Institut de Física d'Altes Energies

Search for heavy neutral scalars in top final states with the ATLAS detector

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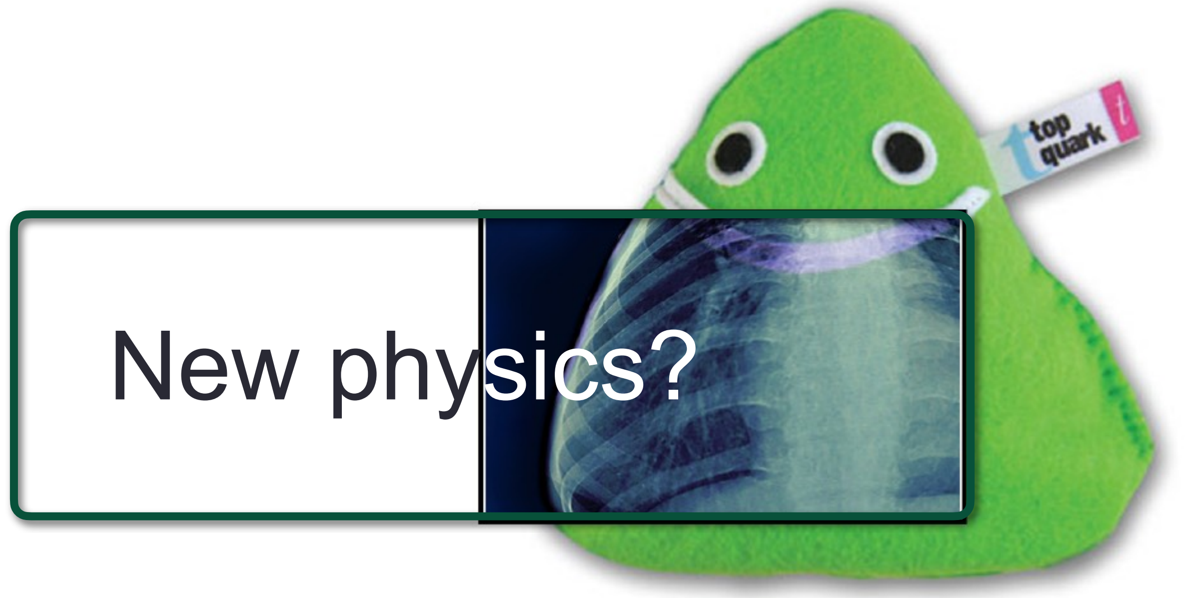
Funded by the European Union
MARIE SKŁODOWSKA-CURIE ACTIONS

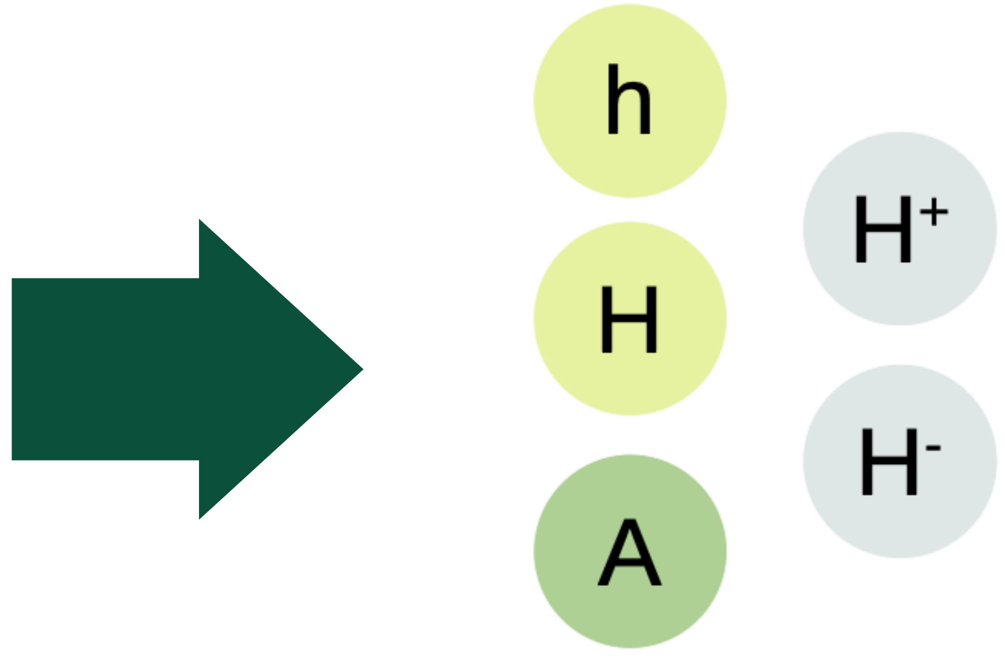
ATLAS EXPERIMENT

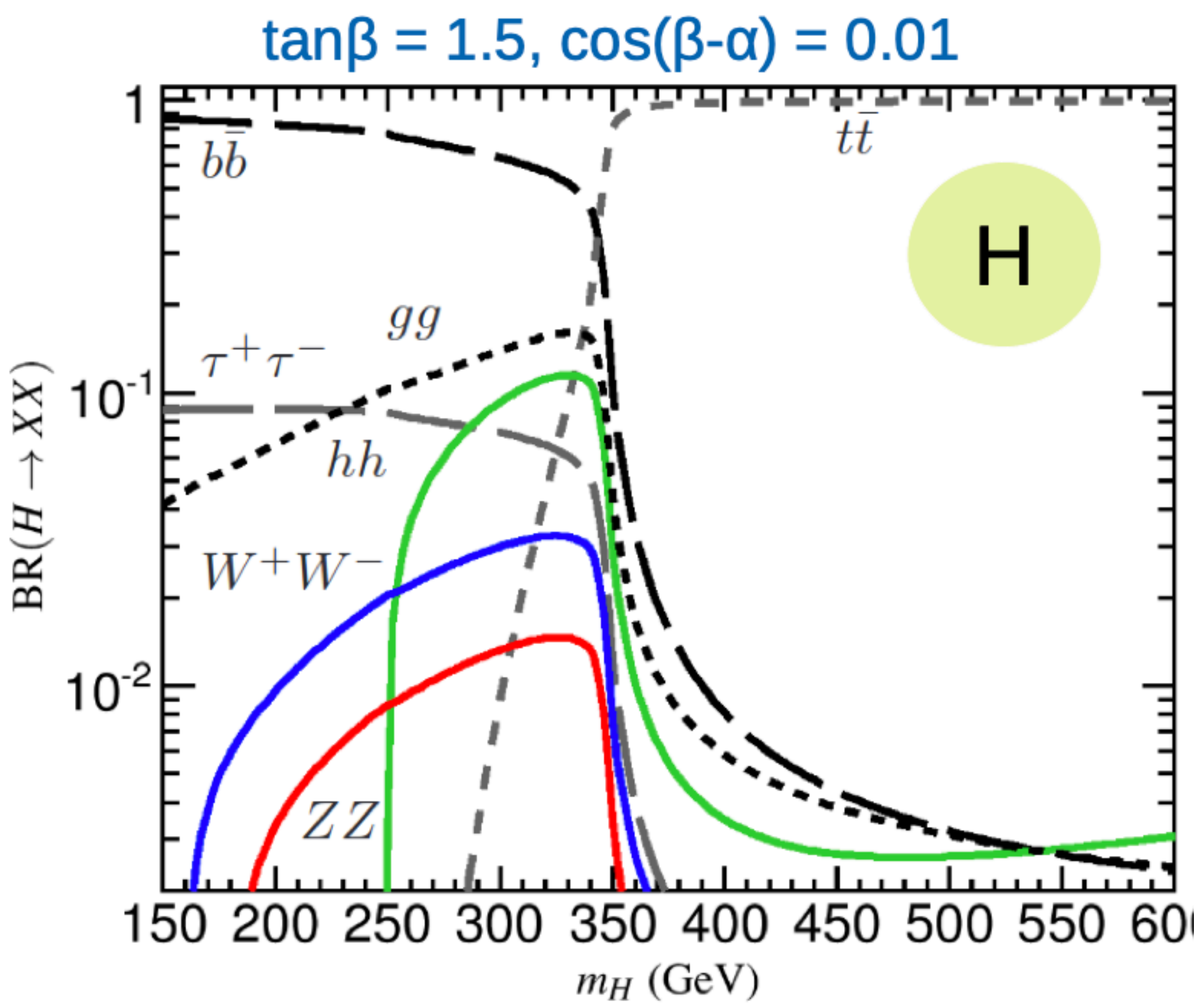
Introduction



- Solution to many issues not addressed by the SM involves an extended Higgs sector
- Two-Higgs-Doublet-Models (2HDMs): required by many BSM theories
  - an additional Higgs doublet

$$\Phi_a = \begin{pmatrix} \phi_a^+ \\ \frac{v_a + \rho_a + i\eta_a}{\sqrt{2}} \end{pmatrix}, \qquad a = 1, 2$$

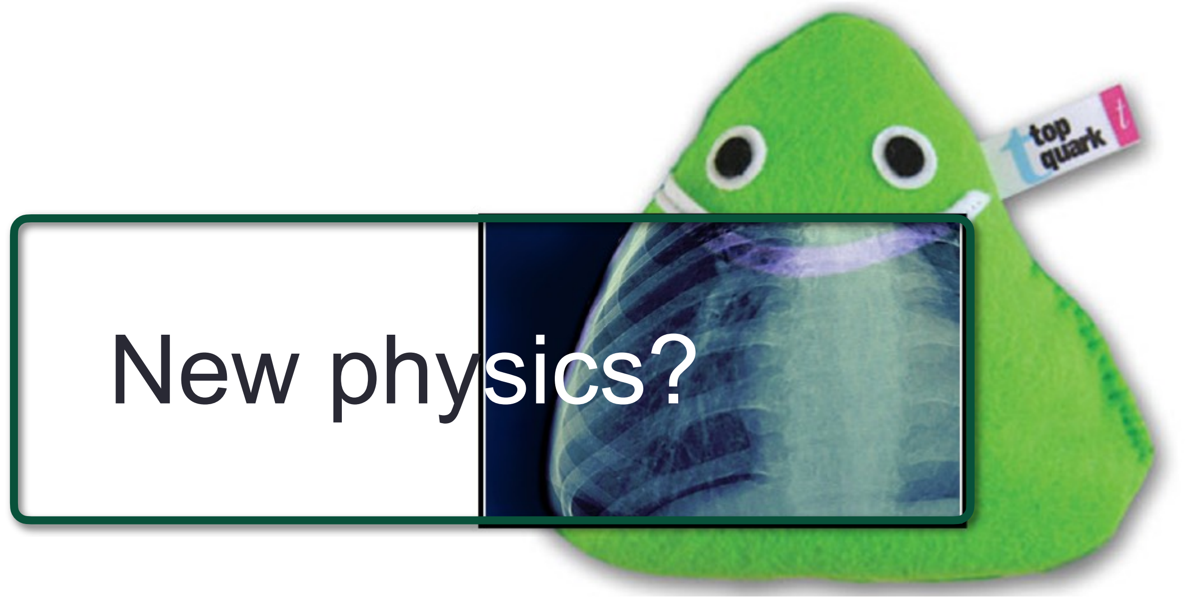


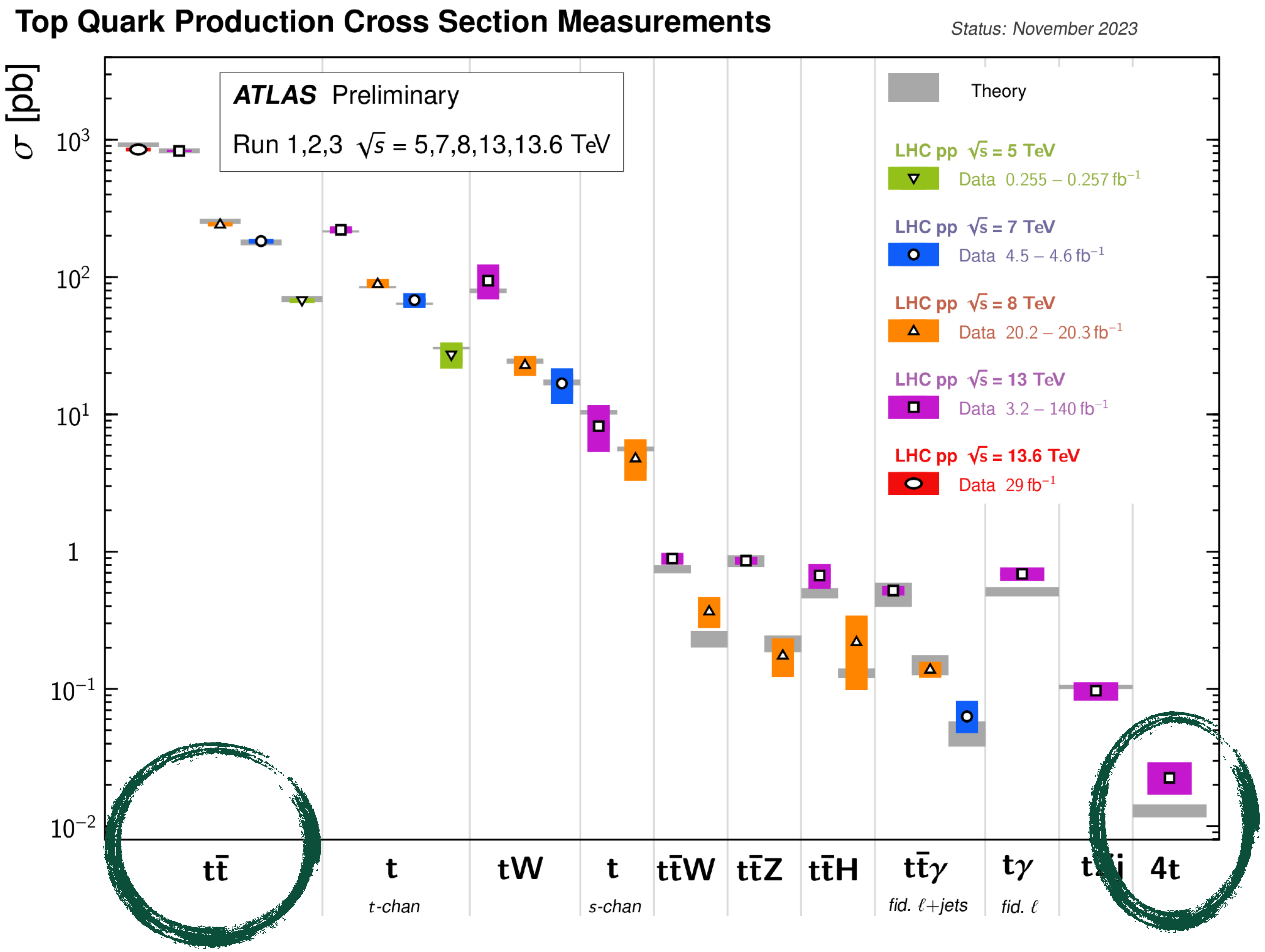


  - parameters: masses of the additional particles, $\tan\beta = v_2/v_1$, α (mixing angle between h and H)
    - alignment limit: $\sin(\beta - \alpha) \sim 1$, where the properties of h aligns with the measured Higgs
- Additional scalars preferably couple to top quarks once beyond the $t\bar{t}$ mass threshold

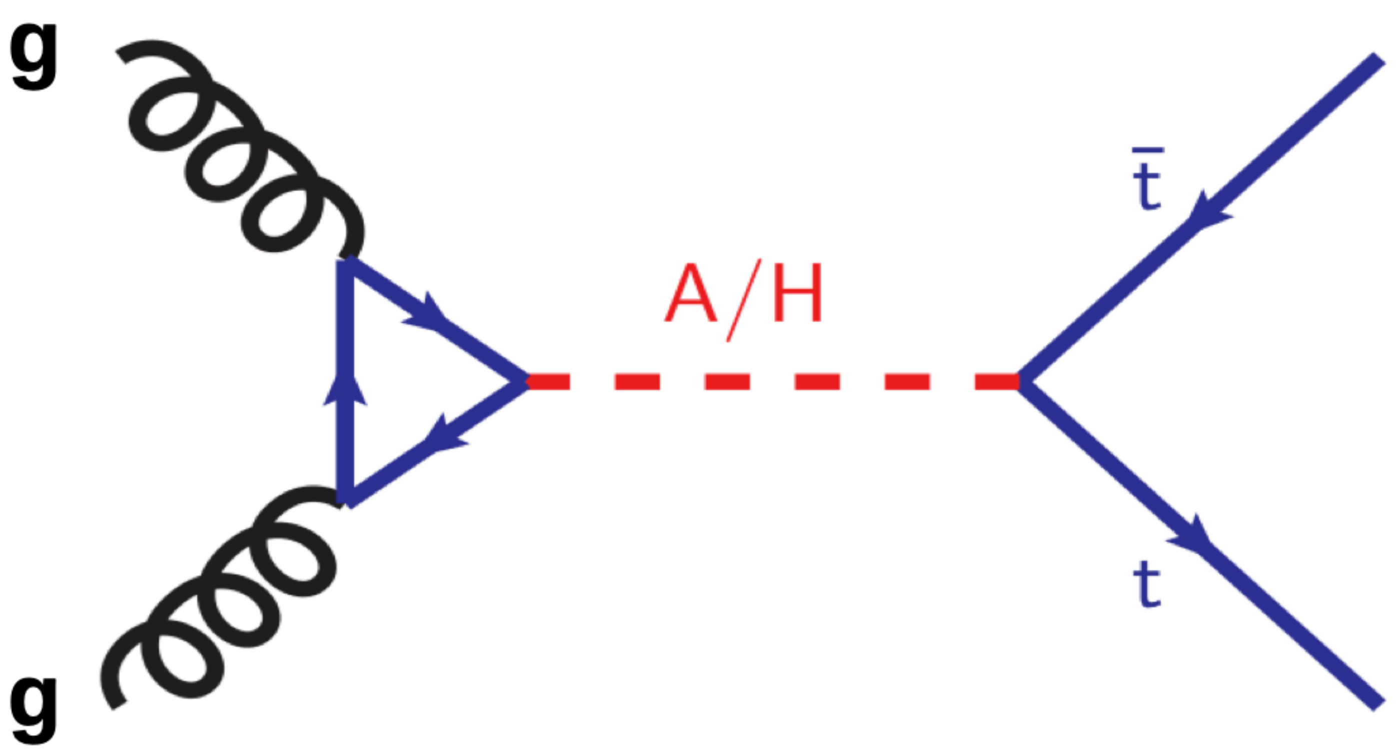
Introduction

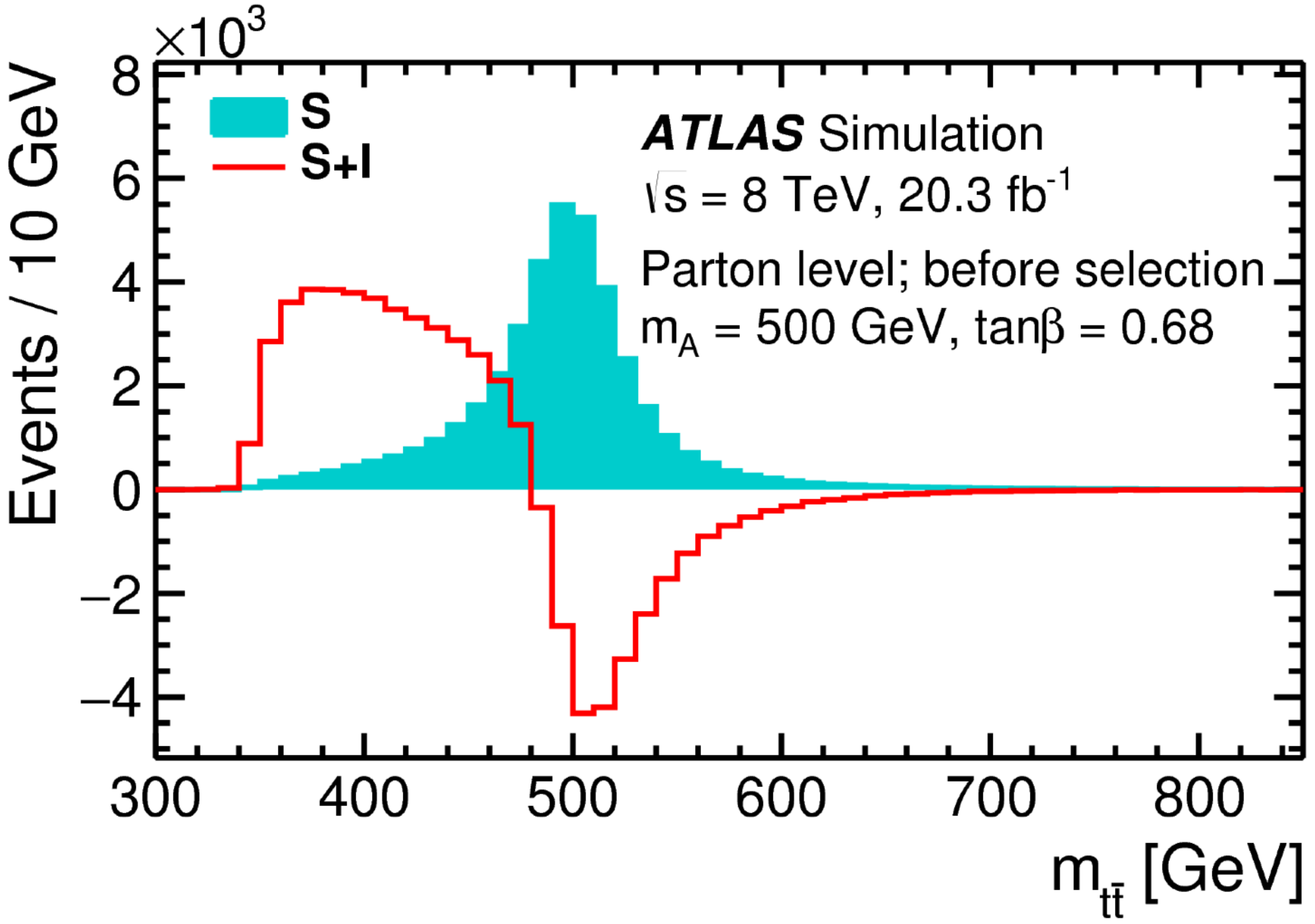
- Accessing small processes ~10 fb
- **Two recent results:**
  - $A/H \to t\bar{t}$: arXiv:2404.18986
  - $t\bar{t}H/A \to t\bar{t}t\bar{t}$: ATLAS-CONF-2024-002





Why different channels?

