REPORT FROM THE LHC DARK MATTER WG

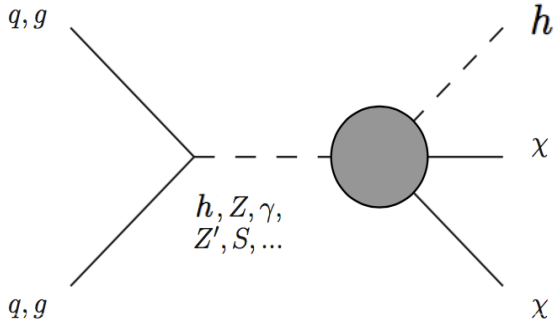
LHC Higgs Cross Section WG3 meeting
11.12.2018

ATLAS: Oleg Brandt and Christian Ohm
CMS: P. Harris
LHCb: Xabier Cid Vidal
TH: U. Haisch and T. Tait
LPCC: M. Mangano
on behalf of LHC DM WG

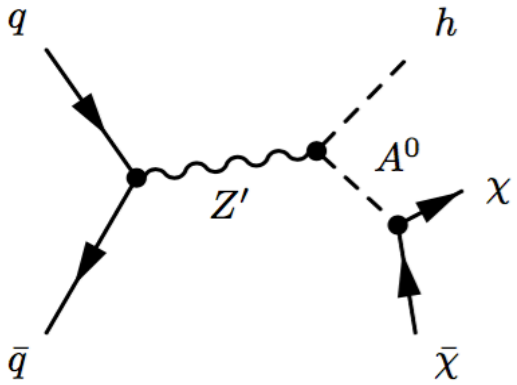
LHC DM WG: WG on Dark Matter Searches at the LHC

- **Role:**
  - Provide **open, collaborative, and friendly** environment for:
    - Discuss new Dark Matter signatures
    - Devise future searches for Dark Matter
    - Provide recommendations for interpretation of Dark Matter searches
  - **Your** ideas very welcome:
    - E.g. extensions of 2HDM, dark photon models, t+MET, you name it!
      - Suggestions for future topics you would like to tackle very welcome!
  - **Facilitate exchange of ideas** through meetings etc:
    - http://simba3.web.cern.ch/simba3/SelfSubscription.aspx?groupName=lhc-dmwg-contributors

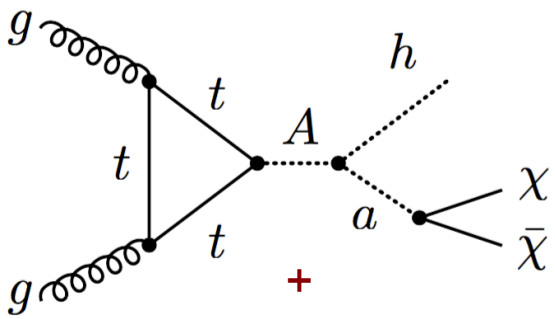
INTERPRETATION OF DARK MATTER (DM) SEARCHES



DMF recommendations
arXiv:1507.00966



Z'-2HDM model
JHEP 06 (2014) 078
+ arXiv:1507.00966



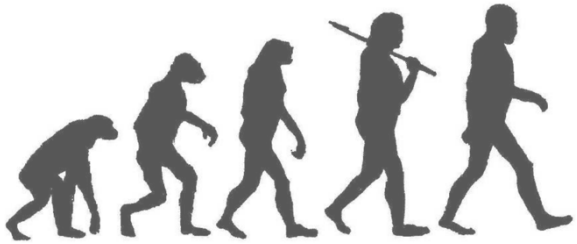
+
many other signatures

2HDM+a model
JHEP 05 (2017) 138
+ arXiv:1810.09420

Focus of this talk

1) Effective field theory **2) Simplified models** **3) Simplified, consistent, & UV-complete models**

Richer kinematics + phenomenology



CERN-LPCC-2018-02

LHC Dark Matter Working Group:

Next-generation spin-0 dark matter models

plots w/o reference are from this White Paper in this talk

Abstract. Dark matter (DM) simplified models are by now commonly used by the ATLAS and CMS Collaborations to interpret searches for missing transverse energy (E_T^{miss}). The coherent use of these models sharpened the LHC DM search program, especially in the presentation of its results and their comparison to DM direct-detection (DD) and indirect-detection (ID) experiments. However, the community has been aware of the limitations of the DM simplified models, in particular the lack of theoretical consistency of some of them and their restricted phenomenology leading to the relevance of only a small subset of E_T^{miss} signatures. This document from the LHC Dark Matter Working Group identifies an example of a next-generation DM model, called 2HDM+a, that provides the simplest theoretically consistent extension of the DM pseudoscalar simplified model. A comprehensive study of the phenomenology of the 2HDM+a model is presented, including a discussion of the rich and intricate pattern of mono-X signatures and the relevance of other DM as well as non-DM experiments. Based on our discussions, a set of recommended scans are proposed to explore the parameter space of the 2HDM+a model through LHC searches. The exclusion limits obtained from the proposed scans can be consistently compared to the constraints on the 2HDM+a model that derive from DD, ID and the DM relic density.

2HDM+a: FEATURES

- **Pseudoscalar DM mediator**
  - Weak constraint from direct detection experiments
    - No tree-level coupling
- **2HDM (II) extension of Higgs sector**
  - Well motivated
  - Avoid Higgs constraints in alignment limit
  - Avoid issues of pure pseudoscalar models
- **Predictiveness:**
  - Minimal particle content for a complete theory
  - Simple enough to parametrise on simple grids
- **Diverse palette of signatures**
  - Confront, combine complementary channels
  - Mono-Z, mono-h play special role

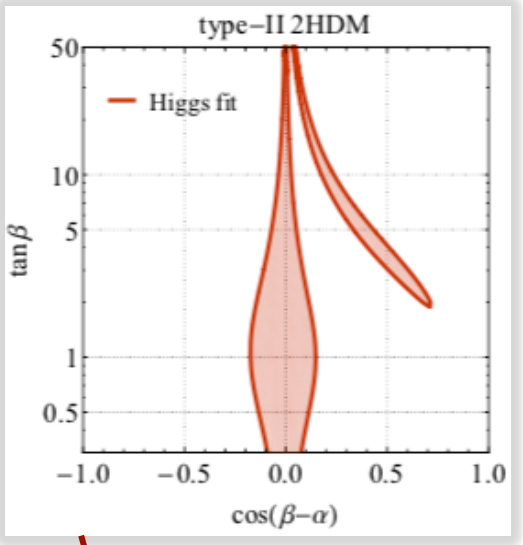
Particle content:
- CP even: h, H
- CP odd: A, a
- Charged: $H^{\pm}$
- Dirac DM: χ

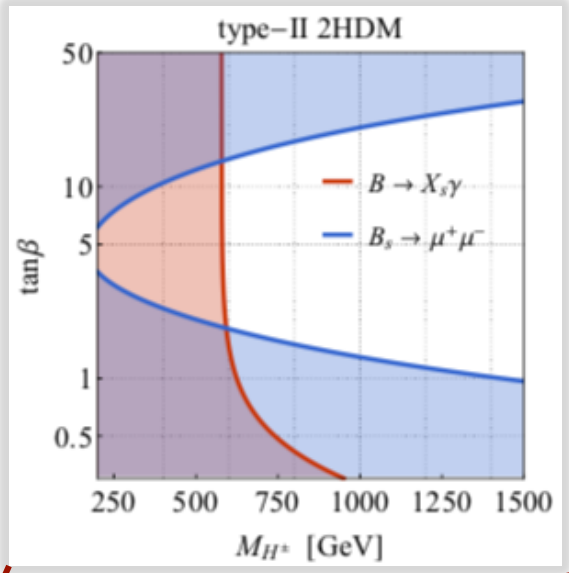
A, a mixed: sinθ

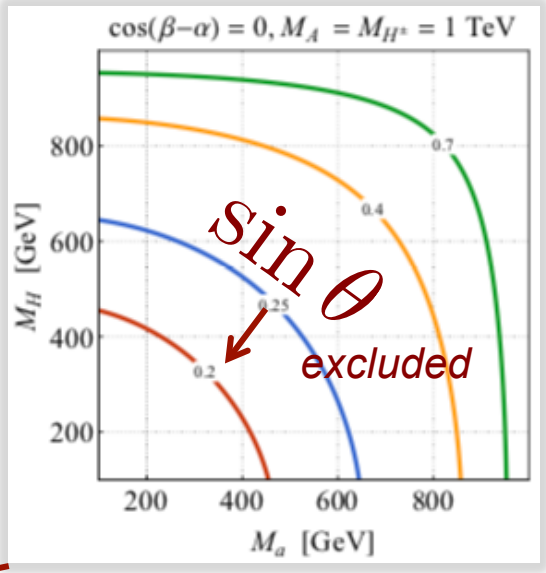
a_0 (before mixing) couples to χ

Simplified scalar models from LHC DM WG exist (arXiv:1603.04156) that map directly to 2HDM for some final states, e.g. monojet, tt+H

2HDM+a: PARAMETERS







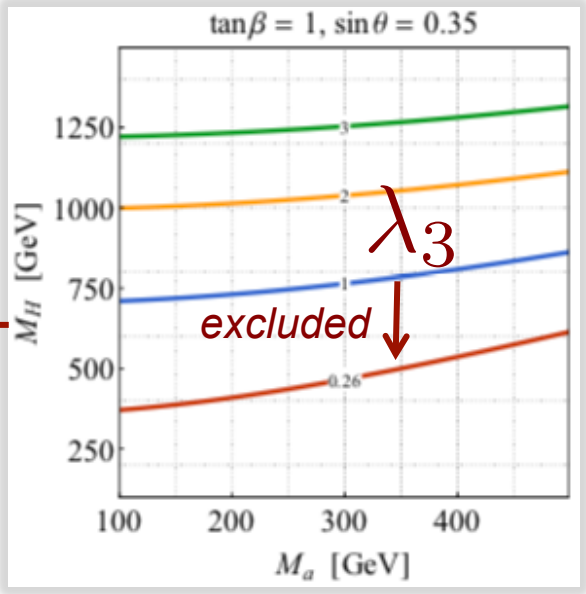
$$M_H = M_A = M_{H^\pm}\,, \quad m_\chi = 10\,\text{GeV}\,,$$

$$\cos(\beta-\alpha) = 0\,, \quad \tan\beta = 1\,, \quad \sin\theta = 0.35\,,$$

$$y_\chi = 1\,, \quad \lambda_3 = \lambda_{P1} = \lambda_{P2} = 3\,.$$

Convenience

Resonant enhancement



- ~~Executive~~ **Experimental summary on model pheno:**
  - 14 parameters to start with
    - **7 parameters fixed:**
      - symmetry, EW-precision measurements, Higgs properties,...

More details in talk by Johanna Gramling
https://indico.cern.ch/event/665524/sessions/260090/

    - **7 "free" parameters:**

- *4 affect MET shape:*
  - m_a
  - m_A
  - m_H
  - $\sin(\theta)$

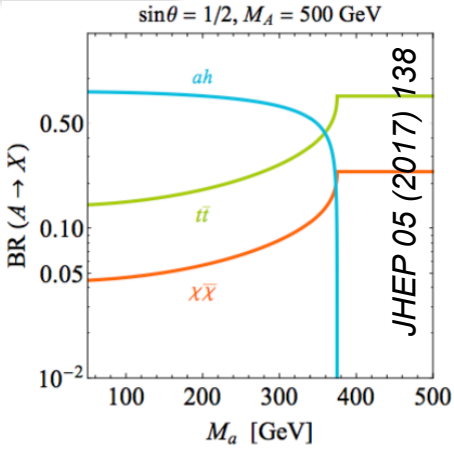
  } *kinematics & channels*

  ← *couplings*

- **3 only affect total cross-section:**
  - $\tan(\beta)$ [1]
  - m_χ [2]
  - y_χ ← *DM Yukawa*

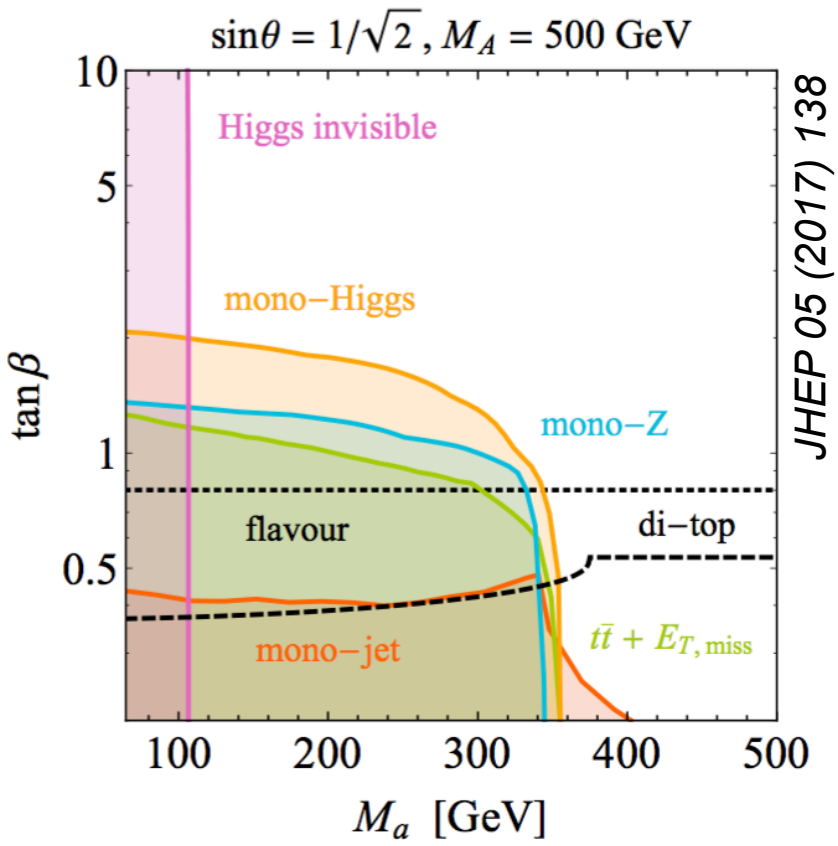
- A/a mixing angle sinθ important, e.g.:

$$\Gamma(A \to \chi\chi) \propto \sin^2\theta \qquad \Gamma(a \to \chi\chi) \propto \cos^2\theta$$
$$\Gamma(A \to ff) \propto \cos^2\theta \qquad \Gamma(a \to ff) \propto \sin^2\theta$$
$$\Gamma(A \to ah) \propto \sin\theta\cos\theta$$

