Search for new resonances in the $X \to SH \to bb\gamma\gamma$ final state with the ATLAS detector

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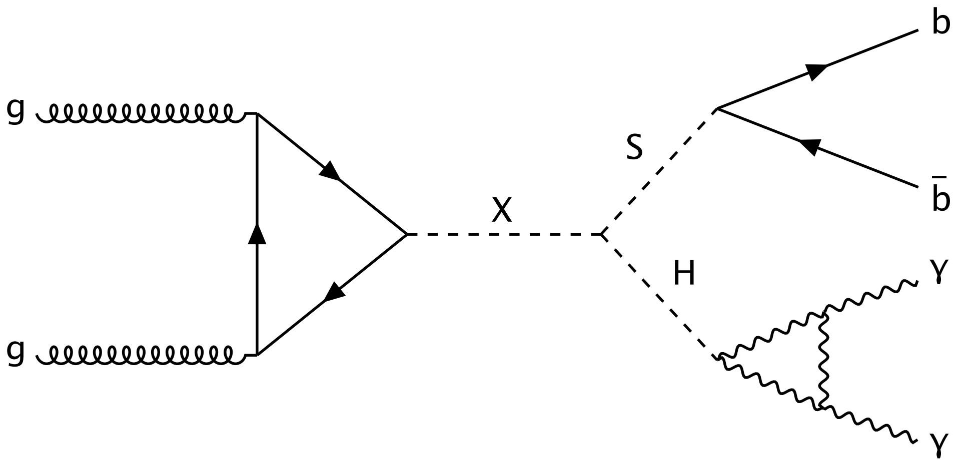
Search for new spin-0 resonances in the $bb\gamma\gamma$ final state

- Specific decay chain $X \to S(bb)H(\gamma\gamma)$

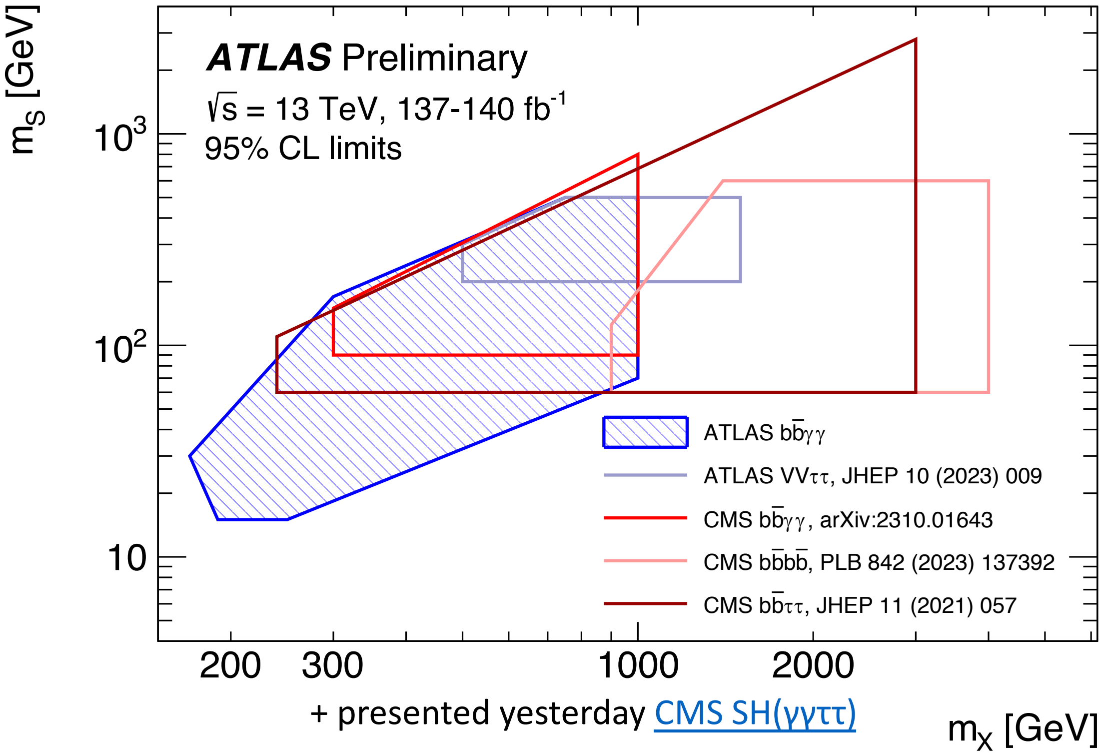
Require $m_X > m_S + m_H$ for $X \to SH$ decay to be allowed.

H is the 125 GeV Higgs boson, same decay modes as SM



Phenomenology arises in many **BSM models** eg.

- SM extension by a complex singlet or two real singlets,
- Complex 2HDM models, 2HDM+S, NMSSM...



+ presented yesterday CMS SH(γγττ)

- We probe 170 < m_X < 1000 GeV and 15 < m_S < 500 GeV
- $B(X \to SH)$ and $B(S \to bb)$ strongly depend on BSM model

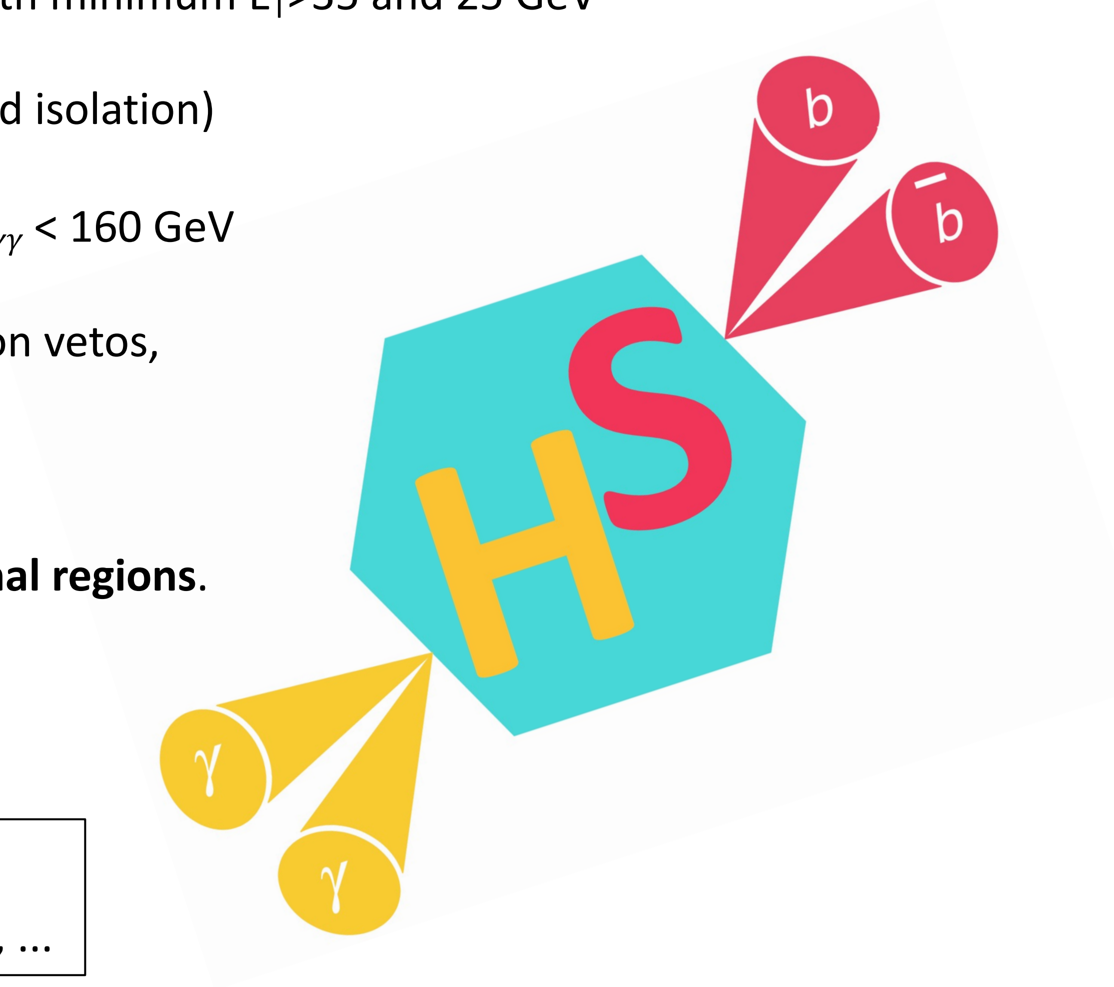
$\Longrightarrow$ Set limits on $\sigma(pp \to X) \times BR(X \to SH \to b\bar{b}\gamma\gamma)$

- Assume width of X, S << m_{bb}, $m_{bb\gamma\gamma}$ experimental resolutions.

Dataset and Event Selections

- Full ATLAS Run-2 L=140 fb^{-1} dataset 2-photon trigger, candidates with minimum E_T>35 and 25 GeV
- 2 tight photons (highest purity γ-category + track, calorimeter based isolation)
- $(H \rightarrow \gamma\gamma)$ kinematics: $p_T(\gamma_1)$> $0.35 m_{\gamma\gamma}$ & $p_T(\gamma_2)$> $0.25 m_{\gamma\gamma}$ & 105 < $m_{\gamma\gamma}$ < 160 GeV
- SM background reduction: $N_{central-jets} \in [2,5]$, electron and muon vetos,
- One or two b-tagged jets defined by the 77% working point.

