HH results - ATLAS

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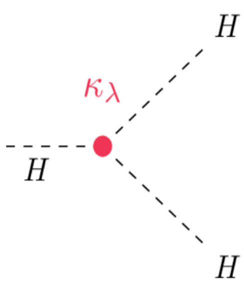
on behalf of ATLAS Collaborations

26th September 2024

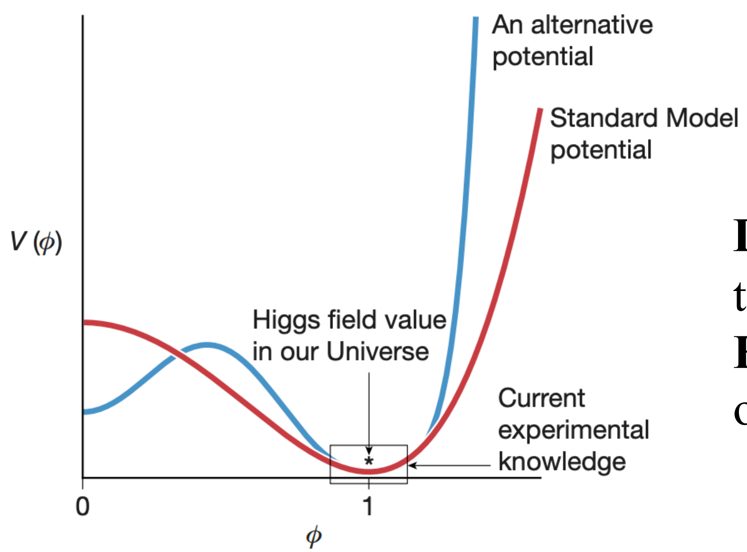
Higgs self-coupling search

- **Higgs self coupling** (λ_3*): one of the most important **piece** of the **Higgs puzzle accessible** at LHC
  - SM prediction $\lambda_3 \approx 0.125$
  - still **missing experimentally**
- The di-Higgs boson production is the only direct way to access $k_\lambda = \lambda_3/\lambda_3^{SM}$
  - <u>but</u> **Higgs pairs** are predicted to be **1000x rarer** than **single Higgs** @ 13TeV
- k_λ gives **access** to the **shape of the Higgs potential** $V(\phi)$ via the λ_3 measurement



$$V(\phi) = \mu^2\phi^\dagger\phi + \lambda_3(\phi^\dagger\phi)^2 \xrightarrow[V(\phi)\to V(h+v)]{\text{EWSB}} V(h) = \frac{1}{2}m_H^2 + \lambda_3 v h^3 + O(h^4)$$

Mass term — Trilinear coupling

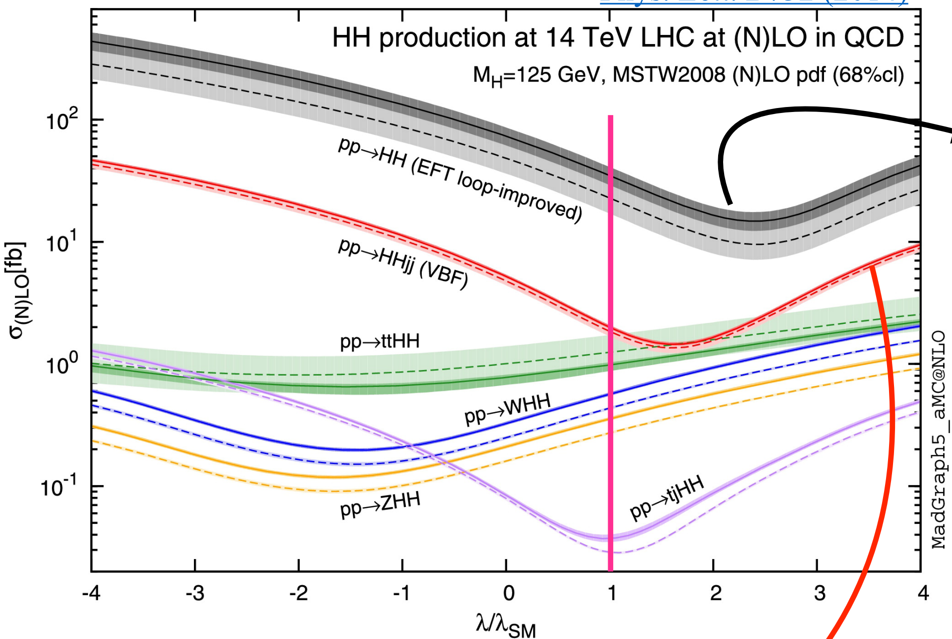


Due to our λ_3 **sensitivity** and **missing sensitivity** to **higher order terms**, current **constraints** on **Higgs potential** are **weak** →difficult to probe other scenarios

* $\lambda_3 = \lambda_{HHH} = m_H^2/(2v^2)$

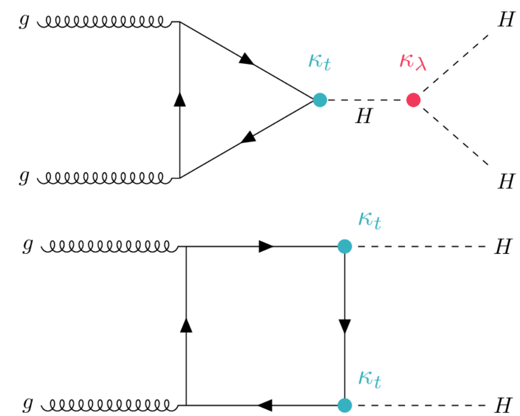
HH production at LHC

Phys. Lett. B732 (2014)



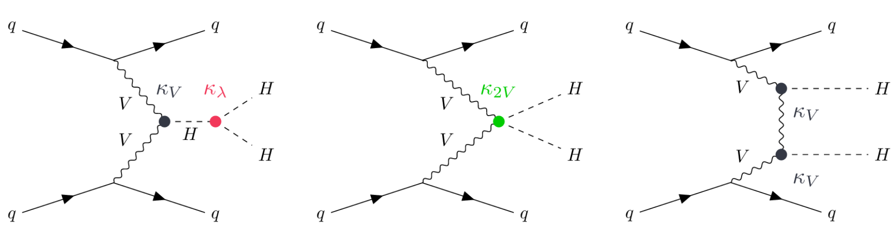
Gluon-gluon fusion (ggF):

- leading production mode
- Sensitive to k_λ and k_t
- $\sigma^{SM}_{ggF}(\text{HH}) = 31.1\ ^{+2.1}_{-7.2}$ fb @ $\sqrt{s} = 13$ TeV



Vector boson fusion (VBF):

- Access to k_{2V} coupling
- $\sigma^{SM}_{VBF}(\text{HH}) = 1.73 \pm 0.04$ fb @ $\sqrt{s} = 13$ TeV



HH decay modes

- Different decay channels to explore detector opportunity
- **No clear golden channel**
- ATLAS Collaboration exploits different channels to increase the sensitivity
  - $b\bar{b}b\bar{b}$ (34%)
    - Most abundant final state
    - Challenging multi-jets background
  - $b\bar{b}\tau^+\tau^-$ (7.3%)
    - Medium decay fraction
    - Good signal purity
  - $b\bar{b}\gamma\gamma$ (0.26%)
    - Low decay fraction
    - Excellent $m_{\gamma\gamma}$ resolution
  - $b\bar{b}\ell^-\ell^+ + E_T^{miss}$ (2.9%)
    - Targeting where one $H \nrightarrow b\bar{b}$
  - Multileptons (6.5%)
    - Targeting where both $H \nrightarrow b\bar{b}$
      - Although including $b\bar{b}ZZ(\rightarrow 4\ell)$

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

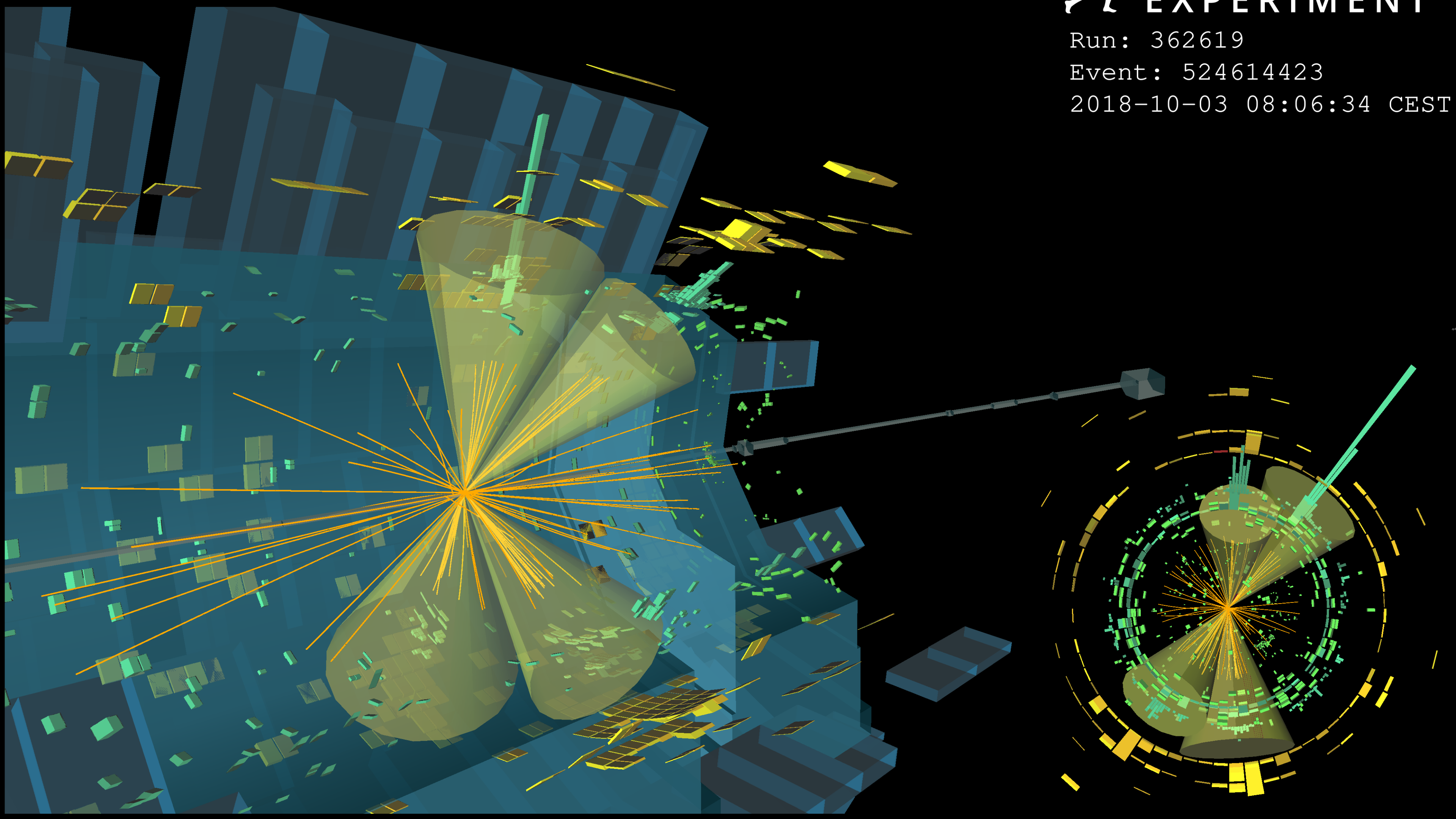
Combination is the key for observation!

Resolved $HH(b\bar{b}b\bar{b})$

Phys. Rev. D 108 (2023) 052003

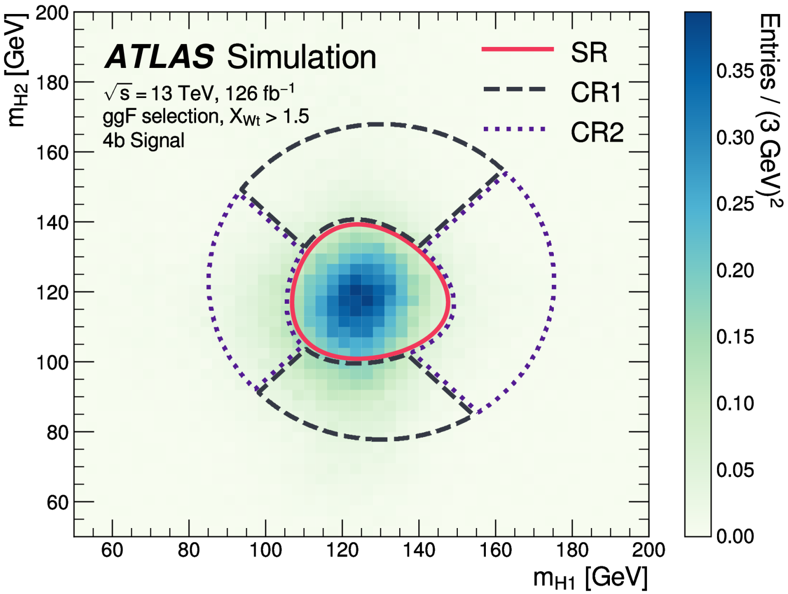
ATLAS EXPERIMENT

Run: 362619
Event: 524614423
2018-10-03 08:06:34 CEST



Event selection and categorisation

- Trigger: **b-jet triggers**
- Preselection:
  - **$\geq$ 4 b-jets** (DL1r @ 77% WP) with $p_T > 40$ GeV and $|\eta| < 2.5$
    - Jet pairing considering the highest-p_T jet pair with the smallest ΔR_{jj} separation
  - **Top veto** discriminant
- Event categories:
  - **VBF category**: $\geq$ 6 jets, $m_{jj} >$ 1TeV, $|\Delta\eta_{jj}| > 3$
  - **ggF category**: $|\Delta\eta_{HH}| < 1.5$

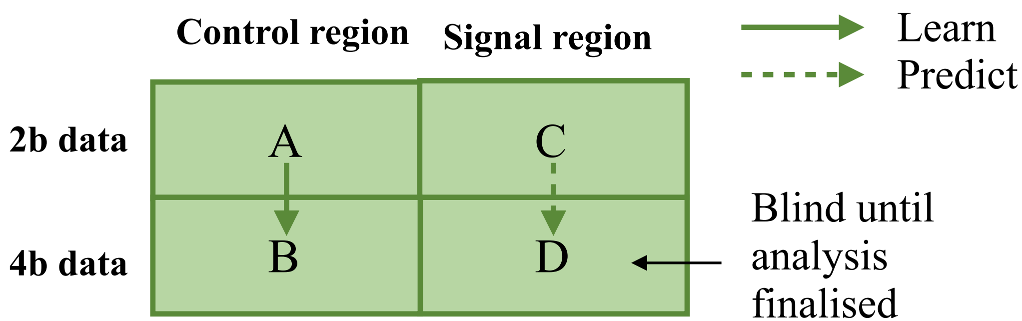


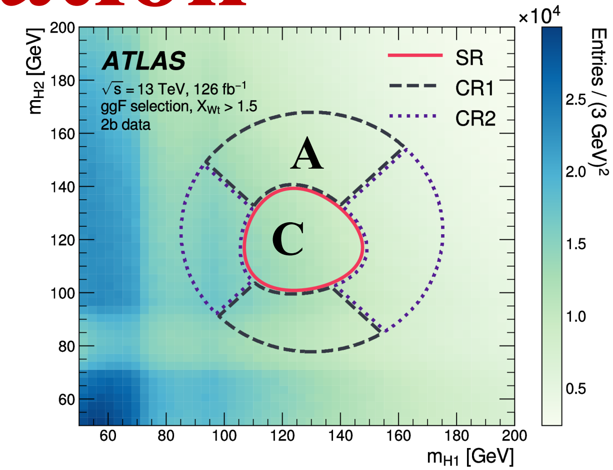
- Signal region (**SR**) definition:
  - $$X_{HH} = \sqrt{\left(\frac{m_{H1} - 124GeV}{0.1 m_{H1}}\right)^2 + \left(\frac{m_{H2} - 117GeV}{0.1 m_{H2}}\right)^2} < 1.6$$
  - Split into X_{HH} and $|\Delta\eta_{HH}|$ categories to enhance the sensitivy

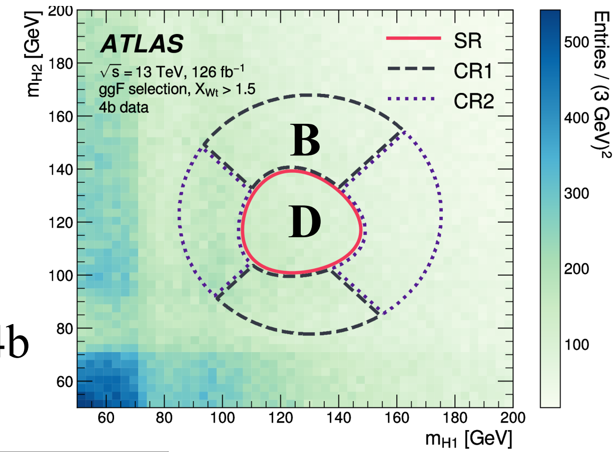
    ➡ **6 SRs** in the ggF category and **2 SRs** in the VBF category.

Background estimation

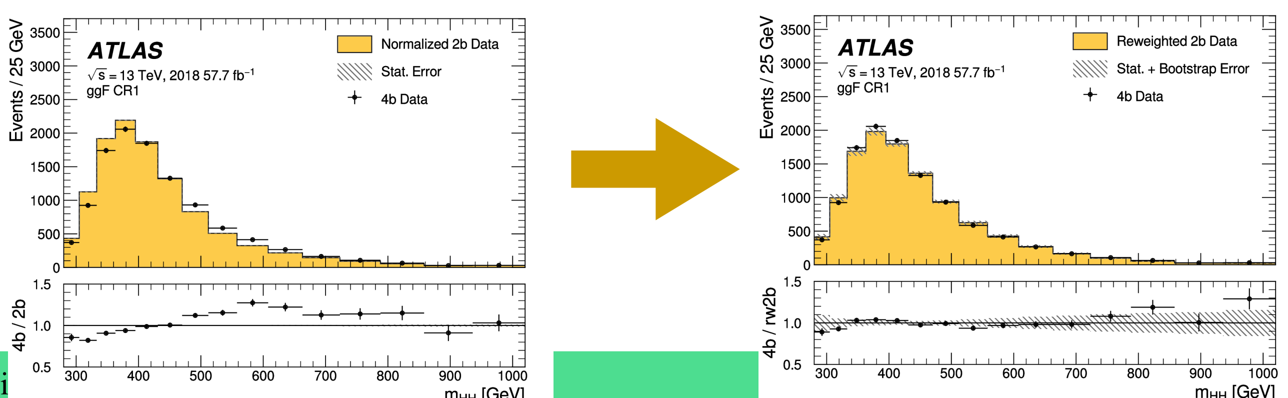
- Dominant background: **QCD multi-jet**
- Difficult to model → extracted using the **data-driven method**
- Alternative event samples with the same selection as the signal region but fewer b-tagged jets to derive the 4b background ("2b events")





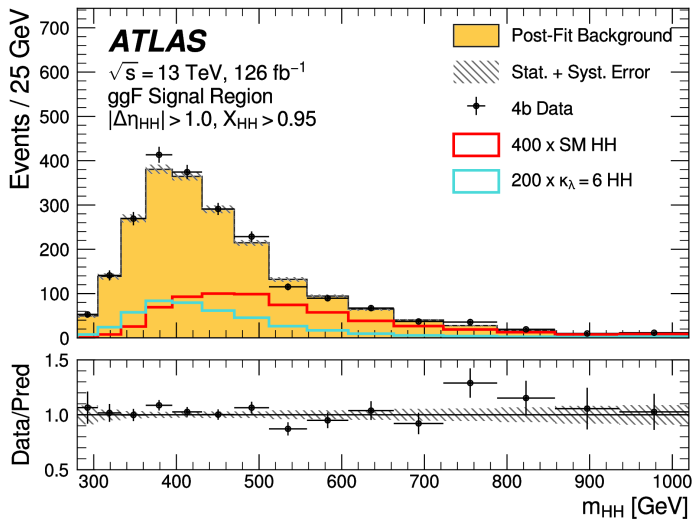


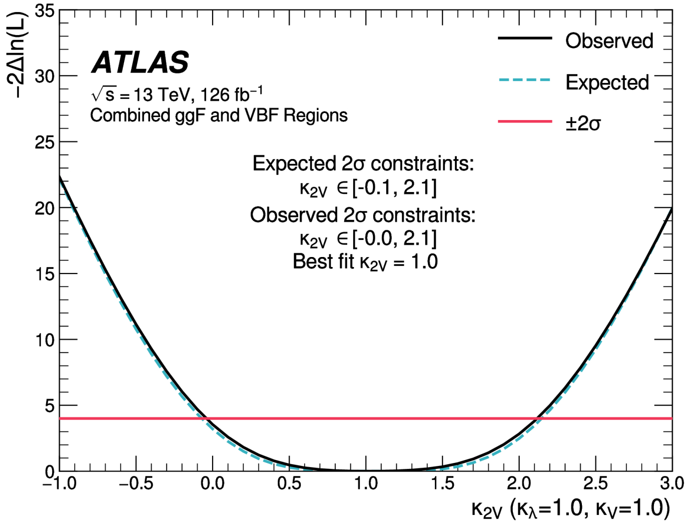
- **Neural networks** to evaluate reweighting function from 2b to 4b events



Results

- Discriminating variable: **invariant mass of the di-Higgs system** m_{HH}
- **Maximum likelihood fit** performed simultaneously to the all ggF and VBF SRs.

