Standard Model at the LHC 2025

April 7-10, Durham

Advances in ttH/tH

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on behalf of the ATLAS and CMS collaborations

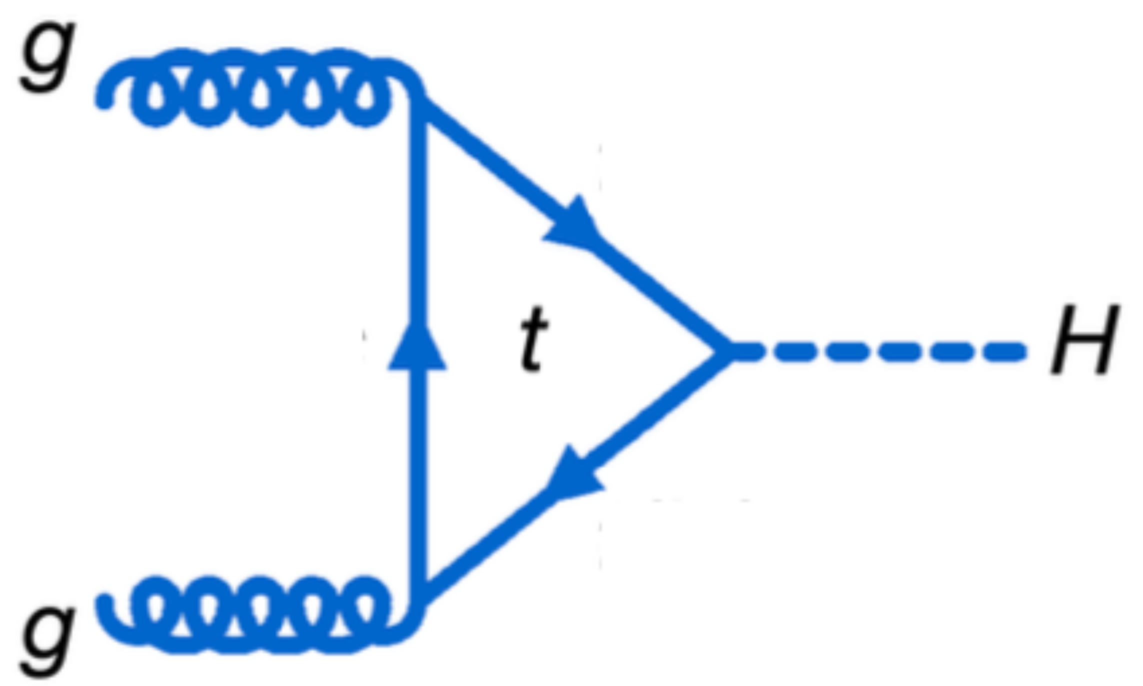
Yale University

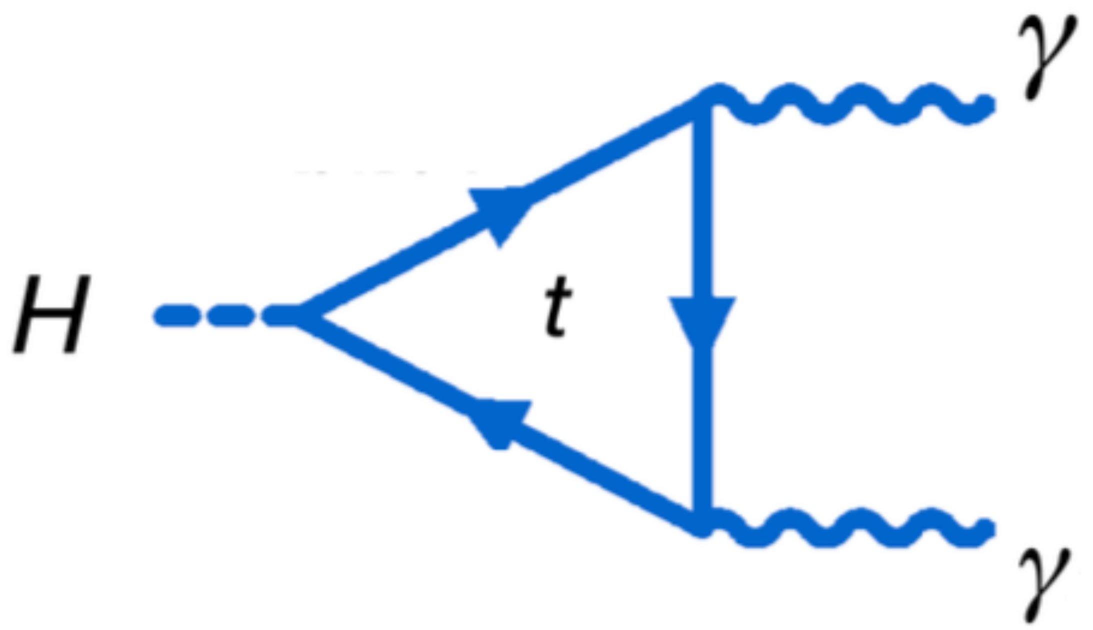
Outline

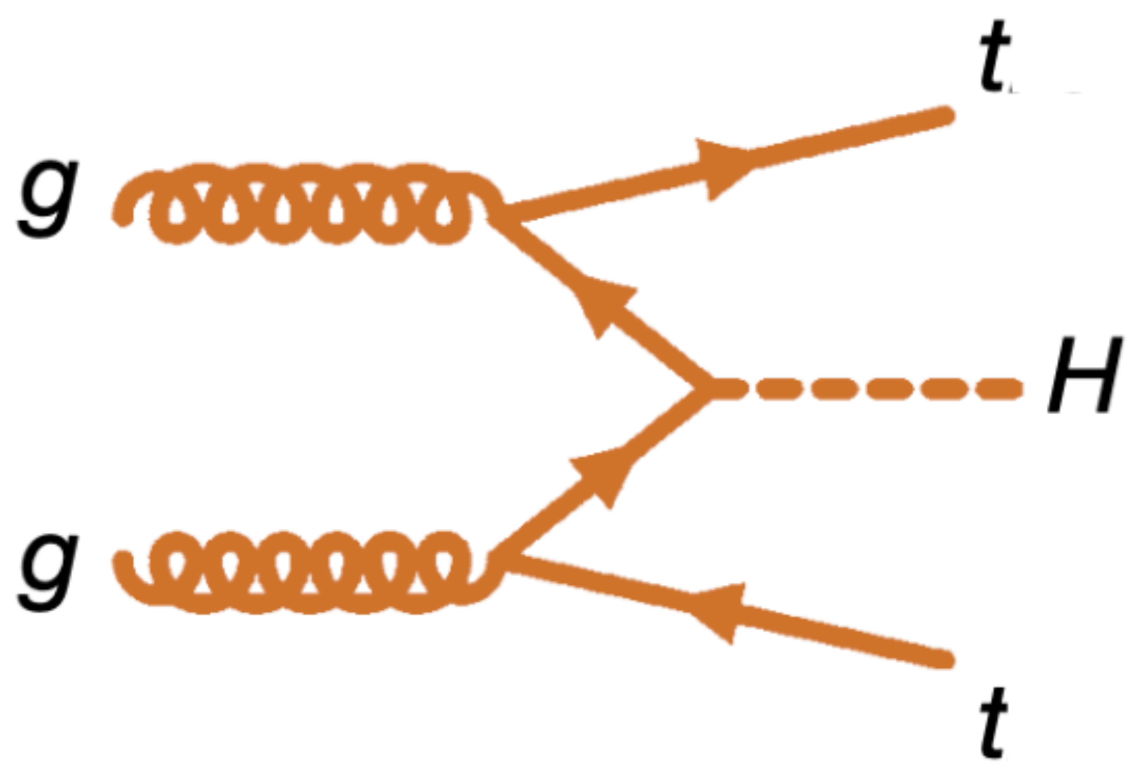
- Top Yukawa interactions and $t\bar{t}H/tH$ production cross-section
- Coupling/STXS with $t\bar{t}H, H \to b\bar{b}$ @ ATLAS and CMS
- Coupling/STXS with $t\bar{t}H, H \to \tau\tau$ @ ATLAS
- Coupling/STXS with $t\bar{t}H, H \to WW$ or $H \to \tau\tau$ @ CMS
- CP nature of the Top-Higgs coupling in $t\bar{t}H, H \to b\bar{b}$ @ ATLAS and CMS
- Summary

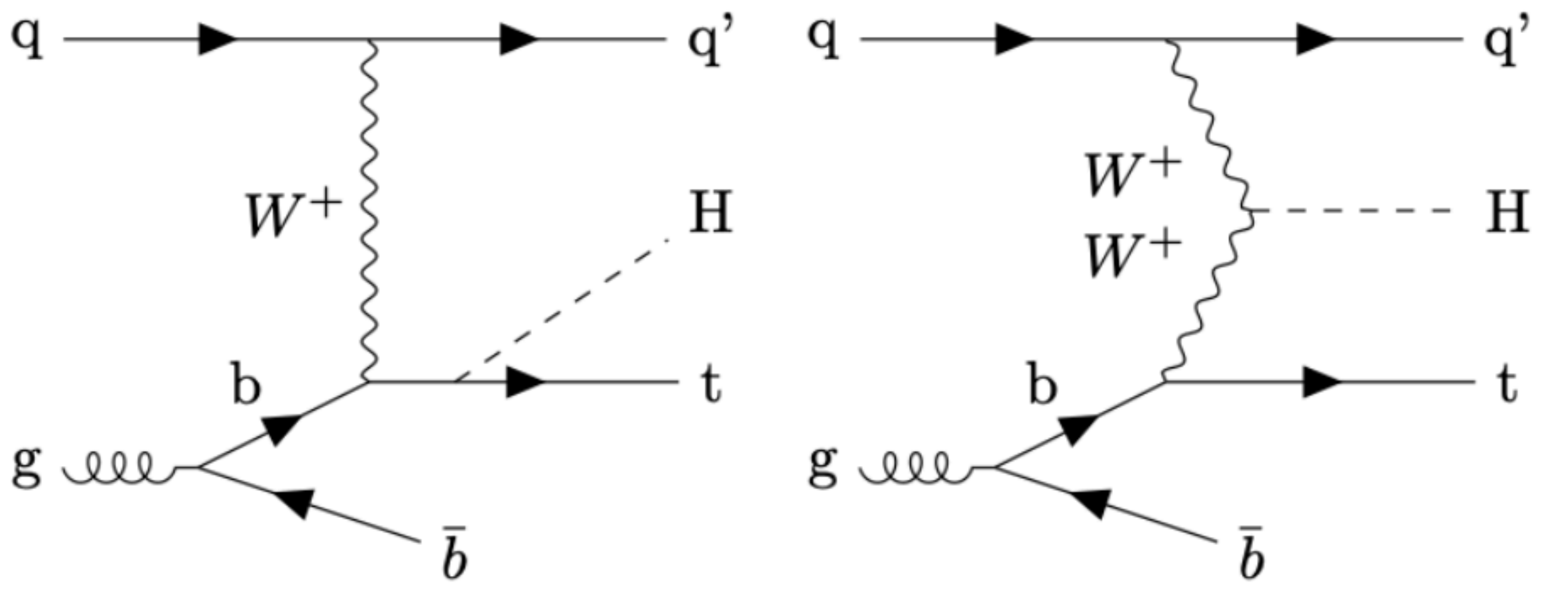
Top Yukawa interaction

- Higgs boson couples to fermions proportionally to their mass
  - The Top quark is the heaviest in the SM -> largest Yukawa coupling $\lambda_t = \dfrac{m_t\sqrt{2}}{v}$
  - ggF and $H \to \gamma\gamma$ enable indirect access to λ_t in a model-dependent way
  - Sensitive probe to physics beyond the standard model (BSM)
- Top-associated Higgs production provides a direct access to λ_t
  - $t\bar{t}H$ is the best process for measuring λ_t ; tree-level process $\sigma_{t\bar{t}H} \propto \lambda_t^2,\ \sigma_{t\bar{t}H} \sim 0.5$ pb
  - tH has a lower xsec ($\sigma_{tH} \sim 0.09$ pb), but the interference between the Top and the W couplings is sensitive to the sign of λ_t and BSM effects





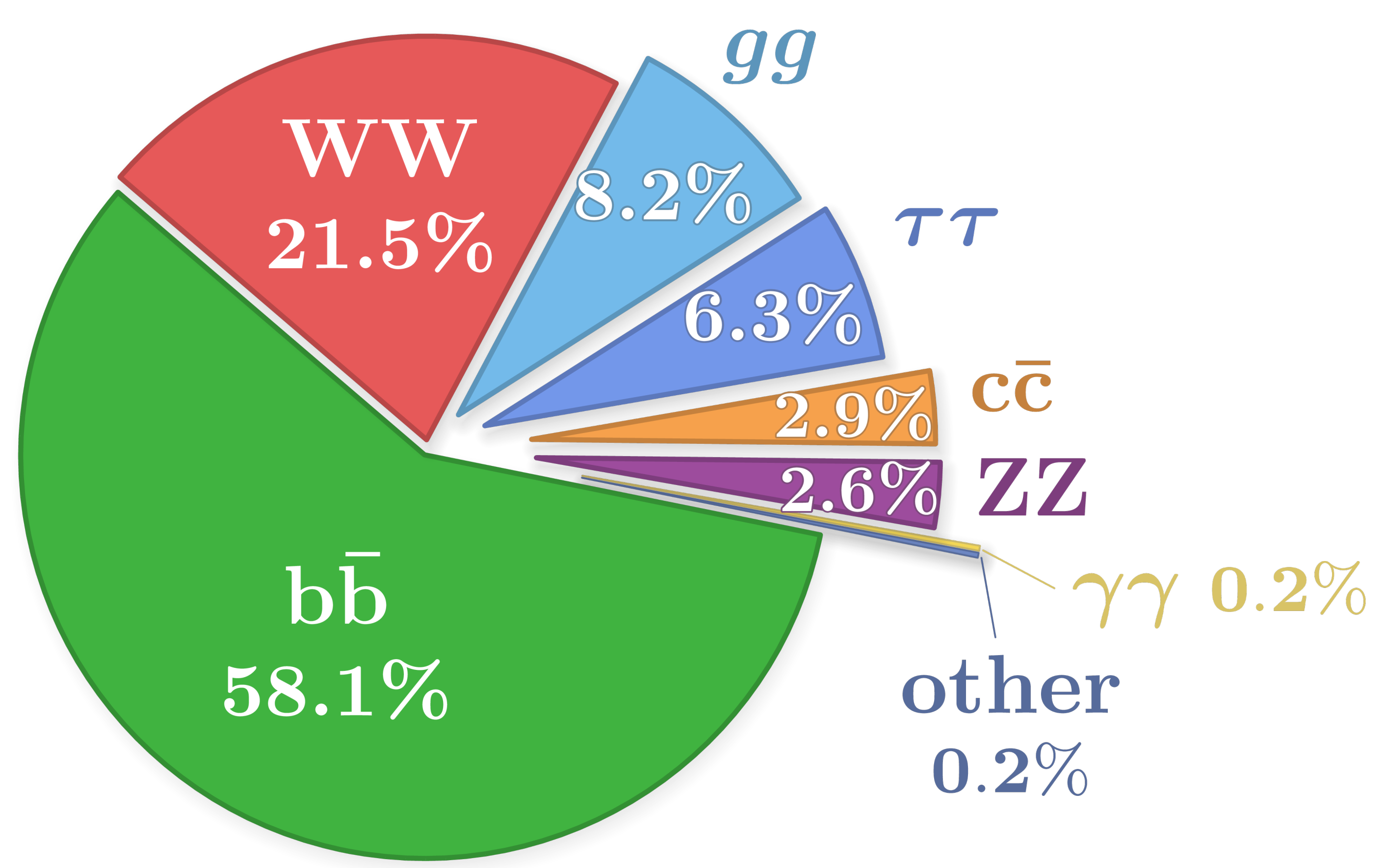




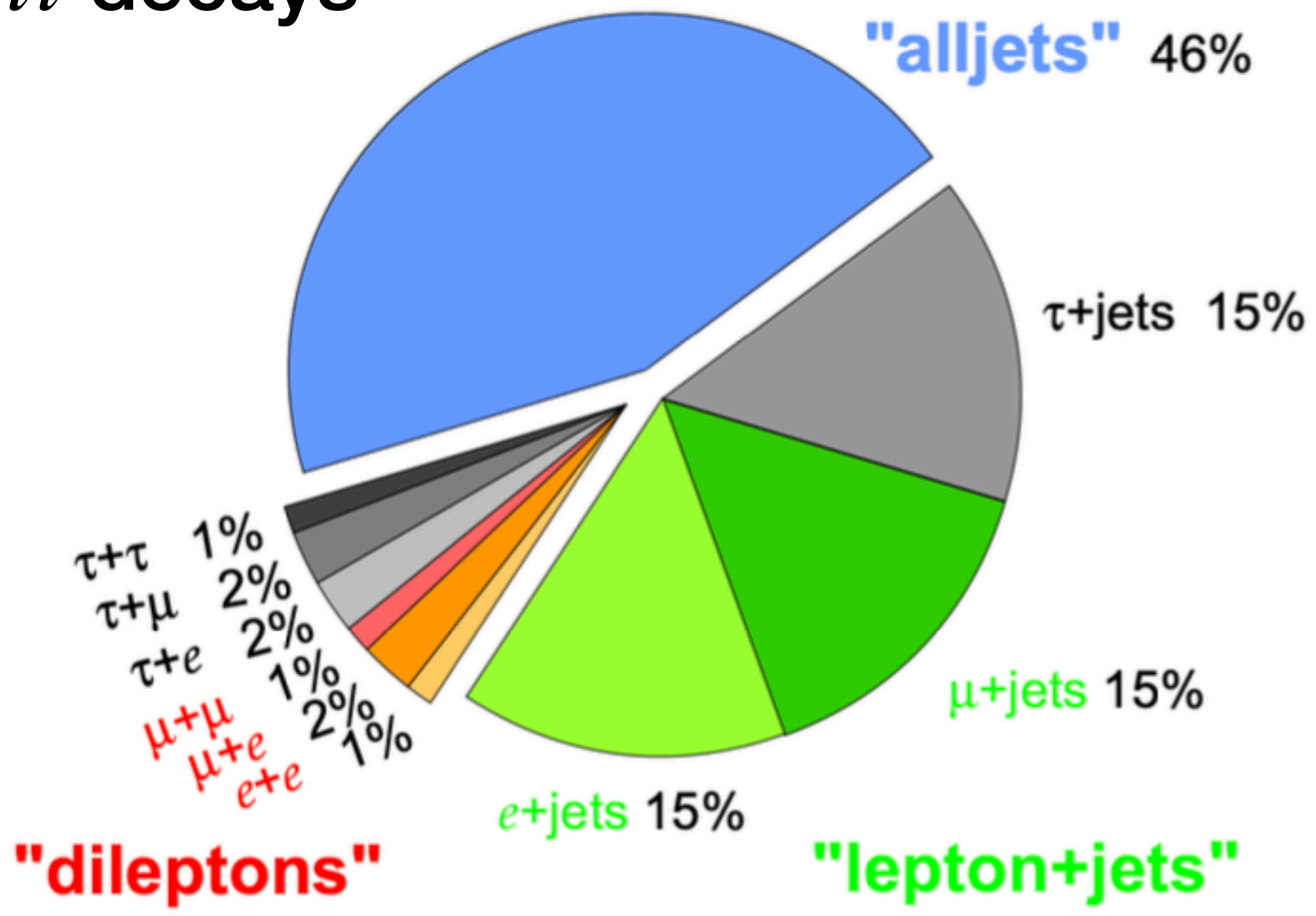
Measuring $t\bar{t}H/tH$ production xsec

