Search for Dark Matter with 2HDM+pseudoscalar model with the ATLAS detector

DPF 2021

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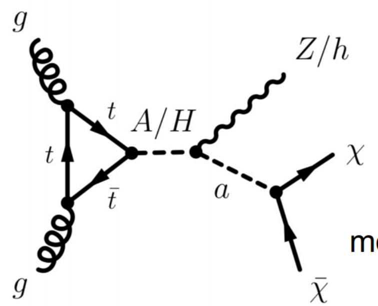
ATLAS EXPERIMENT

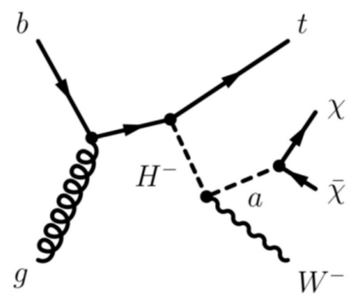
UNIVERSITY OF MICHIGAN

Introduction

- 2HDM+pseudoscalar Dark matter model (arXiv:1701.07427)
    - Type-II 2HDM coupling structure
    - Fermionic DM
    - Additional pseudoscalar mediators between visible and dark sectors
    - Considered as a benchmark model for ATLAS/CMS by the LHC DM Working Group (arXiv:1810.09420)
- Representative physics processes:



mono-H/Z

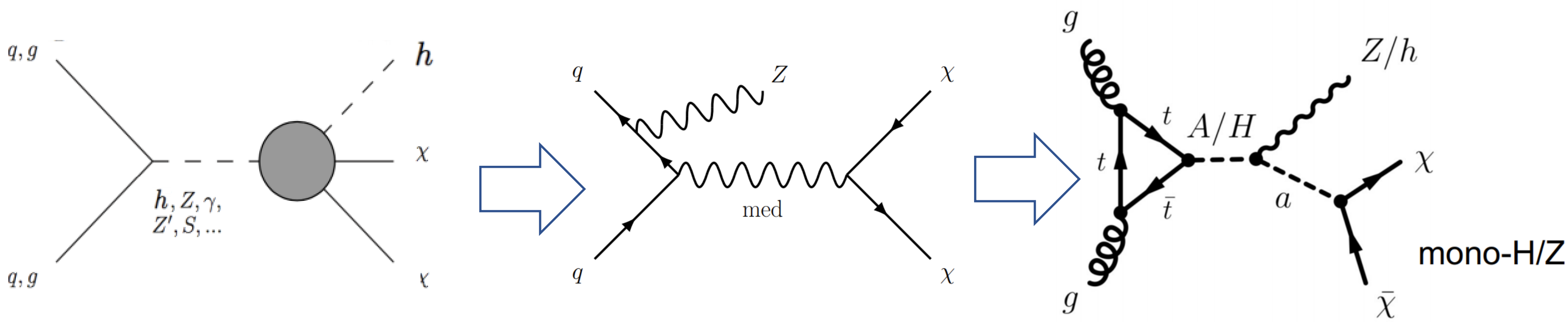


Wt+MET

- This talk: Latest combination/summary of ATLAS analyses exploring this 2HDMa model, based on 140/fb of 13 TeV data.
- Caveat: this analysis hasn’t been published yet. Will only show expected results.

Introduction

- For DM searches, theoretical benchmarks are necessary to sharpen the regions of interest
  - To optimize searches and characterize a possible discovery
  - Define a theoretical framework for comparison with non-collider results



DMF EFT (arXiv: 1507.00966)

Simplified DM model (arXiv:1507.00966)

2HDMa (arXiv:1701.07427)

Comparing 2HDMa to DM-EFT and DMsimp:

- Gauge-invariant and renormalizable
- Richer kinematics + phenomenology

Model parameters

- The 2HDM+a Dark matter model is fully defined by 14 parameters
  - Masses of the CP-even bosons: m_H, m_h
  - Masses of the CP-odd bosons: m_A, m_a
  - Masses of the charged Higgs bosons: m_{H^+}, m_{H^-}
  - Mass of the Dark Matter candidate: m_χ
  - Yukawa coupling constant between a and χ: g_χ
  - Three quartic couplings between the scalar doublets and pseudoscalars: $\lambda_3, \lambda_{p1}, \lambda_{p2}$
  - Mixing angle between CP-even bosons: α
  - Mixing angle between CP-odd bosons: θ
  - Ratio of the vacuum expectation values of the two Higgs doublets: $\tan\beta$
  - EW VEV: v
- Reduced to m_A, m_a, $\tan\beta$, $\sin\theta$ and m_χ with conditions
  - $m_H = m_{H^\pm} = m_A$
  - $g_\chi = 1$
  - The alignment limit: $\cos(\beta - \alpha) = 0$, v = 246 GeV, m_h = 125 GeV
  - $\lambda_3 = \lambda_{p1} = \lambda_{p2} = 3$

Full Run2 ATLAS analyses

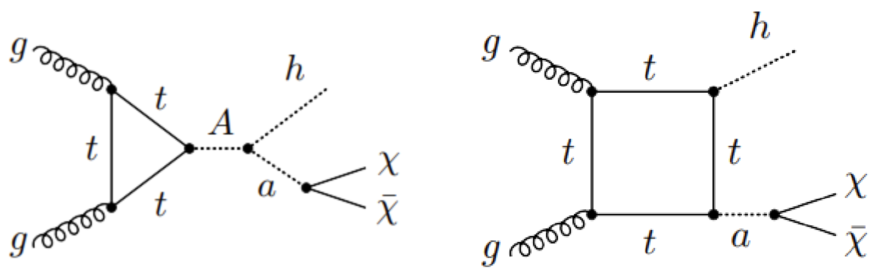
- Previous results can be found in ATLAS 36/fb DM summary paper .
- In LHC Run 2, this model has been explored by more analyses in ATLAS
- The following analyses with **139/fb** full run2 dataset collected by ATLAS have been included, aiming for **an EPS Conference note**.

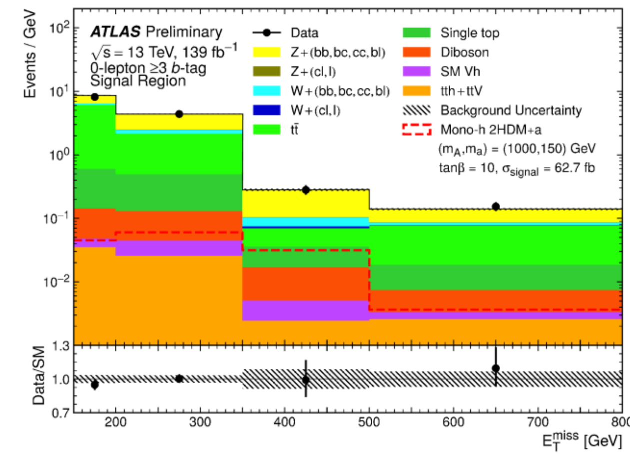
Final states with MET signatures	mono-*H*	*bb*
		γγ
	mono-*Z*	*ll*
	Wt +*MET*	1L, 2L
Final states without MET signatures		H+tb

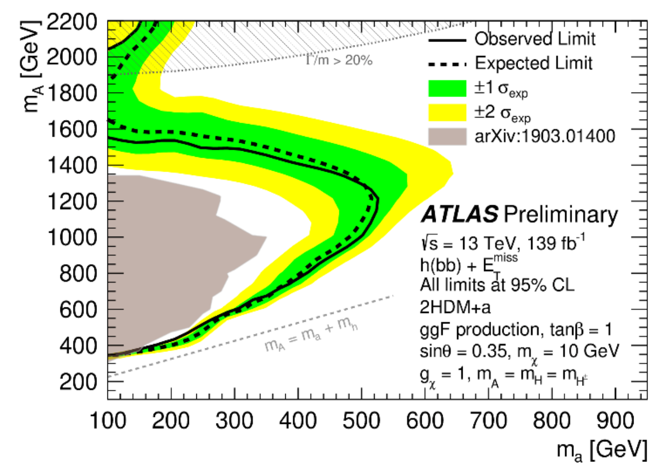
- Additionally, a statistical combination of mono-H(bb), mono-Z(ll) analyses is performed to improve the sensitivity.

