Measurements of Higgs boson production with top quarks with the ATLAS detector

Levi Evans

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https://indico.in2p3.fr/event/33627/contributions/154131/

ATLAS EXPERIMENT

DESY.

Why care about top-Higgs interactions?

See talk by B.Moser for c/b probing at ATLAS!

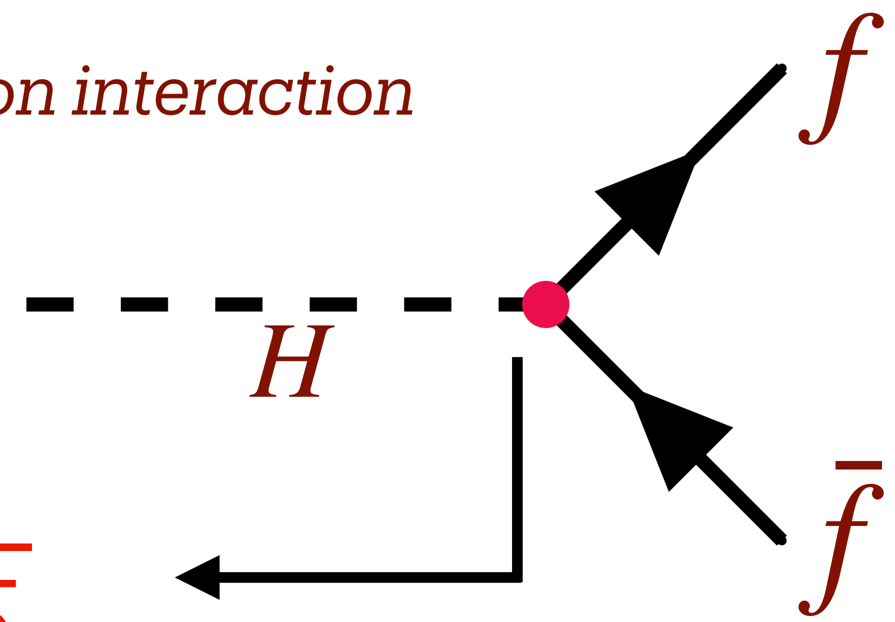
- Higgs Yukawa sector is of particular importance to measure and probe to high precision

$$\mathscr{L} = m_f \bar{\psi}_f \psi_f + \frac{m_f}{v} H \bar{\psi}_f \psi_f$$

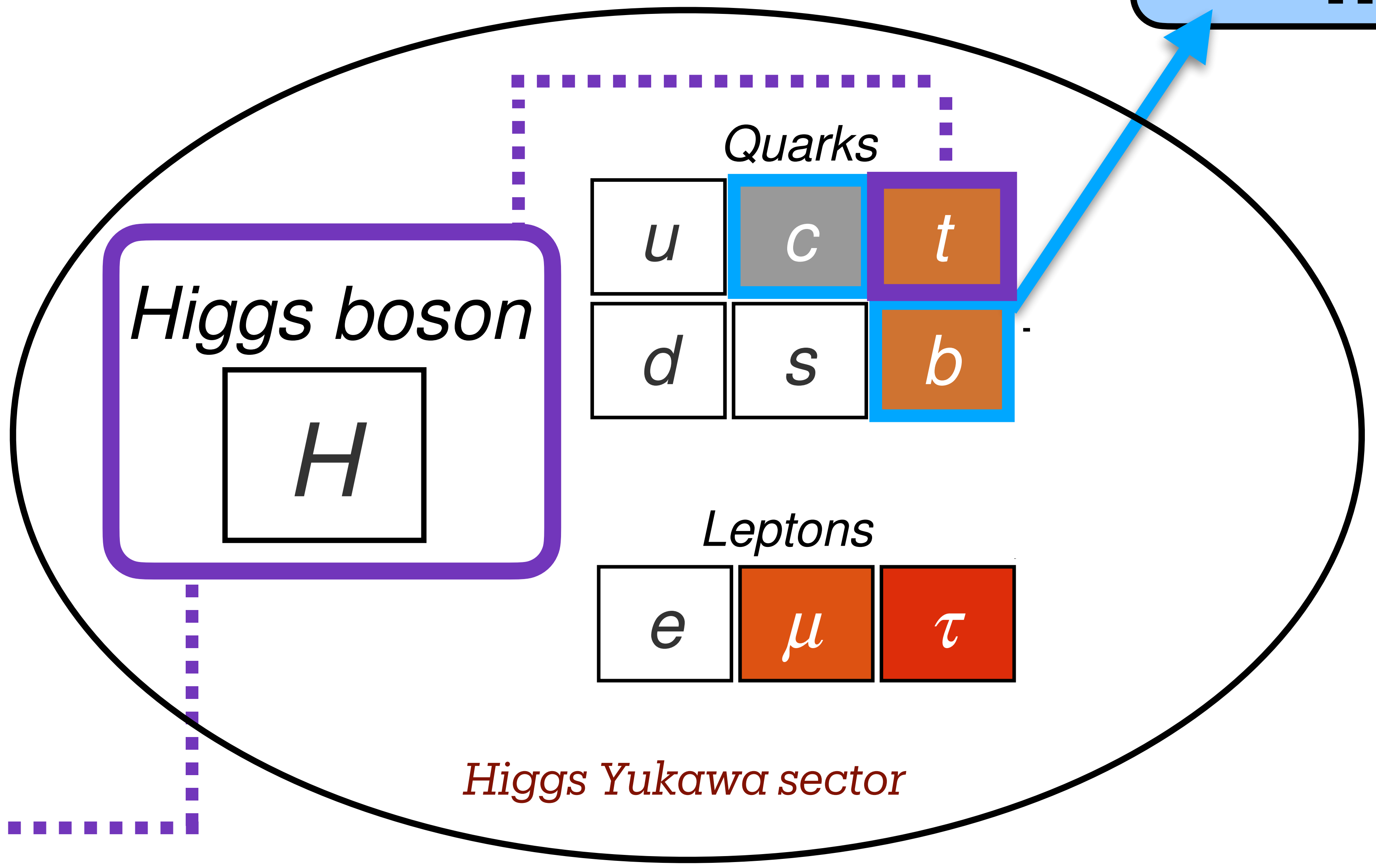
fermion masses

Higgs-fermion interaction

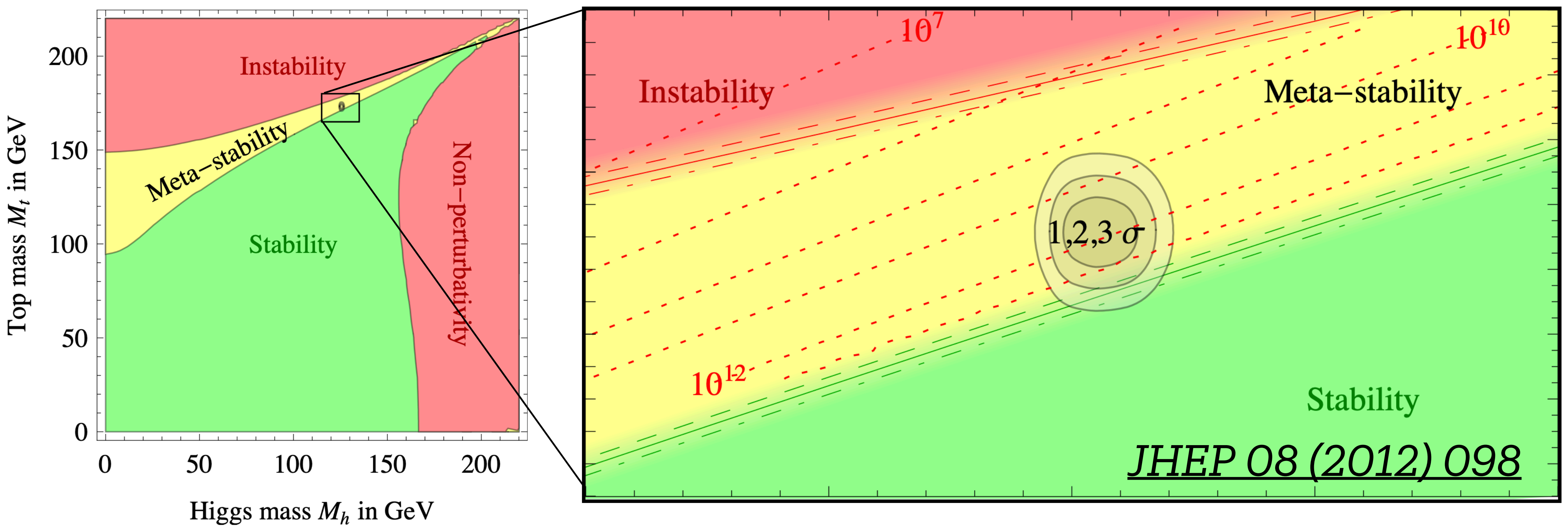
$$\frac{m_f}{v} \rightarrow \frac{y_f}{\sqrt{2}}$$



at tree-level



- Top-Higgs interactions very compelling to study
  - Largest predicted Higgs-Yukawa coupling in SM, $y_t \sim 1$
    - Sensitive to potential new physics
    - role in stability of EW Vacuum
      $\rightarrow$ running of Higgs self-coupling λ
  - Source of CP Violation for baryogenesis
- So, how can we probe these interactions and measure y_t?



JHEP 08 (2012) 098

How to access top-Higgs coupling (y_t)?

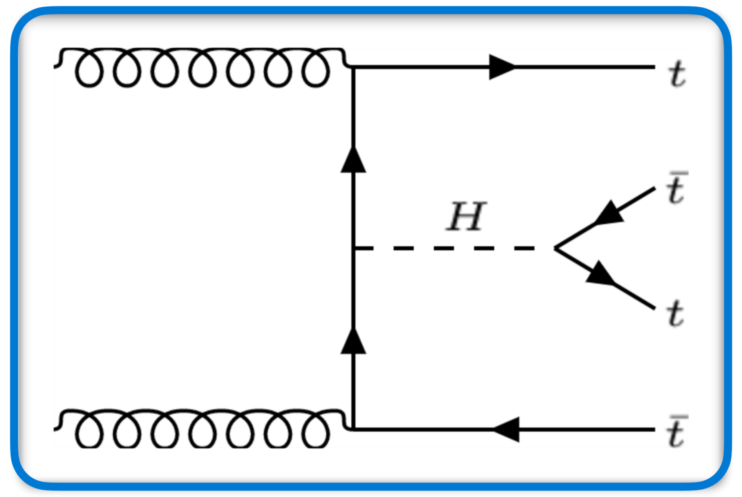
Two approaches to extract y_t from data

Indirect

- Loop-induced single Higgs processes
  - ggF production, $H \to \gamma\gamma$

Cons: assumes no BSM phenom. in loops

- Virtual contributions to top production mechanisms
  - e.g. $t\bar{t}t\bar{t}$ (4-Top) production cross-section



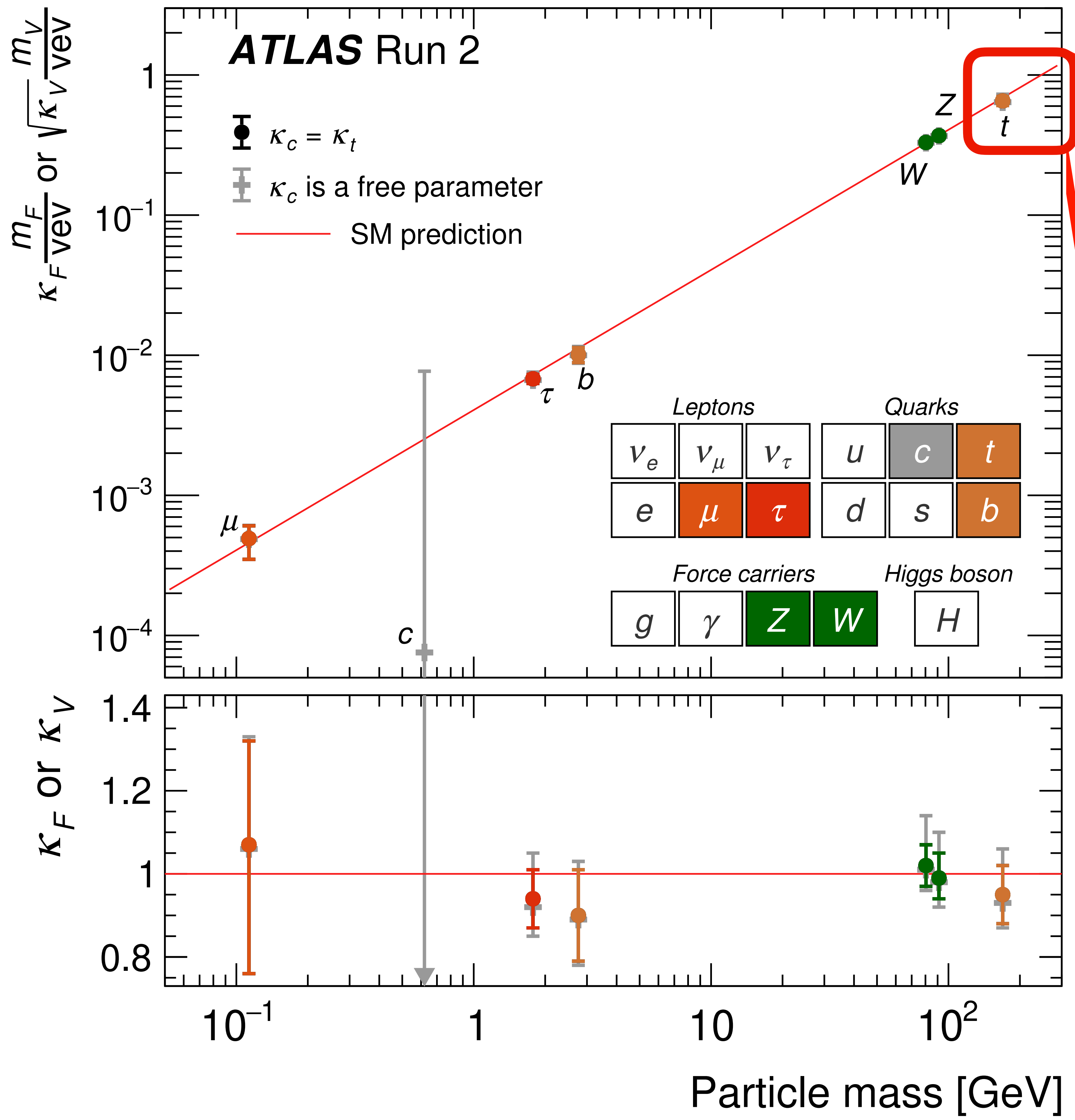
Cons: very rare!

Direct

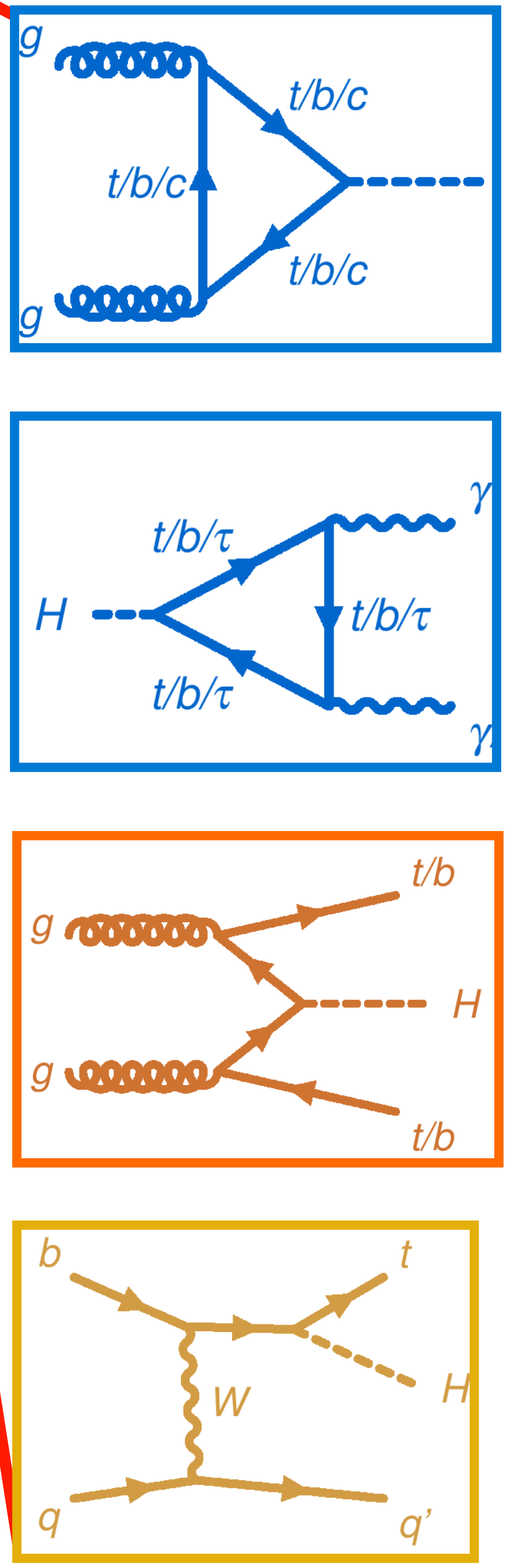
- Tree-level access via $t\bar{t}H$,tH production, $\sigma_{t\bar{t}H} \sim |y_t|^2$
- The focus of this talk today! $\sigma_{tH} \sim (\kappa_t - \kappa_V)^2$

Challenge: small relative production cross-sections

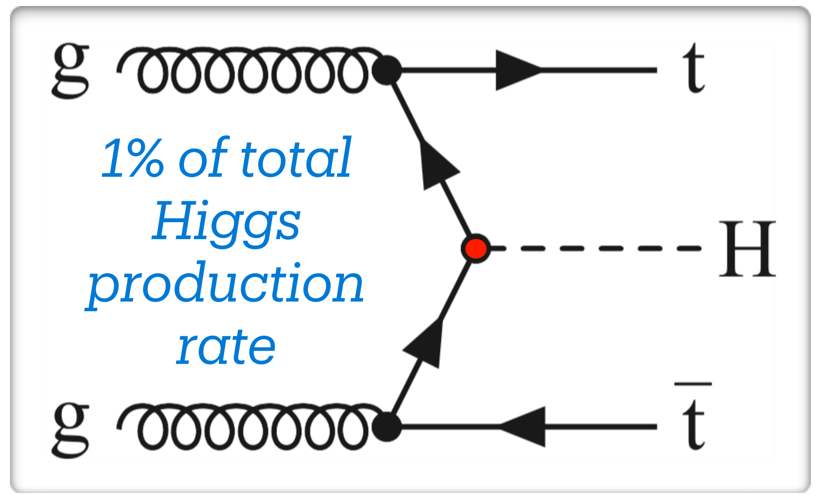
Nature 607 , 52-59 (2022)



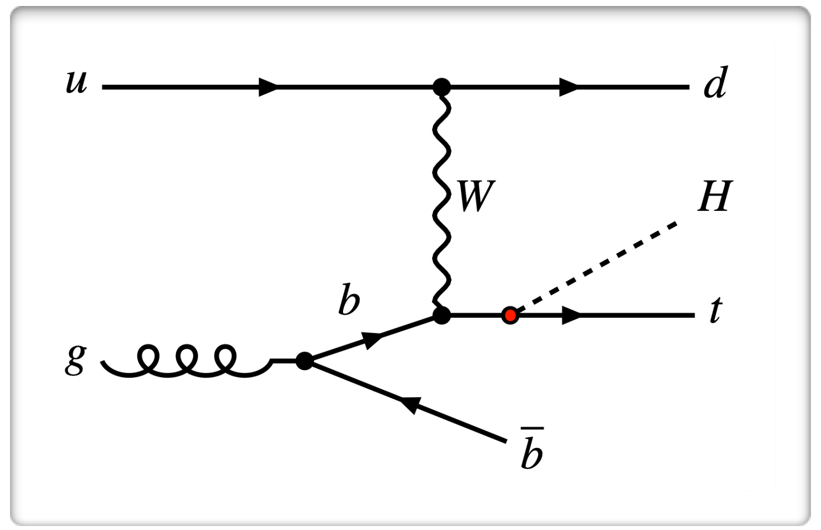
Combination in various production × decay channels



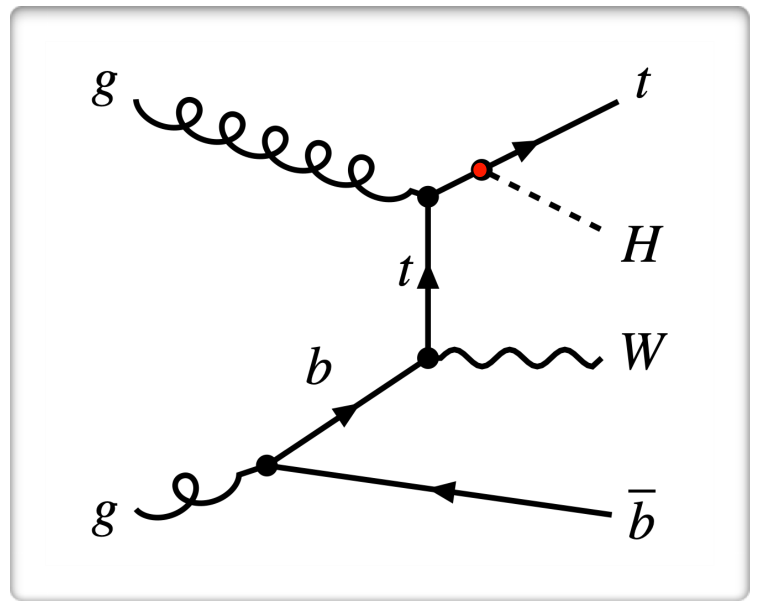
The landscape of *direct access*



$\sigma_{t\bar{t}H} = 507$ fb



$\sigma_{tHq} = 74$ fb



$\sigma_{tHW} = 15$ fb

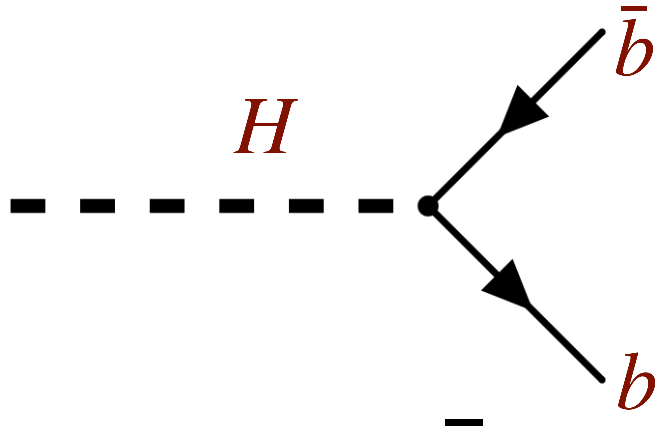
All cross-section at $\sqrt{s} = 13$ TeV

