*Probing new frontiers: Unraveling **Dark Matter** with novel collider signatures in Type I 2HDM+a*

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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 may be violated: Interactions between DM mediator and SM fermions are not gauge invariant arXiv:1510.02110

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

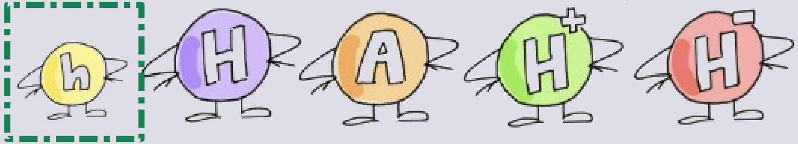
Two Higgs Doublet Model with an additional pseudoscalar DM mediator 2HDM+a: simplest gauge-invariant and renormalisable extension of the simplified pseudoscalar DM model

→ New channels for particle interaction → More distinctive collider signatures

2HDM+a theory

- **Two Higgs doublets H_1, H_2 , one pseudoscalar singlet P**
- Scalar potential: $V = V_H + V_{HP} + V_P$

Five Higgs bosons



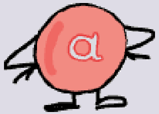
SM Higgs

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

  Previous ATLAS and CMS searches: **BSM 2HDM states degenerate in mass $\mathbf{m_A=m_H=m_{H\pm}}$**

  Many signatures are not kinematically allowed with this restriction: **$A \rightarrow Ha$, $A \rightarrow HZ$, $A \rightarrow H^+W^-$**

One DM mediator



Model Parameters

- 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)

  → sinθ choice affects pseudoscalar branching ratios

- Couplings

	up-type	down-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**

Couplings in Type I in alignment limit cos(β-α)=0

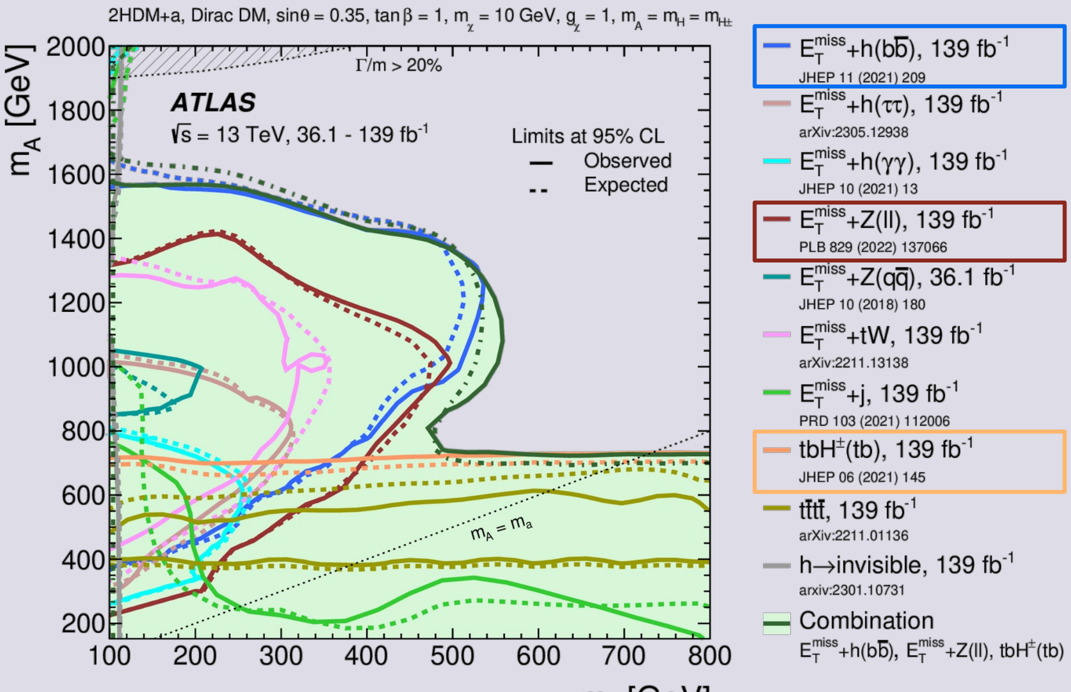
$$g_{Hf\bar{f}} = y_f \cot\beta \qquad g_{Af\bar{f}} = \eta_f \, y_f \cot\beta \cos\theta$$

$$g_{af\bar{f}} = \eta_f \, y_f \cot\beta \sin\theta$$

Previous searches

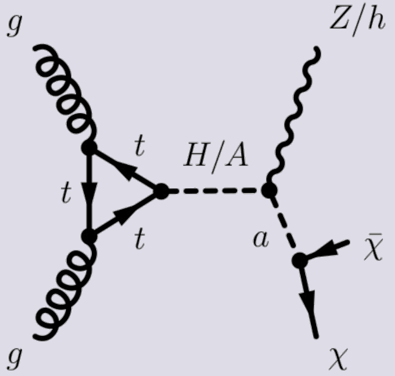
Exclusion m_A-m_a plane

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

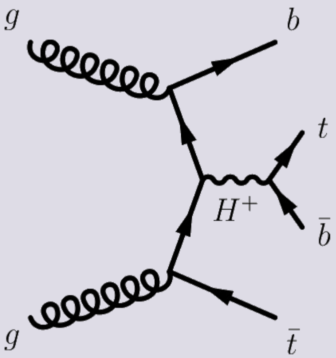


arxiv.2306.00641

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

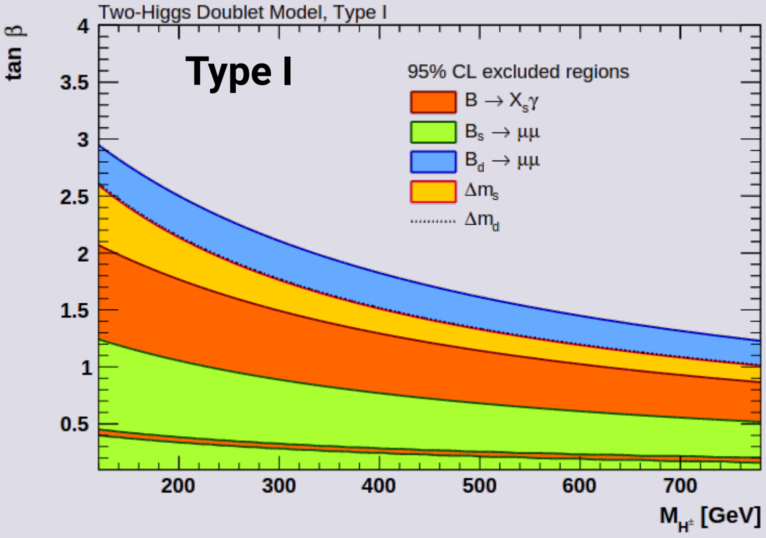


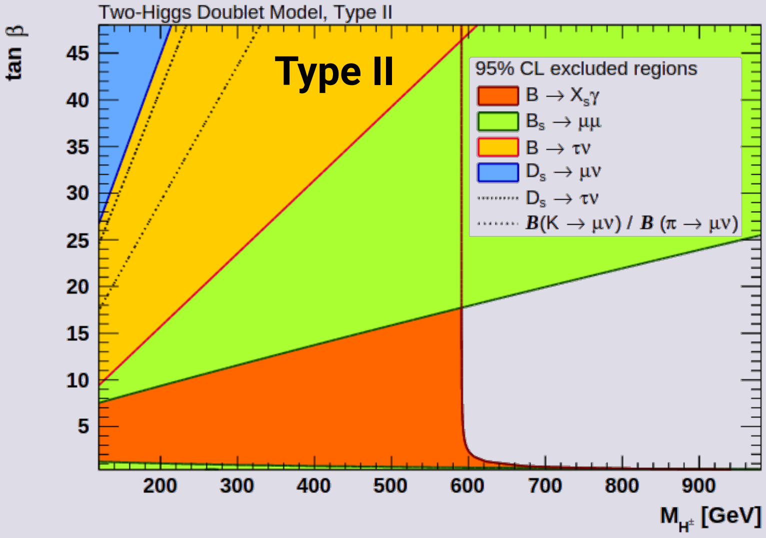
- tbH± provides complementary sensitivity



