universität freiburg

*Unraveling **Dark Matter** with novel collider signatures in Type-I 2HDM+a*

Roadmap of Dark Matter models for Run 3

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Motivation

Open question: Dark Matter nature

- **Initial simplified DM models**: Add a singlet acting as mediator between the visible and dark sectors arXiv:1506.03116

- **Problem**: Unitarity is be violated: Interactions between DM mediator and SM fermions are not gauge invariant arXiv:1510.02110

- **Solution**: Extend the SM Higgs sector

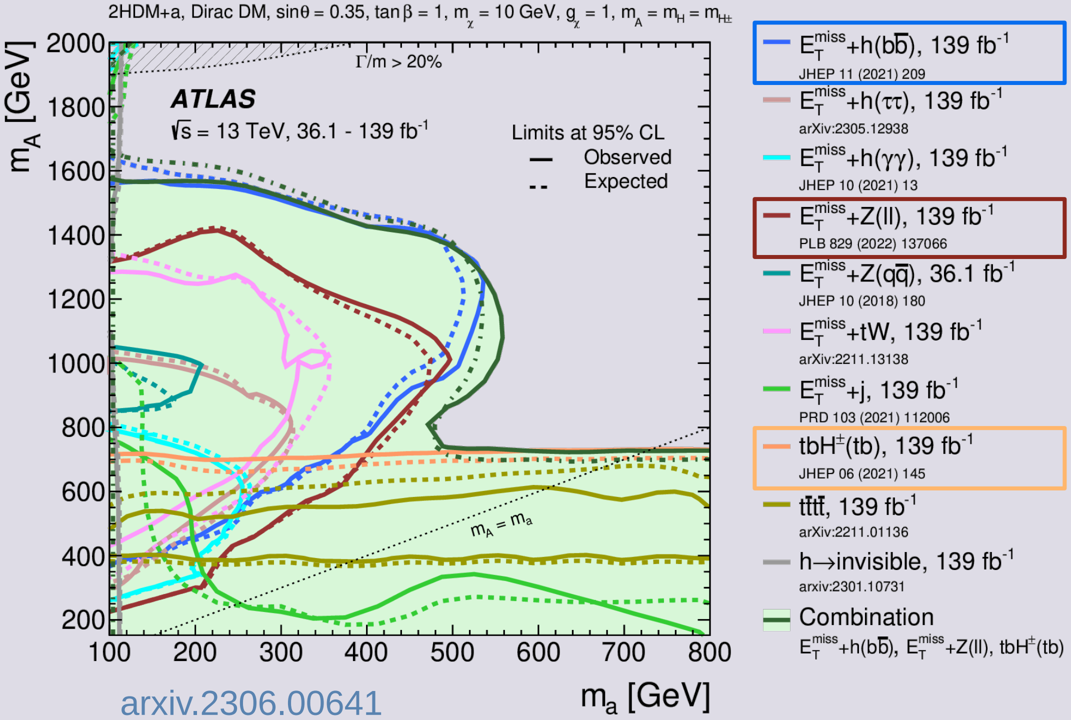
Two Higgs Doublet Model with an additional pseudoscalar DM mediator 2HDM+a: simplest gauge-invariant and renormalisable extension of the simplified pseudoscalar DM model

→ New channels for particle interaction → More distinctive collider signatures

Previous searches

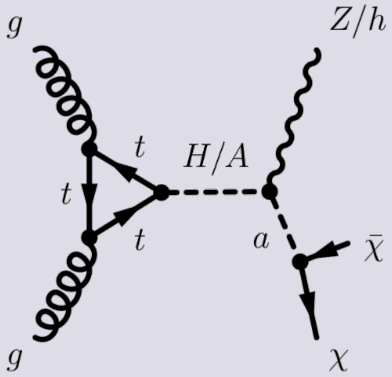
Exclusion m_A-m_a plane

No mass hierarchy: m_A=m_H=$m_{H\pm}$

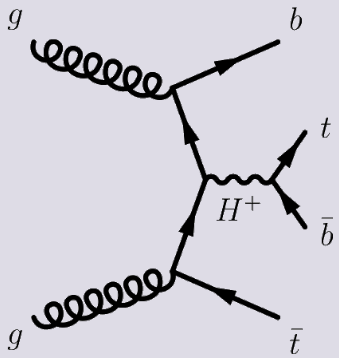


arxiv.2306.00641

- E_T^{miss}+h($b\bar{b}$) and E_T^{miss}+Z($l\bar{l}$) dominate the sensitivity



- tbH$^{\pm}$ provides complementary sensitivity

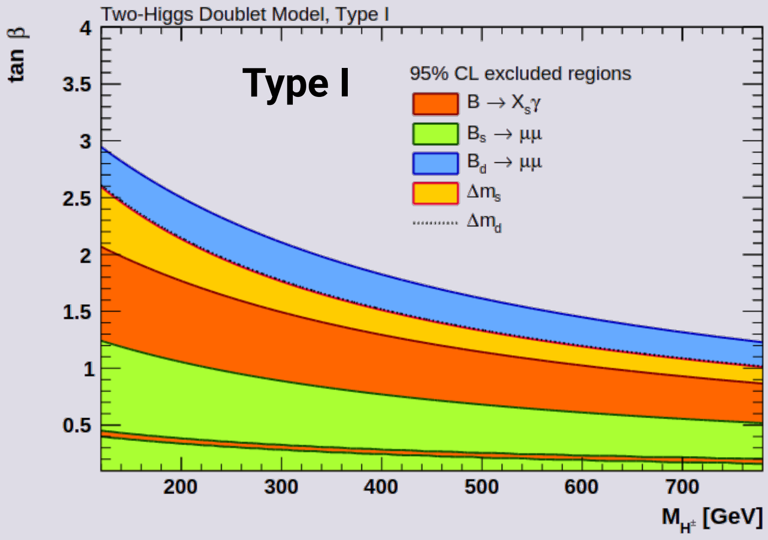


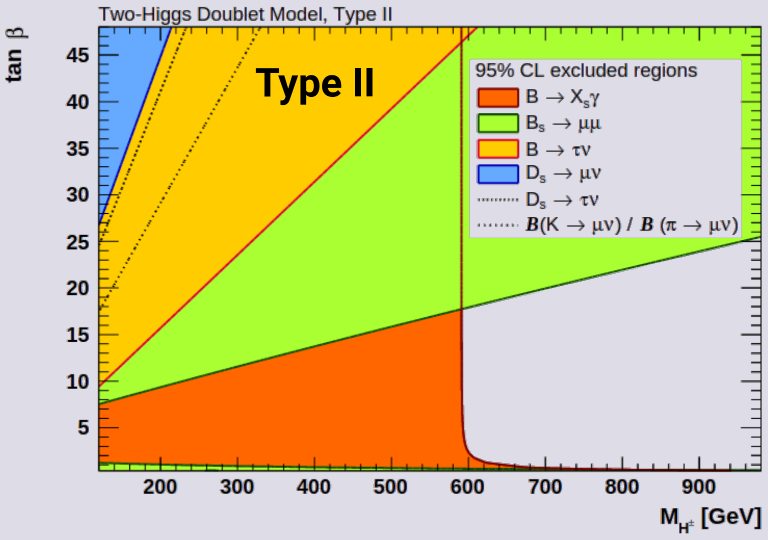
2HDM TypeI

Why Type I?

All previous LHC searches consider only Type II Yukawa sector

- Constraints from flavour physics on charged Higgs mass are very weak in Type I → allow lower $H^{\pm}$ masses



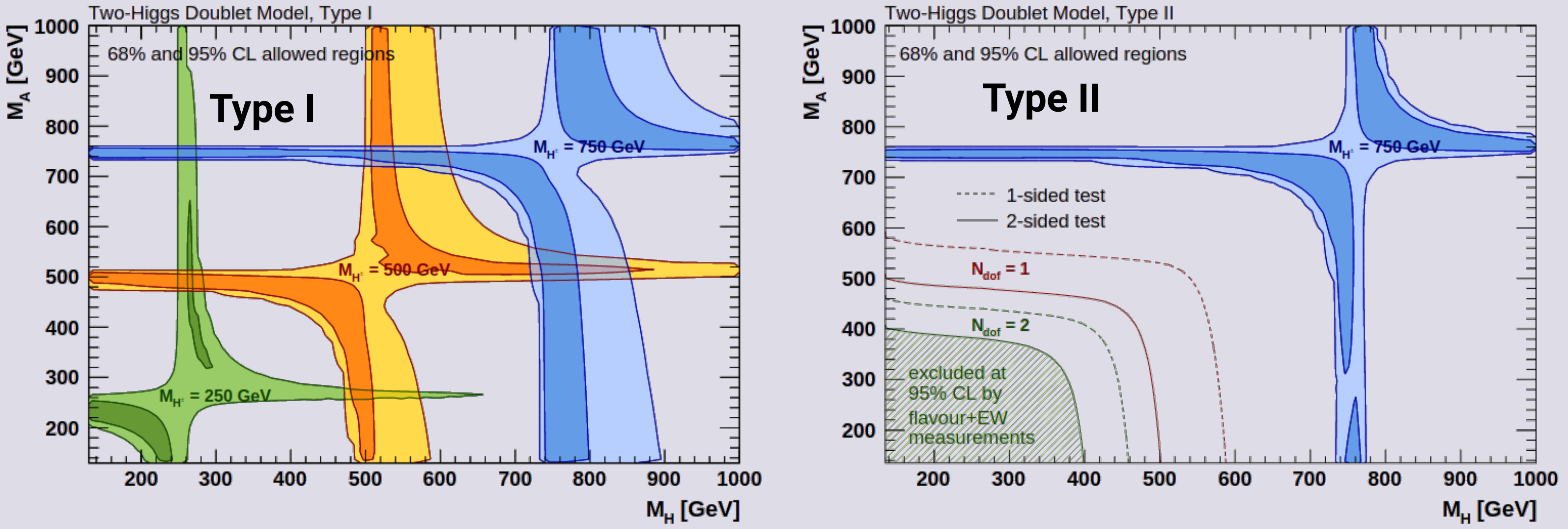


arxiv.1803.01853

2HDM TypeI

Why Type I?

