

Observed Upper Limits and Combination

- Observed (expected) upper limits on $\mathcal{B}(t \to Hq)$ of this analysis:

$$\mathcal{B}(t \to Hu) < 2.8\ (3.0) \times 10^{-4} \ \text{ and } \ \mathcal{B}(t \to Hc) < 3.3\ (3.8) \times 10^{-4}$$

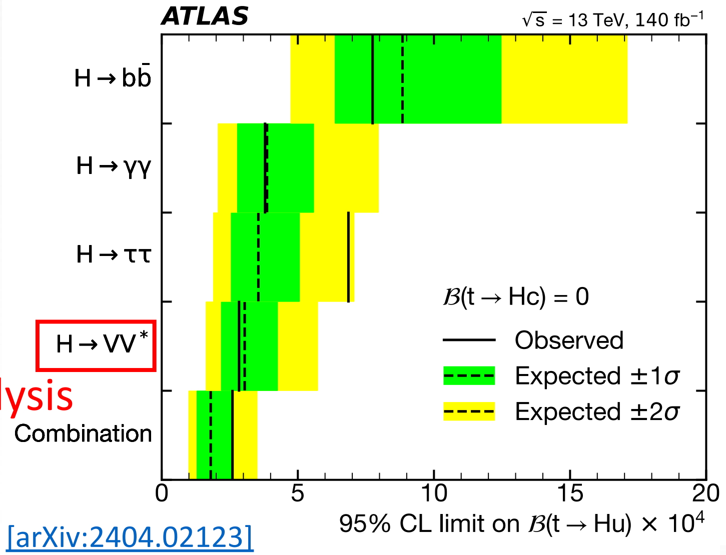
- Results are **combined** with **ATLAS tHq FCNC searches** in different Higgs-boson decay modes ($H \to b\bar{b}$ [1], $H \to \gamma\gamma$ [2] and $H \to \tau^+\tau^-$ [3])

$$\mathcal{B}(t \to Hu) < 2.6\ (1.8) \times 10^{-4} \ \text{ and } \ \mathcal{B}(t \to Hc) < 3.4\ (2.3) \times 10^{-4}$$

- Transformed limits on the EFT Wilson coefficients (at EFT scale of $\Lambda = 1$ TeV):

$$\left|C_{u\phi}^{ut,tu}\right| < 0.71\ (0.73) \ \text{ and } \ \left|C_{u\phi}^{ct,tc}\right| < 0.76\ (0.82)$$

- $\mathcal{B}(t \to Hq)$ BSM predictions are as high as 10^{-4}



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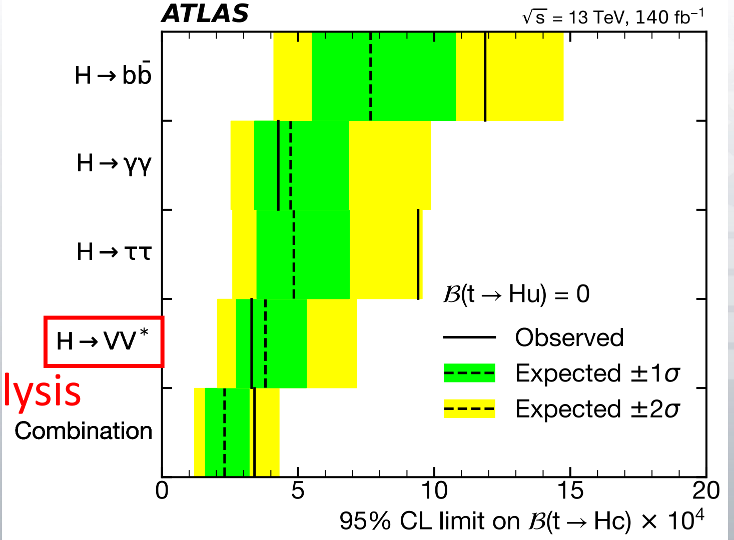


[1] JHEP 07 (2023) 199 [2] JHEP 12 (2023) 195 [3] JHEP 06 (2023) 155

Comparison to CMS analysis

Search for tHq FCNC couplings in multilepton final states and combination
[CMS-PAS-TOP-22-002]

Differences between ATLAS and CMS Analyses

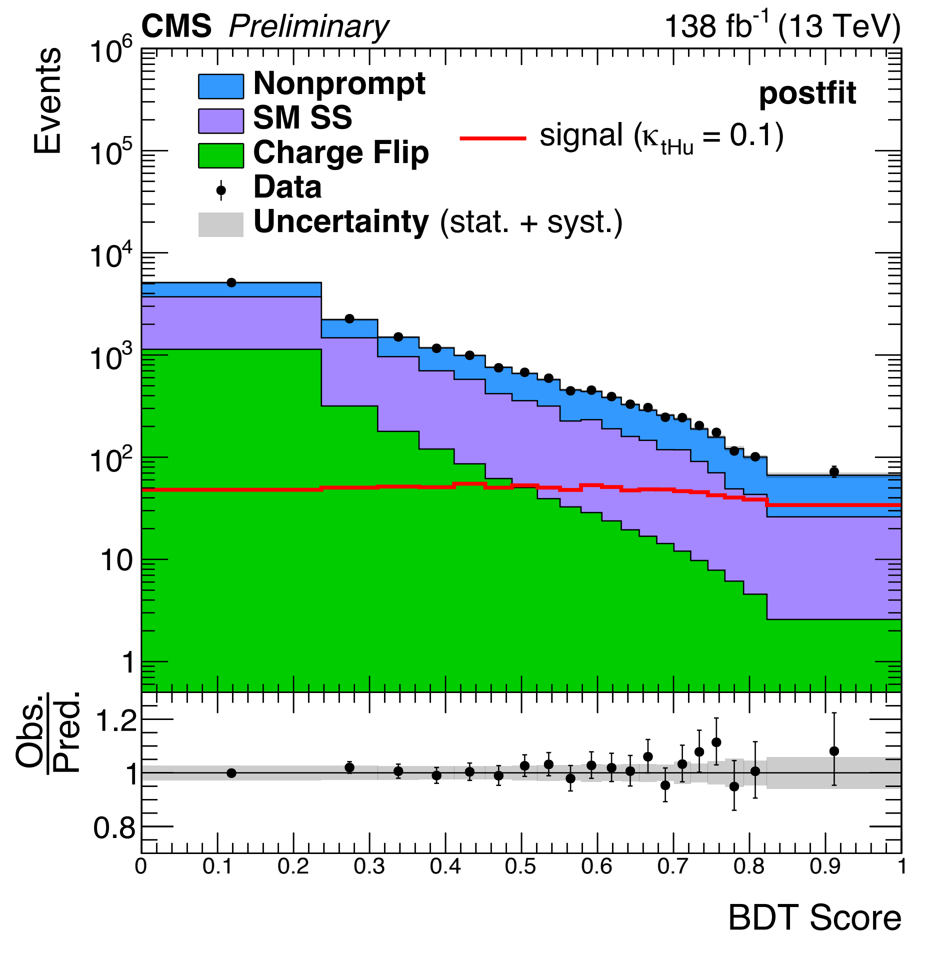
	Event selection	Background Estimation	Signal-Background Separation and Profile-Likelihood Fit
ATLAS EXPERIMENT	• **2ℓSS and 3ℓ** final states (treated separately) • **Looser** $p_T(\ell)$ cuts and no $m(ee)$-cut in 3ℓ final state	• **HF-decay semi-data-driven** with normalisation free-floating in final fit • $\boldsymbol{t\bar{t}W}$, $\boldsymbol{t\bar{t}Z}$ **and** $\boldsymbol{VV}$ background given **specific treatment**	• Extensive reconstruction • **Individual NNs** trained per signal process and per SR$2\ell/3\ell$ Dec/Prod • **Separate CRs** included in fit • **41 Bins** in total (with 5 free-floating normalisation factors)
CMS	• **2ℓSS + $\boldsymbol{n}\cdot\ell$**, $n = 0,1,2,\ldots$ (all treated as one) • **Tighter** p_T-cut and global cut $\lvert m(ee) - m_Z \rvert > 20$ GeV	• **HF-decay data-driven** by comparing *tight* and *loose* lepton selection *("tight-to-loose ratio method")* • **All prompt lepton background processes from MC** simulation	• Reconstruction of invariant masses and H_T • **One BDT per signal process** trained on entire phase space • **Only this BDT** distribution included in the fit • **20 bins** in total

