Constraining the Shape of the Higgs Potential Through a Search for **Higgs Boson Pairs** in the **bbττ** Final State with the **ATLAS** Experiment

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on behalf of the ATLAS collaboration

Higgs 2023 - Beijing

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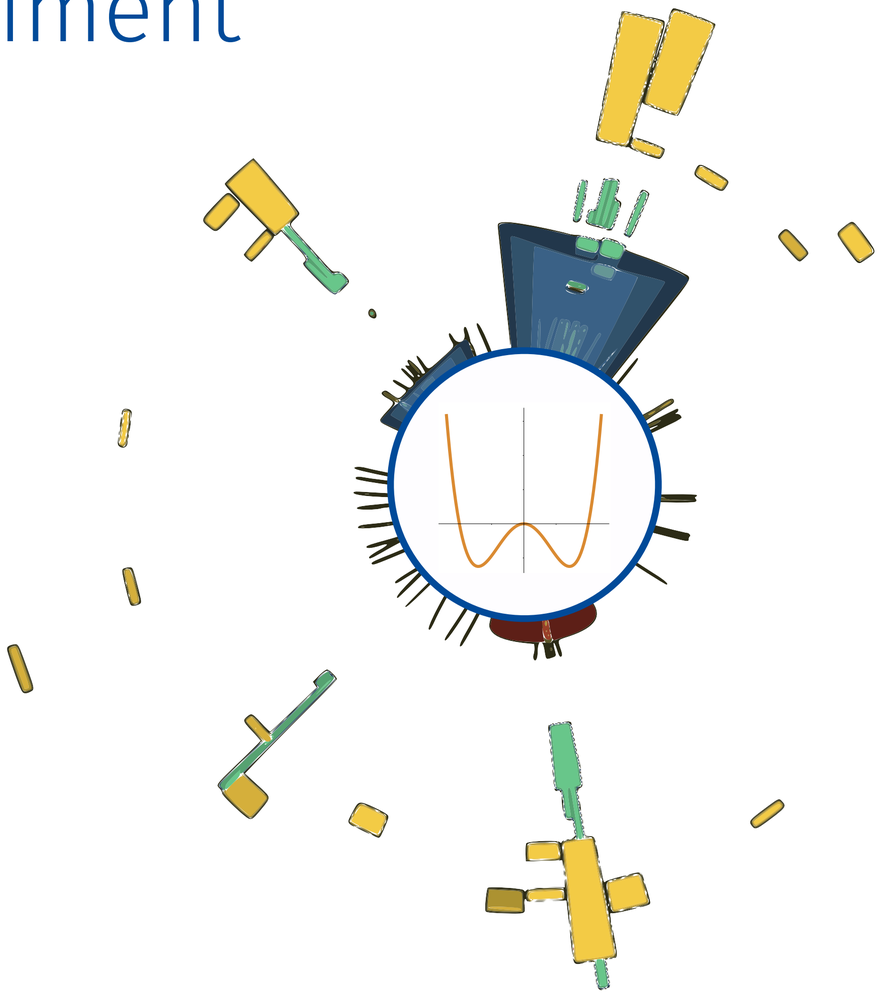
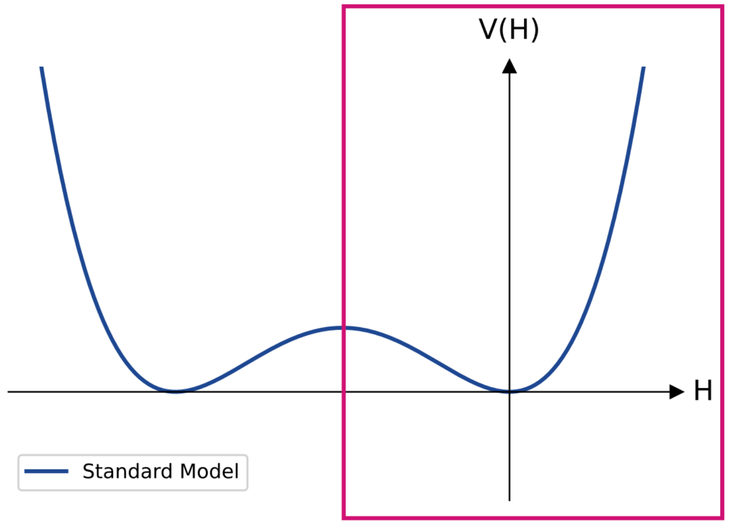


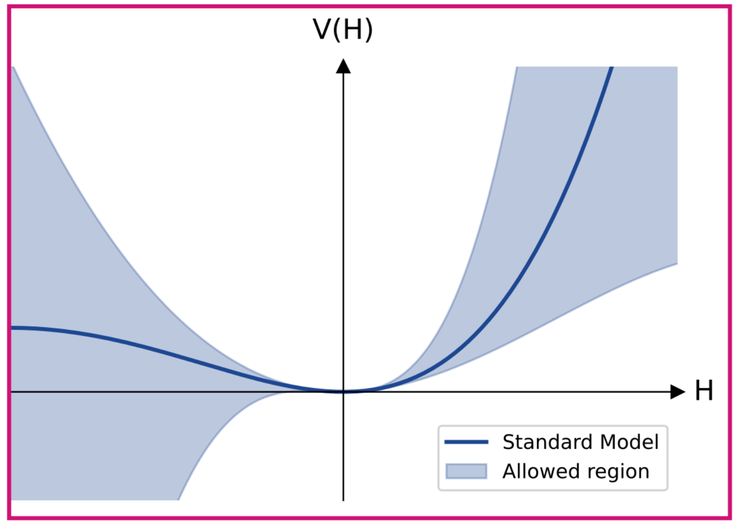
The Higgs potential and searches for HH

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

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

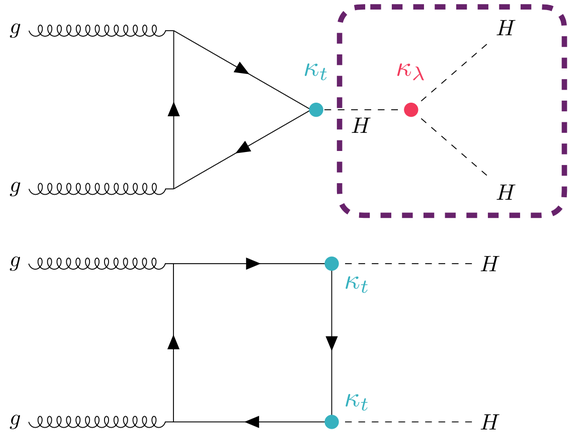
What the SM predicts vs what we know experimentally





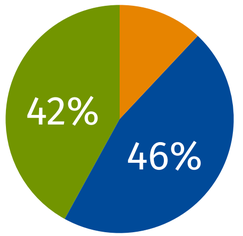
[using current ATLAS limits @ 95% CL]

