Di-Higgs production measurements and EFT interpretations

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on behalf of the ATLAS & CMS Collaborations

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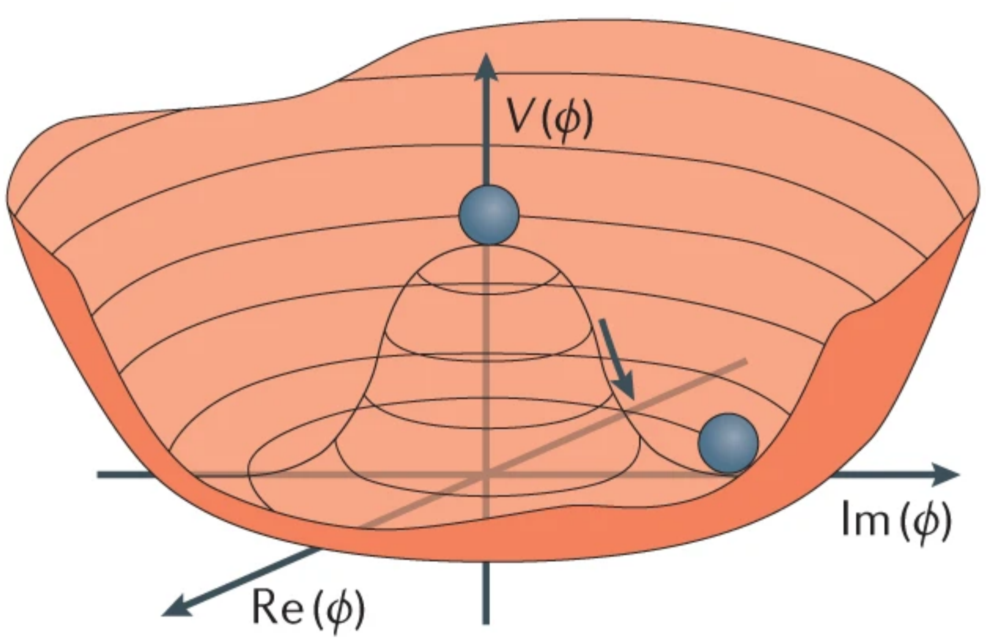
The Higgs Potential

- The Higgs field has non-zero vacuum expectation value
  - Leads to electroweak symmetry breaking

- The Higgs mechanism explains non-zero gauge boson masses
  - Also produces fermion masses!

- Higgs Boson is an excitation of the Higgs field
  - Forms unique probe of the Higgs field
  - Provides means of indirectly observing Higgs Potential



Higgs Potential: $V\left(\phi\right) = \frac{1}{2}\mu^2\phi^2 + \frac{1}{4}\lambda\phi^4$

When $\mu^2 < 0$ the potential has a minimum at:

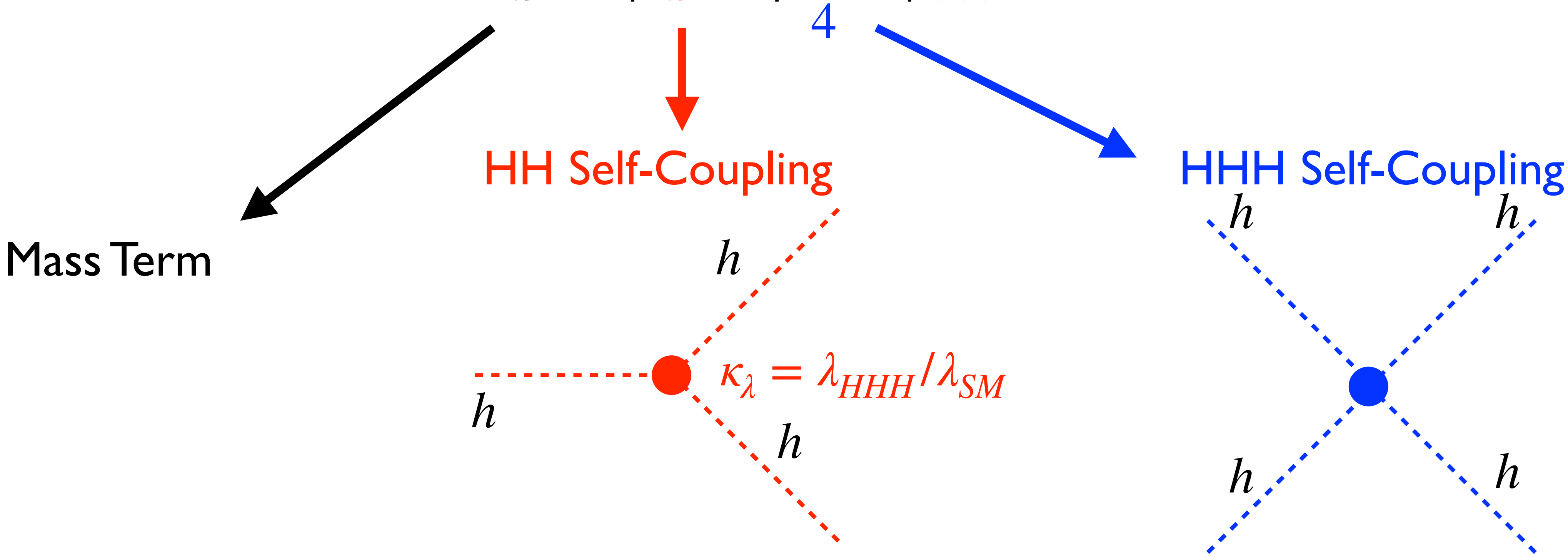
$$\left|\phi\right|_{min} = \sqrt{-\frac{\mu^2}{2\lambda}} \equiv \frac{\nu}{2\lambda}, \nu = 246 \text{ GeV}$$

$$\lambda = \frac{m_H^2}{2\nu^2} \approx 0.13$$

Higgs Self-Coupling

- Expanding the potential around the minimum yields:

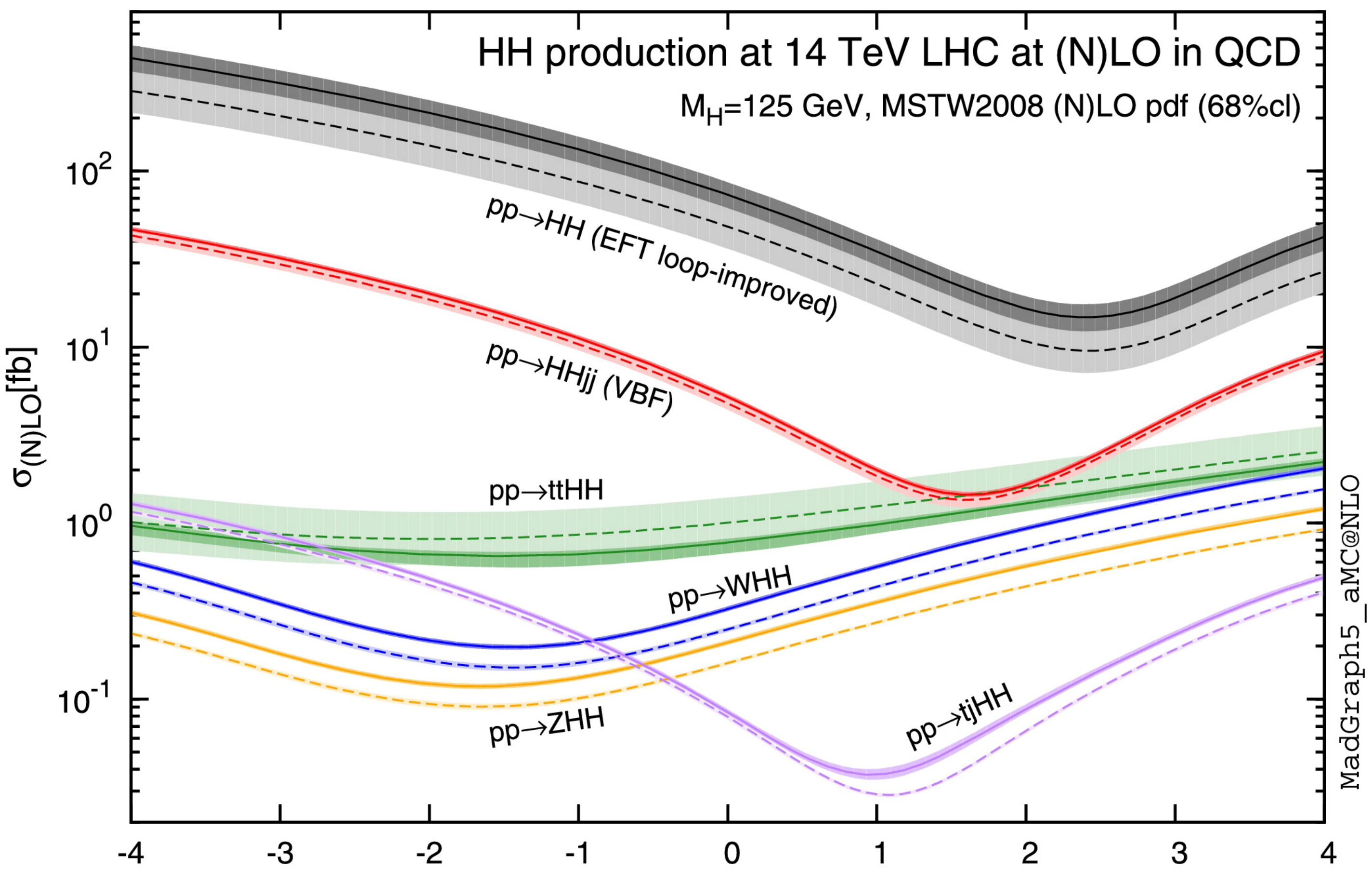
$$V(\phi) = \frac{1}{2}\mu^2\phi^2 + \frac{1}{4}\lambda\phi^4$$
$$= \lambda\nu^2h^2 + \lambda\nu h^3 + \frac{\lambda}{4}h^4 + \ldots$$



- Higgs self-coupling provides direct measurement of Higgs potential
- Helps identify precise shape of the Higgs potential

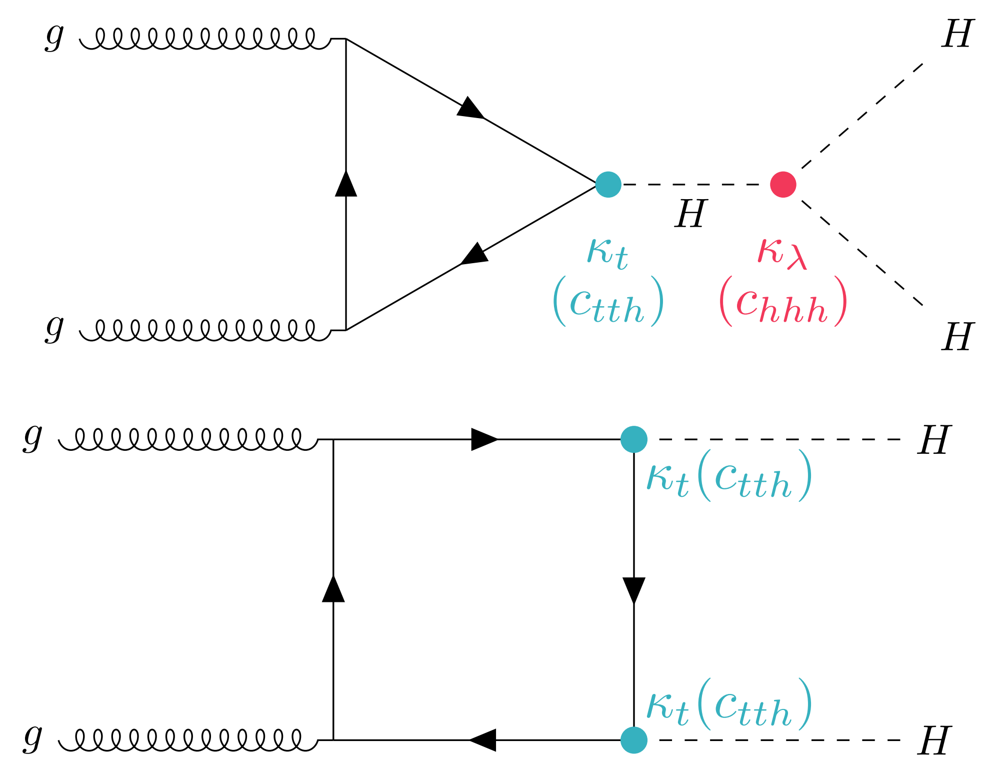
Measurement of λ is crucial for reconstructing the Higgs potential and testing the Higgs mechanism

Higgs Boson Pair Production



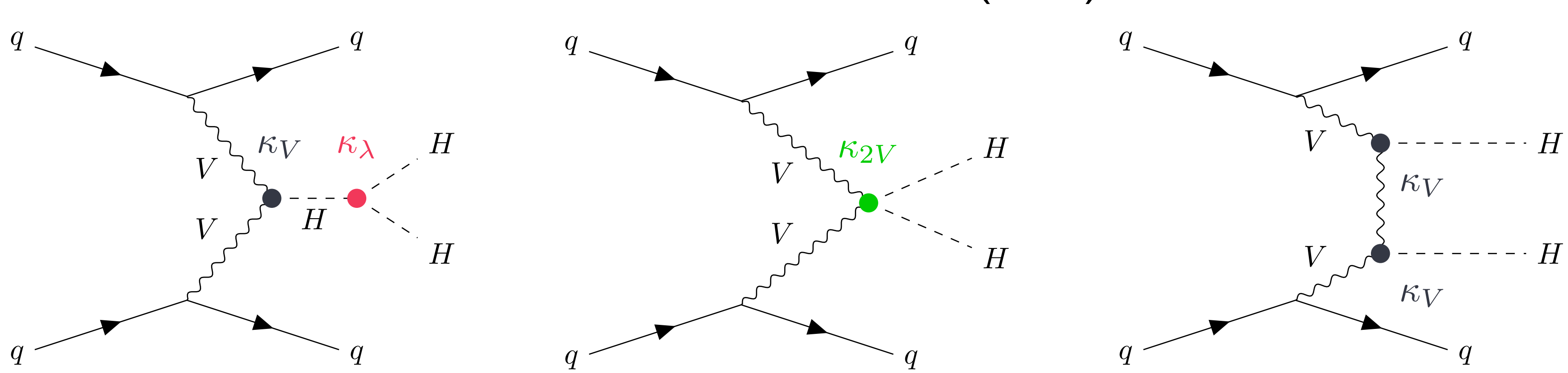
Physics Letters B 732 (2014)

gluon-gluon Fusion Production (ggF)



$\sigma^{SM}_{ggF}(HH) = 31.05^{+6\%}_{-23\%}$(scale + m_{top}) $\pm$ 3.0 % (PDF + α_s) fb

Vector Boson Fusion (VBF)



$\sigma^{SM}_{VBF}(HH) = 1.73^{+0.03\%}_{-0.04\%}$(scale + m_{top}) $\pm$ 2.1 % (PDF + α_s) fb

SM σ_{HH} is ~33 fb at 13 TeV

HH Decay Modes

- No perfect channel to study

- bbbb (34%):
  - Most abundant final state
  - Challenging multi-jet backgrounds
- bbγγ (0.26%):
  - Low decay fraction
  - Excellent $m_{\gamma\gamma}$ resolution
- bbττ (7.3%):
  - Good all round

- Other channels provide valuable data
  - Investigated by ATLAS and CMS
  - Various combinations available

Large Decay Fraction

	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%

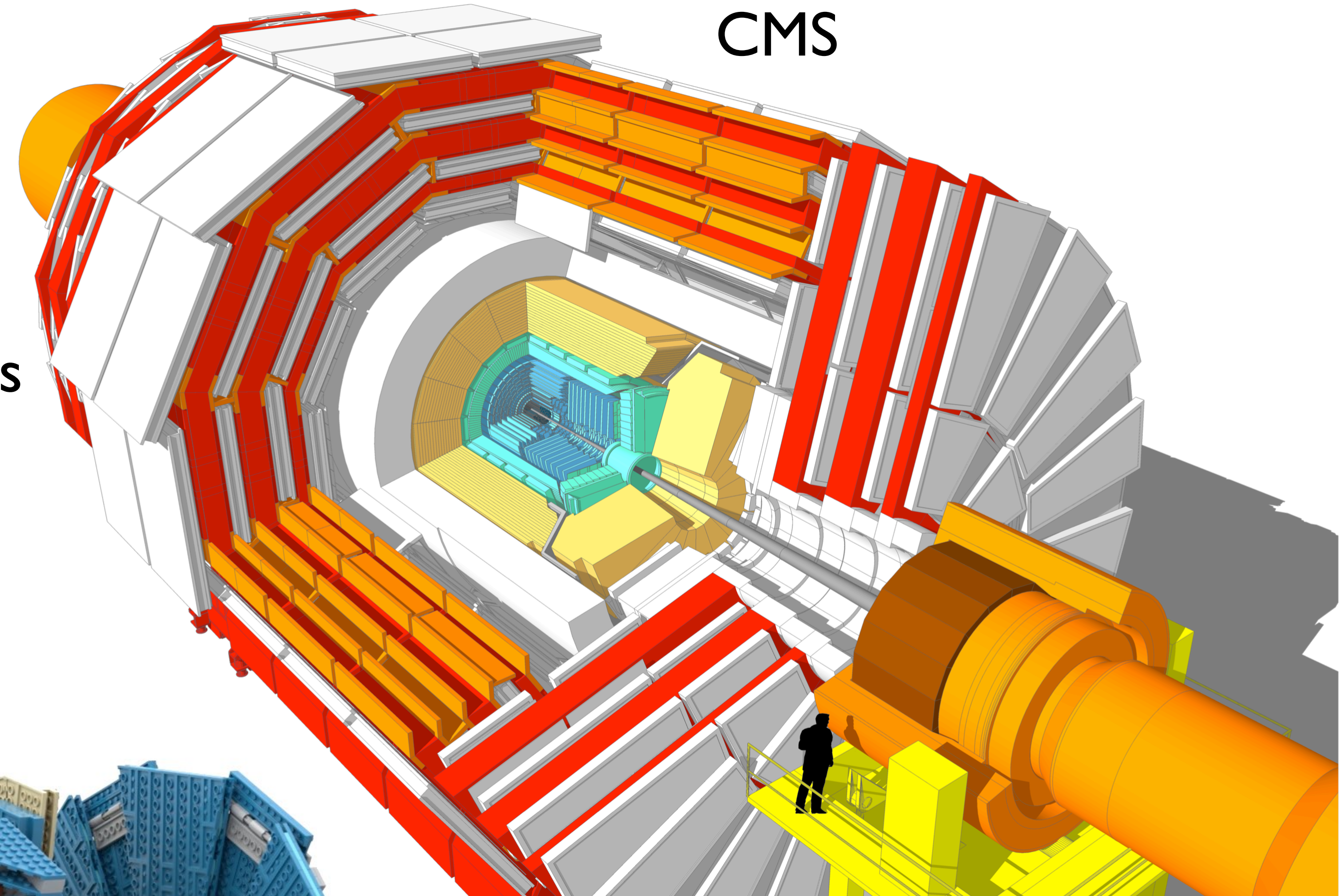
Clean Final State

Seminar by Rui Zhang

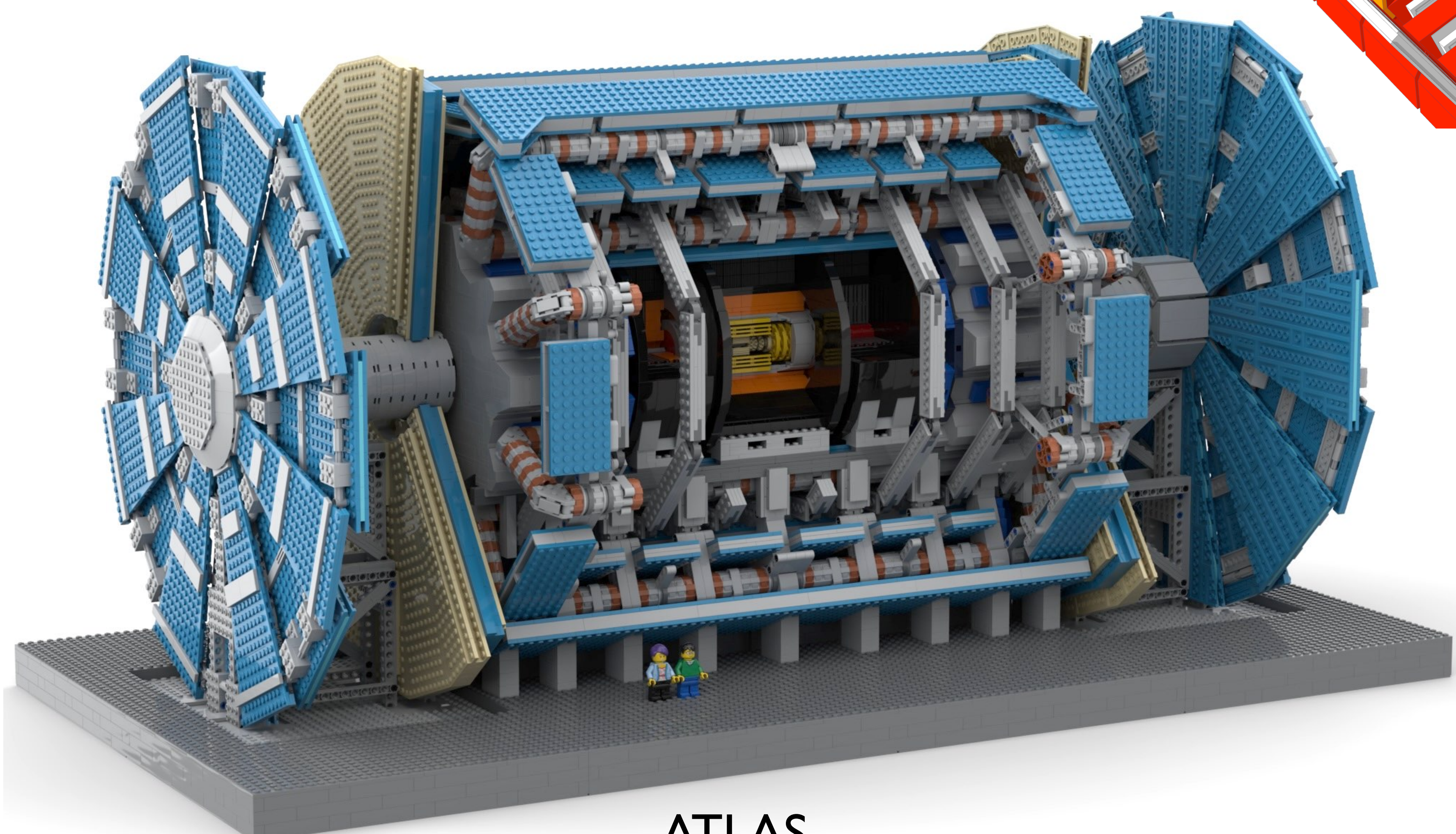
ATLAS and CMS

- LHC hosts two general purpose detectors
  - Different construction techniques
  - Similar science goals

- Designed to investigate wide range of physics
- Study of Higgs boson is key topic

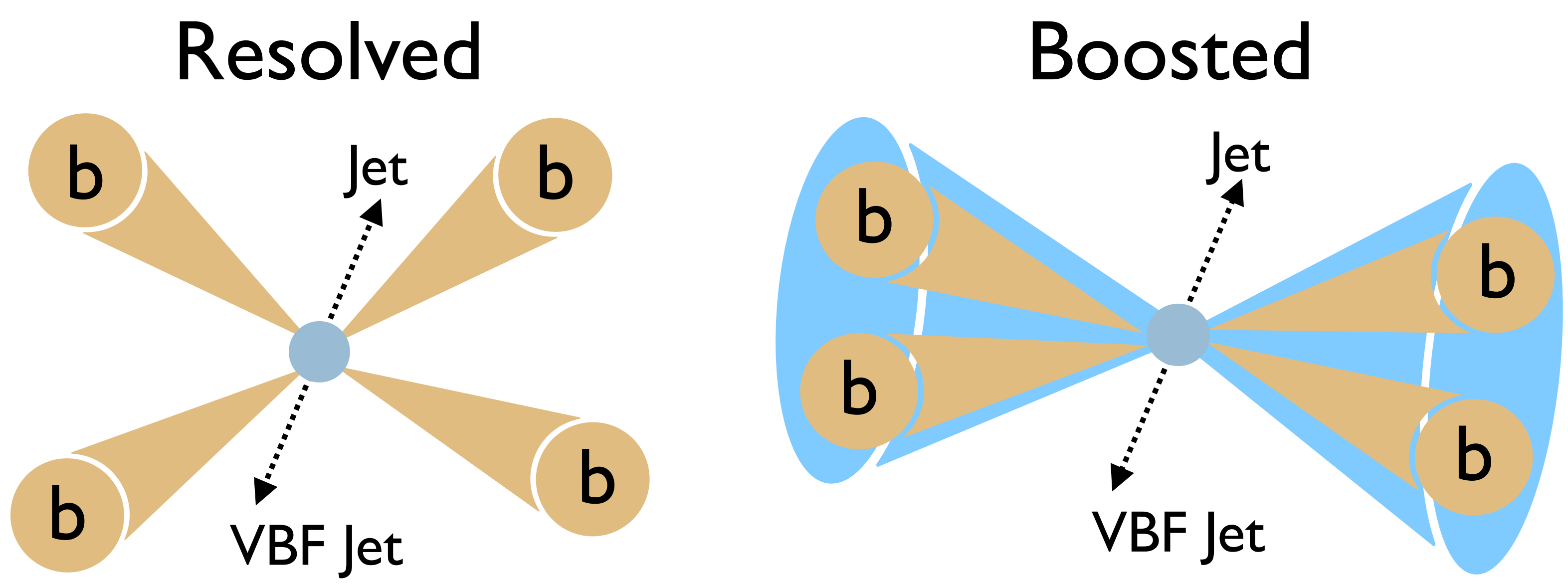


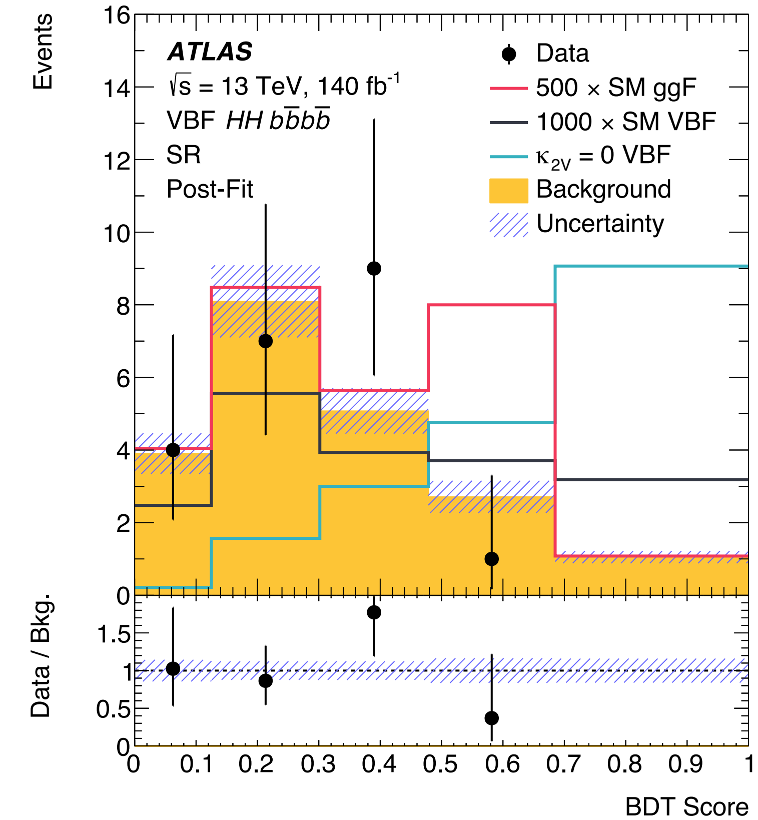
CMS



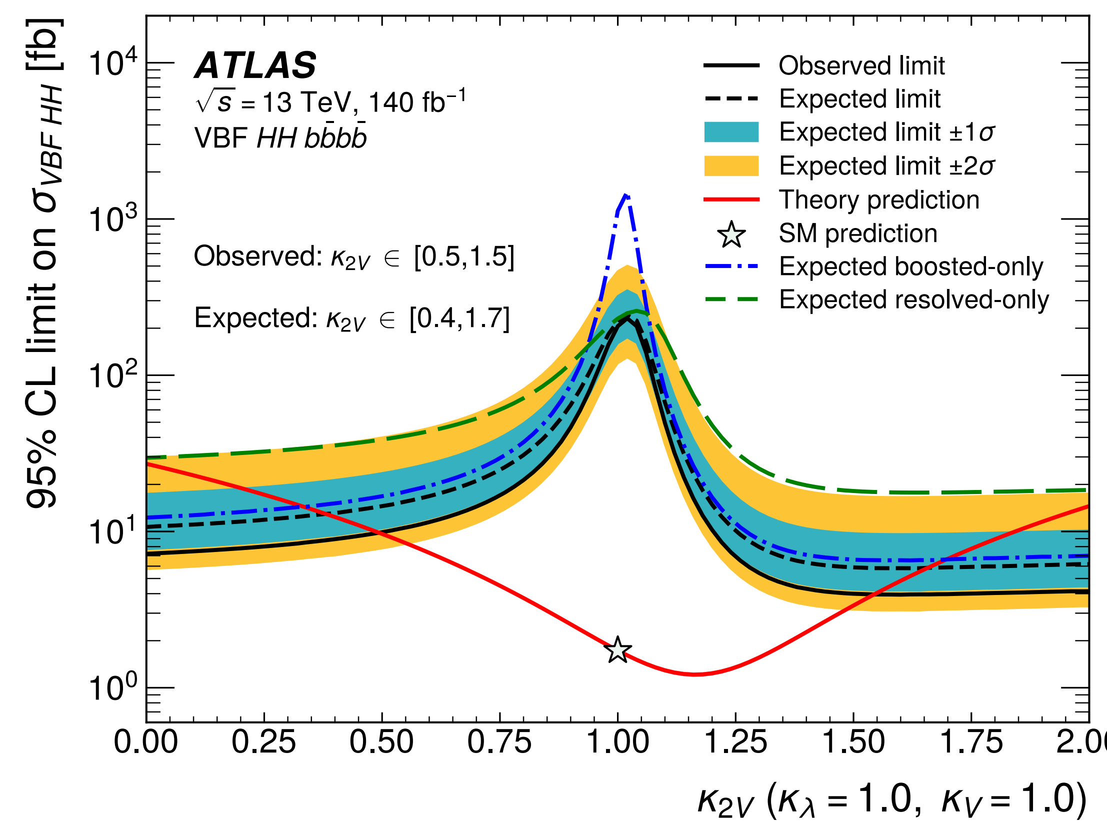
ATLAS

HH→bbbb (ATLAS)





- Fit to m_{HH} (BDT) in Resolved (Boosted) analysis
- Main background from QCD multijet
  - Data driven normalisation from signal region sidebands
  - Simple scale factor (neural net) in Resolved (Boosted)



- Dominant systematic uncertainties:
  - Xbb calibration
  - Background estimation
  - Signal cross section calculation

- Observed 95% CL limits:

	μ_{HH}	κ_λ	κ_{2V}
Resolved	5.4	[-3.5, 11.3]	[-0.0, 2.1]
Boosted			[0.52, 1.52]
Combined			[0.55, 1.49]

HH→bbbb (CMS)

CMS-PAS-B2G-21-001 (Preliminary)

- Boosted analysis targeting VBF events
- Higgs candidates from two highest p_T large-R jets

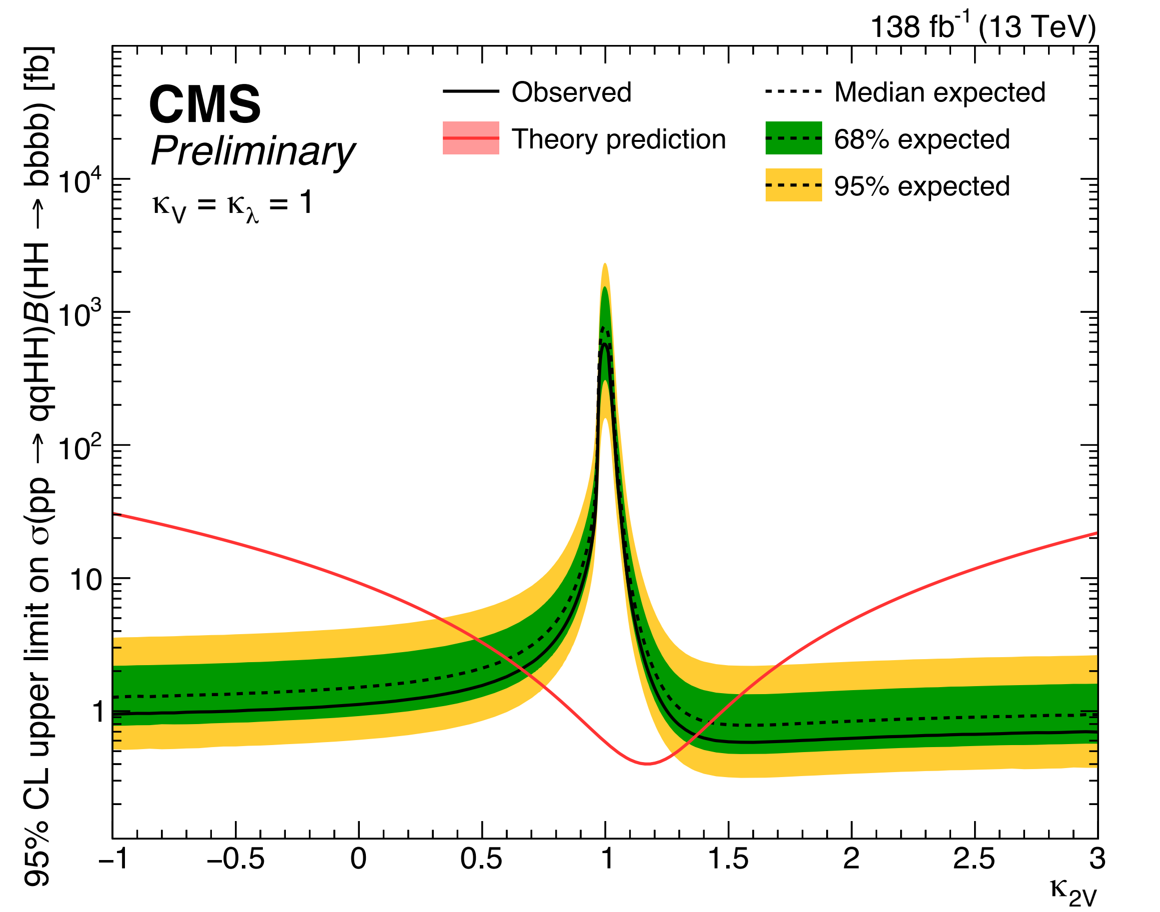
- Novel approach using *ParticleNet* (link, link)
  - Multivariate classifier based on graph convolutional neural networks
  - Ensures efficient reconstruction of b-jets
  - Significant rejection of light-quark or gluon jets

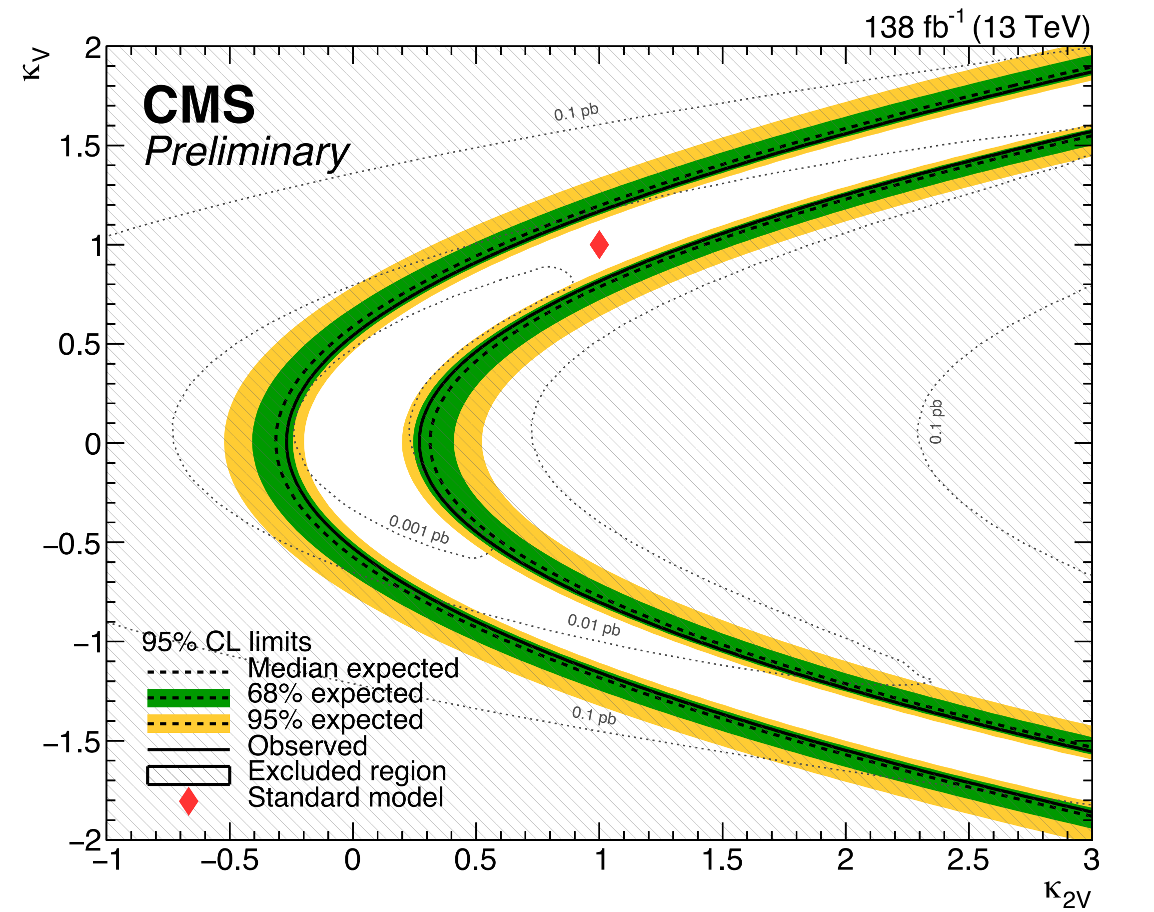
- Background dominated by QCD multijet and $t\bar{t}$
  - Background enriched control regions defined
  - Contributions estimated through simultaneous fit to m_{HH}

- Fit performed on m_{HH} templates

- Dominant systematic uncertainty:
  - Calibration of *ParticleNet* H→bb ID algorithm

- 95% CL limits:
  - $0.6 < \kappa_{2V} < 1.4$
  - $-1.2 < \kappa_V < 0.8$ or $-0.8 < \kappa_V < 1.2$
  - (Note κ_V, not κ_λ)





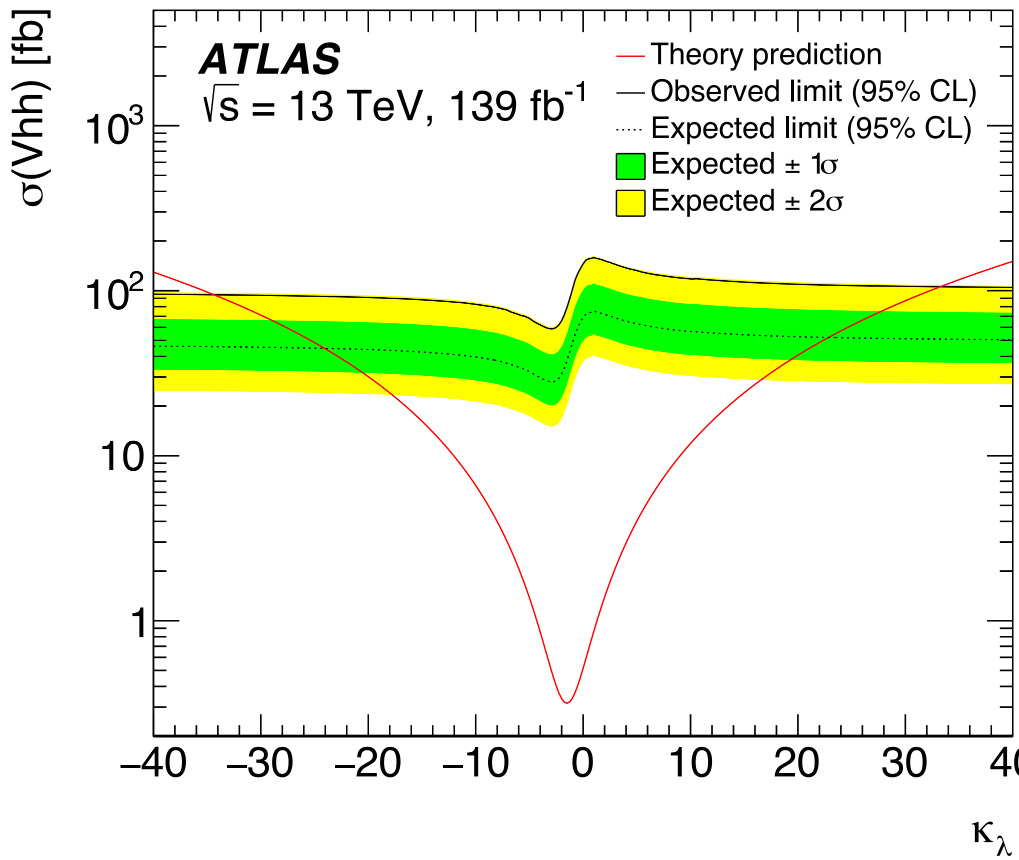
VHH→Vbbbb(→ℓℓ) (ATLAS, CMS)

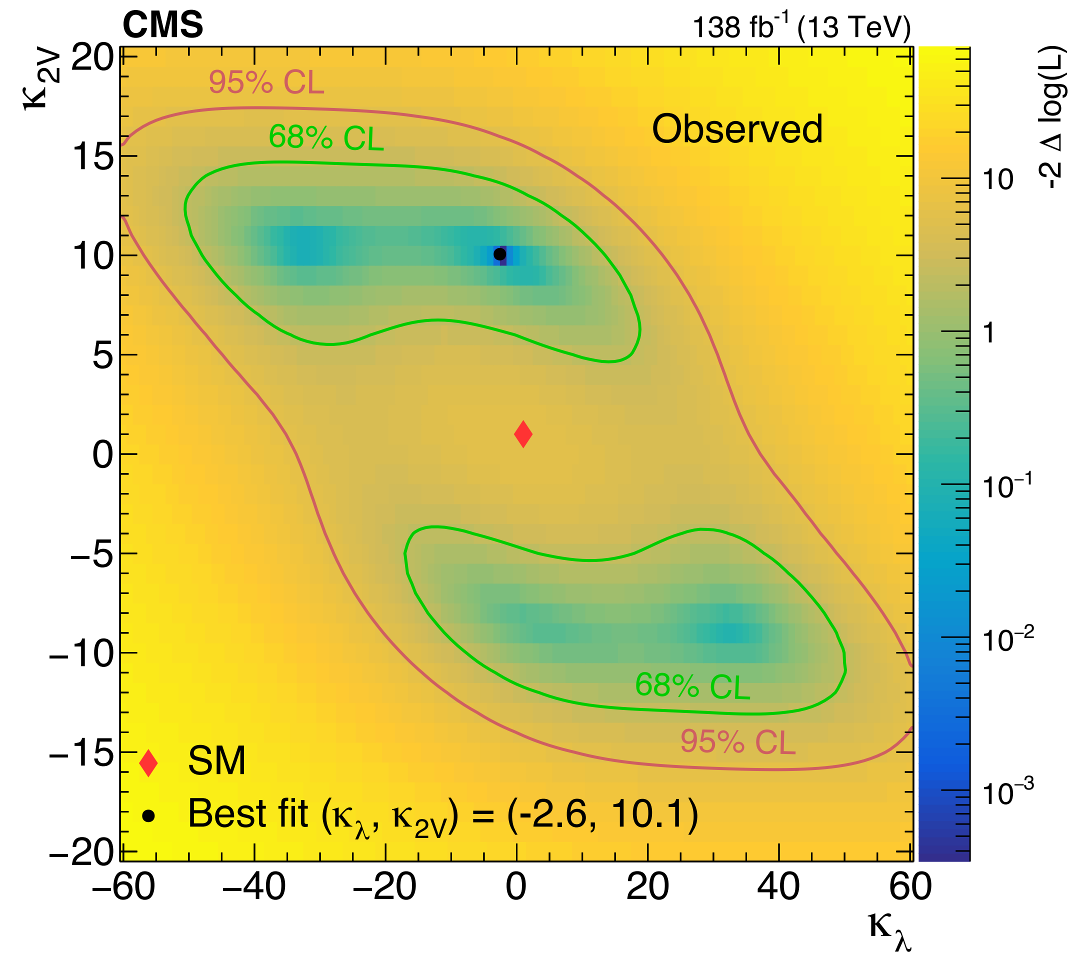
Eur. Phys. J. C 83 (2023) 519 (ATLAS)
HIG-22-006 (Accepted by JHEP) (CMS)

- Search for HH→bbbb with associated V
  - V=W→ℓν, Z→ee, μμ, νν
- Backgrounds include:
  - $t\bar{t}$, single top quarks, V+jets, multi-jet events

- ATLAS
  - Multivariate analysis
  - Eight BDTs generated (inc. for A→ZH search)
  - Jet energy scale/resolution uncertainties dominate
  - 95% CL limits:
    - μ_{HH} < 183 (87 exp)
    - $-34.3 < \kappa_\lambda < 33.3$
    - $-8.6 < \kappa_{2V} < 10.0$

- CMS
  - Categories optimised for sensitivity to κ_λ, κ_{2V}
  - Uncertainties dominated by
    - B-tagging efficiency
    - Background modelling
  - 95% CL limits:
    - μ_{HH} < 294 (124 exp)
    - $-37.7 < \kappa_\lambda < 37.2$
    - $-12.2 < \kappa_{2V} < 13.5$

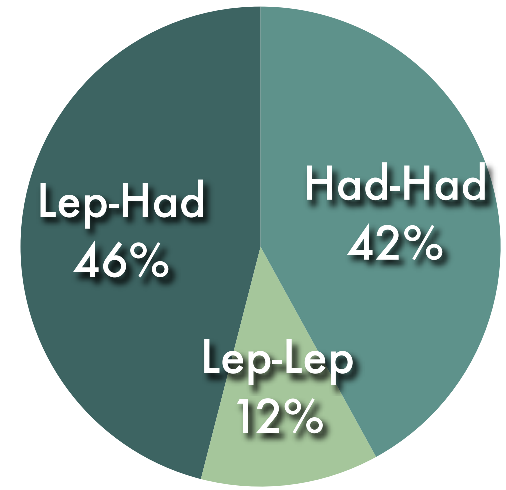




HH→bbττ (ATLAS)