Results of the CMS Analysis

- Upper exclusion limits:

	95% CL observed (expected) limits on	
	$\mathcal{B}(t \to Hu)\ /10^{-4}$	$\mathcal{B}(t \to Hc)\ /10^{-4}$
ATLAS EXPERIMENT	2.8 (3.0)	3.3 (3.8)
CMS	7.2(5.9)	4.3 (6.2)

- Additional sensitivity in ATLAS (probably) due to
  - ➢ More inclusive event selection → Larger signal statistics
  - ➢ Larger number of (signal-sensitive) bins
  - ➢ Dedicated treatment of production signal (tHu specifically)



Post-fit BDT distribution in the tHu channel

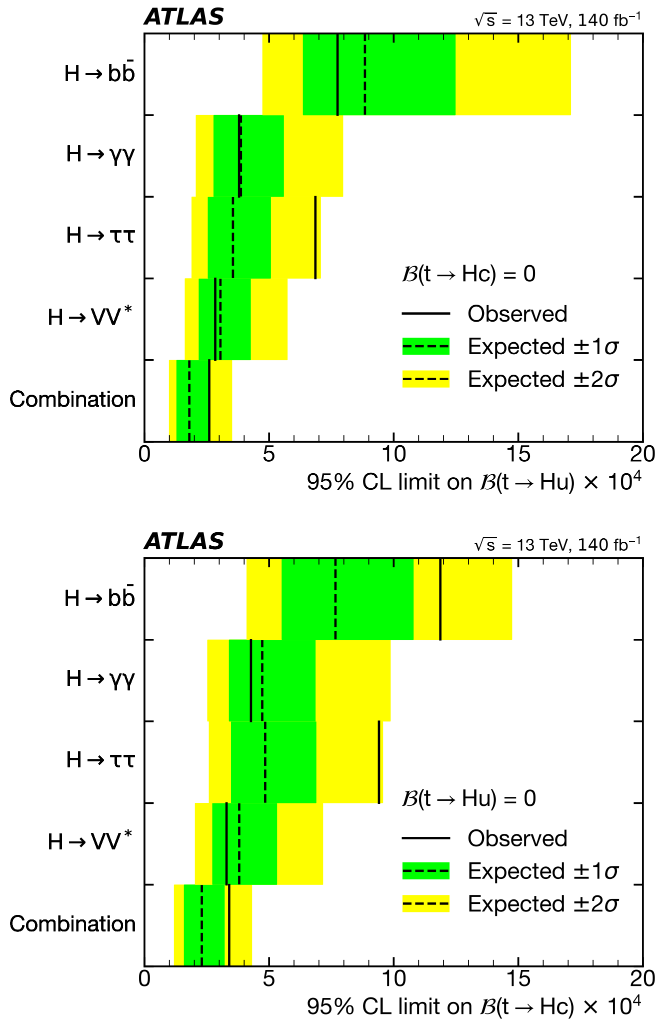
[CMS-PAS-TOP-22-002]

Comparisons of Combinations

- **No $H \to \tau\tau$ channel in CMS** combination
- In ATLAS: Strong **upward-fluctuation** in $H \to \tau\tau$ analysis (both tHu and tHc channel)
- In CMS: Strong **downward-fluctuation** in $H \to \gamma\gamma$ analysis (only tHu channel)
- Resulting combined limits:

	95% CL observed (expected) limits on	
	$\mathcal{B}(t \to Hu)\ /10^{-4}$	$\mathcal{B}(t \to Hc)\ /10^{-4}$
ATLAS	2.6 (1.8)	3.4 (2.3) ☆
CMS	1.9 (2.7) ☆	3.7 (3.5)

