Searches for BSM Higgs at ATLAS

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on behalf of the ATLAS collaboration

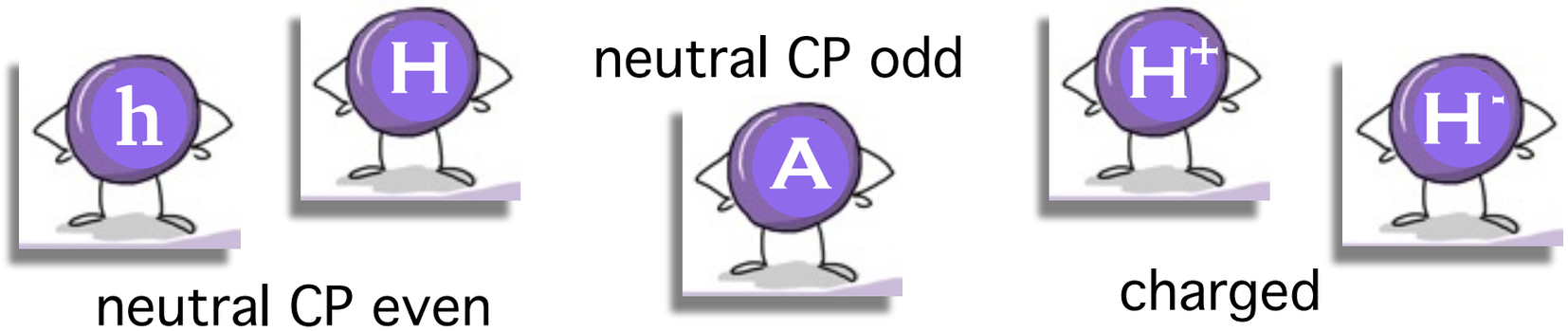
Introduction

- Is h(125 GeV) THE Higgs boson or A Higgs boson?
- Extended Higgs sectors common to many Beyond-the-Standard-Model (BSM) theories
  - E.g. SUSY, dark matter, axions, baryogenesis models …

2HDM = 2 Higgs Doublets Model

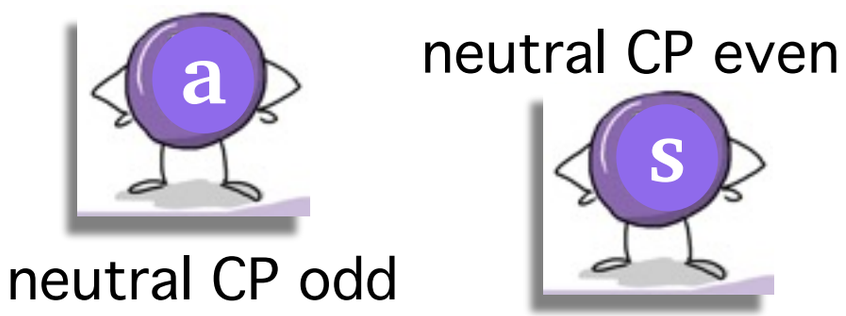
- add another SU(2) Higgs doublet to the SM

- 5 physical states:
  (CP conserving case)



2HDM + S (singlet)

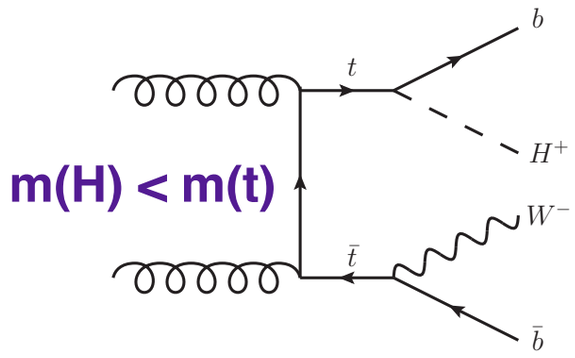
- 2 additional physical states:
  - ➡ Possibly light ($m < m_h$)
  - ➡ e.g. NMSSM

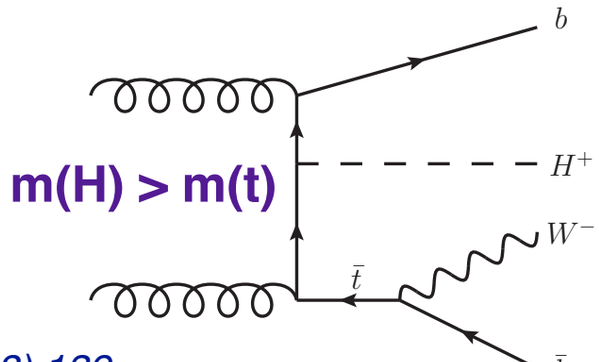


Charged Higgs

- Searches in 2 channels:

H→τν





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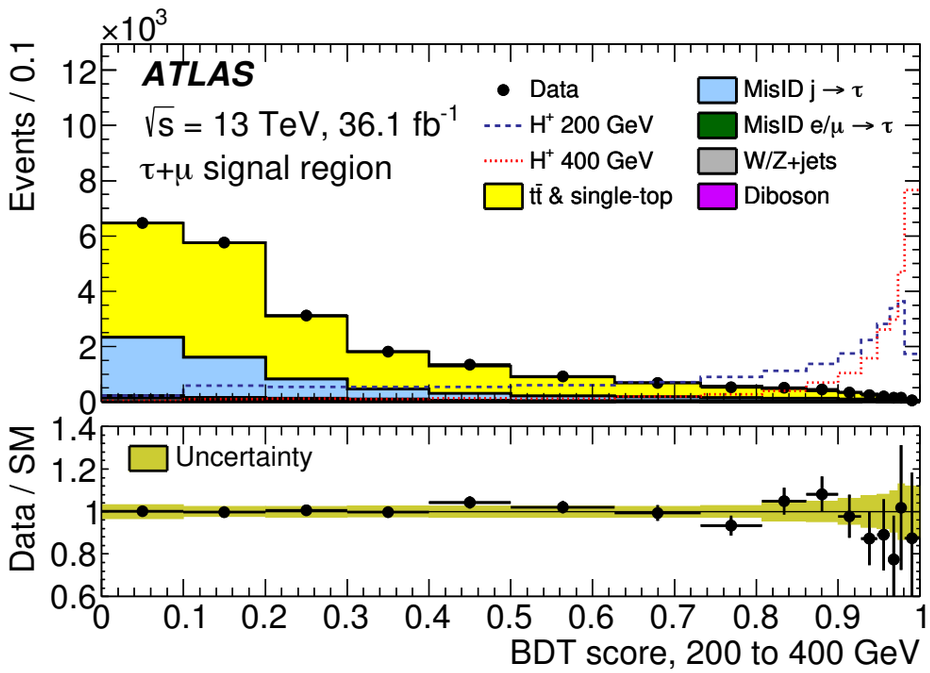
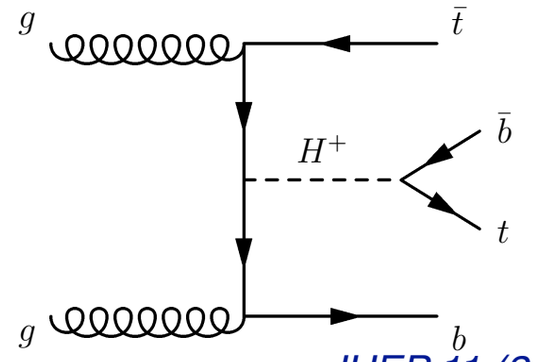
- Tau polarisation used to discriminate between $t \to bH^+$ and $t \to bW$:

$$\Upsilon = \frac{E_{\mathrm{T}}^{\pi^\pm} - E_{\mathrm{T}}^{\pi^0}}{E_{\mathrm{T}}^{\tau}} \approx 2\frac{p_{\mathrm{T}}^{\tau\text{-track}}}{p_{\mathrm{T}}^{\tau}} - 1$$

Asymmetry between charged and neutral pions



H→tb



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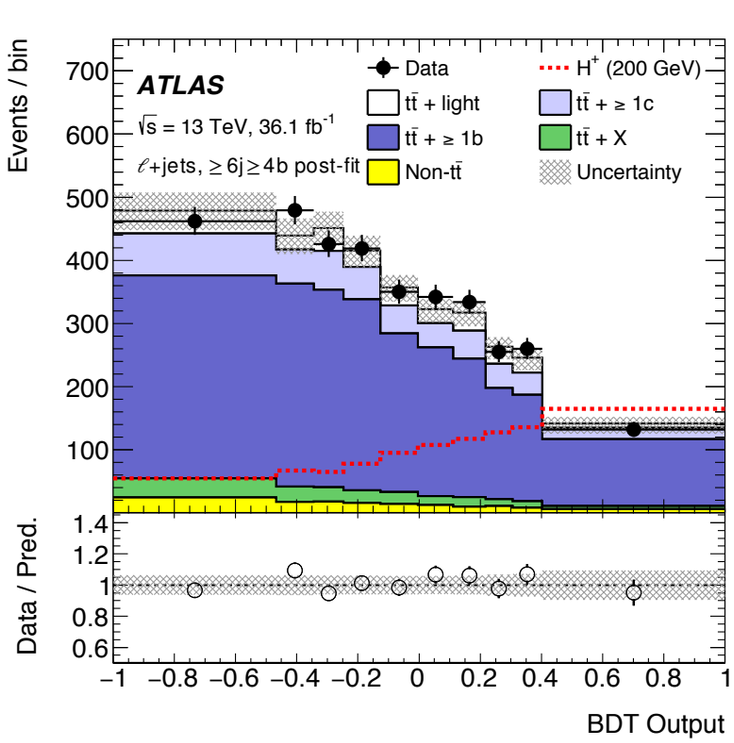
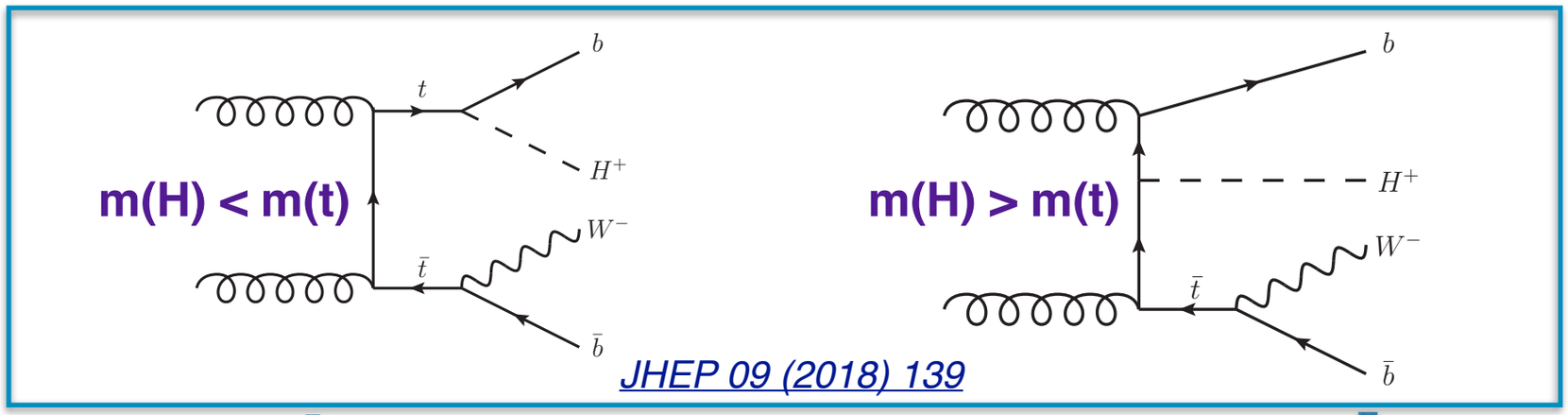


- Both analyses use BDT to discriminate between the signal and the SM backgrounds

Charged Higgs

- Searches in 2 channels: **H→τν** **H→tb**



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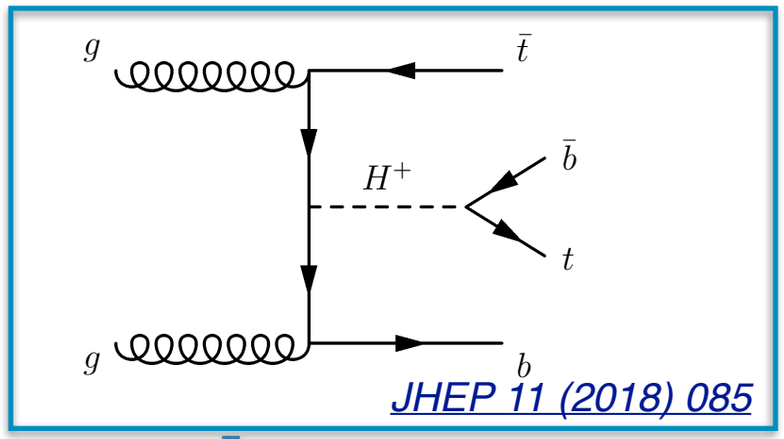

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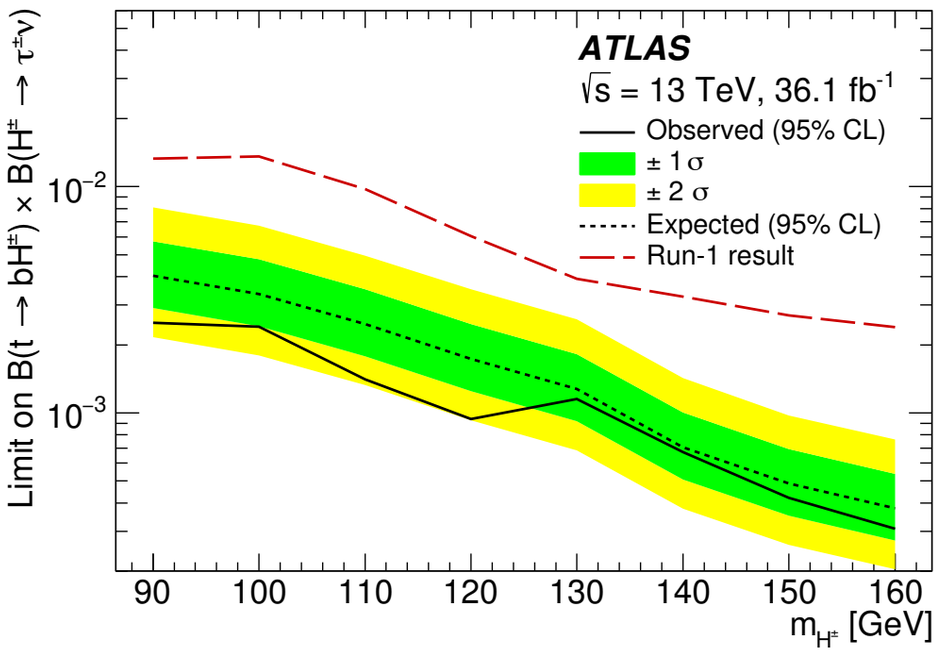
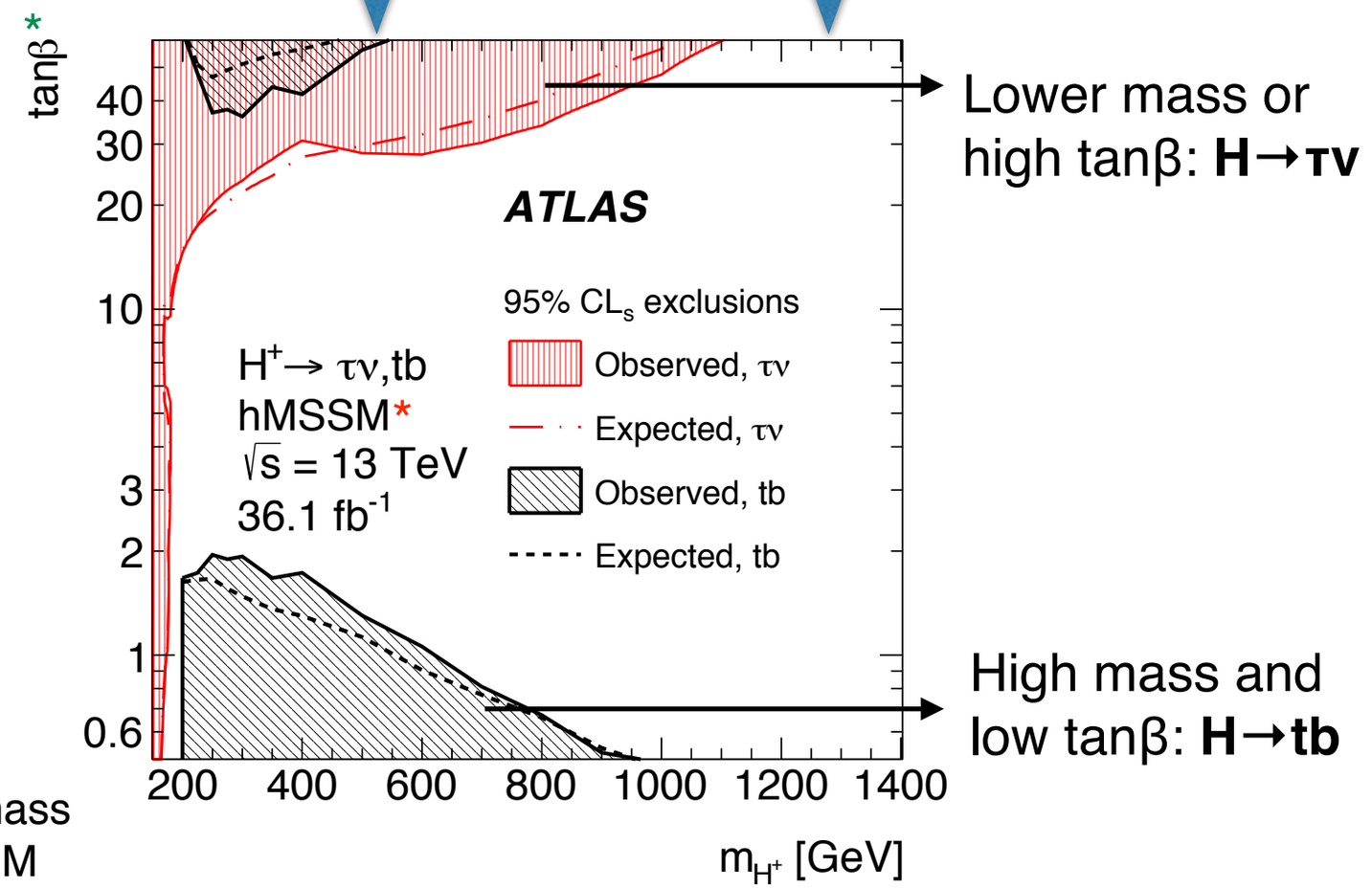




