Searches for additional Higgs bosons in ATLAS

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Introduction

So far excellent agreement of measurements with predictions from Standard Model (SM) Higgs boson assumptions.

The SM is not the ultimate theory of nature since there are serious shortcomings (hierarchy problem, baryon asymmetry, dark matter/energy…).

↪many Beyond Standard Model (BSM) theories predict **modified and extended Higgs sectors with additional Higgs.**

↪e.g. Two-Higgs-Doublet models (2HDM) and Three-Higgs-Doublet models (3HDM), which predict neutral and charged Higgs bosons.

↪ these bosons can decay into a SM **Higgs boson pair (HH),** motivating these resonant production searches.

↪ any deviation from the SM predictions would open a window to new BSM physics.

Lots of searches for additional Higgs bosons have been performed at LHC with Run 2 dataset, in a wide mass range.

ATLAS search program

Run 2 @13 TeV
$\mathscr{L} = 139\text{fb}^{-1}$

Many searches for additional Higgs bosons were performed and some of them include:

↪ Searches for singly or doubly **charged Higgs bosons:**

$H^{\pm} \to cb$ (ATLAS-CONF-2021-037) NEW

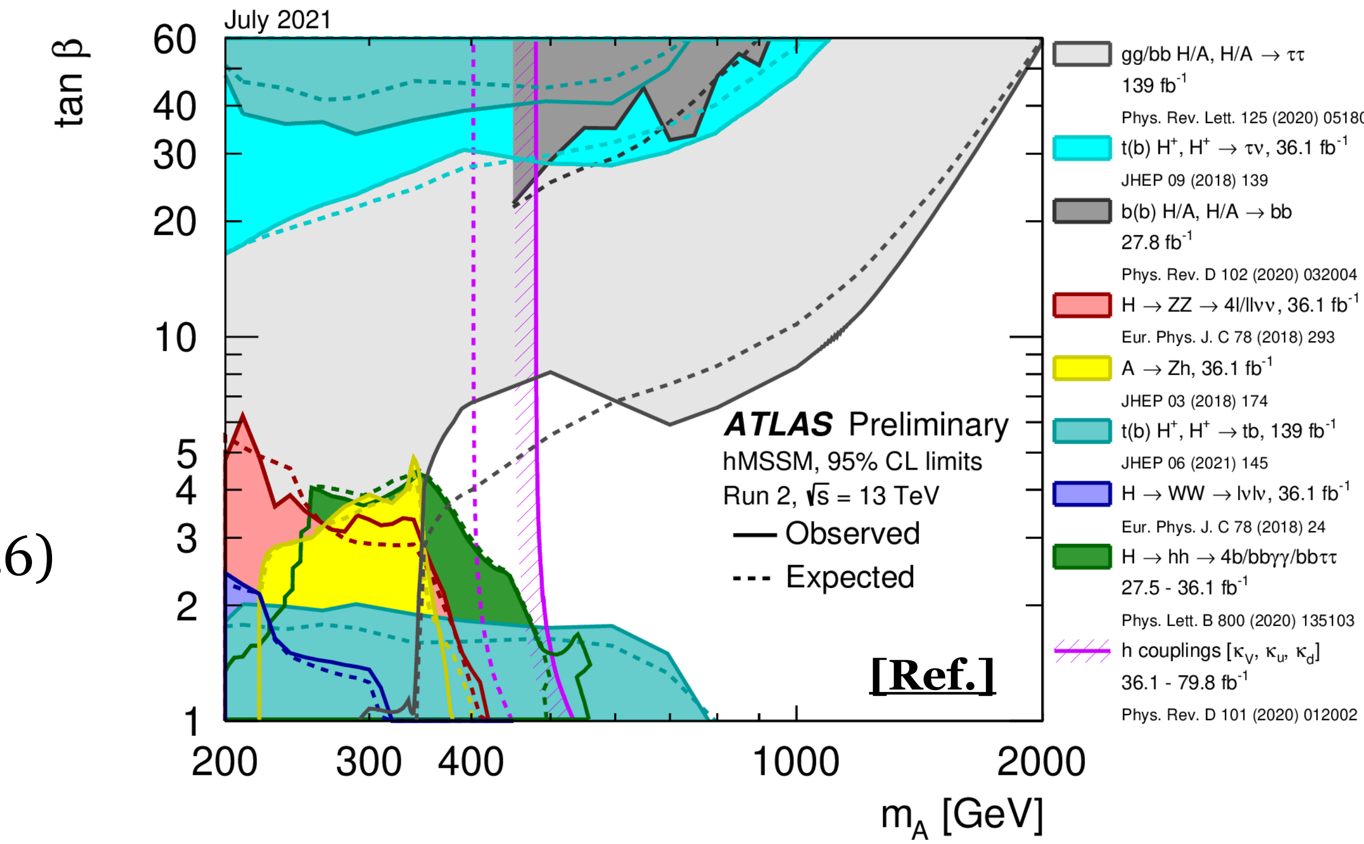
$H^{+} \to tb$ (JHEP 06 (2021) 145)
$H^{\pm\pm} \to W^{\pm}W^{\pm}/H^{\pm} \to W^{\pm}Z$ (JHEP 06 (2021) 146)

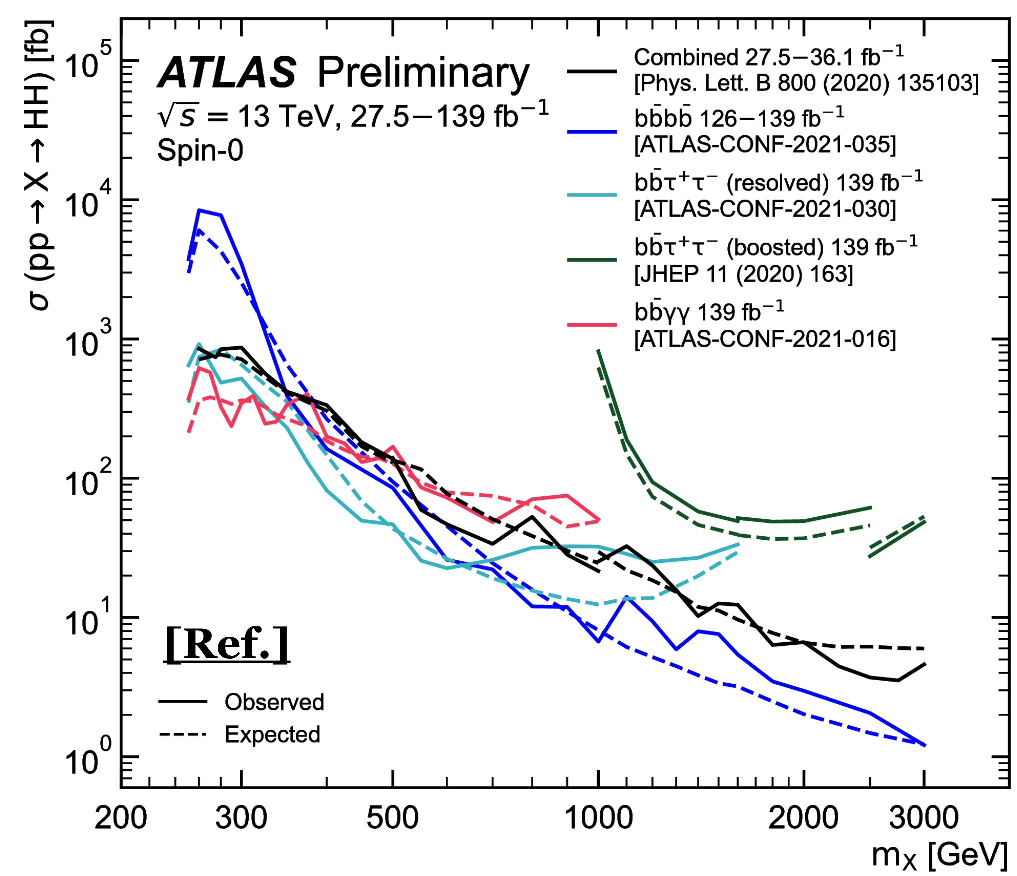
↪ Searches for additional neutral Higgs bosons in all possible decay modes ($ZZ, WW, Z\gamma, \gamma\gamma, hh, \tau\tau, tt, bb$).

↪ **Di-Higgs production:**

$HH \to b\bar{b}\tau^{+}\tau^{-}$ (ATLAS-CONF-2021-030) NEW
$HH \to b\bar{b}b\bar{b}$ (ggF) (ATLAS-CONF-2021-035)

$HH \to bb\gamma\gamma$ (ATLAS-CONF-2021-016)
$HH \to b\bar{b}\tau^{+}\tau^{-}$ (boosted) (JHEP 11 (2020) 163)
$HH \to b\bar{b}b\bar{b}$ (VBF) (JHEP 07 (2020) 108)

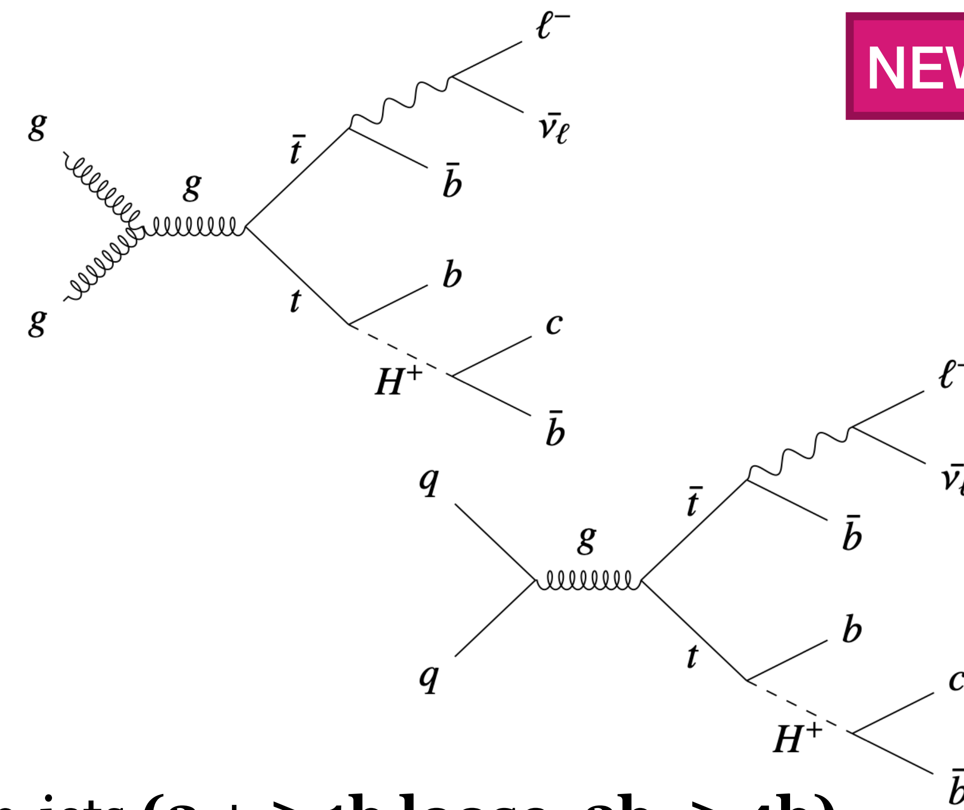




[ATLAS-CONF-2021-037]

NEW

$H^{\pm} \rightarrow cb$



Search for a **light charged Higgs** produced in top decays $t \rightarrow H^{\pm}b$ and decaying to $H^{\pm} \rightarrow cb$.

↪ **2/3HDM** features two charged Higgs bosons $H^{\pm}$ that can be lighter than the top quark $m_{H^{\pm}} < m_{top}$.

↪ $m_{H^{\pm}}$ **between 60 GeV and 160 GeV**.

↪ first time for a search in this channel within ATLAS.