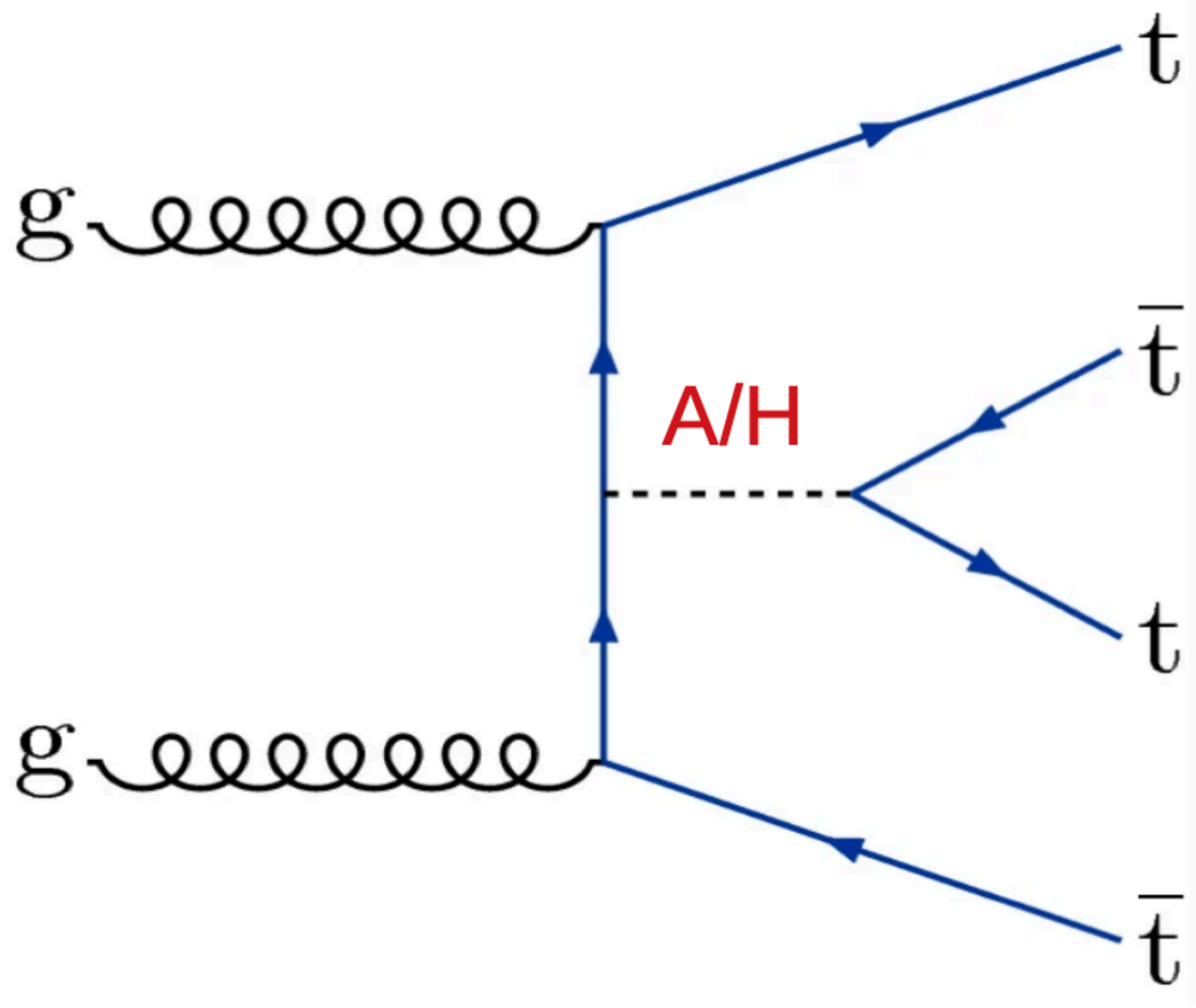




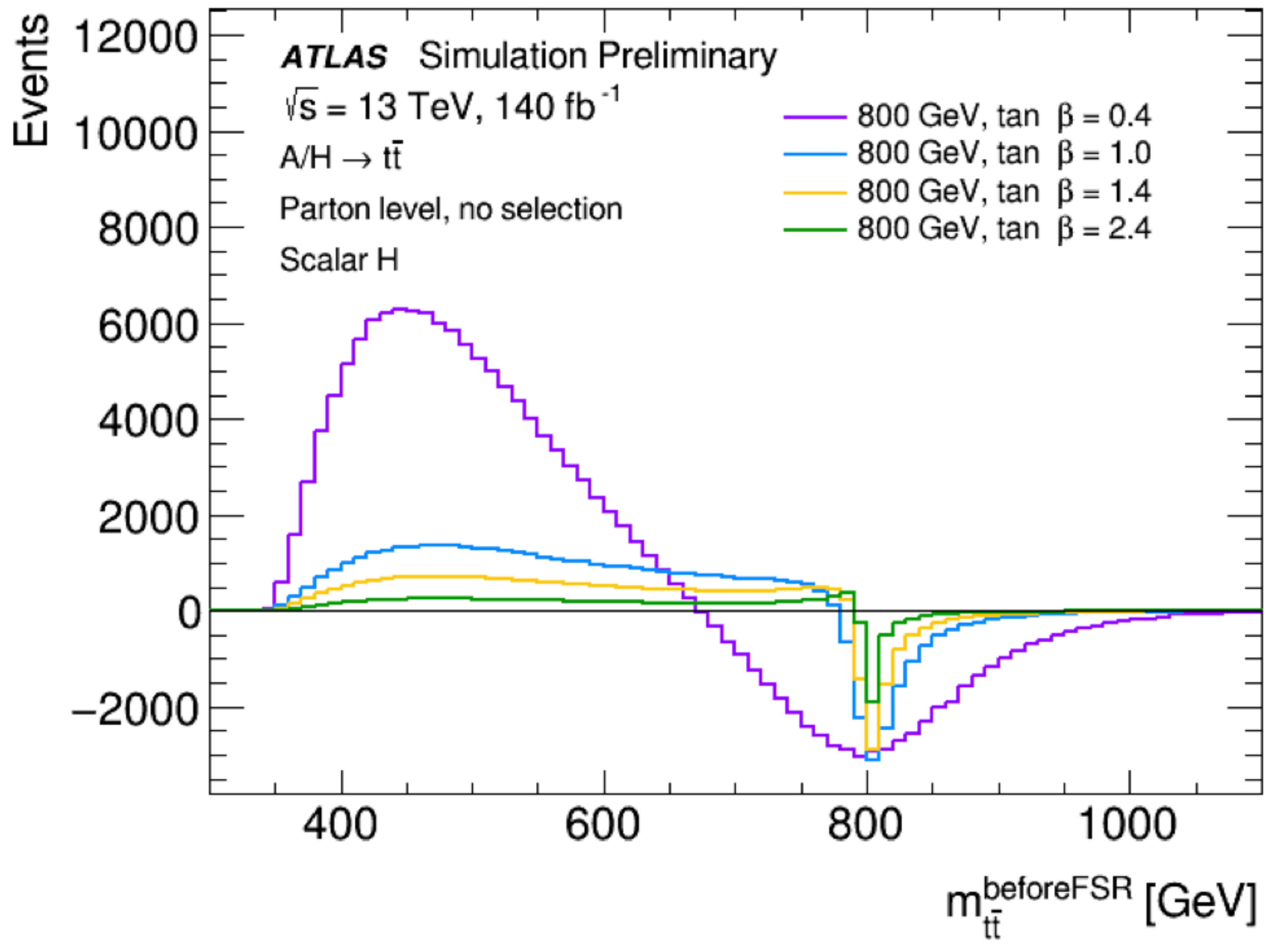
- Completeness
- Different phenomenology
  - $A/H \rightarrow t\bar{t}$:

    strong interference with SM $t\bar{t}$ leading to lead-dip like signal shape
  - $t\bar{t}H/A \rightarrow t\bar{t}t\bar{t}$:

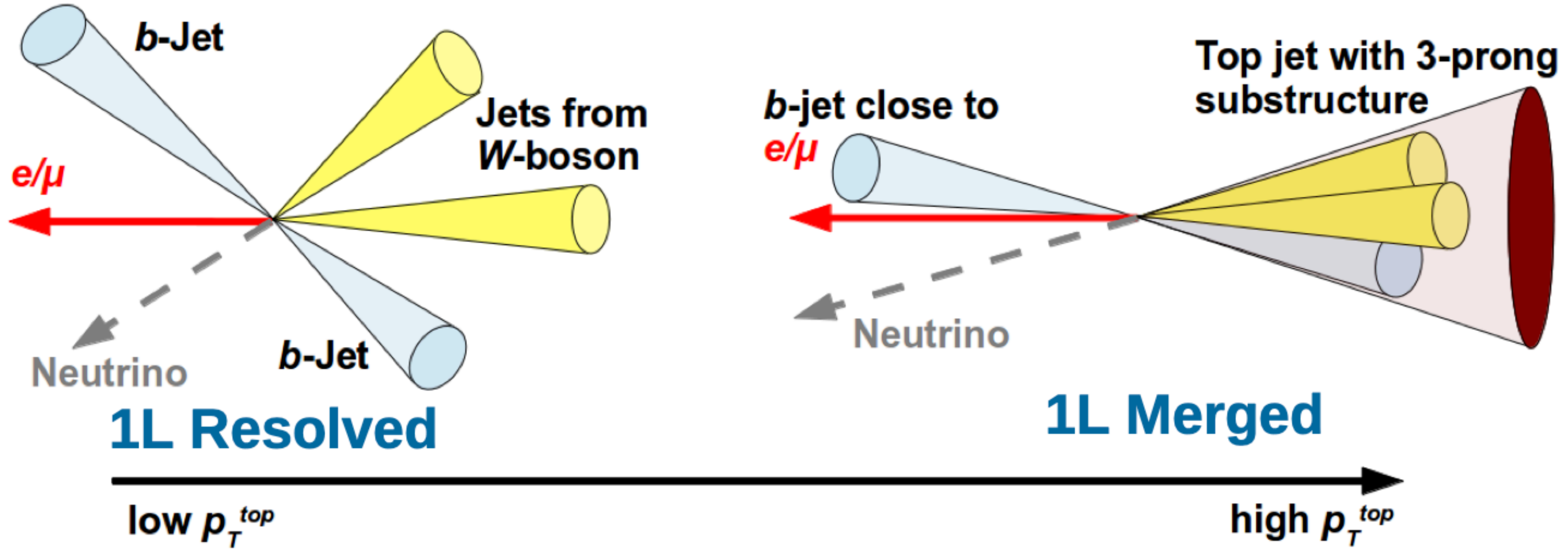
    tree level production - less susceptible to interference effect (%-level)
- Massive $t\bar{t}t\bar{t}$ final state reduces the background

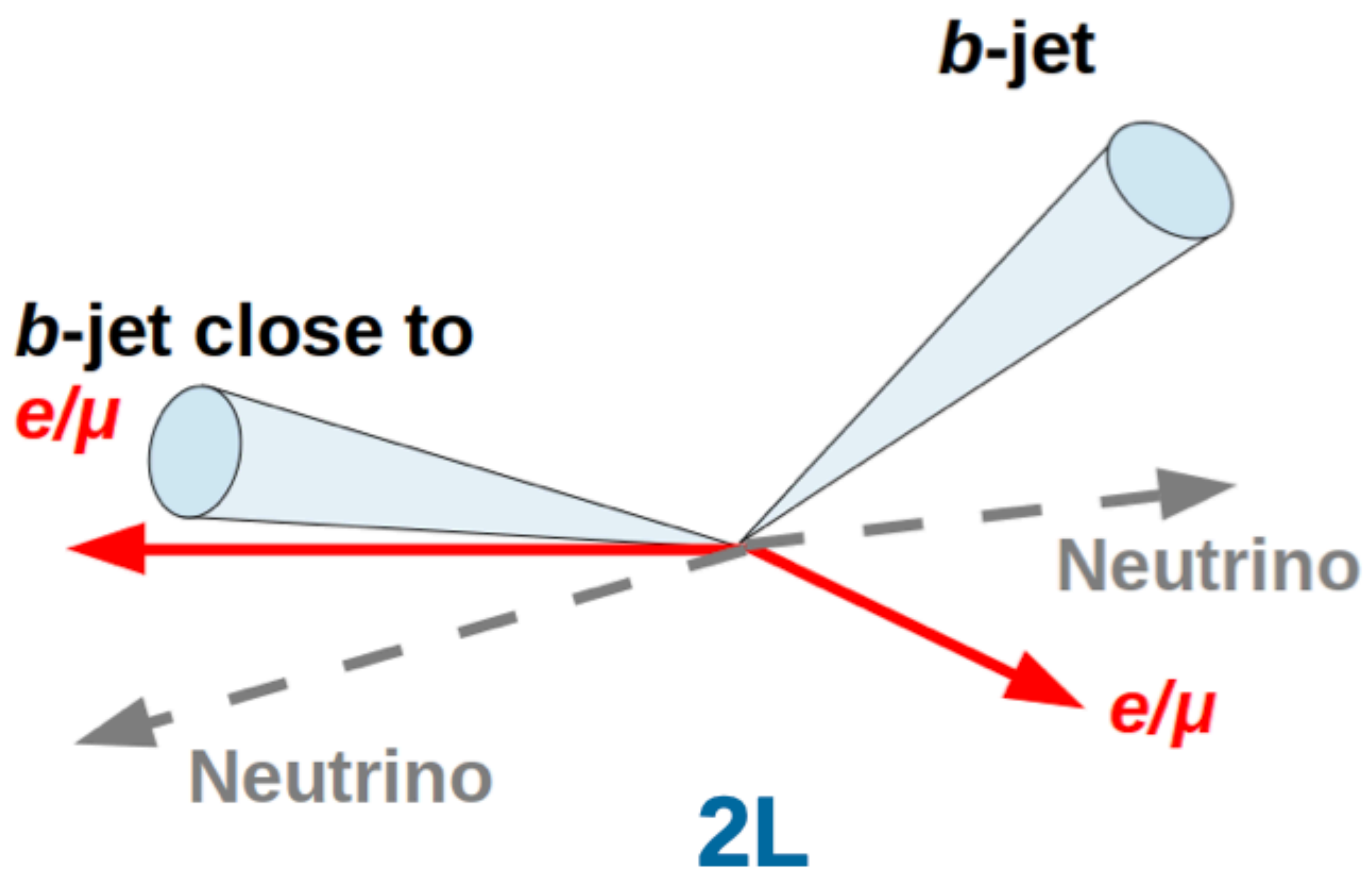


Search for $A/H \to t\bar{t}$



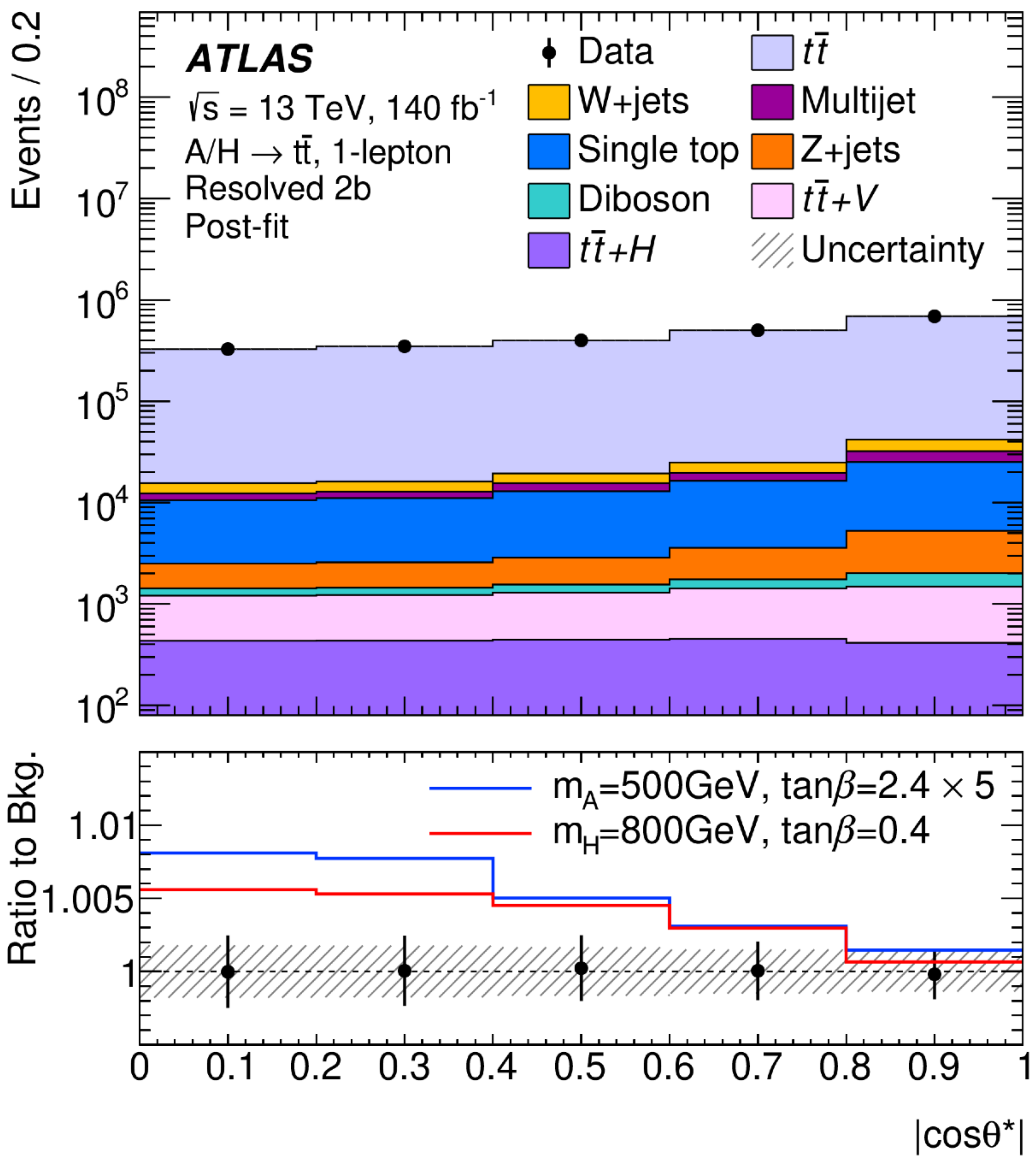
- Signal+interference modelled using MadGraph at LO + NLO k-factor
  - strong dependence on model parameters
- Using events with 1 or exactly 2 opposite-sign e/μ
- 1L channel: reconstruct $m_{t\bar{t}}$
  - resolved: χ^2 reconstruction
  - merged: large variable R jets ($R_{\max}$=1.5) optimised for intermediate top boosts ($m_{t\bar{t}}$ ~ 1 TeV)
- 2L channel: use m_{llbb} as proxy for the $m_{t\bar{t}}$

