# Searches for additional scalar or Higgs-like particles

Fabio Ravera on behalf of the ATLAS and CMS Collaborations

Higgs 2021

20 October 2021

Why hunting Higgs-like particles?

- Most BSM models foresee extensions of the Higgs sector
  - **Observation of a new Higgs-like particle would be an unequivocal proof of BSM physics**

- Extensions known as two-Higgs-doublet models (2HDMs) predict
  - CP-even h and H, CP-odd A
  - Singly-charged H^+ and H^-

- Extensions with a scalar singlet 2HDM+S (e.g. NMSSM)
  - 2 additional Higgs bosons h_S and A_S

- Higgs triplet models (HTMs) extend the sector by addition of scalar triplet(s):
  - Georgi-Machacek model adds one real & one complex SU(2) triplet
  - Doubly-charged Higgs bosons $H^{\pm\pm}$

- Extra scalars predicted by many other SM extensions

Searches covered in this talk

- Several searches for additional scalar and Higgs-like particles published by ATLAS and CMS Collaborations
  - Present just a subset of recent results

Channel	Collaboration	Reference	
$H^\pm \to cb$	ATLAS	ATLAS-CONF-2021-037	**Charged**
$H^\pm \to W^\pm A$	ATLAS	ATLAS-CONF-2021-047	
$H^\pm \to W^\pm Z$ and $H^{\pm\pm} \to W^\pm W^\pm$	CMS	arXiv:2104.04762	
$X^\pm \to W^\pm \gamma$ and $X^0 \to Z\gamma$	ATLAS	ATLAS-CONF-2021-041	
$X^0 \to \gamma\gamma$	ATLAS	arXiv:2102.13405	**Neutral**
H from SUSY cascade decays	CMS	CMS-PAS-HIG-20-018	
$H \to hh_S \to \tau\tau bb$	CMS	arXiv:2106.10361	

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And many more published!

Neutral Higgs

$H/A \to \tau\tau$
arXiv:1803.06553 (CMS)
arXiv:2002.12223 (ATLAS)

$H/A \to b\bar{b}$
arXiv:1805.12191 (CMS)
arXiv:2108.13391 (ATLAS)

$H/A \to t\bar{t}$
arXiv:1704.07323 (CMS)

$H/A \to \mu\mu$
arXiv:1907.03152 (CMS)
arXiv:1901.08144 (ATLAS)

$H/A \to \gamma\gamma$
arXiv:1809.00327 (CMS)
arXiv:2102.13405 (ATLAS)

$H/A \to Zh$
arXiv:1903.00941 (CMS)
arXiv:1712.06518 (ATLAS)

$H/A \to ZH/A$
arXiv:1911.03781 (CMS)
arXiv:2011.05639 (ATLAS)

$H/A \to WW$
arXiv:1912.01594 (CMS)
arXiv:1710.01123 (ATLAS)

$H/A \to ZZ$
arXiv:1804.01939 (CMS)
arXiv:2009.14791 (ATLAS)

Single Charged Higgs

$H^+ \to \tau\nu$
arXiv:1903.04560 (CMS)
arXiv:1807.07915 (ATLAS)

$H^+ \to tb$
arXiv:1908.09206 (CMS)
arXiv:2001.07763 (CMS)
arXiv:2102.10076 (ATLAS)

$H^+ \to cs$
arXiv:2005.08900 (CMS)

$H^+ \to WZ$
arXiv:2109.06055 (CMS)
arXiv:2101.11961 (ATLAS)

Double Charged Higgs

$H^{++} \to W^+W^+$
arXiv:2109.06055 (CMS)
arXiv:2101.11961 (ATLAS)

Others

$X \to SS$
arXiv:1811.11028v2 (ATLAS)

All results can be found here:

https://twiki.cern.ch/twiki/bin/view/AtlasPublic

https://cms.cern/news/physics-results

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Light charged Higgs: $H^\pm \to cb$
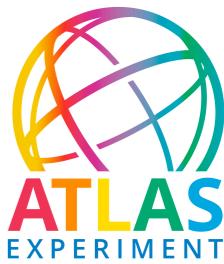
- Charged Higgs can be lighter (60 - 160 GeV) than top quark
  $t \to H^\pm b$ with $H^\pm \to cb$

  - lower irreducible SM background from $t\bar{t}$ and W decays compared to $H^\pm \to \tau v/cs$

 - First ATLAS search for this process

- Event selection: 1 e/μ + $\geq$ 4 jets ($\geq$ 2 b-jets)

- 9 analysis regions (AR) based on # of jets and b-jets

  - data driven corrections (3 ARs)

  - mainly background control and corrections (4 ARs)

  - main signal regions (2 ARs)

- Main BKG: $t\bar{t}$ + jets (> 80%)

- NN classifier exploits kinematic observables and flavour tagging information

  - parametrized as a function of $m_{H^\pm}$

Charged Higgs: $H^{\pm} \to cb$
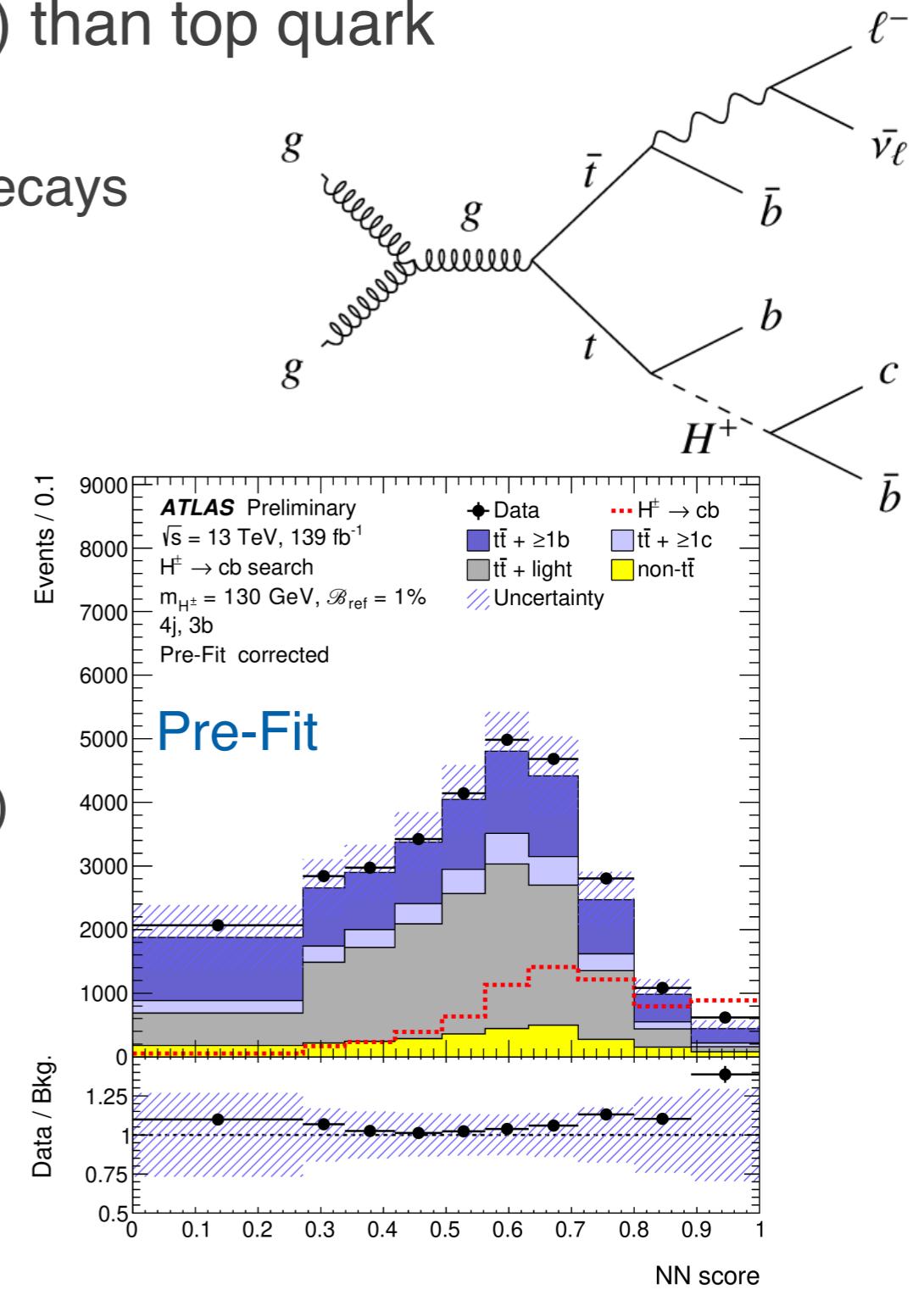
- Signal extracted via simultaneous fit of NN score distribution in various ARs

$$\mathcal{B} = \mathcal{B}(t \to H^{\pm}b) \times \mathcal{B}(H^{\pm} \to cb)$$
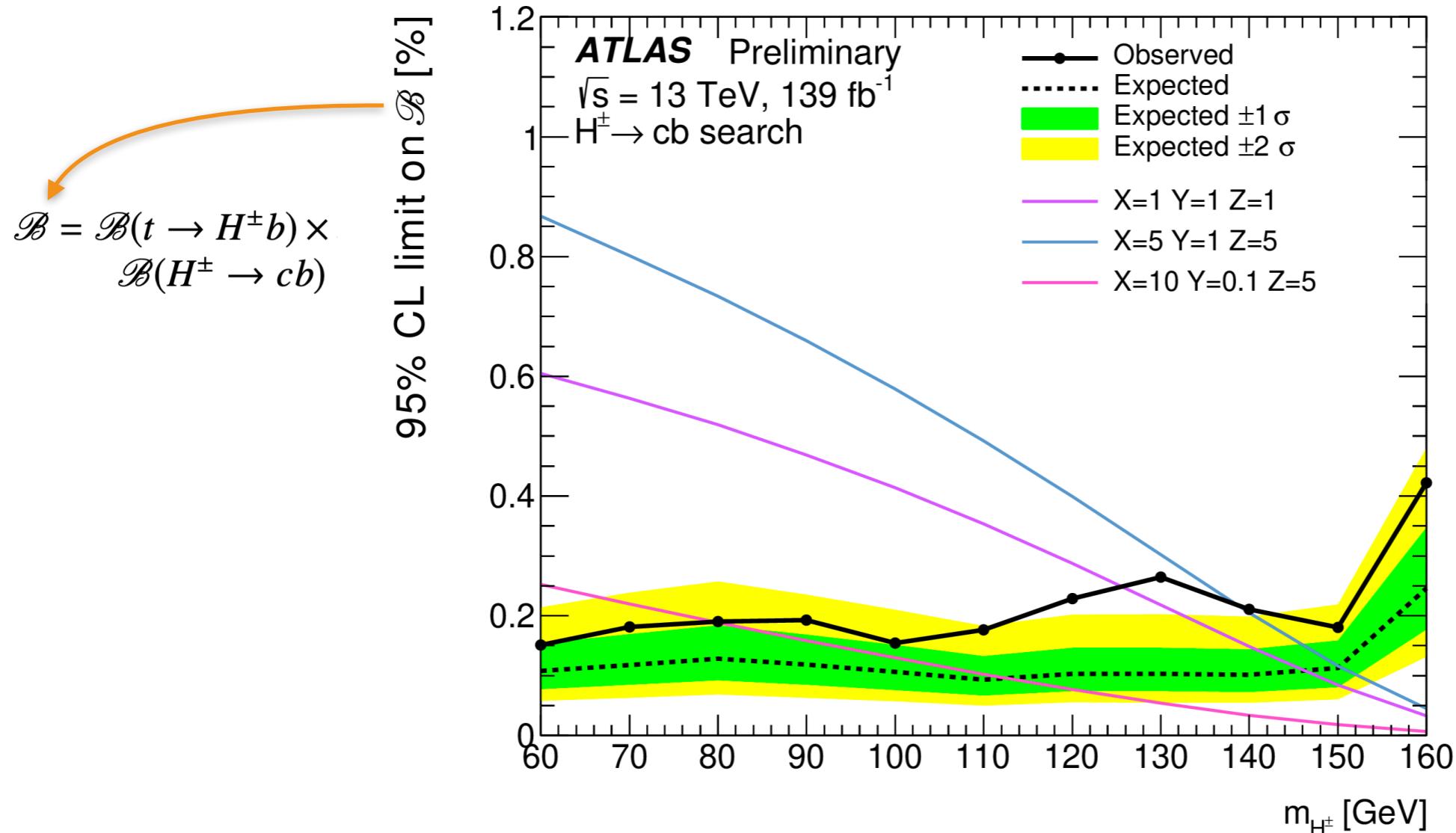
- Largest excess at 130 GeV with global (local) significance of ~2(3)σ
- Upper limits compared with 3HDM predictions for for a few benchmark scenarios

$H^{\pm} \rightarrow W^{\pm}A \rightarrow W^{\pm}\mu\mu$ in $t\bar{t}$ events

- If $H^{\pm} \rightarrow W^{\pm}A$ decay kinematically allowed, BR can be significant

- Event selection: $\mu^{+}\mu^{-}$ + $e^{\pm}$ + ≥ 3 jets (≥ 1 b-jet)

- Main BKG: $t\bar{t}$, $t\bar{t}Z$, Z + heavy flavour
  - Yields scaled to data with no constraint in the fit of 3 CRs

- Searching for excess in $m_{\mu\mu}$ spectrum

- Signal extraction: counting experiment in mass window centered around tested m_A

  - Removes $m_{H^{\pm}}$ dependence in m_A shape
  - $m_{H^{\pm}}$ dependence enters only in the efficiency

- No explicit reconstruction of $H^{\pm}$

  - sensitive to other A production modes
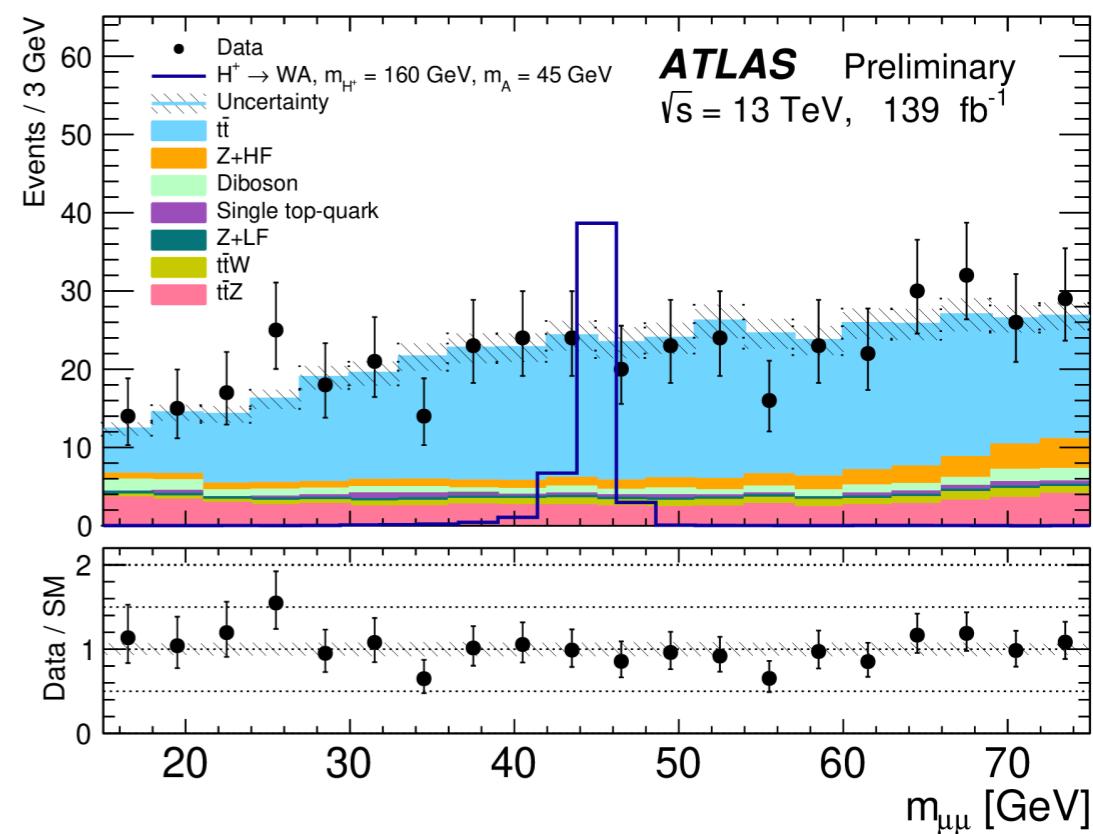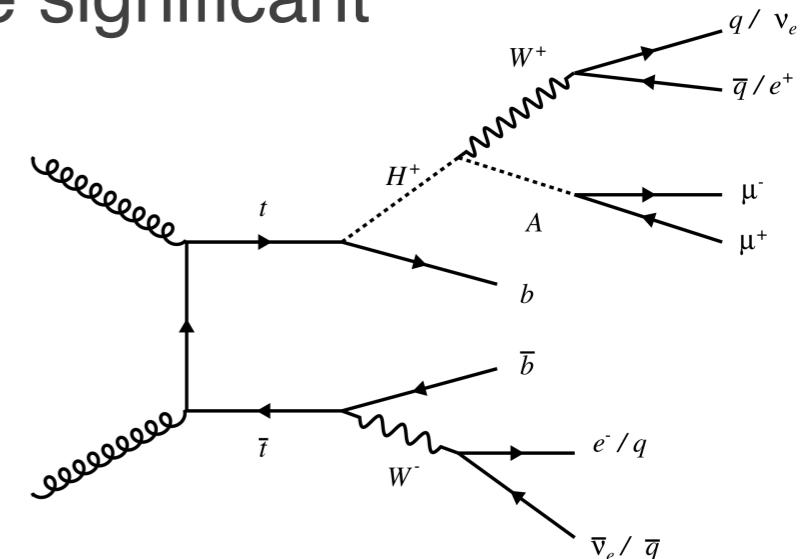
- No significant deviation from SM predictions
  - Largest excess at m_A = 24 GeV with 1.24σ local significance
- 95% CL upper limits set on the product of the branching ratios of $t \to bH^{\pm}$, $H^{\pm} \to W^{\pm}A$ and $A \to \mu^{+}\mu^{-}$
- The results interpreted in type-I 2HDM

