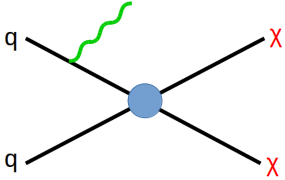
Dark Matter Searches in ATLAS

Katharina Behr

DESY LHC Physics Discussion
06.11.2017

In a nutshell

- Searches in many final states and probing a wide variety of models
- Models of varying complexity
  - EFTs: model-independent, few signatures



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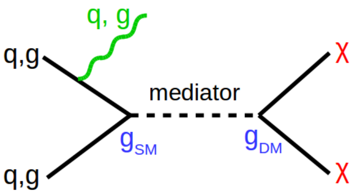

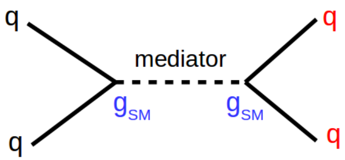

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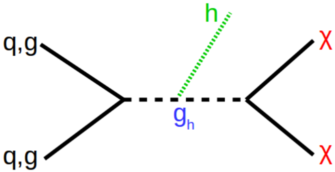
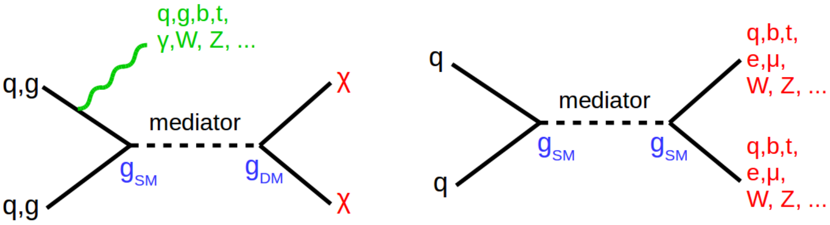


In a nutshell

- Searches in many final states and probing a wide variety of models
- Models of varying complexity
  - EFTs: model-independent, few signatures
  - Simplified models: reduced model dependency, complementary searches
  - BSM theories, e.g. SUSY: consistent, UV-complete, rich phenomenology



Public Results on 2015+2016 Data

Mono-X searches

- Mono-jet [ATLAS-CONF-2017-060]
- Mono-photon [arxiv:1704.03848]

Mediator searches

- Dijet resonances [arxiv:1703.09127]
- Dilepton resonances [arxiv:1707.01302]
- BSM $A/H \to \tau\tau$ [arxiv:1709.07242]
- BSM $A/H \to t\bar{t}$ [arxiv:1707.06025]

Mono-Higgs searches

- Mono-$h(b\bar{b})$ [arxiv:1707.01302]
- Mono-$h(\gamma\gamma)$ [arxiv:1706.03948]

Invisible Higgs decays

- $Z + h(\text{inv.})$ [arxiv:1708.09624]

Many more searches in progress!

Outline

Focus on selected models and final states:

1. Simplified model with a vector or axialvector mediator
   - Complementarity of mono-X and resonance searches
2. Simplified model: 2HDM+Z'
   - Complementarity of mono-h searches
3. Less simplified model: 2HDM+pseudoscalar
   - Rich collider phenomenology
   - New ATLAS/CMS benchmark model

http://clipart-library.com

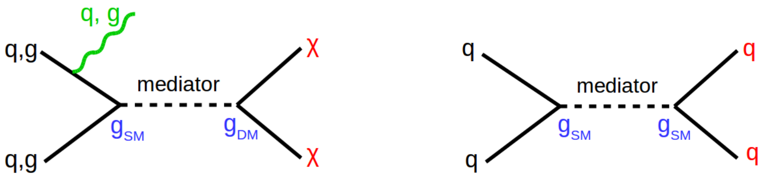
Disclaimer:

Will not cover SUSY models, EFTs, FCNC models, ...or more exotic signatures such as emerging jets, ...

