UPPSALA UNIVERSITET

EFT interpretations of HH searches in ATLAS

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ATLAS EXPERIMENT

Fysikdagarna, Lund

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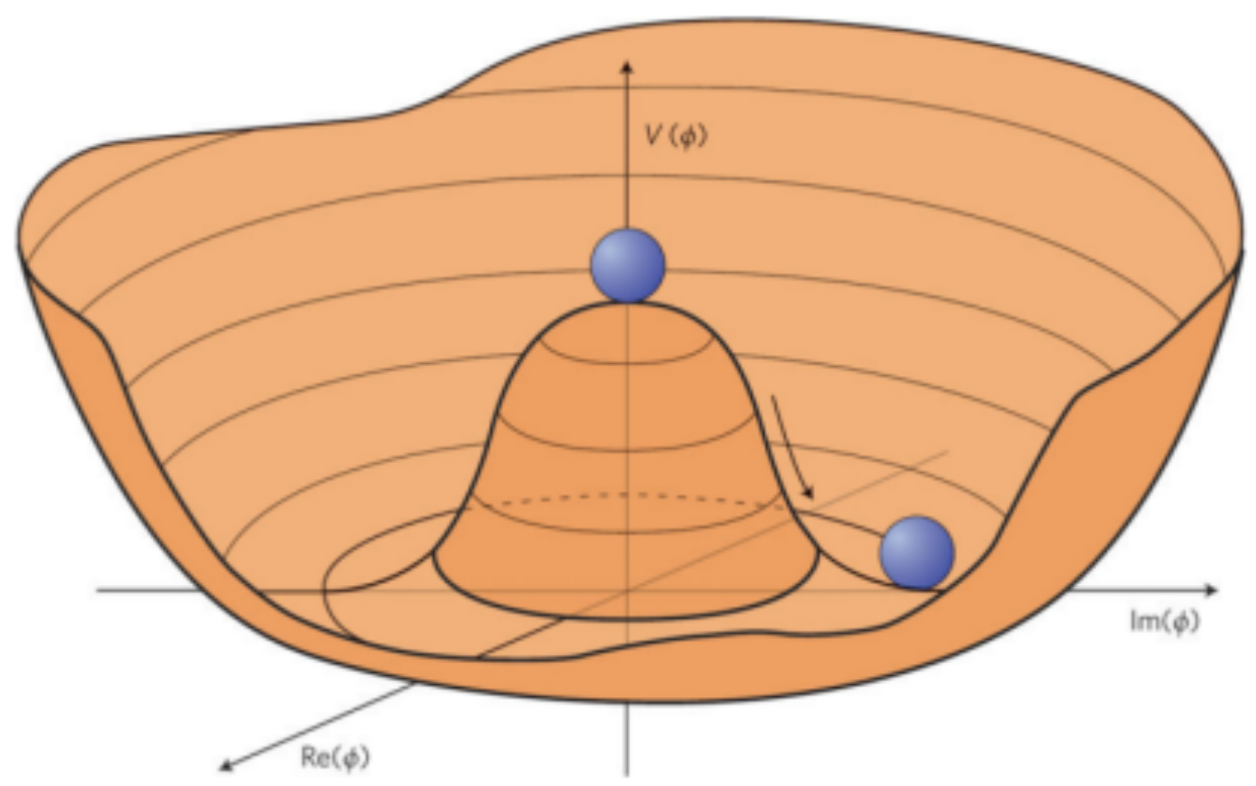
UNIVERSITÄT BONN

Why look for Higgs boson pairs?

- Great progress in our understanding of the Higgs boson since its discovery in 2012

- But still very little knowledge about the Higgs potential

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



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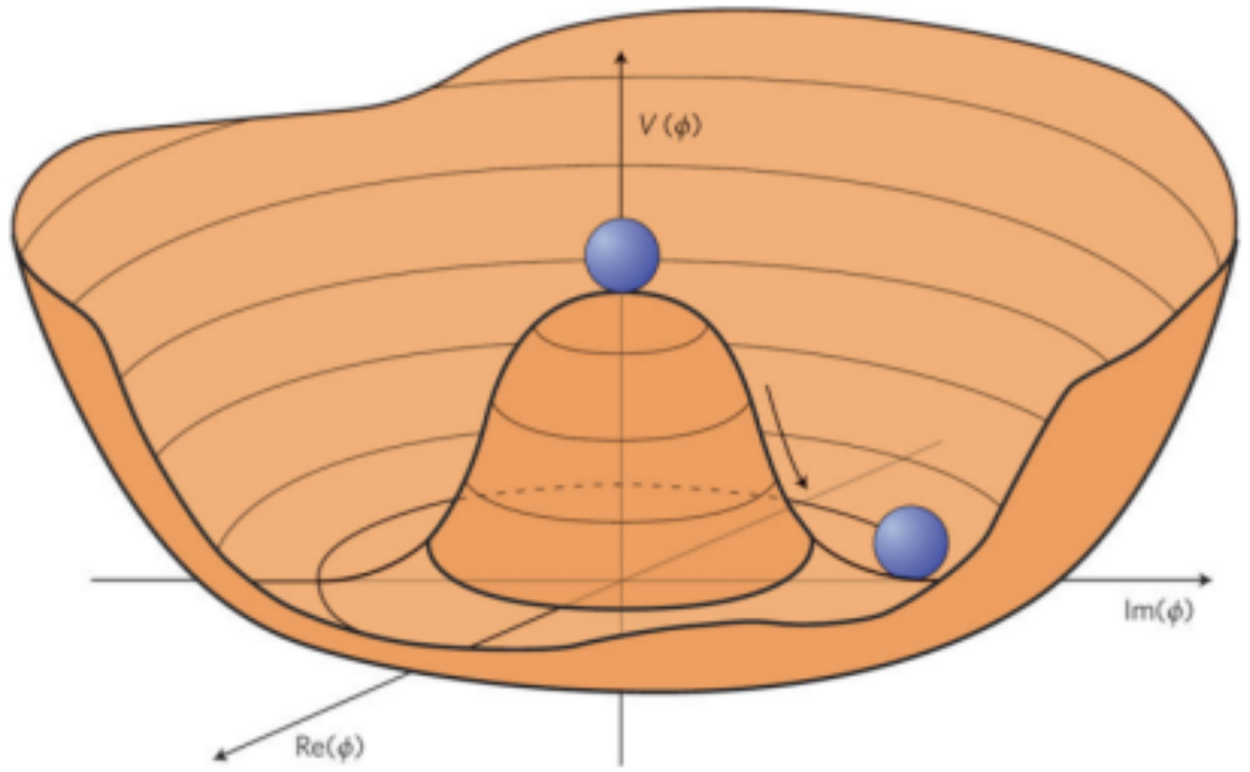
Mass term: minimum of the potential



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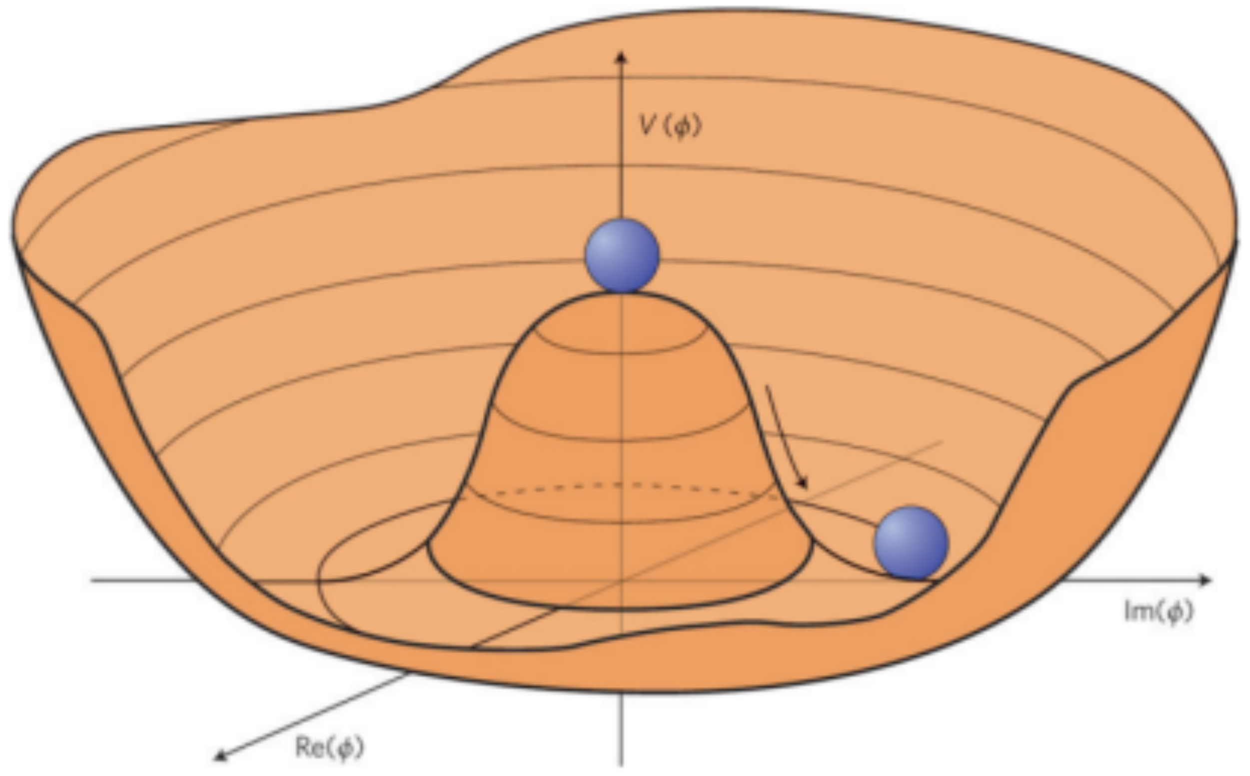
$$V(H) = \frac{1}{2} m_H H^2 + \boxed{\lambda v H^3} + \frac{1}{4}\lambda H^4 + \dots$$

Directly measure λ_{HHH} via HH production

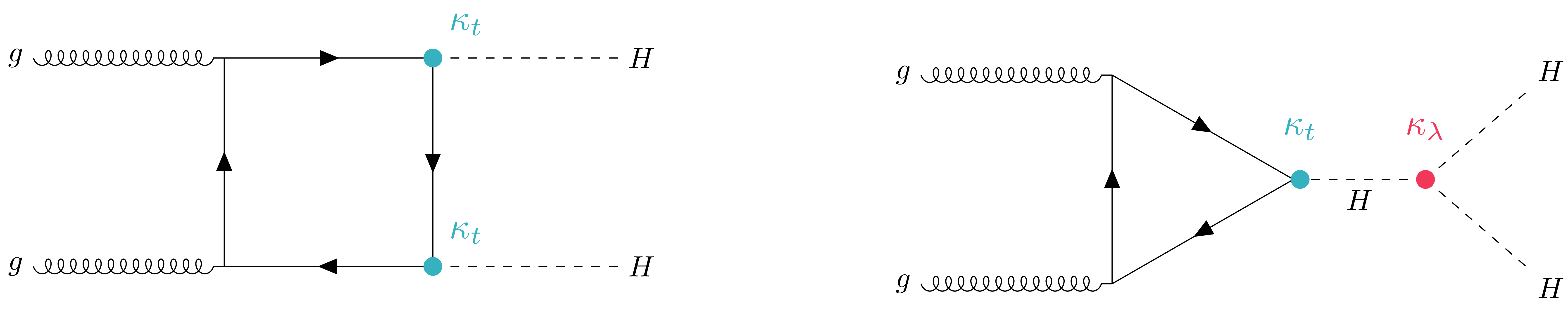


- SM HH rate very small, but many models predict increases to the cross-section

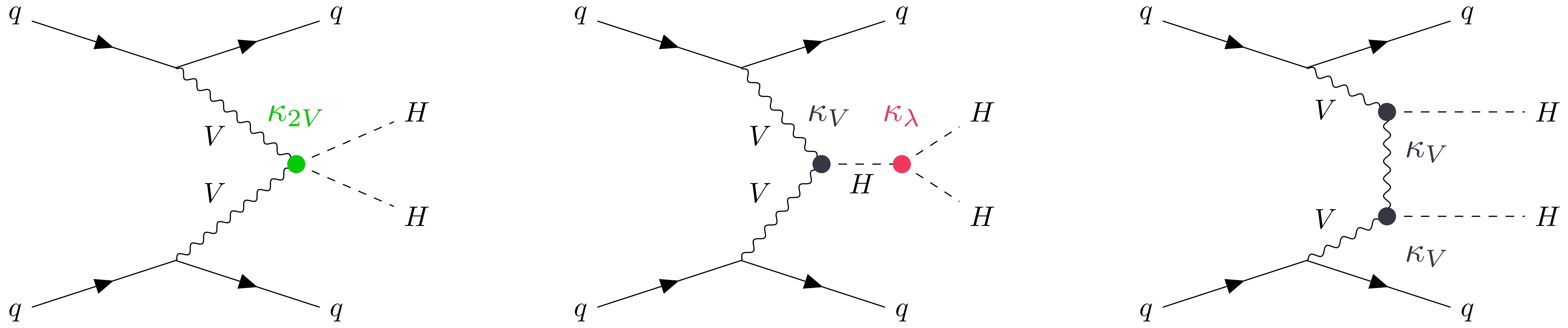
- Probe some of the Higgs EFT operators

HH production at the LHC

Gluon-gluon fusion $\sigma_{\mathrm{ggF}}(\mathrm{pp} \to \mathrm{HH}) = 31.05\ \mathrm{fb}$



Vector-boson fusion $\sigma_{\mathrm{VBF}}(\mathrm{pp} \to \mathrm{HH}) = 1.73\ \mathrm{fb}$

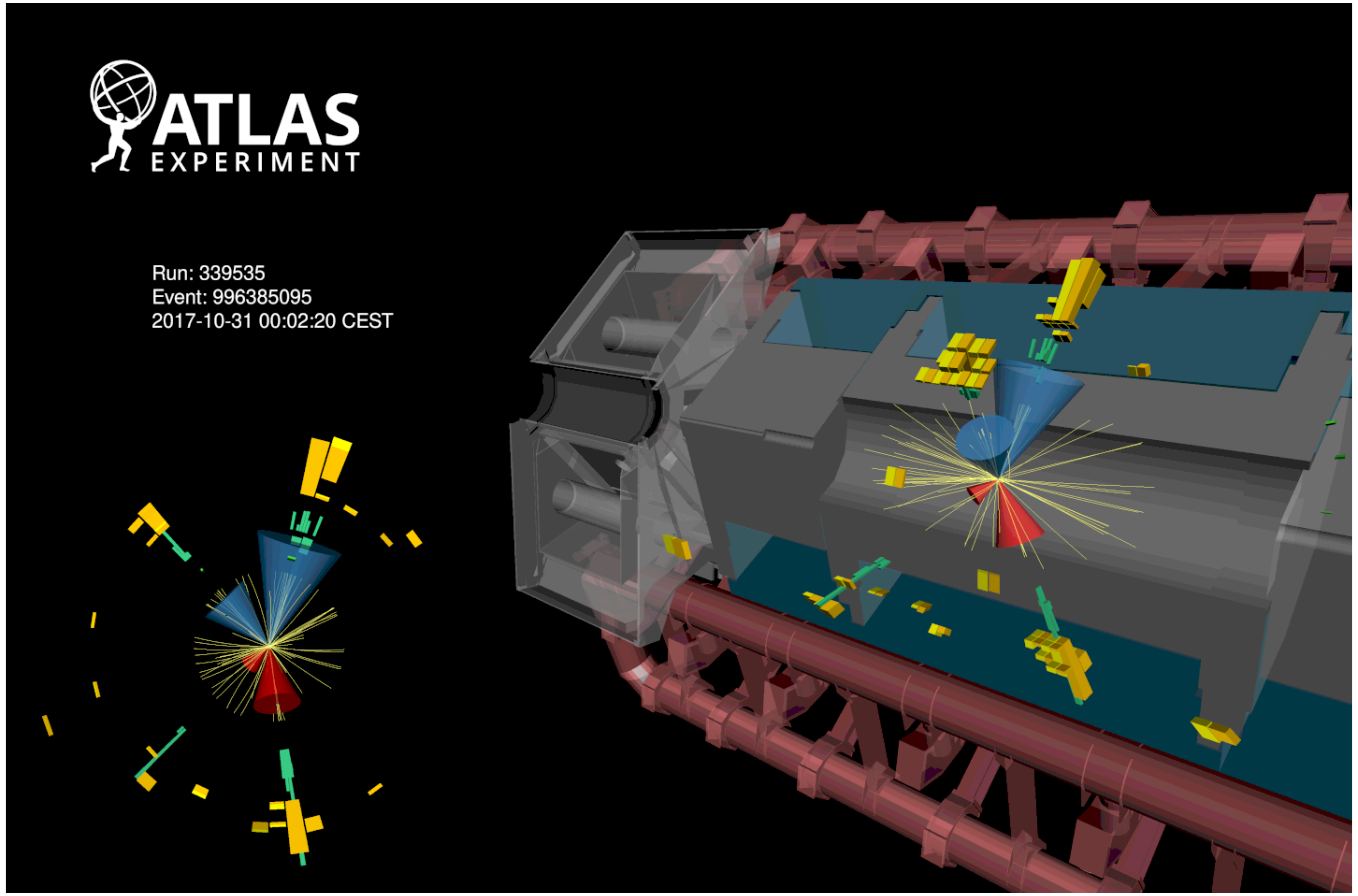


HH decay modes

	bb	WW	ττ	ZZ	γγ
bb	34%				
WW	25%	4.6%			
ττ	7.3%	2.7%	0.39%		
ZZ	3.1%	1.1%	0.33%	0.069%	
γγ	0.26%	0.10%	0.028%	0.012%	0.0005%

