ATLAS Run 2 non-resonant HH measurements of Higgs Boson self-coupling from main channels and combination

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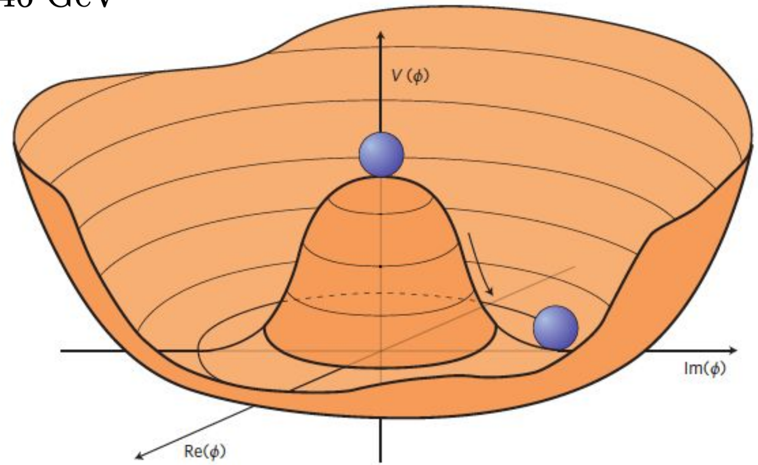
The Higgs field and the Standard Model

- Higgs field:
  - has non-0 vacuum expectation value (VEV)
  - key to spontaneous electroweak symmetry breaking
- Higgs mechanism:
  - explains how Z and $W^{\pm}$ gauge bosons acquire mass
  - reason why fermions acquire mass
- Higgs boson:
  - quantum excitation of the Higgs field
  - discovery announced from ATLAS and CMS in 2012

The Higgs potential

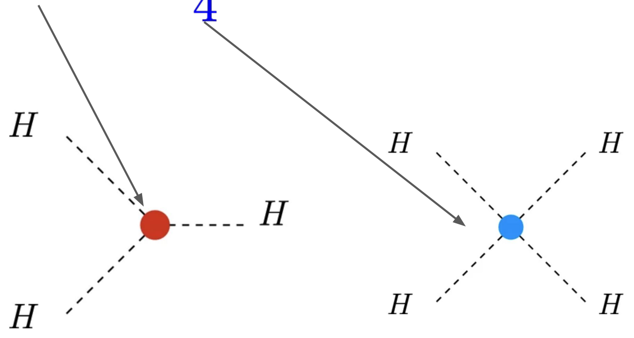
- $V(\phi) = \frac{1}{2}\mu^2\phi^2 + \frac{1}{4}\lambda\phi^4$
- this has a minimum in $\phi_{\min} = \sqrt{-\frac{\mu^2}{2\lambda}} = \frac{\nu}{\sqrt{2}}; \nu = 246 \text{ GeV}$
- Measurements of λ (Higgs self-coupling) are crucial for the reconstruction of the Higgs potential
  - we can test the Higgs mechanism and its validity in the framework of the SM
  - tests of BSM Physics
  - important to check the stability or lack thereof of the EW vacuum



Higgs self-coupling

- Expanding the Higgs potential close to the vacuum

$$V(h+\nu) \sim \lambda\nu h^2 + \lambda\nu h^3 + \frac{\lambda}{4}h^4$$



- Measuring the Higgs self-coupling is key in trying to precisely determine the shape of the Higgs potential

- Processes involving the production of Higgs boson pairs (HH) can help in this

Main contributions to HH production

HH production at the LHC mainly happens through:

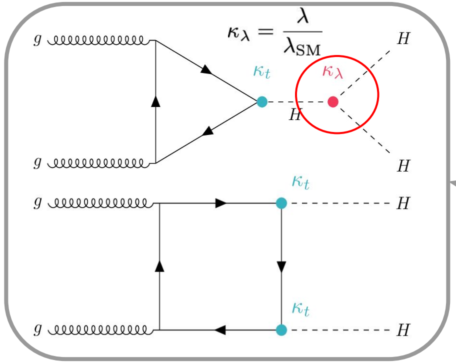
- gluon-gluon fusion (ggF)

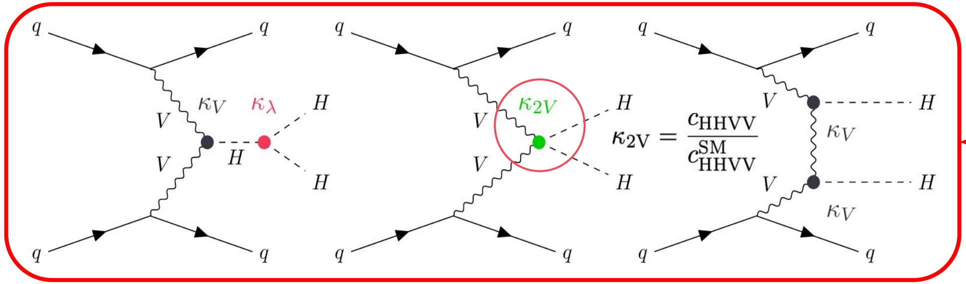
$$\sigma^{\text{SM}}_{\text{ggF}}(HH) = 31.05^{+6\%}_{-23\%}(\text{scale} + m_{\text{top}}) \pm 3.0\%(\text{PDF} + \alpha_s)\ \text{fb}$$

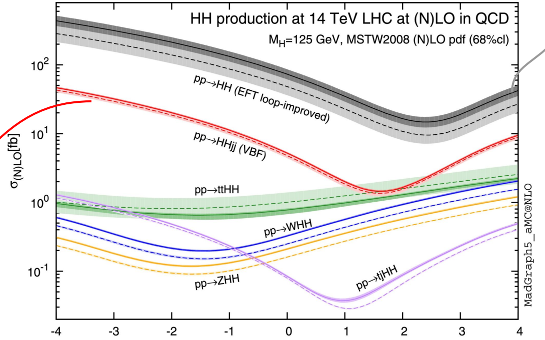
- vector boson fusion (VBF)

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

$$\text{SM } \sigma_{\text{HH}}@13\ \text{TeV} \sim 33\ \text{fb}$$

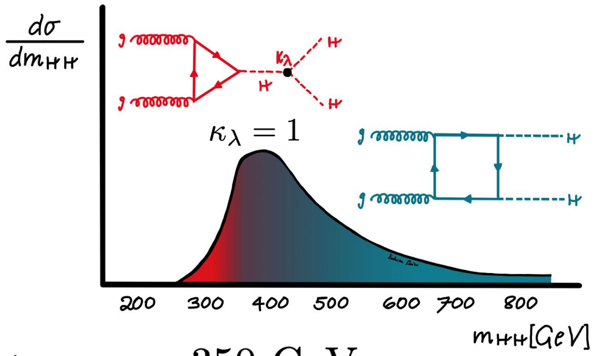




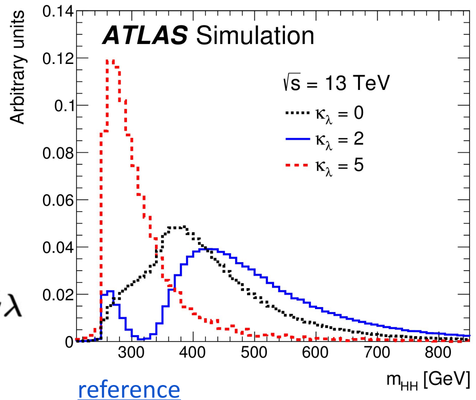


Physics Letters B 732 (2014)

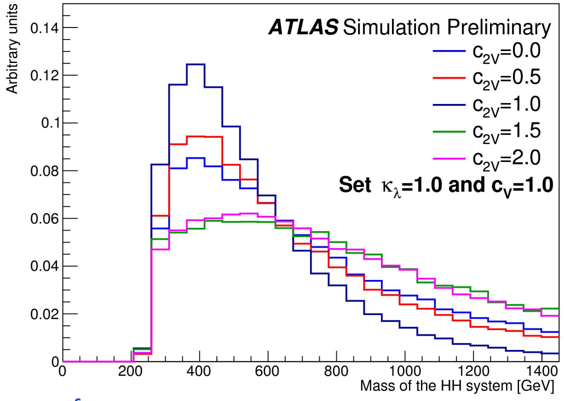
Main challenges



- In the case of ggF, the triangle and box diagrams interfere destructively, giving a small cross section
- The maximum destructive interference happens for $\kappa_\lambda \sim 2.4 \rightarrow m_{\mathrm{HH}} \sim 350\ \mathrm{GeV}$
- **Soft** kinematics for large k_λ
- **Hard** kinematics for large k_{2V}
- Key points:
  - m_{HH} strongly depends on κ_λ