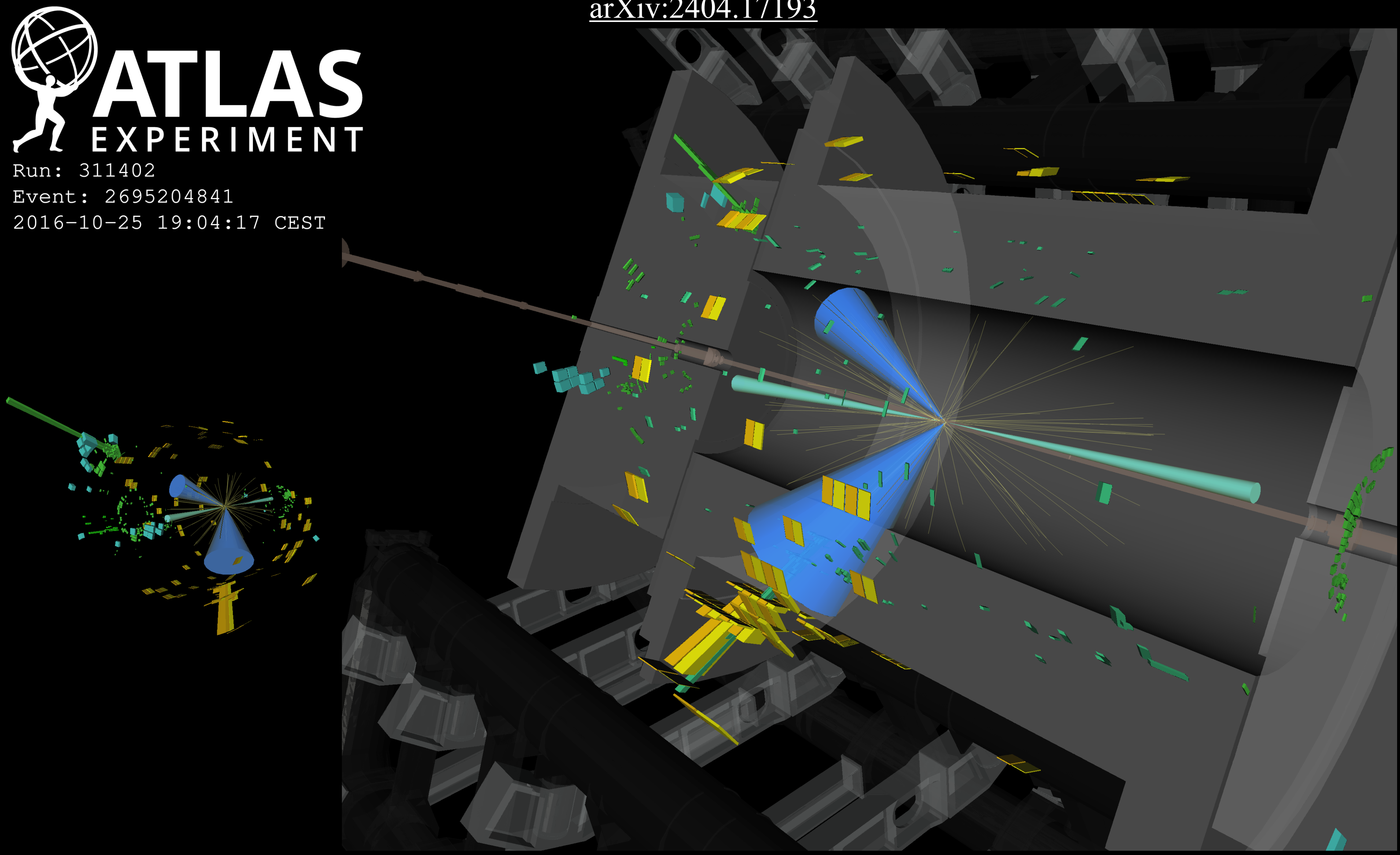




- **Observed (expected) limits** on μ_{HH} of **5.4 (8.1) x SM @ 95% CL**
- Observed $k_\lambda \in$ [-3.5, 11.3] @ 95% CL
- Observed $k_{2V} \in$ [0.0, 2.1] @ 95% CL
- **Dominant uncertainties:**
  - Background modelling uncertainties
  - Theoretical predictions

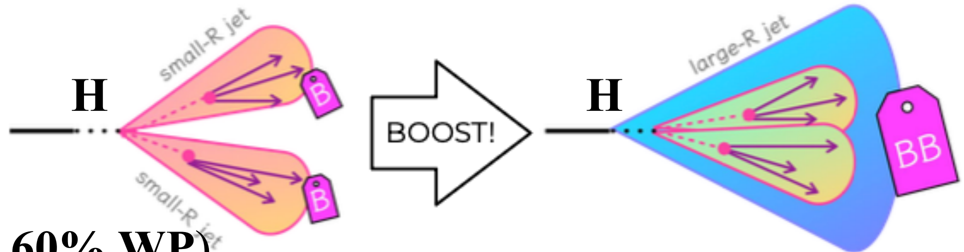
Boosted *VBF HH*($b\bar{b}b\bar{b}$)

arXiv:2404.17193



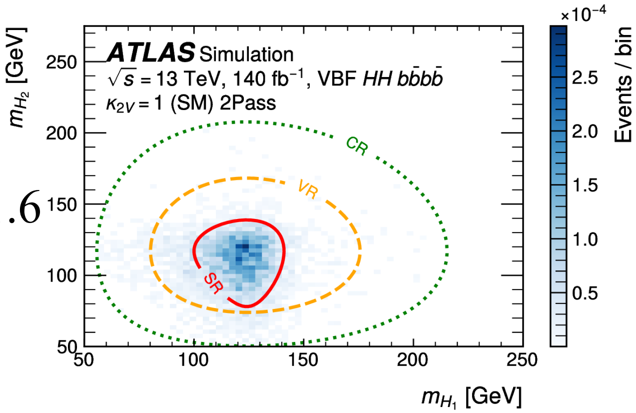
Event selection and categorisation

- Trigger: **large-R jet triggers**
- Preselection:
  - **≥ 2 large-R jets** with $p_T > 250$ GeV
    - **≥ 2 double b-tagged jets** (Xbb @ **60% WP**)
  - $p_T(H_1) > 450$ GeV and $p_T(H_2) > 250$ GeV
  - **≥ 2 small-R jets** assigned as VBF jets
    - $m_{jj} > 1$ TeV and $|\Delta\eta_{jj}| > 3$



→ **Only VBF topology** is **studied**

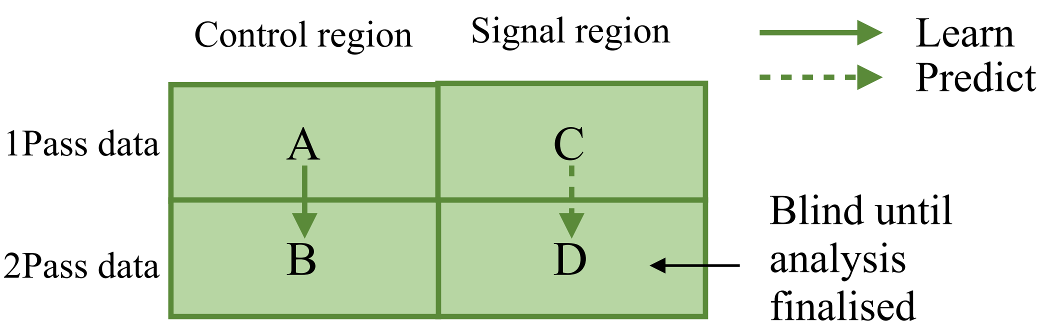
- **Signal region (SR)** definition:
  - $$X_{HH} = \sqrt{\left(\frac{m_{H1} - 124GeV}{1500\,\text{GeV}/m_{H1}}\right)^2 + \left(\frac{m_{H2} - 117GeV}{1900\,\text{GeV}/m_{H2}}\right)^2} < 1.6$$



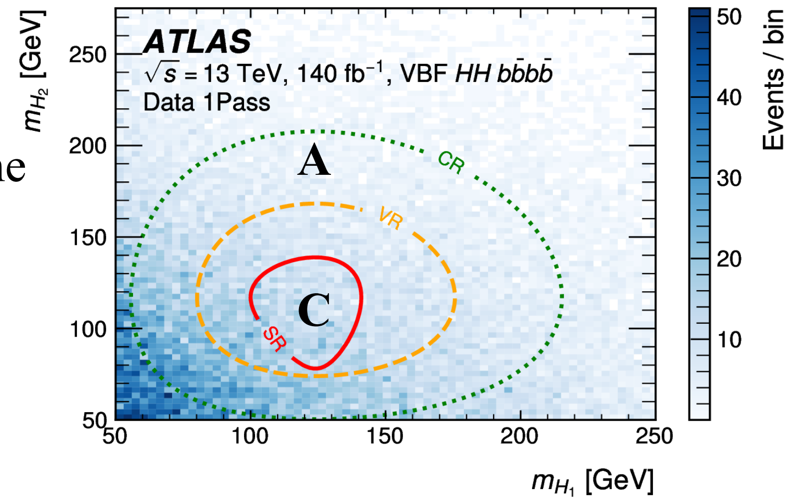
- **Control region (CR)** and **Validation region (VR)** definition applying different cuts in the mass plain of the two Higgs candidate
- Boosted decision tree (**BDT**) used to **separate signal** (VBF HH k_{2V}=0) from **background events** (QCD multi-jet + SM ggF and VBF HH)

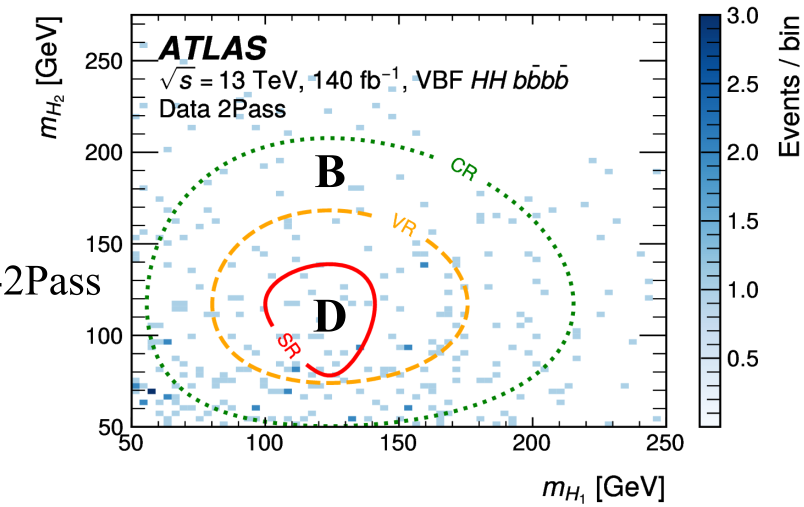
Background estimation

- **Data-driven method** to estimate the **QCD multi-jet** contribution
- Alternative event samples with the same selection as the signal region but looser btag requirement ("1Pass")



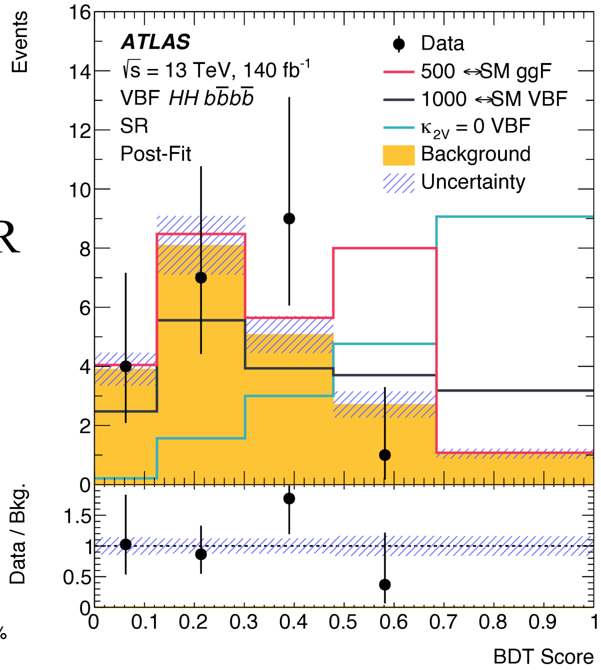
- Use the **CR to extract 1Pass-to-2Pass normalisation**
- Apply this to the SR-1Pass to predict the background in SR-2Pass
- VR used to extract the systematics uncertainty

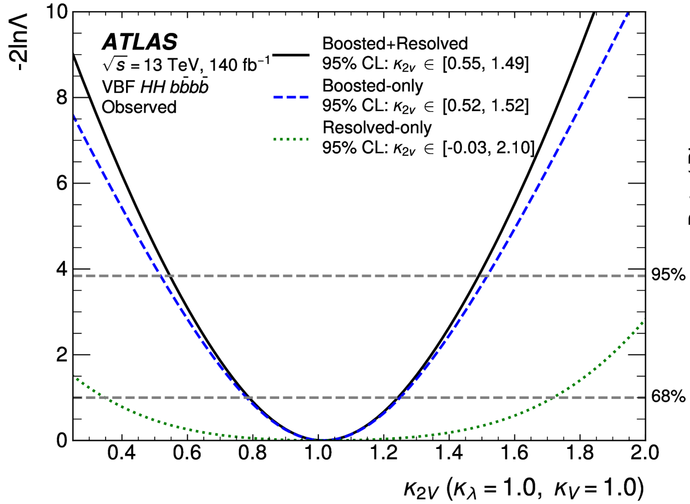




Results

- **Binned maximum-likelihood fit** to the **BDT distribution** in SR
- Results of the **boosted analysis** are combined with the **HH(4b) resolved**



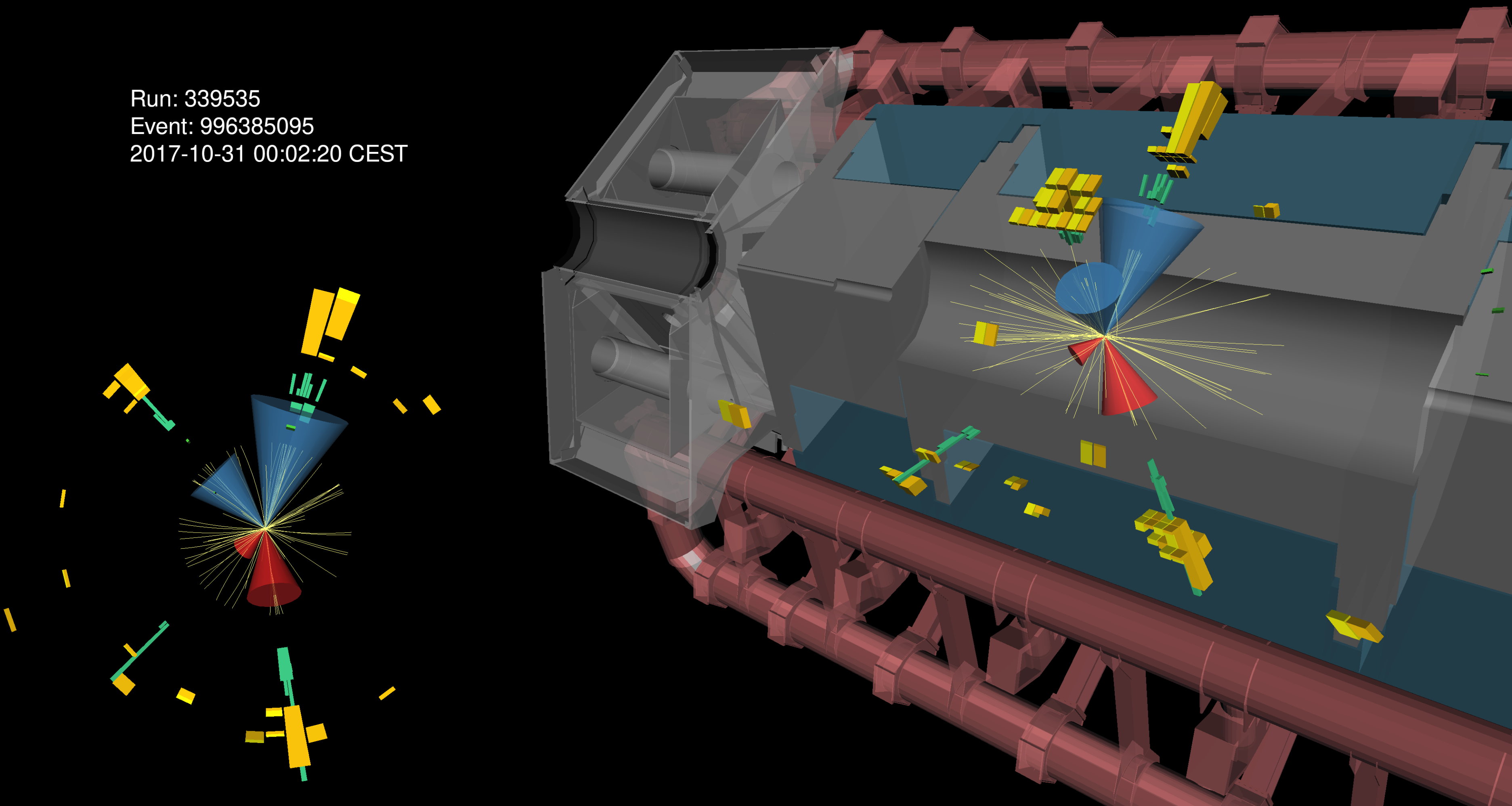


- **Observed $k_{2V} \in$ [0.55, 1.49] @ 95% CL → leading channel in k_{2V} constraints!**
  - **HH(4b) boosted analysis** dominates our sensitivity to k_{2V}
  - k_{2V} **=0 excluded** with an **observed** (expected) significance of **3.8** (3.3) σ
- Boosted analysis **statistical dominated** but **dominant systematics uncertainties:**
  - Double b-tagging algorithm
  - Background estimation
  - Theoretical modelling predictions

$HH(b\bar{b}\tau^+\tau^-)$

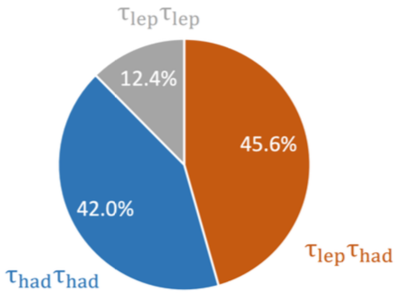
Phys. Rev. D 110 (2024) 032012

ATLAS EXPERIMENT

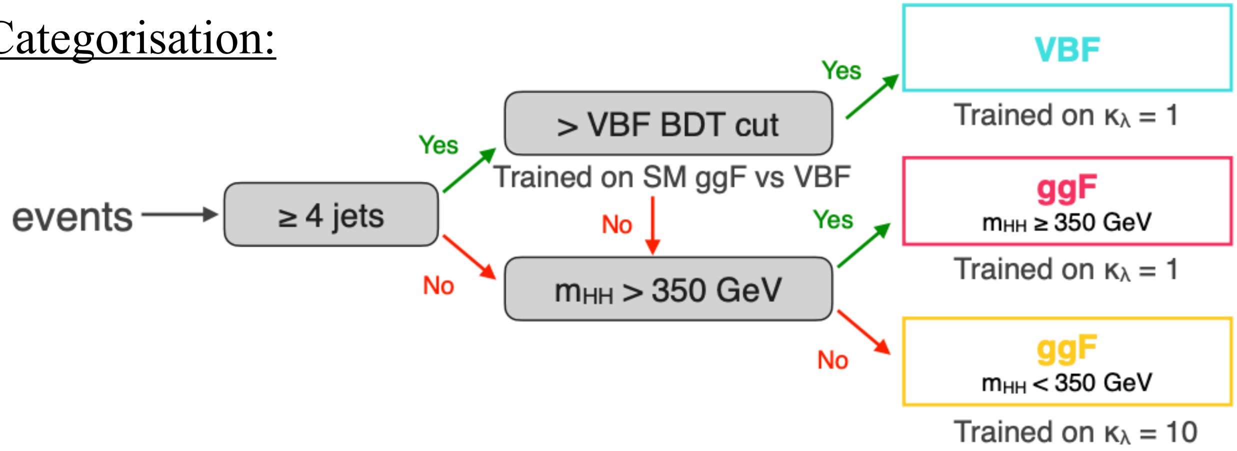


Event selection and categorisation

- $b\bar{b}\tau_{had}\tau_{had}$ and $b\bar{b}\tau_{had}\tau_{lep}$ studied in the analysis



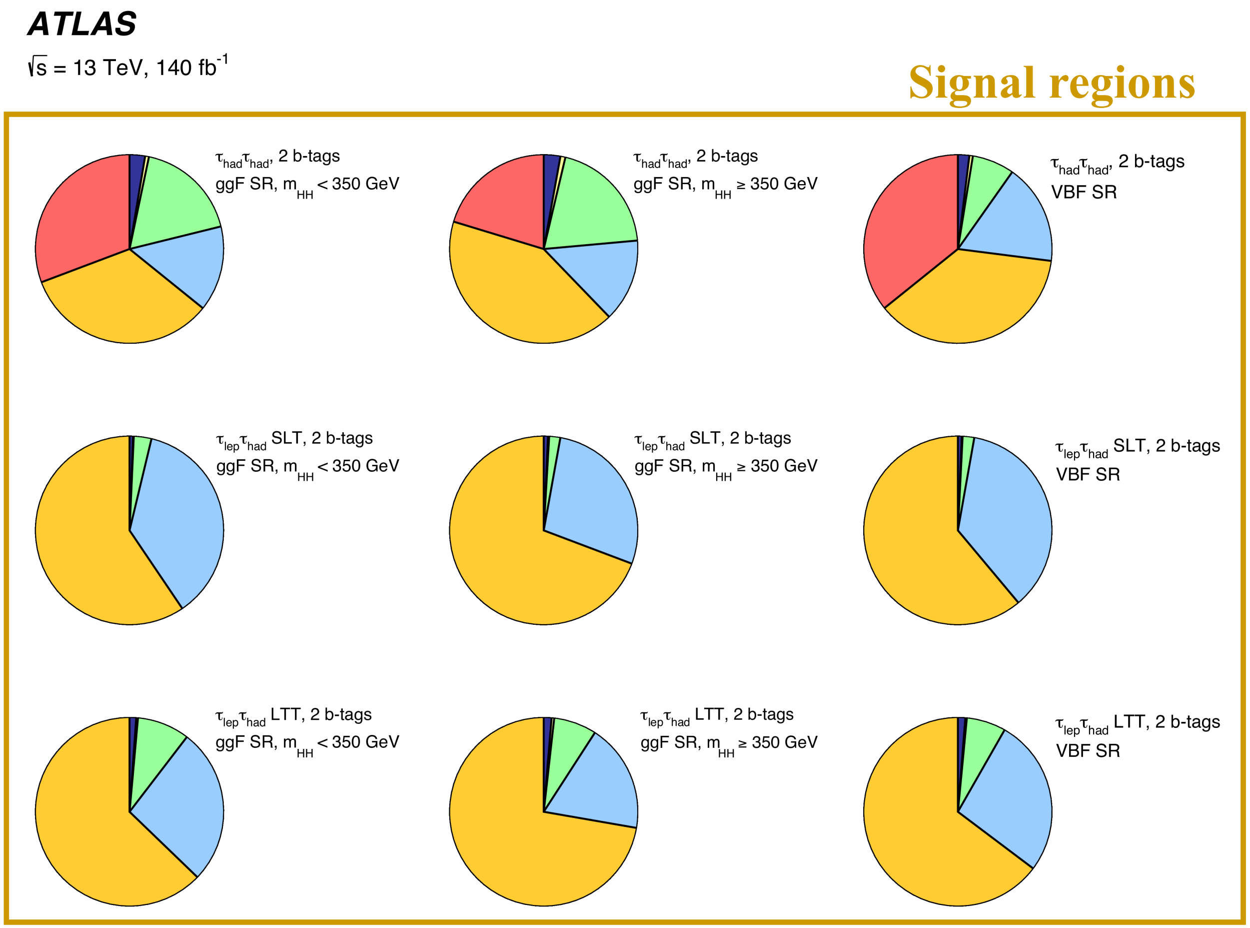
- Trigger:
  - $\tau_{had}\tau_{had}$ channel: single τ_{had} and di-τ_{had} triggers
  - $\tau_{had}\tau_{lep}$ channel:
    - single lepton trigger (SLT)
    - single lepton + τ_{had} trigger (LTT)
- Preselection:
  - **2 b-jets** (DL1r @ **77% WP**) with $p_T(b_1) > 45$ GeV and $p_T(b_2) > 20$ GeV
  - $m_{\tau\tau}$ **> 60 GeV**
- Categorisation:

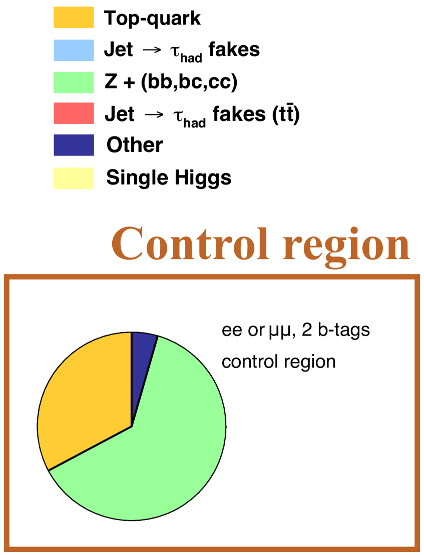


x 3 types of triggers → **9 SRs**

- **BDT** is **trained in each SR** to better separate signal from backgrounds events.

