# Constraining the Shape of the Higgs Potential Through a Search for **Higgs Boson Pairs** in the **$bb\tau\tau$** Final State with the **ATLAS** Experiment

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on behalf of the ATLAS collaboration

Higgs 2023 - Beijing

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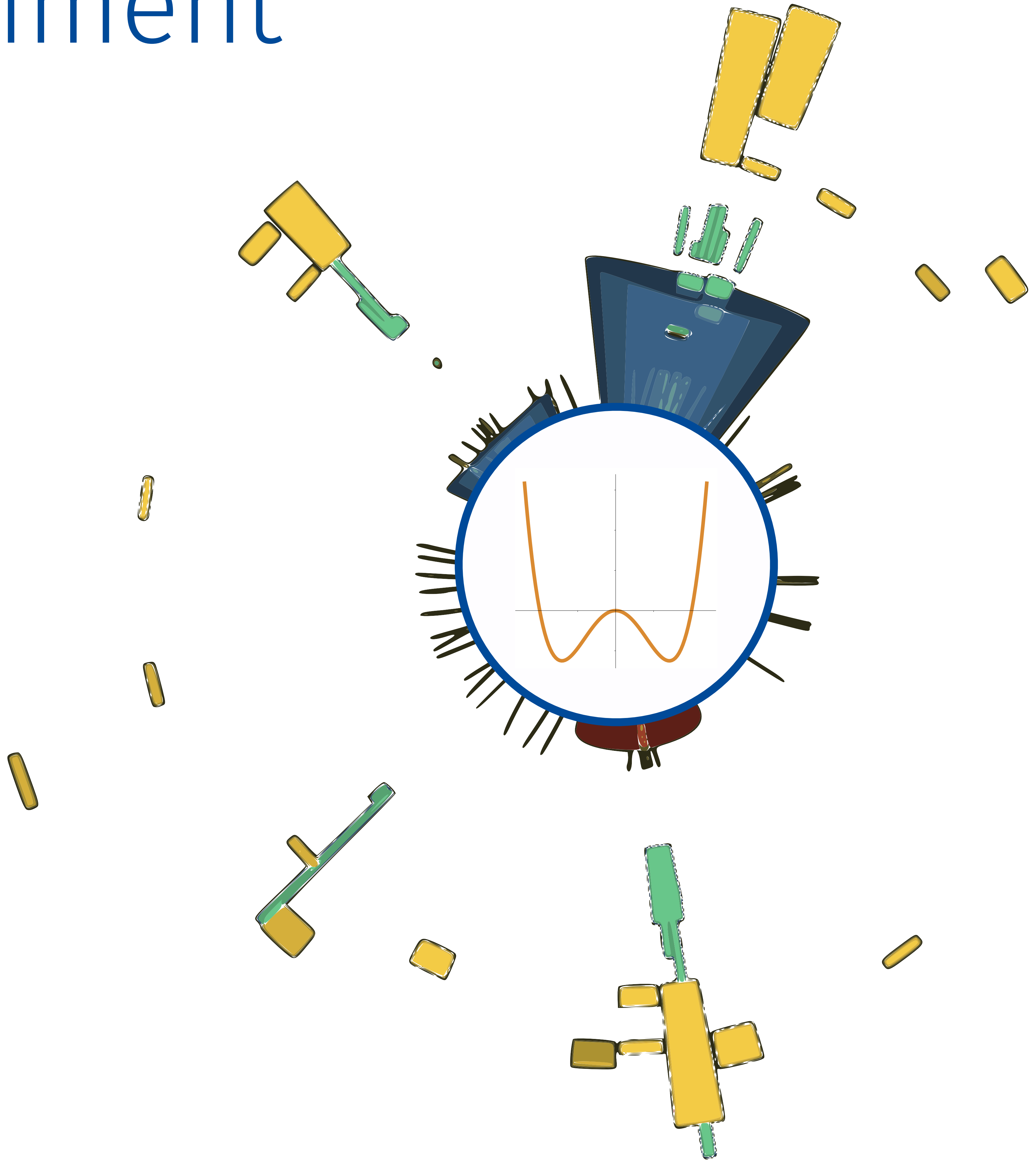
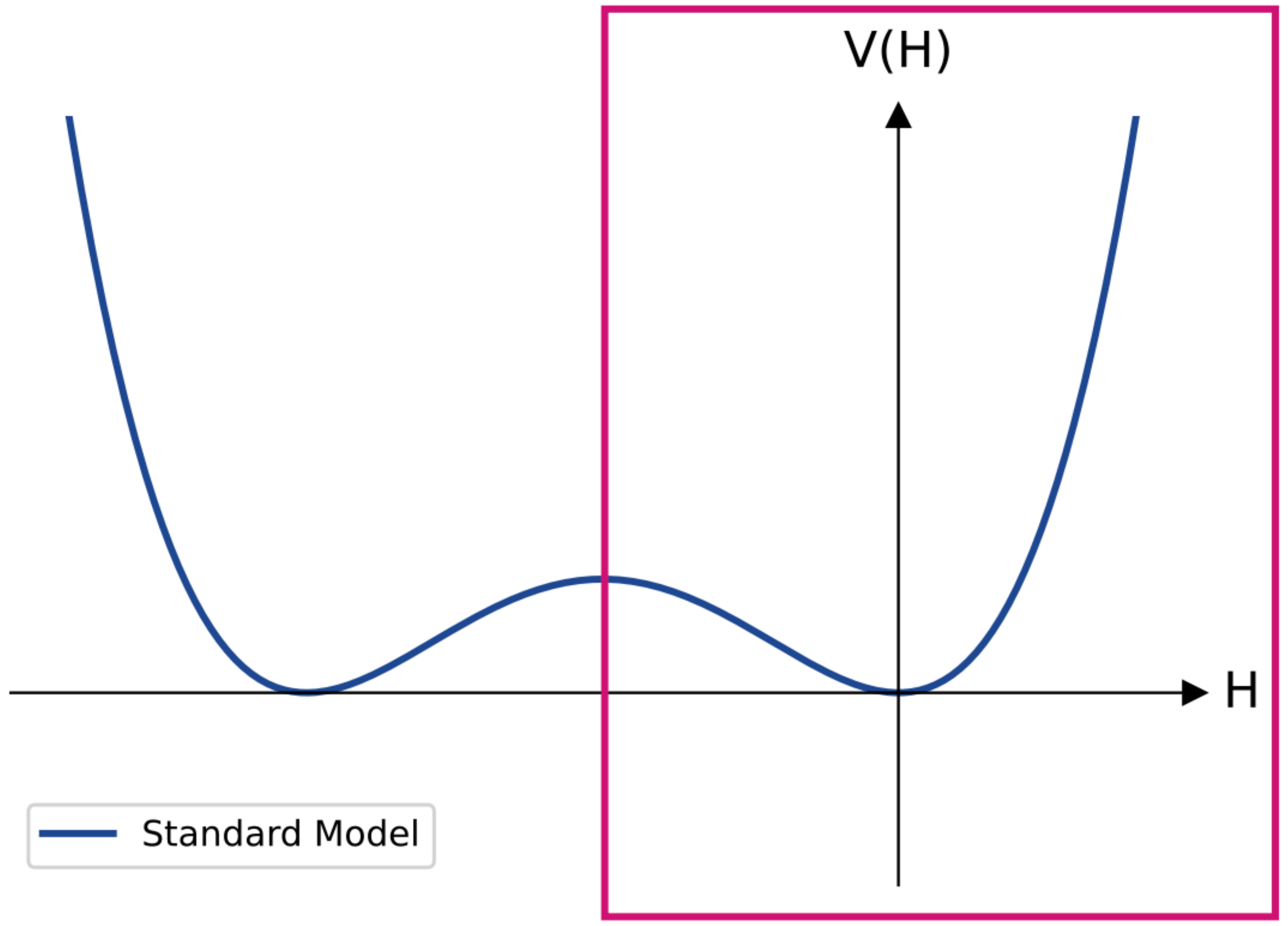


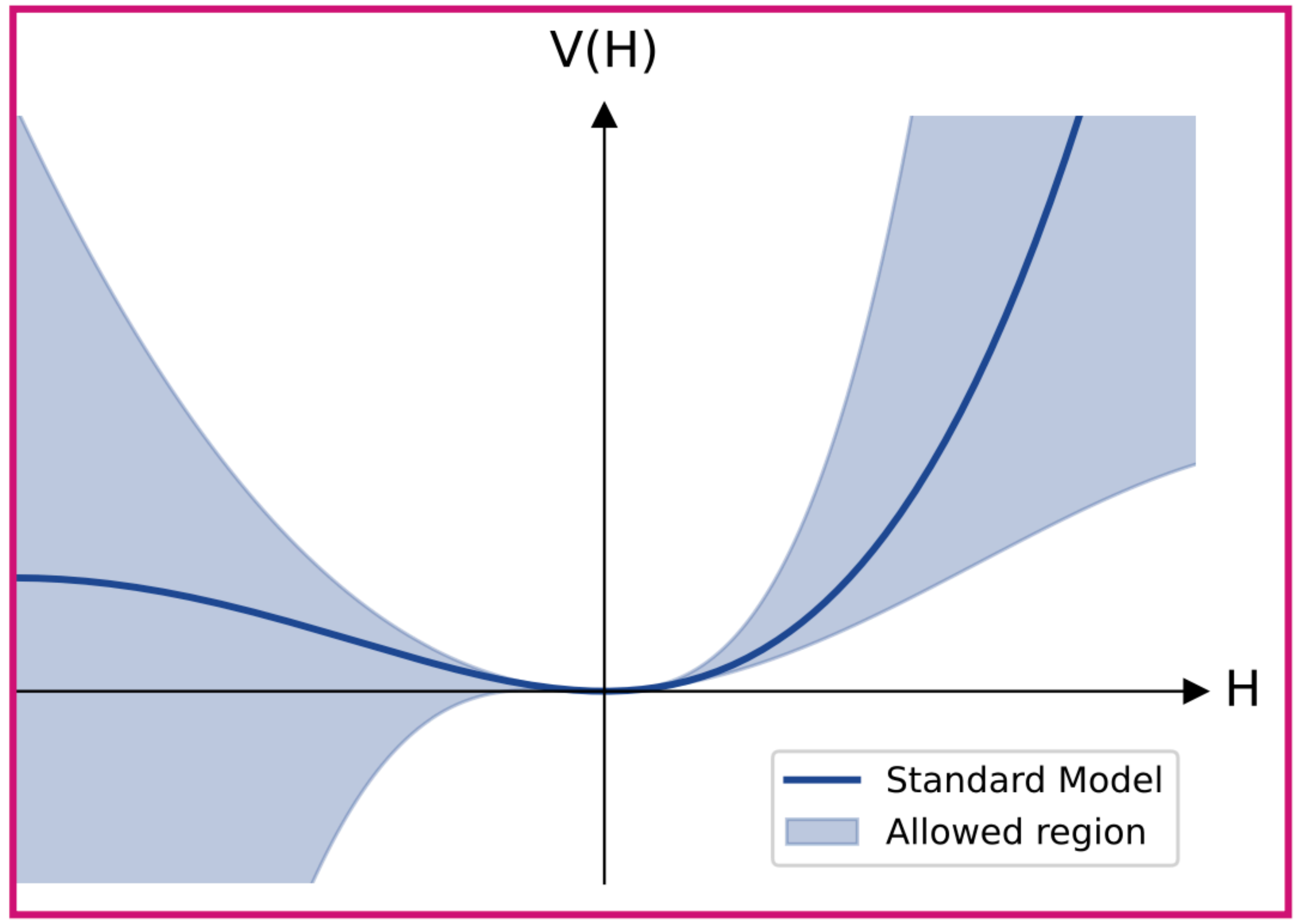
# The Higgs potential and searches for HH

$$\kappa_i = \frac{\text{measured coupling i}}{\text{SM prediction}}$$

- Despite its significance the shape of the Higgs potential remains largely unconstrained

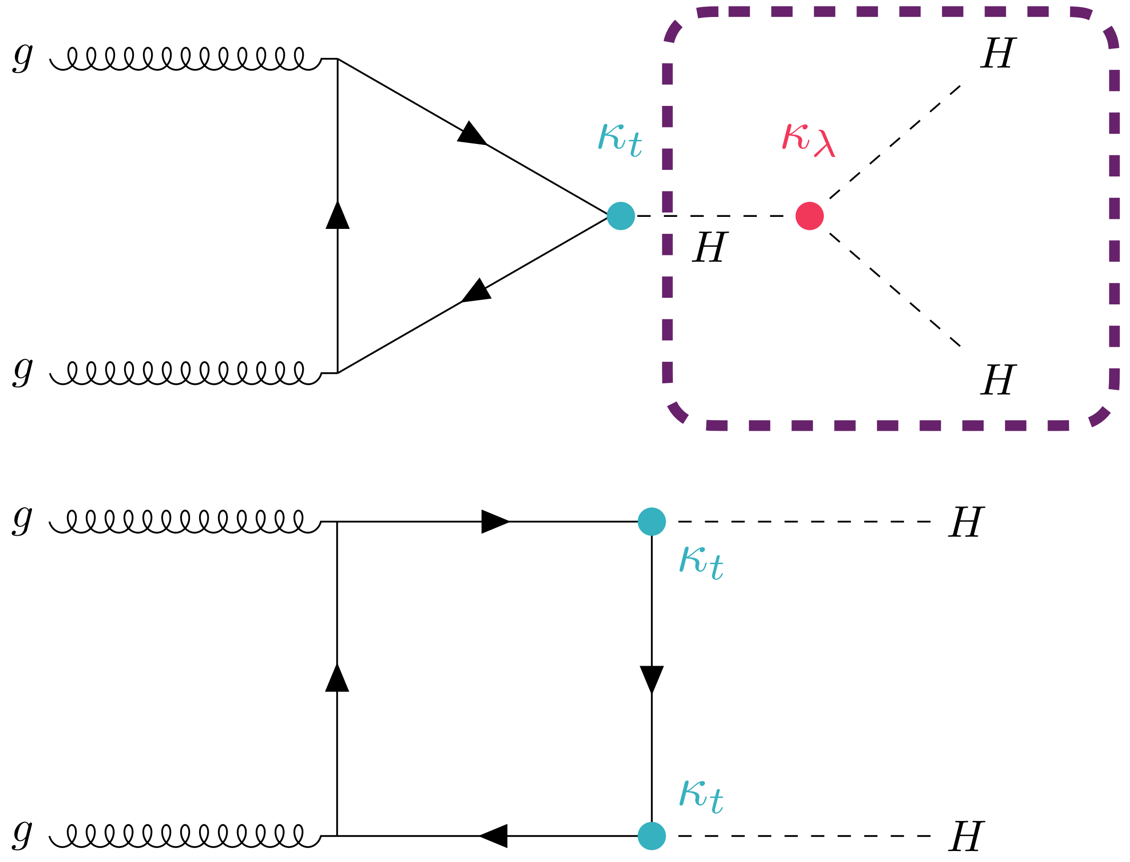
What the SM predicts vs what we know experimentally