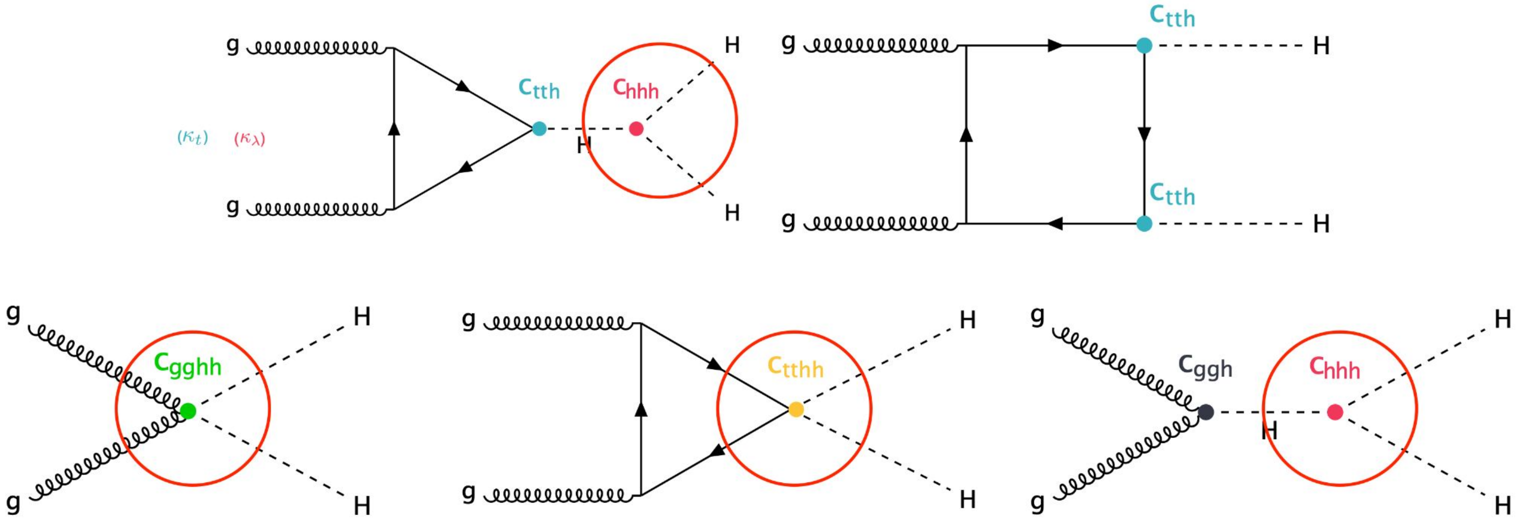


reference



reference

HH in the HEFT framework



- Other processes could contribute to HH production at higher scales, these are accounted for in HEFT (Higgs Effective Field Theory), HH can help constraint these coefficients

HH decays

larger 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%

cleaner final state

All channels have their pros and cons:

- 4b (34%)
  - most probable final state
  - challenging multi-jet backgrounds
- bbγγ (0.26%)
  - low decay fraction
  - excellent $m_{\gamma\gamma}$ resolution
- bbττ (7.3%)
  - somewhere in the middle

Focus of this talk

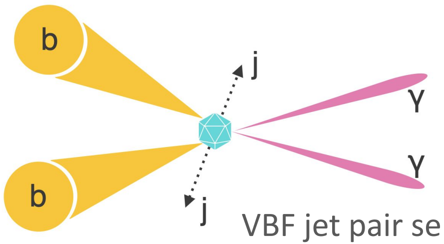
Nonresonant HH results	References
Full Run 2 bbγγ	JHEP 01 (2024) 066
Full Run 2 bbbb	resolved: Phys. Rev. D 108 (2023) 052003 boosted: arXiv:2404.17193
Full Run 2 bbττ	Phys. Rev. D 110 (2024) 032012
Full Run 2 Combination*	Phys. Rev. Lett. 133 (2024) 101801
HL-LHC prospects	ATL-PHYS-PUB-2022-053

* 5 analyses are combined here, but only 3 of them are part of this talk

bbγγ

JHEP 01 (2024) 066

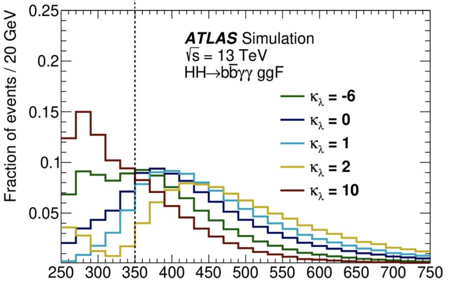
bbγγ selection and categorisation



VBF jet pair selected by a dedicated BDT

- Diphoton triggers
- 2 b-jets and 2 photons
  - $105 < m_{\gamma\gamma} < 160$ GeV
- to suppress ttH and tt backgrounds
  - Lepton (e, μ) veto
  - < 6 central jets

Targets BSM κλ | High mass sensitive for SM and BSM κ2V

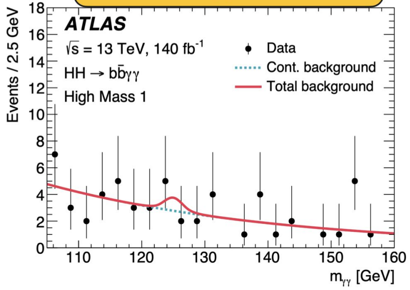


$m_{b\bar{b}\gamma\gamma} + (125 - m_{b\bar{b}}) + (125 - m_{\gamma\gamma})$ GeV

High mass BDT
3 categories defined by BDT score

Low mass BDT
4 categories defined by BDT score

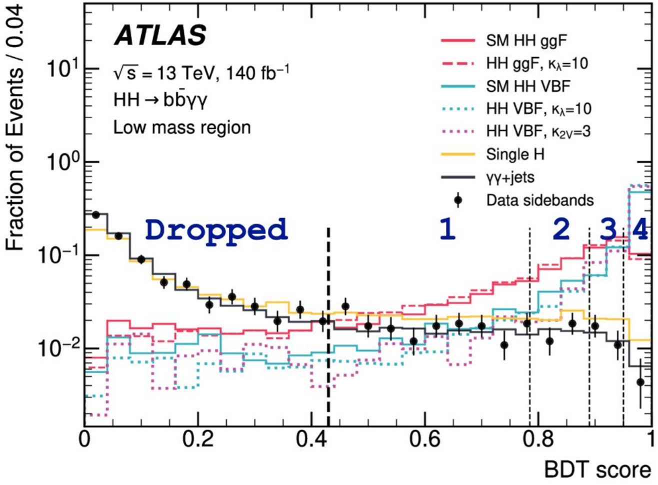
Fit 7 $m_{\gamma\gamma}$ spectra

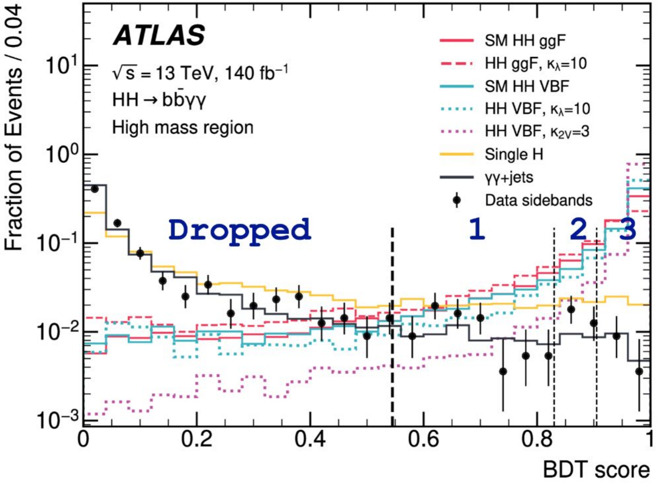


BDT categorization

Low mass BDT
Optimise for large value κ_λ
(soft spectrum)

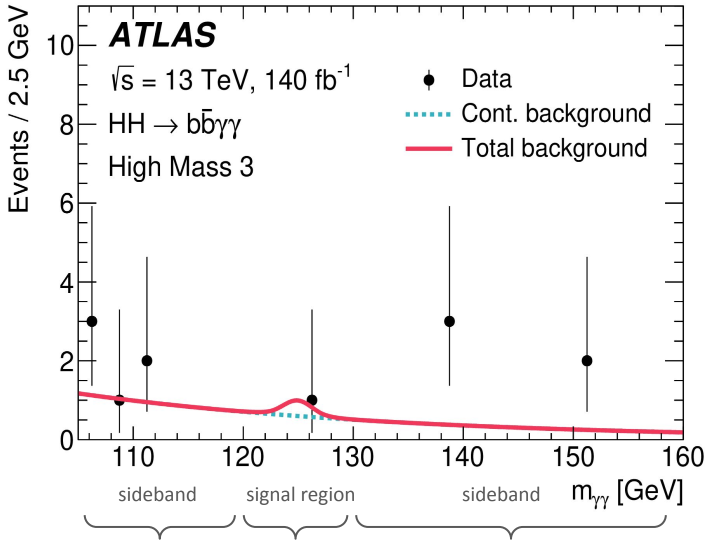
High mass BDT
optimise for SM value κ_λ and κ_{2V}
(hard spectrum)





