Searches for Higgs boson pair production with the full LHC Run-2 dataset in ATLAS

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on behalf of the ATLAS Collaboration

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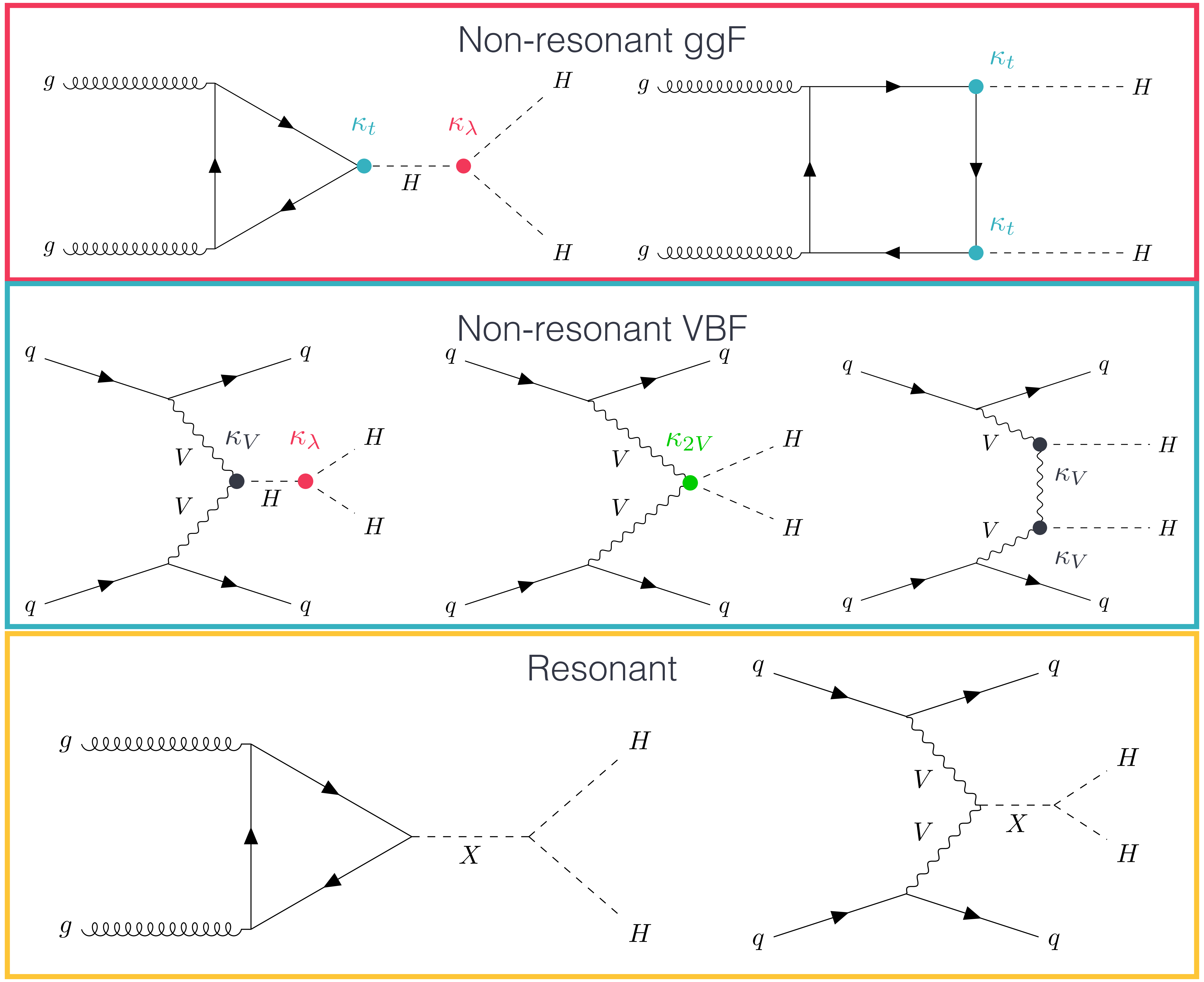
Introduction

- A direct probe of the self-coupling of the Higgs boson is possible by studying Higgs boson pair production
- A number of results have been previously published by the ATLAS and CMS collaborations

	bb	WW	ττ	ZZ	γγ
bb	33%				
WW	25%	4.6%			
ττ	7.4%	2.5%	0.39%		
ZZ	3.1%	1.2%	0.34%	0.076%	
γγ	0.26%	0.10%	0.029%	0.013%	0.0005%



Searches with full Run 2 dataset

- *Non-resonant HH→ bblvlv*
- *VBF HH→ bbbb*
- *HH→ bbγγ*

Non-resonant $HH \rightarrow bbl\nu l\nu$

Non-resonant $HH \to bbl\nu l\nu$

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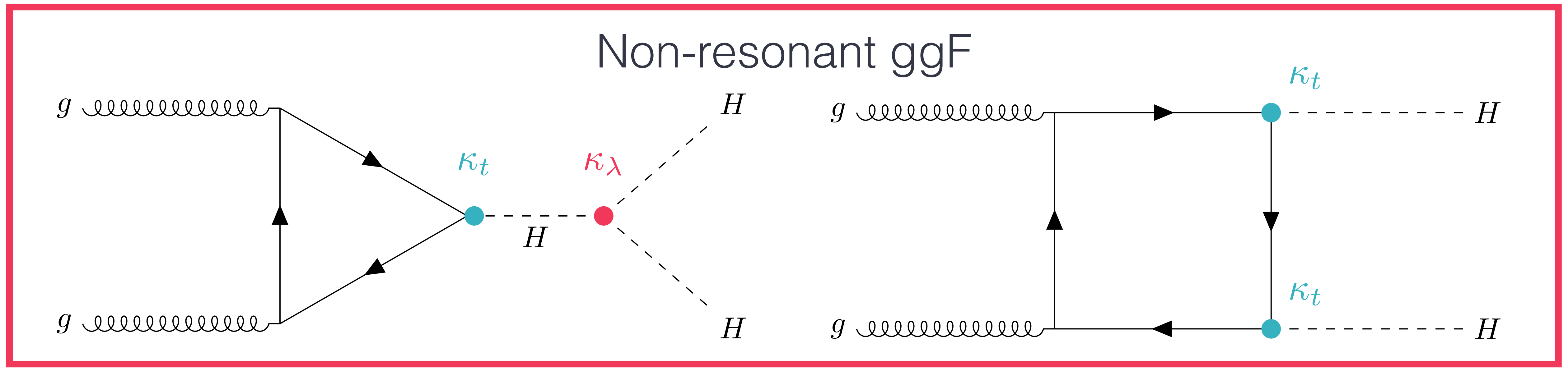
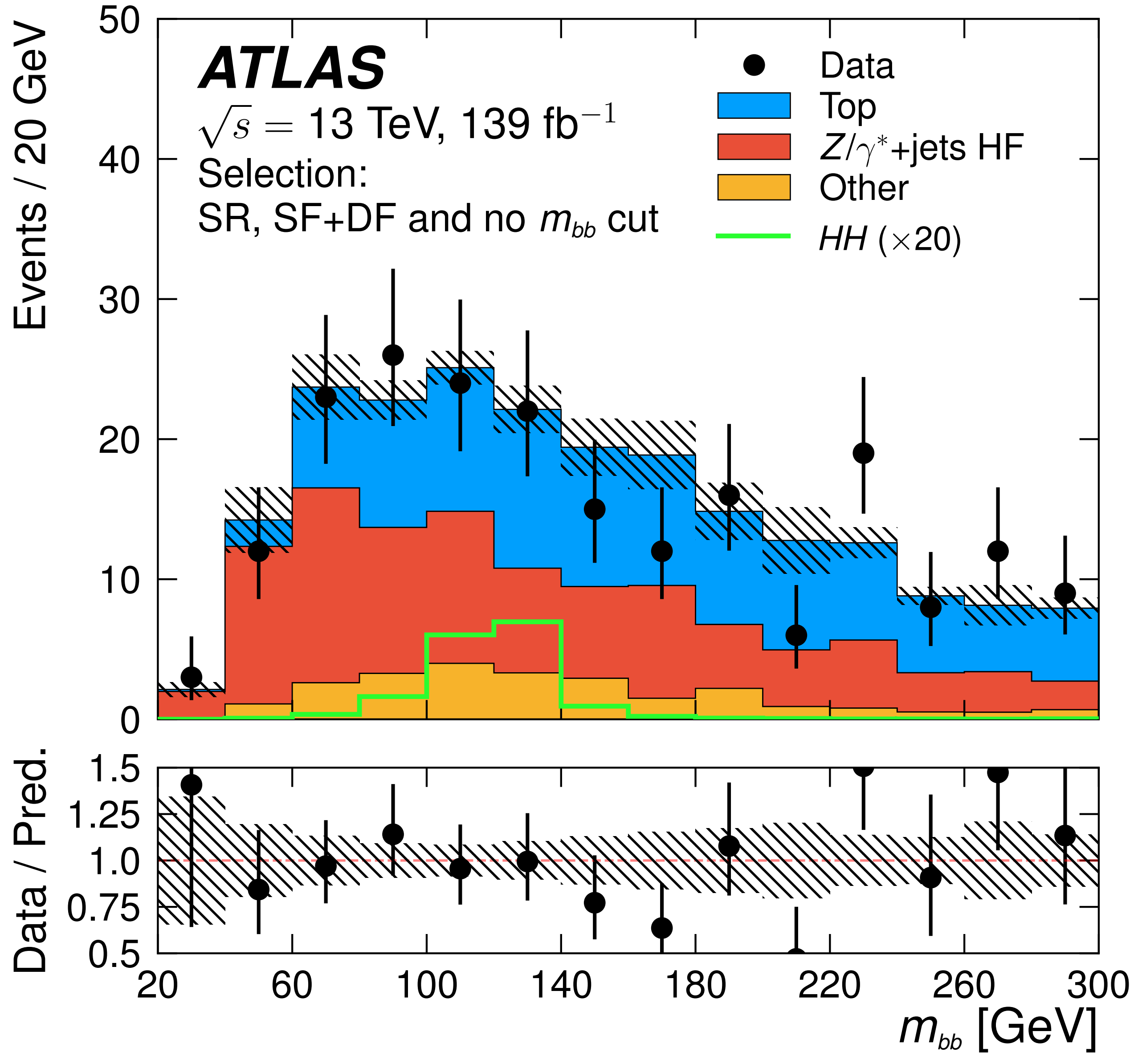
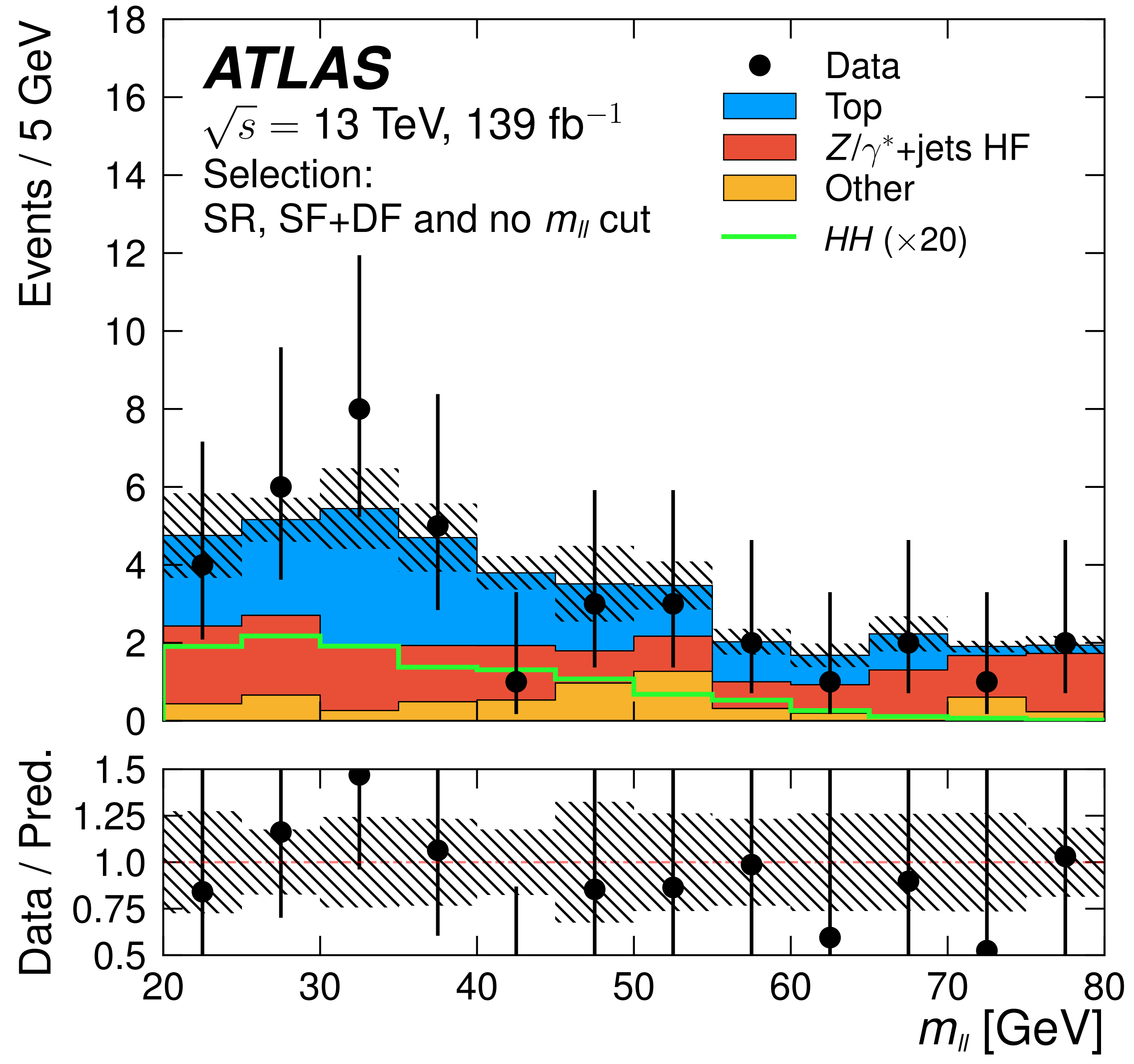




- First $HH \to bbl\nu l\nu$ result from ATLAS
- Analysis optimized for non-resonant ggF production
  - All objects in the event final state topology are fully resolved
  - Contributions from three different processes
    - $HH \to bbWW$ (90% of total signal yield in SR)
    - $HH \to bb\tau\tau$ (9%)
    - $HH \to bbZZ$ (1%)
- Dominant background contributions from Top production and Z/γ^* in association with jets from heavy flavors