The **number of b-tagged jets** is used to define **one-** and **two b-tag signal regions**.



With these selections **main backgrounds** are:

$\gamma\gamma$+jets (including photons misidentified as jets), *ttH*, *ZH*, *ggF H*, ...

Signal Regions (SR)

- 120 < $m_{\gamma\gamma}$ < 130 GeV
- **1** and **2** ***b*-tagged signal regions**

1 *b*-tag signal region: Boosted S ($m_X >> m_S + m_H$)

1 and 2 *b*-tagged Sidebands (SB) = Control Regions
$m_{\gamma\gamma} \in [105,120] \cup [130,160]$ GeV

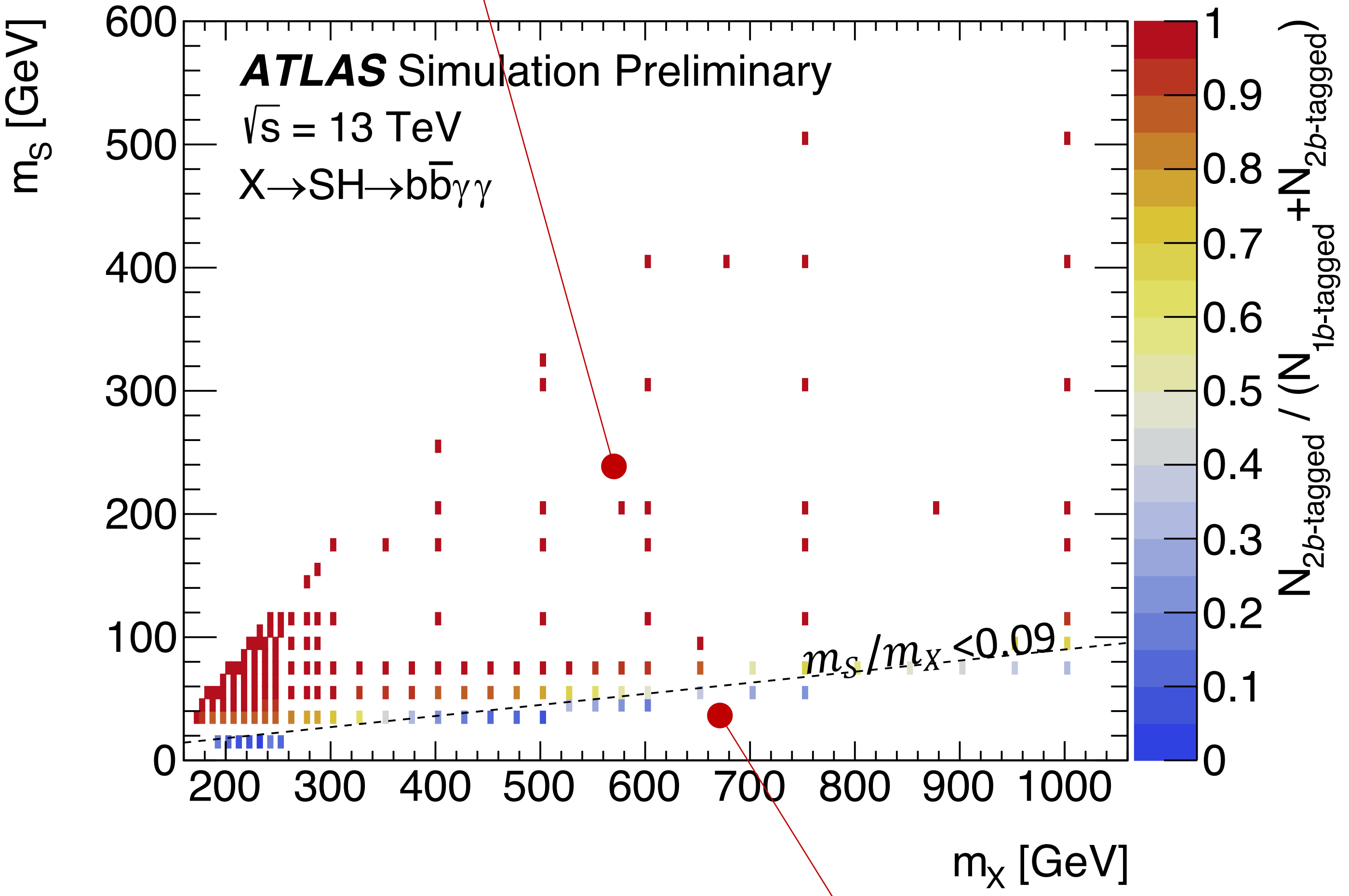
Parameterised Neural Network (PNN)

⟹ final signal/background discriminant.

1 and 2 *b*-tagged Sidebands used to:

- ➢ Validate modelling of PNN input variables
- ➢ Validate PNN output shape
- ➢ Normalise the non-resonant $\gamma\gamma$-background

2 b-tagged signal region "resolved $S \rightarrow bb$"



1 b-tagged signal region "merged $S \rightarrow bb$"

Signal Regions (SR)

- $120 < m_{\gamma\gamma} < 130$ GeV
- **1 and 2 b-tagged signal regions**

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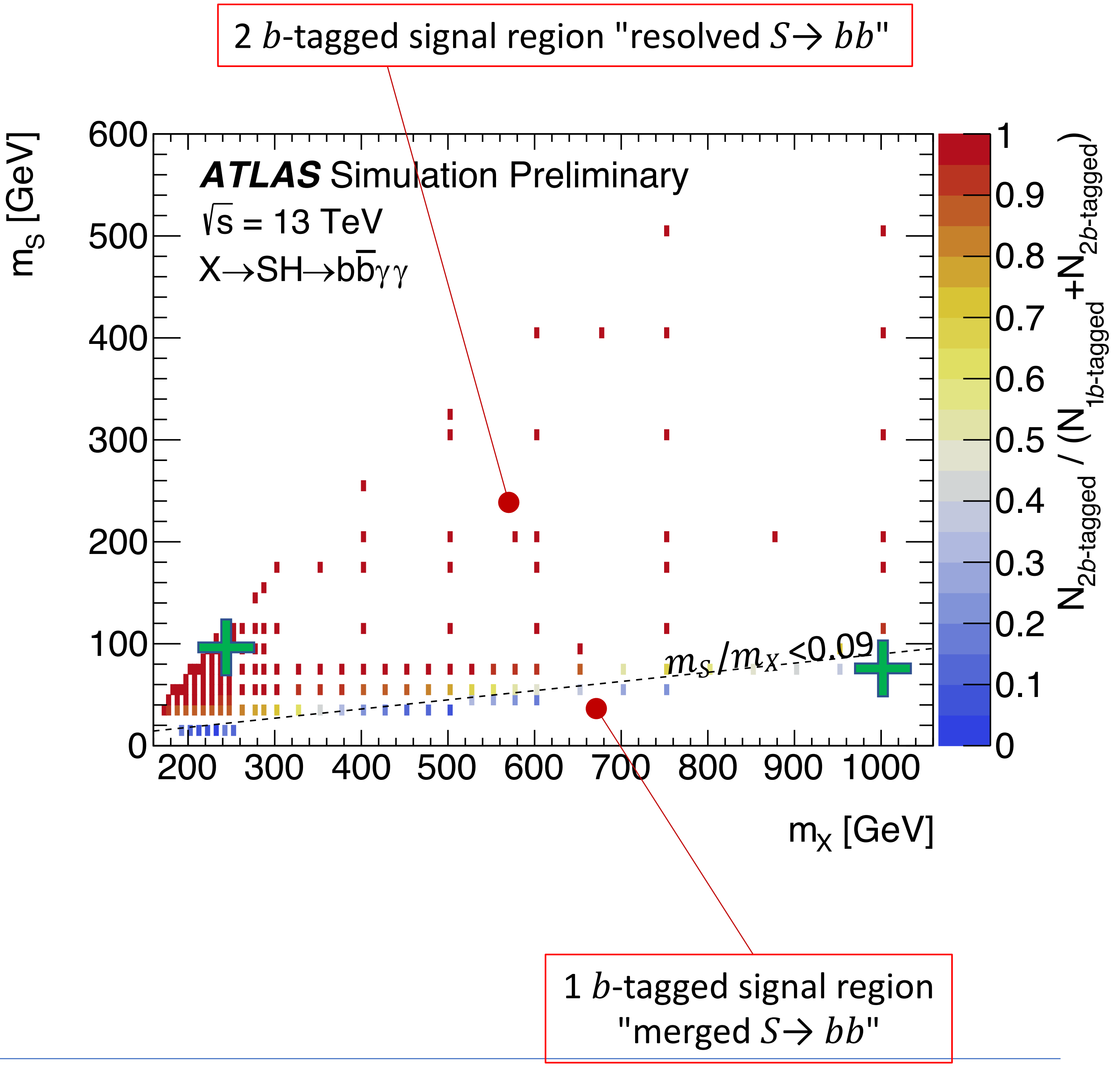


Final discriminant: Parameterised Neural Network (PNN)

One PNN per signal region: *1 b-tagged* and *2b-tagged* SR

Inputs:

- Vector of *event characteristics* x: "event variables"
- Vector of *phase space parameters* θ: "model parameters"

Yields a response function that is parameterised in θ

$\theta = (m_S, m_X)$ in the *2 b-tagged* region

$\theta = (m_X)$ in the 1 *b-tagged* region

Event characteristics

1 b-tagged SR $x = (p_T^b, m^*_{b\gamma\gamma})$ with $m^*_{b\gamma\gamma} = m_{b\gamma\gamma} - (m_{\gamma\gamma} - 125\text{ GeV})$

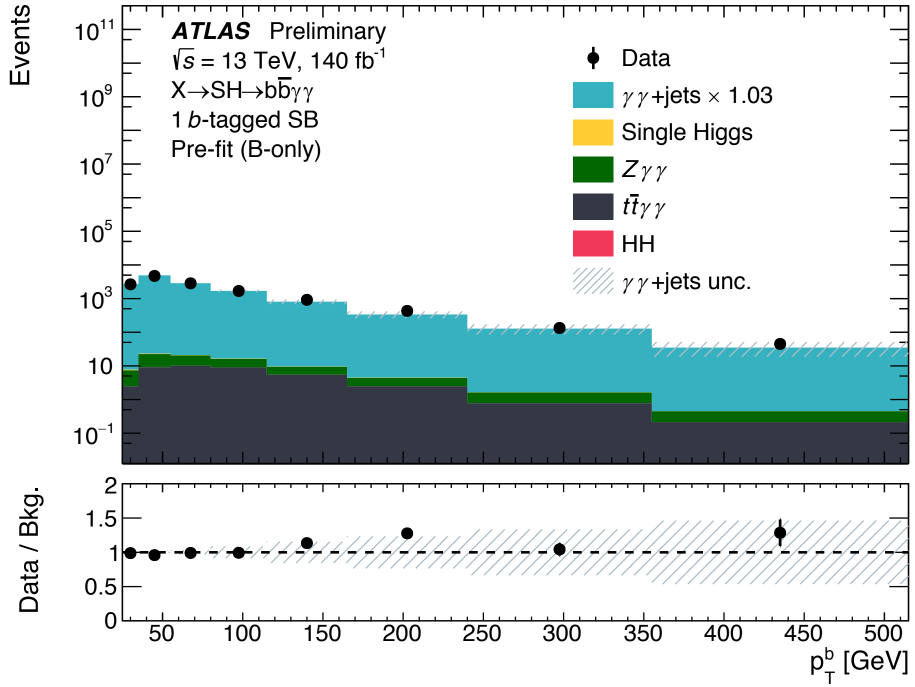
2 b-tagged SR $x = (m_{bb}, m^*_{bb\gamma\gamma})$ with $m^*_{bb\gamma\gamma} = m_{bb\gamma\gamma} - (m_{\gamma\gamma} - 125\text{ GeV})$

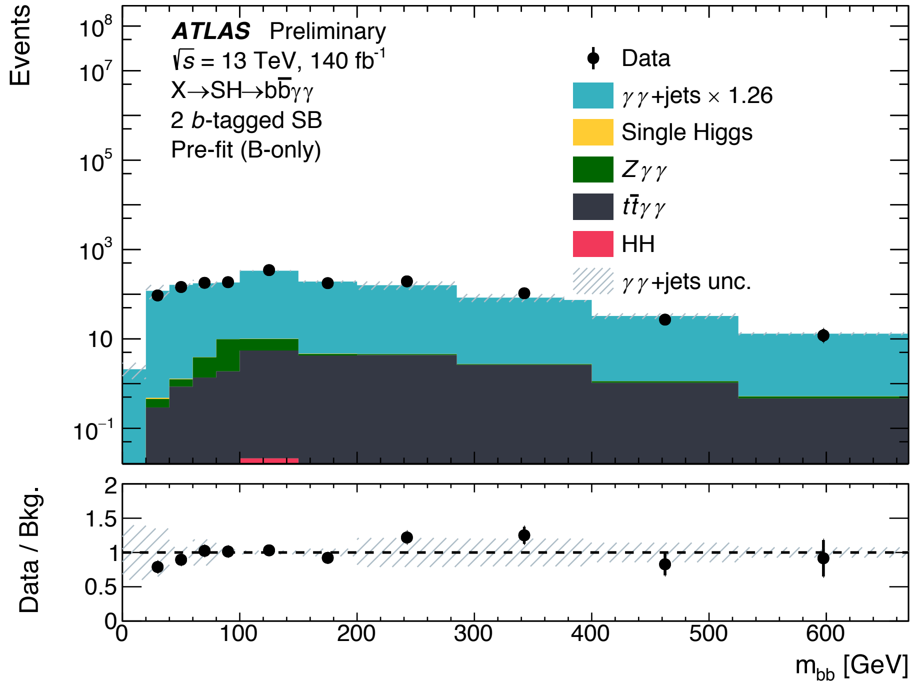
PNN Training

Trained with backgrounds: non-resonant $\gamma\gamma$+jets, ttH, ZH and ggF H

2 b-tagged PNN trained on signal points with $m_X \geq 170$ GeV, $m_S \geq 30$ GeV

1 b-tagged PNN trained in eleven points with $15 \leq m_S \leq 70$ GeV





Backgrounds

1) $\gamma\gamma$+jets background

Includes dijet and γ+jets events with 2 or 1 jets misidentified as photons.

Use double 2-dimensional sideband method (JHEP **11** (2021) 169) to

- Determine fraction of $\gamma\gamma$+jets events with fake photons (~15%)
- Derive $m_{\gamma\gamma}$ shape for the different $\gamma\gamma$+jets components
- Derive shape of the PNN input variables in Sidebands
- Derive shape of the PNN in Sidebands

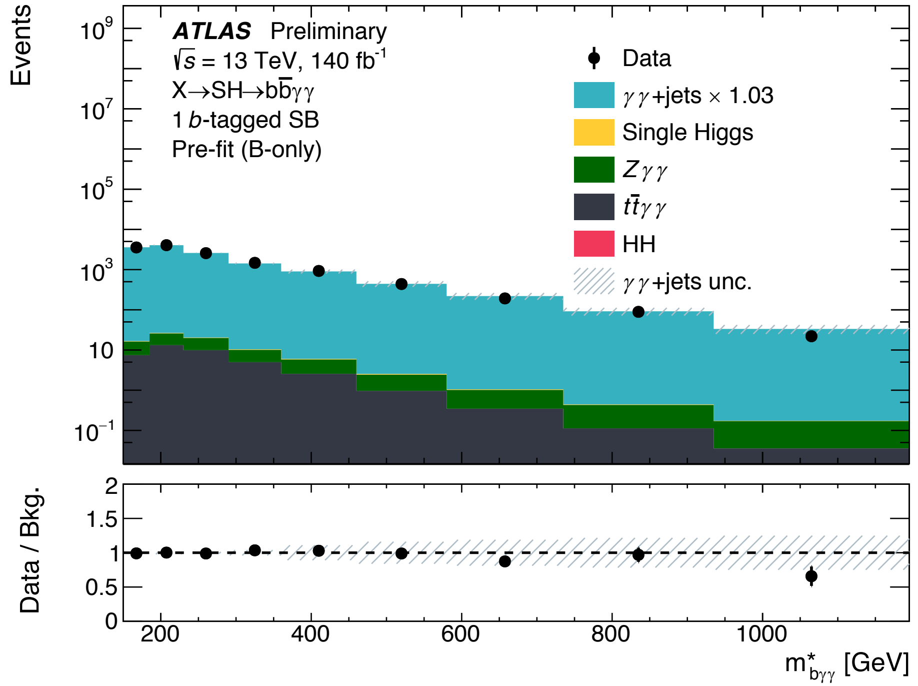
Small difference b/w $\gamma\gamma$+jets Sherpa 2.2.4 and data-driven shapes.
$\Longrightarrow$ Use $\gamma\gamma$+jets Sherpa 2.2.4 as model of the $\gamma\gamma$+jets background,
Apply systematics to normalization & shape (exp., modelling, theory)

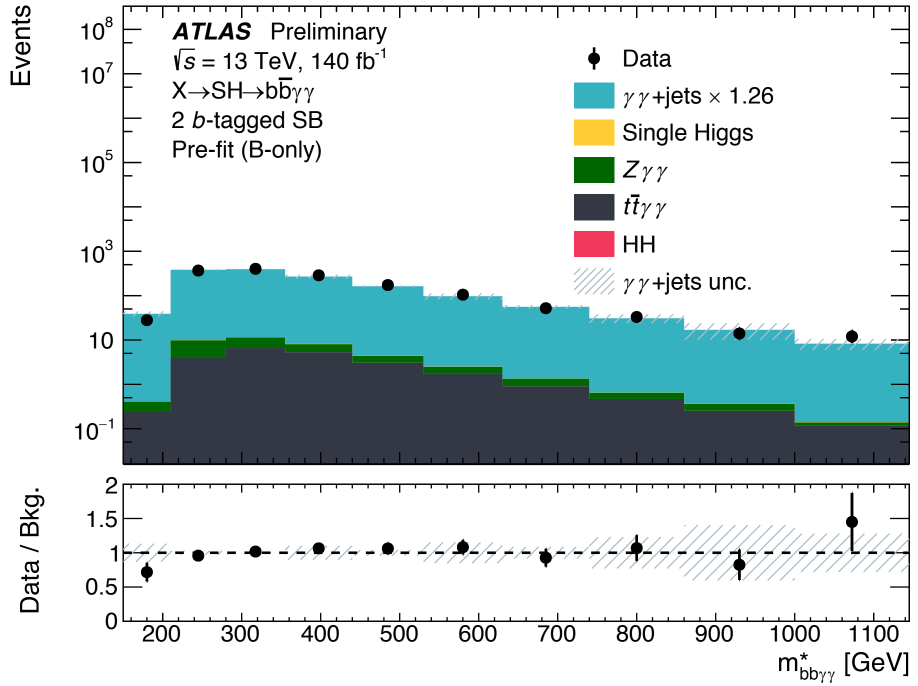
2) SM Higgs boson processes

Primarily *ggF+bbH*, *ttH* and *ZH,* also *VBF H, WH, tHq, tHW, HH..*

Derived from simulation.