Lower mass or high tanβ: **H→τν**

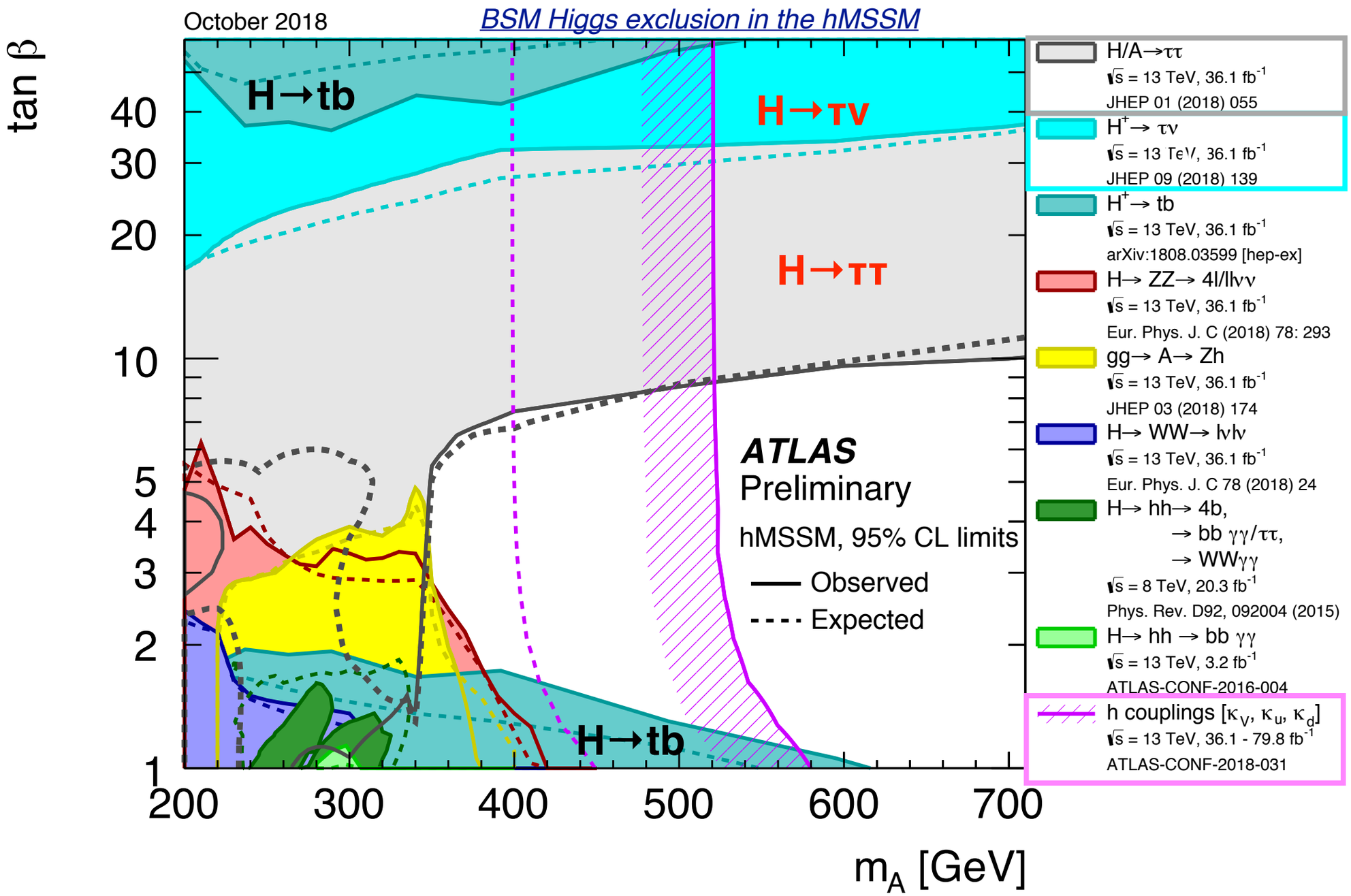
High mass and low tanβ: **H→tb**

*tanβ = ratio of VEVs of the 2 H-doublets

*hMSSM: h(125) is the lightest CP-even H and its mass is used to predict the masses and couplings of MSSM

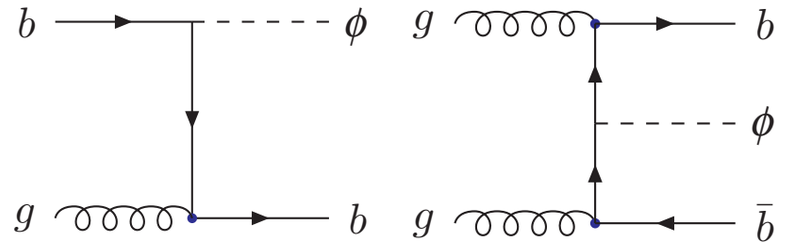
Limits in hMSSM

- h(125) couplings combinations set the lower limit on m_A at ~540 GeV
- **$H^+ \to \tau\nu$** and **$H/A \to \tau\tau$** extend the limit on m_A to above 1 TeV values for large tanβ



H→bb

- Search for b-associated heavy neutral H production
- Purely b-jets final state, multi-jet backgrounds challenging!
- Uses b-tagging both online (trigger) and offline



- **Limits in hMSSM comparable to $H^+ \to \tau\nu$, but not as good as $H/A \to \tau\tau$**

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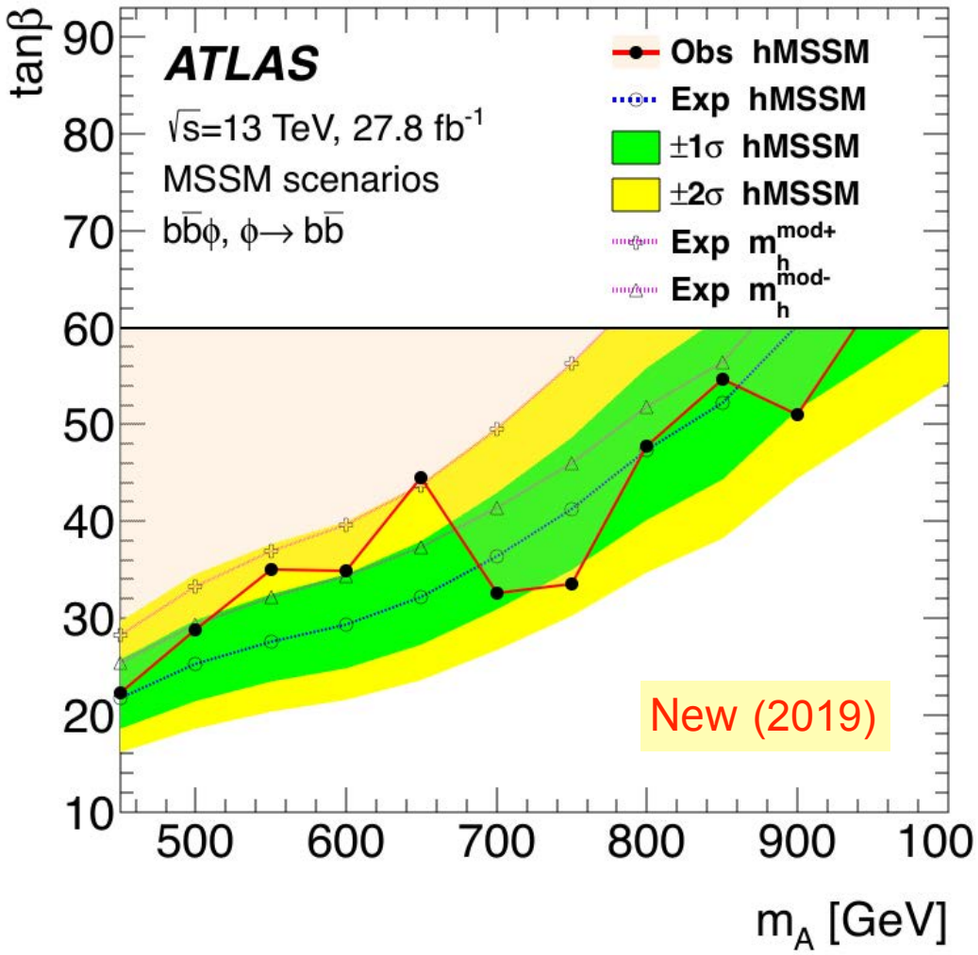
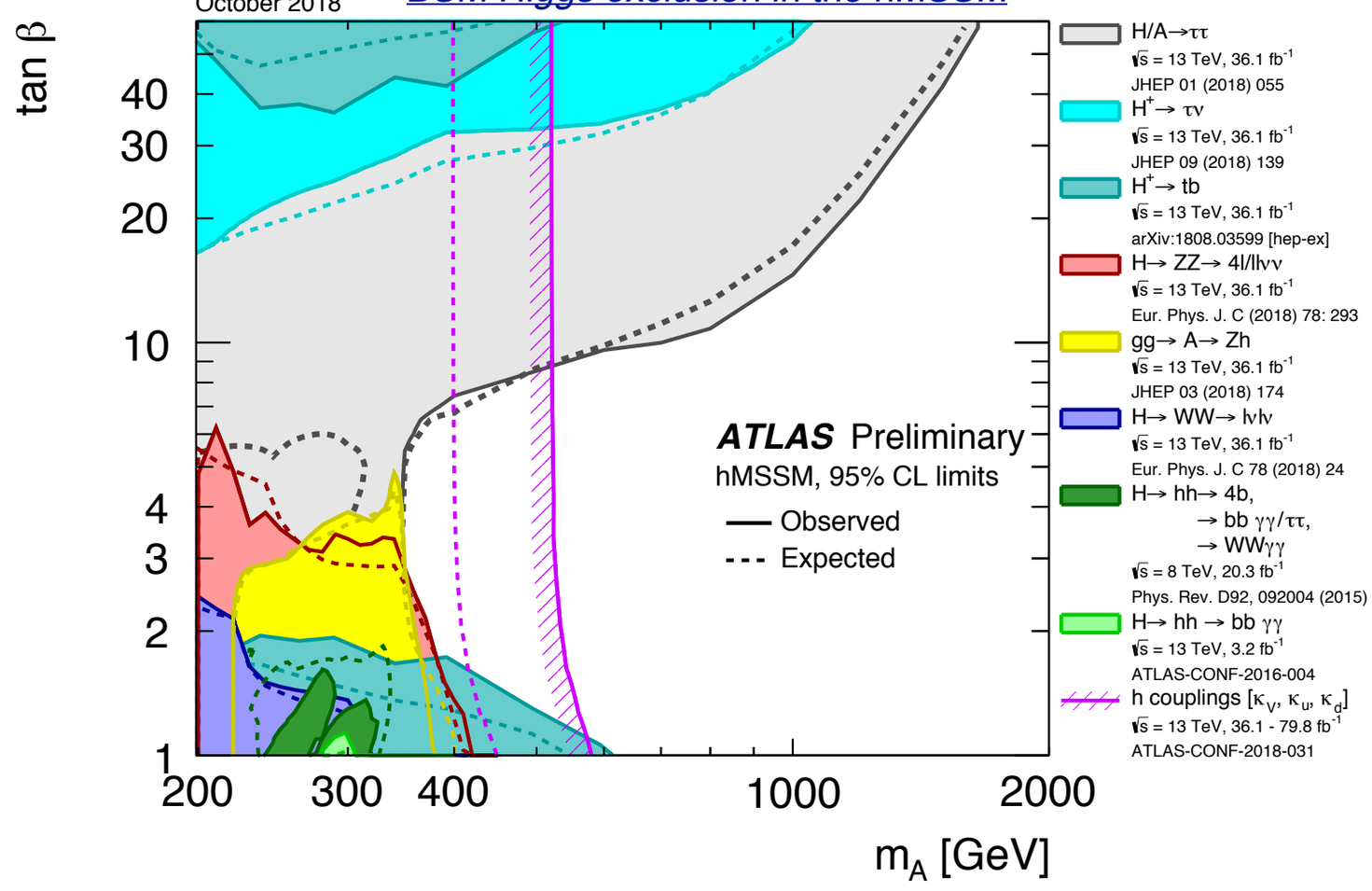
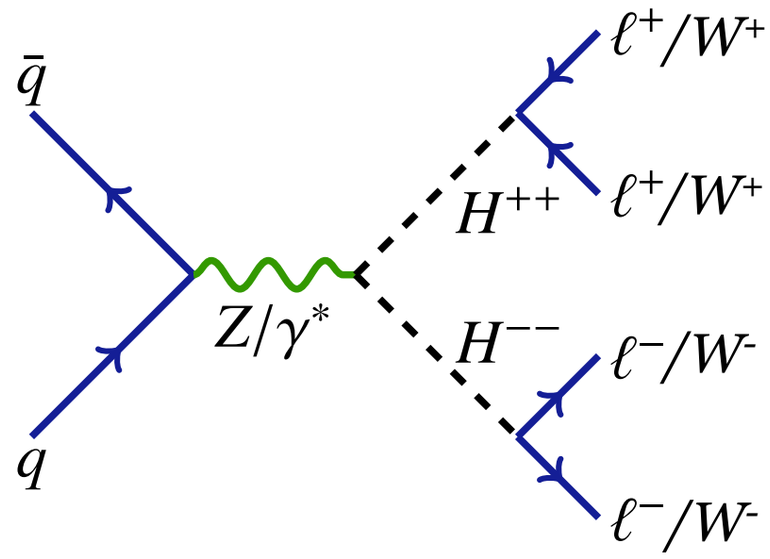


BSM Higgs exclusion in the hMSSM

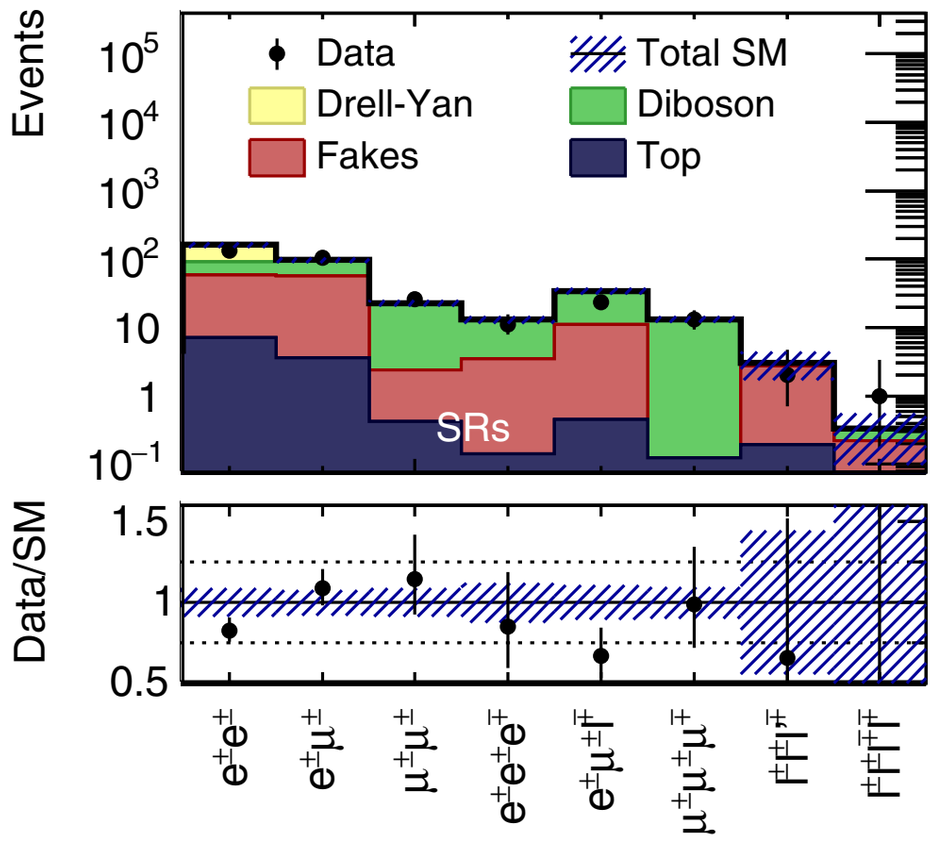


Doubly charged H

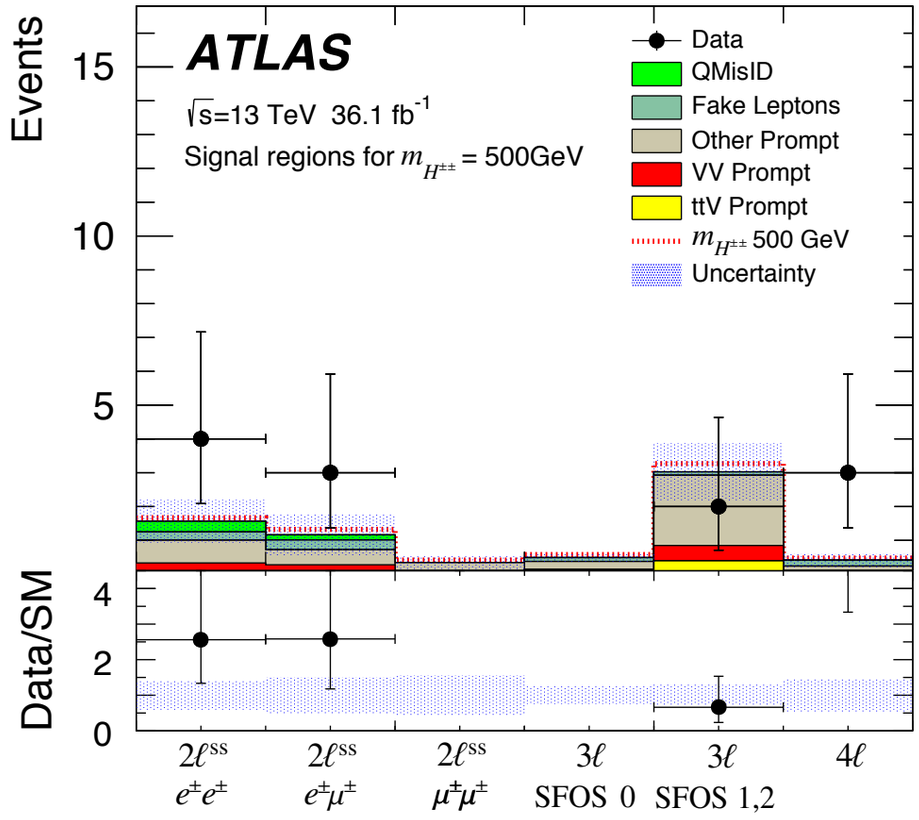
- Scalar triplet (e.g. Type II seesaw models), in addition to the SM scalar doublet
  - 7 physical states, including doubly charged H bosons
  - Depending on the VEV of the triplet, **$H^{++/--}$ can decay preferentially to leptons or to W-bosons**
- Multiple signal regions with varying number of leptons



$H^{++} \to \ell^+\ell^+$ *Eur. Phys. J. C (2018) 78:199*



$H^{++} \to W^+W^+$ *Eur. Phys. J. C (2019) 79: 58*



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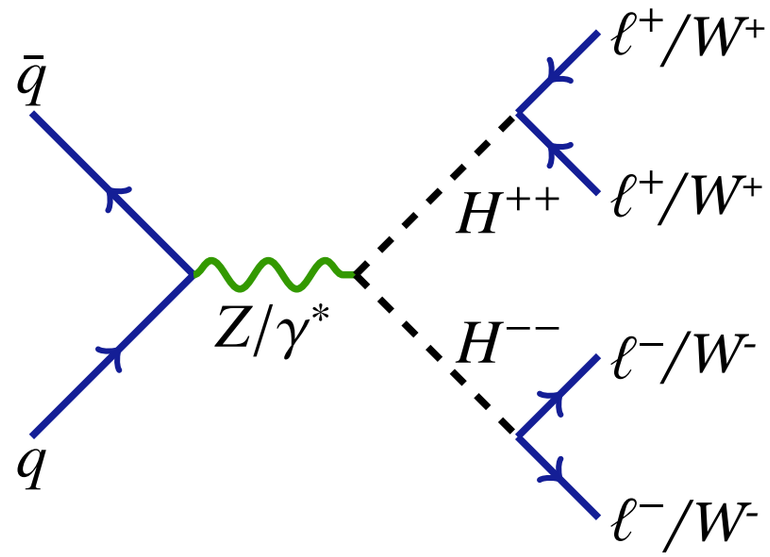
  - 7 physical states, including doubly charged H bosons
  - Depending on the VEV of the triplet, **$H^{++/--}$ can decay preferentially to leptons or to W-bosons**
- Multiple signal regions with varying number of leptons
- No significant deviations from the SM observed