☆ Strongest observed limits to date



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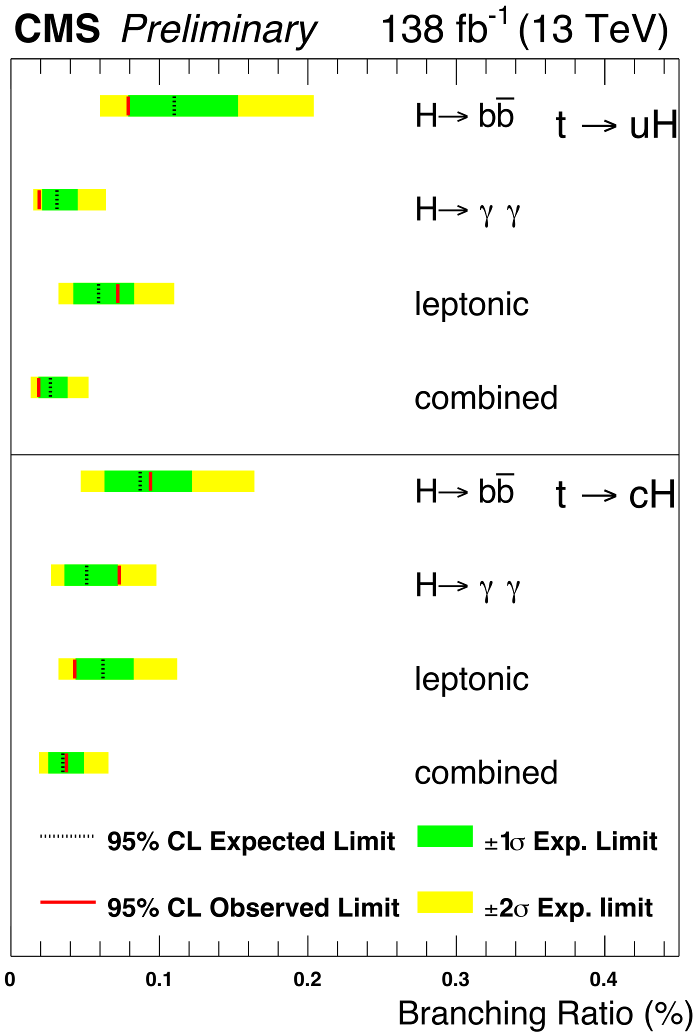
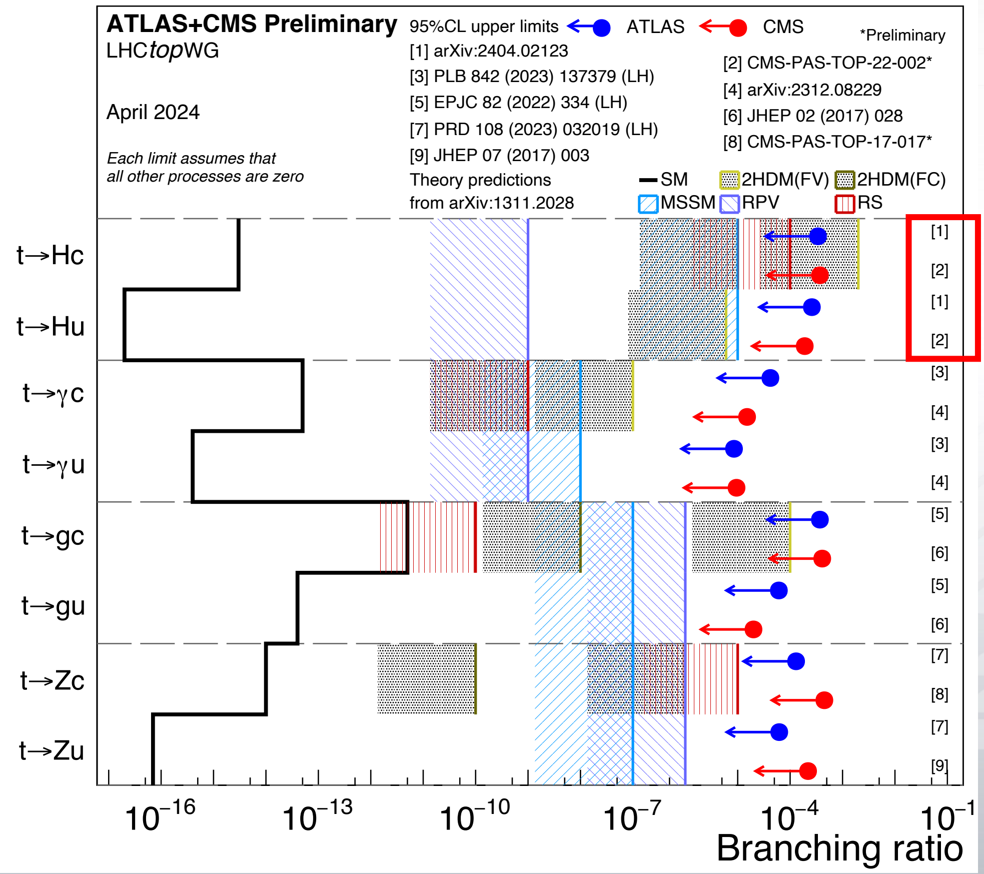


[CMS-PAS-TOP-22-002]

Conclusion

- Searches for tHq FCNC couplings in multilepton final states together with combinations
- ATLAS search in multilepton final states most sensitive single-channel search to date
- Both ATLAS and CMS combinations show very high sensitivity

	95% CL observed (expected) limits on	
	$\mathcal{B}(t \to Hu)\ /10^{-4}$	$\mathcal{B}(t \to Hc)\ /10^{-4}$
ATLAS EXPERIMENT	2.6 (1.8)	3.4 (2.3) ☆
CMS	1.9 (2.7) ☆	3.7 (3.5)

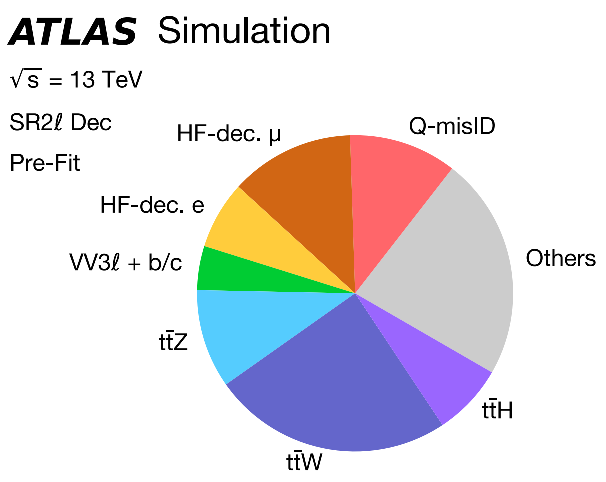


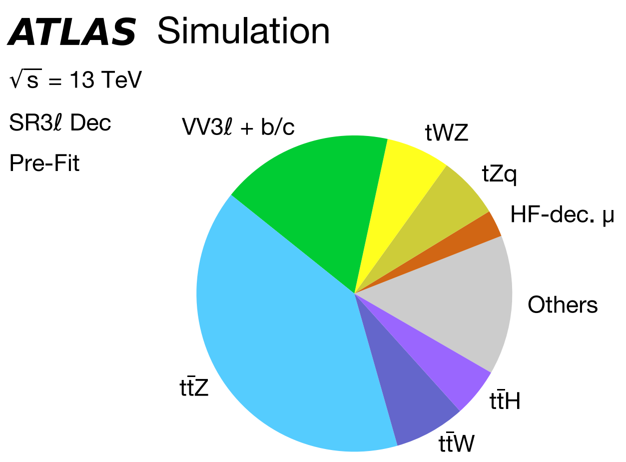
[LHCtopWG Summary Plots]

