HH → $b\bar{b}\gamma\gamma$ search with ATLAS

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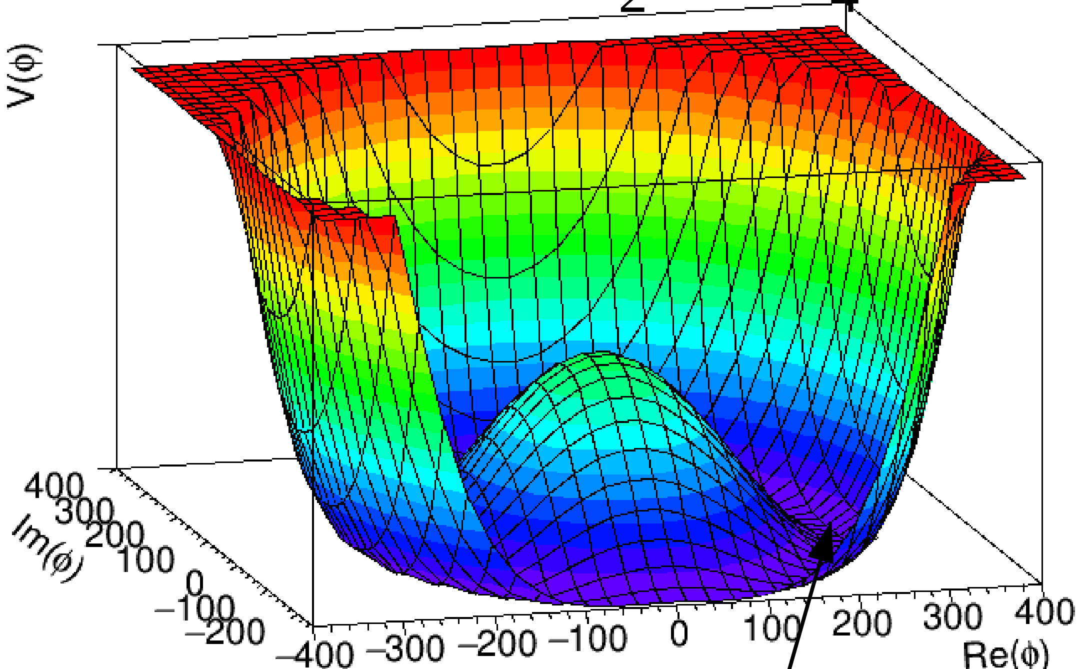
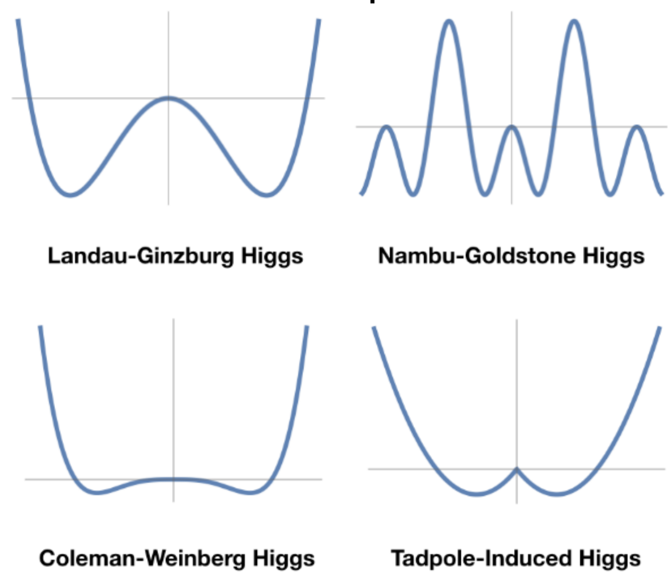
Why measuring the Higgs potential?

- Higgs potential: $V(\Phi) = \frac{1}{2}\mu^2\Phi^2 + \frac{1}{4}\lambda\Phi^4$



SM and non-SM potentials:



- Approximation around the v.e.v:

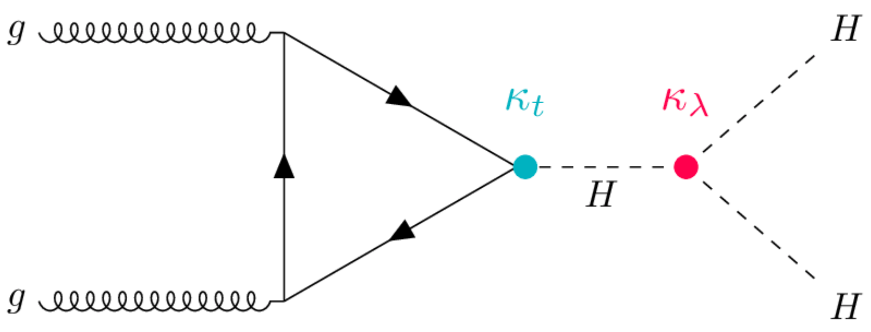
$$V(\Phi) \approx \lambda v^2 h^2 + \lambda v h^3 + \frac{1}{4}\lambda h^4$$

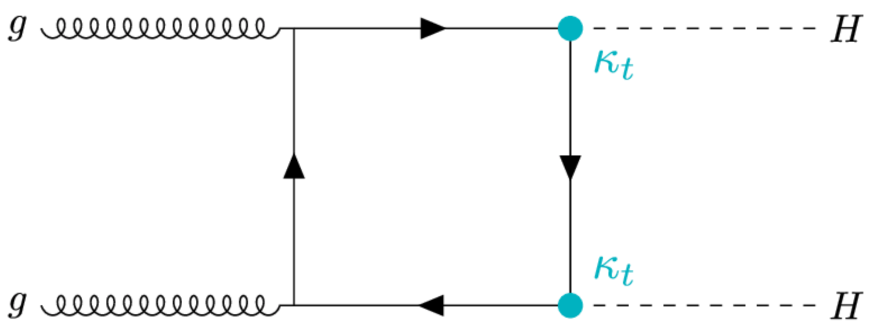
mass term self-coupling terms

- λ known from v.e.v and Higgs mass: $\lambda = \frac{m_H^2}{2 \cdot v^2} \approx 0.13$
- BSM effects could change $\lambda \Rightarrow$ define deviation of tri-linear term: $\kappa_\lambda = \frac{\lambda_{HHH}}{\lambda_{HHH}^{SM}}$
  - no quartic terms considered here

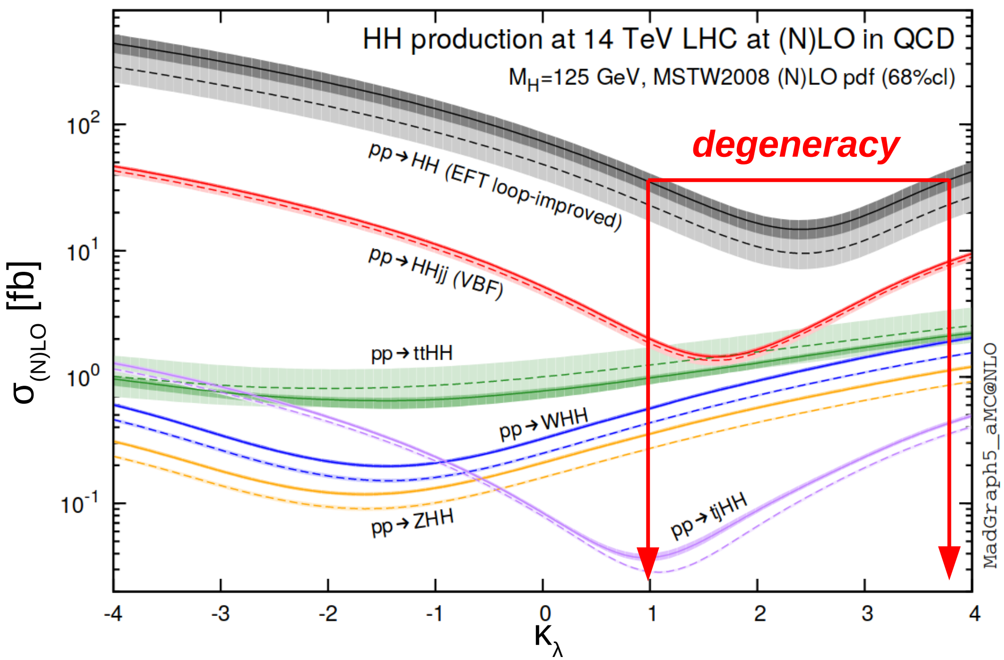
Why looking for HH production?