- $H^{\pm}$ should be close to the mass of A or H: Allow smaller $m_{H\pm}$ → Smaller allowed masses for A/H → ***Explore masses below the SM Higgs mass***



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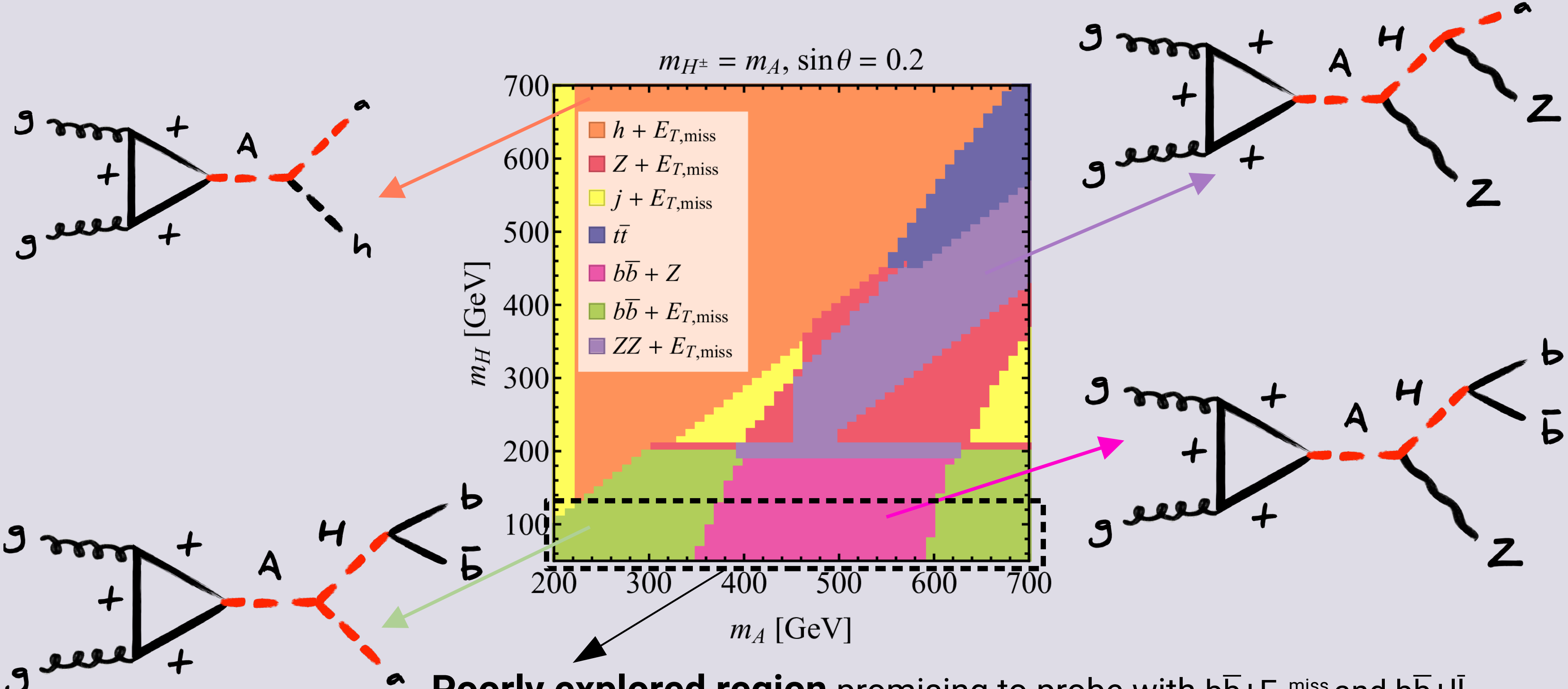
A-boson dominant decays

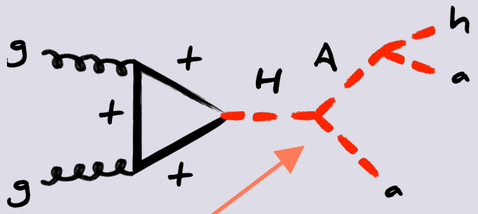
New channel

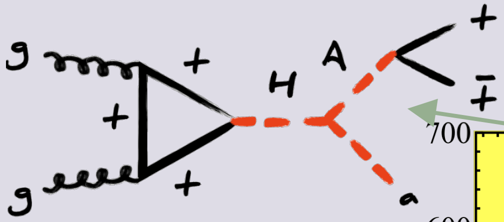


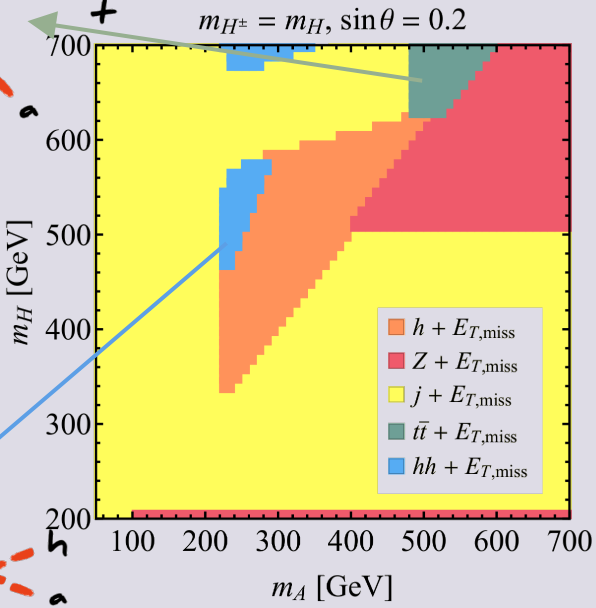
Poorly explored region promising to probe with $b\bar{b}+E_T^{miss}$ and $b\bar{b}+l\bar{l}$

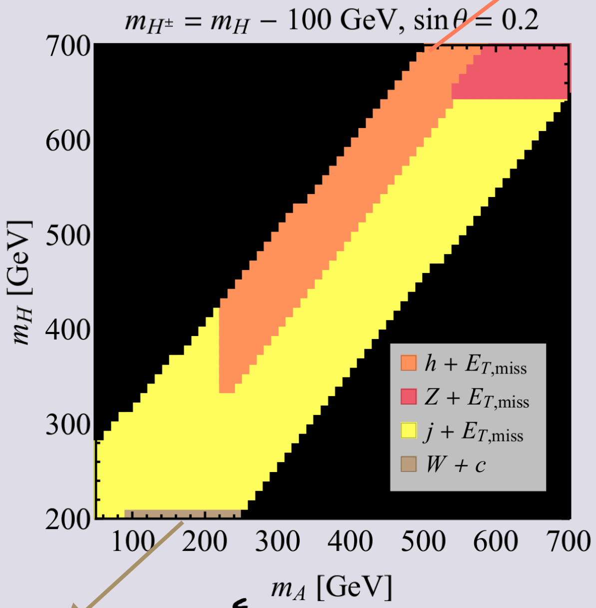
H-boson dominant decays

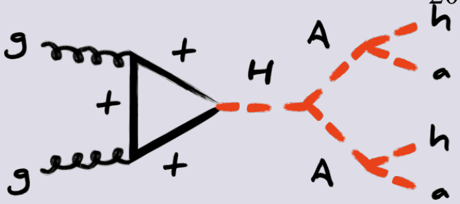
H decays provide new channels

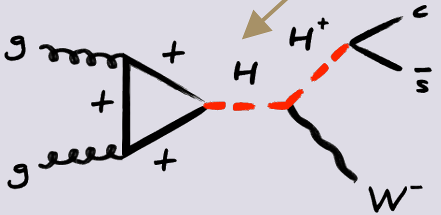












In the following we focus on $b\bar{b}+E_T^{miss}$ and $l\bar{l}+b\bar{b}$ produced with an A-boson resonance

