Study of Higgs boson pair production in the $\mathbf{HH \to b\bar{b}\gamma\gamma}$ final state with $\mathbf{308\ fb^{-1}}$ of data collected at $\sqrt{s} = 13$ TeV and 13.6 TeV by ATLAS experiment

Yong Zhou
Nanjing University

arXiv:2507.03495

CLHCP 2025

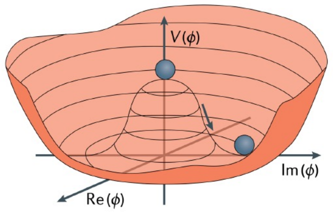
Xinxiang, Henan, China

Motivation

- The Higgs potential describes the self-interaction of the Higgs field and governs electroweak symmetry breaking(EWSB). After EWSB, the Higgs potential is given by:

$$V(\phi)=\frac{1}{2}\mathrm{m}_H\mathrm{H}^2+\lambda_3 vH^3+\frac{\lambda_4}{4}H^4$$

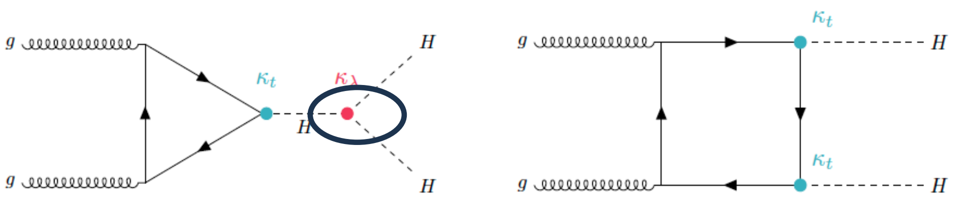
(In the SM , $v \approx 246GeV$, $m_H \approx 125GeV, \lambda_3=\lambda_4=\lambda_{SM}=\frac{m_H}{2v^2}\approx 0.13$)



- Searching for di-Higgs production is the **unique experimental** means to **directly probe** the Higgs trilinear self coupling($\kappa_\lambda=\frac{\lambda_{3,\mathrm{obs}}}{\lambda_{\mathrm{SM}}}$).

➢ Non-resonant HH production

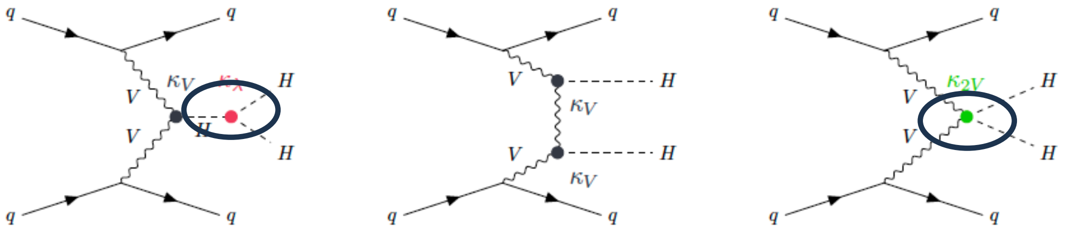
Probe to κ_λ



(a) ggF trilinear Higgs coupling

(b) ggF box diagram

Unique probe to κ_{2V}



(c) VBF trilinear Higgs coupling

(d) VBF double VVH

(e) VBF $VVHH$ vertex

Gluon-gluon fusion(ggFHH)

σ_{HH}^{ggF} = 30.77 fb @ 13 TeV

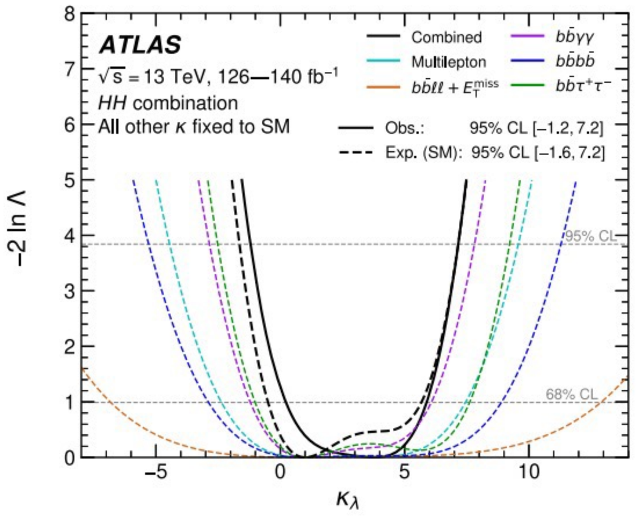
σ_{HH}^{ggF} = 34.13 fb @ 13.6 TeV

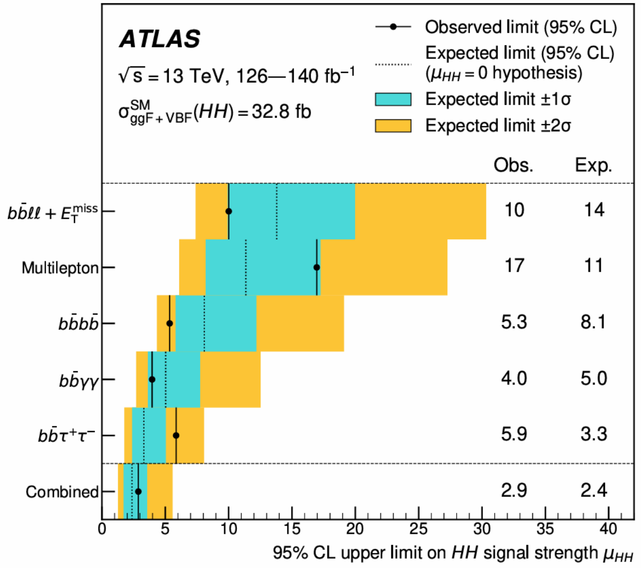
Vector boson fusion(VBFHH)

σ_{HH}^{VBF} = 1.69 fb @ 13 TeV

σ_{HH}^{VBF} = 1.87 fb @ 13.6 TeV

$HH \rightarrow bb\gamma\gamma$ channel



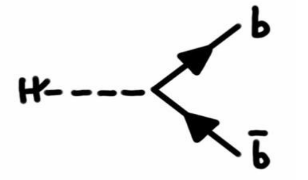


	bb	WW	ττ	ZZ	γγ
bb	34%				
WW	25%	4.6%			
ττ	7.3%	2.7%	0.39%		
ZZ	3.1%	1.1%	0.33%	0.069%	
γγ	0.26%	0.10%	0.028%	0.012%	0.0005%

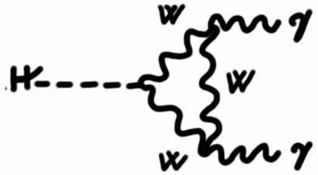
Run2 Combination (PhysRevLett.133.101801)

HH decay branching ratio

- HH→ $bb\gamma\gamma$ channel is one of the golden channels in HH combination
- HH→ $bb\gamma\gamma$ final state:
  - ✓ **Highest branching ratio (59%)**
  - x Large QCD background.



  - x Very Low branching ratio**(0.23%)**
  - ✓ **Excellent photon trigger and reconstruction efficiency**
  - ✓ **Excellent $m_{\gamma\gamma}$ resolution(1-2GeV)**



Data and MC sample

- **Data samples :** Full run2($\mathbf{140fb^{-1}}$) + partial run3($\mathbf{168fb^{-1}}$) dataset.
- Diphoton trigger are used for all years(negligible impact from single photon trigger)

Datasets & GRL

	luminosity (fb^{-1})	GRL
2015	3.24	data15_13TeV.periodAllYear_DetStatus-v89-pro21-02_Unknown_PHYS_StandardGRL_All_Good_25ns.xml
2016	33.40	data16_13TeV.periodAllYear_DetStatus-v89-pro21-01_DQDefects-00-02-04_PHYS_StandardGRL_All_Good_25ns.xml
2017	44.63	data17_13TeV.periodAllYear_DetStatus-v99-pro22-01_Unknown_PHYS_StandardGRL_All_Good_25ns_Triggerno17e33prim.xml
2018	58.79	data18_13TeV.periodAllYear_DetStatus-v102-pro22-04_Unknown_PHYS_StandardGRL_All_Good_25ns_Triggerno17e33prim.xml
2022	31.39	data22_13p6TeV.periodAllYear_DetStatus-v109-pro28-04_MERGED_PHYS_StandardGRL_All_Good_25ns_ignore_TRIGMUO_TRIGLAR.xml
2023	27.23	data23_13p6TeV.periodAllYear_DetStatus-v110-pro31-06_MERGED_PHYS_StandardGRL_All_Good_25ns_ignoreTRIG_JETCTPIN.xml
2024	109.4	physics_25ns_data24.xml

Triggers

	trigger
2015	HLT_g35_loose_g25_loose
2016	HLT_g35_loose_g25_loose
2017	HLT_g35_medium_g25_medium_L12EM20VH
2018	HLT_g35_medium_g25_medium_L12EM20VH
2022	HLT_g35_medium_g25_medium_L12EM20VH
2023	HLT_g35_medium_g25_medium_L12eEM24L
2024	HLT_g35_medium_g25_medium_L12eEM24L

MC samples

Process	Generator	PDF set	Showering	Tune	Accuracy	Order of σ calculation
ggF HH	Powheg Box v2 [59–63]	PDF4LHC21 [64]	Pythia 8.309 [67]	A14 [68]	NLO	NNLO
VBF HH	MadGraph5_aMC@NLO [65]	NNPDF3.0nlo [66]	Pythia 8.309	A14	LO	N^{3}LO
ggF H	NNLOPS [59–61, 69, 70]	PDF4LHC15nlo (PDF4LHC21)	Pythia 8.309	AZNLO [71] (A14)	NNLO	N^{3}LO
VBF H	Powheg Box v2 [59–61, 72]	PDF4LHC15nlo (PDF4LHC21)	Pythia 8.309	AZNLO (A14)	NLO	NNLO
WH	Powheg Box v2 [59–61, 73]	PDF4LHC15nlo (PDF4LHC21)	Pythia 8.309	AZNLO (A14)	NLO	NNLO
$qq \to ZH$	Powheg Box v2 [59–61, 73]	PDF4LHC15nlo (PDF4LHC21)	Pythia 8.309	AZNLO (A14)	NLO	NNLO
$gg \to ZH$	Powheg Box v2 [59–61, 73]	PDF4LHC15nlo (PDF4LHC21)	Pythia 8.309	A14	LO	NLO
$t\bar{t}H$	Powheg Box v2 [59–61, 74]	NNPDF3.0nlo (PDF4LHC21)	Pythia 8.309	A14	NLO	NNLO
$b\bar{b}H$	Powheg Box v2 [59–61, 75]	NNPDF3.0nlo (PDF4LHC21)	Pythia 8.309	A14	NLO	NNLO
tHq	MadGraph5_aMC@NLO	NNPDF3.0nlo	Pythia 8.309	A14	NLO	NLO
tHW	MadGraph5_aMC@NLO	NNPDF3.0nlo	Pythia 8.309	A14	NLO	NLO
$\gamma\gamma$+jets	Sherpa 2.2.14 [76]	NNPDF3.0nnlo	Sherpa 2.2.14	–	–	–
$\gamma\gamma b\bar{b}$	Sherpa 2.2.14	NNPDF3.0nnlo	Sherpa 2.2.14	–	–	–

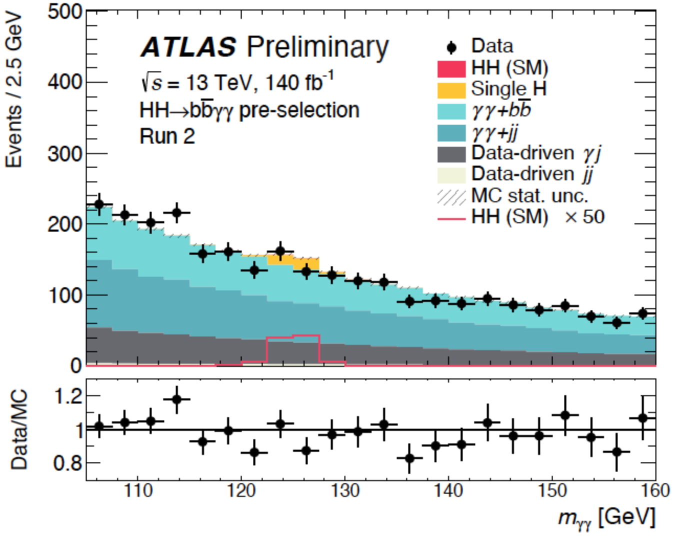
HH signal
- ggFHH:SM+5BSM sample
- VBFHH:SM+12BSM sample

Single H background

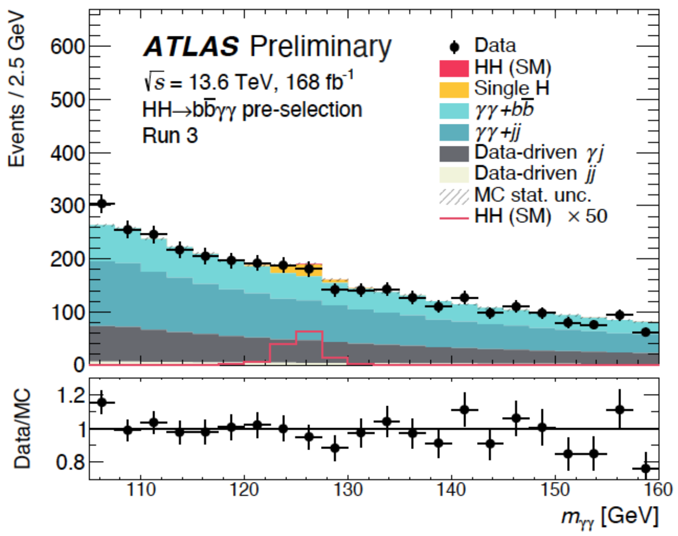
Continuum background

Pre-Selection

$H \to \gamma\gamma$ Selection	$H \to bb$ Selection	ttH reduction
• 2 tight and isolated photons • $p_T/m_{\gamma\gamma} > 0.35(0.25)$ for leading (sub-leading) photon. • 105 GeV< $m_{\gamma\gamma}$ <160 GeV .	• $N_{b-jets} \geq 2$ at GN2 85% WP • μ-in-jet+p_T-Reco Correction • Kinematic Fit.	• $N_{lep} = 0$ • $N_{central\ jets} < 6$



(a) Run 2



(b) Run 3

Selection	Yields	Entries	Efficiency [%]	Cumul. Eff. [%]
All events	11.40	1,580,000	100.00	100.00
event clean and dalitz filter	11.33	1,570,299	99.38	99.38
Pass trigger	7.00	971,617	61.78	61.39
2 loose photons	6.35	882,345	90.75	55.71
trigger matching	6.31	877,171	99.42	55.39
2 tight ID photon	5.55	772,417	87.93	48.71
2 tight ID and Iso photons	4.99	695,346	89.88	43.78
rel. pT cuts	4.58	639,762	91.87	40.22
myy in [105,160]GeV	4.58	639,030	99.88	40.17
Nlep =0	4.56	636,918	99.66	40.04
at least 2 Nj	4.03	563,660	88.25	35.33
Nj central<6	3.94	550,899	97.75	34.54
At least 2 b-jets with 85% WP	1.96	276,953	49.89	17.23

Table 11: Cutflow for HH ggF signal sample (SM) - AF3 in Run2.