Associated systematics uncertainties: experimental, theory.

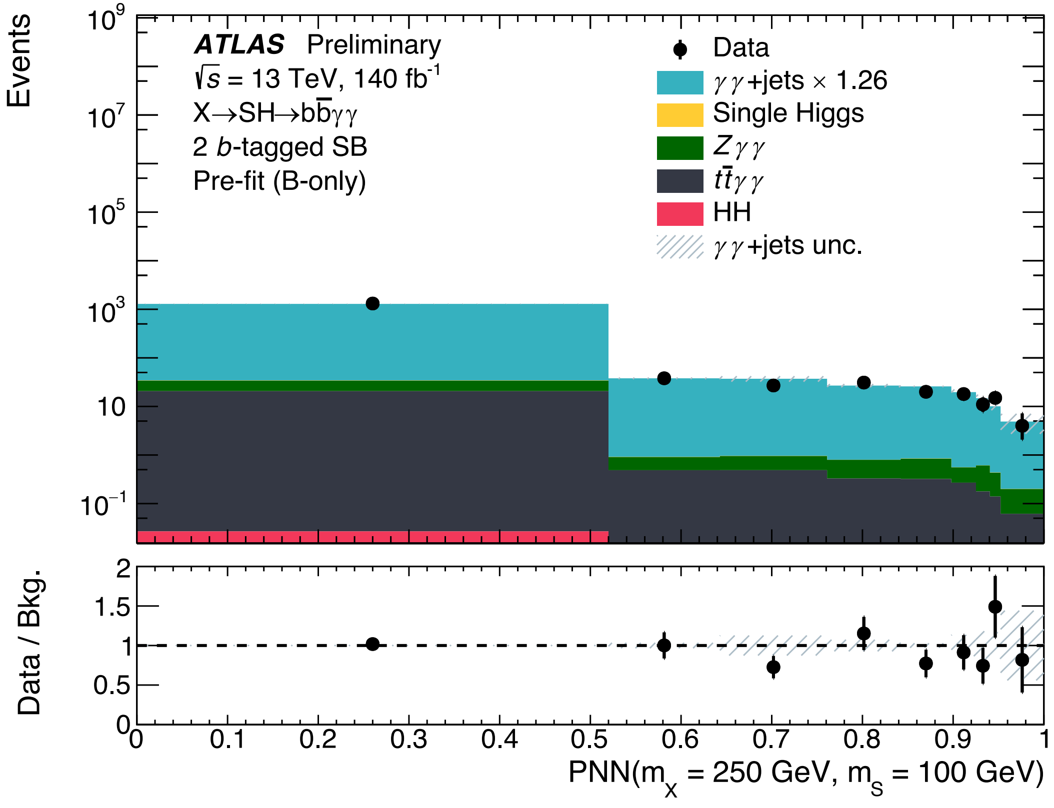


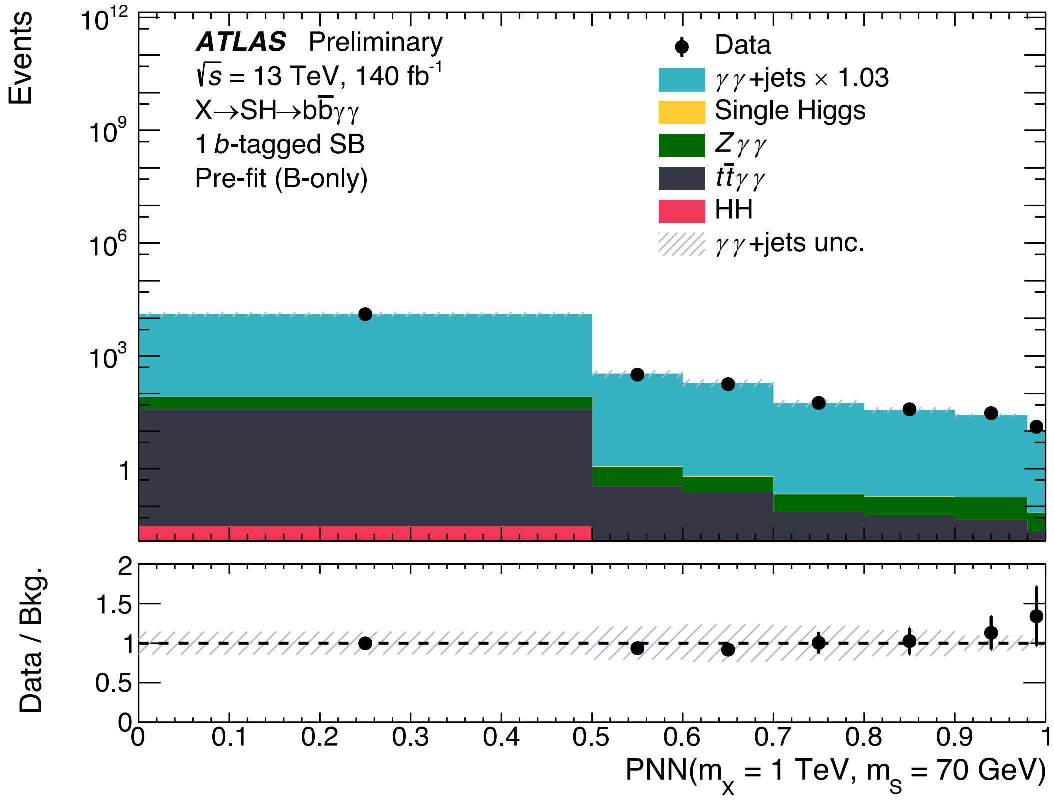


PNN in Sidebands Control Region

Excellent data-model agreement in the sidebands for the input variables and for the PNN output shapes

PNN(θ) distribution compared b/w model and data for more than 100 points in the phase space parameter θ





Background-only Fit

Example of background-only fits including signal region and sidebands

Most signal-like PNN bin shown

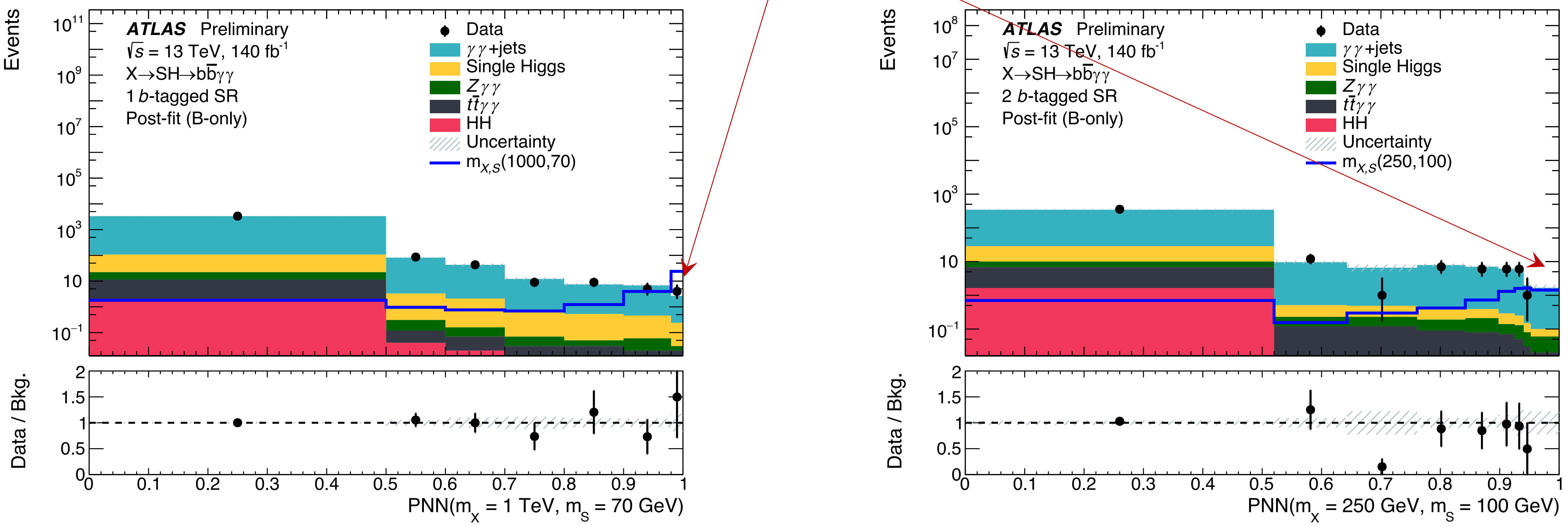
Background	2 b-tagged region Sideband	Signal region	Signal-like bin	1 b-tagged region Sideband	Signal Region	Signal-like bin
Non-res. $\gamma\gamma$	1480 ± 37	372 ± 16	1.64 ± 0.37	13450 ± 110	3393 ± 53	2.45 ± 0.43
Single Higgs	0.46 ± 0.11	19.9 ± 5.3	0.04 ± 0.01	2.3 ± 1.1	89 ± 44	0.21 ± 0.10
ggF+$b\bar{b}H$	0.14 ± 0.11	6.5 ± 5.2	0.01 ± 0.01	1.5 ± 1.1	56 ± 43	0.11 ± 0.09
$t\bar{t}H$	0.21 ± 0.01	7.91 ± 0.77	$0.01 \pm < 0.01$	0.31 ± 0.01	11.4 ± 1.1	$0.03 \pm < 0.01$
ZH	$0.08 \pm < 0.01$	3.56 ± 0.30	$0.02 \pm < 0.01$	0.17 ± 0.01	7.35 ± 0.60	$0.02 \pm < 0.01$
Other	0.03 ± 0.01	1.94 ± 0.70	< 0.005	0.40 ± 0.23	17 ± 10	0.05 ± 0.03
Di-Higgs	$0.03 \pm < 0.01$	1.65 ± 0.25	< 0.005	$0.03 \pm < 0.01$	1.79 ± 0.27	$0.01 \pm < 0.01$
Total	1480 ± 37	394 ± 16	1.67 ± 0.37	13450 ± 110	3486 ± 48	2.67 ± 0.45
Signal (m_X, m_S)						
(250,100) GeV	0.38 ± 0.04	8.3 ± 1.2	1.43 ± 0.21			
(1000,70) GeV				0.97 ± 0.10	33.3 ± 5.8	23.9 ± 4.2
Data	1479	395	0	13450	3491	4

