Di-Higgs production: ATLAS experimental overview

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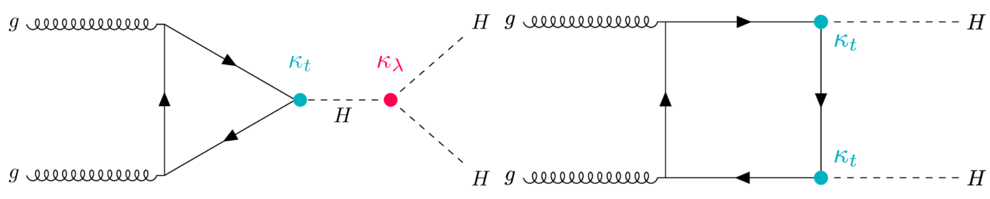
on behalf of the ATLAS Collaboration

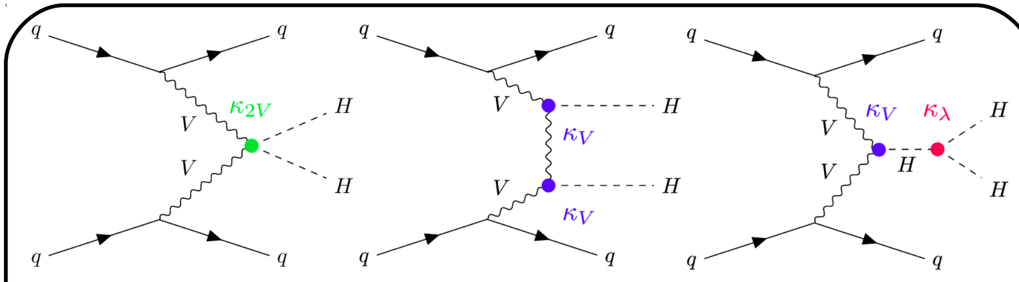
LHCHWG meeting
14th of November 2023

Summary of ATLAS results with full Run 2

- Non-resonant production:



$\sigma_{\text{ggF}} = 31.05^{+1.86}_{-7.14} \pm 0.93\,\text{fb}$



$\sigma_{\text{VBF}} = 1.73^{+0.01}_{-0.01} \pm 0.04\,\text{fb}$

No longer preliminary **New since last year**

Decay channel	Target production mode	Reference	Release date
bbγγ	ggF+VBF	arxiv:2310.12301	18-10-2023
bbττ	ggF+VBF*	JHEP 07 (2023) 040	22-09-2022
bbbb	ggF+VBF + EFT interpretation	Phys. Rev. D 108 (2023) 052003	09-01-2023
	VHH	Eur. Phys. J. C 83 (2023) 519	11-10-2022
bbWW dilepton	ggF+VBF	Phys. Lett. B 801 (2020) 135145	19-08-2019
bbll+ETmiss	ggF+VBF	arXiv:2310.11286	17-10-2023
Combination	Non-resonant + single-Higgs	Phys. Lett. B 843 (2023) 137745	03-11-2023
Prospects	Non-resonant	ATL-PHYS-PUB-2022-053	08-11-2022

*VBF accounted for, but not specifically targeted

HH → b$\bar{b}$γγ (1)

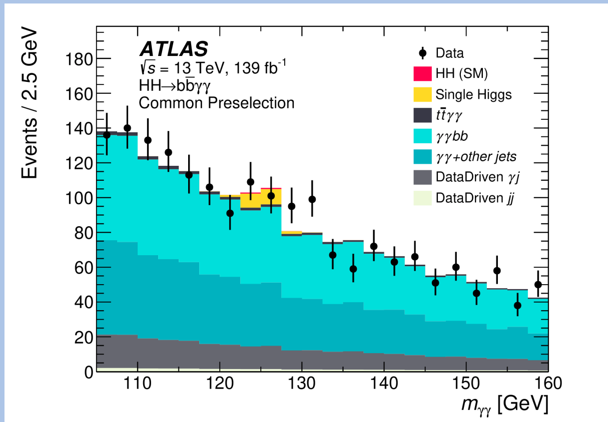
- Run 2 Legacy paper: VBF included in training

Preselection

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

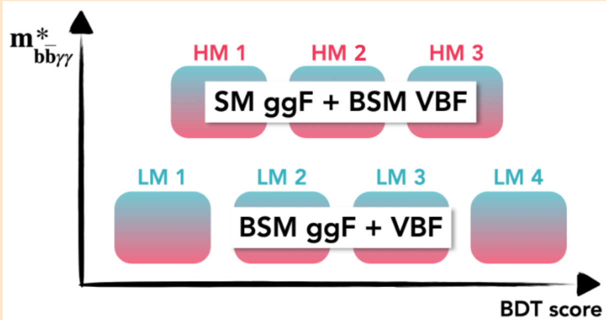
b-jets
- exactly 2 with 77% efficiency
- μ and lost energy corrections

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

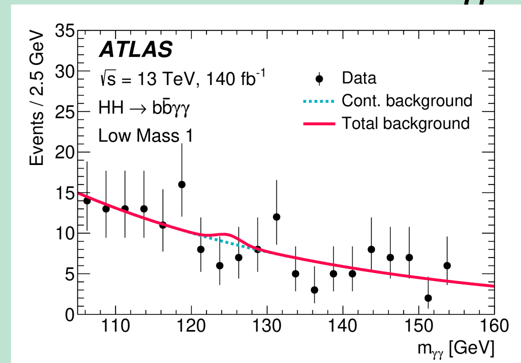


VBF jets tagger
BDT classifier

Categories



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



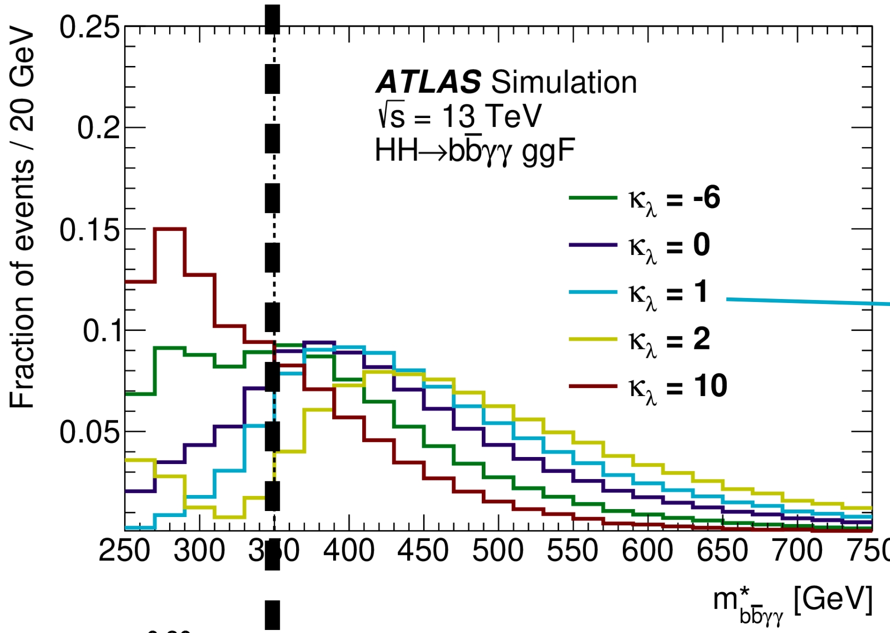
Interpretations

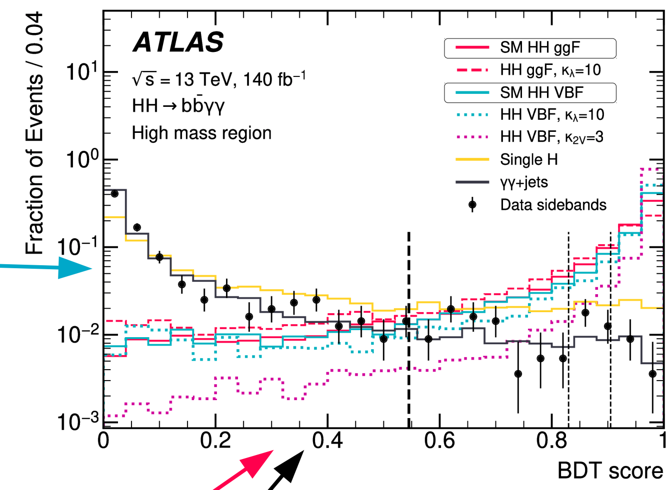
HH → $b\bar{b}\gamma\gamma$ (2)

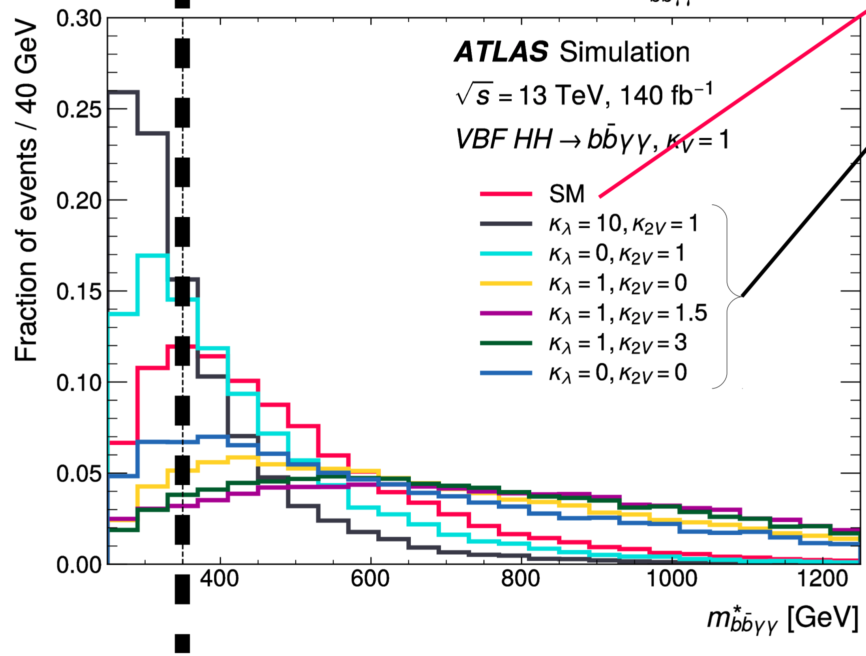
- Mass categories + BDT selection

Low-mass

High-mass



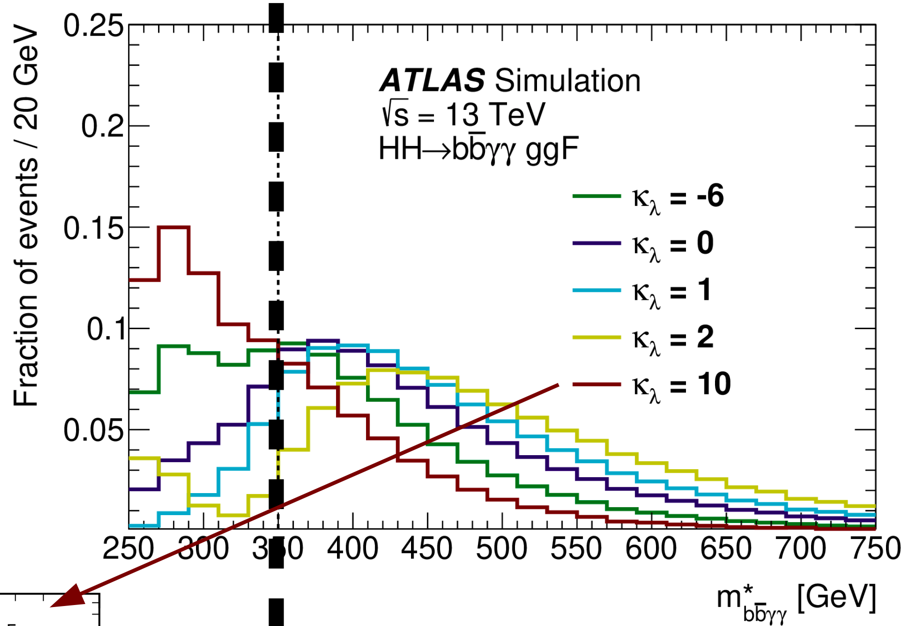




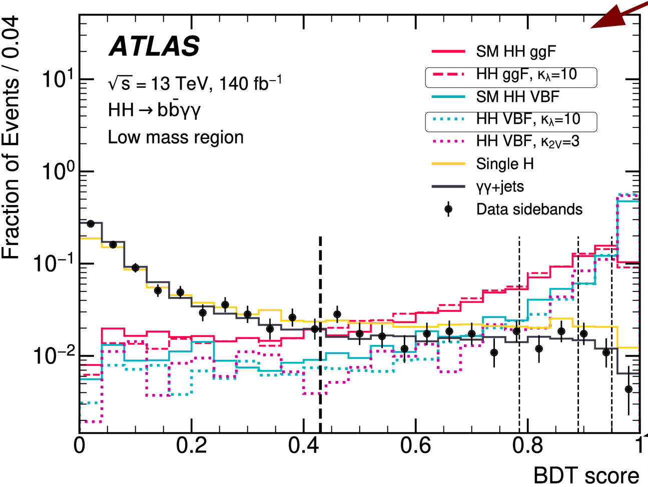
HH → b$\bar{b}$γγ (2)