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



- 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

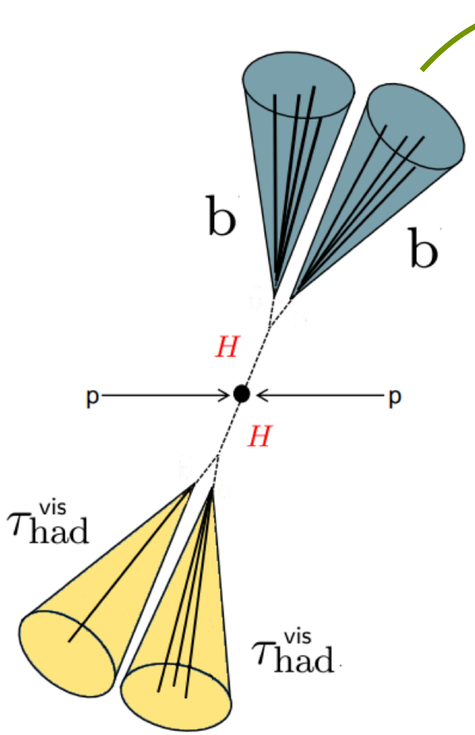
The search for pp→HH→bbττ



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-τ_{had} triggers	single ℓ triggers	ℓ + τ_{had} triggers
exactly two τ_{had}	exactly one τ_{had}	
lepton veto	m_{bb} < 150 GeV	

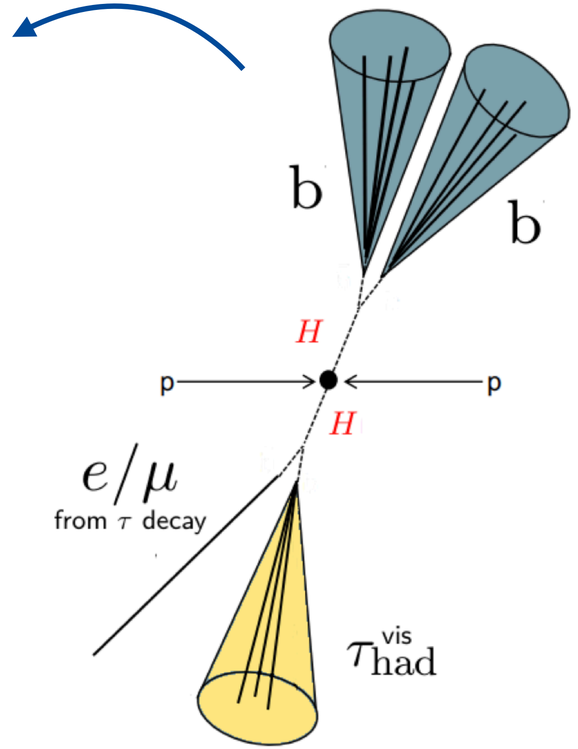
trigger dependent thresholds on e/μ/τ_{had} and jets

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

exactly two b-tagged jets (ε_b = 77%)

opposite electrical charge sign of leptons

Acc x ϵ = 4%	Acc x ϵ = 4%	Acc x ϵ = 1%

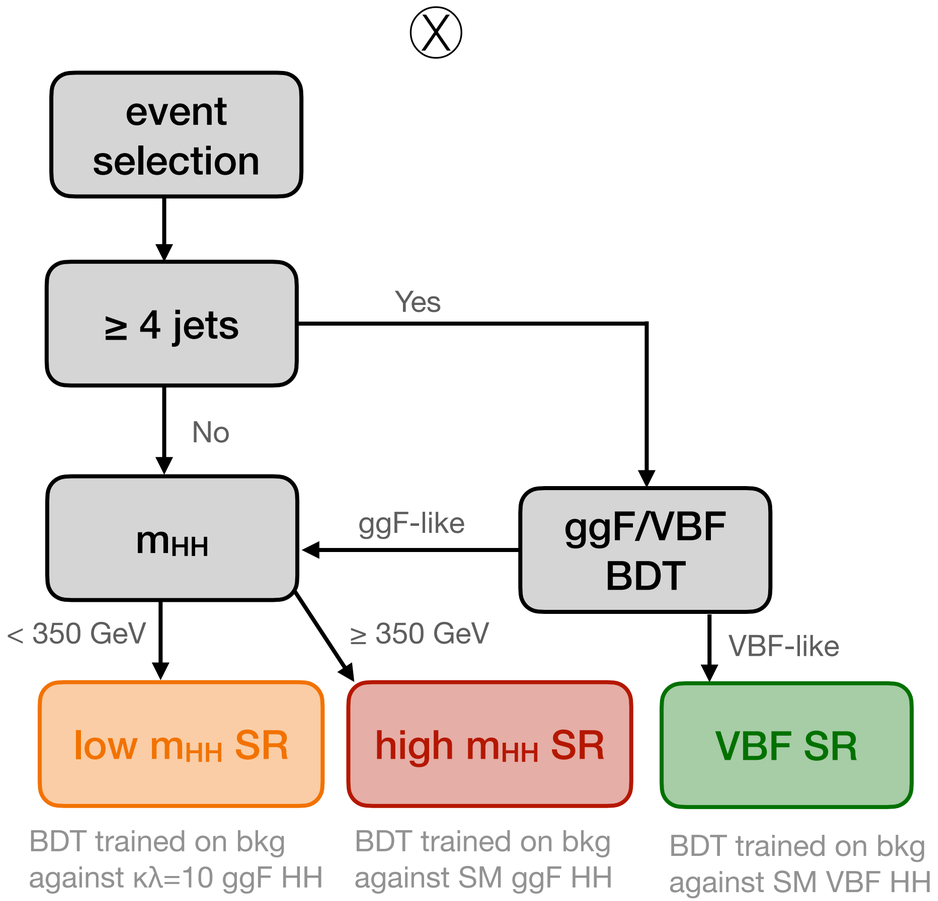


- Existing Run 2 analysis: compromise between resonant and non-resonant [JHEP 07 (2023) 040]
- New: re-analysis of the Run 2 data set focusing on the non-resonant part [public page]

Event selection

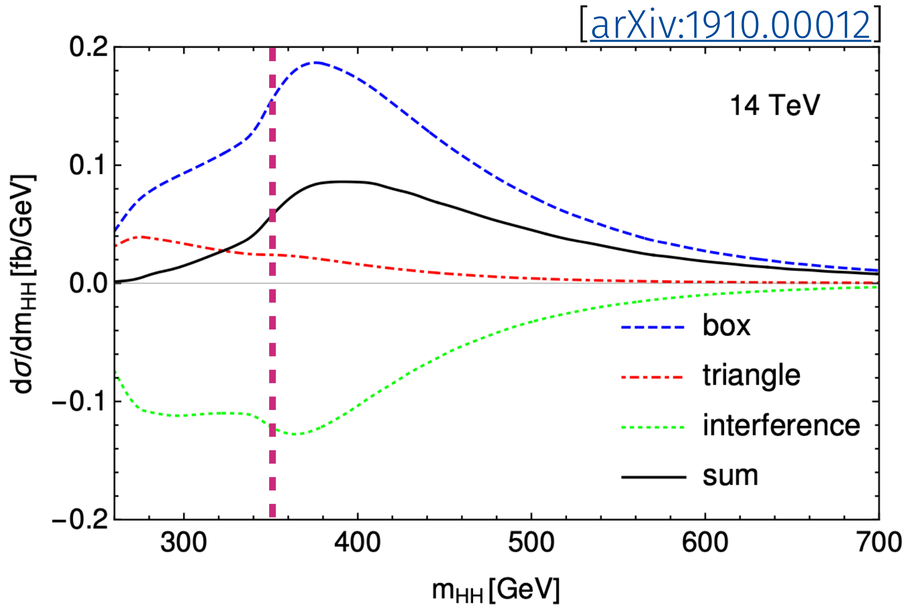
- Extended categorization to improve constraints on HHH and HHVV coupling

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



m_{HH} categorization to improve the κ_λ constraint

[arXiv:1910.00012]