@1fb

PNN(m_X = 250 GeV, m_S = 100 GeV) PNN(m_X = 1000 GeV, m_S = 70 GeV)

Signal regions

Most signal-like PNN bins



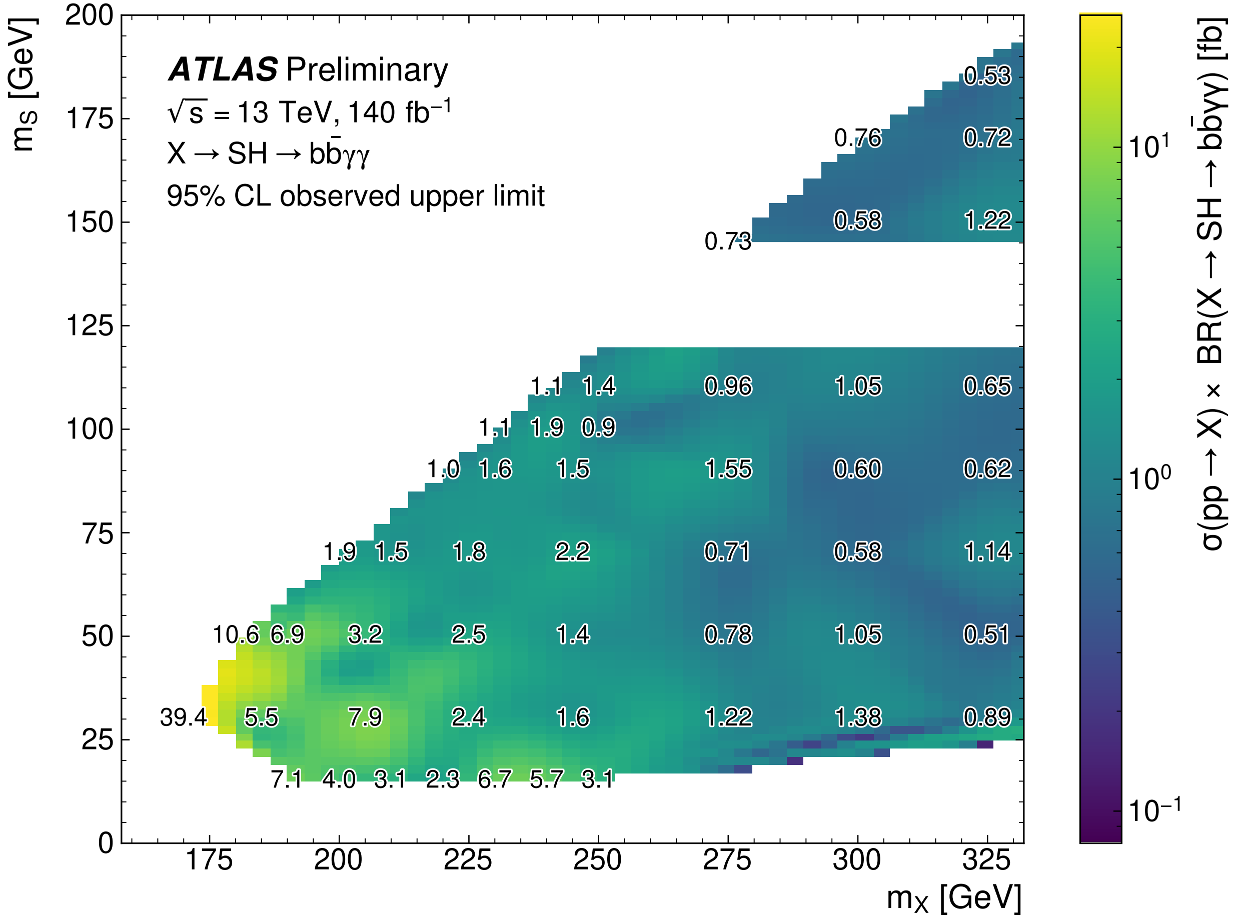
Examples of Background-only fits in the 1 and 2 b-tag signal regions

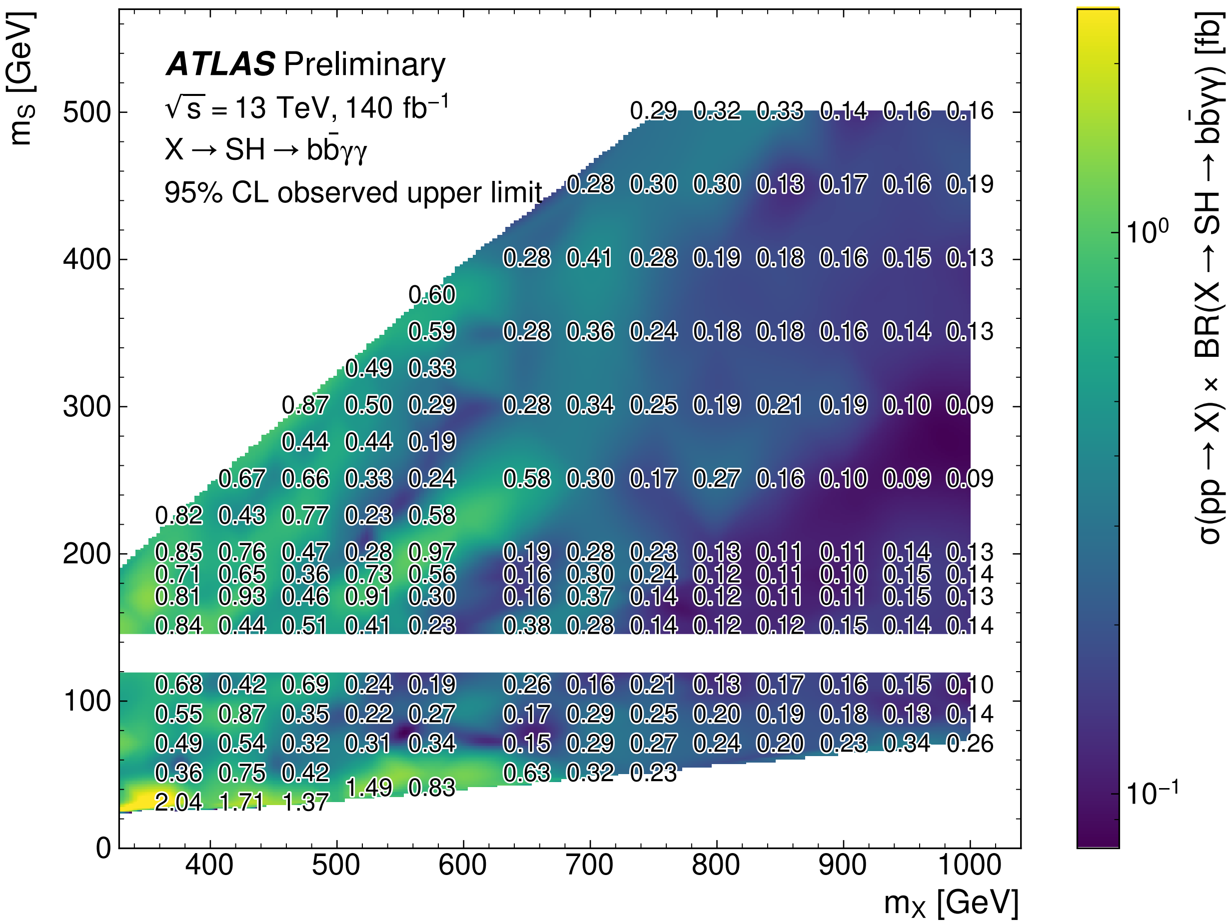
Signals superimposed with a 1 fb cross section.