- Main production mode: ggF
  - destructive interference between triangle and box diagrams ⇒ σ(HH)/σ(H) = 0.1%





- Self-couplings through total HH cross section, and diff. cross section $d\sigma/dm_{HH}$:



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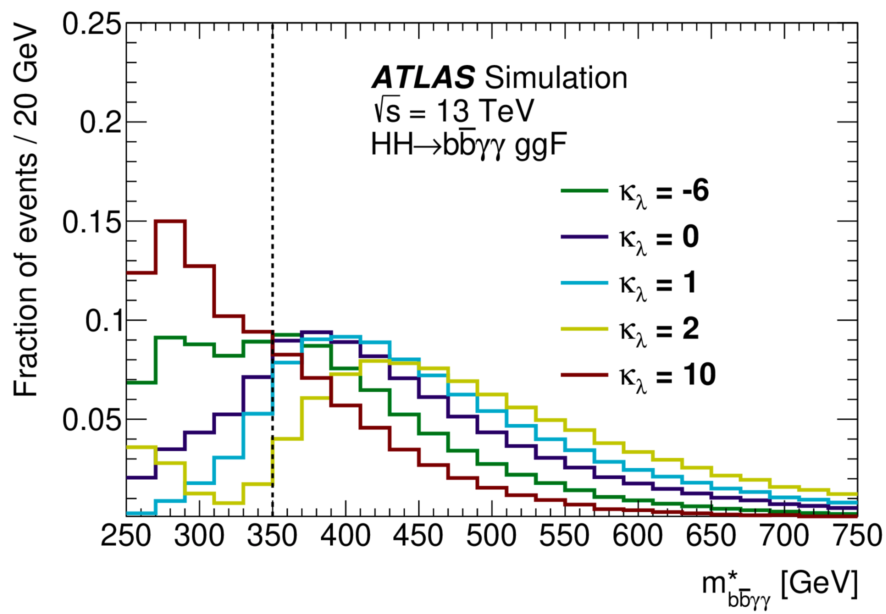
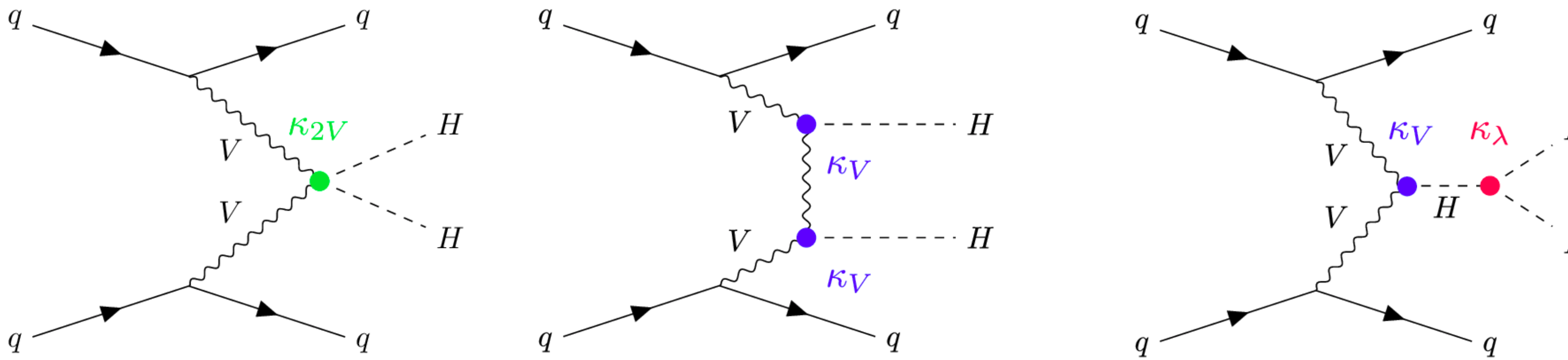


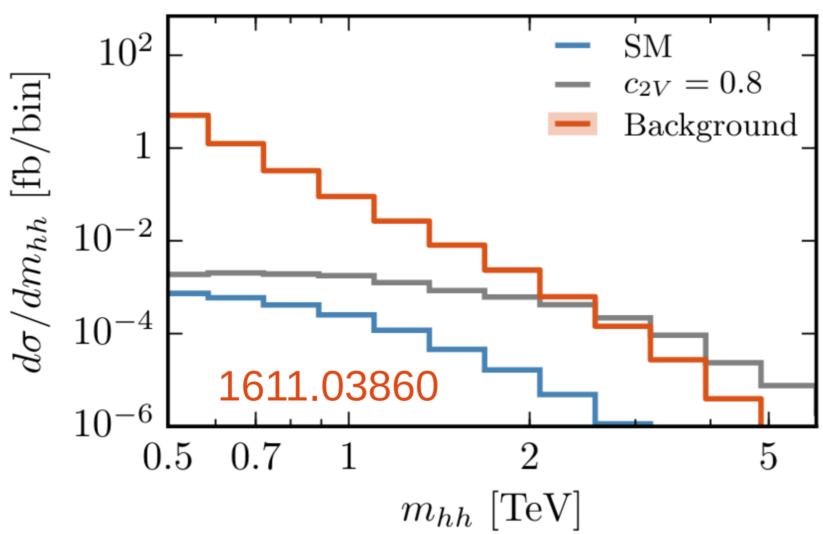
Why looking for VBF HH production?

- SM at 13 TeV: $\sigma_{ggF} = 31.05$ fb , $\sigma_{VBF} = 1.73$ fb
- HH production via VBF has unique sensitivity for the so far unmeasured HHVV coupling κ_{2V}



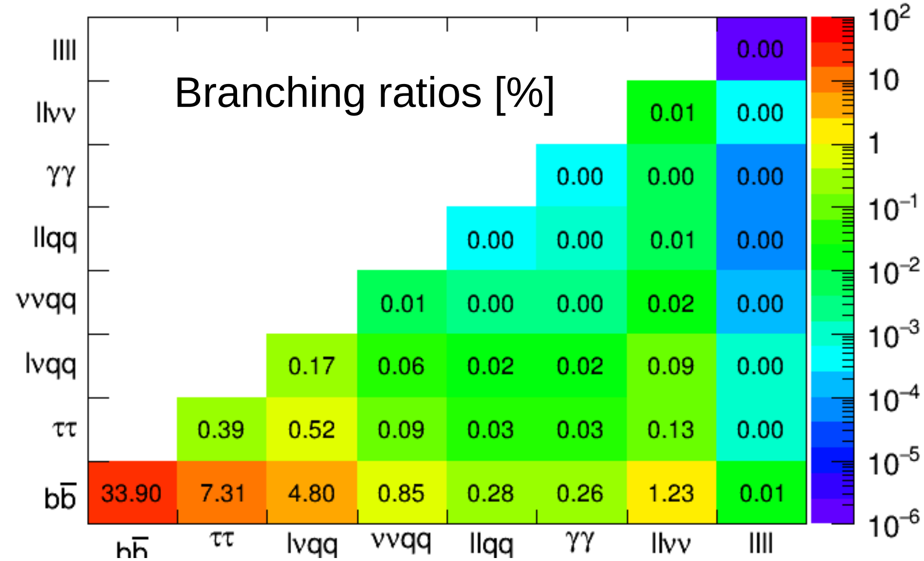
  - SM predicts $\kappa_{2V} = \kappa_V = 1$, cancellation of the first two diagrams, tiny cross section

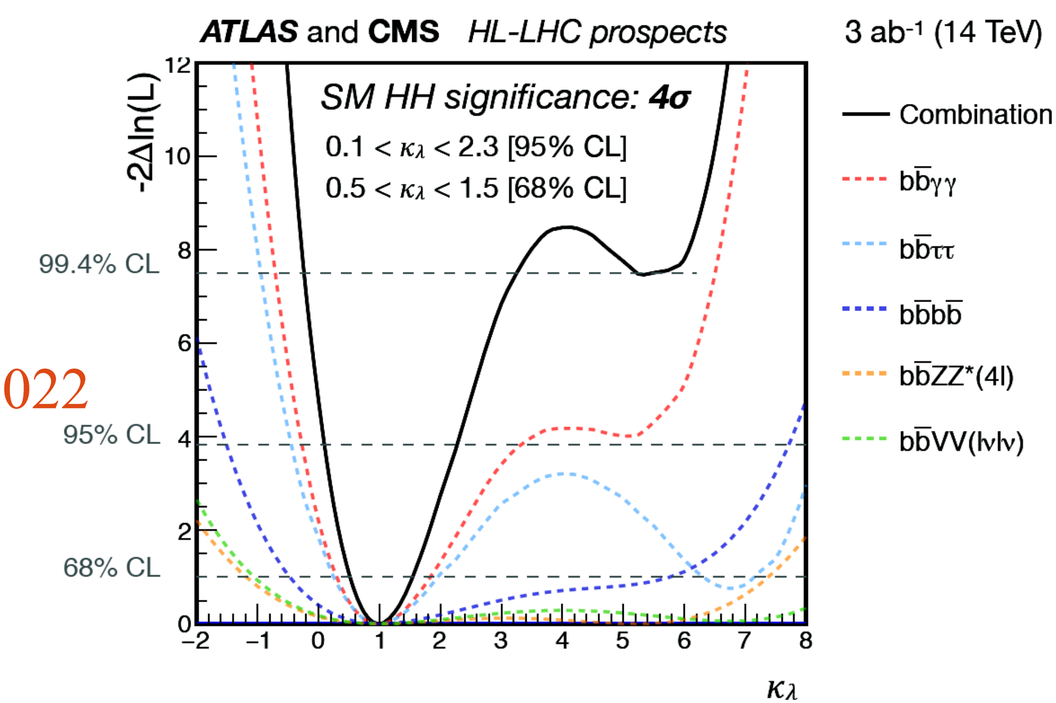
- New physics can manifest as $\kappa_{2V} \neq \kappa_V^2$
  - enhanced production rate, especially at high m_{HH}



