Probing the nature of electroweak symmetry breaking with Higgs boson pairs in ATLAS

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on behalf of the ATLAS Collaboration

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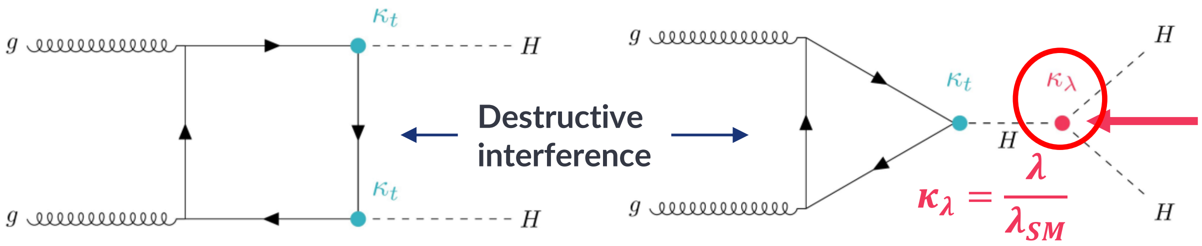
Higgs pair production at the LHC

- Rare event: ~10^3 times smaller Standard Model (SM) cross-section than single Higgs; expect only ~4600 events in whole ATLAS Run-2 dataset
- Dominant SM process: **gluon-gluon fusion** (**ggF**), with cross-section 31.05 fb

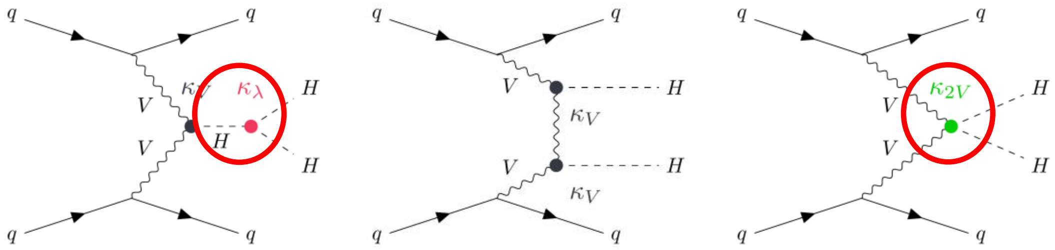


Destructive interference

$$\kappa_\lambda = \frac{\lambda}{\lambda_{SM}}$$

Higgs self-coupling determines **shape of Higgs potential** and hence the **electroweak symmetry breaking** mechanism

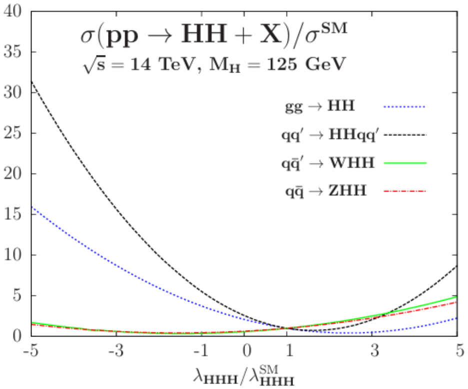
- SM process with second-highest cross-section: **vector boson fusion** (**VBF**), 1.73 fb



- ATLAS di-Higgs (HH) searches set constraints on both $\boldsymbol{\kappa_\lambda}$ and $\boldsymbol{\kappa_{2V}}$ coupling modifiers

Physics beyond the Standard Model in HH production

- Modification of κ_λ results in large variation in production **cross-section**
- Di-Higgs invariant mass $\boldsymbol{m_{HH}}$ **distribution** strongly depends on κ_λ and κ_{2V}



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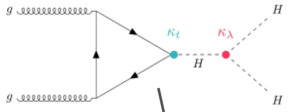
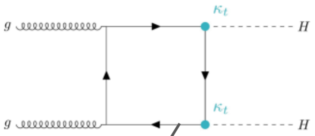
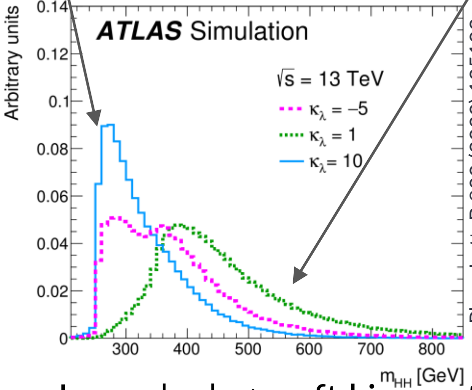
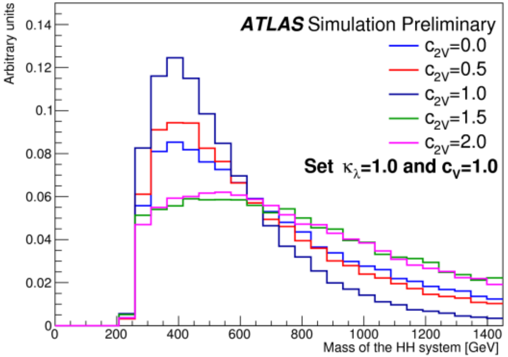






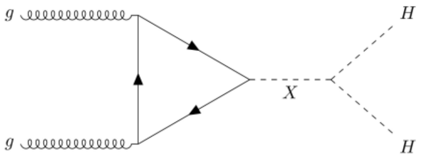
Phys. Lett. B 800 (2020) 135103



ATL-PHYS-PUB-2019-007

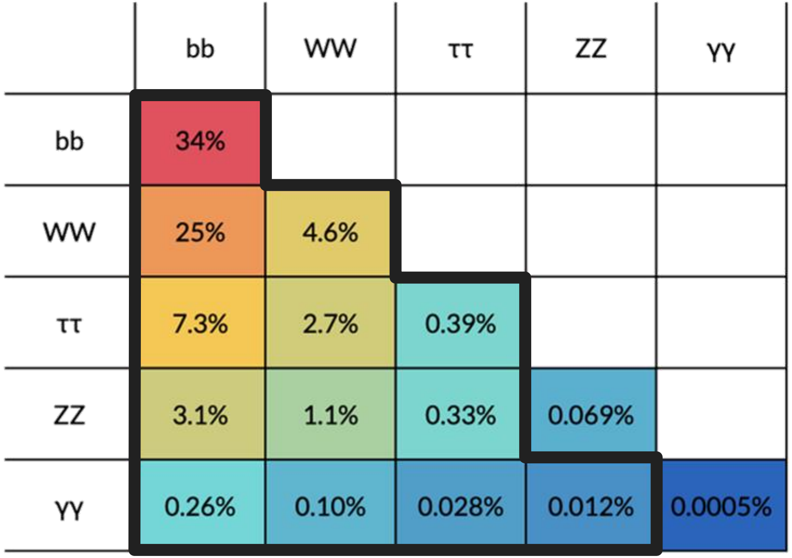
- Large $|\kappa_\lambda| \to$ soft kinematics, difficult to detect
- Large $|\kappa_{2V}| \to$ hard kinematics

- BSM resonances decaying to HH would enhance production rate and modify kinematics



See talks by Tong Qiu and Weitao Wang

HH decay channels and ATLAS searches

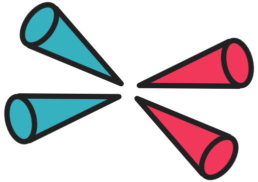


	bb	WW	ττ	ZZ	γγ
bb	34%				
WW	25%	4.6%			
ττ	7.3%	2.7%	0.39%		
ZZ	3.1%	1.1%	0.33%	0.069%	
γγ	0.26%	0.10%	0.028%	0.012%	0.0005%

- ATLAS searches cover >50% of HH decays
- Presented here the latest **nonresonant** searches with **full Run-2** data at 13 TeV, their **combination** and **prospects for the High-Luminosity LHC**

- **$b\bar{b}b\bar{b}$ (34%)** – most abundant, but challenging multijet background
- **$b\bar{b}\gamma\gamma$ (0.26%)** – low branching ratio, but clean final state, excellent $m_{\gamma\gamma}$ resolution
- **$b\bar{b}\tau^-\tau^+$ (7.3%)** – in between in terms of signal vs background trade-off, dedicated search requires at least one hadronic τ decay
- **$b\bar{b}\ell^-\ell^+$ + missing E_T** (2.9%) – targeting events where one $H \nrightarrow b\bar{b}$
- **Multilepton** (6.5%) – targeting $b\bar{b}ZZ(\to 4\ell)$ and states where both $H \nrightarrow b\bar{b}$ (9 subchannels)

Nonresonant $HH \to b\bar{b}b\bar{b}$

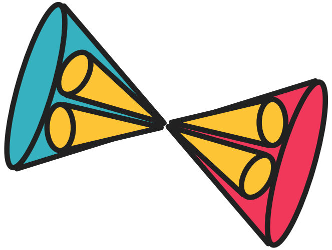


Resolved (Phys. Rev. D 108 (2023) 052003)

- b-jet trigger
- ≥ 4 b-jets with $p_{\mathrm{T}} > 40$ GeV, $|\eta| < 2.5$
    - ○ **VBF**: ≥ 6 jets, $m_{jj} > 1$ TeV, $|\Delta\eta_{jj}| > 3$
    - ○ **ggF**: $|\Delta\eta_{HH}| < 1.5$

Not b-tagged

- Jet pairing minimises angular separation in the higher-p_{T} Higgs candidate
- Top veto discriminant
- Signal region:
    - ○ $X_{HH} = \sqrt{\left(\frac{m_{H1} - 124\text{ GeV}}{0.1 m_{H1}}\right)^2 + \left(\frac{m_{H2} - 117\text{ GeV}}{0.1 m_{H2}}\right)^2} < 1.6$
    - ○ Split into X_{HH} and $|\Delta\eta_{HH}|$ categories to enhance sensitivity



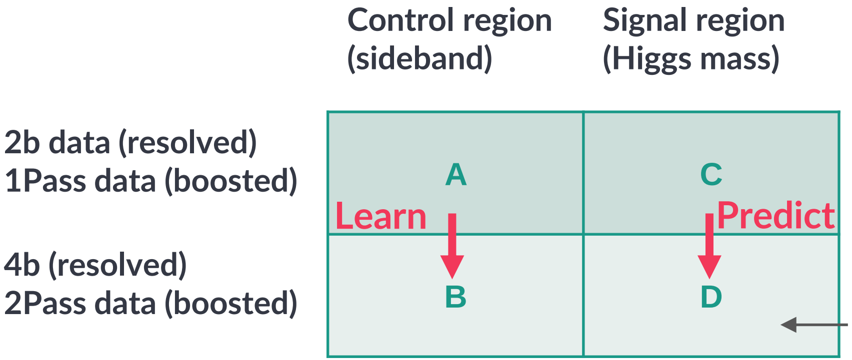
Boosted (arXiv:2404.17193)

- Large-radius jet trigger
- ≥ 2 double-b-tagged jets
- $p_{\mathrm{T}} > 450$ GeV for leading, 250 GeV sub-leading Higgs candidate
- $m_{jj} > 1$ TeV, $|\Delta\eta_{jj}| > 3$ for VBF jets
- Only considers VBF topology (relatively high sensitivity)
- Signal region:

$$\sqrt{\left(\frac{m_{H1} - 124\text{ GeV}}{1500\text{ GeV}/m_{H1}}\right)^2 + \left(\frac{m_{H2} - 117\text{ GeV}}{1900\text{ GeV}/m_{H2}}\right)^2} < 1.6\text{ GeV}$$

Nonresonant $b\bar{b}b\bar{b}$ background estimation

- Dominant background: **QCD multijet**
- Difficult to model → fully **data-driven** estimate
- Uses alternative event samples with same selection as signal, but fewer b-tagged jets to derive 4b background



Control region (sideband)

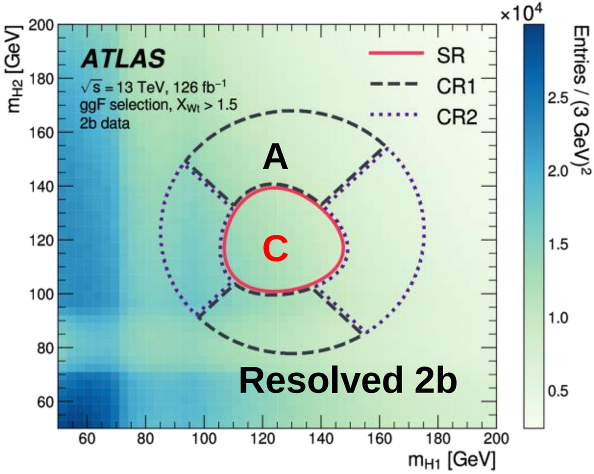
Signal region (Higgs mass)

