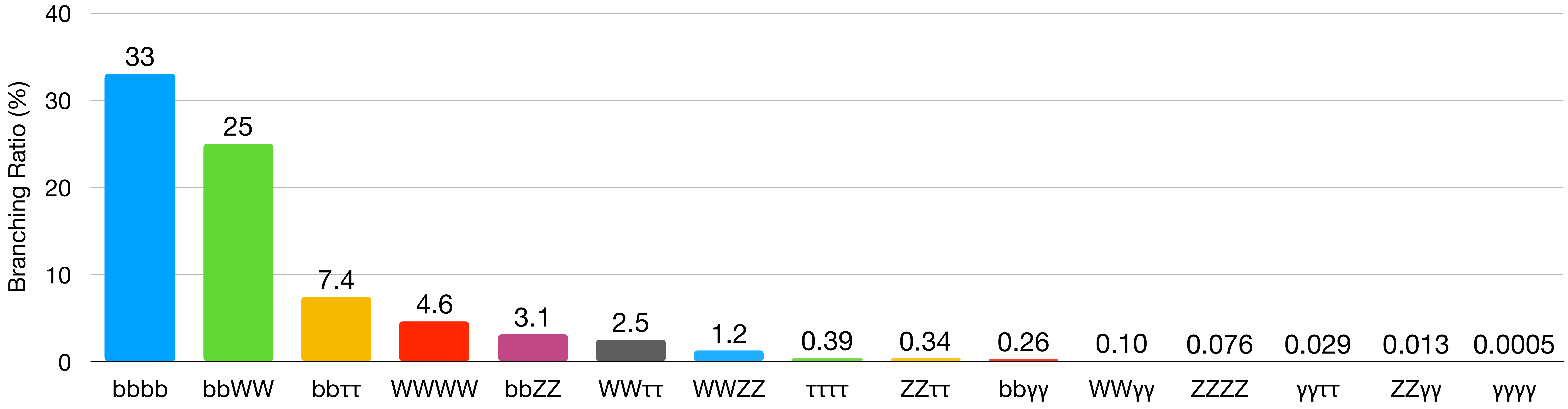
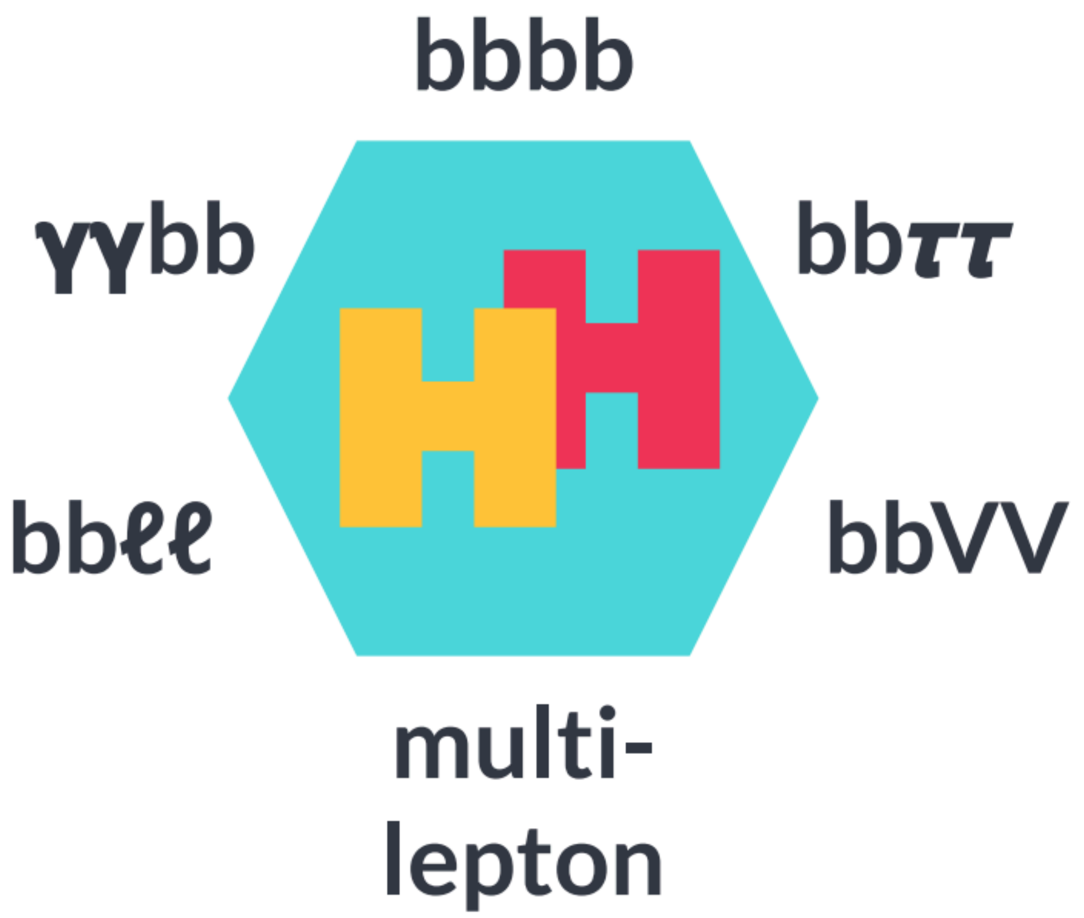
ATLAS HH Overview

Tülin Varol Mete
Academia Sinica
on behalf of the ATLAS HH analysis teams

Higgs Pairs Mini-Workshop
29/09/2021

ATLAS HH Analyses





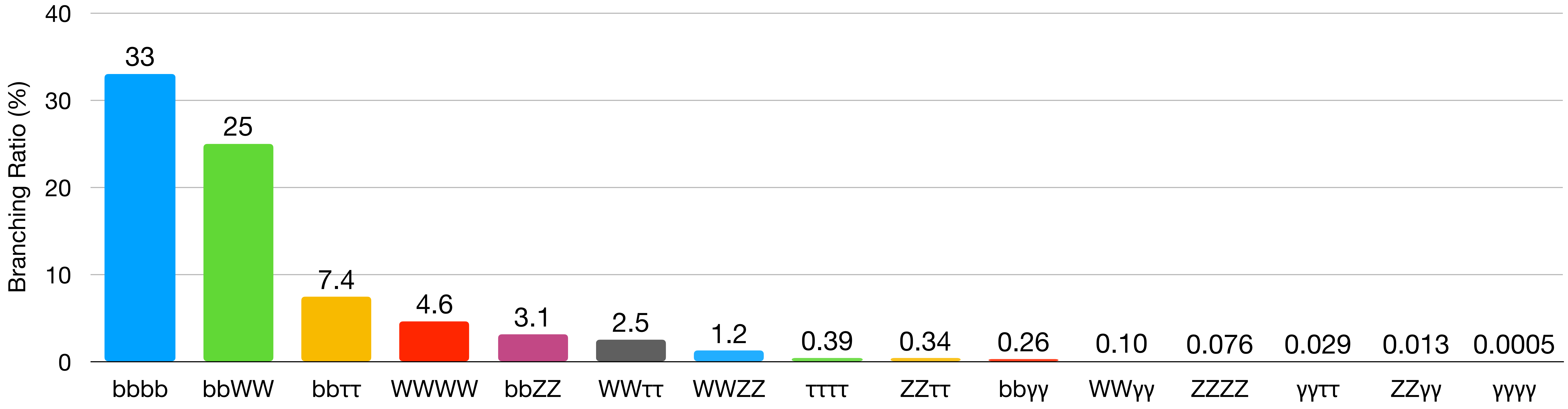
With Run-II 2015 + 2016 datasets (36.1 fb^{-1} of 13 TeV data)

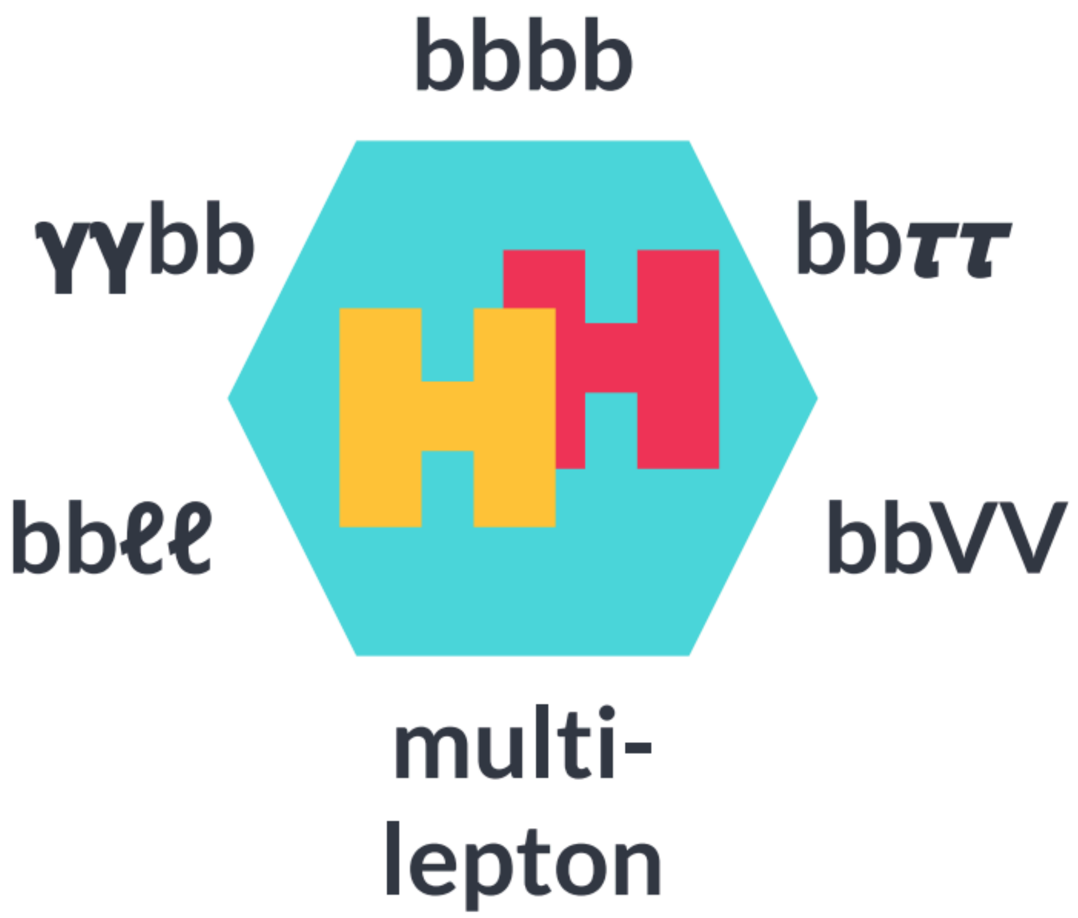
- HH→bbbb 1804.06174
- HH→bbγγ 1807.04873
- HH→γγWW*(γγlvjj) 1807.08567
- HH→bbττ 1808.00336
- HH→bbWW* (bblvqq) 1811.04671
- HH→WW*WW* (2SSl, 3l, 4l) 1811.11028
- HH Combination 1906.02025

With full Run-II datasets (126-139 fb^{-1} of 13 TeV data)

- VBF HH→bbbb 2001.05178
- Boosted HH→bbττ 2007.14811
- HH→bblvlv (bbWW*, bbZZ, bbττ) 1908.06765
- Resonant HH→bbbb ATLAS-CONF-2021-035
- HH→bbττ ATLAS-CONF-2021-030
- HH→bbγγ ATLAS-CONF-2021-016

ATLAS HH Analyses





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- HH→bbγγ ATLAS-CONF-2021-016

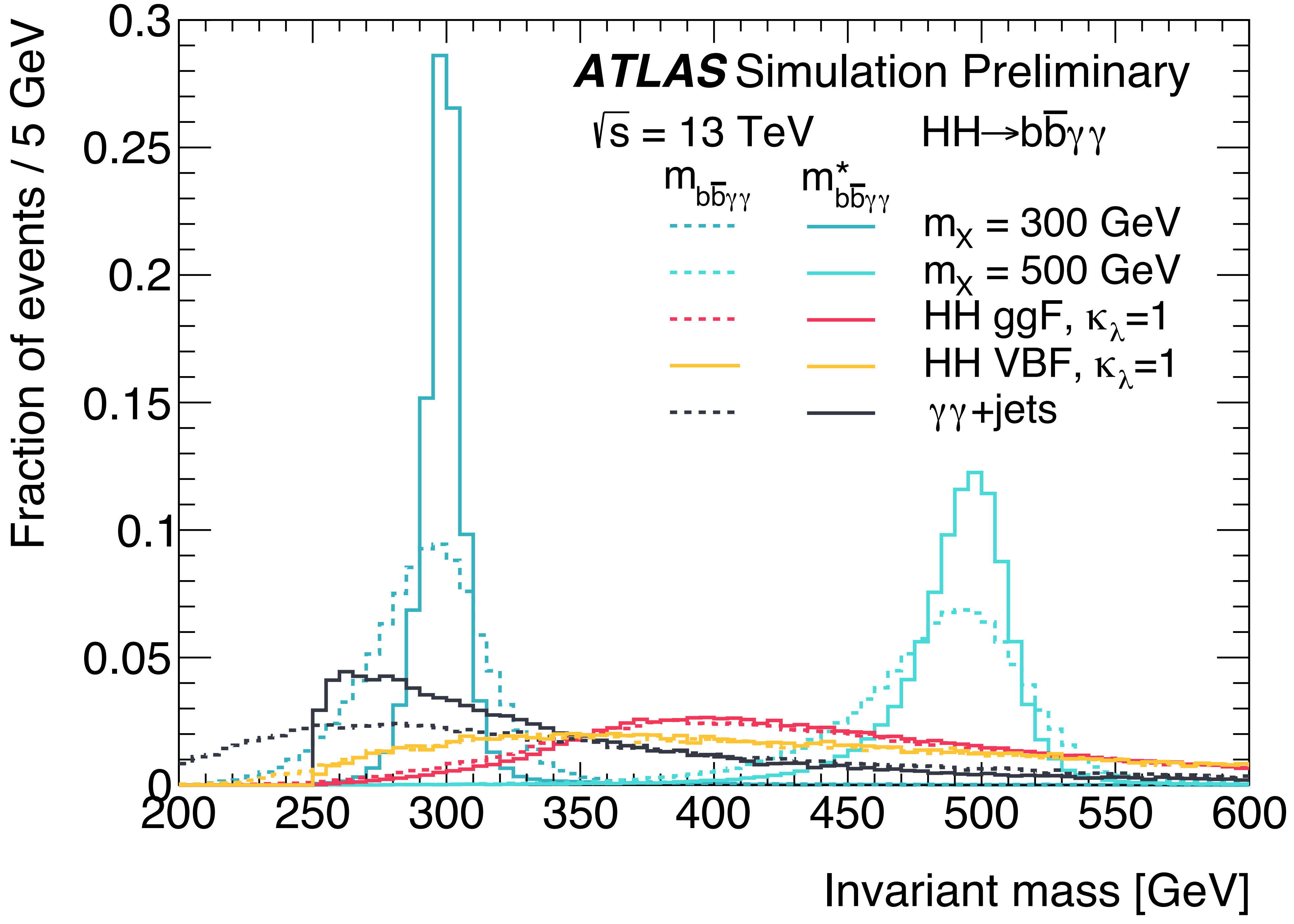
Will cover the results with full Run-II data today!

$HH \rightarrow bb\gamma\gamma$

Publication: ATLAS-CONF-2021-016
Physics Briefing: Twice the Higgs, twice the challenge

HH→bbγγ: Analysis Overview

- Search for **non-resonant (ggF+VBF)** and **resonant HH production** using **139 fb^{-1}** of pp data
  - Using di-photon triggers
  - Selecting events with 2 photons and 2 b-tagged jets (with 77% b-tag efficiency)
    - 105 GeV < $m_{\gamma\gamma}$ < 160 GeV
    - p_T^{γ} lead. (sub-lead.) > 0.35 (0.25) * $m_{\gamma\gamma}$



- Using **MVA** for the signal/background discrimination
- To improve the 4-object resolution, **$m_{bb\gamma\gamma}^*$** variable is defined:

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

- Non-resonant γγ+jets background fitted to the data sidebands in $m_{\gamma\gamma}$
- Single-H background taken from MC

- **Simultaneous likelihood fit in $m_{\gamma\gamma}$** to all relevant categories
  - Non-Resonant: Limits on σ_{HH} & σ_{HH} vs κ_λ
  - Resonant: Limits on σ_{HH} vs m_X (a heavy spin-0 resonance)