Simplified model with a vector or axialvector mediator

Vector or Axialvector Mediator

- Benchmark models suggested by LHC DM WG
- Mediator with vector or axialvector interactions (*s*-channel)
- Probed by both mono-X and resonance searches



- 6 free parameters
- Mediator couplings: $g_\ell, g_q, g_{\mathrm{DM}}$
- Masses $m_{A/V}$ and m_{DM}
- Mediator width $\Gamma_{A/V}$ fixed minimal allowed value for chosen masses and couplings

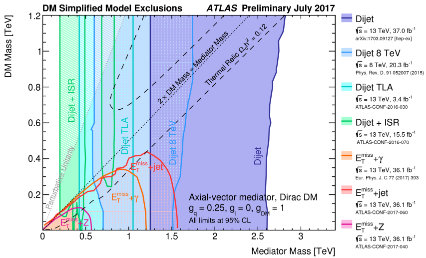
Benchmark Scenarios

Goal of scenario	Mediator type	g_q	g_{lep}	g_{DM}
A1: previous ATLAS benchmark	Axialvector	0.25	0.00	1.00
A2: highlight contribution of dilepton search (close to previous dilepton benchmark)	Axialvector	0.10	0.10	1.00
V1: highlight contribution of dijet searches in leptophobic case (close to previous ATLAS benchmark)	Vector	0.25	0.00	1.00
V2: highlight complementarity of DM/dilepton/dijet searches	Vector	0.10	0.01	1.00

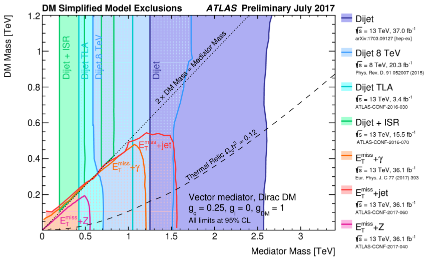
Results for A1 and V1

- Complementarity between mono-X and resonance searches
- No couplings to leptons
- Observed limits

A1



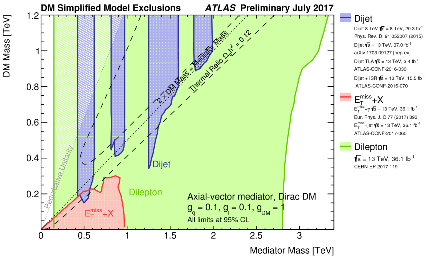
V1



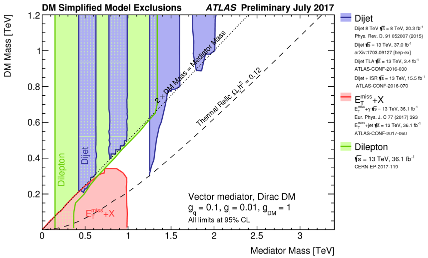
Results for A2 and V2

- Complementarity between mono-X and resonance searches
- Non-zero couplings to leptons
- Observed limits only

A2



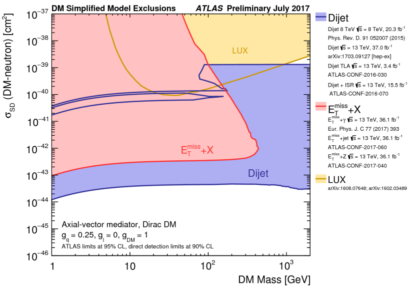
V2



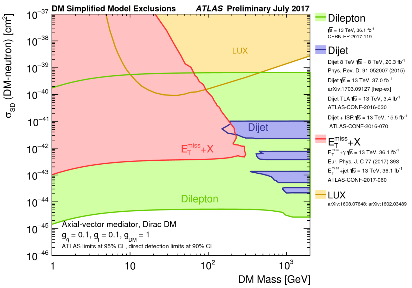
Comparison with Direct Detection Results

- Complementarity of LHC and direct detection searches
- Caveat: ATLAS limits at 95% CL compared to 90% for direct detection

A1 (neutron)



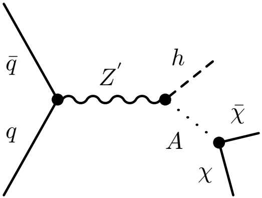
A2 (neutron)



Simplified model: 2HDM+Z'

2HDM+Z': The Model [arxiv:1402.7074]

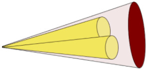
- Extension of 2HDM (type-II) in the alignment limit
  - 5 Higgs bosons: scalars h, H, pseudoscalar A, charged $H^{\pm}$
- Heavy vector Z' mediator mixes with Z boson