HH→bbττ

- Moderate branching ratio
- Relatively clean final state

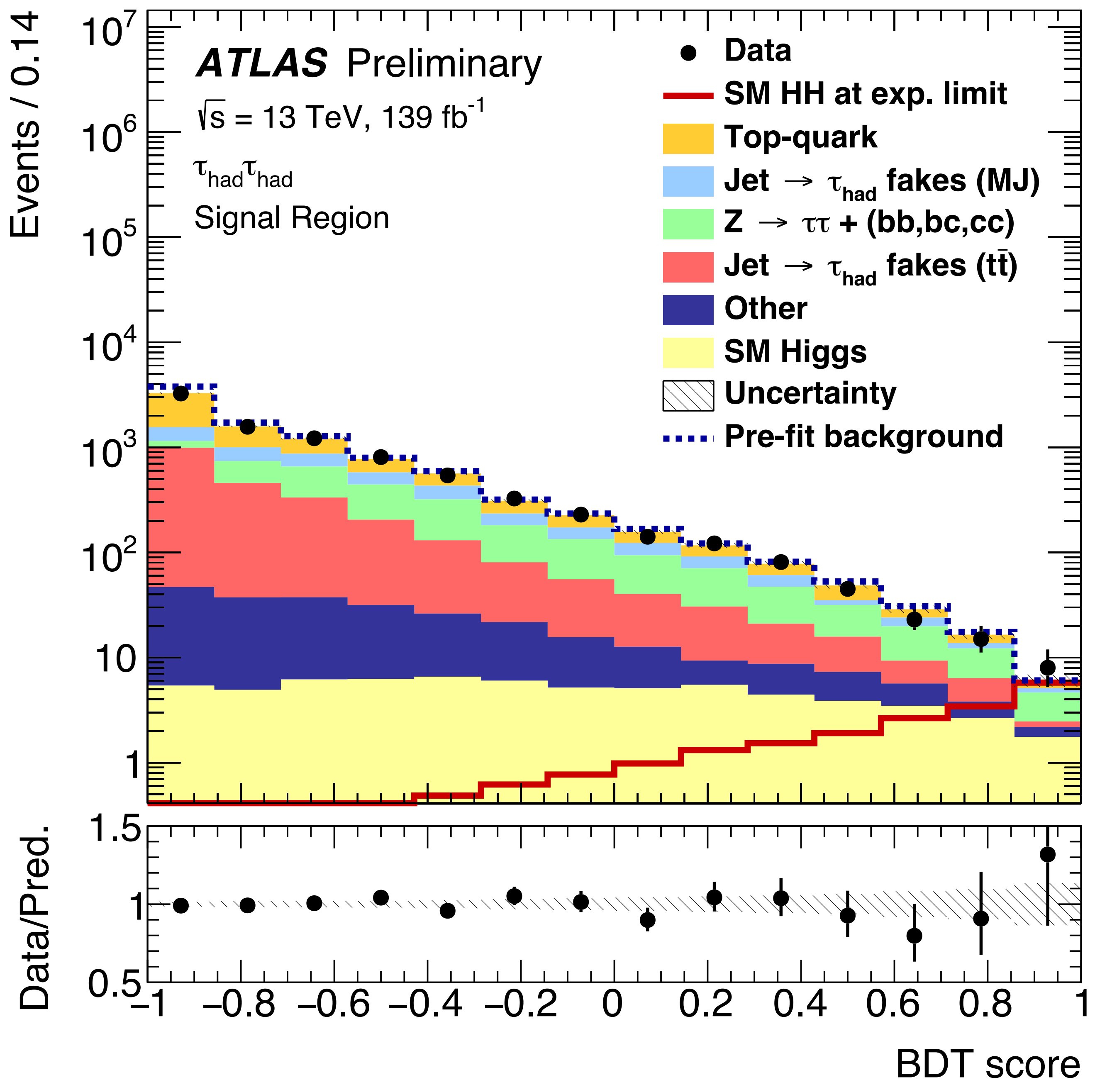


ATLAS-CONF-2021-030

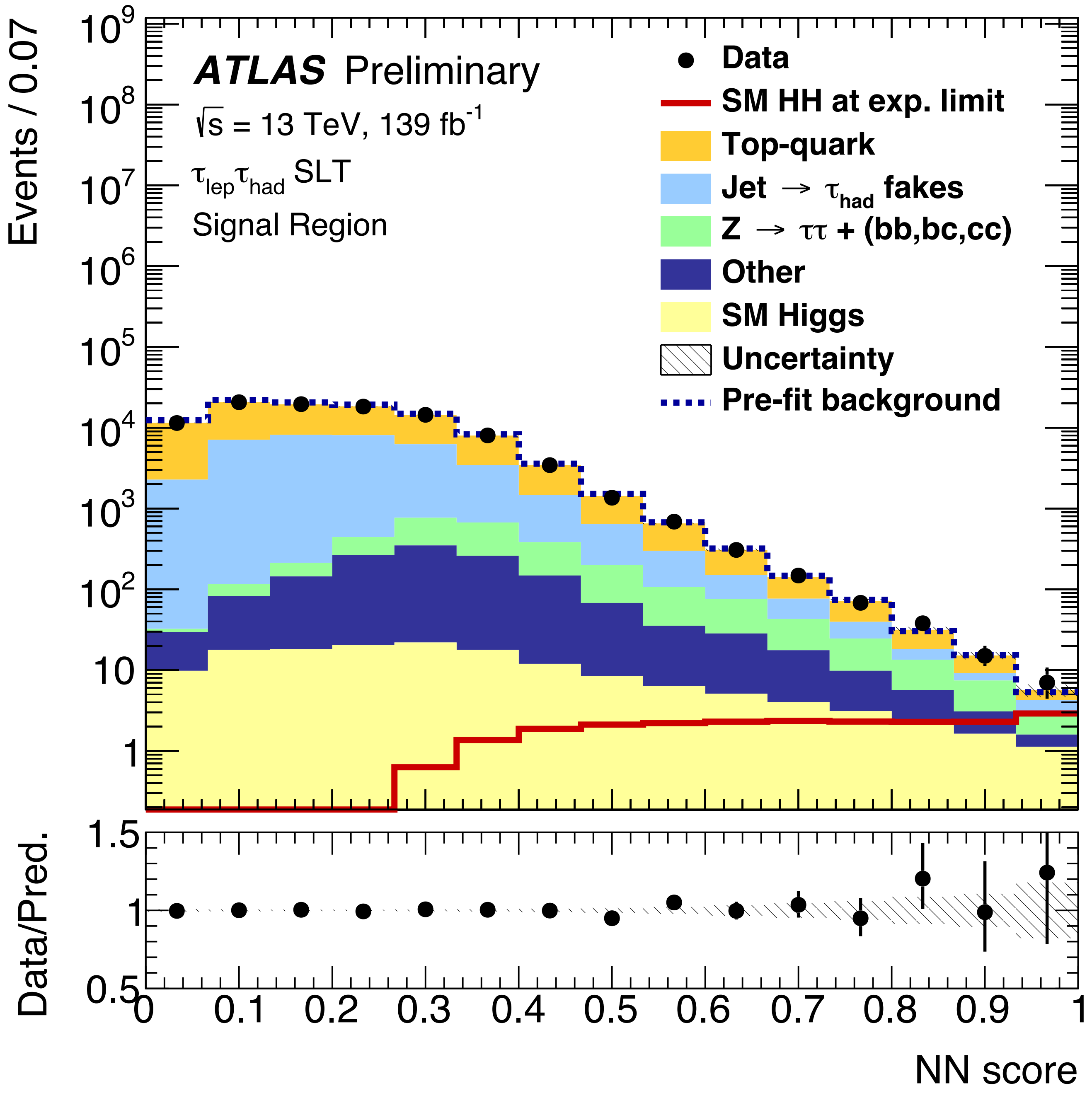
HH→bbττ analysis overview

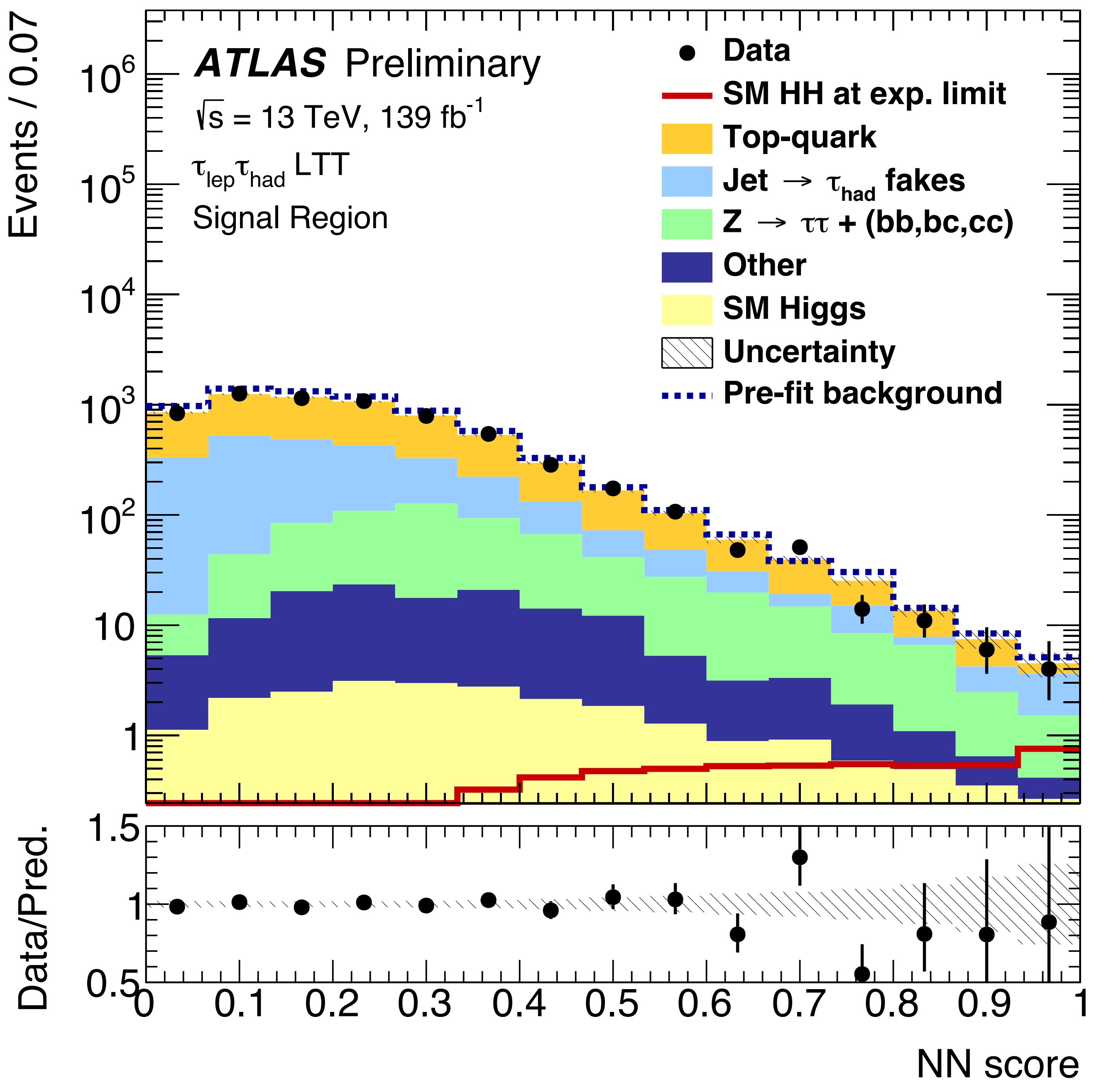
- 3 signal regions: $\tau_{had}\tau_{had}$, $\tau_{lep}\tau_{had}$ (SLT), $\tau_{lep}\tau_{had}$ (LTT)
  - $bb\tau_{had}\tau_{had}$: exactly two τ_{had} , lepton-veto
  - $bb\tau_{lep}\tau_{had}$: exactly one τ_{had} and an e or μ
- In both channels:
  - exactly two b-jets are required
  - $m_{\tau\tau}^{MMC}$ > 60 GeV
  - trigger-dependent thresholds on e, μ, τ_{had} and jets

Fully hadronic: Boosted Decision Tree



Semi-leptonic: Neural Networks





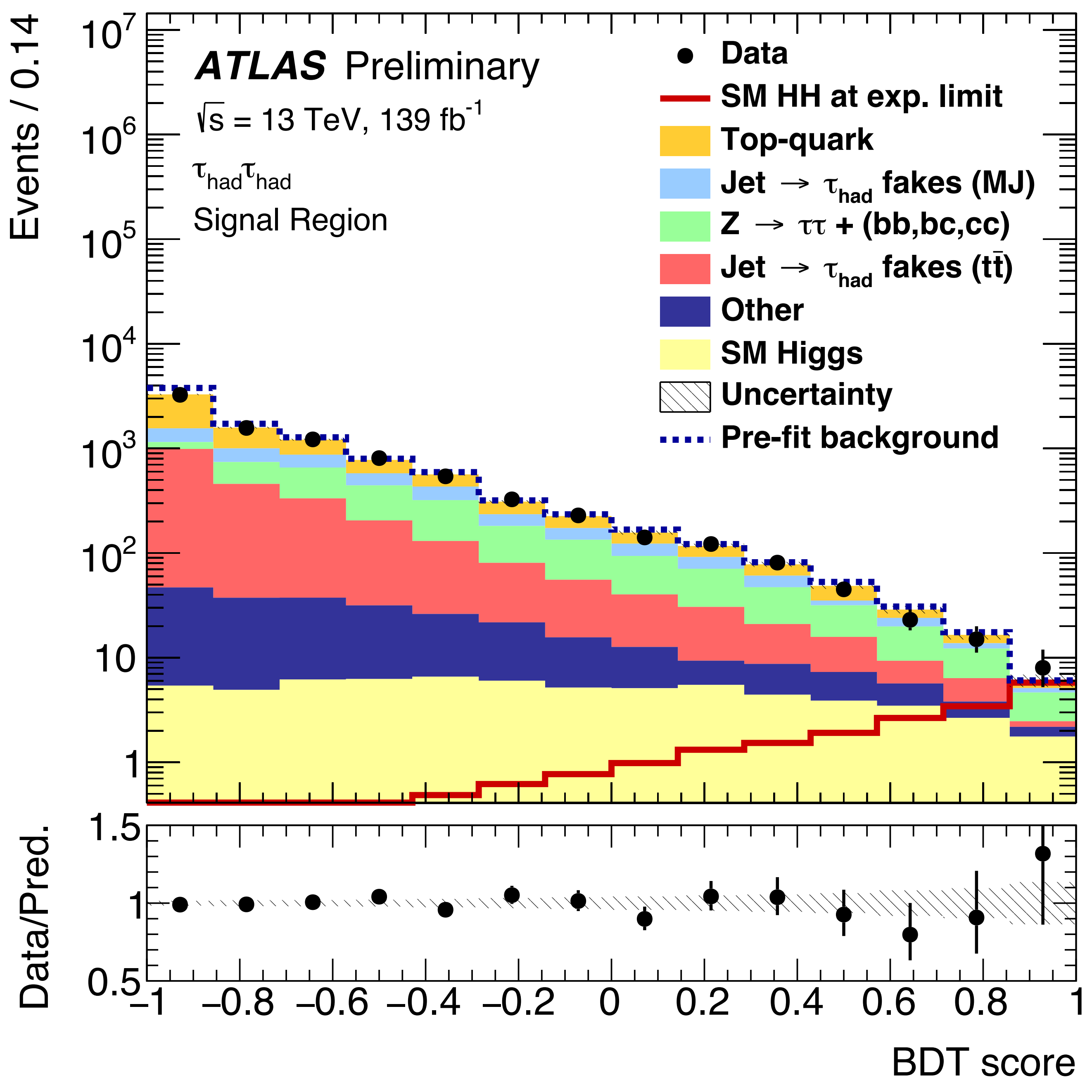
HH→bbττ analysis overview

- MVAs trained on SM signal vs. all backgrounds using high-level variables like:

  $m_{\mathrm{HH}}, m_{bb}, m_{\tau\tau}^{\mathrm{MMC}}, \Delta R(b,b), \Delta R(\tau,\tau)$, etc.

- Binned profile likelihood fit on the MVA classifiers in all three SRs together with the m_{ll} in $Z + \mathrm{HF}$ CR

Fully hadronic: Boosted Decision Tree



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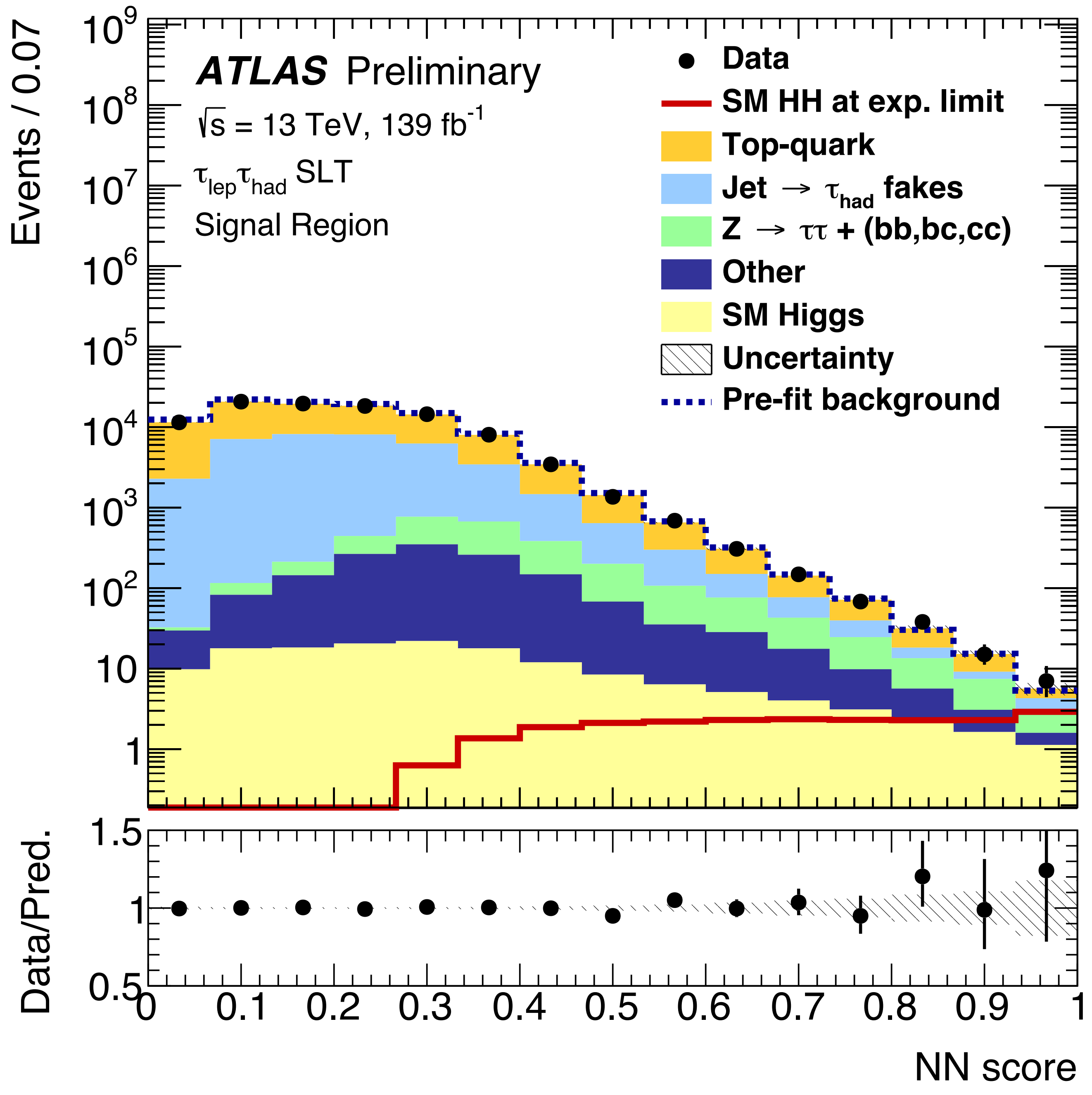