HH→bbγγ: Analysis Overview

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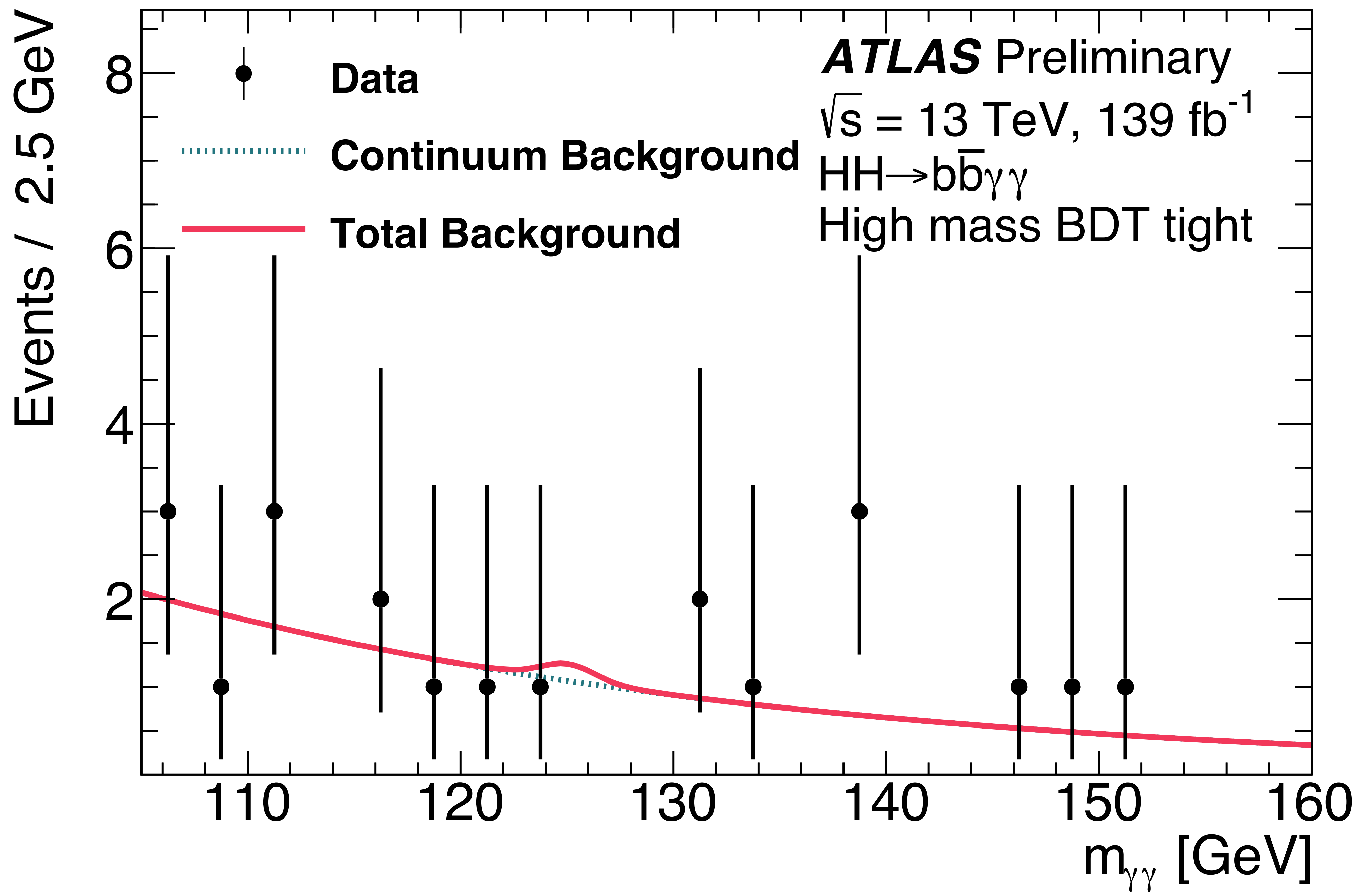
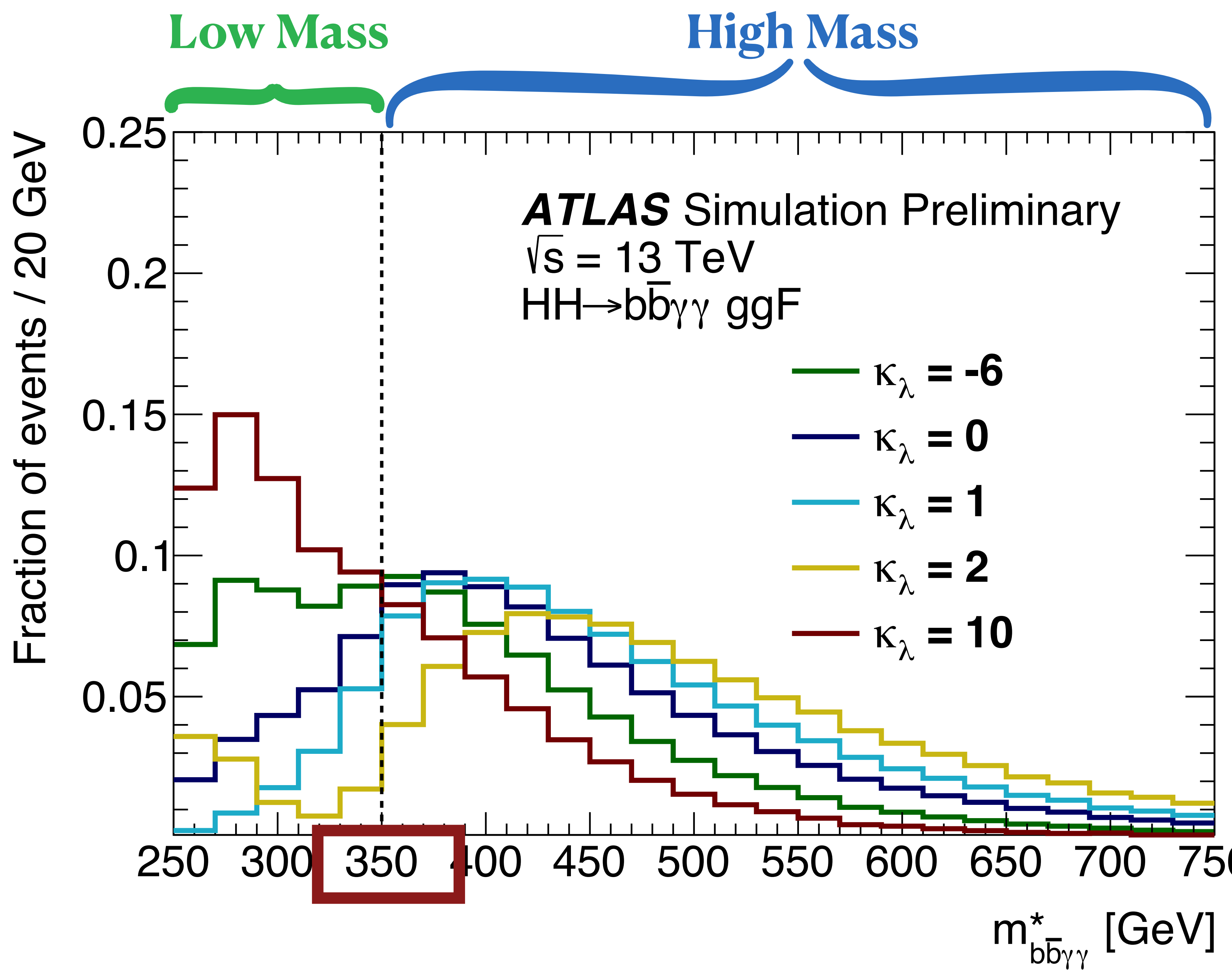
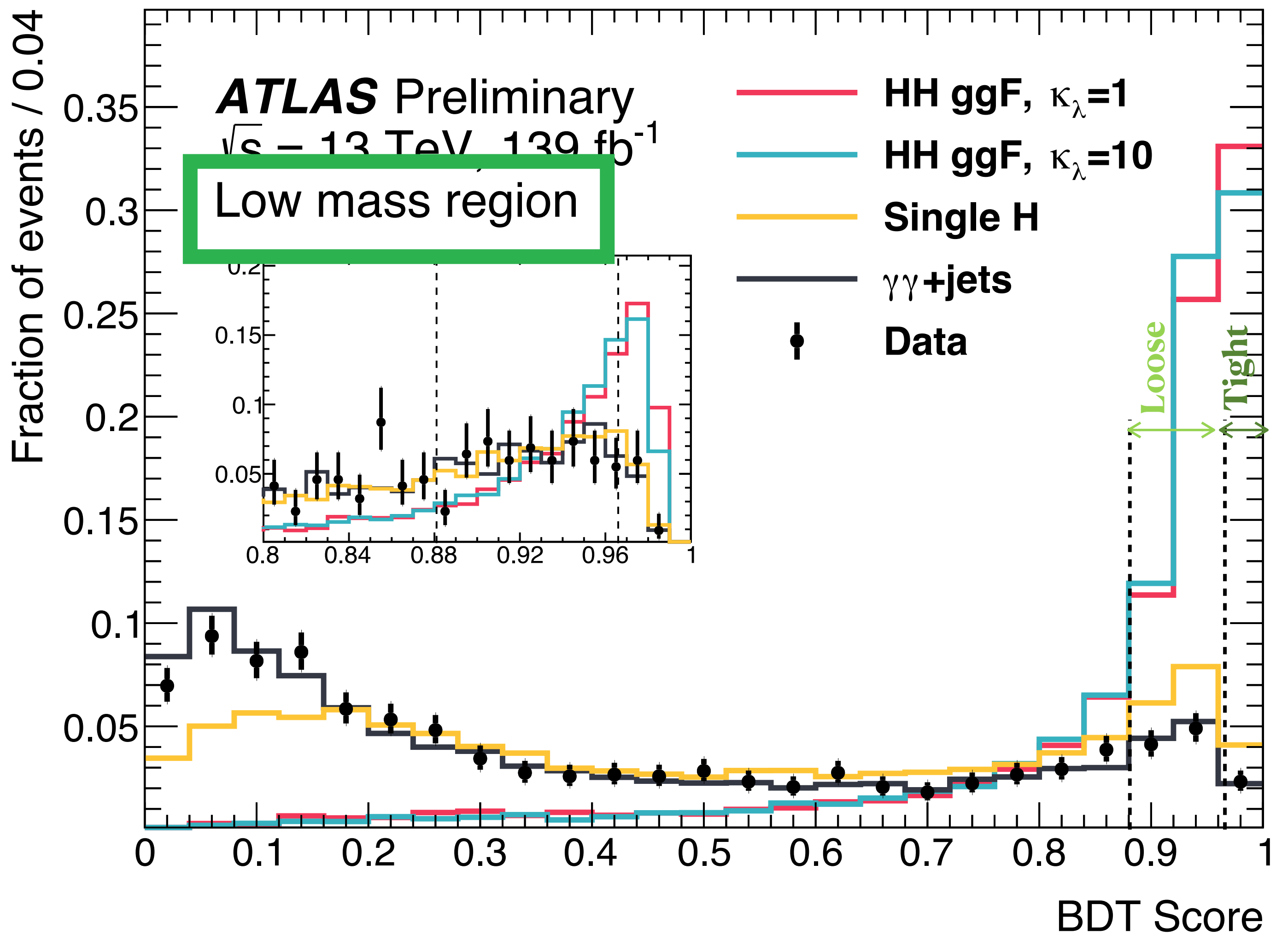
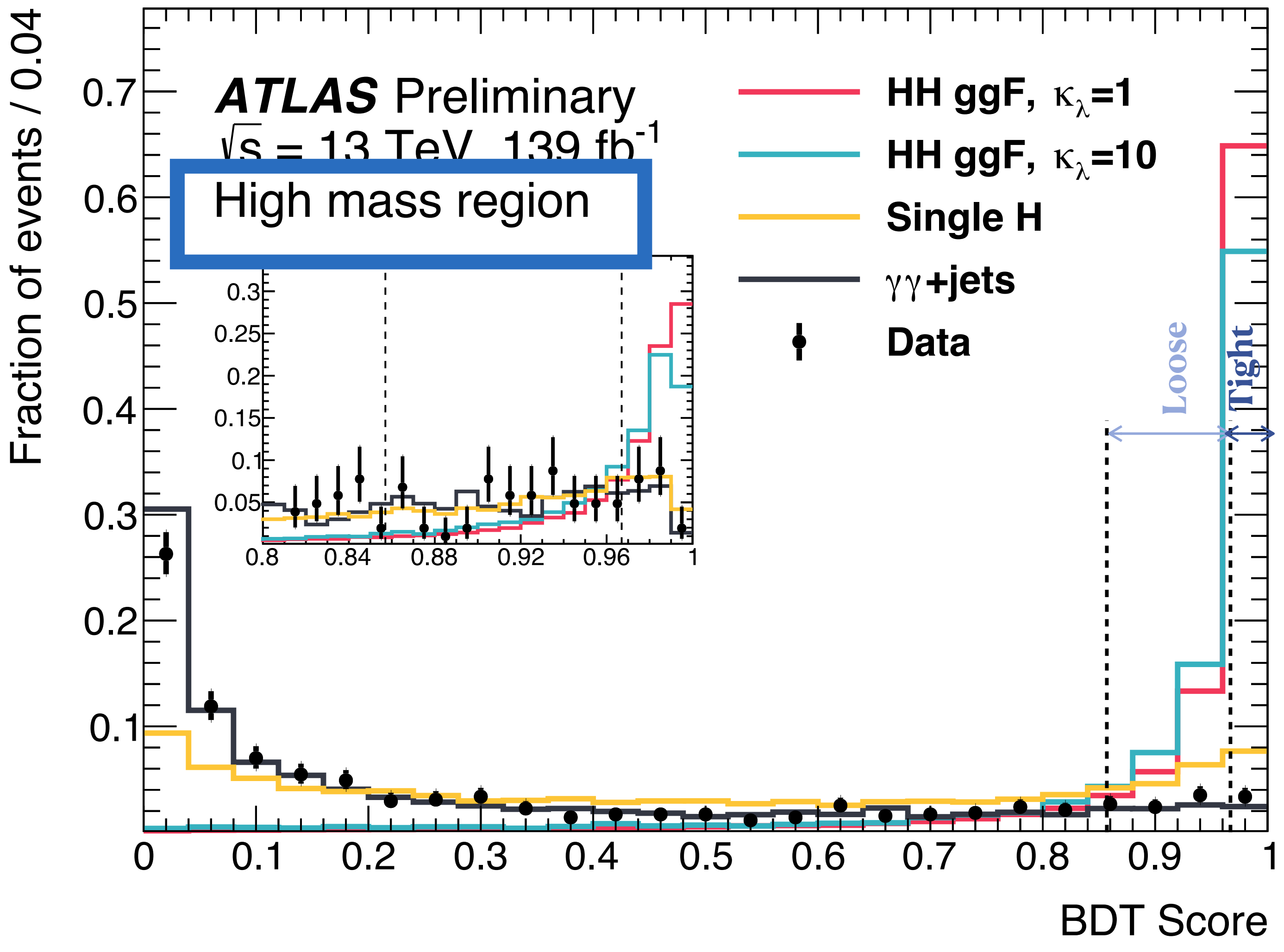


HH→bbγγ: Non-Resonant Analysis

- Train **two BDTs** for ggF in two $\mathbf{m_{bb\gamma\gamma}^{*}}$ regions
  - High mass region ($\mathbf{m_{bb\gamma\gamma}^{*} > 350}$ **GeV**), training with κ_λ **= 1** (SM HH) signal
  - Low mass region ($\mathbf{m_{bb\gamma\gamma}^{*} < 350}$ **GeV**), training with κ_λ **= 10** (BSM HH) signal
- Further divide each mass region into **low and high BDT score regions**
- BDT trained with the ggF HH signal used for both ggF and VBF







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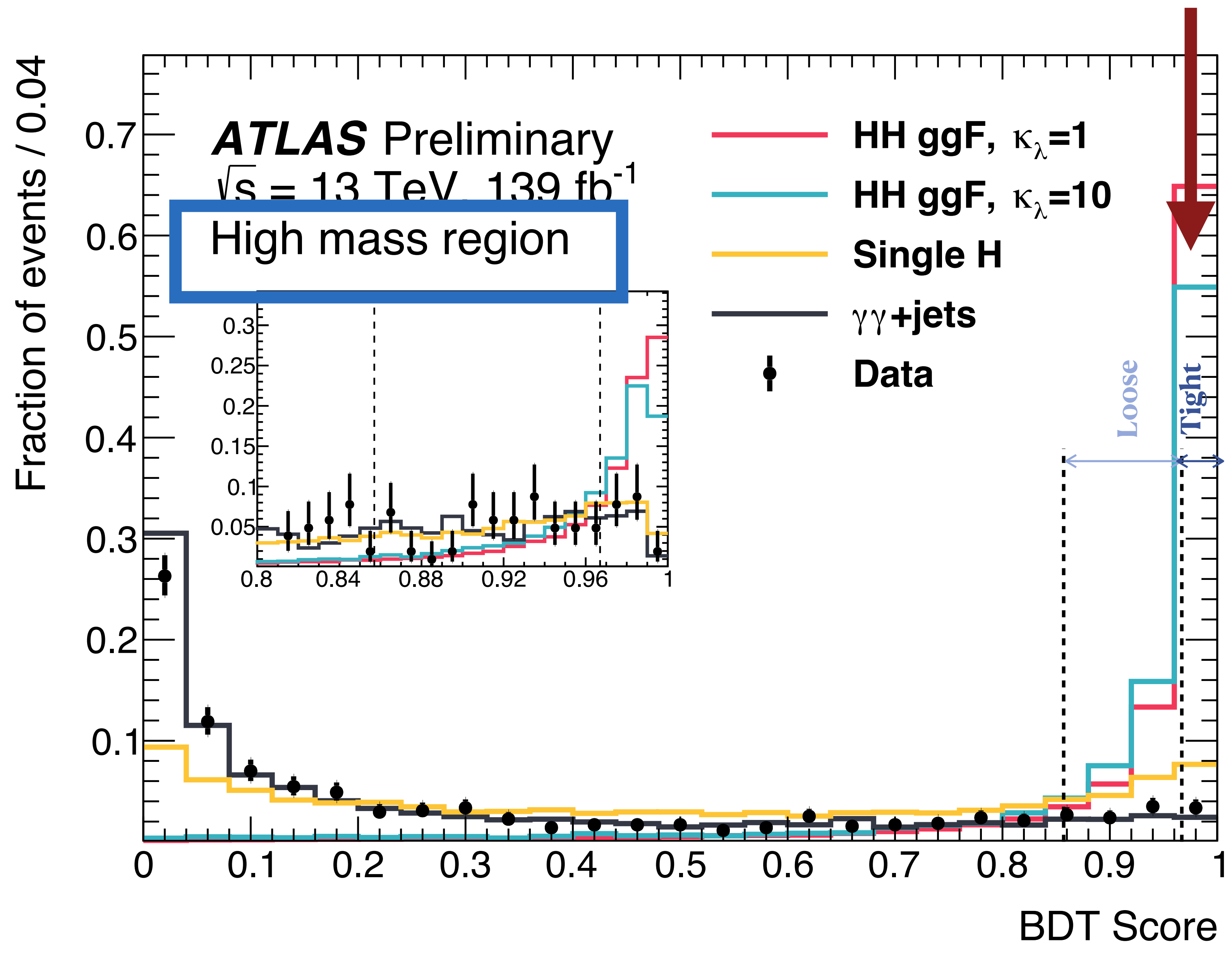
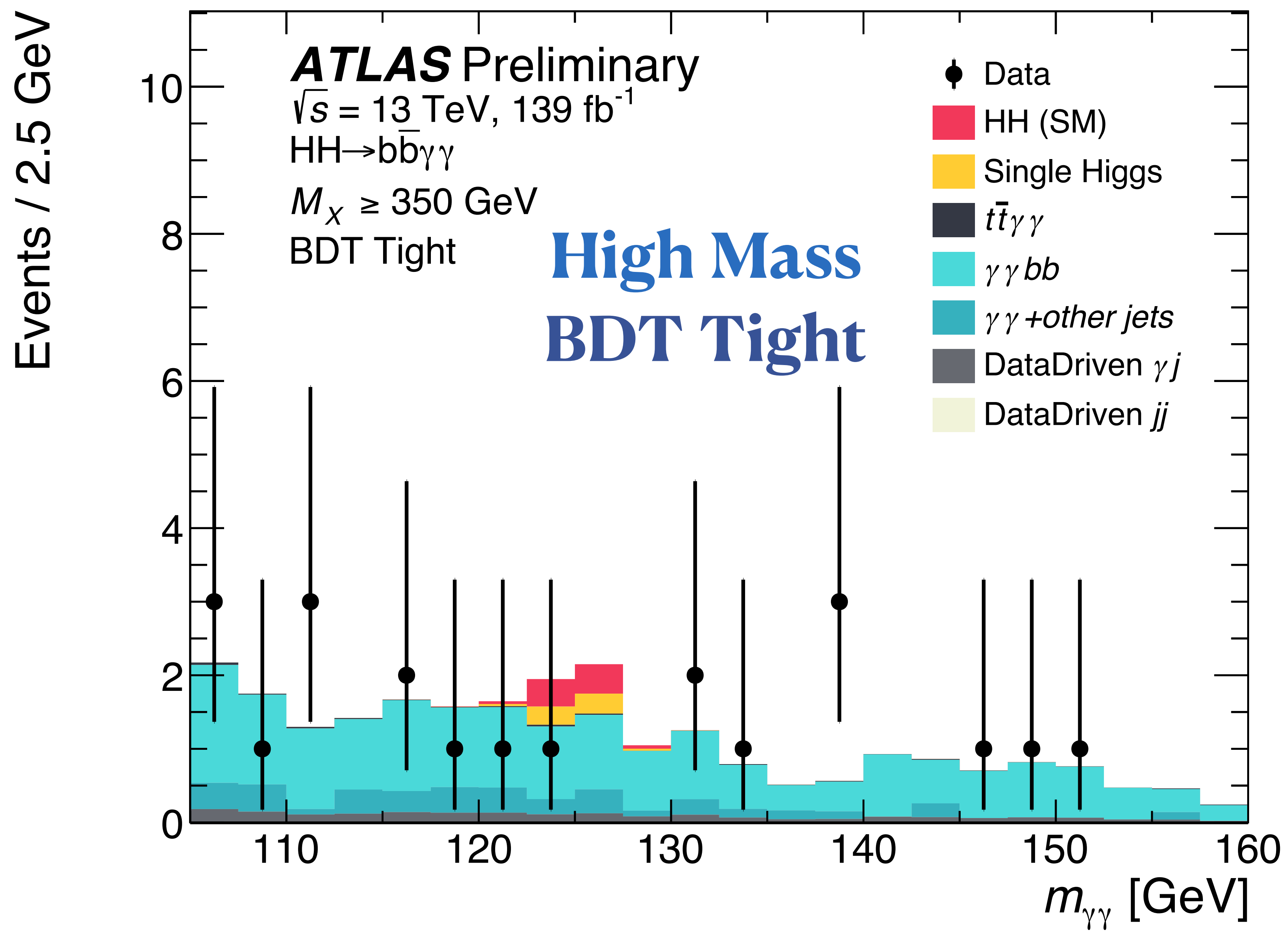
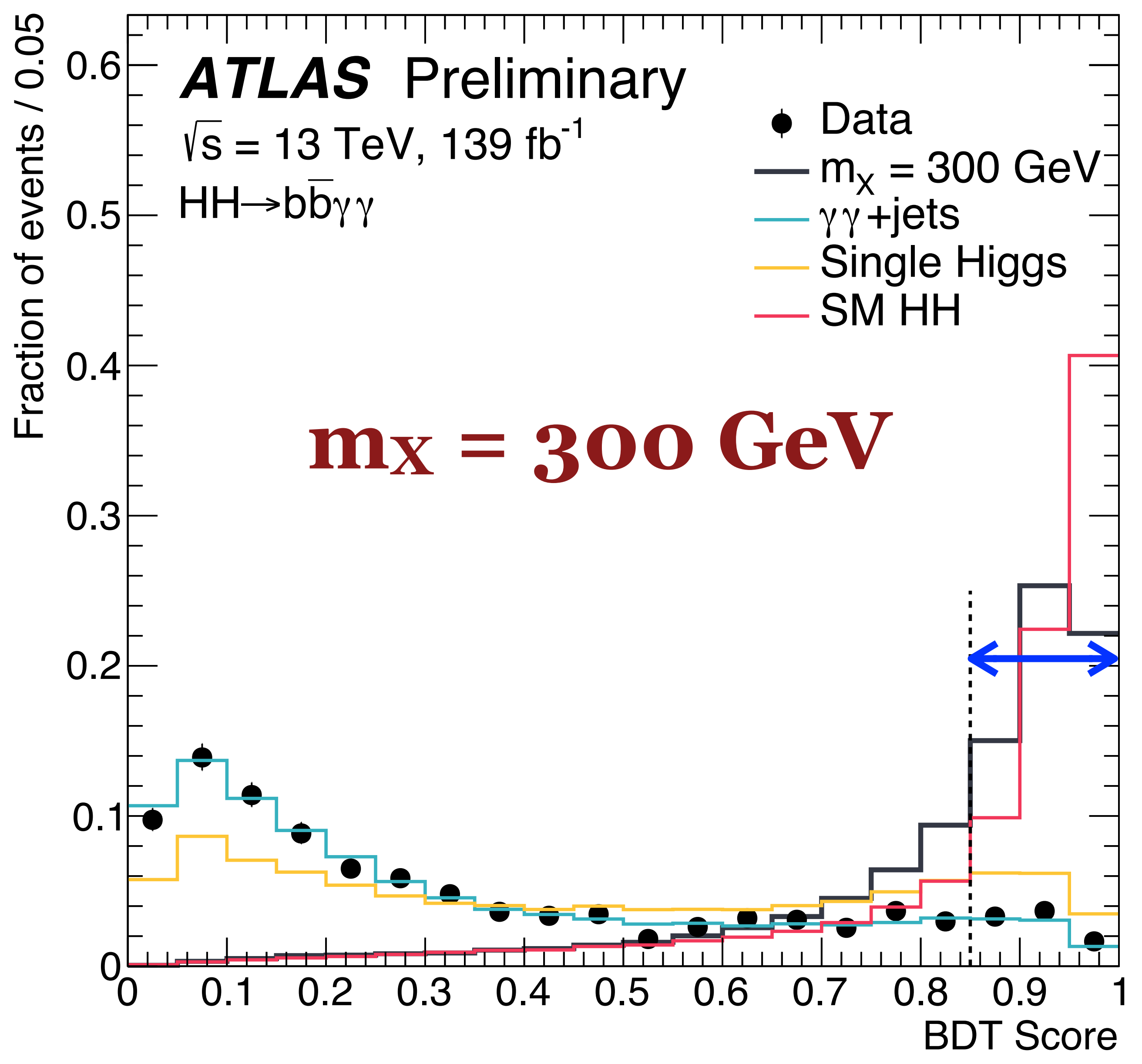
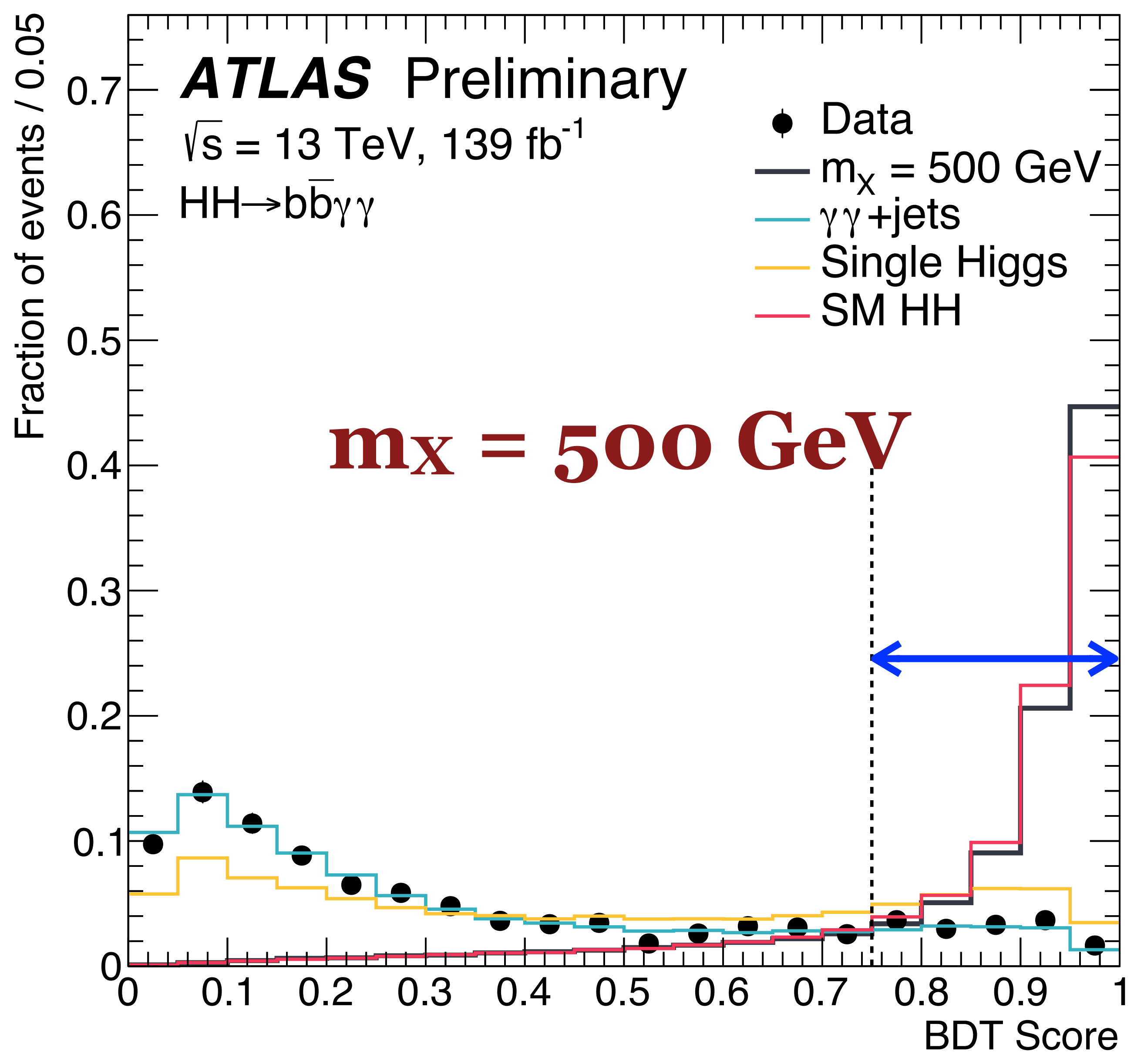