Non-resonant *HH*→*bblνlν*

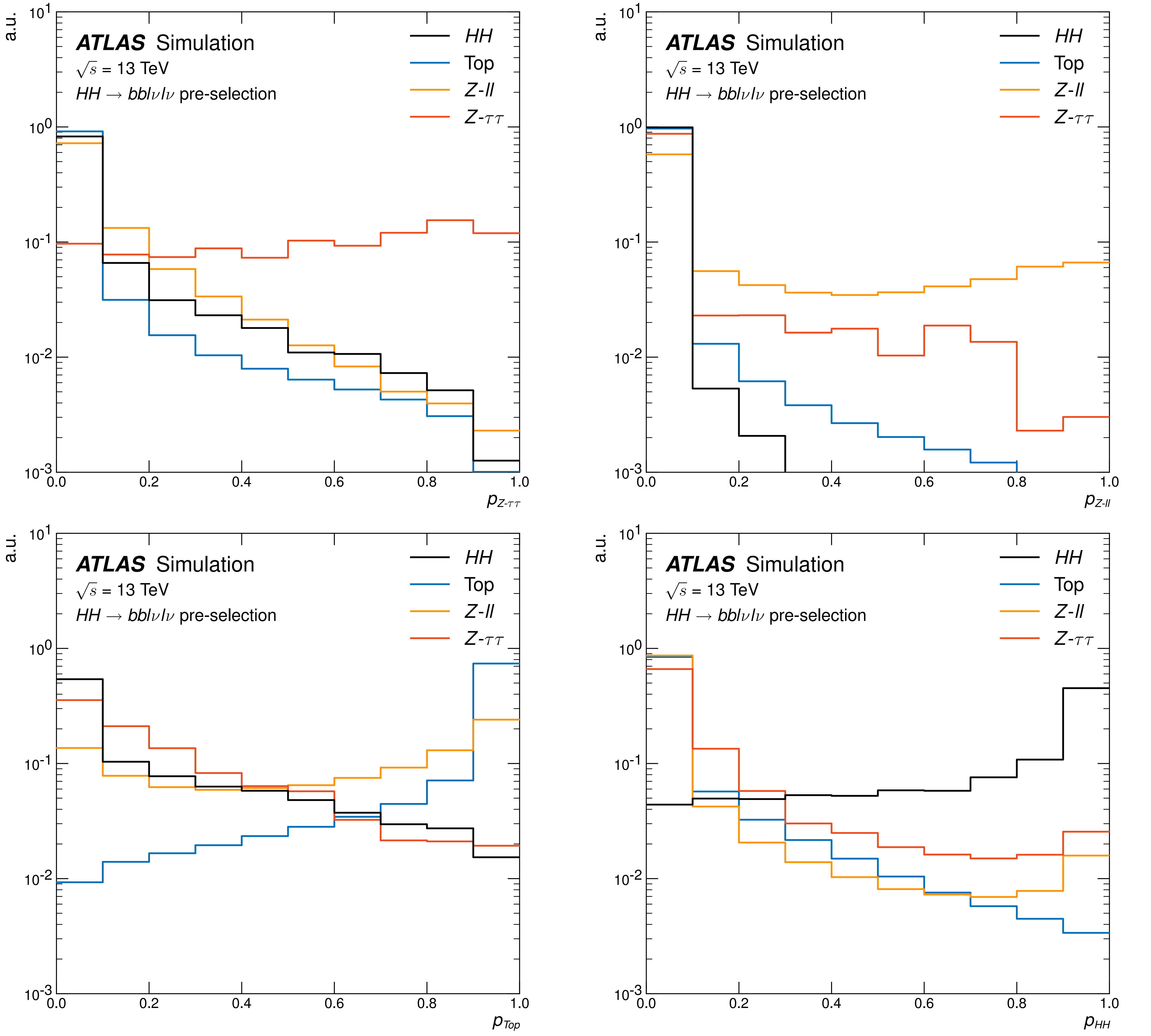
[Phys. Lett. B 801 (2020) 135145](#) [HDBS-2018-33](#)

- Machine Learning approach to target *HH*
  - Multi-class neural network
  - Signal trained on *HH*→*bbWW* component only, due to larger branching fraction
  - Final discriminant build from the class outputs

(p_T, η, ϕ)
Dilepton flavour
$\Delta R_{\ell\ell}, |\Delta\phi_{\ell\ell}|$
$m_{\ell\ell}, p_T^{\ell\ell}$
$E_{\mathrm{T}}^{\mathrm{miss}}, E_{\mathrm{T}}^{\mathrm{miss}}\text{-}\phi$
$|\Delta\phi(\mathbf{p}_{\mathrm{T}}^{\mathrm{miss}}, \mathbf{p}_{\mathrm{T}}^{\ell\ell})|$
$|\mathbf{p}_{\mathrm{T}}^{\mathrm{miss}} + \mathbf{p}_{\mathrm{T}}^{\ell\ell}|$
Jet multiplicities
$|\Delta\phi_{bb}|$
m_{T2}^{bb}

$$H_{\mathrm{T2}} = |\mathbf{p}_{\mathrm{T}}^{\mathrm{miss}} + \mathbf{p}_{\mathrm{T}}^{\ell,0} + \mathbf{p}_{\mathrm{T}}^{\ell,1}| + |\mathbf{p}_{\mathrm{T}}^{b,0} + \mathbf{p}_{\mathrm{T}}^{b,1}|$$

$$H_{\mathrm{T2}}^{\mathrm{R}} = H_{\mathrm{T2}}/(E_{\mathrm{T}}^{\mathrm{miss}} + |\mathbf{p}_{\mathrm{T}}^{\ell,0}| + |\mathbf{p}_{\mathrm{T}}^{\ell,1}| + |\mathbf{p}_{\mathrm{T}}^{b,0}| + |\mathbf{p}_{\mathrm{T}}^{b,1}|)$$



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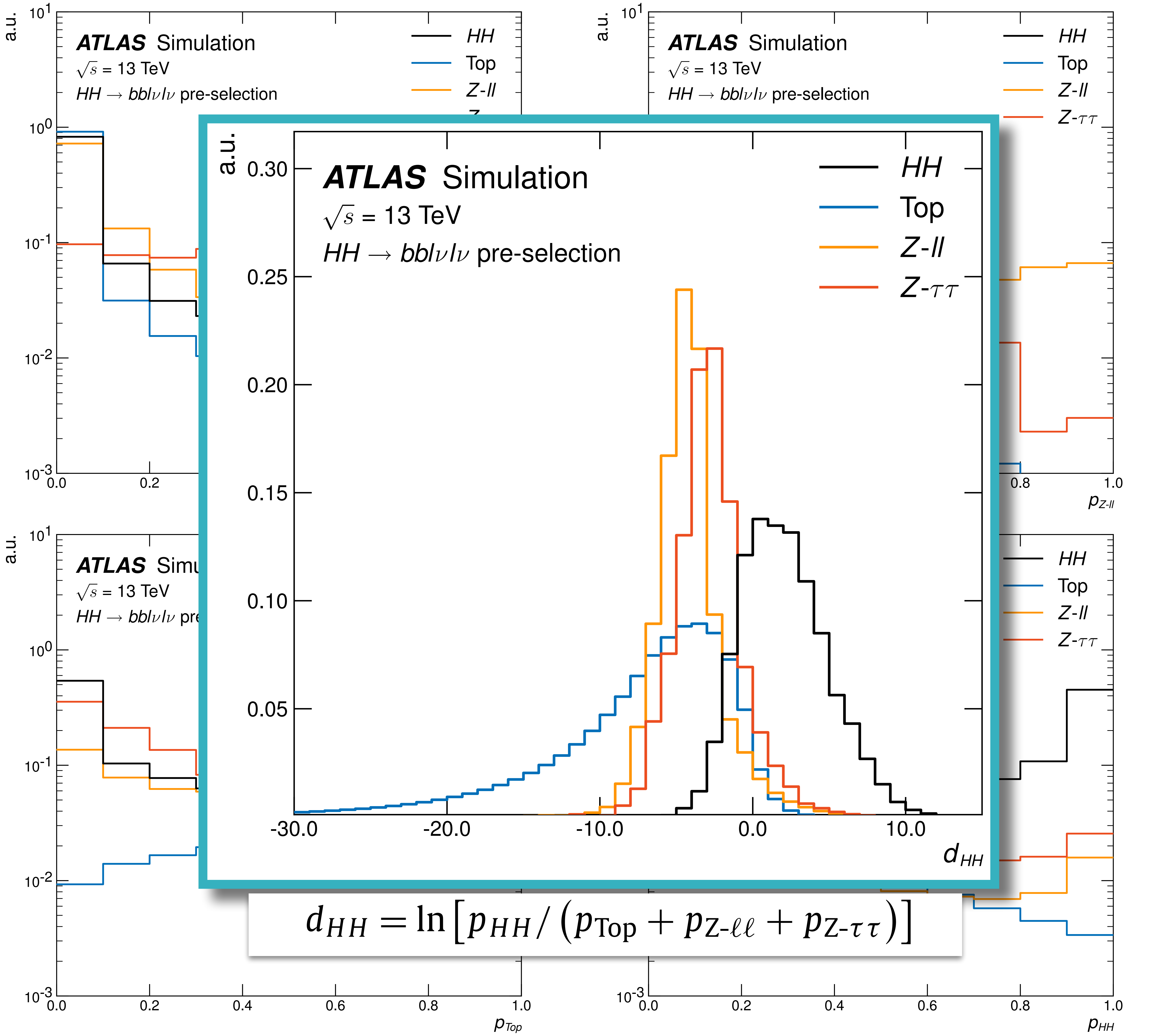

$$d_{HH} = \ln\left[p_{HH}/\left(p_{\mathrm{Top}} + p_{Z\text{-}\ell\ell} + p_{Z\text{-}\tau\tau}\right)\right]$$

Non-resonant $HH \rightarrow bbl\nu l\nu$

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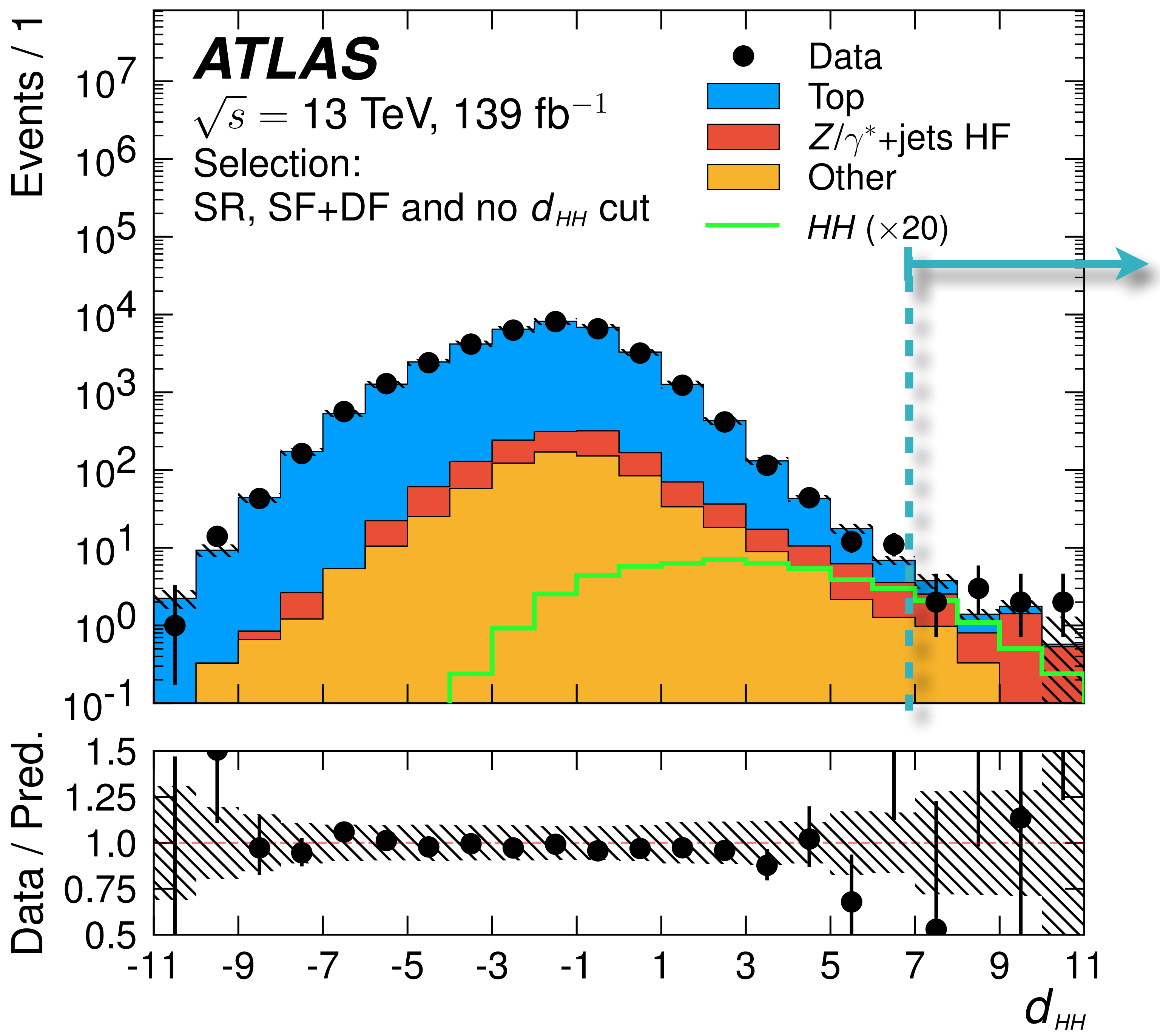
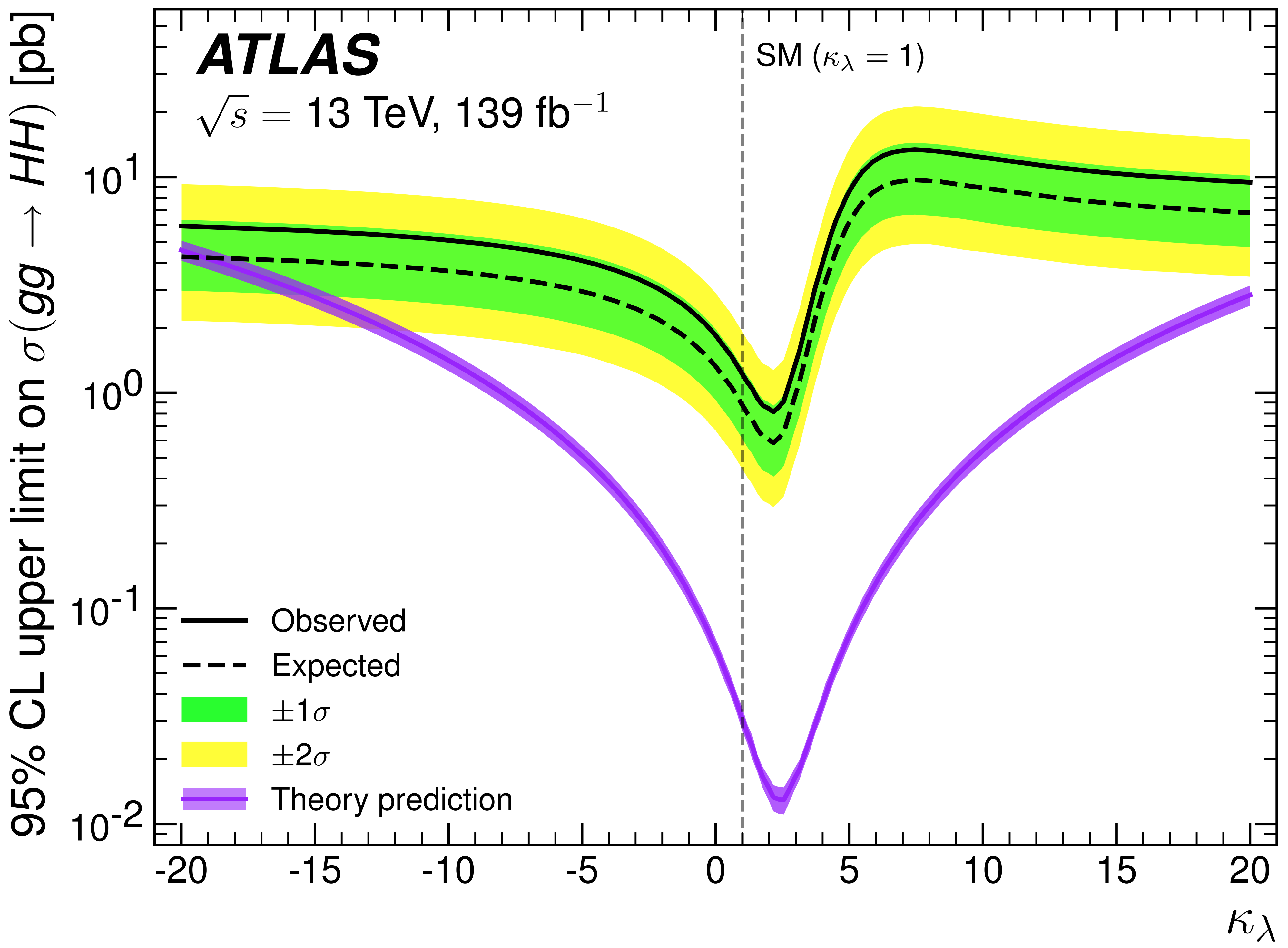