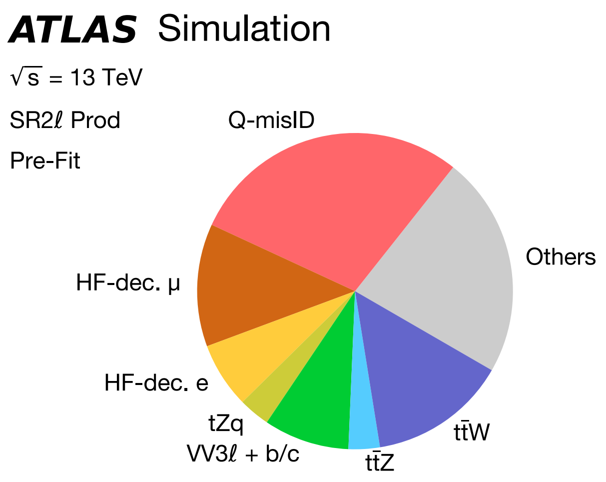
Thank you for your attention! ☺

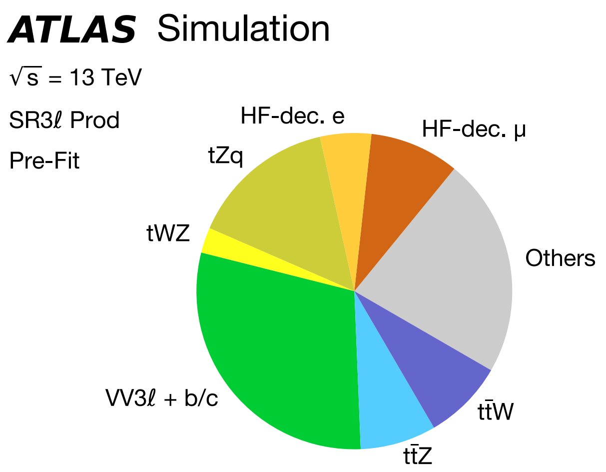
Backup

Signal region background composition



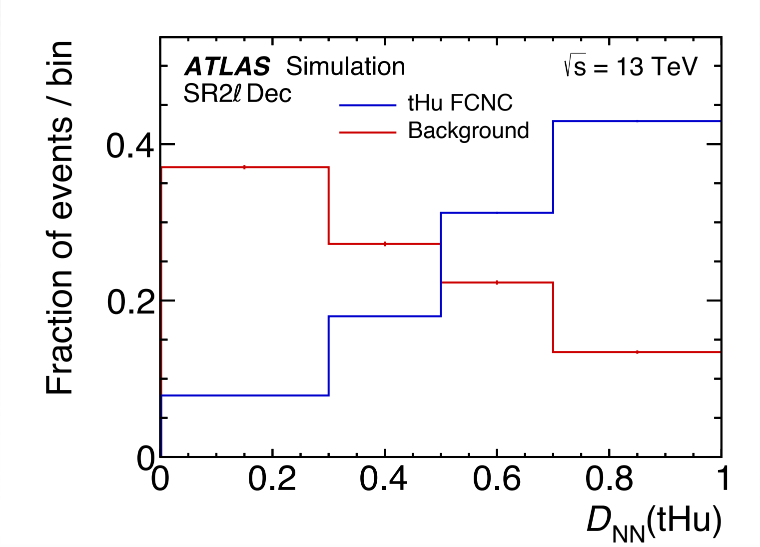


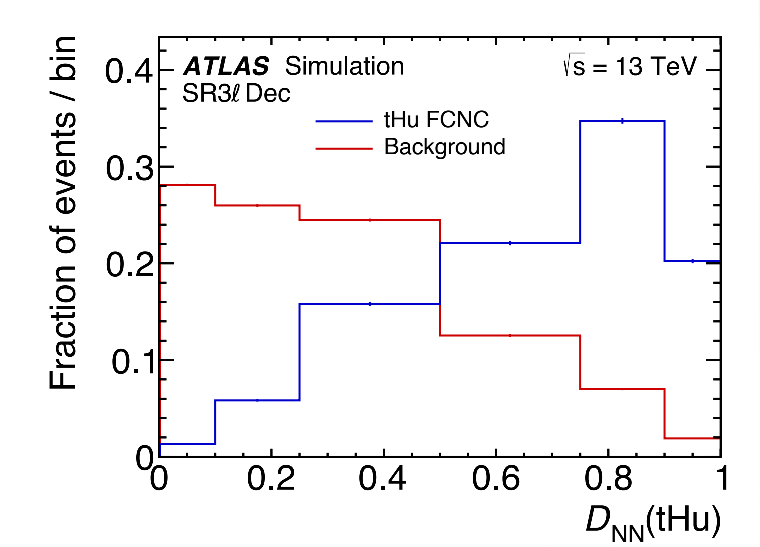


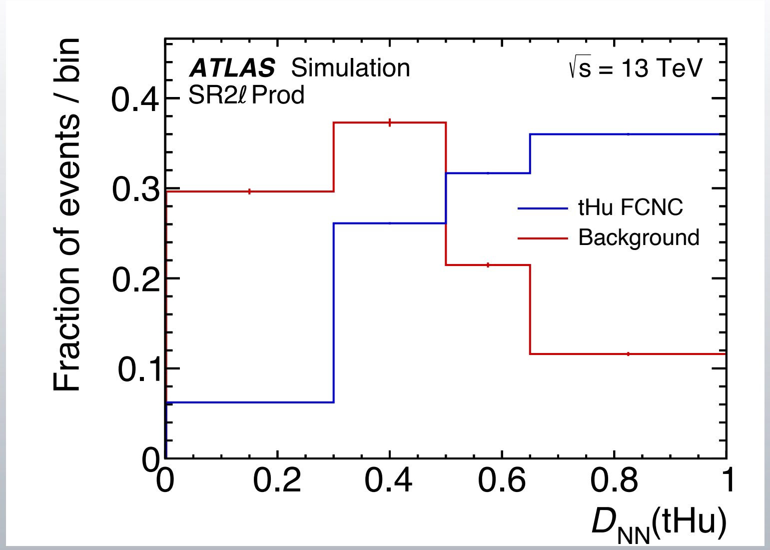


[arXiv:2404.02123]