$H^\pm \rightarrow W^\pm Z$ and $H^{\pm\pm} \rightarrow W^\pm W^\pm$
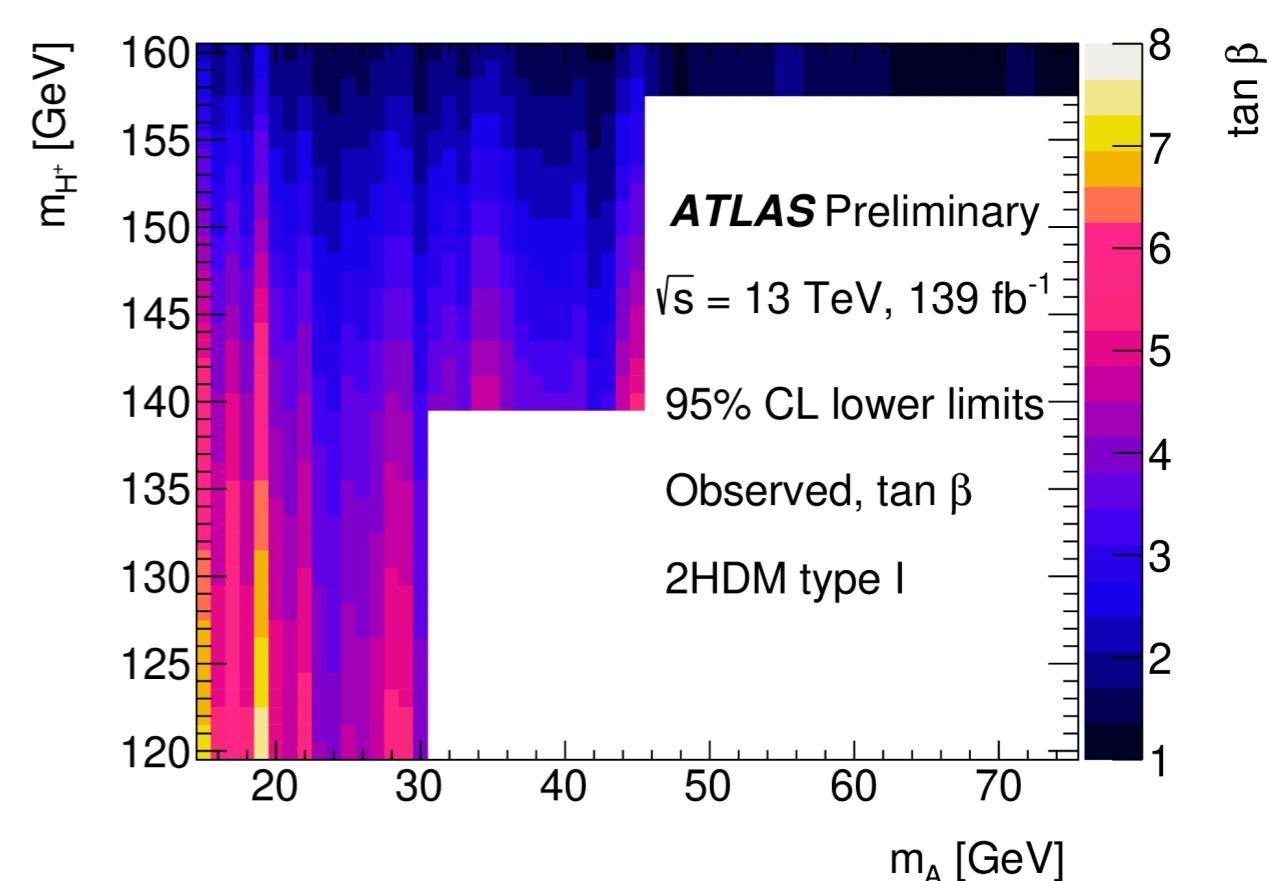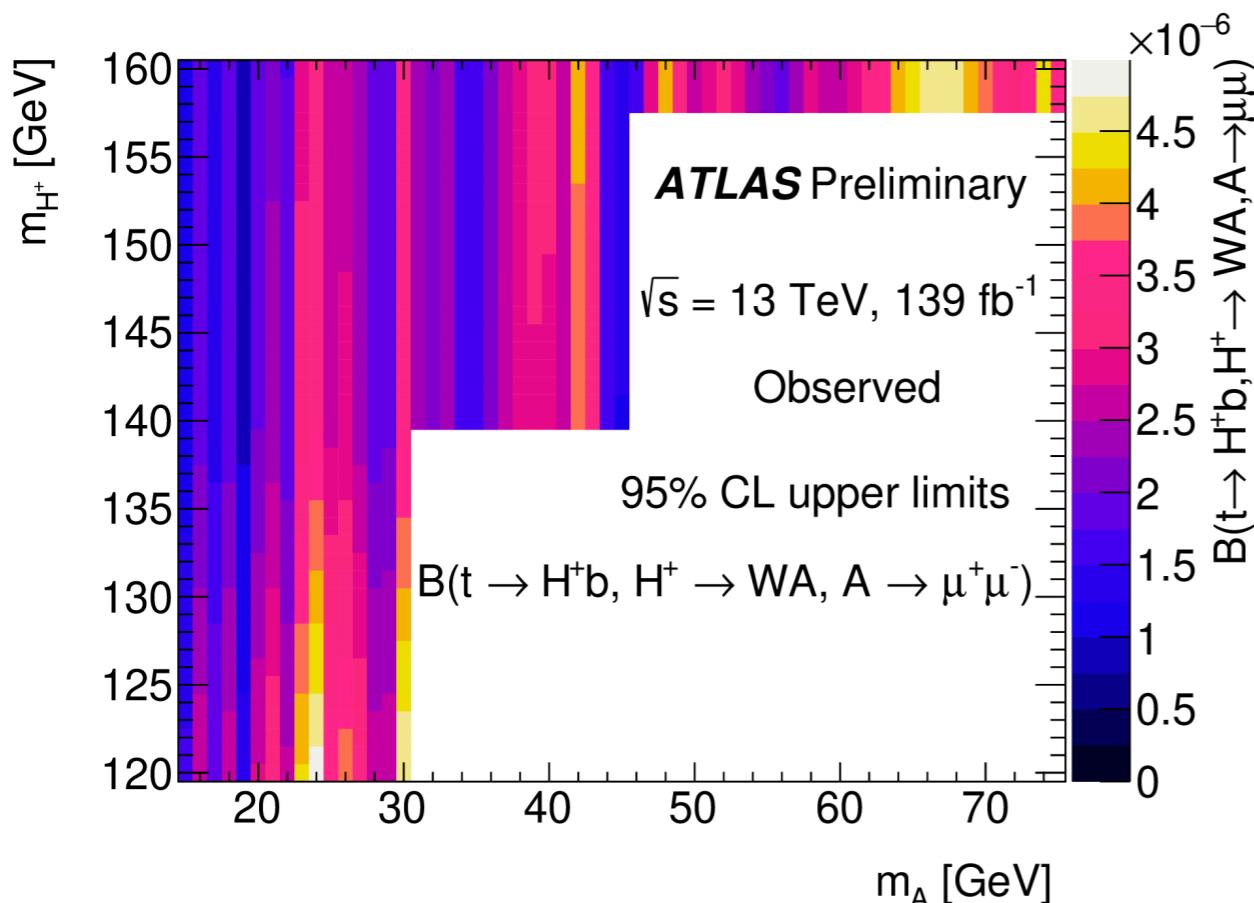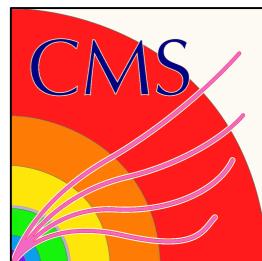
- Extensions of Higgs sector foresee singly or double charged Higgs bosons

- $H^\pm$ event selection:
  - $\ell^+\ell^-\ell^\pm$ + p_T^{miss} + $\geq$ 2 jets with large $|\Delta\eta_{jj}|$ and m_{jj}
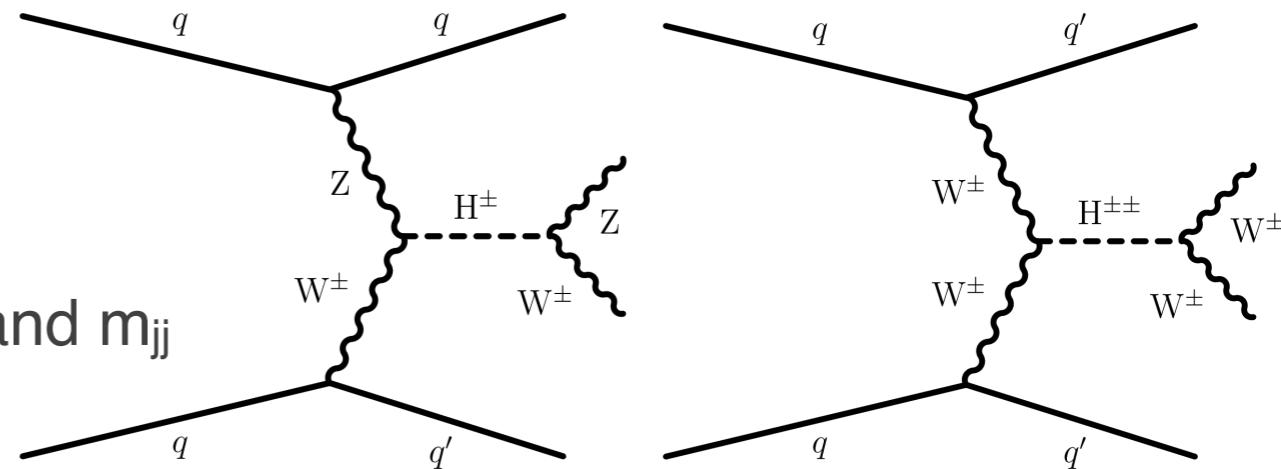
- $H^{\pm\pm}$ event selection:
  - $\ell^\pm\ell^\pm$ + p_T^{miss} + $\geq$ 2 jets with large $|\Delta\eta_{jj}|$ and m_{jj}

- Main BKG
  - Non-prompt from data CR (invert ℓ ID)
  - WW and WZ from simulation (CR-validated)
  - Prompt irreducible from MC (tZq & ZZ CR)
    - normalization is a free parameter of the fit

$$m_T^{VV} = \sqrt{\left(\sum_i E_i\right)^2 - \left(\sum_i p_{z,i}\right)^2}$$
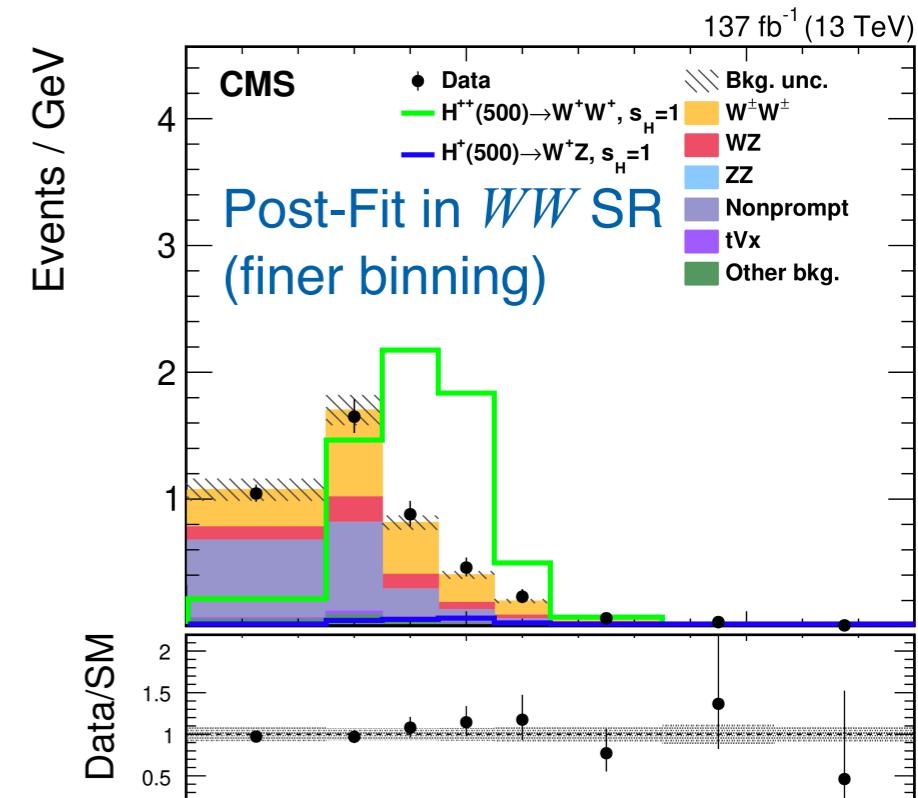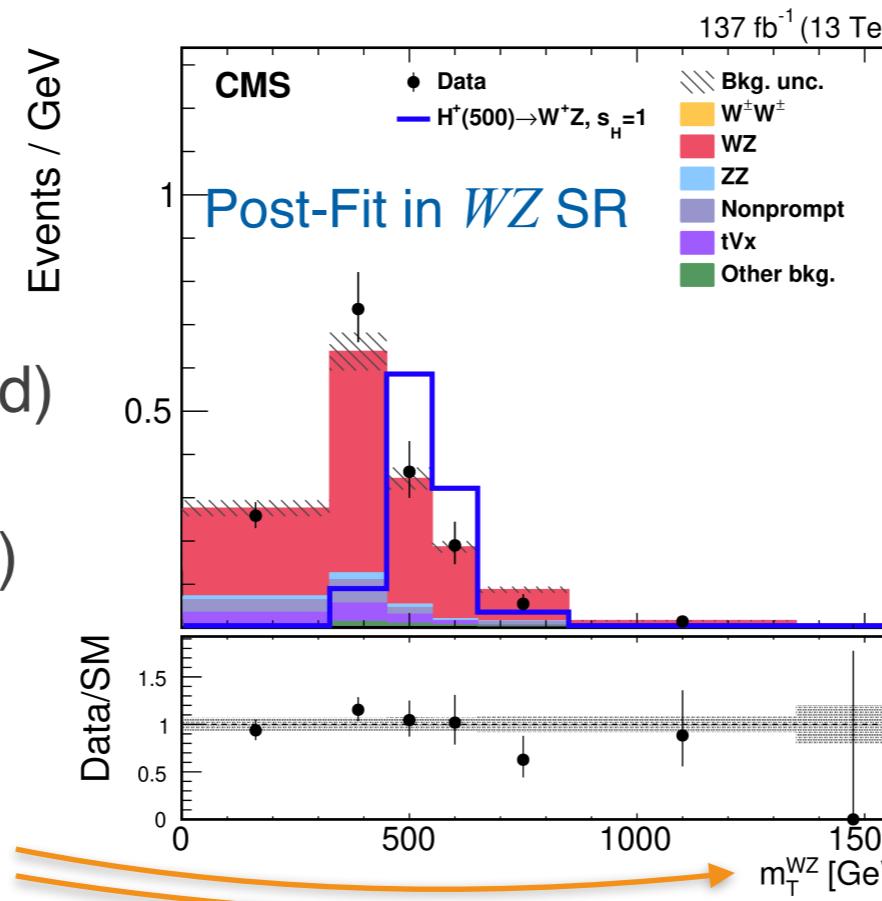
$H^\pm \to W^\pm Z$ and $H^{\pm\pm} \to W^\pm W^\pm$
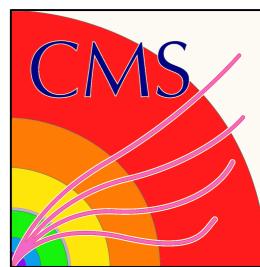
- Fit of m_T^{VV} and m_{jj} in 2 SRs and 3 CRs:

  - Ignore $H^{\pm\pm}$ in $\sigma_{H^\pm} \times \mathrm{BR}(H^\pm \to W^\pm Z)$

  - Ignore $H^\pm$ in $\sigma_{H^{\pm\pm}} \times \mathrm{BR}(H^{\pm\pm} \to W^\pm W^\pm)$

  - In Georgi-Machacek model
    $m_{H^\pm} = m_{H^{\pm\pm}} = m_{H_5}$ at tree level

