Higgs EFT interpretation of the search for $HH \to b\bar{b}\gamma\gamma$ in the ATLAS detector

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Nordic Particle Physics Conference

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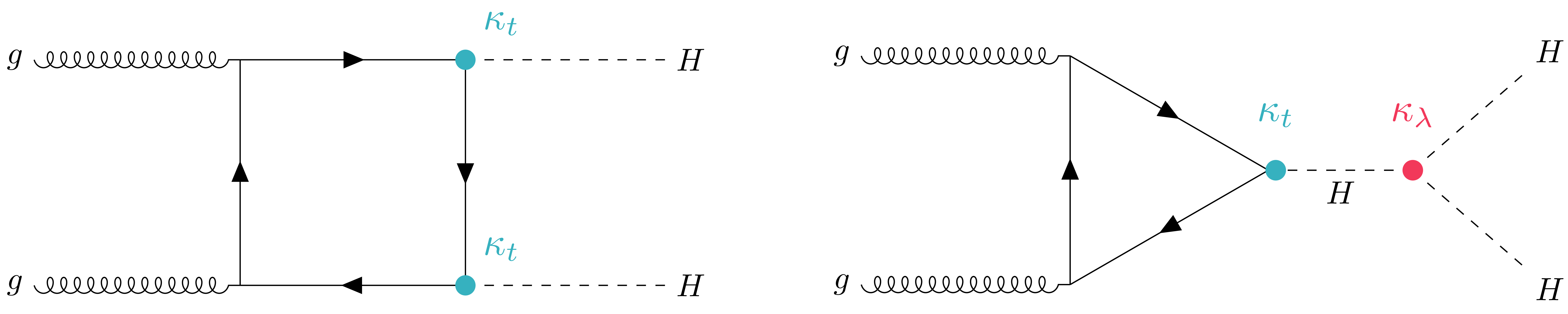
$ggF\ HH$ production

- Measuring HH production will gives us access to the triple Higgs coupling (self coupling) λ_3, which gives information of the shape of the Higgs potential $V(H) = \frac{1}{2}m_H^2H^2 + \lambda_3 \nu H^3 + \frac{1}{4}\lambda_4 \nu H^4 + O(H^5)$.

- The leading HH production mode is gluon gluon fusion (ggF):



- The coupling modifier κ_λ controls the strength of the Higgs self coupling with respect to SM: $\kappa_\lambda = \lambda_3/\lambda_3^{SM}$

- Destructive interference between the two diagrams results in a very small SM cross section of $\sigma_{ggF}^{HH} = 31.05$ fb at $\sqrt{s} = 13$ TeV.

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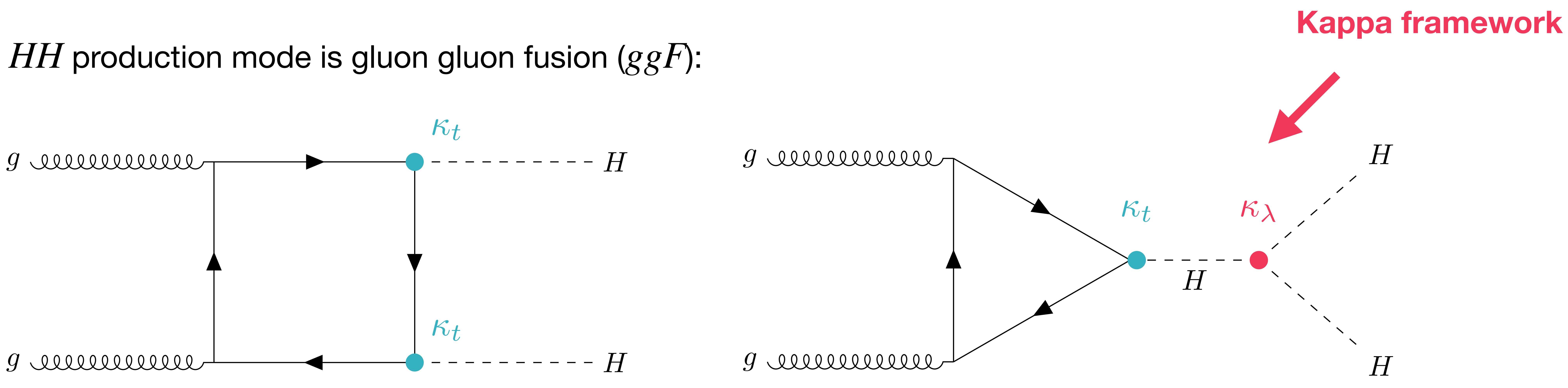

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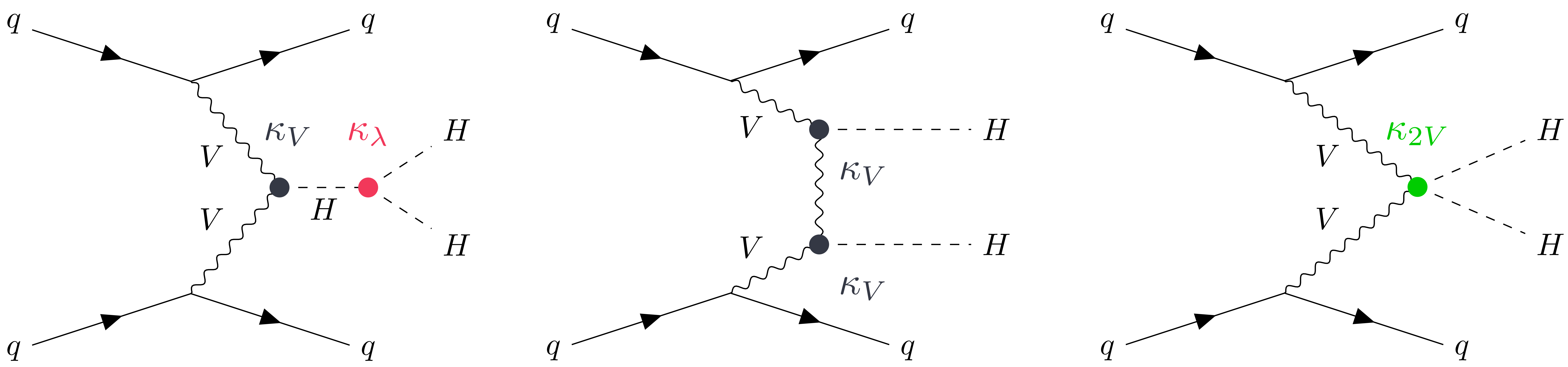
$VBF\ HH$ production

- HH production through VBF is the sub-leading HH production mode with a SM cross section of $\sigma^{HH}_{VBF} = 1.73$ fb at $\sqrt{s} = 13$ TeV (calculated at N3LO)
- The coupling modifiers κ_λ, κ_V and κ_{2V} control the strength of the $g_{HHH} = \frac{3m_H}{v^2}$, $g_{VVH} = \frac{2m_V^2}{v}$ and $g_{VVHH} = \frac{2m_V^2}{v^2}$ couplings with respect to the SM value.