- Large variety of final states: Higgs + Top quark(s) decays
- $t\bar{t}H$ production mode observed combining several final states in ATLAS and CMS with > 5σ significance
- tH not yet observed
- $t\bar{t}H$ is part of the **Simplified Template X-Section** analysis
  - Used to study the Higgs couplings in bins of p_T^H

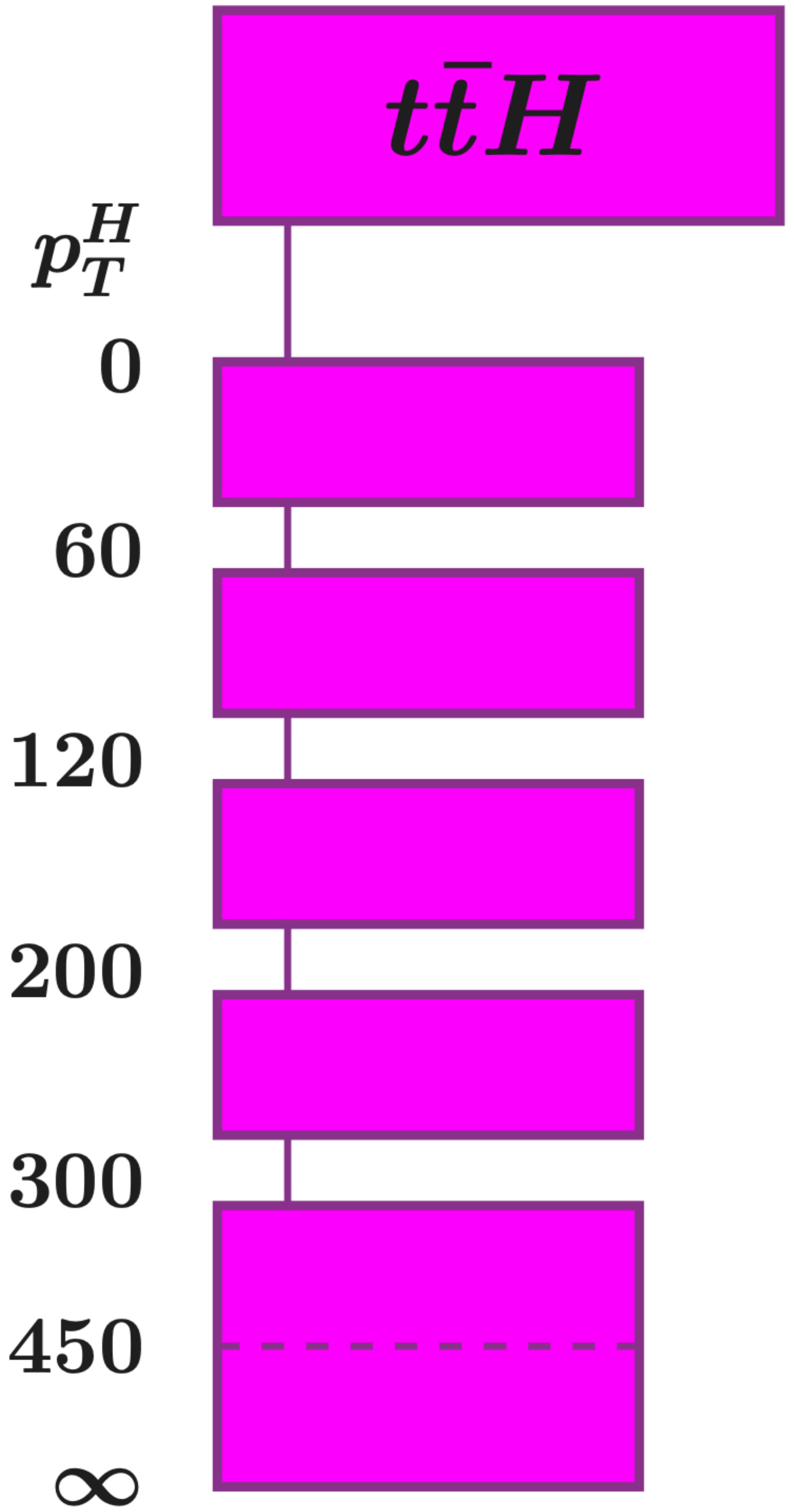
H decays



$t\bar{t}$ decays

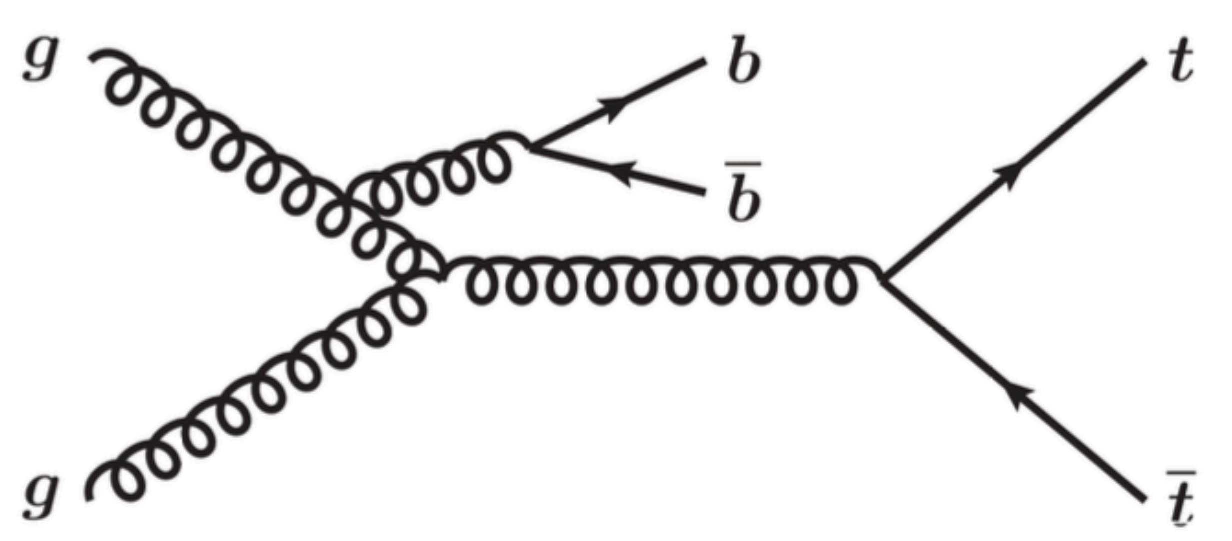


Stage 1.2

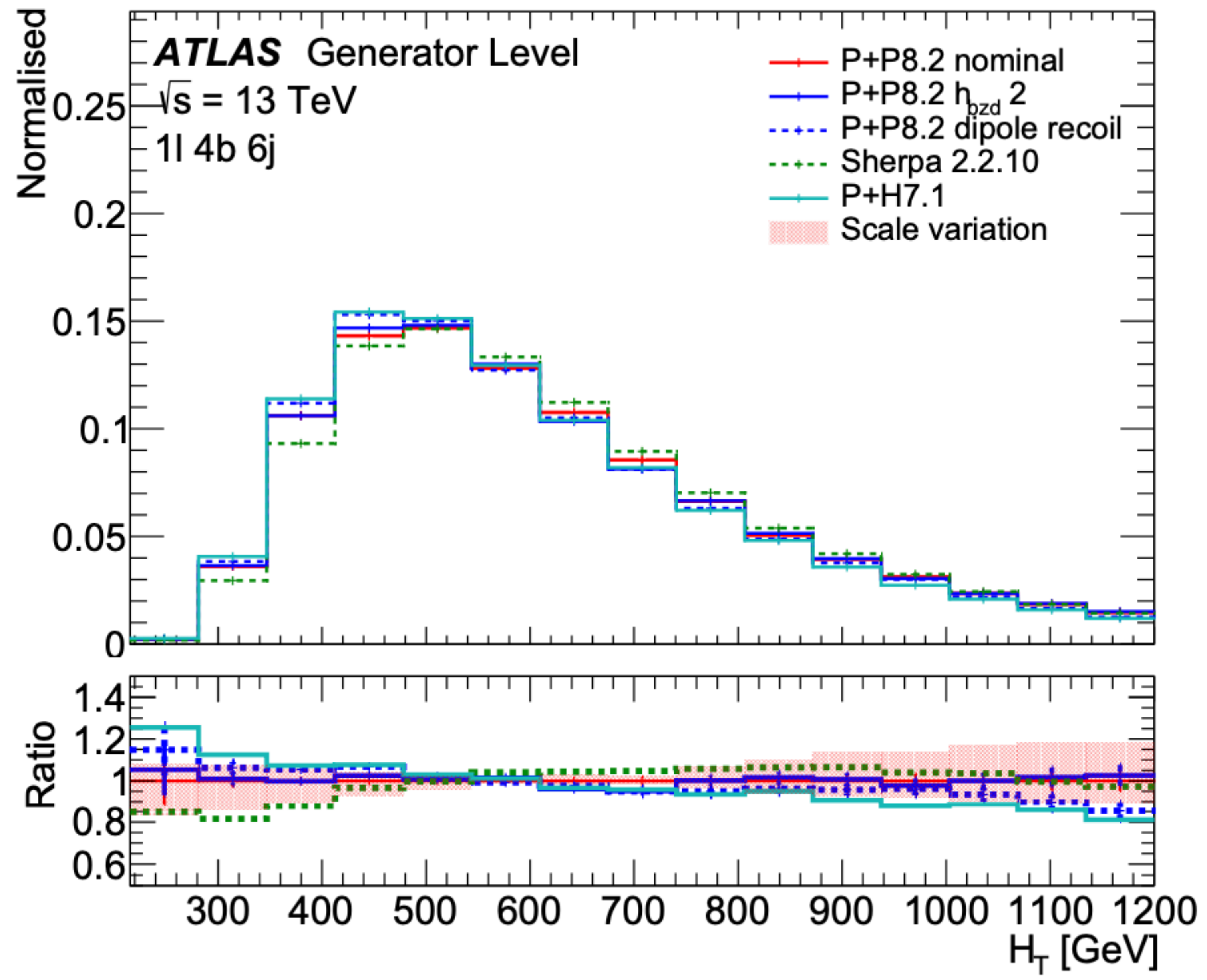


Coupling/STXS with $t\bar{t}H, H \to b\bar{b}$ @ ATLAS

- New analysis of the full Run 2 dataset [Eur. Phys. J. C 85 (2025) 210] superseding the previous one [JHEP 06 (2022) 97]



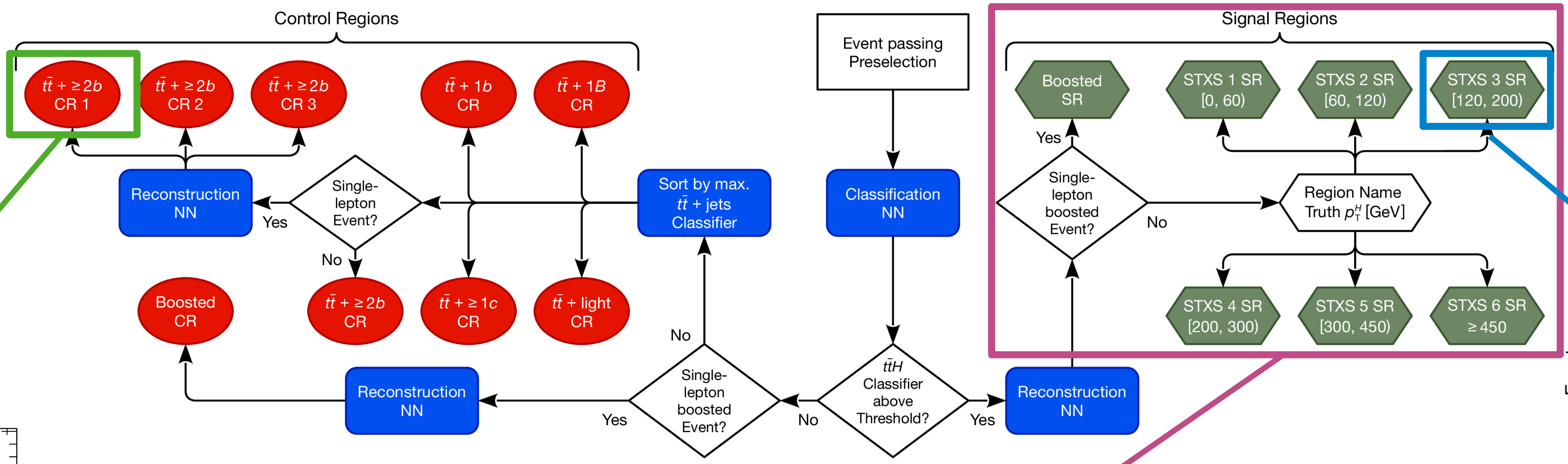
- Events categorized based on the $t\bar{t}$ decay: **single-** and **di-lepton** channels
- The **single-lepton** channel uses two separate categories: boosted and resolved
    - The boosted category selects high-pT Higgs (pT>300 GeV) making a collimated large-R jet

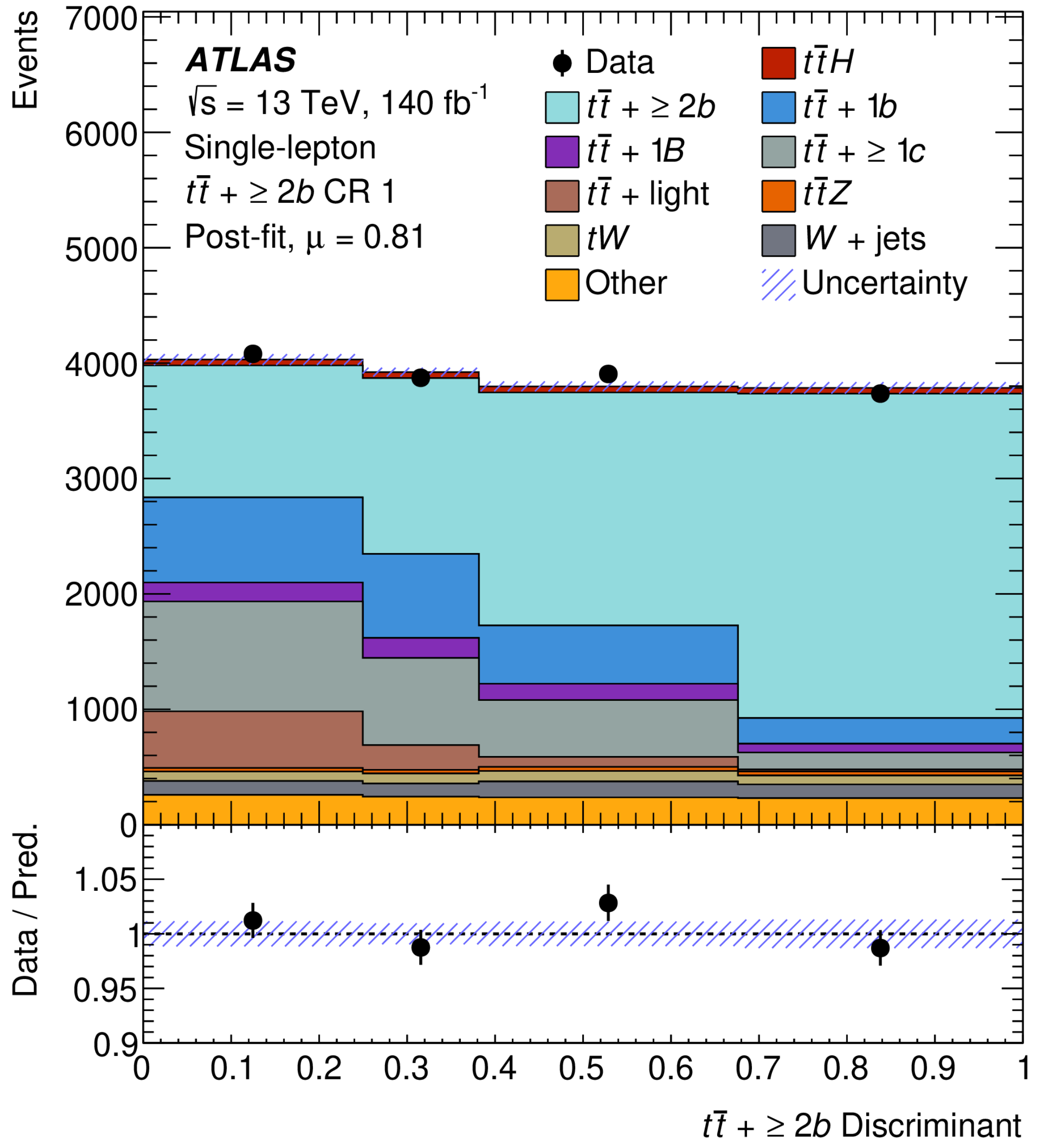


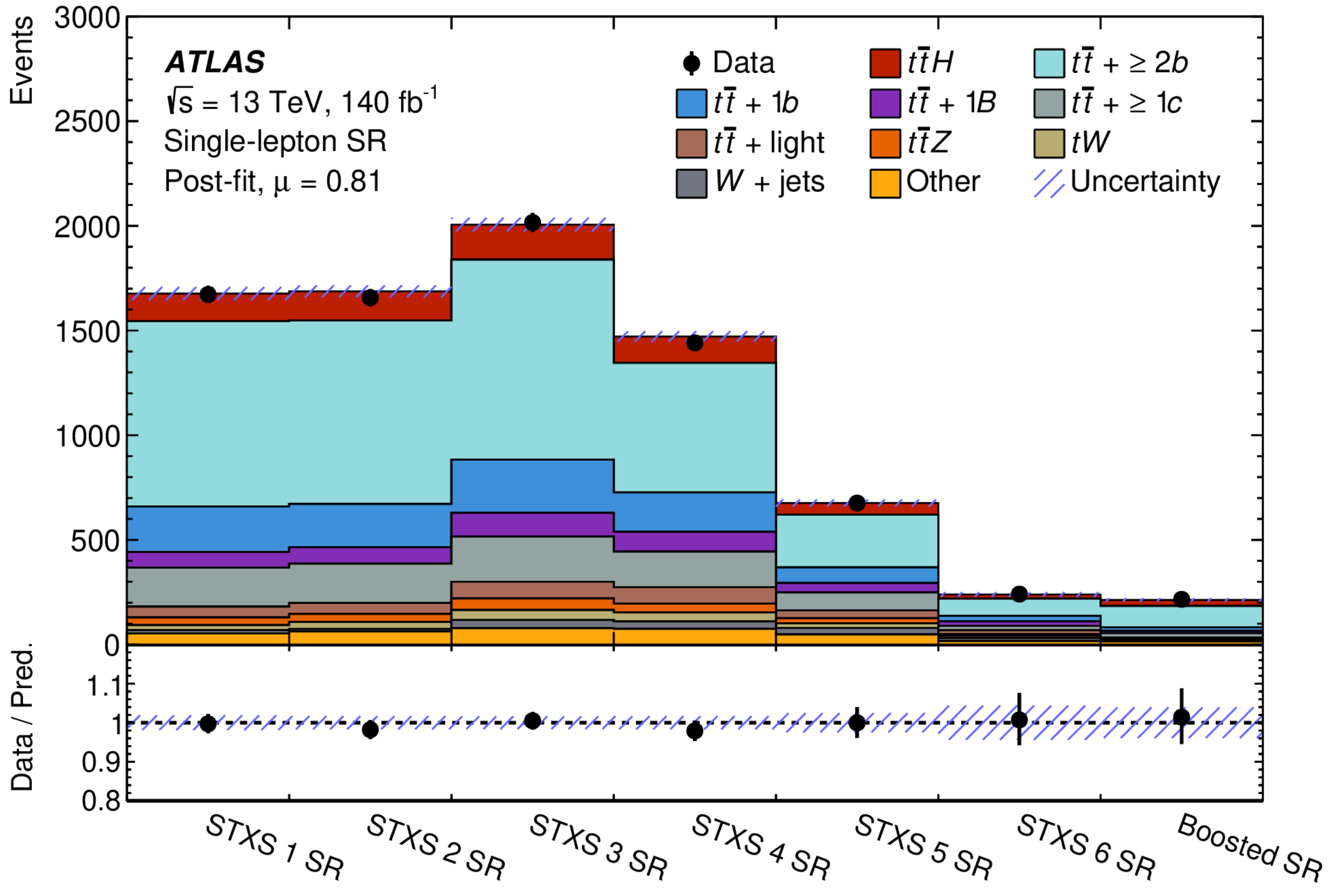
- Large and irreducible background from $t\bar{t}$***+b-jets***
- Major improvements of this analysis:
    - Advanced *b*-jet identification algorithm
    - Improved $t\bar{t} + n \geq 1$ *b-jet* modeling using new Monte Carlo sample with optimized POWHEG+PYTHIA8 parameters with better associated systematics (ATL-PHYS-PUB-2022-006)