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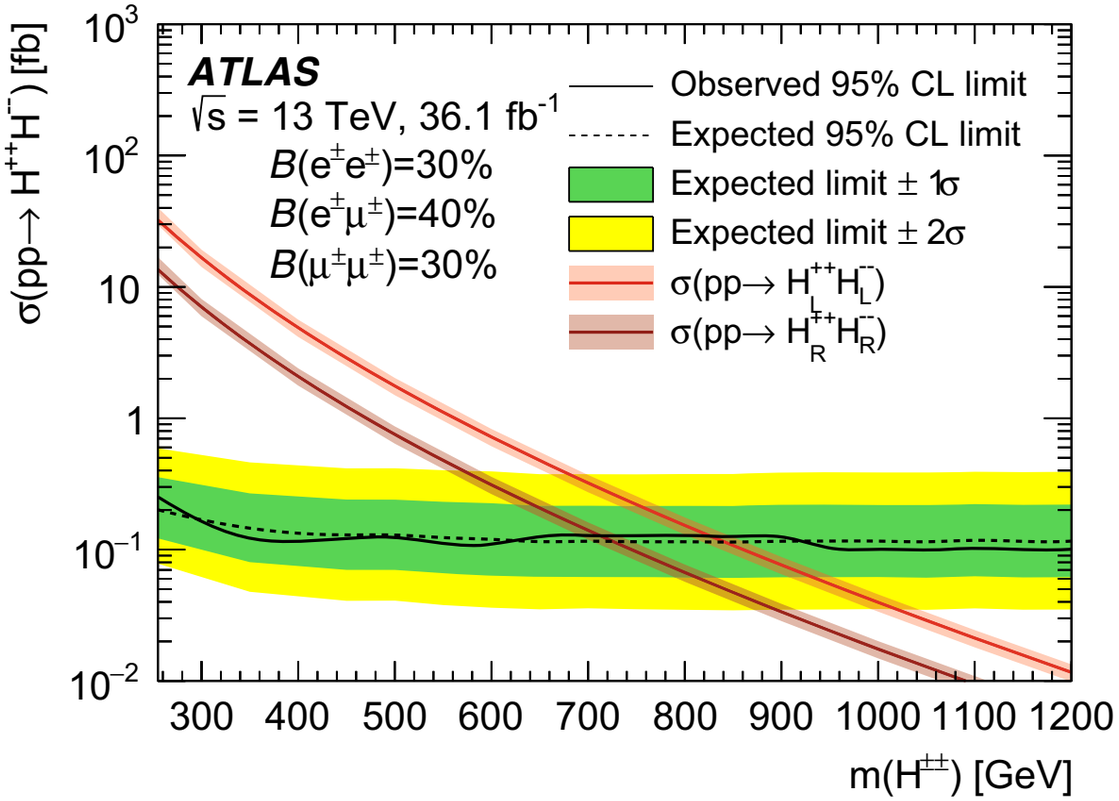

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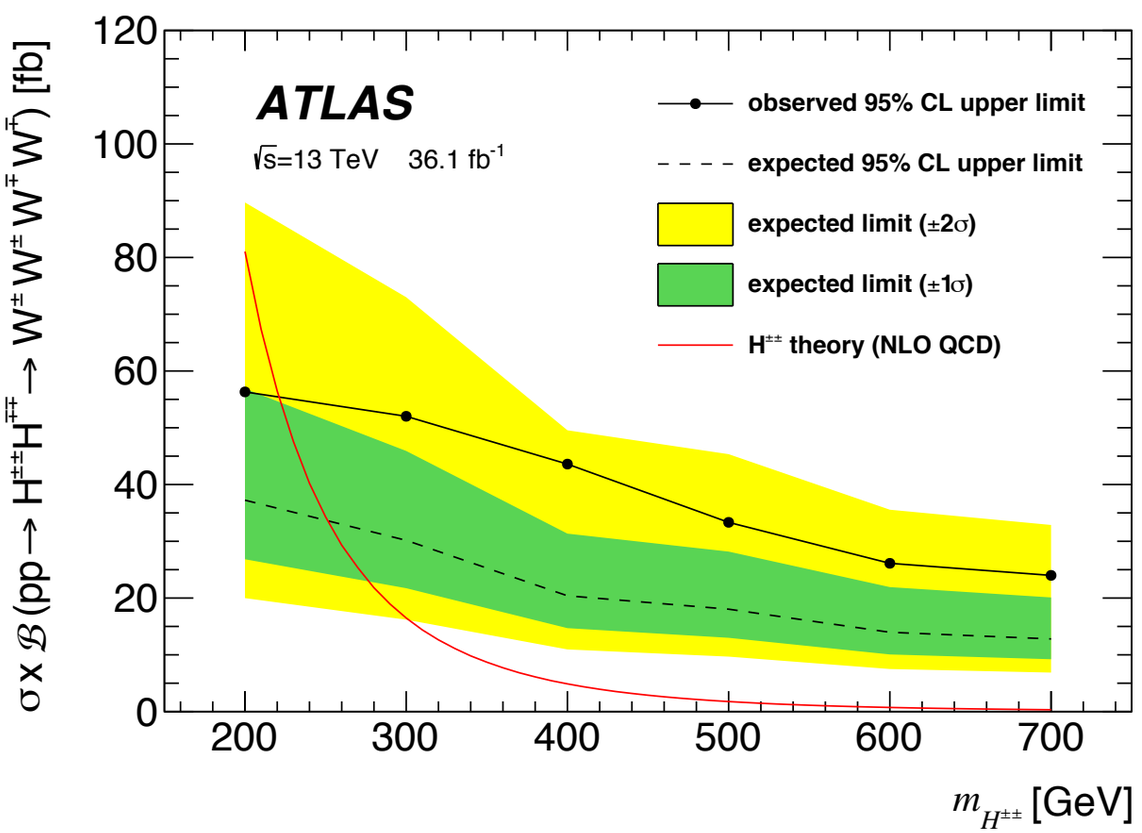

Exotic Higgs decays

- Current constraint from fits to SM Higgs couplings: **Br(h→BSM) < 47%** at 95% CL

➡Still a lot of space for new physics in Higgs decays!

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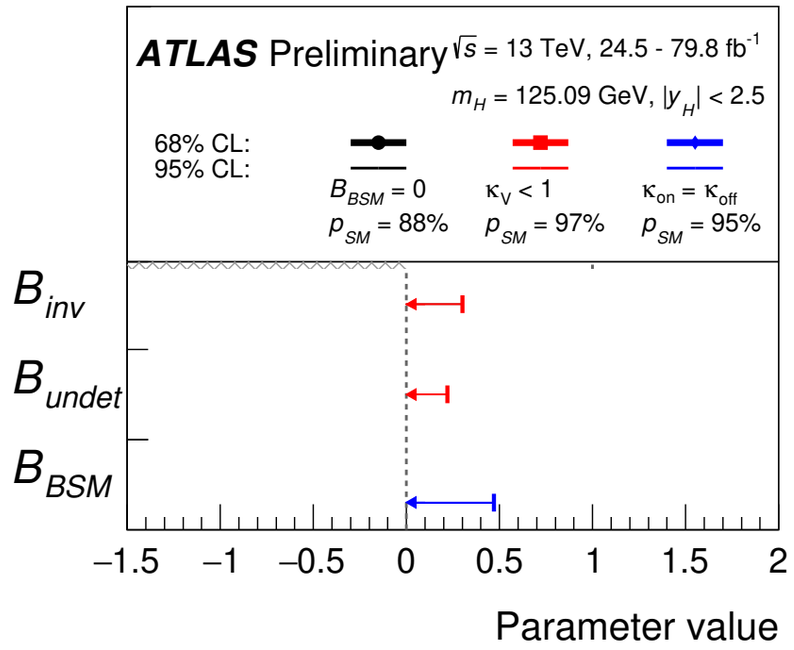
- **New physics could couple to the SM only through Yukawa couplings**

Standard Model: SU(3)xSU(2)xU(1)

mediator

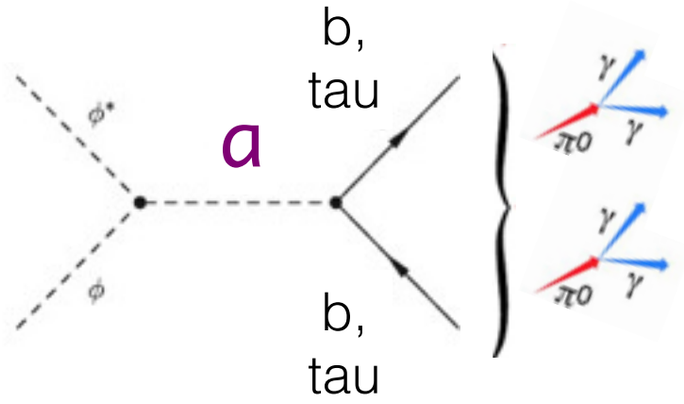
a

Hidden sectors: no SM charges DM?



- Excess of gamma-rays (E ~ 1-3 GeV) coming from the centre of the galaxy observed by the Fermi-LAT telescope *(ArXiv: 1511.02938)*

➡ Could be a result of DM annihilations through a light (pseudo)scalar mediator



h→aa→4b

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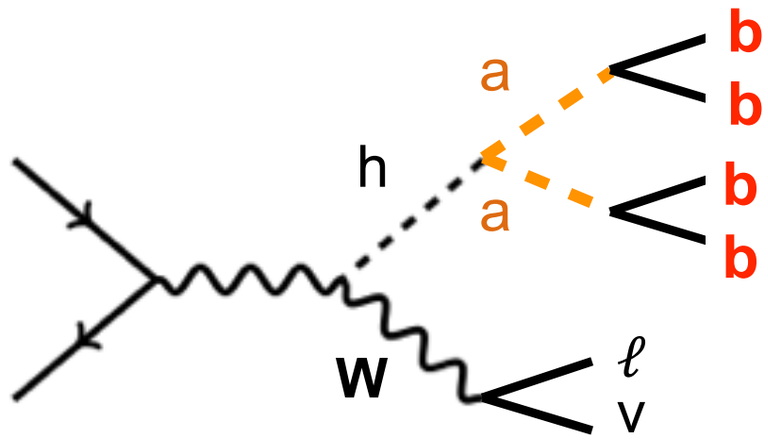
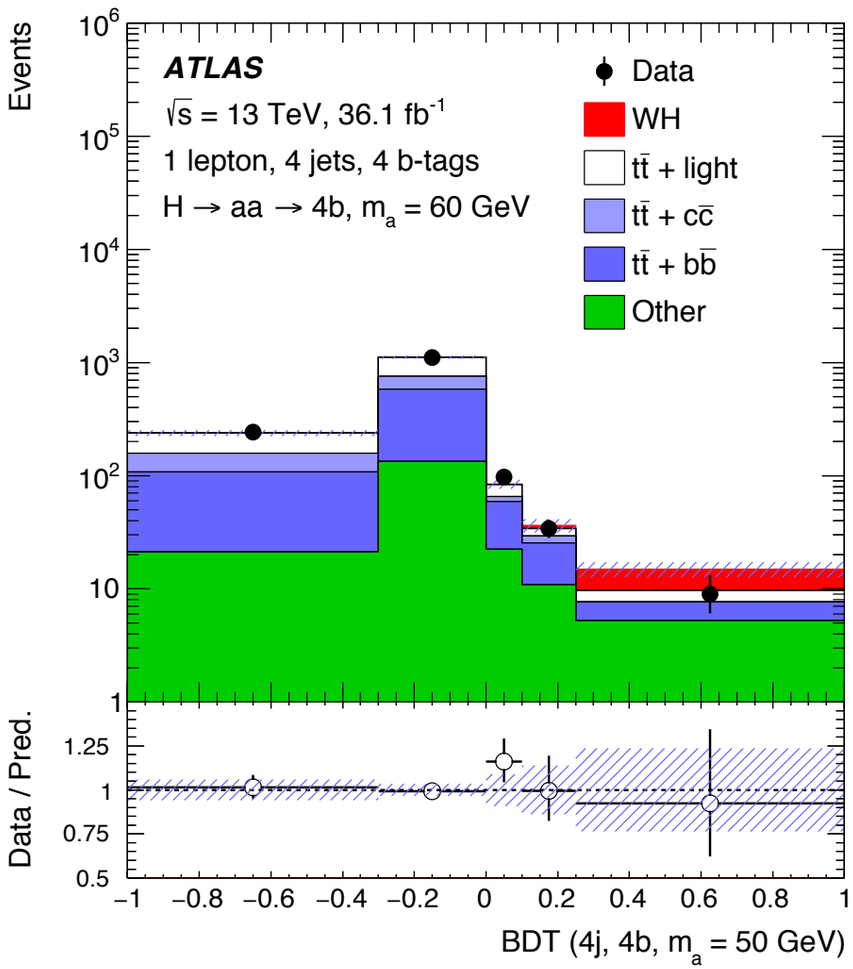
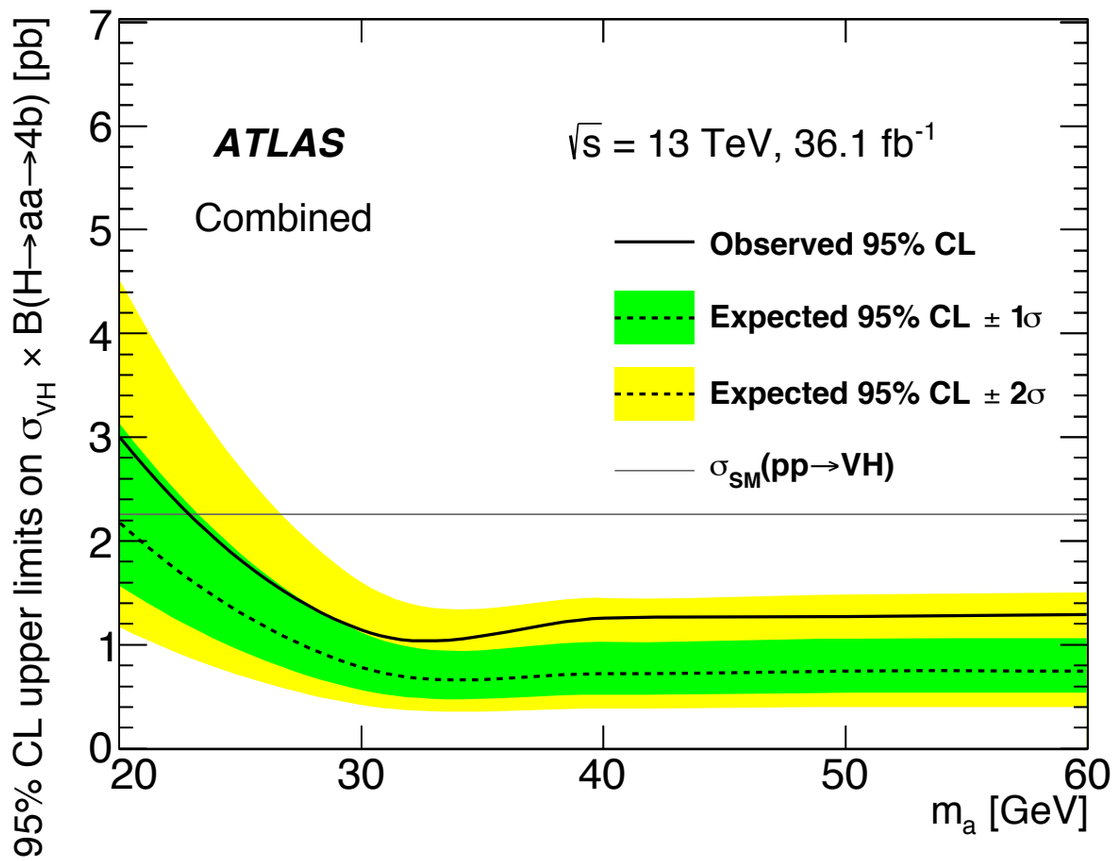
- **Look for W/Z associated production**
  - Trigger on leptons from W/Z decays
  - Suppresses multijet backgrounds
- **BDT discriminant to separate the signal from the SM backgrounds** (tt & DY+jets)







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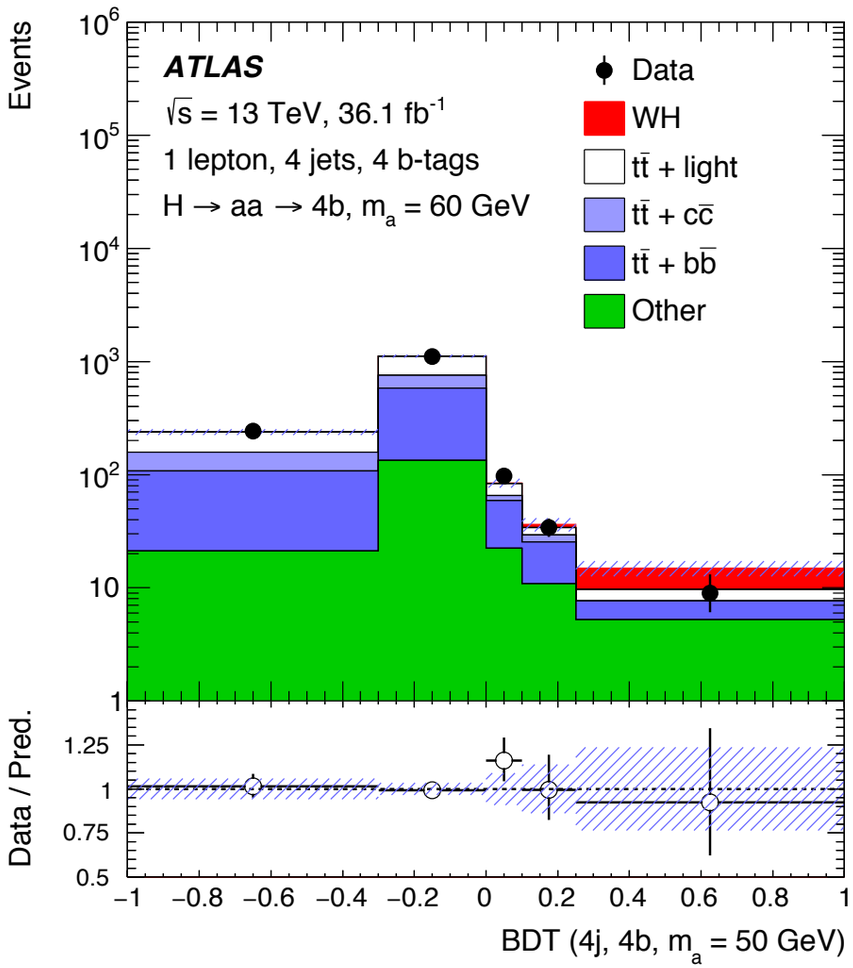
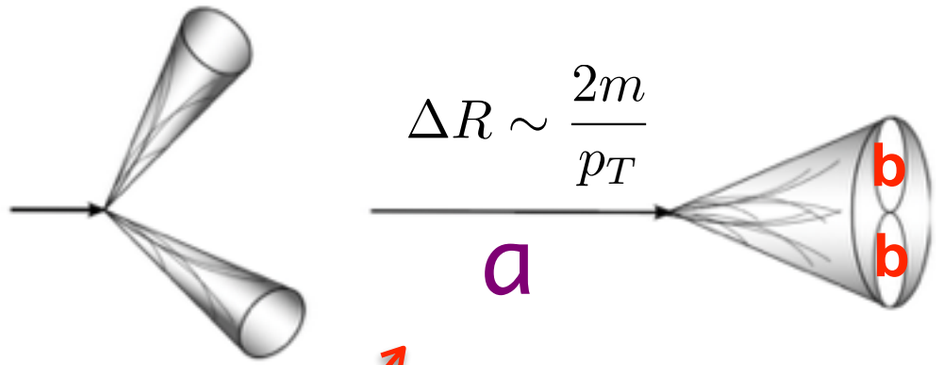
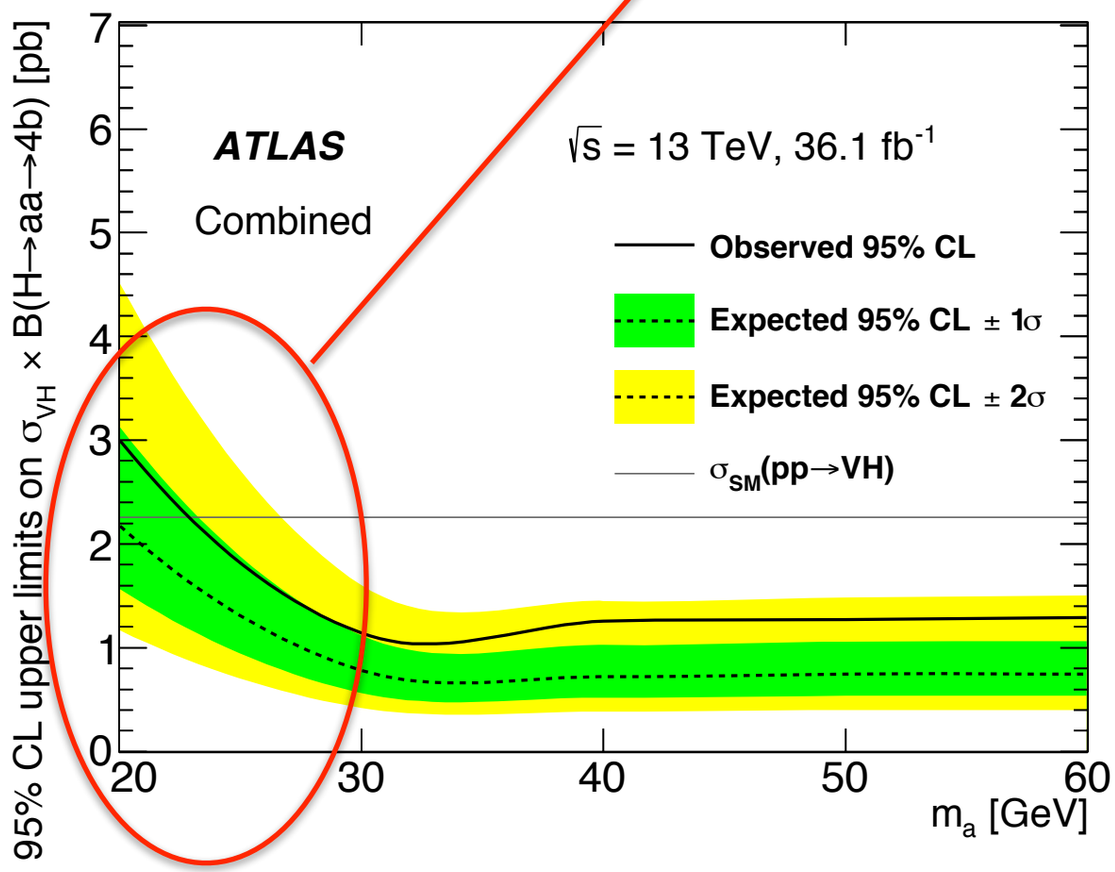