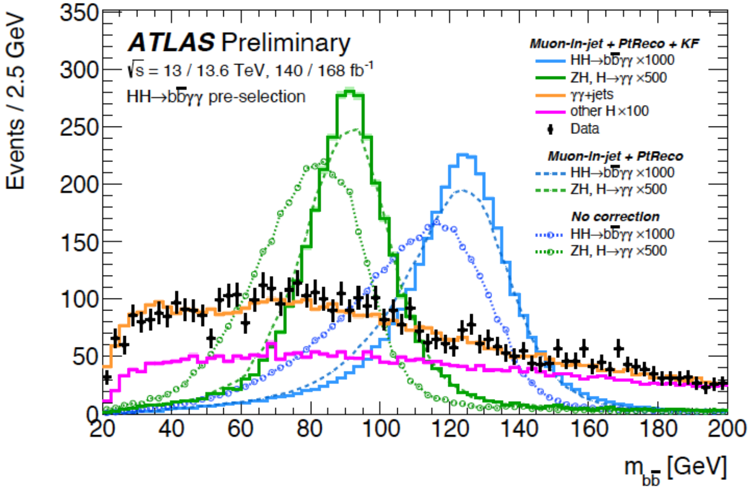
Kinematic Fit

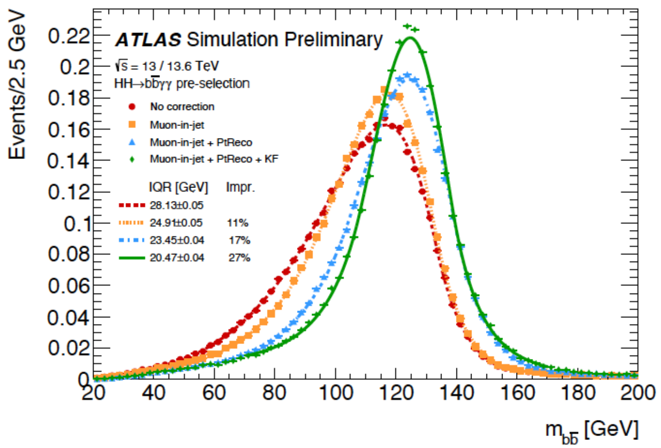
- The Kinematic Fit is an event-by-event correction to calibrate the HH system in the transverse plane by using the $H \rightarrow \gamma\gamma$ system to balance the $H \rightarrow bb$ system.

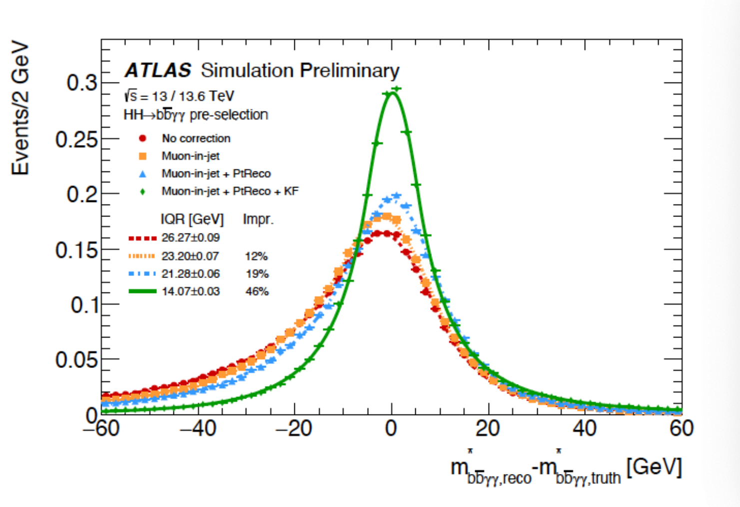
- The KF using log-likelihood minimization, The likelihood function contains two iterations and defined by :

$$-2\ln(\mathcal{L}) = \sum_{j=jets}\left[-2\ln\left[\mathrm{TF}\left(\frac{\alpha_j \cdot E^j_{Reco} - E^j_{Reco}}{\alpha_j \cdot E^j_{Reco}}\right)\right] - 2\ln\left[\mathrm{TF}\left(\frac{\alpha_j \cdot p^j_{T,Reco} - p^j_{T,Reco}}{\alpha_j \cdot p^j_{T,Reco}}\right)\right]\right] + \\ -2\lambda\ln\left[f_p(p_X)\right] - 2\lambda\ln\left[f_p(p_Y)\right] \underbrace{+\lambda_m(m_{b\bar{b}} - m_H)^2}_{\text{included in KF 2nd iteration}}$$

- **1st iteration:** without m_{bb} constain to calculate unbiased m_{bb}.
- **2nd iteration**: with m_{bb} constrain to improve the $m_{bb\gamma\gamma}$ resolution.







- The KF improved the m_{bb} and $m_{bb\gamma\gamma}$ resolutions by 27%(13%) and 46%(33%) with respect to No correction(b-jet calibration).

Event classification

- The modified invariant mass($m^*_{bb\gamma\gamma} = m_{bb\gamma\gamma} - (m_{bb} - 125GeV) - (m_{\gamma\gamma} - 125GeV)$) is used to split the events into **High mass region**($m^*_{bb\gamma\gamma} > 350GeV$,target SM signal) and **Low mass region**($m^*_{bb\gamma\gamma} < 350GeV$,target BSM signal).
- In each region. A dedicated BDT model is trained by combining the run2 and run3 MC sample using XGboost.

Variable	Definition
Photon candidates	
$p_T/m_{\gamma\gamma}$	Transverse momentum of each photon divided by the di-photon invariant mass $m_{\gamma\gamma}$
η and ϕ	Pseudorapidity and azimuthal angle of each photon
$\Delta R(\gamma_1, \gamma_2)$	Angular distance between the two photons
***b*-jet candidates**	
b-tag status	Tightest fixed b-tag working point (60%, 70%, 77%, 85%) that each jet fulfills
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 b-jets
$m_{b\bar{b}}$	Invariant mass of the two b-jets
Single topness	Variable used to identify $t \to Wb \to q\bar{q}'b$ decays. For the definition, see Ref. [JHEP 01 (2024) 066].
Other jets (only first two, if present, ranked by discrete *b*-tagging score)	
b-tag status	Tightest fixed b-tag working point that each jet fulfills
p_T, η and ϕ	Transverse momentum, pseudorapidity and azimuthal angle of each jet
VBF-jet candidates	
$\Delta\eta_{jj}$, 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 Refs. [EPJC 72 2211, PRD 79 074017, JHEP 01 (2024) 066]
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 four-body invariant mass of the two photons and two b-jets, $m^*_{b\bar{b}\gamma\gamma} = m_{b\bar{b}\gamma\gamma} - (m_{b\bar{b}} - 125\text{ GeV}) - (m_{\gamma\gamma} - 125\text{ GeV})$

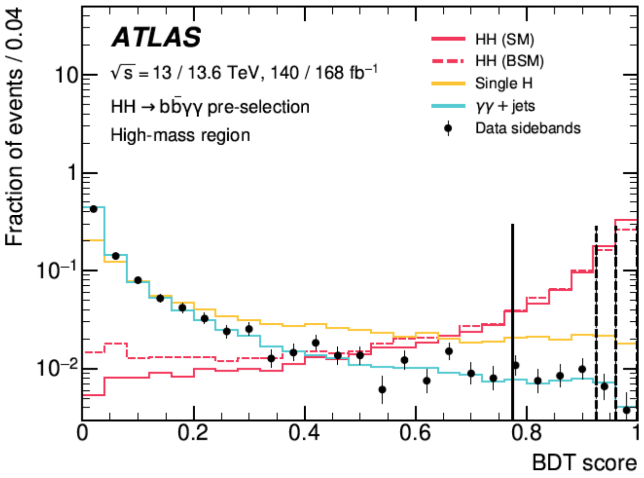
Training and test samples	
Low $m^*_{b\bar{b}\gamma\gamma}$ region	**High $m^*_{b\bar{b}\gamma\gamma}$ region**
Target signal	
ggF *HH*	
$\kappa_\lambda = 10, 5$	$\kappa_\lambda = 1$
VBF *HH*	
$\kappa_\lambda = 0, \kappa_{2V} = 1, \kappa_V = 1$	$\kappa_\lambda = 1, \kappa_{2V} = 1, \kappa_V = 1$
$\kappa_\lambda = 1, \kappa_{2V} = 1.5, \kappa_V = 1$	$\kappa_\lambda = 0, \kappa_{2V} = 1, \kappa_V = 1$
$\kappa_\lambda = 1, \kappa_{2V} = 3, \kappa_V = 1$	$\kappa_\lambda = 1, \kappa_{2V} = 1.5, \kappa_V = 1$
$\kappa_\lambda = -5, \kappa_{2V} = 1, \kappa_V = 0.5$	$\kappa_\lambda = 1, \kappa_{2V} = 3, \kappa_V = 1$
$\kappa_\lambda = 10, \kappa_{2V} = 1, \kappa_V = 1$	$\kappa_\lambda = -5, \kappa_{2V} = 1, \kappa_V = 0.5$
	$\kappa_\lambda = 10, \kappa_{2V} = 1, \kappa_V = 1$
Background	
ggF H, VBF H, $W^\pm H$, $b\bar{b}H$, $qq \to ZH$, $gg \to ZH$, $tHjb$, tWH, $t\bar{t}H$, $\gamma\gamma$+jets	
Sample split	
Training	`event_number % 4 ≤ 1`
Validation (during training)	`event_number % 4 == 2`
Test	`event_number % 4 == 3`

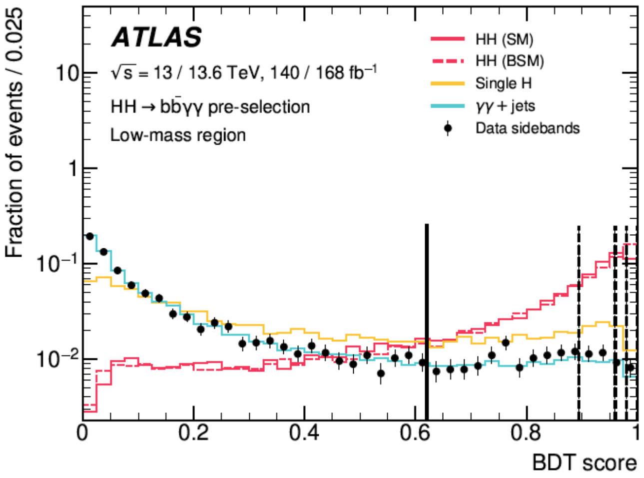
Event Categorization

- The event categories are defined based on the HM and LM BDT score distributions. 3HM and 4 LM categories are extracted for Run2 and Run3 separately:
  - The category boundaries are determined by **maximizing the number-counting significance**:

$$Z_{cat} = \sqrt{2[(S+B).\log\left(1+\frac{S}{B}\right) - S]}\ ,\quad Z_{tot} = \sqrt{\sum_{cat} Z_{cat}^2}$$

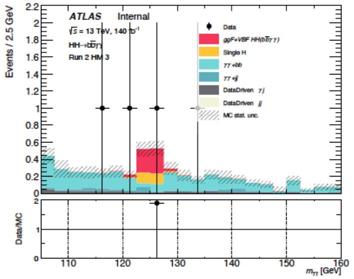
  - Requiring **at least 11** $\gamma\gamma + jets$ events for each sub category to ensure enough events for background modeling.
  - The same boundaries score are applied for Run2 and Run3 separately. (14 categories in total)



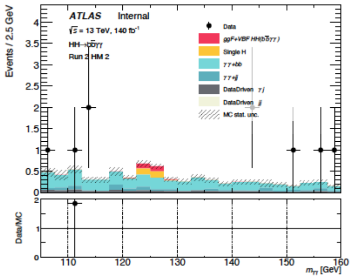


Category	Selection criteria
High Mass 1	$m^*_{b\bar{b}\gamma\gamma} \geq 350$ GeV, BDT score $\in [0.775, 0.925]$
High Mass 2	$m^*_{b\bar{b}\gamma\gamma} \geq 350$ GeV, BDT score $\in [0.925, 0.960]$
High Mass 3	$m^*_{b\bar{b}\gamma\gamma} \geq 350$ GeV, BDT score $\in [0.960, 1.000]$
Low Mass 1	$m^*_{b\bar{b}\gamma\gamma} < 350$ GeV, BDT score $\in [0.620, 0.895]$
Low Mass 2	$m^*_{b\bar{b}\gamma\gamma} < 350$ GeV, BDT score $\in [0.895, 0.960]$
Low Mass 3	$m^*_{b\bar{b}\gamma\gamma} < 350$ GeV, BDT score $\in [0.960, 0.980]$
Low Mass 4	$m^*_{b\bar{b}\gamma\gamma} < 350$ GeV, BDT score $\in [0.980, 1.000]$