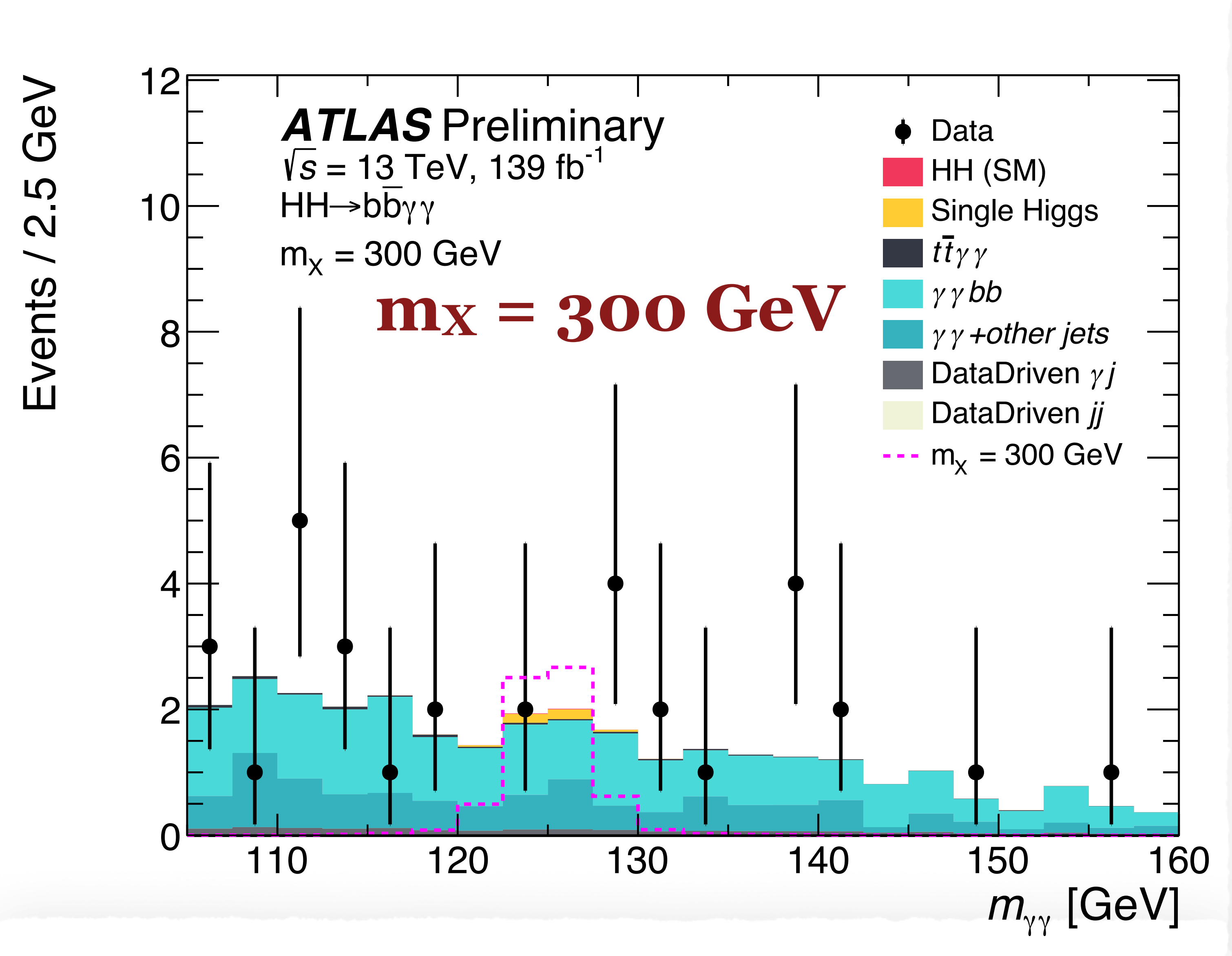


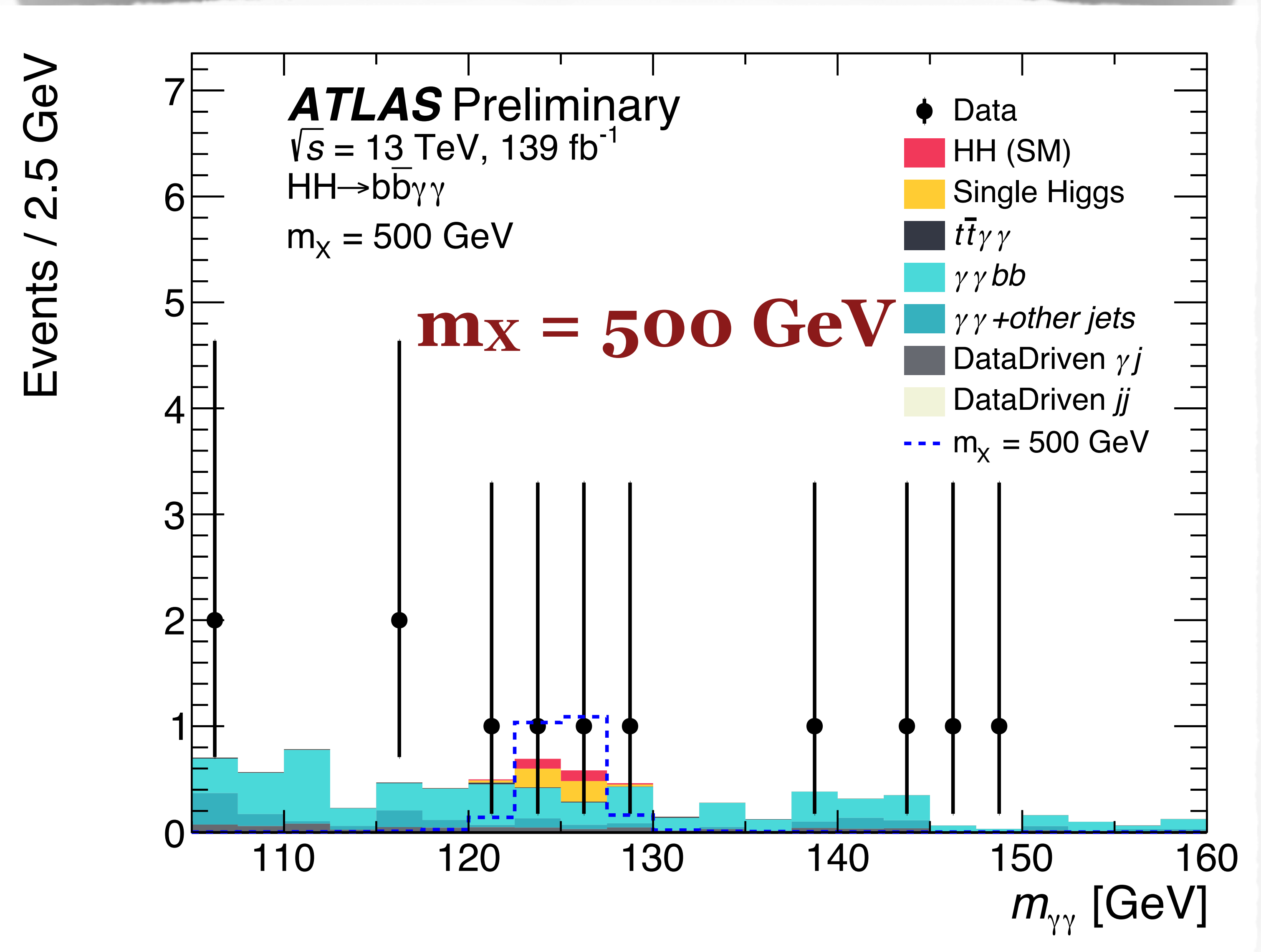
HH→bbγγ: Resonant Analysis

- **Two BDTs trained** to better separate the signal from backgrounds of different nature:
  - <u>$BDT_{\gamma\gamma}$:</u> γγ + ttγγ background
  - <u>$BDT_{singleH}$:</u> single-H backgrounds (ZH and ttH are the dominant bkgs)
- **Two BDT scores** are combined in **BDT_{tot}**
- **Mass-dependent cuts** are applied **on BDT_{tot}** to define the SR for each mass



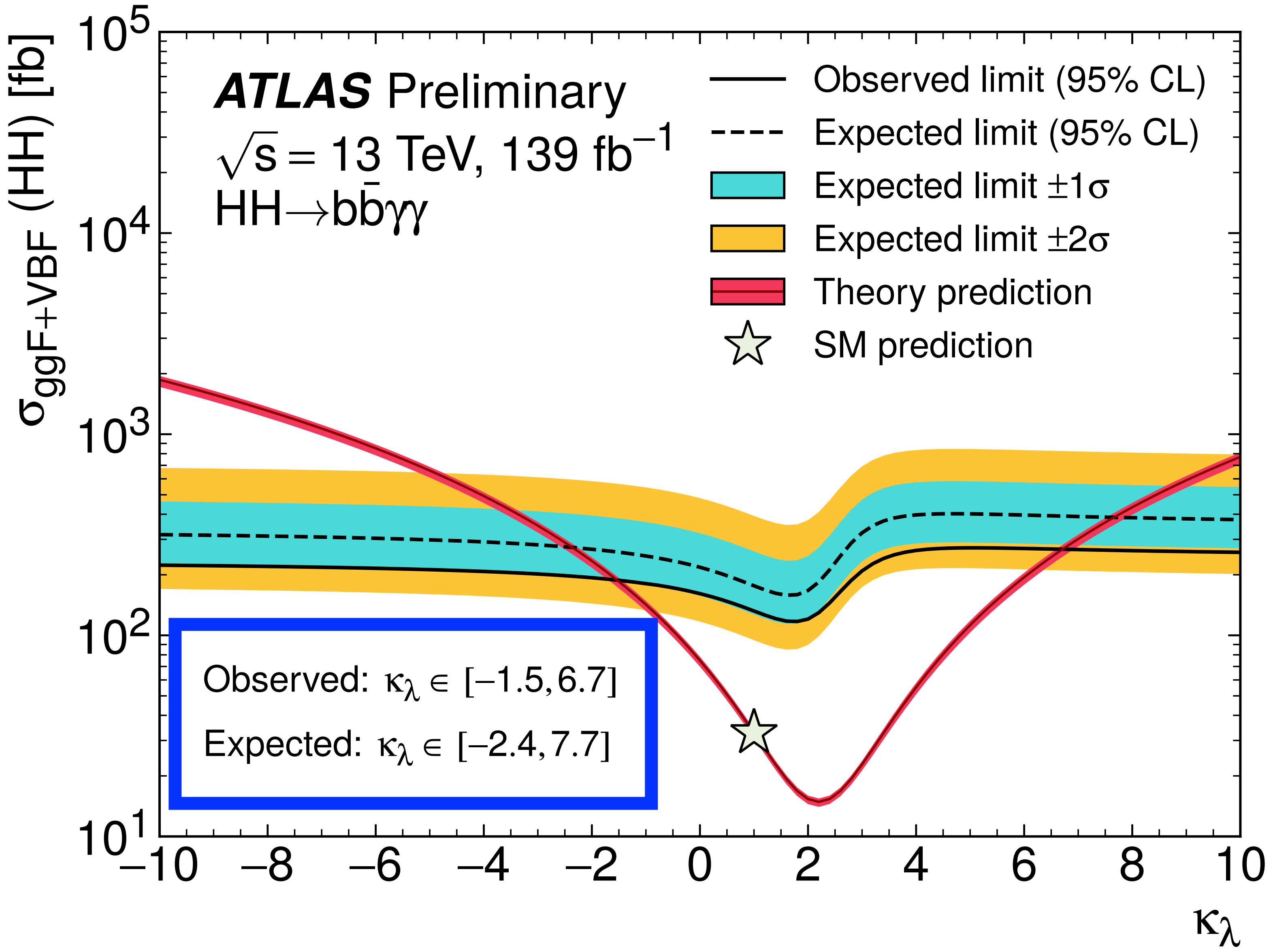






HH→bbγγ: Results

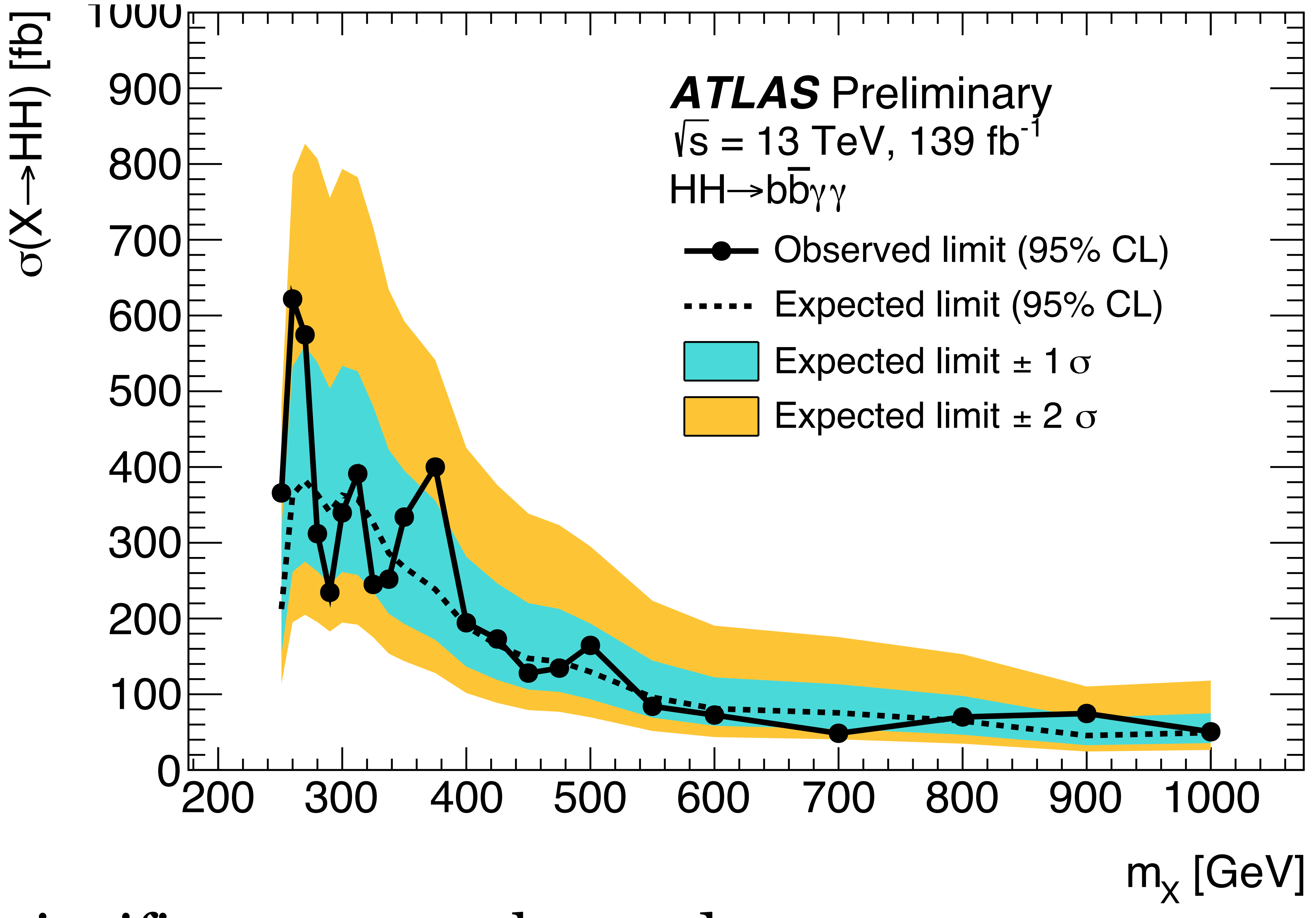
Non-Resonant Results



ggF+VBF	Limit on σ_{HH} [fb]	Limit on μ (σ/σ_{SM})
Obs (Exp)	130 (180)	4.1 (5.5)