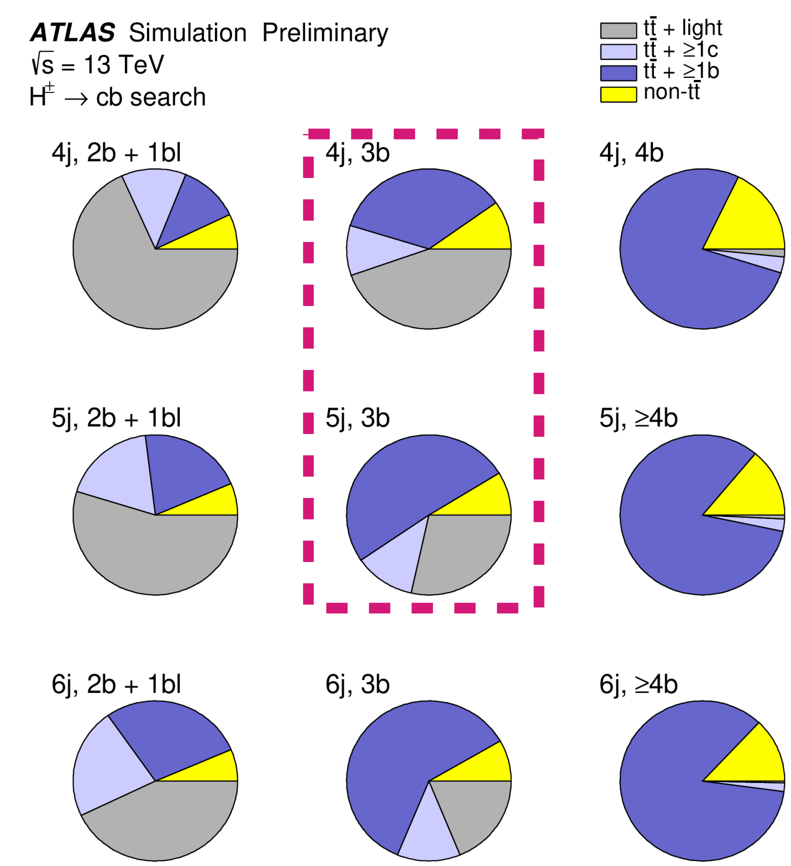
Signal signature: 1 isolated e^- or μ + $\geq$ 4 jets ($\geq$ 2 b-tagged).

↪ regions based on number of jets **(4j,5j,6j)** and the number of b-jets **(2 + ≥ 1b loose, 3b, ≥ 4b)**.

Main background comes from SM $t\bar{t} \rightarrow WbWb$

↪split in flavour components: $t\bar{t} + \geq b$, $t\bar{t} + \geq c$ and $t\bar{t} + light$.

Nb ⇨ / **Nj** ⇩	**2b + 1bl** (exactly two b-tagged jets plus one loose b-tagged jet)	**3b** (exactly three b-tagged jets)	**≥4b** (at least four b-tagged jets)
4j (exactly four jets)	**4j, 2b + 1bl** (MC corrections)	**4j, 3b** (main signal region)	**4j, 4b** ($t\bar{t}+b$ background control and large S/B region)
5j (exactly five jets)	**5j, 2b + 1bl** (MC corrections)	**5j, 3b** (main signal region)	**5j, ≥4b** ($t\bar{t}+b$ background control and large S/B region)
6j (exactly six jets)	**6j, 2b + 1bl** (MC corrections)	**6j, 3b** (shape correction for the NN discriminant in background dominated region)	**6j, ≥4b** ($t\bar{t}+b$ background control 1 bin)



$H^{\pm} \rightarrow cb$

[ATLAS-CONF-2021-037]

NEW

To discriminate signal and background a **NN classifier** is built:

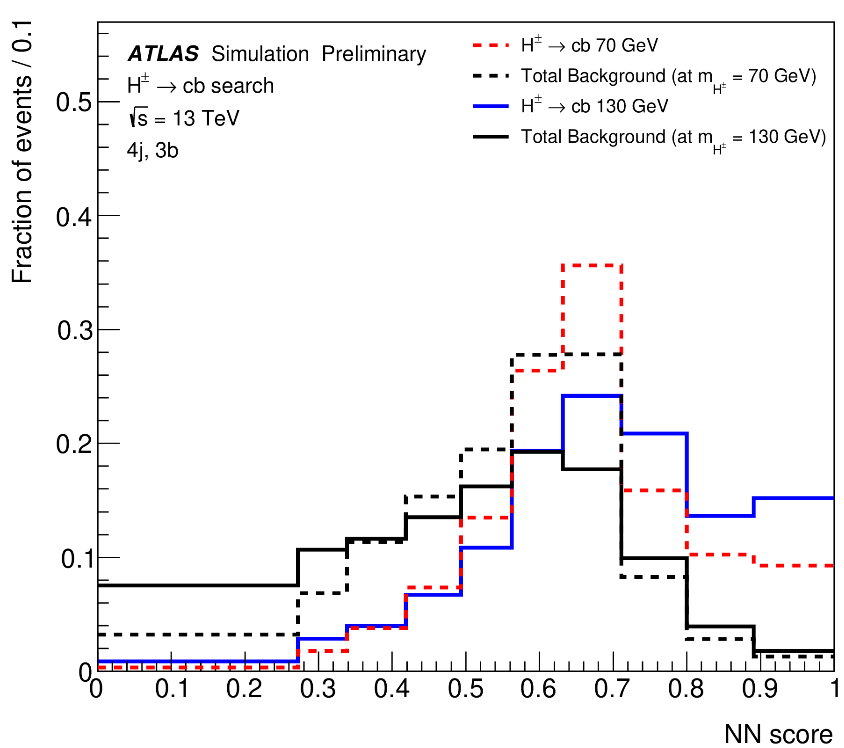
↪ **trained with signal events against $t\bar{t}$ events in ≥ 4j,3b regions**.

↪ input variables: jets and lepton kinematics, b-tagging information, invariant mass variables.

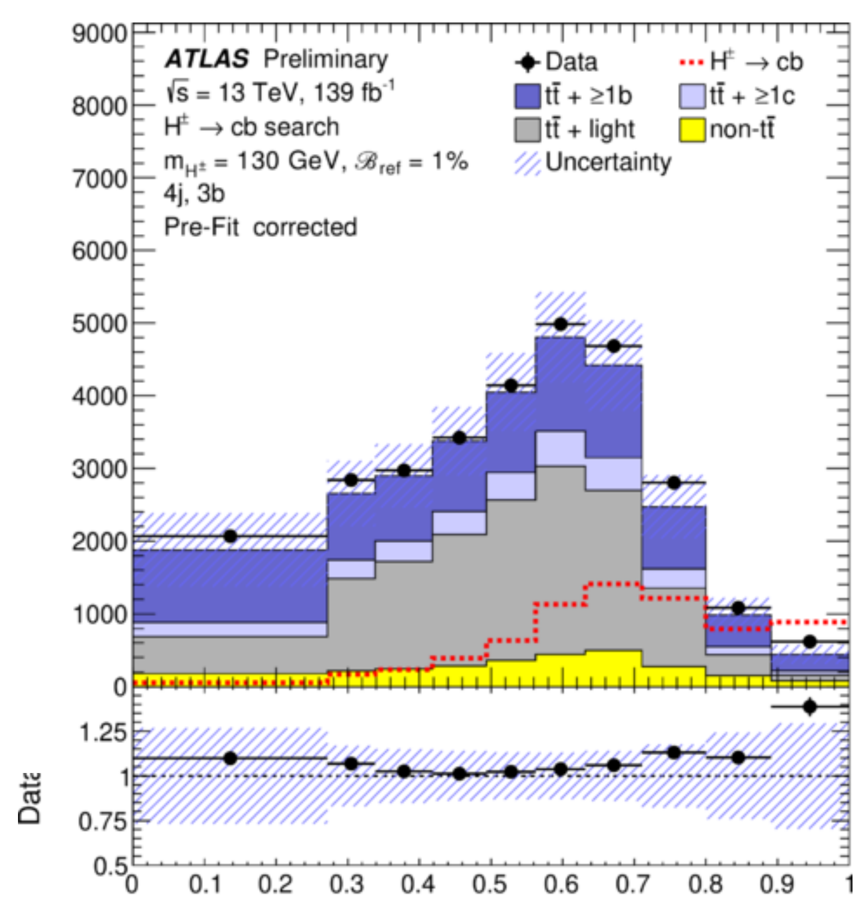
↪NN parametrized as a function of $m_{H^{\pm}}$ and trained all signals together.

⇒ **Perform binned profile likelihood fit over discriminant output across 3b and 4b regions** to calibrate background and reduce the impact of systematic uncertainties.

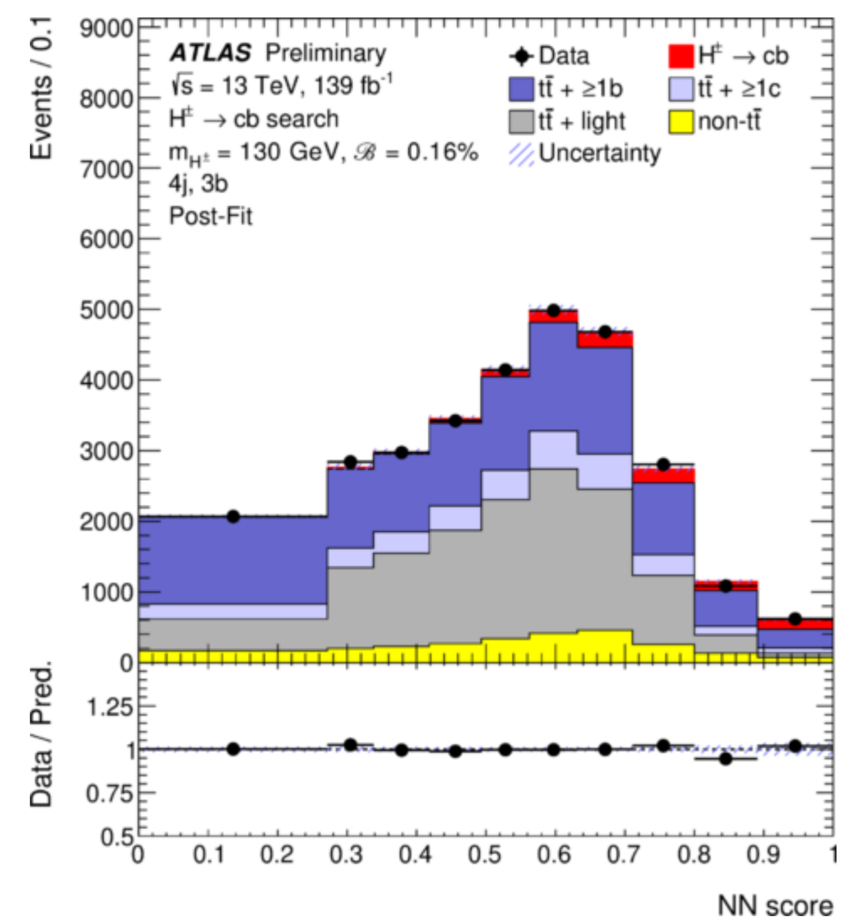
NN discriminant output in 4j,3b region



Pre-Fit NN score in 4j,3b region



Post-Fit NN score in 4j,3b region



$H^{\pm} \rightarrow cb$

[ATLAS-CONF-2021-037]