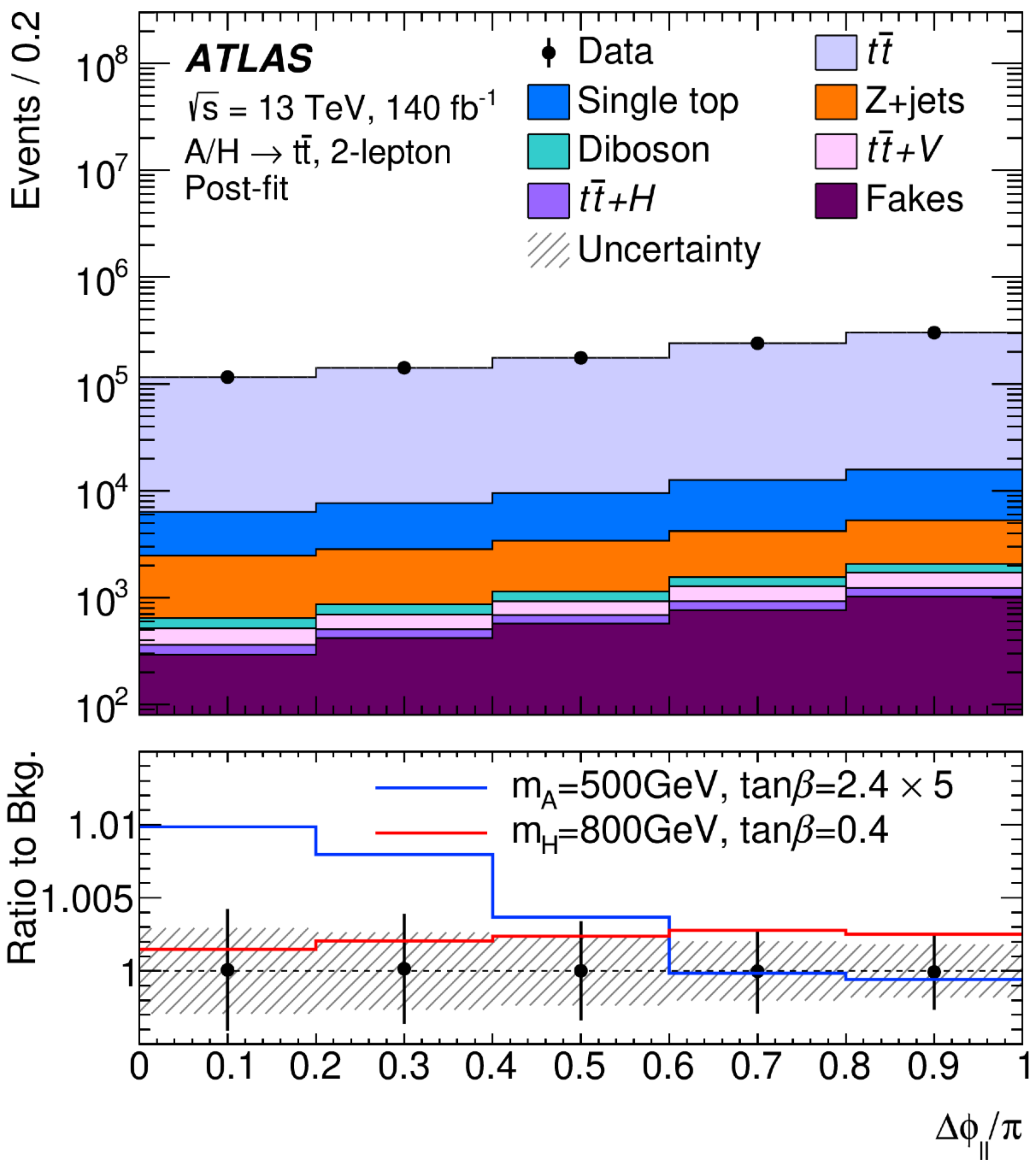


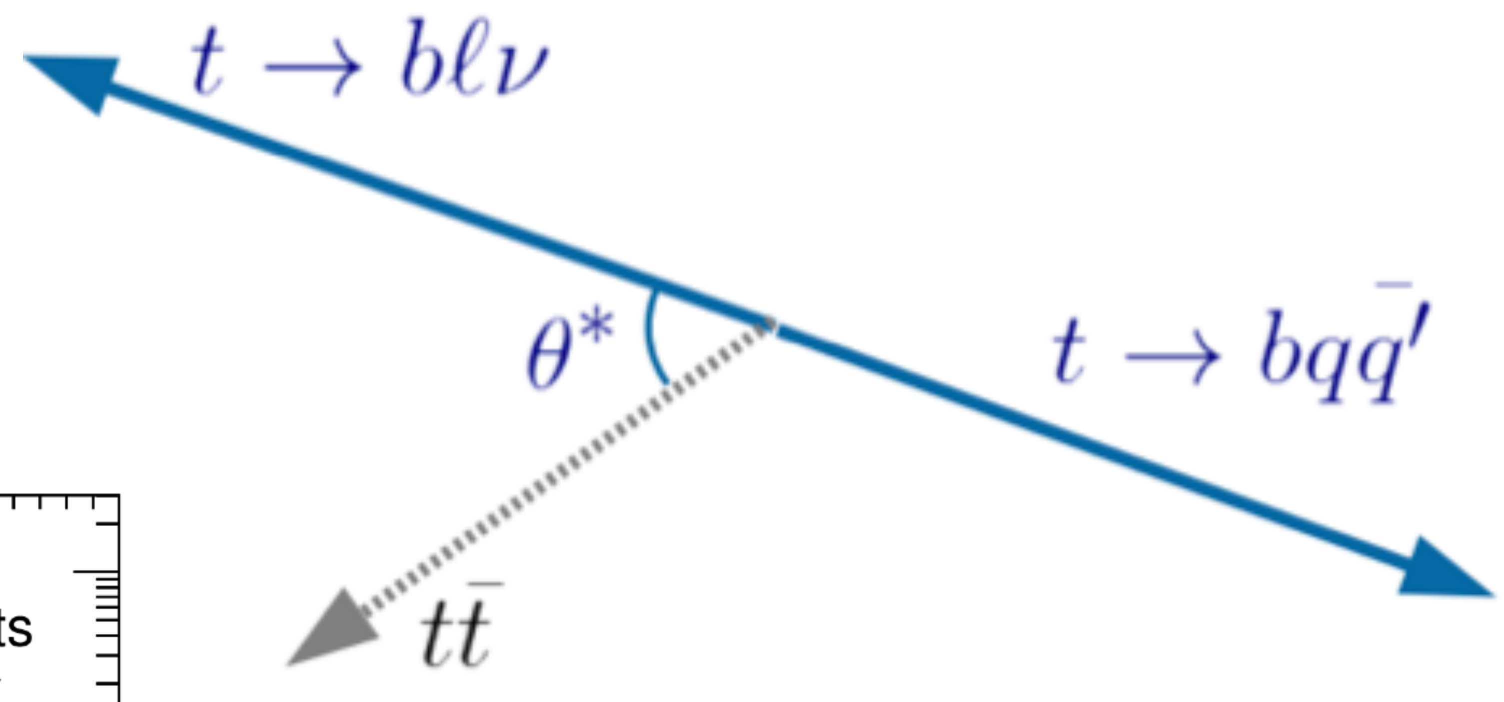


Search for $A/H \to t\bar{t}$

- Exploiting spin information: 1L $\cos\theta^*$; 2L $\Delta\phi_{ll}$
  - Improves sensitivity by ~20%
- Defines 16 orthogonal signal regions





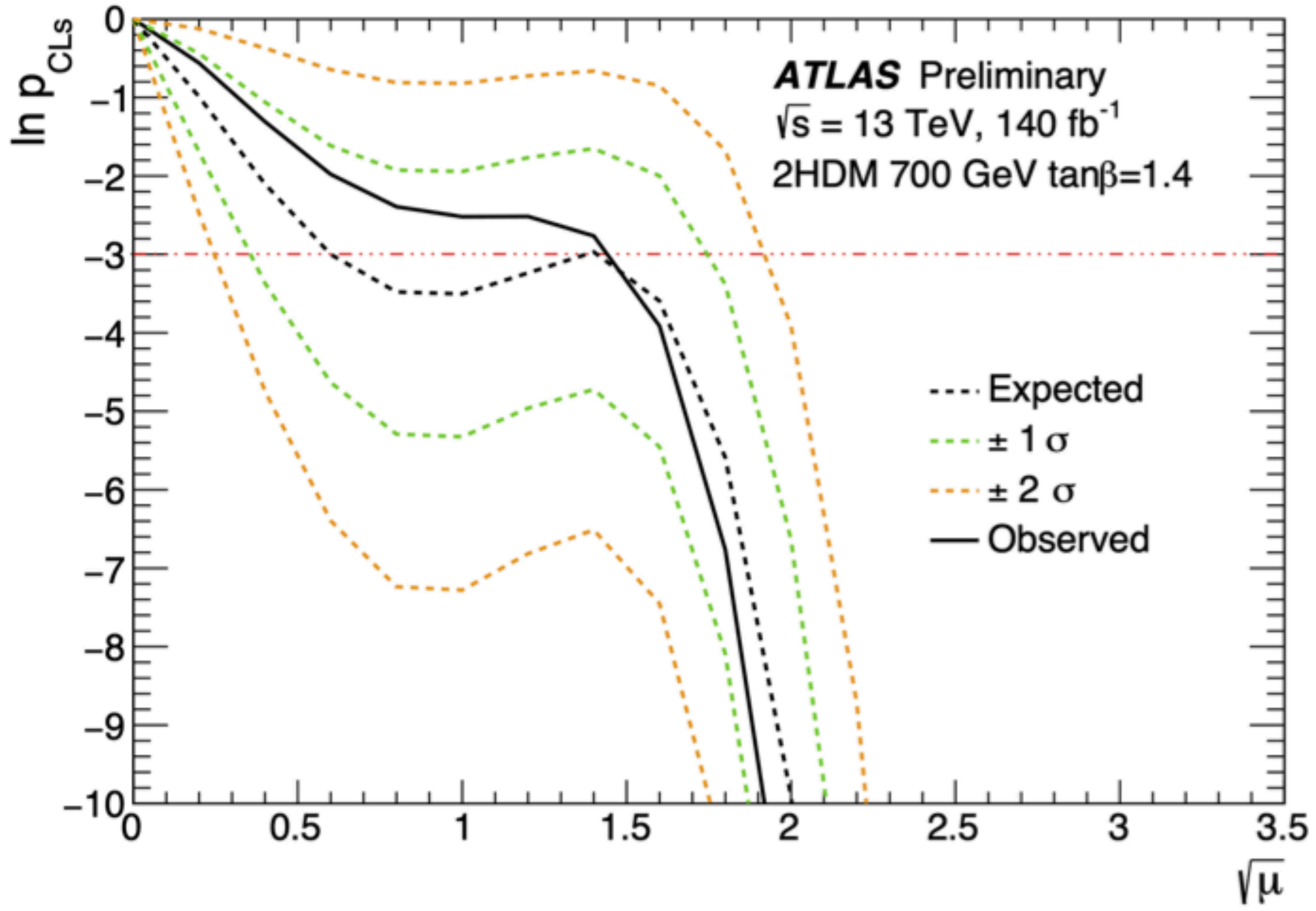


Search for $A/H \to t\bar{t}$

- Proper statistical treatment of the interference term

  $$\mu \cdot S + \sqrt{\mu} \cdot I + B = (\mu - \sqrt{\mu}) \cdot S + \sqrt{\mu} \cdot (S + I) + B$$

  - requires going beyond the common statistical approach to handle the issues due to the √μ term



- Two stages
  - The search stage: test the agreement between data and S+I+B hypotheses for different signals

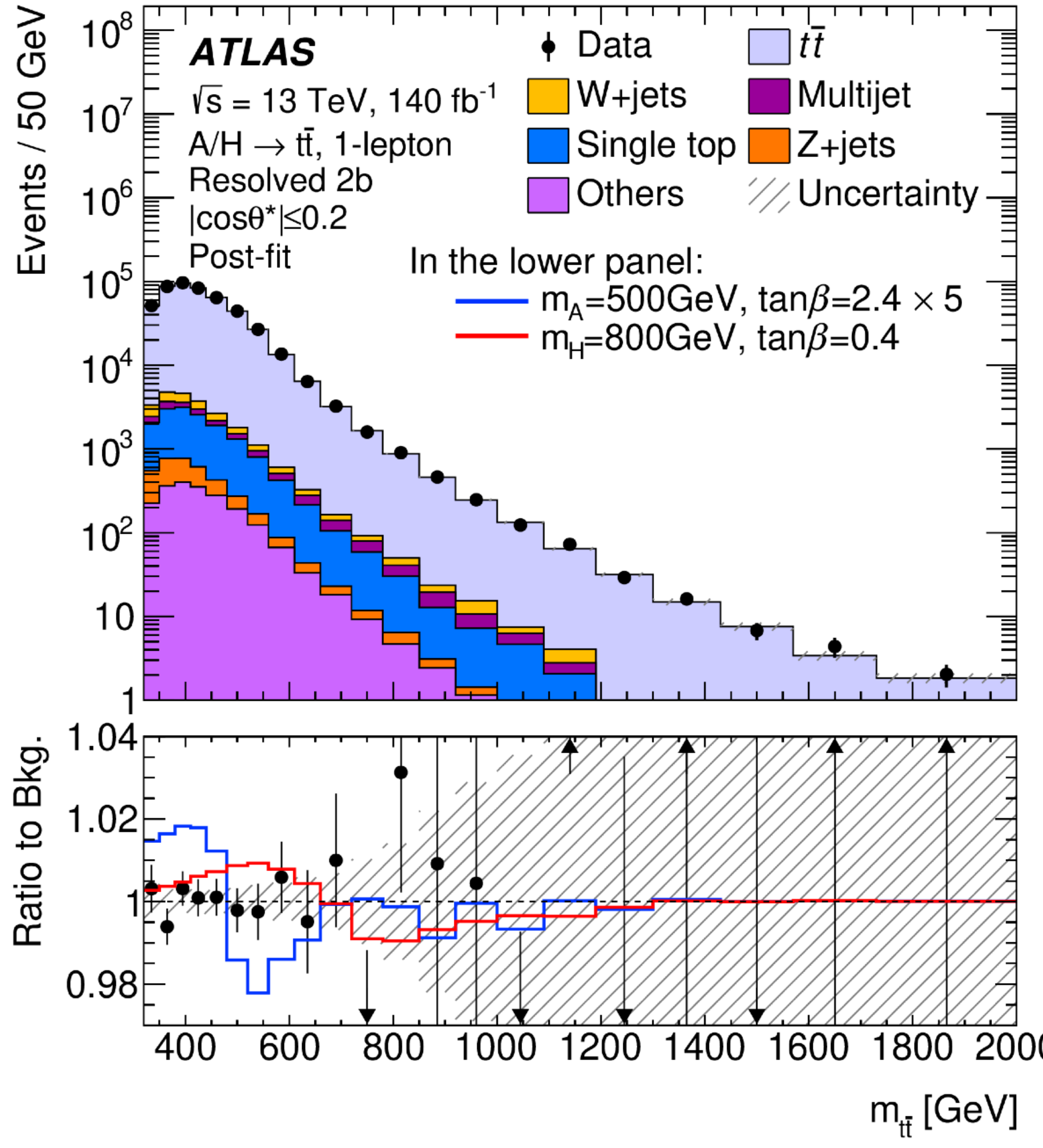
    $$q_0 = -2\ln\frac{\mathcal{L}(0, \hat{\hat{\theta}}_0)}{\mathcal{L}(\hat{\sqrt{\mu}}, \hat{\theta}_{\hat{\sqrt{\mu}}})}$$

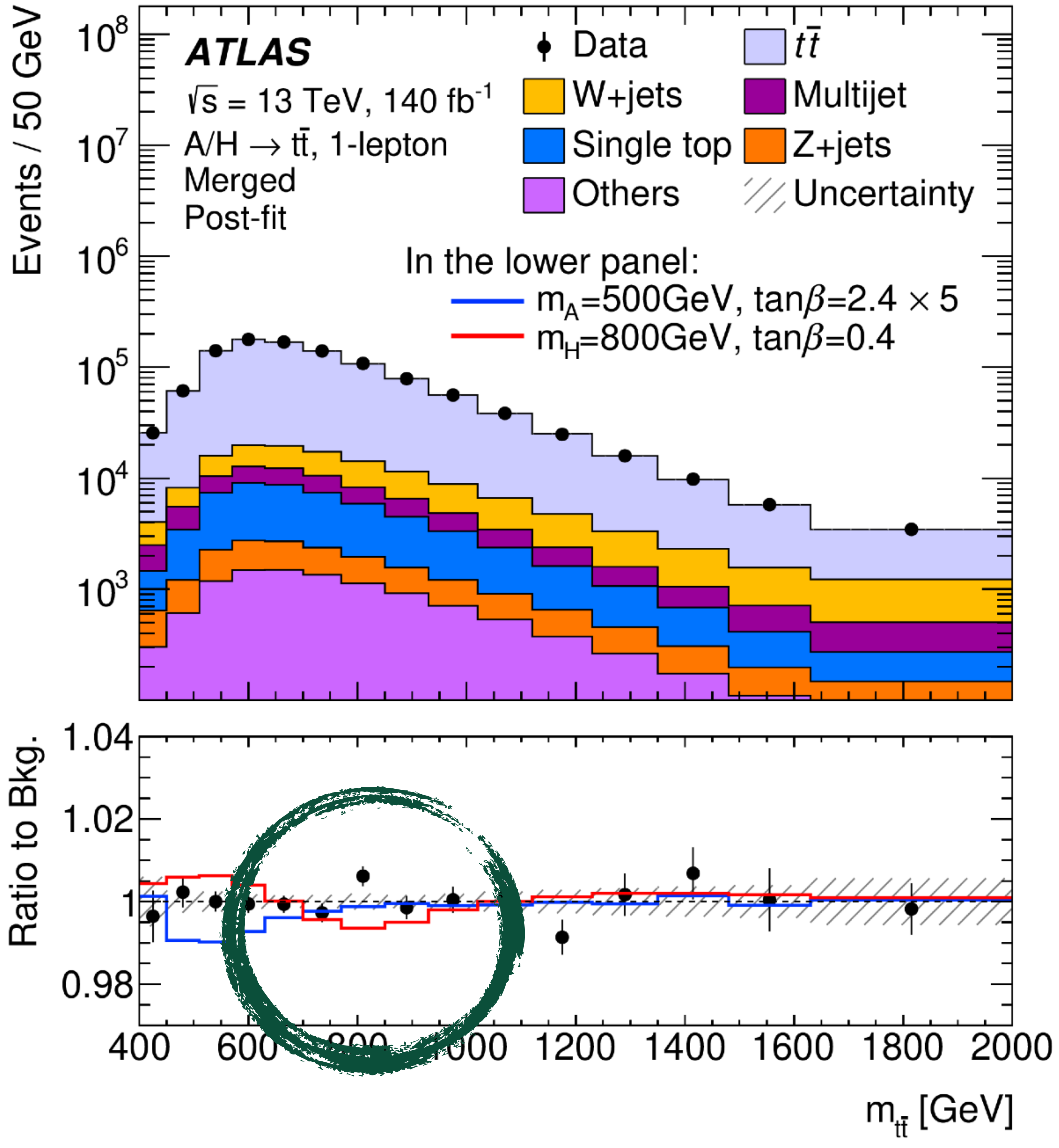
  - The exclusion stage: Test (dis)agreement of data with specific interference pattern of tested signal hypothesis

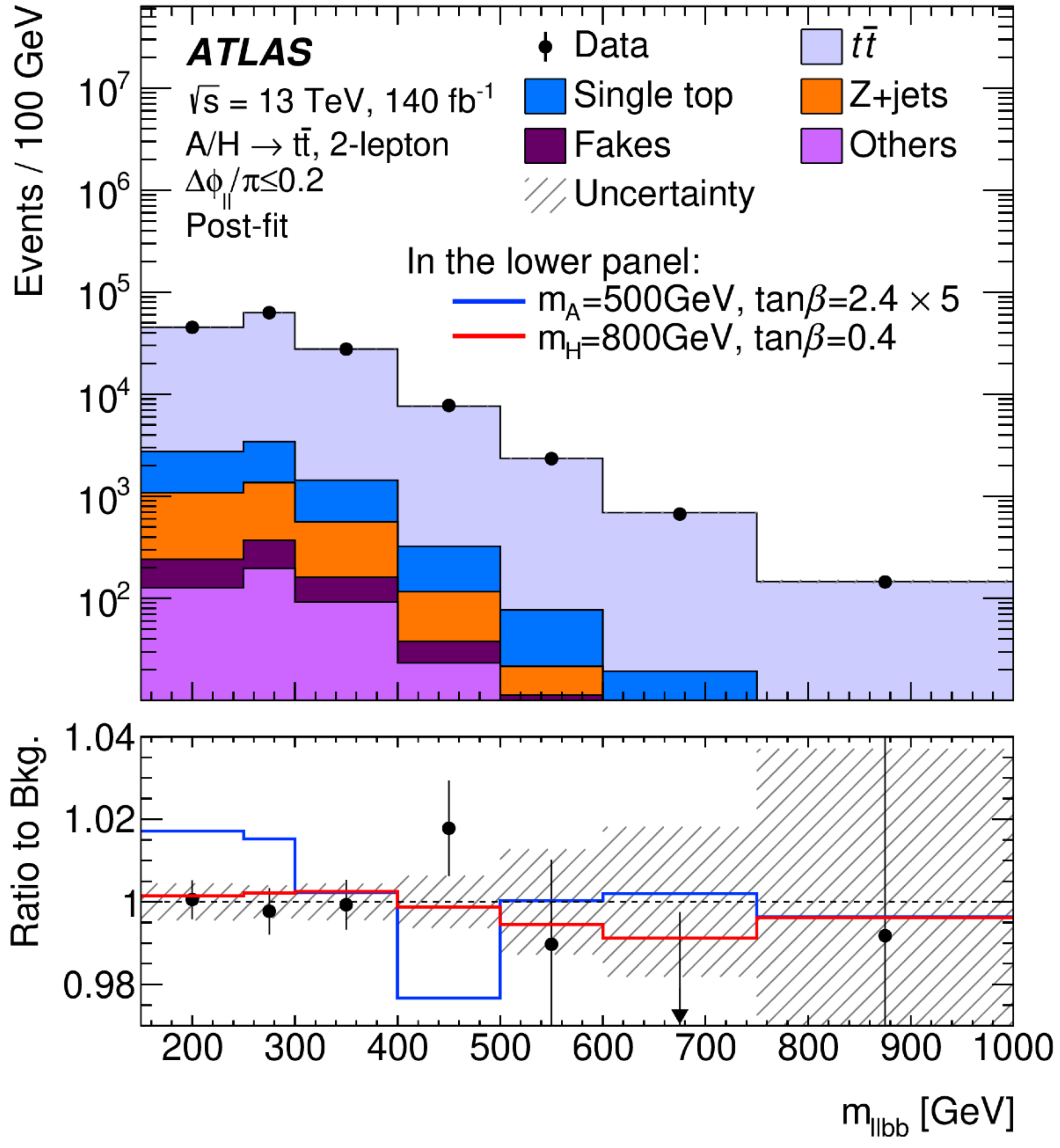
    $$q_{1,0} = -2\ln\frac{\mathcal{L}(1, \hat{\hat{\theta}}_1)}{\mathcal{L}(0, \hat{\hat{\theta}}_0)}$$