Direct access via top-associated production mechanisms: $t\bar{t}H$, tHq (tHW)

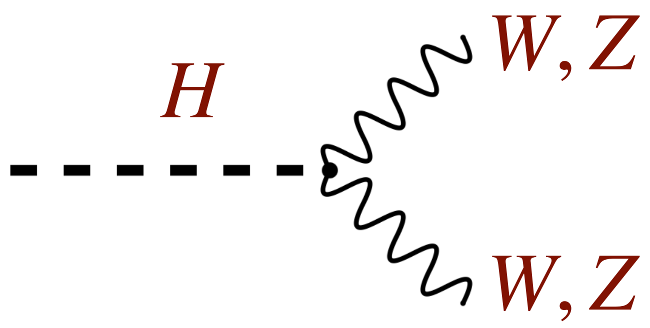
Range of accessible final states to explore, each with benefits/challenges

Higher Statistics

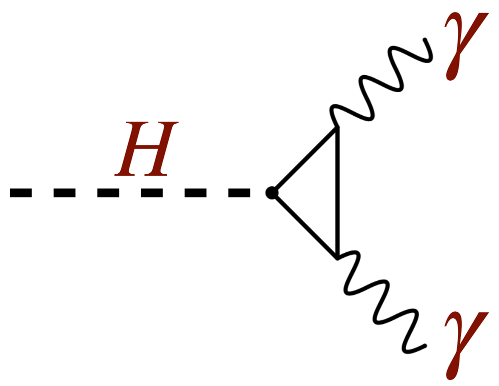
Very small branching ratio



$H \to b\bar{b}$

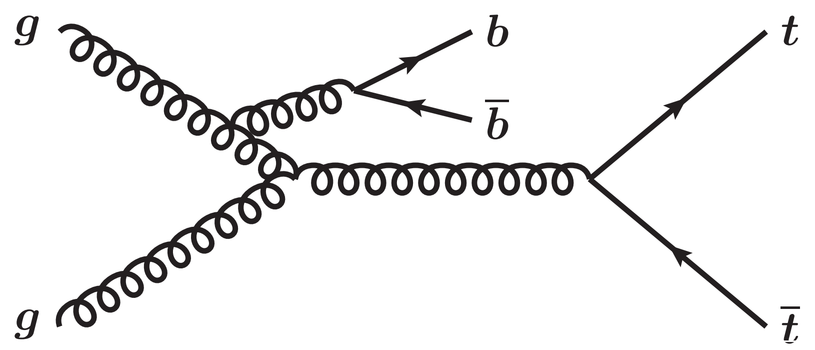


$H \to WW^{\star}, ZZ^{\star}, \tau\tau$

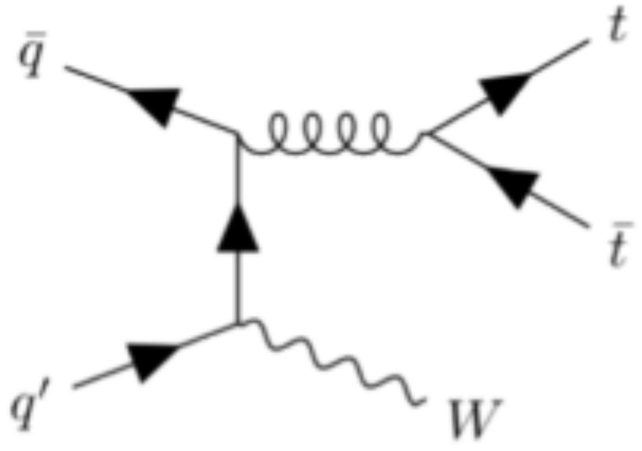


$H \to \gamma\gamma, ZZ \to 4\ell$

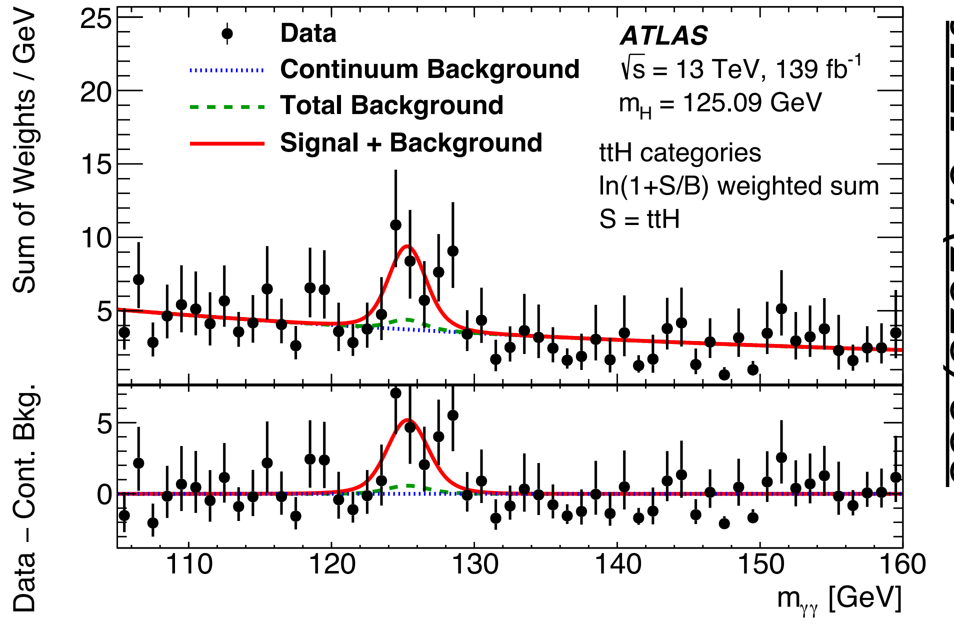
Challenging backgrounds



$t\bar{t} + b\bar{b}$



$t\bar{t}W$



JHEP 07 (2023) 088

Low S/B

Clean peak

Overview of cross-section measurements in ATLAS

- Rich set of $t\bar{t}H$, tH measurements performed with Run-2 data!
- Both inclusive cross-sections and differential (within STXS framework)
- Individual analyses are vital for measurement optimisation...

Dedicated Measurements

$t\bar{t}H(H \rightarrow WW^{\star}, ZZ^{\star}, \tau\tau)$ $\mathscr{L} = 80\,\mathrm{fb}^{-1}, \sqrt{s} = 13\,\mathrm{TeV}$
ATLAS-CONF-2019-045

★ $t\bar{t}H(H \rightarrow b\bar{b})$ $\mathscr{L} = 140\,\mathrm{fb}^{-1}, \sqrt{s} = 13\,\mathrm{TeV}$
Eur. Phys. J. C 85 (2025) 210

Measured with other production modes

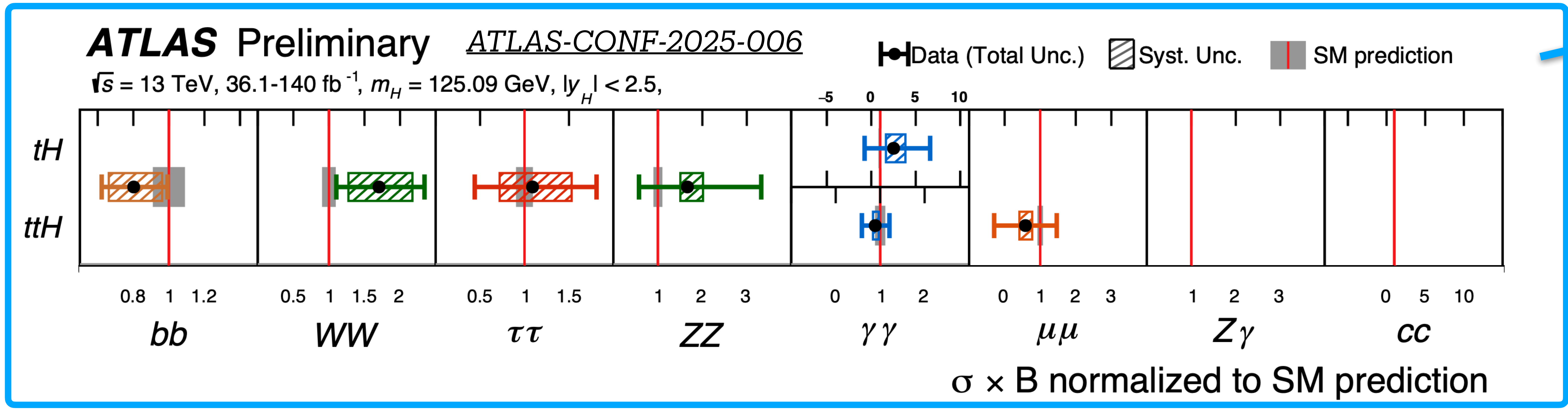
$H \rightarrow ZZ \rightarrow 4l$ $\mathscr{L} = 139\,\mathrm{fb}^{-1}, \sqrt{s} = 13\,\mathrm{TeV}$
Eur. Phys. J C 80 (2020) 957

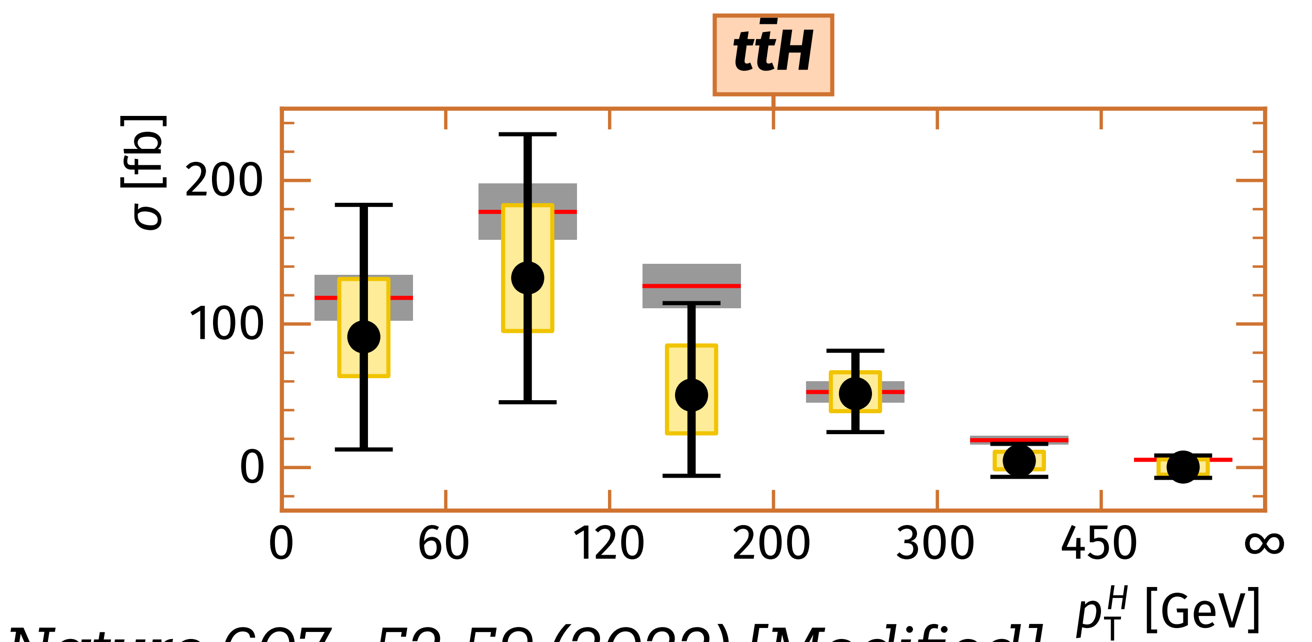
$t\bar{t}H + tH(H \rightarrow \gamma\gamma)$ $\mathscr{L} = 139\,\mathrm{fb}^{-1}, \sqrt{s} = 13\,\mathrm{TeV}$
JHEP 07 (2023) 088

$H \rightarrow \tau\tau$ $\mathscr{L} = 140\,\mathrm{fb}^{-1}, \sqrt{s} = 13\,\mathrm{TeV}$
JHEP 03 (2025) 010

...But, ultimate sensitivity comes from combination of all accessible final states

See talk by Z.Wolffs for updated combination results!





Nature 607 , 52-59 (2022) [Modified]

Overview of property measurements in ATLAS

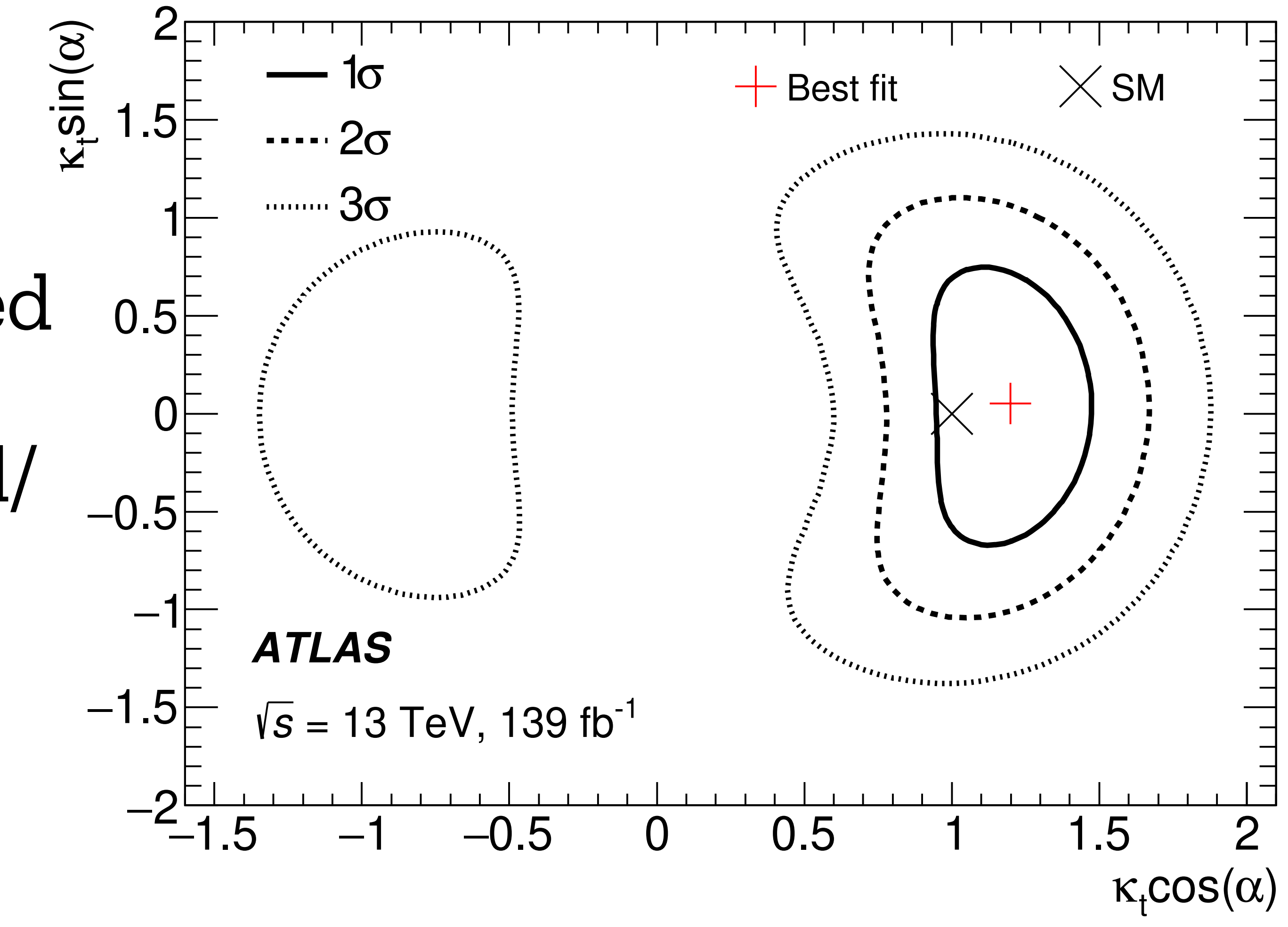
- Can also probe CP properties of top-Higgs interactions and relative sign of y_t
  - Form of interference between t-H and W-H in tH determines relative sign
  - Modified couplings alter both kinematics and production rates of $t\bar{t}H$, tH

$$\mathscr{L} = -\kappa_t' y_t \phi \bar{\psi}_t (\cos\alpha + i\gamma_5 \sin\alpha)\psi_t$$

See talk by M.Kholodenko for more CP property measurements with ATLAS!

$t\bar{t}H + tH(H \to \gamma\gamma)$

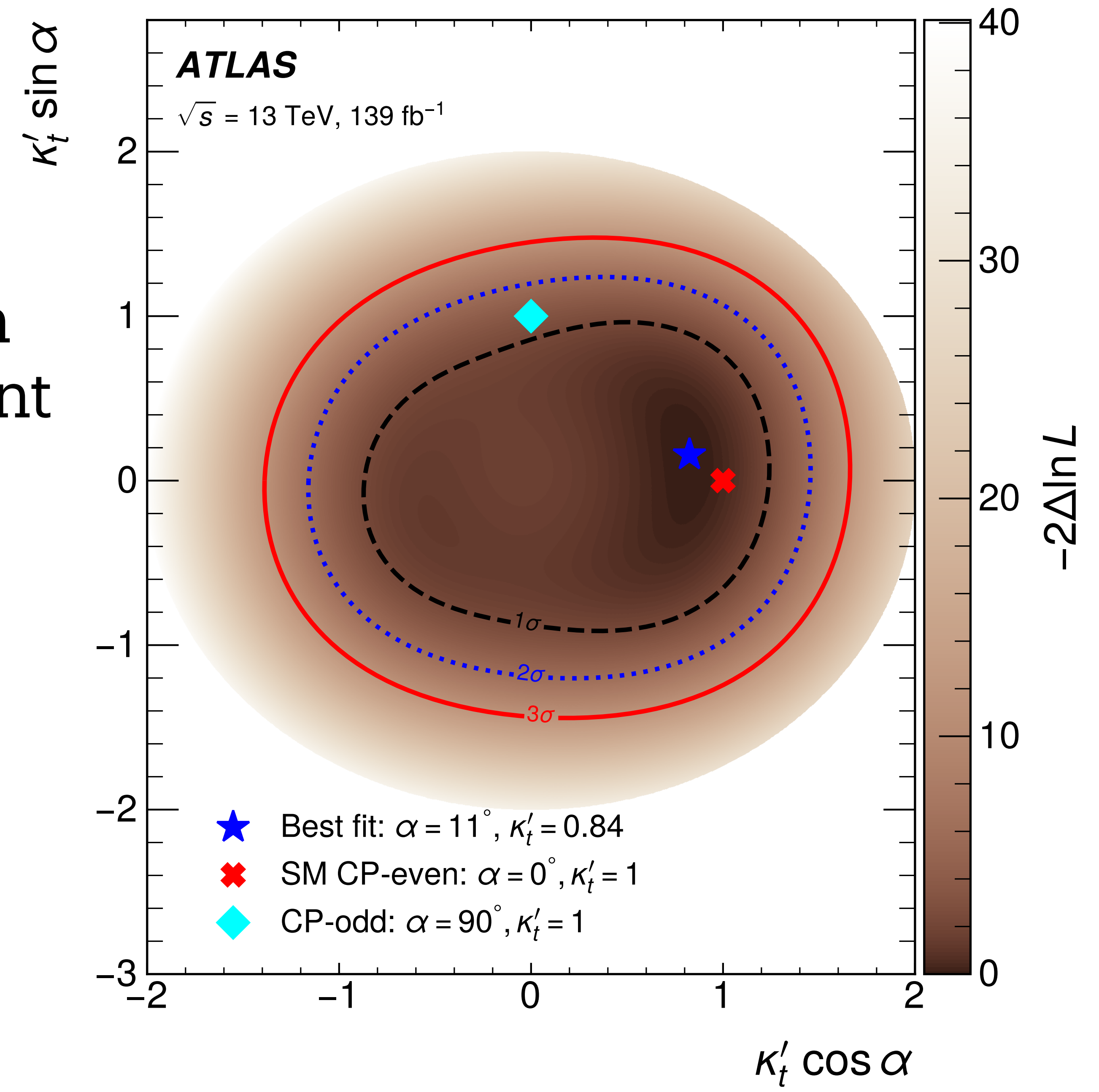
Phys. Rev. Lett. 125 (2020) 061802



- Selected events categorised by 2D BDT for background discrimination and CP odd/even discrimination
  - Top reco. BDT for jet assignment
  - Angular and kinematic observables
- $|\alpha| > 43^\circ$ excluded at 95% C.L.
- Inverted top coupling excluded at 2.5σ
  - $H \to \gamma\gamma$ BR also provides constraints, but model-dependent
- Pure CP-odd hypothesis ($\alpha = 90^\circ$) excluded at 3.9σ

$t\bar{t}H + tH(H \to b\bar{b})$

Phys. Lett. B 849 (2024) 138469



- Analysis design inherited from first full Run-2 SM measurement JHEP 06 (2022) 97
- Events first categorised by jet and b-jet multiplicities
- Further 2D categorisation based on classification BDTs and angular variables sensitive to mixing angle (b_2, b_4)
  - Best fit results: $\alpha = 11^{\circ}{}^{+52^\circ}_{-73^\circ}$, $\kappa_t = 0.84^{+0.30}_{-0.46}$
  - Pure CP-odd hypothesis ($\alpha = 90^\circ$) excluded at 1.2σ