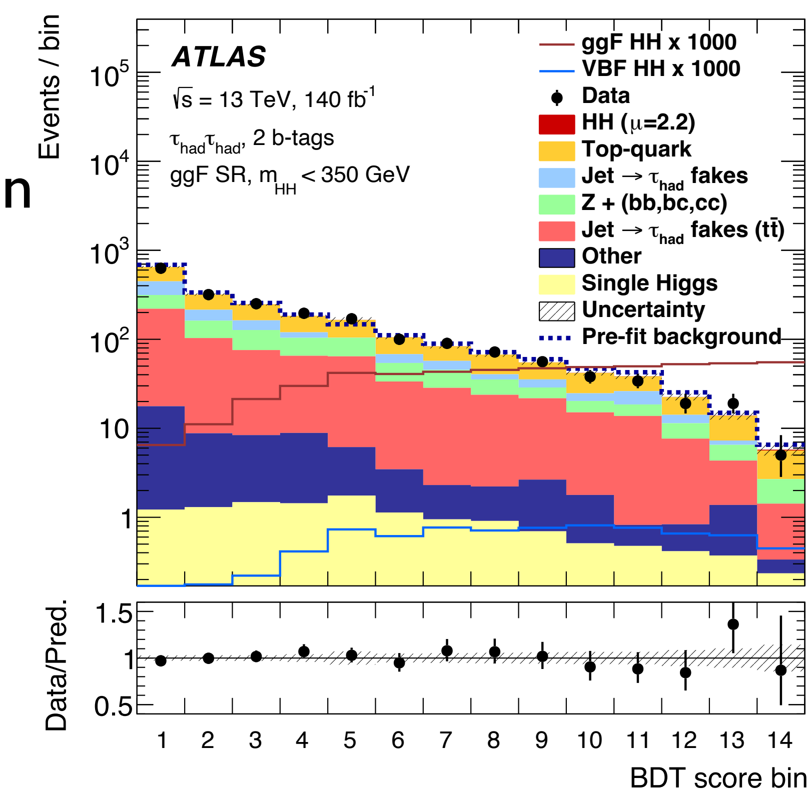
Phys. Rev. D 110 (2024) 032012

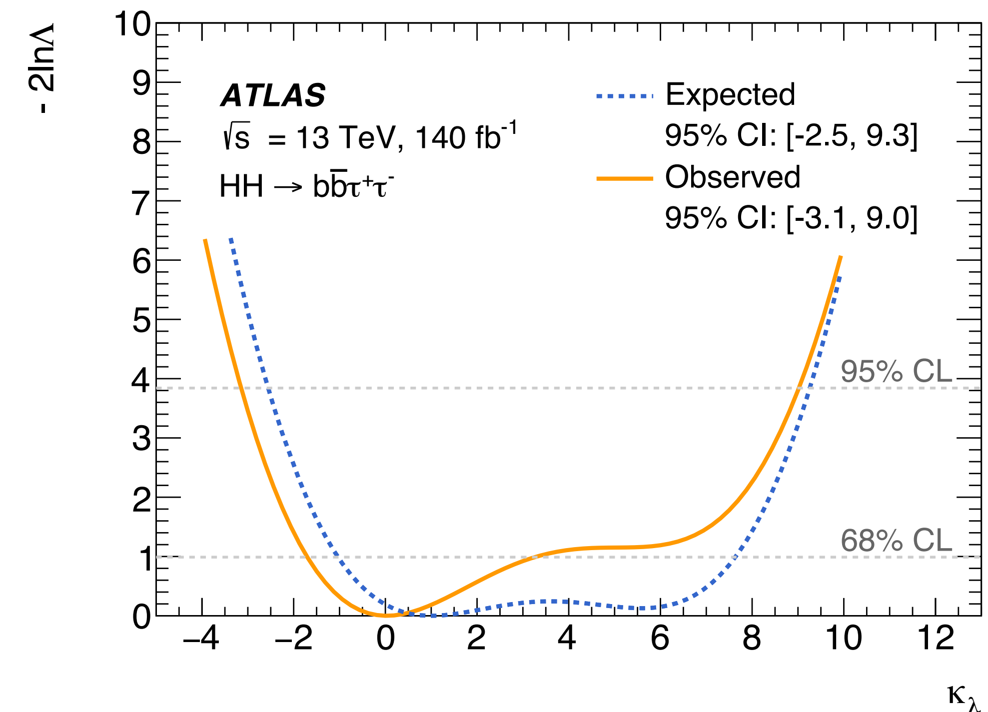
- $\tau_{Had}\tau_{Had}$:
  - Single-τ_{Had} and di-τ_{Had} triggers (high purity) → 2 τ_{Had}, e/μ veto
- $\tau_{Lep}\tau_{Had}$:
  - Single ℓ trigger (large acceptance) → 1 τ_{Had}, 1 e/μ
  - ℓ + τ_{Had} trigger (low ℓ p_T) → 1 τ_{Had}, 1 e/μ
- $\tau_{Lep}\tau_{Lep}$ not considered



- Events split to nine categories based on trigger, m_{HH}, BDTs
- Background dominated by $t\bar{t}$, QCD multi-jet, Z+heavy jets
- Signal/Background separation from BDT (one trained per signal region)

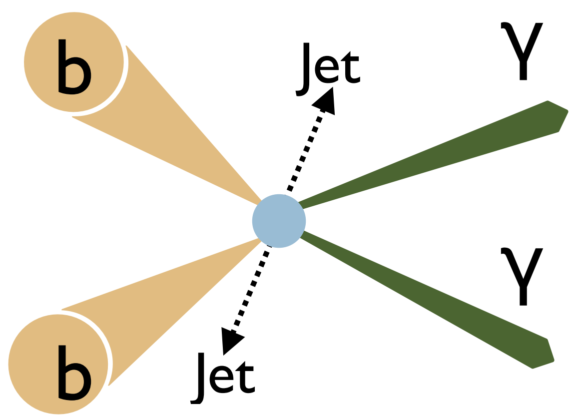
- Dominant uncertainties:
  - Data statistics
  - Modelling uncertainties on top-quark and single-H background
- 95% CL limits:
  - μ_{HH} < 5.9 (3.3 exp)
  - $-3.1 < \kappa_\lambda < 9.0$
  - $-0.5 < \kappa_{2V} < 2.7$

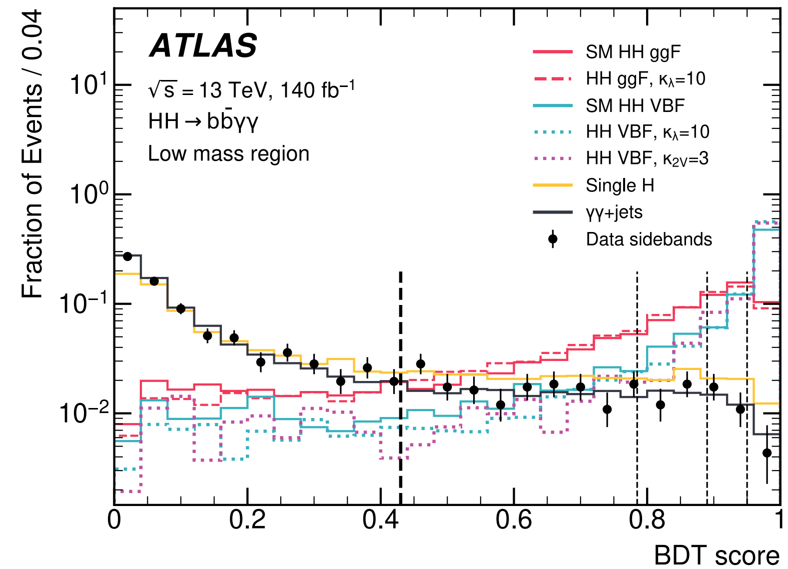


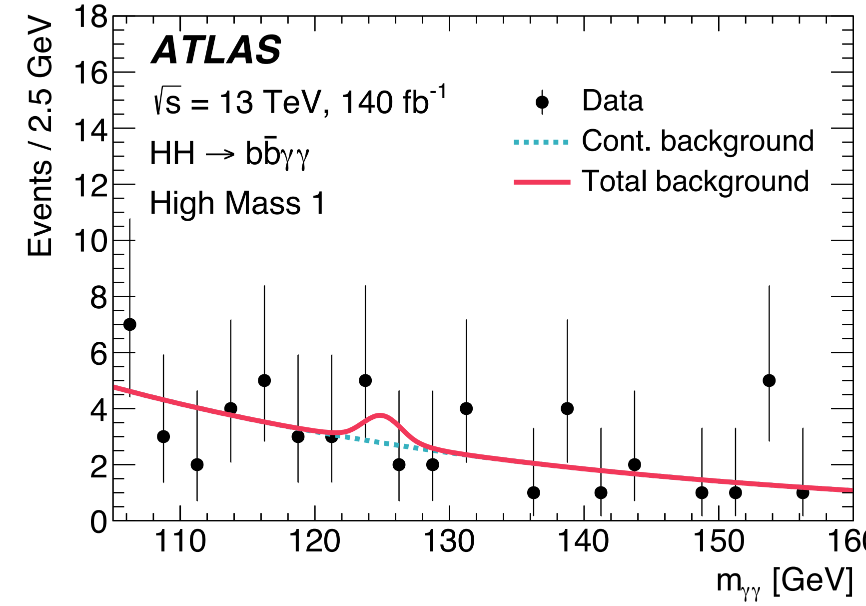


HH→bbγγ (ATLAS)

JHEP 01 (2024) 066

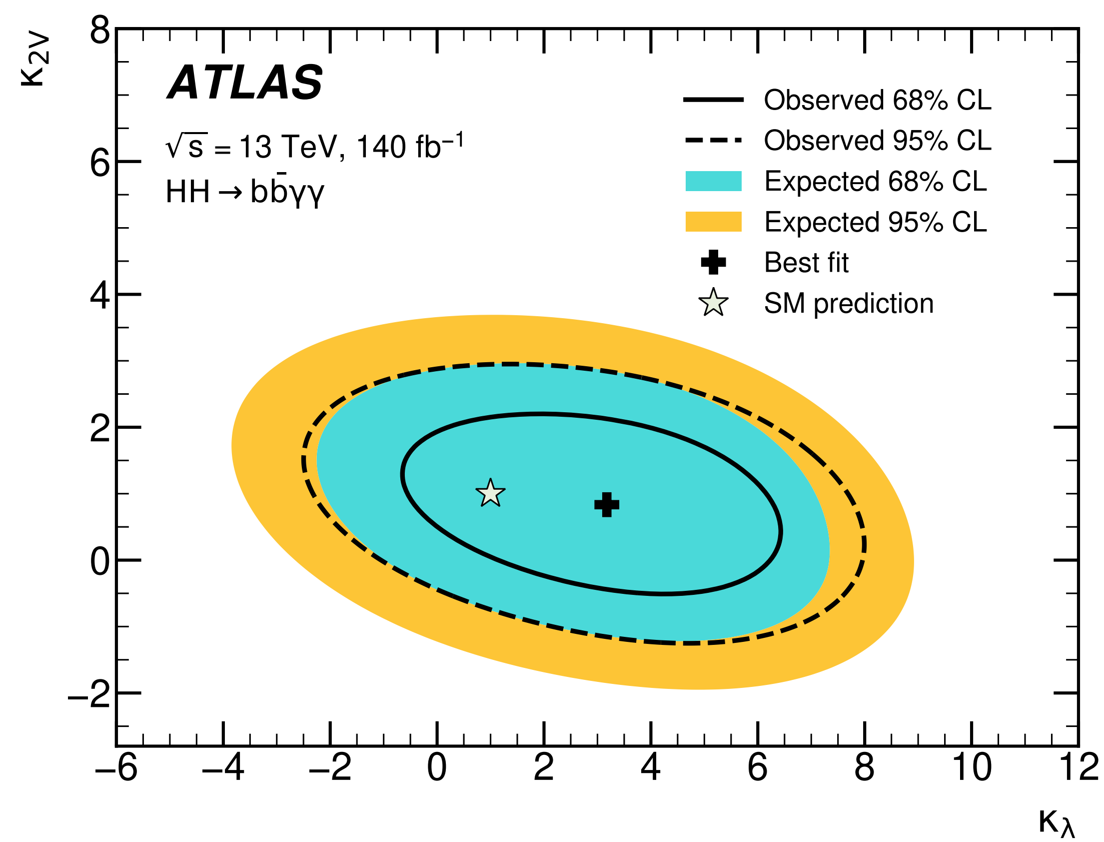






- Events selected with 2 b-jets and 2 photons
- Events classified using modified $m_{bb\gamma\gamma}$:
  - $m^*_{bb\gamma\gamma} = m_{bb\gamma\gamma} - (m_{bb} - 125\text{ GeV}) - (m_{\gamma\gamma} - 125\text{ GeV})$
- Define high/low mass regions at $m^*_{bb\gamma\gamma} = 350$ GeV
  - One BDT per region, categorise based on score
  - High mass region: 4 categories
  - Low mass region: 3 categories

- 95% CL limits:
  - $\mu_{HH} < 4.0$ (5.0 exp)
  - $-1.4 < \kappa_\lambda < 6.9$
  - $-0.5 < \kappa_{2V} < 2.7$

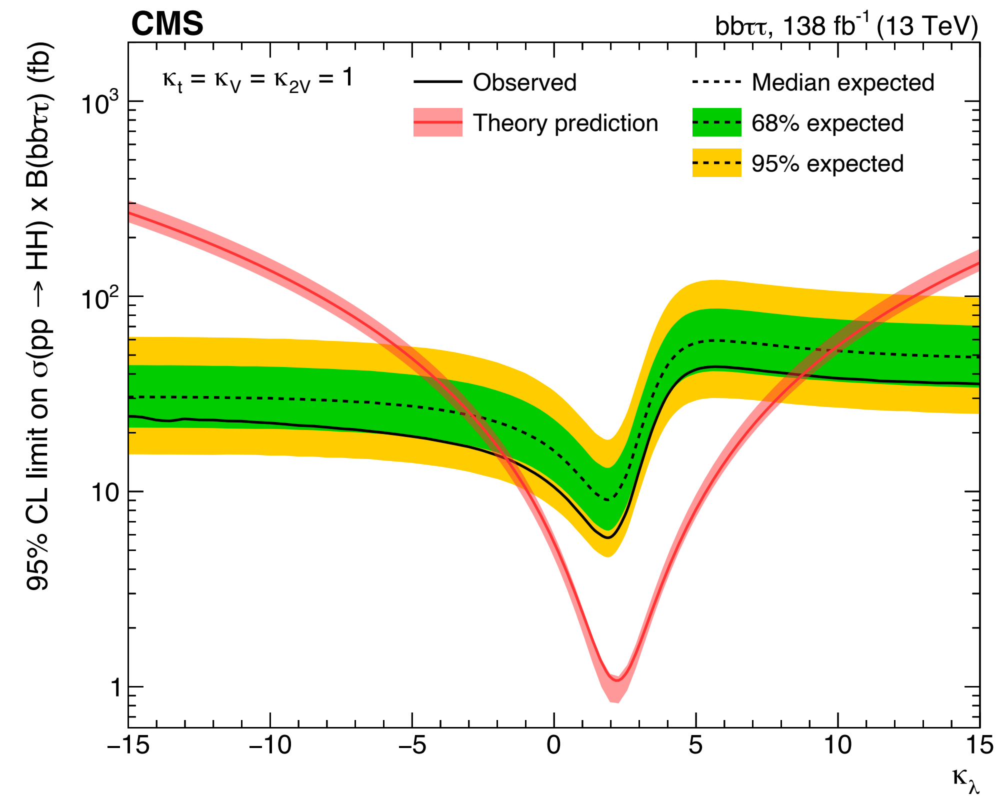


- Signal and Background modelled using $m_{\gamma\gamma}$:
  - HH and Single H (double sided Crystal Ball)
  - γγ+jets background (exponential)
  - Fit performed on $m_{\gamma\gamma}$ in each category
- Dominant uncertainties:
  - Data statistics
  - Theory uncertainties on HH cross-section

HH→bbττ, bbγγ (CMS)

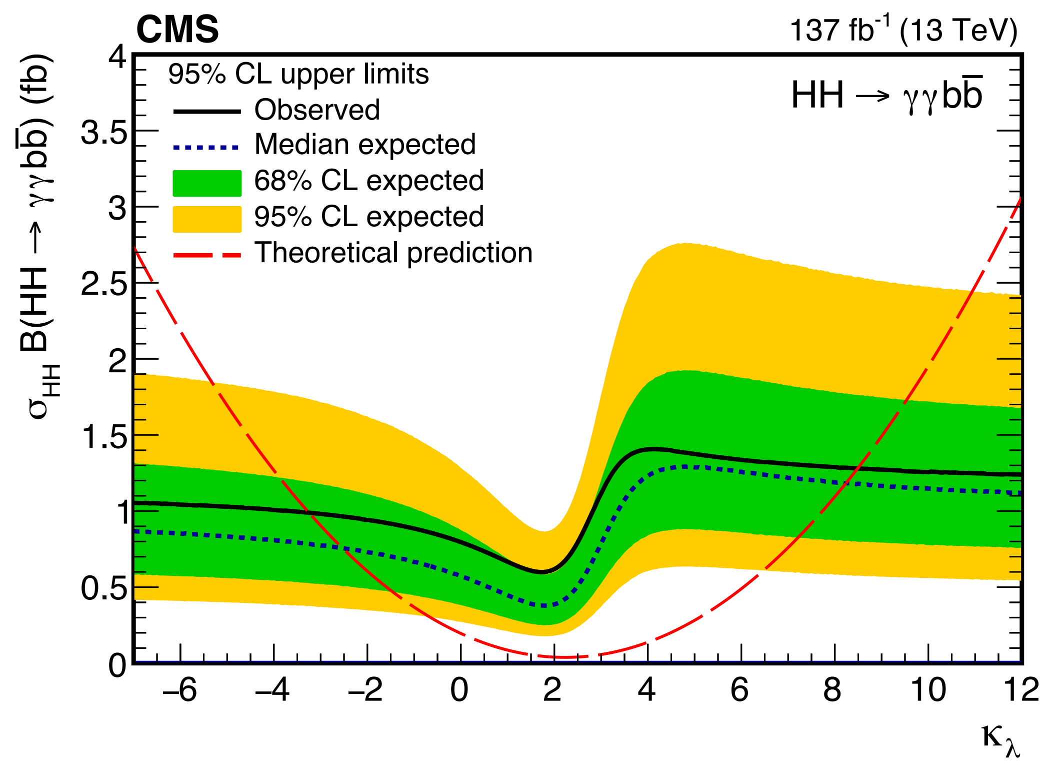
- bbττ:
  - Events split into 8 orthogonal categories
  - Deep neural network for event selection/categorisation
  - Background: $t\bar{t}$, QCD multi-jet, Z+heavy jets

  - 95% CL limits:
    - $\mu_{HH} < 3.3$ (5.2 exp)
    - $-1.7 < \kappa_\lambda < 8.7$
    - $-0.4 < \kappa_{2V} < 2.6$



- bbγγ:
  - Analysis originally developed the $m^*_{bb\gamma\gamma}$ variable
  - Dedicated event classifier for $t\bar{t}$ background rejection
    - Custom DNN combining feed-forward and long short-term memory neural networks
  - BDT separates signal from background:
    - non-resonant γγ+jets, γ+jets
  - Events split into 14 categories based on BDT output

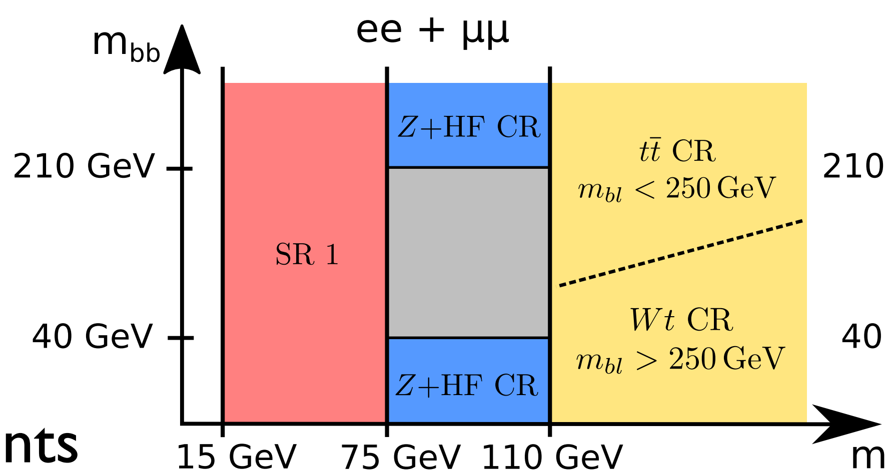
  - 95% CL limits:
    - $\mu_{HH} < 8.4$ (5.5 exp)
    - $-3.3 < \kappa_\lambda < 8.5$

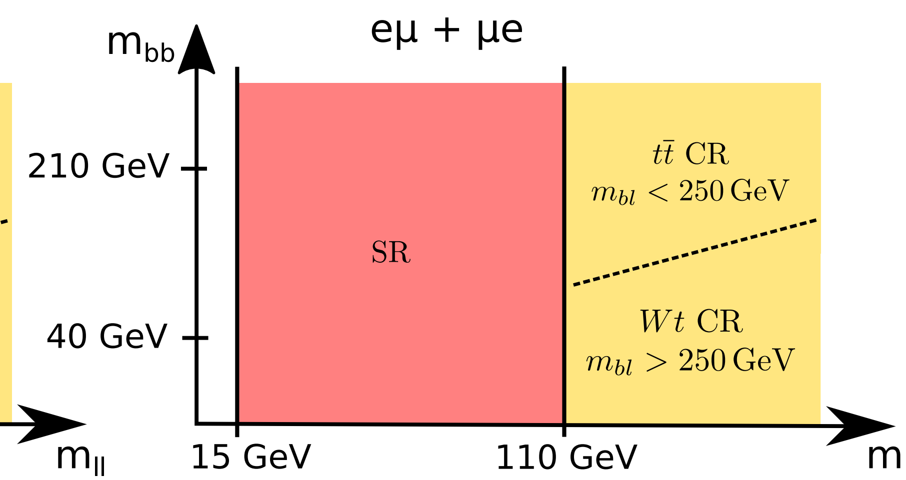


$HH \to bb\ell\ell + E_T^{miss}$ (ATLAS)

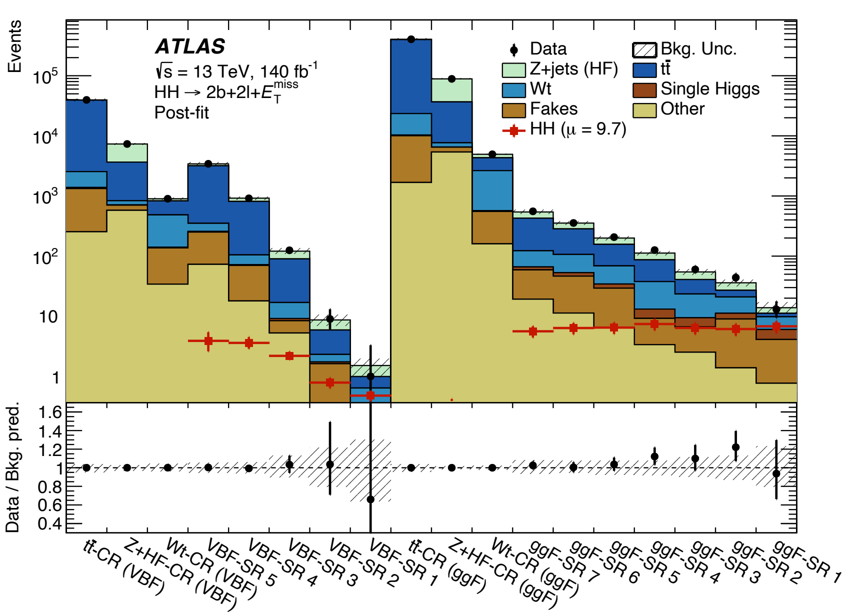
JHEP 02 (2024) 037

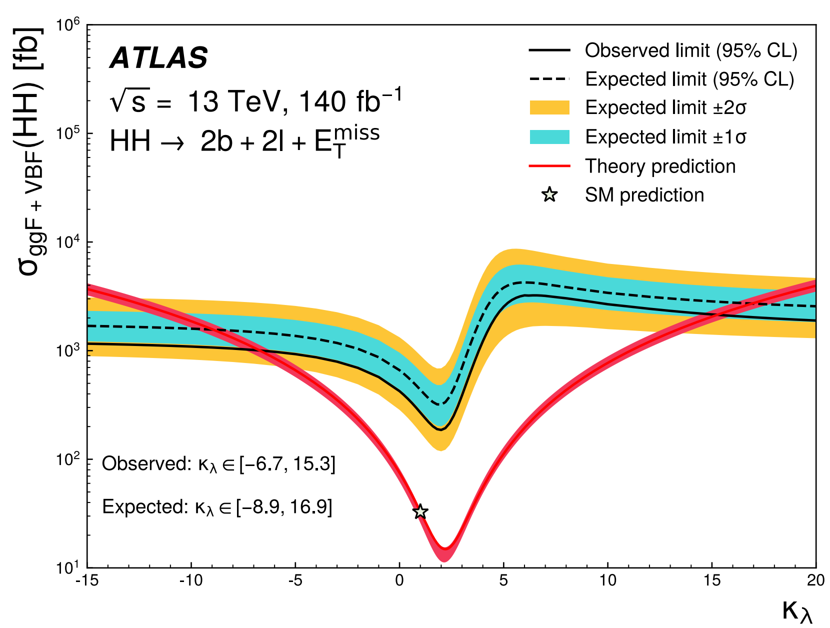
- Consider:
  - $HH \to bbWW$
  - $HH \to bbZZ$
  - $HH \to bb\tau\tau$
- Events split to VBF/ggF categories
- DNN (BDT) selects ggF (VBF) events
  - Outputs used as discriminant in fit

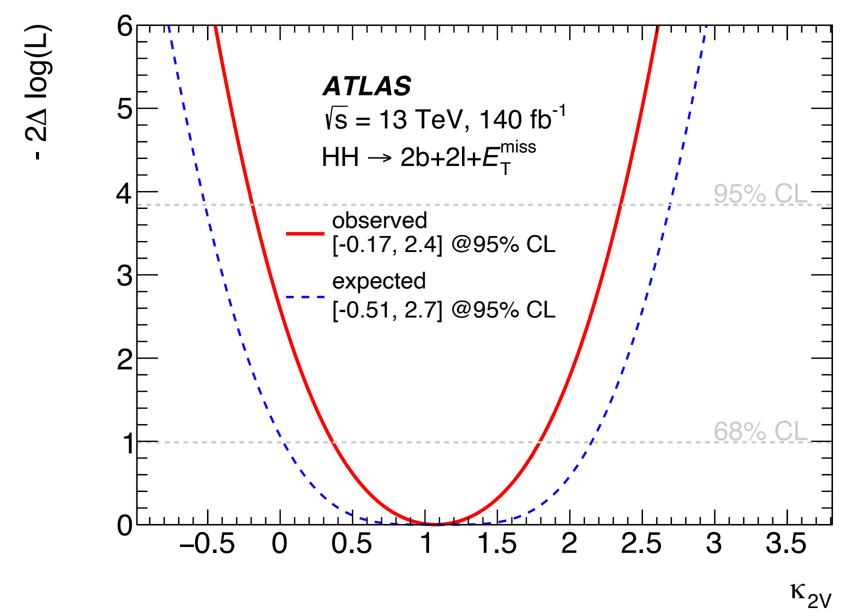




- Multiple backgrounds:
  - $t\bar{t}$ and tW
  - Single Higgs
  - Z+ heavy flavour
  - “Fake” leptons
- Dominant uncertainties:
  - Data statistics
  - Z+jets modelling
- 95% CL limits:
  - $\mu_{HH} < 9.7$ (16.2 exp)
  - $-6.7 < \kappa_\lambda < 15.3$
  - $-0.17 < \kappa_{2V} < 2.4$

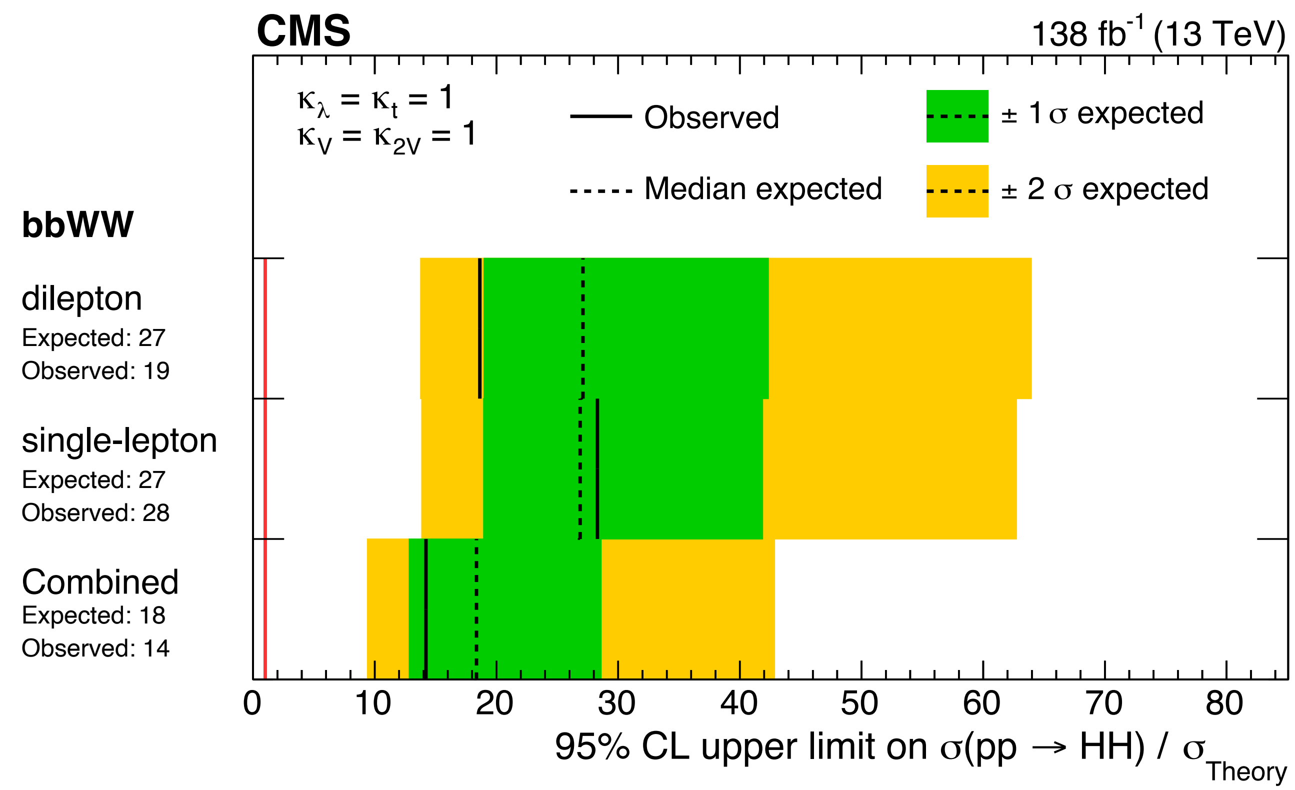




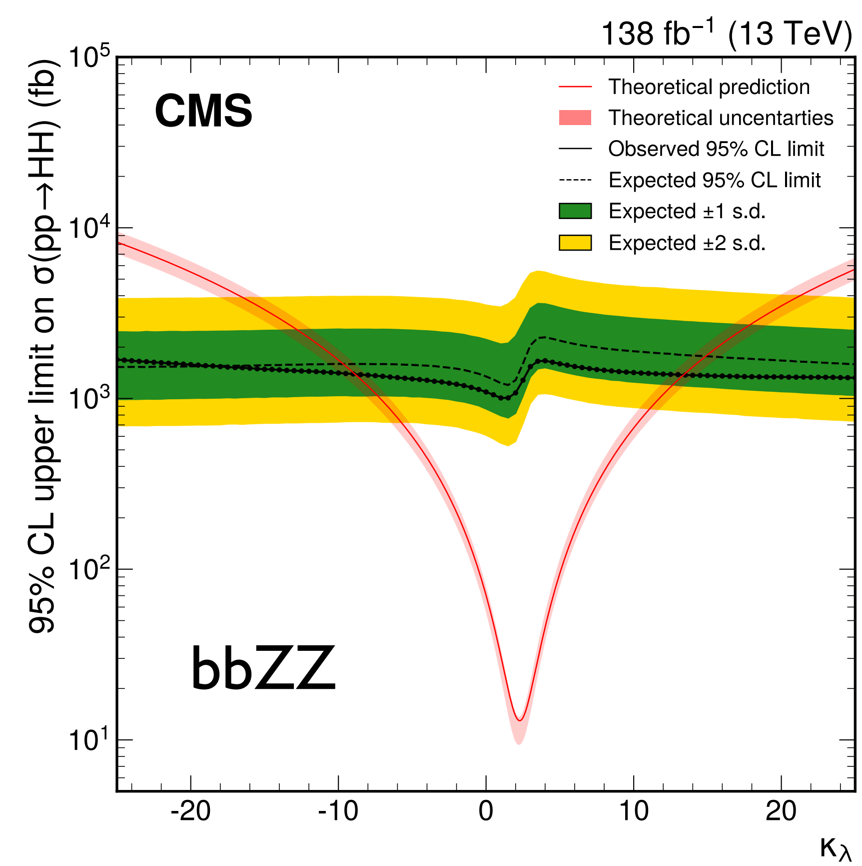


HH→bbWW, bbZZ(4l) (CMS)

- bbWW:
  - Events categorised by trigger
    - Single-lepton, dilepton
  - Sub-categories based on DNN classification
  - Background includes $t\bar{t}$, single top, W+jets
  - DNN score fitted
  - 95% CL limits:
    - $\mu_{HH} < 14$ (18 exp)
    - $-7.2 < \kappa_\lambda < 13.8$
    - $-1.1 < \kappa_{2V} < 3.2$
  - ATLAS constrains κ_{2V} more strongly
    - Dedicated VBF category helps



- bbZZ(4l):
  - Events split to nine categories using BDT
  - Nine BDT distributions in data are fitted
  - Main backgrounds from H, qq, gg decaying to ZZ
  - 95% CL limits:
    - $\mu_{HH} < 32.4$ (39.6 exp)
    - $-8.8 < \kappa_\lambda < 13.4$



HH→Multilepton (ATLAS)

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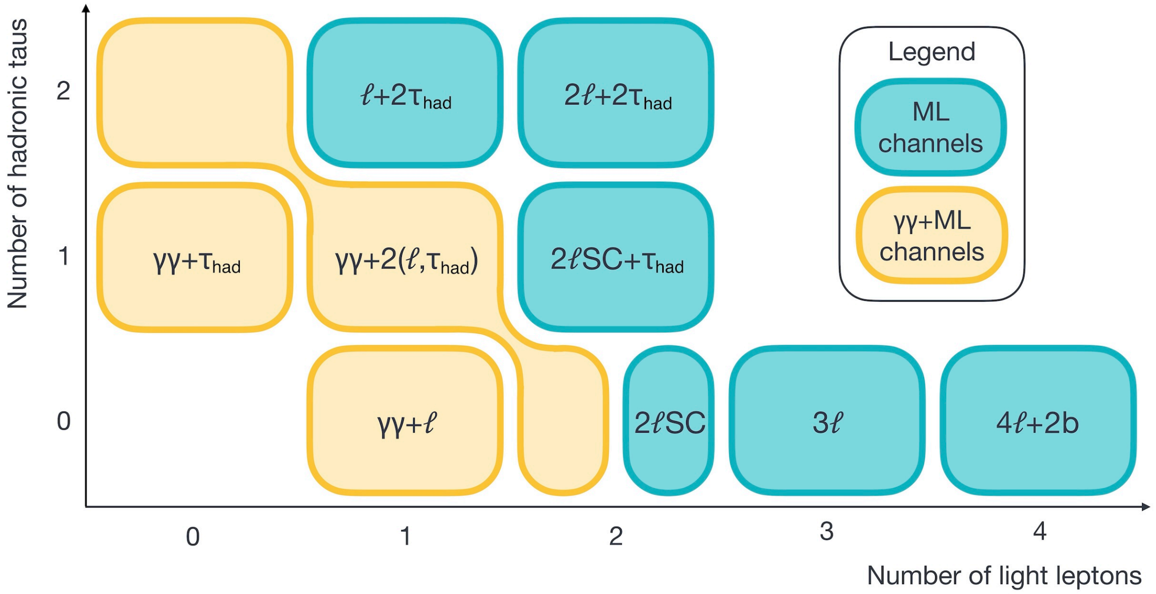
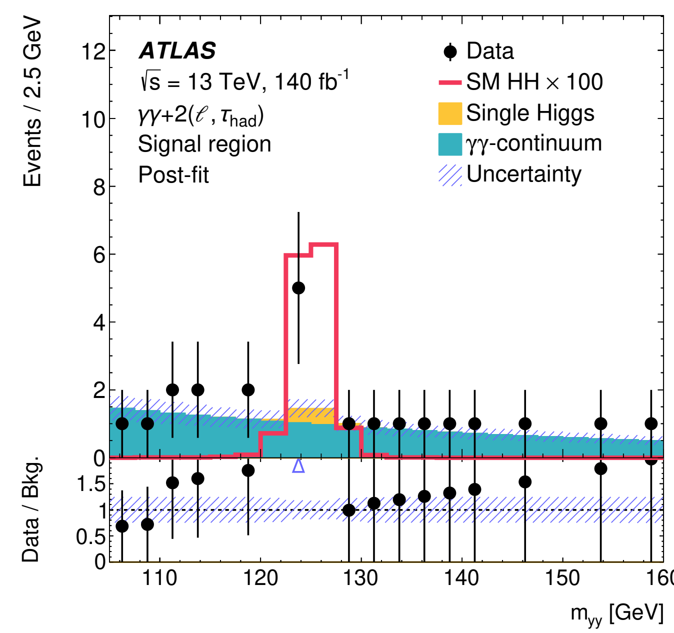
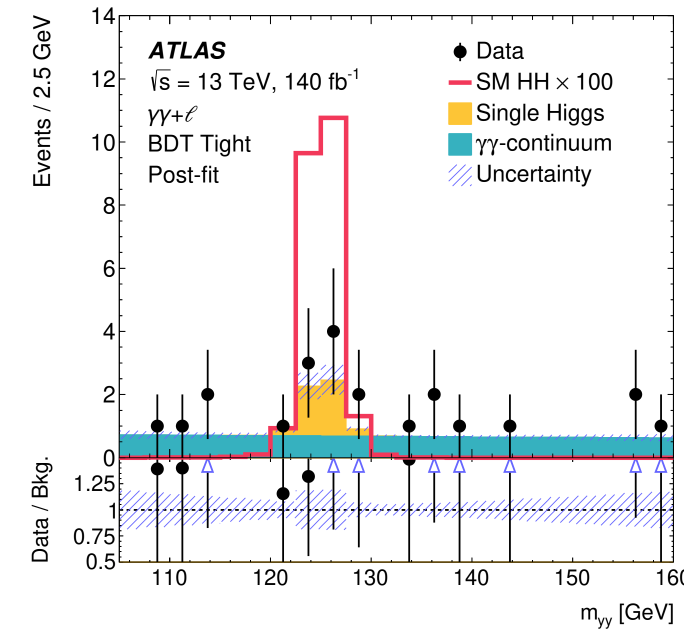




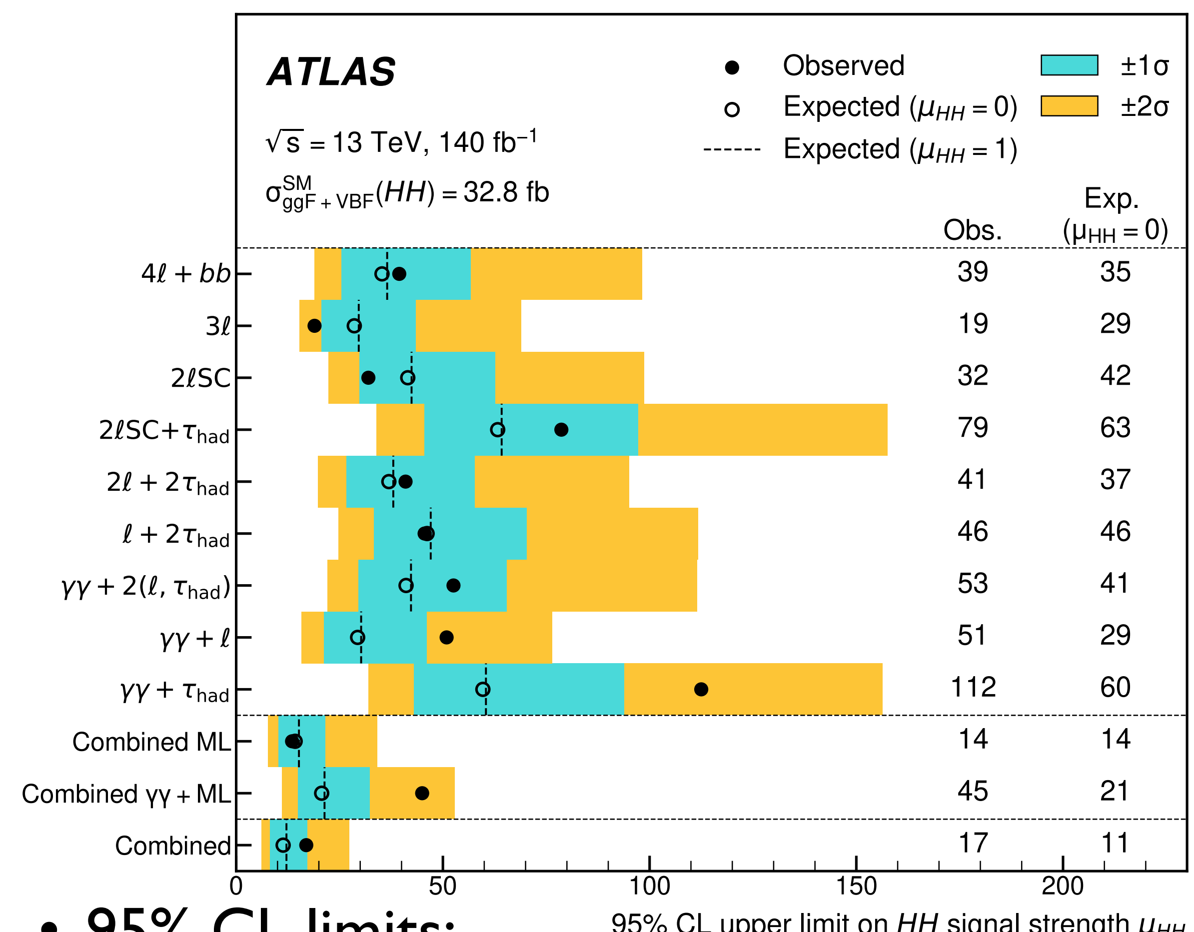


- Targets decay modes: 4V, VVττ, 4τ, γγVV, γγττ

- Background estimation:
  - Prompt leptons from SM processes
  - Non-prompt leptons
  - Mis-assigned charge
  - Mis-identified tau
  - Non-resonant γγ production

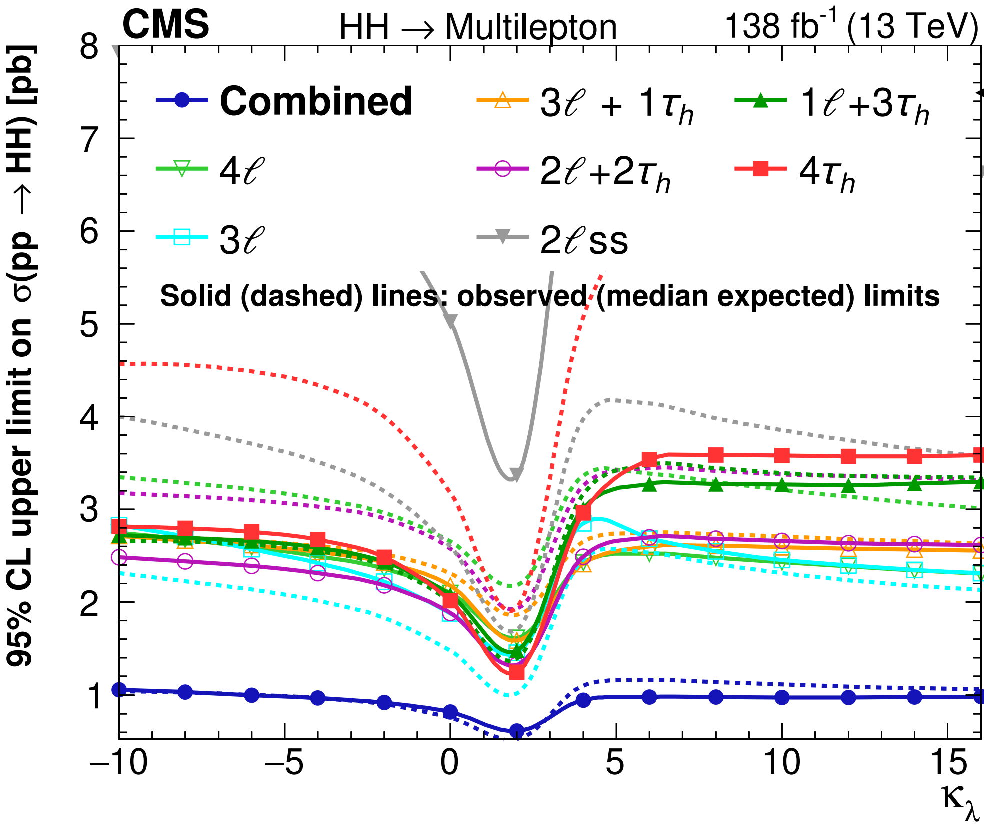
- BDT is trained in each sub-channel
  - Score used as discriminant

- Dominant uncertainty:
  - Data statistics
  - Theoretical uncertainty on signal modelling



- 95% CL limits:
  - $\mu_{HH} < 17$ (11 exp)
  - $-6.2 < \kappa_\lambda < 11.6$
  - $-2.5 < \kappa_{2V} < 4.6$

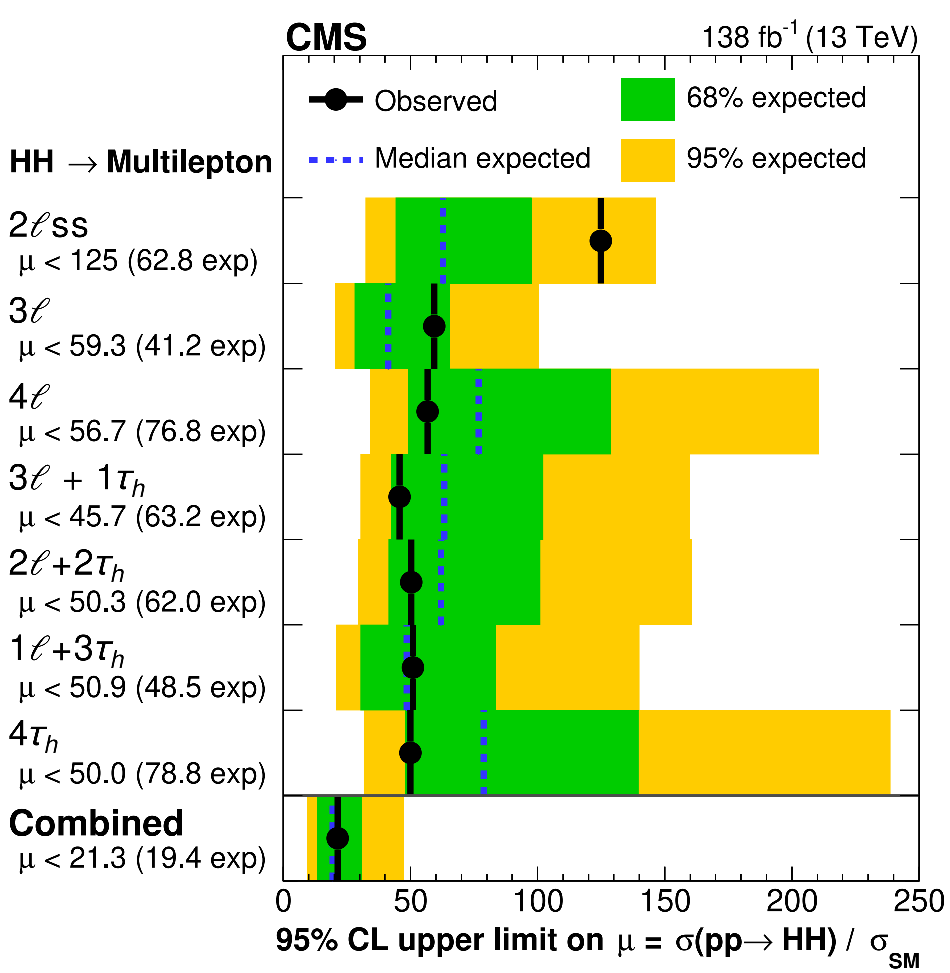
HH→Various (CMS)