- Current analysis not optimized for a κ_λ scan



- Significant improvements in analysis techniques leading to improvements in sensitivity
  - CMS $HH \rightarrow bbl\nu jj$ @36 fb^{-1} σ_{EXP}/σ_{SM} = 89 JHEP 01 (2018) 054

	-2σ	-1σ	**Expected**	$+1\sigma$	$+2\sigma$	**Observed**
$\sigma(gg \rightarrow HH)$ [pb]	0.5	0.6	0.9	1.3	1.9	1.2
$\sigma(gg \rightarrow HH)/\sigma^{SM}(gg \rightarrow HH)$	14	20	29	43	62	40

VBF $HH \rightarrow bbbb$

VBF $HH \rightarrow bbbb$

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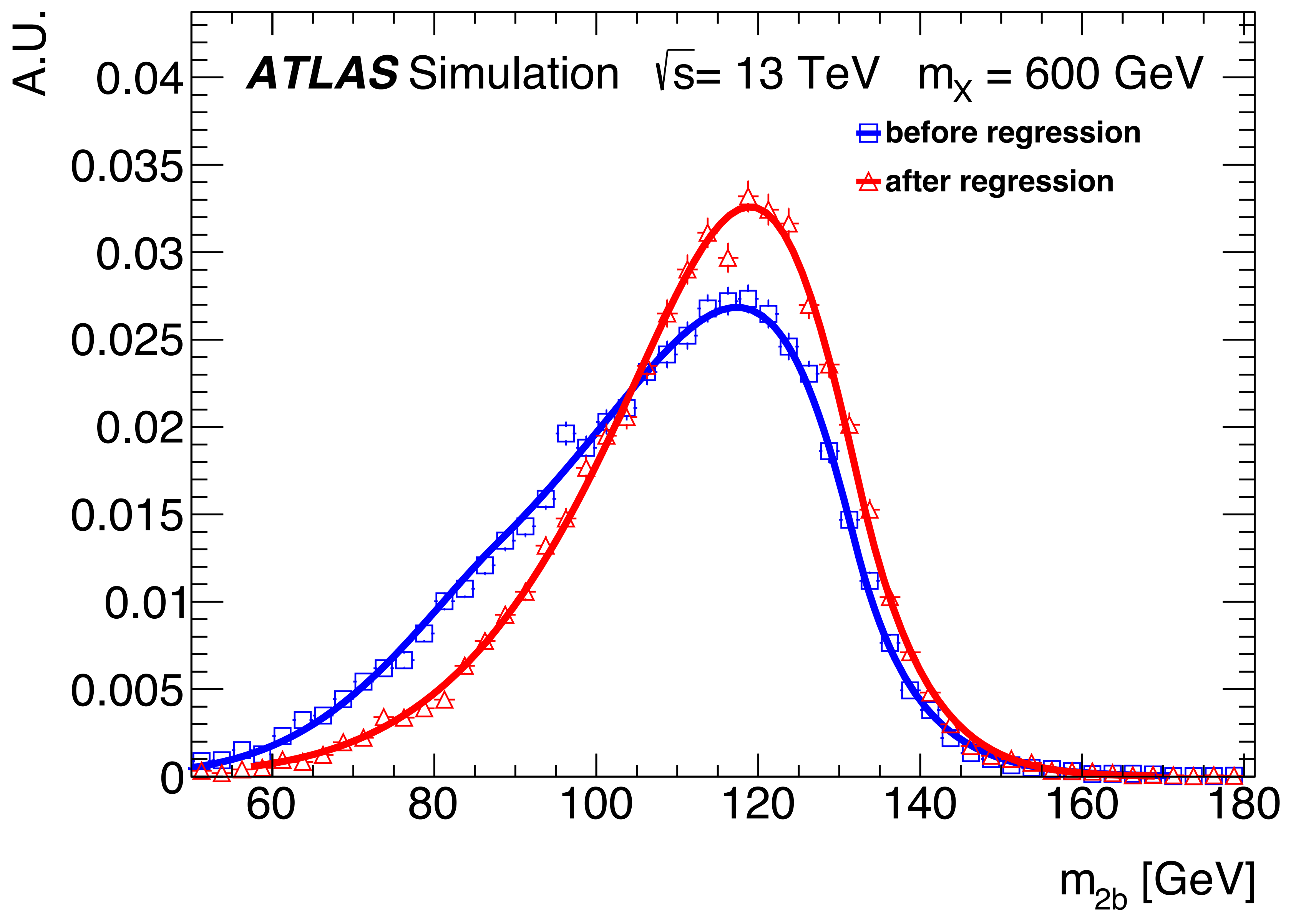
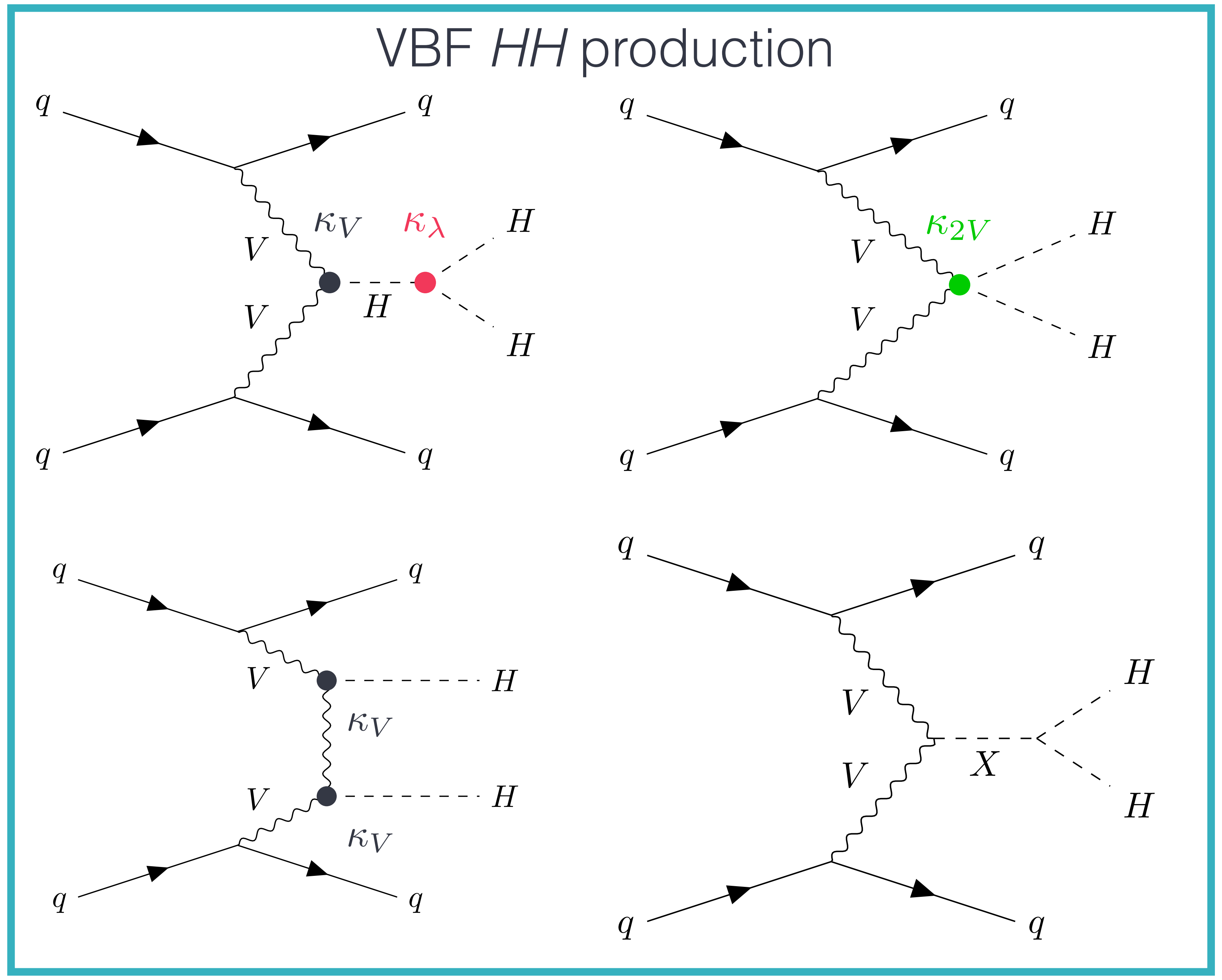
- Focuses on Vector Boson Fusion production
  - VBF searches make it possible to probe κ_{2V}
    - *ggF* production searches are more sensitive to κ_λ
  - Characterized by presence of two jets with large rapidity gap
- Dominant background contributions from *tt* and Multijet events
- Corrections to b-jet energy derived using Boosted Decision Tree improve m_{bb} resolution





VBF $HH \rightarrow bbbb$

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- Combinatorics of the *4b* system play an important role
  - Pairs of b-jets with invariant mass close to m_H should be optimal
  - Pairs that minimize D_{HH} are selected as Higgs candidates

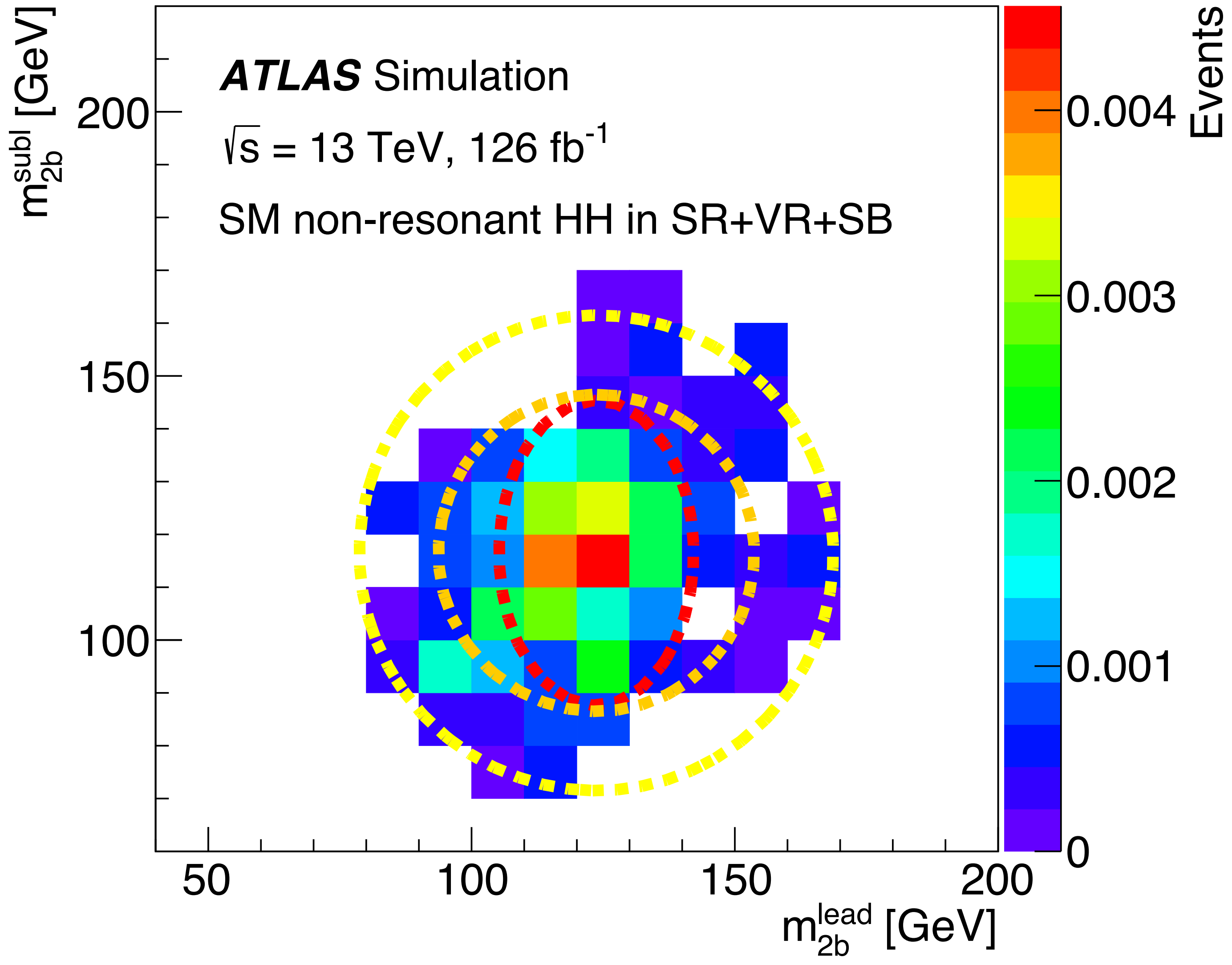
$$D_{HH} = \sqrt{(m_{2b}^{\text{lead}})^2 + (m_{2b}^{\text{subl}})^2} \left| \sin\left(\tan^{-1}\left(\frac{m_{2b}^{\text{subl}}}{m_{2b}^{\text{lead}}}\right) - \tan^{-1}\left(\frac{116.5}{123.7}\right)\right)\right|$$