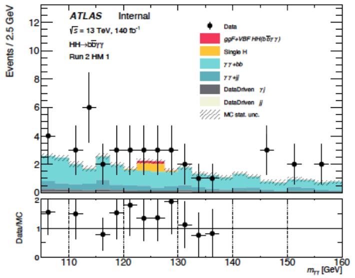
Analysis Categories



(a) Run2 HM3

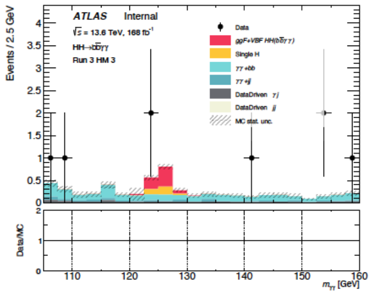


(b) Run2 HM2

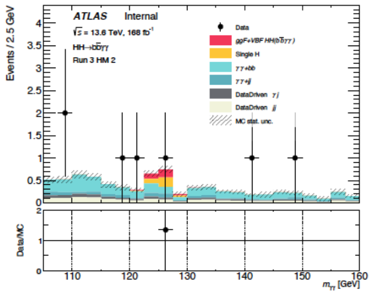


(c) Run2 HM1

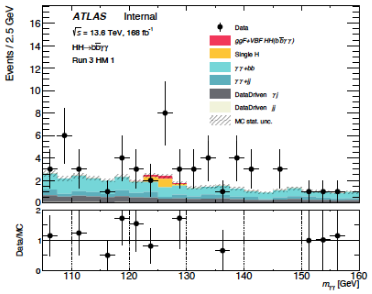
Run2 HM



(a) Run3 HM3

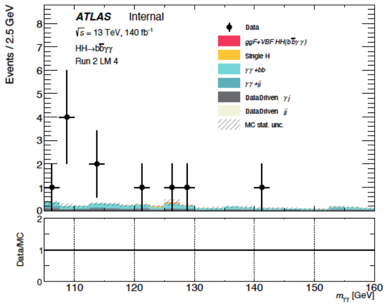


(b) Run3 HM2

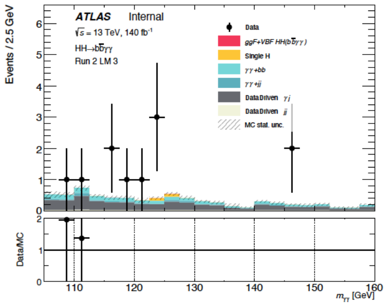


(c) Run3 HM1

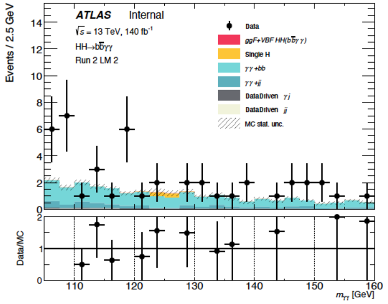
Run3 HM



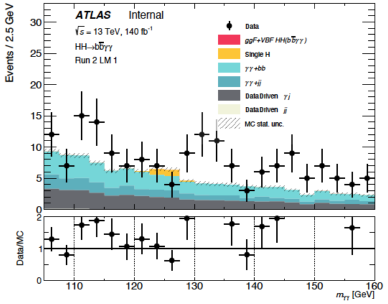
(a) Run2 LM4



(b) Run2 LM3

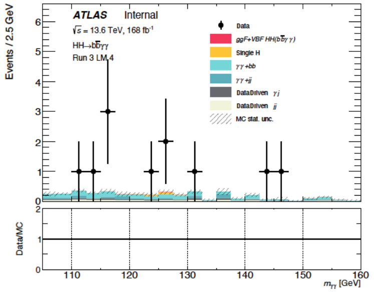


(c) Run2 LM2

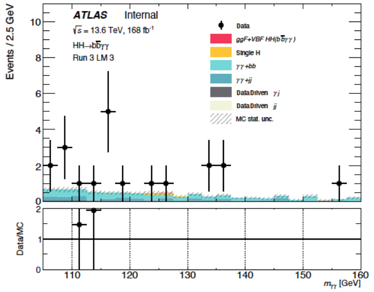


(d) Run2 LM1

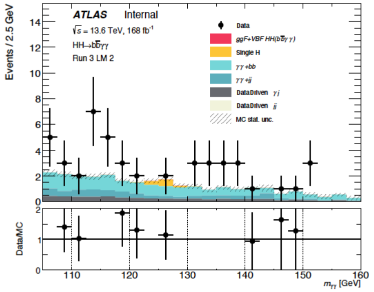
Run2 LM



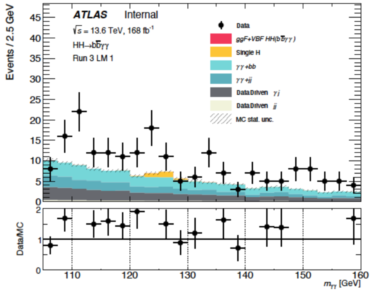
(a) Run3 LM4



(b) Run3 LM3



(c) Run3 LM2

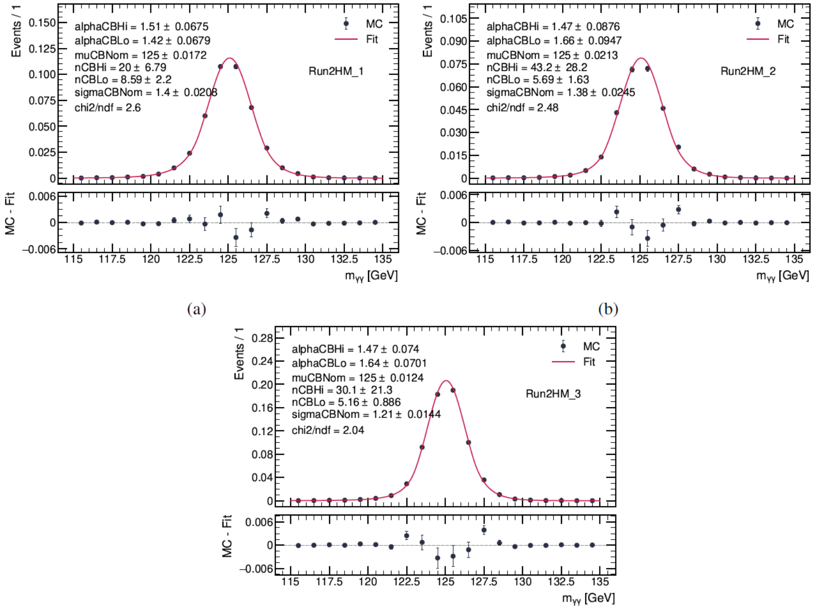


(d) Run3 LM1

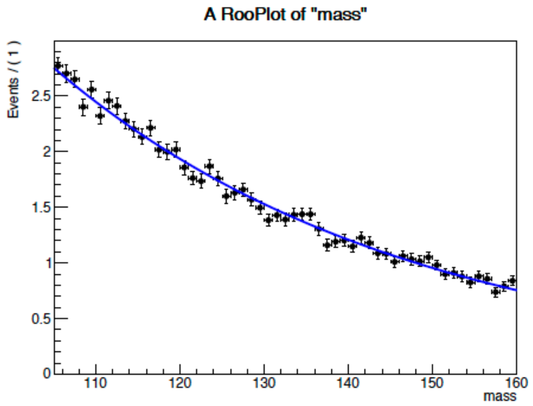
Run3 LM

Signal and Background Modeling

- **Signal Modelling**
  - The $m_{\gamma\gamma}$ distribution of the di-Higgs signal and single Higgs background are modelled with a Double-side Crystal Ball (DSCB) function.
  - The shape parameters are extracted by an unbinned likelihood fit to the SM ggF and VBF HH MC samples.
  - The shape parameters are shared between di-Higgs signals and signal Higgs backgrounds for each categories.
- **Background Modelling**
  - **Single H Modelling** : DSCB function , the same shape parameter as HH.
  - **Continuum background Modelling**:
    - The continuum background is modelled using an exponential function: $\boldsymbol{N_{bkg}.\exp(-\beta m_{\gamma\gamma})}$.
    - The exponential slopes are the same for each Run2 and Run3 category pair, while the normalization of backgrounds are determined separately in the final fit(7 slope+14 Norm).



(a) (b) (c)



(a) Run 2 + Run 3 High Mass 1

Systematic Uncertainties

- The systematic uncertainties are mainly relevant for the HH signal and resonant background.
- The spurious signal uncertainties are the only source of uncertainties relevant for continuum background.

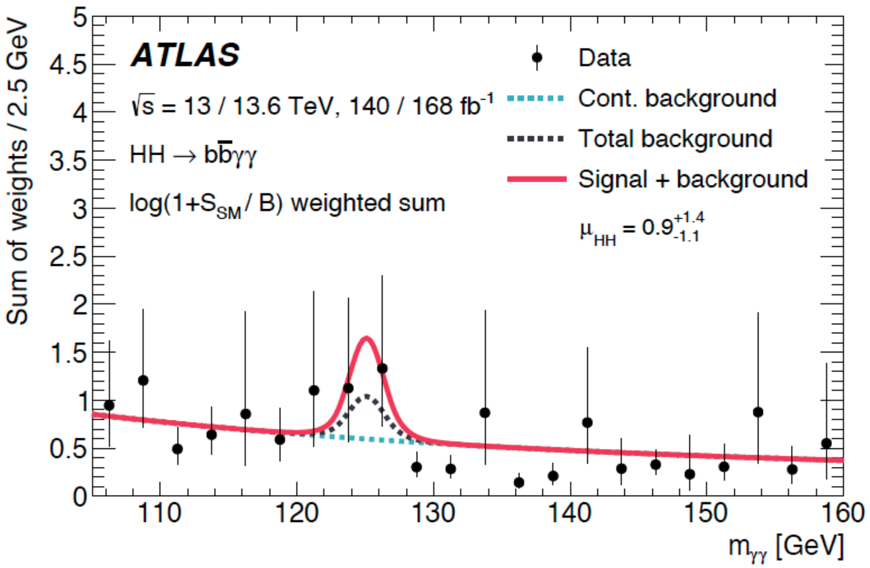
Source of systematic uncertainty	Relative impact [%] Up	Down
Experimental		
Photon energy scale	+20	−30
Photon energy resolution	+13	−6.8
Photon efficiency	+13	−2.5
Jet	+9.6	−6.4
Luminosity	+6.3	−1.1
Theory		
QCD scale + m_{top}, PDF+α_S	+34	−4.5
$\mathcal{B}(H \to \gamma\gamma, b\bar{b})$	+9.9	−2.1
Parton showering model	±15	
Heavy-flavour content	±29	
Background model		
Spurious signal	±6.5	

- **Correlation Scheme:**
  - Trigger: Uncorrelated between run2 and run3.The decorrelation between 2022 and 2023/2024 due to L1 trigger change.
  - JetMet: Partial correlated.
  - Muon ,theory, spurious uncertainties: full correlated
  - The Rest of experimental uncertainties are uncorrelated.

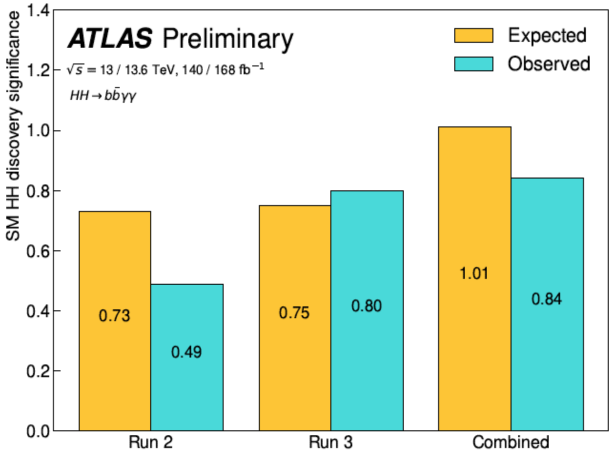
- The total uncertainty still dominant by statistical uncertainty

Results

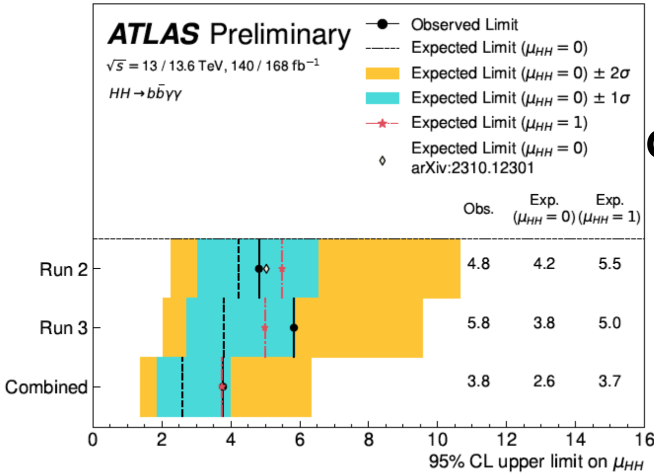
- The results are extracted from a simultaneous profile-likelihood fit to the $m_{\gamma\gamma}$ distribution in all categories.



"Weighted" plot of $m_{\gamma\gamma}$ by summing the contribution for each category and weighting for each contribution with $w_c = \log(1 + \frac{S_c}{B_c})$.