  - $H^{\pm\pm}$ - $H^\pm$ simultaneous contribution excludes
    $s_H > 0.20$ - 0.35 for $m_{H_5} = 0.2$ - 1.5 TeV
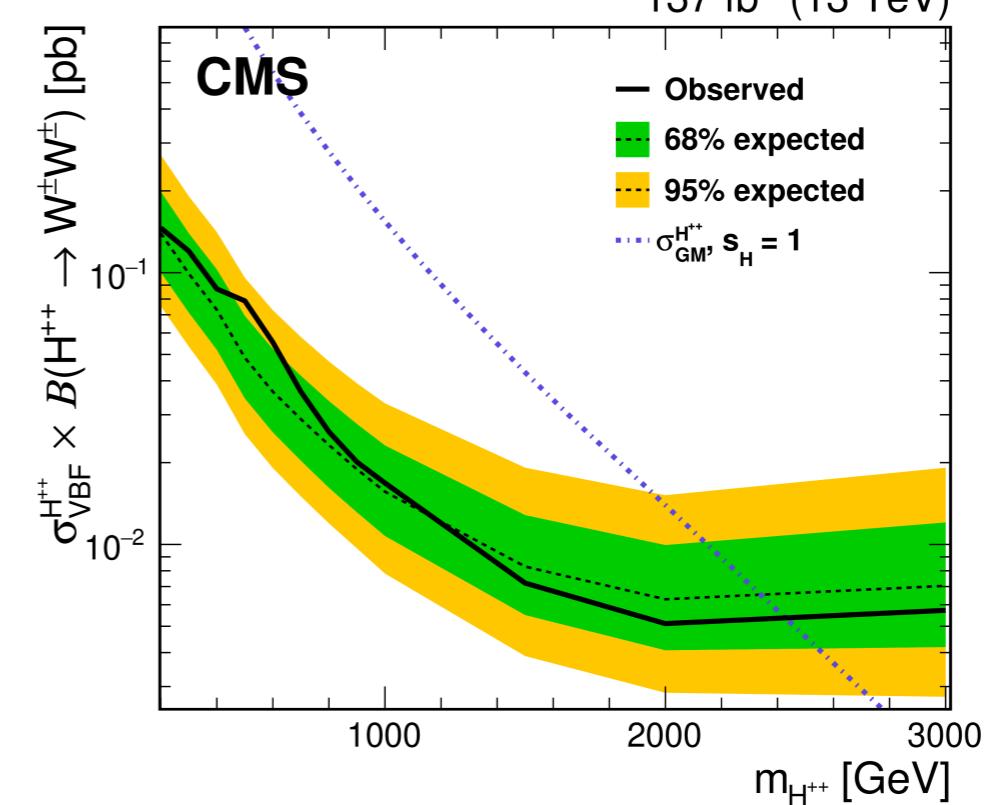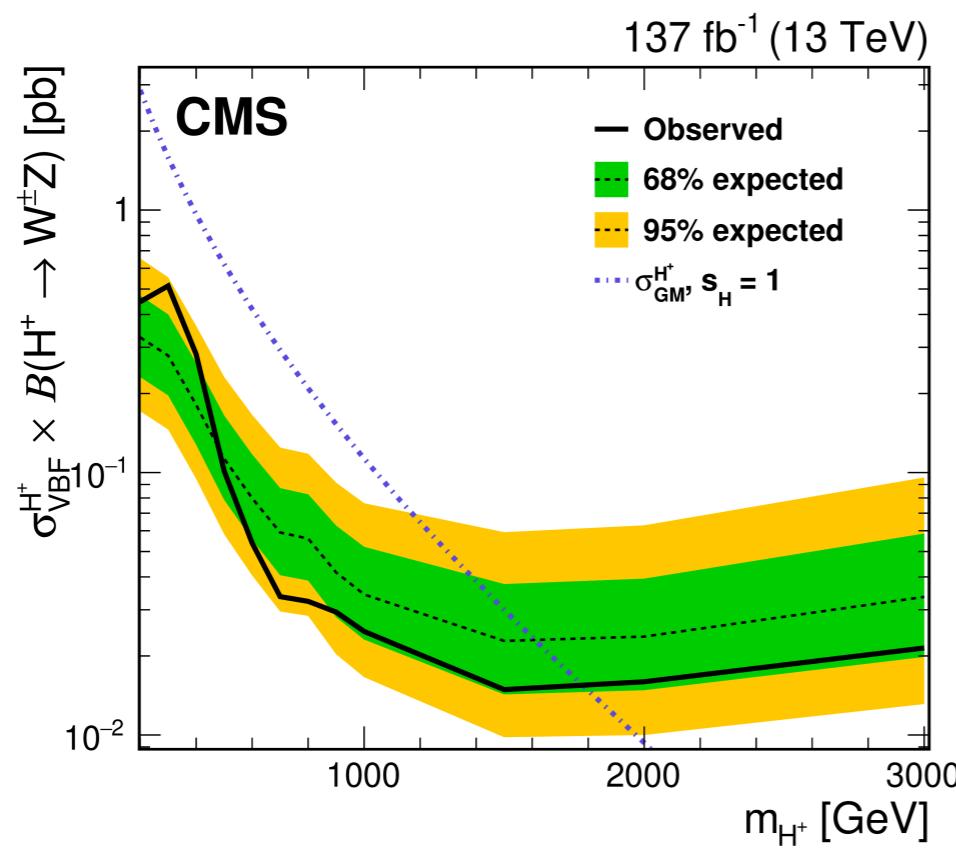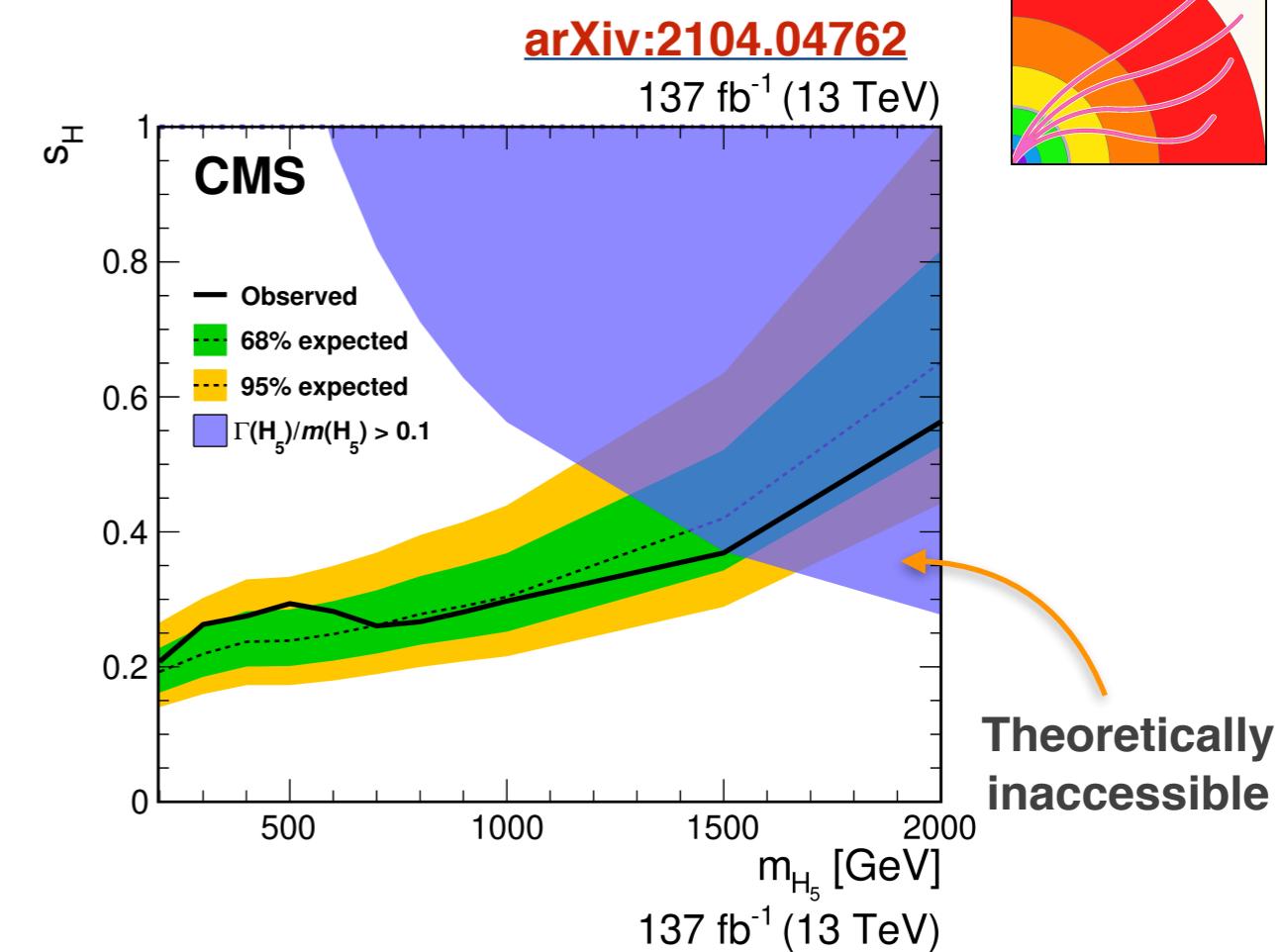
High mass $W\gamma$ and $Z\gamma$ resonances

- Search for spin 0/2 neutral (X^0) and spin 1 charged bosons (X^+)
  - ggF and $q\bar{q}$ production considered

- W and Z boosted hadronic decay considered

- Event selection: ≥ 1 central γ + ≥ 1 high p_T jet

- Orthogonal categories to optimize sensitivity
  - BTAG: 2 b-tag + jet substructure + Z mass
  - D2: jet substructure + $Z(W)$ mass
  - ZMASS (WMASS): $Z(W)$ mass

- Main BKG: SM γ+jet, SM γ+$Z(W)$

- BGK and signal parametrization vs $m_{J\gamma}$
  - BKG: $B(x;\mathbf{p})=(1-x)^{p_1} x^{p_2+p_3\log(x)}$ with $x = m_{J\gamma}/\sqrt{s}$
    - function choice validated in CR with forward γ
  - Signal: double-sided crystal ball
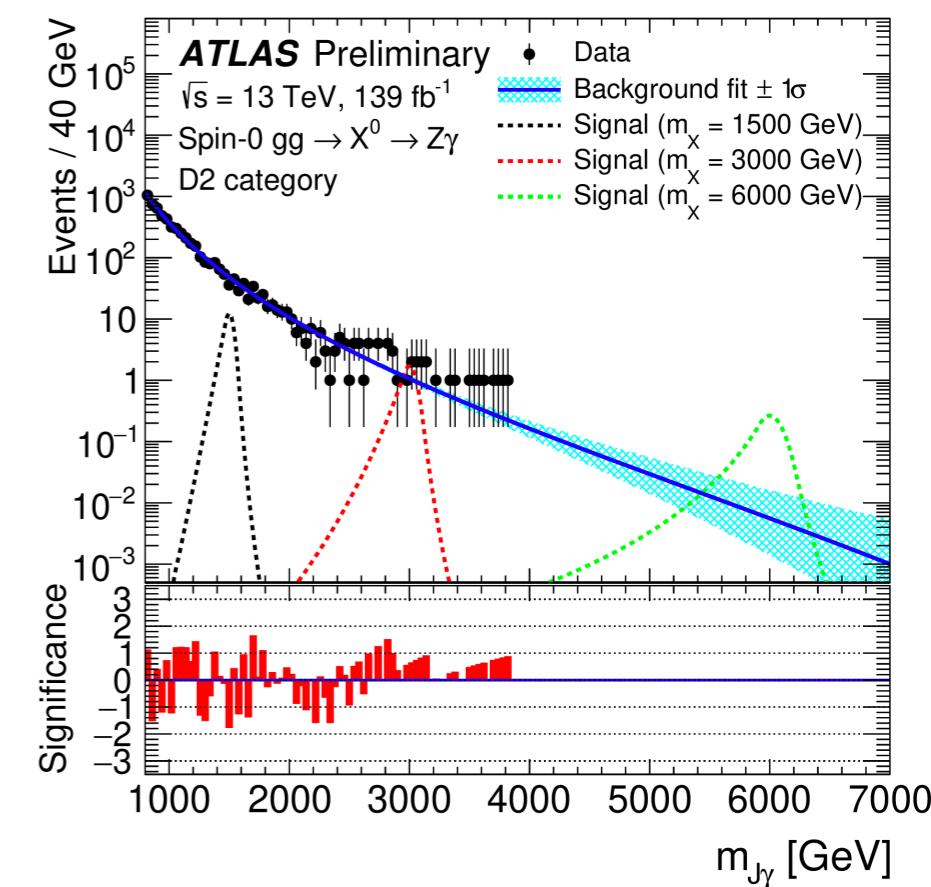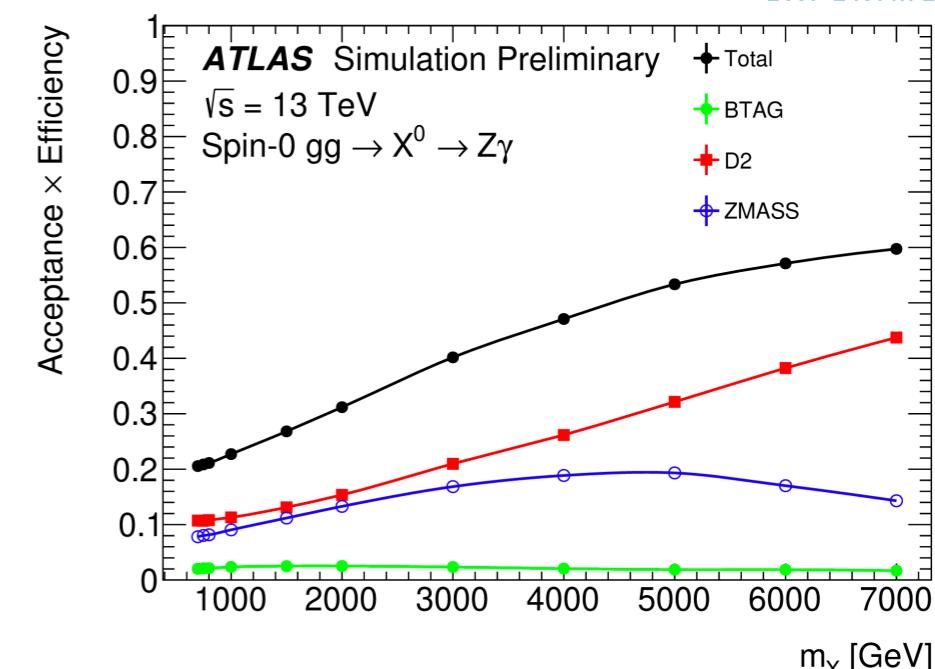
High mass $W\gamma$ and $Z\gamma$ resonances

- Signal Extraction: unbinned likelihood fit to the $m_{J\gamma}$ spectrum

- Largest excess for spin-0 $gg{\rightarrow}X^0{\rightarrow}Z\gamma$ at m_X = 3640 GeV with local significance of ~2.5σ

- 95% CL upper limits σ×BR presented (more in backup)
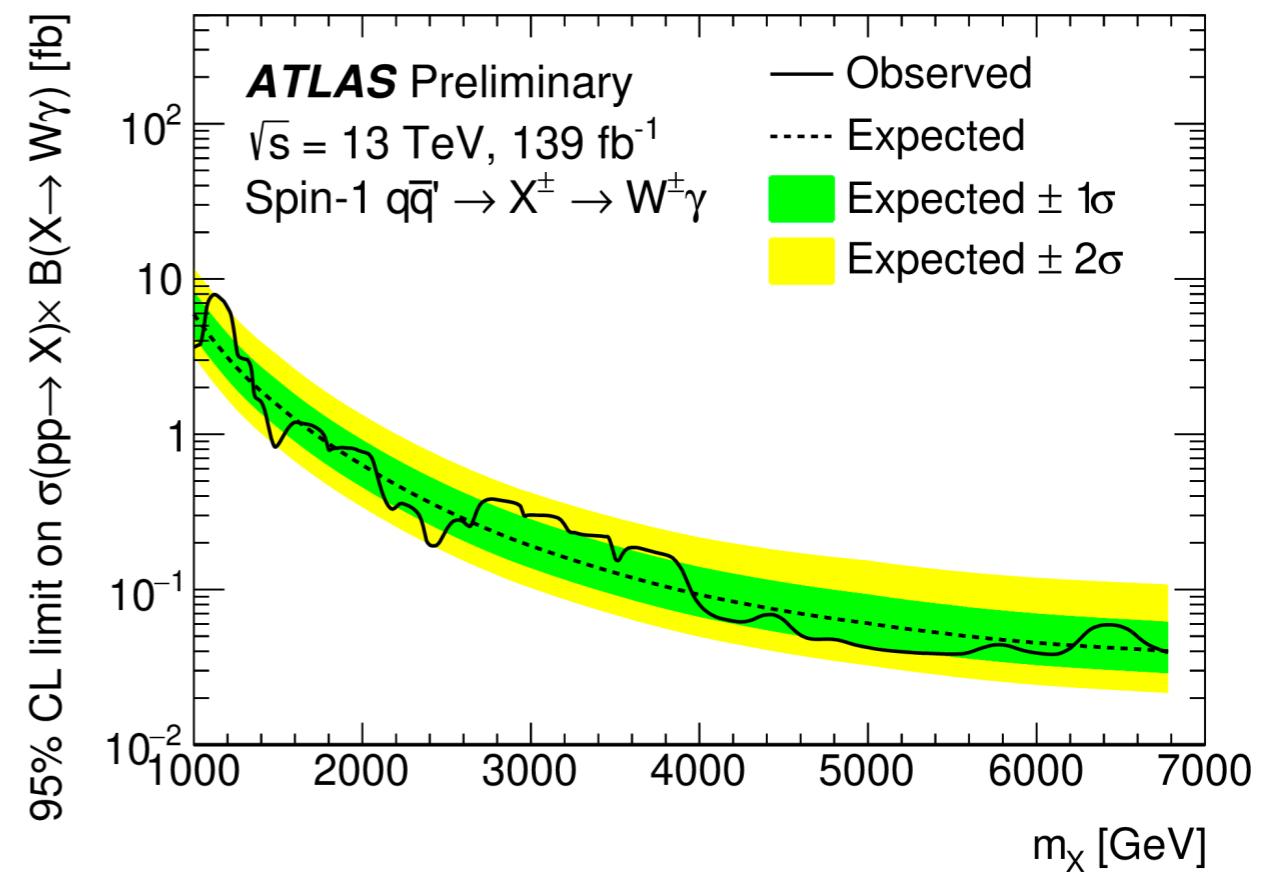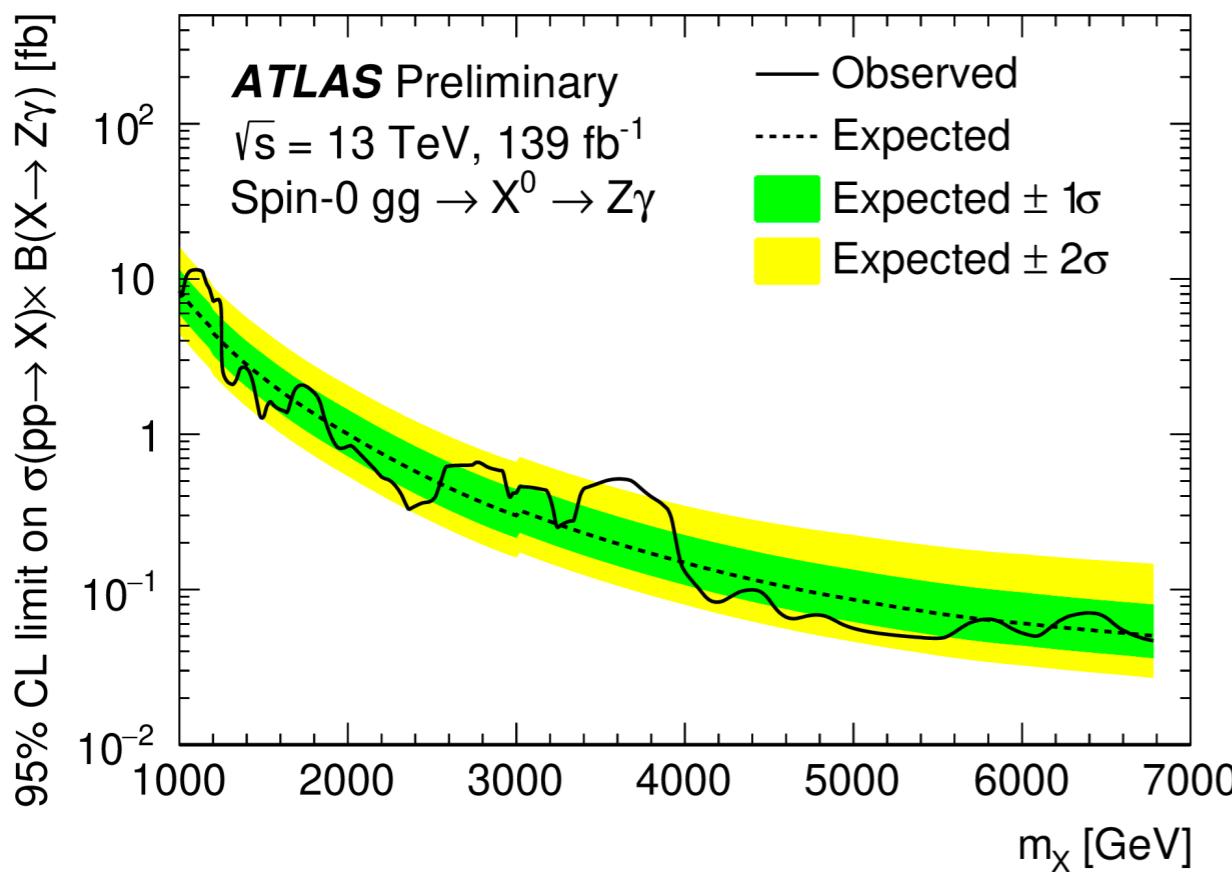
High mass $\gamma\gamma$ resonances

- Search for spin-0 and spin-2 neutral bosons

- Event selection: ≥ 2 isolated γ with tight ID, $E_T > 22$ GeV and $|\eta_\gamma| < 2.37$