when $m_a << m_H$:
jets from a-decays become collimated

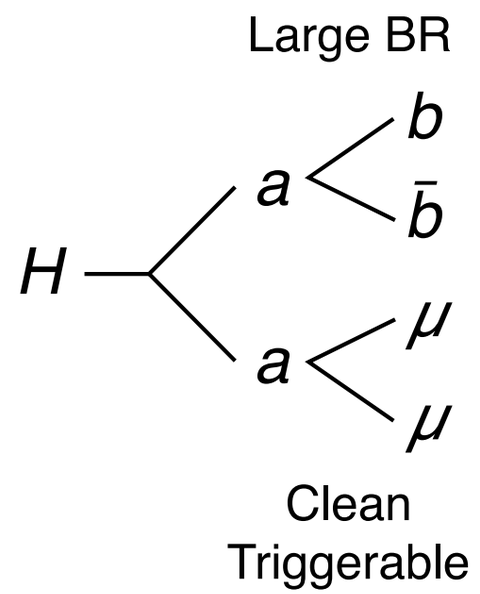


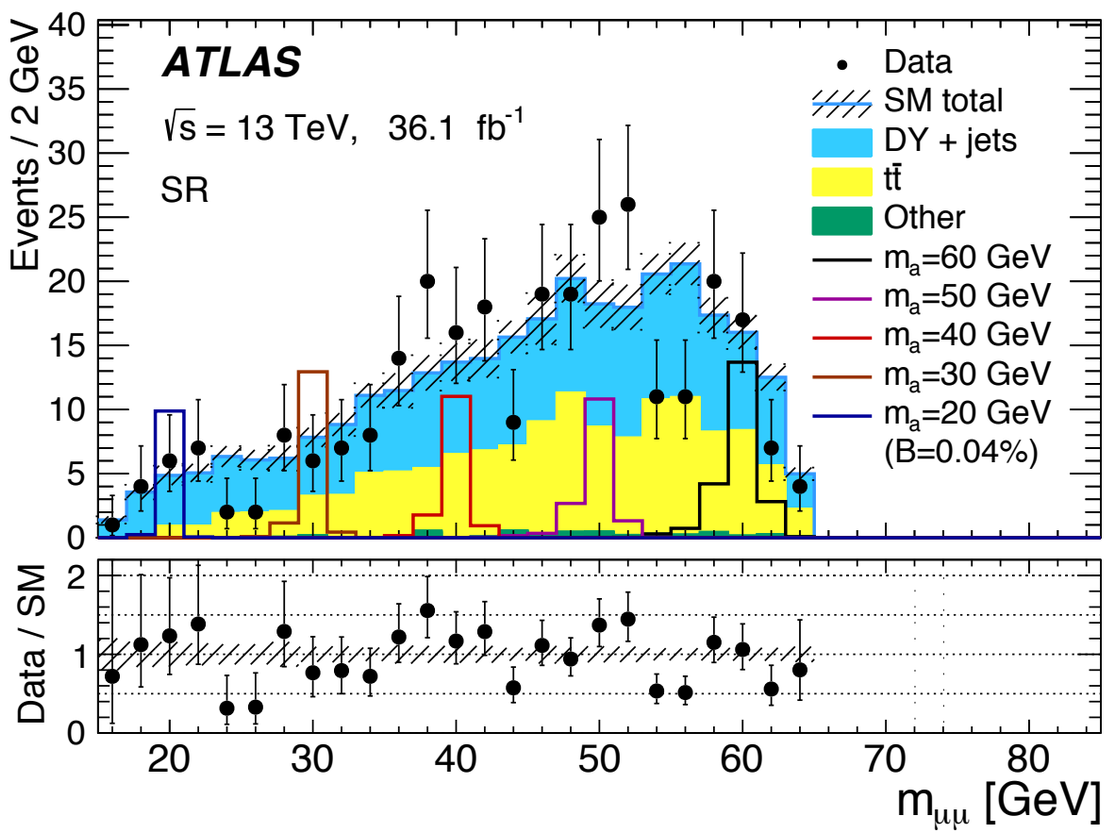


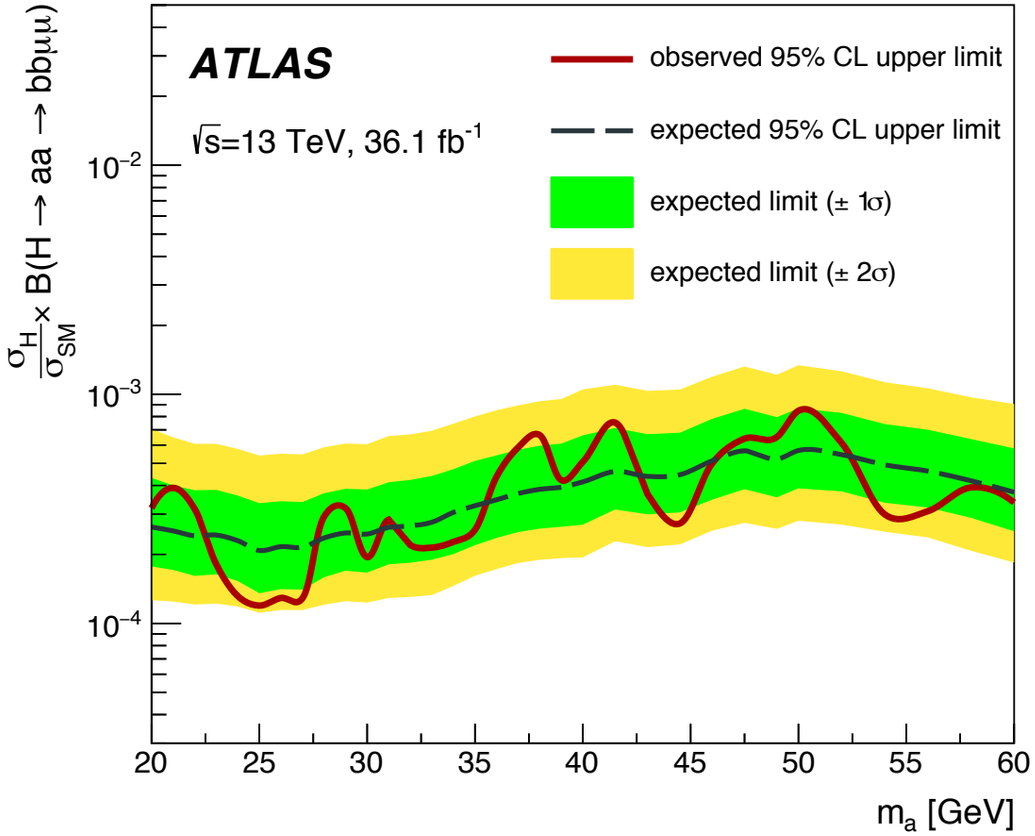
h→aa→2b2μ

[Phys. Lett. B 790 (2019) 1](#)

- **Target ggF Higgs production** (the largest production cross-section)
  - Trigger on muons from the signal decay
- Dominant backgrounds:
  - Drell-Yan + jets: data-driven template
  - tt: MC simulation normalized to the data in the control region
- **Look for narrow peak in $m_{\mu\mu}$ spectrum**

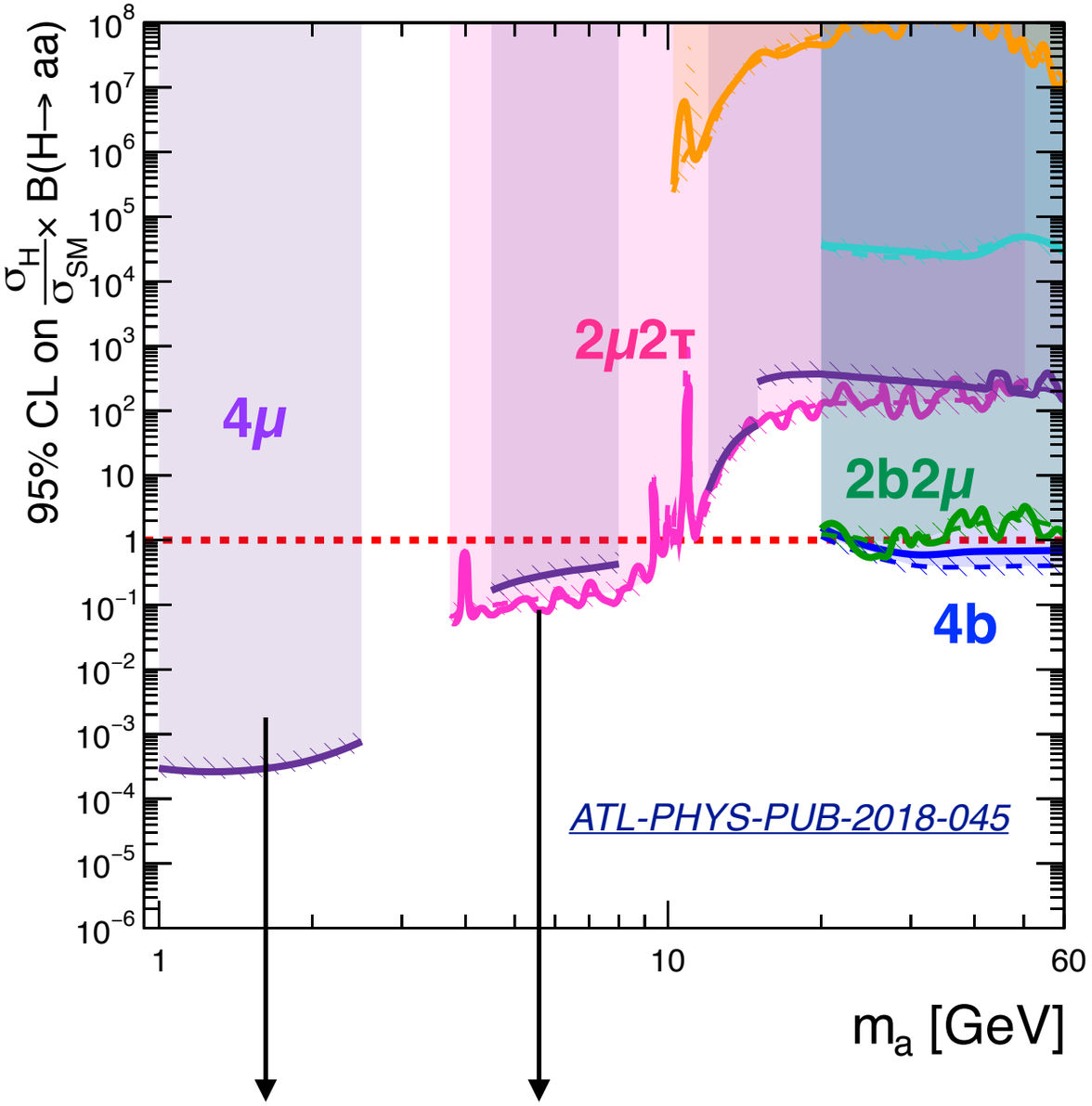






h→aa summary

- Model independent limits on Br(h→aa→xx yy) translated into limits on Br(h→aa) under the assumption of a particular 2HDM+S scenario that determines Br(aa→xx yy)



ATLAS Preliminary

Run 1: $\sqrt{s}$ = 8 TeV, 20.3 fb^{-1}
Run 2: $\sqrt{s}$ = 13 TeV, 36.1 fb^{-1}

2HDM+S Type-II, tanβ = 2 → E.g. NMSSM

expected ± 1 σ
observed

Run 1 H→ aa→ μμττ
arXiv: 1505.01609

Run 1 H→ aa→ γγγγ
arXiv: 1509.05051

Run 2 H→ aa→ μμμμ
arXiv: 1802.03388

Run 2 H→ aa→ γγjj
arXiv: 1803.11145

Run 2 H→ aa→ bbbb
arXiv: 1806.07355

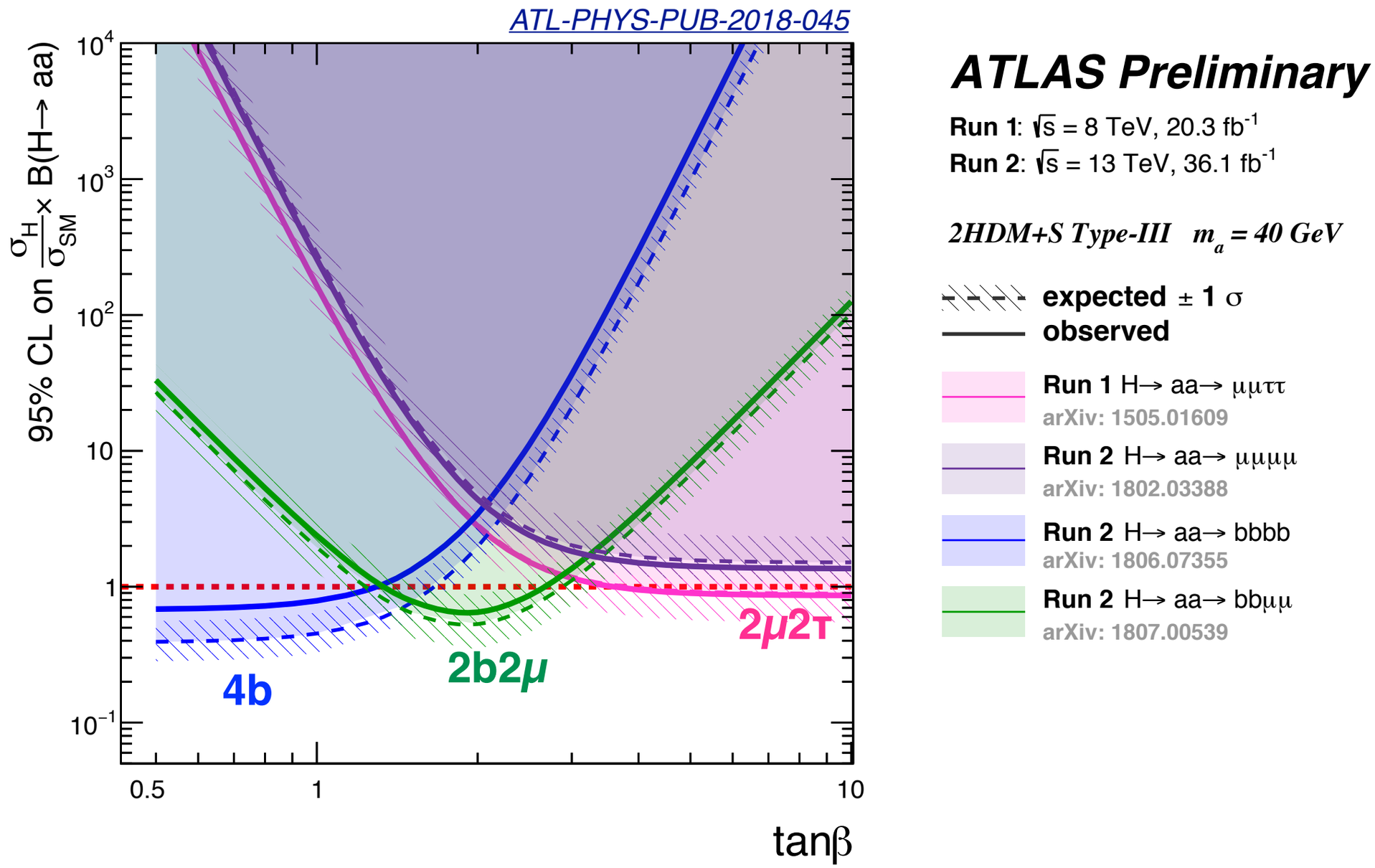
Run 2 H→ aa→ bbμμ
arXiv: 1807.00539

→ H→aa→gg γγ motivated for a fermiophobic "a"

H→aa→4μ & H→aa→ 2μ2τ important for $m_a < 2m_b$

h→aa summary

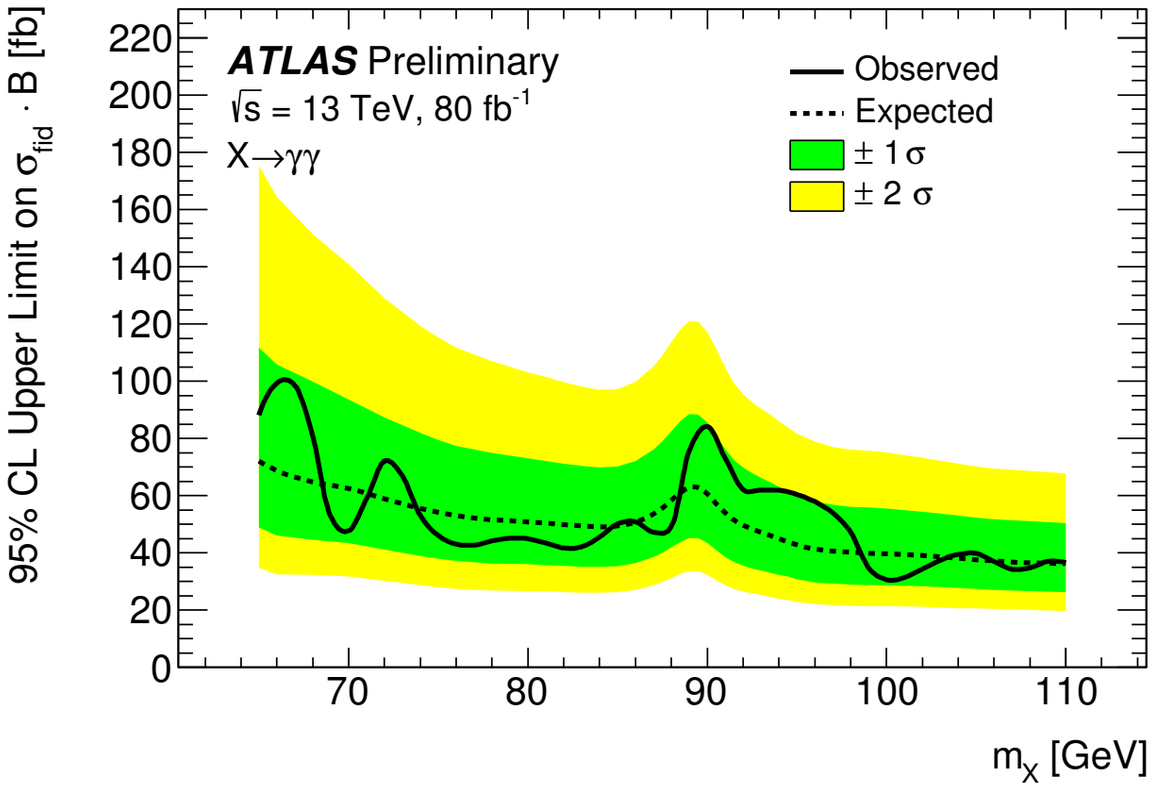
- Couplings depend on tanβ
  - ➡ **Different channels important at different values of tanβ**
- Searches nicely complementary