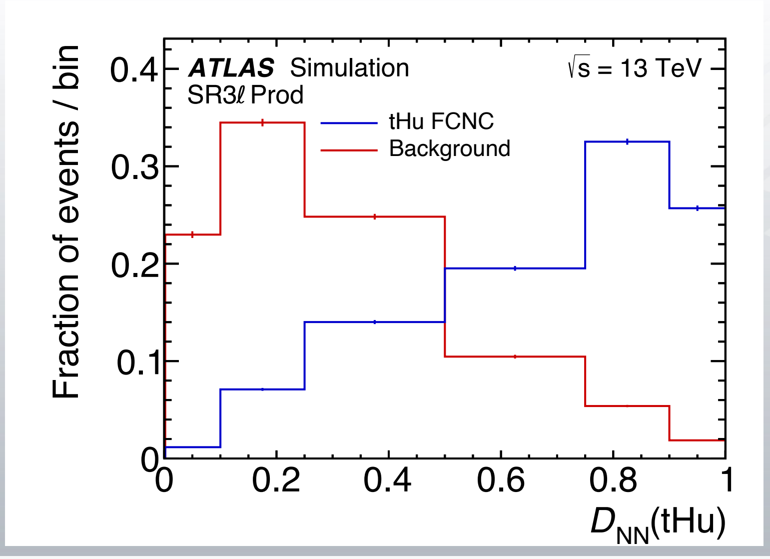
Neural Network distributions







[arXiv:2404.02123]