Search for $A/H \to t\bar{t}$

- Search stage: tested a range of S+I+B hypotheses with masses [400, 1400] GeV and width of [1, 40]%
- most significant deviation from SM-only (2.3σ local): 800 GeV, width of 10%, fitted $\sqrt{\mu}$=4.0
  - driven by the narrow upward fluctuation at 800 GeV in the merged region

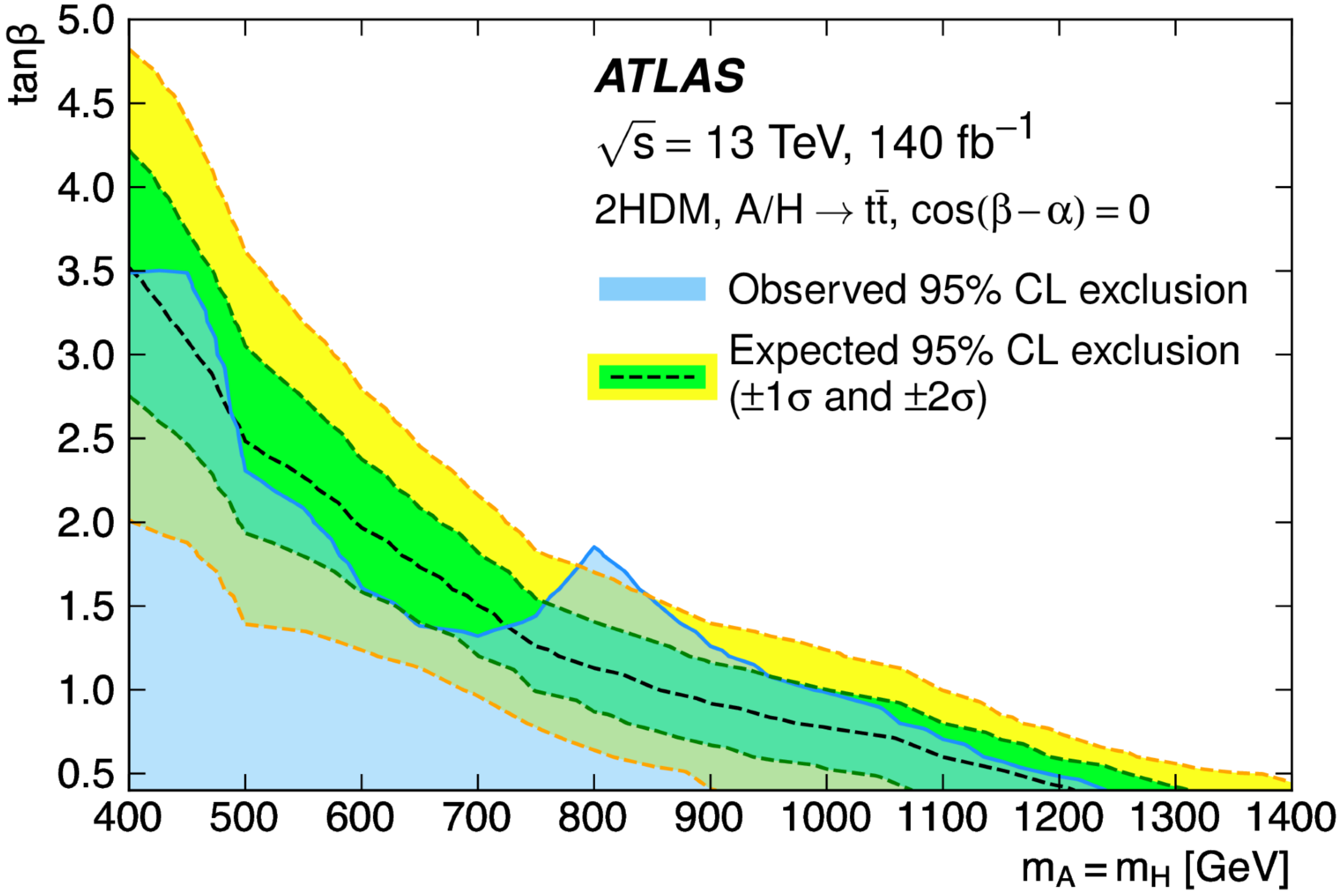


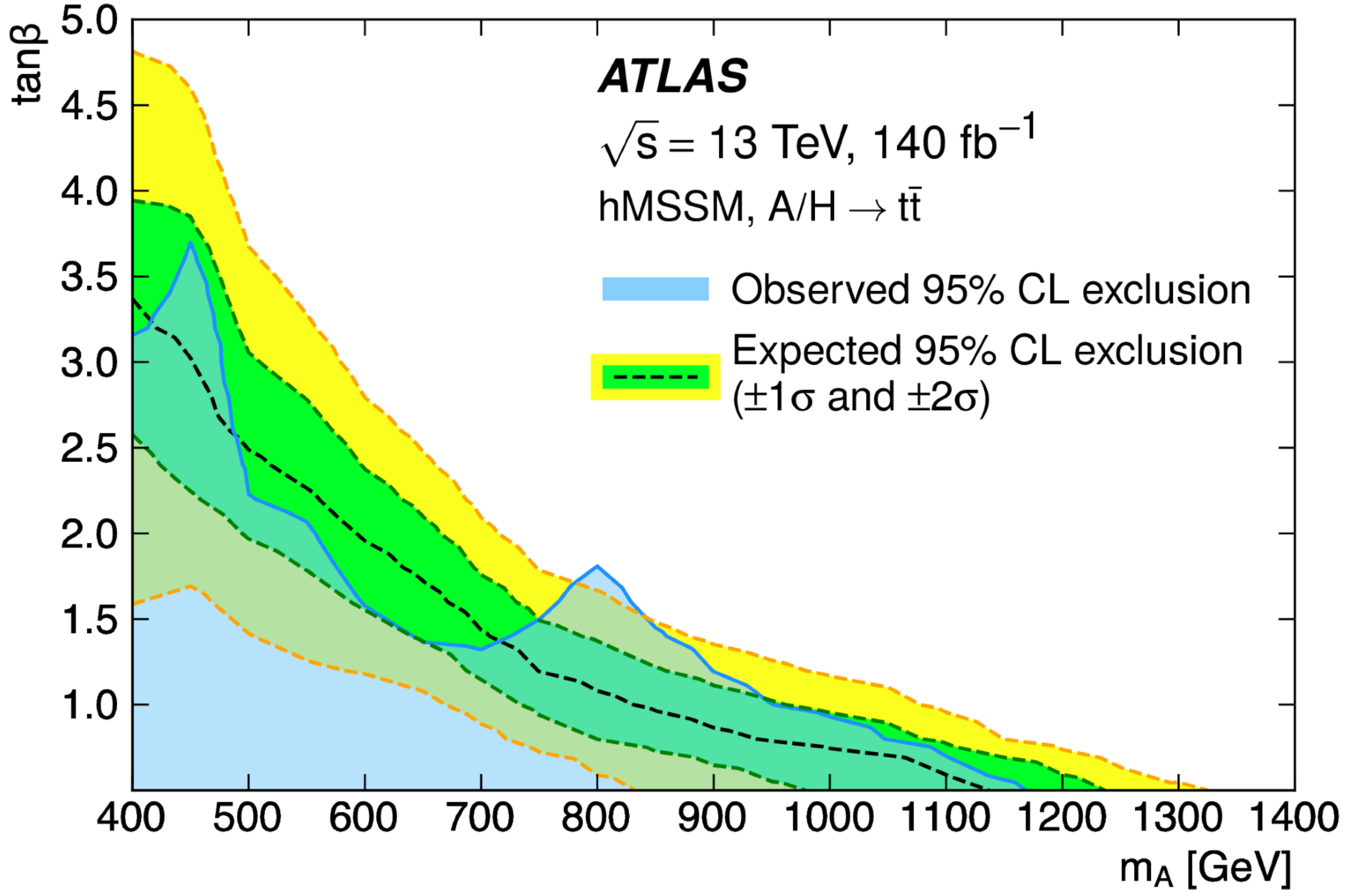




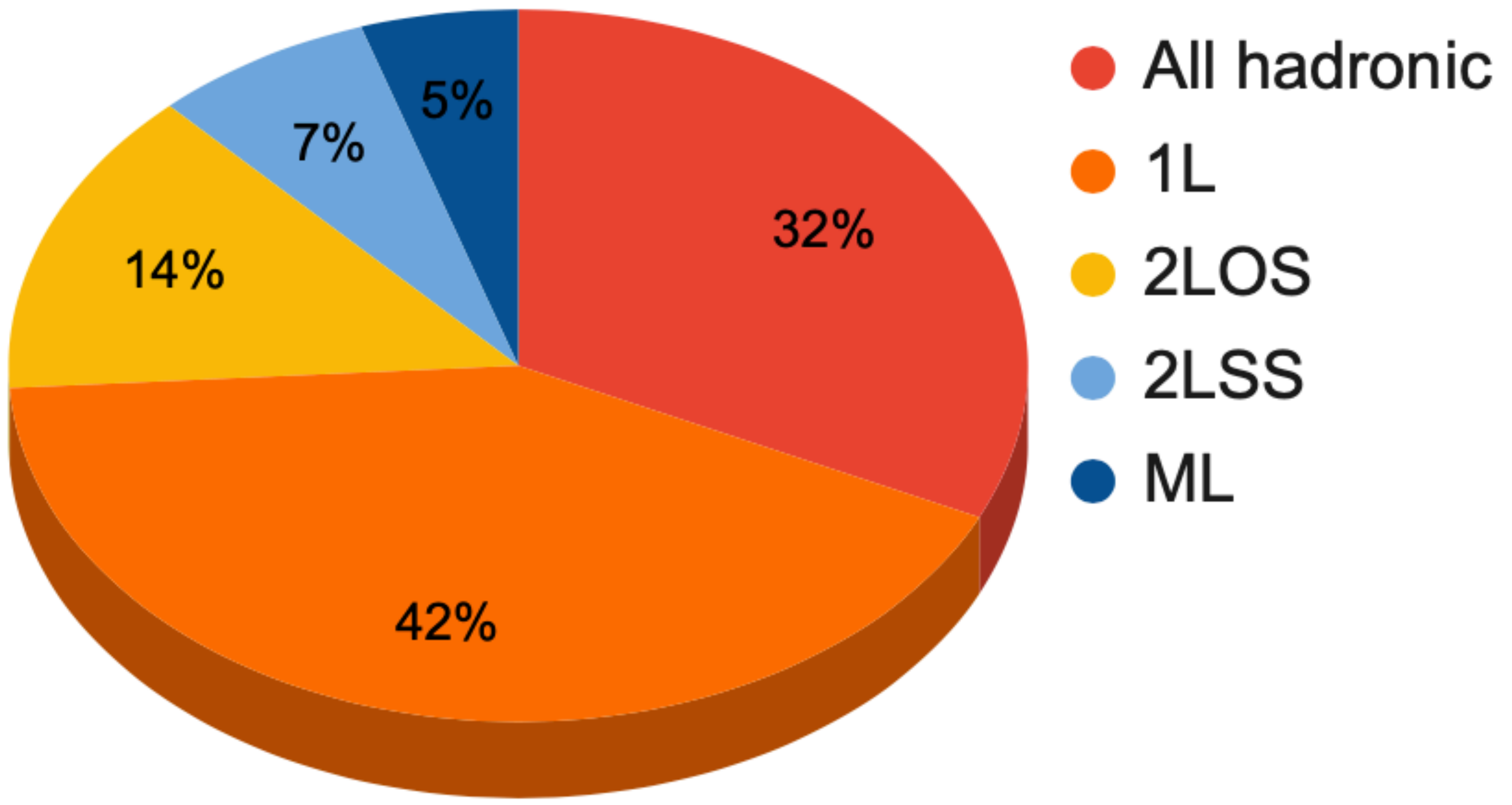
Search for $A/H \rightarrow t\bar{t}$

- Exclusion: strongest mass limit at low $\tan\beta$ to date
- significantly improved $\tan\beta$ exclusion at low mass compared to the previous results at 8 TeV
- Additional interpretation can be found in the paper