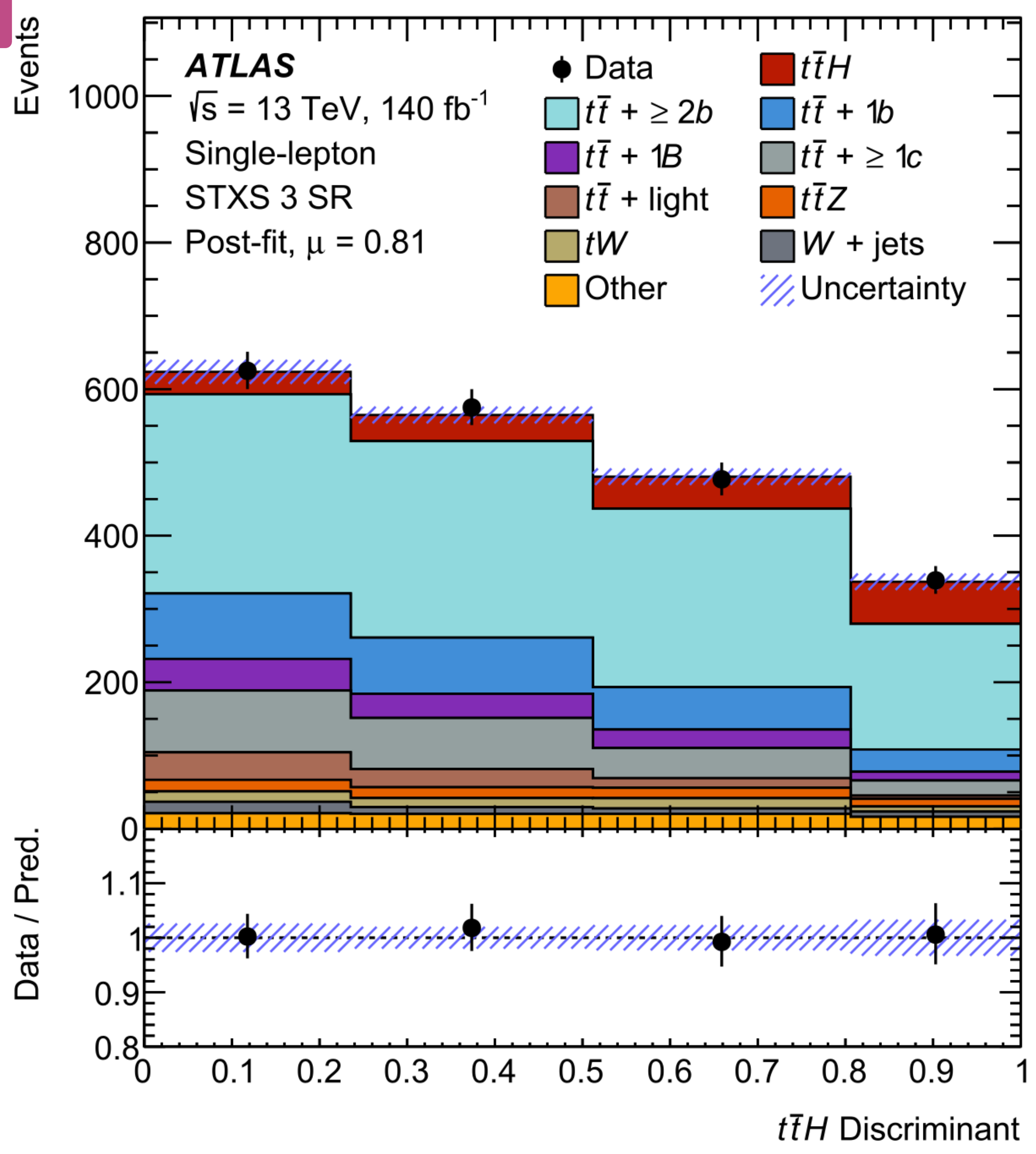
Coupling/STXS with $t\bar{t}H, H \rightarrow b\bar{b}$ @ ATLAS

- For the single-lepton (dilepton) channel signal region, >97% (94%) of the Higgs decay mode is $H \rightarrow b\bar{b}$ followed by $H \rightarrow WW$ decays
- Enhanced categorization and classification allowed loosen the preselection cuts and >x3 the signal acceptance
- The boundaries of the regions are optimized to maximize the fraction of the events with the corresponding truth p_{T}^{H}



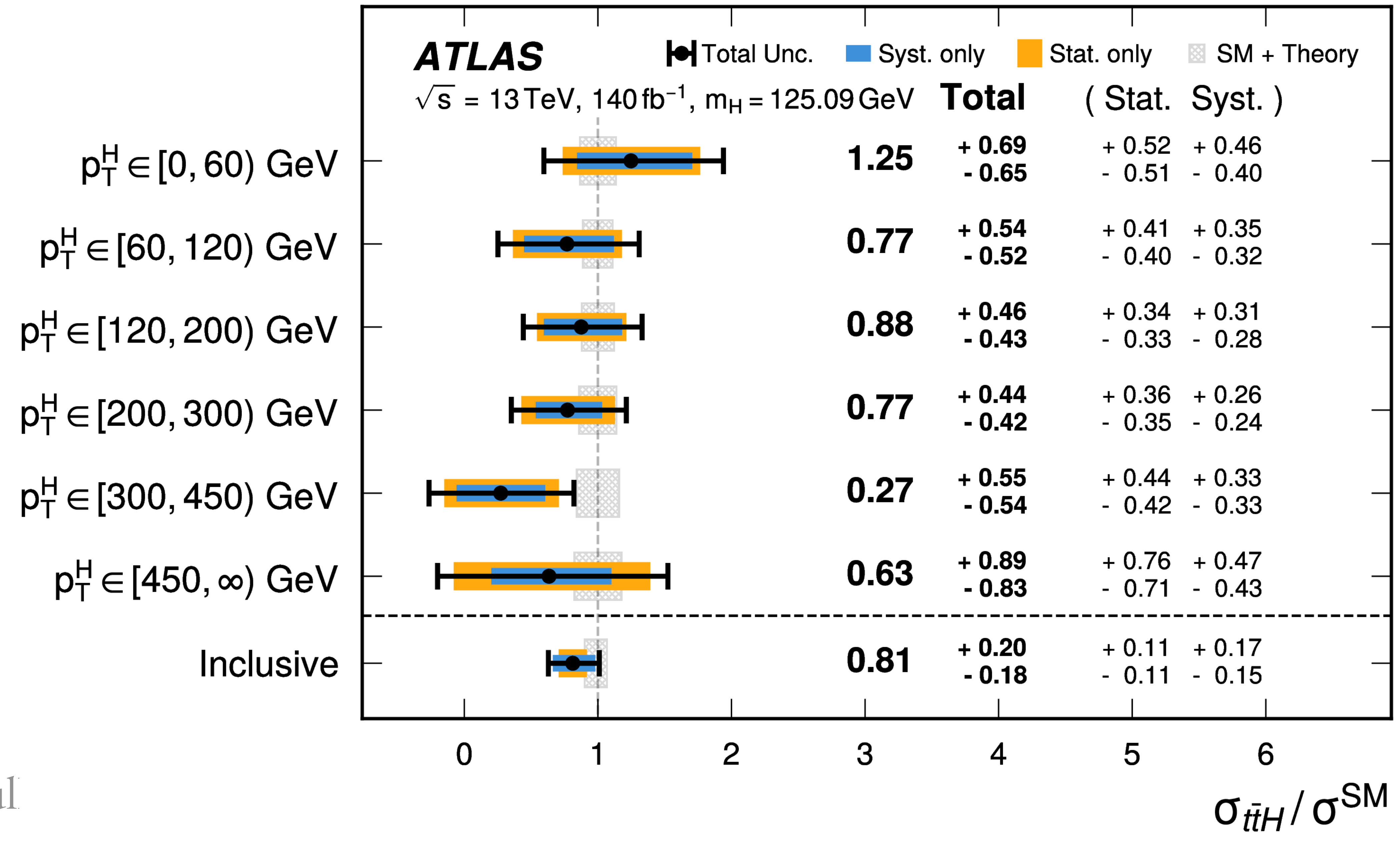


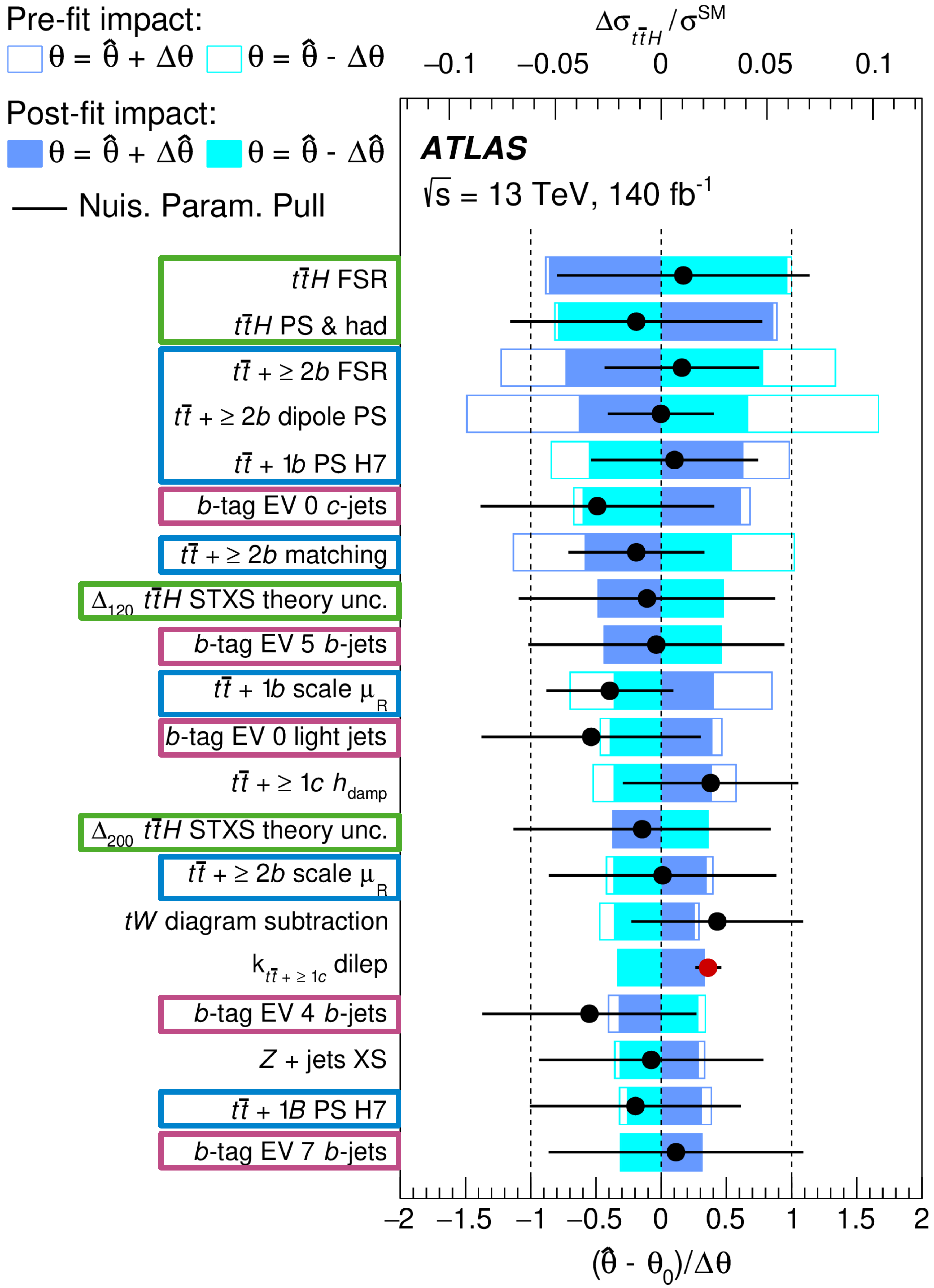




Coupling/STXS with $t\bar{t}H, H \rightarrow b\bar{b}$ @ ATLAS

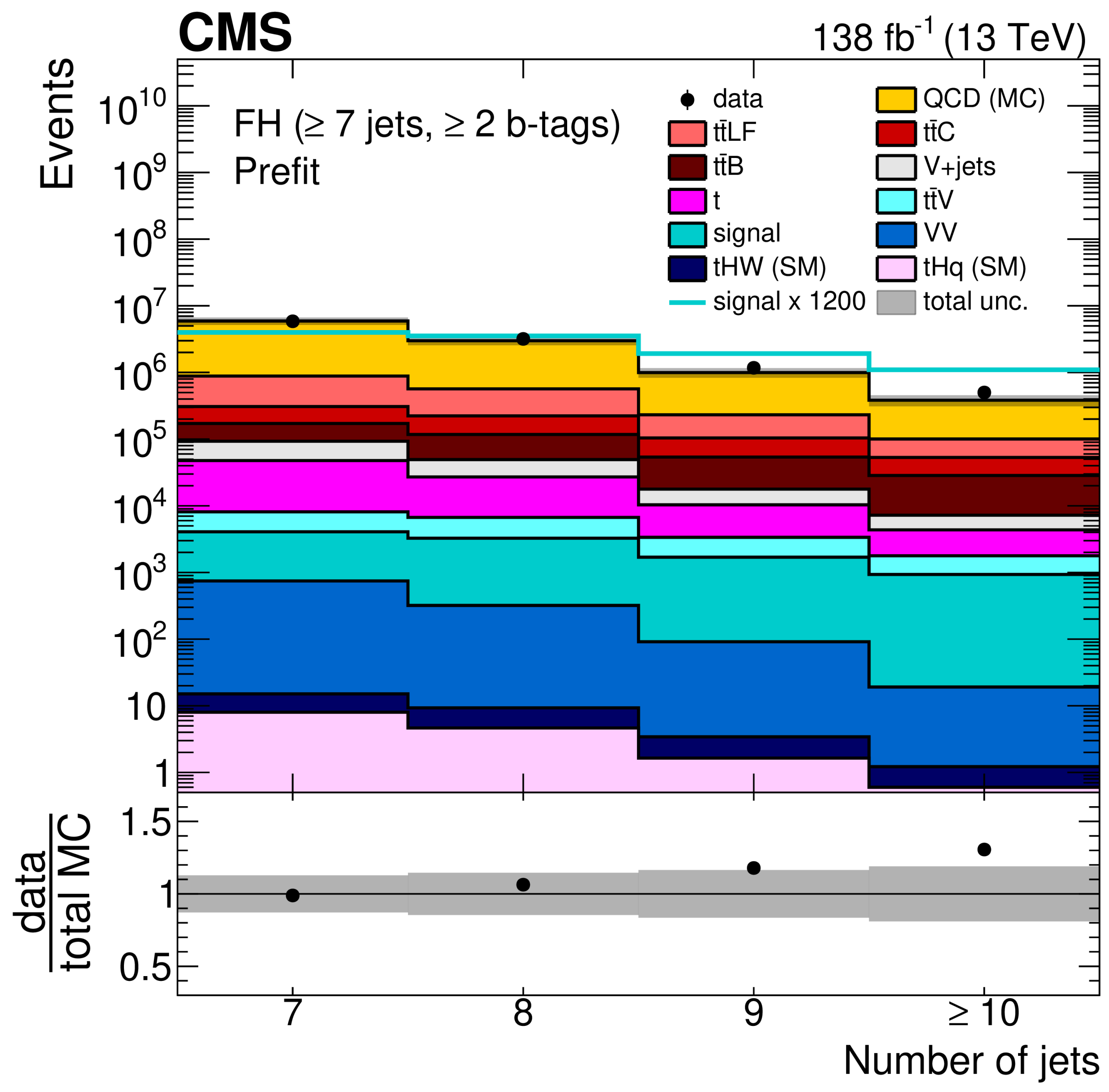
- Simultaneous profile likelihood fit with 13 SRs and 13 CRs
  - Signal x-sec and background normalization free floating
- Observed (expected) signal significance: 4.6 (5.4) σ
  - Compared to 1.0 (2.7) σ in previous round
- The measured signal strength is $\mu_{t\bar{t}H} = 0.81 \pm 0.11(\text{stat.})^{+0.20}_{-0.16}(\text{syst.})$
- Full STXS stage 1.2 (6 Higgs pT bins)
  - STXS Compatibility with SM: 89%
- Sensitivity dominated by signal modeling, $t\bar{t} + n \geq 1b$-jet modeling and b-tagging
- **Best accuracy achieved so far in inclusive and differential!**