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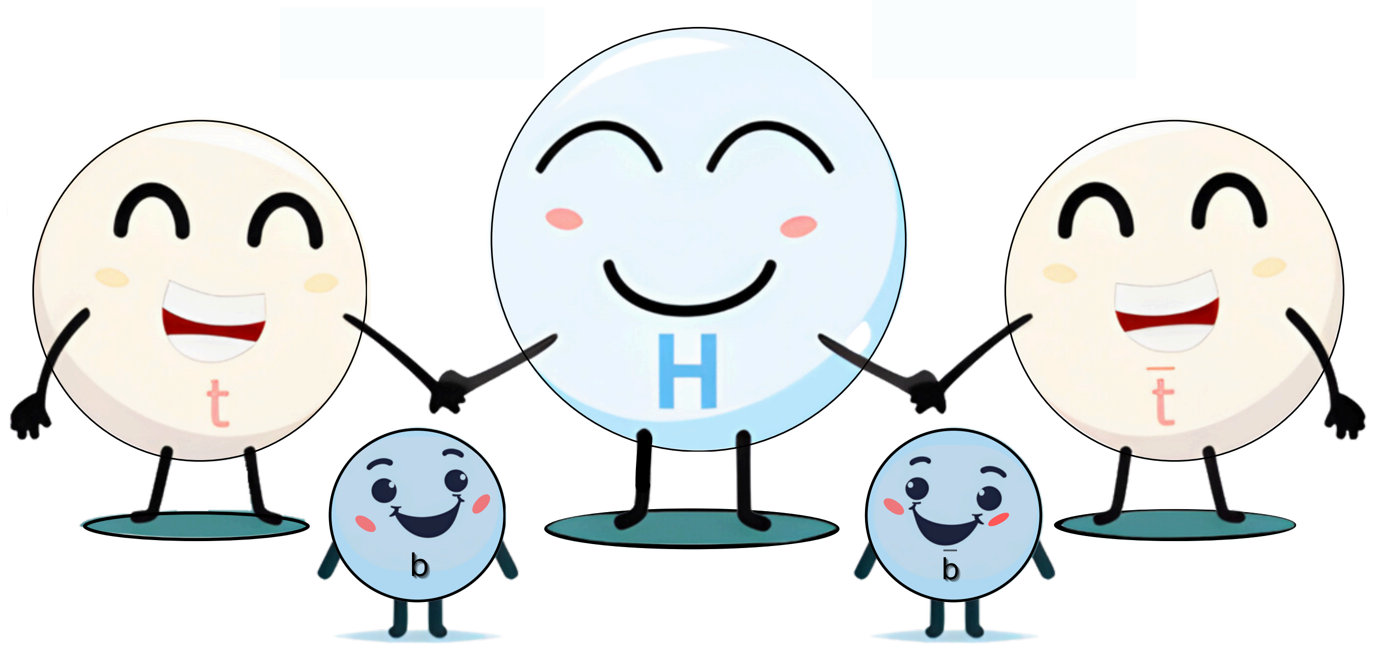
Highlight of Today's talk



Updated $t\bar{t}H\,(H \rightarrow b\bar{b})$ measurement

Goals:

- Measure inclusive cross-section $\sigma_{t\bar{t}H}$
- Measure differential cross-section in bins of p_T^H (STXS v1.2)
  - $H \rightarrow b\bar{b}$ provides critical precision at high p_T^H

Ingredients:

- Improved object definitions and detector reconstruction
- Upgraded flavour tagging algorithm
- New $t\bar{t}$ + jets treatment and uncertainty model
- State-of-the-art event classification and reconstruction with transformer NNs
- Larger statistics by accessing more of the phase-space

First Full Run-2 Measurement

JHEP 06 (2022) 97

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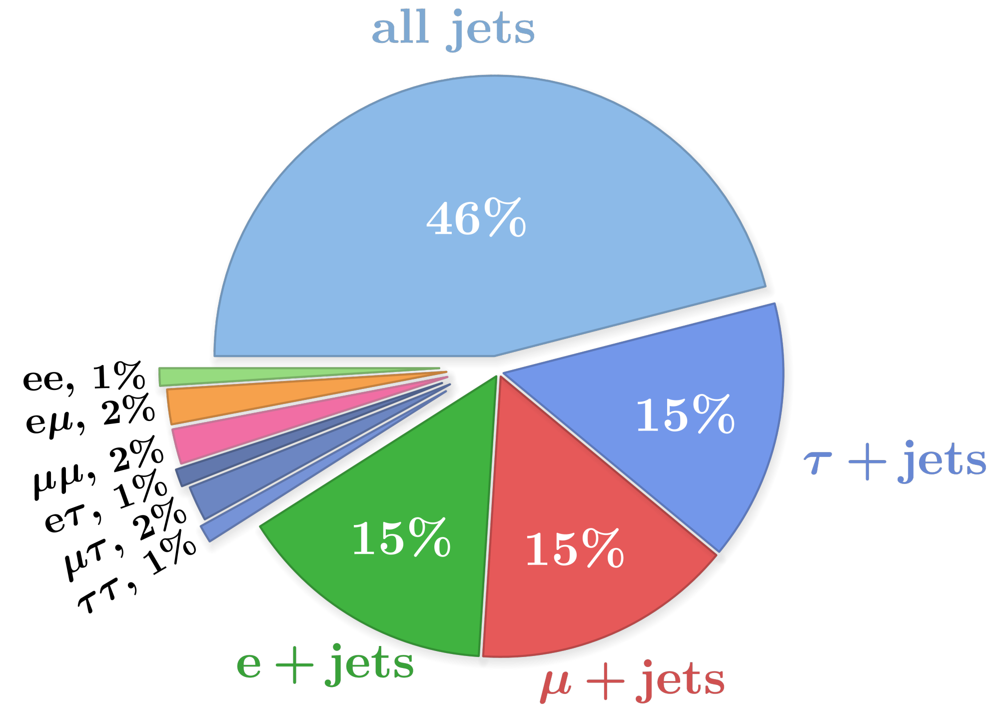
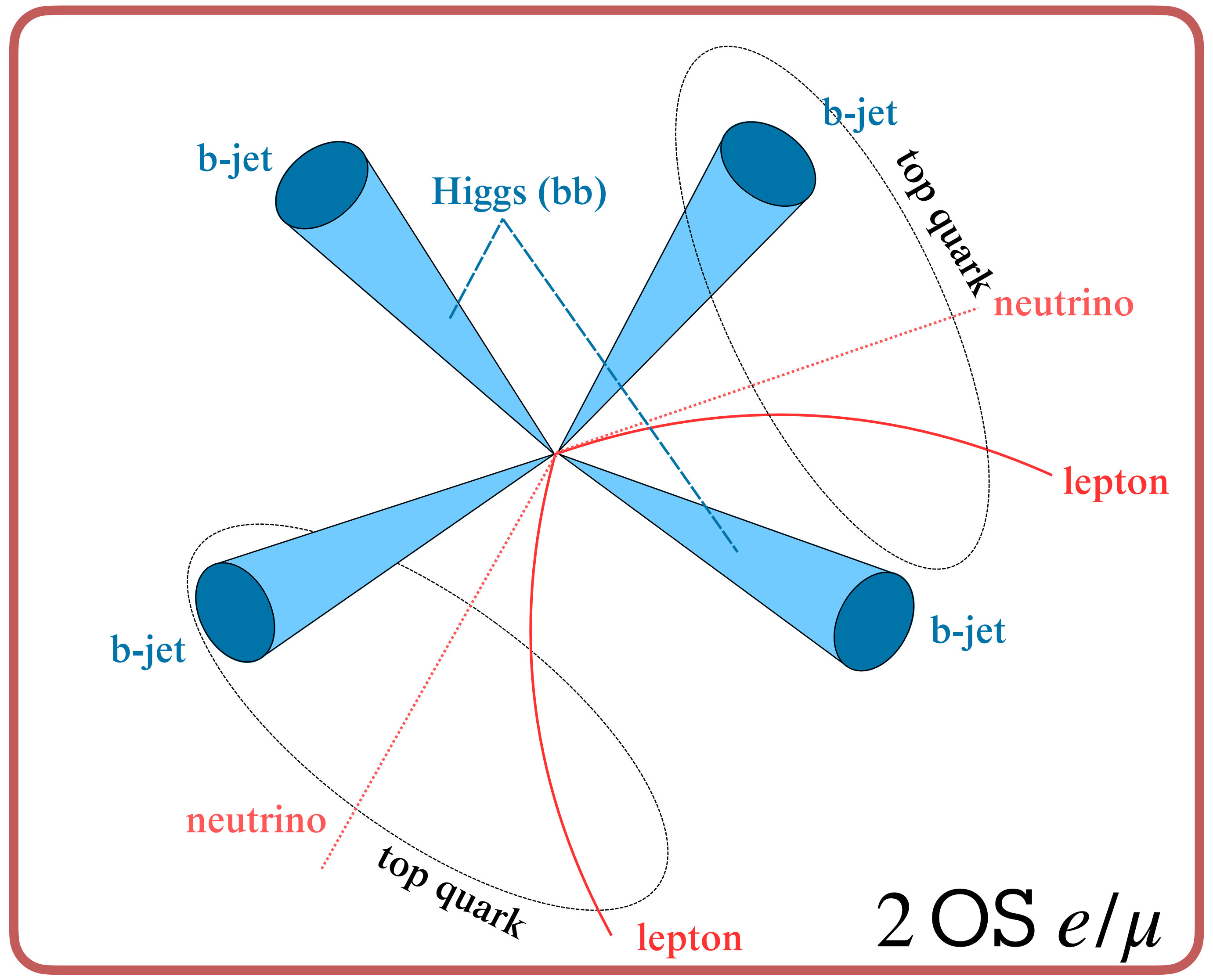
$t\bar{t}H\,(H \rightarrow b\bar{b})$: Analysis Strategy

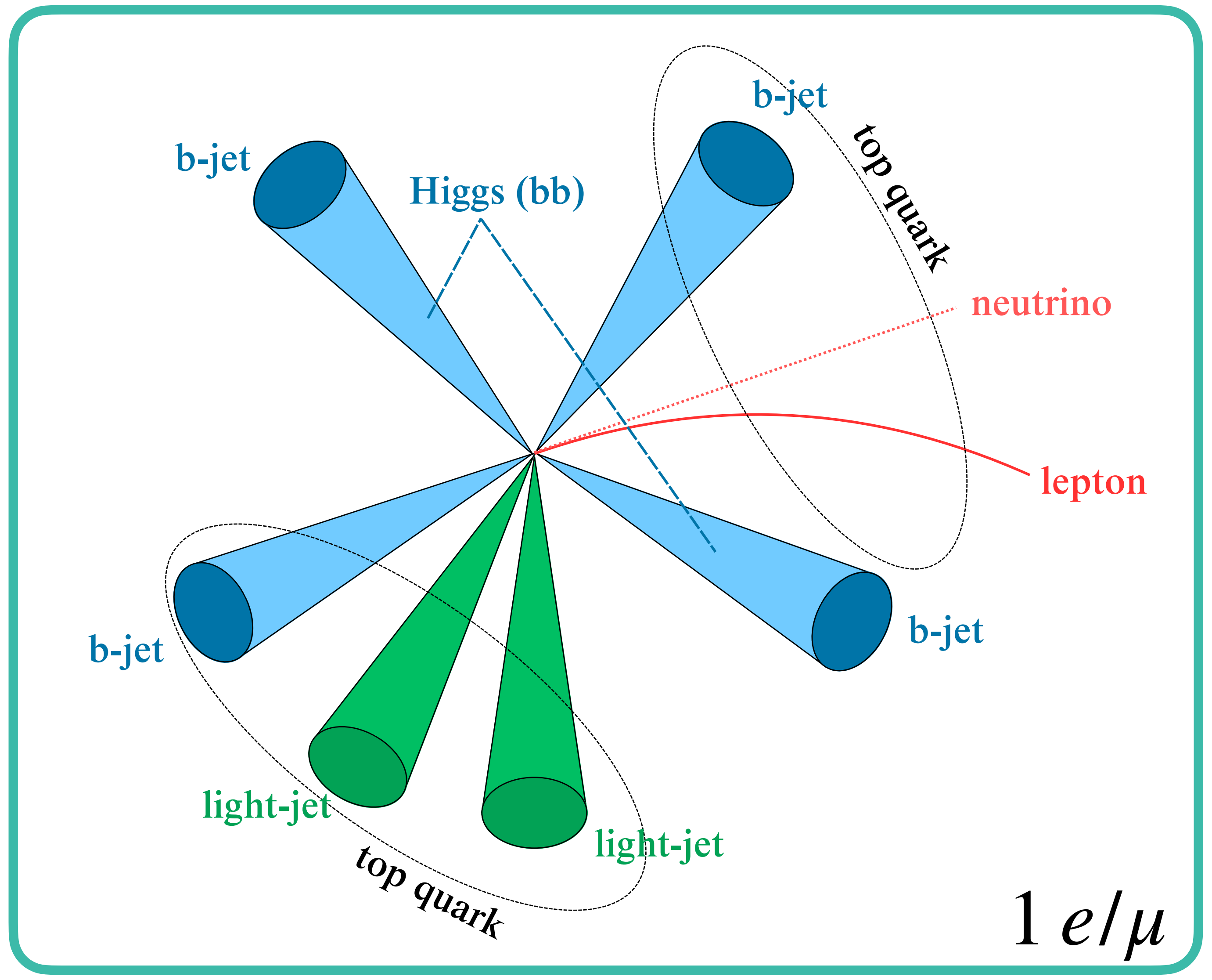


- Analysis performed using $\mathscr{L} = 140\,\text{fb}^{-1}$ of collision data at $\sqrt{s} = 13$ TeV
- Target leptonic decays of top-quark pair to mitigate QCD multi-jet background events

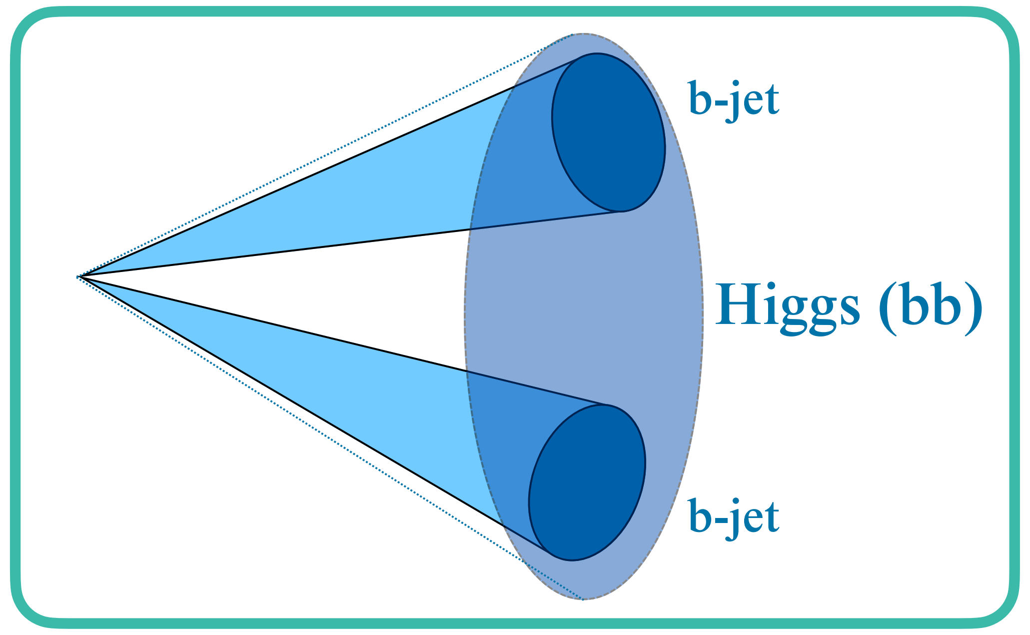
Dilepton



Single-lepton (Resolved)



Single-lepton (Boosted)



Dedicated event category to target collimated (boosted) Higgs decays

- Define a wide pre-selection phase-space to:
  - Maximise the signal acceptance (6.3%!)
  - Maximise statistics for constraining backgrounds

Utilise DL1r b-tagging algorithm

625 (12) light- (charm-) jet rejection

Channel	# Jets	# b-tags (DL1r) 70% WP	# b-tags (DL1r) 85% WP	# e/μ	# τ_{had}	# RC Jets
dilepton	≥ 3	≥ 2	≥ 3	2	0	-
ℓ+jets resolved	≥ 5	≥ 3	≥ 3	1	≤ 1	-
ℓ+jets boosted	≥ 4	-	≥ 3	1	≤ 1	≥ 1

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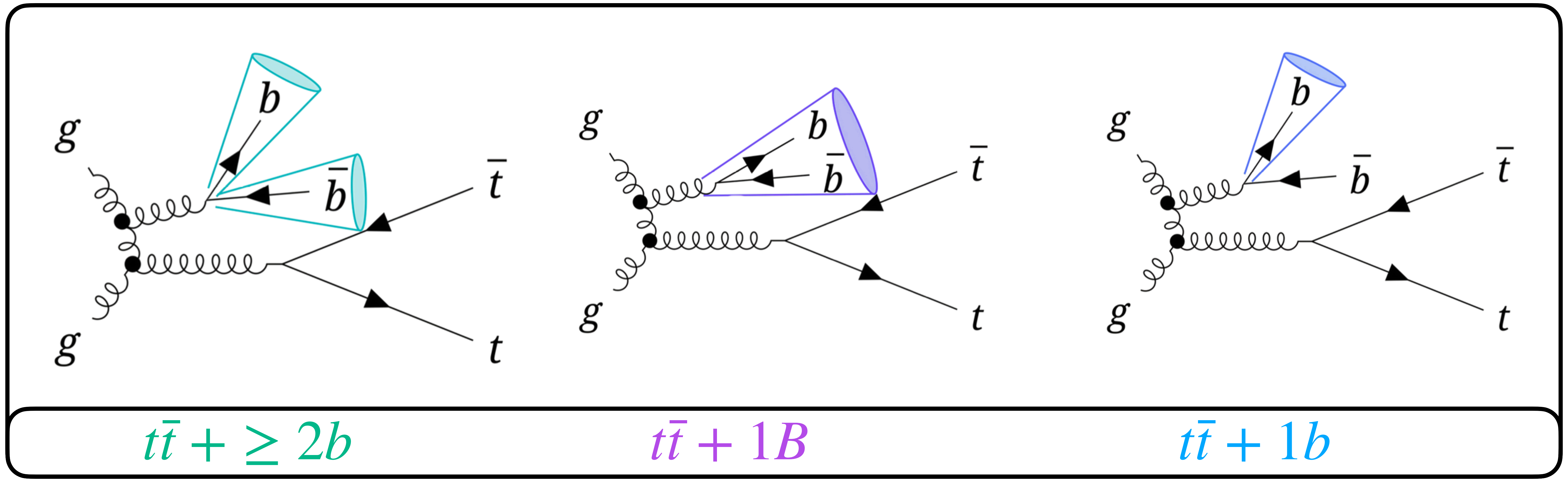
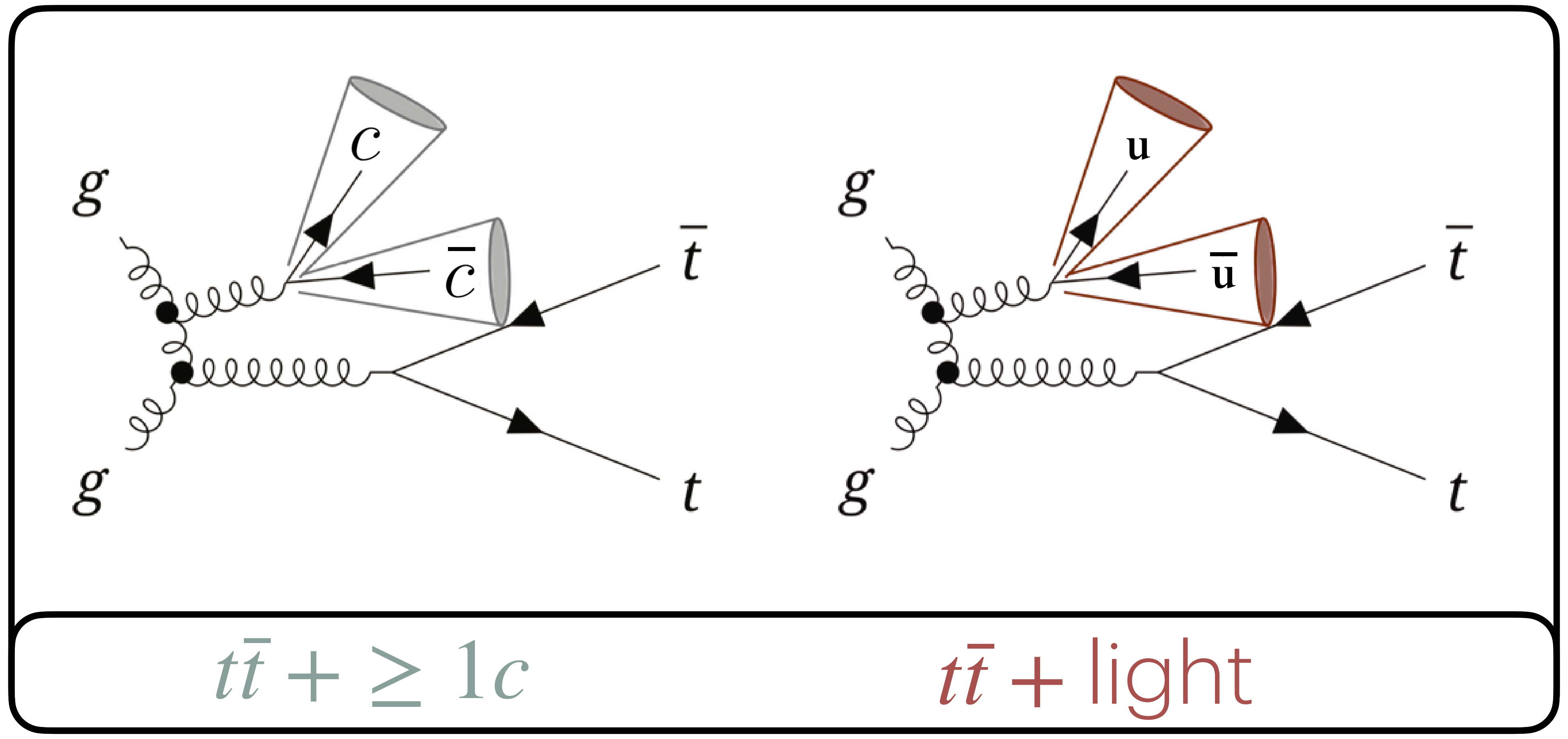
$t\bar{t}H\,(H \rightarrow b\bar{b})$: Background Modelling

- The dominant, irreducible background from $t\bar{t}$ + jets, $t\bar{t} + b\bar{b}$ in particular, very difficult to model
- Additional jets beyond $t\bar{t}$ system are classified via particle-level matching, giving rise to 5 categories

$t\bar{t}b\bar{b}$ 4FS NLO PowhegPythia8



Inclusive $t\bar{t}$ 5FS NLO PowhegPythia8



Credit: C. Scheulen

- Dedicated work performed to derive $t\bar{t}b\bar{b}$ MC settings that better describe data and an improved systematic model

  → Coherent $t\bar{t}b\bar{b}$ uncertainty treatment all within 4-flavour scheme, optimised QCD scale variations
- Data-driven corrections applied pre-fit to correct flavour-fractions, and H_T mis-modelling in 5FS predictions
- Independent set of systematics and free-floating normalisation for each flavour component