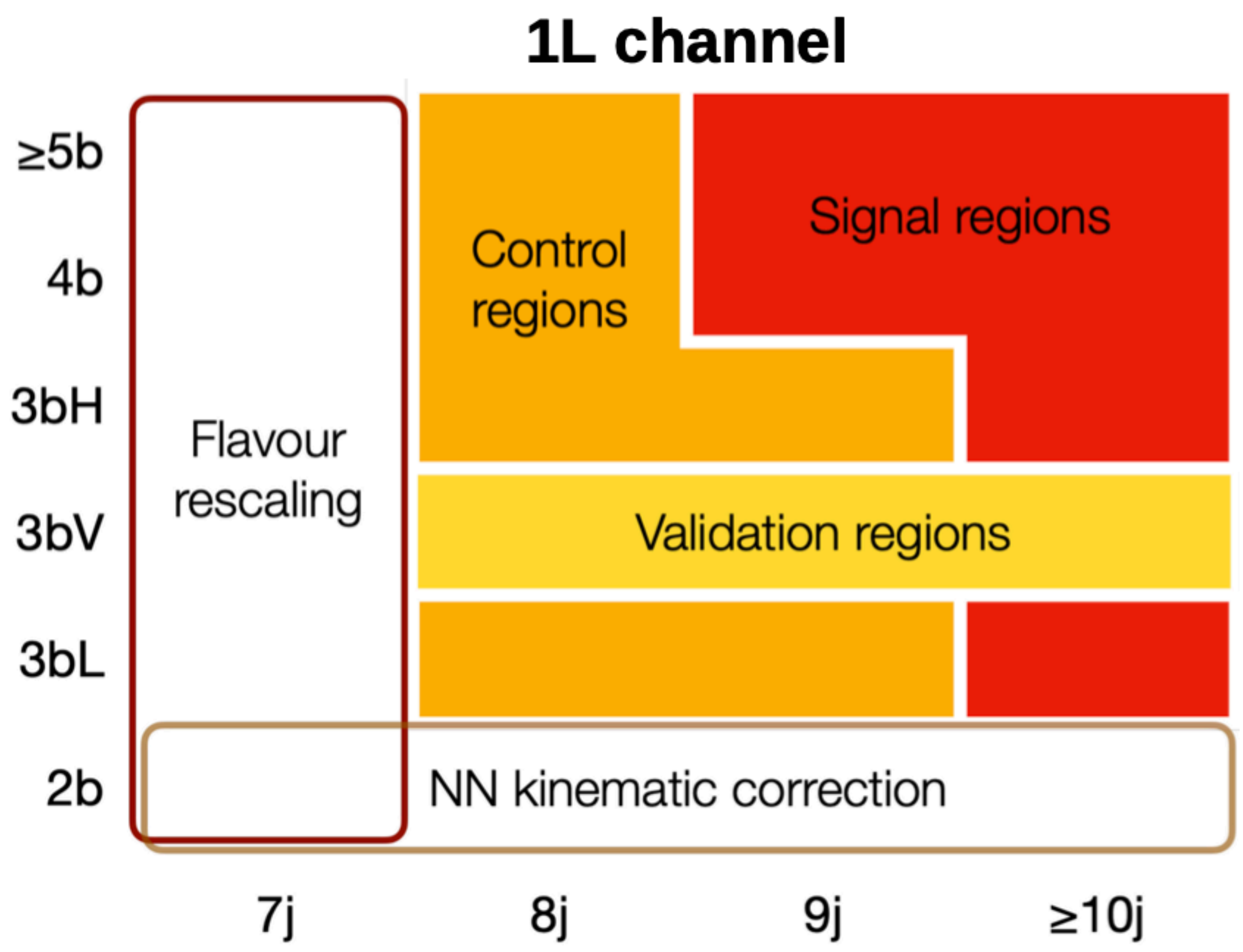


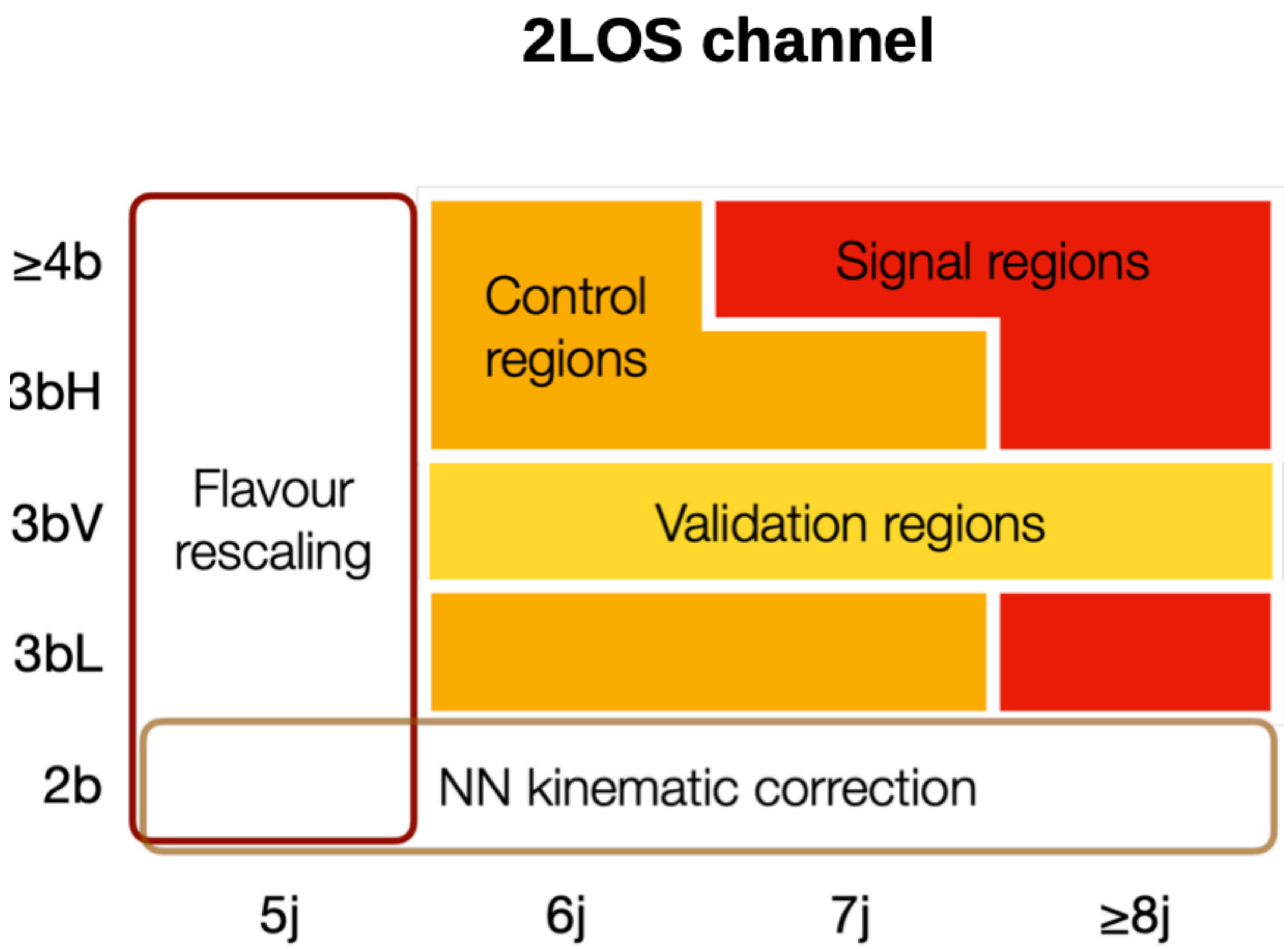


Search for $t\bar{t}A/H \to t\bar{t}t\bar{t}$



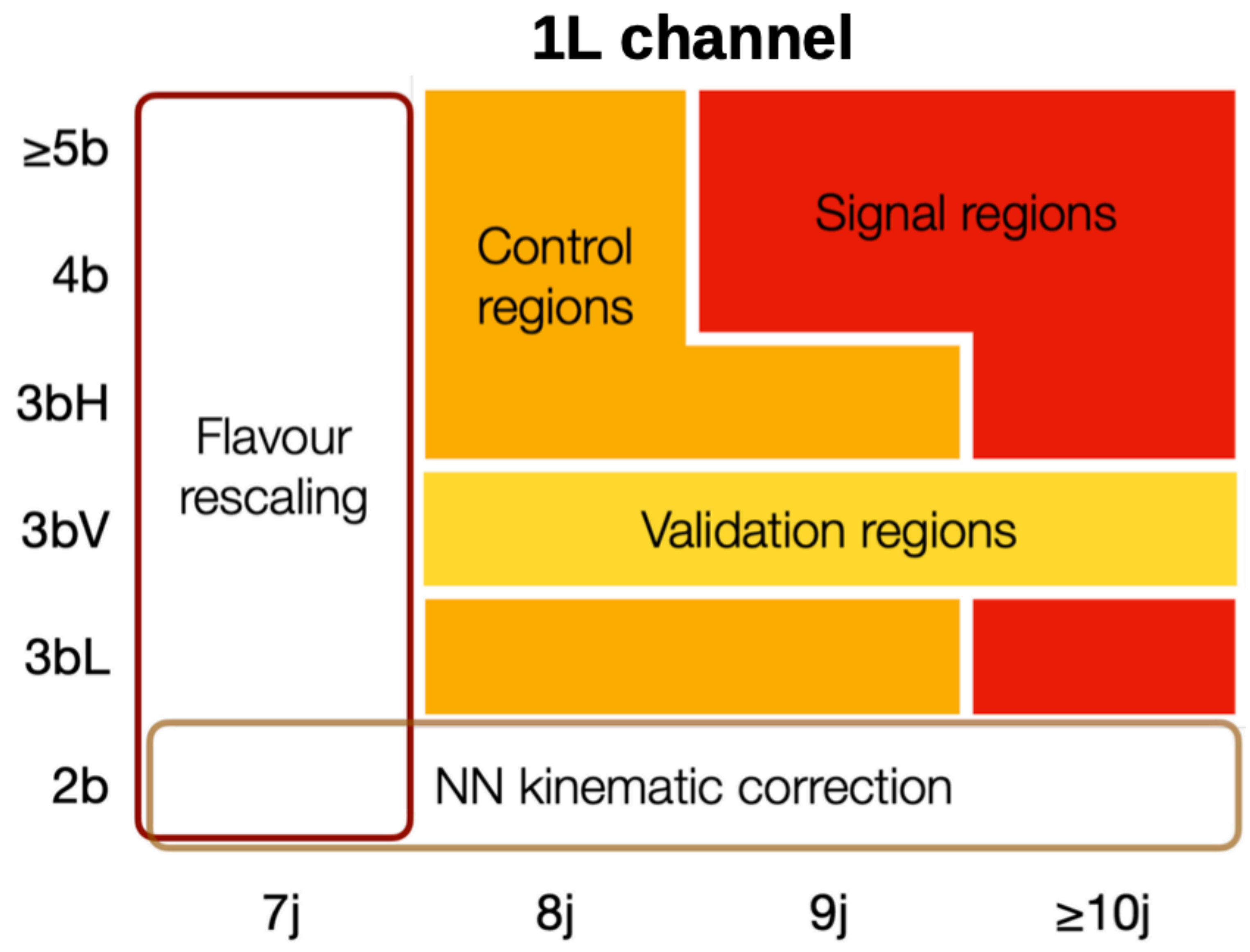
- Challenging final states with high object-multiplicity
- Analyses performed in different leptonic final states
    - Previous result in 2LSS+ML (most sensitive), 139 fb[-1] @ 13 TeV
- **1L+2LOS channel**
    - large branching fraction but also large background from $t\bar{t}$+jets, especially heavy flavour (HF) jets
    - low sensitivity compared to 2LSS/ML but complementary

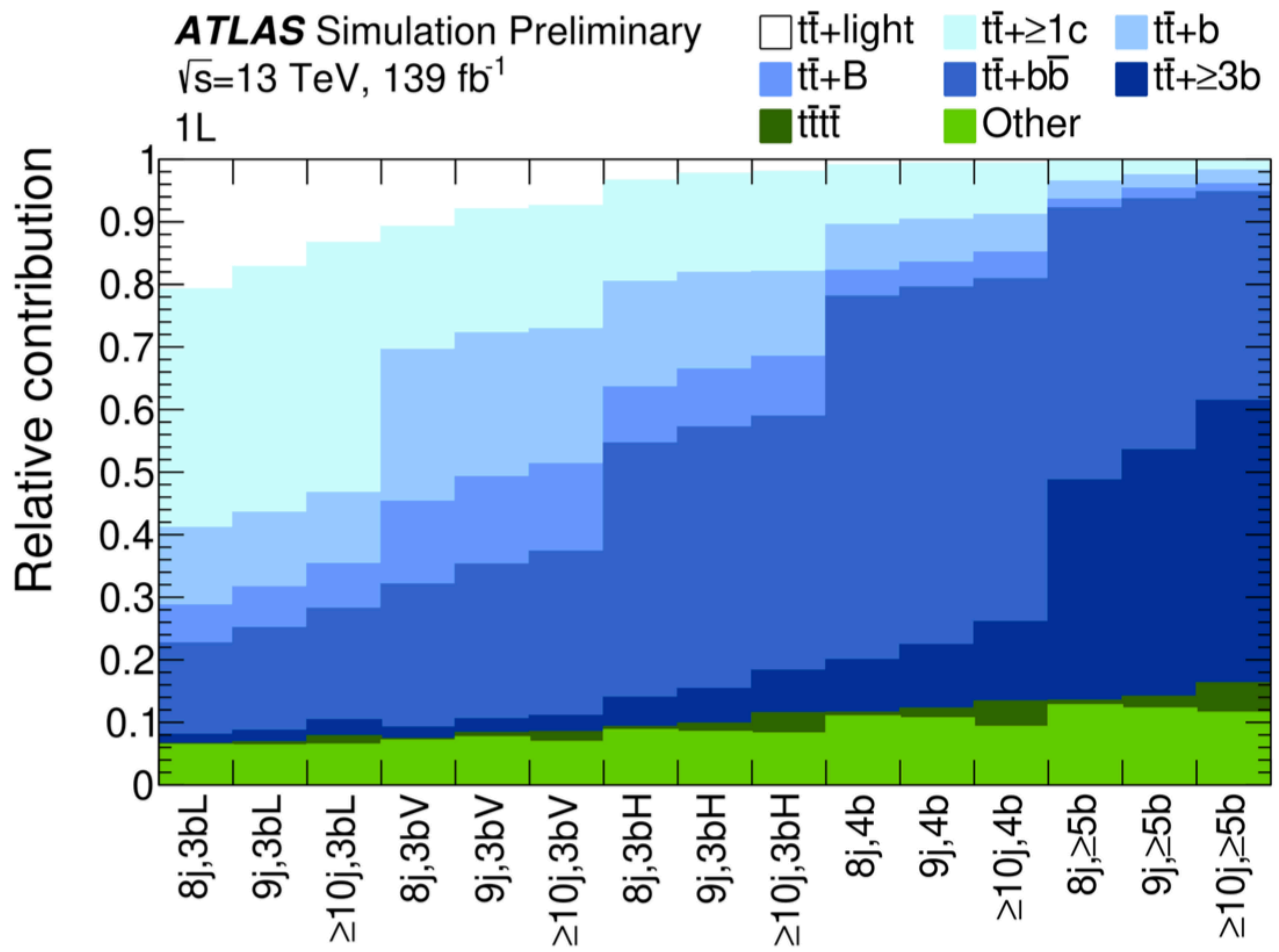




Search for $t\bar{t}A/H \to t\bar{t}t\bar{t}$

- Classify the dominant $t\bar{t}$+jets into $t\bar{t}$+≥1b, $t\bar{t}$+≥1c and $t\bar{t}$+light
  - using particle level jets matched to b/c hadrons
  - $t\bar{t}$+≥1b: $t\bar{t}$+b/B/bb/≥3b
    - according number of jets matched to b-hadrons
    - b vs. B: a single vs. a pair of b-hadrons matched to a particle-level jet
- different background compositions using flavour tagging information

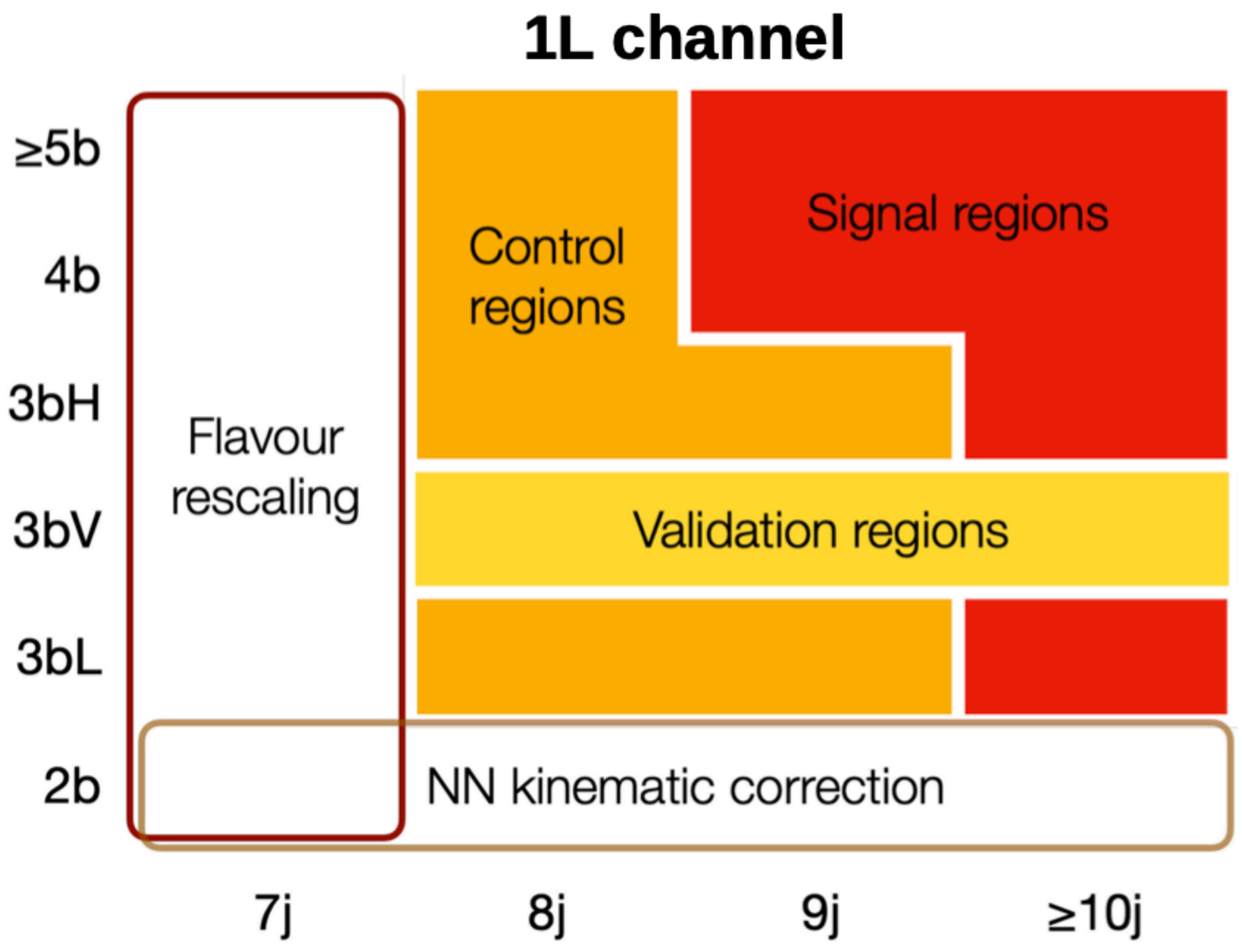




3bL = Light-flavour enriched
3bH = Heavy-flavour enriched
3bV = Validation region

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	-

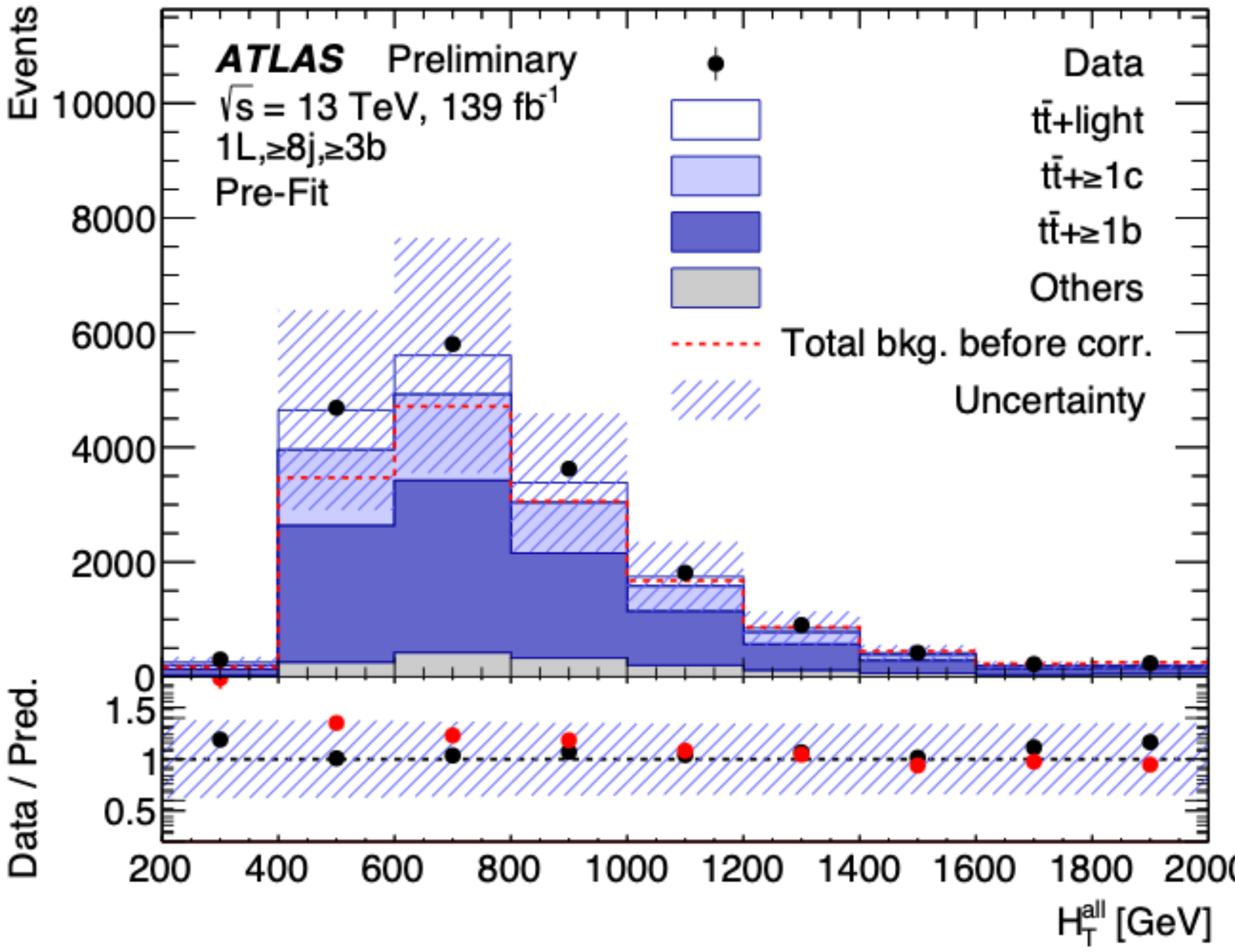
Search for $t\bar{t}A/H \rightarrow t\bar{t}t\bar{t}$

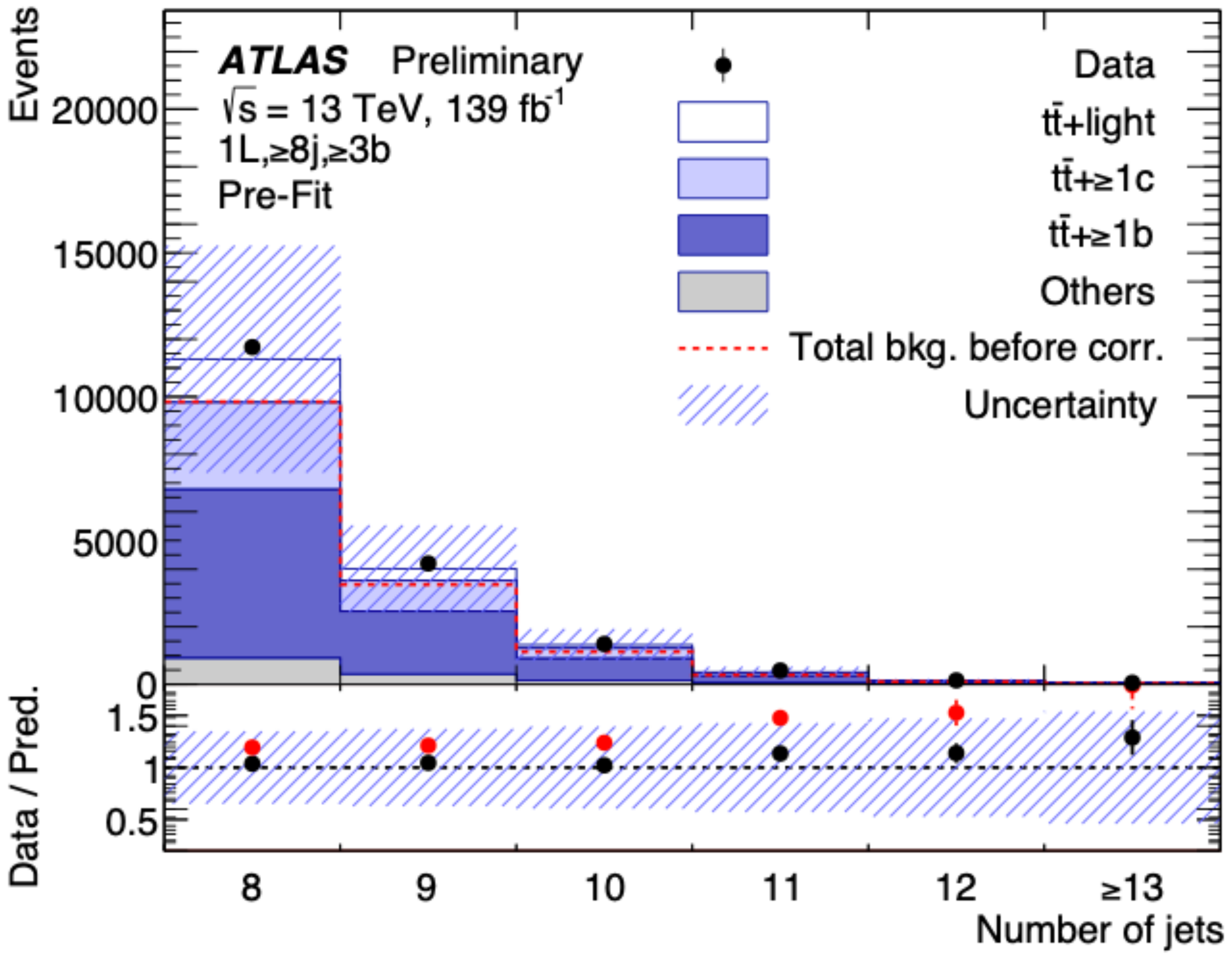


- Data-driven corrections on $t\bar{t}$+jets background
  - Flavour rescaling: fit to data in different b-tag regions to extract normalisation correction factors on $t\bar{t}$+≥1b, $t\bar{t}$+≥1c and $t\bar{t}$+light
  - Kinematic reweighting based on a neural network (NN) trained as a binary classifier of data vs. $t\bar{t}$ simulation