$H \rightarrow \gamma\gamma$

- **Search for an additional Higgs boson in 65-110 GeV mass range**
- Main backgrounds:
  - Continuum: γγ, γj, jj (jets misidentified as photons)
  - $Z/\gamma^* \rightarrow e^+e^-$ (Drell-Yan): electrons reconstructed as photons

  ➡ Described with analytic functions validated on the data



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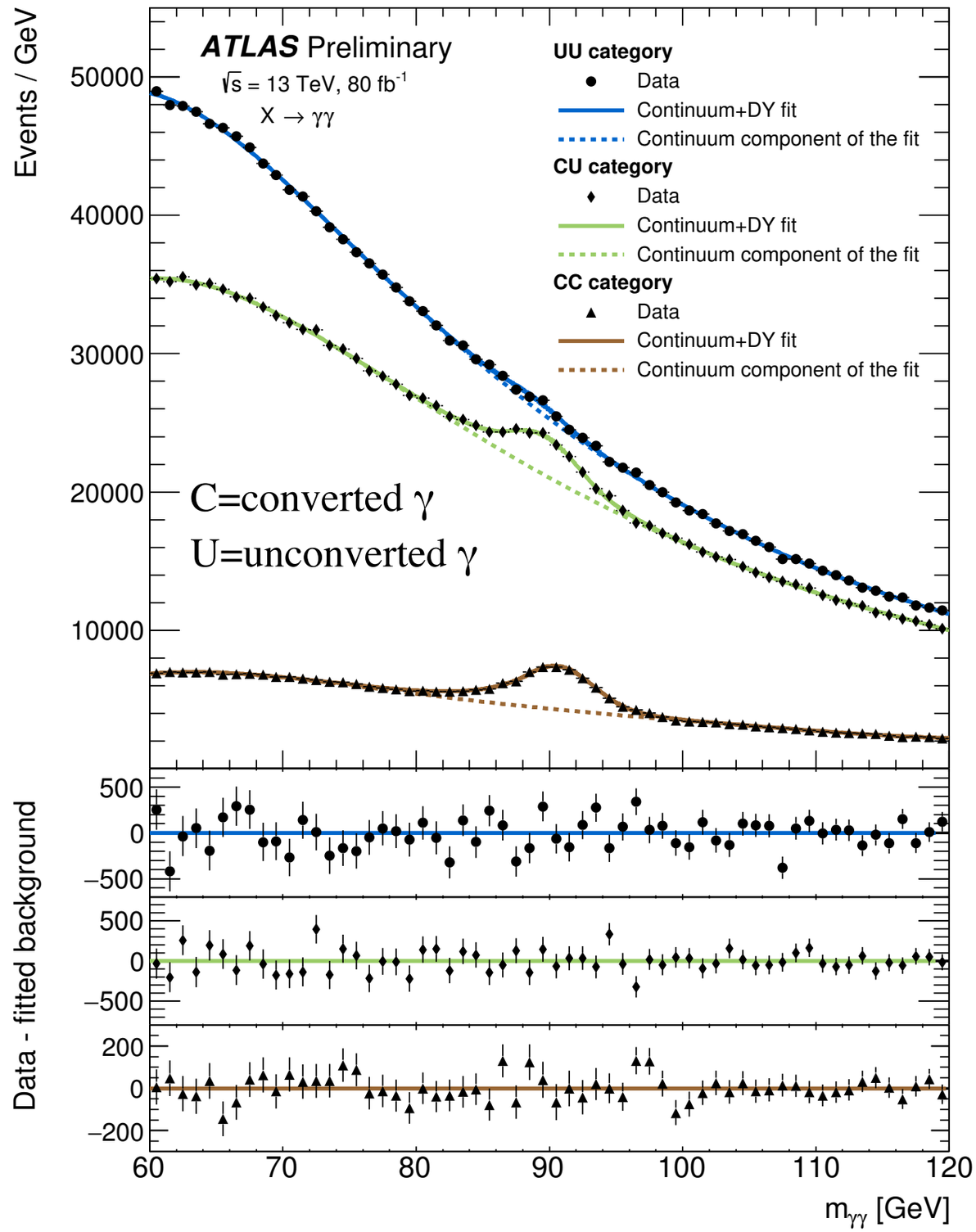
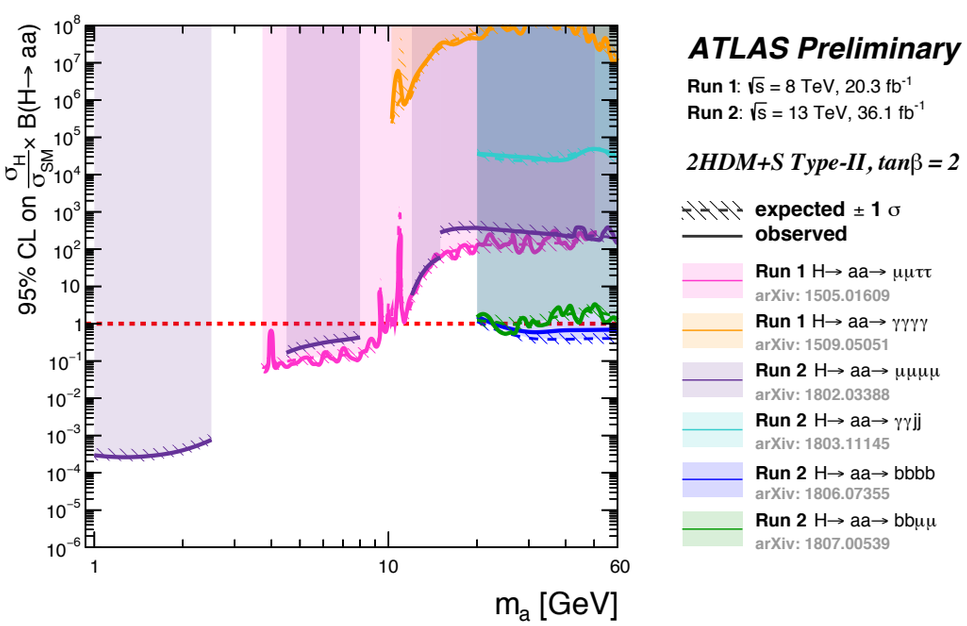


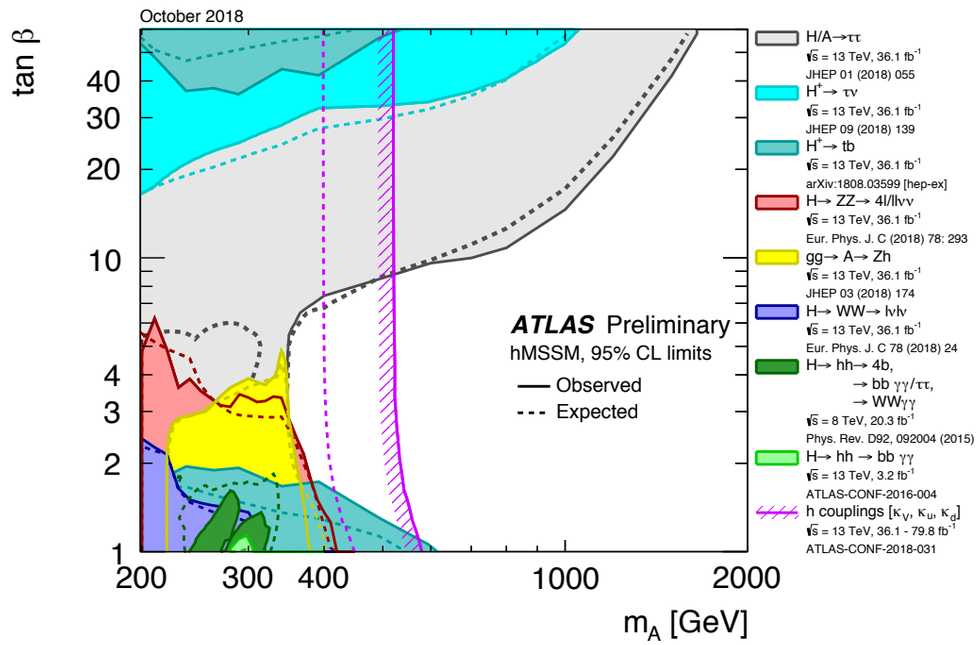
Summary

- Extensive searches for additional Higgs boson:
  - High/low-mass
  - Neutral, charged, doubly charged
  - Direct production or produced in h(125 GeV) decays

- No significant deviations from the SM predictions observed so far

- Many new results with the full Run 2 dataset (~140 fb^{-1}) coming out soon!

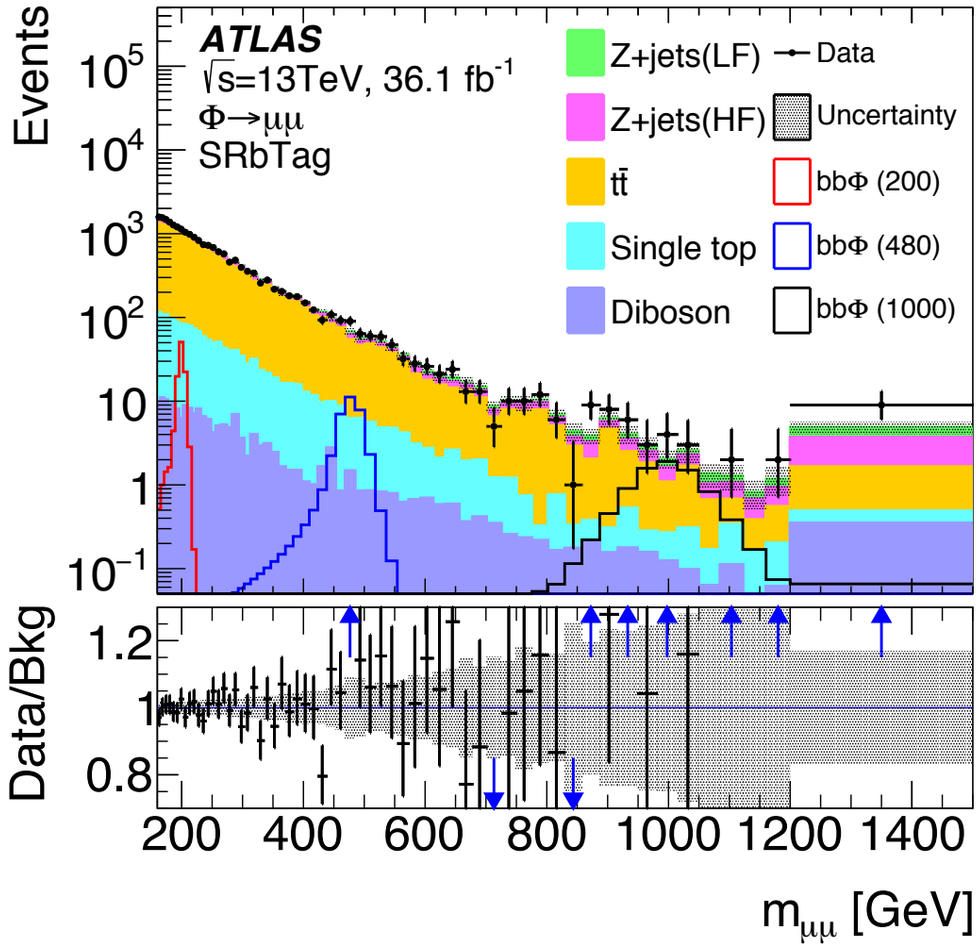


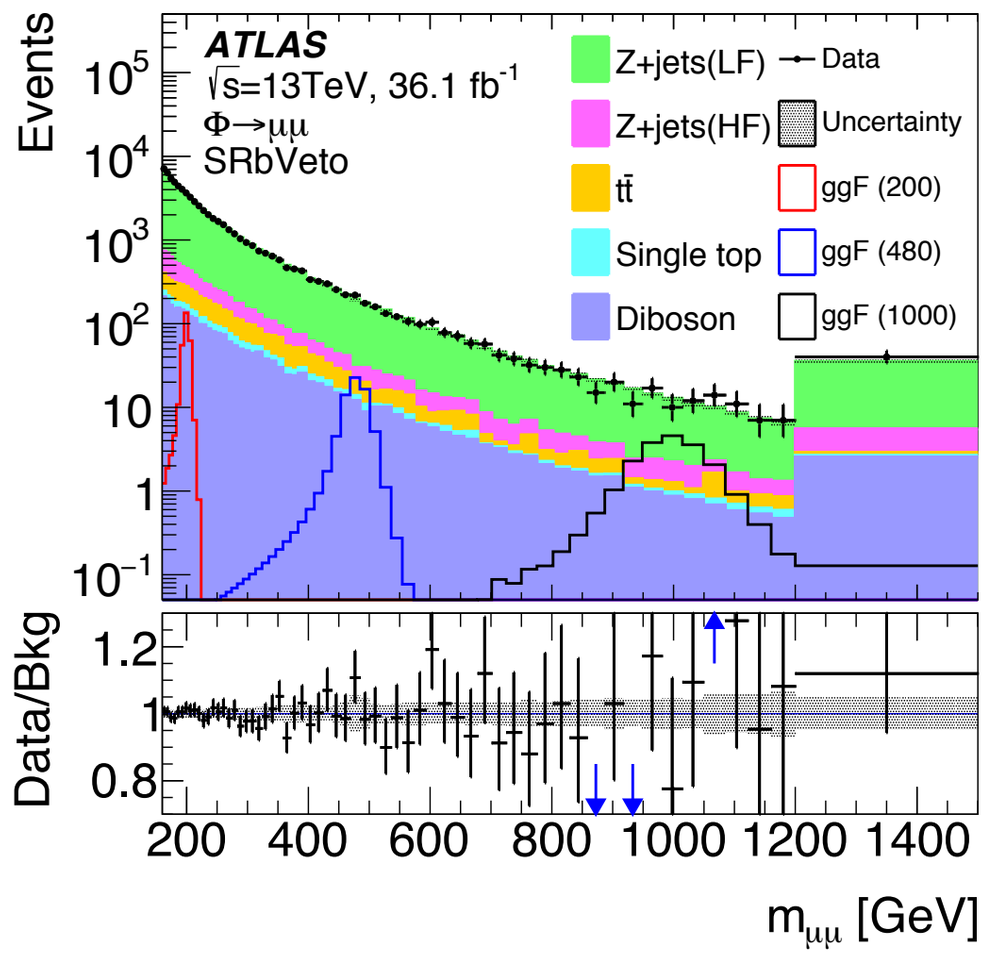


Backup

H→μμ

- In some models coupling to muons could be larger than coupling to taus (Flavourful Higgs model: *1610.02398*)
- Targeting both ggH & bbH production: 0 and >=1 b-tagged jet categories
- Dominant backgrounds: Z/y*+jets & tt
  - Modelled with MC simulation & normalized to the data