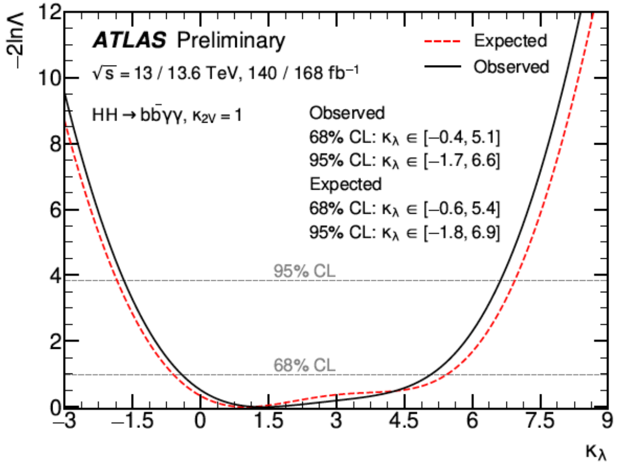
Observed significance: 0.84σ
(Expected : 1.01σ)

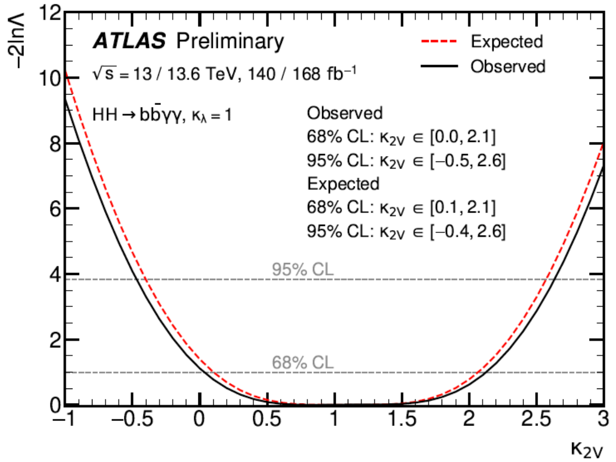


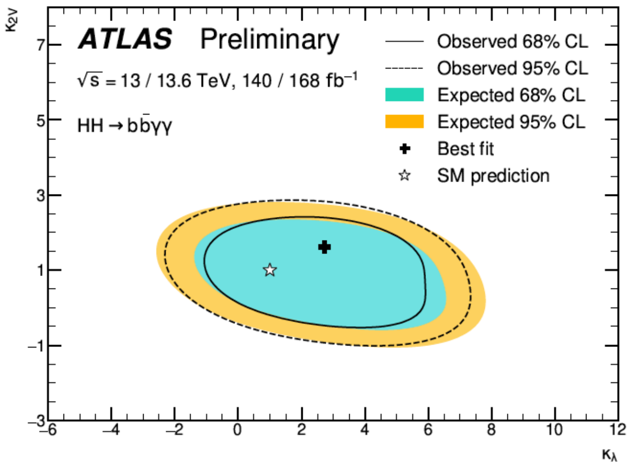
(b) upper limit

Observed upper limit : μ_{HH} < 3.8
(Expected : μ_{HH} < 2.6)

Results







	Run 2		Run 3		Combined	
	observed	expected	observed	expected	observed	expected
μ_{HH}	$0.6^{+1.8}_{-1.1}$	$1^{+2.1}_{-1.3}$	$1.4^{+2.2}_{-1.7}$	$1^{+1.9}_{-1.3}$	$0.9^{+1.4}_{-1.1}$	$1^{+1.3}_{-1.0}$
κ_λ (68% CI)	[−0.2, 4.3]	[−1.2, 6.3]	[−1.5, 7.1]	[−1.0, 6.0]	[−0.4, 5.1]	[−0.6, 5.4]
κ_λ (95% CI)	[−1.8, 6.4]	[−2.9, 8.0]	[−3.3, 8.5]	[−2.6, 7.7]	[−1.7, 6.6]	[−1.8, 6.9]
κ_{2V} (68% CI)	[−0.2, 2.4]	[−0.2, 2.3]	[−0.2, 2.3]	[−0.1, 2.2]	[0.0, 2.1]	[0.1, 2.1]
κ_{2V} (95% CI)	[−0.9, 3.1]	[−0.9, 3.0]	[−0.8, 3.0]	[−0.7, 2.9]	[−0.5, 2.6]	[−0.4, 2.6]

- **Observed κ_λ constrain at 95% CL: [-1.7,6.6]**
  (Expected:[-1.8,6.9])
- **Observed κ_{2V} constrain at 95% CL: [-0.5,2.6]**
  (Expected: [-0.4,2.6])

Summary

- **Search for Non-resonant HH Pair Production in $bb\gamma\gamma$ final state with full run2 and partial run3 dataset is presented**
  - First ATLAS analysis with more than 300 fb^{-1} dataset

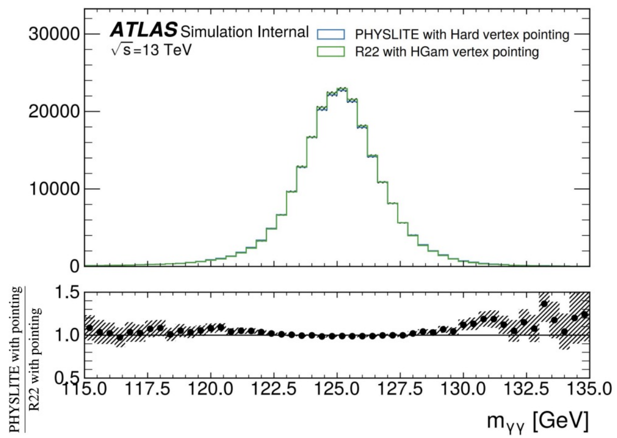
- **The Analysis strategy has been improved in multiple ways over the previous analysis**
  - ➢ Addition of 168 fb^{-1} data from Run3
  - ➢ GN2 for b-tagging and relaxing the number of b-jet requirement
  - ➢ Kinematic Fit for improve the m_{bb} resolution
  - ➢ Tighter category cuts with Run2+3 combination

- **Relative improvement with respect to previous analysis :**
  - ✓ Expected upper limit on μ_{HH} improved by ~100%
  - ✓ Expected κ_{λ} constrain at 95% CL improved by ~20%
  - ✓ Expected κ_{2V} constrain at 95% CL improved by ~30%

Backup

Difference with respect to legacy analysis

- **Production Framework : HGamCore → Easyjet(common HH fwk)**:
  - DAOD derivation : **HIGG1D1 → PHYSLITE**
  - Primary vertex: **NN vertex → Hardest vertex(highest track $\sum p_T^2$).**



- **b-tagging algorithm : DL1r → GN2**:
  - GN2 has **much better background rejection** power compare to DL1r.
  - Relax the b-jet requirements: b-tag WP **77% → 85%** and $N_{b-jet} = 2 \ \rightarrow N_{b-jet} \geq 2$.
- **Other changes and improvements**:
  - Adopt the **Kinematic Fit** method to further improve the m_{bb} resolution.
  - Additional **partial Run3 dataset**: 2022 - 2024 data(168fb^{-1}).
  - MC generator and PDF set update
  - Retrain the BDT model and background shape correlation.
  - Powheg bug fixed,AF3,CP recommendations…

MC samples

603559	SM ggF HH ($\kappa_\lambda = 1$)	FS+AF3
603558	ggF HH $\kappa_\lambda = 0$	AF3
603560	ggF HH $\kappa_\lambda = 5$	AF3
603697	ggF HH $\kappa_\lambda = -1$	AF3
603695	ggF HH $\kappa_\lambda = 2.5$	AF3
603696	ggF HH $\kappa_\lambda = 10$	AF3
525376	SM VBF HH ($\kappa_\lambda = 1$, $\kappa_{2V} = 1$, $\kappa_V = 1$)	FS+AF3
525377	VBF HH $\kappa_\lambda = 0$, $\kappa_{2V} = 1$, $\kappa_V = 1$	AF3
525378	VBF HH $\kappa_\lambda = 2$, $\kappa_{2V} = 1$, $\kappa_V = 1$	AF3
525379	VBF HH $\kappa_\lambda = 10$, $\kappa_{2V} = 1$, $\kappa_V = 1$	AF3
525380	VBF HH $\kappa_\lambda = 1$, $\kappa_{2V} = 0$, $\kappa_V = 1$	AF3
525381	VBF HH $\kappa_\lambda = 1$, $\kappa_{2V} = 0.5$, $\kappa_V = 1$	AF3
525382	VBF HH $\kappa_\lambda = 1$, $\kappa_{2V} = 1.5$, $\kappa_V = 1$	AF3
525383	VBF HH $\kappa_\lambda = 1$, $\kappa_{2V} = 2$, $\kappa_V = 1$	AF3
525384	VBF HH $\kappa_\lambda = 1$, $\kappa_{2V} = 3$, $\kappa_V = 1$	AF3
525385	VBF HH $\kappa_\lambda = 1$, $\kappa_{2V} = 1$, $\kappa_V = 0.5$	AF3
525386	VBF HH $\kappa_\lambda = 1$, $\kappa_{2V} = 1$, $\kappa_V = 1.5$	AF3
525387	VBF HH $\kappa_\lambda = 0$, $\kappa_{2V} = 0$, $\kappa_V = 1$	AF3
525388	VBF HH $\kappa_\lambda = -5$, $\kappa_{2V} = 1$, $\kappa_V = 0.5$	AF3
343981/602421	ggH	FS
346214/601482	VBF	FS
345318/601484	W^+H	FS
345317/601483	W^-H	FS
345319/601523	$qq \to ZH$	FS
345061/601522	$gg \to ZH$	FS
346525/602422	ttH	FS
345315/601710	bbH	FS
545636	tHjb	FS
545639	tHW	FS
700980	$\gamma\gamma$+0,1(NLO),2,3(LO), $m_{\gamma\gamma} \in (90, 175)$ GeV	AF3
700711	$\gamma\gamma + b\bar{b}$(NLO), $m_{\gamma\gamma} \in (90, 175)$ GeV	AF3

Objects definition

- **Photons:**
  - **Tight ID** and **FixedCutLoose** Isolation.
  - $|\eta| < 1.37 \text{ or } 1.52 < |\eta| < 2.37.$

- **Jets:**
  - PFlow jets +Jet-Vertex Tagger(JVT) +FJVT.
  - Anti-kt R = 0.4,$p_T > 25\ GeV, |\eta| < 4.5$
  - b-tagging: GN2 with 85% WP + b-jet correction
  - VBF jets(Additional jets except H→bb candidate): the pair of jets with the highest m_{jj} .

- **Leptons:**
  - Electrons: $p_T > 4.5\ GeV$, $|\eta| < 1.37 \text{ or } 1.52 < |\eta| < 2.37$.Medium ID and Loose_VarRad Isolation.
  - Muons: $p_T > 3\ GeV$, $|\eta| < 2.5$.Medium ID and pflowLoose_VarRad Isolation.
- **Overlap removal:**
  - Use The common Athena OR instead of dedicate HGam OR (negligible impact)

Cutflow

Selection	Yields	Entries	Efficiency [%]	Cumul. Eff. [%]
All events	11.40	1,580,000	100.00	100.00
event clean and dalitz filter	11.33	1,570,299	99.38	99.38
Pass trigger	7.00	971,617	61.78	61.39
2 loose photons	6.35	882,345	90.75	55.71
trigger matching	6.31	877,171	99.42	55.39
2 tight ID photon	5.55	772,417	87.93	48.71
2 tight ID and Iso photons	4.99	695,346	89.88	43.78
rel. pT cuts	4.58	639,762	91.87	40.22
myy in [105,160]GeV	4.58	639,030	99.88	40.17
Nlep =0	4.56	636,918	99.66	40.04
at least 2 Nj	4.03	563,660	88.25	35.33
Nj central<6	3.94	550,899	97.75	34.54
At least 2 b-jets with 85% WP	1.96	276,953	49.89	17.23

Table 11: Cutflow for HH ggF signal sample (SM) - AF3 in Run2.

Selection	Yields	Entries	Efficiency [%]	Cumul. Eff. [%]
All events	15.16	2,050,000	100.00	100.00
event clean and dalitz filter	14.96	2,023,037	98.68	98.68
Pass trigger	8.79	1,192,882	58.75	57.97
2 loose photons	8.11	1,101,256	92.30	53.51
trigger matching	8.05	1,093,066	99.26	53.11
2 tight ID photon	7.17	973,849	89.00	47.27
2 tight ID and Iso photons	6.51	886,484	90.88	42.96
rel. pT cuts	6.01	818,886	92.22	39.61
myy in [105,160]GeV	6.00	817,923	99.89	39.57
Nlep =0	5.98	815,302	99.67	39.44
at least 2 Nj	5.28	721,369	88.27	34.81
Nj central<6	5.16	705,014	97.71	34.01
At least 2 b-jets with 85% WP	2.54	349,658	49.18	16.73

Table 13: Cutflow for HH ggF signal sample (SM) - AF3 in Run3

Selection	Yields	Entries	Efficiency [%]	Cumul. Eff. [%]
All events	0.62	3,954,000	100.00	100.00
event clean and dalitz filter	0.62	3,915,533	99.02	99.02
Pass trigger	0.35	2,186,581	55.96	55.41
2 loose photons	0.31	1,959,665	89.56	49.63
trigger matching	0.31	1,945,370	99.27	49.27
2 tight ID photon	0.27	1,695,042	87.10	42.91
2 tight ID and Iso photons	0.24	1,514,105	89.34	38.34
rel. pT cuts	0.22	1,378,053	91.01	34.89
myy in [105,160]GeV	0.22	1,371,077	99.49	34.71
N_lep =0	0.22	1,365,482	99.59	34.57
at least 2 N_j	0.21	1,299,181	95.15	32.90
N_j central<6	0.20	1,291,511	99.41	32.70
At least 2 b-jets with 85% WP	0.07	458,752	35.56	11.63

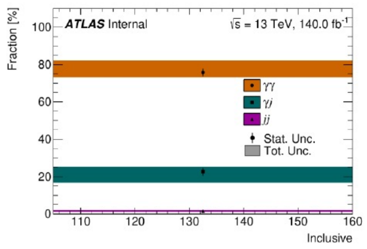
Table 12: Cutflow for HH VBF signal sample (SM) - AF3 in Run2.