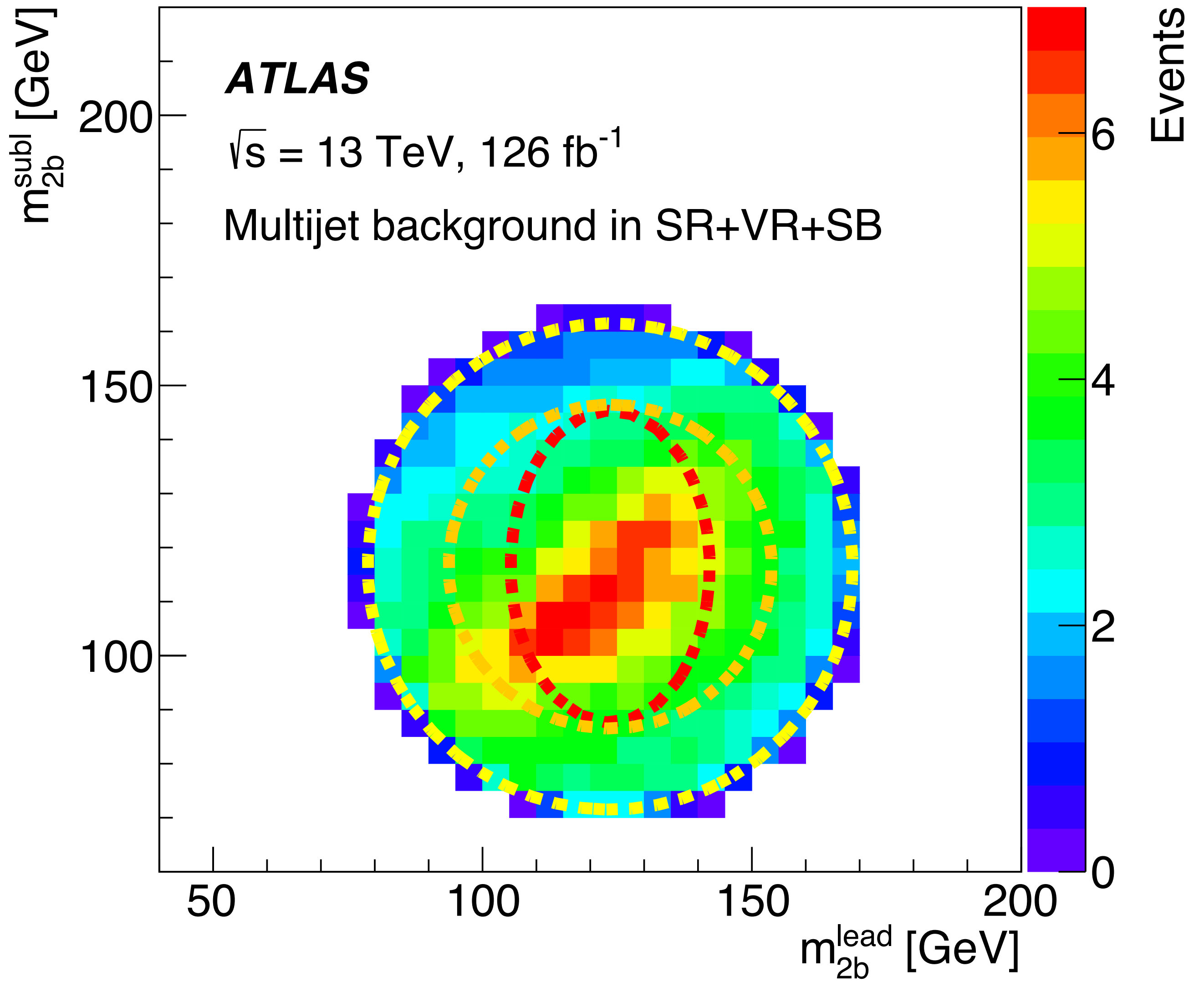
- Signal, Validation and Sideband regions are defined in mass plane of the two Higgs candidates

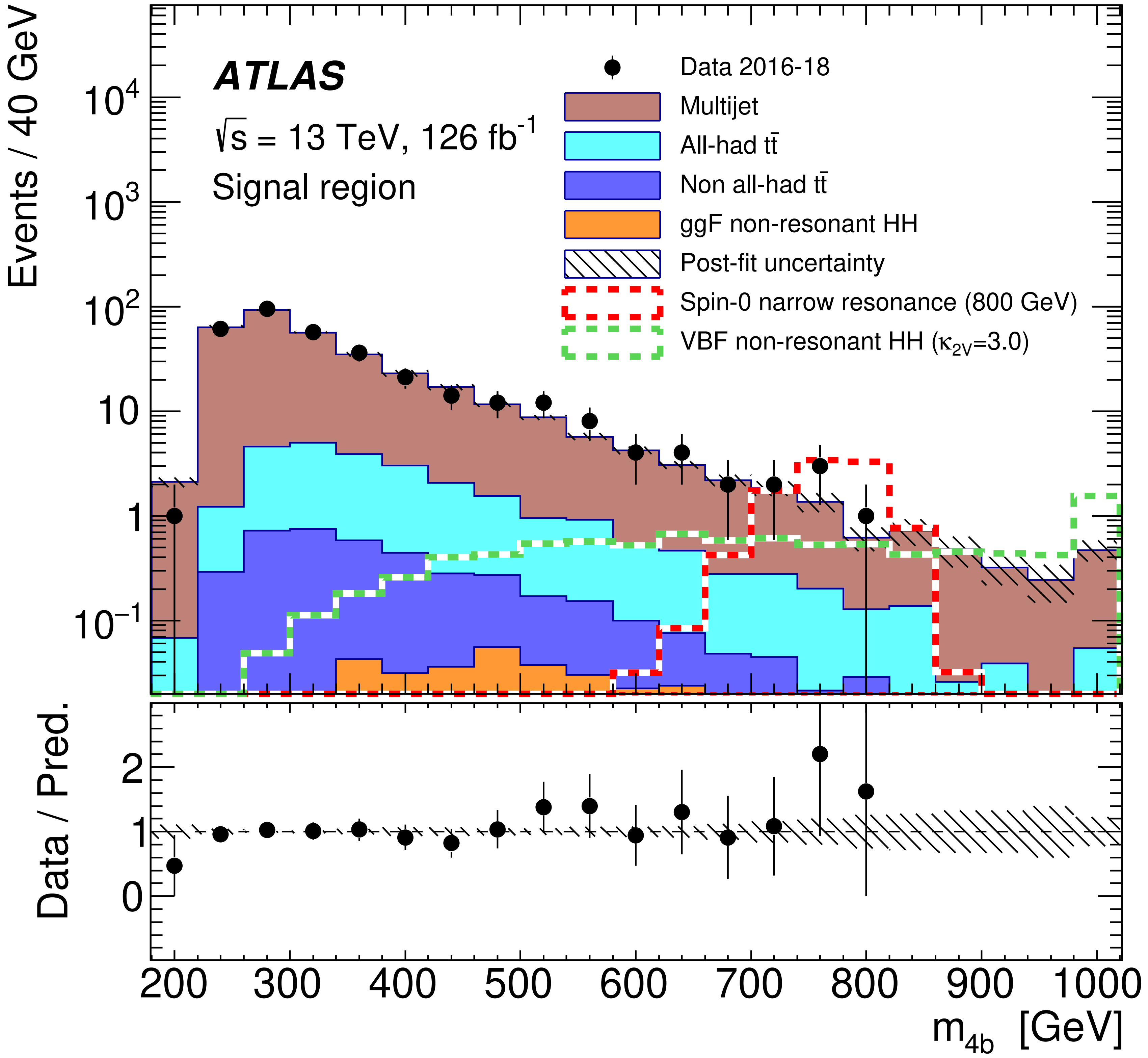
SR defined by

$$X_{HH} = \sqrt{\left(\frac{m_{2b}^{\text{lead}} - 123.7\text{ GeV}}{11.6\text{ GeV}}\right)^2 + \left(\frac{m_{2b}^{\text{subl}} - 116.5\text{ GeV}}{18.1\text{ GeV}}\right)^2} < 1.6$$

Invariant mass of selected b-jets used as final discriminant







VBF $HH \rightarrow bbbb$

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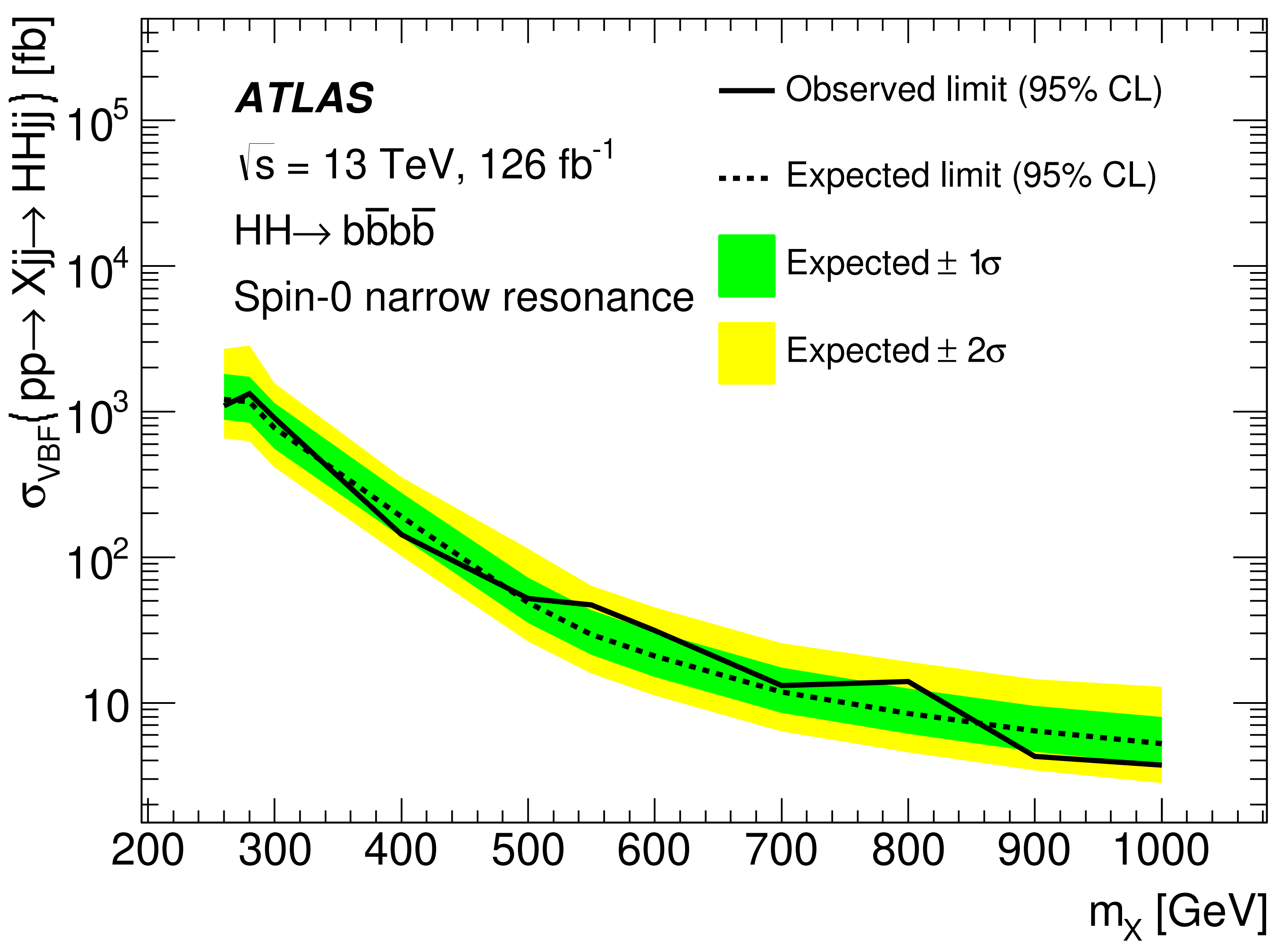
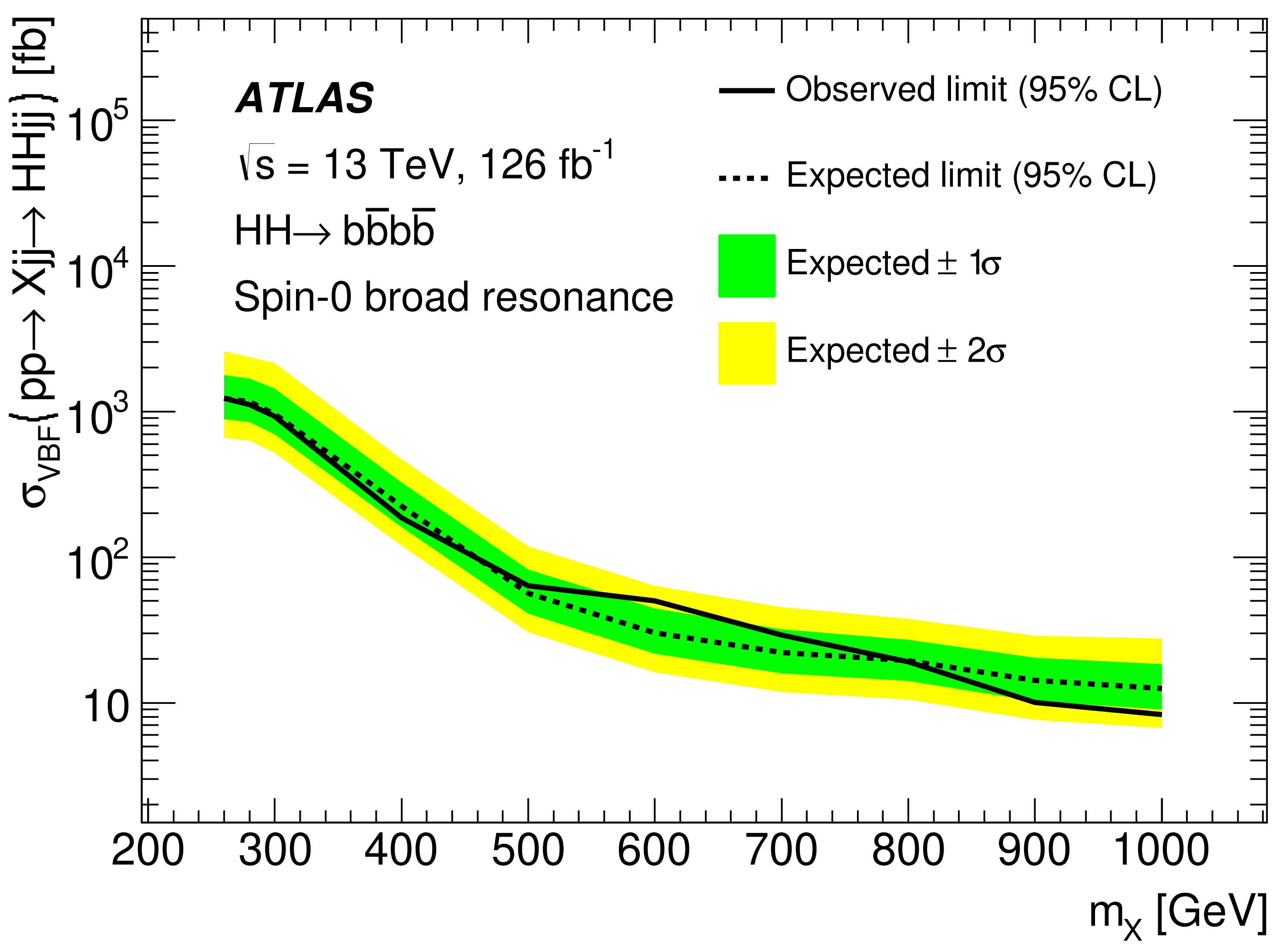
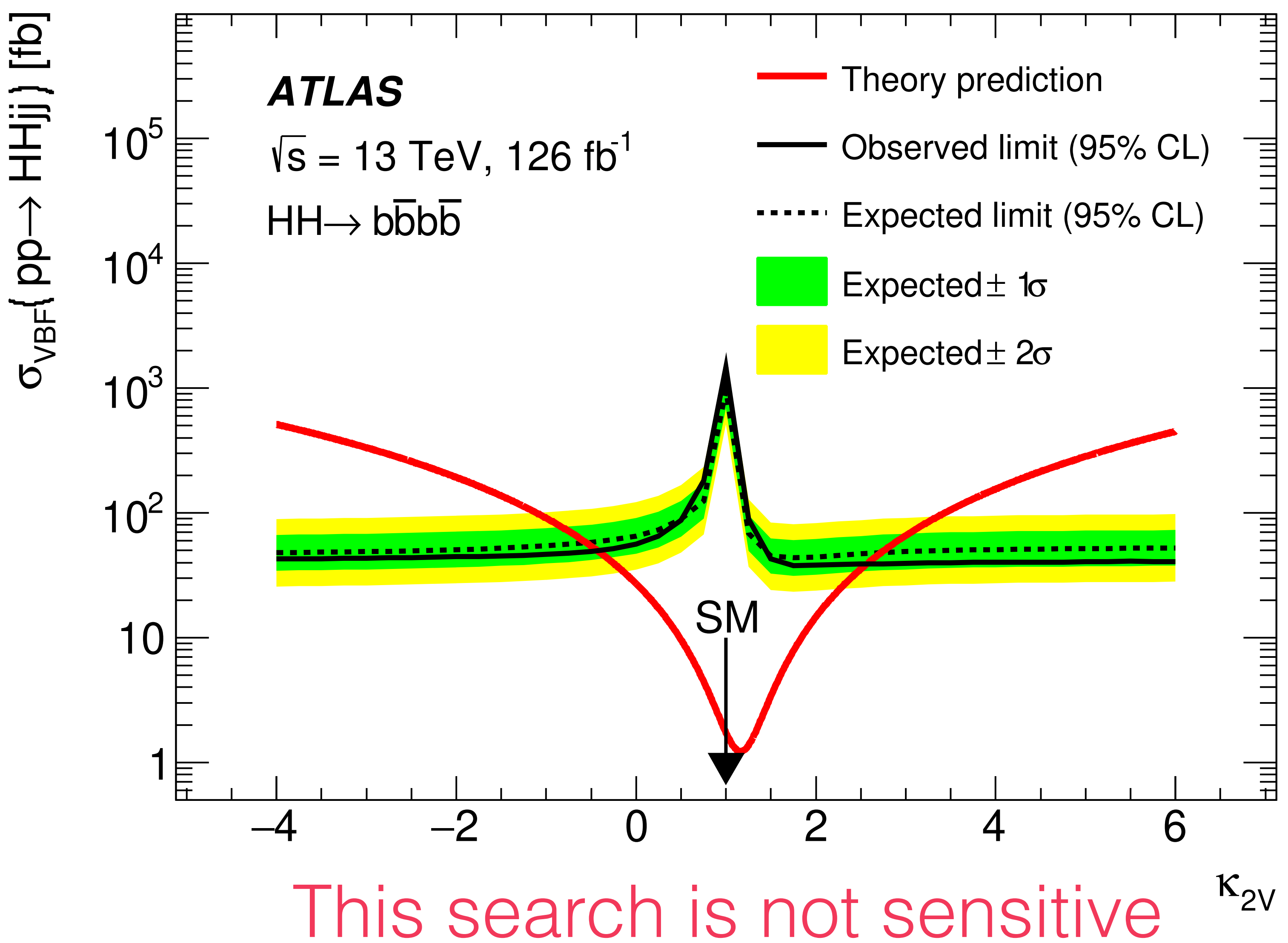
- Limits set for two Spin-0 scenarios
  - Narrow fixed width (4 GeV)
  - 2HDM Type II, *tan(β)* = 2.0, *sin(β-α)* = 0.6
    - α mixing between CP-even Higgs bosons