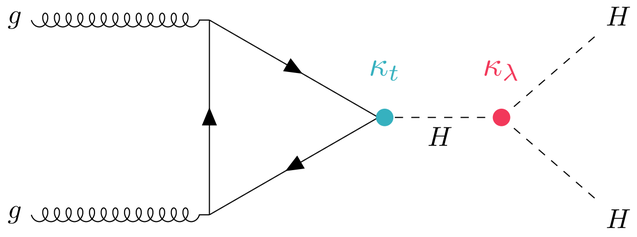


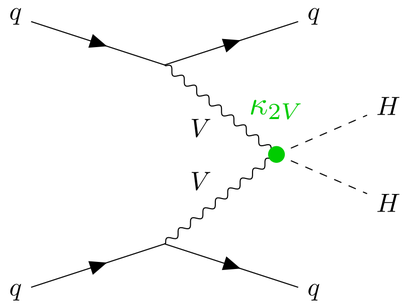
<u>Improved BDT</u>:

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

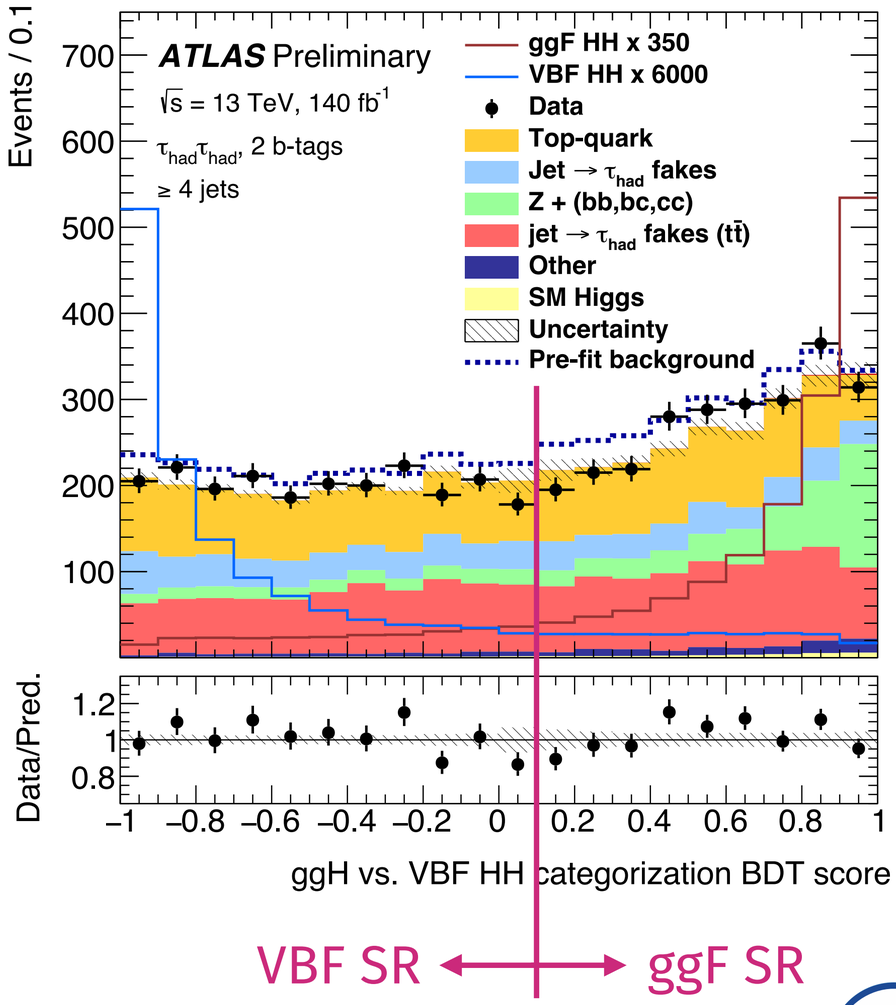
ggF HH vs. VBF HH categorization BDT

- Introduction of a **dedicated VBF HH SR** to improve the κ_{2V} constraint and to reduce the correlation with the κ_λ 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}, ΔR_{jj}^{VBF}, $\eta_{jet1} \times \eta_{jet2}$ as well as **event shape variables** (Fox Wolfram Moments)
- Categorization cut chosen not to penalize k_λ 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]

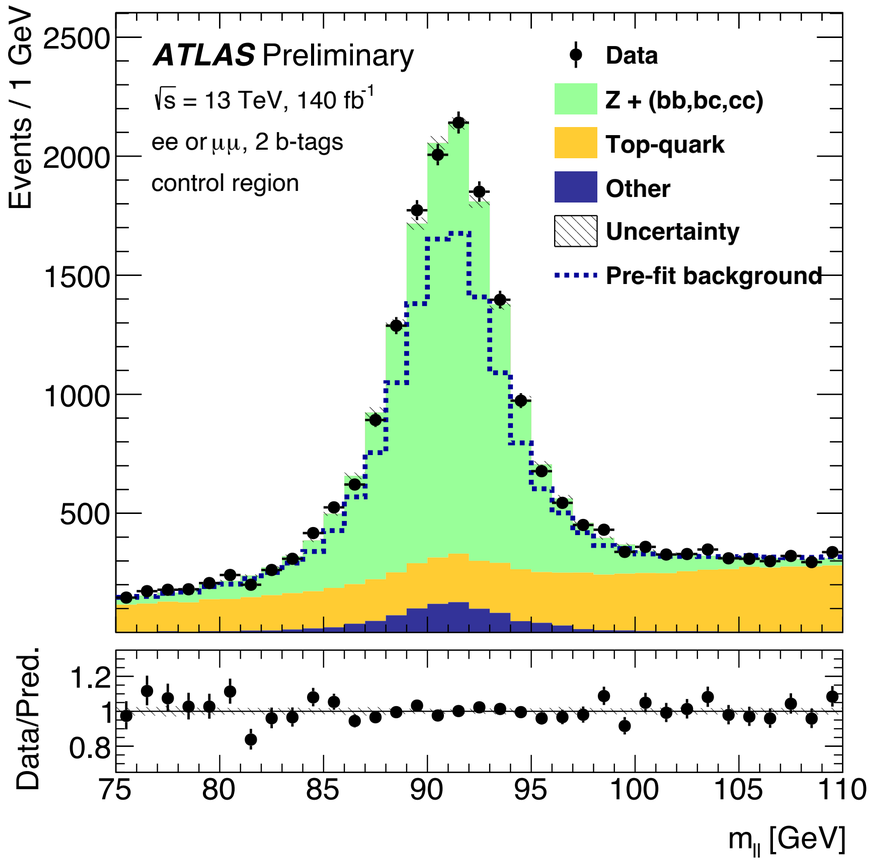
- single top
- single Higgs
- diboson

from simulation

- ttbar with jet→τ_{had} fakes
- QCD multijet with jet→τ_{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