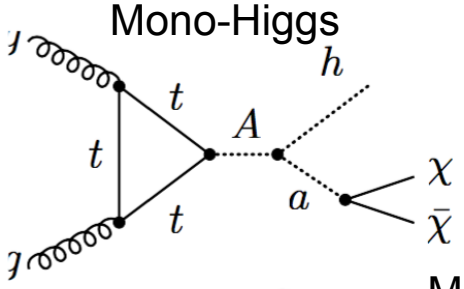


[1] can change shapes if u/d-type couplings process-relevant
[2] statement true if decay mediator on-shell

- **Diverse palette of signatures:**

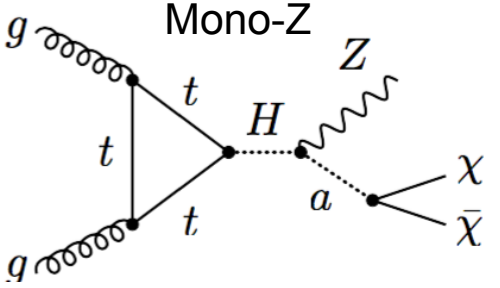


Mono-Higgs

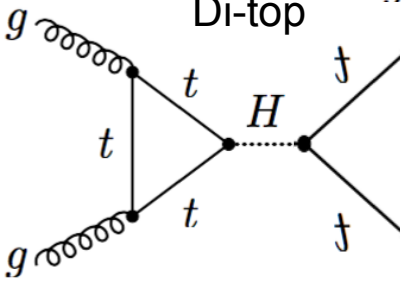


+ many other signatures

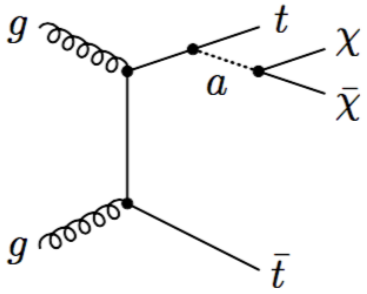
Mono-Z



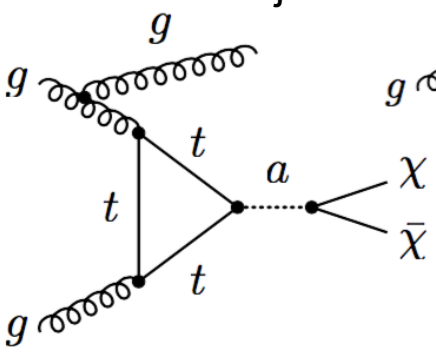
Di-top



tt + MET



Mono-jet



- **The interplay is experimentally exciting!**
- **Today's talk:**
  - Phenomenology + recommendations
  - First interpretations with this model

2HDM+a: (NON-) RESONANT SIGNATURES

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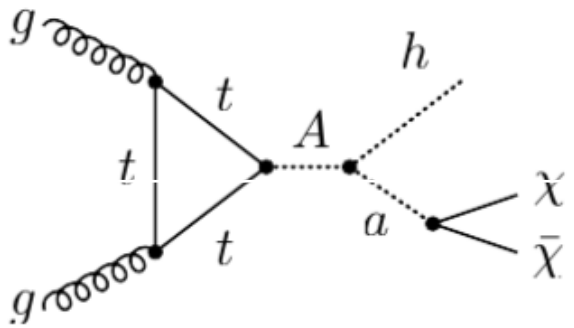
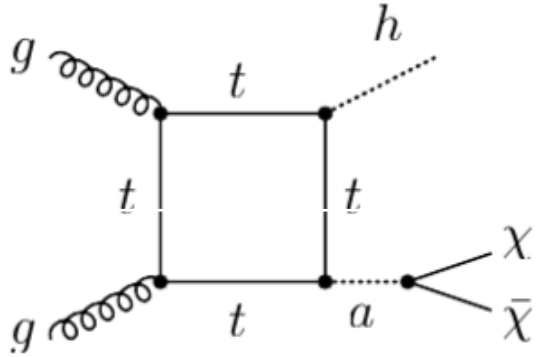
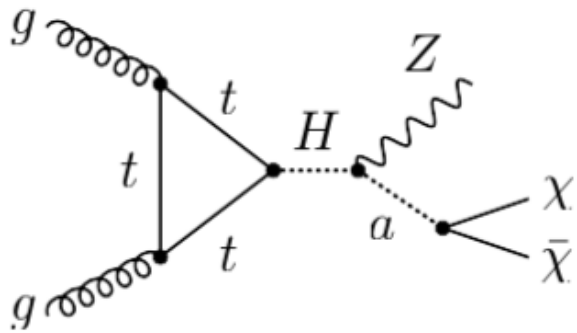
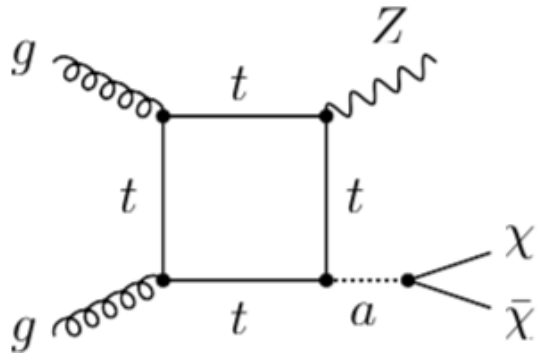
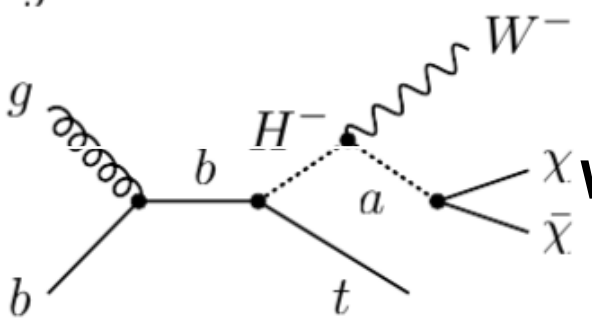
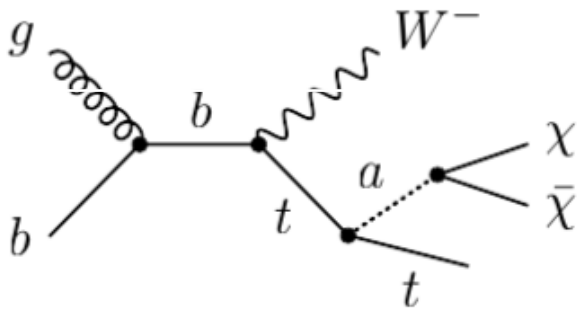
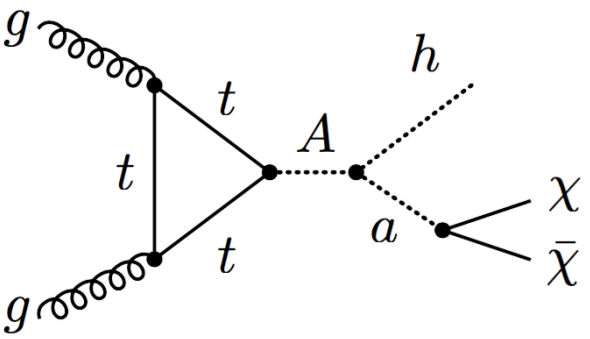
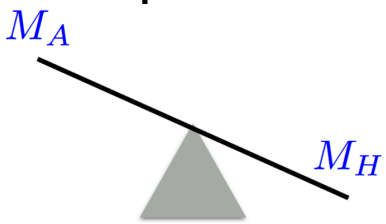
Resonant		Non-Resonant
	**h + DM**	
	**Z + DM**	
	**Wt + DM**	

+ many other signatures

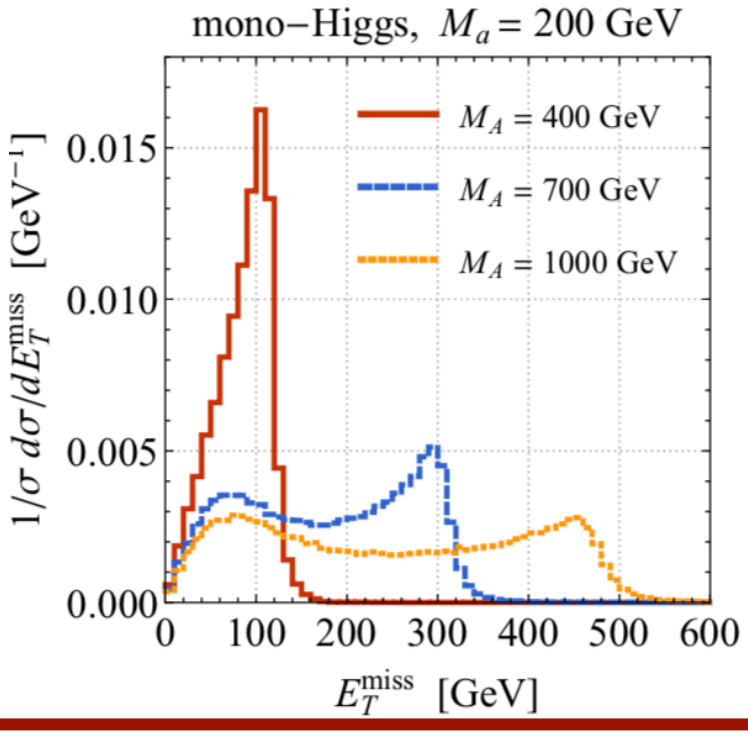
2HDM+a: h + DM

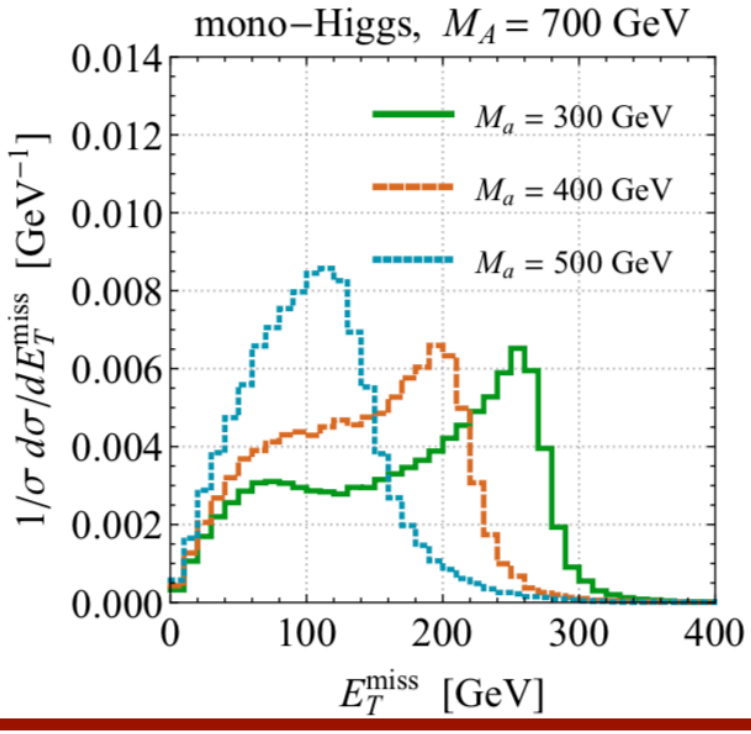
- General:
  - **Can be resonantly enhanced**
    - → driving sensitivity for 2HDM+a
  - **h + E_T^{miss} dominant** over Z + E_T^{miss} if





$$\Rightarrow M_H = M_{H^\pm} = M_A$$





- General:
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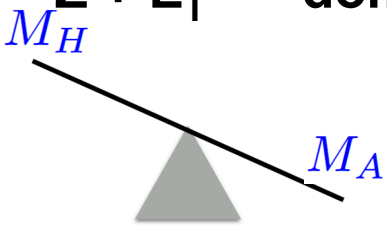