Mono-H(bb)

- Full run-2 results released in 2021 Moriond CONF NOTE:
  - Both resolved and merged topologies with different H→bb reconstructions employed.
  - No significant excess against Standard Model prediction



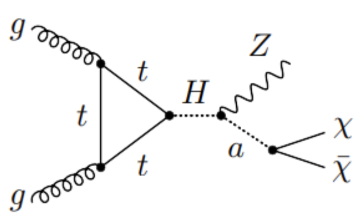


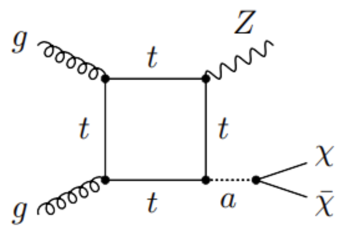


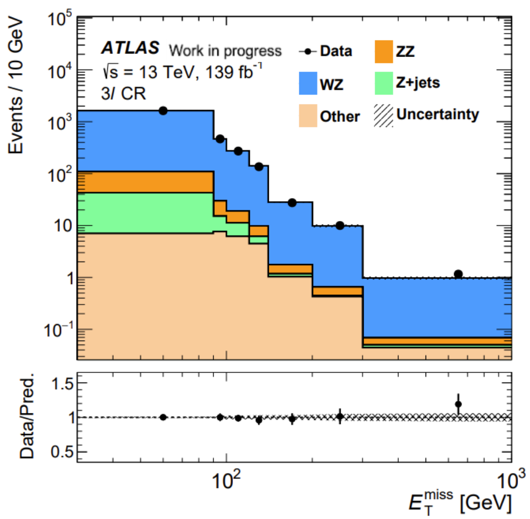
	0 lepton	1 muon	2 leptons
Aim	Signal regions	$t\bar{t}$ and W+HF control region	Z+HF control regions
Fitted observable	m_h distribution	Muon charge (2 b-tag) Yields (≥3 b-tag)	Yields
b-tag multiplicities	resolved (small-R jets): 2, ≥3 merged (variable-R track-jets): 2 (inside h candidate), ≥3 (2 inside h candidate)		
E_T^{miss} proxy	E_T^{miss}	$E_{T,\text{lep. invis.}}^{miss}$	$E_{T,\text{lep. invis.}}^{miss}$
Bins in E_T^{miss} proxy	resolved: [150, 200], [200, 350] and [350, 500] GeV 2 b-tag merged signal regions (0 lepton): [500, 750] and [750, ∞) GeV Other merged regions: [500, ∞) GeV		

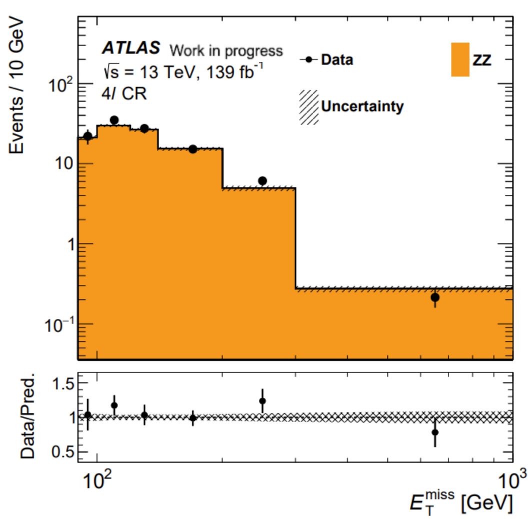
- Analysis not published yet (only control region data/MC shown here).
  - Select events with a leptonically-decaying Z against significant MET.
  - Dedicated CRs developed to constrain the major backgrounds in a simultaneous fit.

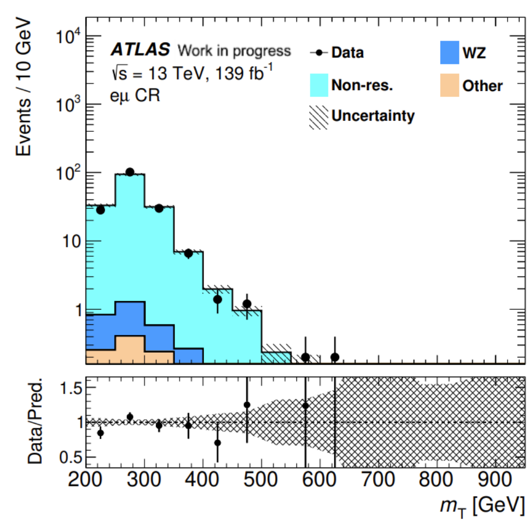
Selection criteria	Background reduced
$p_T^{\ell_1}$ ($p_T^{\ell_2}$) > 30 (20) GeV	—
Veto events with $p_T^{\ell_3} > 7$ GeV	WZ
$76 < m_{\ell\ell} < 106$ GeV	Non-resonant $\ell^+\ell^-$
$E_T^{miss} > 90$ GeV	Z+jets
E_T^{miss} significance > 9	Z+jets
$\Delta R(\ell\ell) < 1.8$	Z+jets, non-resonant $\ell^+\ell^-$
Veto events with a b-jet	Single top, $t\bar{t}$