Why the HH→ bbγγ channel?

bbbb	Largest BR ☺ Large multijet and tt bkg ☹
bbττ	Sizeable BR ☺ Relatively small bkg ☺
bbγγ	Small BR ☹ Good diphoton resolution ☺ Relatively small bkg ☺
bbVV (→lνlν)	Large BR ☺ Large bkg ☹
bbZZ (→4l)	Very small BR ☹ Very small bkg ☺





- First Run 2 paper published in Sep 2022
- Legacy Run 2 paper submitted last Wednesday (arxiv)
  - new dedicated VBF selection

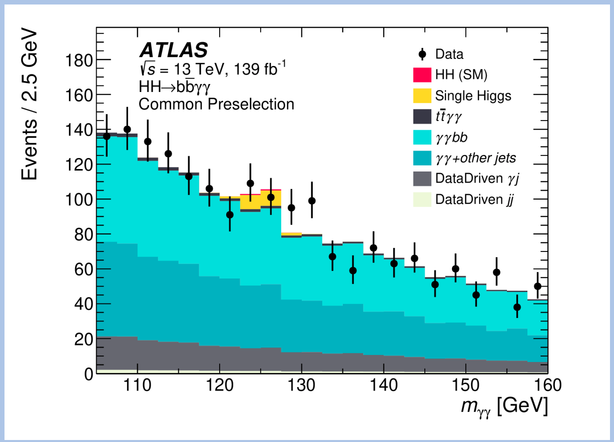
Analysis strategy

Preselection

Photons
- di-photon trigger
- well-isolated and identified
- ET/myy > 0.35/0.25

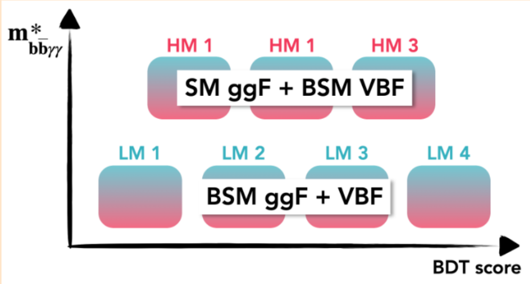
b-jets
- exactly 2 with 77% efficiency
- μ and lost energy corrections

ttH veto
- veto events with leptons
- veto events with > 5 central jets

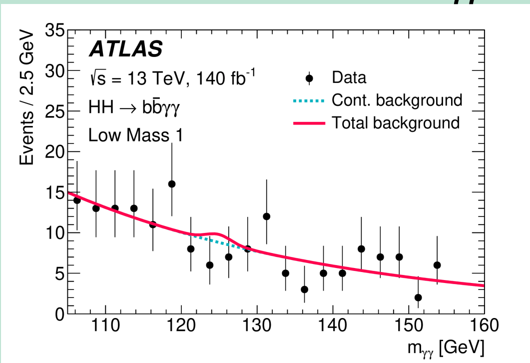


VBF jets tagger

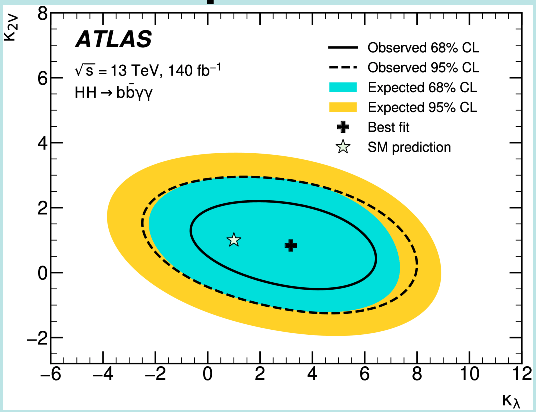
Categories



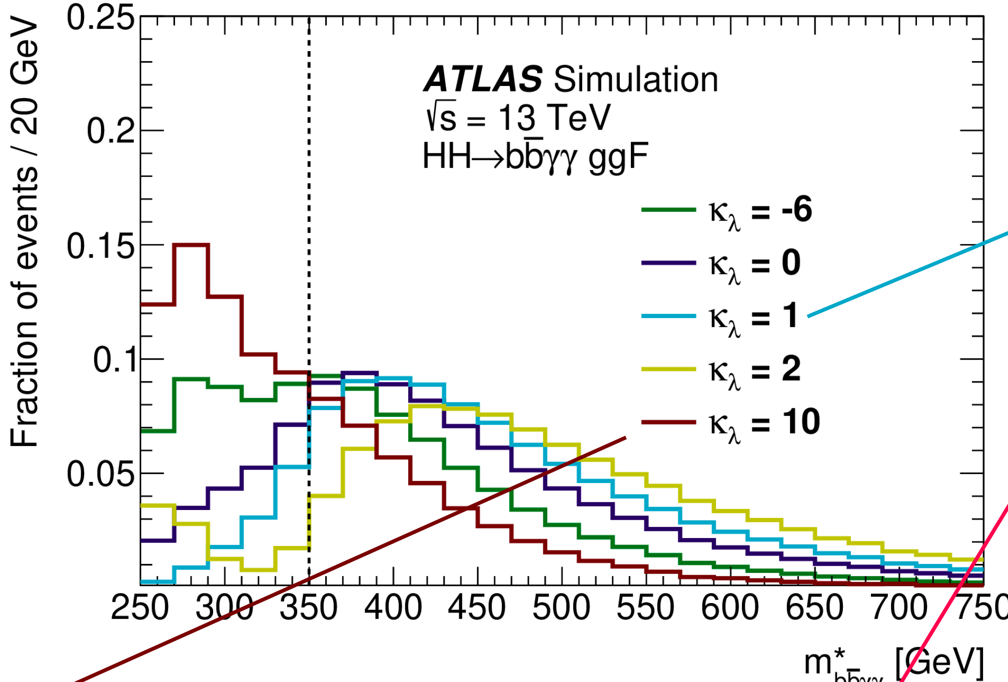
Unbinned maximum likelihood fit of $m_{\gamma\gamma}$