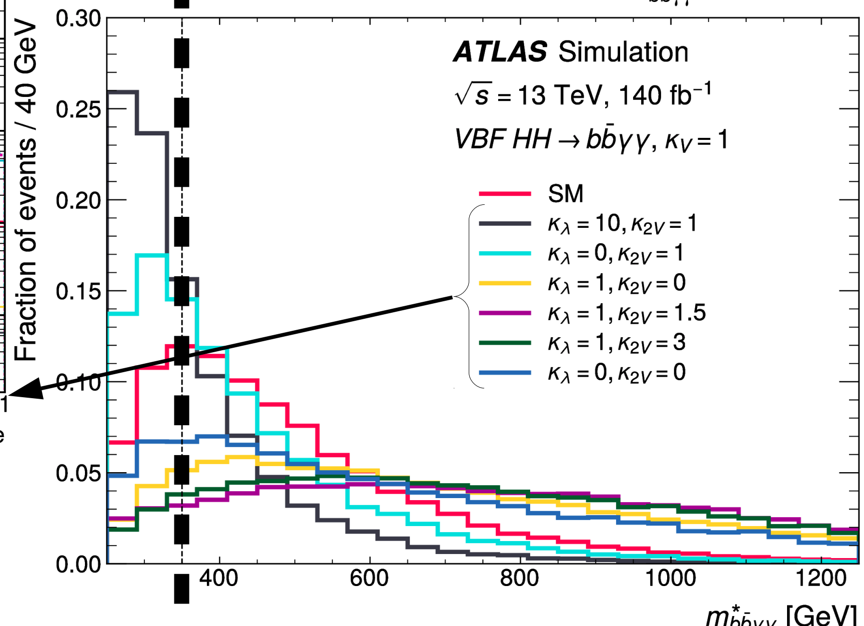
- Mass categories + BDT selection

High-mass



Low-mass



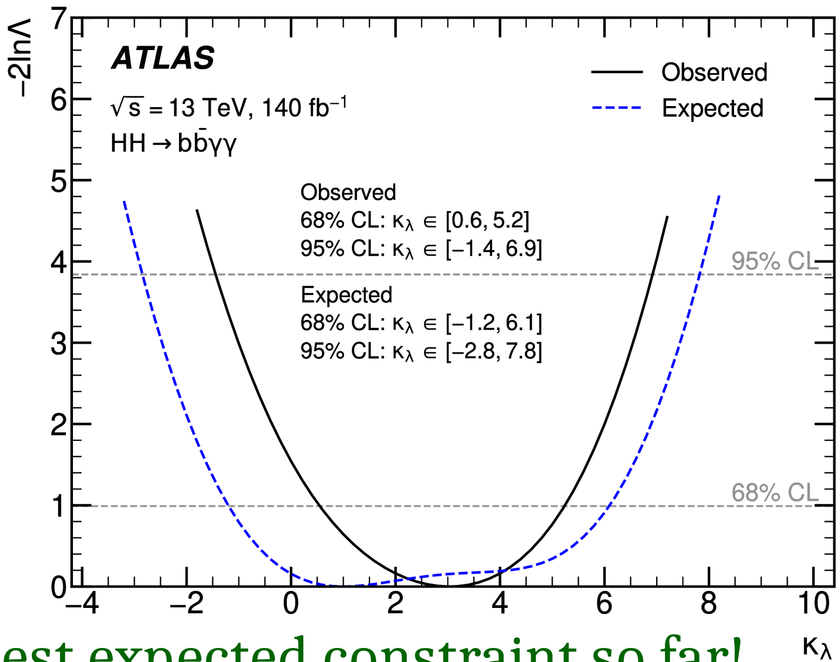


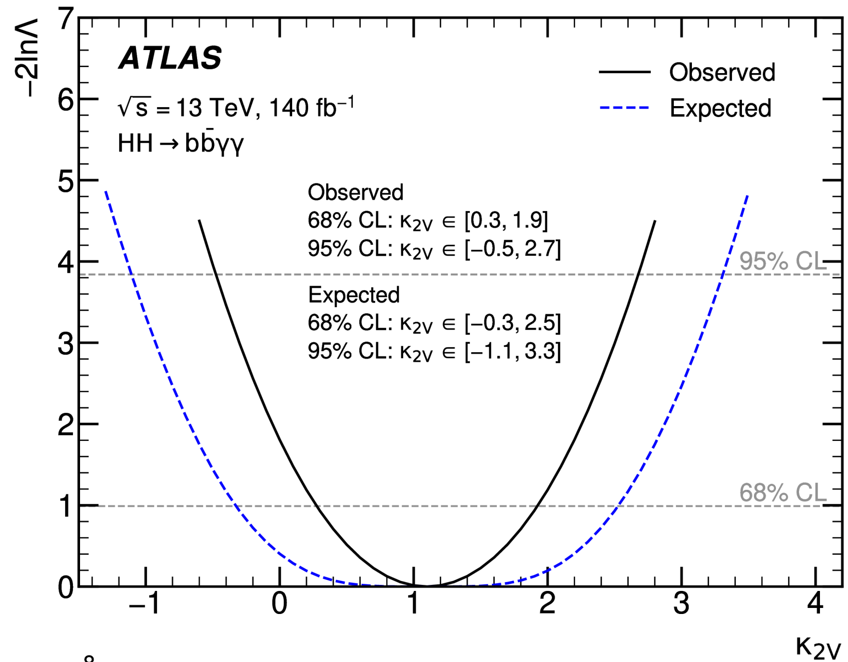
HH → $b\bar{b}\gamma\gamma$ (3)

- 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

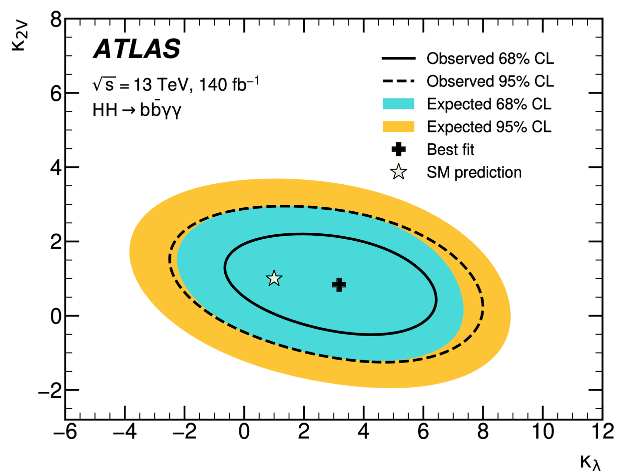
- Constraints on κ_λ and κ_{2V}:





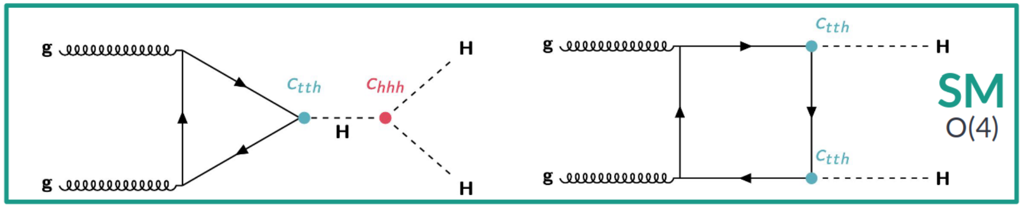
Best expected constraint so far!

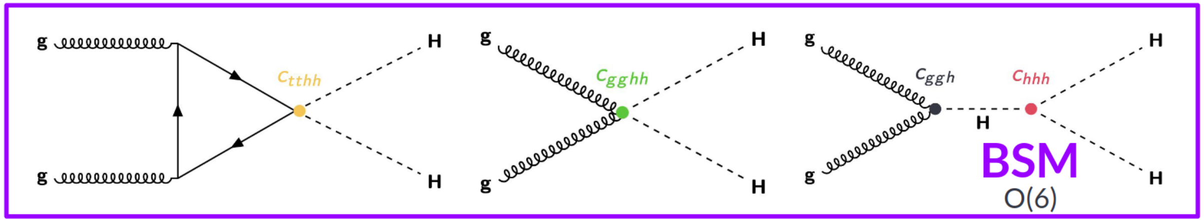
- Improvement wrt previous analysis (same dataset):
  - κ_λ: 6%
  - κ_{2V}: 17%



HH → $b\bar{b}b\bar{b}$, HH → $b\bar{b}\gamma\gamma$: EFT interpretation (1)

- HEFT: Higgs effective field theory

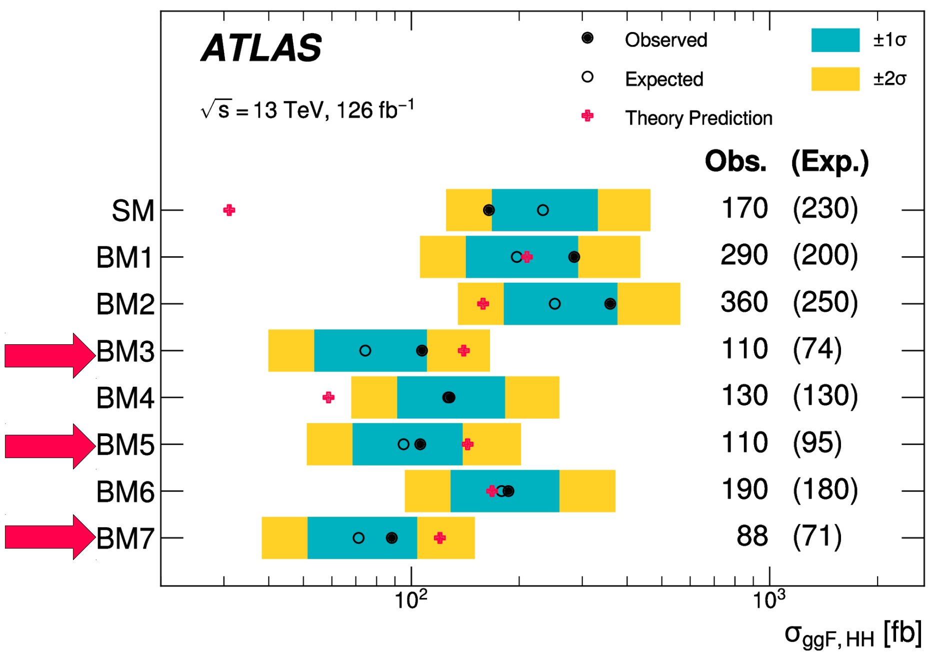




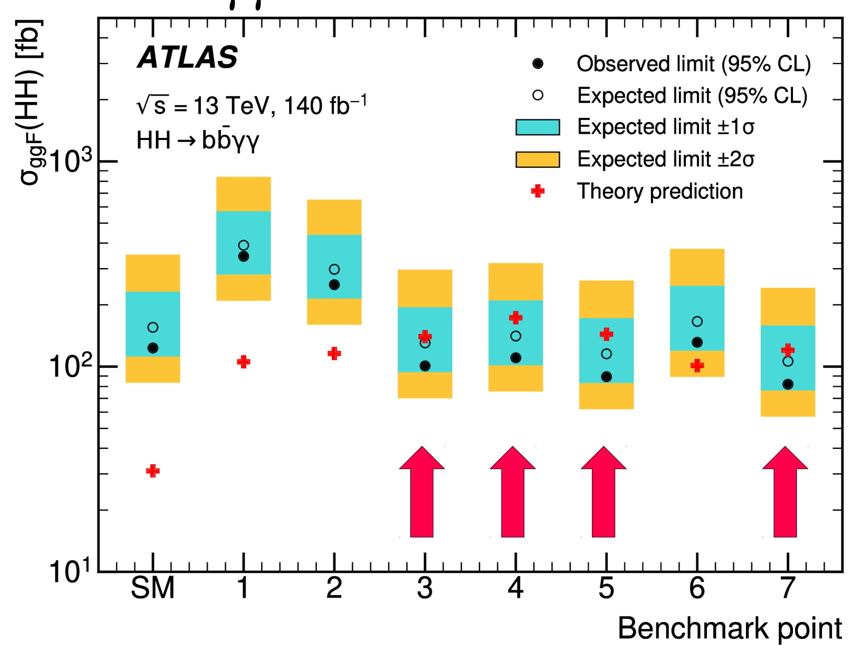
Benchmarks points: distinct, representative kinematic shapes in 5D HEFT phase space

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

- HH → $b\bar{b}b\bar{b}$:



- HH → $b\bar{b}\gamma\gamma$:



- Benchmarks 3, 4, 5, 7 excluded at a 95% CL

HH → $b\bar{b}b\bar{b}$, HH → $b\bar{b}\gamma\gamma$: EFT interpretation (2)

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

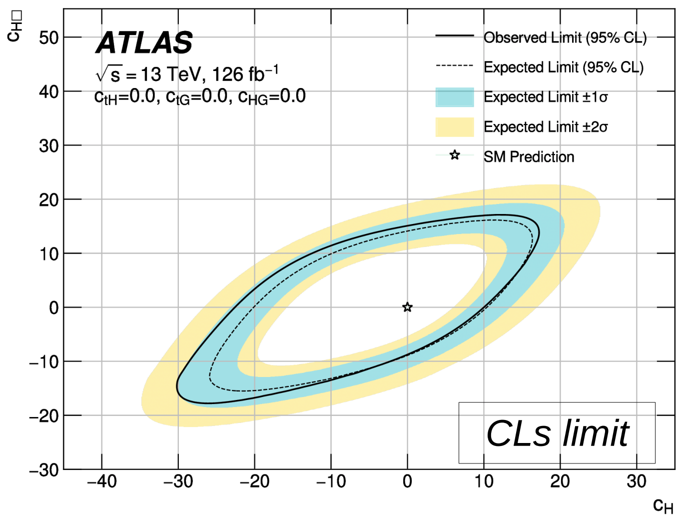
In SM: $C_H = C_{tH} = C_{tG} = C_{HG} = C_{H\Box} = 0$.