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
  - $H^{\pm}$ 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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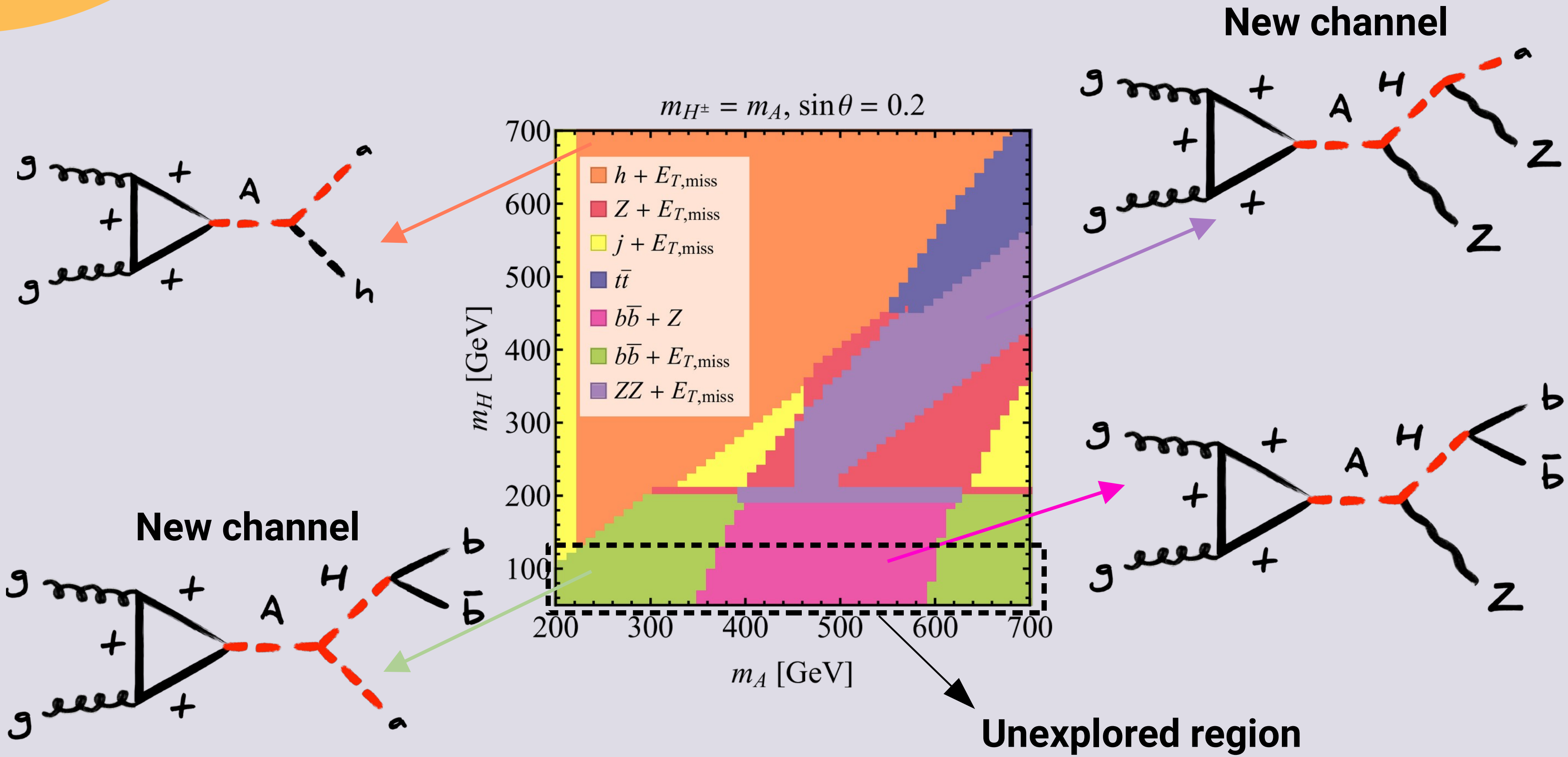
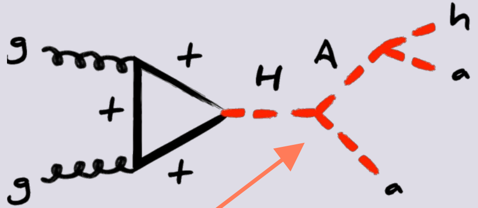
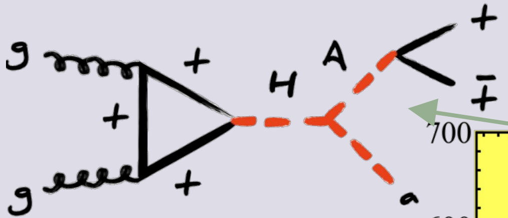
A boson dominant decays