- Training against background: single Higgs and γγ-continuum
- In the high-mass region SM samples, low-mass region BSM

bbγγ signal and background modeling

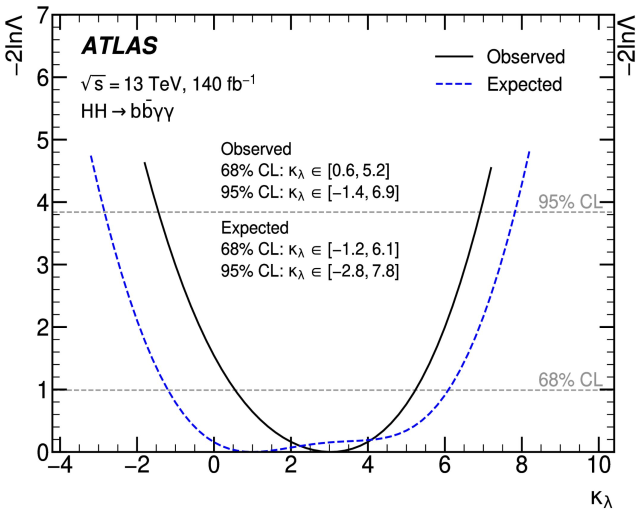


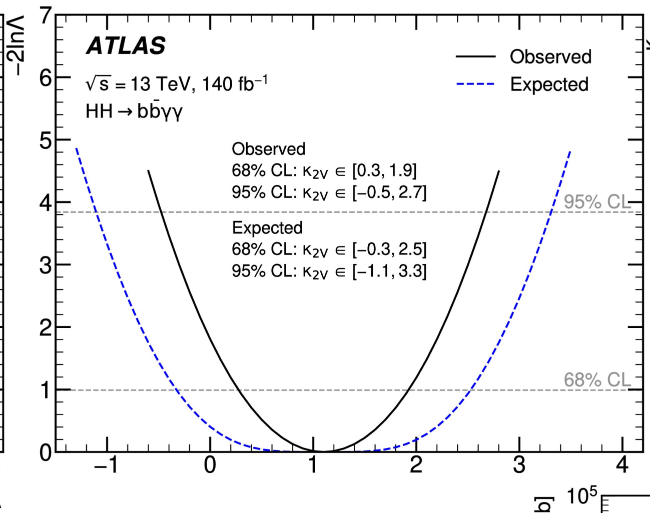
- Signal region
  - HH and single H
  - modelled by double-sided Crystal Ball function
  - parameters of the function are extracted from MC
- Continuum background
  - γγ+something
  - modelled using an exponential function
  - parameters of the function are derived from the sidebands

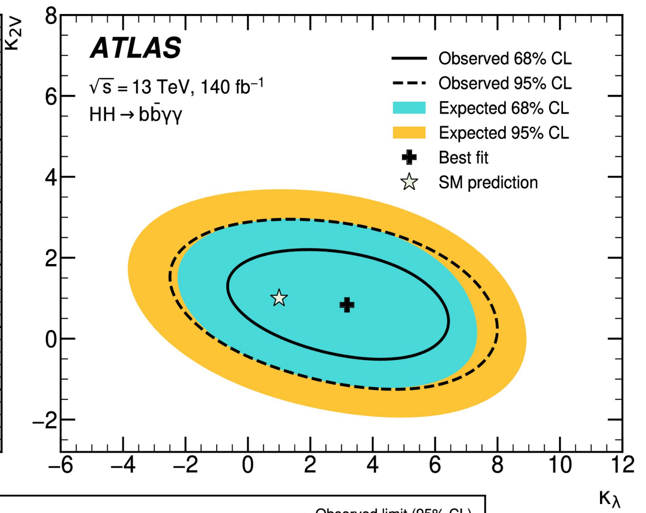
	High Mass 1	High Mass 2	High Mass 3	Low Mass 1	Low Mass 2	Low Mass 3	Low Mass 4
Total background	$12.8^{+1.6}_{-1.6}$	$3.7^{+0.9}_{-0.8}$	$3.4^{+0.8}_{-0.8}$	$38.9^{+2.9}_{-2.9}$	$11.3^{+1.5}_{-1.5}$	$4.7^{+0.9}_{-1.0}$	$1.3^{+0.5}_{-0.5}$
Data	12	4	1	29	8	5	4

Downward fluctuations in data

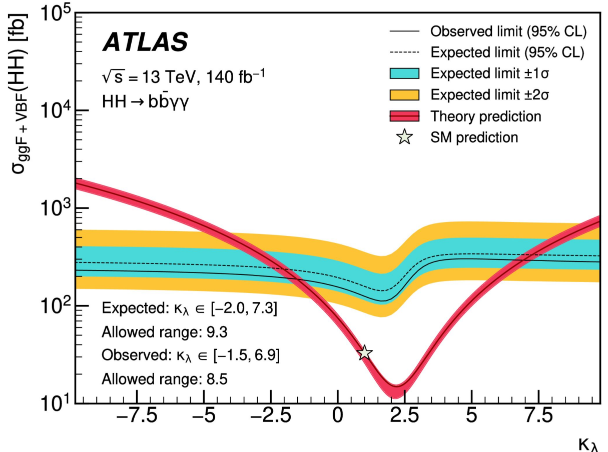
bbγγ results







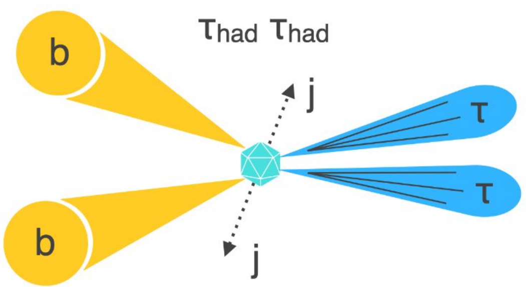
- 95% CL interval -1.4 < k_λ< 6.9:
  - this makes bbyy the leading channel in k_λ constraint
- 95% CL interval -0.5 < k_{2V} < 2.7
- 95% CL limit mu_HH < 4.0 (5.0 exp)
- dominant uncertainties:
  - data statistics
  - theory uncertainties on HH cross-section
- constraints on HEFT and SMEFT coefficients and seven HEFT benchmark scenarios.
- up to 17% sensitivity improvement wrt previous Run 2 result