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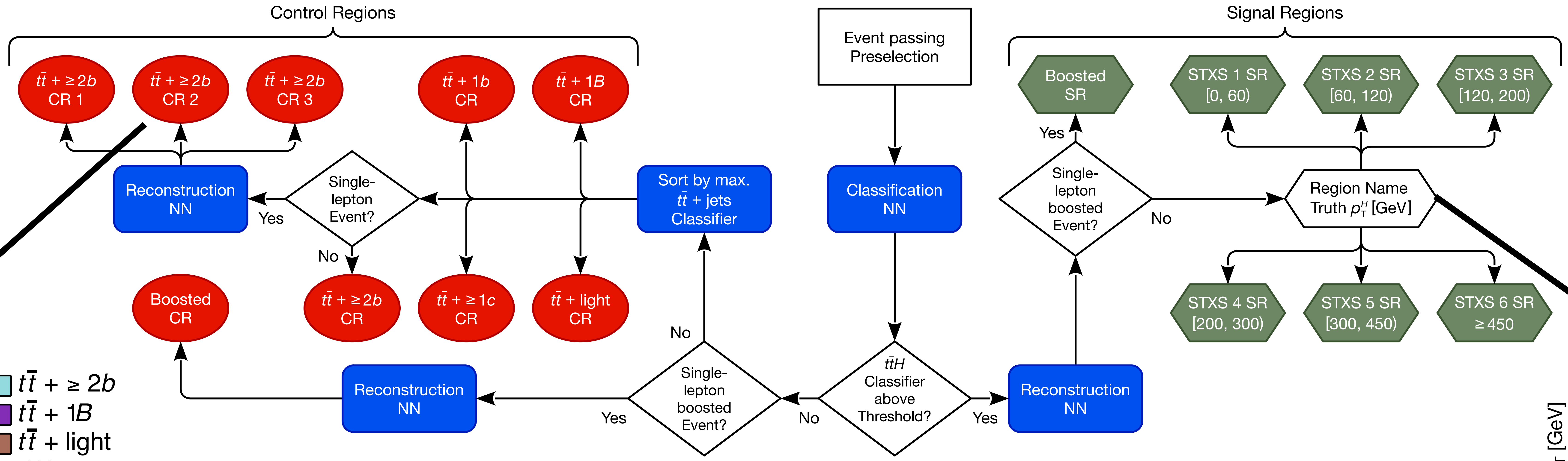
$t\bar{t}H\,(H \to b\bar{b})$: Analysis Design

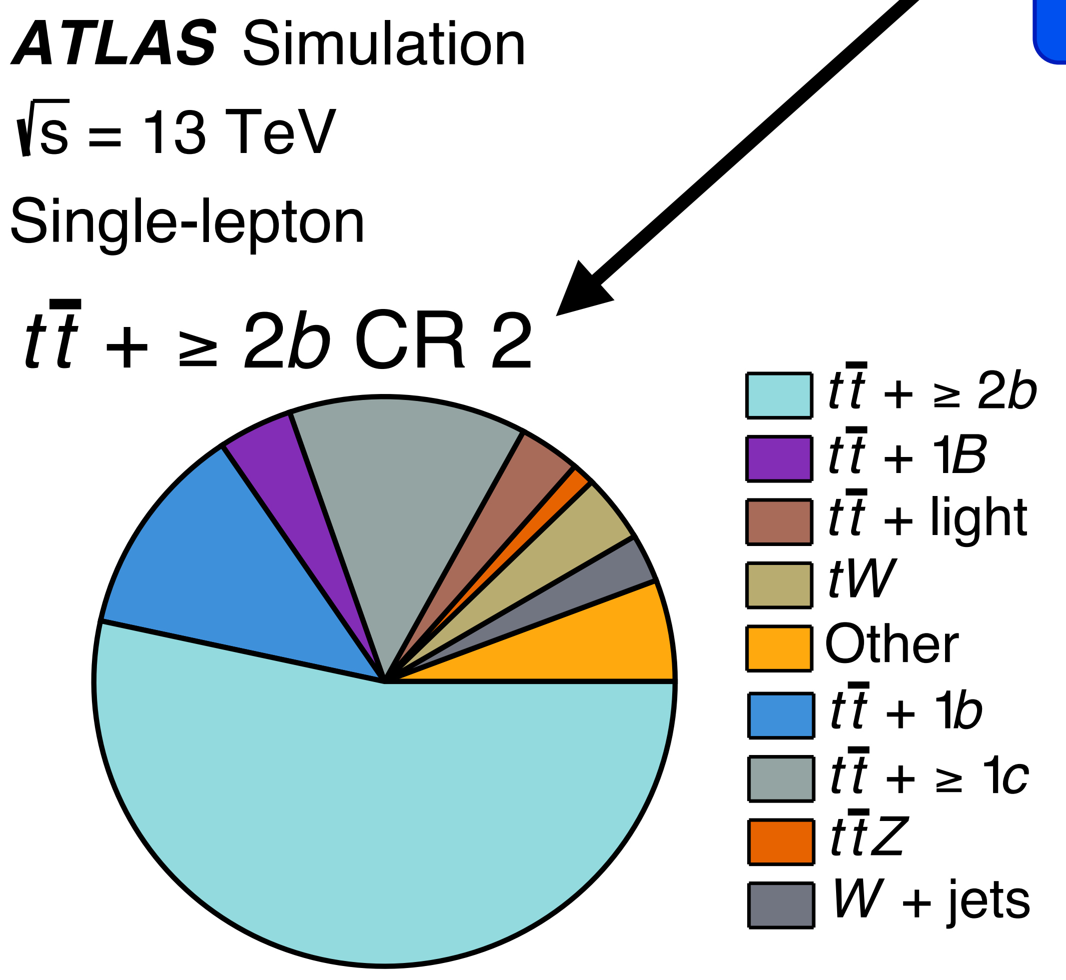
- ML-based region definitions utilised in the analysis

→ Two transformer-based neural networks used, with different strategies in the final layers for downstream task

Classification NN → $t\bar{t}H$, $t\bar{t}+\geq 2b$, $t\bar{t}+1B$, $t\bar{t}+1b$, $t\bar{t}+\geq 1c$, $t\bar{t}$ + light

Reconstruction NN → Identify jets originating from Higgs decay



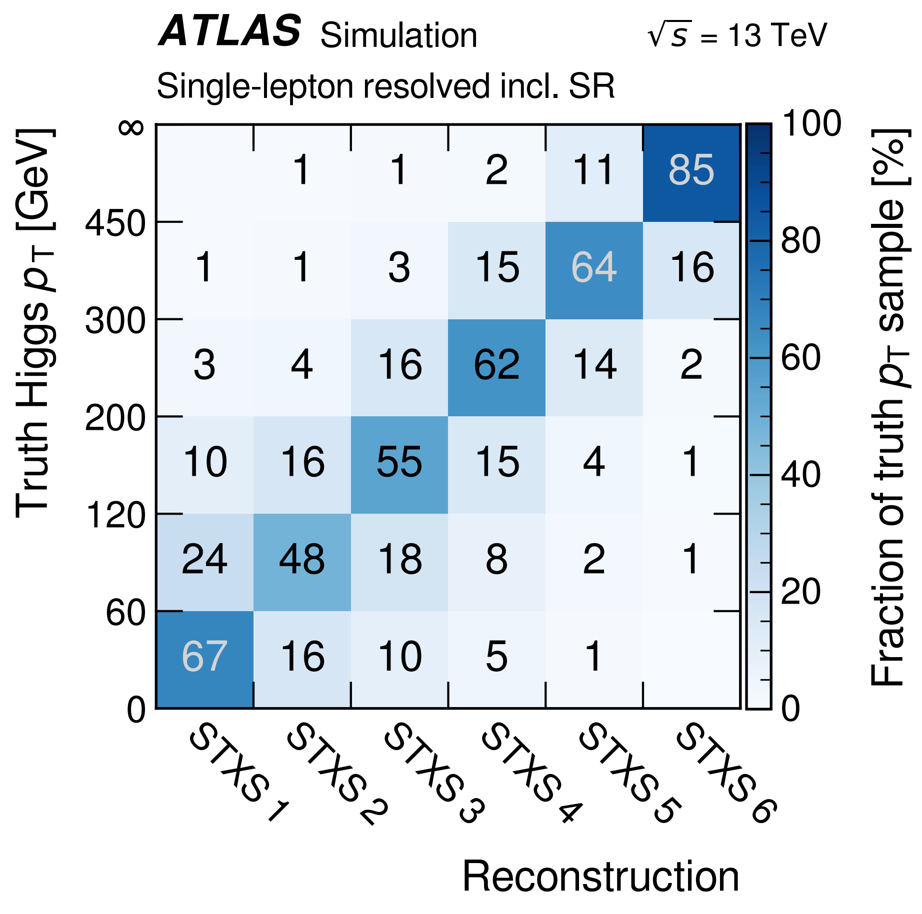


Pre-fit region composition

What are the benefits?

- *Dedicated* & *enriched* control region for each flavour-component of $t\bar{t}$ + jets background
- High signal purity, with S/B ranging from 10-17% in SRs
- Use NN discriminants as observables for cross-section extraction in likelihood fit

Performance



$t\bar{t}H\,(H \rightarrow b\bar{b})$: Results

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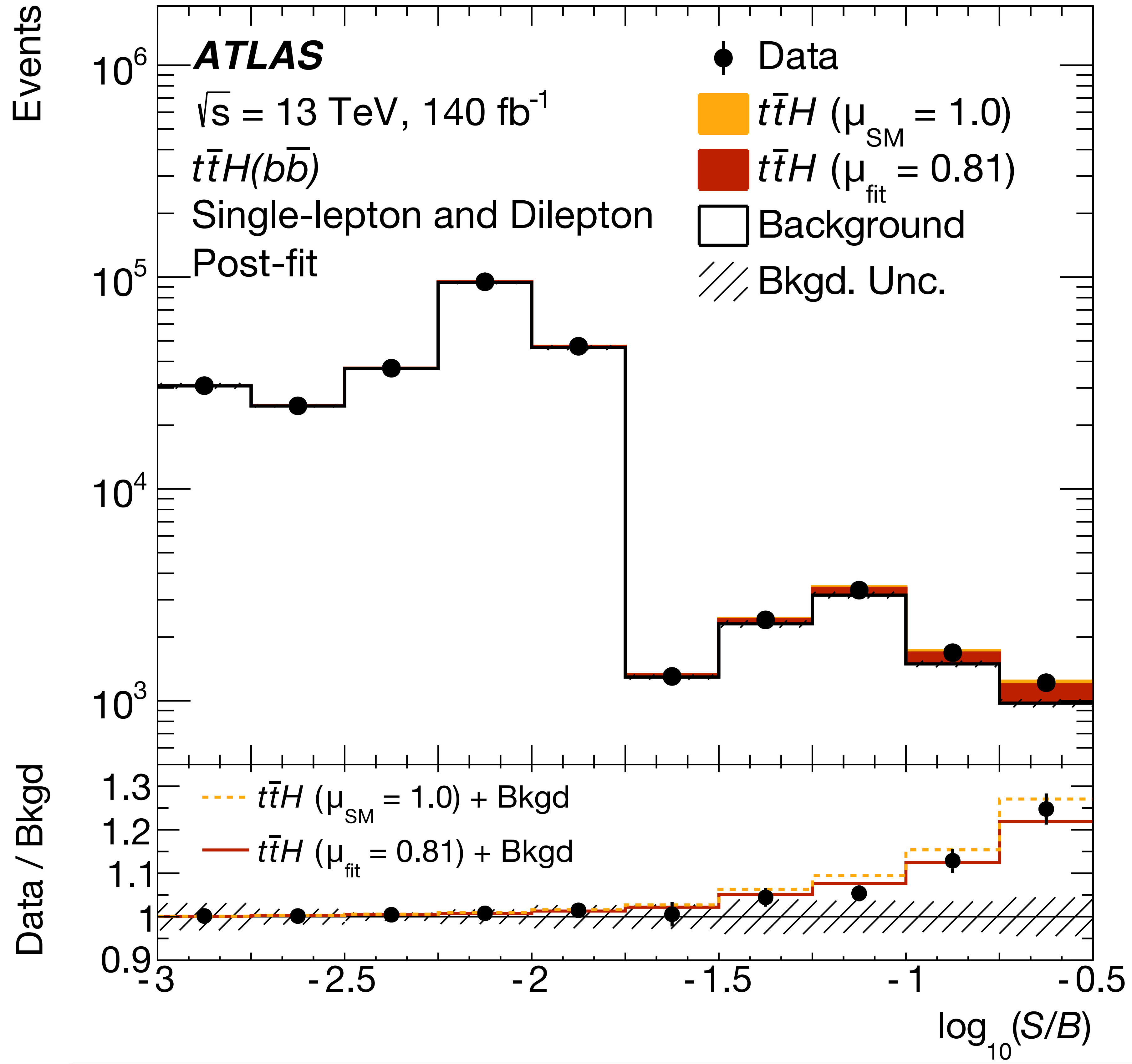
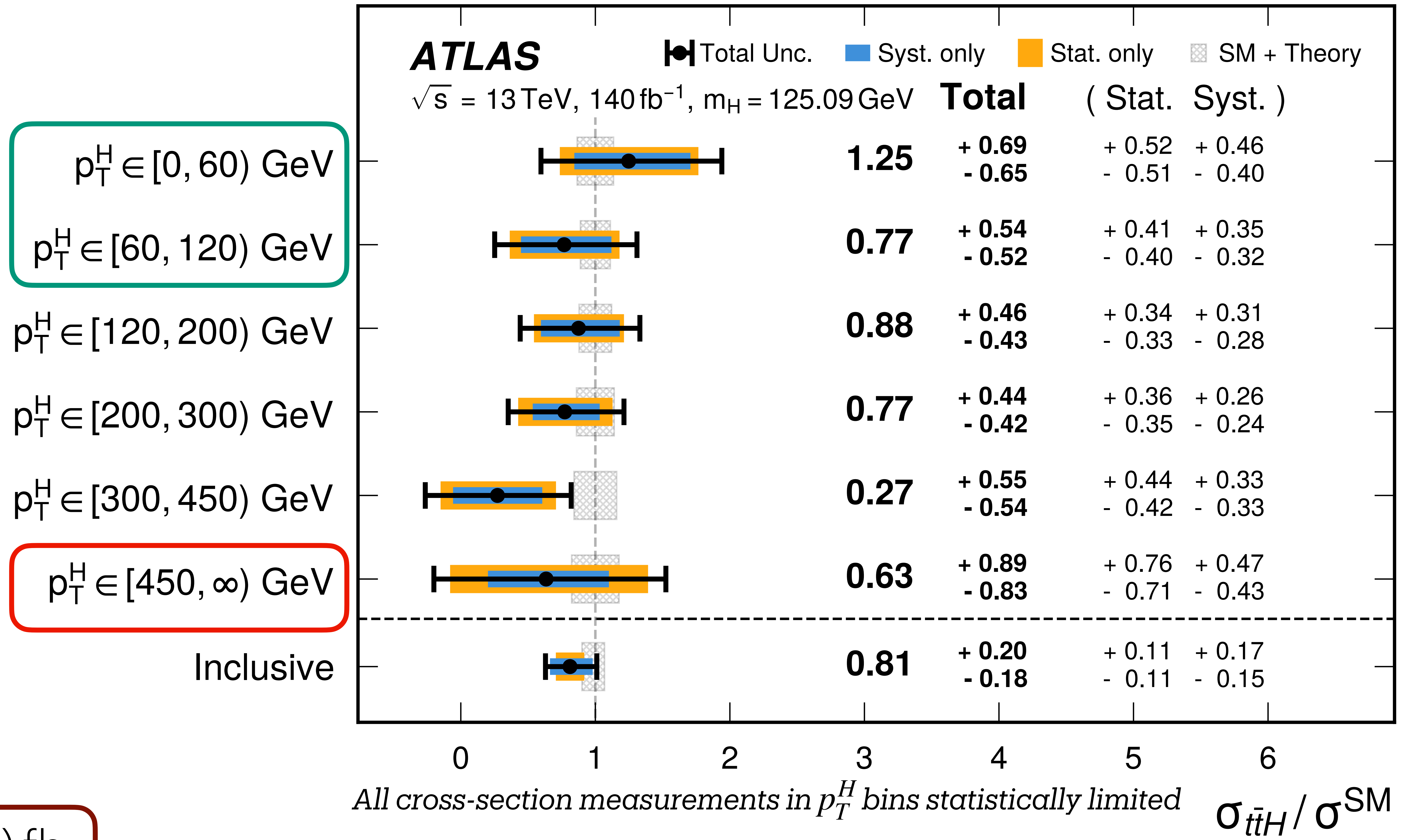
- Cross-section(s) extracted through simultaneous binned profile likelihood fit to all signal and control regions
- Excellent agreement with the Standard Model observed



$$\sigma_{t\bar{t}H} = 411^{+101}_{-92}\ \text{fb} = 411 \pm 54\,(\text{stat.})^{+85}_{-75}\ (\text{syst.})\ \text{fb}$$

- Observed (Expected) significance of $4.6\,(5.4)\,\sigma$



All cross-section measurements in p_T^H bins statistically limited

- Differential measurements in bins of p_T^H
  - Lowest bins resolved for the first time
  - Boosted category improves precision in $p_T^H \in [450,\infty)$ by 15%

$t\bar{t}H\,(H \to b\bar{b})$: Uncertainties

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- Breakdown of contributions to uncertainty

Modelling uncertainties

- Leading contributions from modelling of $t\bar{t}H$ signal
  - Pertaining to variations in amount of final-state radiation
  - parton-shower algorithm choice
- Large contributions from modelling of $t\bar{t} + b\bar{b}$ background
  - Primarily from $t\bar{t} + \geq 2b$ component
    - Variations in amount of final-state radiation
    - Recoil scheme in Pythia-based Parton shower
  - Parton-shower algorithm choice in $t\bar{t} + 1b$

Experimental uncertainties

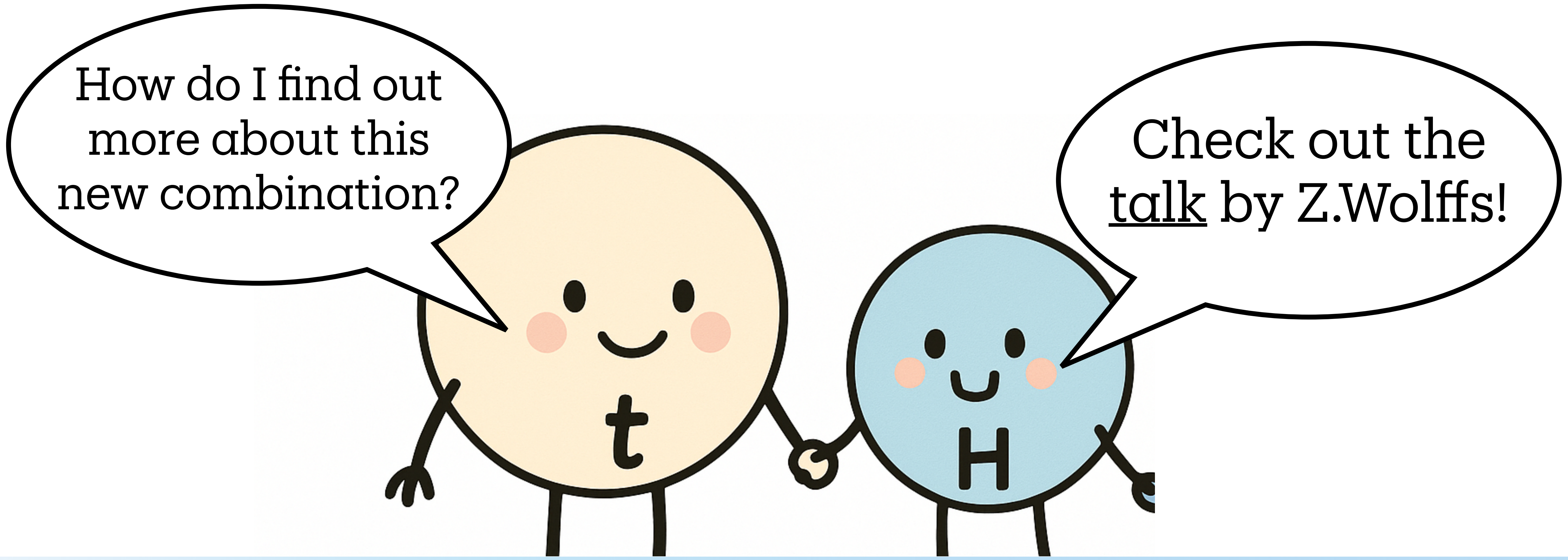
- Main contribution from flavour tagging efficiencies
- Other smaller contributions from jet modelling

Uncertainty source	$\Delta\sigma_{t\bar{t}H}$ (fb)		$\Delta\sigma_{t\bar{t}H}/\sigma_{t\bar{t}H}$ (%)	
Process modelling				
$t\bar{t}H$ modelling				
$t\bar{t}H$ radiation	+35	−21	+9	−5
$t\bar{t}H$ parton shower	+32	−19	+8	−5
$t\bar{t}H$ matching	<0.1	−0.3	<0.1	−0.1
$t\bar{t}H$ theory	+25	−17	+6	−4
$t\bar{t} + \geq 1b$ modelling				
$t\bar{t} + \geq 1b$ radiation	±31		±8	
$t\bar{t} + \geq 1b$ parton shower	±29		±7	
$t\bar{t} + \geq 1b$ matching	±19		±5	
$t\bar{t} + \geq 1c$ modelling	±18		±4	
$t\bar{t}$ + light modelling	±5		±1	
tW modelling	±16		±4	
Minor background modelling	±19		±5	
Flavour tagging	±36		±9	
Jet modelling	±22		±5	
Monte-Carlo statistics	±17		±4	
Other instrumental	±10		±2	
Total systematic uncertainty	+85	−75	+21	−18
Normalisation factors	±21		±5	
Total statistical uncertainty	±54		±13	
Total uncertainty	+101	−92	+25	−22

The Fruits of Labour

How is this result already being utilised?