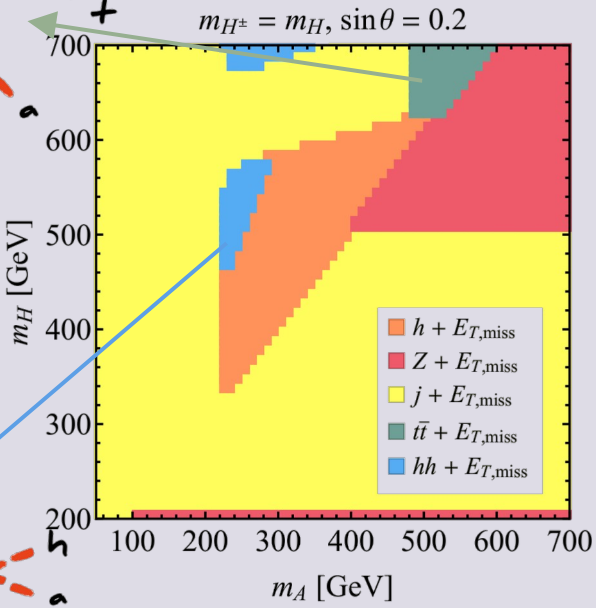


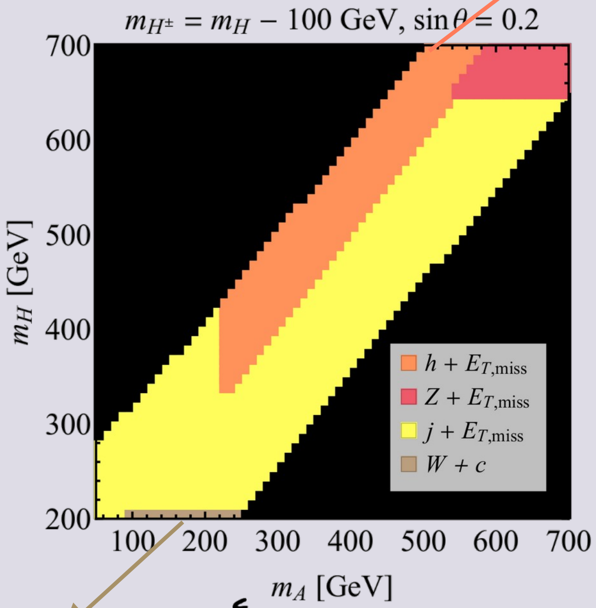
H boson dominant decays

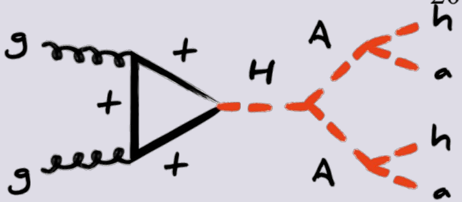


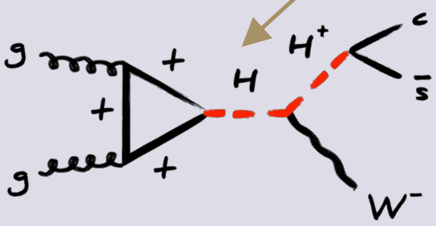
H decays provide new channels







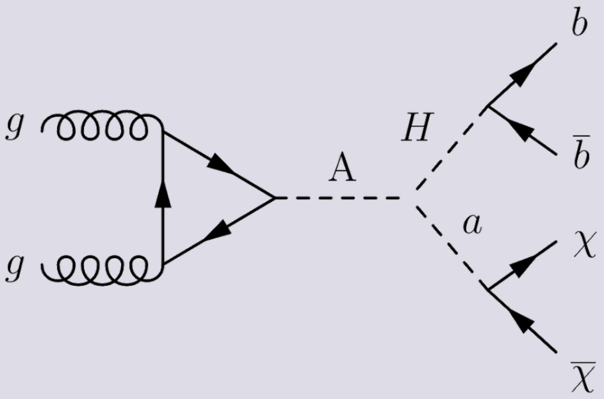


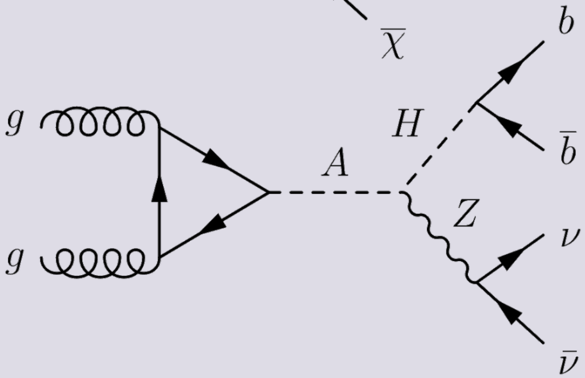


In the following we focus on $b\bar{b}+E_T^{miss}$ and $l\bar{l}+b\bar{b}$

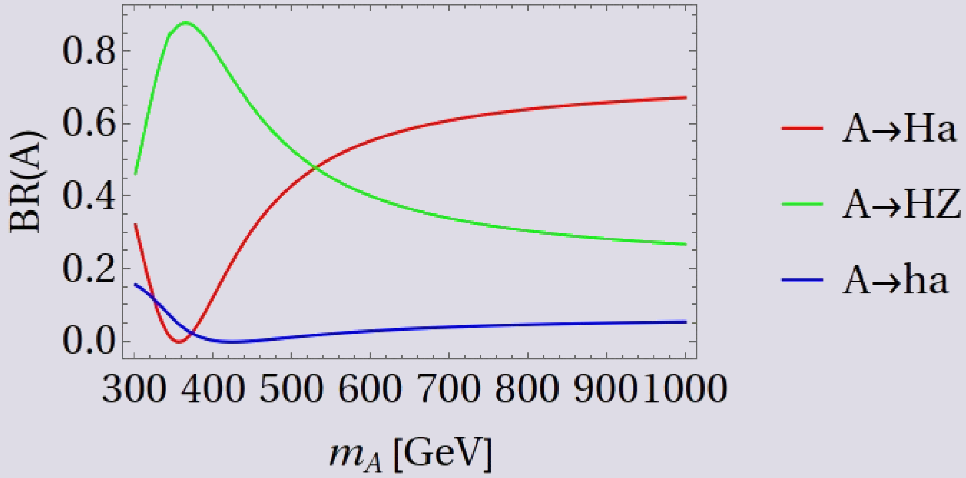
$b\bar{b}+E_T^{miss}$ signature

- **Study of $b\bar{b}+E_T^{miss}$ final state:** Increased sensitivity due to resonant production, enhanced $H \to b\bar{b}$ branching ratio for smaller m_H, not complicated final state





$m_H = m_a = 100$ GeV



- $A \to Ha$ decay dominates over $A \to HZ$ for larger m_A values
- Both decay modes should be consider for $b\bar{b}+E_T^{miss}$ final state

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

Event reconstruction

Requirements

- **0 leptons**
  leptons: p_T > 7GeV, |η| < 2.47(e) / 2.5(μ)
- **Exactly 2 b-jets** with m_{bb}>50GeV
  jets: anti-kT p_T > 20GeV, |η| < 2.5
- **E_T^{miss} > 150GeV**

Further cuts

- Less than 6 jets
- E_T^{miss} significance ($E_t^{miss}/\sqrt{\Sigma p_T^{jets}}$) > 10
- $\min\Delta\varphi(E_T^{miss},\text{jets})>\pi/10$
- $\Delta R(b_1,b_2)<3.3$
- $N_\tau=0$
- $m_{top}^{near(far)}$>180(200) GeV

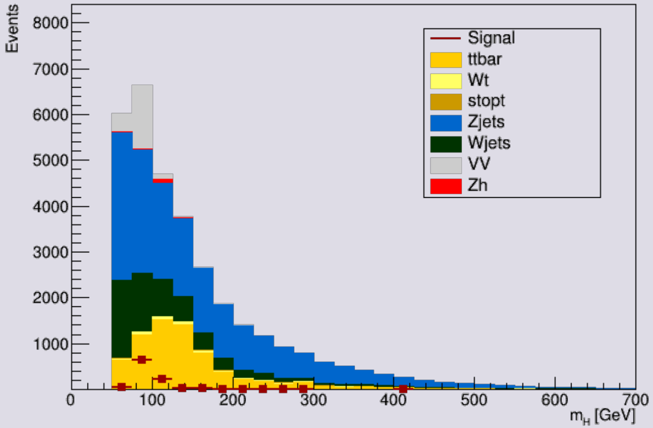
Cuts similar to the ATLAS A → Z(νν)H(bb) analysis