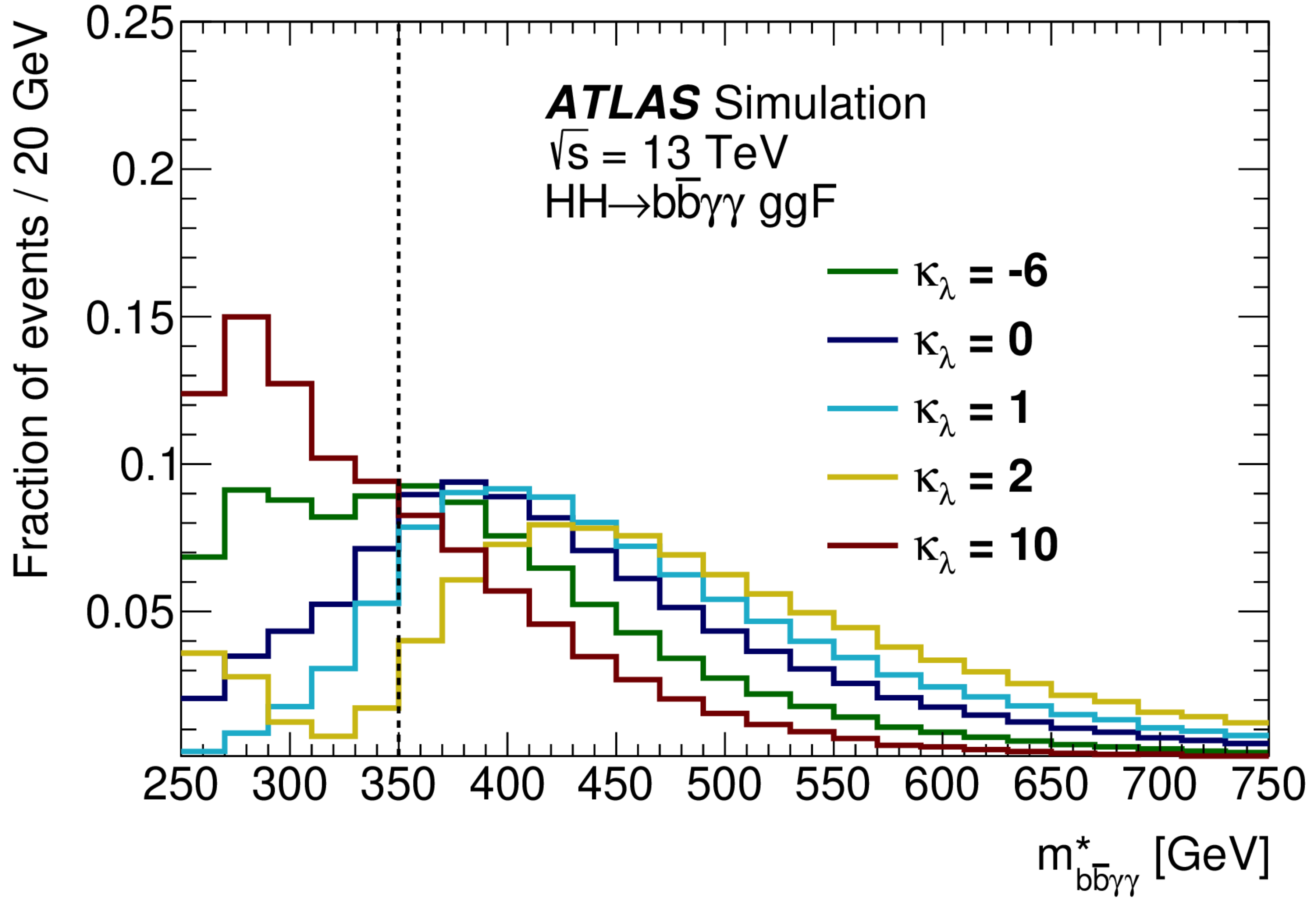


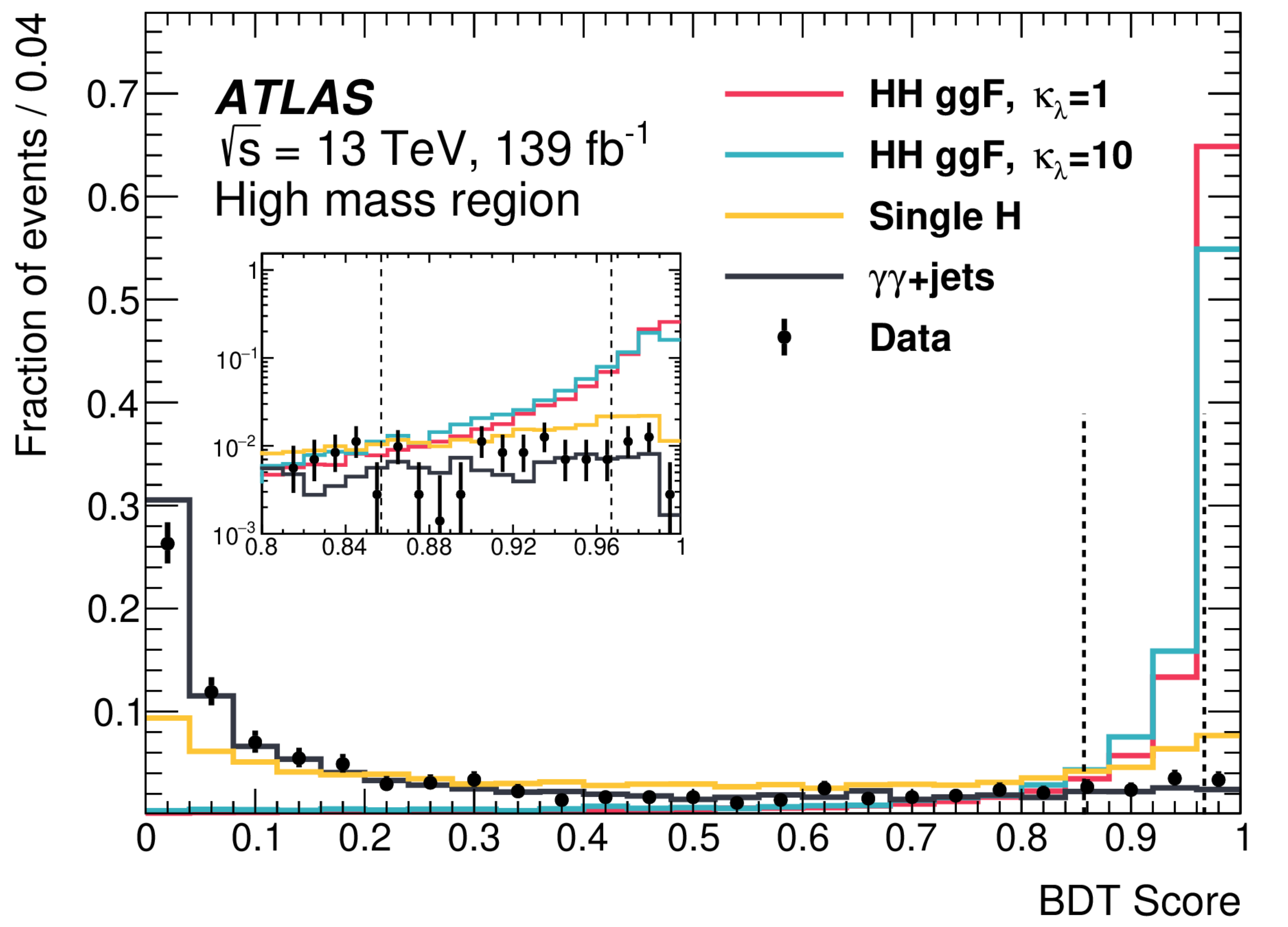
- Given the larger cross section, searches for $ggF\ HH$ production provide better sensitivity to κ_λ but the VBF topology has a unique sensitivity to κ_{2V}.

$HH \to b\bar{b}\gamma\gamma$ event selection

- The paper (optimised for ggF HH production) has been published in PhysRevD
- Events with 2 isolated photons, 2 b-jets at 70% WP and zero leptons are selected and divided in two regions:
  - High mass region: $m^*_{b\bar{b}\gamma\gamma} > 350$ GeV $\to$ sensitive to SM
  - Low mass region: $m^*_{b\bar{b}\gamma\gamma} < 350$ GeV $\to$ sensitive to BSM
- Independent BDTs are trained in each region to separate signal from background.
- Two regions are defined from each BDT resulting in 4 final categories optimised for ggF HH $\kappa_\lambda = 1$ and $\kappa_\lambda = 10$:

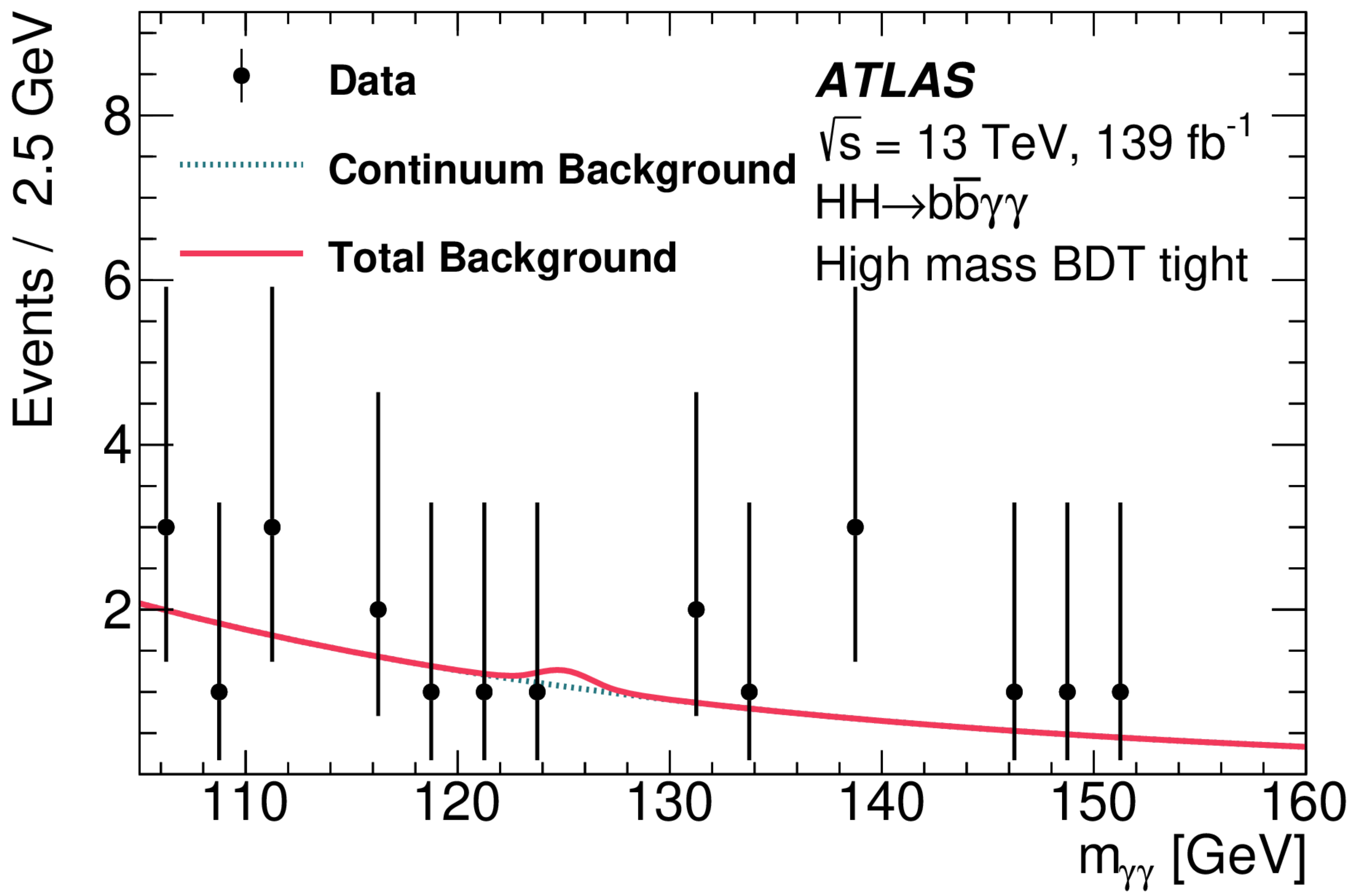
Category	Selection criteria
High mass BDT tight	$m^*_{b\bar{b}\gamma\gamma} \geq 350$ GeV, BDT score $\in [0.967, 1]$
High mass BDT loose	$m^*_{b\bar{b}\gamma\gamma} \geq 350$ GeV, BDT score $\in [0.857, 0.967]$
Low mass BDT tight	$m^*_{b\bar{b}\gamma\gamma} < 350$ GeV, BDT score $\in [0.966, 1]$
Low mass BDT loose	$m^*_{b\bar{b}\gamma\gamma} < 350$ GeV, BDT score $\in [0.881, 0.966]$

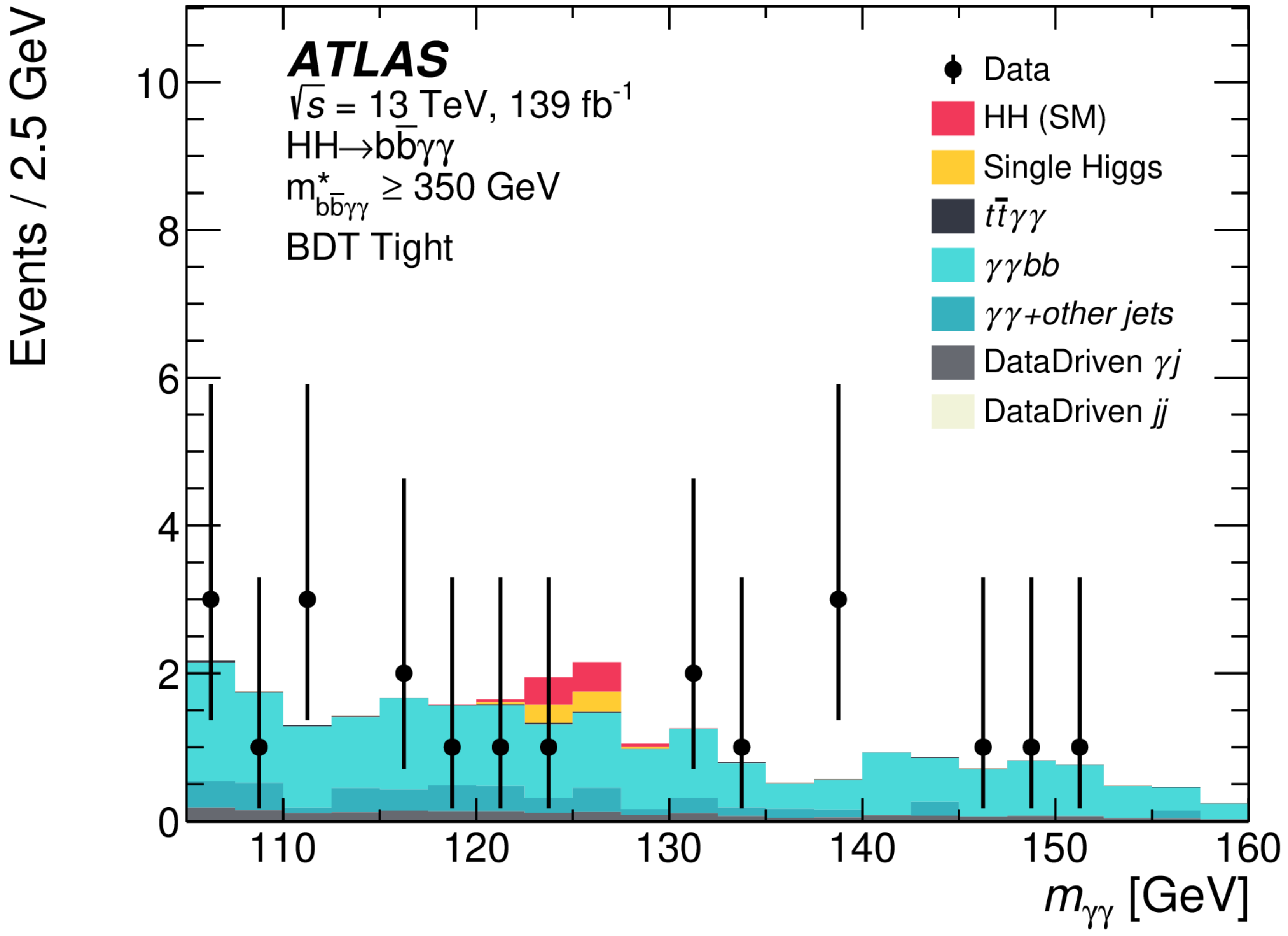




$HH \to b\bar{b}\gamma\gamma$ fit

- A likelihood fit to the $m_{\gamma\gamma}$ is performed
- The non-resonant background is parametrised as an exponential function where the shape is estimated from simulation while the normalisation is estimated from data through a fit to the $m_{\gamma\gamma}$ side band (120 GeV < $m_{\gamma\gamma}$ > 130 GeV).
- The resonant processes are parametrised from a double side crystal ball function in the 120 > $m_{\gamma\gamma}$ < 130 GeV region, where the shape and normalisation is obtained from simulation.



