Searches for resonances decaying to pairs of Higgs bosons at ATLAS

Higgs2024, Uppsala

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on behalf of the ATLAS collaboration

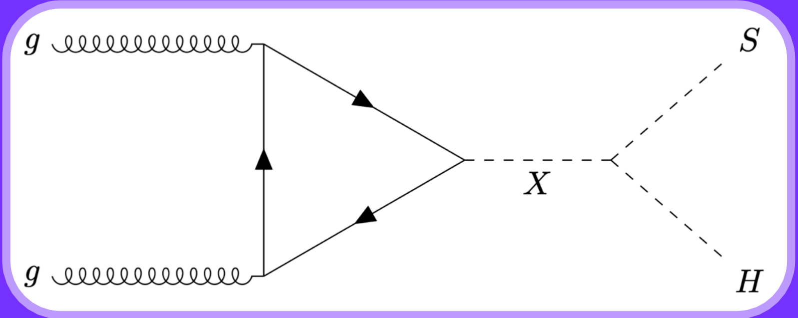
Theoretical motivations

Sensitive to BSM physics – effects parametrised by resonance mass m_X

→ signals have a peak in m_{HH}

→ constrains free parameters in the BSM models

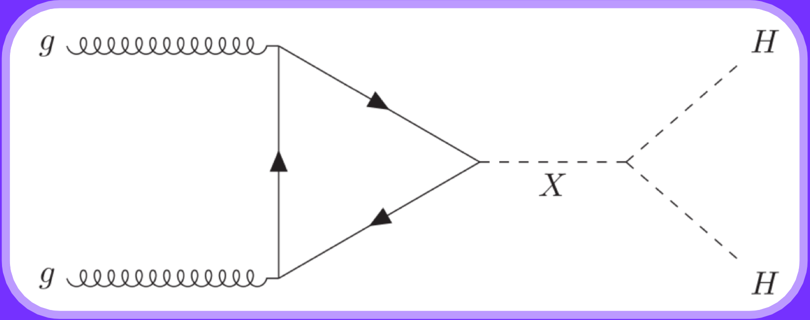
$X \rightarrow SH$



SM Higgs mixing with additional scalars

- 2 additional singlets (TRSM)
- 2-Higgs-doublet + singlet (2HDM+S) including NMSSM

$X \rightarrow HH$



Common in all extended Higgs sectors

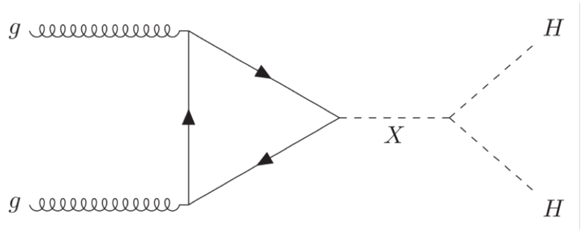
- Additional weak isospin singlets, doublets, triplets (2HDM, MSSM)
- Warped extra dimensions → generic resonances

Searches at ATLAS

New!

Resonant *HH* combination

- $X \to HH \to b\bar{b}b\bar{b} / b\bar{b}\tau^+\tau^- / b\bar{b}\gamma\gamma$
  [CERN-EP-2023-271]

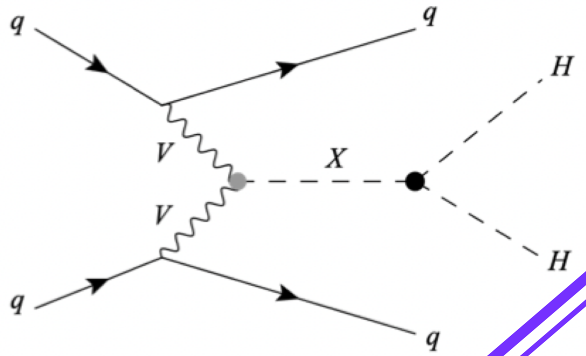


$X \to HH$

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

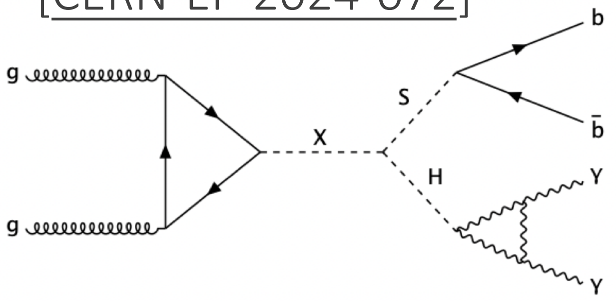
- Resolved [CERN-EP-2019-267]
- Boosted [CERN-EP-2024-092]

New!



$X \to S(\to b\bar{b})H(\to \gamma\gamma)$

[CERN-EP-2024-072]



$X \to S(\to W^+W^-/ZZ)H(\to \gamma\gamma)$

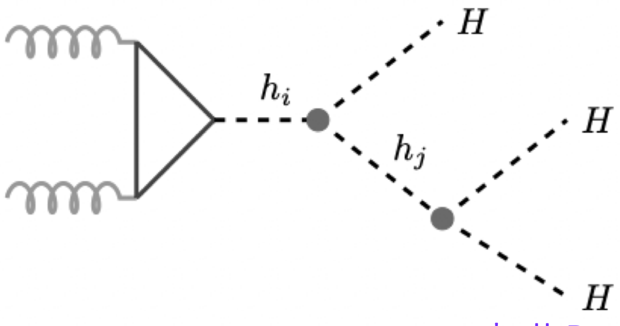
[CERN-EP-2024-147]

$X \to SH$

New!

$X \to SH \to HHH \to 6b$

[CERN-EP-2024-285]



*all Run-2 results

$$X \to HH$$

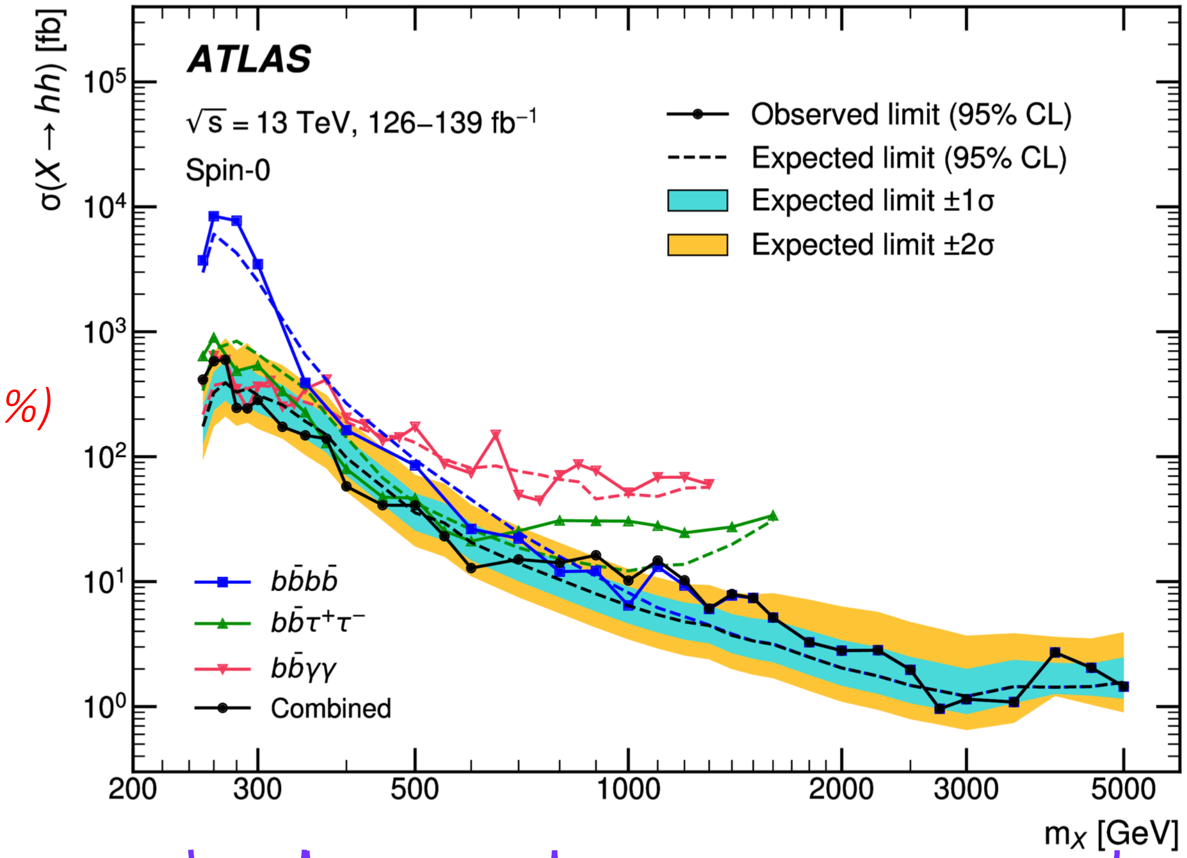
$X \rightarrow HH$ combination

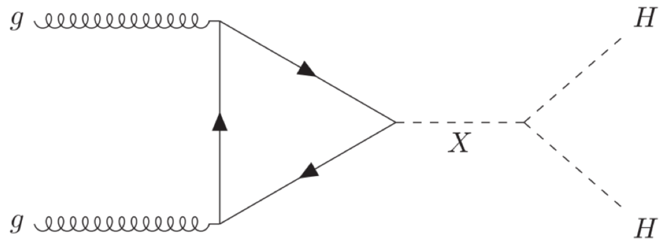
$b\bar{b}\gamma\gamma$

Lowest branching ratio (0.3%)

High γ trigger & reconstruction efficiencies

Excellent $m_{\gamma\gamma}$ resolution





$b\bar{b}b\bar{b}$

Highest branching ratio (33.9%)

High p_T b-jet trigger thresholds

Challenging b-jet pairing

Large QCD multi-jet background

New!

Most sensitive decay channel: $b\bar{b}\gamma\gamma$ $b\bar{b}\tau^+\tau^-$ $b\bar{b}b\bar{b}$

Intermediate branching ratio (7.3%)

Moderate background contamination

Obs. upper limits on $\sigma(X \rightarrow hh)$

- 0.96 - 600 fb
- Improved by of a factor of 2-5 from partial Run-2 results (36 fb^{-1})

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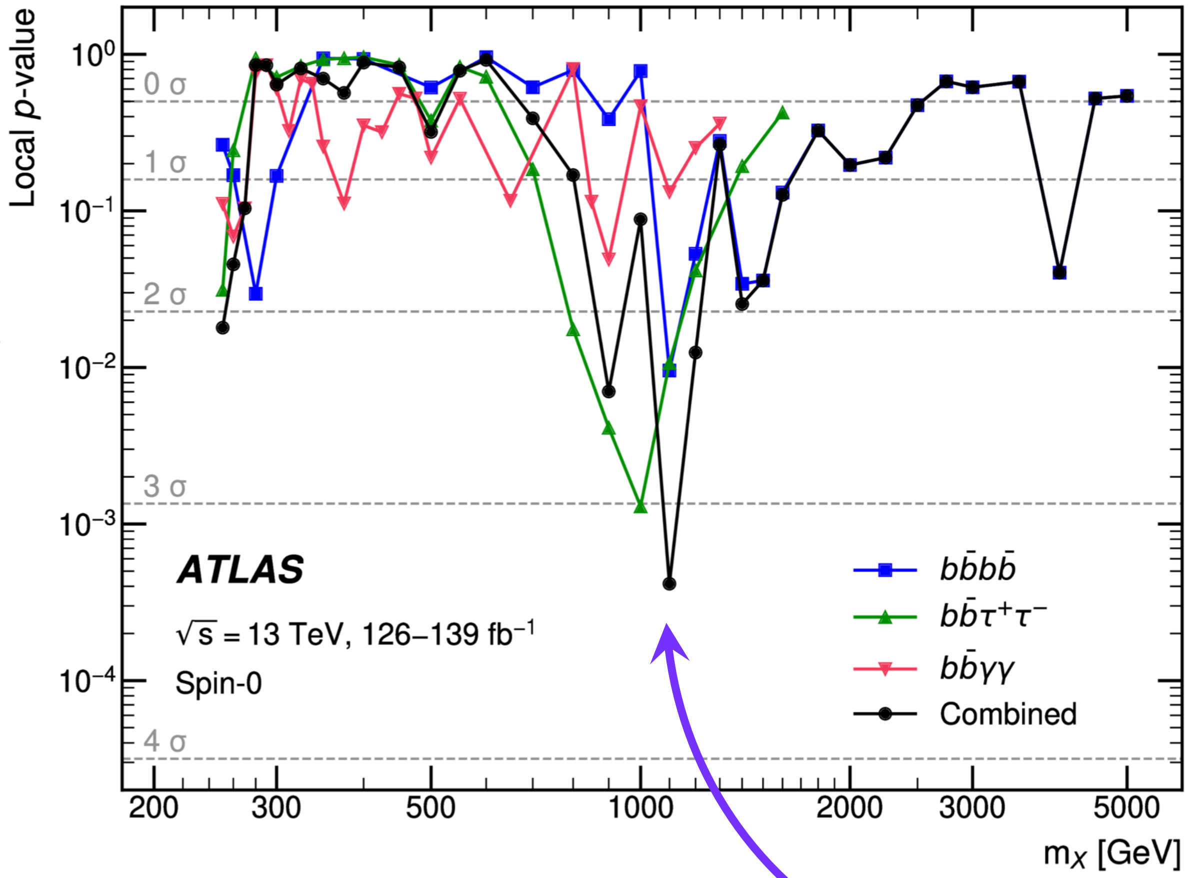
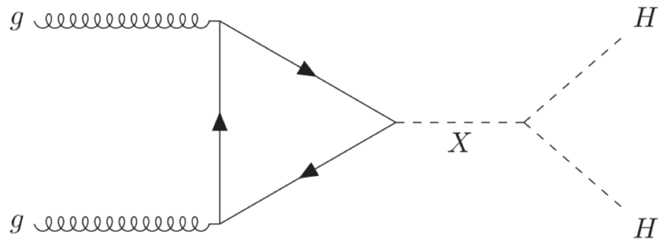
$X \rightarrow HH$ combination

No significant evidence of a signal observed





Largest deviation from SM @ m_X = 1.1 TeV, mainly driven by $b\bar{b}\tau^+\tau^-$ and $b\bar{b}b\bar{b}$

A local (global) significance of 3.3σ (2.1σ)

New!