No significant excess observed on the entire (m_X, m_S) grid

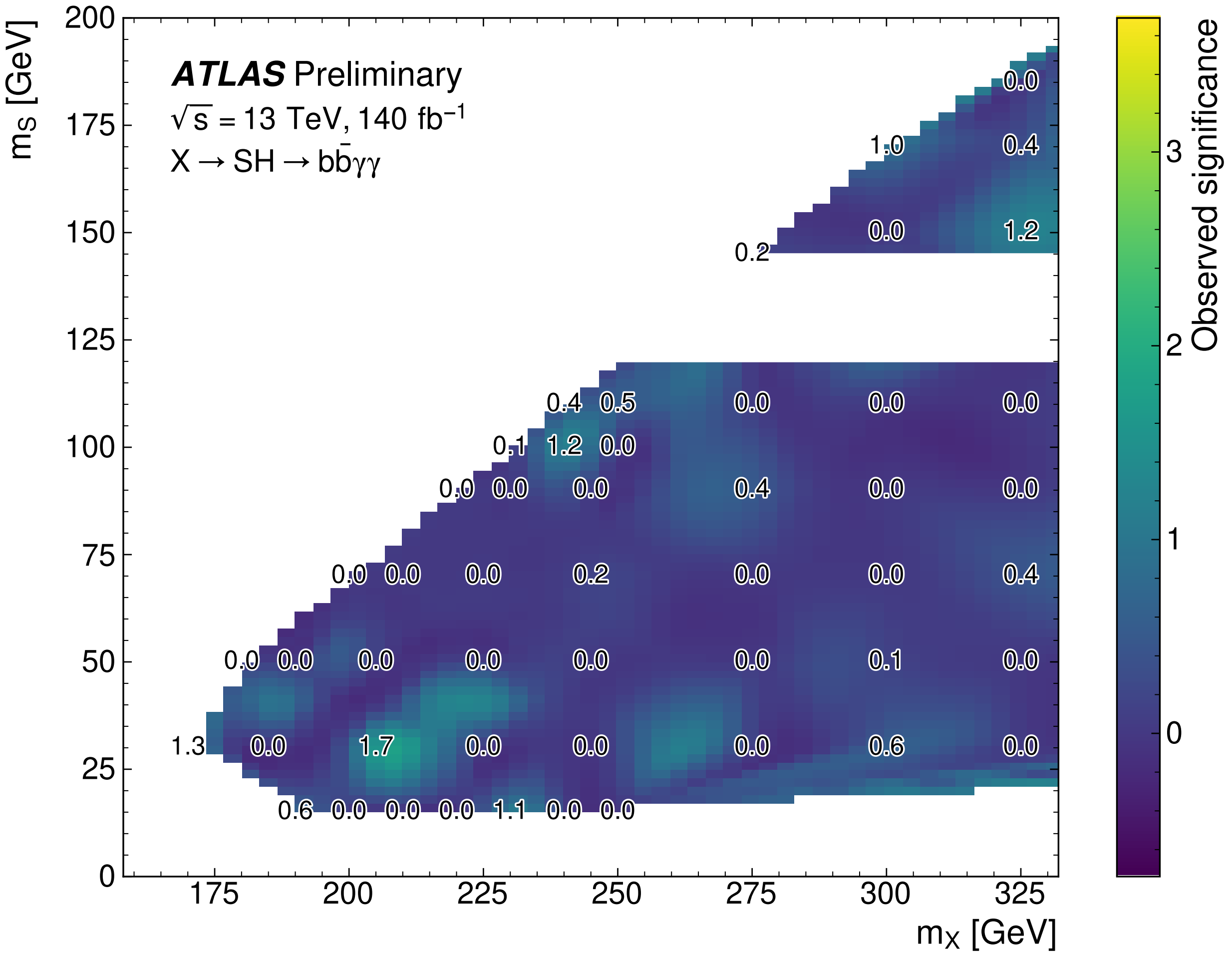
Proceed to set upper limits on $\sigma(pp \to X) \times BR(X \to SH \to b\bar{b}\gamma\gamma)$

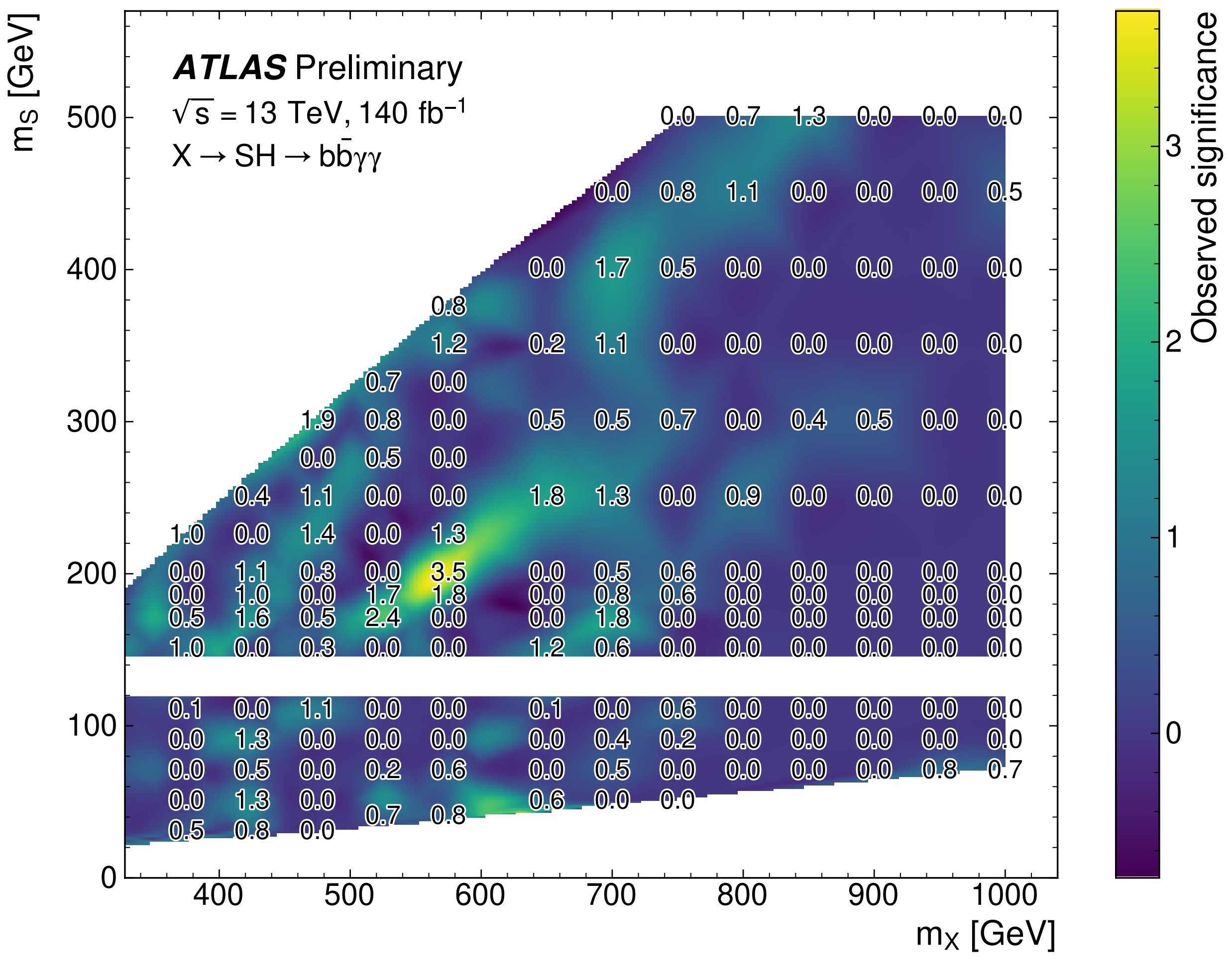
Limit Results on $\sigma(pp \to X) \times BR(X \to SH \to b\bar{b}\gamma\gamma)$