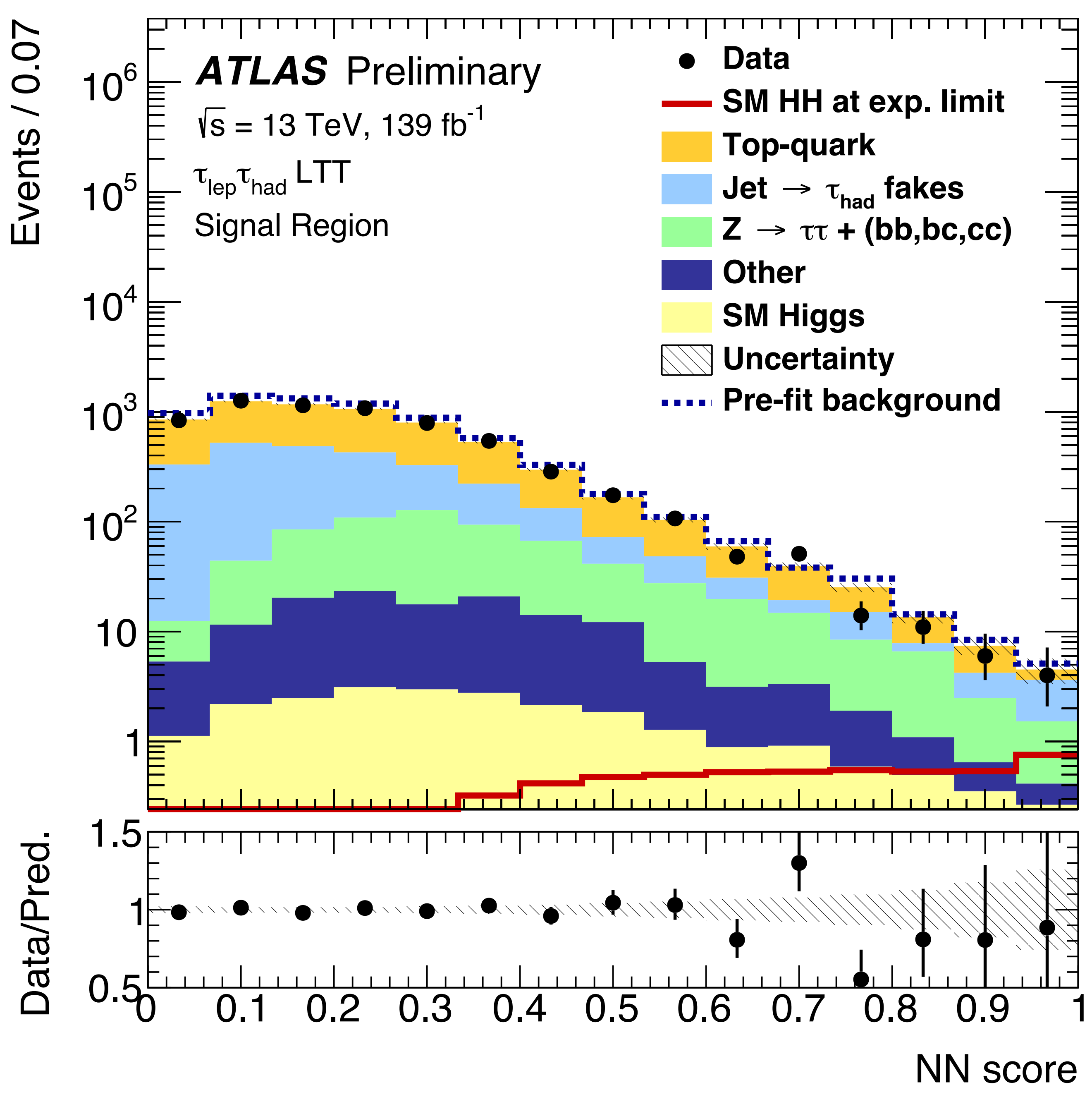

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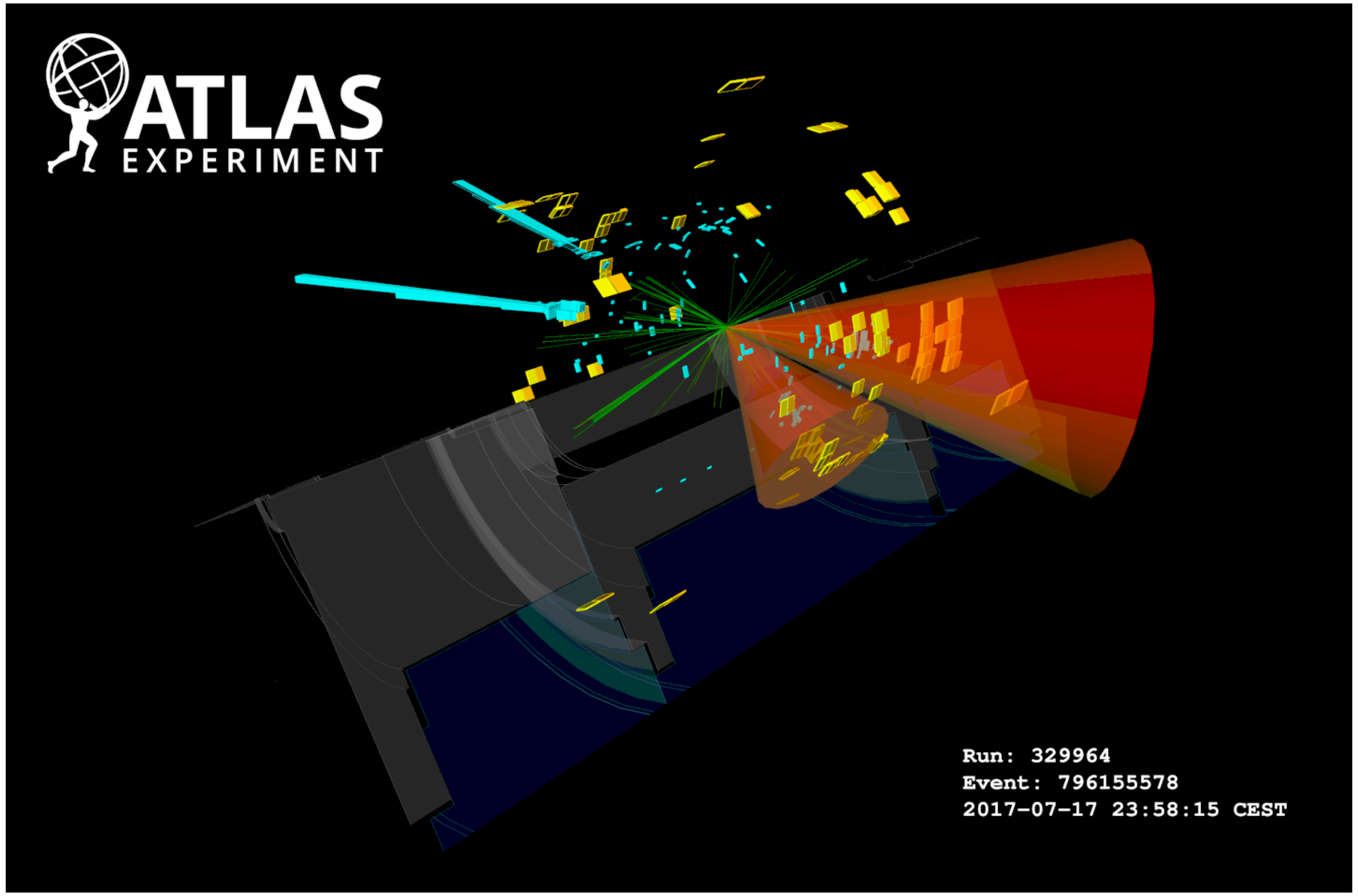


HDBS-2018-34

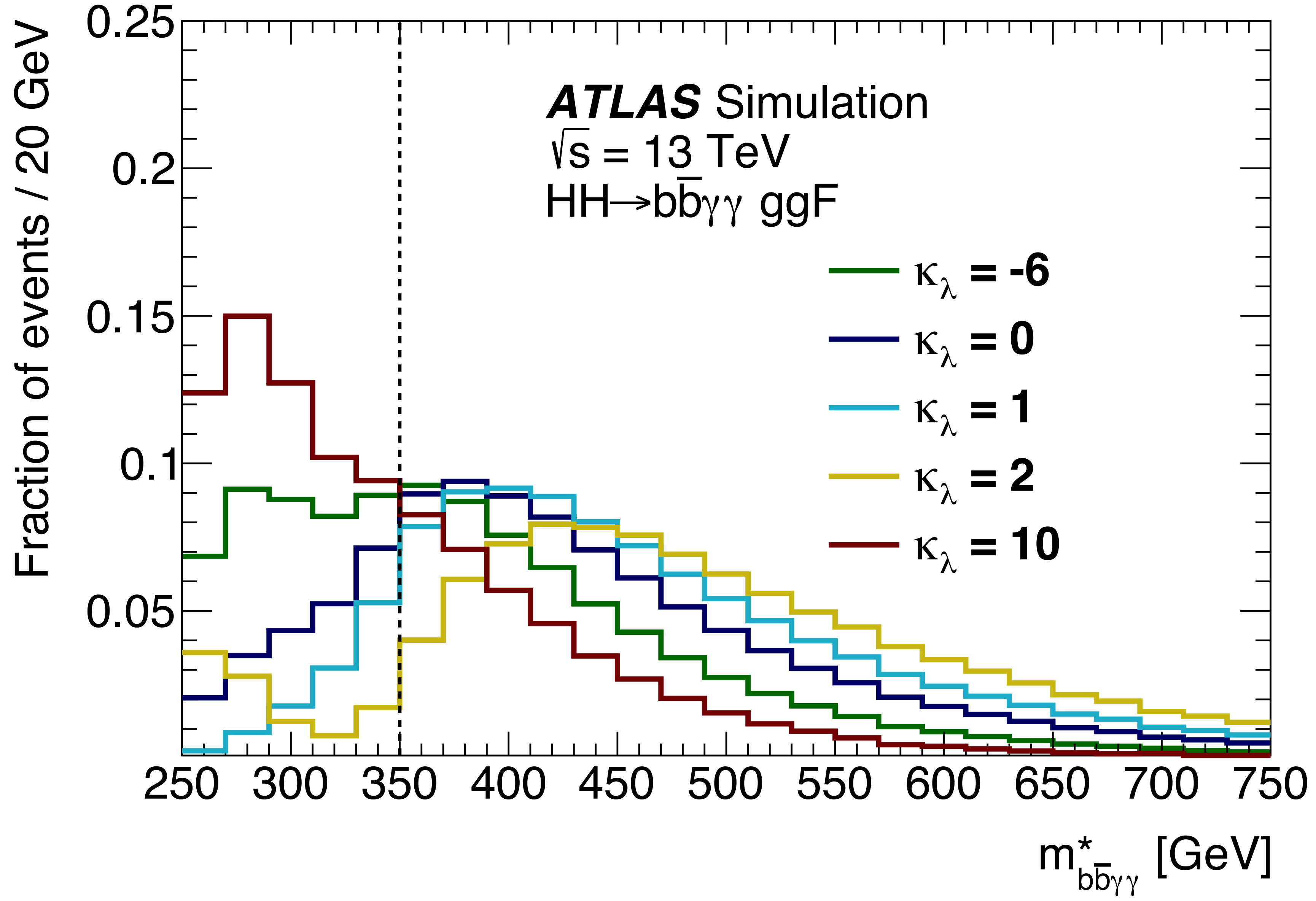
HH→bbγγ

- Tiny branching fraction
- Very clean final state
- Excellent di-photon mass resolution

HH→bbγγ analysis overview

HDBS-2018-34

- Event selection:
  - at least 2 photons
  - exactly 2 *b*-tagged jets
- Split events into low- and high-m_{HH} regions to target different signal hypotheses
- Separate BDTs trained in low- and high-mass regions
- *Loose* and *Tight* signal regions for each mass region → 4 SRs in total
- Simultaneous unbinned maximum likelihood fit to the $m_{\gamma\gamma}$ distributions in each SR



HH→bbγγ analysis overview

HDBS-2018-34

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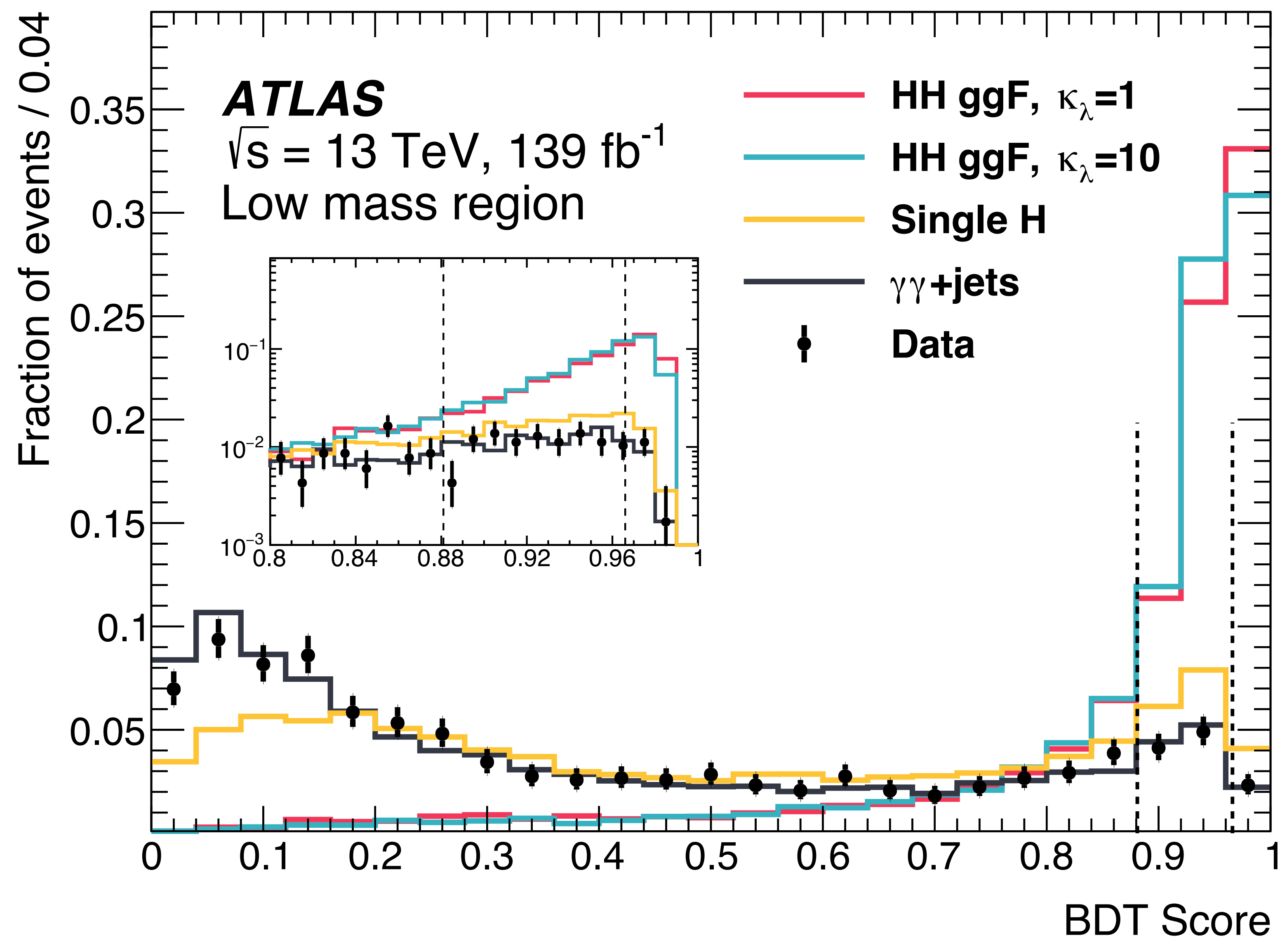
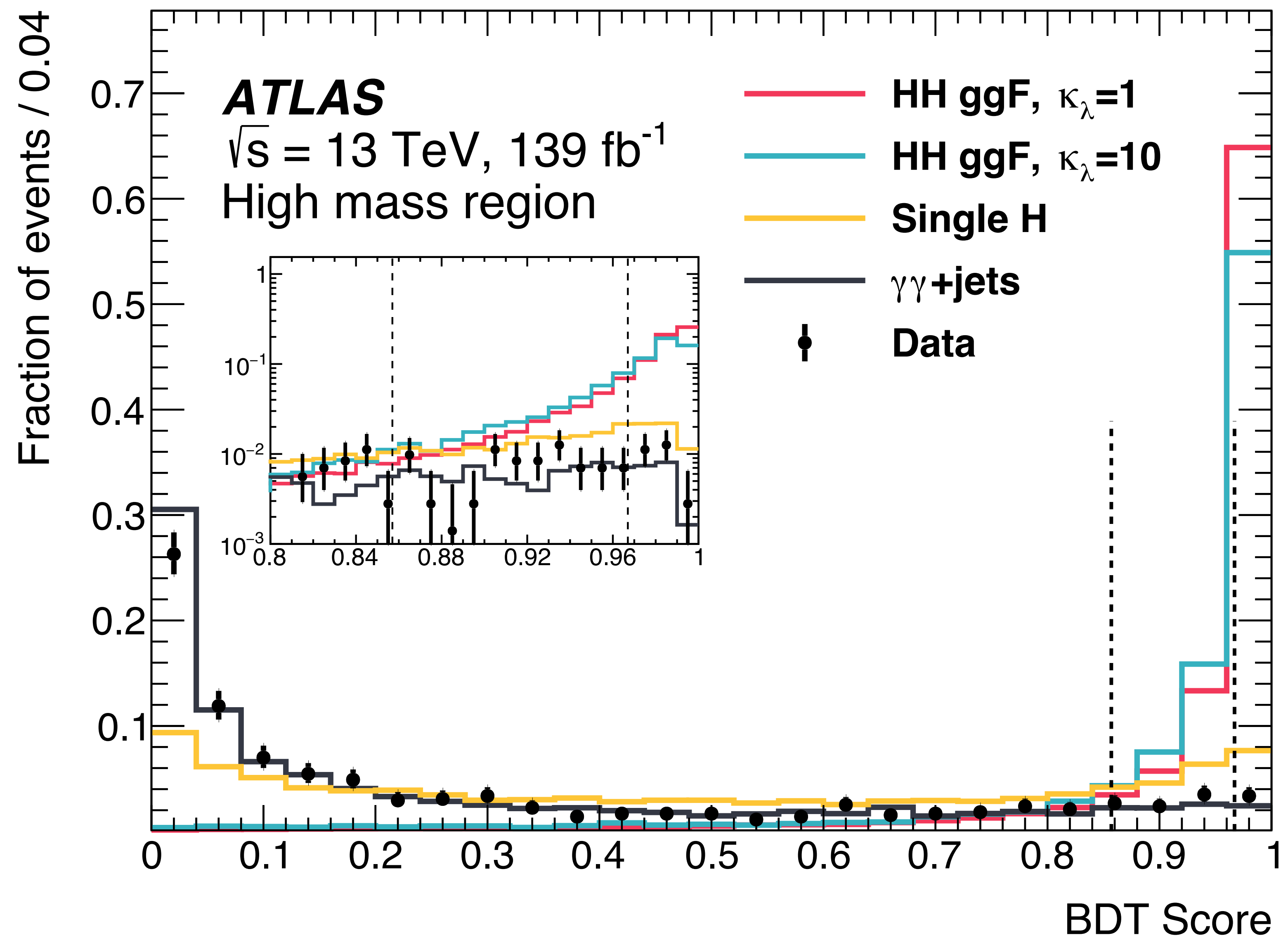
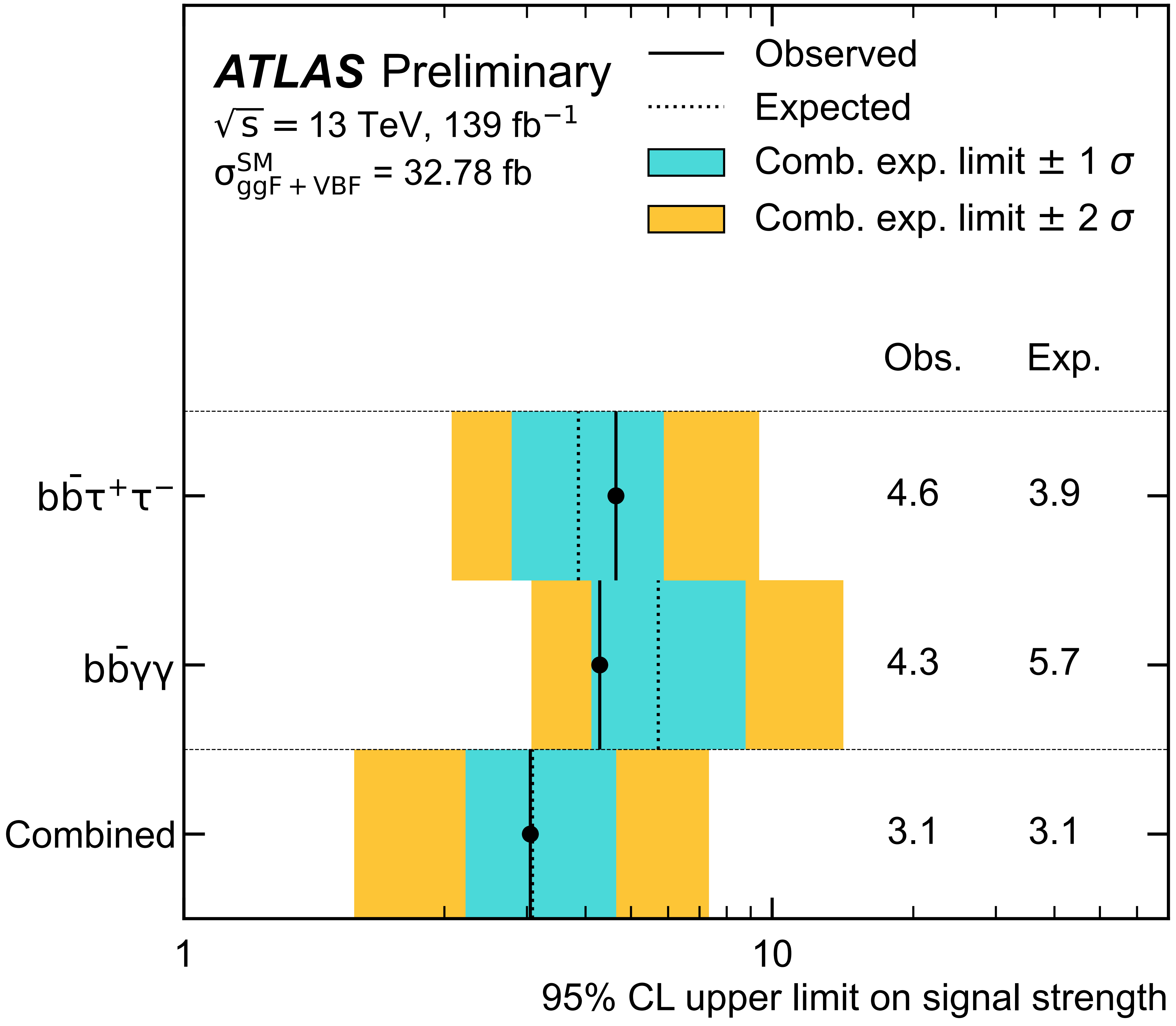
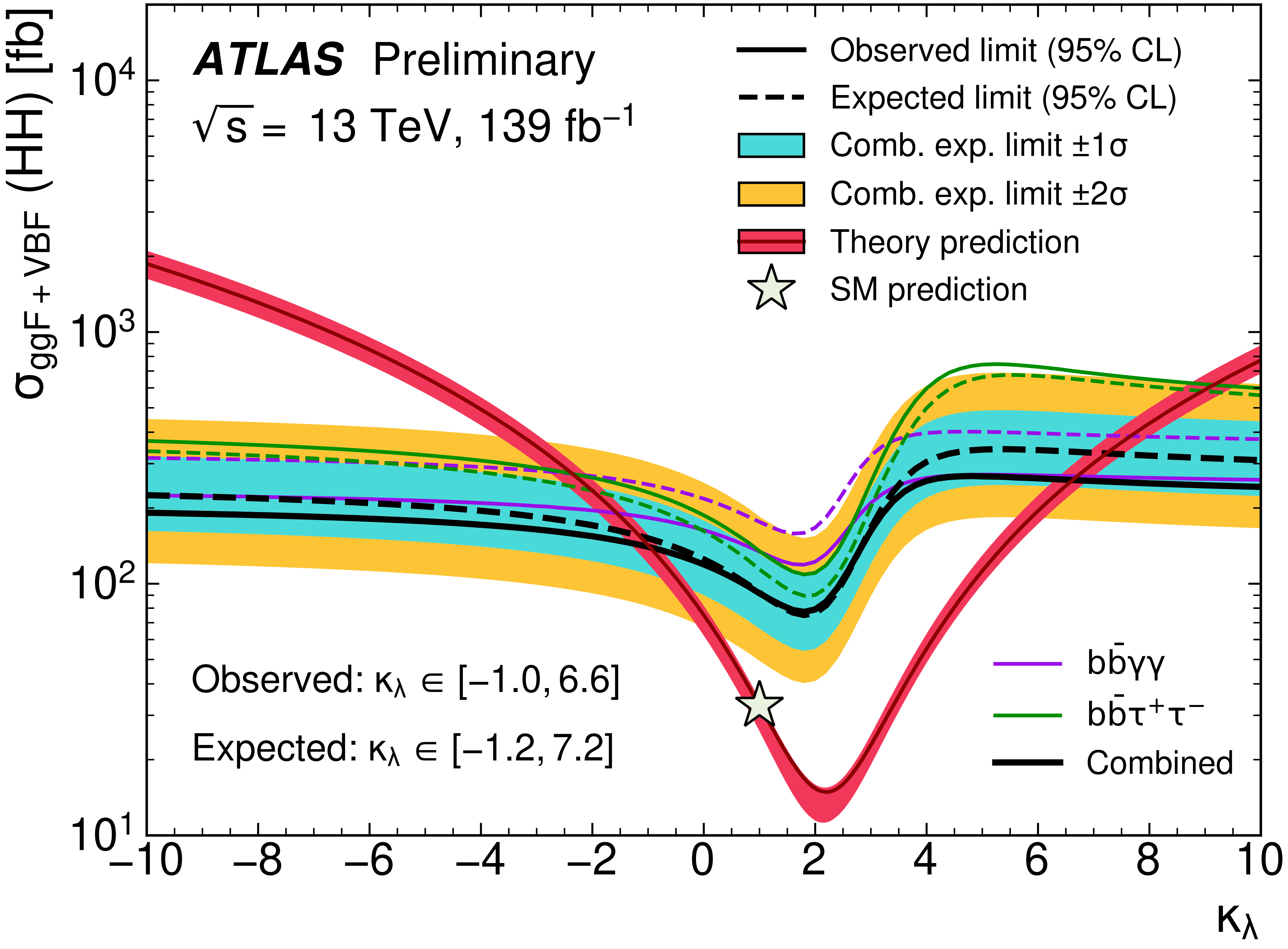