- κ_{2V} exclusion
  - Expected: κ_{2V} < -0.91, κ_{2V} > 3.11
  - Observed: κ_{2V} < -0.76, κ_{2V} > 2.90
  - κ_{2V}=0 not yet excluded

	Observed	-2σ	-1σ	Expected	$+1\sigma$	$+2\sigma$
σ_{VBF} [fb]	1460	510	690	950	1330	1780
$\sigma_{\mathrm{VBF}}/\sigma_{\mathrm{VBF}}^{\mathrm{SM}}$	840	290	400	550	770	1030

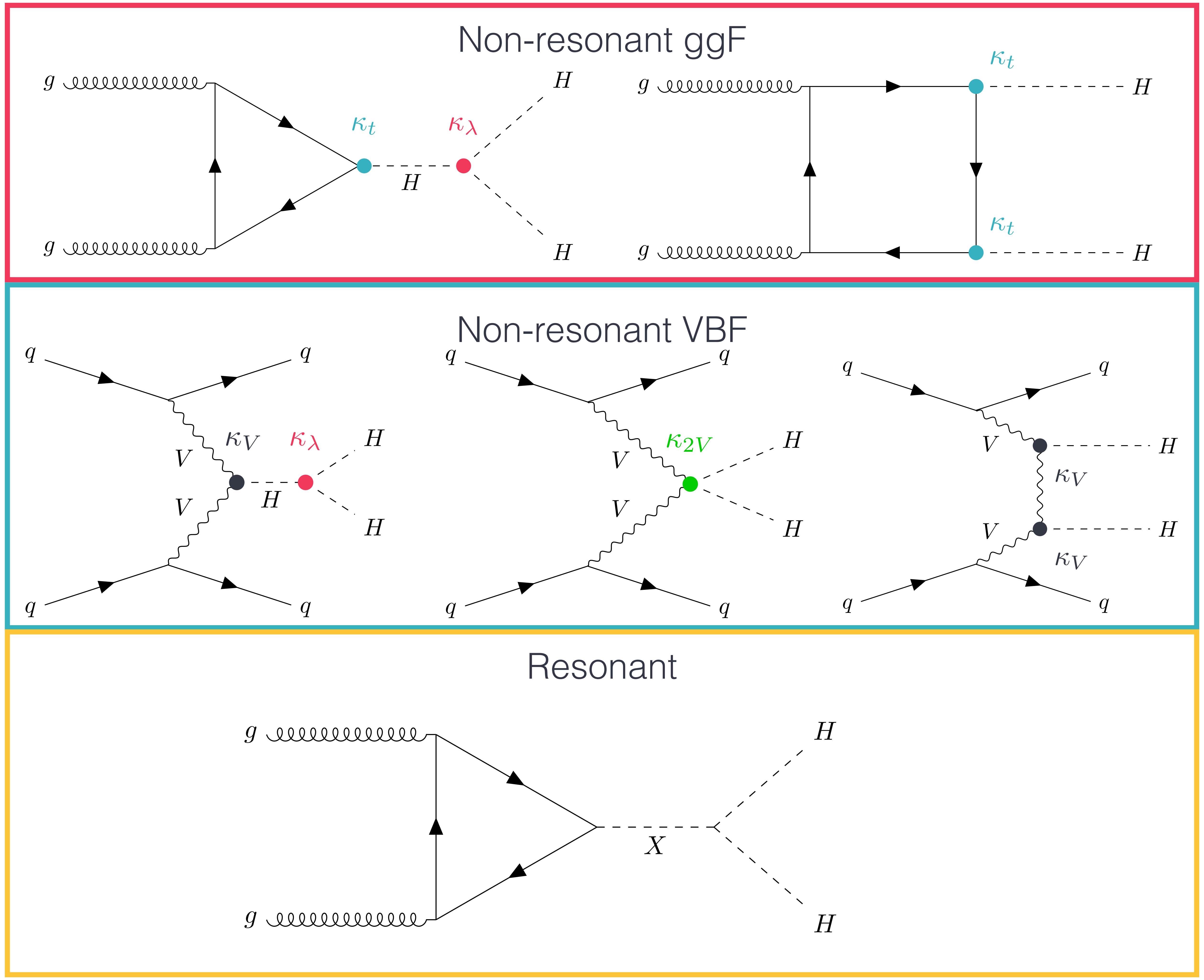


This search is not sensitive to SM (κ_{2V}=1)

$HH \rightarrow bb\gamma\gamma$

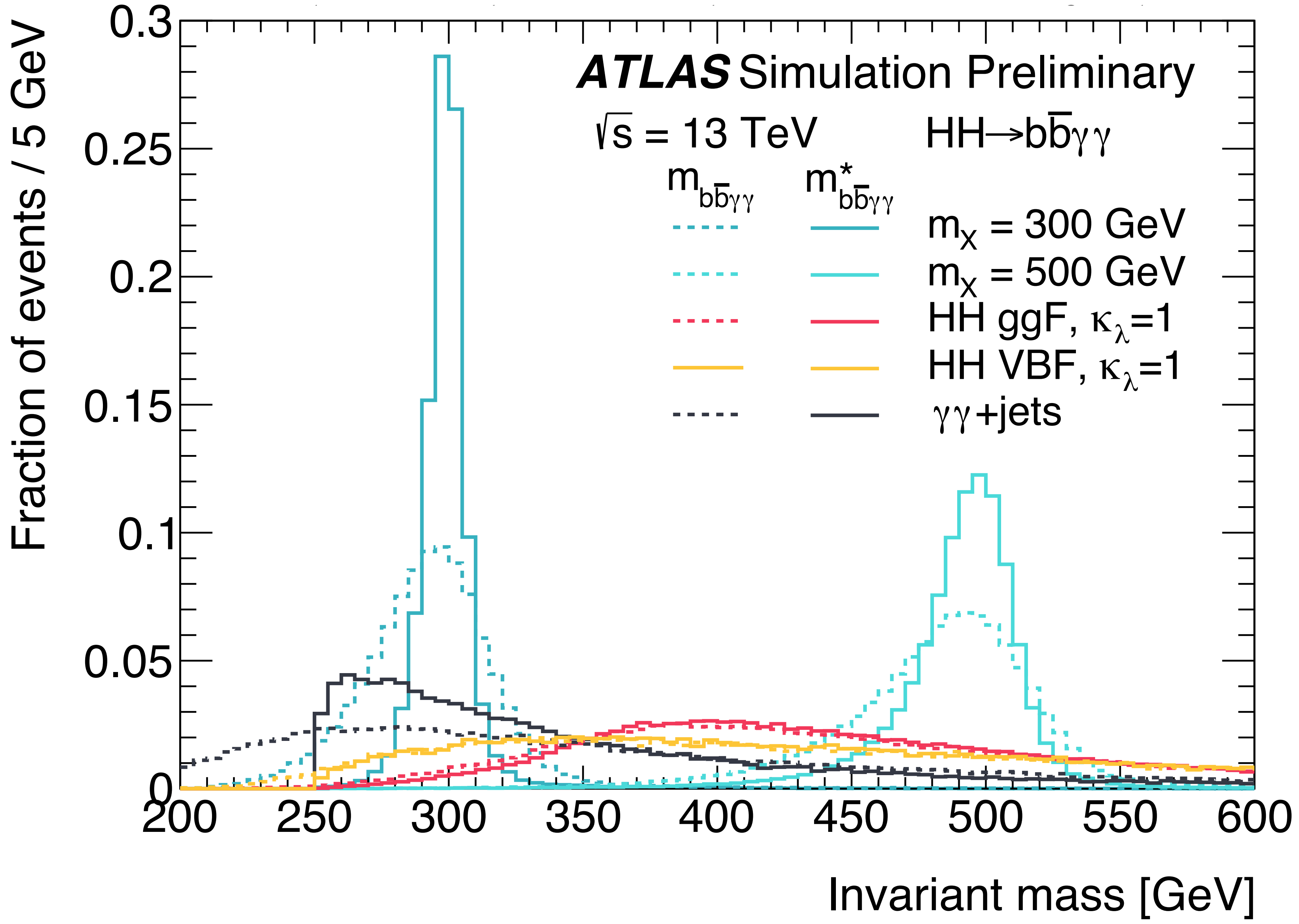
$HH \rightarrow bb\gamma\gamma$

ATLAS-CONF-2021-016



- *ggF* and *VBF* production mechanisms are considered in order to increase sensitivity to κ_λ (optimized for *ggF*)
- Events are selected based on presence of two photons with mass $105 < m_{\gamma\gamma} < 160$
- Extensive use of multivariate techniques for signal discrimination
- Detector resolution effects mitigated by definition of $m^*_{bb\gamma\gamma}$
  - Large improvements in signal sensitivity achieved

$$m^*_{b\bar{b}\gamma\gamma} = m_{b\bar{b}\gamma\gamma} - m_{b\bar{b}} - m_{\gamma\gamma} + 250 \text{ GeV}$$