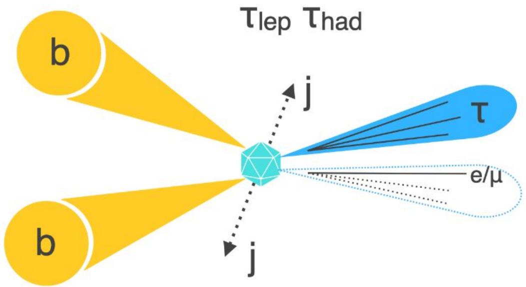


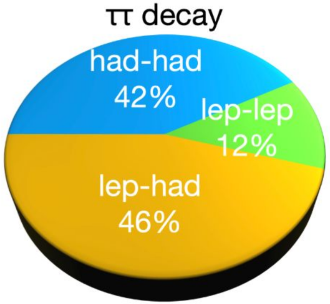
$bb\tau\tau$

Phys. Rev. D 110 (2024) 032012

bbττ selection and categorisation





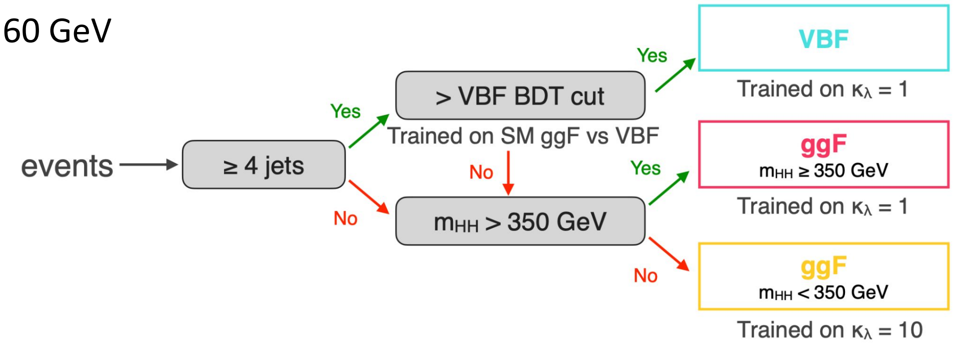


- Single-τ_{had} and di-τ_{had} triggers (high purity)
- 2 τ_{had}, e/μ veto

- 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

- 2b-jets, $m_{\tau\tau} > 60$ GeV

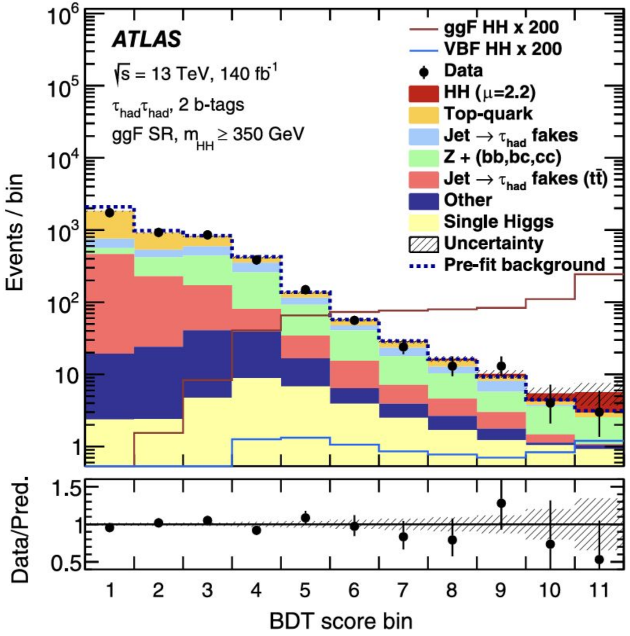


x3 types of triggers = 9 total categories

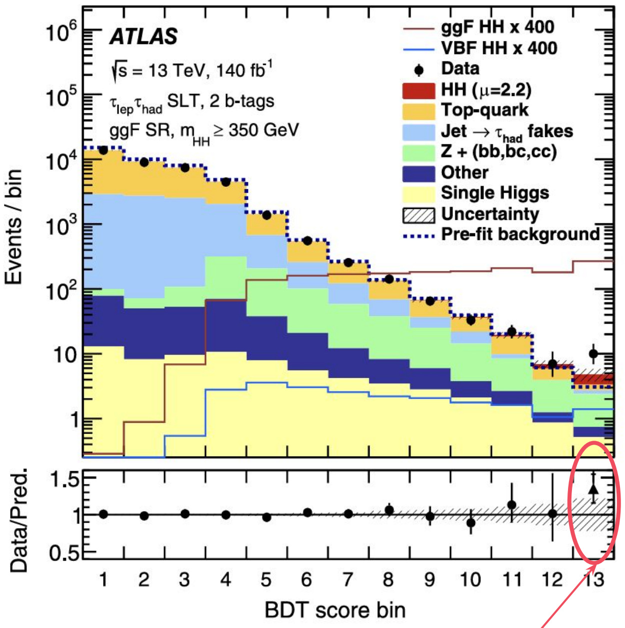
Signal/background separation

- each SR has its own BDT -> 9 in total

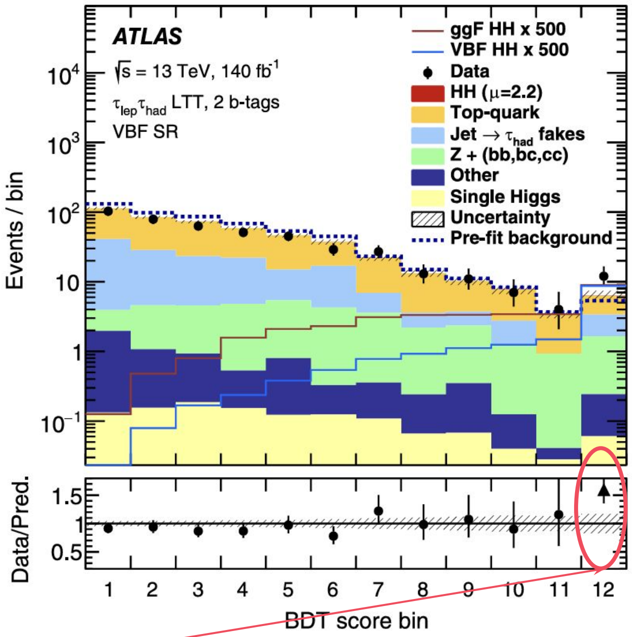
$\tau_{had}\tau_{had}$ ggF SR m_{HH}≥350 GeV



$\tau_{lep}\tau_{had}$ ggF SR m_{HH}≥350 GeV

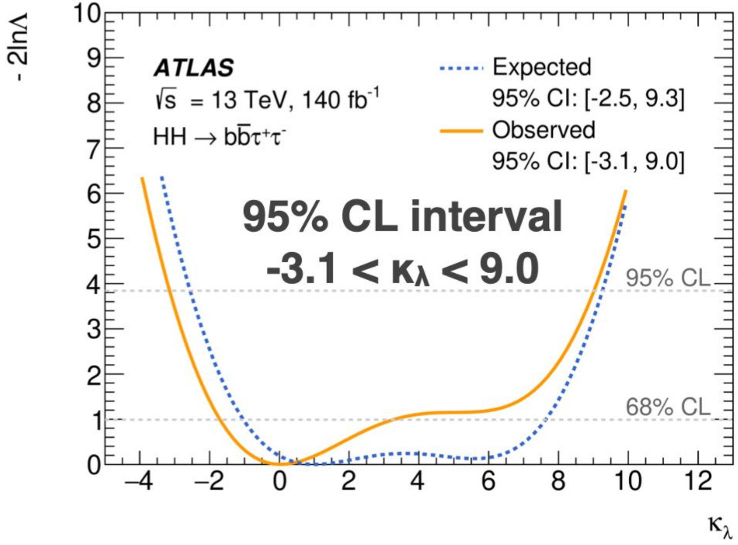


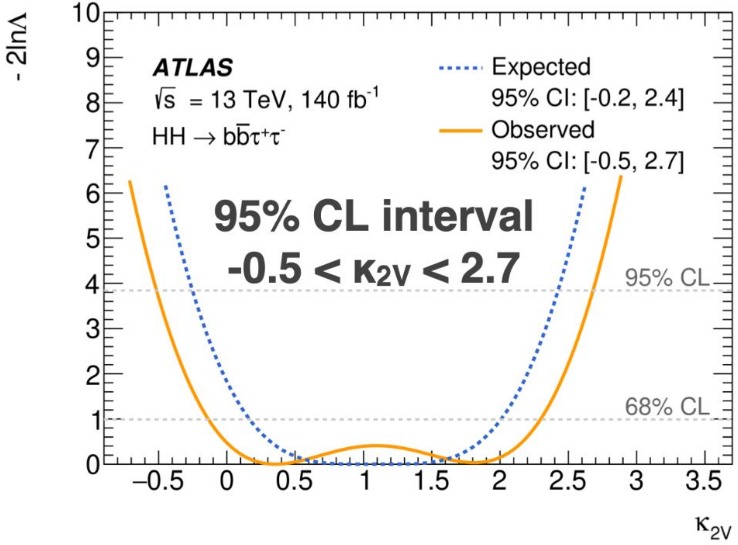
$\tau_{lep}\tau_{had}$ VBF SR



upward fluctuations in data

bbττ results



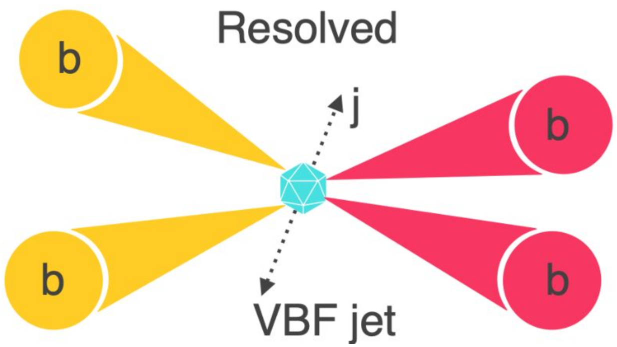


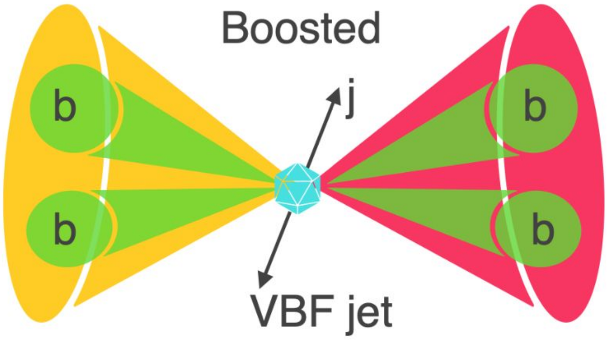
- 95% CL limit μ_{HH}< 5.9 (3.3 exp) makes this the leading channel in SM HH search
- Dominant uncertainties:
  - stat
  - modelling of top and single-H backgrounds
- Constraints on HEFT and SMEFT coefficients and seven HEFT benchmark scenarios

bbbb

Phys. Rev. D 108 (2023) 052003
arXiv:2404.17193

bbbb selection and categorisation





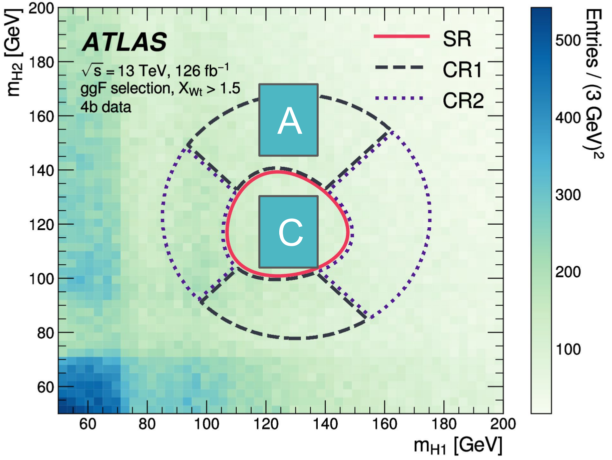
- b-jet trigger
- ≥ 4-bjets with p_T > 40 GeV
- $|\Delta\eta_{HH}|$ < 1.5
- veto top-quark decay
- categorised based on
  - VBF jets $|\Delta\eta_{HH}|$ > 3, m_{jj} > 1 TeV
  - $X_{HH} = \sqrt{\left(\frac{m_{H1} - 124\text{ GeV}}{0.1 m_{H1}}\right)^2 + \left(\frac{m_{H2} - 117\text{ GeV}}{0.1 m_{H2}}\right)^2}$