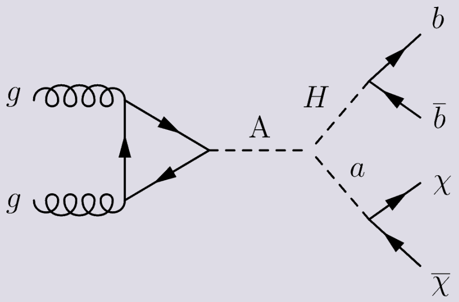
$b\bar{b}+E_T^{miss}$ signature

Requirements

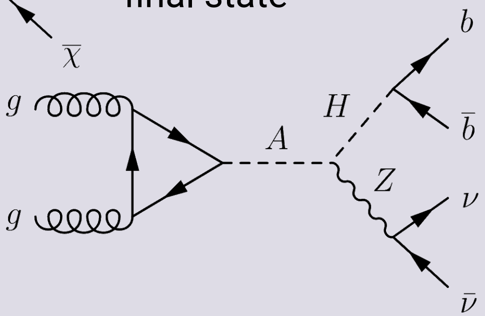
- **0 leptons, exactly 2 b-jets, E_T^{miss} > 150GeV**

Reconstruction

- **a or Z**: Missing transverse momentum
- **H candidate**: 2 b-jets
- Transverse mass for **A candidate**: H+E_T^{miss}

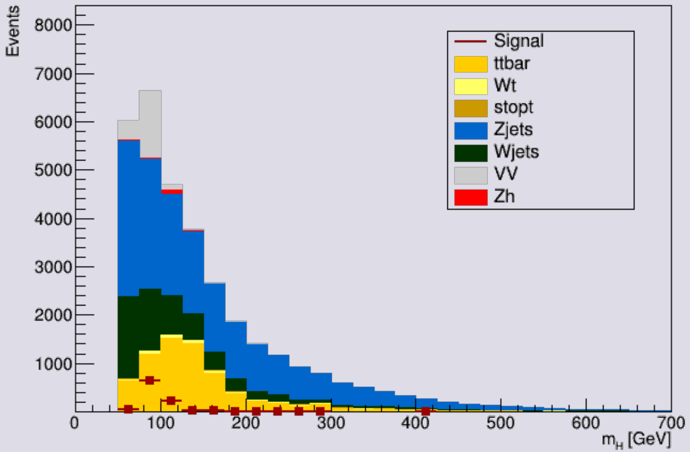


Consider both signal processes for $b\bar{b}+E_T^{miss}$ final state



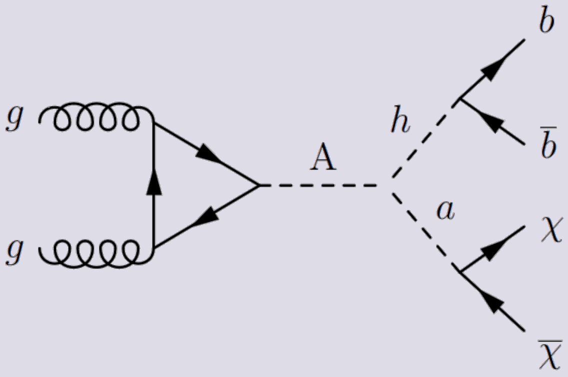
Apply cuts to improve sensitivity, similar to the ATLAS A → Z(νν)H(bb) analysis arXiv:2311.04033

Calculate sensitivity with m_H

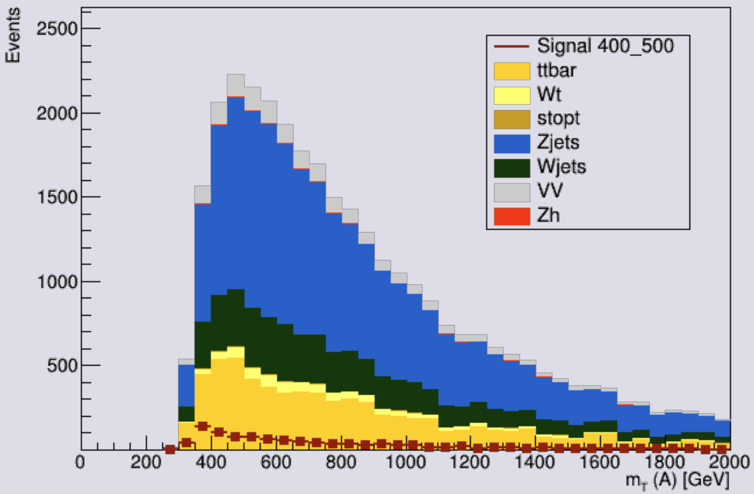


$h+E_T^{miss}$ signature

- Complementary exclusion for the phase space where A → Ha decay is not kinematically allowed
- Same cuts and reconstruction as $b\bar{b}+E_T^{miss}$

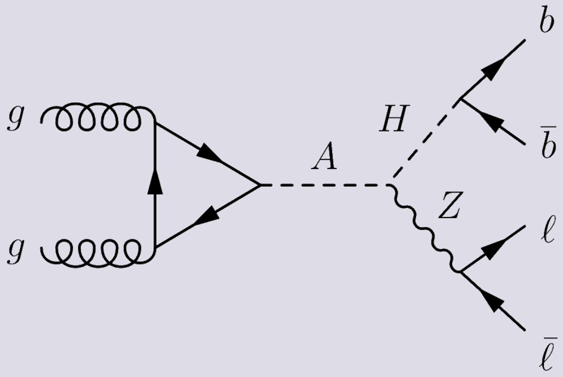


Calculate sensitivity with $m_T(A)$



$b\bar{b}+l\bar{l}$ signature

- Previous A→ZH→llbb analyses both in ATLAS and CMS cover $\mathbf{m_{b\bar{b}}}$ **above 125 GeV**



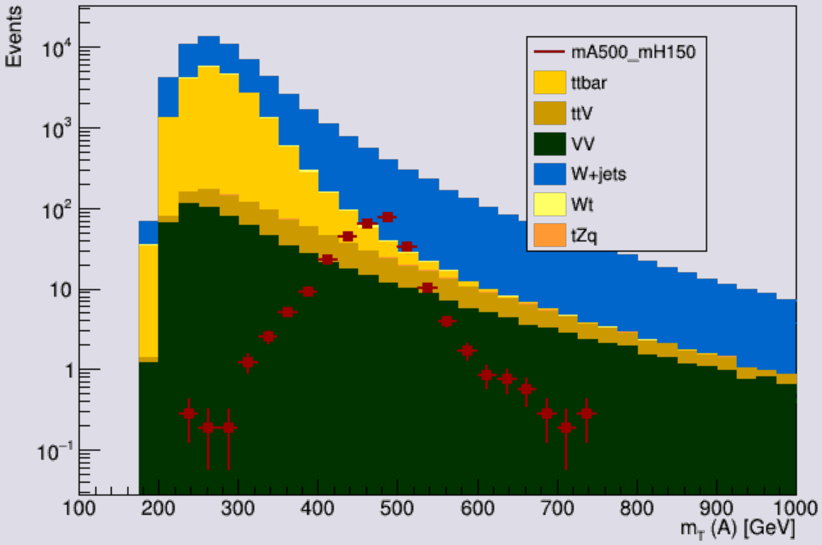
- **Z**: OSSF lepton-pair ($\mu^+\mu^-/e^+e^-$)
- **H candidate**: 2 b-jets
- **A candidate**: H+Z

Cuts inspired from the ATLAS A→ZH→llbb analysis

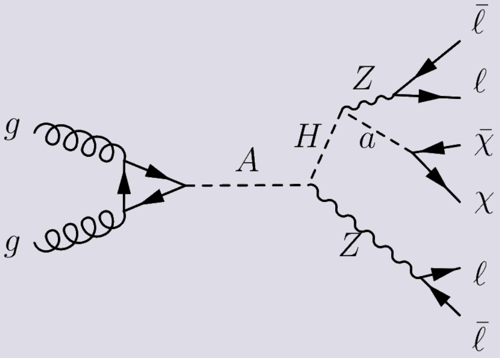
arXiv:2011.05639

- Apply $\mathbf{m_{bb}}$ **window**: $0.85m_H - 20 < m_{bb} < m_H + 20$ → Increase sensitivity