- No significant excess observed
- **5 x improvement** on the previous result (~26 x SM, with 36 fb^{-1})
  - 3 x improvement as a result of analysis improvements
- Statistically dominated, few % impact from systematics

Resonant Results



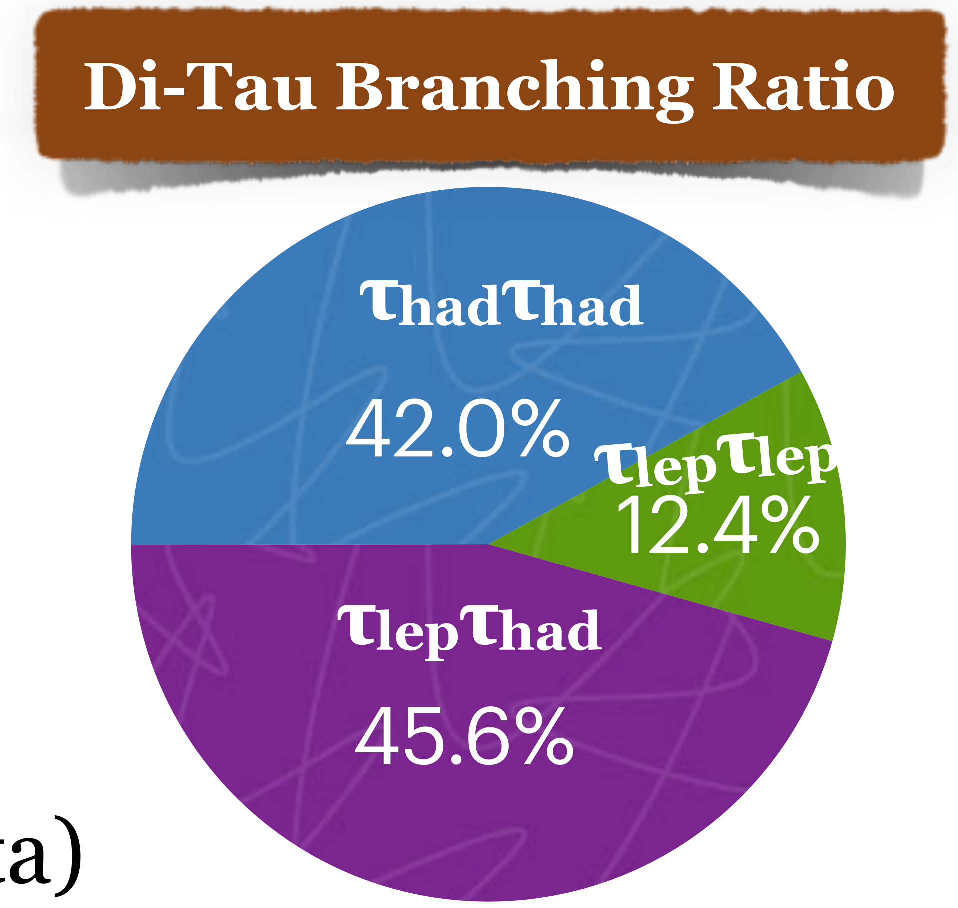
- No significant excess observed
- Limits set on narrow width scalar resonances from 251 GeV to 1000 GeV
  - **Obs (exp)** varies between **610-47 fb (360-43 fb)**
  - **2 x-3 x improvement** depending on m_X
    - 1/3 x improvement from the BDT strategy

HH→$bb\tau\tau$

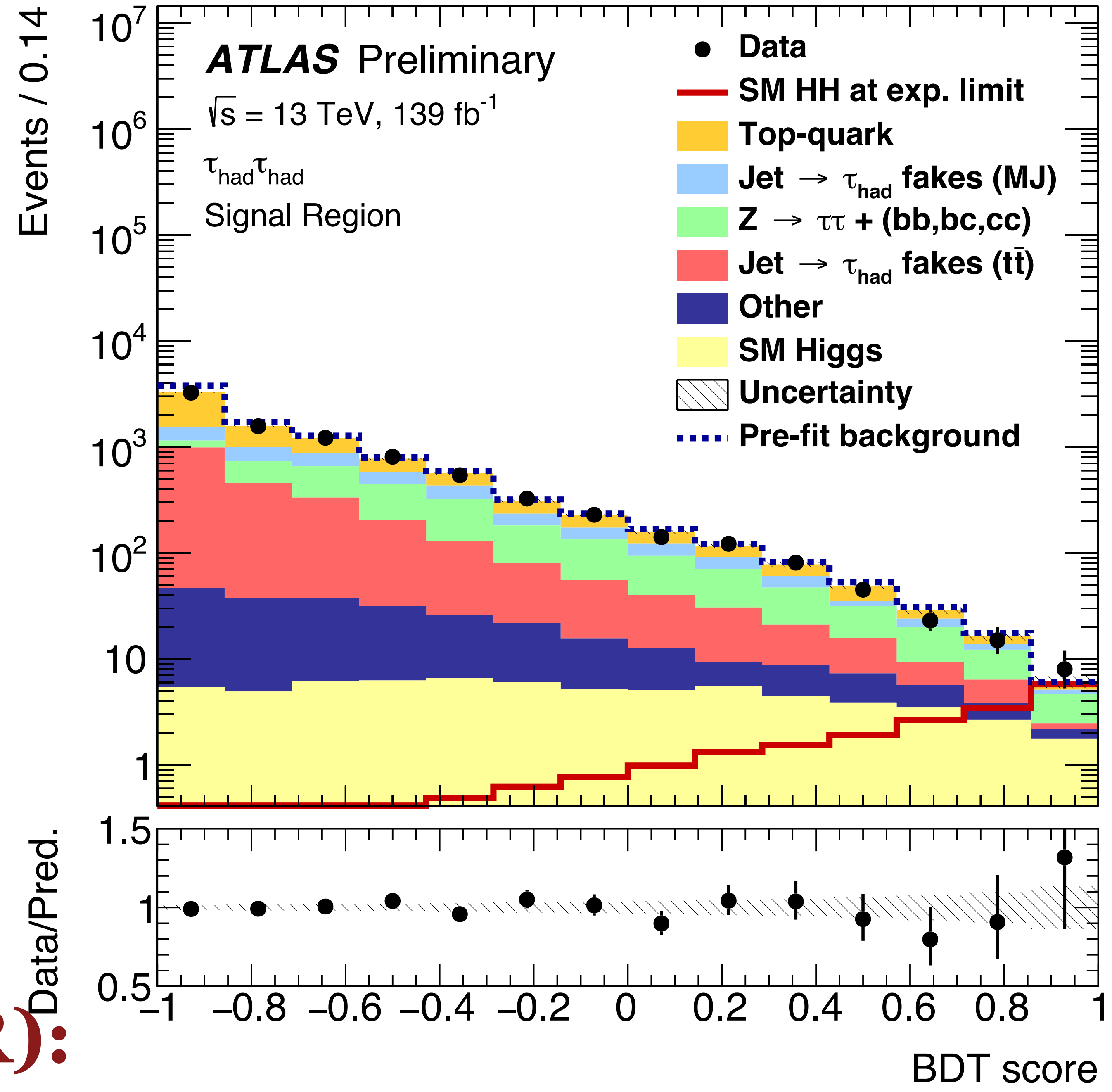
Publication: ATLAS-CONF-2021-030
Physics Briefing: Two Higgs bosons are better than one

HH→bbττ: Analysis Overview

- Search for **non-resonant (ggF+VBF)** and **resonant HH production** using **139 fb^{-1}** of pp data
  - 2 b-jets and 2 τ-leptons



- **Two initial categories** based on the di-τ decay mode:
  - **τlepτhad:** e/μ and oppositely charged τ_{had}
  - **τhadτhad:** two oppositely charge τ_{had}



- **Backgrounds:**
  - True τ_{had} in ttbar and Z+HF (from MC, normalization from data)
  - Fake τ_{had} (jets faking τ_{had}) in ttbar and multi-jet (data-driven)

- **Likelihood fits to MVA scores** in **3 signal regions (SRs)** and **1 control region (CR):**
  - τlepτhad Single Lepton Trigger (SLT) SR - high acceptance, large ttbar contamination
  - τlepτhad Lepton Tau Trigger (LTT) SR - lowered $p_T^{(l)}$ improves low-mass sensitivity
  - τhadτhad Single- and Di- Tau Triggers (STT/DTT) SR - high purity
  - Z(→ll)+HF CR - measurement in bbll final state, m_{ll} used as a discriminant

	Resonant	Non-Resonant	
		τhadτhad	τlepτhad
MVA	PNN	BDT	NN

HH→bbττ: Non-Resonant Results

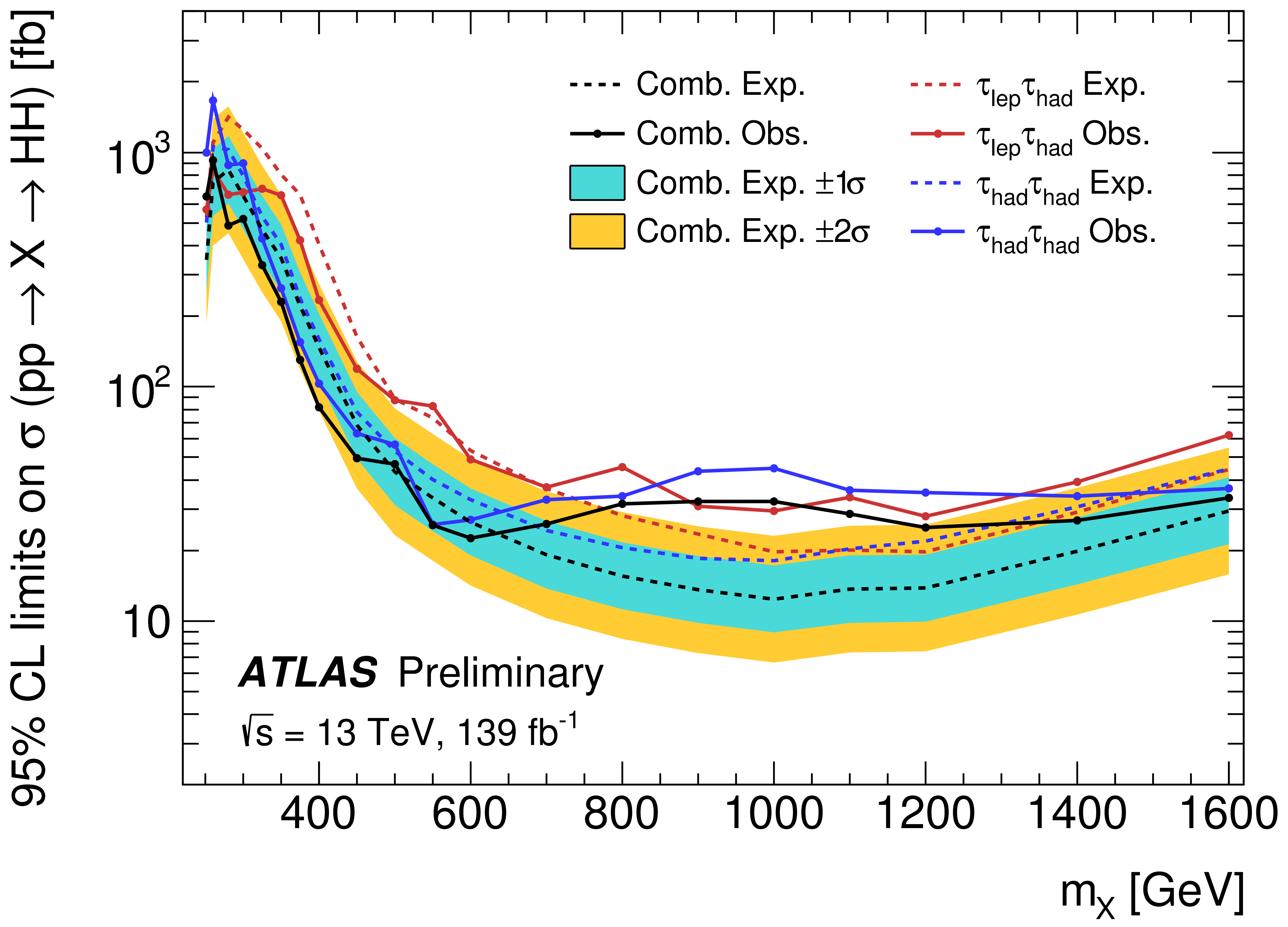
- **4 x improvement** wrt previous SM limits (with 36 fb^{-1})
  - 2 x due to improvements in τ_{had} and b-jet reconstruction/identification, and improvements in the MVA classification strategy and the fake estimation methods
- Statistically dominated, largest systematics from background modelling

		Observed	$-2\,\sigma$	$-1\,\sigma$	Expected	$+1\,\sigma$	$+2\,\sigma$
$\tau_{had}\tau_{had}$	$\sigma_{ggF+VBF}$ [fb]	145	70.5	94.6	131	183	245
	$\sigma_{ggF+VBF}/\sigma^{SM}_{ggF+VBF}$	4.95	2.38	3.19	4.43	6.17	8.27
$\tau_{lep}\tau_{had}$	$\sigma_{ggF+VBF}$ [fb]	265	124	167	231	322	432
	$\sigma_{ggF+VBF}/\sigma^{SM}_{ggF+VBF}$	9.16	4.22	5.66	7.86	10.9	14.7
Combined	$\sigma_{ggF+VBF}$ [fb]	135	61.3	82.3	114	159	213
	$\sigma_{ggF+VBF}/\sigma^{SM}_{ggF+VBF}$	4.65	2.08	2.79	3.87	5.39	7.22

Limits on μ include the new cross-section uncertainties

The highest expected sensitivity to non-resonant HH production to date

HH→bbττ: Resonant Results



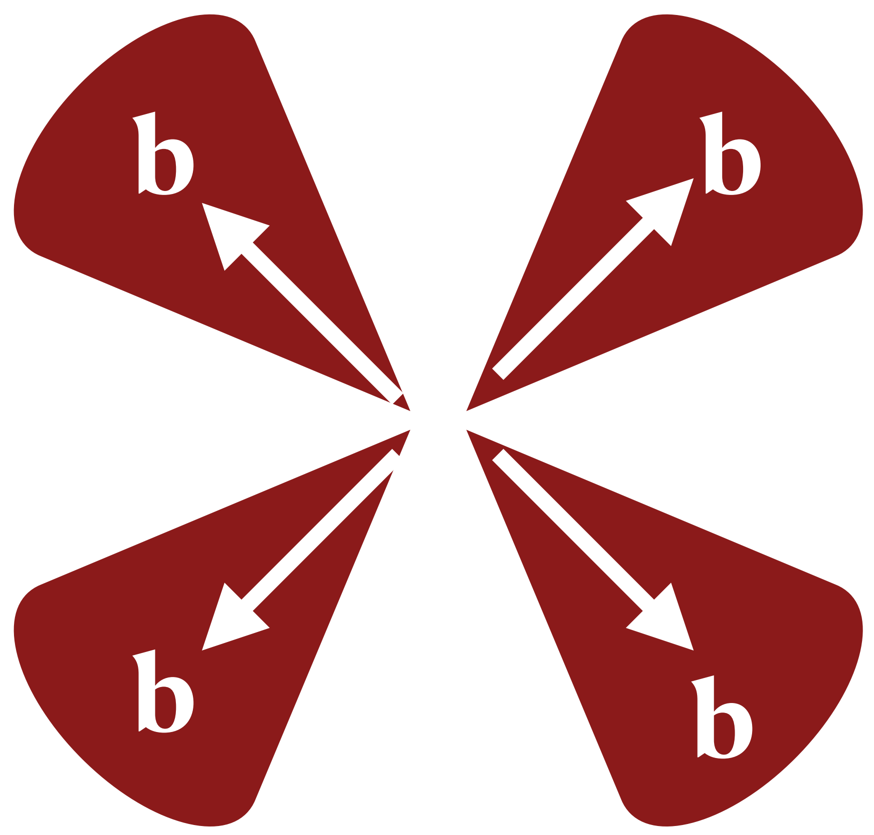
- The most significant excess for $\tau_{had}\tau_{had}$ ($\tau_{lep}\tau_{had}$) at 1 TeV (1.1 TeV), a local significance of 2.8σ (1.5σ)
- The most significant **combined excess** is at **m_X=1 TeV** with a local significance of 3.0σ and **a global significance of 2.0(+0.4, -0.2)σ**

HH→bbbb

Publication: ATLAS-CONF-2021-035
Physics Briefing: Probing new physics with pairs of Higgs bosons

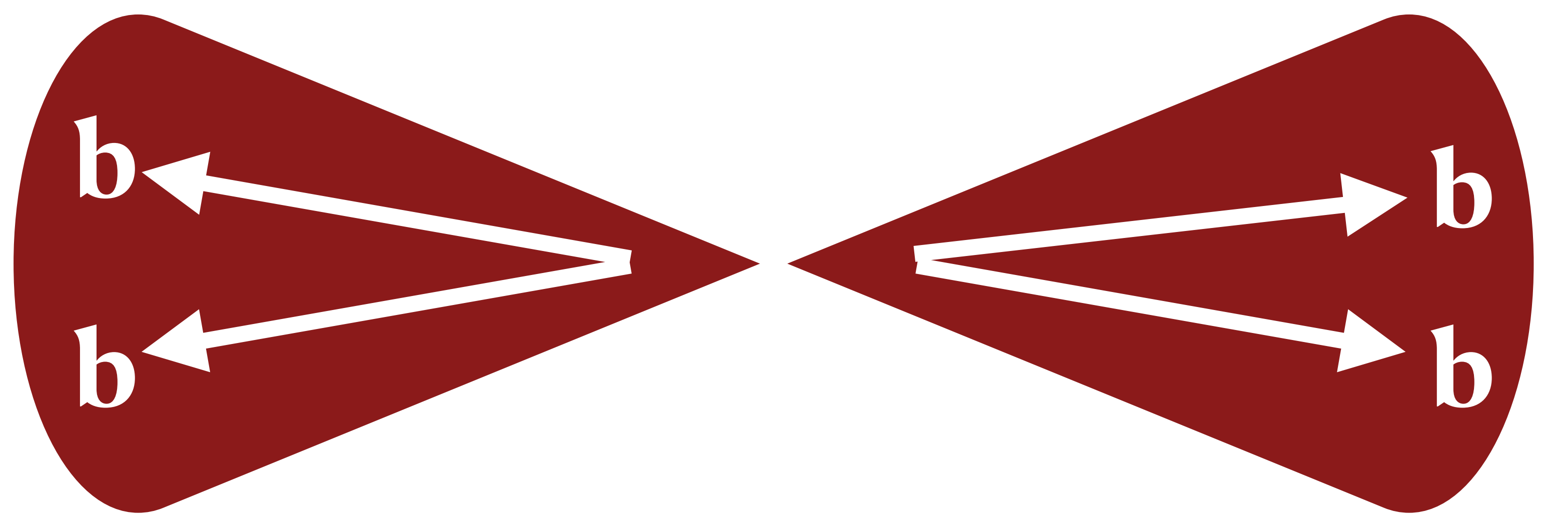
HH→bbbb

- Search for **resonant HH production in resolved (boosted) channels** using **126 (139) fb⁻¹** of pp data
  - Narrow-width spin-0 resonance and spin-2 Kaluza-Klein graviton