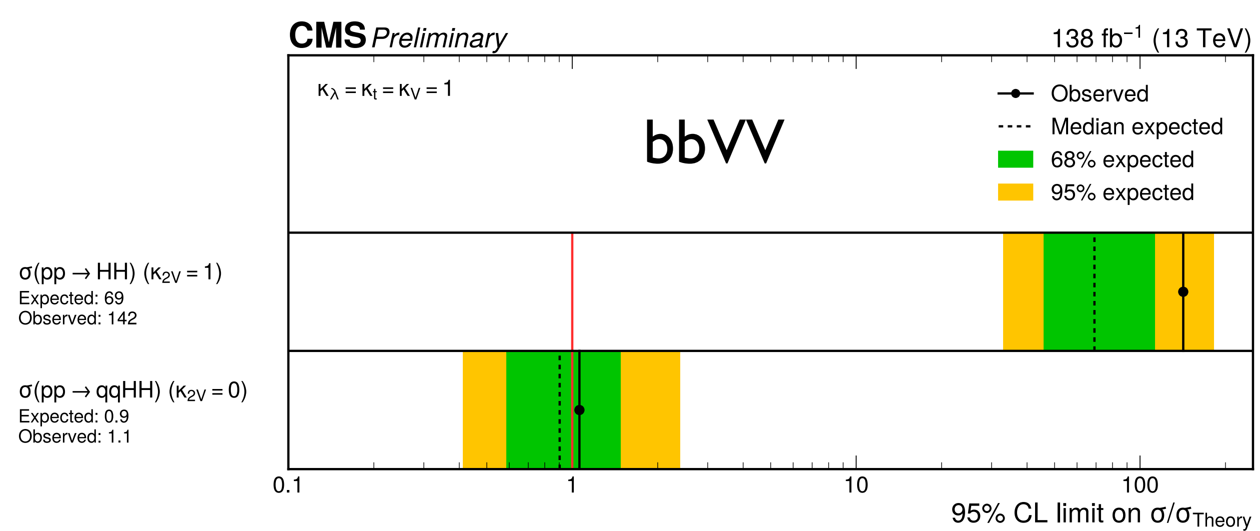


CMS Multilepton

- Multilepton targets 4W, WWττ, 4τ states
  - Events contain 2,3,4 leptons
  - Electrons, muons and hadronic taus studied

- bbVV:
  - Both Higgs bosons are highly Lorentz-boosted
  - Signature of two large-radius jets
  - Novel multivariate classifier based on graph convolutional neural networks, *ParticleNet*, to identify the jets that correspond to H→bb





HH Combination (ATLAS)

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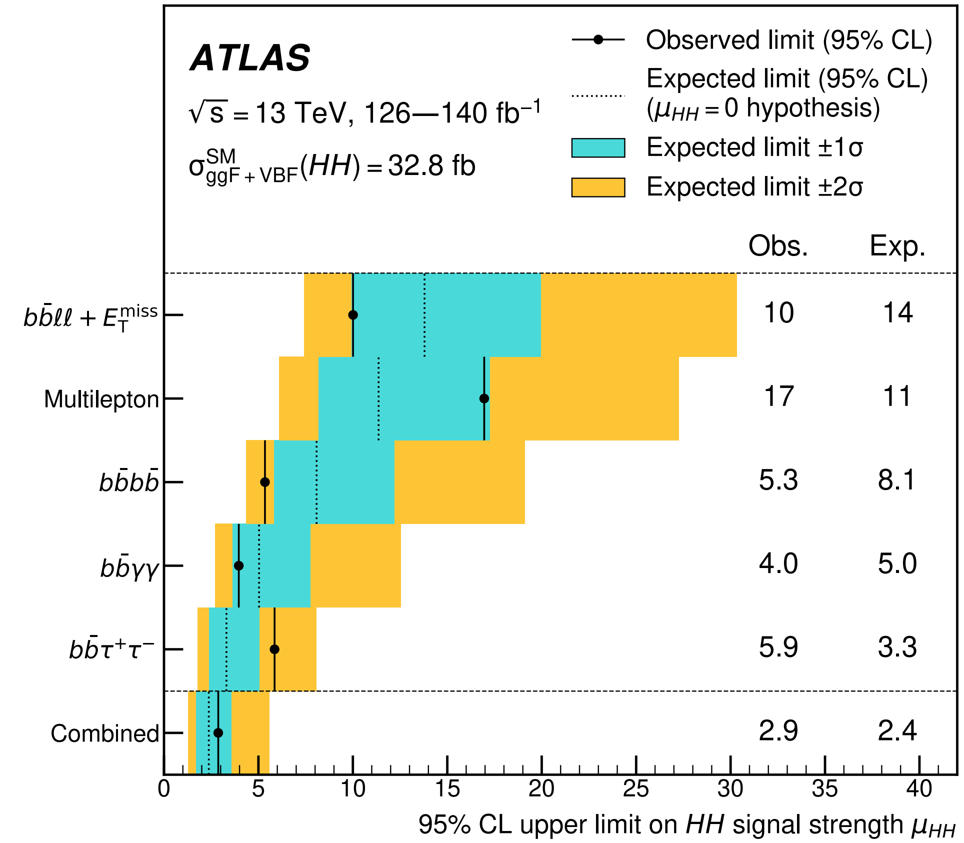
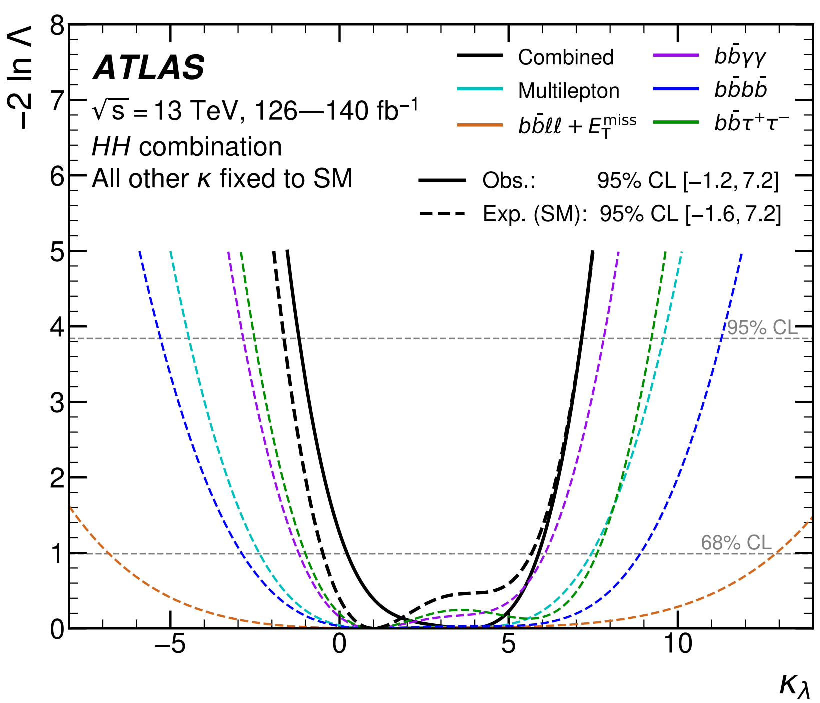
- Combines channels:
  - bbbb, bbγγ, bbττ, bbℓℓ + E_T^{miss}, Combined Multilepton
- Common sources of uncertainty correlated unless:
  - Different calibrations used
  - Different post fit profilings from different phase space

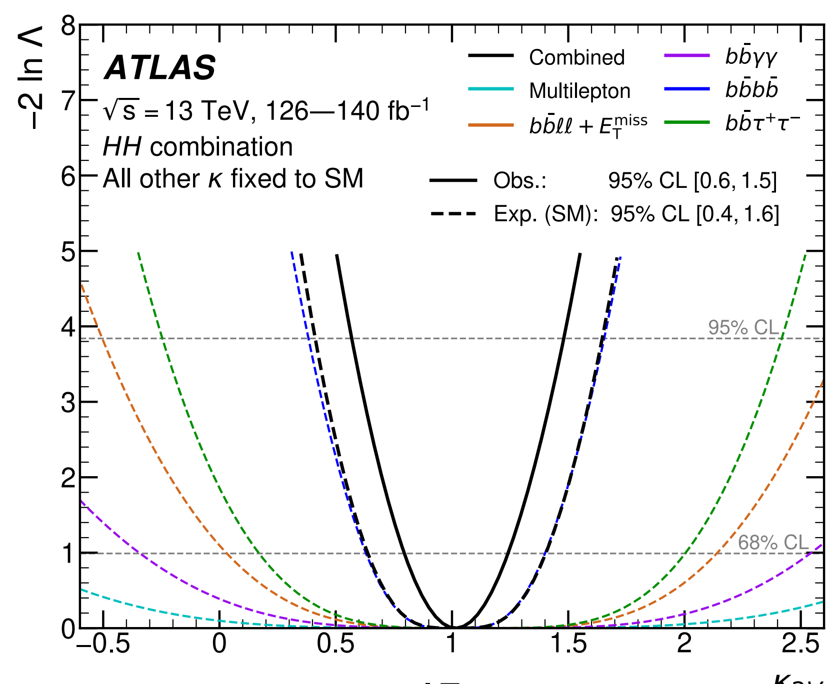


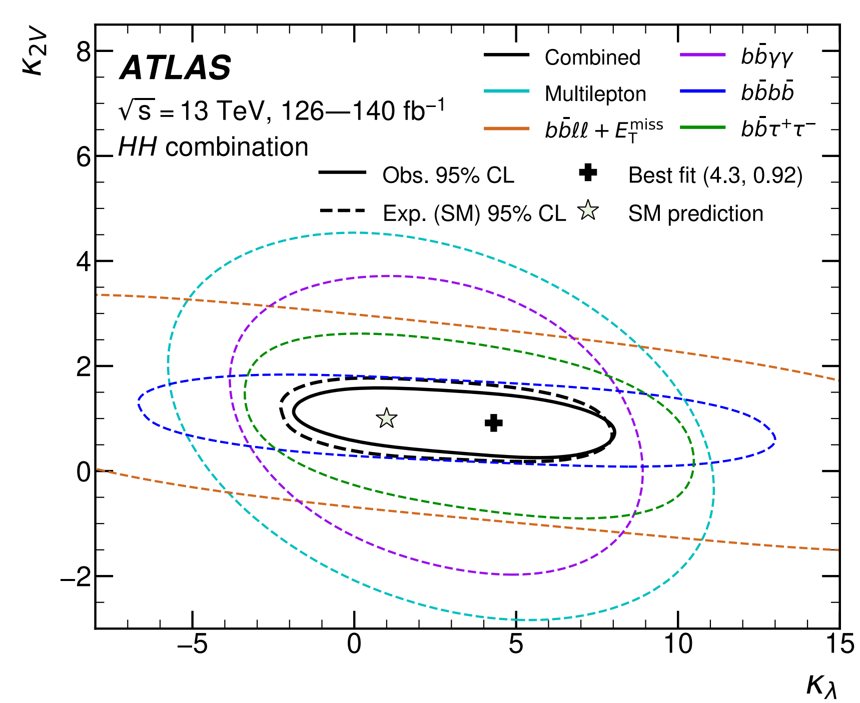
- Dominant uncertainties:
  - HH QCD scale + m_{top} ($^{+6\%}_{-23\%}$ on ggF HH)
  - Modelling of single H associated with b-jets
  - Background estimation in 4b

- Combination 95% CL limits:
  - $\mu_{HH} < 2.9$ (2.4 exp)
  - $\sigma_{HH} < 85.8$ (71.1 exp) fb

	Best Fit	Obs 95% CL	Exp 95% CL	Leading Channel
κ_λ	3.8	[-1.2, 7.2]	[-1.6, 7.2]	bbγγ, bbττ
κ_{2V}	1.0	[0.6, 1.5]	[0.4, 1.6]	bbbb (boosted)







HH Combination: HEFT interpretation (ATLAS)

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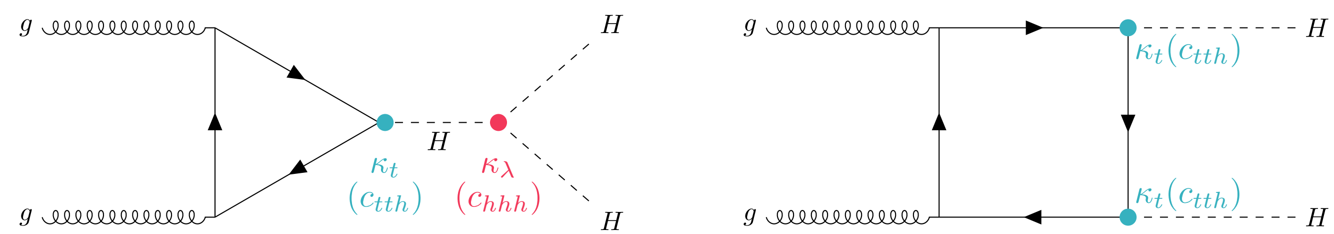
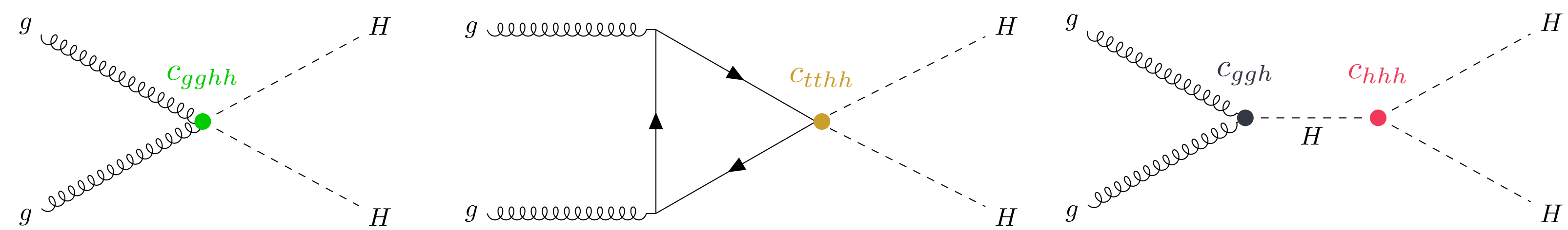
ggF production:

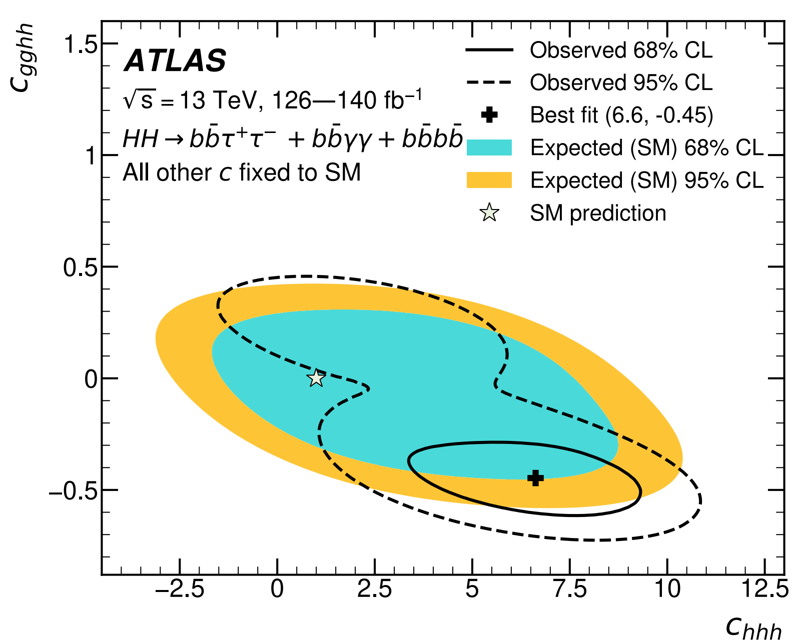


Additional ggF in BSM scenario:

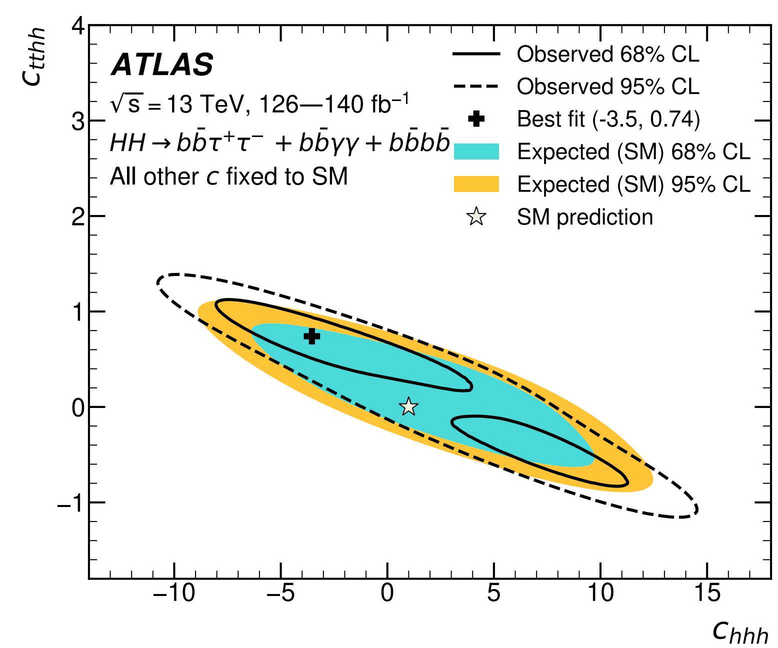


- Each diagram sensitive to specific coupling factors
- Some diagrams appear if deviations from SM predictions in coefficients c_{ggh}, c_{gghh}, c_{tthh}
- HEFT parameterisation has quadratic structure, hence multiple minima
- Best fit driven by bbbb where data-driven background modelling not perfectly accurate
  - Fits in channel favour non-SM signals

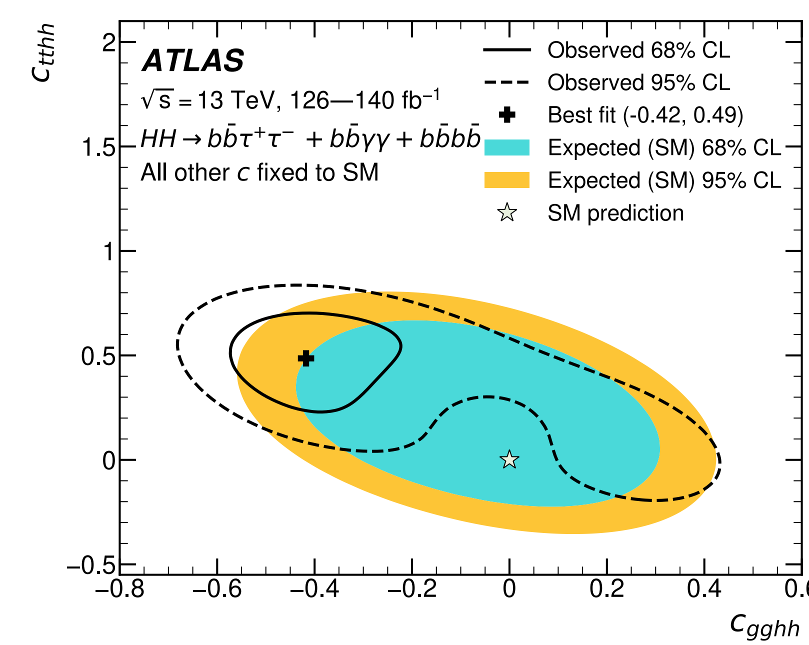
Chhh-Cgghh



Chhh-Cgghh

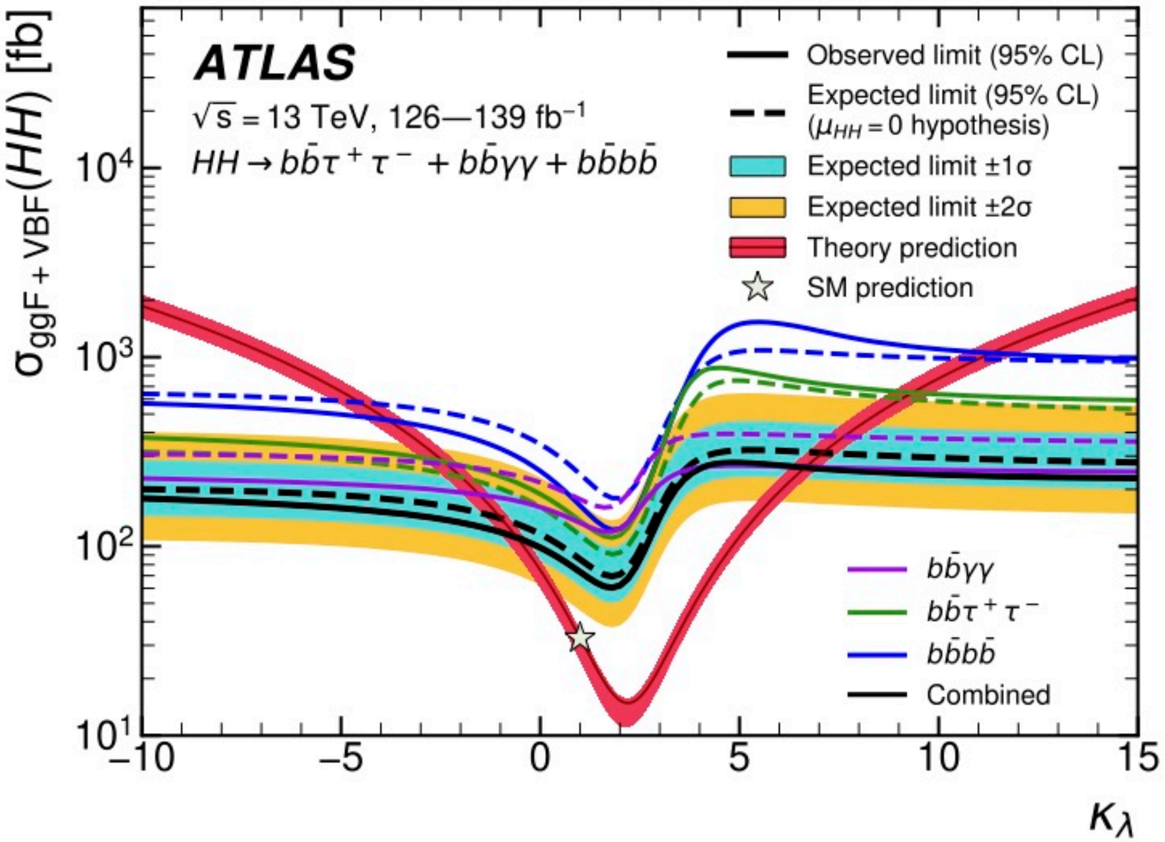


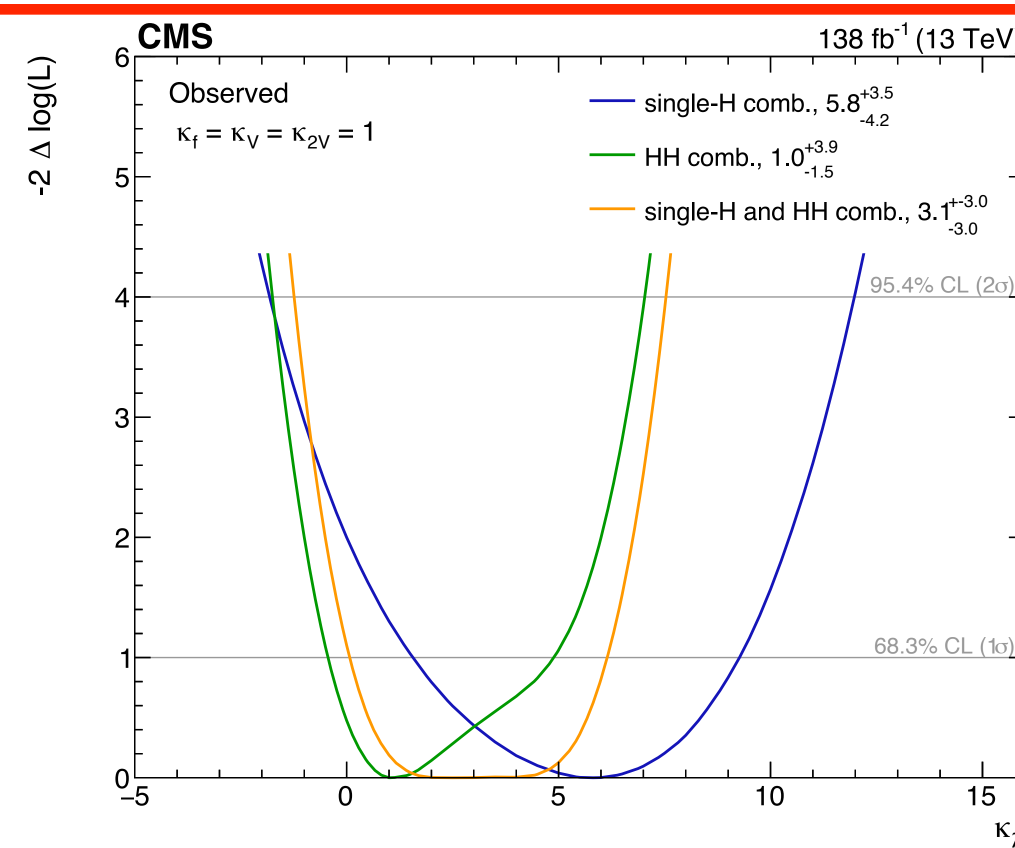
Cgghh-Ctthh

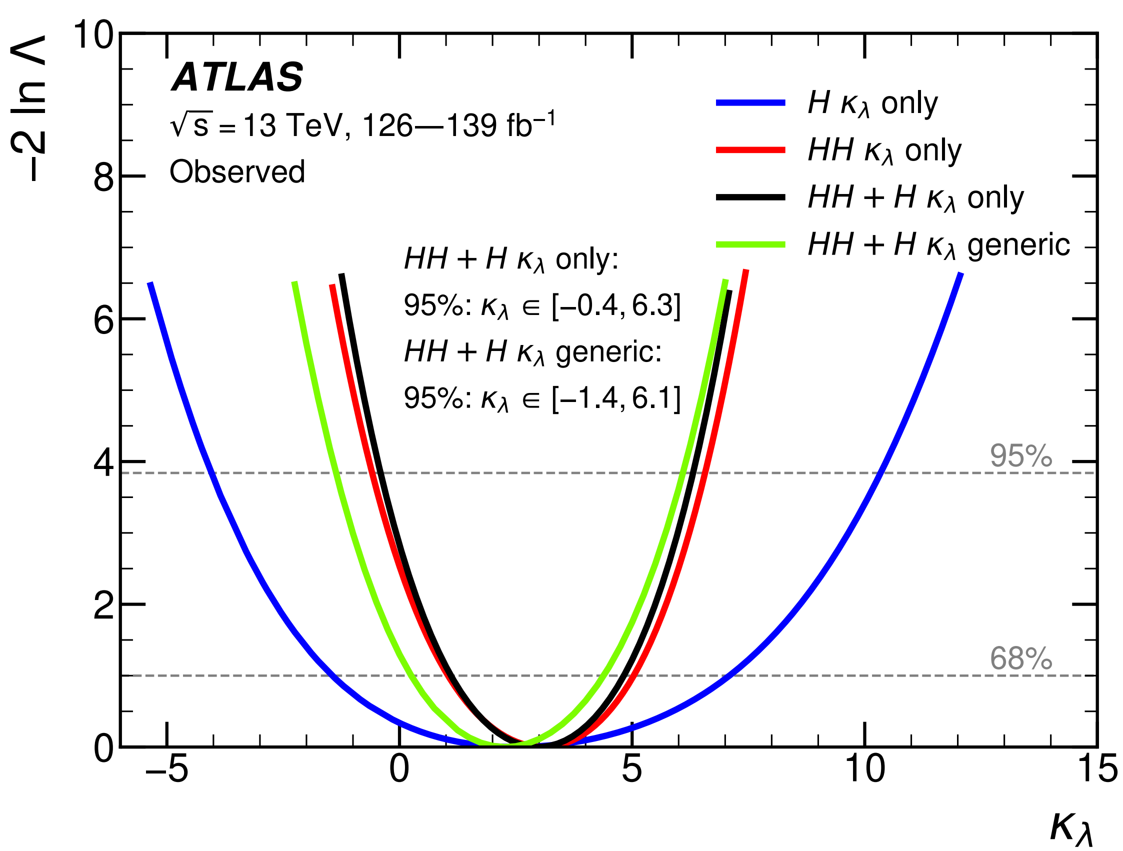


Single H and HH Constraints

Phys. Lett. B 843 (2023) 137745 (ATLAS)
HIG-23-006 (Submitted to Phys. Lett. B) (CMS)







- Single Higgs production constrains self-coupling
  - NLO electroweak corrections from self-coupling
  - Corrections affect:
    - Higgs cross-section
    - Branching fractions
    - Kinematics
  - Can be used to constrain κ_λ

- Wide selection of processes combined

- ATLAS: $-0.4 < \kappa_\lambda < 6.3$
- CMS: $-1.2 < \kappa_\lambda < 7.5$

The HL-LHC…

- The High-Luminosity LHC (HL-LHC) will:
  - Increase peak luminosity to 5-7.5x10^{34} $cm^{-2}s^{-1}$
  - Provide at least 3000fb^{-1} of data at 14TeV
  - Allow precision measurements of Higgs couplings and differential cross-sections
  - Provide access to rare decays and probes for New Physics

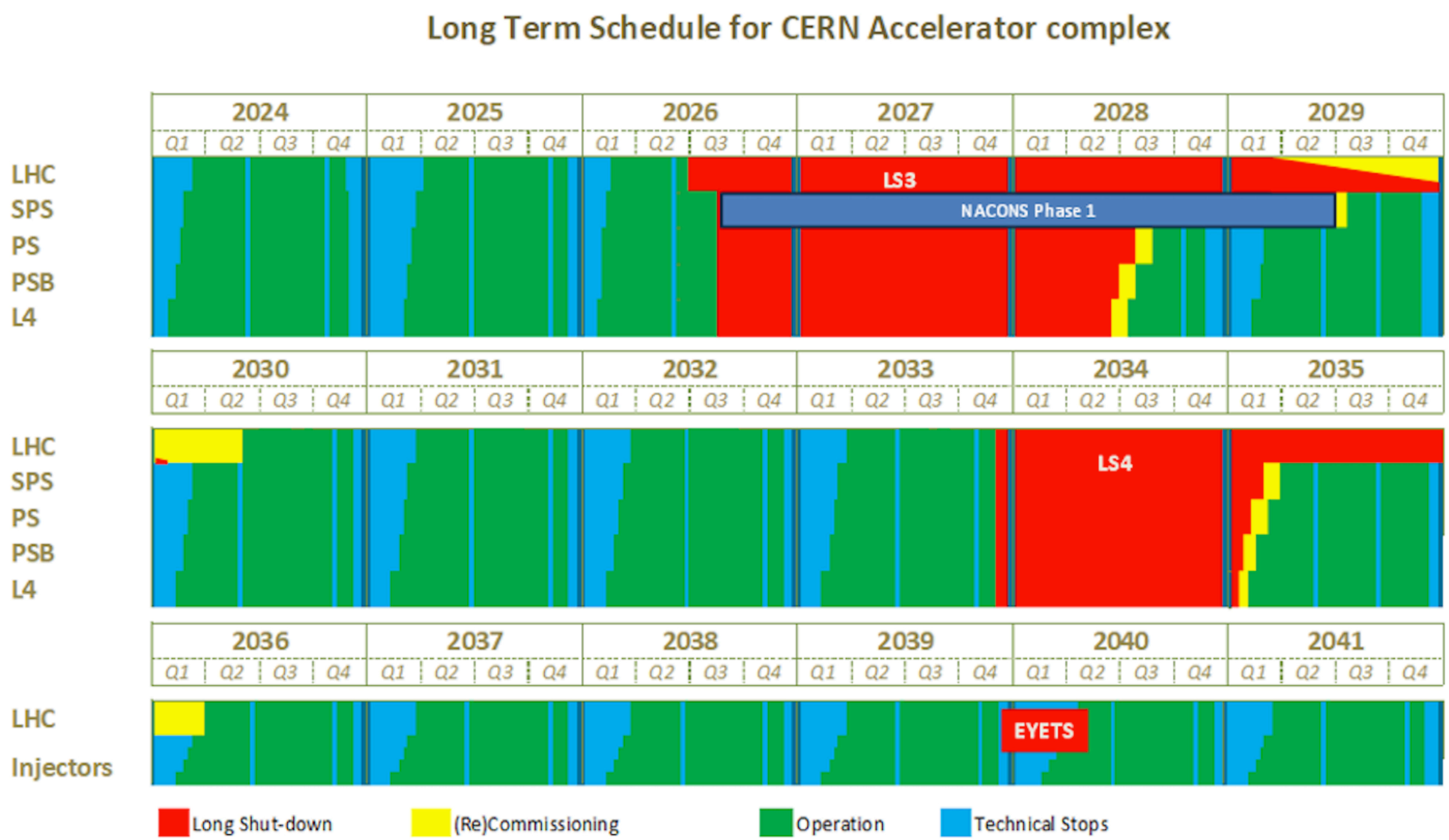


Image: Jean-Philippe Tock

Updated Schedule

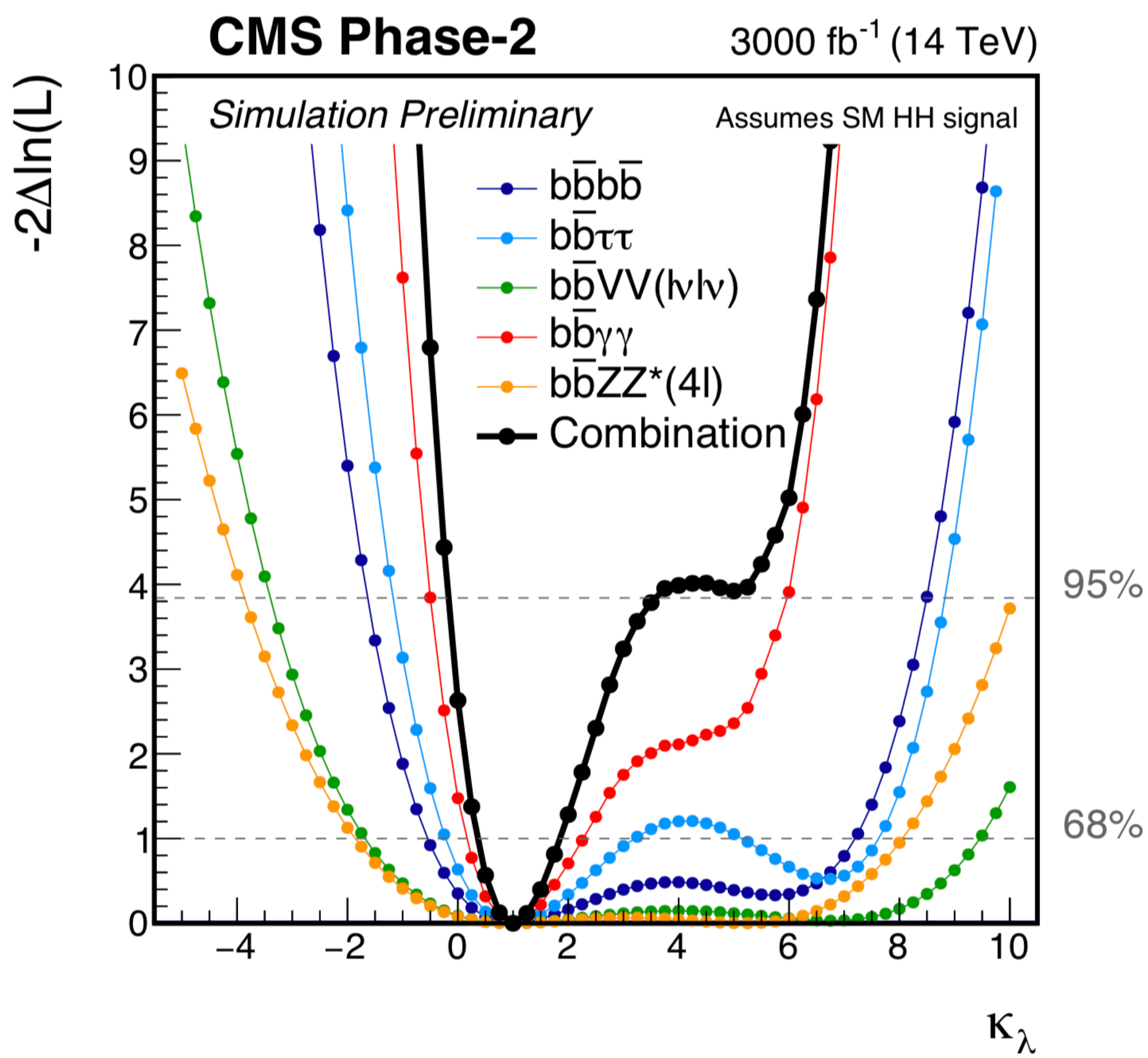
The HL-LHC: CMS prospects

- Initial prospects study performed in 2018
  - Based on best HH result available at that time

- Signals normalised to 14 TeV cross-section and luminosity
- Background yields scaled to 3000 fb^{-1}
- Parametric functions model upgraded detector response
- Assume theory/modelling & b-tagging 2x better, other objects are Run 2-like (conservative)

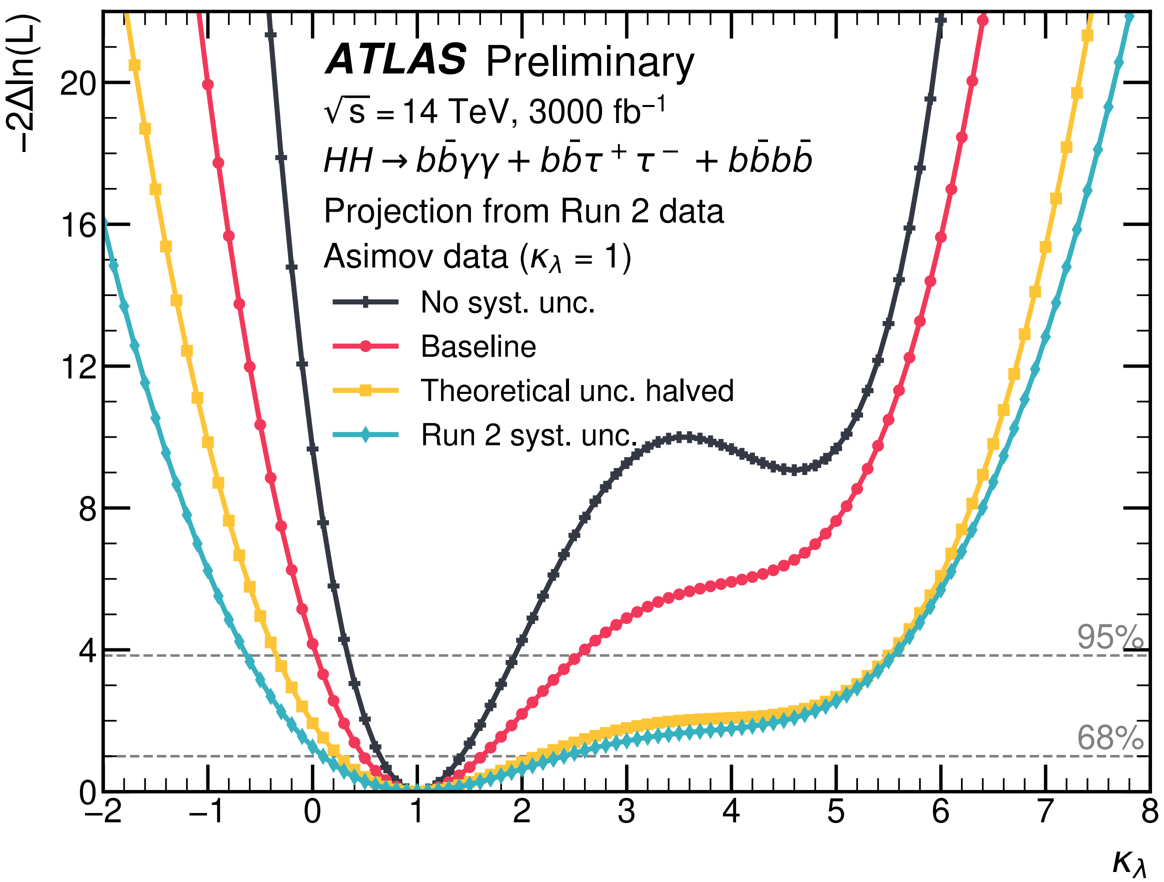
- Combination places constraints on κ_λ:
  - $0.35 < \kappa_\lambda < 1.9$ at 68% CL
  - $-0.18 < \kappa_\lambda < 3.6$ at 95% CL

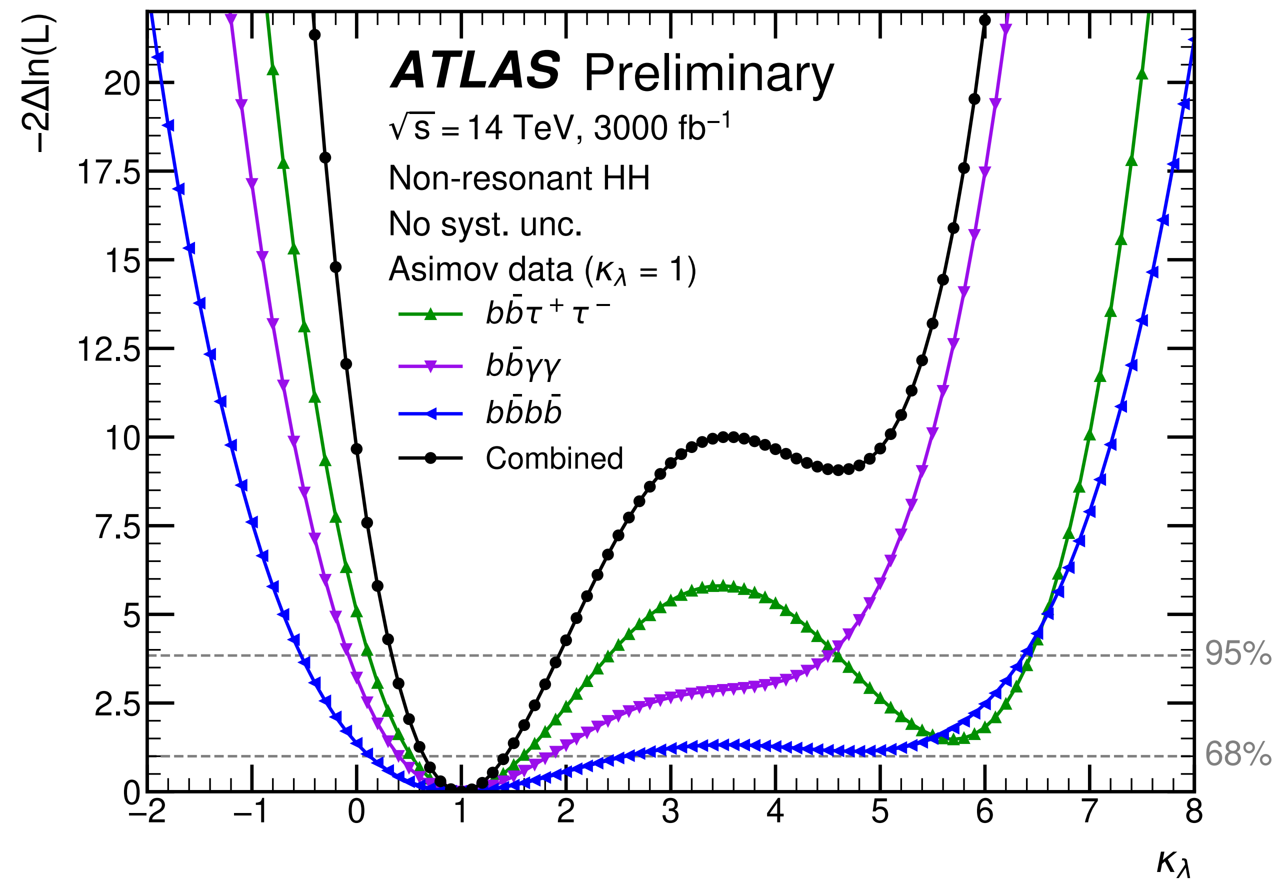
Channel	Significance		95% CL limit on $\sigma_{HH}/\sigma_{HH}^{SM}$	
	Stat. + syst.	Stat. only	Stat. + syst.	Stat. only
bbbb	0.95	1.2	2.1	1.6
bb$\tau\tau$	1.4	1.6	1.4	1.3
bbWW($\ell\nu\ell\nu$)	0.56	0.59	3.5	3.3
bb$\gamma\gamma$	1.8	1.8	1.1	1.1
bbZZ($\ell\ell\ell\ell$)	0.37	0.37	6.6	6.5
Combination	2.6	2.8	0.77	0.71



ATL-PHYS-PUB-2022-053, ATL-PHYS-PUB-2022-001, ATL-PHYS-PUB-2021-044

- Combination of bbbb + bbττ + bbγγ
  - Assume theory/modelling & b-tagging 2x better, other objects are Run 2-like (conservative)
  - HH discovery significance of 3.4σ; κ_λ constrained within [0.0, 2.5] at 95% CL
- Sensitivity driven by theoretical uncertainties on HH cross-section and:
  - b-tag performance in bbbb (potential improvement from ITk and better b-tagging)
  - background modelling uncertainty in bbγγ
  - additional heavy-flavour jet radiation in single Higgs background





Uncertainty scenario	Significance [σ] $b\bar{b}\gamma\gamma$	$b\bar{b}\tau^+\tau^-$	$b\bar{b}b\bar{b}$	Combination	Combined signal strength precision [%]
No syst. unc.	2.3	4.0	1.8	4.9	−21/+22
Baseline	2.2	2.8	0.99	3.4	−30/+33
Theoretical unc. halved	1.1	1.7	0.65	2.1	−47/+48
Run 2 syst. unc.	1.1	1.5	0.65	1.9	−53/+65

Uncertainty scenario	κ_λ 68% CI	κ_λ 95% CI
No syst. unc.	[0.7, 1.4]	[0.3, 1.9]
Baseline	[0.5, 1.6]	[0.0, 2.5]
Theoretical unc. halved	[0.3, 2.2]	[−0.3, 5.5]
Run 2 syst. unc.	[0.1, 2.4]	[−0.6, 5.6]

Summary

- Study of HH events provides unique experimental reconstruction of Higgs Potential

- HH events are rare process
  - No observation yet!
  - Cross-section of 33 fb means ~4600 SM events in Run 2 dataset
  - Requires highly efficient analyses from ATLAS and CMS

- Combinations with Single H events can further constrain Higgs potential

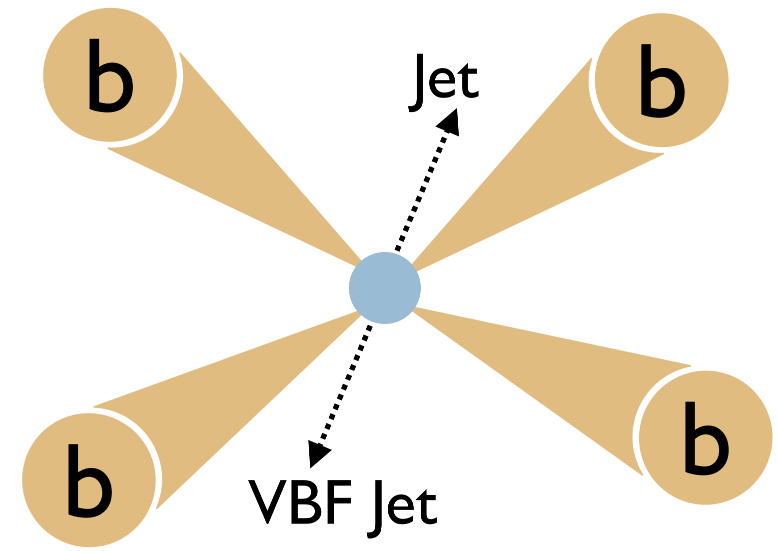
- Best constraints on HH cross-section:
  - ATLAS: $\mu_{HH} < 2.9$ (2.4 exp)
  - CMS: $\mu_{HH} < 3.4$ (2.5 exp)

- Best constraints on Higgs self-coupling:
  - ATLAS: $-1.2 < \kappa_\lambda < 7.2$ ($-1.6 < \kappa_\lambda < 7.2$ exp)
  - CMS: $-1.24 < \kappa_\lambda < 6.49$

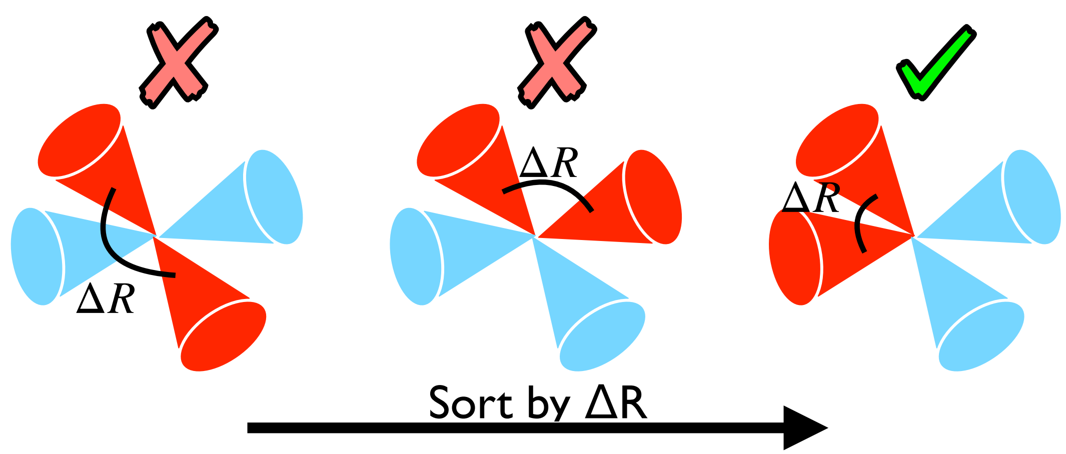
- Exciting prospects for future analyses!