arXiv:2311.04033

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

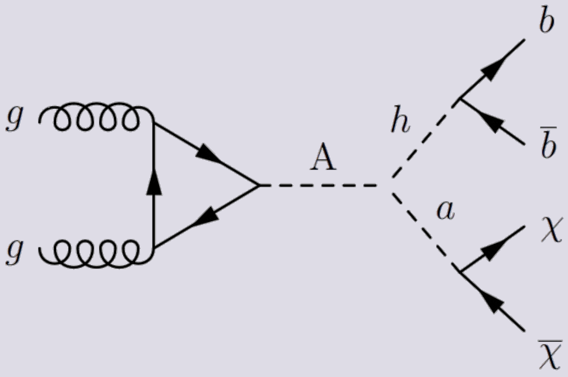
$$m_T = \sqrt{m^2 + p_x^2 + p_y^2}$$

Calculate sensitivity with m_H

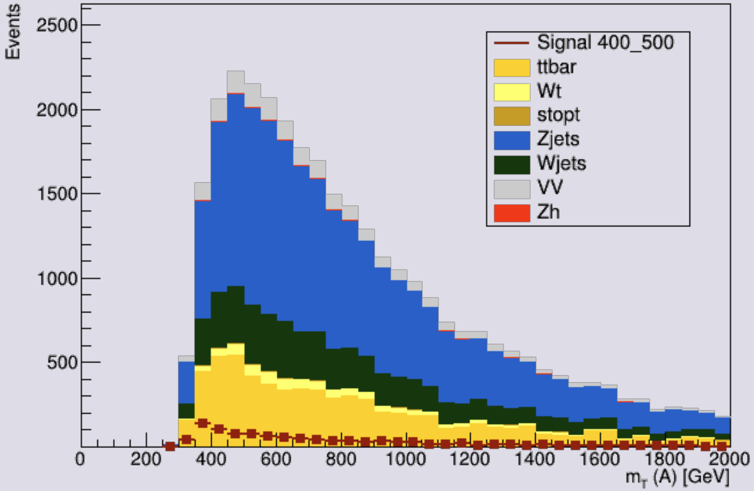


h+E_T^{miss} signature

- 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}

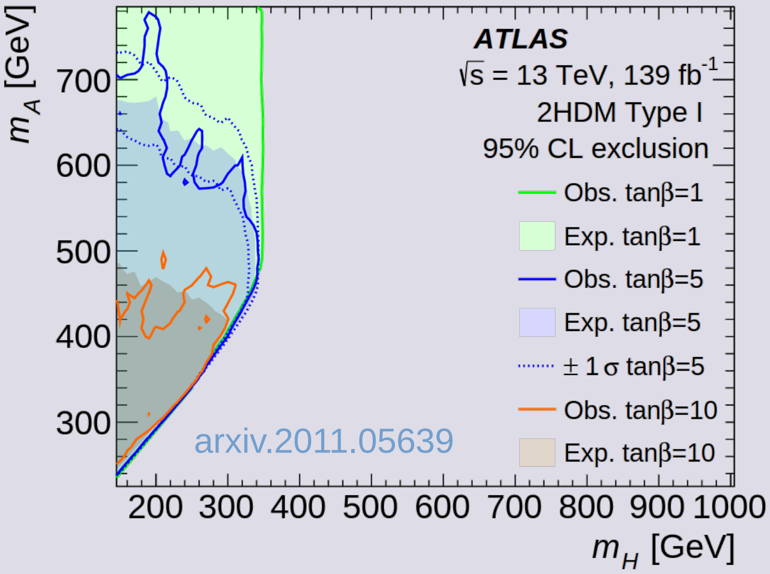


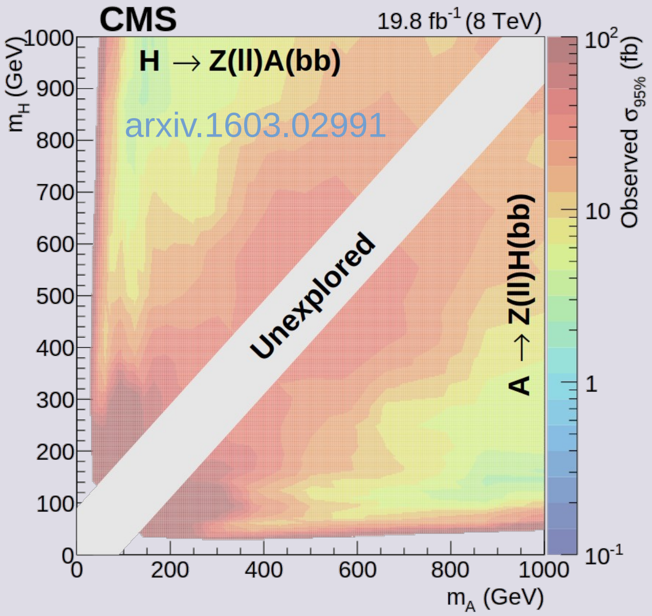
Calculate sensitivity with m_T(A)



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

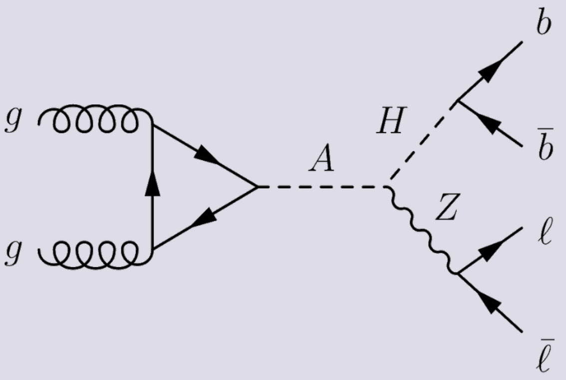
- Previous A→ZH→llbb analyses both in ATLAS and CMS (full Run-2) cover $m_{b\bar{b}}$ above the SM Higgs





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

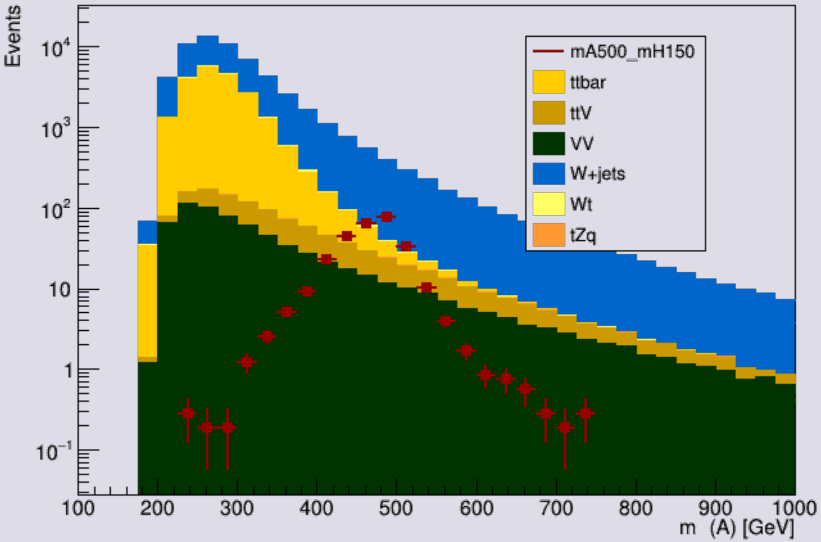
- **Z**: lepton-pair
- **H candidate**: 2 b-jets
- **A candidate**: H+Z



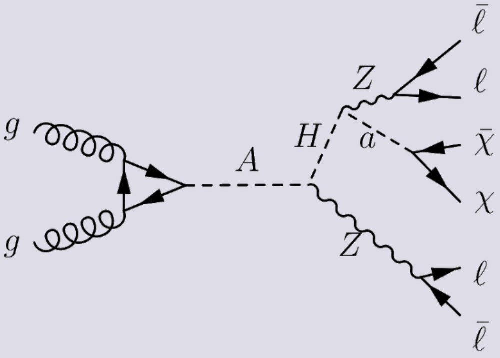
Cuts inspired from the ATLAS A→ZH→llbb analysis
arXiv:2011.05639

- One opposite sign same flavour lepton pair
- Exactly two b-jets
- Less than 6 jets
- $80<m_Z<100$GeV
- $p_T(l_1)>27$GeV, $p_T(l_2)>13$GeV
- E_T^{miss} significance ($E_t^{miss}/\sqrt{\Sigma p_T^{jets}}$) < 3.5
- $\sqrt{\Sigma p_T^2}$(leptons+jets)/m_{bbll} >0.4
- m_{bb} window: $0.85m_H - 20 < m_{bb} < m_H+20$