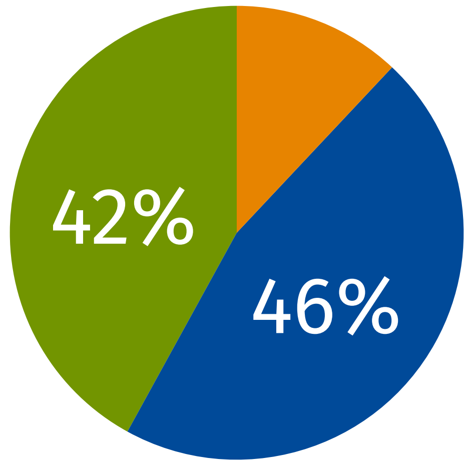

[using current ATLAS limits @ 95% CL]

$$V(H) = \frac{1}{2}m_H^2 H^2 + \lambda \text{ vev } H^3 + \frac{1}{4}\lambda H^4$$




- The shape is probed through determining the strength of Higgs boson self-interactions λ in searches for HH production [in SM: λ ~ 1/8]
- pp→HH→bbττ: rel. high BR (~7.3%) and multijet rejection from di-τ system → one of the most sensitive channels

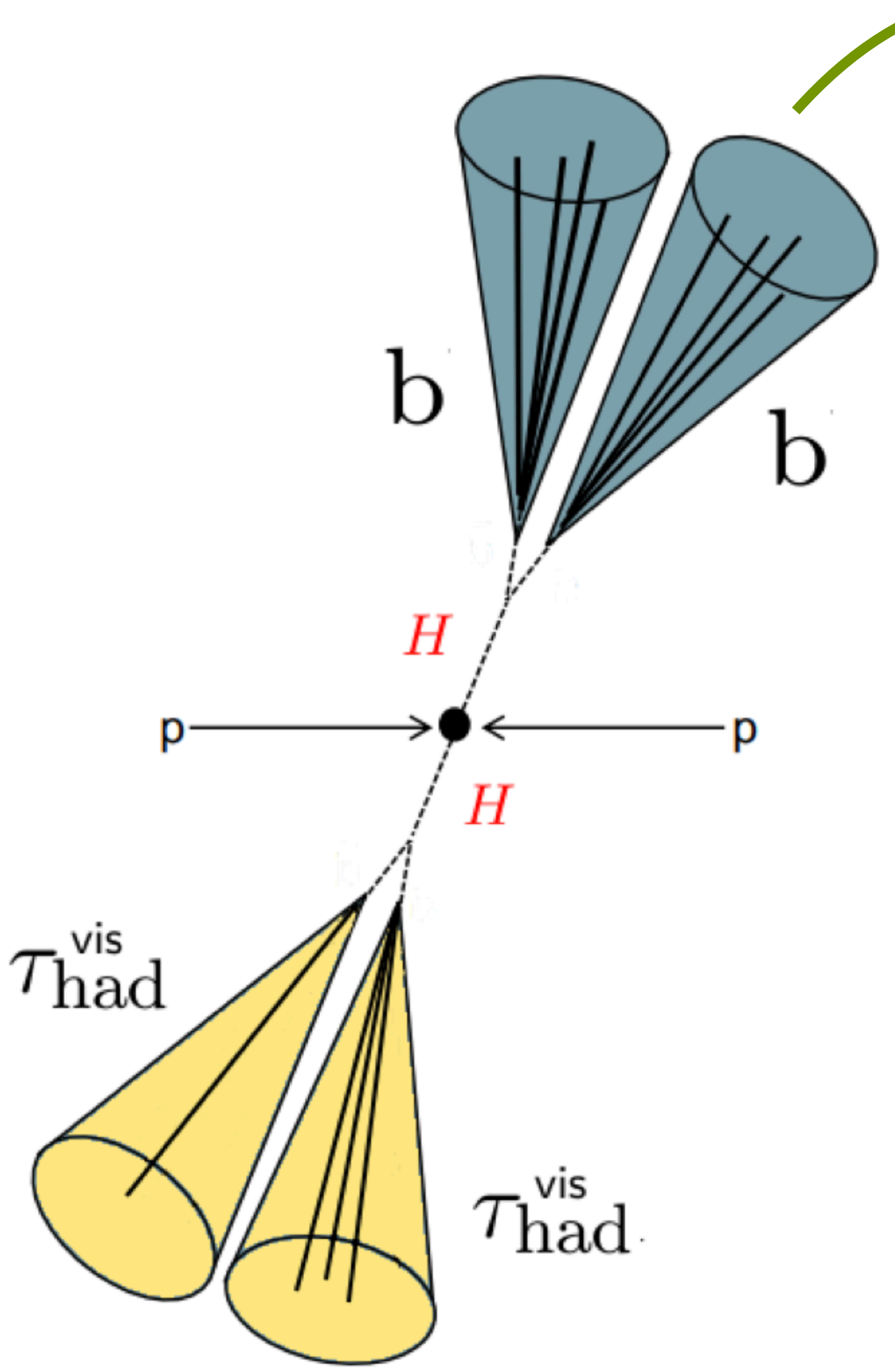
# The search for pp→HH→bbττ




τ BRs

had had
lep had
lep lep

- Two analysis channels, depending on the τ decays: $\tau_{had}\tau_{had}$ and $\tau_{lep}\tau_{had}$ [$\tau_{lep}\tau_{lep}$ is included in the pp→HH→bbll analysis, arXiv:2310.11286]




| $\tau_{had}\tau_{had}$ | $\tau_{lep}\tau_{had}$ (SLT) | $\tau_{lep}\tau_{had}$ (LTT) |
|---|---|---|
| single and di-$\tau_{had}$ triggers | single $\ell$ triggers | $\ell$ + $\tau_{had}$ triggers |
| exactly two $\tau_{had}$ | exactly one $\tau_{had}$ | |
| lepton veto | $m_{bb}$ < 150 GeV | |

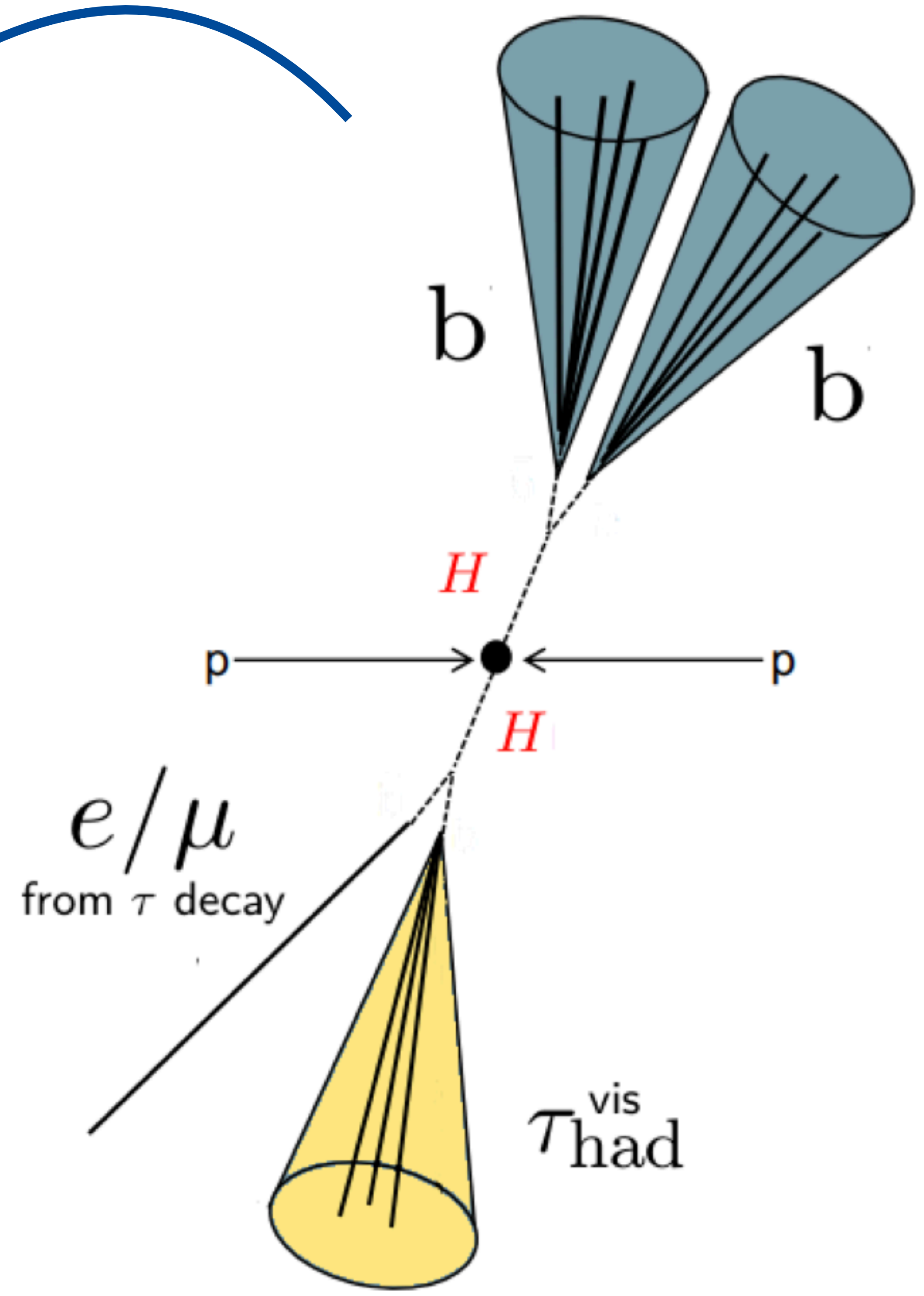
trigger dependent thresholds on e/μ/$\tau_{had}$ and jets

$m_{\tau\tau}^{MMC}$ > 60 GeV

exactly two b-tagged jets ($\varepsilon_b$ = 77%)

opposite electrical charge sign of leptons

| Acc x ϵ = 4% | Acc x ϵ = 4% | Acc x ϵ = 1% |
|---|---|---|

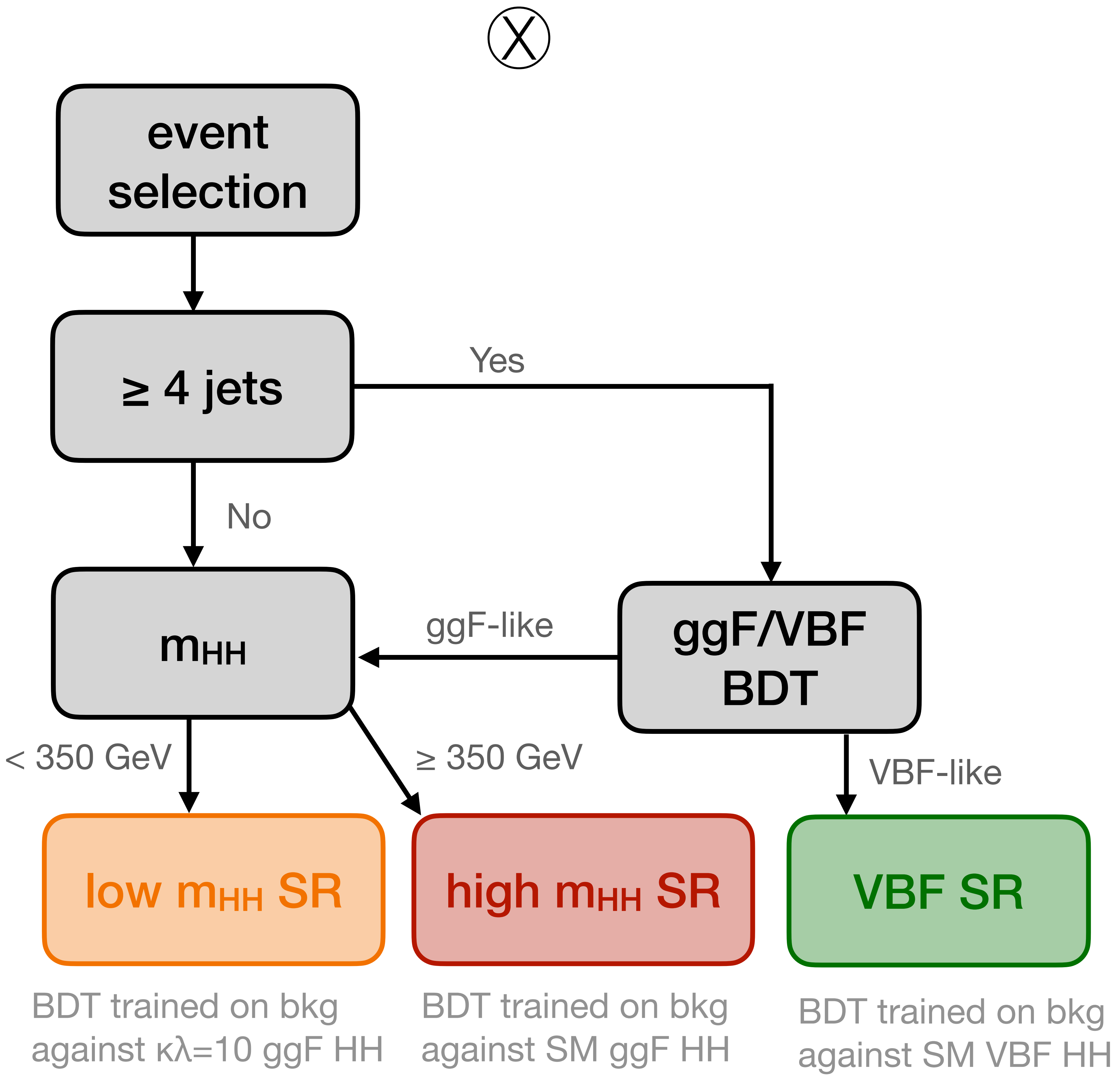



- Existing Run 2 analysis: compromise between resonant and non-resonant [JHEP 07 (2023) 040]
- **New: re-analysis of the Run 2 data set focusing on the non-resonant part** [public page]