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

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

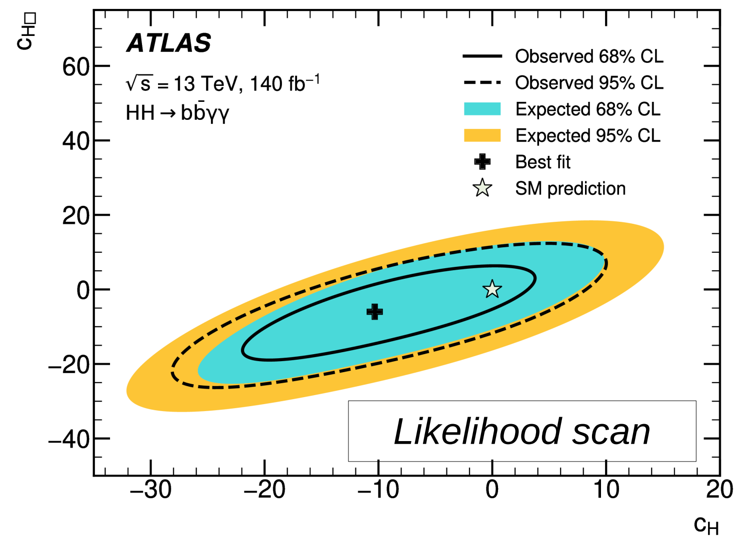
Wilson Coefficient	Operator
c_H	$(H^\dagger H)^3$
$c_{H\Box}$	$(H^\dagger H)\Box(H^\dagger H)$
c_{tH}	$(H^\dagger H)(\bar{Q}\tilde{H}t)$
c_{HG}	$H^\dagger H G^A_{\mu\nu} G^{\mu\nu}_A$
c_{tG}	$(\bar{Q}\sigma^{\mu\nu}T^A t)\tilde{H}G^A_{\mu\nu}$

- HH → $b\bar{b}b\bar{b}$:



Parameter	Expected Constraint		Observed Constraint	
	Lower	Upper	Lower	Upper
c_H	−20	11	−22	11
c_{HG}	−0.056	0.049	−0.067	0.060
$c_{H\Box}$	−9.3	13.9	−8.9	14.5
c_{tH}	−10.0	6.4	−10.7	6.2
c_{tG}	−0.97	0.94	−1.12	1.15

- HH → $b\bar{b}\gamma\gamma$:



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

HH → $b\bar{b}$ + ll + E_T^{miss} (1)

- HH → $b\bar{b}$ + WW*, ZZ*, ττ → $b\bar{b}$ + 2 opp. charge leptons + E_T^{miss}

Preselection

Leptons
- Single and dilepton triggers
- Exactly two light opposite charge pT > 9 GeV leptons

b-jets
- Exactly two pT > 20 GeV DL1r (77 % WP) *b*-tagged jets

E_T^{miss}
- no selection

VBF selection

≥ 2 additional pT > 30 GeV jets:
- max ($\Delta\eta_{jj}$) > 4
- max (m_{jj}) > 600 GeV

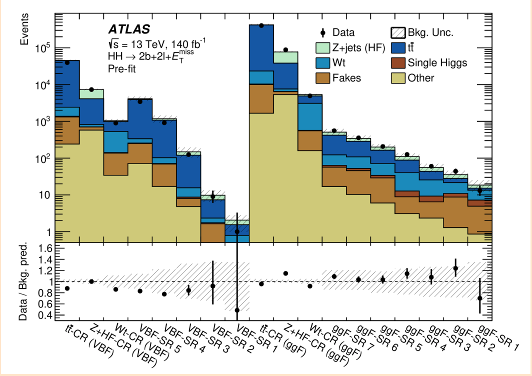
yes → VBF BDT

no → ggF DNN

Signal and Control regions

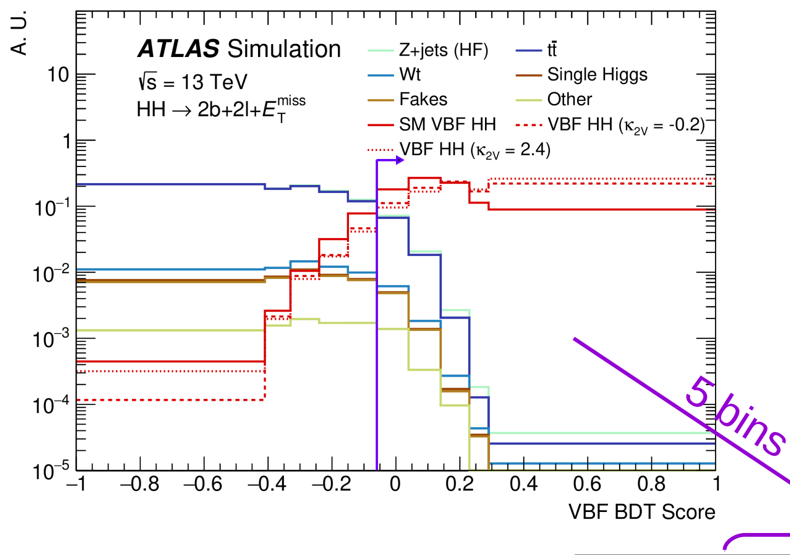
based on mll, mbb, mbl
- Z + heavy flavour
- $t\bar{t}$
- Wt

Simultaneous maximum-likelihood fit of all regions

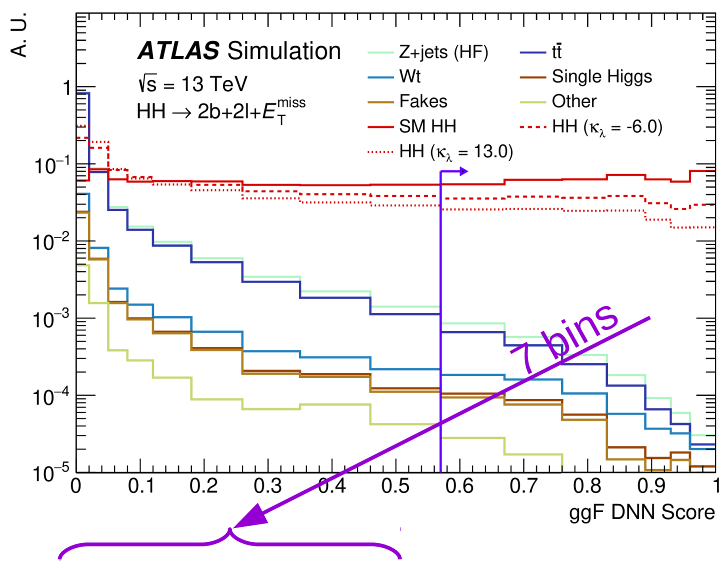


$HH \rightarrow b\bar{b} + ll + E_T^{miss}$ (2)

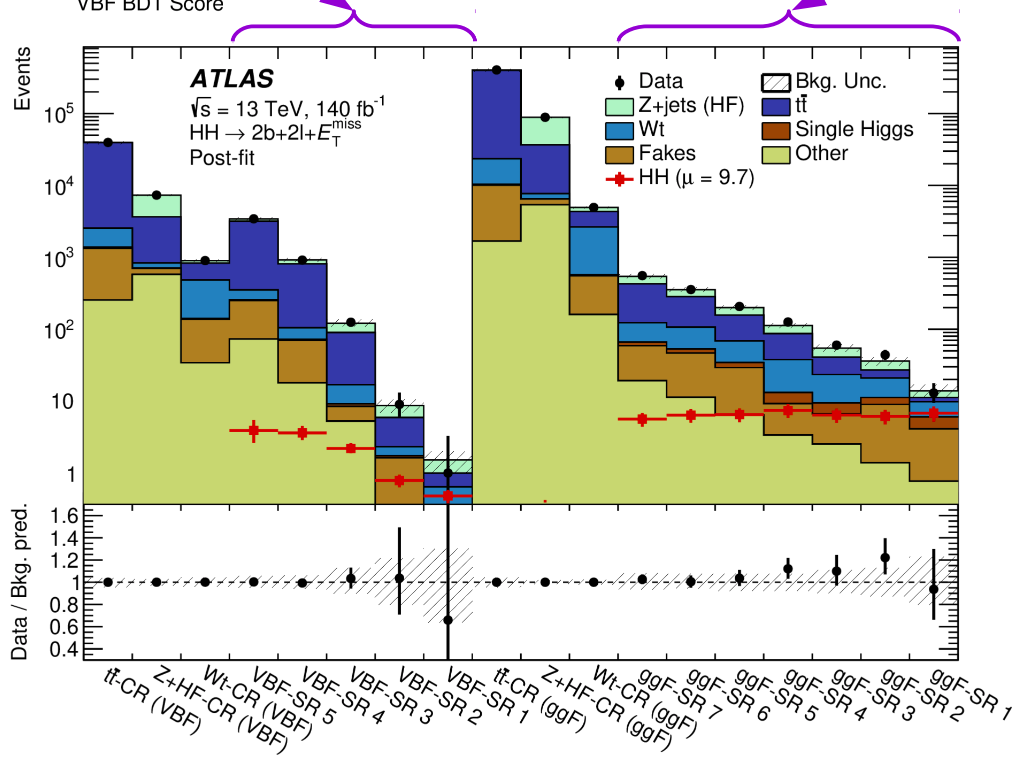
- BDT for VBF:



- DNN for ggF:

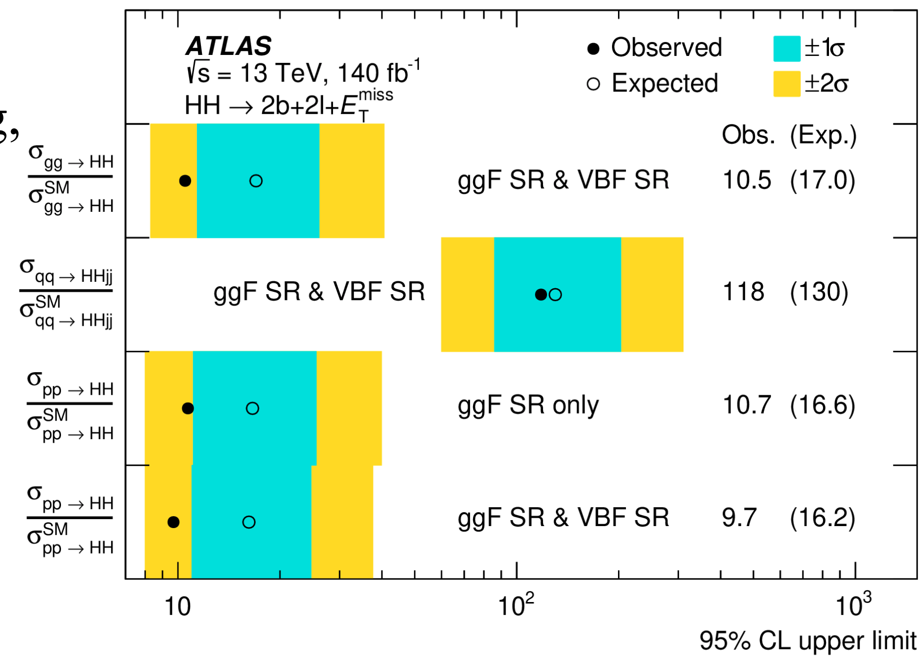


- Post-fit scores:



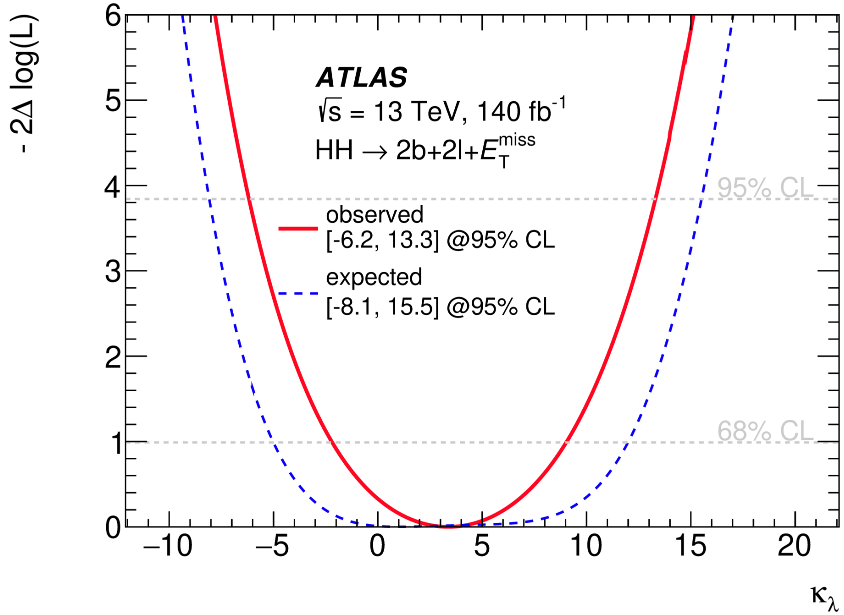
HH → $b\bar{b}$ + ll + E_T^{miss} (3)

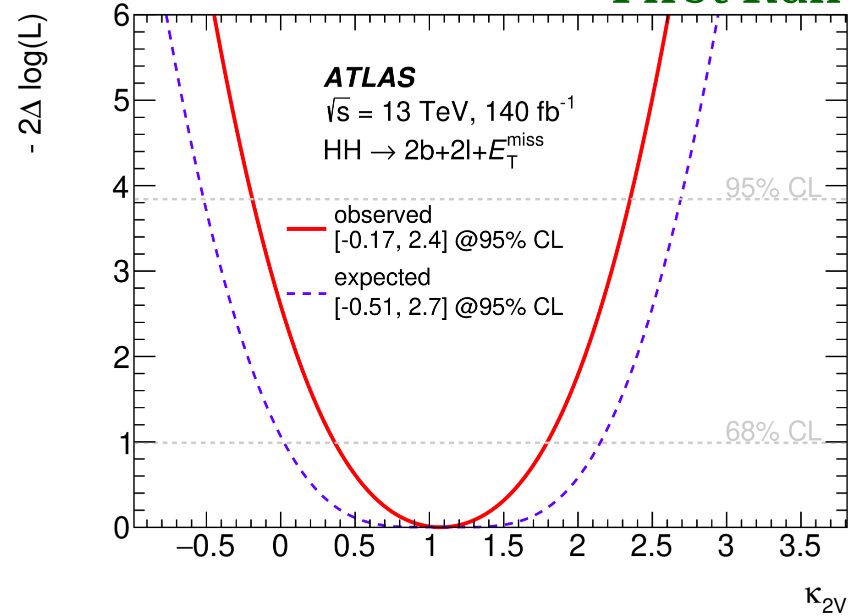
- 95% CL upper limits:
  - main syst in SR: background modelling, exp, signal normalisation
  - most sensitive bins: dominated by stat



- Constraints on κ_λ and κ_{2V}:

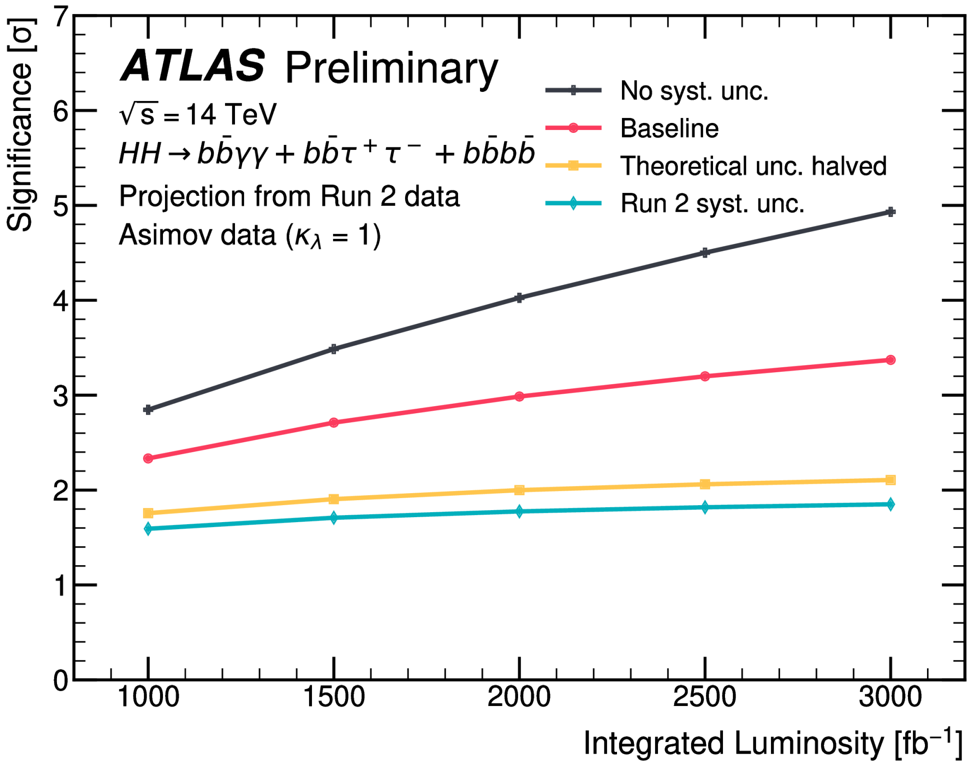
First Run 2 limits!





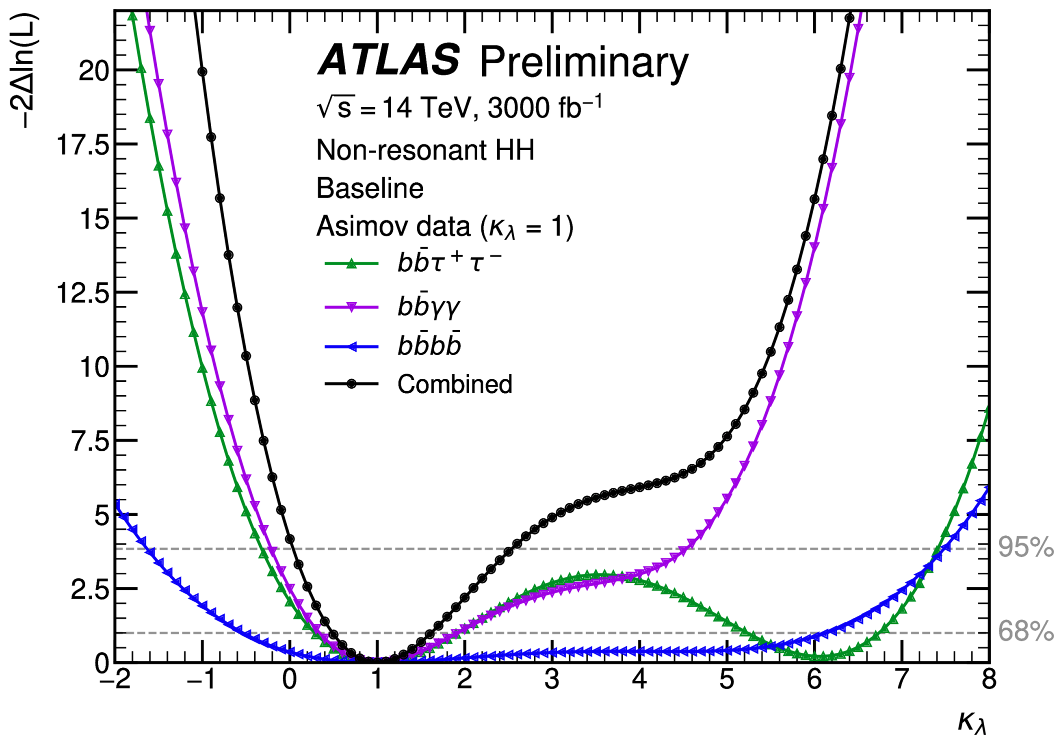
HL-LHC Prospects

- Legacy 4b, non-legacy $b\bar{b}\tau\tau$ and $b\bar{b}\gamma\gamma$
- Expected significance:



	Stat-only	Stat+Syst
YR2019	3.5σ	3.0σ
ATL-PHYS-PUB-2022-05	4.9σ	3.4σ

- Constraints on κ_λ:



– 68% Confidence Intervals:

	Stat-only	Stat+Syst
YR2019	[0.4 ; 1.7]	[0.25 ; 1.9]
ATL-PHYS-PUB-2022-05	[0.7 ; 1.4]	[0.5 ; 1.6]

ATLAS-only ~ previous ATLAS+CMS

Conclusion

- Most of legacy results available: 4b, $b\bar{b}\gamma\gamma$, $b\bar{b}ll$
  - a few more to go
- Legacy results optimised for both ggF and VBF signals
  - constraints on κ_λ and κ_{2V}
  - EFT interpretations

- Expected limits and constraints at 95% CL:

No longer preliminary **New since last year**

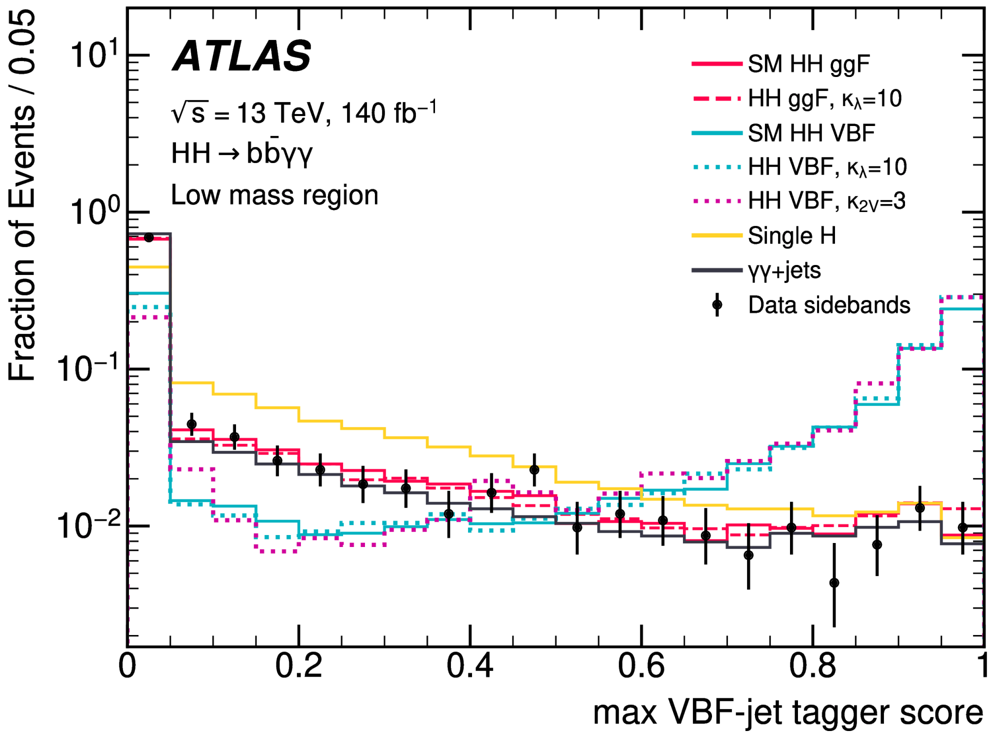
Decay channel	Target production mode	μ_{HH}	κ_λ	κ_{2V}
bbγγ	ggF+VBF	5.0	[-2.8 ; 7.8]	[-1.1 ; 3.3]
bbττ	ggF+VBF*	3.9	[-3.1 ; 10.2]	[-0.5 ; 2.7]
bbbb	ggF+VBF	8.1	[-5.4 ; 11.4]	[-0.1 ; 2.1]
bbll+ETmiss	ggF+VBF	16.2	[-8.1; 15.5]	[-0.5; 2.7]