Resolved:

- Require 4 small R-jets (R=0.4)
- Targets low-medium mass resonances:
  - m_X = 251-1500 GeV



Boosted:

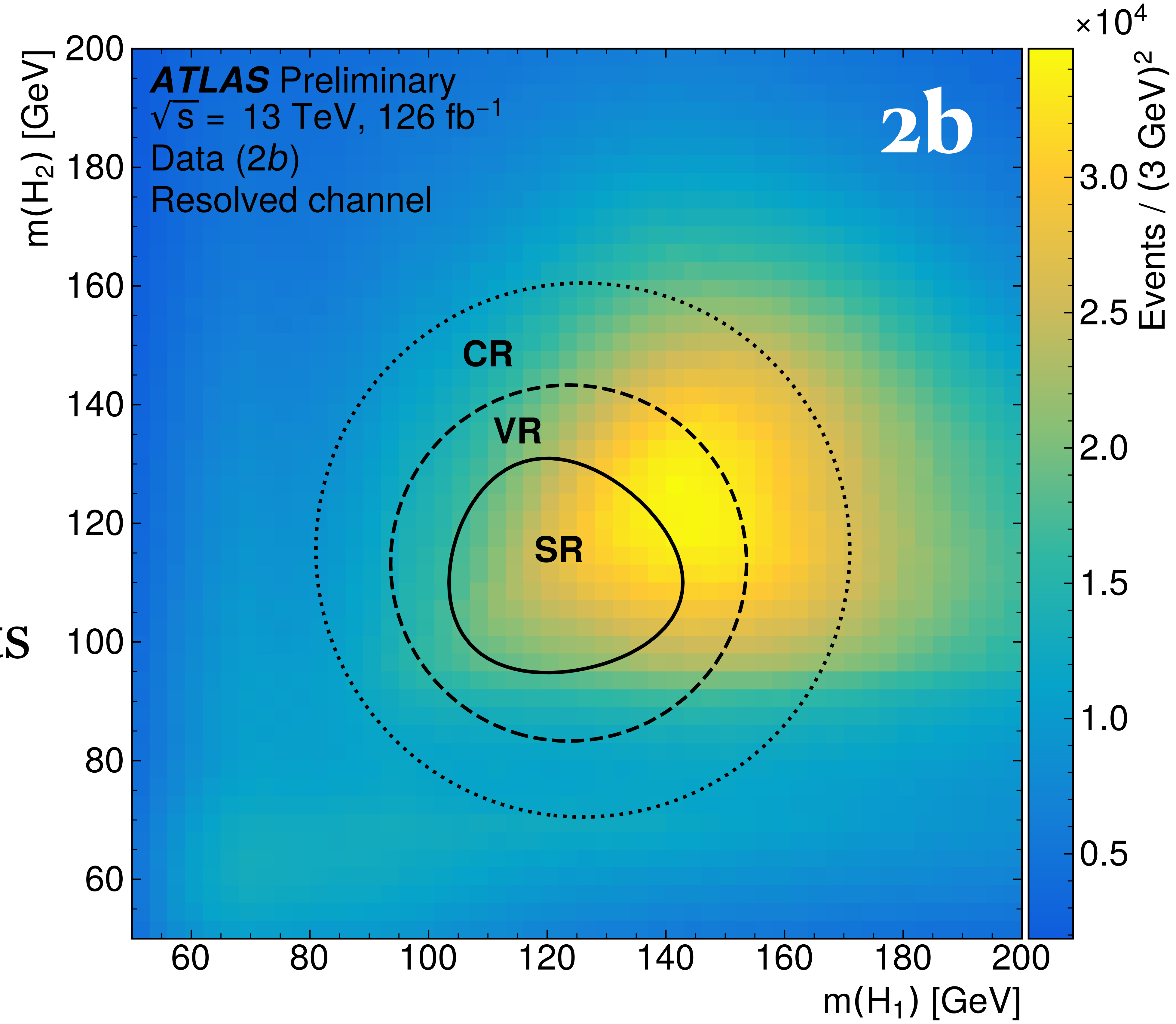
- Require 2 large R-jets (R=1.0)
  - Variable-radius track jets are used for b-tagging
- Targets high mass resonances:
  - m_X = 900-3000 GeV

Two channels statistically combined in the overlap mass range

HH→bbbb: Resolved Analysis Overview

- Uses a combination of b-jet, jet and H_T ($\sum_{jets} |E_T|$) triggers
- At least 4 small R-jets is required in an event
- BDT is used to pair the jets into Higgs boson candidates

- **Two categories:**
  - 4b signal region: 4 b-jets
  - 2b category for background estimate: 2 b-jets + 2 untagged jets
    - Fully data-driven background estimation:
      - ~95% multijet, ~5% from ttbar
      - Derive weights in the CR, mapping from 2b to 4b
      - Apply weights in 2b SR to get a model of background in the 4b SR



- Likelihood fit in bins of "corrected m_{HH}"

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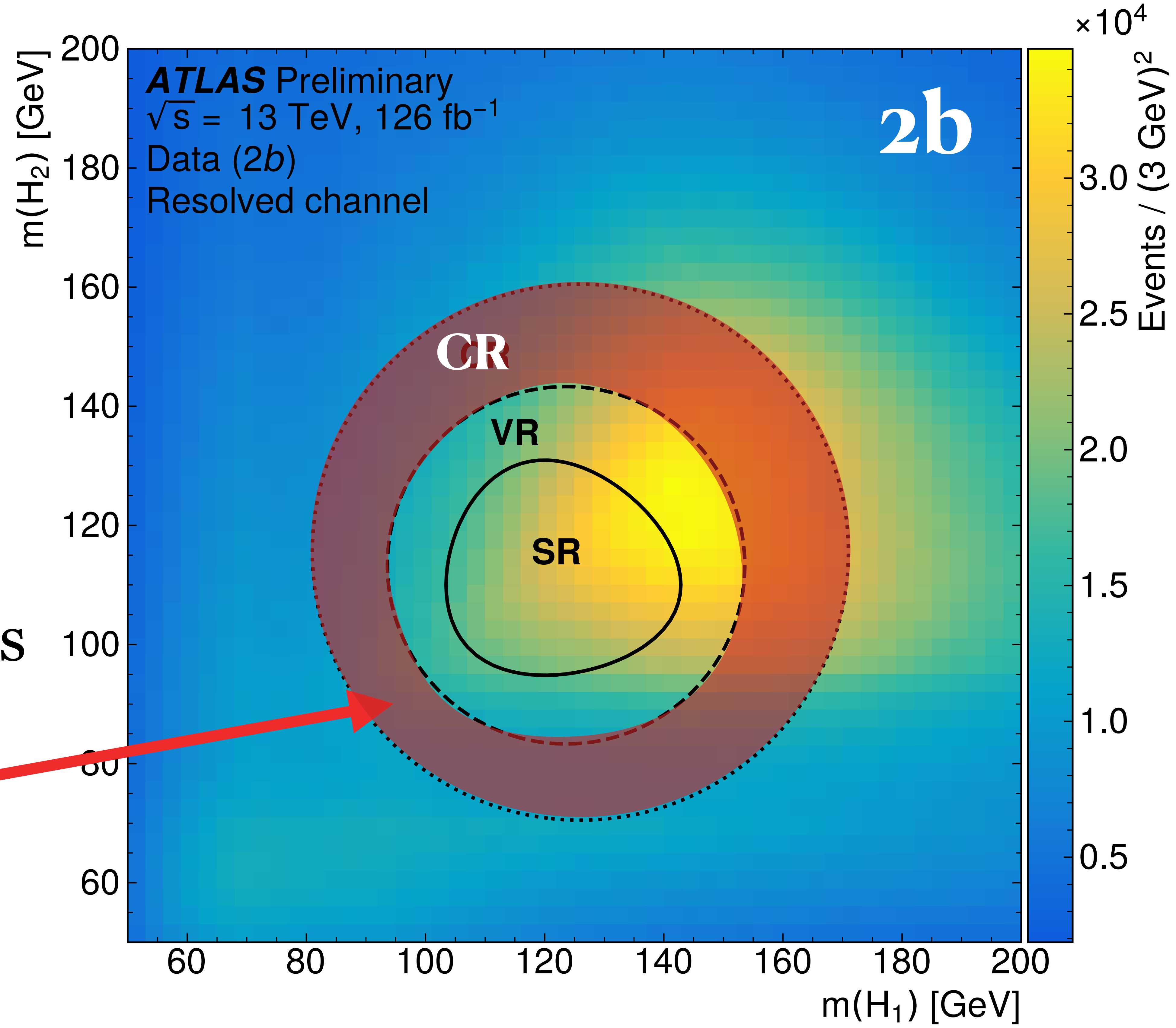

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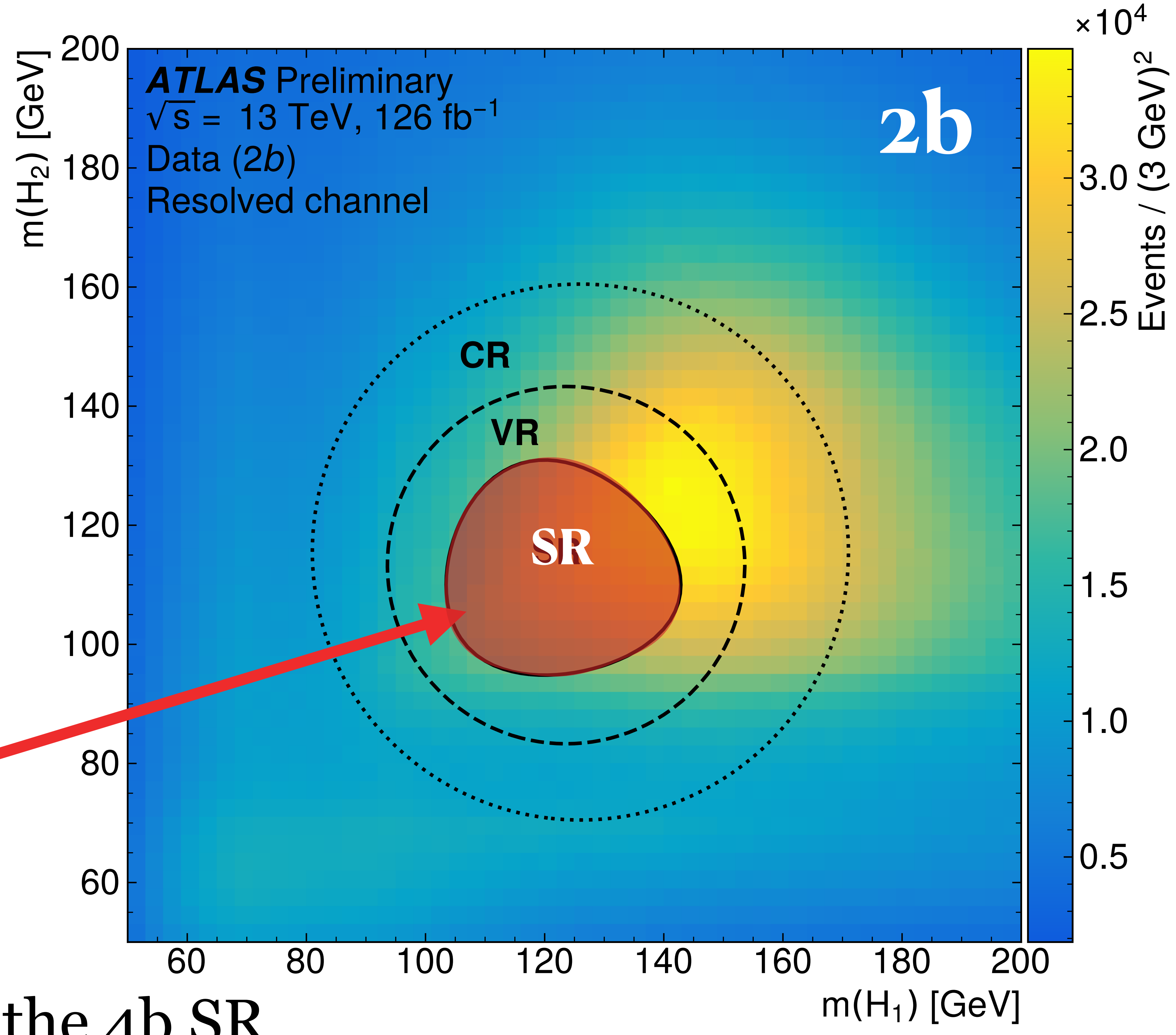

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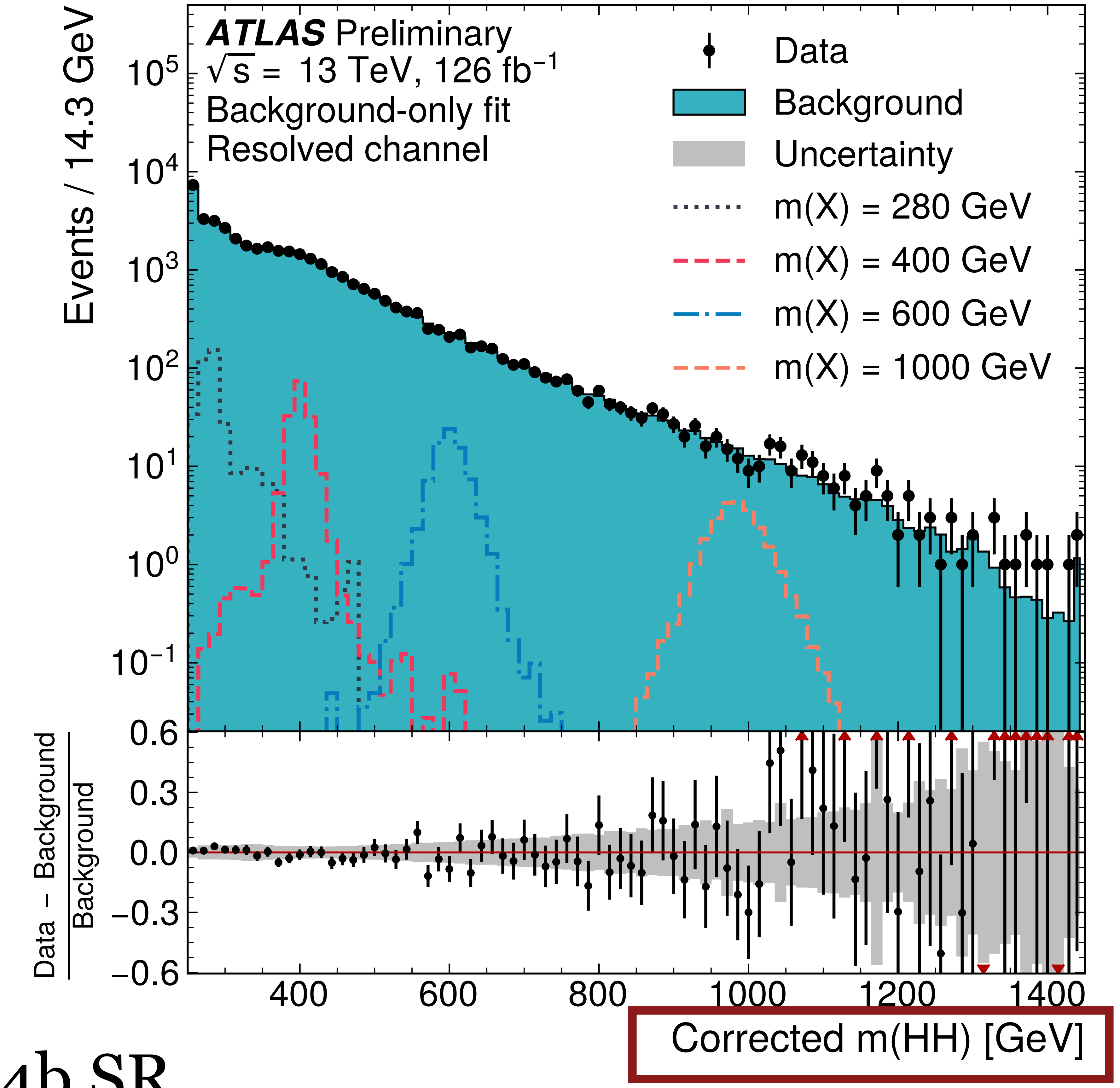


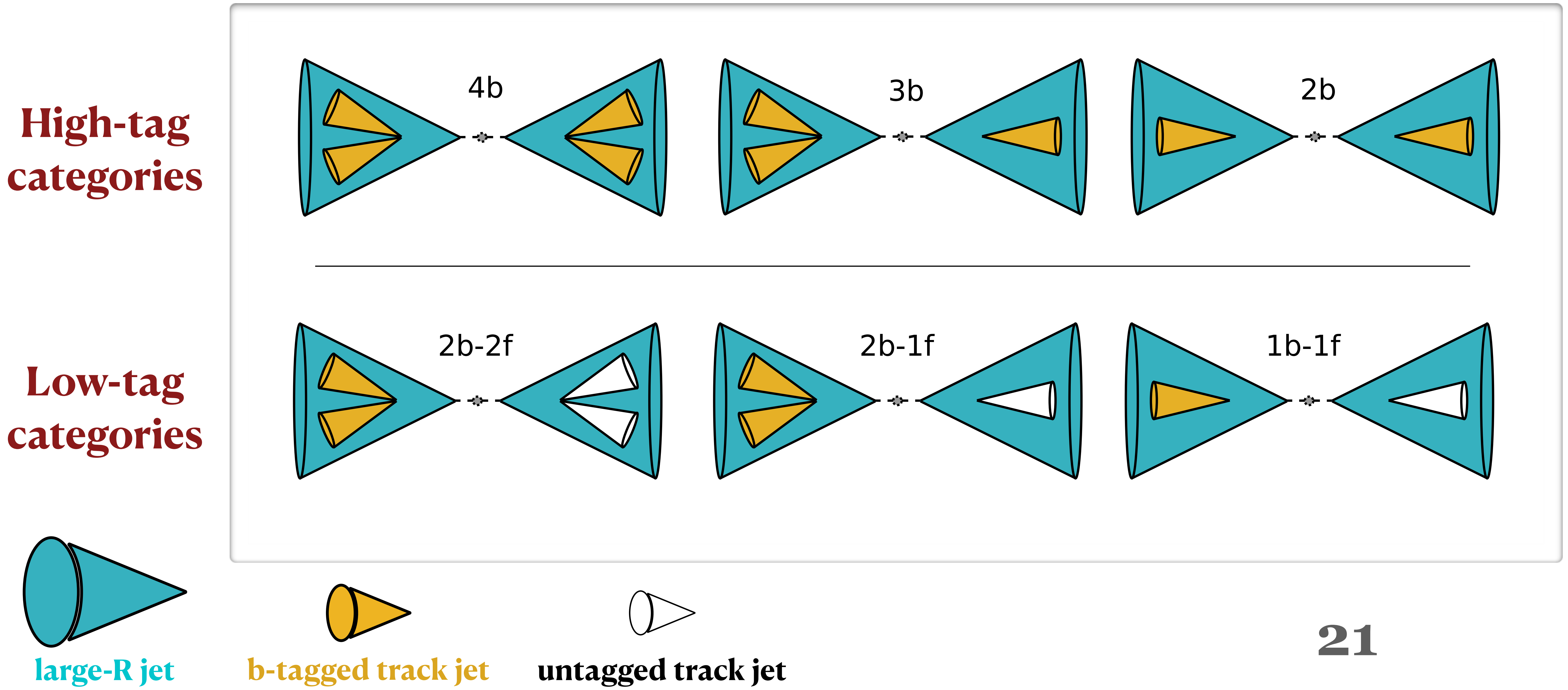
"corrected m_{HH}" calculated by

- rescaling Higgs candidates' 4-vectors such that m(H1)=m(H2)=125 GeV
- sum the rescaled 4-vectors and take the invariant mass

- **Likelihood fit** in bins of **"corrected m_{HH}"**

HH→bbbb: Boosted Analysis Overview

- Uses single large-R jet trigger
- At least two large-R jets required
- Fully data-driven multijet background estimation
- The remainder from ttbar, from MC
  - Up to 30% contribution
  - Data-driven corrections applied in 2b and 3b categories
- 3 SRs are defined: 2b, 3b, 4b categories