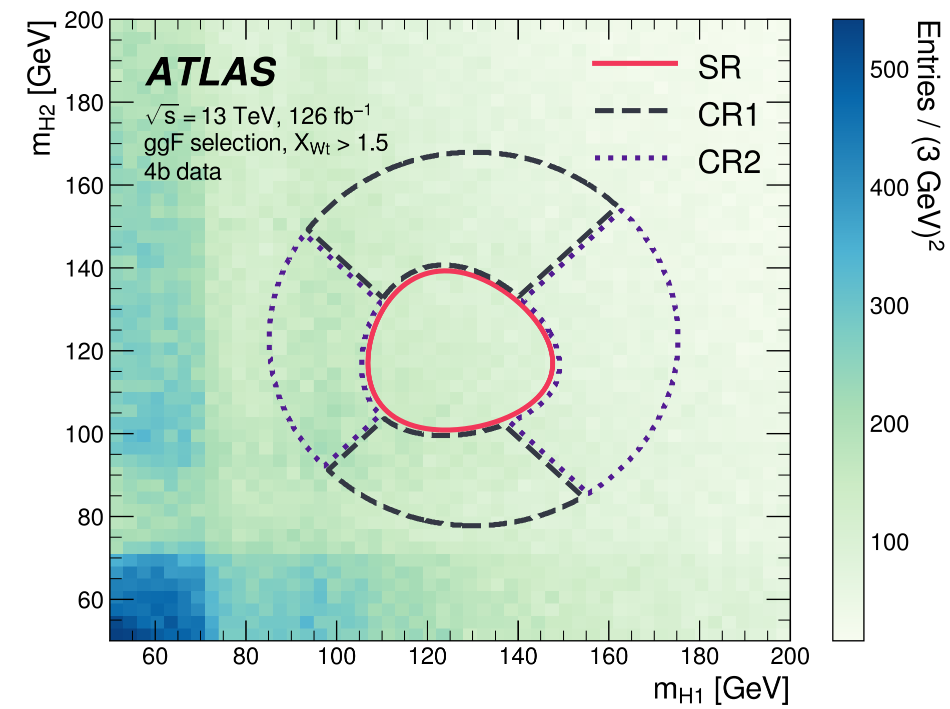
Backup

- Event selection:
  - b-jet trigger
  - ≥ 4 b-jets with p_T > 40 GeV
  - $|\Delta\eta_{HH}| < 1.5$
  - Veto Top-quark decay



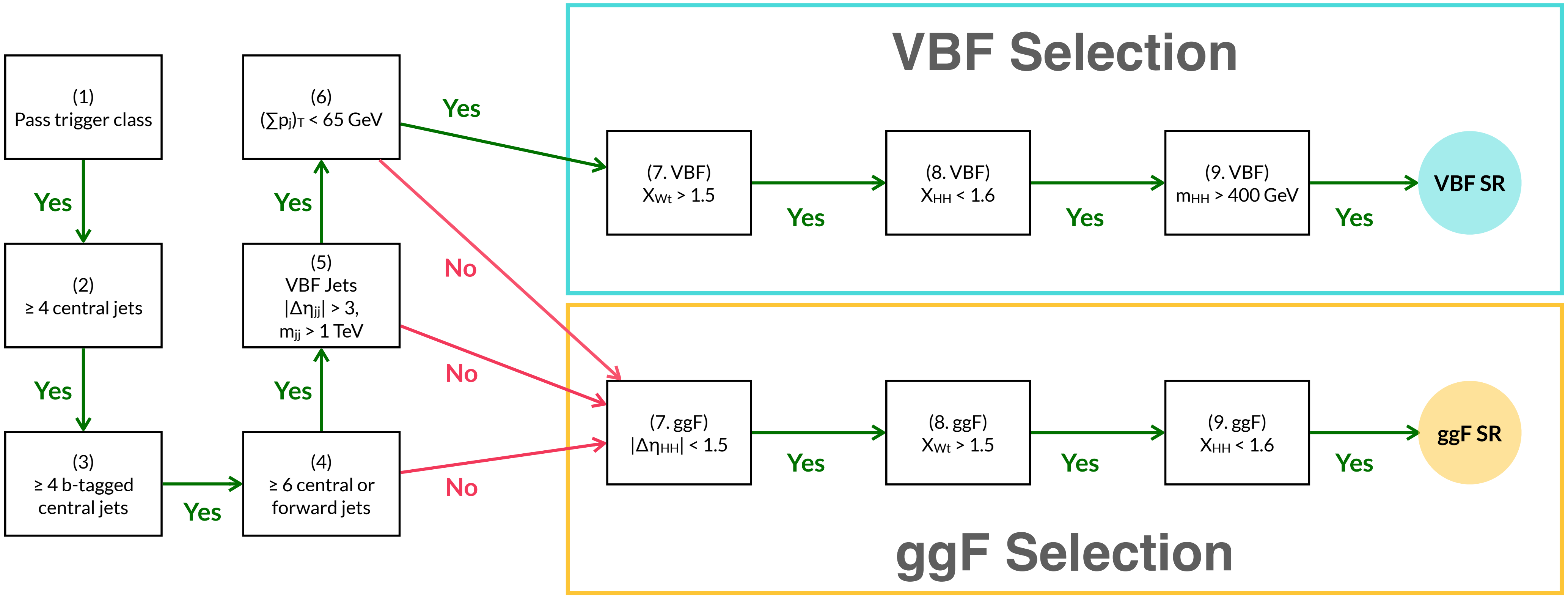
- Higgs reconstructed by minimising ΔR_{jj} in leading Higgs (H_1)
  - No mass information used - avoids sculpting H_1-H_2 mass plane





- Categories based on $|\Delta\eta_{HH}|$ and X_{HH}:
  - $X_{HH} = \sqrt{\left(\frac{m_{H1} - 124\text{ GeV}}{0.1 m_{H1}}\right)^2 + \left(\frac{m_{H2} - 117\text{ GeV}}{0.1 m_H 2}\right)^2}$
- VBF categories also require:
  - $|\Delta\eta_{jj}| > 3$ and $m_{jj} > 1$ TeV

Cutflow

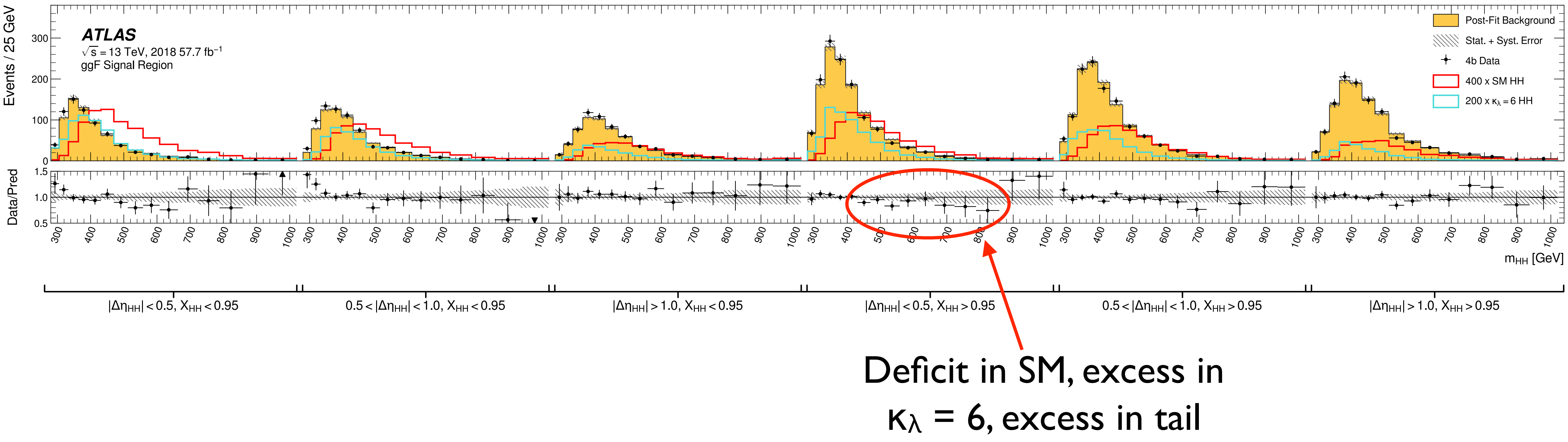


	Data	ggF Signal SM	ggF Signal $\kappa_\lambda = 10$	VBF Signal SM	VBF Signal $\kappa_{2V} = 0$
Common preselection					
Preselection	5.70×10^8	530	7300	22	630
Trigger class	2.49×10^8	380	5300	16	410
ggF selection					
Fail VBF selection	2.46×10^8	380	5200	14	330
At least 4 *b*-tagged central jets	1.89×10^6	86	1000	1.9	65
$\lvert\Delta\eta_{HH}\rvert < 1.5$	1.03×10^6	72	850	0.94	46
$X_{Wt} > 1.5$	7.51×10^5	60	570	0.74	43
$X_{HH} < 1.6$ (ggF signal region)	1.62×10^4	29	180	0.24	23
VBF selection					
Pass VBF selection	3.30×10^6	5.2	81	2.2	71
At least 4 *b*-tagged central jets	2.71×10^4	1.1	15	0.74	28
$X_{Wt} > 1.5$	2.18×10^4	1.0	11	0.67	26
$X_{HH} < 1.6$	5.02×10^2	0.48	3.1	0.33	17
$m_{HH} > 400$ GeV (VBF signal region)	3.57×10^2	0.43	1.8	0.30	16

HH→bbbb (Resolved) (ATLAS)

Phys. Rev. D 108 (2023) 052003 (Resolved)

Discriminant

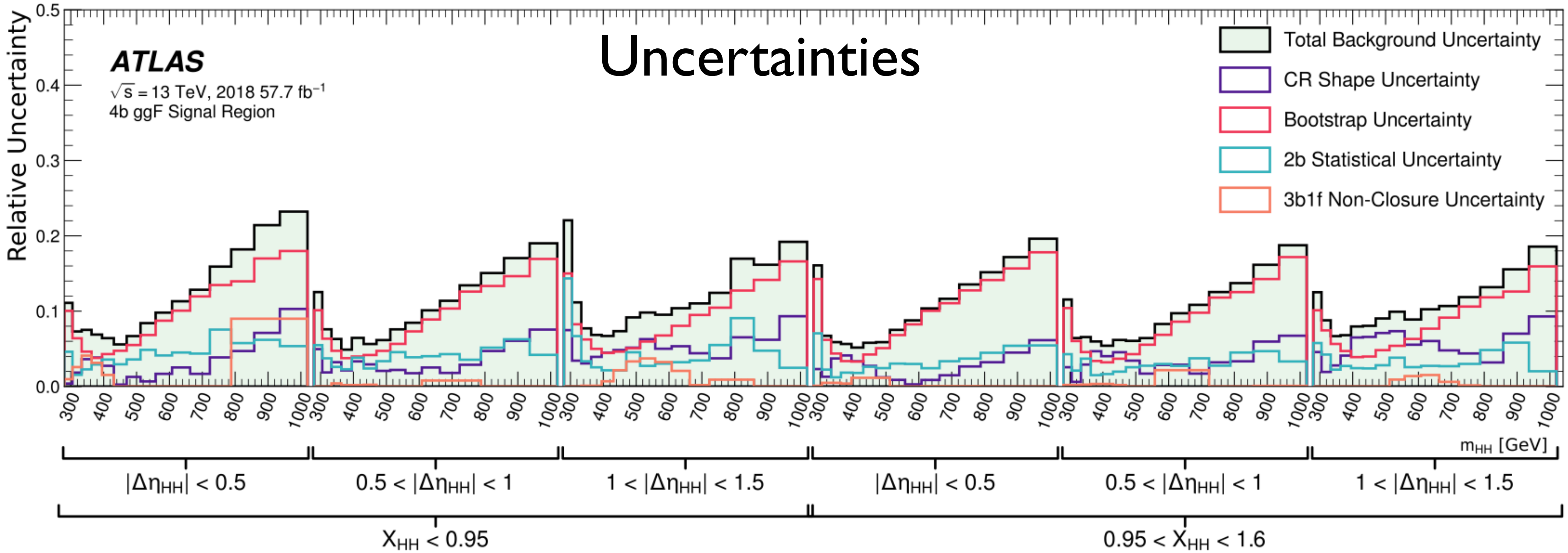


Category	Data	Expected Background	ggF Signal SM	VBF Signal SM
ggF signal region				
$\lvert\Delta\eta_{HH}\rvert < 0.5$, $X_{HH} < 0.95$	1940	1935 ± 25	7.0	0.038
$\lvert\Delta\eta_{HH}\rvert < 0.5$, $X_{HH} > 0.95$	3602	3618 ± 37	6.5	0.036
$0.5 < \lvert\Delta\eta_{HH}\rvert < 1.0$, $X_{HH} < 0.95$	1924	1874 ± 21	5.1	0.037
$0.5 < \lvert\Delta\eta_{HH}\rvert < 1.0$, $X_{HH} > 0.95$	3540	3492 ± 35	4.7	0.040
$\lvert\Delta\eta_{HH}\rvert > 1.0$, $X_{HH} < 0.95$	1880	1739 ± 22	2.9	0.043
$\lvert\Delta\eta_{HH}\rvert > 1.0$, $X_{HH} > 0.95$	3285	3212 ± 37	2.8	0.041
VBF signal region				
$\lvert\Delta\eta_{HH}\rvert < 1.5$	116	125.3 ± 4.4	0.37	0.090
$\lvert\Delta\eta_{HH}\rvert > 1.5$	241	230.6 ± 5.3	0.06	0.21

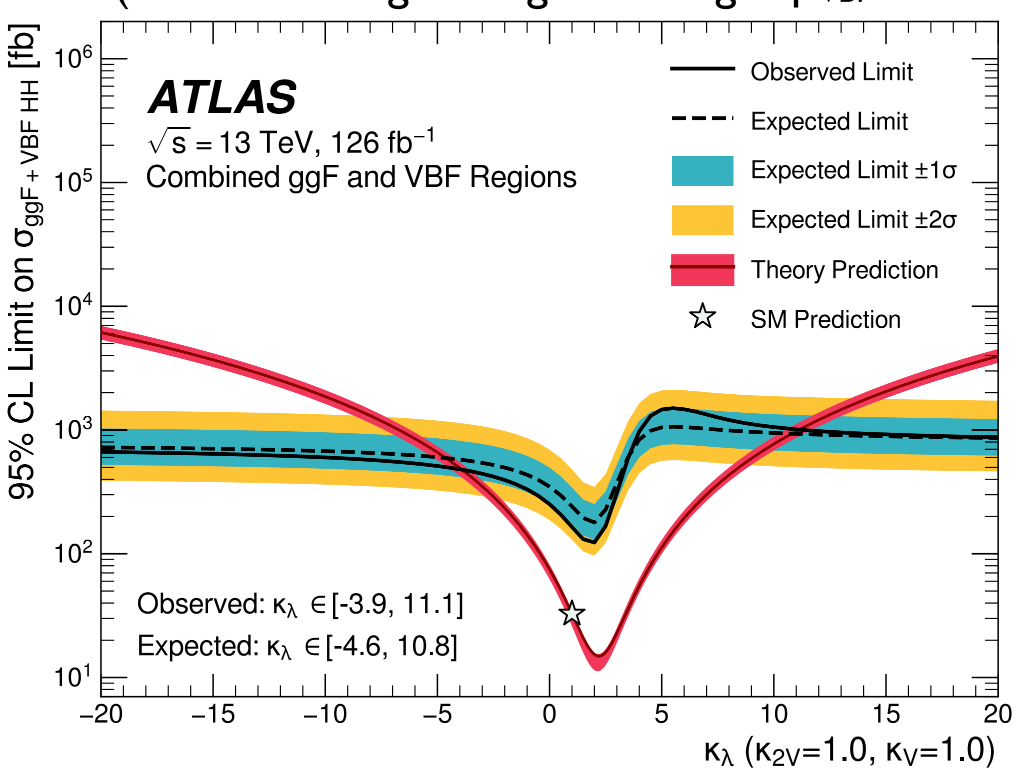
Source of Uncertainty	$\Delta\mu/\mu$
Theory uncertainties	
Theory uncertainty in signal cross-section	−9.0%
All other theory uncertainties	−1.4%
Background modeling uncertainties	
Bootstrap uncertainty	−7.1%
CR to SR extrapolation uncertainty	−7.5%
3b1f nonclosure uncertainty	−2.0%

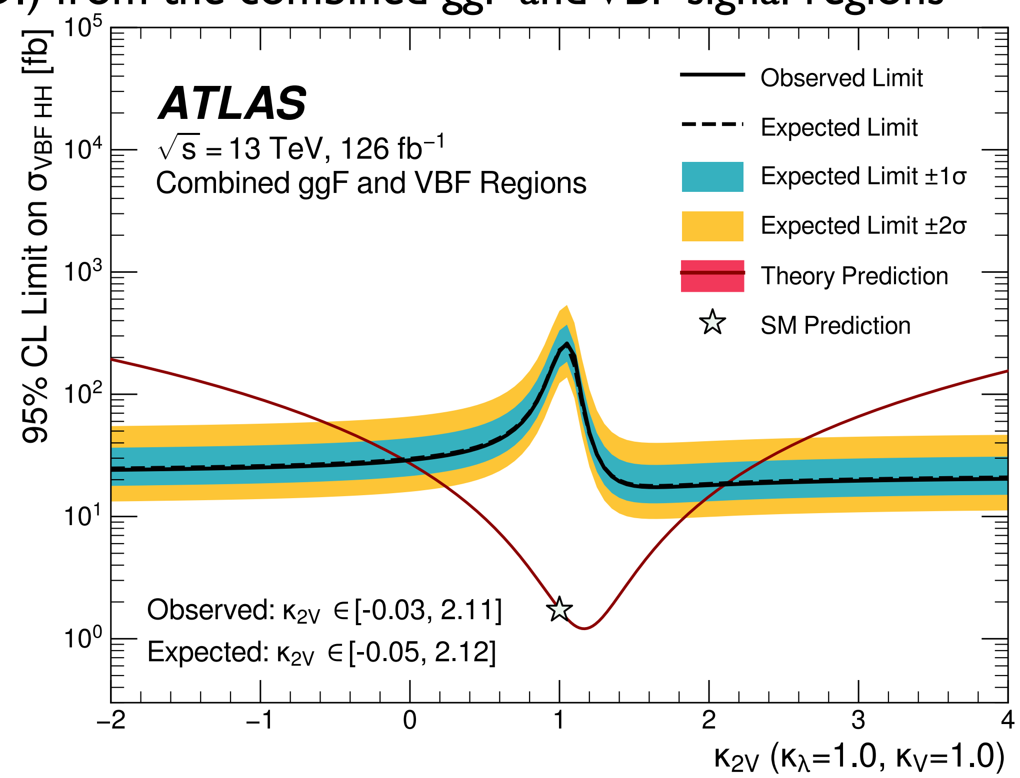
HH→bbbb (Resolved) (ATLAS)

Phys. Rev. D 108 (2023) 052003 (Resolved)



95% CL exclusion limits as a function of κ_λ (obtained using the signal strength $\mu_{ggF+VBF}$ as the POI) and (b) κ_{2V} (obtained using the signal strength μ_{VBF} as the POI) from the combined ggF and VBF signal regions

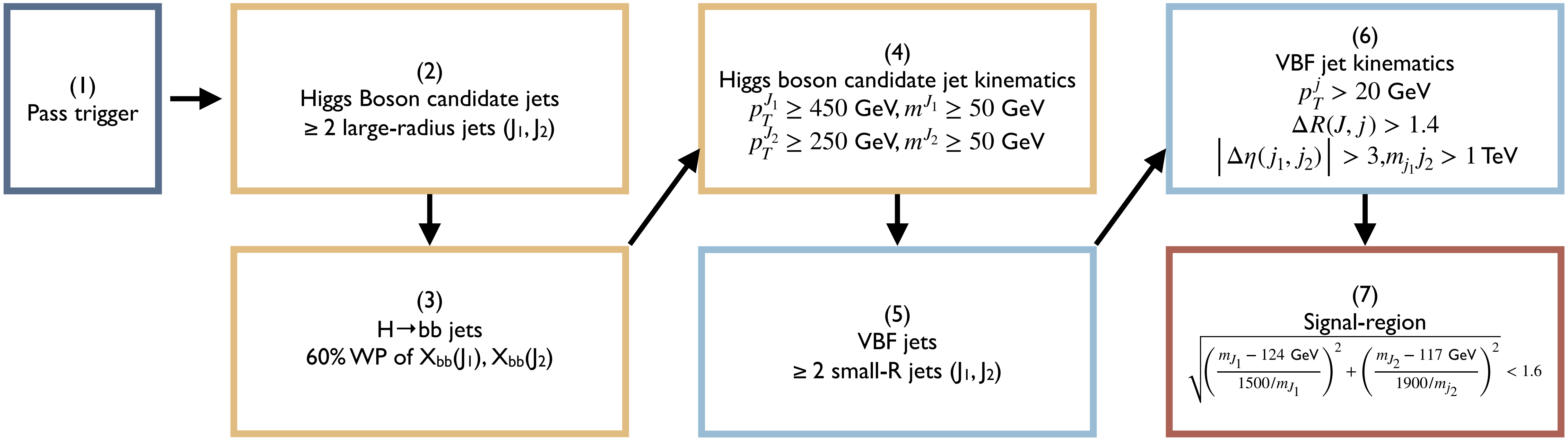




HH→bbbb (Boosted) (ATLAS)

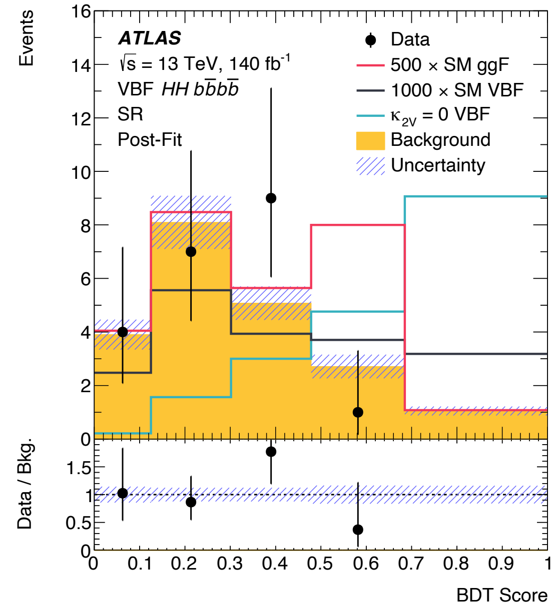
Phys. Lett. B 858 (2024) 139007 (Boosted)

Cutflow

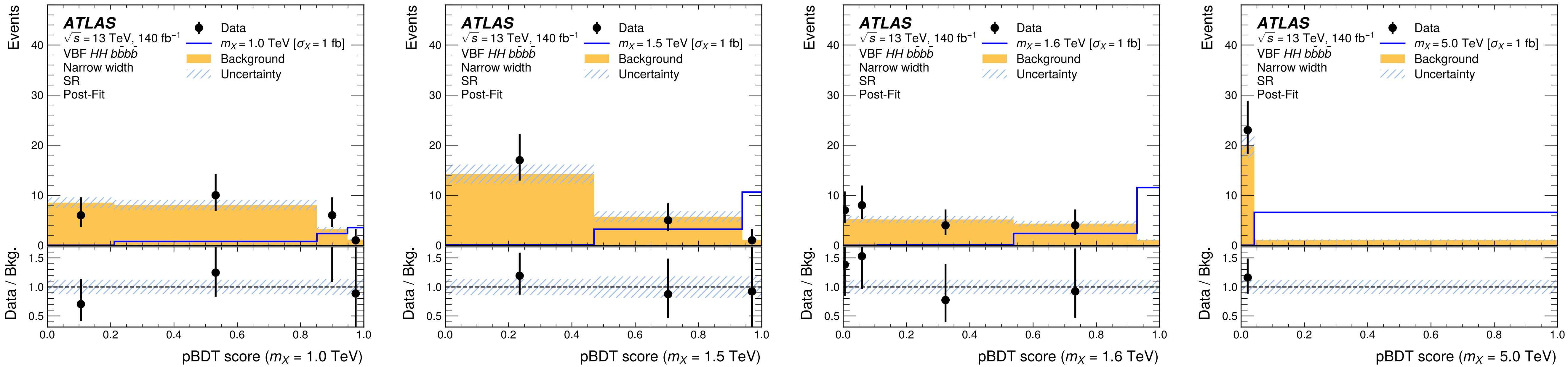


Selection	Data	Nonresonant SM ggF	Nonresonant VBF $(\kappa_\lambda, \kappa_{2V}, \kappa_V) =$ (1, 1, 1)	(1, 0, 1)	Spin-0 resonant VBF Narrow-width m_X 1.00 TeV	5.00 TeV
Raw events	16 854 036 422	1480	82.0	1290	140	140
Trigger & upstream selection	63 944 638	20.9	1.15	235	70.7	126
$\geq$ 2 large-R jets (η, m)	57 510 800	14.1	0.531	168	48.7	119
Double b-tagging	12 875	5.35	0.131	77.4	25.2	24.9
$\geq$ 2 small-R jets	5762	2.24	0.105	57.2	18.8	16.0
Large-R jets (p_{T})	3902	1.41	0.0700	48.3	13.7	16.0
Small-R jets $(\Delta\eta(j, j), m_{jj})$	314	0.148	0.0380	32.3	8.58	12.0
Signal region	23	0.0970	0.0290	24.5	6.68	6.59
Veto resolved selection	21	0.0590	0.0200	18.8	-	-

Discriminant



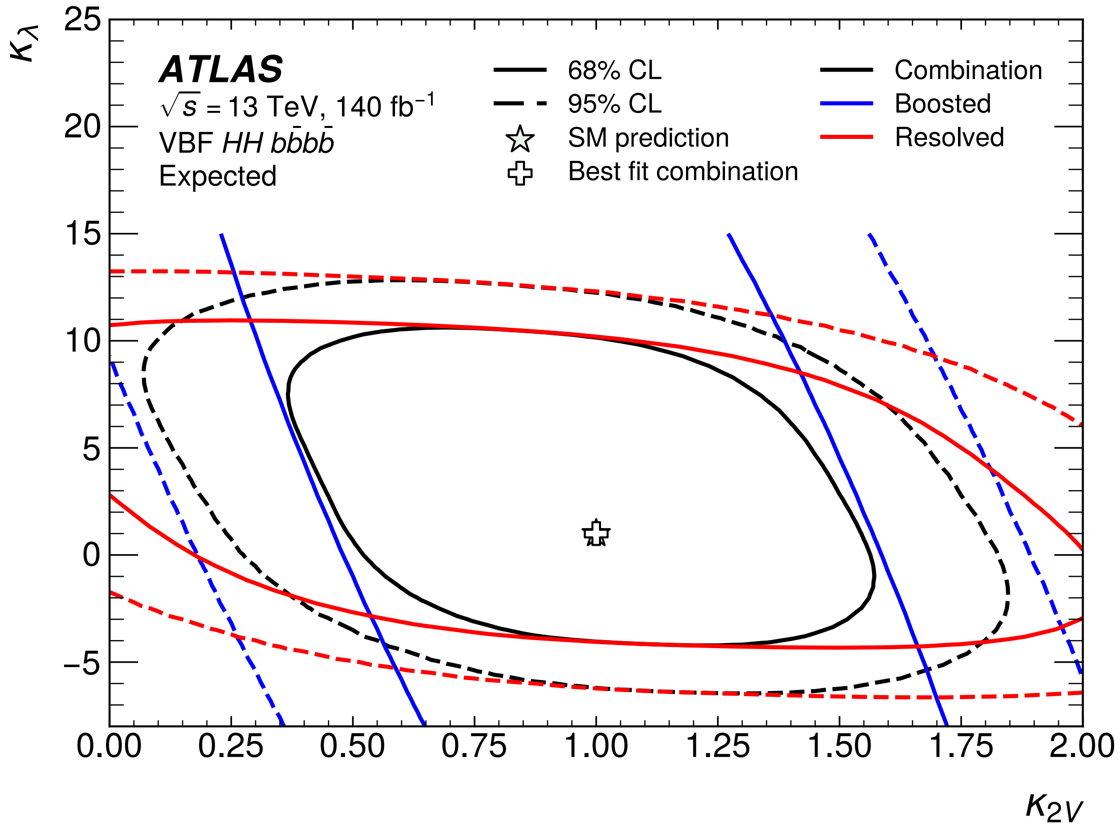
Non-resonant

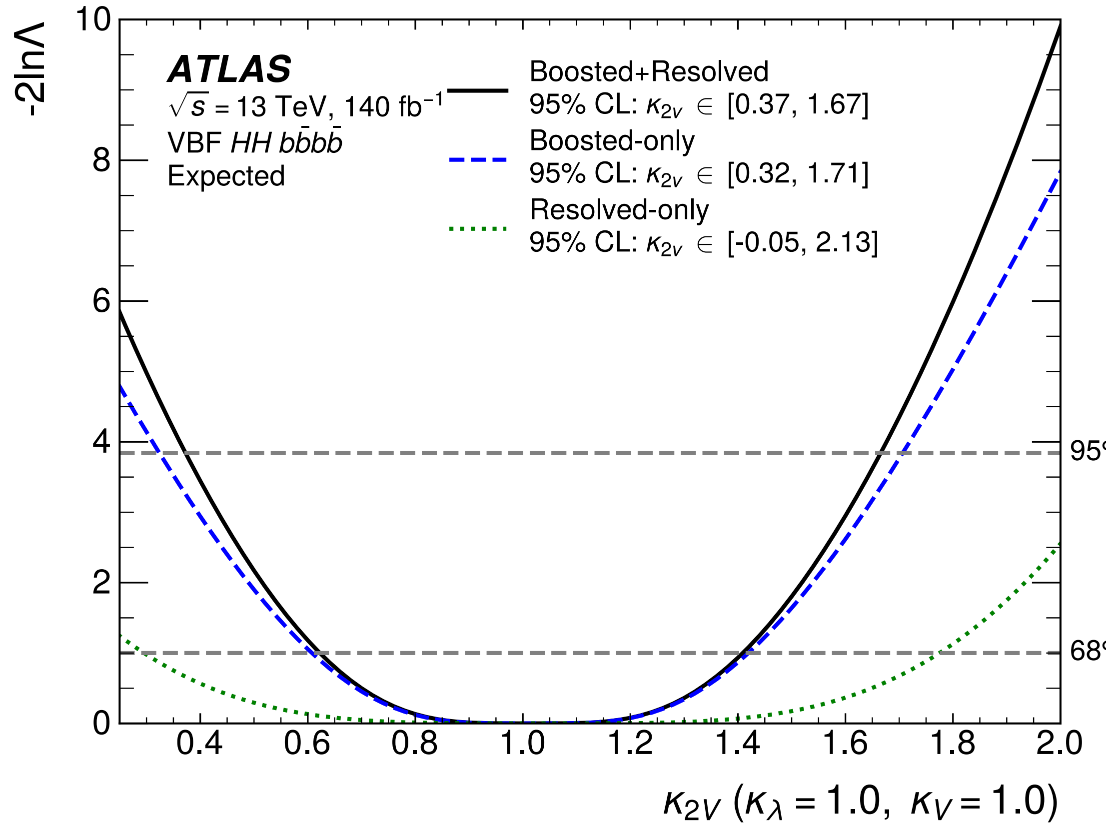


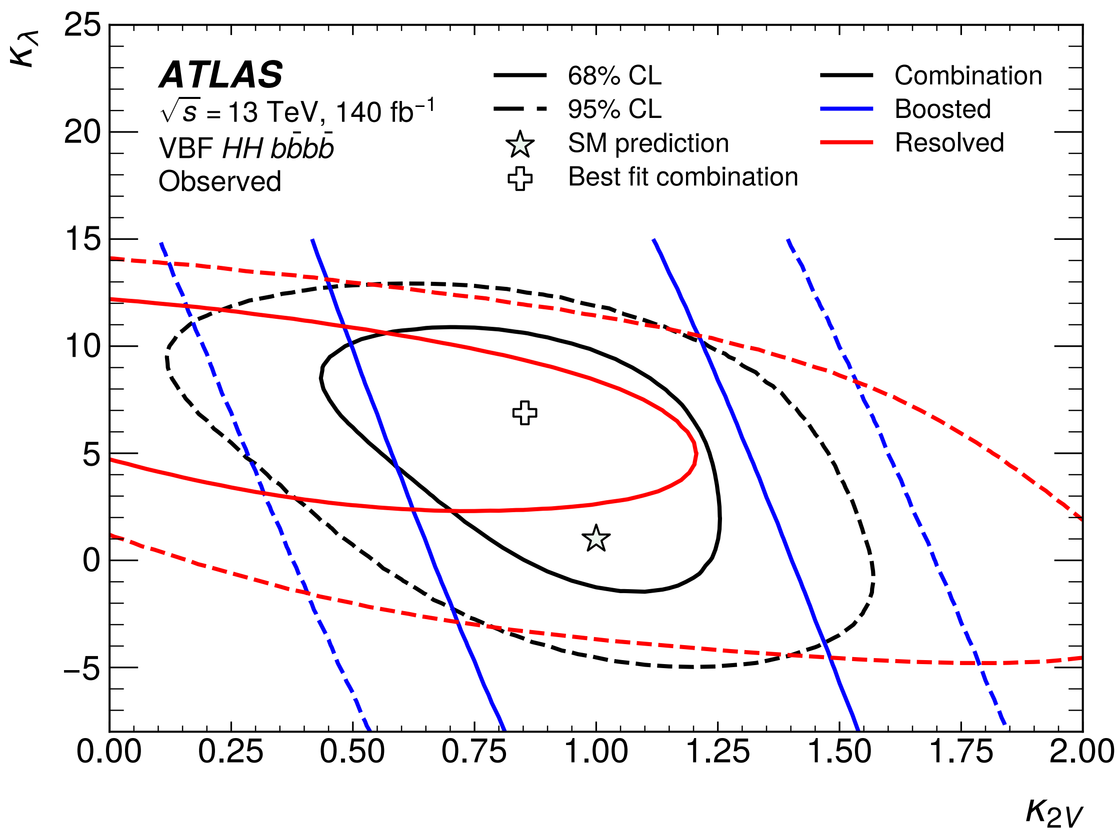
Resonant parameterised BDT

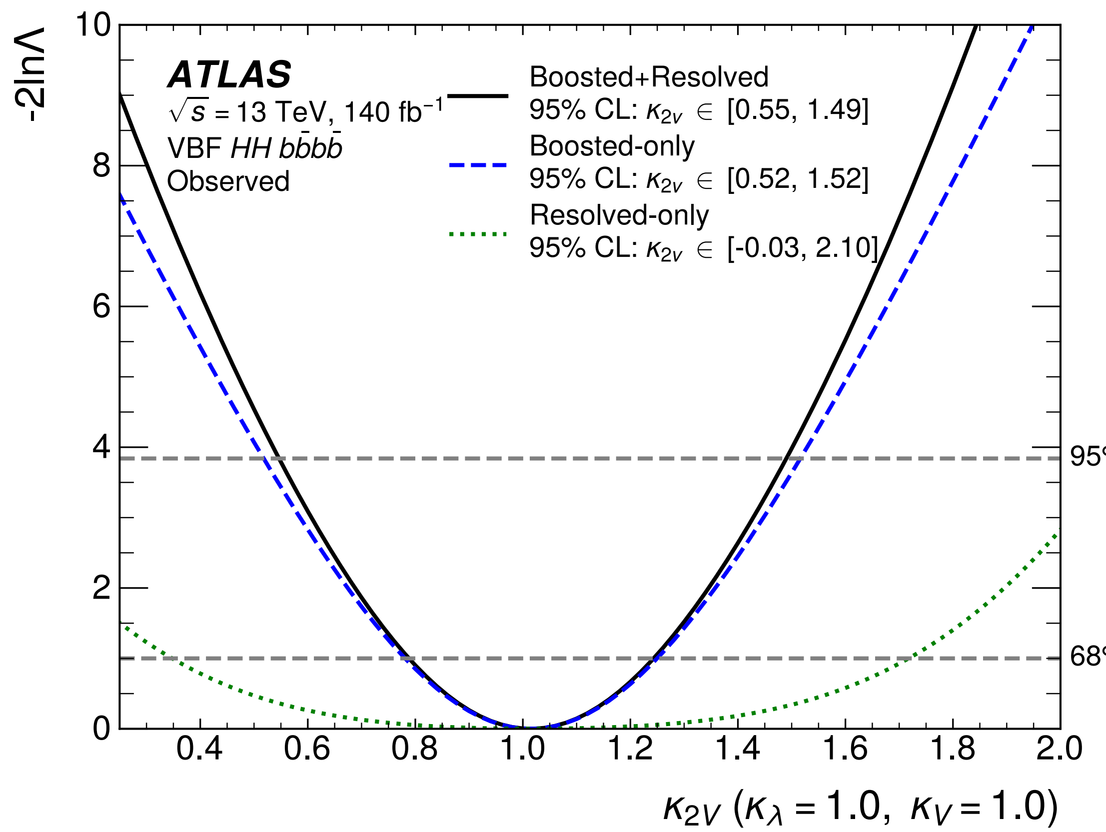
HH→bbbb (Boosted) (ATLAS)

Phys. Lett. B 858 (2024) 139007 (Boosted)

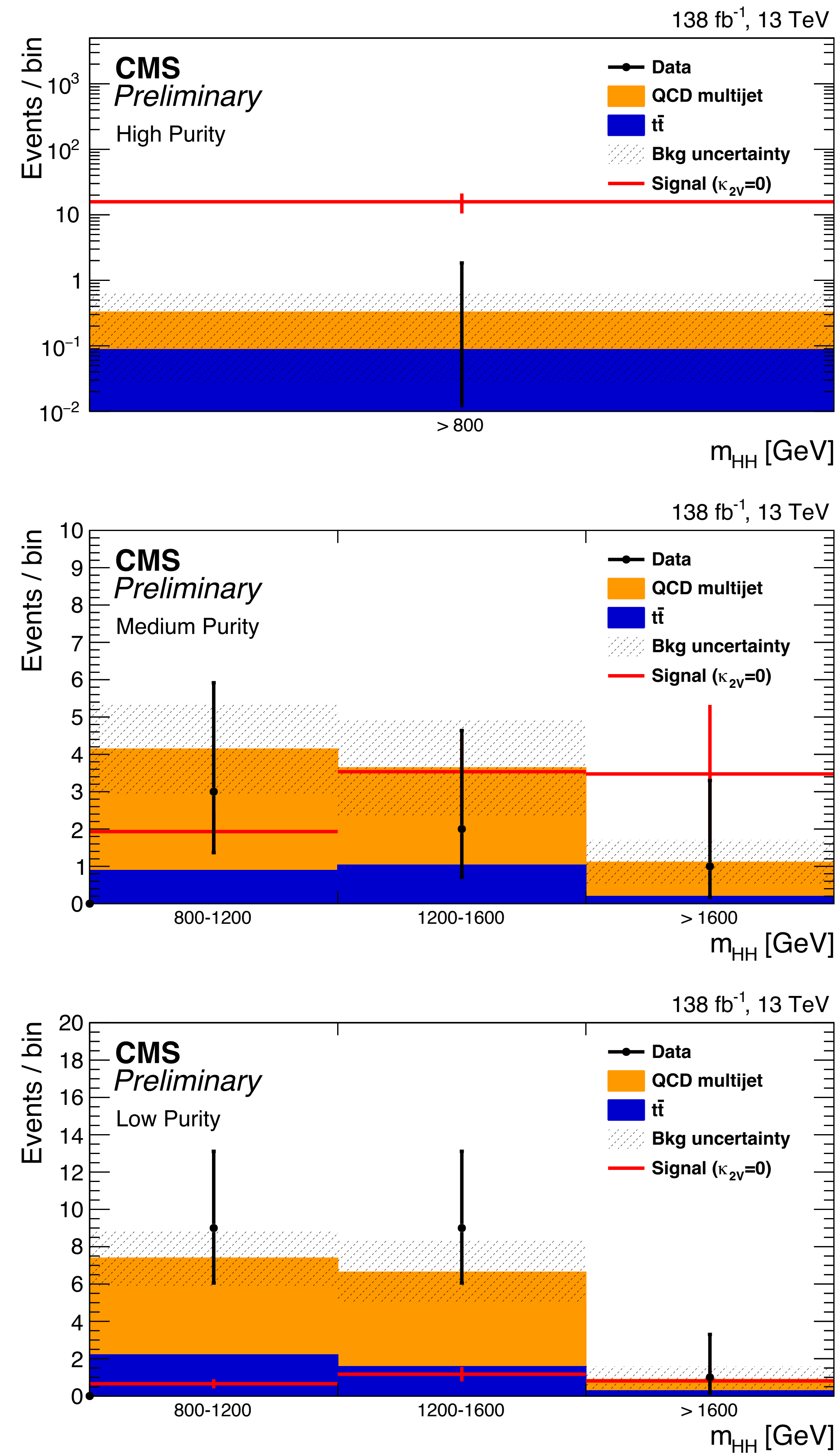








The distributions of the invariant mass of the HH system after a background-only fit to the data, for the high-purity (upper), medium-purity (middle), and low-purity (lower) categories.