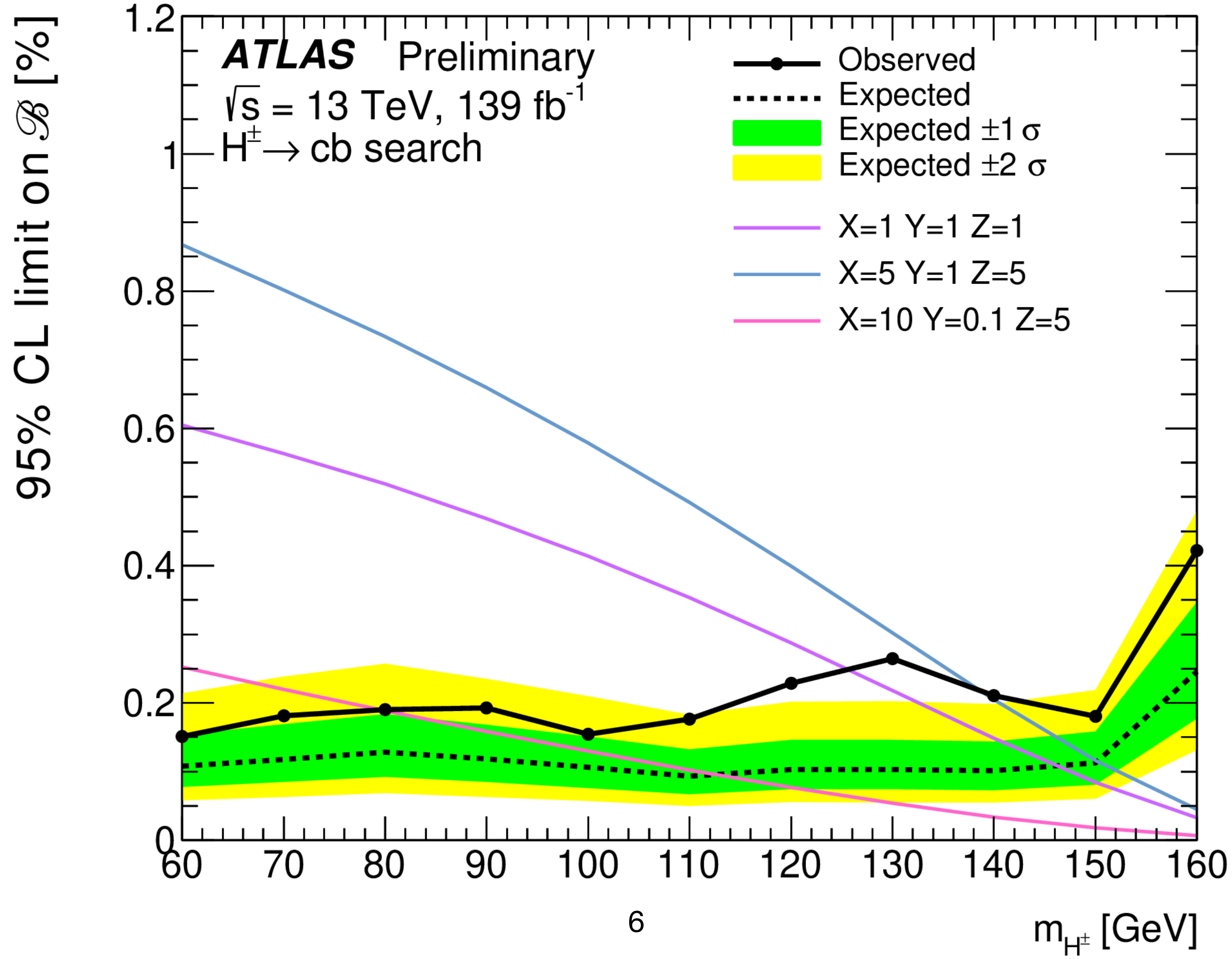
NEW

Upper limits on $\mathscr{B}(t \rightarrow H^{\pm}b) \times \mathscr{B}(H^{\pm} \rightarrow cb)$ @ 95% CL.

⇒ The observed (expected) limits vary between 0.15%(0.09%) and 0.42%(0.13%) depending on $m_{H^{\pm}}$.
↪The observed exclusion limits are consistently weaker than the expectation.

⇒ The largest excess in data is seen at $m_{H^{\pm}}$ = 130 GeV with a local (global) significance of $\sim 3\sigma$ (2σ).

The behavior of the limits vs. $m_{H^{\pm}}$ is consistent with the $m_{H^{\pm}}$ mass resolution.

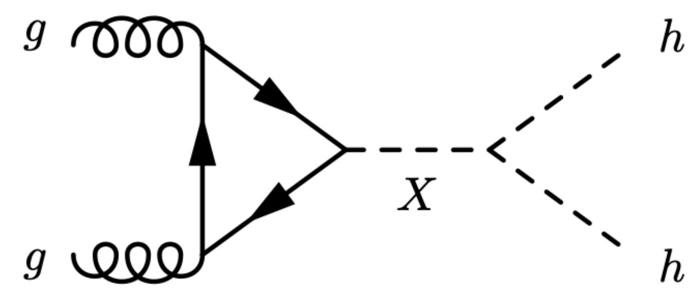


$HH \to b\bar{b}\tau^+\tau^-$

[ATLAS-CONF-2021-030]

NEW

Resonant production
⇒ decay of scalar resonances produced in ggF into **SM Higgs pairs**
↪ **heavy neutral scalar of the 2HDM** used as benchmark, in the narrow width approximation
↪ m_X **from 251 GeV up to 1.6 TeV**



→ $bb\tau\tau$ final state has relatively large branching fraction (7.3 %) and clean signature.

Signal signature: two b-tagged jets and two τ with opposite charge
↪ both decay combinations are considered $\tau_{had}\tau_{had}$ and $\tau_{lep}\tau_{had}$
↪ 3 categories based on different decay modes and trigger selections **(HadHad, SLT, LTT)**
→ 3 signal regions (SR)

Channel	Triggers	Properties
HadHad	single-τ and di-τ triggers	high purity
LepHad (SLT)	single-lepton trigger	high acceptance, large $t\bar{t}$ background
LepHad (LTT)	lepton+τ trigger	lower p_T^ℓ increases low-mass sensitivity

$HH \to b\bar{b}\tau^+\tau^-$

[ATLAS-CONF-2021-030]

NEW

Backgrounds

↪ $t\bar{t}$ with true τ_{had} and $Z \to \tau\tau$ + HF modeled with simulation and normalizations determined from control regions (CR) in the final fit ($bb\ell\ell$ channel).

↪ in HadHad, fake τ from $t\bar{t}$ and QCD background estimated from data-driven methods (scale factor and fake factor methods).

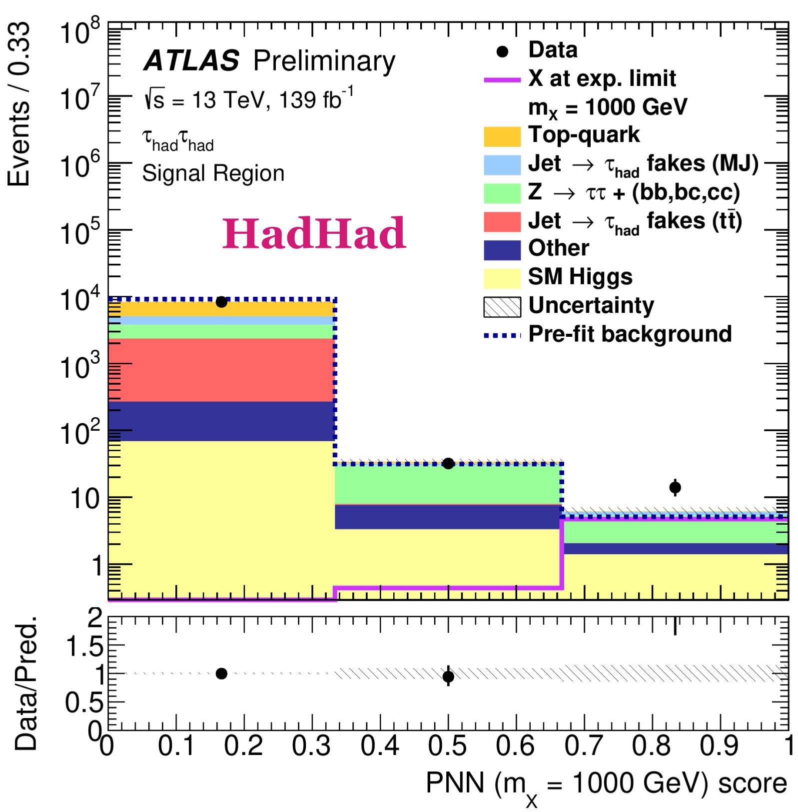
MVA-based analysis

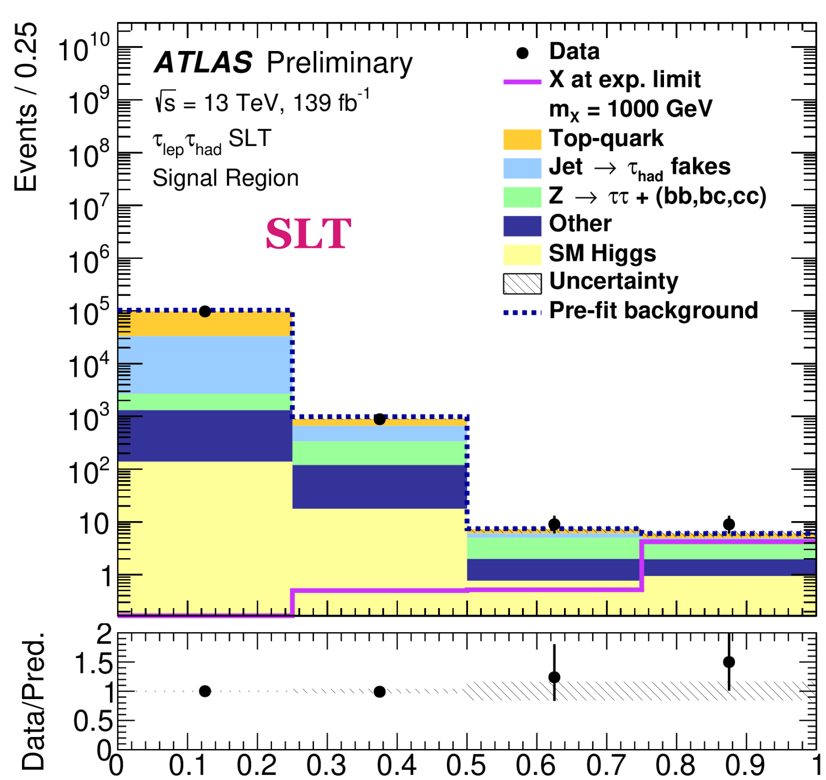
↪ **Parametric Neural Network (PNN)**

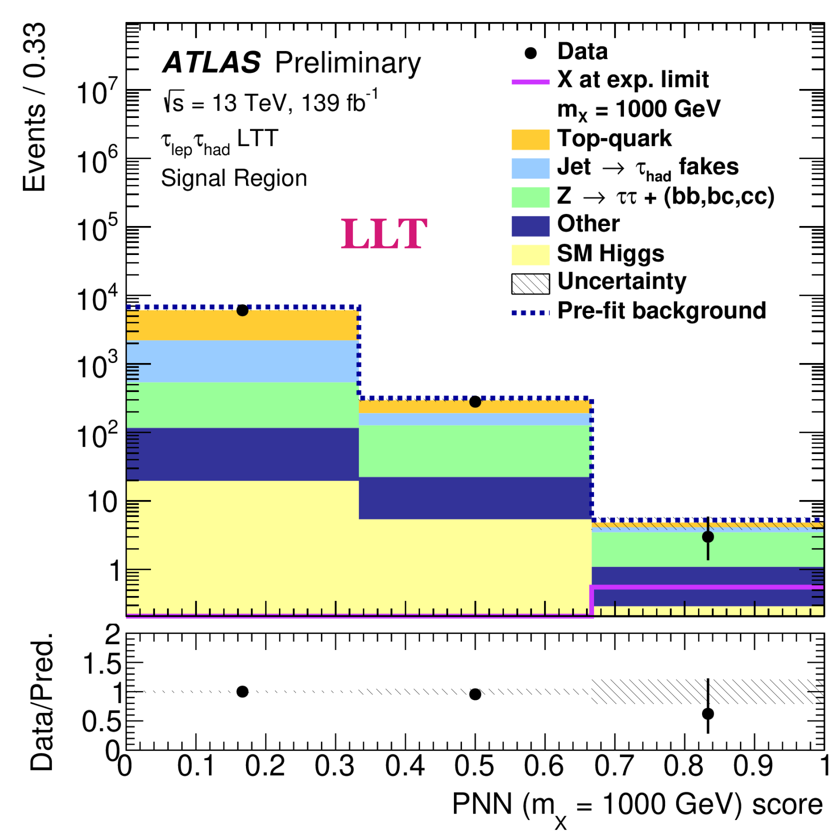
↪ signal classifier for all signal hypothesis.

↪ separate trainings for the 3 signal regions (HadHad, LepHad SLT and LepHad LTT).