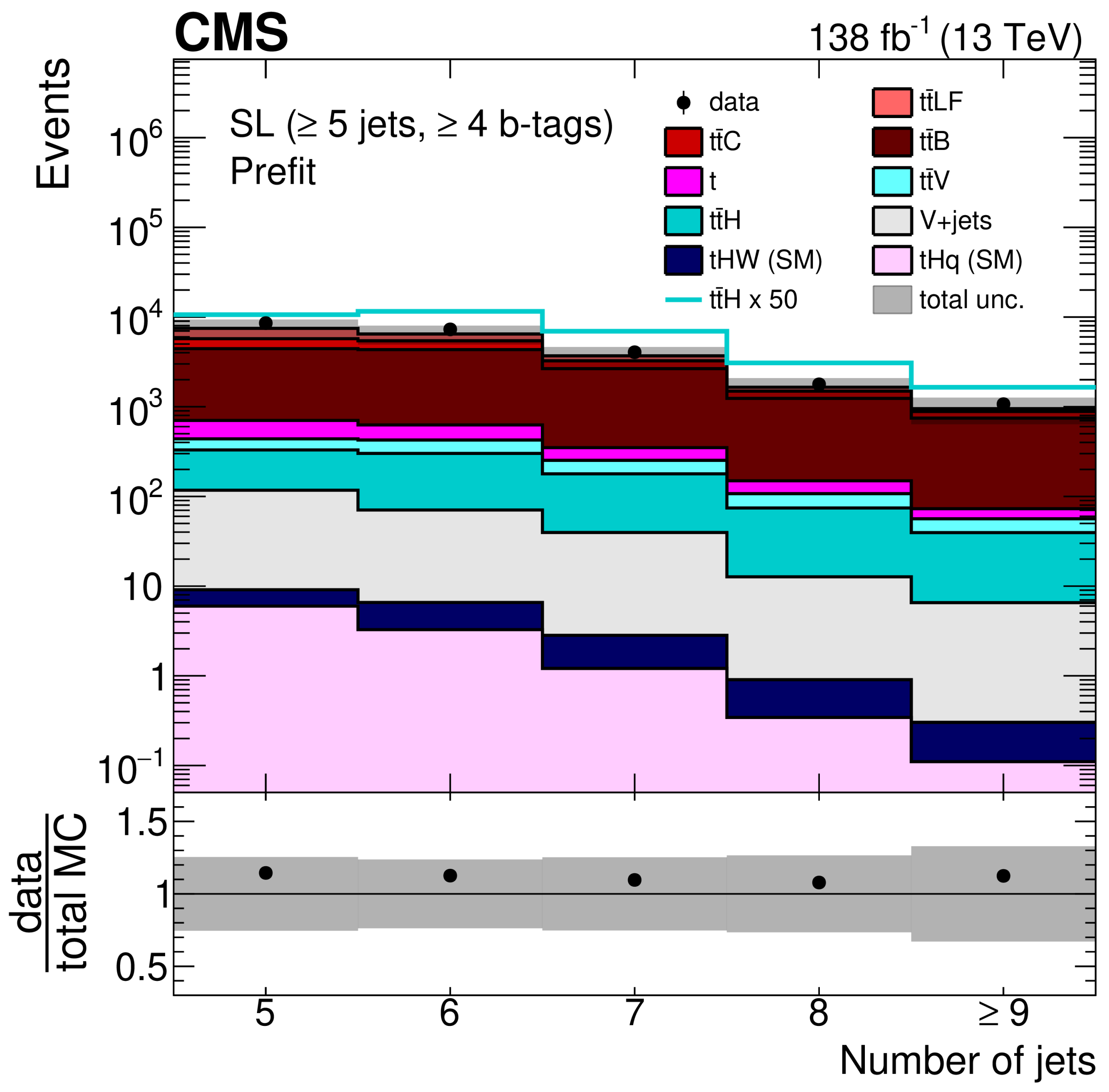


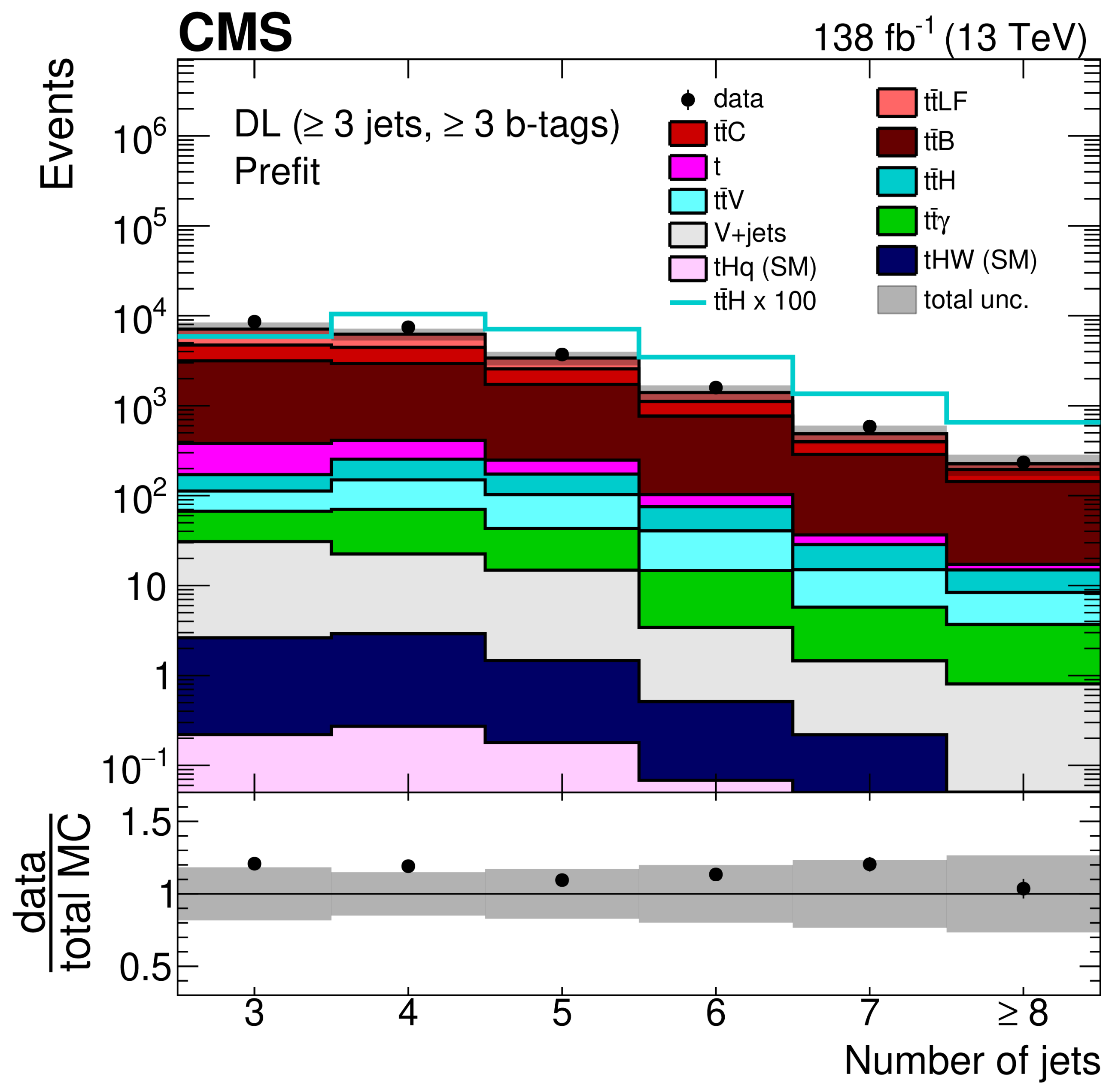


Coupling/STXS with $t\bar{t}H, H \rightarrow b\bar{b}$ @ CMS

- New analysis of the full Run 2 dataset [JHEP02(2025)097]() superseding the previous one [CMS-PAS-HIG-19-011]()
- Three channels are considered based on the $t\bar{t}$ decay: fully hadronic, single- and di-lepton
- Large and irreducible background from $t\bar{t}$+*b-jets*
- Each channel categorizes the events based on the jet and *b*-jet multiplicity
- QCD multijet background not well modeled by the MC simulation in the fully hadronic channel -> data-driven estimate

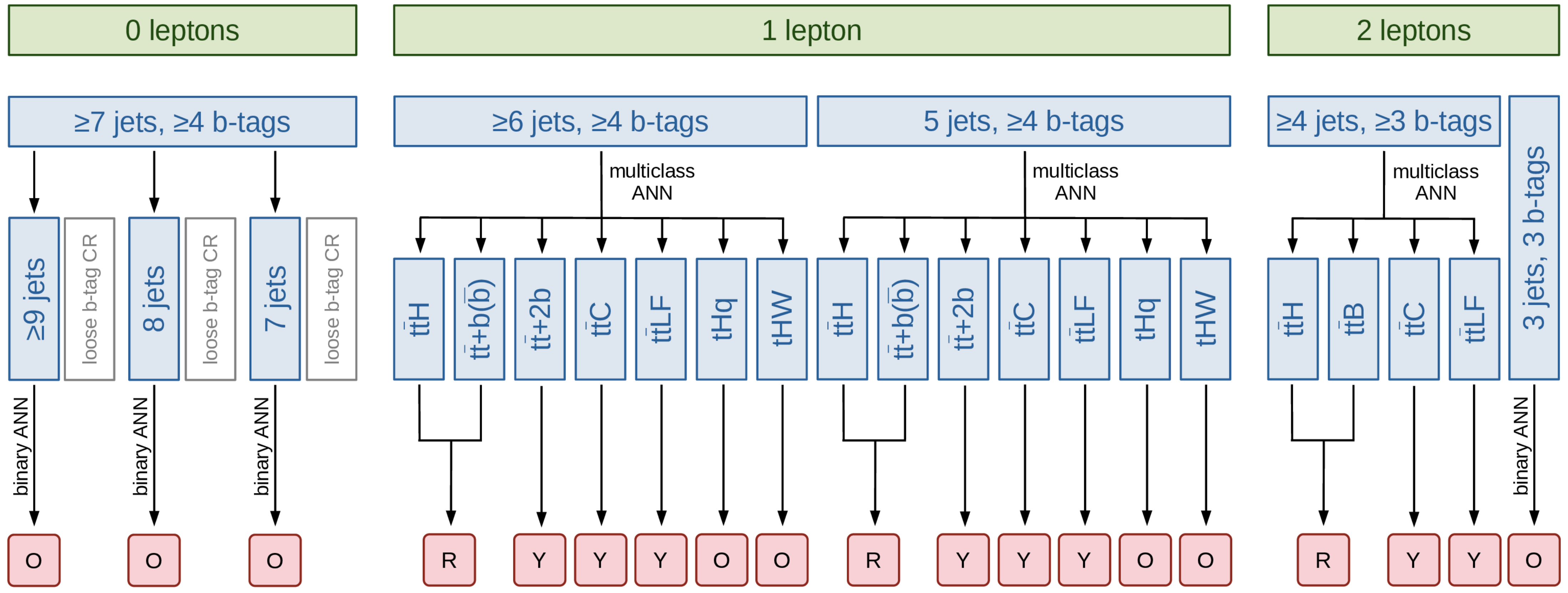






Coupling/STXS with $t\bar{t}H, H \to b\bar{b}$ @ CMS

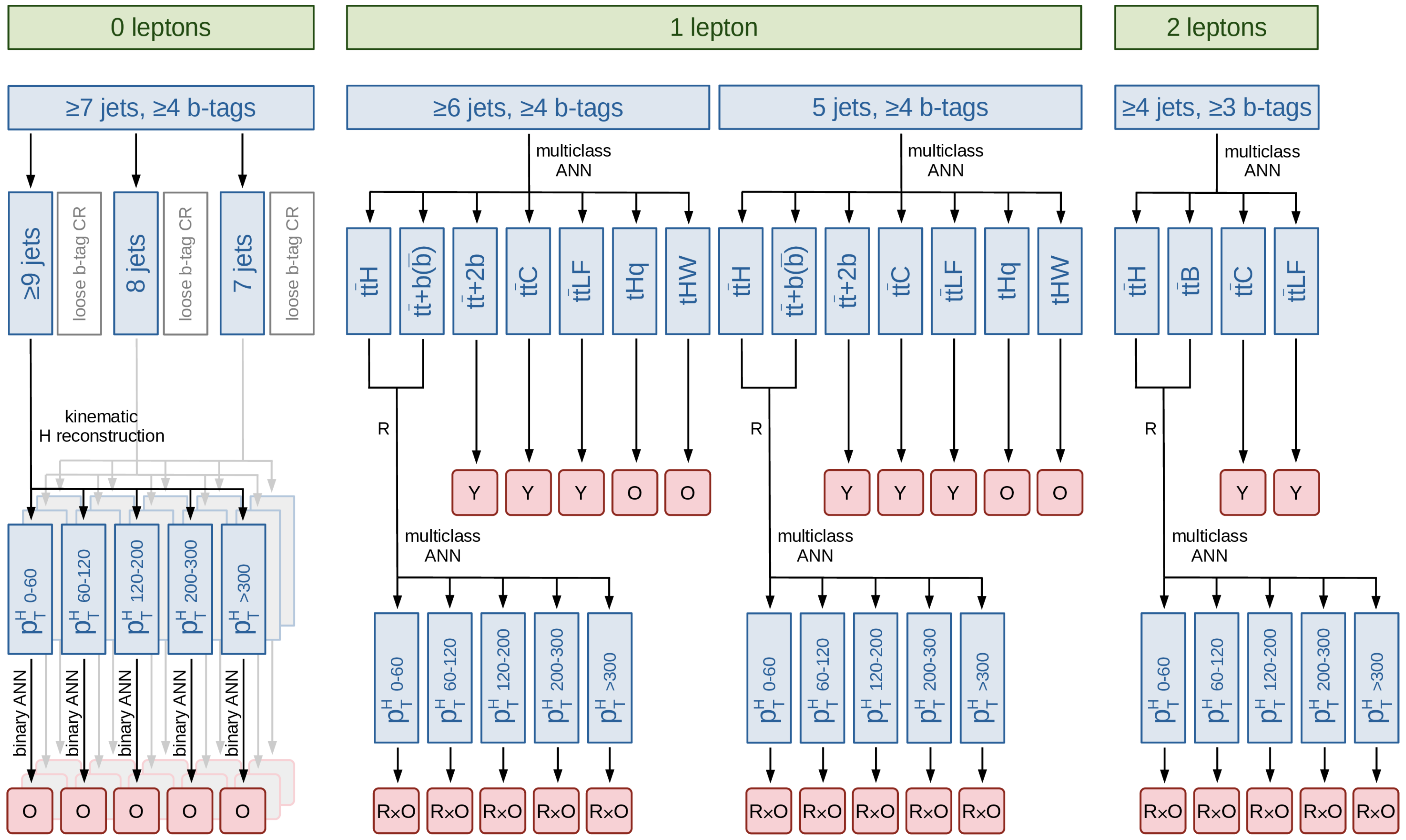
- The signal categories are optimized for the inclusive measurements as well as for the coupling and CP measurement
- For the STXS, five additional sub-categories are added for the $t\bar{t}H$ signal (corresponding to the 5 STXS bins)
- In the channels with leptons, events are separated based on the jet and b-tagged jet multiplicity
- In each of the two SL categories and in the (≥4 jets, ≥3 b tags) DL category, events are further categorized based on the output of multi-classification ANNs, which are designed to separate between different signal and background processes
  - The output values of the ANNs are subsequently used to compute the final discriminant R_{SL}



Distribution in template fit, event yield (Y), ANN output (O), likelihood ratio of ANN outputs (R)

$$R_{SL} = \frac{O(t\bar{t}H)}{O(t\bar{t}H) + O(t\bar{t}+b(\bar{b})) + O(t\bar{t}+2b)}$$

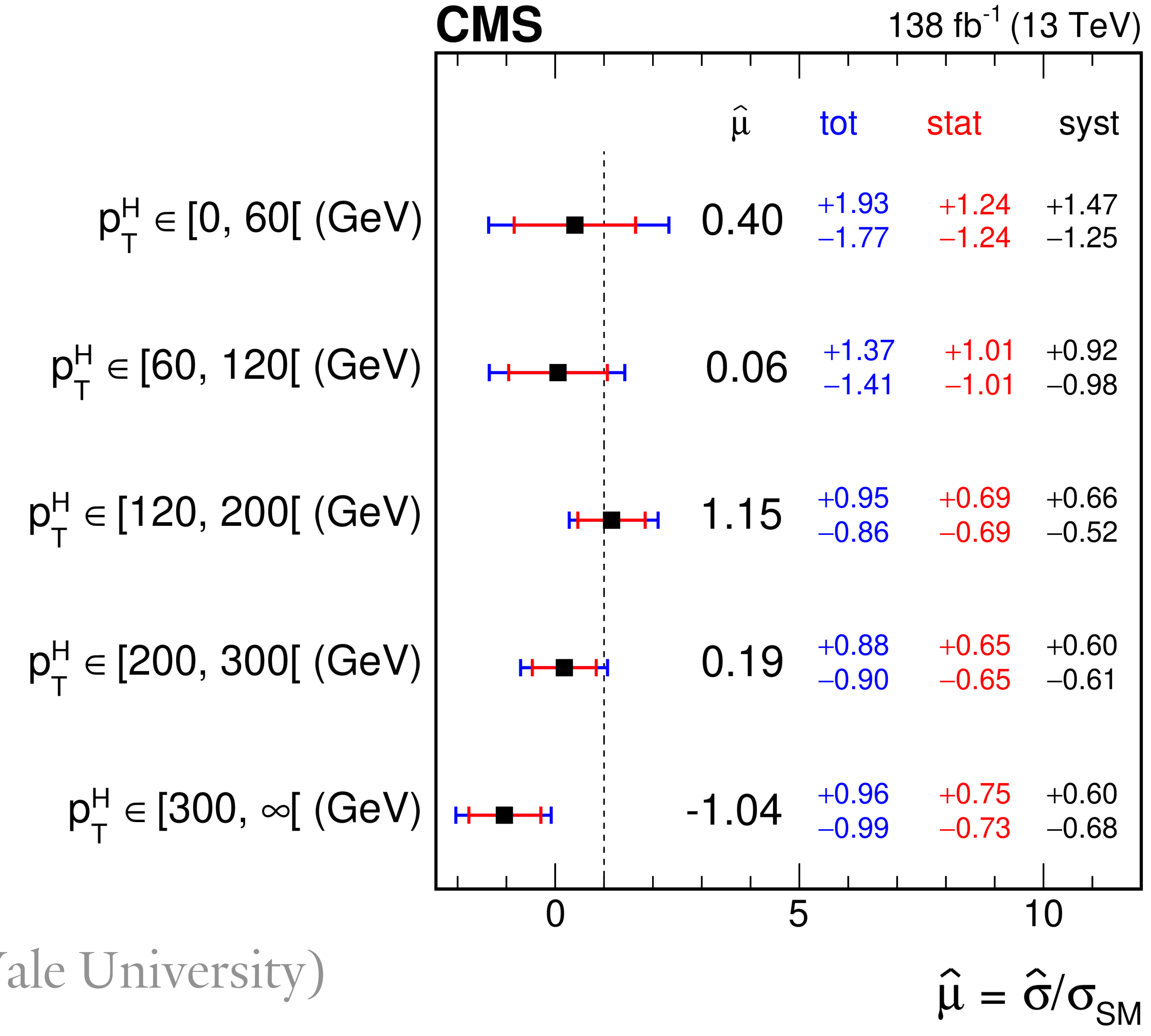
$$R_{DL} = \frac{O(t\bar{t}H)}{O(t\bar{t}H) + O(t\bar{t}B)}$$