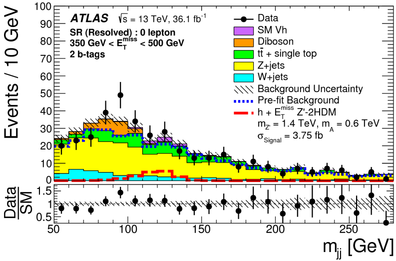


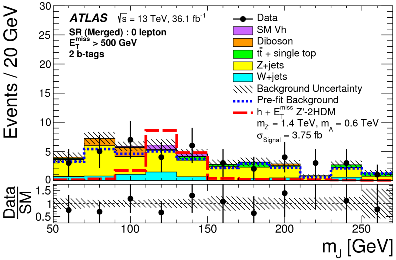
- Parameters as recommended by LHC DM WG: $\tan\beta = 1$, $g_{Z'} = 0.8$, $m_{\chi} = 100$ GeV
- Charged Higgs bosons: $m_{H^{\pm}} = 300$ GeV (CMS: $m_{H^{\pm}} = m_A$)

2HDM+Z': Mono-$h(b\bar{b})$

- Dominant decay channel with BR($h \to b\bar{b}$)=57%
- Trigger on $E_{\mathrm{T}}^{\mathrm{miss}} > 110$ GeV $\Rightarrow$ Offline: $E_{\mathrm{T}}^{\mathrm{miss}} > 150$ GeV
- 8 signal regions
  - (4 $E_{\mathrm{T}}^{\mathrm{miss}}$ bins) $\times$ (1 or 2 b-tags)
- Merged approach for $E_{\mathrm{T}}^{\mathrm{miss}} > 500$ GeV
  - Single AKT10 jet with associated b-tagged track jets

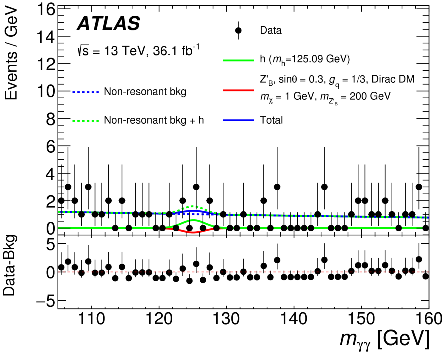






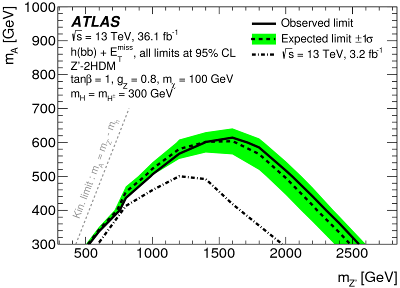
2HDM+Z': Mono-$h(\gamma\gamma)$

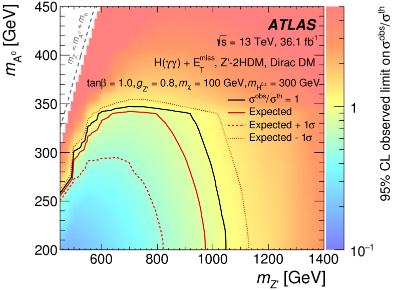
- Clean decay channel with small BR($h \to \gamma\gamma$)=0.24%
- Diphoton trigger
- Main DM sensitive signal region:
  - $E_{\mathrm{T}}^{\mathrm{miss}} / \sum E_T > 7$, $p_T^{\gamma\gamma} > 90$ GeV, lepton veto
- Likelihood fit to $m_{\gamma\gamma}$ distribution around Higgs mass
  - 105 GeV $< m_{\gamma\gamma} <$ 160 GeV



2HDM+Z': Constraints

- Complementary exclusion from mono-$h(\gamma\gamma)$ and mono-$h(b\bar{b})$
  - Mono-$h(b\bar{b})$ dominates for $p_T^h > 150$ GeV
  - Mono-$h(\gamma\gamma)$ can probe lower m_A and $m_{Z'}$

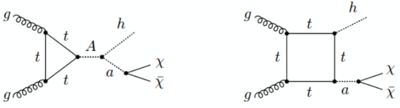




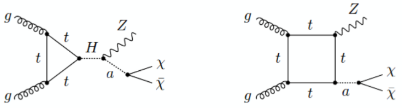
Less simplified model: 2HDM+pseudoscalar

2HDM+Pseudoscalar [arxiv:1701.07427]