Observed significance





Largest excess at (m_X, m_S)=(575,200) GeV

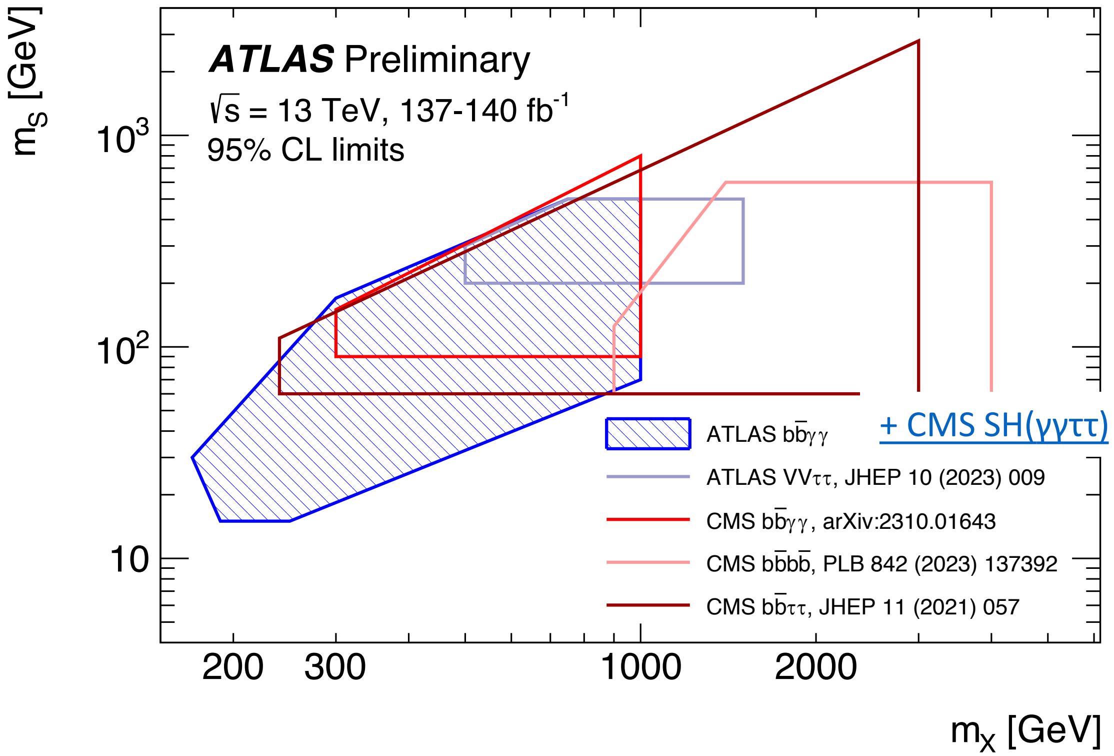
Local (global) significance of 3.5 (2.0) standard deviations

Conclusions

- We searched for hypothetical scalars X and S in the decay chain $X \rightarrow S(bb)H(\gamma\gamma)$ with ATLAS Run-2 data

- Two signal regions targeting ***resolved*** and ***boosted*** $S \rightarrow bb$ decays were analyzed.

- Expands earlier LHC results to lower masses
  - Limits are set on $\sigma(X \rightarrow SH \rightarrow bb\gamma\gamma)$ in the range
  - $170 \leq m_X \leq 1000$ GeV and $15 \leq m_S \leq 500$ GeV.

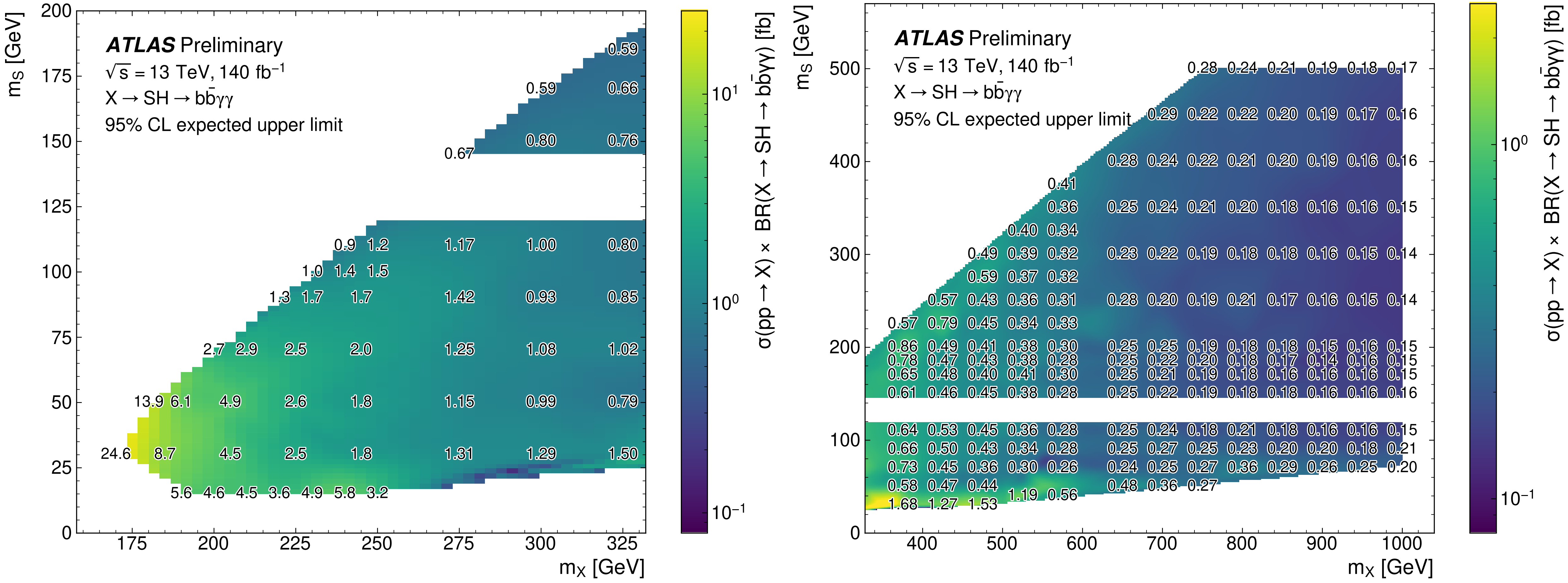


- At $(m_X, m_S) = (650, 90)$ GeV where CMS reported an excess, we observe good agreement with the background-only hypothesis ($p_0 > 0.5$) and set a 95% CL upper limit on the signal cross section of 0.2 fb.

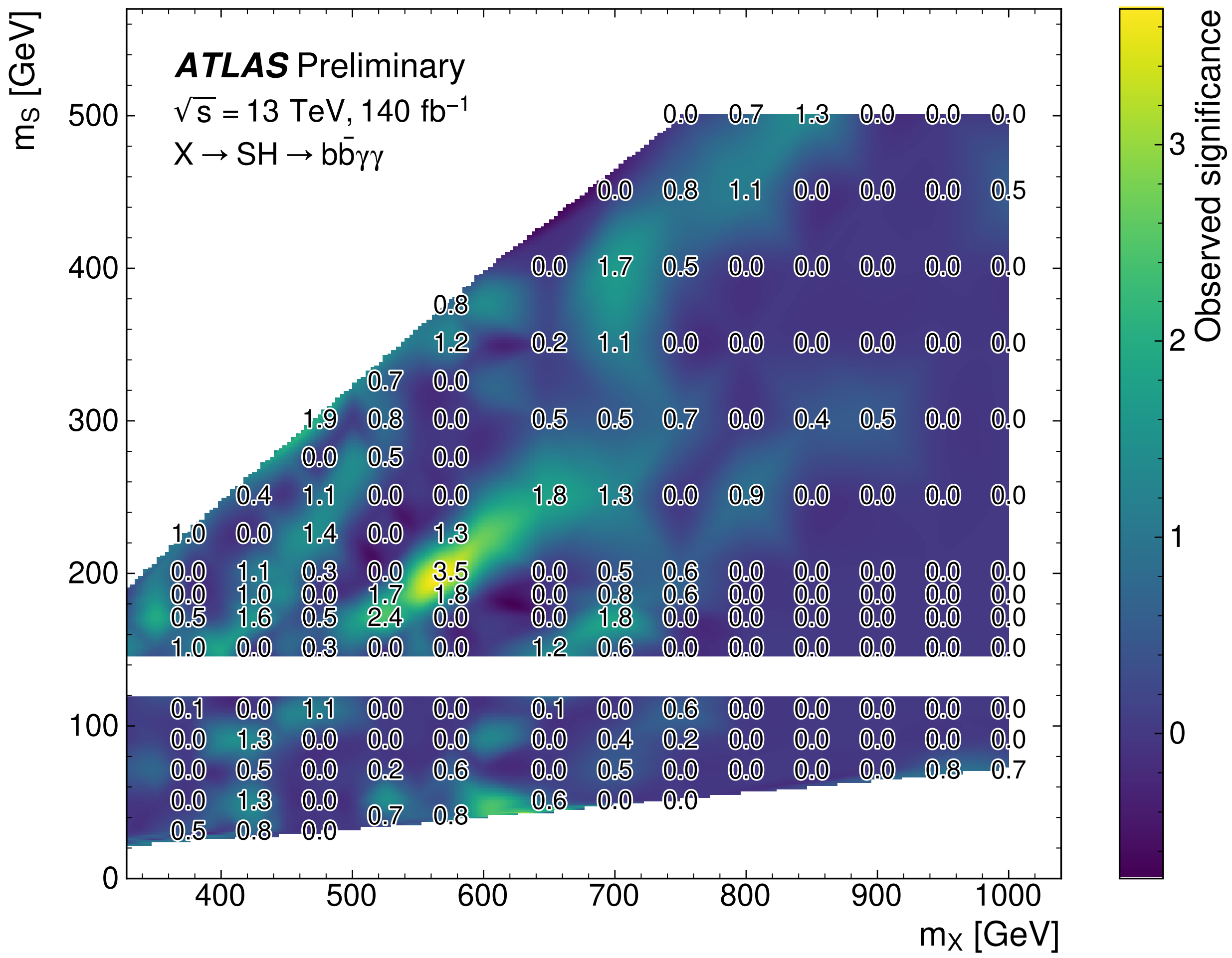
- Largest **deviation** from the background-only expectation occurs for $(m_X, m_S) = (575, 200)$ GeV with a local (global) significance of 3.5 (2.0) standard deviations