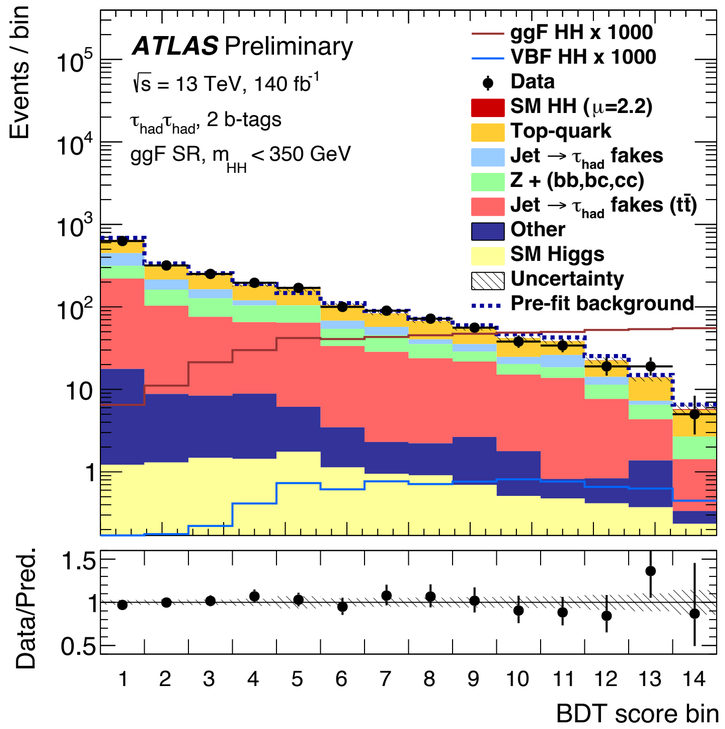
Fit results

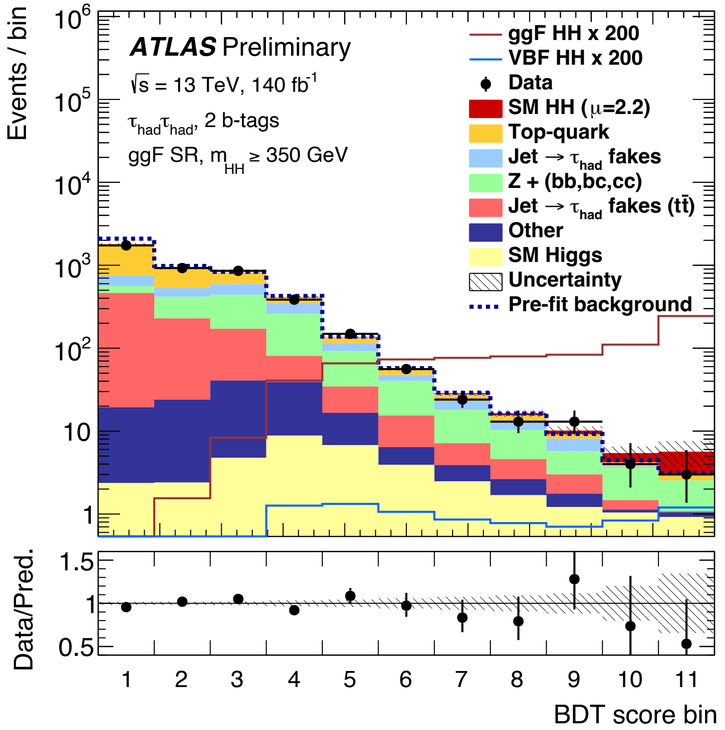
low m_{HH} SR

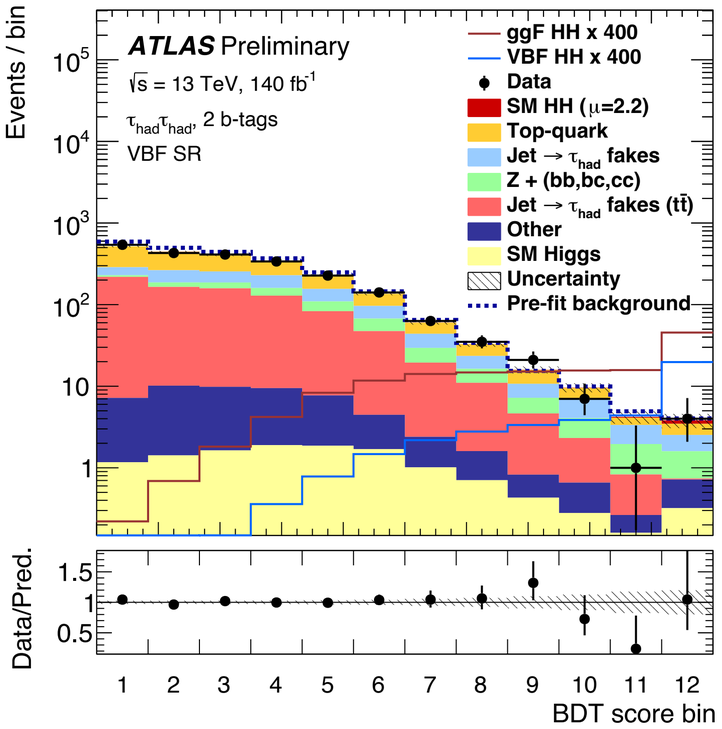
high m_{HH} SR

VBF SR

τhad τhad







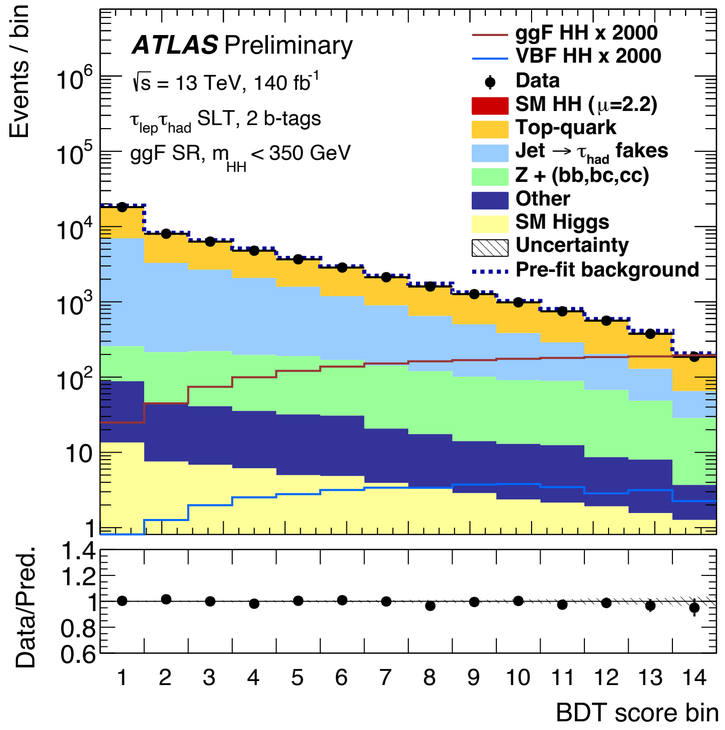
- HH signal scaled to combined signal strength included in both the stack and the ratio

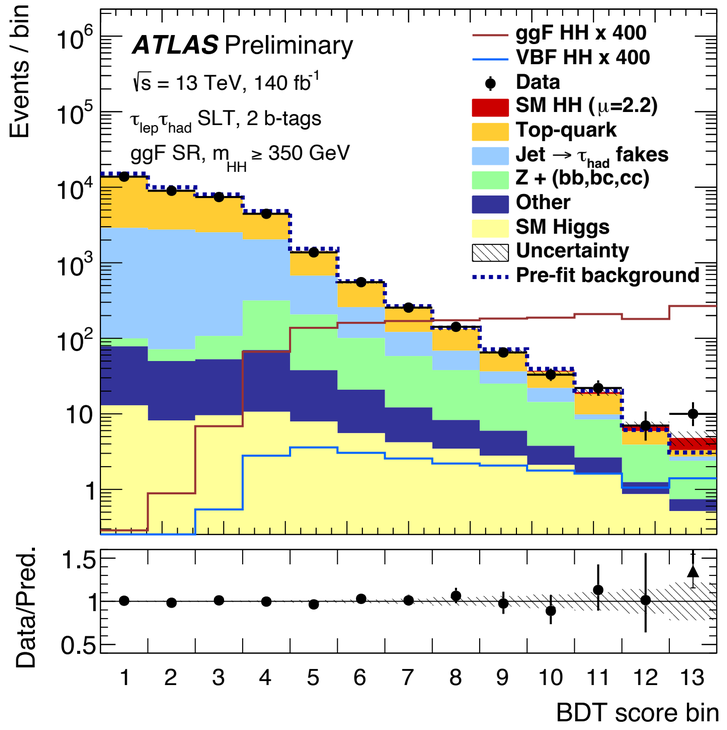
Fit results
$\tau_{lep}\tau_{had}$ (SLT)