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Type-I 2HDM constraints

Sensitive to $\cos(\beta - \alpha)$ values not probed by SM Higgs boson coupling measurements

- E.g. $\cos(\beta - \alpha) = -0.1, \tan\beta = 10$, $270 < m_H < 810$ GeV excluded

2HDM – extends the SM with an additional Higgs doublets

After EWSB, leads to:

3 neutral Higgs: h, H (CP-even), and A (CP-odd)

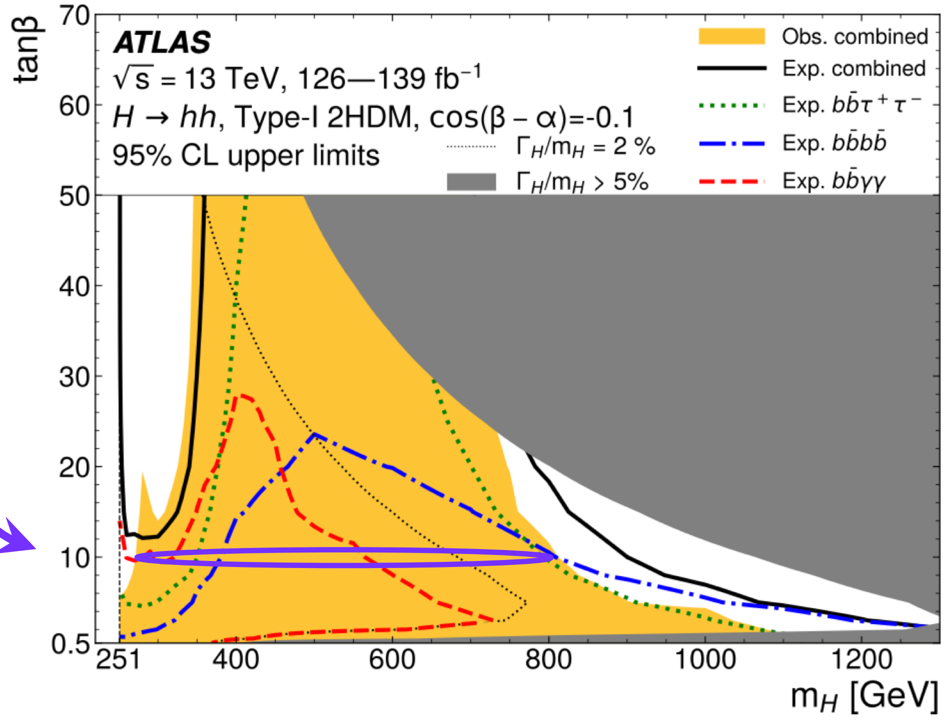
2 charged Higgs: $H^{\pm}$

Free parameters: $\tan\beta$ (ratio of vev of the 2 Higgs doublets)

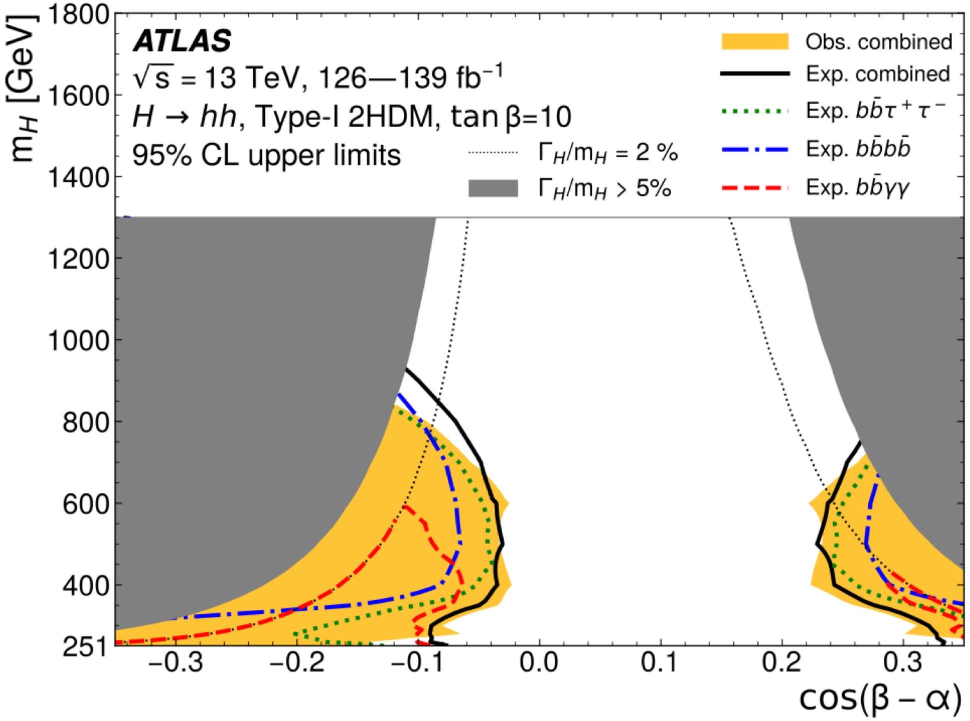
α (mixing angle between CP-even Higgs)

m_H (mass of the heavy CP-even Higgs H)

Fixed $\cos(\beta - \alpha)$



Fixed $\tan\beta$



New!

MSSM constraints

Combination excludes region $2 < \tan\beta < 5$

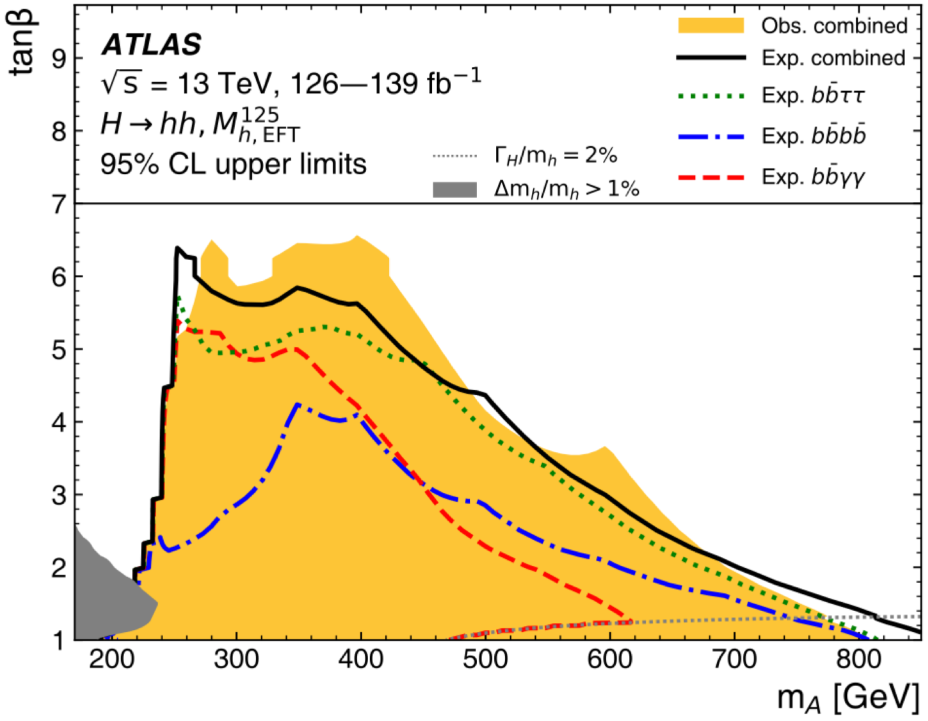
- Not excluded by $H/A \rightarrow \tau\tau$, $A \rightarrow Zh$, $H \rightarrow ZZ$ or $H^{\pm} \rightarrow tb$ searches!

MSSM – a. subset of type II 2HDM

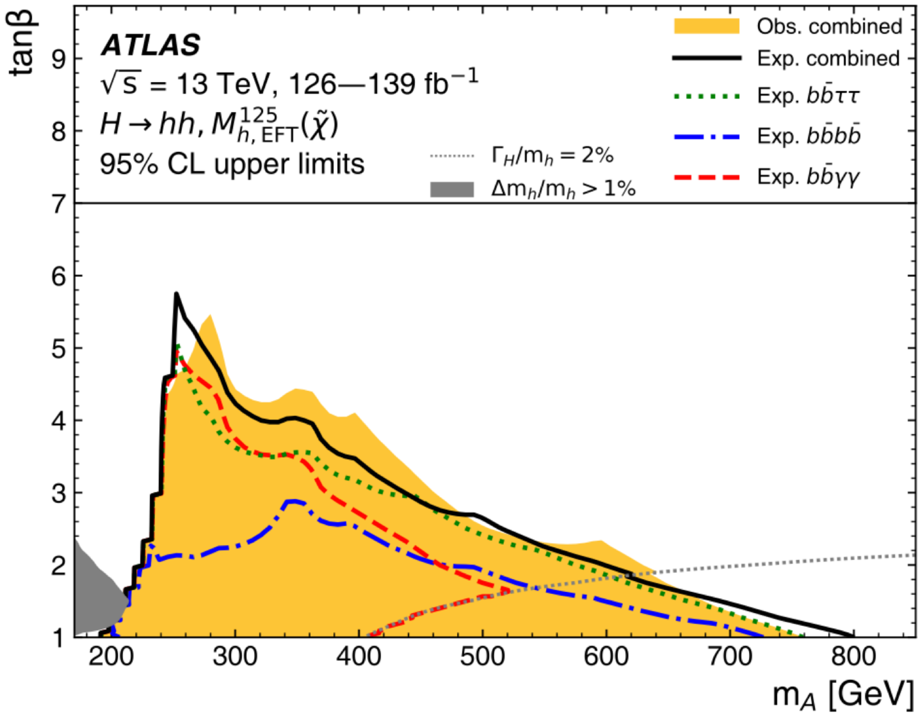
SUSY constrains the number of free parameters to 2: m_A and $\tan\beta$

$M_{h,EFT}^{125}$ and $M_{h,EFT}^{125}(\tilde{\chi})$ scenarios used

$M_{h,EFT}^{125}$



$M_{h,EFT}^{125}(\tilde{\chi})$



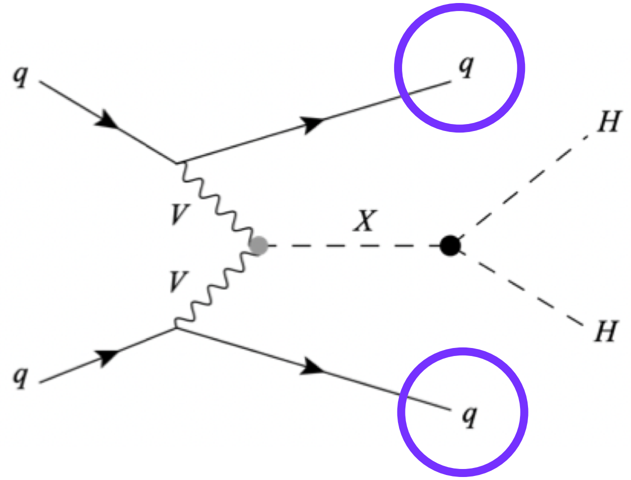
New!

VBF $X \to HH$

Resolved VBF $X \to HH$ production
[CERN-EP-2019-267]

Search for heavy spin-0 scalars with $260 < m_X < 1000$ GeV

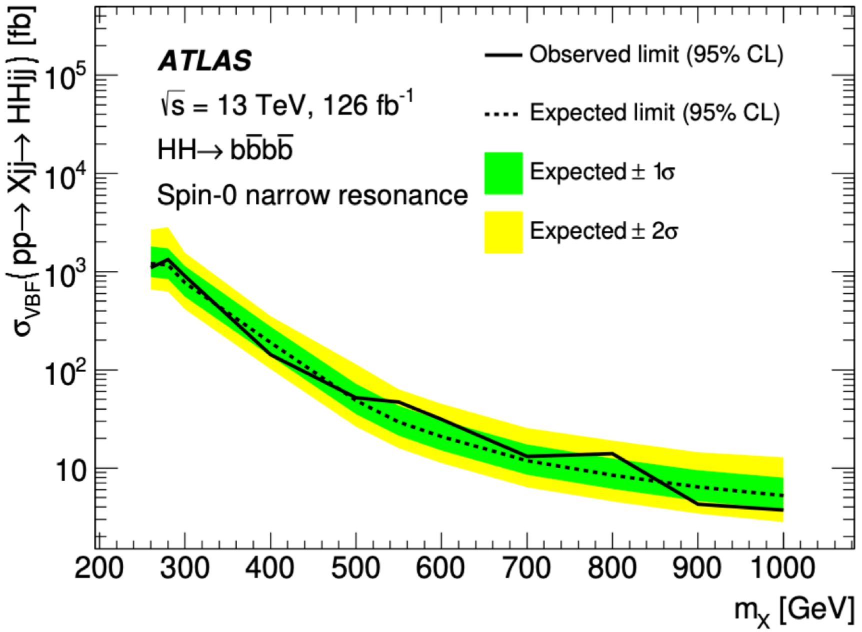
Largest deviation @ $m_X = 550$ GeV w/ a local significance of 1.5σ



2 VBF jets with large invariant mass & η separation

Narrow resonance

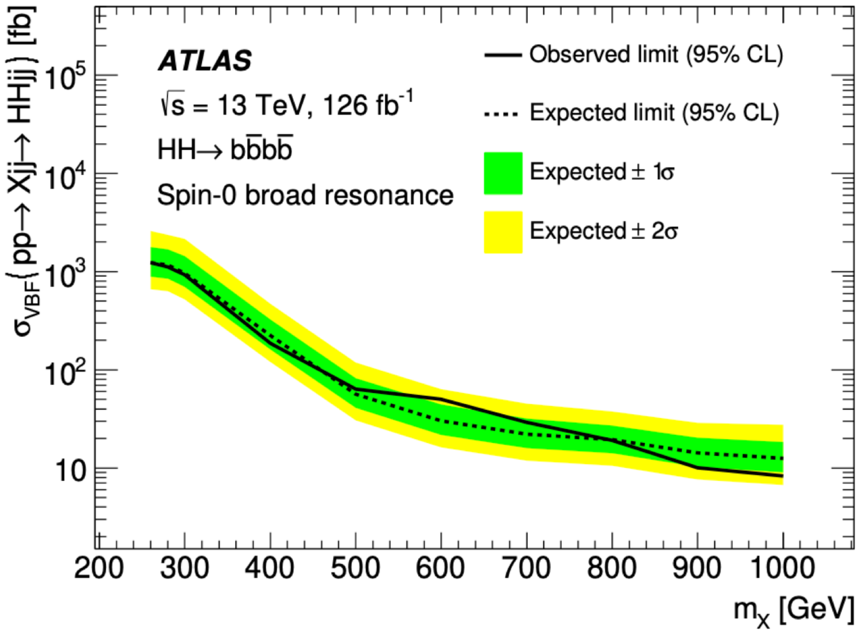
Fixed width of 4 MeV



Broad resonance

Width 10-20% of m_X

Heavy scalar of 2HDM Type II model



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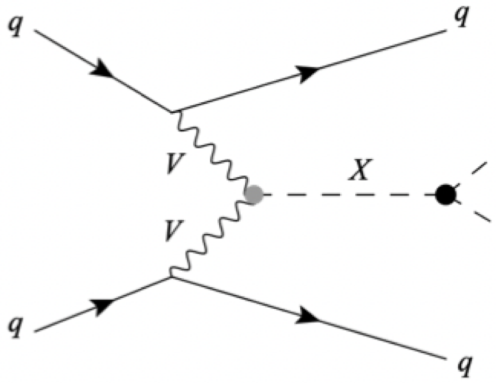
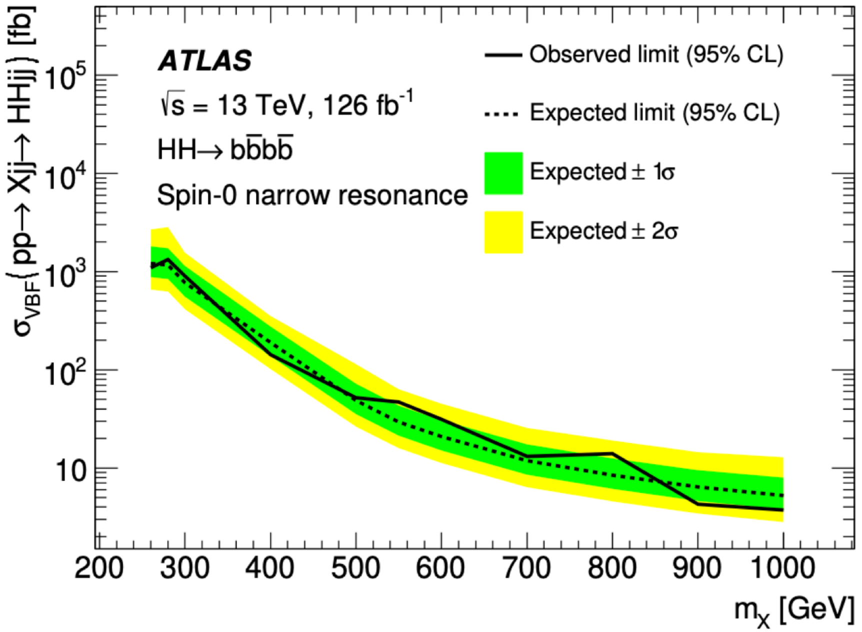