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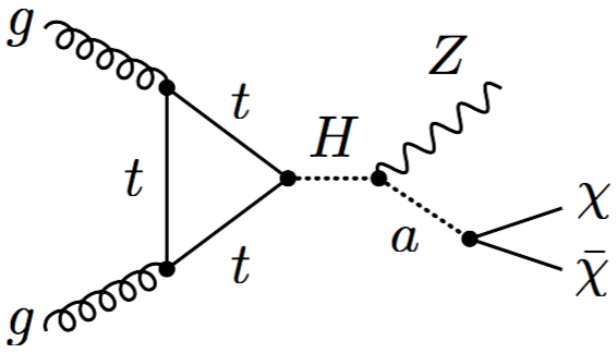
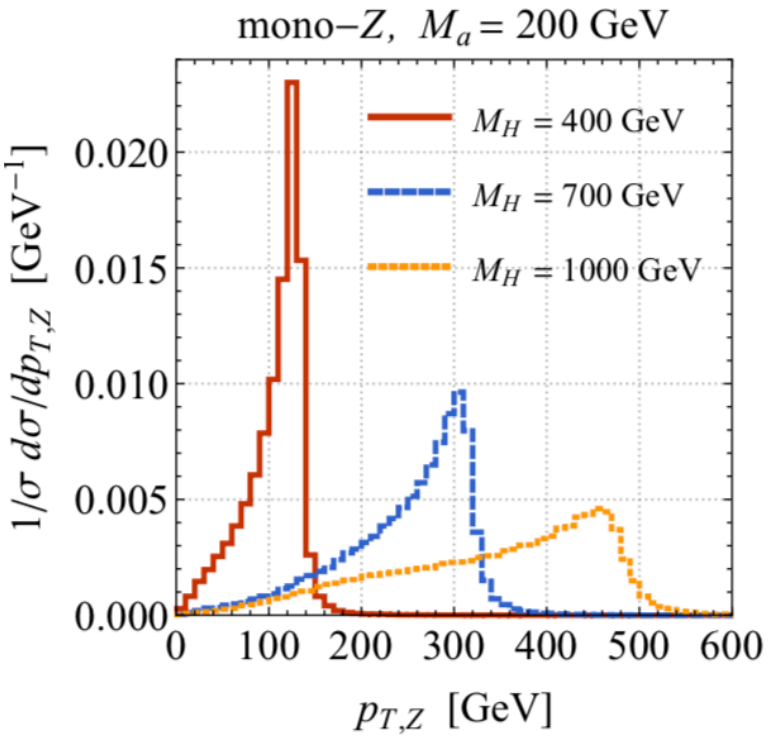
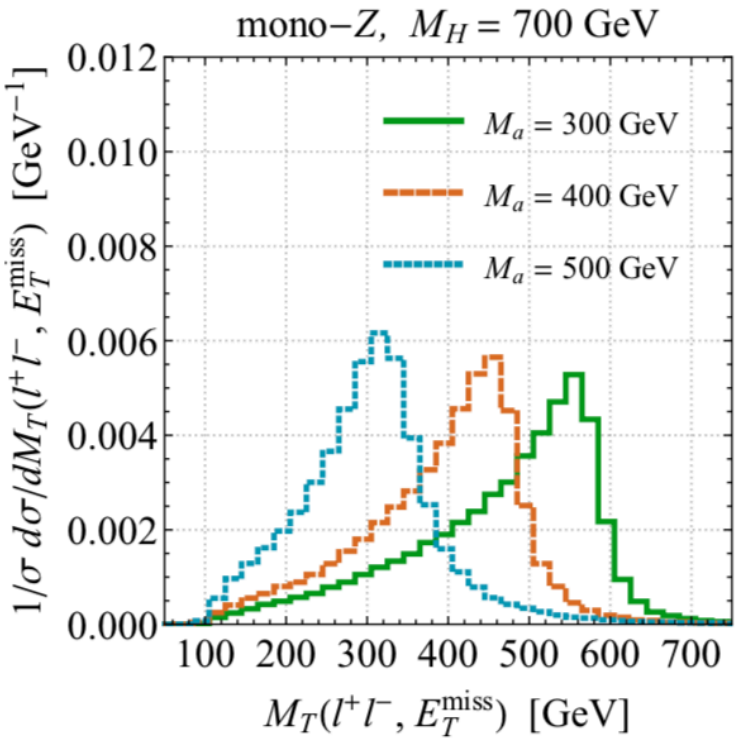
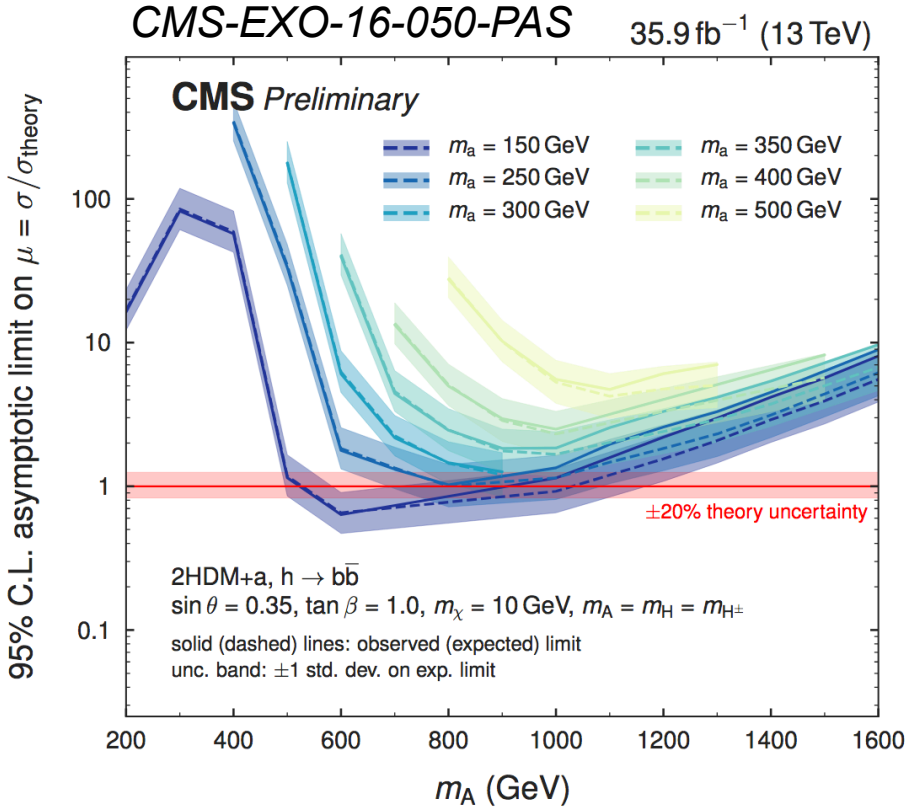
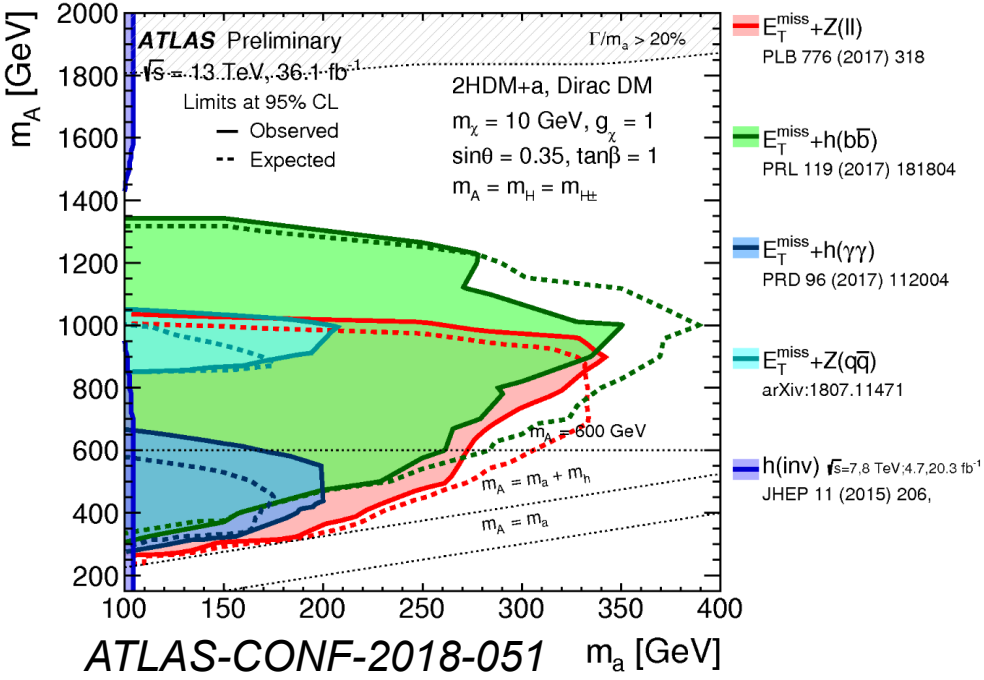






2HDM+a: FIRST RESULTS FOR M_A,M_a



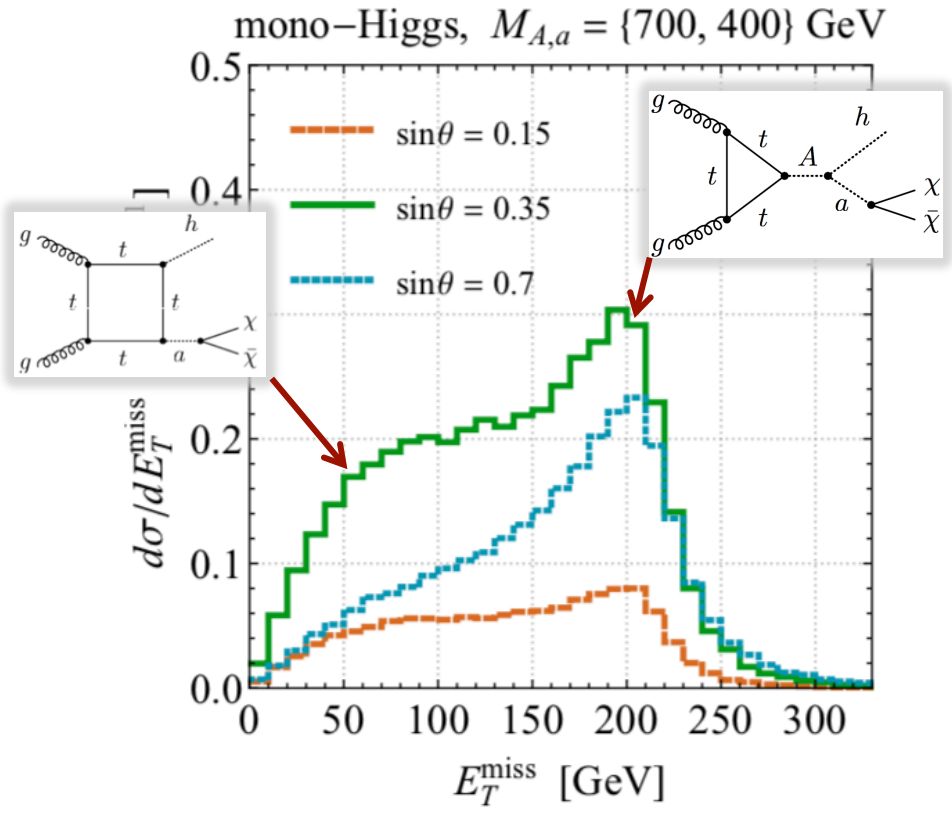


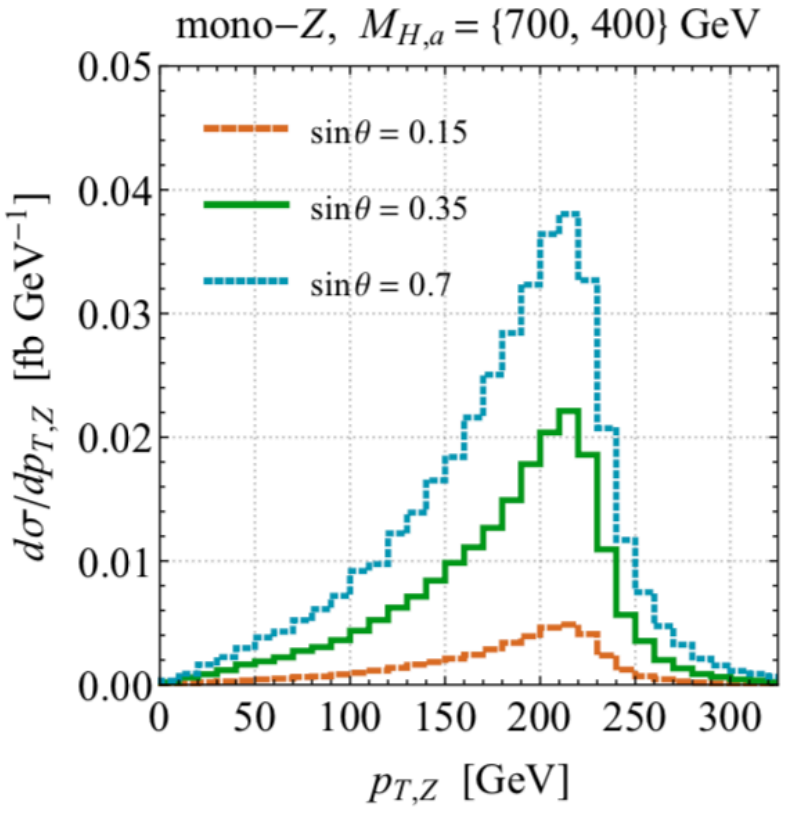
2HDM+a: DEPENDENCE ON SINθ

- Sinθ: a, A mixing angle

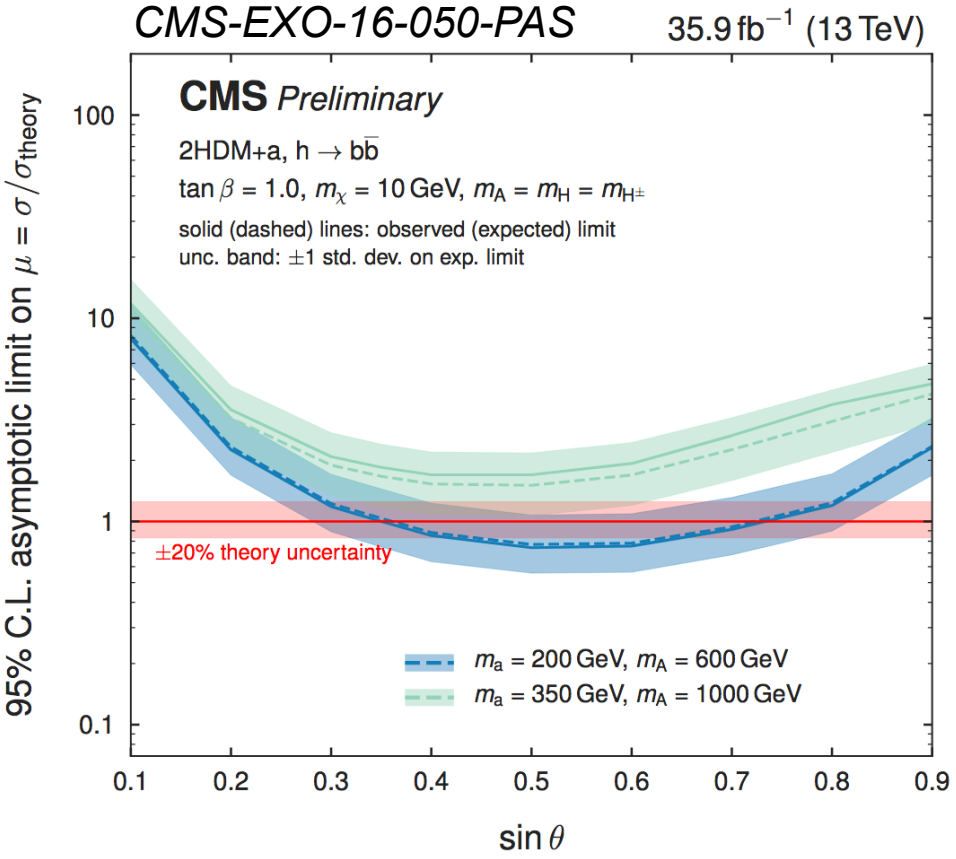
$$\Gamma(A \to \chi\chi) \propto \sin^2\theta \quad \Gamma(a \to \chi\chi) \propto \cos^2\theta$$
$$\Gamma(A \to ff) \propto \cos^2\theta \quad \Gamma(a \to ff) \propto \sin^2\theta$$
$$\Gamma(A \to ah) \propto \sin\theta\cos\theta$$