Event Selection

Trigger	Combination of H_T and single-jet triggers
Higgs boson candidates	≥ 2 large-radius jets with $\lvert\eta\rvert < 2.4$ $p_T^{lead} > 500$ GeV, $p_T^{subl} > 400$ GeV $\Delta\phi > 2.6$, $\Delta\eta < 2.0$
Lepton veto	$N_e = 0$, $N_\mu = 0$
$H \to b\bar{b}$ identification with ParticleNet	Three exclusive search categories based on D_{bb} working points: high purity (HP), medium purity (MP) and low purity (LP)
VBF selections	≥ 2 small-radius jets with $p_T > 25$ GeV, $\lvert\eta\rvert < 4.7$ $m_{jj} > 500$ GeV, $\Delta\eta_{jj} > 4.0$
Signal mass range	$110 < m^{lead} < 150$ GeV, $100 < m^{subl} < 145$ GeV

BDT training variables

Variable	0L Vhh	0L VH	0L $A \to ZH$	1L Vhh	1L VH	2L Vhh	2L VH	2L $A \to ZH$
	Channel and signal model							
$m_{h_1} + m_{h_2}$	✓	✓	✓	✓	✓	✓	✓	✓
$m_{h_1} - m_{h_2}$	✓	✓	✓	✓	✓	✓	✓	✓
N_{jets}	✓	✓	✓	✓	✓	✓	✓	✓
H_{T}^{ex}	✓	✓	✓	✓	✓	✓	✓	✓
$\sum s_{b\text{-tag}}^{\text{pc}}$	✓	✓	✓	✓	✓	✓	✓	✓
$m_{h_1}^{\text{FSR}}$	✓	✓	✓	✓	✓	✓	✓	✓
$m_{h_2}^{\text{FSR}}$	✓	✓	✓	✓	✓	✓	✓	✓
m_{hh}	✓			✓		✓		
p_{T}^{hh}	✓	✓		✓	✓	✓	✓	
$E_{\text{T}}^{\text{miss}}$	✓	✓		✓	✓	✓	✓	✓
p_{T}^{V}				✓	✓	✓	✓	
m_{T}^{W}				✓				
$\cosh(\Delta\eta)_1 - \cos(\Delta\phi)_1$	✓	✓		✓	✓	✓	✓	
$\cosh(\Delta\eta)_2 - \cos(\Delta\phi)_2$	✓	✓		✓	✓	✓	✓	
$\lvert y_{h_1} - y_{h_2} \rvert$	✓	✓		✓	✓	✓	✓	
$\lvert y_V - y_{hh} \rvert$						✓	✓	

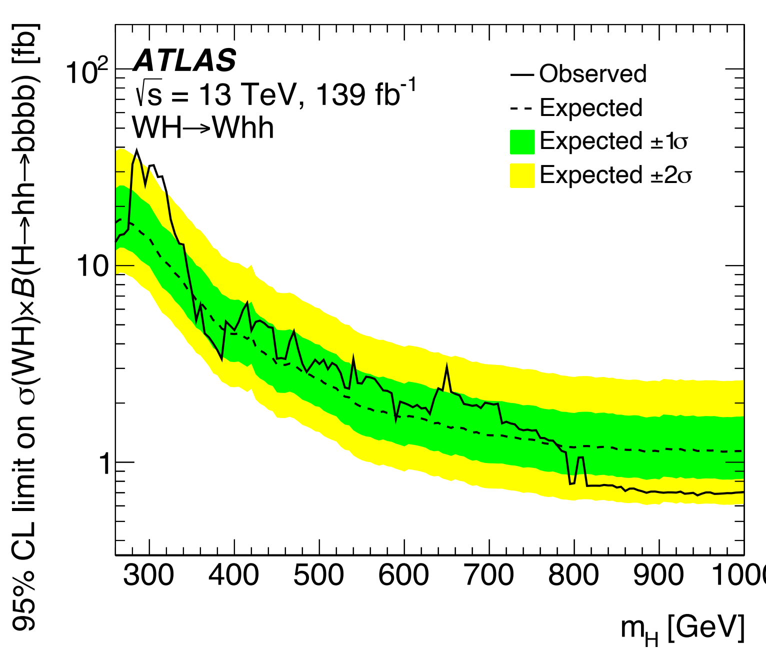
Selection criteria

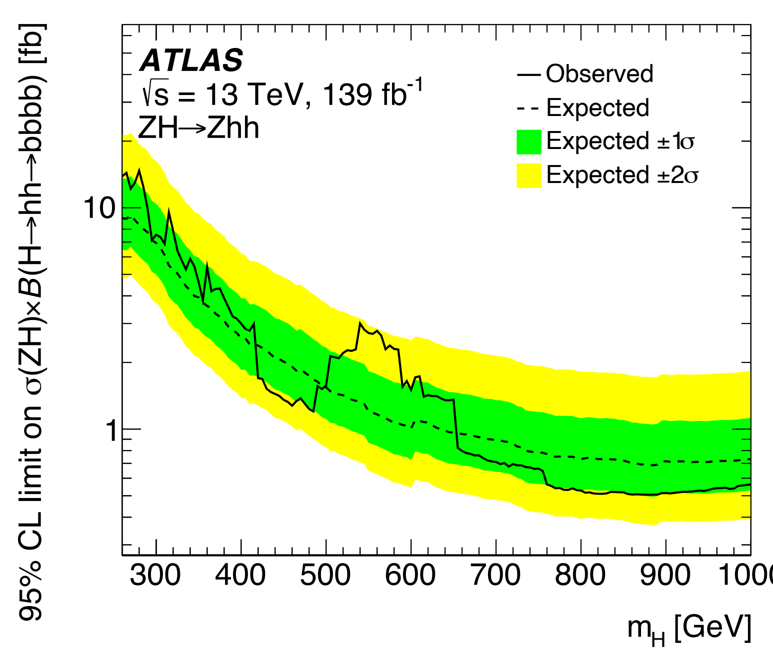
	Signal regions: 0L	Signal regions: 1L (1L+/1L−)	Signal regions: 2L	Control regions: $t\bar{t}$	Control regions: V + jets
Trigger	$E_{\text{T}}^{\text{miss}}$	single-lepton	single-lepton	single-lepton	single-photon
Lepton or photon	0 *loose* leptons, 0 identified τ_h	= 1 *tight* electron with $p_{\text{T}} > 27$ GeV OR 1 *medium* muon with $p_{\text{T}} > 25$ GeV, 0 additional *loose* leptons, 0 identified τ_h	= 2 *loose* leptons (e^+e^- or $\mu^+\mu^-$), ≥ 1 lepton with $p_{\text{T}} > 27$ GeV, $81 < m_{\ell\ell} < 101$ GeV	= 2 *loose* leptons ($e^{\pm}\mu^{\mp}$), ≥ 1 lepton with $p_{\text{T}} > 27$ GeV	= 1 photon with $p_{\text{T}} > 150$ GeV, 0 *loose* leptons, 0 identified τ_h
$p_{\text{T}}^{\text{miss}}$	$E_{\text{T}}^{\text{miss}} > 150$ GeV, $S(E_{\text{T}}^{\text{miss}}) > 12$, $\lvert\Delta\phi(\boldsymbol{p}_{\text{T}}^{\text{miss}}, h)\rvert > 1$	$E_{\text{T}}^{\text{miss}} > 30$ GeV	—	—	—
Jets	≥ 4 jets with $p_{\text{T}} > 20$ GeV and passing the 85% b-tagging WP				

Dominant uncertainties

Model	Vhh like in SM	WH	ZH	NW $A \to ZH$	LW $A \to ZH$
Systematic uncertainty source	$\Delta\mu/\mu$ [%]				
Background modelling	+20, −15	+14, −11	+4.7, −3.0	+17, −13	+20, −18
MC statistics	+12, −9.1	+13, −7.8	+4.8, −2.2	+7.2, −4.1	+10, −8.3
Objects	+12, −8.6	+8.0, −5.2	+4.5, −2.2	+19, −11	+16, −12
Signal modelling	+10, −4.7	+12, −4.9	+8.6, −3.0	+14, −5.1	+17, −7.6
VR non-closure	+14, −11	+11, −9.4	+4.4, −3.0	+4.9, −3.7	+12, −10
Total systematic uncertainty	+30, −22	+27, −18	+12, −5.8	+30, −18	+33, −24
Statistical uncertainty	+44, −39	+52, −43	+68, −49	+59, −47	+42, −37
Total	+52, −44	+59, −47	+69, −49	+66, −50	+53, −45

Observed/expected 95% CL upper limits on the production cross-section at √s=13 TeV of a heavy narrow scalar resonance H in the decay mode H→ hh→ bbbb in association with (left) a W boson and (right) a Z boson





BDT training variables

Input variable	$BDT_{Cat.}$ MET/1L	FH	BDT_{SvB} MET (S)	1L (S)	MET/1L (L)	Input variable	$BDT_{Cat.}$ 2L	BDT_{SvB} 2L
$p_T(V)$, $p_T(H_1)$	✓	✓	✓	✓	✓	$p_T(V)$, $p_T(H_1)$	✓	✓
$p_T(H_2)$, $p_T(HH)$	✓		✓	✓	✓	m_{HH}	✓	✓
m_{H_1}, m_{H_2}	✓		✓	✓	✓	$\Delta R(H_1, H_2)$	✓	✓
m_{HH}	✓	✓	✓	✓	✓	$\Delta\phi(V, H_2)$	✓	✓
$\Delta R(H_1, H_2)$	✓	✓				$p_T(H_2)/p_T(H_1)$	✓	
$\Delta\phi(V, H_2)$	✓	✓	✓	✓	✓	$p_T(HH)$		✓
$p_T(H_2)/p_T(H_1)$	✓	✓				m_{H_1}, m_V		✓
$\Delta\eta(H_1, H_2)$	✓	✓	✓			$\Delta\eta(H_1, H_2)$		✓
$\Delta\phi(H_1, H_2)$	✓	✓	✓	✓	✓	Energy of H_1		✓
Energy of H_1	✓	✓				Energy of HH		✓
Energy of H_2	✓	✓				$p_T(\ell_2)/p_T(\ell_1)$	✓	✓
Energy of HH	✓	✓				$\Delta\phi(\ell_1, \ell_2)$	✓	✓
η_{HH}	✓	✓				$\Delta\eta(\ell_1, \ell_2)$	✓	✓
η_{H_1}		✓	✓			$\Delta R(j_{1,H_2}, j_{2,H_2})$	✓	
$\phi(V)$			✓	✓	✓	$\Delta R(j_{1,H_1}, j_{2,H_1})$	✓	
$s_{b\text{-tag}}(j_{1,2,3,4})$			✓	✓		$p_T(\ell_1)/m_V$	✓	
H_T^{ex}			✓			$p_T(\ell_1)$	✓	
N_{jets}			✓			$p_T(j_{3,4})$		✓
$\tau_2/\tau_1(H_1, H_2)$					✓	H_T^{VHH}		✓
$\tau_3/\tau_2(H_1, H_2)$					✓	$p_T(V)/p_T(HH)$		✓
						$\Delta\phi(V, HH)$		✓
						$p_T(\ell_1)/m_V$		✓

Categorisation in channels

Variable for categorization	$BDT_{Cat.}$	N_b, $D_{b\bar{b}}$	r_{HH}, δ_{HH}, m_V	Year split	N(regions)
Signal regions					
MET small-radius	κ_λ, κ_{2V}	$N_b \geq 3$	SR+CR	Per year	6
MET large-radius	κ_{2V}	HP, LP	SR+CR	Per year	6
1L small-radius	κ_λ, κ_{2V}	$N_b \geq 3$	SR+CR	Per year	6
1L large-radius	κ_{2V}	HP, LP	SR+CR	Per year	6
2L	κ_λ, κ_{2V}	$N_b = 3$ or 4	SR,CR	Combined	8
FH	κ_λ, κ_{2V}	$N_b = 4$	SR	Per year	6
Control regions					
MET small-radius	—	$N_b \geq 3$	SB	Per year	3
MET large-radius	—	HP, LP	SB	Per year	6
1L small-radius	—	$N_b \geq 3$	SB	Per year	3
1L large-radius	—	HP, LP	SB	Per year	6
2L (DY)	—	$N_b = 3$ or 4	DY CR	Combined	2
2L (TT)	—	$N_b \geq 3$	$t\bar{t}$ CR	Combined	1

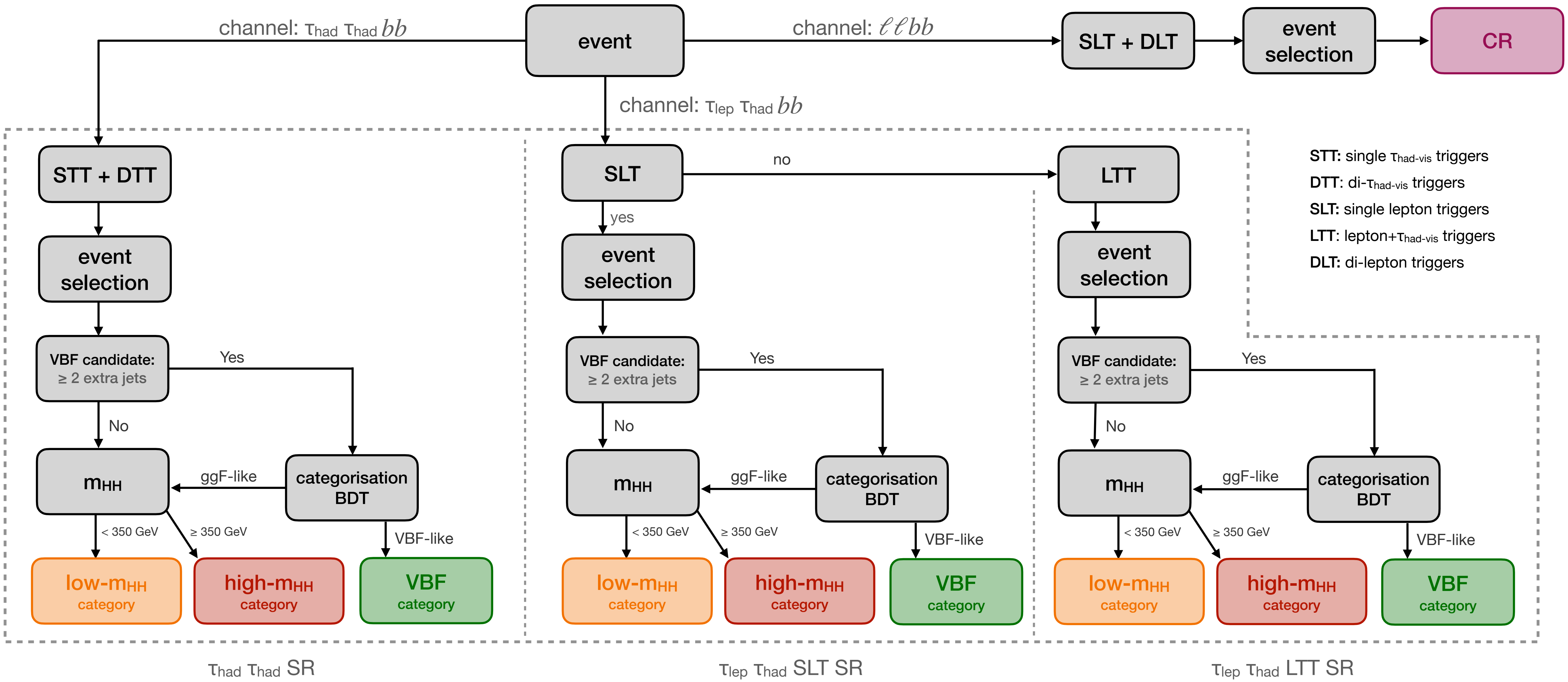
Summary of uncertainties

Uncertainty sources	2L	1L	MET	FH	Combined
Systematic uncertainty	+54%/−40%	+47%/−40%	+64%/−45%	+51%/−36%	+68%/−49%
Theory	+16%/−3%	+3%/−12%	+23%/−10%	+15%/−2%	+17%/−7%
Integrated luminosity	+6%/−0%	+5%/−1%	+8%/−1%	+4%/−0%	+6%/−4%
Lepton	+2%/−1%	+4%/−1%	+0%/−1%	+0%/−0%	+3%/−4%
Pileup	+3%/−6%	+4%/−2%	+8%/−7%	+3%/−0%	+9%/−14%
Small-radius jet	+17%/−5%	+15%/−5%	+26%/−23%	+21%/−2%	+26%/−16%
b tagging	+41%/−4%	+35%/−3%	+56%/−29%	+36%/−1%	+62%/−34%
Large-radius jet	+2%/−0%	+12%/−18%	+3%/−3%	+1%/−0%	+5%/−17%
Background modeling	+53%/−38%	+37%/−19%	+54%/−29%	+44%/−19%	+62%/−40%
Normalization	+40%/−12%	+34%/−4%	+52%/−25%	+35%/−0%	+58%/−32%
Reweighting	+34%/−36%	+13%/−17%	+22%/−13%	+12%/−1%	+25%/−19%
Kinematic	+11%/−10%	+17%/−3%	+13%/−4%	+24%/−24%	+19%/−14%
Statistical uncertainty	+84%/−91%	+88%/−92%	+77%/−89%	+86%/−93%	+73%/−87%
Signal strength and uncertainty	101^{+136}_{-99}	12^{+111}_{-83}	283^{+161}_{-123}	190^{+163}_{-132}	145^{+81}_{-63}

95% CL on coupling modifiers

	κ_λ	κ_{2V}	κ_V	κ_{2Z}	κ_{2W}
Observed	(−37.7, 37.2)	(−12.2, 13.5)	(−3.7, 3.8)	(−17.4, 18.5)	(−14.0, 15.4)
Expected	(−30.1, 28.9)	(−7.2, 8.9)	(−3.1, 3.1)	(−10.5, 11.6)	(−10.2, 11.6)

Event Selection



HH→bbττ (ATLAS)

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ggF vs VBF

Variable	$\tau_{had}\tau_{had}$	$\tau_{lep}\tau_{had}$ SLT	$\tau_{lep}\tau_{had}$ LTT
m_{jj}^{VBF}	✓	✓	✓
$\Delta\eta_{jj}^{VBF}$	✓	✓	✓
VBF $\eta_0 \times \eta_1$	✓	✓	
$\Delta\phi_{jj}^{VBF}$	✓		
ΔR_{jj}^{VBF}		✓	✓
$\Delta R_{\tau\tau}$	✓		
m_{HH}	✓		
f_2^a	✓		
C^a		✓	✓
m_{Eff}^a		✓	✓
f_0^c		✓	
f_0^a			✓
h_3^a			✓

ggF

Variable	$\tau_{had}\tau_{had}$	$\tau_{lep}\tau_{had}$ SLT	$\tau_{lep}\tau_{had}$ LTT
m_{HH}	✓	✓	✓
m_{bb}	✓	✓	✓
$m_{\tau\tau}^{MMC}$	✓	✓	✓
ΔR_{bb}	✓	✓	
$\Delta R(\tau_0, \tau_1)$	✓	✓	
VBF $\eta_0 \times \eta_1$	✓		✓
$\Delta\eta_{jj}^{VBF}$	✓	✓	
$\Delta\phi_{jj}^{VBF}$	✓		
ΔR_{jj}^{VBF}	✓	✓	
m_{jj}^{VBF}	✓	✓	✓
N(jets)			✓
H_T		✓	
S_T			✓
T_2			✓
m_T^W			✓
$\Delta\eta_{HH}$		✓	
$p_T(HH)$			✓
m_{HH}^*			✓
m_{HH} scaled			✓
$p_T(\tau_0)$			✓
$p_T(\tau\tau)$			✓
$p_T(b_0)$			✓
$\eta(\tau_0)$	✓		
$\eta(\tau_1)$	✓		
$\Delta R(b_0, \tau_0)$			✓
Thrust^a	✓		
Circularity^a	✓		
Planar Flow^a		✓	
f_0^a		✓	
f_2^a		✓	
f_4^a		✓	
m_{Eff}^a		✓	
cos θ^*			✓
$\cos(\Delta\theta_{\tau\tau}^{H\to\tau\tau \text{ rest frame}})$			✓

VBF

Variable	$\tau_{had}\tau_{had}$ low-m_{HH}	$\tau_{had}\tau_{had}$ high-m_{HH}	$\tau_{lep}\tau_{had}$ SLT low-m_{HH}	$\tau_{lep}\tau_{had}$ SLT high-m_{HH}	$\tau_{lep}\tau_{had}$ LTT low-m_{HH}	$\tau_{lep}\tau_{had}$ LTT high-m_{HH}
m_{bb}	✓	✓	✓	✓	✓	✓
$m_{\tau\tau}^{MMC}$	✓	✓	✓	✓	✓	✓
m_{HH}	✓	✓	✓	✓	✓	✓
ΔR_{bb}	✓	✓	✓	✓	✓	
$\Delta R(\tau_0, \tau_1)$	✓	✓	✓	✓	✓	✓
N(jets)	✓	✓	✓			
$p_T(HH)$		✓	✓			
H_T	✓			✓	✓	✓
T_1		✓	✓	✓	✓	✓
T_2	✓				✓	✓
E_T^{miss}	✓	✓	✓			
E_T^{miss} centrality					✓	
M_{T2}	✓				✓	
m_T^W			✓	✓	✓	
$m_T(\tau_1)$		✓		✓	✓	
$p_T(\tau_0)$	✓		✓	✓		
$p_T(\tau_1)$	✓		✓	✓		
$p_T(b_0)$	✓		✓			✓
$p_T(b_1)$				✓		
$p_T(bb)$						✓
$p_T(\tau\tau)$						✓
$\Delta p_T(\tau_0, \tau_1)$					✓	✓
$\eta(\tau_0)$	✓	✓				
$\eta(\tau_1)$	✓	✓				
$\Delta\eta(\tau_0, \tau_1)$					✓	
$\Delta\phi(bb, E_T^{miss})$	✓	✓				
$\Delta\phi(bb, \tau\tau)$	✓	✓				✓
$\Delta\phi(\tau\tau, E_T^{miss})$			✓	✓	✓	✓
$\Delta\phi(\tau_1, E_T^{miss})$					✓	✓
DL1r quantile(b_0)	✓	✓		✓		
DL1r quantile(b_1)	✓	✓		✓		
$\Delta R(b_0, \tau_0)$	✓	✓	✓			
$\Delta R(b_1, \tau_1)$		✓	✓			
$\Delta R(b_1, \tau_0)$			✓	✓		
m_{Eff}^c	✓					
m_{Eff}^b						✓
$m(b_0\tau_0)$						✓
$m(b_1\tau_0)$						✓
m_{HH}^*	✓					✓
m_{HH}^{scaled}						✓
C^b	✓	✓				
Sphericity^b	✓	✓				
Planar flow^b		✓				
$\cos(\Delta\theta_{bb}^{H\to b\bar{b} \text{ rest frame}})$			✓	✓		

HH→bbττ (ATLAS)

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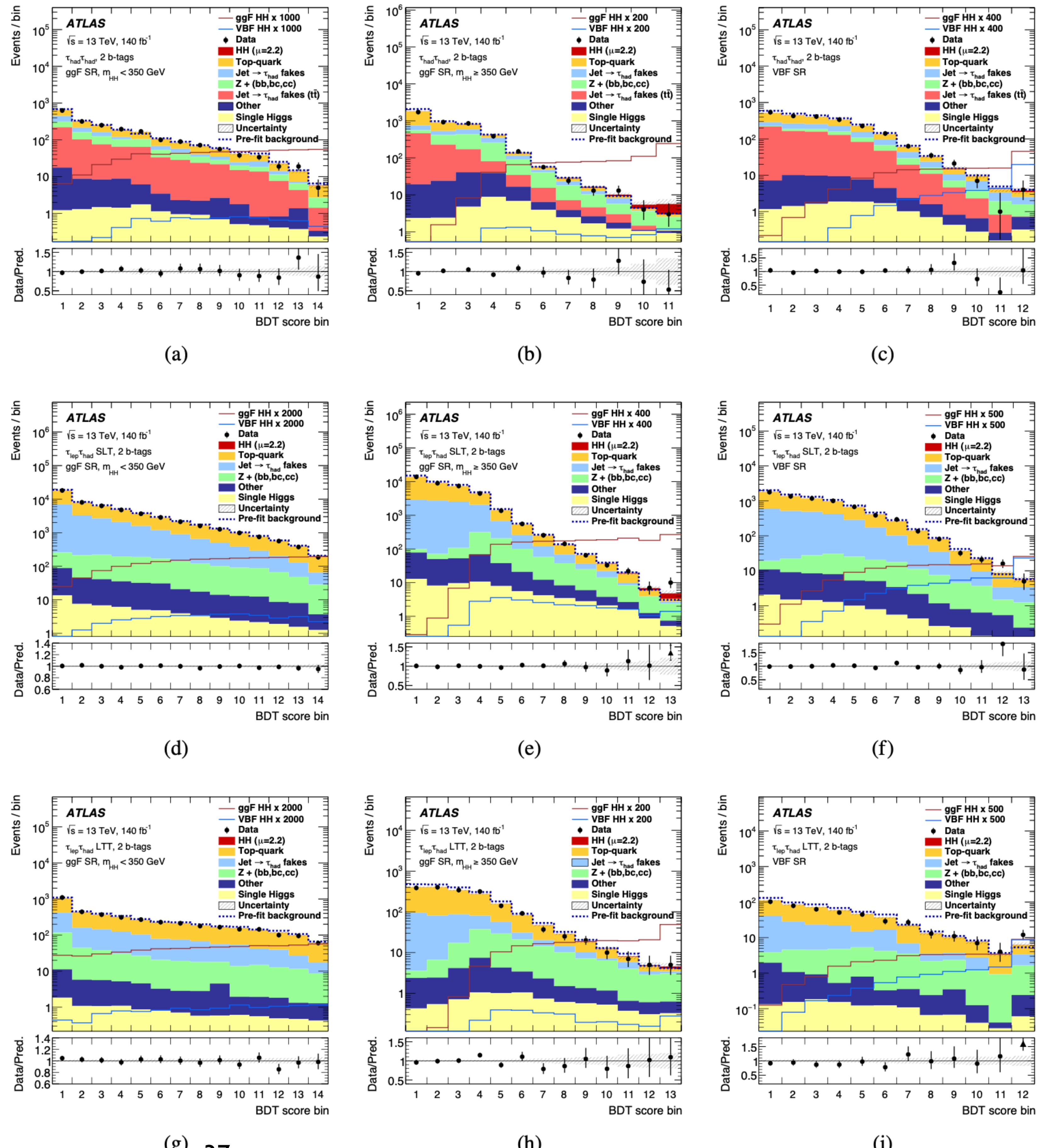
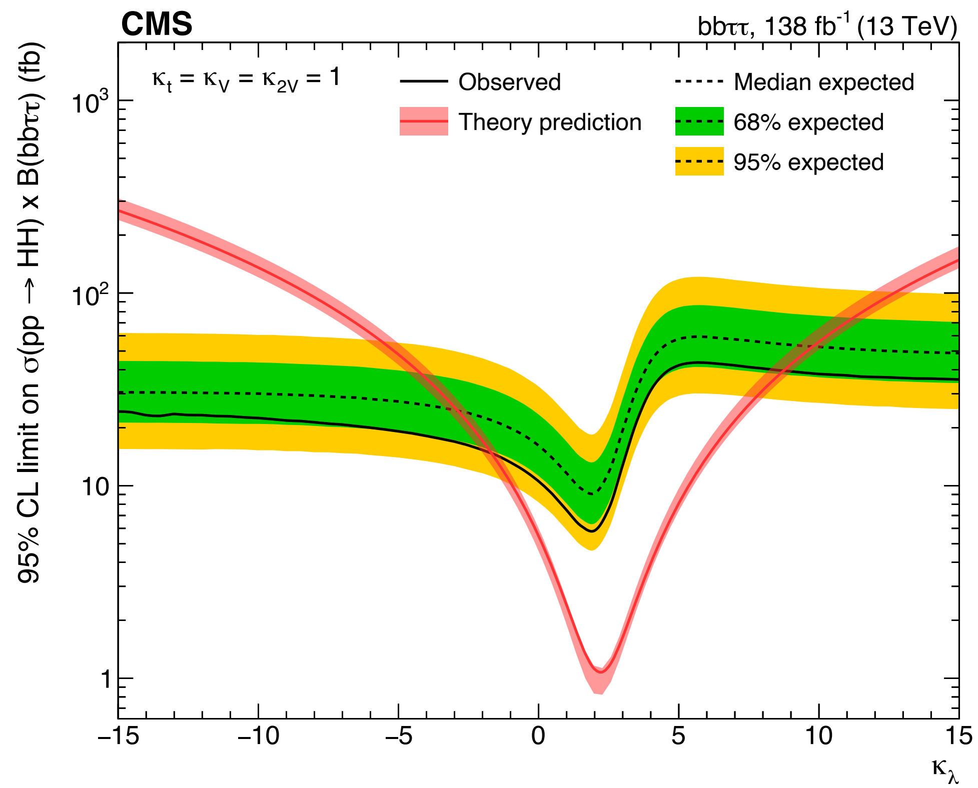
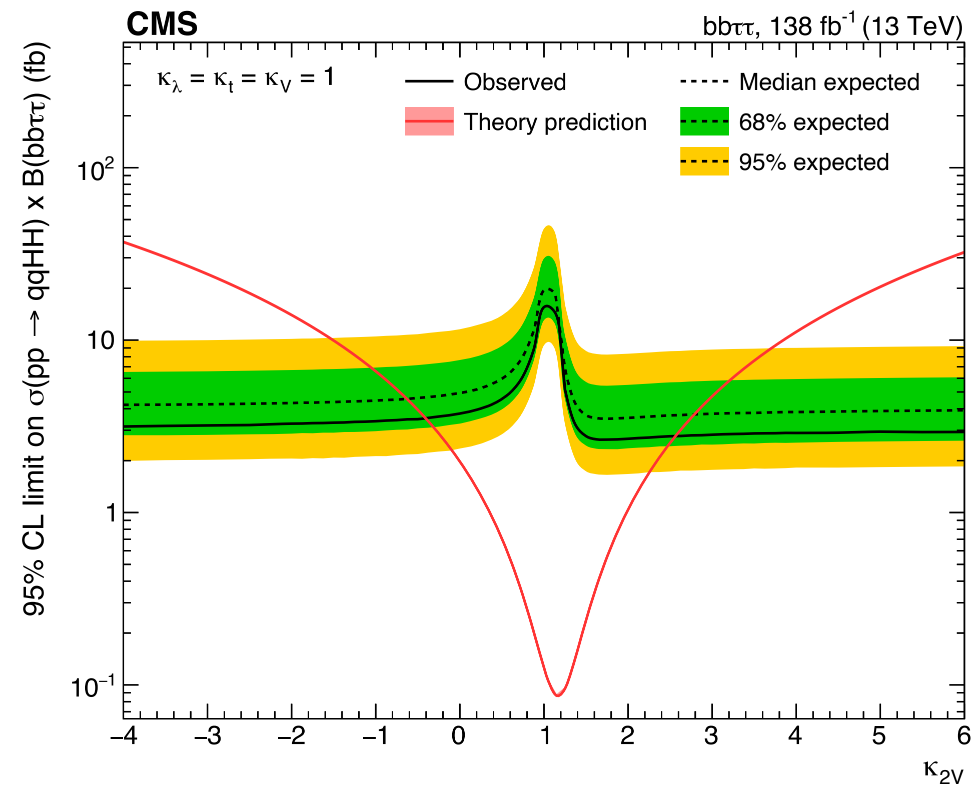
bbττ BDT distributions in 9 categories

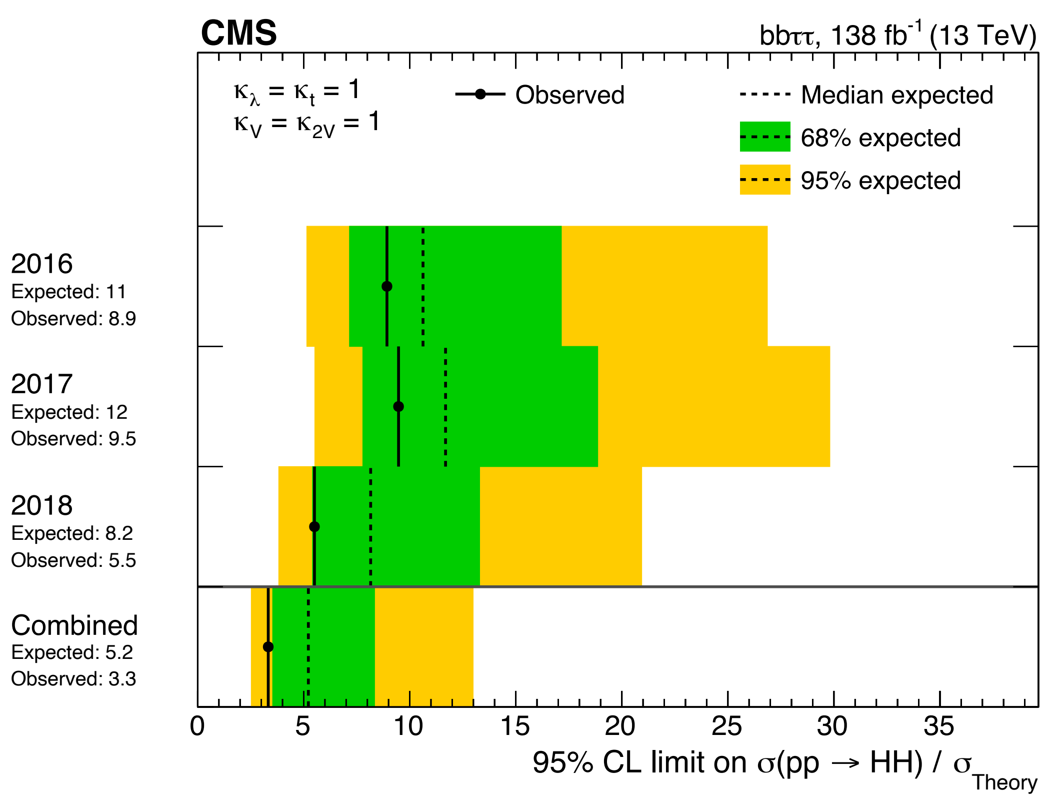


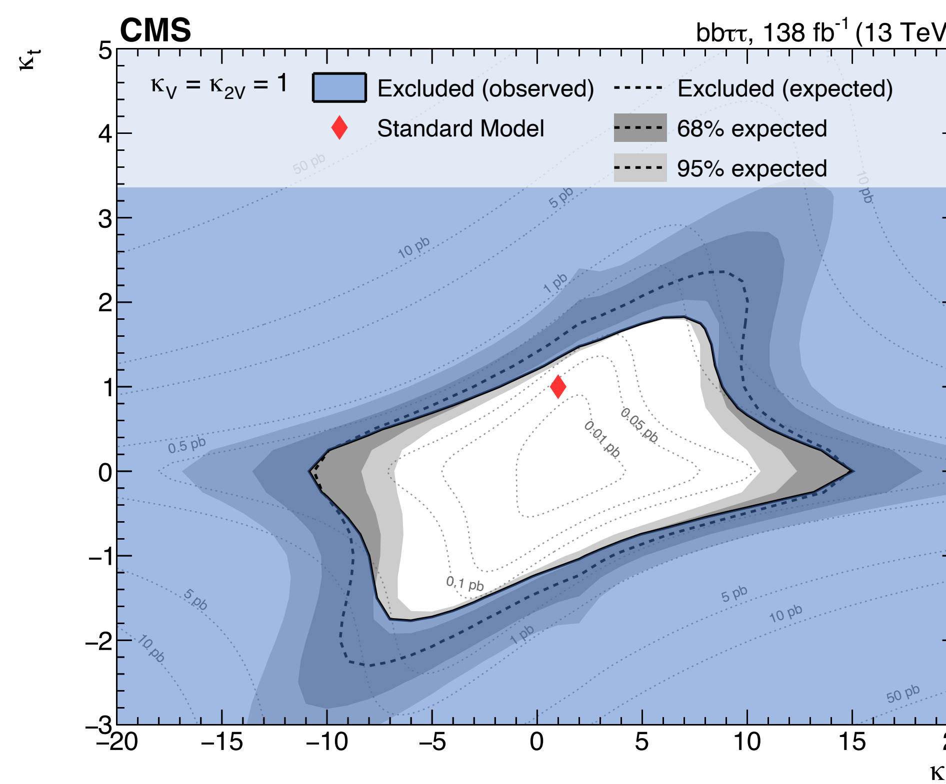
HH→bbττ (CMS)

Phys. Lett. B 842 (2023) 137531









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bbγγ BDT training variables

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.(1).
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. [83], Ref. [84], and Eq. (2)
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, $m^*_{b\bar{b}\gamma\gamma} = m_{b\bar{b}\gamma\gamma} - (m_{b\bar{b}} - 125\text{ GeV}) - (m_{\gamma\gamma} - 125\text{ GeV})$

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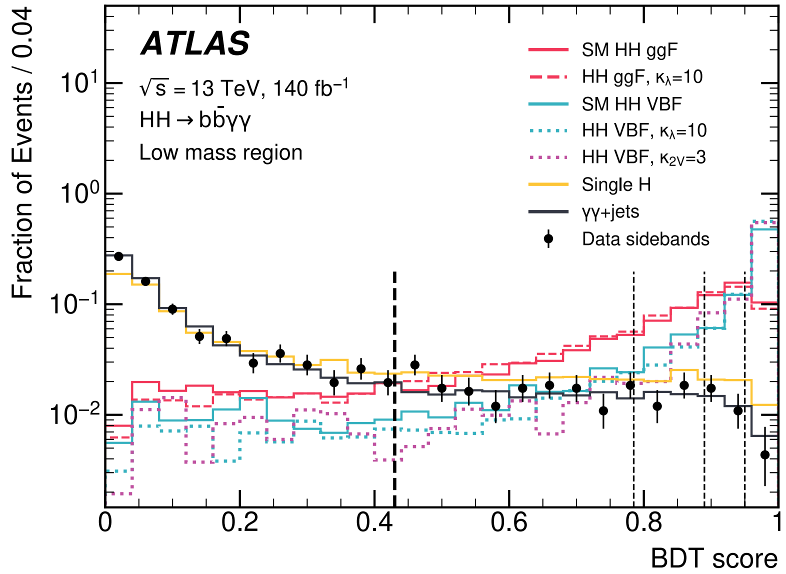
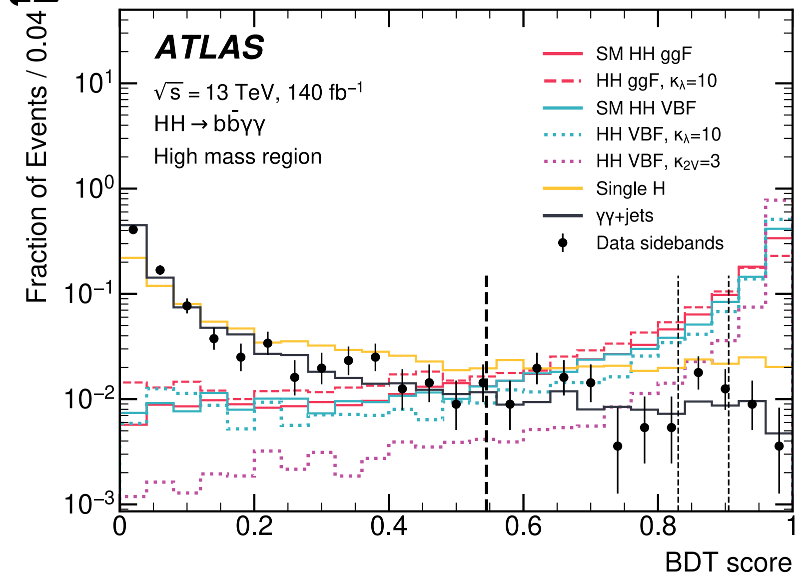
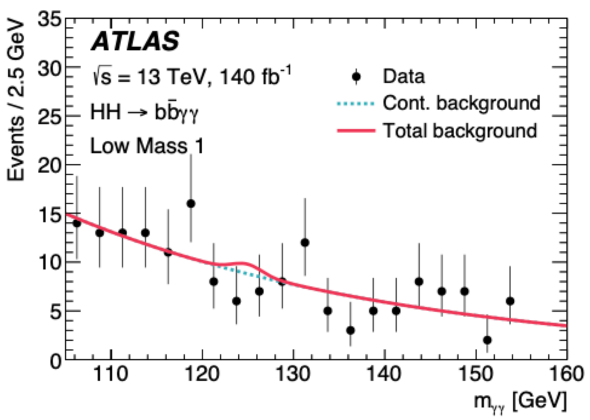
bbγγ discriminants



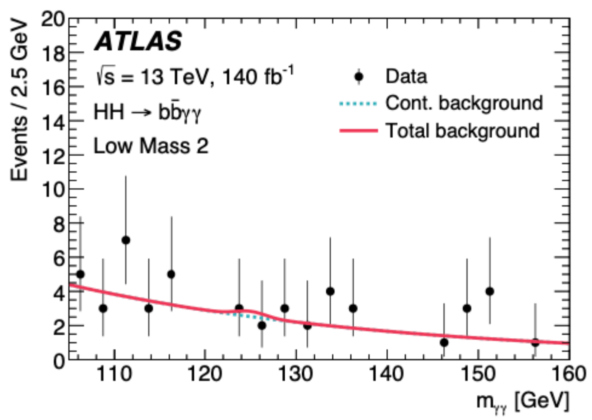


Low mass categories

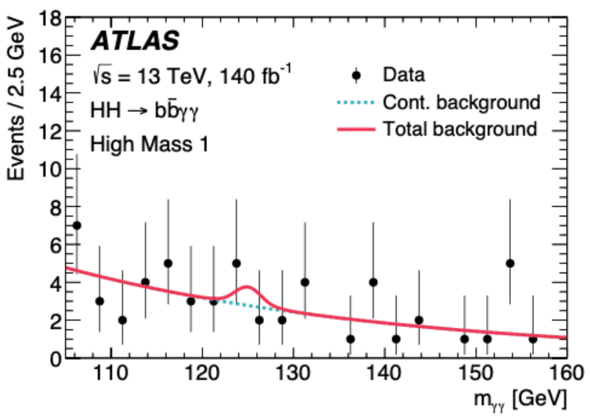
High mass categories



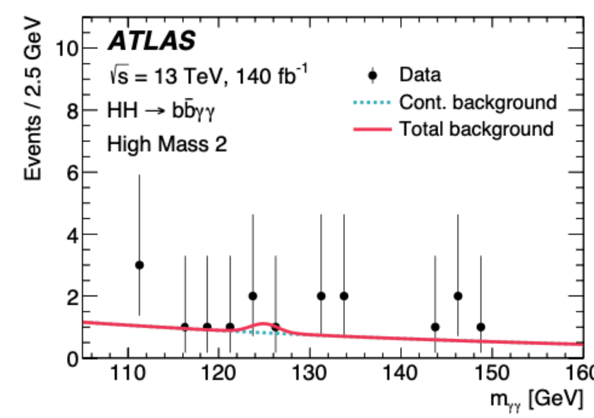
(a) Low Mass 1



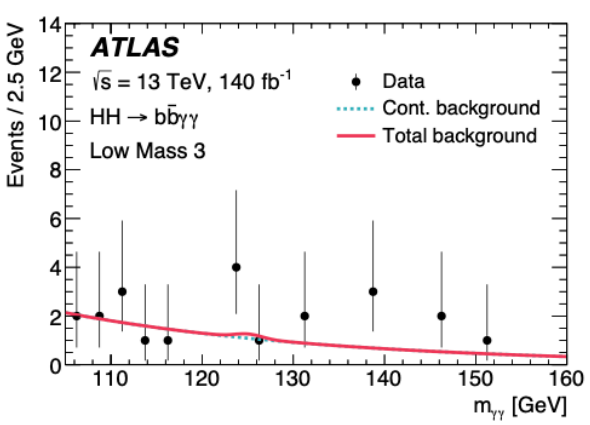
(b) Low Mass 2



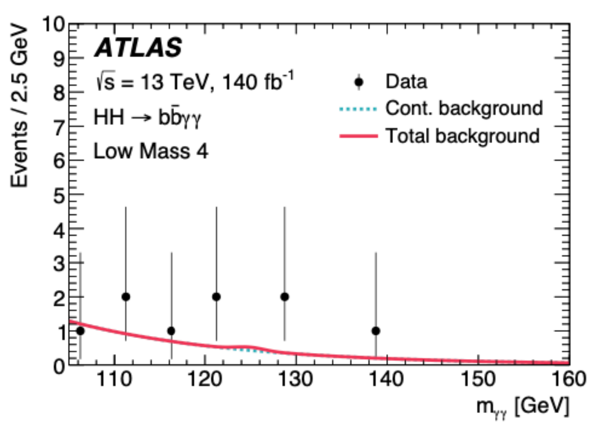
(e) High Mass 1



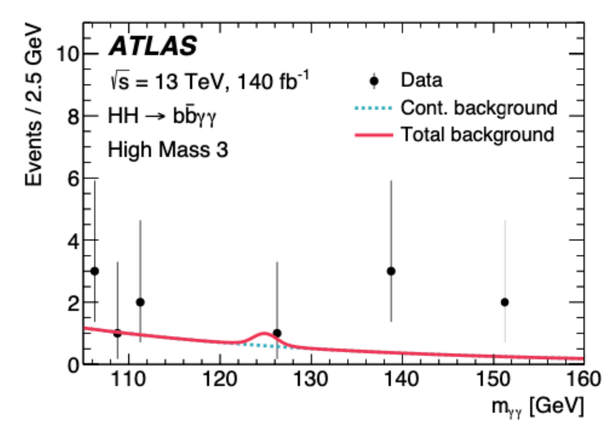
(f) High Mass 2



(c) Low Mass 3



(d) Low Mass 4



(g) High Mass 3

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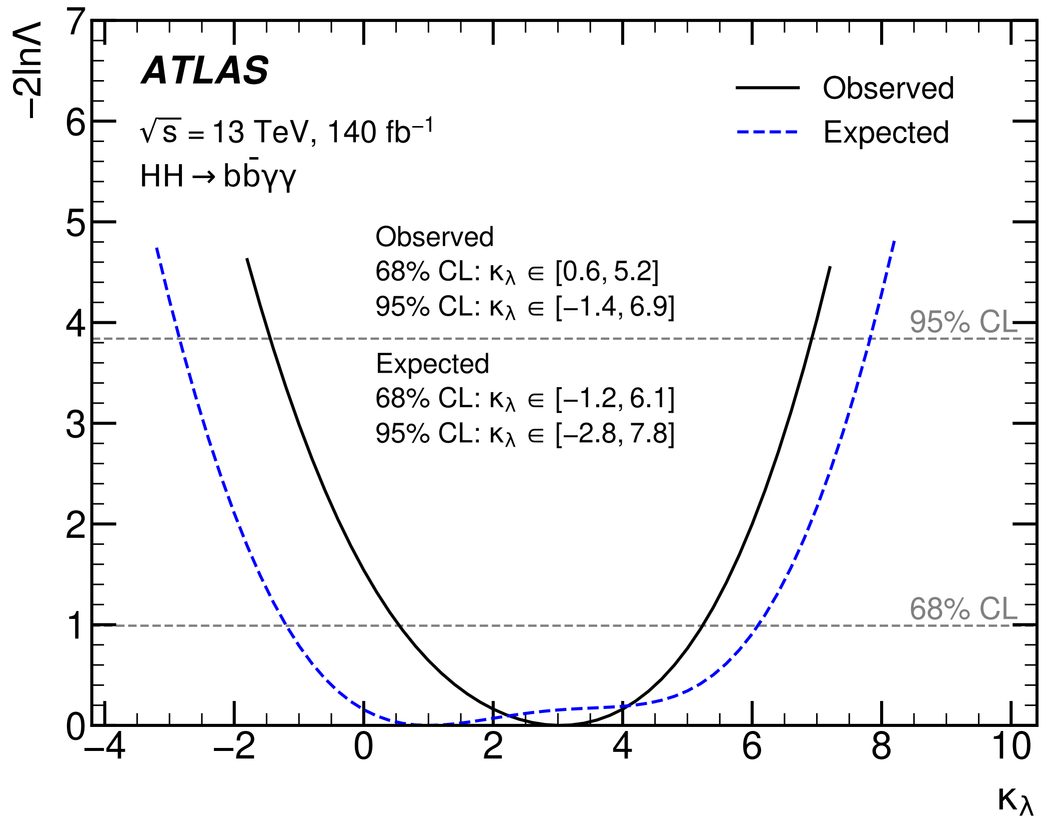
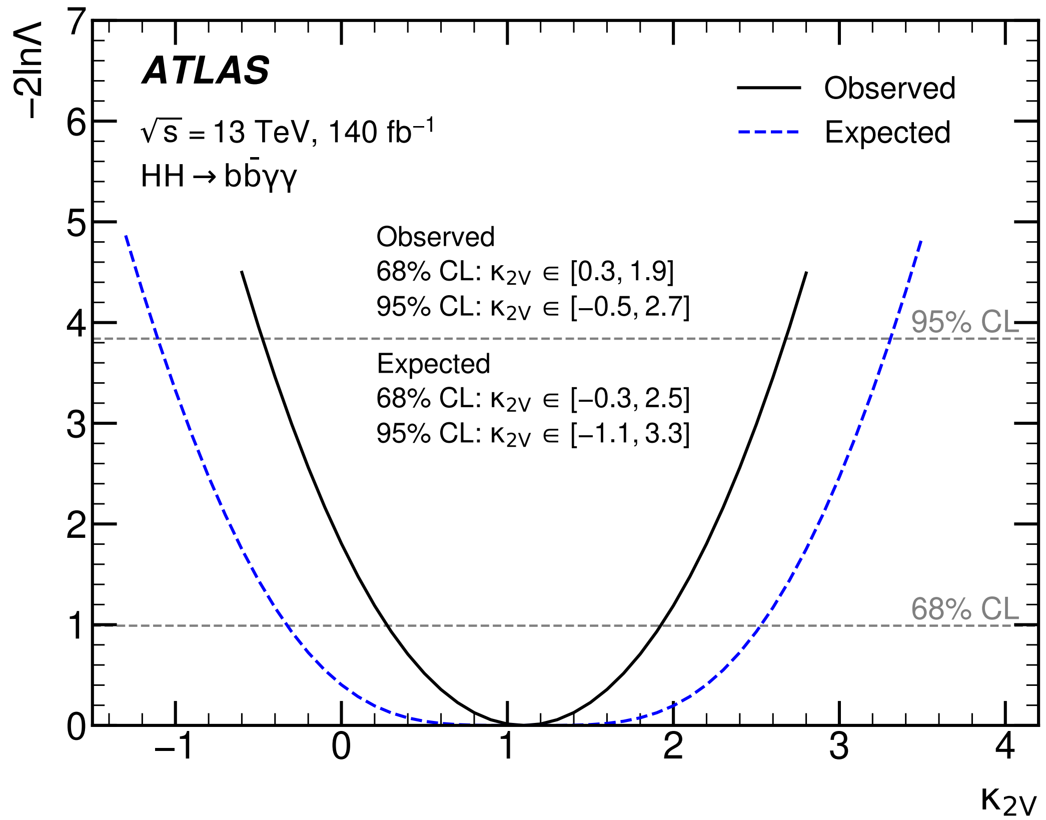
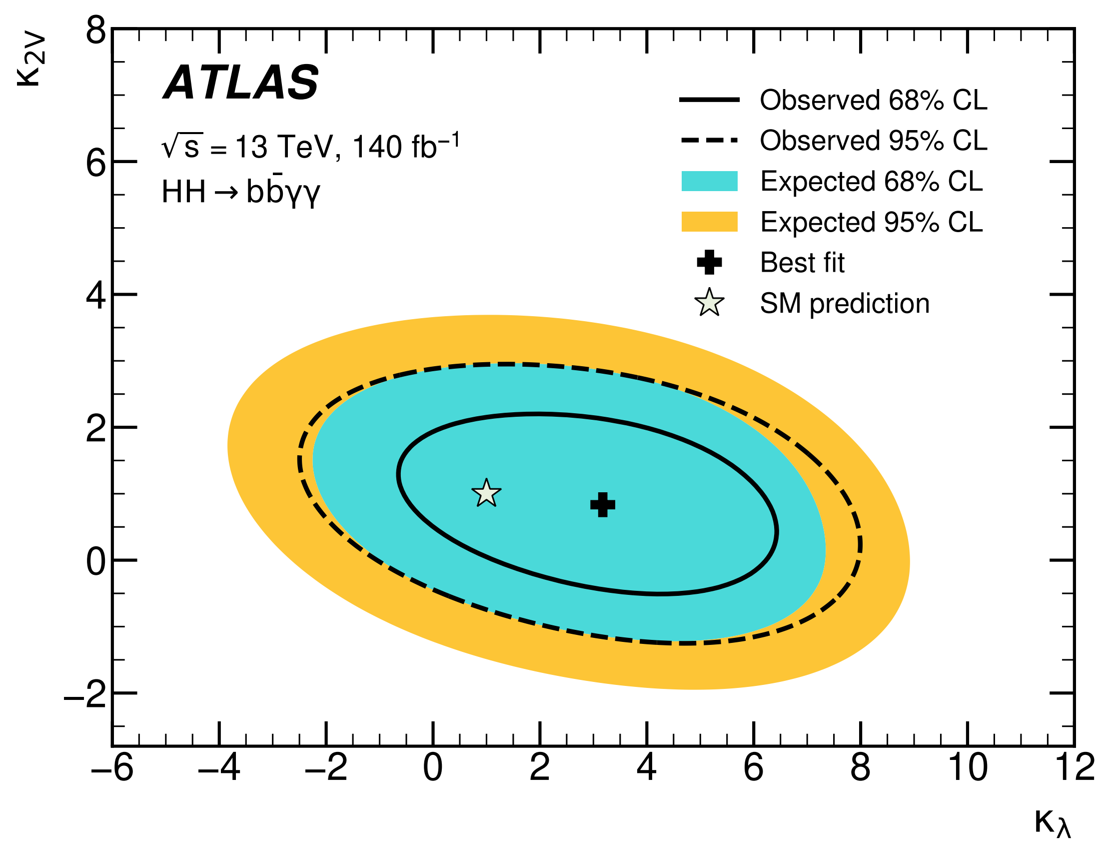
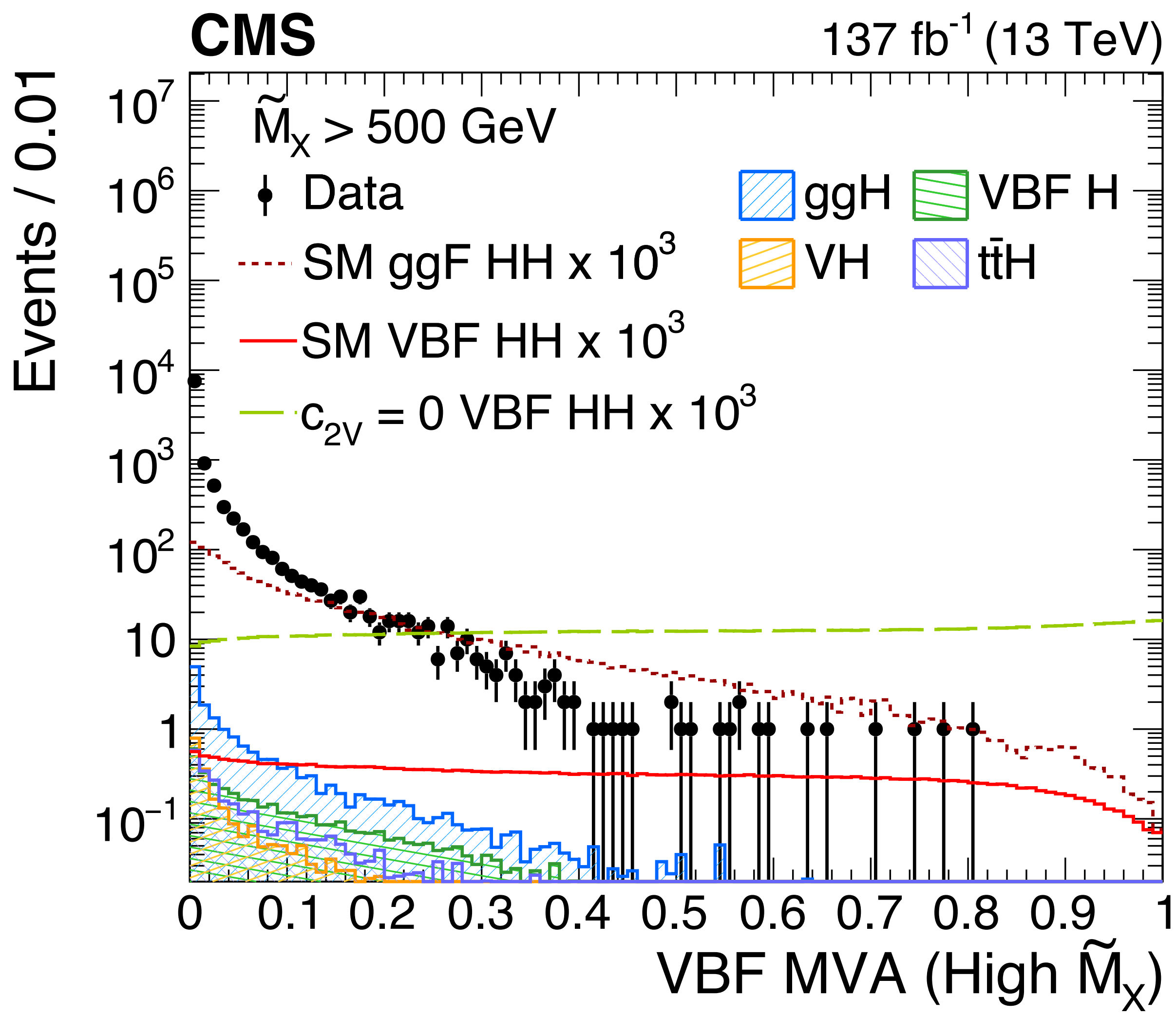
Observed/expected limits of k_λ and k_{2V}