Interpretations

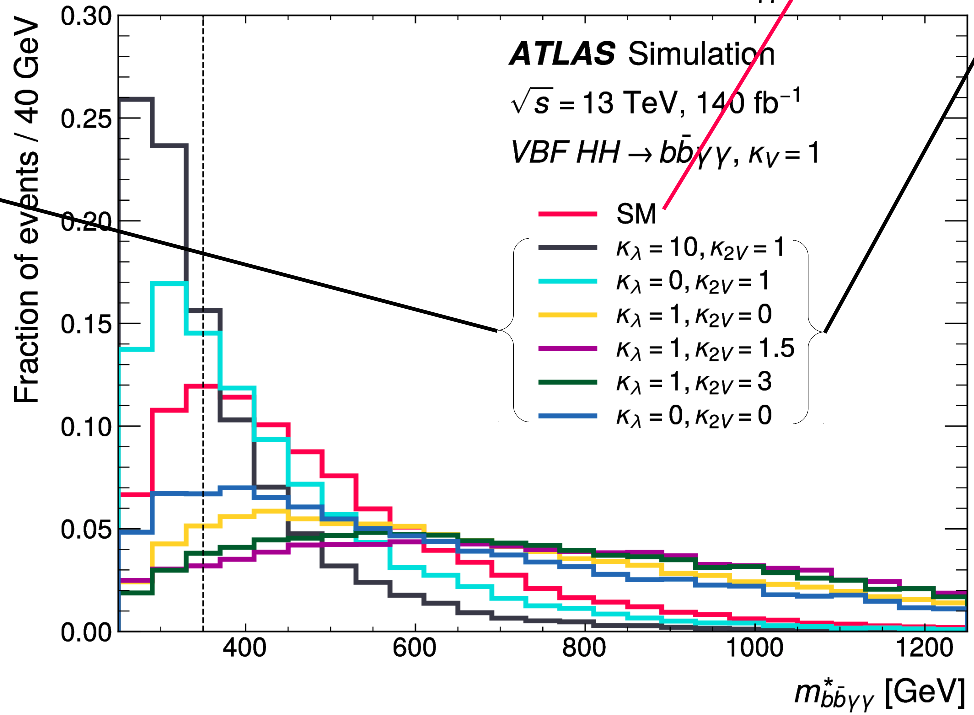


Mass categories



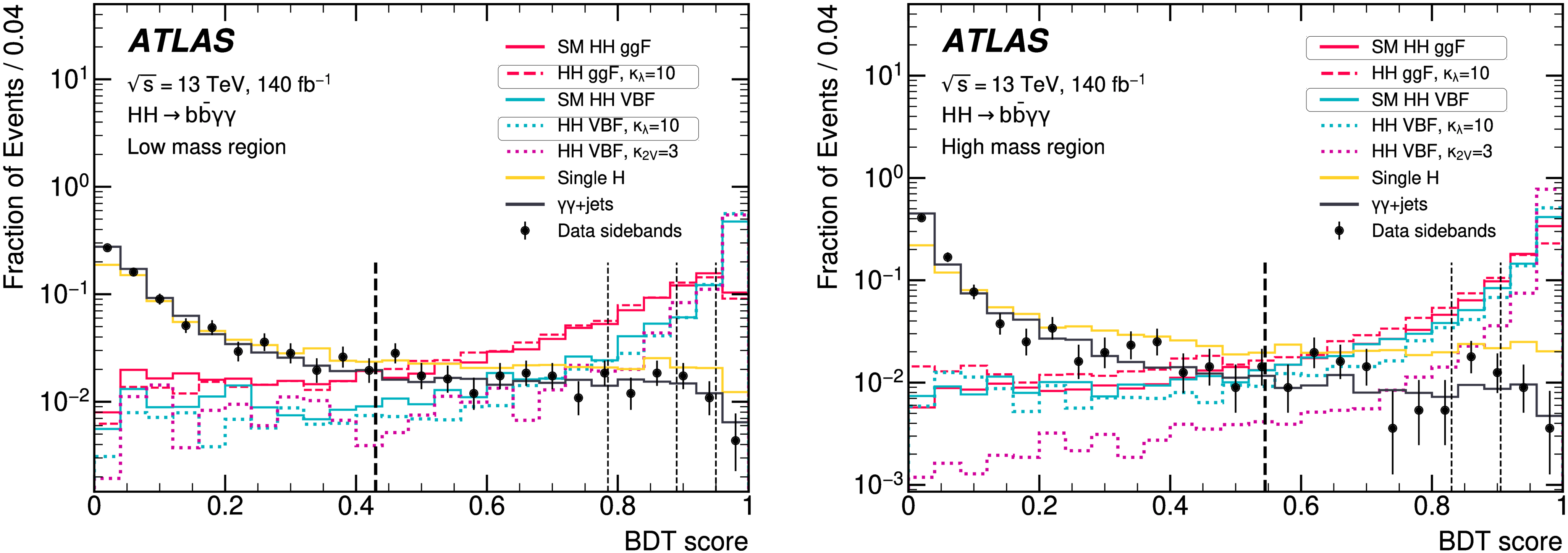
- ♦ High-mass
  - SM ggF
  - SM VBF
  - 5 non-SM VBF points

- ♦ Low-mass
  - ggF κλ = 10 and 5.6
  - non-SM VBF points



BDT selection

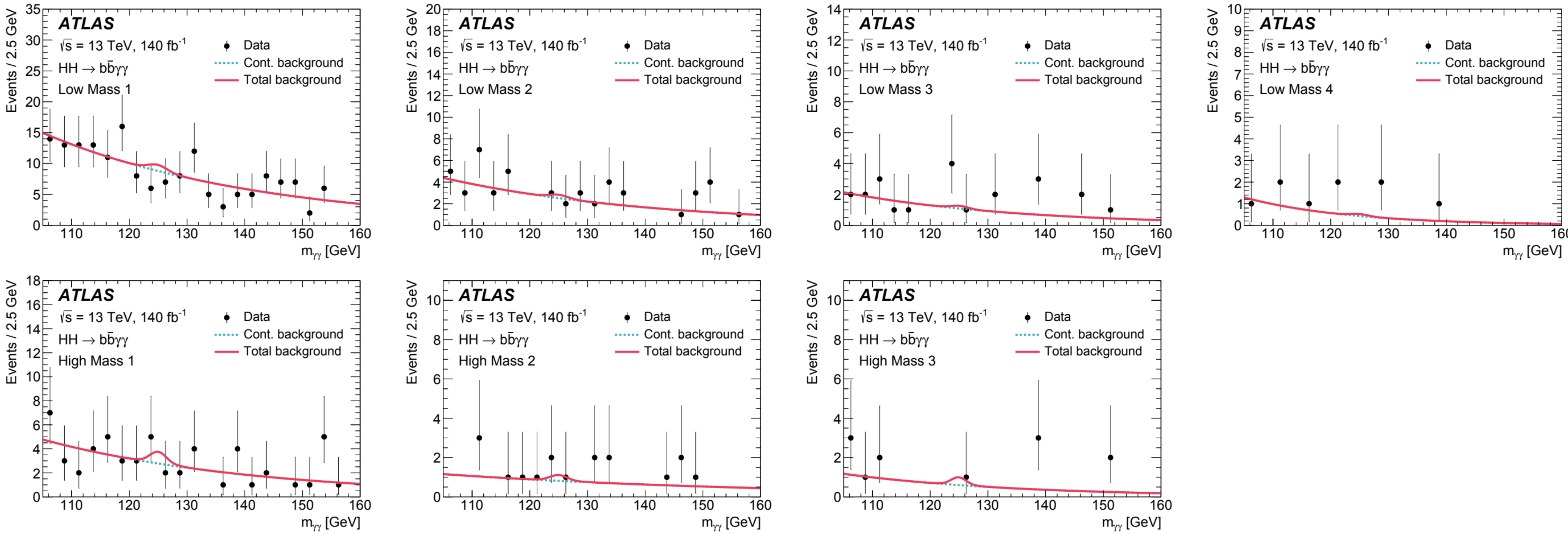
- Kinematics of photon and jets
- Extra HH related variables: $m_{bb\gamma\gamma}$*, $\Delta R_{\gamma\gamma}$, ΔR_{bb}
- VBF related variables:
  - BDT to select the VBF jet
  - kinematics and b-tag score of 3rd and 4th jet
  - m_{jj}, $\Delta\eta_{jj}$, event-shape variables



- 7 categories based of the maximum significance
  - SM ggF+VBF at high-mass
  - ggF κ_λ=5.6 + VBF κ_λ=10 at low-mass

Fits

- Simultaneous unbinned maximum likelihood fit in all categories:

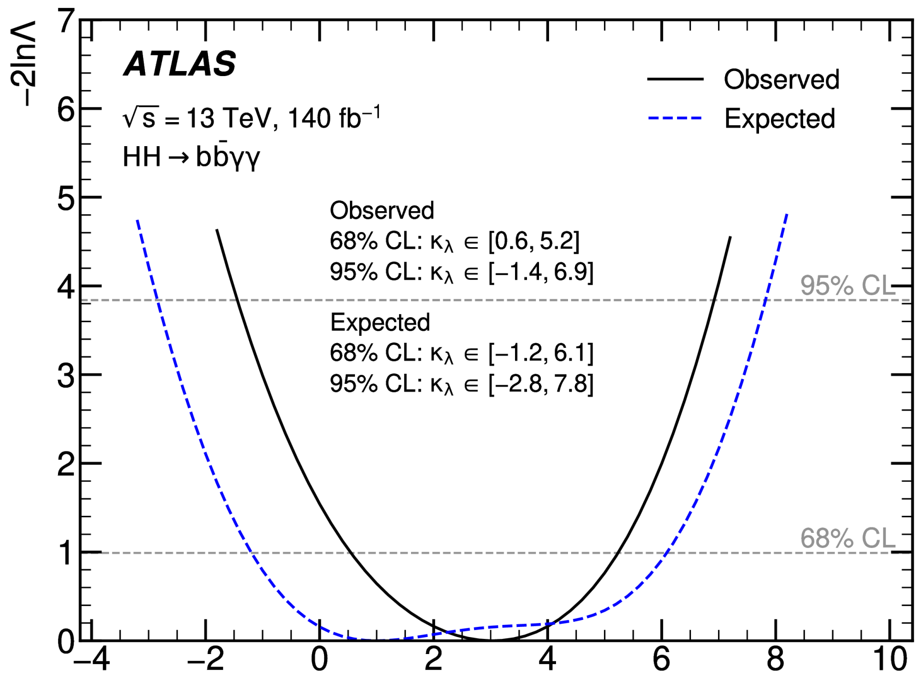


  – no significant excess observed in data

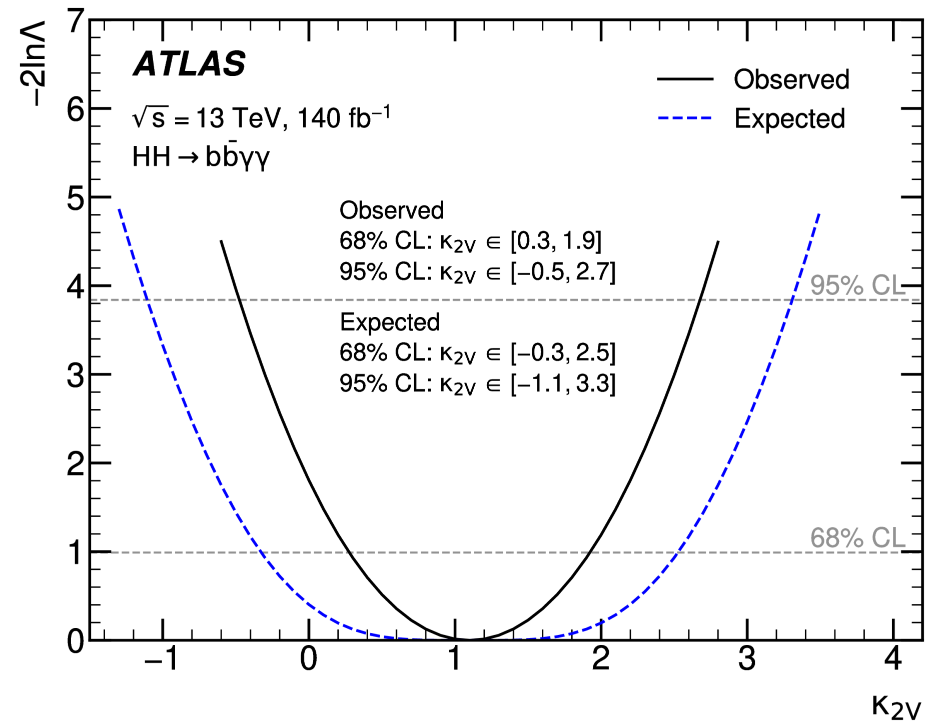
- Upper limits on signal strength (μ):
  – 12% improvement wrt previous analysis

	Observed	median expected
μ_{VBF}	≤ 96	≤ 154
μ_{ggF}	≤ 4.1	≤ 5.3
$\mu_{ggF+VBF}$	≤ 4.0	≤ 5.0

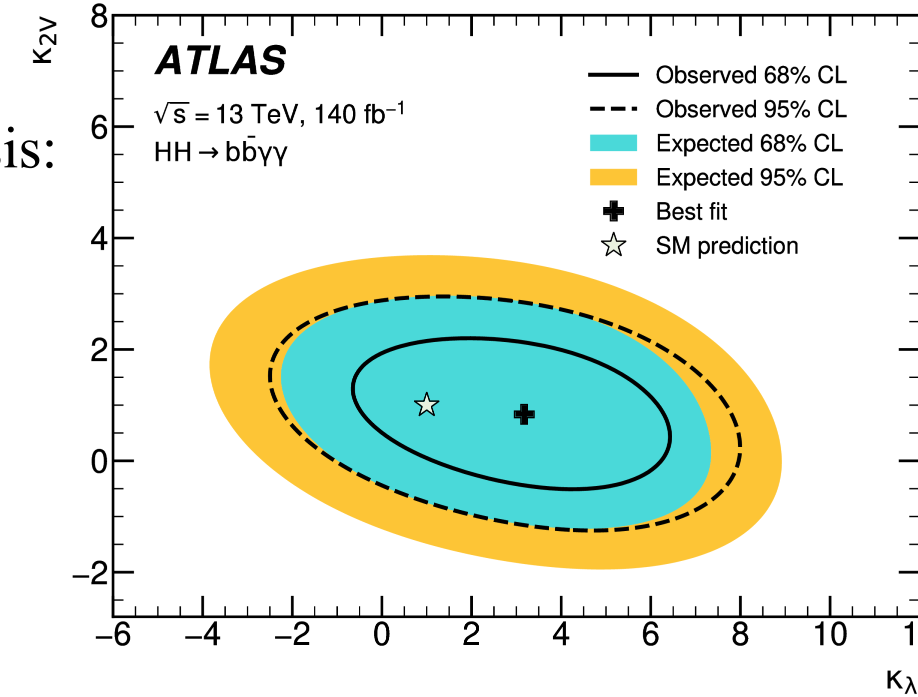
Constraints on κ_λ and κ_{2V}



best expected constraint so far!



- Improvement wrt previous analysis:
  - κ_λ: 6%
  - κ_{2V}: 17%

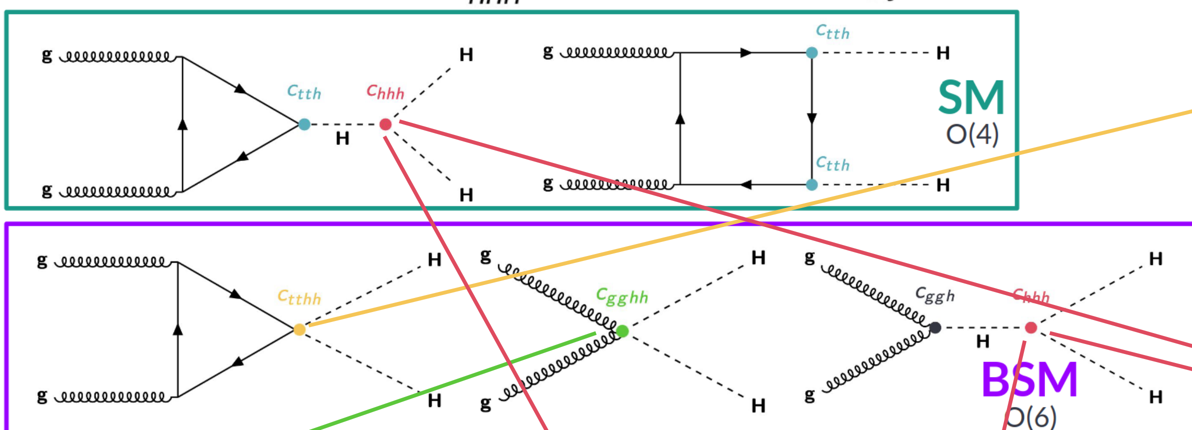


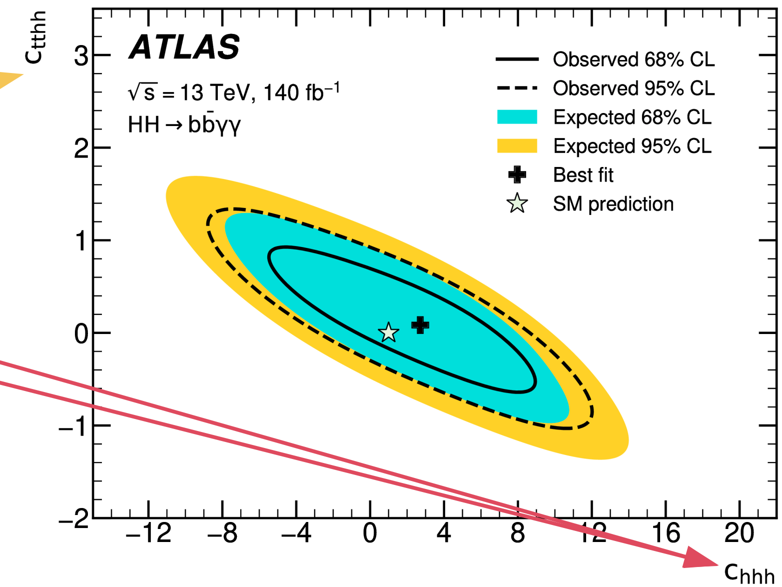
Limits on EFT models (1)