Calculate sensitivity with m_A



$ZZ+E_T^{miss}$ signature

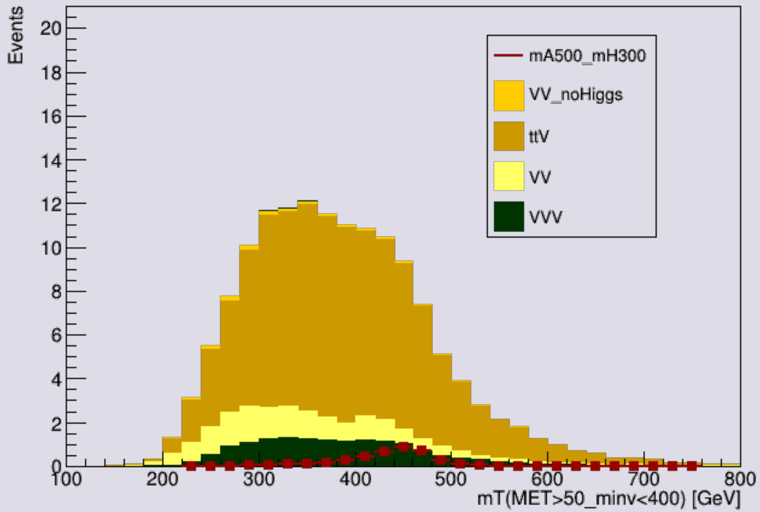


Cuts inspired from the ATLAS A→ZH→llll+MET analysis arXiv:2401.04742

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

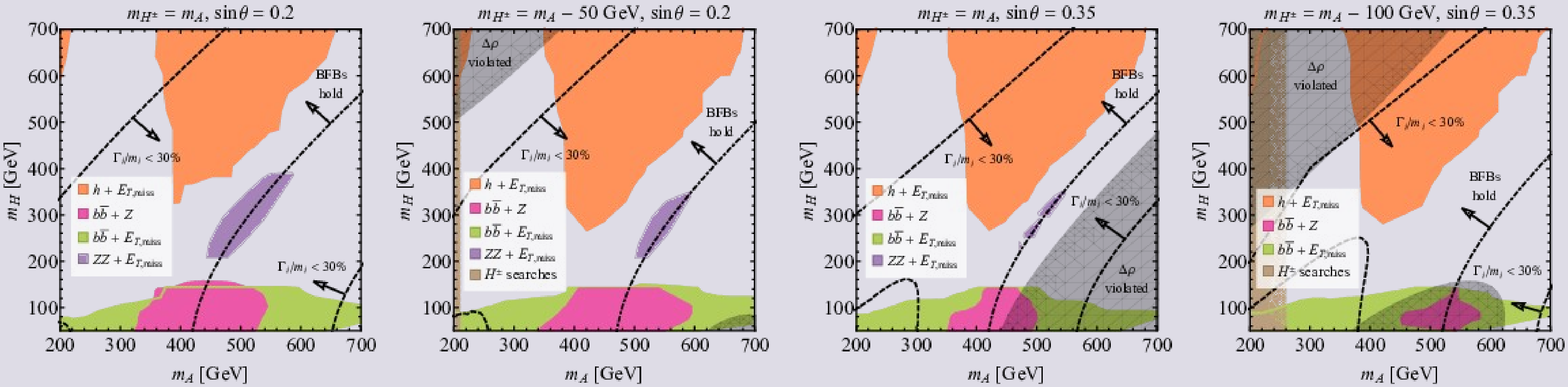
- Transverse mass for **A candidate**: $m^{inv}(4l)+E_T^{miss}$

Calculate sensitivity with $m_T(A)$



Exclusion

- Show four different benchmark points for different $\Delta m = m_A - m_{H^\pm}$ and $\sin\theta$
- Expand exclusion to masses below the mass of the SM Higgs boson
- Larger Δm allows the resonant production of $H^\pm$ through $A \to H^+W^-$



- $\Delta\rho$ 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

Conclusion

- **2HDM+a for 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:** $A \to a\, H(bb)$, $A \to Z\, H(aZ)$
  $H \to a\, A(tt)$, $H \to H^+ W^-$
- $b\bar{b}+E_T^{miss}$ 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

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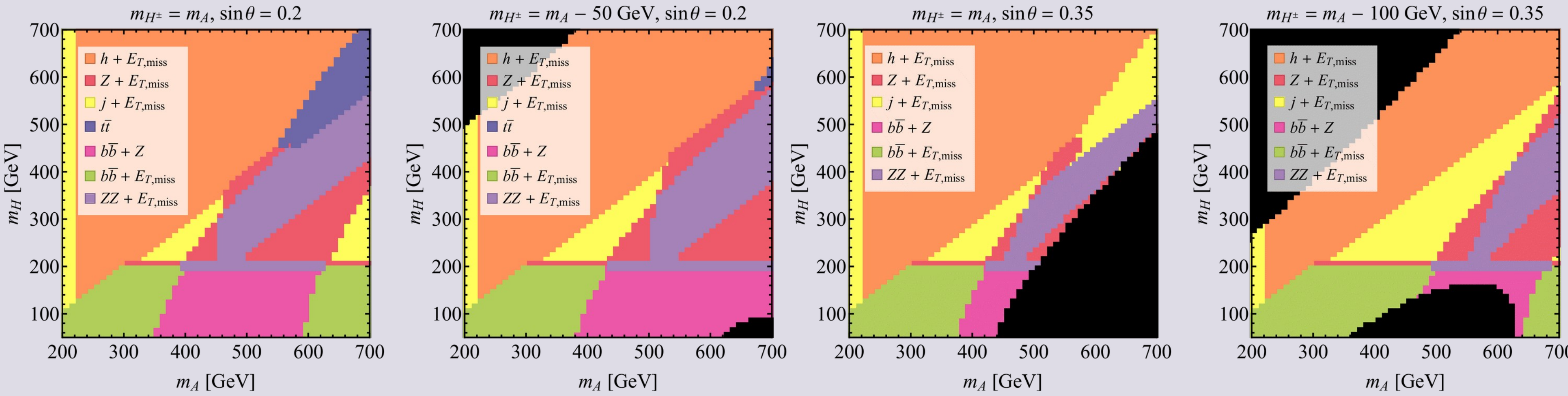
Thank you!

Back-up slides

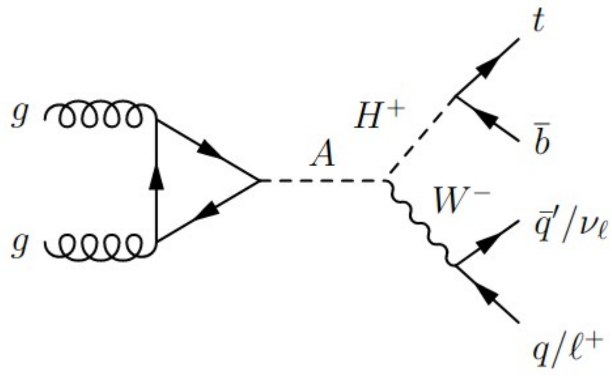
Benchmark scenarios

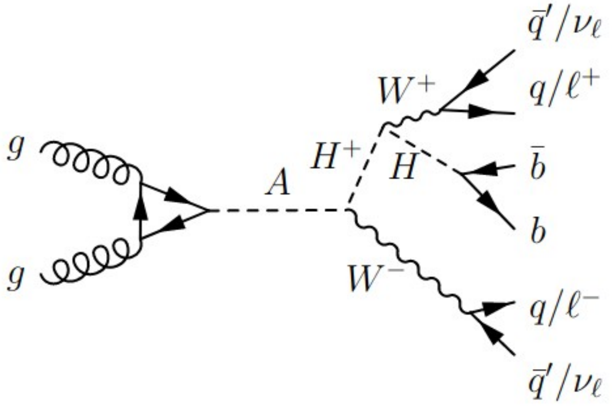
Study four benchmark points for different $\Delta m = m_A - m_{H^\pm}$ and $\tan\beta$