HH→bbττ + bbγγ results (139 fb^{-1})



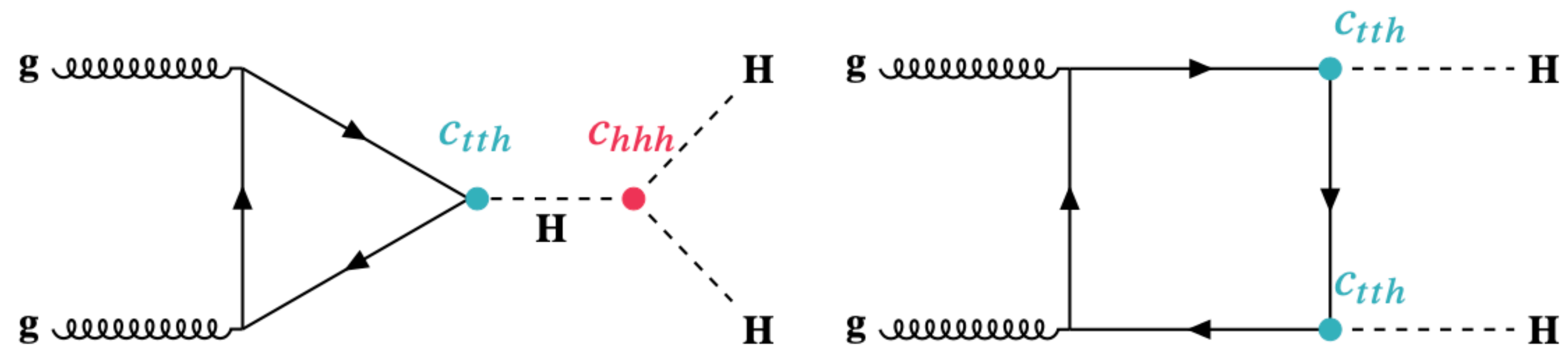


ATLAS-CONF-2021-052

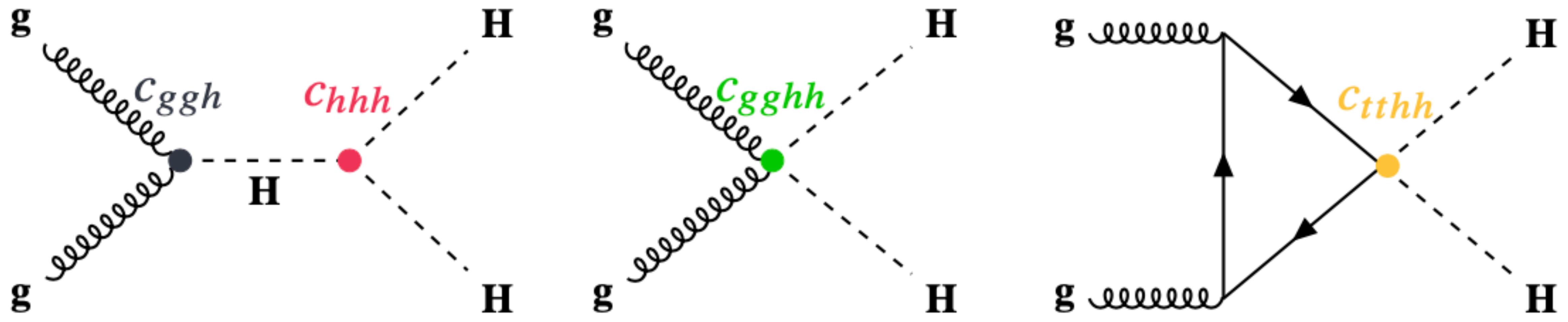
Higgs Effective Field Theory (HEFT)

- Treating Higgs field as EW singlet
- Five independent effective coupling coefficients

$$\mathscr{L}_{\mathrm{HEFT}} \supset -m_t\left(c_{tth}\frac{h}{v}+c_{tthh}\frac{h^2}{v^2}\right)\bar{t}t - c_{hhh}\frac{m_h^2}{2v}h^3+\frac{\alpha_s}{8\pi}\left(c_{ggh}\frac{h}{v}+c_{gghh}\frac{h^2}{v^2}\right)G^a_{\mu\nu}G^{a,\mu\nu}$$



SM



BSM

- Variations of the EFT coefficients change their relative contributions and modify m_{HH} spectrum

HEFT shape benchmarks

- Seven benchmarks with representative m_{HH} shape features
- Cluster analysis to group the shapes of m_{HH} predicted by HEFT

JHEP03(2020)091

Benchmark	c_{hhh}	c_{tth}	c_{tthh}	c_{ggh}	c_{gghh}
SM	1	1	0	0	0
1	3.94	0.94	−1/3	0.5	1/3
2	6.84	0.61	1/3	0.0	−1/3
3	2.21	1.05	−1/3	0.5	0.5
4	2.79	0.61	1/3	−0.5	1/6
5	3.95	1.17	−1/3	1/6	−0.5
6	5.68	0.83	1/3	−0.5	1/3
7	−0.10	0.94	1	1/6	−1/6

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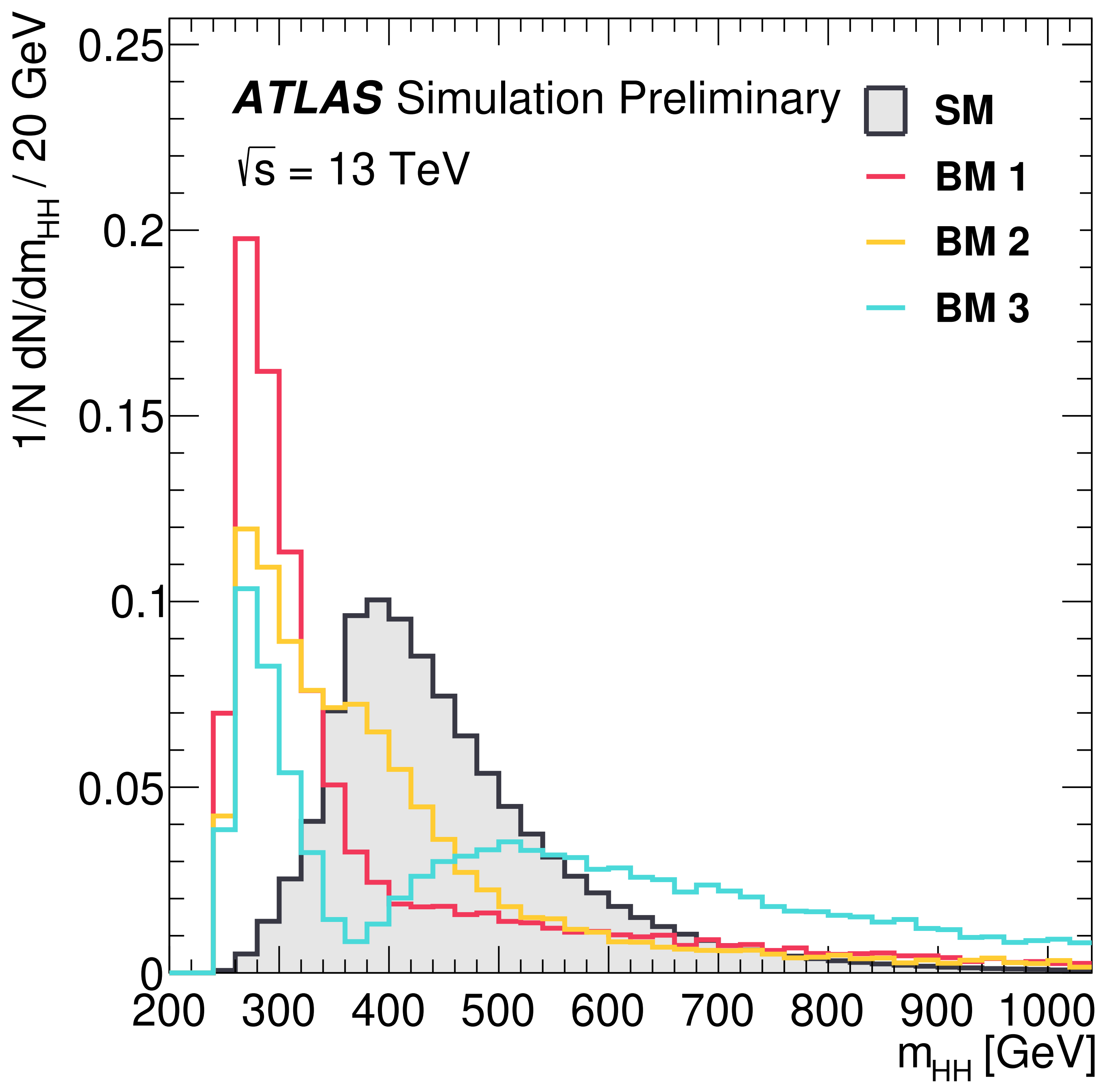

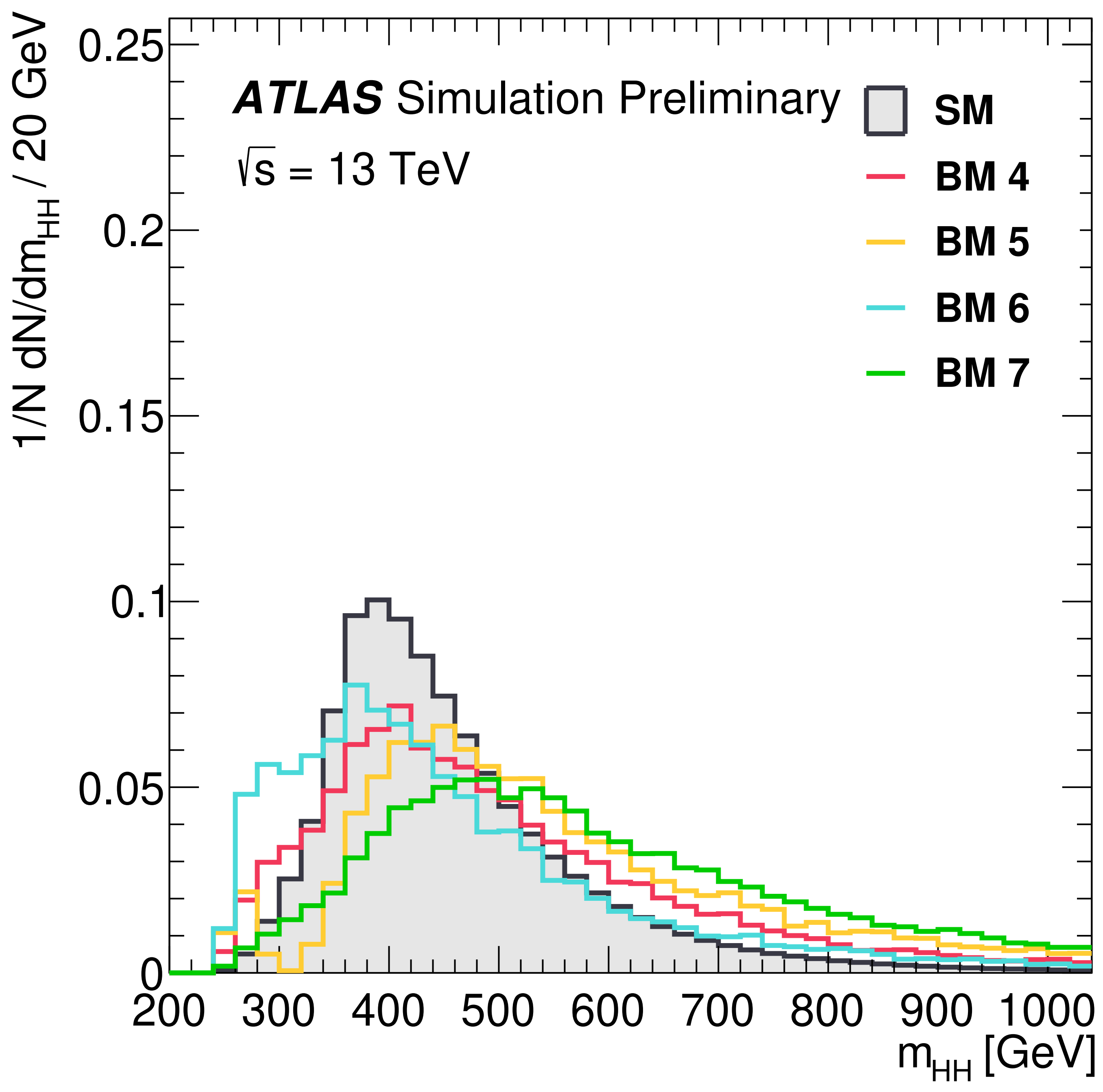

HEFT reweighting

- Generating Monte Carlo (MC) samples is computationally expensive
- Scans in HEFT space with dedicated MC samples not practical
- Reweight SM sample by differential A_i coefficients

$$
\begin{aligned}
\sigma^{\rm NLO}/\sigma^{\rm NLO}_{SM} = & \; A_1\, c_t^4 + A_2\, c_{tt}^2 + A_3\, c_t^2 c_{hhh}^2 + A_4\, c_{ggh}^2 c_{hhh}^2 + A_5\, c_{gghh}^2 + A_6\, c_{tt} c_t^2 + A_7\, c_t^3 c_{hhh} \\
& + A_8\, c_{tt} c_t\, c_{hhh} + A_9\, c_{tt} c_{ggh} c_{hhh} + A_{10}\, c_{tt} c_{gghh} + A_{11}\, c_t^2 c_{ggh} c_{hhh} + A_{12}\, c_t^2 c_{gghh} \\
& + A_{13}\, c_t c_{hhh}^2 c_{ggh} + A_{14}\, c_t c_{hhh} c_{gghh} + A_{15}\, c_{ggh} c_{hhh} c_{gghh} \\
& + A_{16}\, c_t^3 c_{ggh} + A_{17}\, c_t c_{tt} c_{ggh} + A_{18}\, c_t c_{ggh}^2 c_{hhh} + A_{19}\, c_t c_{ggh} c_{gghh} \\
& + A_{20}\, c_t^2 c_{ggh}^2 + A_{21}\, c_{tt} c_{ggh}^2 + A_{22}\, c_{ggh}^3 c_{hhh} + A_{23}\, c_{ggh}^2 c_{gghh}\,.
\end{aligned}
$$