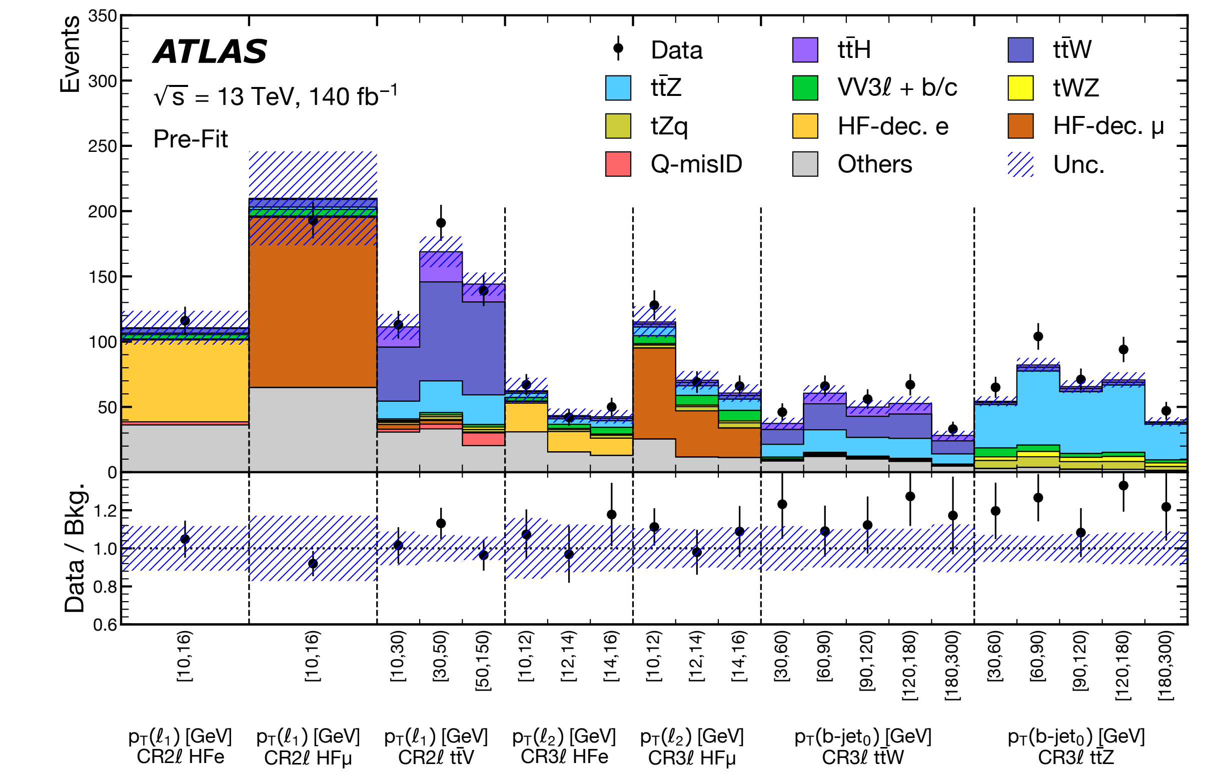


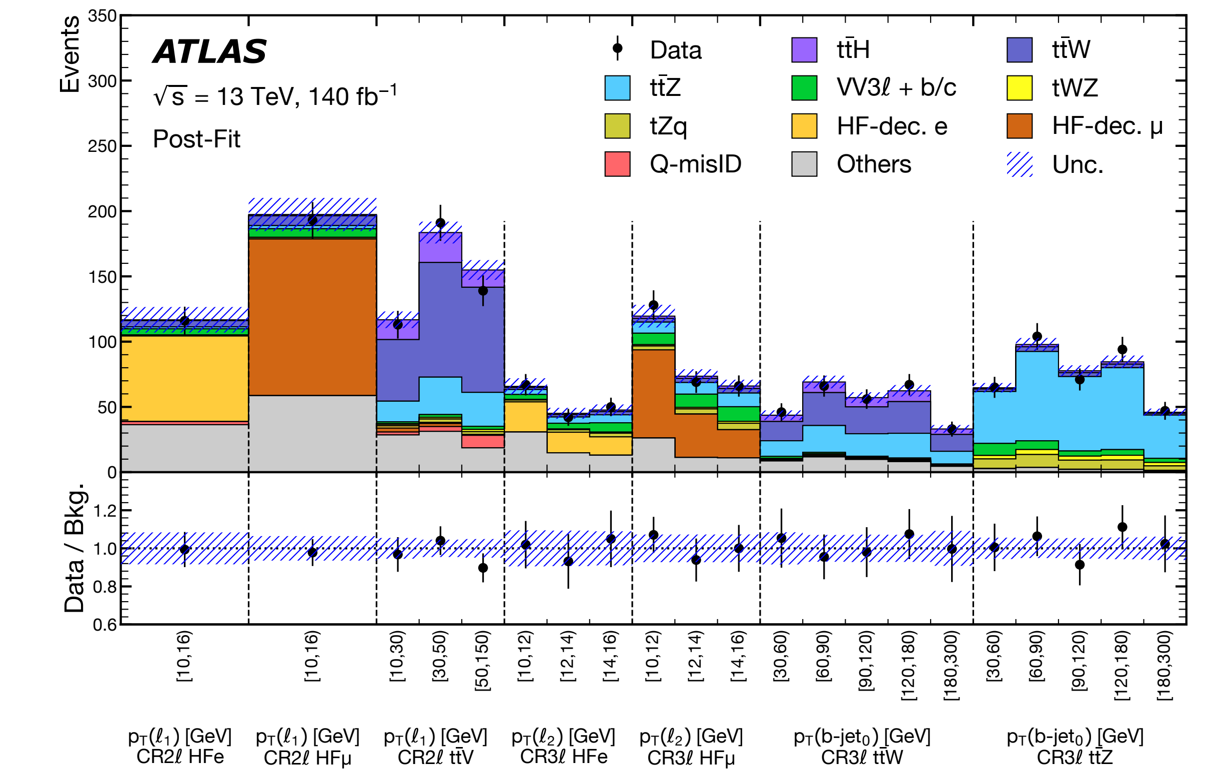
Normalisation factors – Post-Fit values

Process	tHu fit	tHc fit
HF-decay e	1.05 ± 0.24	1.02 ± 0.23
HF-decay μ	0.94 ± 0.18	0.92 ± 0.18
$VV3\ell + b/c$	1.41 ± 0.23	1.37 ± 0.24
$t\bar{t}W$	1.15 ± 0.14	1.19 ± 0.14
$t\bar{t}Z$	1.16 ± 0.11	1.17 ± 0.11

[arXiv:2404.02123]

Control Regions – Pre- and Post-Fit

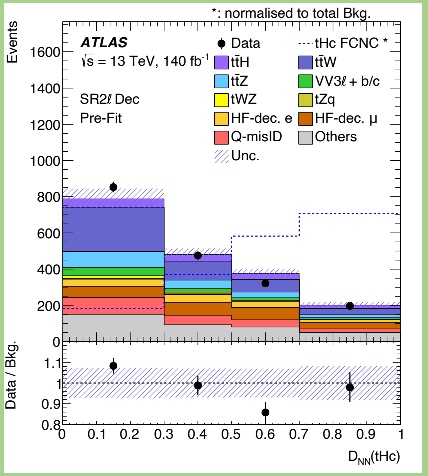


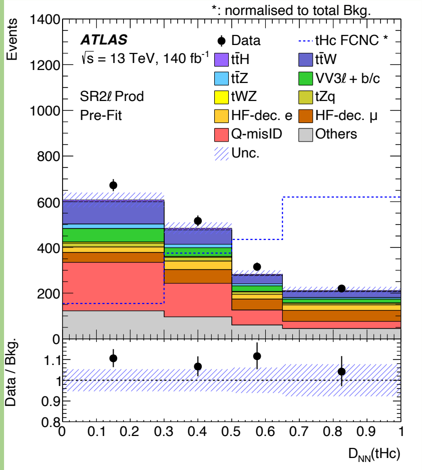


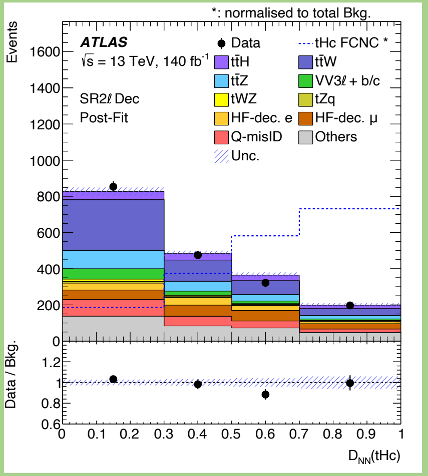
[arXiv:2404.02123]

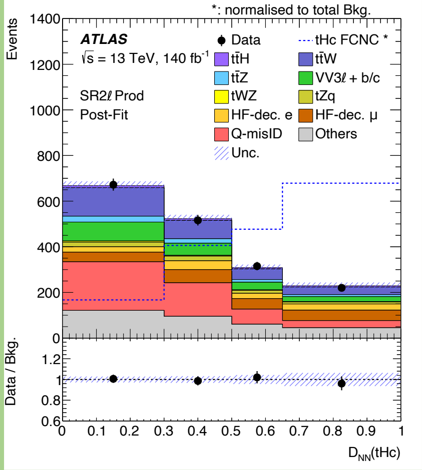
Signal regions (tHc) – Pre- and Post-Fit

$2\ell SS$









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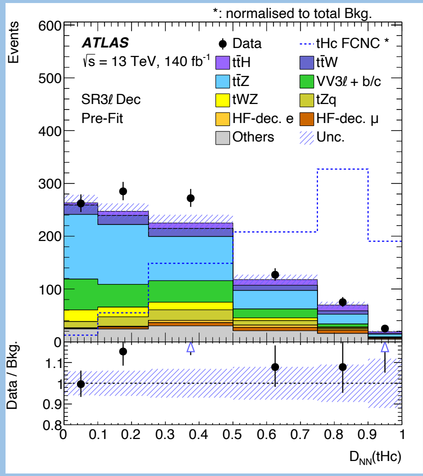
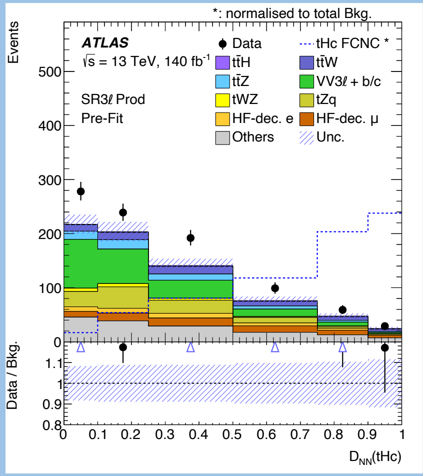
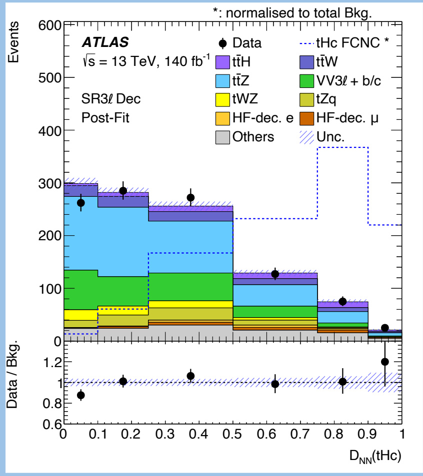
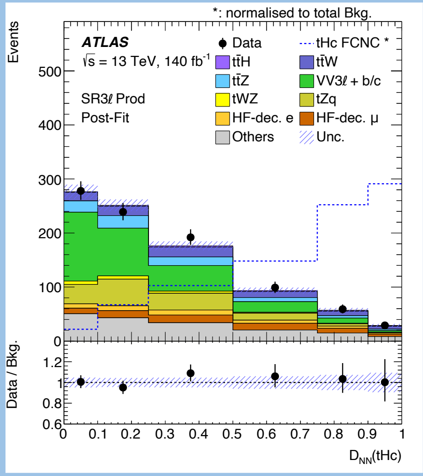