# Event selection

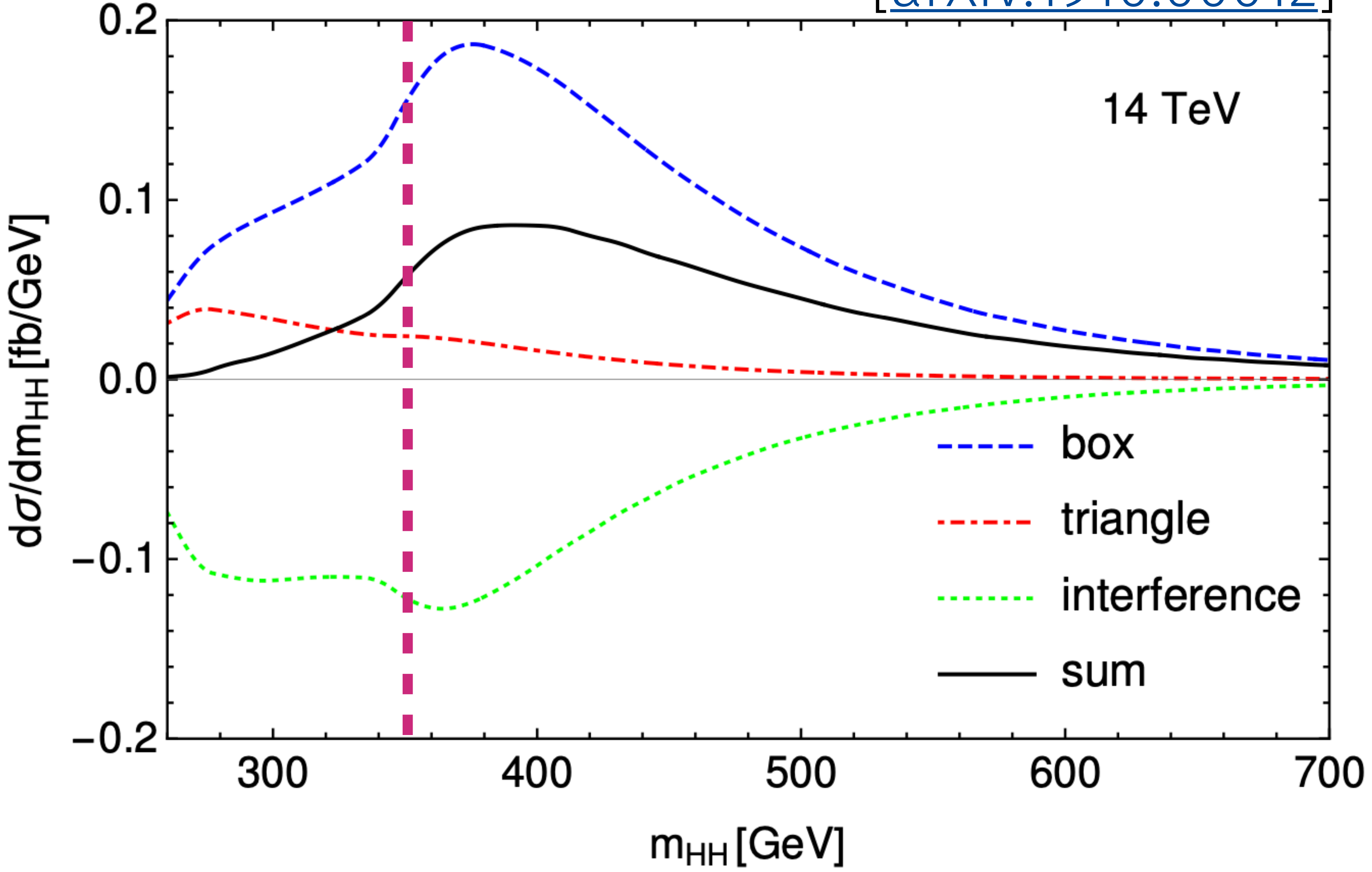
- Extended categorization to improve constraints on HHH and HHVV coupling

$\tau_{had}\tau_{had}$ $\tau_{lep}\tau_{had}$ (SLT) $\tau_{lep}\tau_{had}$ (LTT)




**$m_{HH}$ categorization** to improve the $\kappa_\lambda$ constraint

[arXiv:1910.00012]

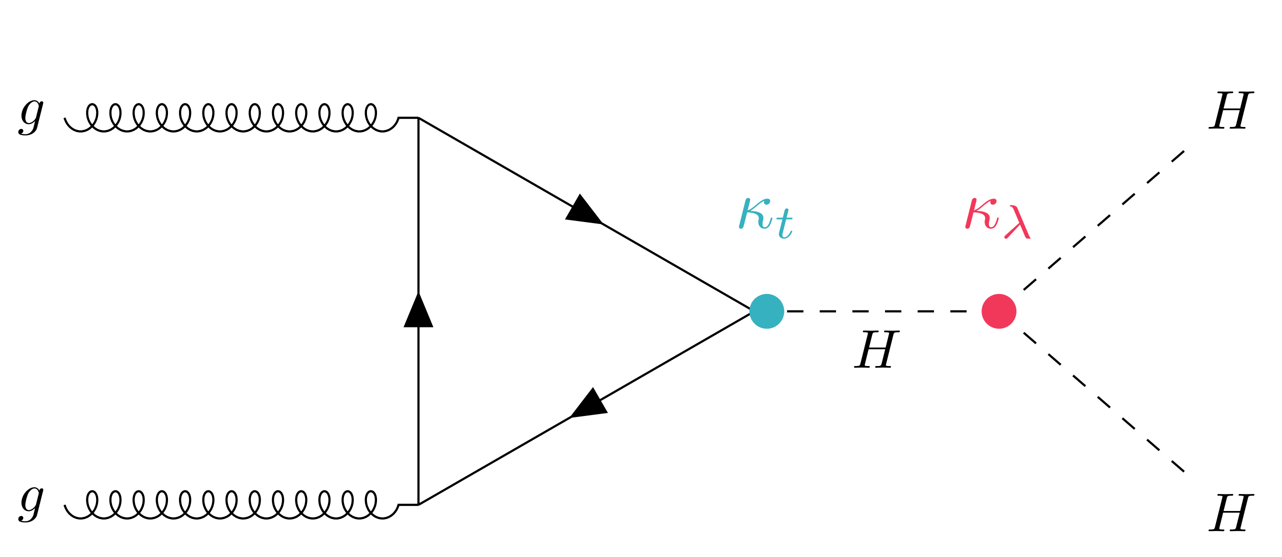


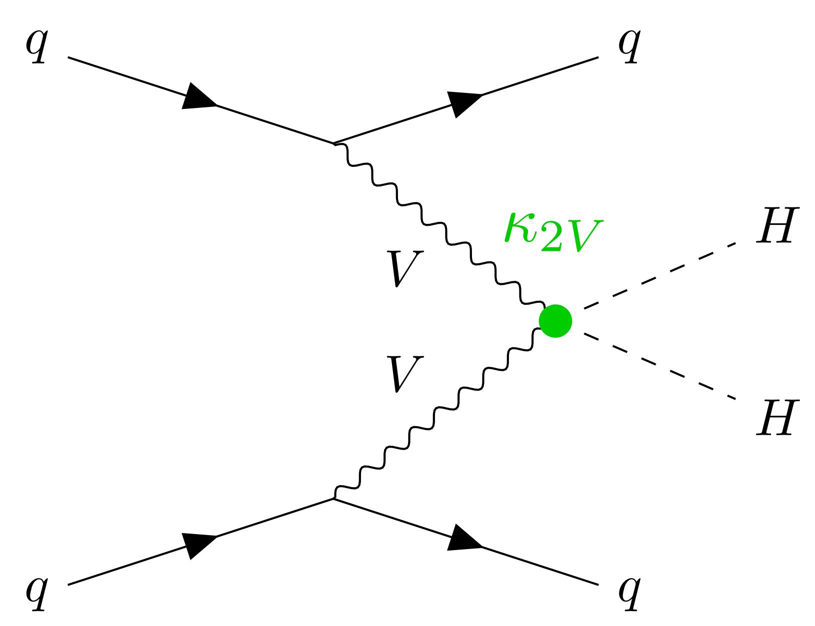

**Improved BDT:**

- Additional inputs (b-tagger quantiles of jets, event shapes, …)
- Separate training against enhanced λ signal in low-$m_{HH}$ region

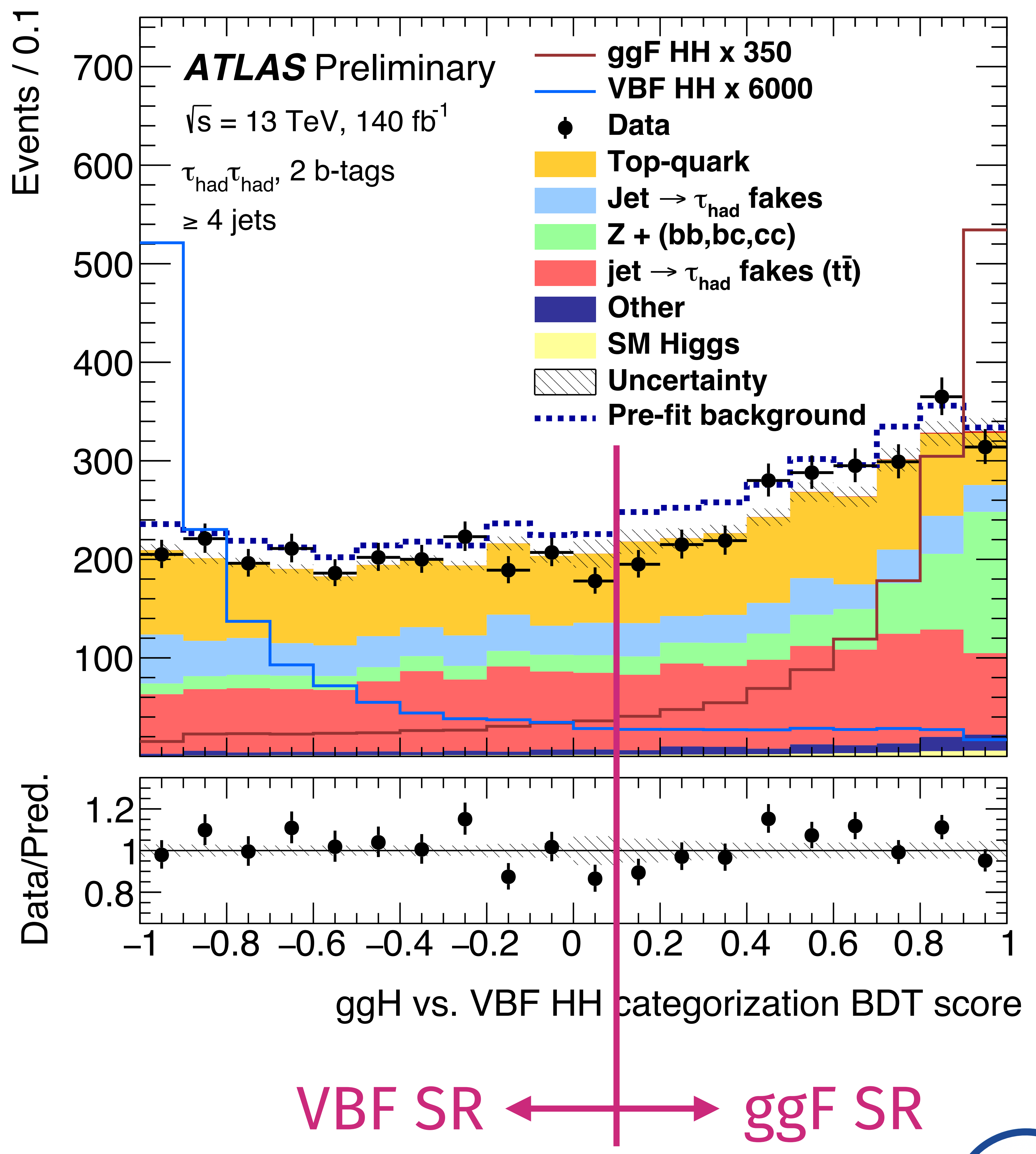
# ggF HH vs. VBF HH categorization BDT

- Introduction of a **dedicated VBF HH SR** to improve the $\kappa_{2V}$ constraint and to reduce the correlation with the $\kappa_\lambda$ constraint




- A BDT is trained to separate ggF HH from VBF HH on events with 4 jets (two VBF-jet candidates + two H→bb)
- Input variables are typical **VBF quantities** like $m_{jj}^{VBF}$, $\Delta R_{jj}^{VBF}$, $\eta_{jet1} \times \eta_{jet2}$ as well as **event shape variables** (Fox Wolfram Moments)
- Categorization cut chosen not to penalize $k_\lambda$ constraint and inclusive HH signal strength limit