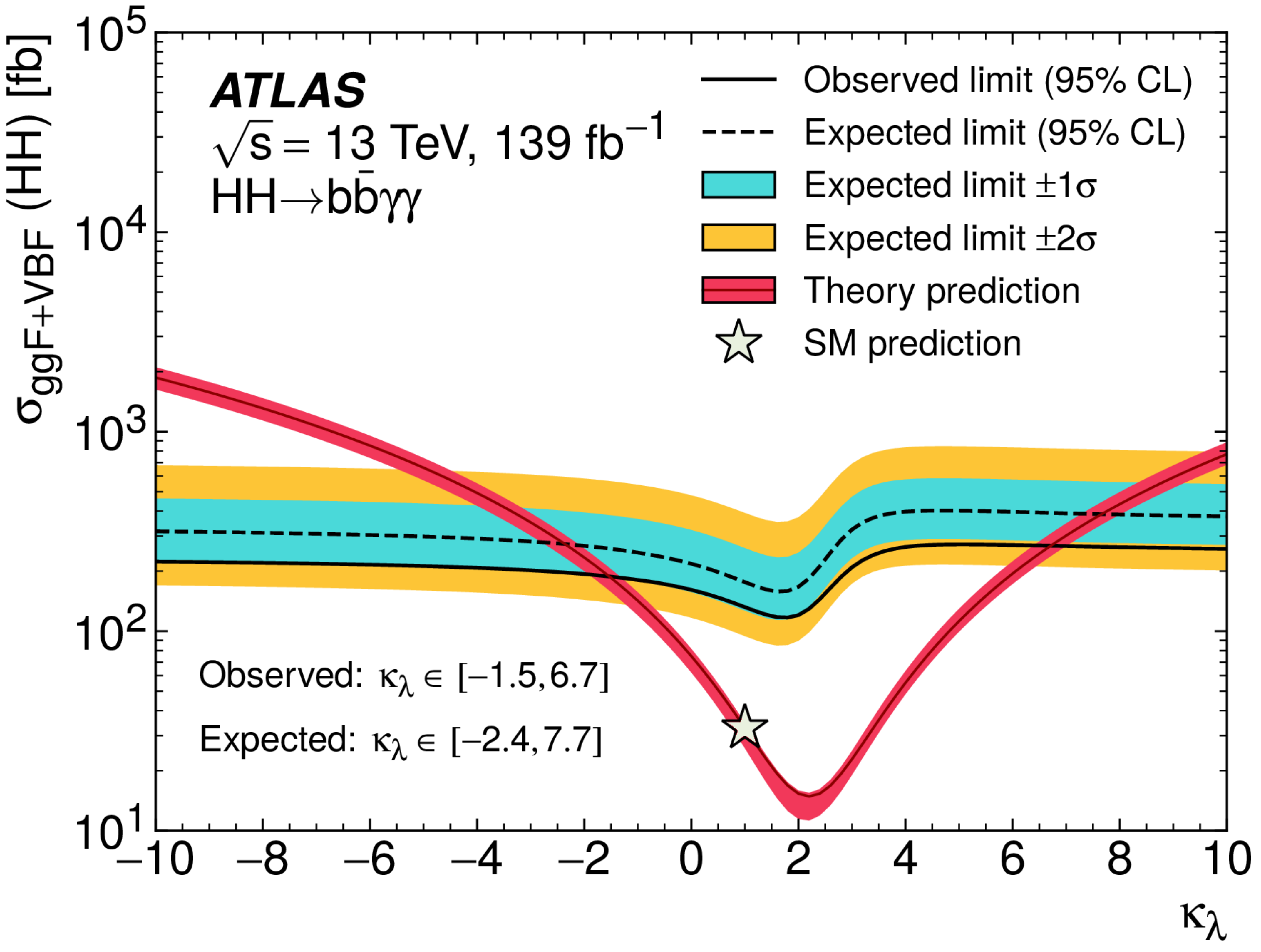


$HH \to b\bar{b}\gamma\gamma$ limits

- The analysis is optimised for $ggF\ HH$, however $VBF\ HH$ events are also considered as signal.

- Observed (expected) limits at 95% CL:
  - $\sigma^{HH}_{ggF+VBF} < 4.2\ (5.7)\ \times \sigma^{HH\ SM}_{ggF+VBF}$
  - $-1.5\ (-2.4) < \kappa_\lambda < 6.7\ (7.7)$

Kappa framework



Higgs EFT interpretation of the

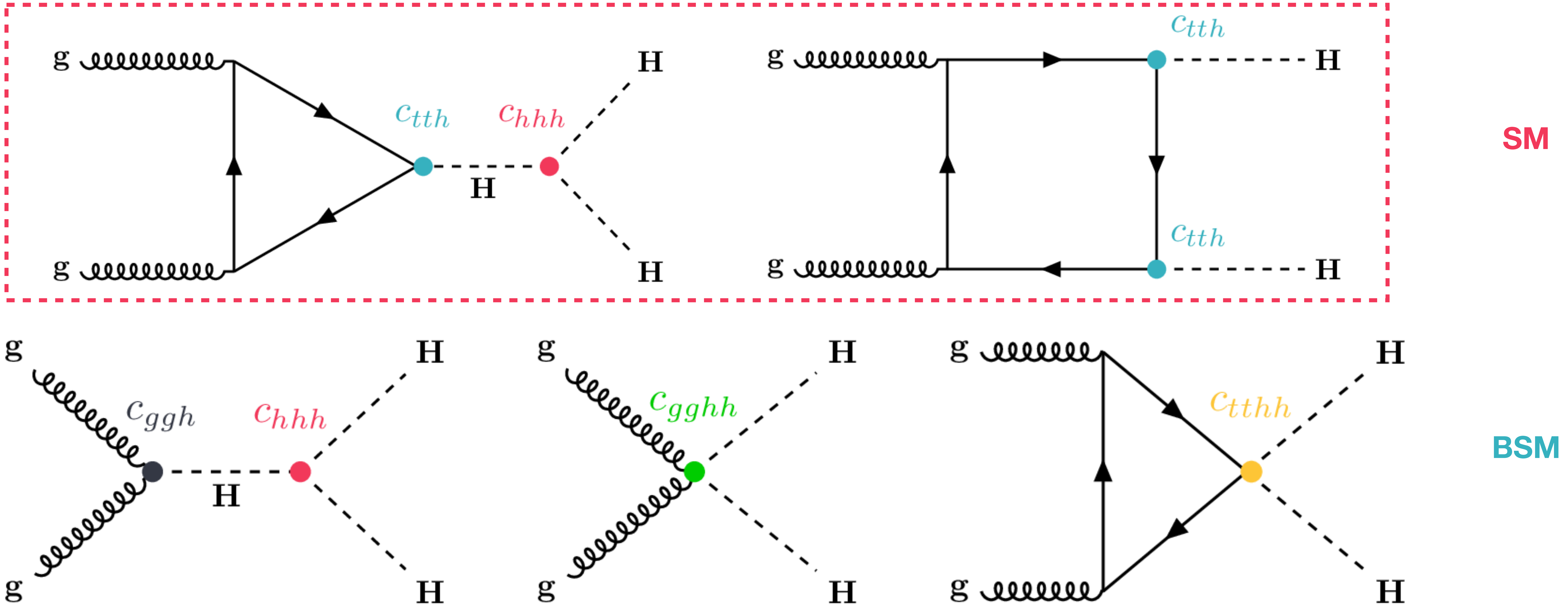
Search for $HH \to b\bar{b}\gamma\gamma$ in the ATLAS detector

HEFT interpretation

- Where $c_{hhh} = \kappa_\lambda$ and $c_{thh} = \kappa_t$
- In the SM: c_{hhh} = c_{thh}= 1 and c_{ggh}= c_{tthh}= c_{gghh} = 0

- The Effective Field Theory (EFT) framework can be used as a tool to:

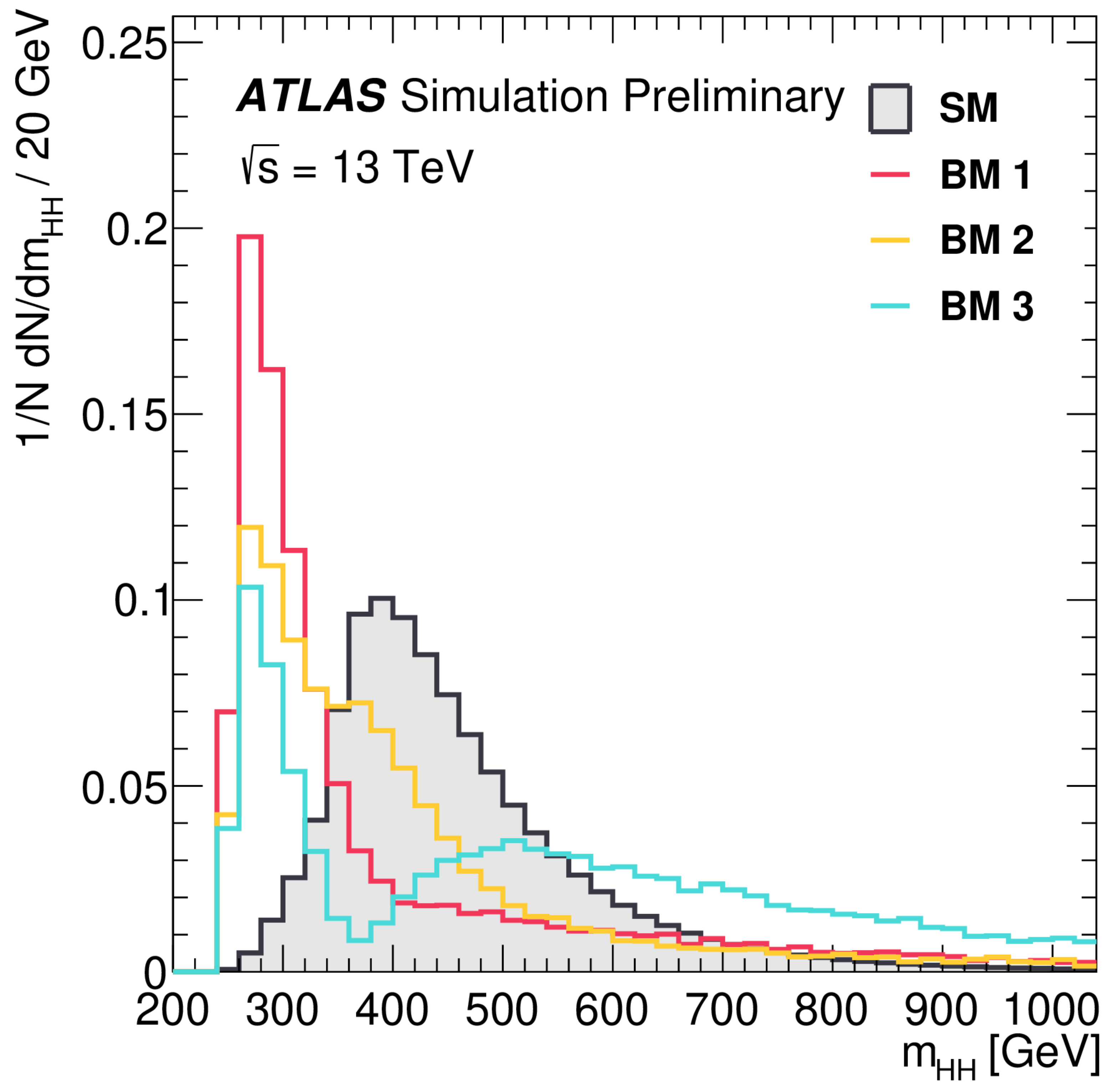
1. Make a more general measurement of the Higgs self-coupling → Natural extension of the kappa framework
2. Explore Beyond-the-Standard-Model scenarios produced a E >> E_{LHC}.



BSM exploration through HEFT

- HEFT shape benchmarks can be used to explore BSM scenarios which are uniquely sensitive to HH production.
    - By varying the EFT couplings we are also modifying the shape of m_{hh}.
    - Theorists have suggested a set of 7 benchmarks that fairly **represent the different shapes** obtained by the coupling variations in HEFT at NLO.

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



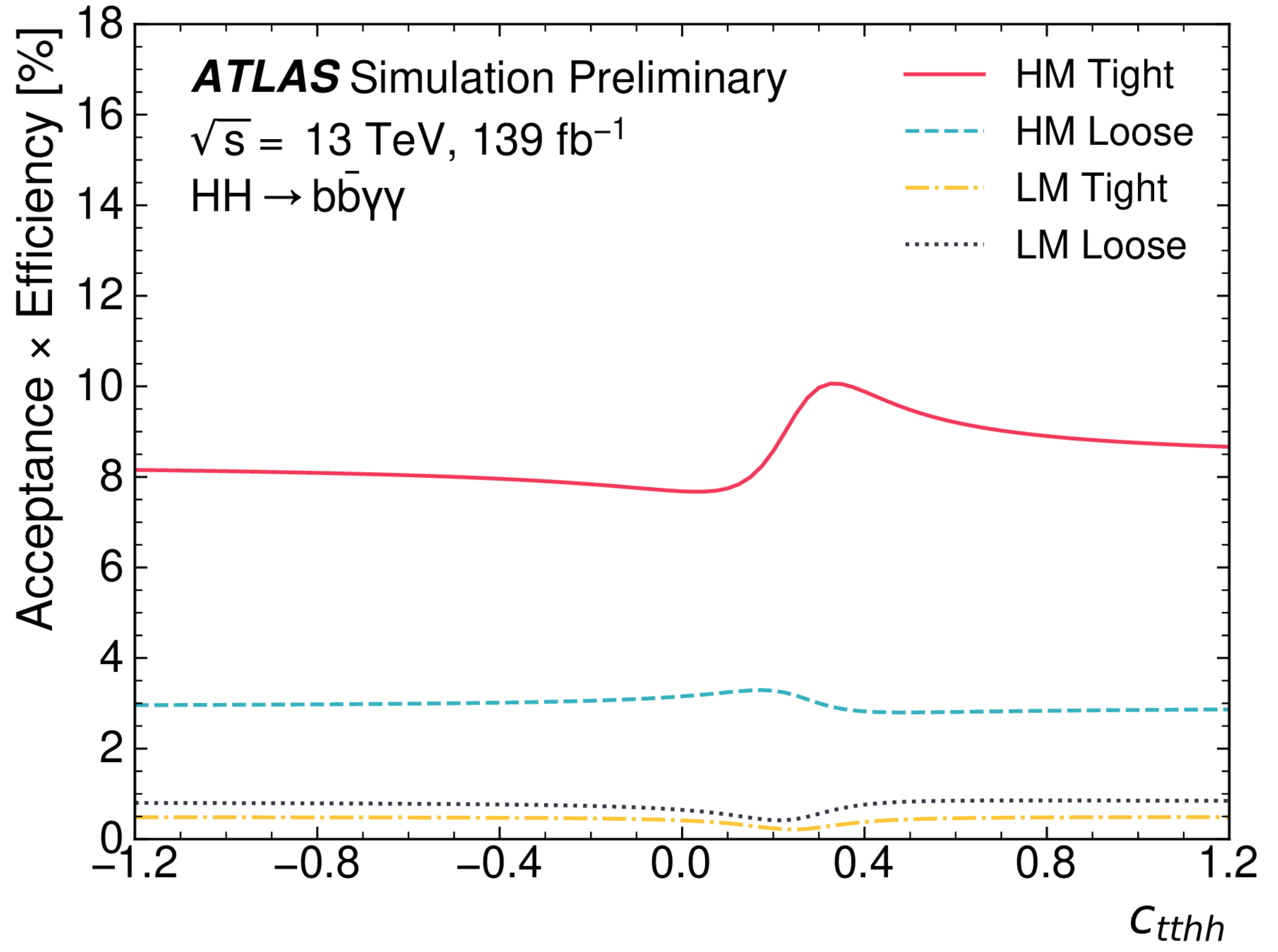
Scans to the HEFT Wilson coefficients

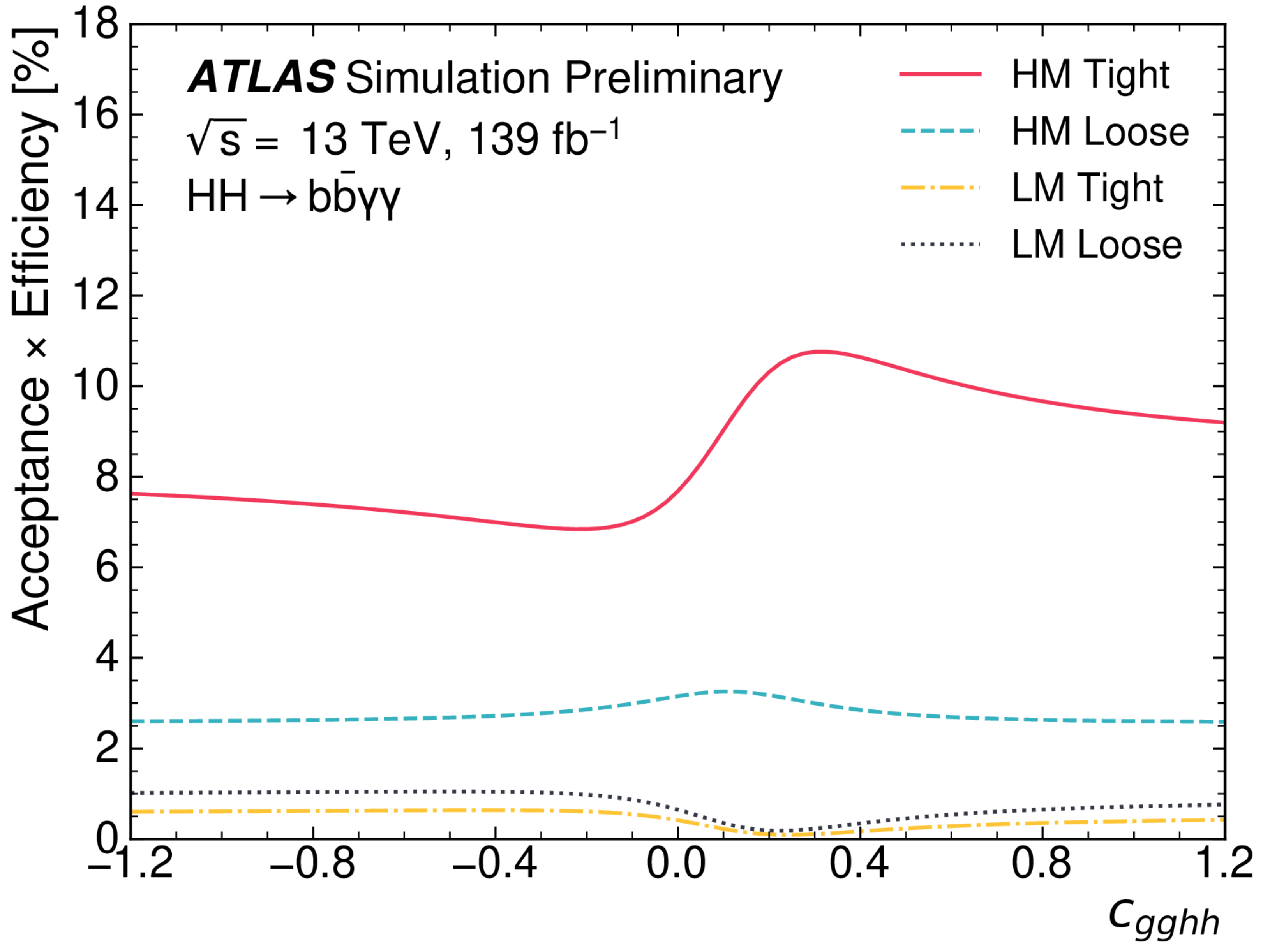
- Limits to $c_{hhh} = \kappa_\lambda$ are already set by the standard $HH \rightarrow bb\gamma\gamma$ analysis.

- In HEFT, the Higgs field is a singlet and therefore $c_{ggh} - c_{gghh}$ and $c_{thh} - c_{tthh}$ are independent:
  - Alternatively, in SMEFT, the Higgs field is a doublet (SM like) and $c_{ggh} - c_{gghh}$ and $c_{thh} - c_{tthh}$ are dependent.

  - The $c_{thh} = \kappa_t$ and c_{ggh} Wilson coefficients are better constrained by single Higgs analyses.

  - HH is uniquely sensitive to the c_{tthh} and c_{gghh} Wilson coefficients.