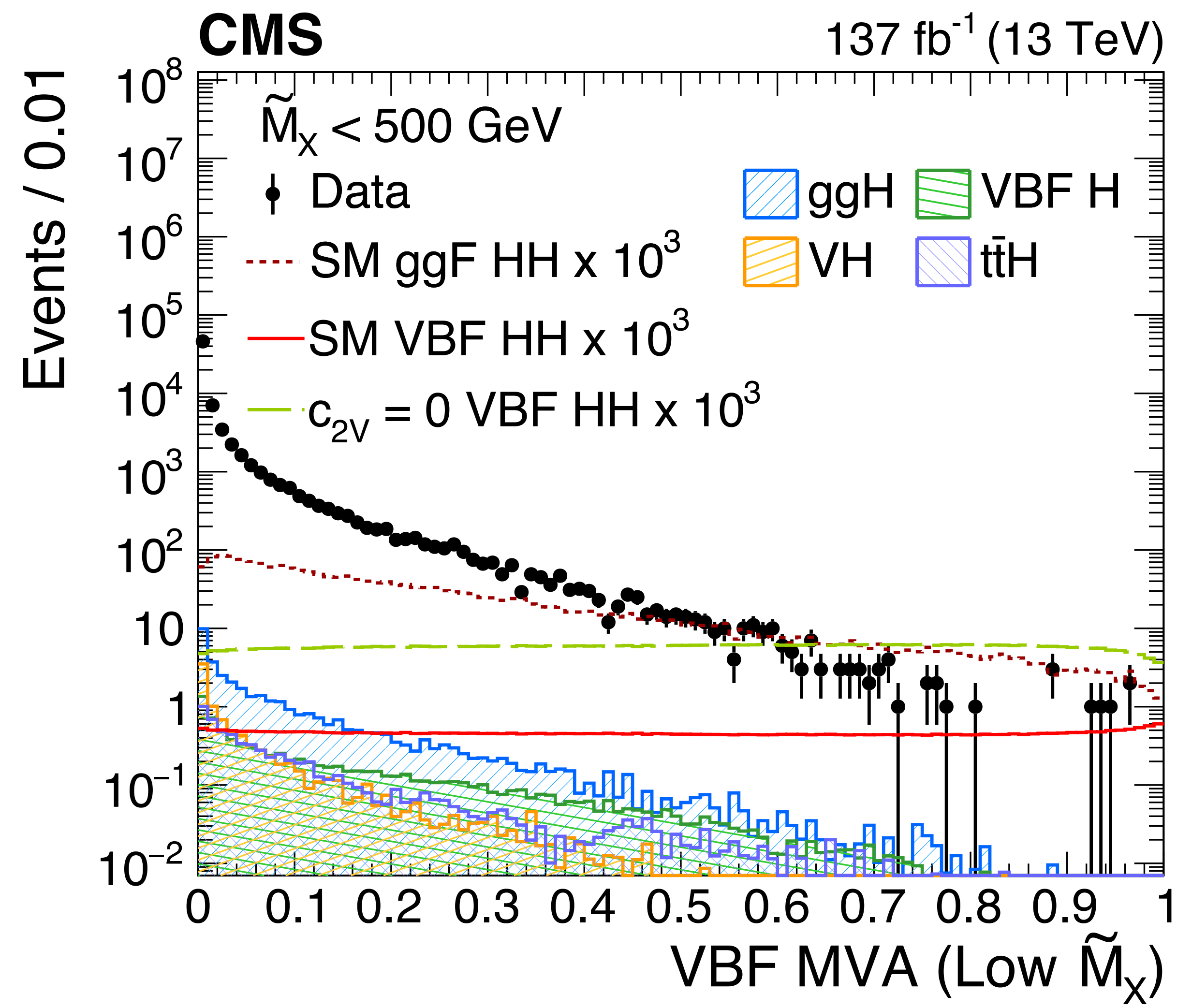






HH→bbγγ (CMS)

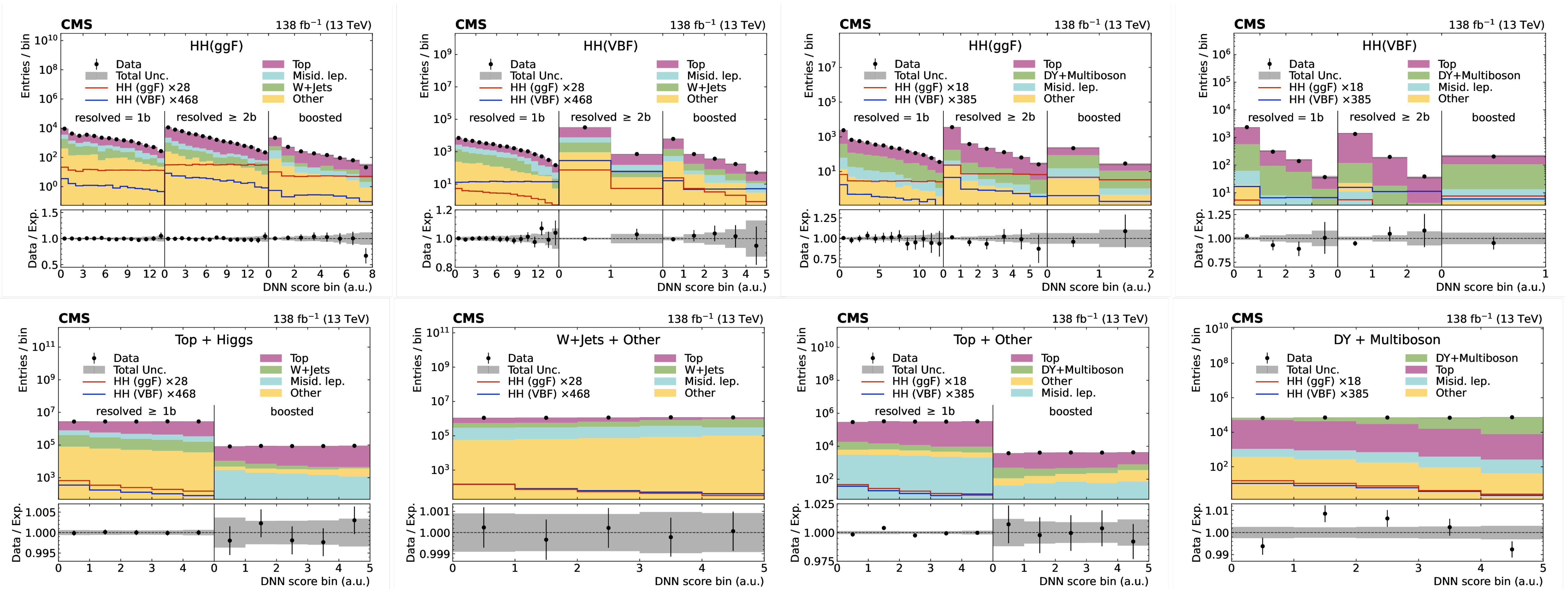




Category	MVA	$\tilde{M}_X$ (GeV)
VBF CAT 0	0.52–1.00	>500
VBF CAT 1	0.86–1.00	250–500
ggF CAT 0	0.78–1.00	>600
ggF CAT 1		510–600
ggF CAT 2		385–510
ggF CAT 3		250–385
ggF CAT 4	0.62–0.78	>540
ggF CAT 5		360–540
ggF CAT 6		330–360
ggF CAT 7		250–330
ggF CAT 8	0.37–0.62	>585
ggF CAT 9		375–585
ggF CAT 10		330–375
ggF CAT 11		250–330

HH→bbWW (CMS)

JHEP 07 (2024) 293 (bbWW)



Single Lepton

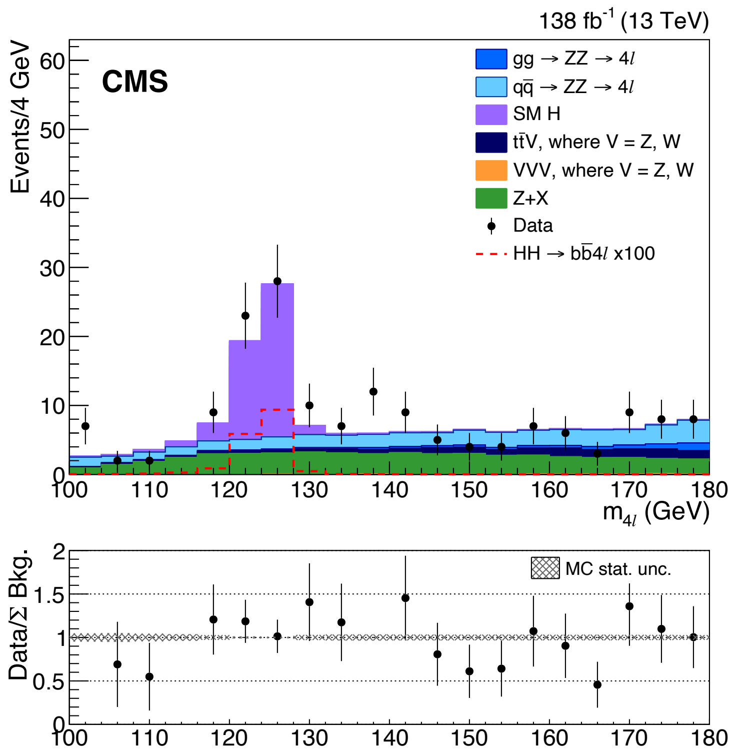
Dilepton

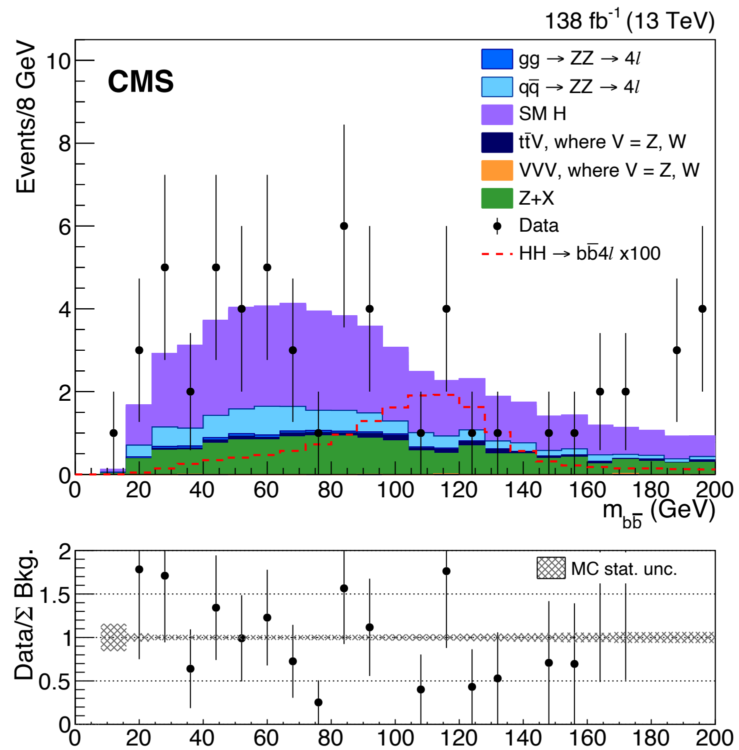
Single-lepton channel			
Categories	Subcategories		
HH (ggF)	Resolved 1b	Resolved 2b	Boosted
HH (VBF)	Resolved 1b	Resolved 2b	Boosted
Top + Higgs	Resolved		Boosted
W+jets + Other	Inclusive		

Dilepton channel			
Categories	Subcategories		
HH (ggF)	Resolved 1b	Resolved 2b	Boosted
HH (VBF)	Resolved 1b	Resolved 2b	Boosted
Top + Other	Resolved		Boosted
DY + Multiboson	Inclusive		

Expected yields in the 4ℓ SR after additionally requiring at least two jets in the event.

Final state	Signal	$t\bar{t}Z$	$t\bar{t}H$	$b\bar{b}H$	ZZ	ggH+VBF	ZH+WH	Others	Z+X	Total expected	Observed
4μ	0.056	0.58	0.68	0.16	3.75	12.35	1.61	0.04	3.87	23.10	29
4e	0.030	0.37	0.39	0.07	1.42	6.16	0.82	0.02	2.65	11.93	12
$2e2\mu$	0.082	0.95	0.91	0.20	4.93	15.56	2.08	0.10	7.22	32.03	33

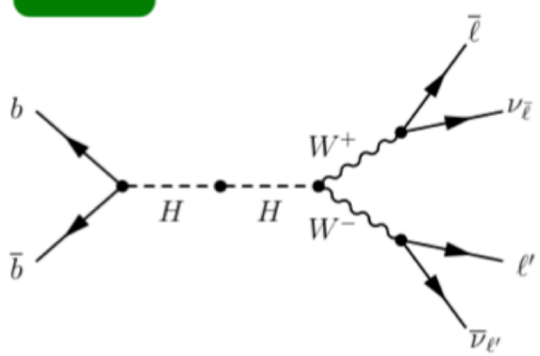




Experimental uncertainties			
Source	2016	2017	2018
Integrated luminosity	1.2%	2.3%	2.5%
Lepton reco./ident. eff.	1.6–15.5%	1.1–12.1%	1.0–11.0%
b-tagging SF	shape	shape	shape
JES	shape	shape	shape
JER	shape	shape	shape
Z+X bkg. uncertainties	30–41%	30–38%	30–37%

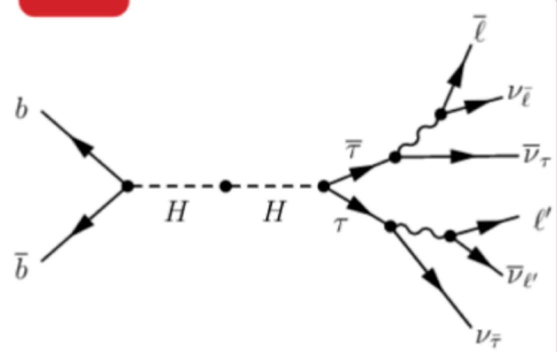
Theory uncertainties	
Branching fractions	
$\mathcal{B}(H \to b\bar{b})$	1.2%
$\mathcal{B}(H \to ZZ)$	1.5%
PDF set and α_S	
HH	3.0%
HH (m_{top} effects)	$^{+4.0}_{-18.0}$ %
ggH (PDF set)	1.9%
ggH (α_S)	2.59–2.62%
VBFH	2.1%
ZH	1.6%
WH	1.3%
$b\bar{b}H$	3.2%
$t\bar{t}H$	3.0%
qqZZ	3.1–3.4%
$t\bar{t}Z$	7–14%
VVV	2–17%
ggZZ	3.2%
Scale uncertainties	
HH	2.2–5%
ggH	4.27–6.49%
VBFH	0.3–0.4%
ZH	2.7–3.5%
$t\bar{t}H$	6.0–9.2%
qqZZ	3.2–4.2%
$t\bar{t}Z$	2–3%
VVV	3%
ggZZ	4.6–6.7%
K-factors	
qqZZ	0.1%
ggZZ	10.0%

$bbWW$



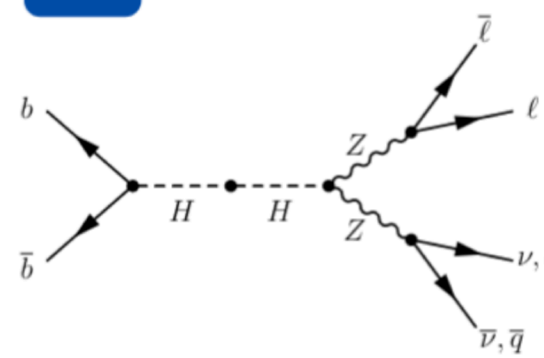
- $\text{BR}_{HH\to bb\ell\ell+\text{MET}} = 1.62\,\%^{\dagger}$
- W-pair has spin correlation
- small $m_{\ell\ell}$ and $\Delta\Phi_{\ell\ell}$

$bb\tau\tau$



- $\text{BR}_{HH\to bb\ell\ell+\text{MET}} = 0.91\,\%^{\dagger}$
- light leptons are collinear to τ-lepton $\Rightarrow m_{\tau\tau}^{\text{coll}}$

$bbZZ$



- $\text{BR}_{HH\to bb\ell\ell+\text{MET}} = 0.095\,\%^{\dagger}$
- $m_{\ell\ell}$ close to Z peak or small for offshell Z
- only same flavour leptons

Event yields

Process	ggF-SR	VBF-SR	$t\bar{t}$-CR	Wt-CR	Z+HF-CR
SM background					
$t\bar{t}$	561220 ± 150	52670 ± 50	436840 ± 130	2270 ± 10	34700 ± 40
$t\bar{t}+V$	1121 ± 4	194.7 ± 1.9	1133 ± 5	97.0 ± 1.1	440.1 ± 1.9
Single top (Wt)	16260 ± 50	1165 ± 12	14100 ± 40	2901 ± 20	1237 ± 13
Single top (s/t-channel)	12.7 ± 0.8	2.48 ± 0.35	1.21 ± 0.28	0.35 ± 0.14	0.25 ± 0.11
$Z \to \ell\ell$ (HF)	16090 ± 180	1178 ± 34	3610 ± 70	525 ± 11	43390 ± 260
$Z \to \ell\ell$ (LF)	2720 ± 170	260 ± 40	600 ± 90	55 ± 8	5470 ± 190
$Z \to \tau\tau$ (HF)	2200 ± 40	154 ± 13	3 ± 7	1.9 ± 0.5	4 ± 6
$Z \to \tau\tau$ (LF)	370 ± 50	24 ± 4	-1.3 ± 1.5	0.11 ± 0.06	0.8 ± 0.5
W+jets	0.7 ± 0.5	0.09 ± 0.08	-0.2 ± 0.4	—	—
Diboson	288 ± 4	32.6 ± 0.8	159.0 ± 2.8	39.0 ± 0.9	226.8 ± 3.3
Single Higgs	601.0 ± 1.1	105.1 ± 0.4	336.5 ± 0.5	22.06 ± 0.12	48.28 ± 0.29
Fakes	18510 ± 170	2390 ± 60	10020 ± 140	529 ± 35	1360 ± 50
Total SM bkg.	619390 ± 350	58170 ± 100	466810 ± 230	6440 ± 40	86890 ± 330
HH signal, ggF					
ggF $HH \to bbWW$	8.318 ± 0.016	0.857 ± 0.005	0.00113 ± 0.00019	0.00033 ± 0.00010	0.0014 ± 0.0002
ggF $HH \to bb\tau\tau$	3.138 ± 0.009	0.3284 ± 0.0029	0.00332 ± 0.00029	0.00068 ± 0.00015	0.0047 ± 0.0004
ggF $HH \to bbZZ$	0.633 ± 0.005	0.0873 ± 0.0018	0.00083 ± 0.00018	0.00020 ± 0.00009	0.0442 ± 0.0013
$\sum$ ggF HH	12.088 ± 0.019	1.272 ± 0.006	0.0053 ± 0.0004	0.00121 ± 0.00020	0.0504 ± 0.0014
HH signal, VBF					
VBF $HH \to bbWW$	0.1518 ± 0.0014	0.2138 ± 0.0017	0.00013 ± 0.00004	—	0.00009 ± 0.00004
VBF $HH \to bb\tau\tau$	0.0537 ± 0.0006	0.0769 ± 0.0007	0.000086 ± 0.000022	0.000048 ± 0.000018	0.00024 ± 0.00004
VBF $HH \to bbZZ$	0.0097 ± 0.0004	0.0184 ± 0.0006	0.000040 ± 0.000024	0.0000029 ± 0.0000016	0.00236 ± 0.00023
$\sum$ VBF HH	0.2152 ± 0.0016	0.3091 ± 0.0019	0.00026 ± 0.00005	0.000051 ± 0.000018	0.00269 ± 0.00024
HH signal, ggF+VBF					
$\sum$ ggF+VBF HH	12.303 ± 0.019	1.582 ± 0.006	0.0055 ± 0.0004	0.00126 ± 0.00020	0.0531 ± 0.0014

ggF NN inputs

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

VBF BDT inputs

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
$p_T^{\ell\ell}$, $\Delta R_{\ell\ell}$, $\Delta\phi_{\ell\ell}$, $m_{\ell\ell}$, $\phi_{centrality}^{\ell\ell}$	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 $m_{\tau\tau}$)

HH→bbℓℓ + E_T^{miss} (ATLAS)

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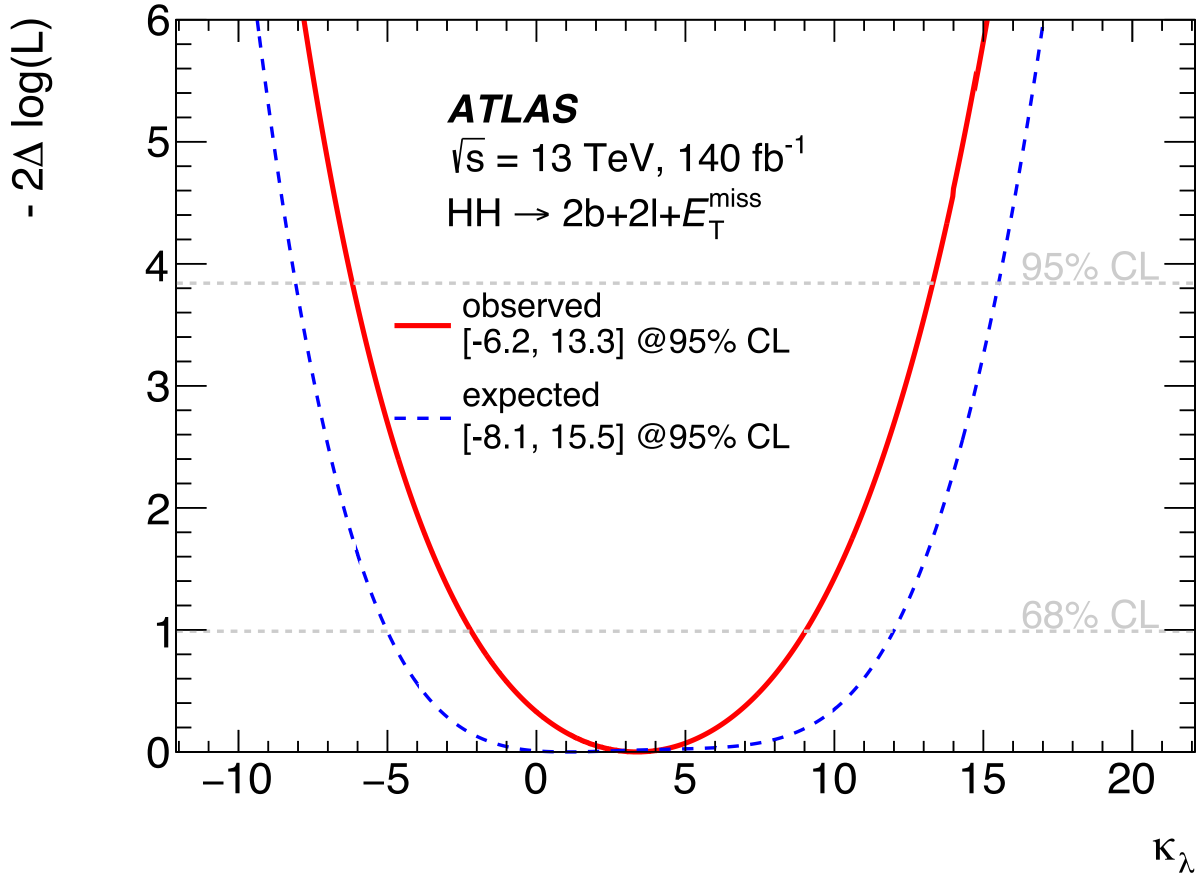

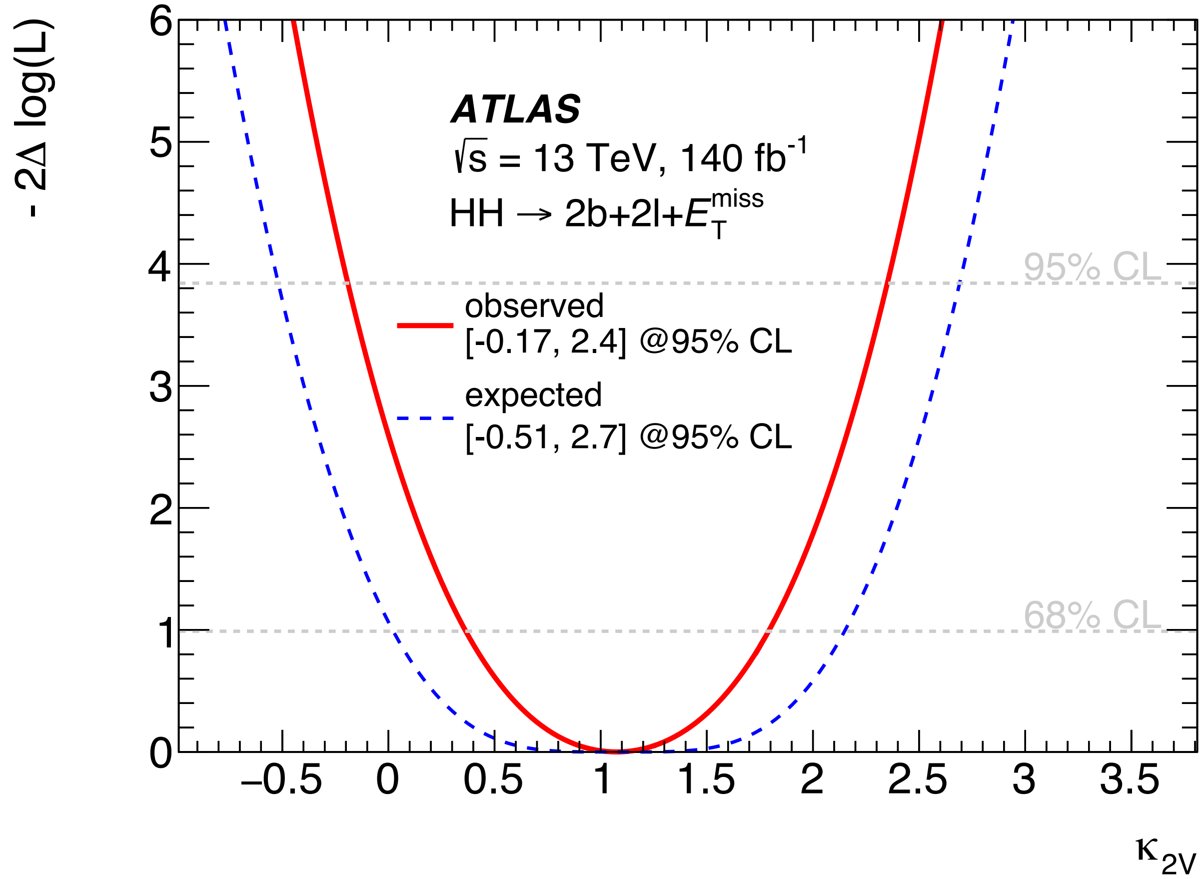

Channel Selection Criteria

Channel	ℓ	$\tau_{\text{had-vis}}$	Jets	b-jets
4ℓ+$2b$	4ℓ(B) $p_T(\ell_1) > 20$ GeV $p_T(\ell_2) > 15$ GeV $p_T(\ell_3) > 10$ GeV ℓ_3 or ℓ_4 pass loose PLV 2 SFOC pairs $50 < m^{\text{SFOC}}_{\text{on-shell-}\ell\ell} < 106$ GeV $5 < m^{\text{SFOC}}_{\text{off-shell-}\ell\ell} < 115$ GeV All 4 pairs $\Delta R(\ell_i, \ell_j) > 0.02$ $\lvert m_{4\ell} - m_Z \rvert > 10$ GeV	$N_\tau = 0$	$N_{\text{jet}} \geq 2$	$1 \leq N_{b\text{-jet}} \leq 3$
3ℓ	3ℓ, sum of charges = ±1 ℓ_{OC}(L) ℓ_{SC1}(T), $p_T > 15$ GeV ℓ_{SC2}(T), $p_T > 15$ GeV All $m^{\text{SFOC}}_{\ell\ell} > 12$ GeV Z-veto $\lvert m_{3\ell} - m_Z \rvert > 10$ GeV	$N_\tau = 0$	$N_{\text{jet}} \geq 1$	$N_{b\text{-jet}} = 0$
2ℓSC	2ℓ(T), $p_T > 20$ GeV, SC $m_{\ell\ell} > 12$ GeV	$N_\tau = 0$	$N_{\text{jet}} \geq 2$	$N_{b\text{-jet}} = 0$
2ℓSC+τ_{had}	2ℓ(T), $p_T > 20$ GeV, SC $m_{\ell\ell} > 12$ GeV	$N_\tau = 1$ $p_T > 25$ GeV OC to ℓ	$N_{\text{jet}} \geq 2$	$N_{b\text{-jet}} = 0$
2ℓ+$2\tau_{\text{had}}$	2ℓ(L), OC $m_{\ell\ell} > 12$ GeV Z-veto	$N_\tau = 2$, OC $\Delta R(\tau_1, \tau_2) < 2$	$N_{\text{jet}} \geq 0$	$N_{b\text{-jet}} = 0$
ℓ+$2\tau_{\text{had}}$	1ℓ(L)	$N_\tau = 2$, OC $\Delta R(\tau_1, \tau_2) < 2$	$N_{\text{jet}} \geq 2$	$N_{b\text{-jet}} = 0$

Channel	ℓ	$\tau_{\text{had-vis}}$	Photons	E_T^{miss}	b-jets
$\gamma\gamma$+$2(\ell, \tau_{\text{had}})$	$N_{\ell(\text{P})} + N_\tau = 2$, OC $m_{2(\ell,\tau)} > 12$ GeV		$N_\gamma = 2$ $E_T(\gamma_1) > 35$ GeV 105 GeV $< m_{\gamma\gamma} <$ 160 GeV $\gamma_1 : p_T/m_{\gamma\gamma} > 0.35$ $\gamma_2 : p_T/m_{\gamma\gamma} > 0.25$	$E_T^{\text{miss}} > 35$ GeV	$N_{b\text{-jet}} = 0$
$\gamma\gamma$+ℓ	$N_{\ell(P)} = 1$	$N_\tau = 0$		$\gamma\gamma$+e: $E_T^{\text{miss}} > 35$ GeV $\gamma\gamma$+μ: –	
$\gamma\gamma$+τ_{had}	$N_{\ell(P)} = 0$	$N_\tau = 1$		$E_T^{\text{miss}} > 35$ GeV	

Control Region Definitions

Channel	Region	Leptons	Jets	b-jets	Additional selections
4ℓ+$2b$	$t\bar{t}$ CR⋆	Off-shell-$\ell\ell$ not SFOC Z-veto	–	–	–
	$t\bar{t}Z$ CR⋆	Off-shell-$\ell\ell$ not SFOC All ℓ pass loose PLV Z-req. $m_{4\ell}$ req. removed	–	–	–
	VV, H CR⋆	All ℓ pass loose PLV	–	$N_{b\text{-jet}} = 0$	–
	Z+jets CR⋆	$p_T(\ell_3) < 10$ GeV $p_T(\ell_4) < 10$ GeV Z-req.		–	– –
	VR	–	–	–	$\lvert m_{4\ell} - m_H \rvert > 10$ GeV
3ℓ	WZ CR⋆	Z-req.	–	–	$E_T^{miss} > 30$ GeV
	HF-e CR⋆	ℓ_{SC1}, ℓ_{SC2} both e No PLV on any ℓ	$N_{jet} \geq 2$	$N_{b\text{-jet}} \geq 2$	
	HF-μ CR⋆	ℓ_{SC1},ℓ_{SC2} both μ No PLV on any ℓ	$N_{jet} \geq 2$	$N_{b\text{-jet}} \geq 2$	
	Mat. conv. CR⋆	$\lvert m_{3\ell} - m_Z \rvert < 10$ GeV ℓ_{SC1} or ℓ_{SC2}: $r_{vtx} > 20$ mm $0 < m_{trk,trk} < 100$ MeV	–	–	–
	VR	–	–	–	BDT < 0.55
2ℓSC	WZ CR⋆	$\geq 3\ell$(T), $p_T > 20$ GeV One SFOC pair Z-req. $m_{\ell\ell}$ (any pair) > 12 GeV $\lvert m_{3\ell} - m_Z \rvert > 10$ GeV	–	–	$E_T^{miss} > 30$ GeV
	VVjj CR⋆	Z-veto (SFSC pair)	$m_{jj} > 300$ GeV	–	BDT < −0.4 $\text{BDT}_{Z\text{+jets}} > -0.8$
	HF-e CR1⋆	ℓ(T)e(T), no PLV	$2 \leq N_{jet} \leq 3$	$N_{b\text{-jet}} = 1$	–
	HF-e CR2⋆	ℓ(T)e(T), no PLV	$2 \leq N_{jet} \leq 3$	$N_{b\text{-jet}} \geq 2$	–
	HF-μ CR⋆	ℓ(T)μ(T), no PLV	$2 \leq N_{jet} \leq 3$	$N_{b\text{-jet}} \geq 1$	–
	Mat. conv. CR⋆	$r_{vtx} > 20$ mm $m_{trk,trk} < 100$ MeV	–	$N_{b\text{-jet}} \geq 1$	–
	Int. conv. CR⋆	$r_{vtx} < 20$ mm $m_{trk,trk} < 100$ MeV	–	$N_{b\text{-jet}} \geq 1$	–
	Q mis-ID	$2e$(T), OC or SC	$N_{jet} < 2$	–	–
	VR	–	–	–	BDT < −0.4

Channel	Region	Leptons	(anti-ID) $\tau_{had\text{-}vis}$	Jets	b-jets	Additional selections
2ℓSC+τ_{had}	VV CR⋆	–	–	–	–	BDT < −0.2
	HF-e CR1⋆	ℓ(T)e(T), no PLV	–	$N_{jet} \geq 2$	$N_{b\text{-jet}} = 1$	–
	HF-e CR2⋆	ℓ(T)e(T), no PLV	–	$N_{jet} \geq 2$	$N_{b\text{-jet}} \geq 2$	–
	HF-μ CR⋆	ℓ(T)μ(T), no PLV	–	–	–	–
	Fake-$\tau_{had\text{-}vis}$ CR	OC leptons Z-veto	–	–	–	–
	Z+jets VR	OC leptons Z-req.	–	–	–	–
	$t\bar{t}$ VR	OC leptons Z-veto	–	$N_{jet} = 2$	$N_{b\text{-jet}} = 1$	–
	VR	–	–	$N_{jet} < 2$	–	
2ℓ+$2\tau_{had}$ and ℓ+$2\tau_{had}$	Z+jets CR	2ℓ(T), OC Z-req.	$N_\tau + N_{\text{anti-ID }\tau} = 2$	$N_{jet} \geq 1$	$N_{b\text{-jet}} = 0$	–
	$t\bar{t}$ CR	2ℓ(T), OC Z-veto	$N_\tau + N_{\text{anti-ID }\tau} = 2$	$N_{jet} \geq 1$	$N_{b\text{-jet}} = 1$	–
2ℓ+$2\tau_{had}$	Fake-$\tau_{had\text{-}vis}$ CR	–	$(N_\tau = 1, N_{\text{anti-ID }\tau} = 1)$ or $N_{\text{anti-ID }\tau} = 2$	–	–	–
	Fake-$\tau_{had\text{-}vis}$ VR	–	SC $\tau_{had\text{-}vis}$	–	–	–
ℓ+$2\tau_{had}$	Fake-$\tau_{had\text{-}vis}$ CR	–	$(N_\tau = 1, N_{\text{anti-ID }\tau} = 1)$ or $N_{\text{anti-ID }\tau} = 2$	–	–	–
	Fake-$\tau_{had\text{-}vis}$ VR	–	SC $\tau_{had\text{-}vis}$	–	–	–

BDT inputs

Variable	Description	4ℓ+$2b$	3ℓ	2ℓSC
$p_{\mathrm{T}}(\ell_i)$	p_{T} of the ith lepton	$i = 1,2,3,4$	–	–
$\lvert\eta(\ell_i)\rvert$	Absolute η of the ith lepton	$i = 1,2,3,4$	–	$i = 1,2$
$E_{\mathrm{T}}^{\Delta R<0.3}/E_{\mathrm{T}}(\ell_i)$	Isolation metric (where $E_{\mathrm{T}}^{\Delta R<0.3}$ = total transverse energy deposited in a cone of radius R = 0.3 around the lepton, and E_{T} = lepton transverse energy)	$i = 1,2,3,4$	–	–
Dilepton type	$\mu\mu$ = 1, $e\mu/\mu e$ = 2, ee = 3	–	–	✓
m_{ℓ_i,ℓ_j}	Invariant mass of the ith and jth leptons	–	$i,j = 1,2$ $i,j = 1,3$ $i,j = 2,3$	$i,j = 1,2$
$m^{\mathrm{SFOC}}_{\text{on-shell-}\ell\ell}$	Invariant mass of pair of SFOC leptons that minimises the difference with the Z boson mass	✓	✓	–
$m^{\mathrm{SFOC}}_{\text{off-shell-}\ell\ell}$	Invariant mass of the other SFOC lepton pair	✓	–	–
min. $m^{\mathrm{SFOC}}_{\ell\ell}$	Minimum invariant mass out of all SFOC pairs	–	✓	–
$m_{4\ell}$	Invariant mass of four leptons	✓	–	–
$m_{3\ell}$	Invariant mass of three leptons	–	✓	–
$m_{\ell_i,\text{close-jet}}$	Invariant mass of the ith lepton and its closest jet	–	$i = 1,2,3$	$i = 1,2$
$m_{3\ell\mathrm{jj}}$	Invariant mass of the three leptons and the leading (or two leading, for events with $N_{\mathrm{jet}} \geq 2$) jets	–	✓	–
m_{jj}	Invariant mass of the two leading jets	✓	–	–
m_{all}	Invariant mass of all selected objects in the event	–	–	✓
$m_{\mathrm{T}}^{W}(\ell_i, E_{\mathrm{T}}^{\mathrm{miss}})$	Transverse mass of the ith lepton and the $E_{\mathrm{T}}^{\mathrm{miss}}$	–	–	$i = 1,2$
$\Delta\eta(\ell_1,\ell_2)$	Separation in η between the first and second leptons	–	–	✓
$\Delta R(\ell_i,\ell_j)$	Separation in R between the ith and jth leptons	–	$i,j = 1,2$ $i,j = 1,3$ $i,j = 2,3$	$i,j = 1,2$
$\Delta R(\ell_i,\text{close-jet})$	Separation in R between the ith lepton and its closest jet	–	$i = 1,2,3$	$i = 1,2$
min. $\Delta R(\ell,\mathrm{j})$	Minimum separation in R between any lepton and any jet	–	–	✓
L_{T}	Scalar sum of the p_{T} of all leptons and the $E_{\mathrm{T}}^{\mathrm{miss}}$	–	✓	✓
H_{T}	Scalar sum of the p_{T} of all jets	–	✓	✓
S_{T}	Scalar sum of the p_{T} of all objects in the event	✓	✓	–
ΣQ_ℓ	Sum of all lepton charges	–	–	✓
N_{jet}	Number of jets in the event	–	–	✓
$N_{b\text{-jet}}$	Number of b-jets in the event	✓	–	–
$p_{\mathrm{T}}(\mathrm{j}_1)$	p_{T} of the leading jet	✓	–	–
$p_{\mathrm{T}}(\mathrm{jj})$	p_{T} of the leading dijet system	✓	–	–
$E_{\mathrm{T}}^{\mathrm{miss}}$	Magnitude of the missing transverse momentum	✓	✓	✓
$\Delta\phi(E_{\mathrm{T}}^{\mathrm{miss}},\mathrm{j}_1)$	ϕ angle between the $E_{\mathrm{T}}^{\mathrm{miss}}$ and the leading jet	✓	–	–

Variable	Description	2ℓSC+τ_{had}	2ℓ+$2\tau_{\mathrm{had}}$	ℓ+$2\tau_{\mathrm{had}}$
Dilepton type	$\mu\mu$ = 1, $e\mu/\mu e$ = 2, ee = 3	–	✓	–
$m_{\ell_1\ell_2}$	Invariant mass of the two leptons	–	✓	–
$m_{\ell_1,\text{close-jet}}$	Invariant mass of the leading lepton and its closest jet	✓	–	✓
$m_{\ell_i\mathrm{j}_j}$	Invariant mass of the ith lepton and jth jet	$i,j = 1,1$ $i,j = 1,2$ $i,j = 2,1$	–	–
$\Delta\eta(\ell,\ell)$	Separation in η between the two leptons	✓	–	–
$\Delta R(\ell,\ell)$	Separation in R between the two leptons	✓	✓	–
$\Delta R(\ell_i,\mathrm{j}_j)$	Separation in R between the ith lepton and jth jet	$i,j = 1,1$	–	$i,j = 1,1$ $i,j = 1,2$
$\Delta R(\ell_i,\text{close-jet})$	Separation in R between the ith lepton and its closest jet	$i = 1,2$	–	–
$p_{\mathrm{T}}(\mathrm{j}_1)$	p_{T} of the leading jet	–	–	✓
$E_{\mathrm{T}}^{\mathrm{miss}}$	Magnitude of the missing transverse momentum	–	–	✓
$\theta^{\text{boost-}\ell\ell}_{\tau_{\mathrm{had}},\mathrm{j}_i}$	Polar angle between the $\tau_{\text{had-vis}}$ and the ith jet after a Lorentz boost to the dilepton system	$i = 1,2$	–	–
$\Delta R^{\text{boost-}\ell_i\tau_{\mathrm{had}}}_{\ell_i,\mathrm{j}_j}$	Separation in R between the ith lepton and jth jet after a Lorentz boost to the $\tau_{\text{had-vis}}$ and ith lepton system	$i,j = 1,2$ $i,j = 2,1$	–	–
$m_{\tau\tau}$	Invariant mass of the two $\tau_{\text{had-vis}}$	–	✓	✓
$\Delta R(\ell_2,\tau_1)$	Separation in R between the second lepton and first $\tau_{\text{had-vis}}$	–	✓	–
$\Delta R(\ell_1,\tau\tau)$	Separation in R between the first lepton and the di-$\tau_{\text{had-vis}}$ system	–	✓	✓
$m_{\ell_2\tau_1}$	Invariant mass of the second lepton and first $\tau_{\text{had-vis}}$	–	✓	–
$m_{\ell\tau\tau}$	Invariant mass of the lepton and two $\tau_{\text{had-vis}}$	–	–	✓
$p_{\mathrm{T}}(\ell + \text{close-jet})$	Vector sum of the p_{T} of the lepton and its closest jet	–	–	✓
$p_{\mathrm{T}}(\tau_1 + \tau_2)$	Vector sum of the p_{T} of the two $\tau_{\text{had-vis}}$	–	✓	✓

Variable	Description	$\gamma\gamma$+ℓ	$\gamma\gamma$+τ_{had}
$p_{\mathrm{T}}(\gamma\gamma)$	p_{T} of the diphoton system	✓	✓
$p_{\mathrm{T}}(\ell)$	p_{T} of the lepton	✓	–
$p_{\mathrm{T}}(\tau_{\text{had-vis}})$	p_{T} of the $\tau_{\text{had-vis}}$	–	✓
$E_{\mathrm{T}}^{\mathrm{miss}}$	Magnitude of the missing transverse momentum	✓	✓
$\phi(E_{\mathrm{T}}^{\mathrm{miss}})$	ϕ direction of the $E_{\mathrm{T}}^{\mathrm{miss}}$	–	✓
$\eta(\ell E_{\mathrm{T}}^{\mathrm{miss}})$	η of the lepton-$E_{\mathrm{T}}^{\mathrm{miss}}$ system	✓	–
$\eta(\gamma_1)$	η of the leading photon	–	✓
$N_{\text{central-jets}}$	Number of jets with $\lvert\eta\rvert < 2.5$	✓	✓
$\Delta R(\ell, E_{\mathrm{T}}^{\mathrm{miss}})$	ΔR between the lepton and the $E_{\mathrm{T}}^{\mathrm{miss}}$	✓	–
$\Delta R(\gamma\gamma, \ell E_{\mathrm{T}}^{\mathrm{miss}})$	ΔR between the diphoton system and the lepton-$E_{\mathrm{T}}^{\mathrm{miss}}$ system	✓	–
$\Delta\phi(\ell/\tau_{\text{had-vis}}, \gamma\gamma)$	Separation in ϕ between the lepton or $\tau_{\text{had-vis}}$ and the diphoton system	✓	✓
$\Delta\phi(\gamma_1, \gamma\gamma)$	Separation in ϕ between the leading photon and the diphoton system	✓	✓
min. $\Delta\phi(E_{\mathrm{T}}^{\mathrm{miss}}, \mathrm{j}, \ell)$	Minimum ϕ angle between any pair of the $E_{\mathrm{T}}^{\mathrm{miss}}$, the lepton, and any jet	✓	–
$\Delta\phi(E_{\mathrm{T}}^{\mathrm{miss}}, \gamma\gamma)$	Separation in ϕ between the $E_{\mathrm{T}}^{\mathrm{miss}}$ and the diphoton system	✓	✓