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

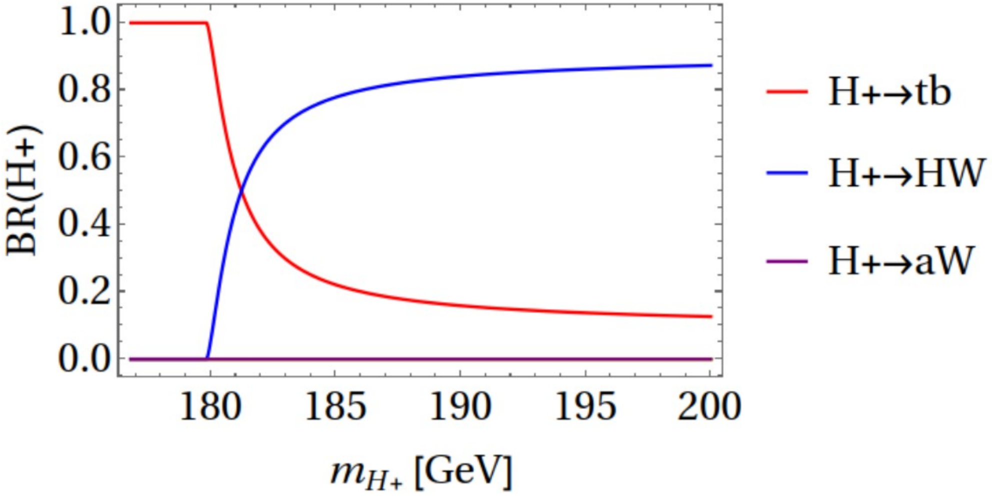
Signatures with charged Higgs





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

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

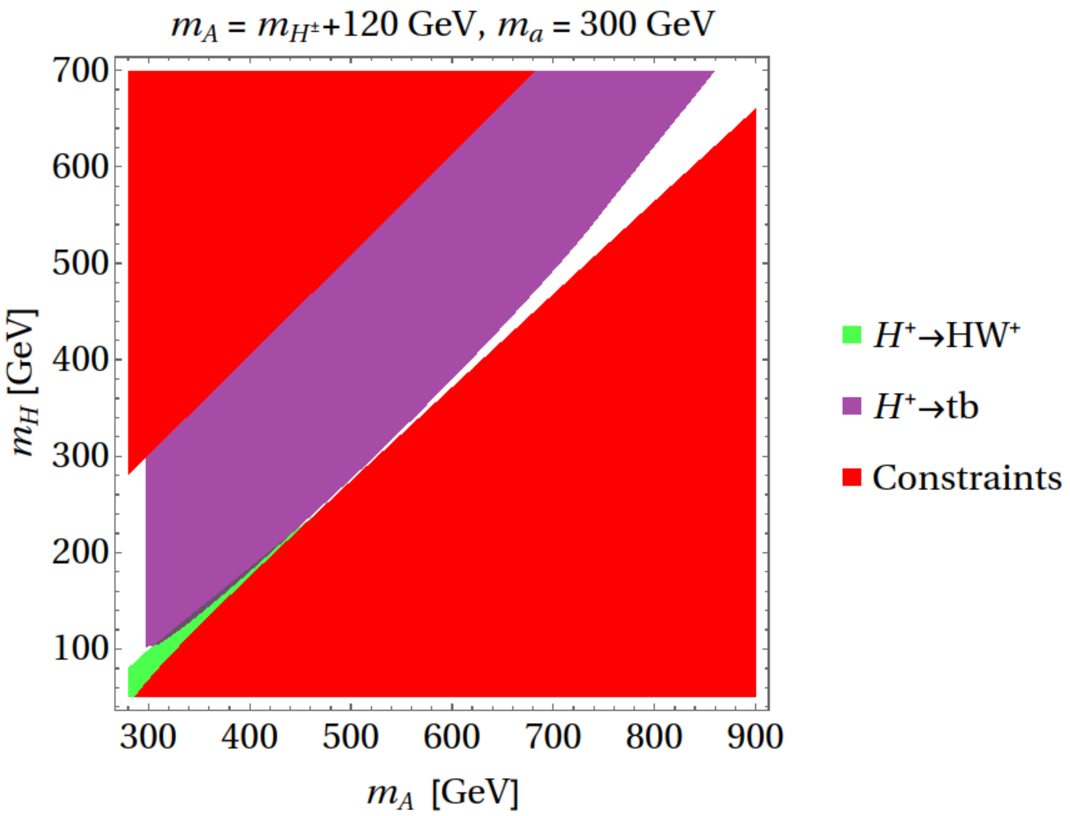


Signatures with charged Higgs

The A → H^+W^- decay

- **No previous A → H^+W^- analysis**

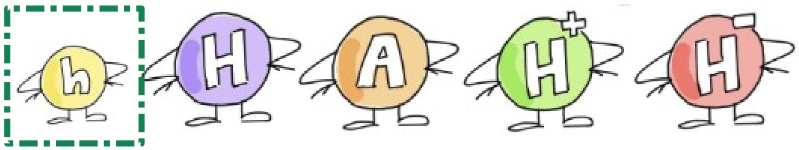
- Only a small region (bottom left corner) is sensitive for the $H^\pm \to W^\pm H$ decay
- Larger region where the $H^\pm \to t\bar{b}$ decay is important
- Both of them give a final state not previously explored



2HDM+a theory

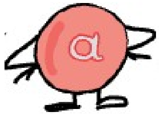
- **Two Higgs doublets H_1, H_2 , one pseudoscalar singlet P**
- Scalar potential $V = V_H + V_{HP} + V_P$
- $$V_H = \mu_1 H_1^\dagger H_1 + \mu_2 H_2^\dagger H_2 + \left(\mu_3 H_1^\dagger H_2 + \text{h.c.}\right) + \lambda_1 \left(H_1^\dagger H_1\right)^2 + \lambda_2 \left(H_2^\dagger H_2\right)^2 + \lambda_3 \left(H_1^\dagger H_1\right)\left(H_2^\dagger H_2\right) + \lambda_4 \left(H_1^\dagger H_2\right)\left(H_2^\dagger H_1\right) + \left[\lambda_5 \left(H_1^\dagger H_2\right)^2 + \text{h.c.}\right]$$
- $$V_{HP} = P\left(i b_P H_1^\dagger H_2 + \text{h.c.}\right) + P^2\left(\lambda_{P1} H_1^\dagger H_1 + \lambda_{P2} H_2^\dagger H_2\right)$$
- $$V_P = \frac{1}{2} m_P^2 P^2$$

Five Higgs bosons



SM Higgs

One DM mediator



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  α → Mixing of CP-even states (H ⇔ h)

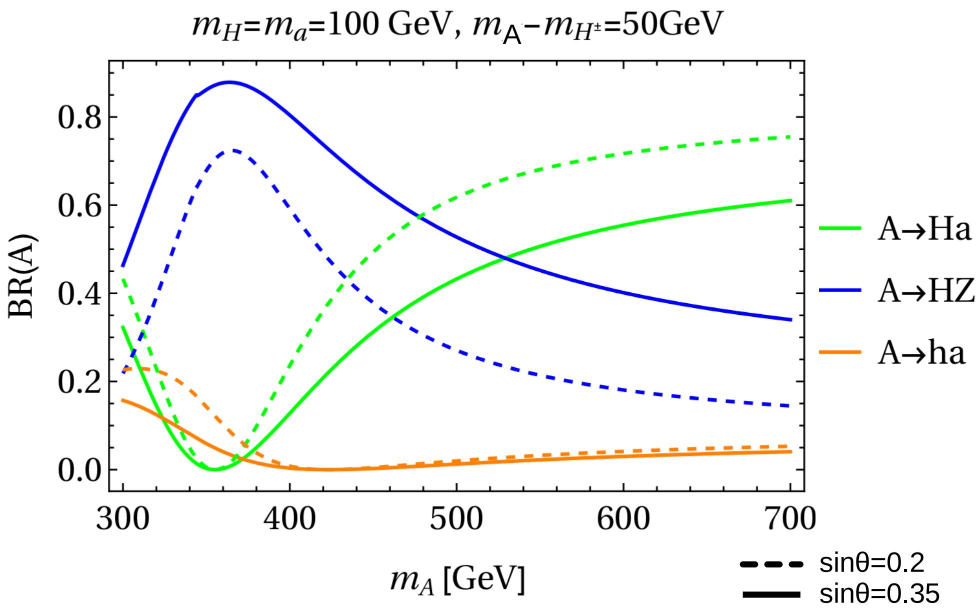
  β → $\tan\beta \equiv \frac{v_2}{v_1}$

  θ → Mixing of CP-odd states (A ⇔ a)