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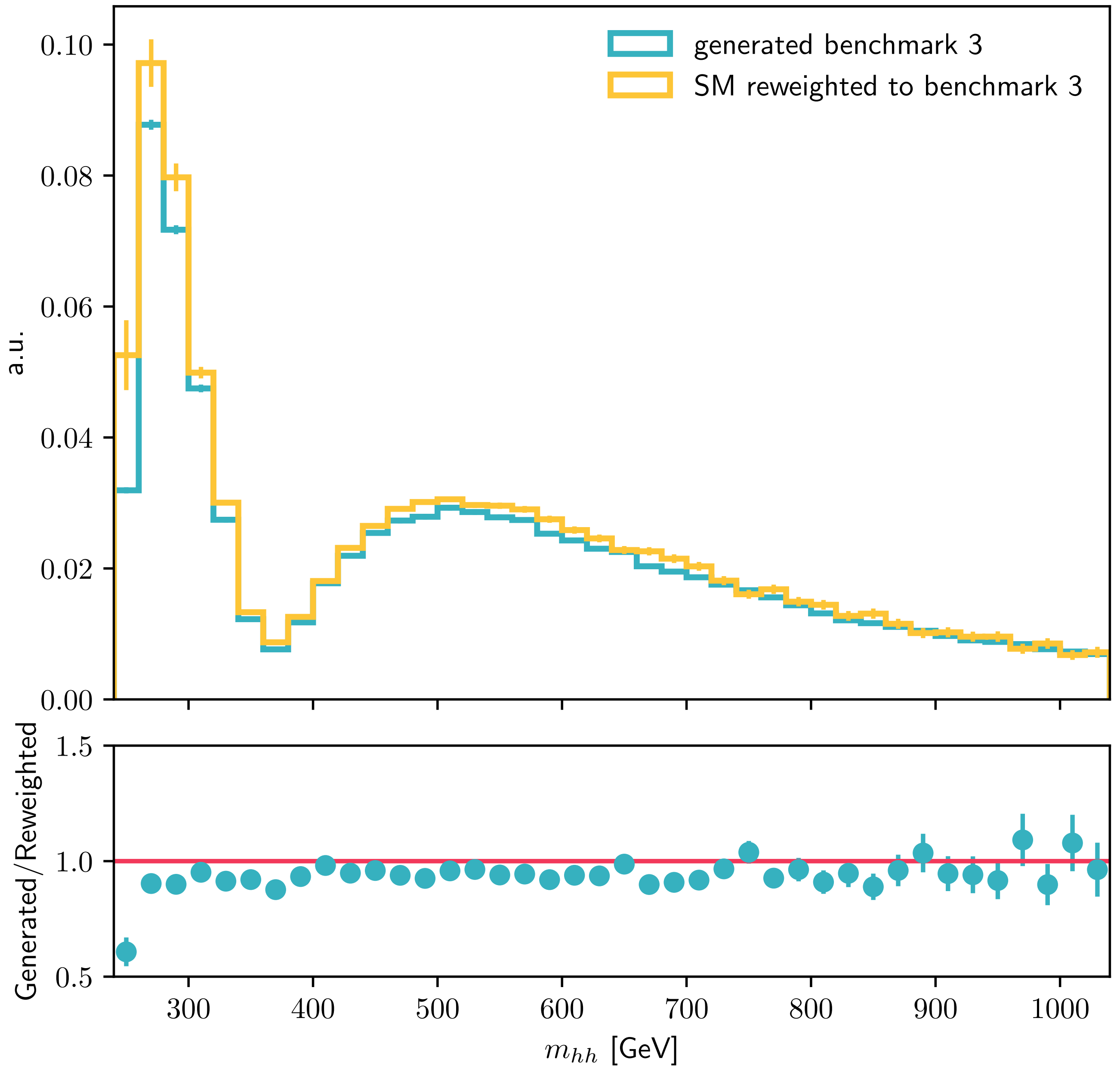
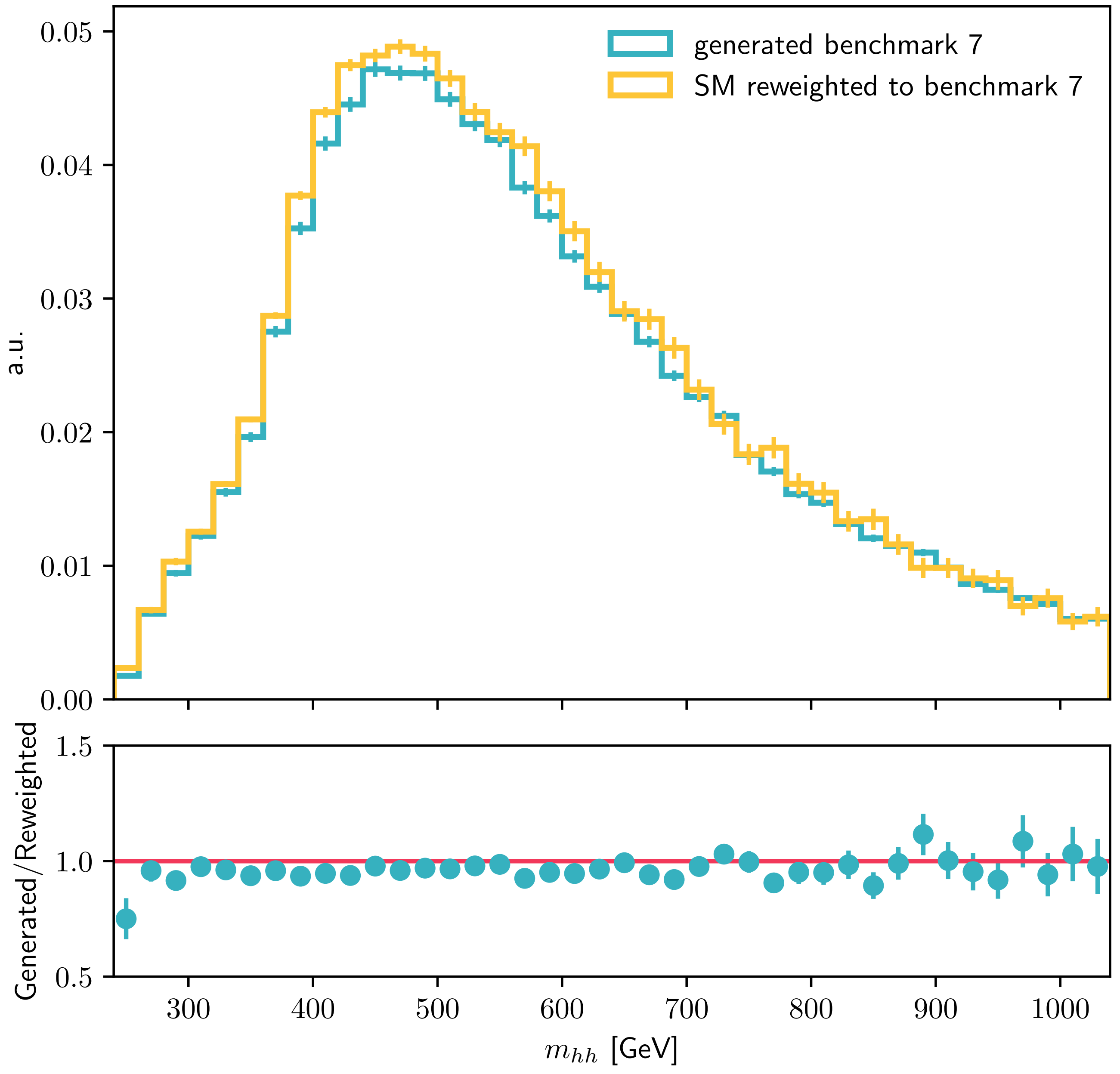




Work in progress

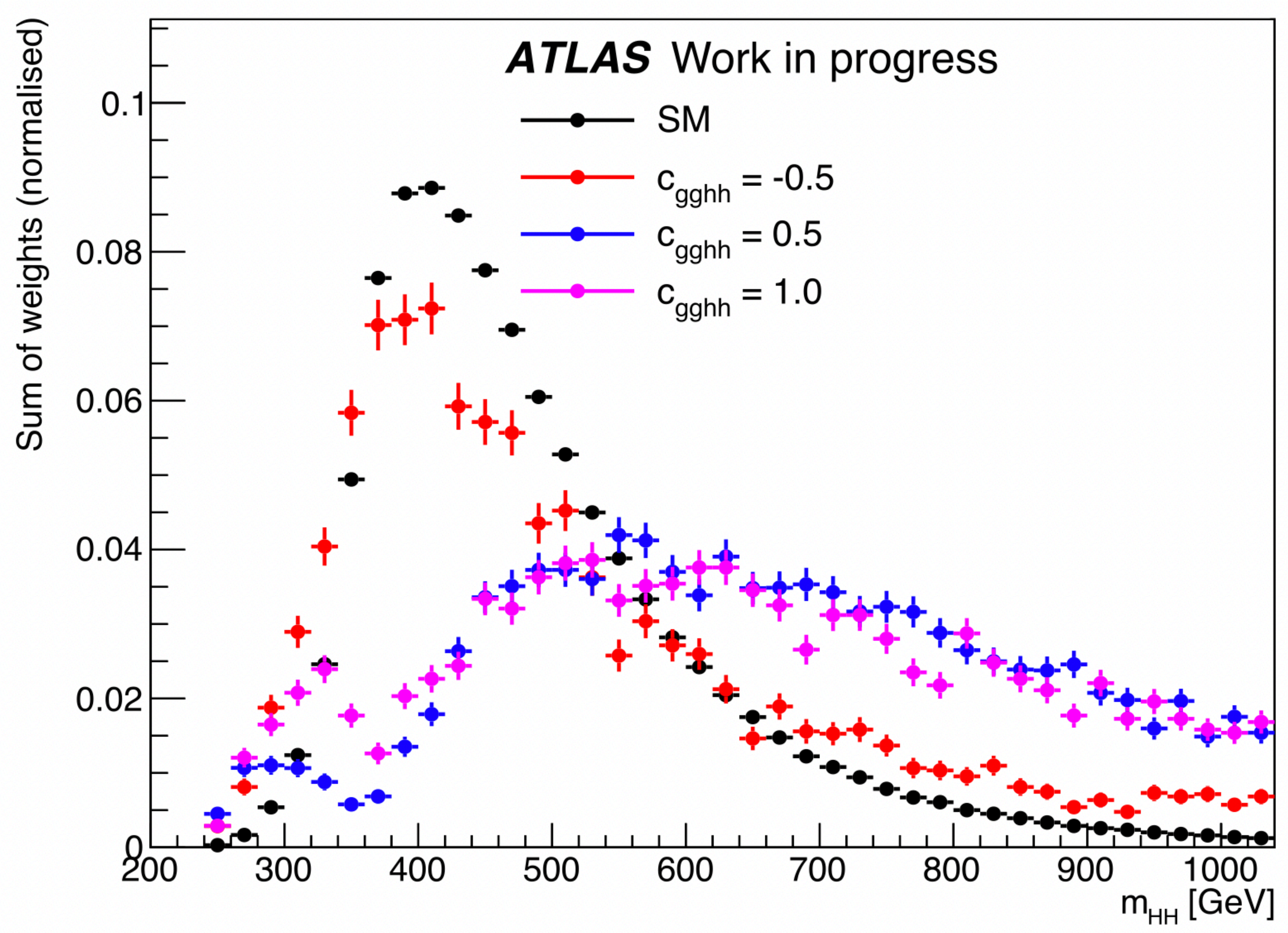
Reweighting validation plots

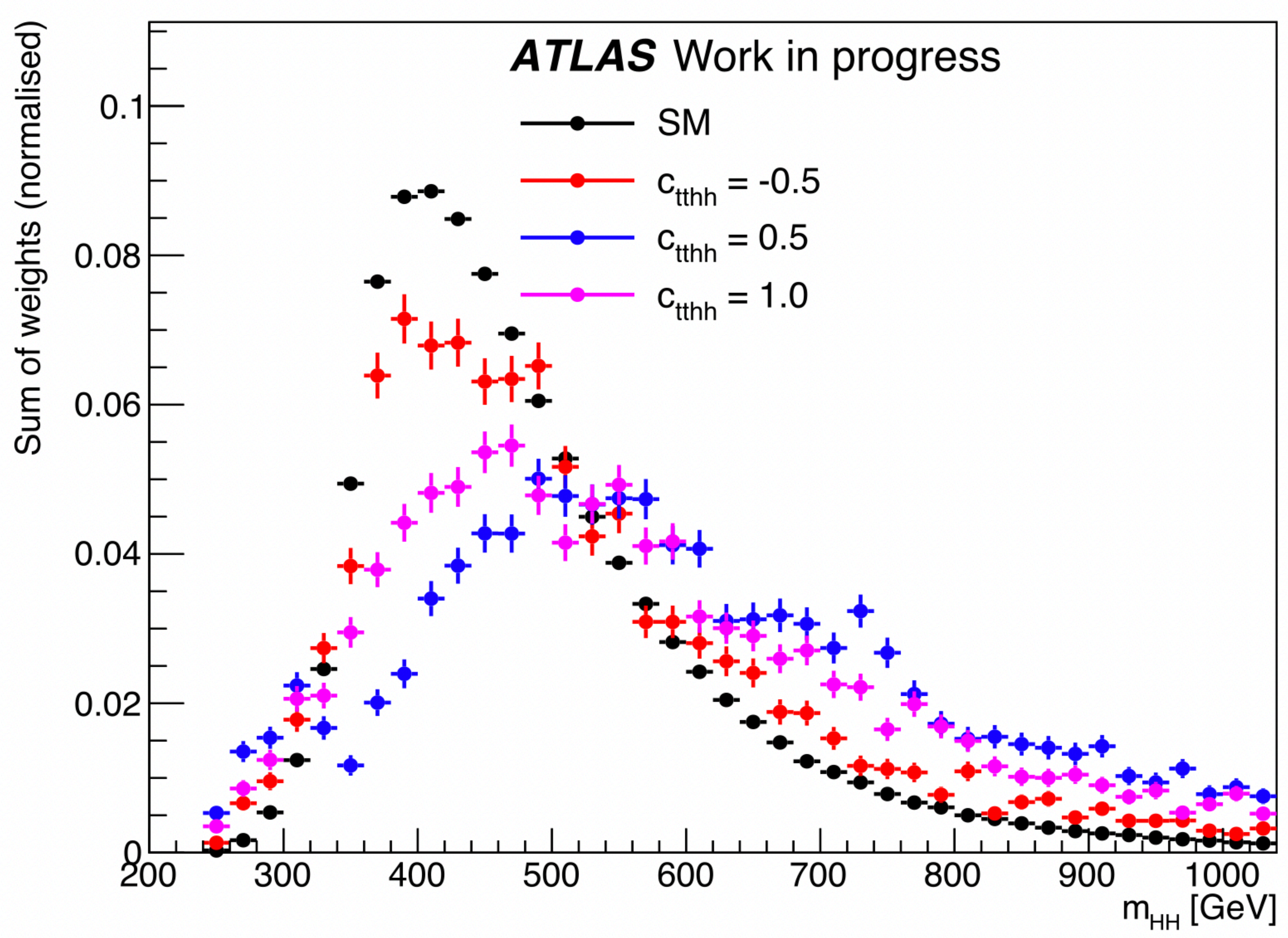
LHCHWG EFT Public Note ⏳

HEFT parameter scans

- In addition to benchmarks, weights also allow for scans of individual Wilson coefficients
- Focus on c_{gghh} and c_{tthh}: HH process gives unique access to these 4-point interactions

Plots include $bb\tau_{\text{had}}\tau_{\text{had}}$ SR selection





HEFT interpretations: results (combined)

L. Pereira Sanchez (SU), S. Ördek (UU), C. Dimitriadi

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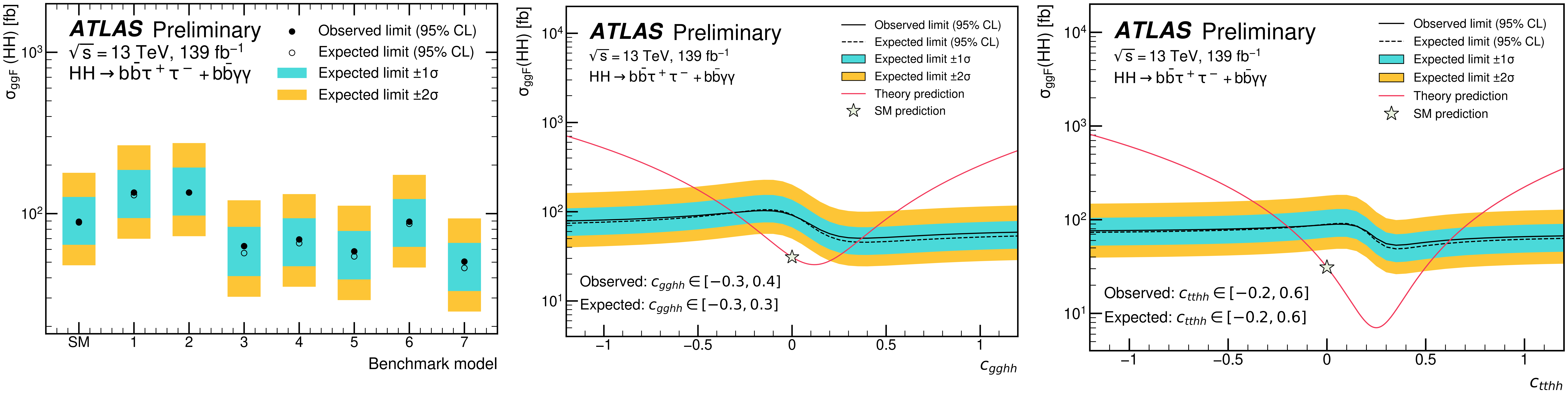


- Less sensitive to low-m_{HH} BMs 1 and 2
- Highest sensitivity to BM 7 due to increased m_{HH}
- Lower individual limits for positive c_{gghh}/c_{tthh} due to increased m_{HH}

Summary

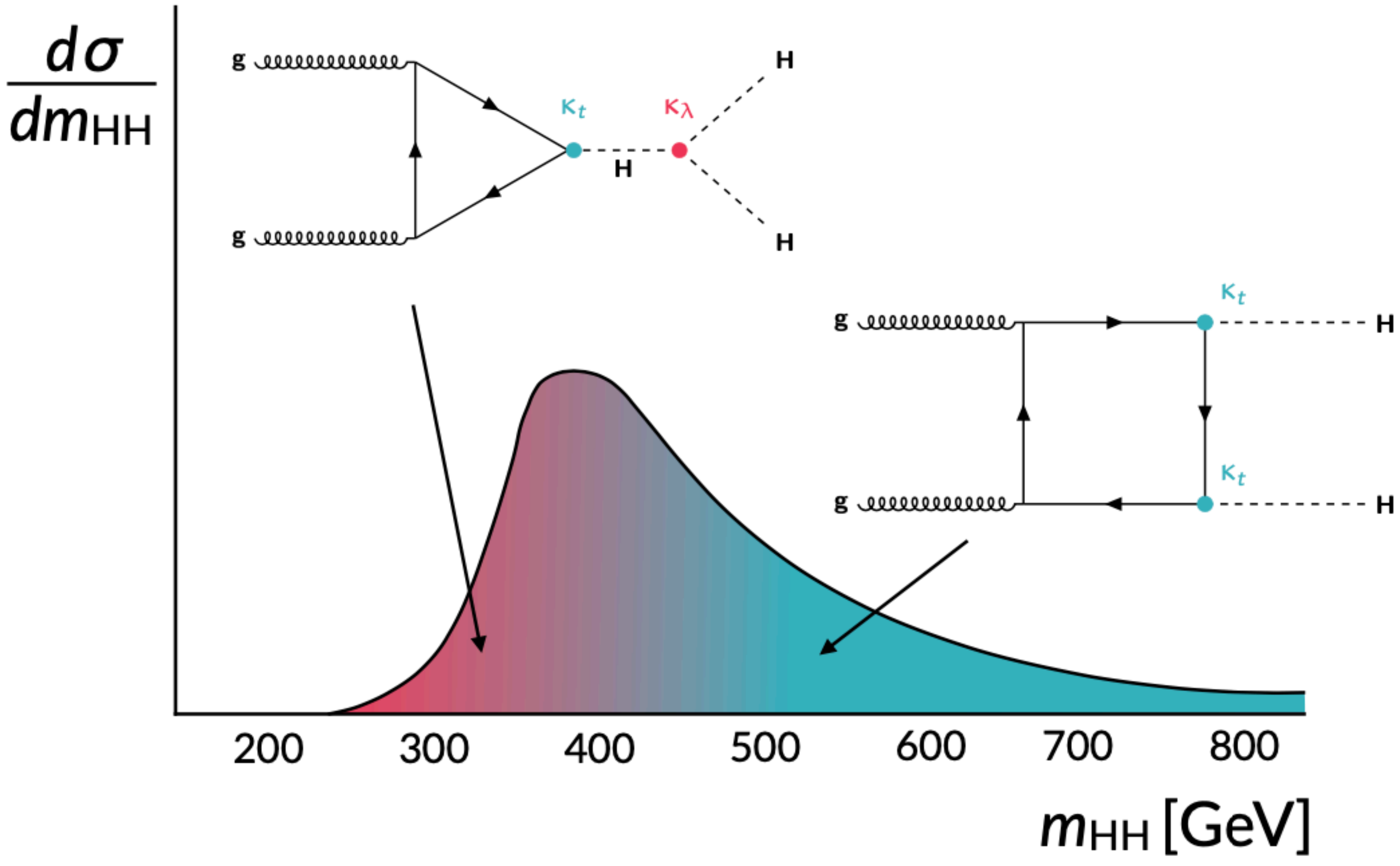
- EFT interpretations becoming increasingly popular in HH searches
- HEFT interpretation of $bb\tau\tau$, $bb\gamma\gamma$ and their combination [ATL-PHYS-PUB-2022-019]
- Upper limits are set for 7 benchmark models and on c_{gghh} and c_{tthh} Wilson coefficients
- Ongoing collaboration with theorists (EFT public note in preparation)
  - Summary of available EFT tools for HH
  - Recommendations for the various EFT parametrisations for HH

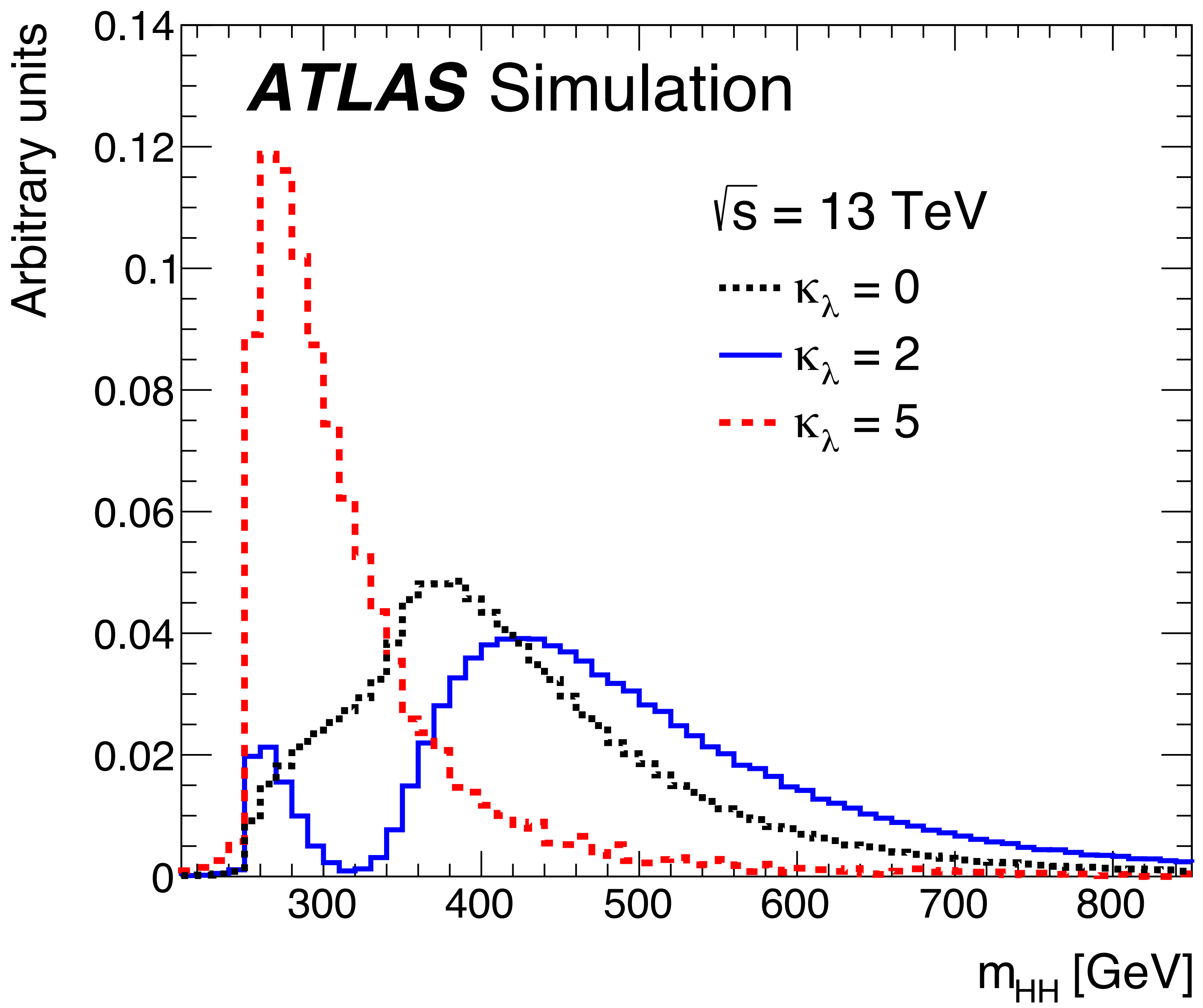
Thank you for your attention!