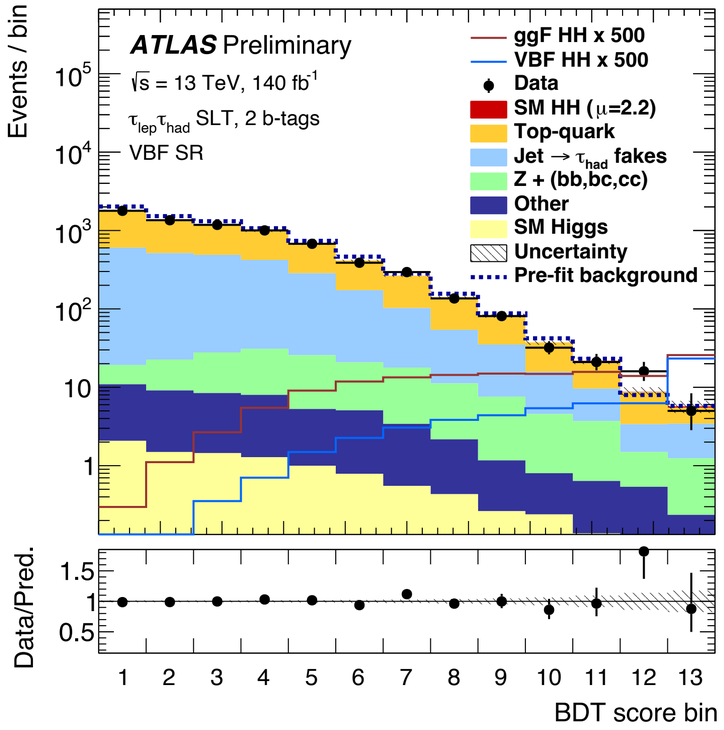
low m_{HH} SR

high m_{HH} SR

VBF SR







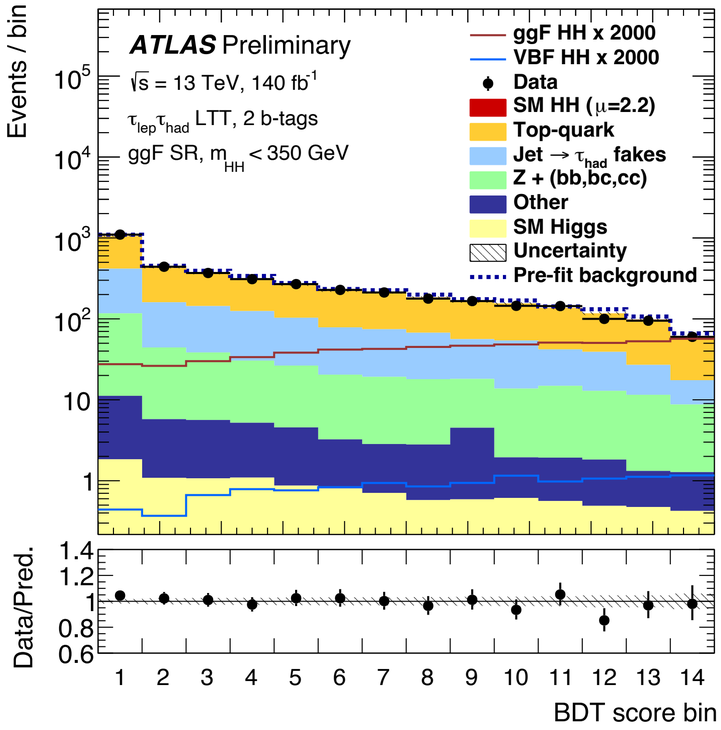
- HH signal scaled to combined signal strength included in both the stack and the ratio

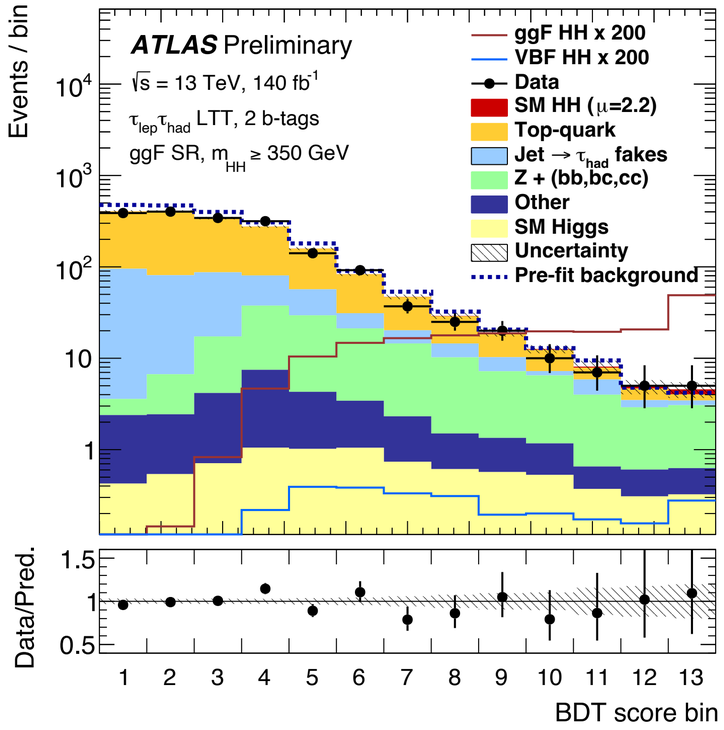
Fit results
$\tau_{lep}\tau_{had}$ (LTT)

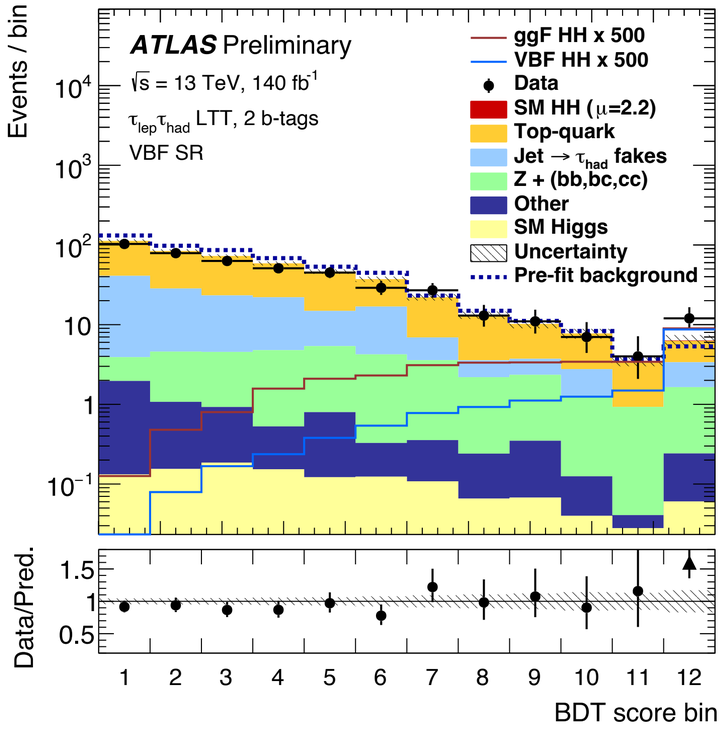
low m_{HH} SR

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

Upper limits at 95% CL:

μ_{HH} < 5.9 observed
< 3.1 expected, 20% reduction wrt previous results

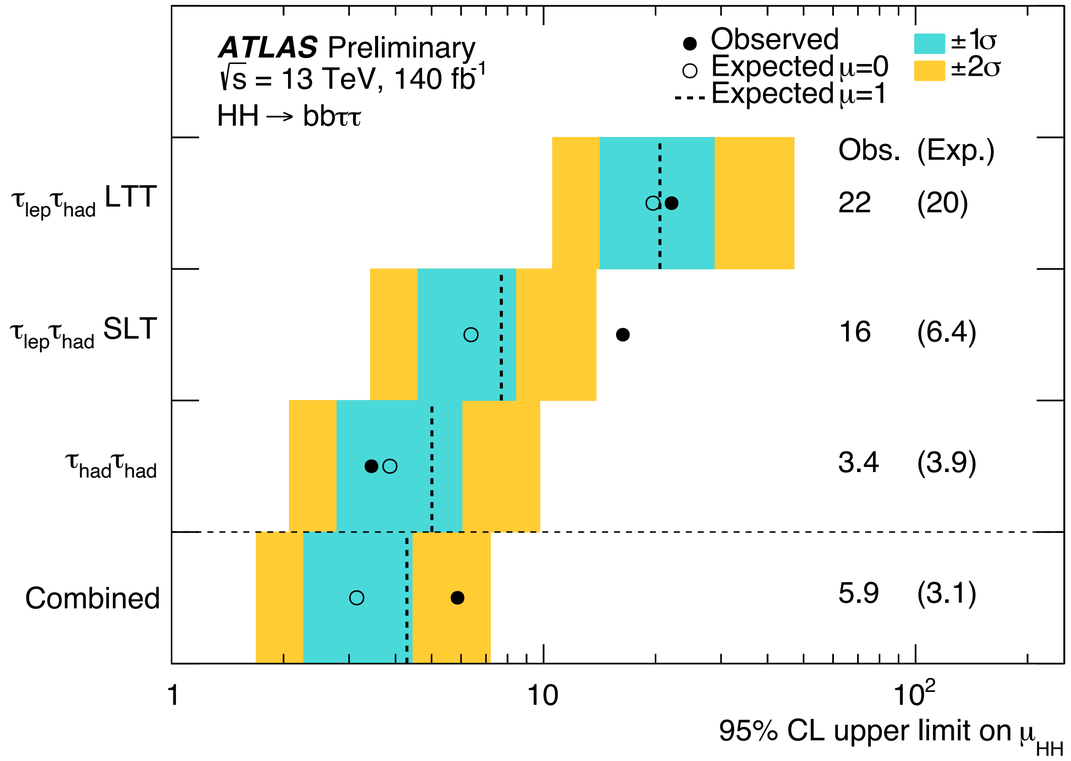
Can set limits **simultaneously** on **ggF** and **VBF** production cross-section thanks to new VBF SR:

μ_{ggF} < 5.8 observed
< 3.2 expected

μ_{VBF} < 91 observed
< 71 expected

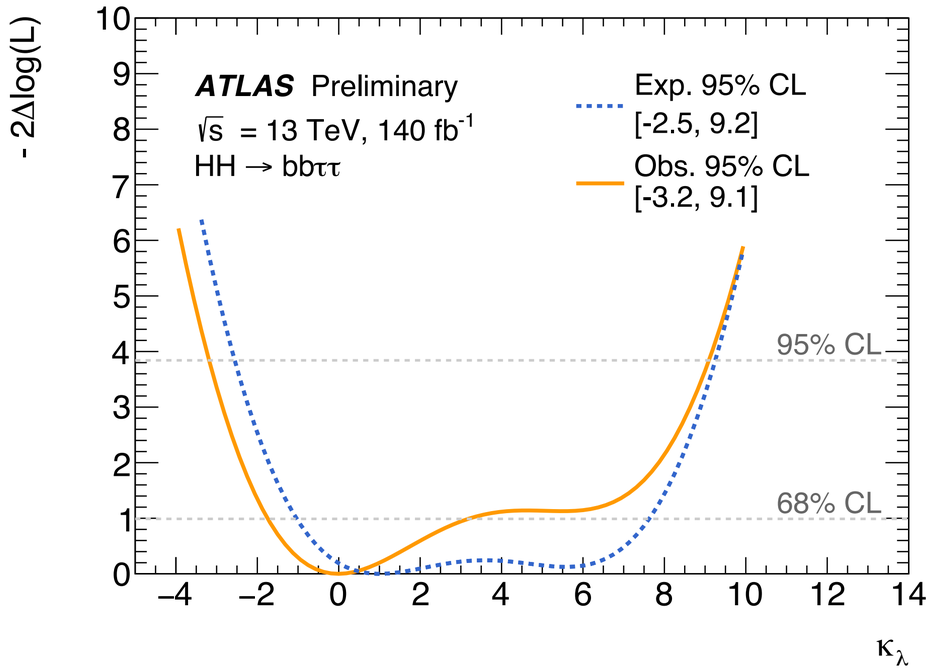
} NEW

bbγγ: μ_{HH} < 5.0 expected bbγγ: μ_{VBF} < 145 expected



Constraining anomalous self couplings

Anomalous HHH coupling:

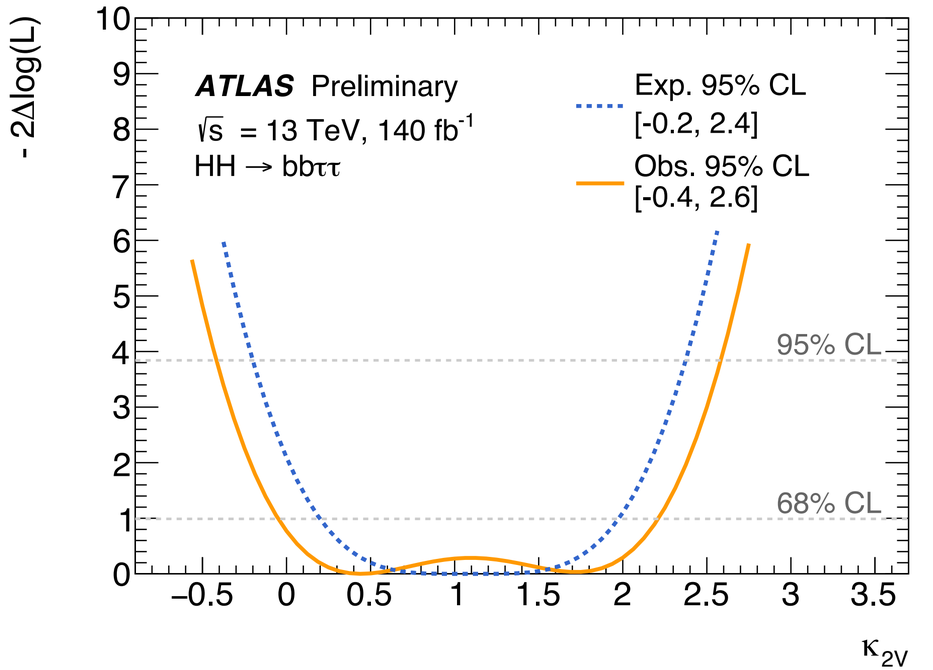


$\kappa_\lambda \in [-3.2, 9.1]$ observed

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

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

Anomalous HHVV coupling:



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

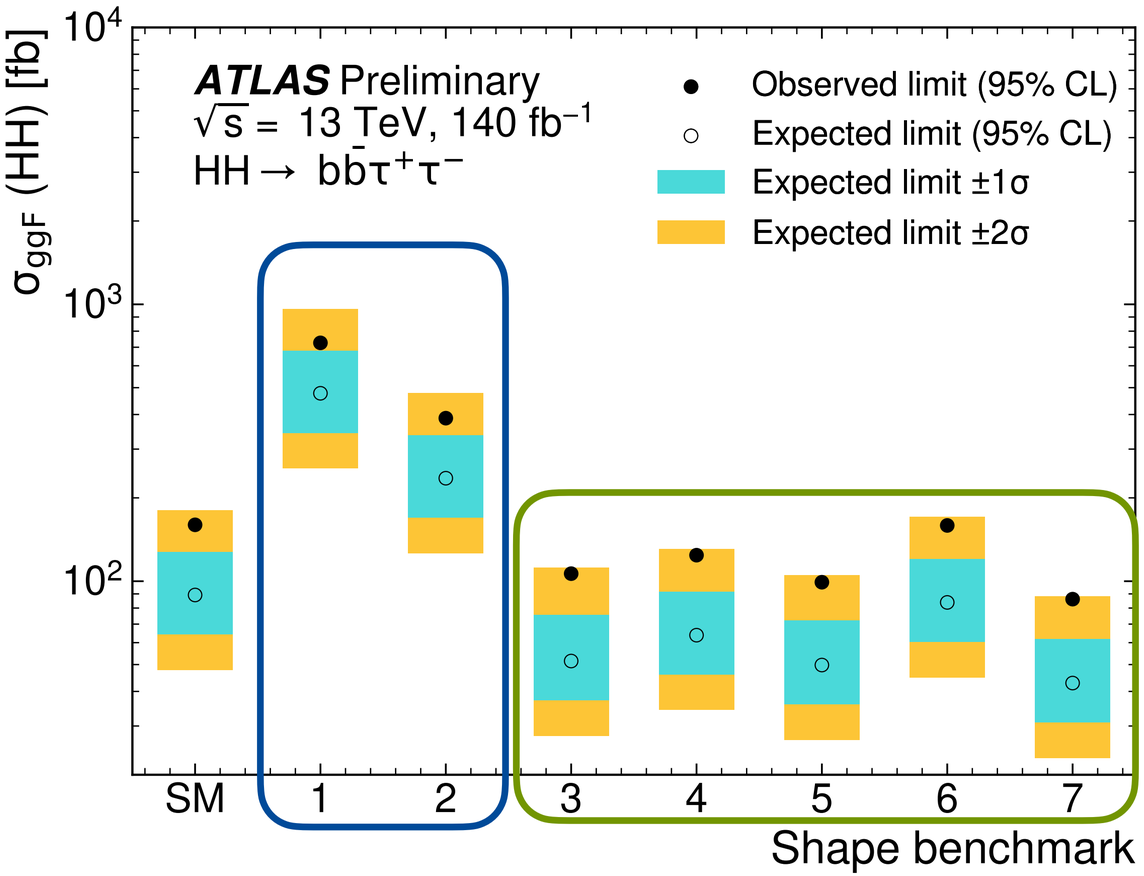
$\in [-0.2, 2.4]$ expected, 19% reduction

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

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

HEFT interpretation

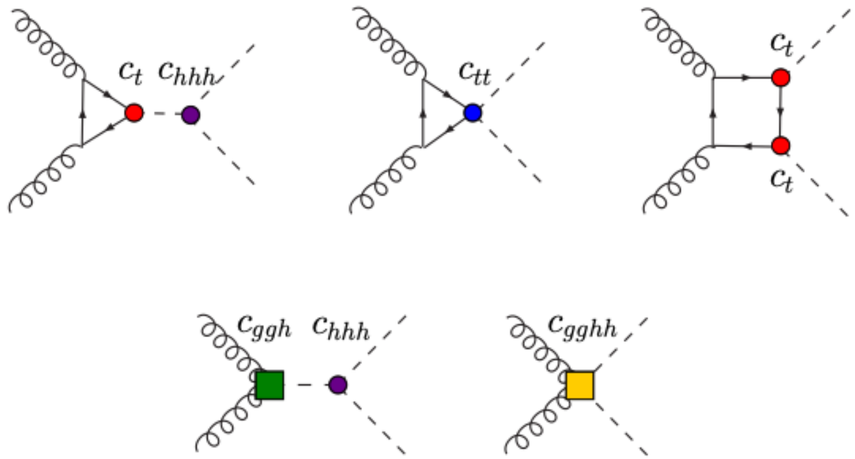
- Using the analysis to constrain 6 add. m_{HH} shape benchmarks within the HEFT framework



Softer m_{HH} spectrum than SM

Harder m_{HH} spectrum than SM

[LHCHWG-2022-004]



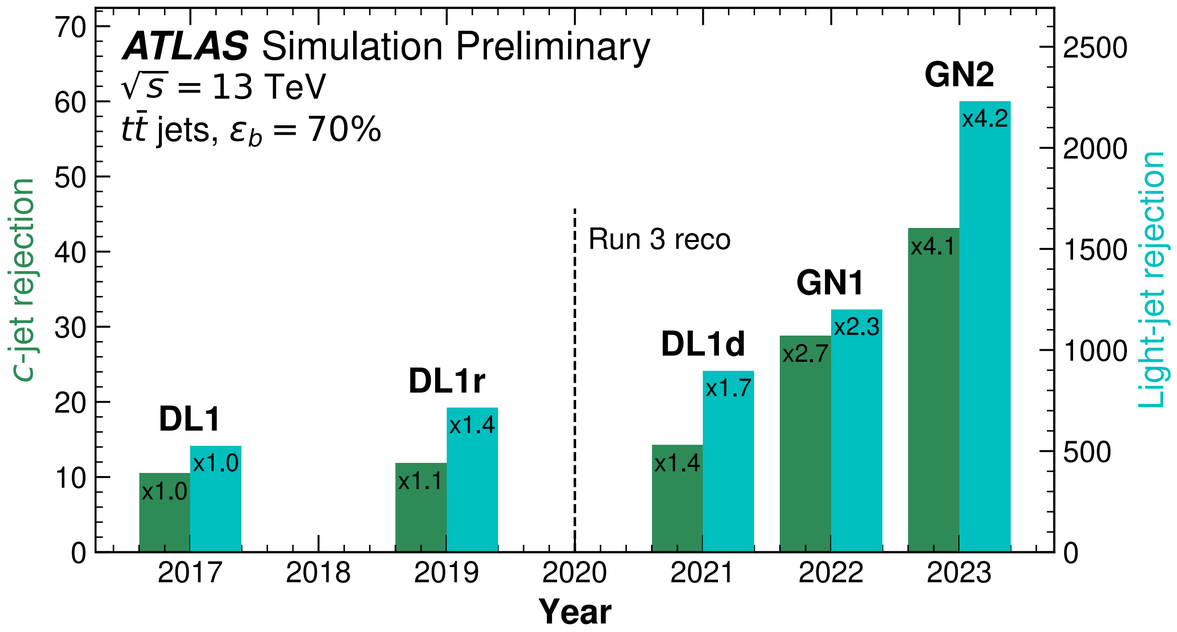
benchmark (* = modified)	c_{hhh}	c_t	c_{tt}	c_{ggh}	c_{gghh}
SM	1	1	0	0	0
1*	5.11	1.10	0	0	0
2*	6.84	1.03	$\frac{1}{6}$	$-\frac{1}{3}$	0
3	2.21	1.05	$-\frac{1}{3}$	$\frac{1}{2}$	$\frac{1}{2}$
4*	2.79	0.90	$-\frac{1}{6}$	$-\frac{1}{3}$	$-\frac{1}{2}$
5	3.95	1.17	$-\frac{1}{3}$	$\frac{1}{6}$	$-\frac{1}{2}$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