⇒ **Binned profile likelihood fit to the MVA scores in 3 SRs and $m_{\ell\ell}$ in the Z+HF CR.**





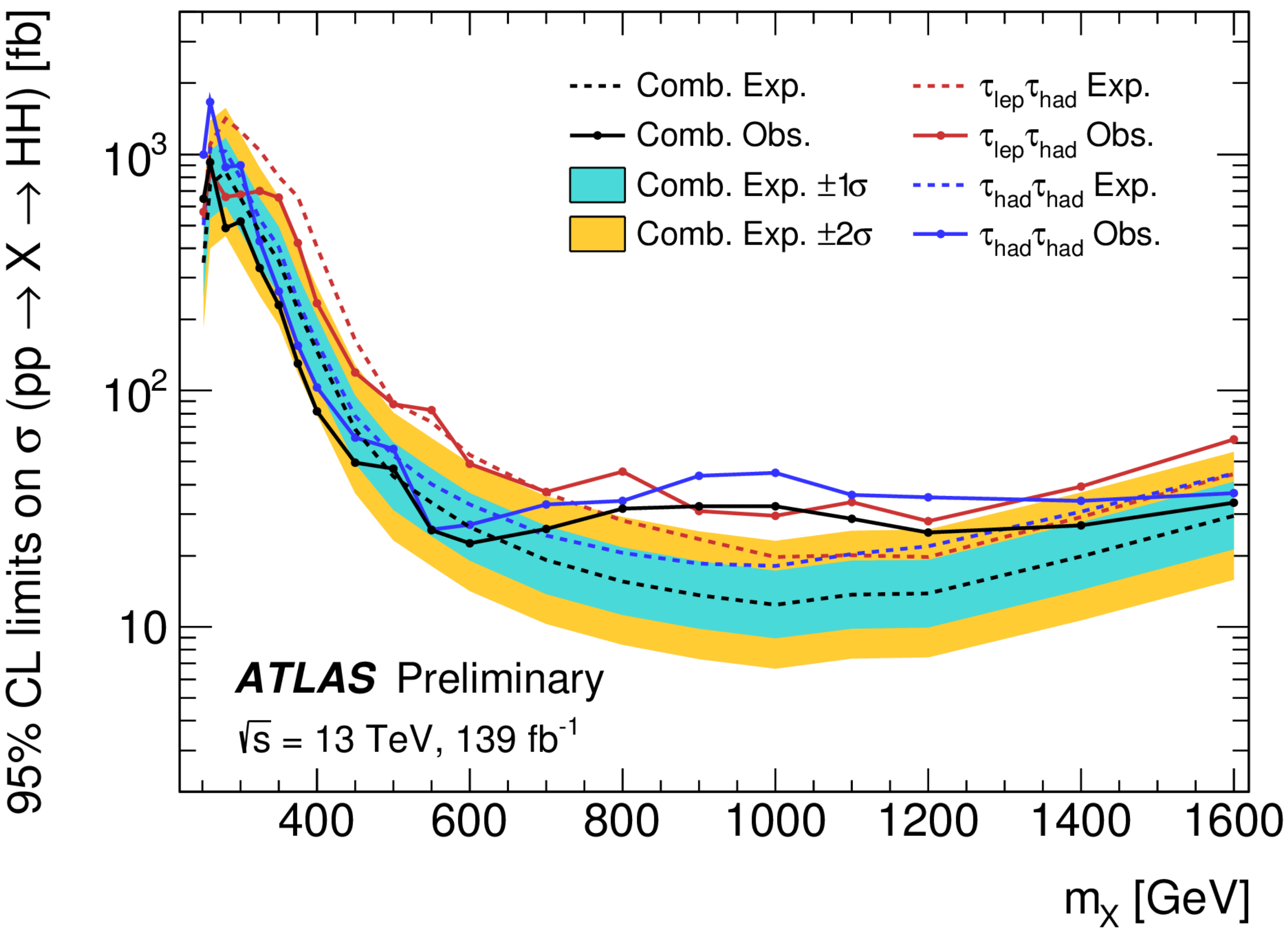


$HH \rightarrow b\bar{b}\tau^+\tau^-$

[ATLAS-CONF-2021-030]

NEW

Cross-section upper limits on resonant (ggF) production of HH.



Resonant

⇒ observed (expected) upper limits on the HH cross-section are set between 26 and 950 fb (12 and 850 fb) depending on the mass region.

⇒ the largest excess in the resonant search is observed at a resonance mass of 1 TeV, with a local (global) significance of $3.0\sigma(2.0^{-0.4}_{-0.2}\sigma)$.

NEW

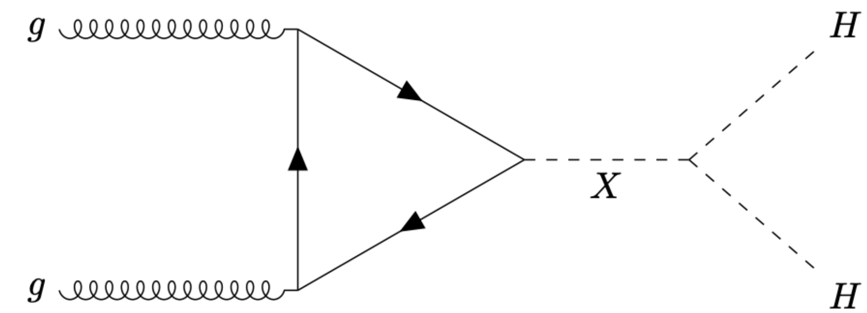
$HH \rightarrow b\bar{b}b\bar{b}$

Search for **resonant di-Higgs** production.

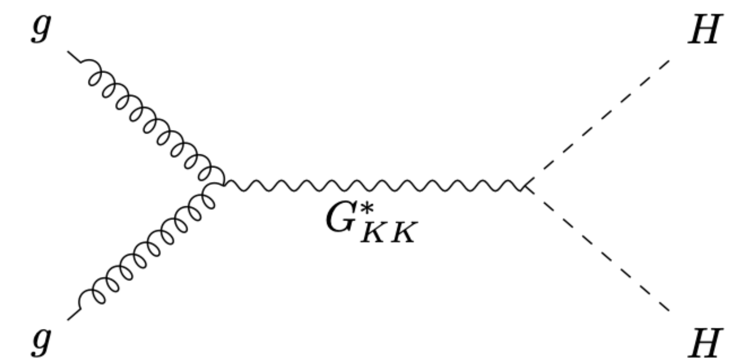
Two benchmark signal models considered:

↪ **spin-0** narrow width scalar (X), e.g. new scalar from 2HDM.

↪ **spin-2** Kaluza-Klein graviton (G^*_{KK}) with $k/\bar{M}_{Pl} = 1$.



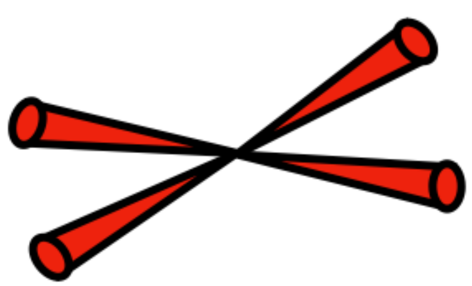
Both assumed to be produced via gluon-gluon fusion, decay to two SM Higgs bosons.



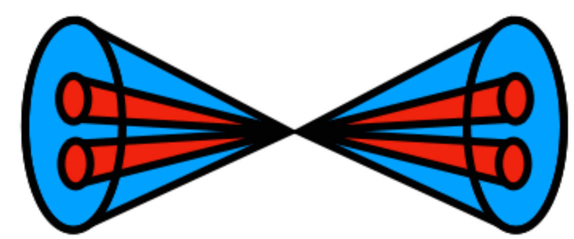
Largest branching ratio of HH is to $b\bar{b}b\bar{b}$ (~34%).

Searches are split into 2 complementary channels:

Resolved → 251 GeV $\leq m_X \leq$ 1.5 TeV



Boosted → 900 GeV $\leq m_X \leq$ 3 TeV



→ these channels are statistically combined in the overlapping region.

Background dominated by QCD multi-jet processes.

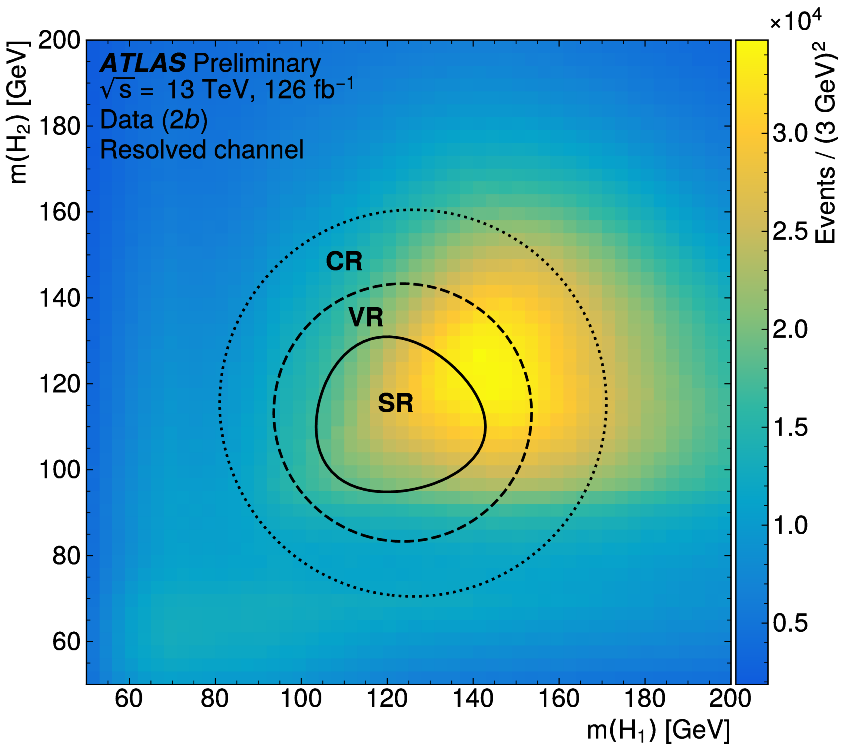
$HH \to b\bar{b}b\bar{b}$

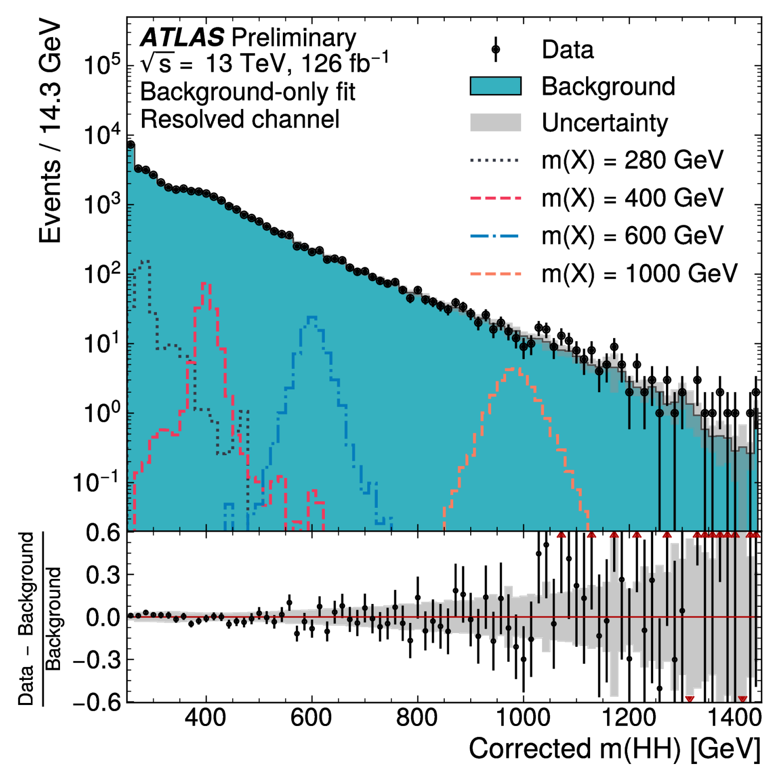
[ATLAS-CONF-2021-035]

NEW

Control Region: background enriched, used to derive background estimate.
Validation Region: "closer to" the signal region, used to assess uncertainties.
Signal Region: final search done here.