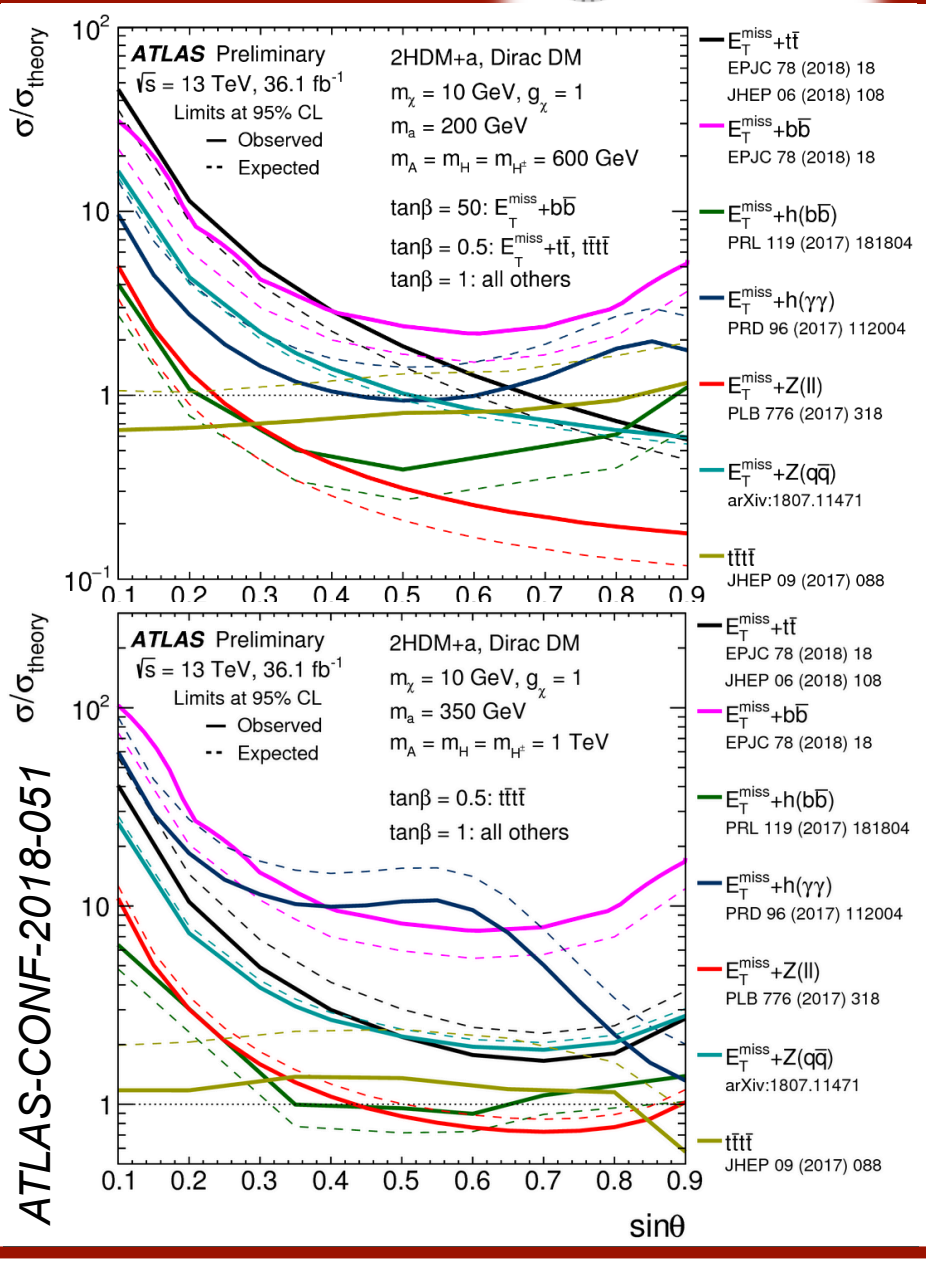
  - Change balance between high-MET peak & low-MET bulk