- Updated $t\bar{t}H(H \rightarrow b\bar{b})$ analysis used as input to new coupling combination
  - *Expected* uncertainty on κ_t reduced by 26%!
  - New analysis driving this sensitivity improvement



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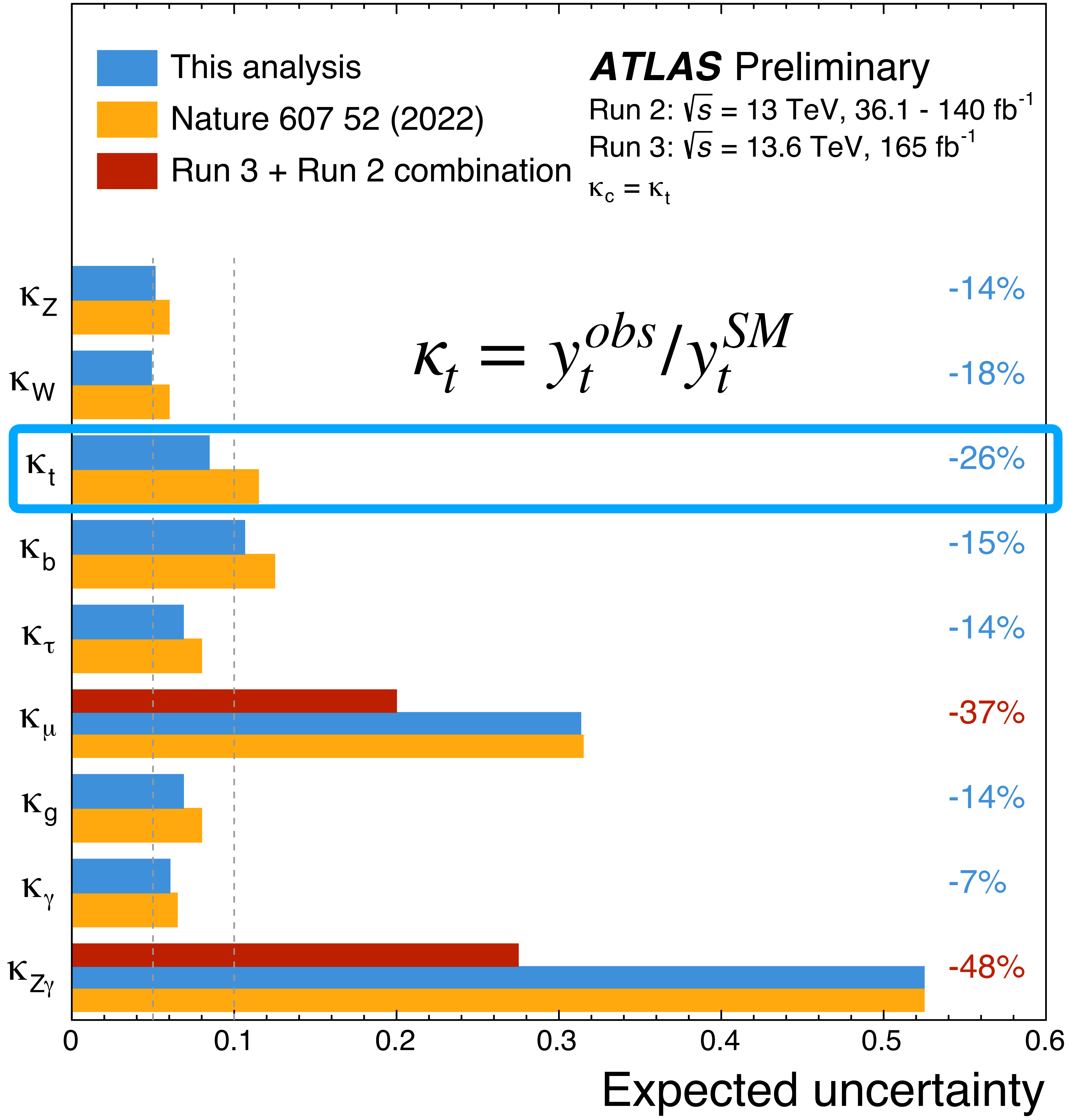

Conclusions and Outlook

- Measurements involving the two heaviest SM particles are vital to test the SM and probe for new physics
- Direct access via $t\bar{t}H$,tH production provides *cleanest* route to probing top-Higgs dynamics
- Highlighted experimental strategy to exploit all decay modes in this production channel for ultimate sensitivity
  - Rich array of measurements from ATLAS using the Run-2 dataset!
- Highlighted property measurements to search for new phenomena, where inclusion of tH is crucial (CP-nature, relative sign of y_t)

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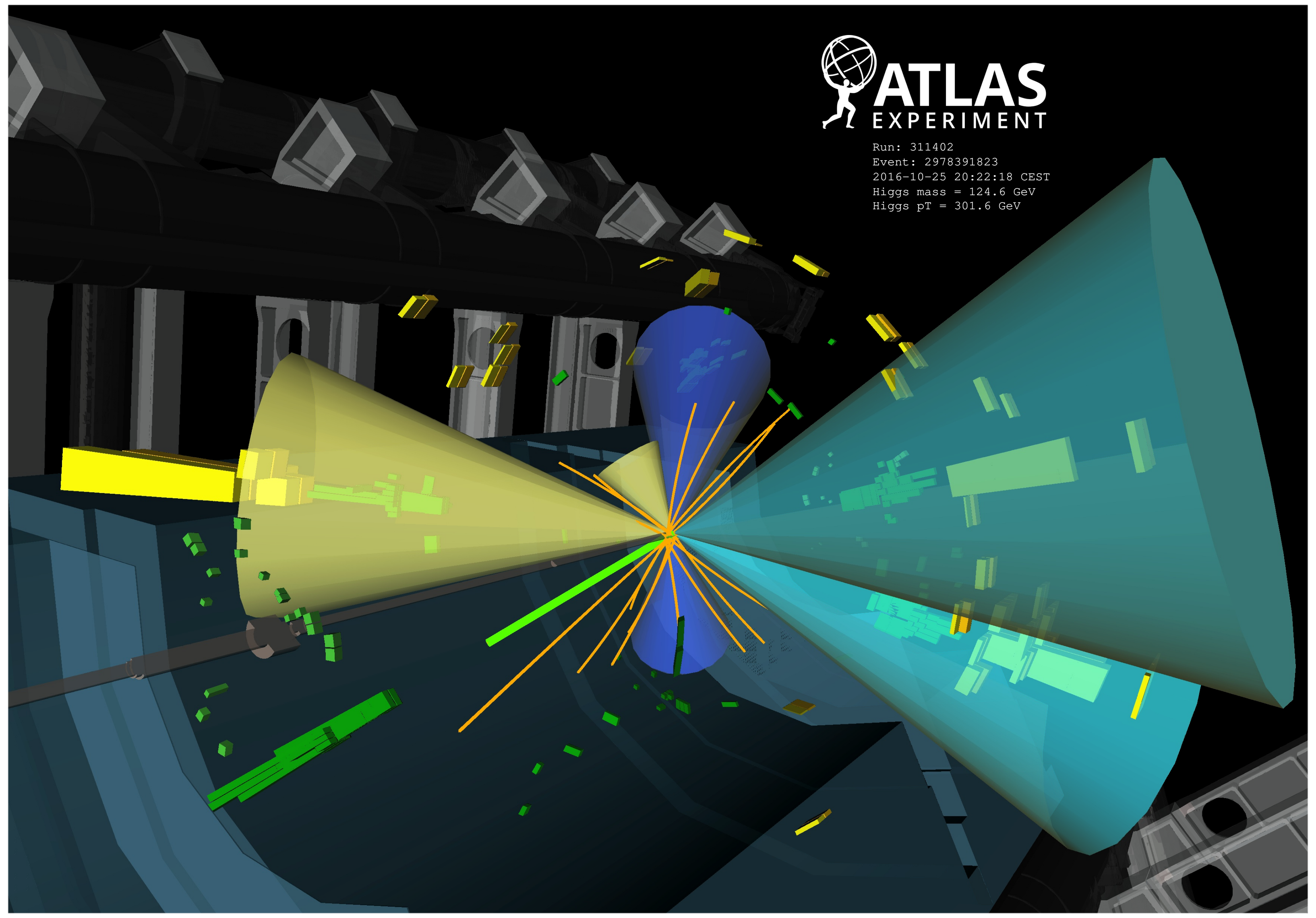


"Event display of $t\bar{t}H(H \to b\bar{b})$ candidate event in the single-lepton decay channel"

- Presented updated $t\bar{t}H\ (H \to b\bar{b})$ analysis: factor 1.8 improvement in uncertainty for inclusive cross-section
  - Vital input to drive increased precision in latest Higgs combination
  - Adds precision at high p_T^H for future STXS combinations

$$\mu_{t\bar{t}H} = 0.81^{+0.22}_{-0.18}\left(^{+0.20}_{-0.16}\ \text{syst.}\right)$$

Relative to SM expectation

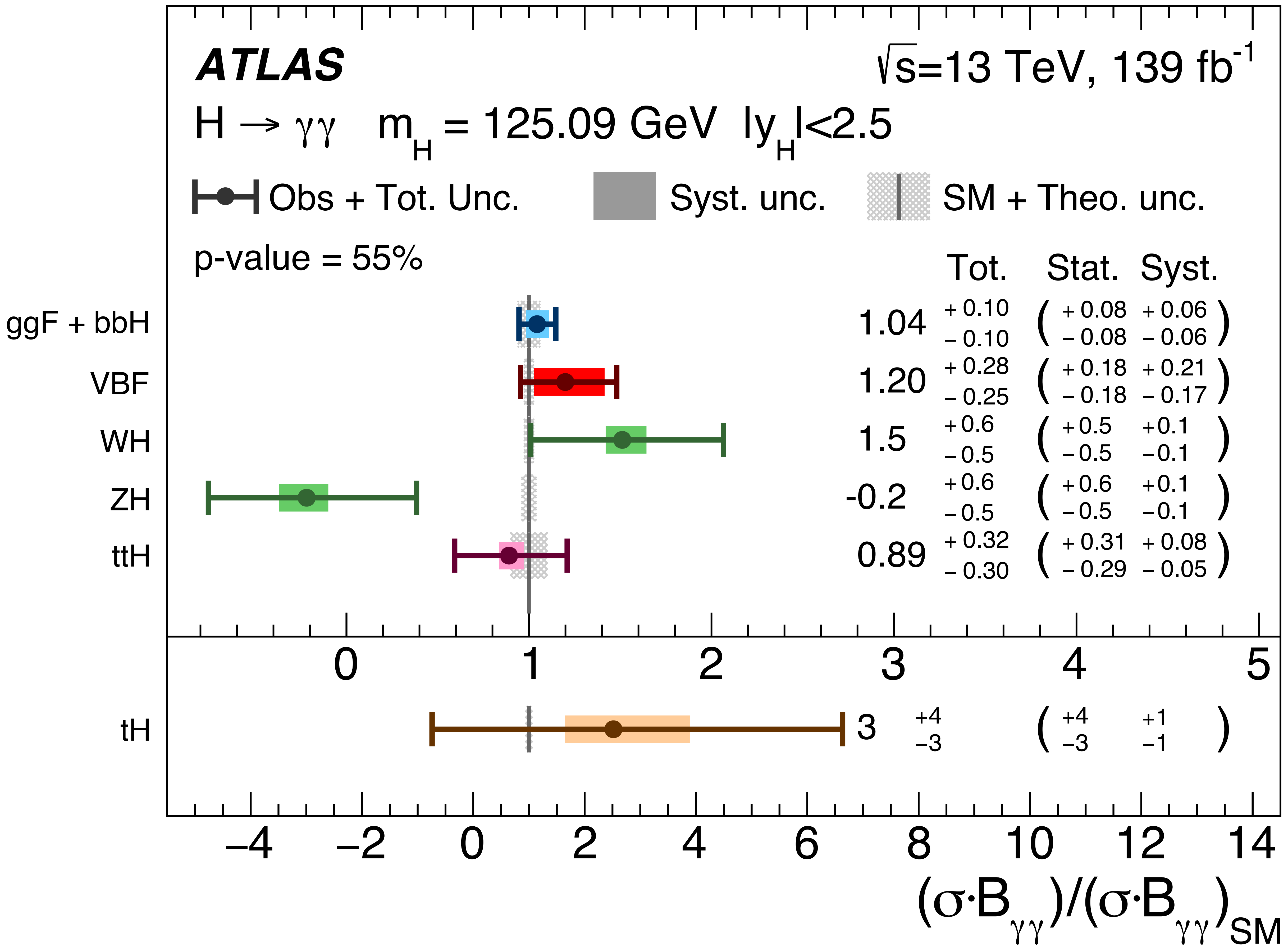
- More statistics from Run-3 will allow for improved precision in STXS measurements

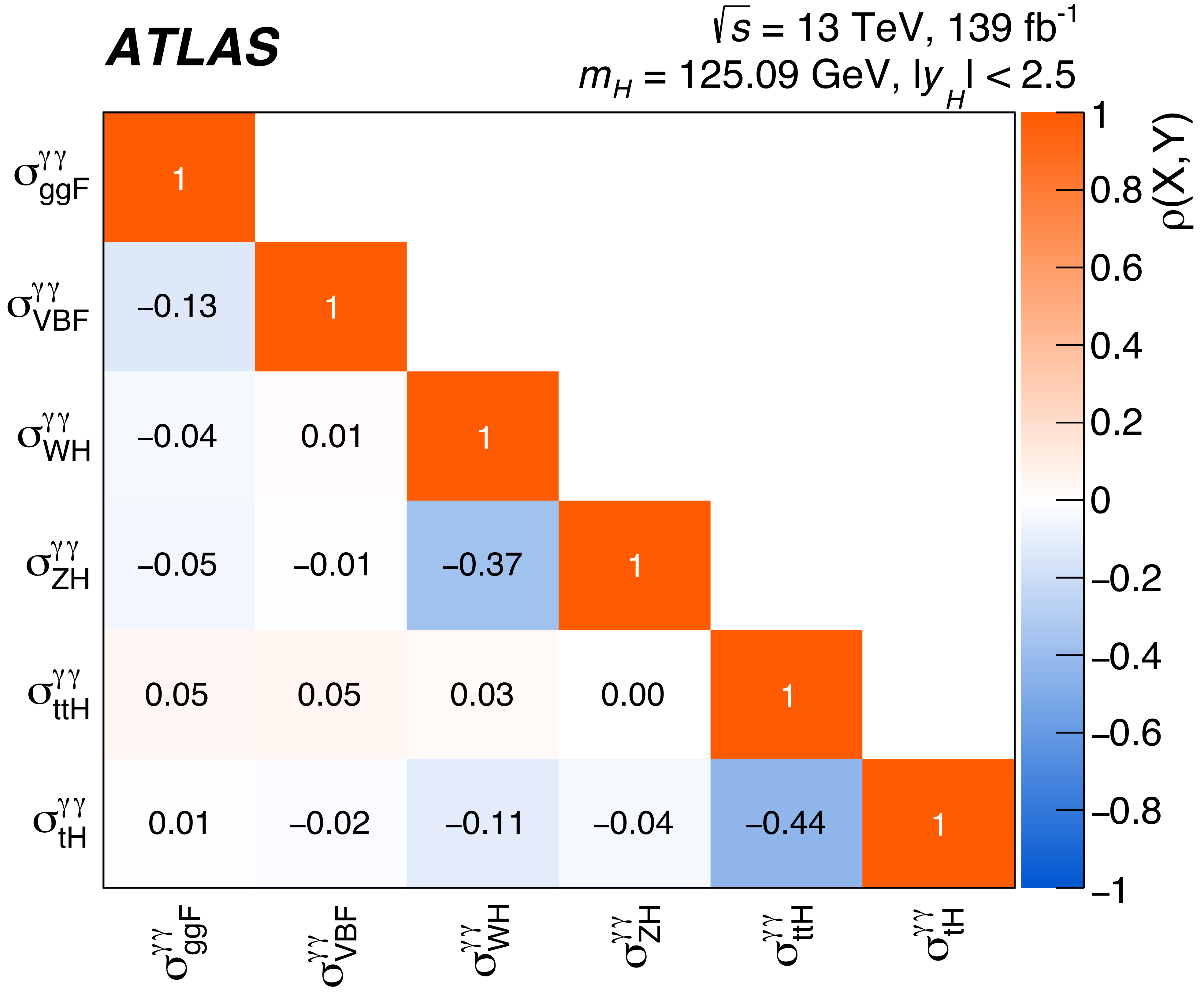
Thank you for your attention!