4 small-radius (R = 0.4), central b-tagged jets from the Higgs boson decay

Narrow resonance

Fixed width of 4 MeV



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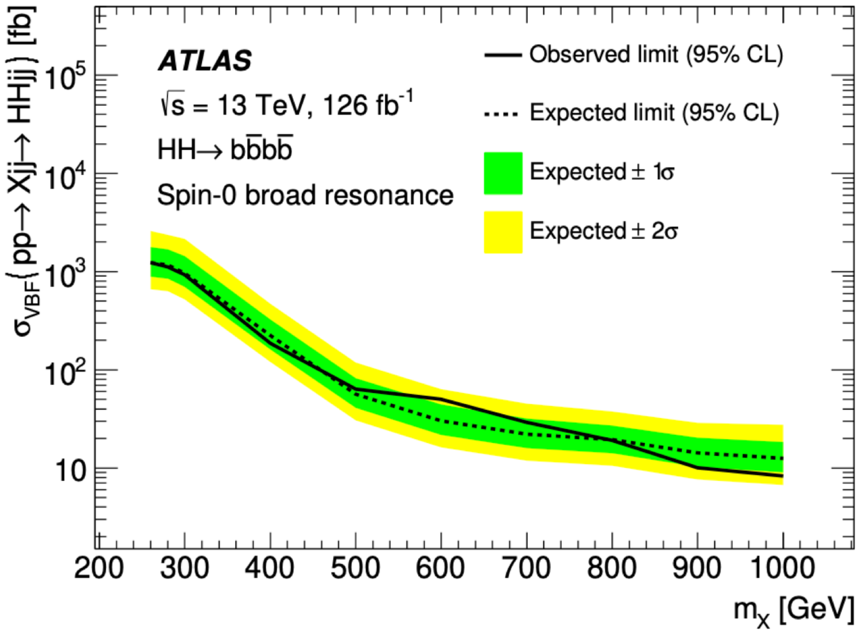
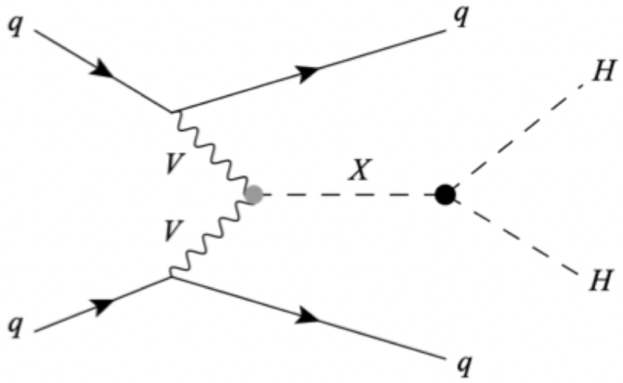


Boosted VBF $X \rightarrow HH$

Boosted VBF $X \rightarrow HH$ production

[CERN-EP-2024-092]

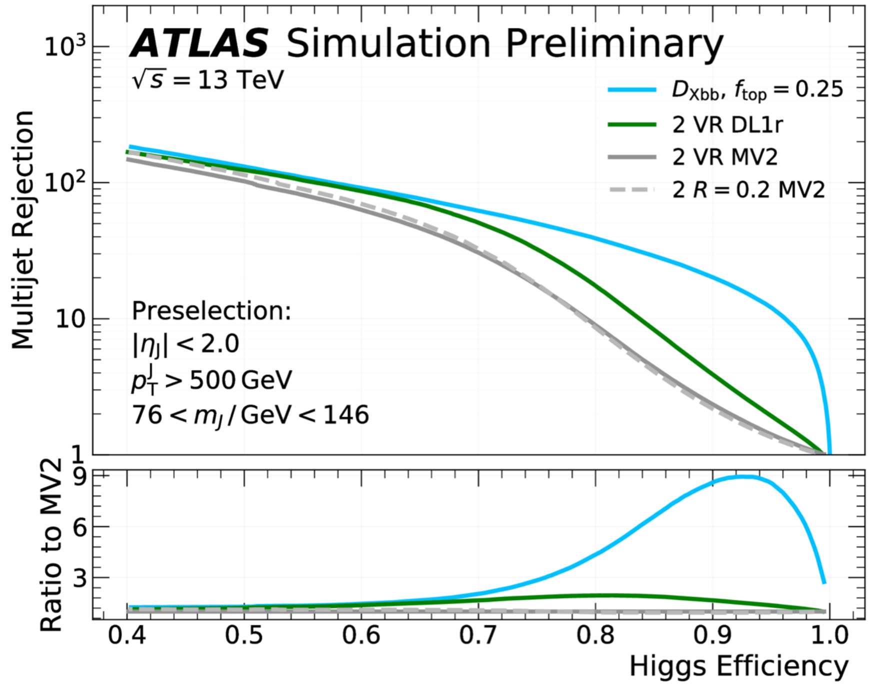
First search for heavy spin-0 scalar with $1 < m_X < 5$ TeV



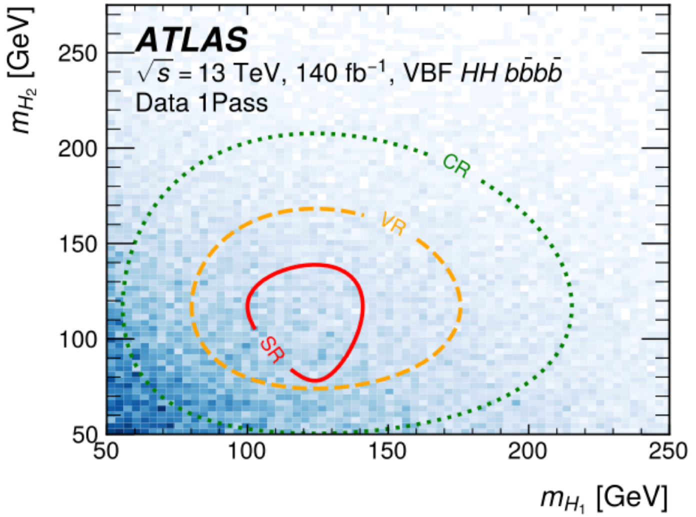
2 large-radius (R = 1.0) jets, identified by a NN-based double b-tagging X_{bb} algorithm [ATL-PHYS-PUB-2020-019]

New!

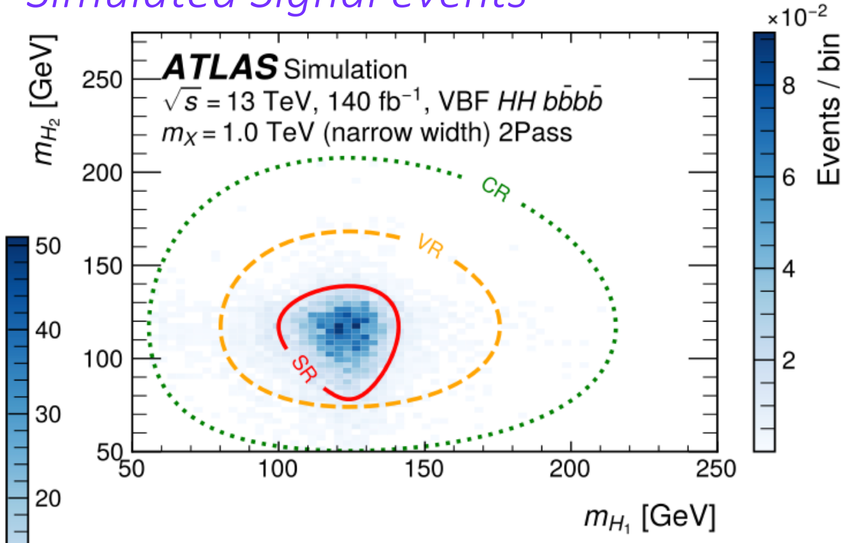
X_{bb} algorithm improves sensitivity by up to 50% in exp. discovery significance for $H \rightarrow b\bar{b}$



Data background events



Simulated Signal events



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Boosted VBF $X \rightarrow HH$

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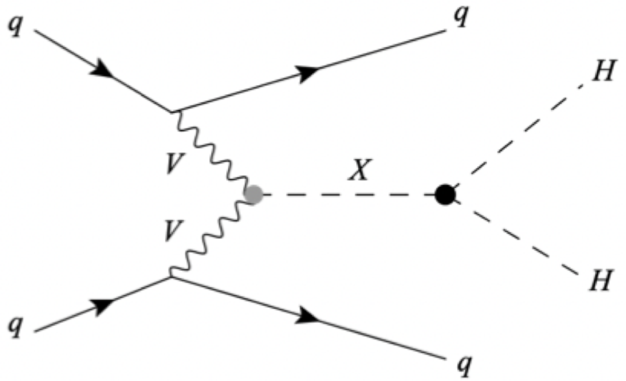

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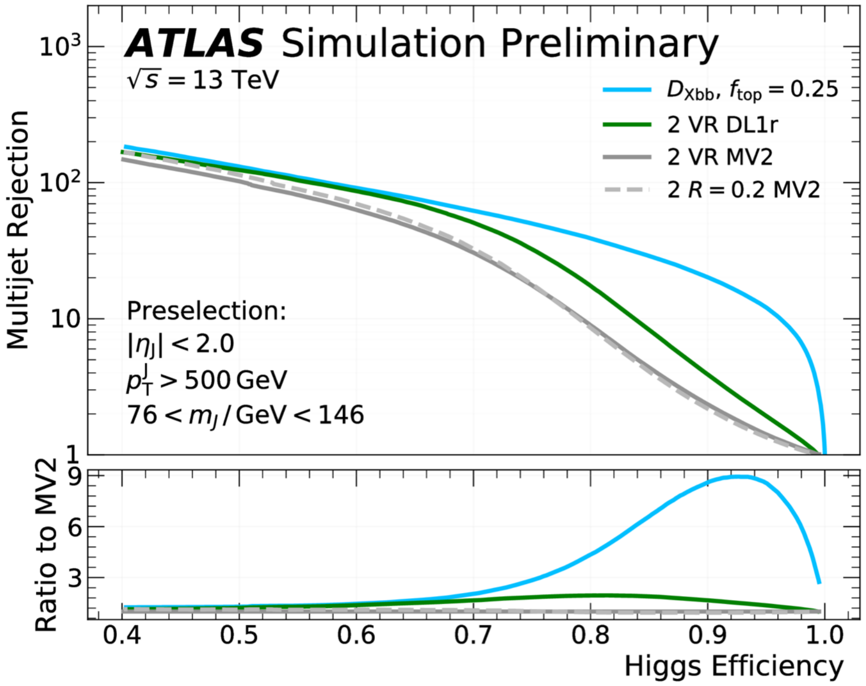
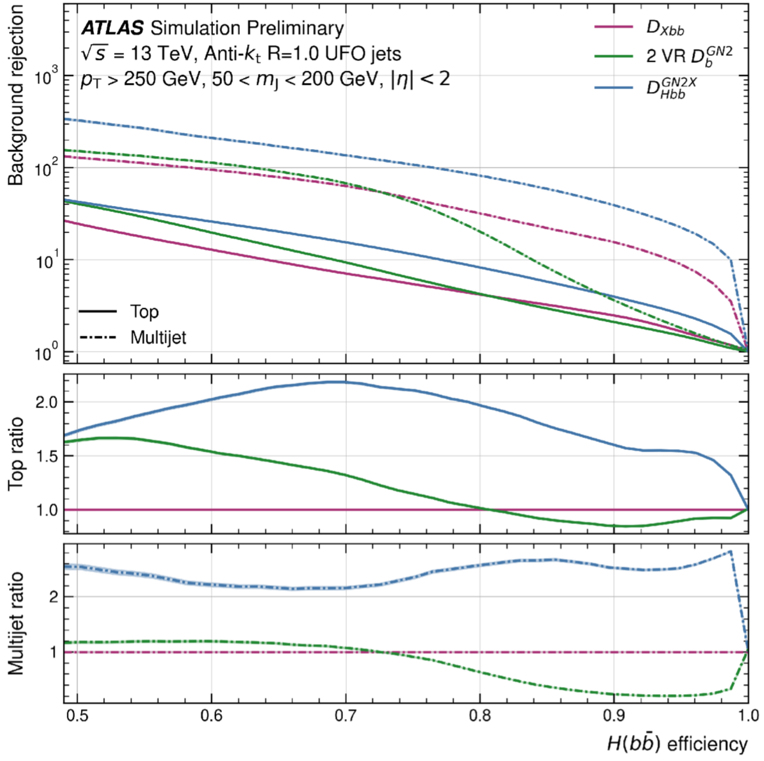
GN2X [ATL-PHYS-PUB-2023-021]



A newer version based on *Graph Neural Network* for future iterations



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Boosted VBF $X \to HH$

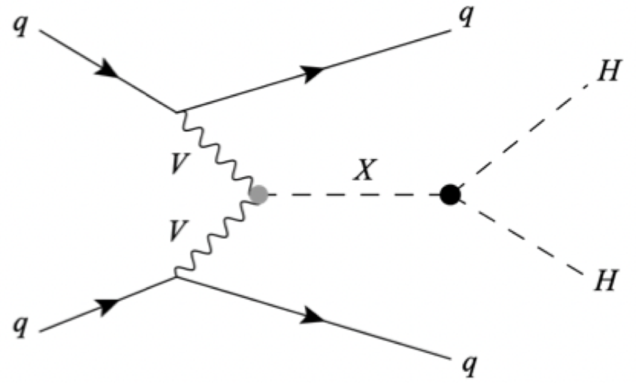
Boosted VBF $X \to HH$ production

[CERN-EP-2024-092]