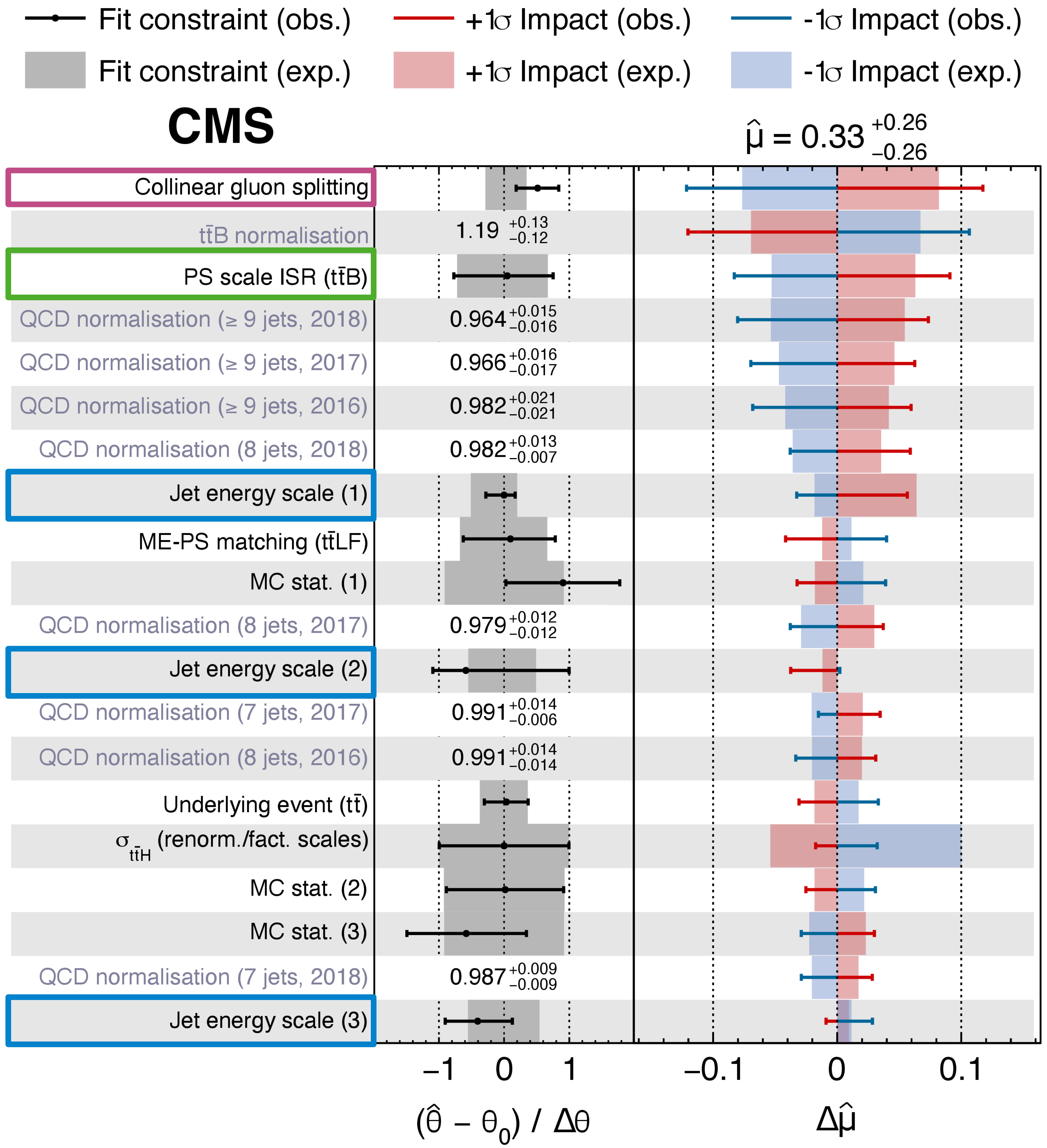


Distribution in template fit, event yield (Y), ANN output (O), likelihood ratio of ANN outputs (R)

Coupling/STXS with $t\bar{t}H, H \rightarrow b\bar{b}$ @ CMS

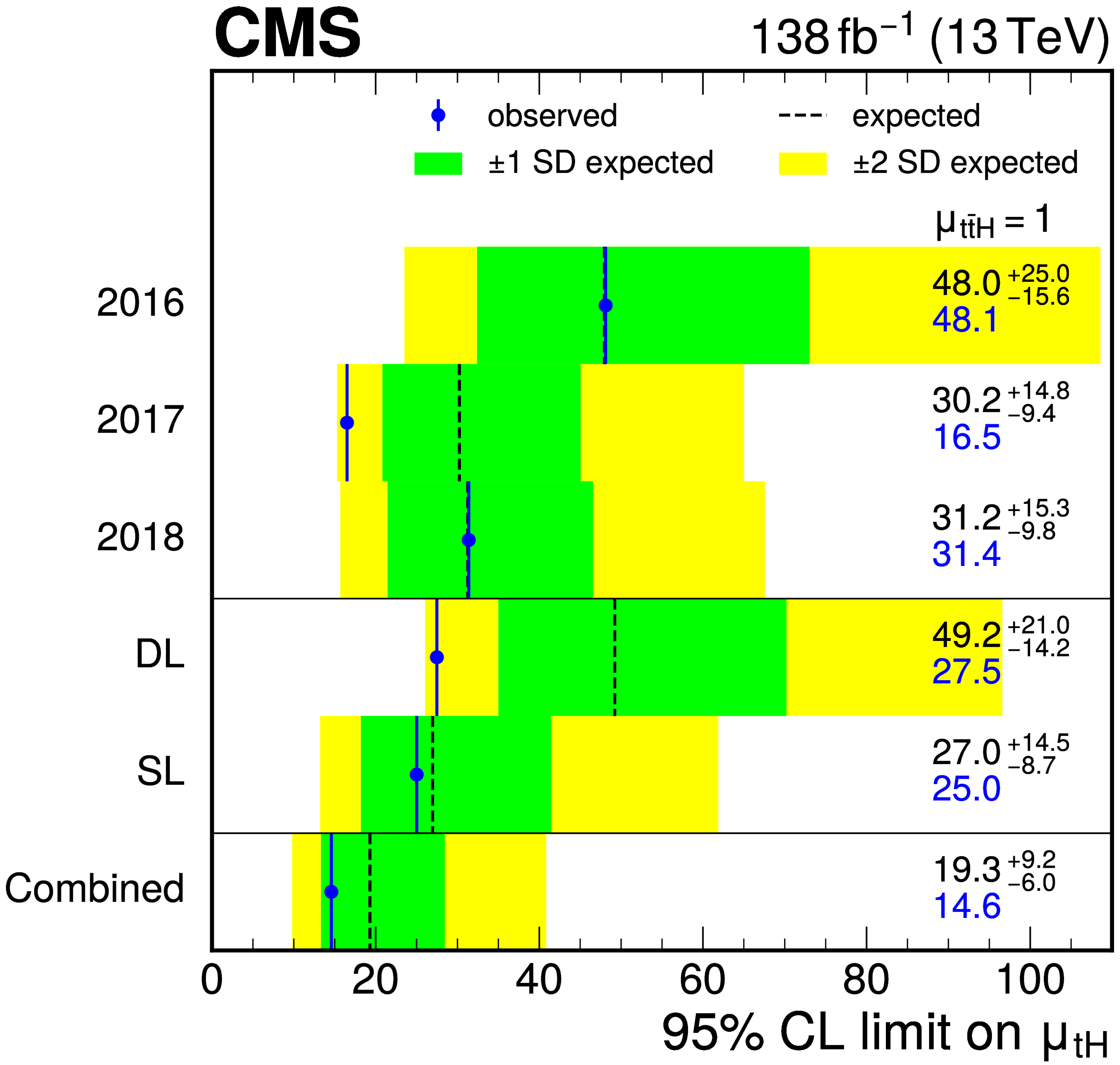
- Simultaneous binned profile likelihood fit with in all channels
  - Background normalizations free floating
- Observed (expected) signal significance: 1.3 (4.1) σ
- The measured signal strength is $\mu_{t\bar{t}H} = 0.33^{+0.17}_{-0.16}(\text{stat.})^{+0.20}_{-0.21}(\text{syst.})$
- Full STXS stage 1.2 (5 Higgs pT bins)
  - STXS Compatibility with SM: 81%
- Systematics with larger impact from $t\bar{t}B$ modeling, jet energy scale and collinear gluon splitting

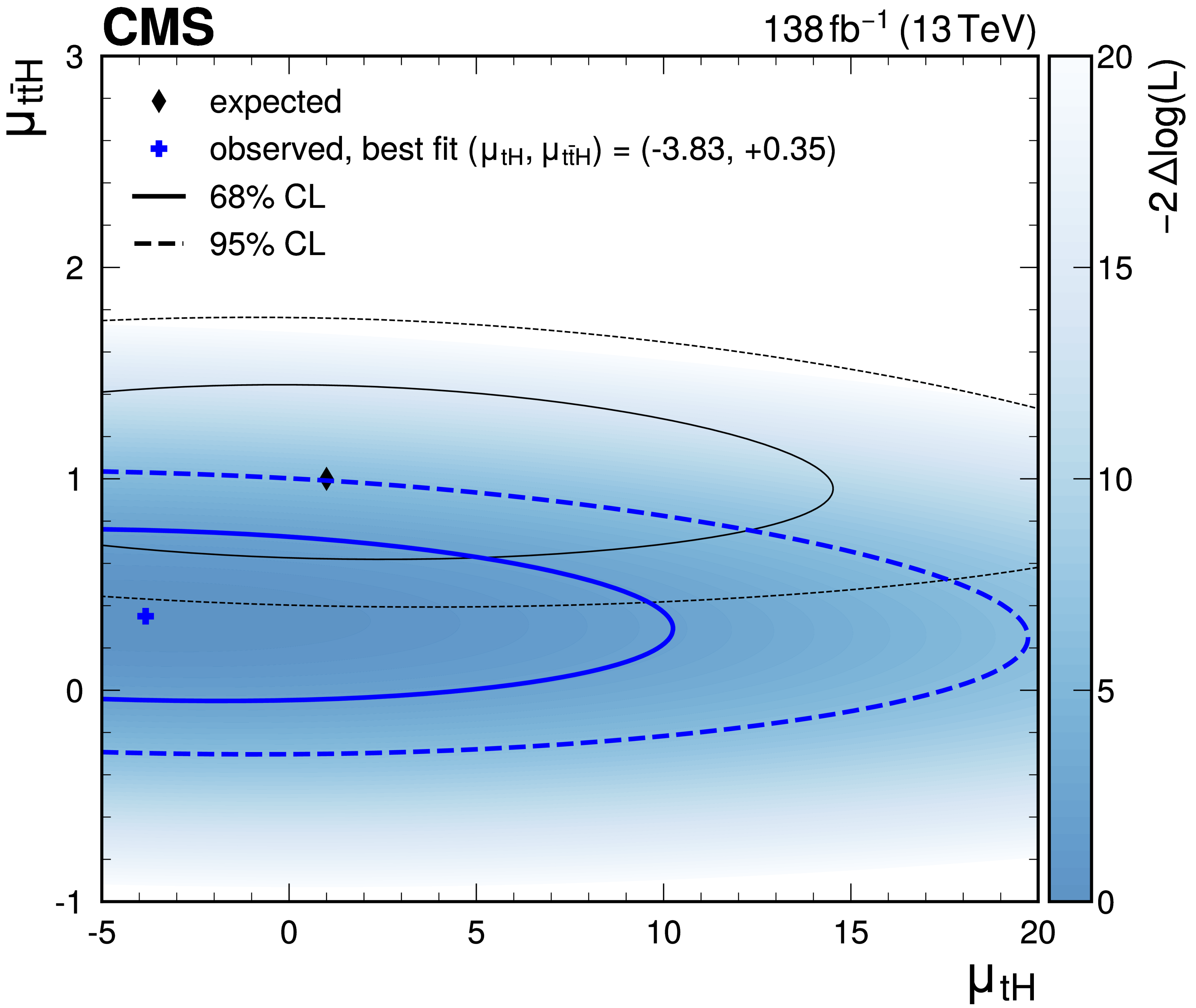




Coupling/STXS with $tH, H \to b\bar{b}$ @ CMS

- An upper limit @ 95% C.L. wrt the SM expectation of 14.6 is observed, with an expectation of $19.3^{+9.2}_{-6.0}$
- Performed also a simultaneous fit of the μ_{tH} and $\mu_{t\bar{t}H}$ with best-fit values of (-3.83, 0.35)





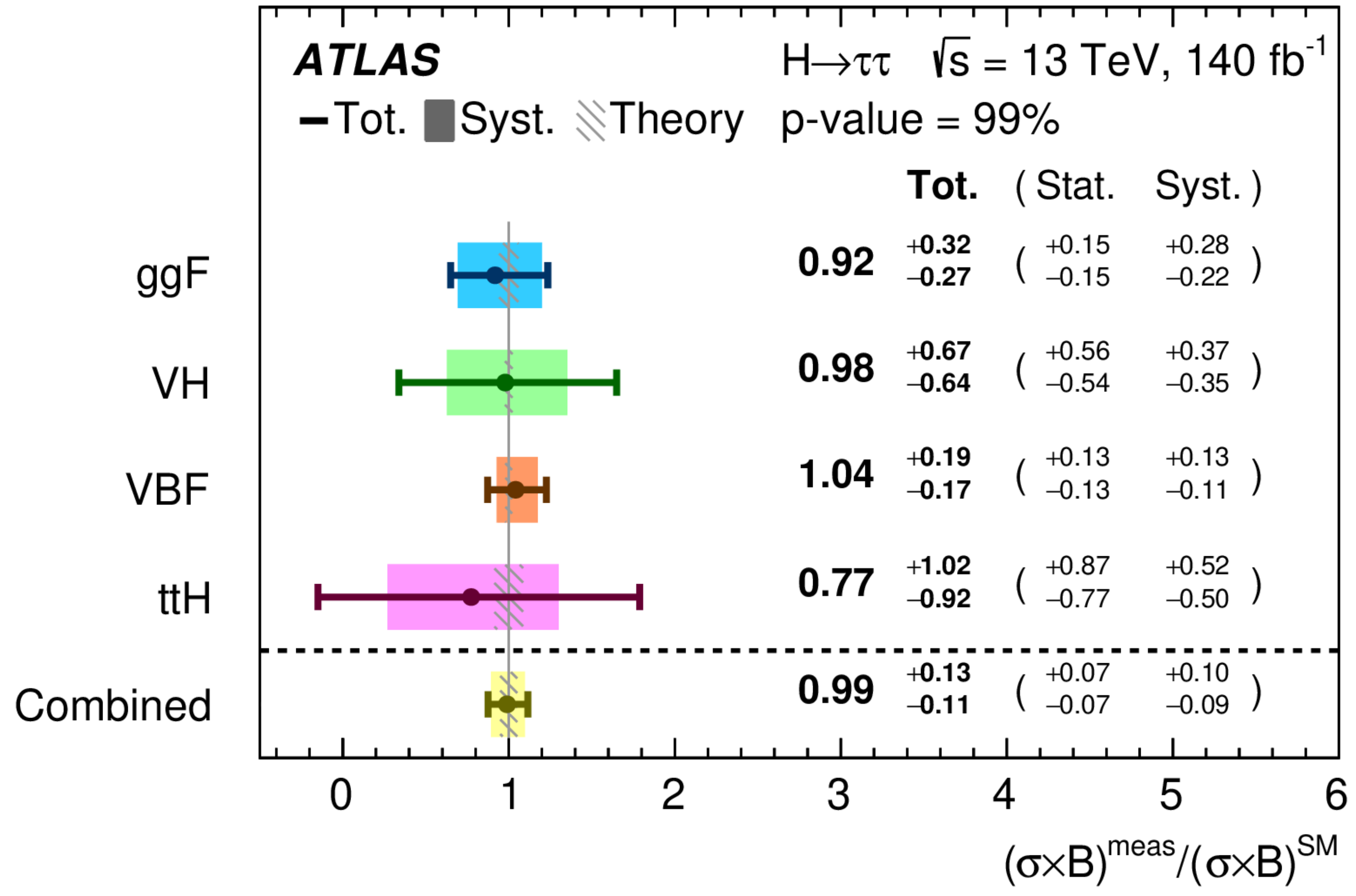
Differential xsec of $t\bar{t}H, H \to \tau\tau$ @ ATLAS

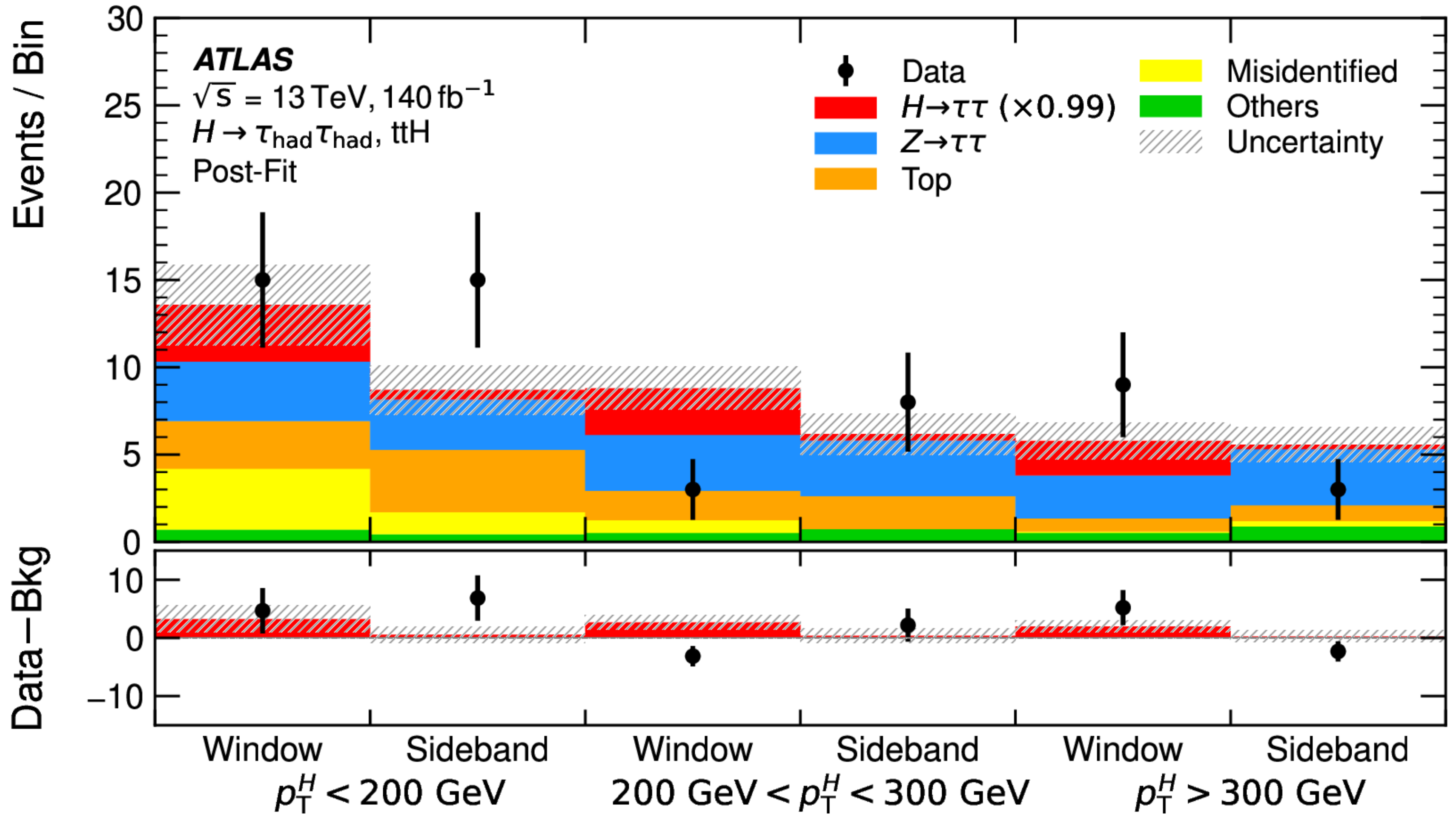
- Previous analysis JHEP 08 (2022) 175 of the $H \to \tau\tau$ final state in the four main production modes. JHEP 03 (2025) 010 supersedes the previous one and extends the study of $t\bar{t}H$ production in the STXS framework
- Events categorized to split the main production modes: VBF, V(had)H, $t\bar{t}H$ and Boosted (ggF with high p_{T}^{H})
- For $t\bar{t}H, H \to \tau\tau$, the full hadronic final state is selected
  - Six jets including at least one *b*-tagged jet, or five jets including at least two *b*-tagged jets
- A BDT multi-classifier is used to separate the signal from $Z(\to \tau\tau)$ and $t\bar{t}$ events
- By inverting the requirement on the score separate control regions are defined
- Three p_{T}^{H} bins included for the $t\bar{t}H, H \to \tau\tau$ STXS interpretation: $[0{,}200{,}300{,}\infty)$ GeV