- Main BGKs: $\gamma\gamma$, γ+jet and 2 jets

- BGK and signal parametrization as a function of $m_{\gamma\gamma}$
  - BKG shape: $f(x; b, a_0, a_1) = N(1 - x^{1/3})^b x^{a_0 + a_1 \log(x)}$ with $x = m_{\gamma\gamma}/\sqrt{s}$
    - derived from MC $\gamma\gamma$ and data-driven γ+jet events
  - Signal shape: double-sided crystal ball
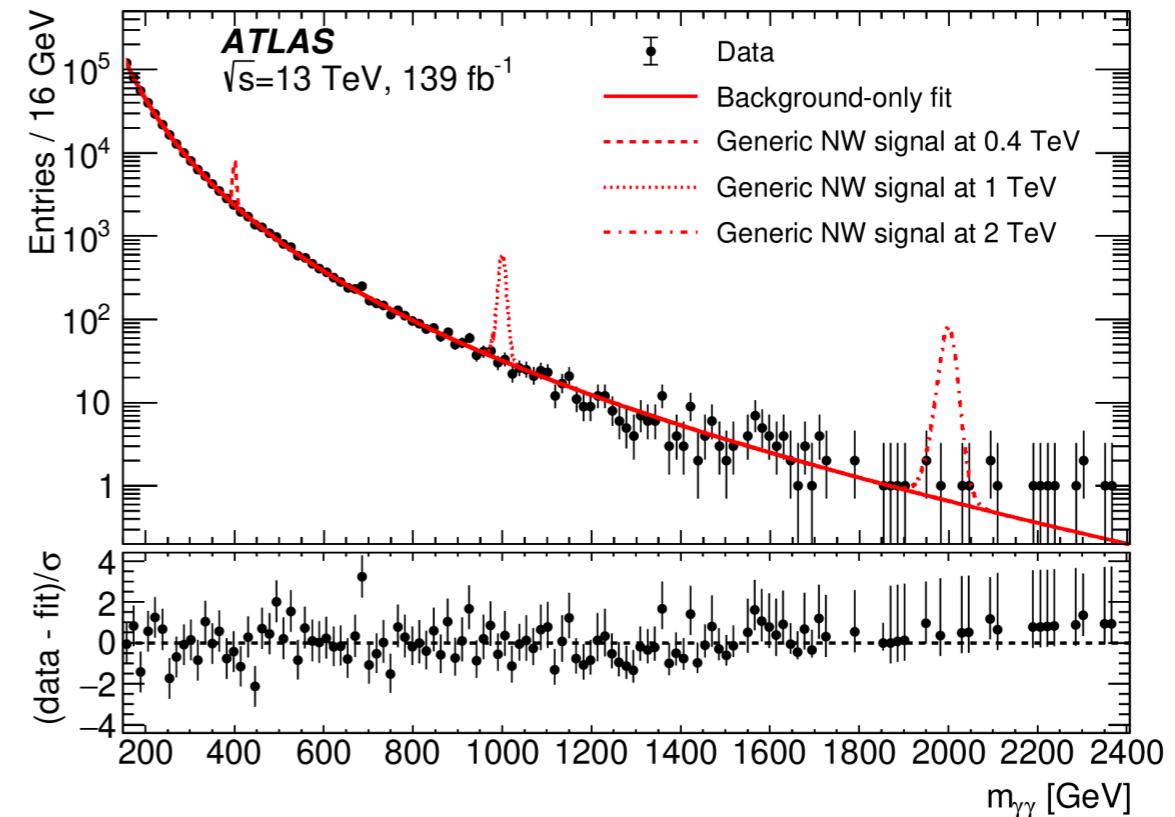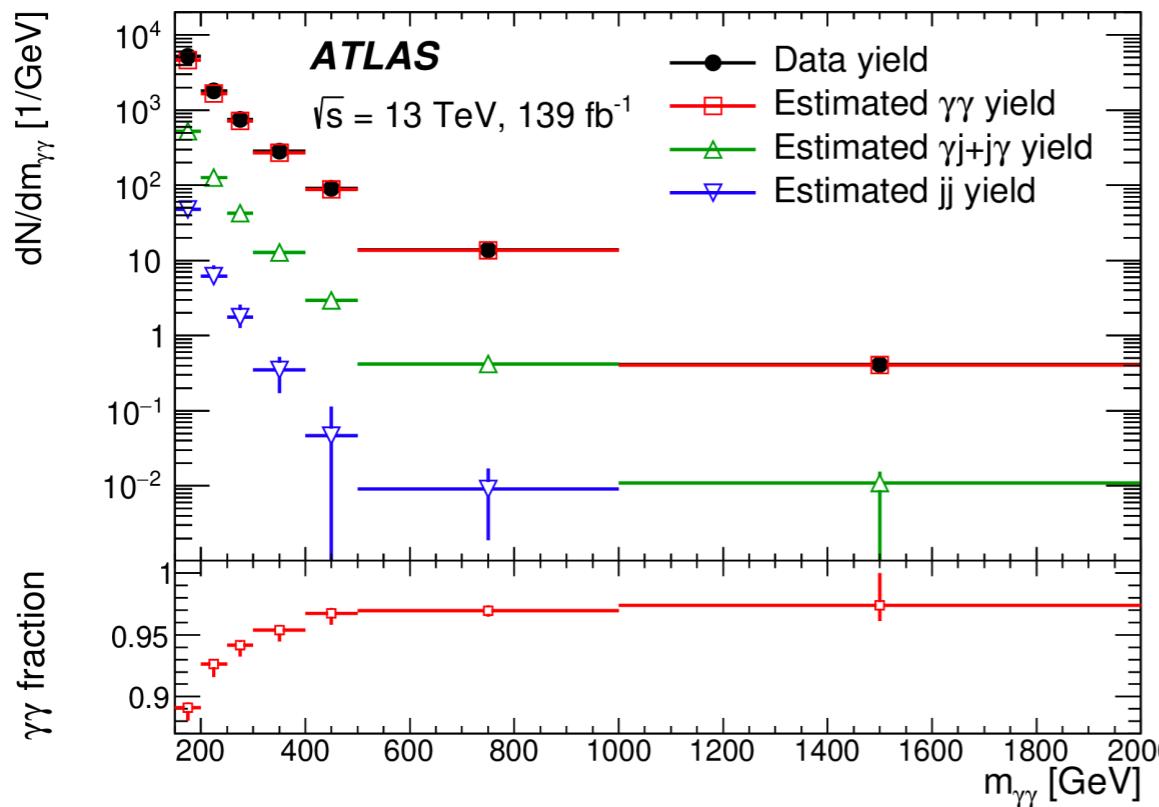
High mass $\gamma\gamma$ resonances

- 95% CL upper limits on the fiducial region and total $\sigma \times BR$ for spin-0 and spin-2 models, respectively
  - fiducial region: two GEN level photons with $|\eta_\gamma| < 2.37$, leading γ $E_T > 0.3$ $m_{\gamma\gamma}$ and subleading γ $E_T > 0.25$ $m_{\gamma\gamma}$

- Largest excess is at ~684 GeV with 1.3σ (3.3σ) global (local) significance

- Scanned signal mass and a range of width/coupling hypotheses (in backup)
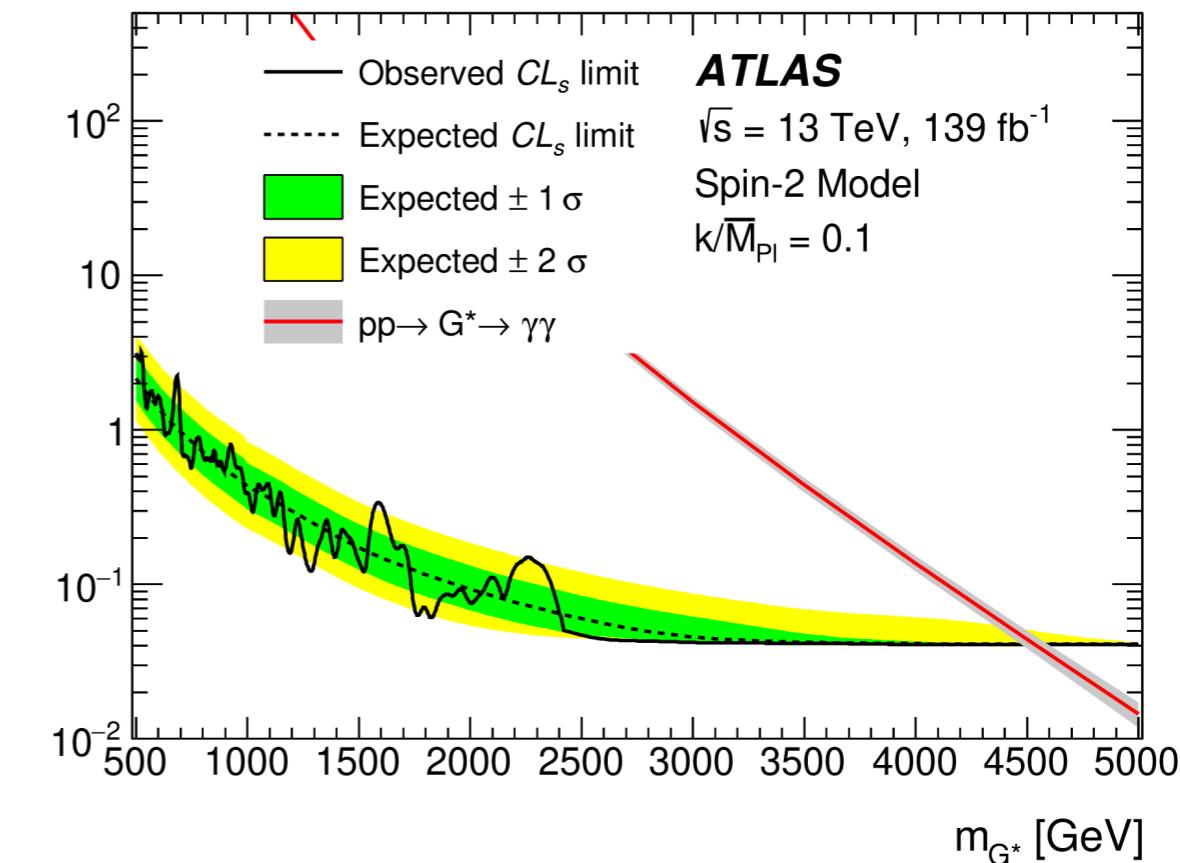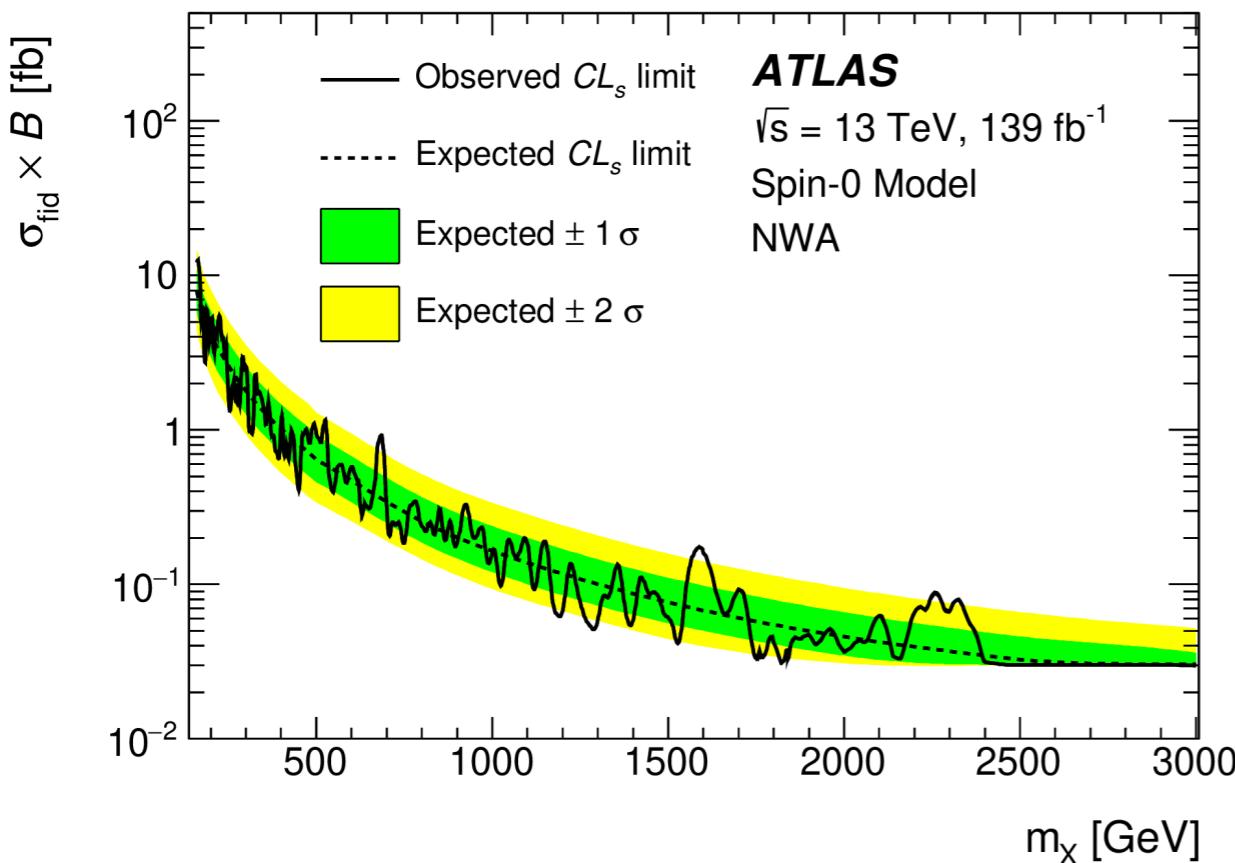
Light H from SUSY cascade decays

- Assuming squark-mass degeneration = M_{SUSY} and SM-like H BR($H_1 \rightarrow bb$)

- Multi-jet (small and large-R) + MET topology investigated

- Event selection: high H_T + ≥ 2 high p_T large-R jets (J_A and J_B) from H_1 decay + ≥ 1 high p_T jet separated from J_A and J_B

- 10 SRs: double b-tag to identify J_A and J_B and $m_{J_A} \sim m_{J_B}$

- Main BKG: multijet-QCD (data-driven) and $t\bar{t}$ (MC)
  - multijet-QCD yields from inverted btag region and sidebands
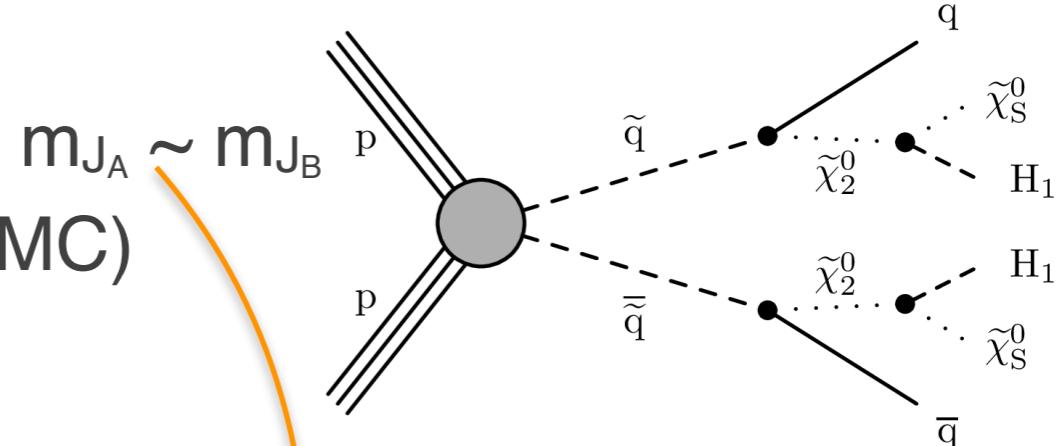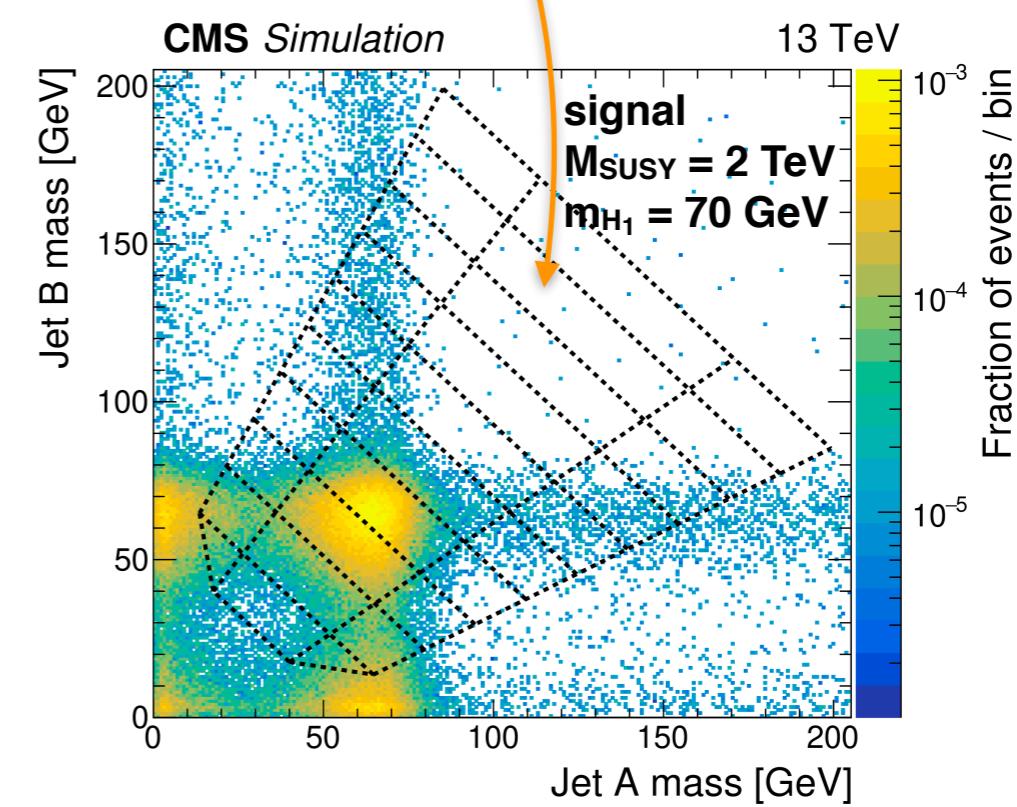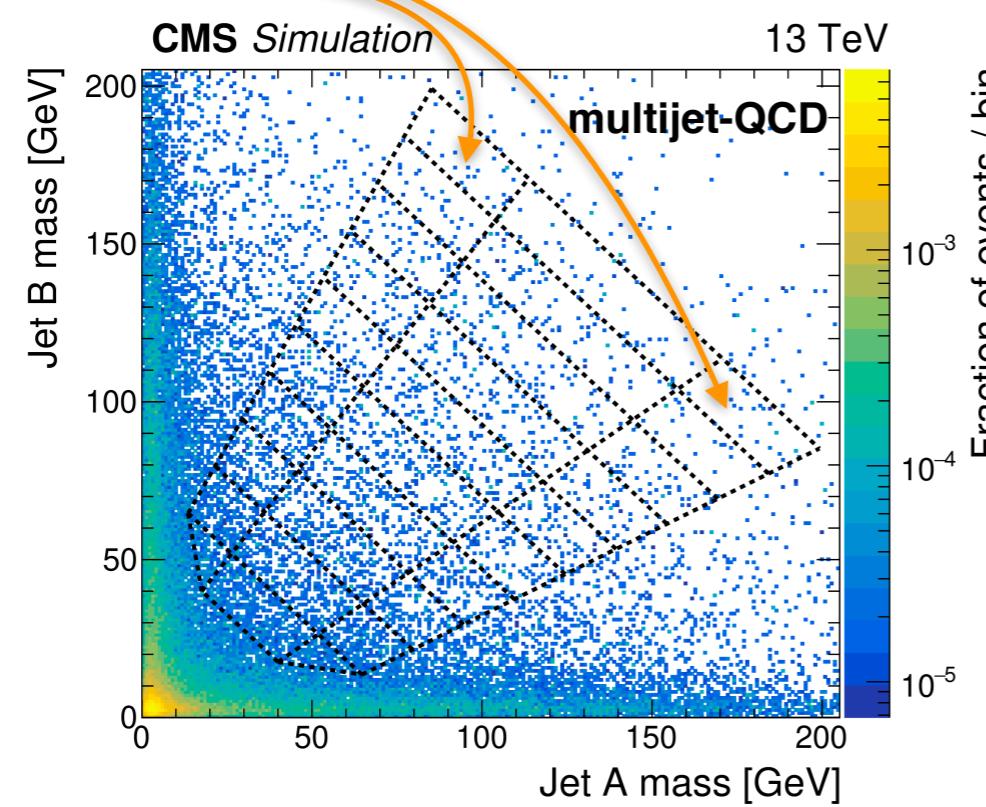
Light H from SUSY cascade decays
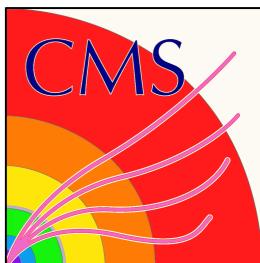
- Signal extraction simultaneous fit of 10 SRs and sidebands (3 H_T bins each)