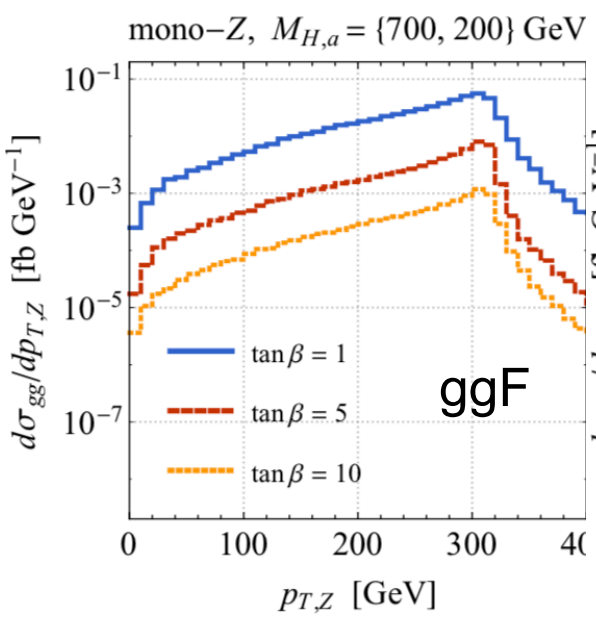


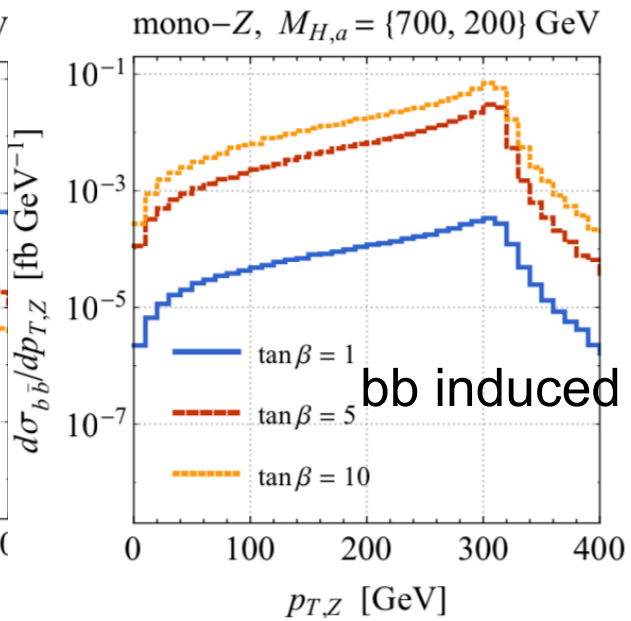
2HDM+a: FIRST RESULTS FOR SINθ

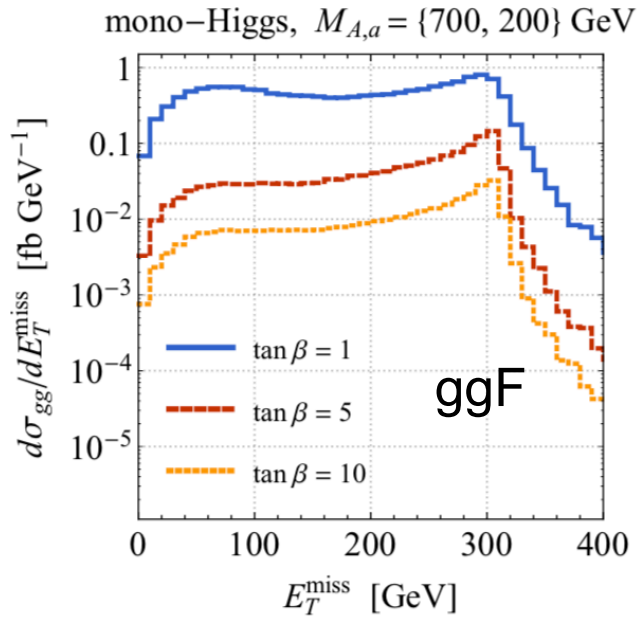


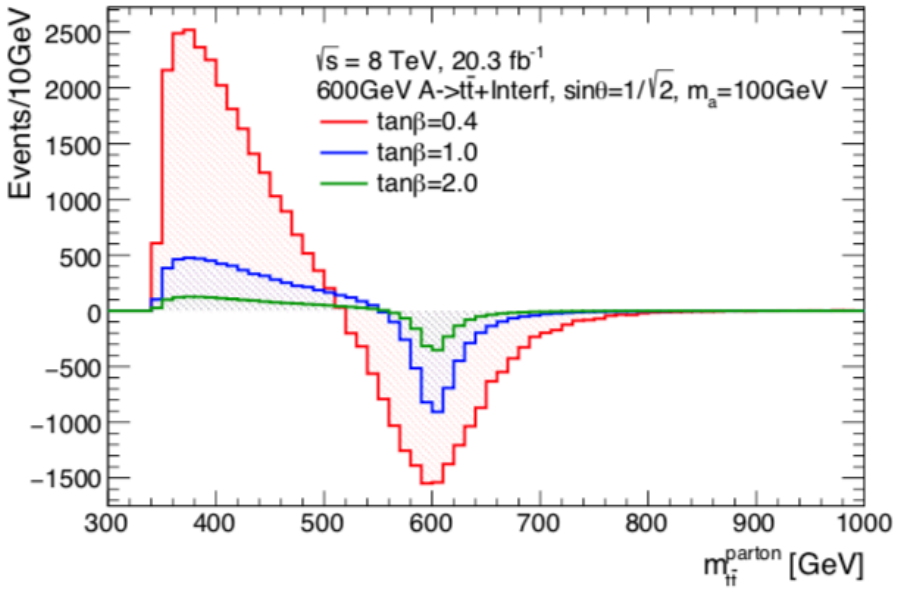


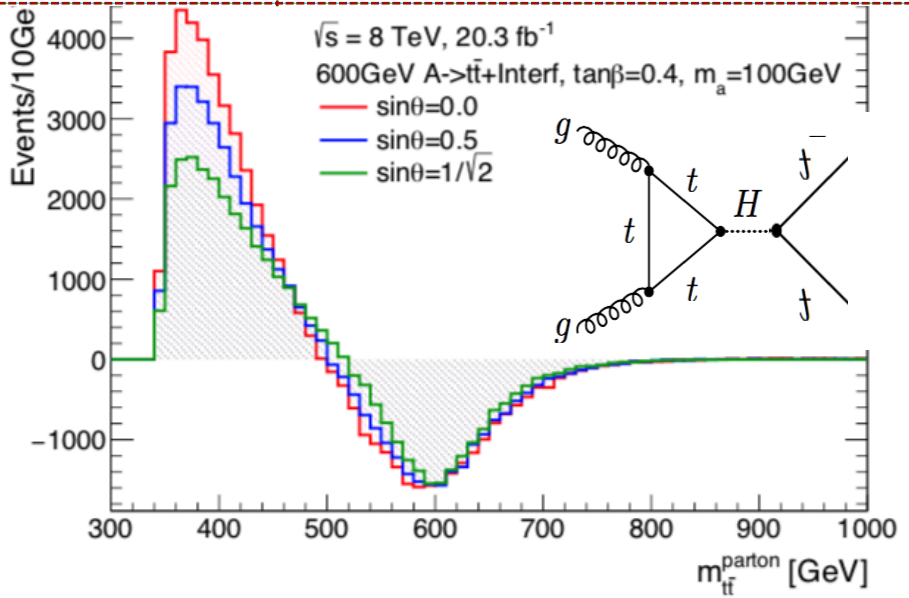
2HDM+a: DEPENDENCE ON TANβ











2HDM+a: FIRST RESULTS FOR M_a,TANβ

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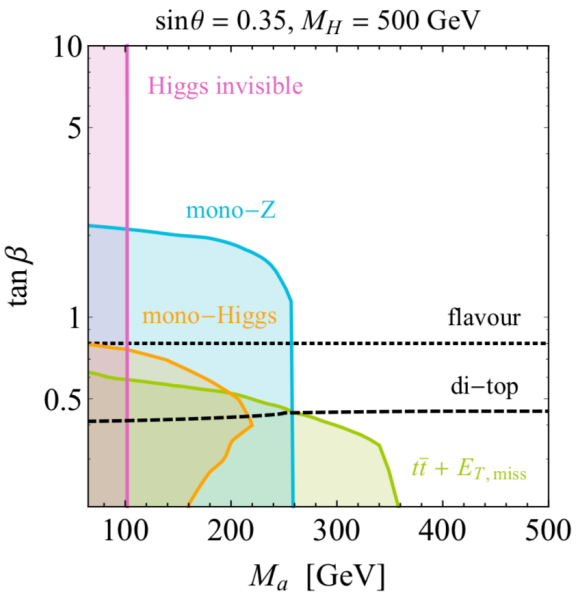
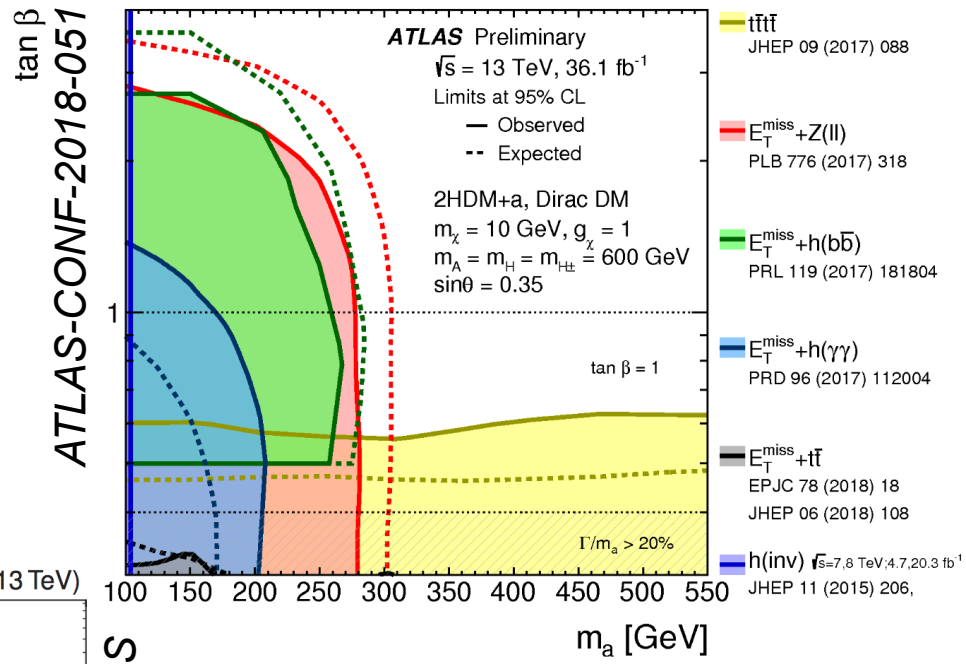
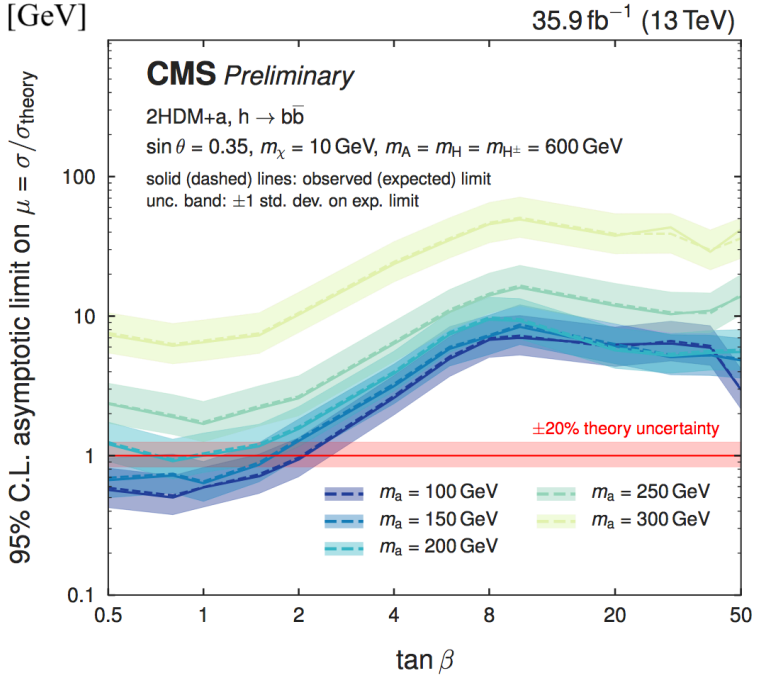
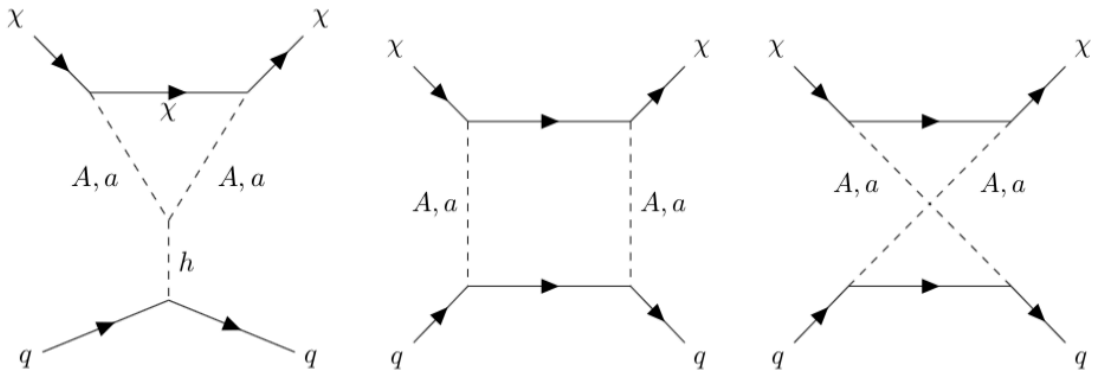


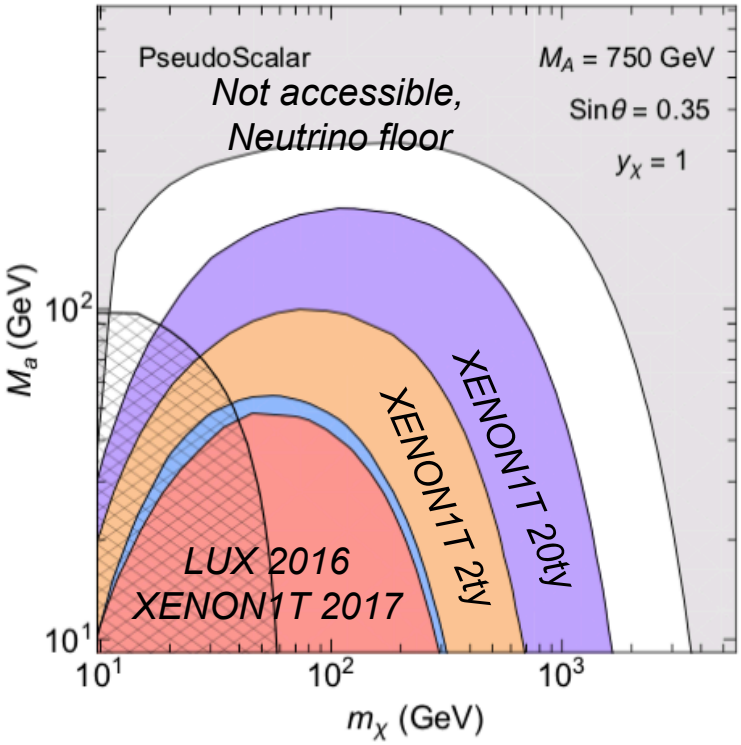


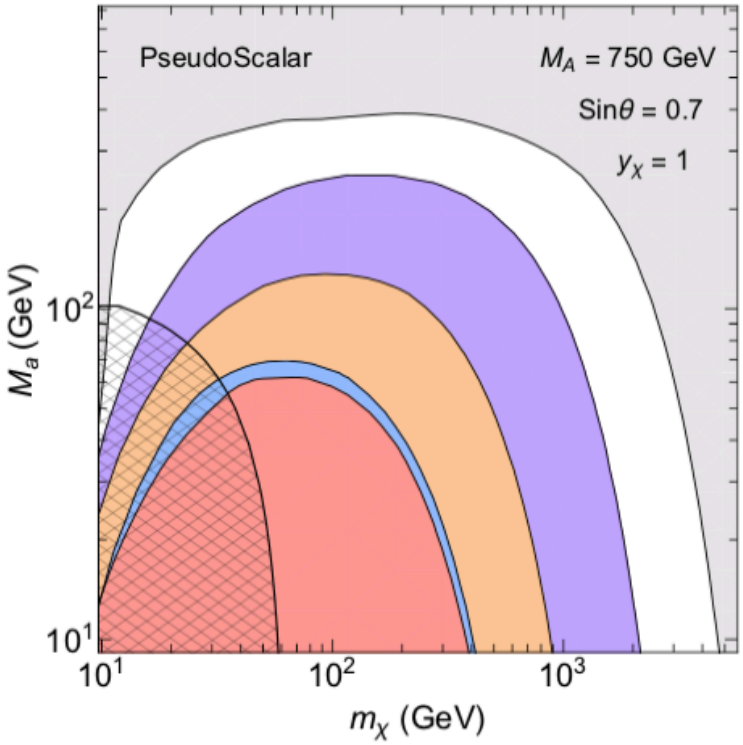


2HDM+a: DIRECT DETECTION

- What can direct detection experiments say about the 2HDM+a?

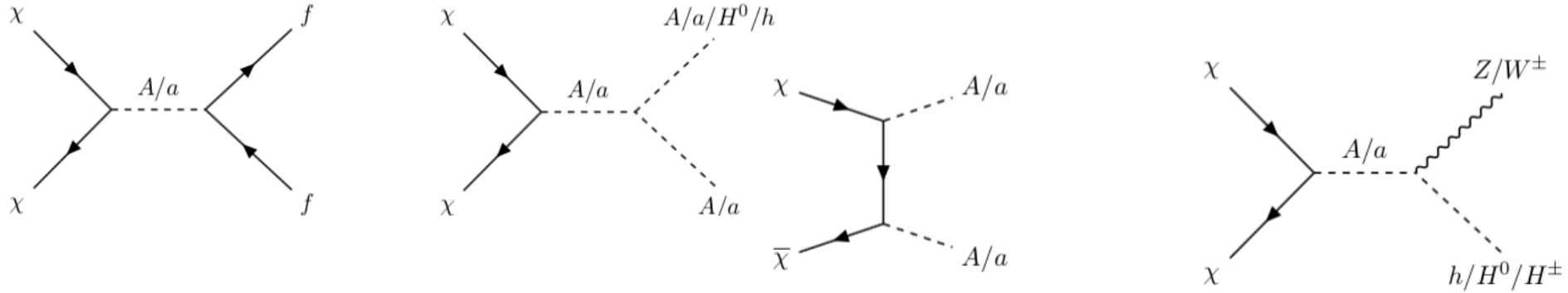


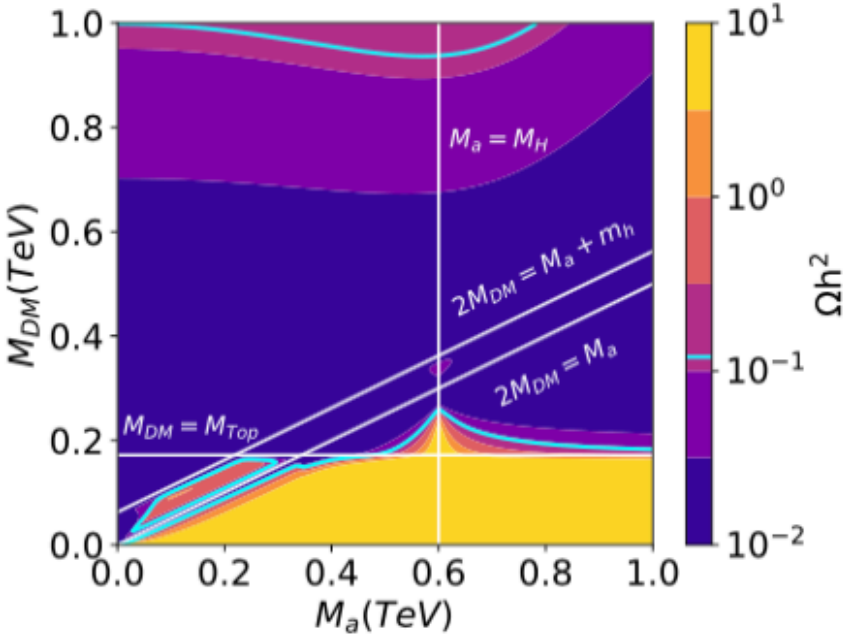


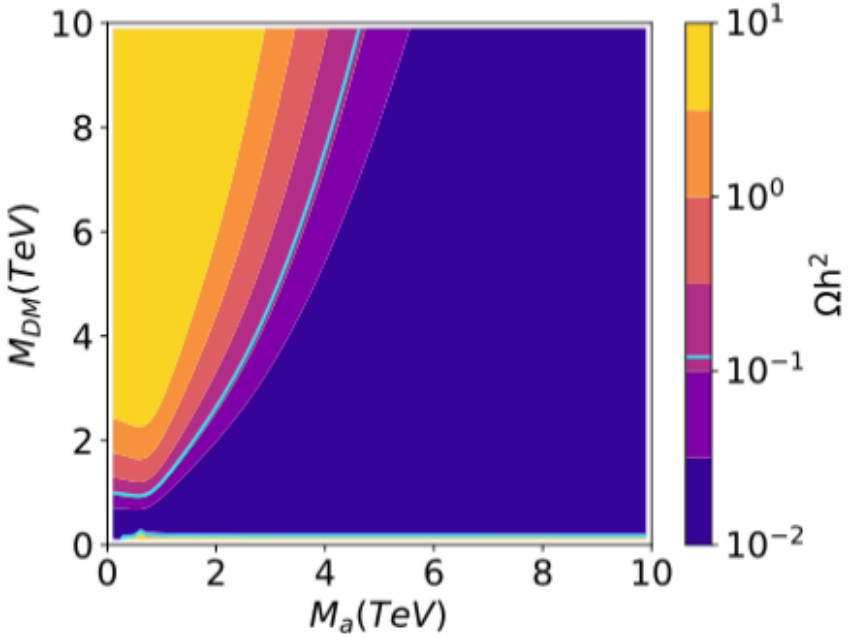


2HDM+a: RELIC DENSITY

- Relic density provides guidance
  - Many annihilation channels to be considered