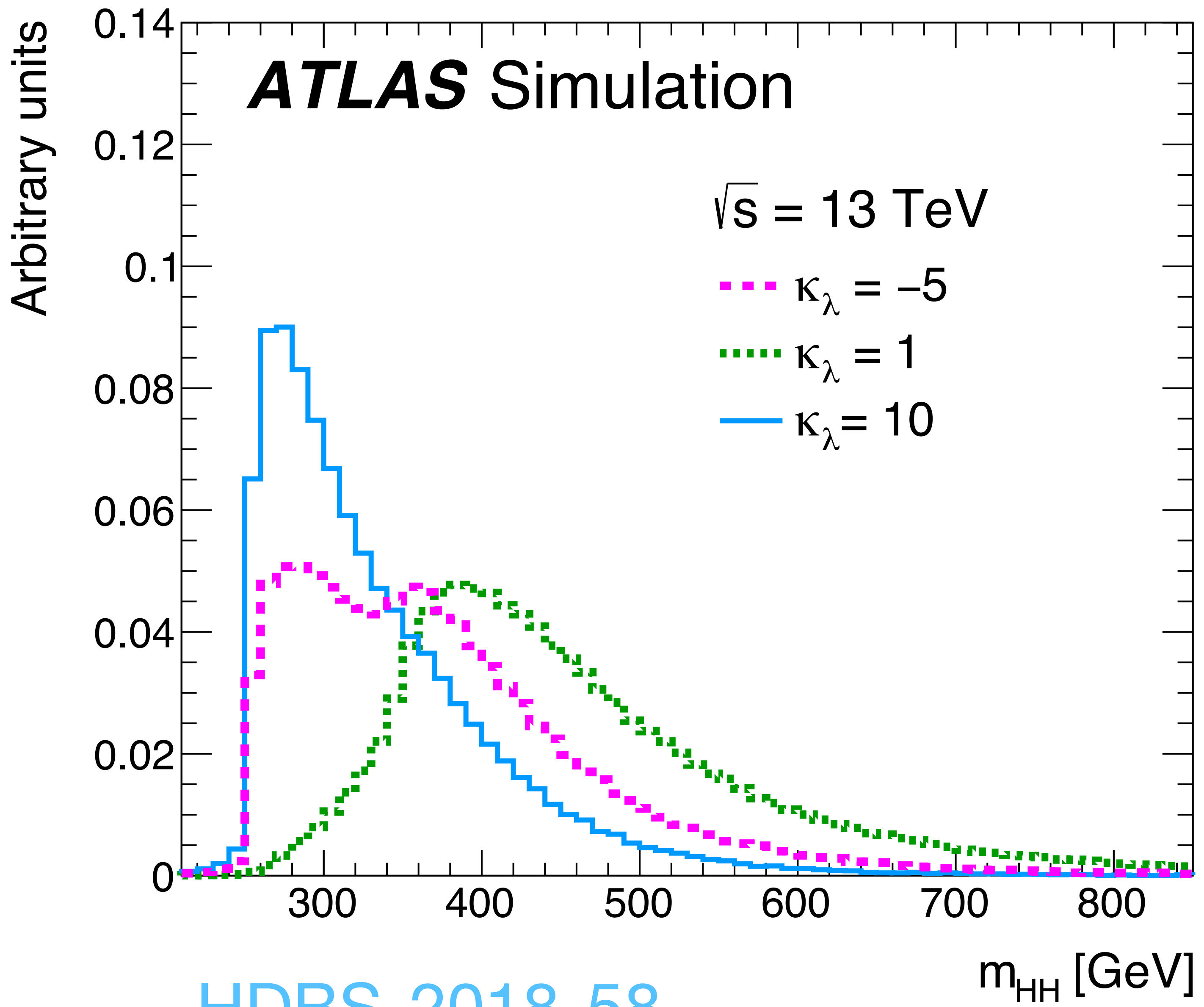
BACK-UP

Varied Higgs self-coupling

Cross-section and shape of m_{HH} distribution changes with the self-coupling signal strength $\kappa_\lambda = \lambda/\lambda_{SM}$







HDBS-2018-58

bbtautau event selection

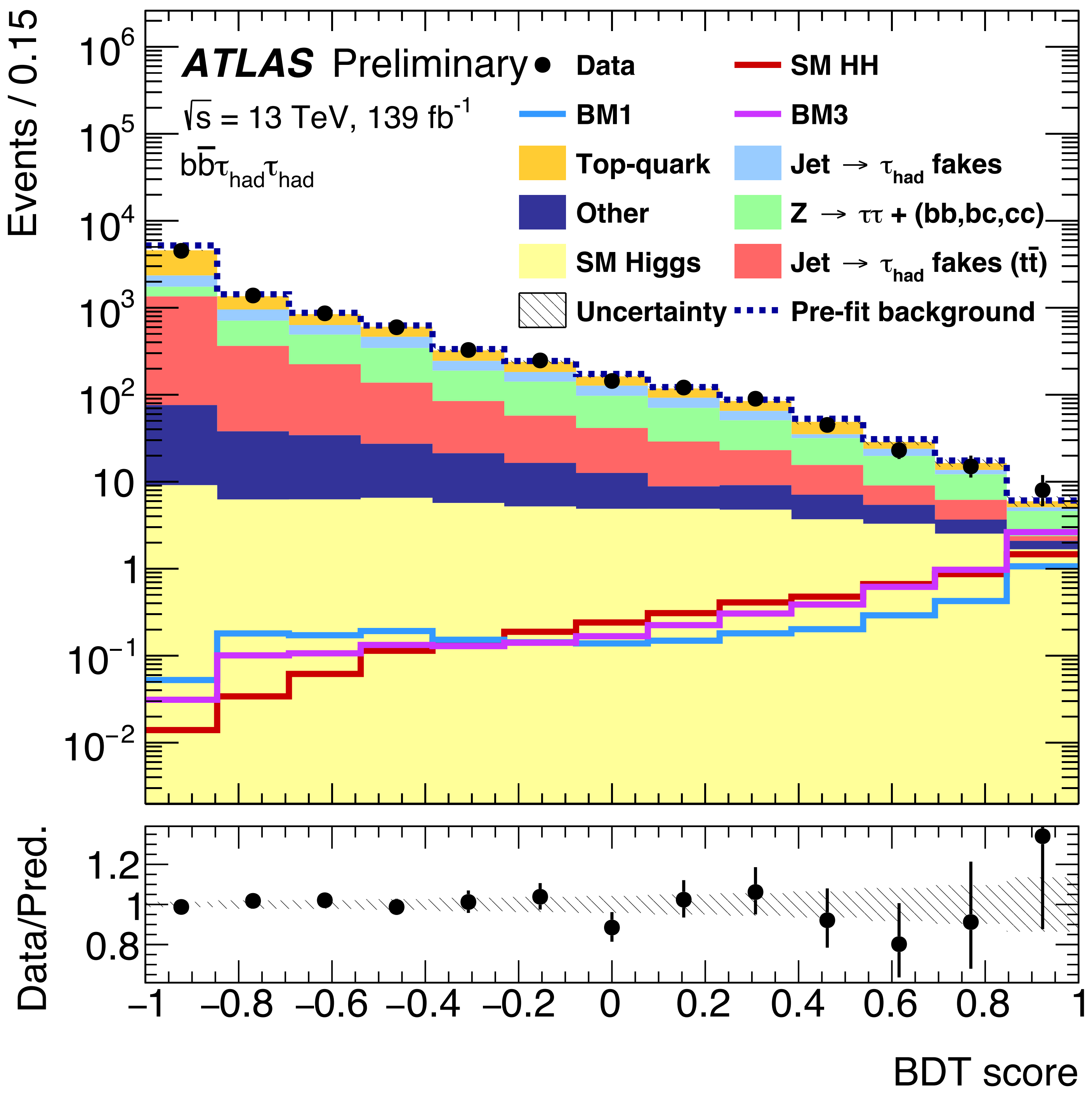
$\tau_{had}\tau_{had}$ category		$\tau_{lep}\tau_{had}$ categories	
STT	DTT	SLT	LTT
e/μ selection			
No loose e/μ with $p_T > 7$ GeV		Exactly one tight e or medium μ	
		$p_T^e > 25, 27$ GeV	$18 \text{ GeV} < p_T^e <$ SLT cut
		$p_T^\mu > 21, 27$ GeV	$15 \text{ GeV} < p_T^\mu <$ SLT cut
		$\lvert\eta^e\rvert < 2.47$, not $1.37 < \lvert\eta^e\rvert < 1.52$	
		$\lvert\eta^\mu\rvert < 2.7$	
$\tau_{had\text{-}vis}$ selection			
Two loose $\tau_{had\text{-}vis}$		One loose $\tau_{had\text{-}vis}$	
$\lvert\eta\rvert < 2.5$		$\lvert\eta\rvert < 2.3$	
$p_T > 100, 140, 180\ (25)$ GeV	$p_T > 40\ (30)$ GeV	$p_T > 20$ GeV	$p_T > 30$ GeV
Jet selection			
≥ 2 jets with $\lvert\eta\rvert < 2.5$			
$p_T > 45\ (20)$ GeV	Trigger dependent	$p_T > 45\ (20)$ GeV	Trigger dependent
Event-level selection			
Trigger requirements passed			
Collision vertex reconstructed			
$m_{\tau\tau}^{MMC} > 60$ GeV			
Opposite-sign electric charges of $e/\mu/\tau_{had\text{-}vis}$ and $\tau_{had\text{-}vis}$			
Exactly two b-tagged jets			
		$m_{bb} < 150$ GeV	

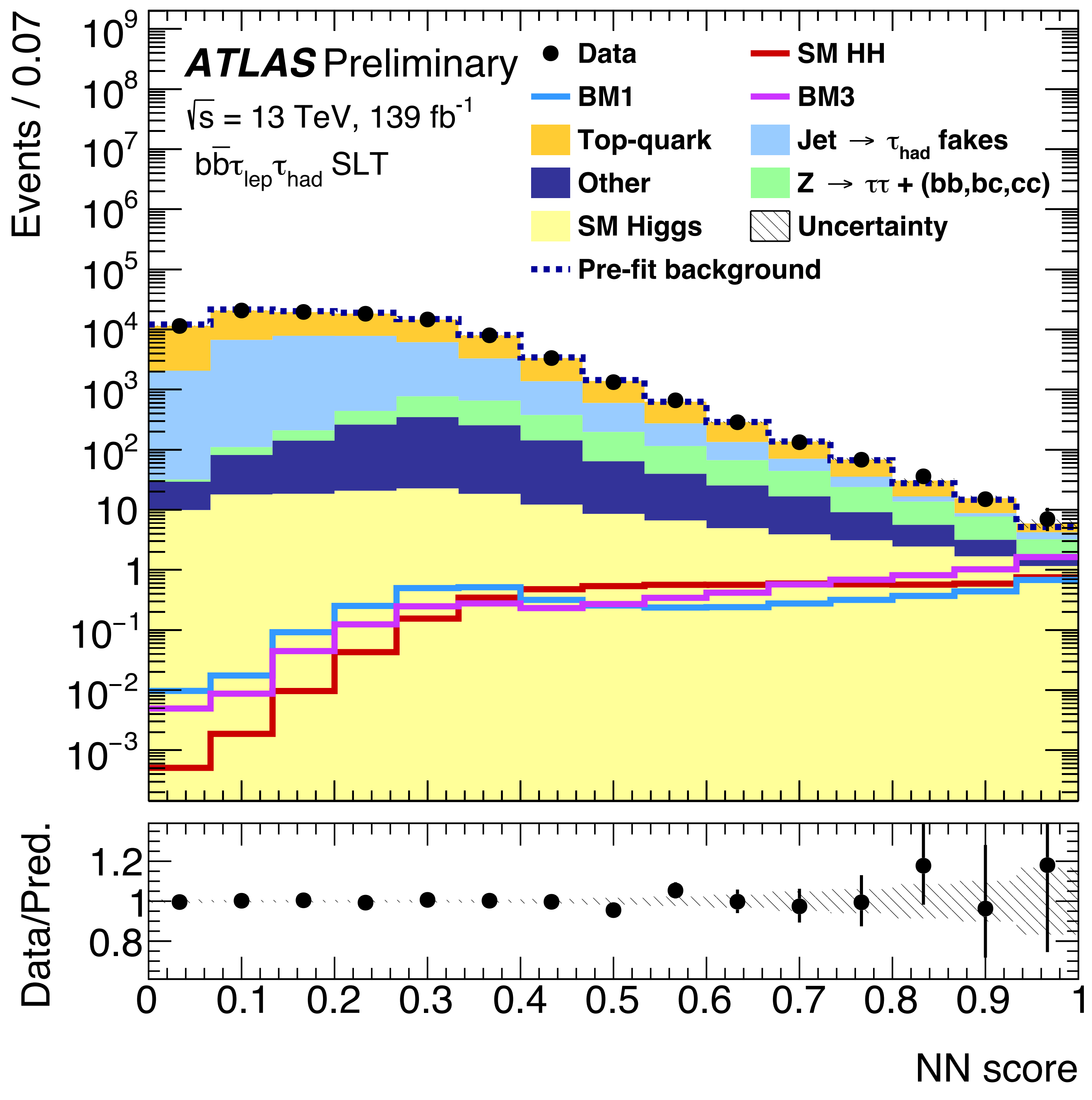
bbtautau uncertainty breakdown

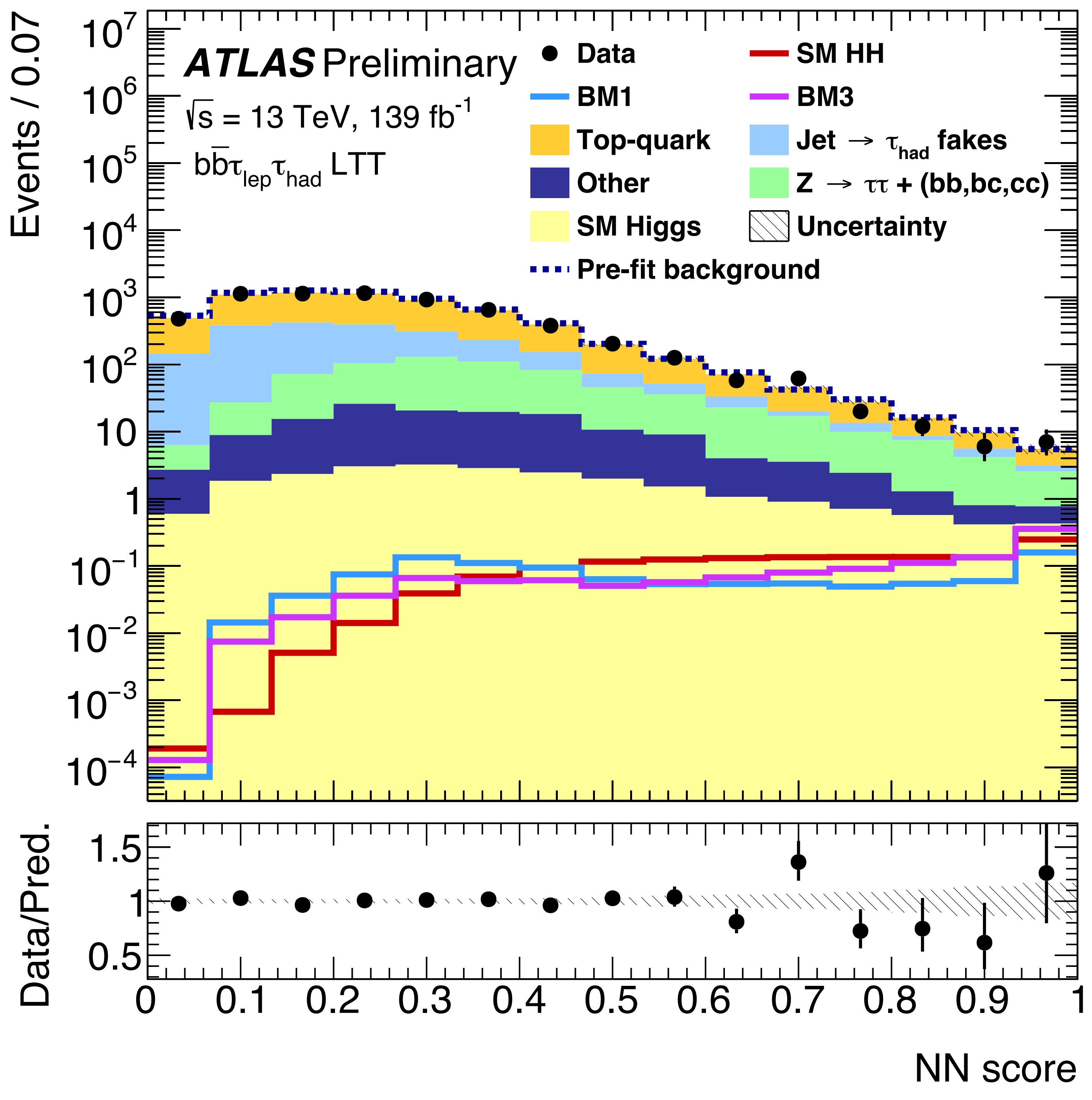
Table 4: Breakdown of the relative contributions to the uncertainty in the extracted signal cross-sections, as determined in the likelihood fit to data. These are obtained by fixing the relevant nuisance parameters in the likelihood fit, and subtracting the obtained uncertainty on the fitted signal cross-sections in quadrature from the total uncertainty, and then dividing the result by the total uncertainty. The sum in quadrature of the individual components differs from the total uncertainty due to correlations between the groups of uncertainties.