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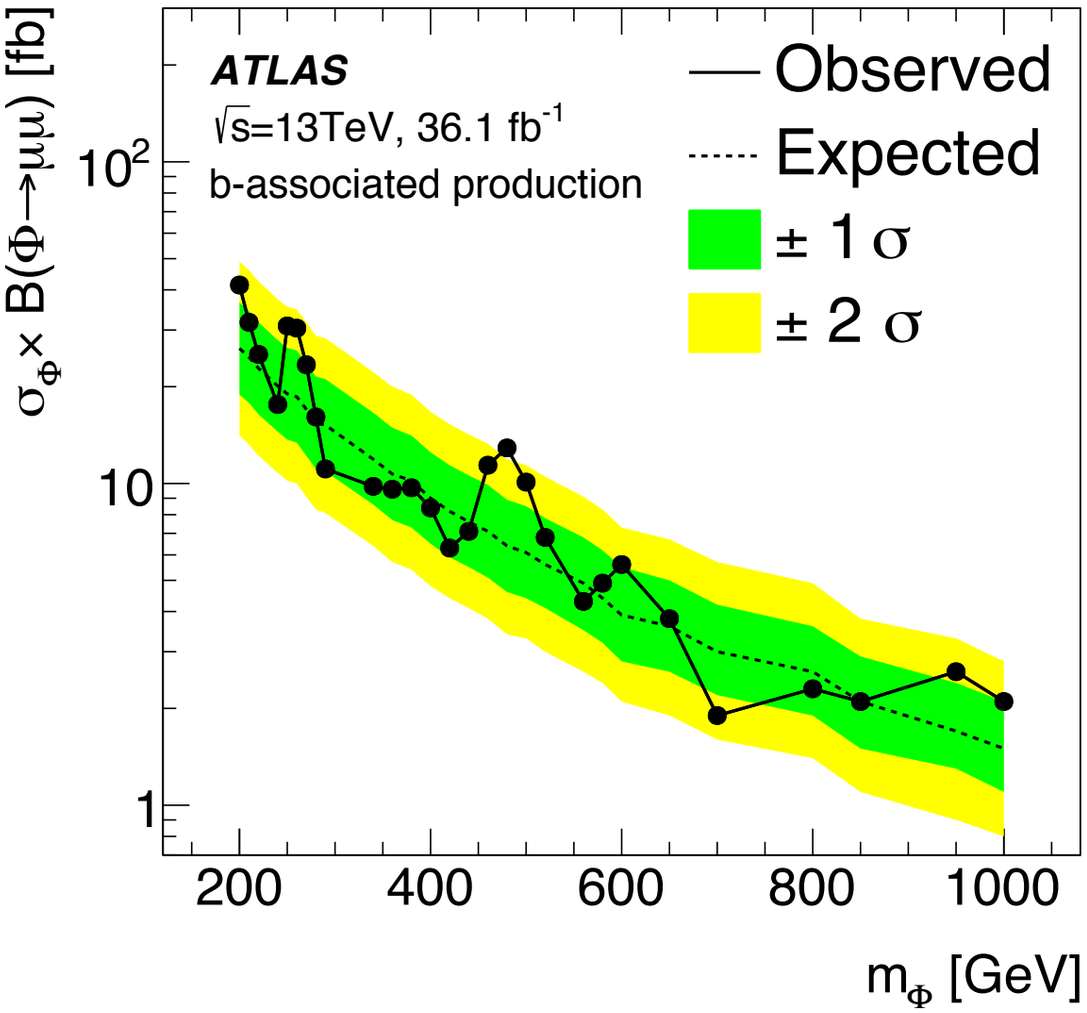
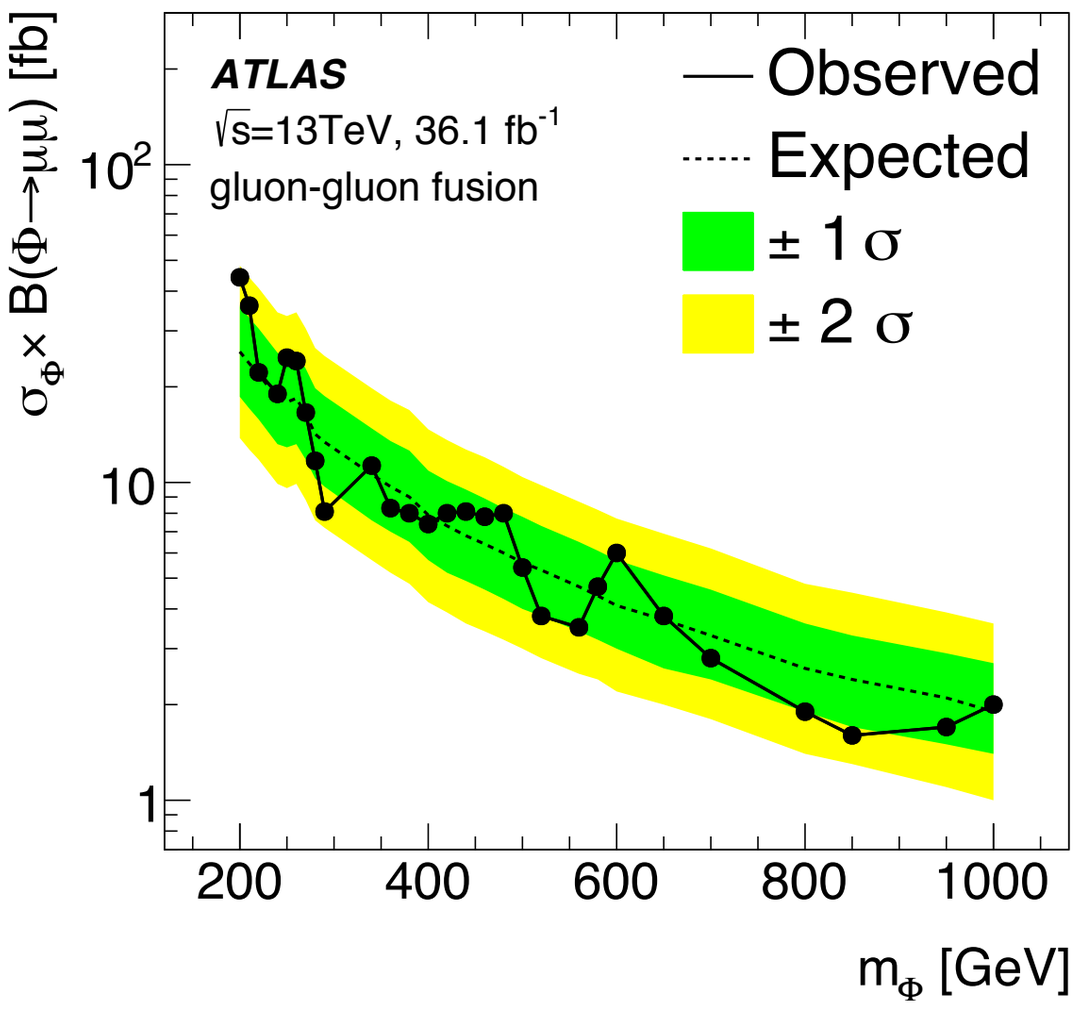
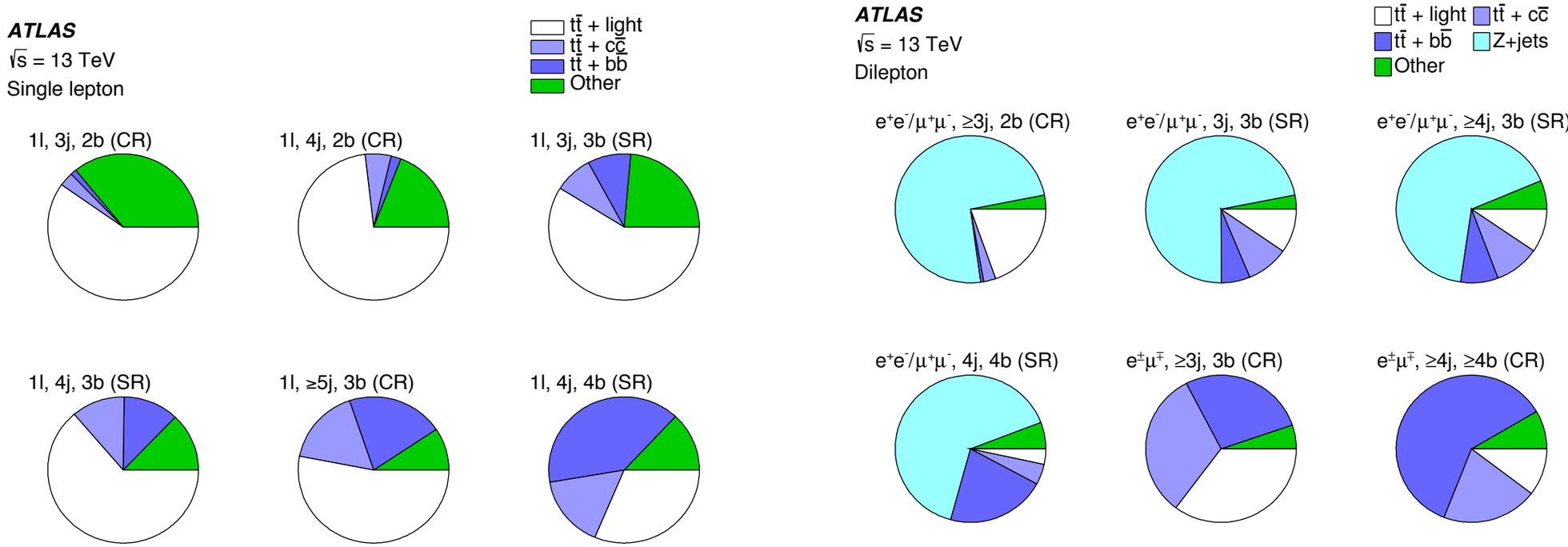




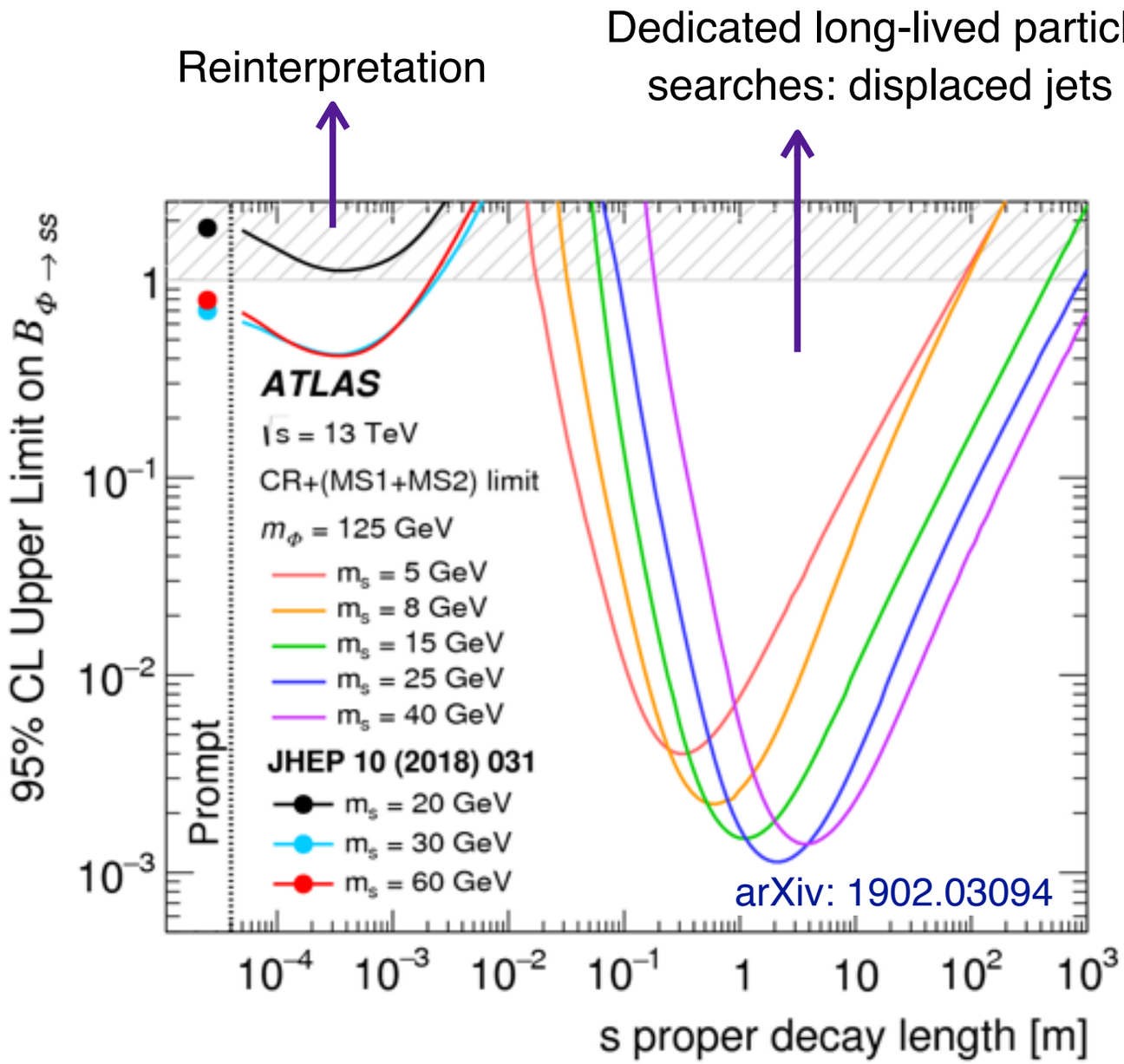
H→aa→4b



Variable	(1ℓ, 3j, 3b)	(1ℓ, 4j, 3b)	(1ℓ, 4j, 4b)	(2ℓ, 3j, 3b)	(2ℓ, ≥4j, 3b)	(2ℓ, ≥4j, ≥4b)
m_{bbb}	✓	✓		✓	✓	
m_{bbbb}			✓			✓
m_{bb1}			✓			✓
m_{bb2}			✓			✓
Average $\Delta R(b,b)$	✓	✓	✓	✓	✓	✓
H_{T}	✓	✓	✓			
p_{T}^{W}	✓					
m_{bbj}		✓				
m_{T2}	✓	✓	✓			
$\Delta R(\ell,\ell)$				✓	✓	✓
$\Delta R(Z,H)$				✓	✓	
$\cos\theta^{*}$						✓
$E_{\mathrm{T}}^{\mathrm{miss}}$				✓	✓	✓

H→aa→4b

- Reinterpretation of prompt H→aa→4b analysis for slightly displaced signals



H→aa→4μ

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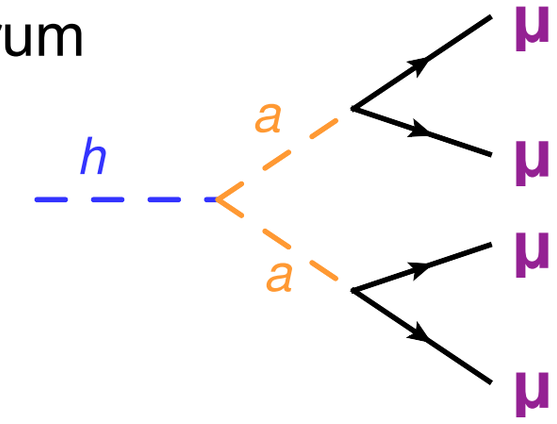
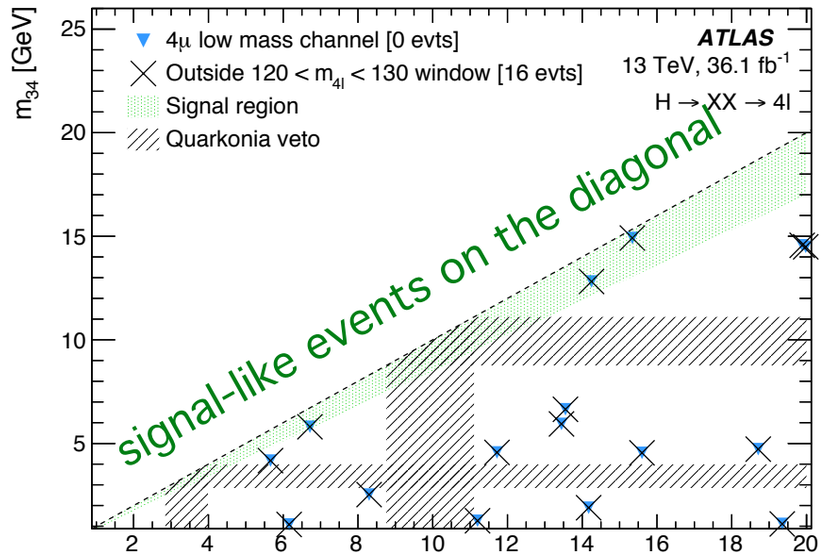
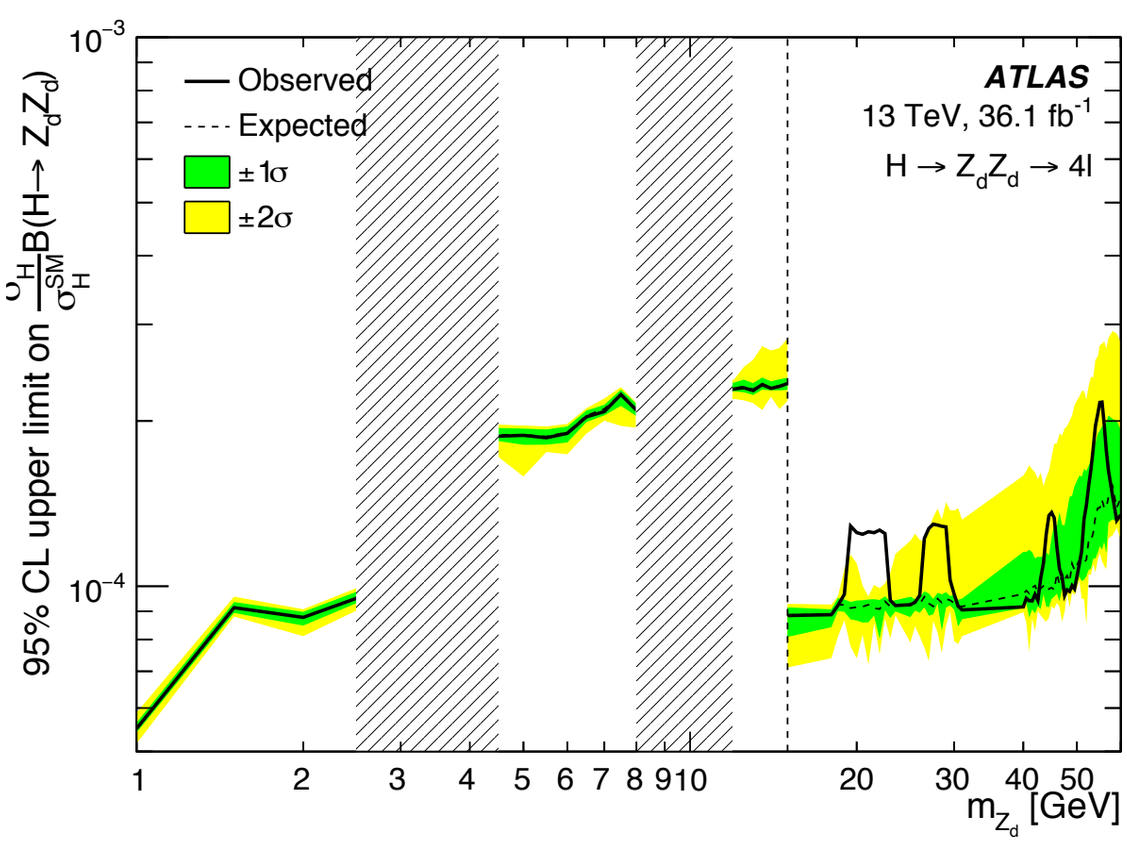
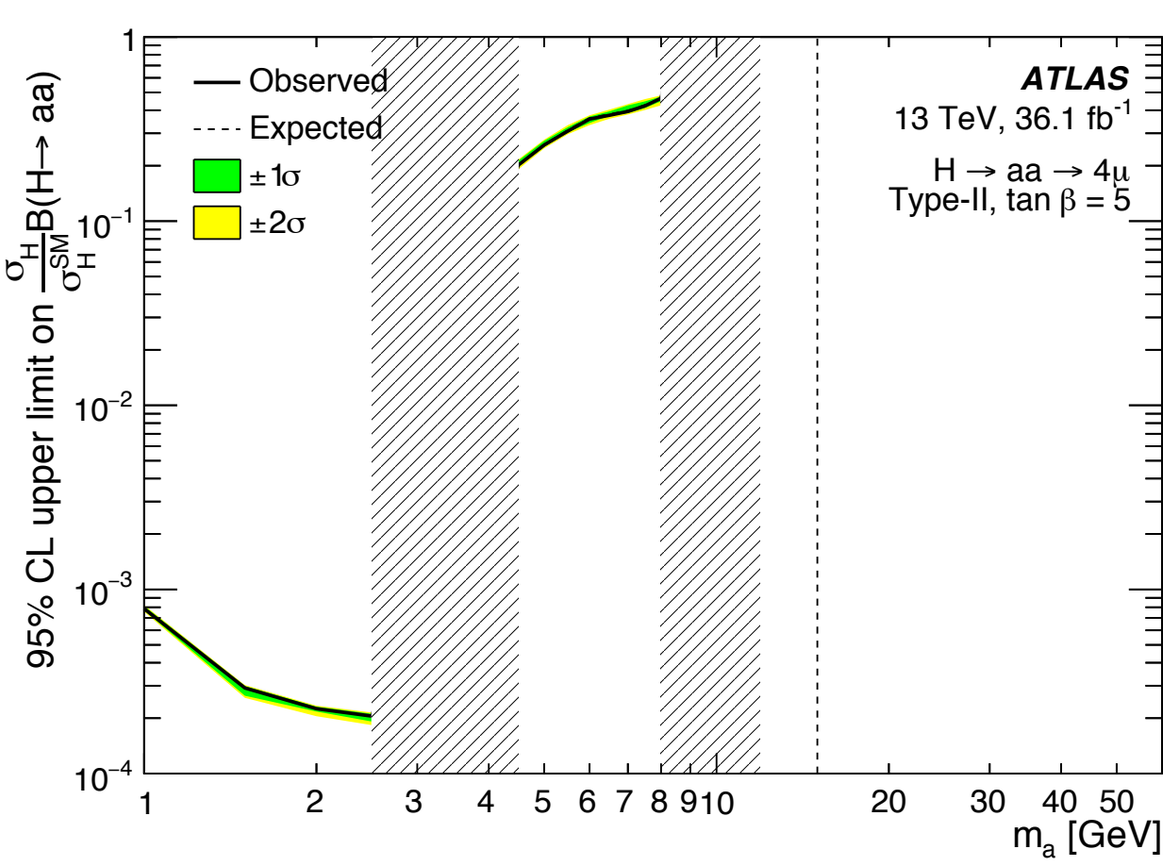
- Look for dark photons and pseudoscalars in 4 lepton final state
- $H \to Z_d Z_d \to 4\text{lep}$ (1-60 GeV), $H \to aa \to 4\mu$ (1-8 GeV)
- Search for excess in 2D $m_{\mu\mu}$ spectrum