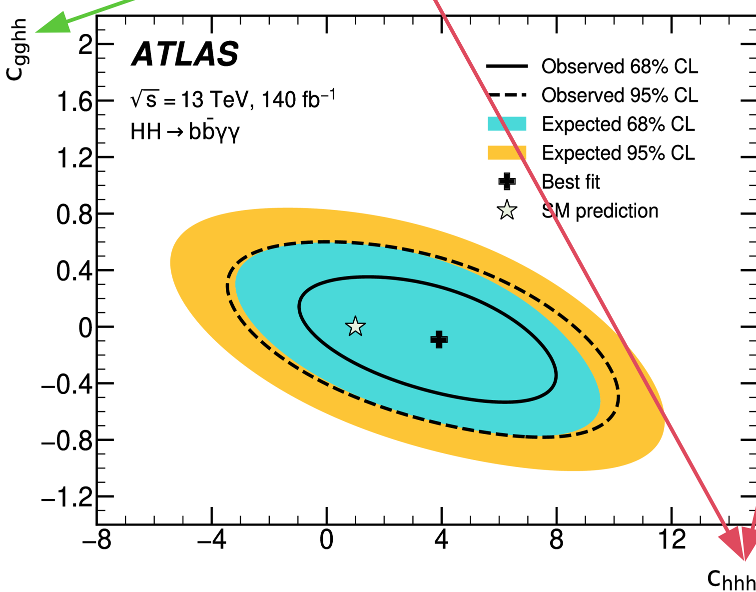
- HEFT: Higgs effective field theory
  - parameterized lagrangian allowing for deviations from SM

$$\mathcal{L}_{BSM} = -c_{hhh}\lambda^{SM}_{HHH} v h^3 - \frac{m_t}{v}(c_{tth} h + \frac{c_{tthh}}{v} h^2)(\bar{t}_L t_R + h.c.) + \frac{\alpha_S}{12\pi v}(c_{ggh} h - \frac{c_{gghh}}{2v} h^2) G^a_{\mu\nu} G^{a,\mu\nu}$$

$$c_{hhh} = \kappa_\lambda = \frac{\lambda_{HHH}}{\lambda^{SM}_{HHH}}, \quad \lambda^{SM}_{HHH} = \frac{m_H^2}{2v^2}, \quad c_{tth} = \frac{y_t}{y_t^{SM}}, \quad y_t^{SM} = \frac{\sqrt{2}m_t^2}{v}$$





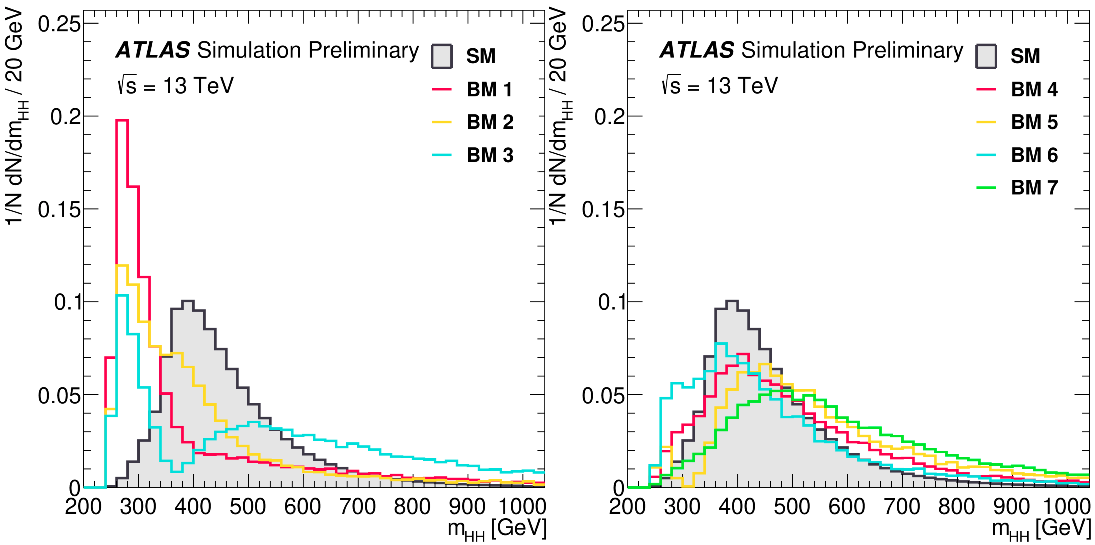


Wilson coefficient	95% CL Observed	95% CL Expected
c_{hhh}	$[-1.7\ ,7.7\ ]$	$[-3.4\ ,8.9\ ]$
c_{tthh}	$[-0.28, 0.73]$	$[-0.48, 0.94]$
c_{gghh}	$[-0.42, 0.52]$	$[-0.59, 0.69]$

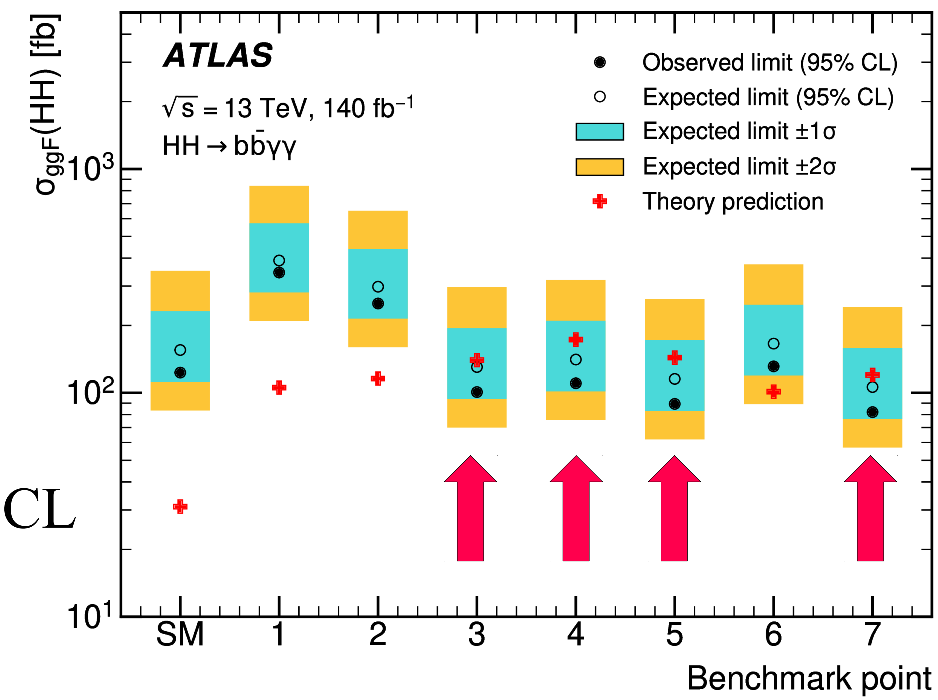
- No significant deviations from SM
- Best fit agrees with SM within 1σ

Limits on EFT models (2)

- HEFT: Additionally search for benchmarks
  - represent distinct, representative kinematic shapes in 5D HEFT phase space



Benchmark	c_{hhh}	c_{tth}	c_{ggh}	c_{gghh}	c_{tthh}
SM	1	1	0	0	0
1	5.11	1.10	0	0	0
2	6.84	1.03	-1/3	0	1/6
3	2.21	1.05	1/2	1/2	-1/3
4	2.79	0.90	-1/3	-1/2	-1/6
5	3.95	1.17	1/6	-1/2	-1/3
6	-0.68	0.90	1/2	0.25	-1/6
7	-0.10	0.94	1/6	-1/6	1



- Benchmarks 3, 4, 5, 7 excluded at a 95% CL
  - partially due to harder m_{HH} spectrum

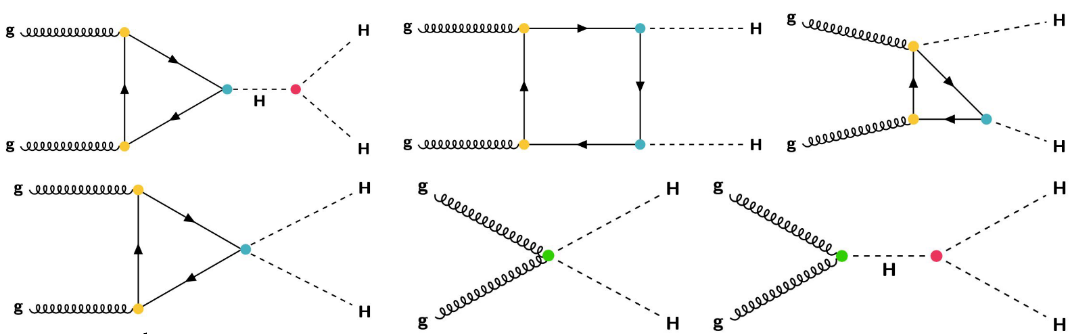
Limits on EFT models (3)

- SMEFT: Standard Model effective field theory
  - expansion of SM lagrangian with dim-6 operators, includes 5 Wilson Coefficients