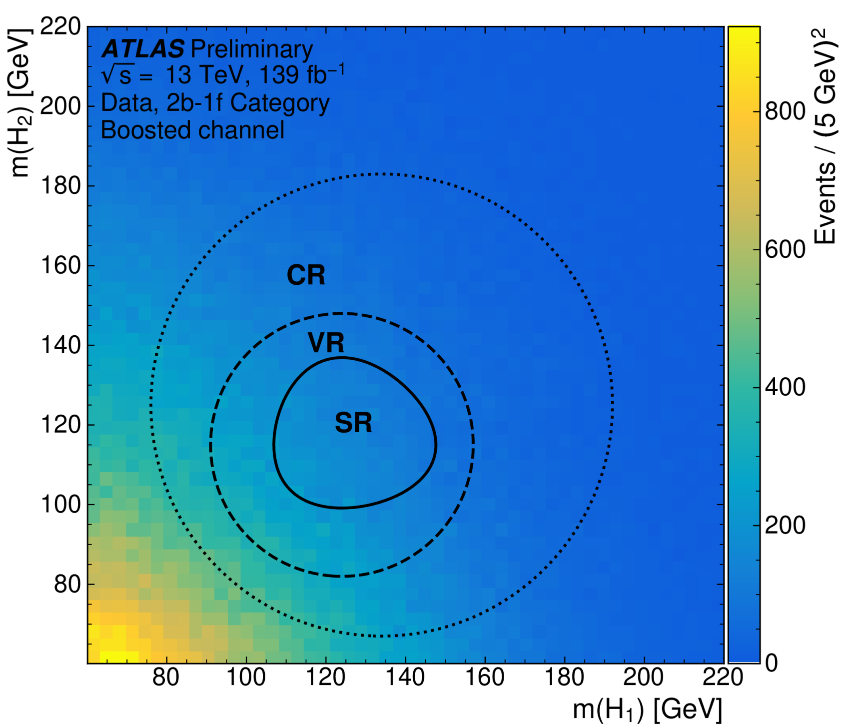
} regions are defined in the 2 Higgs candidate mass plane

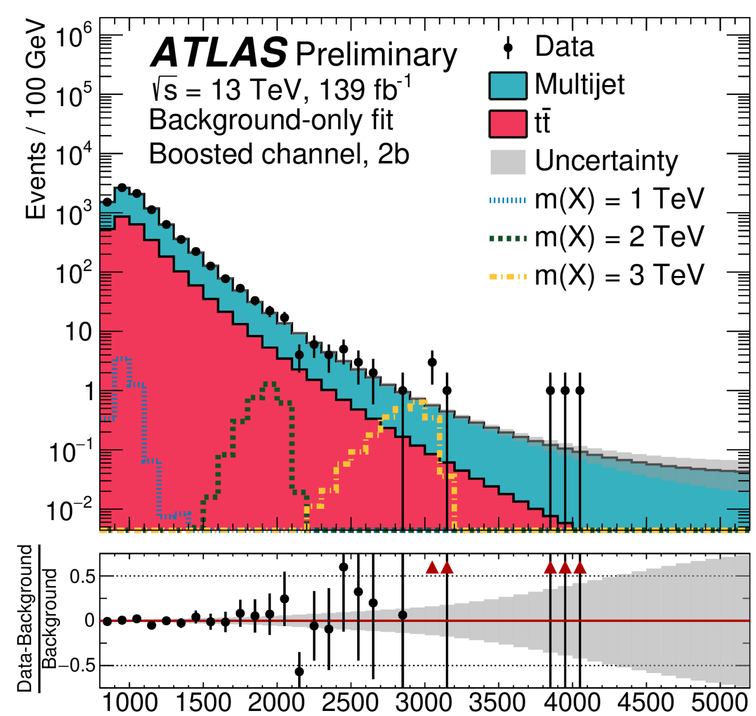




Resolved channel

For each H: two b-tagged jets of R=0.4 size.
Data-driven background estimate using neural network
↪derived using events with 2 b-tagged jets.
↪ BDT based jet pairing algorithm.
Fit to m_{HH} corrected so $m_{H_1} = m_{H_2} = 125$ GeV.





Boosted channel

For each H: merged R = 1.0 calorimeter jet.
b-tagging applied to variable radius track jets
↪three signal regions: 4b, 3b, 2b.
Data-driven background estimate
↪derived using low-tag events that fail the b-tagging requirement.

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

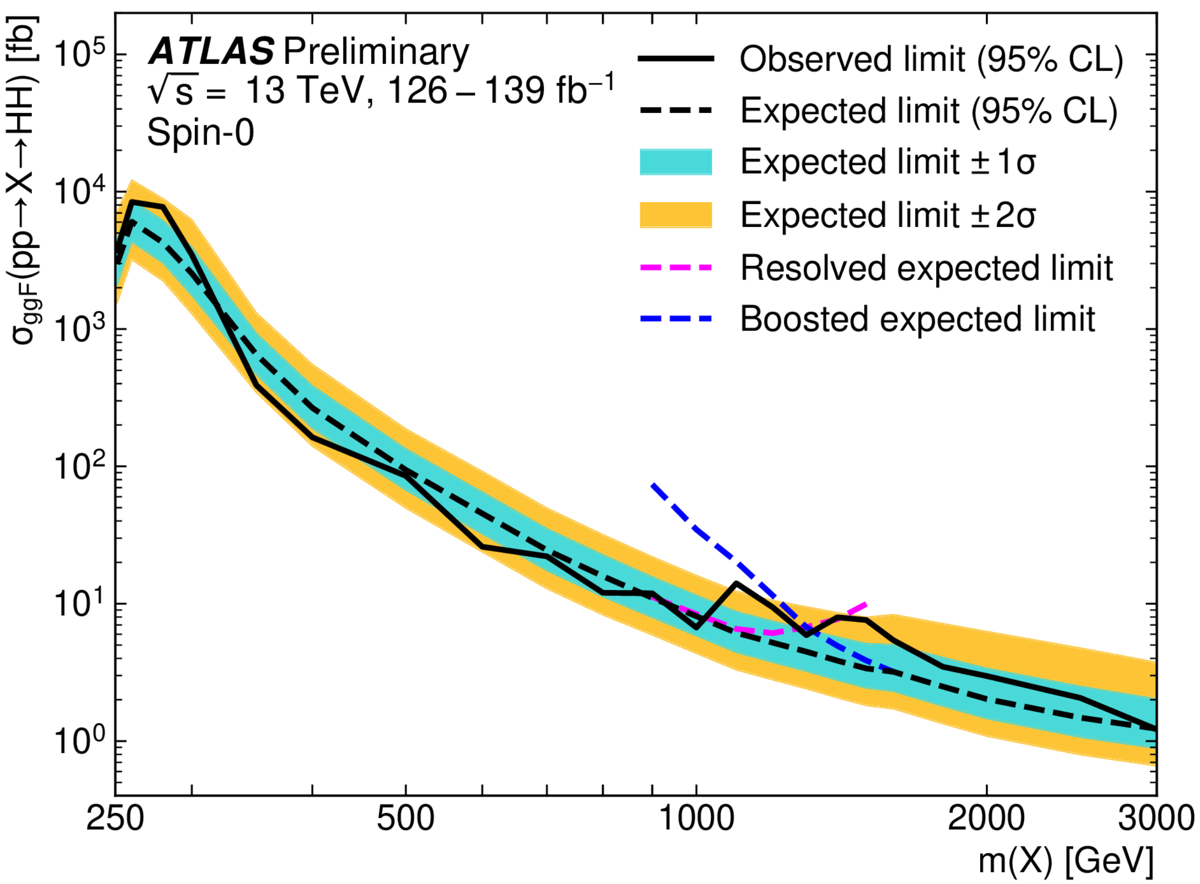
[ATLAS-CONF-2021-035]

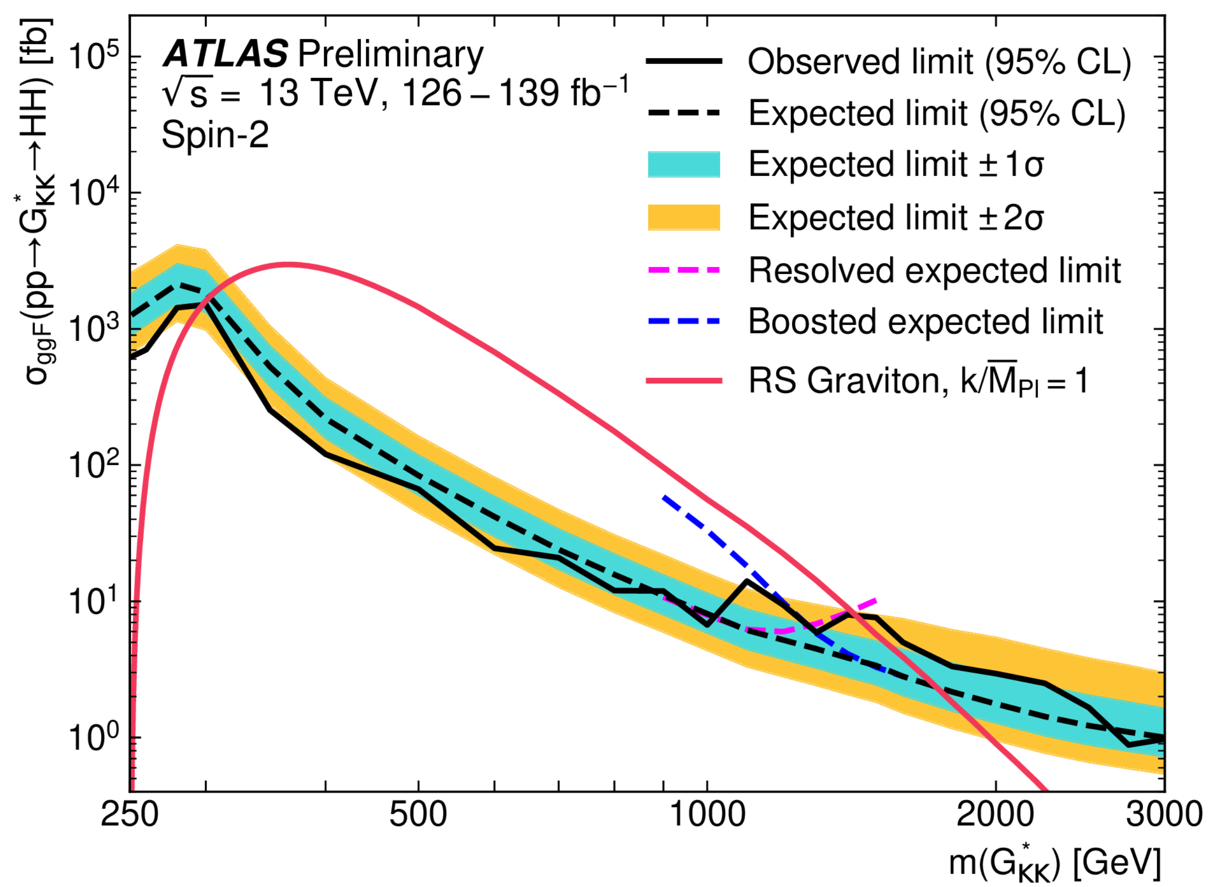
NEW

Upper limits on the production cross-section times branching ratio to Higgs boson pairs for spin-0 and spin-2 benchmark models.

The largest excess is observed at a mass of 1.1 TeV with a local significance of 2.6 σ for the spin-0 signal and 2.7 σ for the spin-2 model.
↪its global significance is 1.0 σ for the spin-0 signal model and 1.2 σ for the spin-2 signal model.

Spin-2 bulk RS model is excluded for graviton masses between 298 GeV and 1440 GeV.





Summary

Presented latest ATLAS Run-2 results for additional Higgs bosons searches.

Light charged Higgs boson $H^{\pm} \rightarrow cb$
↪ search on this channel for the first time in ATLAS

Di-Higgs production with $b\bar{b}\tau^{+}\tau^{-}$ **and** $b\bar{b}b\bar{b}$ **decays.**
↪ complementary with other Run-2 results.

Better object identification and reconstruction, optimization of analyses: including better background modeling and sequences of (deep) neural networks to better discriminate signals from backgrounds led to improvement beyond the gain from luminosity.

⇒ **No significant excess in data seen.**
Significant update of constraints on various BSM models.

More results will be available soon!

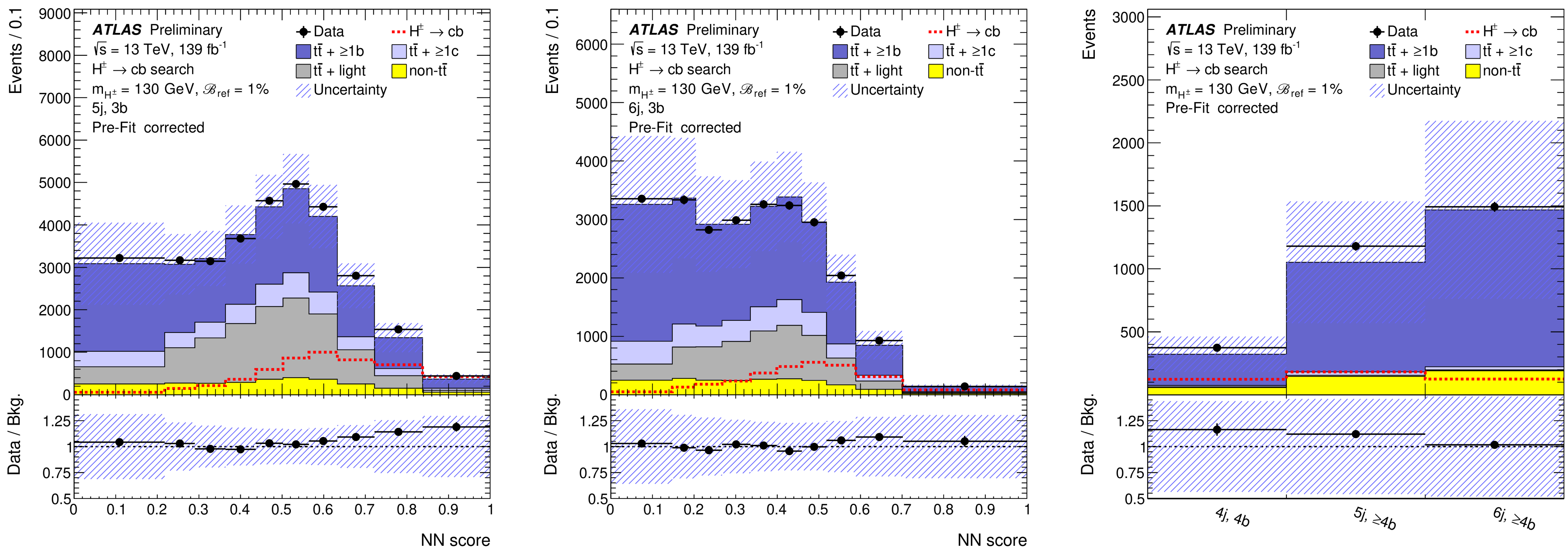
THANKS FOR
YOUR ATTENTION!