- No deviation from SM observed, 95% CL upper limits set on σ × BR($H_1 \to b\bar{b}$)

- Upper limits compared to predictions of NMSSM
  - excluded $1200 < M_{SUSY} < 2500$ GeV and $40 < m_{H_1} < 120$ GeV at 95% CL
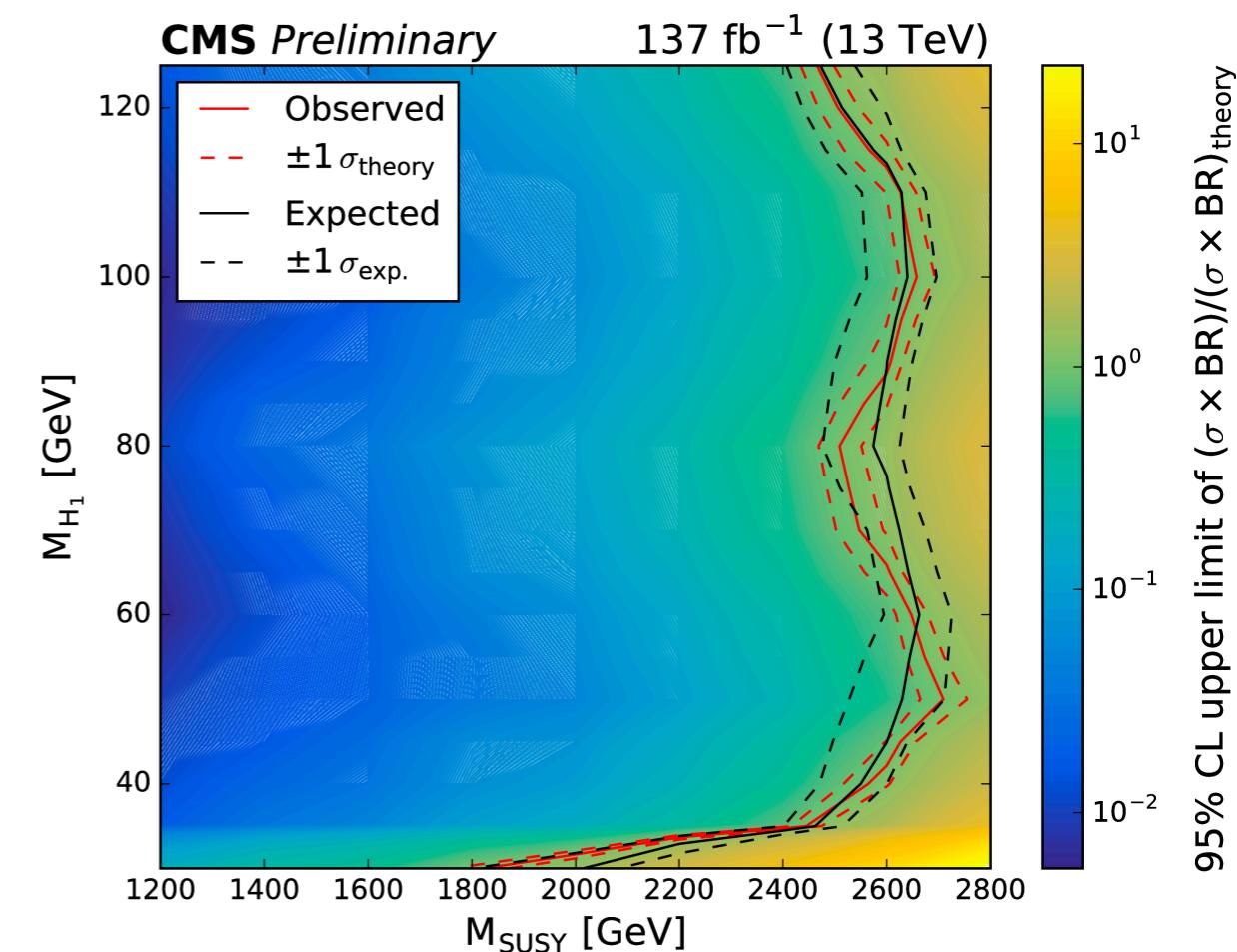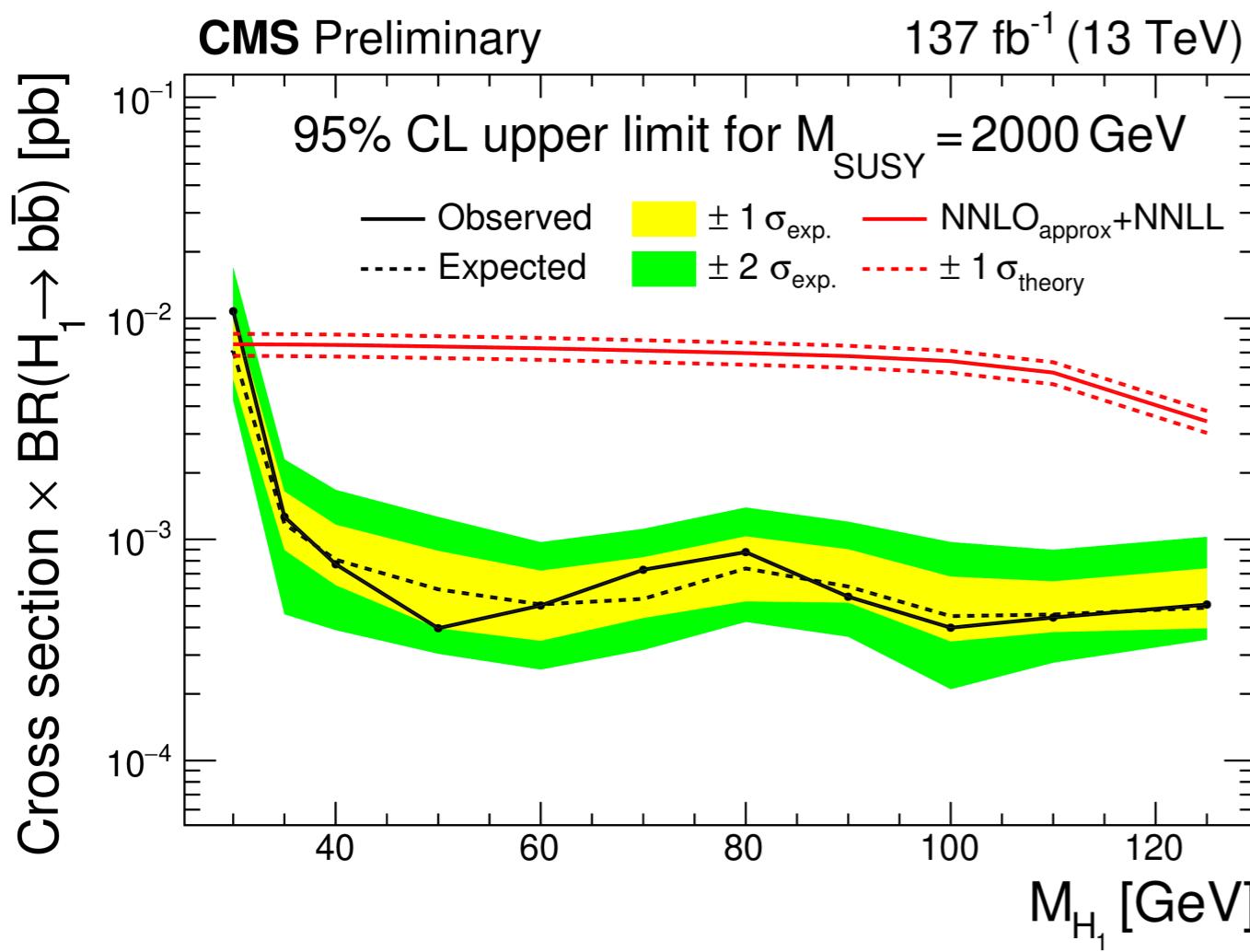
$H \to hh_S \to \tau\tau bb$ with $m_h = 125$ GeV

- Considered final states: $b\bar{b}$ + $e\tau_h$, $\mu\tau_h$ or $\tau_h\tau_h$
- Event selection: 1ℓ $1\tau_h$ $(2\tau_h)$ + ≥ 2 jets (≥ 1 b-jet)
- Main BKG: $t\bar{t}$, multijet QCD, Z, WW
- 3 BKG estimation methods
  - Genuine $\tau\tau$ with τ-embedding
  - Misidentified τ_h (jet $\to \tau_h$) with misidentification rates
  - $Z/t\bar{t}/WW$ into prompt $\ell = e, \mu$ from simulation

420 mass points!
$240 < m_H < 3000$ GeV
$60 < m_{h_S} < 2800$ GeV
H and h_s assumed to be narrow

- NN multi-classification with s+4b categories for each final state (68 NN!)

$H \rightarrow hh_S \rightarrow \tau\tau bb$ with $m_h = 125$ GeV
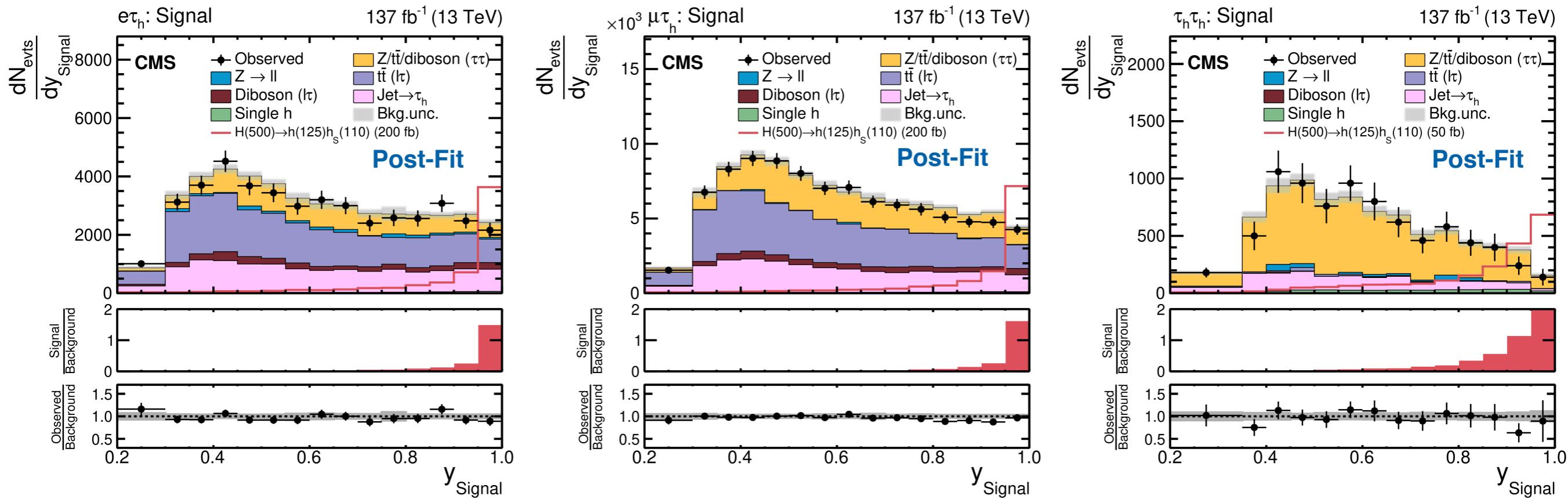
- Signal extraction: maximum likelihood fit on all NN scores

- No deviation from SM observed, 95% CL upper limits on $\sigma \times$ BR extracted

- NMSSM constrained for $400 \lesssim m_H \lesssim 600$ GeV and $60 \leq m_{h_S} \lesssim 200$ GeV

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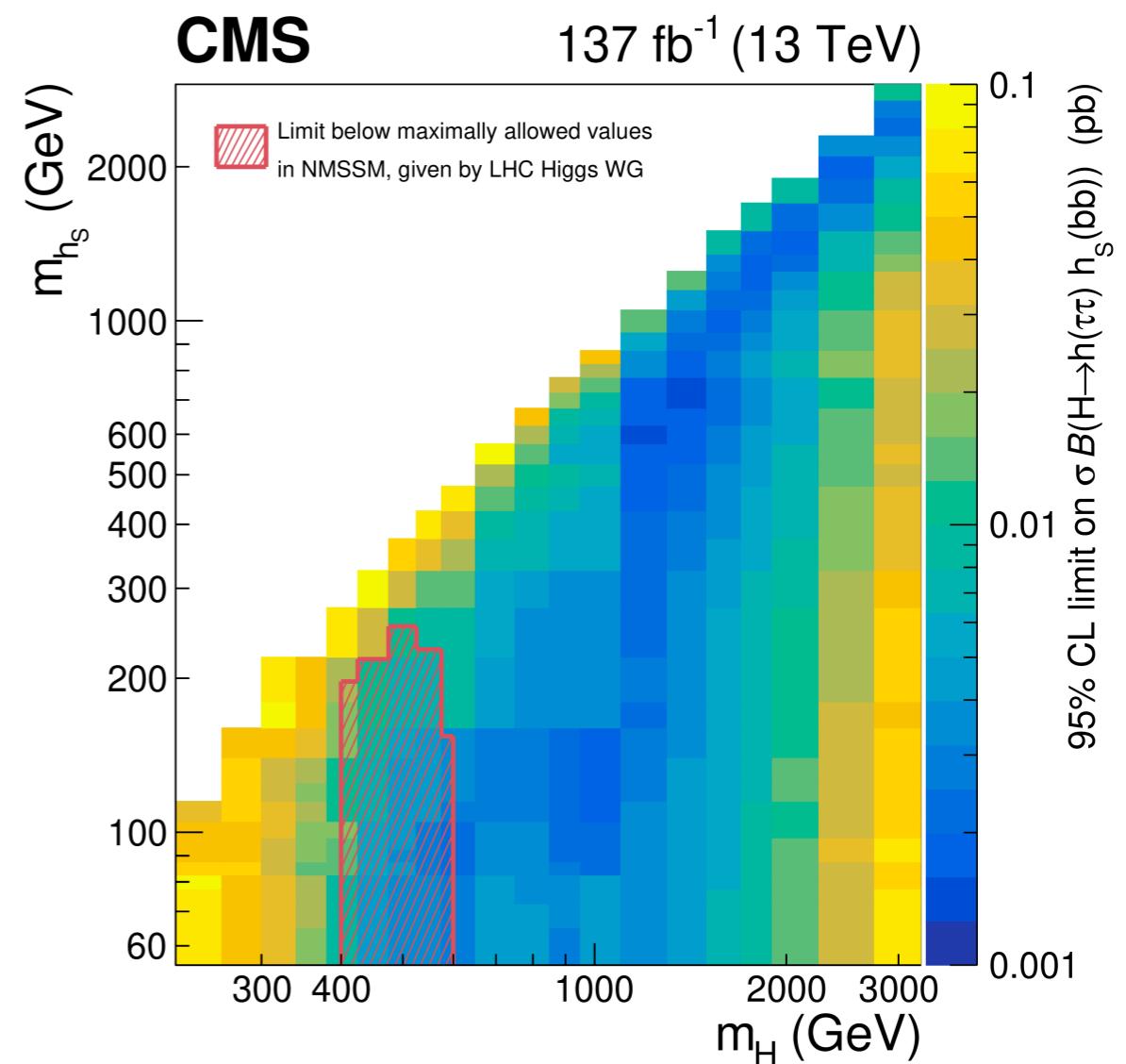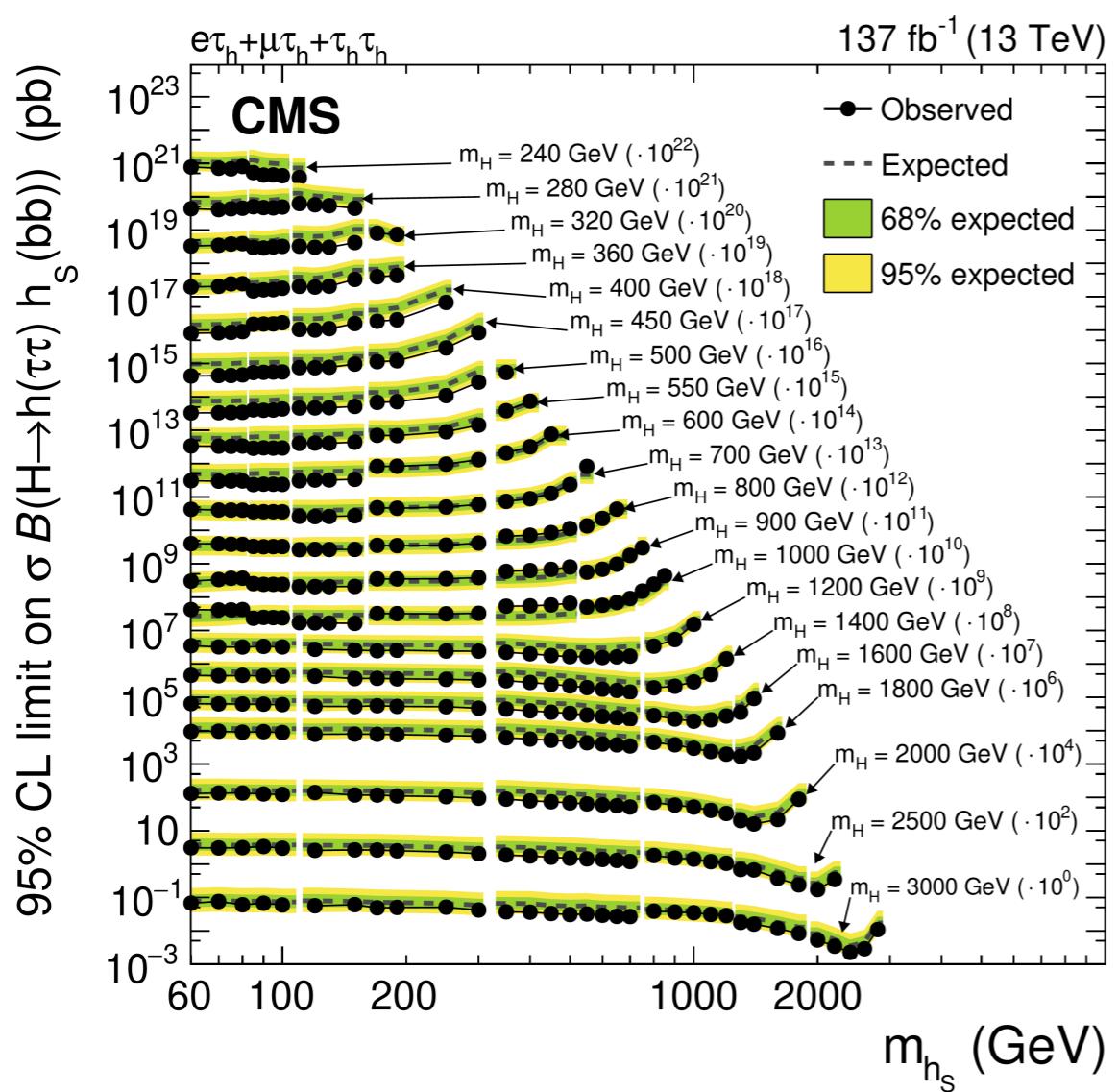
Summary

- Presented latest searches for scalar and Higgs-like particles by ATLAS and CMS

- Achieving more and more sensitive results
  - Larger dataset and more advanced analysis techniques

- No evidence for BSM physics observed yet
  - Large part of parameter space excluded but still plenty left untouched
  - More complex models being investigated

- Large effort by the two Collaborations on searches for Higgs-like particles
  - Several new results are coming

- Stay tuned!