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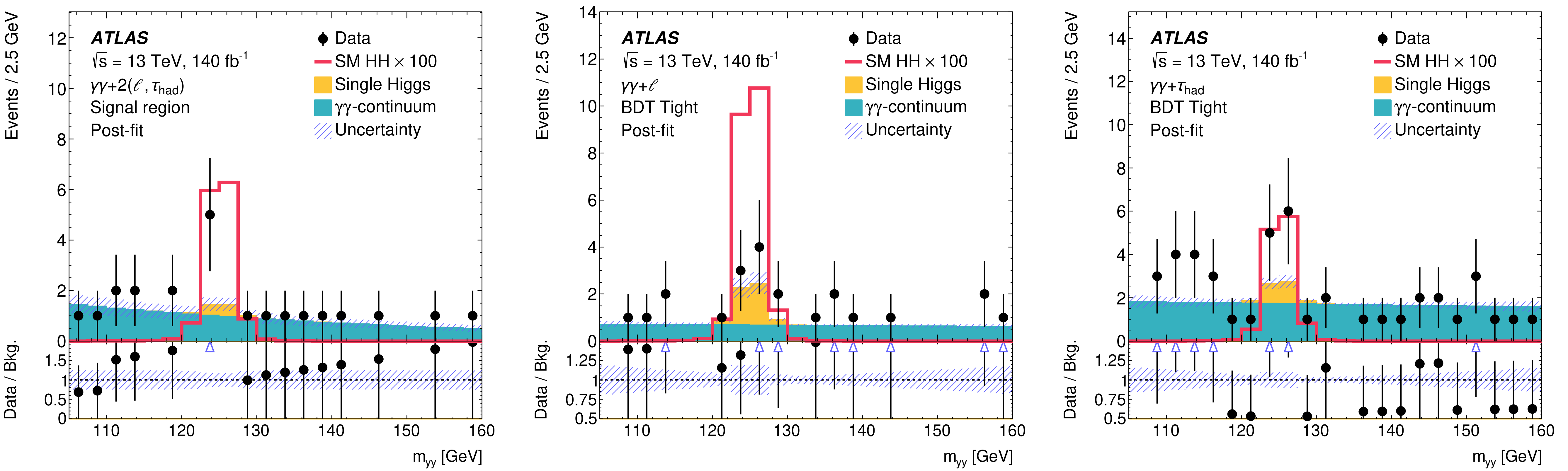
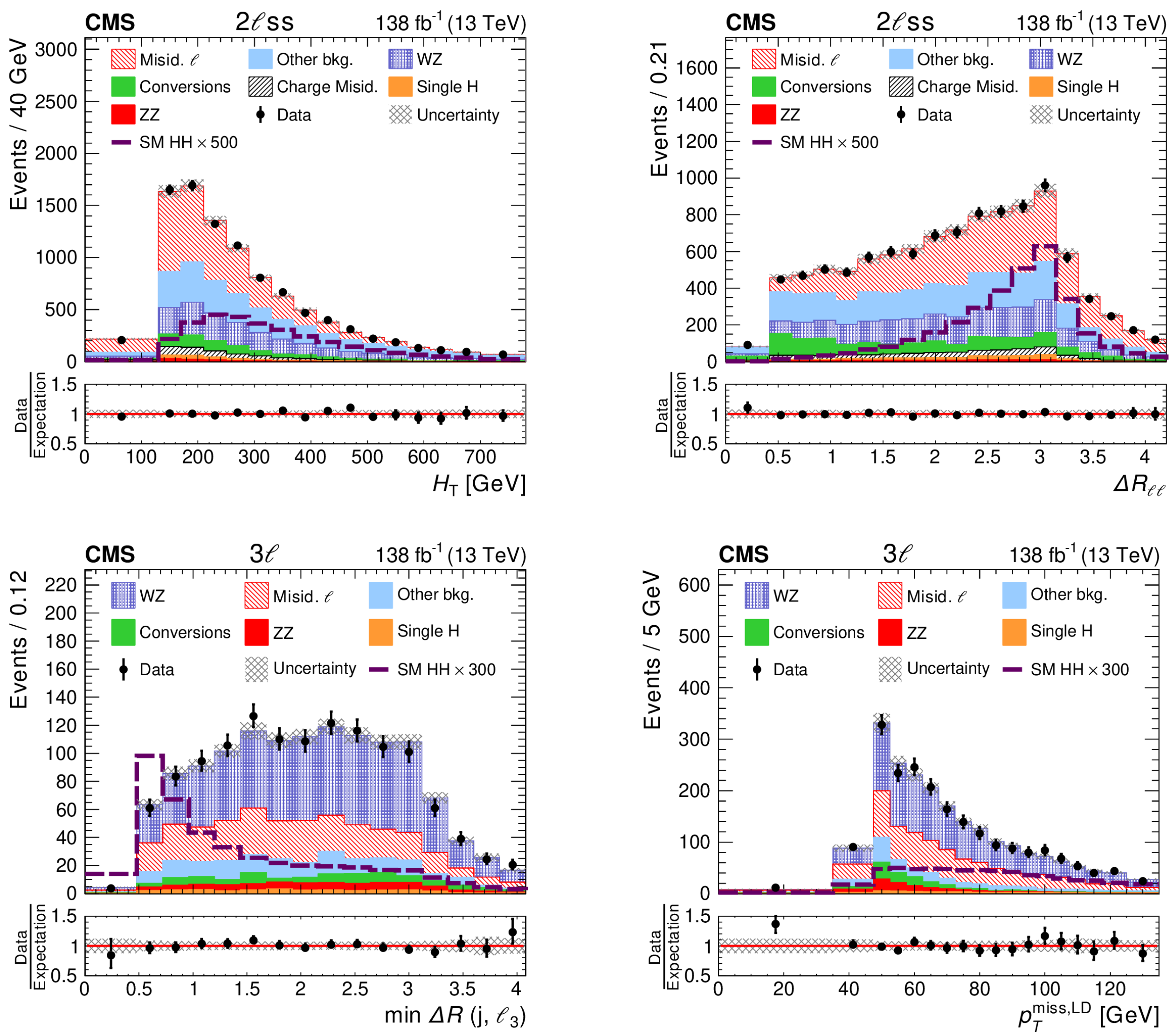
Systematic Uncertainties

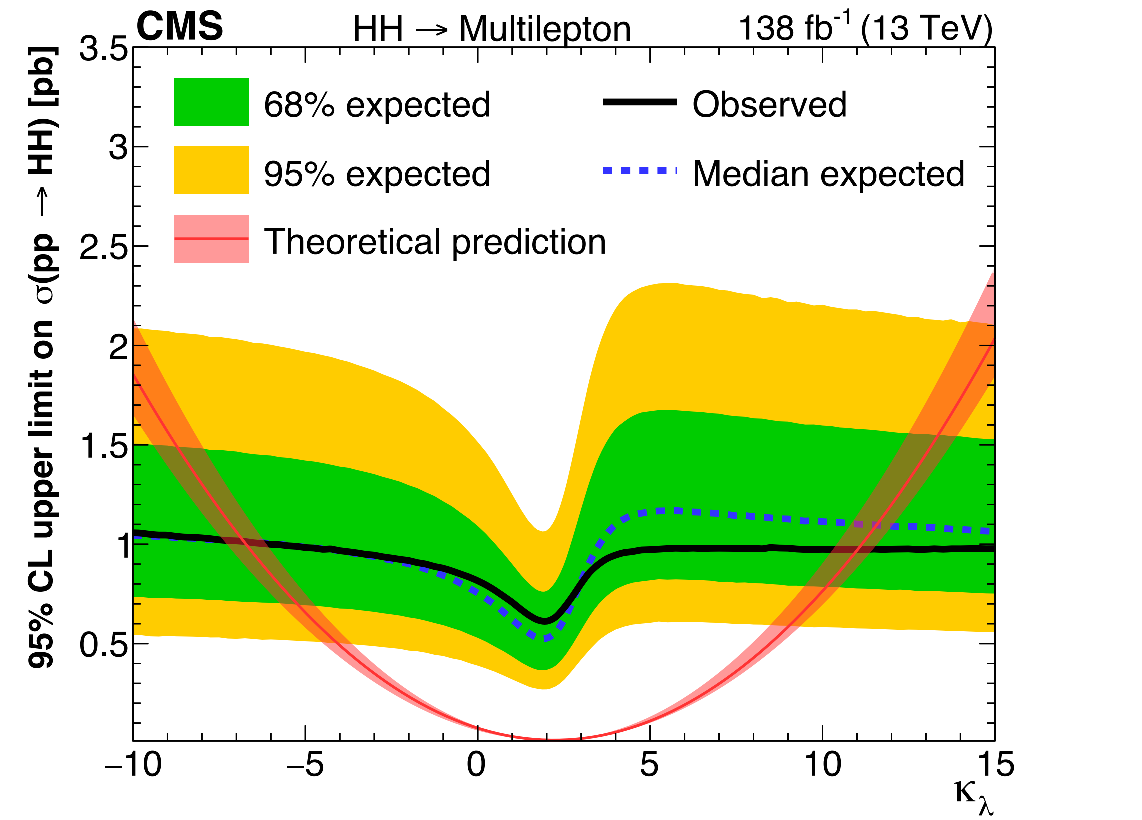
Systematic uncertainty source	Relative impact of systematic uncertainties [%]		
	ML channels	$\gamma\gamma$+ML channels	Combination
Total	22	14	19
MC statistics	5	<1	3
Experimental	5	<1	3
Detector response	4		3
Jets and E_T^{miss}	3		2
Flavour tagging	1		<1
Background estimate	<1	<1	<1
Theoretical	13	14	13
Signal	10	12	11
Backgrounds	4	2	3
Top quark	1	–	<1
Vector boson	3	–	2
Single Higgs boson	1	2	1
Other	<1	–	<1

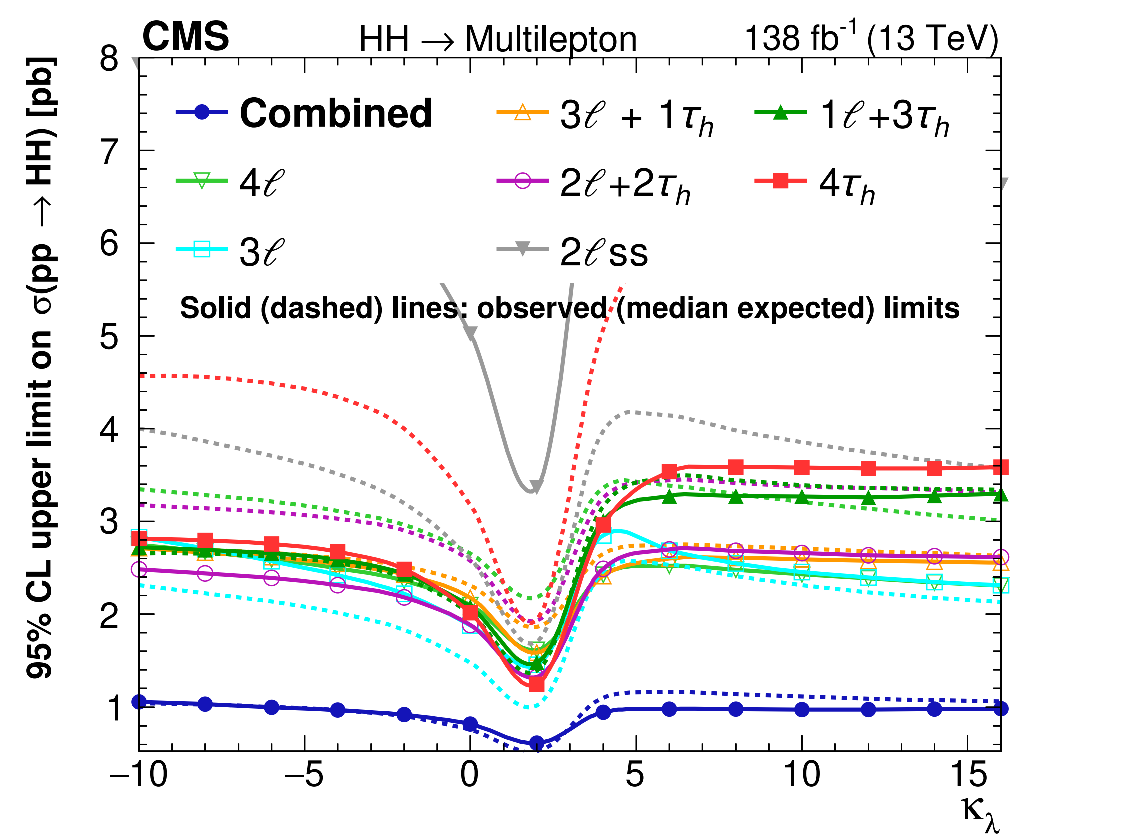


JHEP 07 (2023) 095 (Multilepton)



Distributions in a few observables used as inputs to the BDT classifiers in the 2ℓss and 3ℓ categories



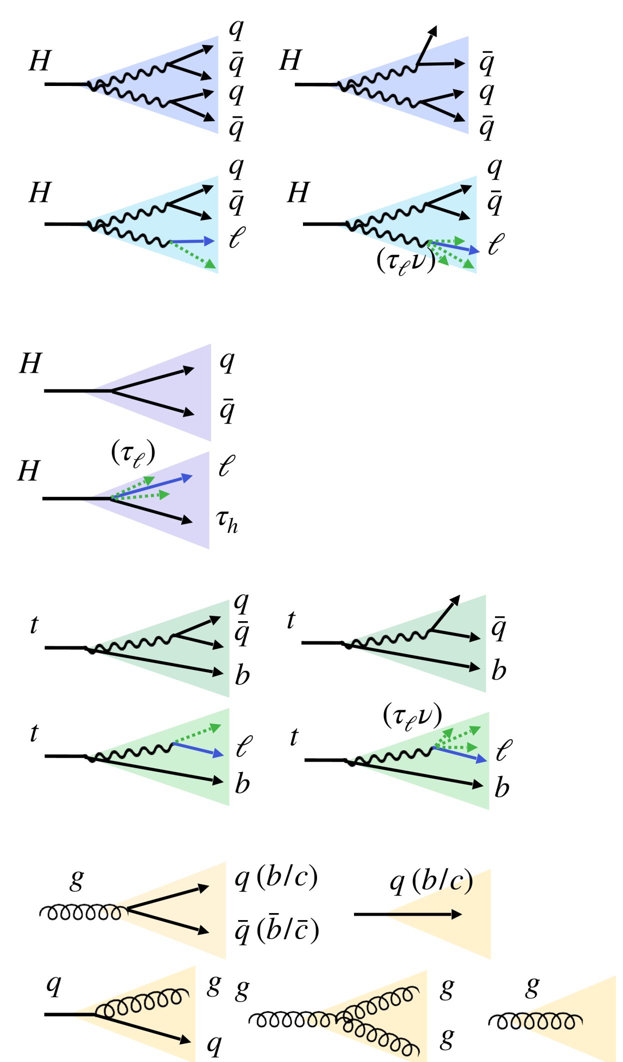


Input features into GloParT

Variable	Definition
charged PF candidates	
$\log p_{T}$	logarithm of the particle p_{T}
$\log E$	logarithm of the particle energy
$\Delta\eta$(jet)	difference in pseudorapidity between the particle and the jet axis
$\Delta\phi$(jet)	difference in azimuthal angle between the particle and the jet axis
$\lvert\eta\rvert$	absolute value of the particle pseudorapidity
q	electric charge of the particle
isMuon	true if the particle is identified as a muon
isElectron	true if the particle is identified as an electron
isChargedHadron	true if the particle is identified as a charged hadron
pvAssociationQuality	flag related to the association of the track to the primary vertices
lostInnerHits	quality flag of the track related to missing hits on the pixel layers
χ^2/dof	χ^2 value of the trajectory fit normalized to the number of degrees of freedom
qualityMask	quality flag of the track
d_z	longitudinal impact parameter of the track
d_z/σ_{d_z}	significance of the longitudinal impact parameter
d_{xy}	transverse impact parameter of the track
$d_{xy}/\sigma_{d_{xy}}$	significance of the transverse impact parameter
η_{rel}	pseudorapidity of the track relative to the jet axis
$p_{T,rel}$ ratio	track momentum perpendicular to the jet axis, divided by the magnitude of the track momentum
$p_{par,rel}$ ratio	track momentum parallel to the jet axis divided by the magnitude of the track momentum
d_{3D}	signed 3D impact parameter of the track
d_{3D}/σ_{3D}	signed 3D impact parameter significance of the track
trackDistance	distance between the track and the jet axis at their point of closest approach
Neutral PF candidates	
$\log p_{T}$	logarithm of the particle's p_{T}
$\log E$	logarithm of the particle's energy
$\Delta\eta$(jet)	difference in pseudorapidity between the particle and the jet axis
$\Delta\phi$(jet)	difference in azimuthal angle between the particle and the jet axis
$\lvert\eta\rvert$	absolute value of the particle pseudorapidity
isPhoton	true if the particle is identified as a photon
isNeutralHadron	true if the particle is identified as a neutral hadron
For SVs within the jet cone	
$\log p_{T}$	logarithm of the SV p_{T}
m_{SV}	invariant mass of the tracks associated with the SV
$\Delta\eta$(jet)	difference in pseudorapidity between the SV and the jet axis
$\Delta\phi$(jet)	difference in azimuthal angle between the SV and the jet axis
$\lvert\eta\rvert$	absolute value of the SV pseudorapidity
N_{tracks}	number of tracks associated with the SV
χ^2/dof	χ^2 value of the SV fit normalized to the number of degrees of freedom
d_{2D}	signed 2D impact parameter (i.e., in the transverse plane) of the SV
d_{2D}/σ_{2D}	signed 2D impact parameter significance of the SV
d_{3D}	signed 3D impact parameter of the SV
d_{3D}/σ_{3D}	signed 3D impact parameter significance of the SV

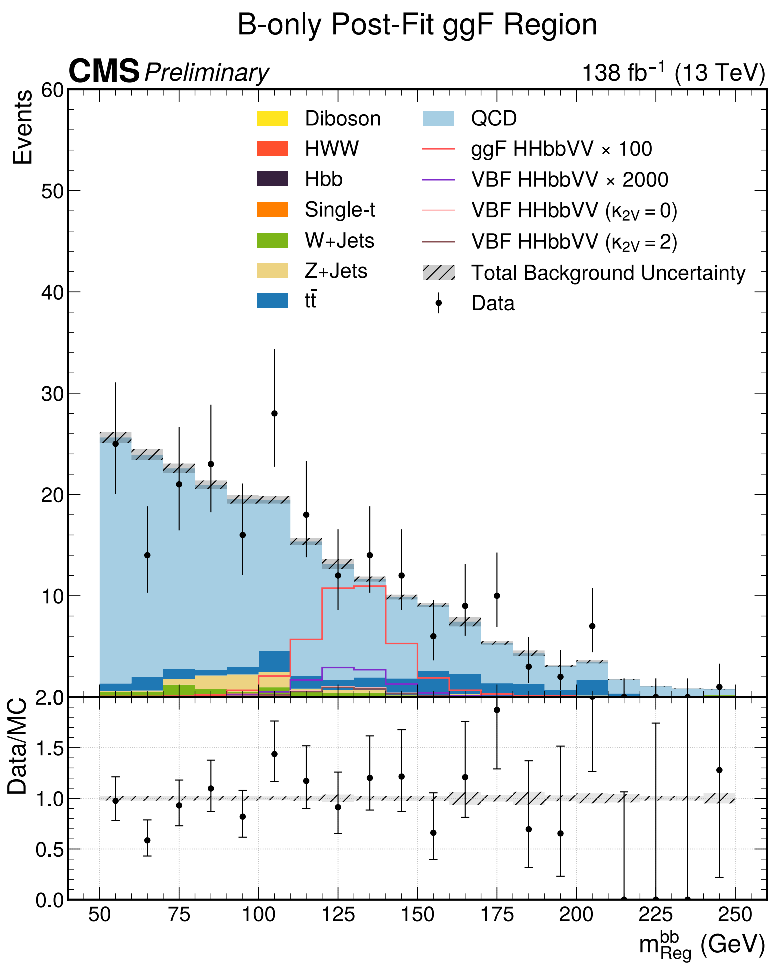
Training jet classes for GloParT

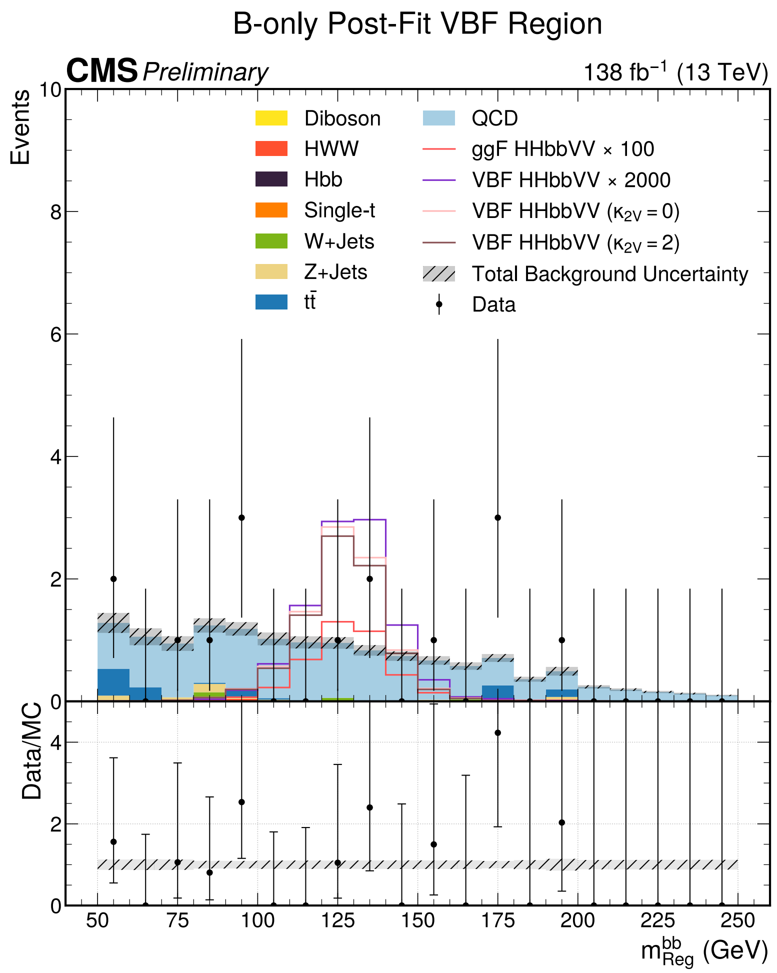
Process	Final state/ prongness	heavy flavour	# of classes
H→VV (full-hadronic)	qqqq	0c/1c/2c	3
	qqq		3
H→WW (semi-leptonic)	eνqq	0c/1c	2
	μνqq		2
	τ$_e$νqq		2
	τ$_μ$νqq		2
	τ$_h$νqq		2
H→qq		bb	1
		cc	1
		ss	1
		qq (q=u/d)	1
H→ττ	τ$_e$τ$_h$		1
	τ$_μ$τ$_h$		1
	τ$_h$τ$_h$		1
t→bW (hadronic)	bqq	1b + 0c/1c	2
	bq		2
t→bW (leptonic)	beν	1b	1
	bμν		1
	bτ$_e$ν		1
	bτ$_μ$ν		1
	bτ$_h$ν		1
QCD		b	1
		bb	1
		c	1
		cc	1
		others (light)	1

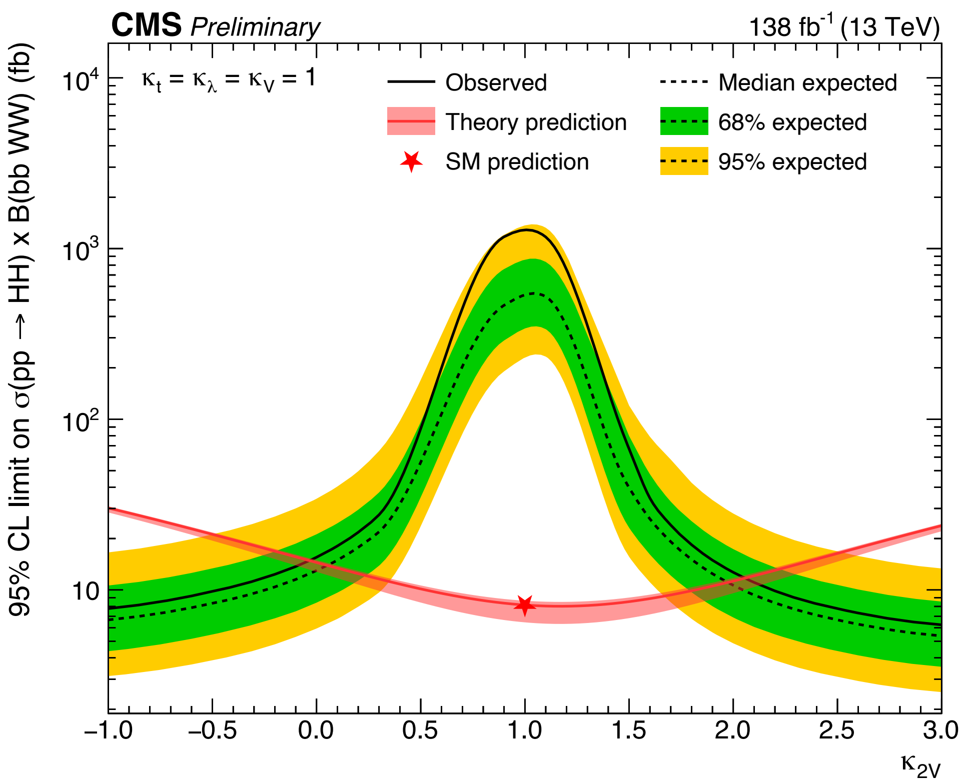


HH→bbVV (CMS)

CMS-PAS-HIG-23-012 (Preliminary) (bbVV)

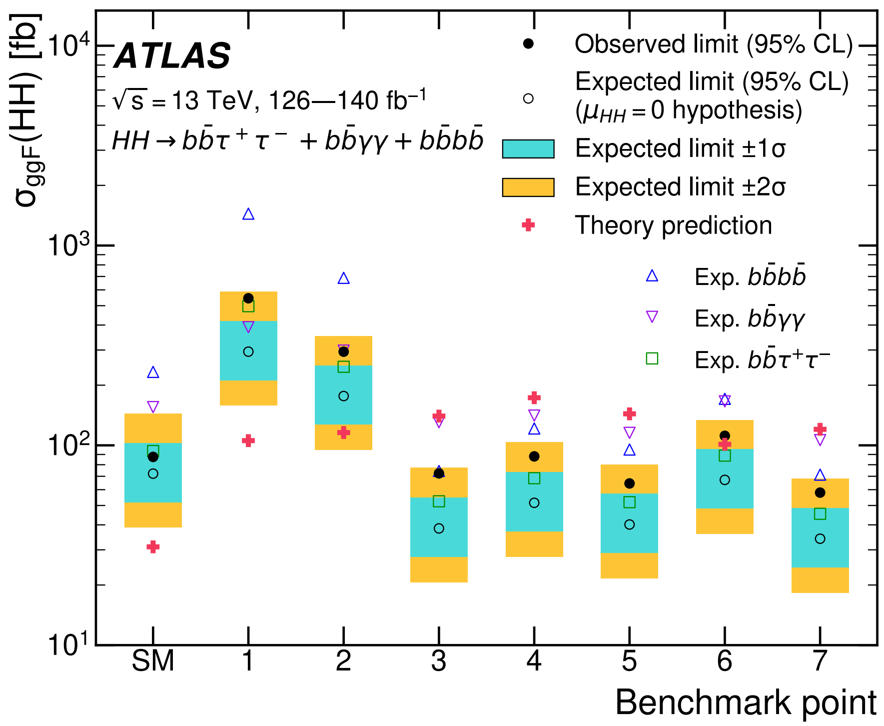




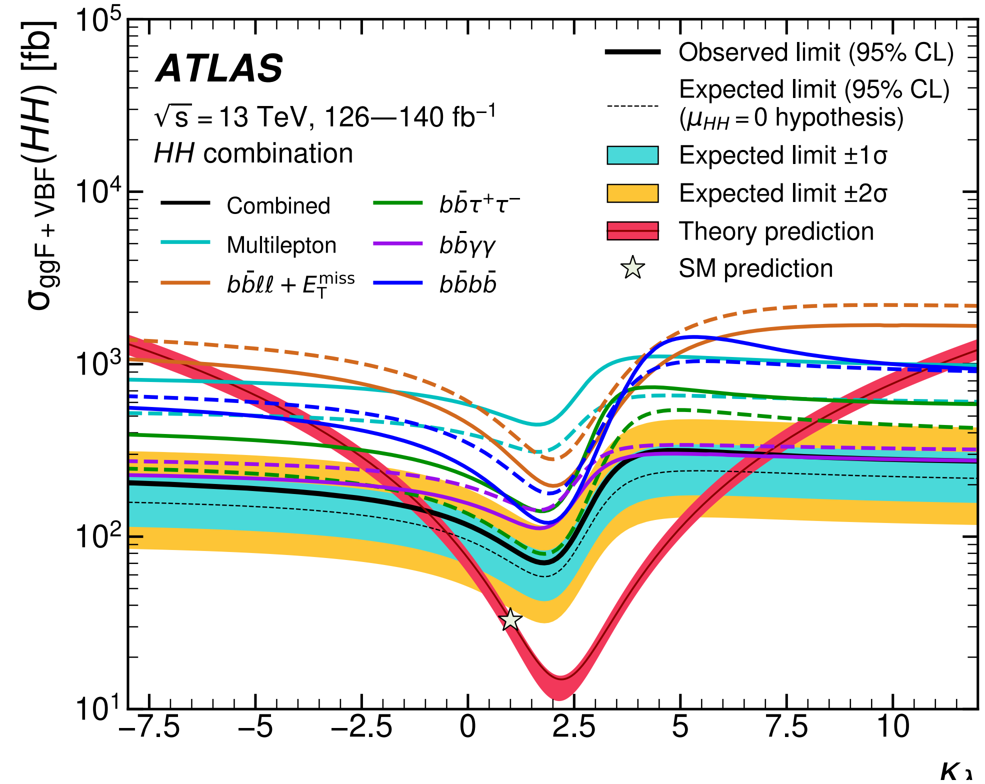


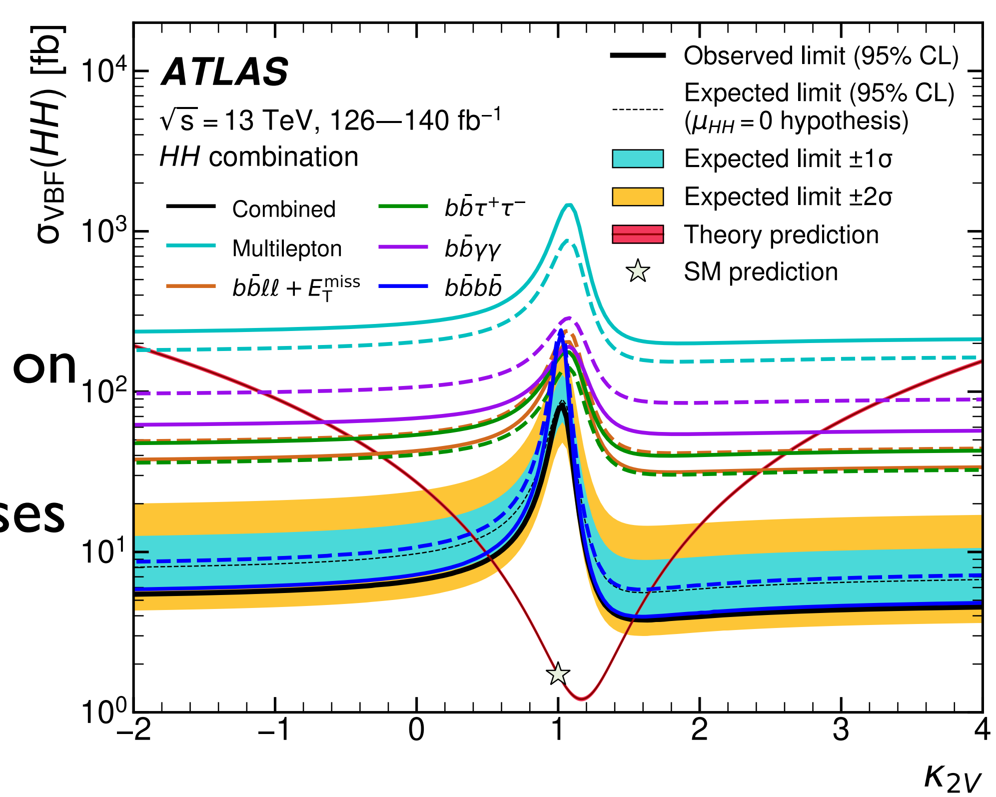
HH Combination (ATLAS)

Phys. Rev. Lett. 133 (2024) 101801



Observed and expected 95% CL combined upper limits on the cross-section for the SM and seven BSM HEFT benchmarks

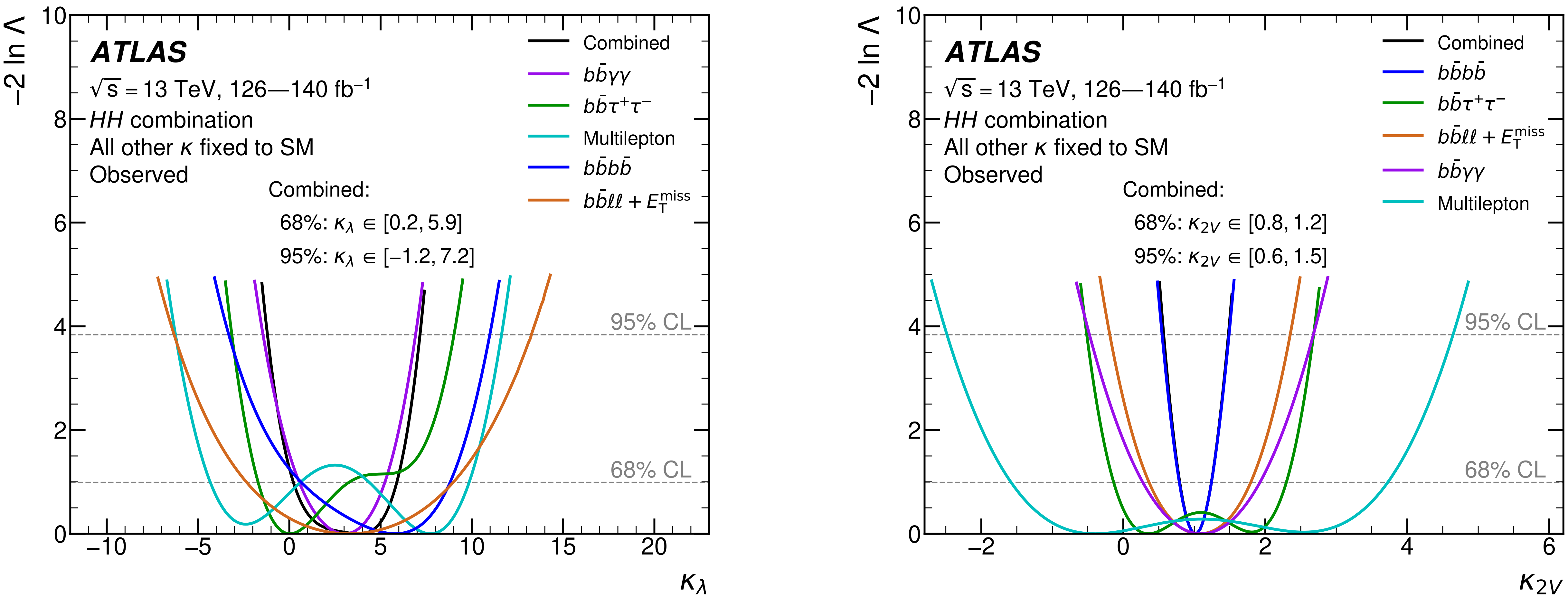




Observed/expected 95% CL limits on HH production cross-sections of (top) inclusive ggF and VBF processes as a function of κ_λ and (b) the VBF process as a function of κ_{2V}

HH Combination: Combined κ results (ATLAS)

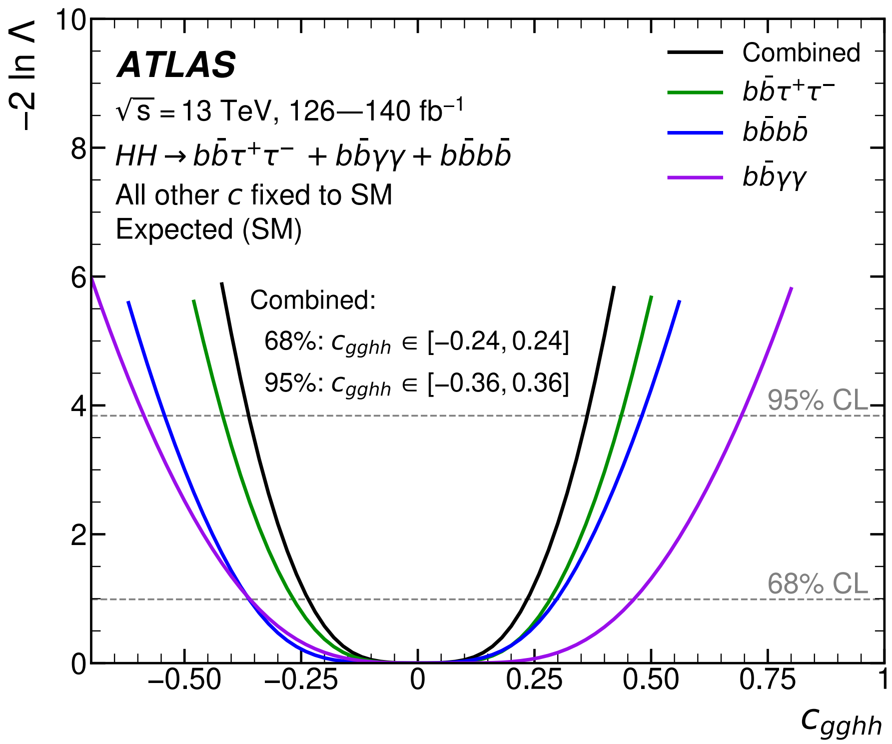
Phys. Rev. Lett. 133 (2024) 101801

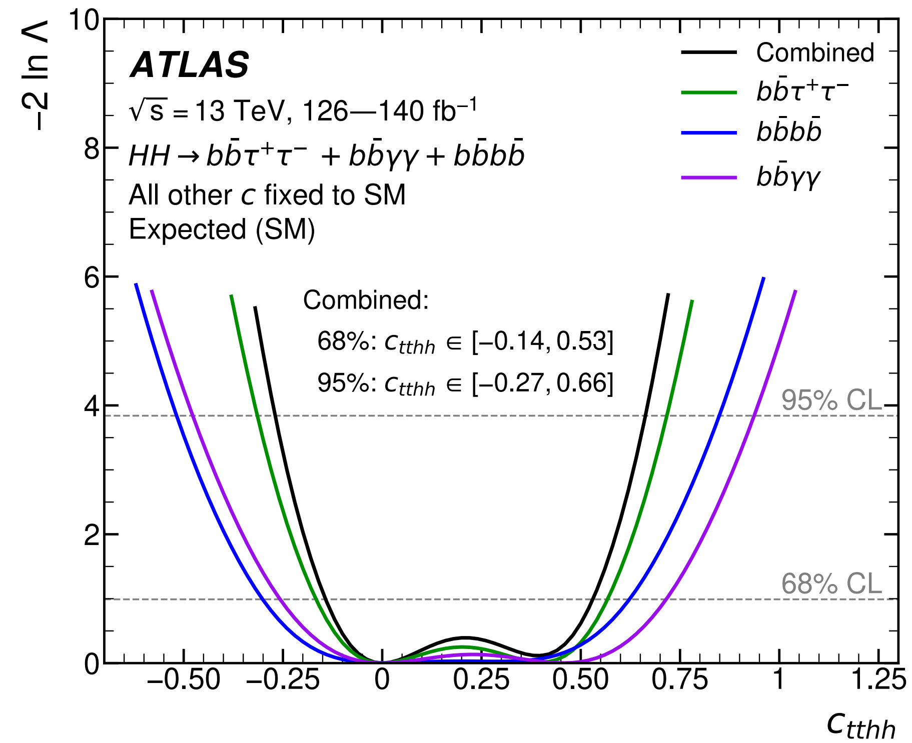


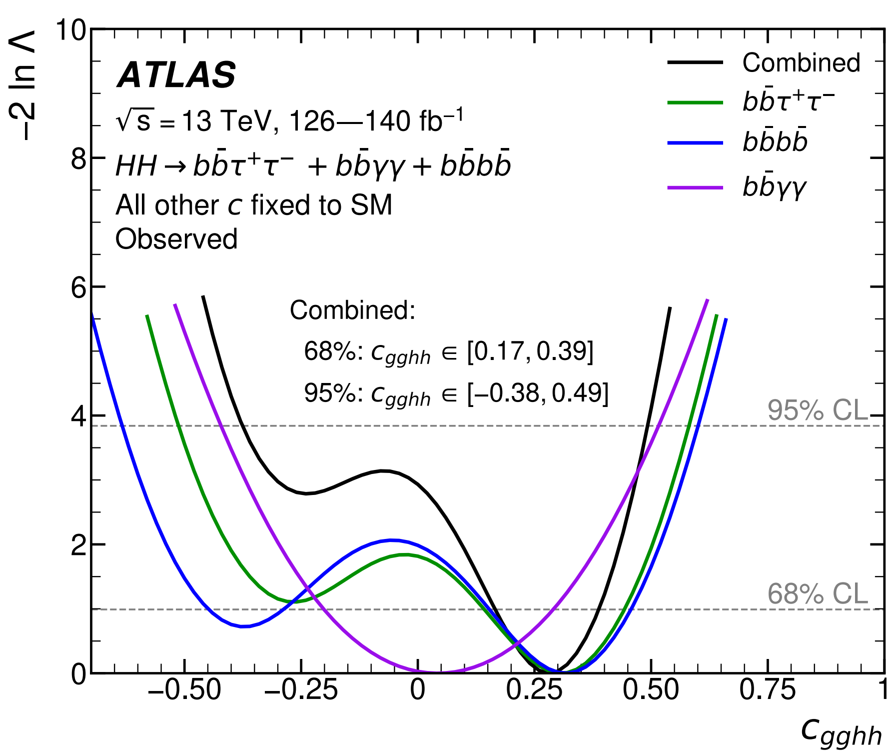
Measurement	κ_λ				κ_{2V}			
	68% CL		95% CL		68% CL		95% CL	
	Obs.	Exp.	Obs.	Exp.	Obs.	Exp.	Obs.	Exp.
κ_λ floating, $\kappa_{2V} = 1$	$3.8^{+2.1}_{-3.6}$	$1.0^{+4.7}_{-1.5}$	[−1.2, 7.2]	[−1.6, 7.2]	–	–	–	–
κ_{2V} floating, $\kappa_\lambda = 1$	–	–	–	–	$1.02^{+0.22}_{-0.23}$	$1.00^{+0.40}_{-0.36}$	[0.6, 1.5]	[0.4, 1.6]
κ_λ, κ_{2V} floating	$4.3^{+1.9}_{-4.0}$	$1.0^{+4.8}_{-1.5}$	[−1.2, 7.5]	[−1.7, 7.4]	$0.92^{+0.27}_{-0.25}$	$1.00^{+0.41}_{-0.38}$	[0.4, 1.4]	[0.3, 1.6]

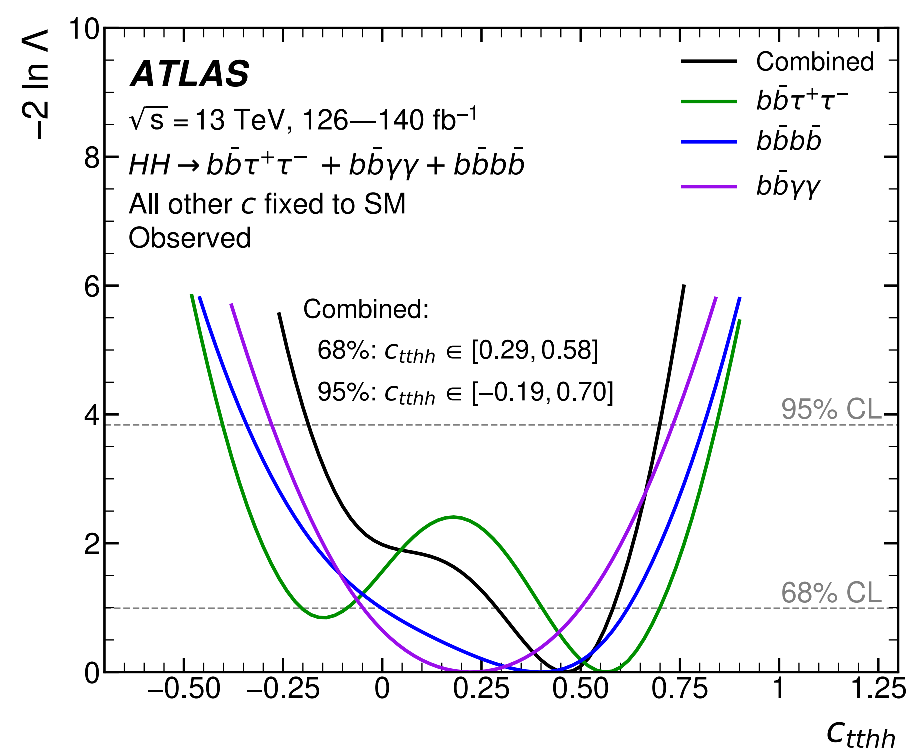
HH Combination: HEFT 1D Scans (ATLAS)