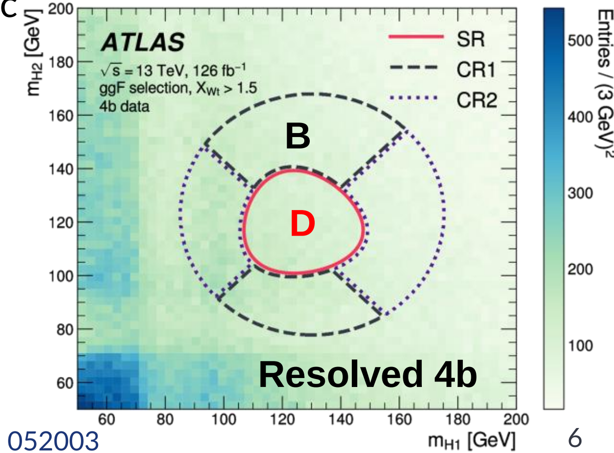
2b data (resolved)
1Pass data (boosted)

4b (resolved)
2Pass data (boosted)

Blinded until analysis finalised

2 control regions to estimate systematic uncertainty



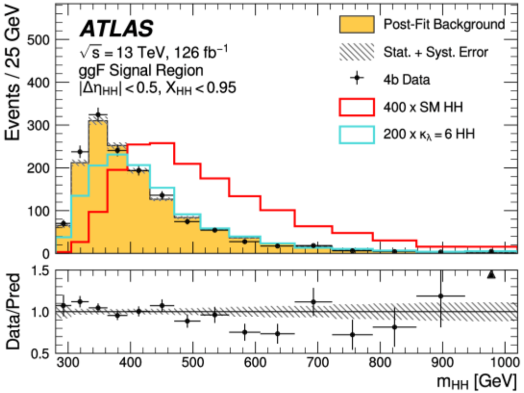


- Boosted analysis derives normalisation factor, while resolved uses neural network to assign weight to each 2b event

Phys. Rev. D 108 (2023) 052003

Nonresonant $b\bar{b}b\bar{b}$ results

- Discriminating variable fitted is m_{HH} for resolved and boosted decision tree (BDT) score for boosted



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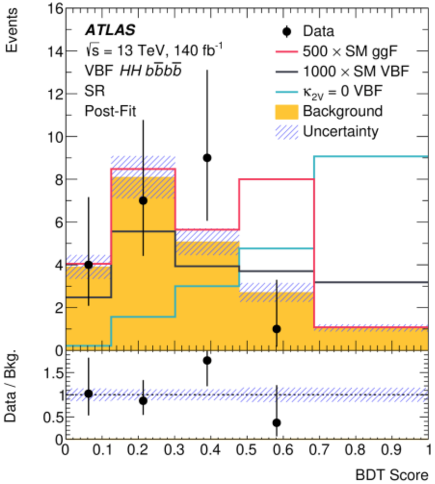

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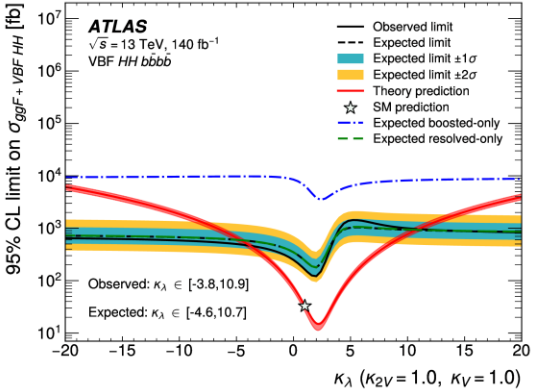
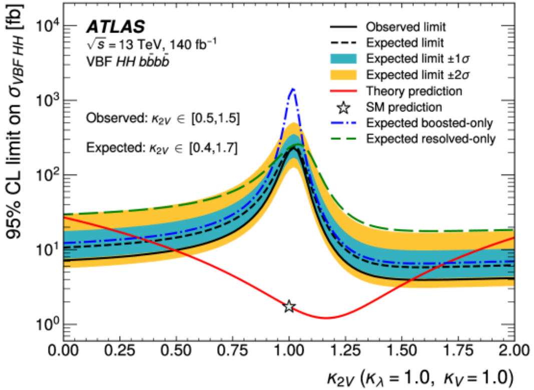




- 95% CL upper limit on c**ross-section** : **5.4** times SM value (8.1 expected)
- $-3 < \kappa_\lambda < 11$, $\boldsymbol{0.55 < \kappa_{2V} < 1.49}$ **– leading channel**
- Dominant uncertainties: double b-tagging algorithm, background estimation, theoretical signal cross-section calculation

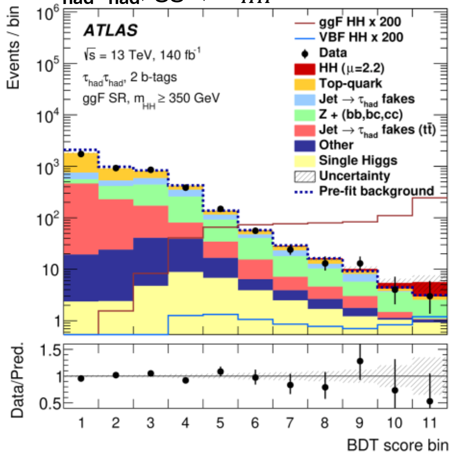
arXiv:2404.17193

Nonresonant $b\bar{b}\tau^{-}\tau^{+}$ analysis

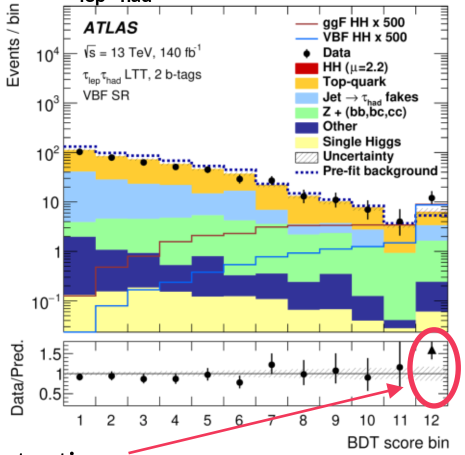
arXiv:2404.12660

- 2 b-jets and 2 τ candidates with $m_{\tau\tau} > 60$ GeV, categorised by τ decay:
  - ○ $\tau_{had}\tau_{had}$ channel: 2 oppositely charged hadronically decaying τ, e/μ veto
  - ○ $\tau_{lep}\tau_{had}$ channel: 1 e/μ + 1 τ_{had} , separated into categories based on trigger – **single-lepton (SLT)** and **lepton + τ_{had} (LTT)**
- VBF events selected by BDT from events with 2 b-jets + ≥ 2 additional jets, otherwise considered as ggF
- ggF separated into $m_{HH} < 350$ GeV and $m_{HH} \geq 350$ GeV
- (VBF + 2 × ggF) × 3 triggers = **9 categories**; **BDT discriminant** trained in each
  - ○ Trained on $\kappa_\lambda = 10$ in ggF $m_{HH} < 350$ GeV category, $\kappa_\lambda = 1$ in others
- Dominant background different in each category, but involves:
  - ○ Fake τ from $t\bar{t}$ or multijets – estimated using data driven methods, deriving fake factors or scale factors from control regions
  - ○ Top quark (true τ), $Z \to \tau\tau$ + heavy flavour, single-Higgs and others – shape from Monte Carlo, normalisation from fit or control region

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



$\tau_{lep}\tau_{had}$ LTT, VBF

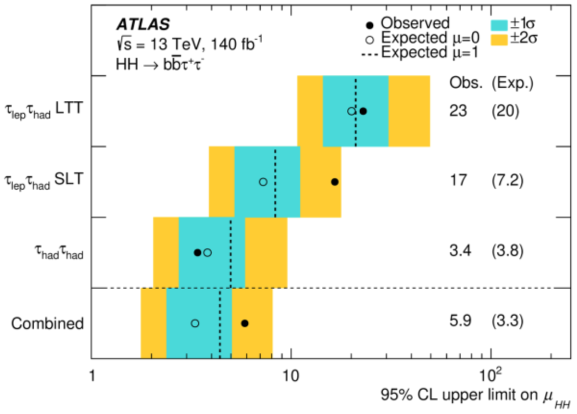


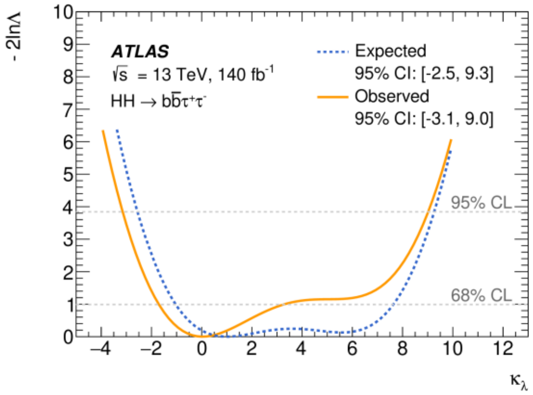
upward fluctuation

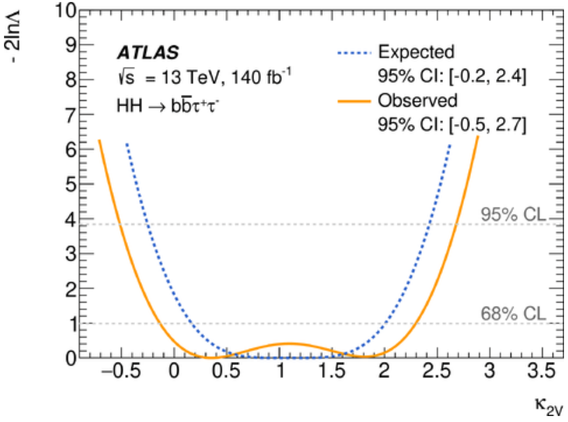
Nonresonant $b\bar{b}\tau^-\tau^+$ results

arXiv:2404.12660

- At 95% confidence level:
    - $\mu_{HH} < 5.9$ (**3.3 expected** assuming no HH – **leading channel**)
    - $-3.1 < \kappa_\lambda < 9.0$
    - $-0.5 < \kappa_{2V} < 2.7$
- Sensitivity improved by up to 20% compared to previous full Run-2 result
- Dominant uncertainties:
    - Data statistics
    - Modelling uncertainties:
        - top-quark background
        - single-Higgs background



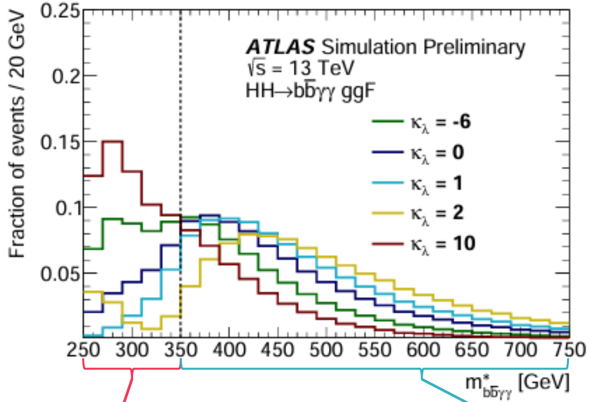




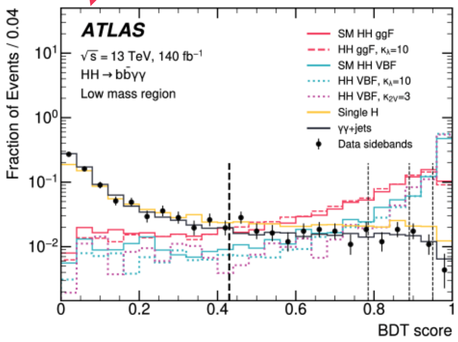
Nonresonant $b\bar{b}\gamma\gamma$ analysis