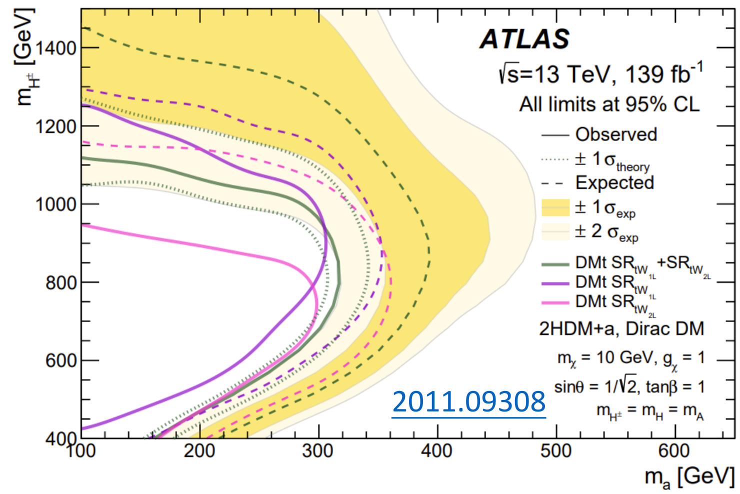




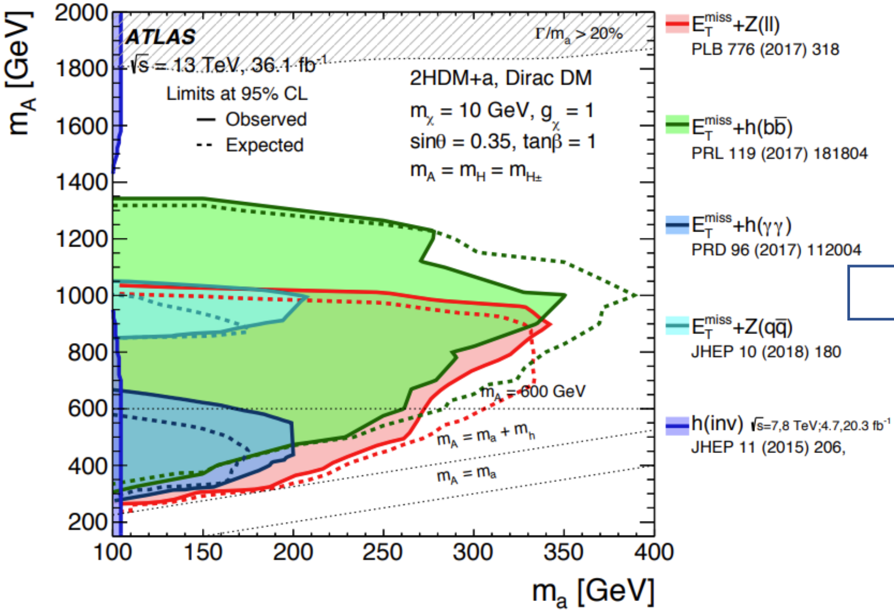




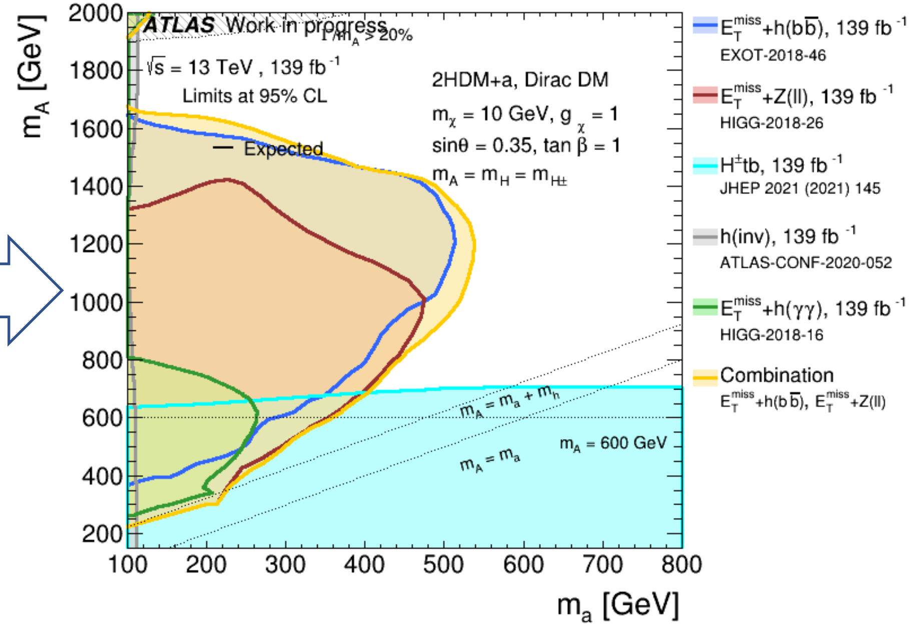
Other channels



- *Wt +MET*
  - Top production in association with a W boson
  - Larger sensitivity at $\sin\theta = 0.7$.
- Mono-H(γγ)
  - Comparing to mono-H(bb), triggered using the photon pair, allowing for much lower and better resolved MET in the event.
- H+tb
  - 2HDM type-II limits reinterpreted in the context of 2HDM+a as the signatures are exactly the same.
- Higgs-invisible
  - 2HDM+a h-invisible decay could be interpretated by BR(h->inv) results
  - The most recent ATLAS public result: < 11%(11%) obs. (exp.)at 95%



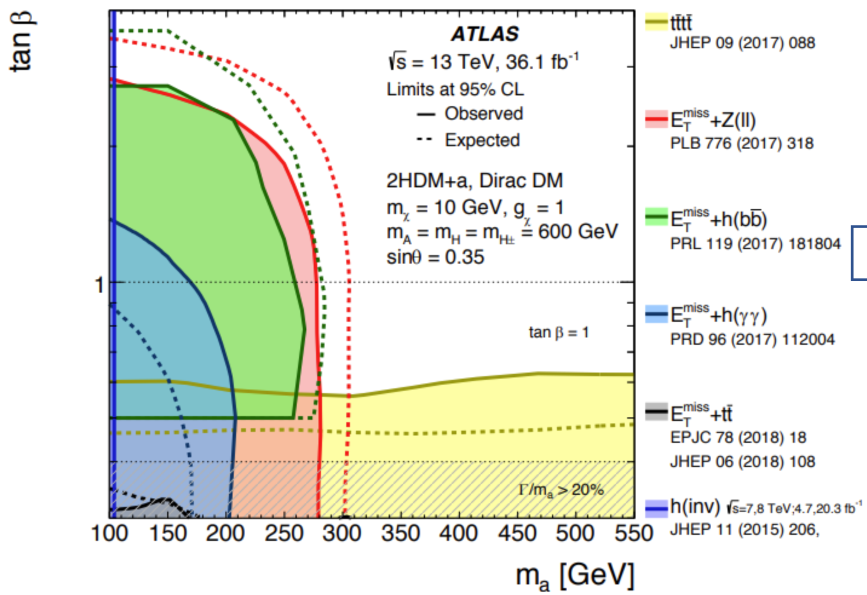
[ATLAS 36/fb DM summary paper]



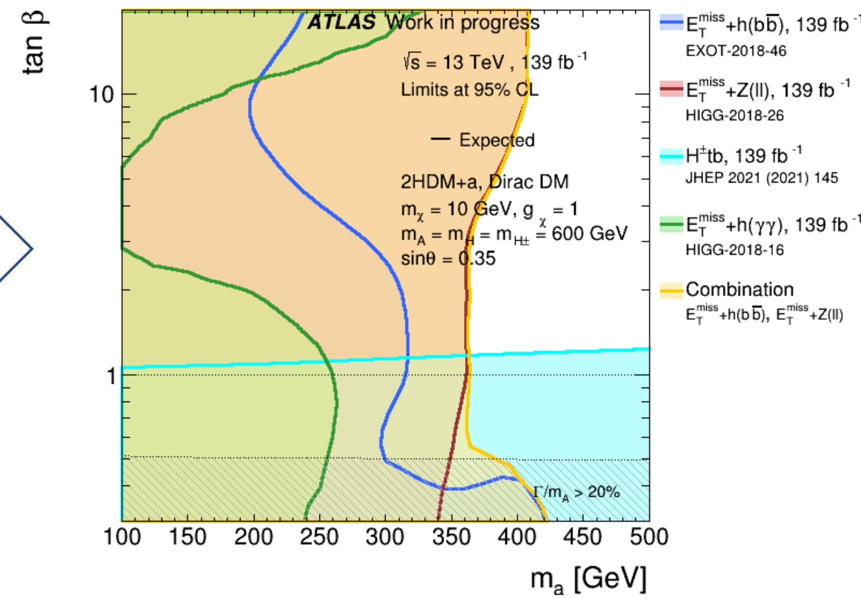
This study (expected results)

m_a- m_A scan at sinθ=0.35 :

- **MonoH** dominates at large mA while **monoZ** dominates at small mA
- Sensitivities further improved by stat-combination.
- Significant complementarity from **H+tb**, due to the small dependence on m_a with its signature.



[ATLAS 36/fb DM summary paper](#)

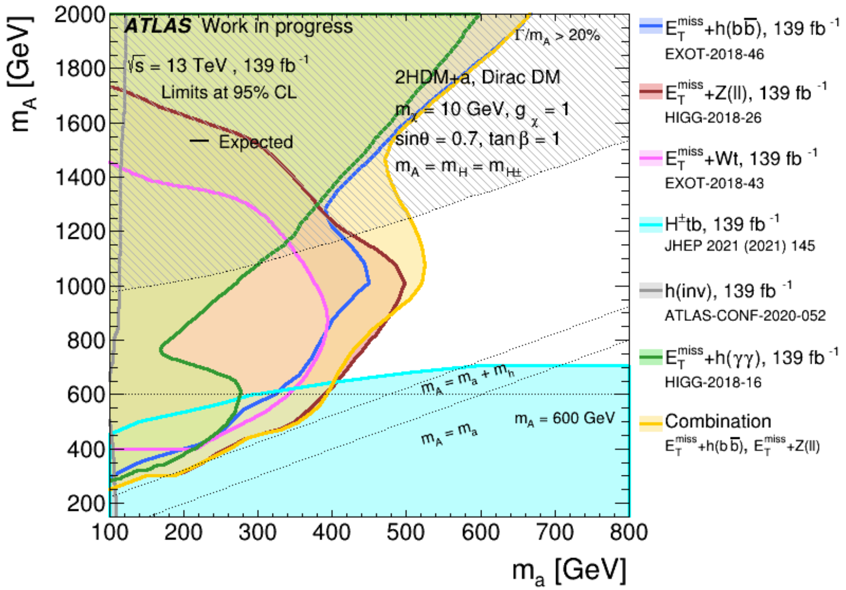


This study (expected results)

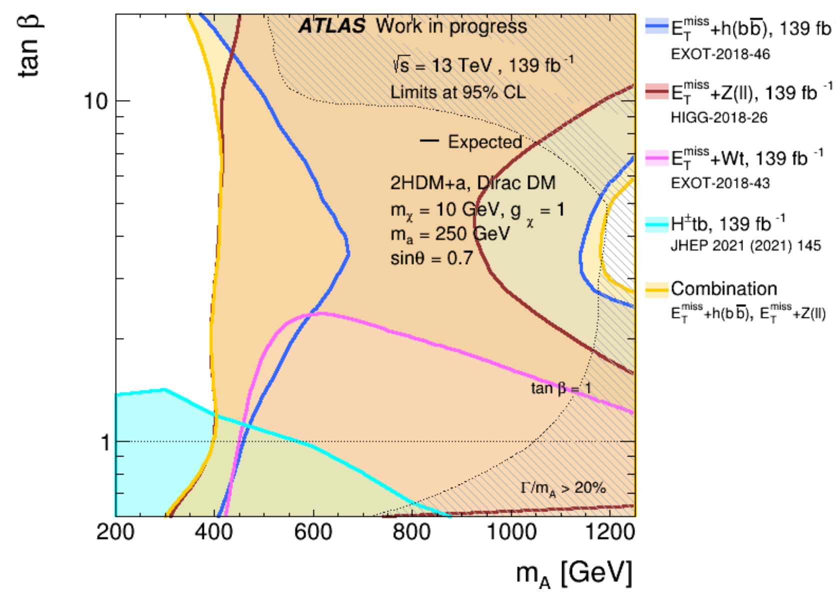
m_a- tanβ scan at sinθ=0.35 :

- **monoZ** dominates the sensitivity.
- Significant complementarity from **H+tb**, due to the small dependence on m_a with its signature.
- Large improvements on high-$tan\beta$ region from the inclusion of bb-induced signature in **monoZ** and **monoH** analyses.