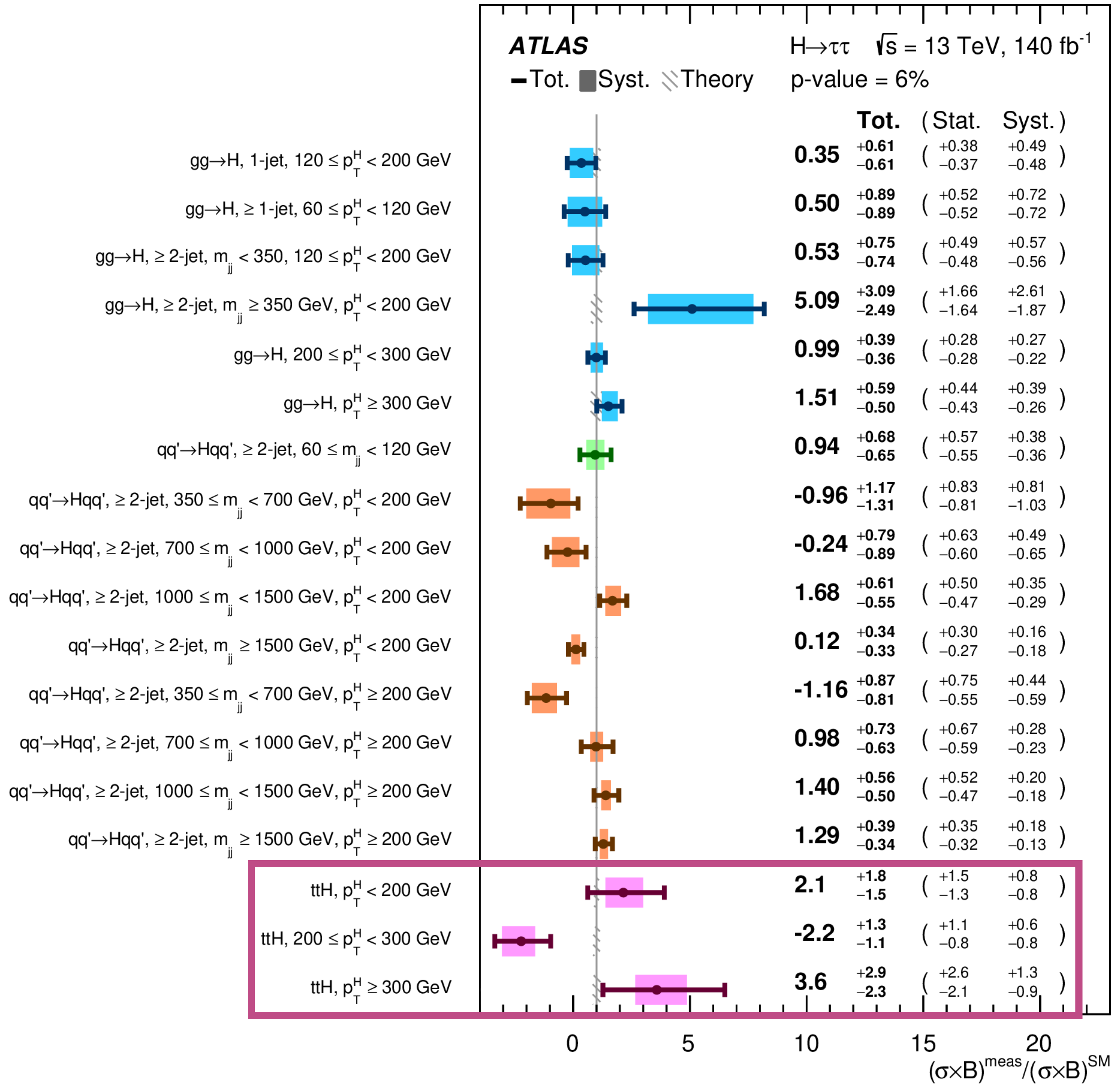
Differential xsec of $t\bar{t}H, H \to \tau\tau$ @ ATLAS

[JHEP 03 (2025) 010]

- The fit model accounts for the various channels:
  - For $t\bar{t}H$, 6 SRs and 2 CRs
- CRs constrain the event yield of specific backgrounds
- The resulting $t\bar{t}H$ inclusive x-sec wrt to the SM is measured to be $0.77^{+1.02}_{-0.92}$







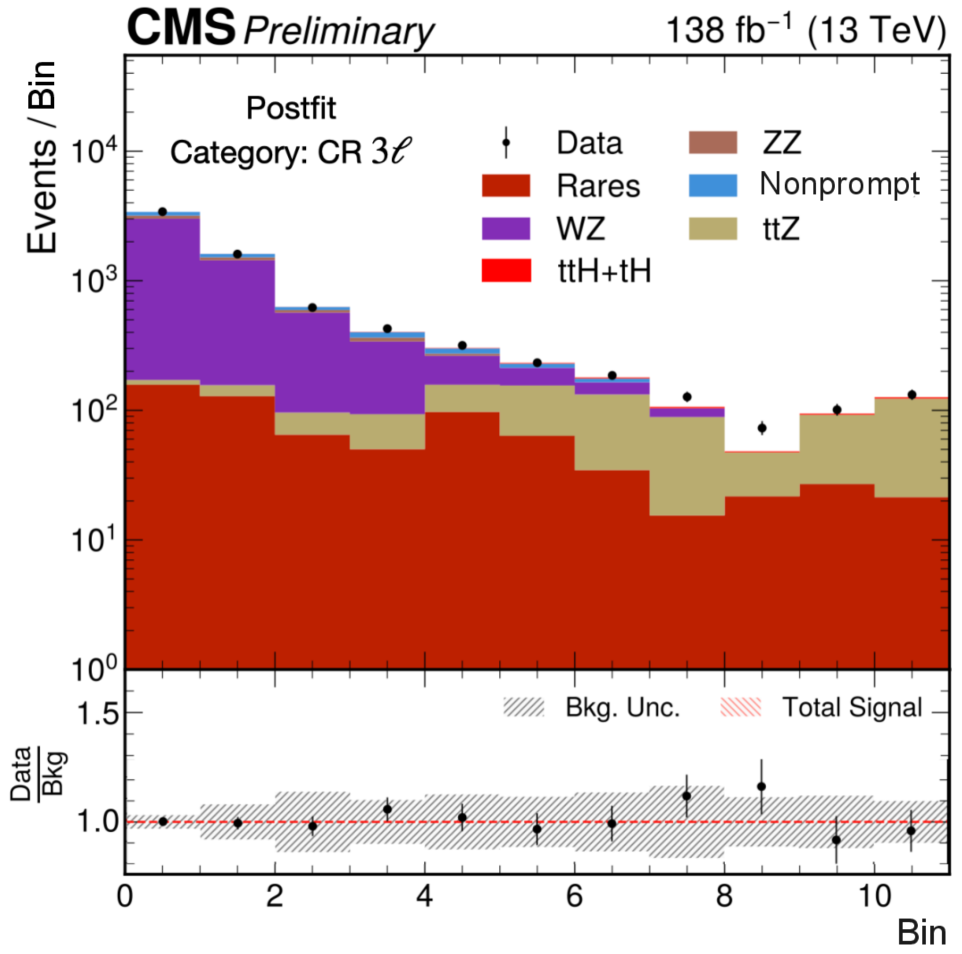
Differential xsec of $t\bar{t}H, H \rightarrow WW$ or $H \rightarrow \tau\tau$ @ CMS

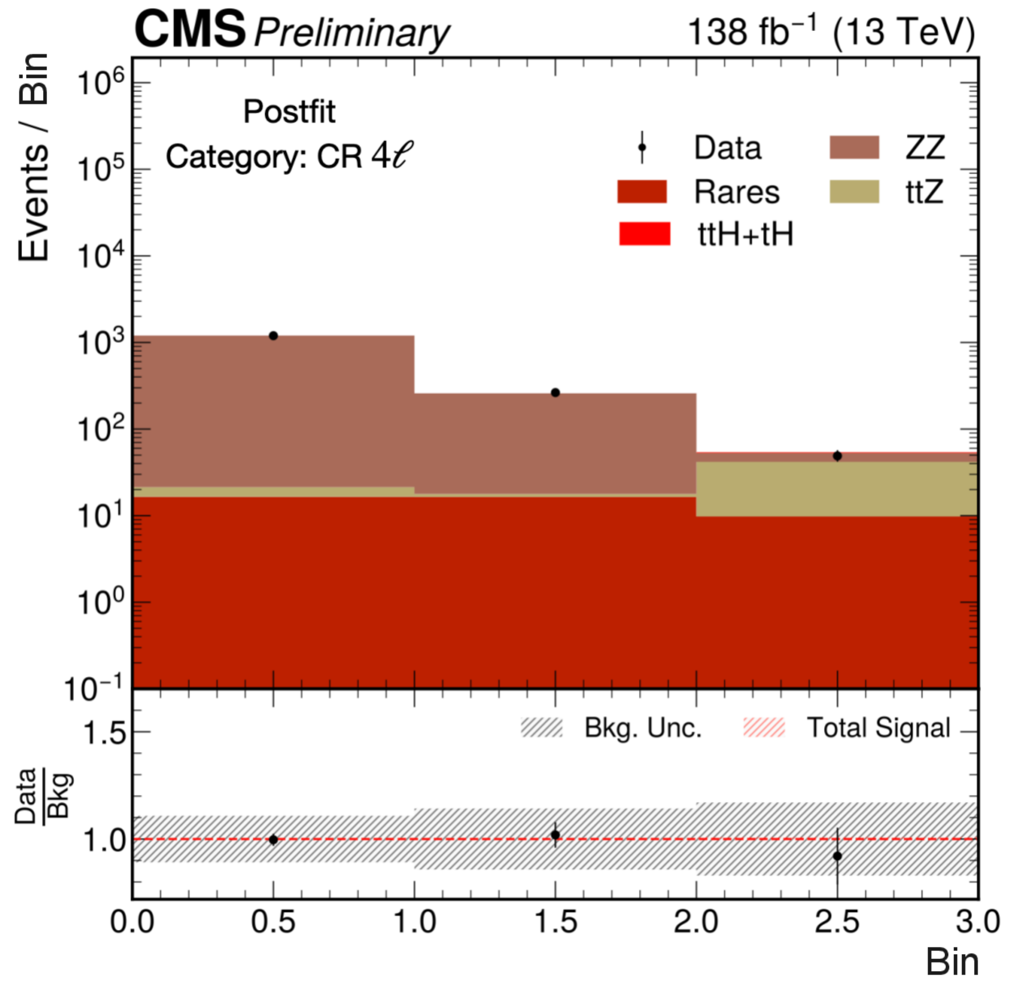
- New analysis of the full Run 2 dataset [CMS-PAS-HIG-23-015] superseding the previous one [Eur. Phys. J. C 81 (2021) 378]
- Events categorized based on number of light leptons and τ_{had}:
  - 2ℓss+0τ_{had}, 2ℓss+1τ_{had}, 3ℓ+1τ_{had}
- Dedicated training of a Deep Neural Network in each channel involving three classes: $t\bar{t}H$-, tH- and background-like
  - An additional $t\bar{t}W$-like class was included in the 2ℓss+0τ_{had} channel
- Irreducible background from $t\bar{t}Z$ and $t\bar{t}W$
  - Contributions derived from 3 different CRs: $t\bar{t}Z$+WZ, $t\bar{t}Z$+ZZ and $t\bar{t}W$ enriched
- Reducible background from: misidentified leptons and τ_{had}, asymmetric photon conversions into electrons and lepton charge mis-measurement
  - Predicted using data-driven methods
- Measurement performed in bins of p_{T}^{H} and $m_{t\bar{t}H}$

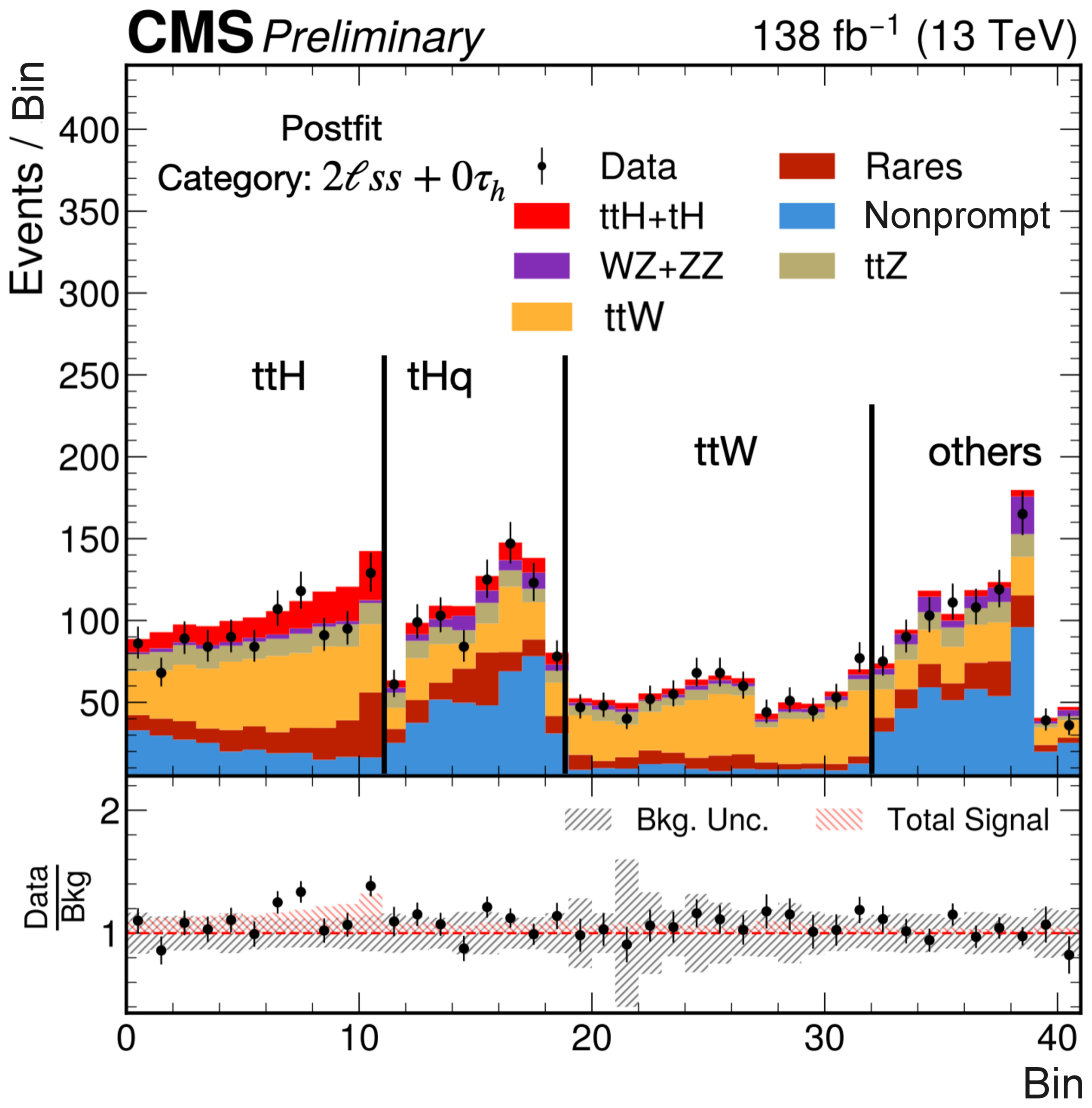
Differential xsec of $t\bar{t}H, H \rightarrow WW$ or $H \rightarrow \tau\tau$ @ CMS