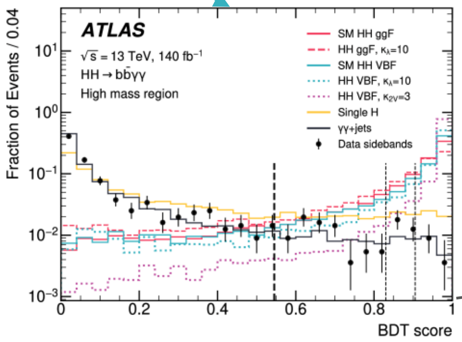
JHEP 01 (2024) 066

- 2 b-jets and 2 photons with $105 < m_{\gamma\gamma} < 160$ GeV
- $t\bar{t}$ and $t\bar{t}H$ suppression: e/μ veto and < 6 central jets
- Divide into categories by $m^*_{b\bar{b}\gamma\gamma}$ and BDT discriminant score
  - ○ $m^*_{b\bar{b}\gamma\gamma} = m_{b\bar{b}\gamma\gamma} + (125\text{ GeV} - m_{b\bar{b}}) + (125\text{ GeV} - m_{\gamma\gamma})$
- Fit $m_{\gamma\gamma}$ in each of 7 categories
  - ○ $\gamma\gamma$-continuum background modelled by exponential fit in sidebands
  - ○ single-Higgs background modelled by Crystal Ball function fit to MC



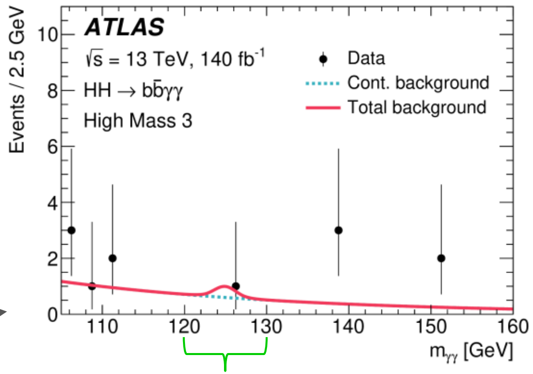
Low mass – targets BSM κ_λ
4 BDT score categories





High mass sensitive to SM and BSM κ_{2V}

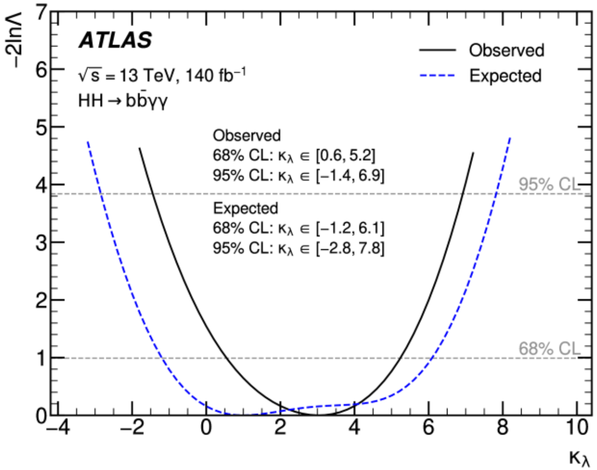
3 BDT score categories

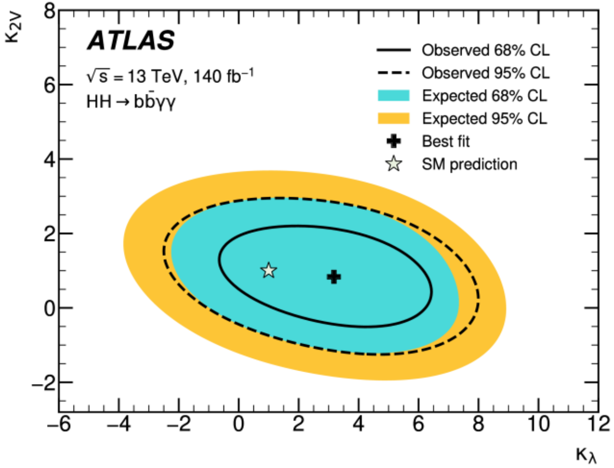


Signal region

Nonresonant $b\bar{b}\gamma\gamma$ results

- At 95% confidence level:
    - ○ $\mu_{HH} < 4.0$ (5.0 expected assuming no HH)
    - ○ **$-1.4 < \kappa_\lambda < 6.9$ – leading channel**
    - ○ $-0.5 < \kappa_{2V} < 2.7$
- Sensitivity improved by up to 17% compared to previous full Run-2 result
- Dominant uncertainties:
    - ○ Data statistics
    - ○ Theory uncertainties on HH production cross-section





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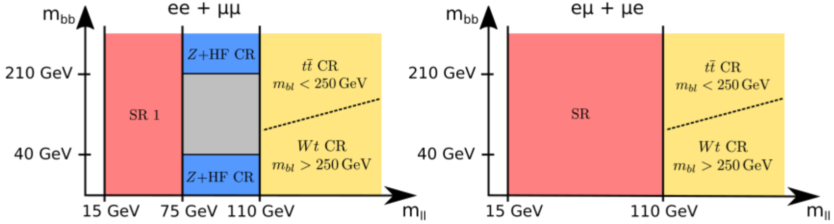
Nonresonant $b\bar{b}\ell\ell$ + missing E_{T} (neutrinos)

JHEP 02 (2024) 037

- Targeting one Higgs decay to $b\bar{b}$ and the other to W^+W^-, $\tau^+\tau^-$ or ZZ → 2 light oppositely charged leptons (can have different flavour) and 2 b-jets
- $\geq$ 2 VBF jets with $p_{\mathrm{T}} > 30$ GeV, max($\Delta\eta_{jj}$) > 4, max(m_{jj}) > 600 GeV

Categories and regions:

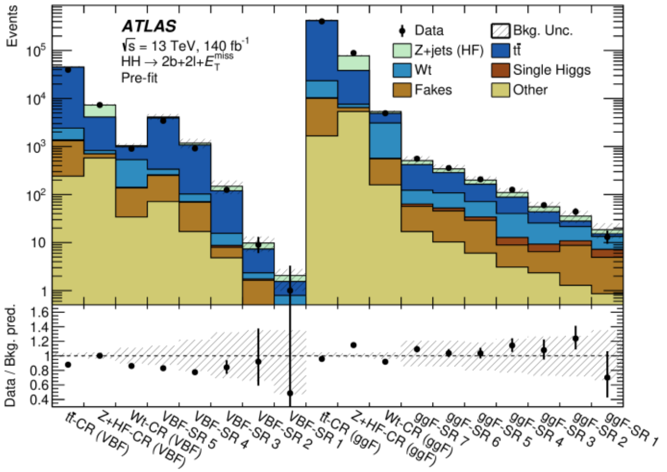


Yes - **VBF**

- Train BDT with $\kappa_\lambda = 0$ signal, background ggF HH and other SM
- Fit 5 most significant bins

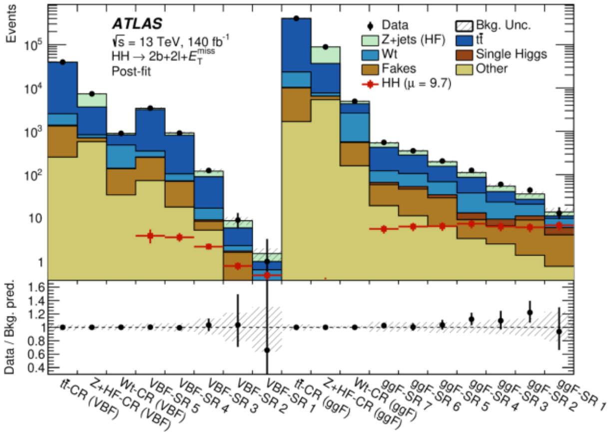
No - **ggF**

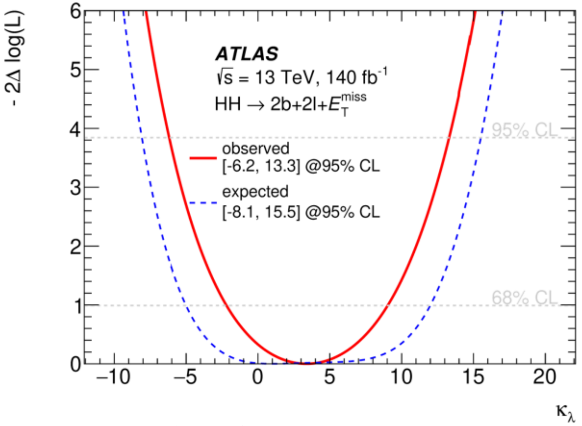
- Train neural network with ggF HH signal, $t\bar{t}$ and tW and other background
- Fit 7 most significant bins

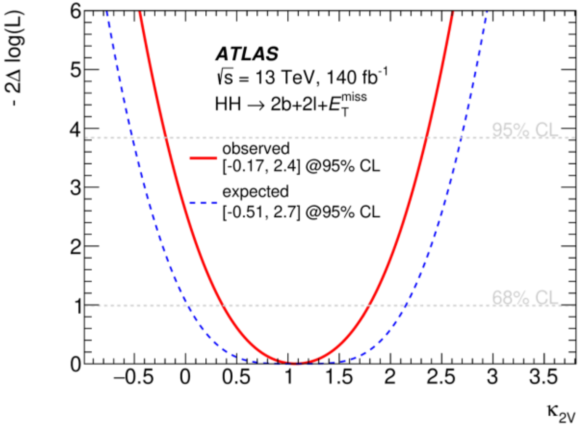


- Dominant backgrounds:
  - Fake leptons – data-driven background estimate
  - Z + heavy flavour, $t\bar{t}$ and tW – shape from MC, normalisation from control regions
  - Single Higgs – estimated from MC

Nonresonant $b\bar{b}\ell\ell$ + missing E_{T} results





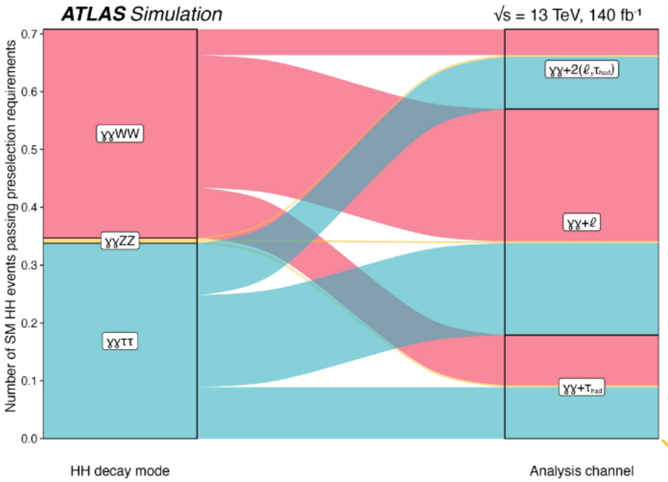


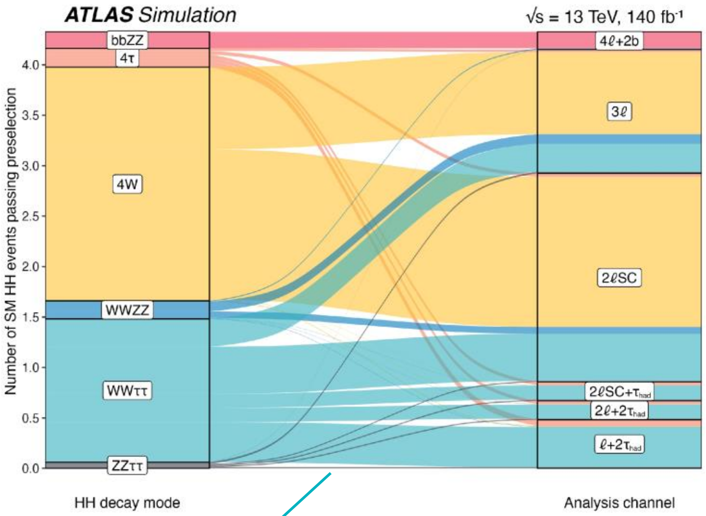
JHEP 02 (2024) 037

- At 95% confidence level:
  - $\mu_{HH} < 9.7$ (16.2 expected assuming no HH)
  - $-6.2 < \kappa_\lambda < 13.3$
  - $-0.17 < \kappa_{2V} < 2.4$
- Sensitivity improved by **factor of 2** compared to previous full Run-2 result

- Dominant uncertainties:
  - Data statistics
  - Modelling of Z + jets background