Calculate sensitivity with $\mathbf{m_A}$



ZZ+E_T^{miss} signature

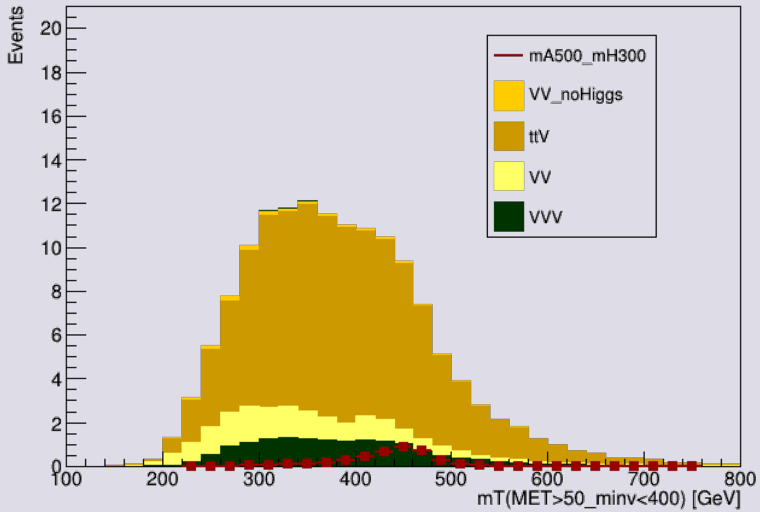


Cuts inspired from the ATLAS llll+MET analysis arxiv.2107.00404

- Exactly four leptons
- E_T^{miss} > 50 GeV
- m(4l) < 400 GeV

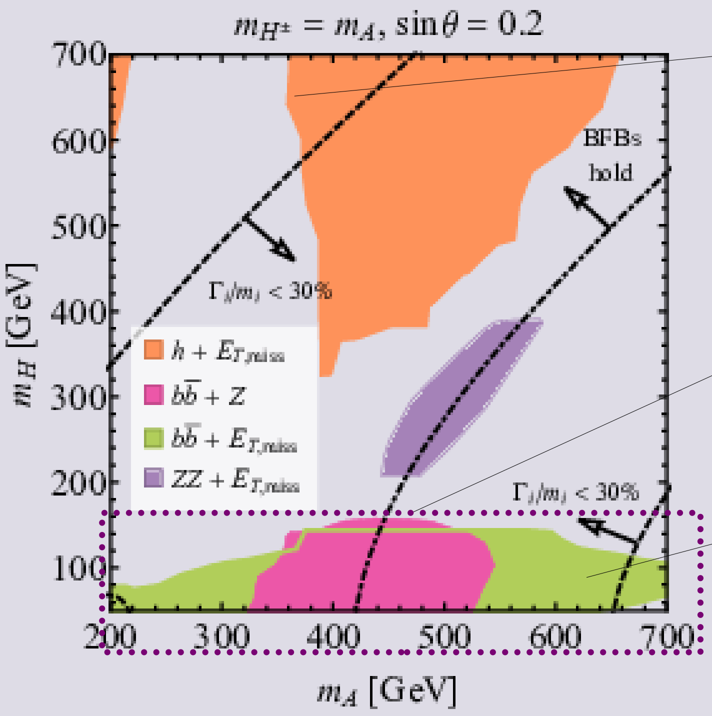
- Transverse mass for **A candidate**: $m^{inv}(4l)+E_T^{miss}$

Calculate sensitivity with $m_T(A)$



Results

- Exclusion shown for Run2 luminosity except ZZ+E_T^{miss} shown for Run2 + Run3



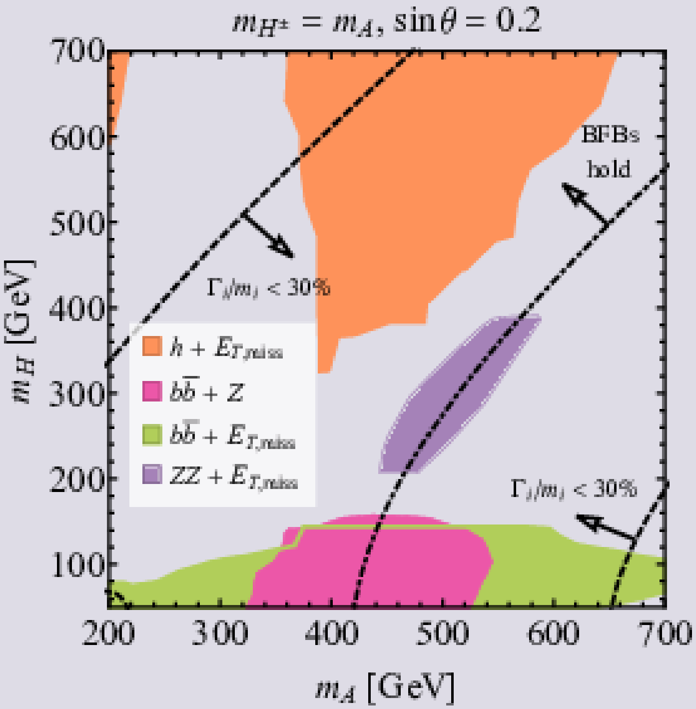
- Minimum requirement on E_T^{miss} sets a lower bound on $m_A \gtrsim 375$ GeV
- This restriction could be overcome be employing new techniques like **new b-jet triggers**

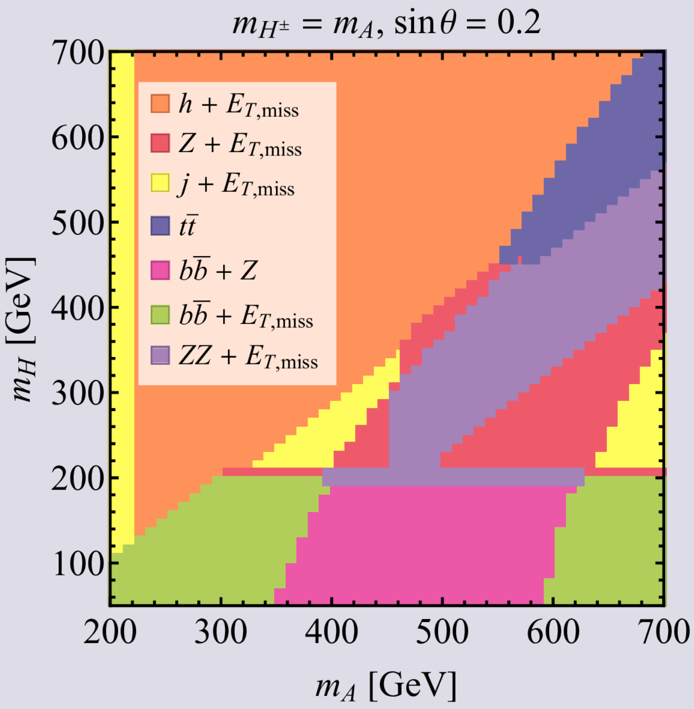
- Br(H → b$\bar{b}$) drops drastically when H→ aa/Za becomes kinematically possible

- Expand exclusion to masses **below** the mass of the **SM Higgs boson** → Particularly interesting to investigate observed small excess at ~95 GeV

Results

- Empty areas in the parameter region can be covered by further signatures such as **$Z+E_T^{miss}$, $j+E_T^{miss}$, $t\bar{t}$**

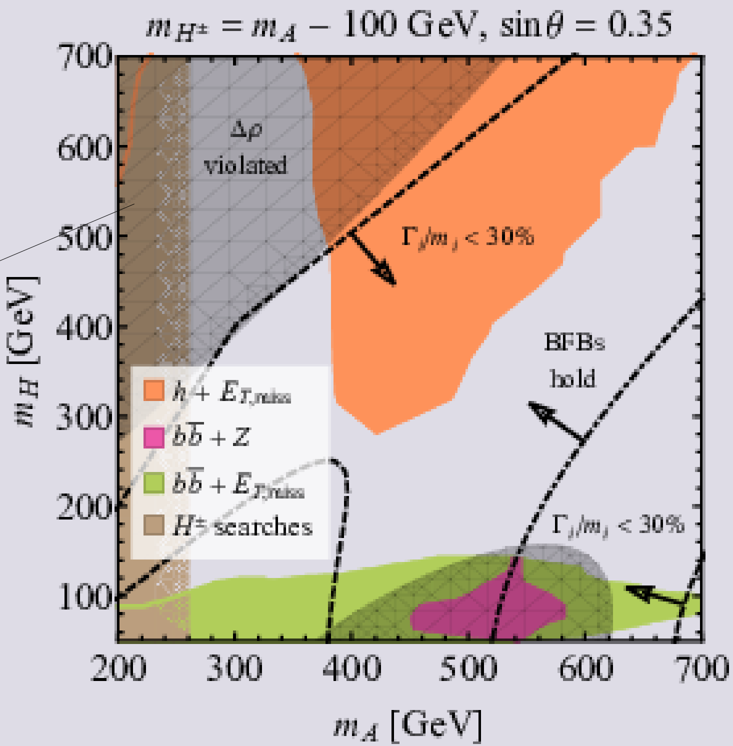




Results

- Allowing larger mass splitting **Δm = m_A-$m_{H\pm}$ = 100 GeV** → **A → H^+W^-** becomes kinematically possible

- **Extra constraints** through **A → H^+W^-**
- Stronger restrictions on allowed parameter space



Conclusion

- **2HDM+a of TypeI is not yet explored →** Leads to promising **new signatures**
- **Goal**: New benchmarks of uncovered final states → **New analyses with Run3 data**
- **New decay channels:** A → a H(bb), A → Z H(aZ)
  H → a A(tt), H → $H^+ W^-$
- $b\bar{b}+E_T^{miss}$ and $l\bar{l}b\bar{b}$ expand exclusion to masses **below the SM Higgs mass**

Novel collider signatures in the type-I 2HDM+a model

arxiv.2404.05704

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Thank you!