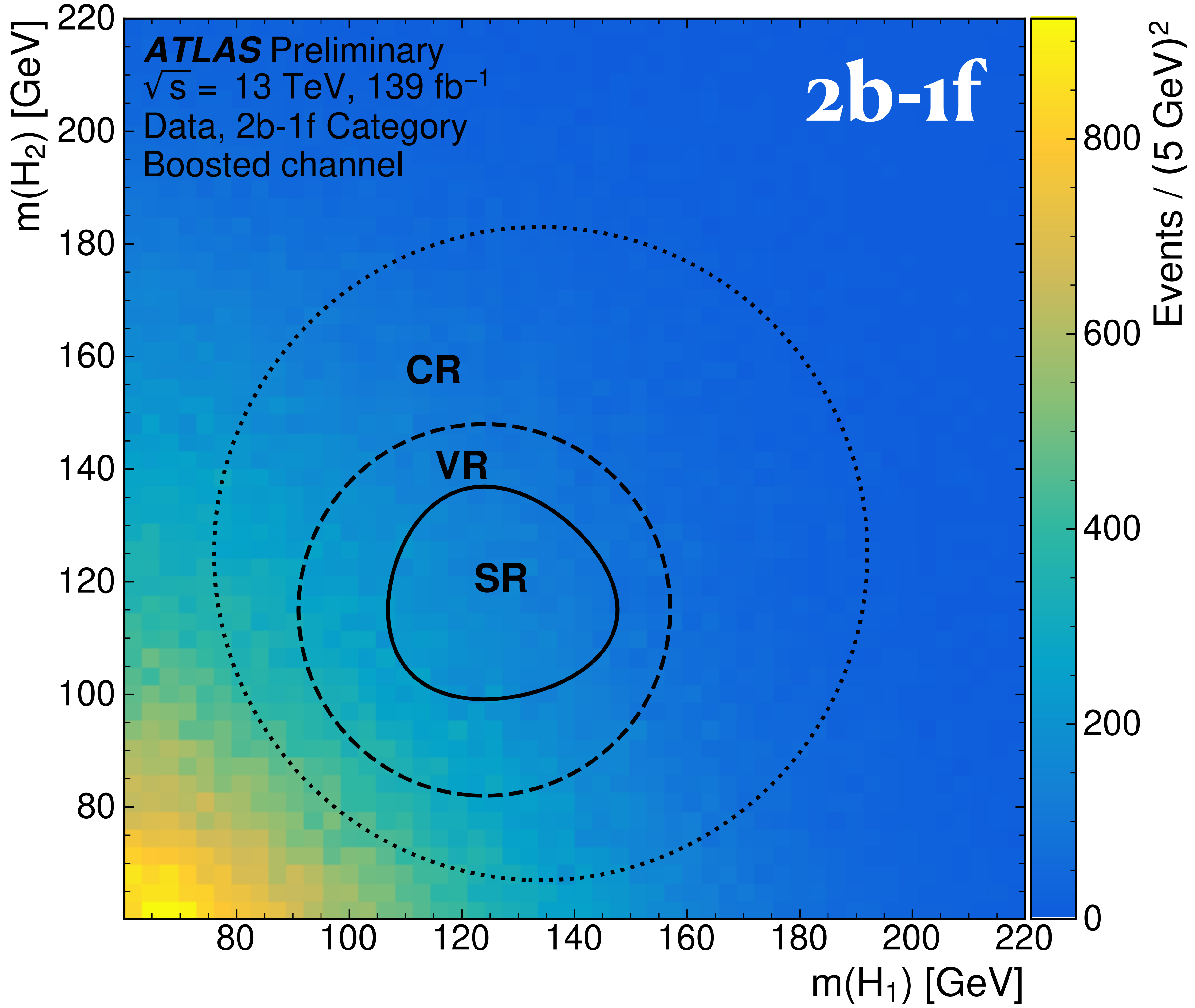


4b background from 2b-2f

3b background from 2b-1f

2b background from 1b-1f

Region definitions slightly different from the resolved analysis



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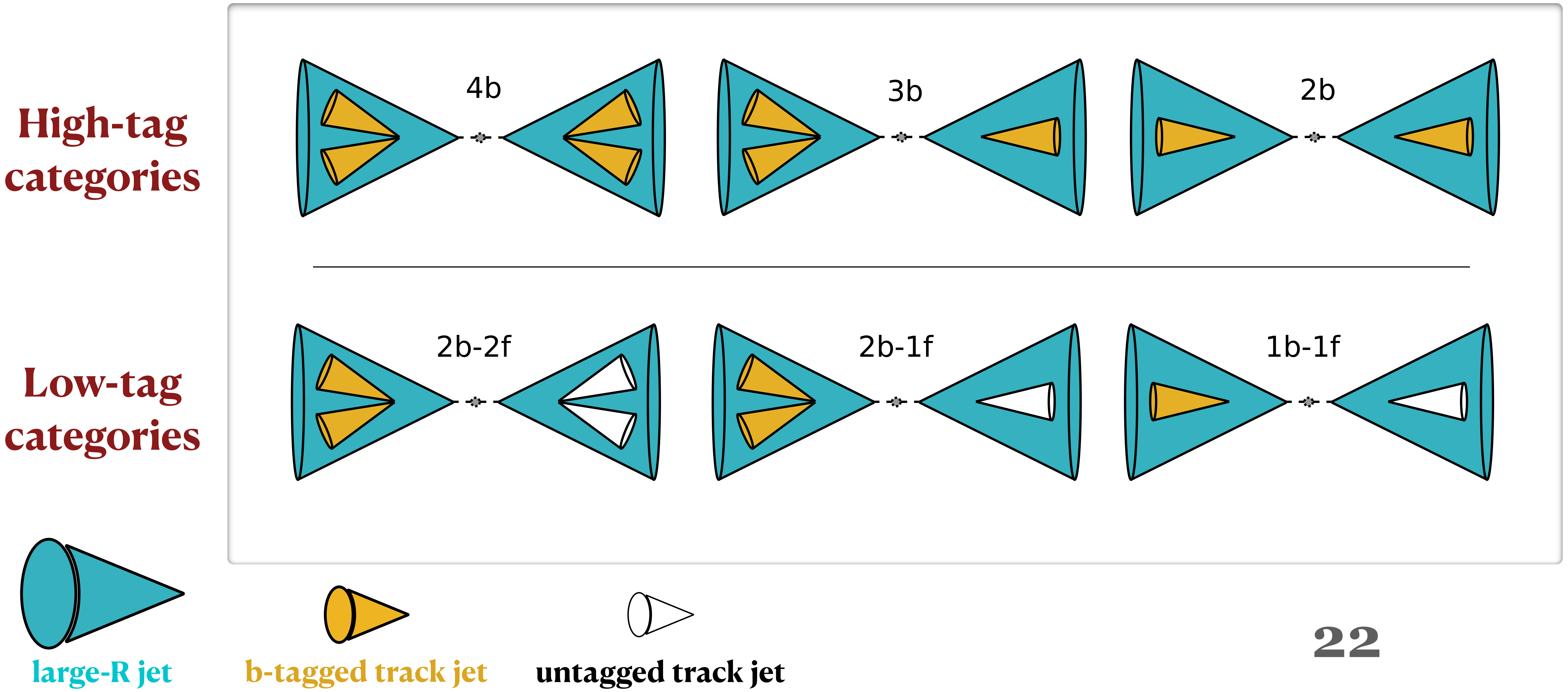
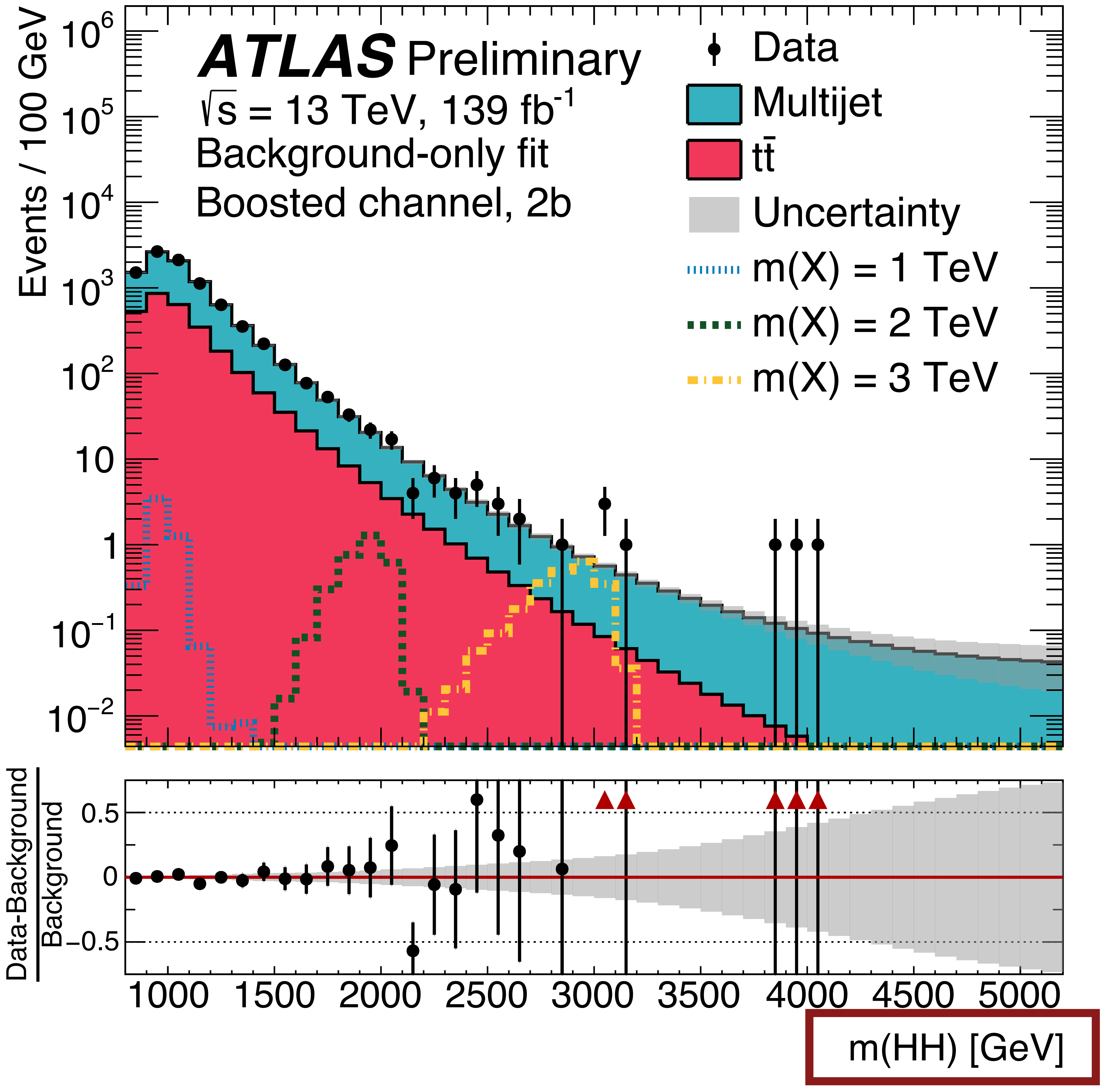
High-tag categories

Low-tag categories

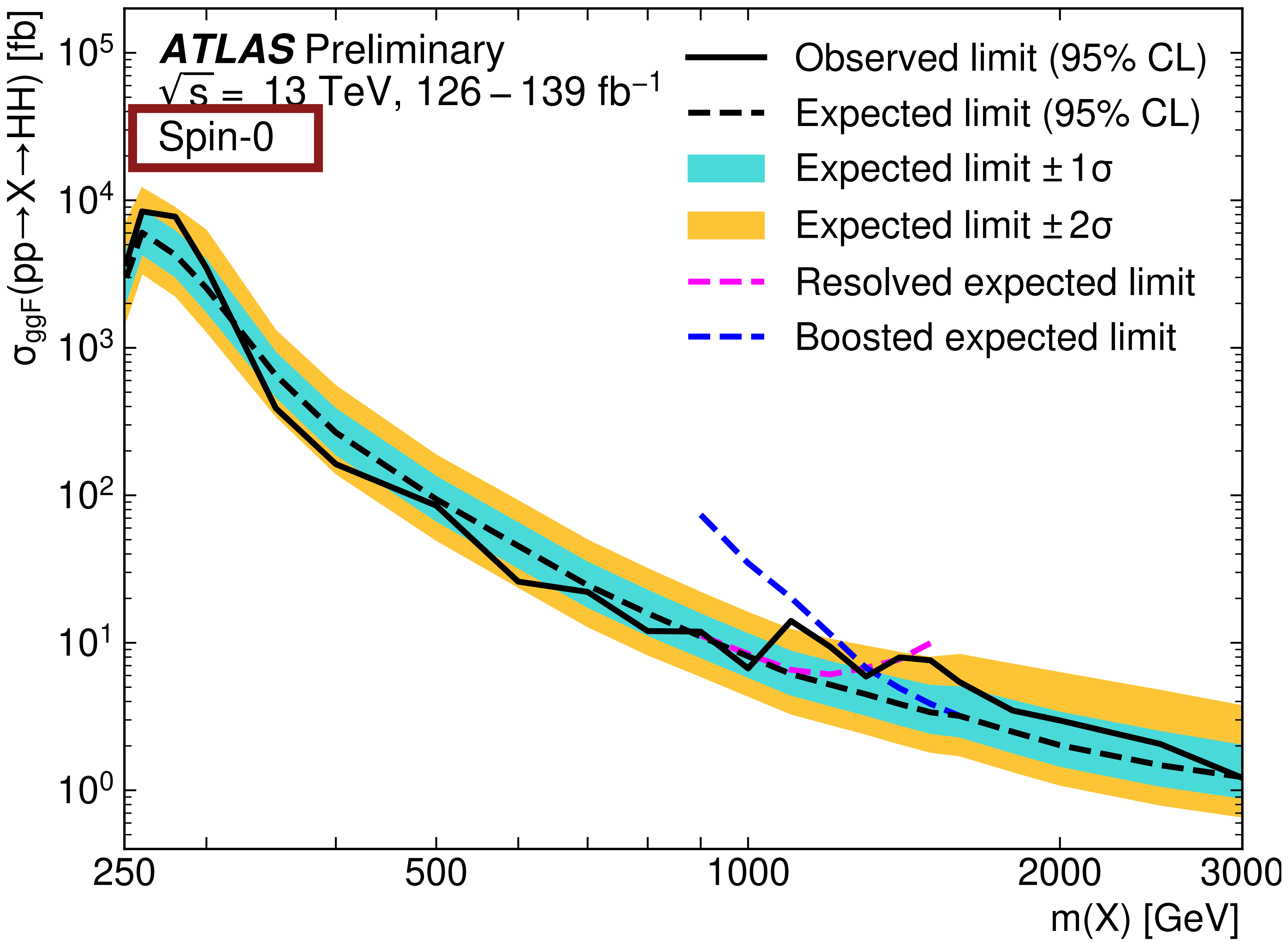


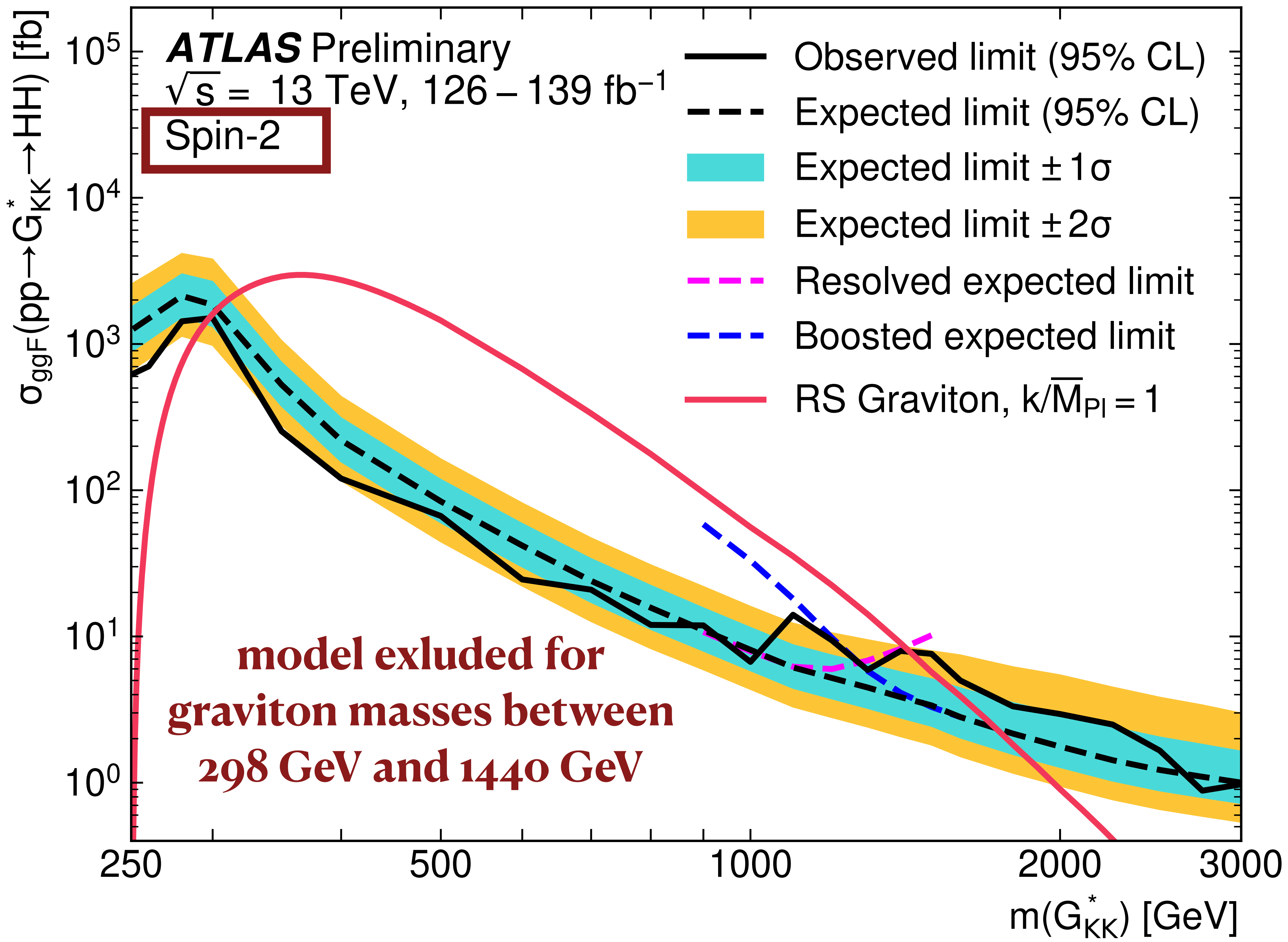
Likelihood fit in bins of m_{HH}



HH→bbbb: Results

- Set upper limits at 95% CL on σxBR of **resonant X/G*$_{KK}$ → HH** production
- The most significant excess **at 1.1 TeV**
  - **Local significance** 2.6σ (2.7σ) for the spin-0 (spin-2) model
  - **Global signifance** 1.0σ (1.2σ) for the spin-0 (spin-2) model
- Statistically dominated, the impact of systematic uncertainties up to ~16%, mainly from the background modelling