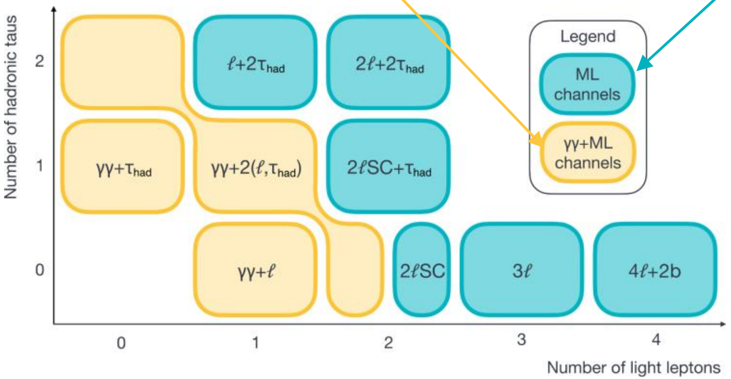
Nonresonant multilepton event selection





- 9 channels for the different HH decays:
  - $4V$
  - $VV\tau\tau$
  - 4τ
  - $b\bar{b}ZZ$
  - $\gamma\gamma VV$
  - $\gamma\gamma\tau\tau$

$V = W, Z$

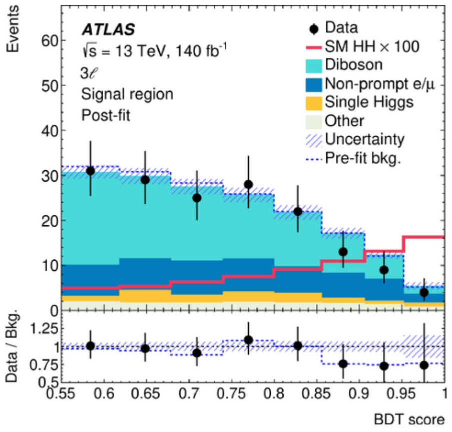


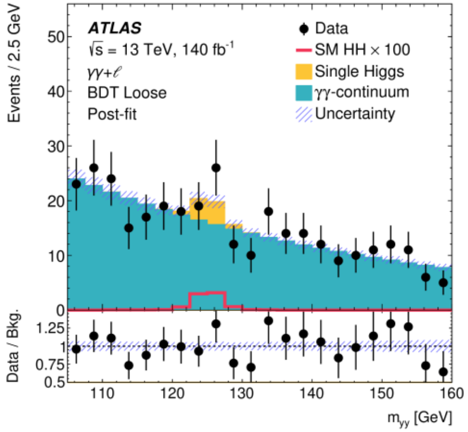
- Triggers:
  - single lepton
  - dilepton
  - diphoton

arXiv:2405.20040

Nonresonant multilepton analysis strategy

- Backgrounds:
  - Leptons - **fake** or **scale factors** derived in dedicated **control regions** or simultaneous fit with signal regions:
    - Prompt leptons from SM processes (dominated by diboson)
    - Non-prompt leptons (photon conversion, hadron decay)
    - Misassigned charge (bremsstrahlung + conversion, mismeasured track curvature)
    - Misidentified τ
  - Photons – **nonresonant $\gamma\gamma$ production** – estimated by **fitting exponential** to diphoton invariant mass $m_{\gamma\gamma}$ in sidebands
- **BDT** trained in each sub-channel:
  - used as **discriminant in multilepton** channels
  - used to define **categories** in which $\boldsymbol{m_{\gamma\gamma}}$ is fit in $\boldsymbol{\gamma\gamma}$ **+ multilepton** channels



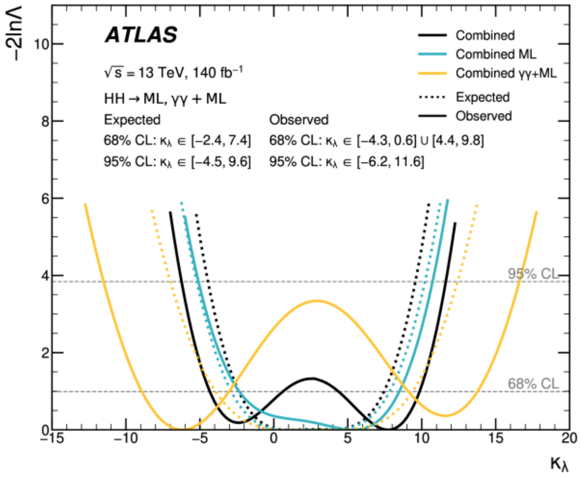


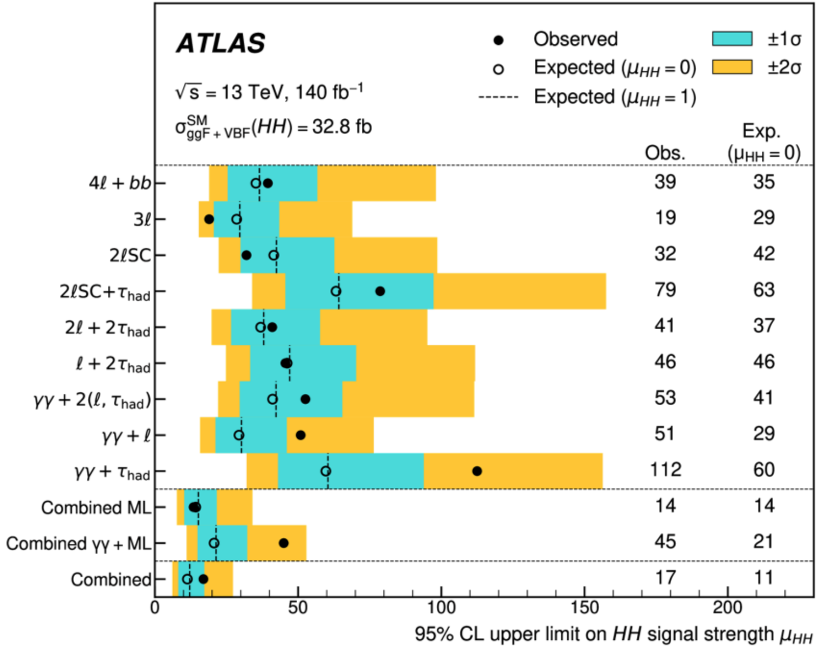
arXiv:2405.20040

Nonresonant multilepton results

arXiv:2405.20040

- At 95% confidence level:
    - $\mu_{HH} < 17$ (11 expected assuming no HH)
    - $-6.2 < \kappa_\lambda < 11.6$
    - $-2.5 < \kappa_{2V} < 4.6$
- Dominant uncertainty: data statistics
- 6 new sub-channels

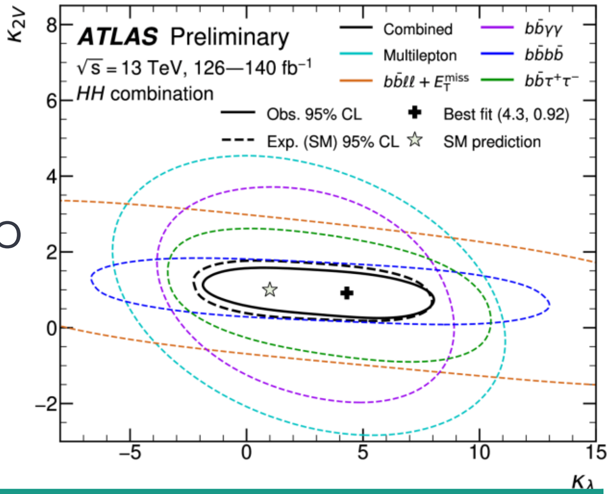


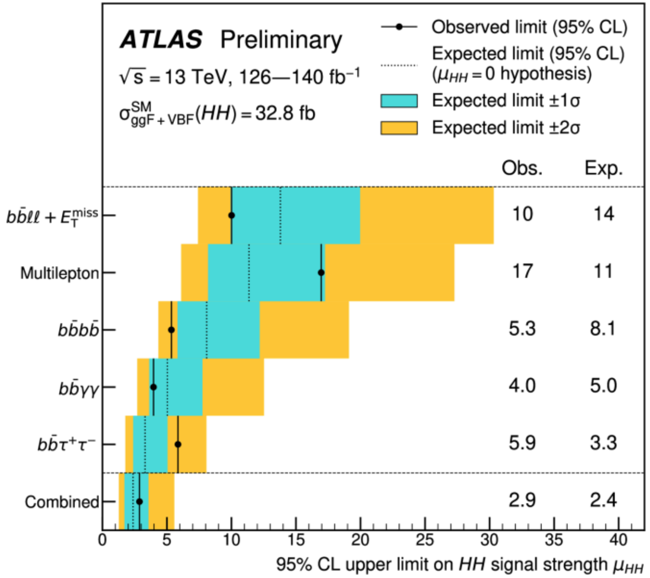


- Sensitivity **improved** by factor **4-9** in channels that were used in previous analysis
    - mainly due to use of **multivariate analysis** (BDT discriminant)

Combination

- Systematic uncertainties correlated where possible
- Higgs self-coupling contributes to single Higgs production through NLO corrections
- Observed (expected from SM) 95% CL constraints:





Best expected sensitivity to date (from any experiment)

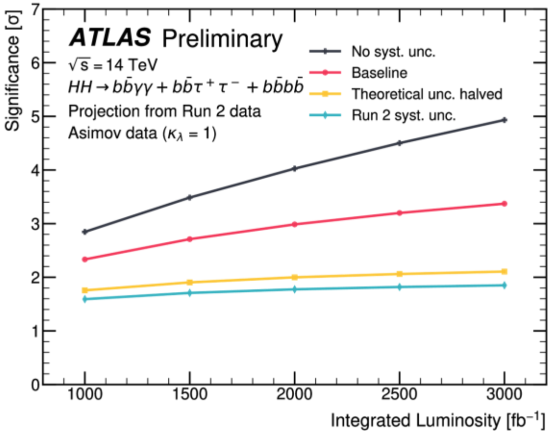
	5 updated HH channels NEW! (ATLAS-CONF-2024-006)	$H + (HH \rightarrow b\bar{b}b\bar{b}, b\bar{b}\tau^+\tau^-, b\bar{b}\gamma\gamma)$ Previous round (Phys. Lett. B, 843 (2023))
μ_{HH}	2.9 observed **2.4 expected**	2.4 observed 2.9 expected
κ_λ	[-1.2, 7.2] observed [-1.6, 7.2] expected	[-0.4, 6.3] observed [-1.9, 7.6] expected
κ_{2V}	[0.57, 1.48] observed [0.41, 1.65] expected	[0.1, 2.0] observed [0.0, 2.1] expected

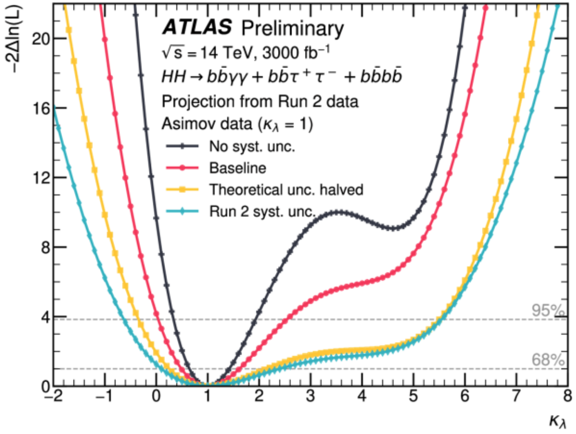
Dominant uncertainty: theory HH cross-section ($^{+6\%}_{-23\%}$ scale + m_{top})

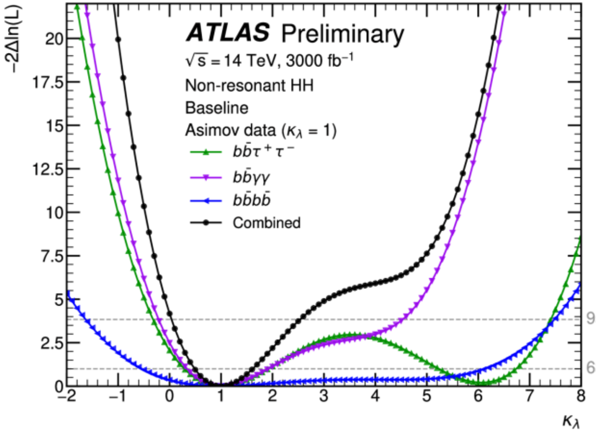
Extrapolation to the High-Luminosity LHC