CMS Higgs PAG twiki

ATL-PHYS-PUB-2021-030

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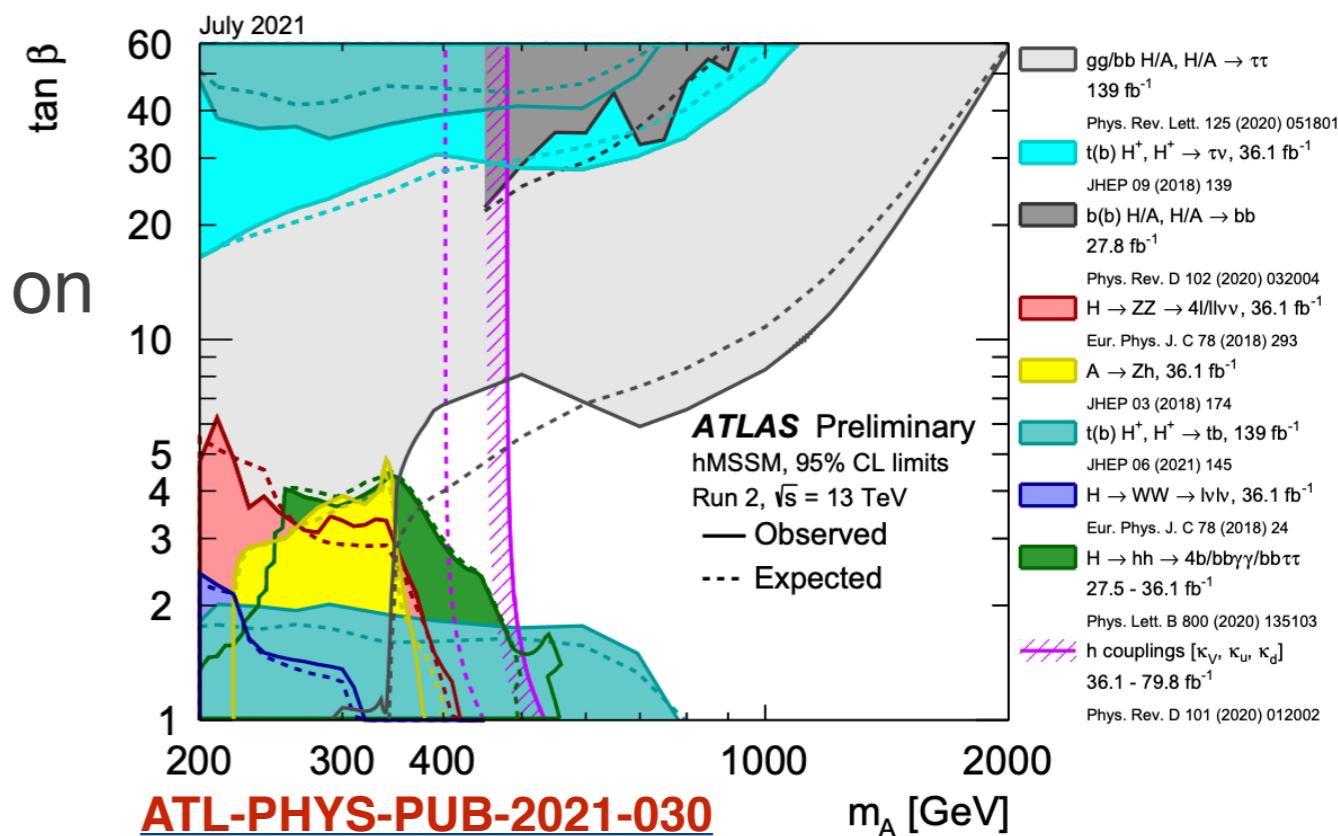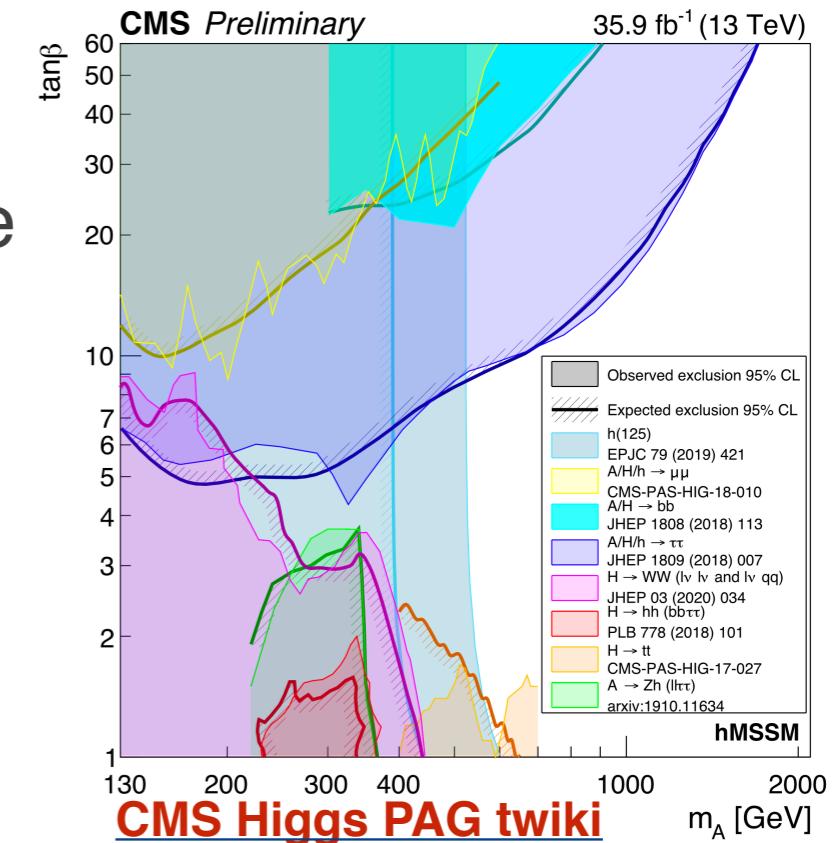
Backup

Charged Higgs: $H^\pm \to cb$

j = jet

b = jet with tighter b-tag (b eff = 60%)

bl = jet with looser b-tag (b eff = 70%)
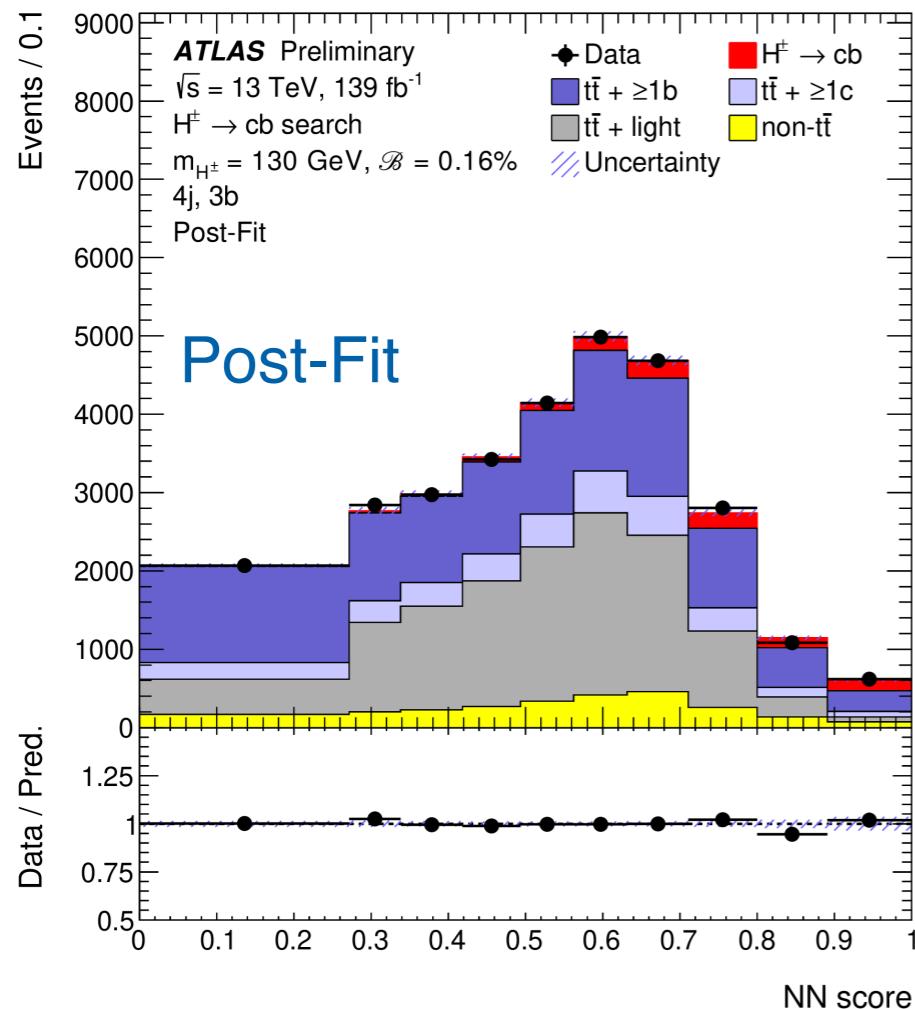
- Signal strength only unconstrained parameter of fit
- Constraints on BKG systematics and adjust $t\bar{t} + \geq 1b$ normalization from fit
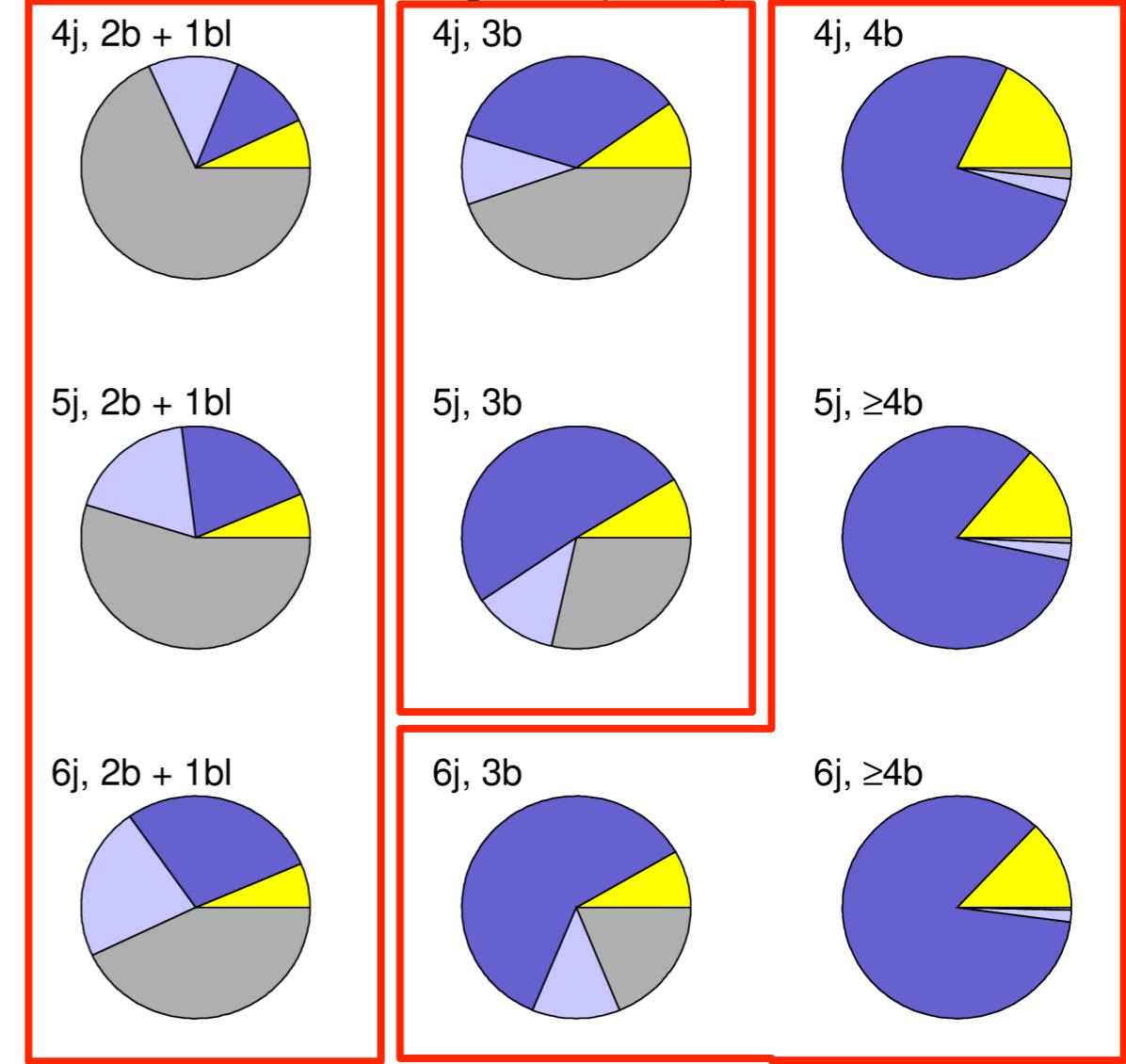
$H^{\pm} \rightarrow W^{\pm}A \rightarrow W^{\pm}\mu\mu$ in $t\bar{t}$ events

ATLAS-CONF-2021-047

- Expected and observed upper limits on the product of the branching ratios of $t \rightarrow bH^{\pm}$, $H^{\pm} \rightarrow W^{\pm}A$ and $A \rightarrow \mu^{+}\mu^{-}$