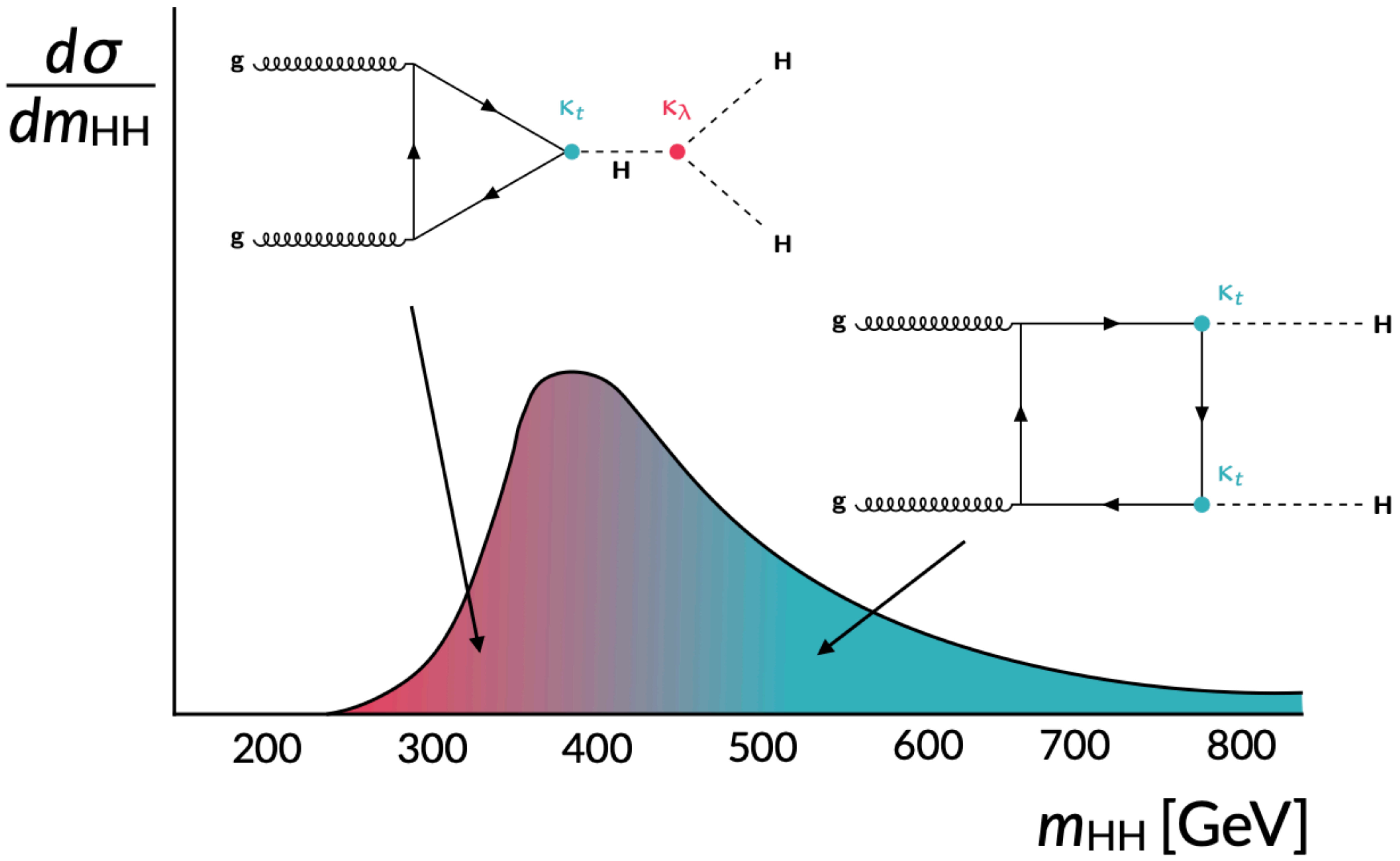




Signal reweighting and uncertainty

- A reweighting of the SM ggF HH signal is used to generate the ggF HEFT signals (arxiv:1806.05162).

$$w_{EFT} = \frac{\sigma(m_{hh})}{\sigma^{SM}(m_{hh})} = \frac{Poly(m_{hh} \,|\, c_{hhh}, c_t, c_{tt}, c_{ggh}, c_{gghh})}{Poly(m_{hh} \,|\, 1,1,0,0,0)}$$



- An uncertainty on the selection efficiency is estimated from simulated events at truth level.

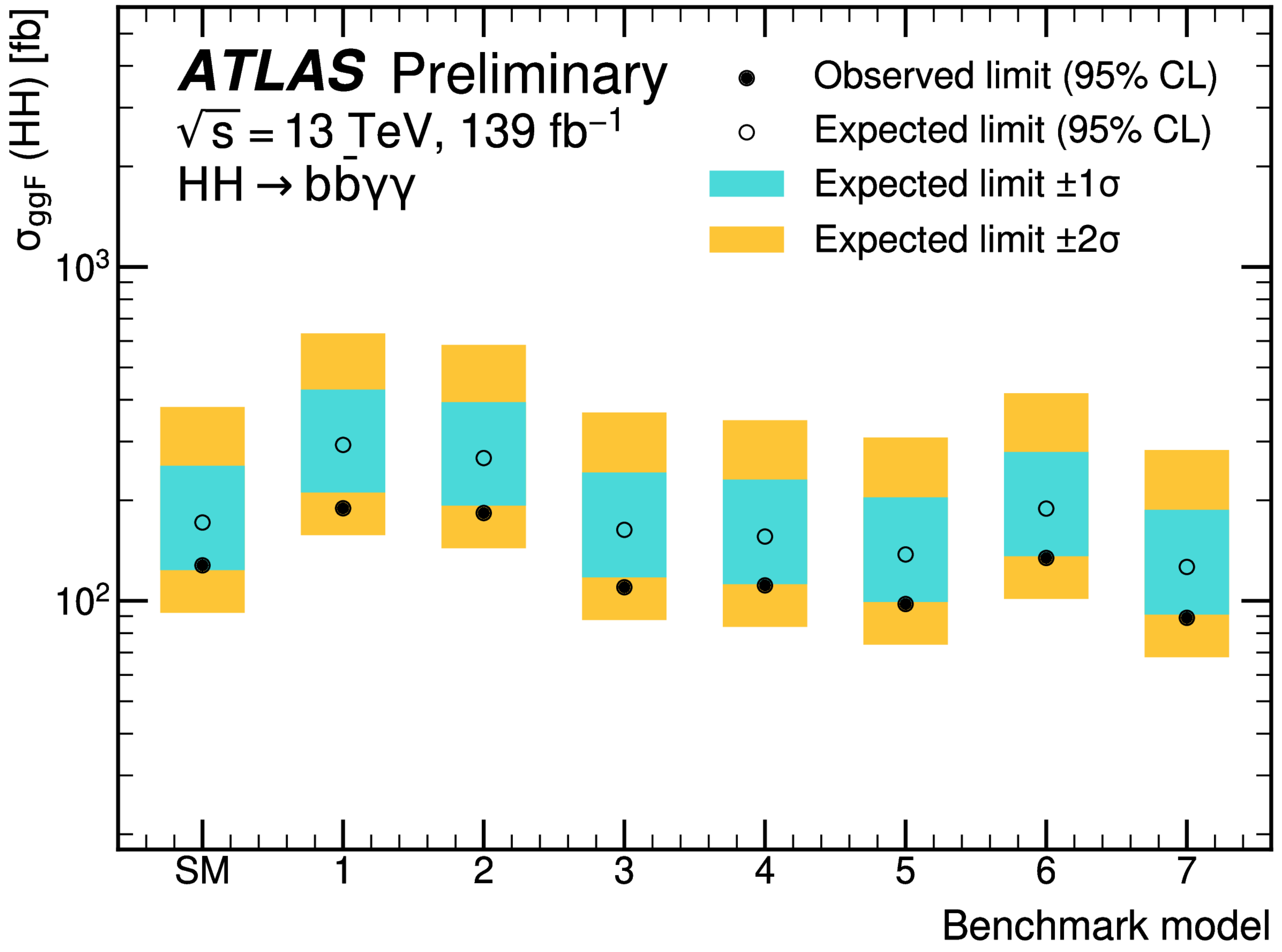
Channel	$b\bar{b}\gamma\gamma$	
Region	LM	HM
BM 1	4.9%	0.4%
BM 2	2.4%	4.2%
BM 3	6.1%	4.7%
BM 4	5.3%	1.4%
BM 5	10.8%	2.5%
BM 6	2.8%	1.3%
BM 7	0.3%	2.3%

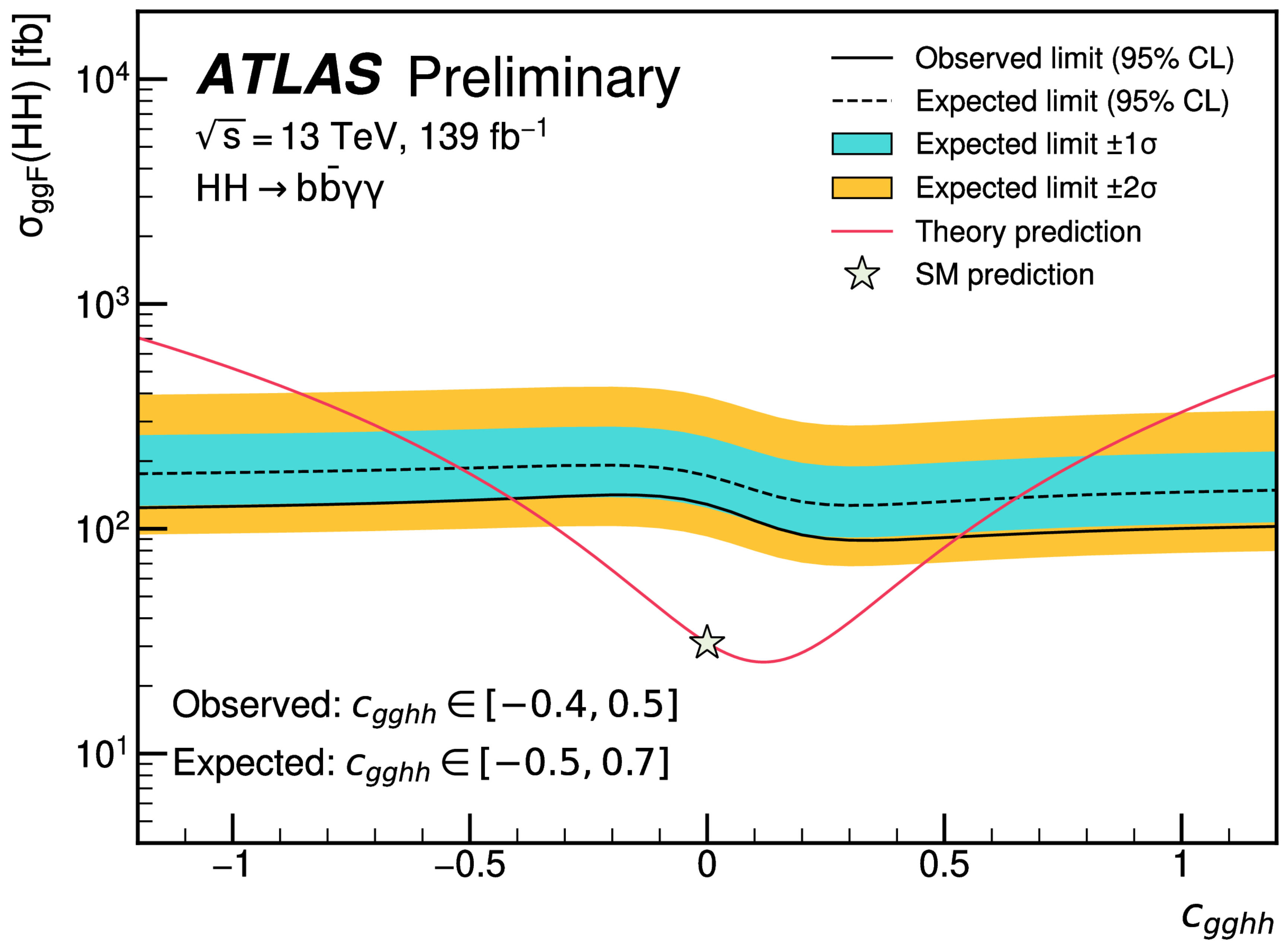
Channel	$b\bar{b}\gamma\gamma$	
Region	LM	HM
c_{gghh}	9.8%	6.2%
c_{tthh}	8.7%	1.6%