BACKUP SLIDES

$t\bar{t}H, tH\,(H \rightarrow \gamma\gamma)$

JHEP 07 (2023) 088





$t\bar{t}H, tH\,(H \to \gamma\gamma)$

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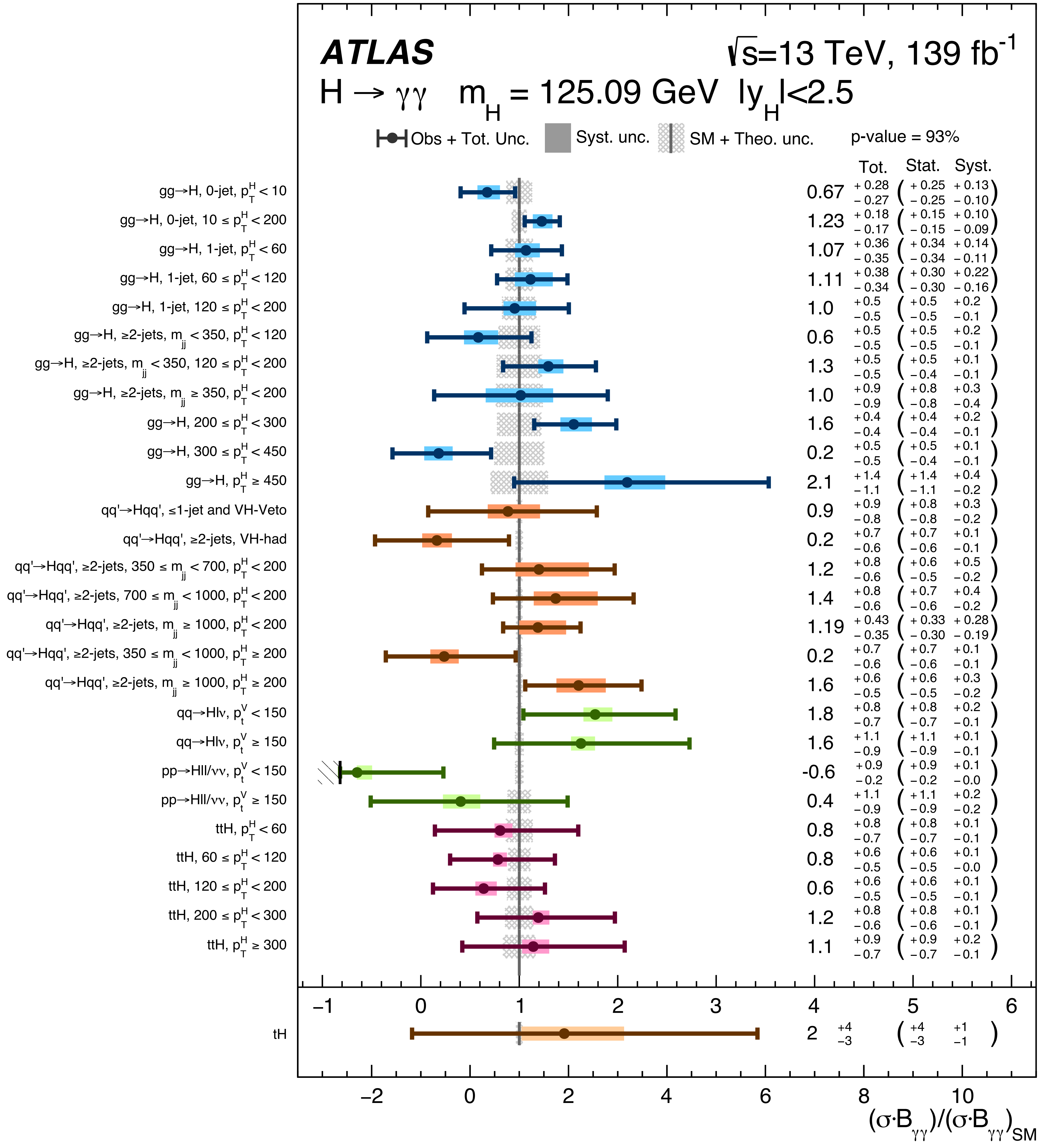
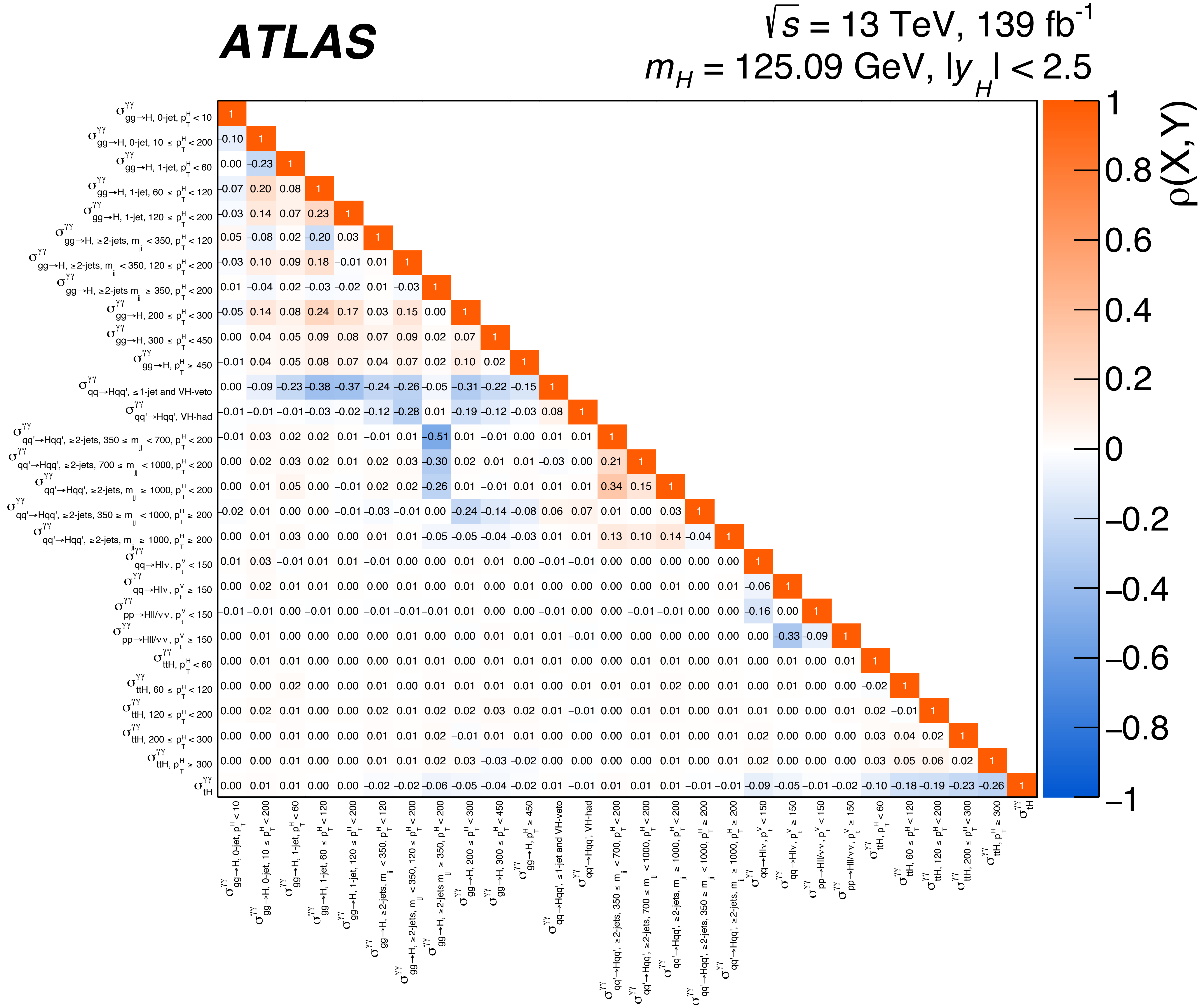
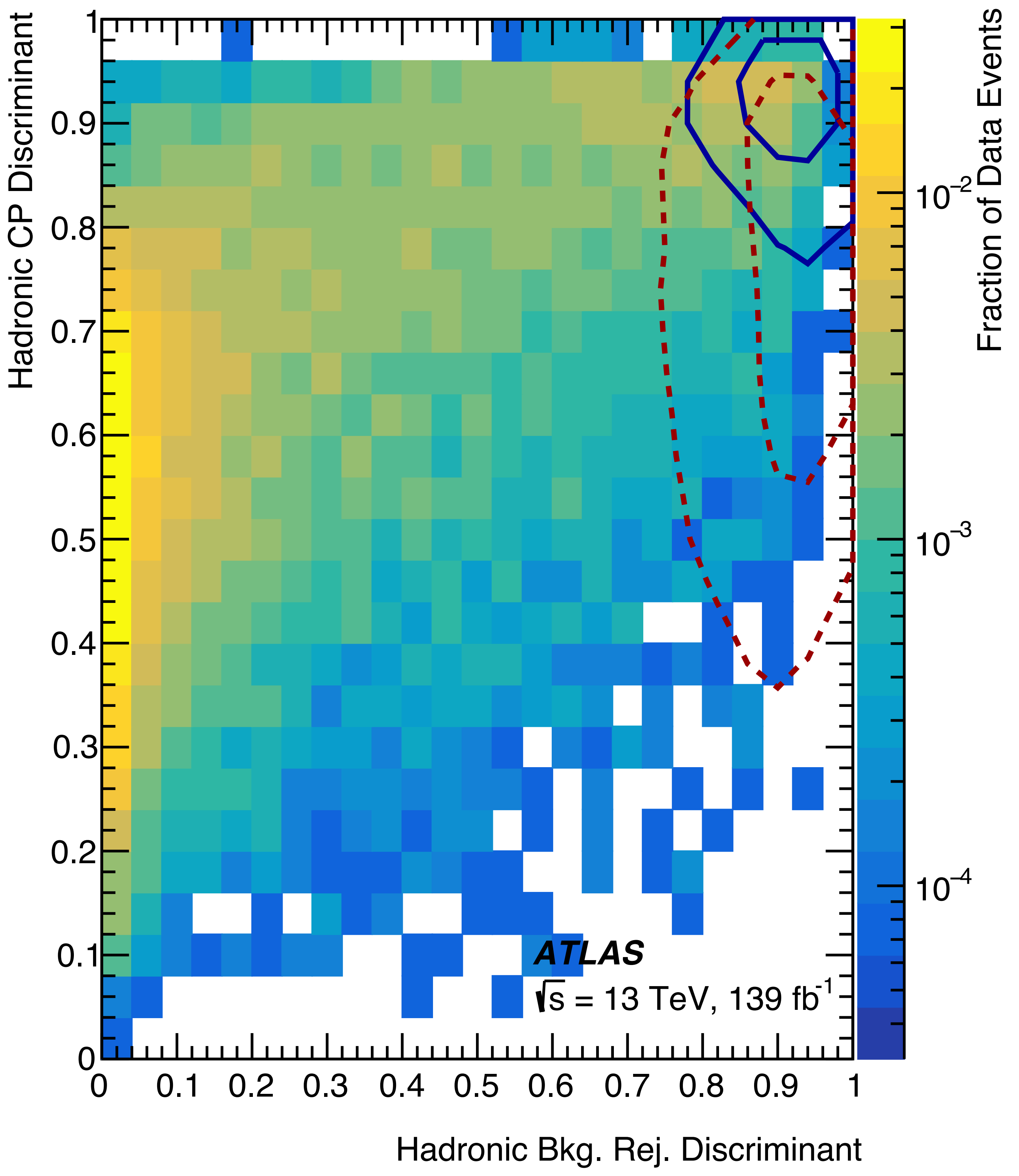
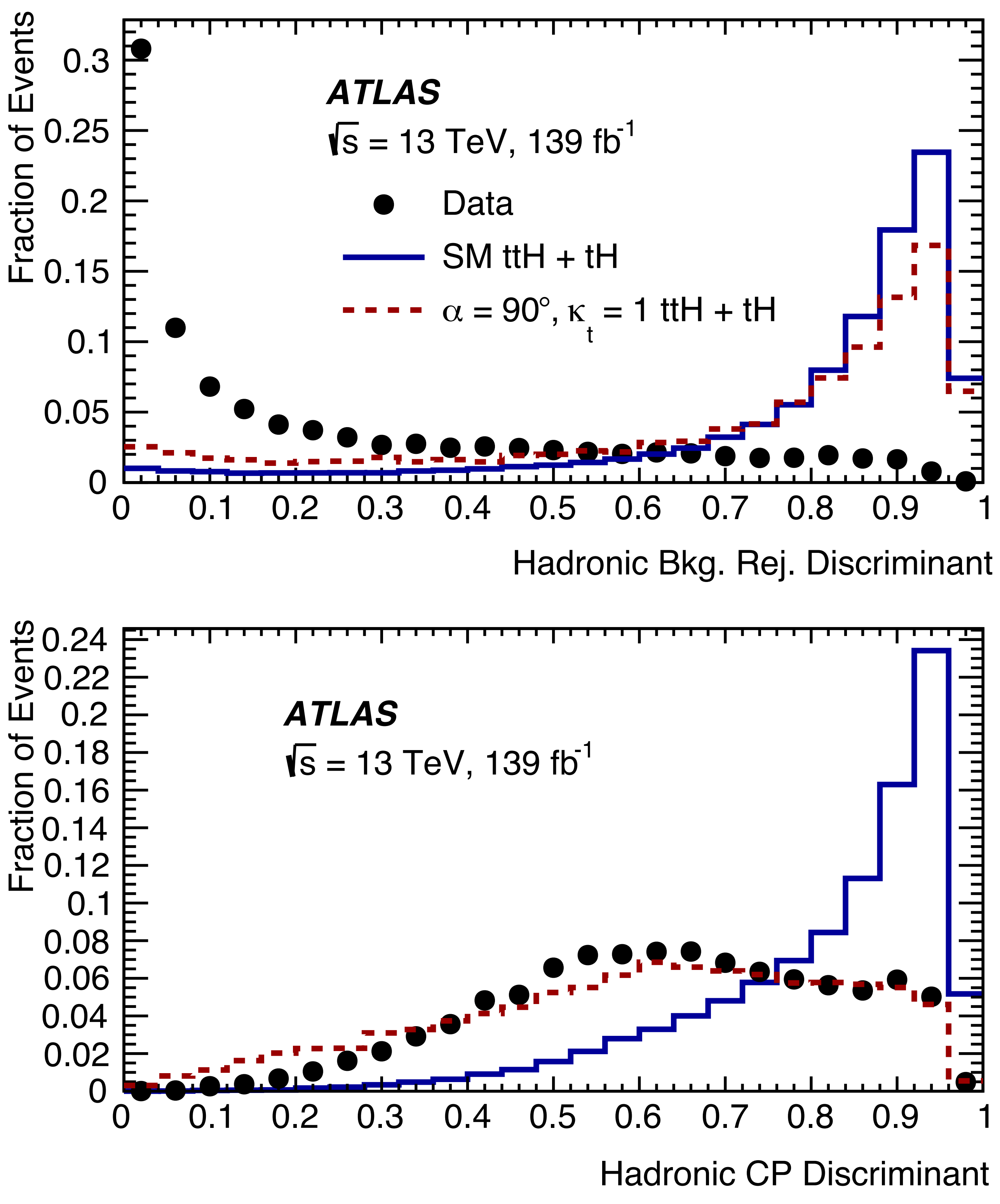


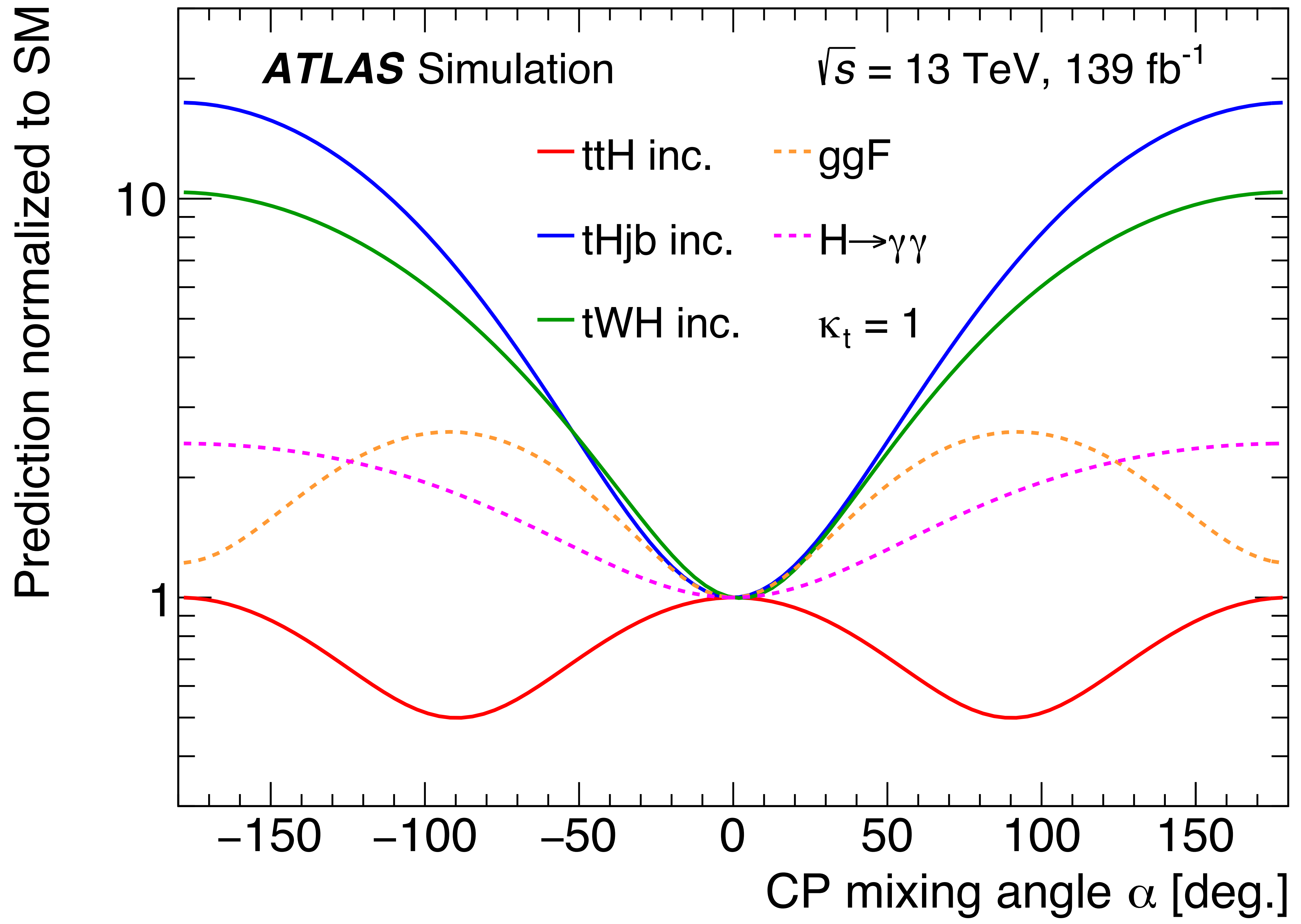


Phys. Rev. Lett. 125 (2020) 061802

$t\bar{t}H, tH\,(H \to \gamma\gamma)$ CP-measurement







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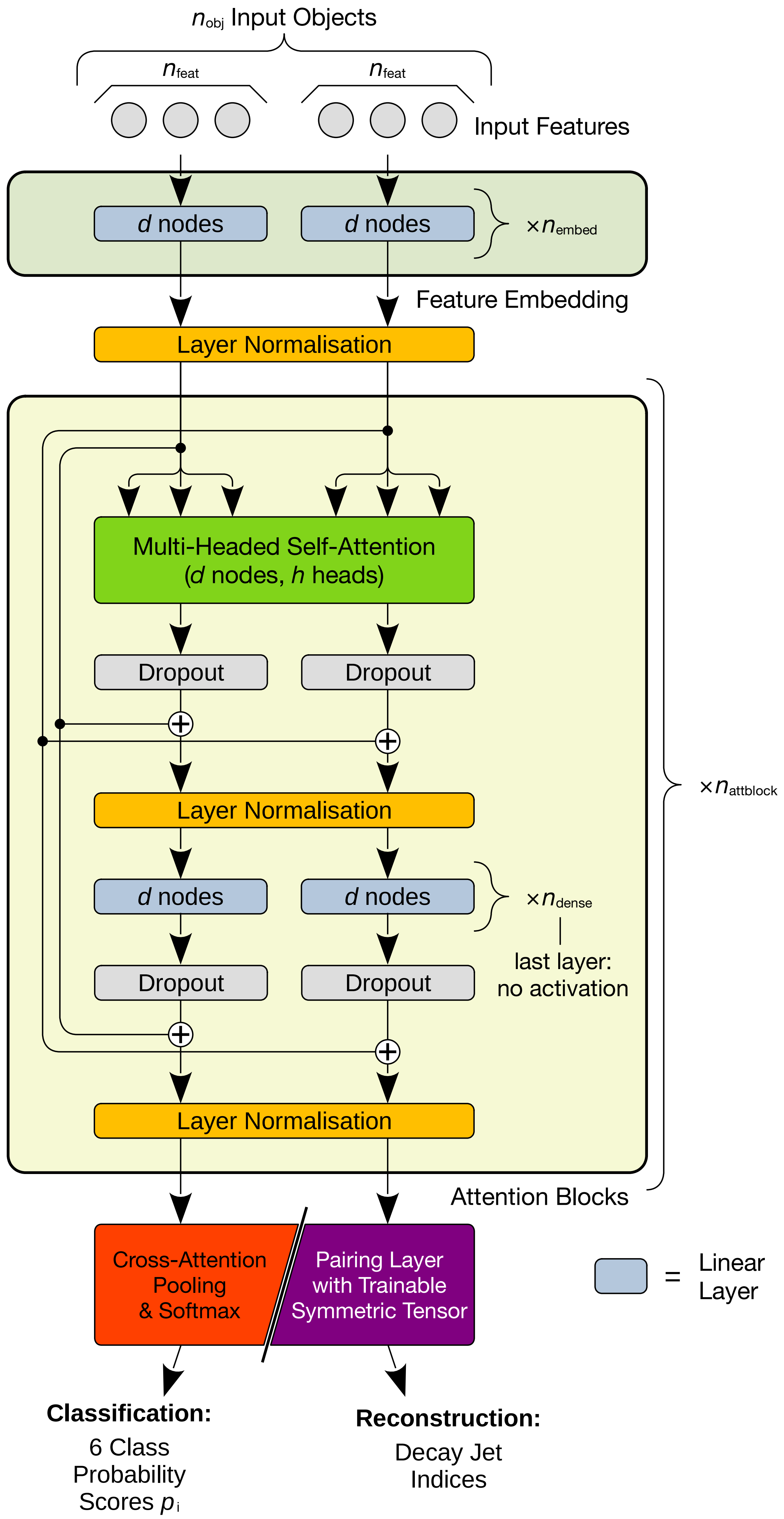
$t\bar{t}H\,(H \to b\bar{b})$: Transformer Architecture

- Transformer encoder trained on low-level object features
- Utilise self-attention mechanism to build rich discriminative latent representations
- Depending on task, different strategy used in final layers
    - Multi-class classification makes use of Cross-attention pooling mechanism
    - Reconstruction makes use of a pairing layer with Trainable Symmetric Tensor



- *Object observables used for transformer training*

Feature	Description
p_x	Object momentum in x-direction.
p_y	Object momentum in y-direction.
p_z	Object momentum in z-direction.
Energy	Object energy.
p_T	Object transverse momentum.
Mass	Object mass.
η	Object pseudo-rapidity.
ϕ	Object azimuthal angle.
cos ϕ	Sine of object azimuthal angle.
sin ϕ	Cosine of object azimuthal angle.
PCBT bin	DL1r pseudo-continuous b-tagging bin assigned to jets in the following manner. Set to 0 for leptons and E_T^{miss}. $$\text{feature} = \begin{cases} 1, & \text{if un-tagged} \\ 2, & \text{if tagged at } [85\%,\ 77\%) \\ 3, & \text{if tagged at } [77\%,\ 70\%) \\ 4, & \text{if tagged at } [70\%,\ 60\%) \\ 5, & \text{if tagged at } 60\%. \end{cases}$$
Lepton type	Lepton type of input objects. Set to 1 for electrons, 2 for muons, and 0 for jets and E_T^{miss}.
Lepton charge	Charge of lepton objects in units of e. Set to 0 for jets and E_T^{miss}.
E_T^{miss} flag	Whether input object is E_T^{miss} (value of 1) or not (value of 0).

- *Optimal hyper-parameter values of the transformer architecture*

Parameter		Classification		Reconstruction	
		Single-lepton	Dilepton	Single-lepton	Dilepton
d	number of latent features	256	256	128	128
h	number of attention heads	4	4	8	8
n_{embed}	number of feature embedding layers	2	2	2	2
$n_{attblock}$	number of attention blocks	11	10	10	8
n_{dense}	number of linear layers per attention block	5	4	3	3
Resulting total number of trainable parameters		6 716 416	5 466 368	1 207 424	976 256

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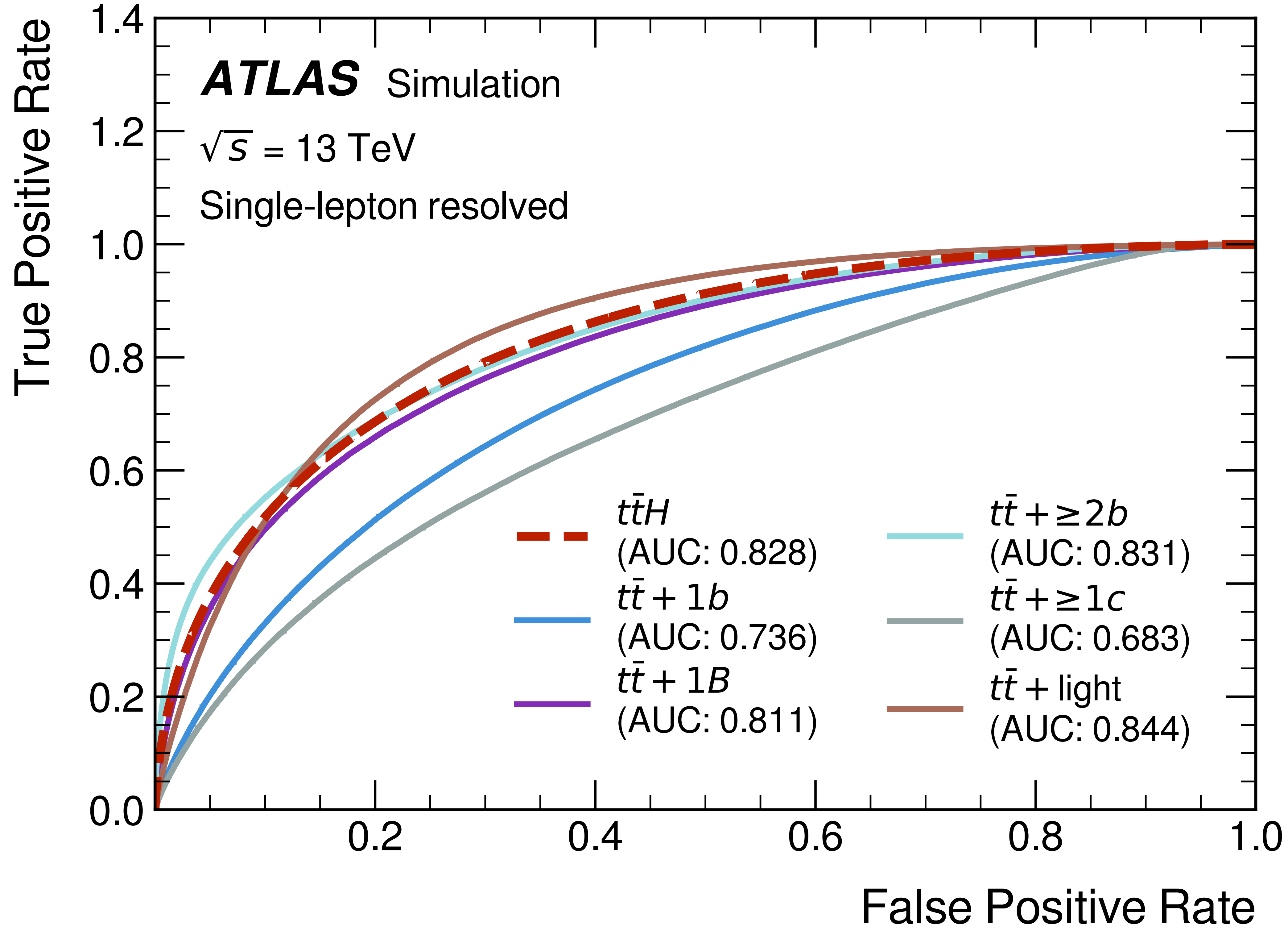
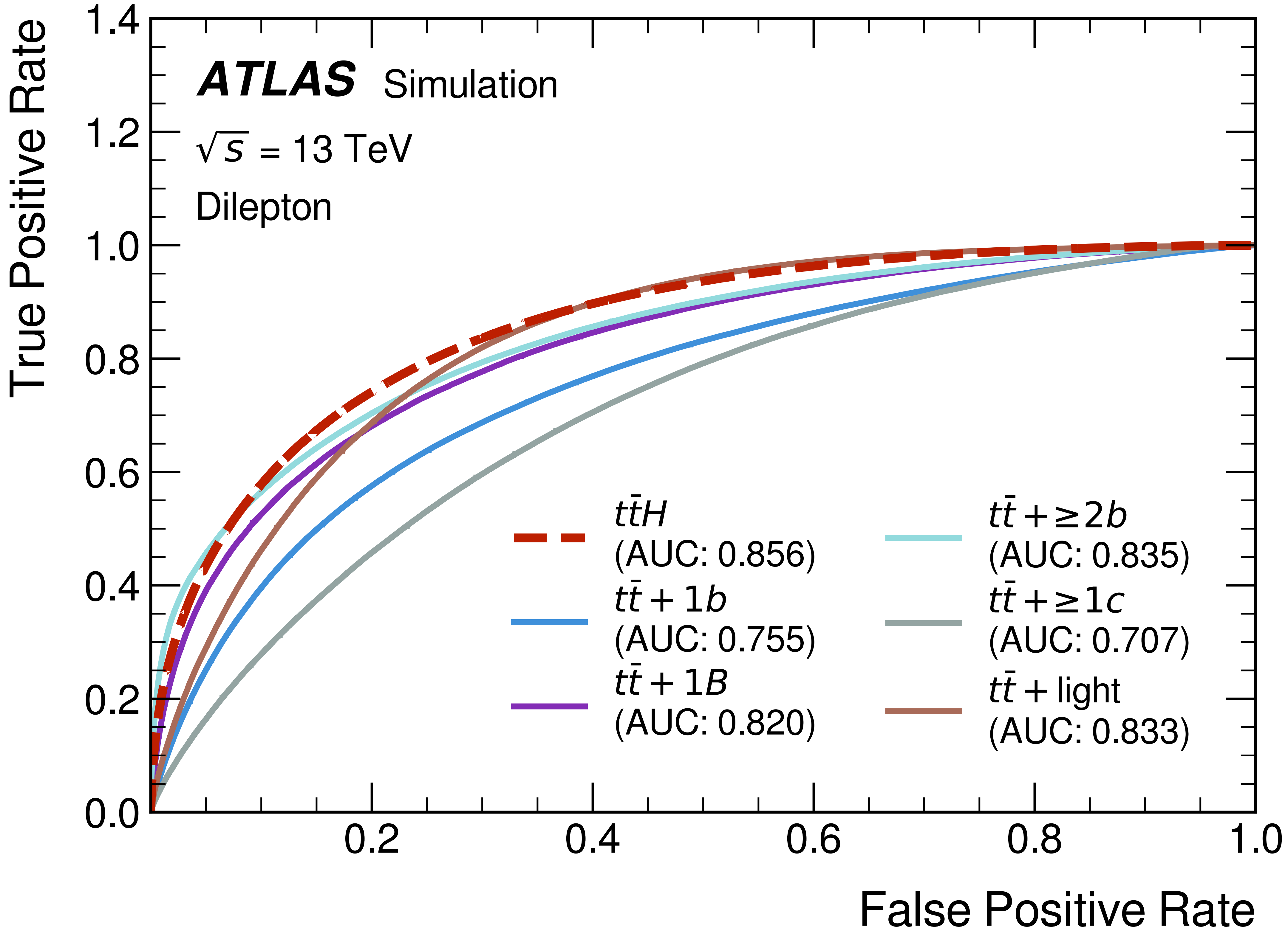
$t\bar{t}H\,(H \to b\bar{b})$: Classification NN Performance