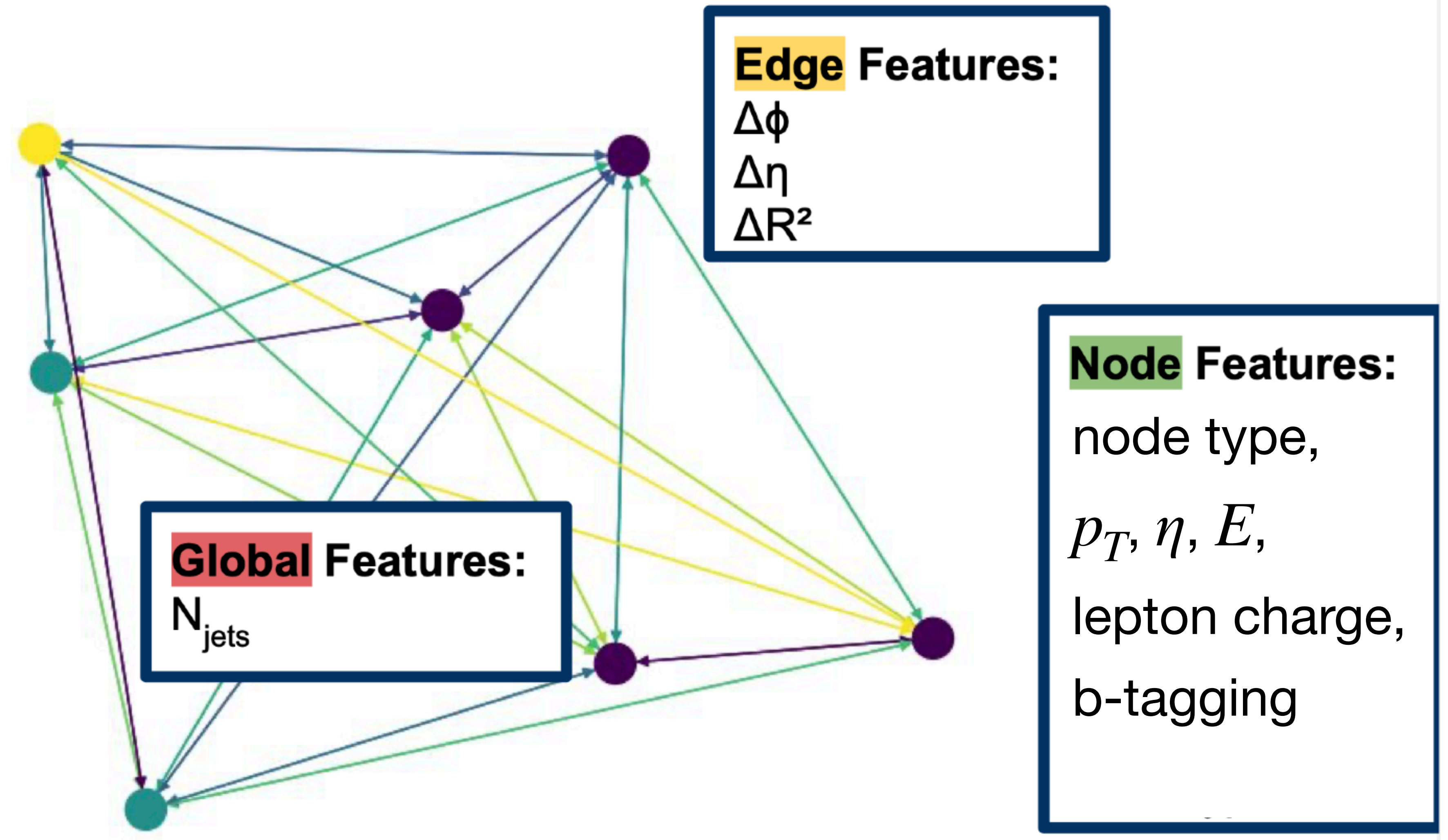
$$O(\mathbf{x}) = P(\text{data}|\mathbf{x}) = \frac{\alpha_{\text{data}} P_{\text{data}}(\mathbf{x})}{\alpha_{\text{data}} P_{\text{data}}(\mathbf{x}) + \alpha_{\text{sim}} P_{\text{sim}}(\mathbf{x})}$$

$$w(\mathbf{x}) = e^{O(\mathbf{x})}$$

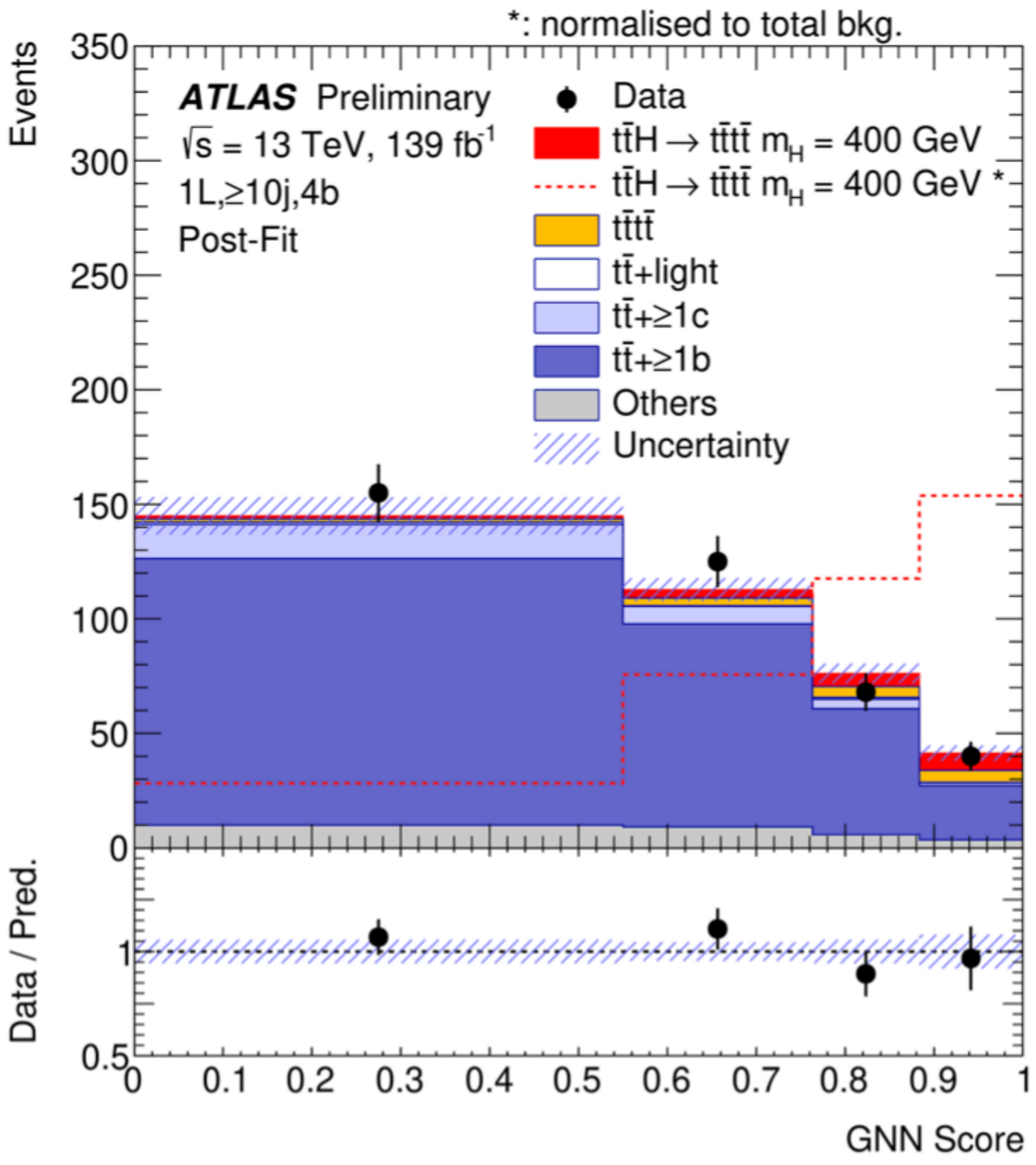


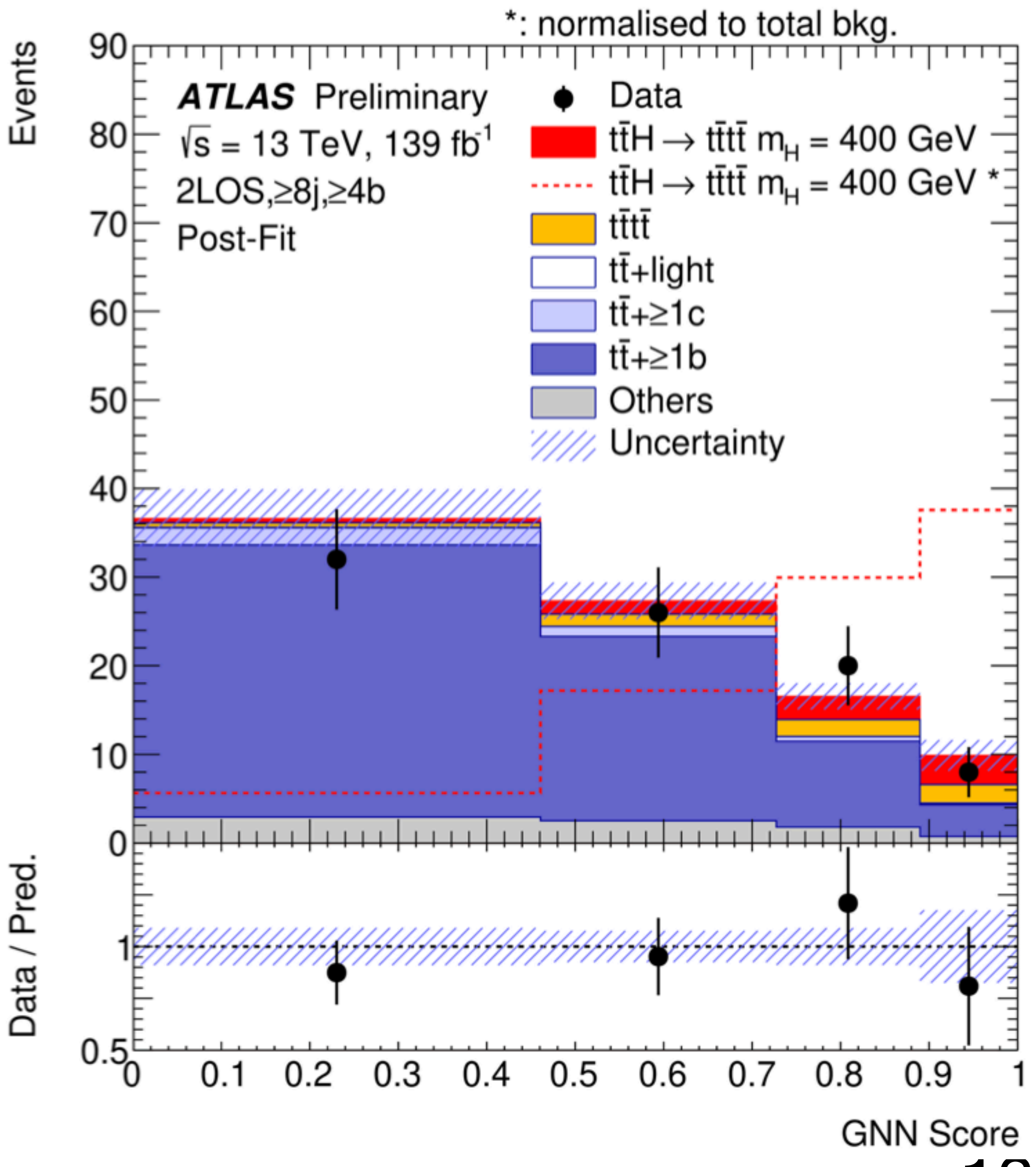


Search for $t\bar{t}A/H \rightarrow t\bar{t}t\bar{t}$



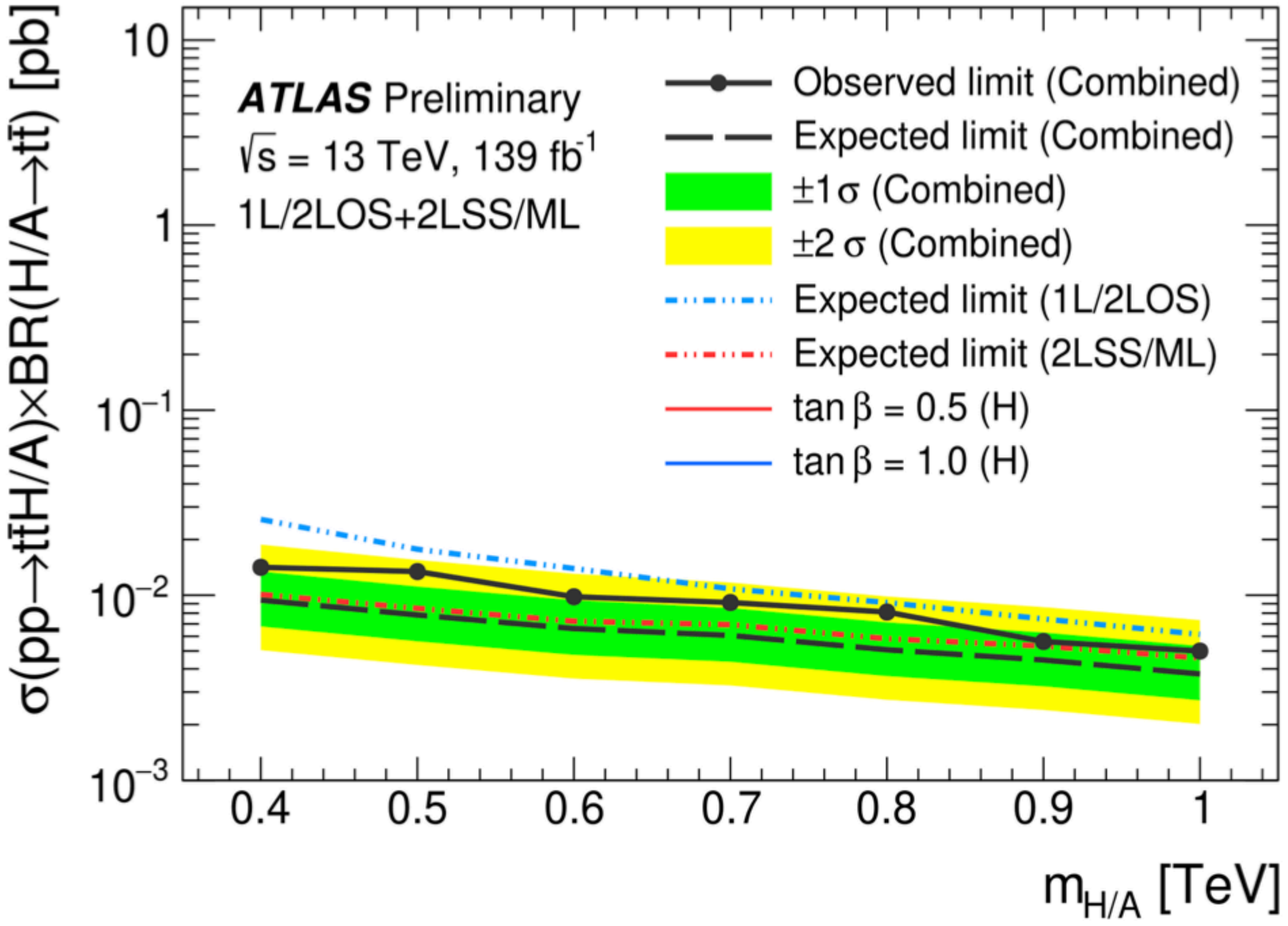
- Graph neural network (GNN) to optimise the signal-background discrimination
- $m_{H/A}$ parametrisation: smooth interpolation between mass points
- **A list of higher-level variable (sum of jet b-tag scores, H_T, ...) included as global features**
    - introduced to for validation purposes
    - also helps the training converge faster and less prone to training statistics
- Most important information from
    - **b-tagging**
    - **node pT**





Search for $t\bar{t}A/H \rightarrow t\bar{t}t\bar{t}$

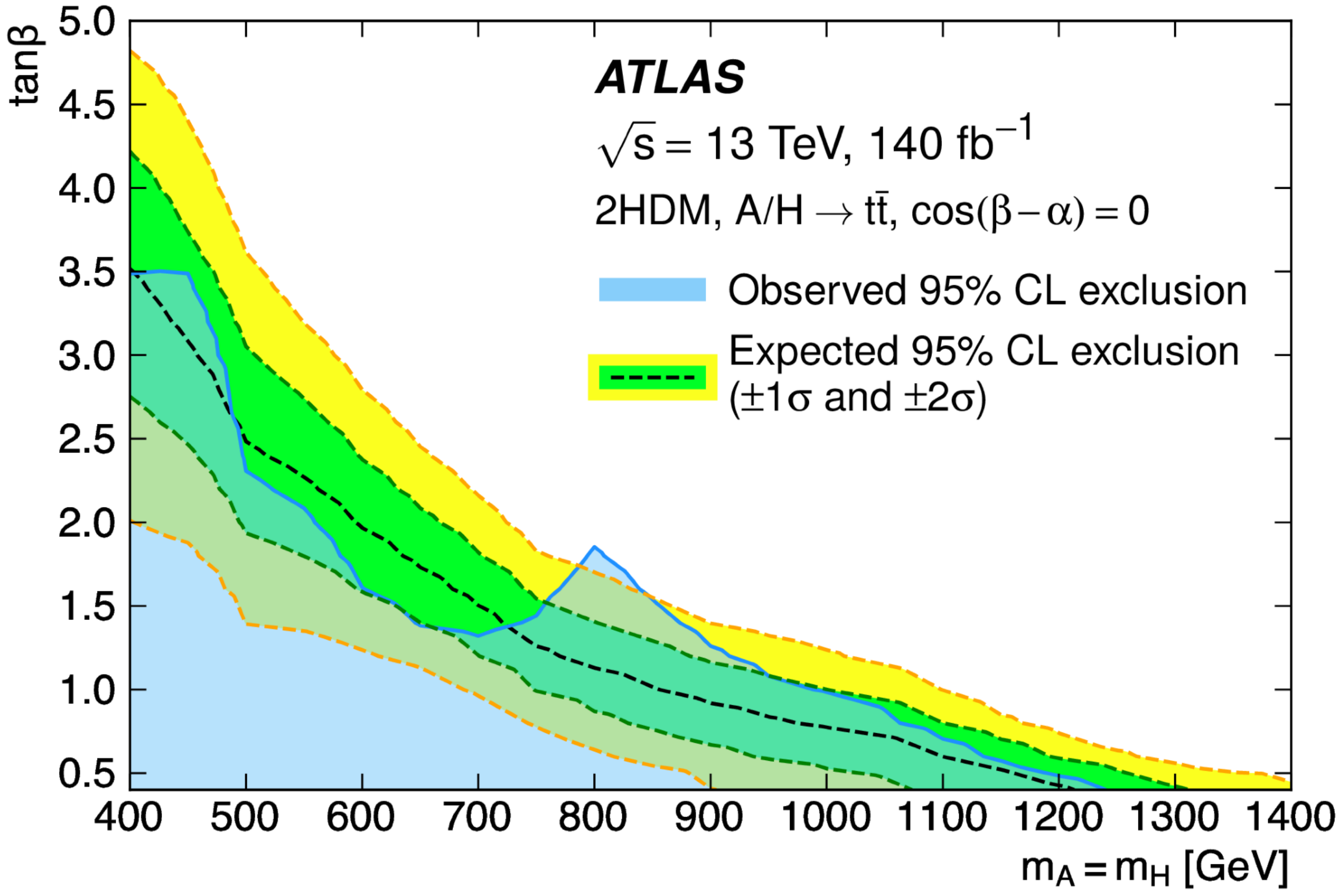
- Combined with the previous analysis using 2LSS+ML channels to achieve optimal sensitivity
  - 2LSS+ML drives the sensitivity
  - 1L+2LOS introduces a larger improvement at high masses
- Sensitivity in 1L+2LOS channels dominated by $t\bar{t}$+≥1b and $t\bar{t}t\bar{t}$ modelling