First search for heavy spin-0 scalar with $1 < m_X < 5$ TeV

No significant excess observed

Loss of sensitivity at high mass due to lower efficiency of the X_{bb} algorithm



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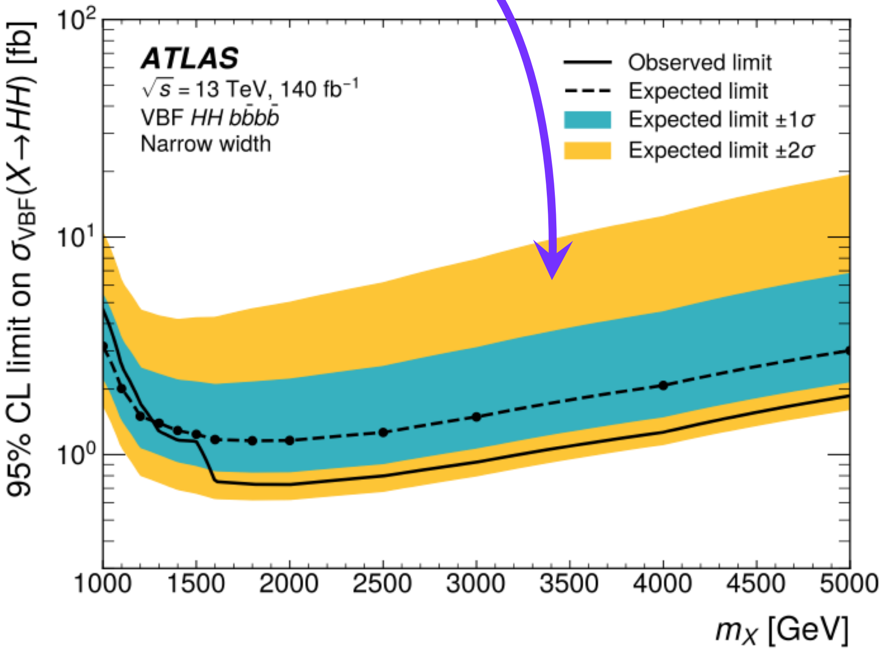
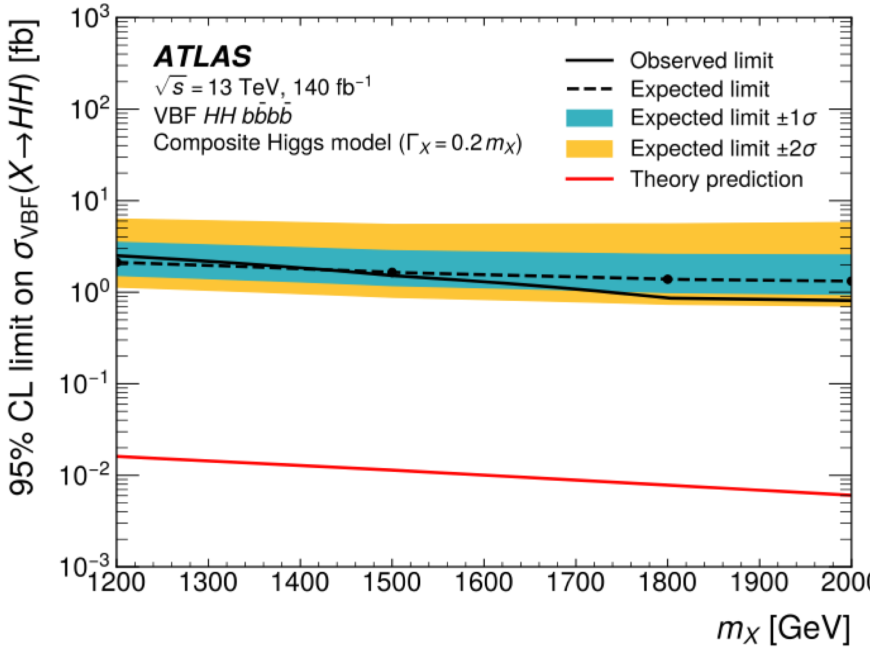
New!

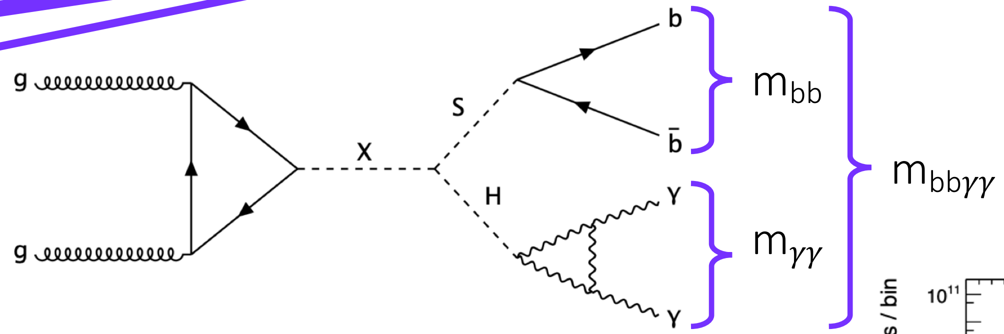




$$X \to SH$$

$X \to S(\to b\bar{b})H(\to \gamma\gamma)$

[CERN-EP-2024-072]



Upper limits are placed on

$$\sigma(X \to SH \to b\bar{b}\gamma\gamma) =$$
$$\sigma(pp \to X) \times BR(X \to SH) \times BR(S \to b\bar{b}) \times BR(H \to \gamma\gamma)$$

Model- & mass-dependent

instead of on specific models

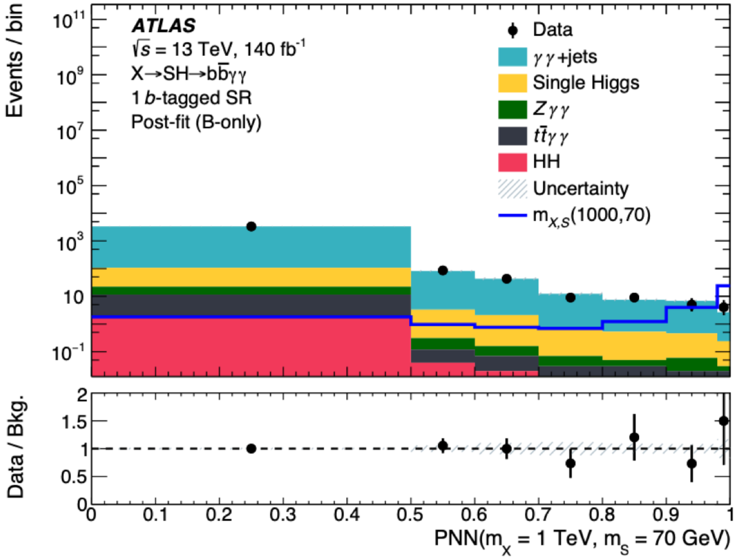
Probing narrow scalar resonances:

- $170 < m_X < 1000$ GeV
- $15 < m_S < 500$ GeV

2 mutually exclusive Signal Regions

PNNs parametrised on:

	1 b-tag	2 b-tags
2 mutually exclusive Signal Regions	*1 b-tag*	*2 b-tags*
PNNs parametrised on:	*m_X*	*m_S, m_X*

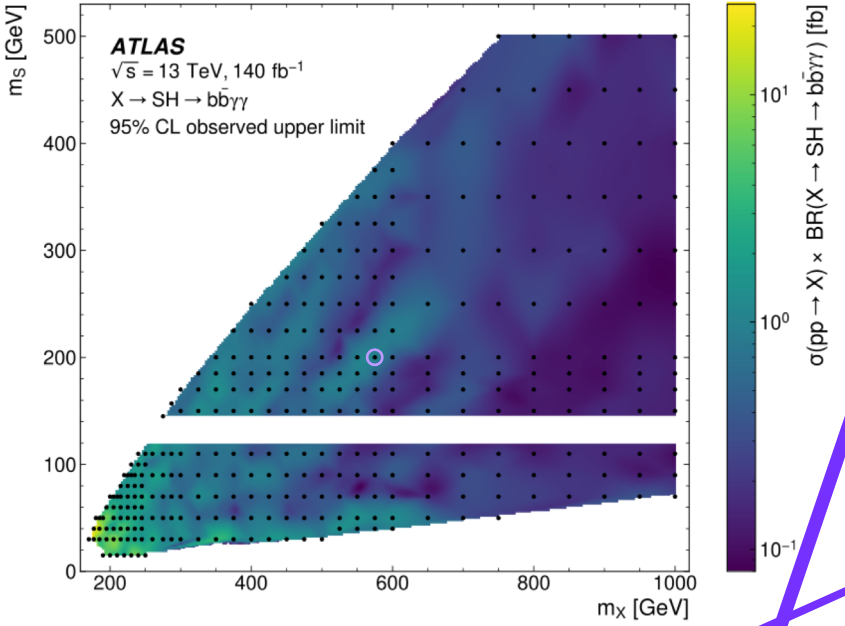


Obs. upper limits on σ_{prod}:
0.09 – 39 fb (Better @ higher m_X)

Largest excess @m_X, m_S = 575, 200 GeV (3.5σ local significance)

Main background:

- Non-resonant $\gamma\gamma$+jets
- MC (shape) & data-driven (norm.)



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$X \rightarrow S(\rightarrow VV)H(\rightarrow \gamma\gamma)$

[CERN-EP-2024-147]

Allows to explore lower mass ranges than other final states with *b*-quarks where they fall < reconstruction threshold

Probing scalars from 2HDM+S:

- $300 < m_X < 1000$ GeV
- $170 < m_S < 500$ GeV

$X \rightarrow S(\rightarrow VV)H(\rightarrow \gamma\gamma)$

1 or 2 leptons (e or μ)

Increase signal-to-background ratio

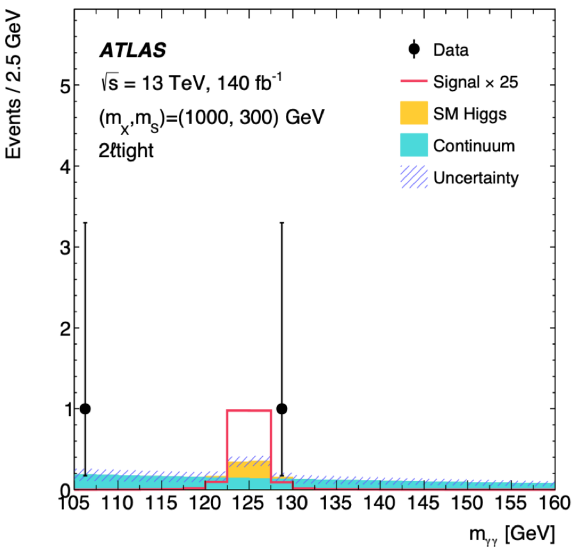
Events categorised by the number and flavour of leptons

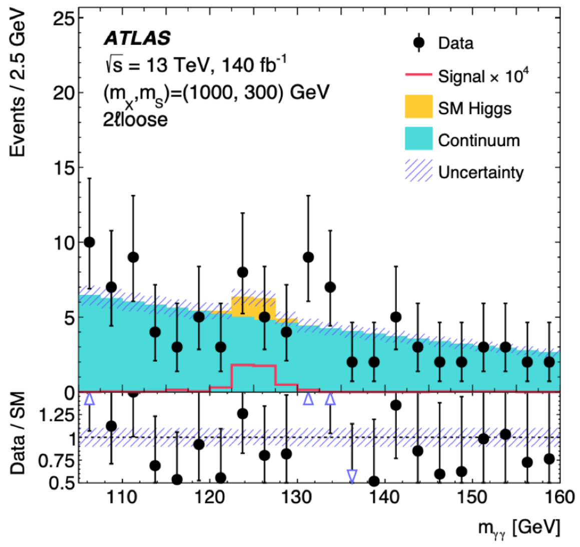
High di-photon triggering efficiency

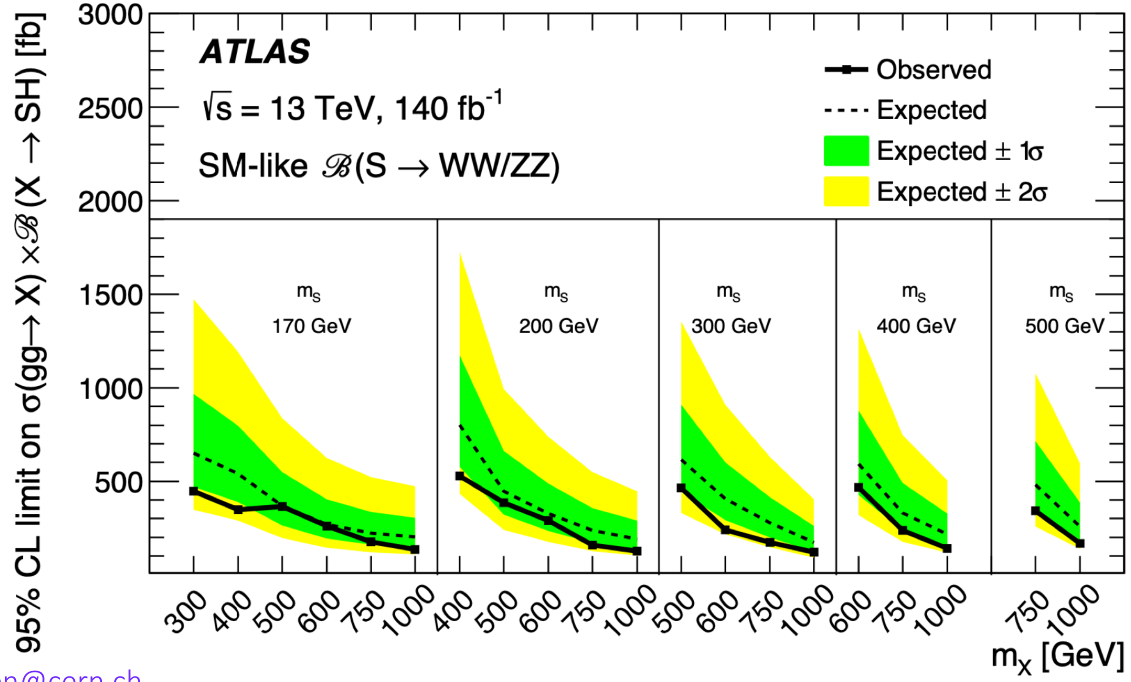
Excellent $m_{\gamma\gamma}$ resolution

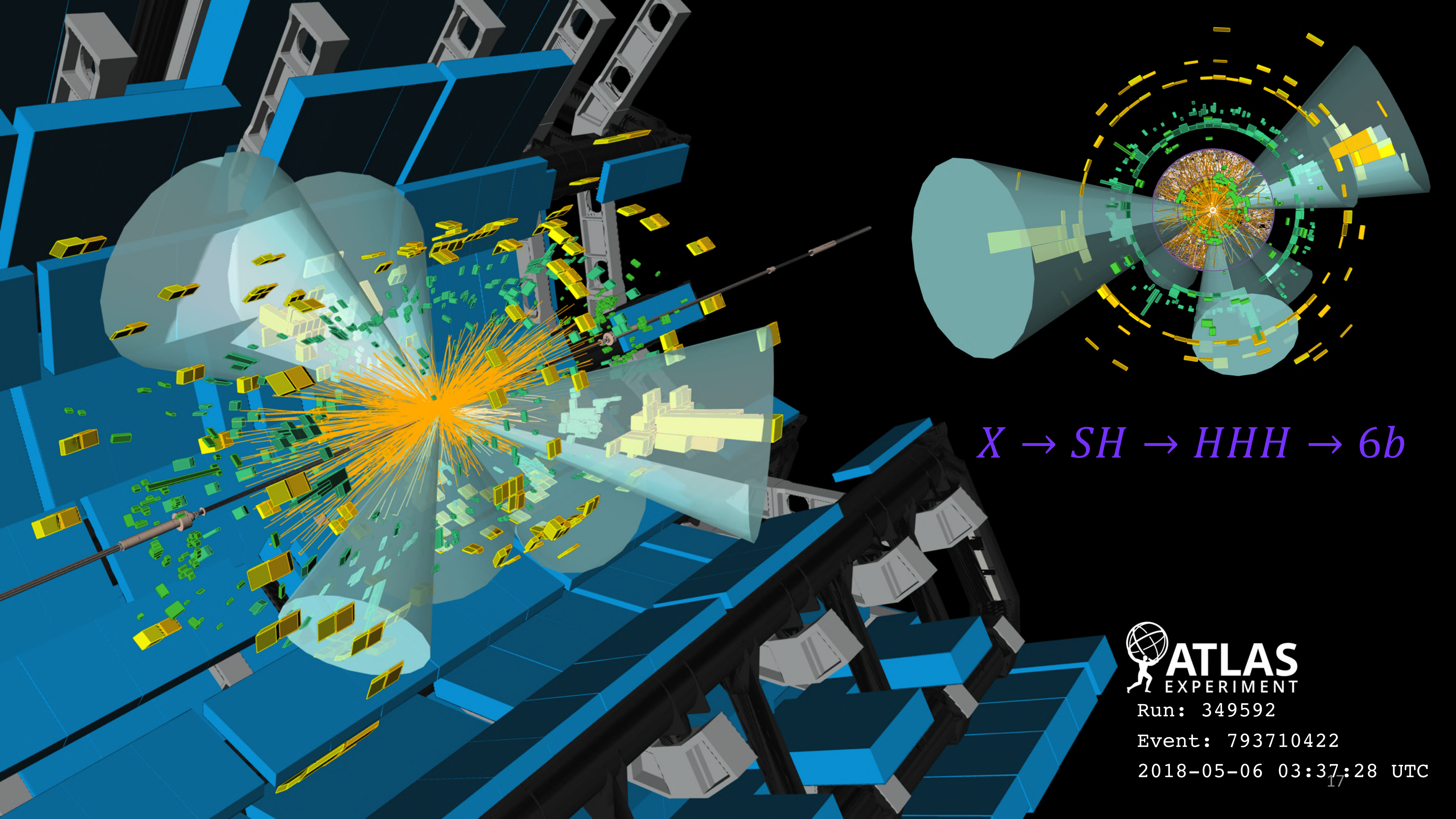
Used as final discriminant

Obs. upper limits on σ_{prod}: 170 – 800 fb








$X \rightarrow SH \rightarrow HHH \rightarrow 6b$
ATLAS
EXPERIMENT
Run: 349592
Event: 793710422
2018-05-06 03:37:28 UTC