Preliminary expected results



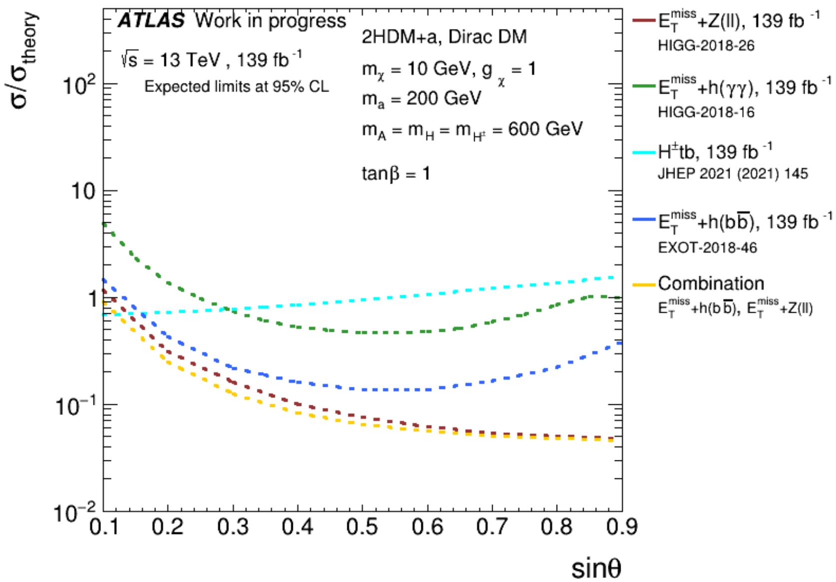
sinθ=0.7, m_A- m_a



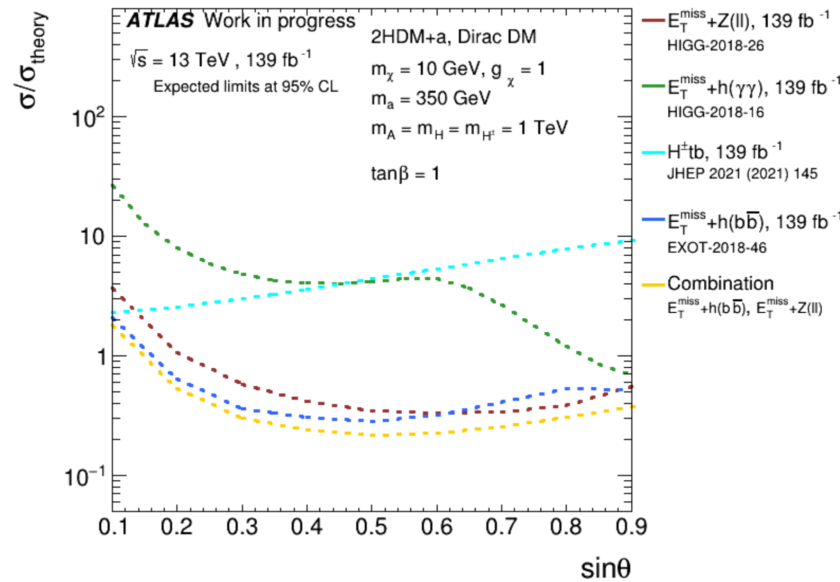
sinθ=0.7, m_A- $tan\beta$

New sin$\theta = 0.7$ parameter scans introduced, to further highlight the rich phenomenology of the model:

- Larger region with of any Higgs boson >20% of its mass. Subjected to additional theoretical uncertainties when sin$\theta = 0.7$.
- Interesting interplay of gg- and bb- induced productions, giving the $tan\beta$-dependent structure.
- Significant improvements from the statistical combination of monoH(bb) and monoZ.



m_a =200 GeV, m_A= 600 GeV



m_a =350 GeV, m_A= 1000 GeV

sinθ scan performed with two benchmark m_a- m_A:

- Non-monotonic feature from monoH due to the enhancement of the aah coupling
- Almost the entire parameter space is excluded from the expectation.
- Large improvements in sensitivity compared to the early Run2 results.

Summary

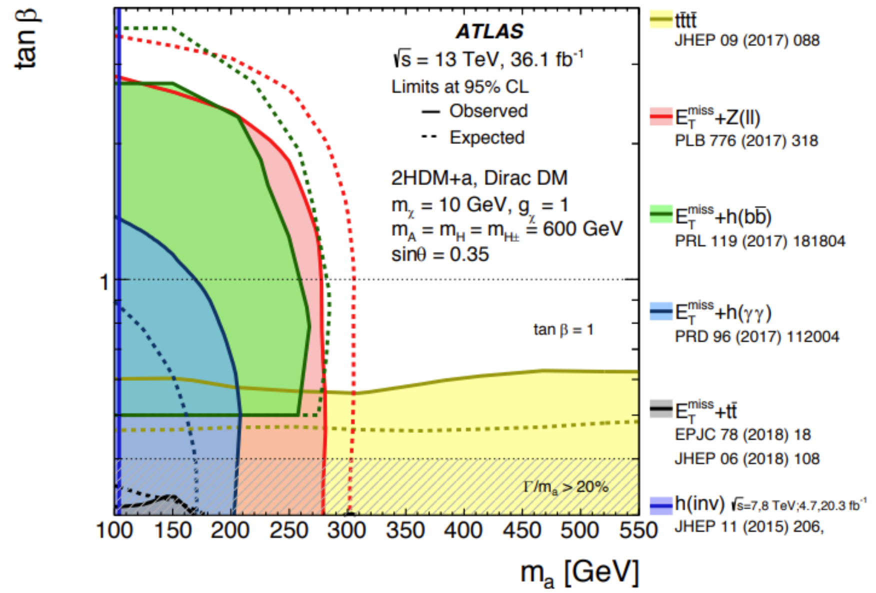
- Large parameter space in 2HDM+a model explored. From expected results:
  - Complementary constraints reached by **overlaying of different signatures**.
  - Larger sensitivity obtained from the **stat-combination of mono-H(bb) and monoZ analyses.**
  - Significant improvements comparing to the early Run 2 ATLAS results.
- Results to become public soon. Stay tuned for updates!