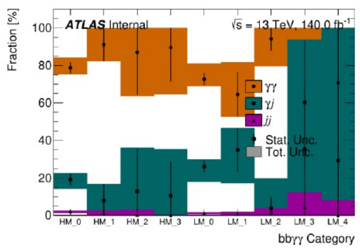
Selection	Yields	Entries	Efficiency [%]	Cumul. Eff. [%]
All events	0.83	440,000	100.00	100.00
event clean and dalitz filter	0.82	432,392	98.27	98.27
Pass trigger	0.43	228,934	53.00	52.08
2 loose photons	0.40	208,964	91.28	47.54
trigger matching	0.39	207,083	99.10	47.11
2 tight ID photon	0.34	181,855	87.82	41.37
2 tight ID and Iso photons	0.31	164,287	90.35	37.38
rel. pT cuts	0.28	150,088	91.34	34.14
myy in [105,160]GeV	0.28	149,303	99.48	33.97
Nlep =0	0.28	148,755	99.63	33.84
at least 2 Nj	0.27	141,079	94.84	32.09
Nj central<6	0.27	140,222	99.39	31.90
At least 2 b-jets with 85% WP	0.09	48,219	34.41	10.98

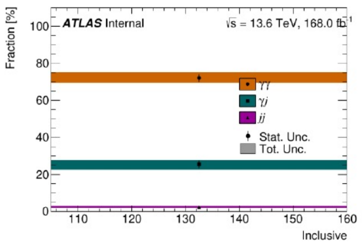
Table 14: Cutflow for HH VBF signal sample (SM) - AF3 in Run3.

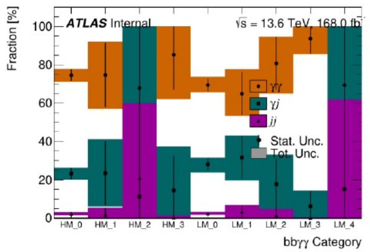
Background decomposition

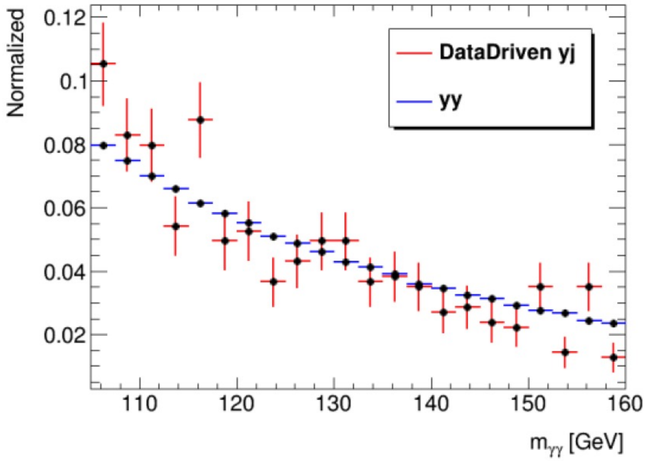
- ABCD method on data sideband to estimate $\gamma\gamma$, $\gamma+\text{jet}$, $\text{jet}+\text{jet}$ component
- similar shape between $\gamma\gamma$ and $\gamma+\text{jet}$



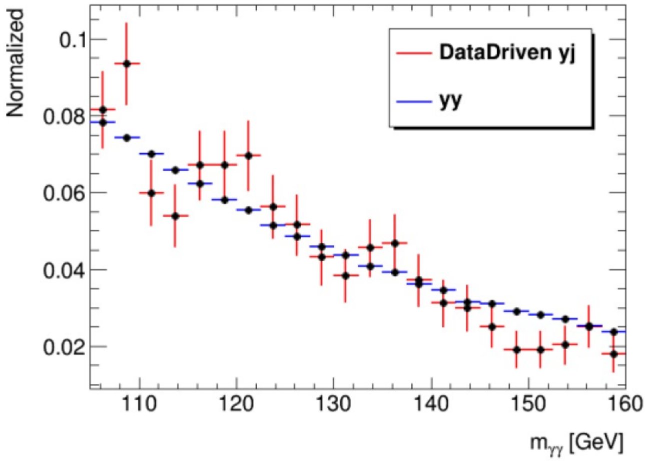








(a) Run2

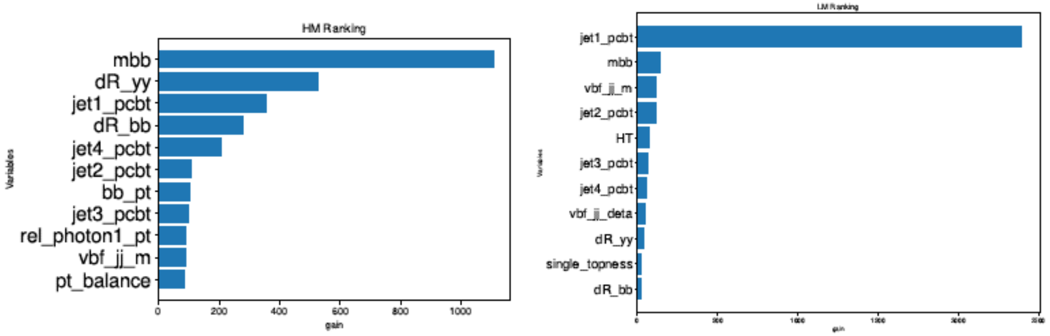


(b) Run3

Hyperparameters

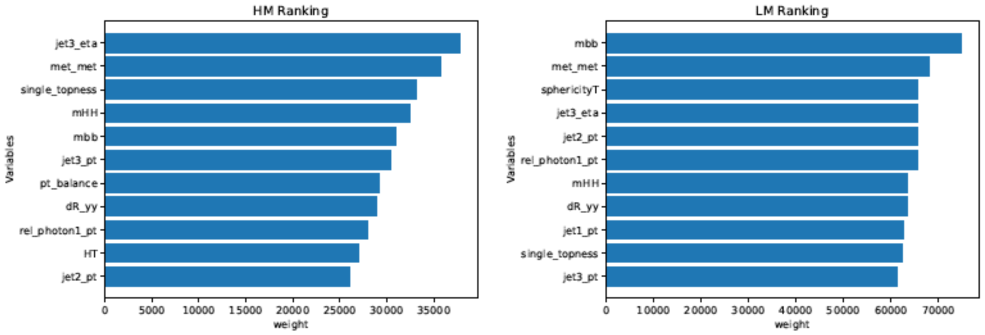
Hyperparameter	Range	Value for Low Mass BDT	Value for High Mass BDT
min child weight	[0,100]	27	84
colsample bytree	[0.3, 1]	0.64	0.76
scale pos weight	[0.0, 9.0]	1.71	1.55
max delta step	[0.0, 20.0]	13.78	8.38
subsample	[0.5, 1.0]	1.0	0.82
eta	[0.01, 0.05]	0.01	0.01
alpha	[0.0, 1.0]	0.40	0.62
lambda	[0.0, 10.0]	9.70	6.76
max depth	[3, 20]	20	20
gamma	[0.0, 10.0]	0.0	3.13
max bin	[10, 512]	286	56
Scale factor	**Range**	**Value for Low Mass BDT**	**Value for High Mass BDT**
SM ggF HH	[1, 200]	-	128.06
SM VBF HH	[1, 200]	-	15.44
ggF HH $\kappa_\lambda = 10$	[1, 200]	83.74	-
ggF HH $\kappa_\lambda = 5$	[1, 200]	1.0	-
VBF HH $\kappa_\lambda = 0, \kappa_{2V} = 1, \kappa_V = 1$	[1, 200]	1.0	5.43
VBF HH $\kappa_\lambda = 1, \kappa_{2V} = 1.5, \kappa_V = 1$	[1, 200]	27.65	56.06
VBF HH $\kappa_\lambda = 1, \kappa_{2V} = 3, \kappa_V = 1$	[1, 200]	1.0	1.0
VBF HH $\kappa_\lambda = -5, \kappa_{2V} = 1, \kappa_V = 0.5$	[1, 200]	68.45	1.0
VBF HH $\kappa_\lambda = 10, \kappa_{2V} = 1, \kappa_V = 1$	[1, 200]	118.76	1.0
$\gamma\gamma$+jets	[1, 200]	183.72	194.15
$t\bar{t}H$	[1,100]	1.0	44.81
$ggH + b\bar{b}H$	[1,100]	1.0	38.65
$qq \to ZH + gg \to ZH$	[1,100]	1.0	3.61

Feature importance



(a) (b)

Figure 19: Feature importances for BDTs trained in the High Mass (left) and Low Mass (right) regions for the Run 2+3 dataset. The importance is measured using "gain", which quantifies how much the feature contributes to reducing the log loss.



(a) (b)

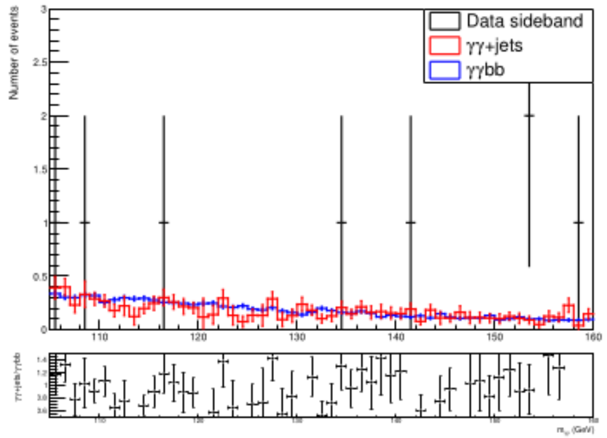
Figure 20: Feature importances for BDTs trained in the High Mass (left) and Low Mass (right) regions for the Run 2+3 dataset. The importance is measured using "split", which quantifies how many times the variable is used in the BDT training to separate signal from background.

Spurious signal test

- The spurious signal test is used to select the function form to describe the non-resonant background and estimate the bias as a system uncertainty on signal yield .
- The spurious signal test procedure :
    - Using non-resonant $\gamma\gamma + bb$ sample as template due to higher statistic.
    - Fit the background-only template using a signal+background model (exponential v.s. power: The exponential and power functions perform similarly and for simplicity the exponential function is chosen for all categories) .
    - Perform multiple fits for $m_{\gamma\gamma} \in [123,127]\ GeV$ in 0.5 GeV intervals.
    - The spurious signal ,N_{sp}, is defined as the Maximum fitted signal events in the $4GeV$ window.

Category	Function	N_{sp}	$\max(N_{sp}/\sigma_{bkg})$ [%]	$\max(\zeta_{sp})$ [%]	$\max(N_{sb}/S_{ref,SM})$	Prob(χ^2) [%]
HM_3	Exponential	0.0421	3.46	0	3.11	66.4
HM_2	Exponential	-0.055	-3.56	0	-9.04	67.5
HM_1	Exponential	-0.149	-4.13	0	-16.4	22.2
LM_4	Exponential	0.108	6.2	0	292	67.2
LM_3	Exponential	-0.242	-10.8	0	-489	79.4
LM_2	Exponential	-0.447	-11.5	0	-439	87.7
LM_1	Exponential	-1.27	-18.1	-3.61	-909	17.3

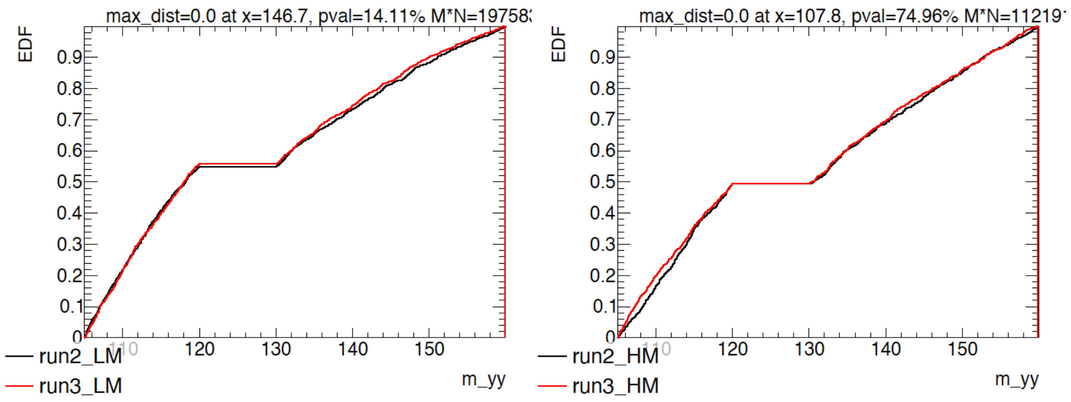
Table 26: Spurious signal for the exponential function evaluated on the $\gamma\gamma$ + HF sample, for the correlated model including 2024. The table shows: N_{sp}, the fitted spurious signal; $\max(N_{sp}/\sigma_{bkg})$, the maximum spurious signal divided by the expected fit uncertainty; $\max(\zeta_{sp})$, the maximum spurious signal divided by the expected fit uncertainty accounting for 2σ fluctuations in the MC template; and Prob(χ^2), the χ^2 probability of the function from a background-only fit.



(c) Run 2 + Run 3 High Mass 3

Checks on background modelling strategy

- Compatibility test between Run2 and Run3 on data
  - Unbinned KS(Kolmogorov-Smirnov) test on data sideband for HM and LM region .
  - P-value :0.14 and 0.75 for LM and HM region .