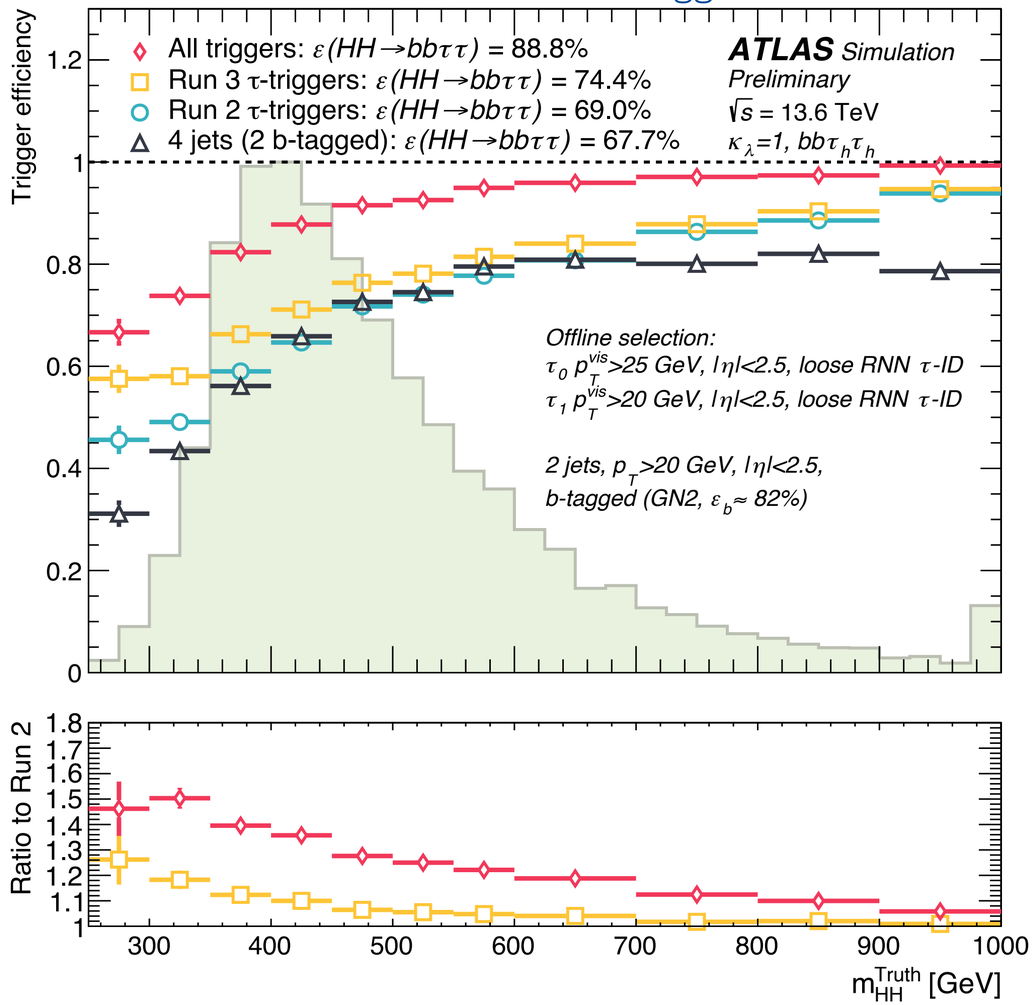
[FTAG-2023-01]



- Run 3 tagger 4x better charm and light rejection at the same ε_b

Triggering

[ATLASTauTriggerPublicResults]



- 30% trigger ε improvements, esp. at low m_{HH}

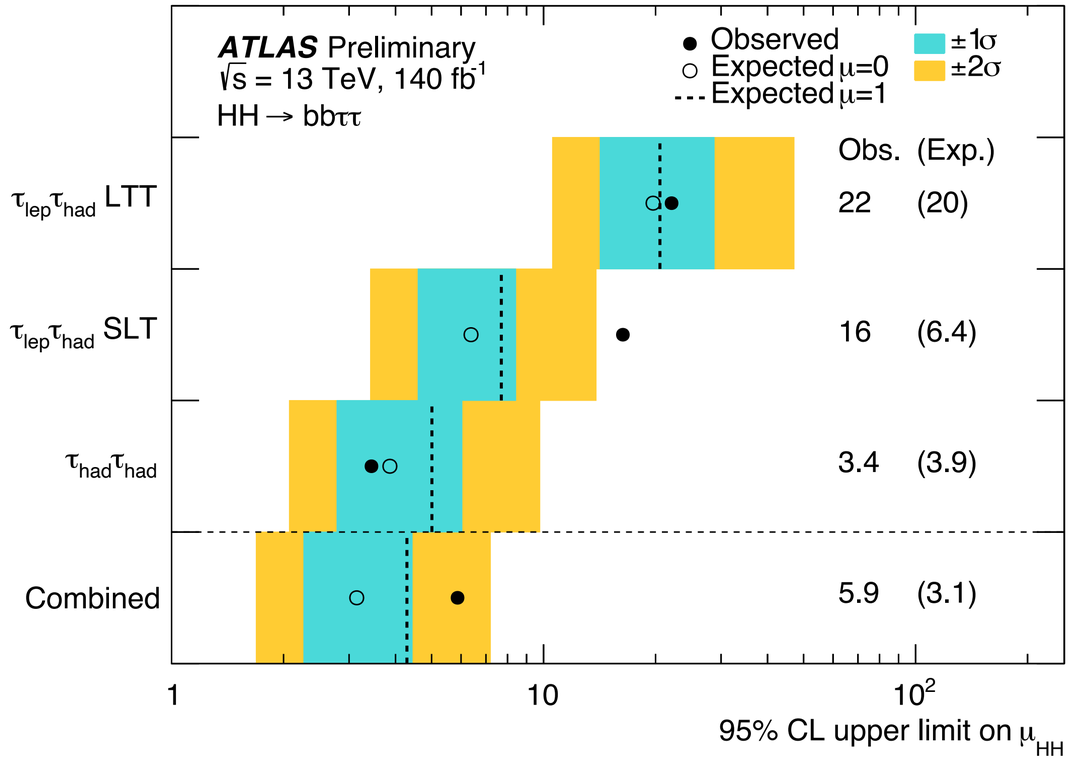
Summary and conclusion

- 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