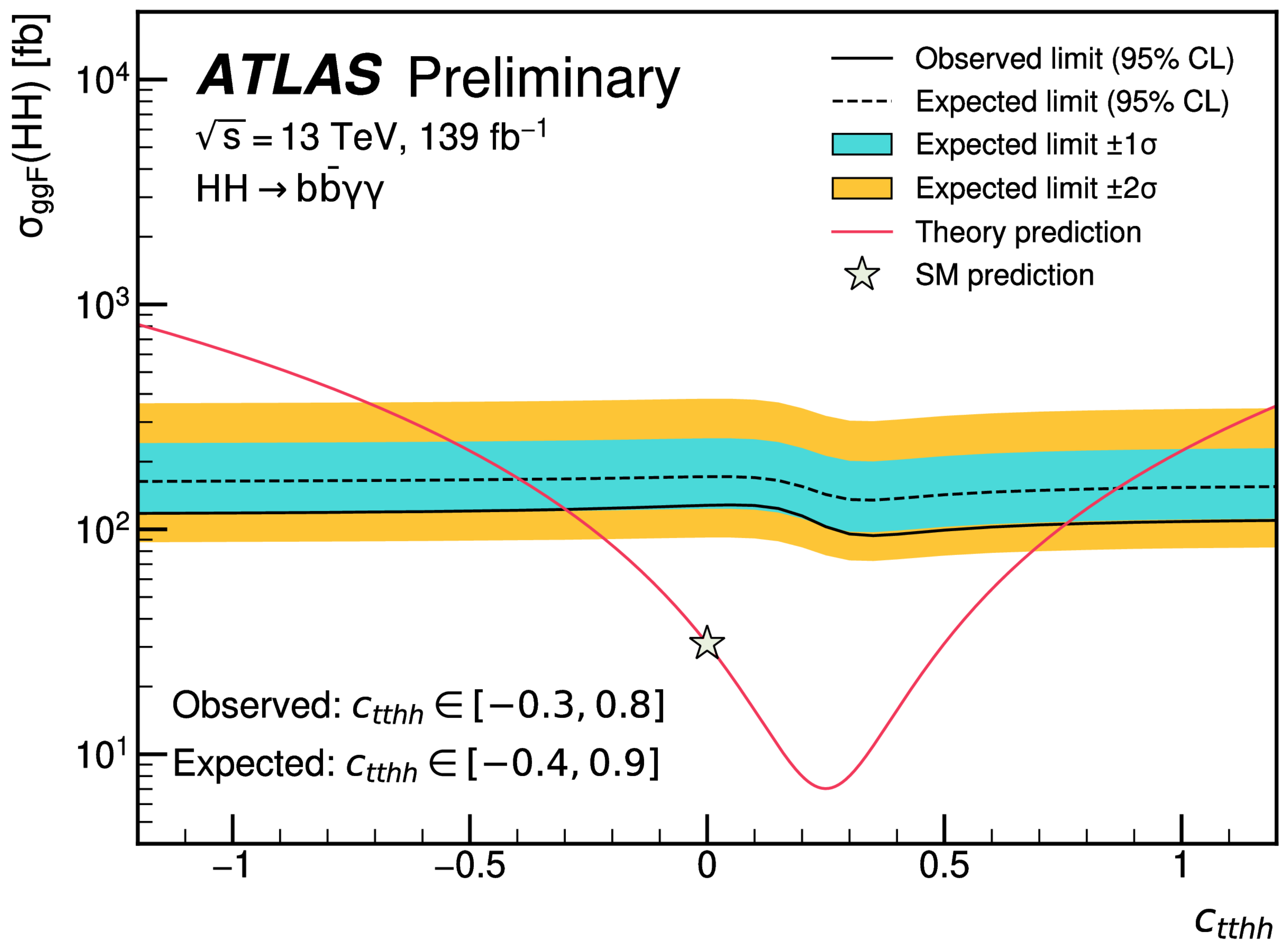
- The effect on the reweighting on the $m_{\gamma\gamma}$ shape is found to be negligible.

HEFT interpretations results

- The SM VBF HH process is treated as background.
- Limits on $\sigma_{ggF}(HH)$ are set at 95% CL on the SM, the 7 shape benchmarks, the c_{tthh} and the c_{gghh} scans.







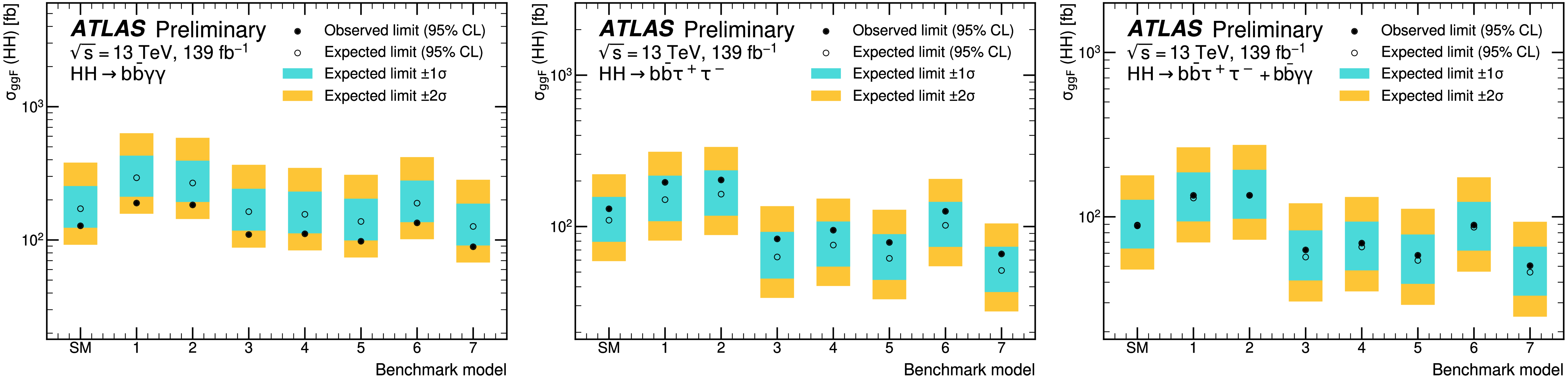
HEFT interpretation of $bb\gamma\gamma$, $bb\tau\tau$ and their combination

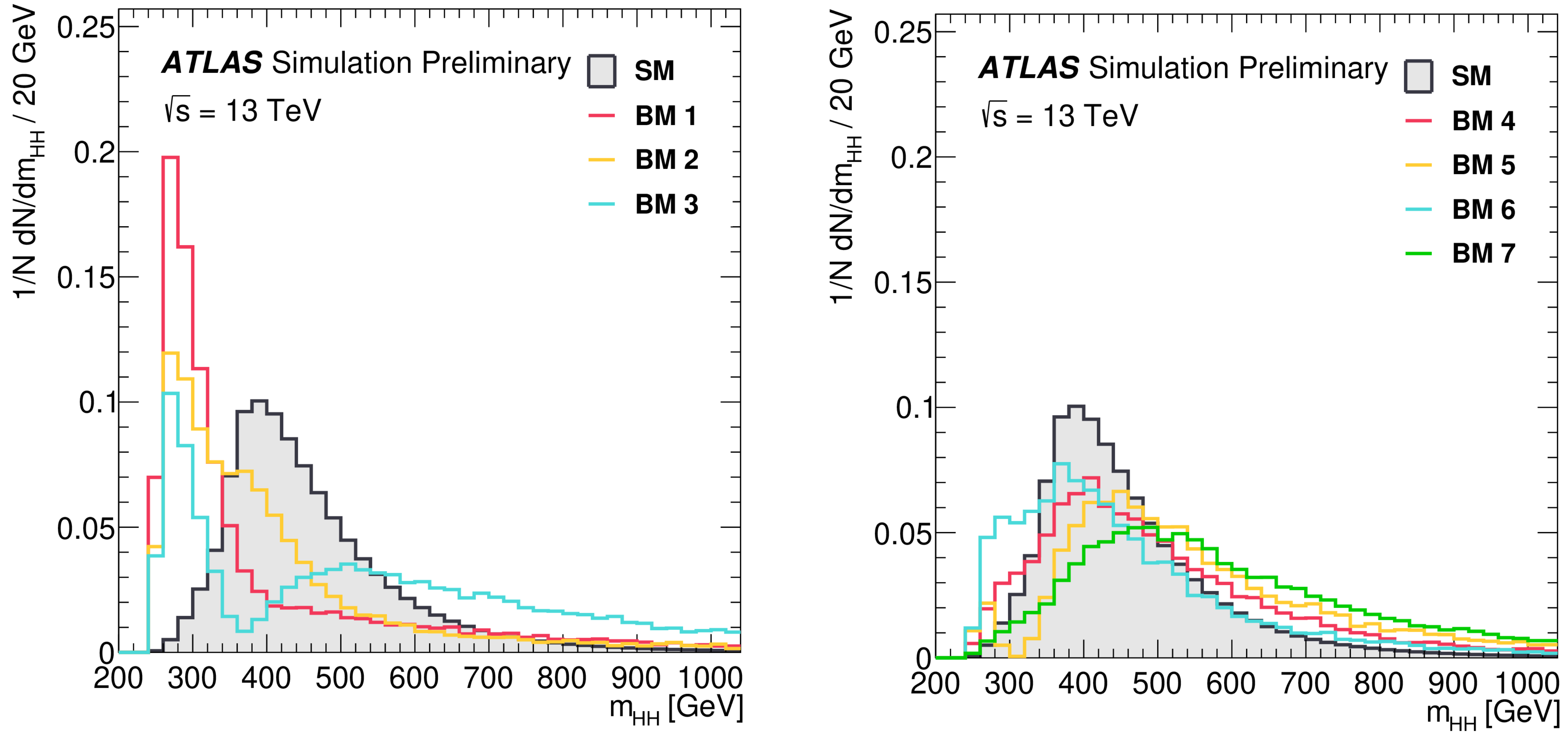
Upper limits at 95% CL on the ggF HH cross-section [fb]											
	$b\bar{b}\gamma\gamma$		$b\bar{b}\tau^+\tau^-$		Combination						
Benchmark	Obs.	Exp.	Obs.	Exp.	Obs.	-2σ	-1σ	Exp.	$+1\sigma$	$+2\sigma$
SM	127.7	171.6	130.9	110.1	88.1	47.8	64.2	89.1	126.9	178.8
BM 1	189.3	293.0	195.8	150.5	135.0	69.9	93.8	130.2	186.3	264.7
BM 2	183.2	267.7	203.1	163.7	135.1	72.5	97.4	135.1	193.1	273.8
BM 3	109.8	163.2	82.8	62.9	62.9	30.6	41.0	56.9	82.7	120.8
BM 4	111.2	155.8	94.6	75.4	69.2	35.2	47.2	65.6	93.5	132.0
BM 5	97.8	137.7	78.5	61.6	58.4	29.1	39.1	54.3	78.1	111.9
BM 6	134.4	188.9	126.1	101.8	89.1	46.4	62.3	86.5	123.3	174.0
BM 7	88.9	126.3	65.9	51.2	50.4	24.7	33.2	46.0	65.8	93.3

	$b\bar{b}\gamma\gamma$		$b\bar{b}\tau^+\tau^-$		Combination	
Wilson coefficient	Obs.	Exp.	Obs.	Exp.	Obs.	Exp.
c_{gghh}	$[-0.4, 0.5]$	$[-0.5, 0.7]$	$[-0.4, 0.4]$	$[-0.4, 0.4]$	$[-0.3, 0.4]$	$[-0.3, 0.3]$
c_{tthh}	$[-0.3, 0.8]$	$[-0.4, 0.9]$	$[-0.3, 0.7]$	$[-0.2, 0.6]$	$[-0.2, 0.6]$	$[-0.2, 0.6]$

Important Swedish contribution from Uppsala and Stockholm University

HEFT interpretation of $bb\gamma\gamma$, $bb\tau\tau$ and their combination





- The tightest limits are set for BM 7 (high m_{HH}) while the less stringent limits are set to BM 1 and 2 (low m_{HH}).
- The $bb\tau\tau$ channel has better sensitivity, specially to high m_{HH}.