- Allowing mass splittings →

  Relatively small sinθ values are allowed

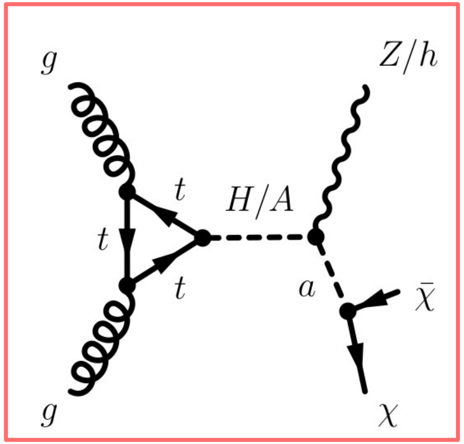
- sinθ choice affects A branching ratio



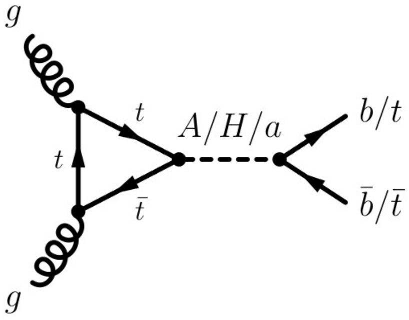
Previous searches

Previous searches:
No mass hierarchy!
$m_A = m_H = m_{H^\pm}$

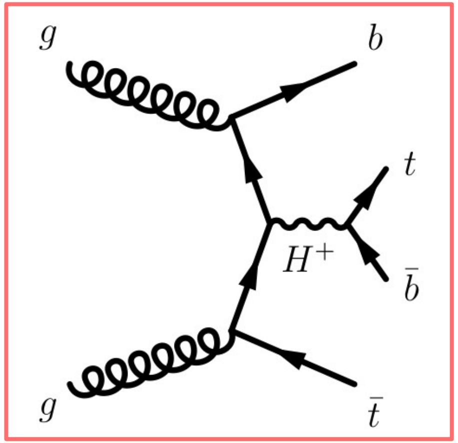
$b\bar{b}/l\bar{l}+E_T^{miss}$



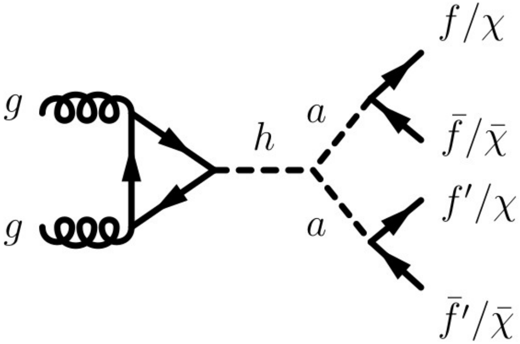
$b\bar{b}/t\bar{t}$ resonance



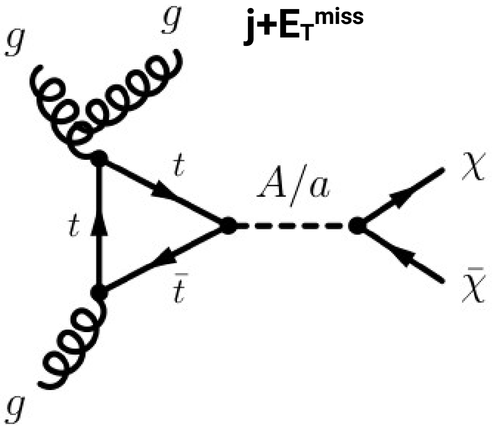
$\bar{t}bt\bar{b}$



$f\bar{f}f'\bar{f}'$ or $h \to$ invisible

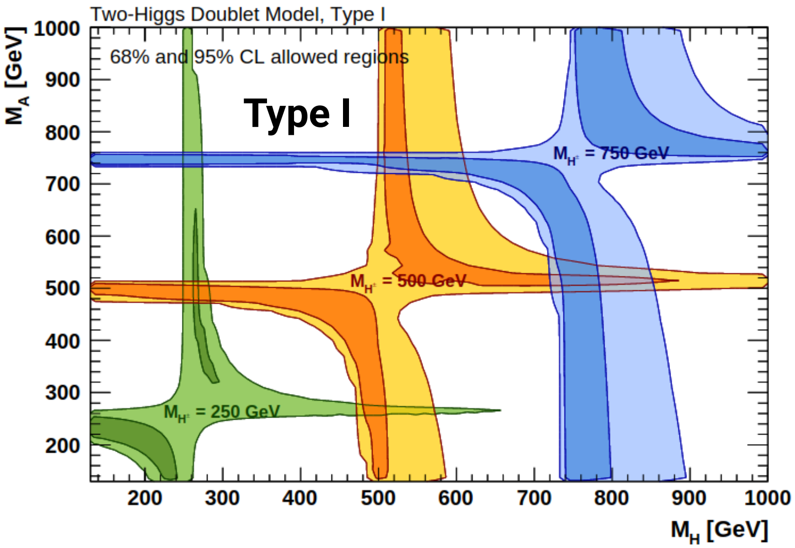


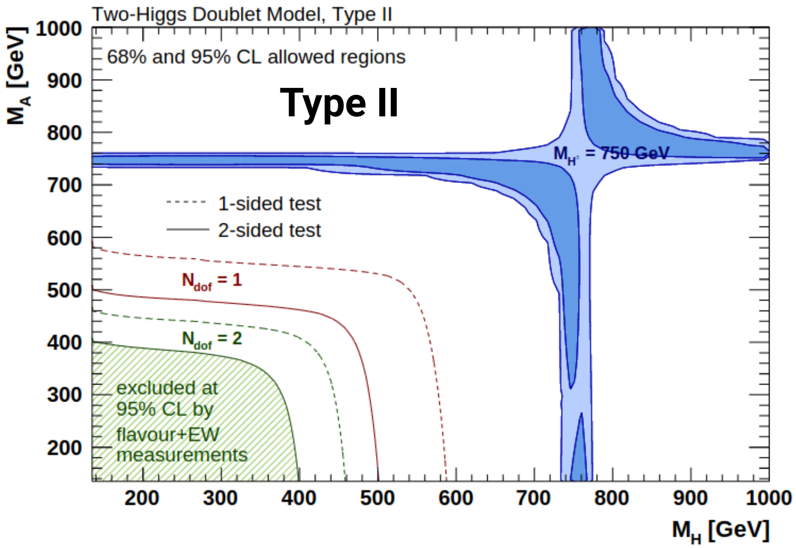
j+E_T^{miss}



2HDM TypeI

- **Why Type I?**
  - We need **tanβ ≥ 3 → Moderately fermiophobic** (pseudo)scalars (~1/tanβ supressed) → The main BSM Higgs bosons decay modes differ significantly compared to Type II (~tanβ for TypeII)





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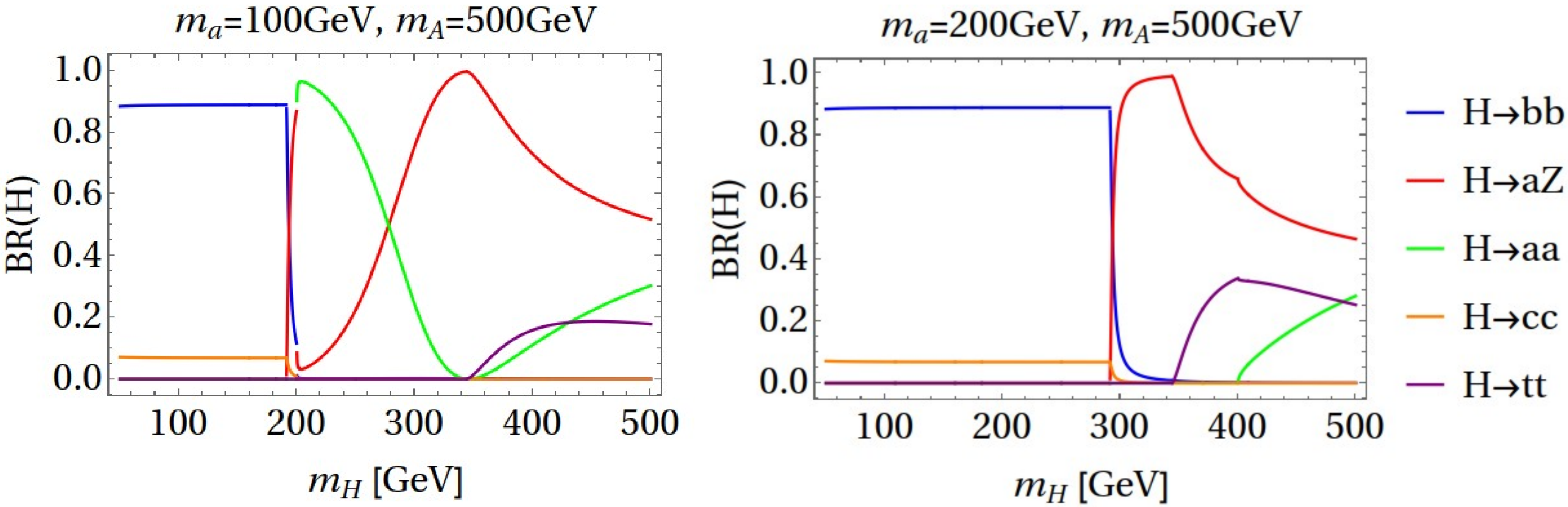
$b\bar{b}+E_T^{miss}$ signature