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$H^\pm \to W^\pm Z$ and $H^{\pm\pm} \to W^\pm W^\pm$
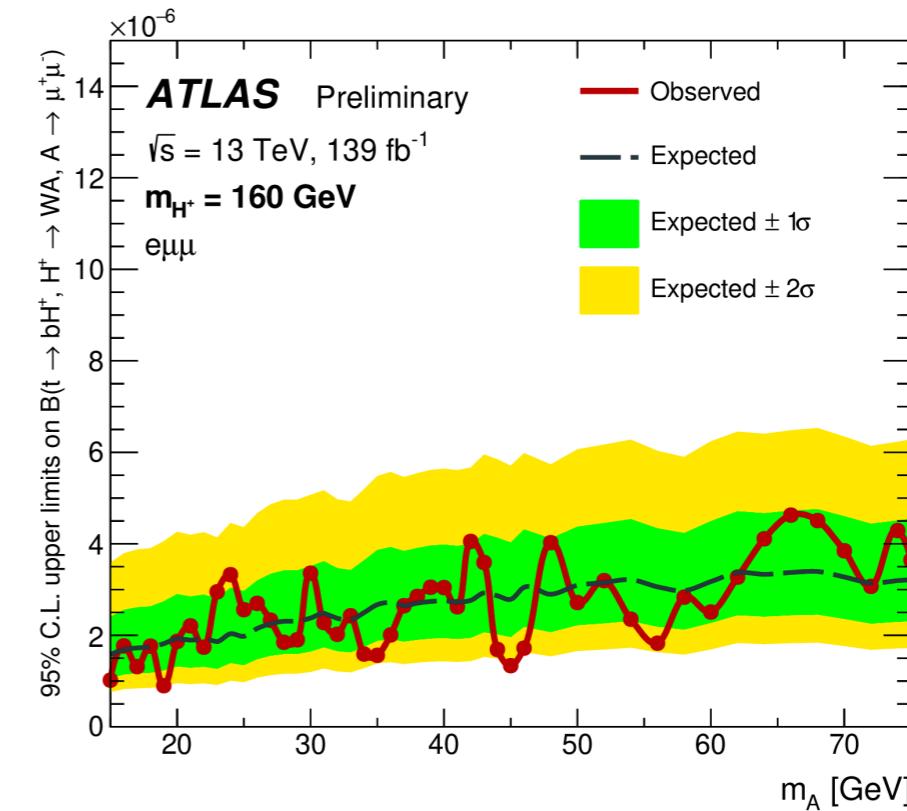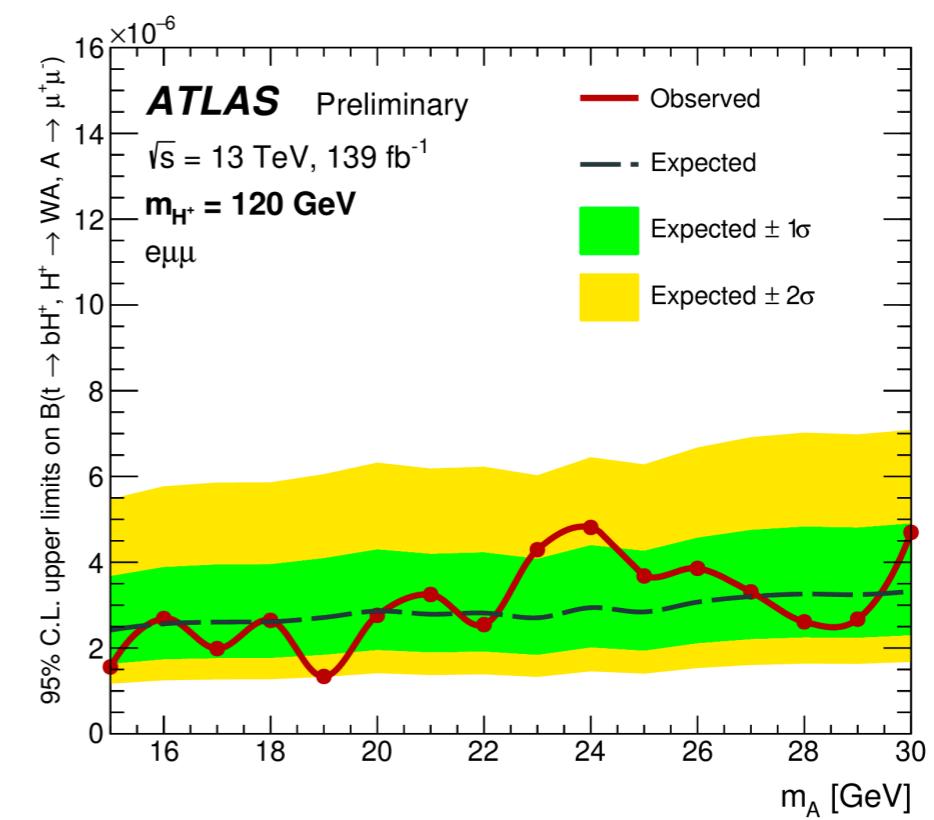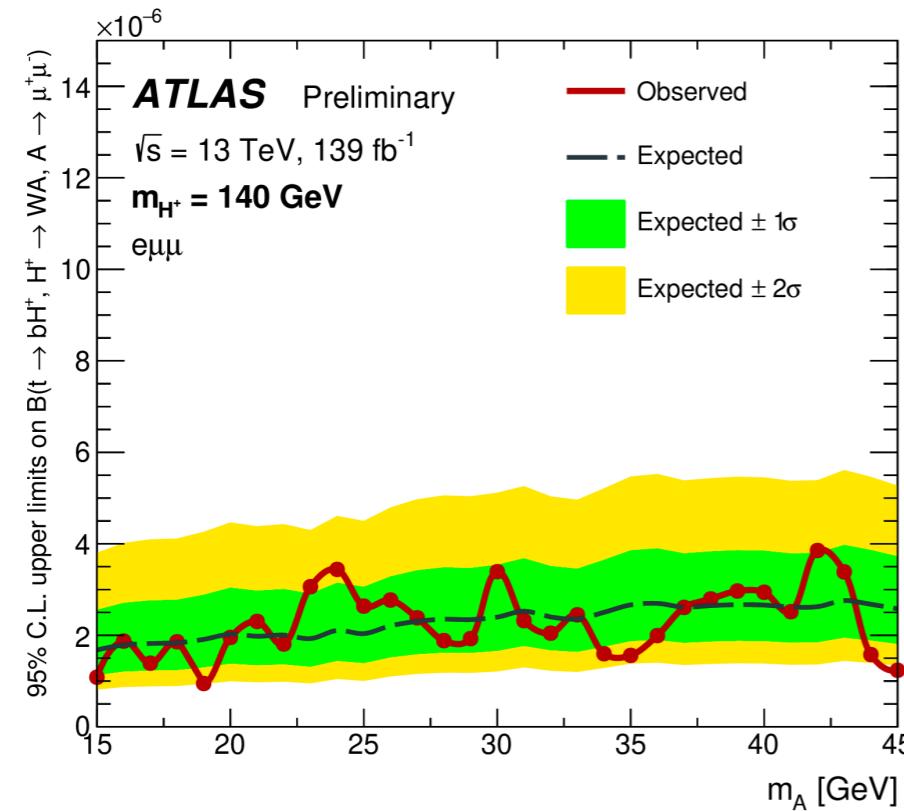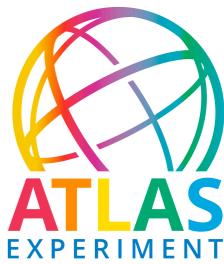
**Distribution of signal, BKG and data for bins used in simultaneous ML fit**
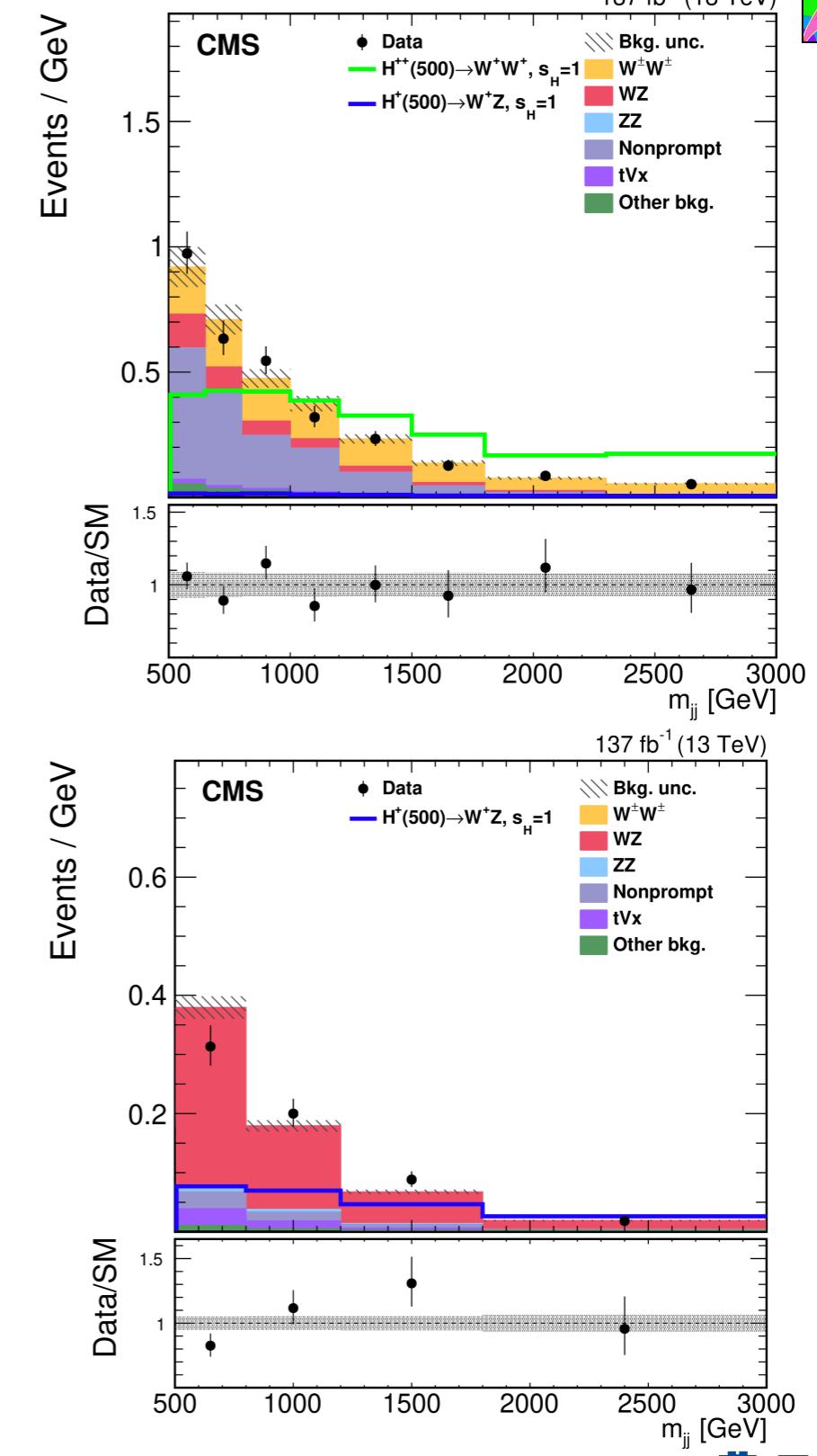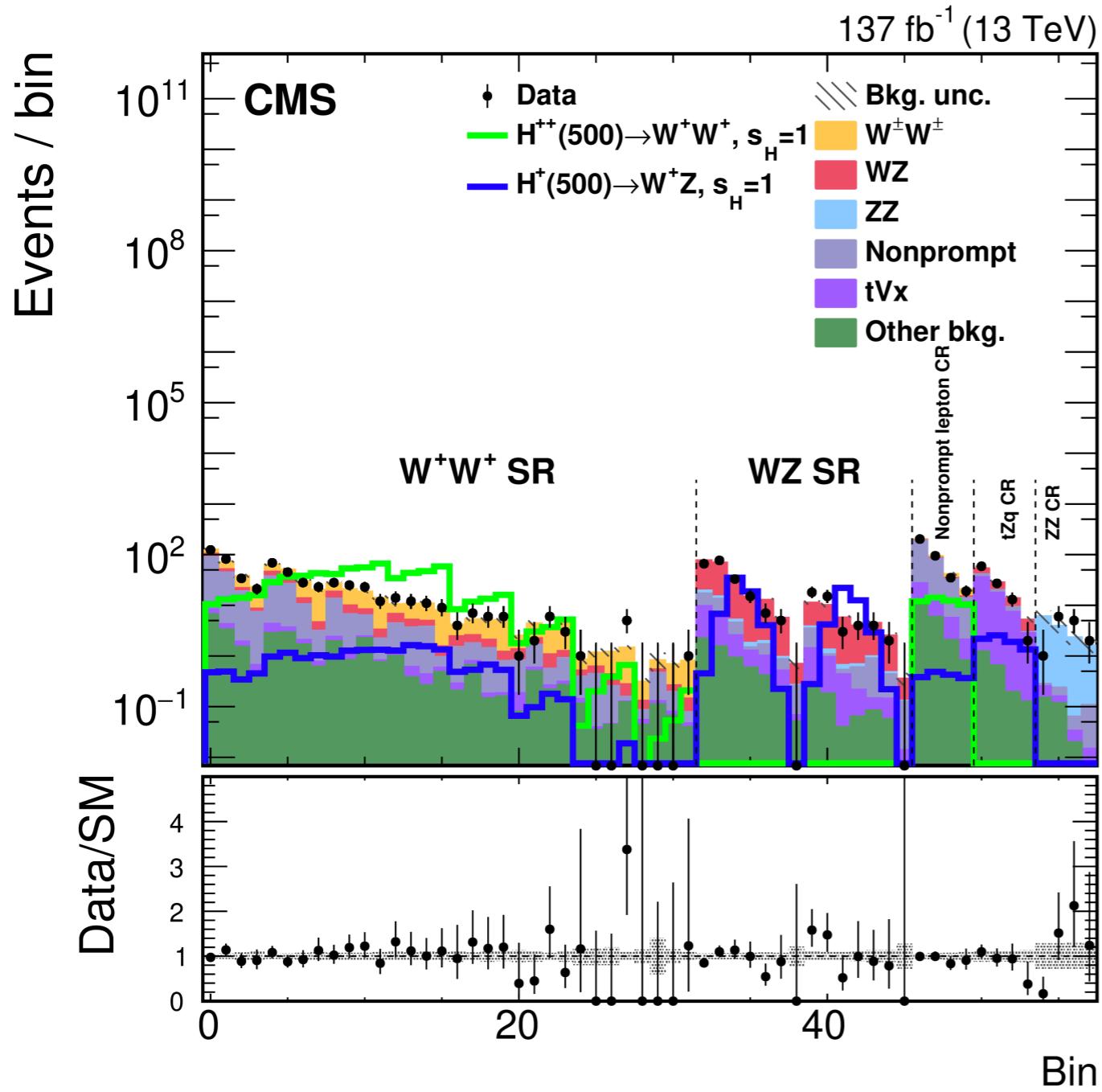
High mass $W\gamma$ and $Z\gamma$ resonances

The flow charts of event categorization

$X^\pm \to W^\pm \gamma$ Categorization

$X^0 \to Z\gamma$ Categorization
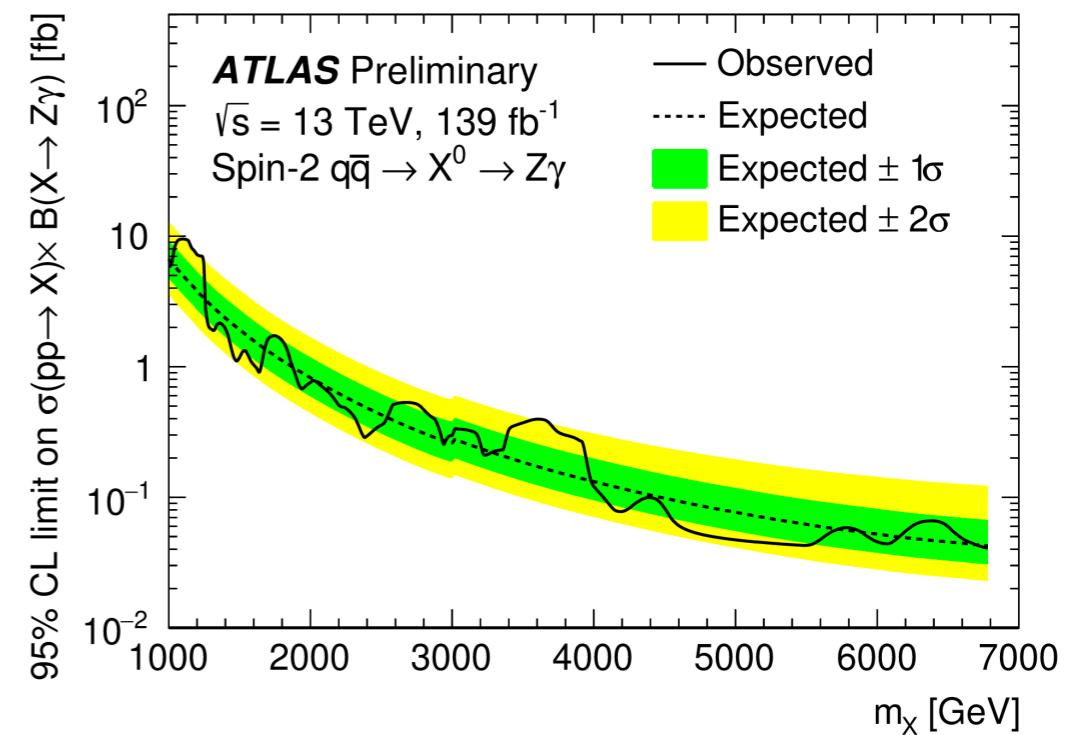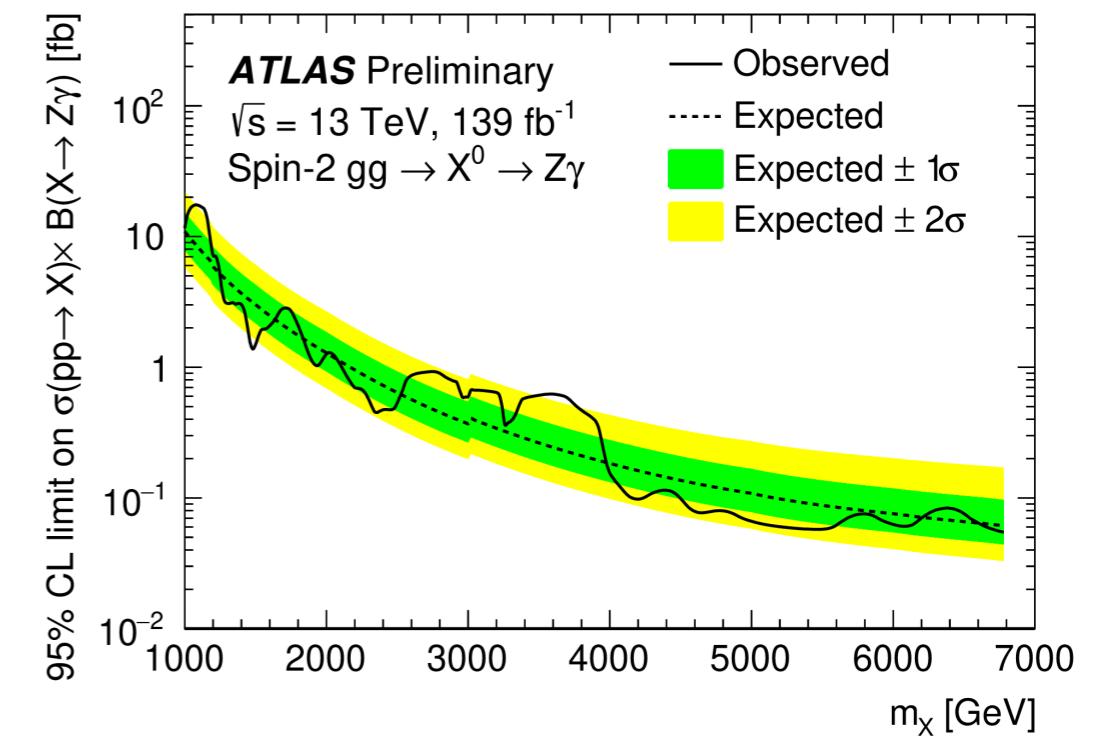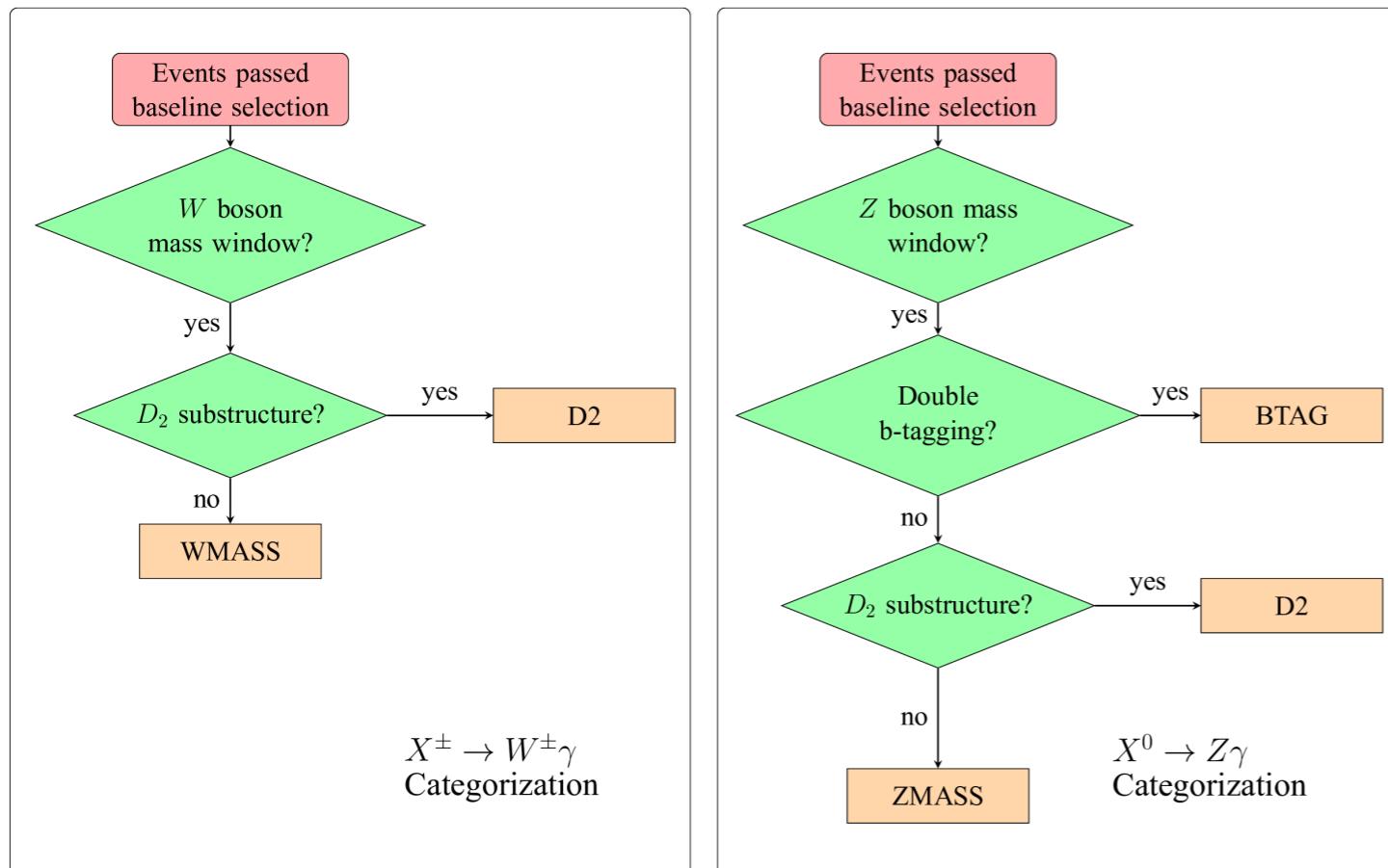
- 2D scan of resonance mass and width/coupling in $\gamma\gamma$ spectrum
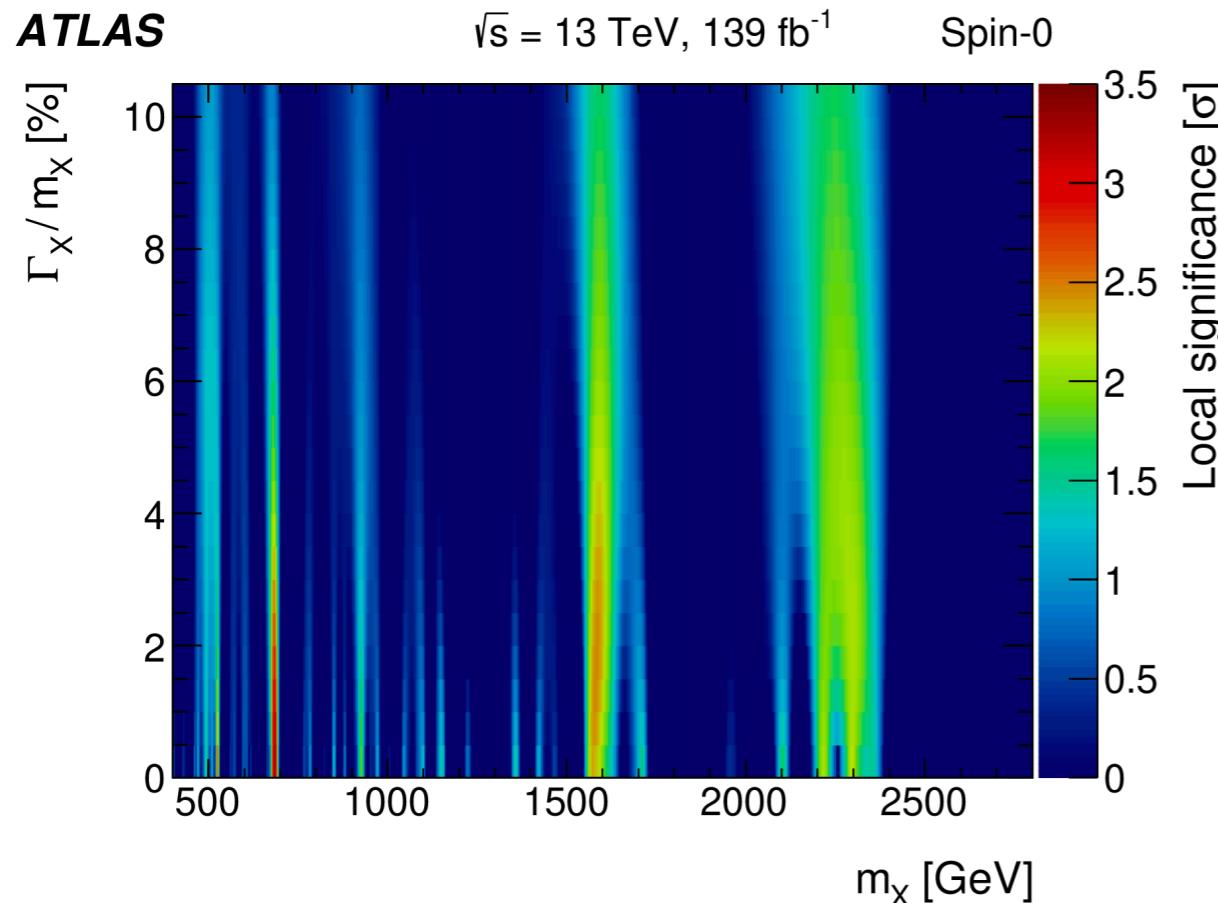
Largest local (global) significance for
m_X ~ 684 GeV and narrow width
approximation → 3.29(1.30)σ
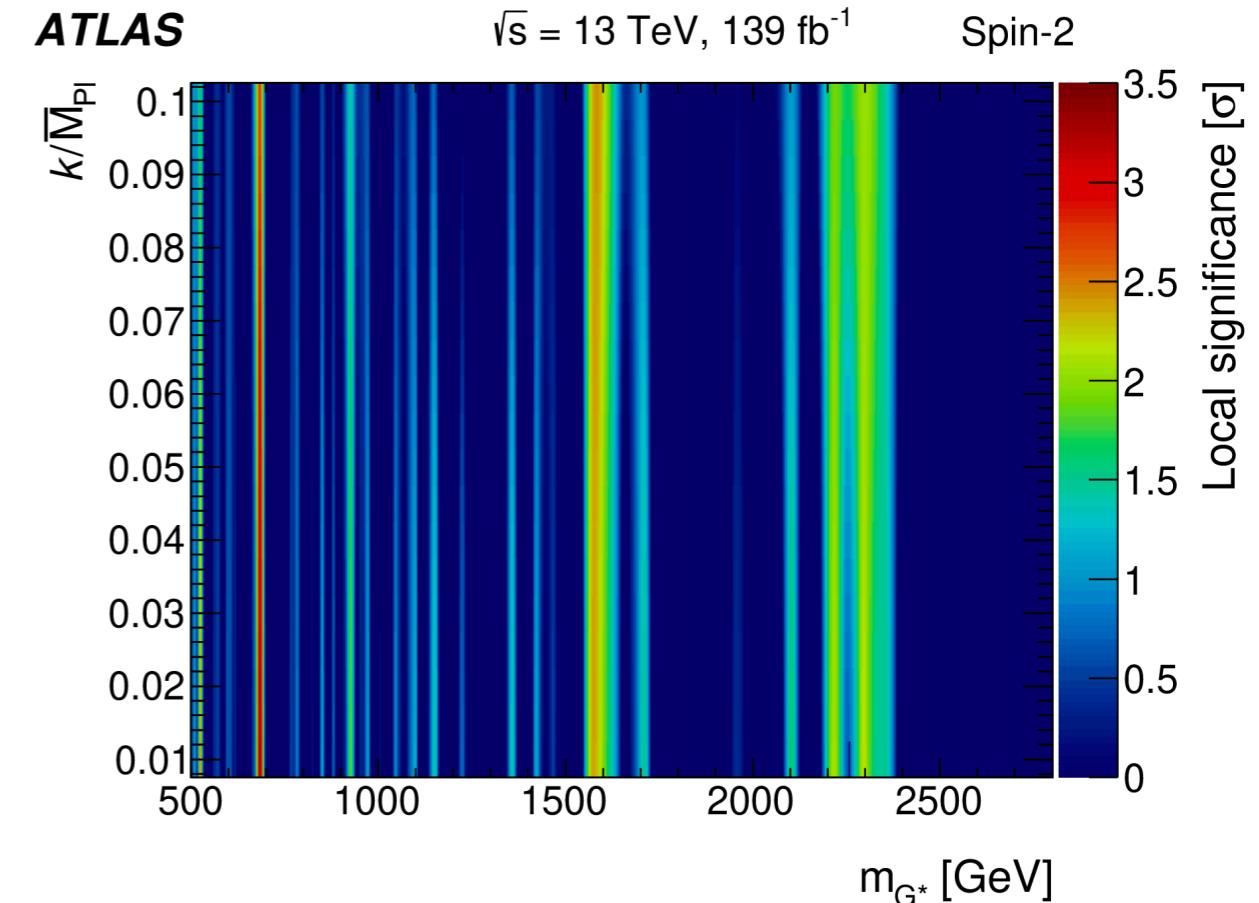
Largest local (global) significance for
m_X ~ 684 GeV and $k/\overline{M}_{Pl}$ = 0.01
→ 3.29(1.36)σ