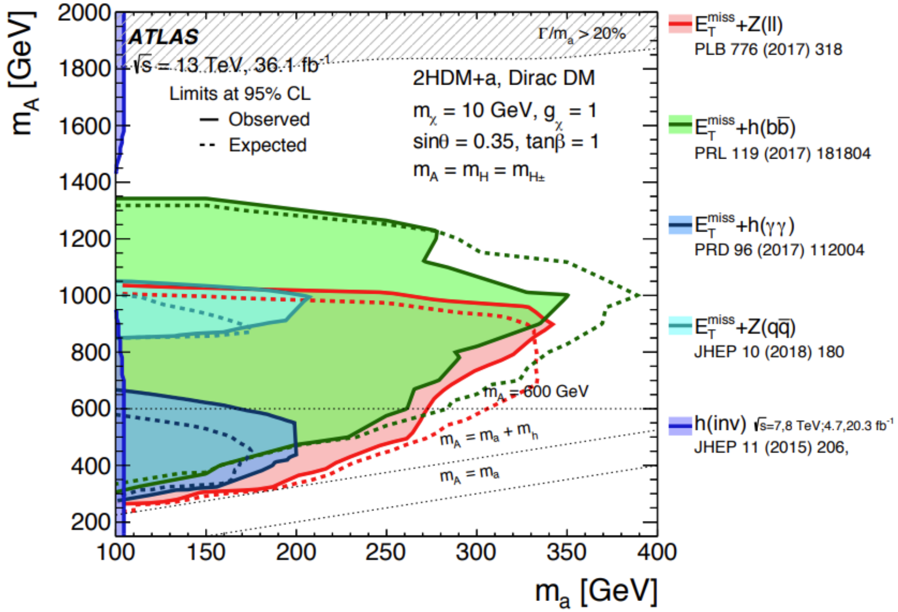
Thanks

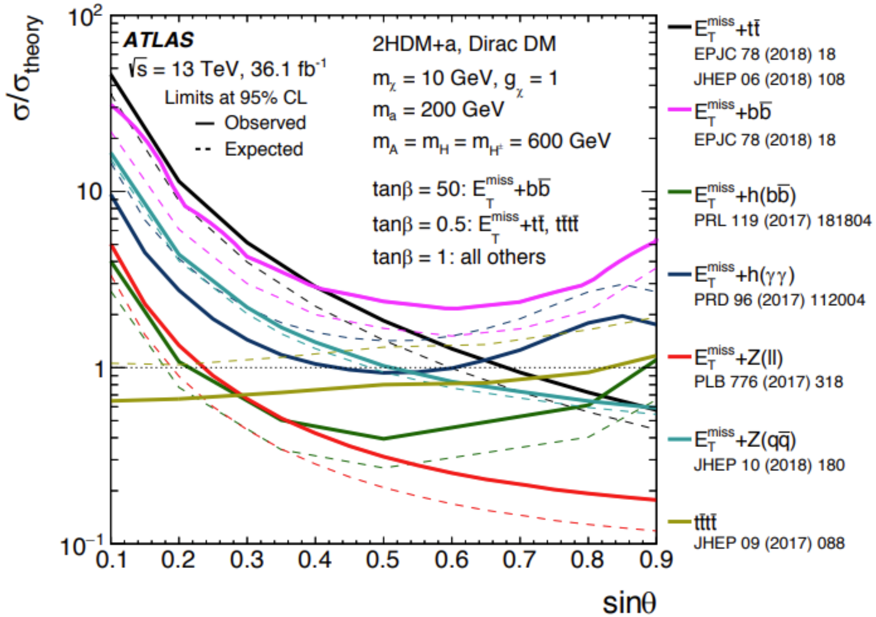
Backup

Early Run 2 results

- Previous results from ATLAS 36/fb DM summary paper







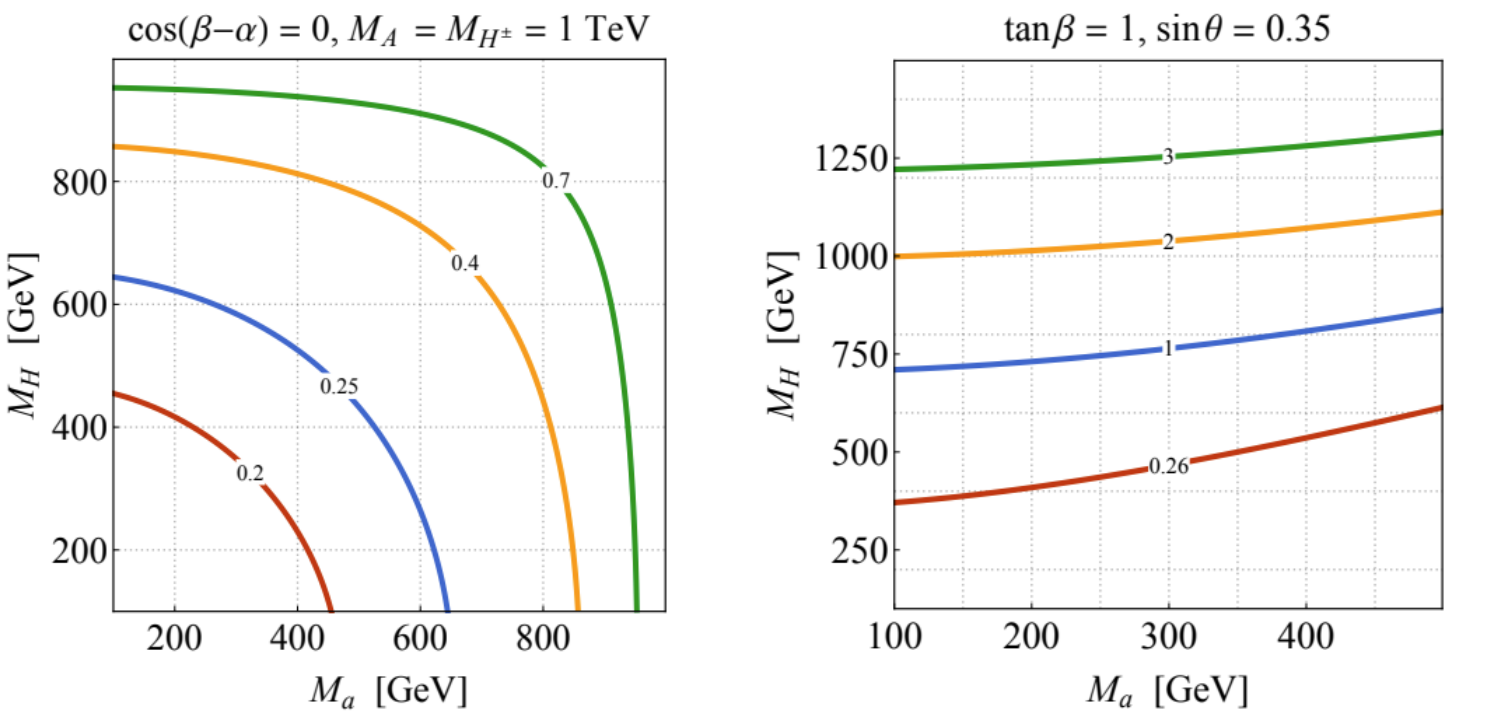
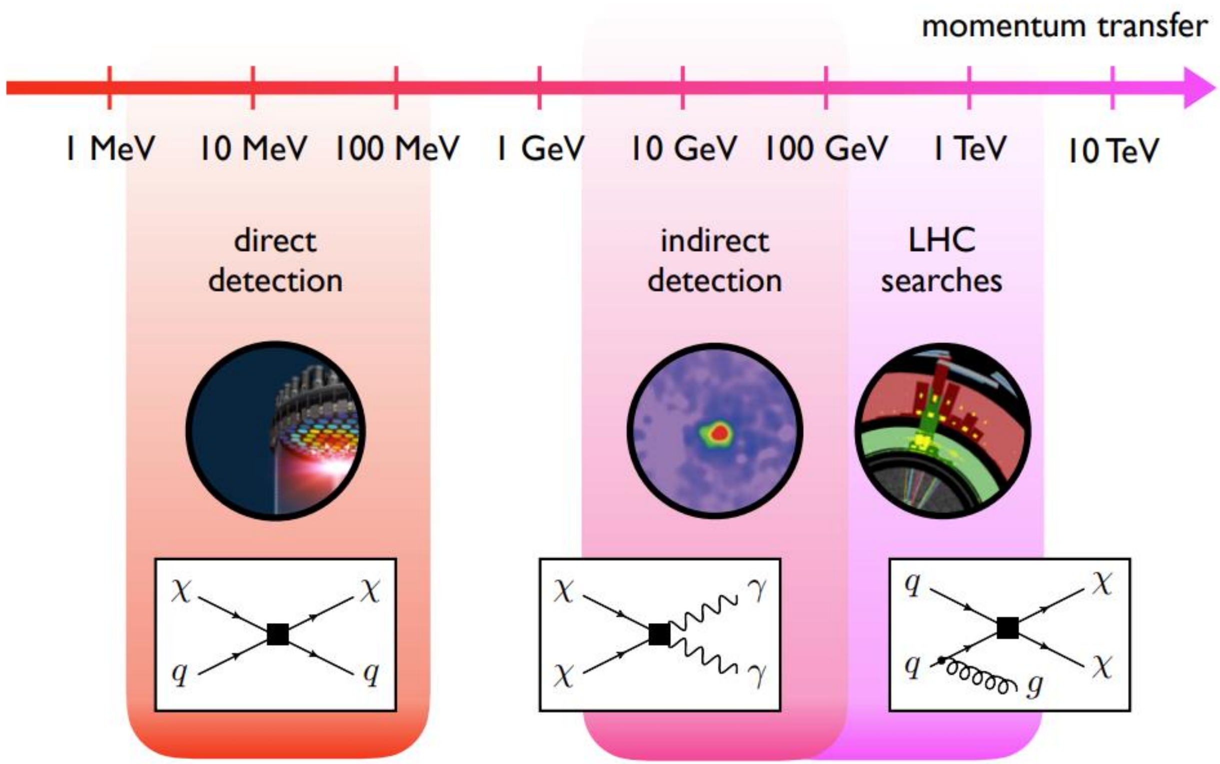
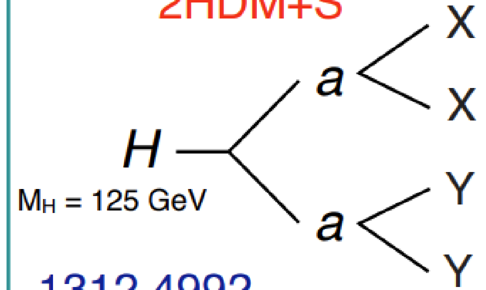