Back-Up

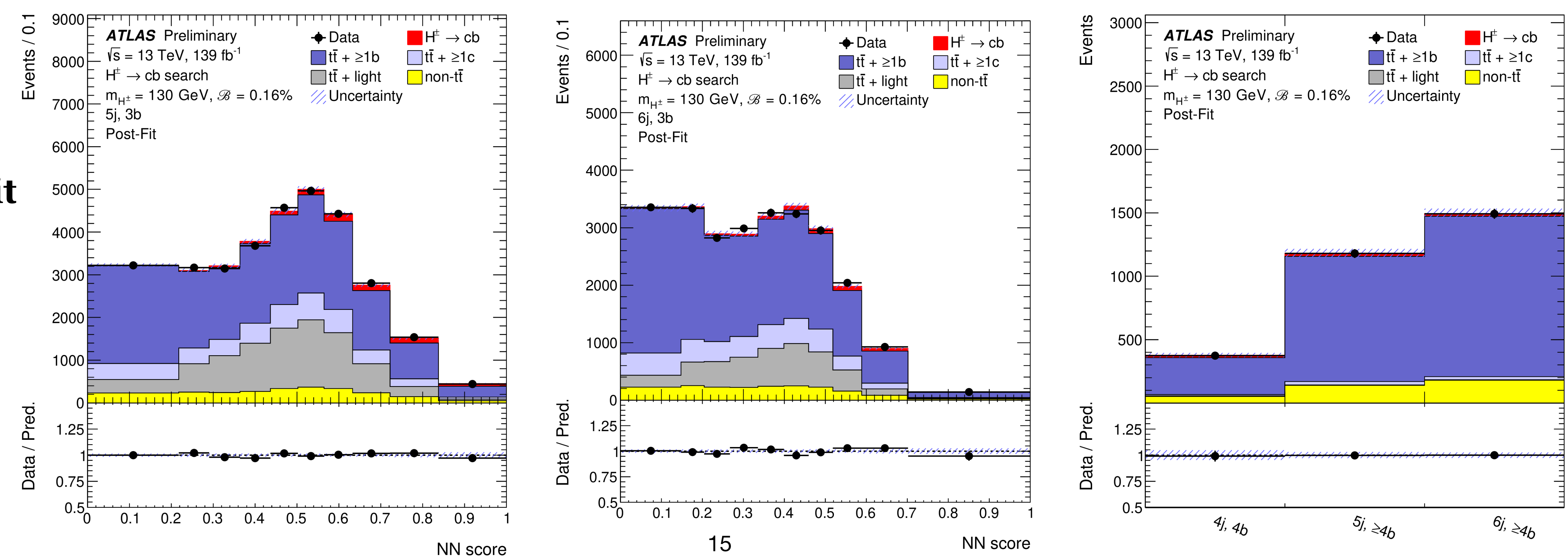
$H^{\pm} \to cb$

NN score in 3b and ≥4b regions

Pre-Fit



Post-Fit



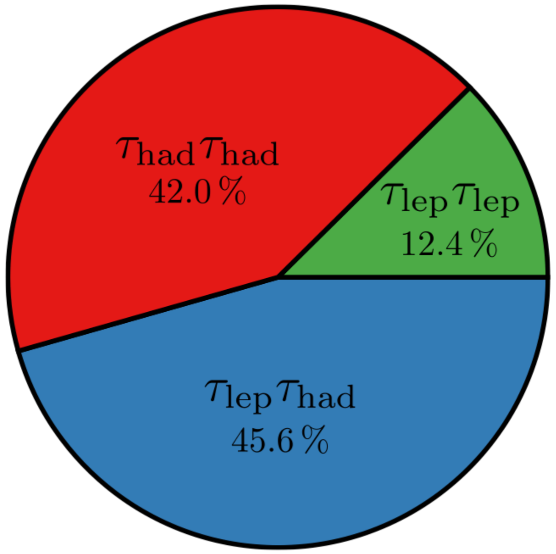
$HH \to b\bar{b}\tau^+\tau^-$

Systematic uncertainties

Uncertainty source	Non-resonant HH	Resonant $X \to HH$ 300 GeV	500 GeV	1000 GeV
Data statistical	81%	75%	89%	88%
Systematic	59%	66%	46%	48%
$t\bar{t}$ and $Z+$HF normalisations	4%	15%	3%	3%
MC statistical	28%	44%	33%	18%
Experimental				
Jet and $E_{\mathrm{T}}^{\mathrm{miss}}$	7%	28%	5%	3%
b-jet tagging	3%	6%	3%	3%
$\tau_{\text{had-vis}}$	5%	13%	3%	7%
Electrons and muons	2%	3%	2%	1%
Luminosity and pileup	3%	2%	2%	5%
Theoretical and modelling				
Fake-$\tau_{\text{had-vis}}$	9%	22%	8%	7%
Top-quark	24%	17%	15%	8%
$Z(\to \tau\tau)+$HF	9%	17%	9%	15%
Single Higgs boson	29%	2%	15%	14%
Other backgrounds	3%	2%	5%	3%
Signal	5%	15%	13%	34%

MVA input variables

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



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

Regions definition

Resolved channel

Signal

$$X_{HH} = \sqrt{\left(\frac{m_{H_1} - 120\,\text{GeV}}{0.1 m_{H_1}}\right)^2 + \left(\frac{m_{H_2} - 110\,\text{GeV}}{0.1 m_{H_2}}\right)^2} \,.\, X_{HH} < 1.6,$$

Validation

$$R_{HH}^{\text{VR}} \equiv \sqrt{\left(m_{H_1} - 1.03 \times 120\,\text{GeV}\right)^2 + \left(m_{H_2} - 1.03 \times 110\,\text{GeV}\right)^2} < 30\,\text{GeV}.$$

Control

$$R_{HH}^{\text{CR}} \equiv \sqrt{\left(m_{H_1} - 1.05 \times 120\,\text{GeV}\right)^2 + \left(m_{H_2} - 1.05 \times 110\,\text{GeV}\right)^2} < 45\,\text{GeV}.$$

Boosted channel

Signal

$$X_{HH} = \sqrt{\left(\frac{m_{H_1} - 124\,\text{GeV}}{0.1 m_{H_1}}\right)^2 + \left(\frac{m_{H_2} - 115\,\text{GeV}}{0.1 m_{H_2}}\right)^2}. \quad X_{HH} < 1.6$$

Validation

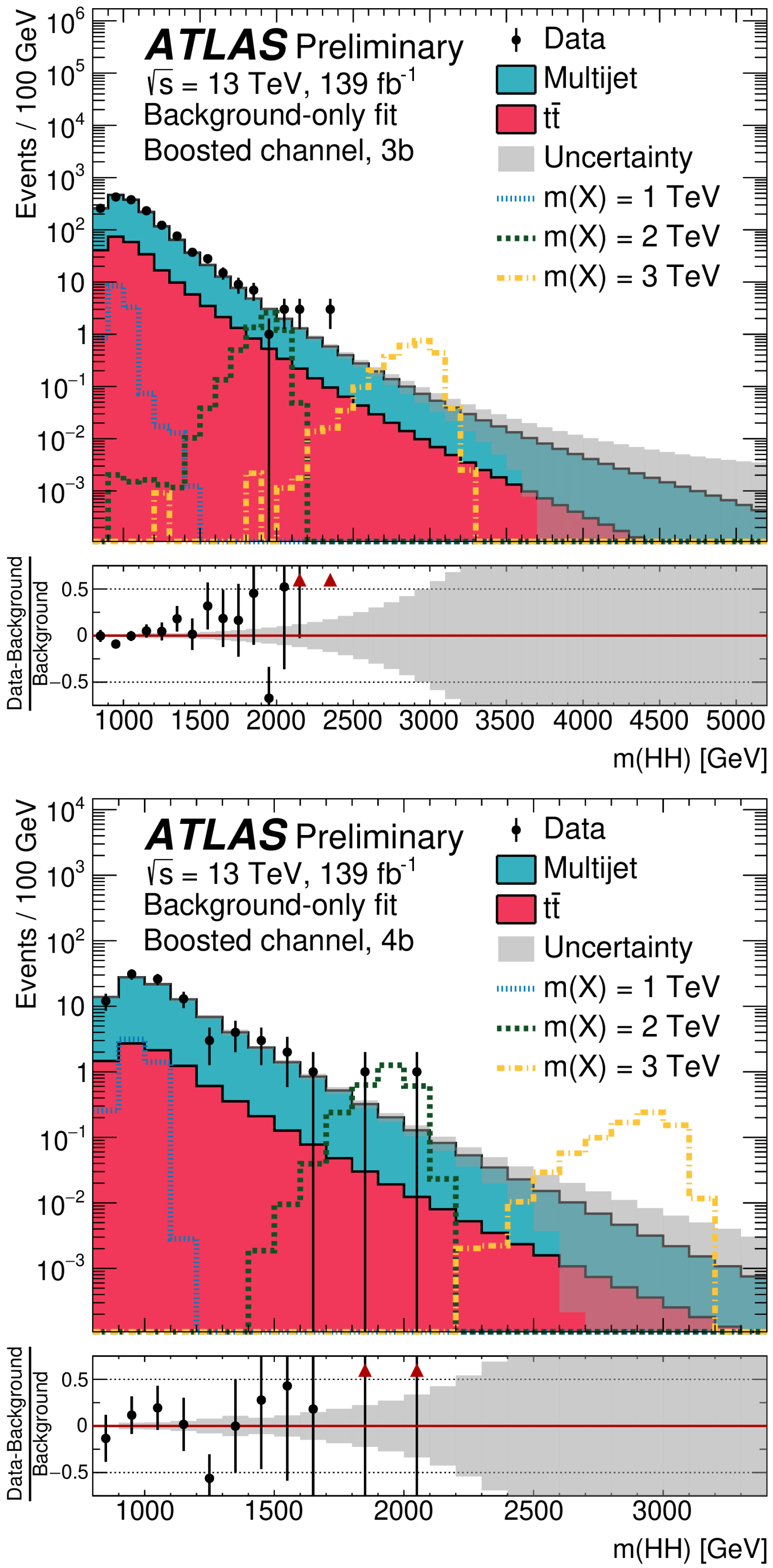
$$R_{HH}^{\text{VR}} \equiv \sqrt{\left(m_{H_1} - 124\,\text{GeV}\right)^2 + \left(m_{H_2} - 115\,\text{GeV}\right)^2} < 33\,\text{GeV}.$$

Control

$$R_{HH}^{\text{CR}} \equiv \sqrt{\left(m_{H_1} - 134\,\text{GeV}\right)^2 + \left(m_{H_2} - 125\,\text{GeV}\right)^2} < 58\,\text{GeV}.$$

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

Boosted channel

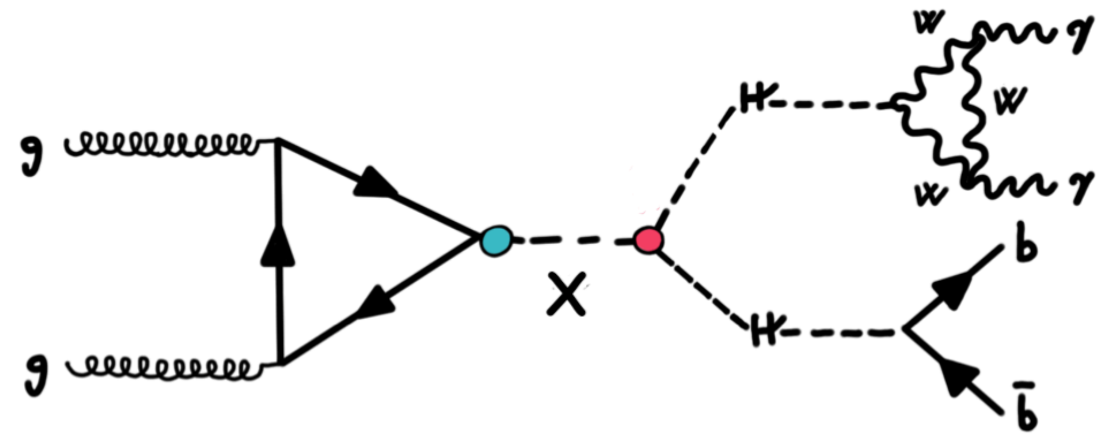


Systematic uncertainties

Uncertainty category	Relative impact (%)		
	280 GeV	600 GeV	1600 GeV
Background $m(HH)$ shape	12	8.7	1.3
Jet momentum/mass scale	0.6	0.1	1.5
Jet momentum/mass resolution	2.1	1.5	7.4
b-tagging calibration	0.7	0.4	1.8
Theory (signal)	0.6	0.6	1.6
Theory ($t\bar{t}$ background)	N/A	N/A	0.7
All systematic uncertainties	16	11	13