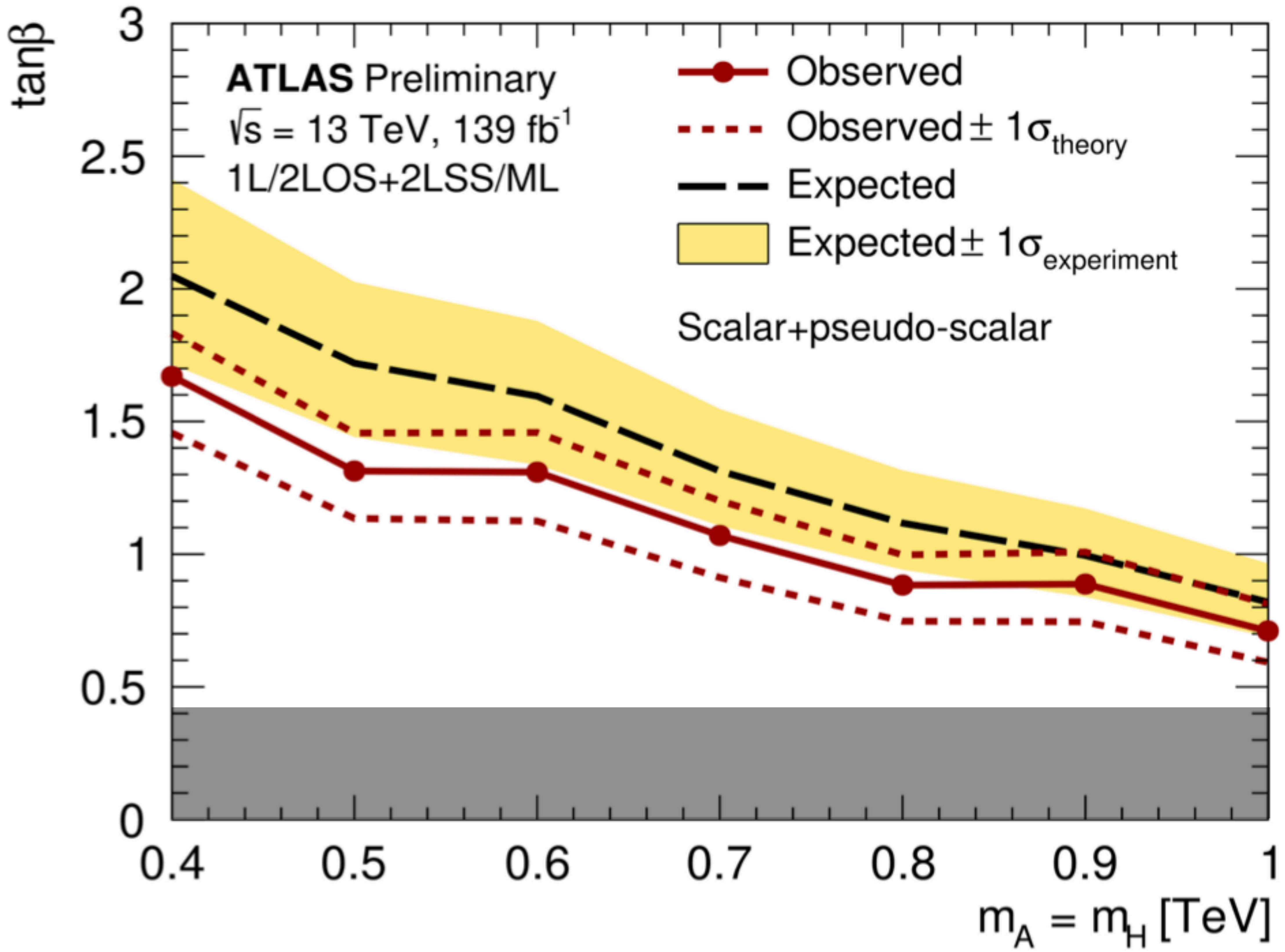


Uncertainty source	$\Delta\sigma_{t\bar{t}H/A\rightarrow t\bar{t}t\bar{t}}$ [fb]					
	$m_{H/A}$=400 GeV		$m_{H/A}$=700 GeV		$m_{H/A}$=1000 GeV	
Signal Modelling						
BSM $t\bar{t}t\bar{t}$ modelling	< 1		+0.1	< 0.1	< 0.1	
Background Modelling						
$t\bar{t}$+≥1b modelling	+11	-10	+3.7	-3.4	+1.9	-1.7
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 and high-p_T extrapolation	+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

$t\bar{t}$ vs. $t\bar{t}t\bar{t}$

- Much better $\tan\beta$ exclusion from $A/H \to t\bar{t}$ at lower masses
    - sensitivity at low $\tan\beta$ driven by the off-shell signal "peak"
- higher masses $t\bar{t}H/A$ becomes competitive





Summary

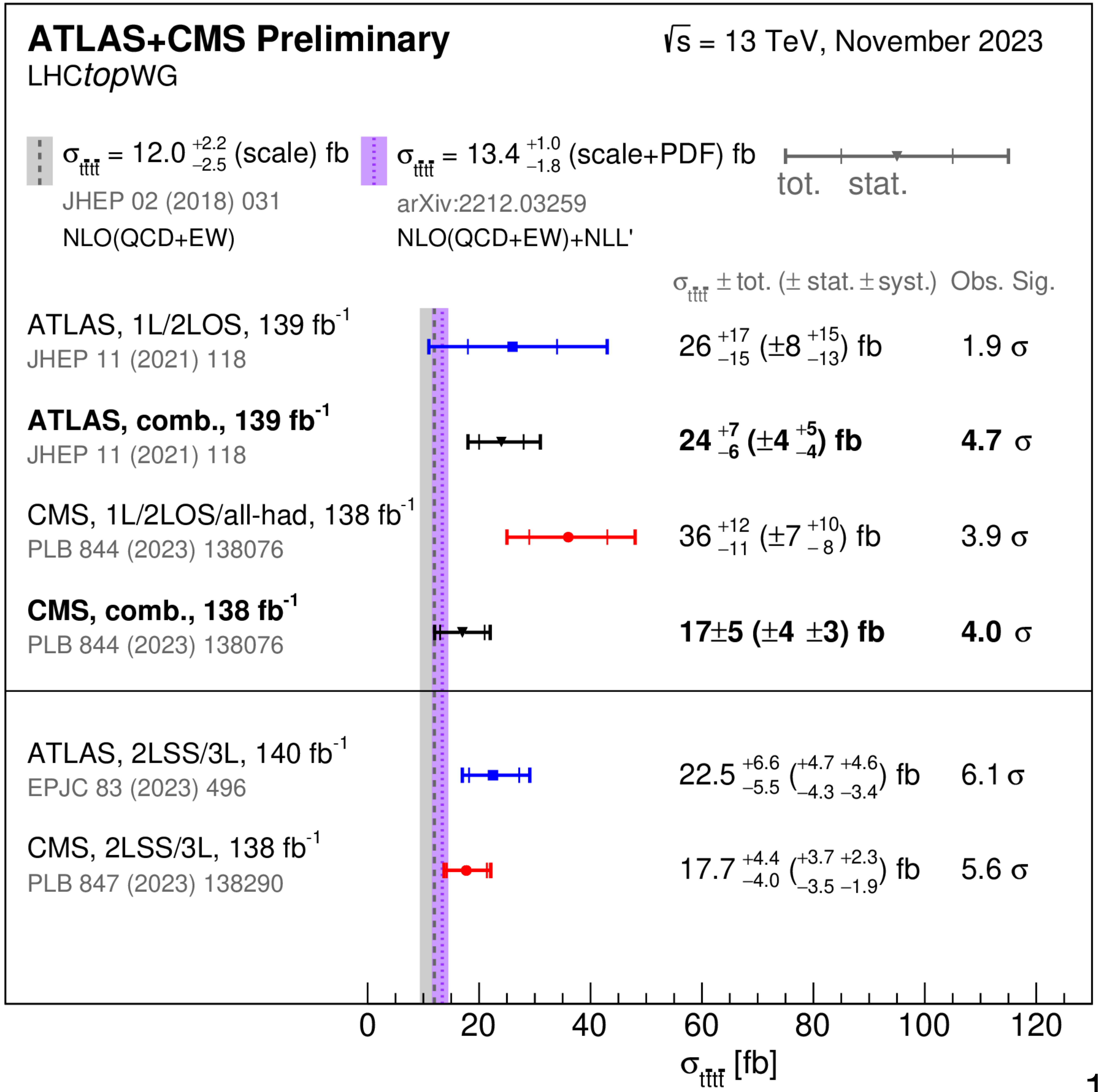
- Presented two recent results from ATLAS on the search for new heavy neutral scalars in top final states
- Search for $A/H \to t\bar{t}$
  - strongest mass exclusion to date on 2HDM/hMSSM at low $\tan\beta$
- Search for $t\bar{t}H/A \to t\bar{t}t\bar{t}$ 1L+2LOS
  - first dedicated search in this final states
  - in combination with 2LSS+ML, competitive sensitivity at high masses
    - further extending the search range could lead to promising results

- Stayed tuned for Run3!

MAY THE TOPS BE WITH YOU

BACKUP

State of the art

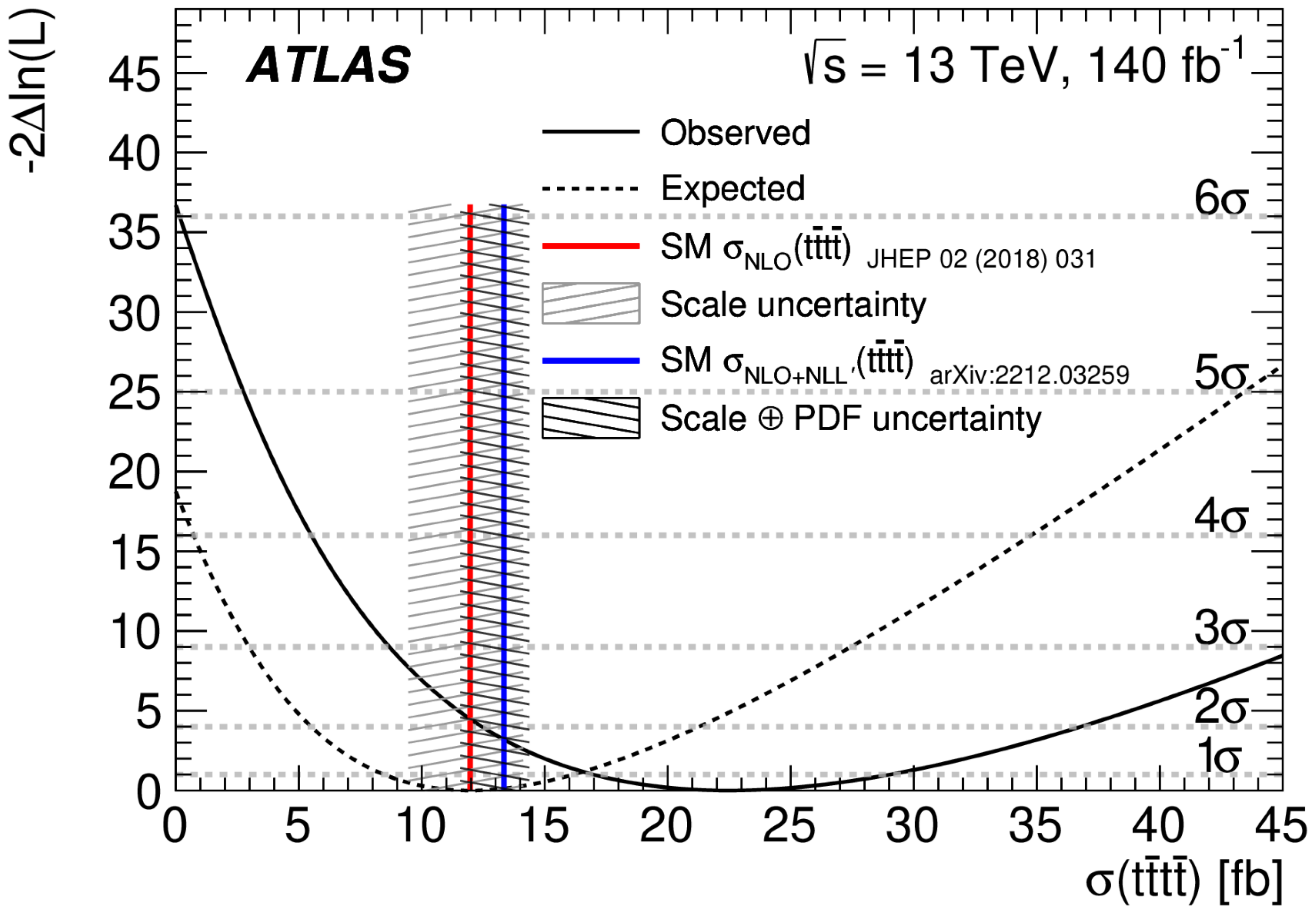


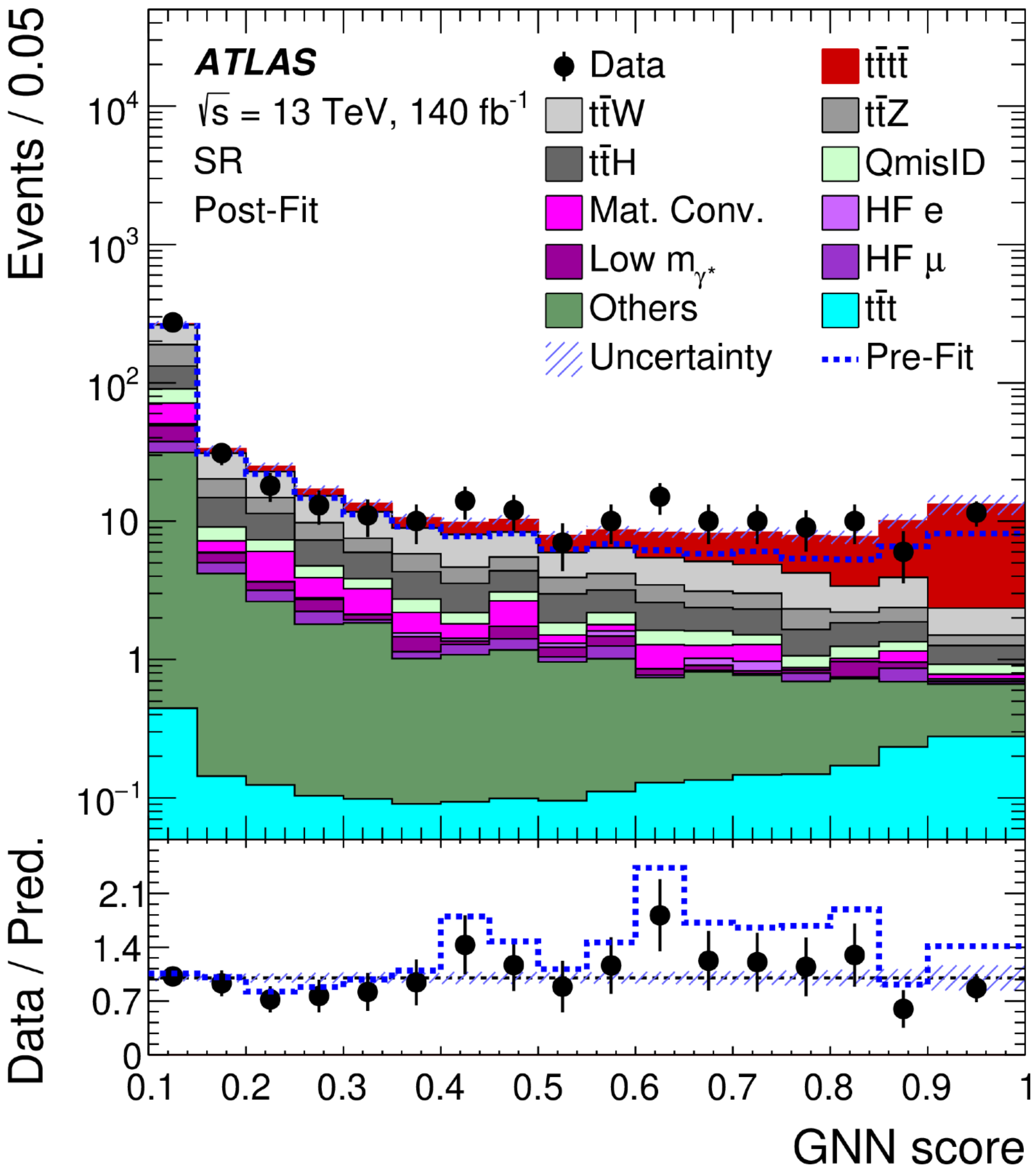
Results - SM $t\bar{t}t\bar{t}$ cross section

- Measured cross section:

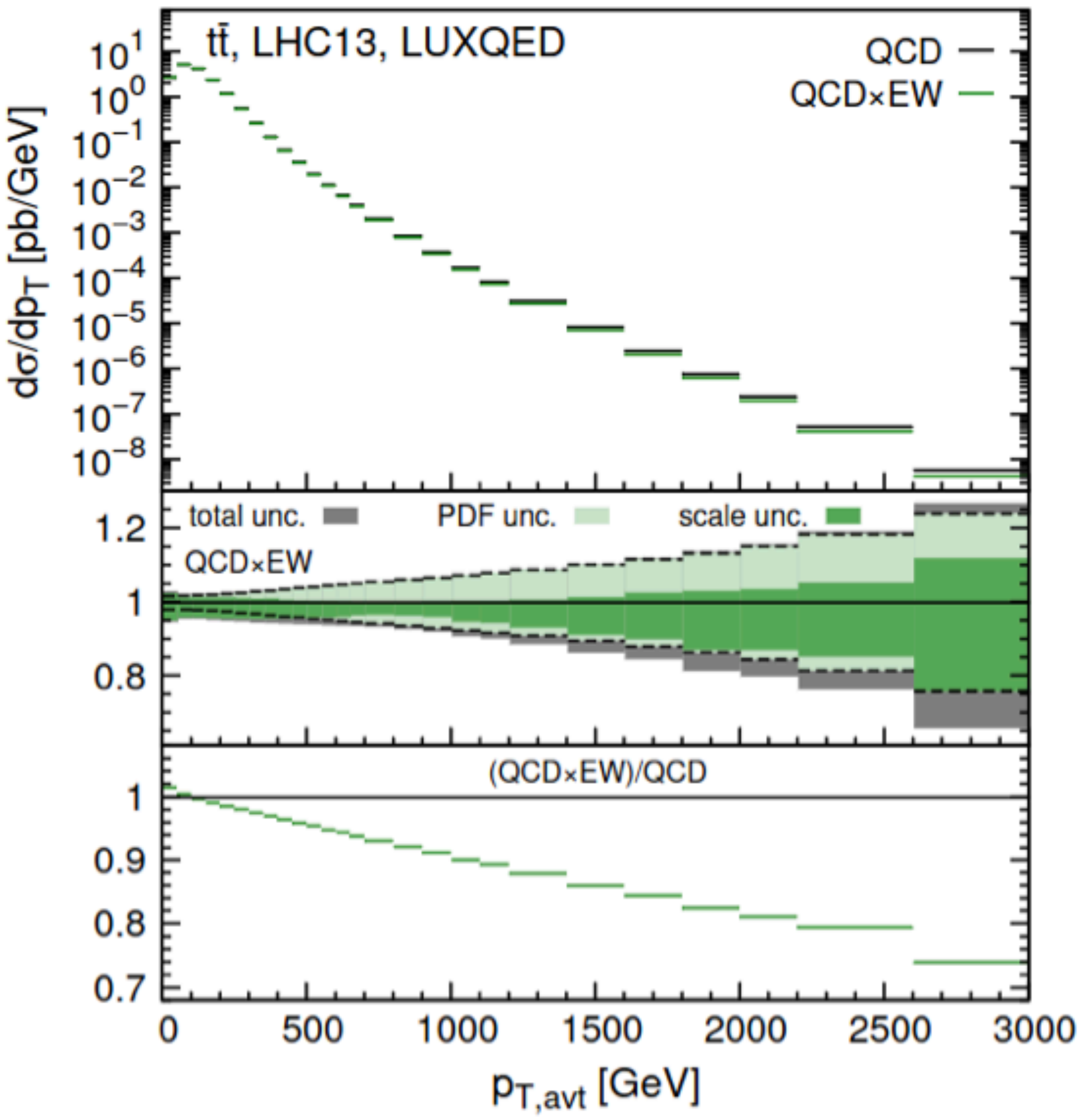
$$\sigma_{t\bar{t}t\bar{t}} = 22.5^{+4.7}_{-4.3}(\text{stat})\,^{+4.6}_{-3.4}(\text{syst})\text{ fb} = 22.5\,^{+6.6}_{-5.5}\text{ fb}.$$