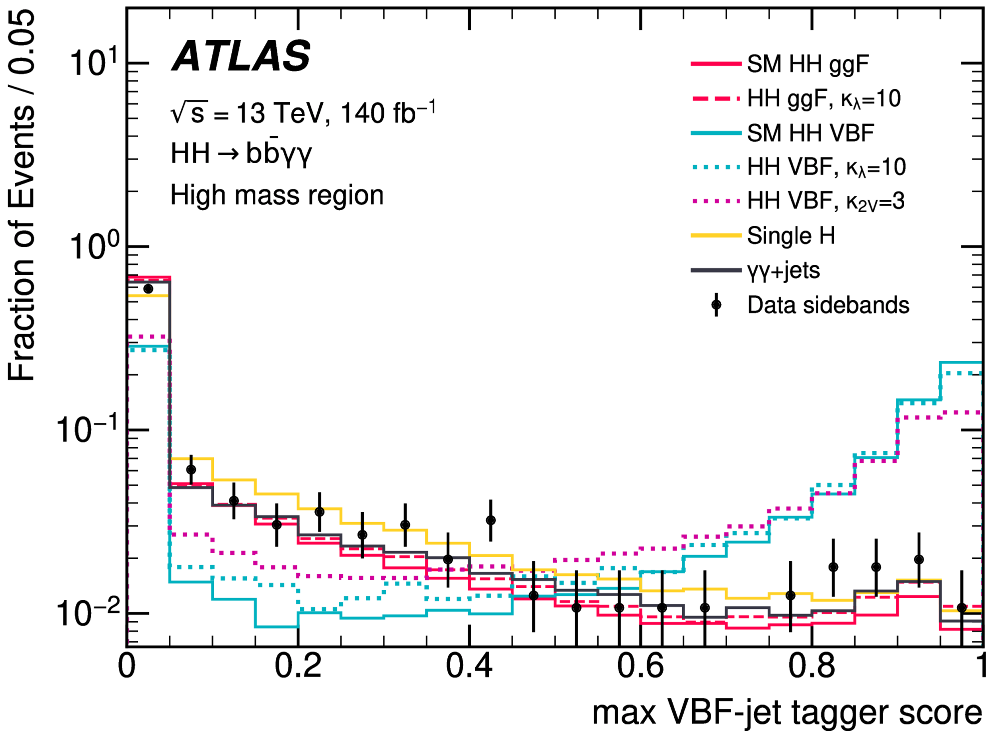
*VBF accounted for, but not specifically targeted

Back-up

$b\bar{b}\gamma\gamma$: VBF BDT tagger

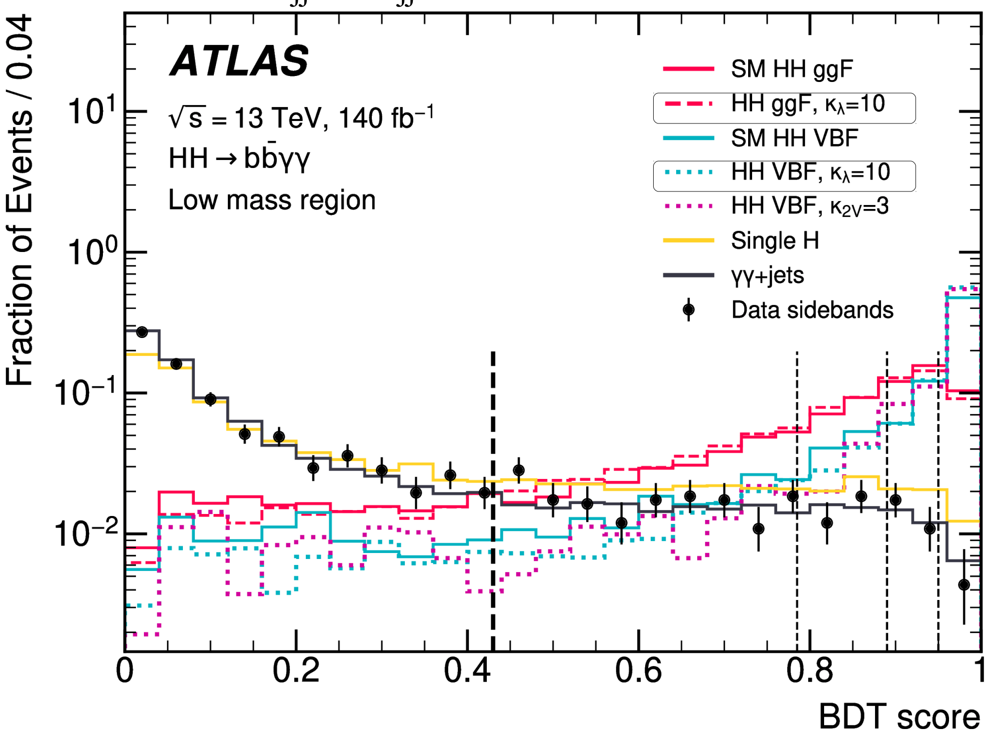
Variable	Definition
p_T^j and η^j	Transverse momentum and pseudorapidity of each of the VBF-jet candidates
$\Delta R(j, \gamma\gamma b\bar{b})$ and $\Delta\eta(j, \gamma\gamma b\bar{b})$	Angular and pseudorapidity separation between the VBF-jet candidates and the $\gamma\gamma b\bar{b}$ system
m_{jj} 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

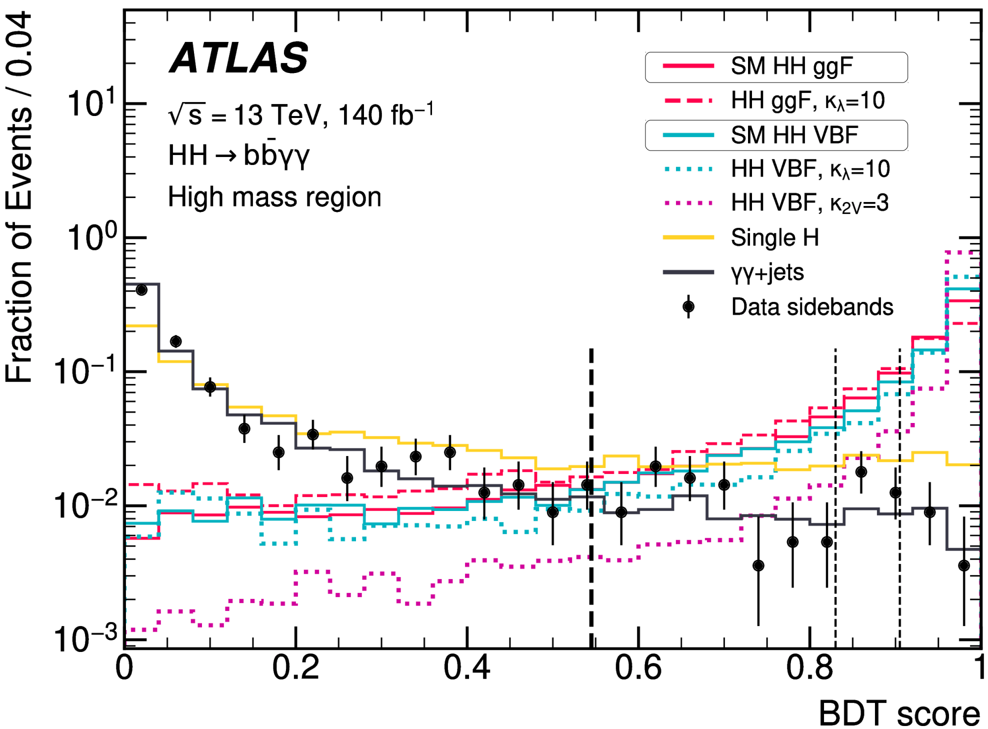




$b\bar{b}\gamma\gamma$: BDT selection

- 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

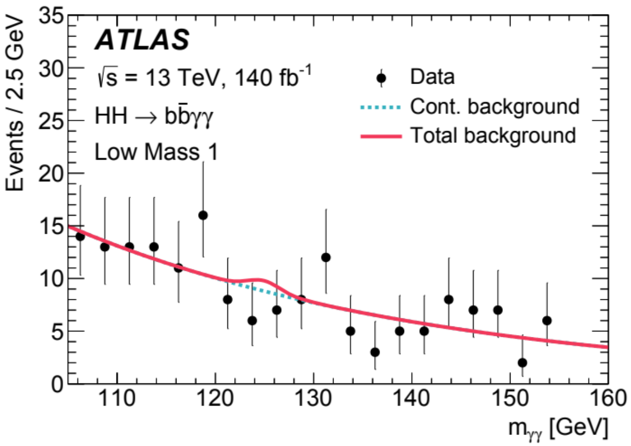


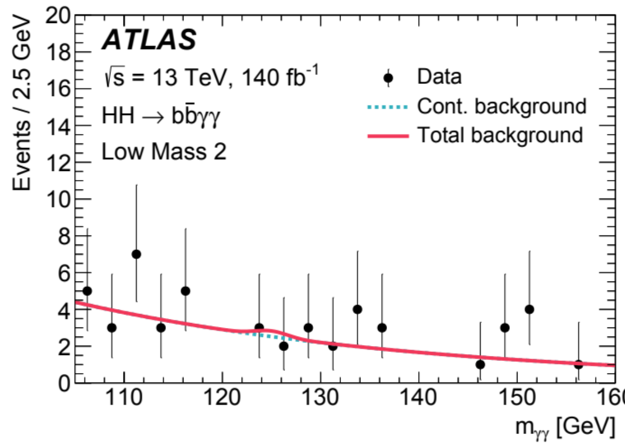


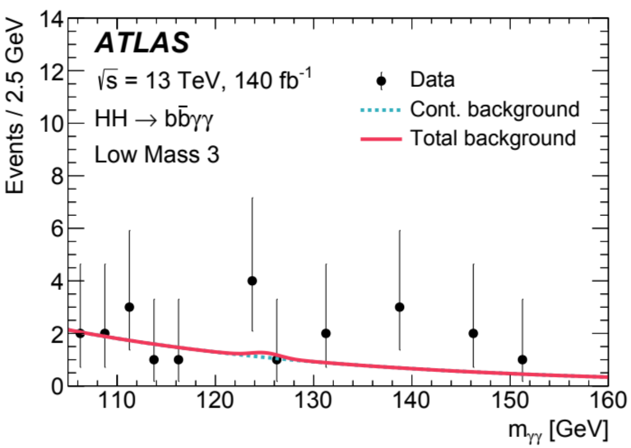
- 7 categories based of the maximum significance
  - SM ggF+VBF at high-mass
  - ggF κ_λ=5.6 + VBF κ_λ=10 at low-mass

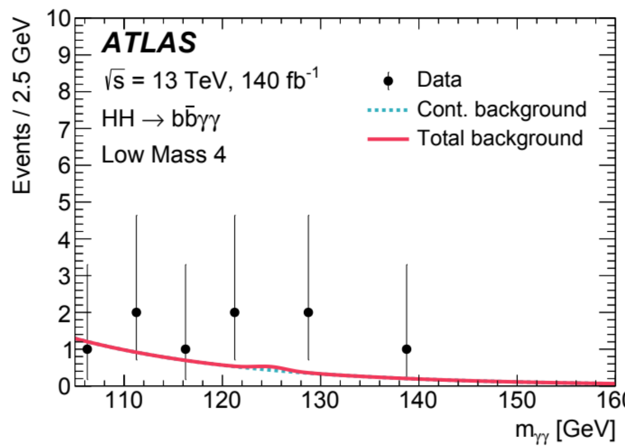
$b\bar{b}\gamma\gamma$: Fits

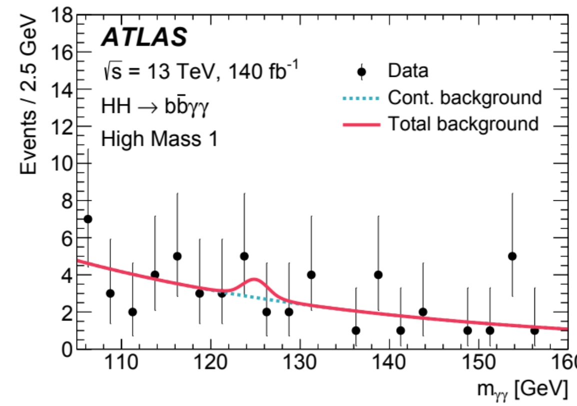
- Simultaneous unbinned maximum likelihood fit in all categories:

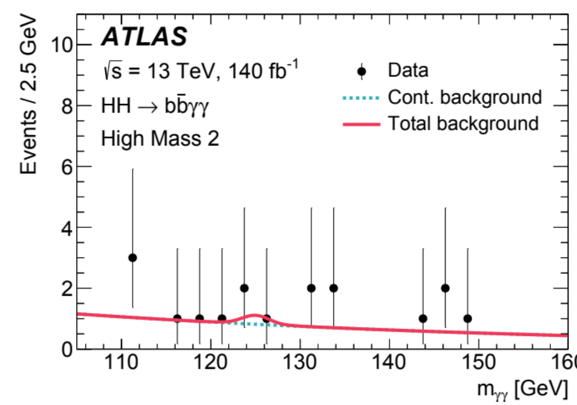


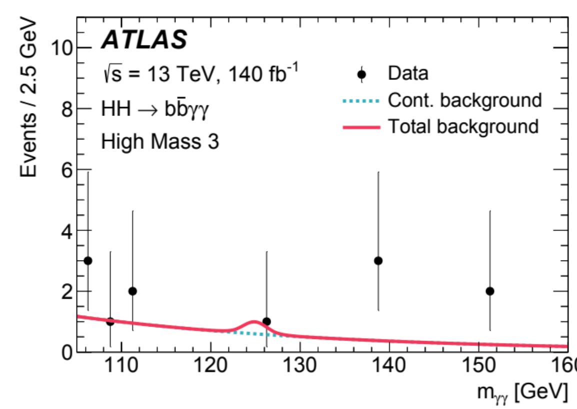












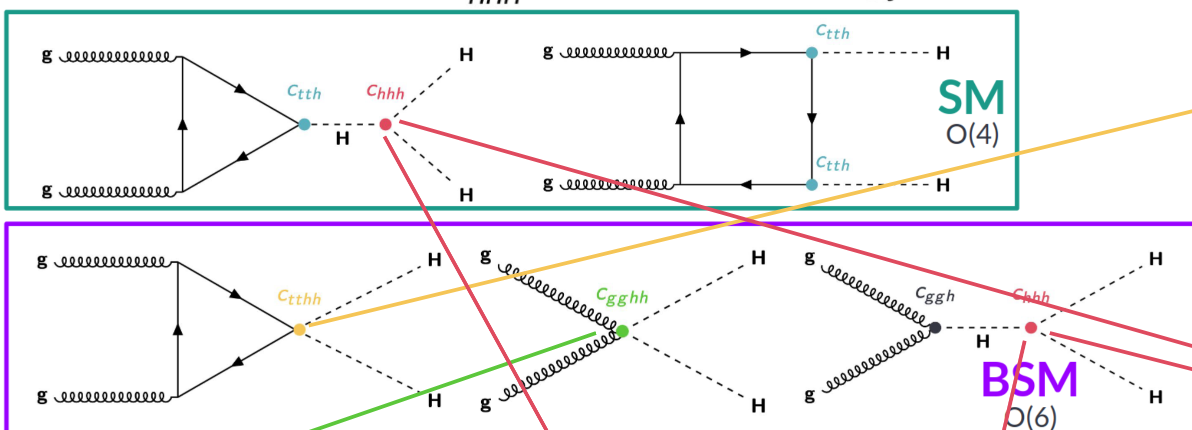
  - no significant excess observed in data

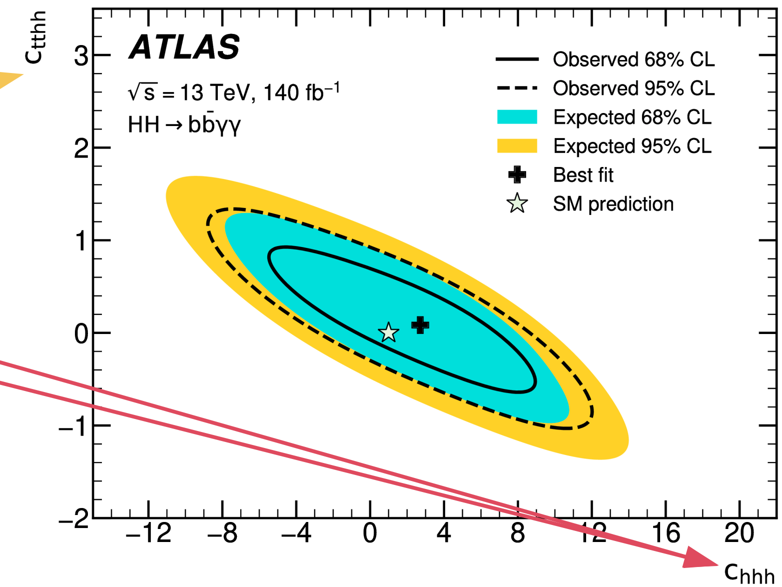
$b\bar{b}\gamma\gamma$: Limits on EFT models (1)

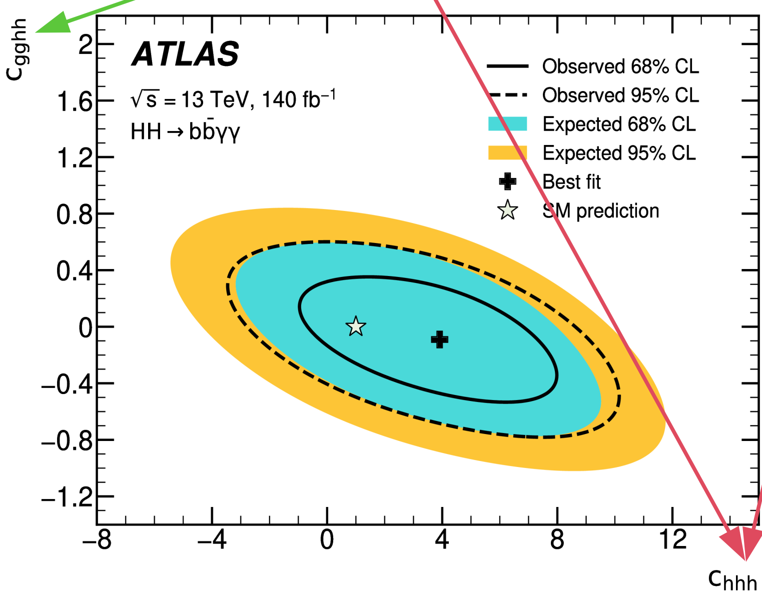
- HEFT: Higgs effective field theory
  - parameterized lagrangian allowing for deviations from SM

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

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







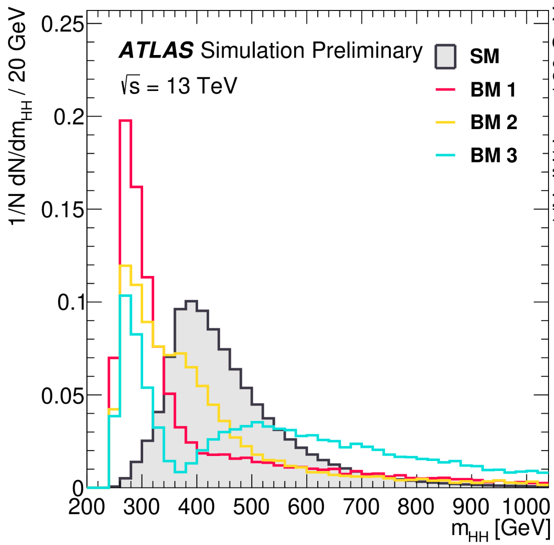
Wilson coefficient	95% CL Observed	95% CL Expected
c_{hhh}	[−1.7 , 7.7]	[−3.4 , 8.9]
c_{tthh}	[−0.28, 0.73]	[−0.48, 0.94]
c_{gghh}	[−0.42, 0.52]	[−0.59, 0.69]

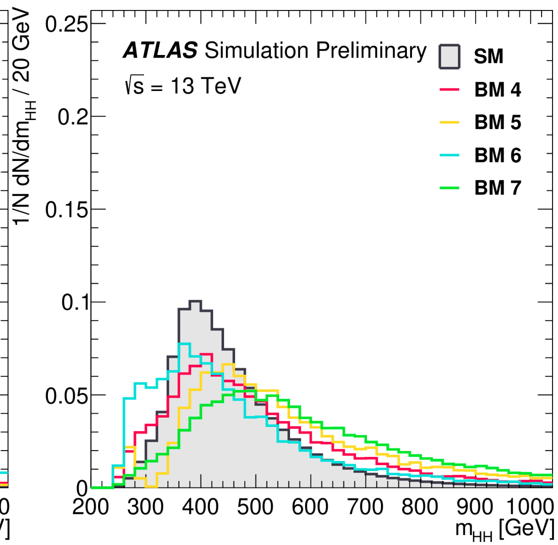
- No significant deviations from SM
- Best fit agrees with SM within 1σ

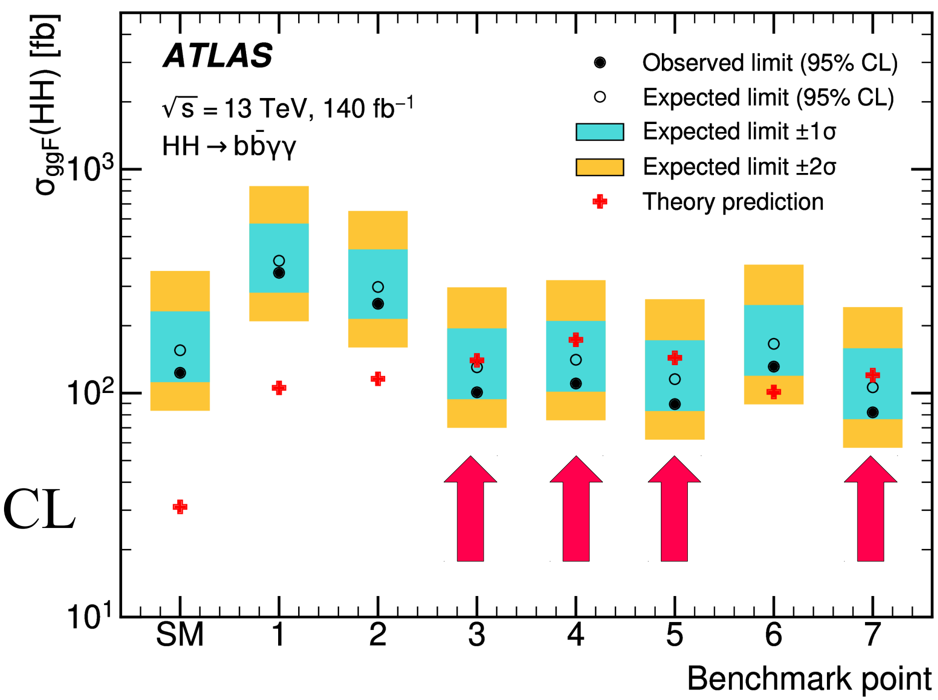
$b\bar{b}\gamma\gamma$: Limits on EFT models (2)

- 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

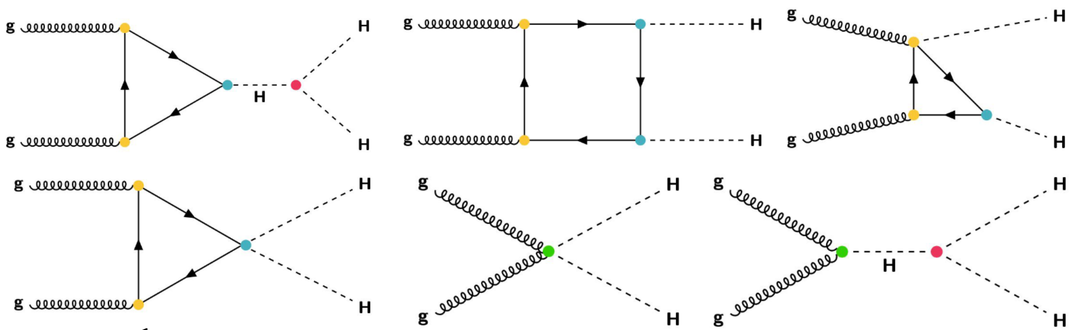
$b\bar{b}\gamma\gamma$: Limits on EFT models (3)

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

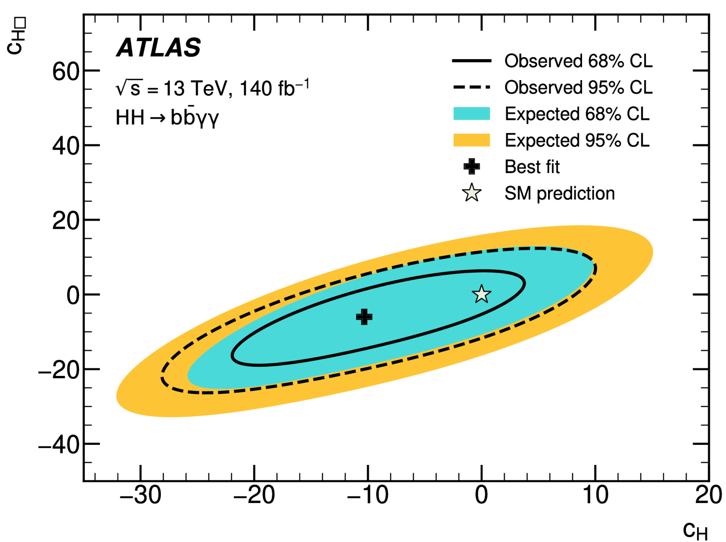
In SM: $C_H = C_{tH} = C_{tG} = C_{HG} = C_{H\Box} = 0$.