Background composition/estimation





Fake-τ_{had} :
- from $t\bar{t}$ and multi-jet
- Estimated with data-driven methods

Top-quark
- Shape from MC
- Normalisation from fit

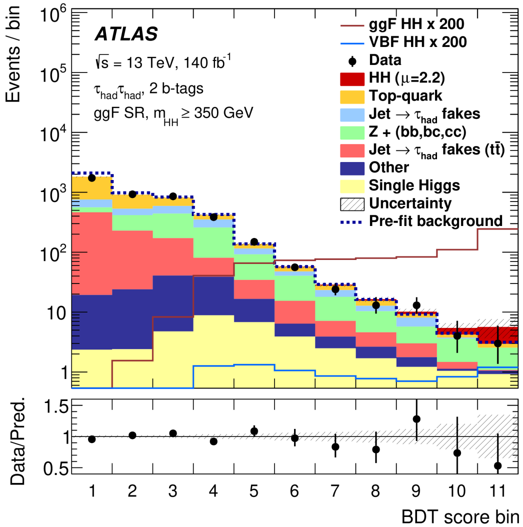
Z($\tau\tau$)+ heavy flavor
- Shape from MC
- Normalisation from CR

Single Higgs & other
- Shape and normalisation from MC

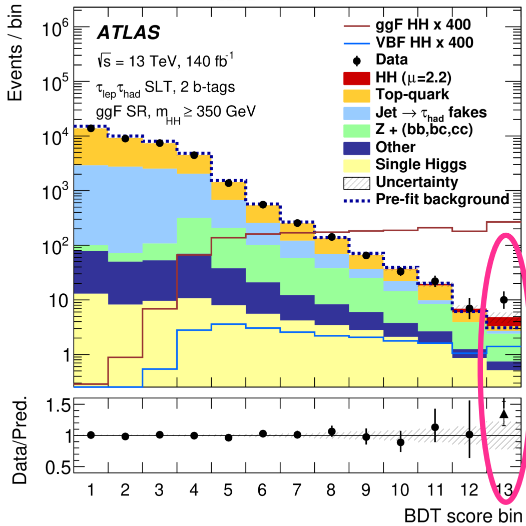
Results

- **Simultaneous binned likelihood** to the **BDT score** ($m_{\ell\ell}$) in the **SRs** (CR)

$\tau_{had}\tau_{had}$
ggF $m_{HH} \geq$ 350 GeV

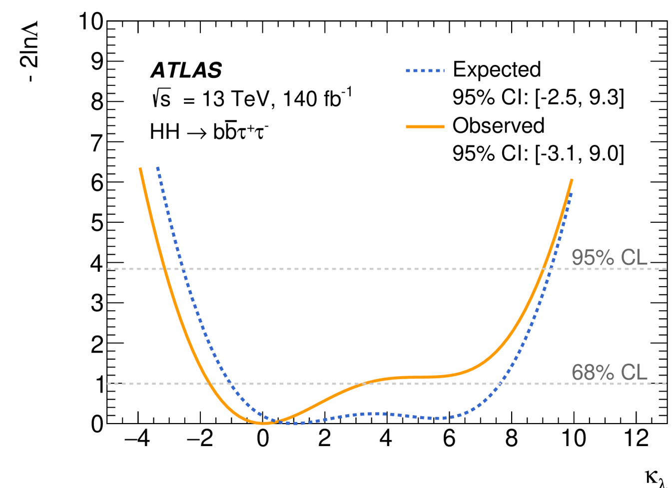


$\tau_{lep}\tau_{had}$, **single lepton trigger**
ggF $m_{HH} \geq$ 350 GeV



Upward fluctuations in data

- **Observed** (**expected**) **limits** on μ_{HH} of **5.9 (3.3) x SM @ 95% CL → leading channel in SM HH search!**
  - 20% improvement wrt previous publication
- **Observed $k_\lambda \in$ [-3.1, 9.0] @ 95% CL**
- **Observed $k_{2V} \in$ [-0.5, 2.7] @ 95% CL**
- **Statistical dominated** and **dominant sys uncertainties:**
  - Theoretical XS uncertainties
  - Statistics precision of the bkg MC samples



$HH(b\bar{b}\gamma\gamma)$

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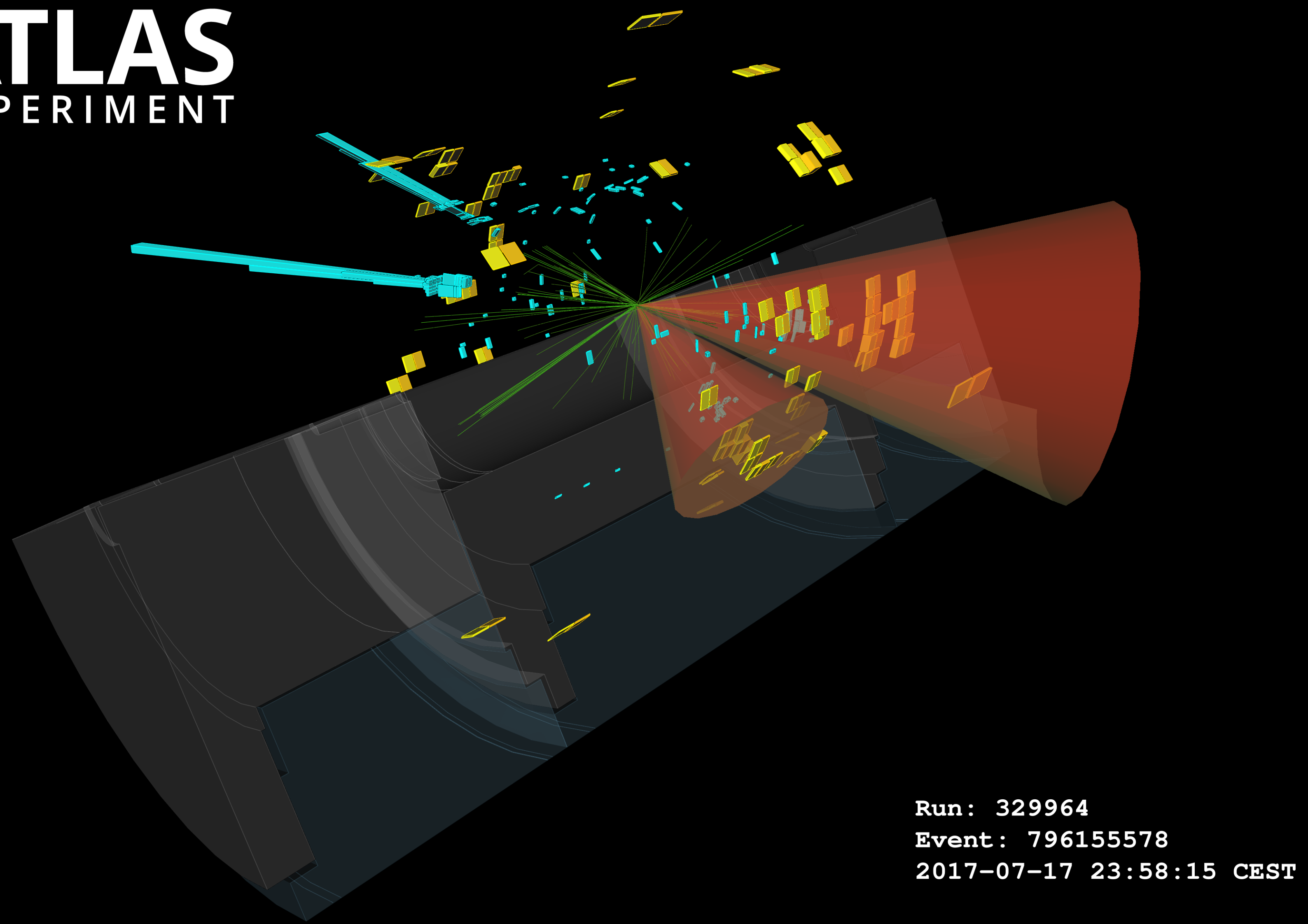
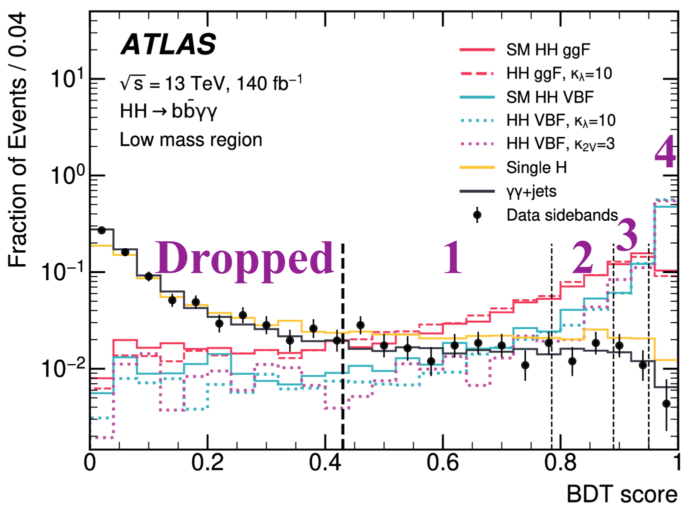
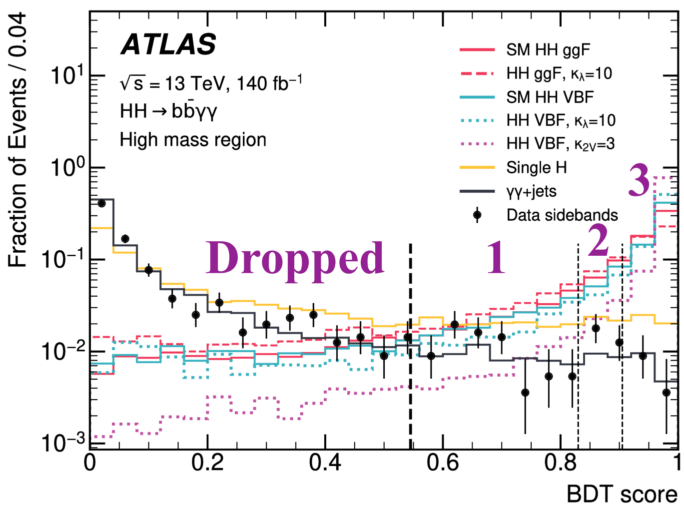


Event selection and categorisation

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

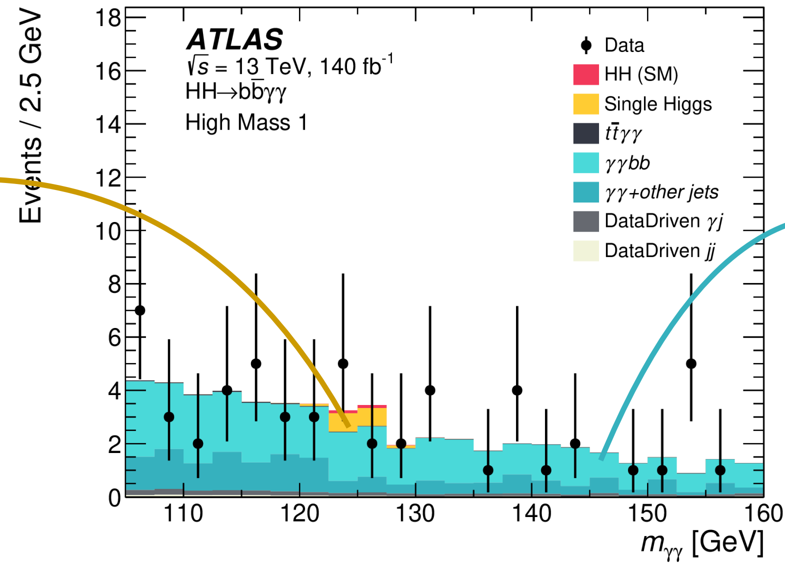
- Trigger: combination of γ and $\gamma\gamma$ triggers
- Preselection:
  - $H \to \gamma\gamma$ **selection**
    - **2 photons**
      - 105 GeV < $m_{\gamma\gamma}$ < 160 GeV
  - $H \to b\bar{b}$ **selection**
    - **2 *b*-jets** (DL1r @ **77% WP**)
    - **No leptons** and $N_{central-jets}$ **< 6**
    - **ttH reduction**
- Categorization:
  - Based on $m^*_{bb\gamma\gamma}$ (Low mass, **≤ 350 GeV** and High mass, **>350 GeV**) region and **BDT output**
  - **4 categories** in the **Low Mass region** and **3 categories** in the **High Mass region**





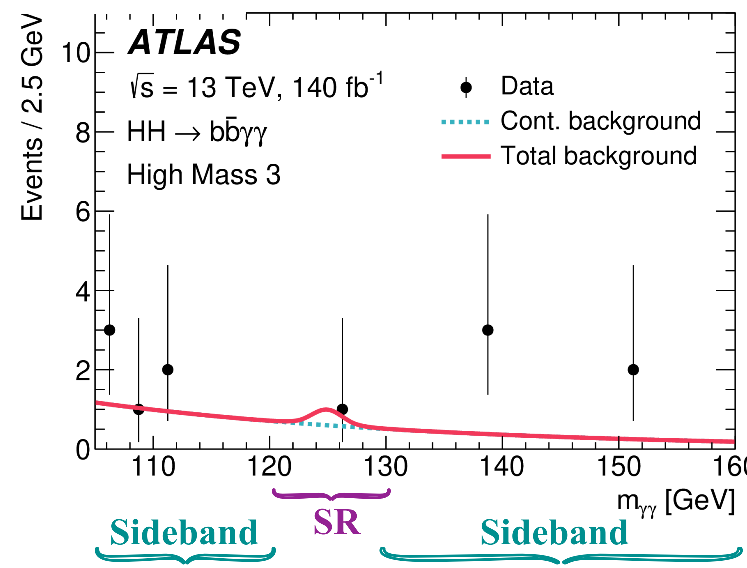
Signal and background modelling

Resonant bkg:
Single-Higgs process



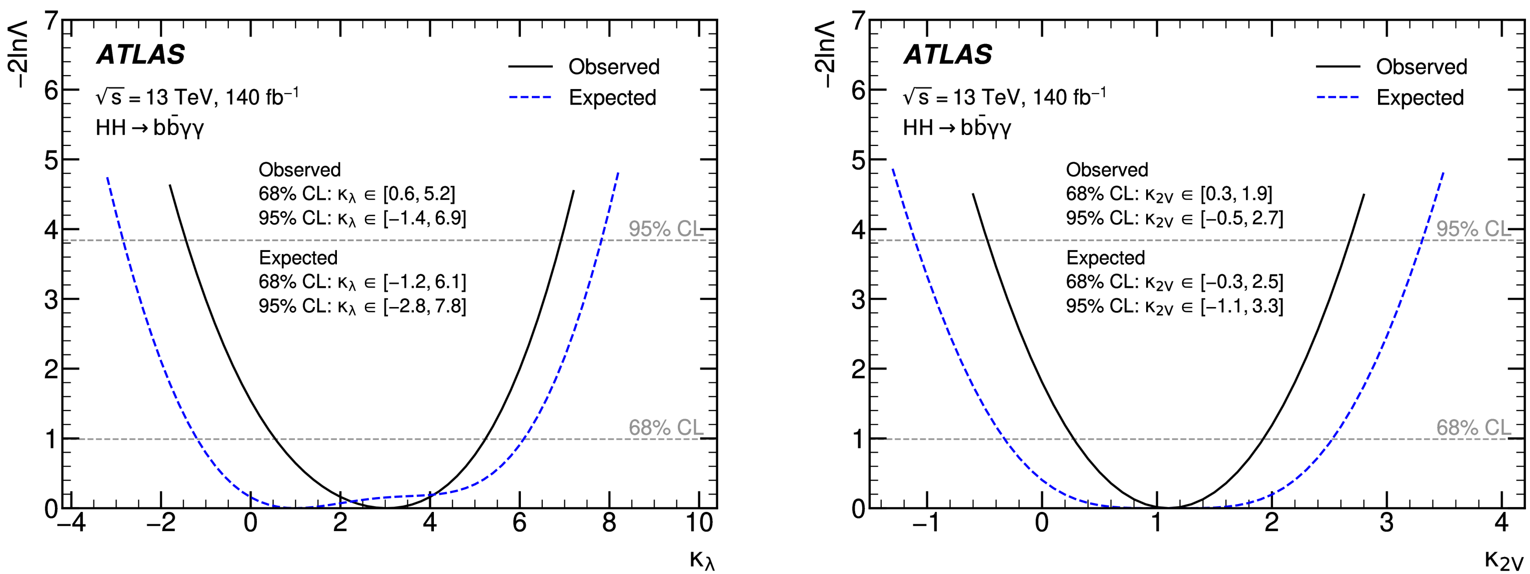
Non-resonant continuum bkg:
$\gamma\gamma$ **+ jets events**

- **Modelling** of signal and background events in the $m_{\gamma\gamma}$ **spectrum**
- **HH** and **H events**
  - Modelled by a **double-sided Crystal ball function** Parameters estimated from MC
- $\gamma\gamma$ **+ jets events**
  - Modelled using **exponential function.** Parameters derived from the data sidebands



Results

- **Simultaneous likelihood fit to** $m_{\gamma\gamma}$ in all the 7 categories
- **Observed (expected) limits** on μ_{HH} **of 4.0 (5.0) x SM @ 95% CL**
  - 12% improvement wrt the old Run2 analysis
- **Observed** $k_\lambda \in$ **[-1.4, 6.9] @ 95% CL → leading channel in** k_λ **constraints**
- **Observed** $k_{2V} \in$ **[-0.5, 2.7] @ 95% CL**



- **Statistical dominated** and **dominant sys uncertainties from theoretical predictions**

$\boldsymbol{HH}(b\bar{b}\ell\ell + E_T^{miss})$

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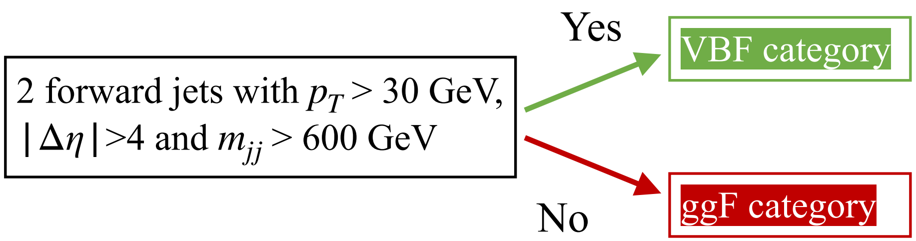
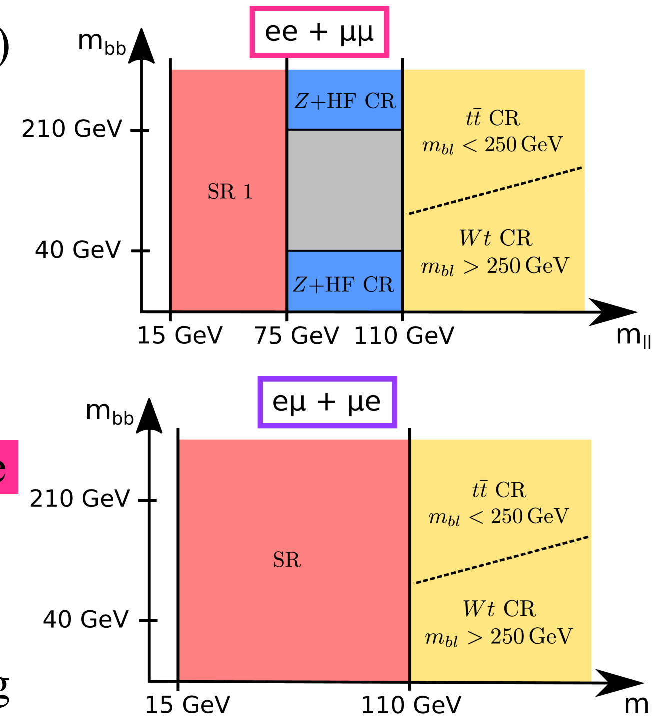
Event selection and categorisation