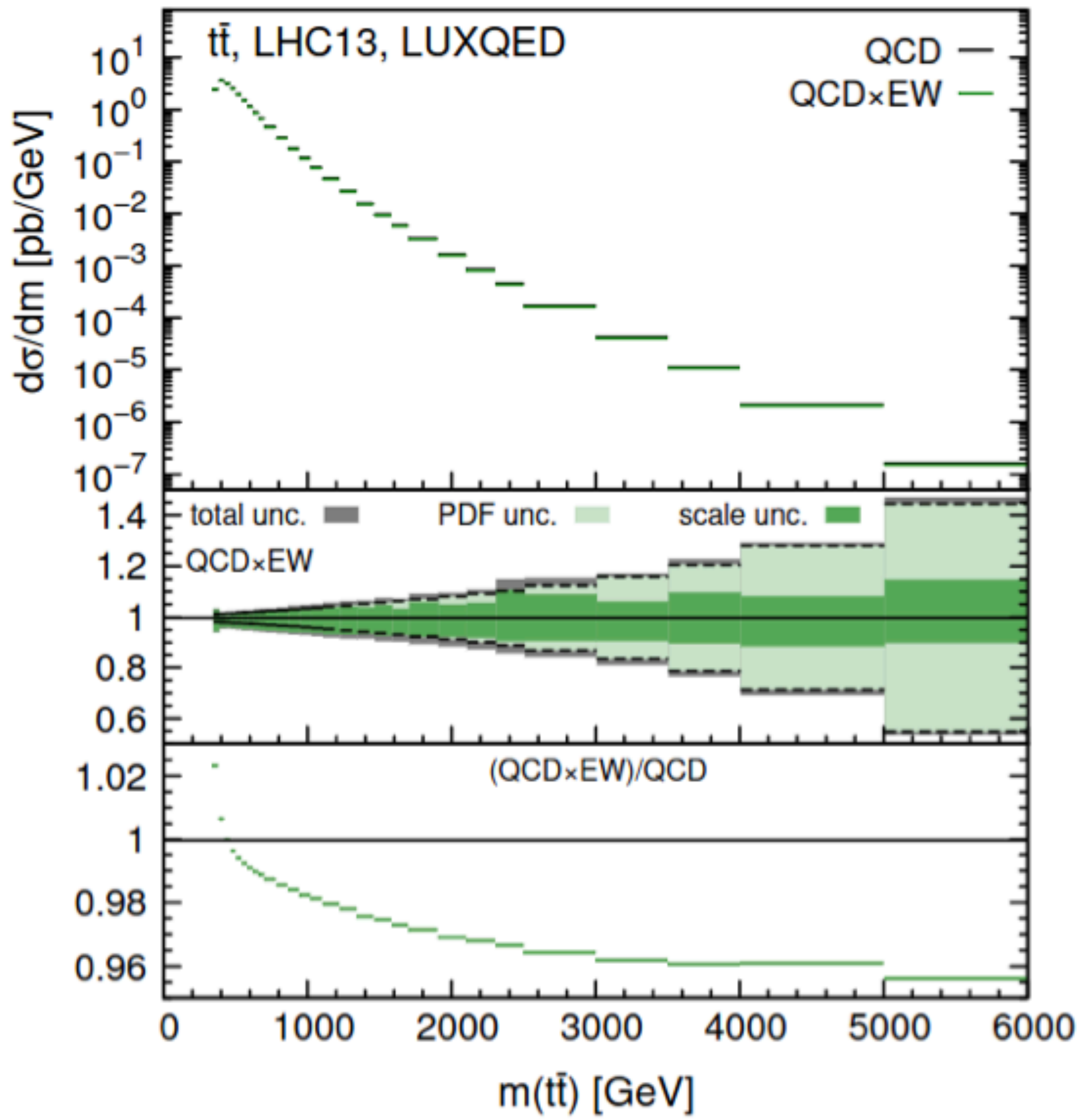
- Agreement with predictions < 2σ

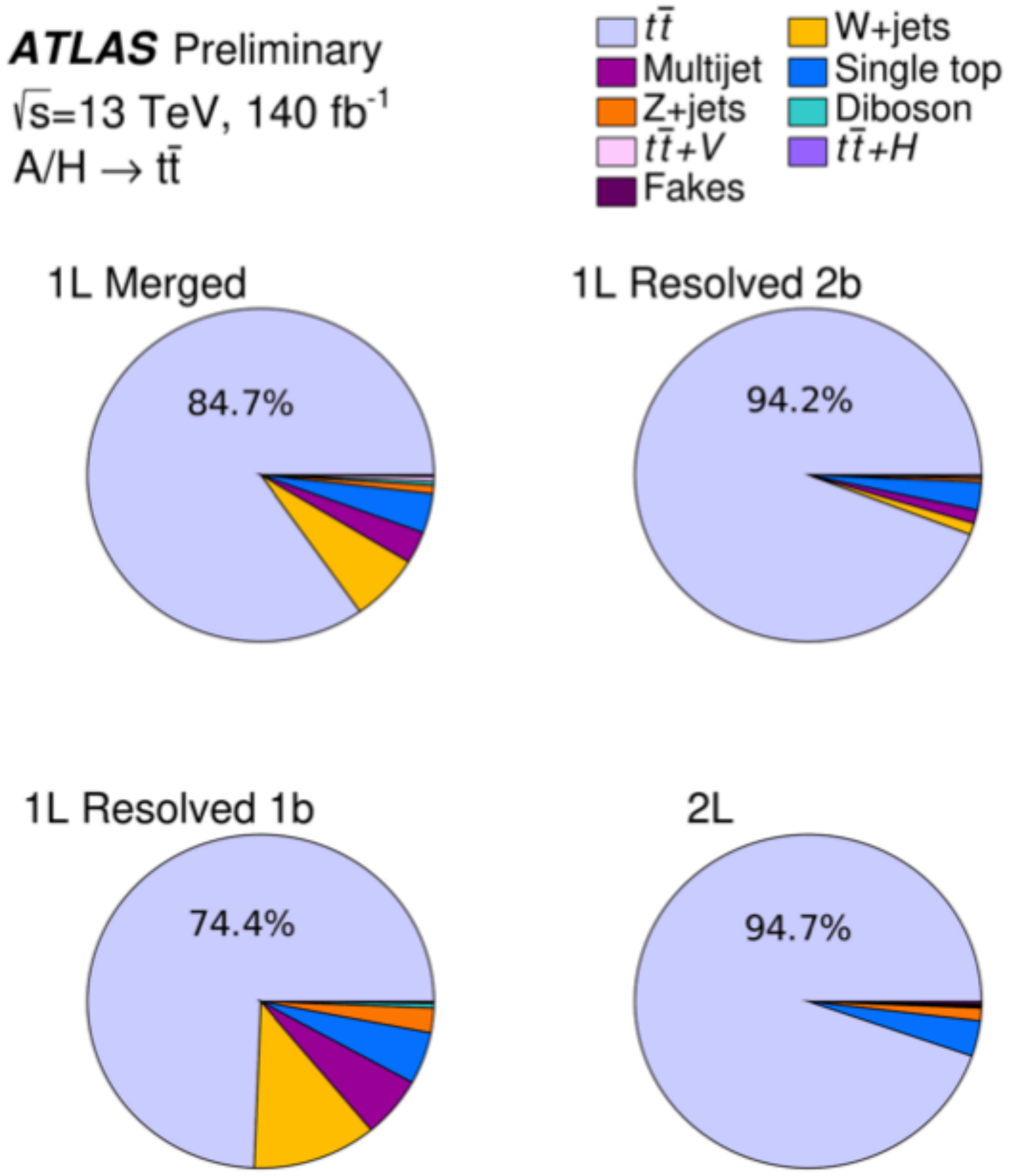




Search for $A/H \to t\bar{t}$







Variable	Description
$\sum_{i\in[1,6]} \text{pcb}_i$	Sum of the pcb scores of the six jets with the highest scores
H_{T}	p_{T} sum of all reconstructed leptons and jets
N_{jets}	Jet multiplicities
$H_{\text{T}}^{\text{ratio}}$	p_{T} sum of the four leading jets in p_{T} divided by the p_{T} sum of the remaining jets
$dR_{jj}^{\text{avg.}}$	Average ΔR across all jet pairs
m_{T}^{W}	W-boson transverse mass calculated using the lepton four-momenta and $E_{\text{T}}^{\text{miss}}$ (1L only)
$\Delta R_{bb}^{\text{min.}}$	Minimum ΔR between any pair of jets b-tagged at the 70% OP
$\Delta R_{\ell b}^{\text{min.}}$	Minimum ΔR between any pair of lepton and jet b-tagged at the 70% OP
$m_{bbb}^{\text{avg.}}$	Average invariant mass of all triplets of jets b-tagged at the 70% OP
$m_{jjj}^{\text{avg.}}$	Average invariant mass of all jet-triplets with an angular separation of $\Delta R < 3$
$\sum d_{12}$	Sum of the first k_t splitting scale d_{12} over all large-R jets
$\sum d_{23}$	Sum of the second k_t splitting scale d_{12} over all large-R jets
$N_{\text{LR-jets}}$	Number of large-R jets with a mass greater than 100 GeV
Centrality	$\sum_i p_{\text{T}}^{i} / \sum_i E_i$ where the sums are performed over all reconstructed jets and leptons
$m_{\ell\ell}$	Invariant mass of the two leptons (2LOS only)

$$\mathcal{O}(\mathbf{x}) = P(\text{data}|\mathbf{x}) = \frac{\alpha_{\text{data}} P_{\text{data}}(\mathbf{x})}{\alpha_{\text{data}} P_{\text{data}}(\mathbf{x}) + \alpha_{\text{sim}} P_{\text{sim}}(\mathbf{x})}, \qquad w(\mathbf{x}) = \frac{\alpha_{\text{data}} P_{\text{data}}(\mathbf{x})}{\alpha_{\text{sim}} P_{\text{sim}}(\mathbf{x})} = \frac{\mathcal{O}(\mathbf{x})}{1 - \mathcal{O}(\mathbf{x})}.$$

- Exponential loss function to help with the training in low-stat regime

$$\mathcal{L} = P_{\text{data}} e^{-\frac{\mathcal{O}(\mathbf{x})}{2}} + P_{\text{sim}} e^{\frac{\mathcal{O}(\mathbf{x})}{2}}.$$

- after minimisation $\mathscr{L} = 0$
- resulting event weight

$$w(\mathbf{x}) = e^{\mathcal{O}(\mathbf{x})}.$$

Search for heavy resonances - H/A

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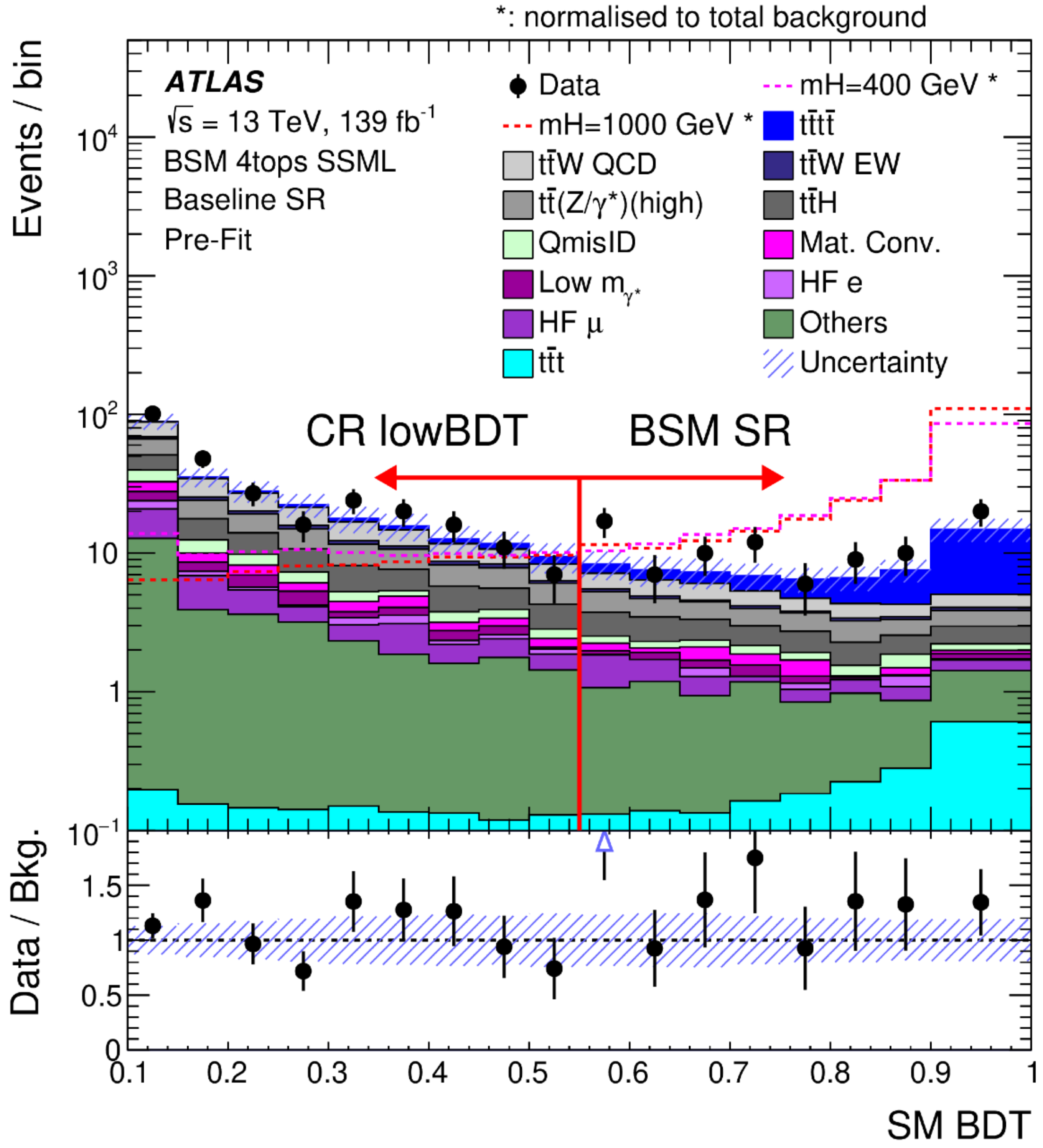
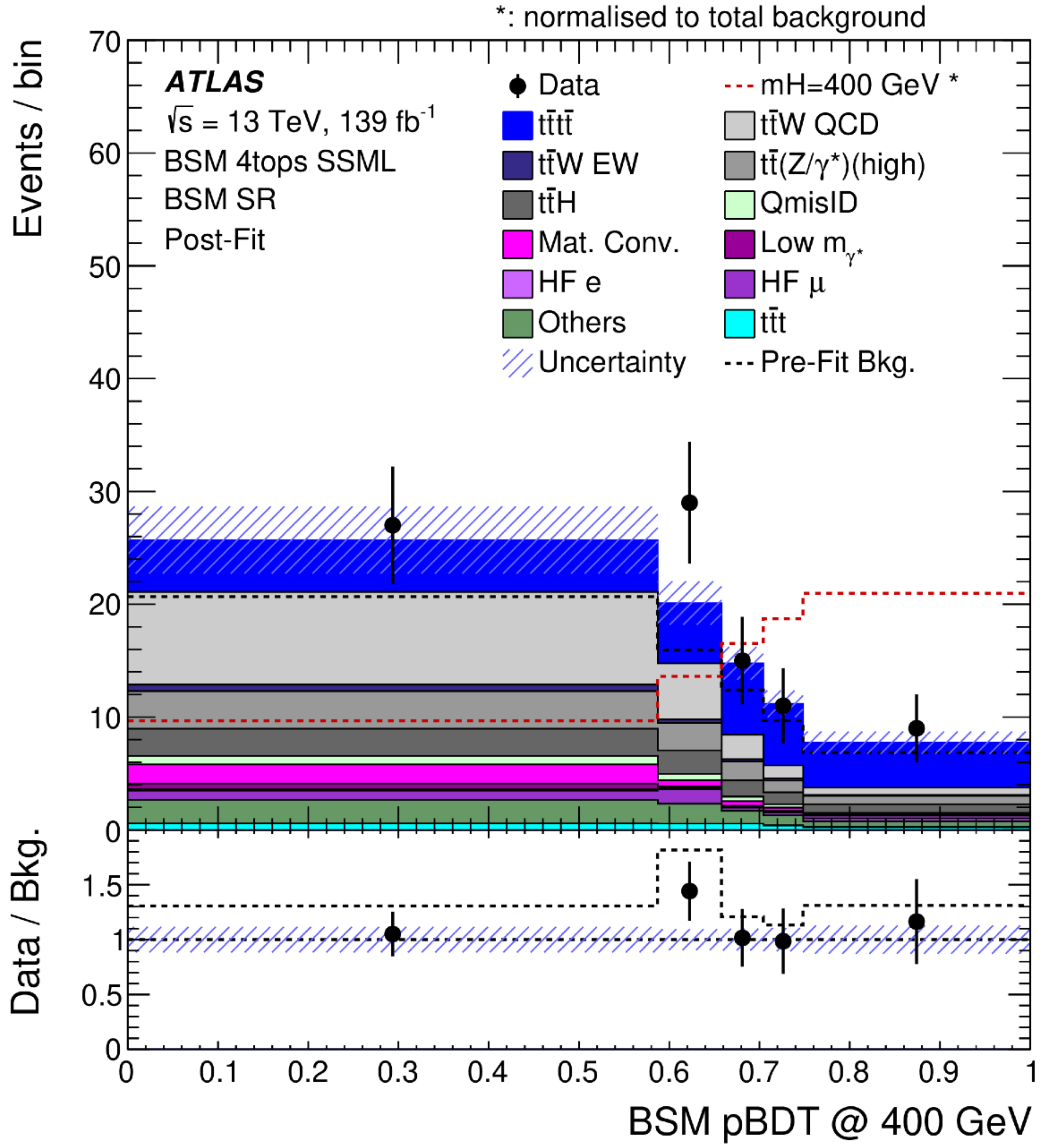
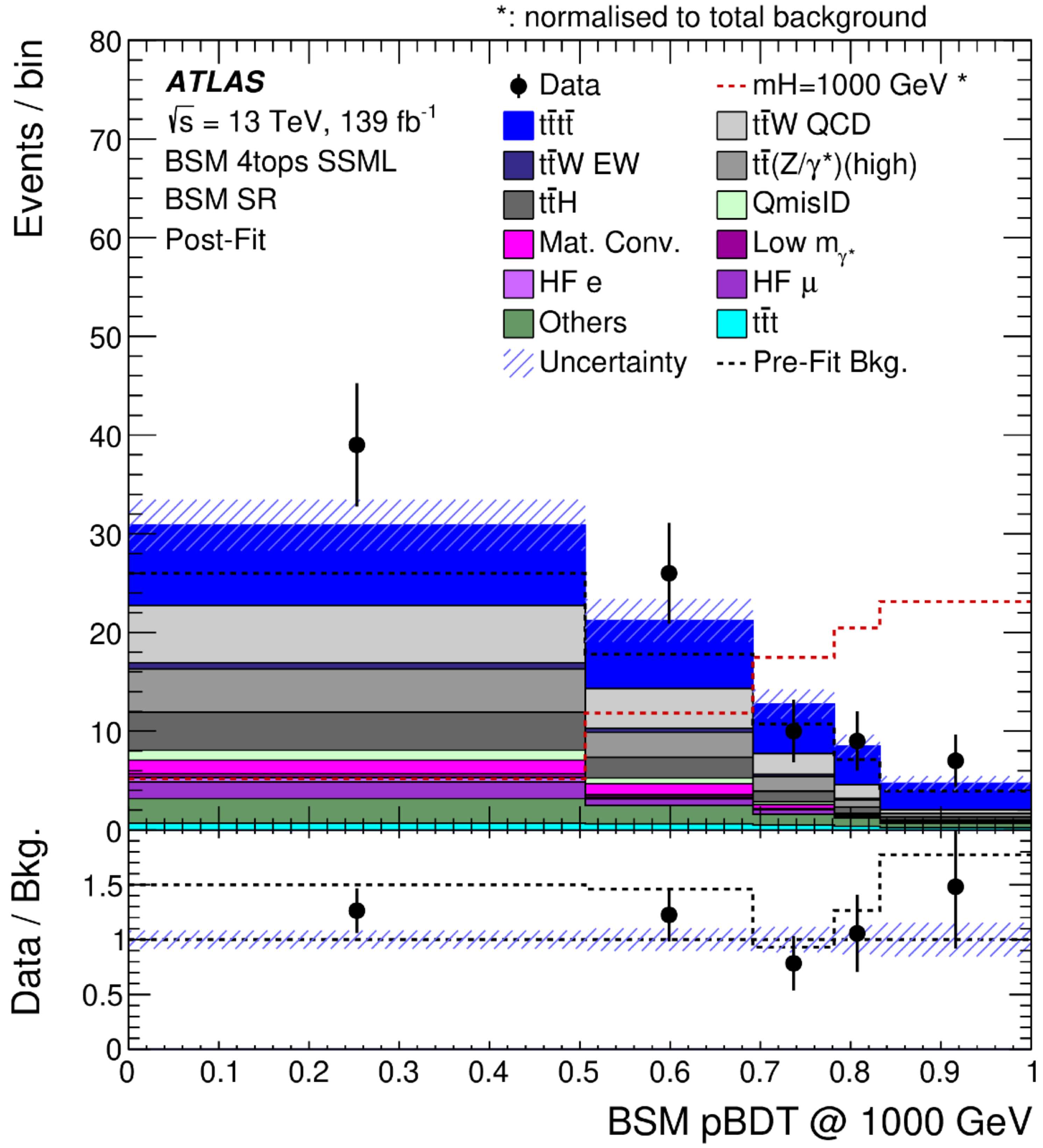
- Same strategy as the SM $t\bar{t}t\bar{t}$ measurement
- additional MVA to separate BSM vs SM $t\bar{t}t\bar{t}$
  - $m_{H/A}$-parametrised BDT allows smooth interpolation between mass points







Search for heavy resonances - H/A

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- Consider 2HDM signal in the alignment limit $\sin(\beta - \alpha) \sim 1$
  - 400 - 1000 GeV, with 100 GeV steps
  - mass width set to 5 - 30 GeV, consistent with $\tan\beta = 1$
- 95% CL upper limit on xsec x BR ~10 fb
- SM $t\bar{t}t\bar{t}$ normalised to 12 fb, with 20% uncertainty on xsec, plus other modelling uncertainties