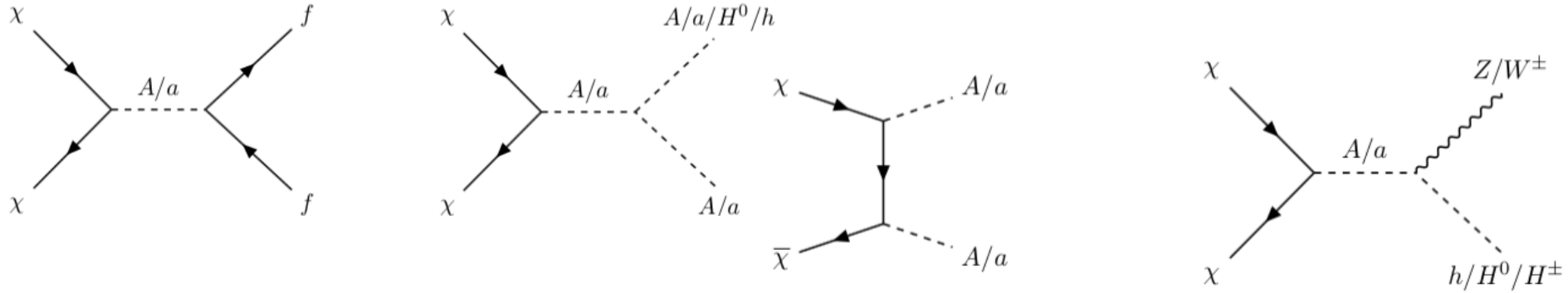


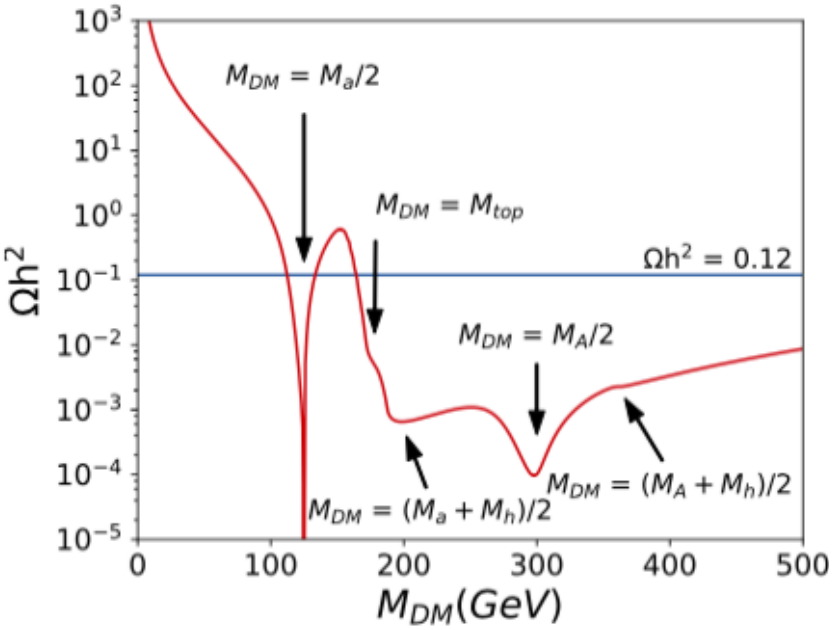


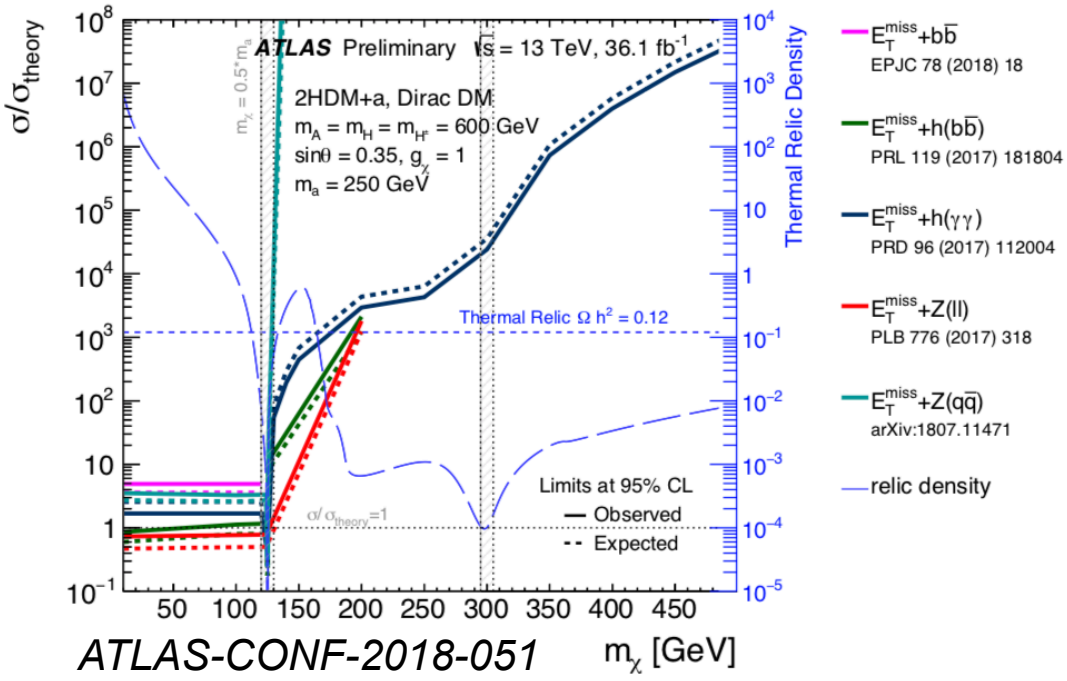


2HDM+a: RELIC DENSITY

- Relic density provides guidance
  - Many annihilation channels to be considered

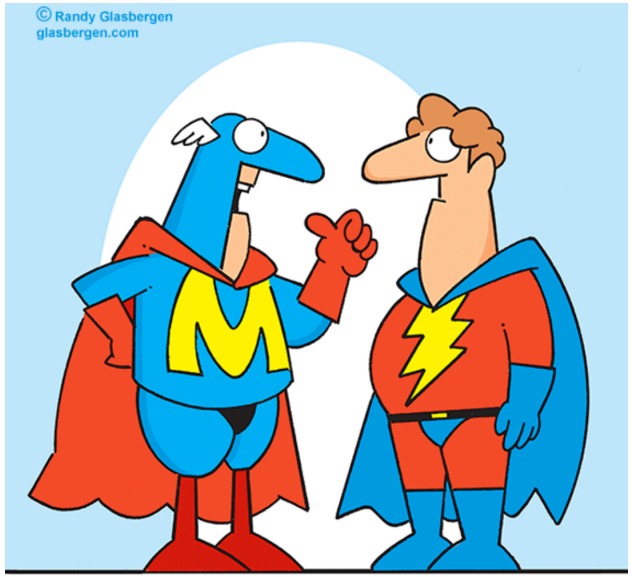






LHC Dark Matter WG: Topical meetings

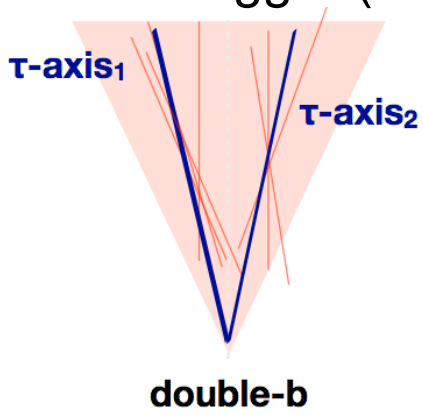
(here: Higgs-related)



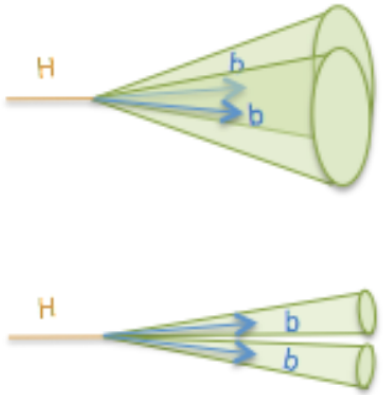
"I'm Meeting Man. My superpower is the ability to keep people awake during PowerPoints!"

- **Topical meeting on mono-h(bb)** (https://indico.cern.ch/event/768106/)
  - Format similar to cross-talk, but through vidyo (more inclusive)
  - **Reviews of the ATLAS + CMS analyses**
    - Details of analysis strategy (e.g. background estimation)
    - Performance aspects, e.g.:
      - Jet reconstruction: only large-radius jet with R=1.5 (CMS), resolved and merged topologies (ATLAS)
      - b-tagging:

double-b-tagger (CMS)

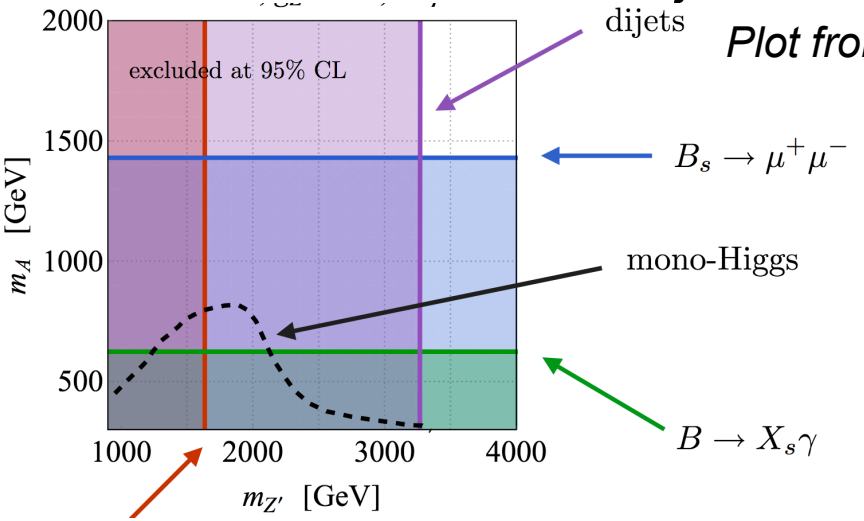


variable-radius track jets (ATLAS)

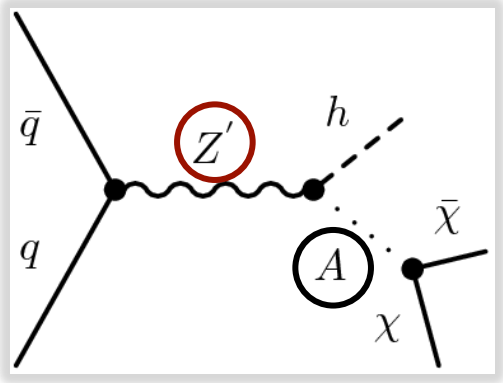


  - Discussion about future interpretations of the analyses
    - Next page

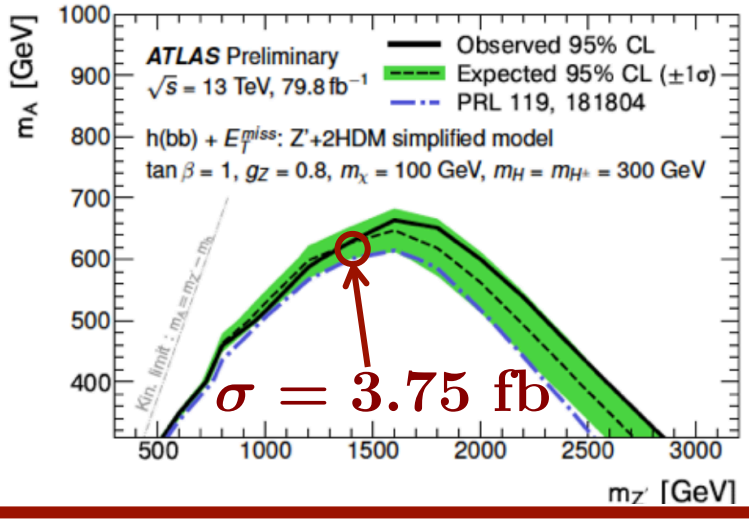
- **Interpretation / Z'-2HDM model** (JHEP 06 (2014) 078 + arXiv:1507.00966):
  - In conflict with b-sector data and dijet constraints

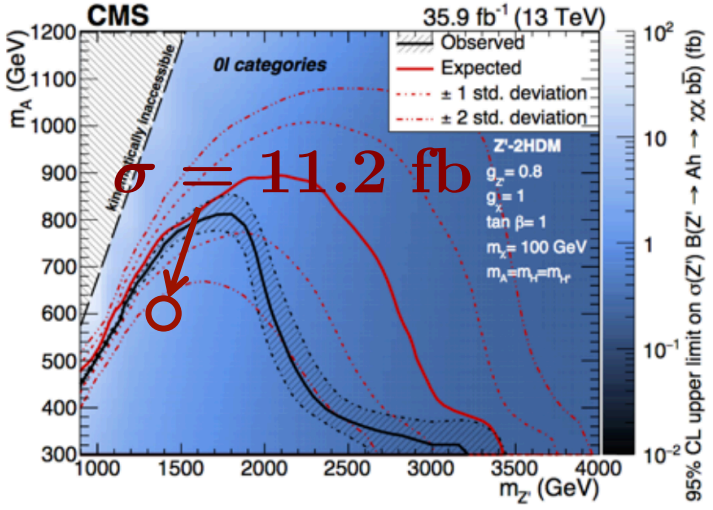


Plot from Uli Haisch

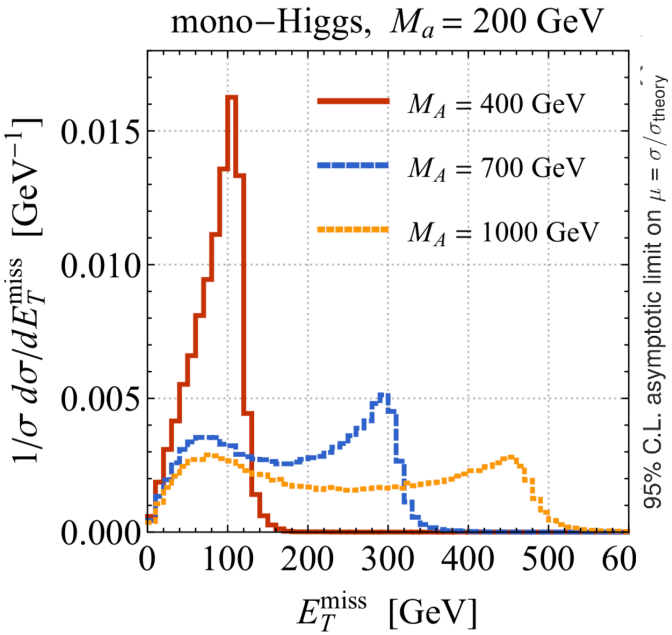


  - Will fix inconsistency: $m_H=m_{H+}=300$ GeV (ATLAS), $m_H=m_{H+}=m_A$ (CMS):