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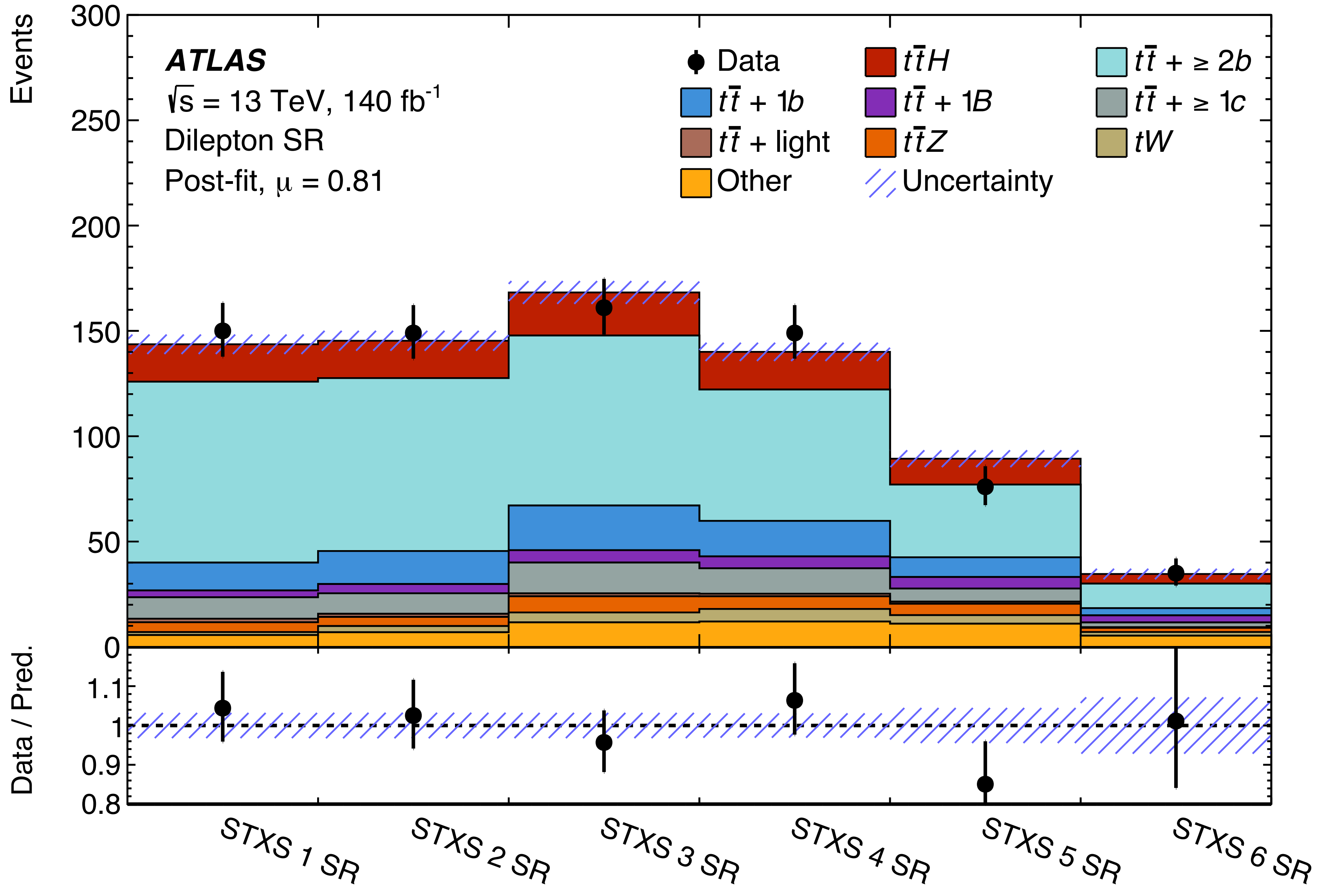
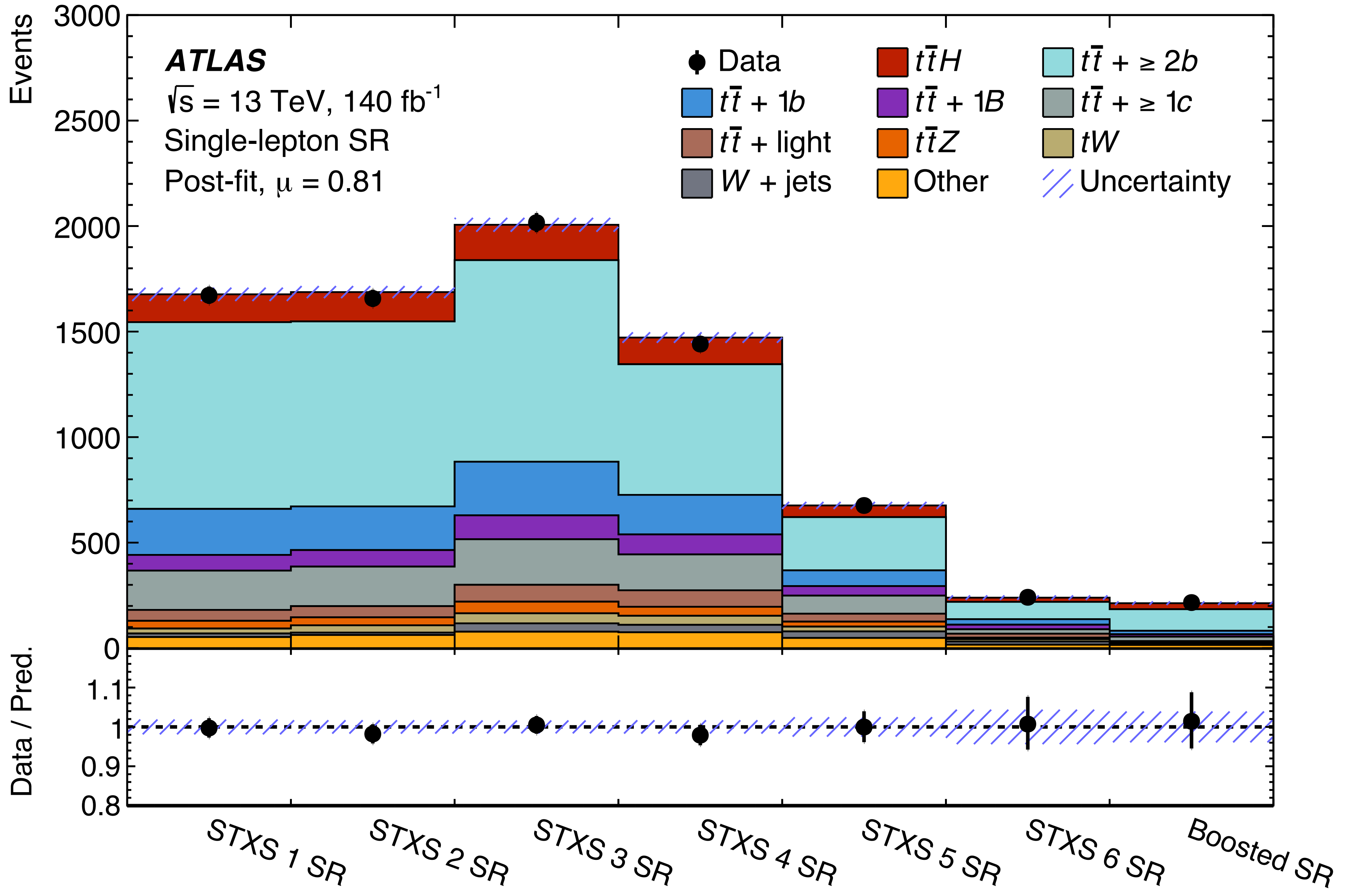
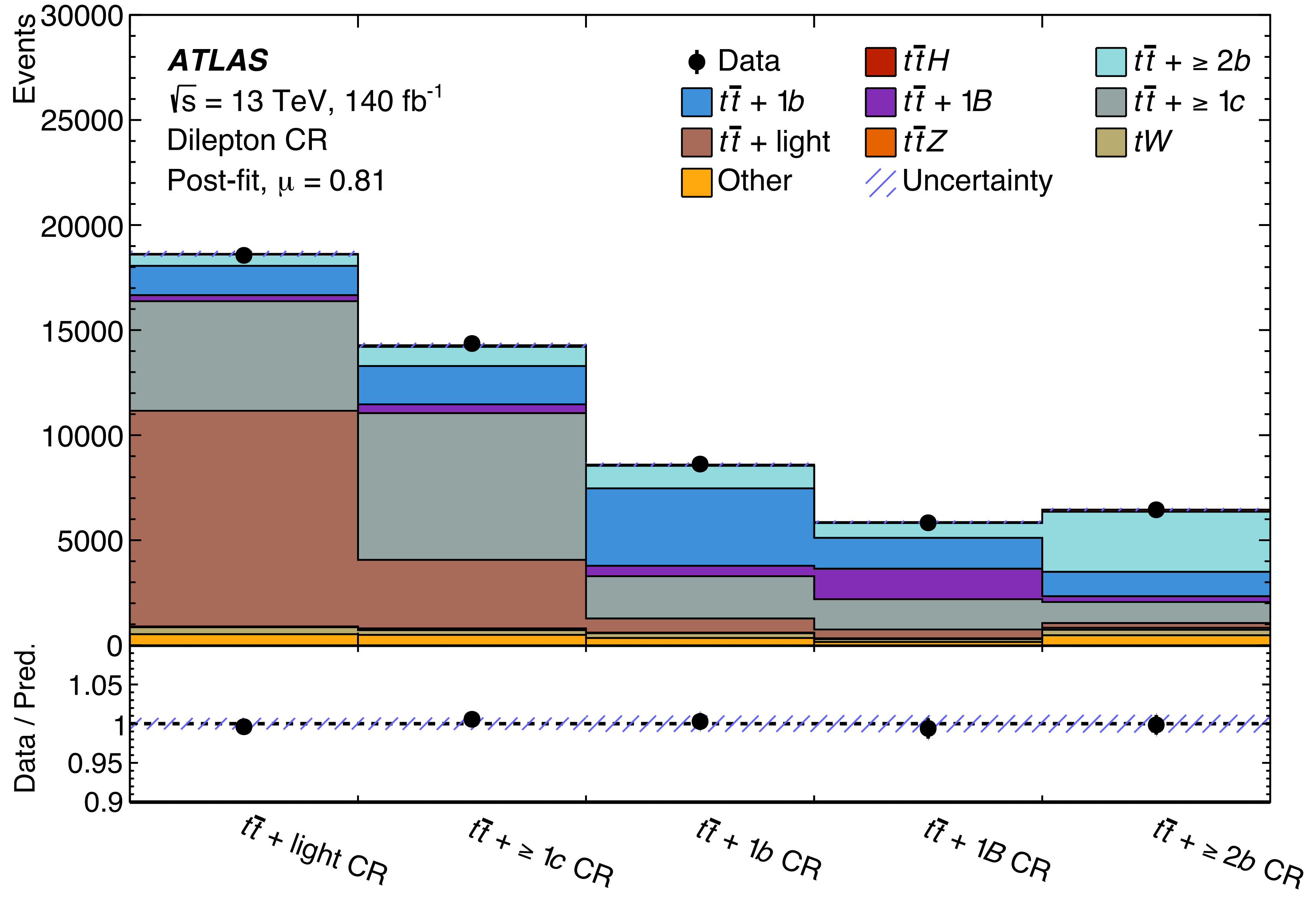
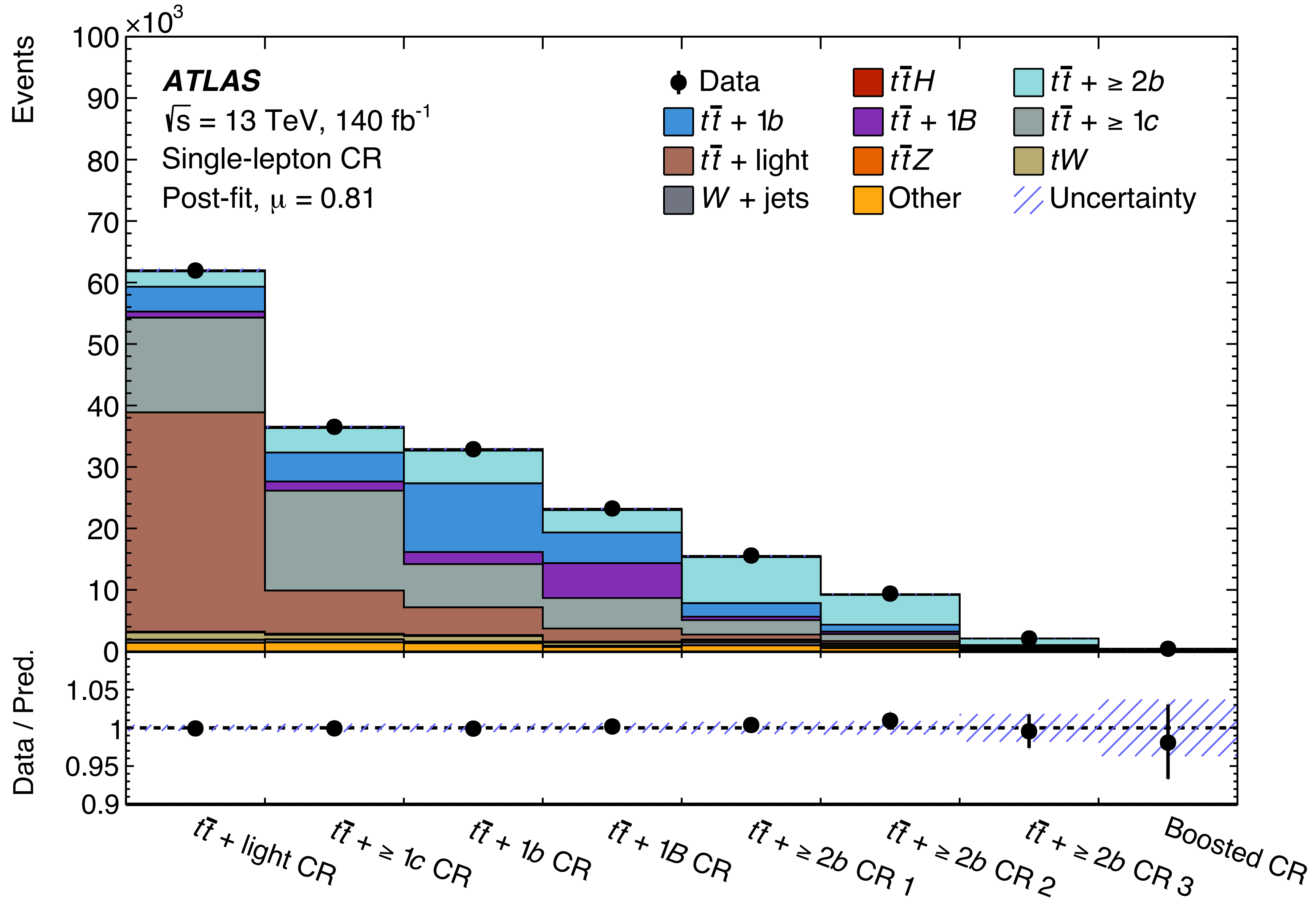
$t\bar{t}H\,(H \rightarrow b\bar{b})$: Post-fit Modelling