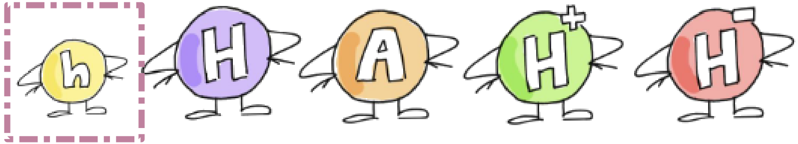
Back-up slides

2HDM+a theory

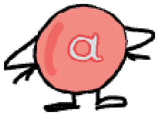
- **Two Higgs doublets H_1, H_2 , one pseudoscalar singlet P**

Five Higgs bosons

SM Higgs



One DM mediator



Mixing angles:

α → Mixing of CP-even states (H ⇔ h)

β → $\tan\beta \equiv \frac{v_2}{v_1}$

θ → Mixing of CP-odd states (A ⇔ a)

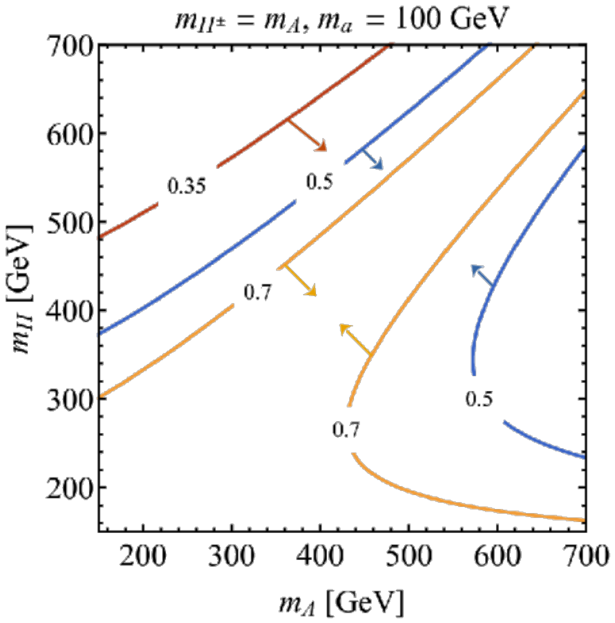
Couplings

	u-type	d-type	leptons	g_A^u	g_A^d
Type I	H_2	H_2	H_2	**1/tanβ**	**-1/tanβ**
Type II	H_2	H_1	H_1	**1/tanβ**	**tanβ**

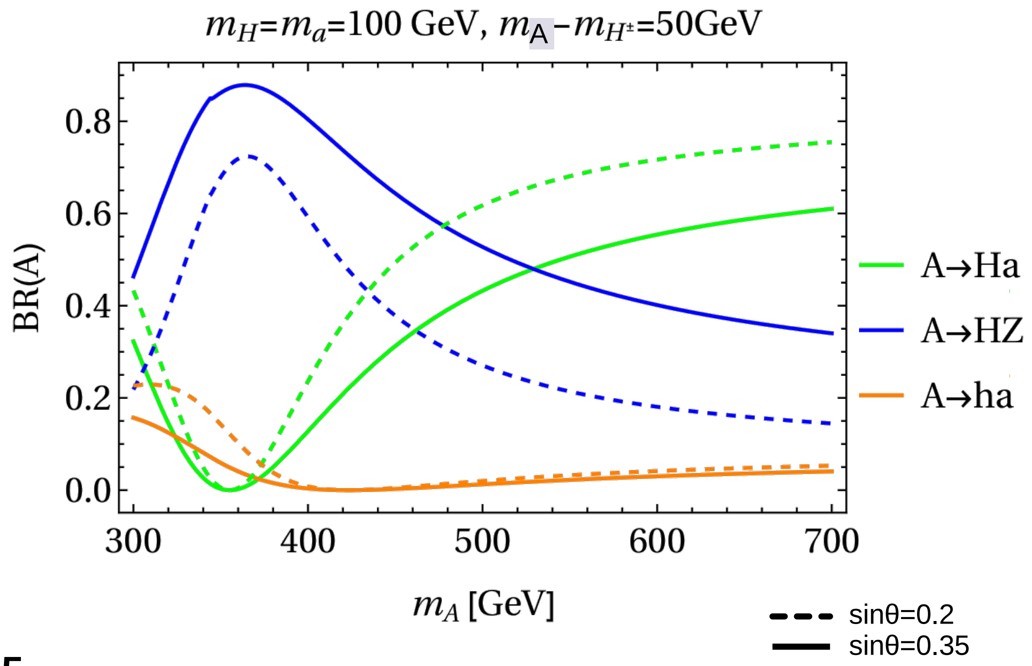
- Masses: $\mathbf{m_A}$, $\mathbf{m_H}$, $\mathbf{m_{H\pm}}$, $\mathbf{m_a}$, $\mathbf{m_\chi}$ (DM mass)

Constraints on mixing angle θ

- Constraints on sinθ from EW precision observables



- sinθ choice affects A branching ratio



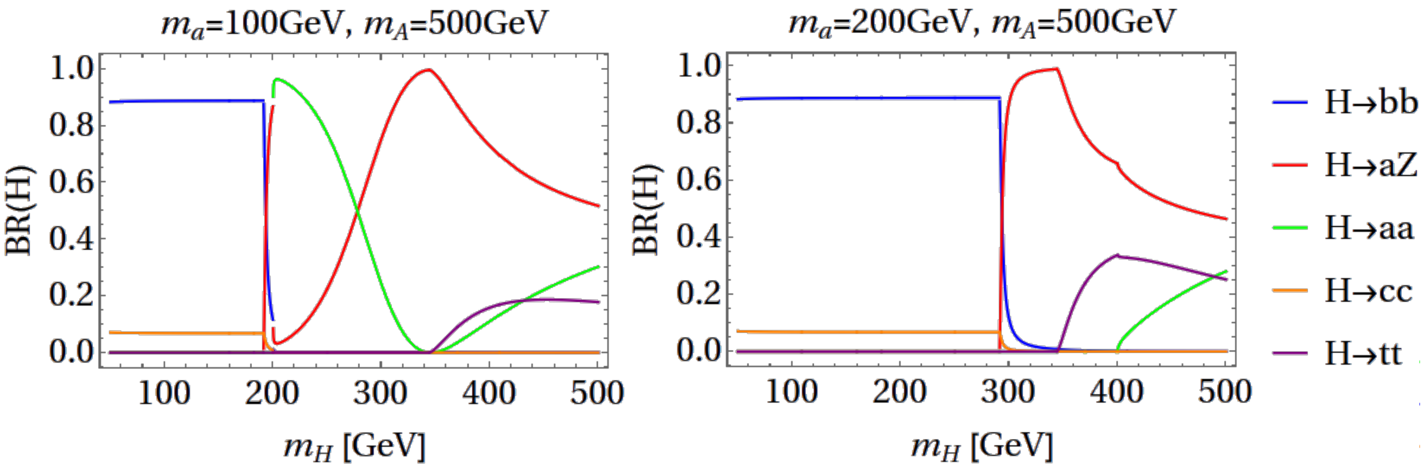
We choose **small sinθ** values of **0.2** and **0.35**

Constraints on Model Parameters

- Measurements for h → invisible constrain $m_a \gtrsim 100$ GeV

m_a choice affects H branching ratios

We choose:
m_a = 100 GeV



- SM Higgs boson couplings → tight constraints on cos(β-α): We choose **cos(β-α)=0** (alignment limit where h → SM Higgs)

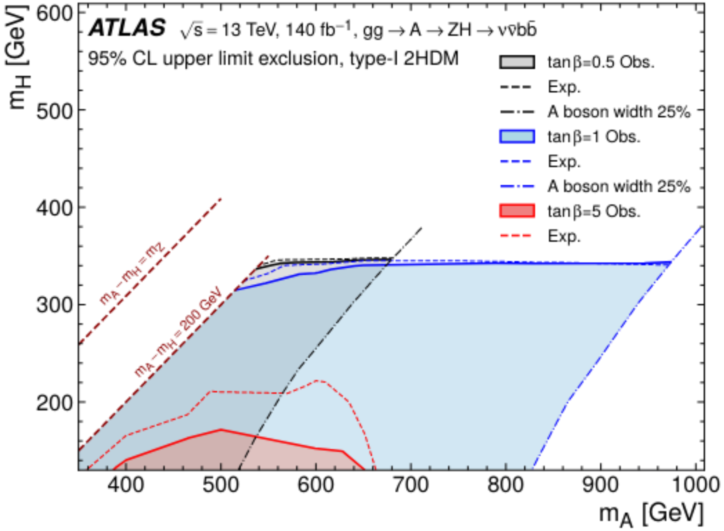
Additional constraints:

- Decay widths of BSM (pseudo)scalars should remain small → narrow width approximation
- Scalar potential should be bounded from below (BFB) to assure stability

$b\bar{b}+E_T^{miss}$ signature

ATLAS A → Z(νν)H(bb) analysis

arXiv:2311.04033

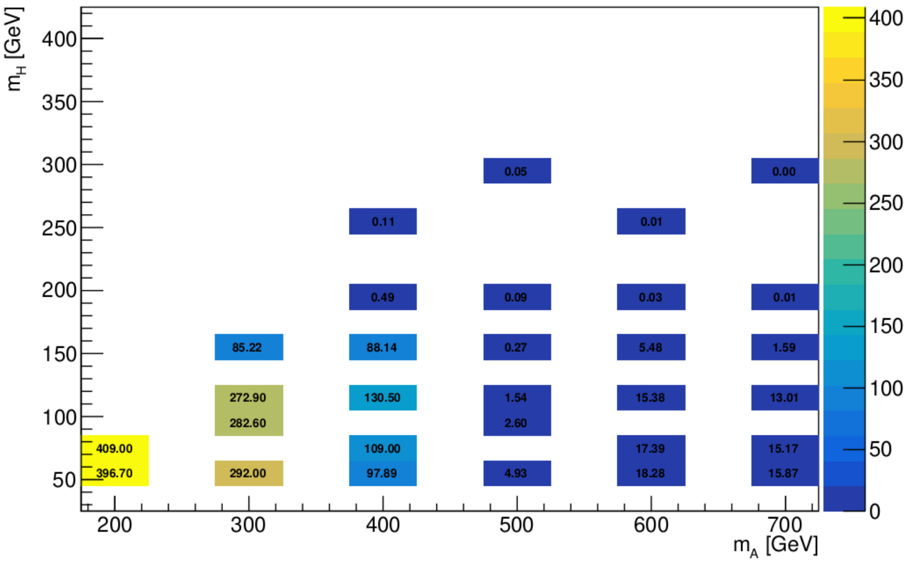


Requirement	Regions				
	2L (CR)	eμ (CR)	1L (VR)	0L Hlo / Hhi (CR)	0L Hin (SR)
Number of jets	2–5				
Number of b-jets	≥ 2				
$m(b\bar{b})$	> 50 GeV				
Number of τ^{had}	0				
$p_T(V)$	> 150 GeV				
$\min_i \Delta\phi(\vec{E}_T^{miss}, \vec{p}_i^{jet})$	$> \pi/10$				
$\Delta R(b_1, b_2)$	< 3.3 (2 b-jets) < 3.5 (≥ 3 b-jets)				
Number of leptons	2		1	0	
Lepton flavour	$ee/\mu\mu$	$e\mu$	e/μ	-	
$p_T(\ell_1)$	> 27 GeV			-	
$\lvert m_Z^{cand} - m_Z \rvert$	< 10 GeV	-			
S_{MET}	< 5	-	> 3	> 10	
m_{top}^{near}	-			> 180 GeV	
m_{top}^{far}	-			> 200 GeV	
$\lvert m(b\bar{b}) - m_H \rvert$	-			$> 0.2 \cdot m_H$	$< 0.2 \cdot m_H$

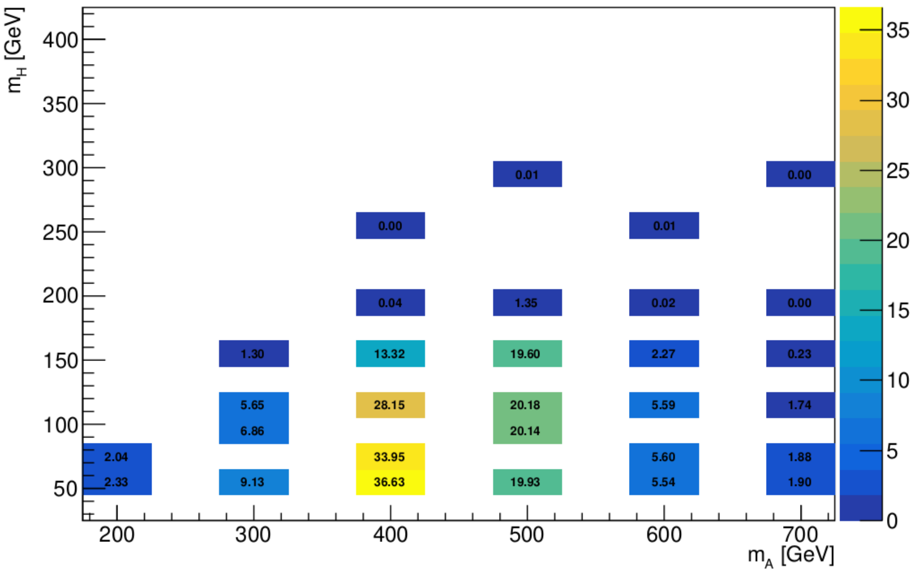
$b\bar{b}+E_T^{miss}$ signature

Cross-sections in fb

σ(ggA) x Br(A → aH) x Br(a → χχ)x Br(H → bb)

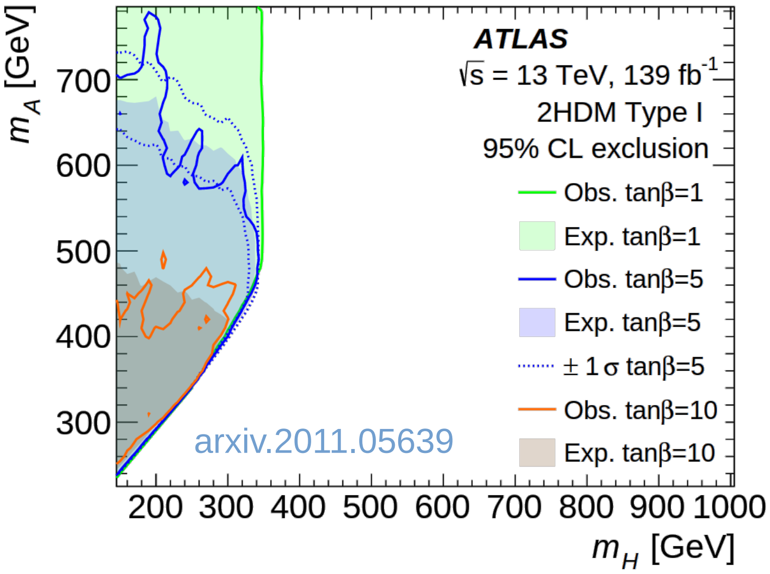


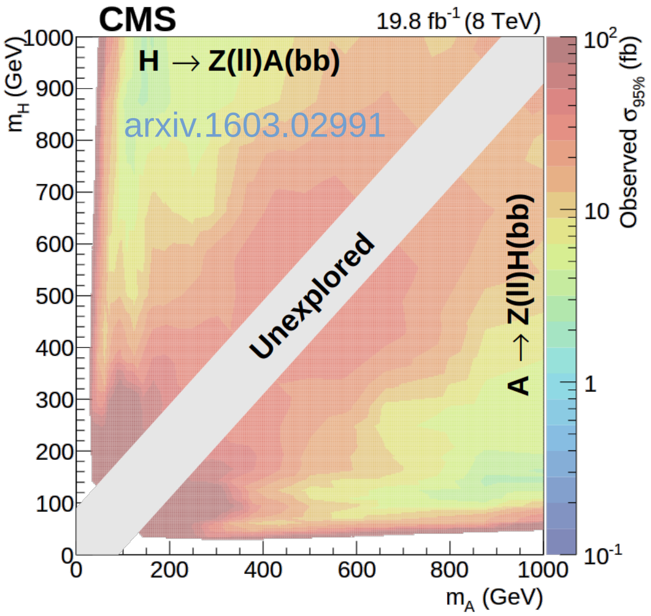
σ(ggA) x Br(A → ZH) x Br(Z → νν)x Br(H → bb)



$b\bar{b}+l\bar{l}$ signature
Previous analyses

- Previous A→ZH→llbb analyses both in ATLAS and CMS cover **$m_{b\bar{b}}$ above 125 GeV**





$b\bar{b}+l\bar{l}$ signature

- A→ZH→llbb in ATLAS
  arxiv.2011.05639

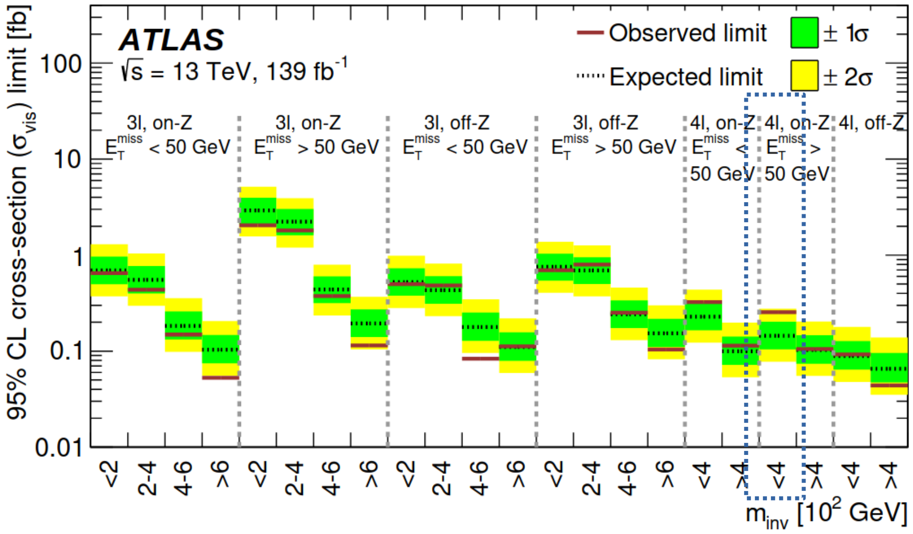
Table 1: Summary of the event selection for signal and control regions in the $A \to ZH \to \ell\ell bb$ channel.