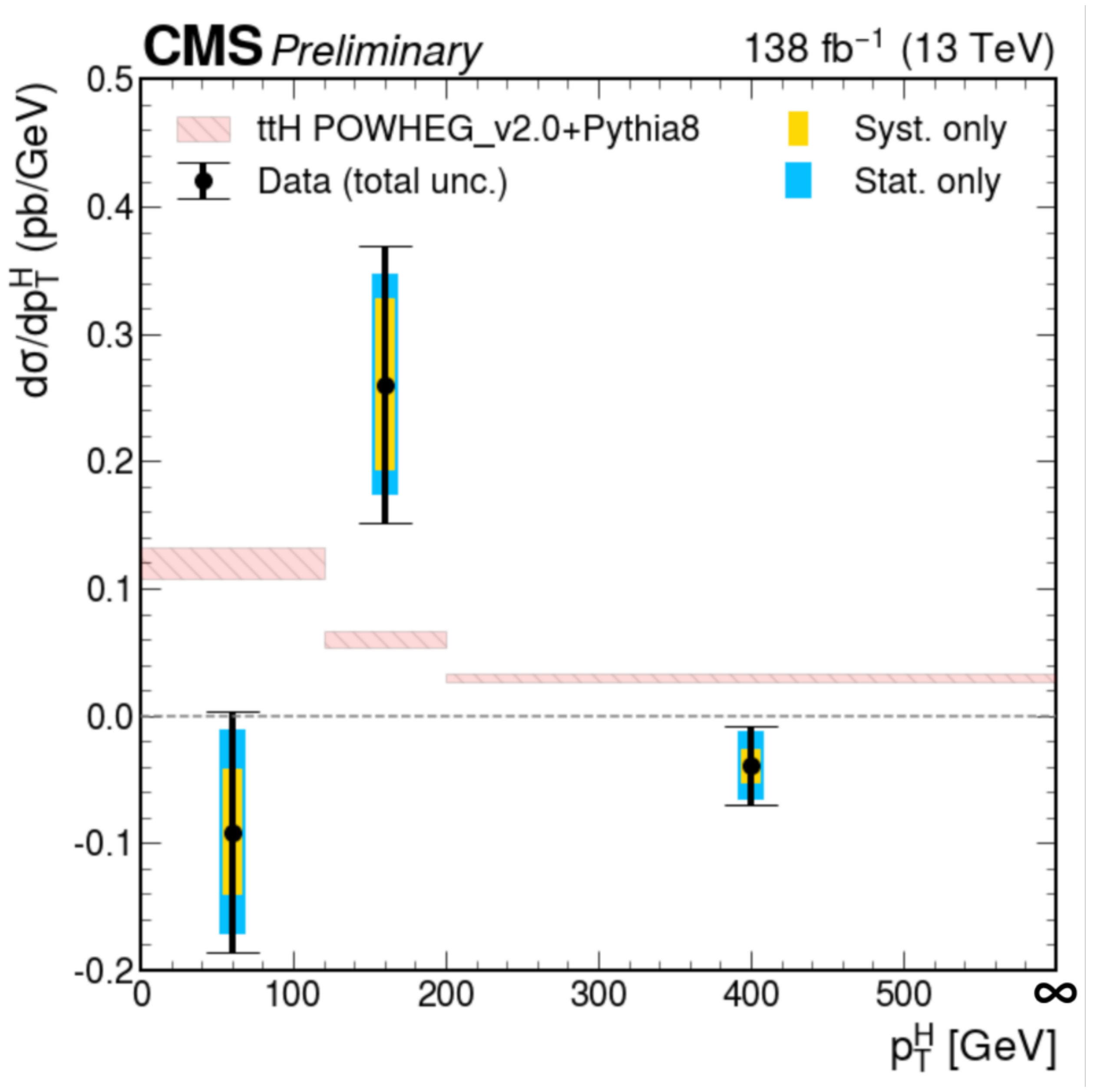
CMS-PAS-HIG-23-015

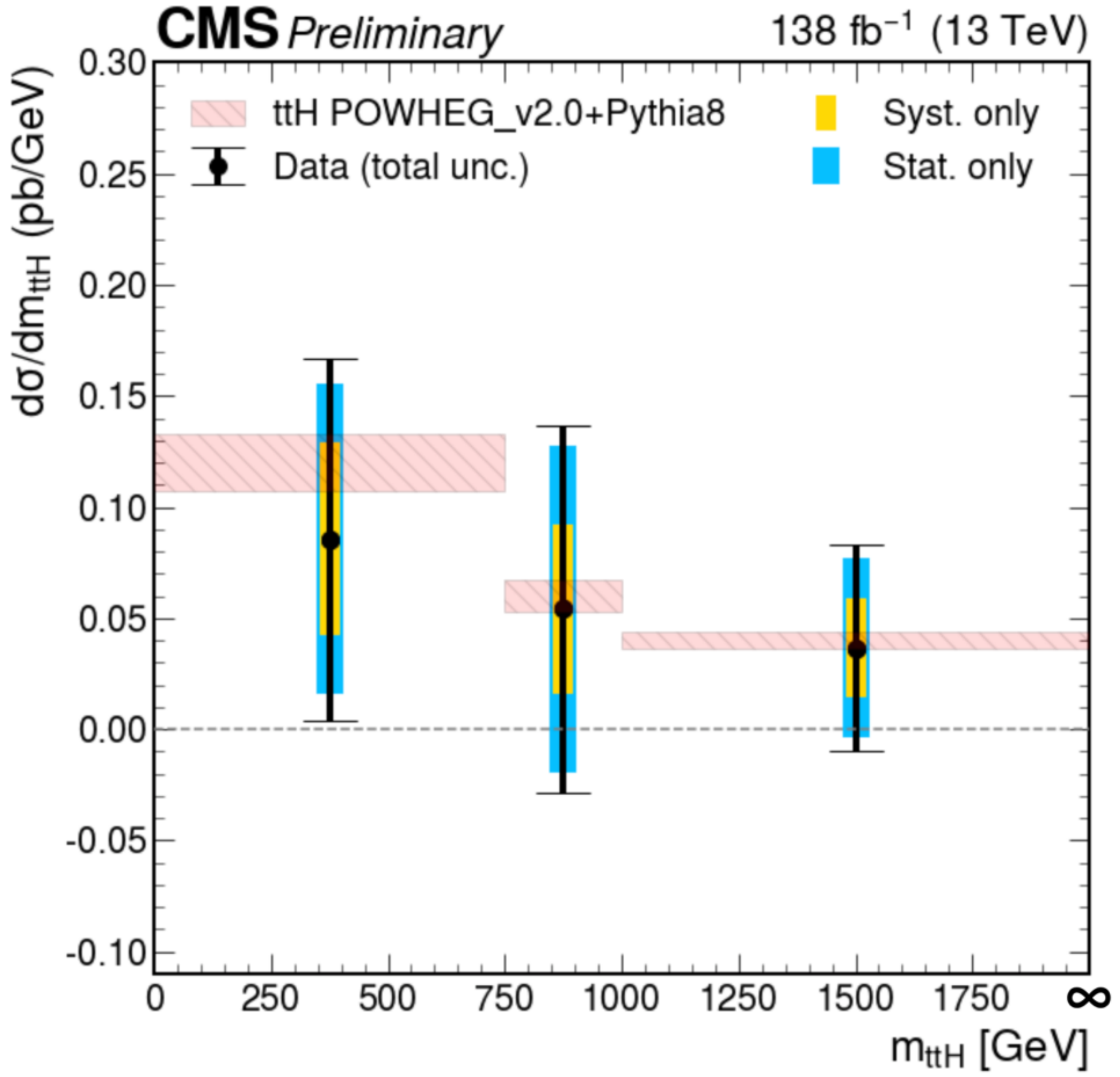
- Signal extracted from profile likelihood ratio fit to the DNN score
  - 3 SRs + 2 CRs used
- The measurement is stat limited
- The main sources of syst uncert are from misidentified lepton and charge mismeasurement as well as theory uncert











CP nature of the Top-Higgs coupling in $t\bar{t}H, H \to b\bar{b}$

- SM predicts the Higgs boson to be a CP-even particle ($J^{CP} = 0^{++}$, scalar)
- Signs of pure CP-odd or CP-mixed couplings to SM particles would be a hint of BSM
- Effective Lagrangian describing top Yukawa coupling can be parametrized as:

$$\mathscr{L} = -\frac{m_t}{v}\{[\bar{\psi}_t\kappa_t' \cos(\alpha) + i\kappa_t' \sin(\alpha)\gamma_5]\psi_t\}H$$

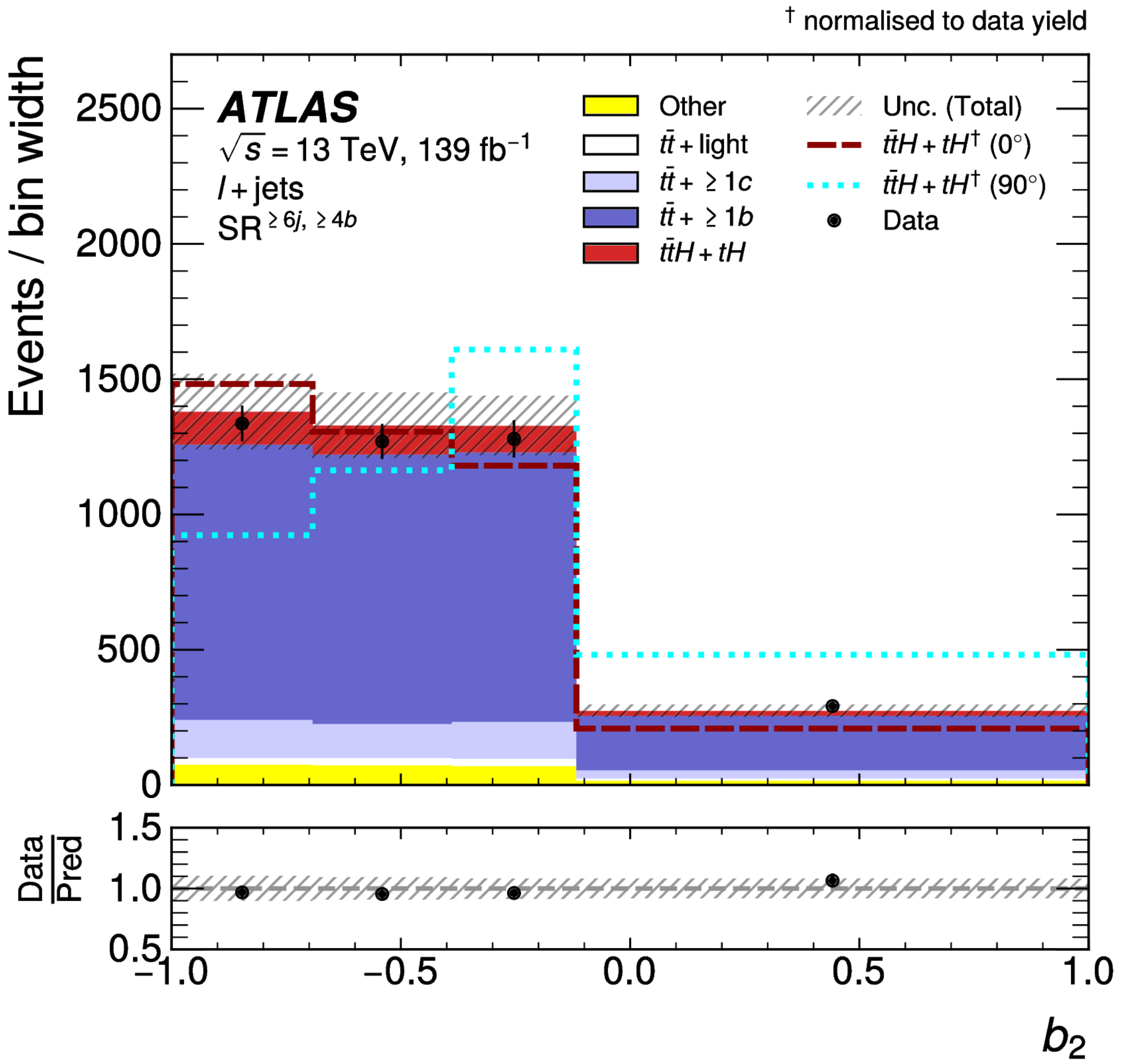
- κ_t: coupling modifier parameter (SM: $\kappa_t = 1$) → $\kappa_t \neq 1$ leads to variations in the cross-section
- α : CP-mixing angle. SM predicts $\alpha = 0°$ while pure CP-odd $\alpha = 90°$
- CP properties of the top Yukawa coupling can be directly probed through $t\bar{t}H/tH$ processes
  - Exploiting $H \to \gamma\gamma$ and $H \to b\bar{b}$

CP nature of the Top-Higgs coupling in $t\bar{t}H, H \to b\bar{b}$ @ ATLAS

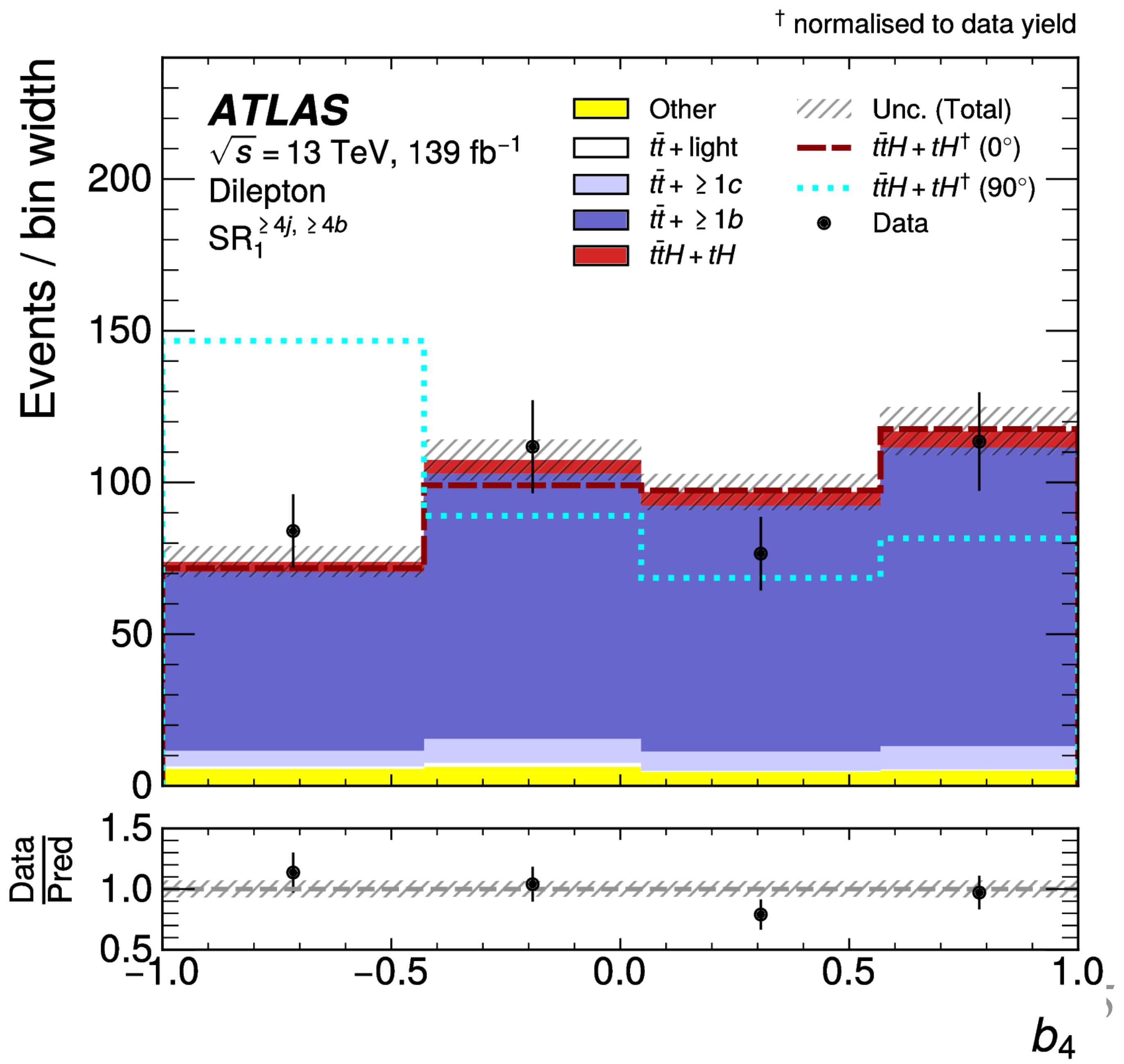
- Similar strategy to previous iteration of $t\bar{t}H, H \to b\bar{b}$ cross-section analysis with full Run 2 data JHEP 06 (2022) 97
  - BDTs used for event reconstruction and event classification (optimized for SM $t\bar{t}H/tH$)
  - Considering $t\bar{t}H$ and tH as signals
- Dedicated CP sensitive observables are built relying on angular separation between reconstructed top quarks
  - **b2**: enhanced for narrower azimuthal separation of top quarks in CP-odd case
  - **b4**: enhanced for top quarks in opposite directions and closer to the beamline
  - Used as fitting observables in the signal regions

PLB 849 (2024) 138469

$$b_2 = \frac{(\vec{p}_1 \times \hat{z}) \cdot (\vec{p}_2 \times \hat{z})}{|\vec{p}_1||\vec{p}_2|}$$



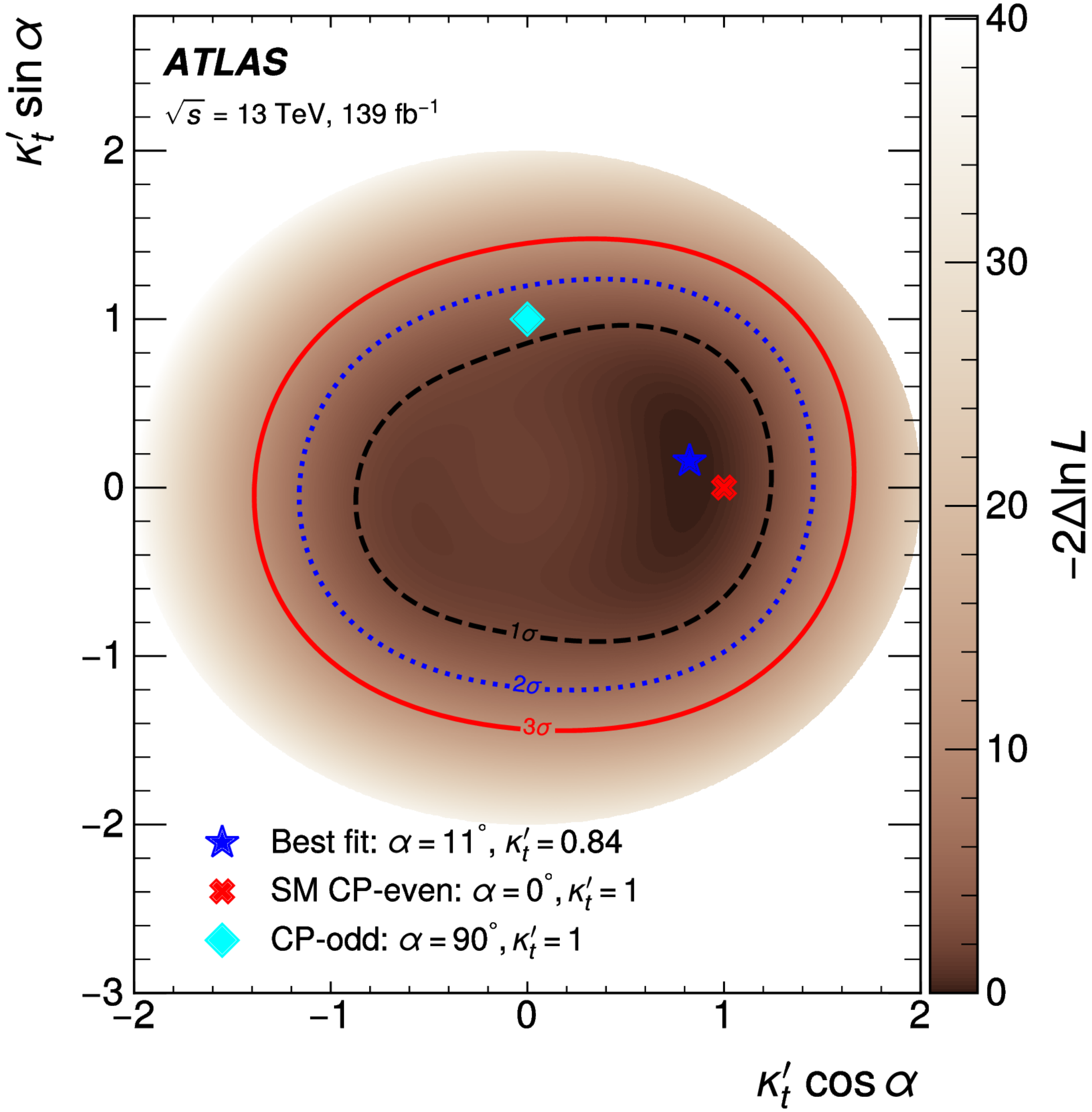
$$b_4 = \frac{(\vec{p}_1 \cdot \hat{z})(\vec{p}_2 \cdot \hat{z})}{|\vec{p}_1||\vec{p}_2|}$$



CP nature of the Top-Higgs coupling in $t\bar{t}H, H \rightarrow b\bar{b}$ @ ATLAS

PLB 849 (2024) 138469

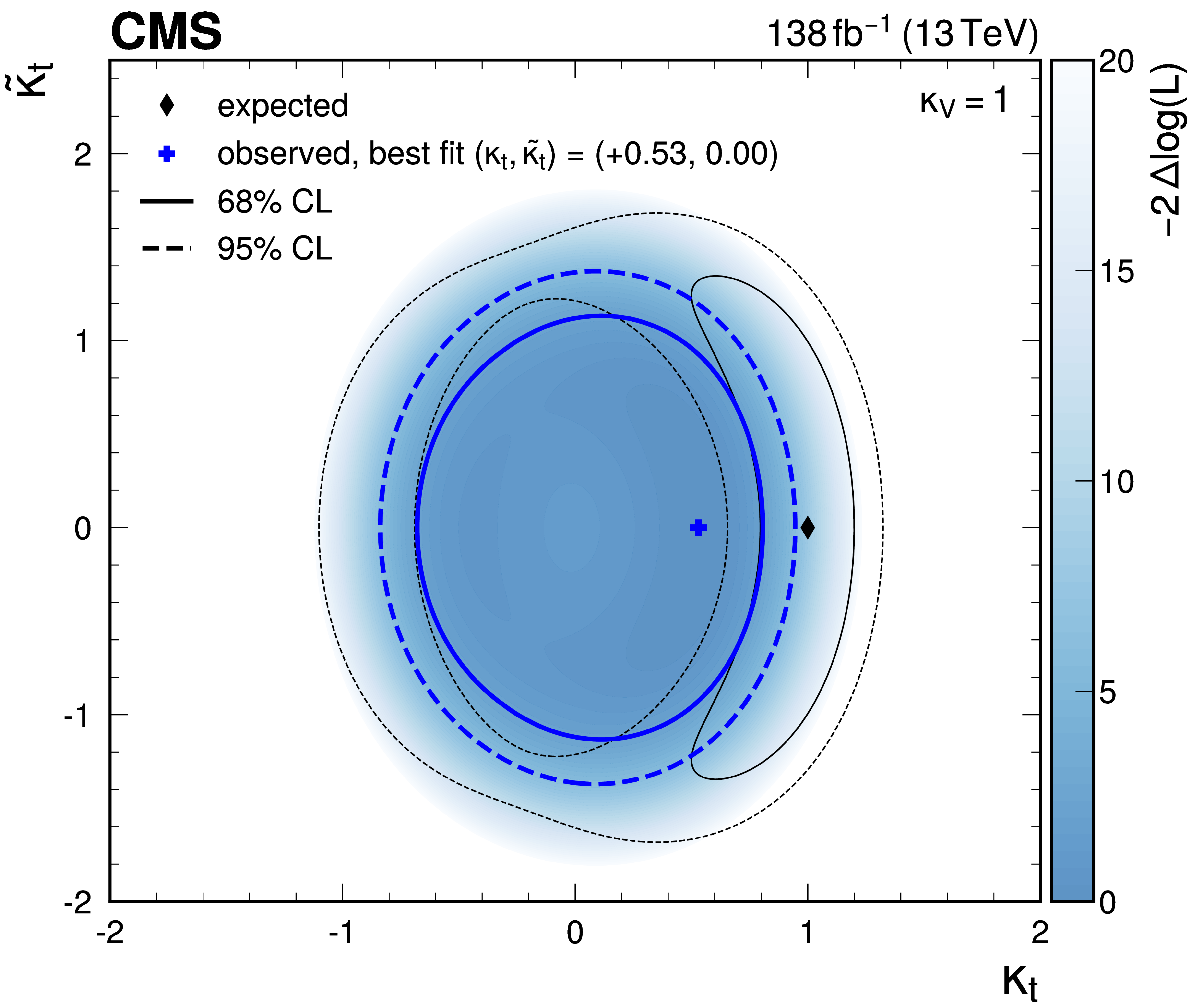
- Best fit values:
  - CP-mixing angle $\alpha = 11^{\circ}{}^{+52^{\circ}}_{-73^{\circ}}$
  - Coupling strength $\kappa_t' = 0.84^{+0.30}_{-0.46}$
- Compatible with $\alpha = 0^{\circ}$ and $\alpha = 90^{\circ}$
- Data prefers SM and disfavors CP-odd hypothesis at 1.2σ significance
- Sensitivity driven by the $t\bar{t} + n \geq 1b$-jets modeling uncertainties:
  - Same as in previous round of $t\bar{t}H, H \rightarrow b\bar{b}$ analysis
  - Would benefit greatly from the improved modeling