Conclusions

- **These results were presented at Moriond 22!**
- This is the first public result of HH EFTs in ATLAS
- The pub note can be found at ATL-PHYS-PUB-2022-019

ATLAS PUB Note

ATL-PHYS-PUB-2022-019

18th March 2022

HEFT interpretations of Higgs boson pair searches in $b\bar{b}\gamma\gamma$ and $b\bar{b}\tau\tau$ final states and of their combination in ATLAS

The ATLAS Collaboration

Backup

HH decay modes

- Due to the large branching ratio (BR), most searches require at least one $H \rightarrow b\bar{b}$. Different decay modes of the second Higgs are considered.

Targeted HH decays shown today

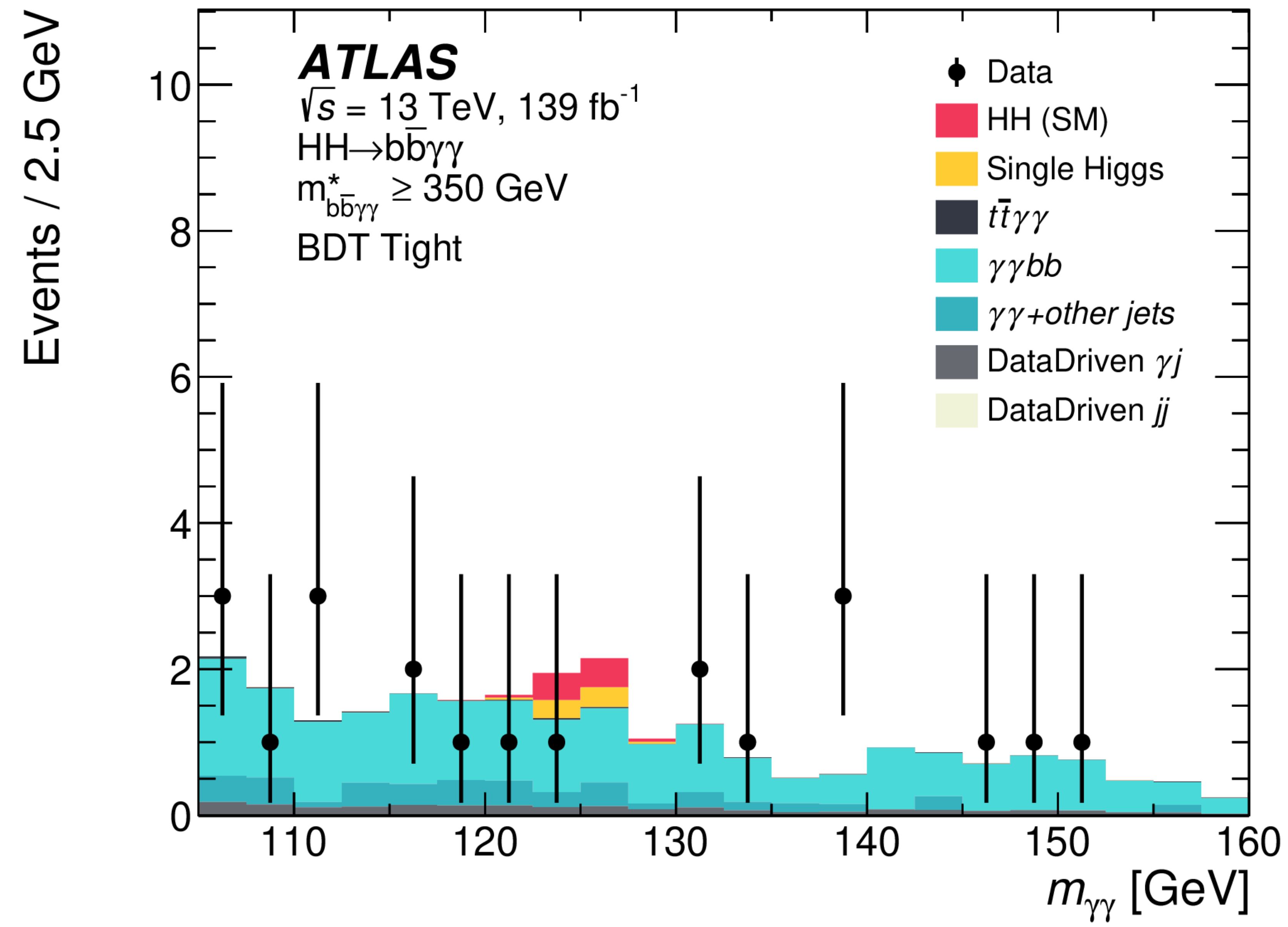
	bb	WW	ττ	ZZ	γγ
bb	33%				
WW	25%	4.6%			
ττ	7.4%	2.5%	0.39%		
ZZ	3.1%	1.2%	0.34%	0.076%	
γγ	0.26%	0.10%	0.029%	0.013%	0.0005%

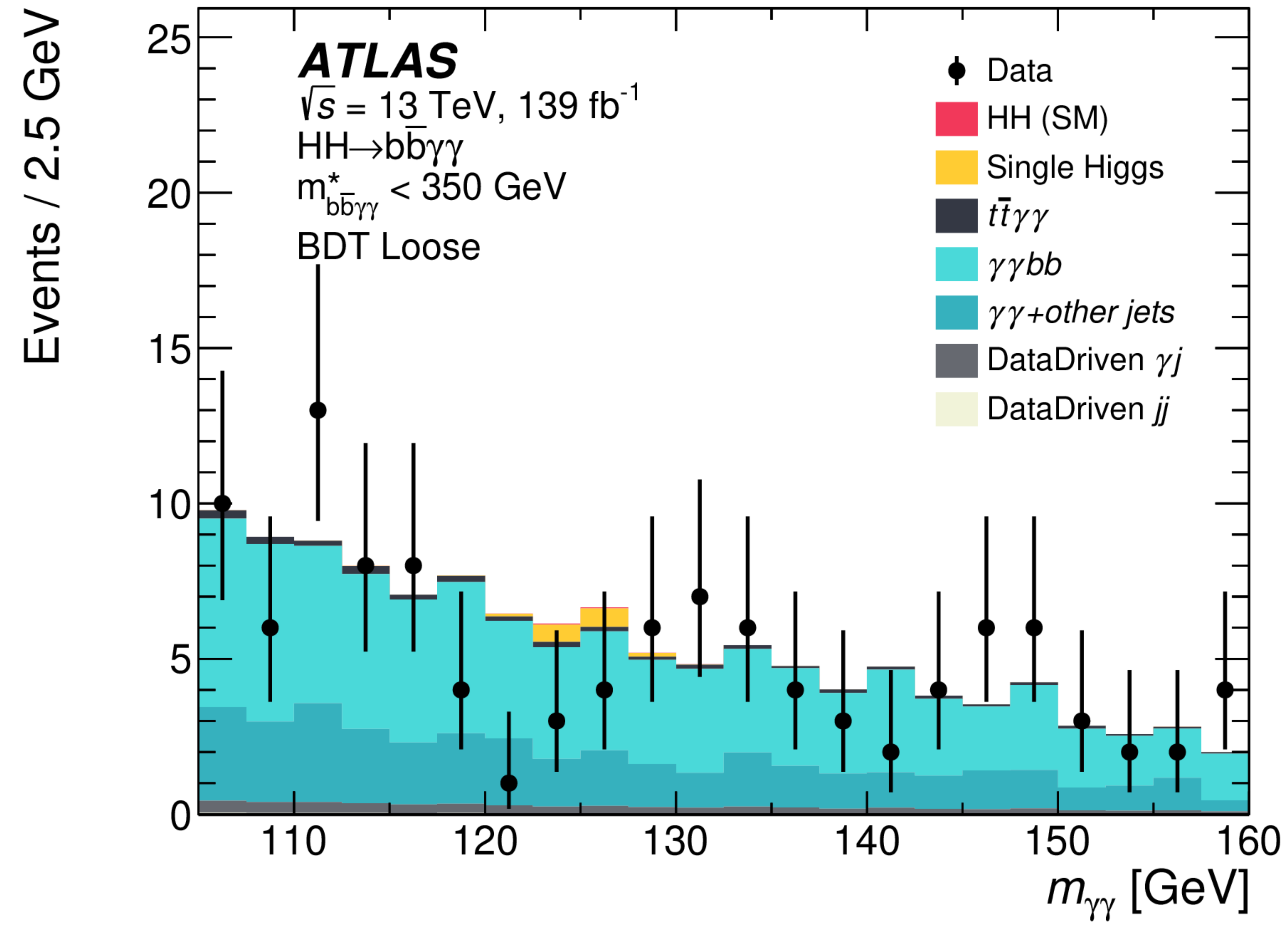
- ATLAS and CMS searches with full run 2 data for the following decay modes are presented:
  - $b\bar{b}b\bar{b}$ has the largest BR but large backgrounds arising from multijet production are challenging.
  - $b\bar{b}WW$, $b\bar{b}ZZ$ and $b\bar{b}\tau\tau$ have smaller BRs and can benefit from using leptons for triggering (hadronic $b\bar{b}\tau\tau$ searches won't be presented).
  - $b\bar{b}\gamma\gamma$ has the smallest BR but it's a very sensitive analysis thanks to the clean $m_{\gamma\gamma}$ resolution.
- Other final states without any $H \rightarrow b\bar{b}$ are also included in the combinations with partial run 2 data.

$HH \to b\bar{b}\gamma\gamma$ table

Table 1: The number of data events observed in the $120 < m_{\gamma\gamma} < 130$ GeV window, the number of HH signal events expected for $\kappa_\lambda = 1$ and for $\kappa_\lambda = 10$, and events expected for single Higgs boson production (estimated using MC simulation), as well as for continuum background. For the single Higgs boson, "Rest" includes the following production modes: VBF, WH, tHq, and tHW. The values are obtained from a fit of the Asimov data set generated under the SM signal-plus-background hypothesis, $\kappa_\lambda = 1$. The continuum background component of the Asimov data set is obtained from the fit of the data sideband. The uncertainties in HH signals and single Higgs boson background include the systematic uncertainties discussed in Section **??**. The uncertainty in the continuum background is given by the sum in quadrature of the statistical uncertainty from the fit to the data and the spurious-signal uncertainty.