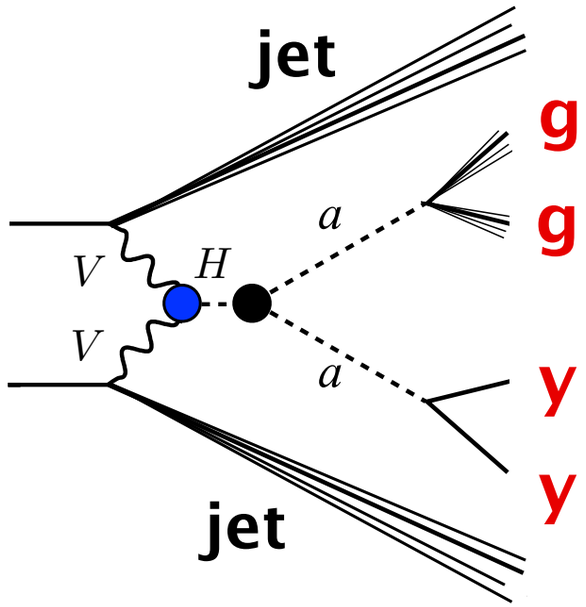


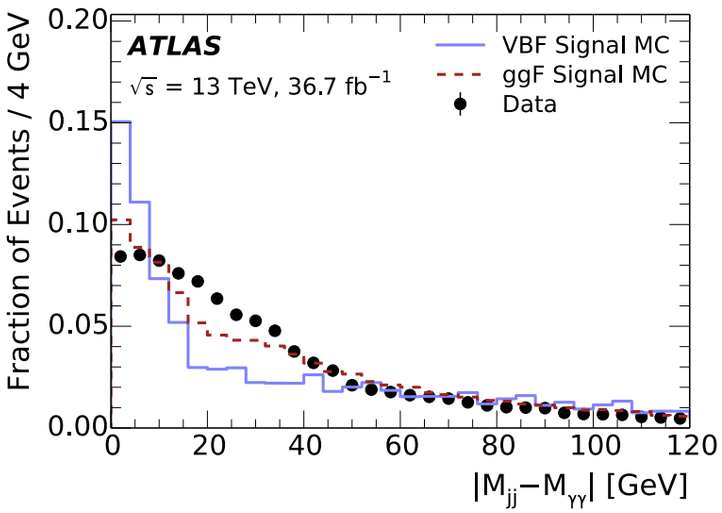
H→aa→jjyy

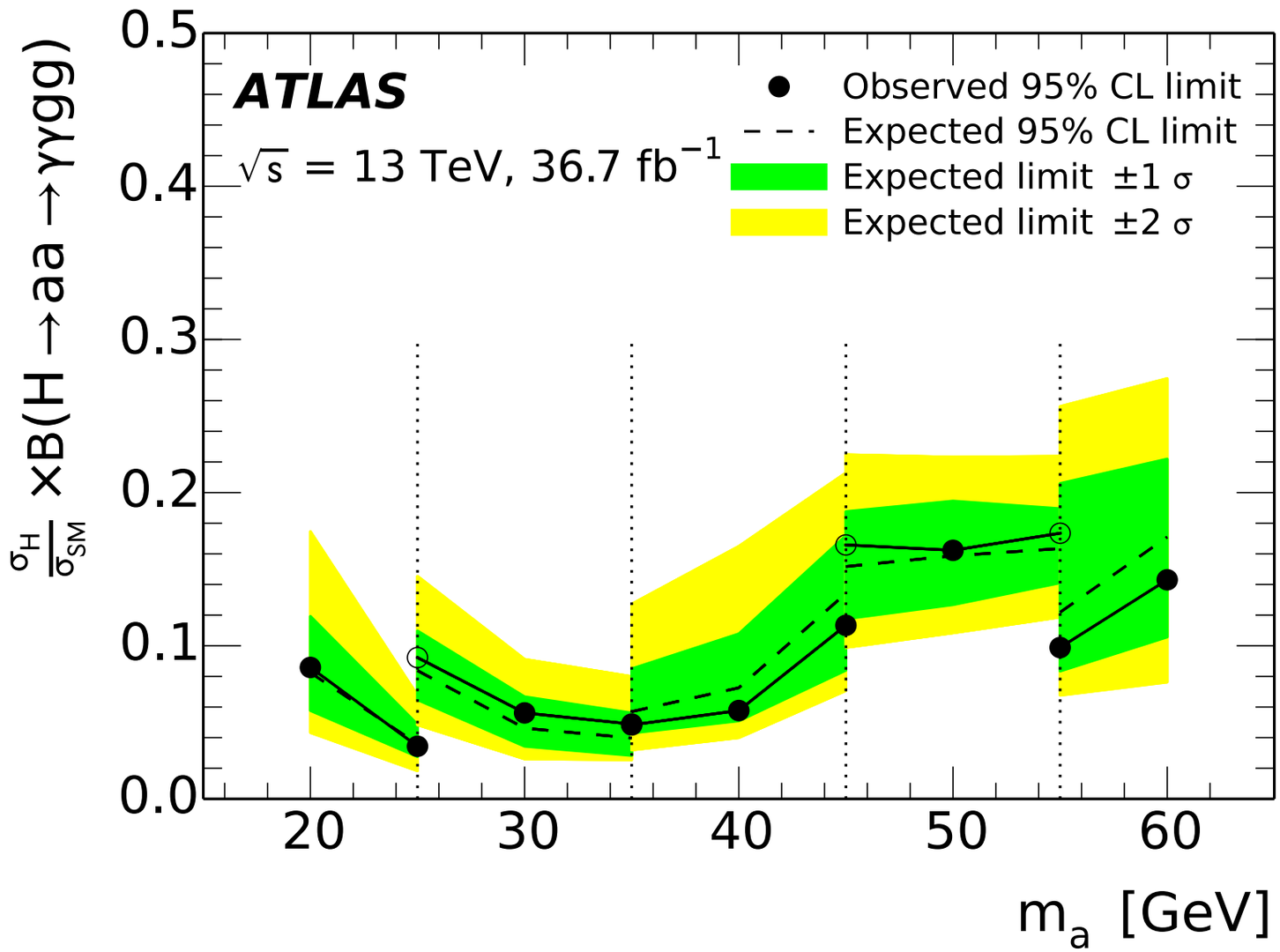
- Fermiophobic a
  - E.g scalar coupled to new charged & coloured vector-like states: $\lambda_i s\bar{\psi}_i\psi_i$

1803.11145

- Dominant yy+multijet background estimated using data-driven "ABCD" method based on inverting y ID and $|M_{jj}-M_{yy}|$ criteria



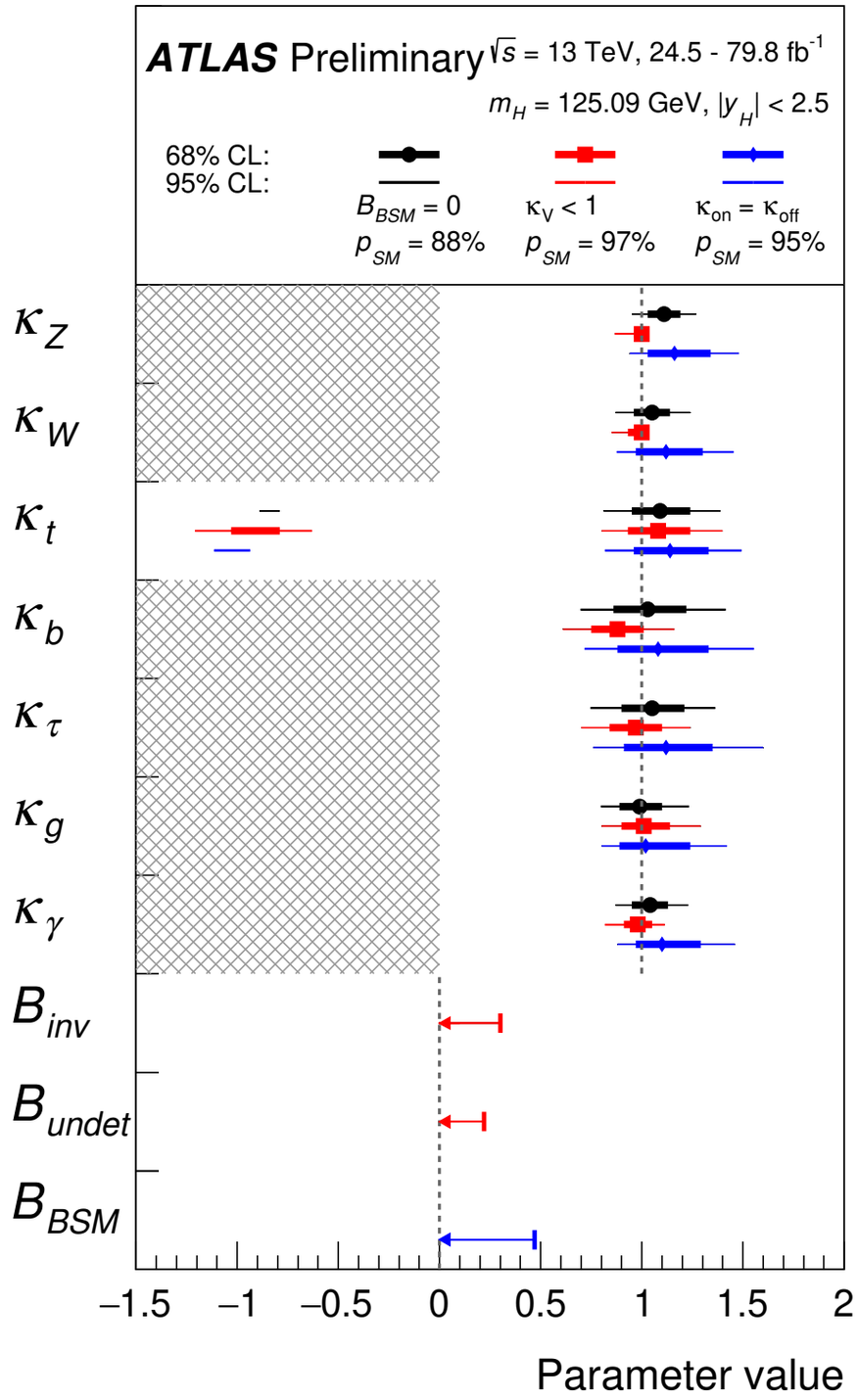




H coupling constraints

ATLAS-CONF-2019-005

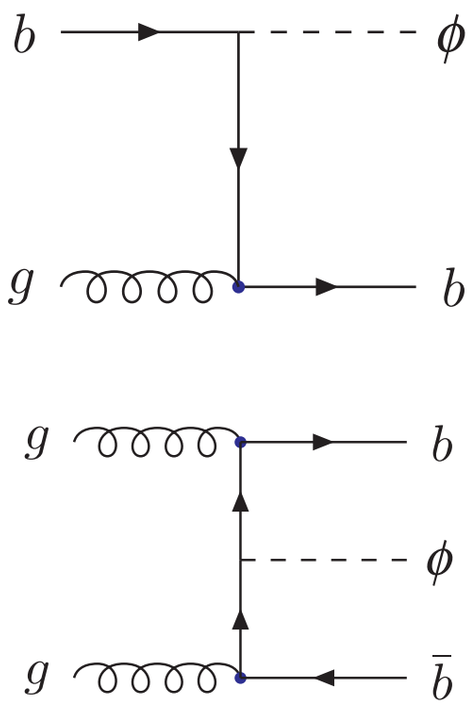
Parameter	(a) $B_{inv} = B_{undet} = 0$	(b) B_{inv} free, $B_{undet} \geq 0$, $\kappa_{W,Z} \leq 1$	(c) $B_{BSM} \geq 0$, $\kappa_{off} = \kappa_{on}$
κ_Z	1.11 ± 0.08	> 0.87 at 95% CL	$1.16^{+0.18}_{-0.13}$
κ_W	1.05 ± 0.09	> 0.85 at 95% CL	$1.12^{+0.18}_{-0.15}$
κ_b	$1.03^{+0.19}_{-0.17}$	0.88 ± 0.13	$1.08^{+0.25}_{-0.20}$
κ_t	$1.09^{+0.15}_{-0.14}$	$[-1.03, -0.79] \cup [0.93, 1.24]$ at 68% CL	$1.14^{+0.19}_{-0.18}$
κ_τ	$1.05^{+0.16}_{-0.15}$	0.97 ± 0.13	$1.12^{+0.23}_{-0.21}$
κ_γ	1.05 ± 0.09	0.98 ± 0.07	$1.10^{+0.19}_{-0.13}$
κ_g	$0.99^{+0.11}_{-0.10}$	$1.01^{+0.13}_{-0.11}$	$1.02^{+0.22}_{-0.13}$
B_{inv}	-	< 0.30 at 95% CL	-
B_{undet}	-	< 0.22 at 95% CL	-
B_{BSM}	-	-	< 0.47 at 95% CL

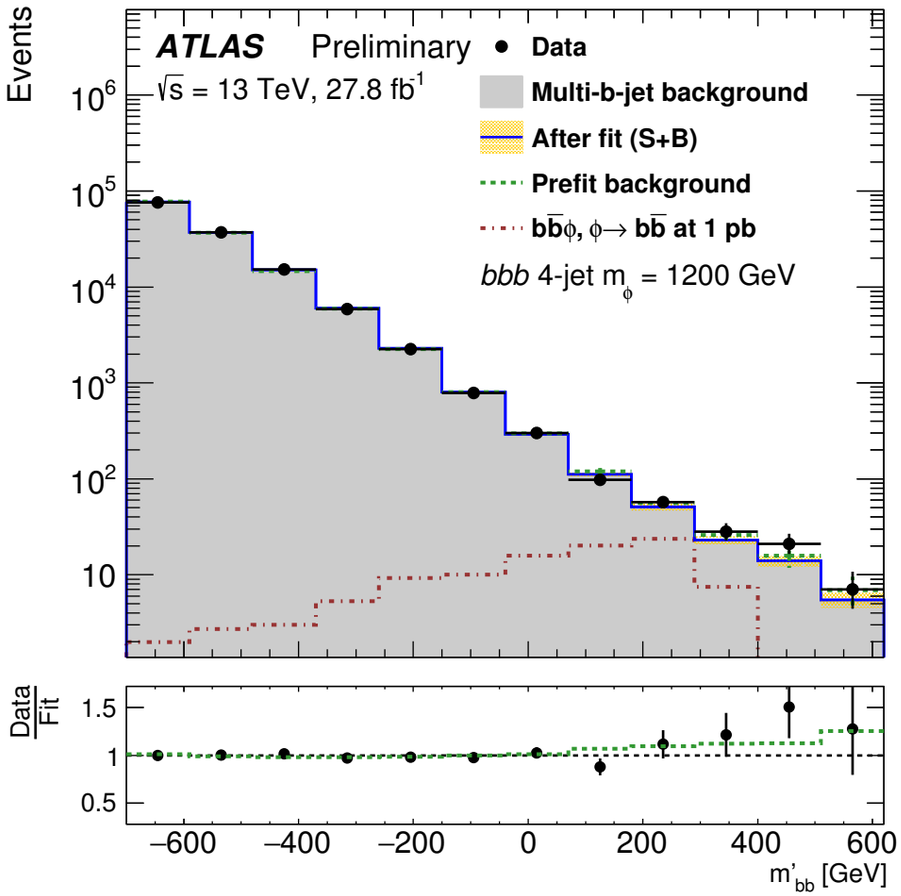


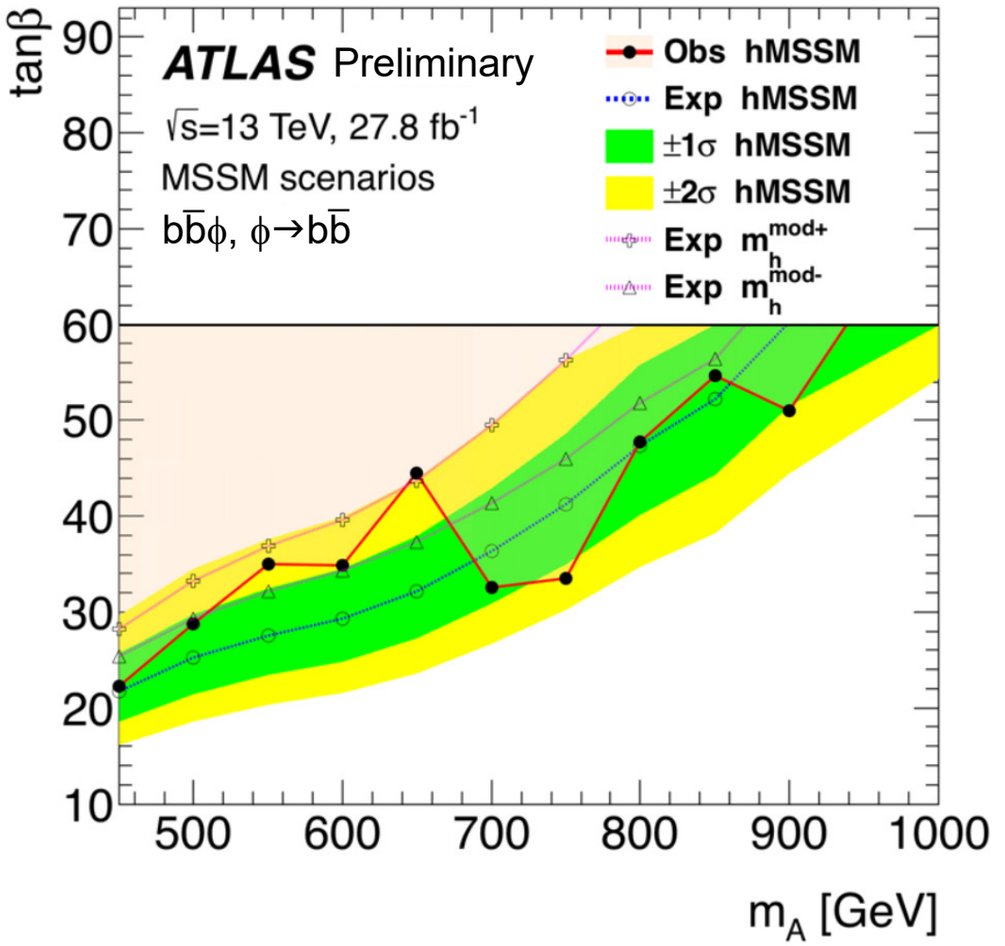
H→bb

[ATLAS-CONF-2019-010]

- Searching for b-associated heavy neutral H production
- Search insensitive to CP of the heavy 2HDM boson (A/H)
- 3 event categories base on number of jets (3, 4 or 5)
  - Signal region: >=3 b-tagged jets
  - Control region: ==2 b-tagged jets
- Background shape and normalisation obtained from the data