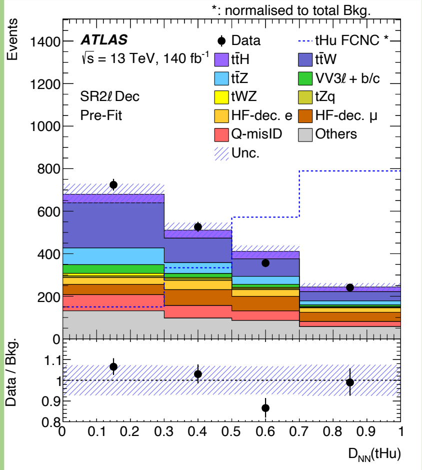


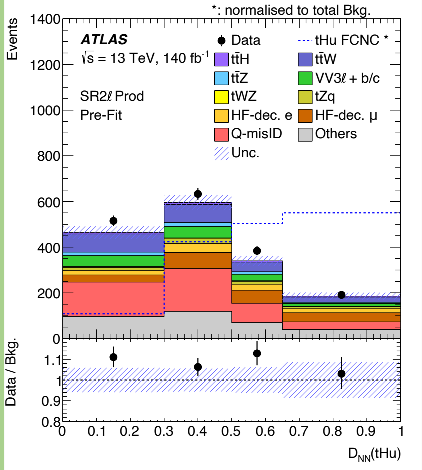


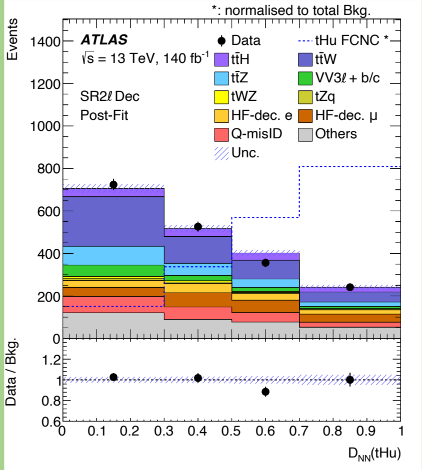
[arXiv:2404.02123]

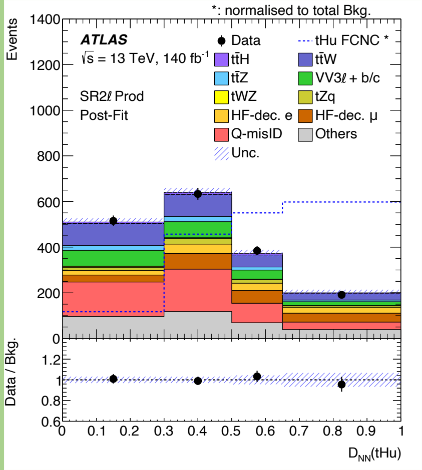
Signal regions (tHu) – Pre- and Post-Fit

$2\ell SS$









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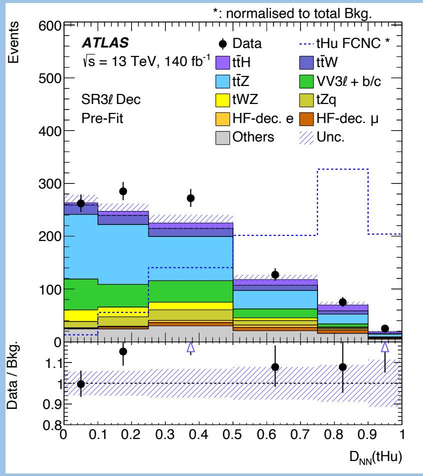
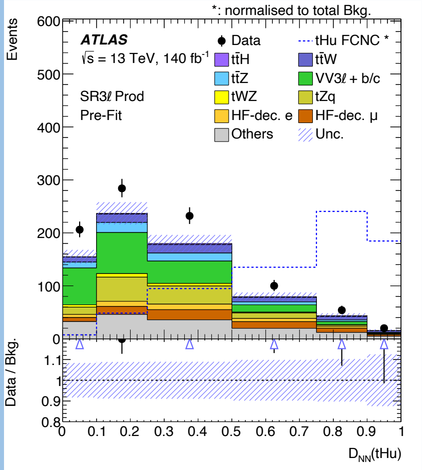
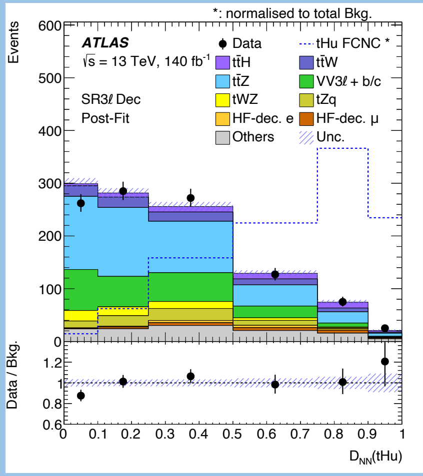
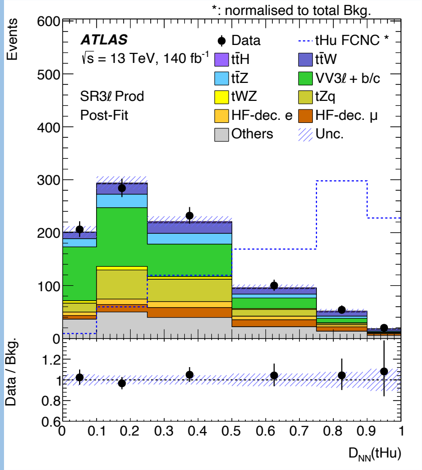