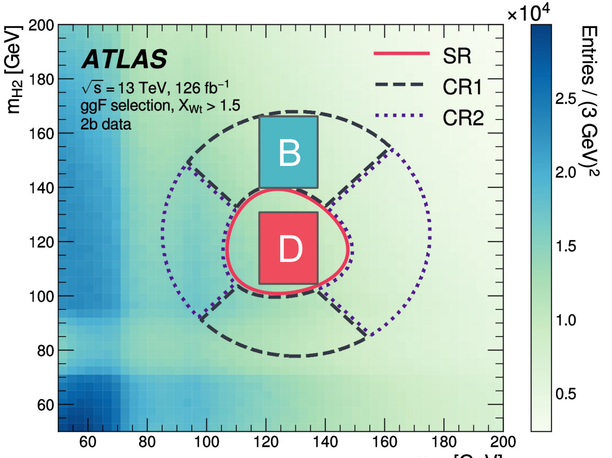
- Large-R jet trigger
- ≥ 2 Xbb-tagged jets
- p_T > 450 (250) GeV for the leading (sub-leading) H
- VBF jets $|\Delta\eta_{jj}|$ > 3, m_{jj} > 1 TeV

VBF categories

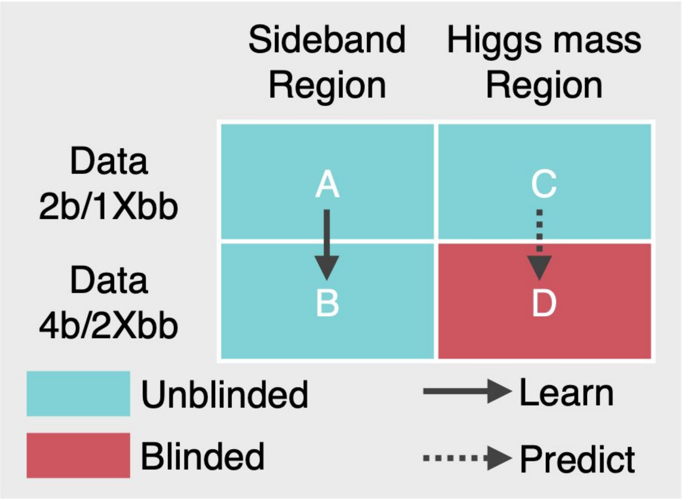
ggF categories

bbbb background estimation



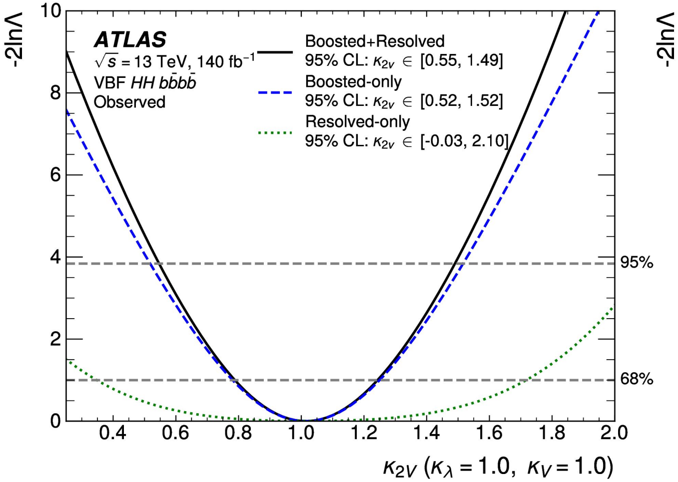


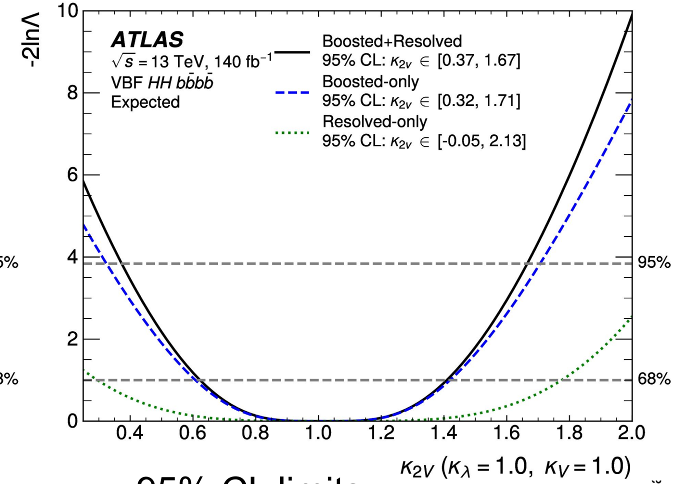
- the main background is QCD multijet



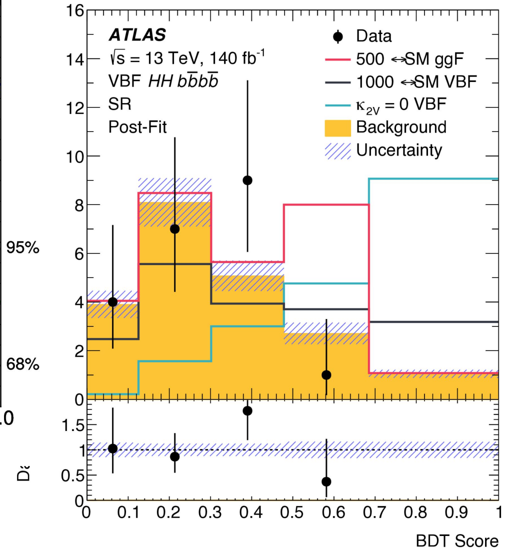
- in the boosted analysis, derived normalization factor
- in resolved, NN learn transfer factor

bbbb results





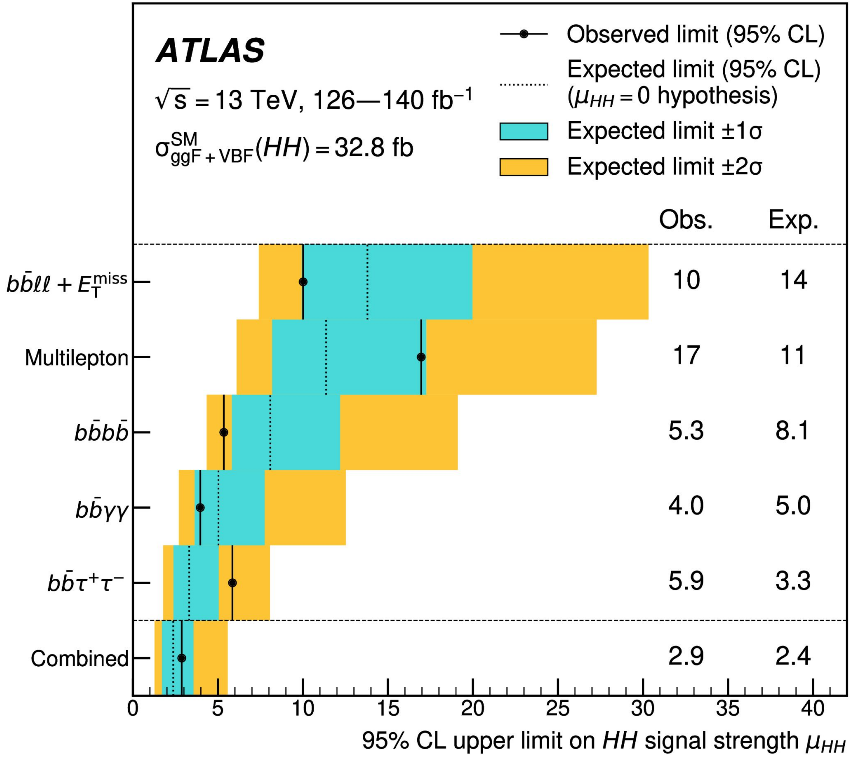
95% CL limits



- to extract results
  - fit m_{HH} (resolved)
  - BDT (boosted)
- μ_{HH}< 5.4 (exp 8.1 assuming no HH)
  - 2.5x improvement
- 2-3x improvement in k intervals
  - 0.55 < k_{2V} < 1.49 leading channel
  - -3 < k_λ < 11
- Dominant Unc.
  - Xbb calibration
  - Bkg estimation
  - Signal xs calculation