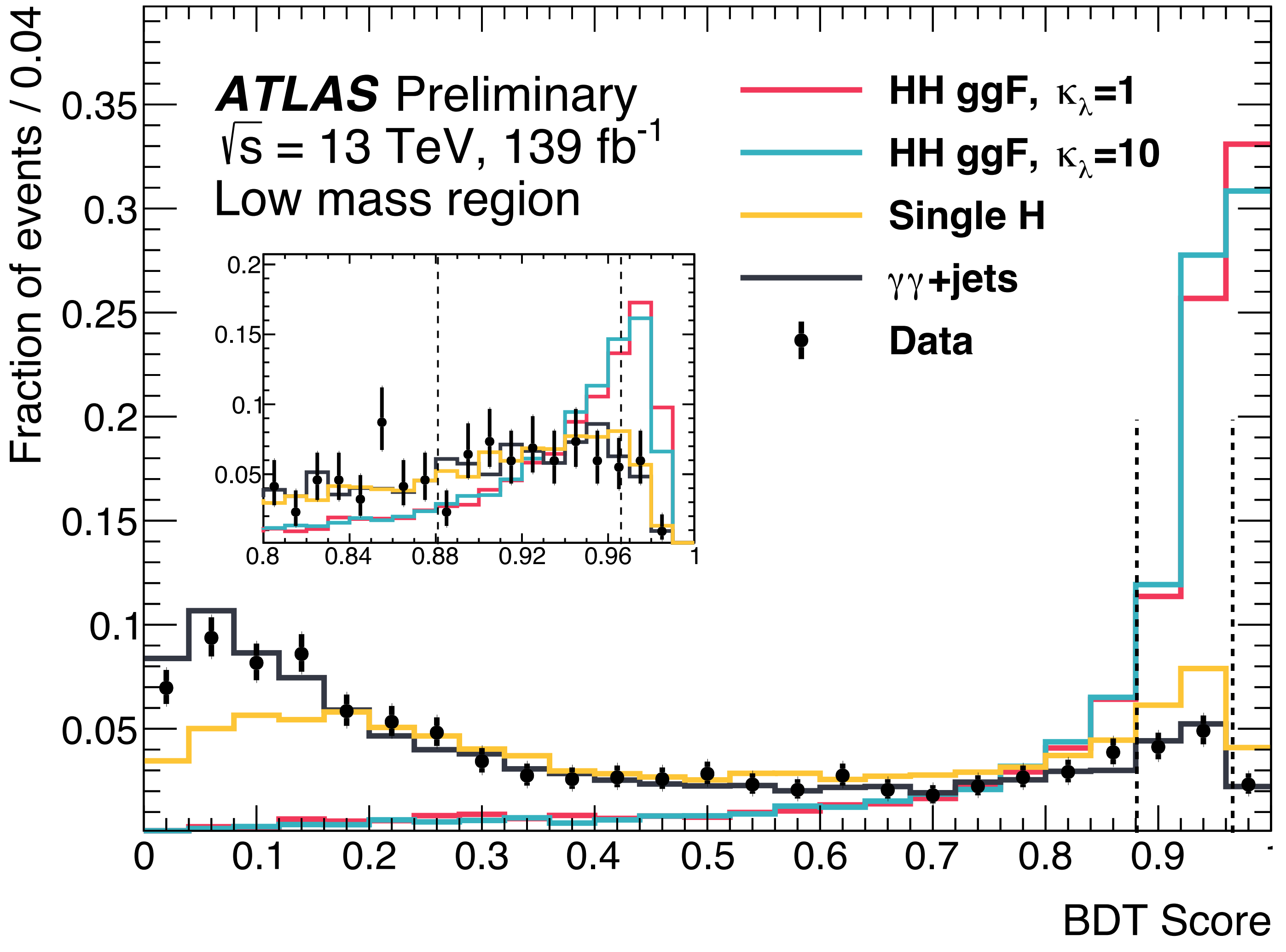
HH→bbγγ

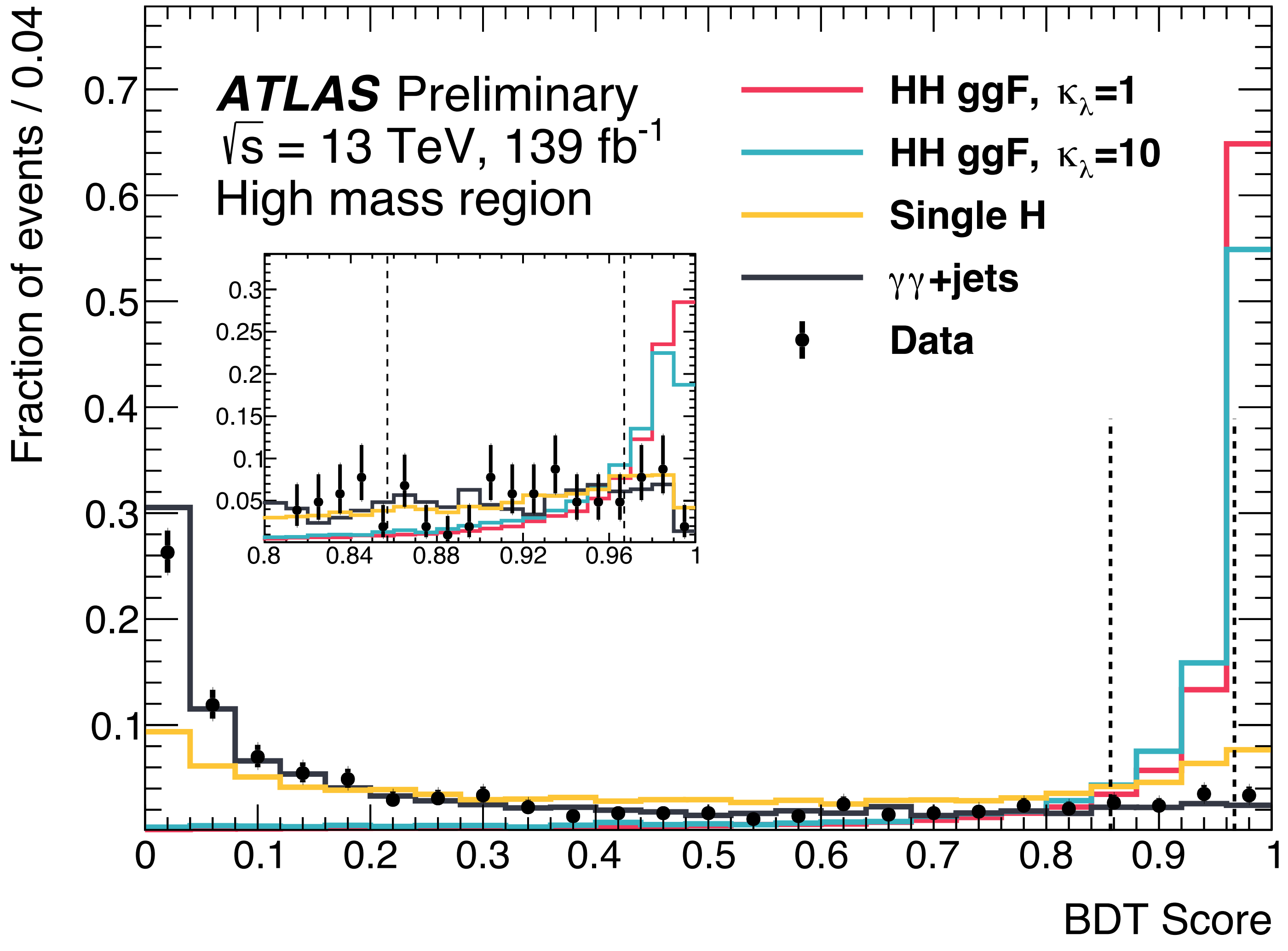
ATLAS-CONF-2021-016

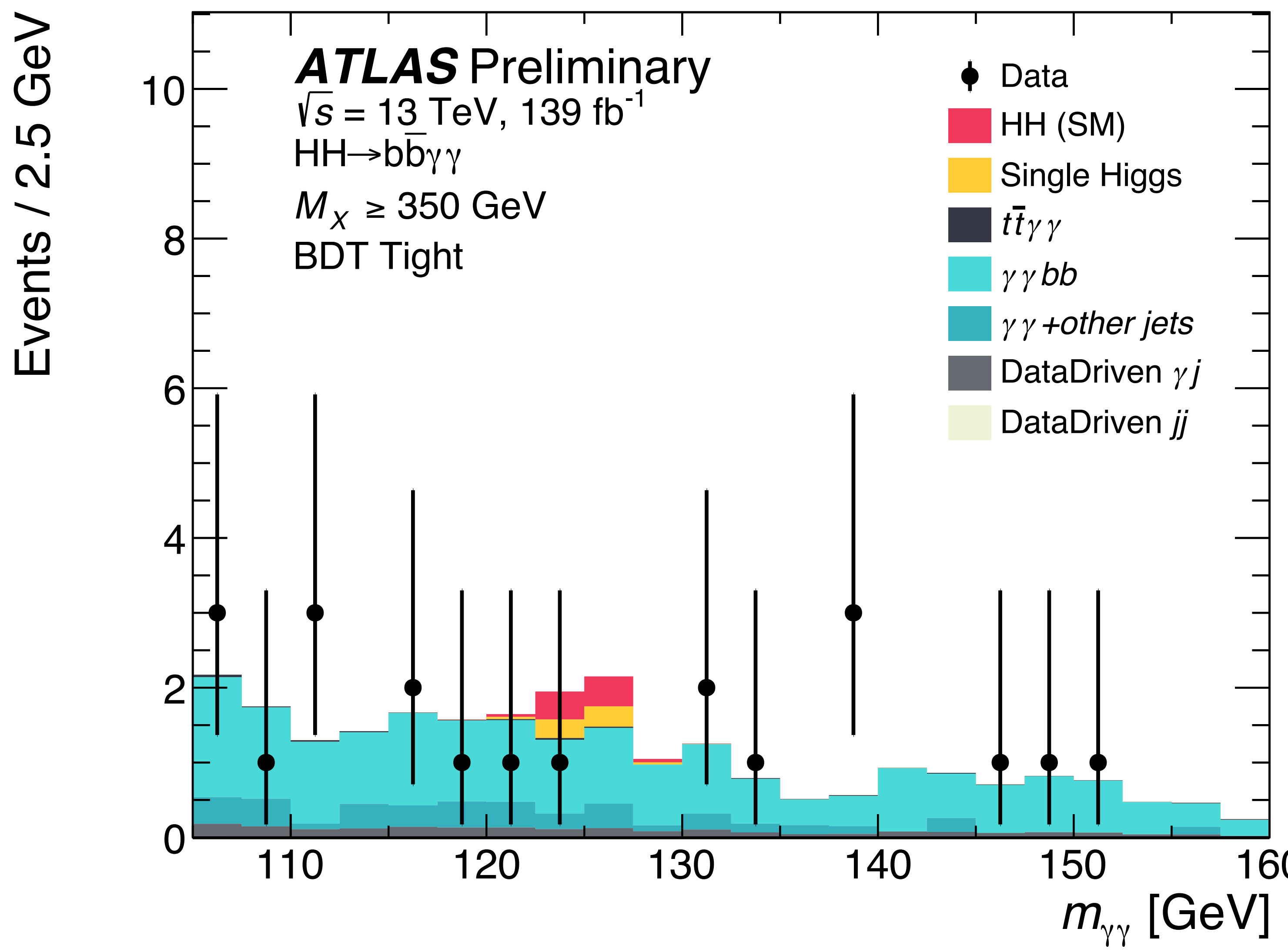
Non-resonant selection

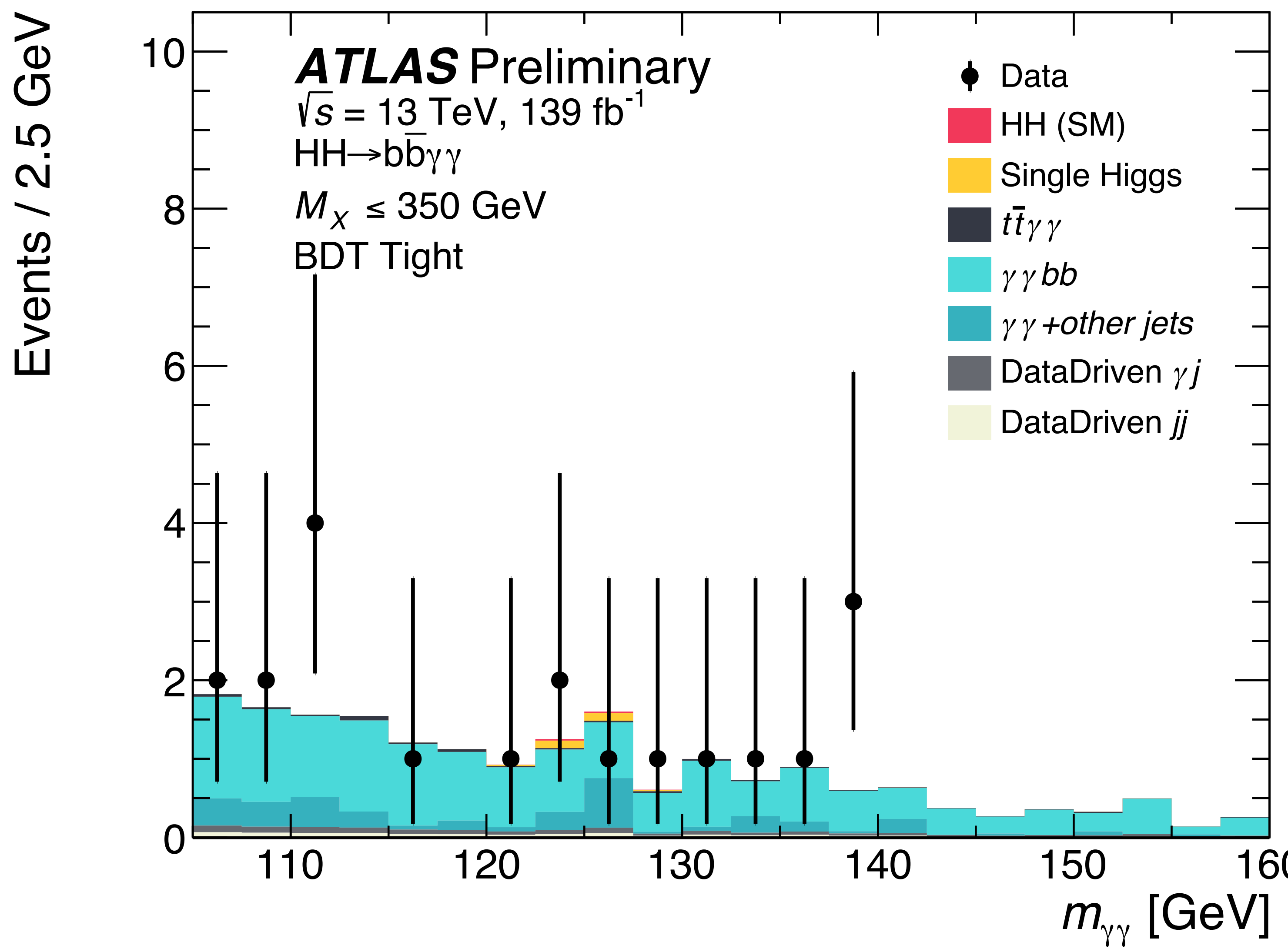
- Dedicated BDTs are used in the low mass ($m^*_{bb\gamma\gamma} < 350$ GeV, trained on $\kappa_\lambda=1$ signal) and high mass regions ($m^*_{bb\gamma\gamma} \geq 350$ GeV, trained on $\kappa_\lambda=10$ signal)
  - Exploits kinematic properties of signal and background and b-tagging information

Category	Selection criteria
High mass BDT tight	$m^*_{b\bar{b}\gamma\gamma} \geq 350$ GeV, BDT score $\in [0.967, 1]$
High mass BDT loose	$m^*_{b\bar{b}\gamma\gamma} \geq 350$ GeV, BDT score $\in [0.857, 0.967]$
Low mass BDT tight	$m^*_{b\bar{b}\gamma\gamma} < 350$ GeV, BDT score $\in [0.966, 1]$
Low mass BDT loose	$m^*_{b\bar{b}\gamma\gamma} < 350$ GeV, BDT score $\in [0.881, 0.966]$