# Main backgrounds and how to control them

**Main backgrounds:**

- ttbar
- Z+ heavy flavour jets

**dedicated control region**
[ee or μμ, 75 GeV < $m_{ll}$ < 110 GeV, $m_{bb}$ < 40 GeV or $m_{bb}$ > 210 GeV]

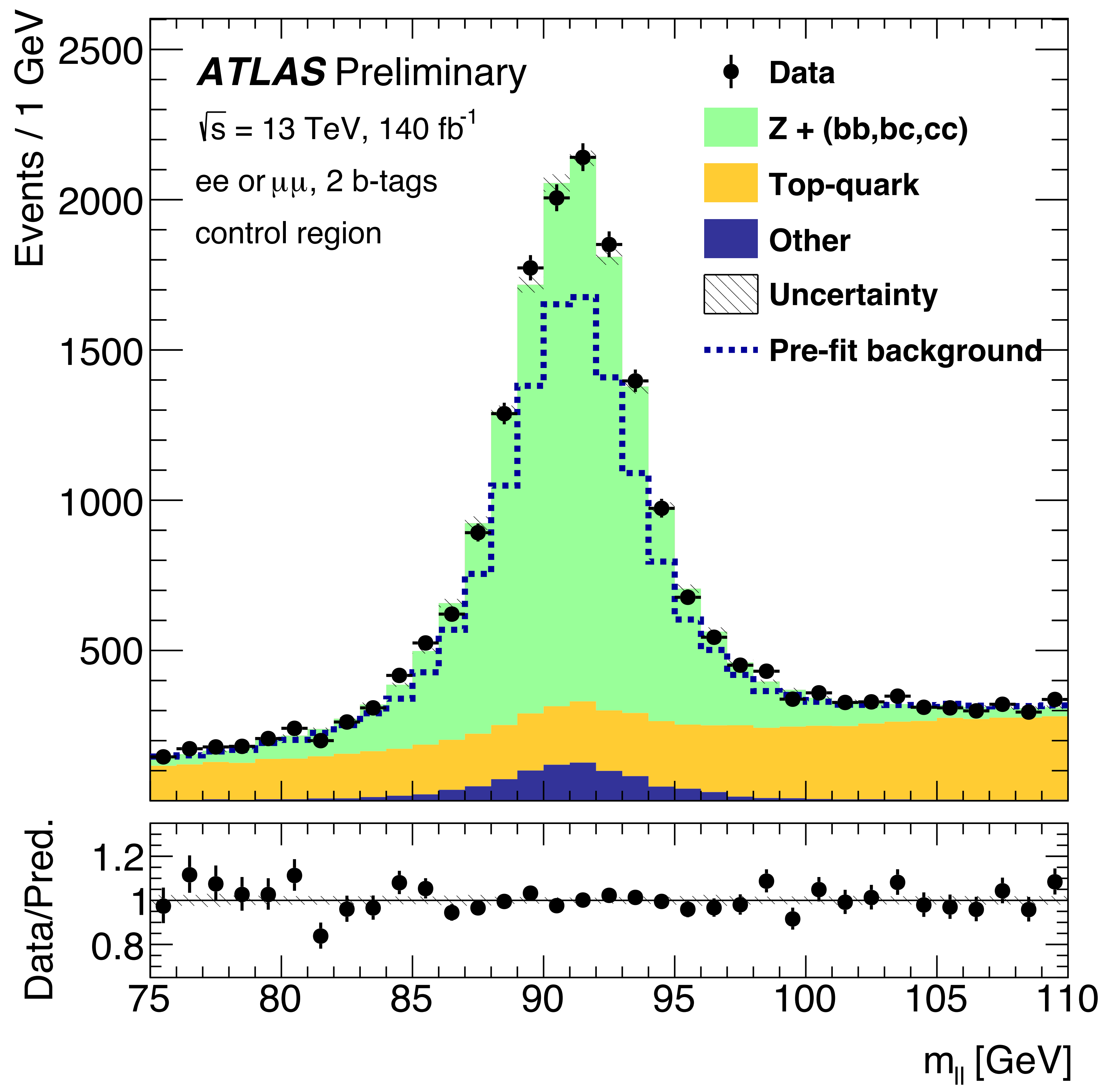
- single top
- single Higgs
- diboson

**from simulation**

- ttbar with jet→$\tau_{had}$ fakes
- QCD multijet with jet→$\tau_{had}$ fakes

**data-driven**
[from anti-ID CR extrapolated into the SR with fake factors]

Control region




**Improvements:**

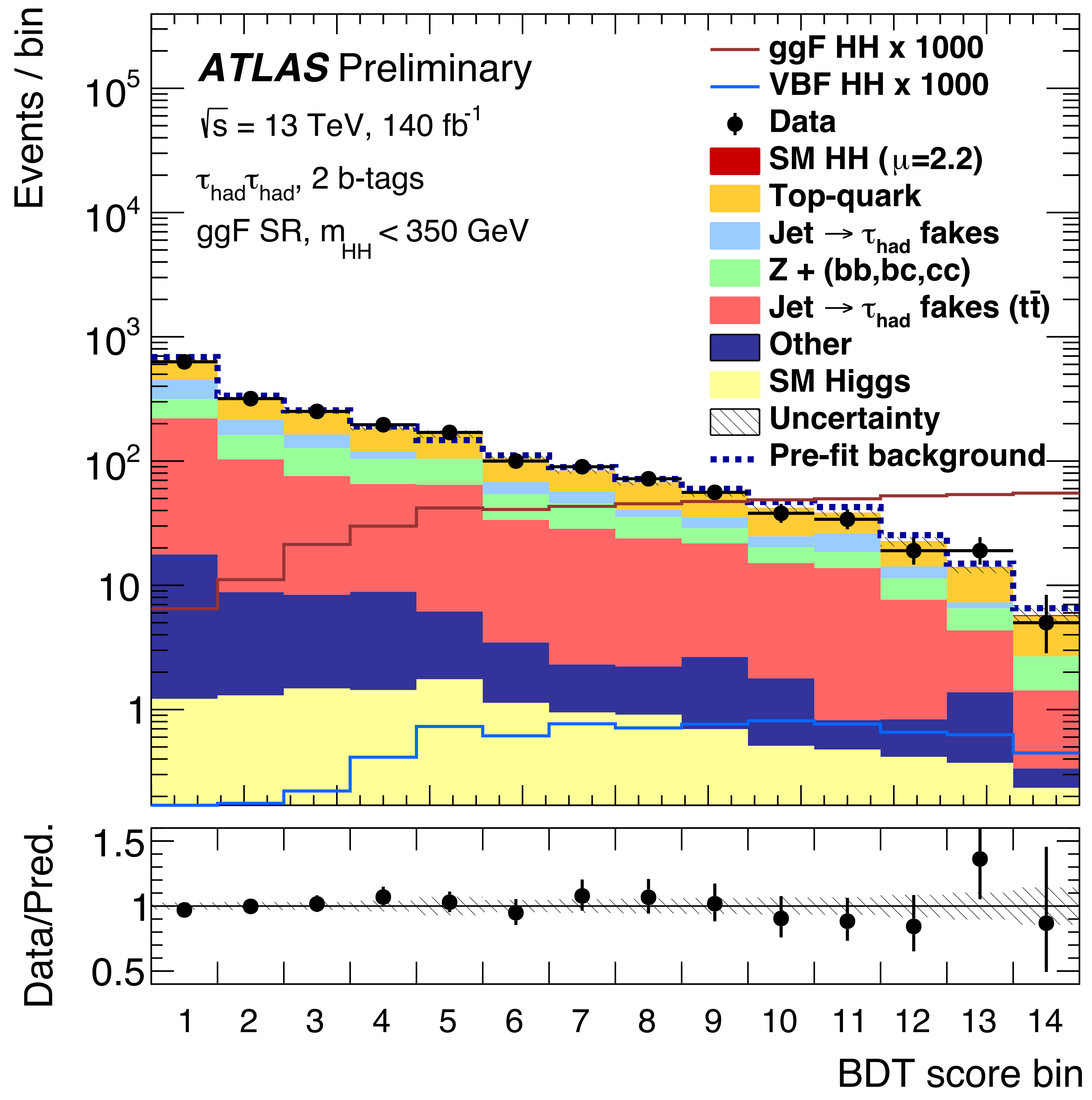
- Improved V+jets simulation
- 4 x more MC statistics for main backgrounds
- Control region kinematically closer to signal region → less reliance on extrapolation unc.