ATL-PHYS-PUB-2022-053

- HL-LHC: $\sqrt{s} = 13$ TeV → **14 TeV**, 140 **fb^{-1}** → **3000 fb^{-1}**, planned start in 2029
- Extrapolation only done with 3 dominant channels ($b\bar{b}b\bar{b} + b\bar{b}\tau^+\tau^- + b\bar{b}\gamma\gamma$), based on **previous round** of full Run-2 results
  - 13% improvement already in reoptimized Run-2 analyses, Run 3 under way
- Baseline assuming 2× reduction in theory modelling uncertainty and 2× better b-tagging
  - HH discovery significance 3.4σ, allowed 95% confidence interval for κ_λ expected to be [0.0, 2.5]







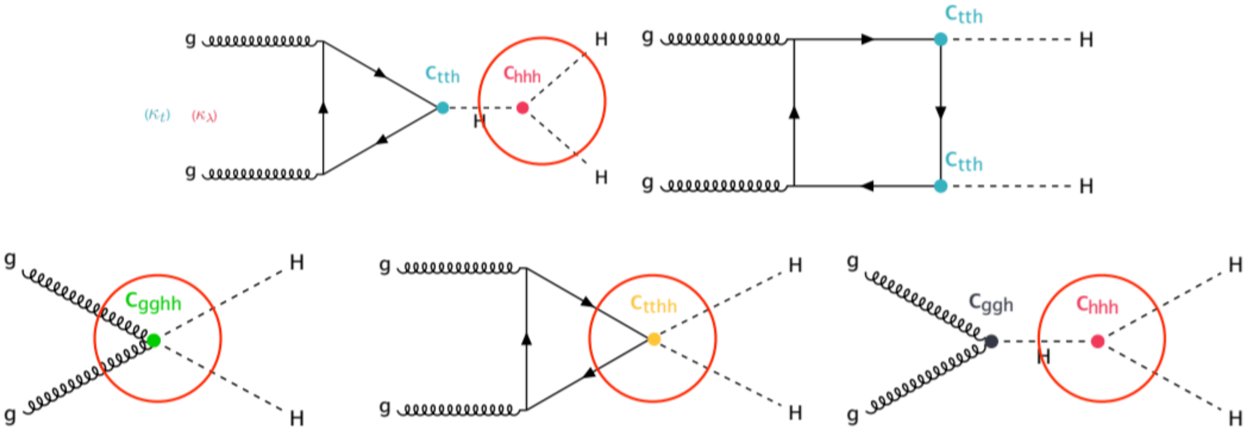
Summary

- Higgs pair production provides a **direct probe** of the **Higgs self-coupling** and therefore the Higgs potential
- HH production is **rare** and requires highly **optimised analyses**
- Searches conducted by ATLAS cover **>50% of Standard Model HH decays**
- Reoptimised full Run-2 analyses significantly improve sensitivity
    - Best expected sensitivity to HH cross-section and Higgs self-coupling to date achieved by ATLAS
        - Signal strength: $\mu_{HH} < 2.9$ **(2.4 expected)**
        - Higgs self-coupling modifier: $-1.2 < \kappa_\lambda < 7.2$ **($-1.6 < \kappa_\lambda < 7.2$ expected)**
    - Dominant uncertainties are in the **theoretical cross-section** and $b\bar{b}b\bar{b}$ **background estimation**
- Promising Run-3 and HL-LHC prospects
    - Discovery significance $> 3\sigma$ expected

Backup

Higgs effective field theory interpretations

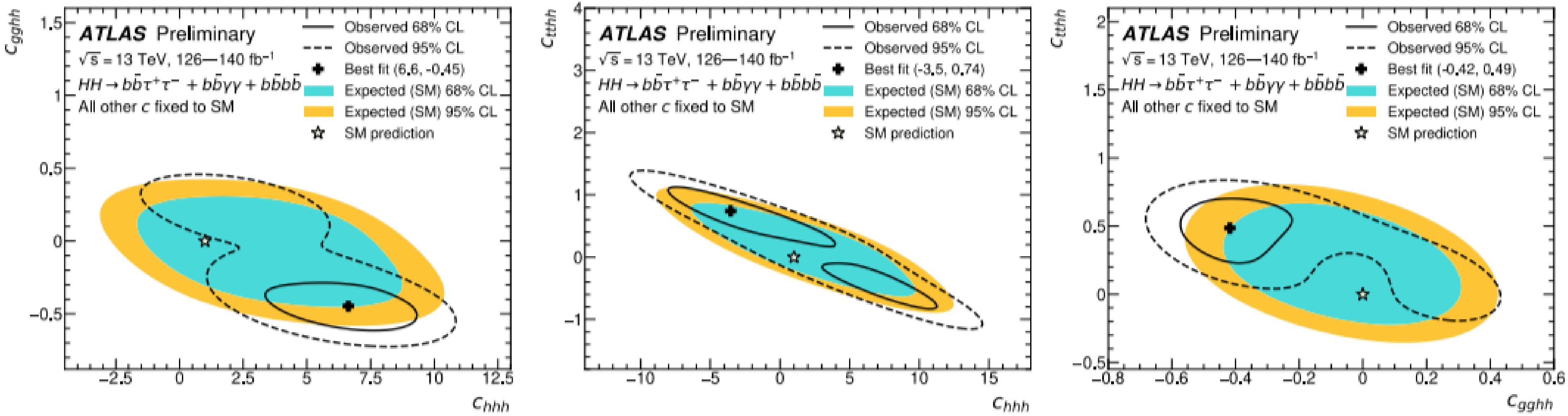
- Effect of BSM physics is parameterised through the addition of higher-orders operators with effective couplings at the low-energy scale
- In HEFT, at leading order there are 5 operators for HH production and their corresponding Wilson coefficients representing the Higgs boson coupling modifiers affecting ggF HH production
- HH production has unique access to c_{hhh}, c_{tthh} and c_{gghh}



HH combination HEFT interpretation

ATLAS-CONF-2024-006

Chhh-Cgghh Chhh-Cgghh Cgghh-Ctthh

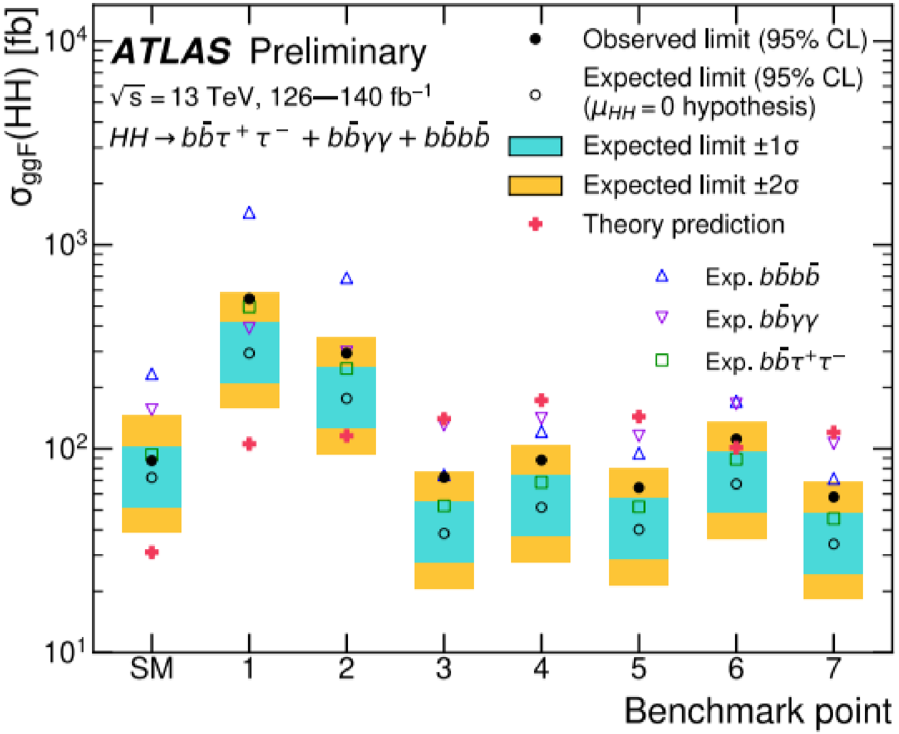


- Two minima are expected because of the quadratic dependence of the cross-section on the coefficients
- Best fit driven by $b\bar{b}b\bar{b}$ – background mismodelling making non-SM signals more favorable

HEFT benchmark models – HH combination

ATLAS-CONF-2024-006

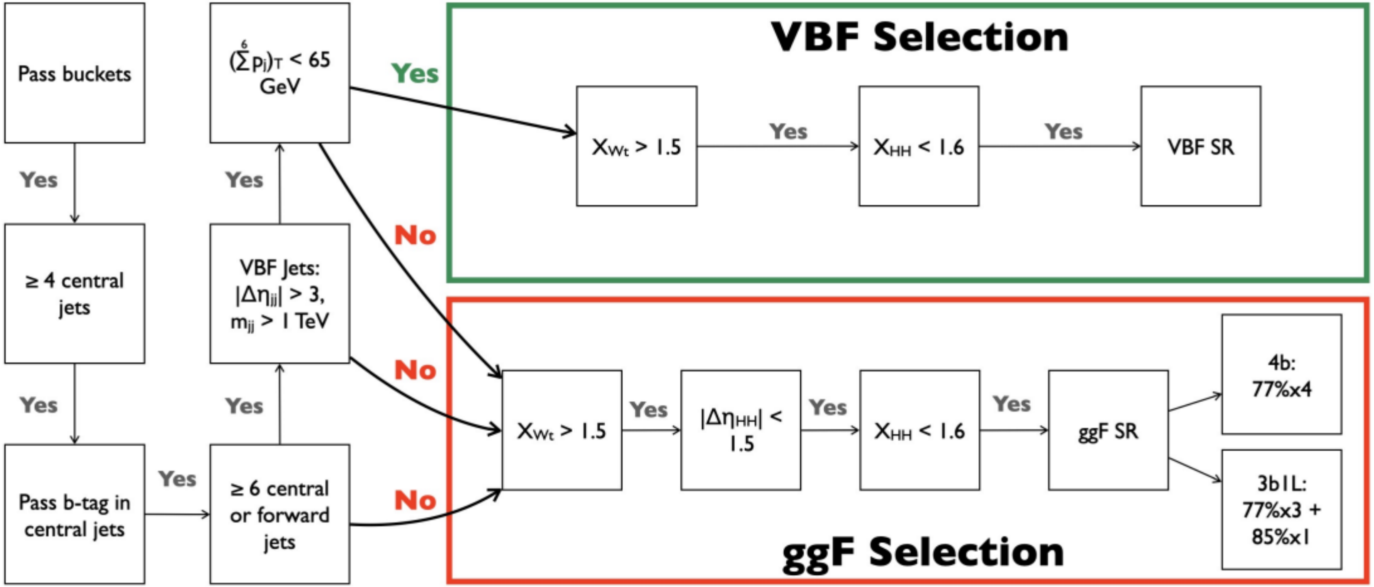
Benchmark	c_{hhh}	c_{tth}	c_{ggh}	c_{gghh}	c_{tthh}
SM	1.00	1.00	0	0	0
1	5.11	1.10	0	0	0
2	6.84	1.03	$-1/3$	0	$1/6$
3	2.21	1.05	$1/2$	$1/2$	$-1/3$
4	2.79	0.90	$-1/3$	$-1/2$	$-1/6$
5	3.95	1.17	$1/6$	$-1/2$	$-1/3$
6	-0.68	0.90	$1/2$	$1/4$	$-1/6$
7	-0.10	0.94	$1/6$	$-1/6$	1



Resolved $b\bar{b}b\bar{b}$ event selection

Phys. Rev. D 108 (2023) 052003

- Top veto: $X_{Wt} = \sqrt{\left(\frac{m_W - 80.4\ \mathrm{GeV}}{0.1 m_W}\right)^2 + \left(\frac{m_t - 172.5\ \mathrm{GeV}}{0.1 m_t}\right)^2} \geq 1.5$



Central jets:

- p_{T} > 40 GeV
- $|\eta|$ < 2.5

Forward jets:

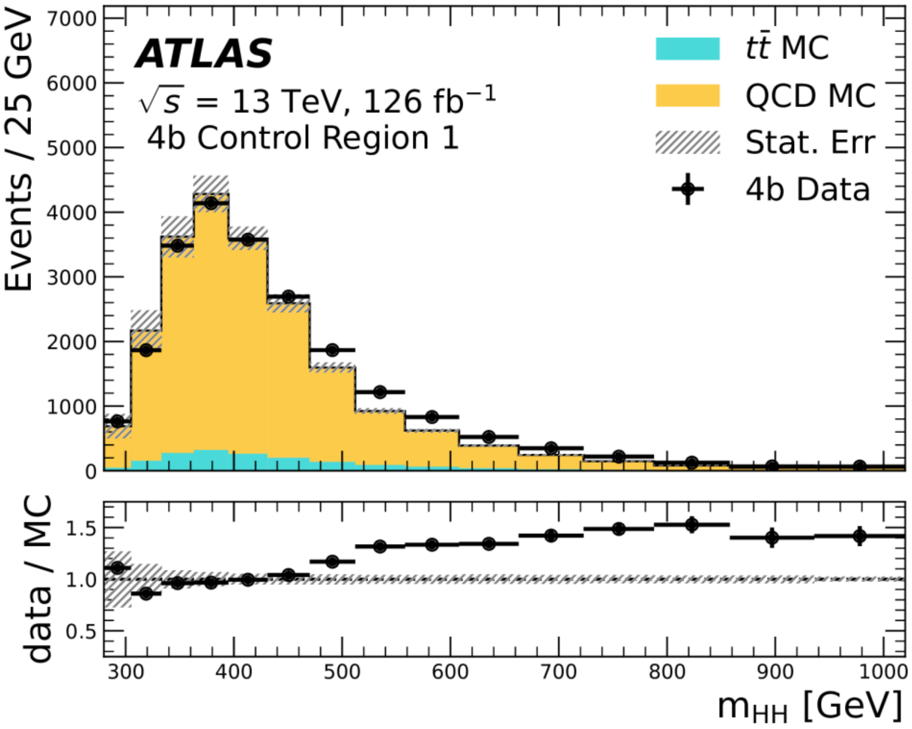
- p_{T} > 30 GeV
- $|\eta|$ > 2.5

VBF jets:

- passing central and forward jet selection
- non-*b*-tagged
- pair with highest m_{jj}

$b\bar{b}b\bar{b}$ background estimation motivation

- Discrepancy between simulated background and data indicates alternative background estimation is needed

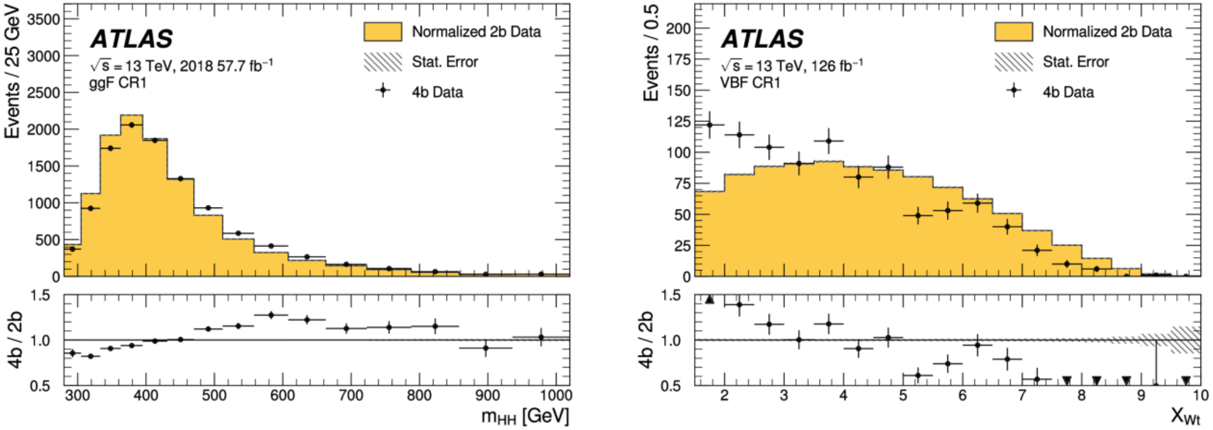


Phys. Rev. D 108 (2023) 052003

Resolved $b\bar{b}b\bar{b}$ background estimation

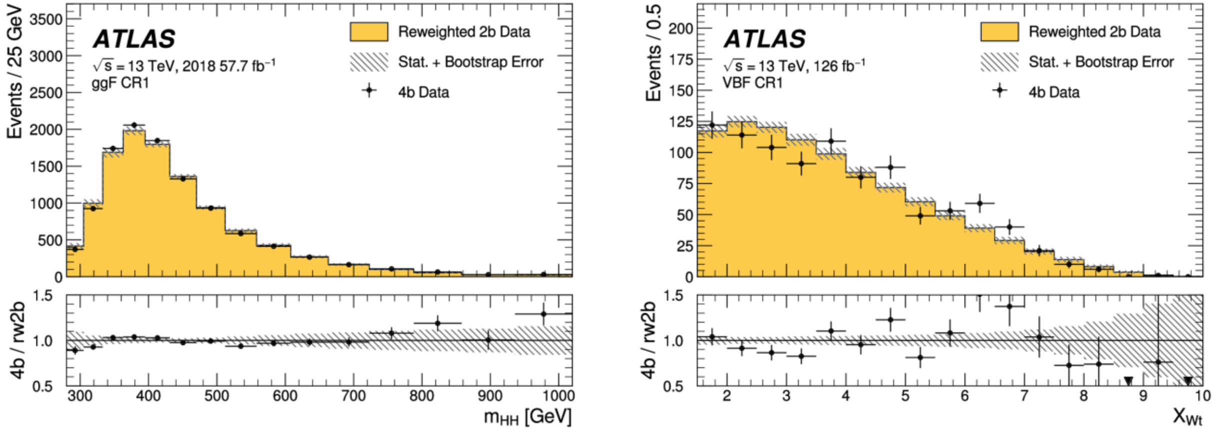
- Control region

  before reweighting:



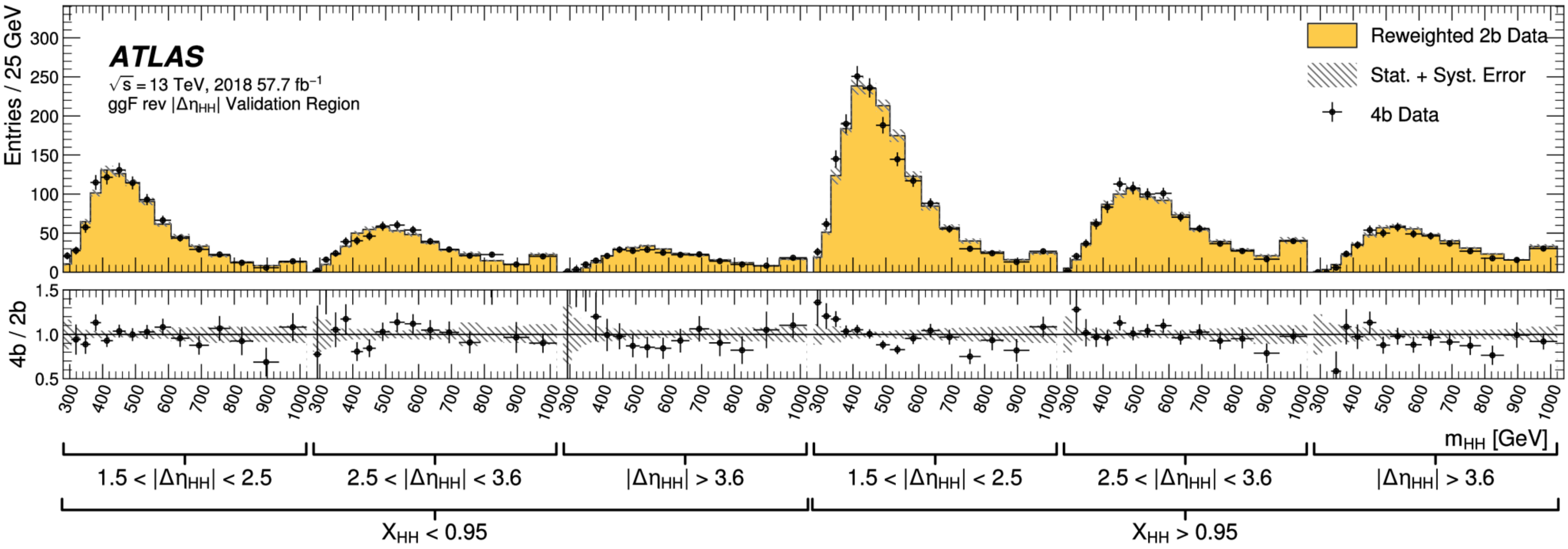
- Control region

  after reweighting:



Phys. Rev. D 108 (2023) 052003

Resolved $b\bar{b}b\bar{b}$ background estimation validation: reverse $|\Delta\eta_{HH}|$ region



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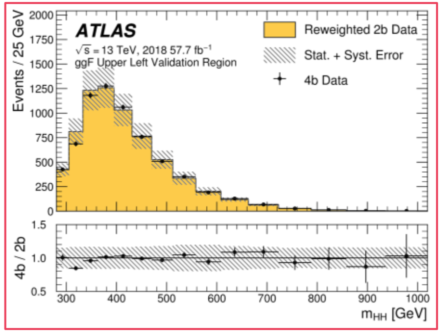
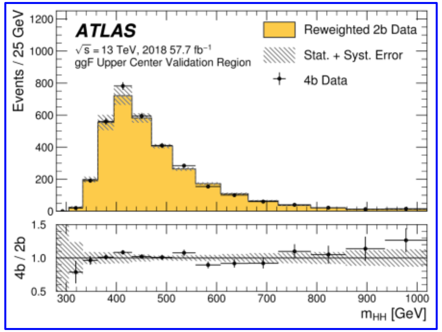
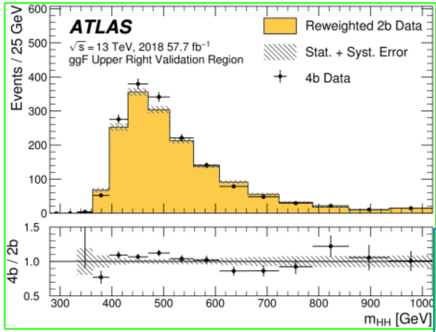
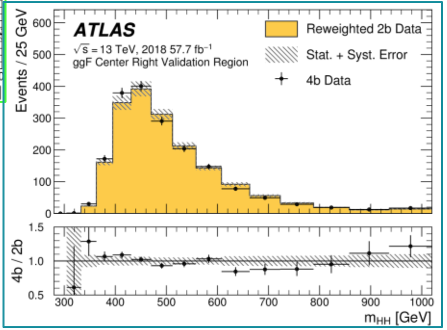
Resolved $b\bar{b}b\bar{b}$ background estimation validation: shifted regions

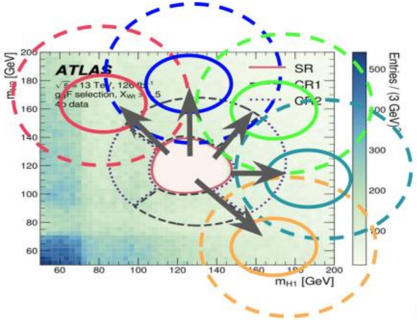


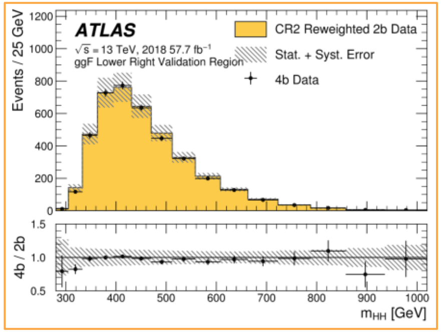






- Background modelling is good in shifted validation regions





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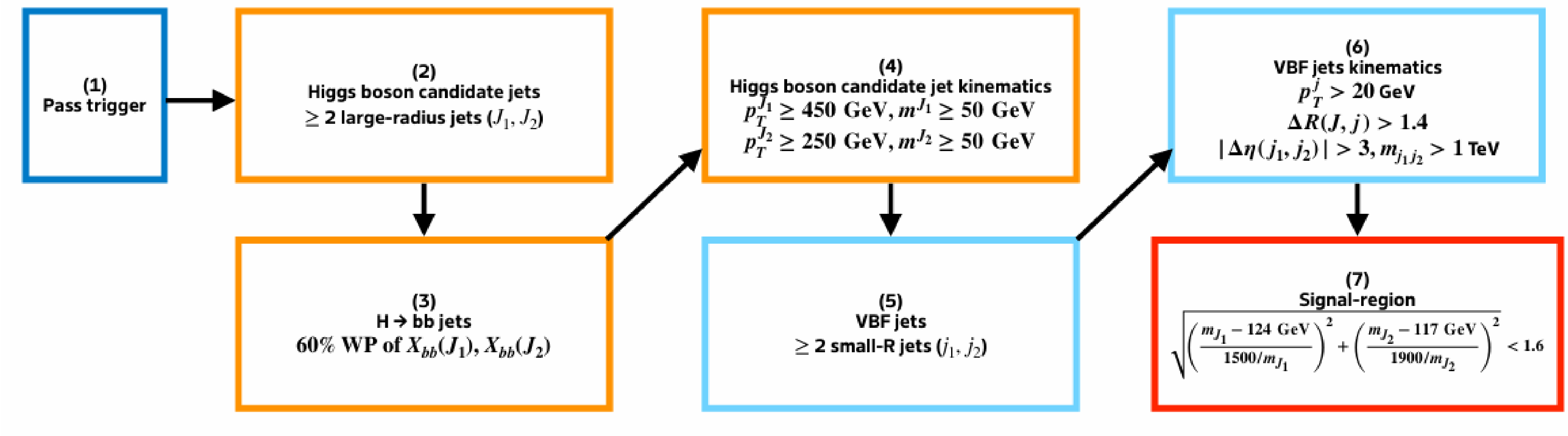
Boosted $b\bar{b}b\bar{b}$ VBF selection

arXiv:2404.17193



(1)
Pass trigger

(2)
Higgs boson candidate jets
$\geq$ 2 large-radius jets (J_1, J_2)