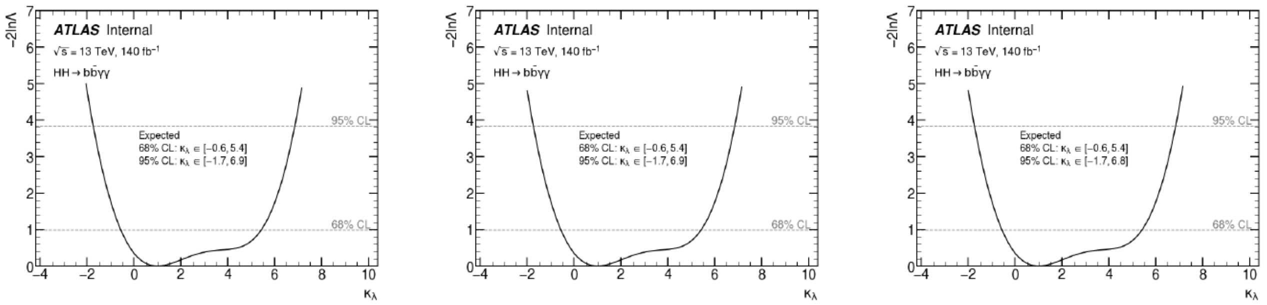


(a) LM (b) HM

- Checks the impact from the potential slope bias on final results
  - Bias=$\pm 10\times|slope_{run2} - slope_{run3}|$
  - Negligible impact on statistical result

Bias in shape	Run2=Run3	Run2=Run3+Bias	Run2=Run3-Bias
Significance from fitting	1.047	1.045	1.052
Upper limit on μ	2.369	2.370	2.364

Table 28: Background shape bias check [61]. By alternating the background shape difference between Run2 and Run3 in each category pair, this introduces negligible changes in the statistical result.



(a) No shift (b) Positive shift (c) Negative shift

Figure 42: Background shape bias check effect on κ_λ limit

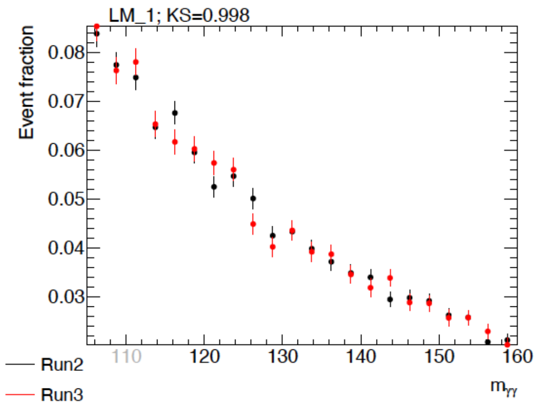
Checks on background modelling strategy

- Compatibility test between run2 and run3 on background shape
  - Using high stats $\gamma\gamma$+bb sample.
  - Hypothesis testing with unbinned NLL: same shape(Null hypothesis) vs different shape(alternative hypothesis).

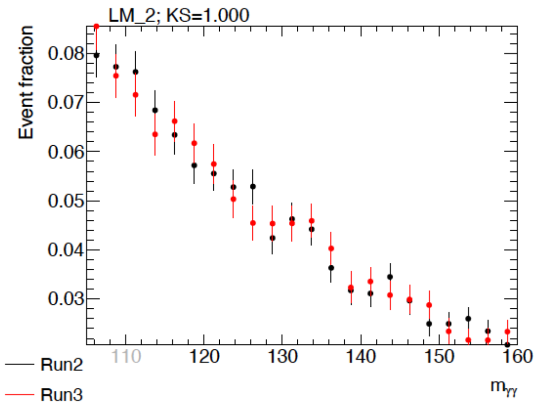
	LM1	LM2	LM3	LM4	HM1	HM2	HM3
Run2	2.599±0.030	2.647±0.050	2.920±0.092	2.748±0.106	2.338±0.045	2.547±0.091	2.611±0.111
Run3	2.566±0.033	2.676±0.055	2.711±0.095	3.017±0.117	2.343±0.049	2.460±0.097	2.517±0.115
Correlated	2.581±0.022	2.663±0.038	2.803±0.067	2.897±0.080	2.342±0.034	2.499±0.067	2.558±0.081
$\frac{2\Delta NLL}{NDOF}$	0.55429	0.15909	2.49586	2.86133	0.00685	0.42782	0.34120
p-value[%]	45.7	69.0	11.4	9.1	93.4	51.3	55.9

Table 25: Background shape (exponential β term) compatibility check with $\gamma\gamma b\bar{b}$ sample [61]. The first three rows show the slope (multiplied by 100) of the exponential function fitted for Run 2, Run 3 and Run 2+Run 3 correlation startegy. The large p-value indicates that the "same shape" hypothesis can not be rejected.

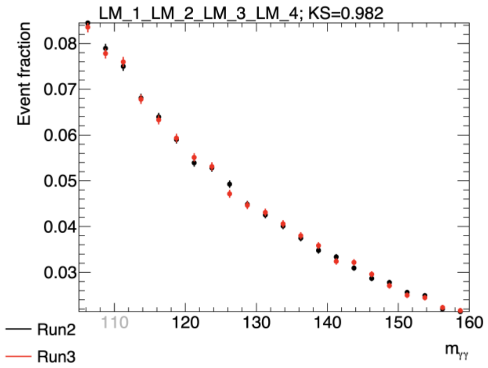
	LM1_LM2_LM3_LM4	HM1_HM2_HM3
Run2	2.639±0.024	2.410±0.038
Run3	2.622±0.026	2.395±0.041
Correlated	2.629±0.018	2.402±0.028
$\frac{2\Delta NLL}{NDOF}$	0.19925	0.07364
p-value [%]	65.5	78.6



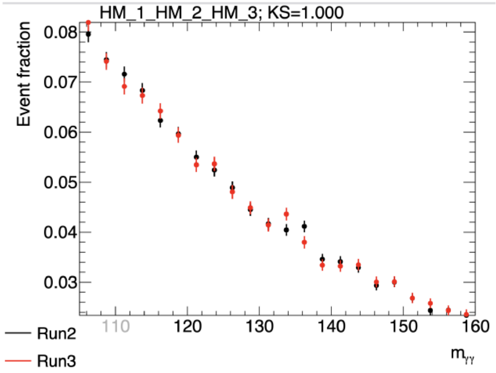
(a) LM1



(b) LM2

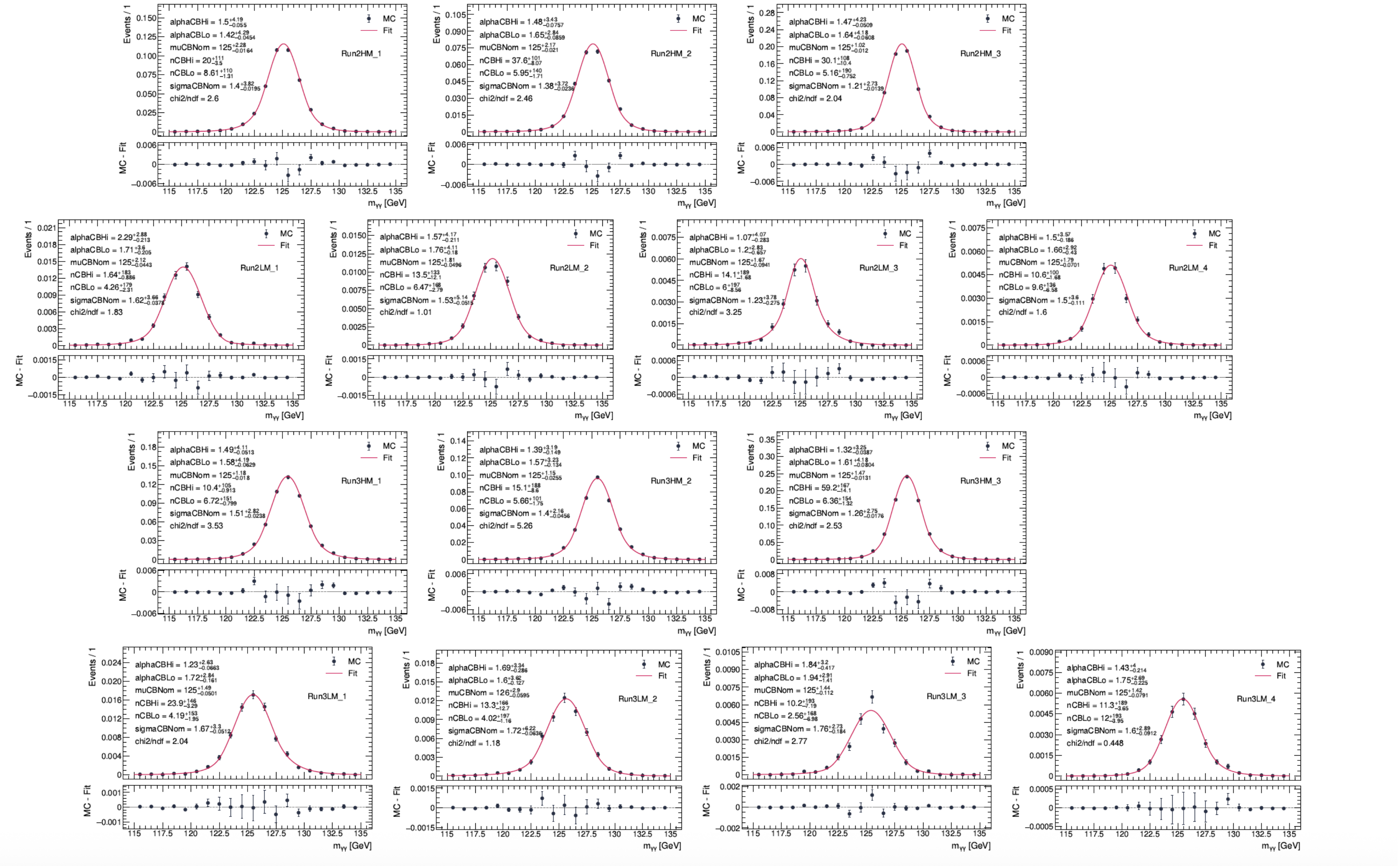


(a) Run2+3 LM1+LM2+LM3+LM4



(b) Run2+3 HM1+HM2+HM3

Signal Modelling plots



Signal Yield parametrization

The **differential signal HH cross sections** ,and hence the respective yields, **can be expressed as a polynomial of the coupling modifiers - κ_λ for ggF and (κ_λ, κ_{2V}, κ_V) for VBF -** by performing a linear combination of the relevant simulated samples.

$$\begin{aligned}\frac{d\sigma_{ggF}}{d\Phi}(\kappa_\lambda) = \Bigg[&\left(1+\frac{1}{5}\kappa_\lambda^2-\frac{6}{5}\kappa_\lambda\right)\cdot\frac{d\sigma_{ggF}}{d\Phi}(0,1)\\ &+\left(\frac{5}{4}\kappa_\lambda-\frac{1}{4}\kappa_\lambda^2\right)\cdot\frac{d\sigma_{ggF}}{d\Phi}(1,1)\\ &+\left(\frac{1}{20}\kappa_\lambda^2-\frac{1}{20}\kappa_\lambda\right)\cdot\frac{d\sigma_{ggF}}{d\Phi}(5,1)\Bigg]\end{aligned}$$

$$\begin{aligned}\frac{d\sigma_{VBF}}{d\Phi}(\kappa_\lambda,\kappa_{2V},\kappa_V) = &\left(\frac{68}{135}\kappa_{2V}^2+\frac{20}{27}\kappa_{2V}\kappa_\lambda\kappa_V-4\kappa_{2V}\kappa_V^2+\frac{1}{9}\kappa_\lambda^2\kappa_V^2-\frac{56}{27}\kappa_\lambda\kappa_V^3+\frac{772}{135}\kappa_V^4\right)\cdot\frac{d\sigma_{VBF}}{d\Phi}(1,1,1)\\ &+\left(-\frac{4}{5}\kappa_{2V}^2+4\kappa_{2V}\kappa_V^2-\frac{16}{5}\kappa_V^4\right)\cdot\frac{d\sigma_{VBF}}{d\Phi}(1,1.5,1)\\ &+\left(\frac{11}{60}\kappa_{2V}^2-\frac{19}{24}\kappa_{2V}\kappa_\lambda\kappa_V+\frac{1}{3}\kappa_{2V}\kappa_V^2-\frac{1}{8}\kappa_\lambda^2\kappa_V^2+\frac{13}{6}\kappa_\lambda\kappa_V^3-\frac{53}{30}\kappa_V^4\right)\cdot\frac{d\sigma_{VBF}}{d\Phi}(2,1,1)\\ &+\left(-\frac{11}{540}\kappa_{2V}^2+\frac{11}{216}\kappa_{2V}\kappa_\lambda\kappa_V+\frac{1}{72}\kappa_\lambda^2\kappa_V^2-\frac{5}{54}\kappa_\lambda\kappa_V^3+\frac{13}{270}\kappa_V^4\right)\cdot\frac{d\sigma_{VBF}}{d\Phi}(10,1,1)\\ &+\left(\frac{88}{45}\kappa_{2V}^2+\frac{4}{9}\kappa_{2V}\kappa_\lambda\kappa_V-\frac{16}{3}\kappa_{2V}\kappa_V^2-\frac{4}{9}\kappa_\lambda\kappa_V^3+\frac{152}{45}\kappa_V^4\right)\cdot\frac{d\sigma_{VBF}}{d\Phi}(1,1,0.5)\\ &+\left(\frac{8}{45}\kappa_{2V}^2-\frac{4}{9}\kappa_{2V}\kappa_\lambda\kappa_V+\frac{4}{9}\kappa_\lambda\kappa_V^3-\frac{8}{45}\kappa_V^4\right)\cdot\frac{d\sigma_{VBF}}{d\Phi}(-5,1,0.5)\end{aligned}$$

Disagreements between the reweighting formula and directly generated samples are taken into account by creating systematic uncertainties.