HH→bbγγ

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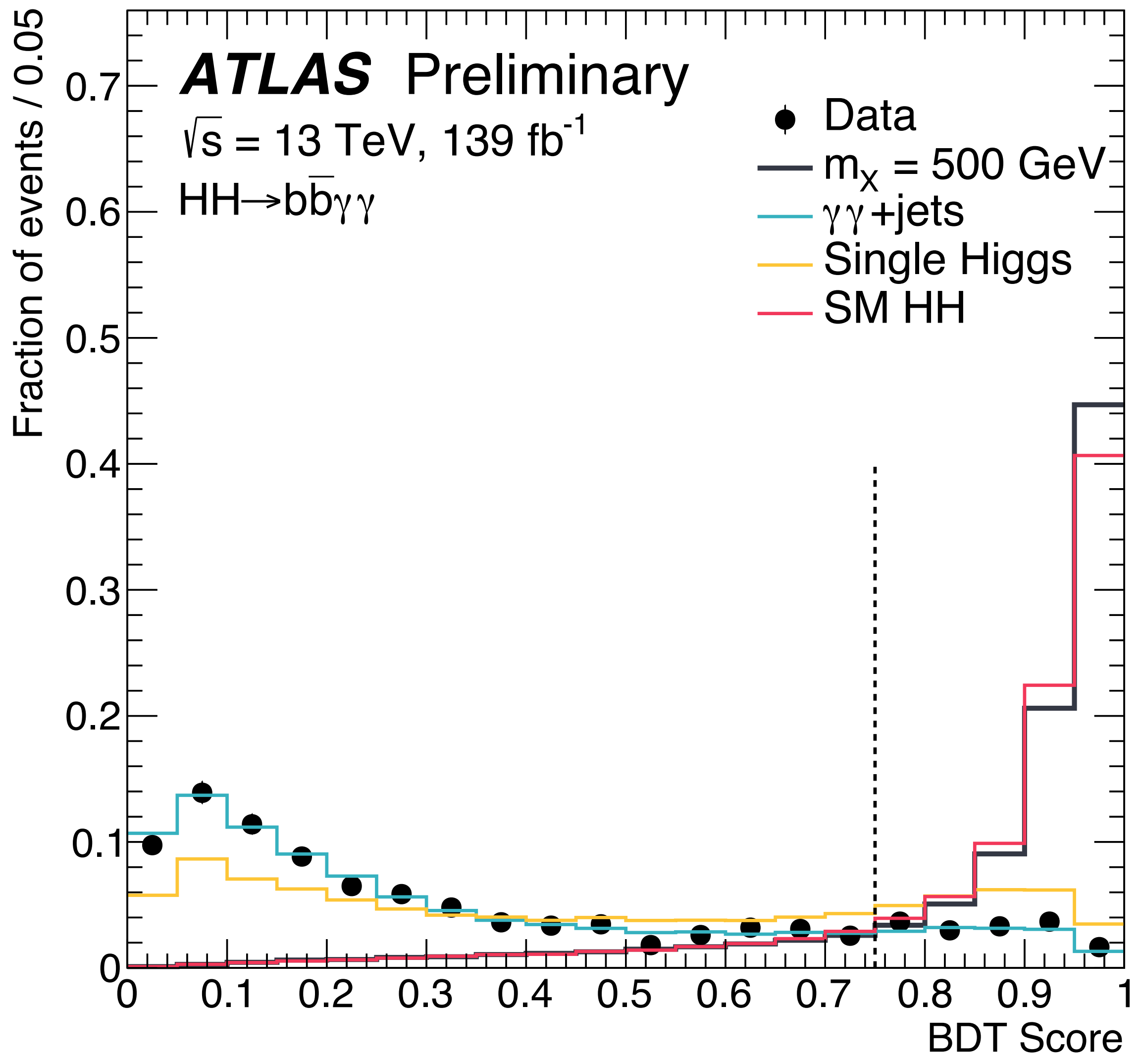
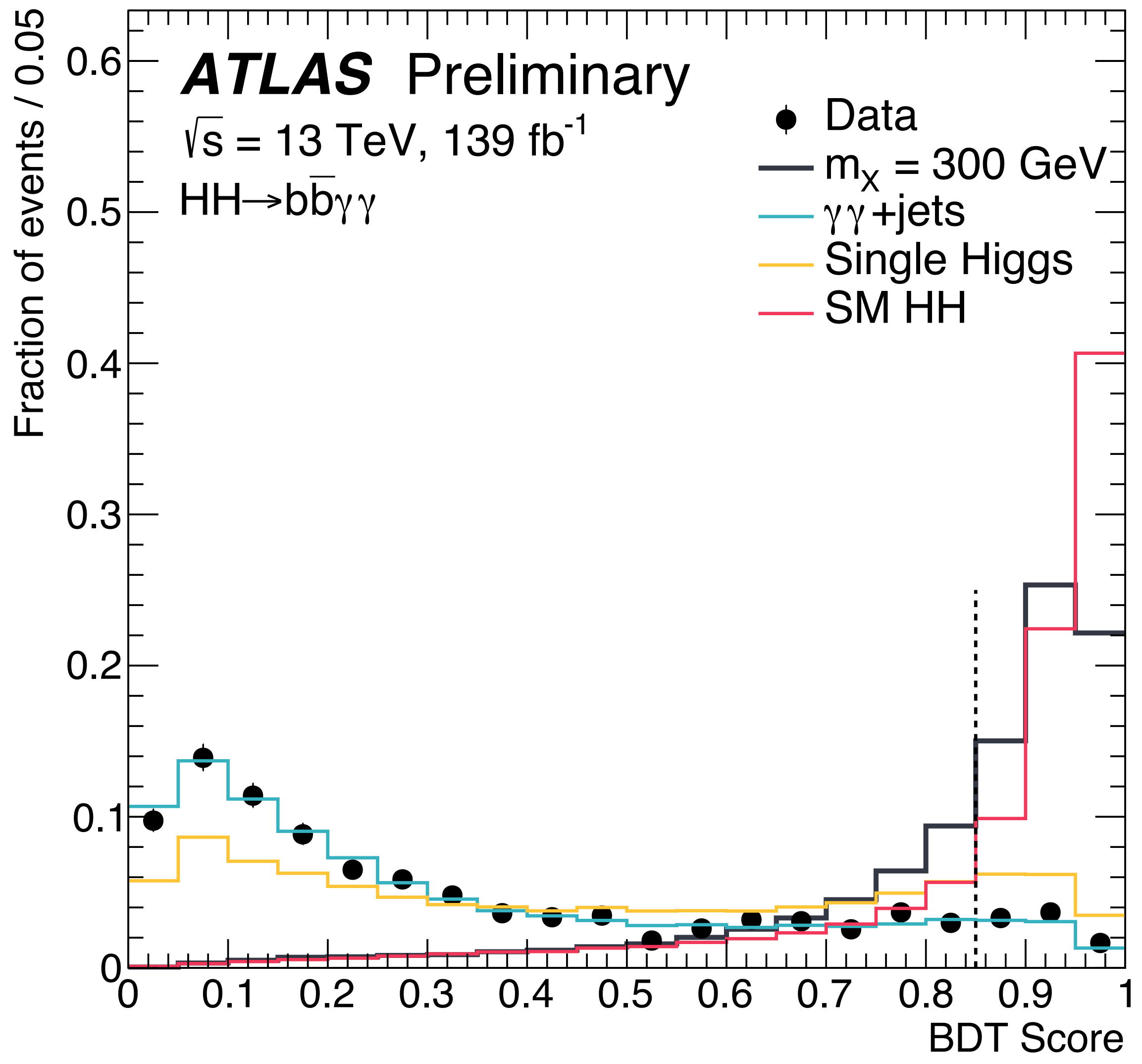
Resonant selection

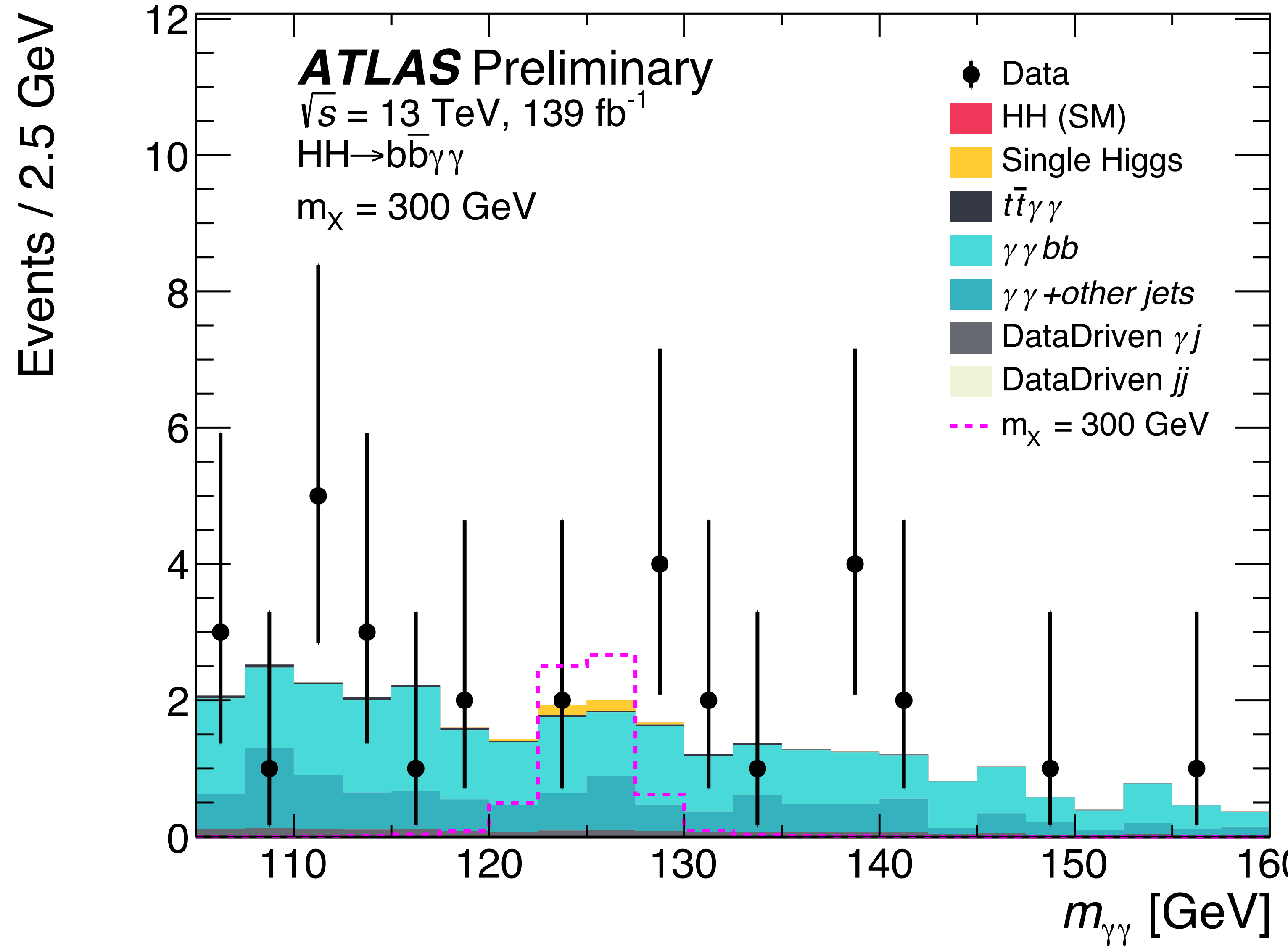
- Two BDTs are used to separate signal from background
  - *γγ + ttγγ*
  - *ZH + ttH*

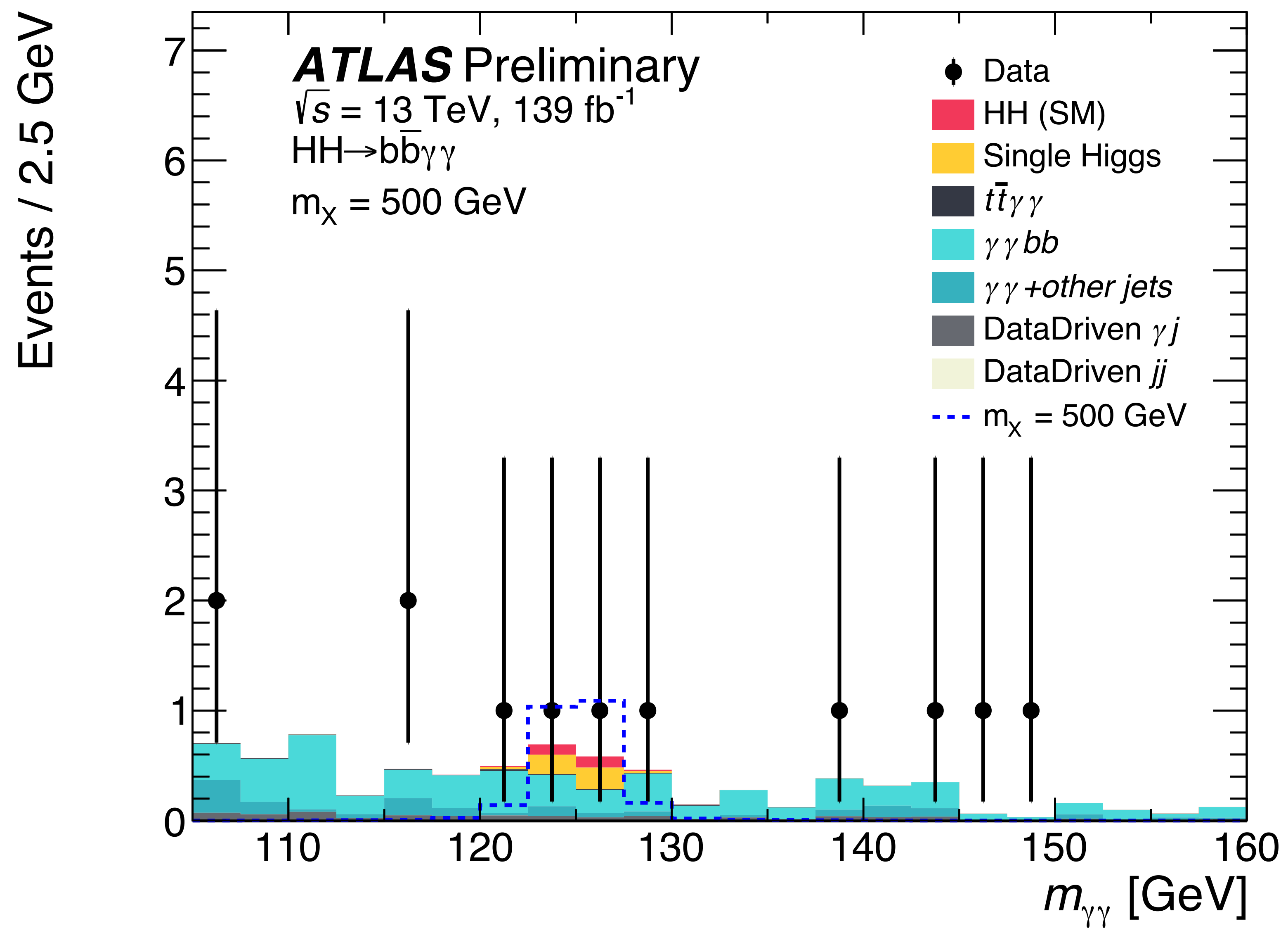
$$\mathrm{BDT_{tot}} = \frac{1}{\sqrt{C_1^2 + C_2^2}}\sqrt{C_1^2\left(\frac{\mathrm{BDT}_{\gamma\gamma}+1}{2}\right)^2 + C_2^2\left(\frac{\mathrm{BDT}_{\mathrm{Single}H}+1}{2}\right)^2}$$

- An event-by-event reweighting is applied to signal match $m^*_{bb\gamma\gamma}$ distribution of background making making BDT training independent of the resonant mass