HH combination

HH signal strength

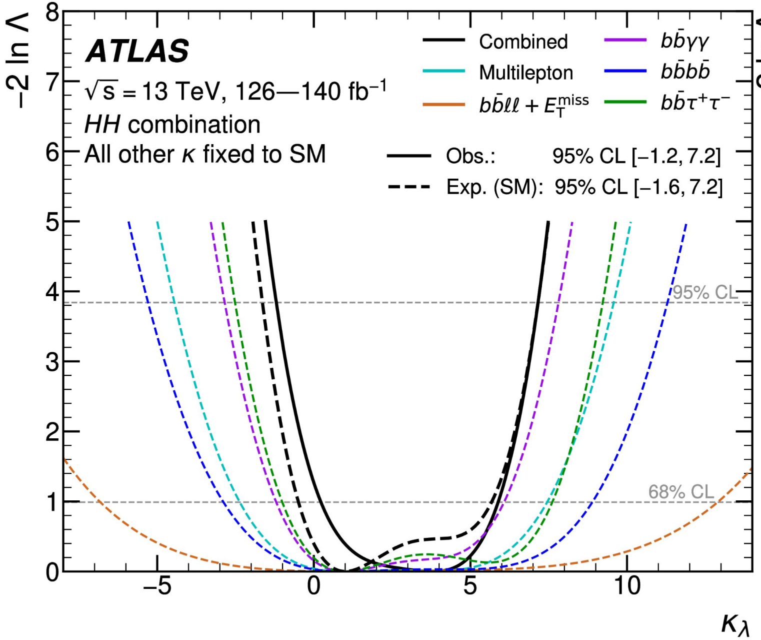


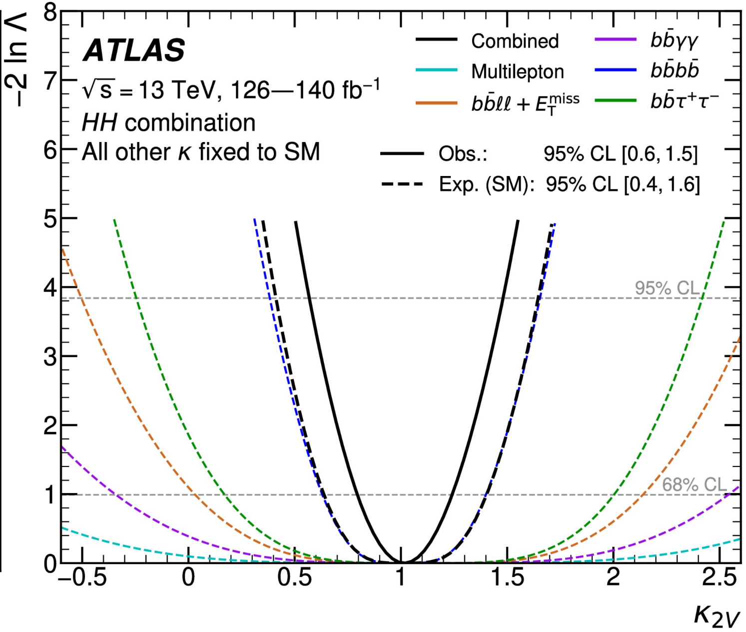
95% CL limits

- μ_{HH} < 2.9 (2.4 exp)
  - μ_{ggF} < 2.9 (2.4 exp)
  - μ_{VBF} < 44.3 (47.5 exp)
- σ_{HH} < 85.8 (71.1 exp) fb
- deficits in
  - bbbb
  - bbγγ
  - bbℓℓ+E_T^{miss}
- excesses in
  - bbττ
  - multilepton

- HH theory cross section uncertainty is the dominant one (+6% - 23% scale + m_{top})
- modelling of single H associated with b-jets is subdominant
- 4b background estimation is the biggest experimental systematic

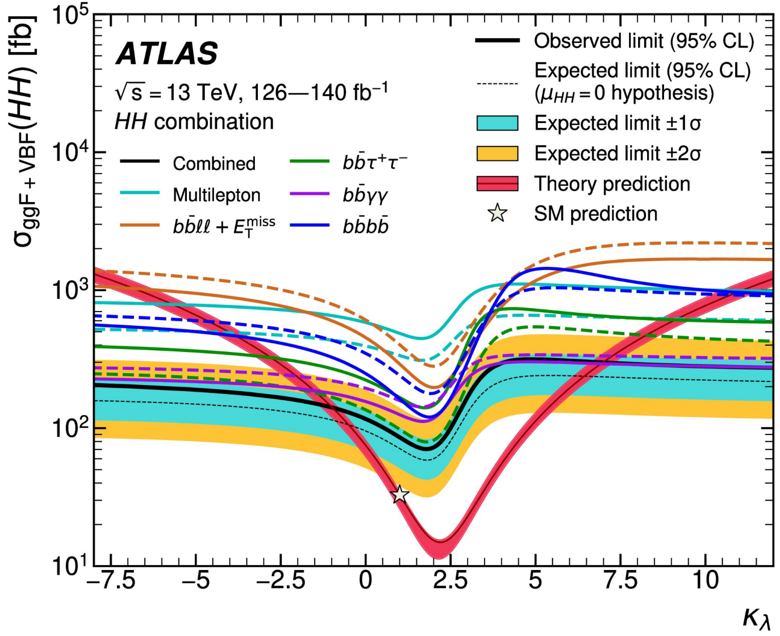
Couplings best fits

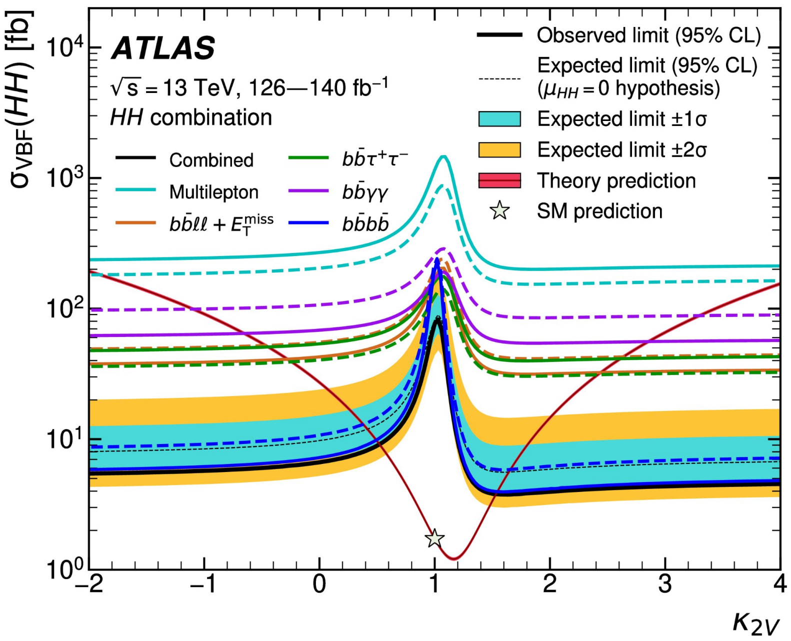




	Best fit	Obs 95% CL	Exp 95% CL	Leading Channel
k_{λ}	3.8	[-1.2, 7.2]	[-1.6, 7.2]	bbγγ, bbττ
k_{2V}	1.0	[0.6, 1.5]	[0.4, 1.6]	bbbb (boosted)

Complementary contributions (95% CL limits)





- bbɣɣ quite good, not the best at SM
- bbbb deficit at SM, excess around k=6
- bbττ very good performance at SM, degrading away from SM

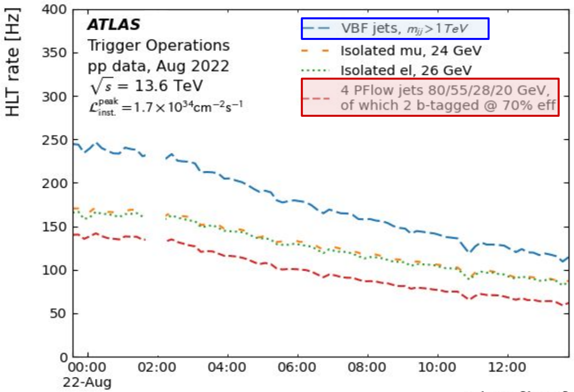
- bbbb strong constraint in general, not the best of all at SM
- bbɣɣ not super sensitive in high kinematics regime

Run 3 improvements and HL-LHC prospects

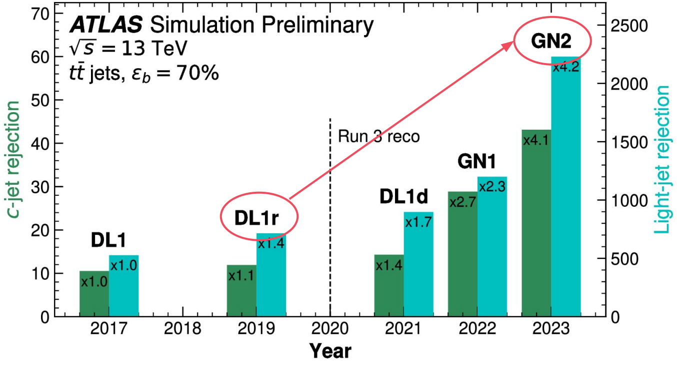
Trigger improvements in HH for Run 3

Trigger improvements for Run 3:

- Ambitious trigger menu increasing the bandwidth
  Run 2: 4 GB/s → Run 3: 8 GB/s
- New Hadronic (VBF + DiHiggs) delayed stream