Parameterization uncertainties

ggF(%)	HM_1	HM_2	HM_3	LM_1	LM_2	LM_3	LM_4
Run2	7.33 ± 2.76	5.00 ± 4.09	8.45 ± 2.88	4.20 ± 2.92	12.67 ± 3.03	6.82 ± 5.06	10.25 ± 6.59
Run3	12.50 ± 2.81	5.89 ± 2.75	5.37 ± 2.81	11.15 ± 3.18	7.26 ± 3.28	22.90 ± 4.09	10.84 ± 6.24
VBF(%)	HM_1	HM_2	HM_3	LM_1	LM_2	LM_3	LM_4
Run2	1.75 ± 1.10	2.90 ± 0.82	2.11 ± 0.77	4.66 ± 3.11	8.46 ± 2.42	6.50 ± 2.43	5.99 ± 1.52
Run3	9.68 ± 4.03	7.31 ± 4.59	6.76 ± 1.68	24.28 ± 6.78	28.80 ± 7.46	15.47 ± 15.13	9.94 ± 5.30

Systematic Uncertainties

Systematic uncertainties relevant for resonant backgrounds

		ggF HH	VBF HH	Single HH
Theory	Cross-section and branching fraction	• BR($\gamma\gamma$) and BR($b\bar{b}$) • PDF + α_S • Scale + m_{top}	• BR($\gamma\gamma$) and BR($b\bar{b}$) • PDF + α_S • Scale + m_{top}	• BR($\gamma\gamma$) • Heavy flavour unc (100% only for ggF, VBF, WH)
	Acceptance/ Yields	ggF HH parametrisation	VBF HH parametrisation	
		Scale, PDF + α_S, Parton shower		
Exp.	Yields	• Luminosity • Pile-up modelling • Di-photon trigger efficiency • Photon ID and iso efficiency • Photon energy scale and resolution • Jet energy scale and resolution • JVT and fJVT efficiency • Flavour tagging efficiency • Missing E_T soft term scale and resolution • Muon scale and resolution	* MC stat uncertainty checked, found to be negligible	
	Shape	• Photon energy scale • Photon energy resolution		

Systematic uncertainty relevant for continuum background

Spurious signal uncertainty calculated by fits to γγ+bb MC sample.
Small impact, e.g. N_{sp} ~ -0.149 in HM1.

Following CP recommendations:
- Trigger: 4%(8%) for 2022 (2023-2024)
- Lumi: 4% for 2022-2023 (2024)

Correlation scheme:
- Trigger: 2022 decorr due to L1 trigger change.
- Lumi: 2024 decorrelated (no measurement)
- JetEtMiss: correlate Run 2/3 except in-situ non closure and AF3/FullSim
- Muon, theory, spurious: fully correlated
- Rest experimental NPs uncorrelated.

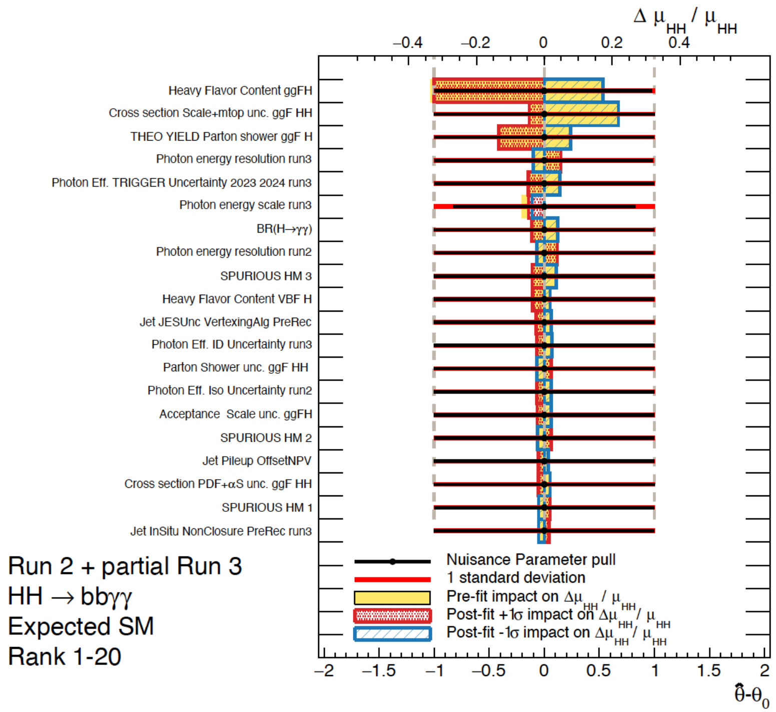
Extrapolation to 2024 dataset:
- FTAG uncertainties have negligible impact, apply 2022+2023 to 2024
- Trigger efficiency uncertainty doubled for 2023-2024

Systematic breakdown

- Evaluate the impact on 95 % μ_{HH} upper limit
- Floating a group of systematics while fixing others to 0,then compare to the stat only result

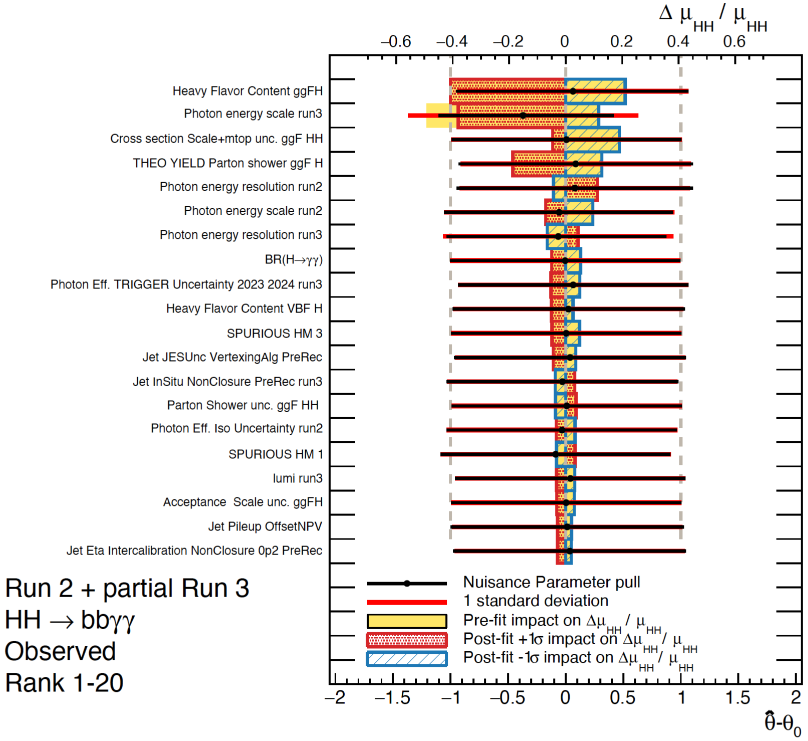
Source of systematic uncertainty	**Relative impact [%]**	
	Up	**Down**
Experimental		
Photon energy scale	+20	−30
Photon energy resolution	+13	−6.8
Photon efficiency	+13	−2.5
Jet	+9.6	−6.4
Luminosity	+6.3	−1.1
Theory		
QCD scale + m_{top}, PDF+α_S	+34	−4.5
$\mathcal{B}(H \to \gamma\gamma, b\bar{b})$	+9.9	−2.1
Parton showering model	±15	
Heavy-flavour content	±29	
Background model		
Spurious signal	±6.5	

NP Ranking Plots



(a)

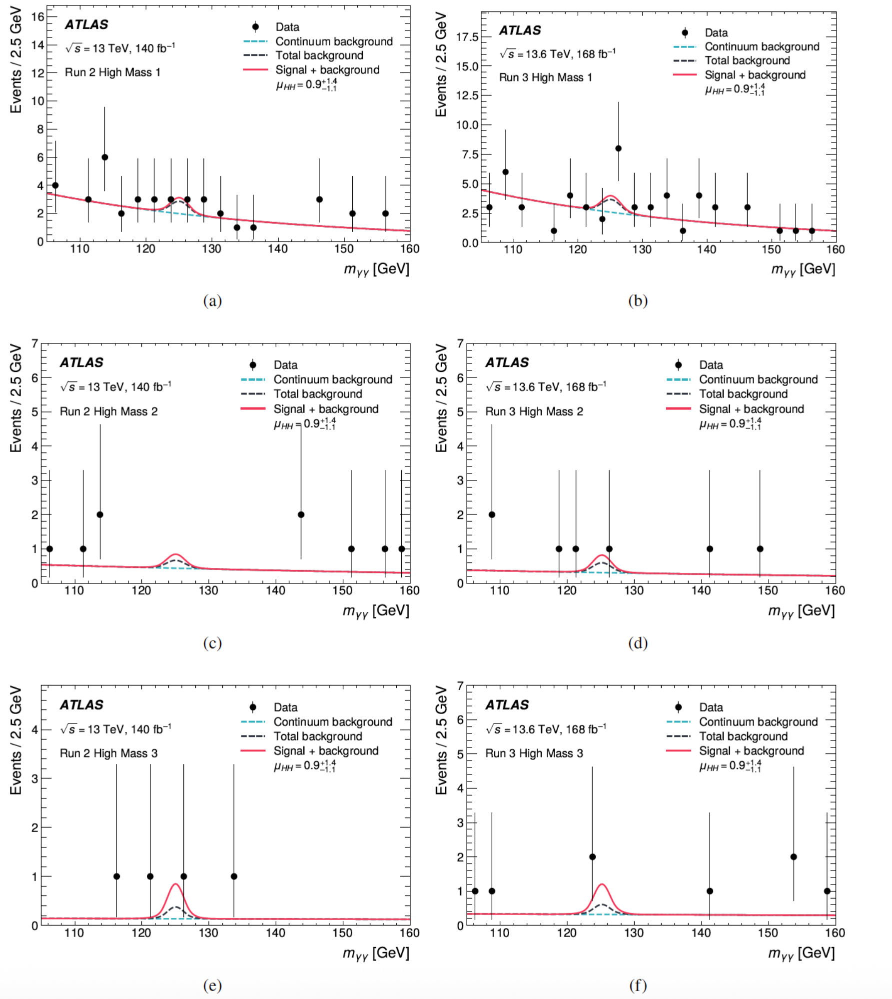
Figure 69: The expected impacts of the systematic uncertainties on the μ_{HH} measurement.



(a)

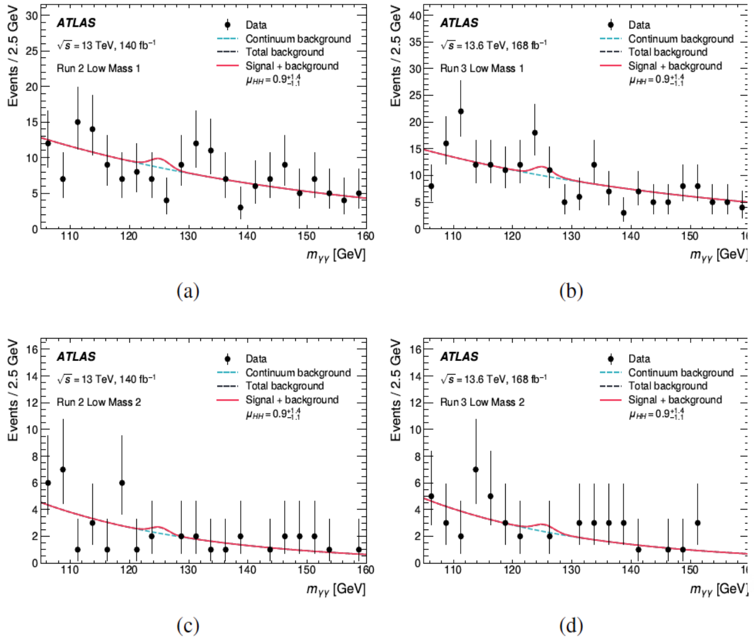
Figure 70: The observed impacts of the systematic uncertainties on the μ_{HH} measurement.

Fit Plots

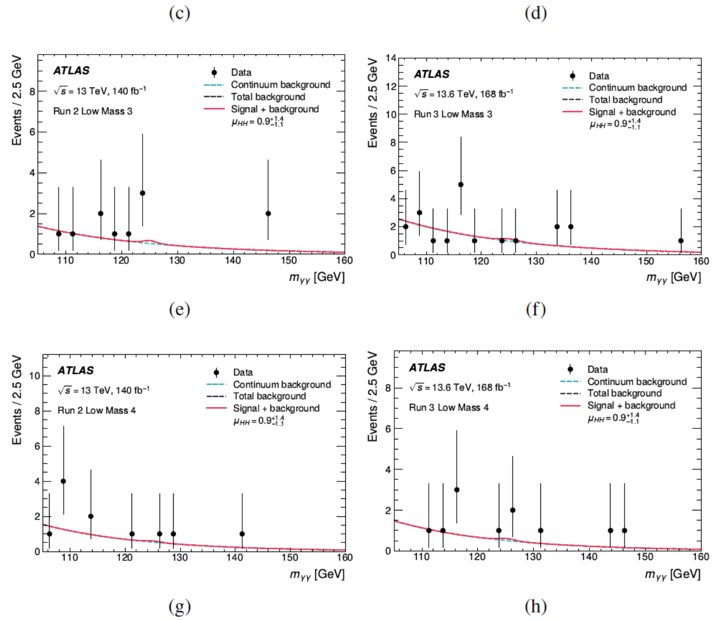


Run2 HM

Run3 HM



Run2 LM



Run3 LM

- The observed sensitivities are similar to legacy analysis due to the deficit of events in signal region.