# Light H from SUSY cascade decays

Post-Fit search region yields

$H \rightarrow hh_S \rightarrow \tau\tau bb$ with $m_h = 125$ GeV
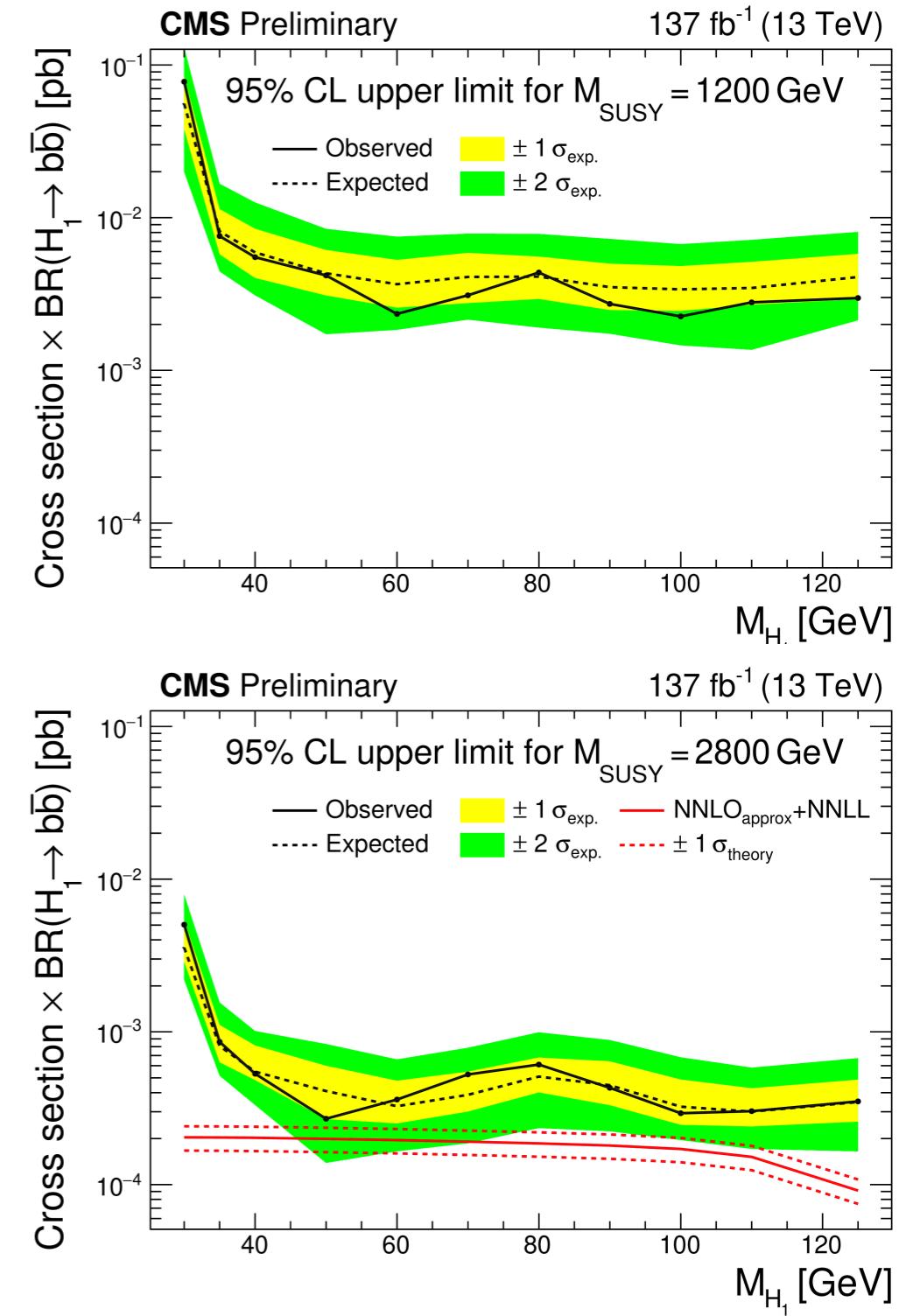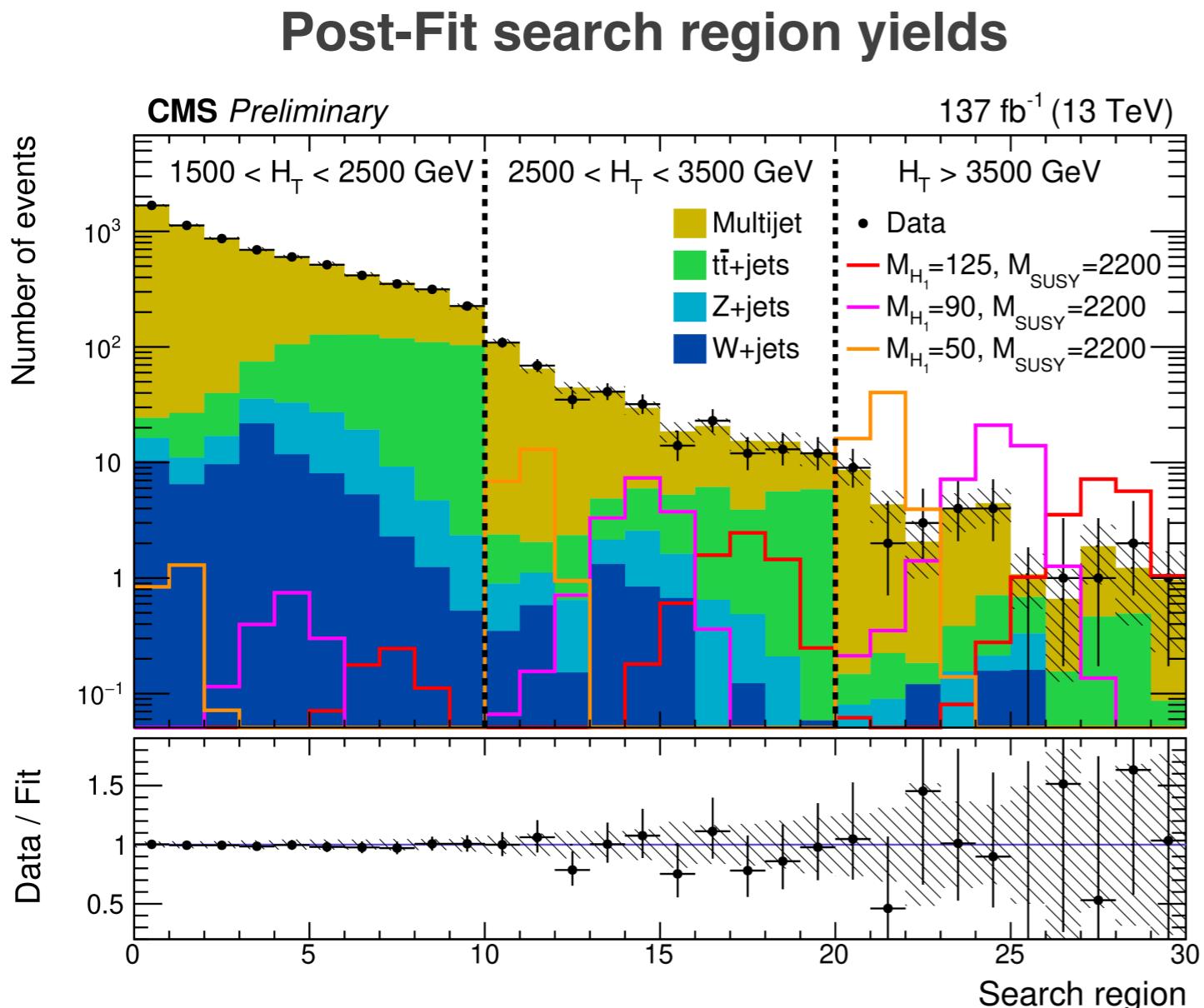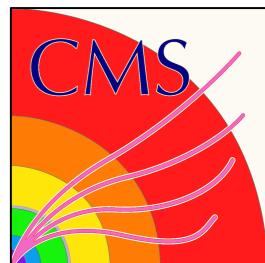
Grouping of signal samples for the NN training
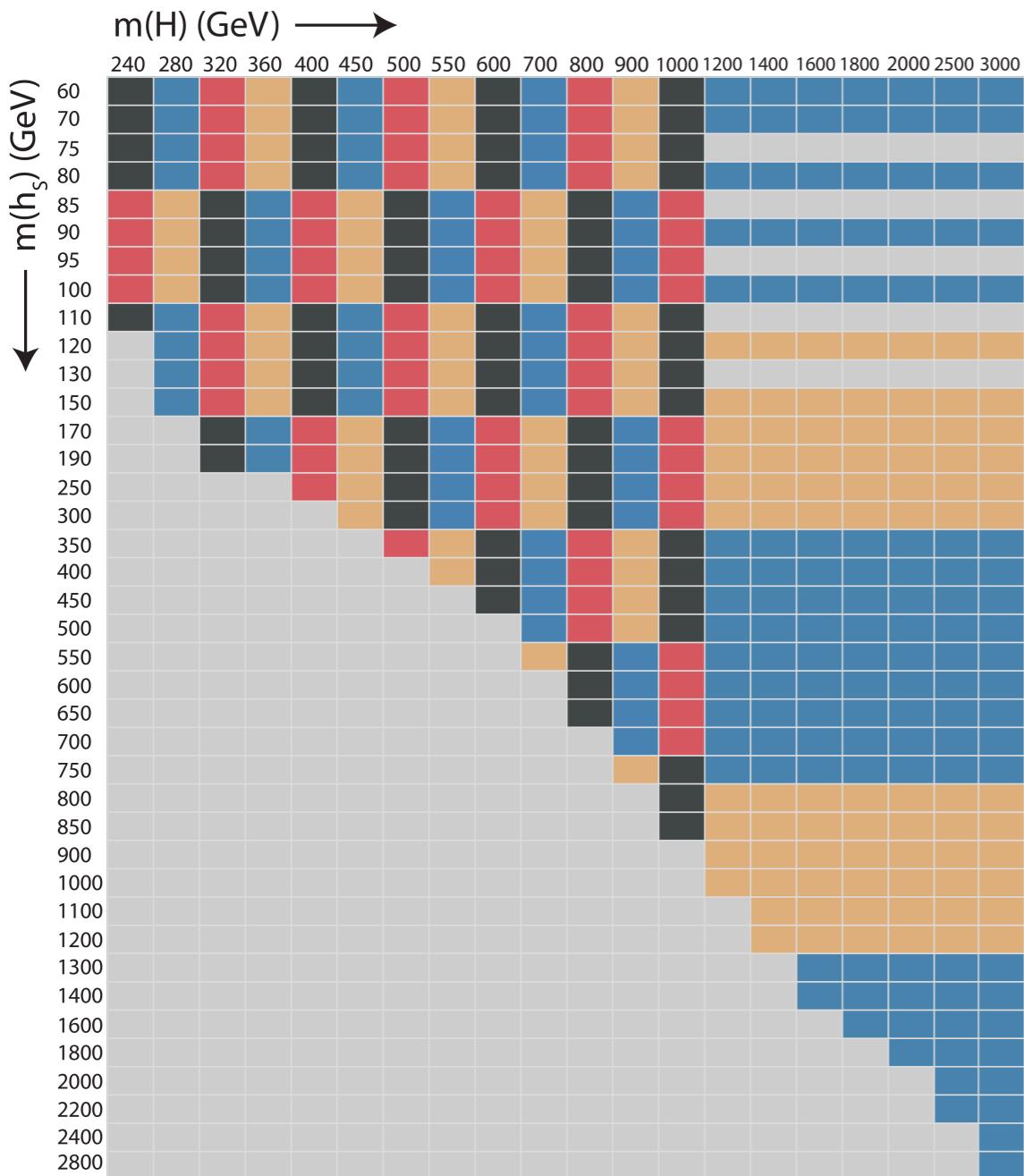
jet $\rightarrow \tau_h$ misidentification rate estimation technique

$$N_{SR} = N_{AR}(\text{data}) \cdot F_F$$

$$F_F = \sum_{i = \{QCD,W,tt\}} \text{frac}^i \cdot F_F^i$$

🔷 **Fermilab**