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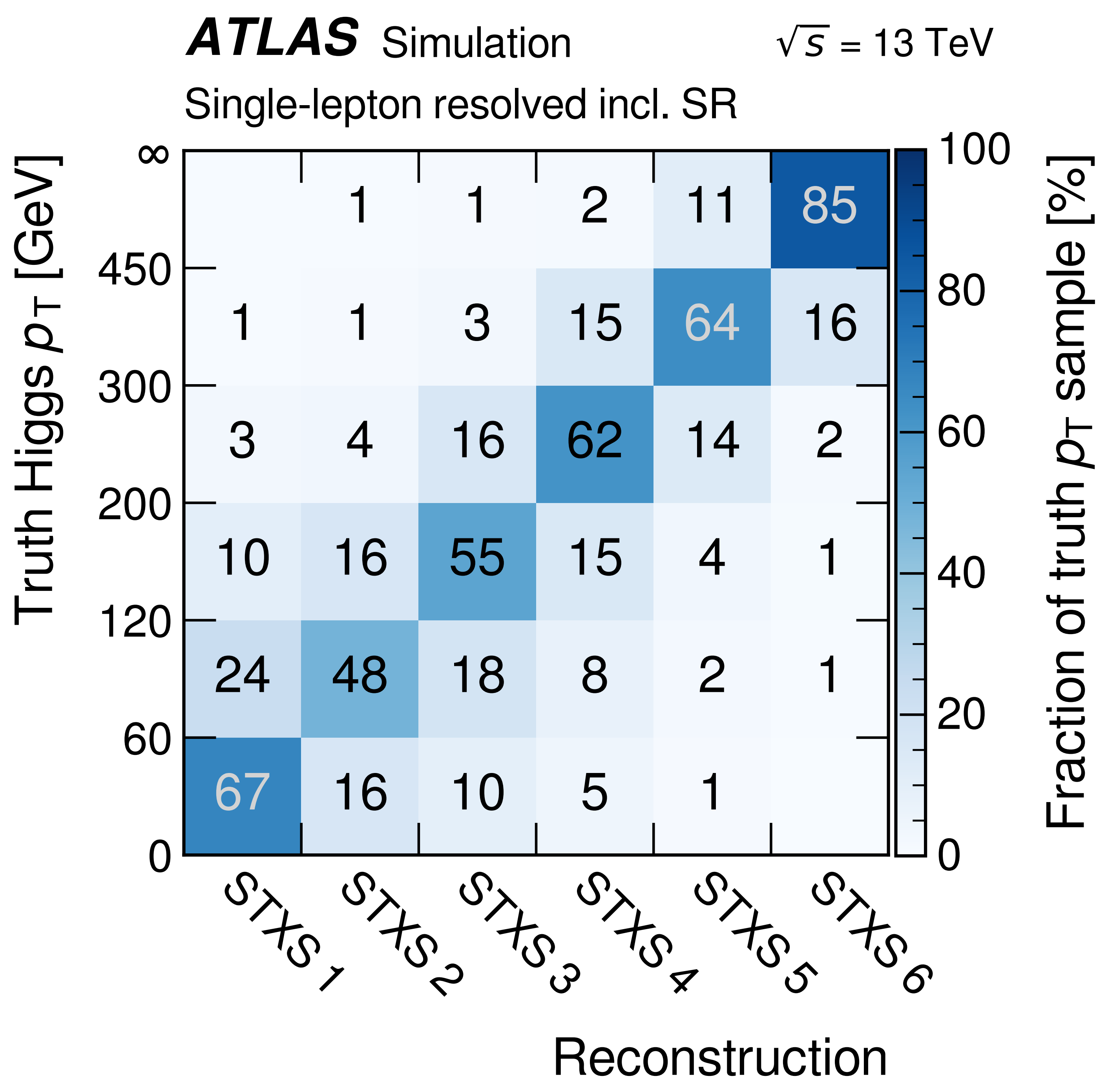
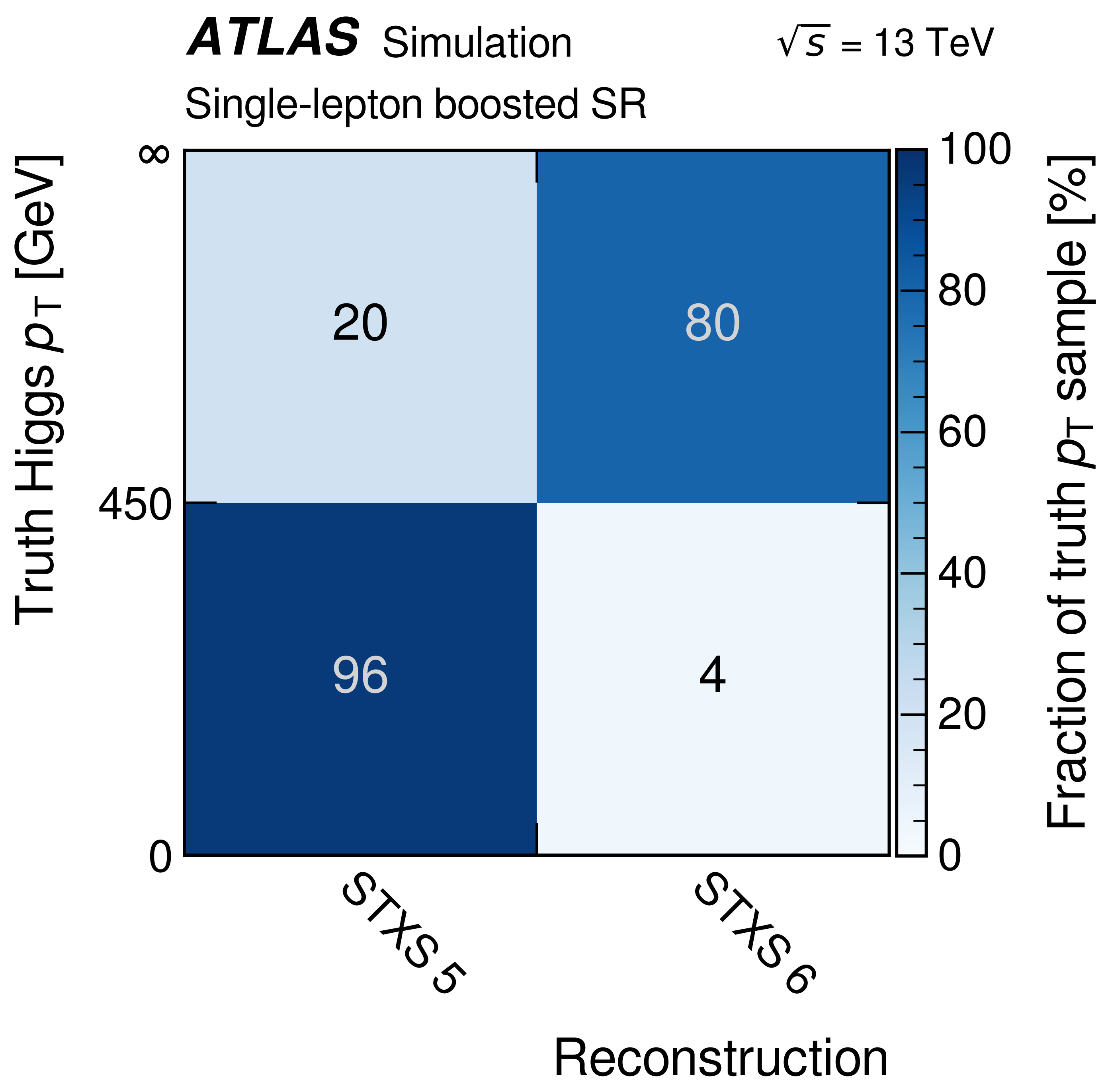
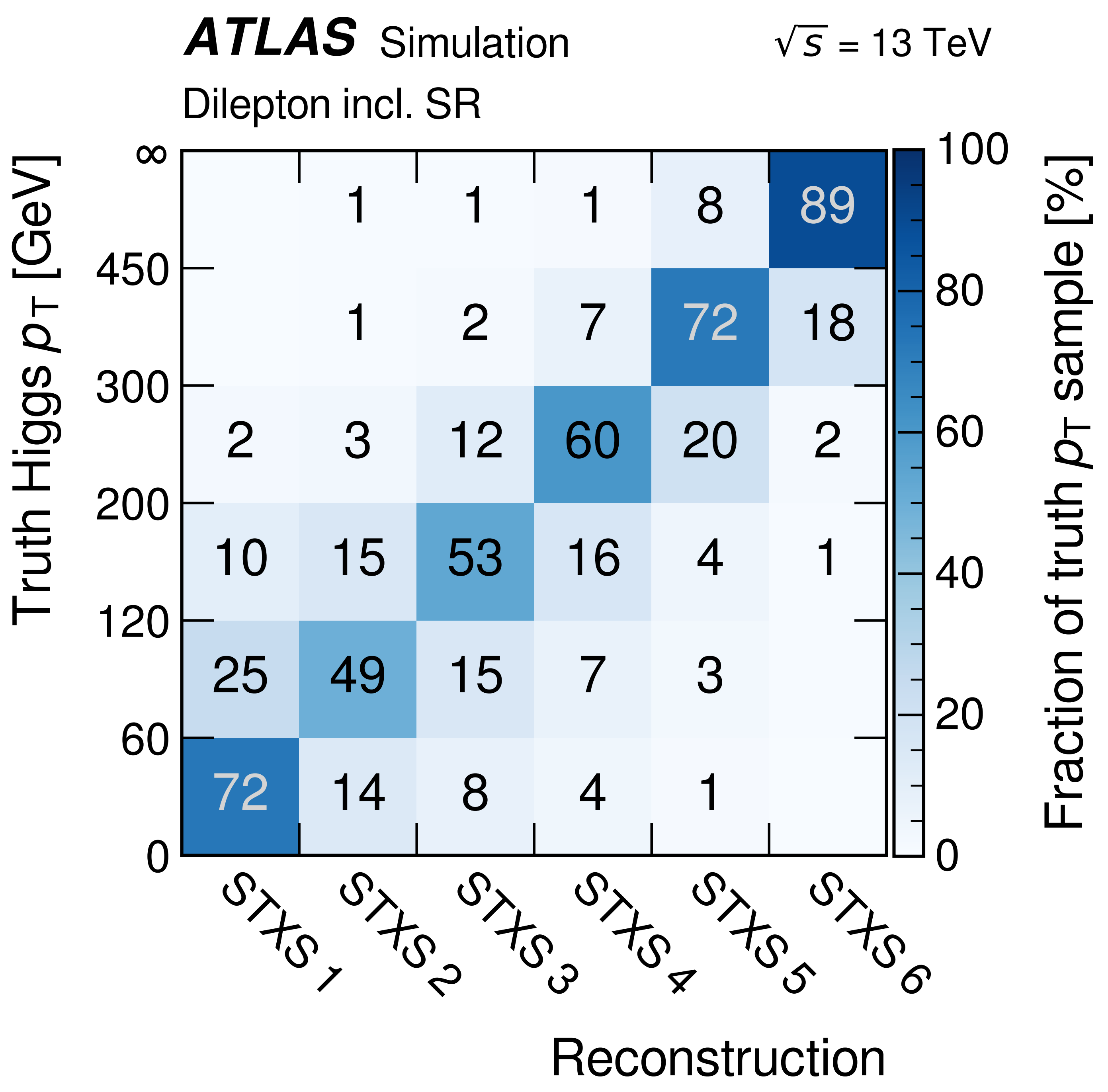
$t\bar{t}H\,(H \to b\bar{b})$: Normalisation factors

Normalisation factor	$t\bar{t}$ + light	$t\bar{t} + \geq 1c$	$t\bar{t} + 1b$	$t\bar{t} + 1B$	$t\bar{t} + \geq 2b$
Single-lepton	$0.78^{+0.08}_{-0.08}$	$1.51^{+0.19}_{-0.18}$	$1.06^{+0.10}_{-0.10}$	$1.15^{+0.15}_{-0.14}$	$0.94^{+0.08}_{-0.08}$
Dilepton	$0.88^{+0.11}_{-0.10}$	$1.36^{+0.10}_{-0.10}$	$1.24^{+0.09}_{-0.09}$		

$t\bar{t}H\ (H \to b\bar{b})$: Reconstruction NN Performance







$t\bar{t}H\,(H \to b\bar{b})$: Pre-fit Region composition

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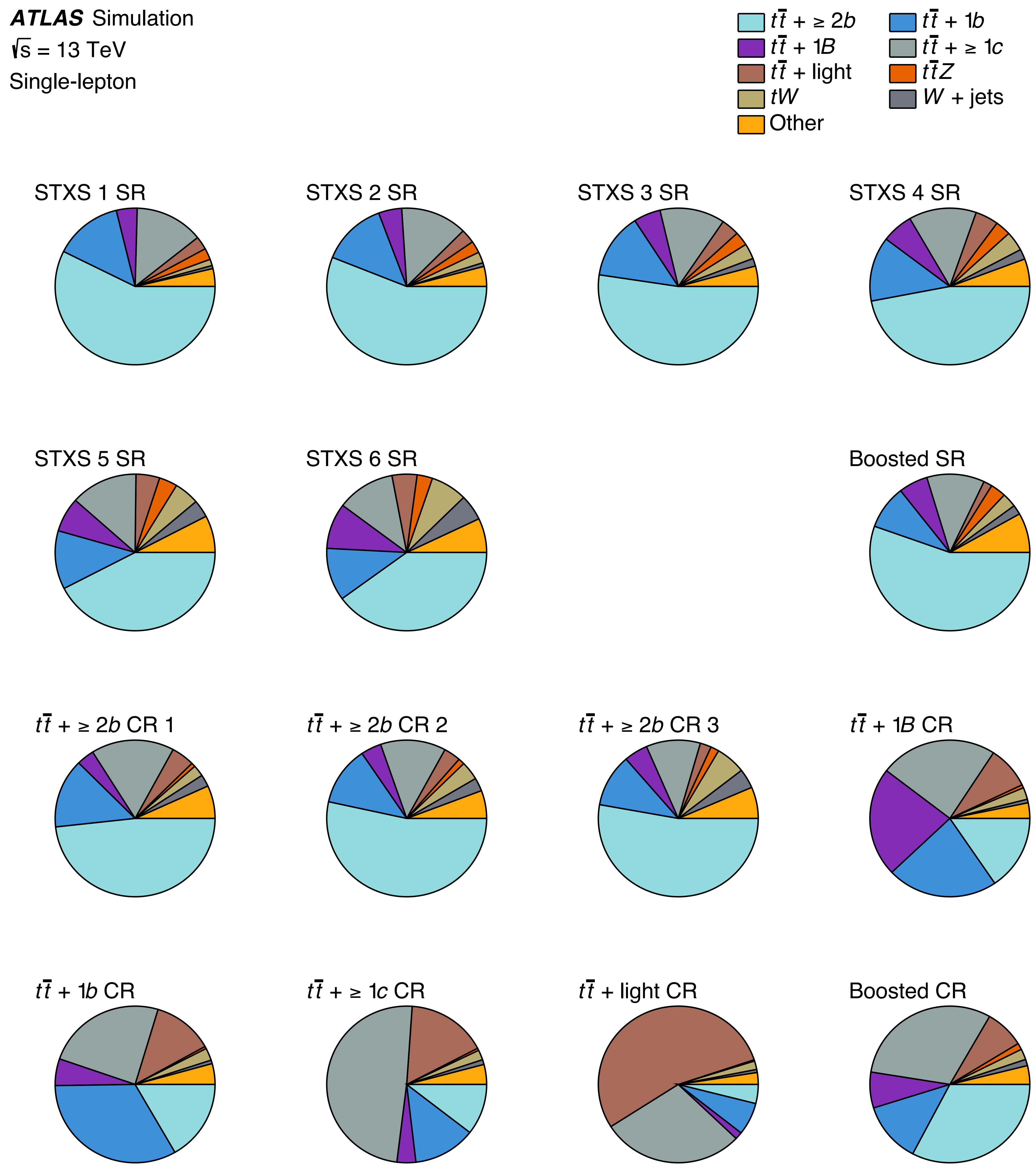

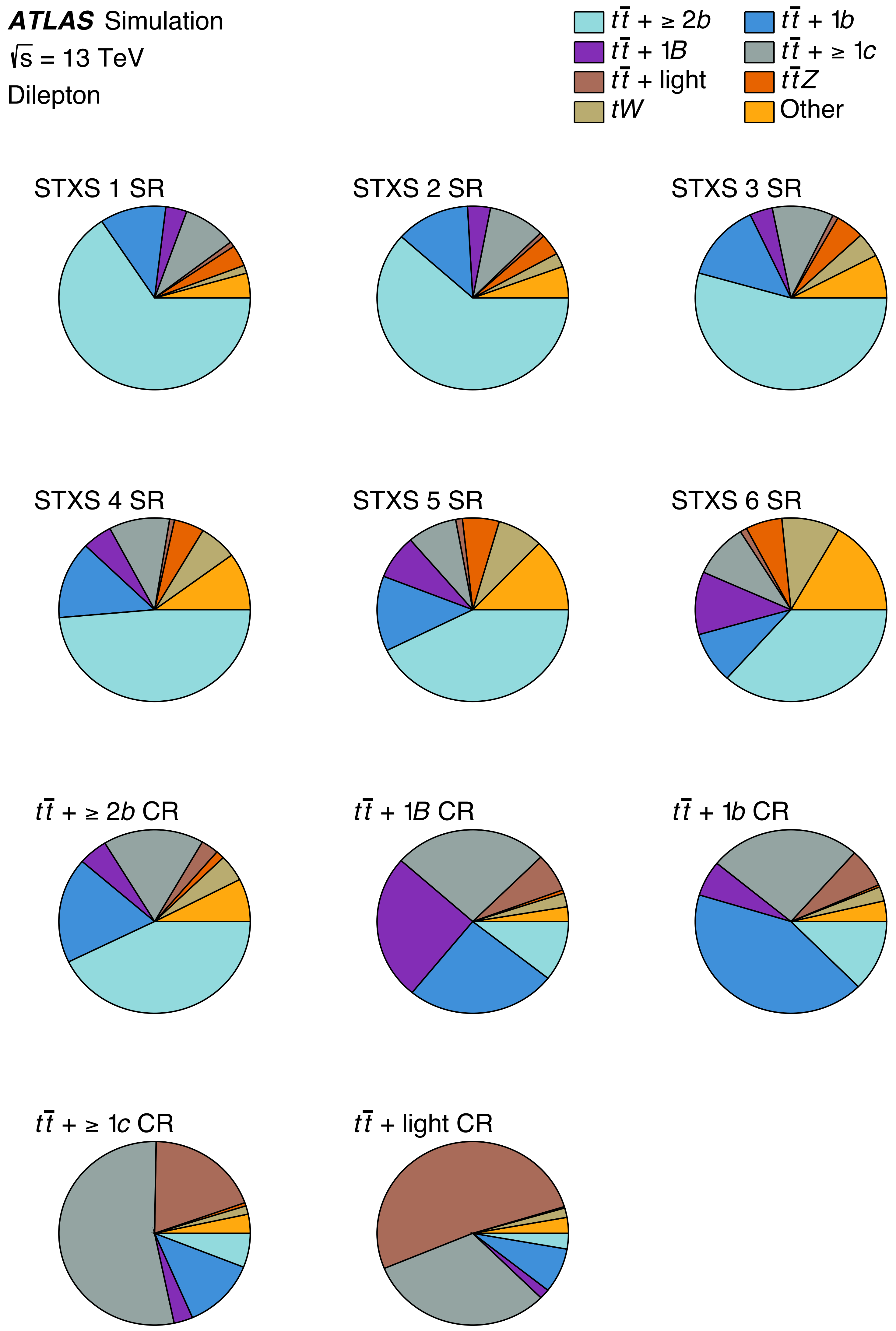

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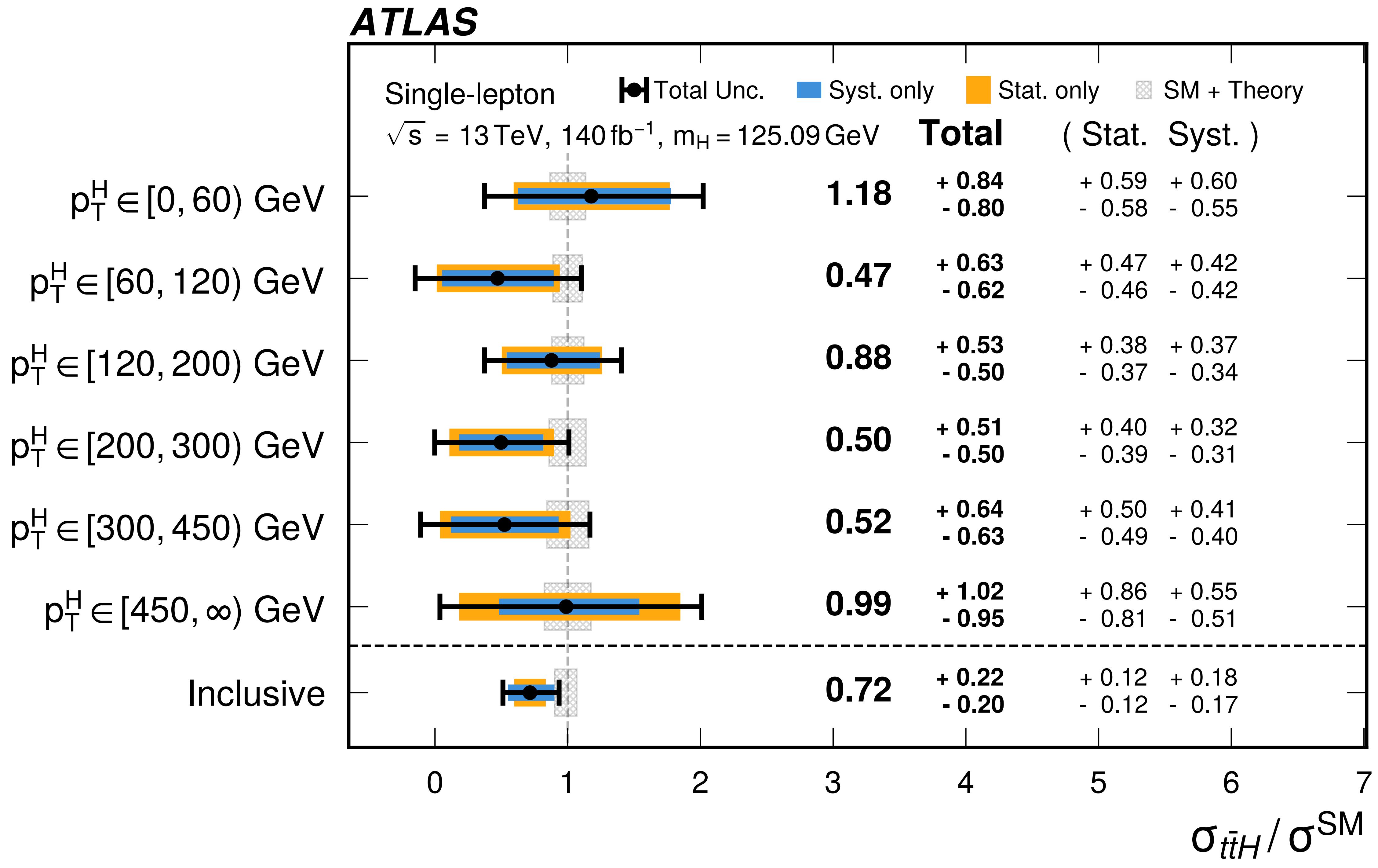
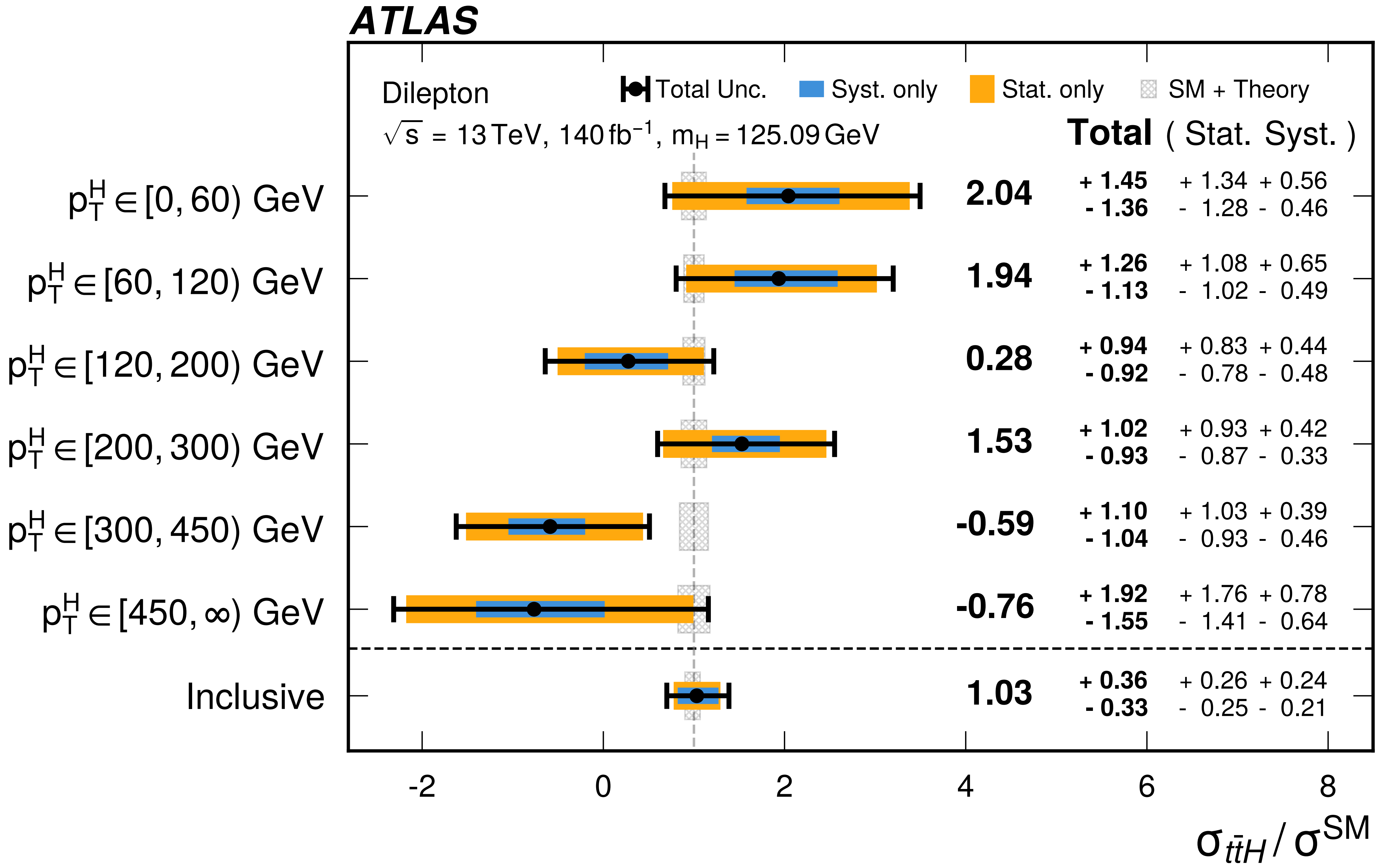
$t\bar{t}H\,(H \to b\bar{b})$: Individual Channel Results





$t\bar{t}H\,(H \to b\bar{b})$: Nuisance Parameter Impact Ranking