More searches for additional Higgs bosons

$HH \to bb\gamma\gamma$

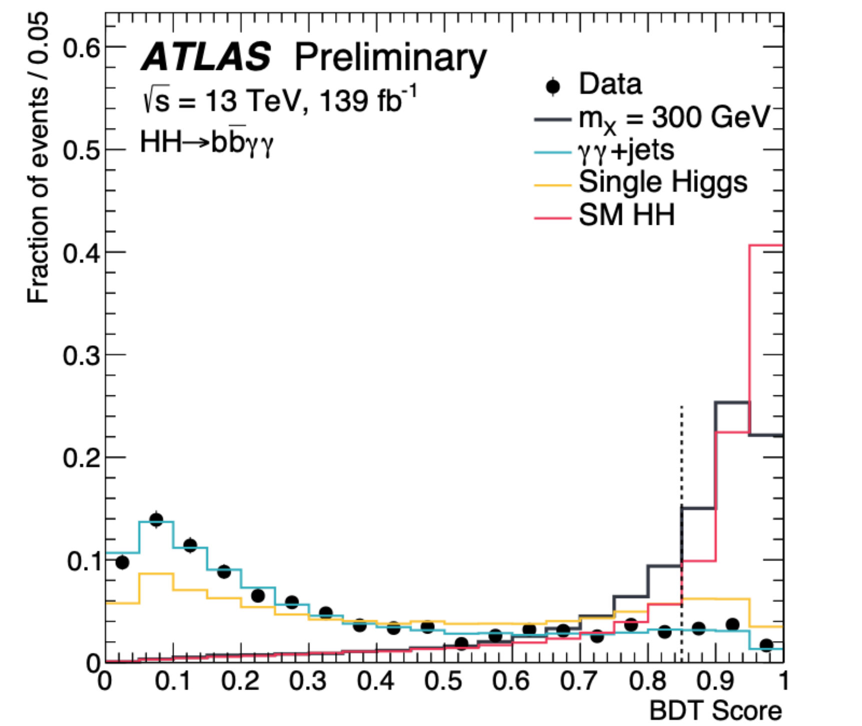


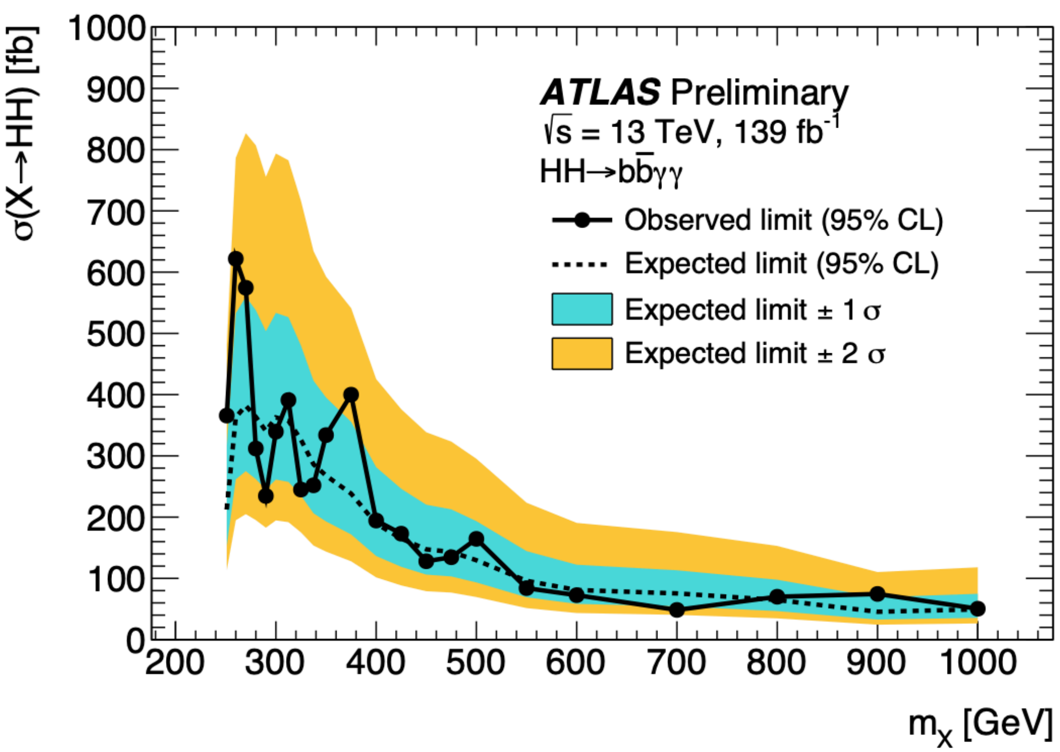
Search for **resonant ggF production of a narrow-width scalar particle.**
↪ benefits from large $bb\gamma\gamma$ branching ratio and excellent $m_{\gamma\gamma}$ resolution.

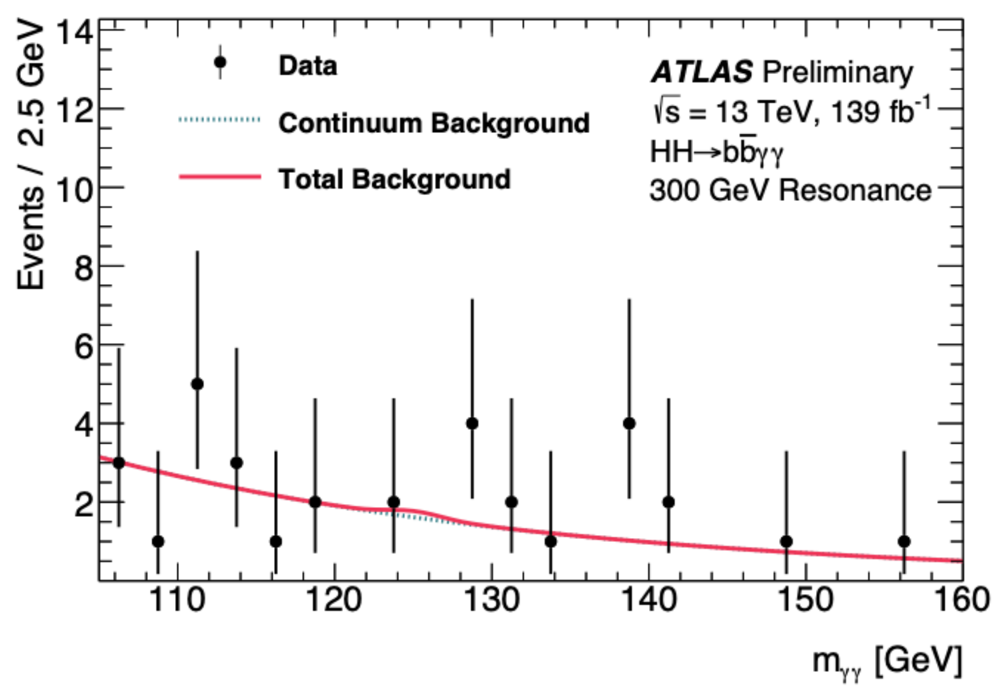
Two **BDTs** are trained to better separate the signal from $\gamma\gamma$ and single Higgs backgrounds.
↪ **combined BDT score is used to select events.**

Maximum likelihood fit of $m_{\gamma\gamma}$.

⇒ The observed (expected) limits on the cross section $X \to HH$ range from 610-47 fb (360–43 fb) in 251 GeV ≤ m_X ≤ 1000 GeV.



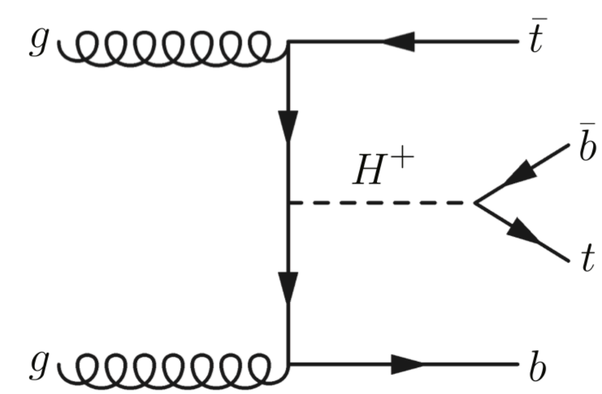




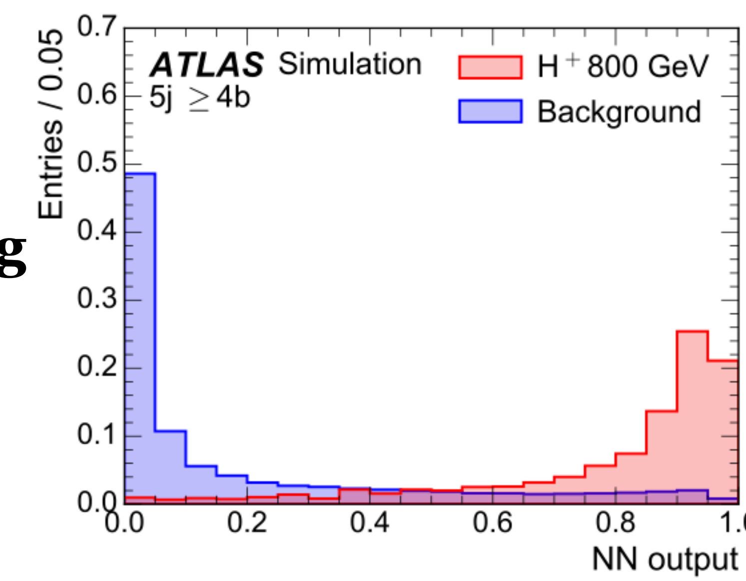
$H^+ \to tb$

[JHEP 06 (2021) 145]
arXiv:2102.10076

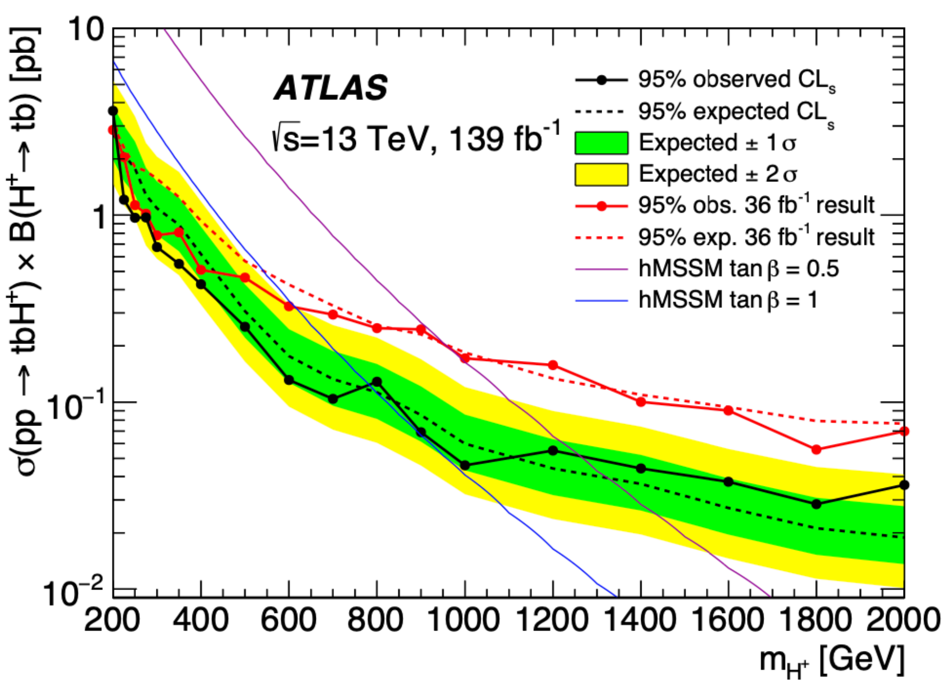
$tbH^+ \to tbtb$ **is explored from 200 GeV $\leq m_{H^+} \leq$ 2000 GeV.**