Figure 4: Left: Values of M_a and M_H allowed by EW precision constraints assuming $\cos(\beta - \alpha) = 0$, $M_A = M_{H^\pm} = 1\,\text{TeV}$ and four different values of $\sin\theta$, as indicated by the contour labels. The parameter space below and to the left of the contours is excluded. Right: Constraints in the $M_a - M_H$ plane following from the BFB requirement. The results shown correspond to $\tan\beta = 1$, $\sin\theta = 0.35$ and degenerate heavy spin-0 boson masses $M_H = M_A = M_{H^\pm}$. The region above each contour is excluded for the indicated value of the quartic coupling λ_3.


momentum transfer
1 MeV
10 MeV
100 MeV
1 GeV
10 GeV
100 GeV
1 TeV
10 TeV
direct detection
indirect detection
LHC searches
χ χ q q
χ χ γ γ
q q χ χ g

- **2HDM+S ("HLRS model") vs 2HDM+a ("CDM model")**
  - Can we show constrains from HLRS & CDM analyses all together in 1 consistent model?
  - *Plan for this summer:* study the acceptance for HLRS analyses for different parameters of 2HDM+a, in discussion with CDM & theorists

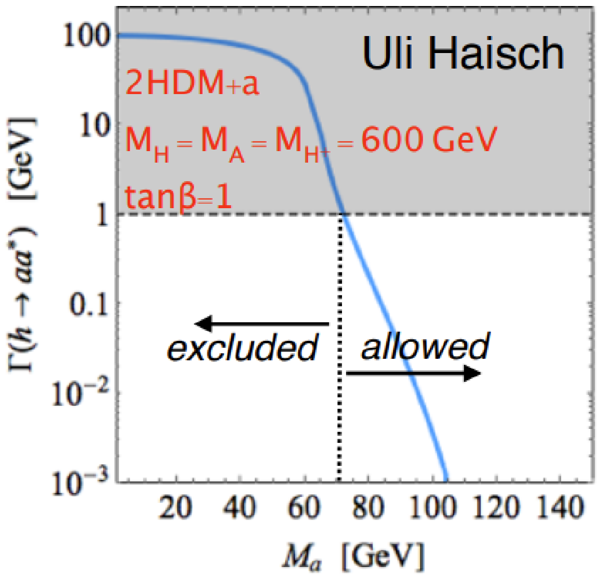
2HDM+S



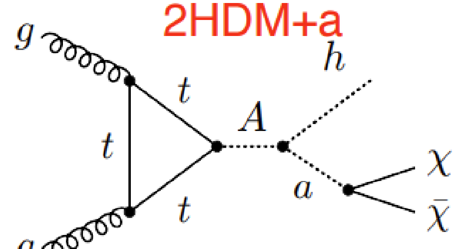
1312.4992

?

- **m_a<70 GeV excluded due to H→invisible & H-width constraints**
  - would need to tune the parameters so as to get **g_{haa}<<1 to allow m_a<70 GeV**
  - i.e. just setting m_{DM}>m_a is not enough to make it work for light a's



2HDM+a



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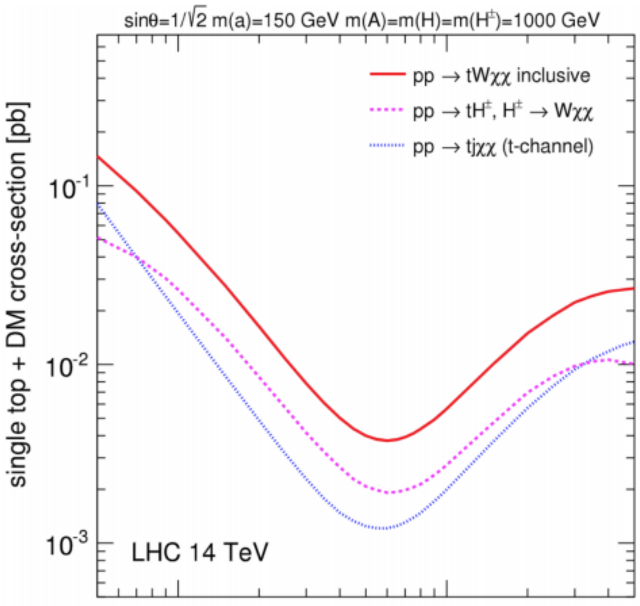
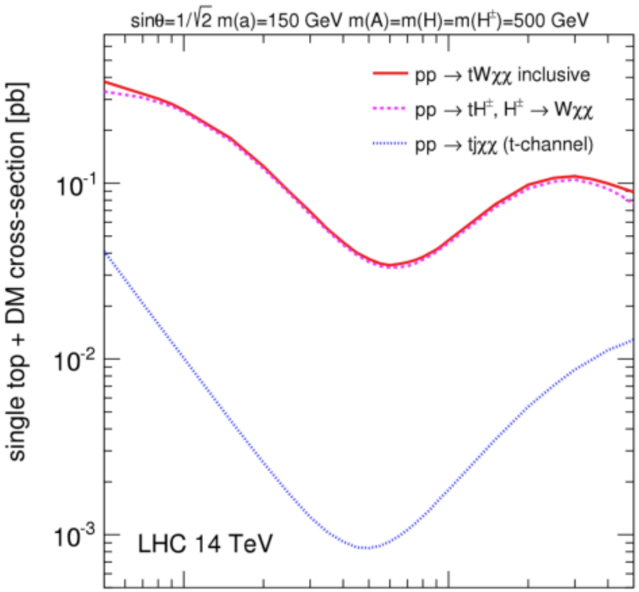

sinθ=1/√2 m(a)=150 GeV m(A)=m(H)=m(H±)=1000 GeV
pp → tWχχ inclusive
pp → tH±, H± → Wχχ
pp → tjχχ (t-channel)
single top + DM cross-section [pb]
10^-1
10^-2
10^-3
LHC 14 TeV


sinθ=1/√2 m(a)=150 GeV m(A)=m(H)=m(H±)=500 GeV
pp → tWχχ inclusive
pp → tH±, H± → Wχχ
pp → tjχχ (t-channel)
single top + DM cross-section [pb]
10^-1
10^-2
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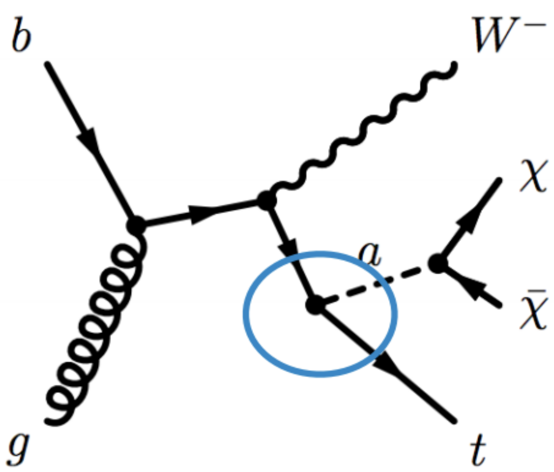
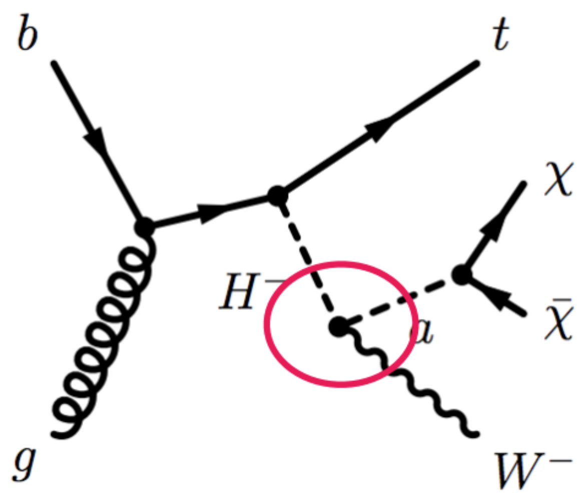
LHC 14 TeV