Backup

Expected Limits



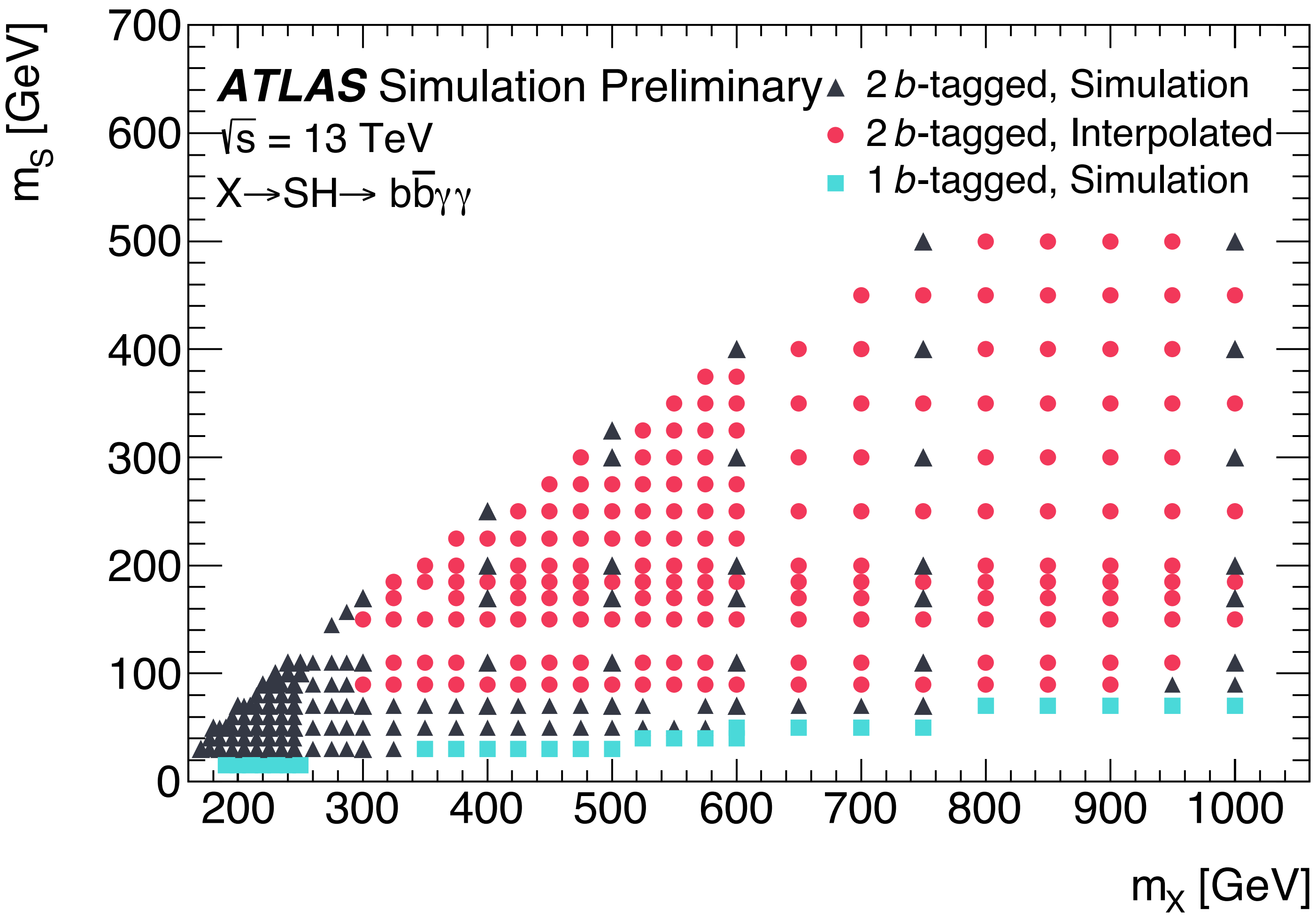
Signal Injection Test at $(m_{X,} m_S)$ =(650, 90) GeV



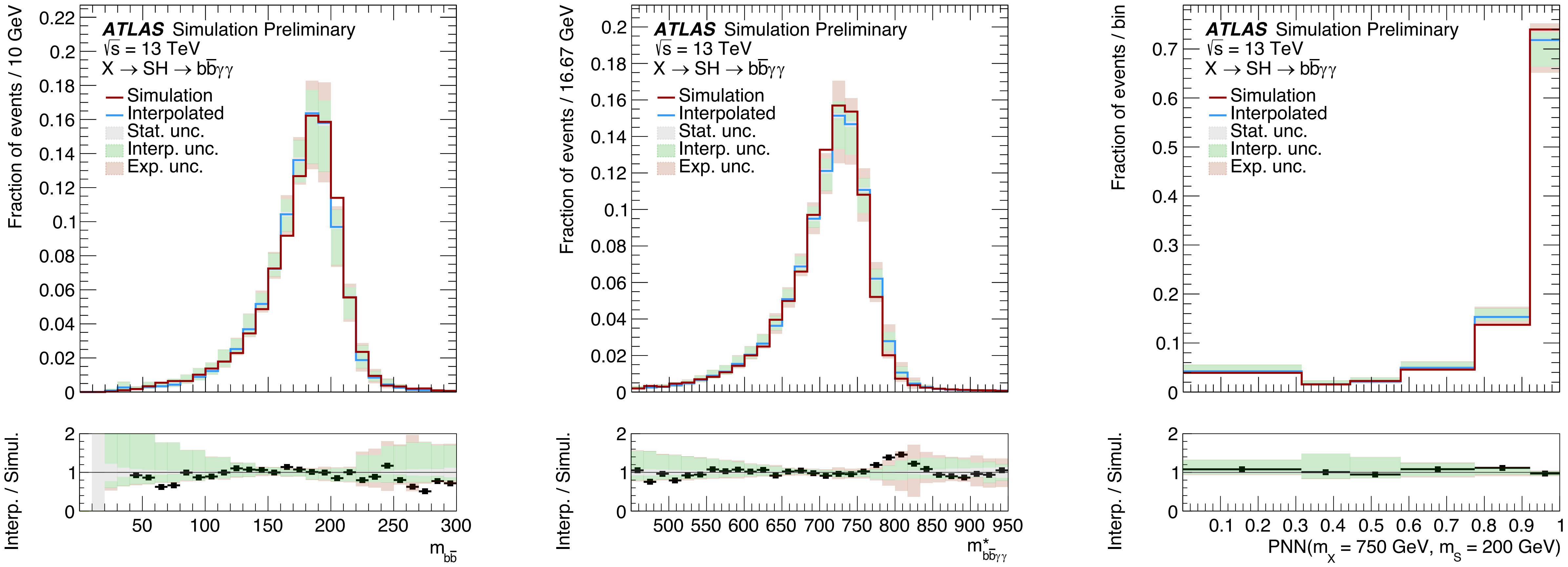
We perform a signal injection at $(m_{X,} m_S)$ =(650, 90) GeV with a cross section of 0.35 fb (the best fit reported by the CMS bb$\gamma\gamma$, arXiv:2310.01643).

This signal injection yields an expected local excess of 2.7 standard deviations.

Instead we observe a good data/bkg only agreement at $(m_{X,} m_S)$ =(650, 90) GeV (p_0>0.5)



(m_X,m_S) signals for which the significance and limits are computed. Simulations are available for the signals marked as black triangles and red squares. For the points marked as blue circles, the limits are derived using the interpolated PNN scores.



Comparison of simulation and interpolation for (a) m_{bb}, (b) $m^{*}_{\mathrm{bb}\gamma\gamma}$ and (c) PNN score,for $m^{\mathrm{target}}{}_{X}$=750 GeV and $m^{\mathrm{target}}{}_{S}$= 200 GeV.

Statistical model

$\gamma\gamma$+jets normalisation is free parameter $\mu_{\gamma\gamma}$.

$f_i^p(\theta)$ PNN output shape

$$\mathcal{L} = \mathrm{Pois}\left(n_{\mathrm{SB}} \middle| \mu_{\gamma\gamma} N_{\mathrm{SB}}^{\gamma\gamma}(\boldsymbol{\theta}) + \sum_p N_{\mathrm{SB}}^p(\boldsymbol{\theta})\right) \cdot \prod_i \mathrm{Pois}\left(n_{\mathrm{SR},i} \middle| \mu_{\gamma\gamma} N_{\mathrm{SR}}^{\gamma\gamma}(\boldsymbol{\theta}) f_i^{\gamma\gamma}(\boldsymbol{\theta}) + \sum_p N_{\mathrm{SR}}^p(\boldsymbol{\theta}) f_i^p(\boldsymbol{\theta})\right) \cdot G(\boldsymbol{\theta})$$

$\gamma\gamma$+jets

Processes other than $\gamma\gamma$+jets

Data vs Bkg model yield in the single bin $m_{\gamma\gamma}$ ***sideband***

Data vs model yield in the multi-PNN bins inside the ***signal region***