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

$b\bar{b}\gamma\gamma$: 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, $m^*_{b\bar{b}\gamma\gamma} = m_{b\bar{b}\gamma\gamma} - (m_{b\bar{b}} - 125\text{ GeV}) - (m_{\gamma\gamma} - 125\text{ GeV})$

$b\bar{b}\gamma\gamma$: 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

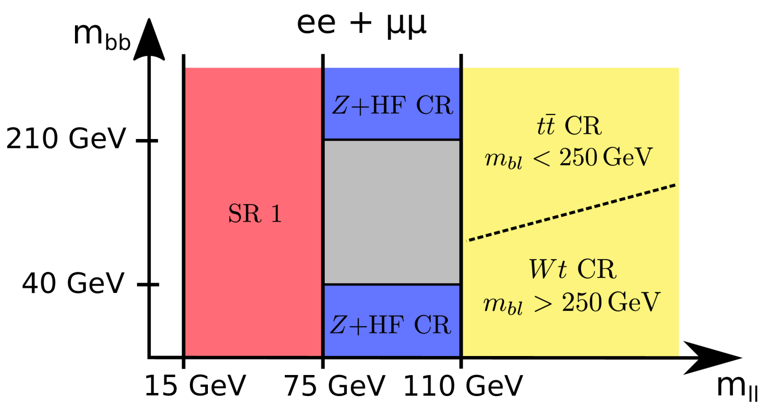
$b\bar{b}\gamma\gamma$: Systematic uncertainties

- Dominant systematic uncertainties in the expected μ_{HH} upper limit at 95% CL
  - relative variation of the expected upper limit when re-evaluating the profile likelihood ratio after fixing the nuisance parameter in question to its best-fit value, while all remaining nuisance parameters remain free to float

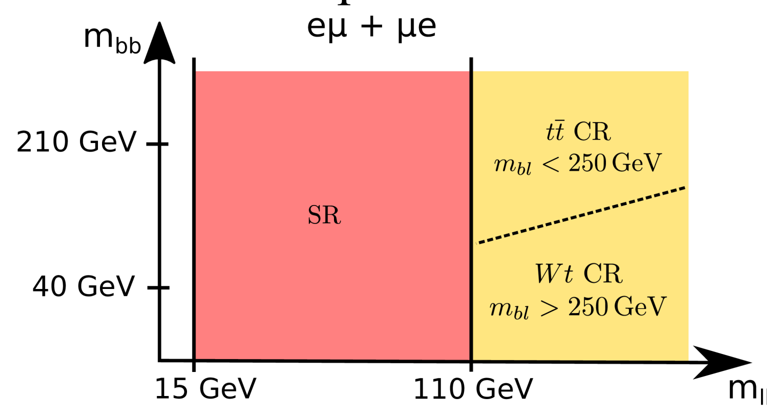
Systematic uncertainty source	Relative impact [%]
Experimental	
Photon energy resolution	0.4
Photon energy scale	0.1
Flavour tagging	0.1
Theoretical	
Factorisation and renormalisation scale	4.8
$\mathcal{B}(H \to \gamma\gamma, b\bar{b})$	0.2
Parton showering model	0.2
Heavy-flavour content	0.1
Background model (spurious signal)	0.1

$b\bar{b}ll+E_T^{miss}$: Signal and Control Regions

- Used to constrain normalisation in SR
  - same lepton flavour:



  - different lepton flavour:

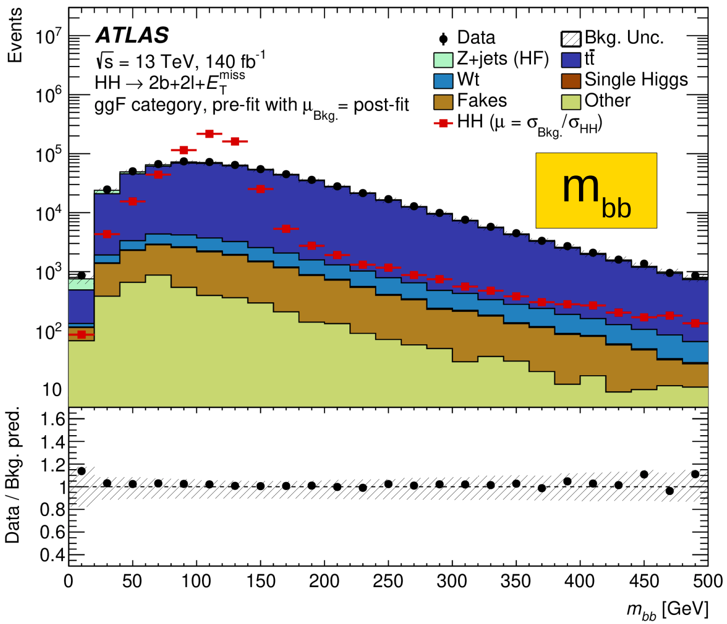


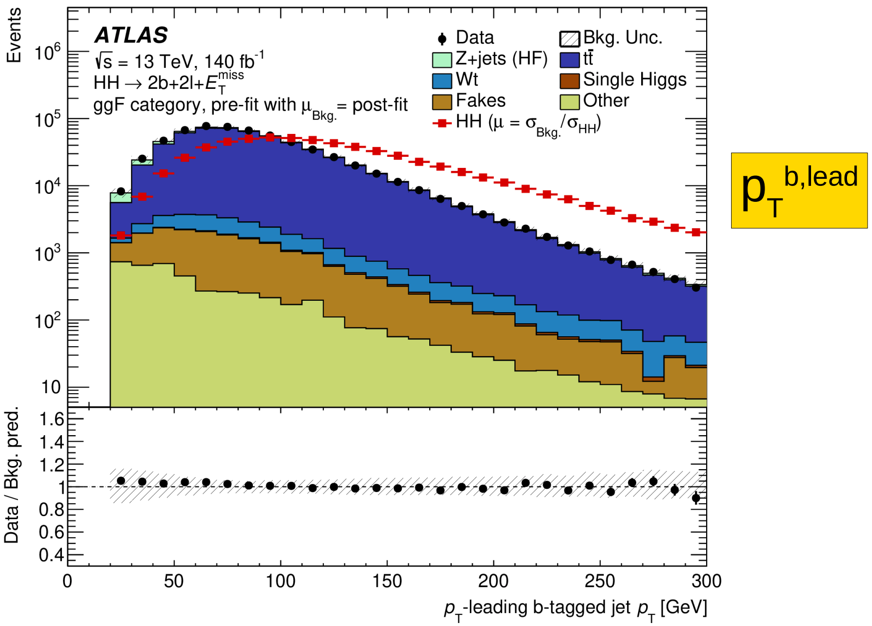
- $m_{b\ell}$ $\min\{\max(m_{b_0\ell_0}, m_{b_1\ell_1}), \max(m_{b_0\ell_1}, m_{b_1\ell_0})\}$

DNN selection for ggF HH (1)

- Variables:

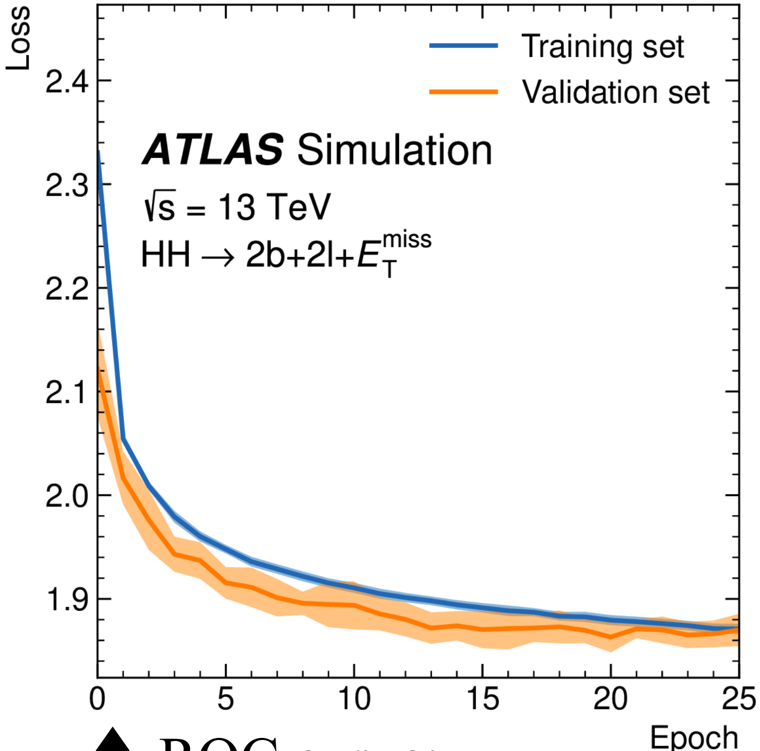
Input feature	Description
same flavour	unity if final state leptons are ee or $\mu\mu$, zero otherwise
p_T^ℓ, p_T^b	transverse momenta of the leptons, b-tagged jets
$m_{\ell\ell}$, $p_T^{\ell\ell}$	invariant mass and the transverse momentum of the di-lepton system
m_{bb}, p_T^{bb}	invariant mass and the transverse momentum of the b-tagged jet pair system
m_{T2}^{bb}	stransverse mass of the two b-tagged jets
$\Delta R_{\ell\ell}$, ΔR_{bb}	ΔR between the two leptons and two b-tagged jets
$m_{b\ell}$	$\min\{\max(m_{b_0\ell_0}, m_{b_1\ell_1}), \max(m_{b_0\ell_1}, m_{b_1\ell_0})\}$
$\min \Delta R_{b\ell}$	minimum ΔR of all b-tagged jet and lepton combinations
$m_{bb\ell\ell}$	invariant mass of the $bb\ell\ell$ system
E_T^{miss}, E_T^{miss}-sig	missing transverse energy and its significance
$m_T(\ell_0, E_T^{miss})$	transverse mass of the p_T-leading lepton with respect to E_T^{miss}
$\min m_{T,\ell}$	minimum value of $m_T(\ell_0, E_T^{miss})$ and $m_T(\ell_1, E_T^{miss})$
H_{T2}^R	measure for boostedness[1] of the two Higgs bosons



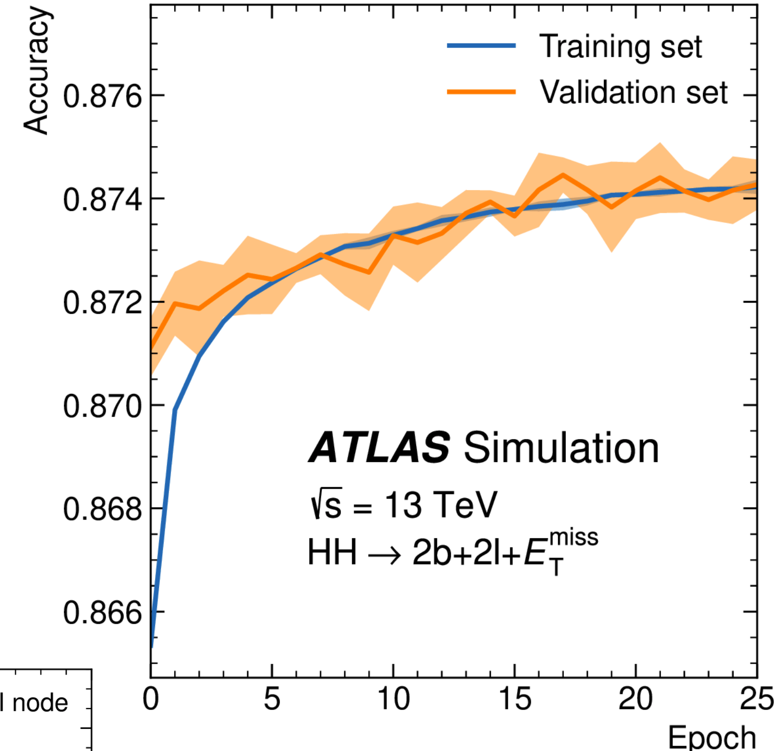


DNN selection for ggF HH (2)