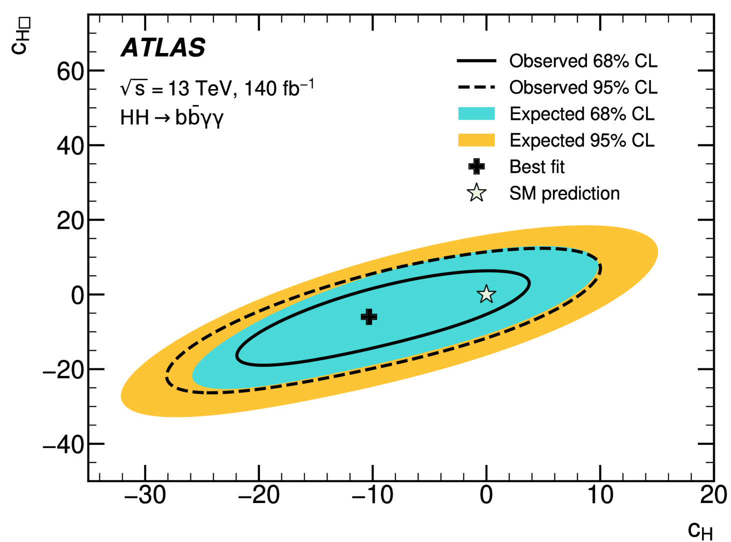
In SM: $C_H = C_{tH} = C_{tG} = C_{HG} = C_{H\Box} = 0$.

coefficients of $O(1/\Lambda^2)$

$$\mathcal{L}_{SMEFT} = C_{H\Box}(H^\dagger H)\Box(H^\dagger H) + C_{HD}\,|(H^\dagger D_\mu H)|^2 + C_H (H^\dagger H)^3 + C_{tH}(H^\dagger H\, q_L H^c t_R + h.c.) + C_{HG}\, H^\dagger H\, tr(G_{\mu\nu}G^{\mu\nu}) + C_{tG}(q_L \sigma_{\mu\nu} T^a H^c t_R G^{\mu\nu}{}_a)$$



- Compared to HEFT:
  - Less general. h is contained in SU(2) doublet (same as SM)
  - More useful for global combination: many other LHC searches use SMEFT



Wilson coefficient	95% CL Observed	95% CL Expected
c_H	[−14.4, 6.2]	[−16.8, 9.7]
$c_{H\Box}$	[− 9.4, 10.2]	[−12.4, 13.7]

- No significant deviations from SM
- Best fit agrees with SM within 1σ

Conclusion

- New Legacy Run 2 analysis for the search for $HH \rightarrow b\bar{b}\gamma\gamma$
  - now dedicated selection for VBF HH
  - constraints on κ_λ and κ_{2V} but also EFT
- Comparison of expected limits on κ_λ an κ_{2V} for different channels:

$b\bar{b}\gamma\gamma$ best for κ_λ

	κ_λ		κ_{2V}	
	ATLAS	CMS	ATLAS	CMS
bbγγ	[-2.8 ; 7.8]	[-2.5 ; 8.2]	[-1.1 ; 3.3]	[-0.9 ; 3.1]
bbττ	[-3.1 ; 10.2]	[-2.9 ; 9.8]	[-0.5 ; 2.7]	[-0.9 ; 3.1]
bbbb (resolved)	[-5.4 ; 11.4]	[-0.5 ; 12.0]	[-0.1 ; 2.1]	[-0.4 ; 2.5]
bbbb (boosted)		[-5.1 ; 12.2]		[0.7 ; 1.4]

boosted $b\bar{b}b\bar{b}$ best for κ_{2V} !

κ_{2V}=0 hypothesis excluded
- at 6σ level when fixing other couplings to SM values
- at 3σ level when fitting κ_{2V} and κ_λ simultaneously

- Combined limit on μ_{HH}: ~3*SM/experiment
  - evidence at reach at the end of Run 3??