$X \to SH \to HHH \to 6b$

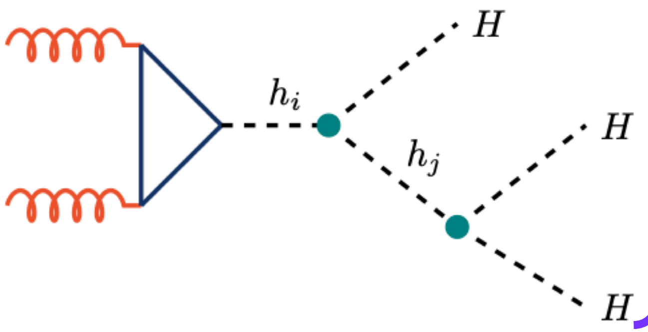
The first ever search of this topology at the LHC!

[CERN-EP-2024-285]

New!

Searching for heavy scalars in TRSM
- $325 < m_X < 575$ GeV
- $200 < m_S < 350$ GeV

& generic heavy resonance
- $500 < m_X < 1500$ GeV
- $275 < m_S < 1000$ GeV



6 small-radius *b*-tagged jets from Higgs boson decay

Large # combinatorics: C(6, 2) = 15
- Mass-based method, minimising:

$$|m_{H1} - 120\ \text{GeV}| + |m_{H2} - 115\ \text{GeV}| + |m_{H3} - 110\ \text{GeV}|$$

TRSM HHH production

Resonant – S on-shell ($m_S > 2\ m_H$)

Low m_{HHH}

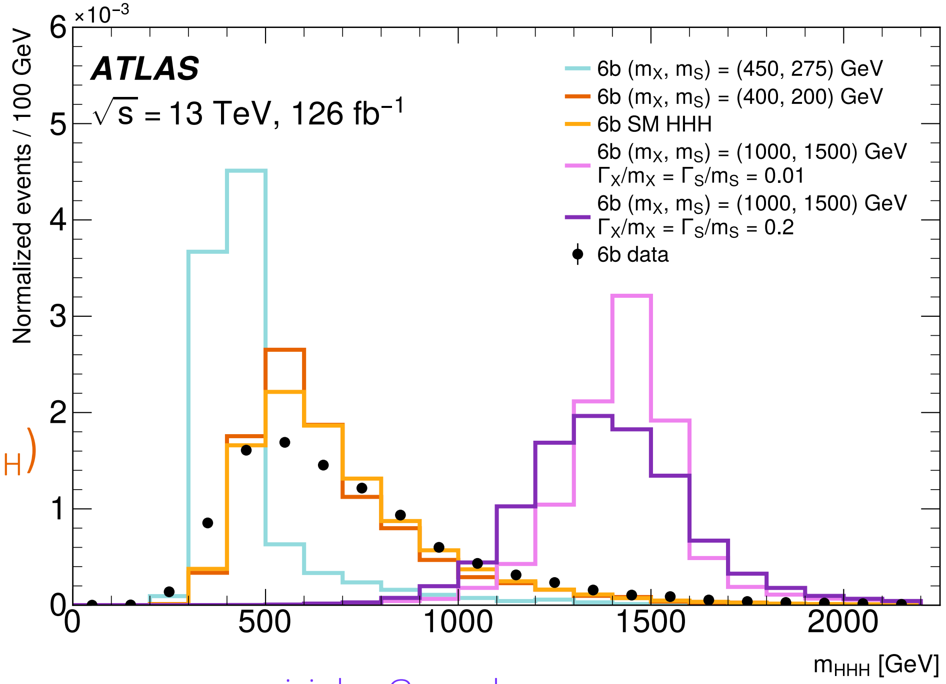
→ low p_T, overlapping *b*-jets

→ more challenging jet pairing

Non-resonant – S off-shell ($m_S \leq 2\ m_H$)

Higher m_{HHH}

More akin to SM HHH production



Heavy resonant production

Highest m_{HHH}

→ boosted, collimated *b*-jets

→ less ambiguity in jet pairing

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$X \to SH \to HHH \to 6b$

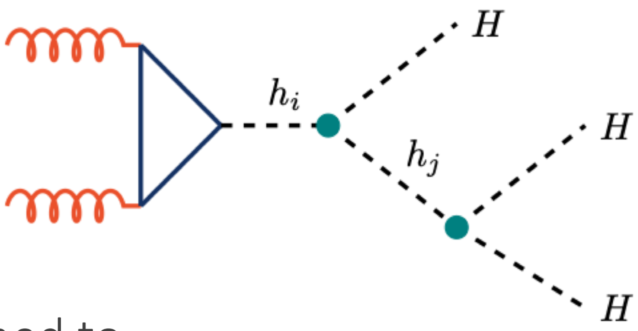
The first ever search of this topology at the LHC!

[CERN-EP-2024-285]

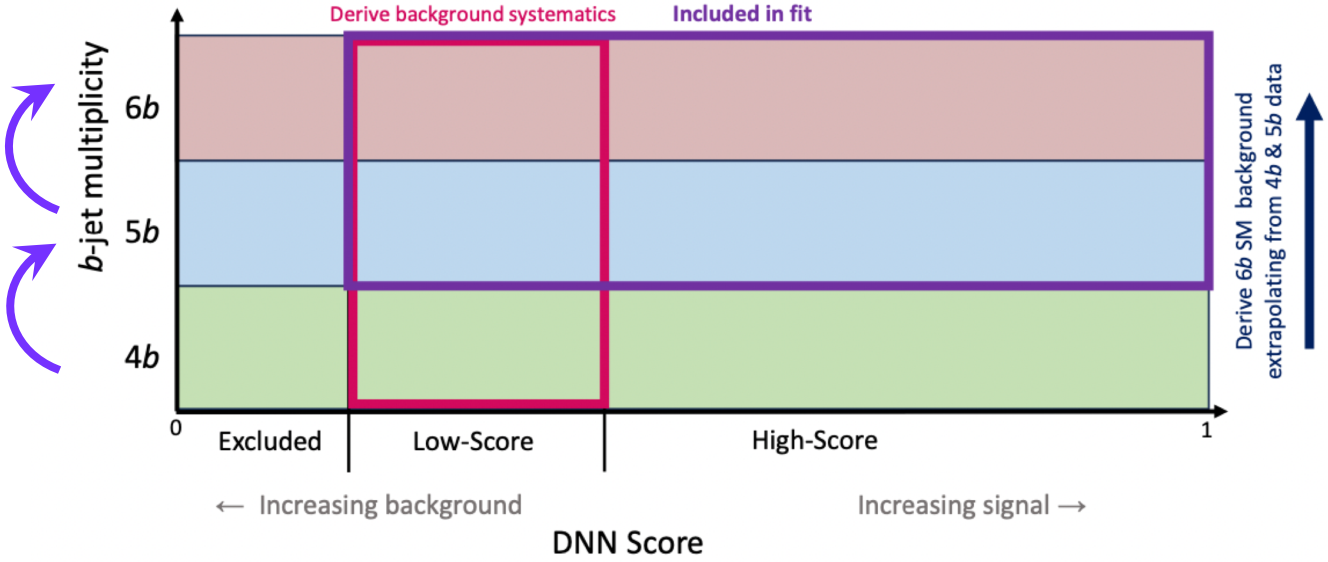
New!

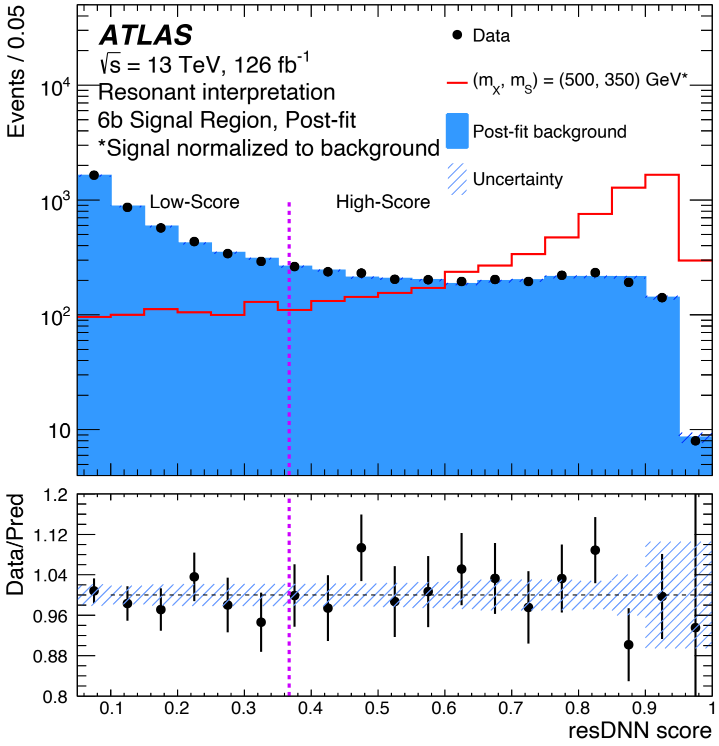
Challenging QCD multi-jet background

- Fully data-driven estimation
- Relies on the kinematic extrapolation in $4b \to 5b \to 6b$(SR) regions
- DNN signal/background discriminator designed to minimise dependency on # b-tags (any differences corrected by systematics)



6 small-radius b-tagged jets from Higgs boson decay





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$X \to SH \to HHH \to 6b$

The first ever search of this topology at the LHC!

[CERN-EP-2024-285]

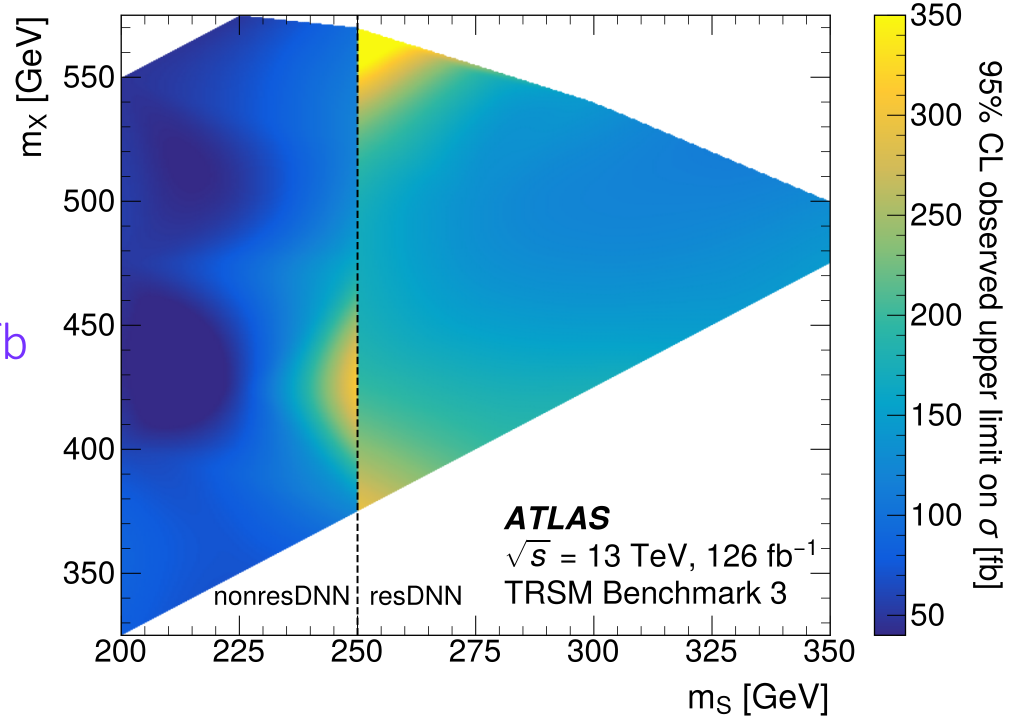
No significant evidence of BSM signals observed

Non-resonant interpretation: constraints placed on the trilinear & quartic Higgs self-coupling modifiers κ_3, κ_4 (see Bill Balunas' talk on non-resonant HH)

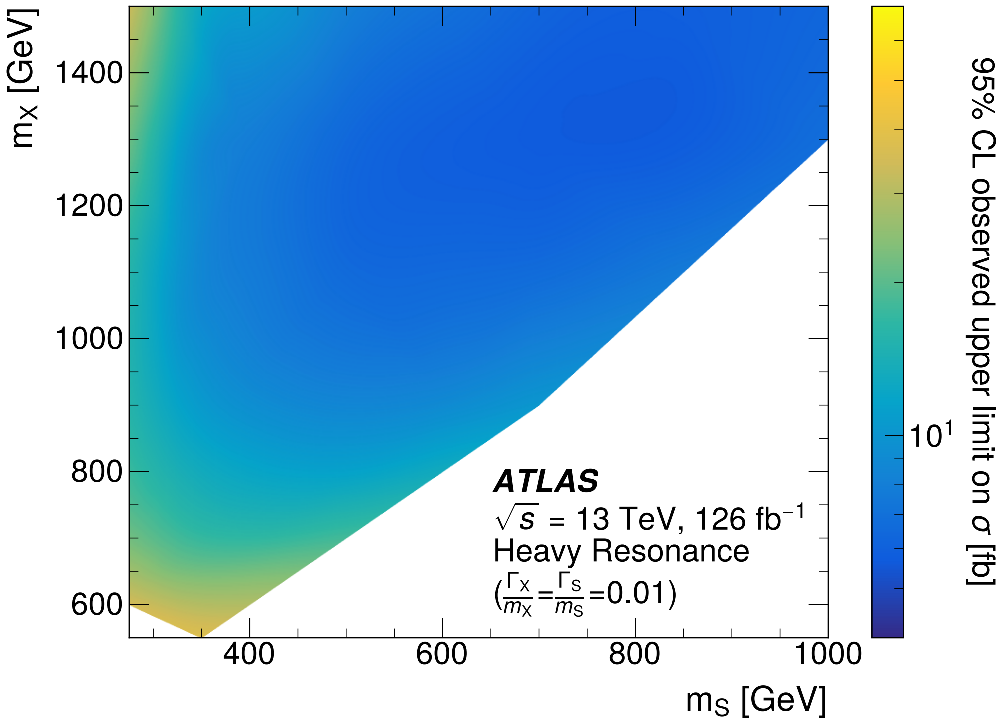
Obs. upper limits on

$\sigma_{TRSM}(X \to SH \to HHH \to 6b)$

48 – 310 fb



$\sigma_{Heavy\ resonance}(X \to SH \to HHH \to 6b)$



5.7 – 38 fb

New!