CP nature of the Top-Higgs coupling in $t\bar{t}H, H \to b\bar{b}$ @ CMS

JHEP02(2025)097

- In the same $t\bar{t}H, H \to b\bar{b}$ coupling paper (JHEP02(2025)097), CMS delivered results also about the *CP* structure of the top-Higgs coupling
- Best fit values: $(\kappa_t, \tilde{\kappa}_t) = (+0.53, 0.00)$
- Data prefers SM and disfavors CP-odd hypothesis at 2σ significance

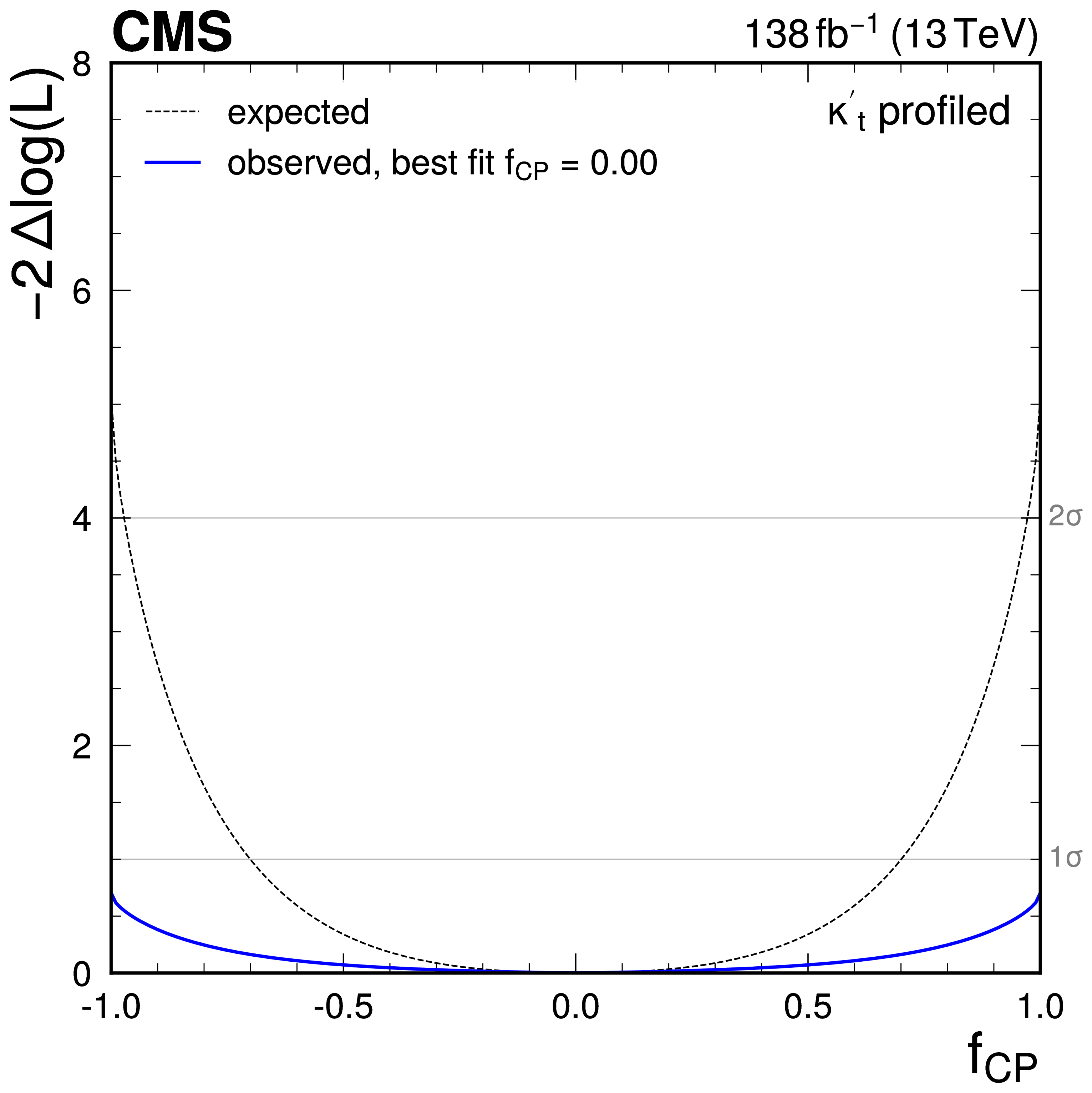


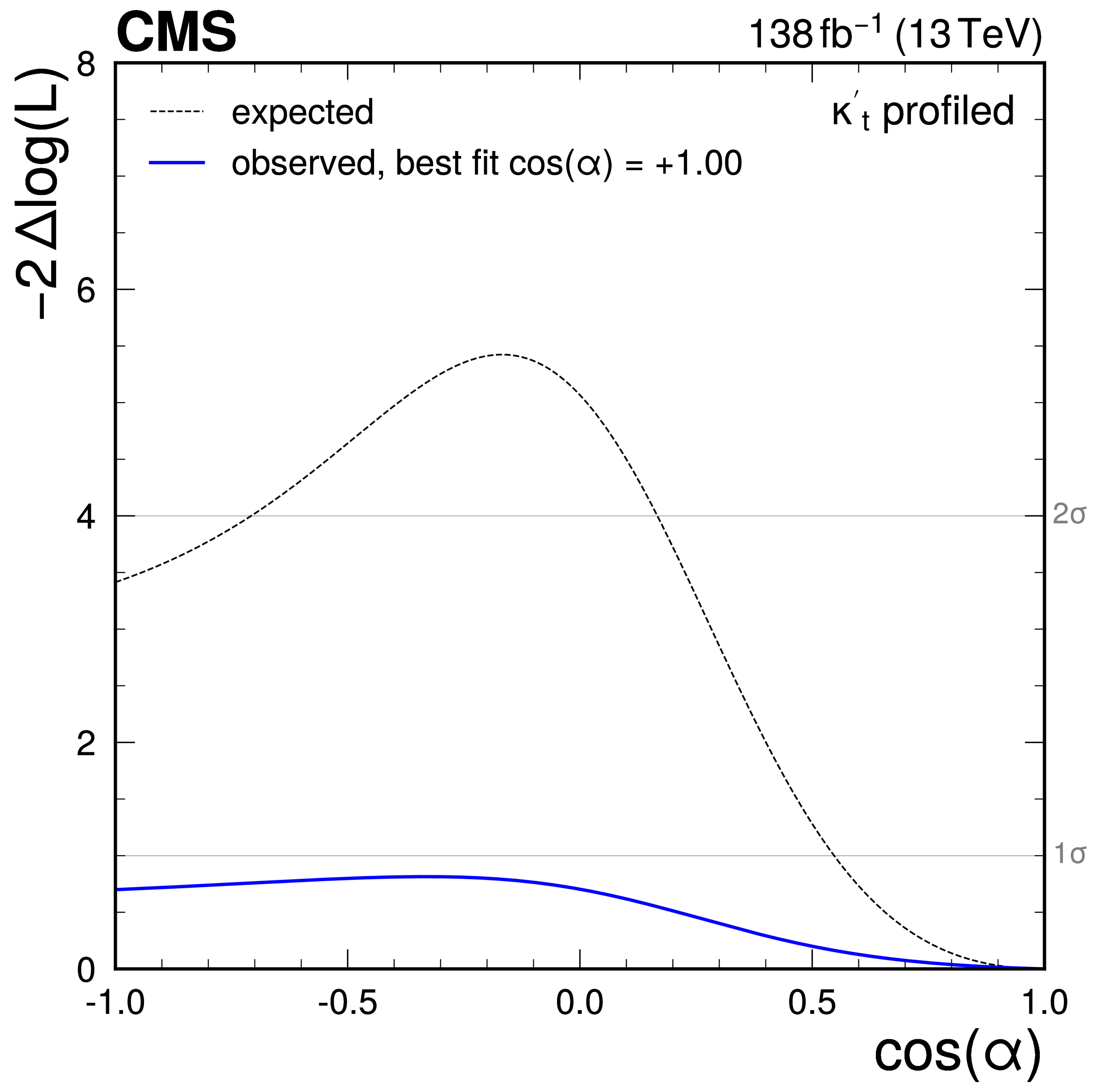
CP nature of the Top-Higgs coupling in $t\bar{t}H, H \to b\bar{b}$ @ CMS

JHEP02(2025)097

- The results were also expressed in terms of

CP-odd fraction: $f_{CP} = \dfrac{\tilde{\kappa}_t^2}{\tilde{\kappa}_t^2 + \kappa_t^2}\mathrm{sign}(\tilde{\kappa}_t/\kappa_t)$, **CP mixing angle**: $\cos\alpha = \dfrac{\kappa_t}{\sqrt{\tilde{\kappa}_t^2 + \kappa_t^2}}$





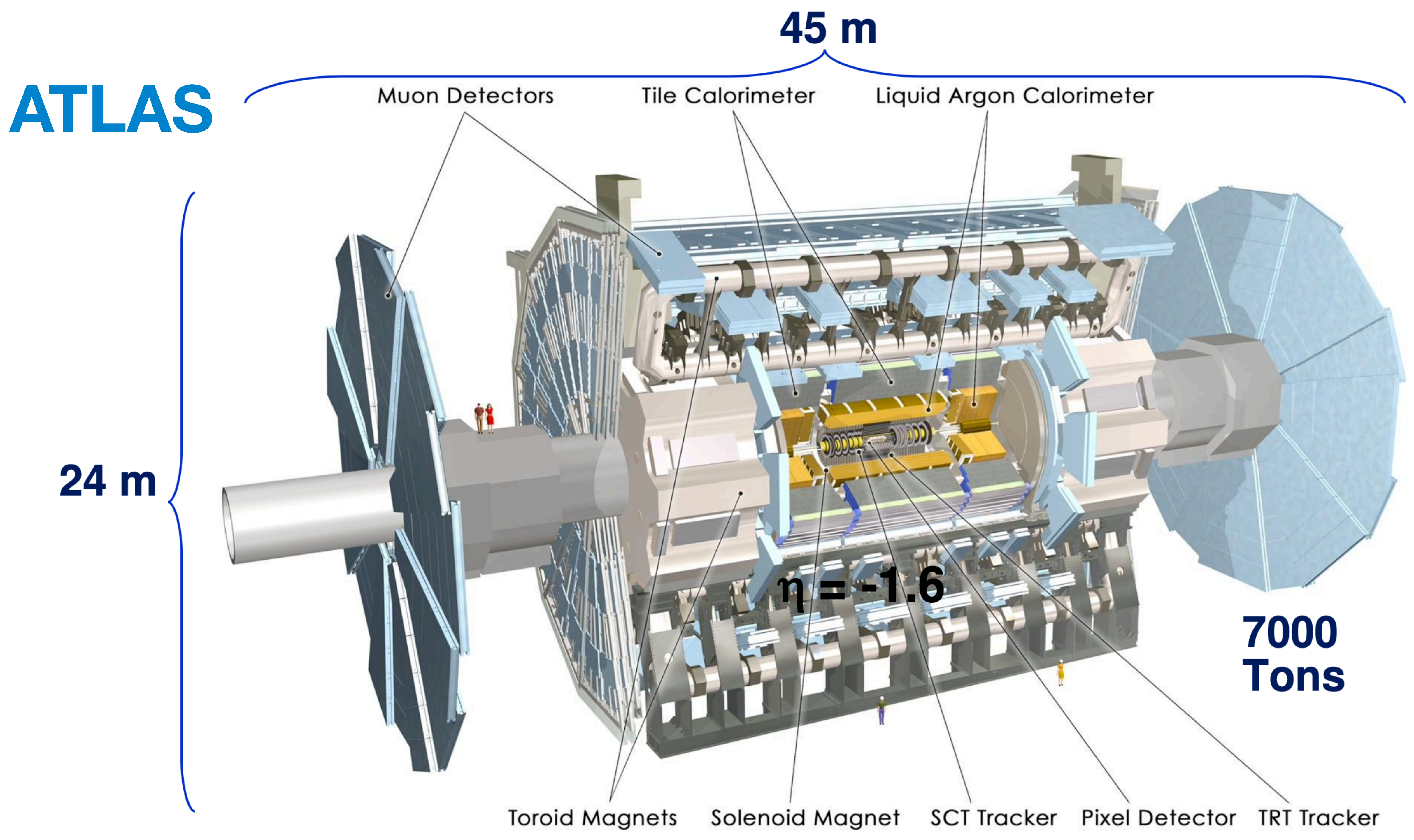
Summary

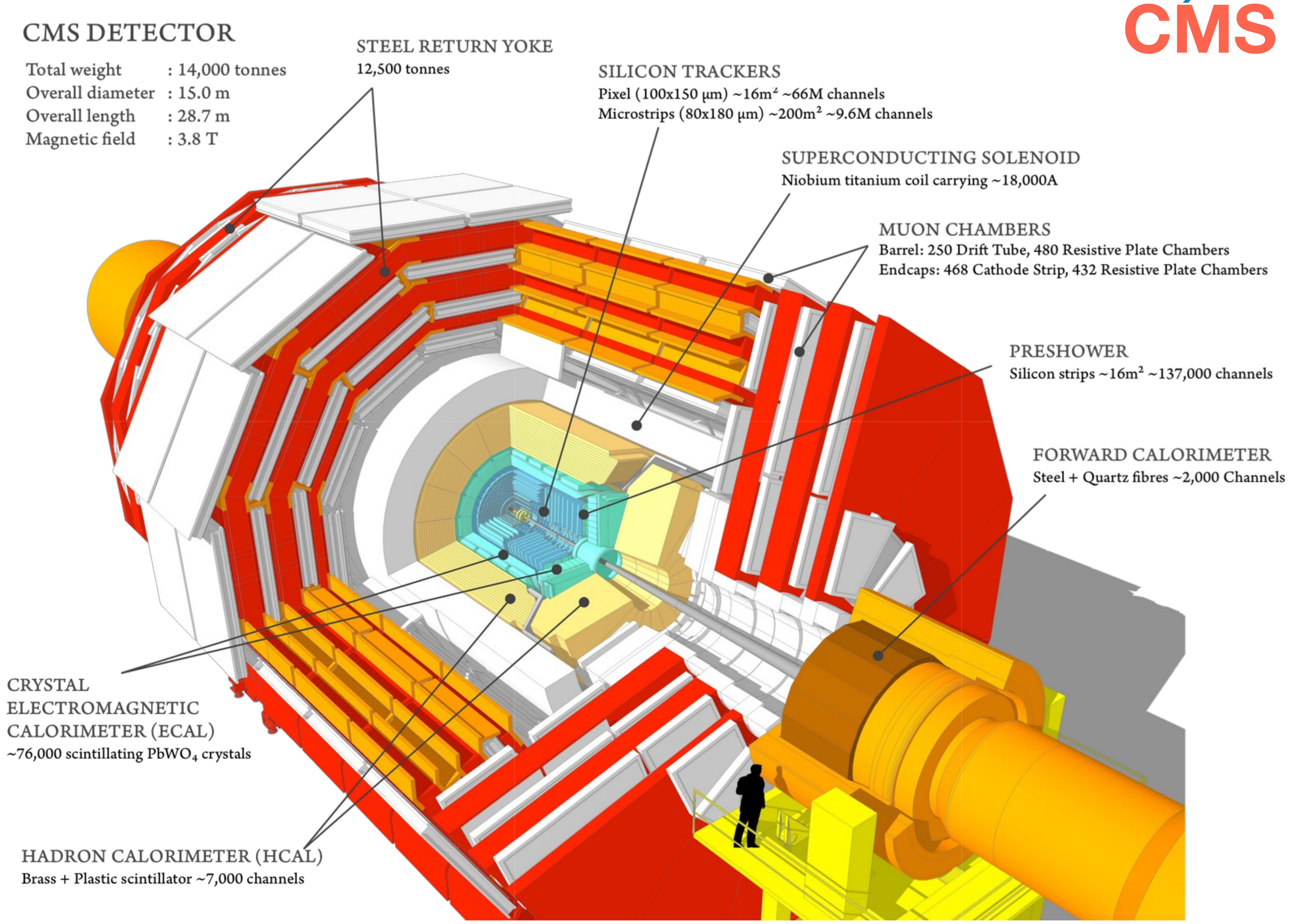
- ATLAS and CMS delivered many measurements of the Top-Higgs Yukawa coupling
- ATLAS and CMS recently published improved results on the STXS for $t\bar{t}H, H \to b\bar{b}$
  - In both experiments, the STXS compatibility with the SM is > 80%
- CMS delivered a new upper limit at 95% C.L. on the tH production x-section of 14.6 times the SM prediction
- ATLAS delivered an updated STXS measurement for $t\bar{t}H, H \to \tau\tau$ using the full Run 2 dataset
- ATLAS and CMS probed the *CP* nature of the Top-Higgs Yukawa coupling in $t\bar{t}H/tH, H \to b\bar{b}$
  - Data prefers SM and disfavors *CP*-odd hypothesis at 1.2σ significance in ATLAS and 2σ in CMS

Backup slides

ATLAS and CMS experiments

- 2 magnet systems (central 2T solenoid and large toroids in muon spectrometer)
- electron scale uncertainty ~0.7% in central region
- muon momentum scale uncertainty 0.05%
- τ energy scale uncertainty 2% (3%) for 1- (3-) prong τ-lepton





- one large 4T solenoid
- electron scale uncertainty ~0.3% (central region)
- muon momentum scale uncertainty 0.2%
- τ energy scale uncertainty < 1.2%

Coupling/STXS with $H \to \gamma\gamma$

JHEP 07 (2023) 088

- Small BR but clear signal peak and low background
- Refined event categorization using Multiclass and binary BDTs → 13 dedicated to $t\bar{t}H/tH$
  - Using $m_{\gamma\gamma}$ as discriminant in the signal extraction fit
- κ_t probed with two different configurations
- **Resolved**: κ_t in ggF and H → γ γ loops
- **Effective**: effective coupling (κ_g and κ_γ) fixed to the SM prediction