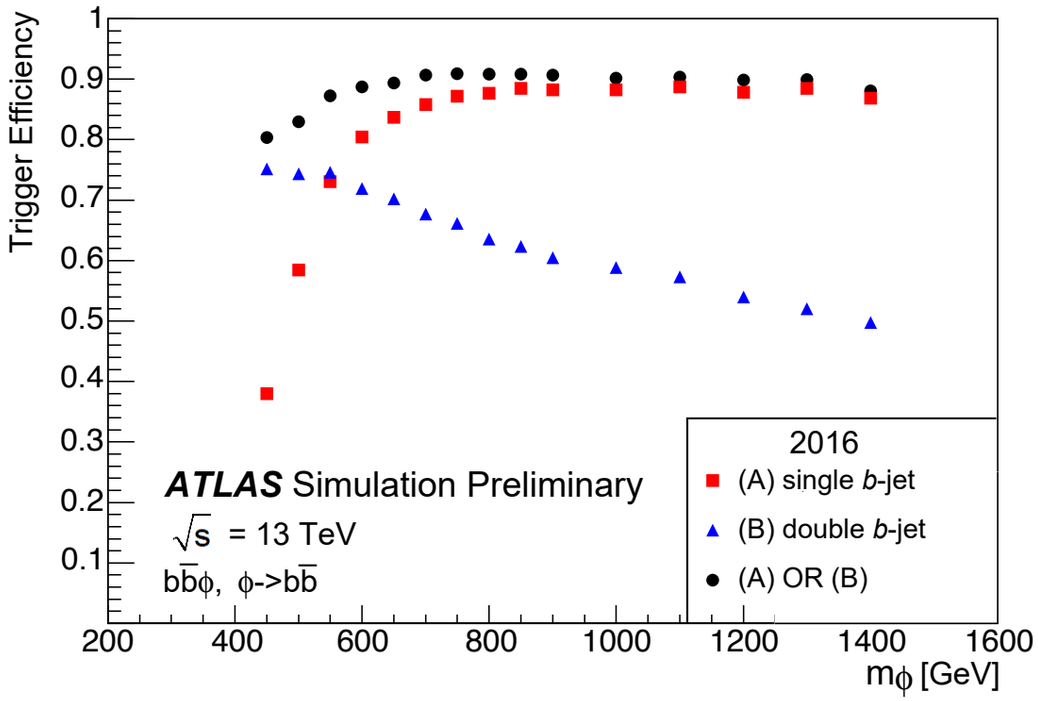


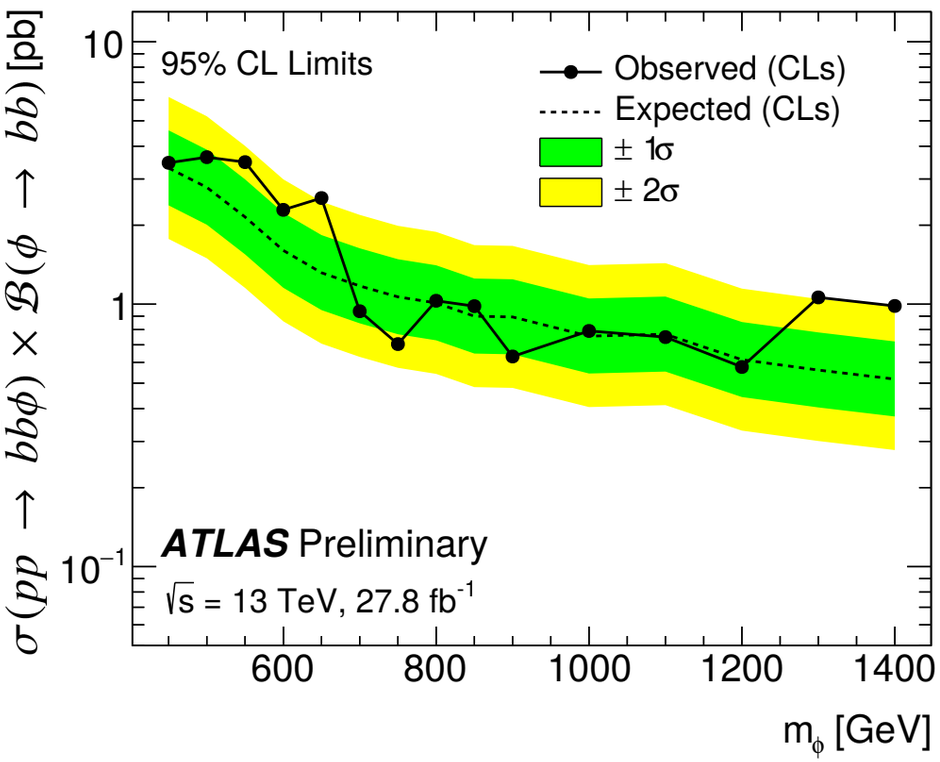




H→bb

[ATLAS-CONF-2019-010]

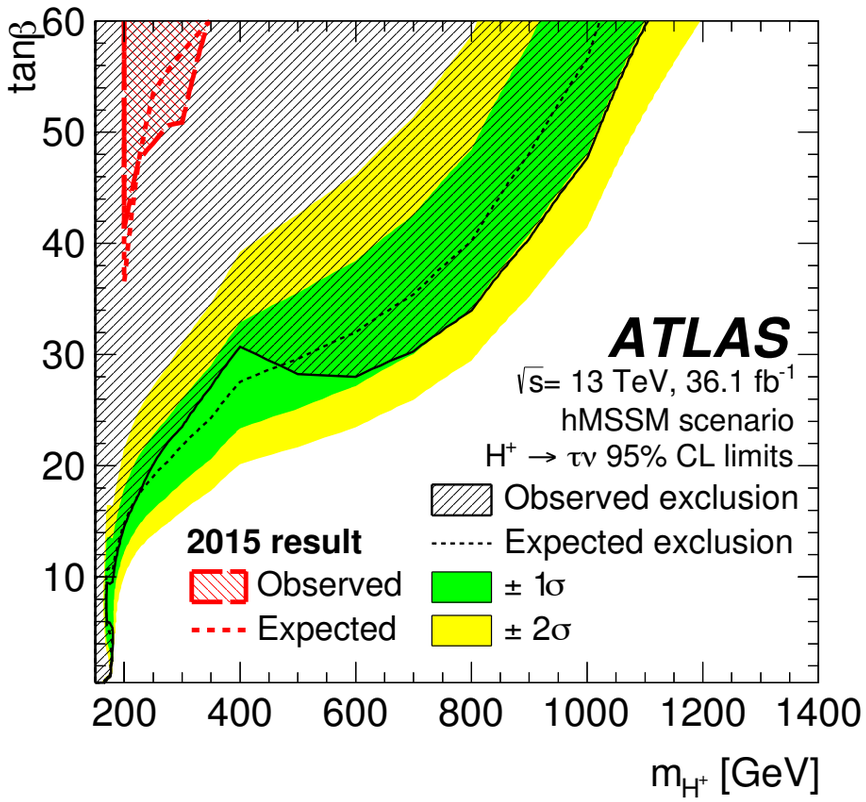


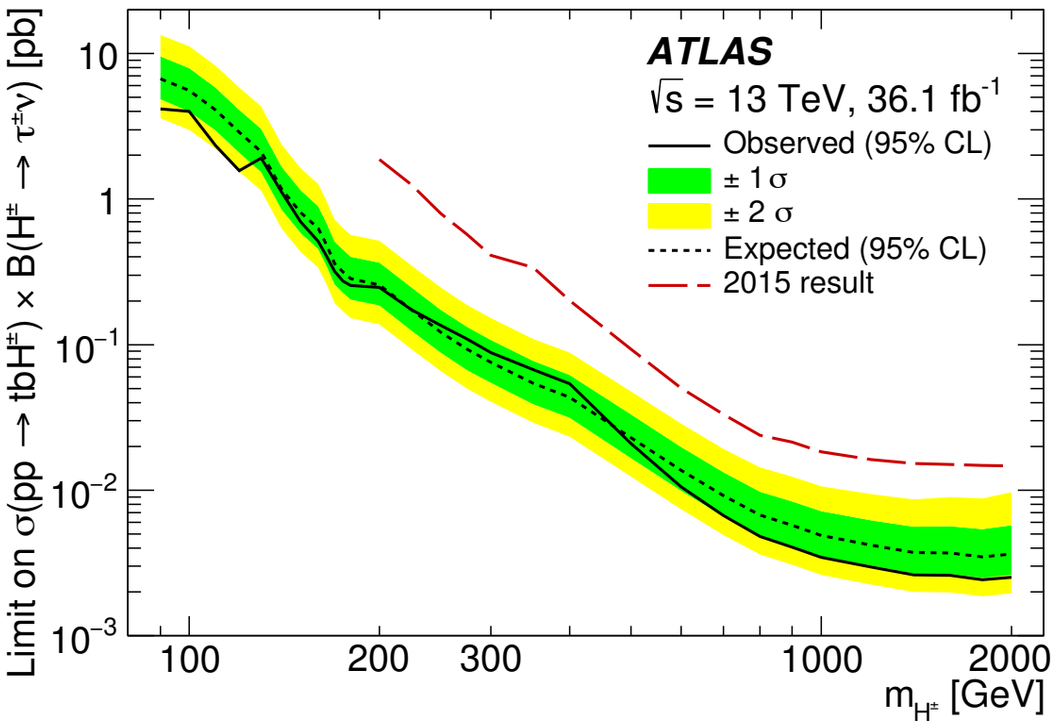


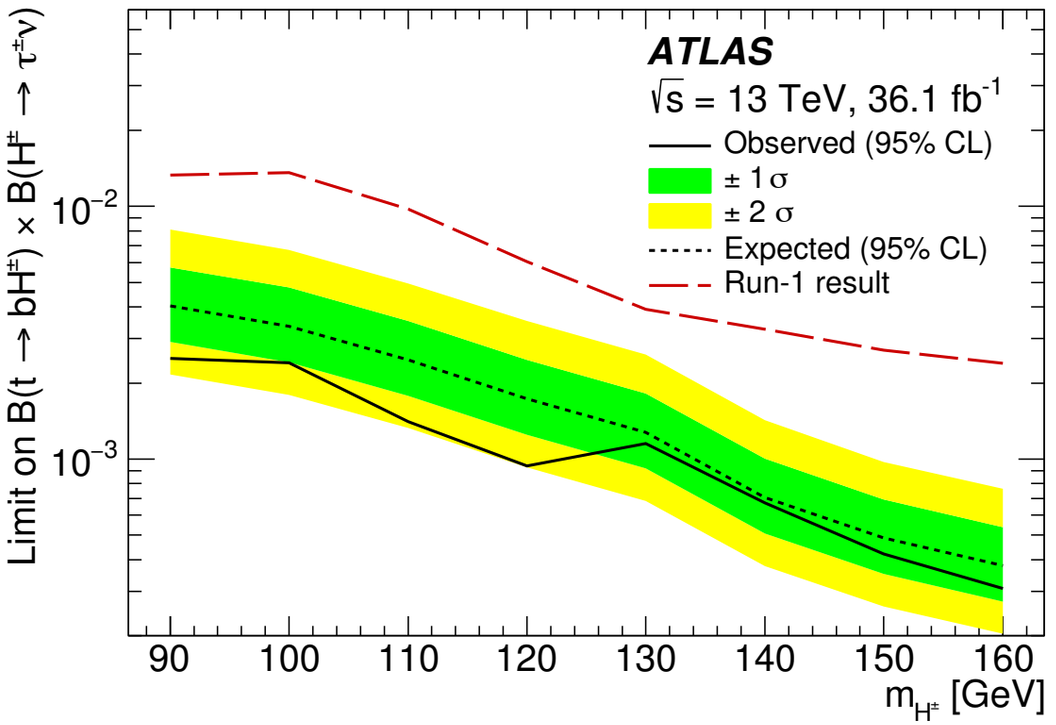
Source of uncertainty	$m_\phi = 600$ GeV $\Delta(\sigma \times \mathcal{B})$ [pb]	$m_\phi = 1200$ GeV $\Delta(\sigma \times \mathcal{B})$ [pb]
Total	0.80	0.29
Statistical	0.77	0.26
Systematic	0.20	0.11
Experimental uncertainties		
Jet-related	0.05	0.05
B-tagging (offline)	0.12	0.05
B-trigger	0.04	0.05
Luminosity	0.02	0.01
Theoretical and modeling uncertainties		
Generator	0.03	0.03
PDF	0.08	0.04
MC statistical	0.09	0.04

$H^+ \to \tau\nu$

BDT input variable	$\tau_{\text{had-vis}}$+jets	$\tau_{\text{had-vis}}$+lepton
$E_{\text{T}}^{\text{miss}}$	✓	✓
p_{T}^{τ}	✓	✓
$p_{\text{T}}^{b\text{-jet}}$	✓	✓
p_{T}^{ℓ}		✓
$\Delta\phi_{\tau_{\text{had-vis}},\ \text{miss}}$	✓	✓
$\Delta\phi_{b\text{-jet},\ \text{miss}}$	✓	✓
$\Delta\phi_{\ell,\ \text{miss}}$		✓
$\Delta R_{\tau_{\text{had-vis}},\ \ell}$		✓
$\Delta R_{b\text{-jet},\ \ell}$		✓
$\Delta R_{b\text{-jet},\ \tau_{\text{had-vis}}}$	✓	
Υ	✓	✓



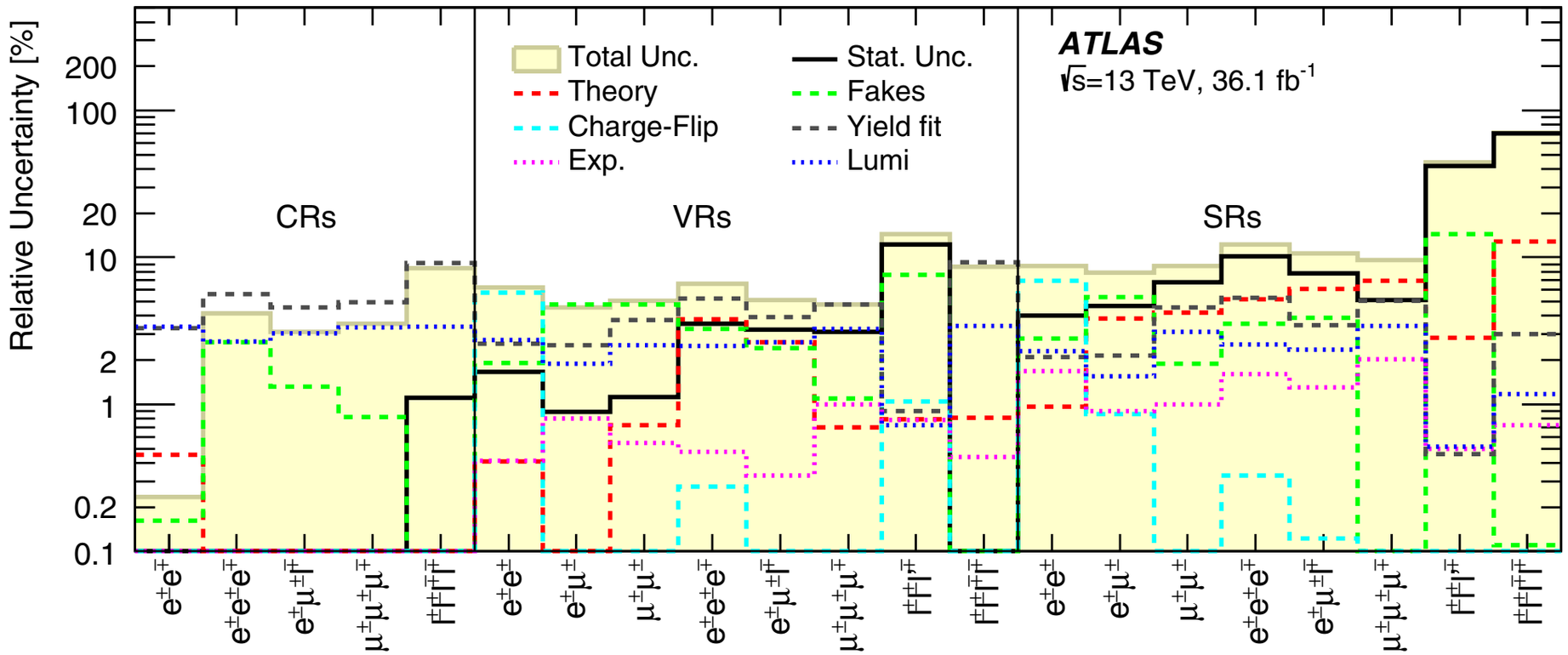




$H^{++} \rightarrow W^+W^+$

	$2\ell^{SS}$			3ℓ		4ℓ
Selection criteria	$e^{\pm}e^{\pm}$	$e^{\pm}\mu^{\pm}$	$\mu^{\pm}\mu^{\pm}$	SFOS 0	SFOS 1,2	
	$m_{H^{\pm\pm}} = 200$ GeV					
$E_{\mathrm{T}}^{\mathrm{miss}}$[GeV]	> 100	> 100	> 100	> 45	> 45	> 60
$m_{x\ell}$[GeV]	[25, 130]	[15, 150]	[35, 150]	> 160	> 170	> 230
$\Delta R_{\ell^{\pm}\ell^{\pm}}$[rad.]	< 0.8	< 1.8	< 0.9	[0.15, 1.57]	[0.00, 1.52]	
$\Delta\phi(\ell\ell, E_{\mathrm{T}}^{\mathrm{miss}})$[rad.]	< 1.1	< 1.3	< 1.3			
S[rad.]	< 0.3	< 0.3	< 0.2			
m_{jets}[GeV]	[140, 770]	[95, 330]	[95, 640]			
$\Delta R_{\ell-\mathrm{jet}}$[rad.]				[0.08, 1.88]	[0.07, 1.31]	
$p_{\mathrm{T}}^{\text{leading jet}}$[GeV]				> 80	> 55	
$p_{\mathrm{T}}^{\ell_1}$[GeV]						> 65
$\Delta R_{\ell^{\pm}\ell^{\pm}}^{\min}$[rad.]						[0.16, 1.21]
$\Delta R_{\ell^{\pm}\ell^{\pm}}^{\max}$[rad.]						[0.27, 2.03]
	$m_{H^{\pm\pm}} = 300$ GeV					

$H^{++} \rightarrow l^{+}l^{+}$



Channel	Region								
	Control regions			Validation regions			Signal regions		
	OCCR	DBCR	4LCR	SCVR	3LVR	4LVR	1P2L	1P3L	2P4L
Electron channel	$e^{\pm}e^{\mp}$	$e^{\pm}e^{\pm}e^{\mp}$	$\ell^{\pm}\ell^{\pm}\ell^{\mp}\ell^{\mp}$	$e^{\pm}e^{\pm}$	$e^{\pm}e^{\pm}e^{\mp}$	$\ell^{\pm}\ell^{\pm}\ell^{\mp}\ell^{\mp}$	$e^{\pm}e^{\pm}$	$e^{\pm}e^{\pm}e^{\mp}$	$\ell^{\pm}\ell^{\pm}\ell^{\mp}\ell^{\mp}$
Mixed channel	–	$e^{\pm}\mu^{\pm}\ell^{\mp}$		$e^{\pm}\mu^{\pm}$	$e^{\pm}\mu^{\pm}\ell^{\mp}$ $\ell^{\pm}\ell^{\pm}\ell'^{\mp}$		$e^{\pm}\mu^{\pm}$	$e^{\pm}\mu^{\pm}\ell^{\mp}$ $\ell^{\pm}\ell^{\pm}\ell'^{\mp}$	
Muon channel	–	$\mu^{\pm}\mu^{\pm}\mu^{\mp}$		$\mu^{\pm}\mu^{\pm}$	$\mu^{\pm}\mu^{\pm}\mu^{\mp}$		$\mu^{\pm}\mu^{\pm}$	$\mu^{\pm}\mu^{\pm}\mu^{\mp}$	
$m(e^{\pm}e^{\pm})$ [GeV]	[130, 2000]	[90, 200)	[60, 150)	[130, 200)	[90, 200)	[150, 200)	[200, ∞)	[200, ∞)	[200, ∞)
$m(\ell^{\pm}\ell^{\pm})$ [GeV]	–	[90, 200)		[130, 200)	[90, 200)		[200, ∞)	[200, ∞)	
$m(\mu^{\pm}\mu^{\pm})$ [GeV]	–	[60, 200)		[60, 200)	[60, 200)		[200, ∞)	[200, ∞)	
b-jet veto	✓	✓	✓	✓	✓	✓	✓	✓	✓
Z veto	–	inverted	–	–	✓	–	–	✓	✓
$\Delta R(\ell^{\pm}, \ell^{\pm}) < 3.5$	–	–	–	–	–	–	✓	✓	–
$p_{\mathrm{T}}(\ell^{\pm}\ell^{\pm}) > 100$ GeV	–	–	–	–	–	–	✓	✓	–
$\sum \lvert p_{\mathrm{T}}(\ell)\rvert > 300$ GeV	–	–	–	–	–	–	✓	✓	–
$\Delta M/\bar{M}$ requirement	–	–	–	–	–	–	–	–	✓