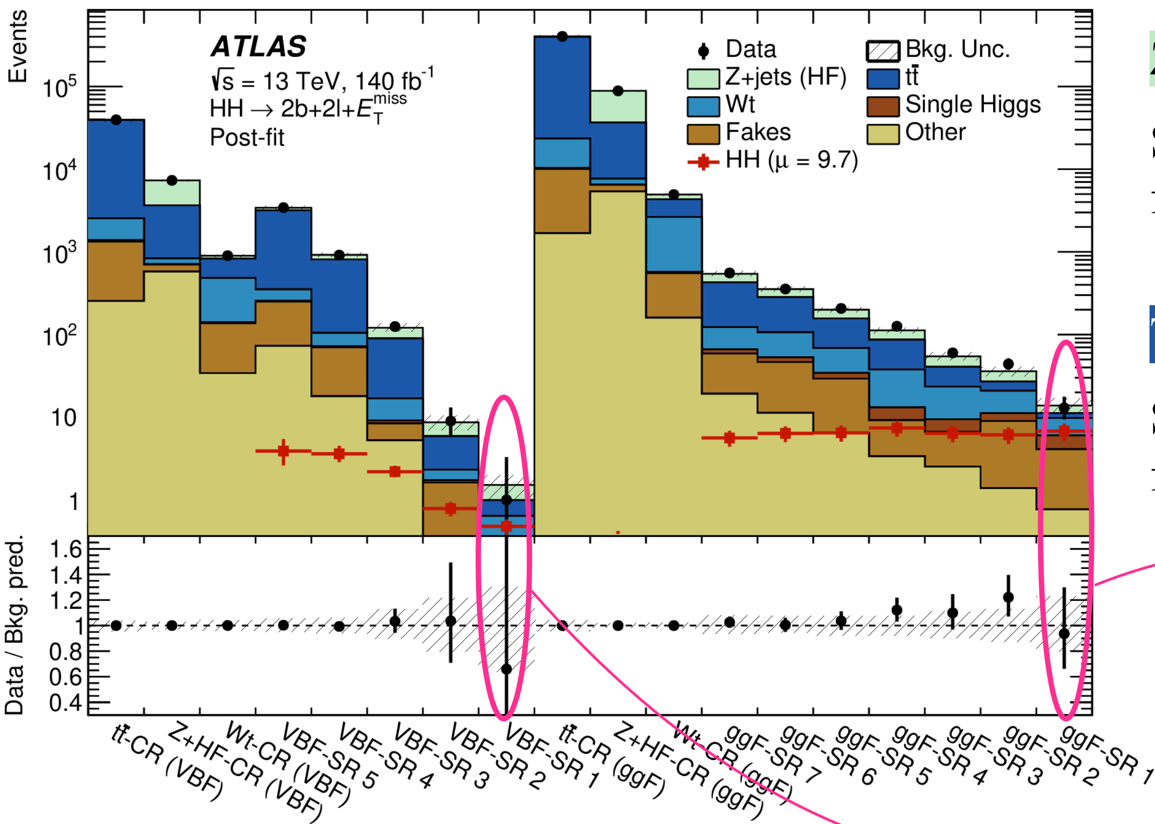
- Target: one H → $b\bar{b}$ and the other one to W^+W^-, $\tau^+\tau^-$, $ZZ \rightarrow$ **$2\ell^+\ell^-$+ 2 b-jets**
- Trigger: single or di-lepton triggers
- Preselection: **2 opposite-sign leptons** + **2 b-jets** (77% WP)
- Categorization:





  - Additional split based on the flavour of the leptons (same flavour vs different flavour)
  - SR and CR definition based on $m_{\ell\ell}$ and m_{bb} cuts
- **DNN** and **BDT** used to **further discriminate** signal from bkg events in the **ggF** and **VBF** categories

Background estimation



Z+ heavy flavour (HF)

Shape from MC, normalisation from Z+HF CR

Top ($t\bar{t}$ and Wt)

Shape from MC, normalisation from $t\bar{t}$ and Wt CRs

Downward fluctuation of the data

Fake leptons

Data-driven using CR defined reverting SR definition (requiring SS leptons)

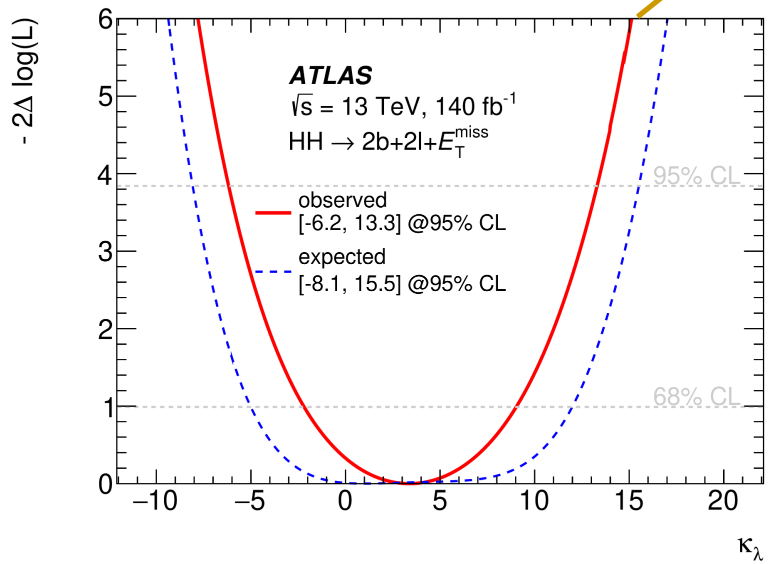
Single Higgs

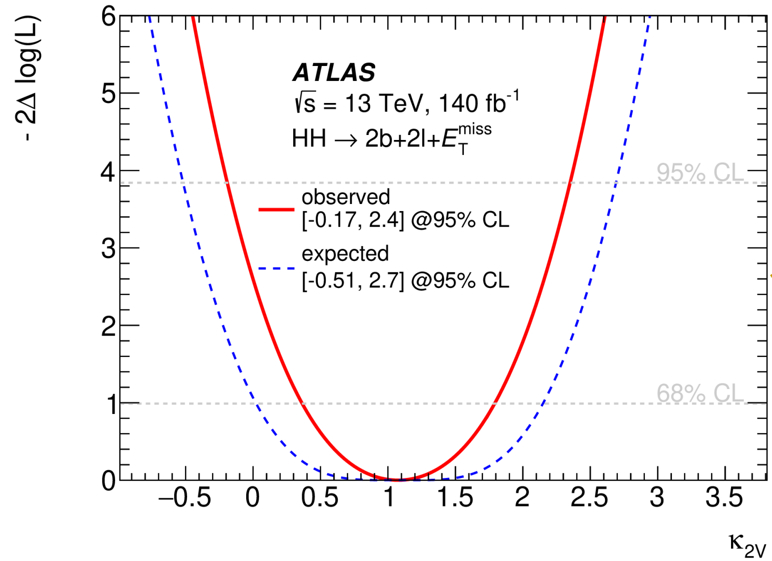
Shape and normalisation from MC

Results

- **Simultaneous likelihood fit to SRs and CRs**
- **Observed (expected) limits** on μ_{HH} **of 9.7 (16.2) x SM @ 95% CL**
- **Observed** $k_\lambda \in$ **[-6.2, 13.3]** @ 95% CL
- **Observed** $k_{2V} \in$ **[-0.17, 2.4]** @ 95% CL

Observed constraints better than **expected constraints** due to the observed **downward data fluctuation**





- **Statistical dominated** and **dominant sys uncertainties** from **bkg modelling of Z+HF**

HH(Multileptons)

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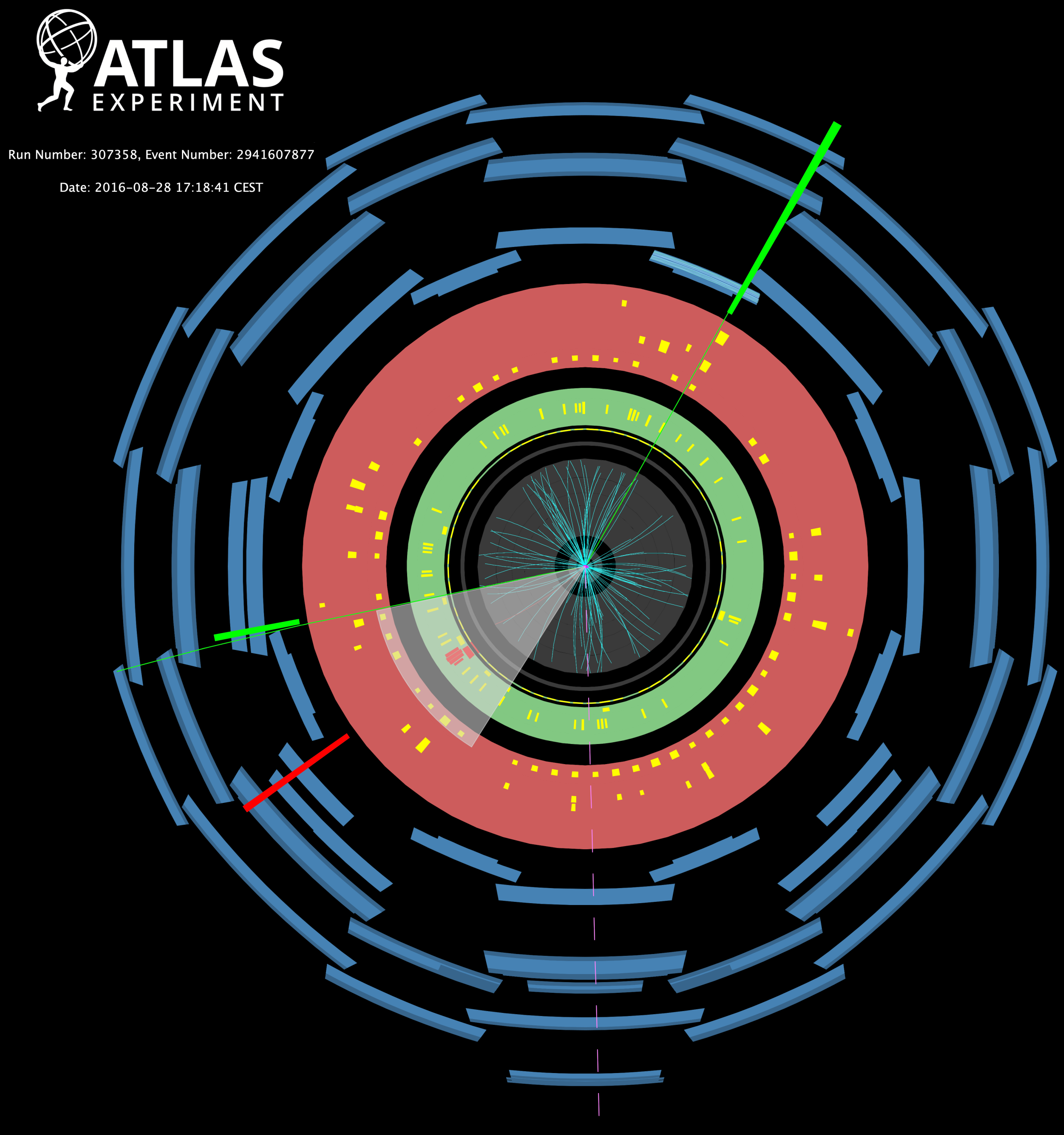
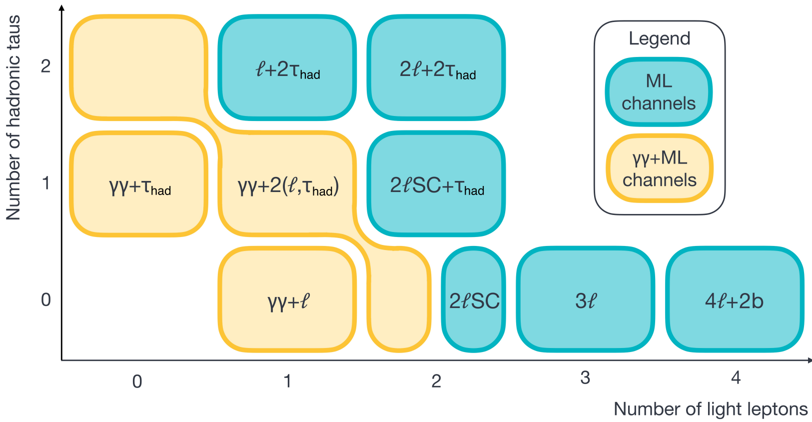


Event selection and categorisation

- Target: $b\bar{b}ZZ$, **4*V*** (V=W or Z), $VV\tau\tau$, 4τ, $\gamma\gamma VV$, $\gamma\gamma\tau\tau$
  - Total HH BR covered: 6.5%
- Trigger:
  - **single or di-lepton triggers** (ML channels);
  - **diphoton triggers** ($\gamma\gamma$+ML channels)

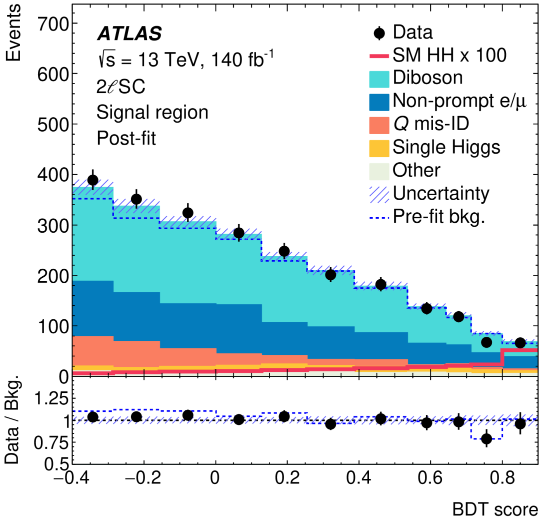
	bb	WW	ττ	ZZ	γγ
bb	34%				
WW	25%	4.6%			
ττ	7.3%	2.7%	0.39%		
ZZ	3.1%	1.1%	0.33%	0.069%	
γγ	0.26%	0.10%	0.028%	0.012%	0.0005%

- Categorization:
  - Based on the **number of leptons** (e, μ), **hadronic taus** (τ_{had}) and **photons**
  - ➡ **9** orthogonal **channels**



- **BDTs** use to **enhance signal** to **background separation** (except for the $\gamma\gamma$+ 2 (ℓ, τ_{had}) channel)
  - Used as final discriminant in ML channels
  - Used to defined categories in which the $m_{\gamma\gamma}$ is fit in $\gamma\gamma$+ML channels

Background estimation



Prompt leptons from SM processes (dominated by diboson)

- Shape from MC, normalization from CRs

Non-prompt leptons (from b-hadron decay or γ conversion)

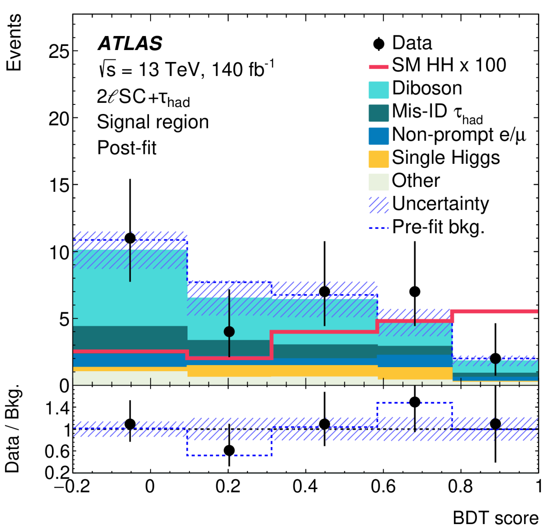
- Template fit to data in CR

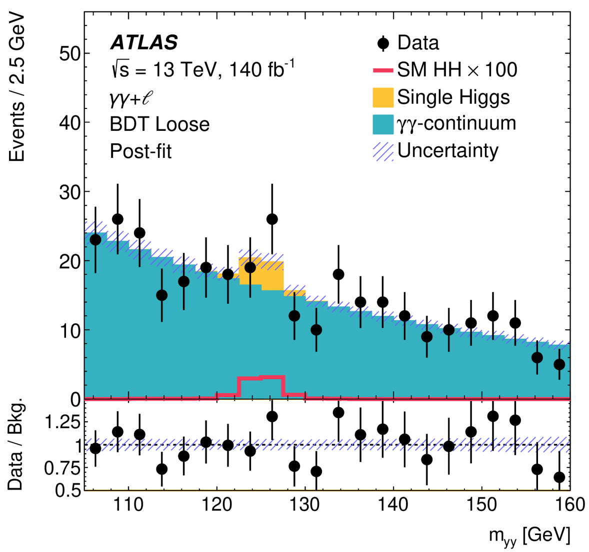
Mis-assigned charge (from leptons with mis-identified charge)

- Template fit to data in CR

Mis-identified τ (from jets misidentified as τ_{had})

- Data-informed corrections to simulations





Single Higgs

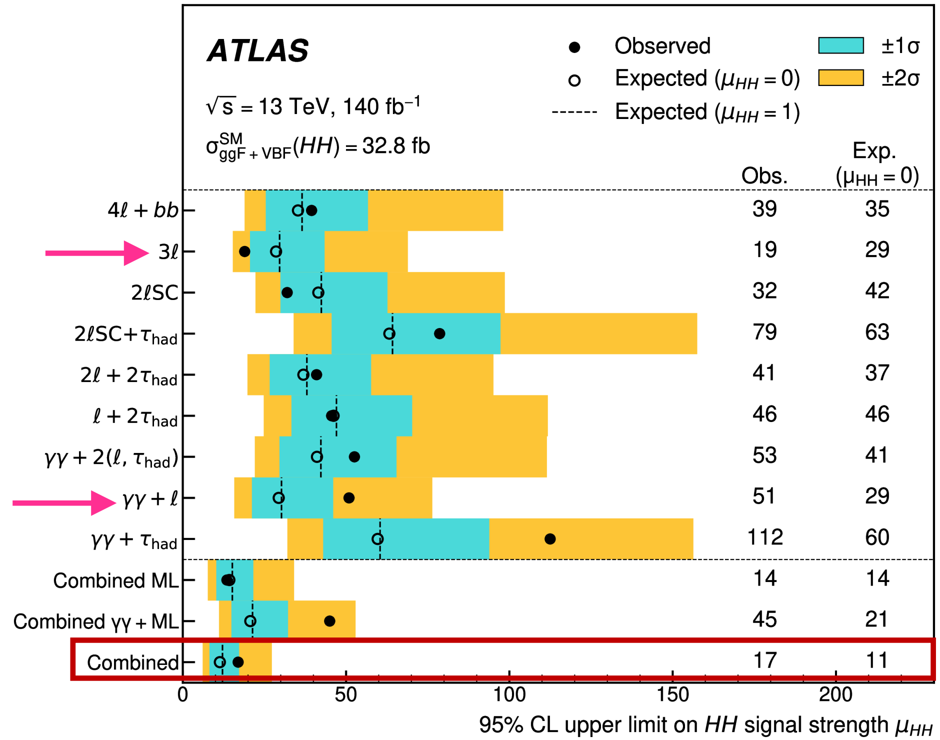
- Estimated using MC

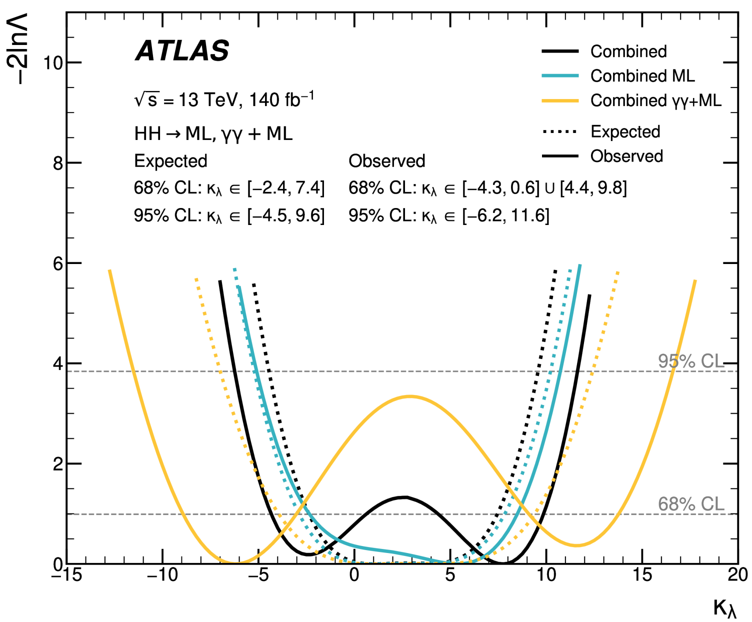
Non-resonant $\gamma\gamma$ process, i.e. $\gamma\gamma$ +jets

- Functional form from $m_{\gamma\gamma}$ sidebands

Results

- **Simultaneous likelihood fit to 9 SRs and CRs**
- **Observed** (expected) **limits on** μ_{HH} **of 17** (11) **x SM @ 95% CL**
- **Observed** $k_{\lambda} \in$ **[-6.2, 11.6]** @ 95% CL
- **Observed** $k_{2V} \in$ **[-2.5, 4.6]** @ 95% CL





- **Statistical dominated** and **dominant sys uncertainties** from **modelling**
  - μ_{HH} **< 9.1 x SM** expected limit without systematics