Phys. Rev. Lett. 133 (2024) 101801





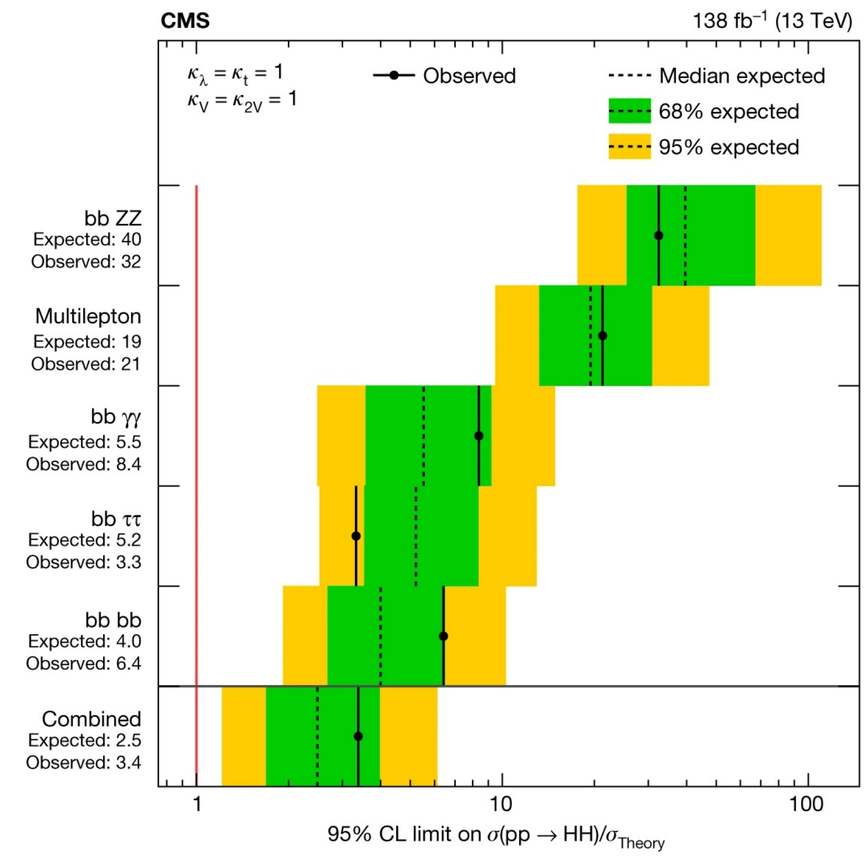




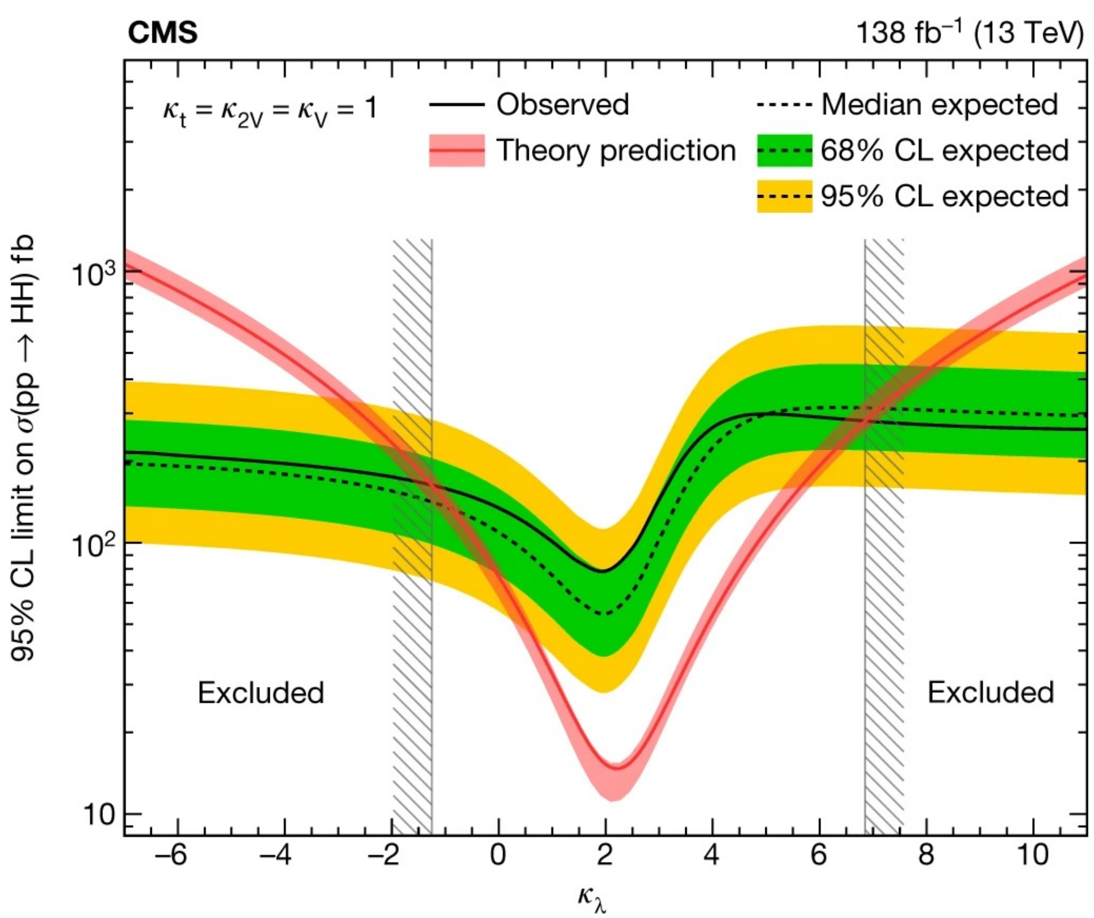
HH Combination (CMS)

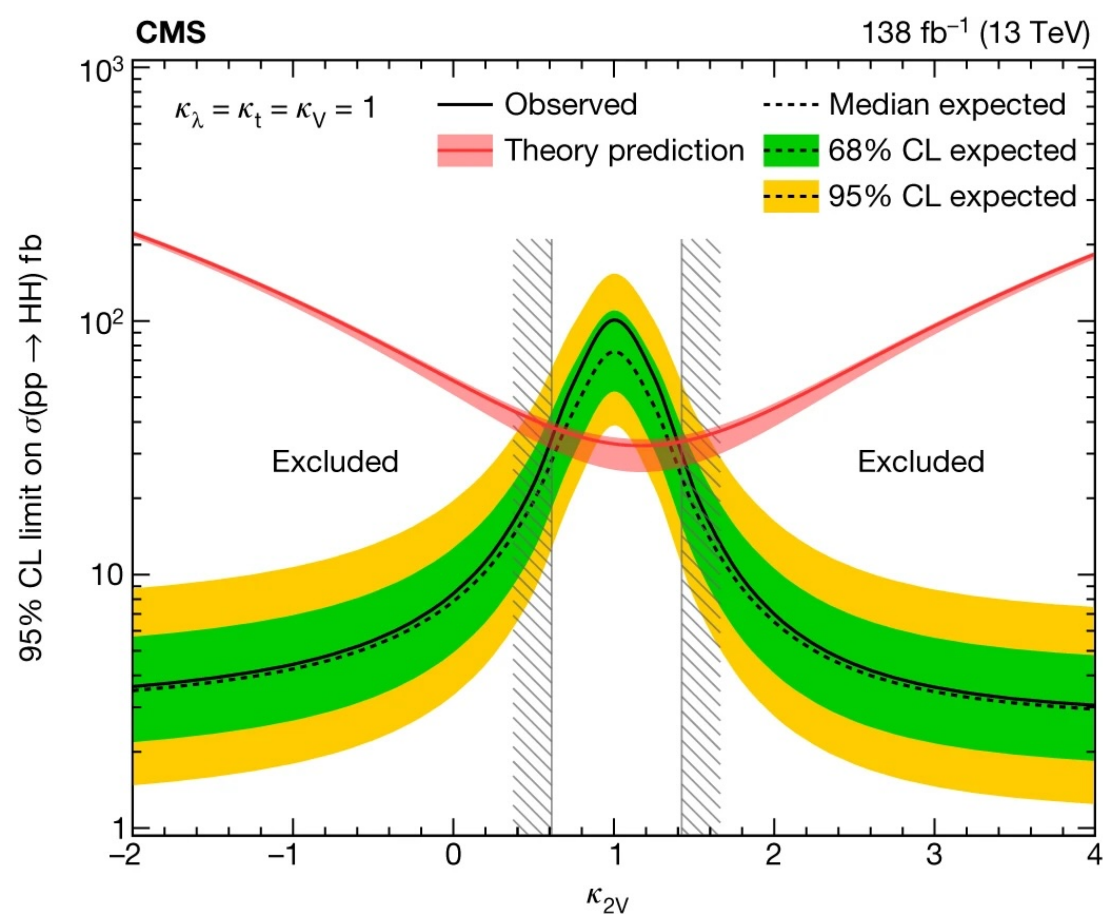
Nature volume 607, pages 60–68 (2022)

Observed and expected 95% CL combined upper limits on the signal strength



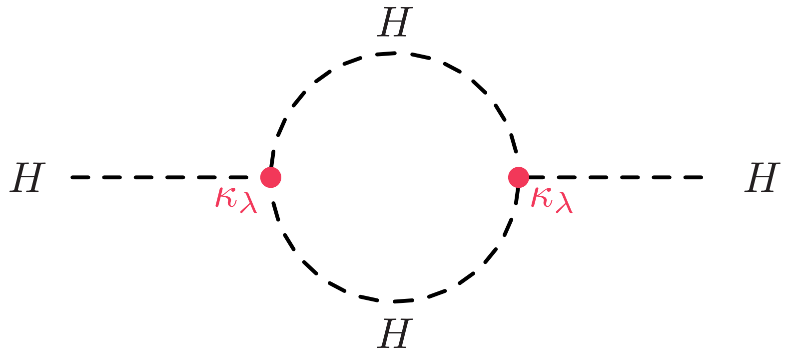
Combined expected and observed 95% CL upper limits on the HH production cross-section for different values of κ_λ (left) and κ_{2V} (right), assuming the SM values for the modifiers of Higgs boson couplings to top quarks and vector bosons

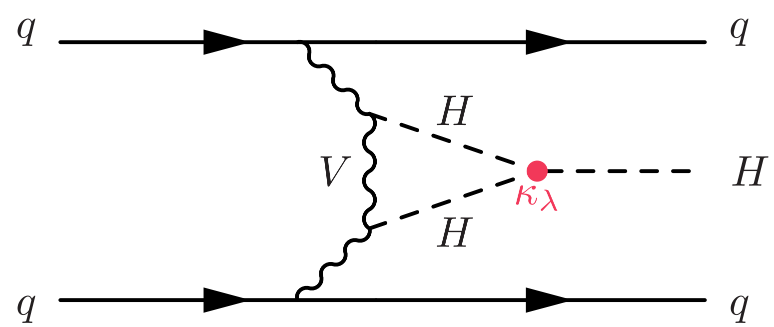




- κ_λ can affect single Higgs processes via NLO electroweak corrections

Higgs Self-Energy





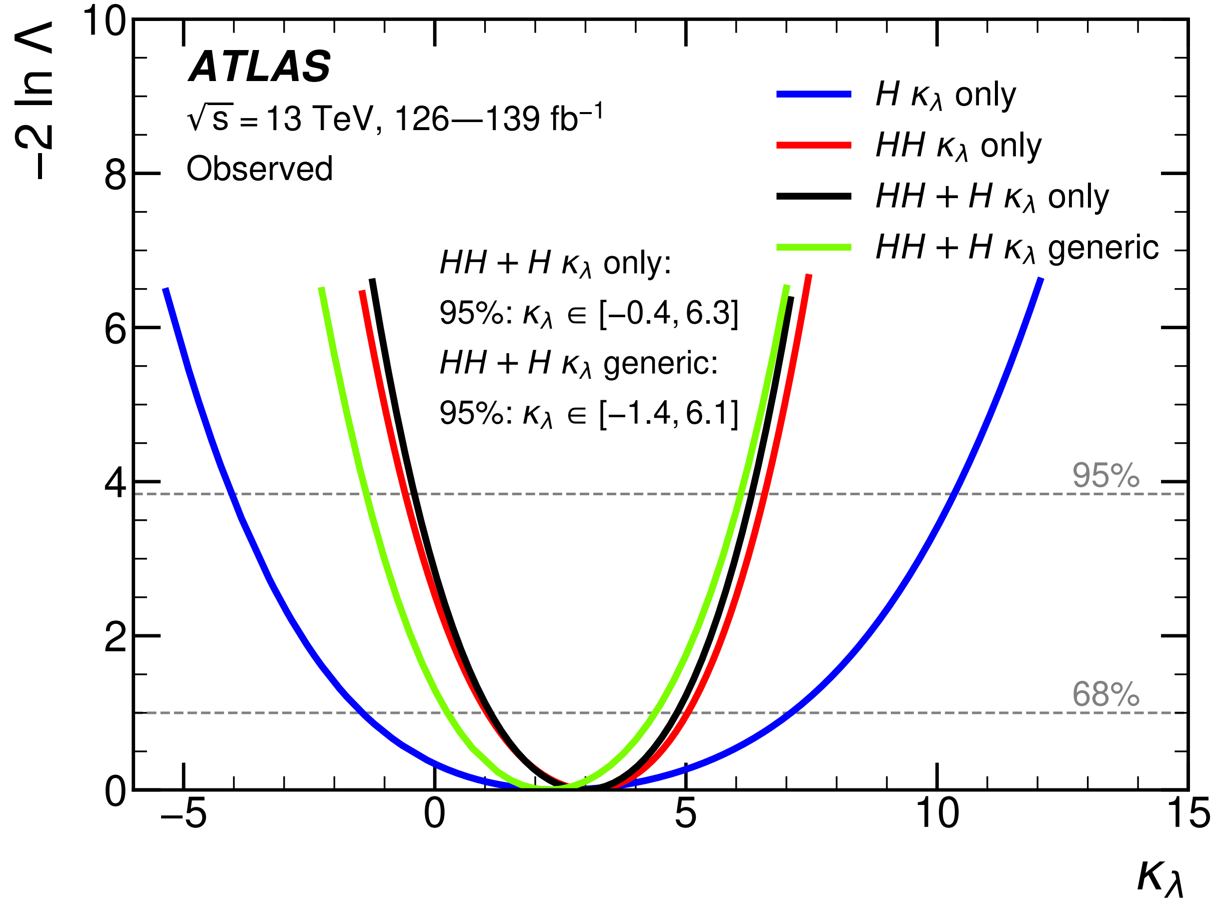
Higgs Production

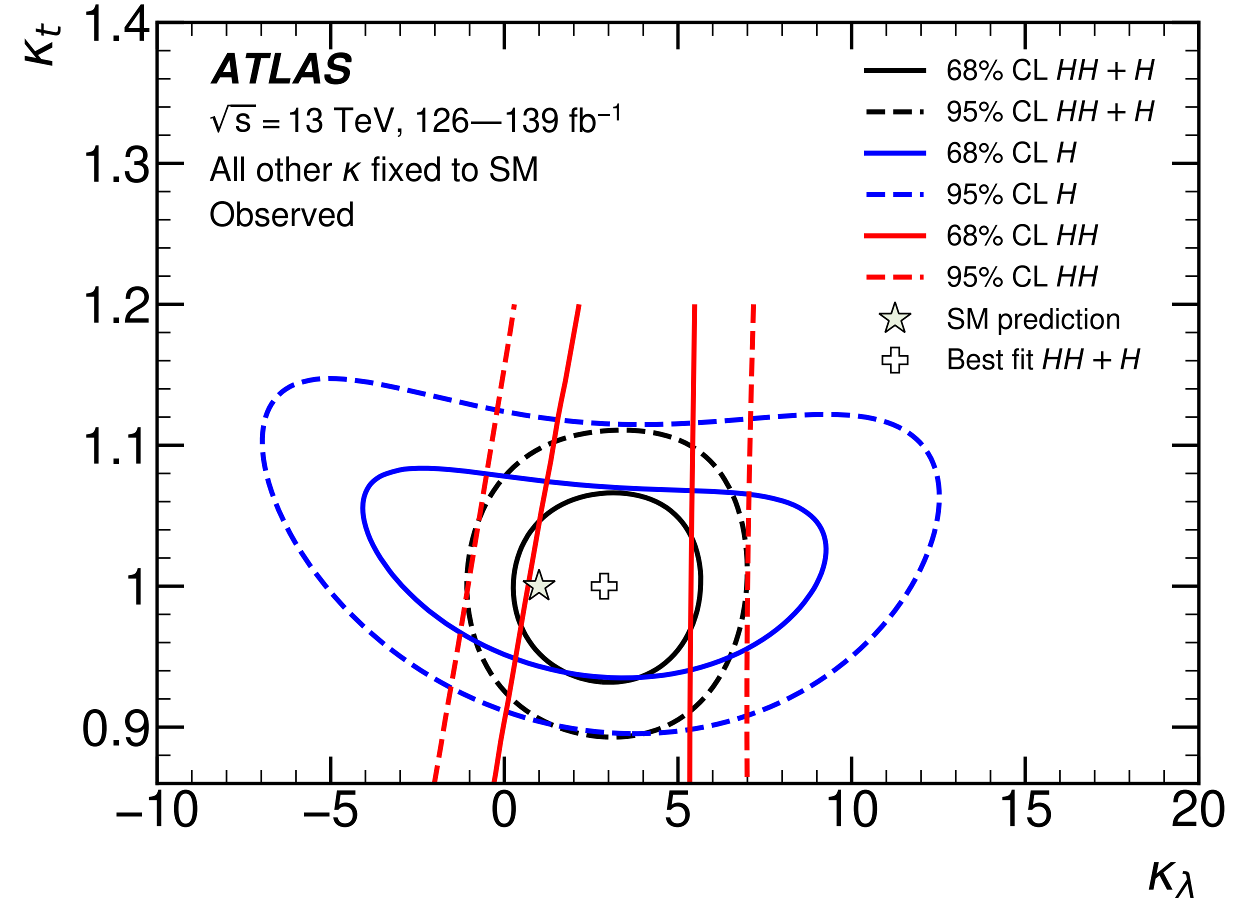
- Generic fit: couplings (κ_λ, κ_t, κ_b, κ_τ, κ_V) are all floating in the fit
- Dominated by HH while H provide strong constraints to other couplings.

Channel	Integrated luminosity [fb^{-1}]	Ref.
$HH \to b\bar{b}\gamma\gamma$	139	[17]
$HH \to b\bar{b}\tau^+\tau^-$	139	[18]
$HH \to b\bar{b}b\bar{b}$	126	[19]
$H \to \gamma\gamma$	139	[58]
$H \to ZZ^* \to 4\ell$	139	[59]
$H \to \tau^+\tau^-$	139	[60]
$H \to WW^* \to e\nu\mu\nu$ (ggF,VBF)	139	[61]
$H \to b\bar{b}$ (VH)	139	[62]
$H \to b\bar{b}$ (VBF)	126	[63]
$H \to b\bar{b}$ $(t\bar{t}H)$	139	[64]

Single H and HH Constraints (ATLAS)

Phys. Lett. B 843 (2023) 137745 (ATLAS)

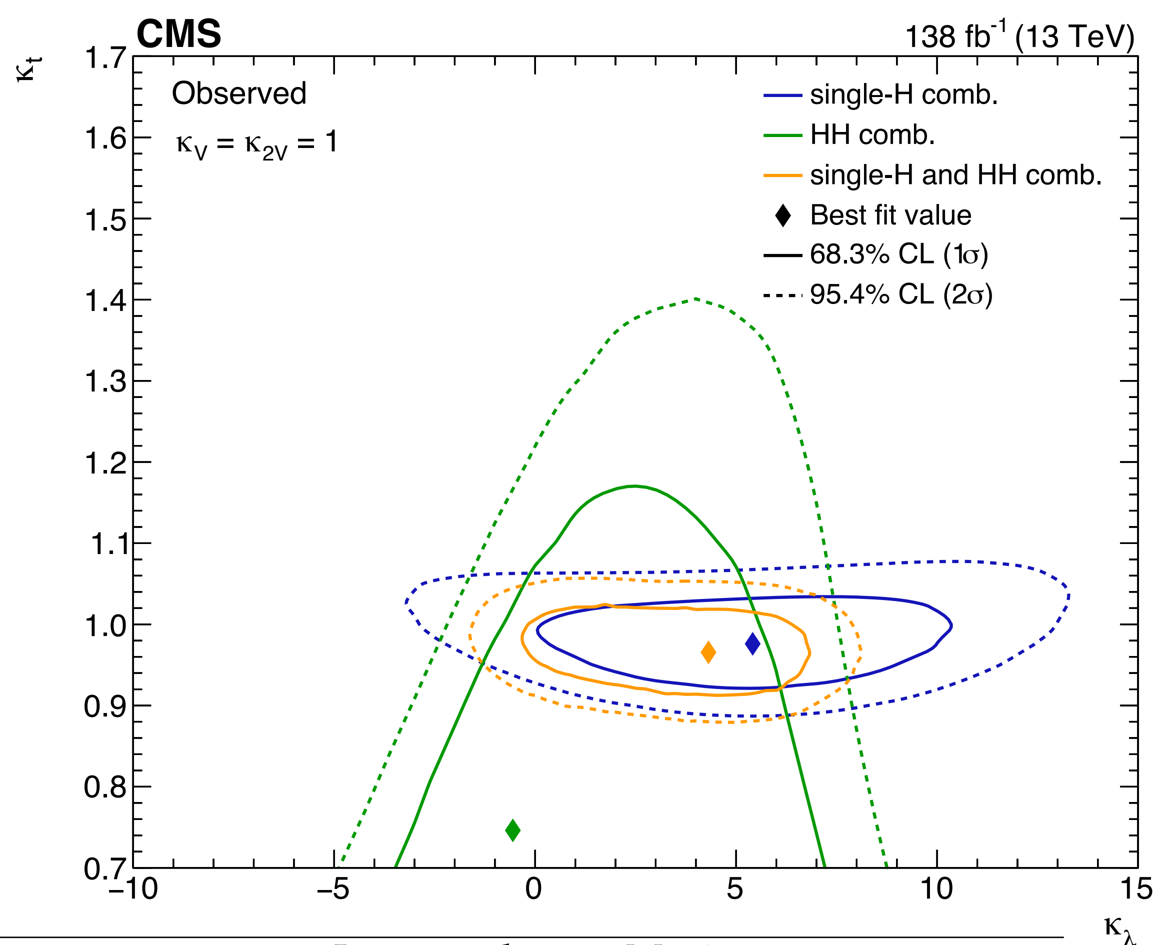


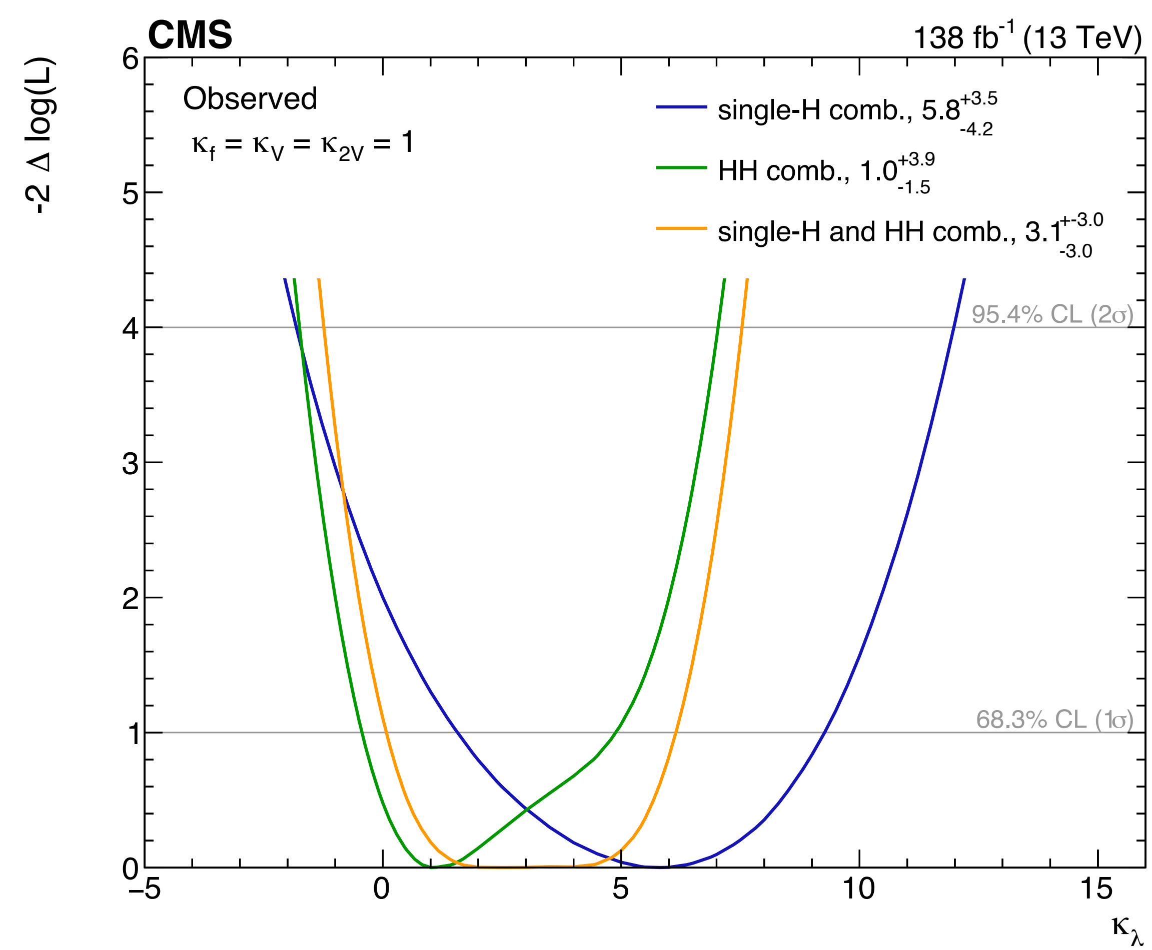


	Best Fit	Obs 95% CL	Exp 95% CL
κ_λ only	3.0	[-0.4, 6.3]	[-1.9, 7.6]
Generic fit	2.3	[-1.4, 6.1]	[-2.2, 7.7]

Single H and HH Constraints (CMS)

HIG-23-006 (Submitted to Phys. Lett. B) (CMS)





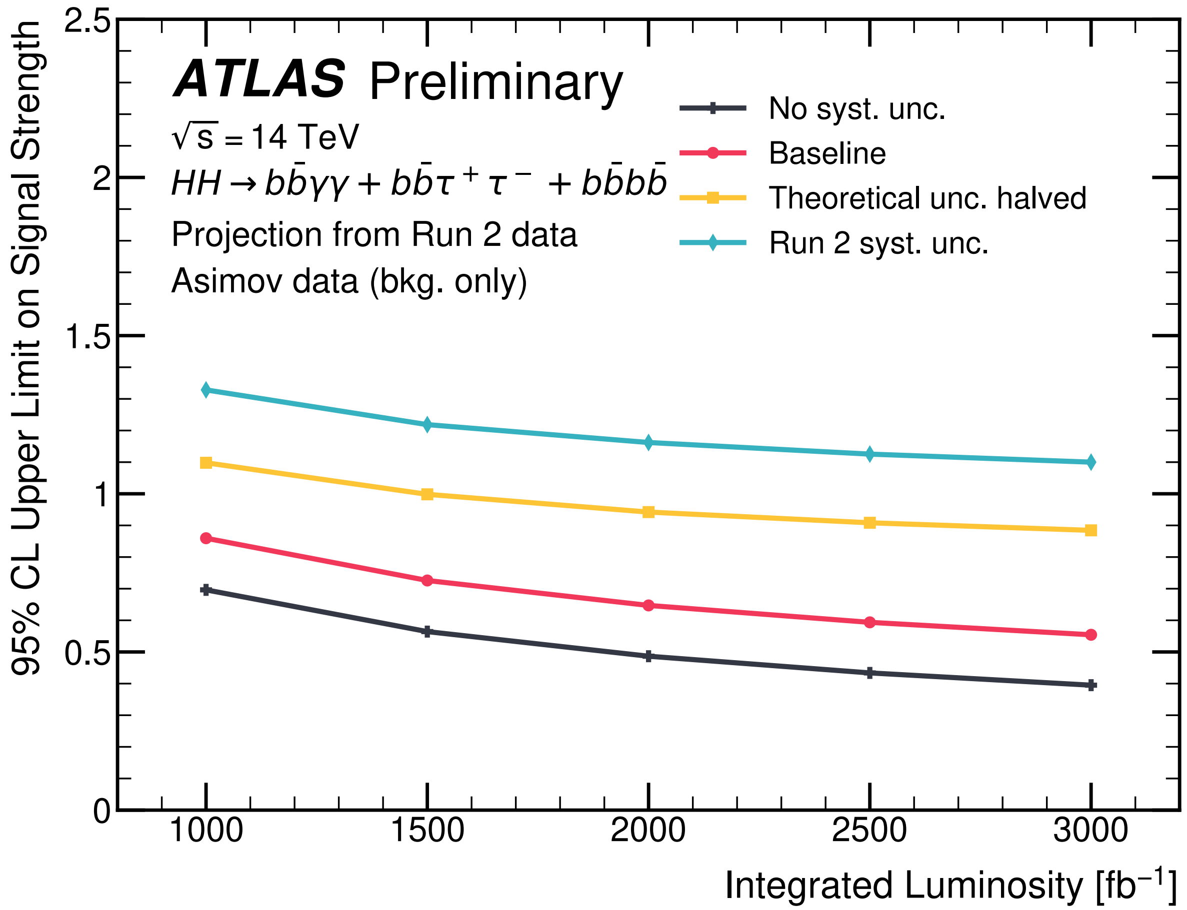
Analysis	Integrated luminosity (fb^{-1})	Maximum granularity	References
$H \to 4l$	138	STXS 1.2	[34]
$H \to \gamma\gamma$	138	STXS 1.2	[35,none]
$H \to WW$	138	STXS 1.2	[37]
$H \to$ leptons ($t\bar{t}H$)	138	Inclusive	[38]
$H \to b\bar{b}$ (ggH)	138	Inclusive	[39]
$H \to b\bar{b}$ (VH)	77	Inclusive	[40,41]
$H \to b\bar{b}$ ($t\bar{t}H$)	36	Inclusive	[42]
$H \to \tau\tau$	138	STXS 1.2	[43]
$H \to \mu\mu$	138	Inclusive	[44]

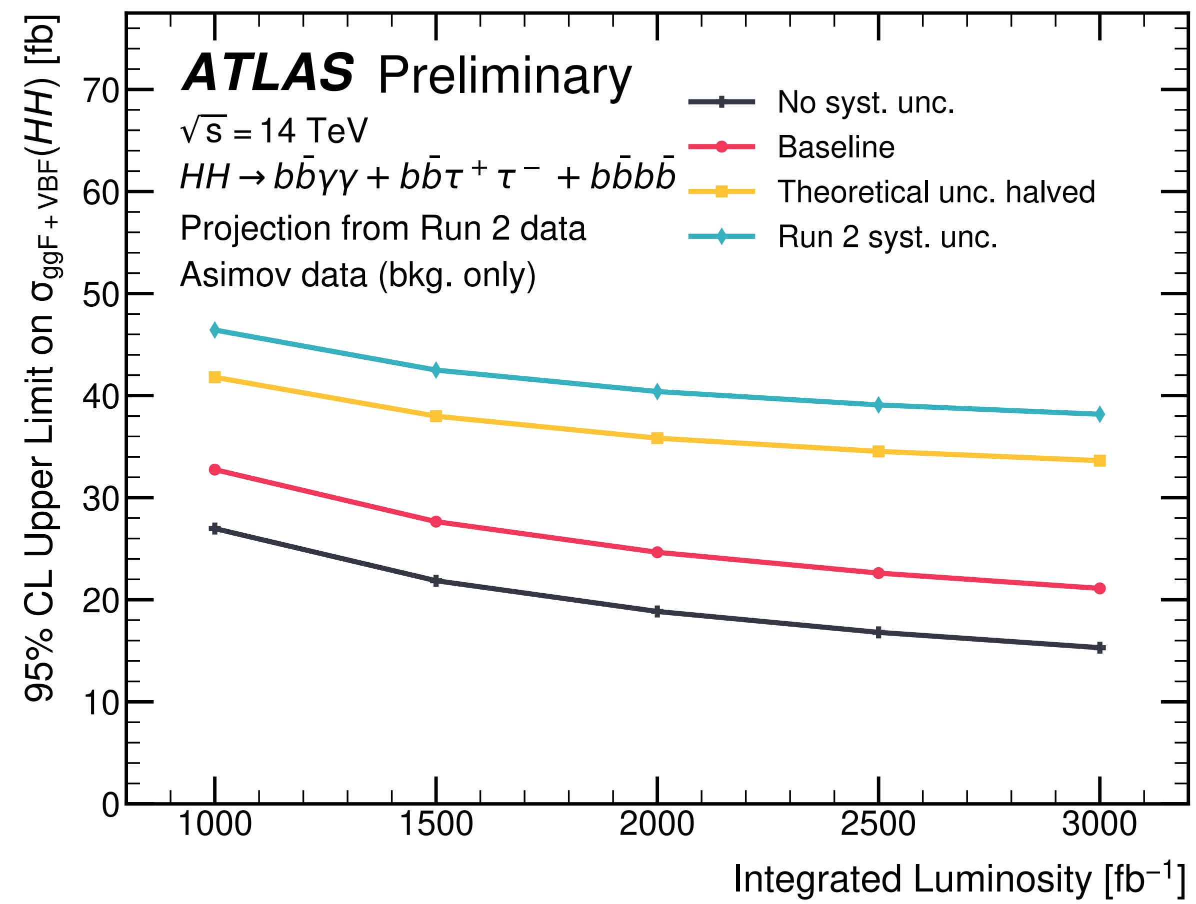
Analysis	Int. luminosity (fb^{-1})	Targeted production modes
$HH \to \gamma\gamma b\bar{b}$	138	ggHH and qqHH
$HH \to \tau\tau b\bar{b}$	138	ggHH and qqHH
$HH \to 4b$	138	ggHH, qqHH and VHH
$HH \to$ leptons	138	ggHH
$HH \to WWb\bar{b}$	138	ggHH and qqHH

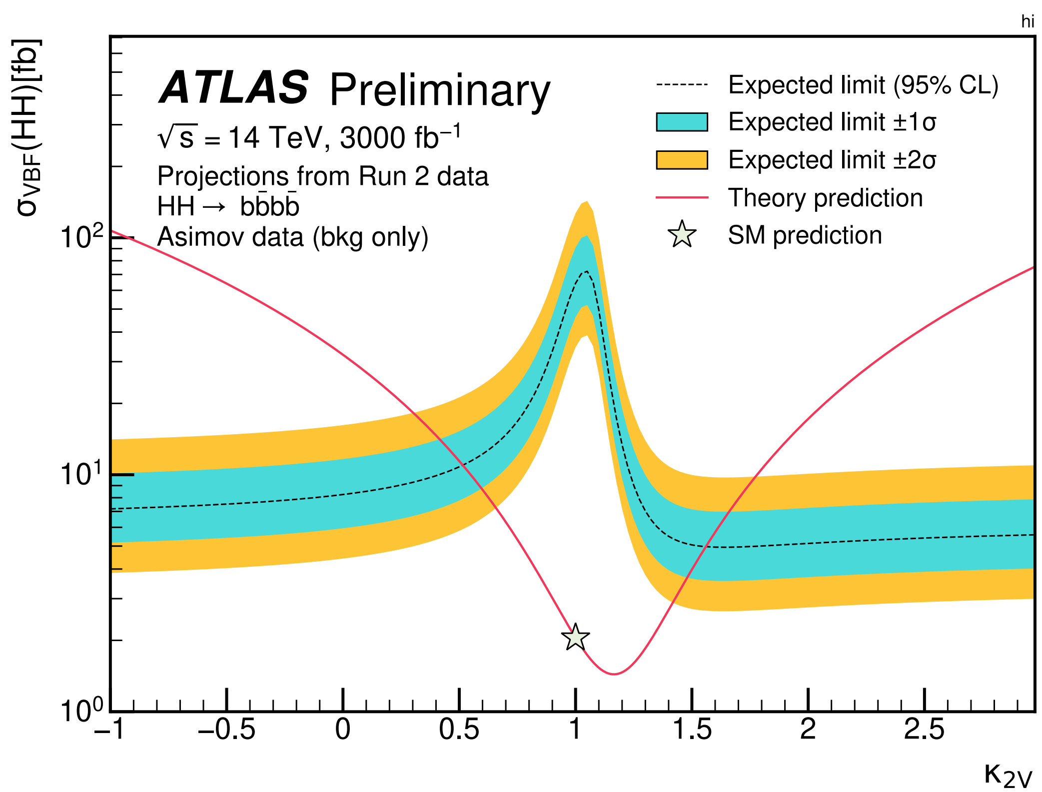
Hypothesis	Best fit $\pm 1\sigma$		95.4% CL interval	
	Expected	Observed	Expected	Observed
Other couplings fixed to SM	$1.0^{+4.6}_{-1.7}$	$3.1^{+3.0}_{-3.0}$	$[-2.0, 7.7]$	$[-1.2, 7.5]$
Floating (κ_V, κ_{2V}, κ_f)	$1.0^{+4.7}_{-1.8}$	$4.5^{+1.8}_{-4.7}$	$[-2.2, 7.8]$	$[-1.7, 7.7]$
Floating (κ_V, κ_t, κ_b, κ_τ)	$1.0^{+4.8}_{-1.8}$	$4.7^{+1.7}_{-4.1}$	$[-2.3, 7.7]$	$[-1.4, 7.8]$
Floating (κ_V, κ_{2V}, κ_t, κ_b, κ_τ, κ_μ)	$1.0^{+4.8}_{-1.8}$	$4.7^{+1.7}_{-4.2}$	$[-2.3, 7.8]$	$[-1.4, 7.8]$

The HL-LHC: ATLAS prospects

ATL-PHYS-PUB-2022-053, ATL-PHYS-PUB-2022-001, ATL-PHYS-PUB-2021-044

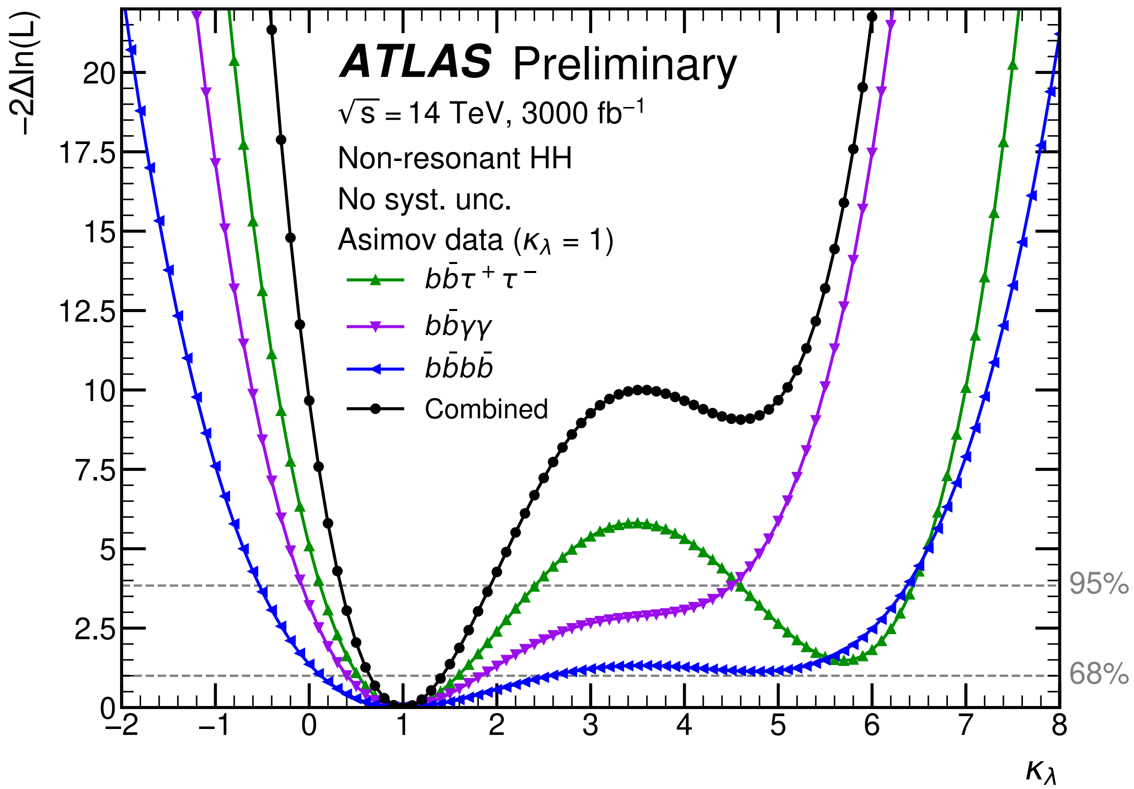


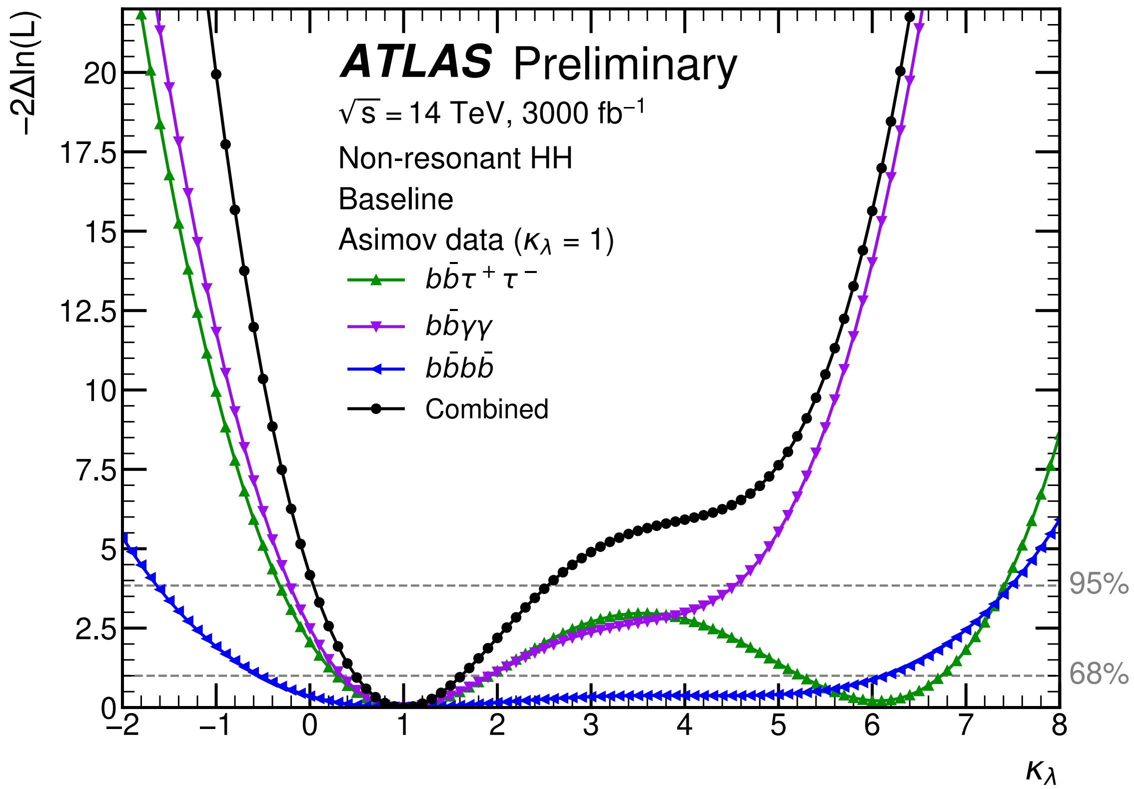


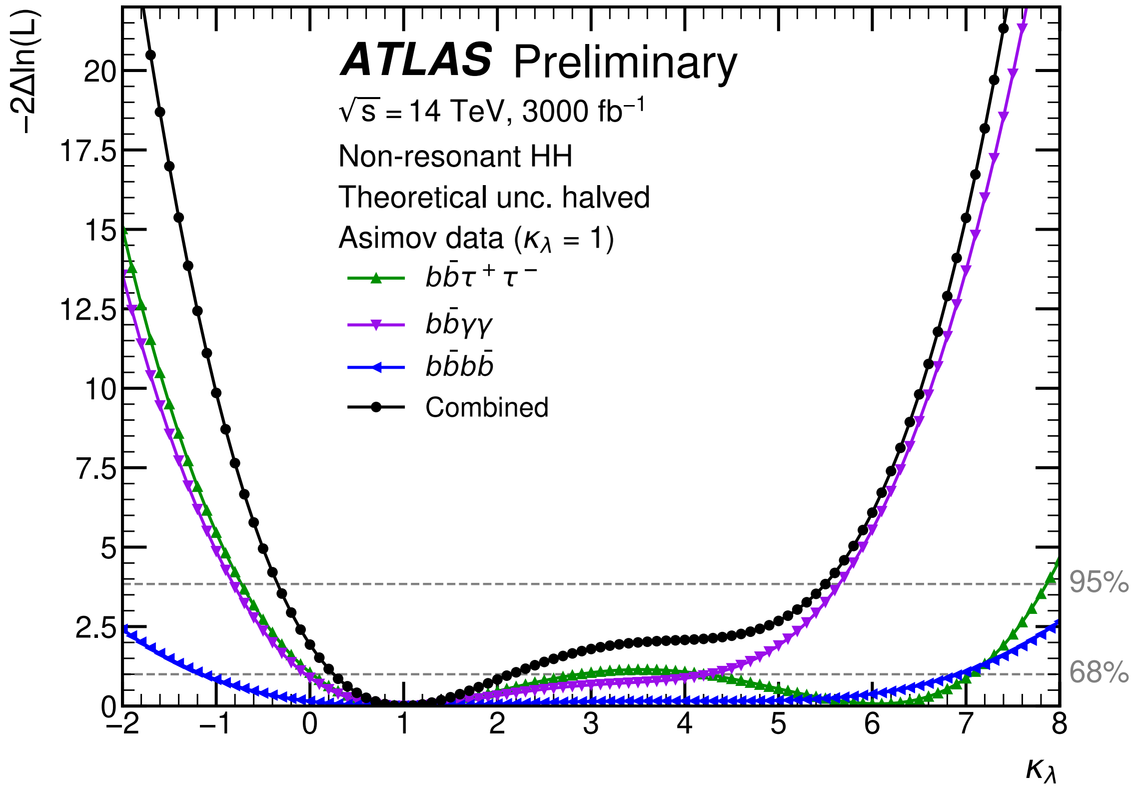


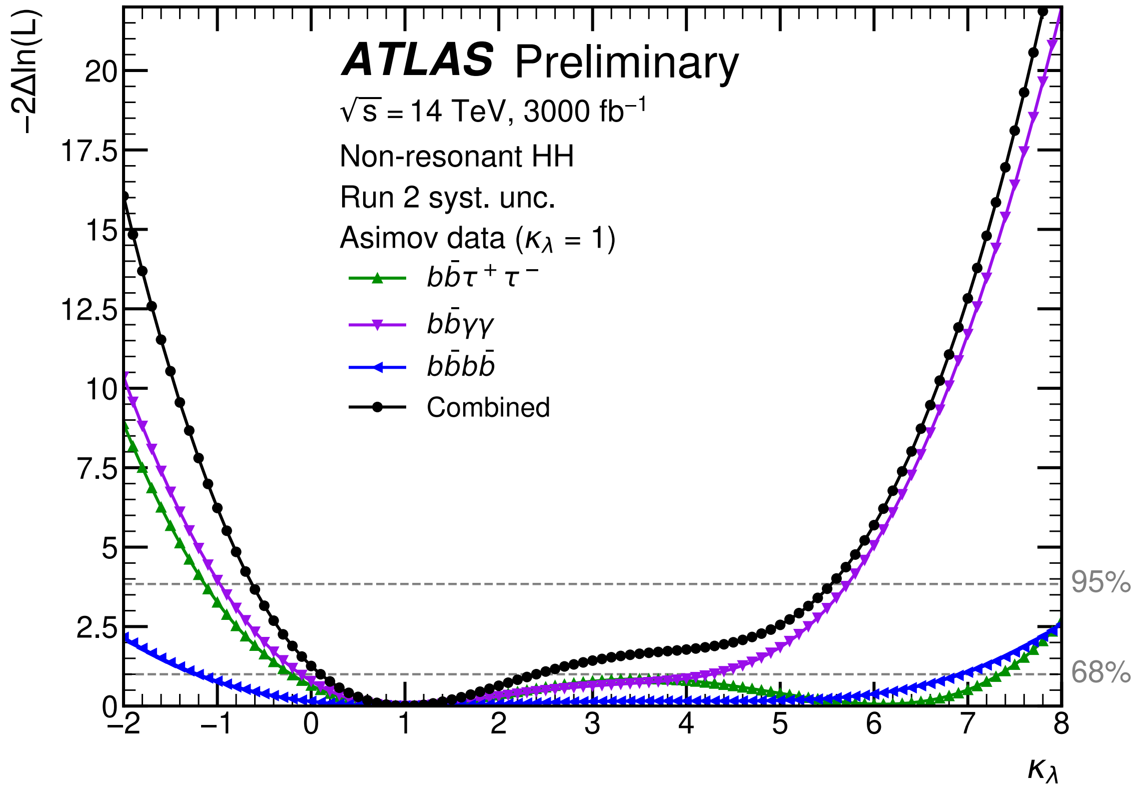
The HL-LHC: ATLAS prospects

ATL-PHYS-PUB-2022-053, ATL-PHYS-PUB-2022-001, ATL-PHYS-PUB-2021-044









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