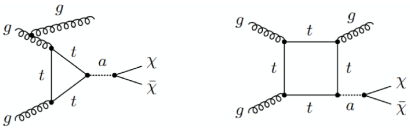
- Extension of 2HDM (type-II) in the alignment limit
- Pseudoscalar mediator a mixes with heavy pseudoscalar A of 2HDM
- Rich phenomenology of $E_{\mathrm{T}}^{\mathrm{miss}}$+X signatures with complementary sensitivity



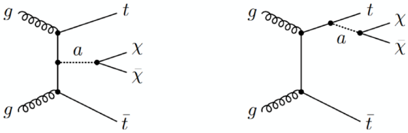
(a) $E_{\mathrm{T}}^{\mathrm{miss}} + h$



(b) $E_{\mathrm{T}}^{\mathrm{miss}} + Z$



(c) $E_{\mathrm{T}}^{\mathrm{miss}}$+jet



(d) $E_{\mathrm{T}}^{\mathrm{miss}}+t\bar{t}$

- Additional sensitivity from resonance searches for A/H ($b\bar{b}$, $\tau\tau$, $t\bar{t}$)

2HDM+PS: Parameters

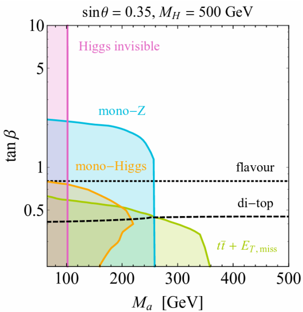
- 14 parameters
- Alignment limit: the lighter of CP-even states h is SM Higgs
  $\Rightarrow \sin(\beta-\alpha)=1,\ m_h = 125$ GeV, $v = 246$ GeV
- Fix quartic couplings such that $\lambda_3 \geq m_h^2/v^2 = 0.258$ (stability of the potential)
  $\Rightarrow \lambda_3 = \lambda_{P1} = \lambda_{P2} = 3$
- Impose EW/flavour constraints
  $\Rightarrow m_A = m_H = m_{H\pm}$
- Fix DM mass and coupling: $m_\chi = 10$ GeV and $y_\chi = 1$

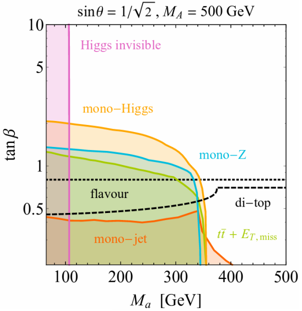
4 free parameters

- m_A: mass of heavy pseudoscalar A
- m_a: mass of mediator a
- $\sin\theta$: mixing angle between a and A
- $\tan\beta$: ratio of VEVs of the two Higgs doublets

2HDM+PS: Scan in $m_a - \tan\beta$

- 4 benchmark scenarios considered in originally
- LHC DM WG deviate from orignal benchmarks to ensure stability/unitarity
  - Mass degeneracy: $m_A = m_H = m_{H^\pm} = 600$ GeV (original: $|m_A - m_H| \sim 250$ GeV)
  - Quartic couplings: $\lambda_3 = \lambda_{P1} = \lambda_{P2} = 3$ (original: $= 0$)



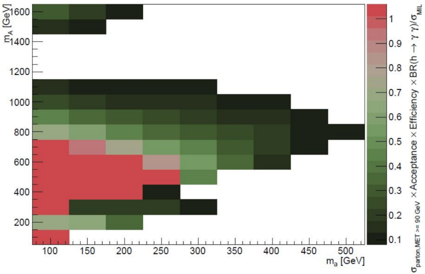


- Note: $t\bar{t} + E_{\mathrm{T}}^{\mathrm{miss}}$ contour for 200 fb^{-1} (40 fb^{-1} for all others)

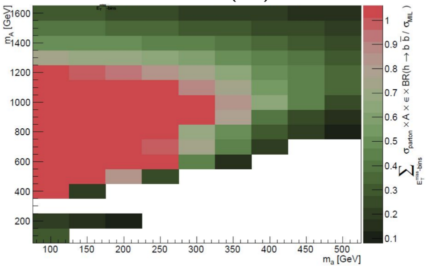
2HDM+PS: Scan in $m_a - m_A$

- Complementarity of mono-$h(\gamma\gamma)$ and mono-$h(b\bar{b})$
  - Fix $\tan\beta = 1.0$, $\sin\theta = 0.35$