Uncertainty source	Non-resonant HH	Resonant $X \to HH$ 300 GeV	Resonant $X \to HH$ 500 GeV	Resonant $X \to HH$ 1000 GeV
Data statistical	81%	75%	89%	88%
Systematic	59%	66%	46%	48%
$t\bar{t}$ and Z + HF normalisations	4%	15%	3%	3%
MC statistical	28%	44%	33%	18%
Experimental				
Jet and $E_{\mathrm{T}}^{\mathrm{miss}}$	7%	28%	5%	3%
b-jet tagging	3%	6%	3%	3%
$\tau_{\text{had-vis}}$	5%	13%	3%	7%
Electrons and muons	2%	3%	2%	1%
Luminosity and pileup	3%	2%	2%	5%
Theoretical and modelling				
Fake-$\tau_{\text{had-vis}}$	9%	22%	8%	7%
Top-quark	24%	17%	15%	8%
$Z(\to \tau\tau)$ + HF	9%	17%	9%	15%
Single Higgs boson	29%	2%	15%	14%
Other backgrounds	3%	2%	5%	3%
Signal	5%	15%	13%	34%

MVA postfit plots







Signal reweighting

- Investigating modified couplings **only for ggF**
- Weights derived by theorists to obtain BSM predictions from SM sample
- Based on dependence of cross-section on couplings

$$\begin{aligned}\sigma^{\mathrm{NLO}}/\sigma_{SM}^{\mathrm{NLO}} =\ & A_1\, c_t^4 + A_2\, c_{tt}^2 + A_3\, c_t^2 c_{hhh}^2 + A_4\, c_{ggh}^2 c_{hhh}^2 + A_5\, c_{gghh}^2 + A_6\, c_{tt} c_t^2 + A_7\, c_t^3 c_{hhh} \\ & + A_8\, c_{tt} c_t\, c_{hhh} + A_9\, c_{tt} c_{ggh} c_{hhh} + A_{10}\, c_{tt} c_{gghh} + A_{11}\, c_t^2 c_{ggh} c_{hhh} + A_{12}\, c_t^2 c_{gghh} \\ & + A_{13}\, c_t c_{hhh}^2 c_{ggh} + A_{14}\, c_t c_{hhh} c_{gghh} + A_{15}\, c_{ggh} c_{hhh} c_{gghh} \\ & + A_{16}\, c_t^3 c_{ggh} + A_{17}\, c_t c_{tt} c_{ggh} + A_{18}\, c_t c_{ggh}^2 c_{hhh} + A_{19}\, c_t c_{ggh} c_{gghh} \\ & + A_{20}\, c_t^2 c_{ggh}^2 + A_{21}\, c_{tt} c_{ggh}^2 + A_{22}\, c_{ggh}^3 c_{hhh} + A_{23}\, c_{ggh}^2 c_{gghh}\,.\end{aligned}$$

- Can apply event weights $\mathrm{Poly}(A) = \sigma^{\mathrm{NLO}}/\sigma_{\mathrm{SM}}^{\mathrm{NLO}}$ to emulate BSM behaviour
- Coefficients A_i available in dependence of m_{HH} and inclusively
- Use $\mathrm{Poly}(A)$ to modify only cross-section, $\mathrm{Poly}(A\,|\,m_{HH})$ also changes shape
- **Scale SM signal with** $\mathrm{Poly}(A\,|\,m_{HH})/\mathrm{Poly}(A)$

HEFT interpretations: results

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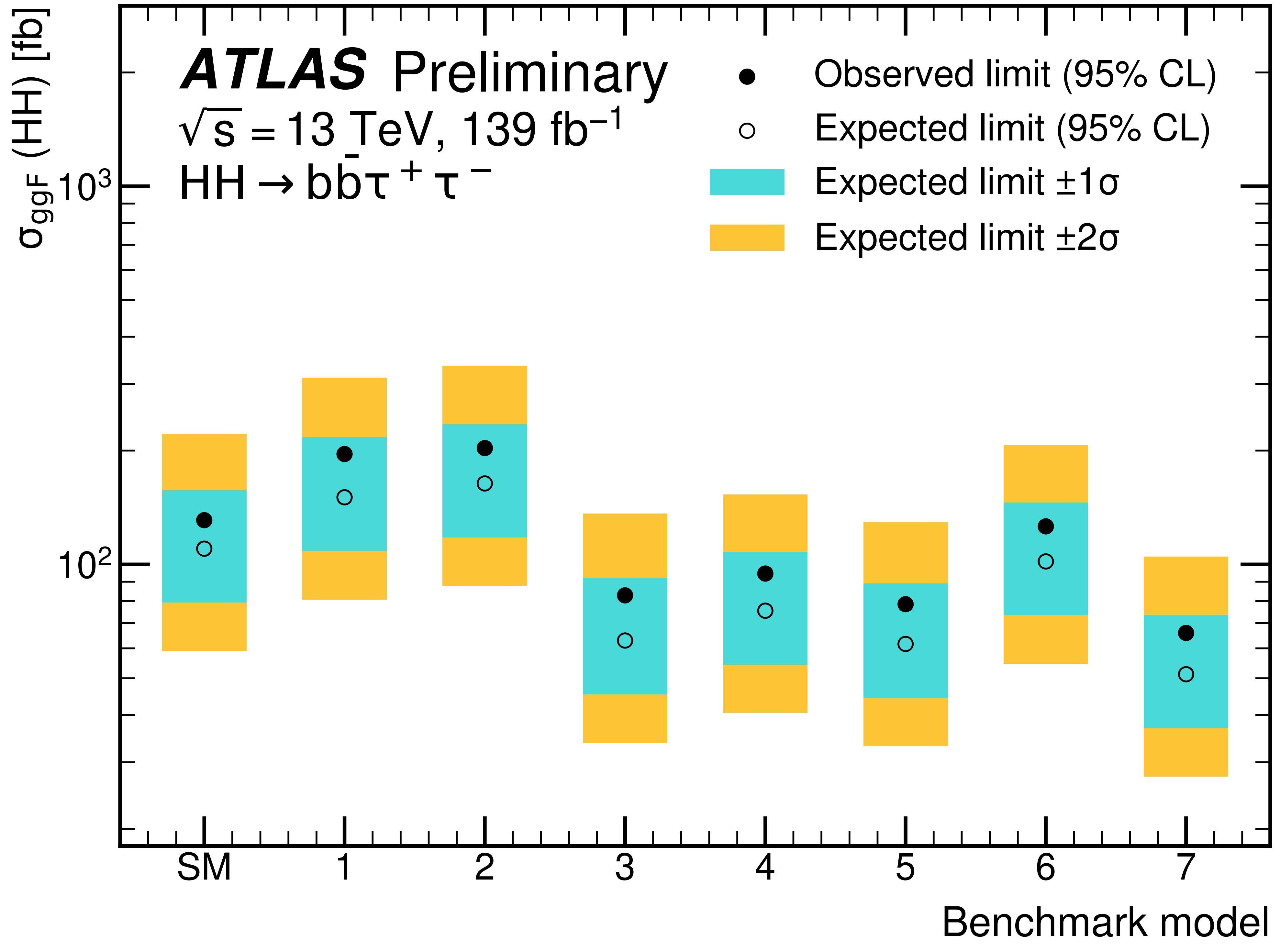

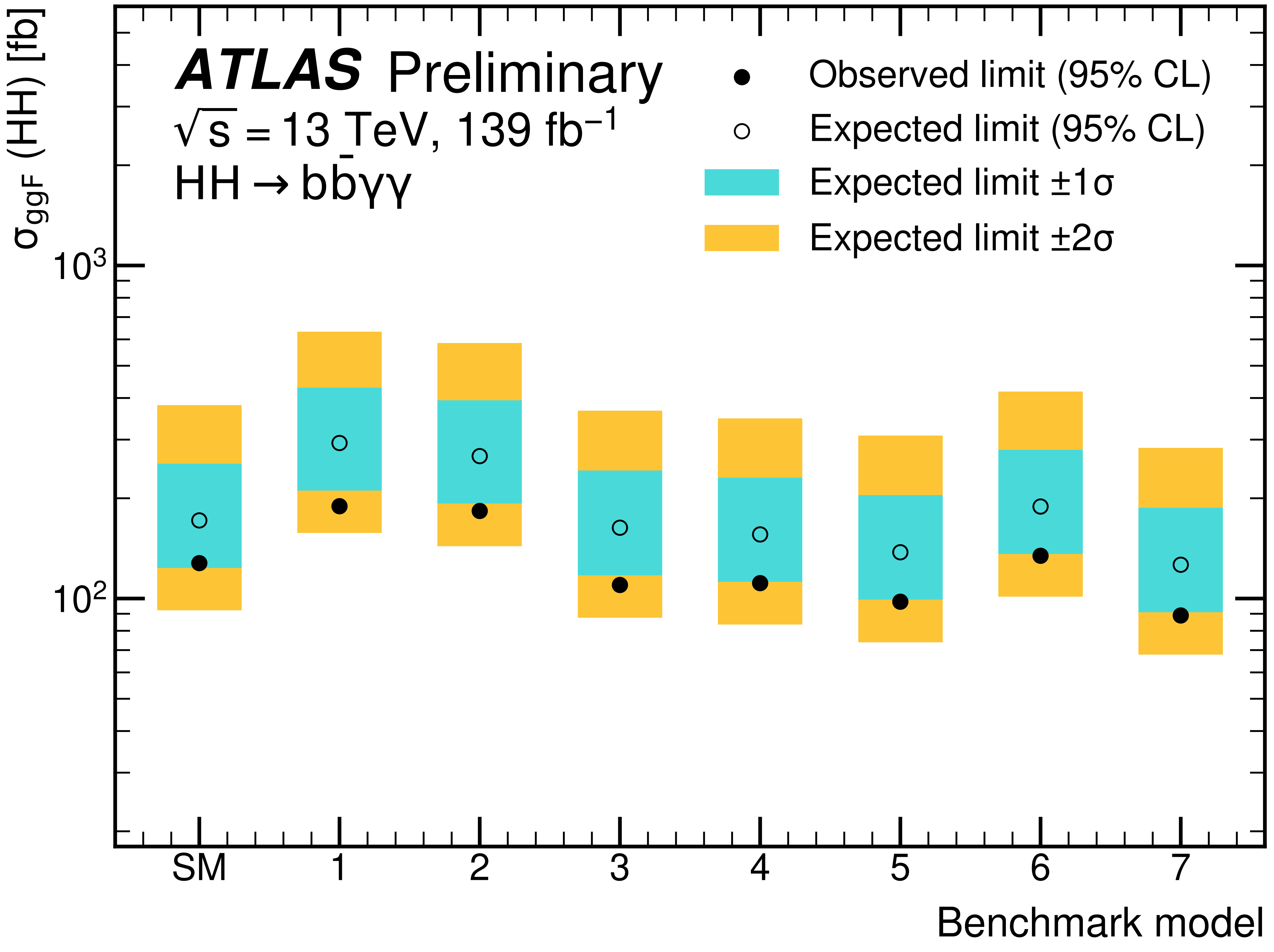

HEFT interpretations: results

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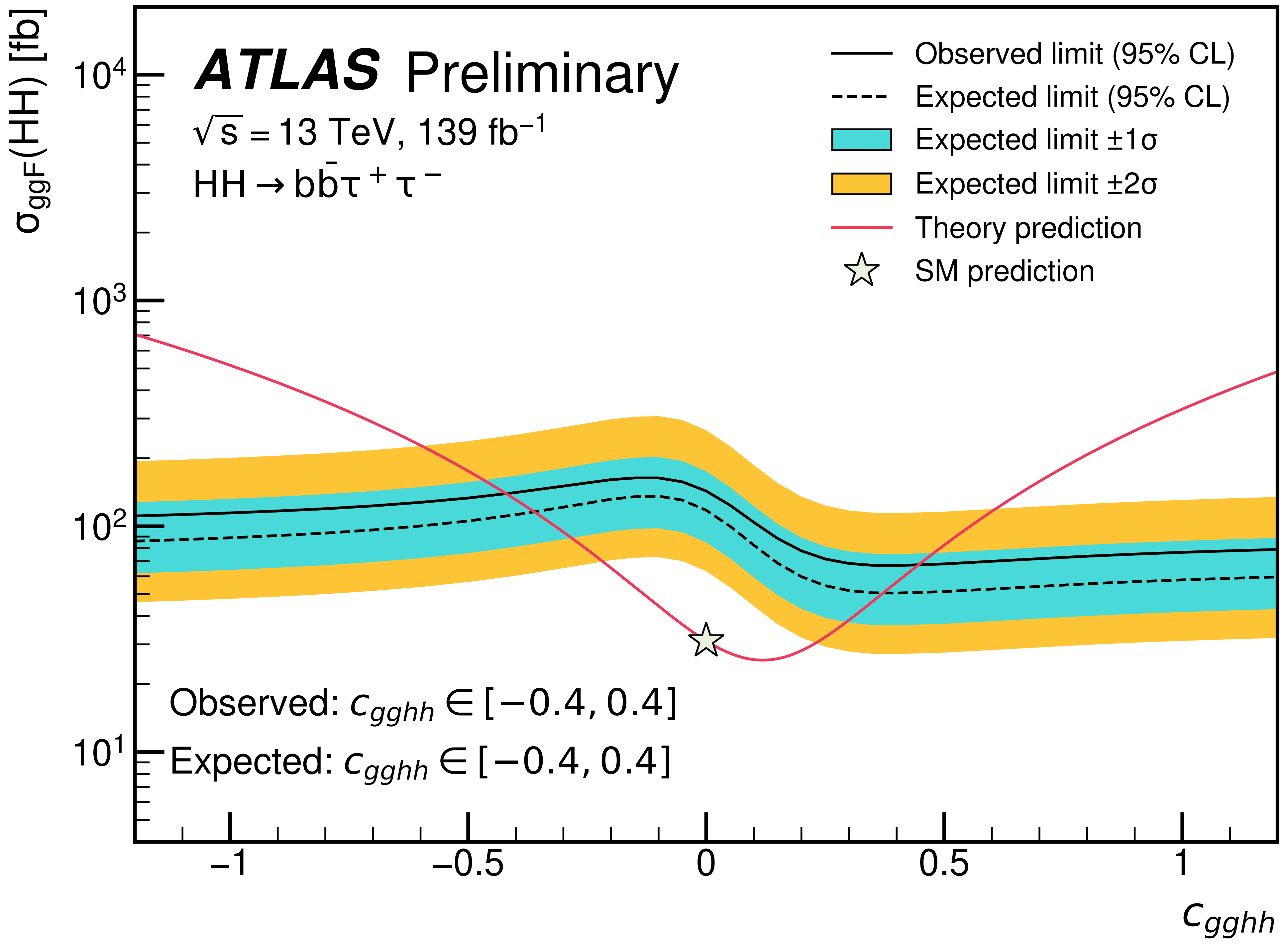
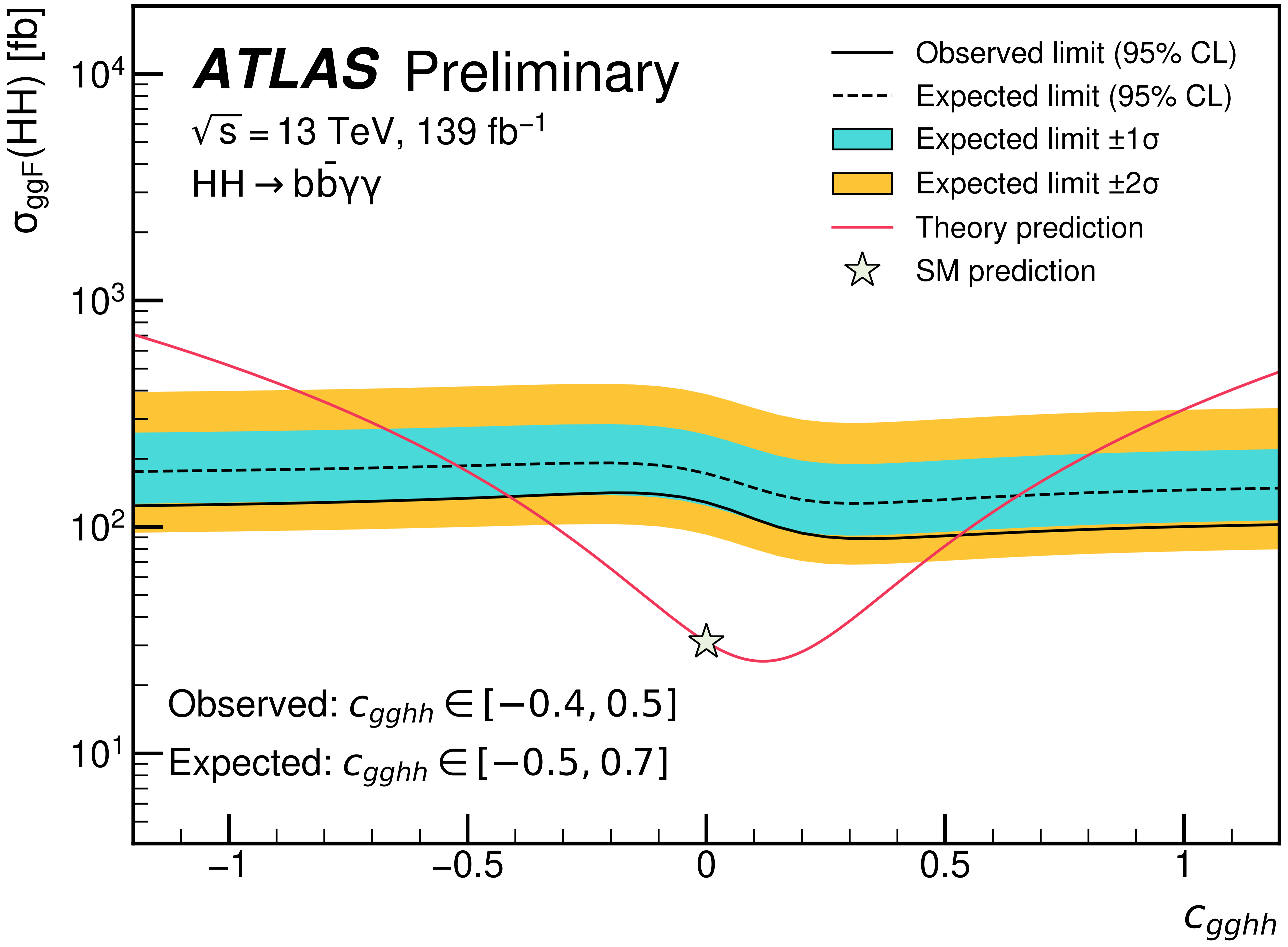
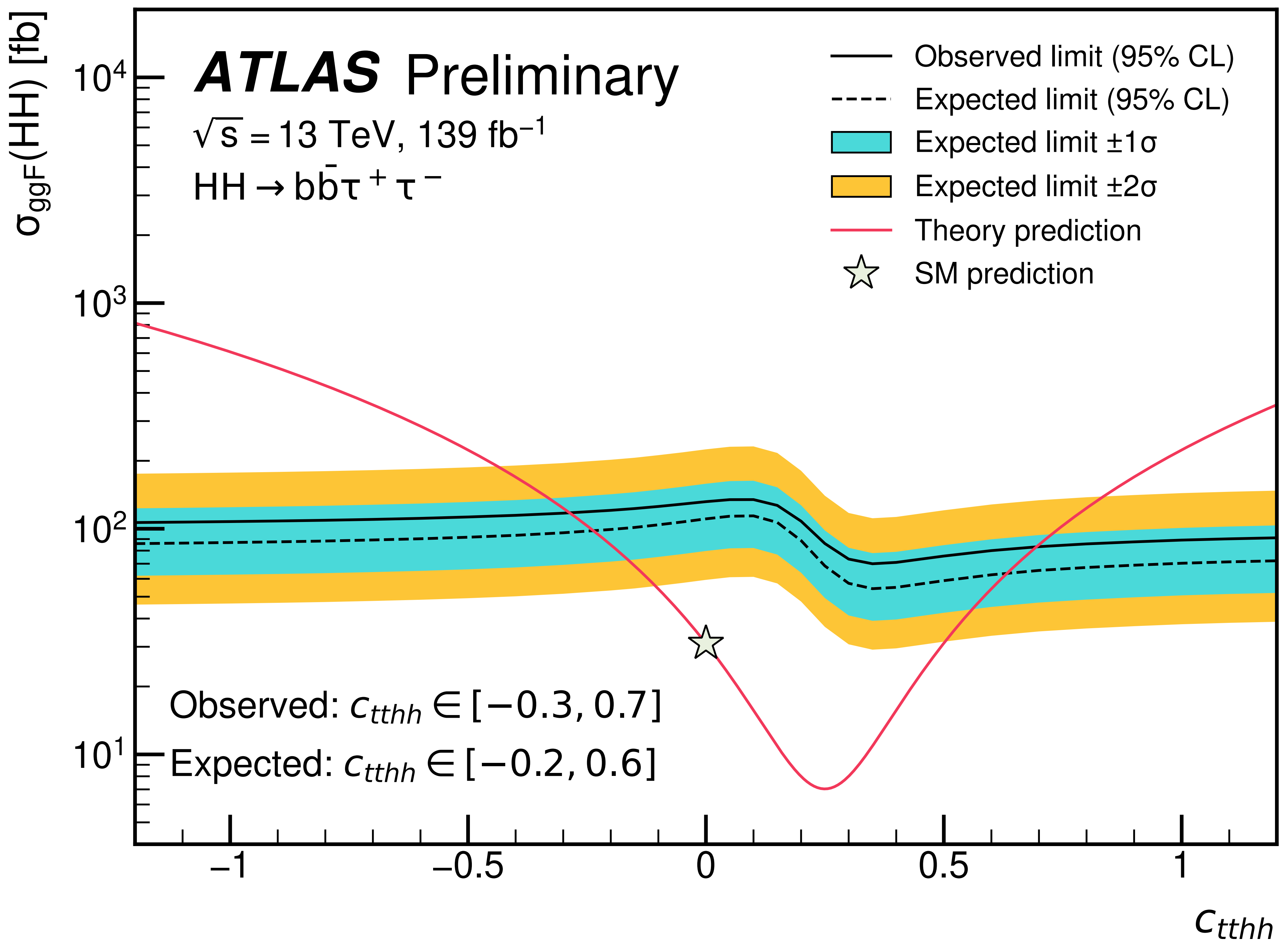
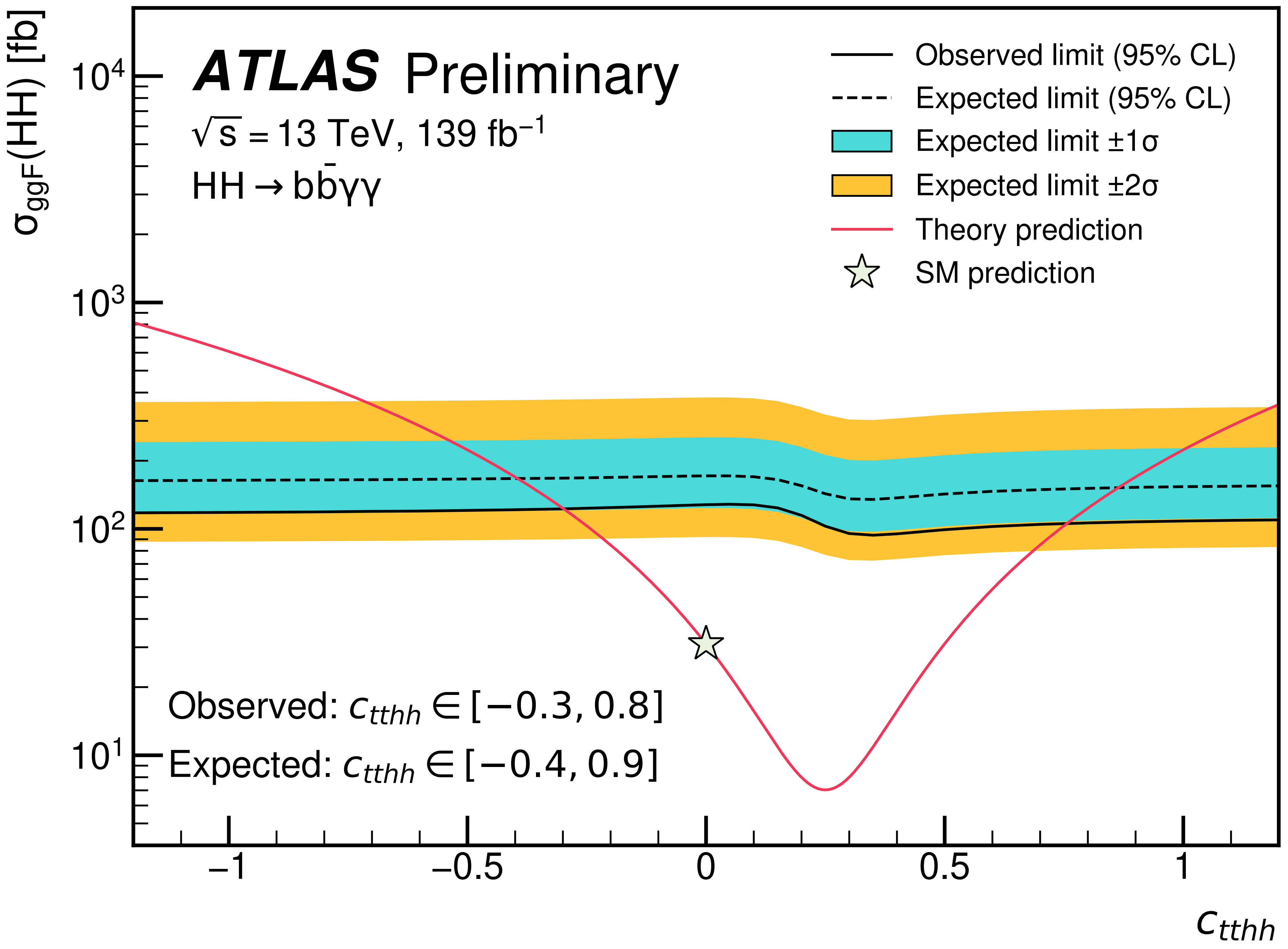