**Signal is extracted through a joint fit to all SRs and the CR**

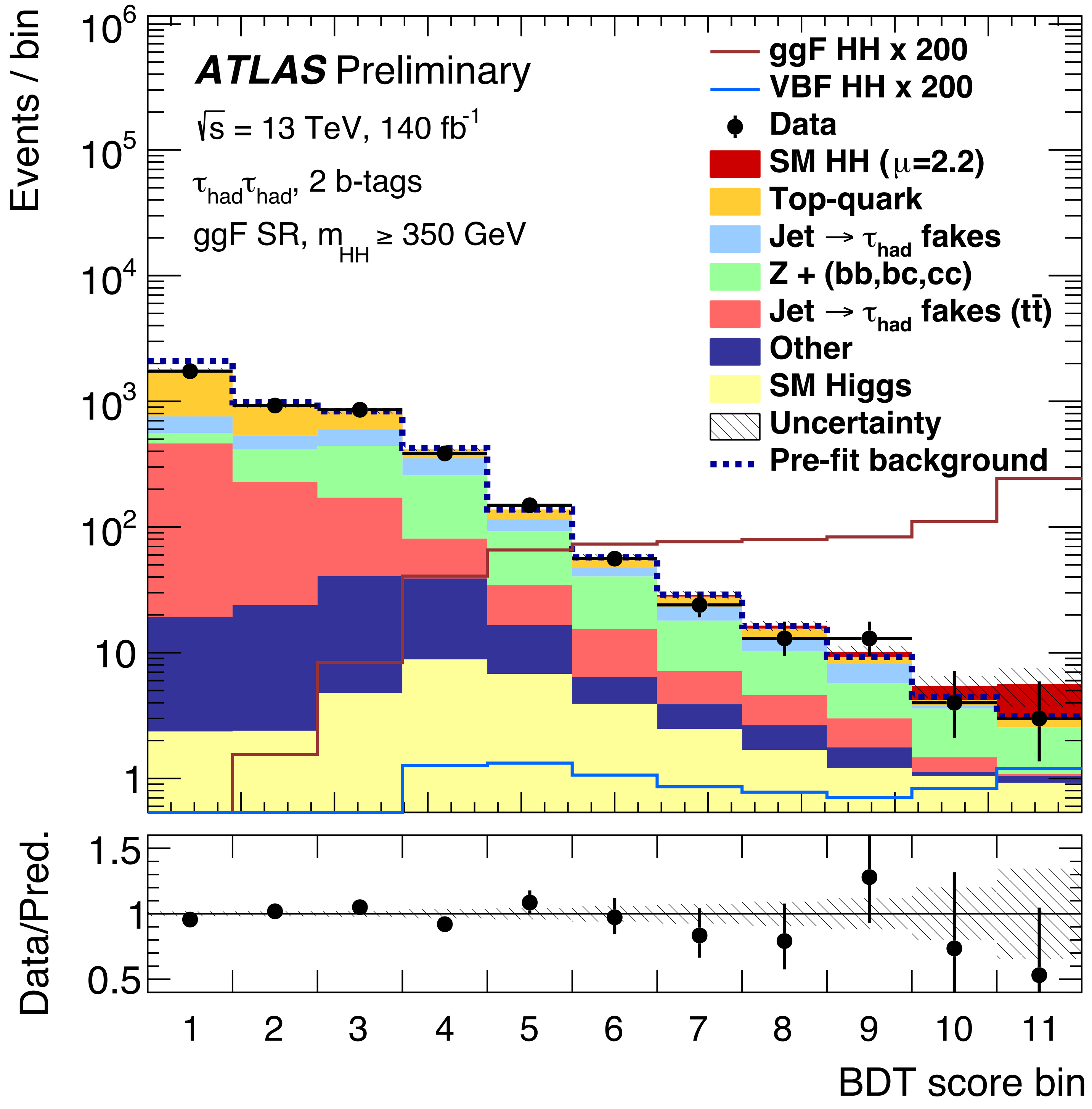
# Fit results

## τhad τhad

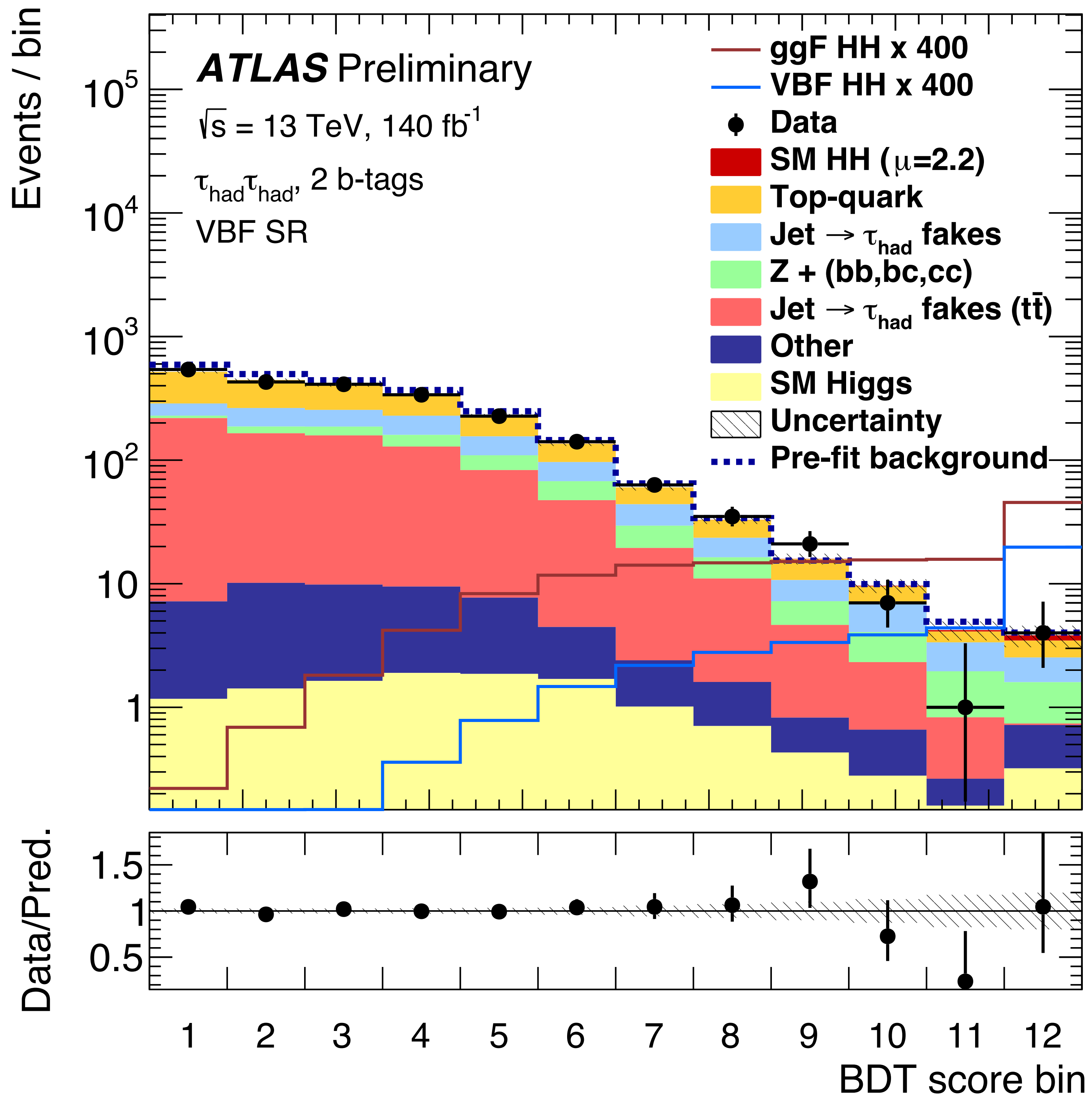
low $m_{HH}$ SR




high $m_{HH}$ SR




VBF SR



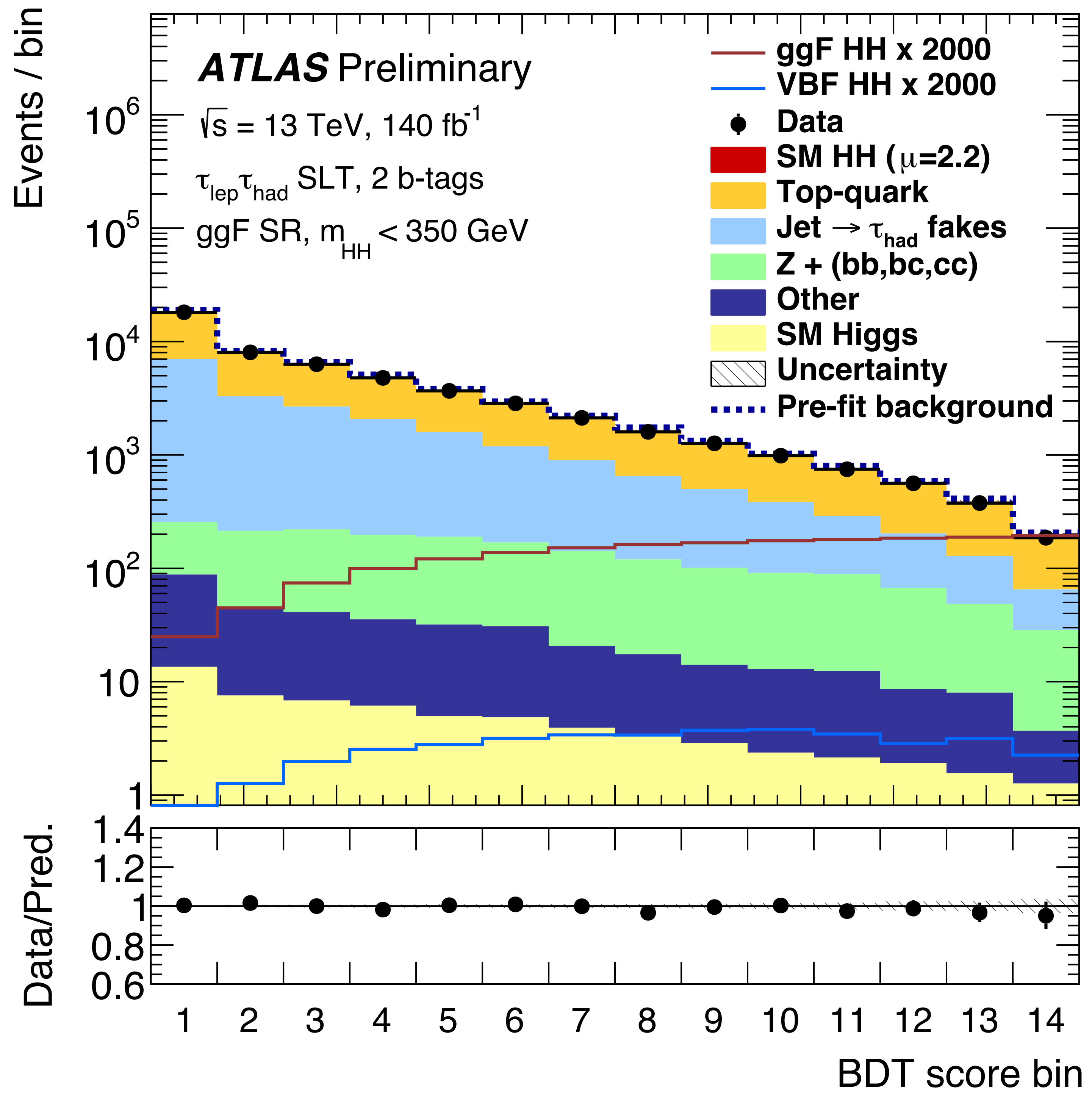

- HH signal scaled to combined signal strength included in both the stack and the ratio

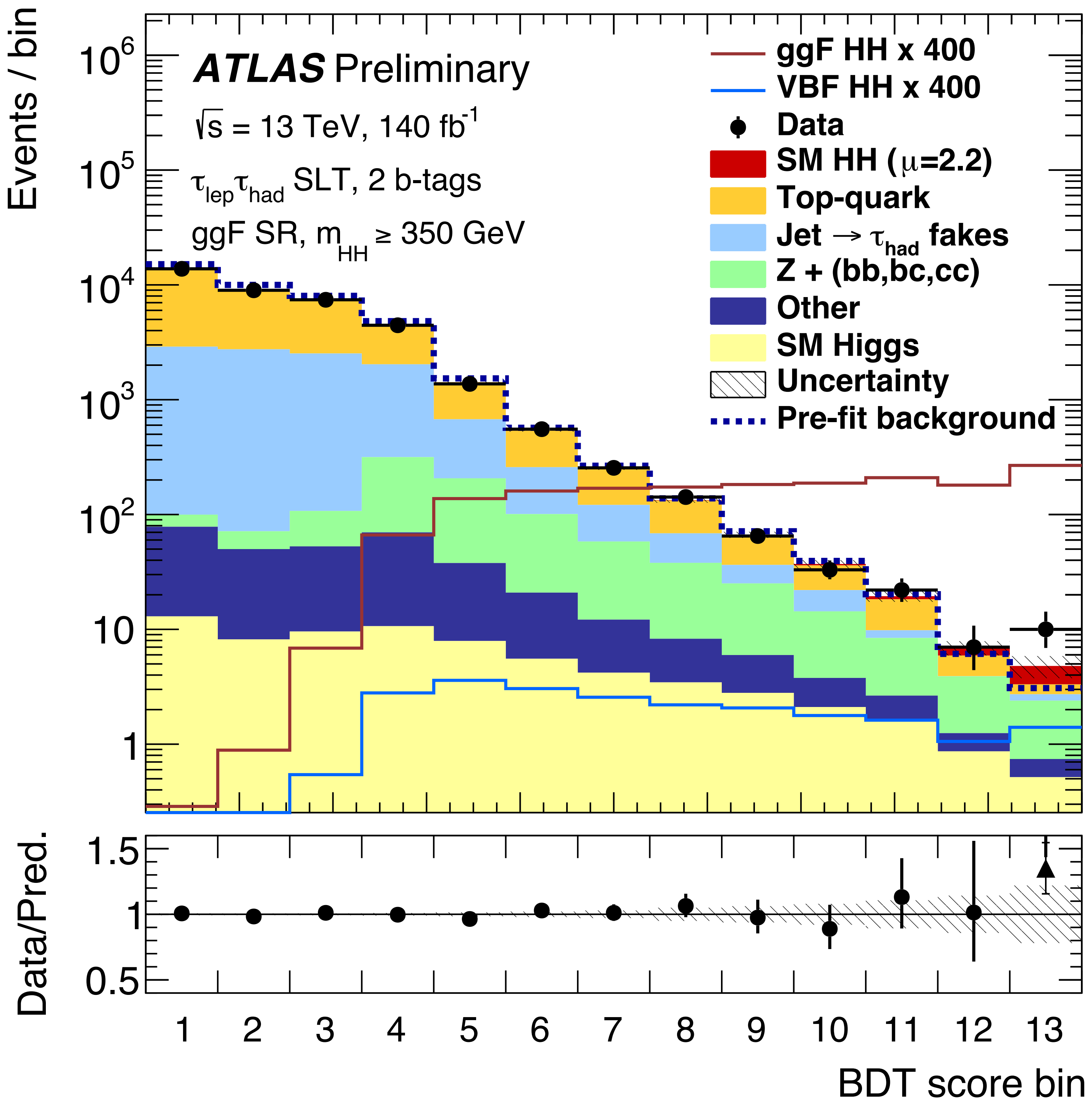
# Fit results
## $\tau_{lep}\tau_{had}$ (SLT)