Diverse searches of resonant HH at ATLAS

Run-2 $X \to HH$ combination

Resolved / boosted VBF $HH \to 4b$

$X \to S(\to b\bar{b})H(\to \gamma\gamma)$

$X \to S(\to VV)H(\to \gamma\gamma)$

$X \to SH \to HHH \to 6b$

Better/first constraints on σ_{prod} & parameters of BSM processes

Larger resonance mass range probed

Looking forward to improved analysis techniques
& tagging algorithms

Backup

Run-2 Resonant HH combination

$b\bar{b}b\bar{b}$:

- Resolved (4 small-R jets) + boosted (2 large-R jets from Higgs with pT > 250 Gev), orthogonal channels
- BDT jet-pairing (resolved)
- 2b, 3b, 4b categories according to # b-tagged track jets in large-R jets (boosted)
- m_{HH} used to define SR, CR, VR, and as the final discriminant

$b\bar{b}\tau^+\tau^-$:

- Event categories defined by the decay mode of τ – lep had, had had
- Lep had – two orthogonal regions separated by triggers (lep had / single-lep)
- Had had – 2 reconstructed τ_{had} candidates w/ opposite charge & no e/μ
- 2 small-R b-jets required
- Mass-parametrised neural network in each signal region – output scores as final discriminant

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

- Single- & di-photon triggers
- Requires 2 photons + 2 b-tagged jets, no e/μ
- 2 BDTs signal/background classifiers against: $t\bar{t}\gamma\gamma$, single-Higgs
- Signal region: $m_{\gamma\gamma} \sim m_H$, $m_{bb\gamma\gamma} \sim m_X$
- $m_{\gamma\gamma}$ as the final discriminant

Type-I 2HDM constraints

2HDM – extends the SM with an additional Higgs doublets

After EWSB, leads to:

3 neutral Higgs: h, H (CP-even), and A (CP-odd)

2 charged Higgs: $H^{\pm}$

Free parameters: $\tan\beta$ (ratio of vev of the 2 Higgs doublets)

α (mixing angle between CP-even Higgs)

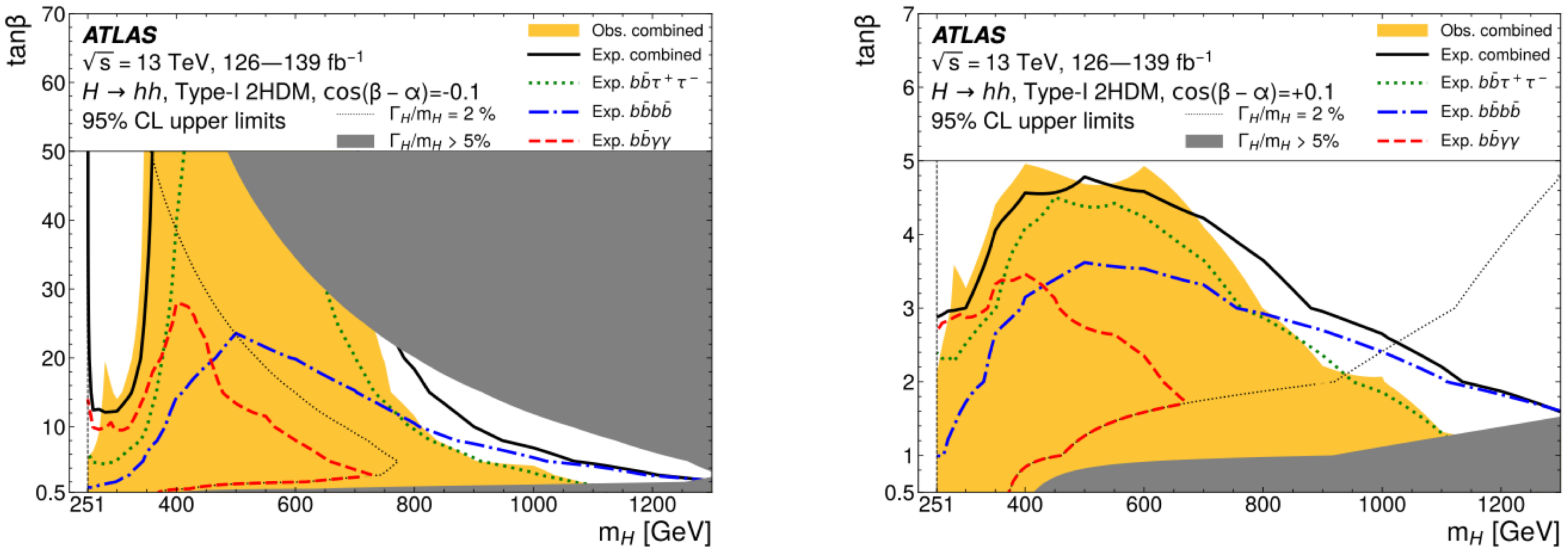
m_H (mass of the heavy CP-even Higgs H)

Sensitive to $\cos(\beta-\alpha)$ values not probed by SM Higgs boson coupling measurements

- E.g. $\cos(\beta-\alpha) = -0.1, \tan\beta = 10$, $270 < m_H < 810$ GeV excluded

Fixed $cos(\beta-\alpha)$

New!



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Type-I 2HDM constraints

Difficult to probe at high $\tan\beta$

- All SM couplings are suppressed

2HDM – extends the SM with an additional Higgs doublets

After EWSB, leads to:

3 neutral Higgs: h, H (CP-even), and A (CP-odd)

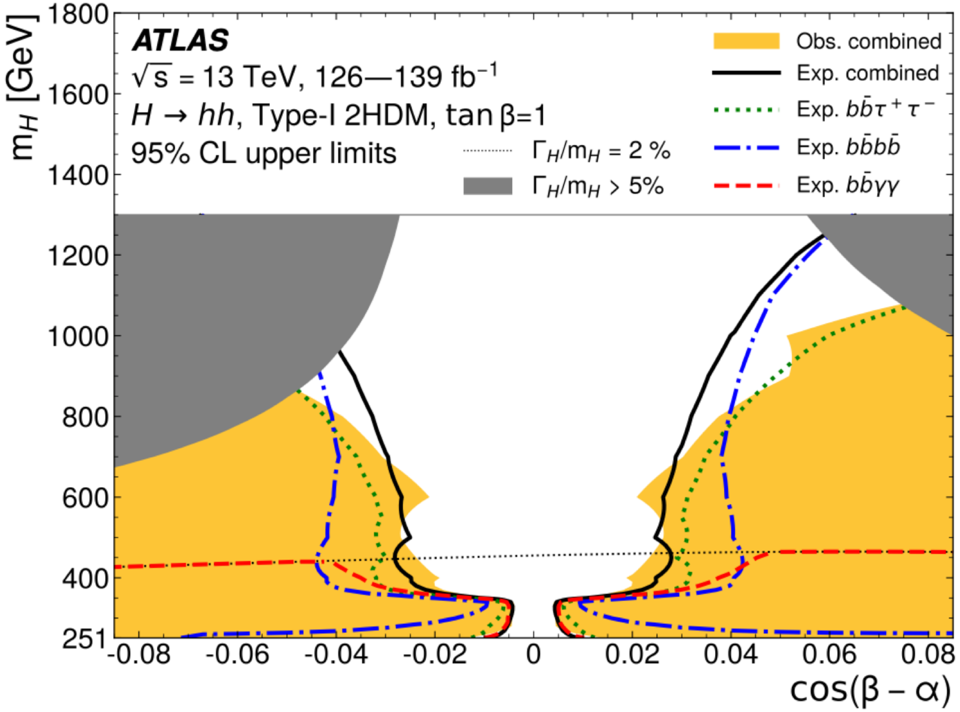
2 charged Higgs: $H^{\pm}$

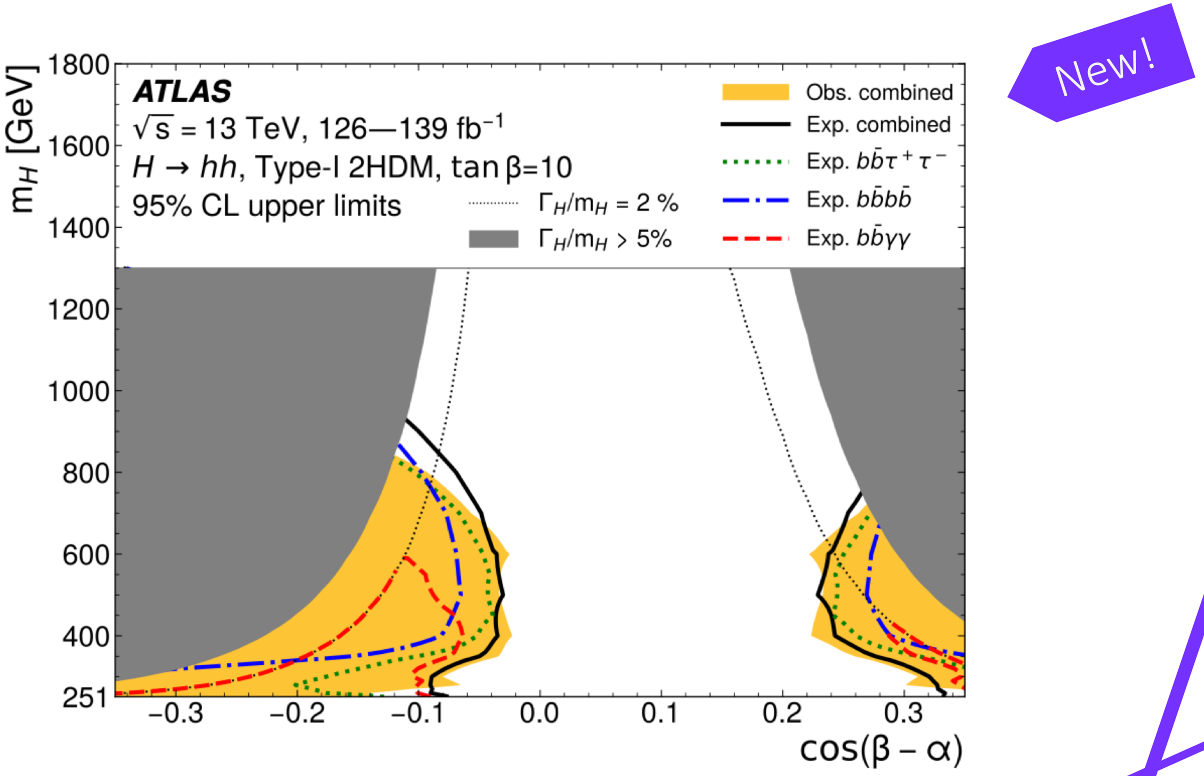
Free parameters: $\tan\beta$ (ratio of vev of the 2 Higgs doublets)

α (mixing angle between CP-even Higgs)

m_H (mass of the heavy CP-even Higgs H)

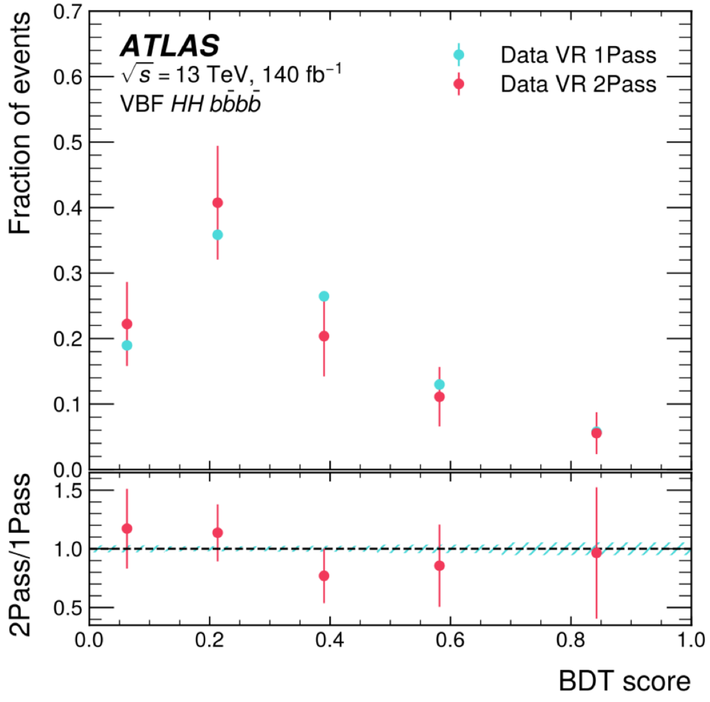
Fixed $\tan\beta$





Boosted VBF $X \rightarrow HH$

- BR($X \rightarrow HH$) set to 100%
- 2 resonance widths considered – narrow (5-6% m_X), broad (20% m_X)
- Large-R jets w/ 250 GeV < pT < 3000 GeV, |η|< 2.0
- 2-pass events: 2 Higgs candidates passing 60% X_{bb} working point
- 1-pass events: used in background estimation
- SR optimised to maximise S/√B
- 2D mass plane – smoothly falling distributions
- Background modelling – multijet & mis-dentified light-jets
  - Data-driven method + 1 pass events
- Mass-parametrised BDT (truth m_X), trained on loose event selections for stats – output as final discriminant
- Shape systematic – difference between 2-pass & 1-pass events



Events in the SR reside in the region defined by

$$\sqrt{\left(\frac{m_{H_1} - 124\,\text{GeV}}{1500\,\text{GeV}/m_{H_1}}\right)^2 + \left(\frac{m_{H_2} - 117\,\text{GeV}}{1900\,\text{GeV}/m_{H_2}}\right)^2} < 1.6\,\text{GeV}.$$

Events in the VR reside in the region bounded by the SR boundary and

$$\sqrt{\left(\frac{m_{H_1} - 124\,\text{GeV}}{0.1\ln(m_{H_1})}\right)^2 + \left(\frac{m_{H_2} - 117\,\text{GeV}}{0.1\ln(m_{H_2})}\right)^2} < 100\,\text{GeV},$$

and events in the CR reside in the region bounded by the VR outer boundary and

$$\sqrt{\left(\frac{m_{H_1} - 124\,\text{GeV}}{0.1\ln(m_{H_1})}\right)^2 + \left(\frac{m_{H_2} - 117\,\text{GeV}}{0.1\ln(m_{H_2})}\right)^2} < 170\,\text{GeV}.$$