(3)
H → bb jets
60% WP of $X_{bb}(J_1)$, $X_{bb}(J_2)$

(4)
Higgs boson candidate jet kinematics
$p_T^{J_1} \geq 450$ GeV, $m^{J_1} \geq 50$ GeV
$p_T^{J_2} \geq 250$ GeV, $m^{J_2} \geq 50$ GeV

(5)
VBF jets
$\geq$ 2 small-R jets (j_1, j_2)

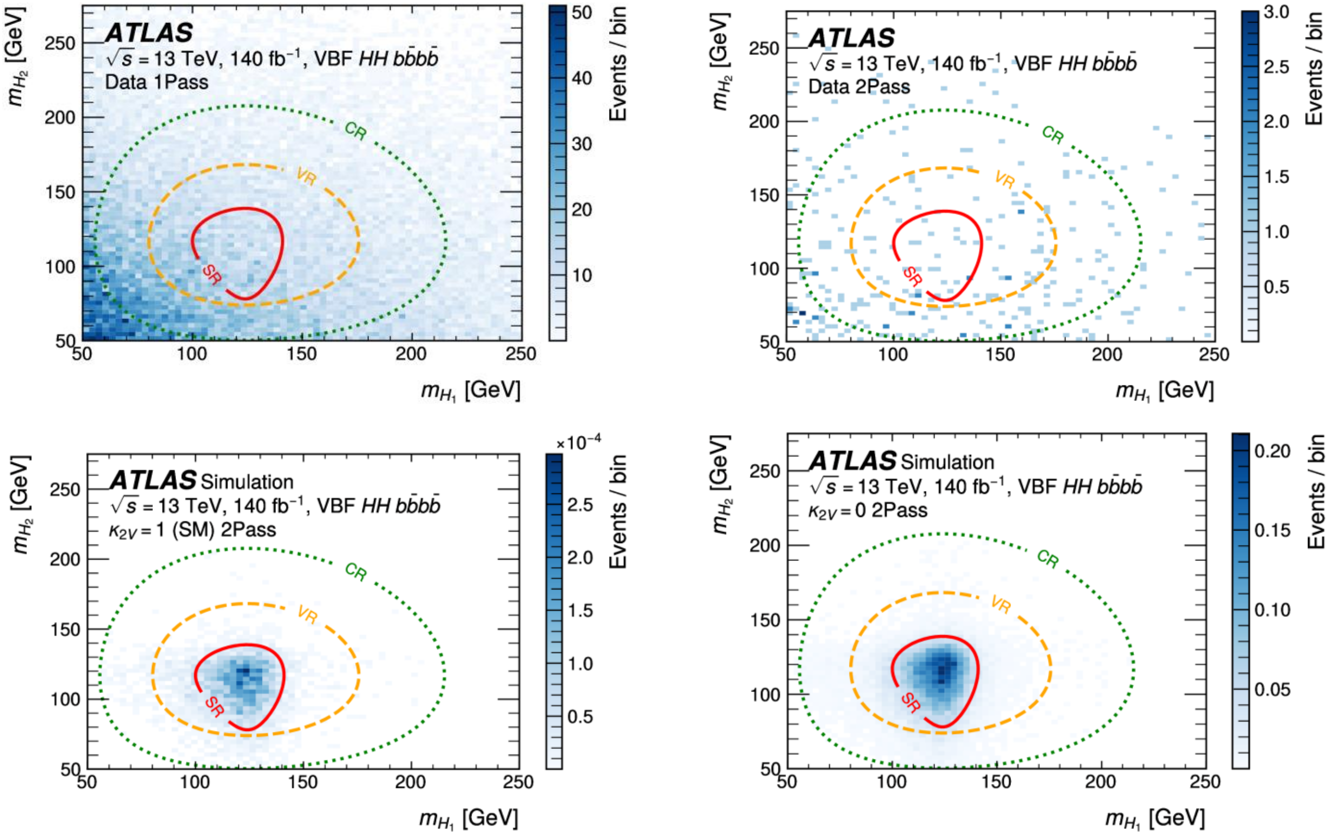
(6)
VBF jets kinematics
$p_T^j > 20$ GeV
$\Delta R(J, j) > 1.4$
$|\Delta\eta(j_1, j_2)| > 3$, $m_{j_1 j_2} > 1$ TeV

(7)
Signal-region

$$\sqrt{\left(\frac{m_{J_1} - 124\ \text{GeV}}{1500/m_{J_1}}\right)^2 + \left(\frac{m_{J_2} - 117\ \text{GeV}}{1900/m_{J_2}}\right)^2} < 1.6$$

Boosted $b\bar{b}b\bar{b}$ mass planes

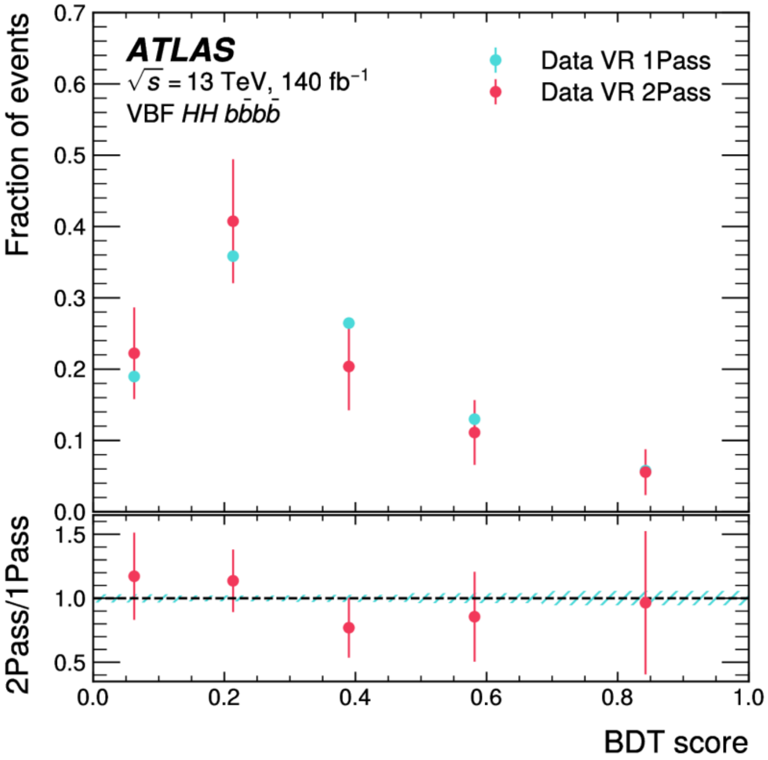
arXiv:2404.17193



Boosted $b\bar{b}b\bar{b}$ background estimation

- BDT score in validation region (VR):

arXiv:2404.17193

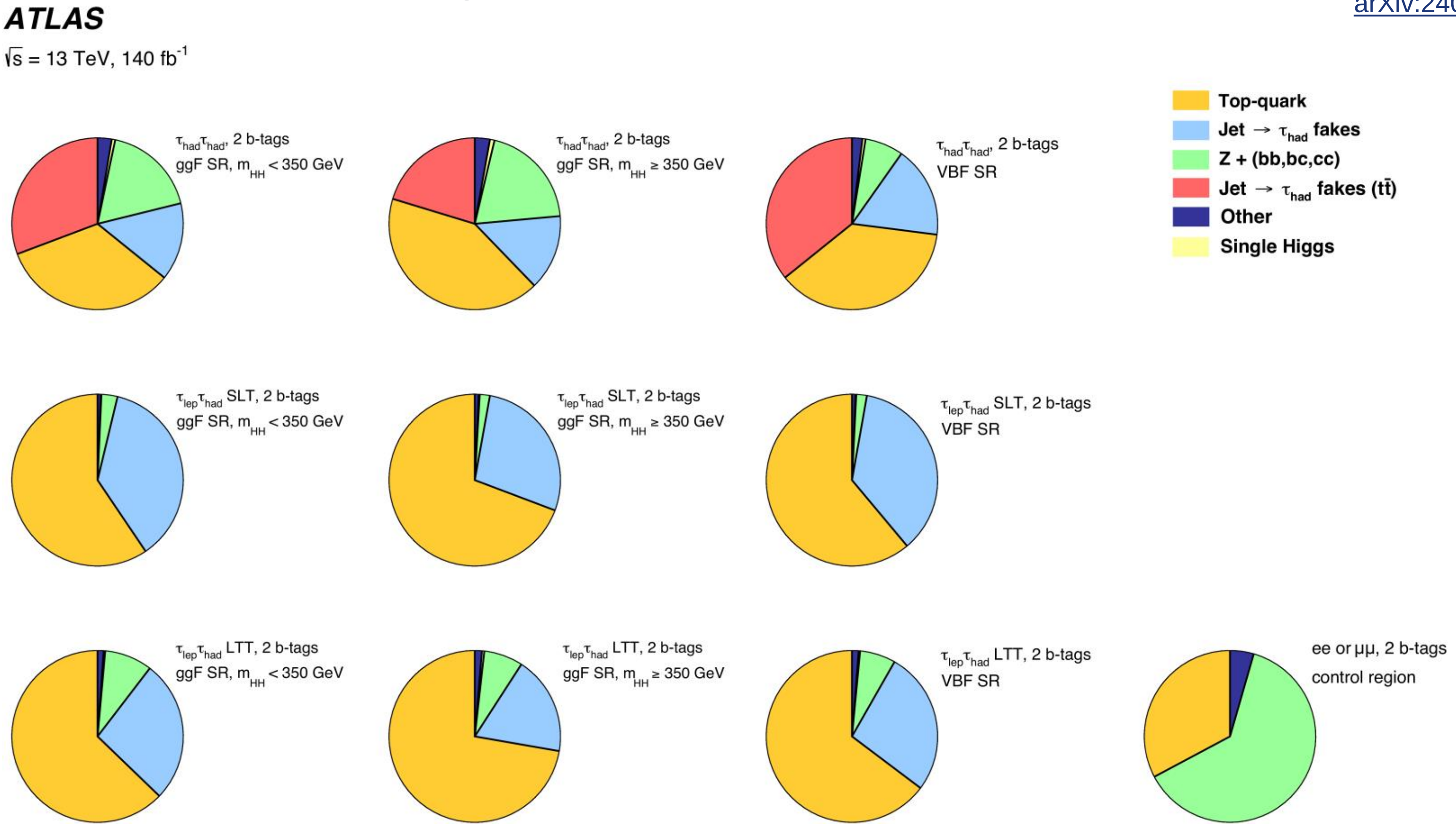


- 1Pass = 1 double-b-tagged large-radius jet
- 2Pass = 2 double-b-tagged large-radius jets
- 1Pass is within statistical uncertainty of 2Pass