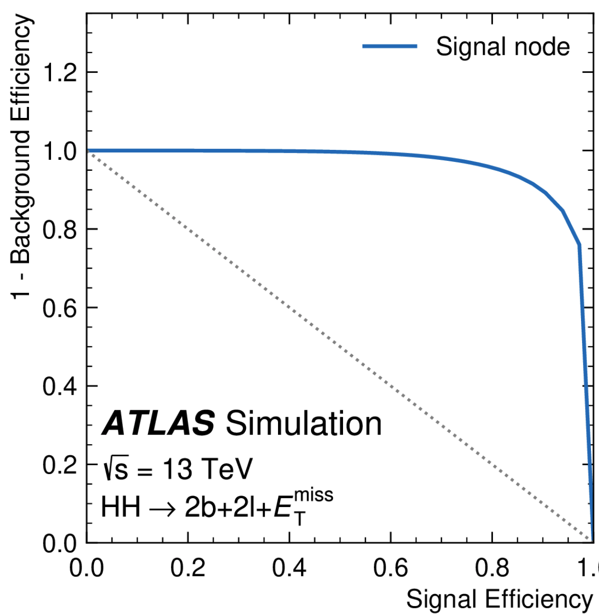
- Loss for the training and validation



- Accuracy for the training and validation

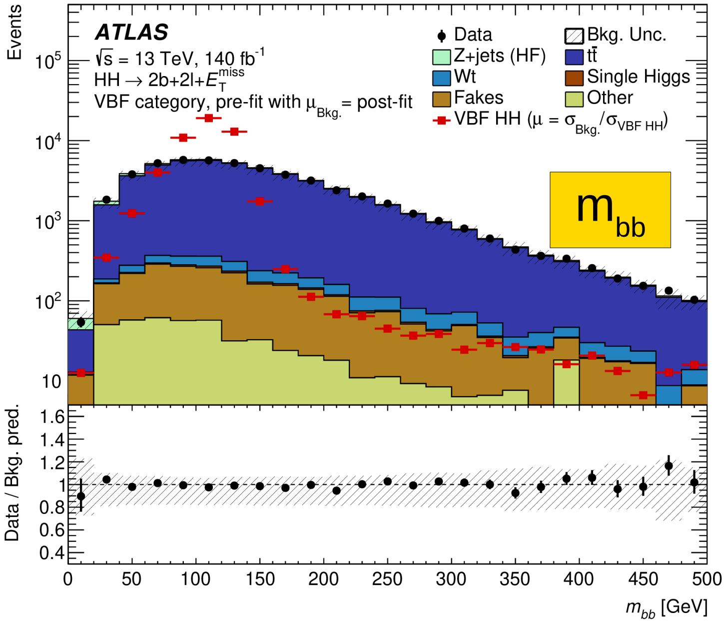


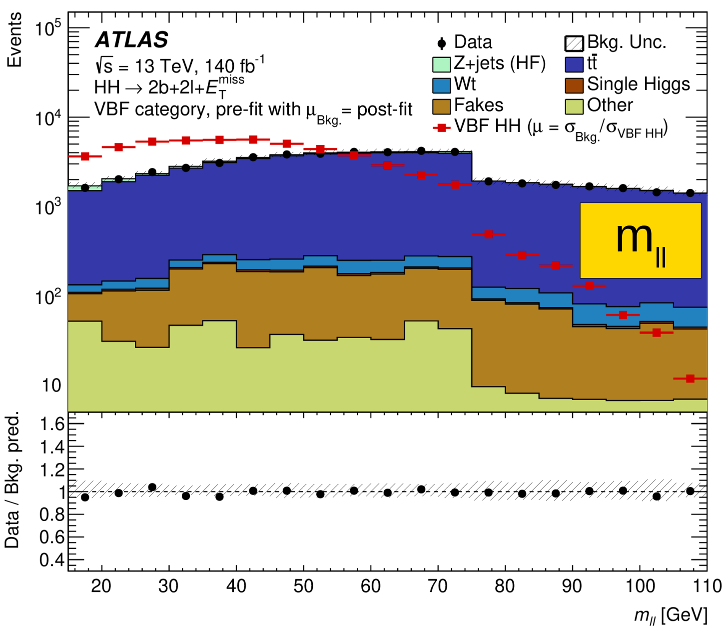
- ROC curve:



BDT selection for VBFHH

- Variables:





Input feature	Description
η_{ℓ_0}, η_{ℓ_1}, ϕ_{ℓ_0}, ϕ_{ℓ_1}, $p_T^{\ell_0}$, $p_T^{\ell_1}$	η, ϕ, p_T of the p_T-(sub)leading lepton
η_{b_0}, η_{b_1}, ϕ_{b_0}, ϕ_{b_1}, $p_T^{b_0}$, $p_T^{b_1}$	η, ϕ, p_T of the p_T-(sub)leading b-tagged jet
η_{j_0}, η_{j_1}, ϕ_{j_0}, ϕ_{j_1}, $p_T^{j_0}$, $p_T^{j_1}$	ϕ, η, p_T of the p_T-(sub)leading non b-tagged jet
E_T^{miss}, $\phi^{E_T^{miss}}$, E_T^{miss}-sig	missing transverse energy, its ϕ and significance
p_T^{bb}, ΔR_{bb}, $\Delta\phi_{bb}$, m_{bb}	p_T, ΔR, $\Delta\phi$ and invariant mass of di-b-jet system
$p_T^{\ell\ell}$, $\Delta R_{\ell\ell}$, $\Delta\phi_{\ell\ell}$, $m_{\ell\ell}$, $\phi^{\ell\ell}_{centrality}$	p_T, ΔR, $\Delta\phi$, p_T and centrality[1] of di-leptons system
$p_T^{bb\ell\ell}$, $m_{bb\ell\ell}$	p_T and invariant mass of the $bb\ell\ell$ system
$p_T^{bb\ell\ell+E_T^{miss}}$, $m_{bb\ell\ell+E_T^{miss}}$	p_T and invariant mass of $bb\ell\ell$ + E_T^{miss} system
$m_{\ell\ell+E_T^{miss}}$	invariant mass of di-lepton + E_T^{miss} system
$p_T^{E_T^{miss}+\ell\ell}$, $\Delta\phi_{E_T^{miss},\ell\ell}$	p_T of and $\Delta\phi$ between E_T^{miss} and di-lepton system
p_T^{tot}	p_T of $bb\ell\ell$ + E_T^{miss}+ p_T-leading and -sub-leading jet
m_{tot}	invariant mass of $bb\ell\ell$ + E_T^{miss}+ p_T-leading and -sub-leading jet
m_t^{KLF}	Kalman fitter top-quark mass
min $\Delta R_{\ell_0 j}$, min $\Delta R_{\ell_1 j}$	minimum ΔR between p_T-(sub)leading ℓ-j couples
$\sum m_{\ell j}$	sum of the invariant masses of all ℓ+jet combinations
max p_T^{jj}, max m_{jj}	maximum p_T and invariant mass of any two non b-tagged jets
max $\Delta\eta_{jj}$, max $\Delta\phi_{jj}$	maximum $\Delta\eta$ and $\Delta\phi$ between any two non b-tagged jets
min $\Delta R_{b\ell}$	minimum ΔR of all b-tagged jet and lepton combinations
$N_{forward\ jets}$, N_j	number of forward jets, number of non b-tagged jets
m_{T2}^{bb}	stransverse mass of the two b-tagged jets
m_{coll}	collinear mass (reconstruction of $m_{\tau\tau}$)
m_{MMC}	value of the MMC algorithm (reconstruction of $m_{\tau\tau}$)

$b\bar{b}ll+E_T^{miss}$: Systematic uncertainties

Uncertainty in region	ggF-SR 7	ggF-SR 6	ggF-SR 5	ggF-SR 4	ggF-SR 3	ggF-SR 2	ggF-SR 1
Total Standard Model expectation	550	363	209	123	60	39	15
Total statistical ($\sqrt{N_{exp}}$)	±23	±19	±14	±11	±8	±6	±4
Total Standard Model systematic	$^{+28}_{-29}$	$^{+19}_{-18}$	$^{+13}_{-14}$	$^{+10}_{-12}$	±6	±5	±4
Background normalization	$^{+6}_{-11}$	$^{+5}_{-8}$	$^{+3.5}_{-5}$	$^{+2.6}_{-3.2}$	$^{+1.5}_{-1.8}$	$^{+1.1}_{-1.3}$	$^{+0.5}_{-0.6}$
Background theory	$^{+40}_{-35}$	$^{+32}_{-27}$	±21	$^{+19}_{-20}$	±11	±7	±6
Experimental	$^{+40}_{-33}$	$^{+27}_{-19}$	$^{+13}_{-17}$	±9	$^{+5}_{-6}$	±4	±1.8
Fake extraction	±0.7	±0.5	±0.4	±0.29	±0.11	±0.11	±0.29
Signal normalization	$^{+5}_{-6}$	±6	±6	±7	±6	±6	$^{+7}_{-8}$
Signal theory	$^{+0.4}_{-1.3}$	$^{+0.4}_{-1.5}$	$^{+0.5}_{-1.5}$	$^{+0.5}_{-1.8}$	$^{+0.5}_{-1.5}$	$^{+0.4}_{-1.5}$	$^{+0.6}_{-1.9}$
Template statistics	±11	±10	±8	±5	$^{+4}_{-4}$	$^{+4}_{-3.5}$	$^{+2.3}_{-2.1}$

Uncertainty in region	VBF-SR 5	VBF-SR 4	VBF-SR 3	VBF-SR 2	VBF-SR 1
Total Standard Model expectation	3430	920	123	8.8	1.3
Total statistical ($\sqrt{N_{exp}}$)	±60	±30	±11	±3.0	±1.2
Total Standard Model systematic	±120	$^{+40}_{-50}$	$^{+11}_{-13}$	±1.7	$^{+0.5}_{-0.6}$
Background normalization	$^{+40}_{-100}$	$^{+11}_{-26}$	$^{+2.3}_{-3.3}$	$^{+0.20}_{-0.24}$	$^{+0.09}_{-0.10}$
Background theory	$^{+230}_{-170}$	$^{+90}_{-80}$	$^{+18}_{-15}$	$^{+0.9}_{-1.0}$	$^{+0.28}_{-0.4}$
Experimental	$^{+170}_{-190}$	$^{+70}_{-80}$	$^{+16}_{-18}$	±1.4	$^{+0.30}_{-0.5}$
Fake extraction	±2.4	±0.7	±0.08	±0.04	±0
Signal normalization	$^{+3.1}_{-3.4}$	$^{+2.9}_{-3.2}$	$^{+1.8}_{-1.9}$	$^{+0.6}_{-0.7}$	±0.4
Signal theory	±0.07	±0.06	±0.04	±0.014	±0.009
Template statistics	±0	±10	±5	$^{+1.5}_{-1.3}$	$^{+0.26}_{-0.23}$

HL-LHC projection

Scenarios considered:

- A scenario where only statistical uncertainties are considered (No syst. unc.).
- A baseline scenario where relevant systematic uncertainties are scaled down, following the improvements expected with the larger HL-LHC dataset available [26]. The data-driven background uncertainties are also reduced according to the integrated luminosity. This consists in a 50% reduction of the bootstrap uncertainty at the HL-LHC, while the shape uncertainty is assumed to be identical to Run 2. Table 1 shows a summary of the considered uncertainty scale factors in this scenario.
- A scenario where Run 2 experimental uncertainties are considered but theoretical uncertainties associated to HH signals are halved (Theoretical unc. halved).
- A scenario where Run 2 experimental uncertainties are left unchanged (Run 2 syst. unc).

Baseline scenario for systematics:

Systematic uncertainties	Scale factors for HL-LHC baseline scenario
Theoretical uncertainty	0.5
b-jet tagging efficiency	0.5
c-jet tagging efficiency	0.5
Light-jet tagging efficiency	1.0
Jet energy scale and resolution	1.0
Luminosity	0.6
Background bootstrap uncertainty	0.5
Background shape uncertainty	1.0

	Scaling factors (sf)	
Uncertainty scenario	Bootstrap unc.	Shape unc.
Pessimistic bkg. unc.	1.0	1.0
Conservative bkg. unc. 1 (fix bootstrap unc.)	1.0	0.2
Conservative bkg. unc. 2 (fix shape unc.)	0.2	1.0
Optimistic bkg. unc.	0.2	0.2