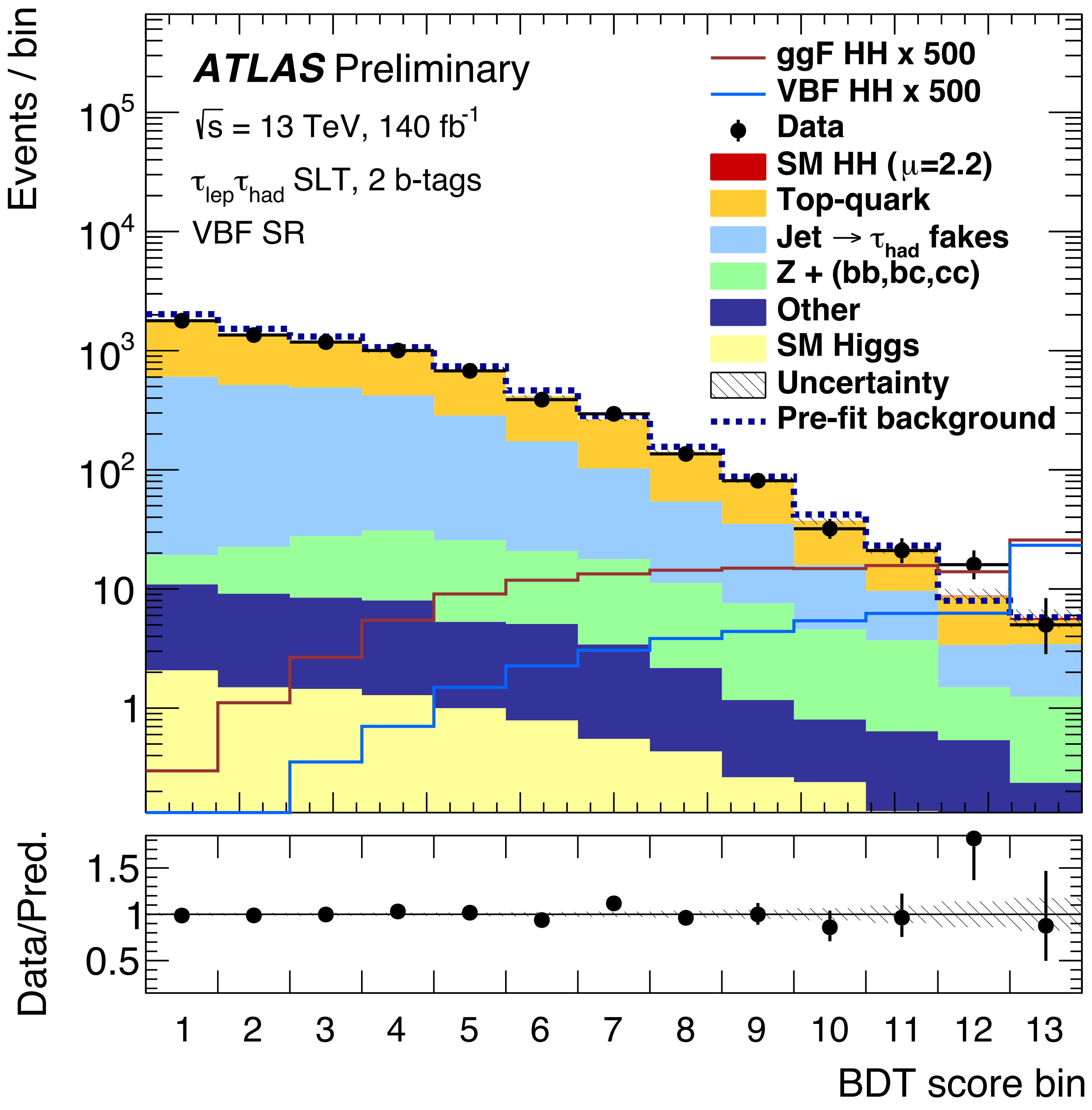
low $m_{HH}$ SR

high $m_{HH}$ SR

VBF SR



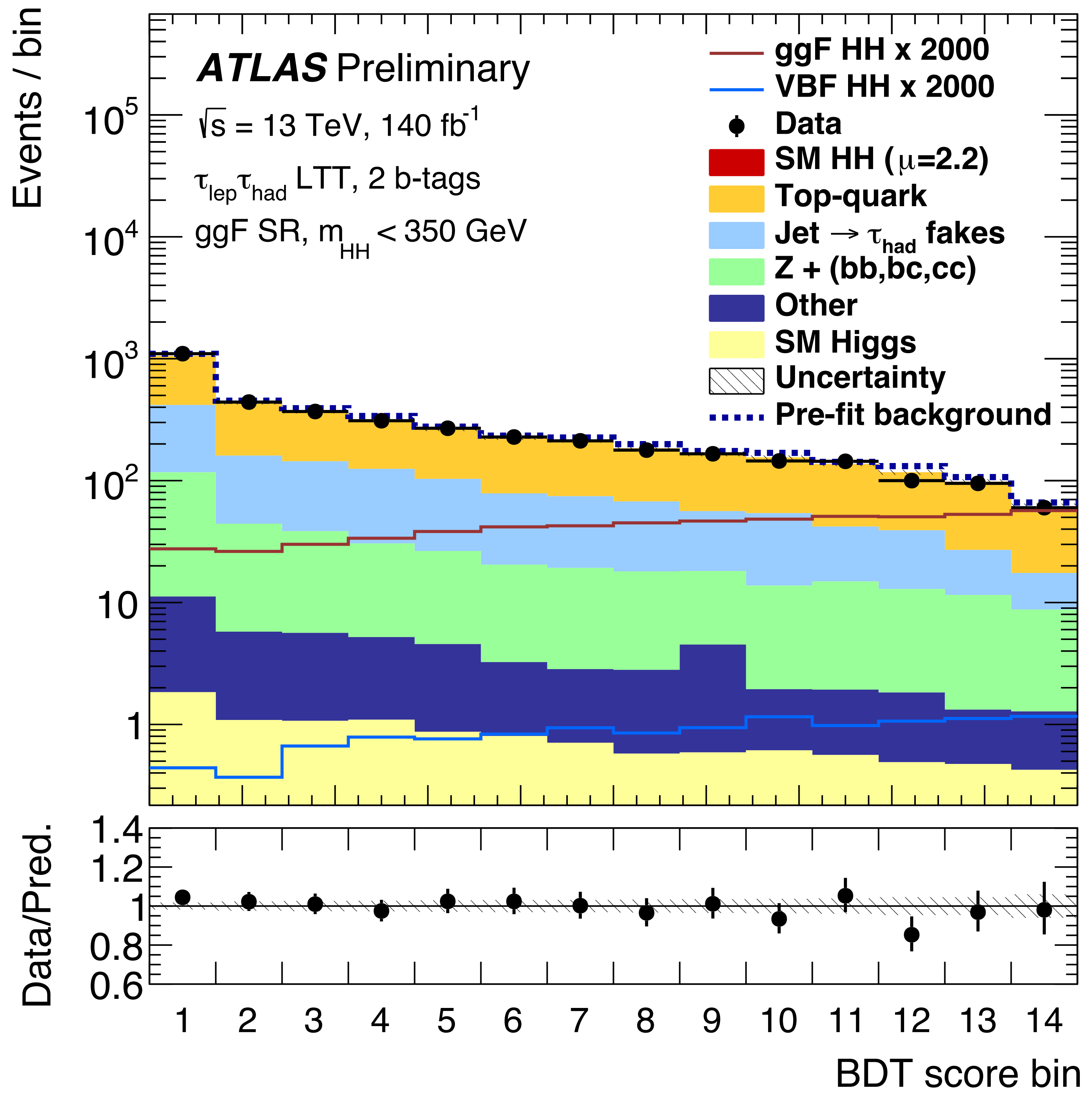



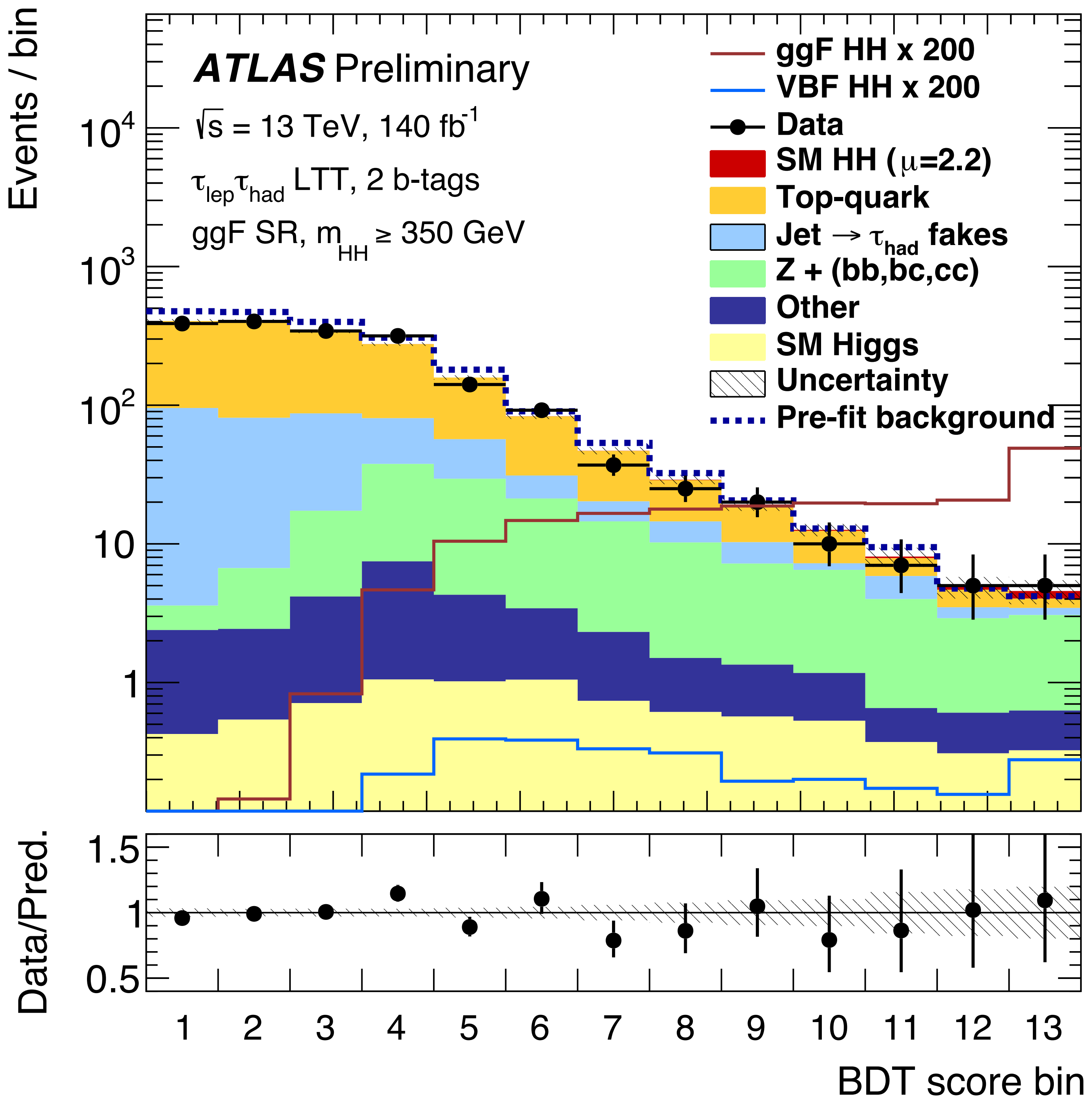

- HH signal scaled to combined signal strength included in both the stack and the ratio

# Fit results
## $\tau_{lep}\,\tau_{had}$ (LTT)

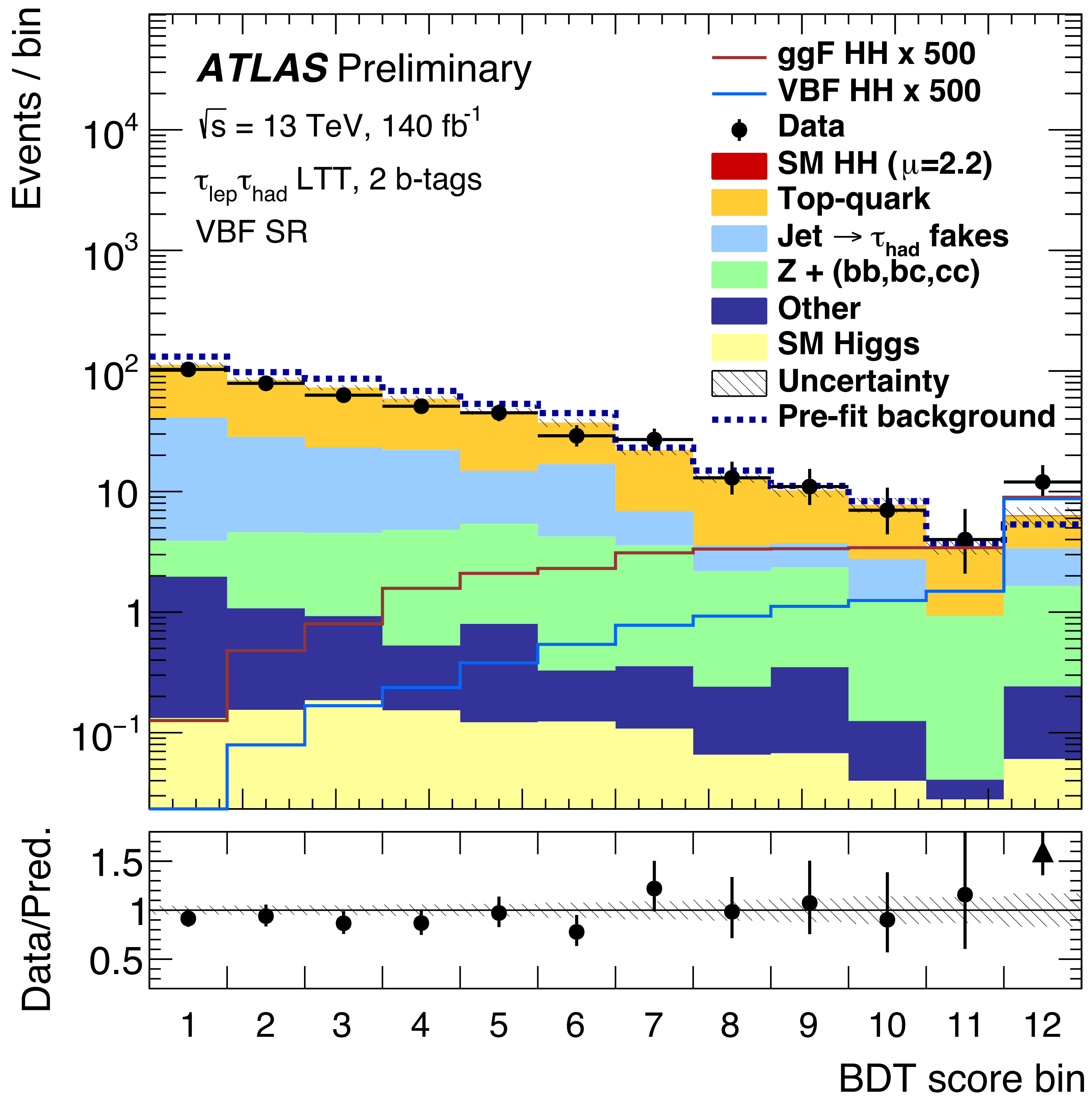
low $m_{HH}$ SR




high $m_{HH}$ SR




VBF SR




- HH signal scaled to combined signal strength included in both the stack and the ratio

# Limits on enhanced pp→HH cross-sections

**No significant excess observed above the SM prediction (μ=1)**

Observed limit higher than expected due to a stat. fluctuation in the $\tau_{lep}\tau_{had}$ SLT high $m_{HH}$ region

<u>**Upper limits at 95% CL:**</u>

$\mu_{HH}$ < 5.9 observed
< 3.1 expected, 20% reduction wrt previous results

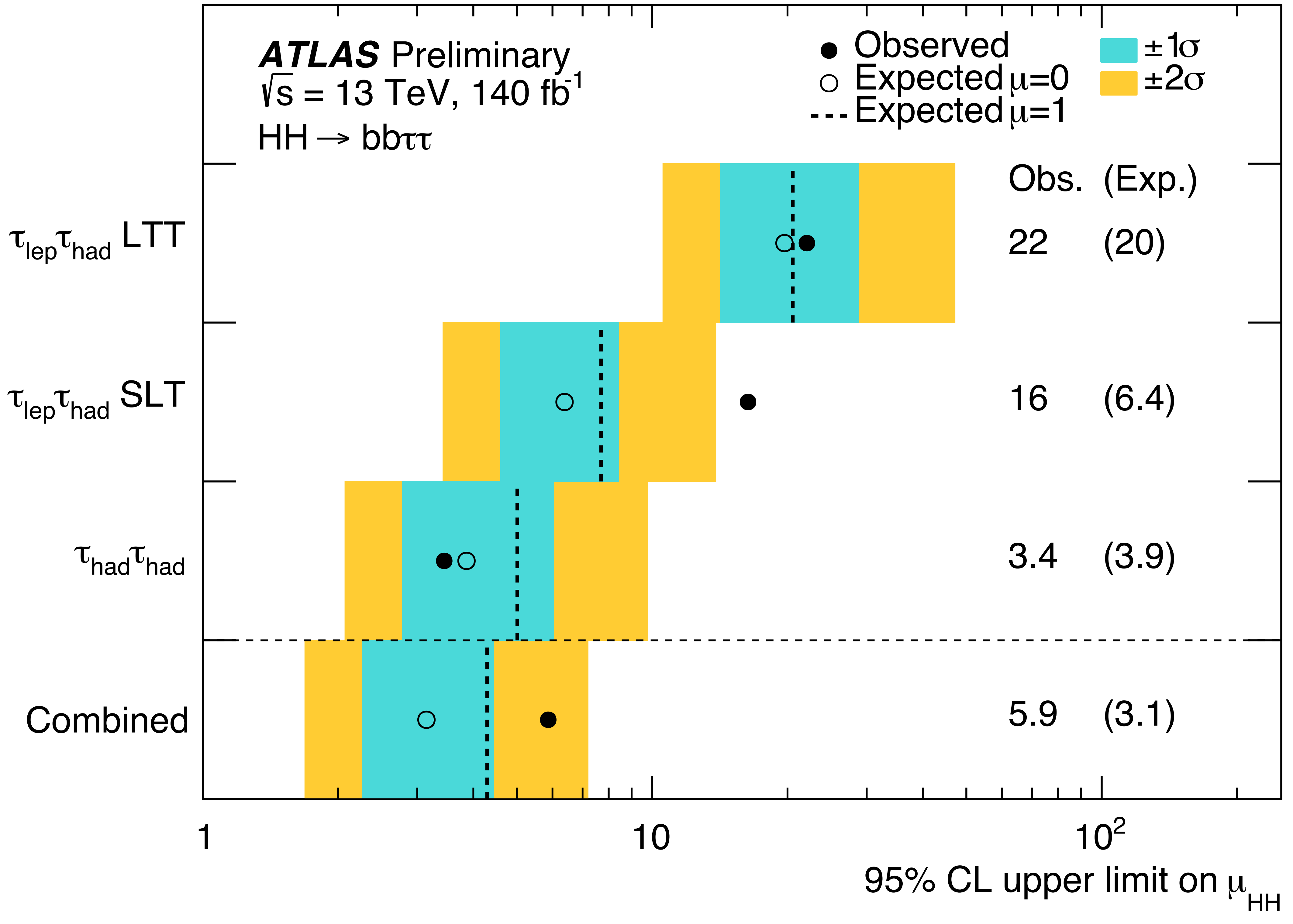
Can set limits **simultaneously** on **ggF** and **VBF** production cross-section thanks to new VBF SR:

$\mu_{ggF}$ < 5.8 observed
< 3.2 expected

$\mu_{VBF}$ < 91 observed
< 71 expected

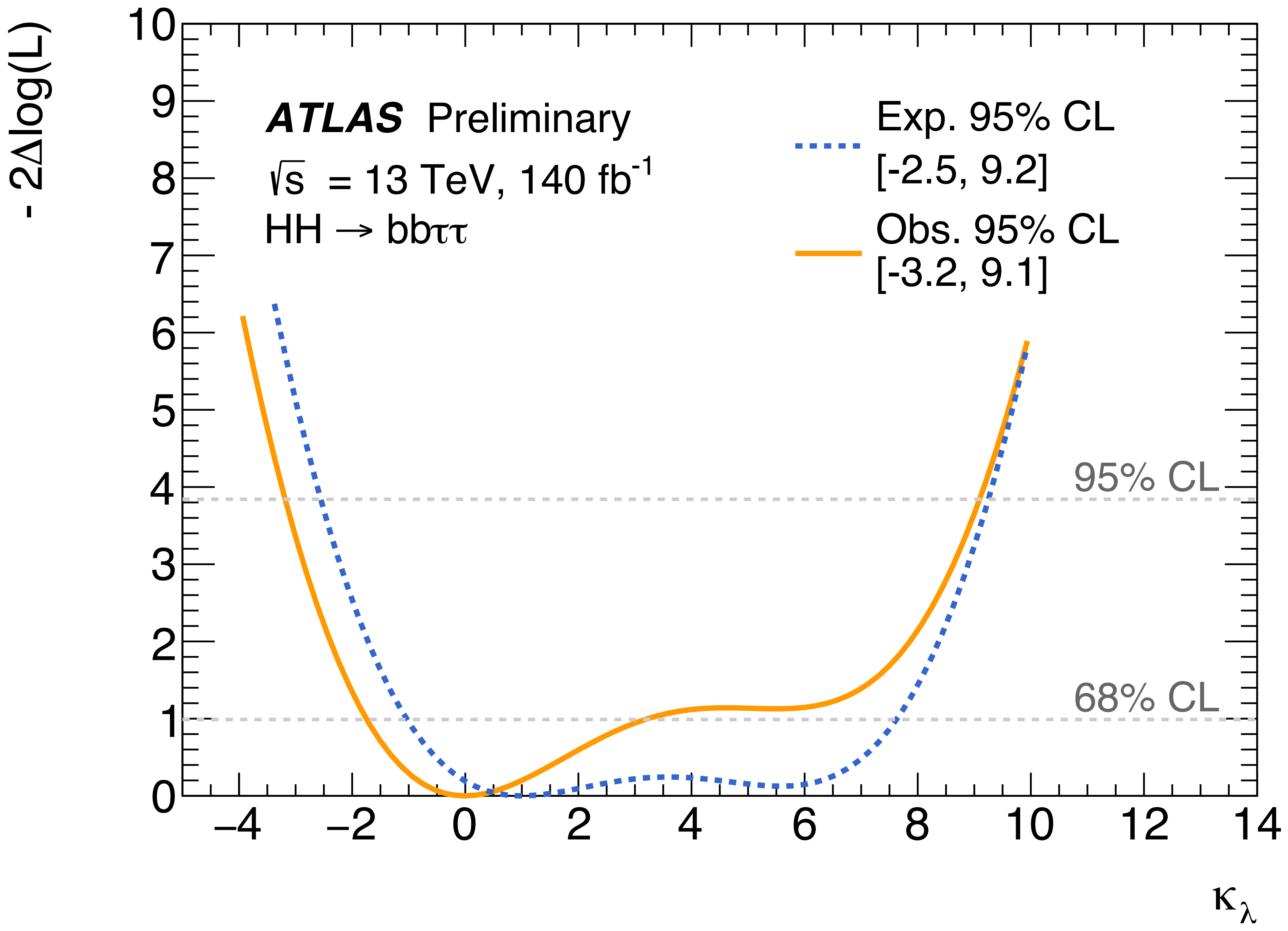
NEW

bbγγ: $\mu_{HH}$ < 5.0 expected        bbγγ: $\mu_{VBF}$ < 145 expected



# Constraining anomalous self couplings

## Anomalous HHH coupling:

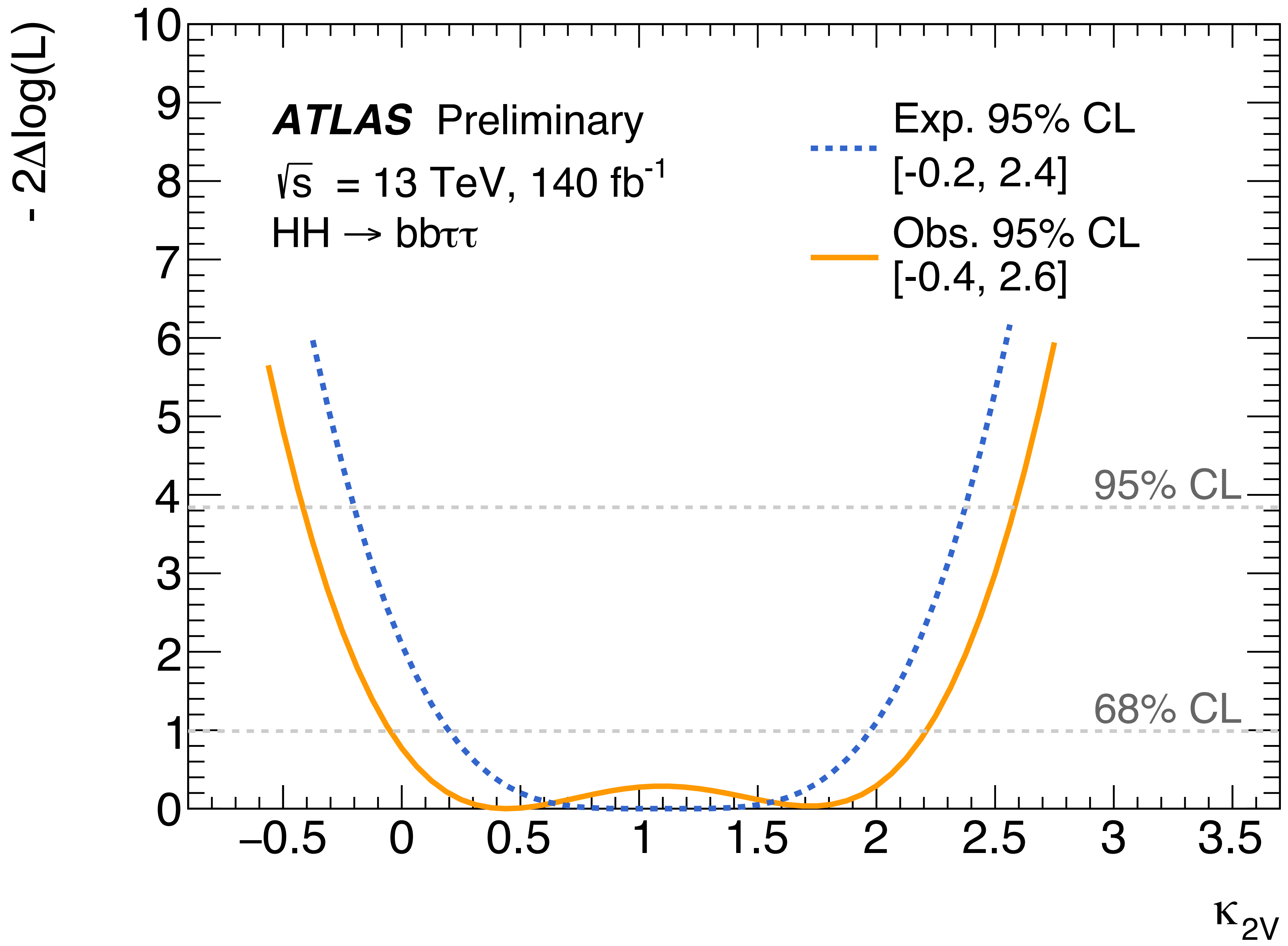



$\kappa_\lambda \in [-3.2, 9.1]$ observed

$\in [-2.4, 9.2]$ expected, 11% reduction

bbγγ: $\kappa_\lambda \in [-2.8, 7.8]$ expected

## Anomalous HHVV coupling:




$\kappa_{2V} \in [-0.5, 2.7]$ observed

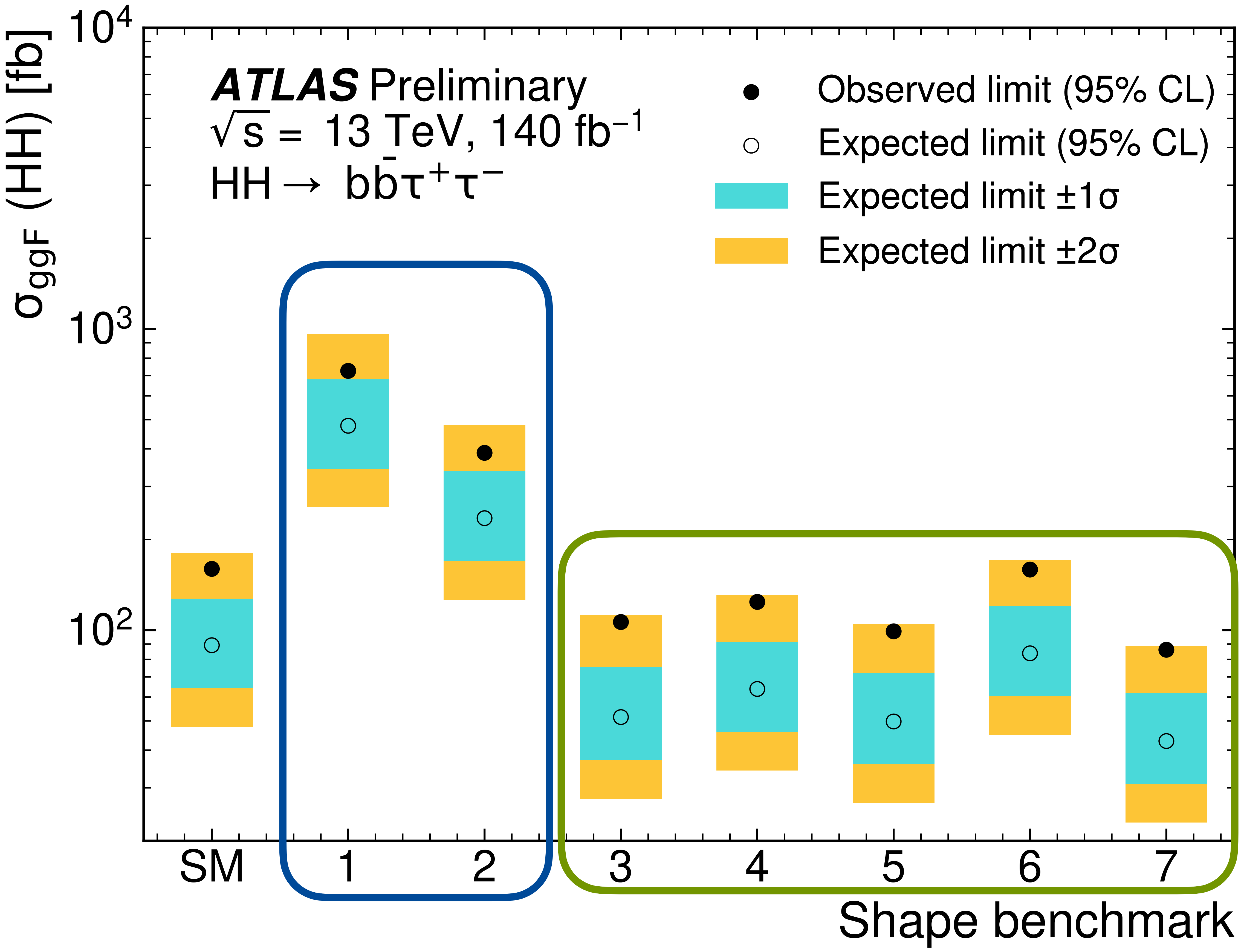
$\in [-0.2, 2.4]$ expected, 19% reduction

bbγγ: $\kappa_{2V} \in [-1.1, 3.3]$ expected

- Little correlation between the two modifiers (-12%)

# HEFT interpretation

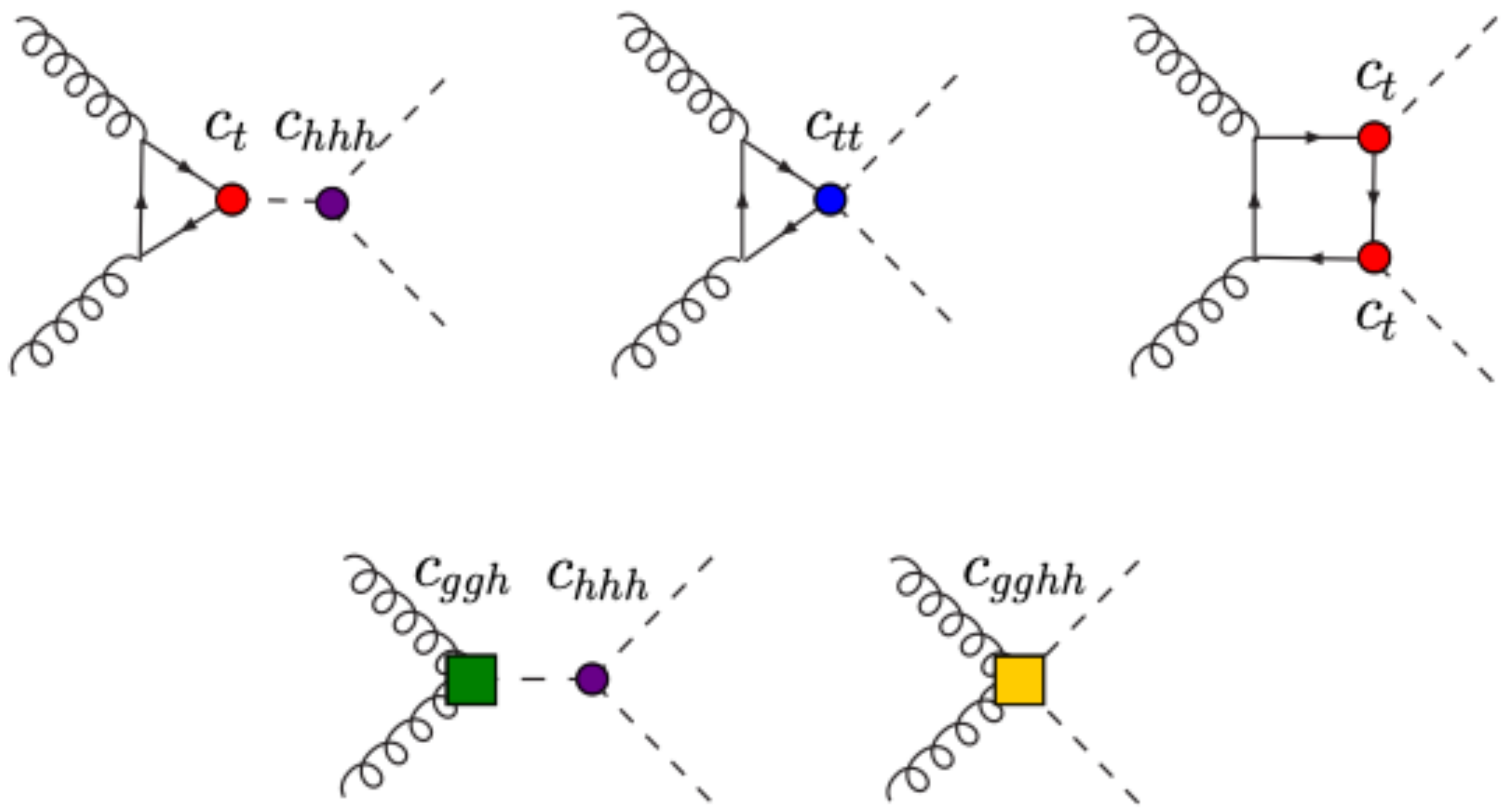
- Using the analysis to constrain 6 add. $m_{HH}$ shape benchmarks within the HEFT framework