HEFT interpretations: results

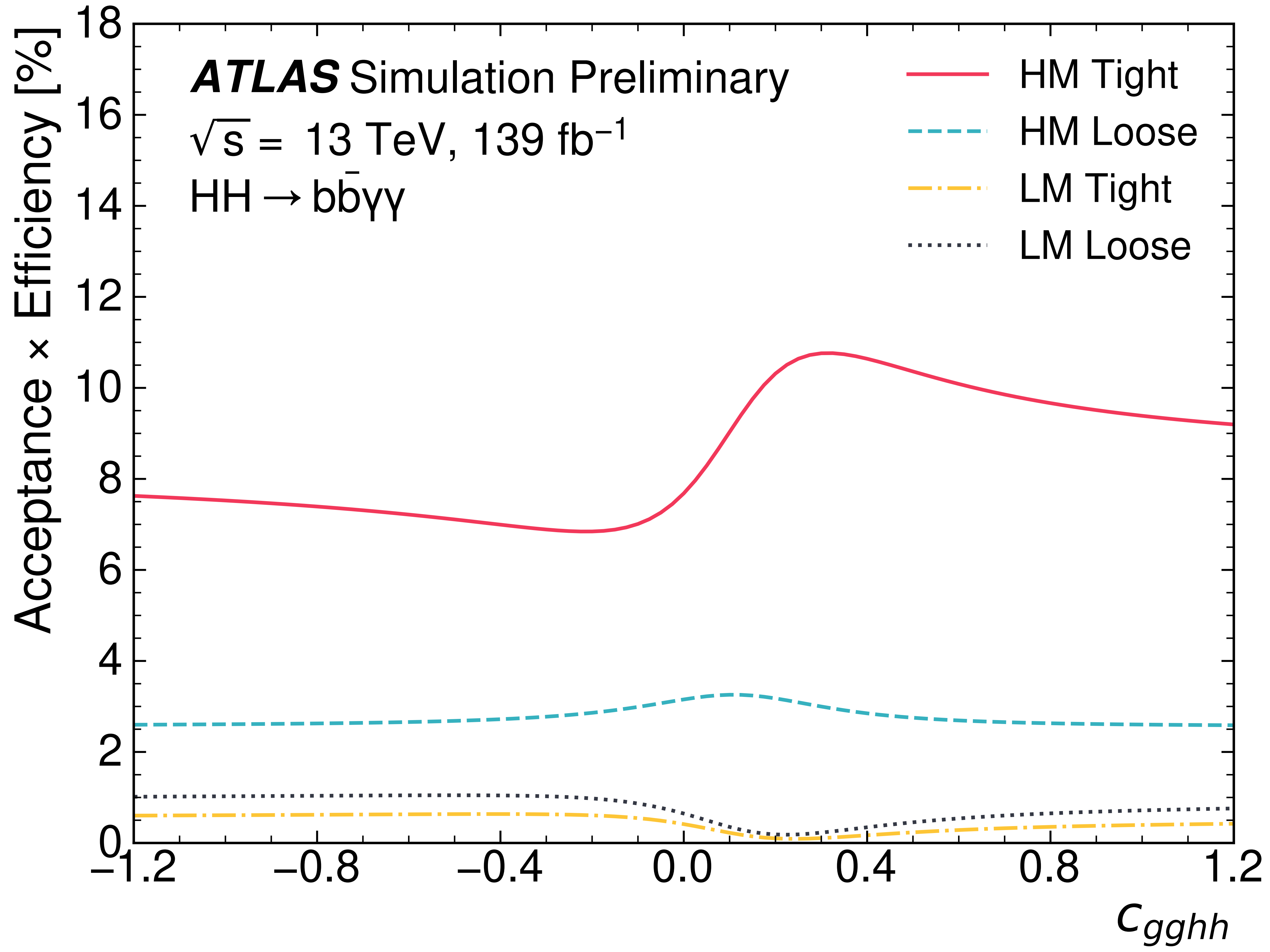
ATL-PHYS-PUB-2022-021

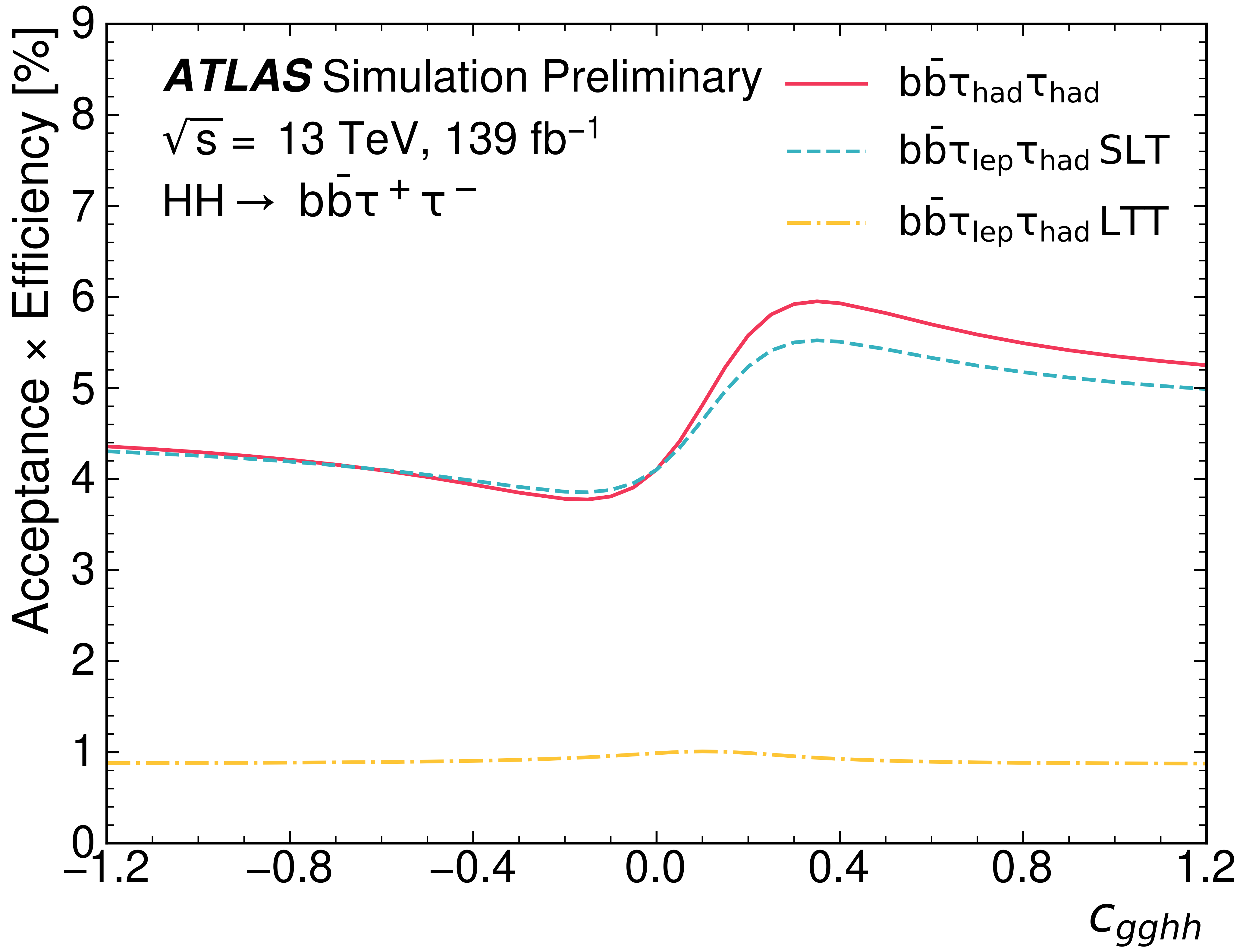




HEFT interpretations: results

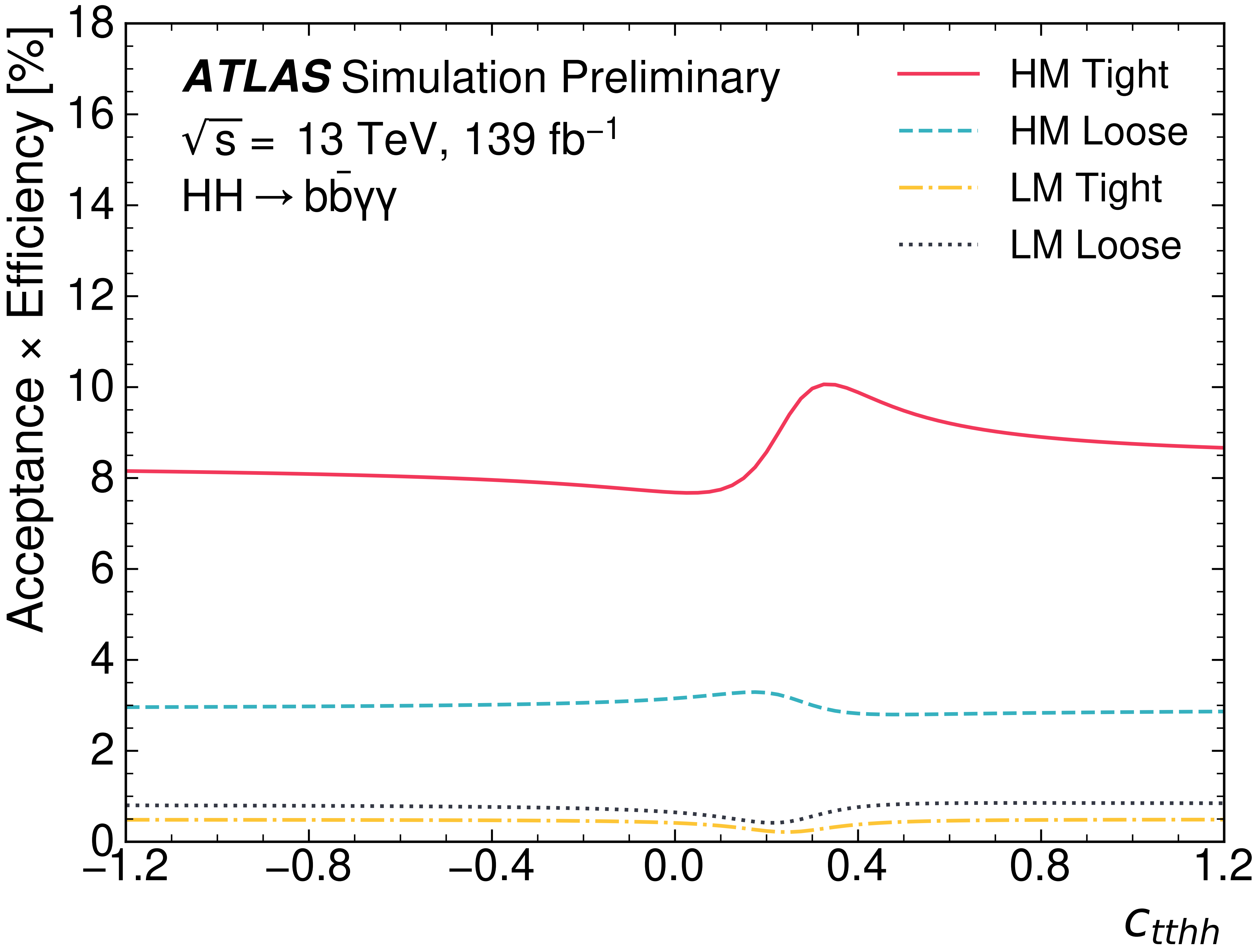
ATL-PHYS-PUB-2022-021

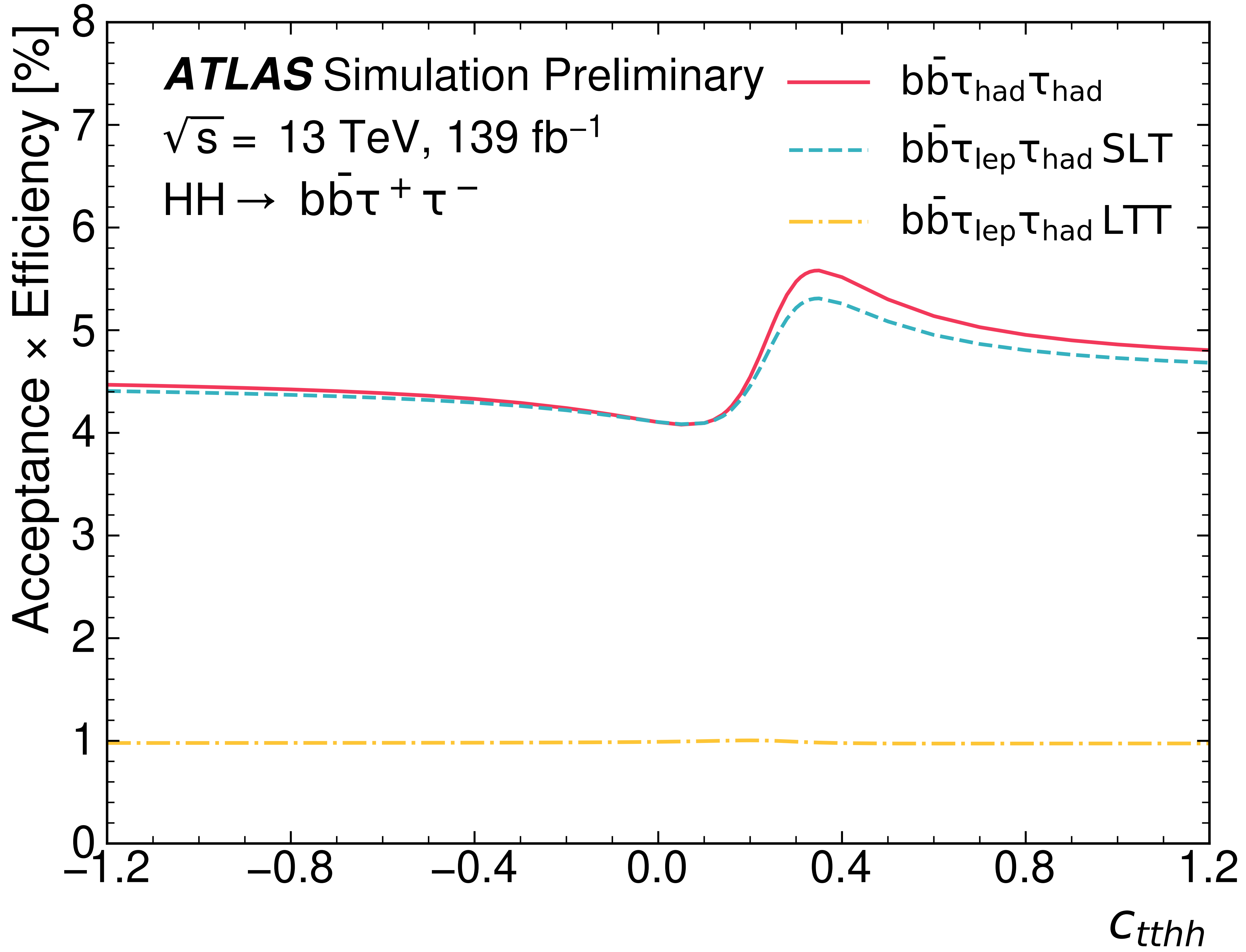




HEFT interpretations: results

ATL-PHYS-PUB-2022-021





HEFT interpretations: results

ATL-PHYS-PUB-2022-021

Acceptance × Efficiency [%]	HM Loose	LM Loose	HM Tight	LM Tight	Total
SM	3.2	0.6	7.7	0.4	11.9
BM 1	1.3	2.9	3.8	1.5	9.5
BM 2	1.8	2.2	4.5	1.2	9.7
BM 3	2.2	1.3	8.3	0.6	12.4
BM 4	2.9	0.7	8.6	0.4	12.6
BM 5	3.1	0.3	9.8	0.1	13.3
BM 6	2.6	1.2	7.0	0.7	11.5
BM 7	3.1	0.3	10.8	0.2	14.4

Acceptance × Efficiency [%]	$b\bar{b}\tau_{\text{lep}}\tau_{\text{had}}$ (SLT)	$b\bar{b}\tau_{\text{lep}}\tau_{\text{had}}$ (LTT)	$b\bar{b}\tau_{\text{had}}\tau_{\text{had}}$	Total
SM	4.1	1.0	4.1	9.2
BM 1	3.2	0.7	2.7	6.6
BM 2	3.3	0.8	2.9	7.0
BM 3	4.7	0.9	4.9	10.5
BM 4	4.6	1.0	4.7	10.3
BM 5	5.0	1.0	5.3	11.3
BM 6	4.0	0.9	4.0	8.9
BM 7	5.5	1.0	5.9	12.4