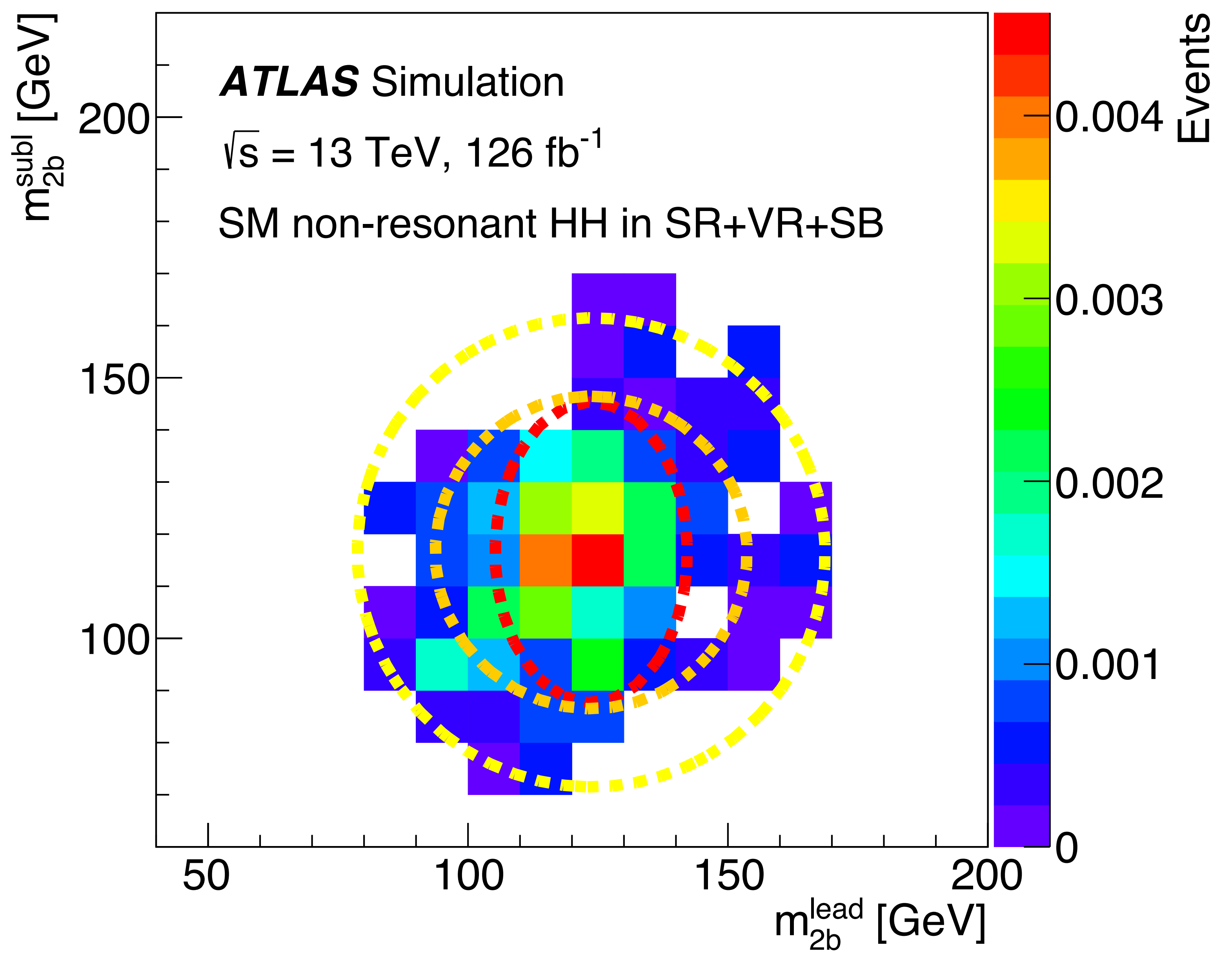


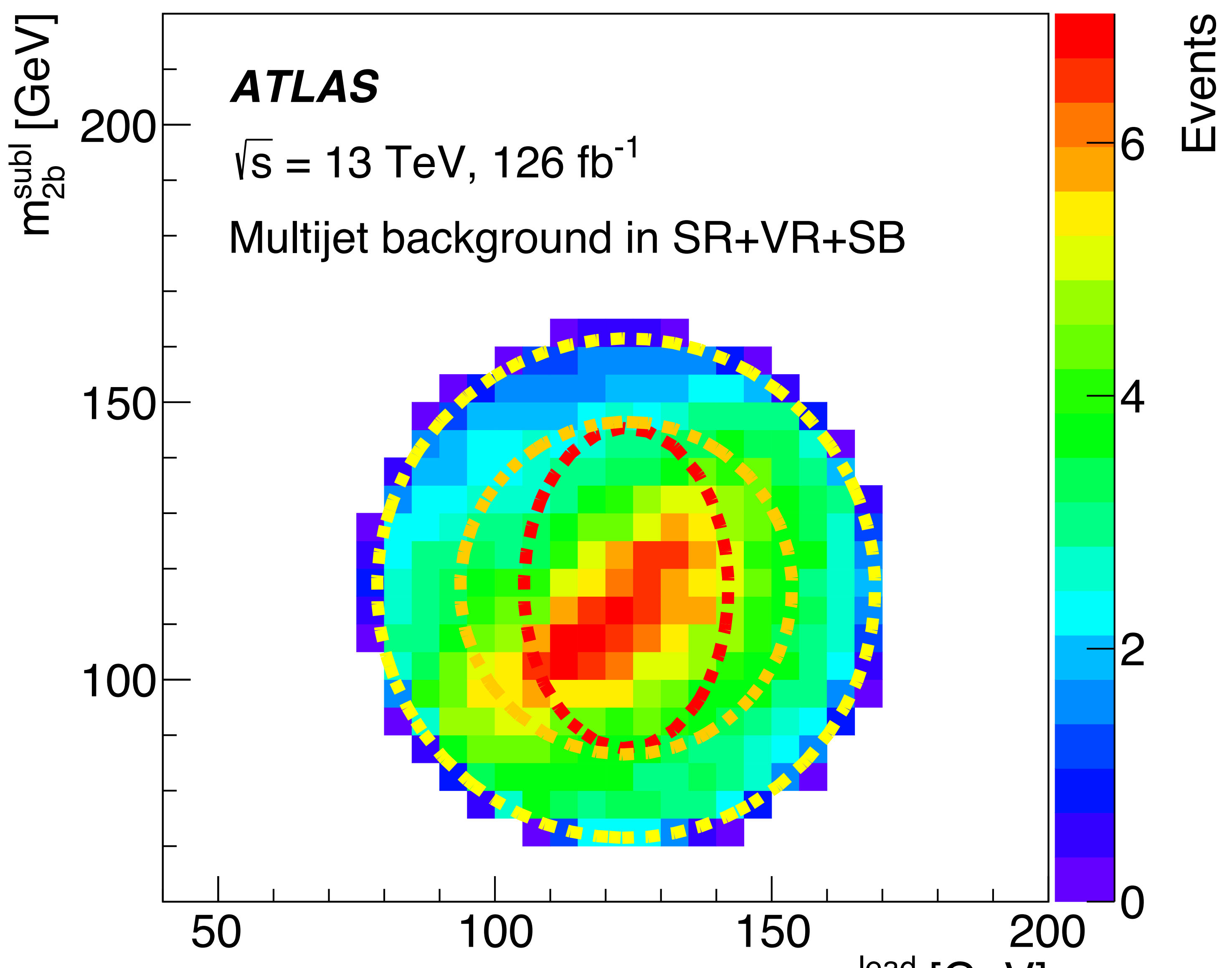
VBF HH→bbbb

Publication: JHEP 07 (2020) 108
Physics Briefing: Double the Higgs for double the difficulty

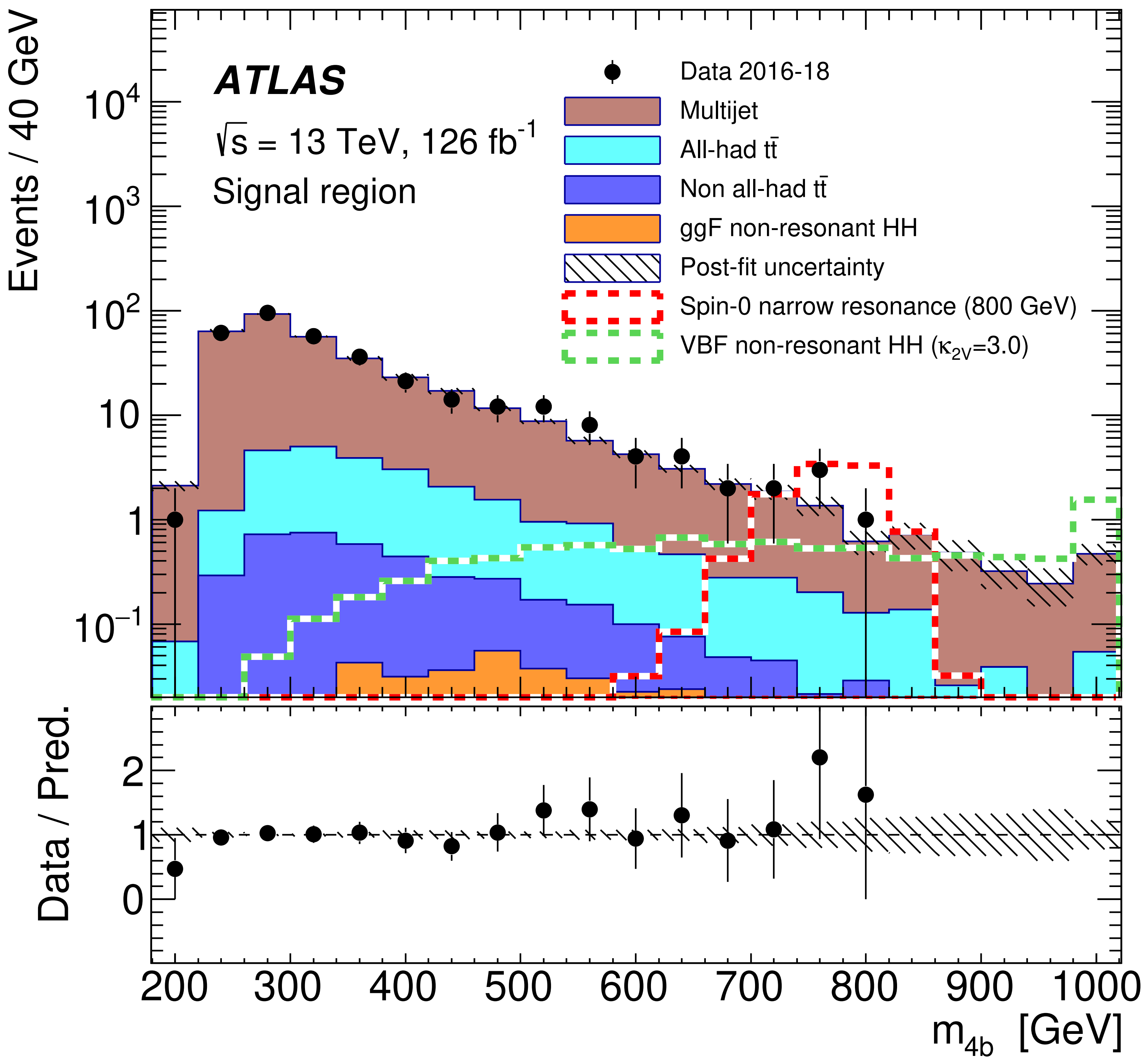
VBF HH→bbbb: Analysis Overview

- Search for **resonant** and **non-resonant VBF HH production** using **126 fb^{-1}** of pp data
  - Use a combination of b-jet triggers
  - Distinct VBF signature: two high p_T jets with a large rapidity gap and invariant mass
- Based on early Run-2 ggF resolved analysis strategy, with optimizations for the VBF HH process
- 95% multijet background (data-driven), 5% ttbar (simulation)
- ggF HH process treated as a background, normalised to the SM expectation





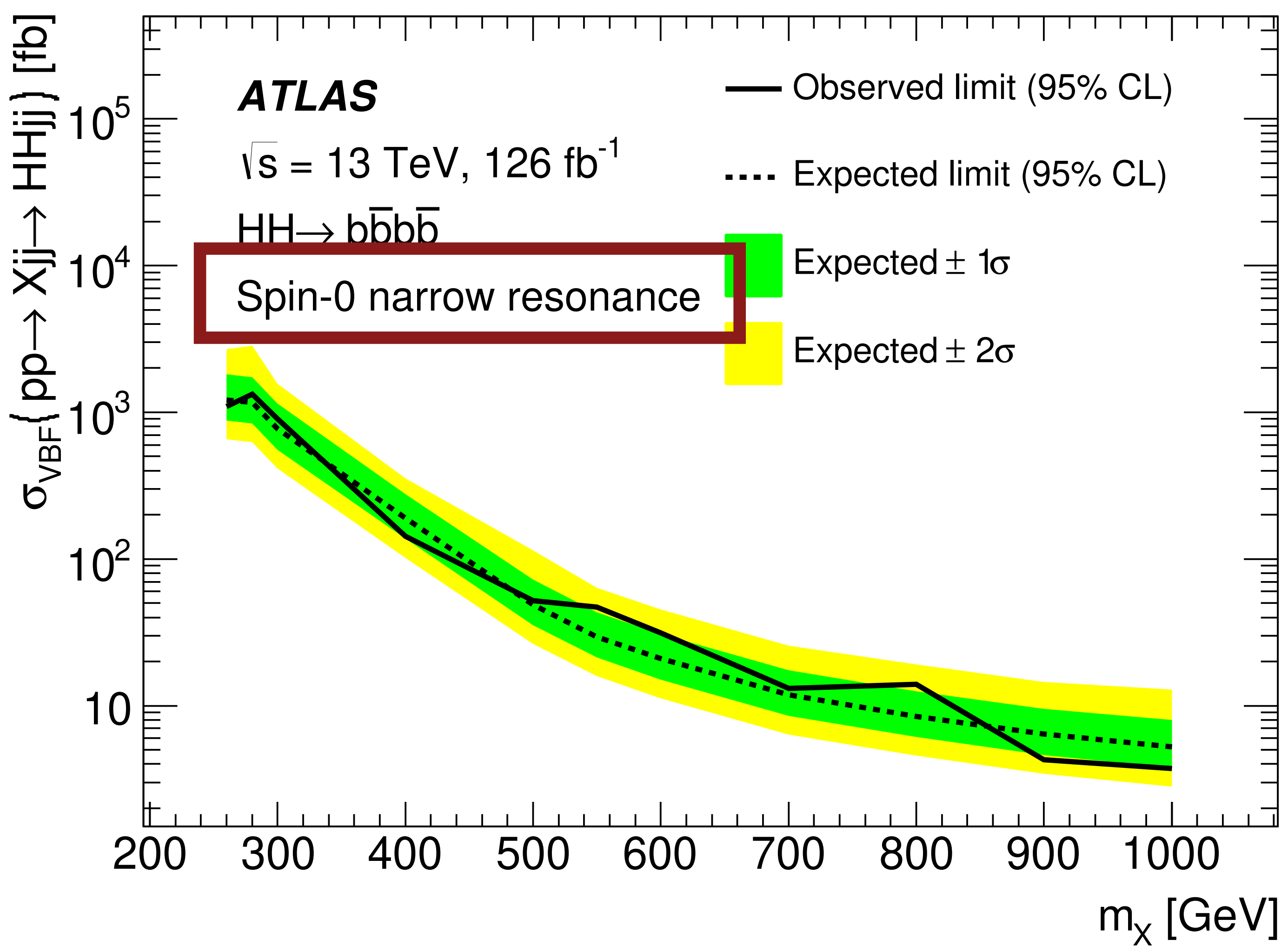
m_{4b} used as a final discriminant

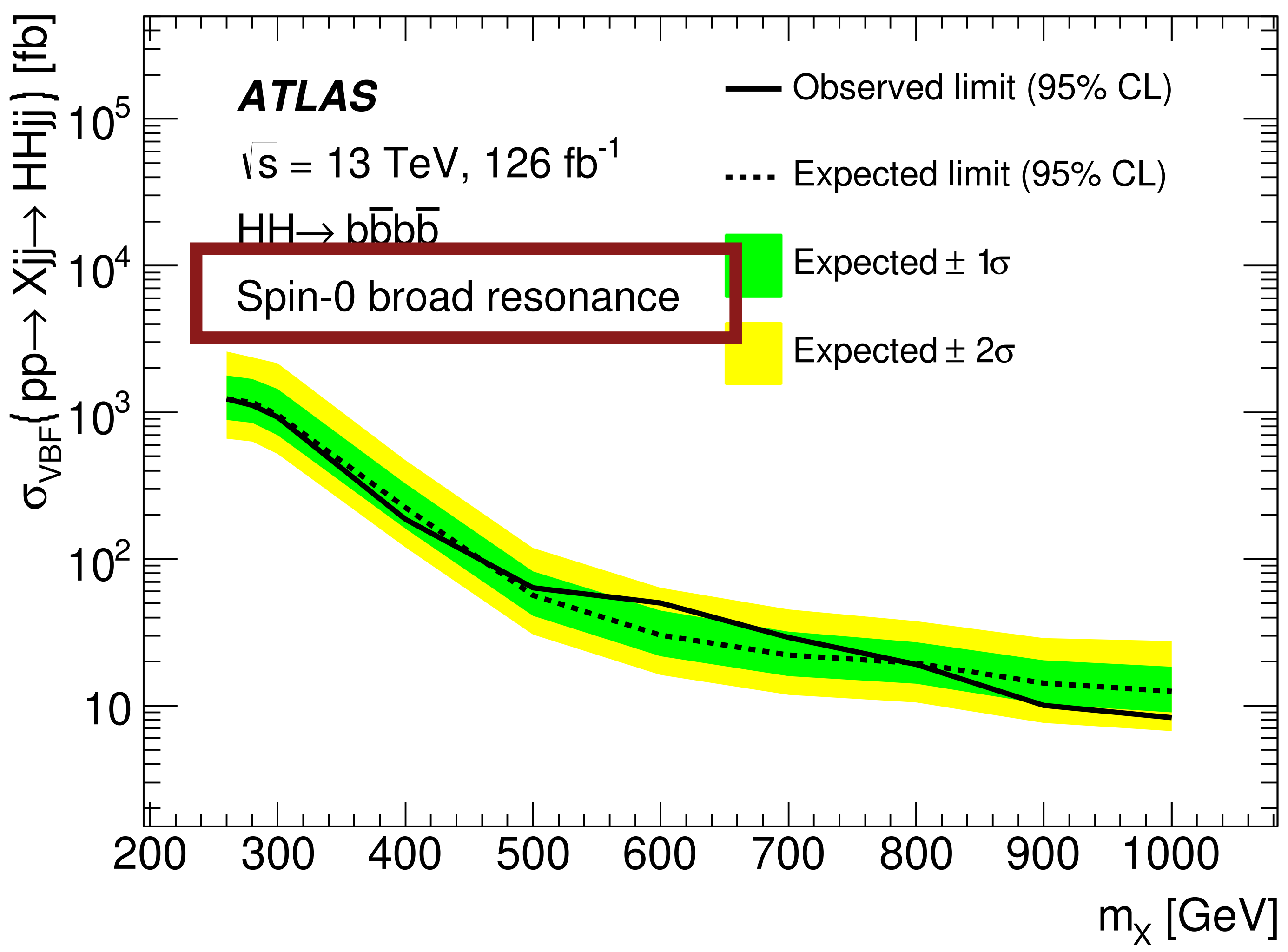


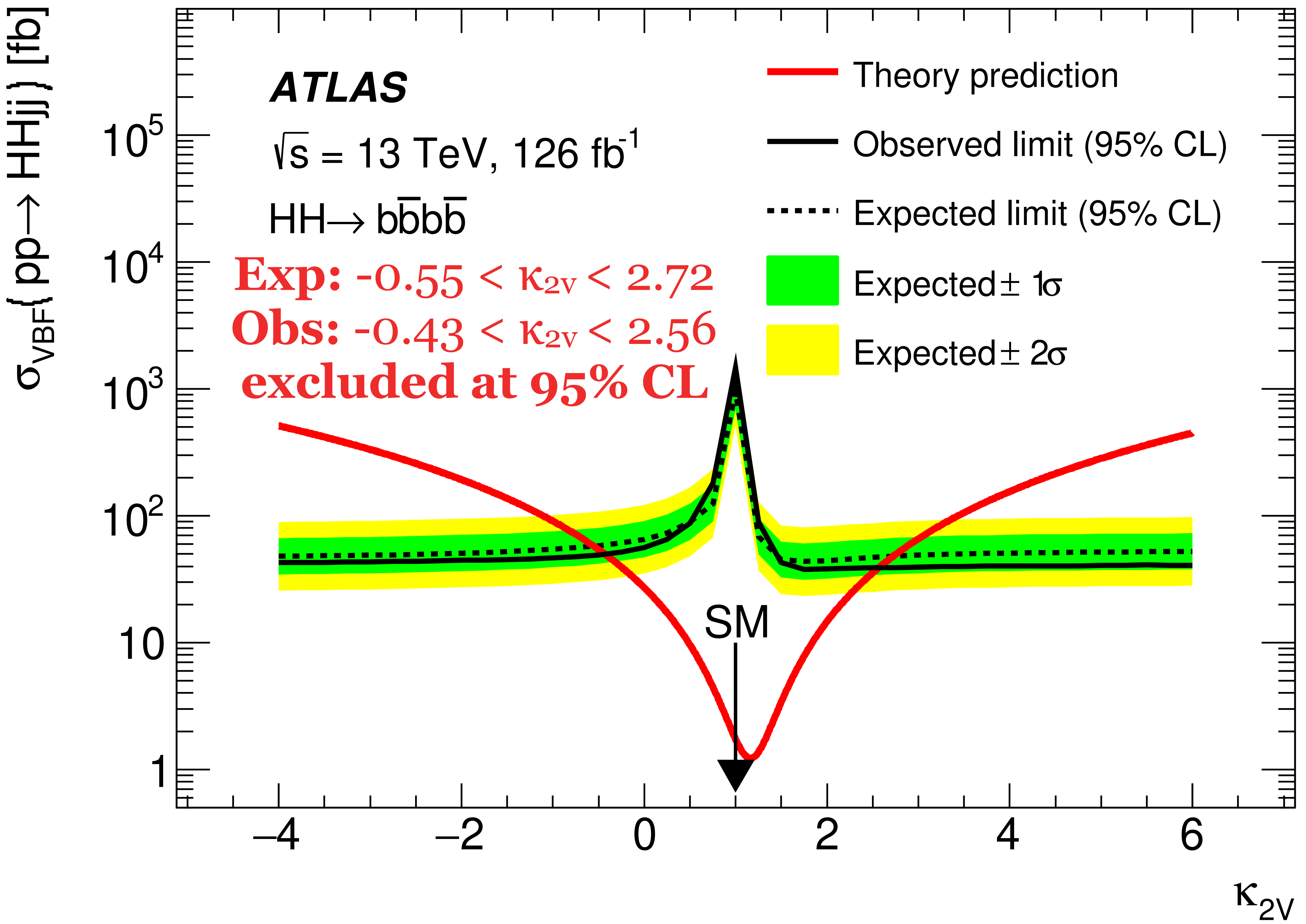
VBF HH→bbbb: Results

- No significant excess observed
- Limits set on:
  - Spin-0 narrow and broad width resonances
  - SM σ_{HH} and κ_{2V}
- Statistically limited, followed by systematics on the multijet background