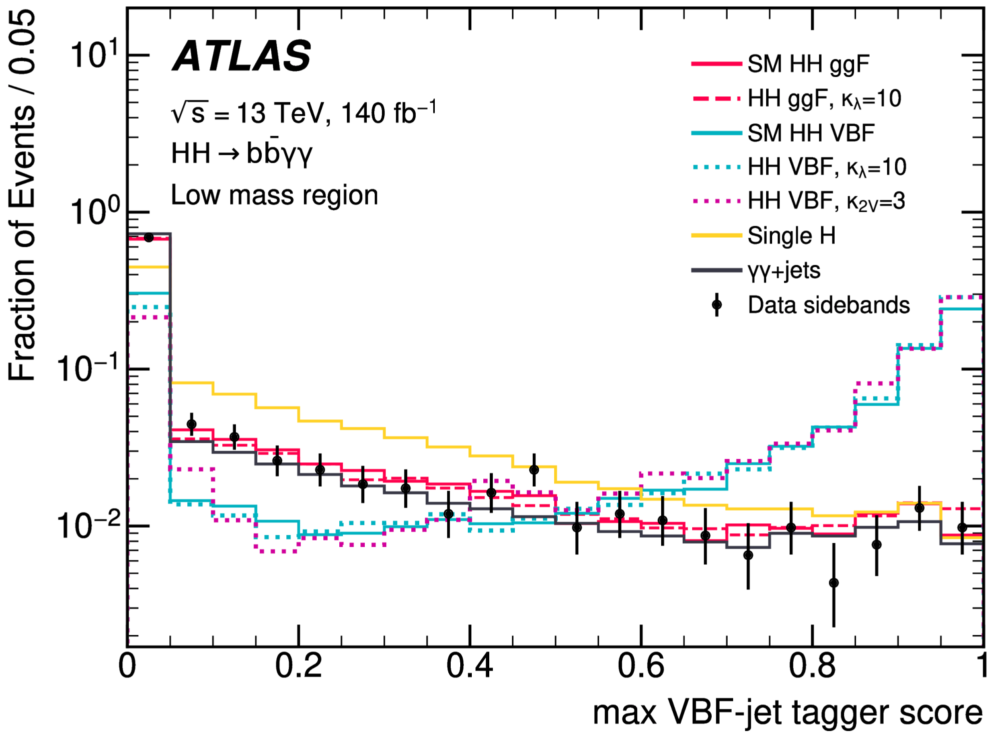
Back-up

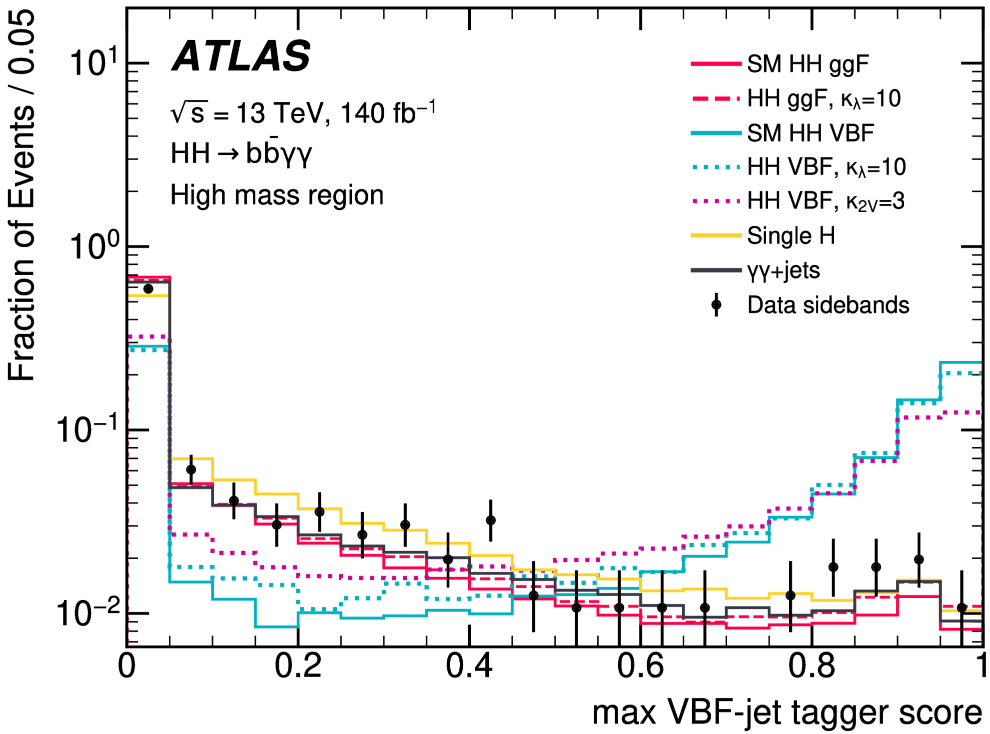
Variables for BDT event selection

Variable	Definition
Photon candidates	
$p_T/m_{\gamma\gamma}$	Transverse momentum of each photon divided by the diphoton invariant mass $m_{\gamma\gamma}$
η and ϕ	Pseudorapidity and azimuthal angle of each photons
$\Delta R(\gamma_1, \gamma_2)$	Angular distance between the two photons
b-jet candidates	
b-tag status	Tightest fixed b-tag working point (60%, 70%, 77%) that each jet passes
p_T, η and ϕ	Transverse momentum, pseudorapidity and azimuthal angle of each jet
$p_T^{b\bar{b}}$, $\eta_{b\bar{b}}$ and $\phi_{b\bar{b}}$	Transverse momentum, pseudorapidity and azimuthal angle of the two-b-jet system
$\Delta R(b_1, b_2)$	Angular distance between the two candidate b-jets
$m_{b\bar{b}}$	Invariant mass of the two candidate b-jets
Single topness	Variable used to identify $t \to Wb \to q\bar{q}'b$ decays. For the definition, see Eq.(**??**).
Other jets (only first two, if present, ranked by discrete b-tagging score)	
b-tag status	Tightest fixed b-tag working point (85% or none) that each jet passes
p_T, η and ϕ	Transverse momentum, pseudorapidity and azimuthal angle of each jet
VBF-jet candidates	
$\Delta\eta(j_1, j_2), m_{jj}$	Pseudorapidity difference and invariant mass of the two jets
Event-level variables	
Transverse sphericity, planar flow, p_T balance	For the definitions, see Ref. , Ref. , and Eq. (**??**)
H_T	Scalar sum of the p_T of the jets in the event
E_T^{miss} and ϕ^{miss}	Missing transverse momentum and its azimuthal angle
$m^*_{b\bar{b}\gamma\gamma}$	The 4-body invariant mass of the two photons and two candidate b-jets, $m^*_{b\bar{b}\gamma\gamma} = m_{b\bar{b}\gamma\gamma} - (m_{b\bar{b}} - 125\text{ GeV}) - (m_{\gamma\gamma} - 125\text{ GeV})$

VBF BDT selection

Variable	Definition
p_T^j and η^j	Transverse momentum and pseudorapidity of each of the VBF-jet candidates
$\Delta R(j, \gamma\gamma b\bar{b})$ and $\Delta\eta(j, \gamma\gamma b\bar{b})$	Angular and pseudorapidity separation between the VBF-jet candidates and the $\gamma\gamma b\bar{b}$ system
m_{jj} and $\Delta\eta(j, j)$	Invariant mass and pseudorapidity separation of the two VBF-jet candidates
$\Delta R(jj, \gamma\gamma b\bar{b})$ and $\Delta\eta(jj, \gamma\gamma b\bar{b})$	Angular and pseudorapidity separation between the VBF-jet candidate pair and the $\gamma\gamma b\bar{b}$ system
$p_T^{\gamma\gamma b\bar{b}jj}$, $\eta^{\gamma\gamma b\bar{b}jj}$, and $m_{\gamma\gamma b\bar{b}jj}$	Transverse momentum, pseudorapidity, and invariant mass of the system formed by the VBF-jet candidate pair, the two photons and the two b-tagged jets
H_T	Scalar sum of the p_T of the jets in the event





Expected number of events

	High Mass 1	High Mass 2	High Mass 3	Low Mass 1	Low Mass 2	Low Mass 3	Low Mass 4
SM $HH(\kappa_\lambda = 1)$ signal	$0.26^{+0.03}_{-0.04}$	$0.194^{+0.021}_{-0.032}$	$0.84^{+0.10}_{-0.14}$	$0.048^{+0.007}_{-0.008}$	$0.038^{+0.004}_{-0.006}$	$0.039^{+0.004}_{-0.006}$	$0.032^{+0.004}_{-0.004}$
ggF	$0.25^{+0.03}_{-0.04}$	$0.188^{+0.021}_{-0.032}$	$0.81^{+0.10}_{-0.14}$	$0.046^{+0.007}_{-0.008}$	$0.036^{+0.004}_{-0.006}$	$0.037^{+0.004}_{-0.006}$	$0.025^{+0.004}_{-0.004}$
VBF $\times 10^3$	$7.9^{+0.6}_{-0.5}$	$5.3^{+0.5}_{-0.4}$	29^{+4}_{-3}	$1.98^{+0.28}_{-0.24}$	$1.71^{+0.16}_{-0.14}$	$1.96^{+0.21}_{-0.19}$	$7.4^{+0.6}_{-0.5}$
Alternative $HH(\kappa_\lambda = 10)$ signal	$2.5^{+0.4}_{-0.3}$	$1.81^{+0.25}_{-0.20}$	$6.2^{+0.8}_{-0.6}$	$5.0^{+1.2}_{-0.9}$	$3.8^{+0.7}_{-0.5}$	$3.7^{+0.7}_{-0.6}$	$3.6^{+0.4}_{-0.4}$
ggF	$2.3^{+0.4}_{-0.3}$	$1.64^{+0.25}_{-0.19}$	$4.9^{+0.8}_{-0.6}$	$4.7^{+1.0}_{-0.8}$	$3.6^{+0.7}_{-0.6}$	$3.3^{+0.7}_{-0.5}$	$2.04^{+0.34}_{-0.27}$
VBF	$0.231^{+0.019}_{-0.017}$	$0.170^{+0.019}_{-0.017}$	$1.29^{+0.15}_{-0.14}$	$0.28^{+0.20}_{-0.11}$	$0.23^{+0.23}_{-0.12}$	$0.36^{+0.10}_{-0.08}$	$1.57^{+0.17}_{-0.16}$
Alternative VBF $HH(\kappa_{2V} = 3)$ signal	$0.23^{+0.04}_{-0.04}$	$0.20^{+0.05}_{-0.04}$	$3.8^{+0.7}_{-0.6}$	$0.03^{+0.04}_{-0.02}$	$0.03^{+0.06}_{-0.02}$	$0.048^{+0.023}_{-0.015}$	$0.17^{+0.04}_{-0.03}$
Single Higgs boson background	$1.5^{+0.5}_{-0.3}$	$0.48^{+0.21}_{-0.10}$	$0.57^{+0.25}_{-0.14}$	$1.72^{+0.31}_{-0.19}$	$0.53^{+0.08}_{-0.06}$	$0.29^{+0.14}_{-0.07}$	$0.16^{+0.06}_{-0.03}$
ggF	$0.5^{+0.5}_{-0.2}$	$0.14^{+0.21}_{-0.09}$	$0.25^{+0.25}_{-0.12}$	$0.29^{+0.31}_{-0.15}$	$0.08^{+0.08}_{-0.04}$	$0.07^{+0.13}_{-0.06}$	$0.04^{+0.06}_{-0.03}$
$t\bar{t}H$	$0.302^{+0.034}_{-0.032}$	$0.069^{+0.009}_{-0.008}$	$0.063^{+0.008}_{-0.007}$	$0.77^{+0.09}_{-0.08}$	$0.214^{+0.029}_{-0.026}$	$0.100^{+0.012}_{-0.012}$	$0.048^{+0.005}_{-0.005}$
ZH	$0.61^{+0.06}_{-0.05}$	$0.174^{+0.020}_{-0.016}$	$0.188^{+0.035}_{-0.029}$	$0.49^{+0.05}_{-0.04}$	$0.149^{+0.028}_{-0.025}$	$0.069^{+0.033}_{-0.023}$	$0.028^{+0.010}_{-0.007}$
Rest	$0.17^{+0.08}_{-0.04}$	$0.089^{+0.030}_{-0.016}$	$0.07^{+0.04}_{-0.02}$	$0.181^{+0.030}_{-0.019}$	$0.089^{+0.016}_{-0.009}$	$0.046^{+0.007}_{-0.004}$	$0.039^{+0.008}_{-0.004}$
Continuum background	$11.3^{+1.5}_{-1.6}$	$3.2^{+0.8}_{-0.8}$	$2.8^{+0.8}_{-0.8}$	$37.2^{+2.9}_{-2.9}$	$10.8^{+1.5}_{-1.5}$	$4.4^{+0.9}_{-1.0}$	$1.1^{+0.5}_{-0.5}$
Total background	$12.8^{+1.6}_{-1.6}$	$3.7^{+0.9}_{-0.8}$	$3.4^{+0.8}_{-0.8}$	$38.9^{+2.9}_{-2.9}$	$11.3^{+1.5}_{-1.5}$	$4.7^{+0.9}_{-1.0}$	$1.3^{+0.5}_{-0.5}$
Data	12	4	1	29	8	5	4

Summary of EFT limits