$HH \rightarrow bb\gamma\gamma$

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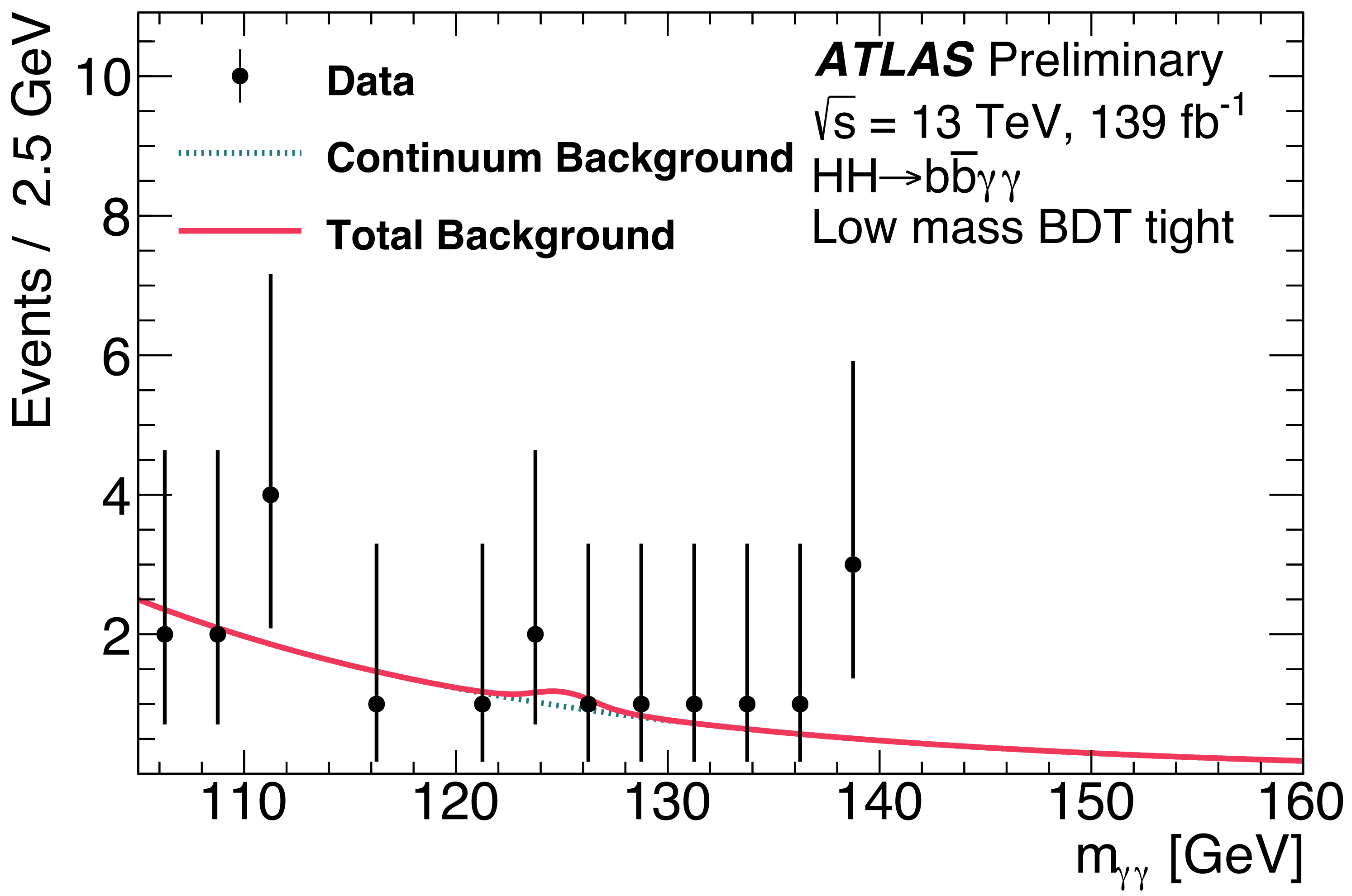
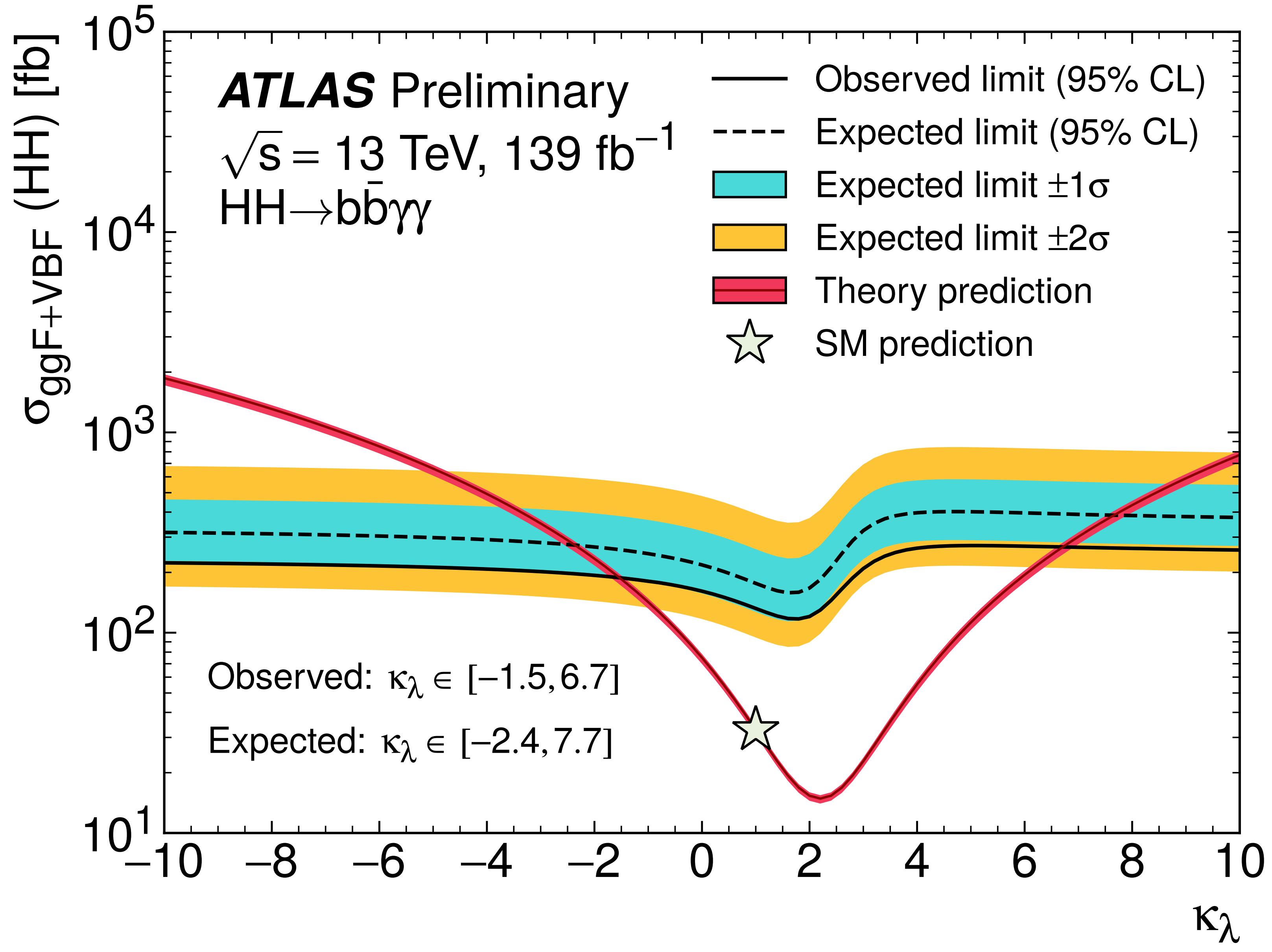
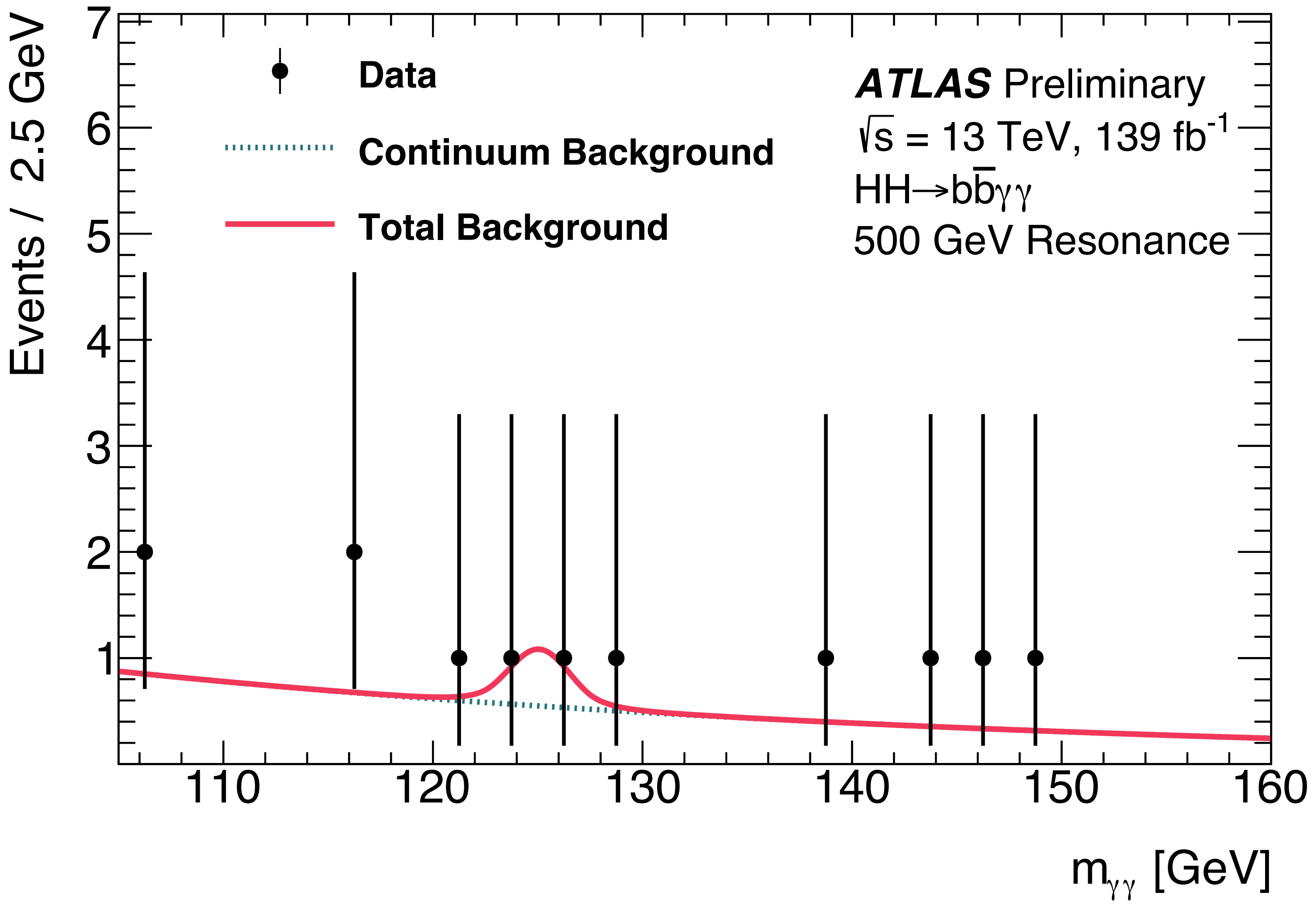
- σ_{HH} limits on non-resonant production cross section:
  - Observed: 130 fb (4.1σ_{SM})
  - Expected: 180 fb (5.5σ_{SM})
- Improvement by factor five

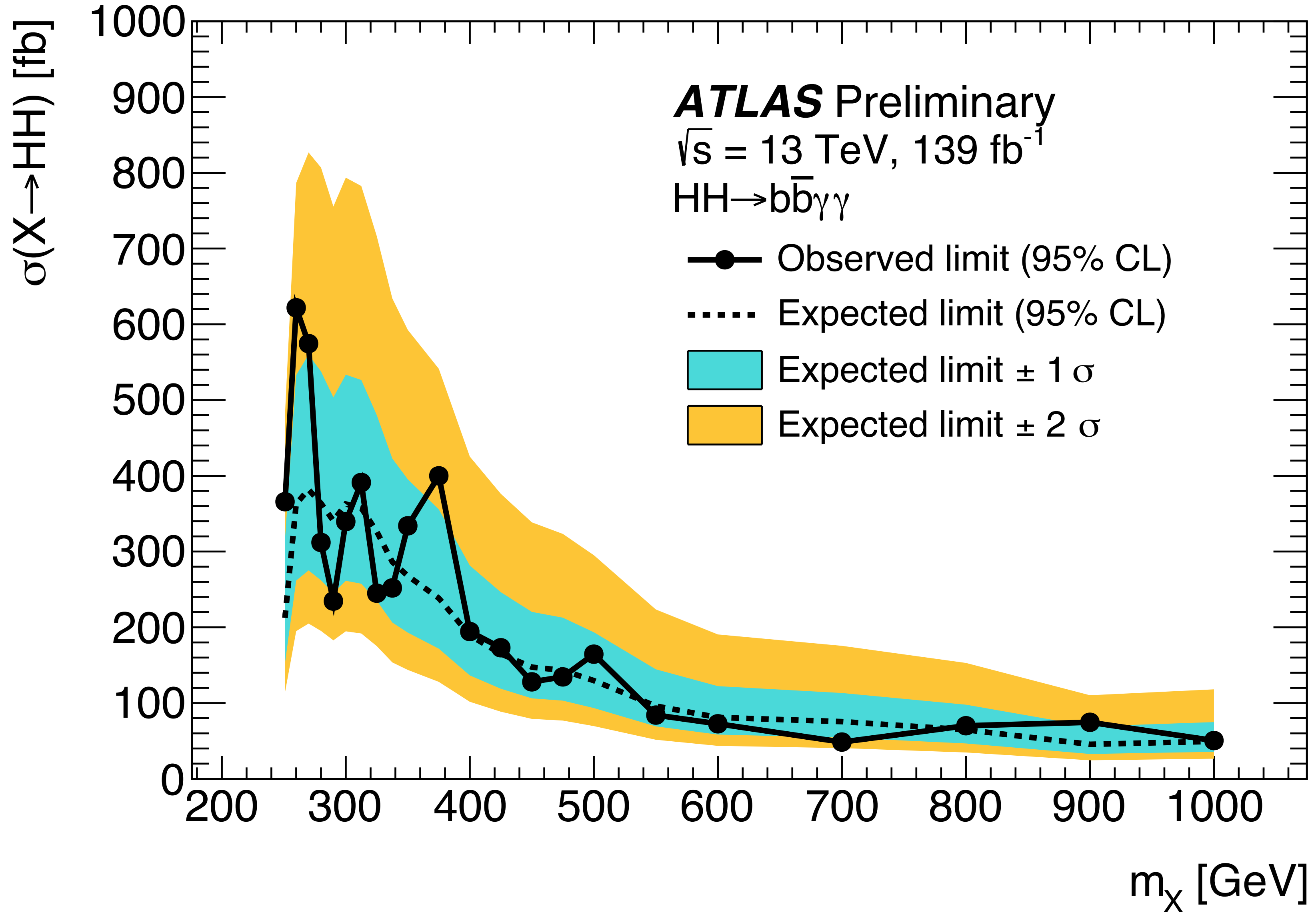
- κ_λ constraints
  - Observed: $-1.5 \leq \kappa_\lambda \leq 6.7$
  - Expected: $-2.4 \leq \kappa_\lambda \leq 7.7$
- Range shrank by factor ~2

[ATLAS @36 ifb JHEP 11 (2018) 040](#)









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Summary

- Higgs boson pair production has been probed with a number of final states
- Searches for Higgs boson pair production are a great probe of the Higgs self-coupling…slowly but steadily closing in on SM
- VBF Higgs pair production can be used to probe the *VVHH* coupling
- ATLAS continues to work with the full Run 2 dataset aiming at releasing results comprising a large number of *HH* final states
- Expect more results soon!

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