Combination

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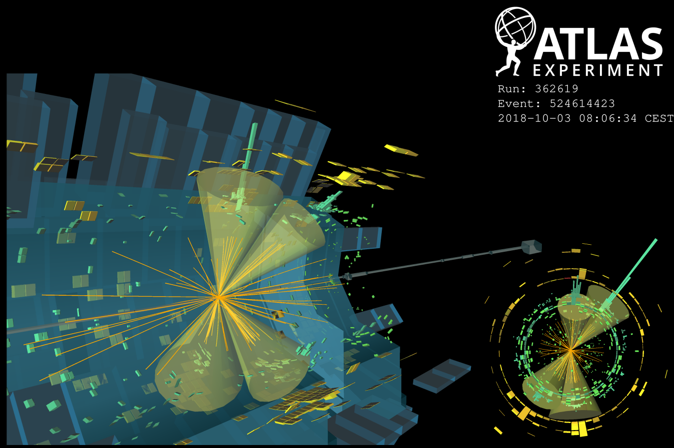
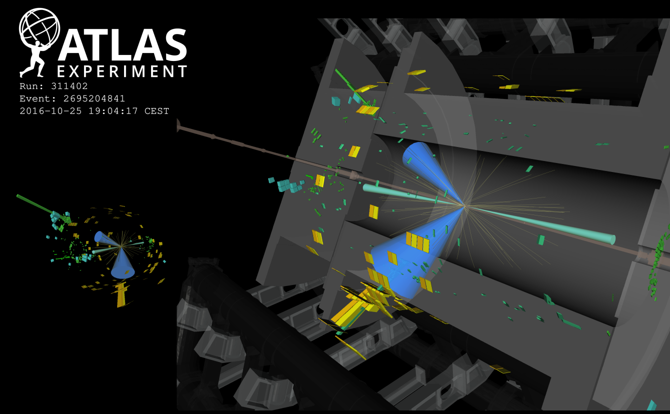
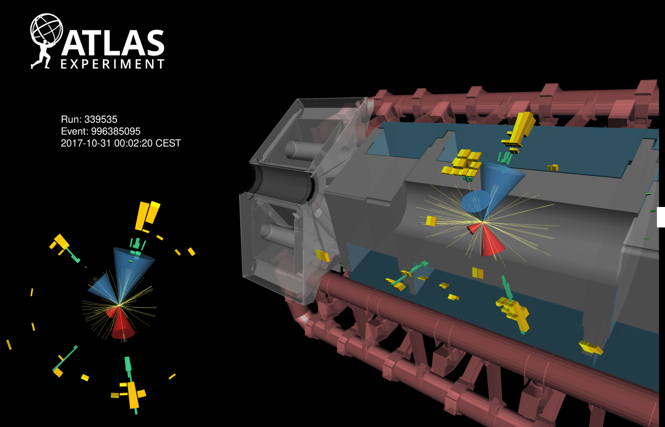
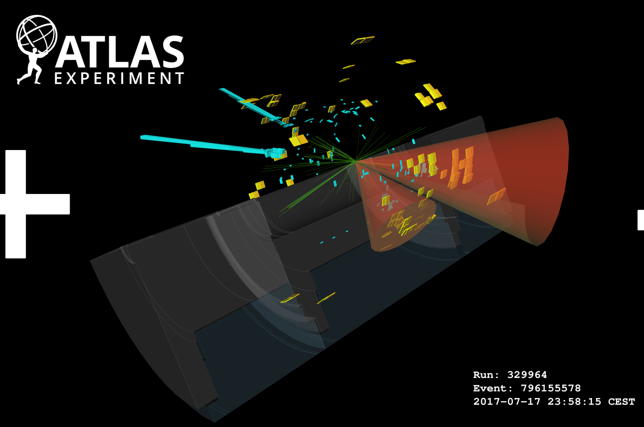
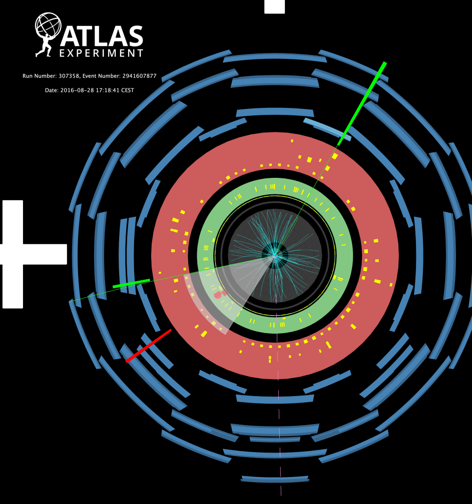




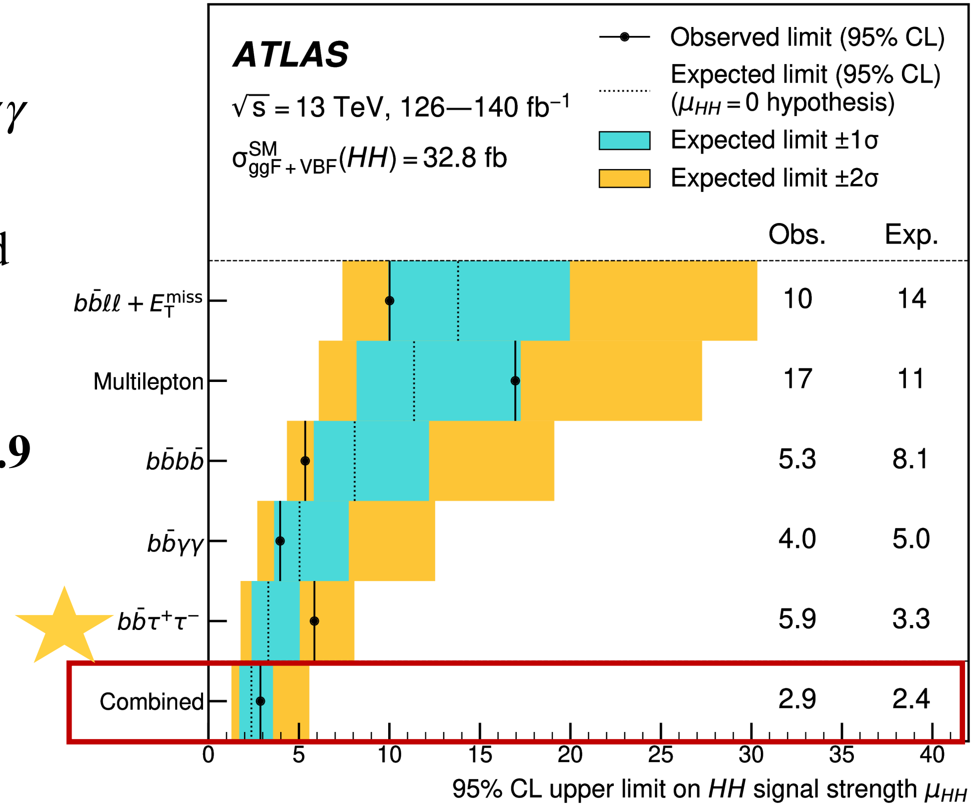






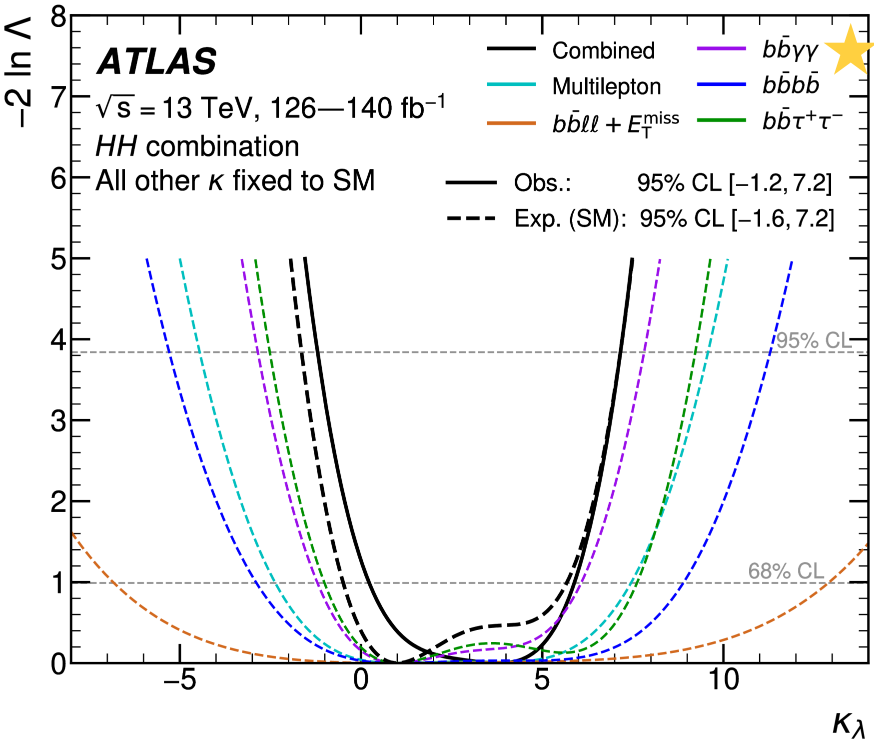
Results: μ_{HH} limits

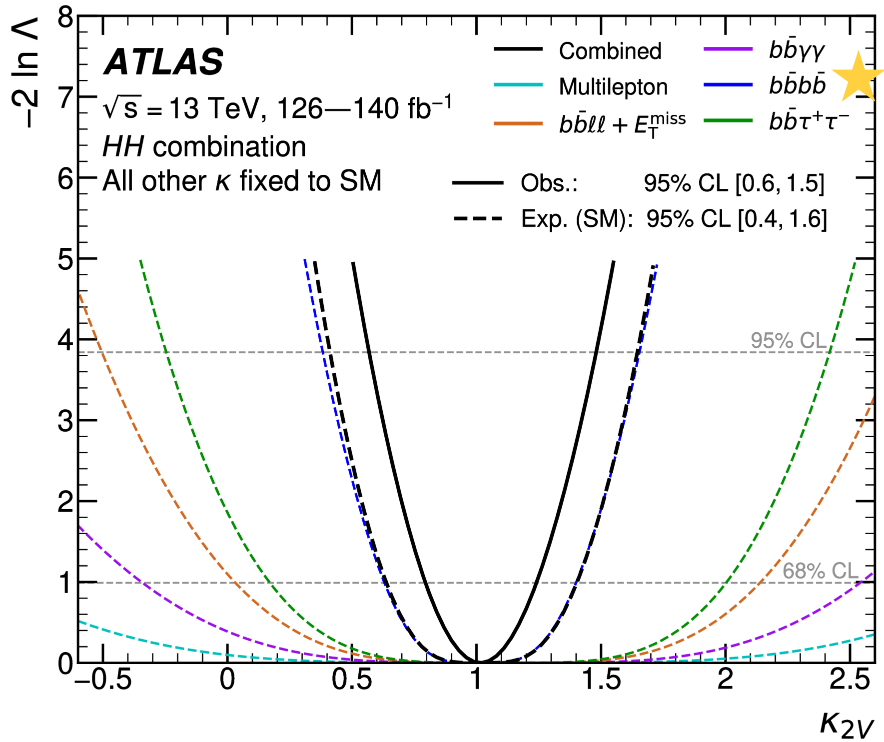
- **Updates:**
  - Improved results from $b\bar{b}\tau\tau$ and $b\bar{b}\gamma\gamma$
  - New boosted VBF HH($b\bar{b}b\bar{b}$)
  - New decay modes: multi-leptons and $b\bar{b}\ell\ell + E_T^{miss}$



- **Observed (expected) limits on μ_{HH} of 2.9 (2.4) x SM @ 95% CL**
  - **17 % improvement** wrt previous publication
    - 13% from $b\bar{b}b\bar{b}$, $b\bar{b}\tau\tau$ and $b\bar{b}\gamma\gamma$ improvements
    - 4% from inclusion of multilepton and $b\bar{b}\ell\ell + E_T^{miss}$
  - ★**Leading contribution from $b\bar{b}\tau\tau$ channel**
- Dominant syst. uncertainties:
  - **theory XS uncertainties**
  - **background modelling**

Results: k_λ and k_{2V} constraints





- **Observed** $k_\lambda \in$ **[-1.2, 7.2]** @ 95% CL
  - ★Leading contribution from $b\bar{b}\gamma\gamma$ channel
- **Observed** $k_{2V} \in$ **[0.6, 1.5]** @ 95% CL
  - ★Leading contribution from $b\bar{b}b\bar{b}$, mostly from boosted channel

HL-LHC projections

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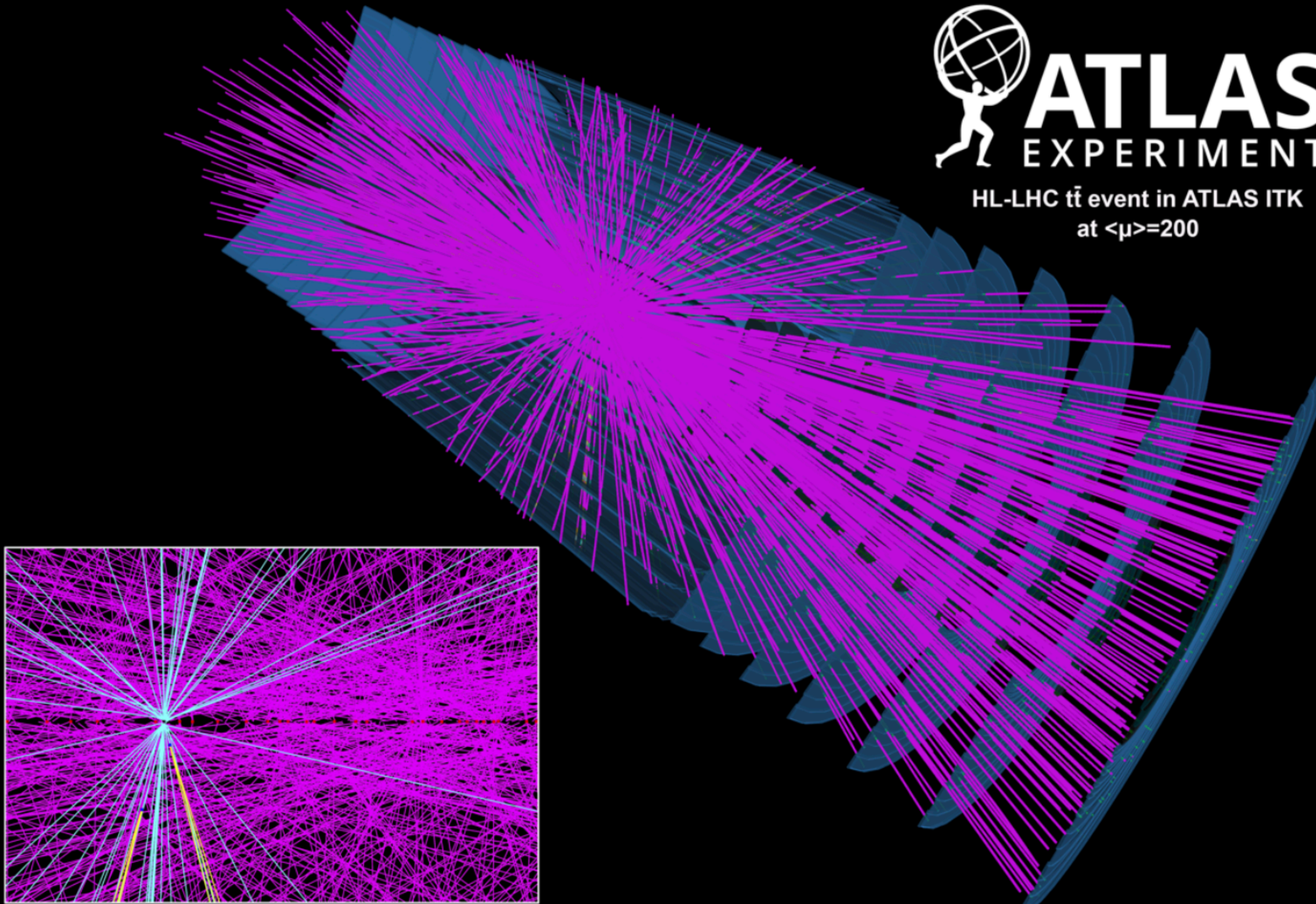
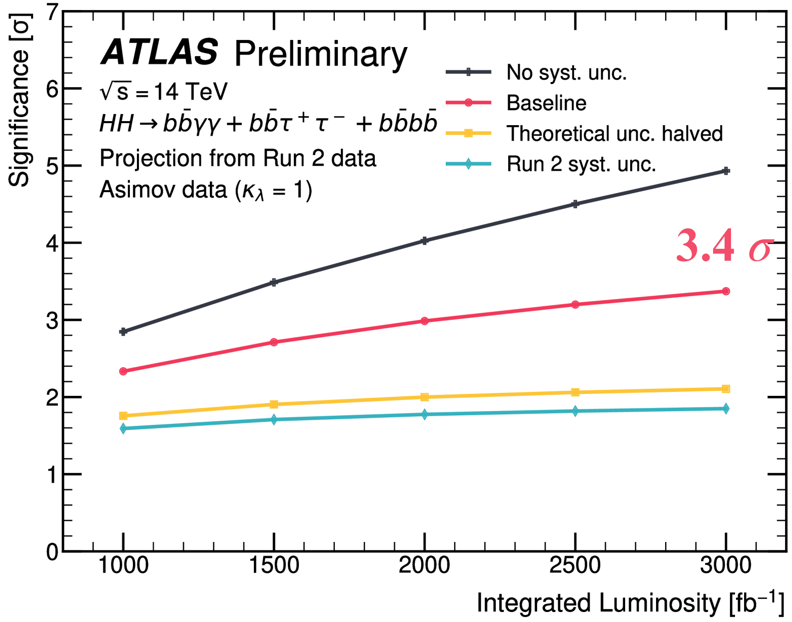
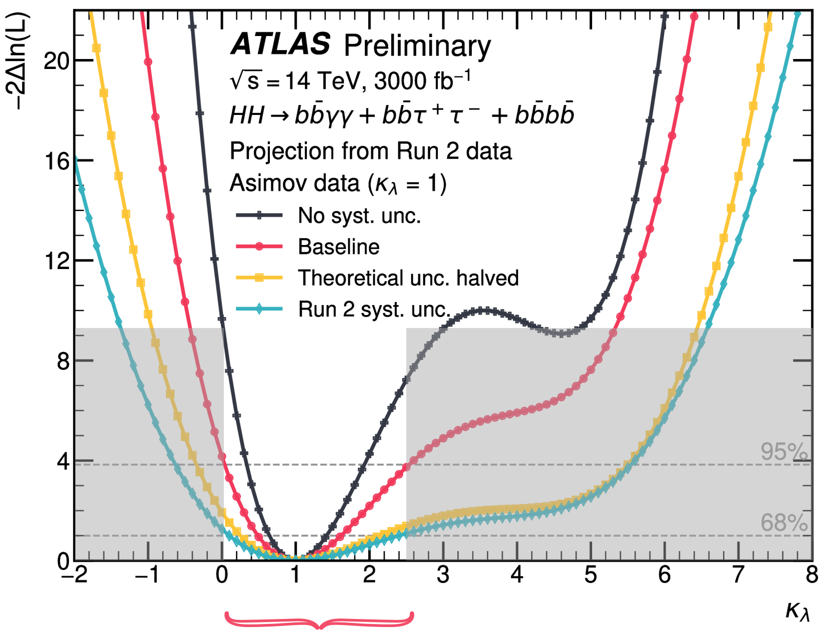


HL-LHC projections

- Extracted for **combination** $b\bar{b}b\bar{b} + b\bar{b}\tau\tau + b\bar{b}\gamma\gamma$
- 18% $\sigma(HH)$ increase due to the $\sqrt{s}$ = 13 TeV →14 TeV.
- Different scenarios for the systematics uncertainties
  - **Baseline**: $\frac{1}{2}$ x theory and experimental uncertainties, $\sqrt{\frac{\mathscr{L}}{\mathscr{L}'}}$ x statistical unc., modelling unc are the same as in Run2.
- Based on previous round of HH analyses →Already 13% improvements with this round



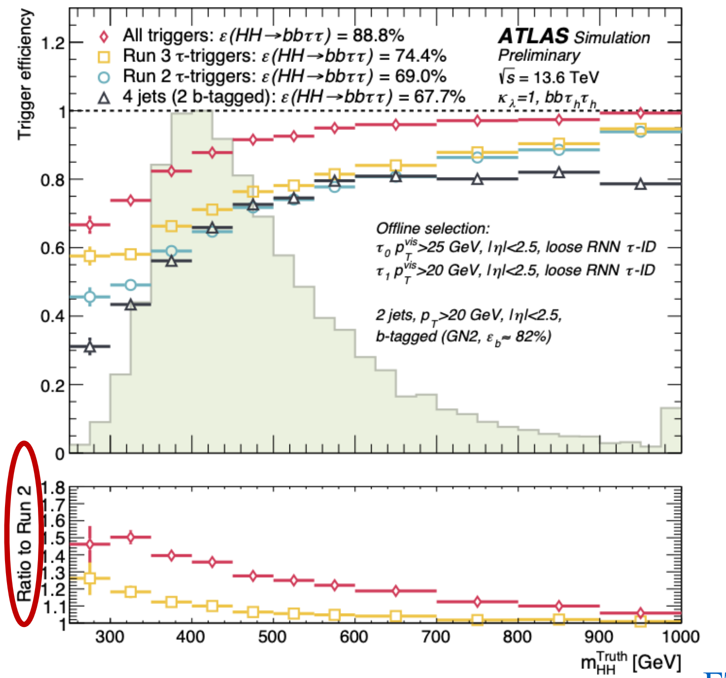


$k_\lambda \in$ **[0.0, 2.5] @ 95% CL**

Towards the (near) future

More data, **better triggers**, **better taggers**, better performance!