Mono-$h(\gamma\gamma)$

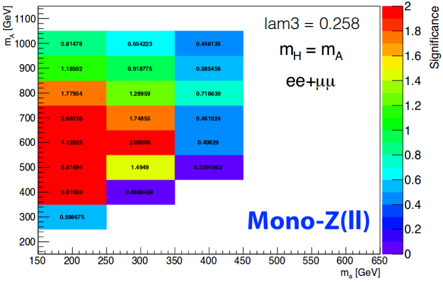


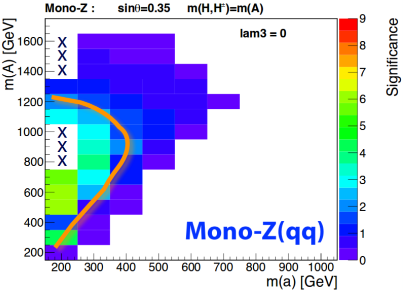
Mono-$h(b\bar{b})$



2HDM+PS: Scan in $m_a - m_A$

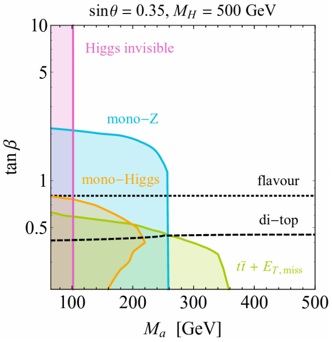
- Complementarity of mono-$Z(\ell\ell)$ and mono-Z(had)
  - Fix $\tan\beta = 1.0$, $\sin\theta = 0.35$





2HDM+PS: Other Scans

- Sensitivity dominated by mono-h and mono-V (resonant production modes)
- $t\bar{t} + E_{\mathrm{T}}^{\mathrm{miss}}$ and $b\bar{b} + E_{\mathrm{T}}^{\mathrm{miss}}$ provide additional constraints



- $t\bar{t} + E_{\mathrm{T}}^{\mathrm{miss}}$ at larger $\sin\theta \Rightarrow$ Scan in $\sin\theta$
- More interesting with more data

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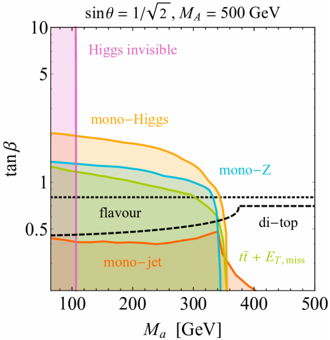

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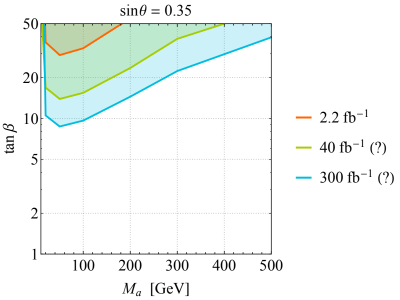
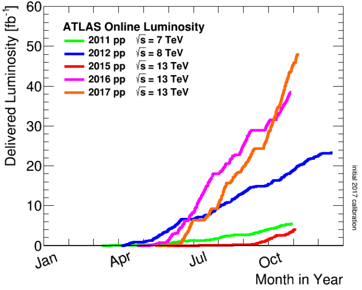


- $b\bar{b} + E_{\mathrm{T}}^{\mathrm{miss}}$ sensitivity at large $\tan\beta$
- Additional constraints from mono-$h(b\bar{b})$?

Summary

- Diverse programme of DM searches in ATLAS
  - Complementarity between different final states
- Probing a variety of benchmark models
  - Trend towards less simplified models with more data
- Cooperation between ATLAS/CMS/Theory via LHC DM WG
  - Whitepaper summarising 2HDM+PS recommendations (in preparation)
- Many more searches in progress...
  ... and more data coming in!