Single-electron or single-muon trigger Exactly 2 leptons (e or μ) ($p_T > 7$ GeV) with the leading one having $p_T > 27$ GeV Opposite electric charge for $\mu\mu$ pairs; 80 GeV $< m_{\ell\ell,\ e\mu} <$ 100 GeV, $\ell = e,\ \mu$ At least 2 b-jets ($p_T > 20$ GeV) with one of them having $p_T > 45$ GeV $E_T^{miss}/\sqrt{H_T} < 3.5\ \mathrm{GeV}^{1/2}$, $\sqrt{\Sigma p_T^2}/m_{\ell\ell bb} > 0.4$		
	$n_b = 2$ category	$n_b \geq 3$ category
	Exactly 2 b-tagged jets	At least 3 b-tagged jets
Signal region	ee or $\mu\mu$ pair $0.85 \cdot m_H - 20$ GeV $< m_{bb} < m_H + 20$ GeV	ee or $\mu\mu$ pair $0.85 \cdot m_H - 25$ GeV $< m_{bb} < m_H + 50$ GeV
Z+jets control region	ee or $\mu\mu$ pair $m_{bb} < 0.85 \cdot m_H - 20$ GeV or $m_{bb} > m_H + 20$ GeV	ee or $\mu\mu$ pair $m_{bb} < 0.85 \cdot m_H - 25$ GeV or $m_{bb} > m_H + 50$ GeV
Top control region	$e\mu$ pair $0.85 \cdot m_H - 20$ GeV $< m_{bb} < m_H + 20$ GeV	$e\mu$ pair $0.85 \cdot m_H - 25$ GeV $< m_{bb} < m_H + 50$ GeV

ZZ+E_T^{miss} signature

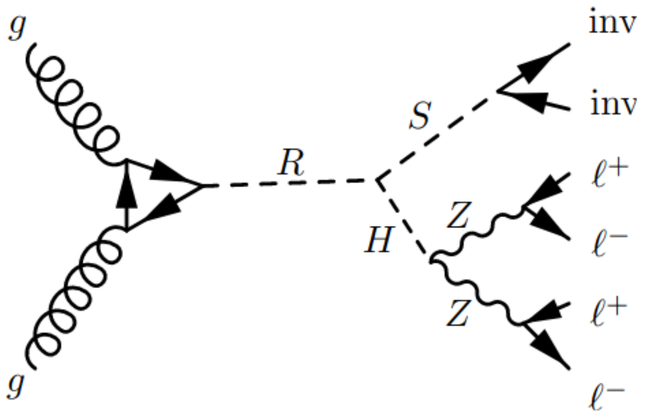
Selection from arxiv.2107.00404

- Exactly four leptons
- $|m_Z-91.2| < 10$ GeV
- $p_T(l)>25$GeV
- $E_T^{miss} > 50$ GeV
- m(4l) < 400 GeV



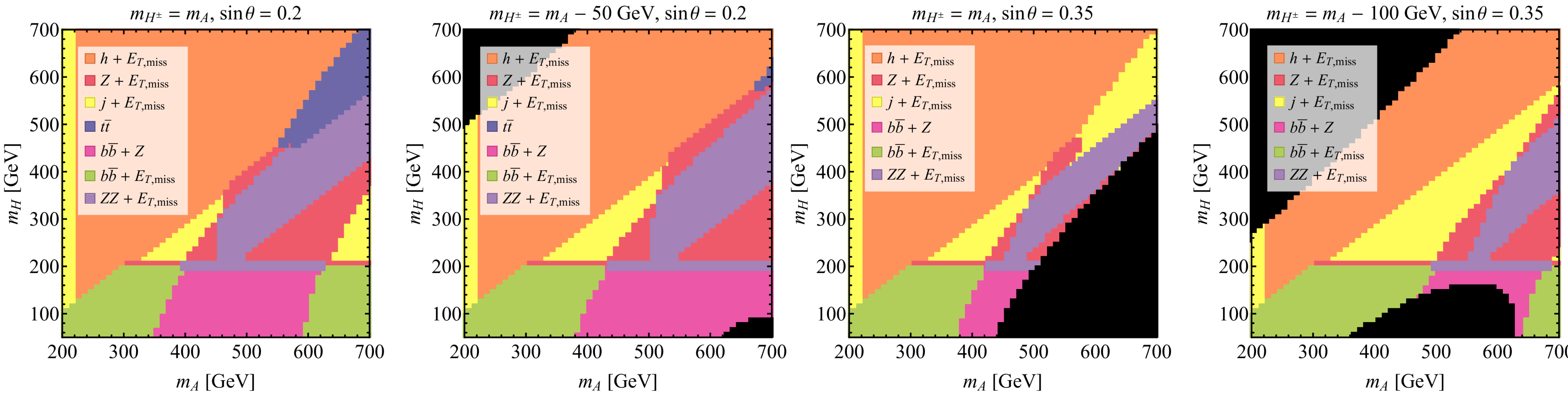
arxiv.2401.04742

Additional ATLAS 4l+MET search with 4l coming from H resonance



Benchmark scenarios

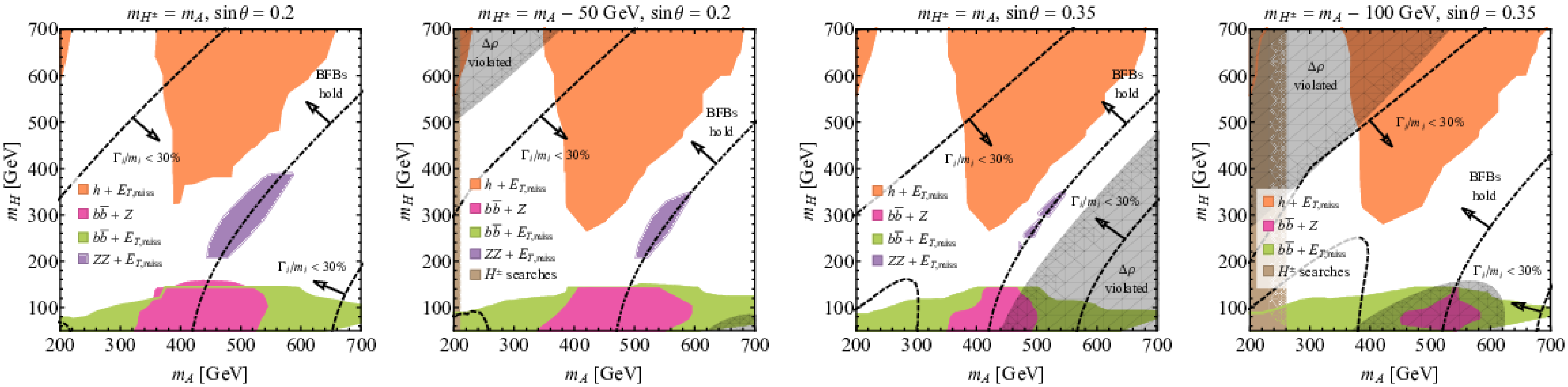
Study four benchmark points for different $\Delta m = m_A - m_{H^\pm}$ and $\tan\beta$