Tau triggers



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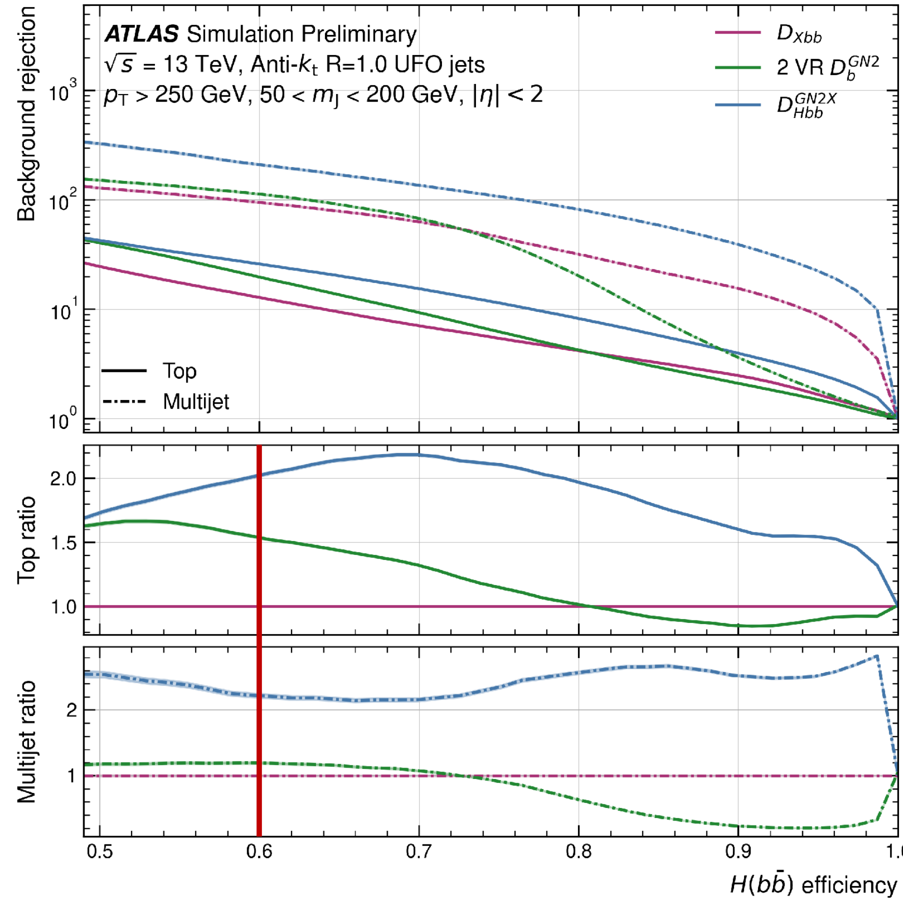

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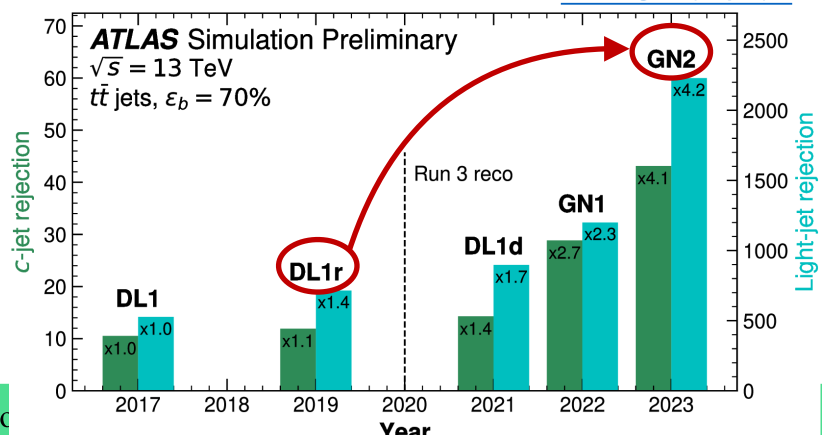


Conclusions

- Di-Higgs is a **unique process to probe the Higgs potential**
- HH is a **rare process** and requires **highly optimised analyses**
- ATLAS conducted searches in HH final states covering 50% of decays
    - **Best expected sensitivity** is obtained by **combining all the HH analyses**
        - Signal strength: μ_{HH} **< 2.9 (2.4 expected)**
        - Higgs self-coupling: $k_\lambda \in$ **[-1.2, 7.2]** @ 95% CL
    - **Promising outlook for Run3 results**:
        - New triggers
        - Improved b(b)-taggers
        - Better object identification
        - Analysis techniques

Stay tuned, more interesting results are coming!

Back-up slides

Higgs potential

- The full expression of the Higgs potential is encoded with μ and λ parameters as:

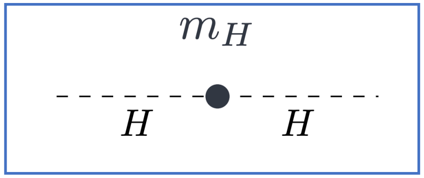
$$V(\phi^\dagger\phi) = \mu^2\phi^\dagger\phi + \lambda(\phi^\dagger\phi)^2$$

- When linearising the Higgs field after the EWSB around the vacuum expected value ν one gets

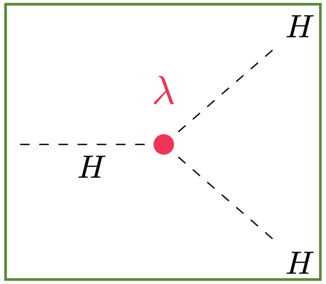
$$V(h) = \mu^2 h^2 + \lambda\nu h^3 + \frac{\lambda}{4}h^4$$

where $\mu^2 = \frac{1}{2}m_H^2$ and $\nu = \sqrt{\frac{\mu^2}{\lambda}}$

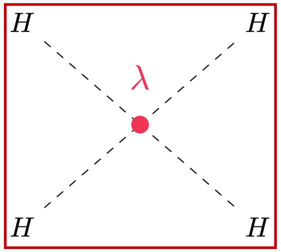
$\mu^2 h^2$: comes from the Higgs mass measurement



$\lambda\nu h^3$: direct access to λ through Higgs pair creation



$\frac{\lambda}{4}h^4$: Quartic interaction even rarer (out of reach even for HL-LHC)



Interference in the ggF HH production

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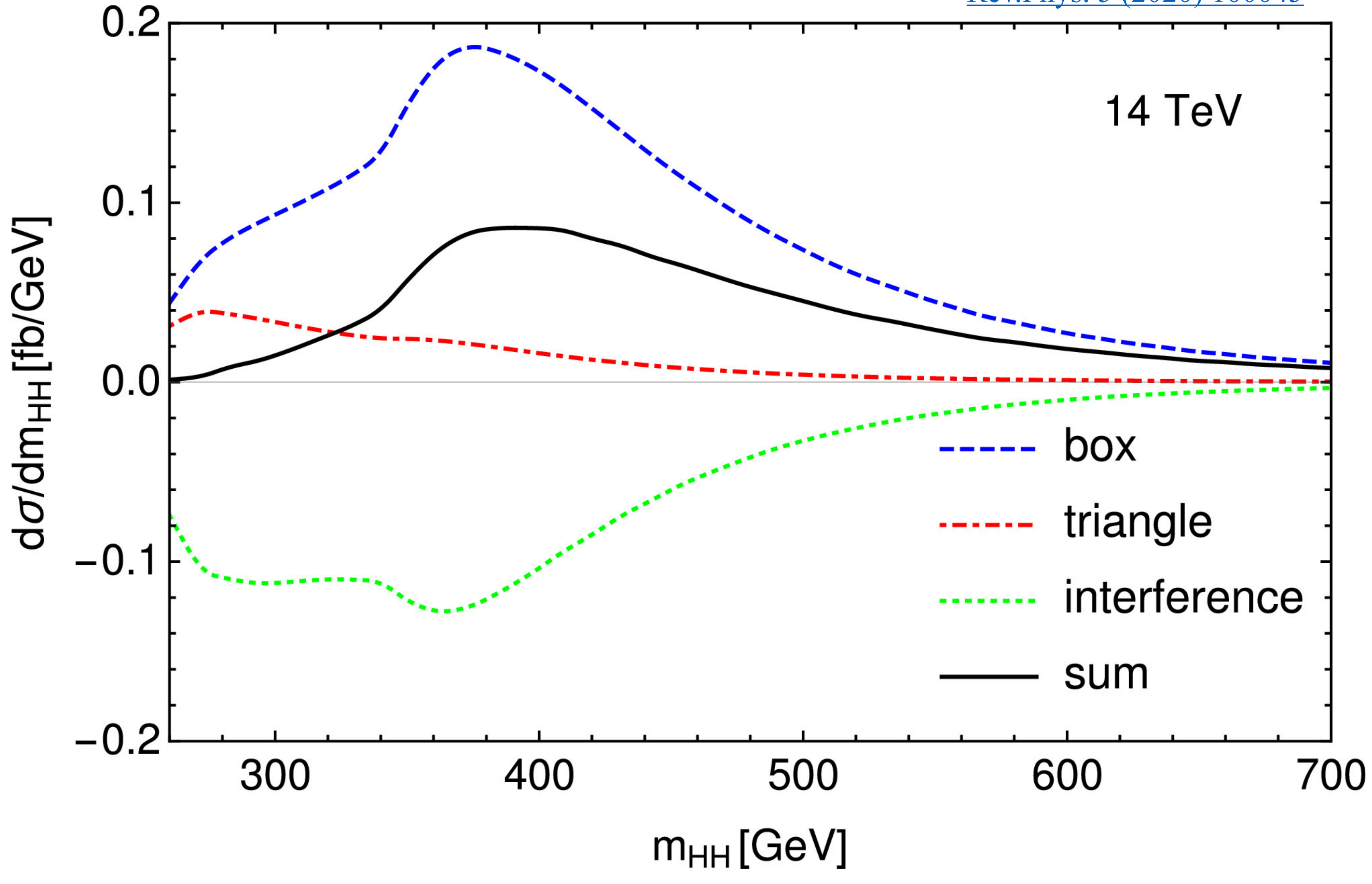
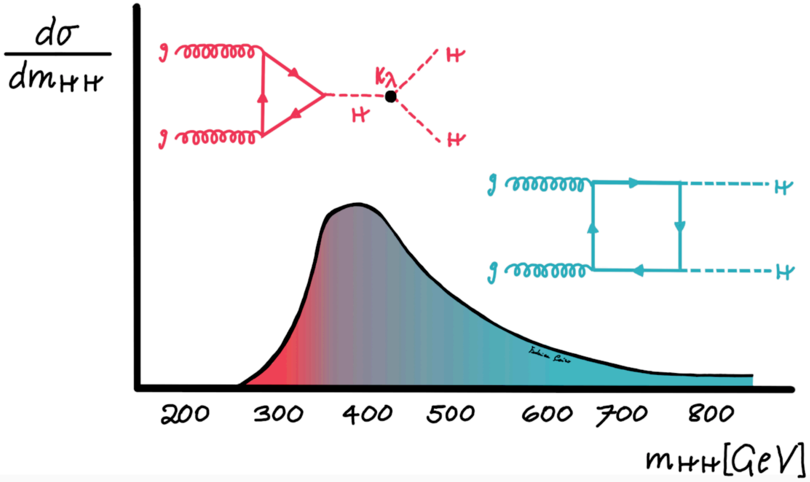
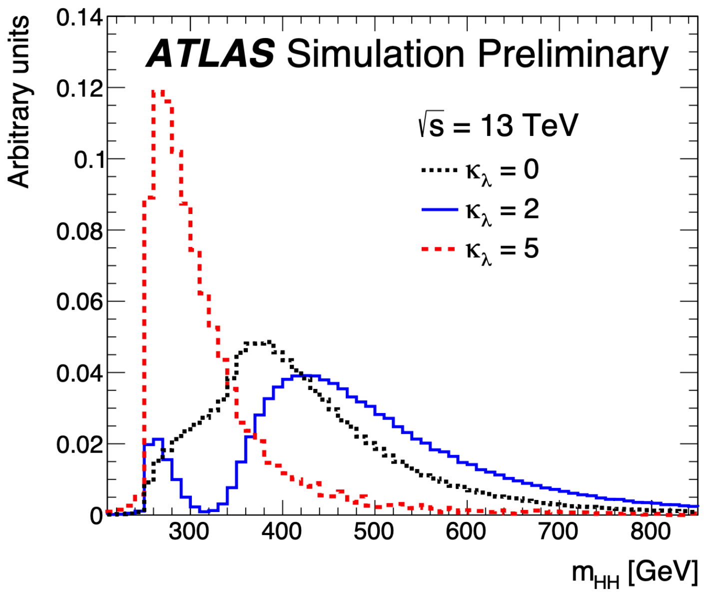
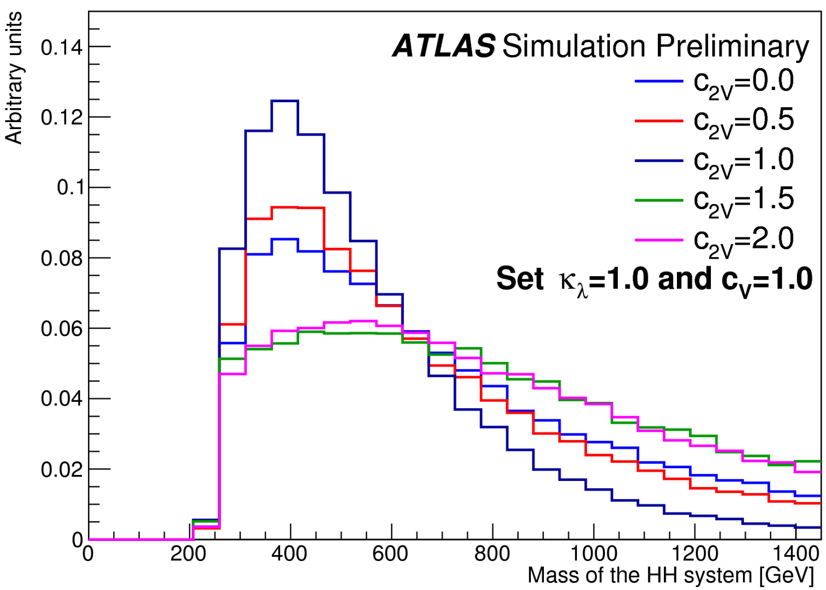


Contribution to the ggF HH



- Low m_{HH}: essential to constrain self coupling k_λ

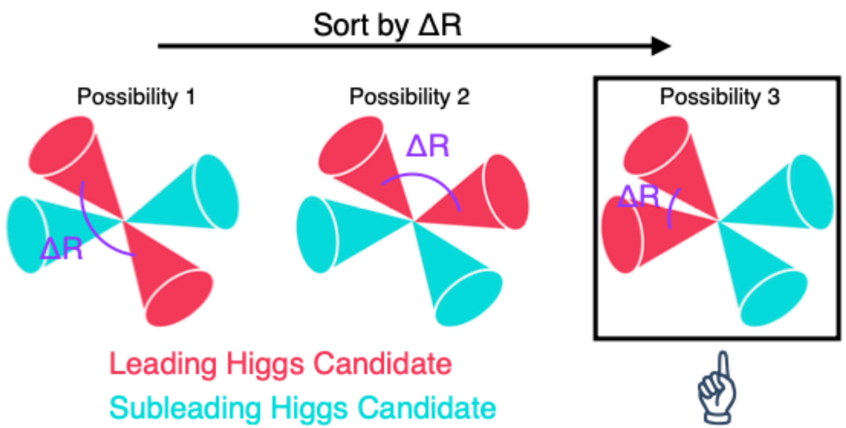




- m_{HH} shape very dependent on k_λ

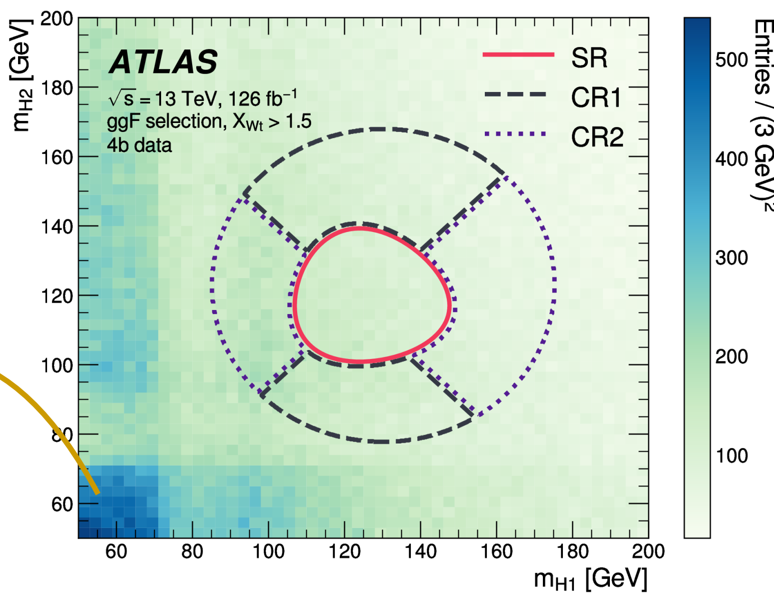
$b\bar{b}b\bar{b}$ resolved pairing

- **4 b-jets** are selected in the events → 3 possible combination pairings

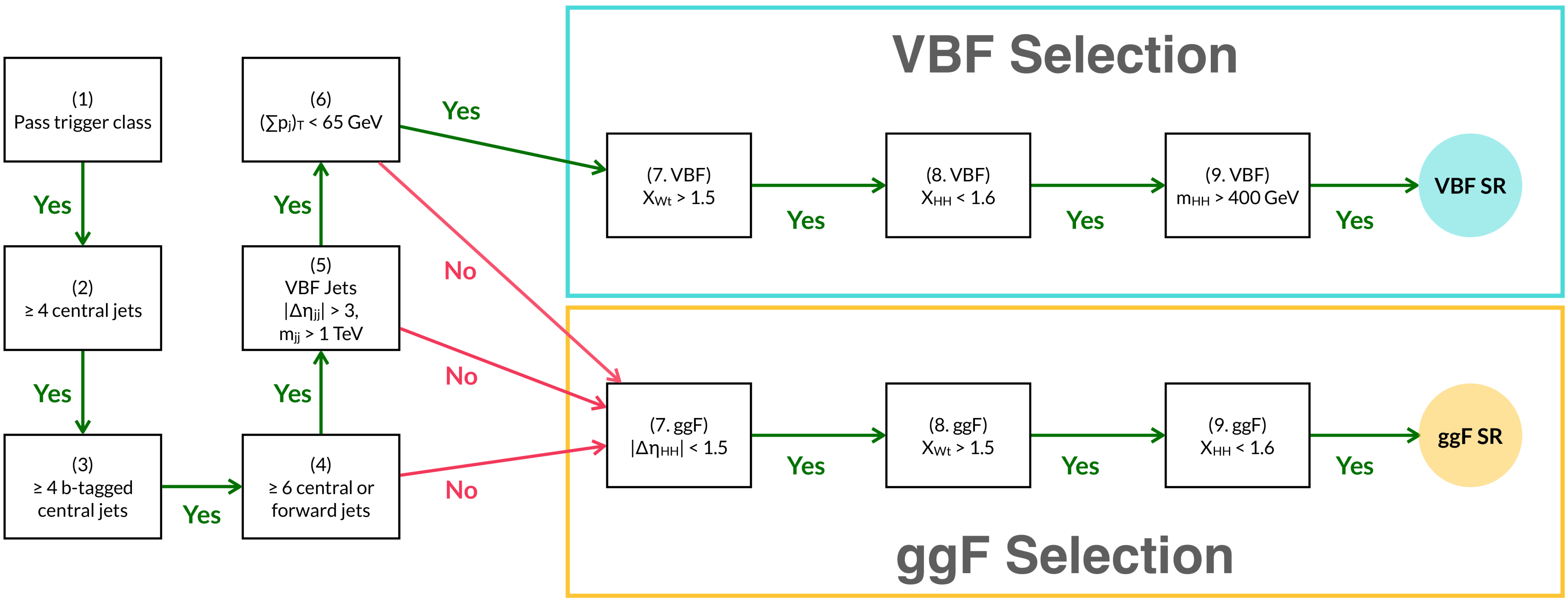


- Jet pairing considering the highest-p_T jet pair with the smallest ΔR_{jj} separation
- Correct pairing in **90% of signal events**
- No background sculpting → smooth background shape in the m_{HH} spectrum

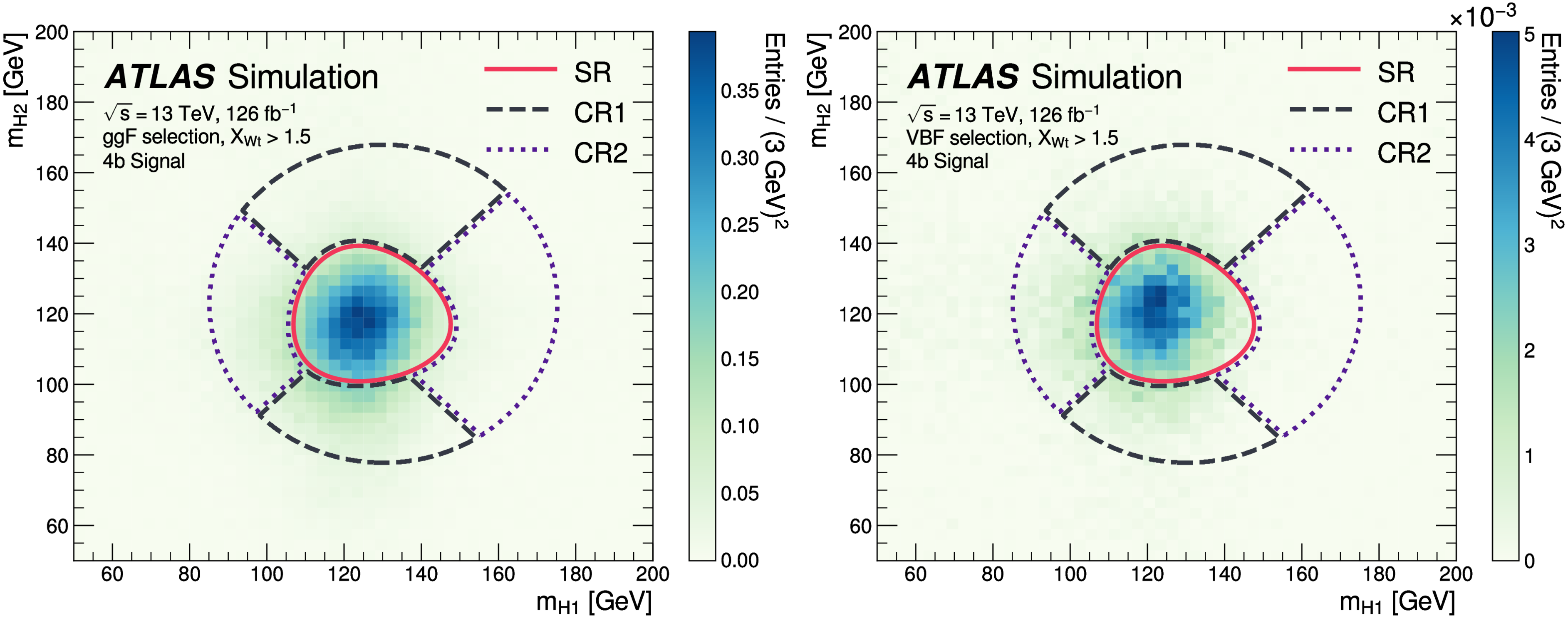
Due to the top discriminant cut



$b\bar{b}b\bar{b}$ resolved: event selection



$b\bar{b}b\bar{b}$ resolved: HH events in SR



- Signal region (SR) definition:
  - $$X_{HH} = \sqrt{\left(\frac{m_{H1} - 124GeV}{0.1m_{H1}}\right)^2 + \left(\frac{m_{H2} - 117GeV}{0.1m_{H2}}\right)^2}$$
  - **124 GeV** and **117 GeV** correspond to the centres of m_{H1} and m_{H2} distribution for HH events
    - **Deviations from 125 GeV** due to **detector effects**, **energy lost by neutrino** from b-hadron decay and out-of-cone effects