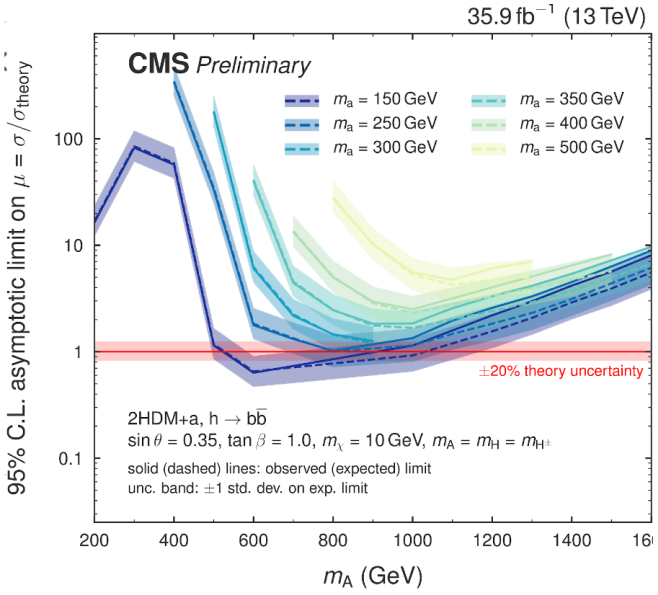




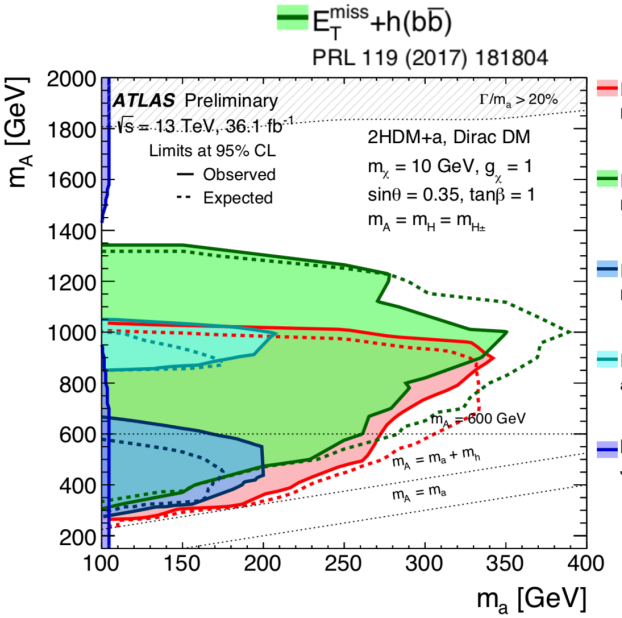
- **Interpretation / 2HDM+a model** (JHEP 05 (2017) 138 +arXiv:1810.09420):
  - Agreed: future main model of this signature
    - Resonant and non-resonant signatures
    - Non-trivial interplay with other channels



arXiv:1810.09420



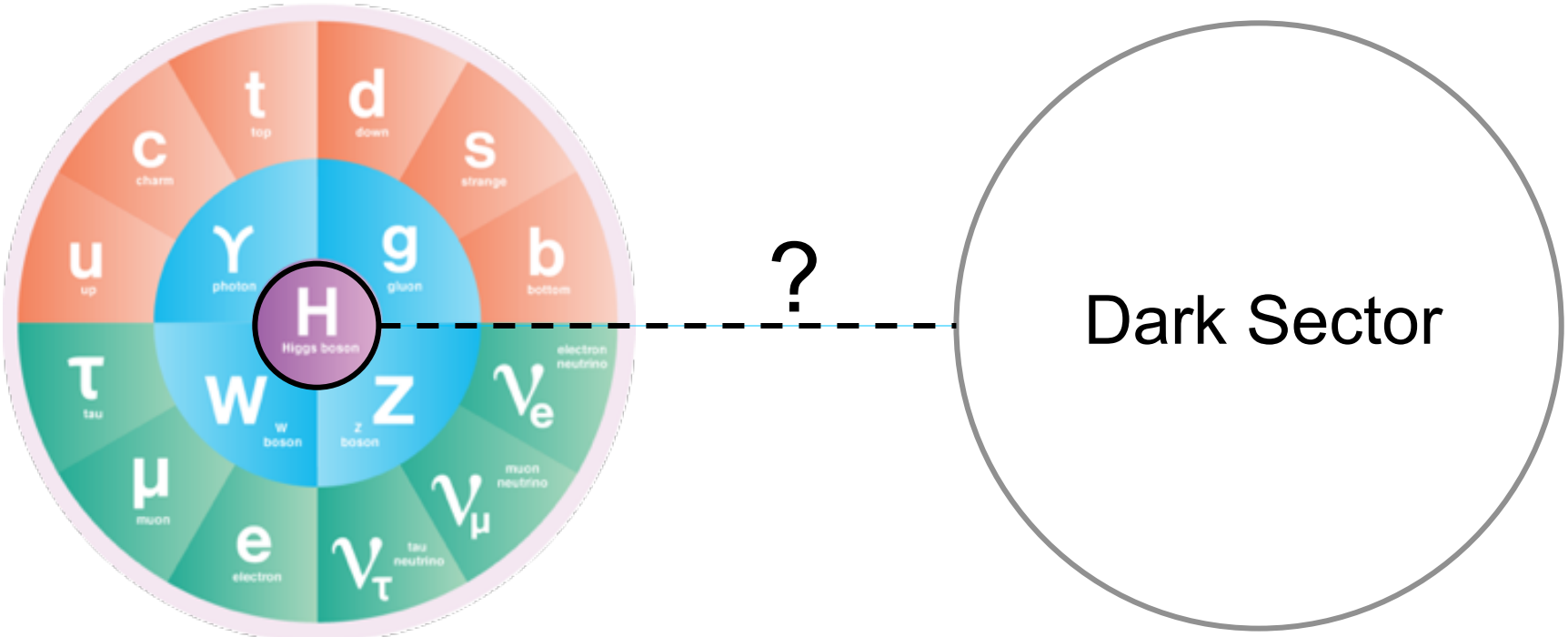
CMS-EXO-16-050-PAS



ATLAS-CONF-2018-051

- Need another cross-check to confirm generation settings are identical
  - Very different sensitivities?
- Finalising generation settings for full Run 2

Higgs-portal models

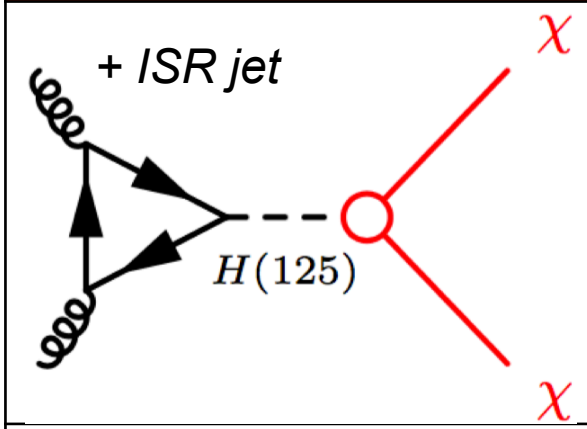
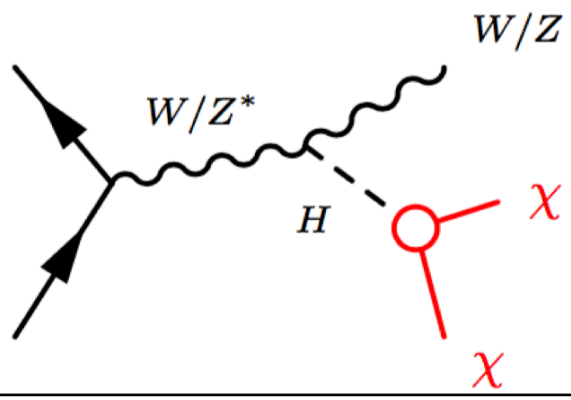
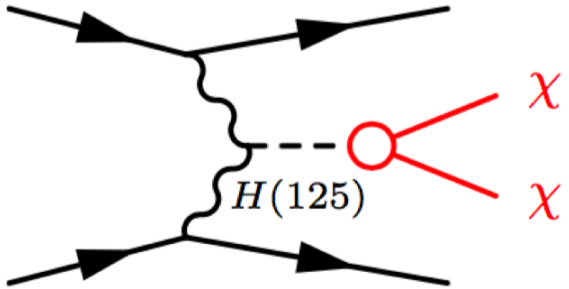


HIGGS → INVISIBLE

- **Motivation:**
  - Higgs couples to massive particles
  - Dark Matter particles massive…
  - $H \to \chi\chi$ possible if $M_\chi \leq M_H$
- **Competitive – Higgs production as tag:**

New

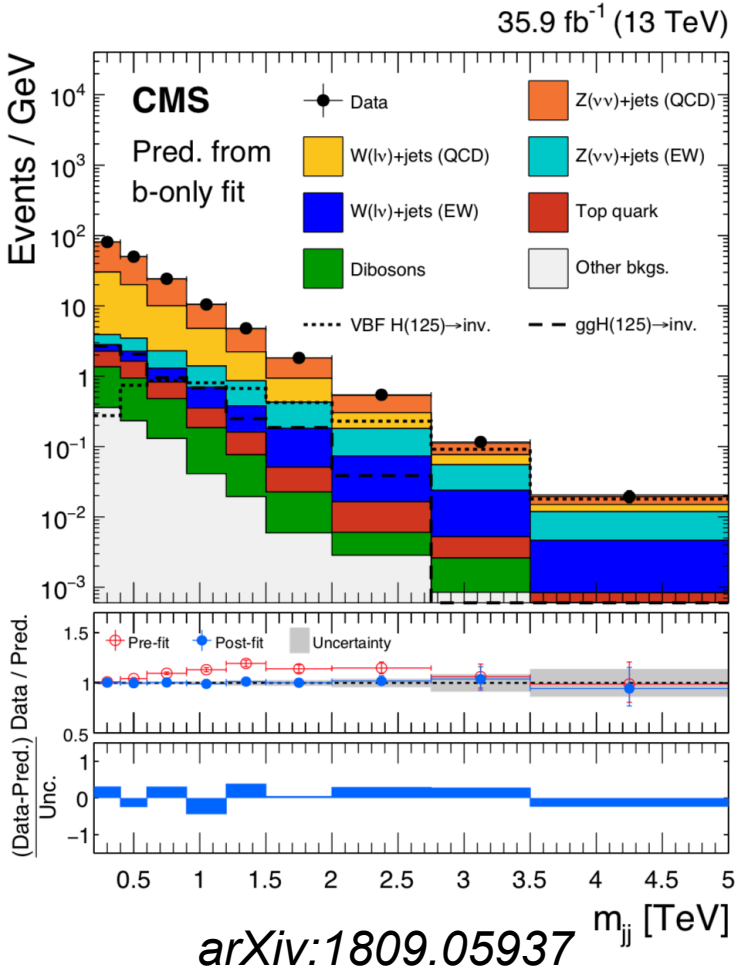
[1] JHEP 10 (2018) 180
[2] PLB 776 (2017) 318
[3] arXiv:1809.06682
[4] ATLAS-CONF-2018-054
[5] PRD 97 (2018) 092005
[6] EPJC 78 (2018) 291
[7] arXiv:1809.05937

ggF H [49 pb]	VH [2.3 pb]	VBF H [3.8 pb]
		
ATLAS	ggF+V(had)H(inv): 0.83 (0.58) [1] Z(ℓℓ)H(inv): 0.67 (0.39) [2]	Combo [4]	0.37 (0.28) [3]
CMS	ggF+V(had)H(inv): 0.53 (0.40) [5] Z(ℓℓ)H(inv): 0.40 (0.42) [6]	Combo [7]	0.33 (0.25) [7]

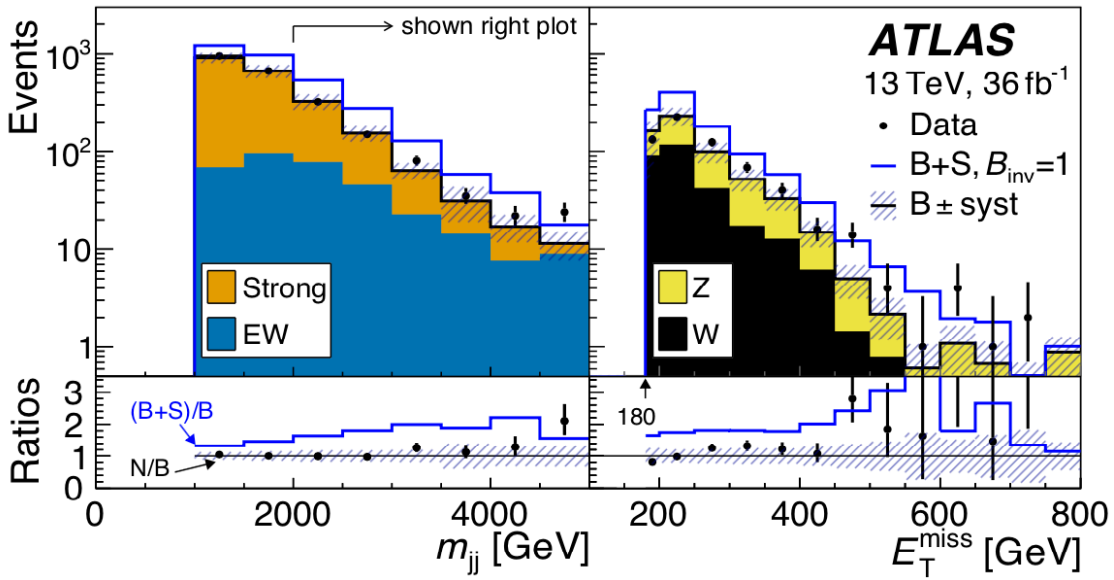
Feynman diagrams: Christian Ohm

- **Strategies:**
  - ATLAS: third jet veto, target high m_{jj}
  - CMS: constrain from low m_{jj}, target high m_{jj}