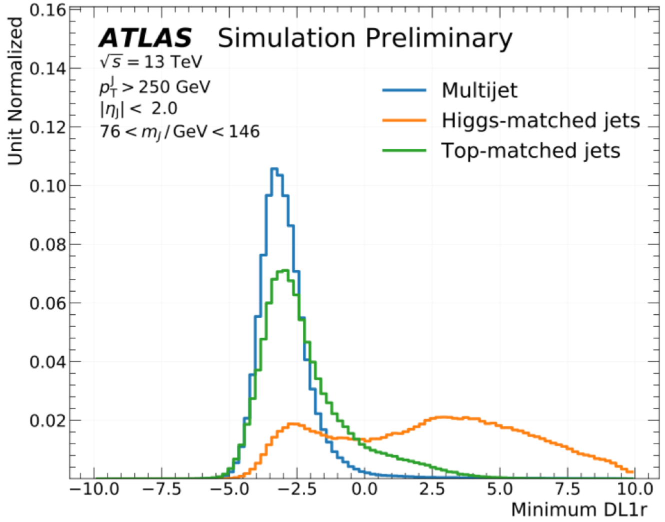
X_{bb} algorithm

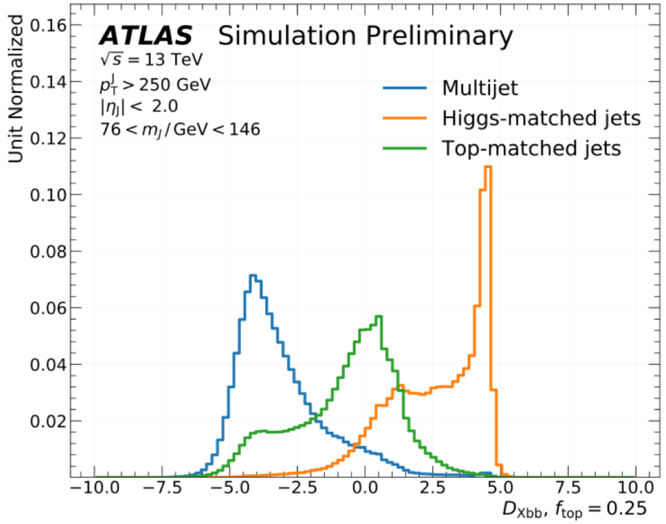
- Signal: jets from $H \to b\bar{b}$ decay
- Background: jets from multijet production & high pT top quarks
- Discriminant defined as:

$$D_{\mathrm{Xbb}} = \ln \frac{p_{\mathrm{Higgs}}}{f_{\mathrm{top}} \cdot p_{\mathrm{top}} + (1 - f_{\mathrm{top}}) \cdot p_{\mathrm{multijet}}}$$

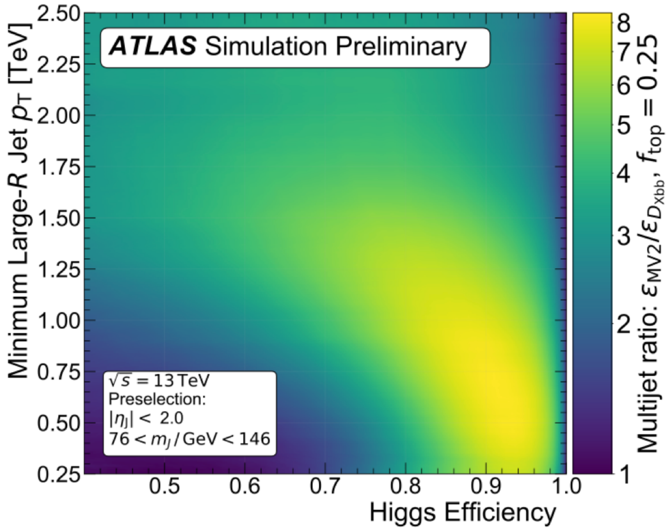
<u>VR jets:</u>

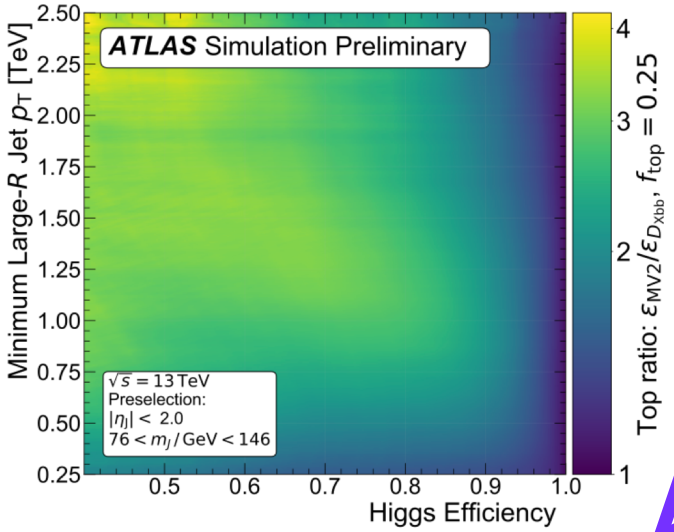
- Various radius – dependent on the pT of the jet & ρ/pT (ρ = 30 GeV)
- 0.02 < R < 0.4
- VR jets ghost associated with large-R jets





Most significant improvement in high jet pT region





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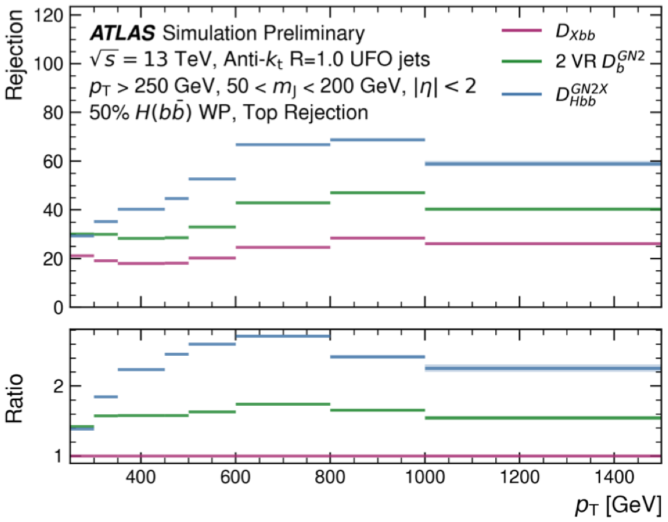
GN2X algorithm

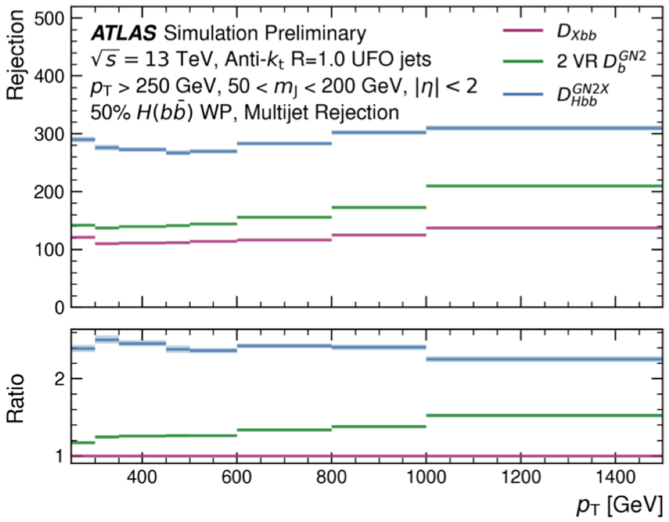
- An additional signal class: $H \rightarrow c\bar{c}$
- Discriminant defined as:

$$D_{\text{Hbb}}^{\text{GN2X}} = \ln\left(\frac{p_{\text{Hbb}}}{f_{\text{Hcc}} \cdot p_{\text{Hcc}} + f_{\text{top}} \cdot p_{\text{top}} + (1 - f_{\text{Hcc}} - f_{\text{top}}) \cdot p_{\text{QCD}}}\right)$$

- Utilises transformer network architecture
- Track representation in embedding space learnt by initialiser networks (deepsets architecture)
- Auxiliary tasks that aid the performance

Most significant improvement for multijet in high jet pT region





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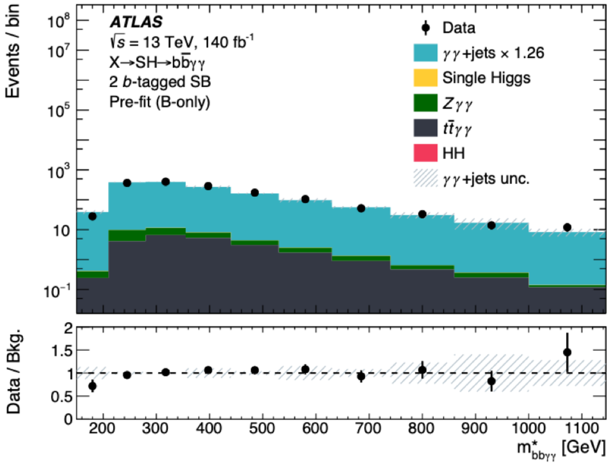
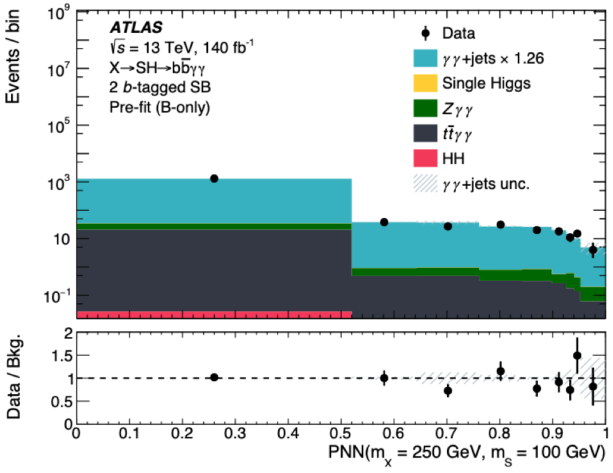
$X \to S(\to b\bar{b})H(\to \gamma\gamma)$
Background estimation

[CERN-EP-2024-072]

2 b-tag region

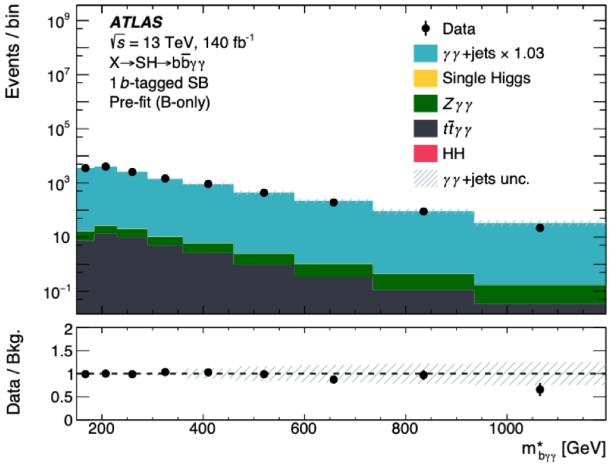


(a)

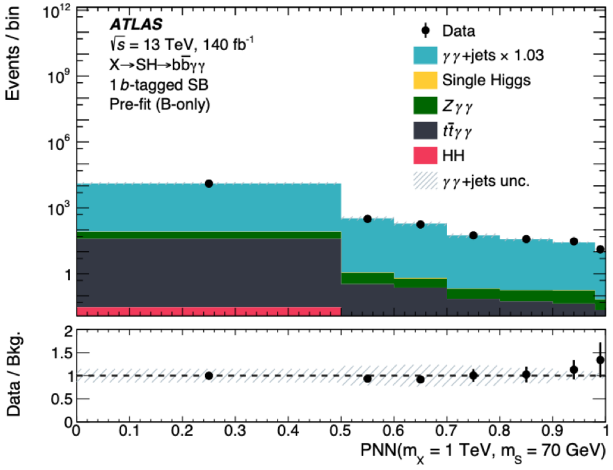


(b)

1 b-tag region



(c)

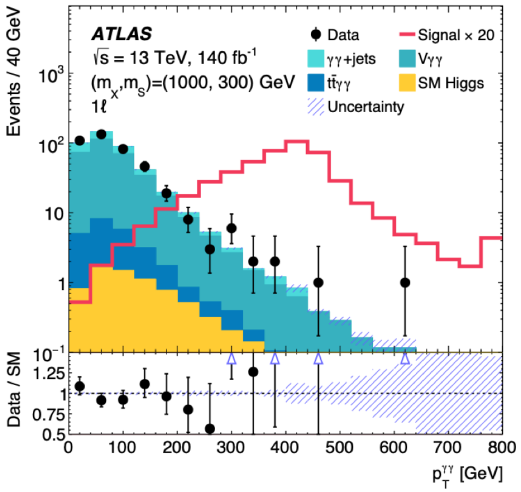


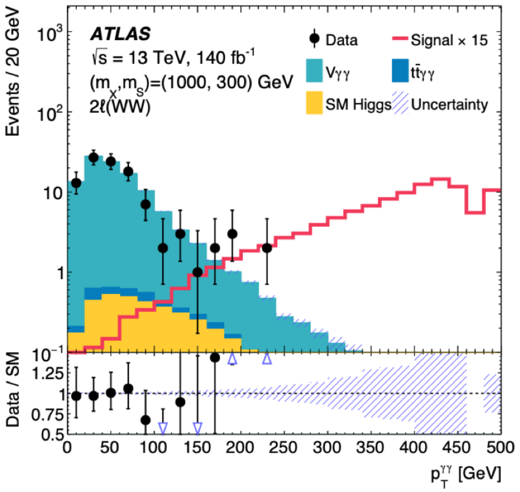
(d)

$X \to SH$

$S(\to bb)H(\to \gamma\gamma)$:

- Natural width of S assumed to be much smaller than experimental resolution
- $S(\to bb)$ the most dominant decay for m_S < 130 GeV
- For $m_X >> m_S + m_H$: S becomes boosted, and 2 *b*-quarks are reconstructed within 1 small-R jet
- For small $m_X - (m_S + m_H)$: 2 small-R *b-jets*
- pNN output as final discriminant





$S(\to VV)H(\to \gamma\gamma)$:

- Events categorised into 4 regions: 1l (1 lep + ⩾2 jets), 2l w/ opp. charge, 2l w/ opp. flavour, 2l w/ same flavor
- 2 BDTs trained in 1l and 2l regions
- $m_{\gamma\gamma}$ limited to 105-160 GeV to exclude Z resonance
- Continuum background: $\gamma\gamma$+jets, V+$\gamma\gamma$, $t\bar{t}\gamma\gamma$
- Data-driven background estimation: analytical function from a fit to data $m_{\gamma\gamma}$ in sideband region
- Sideband - looser photon identification isolation