$b\bar{b}b\bar{b}$ resolved: Top veto discriminant

- Top veto discriminant:

$$\chi_{Wt} = \min \left[\sqrt{\left(\frac{m_{jj} - m_W}{0.1 m_{jj}}\right)^2 + \left(\frac{m_{jjb} - m_t}{0.1 m_{jjb}}\right)^2} \right]$$

where

- $m_W = 80.4$ GeV and $m_t = 172.5$ GeV
- m_{jj} and m_{jjb} are the invariant mass of W boson and top quark candidates

- Selected events in the analysis have χ_{Wt} **< 1.5**
  - $t\bar{t}$ **reduction** by a **factor 2;**
  - **15% HH signal loss**
  - **15% reduction** of **multi-jets** and **non-$t\bar{t}$ backgrounds**

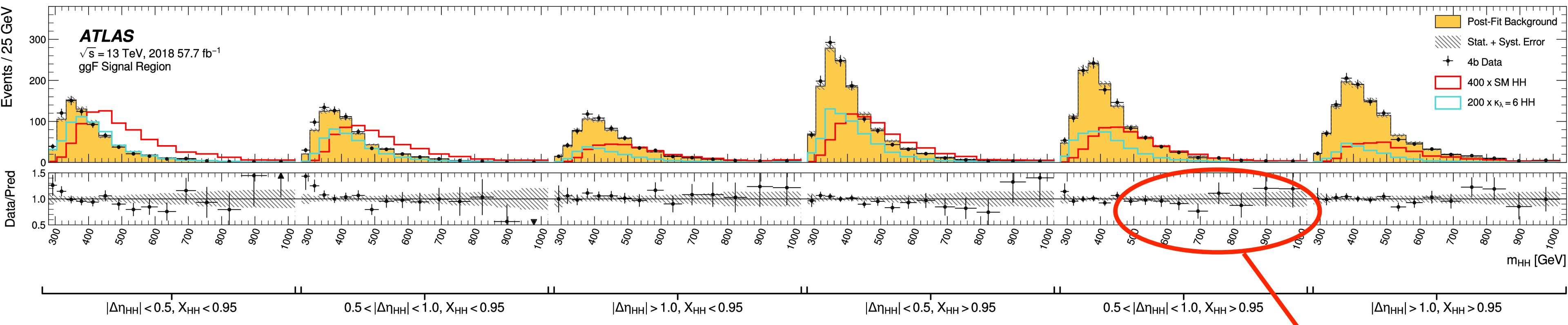
$b\bar{b}b\bar{b}$ resolved: reweighing technique

- Different kinematics for *2b events* and *4b events* due to different processes

$b\bar{b}b\bar{b}$ resolved: input variable of reweighing technique

ggF	VBF
1. $\log(p_{\mathrm{T}})$ of the 2^{nd} leading Higgs boson candidate jet 2. $\log(p_{\mathrm{T}})$ of the 4^{th} leading Higgs boson candidate jet 3. $\log(\Delta R)$ between the closest two Higgs boson candidate jets 4. $\log(\Delta R)$ between the other two Higgs boson candidate jets 5. Average absolute η value of the Higgs boson candidate jets 6. $\log(p_{\mathrm{T}})$ of the di-Higgs system 7. ΔR between the two Higgs boson candidates 8. $\Delta\phi$ between jets in the leading Higgs boson candidate 9. $\Delta\phi$ between jets in the subleading Higgs boson candidate 10. $\log(X_{Wt})$ 11. Number of jets in the event 12. Trigger class index as one-hot encoder	1. Maximum dijet mass from the possible pairings of the four Higgs boson candidate jets 2. Minimum dijet mass from the possible pairings of the four Higgs boson candidate jets 3. Energy of the leading Higgs boson candidate 4. Energy of the subleading Higgs boson candidate 5. Second-smallest ΔR between the jets in the leading Higgs boson candidate (from the three possible pairings for the leading Higgs candidate) 6. Average absolute η value of the four Higgs boson candidate jets 7. $\log(X_{Wt})$ 8. Trigger class index as one-hot encoder 9. Year index as one-hot encoder (for years inclusive training)

$b\bar{b}b\bar{b}$ resolved: post-fit plots

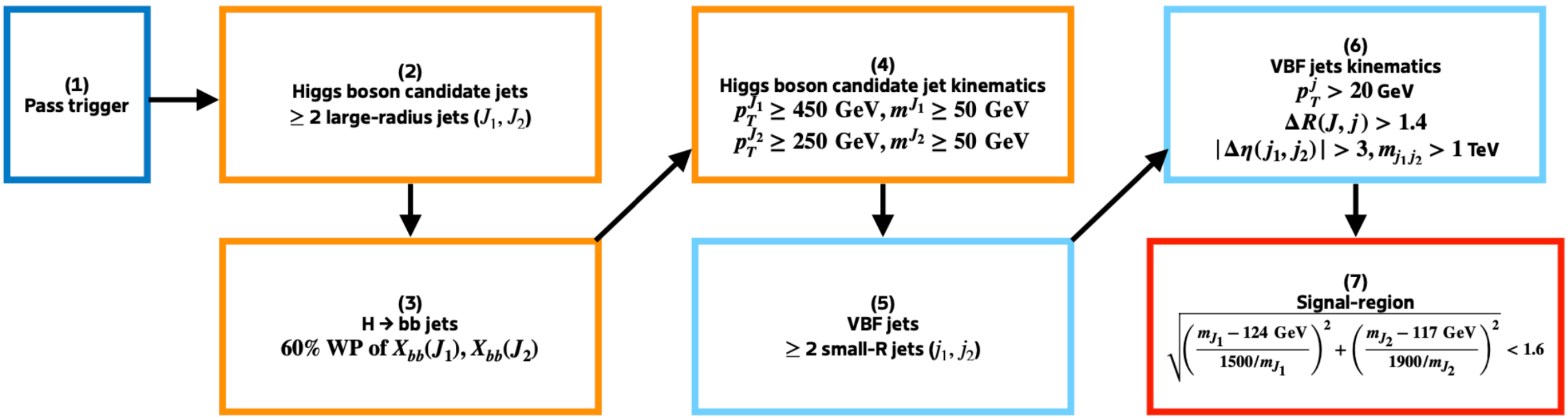


Deficit in SM, excess in k_λ=6

$b\bar{b}b\bar{b}$ resolved: breakdown

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%

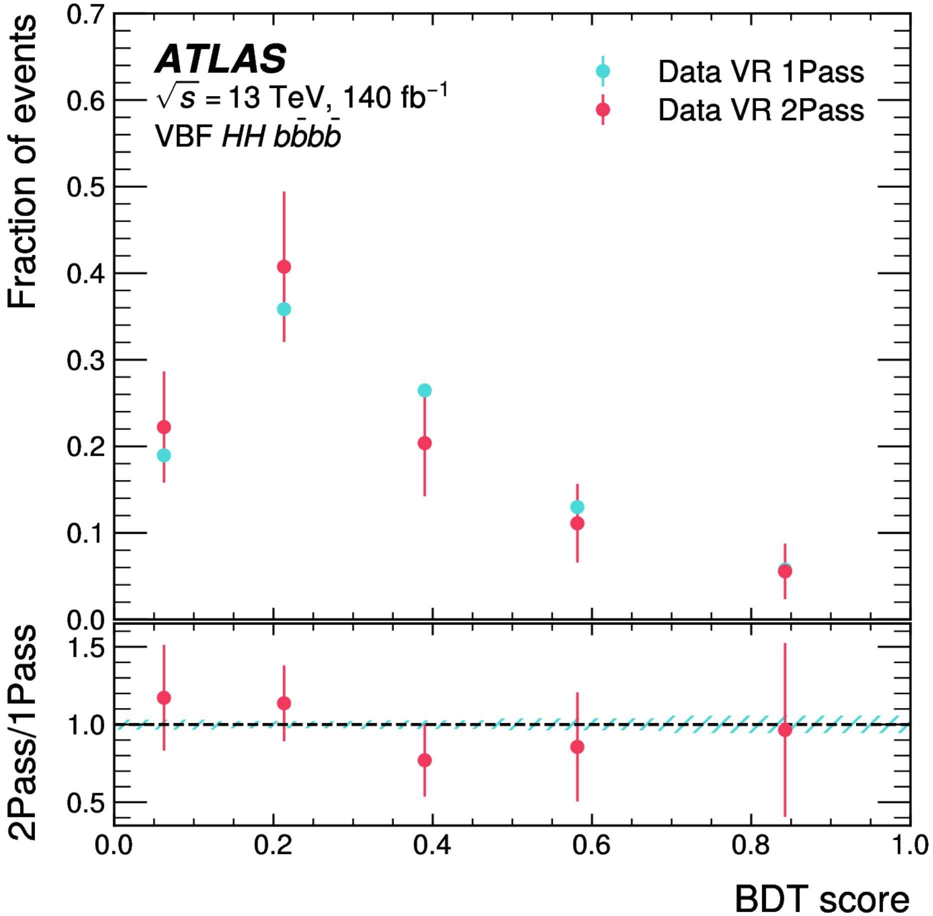
$b\bar{b}b\bar{b}$ boosted: event selection



$b\bar{b}b\bar{b}$ boosted: BDT input variables

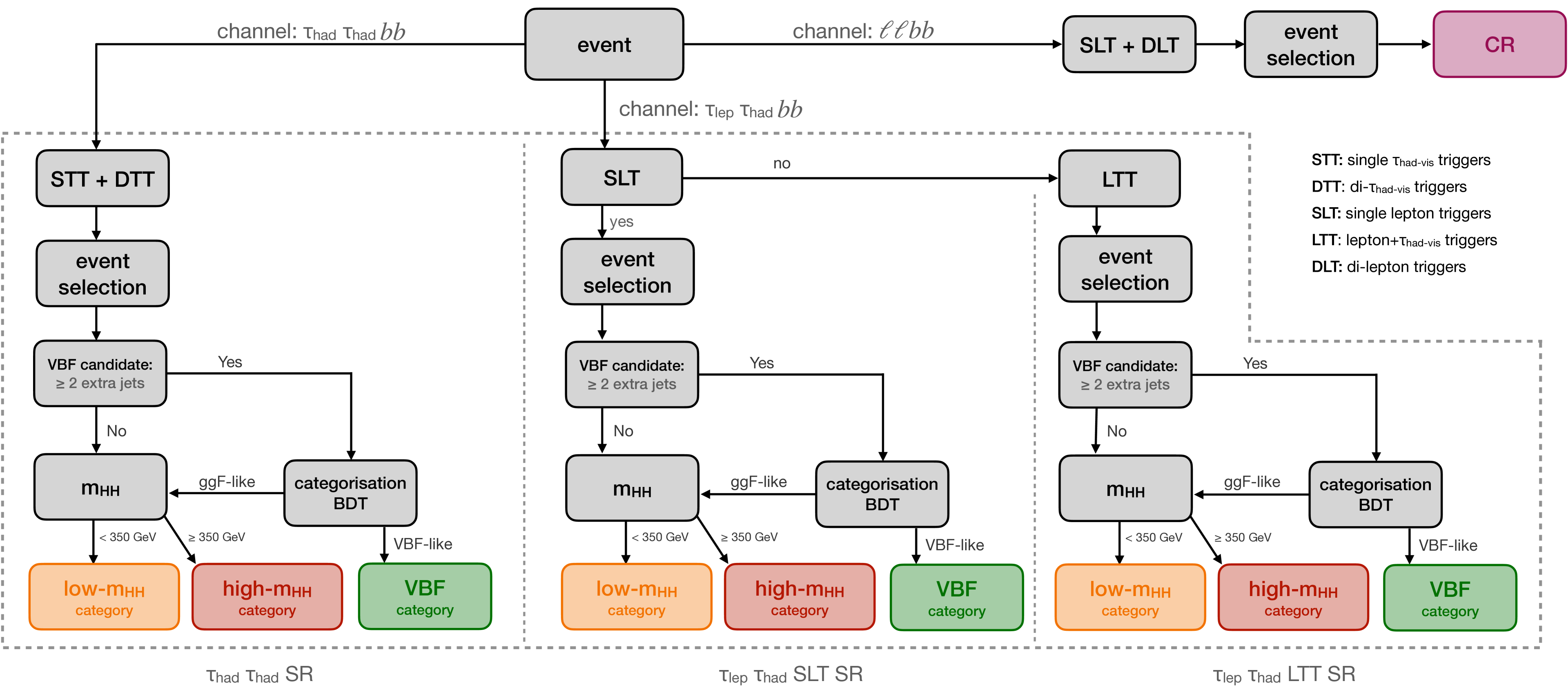
Physics objects	BDT input variables
Higgs boson candidate ($H_i, i = 1, 2$)	$p_{\mathrm{T}}^{H_i}, \eta_{H_i}$
Di-Higgs boson system (HH)	$p_{\mathrm{T}}^{HH}, \eta_{HH}, m_{HH}$
VBF jets ($j_i, i = 1, 2$)	$p_{\mathrm{T}}^{j_i}, \eta_{j_i}, E_{j_i}$

BDT score shape: data shape



- Same shape for data in 1Pass and 2Pass → difference is within the statistical uncertainties

$b\bar{b}\tau\tau$: event selection



$b\bar{b}\tau\tau$: BDT input variables

ggF vs VBF

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

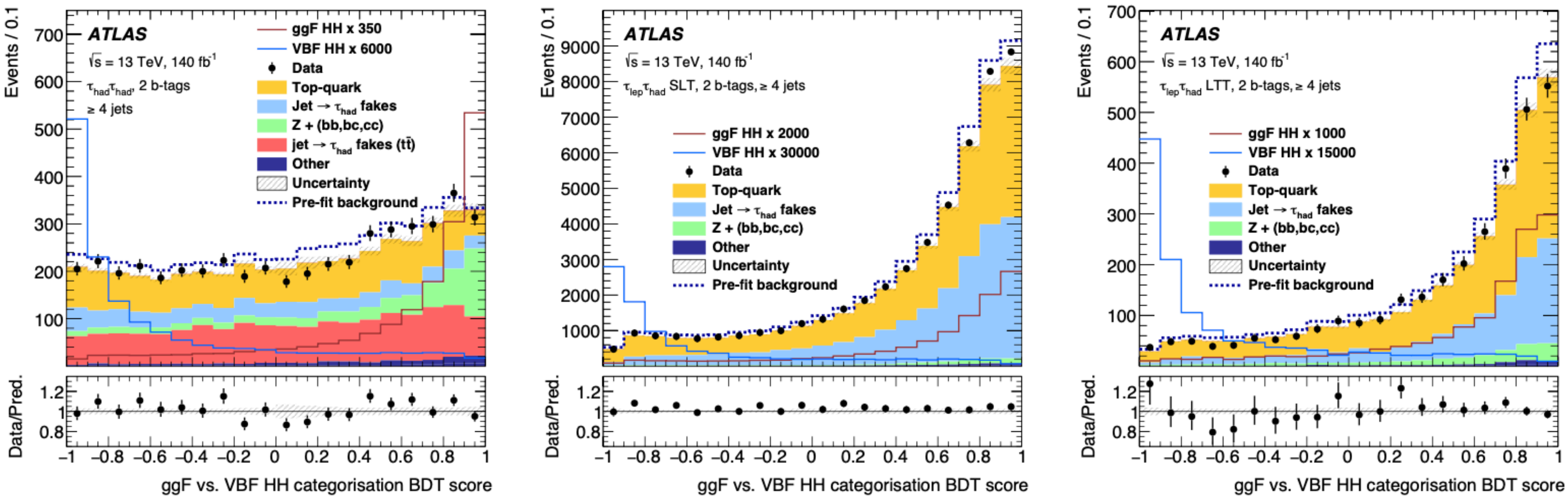
ggF categories

Variable	$\tau_{\text{had}}\tau_{\text{had}}$		$\tau_{\text{lep}}\tau_{\text{had}}$ SLT		$\tau_{\text{lep}}\tau_{\text{had}}$ LTT	
	low-m_{HH}	high-m_{HH}	low-m_{HH}	high-m_{HH}	low-m_{HH}	high-m_{HH}
m_{bb}	✓	✓	✓	✓	✓	✓
$m_{\tau\tau}^{\text{MMC}}$	✓	✓	✓	✓	✓	✓
m_{HH}	✓	✓	✓	✓	✓	✓
ΔR_{bb}	✓	✓	✓	✓	✓	
$\Delta R(\tau_0, \tau_1)$	✓	✓	✓	✓	✓	✓
N(jets)	✓	✓	✓			
$p_{\text{T}}(HH)$		✓	✓			
H_{T}	✓			✓	✓	✓
T_1		✓	✓	✓	✓	✓
T_2	✓				✓	✓
$E_{\text{T}}^{\text{miss}}$	✓	✓	✓			
$E_{\text{T}}^{\text{miss}}$ centrality					✓	
M_{T2}	✓				✓	
m_T^W			✓	✓	✓	
$m_{\text{T}}(\tau_1)$		✓		✓	✓	
$p_{\text{T}}(\tau_0)$	✓		✓	✓		
$p_{\text{T}}(\tau_1)$	✓		✓	✓		
$p_{\text{T}}(b_0)$	✓		✓			✓
$p_{\text{T}}(b_1)$				✓		
$p_{\text{T}}(bb)$						✓
$p_{\text{T}}(\tau\tau)$						✓
$\Delta p_{\text{T}}(\tau_0, \tau_1)$					✓	✓
$\eta(\tau_0)$	✓	✓				
$\eta(\tau_1)$	✓	✓				
$\Delta\eta(\tau_0, \tau_1)$					✓	
$\Delta\phi(bb, E_{\text{T}}^{\text{miss}})$	✓	✓				
$\Delta\phi(bb, \tau\tau)$	✓	✓				✓
$\Delta\phi(\tau\tau, E_{\text{T}}^{\text{miss}})$			✓	✓	✓	✓
$\Delta\phi(\tau_1, E_{\text{T}}^{\text{miss}})$					✓	✓
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		✓				
$\cos(\Delta\theta_{bb}^{H\to b\bar{b} \text{ rest frame}})$			✓	✓		

VBF categories

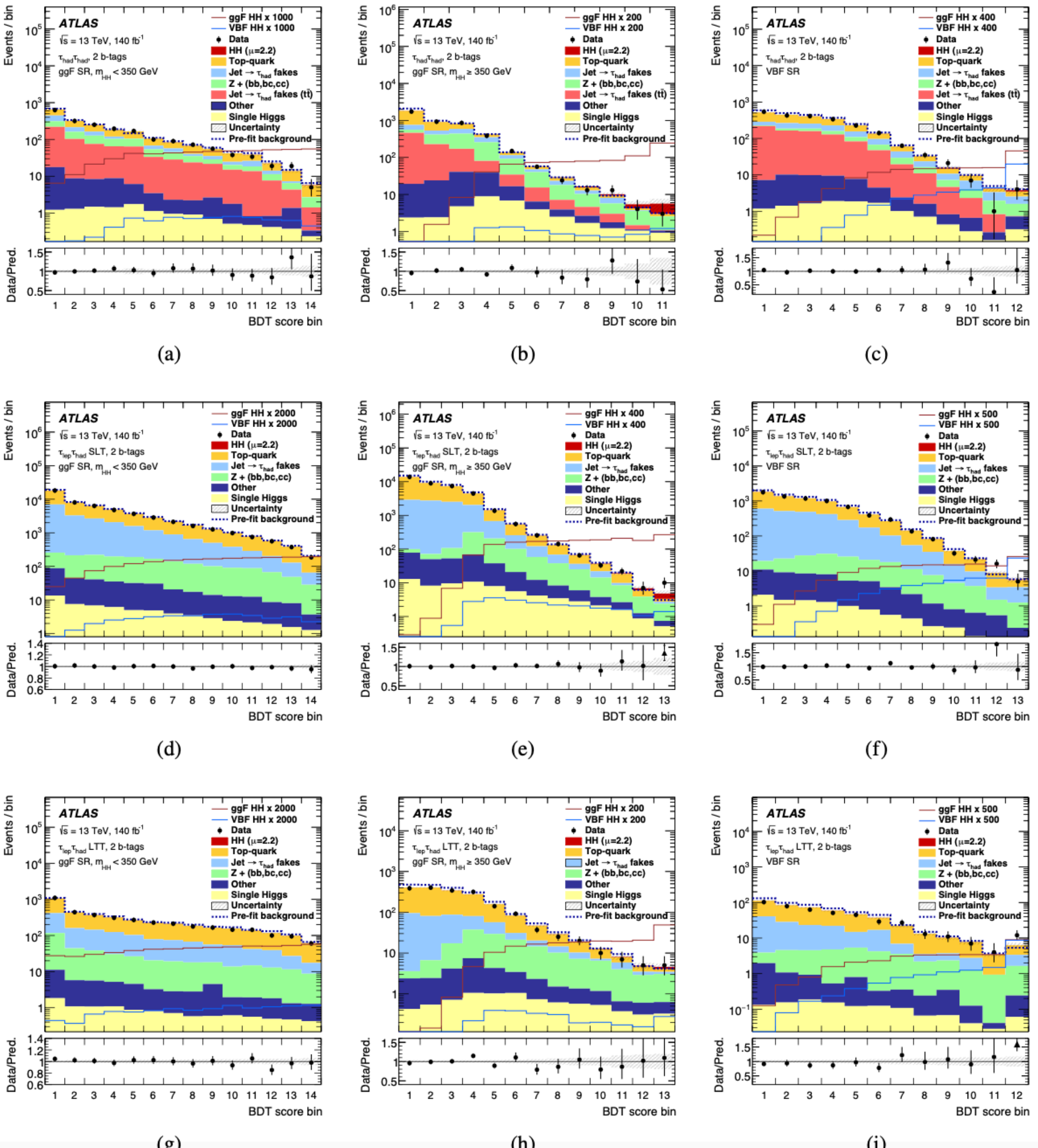
Variable	$\tau_{\text{had}}\tau_{\text{had}}$	$\tau_{\text{lep}}\tau_{\text{had}}$ SLT	$\tau_{\text{lep}}\tau_{\text{had}}$ LTT
m_{HH}	✓	✓	✓
m_{bb}	✓	✓	✓
$m_{\tau\tau}^{\text{MMC}}$	✓	✓	✓
ΔR_{bb}	✓	✓	
$\Delta R(\tau_0, \tau_1)$	✓	✓	
VBF $\eta_0 \times \eta_1$	✓		✓
$\Delta\eta_{jj}^{\text{VBF}}$	✓	✓	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