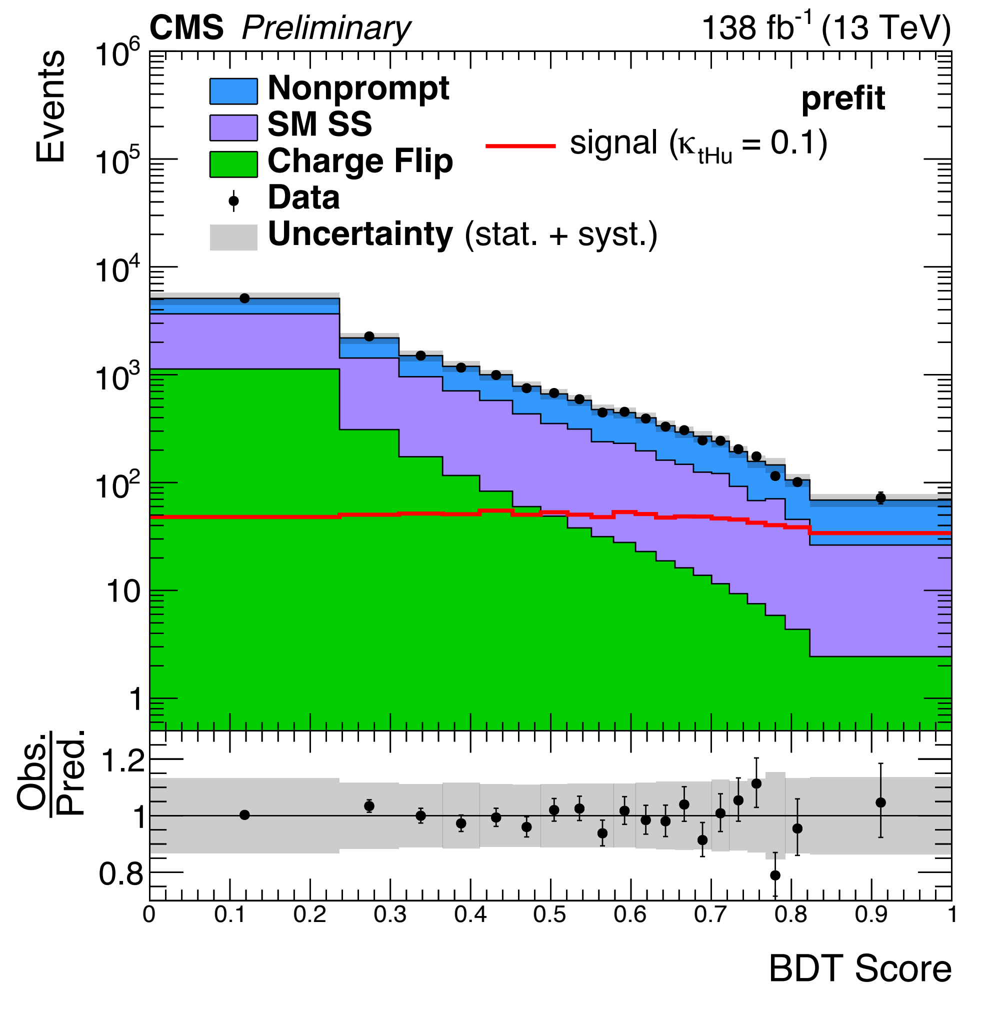


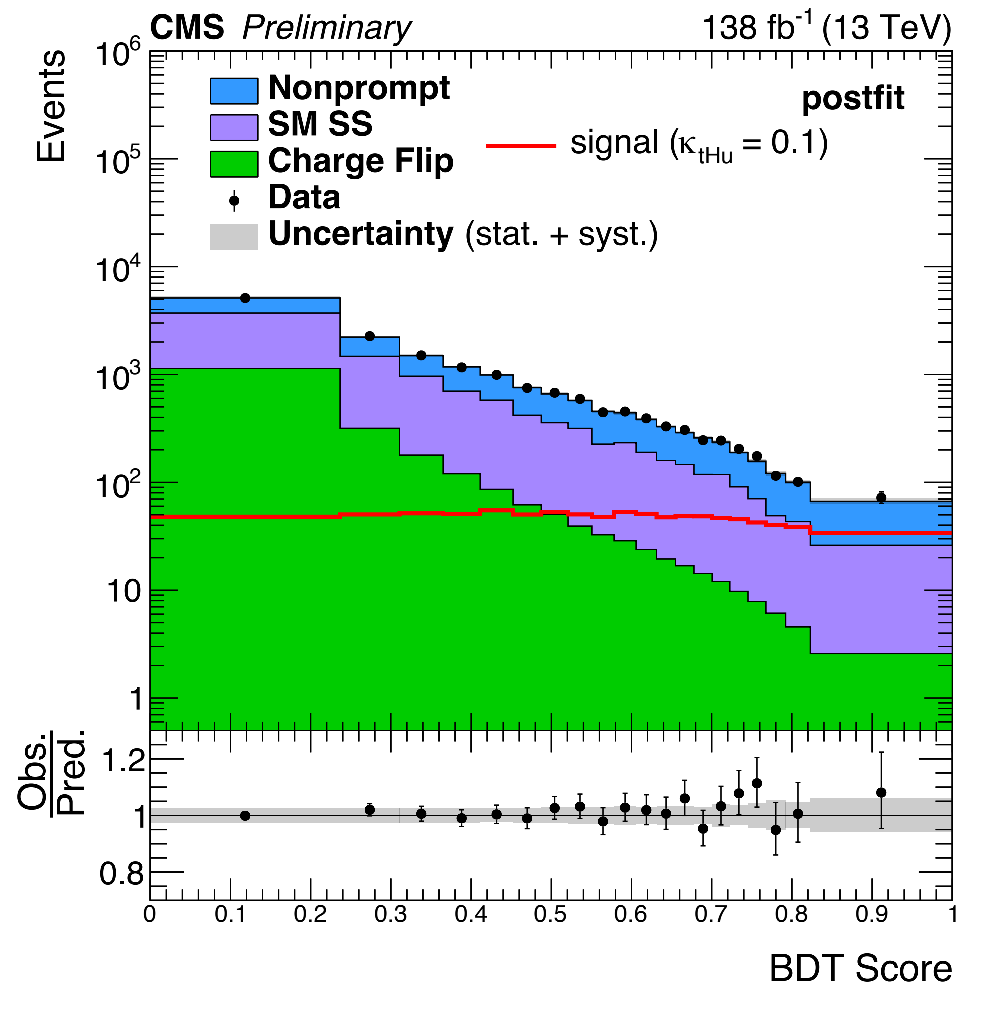


[arXiv:2404.02123]

CMS BDT (tHu) – Pre- and Post-Fit

[CMS-PAS-TOP-22-002]





CMS BDT (tHc) – Pre- and Post-Fit

[CMS-PAS-TOP-22-002]