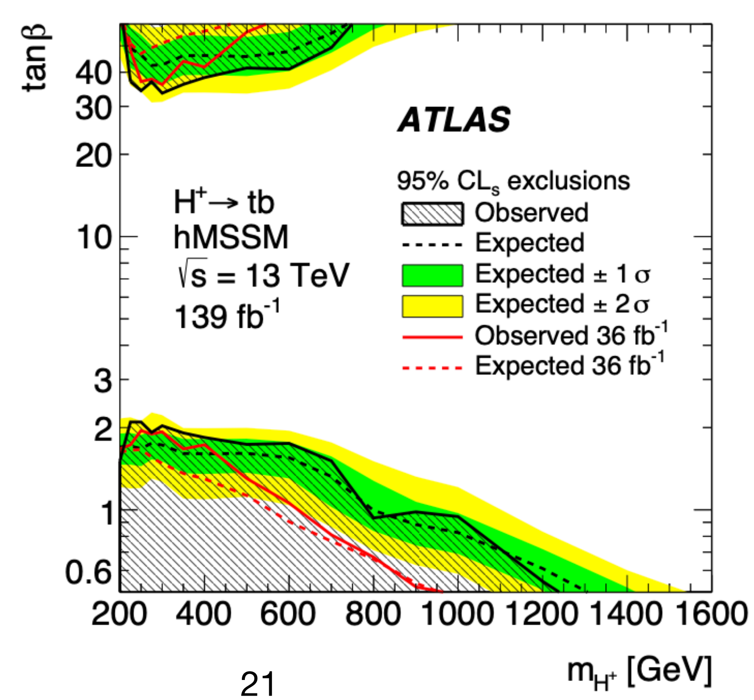


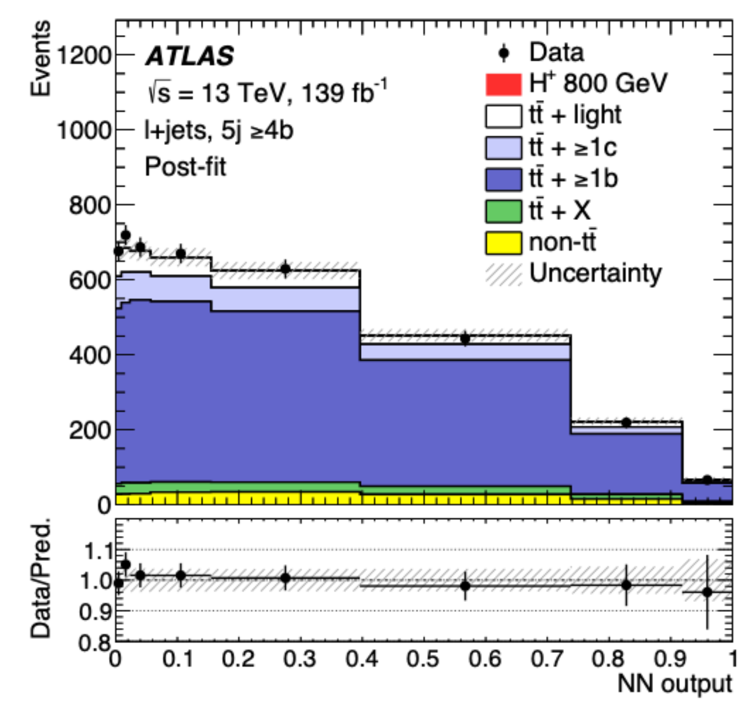
↪1 isolated e^-/μ+jets events are categorized according to the number of jets and b-tagged jets : **5j(3b), 5j(≥4b), ≥6j(3b) and ≥6j(≥4b)**.
↪a Neural Network is used to discriminate between signal and background events.
↪background dominated by $t\bar{t}$ (estimated from simulation but corrected in data control regions).



Exclusion limits for the production cross-section times branching ratio of a charged Higgs boson as a function of its mass.
↪they range from 3.6 pb at 200 GeV to 0.036 pb at 2000 GeV at 95% CL (improvement by 5% to 70% w.r.t. 2016 results).
↪**the results are interpreted in the hMSSM and M_h^{125} scenarios.**
↪some values of tan beta (0.5-2.1) excluded for 200-1200 GeV.







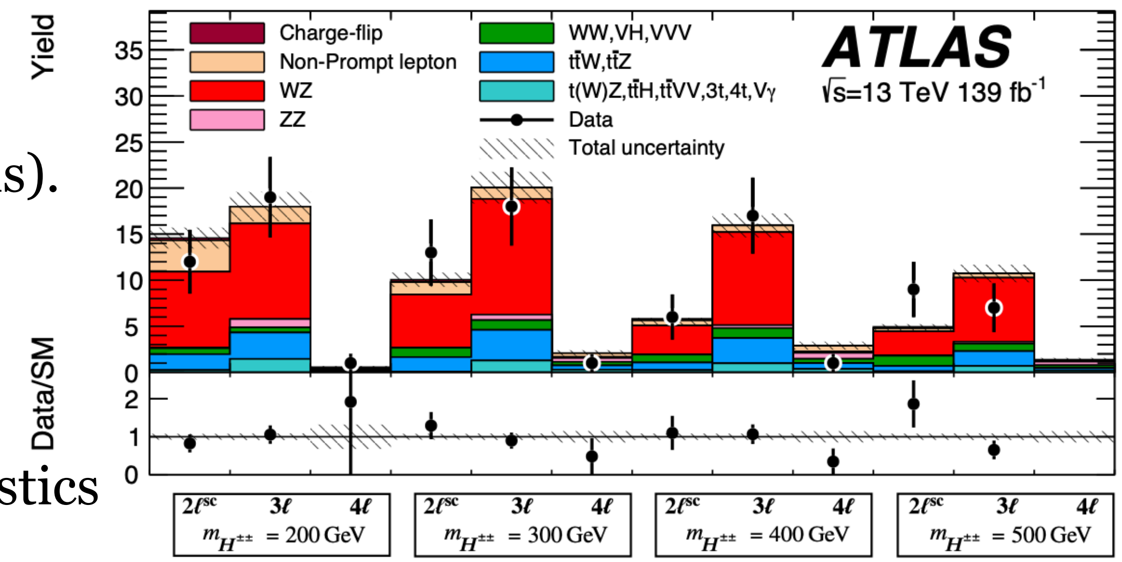
$H^{\pm\pm} \rightarrow W^{\pm\pm}W^{\pm\pm} / H^{\pm} \rightarrow W^{\pm}Z$

[JHEP 06 (2021) 146]
arXiv:2101.11961

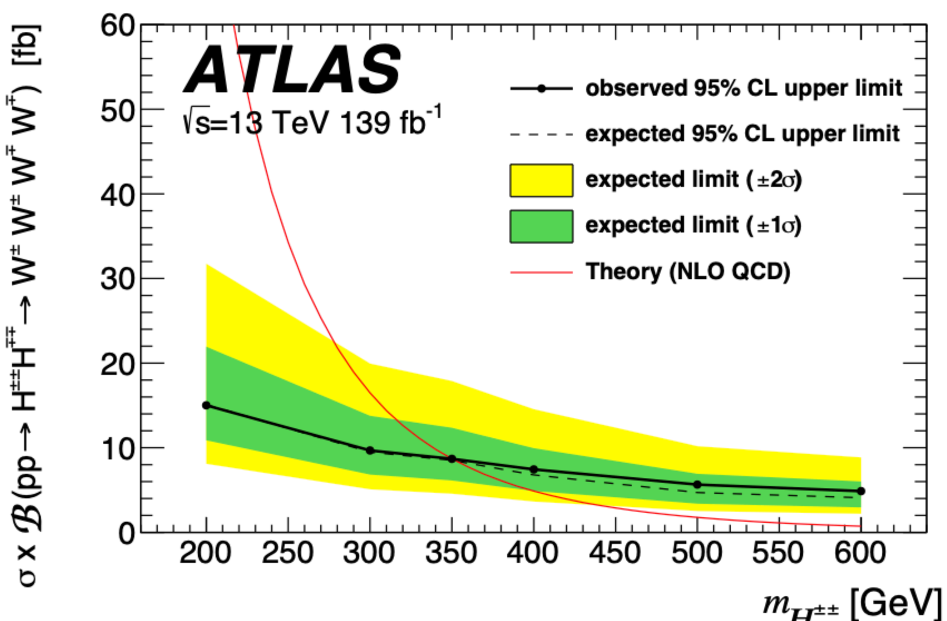
Doubly and singly charged Higgs bosons are predicted in Type II seesaw model
↪ $H^{\pm\pm}$ **pair production** / $H^{\pm\pm}$ **and** $H^{\pm}$ **associated production**

Three final states: **two same-charge leptons ($2\ell^{sc}$), three leptons (3ℓ) and four leptons (4ℓ).**

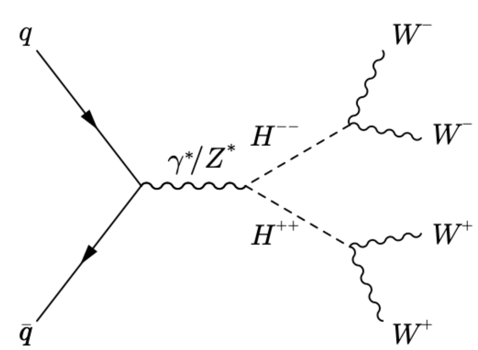
Backgrounds
↪ leptons from prompt leptonic decays of W and Z bosons (estimated with simulations normalized to the SM cross sections).
↪ WZ normalization corrected using data, with a dedicated CR.
↪ Electron charge-flip and Non-prompt leptons (data driven methods using fake factor in dedicated channels)

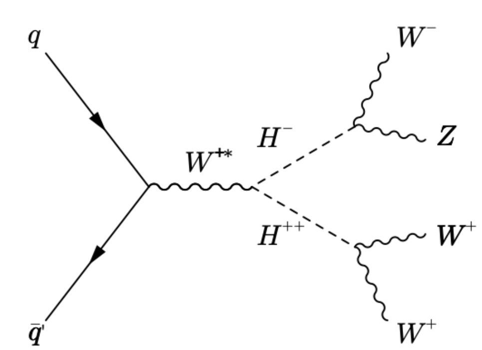


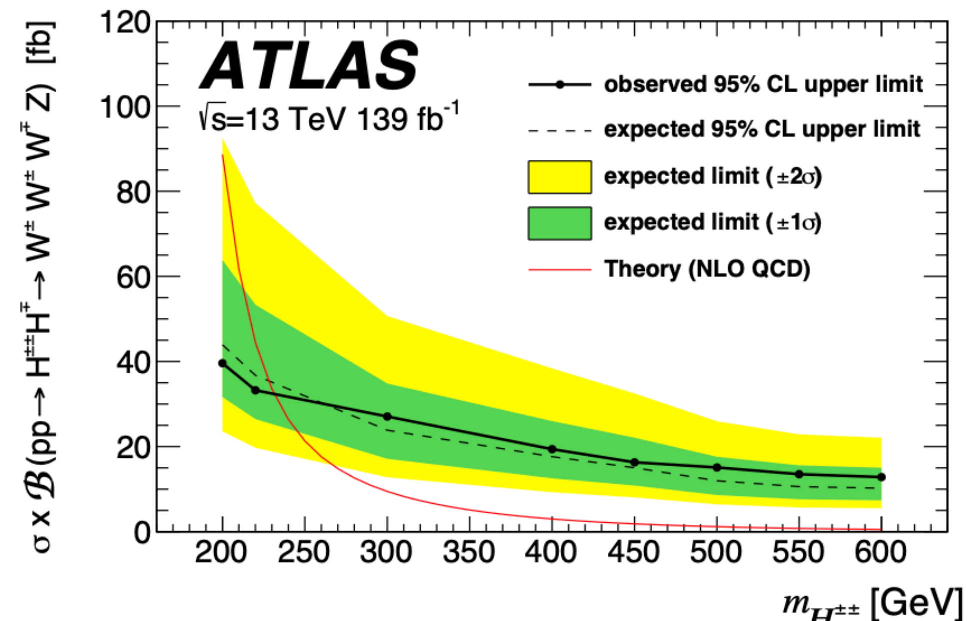
Profiling likelihood ratio test, constructed by Poisson statistics of counting experiments for different channels.
↪ each channel as an individual bin of a histogram.



Pair production
15-5 fb exclude $H^{\pm\pm}$ up to 350 GeV







Associated production
40-10 fb exclude $H^{\pm\pm}$ up to 230 GeV