$b\bar{b}\tau\tau$: ggF vs VBF BDTs

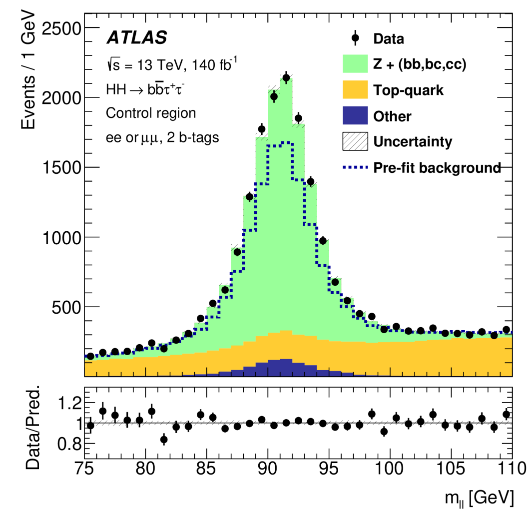


$b\bar{b}\tau\tau$: BDTs

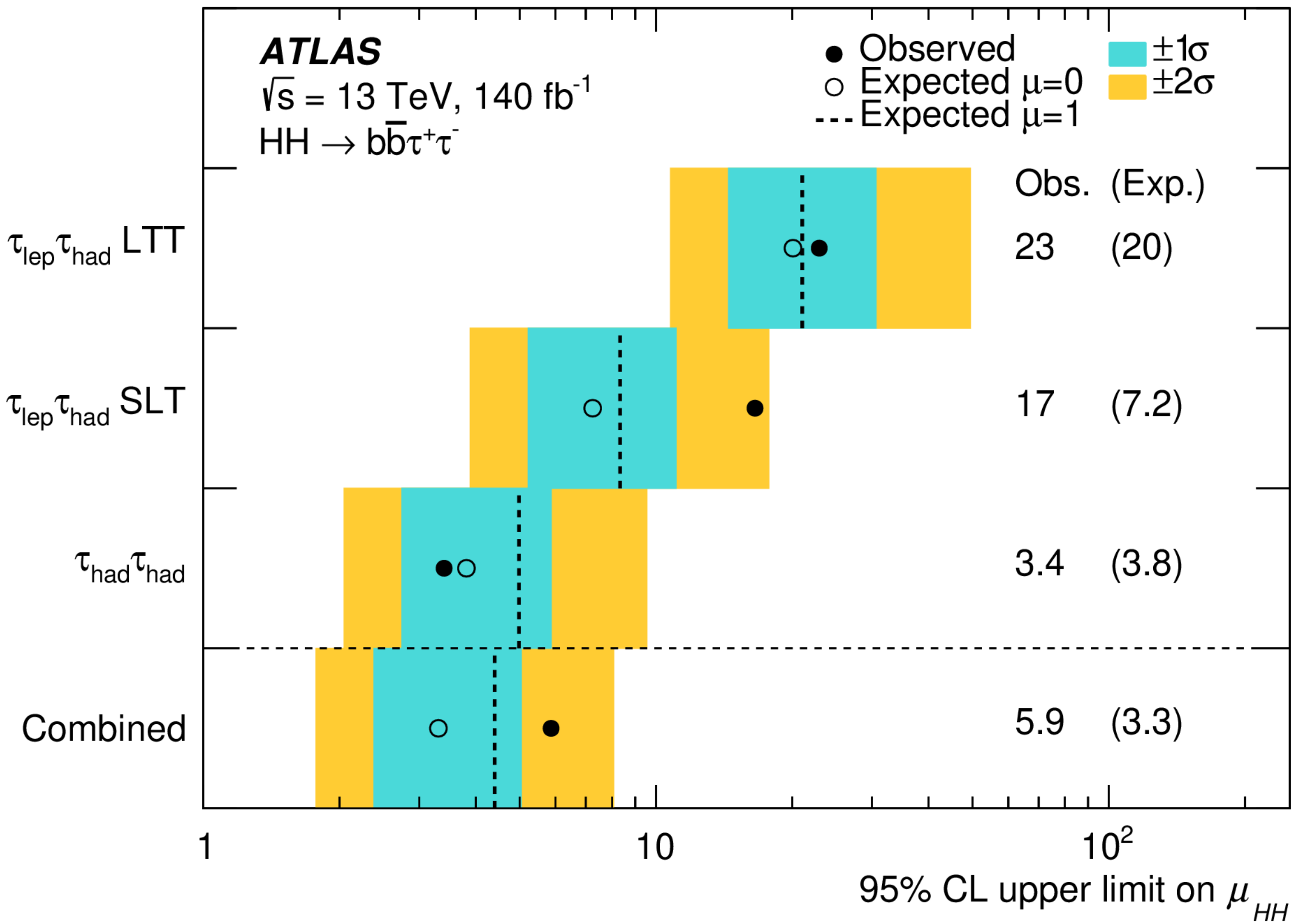
SRs



CR



$b\bar{b}\tau\tau$: limits



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

$b\bar{b}\gamma\gamma$: VBF BDT input variables

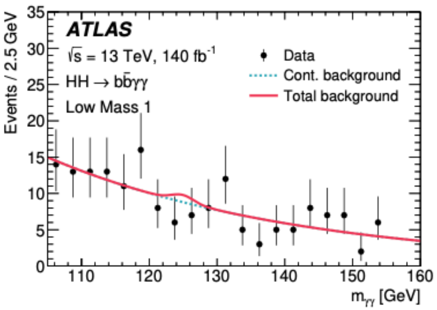
Variable	Definition
p_{T}^{j} and η^{j}	Transverse momentum and pseudorapidity of each of the VBF-jet candidates
$\Delta R(j, \gamma\gamma b\bar{b})$ and $\Delta\eta(j, \gamma\gamma b\bar{b})$	Angular and pseudorapidity separation between the VBF-jet candidates and the $\gamma\gamma b\bar{b}$ system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

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

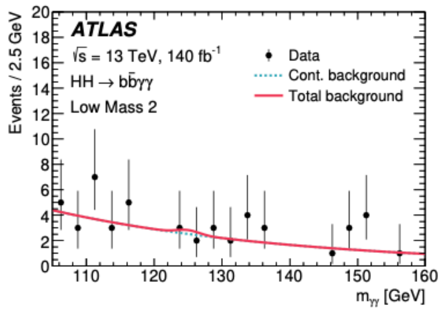
	High Mass 1	High Mass 2	High Mass 3	Low Mass 1	Low Mass 2	Low Mass 3	Low Mass 4
SM $HH(\kappa_\lambda = 1)$ signal	$0.26^{+0.03}_{-0.04}$	$0.194^{+0.021}_{-0.032}$	$0.84^{+0.10}_{-0.14}$	$0.048^{+0.007}_{-0.008}$	$0.038^{+0.004}_{-0.006}$	$0.039^{+0.004}_{-0.006}$	$0.032^{+0.004}_{-0.004}$
ggF	$0.25^{+0.03}_{-0.04}$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

Downward fluctuations in data

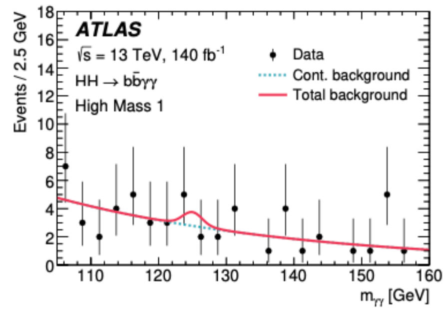
$b\bar{b}\gamma\gamma$: postfit distributions



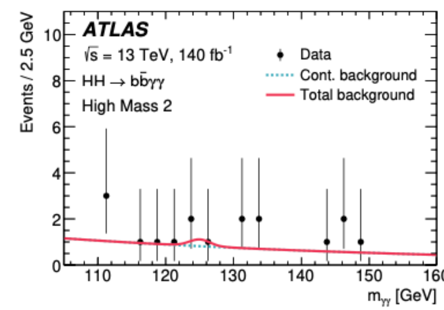
(a) Low Mass 1.



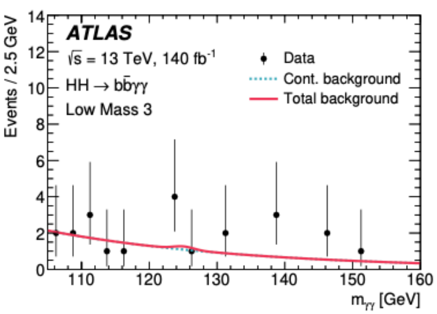
(b) Low Mass 2.



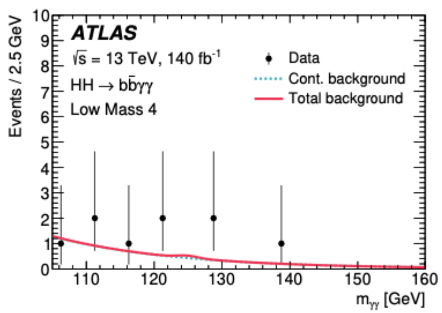
(e) High Mass 1.



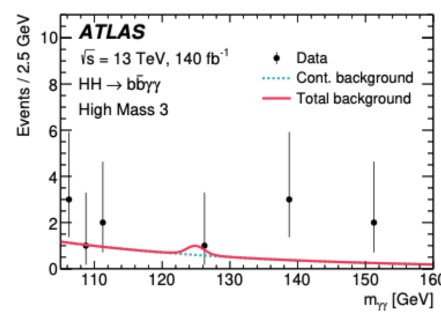
(f) High Mass 2.



(c) Low Mass 3.



(d) Low Mass 4.



(g) High Mass 3.

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

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

$b\bar{b}\gamma\gamma$: breakdown uncertainties (2)

This $HH \to b\bar{b}\gamma\gamma$ Run 2 analysis

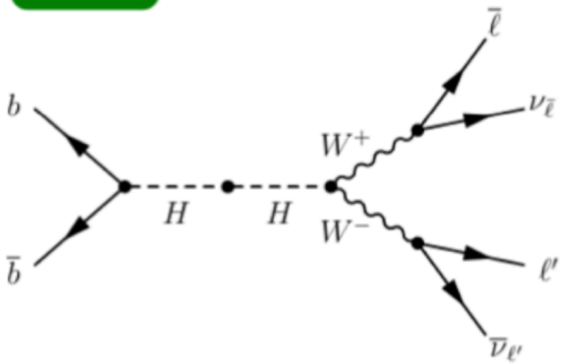
Systematic uncertainty source	Relative impact [%]
Experimental	
Photon energy resolution	0.4
Photon energy scale	0.1
Flavour tagging	0.1
Theoretical	
Factorisation and renormalisation scale	4.8
$\mathcal{B}(H \to \gamma\gamma, b\bar{b})$	0.2
Parton showering model	0.2
Heavy-flavour content	0.1
Background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

Old $HH \to b\bar{b}\gamma\gamma$ Run 2 analysis

		Relative impact of the systematic uncertainties [%]	
Source	Type	Nonresonant analysis HH	Resonant analysis $m_X = 300$ GeV
Experimental			
Photon energy resolution	Norm. + Shape	0.4	0.6
Jet energy scale and resolution	Normalization	< 0.2	0.3
Flavor tagging	Normalization	< 0.2	0.2
Theoretical			
Factorization and renormalization scale	Normalization	0.3	< 0.2
Parton showering model	Norm. + Shape	0.6	2.6
Heavy-flavor content	Normalization	0.3	< 0.2
$\mathcal{B}(H \to \gamma\gamma, b\bar{b})$	Normalization	0.2	< 0.2
Spurious signal	Normalization	3.0	3.3

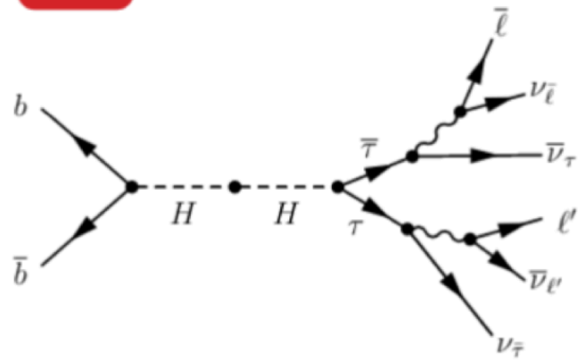
$b\bar{b}\ell\ell + E_T^{miss}$: targeted processes

$bbWW$



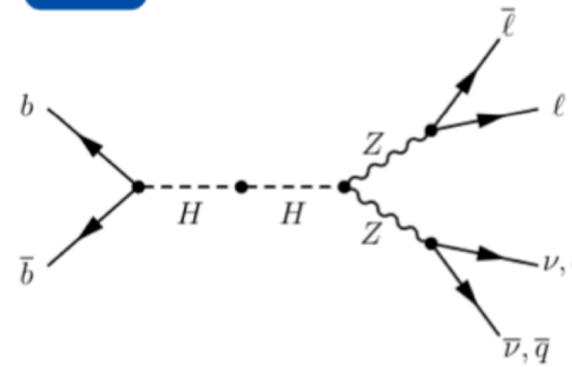
- $\text{BR}_{HH \to bb\ell\ell + \text{MET}} = 1.62\,\%^\dagger$
- W-pair has spin correlation
- small $m_{\ell\ell}$ and $\Delta\Phi_{\ell\ell}$

$bb\tau\tau$



- $\text{BR}_{HH \to bb\ell\ell + \text{MET}} = 0.91\,\%^\dagger$
- 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

Decay	BR	BR/BR ($bb\ell\ell$)	σ/fb	expected events
$bbWW$ ($WW \to \ell\ell$)	0.01624	0.5510	0.5322	73.9758
$bb\tau\tau$	0.009059	0.3074	0.2969	41.2691
$bbZZ$ ($ZZ \to \ell\ell\nu\nu$)	0.0008724	0.0296	0.0286	3.9754
$bbZZ$ ($ZZ \to \ell\ell qq$)	0.00304935	0.1035	0.0999	13.8861
$bb\mu\mu$	0.00025346	0.0086	0.0083	1.1537

$b\bar{b}\ell\ell + E_T^{miss}$: prefit 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

$b\bar{b}\ell\ell + E_T^{miss}$: mva input variables

ggF categories

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
$m_{\ell\ell}$, $p_{\mathrm{T}}^{\ell\ell}$	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
$E_{\mathrm{T}}^{\mathrm{miss}}$, $E_{\mathrm{T}}^{\mathrm{miss}}$-sig	missing transverse energy and its significance
$m_{\mathrm{T}}(\ell_0, E_{\mathrm{T}}^{\mathrm{miss}})$	transverse mass of the p_{T}-leading lepton with respect to $E_{\mathrm{T}}^{\mathrm{miss}}$
$\min m_{\mathrm{T},\ell}$	minimum value of $m_{\mathrm{T}}(\ell_0, E_{\mathrm{T}}^{\mathrm{miss}})$ and $m_{\mathrm{T}}(\ell_1, E_{\mathrm{T}}^{\mathrm{miss}})$
$H_{\mathrm{T2}}^{\mathrm{R}}$	measure for boostedness[1] of the two Higgs bosons

VBF categories

Input feature	Description
η_{ℓ_0}, η_{ℓ_1}, ϕ_{ℓ_0}, ϕ_{ℓ_1}, $p_{\mathrm{T}}^{\ell_0}$, $p_{\mathrm{T}}^{\ell_1}$	η, ϕ, p_{T} of the p_{T}-(sub)leading lepton
η_{b_0}, η_{b_1}, ϕ_{b_0}, ϕ_{b_1}, $p_{\mathrm{T}}^{b_0}$, $p_{\mathrm{T}}^{b_1}$	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}, $p_{\mathrm{T}}^{j_0}$, $p_{\mathrm{T}}^{j_1}$	ϕ, η, p_{T} of the p_{T}-(sub)leading non b-tagged jet
$E_{\mathrm{T}}^{\mathrm{miss}}$, $\phi^{E_{\mathrm{T}}^{\mathrm{miss}}}$, $E_{\mathrm{T}}^{\mathrm{miss}}$-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
$p_{\mathrm{T}}^{\ell\ell}$, $\Delta R_{\ell\ell}$, $\Delta\phi_{\ell\ell}$, $m_{\ell\ell}$, $\phi_{\mathrm{centrality}}^{\ell\ell}$	p_{T}, ΔR, $\Delta\phi$, p_{T} and centrality[1] of di-leptons system
$p_{\mathrm{T}}^{bb\ell\ell}$, $m_{bb\ell\ell}$	p_{T} and invariant mass of the $bb\ell\ell$ system
$p_{\mathrm{T}}^{bb\ell\ell+E_{\mathrm{T}}^{\mathrm{miss}}}$, $m_{bb\ell\ell+E_{\mathrm{T}}^{\mathrm{miss}}}$	p_{T} and invariant mass of $bb\ell\ell$ + $E_{\mathrm{T}}^{\mathrm{miss}}$ system
$m_{\ell\ell+E_{\mathrm{T}}^{\mathrm{miss}}}$	invariant mass of di-lepton + $E_{\mathrm{T}}^{\mathrm{miss}}$ system
$p_{\mathrm{T}}^{E_{\mathrm{T}}^{\mathrm{miss}}+\ell\ell}$, $\Delta\phi_{E_{\mathrm{T}}^{\mathrm{miss}},\ell\ell}$	p_{T} of and $\Delta\phi$ between $E_{\mathrm{T}}^{\mathrm{miss}}$ and di-lepton system
$p_{\mathrm{T}}^{\mathrm{tot}}$	p_{T} of $bb\ell\ell$ + $E_{\mathrm{T}}^{\mathrm{miss}}$+ p_{T}-leading and -sub-leading jet
m_{tot}	invariant mass of $bb\ell\ell$ + $E_{\mathrm{T}}^{\mathrm{miss}}$+ 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
$\max p_{\mathrm{T}}^{jj}$, $\max m_{jj}$	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
$N_{\mathrm{forward\ jets}}$, 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 $m_{\tau\tau}$)

Multilepton: selection

ML channels

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 $\Delta R(\tau_1, \tau_2) < 2$	$N_{\text{jet}} \geq 2$	$N_{b\text{-jet}} = 0$

$\gamma\gamma$ML channels

Channel	ℓ	$\tau_{\text{had-vis}}$	Photons	E_T^{miss}	b-jets
$\gamma\gamma$+$2(\ell, \tau_{\text{had}})$	$N_{\ell(P)} + N_\tau = 2$, 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	

Multilepton: CR definition

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	$N_{jet} \geq 2$	$N_{b\text{-jet}} \geq 2$	
		No PLV on any ℓ			
	HF-μ CR*	ℓ_{SC1},ℓ_{SC2} both μ	$N_{jet} \geq 2$	$N_{b\text{-jet}} \geq 2$	
		No PLV on any ℓ			
	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	–	–	$E_T^{miss} > 30$ GeV
		One SFOC pair			
		Z-req.			
		$m_{\ell\ell}$ (any pair) > 12 GeV			
		$\lvert m_{3\ell} - m_Z\rvert > 10$ GeV			
	VVjj CR*	Z-veto (SFSC pair)	$m_{jj} > 300$ GeV	–	BDT < −0.4
					BDT$_{Z+jets}$ > −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	–	$N_{b\text{-jet}} \geq 1$	–
		$m_{trk,trk} < 100$ MeV			
	Int. conv. CR*	$r_{vtx} < 20$ mm	–	$N_{b\text{-jet}} \geq 1$	–
		$m_{trk,trk} < 100$ MeV			
	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	–	$N_{jet} = 2$	$N_{b\text{-jet}} = 1$	–
		Z-veto				
	VR	–	–	$N_{jet} < 2$	–	
2ℓ+$2\tau_{had}$ and ℓ+$2\tau_{had}$	Z+jets CR	2ℓ(T), OC	$N_\tau + N_{anti\text{-}ID\ \tau} = 2$	$N_{jet} \geq 1$	$N_{b\text{-jet}} = 0$	–
		Z-req.				
	$t\bar{t}$ CR	2ℓ(T), OC	$N_\tau + N_{anti\text{-}ID\ \tau} = 2$	$N_{jet} \geq 1$	$N_{b\text{-jet}} = 1$	–
		Z-veto				
2ℓ+$2\tau_{had}$	Fake-$\tau_{had\text{-}vis}$ CR	–	($N_\tau = 1$, $N_{anti\text{-}ID\ \tau} = 1$)	–	–	–
			or $N_{anti\text{-}ID\ \tau} = 2$			
	Fake-$\tau_{had\text{-}vis}$ VR	–	SC $\tau_{had\text{-}vis}$	–	–	–
ℓ+$2\tau_{had}$	Fake-$\tau_{had\text{-}vis}$ CR	–	($N_\tau = 1$, $N_{anti\text{-}ID\ \tau} = 1$)	–	–	–
			or $N_{anti\text{-}ID\ \tau} = 2$			
	Fake-$\tau_{had\text{-}vis}$ VR	–	SC $\tau_{had\text{-}vis}$	–	–	–

Multilepton: breakdown 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 $E_{\mathrm{T}}^{\mathrm{miss}}$	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

HL-LHC projection: scenarios

- **No syst unc:** optimistic scenario where no systematics uncertainties are considered
- **Baseline:** experimental and theoretical uncertainties halved, modelling uncertainties the same as in Run2
- Theoretical unc halved: theoretical un halved while experimental and modelling uncertainties are the same as in Run2
- **Run2 sys. unc:** pessimistic scenario with the same unc as in Run2.