	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







HH→bblνlν

Publication: Phys. Lett. B 801 (2020) 135145

HH→bblνlν: Analysis Overview

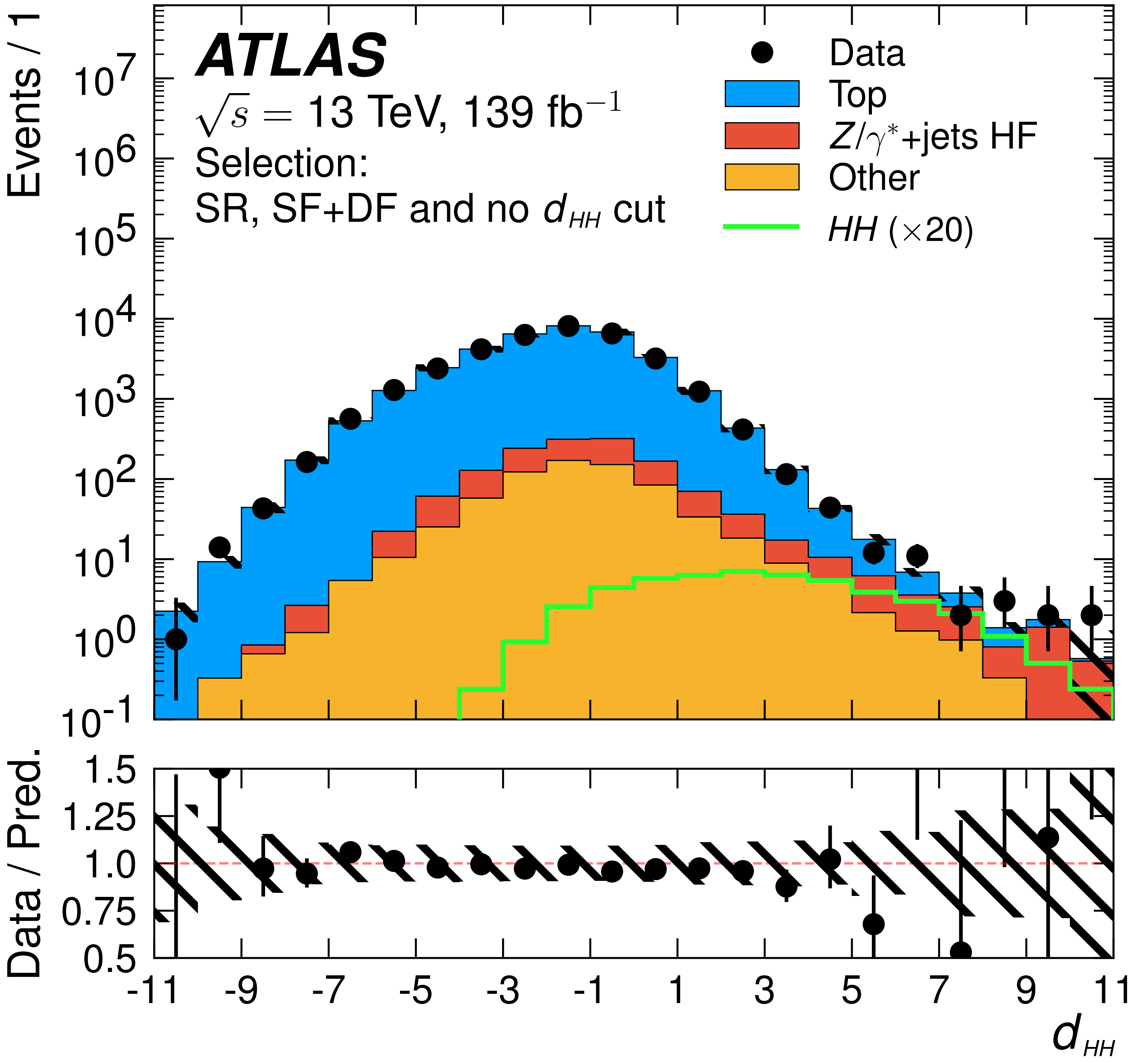
- Search for **non-resonant (ggF) HH production** using **139 fb^{-1}** of pp data
  - Contributions from HH→bbWW* (90% of the total signal yield), HH→bbττ (9%), HH→bbZZ* (1%)
  - At least 2 b-jets and exactly 2 opposite-sign leptons (e or μ)

- **Main backgrounds** from Top production and Z/γ* + HF
- **A multi-class deep neural network (DNN)** used to discriminate signal and the SM background
  - Trained only with the HH→bbWW* signal, due to its larger BR
  - Final discriminant defined using the DNN outputs
    - $\mathbf{d_{HH} = \ln[p_{HH}/(p_{Top} + p_{Z\text{-}ll} + p_{Z\text{-}\tau\tau})]}$, ($p_i$=[0-1], where 1 indicates the event likely belongs to class i)

- Perform **a counting experiment with a likelihood fit** simultaneously across:
  - Top and Z+HF CRs
  - The same flavour (SF) and different flavour (DF) SRs

HH→bblνlν: Results

- Dominant uncertainties from Top and Z+HF background modelling

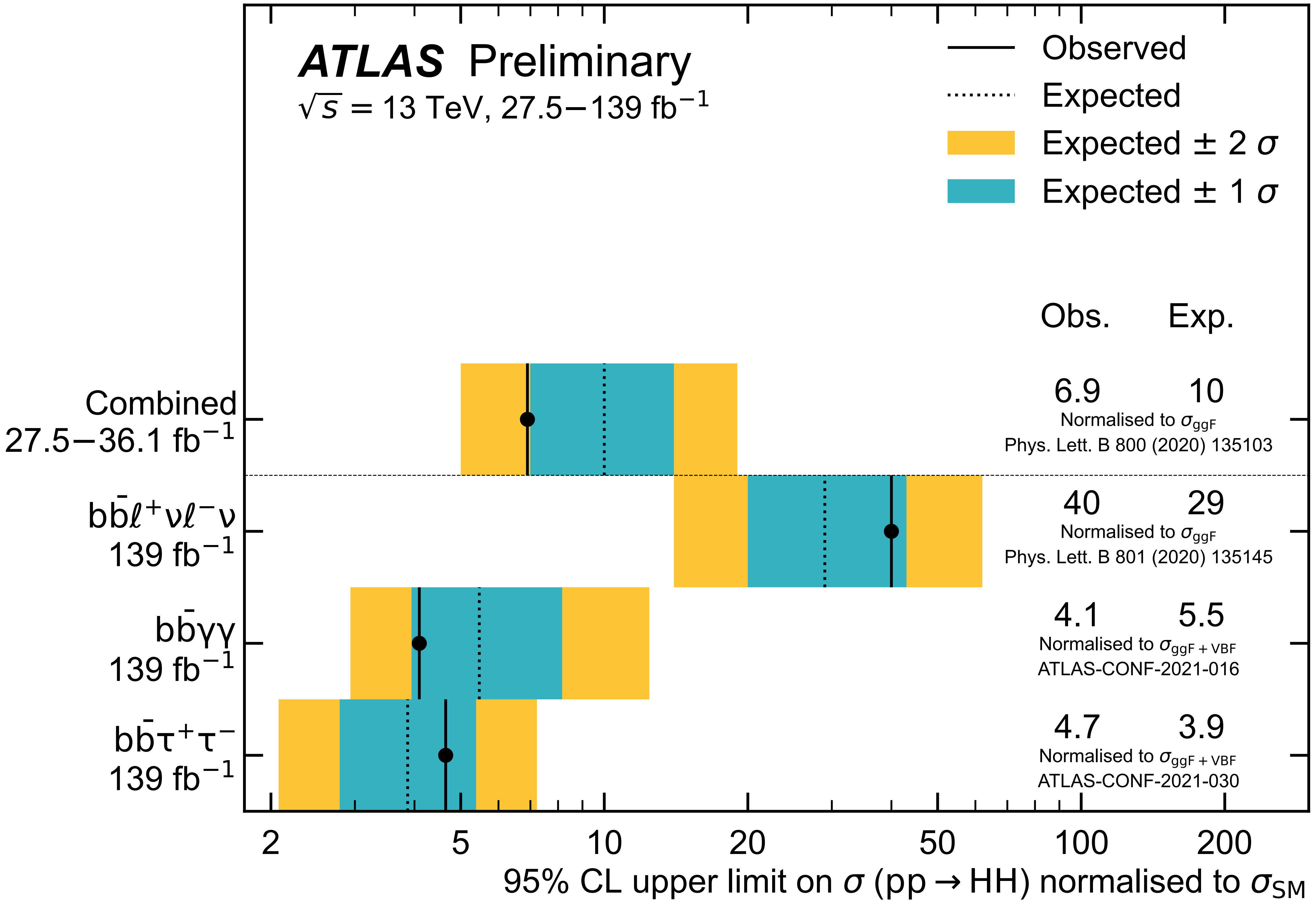


	-2σ	-1σ	**Expected**	$+1\sigma$	$+2\sigma$	**Observed**
$\sigma(gg \to HH)$ [pb]	0.5	0.6	0.9	1.3	1.9	1.2
$\sigma(gg \to HH)/\sigma^{\text{SM}}(gg \to HH)$	14	20	29	43	62	40

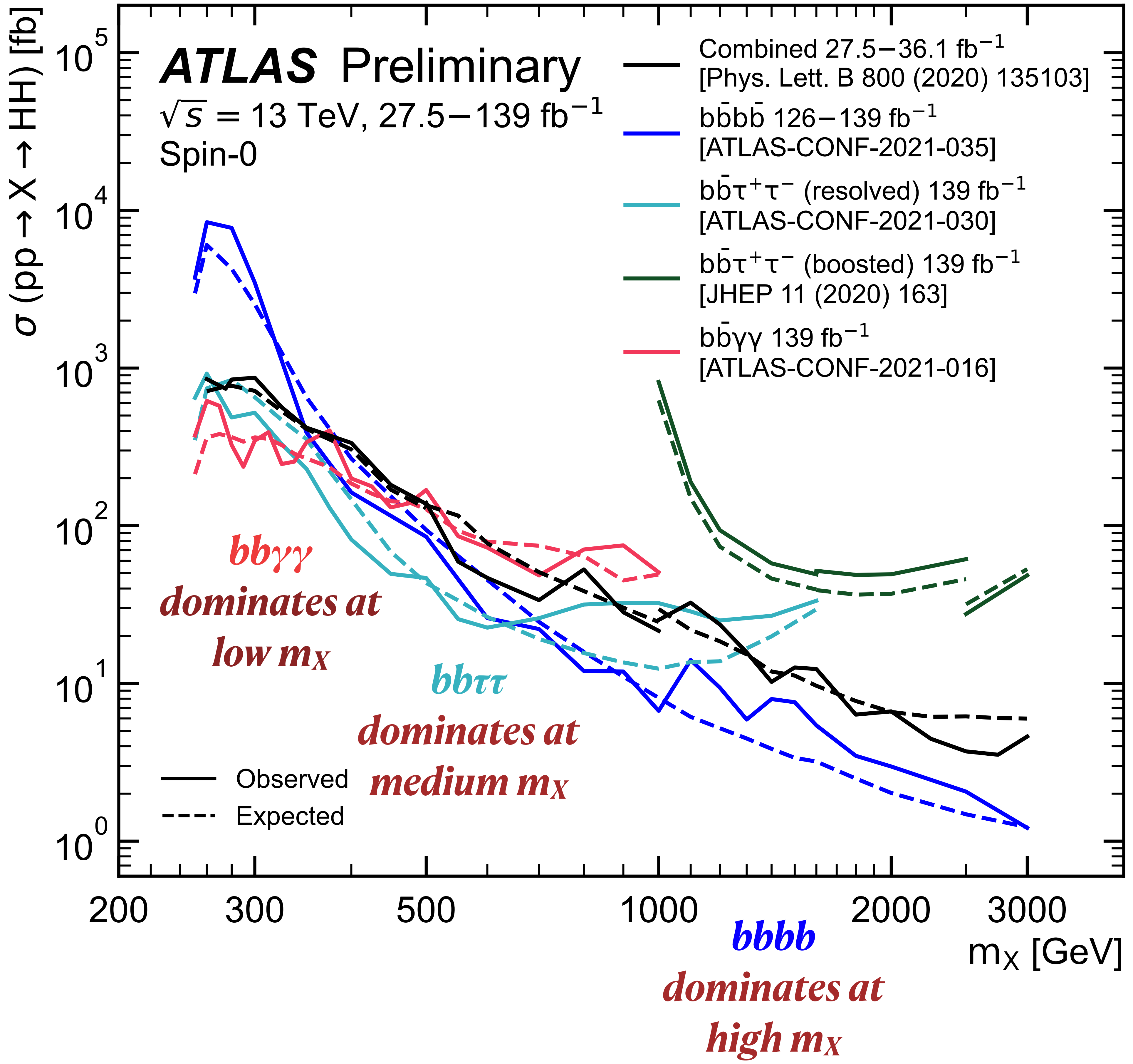
Summary

Summary of Results

Non-Resonant - SM HH



Resonant - Spin-0



Even better results from the individual channels compared to the 36 fb⁻¹ HH combination!

ATL-PHYS-PUB-2021-031

Projections for HL-LHC

- **Prospects study for the non-resonant HH production at the HL-LHC**
  - 3 ab^{-1} of data assumed → ~21 x full Run-2 dataset
  - Based on analysis performed with 36 fb^{-1} of data
    - Except bbγγ prospects are from a dedicated analysis on 14 TeV simulation

Channel	Statistical-only	Statistical + Systematic
$HH \rightarrow b\bar{b}b\bar{b}$	1.2	0.5
$HH \rightarrow b\bar{b}\tau^+\tau^-$	2.3	2.0
$HH \rightarrow b\bar{b}\gamma\gamma$	2.1	2.0
Combined	3.3 σ	2.9 σ

ATL-PHYS-PUB-2020-005

Conclusion

- Searches for Higgs pair production performed in multiple final states with the ATLAS detector

- Results include:
  - Limits on σ_{HH}
  - Constraints on κ_λ, κ_{2V}
  - Limits on σ_{HH} vs m_X, for a spin-0 heavy resonance
  - Limits on σ_{HH} vs $m(G_{KK})$, for a spin-2 graviton

- Large improvements in sensitivity compared to the previous iterations

BACK UP

HH→bbγγ: BDT Input Variables (Non-Res)

Variable	Definition
Photon-related kinematic variables	
$p_T/m_{\gamma\gamma}$	Transverse momentum of the two photons scaled by their invariant mass $m_{\gamma\gamma}$
η and ϕ	Pseudo-rapidity and azimuthal angle of the leading and sub-leading photon
Jet-related kinematic variables	
b-tag status	Highest fixed b-tag working point that the jet passes
p_T, η and ϕ	Transverse momentum, pseudo-rapidity and azimuthal angle of the two jets with the highest b-tagging score
$p_T^{b\bar{b}}$, $\eta_{b\bar{b}}$ and $\phi_{b\bar{b}}$	Transverse momentum, pseudo-rapidity and azimuthal angle of b-tagged jets system
$m_{b\bar{b}}$	Invariant mass built with the two jets with the highest b-tagging score
H_T	Scalar sum of the p_T of the jets in the event
Single topness	For the definition, see Eq. (1)
Missing transverse momentum-related variables	
E_T^{miss} and ϕ^{miss}	Missing transverse momentum and its azimuthal angle

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 $\in [0.881, 0.966]$

Highest discriminating power against the γγ+jets continuum background

HH→bbγγ: BDT Input Variables (Resonant)

Variable	Definition
Photon-related kinematic variables	
$p_{\mathrm{T}}^{\gamma\gamma}$, $y^{\gamma\gamma}$	Transverse momentum and rapidity of the di-photon system
$\Delta\phi_{\gamma\gamma}$ and $\Delta R_{\gamma\gamma}$	Azimuthal angular distance and ΔR between the two photons
Jet-related kinematic variables	
$m_{b\bar{b}}$, $p_{\mathrm{T}}^{b\bar{b}}$ and $y_{b\bar{b}}$	Invariant mass, transverse momentum and rapidity of the b-tagged jets system
$\Delta\phi_{b\bar{b}}$ and $\Delta R_{b\bar{b}}$	Azimuthal angular distance and ΔR between the two b-tagged jets
N_{jets} and $N_{b-\mathrm{jets}}$	Number of jets and number of b-tagged jets
H_{T}	Scalar sum of the p_{T} of the jets in the event
Photons and jets-related kinematic variables	
$m_{b\bar{b}\gamma\gamma}$	Invariant mass built with the di-photon and b-tagged jets system
$\Delta y_{\gamma\gamma,b\bar{b}}$, $\Delta\phi_{\gamma\gamma,b\bar{b}}$ and $\Delta R_{\gamma\gamma,b\bar{b}}$	Distance in rapidity, azimuthal angle and ΔR between the di-photon and the b-tagged jets system

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

HH→bbττ: Event Selection

$\tau_{had}\tau_{had}$ category		$\tau_{lep}\tau_{had}$ categories	
STT	DTT	SLT	LTT
e/μ selection			
No loose e/μ with $p_T > 7$ GeV		Exactly one tight e or medium μ	
		$p_T^e > 25, 27$ GeV	18 GeV $< p_T^e <$ SLT cut
		$p_T^\mu > 21, 27$ GeV	15 GeV $< p_T^\mu <$ SLT cut
		$\lvert\eta^e\rvert < 2.47$, not $1.37 < \lvert\eta^e\rvert < 1.52$	
		$\lvert\eta^\mu\rvert < 2.7$	
$\tau_{\text{had-vis}}$ selection			
Two loose $\tau_{\text{had-vis}}$		One loose $\tau_{\text{had-vis}}$	
$\lvert\eta\rvert < 2.5$		$\lvert\eta\rvert < 2.3$	
$p_T > 100, 140, 180$ (25) GeV	$p_T > 40$ (30) GeV	$p_T > 20$ GeV	$p_T > 30$ GeV
Jet selection			
≥ 2 jets with $\lvert\eta\rvert < 2.5$			
$p_T > 45$ (20) GeV	Trigger dependent	$p_T > 45$ (20) GeV	Trigger dependent
Event-level selection			
Trigger requirements passed			
Collision vertex reconstructed			
$m_{\tau\tau}^{\text{MMC}} > 60$ GeV			
Opposite-sign electric charges of $e/\mu/\tau_{\text{had-vis}}$ and $\tau_{\text{had-vis}}$			
Exactly two b-tagged jets			
		$m_{bb} < 150$ GeV	

HH→bbττ: Input Parameters in MVA

Variable	$\tau_{\rm had}\tau_{\rm had}$	$\tau_{\rm lep}\tau_{\rm had}$ SLT	$\tau_{\rm lep}\tau_{\rm had}$ LTT
m_{HH}	✓	✓	✓
$m_{\tau\tau}^{\rm MMC}$	✓	✓	✓
m_{bb}	✓	✓	✓
$\Delta R(\tau,\tau)$	✓	✓	✓
$\Delta R(b,b)$	✓	✓	
$\Delta p_{\rm T}(\ell,\tau)$		✓	✓
Sub-leading b-tagged jet $p_{\rm T}$		✓	
$m_{\rm T}^W$		✓	
$E_{\rm T}^{\rm miss}$		✓	
$\mathbf{p}_{\rm T}^{\rm miss}$ ϕ centrality		✓	
$\Delta\phi(\ell\tau, bb)$		✓	
$\Delta\phi(\ell, \mathbf{p}_{\rm T}^{\rm miss})$			✓
$\Delta\phi(\ell\tau, \mathbf{p}_{\rm T}^{\rm miss})$			✓
$S_{\rm T}$			✓