Softer $m_{HH}$ spectrum than SM

Harder $m_{HH}$ spectrum than SM

[LHCHWG-2022-004]



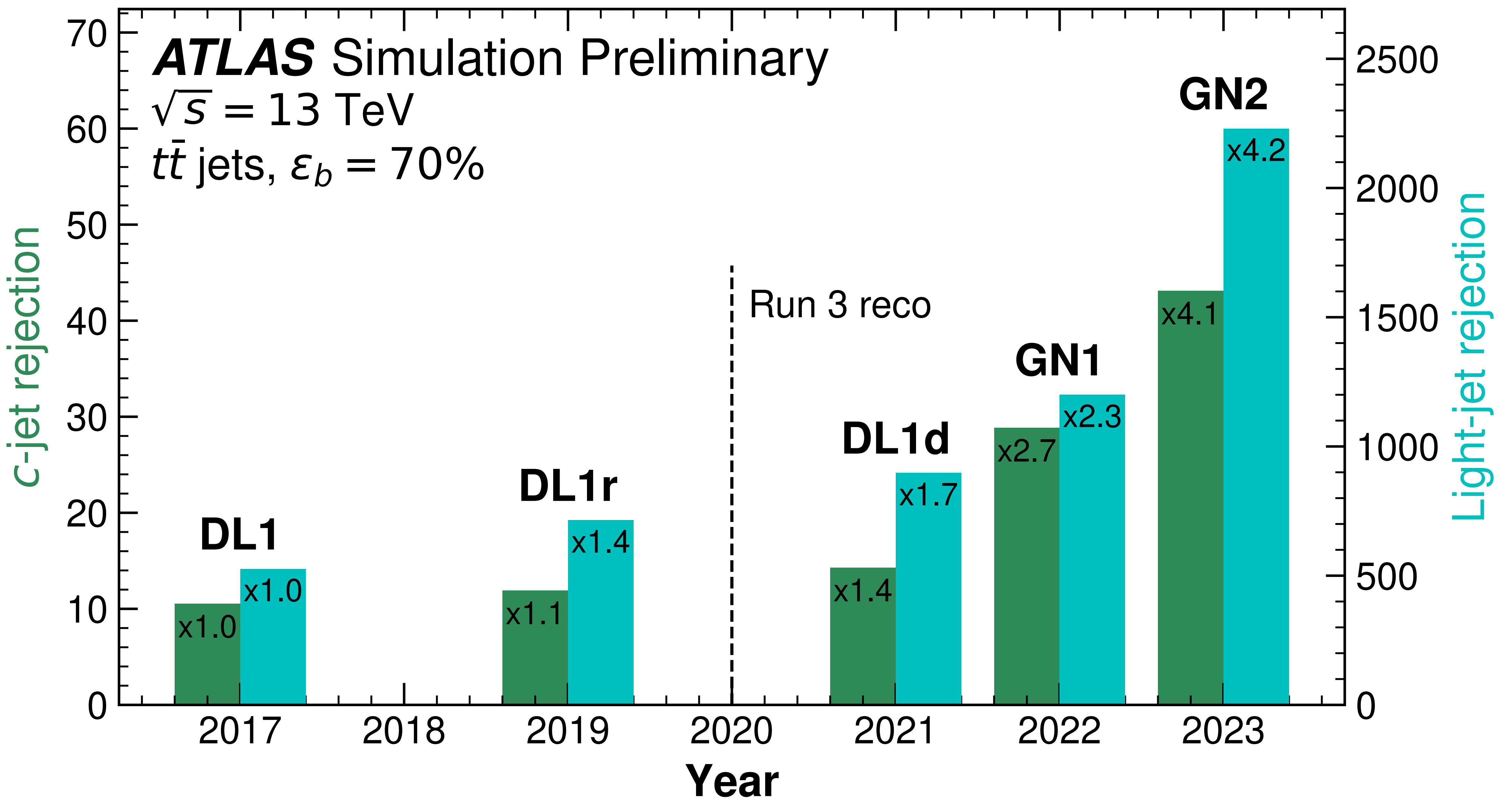

| benchmark (* = modified) | $c_{hhh}$ | $c_t$ | $c_{tt}$ | $c_{ggh}$ | $c_{gghh}$ |
|---|---|---|---|---|---|
| SM | 1 | 1 | 0 | 0 | 0 |
| 1* | 5.11 | 1.10 | 0 | 0 | 0 |
| 2* | 6.84 | 1.03 | $\frac{1}{6}$ | $-\frac{1}{3}$ | 0 |
| 3 | 2.21 | 1.05 | $-\frac{1}{3}$ | $\frac{1}{2}$ | $\frac{1}{2}$ |
| 4* | 2.79 | 0.90 | $-\frac{1}{6}$ | $-\frac{1}{3}$ | $-\frac{1}{2}$ |
| 5 | 3.95 | 1.17 | $-\frac{1}{3}$ | $\frac{1}{6}$ | $-\frac{1}{2}$ |
| 6* | −0.68 | 0.90 | $-\frac{1}{6}$ | $\frac{1}{2}$ | 0.25 |
| 7 | −0.10 | 0.94 | 1 | $\frac{1}{6}$ | $-\frac{1}{6}$ |

# Towards Run 3

- Ongoing performance improvements will benefit future analyses in this channel

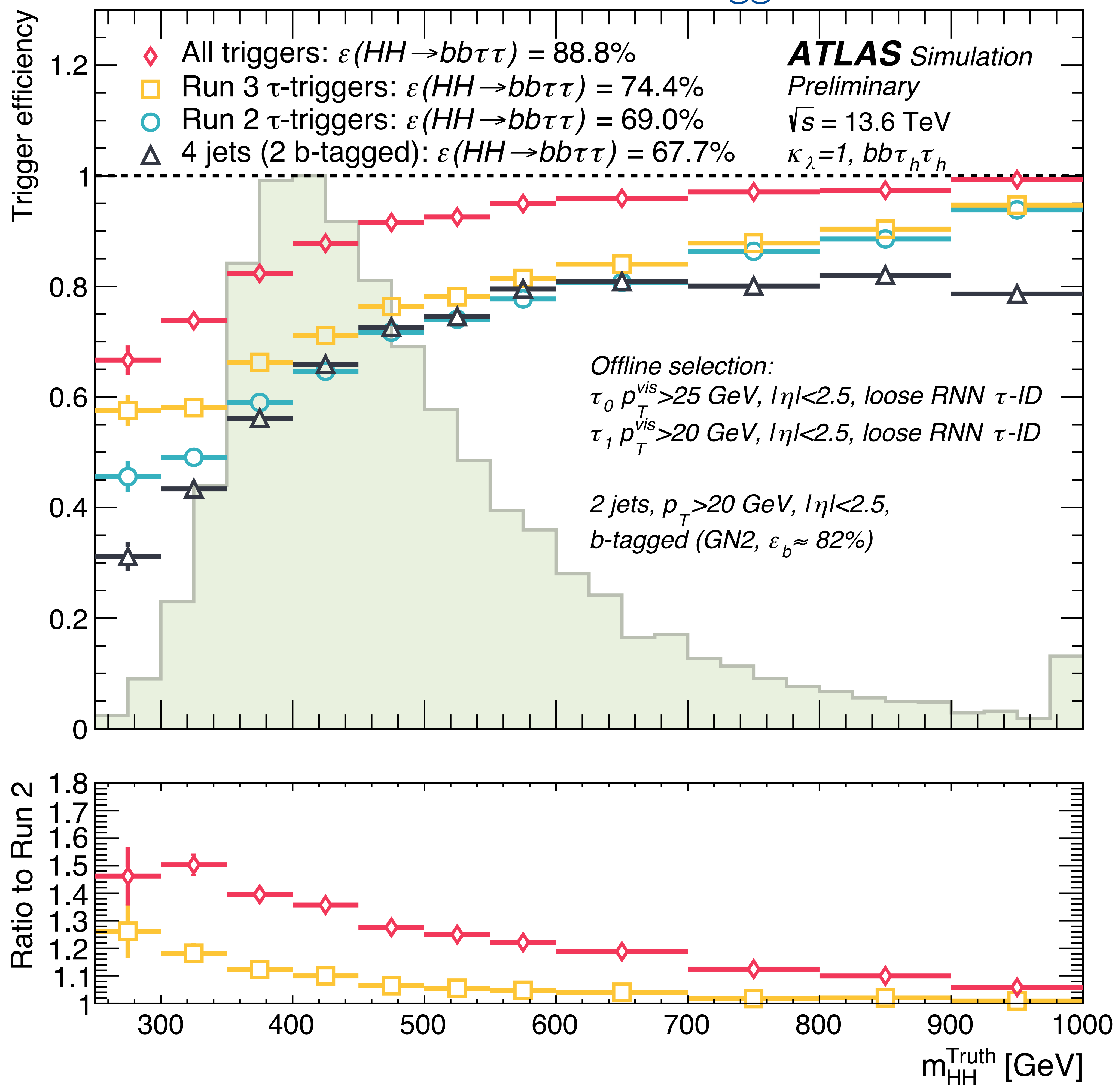
## b-tagging

[FTAG-2023-01]




## Triggering

[ATLASTauTriggerPublicResults]




- Run 3 tagger 4x better charm and light rejection at the same $\varepsilon_b$
- 30% trigger $\varepsilon$ improvements, esp. at low $m_{HH}$

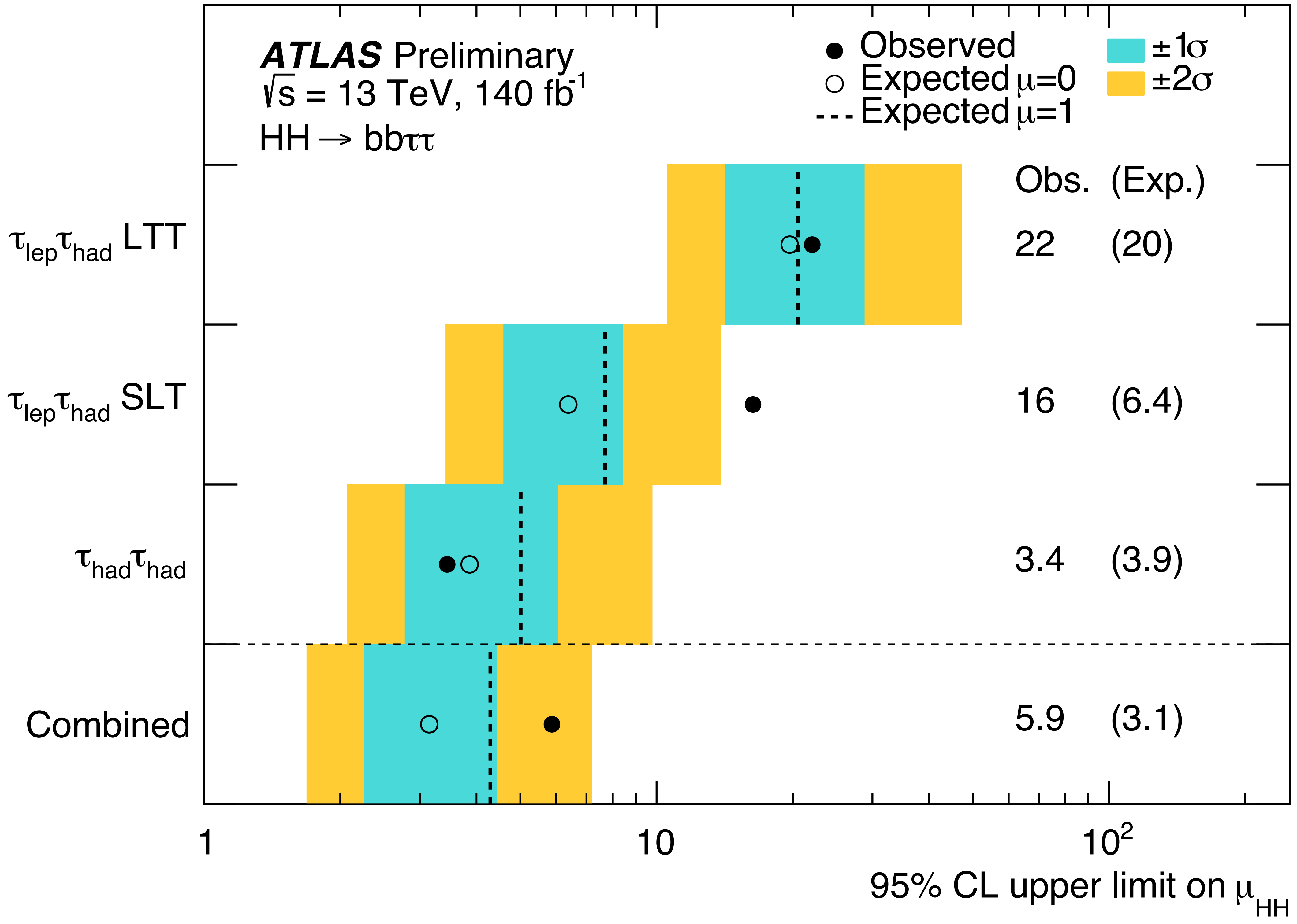
# Summary and conclusion

- pp→HH→bbττ re-analysis of the Run 2 data set with focus on non-resonant part
  [similar to what has already been done for pp→HH→bbγγ, arXiv:2310.12301]

- Expected improvements of 20% on signal strength
  →bbττ is strongest contributor to ATLAS HH combination
  →equivalent of adding a new HH analysis with a limit of 5 x SM

- Improvements on HHH and HHVV coupling strengths limits of 10% - 20%

- Run 3 awaits with further improvements




**Exciting times ahead!**

# Backup