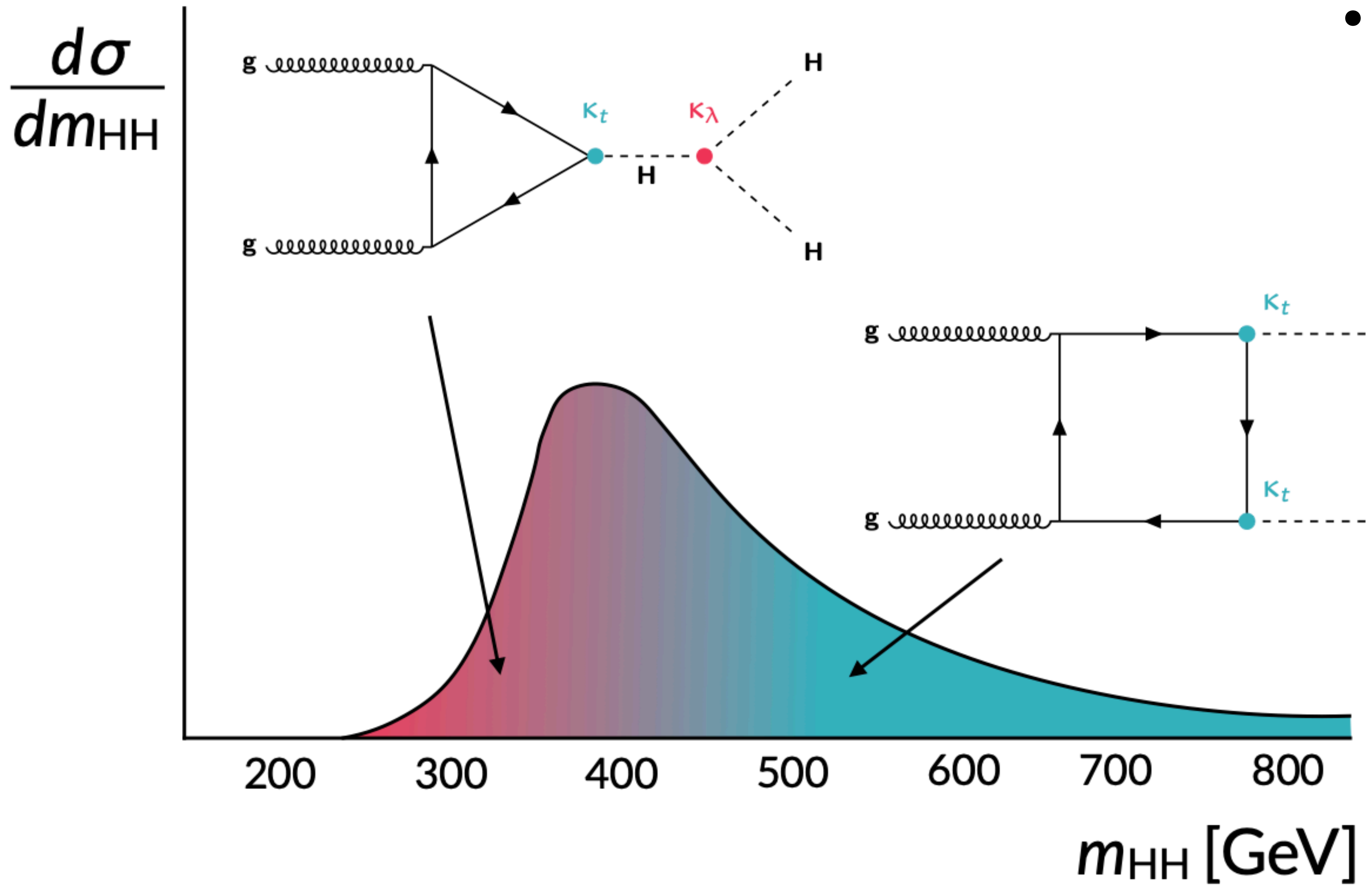
	High mass BDT tight	High mass BDT loose	Low mass BDT tight	Low mass BDT loose
Continuum background	$4.9^{+1.1}_{-1.3}$	$9.5^{+1.5}_{-1.7}$	$3.7^{+0.9}_{-1.1}$	$24.9^{+2.3}_{-2.5}$
Single Higgs boson background	$0.67^{+0.29}_{-0.13}$	$1.6^{+0.6}_{-0.2}$	$0.23^{+0.09}_{-0.03}$	$1.40^{+0.33}_{-0.16}$
ggF+bbH	$0.26^{+0.28}_{-0.16}$	$0.4^{+0.5}_{-0.2}$	$0.07^{+0.08}_{-0.04}$	$0.27^{+0.27}_{-0.16}$
$t\bar{t}H$	$0.19^{+0.03}_{-0.03}$	$0.49^{+0.09}_{-0.07}$	$0.107^{+0.022}_{-0.017}$	$0.75^{+0.13}_{-0.11}$
ZH	$0.142^{+0.035}_{-0.025}$	$0.48^{+0.09}_{-0.07}$	$0.040^{+0.020}_{-0.014}$	$0.27^{+0.06}_{-0.04}$
Rest	$0.074^{+0.032}_{-0.014}$	$0.16^{+0.07}_{-0.03}$	$0.012^{+0.008}_{-0.004}$	$0.111^{+0.030}_{-0.012}$
SM $HH(\kappa_\lambda = 1)$ signal	$0.87^{+0.10}_{-0.18}$	$0.37^{+0.04}_{-0.07}$	$0.049^{+0.006}_{-0.010}$	$0.078^{+0.008}_{-0.015}$
ggF	$0.86^{+0.10}_{-0.18}$	$0.35^{+0.04}_{-0.07}$	$0.046^{+0.006}_{-0.010}$	$0.072^{+0.008}_{-0.015}$
VBF	$(12.6^{+1.3}_{-1.2}) \cdot 10^{-3}$	$(16.1^{+1.4}_{-1.2}) \cdot 10^{-3}$	$(3.2^{+0.4}_{-0.4}) \cdot 10^{-3}$	$(6.9^{+0.5}_{-0.6}) \cdot 10^{-3}$
Alternative $HH(\kappa_\lambda = 10)$ signal	$6.5^{+1.0}_{-0.8}$	$3.6^{+0.6}_{-0.4}$	$4.5^{+0.7}_{-0.6}$	$8.5^{+1.3}_{-1.0}$
Data	2	17	5	14





Signal reweighting

- The σ_{HH} depends only on m_{hh} and can be parametrised as a polynomial $Poly(A) = \sum_{i=1}^{N} A_i * c_j$, where A_i are some coefficients obtained from a fit and c_j are combinations of the 5 EFT couplings that play a role in HH production.

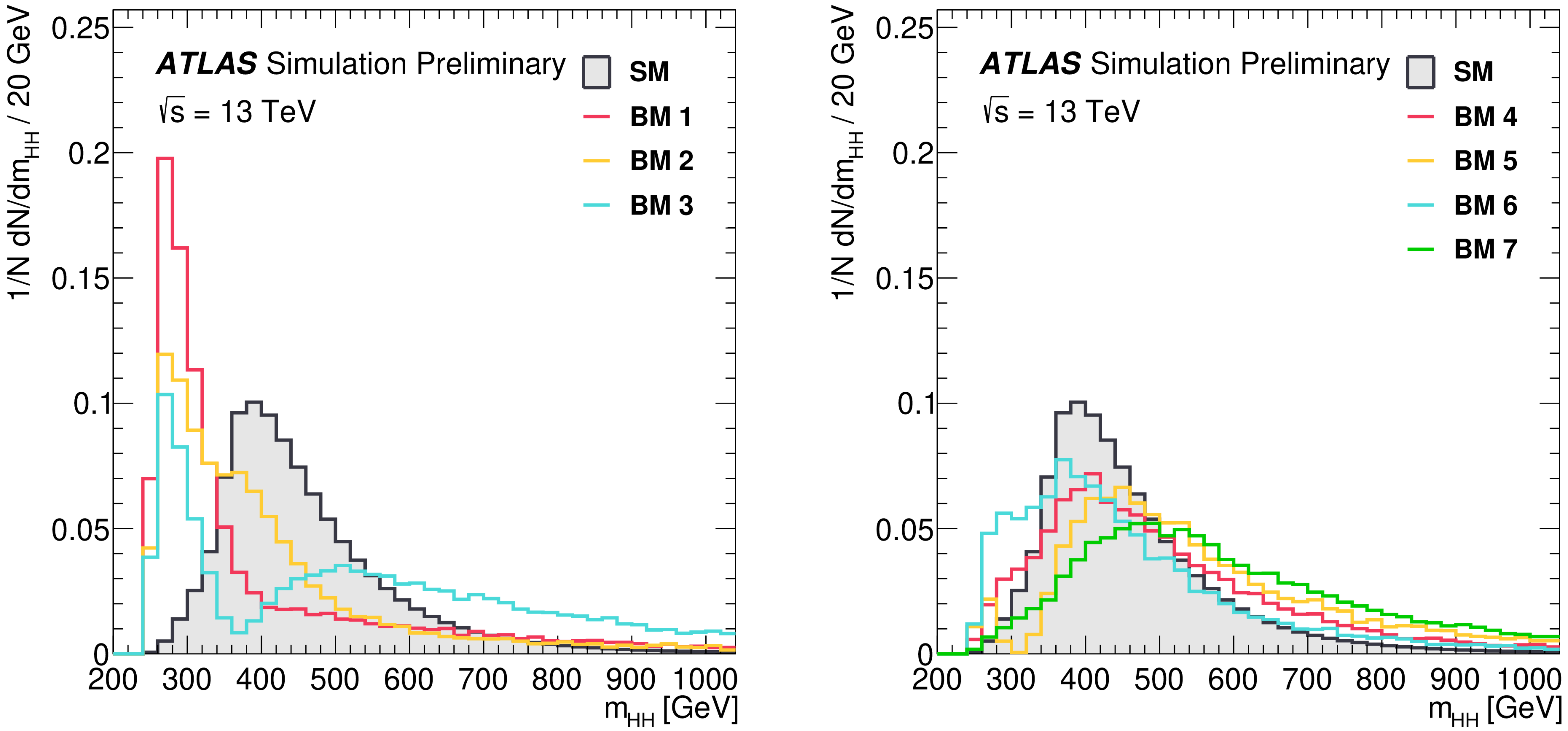


- From arxiv:1806.05162: A_{1-23} coefficients to predict σ_{HH}^{NLO}

$$w_{EFT} = \frac{\sigma(m_{hh})}{\sigma^{SM}(m_{hh})} = \frac{Poly(m_{hh}\,|\,c_{hhh}, c_t, c_{tt}, c_{ggh}, c_{gghh})}{Poly(m_{hh}\,|\,1,1,0,0,0)}$$

→ We can re-weight SM to any HEFT BSM point!

Benchmarks



ATLAS Simulation Preliminary
√s = 13 TeV
SM
BM 1
BM 2
BM 3
BM 4
BM 5
BM 6
BM 7
1/N dN/dm_HH / 20 GeV
m_HH [GeV]
0
0.05
0.1
0.15
0.2
0.25
200
300
400
500
600
700
800
900
1000

Signal selection efficiency

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