→ only need to derive normalization factor to interpolate to signal region

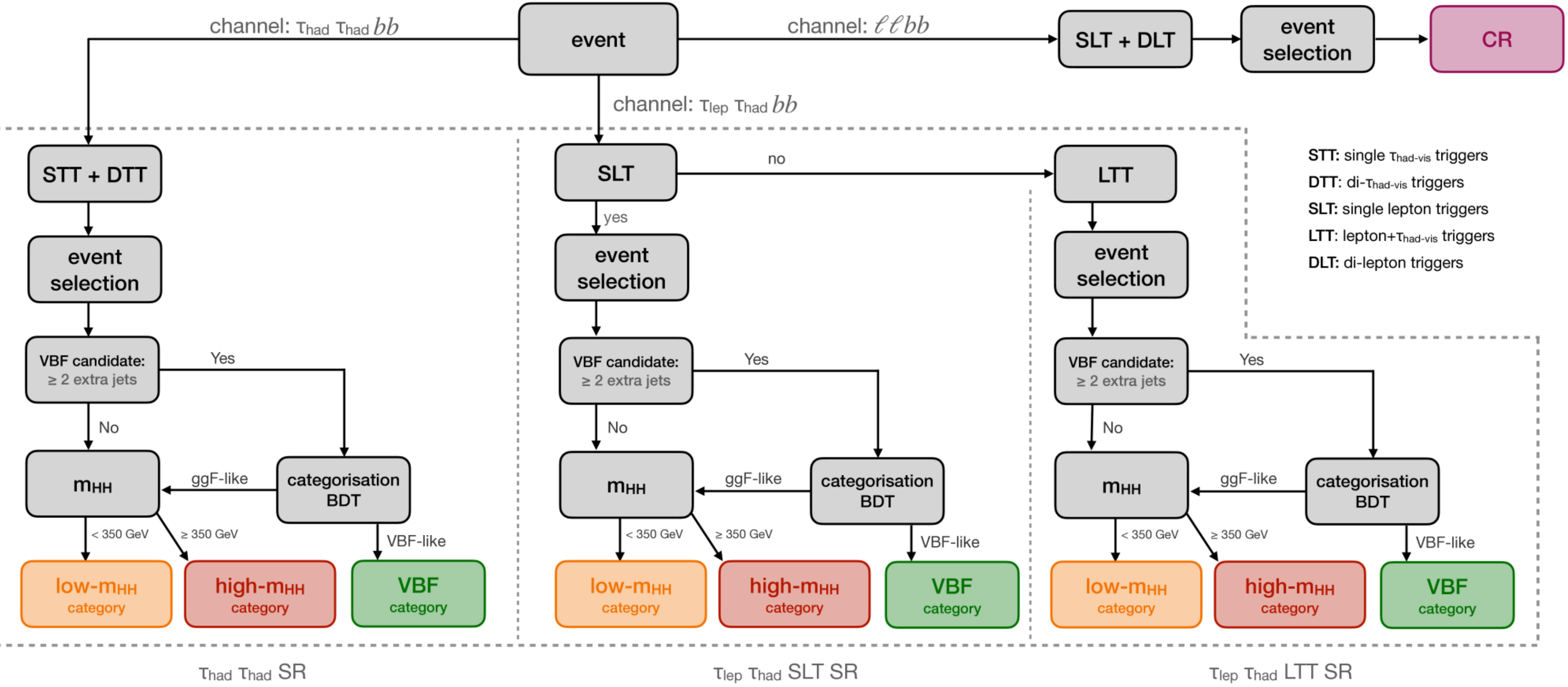
$b\bar{b}\tau^-\tau^+$ background composition

arXiv:2404.12660



$b\bar{b}\tau^-\tau^+$ category and region definitions

arXiv:2404.12660



channel: $\tau_{had}\tau_{had}bb$

event

channel: $\ell\ell bb$

SLT + DLT

event selection

CR

channel: $\tau_{lep}\tau_{had}bb$

STT + DTT

event selection

VBF candidate: ≥ 2 extra jets

Yes

No

m_{HH}

ggF-like

categorisation BDT

< 350 GeV

≥ 350 GeV

VBF-like

low-m_{HH} category

high-m_{HH} category

VBF category

SLT

no

yes

LTT

event selection

VBF candidate: ≥ 2 extra jets

Yes

No

m_{HH}

ggF-like

categorisation BDT

< 350 GeV

≥ 350 GeV

VBF-like

low-m_{HH} category

high-m_{HH} category

VBF category

event selection

VBF candidate: ≥ 2 extra jets

Yes

No

m_{HH}

ggF-like

categorisation BDT

< 350 GeV

≥ 350 GeV

VBF-like

low-m_{HH} category

high-m_{HH} category

VBF category

STT: single $\tau_{had\text{-}vis}$ triggers

DTT: di-$\tau_{had\text{-}vis}$ triggers

SLT: single lepton triggers

LTT: lepton+$\tau_{had\text{-}vis}$ triggers

DLT: di-lepton triggers

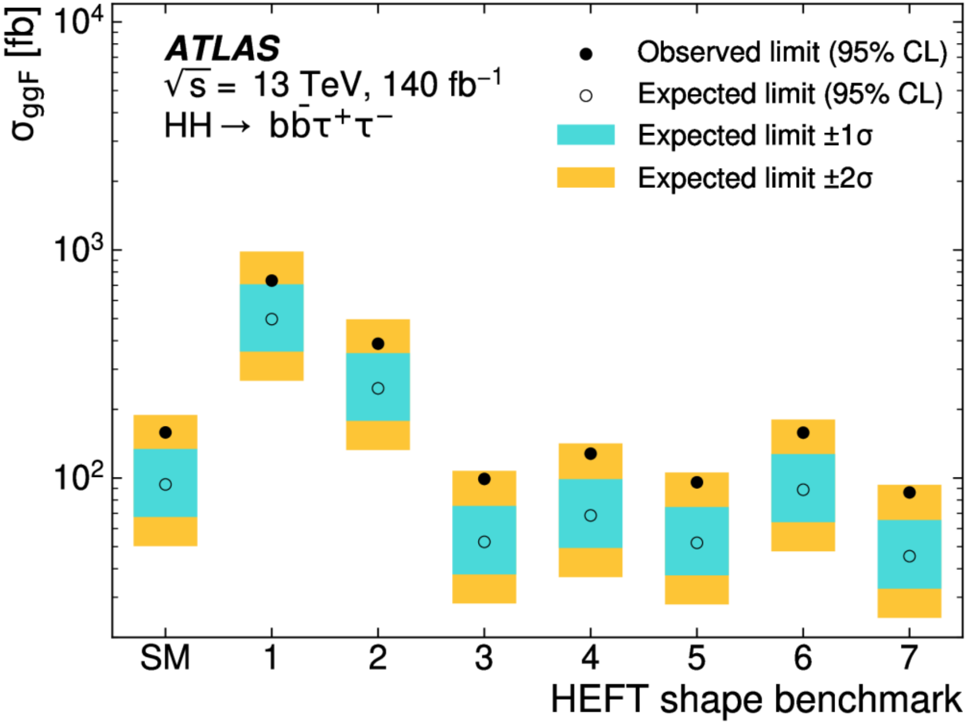
$\tau_{had}\tau_{had}$ SR

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

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

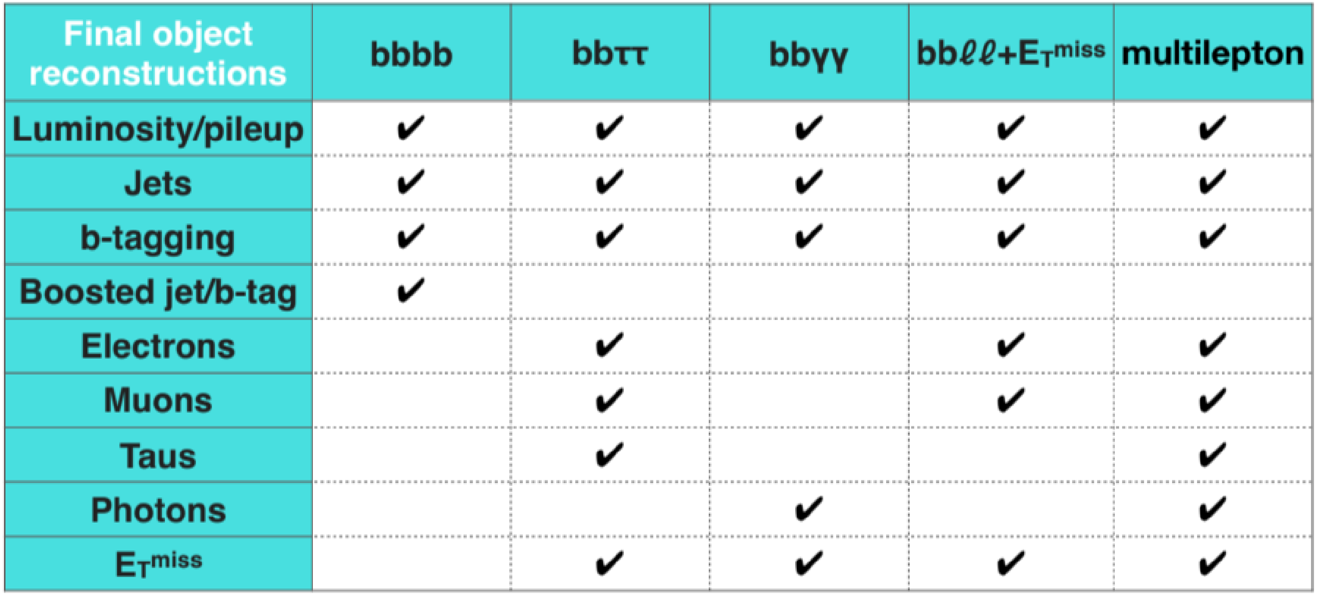
$b\bar{b}\tau^-\tau^+$ HEFT results

arXiv:2404.12660



Systematic uncertainties and correlation

- No additional pruning is applied in the combination



Final object reconstructions	bbbb	bb$\tau\tau$	bb$\gamma\gamma$	bb$\ell\ell$+E_T^{miss}	multilepton
Luminosity/pileup	✓	✓	✓	✓	✓
Jets	✓	✓	✓	✓	✓
b-tagging	✓	✓	✓	✓	✓
Boosted jet/b-tag	✓				
Electrons		✓		✓	✓
Muons		✓		✓	✓
Taus		✓			✓
Photons			✓		✓
E_T^{miss}		✓	✓	✓	✓

- Common sources are correlated except if:
    - Different calibrations used
    - Different post fit profilings from different phase space

From Rui Zhang's seminar

Systematic uncertainties and correlation

HH signal modelling	bbbb	bbττ	bbγγ	$bb\ell\ell+E_T^{miss}$	multilepton
QCD scale + m_{top}	✔	✔	✔	✔	✔
PDF + α_S	✔	✔	✔	✔	✔
H branching ratio	✔	✔	✔	✔	✔
Parton shower	✔	✔	✔	✔	✔
κ interpolation	✔	✔	✔	✔	
Bkg. modelling	**bbbb**	**bbττ**	**bbγγ**	**$bb\ell\ell+E_T^{miss}$**	**multilepton**
Single Higgs		✔	✔		✔
Top quark		✔		✔	
Z + jets		✔		✔	✔
Diboson		✔			✔
Specific per chan.	✔	✔	✔	✔	✔

From Rui Zhang's seminar

- Dominant uncertainties:
  - HH cross section theory calculation QCD scale + m_{top} (pre-fit +6%, –23% on ggF HH)
  - Normalisation of single H + heavy-flavour jets on ggF (pre-fit 100% on ggF H yields)

Channels and assumptions in combination

- Combinations assume that new physics affects only the Higgs boson self-coupling
- $HH + H$ combination provides results from a fit allowing more coupling modifiers accounting for interactions of the Higgs boson with other Standard Model particles:
    - $-1.4 < \kappa_\lambda < 6.1$ at 95% CL
- $HH + H$ combination analysis channels:

Phys. Lett. B, 843 (2023)

HH	H
$HH \to b\bar{b}b\bar{b}$ $HH \to b\bar{b}\tau^+\tau^-$ $HH \to b\bar{b}\gamma\gamma$	$H \to \gamma\gamma$ $H \to ZZ^* \to 4\ell$ $H \to \tau^+\tau^-$ $H \to WW^* \to e\nu\mu\nu$ (ggF, VBF) $H \to b\bar{b}$ (VH) $H \to b\bar{b}$ (VBF) $H \to b\bar{b}$ $(t\bar{t}H)$