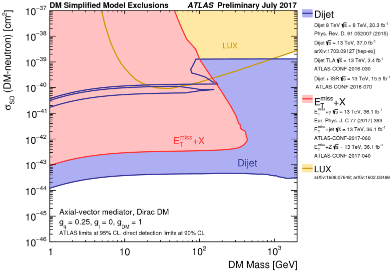


BACKUP

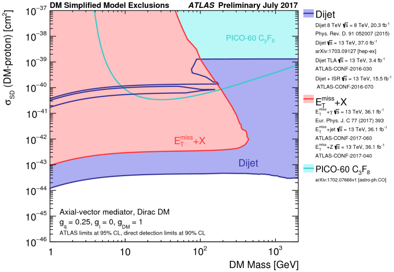
Comparison with Direct Detection Results

- Complementarity of LHC and direct detection searches
- Caveat: ATLAS limits at 95% CL compared to 90% for DD

A1 - Neutron



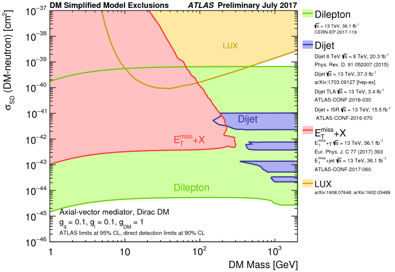
A1 - Proton



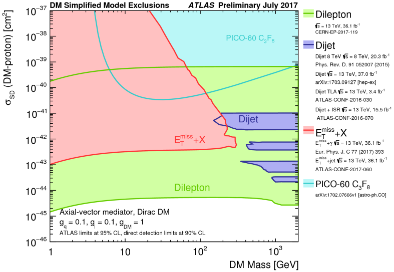
Comparison with DD for A2

- Complementarity of LHC and direct detection searches
- Caveat: ATLAS limits at 95% CL compared to 90% for DD

A2 - Neutron



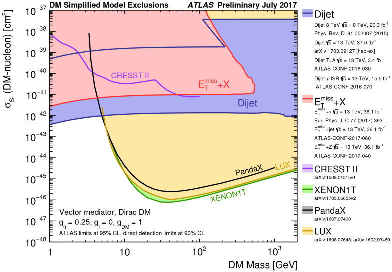
A2 - Proton



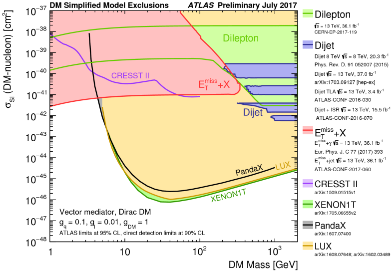
Comparison with DD for V1 and V2

- Caveat: ATLAS limits at 95% CL compared to 90% for DD

V1 - Nucleon

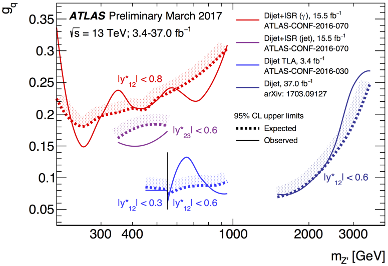


V2 - Nucleon



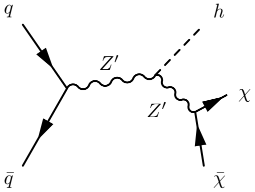
Scan in g_q

- Current version from March 2017



Baryonic Z'

- Simplified model [arxiv:1312.2592]
- Gauge symmetry $U(1)_B$ for conservation of baryon number $B \Rightarrow$ gauge boson Z'_B
- Spontaneously broken by baryonic Higgs h_b that mixes with SM Higgs with angle θ



- Parameters as recommended by LHC DM WG
- $g_q = 1/3$, $g_\chi = 1$, $g_{hZ'Z'} = m_{Z'}$, $\sin\theta = 0.3 \Rightarrow$ Mono-h signature!