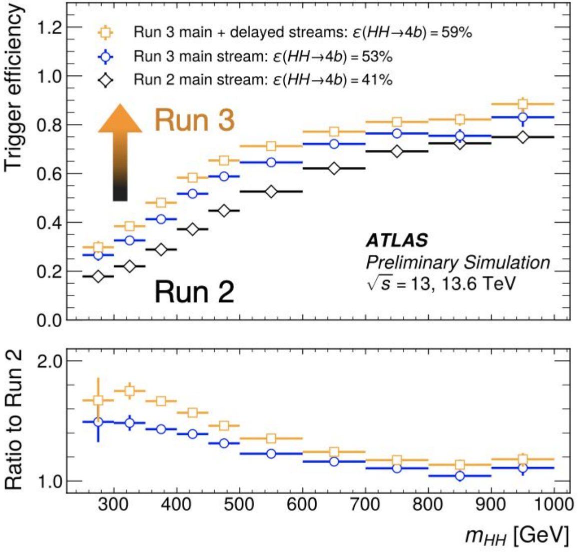
[Trigger Operation Public Results](#)



[FTAG-2023-01](#)

x4 improvement in c- and light-jet rejection with the new GN2 tagger

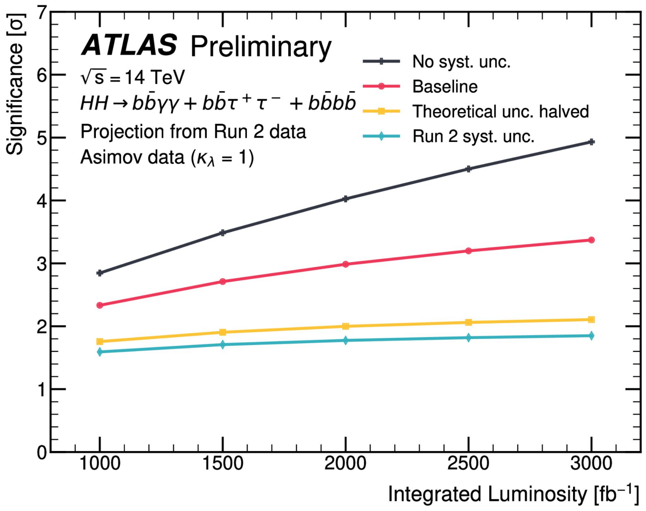
80% increased in trigger efficiency for the HH → 4b signal

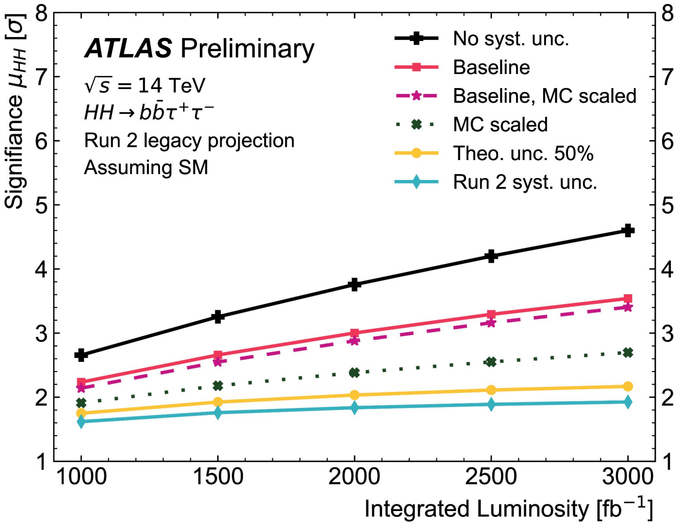


[B Jet Trigger Public Results](#)

HL-LHC Prospects

- ATLAS and CMS combination in the Yellow report [CERN-2019-007] and Snowmass White paper [ATL-PHYS-PUB-2022-018]
- Latest ATLAS combination results using the three most sensitive channels $HH \to bb\gamma\gamma$, $HH \to bb\tau\tau$ and $HH \to bbbb$ [ATL-PHYS-PUB-2022-053]
- Updated ATLAS projection of the $HH \to bb\tau\tau$ channel [ATL-PHYS-PUB-2024-016]





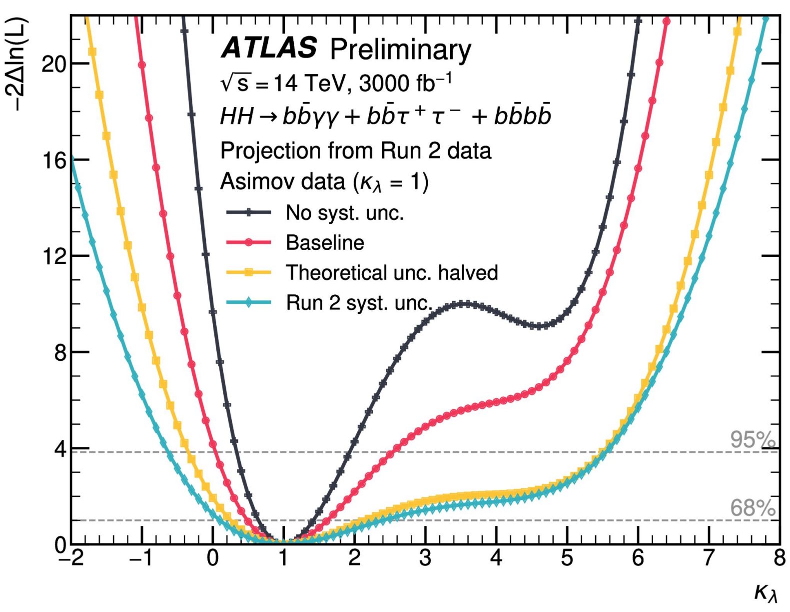
- results for the $bb\tau\tau$ channel are updated on the right plot wrt to ones included in the combination (left plot)
- improvement of around 20%
- as good as the combination after being updated

HL-LHC Prospects

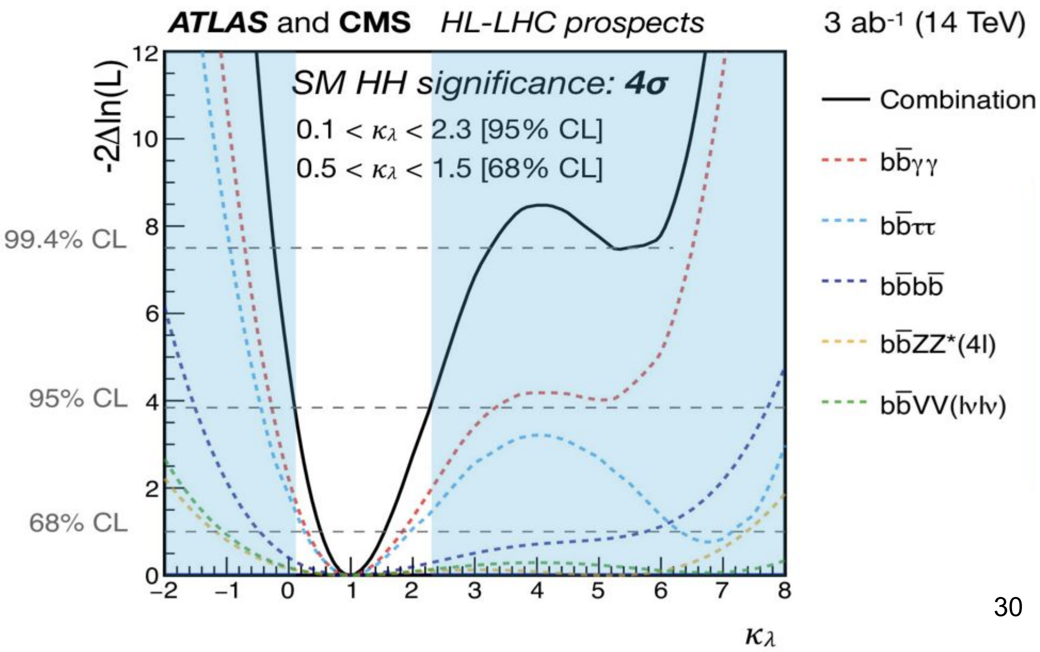
HL-LHC (3000 fb^{-1}):

- 3.4σ SM HH evidence combining bb$\gamma\gamma$, bb$\tau\tau$ and bbbb in ATLAS
- 5σ SM HH observation expected to be reached combining ATLAS and CMS

ATL-PHYS-PUB-2022-053



Yellow report [CERN-2019-007]



Summary

- Measuring the Higgs self-coupling is crucial for reconstructing the Higgs potential and validating the Higgs mechanism in SM and BSM scenarios
- HH production provides a direct way to probe the Higgs self-coupling, in this talk:
  - bbγγ leads in constraining k_λ
  - bbττ most sensitive for the SM HH
  - bbbb leads in constraining k_{2V}
  - HH combination
- The HL-LHC is expected to significantly increase sensitivity to HH production, potentially leading to 3.4σ SM HH evidence in ATLAS and a 5σ observation combining ATLAS and CMS data.

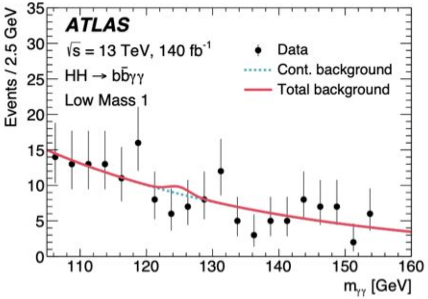
Thank you for your attention!