TRSM HHH production

Resonant production

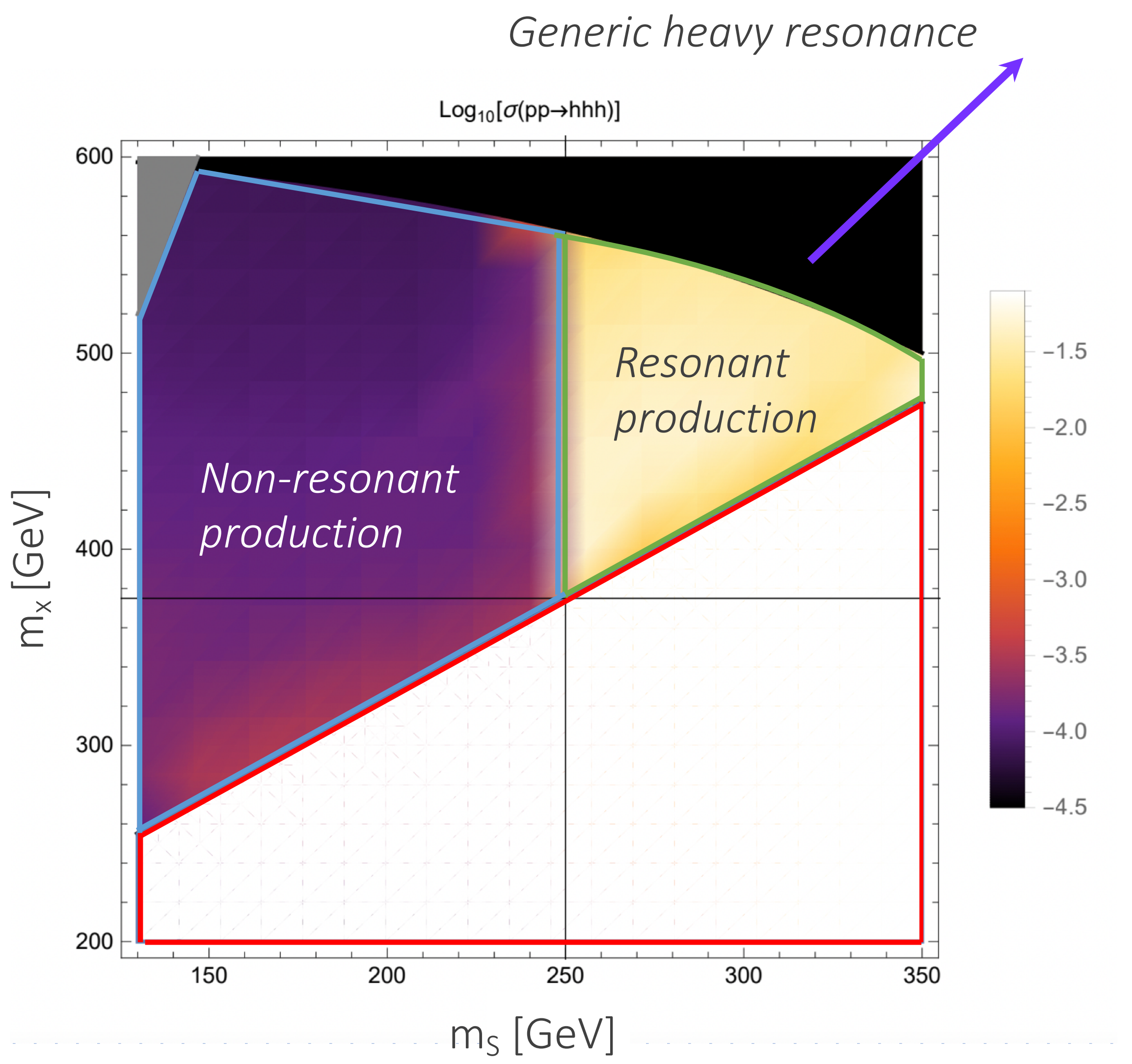
- $m_S \geqslant 2\ m_H$ (250 GeV)

Non-resonant production

- $m_S < 2\ m_H$ (250 GeV)
- SM HHH production

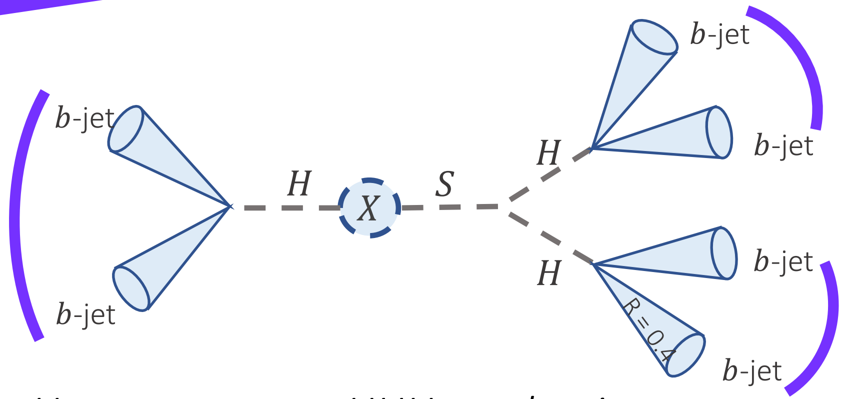
Heavy resonance HHH production

- Generic heavy resonances (narrow & wide decay widths)
    - $m_S > 275$ GeV, $m_X > 550$ GeV



arXiv:2101.00037

$HHH \to 6b$ pairing



Resonant TRSM HHH production

Softer m_{HHH} spectrum and jets

More overlap between jets

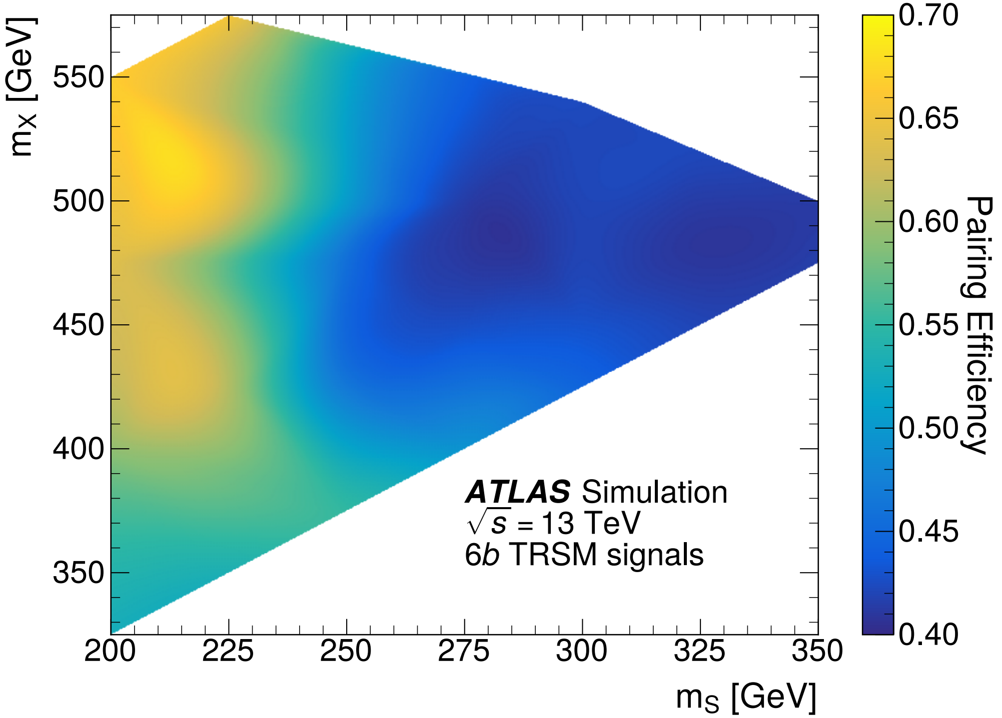
Larger pairing ambiguity

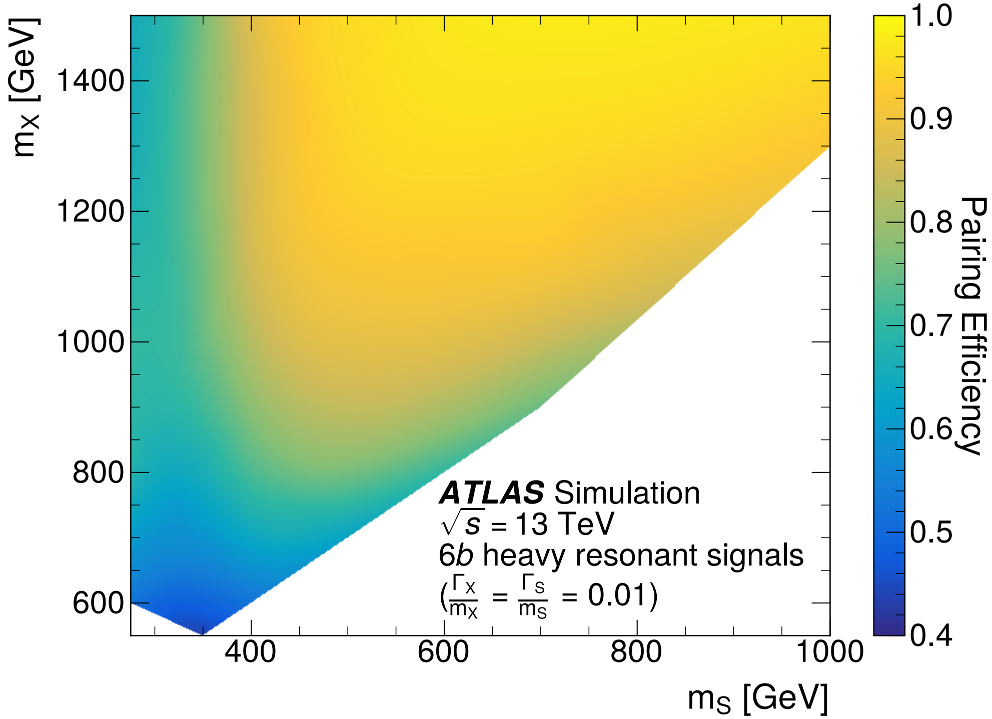
Heavy-resonant HHH production

More boosted Higgs candidates

More collimated b-jets

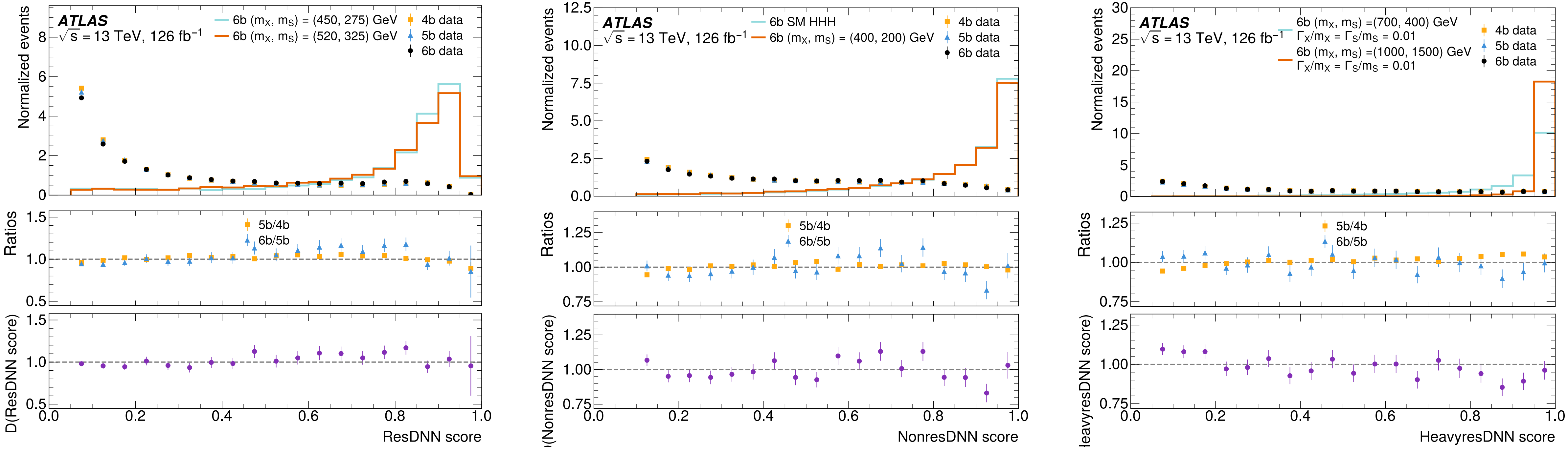
Smaller pairing ambiguity





$HHH \to 6b$ background estimation

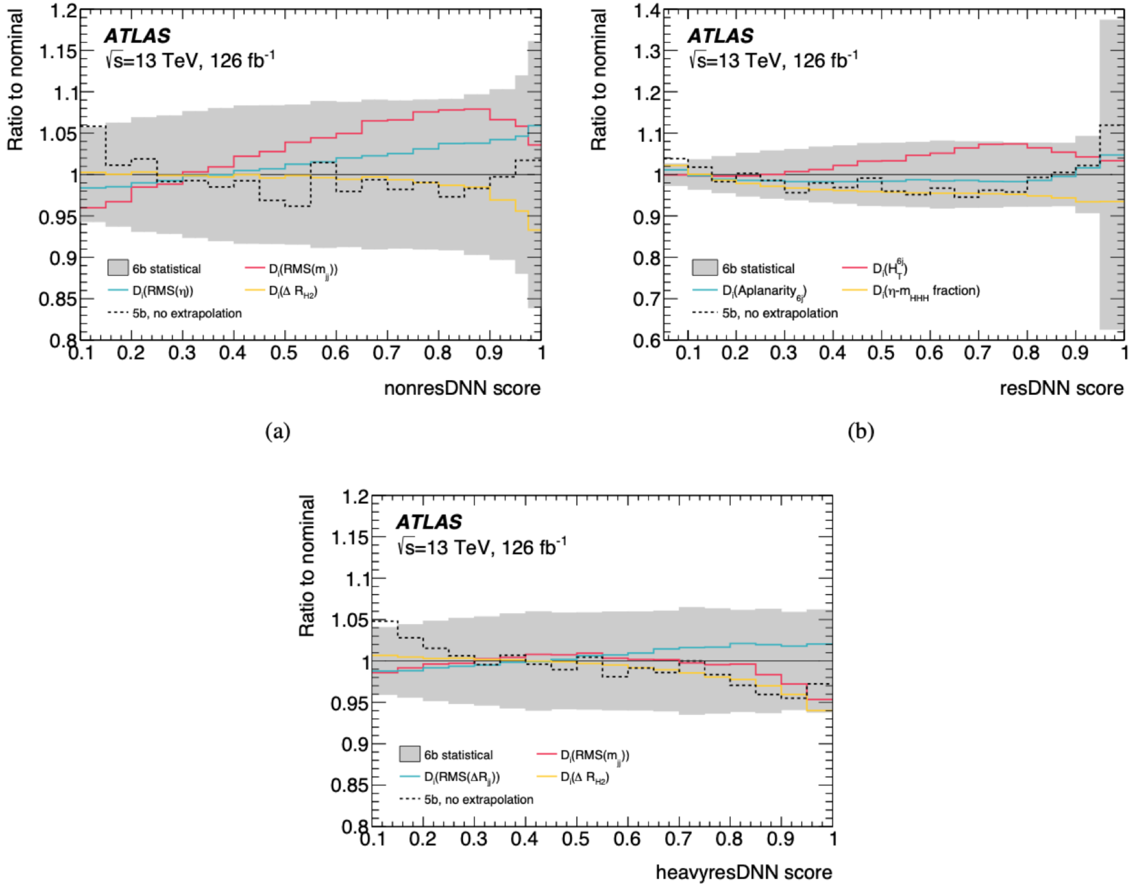
Unblinded NN scores of 6b data – good agreement between b-tag regions in low- & high-score



$HHH \to 6b$ background estimation

Shape systematics: variations in DNN output decomposed into variations in individual input features

- They are well-covered by the 3 ‘eigenvariation’
- All below 6b statistical uncertainty
- Impacts background by $\sim 10\%$
- Dominant systematic uncertainty



(c)