Post-fit yields

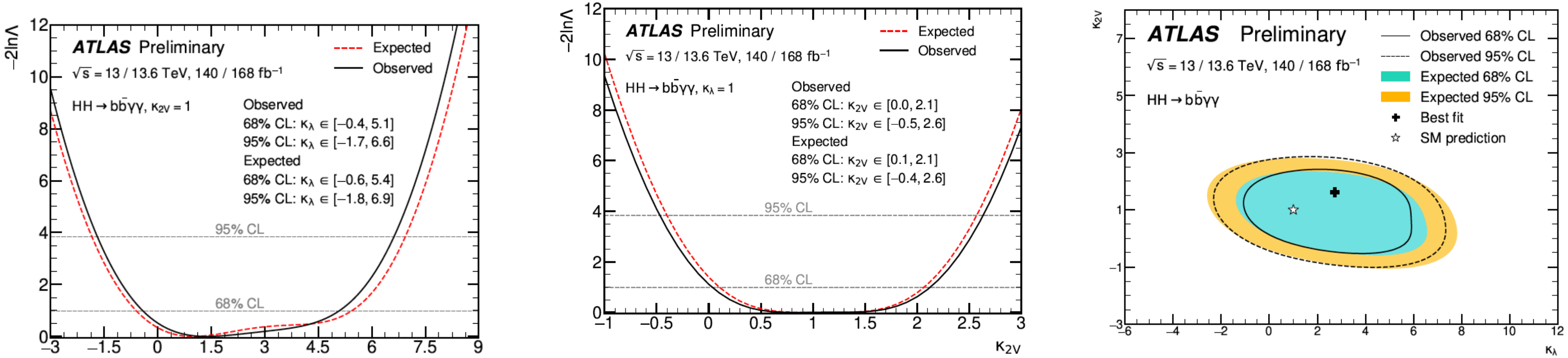
	HM 1	HM 2	HM 3	LM 1	LM 2	LM 3	LM 4
SM HH signal	$0.41^{+0.04}_{-0.07}$	$0.28^{+0.03}_{-0.04}$	$0.66^{+0.07}_{-0.11}$	$0.058^{+0.012}_{-0.006}$	$0.043^{+0.009}_{-0.005}$	$0.021^{+0.004}_{-0.003}$	$0.019^{+0.003}_{-0.002}$
ggF ($\kappa_\lambda = 1$)	$0.40^{+0.04}_{-0.07}$	$0.27^{+0.03}_{-0.04}$	$0.64^{+0.07}_{-0.10}$	$0.055^{+0.011}_{-0.006}$	$0.040^{+0.009}_{-0.004}$	$0.019^{+0.004}_{-0.003}$	$0.013^{+0.003}_{-0.002}$
VBF ($\kappa_\lambda = 1$)	$0.012^{+0.001}_{-0.001}$	$0.007^{+0.001}_{-0.000}$	$0.021^{+0.002}_{-0.001}$	$0.003^{+0.000}_{-0.000}$	$0.002^{+0.000}_{-0.000}$	$0.002^{+0.000}_{-0.000}$	$0.006^{+0.000}_{-0.000}$
Alternative BSM HH signals							
ggF HH ($\kappa_\lambda = 5$)	$0.33^{+0.07}_{-0.05}$	$0.17^{+0.04}_{-0.03}$	$0.30^{+0.07}_{-0.05}$	$0.95^{+0.16}_{-0.17}$	$0.68^{+0.15}_{-0.14}$	$0.28^{+0.05}_{-0.05}$	$0.22^{+0.04}_{-0.04}$
VBF HH ($\kappa_\lambda = 10$)	$0.38^{+0.03}_{-0.03}$	$0.28^{+0.02}_{-0.02}$	$1.03^{+0.08}_{-0.08}$	$0.38^{+0.05}_{-0.04}$	$0.40^{+0.05}_{-0.05}$	$0.34^{+0.05}_{-0.04}$	$1.40^{+0.15}_{-0.13}$
VBF HH ($\kappa_{2V} = 3$)	$0.41^{+0.03}_{-0.03}$	$0.32^{+0.03}_{-0.02}$	$3.7^{+0.3}_{-0.3}$	$0.042^{+0.006}_{-0.005}$	$0.043^{+0.006}_{-0.005}$	$0.037^{+0.005}_{-0.004}$	$0.159^{+0.017}_{-0.015}$
Single Higgs boson background	$1.3^{+0.4}_{-0.2}$	$0.33^{+0.18}_{-0.09}$	$0.30^{+0.18}_{-0.09}$	$2.1^{+0.4}_{-0.3}$	$0.71^{+0.12}_{-0.08}$	$0.19^{+0.04}_{-0.02}$	$0.10^{+0.07}_{-0.02}$
ggH	$0.4^{+0.4}_{-0.2}$	$0.14^{+0.17}_{-0.08}$	$0.18^{+0.18}_{-0.09}$	$0.28^{+0.30}_{-0.17}$	$0.10^{+0.10}_{-0.05}$	$0.027^{+0.030}_{-0.013}$	$0.018^{+0.070}_{-0.019}$
$t\bar{t}H$	$0.22^{+0.03}_{-0.03}$	$0.045^{+0.010}_{-0.008}$	$0.027^{+0.005}_{-0.005}$	$1.10^{+0.13}_{-0.12}$	$0.39^{+0.05}_{-0.05}$	$0.098^{+0.012}_{-0.012}$	$0.035^{+0.005}_{-0.005}$
ZH	$0.47^{+0.07}_{-0.06}$	$0.091^{+0.020}_{-0.018}$	$0.064^{+0.011}_{-0.009}$	$0.41^{+0.06}_{-0.06}$	$0.12^{+0.03}_{-0.02}$	$0.032^{+0.012}_{-0.009}$	$0.014^{+0.004}_{-0.003}$
Other H	$0.19^{+0.06}_{-0.04}$	$0.046^{+0.017}_{-0.010}$	$0.031^{+0.020}_{-0.012}$	$0.28^{+0.05}_{-0.04}$	$0.101^{+0.018}_{-0.014}$	$0.035^{+0.007}_{-0.005}$	$0.037^{+0.005}_{-0.005}$
Continuum background	$8.0^{+1.2}_{-1.4}$	$1.7^{+0.6}_{-0.6}$	$0.5^{+0.3}_{-0.3}$	34^{+3}_{-3}	$8.9^{+1.4}_{-0.3}$	$2.1^{+0.7}_{-0.6}$	$2.1^{+0.7}_{-0.7}$
Total background	$9.2^{+1.3}_{-1.4}$	$2.1^{+0.6}_{-0.6}$	$0.8^{+0.4}_{-0.3}$	37^{+3}_{-3}	$9.6^{+1.4}_{-1.3}$	$2.3^{+0.7}_{-0.6}$	$2.2^{+0.7}_{-0.7}$
Data	12	0	2	28	5	4	3

	HM 1	HM 2	HM 3	LM 1	LM 2	LM 3	LM 4
SM HH signal	$0.54^{+0.08}_{-0.08}$	$0.35^{+0.05}_{-0.06}$	$0.84^{+0.13}_{-0.14}$	$0.072^{+0.015}_{-0.010}$	$0.054^{+0.013}_{-0.009}$	$0.027^{+0.006}_{-0.005}$	$0.025^{+0.006}_{-0.005}$
ggF ($\kappa_\lambda = 1$)	$0.53^{+0.08}_{-0.08}$	$0.34^{+0.05}_{-0.06}$	$0.81^{+0.13}_{-0.14}$	$0.069^{+0.015}_{-0.010}$	$0.050^{+0.013}_{-0.009}$	$0.024^{+0.006}_{-0.004}$	$0.017^{+0.005}_{-0.004}$
VBF ($\kappa_\lambda = 1$)	$0.015^{+0.002}_{-0.001}$	$0.009^{+0.001}_{-0.001}$	$0.026^{+0.003}_{-0.003}$	$0.003^{+0.001}_{-0.000}$	$0.003^{+0.001}_{-0.001}$	$0.002^{+0.000}_{-0.000}$	$0.008^{+0.002}_{-0.001}$
Alternative BSM HH signals							
ggF HH ($\kappa_\lambda = 5$)	$0.42^{+0.12}_{-0.08}$	$0.22^{+0.05}_{-0.04}$	$0.39^{+0.10}_{-0.06}$	$1.2^{+0.3}_{-0.2}$	$0.83^{+0.20}_{-0.16}$	$0.38^{+0.12}_{-0.10}$	$0.30^{+0.09}_{-0.07}$
VBF HH ($\kappa_\lambda = 10$)	$0.50^{+0.08}_{-0.06}$	$0.36^{+0.05}_{-0.04}$	$1.19^{+0.18}_{-0.15}$	$0.48^{+0.15}_{-0.11}$	$0.53^{+0.18}_{-0.13}$	$0.43^{+0.10}_{-0.10}$	$1.8^{+0.5}_{-0.3}$
VBF HH ($\kappa_{2V} = 3$)	$0.57^{+0.09}_{-0.07}$	$0.44^{+0.06}_{-0.06}$	$4.9^{+0.8}_{-0.6}$	$0.052^{+0.017}_{-0.012}$	$0.048^{+0.017}_{-0.012}$	$0.049^{+0.012}_{-0.011}$	$0.19^{+0.05}_{-0.04}$
Single Higgs boson background	$1.6^{+0.7}_{-0.4}$	$0.40^{+0.18}_{-0.11}$	$0.36^{+0.27}_{-0.12}$	$2.7^{+0.8}_{-0.5}$	$0.89^{+0.20}_{-0.14}$	$0.26^{+0.10}_{-0.05}$	$0.16^{+0.08}_{-0.04}$
ggH	$0.5^{+0.7}_{-0.3}$	$0.15^{+0.17}_{-0.08}$	$0.18^{+0.27}_{-0.11}$	$0.6^{+0.7}_{-0.4}$	$0.15^{+0.17}_{-0.08}$	$0.06^{+0.10}_{-0.04}$	$0.04^{+0.06}_{-0.03}$
$t\bar{t}H$	$0.29^{+0.06}_{-0.06}$	$0.053^{+0.016}_{-0.014}$	$0.030^{+0.021}_{-0.013}$	$1.42^{+0.20}_{-0.17}$	$0.52^{+0.07}_{-0.07}$	$0.12^{+0.02}_{-0.02}$	$0.051^{+0.009}_{-0.008}$
ZH	$0.60^{+0.12}_{-0.10}$	$0.13^{+0.05}_{-0.04}$	$0.098^{+0.021}_{-0.017}$	$0.47^{+0.10}_{-0.08}$	$0.14^{+0.04}_{-0.03}$	$0.039^{+0.022}_{-0.013}$	$0.018^{+0.030}_{-0.013}$
Other H	$0.23^{+0.10}_{-0.05}$	$0.069^{+0.019}_{-0.011}$	$0.050^{+0.023}_{-0.012}$	$0.29^{+0.06}_{-0.05}$	$0.080^{+0.020}_{-0.013}$	$0.043^{+0.012}_{-0.007}$	$0.048^{+0.021}_{-0.010}$
Continuum background	$10.4^{+1.4}_{-1.5}$	$1.2^{+0.5}_{-0.5}$	$1.3^{+0.6}_{-0.5}$	40^{+3}_{-3}	$9.5^{+1.4}_{-1.4}$	$3.9^{+0.9}_{-0.9}$	$2.1^{+0.7}_{-0.6}$
Total background	$11.9^{+1.5}_{-1.5}$	$1.6^{+0.5}_{-0.5}$	$1.7^{+0.6}_{-0.5}$	43^{+3}_{-3}	$10.4^{+1.4}_{-1.4}$	$4.2^{+0.9}_{-0.9}$	$2.2^{+0.7}_{-0.6}$
Data	16	2	2	46	4	2	3

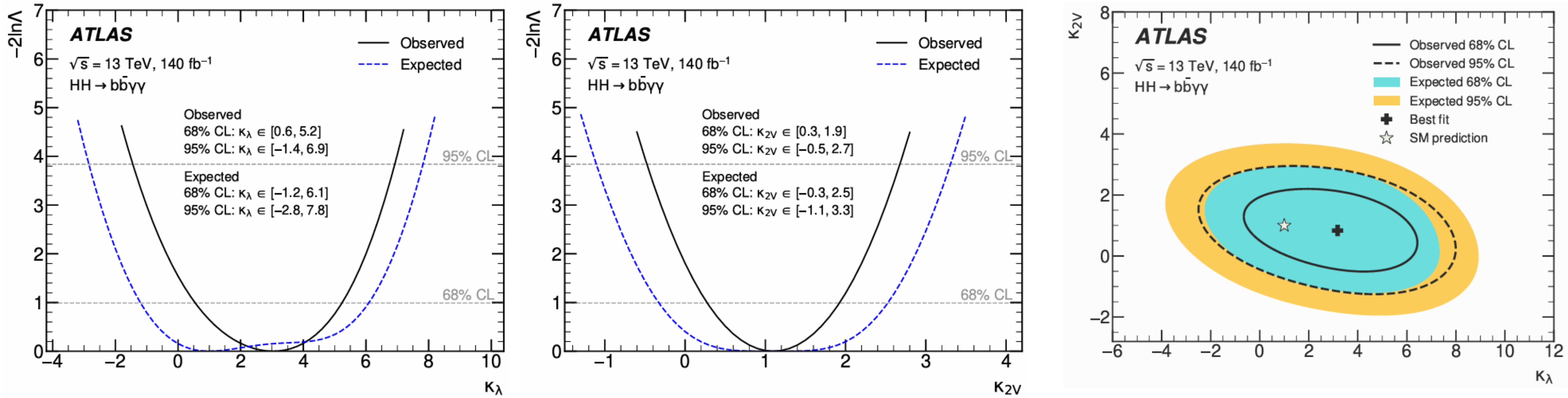
Run2 **Run3**

- The observed sensitivities are similar to legacy analysis due to the deficit of events in signal region.

Results compare to legacy



New results



Old results in legacy run2

- ~20% improvement on the expected 95% $CL\ \kappa_\lambda$ wrt the legacy analysis
- ~30% improvement on the expected 95% $CL\ \kappa_{2V}$ wrt the legacy analysis
- Smaller improvement as expected due to the Powheg bug fix, Smaller ggFHH Xsec and VBFHH Xec.