BACKUP

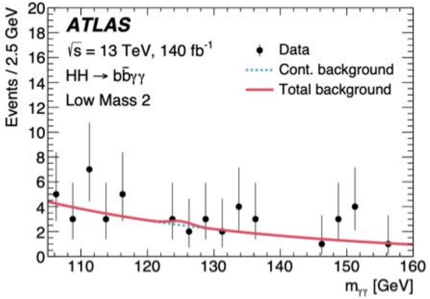
bbɣɣ BDT training variables

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 $t \rightarrow Wb \rightarrow q\bar{q}'b$ 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, $m^*_{b\bar{b}\gamma\gamma} = m_{b\bar{b}\gamma\gamma} - (m_{b\bar{b}} - 125\text{ GeV}) - (m_{\gamma\gamma} - 125\text{ GeV})$

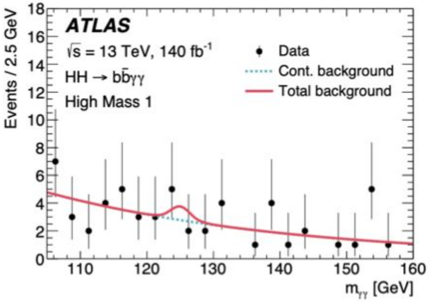
bbγγ 7 mass regions



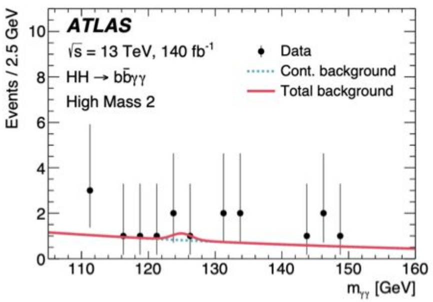
(a) Low Mass 1



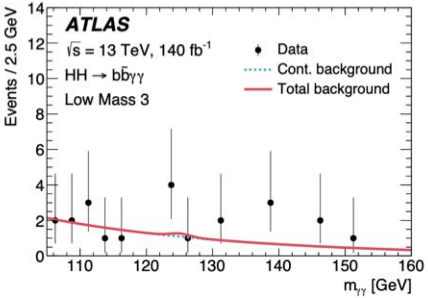
(b) Low Mass 2



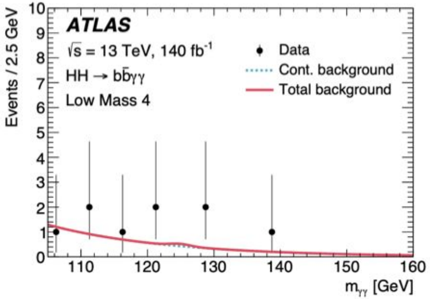
(e) High Mass 1



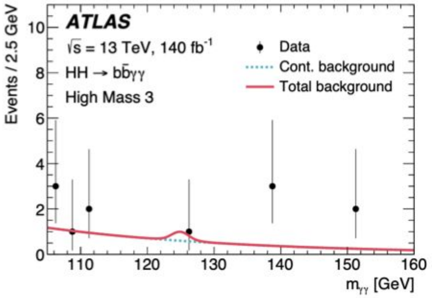
(f) High Mass 2



(c) Low Mass 3



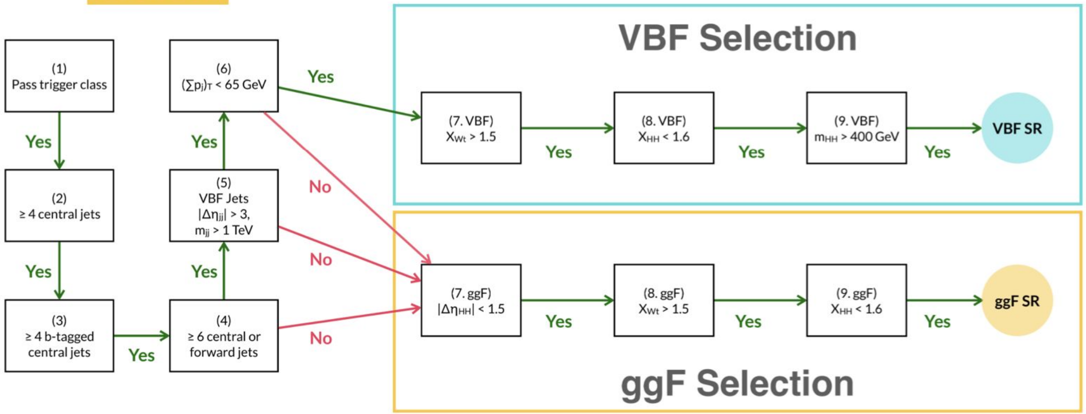
(d) Low Mass 4



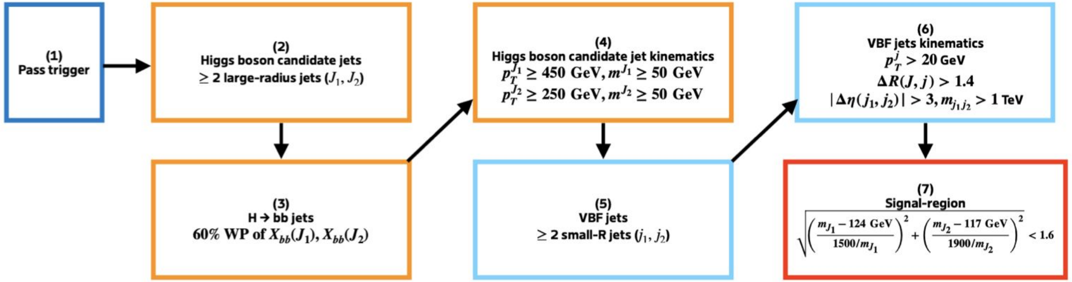
(g) High Mass 3

bbbb event selection

Resolved



Boosted

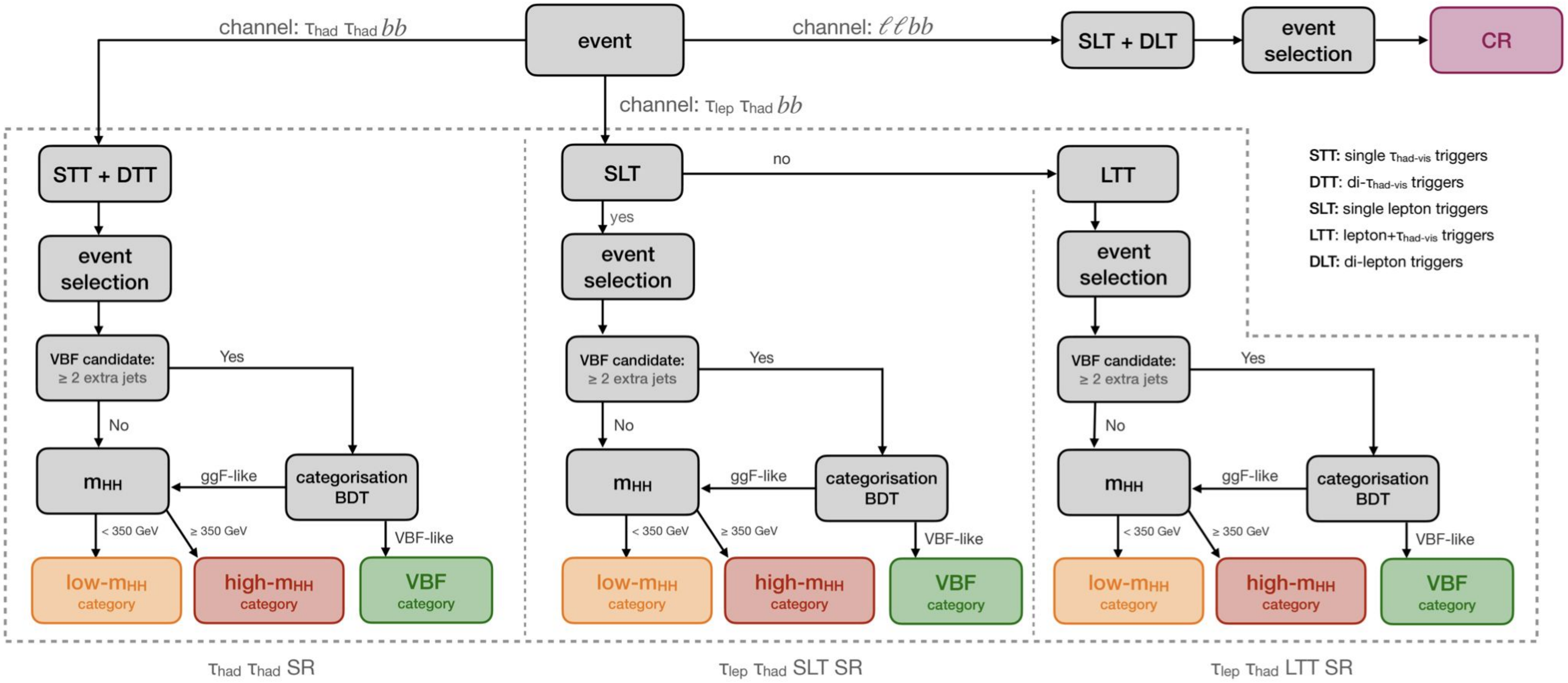


bbbb tables

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%
$3b1$f nonclosure uncertainty	−2.0%

bbττ event selection



Combined μ results