H Branching Ratio

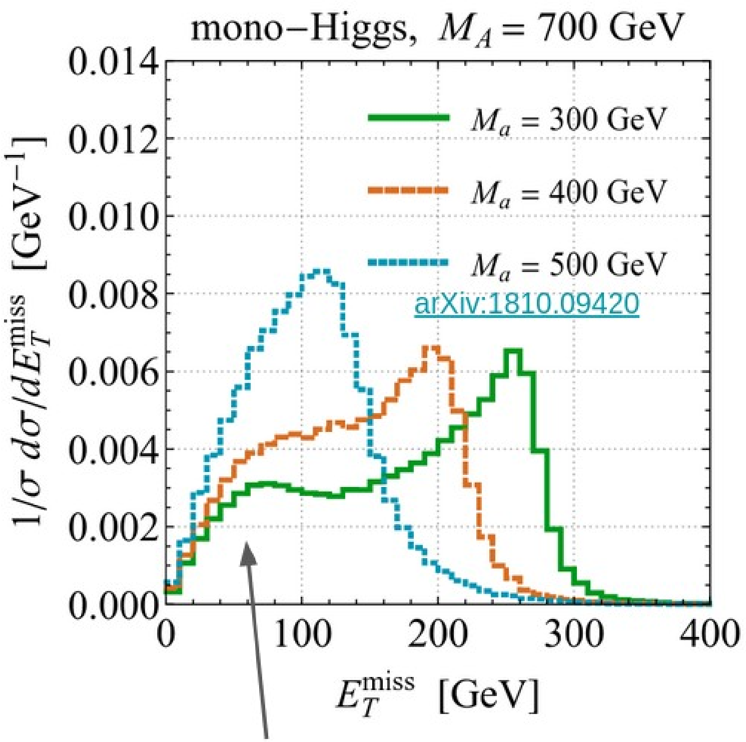
- **The a mass choice affects the H branching ratios**



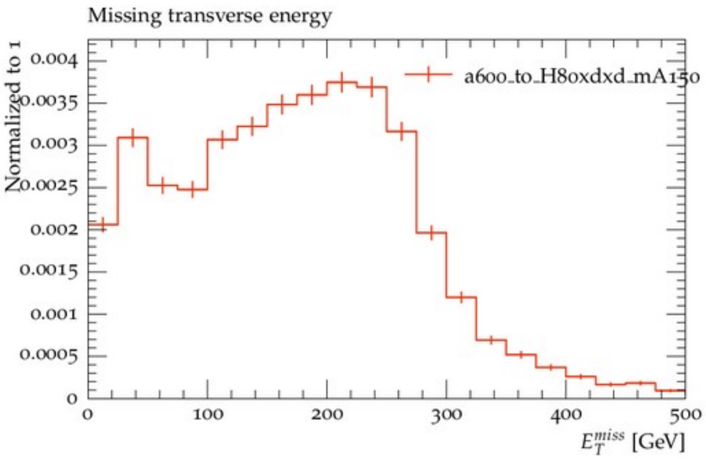
- $H \to b\bar{b}$ is dominant for lower m_H
- $H \to aZ/aa$ start to dominate for $m_H>m_a+m_Z$

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

Impact of Box Diagrams

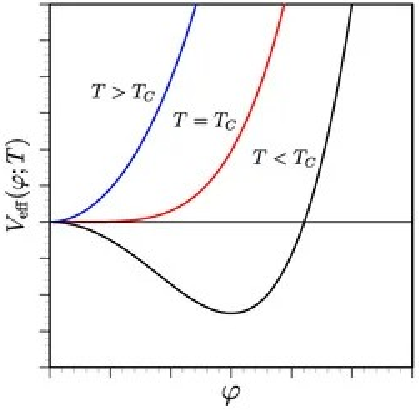


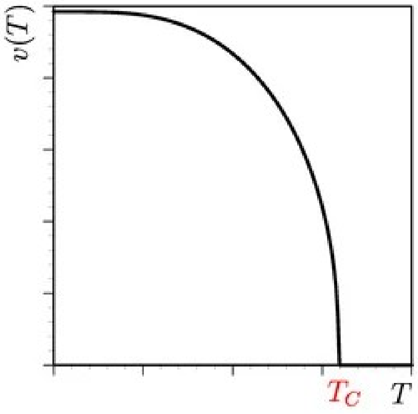
Box diagrams become important for large mass difference between a and A (decay A $\rightarrow h_{SM}$ a(xdxd))

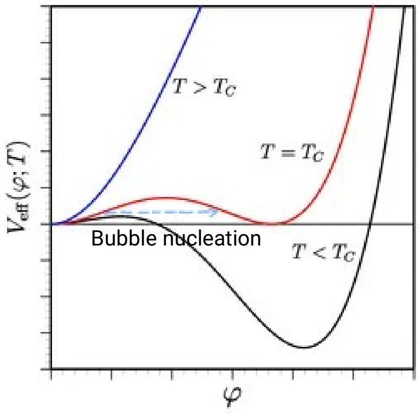


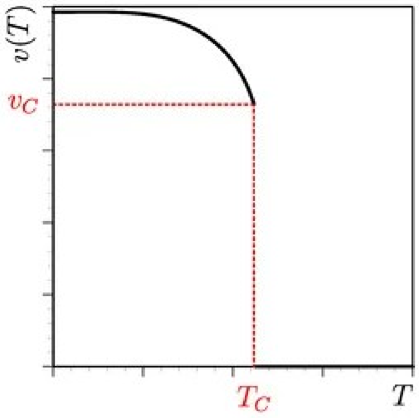
- decay a $\rightarrow$ H(bb) A(xdxd), with ma=600GeV, mA=150GeV and mH=80GeV
- Visible impact of box diagrams

EW Phase Transition

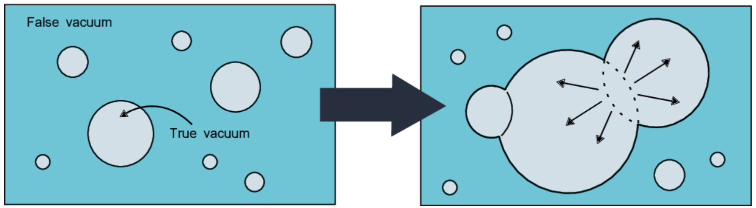








- In SM **smooth crossover** (given the large Higgs mass) → Continuous transition from symmetric vacuum to EW vacuum



- In 2HDM **first order EW phase transition →** Abrupt transition from symmetric vacuum to EW vacuum
- **Necessary condition for baryogenesis**