Coupling of a with t goes as sinp-> xsec goes as sinp^2

$$\Gamma\left(a \to f\bar{f}\right) = \frac{N_c^f \left(\xi_f^{\mathrm{M}}\right)^2}{8\pi} \frac{m_f^2}{v^2} M_a \beta_{f/a} \sin^2\theta$$



Decay width of H+->aW goes as sinp^2, but it competes with the decay H+->tb, which does not depend on sinp -> BR not linear in sinp^2

$$\Gamma\left(H^+ \to aW^+\right) = \frac{1}{16\pi} \frac{\lambda^{3/2}(M_{H^\pm}, M_a, M_W)}{M_{H^\pm}^3 v^2} \sin^2\theta\,,$$

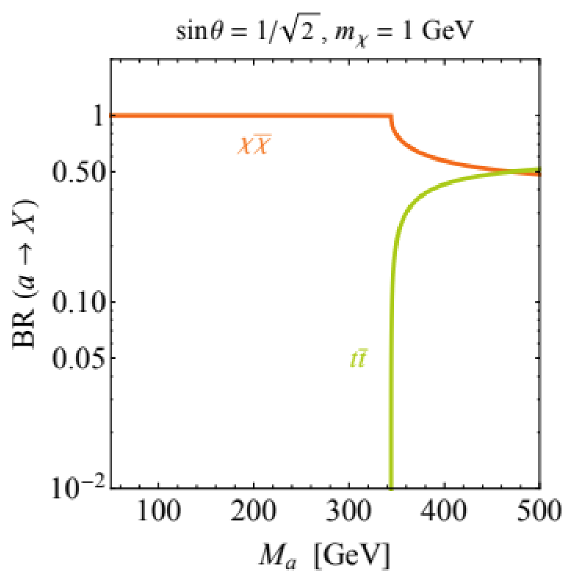
$$\Gamma\left(H^+ \to t\bar{b}\right) = \frac{N_c^t\,|V_{tb}|^2 \left(\xi_t^{\mathrm{M}}\right)^2}{8\pi} \frac{m_t^2}{v^2} M_{H^\pm} \left(1 - \frac{m_t^2}{M_{H^\pm}^2}\right)^2$$

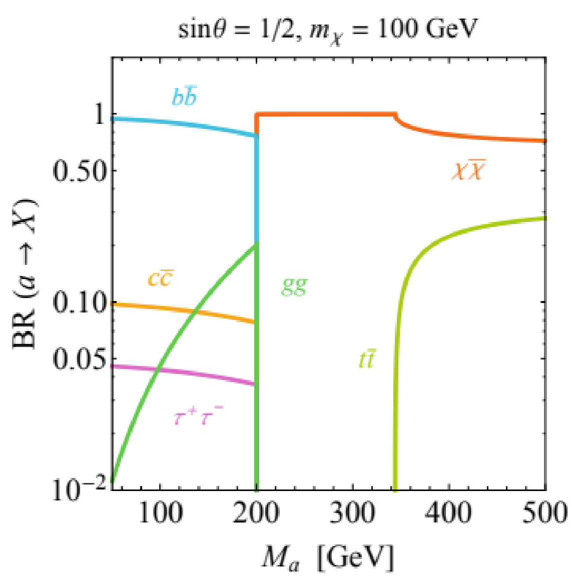
$$\xi_t^{\rm I} = \xi_b^{\rm I} = \xi_\tau^{\rm I} = -\cot\beta\,, \quad (\text{type I})\,,$$

$$\xi_t^{\rm II} = -\cot\beta\,, \qquad \xi_b^{\rm II} = \xi_\tau^{\rm II} = \tan\beta\,, \quad (\text{type II})\,,$$

$$\xi_t^{\rm III} = \xi_b^{\rm III} = -\cot\beta\,, \qquad \xi_\tau^{\rm III} = \tan\beta\,, \quad (\text{type III})\,,$$

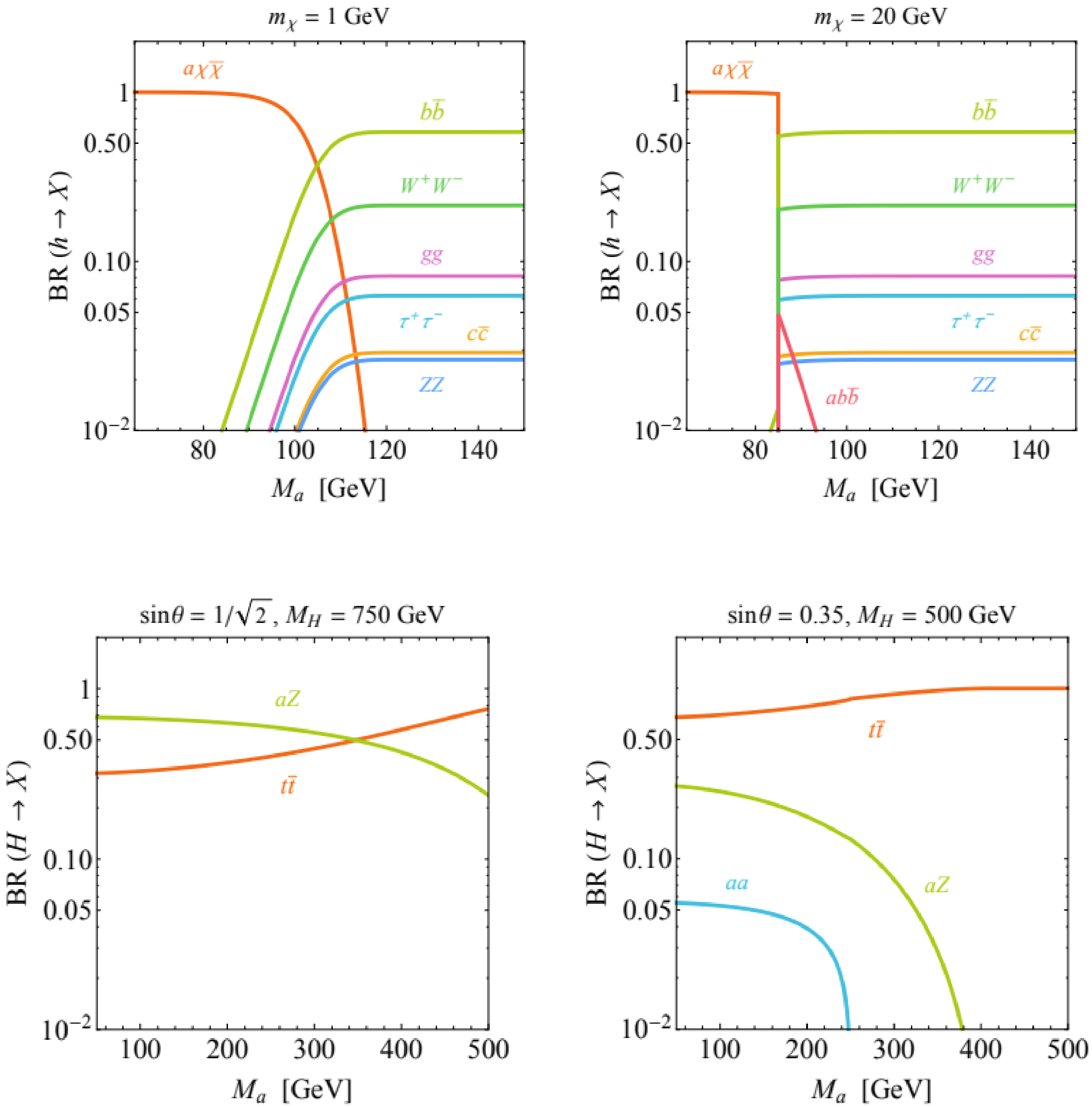
$$\xi_t^{\rm IV} = \xi_\tau^{\rm IV} = -\cot\beta\,, \qquad \xi_b^{\rm IV} = \tan\beta\,, \quad (\text{type IV})\,.$$





$$\Gamma\left(a \to \chi\bar{\chi}\right) = \frac{y_\chi^2}{8\pi} M_a \beta_{\chi/a} \cos^2\theta\,,$$

$$\Gamma\left(a \to f\bar{f}\right) = \frac{N_c^f \left(\xi_f^{\rm M}\right)^2}{8\pi} \frac{m_f^2}{v^2} M_a \beta_{f/a} \sin^2\theta\,,$$



$$\Gamma(h \to aa) = \frac{1}{32\pi}\, g_{haa}^2\, M_h \beta_{a/h}\,,$$

$$g_{haa} = \frac{1}{M_h v}\Big[\left(M_h^2 - 2M_H^2 + 4M_{H^\pm}^2 - 2M_a^2 - 2\lambda_3 v^2\right)\sin^2\theta - 2\left(\lambda_{P1}\cos^2\beta + \lambda_{P2}\sin^2\beta\right) v^2\cos^2\theta\Big]\,.$$

$$\Gamma(h \to a\chi\bar{\chi}) = \frac{y_\chi^2}{32\pi^3}\, g_{haa}^2\, M_h \beta_{\chi/a}\, g(\tau_{a/h})\cos^2\theta\,,$$