Black: Constraints from EW precision measurements and decay widths > 30%

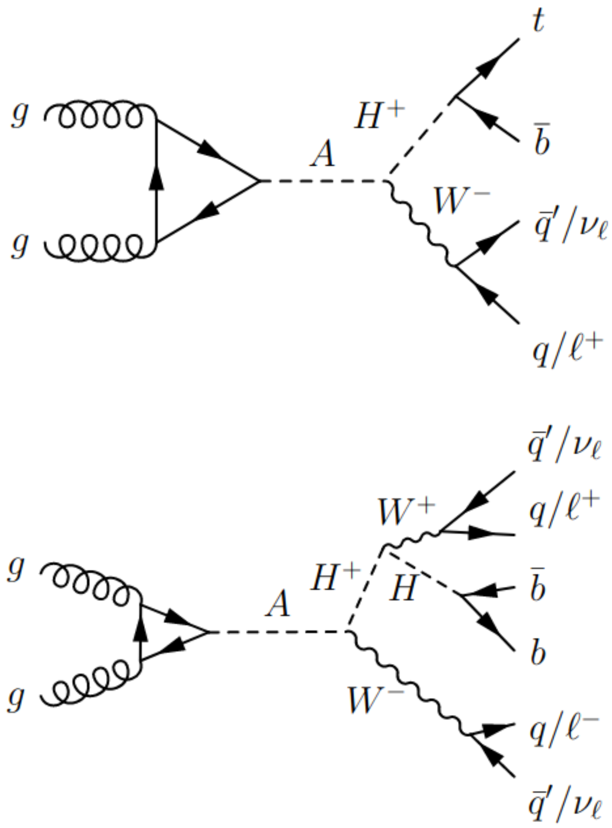
Exclusion

- Show four different benchmark points for different $\Delta m = m_A - m_{H^\pm}$ and $\sin\theta$



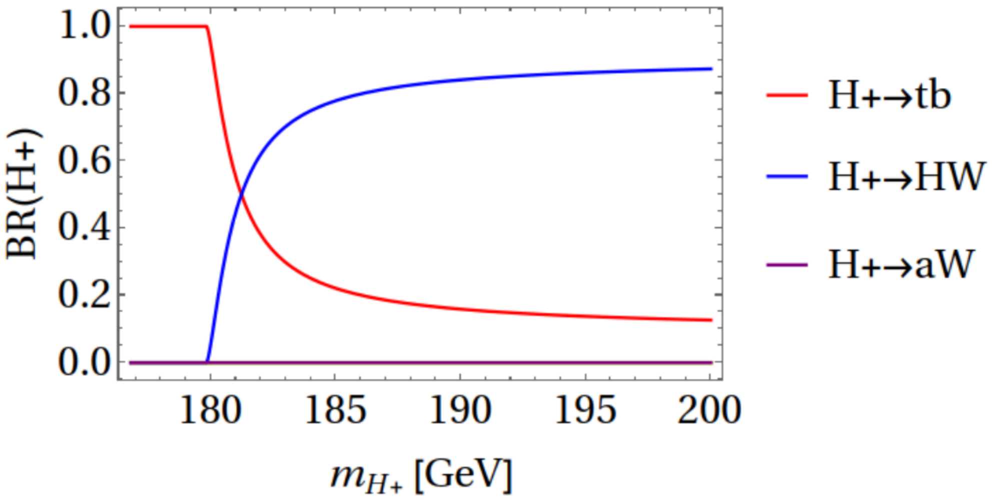
- $\Delta\rho$ violated: Constraints from electroweak precision observables
- BFBs hold: Scalar potential is bounded from below
- $\Gamma_i/m_i < 30\%$: Decay widths of scalars should remain small

Signatures with charged Higgs



- Allowing **larger mass splitting between m_A and $m_{H\pm}$** makes further **new unexplored signal signatures** kinematically possible such as **$A \to H^+W^-$**

$m_{H\pm}=m_A$-120, m_H=100GeV, m_a=600GeV

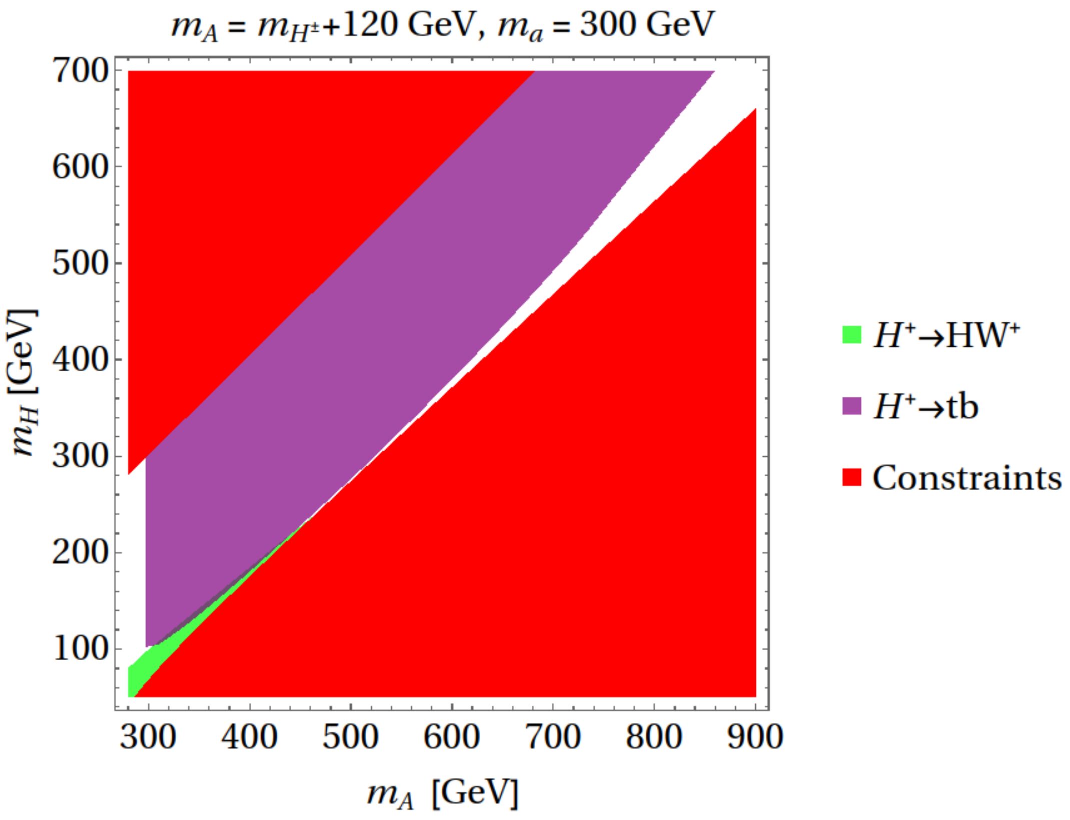


Signatures with charged Higgs

The A → H^+W^- decay

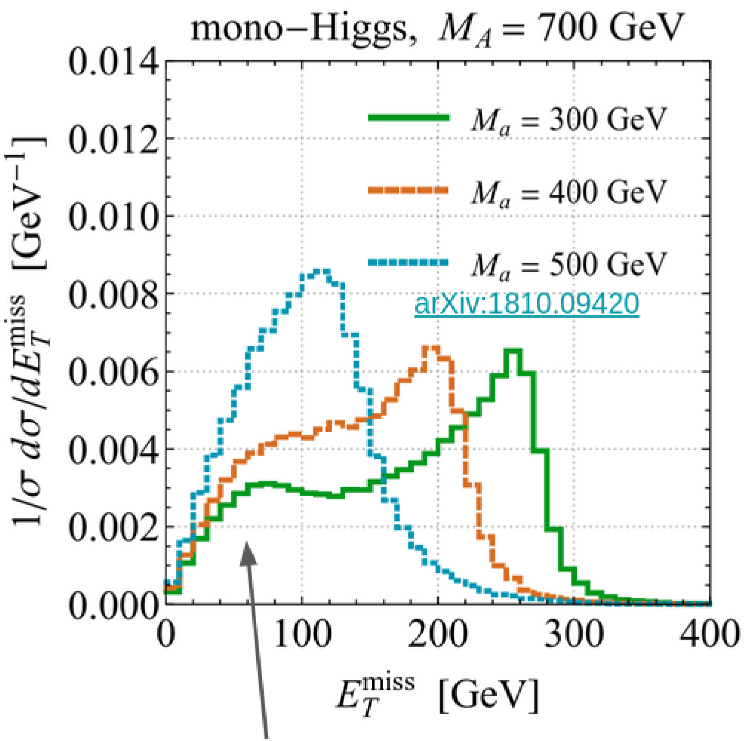
- **No previous A → H^+W^- analysis**

- Only a small region (bottom left corner) is sensitive for the $H^\pm \to W^\pm H$ decay
- Larger region where the $H^\pm \to t\bar{b}$ decay is important
- Both of them give a final state not previously explored



$b\bar{b}+E_T^{miss}$ signature

Impact of Box Diagrams



Box diagrams become important for large mass difference between a and A (decay A $\rightarrow h_{SM}\, a(\chi\bar{\chi})$)

$$E_{\mathrm{T,max}}^{\mathrm{miss}} \approx \frac{\lambda^{\frac{1}{2}}(M_A, M_{h,H}, M_a)}{2M_A}$$

with

$$\lambda(M_A, M_{h,H}, M_a) = (M_A^2 - M_{h,H}^2 - M_a^2)^2 - 4M_{h,H}^2 M_a^2$$