2HDM+PS: lighter scalar h

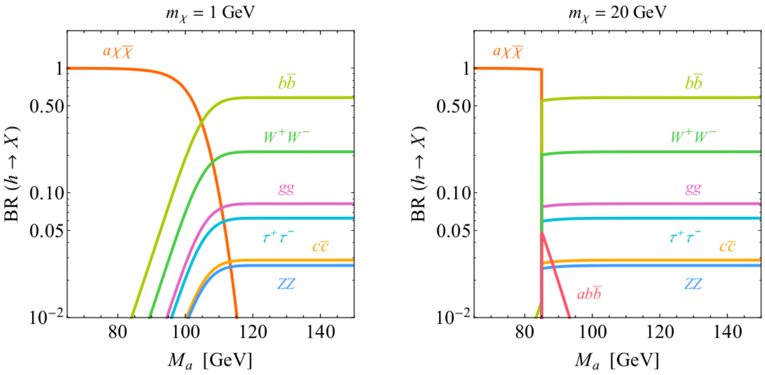


Figure 2. Branching ratios of the lighter scalar h as a function of the pseudoscalar mass M_a for two different choices of m_χ as indicated in the headline of the plots. The other relevant parameters have been set to $\tan\beta = 1$, $M_H = M_A = M_{H^\pm} = 750\,\text{GeV}$, $\sin\theta = 1/\sqrt{2}$, $\lambda_3 = \lambda_{P1} = \lambda_{P2} = 0$ and $y_\chi = 1$.

2HDM+PS: mediator a

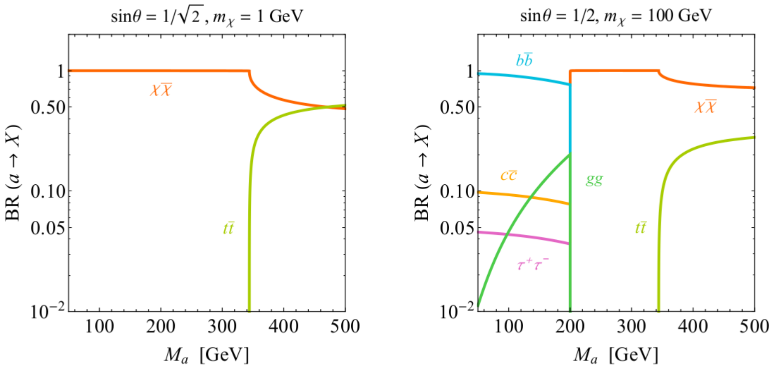
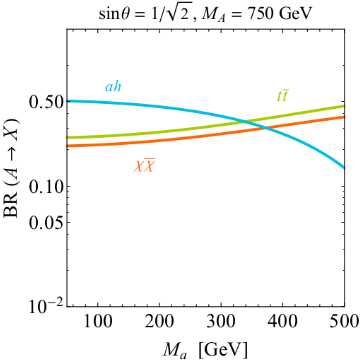


Figure 1. Branching ratios of the lighter pseudoscalar a as a function of its mass for two different choices of $\sin\theta$ and m_χ as indicated in the headline of the plots. The other relevant parameters have been set to $\tan\beta = 1$, $M_H = M_A = M_{H^\pm} = 750$ GeV and $y_\chi = 1$. Notice that for this specific $\tan\beta$ value the branching ratios of the pseudoscalar a do not depend on the choice of Yukawa sector.

2HDM+PS: pseudoscalar A



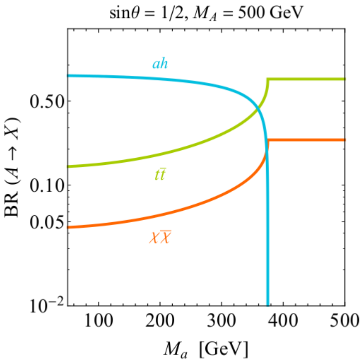


Figure 4. Branching ratios of the heavier pseudoscalar A as a function of M_a for two different choices of M_A and $\sin\theta$ as indicated in the headline of the plots. The other parameter choices are $\tan\beta = 1$, $M_H = M_{H^\pm} = 750\,\text{GeV}$, $\lambda_3 = \lambda_{P1} = \lambda_{P2} = 0$, $y_\chi = 1$ and $m_\chi = 1\,\text{GeV}$.

2HDM+PS: heavier scalar H

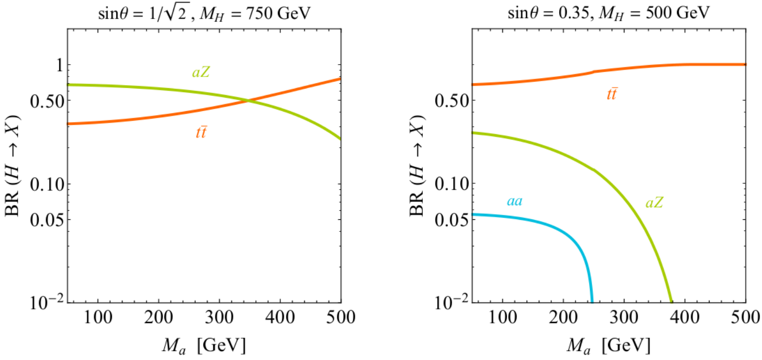


Figure 3. Branching ratios of the heavier scalar H as a function of M_a for two different choices of $\sin\theta$ and M_H as indicated in the headline of the plots. The other used input parameters are $\tan\beta = 1$, $M_A = M_{H^\pm} = 750\,\text{GeV}$, $\lambda_3 = \lambda_{P2} = 0$ and $\lambda_{P1} = 1$.