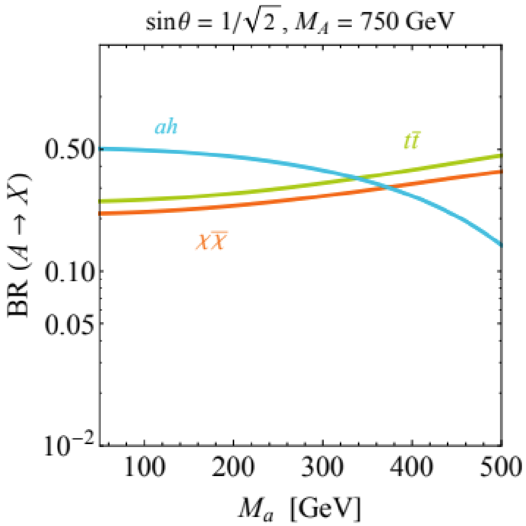
$$\Gamma(h \to af\bar{f}) = \frac{N_c^f\left(\xi_f^{\rm M}\right)^2}{32\pi^3}\frac{m_f^2}{v^2}\, g_{haa}^2\, M_h \beta_{f/a}\, g(\tau_{a/h})\sin^2\theta\,,$$

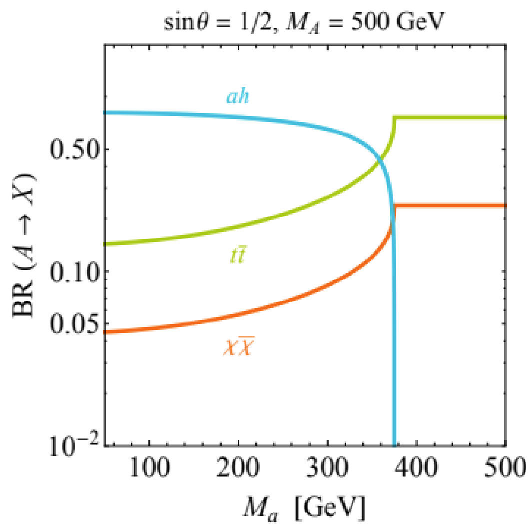
$$\Gamma(H \to f\bar{f}) = \frac{N_c^f\left(\xi_f^{\rm M}\right)^2}{8\pi}\frac{m_f^2}{v^2}\, M_H \beta_{f/H}^3\,,$$

$$\Gamma(H \to aa) = \frac{1}{32\pi}\, g_{Haa}^2\, M_H \beta_{a/H}\,,$$

$$\Gamma(H \to aZ) = \frac{1}{16\pi}\frac{\lambda^{3/2}(M_H, M_a, M_Z)}{M_H^3 v^2}\sin^2\theta\,,$$

$$g_{Haa} = \frac{1}{M_H v}\Big[\cot(2\beta)\left(2M_h^2 - 4M_H^2 + 4M_{H^\pm}^2 - 2\lambda_3 v^2\right)\sin^2\theta + \sin(2\beta)\left(\lambda_{P1} - \lambda_{P2}\right) v^2\cos^2\theta\Big]\,,$$

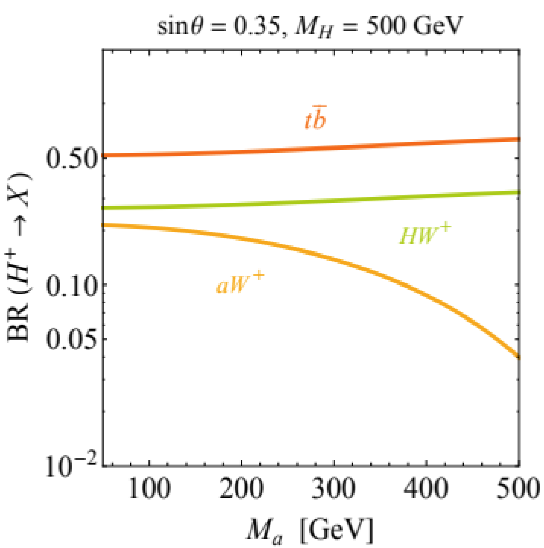


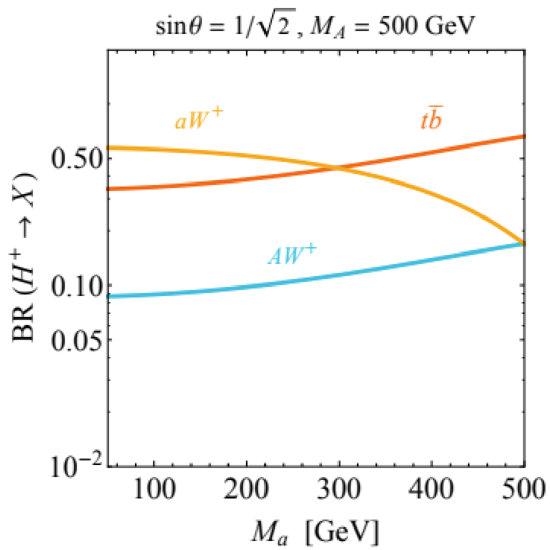


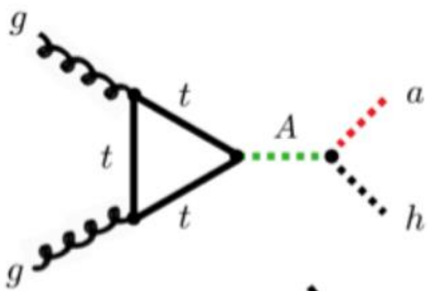
$$\Gamma\left(A \to \chi\bar{\chi}\right) = \frac{y_\chi^2}{8\pi} M_A \beta_{\chi/A} \sin^2\theta \,,$$

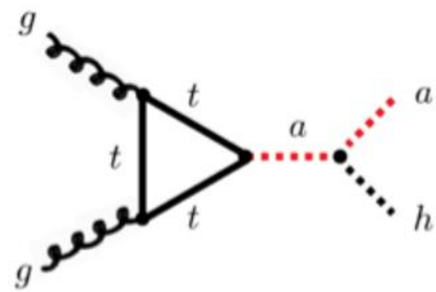
$$\Gamma\left(A \to f\bar{f}\right) = \frac{N_c^f \left(\xi_f^{\mathrm{M}}\right)^2}{8\pi} \frac{m_f^2}{v^2} M_A \beta_{f/A} \cos^2\theta \,,$$

$$\Gamma\left(A \to ah\right) = \frac{1}{16\pi} \frac{\lambda^{1/2}(M_A, M_a, M_h)}{M_A} g_{Aah}^2 \,,$$









$$\mathcal{A}\,(gg \to ha) \propto \frac{\left(M_A^2 - M_a^2 + M_h^2\right)\cos^2\theta}{\hat{s} - M_A^2 - i\,\Gamma_A M_A} + \frac{\left(2\left(M_A^2 - M_a^2\right) + M_h^2\right)\sin^2\theta - 2v^2\lambda}{\hat{s} - M_a^2 - i\,\Gamma_a M_a}$$

$$\simeq \frac{\left(2\left(M_A^2 - M_a^2\right) + M_h^2\right)\sin^2\theta - 2v^2\lambda}{M_A^2 - M_a^2} + i\,\frac{\left(M_A^2 - M_a^2 + M_h^2\right)\cos^2\theta}{\Gamma_A M_A}$$

$\hat{s} \simeq M_A^2$

Notice that only the internal A can go on-shell but not the internal a