2HDM+PS: charged Higgs $H^{\pm}$

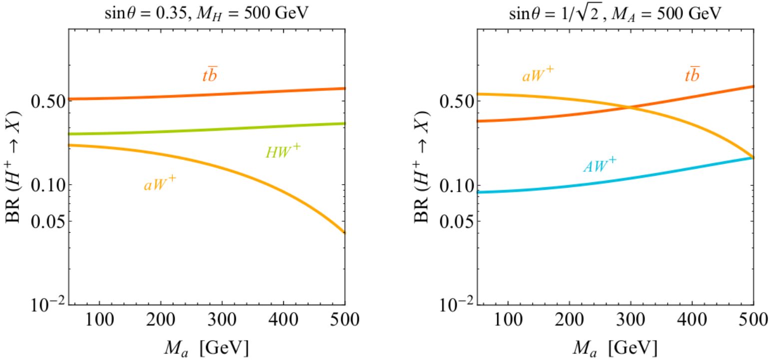


Figure 5. Branching ratios of the charged scalar H^+ as a function of M_a for two different sets of input parameters as indicated in the headline of the plots. In the left (right) panel in addition $\tan\beta = 1$ and $M_A = M_{H^\pm} = 750\,\text{GeV}$ ($M_H = M_{H^\pm} = 750\,\text{GeV}$) is used.

2HDM+PS: Sensitivity for mono-$h(b\bar{b})$

- **Use limits on visible cross-section**
  - "Model-independent" limits

1. simulate parton-level x-sec
2. bin into 4 MET bins
3. fold (bin-by-bin) with $\mathcal{A} \times \varepsilon$
4. multiply with SM BR(h→bb)
5. divide (bin-by-bin) by observed upper limit on $\sigma^{\text{obs}}_{\text{vis},h+\text{DM}}$
6. sum over 4 MET bins

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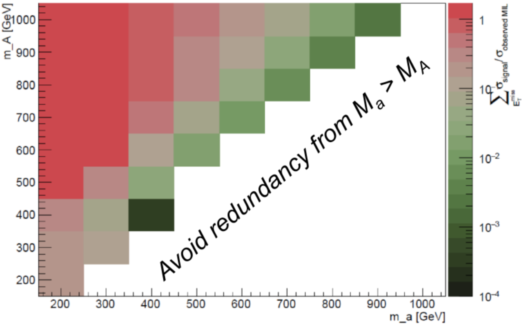
Range in E_T^{miss}/GeV	$\sigma^{\text{obs}}_{\text{vis},h+\text{DM}}$ [fb]	$\sigma^{\text{exp}}_{\text{vis},h+\text{DM}}$ [fb]	$\mathcal{A} \times \varepsilon$ %
[150, 200)	19.1	$18.3^{+7.2}_{-5.1}$	15
[200, 350)	13.1	$10.5^{+4.1}_{-2.9}$	35
[350, 500)	2.4	$1.7^{+0.7}_{-0.5}$	40
[500, ∞)	1.7	$1.8^{+0.7}_{-0.5}$	55

Signal significance, summed over the four E_T^{miss} bins



Additional 1D Scans

- Scans in $\sin\theta$ for two points in $m_a - m_A$ grid ($\tan\beta = 1$)
  - $m_a = 200$ GeV, $m_A = 600$ GeV
  - $m_a = 350$ GeV, $m_A = 1000$ GeV
- Scan in m_{DM} fixing $m_a = 250$ GeV, $m_A = 600$ GeV, $\tan\beta = 1$, $\sin\theta = 0.35$
  - Current default: $m_{\mathrm{DM}} = 10$ GeV (authors assumed $m_{\mathrm{DM}} = 1$ GeV)
  - Higher values of m_{DM} preferred by relic density constraints
  - [Details]