⇨ Similar sensitivities

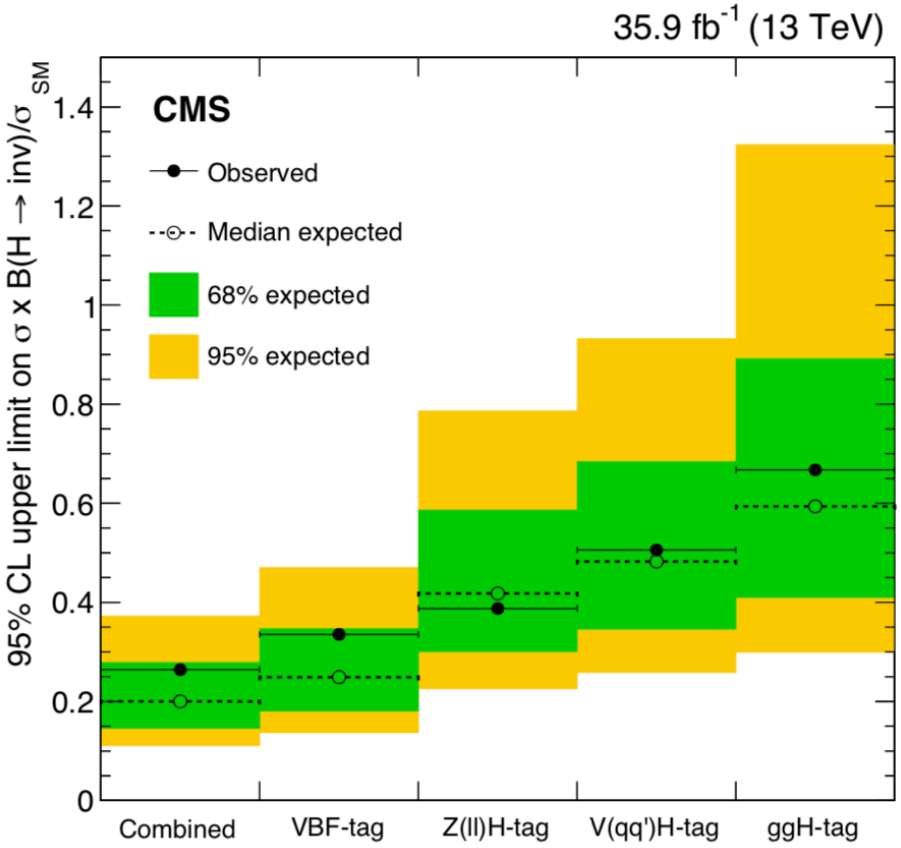


arXiv:1809.05937



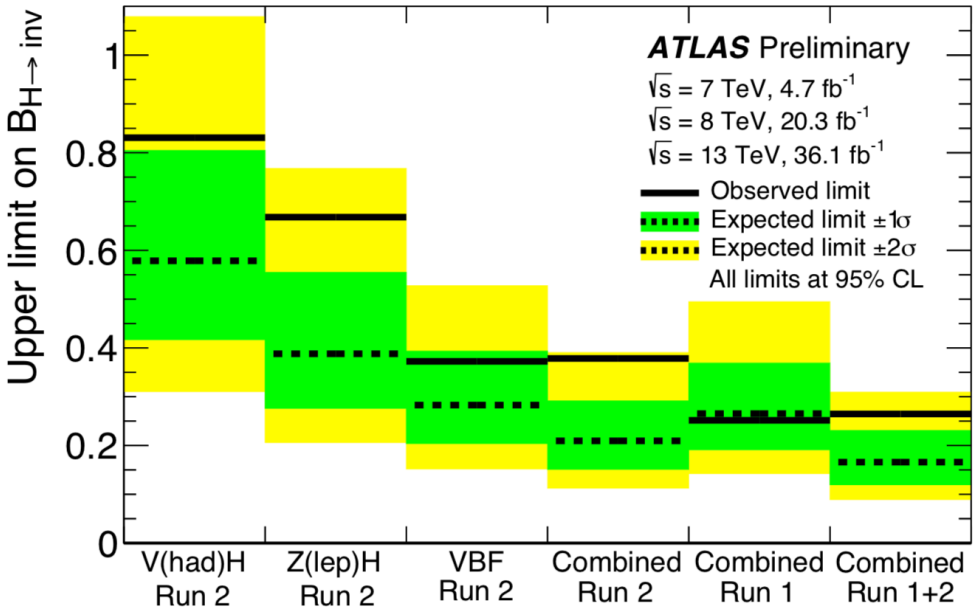
arXiv:1809.06682

Provides dominant constraints on singlet mixing model!



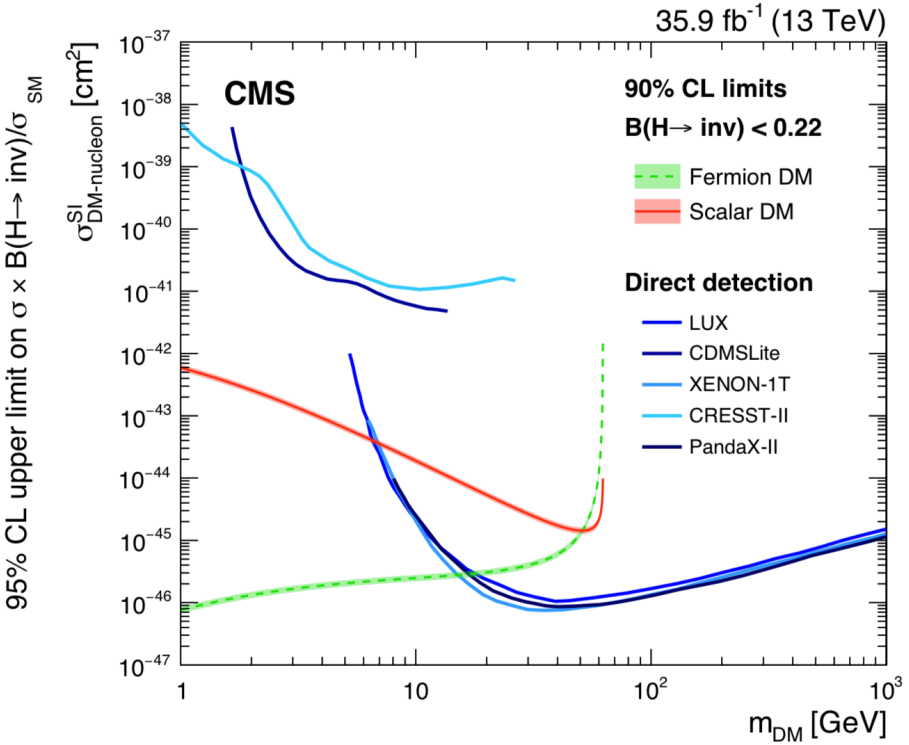
$B_{H\to inv} < 0.26\ (0.20)$

arXiv:1809.05937



$B_{H\to inv} < 0.26\ (0.17)$

ATLAS-CONF-2018-054



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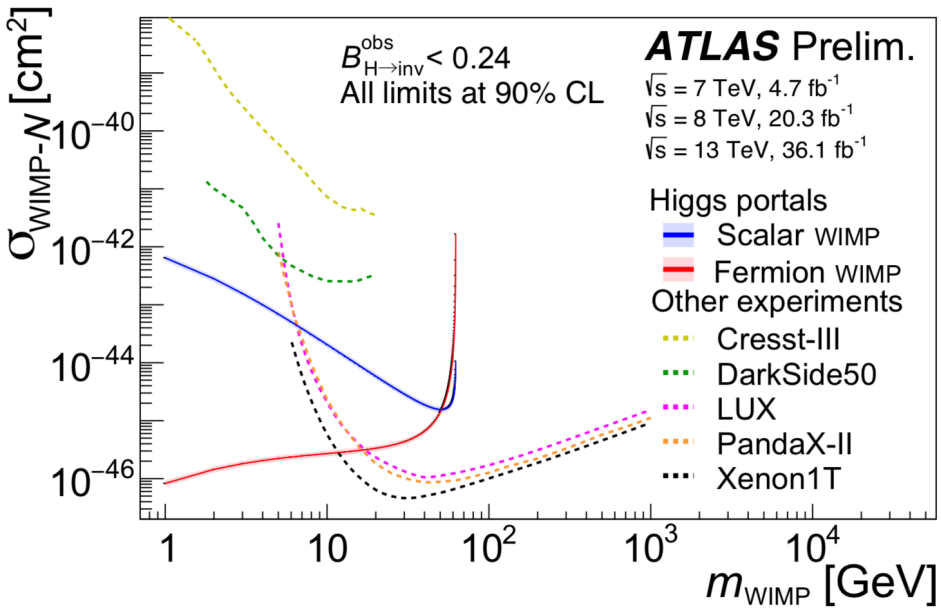


ATLAS-CONF-2018-054

SUMMARY + OUTLOOK

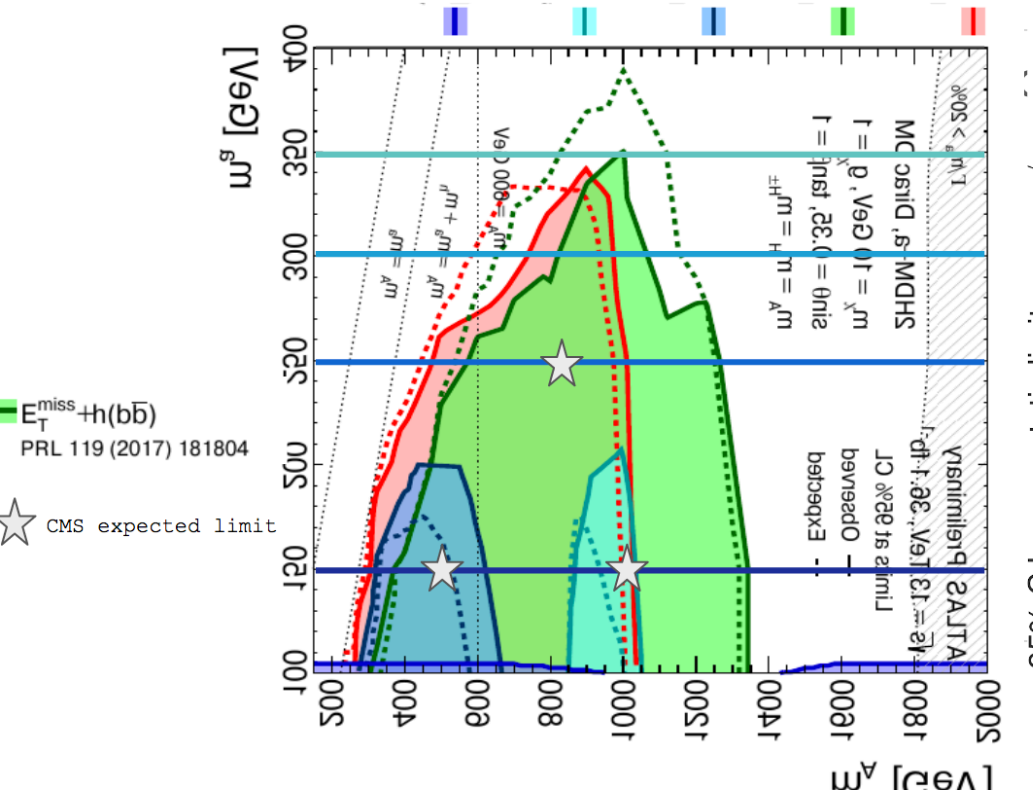
- **2HDM+a:**
  - simplified, consistent, UV-complete model
  - **Rich phenomenology:**
    - Interesting complementarity between signatures
    - Resonant production of DM + distinct SM signatures
  - **Main resonant signatures:**
    - Z + MET
    - h + MET

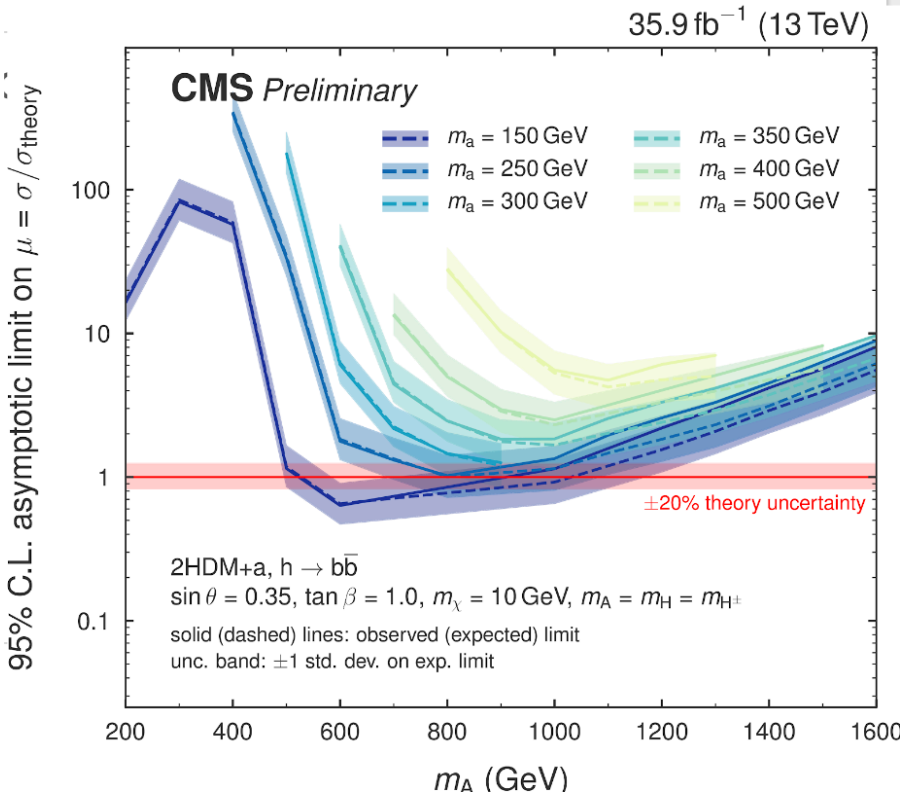
    } Main scans: (m_A, m_a), $(m_a, \tan\beta)$, $\sin\theta$, m_χ
  - **+ Many other signatures**
- **Mono-h(bb) topical meeting:**
  - 2HDM+a main model for interpretation
  - Consistency of Z'-2HDM in the future
- **Higgs portal models:**
  - Major production modes covered using 36 fb^{-1}
  - No big surprises, but both see a mild excess

Spares

MONO-H(BB) EXCLUSION DIFFERENCES

- Very different sensitivities
  - Different generation settings somewhere?





Comparison artwork: Philipp Gadow

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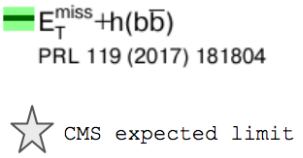

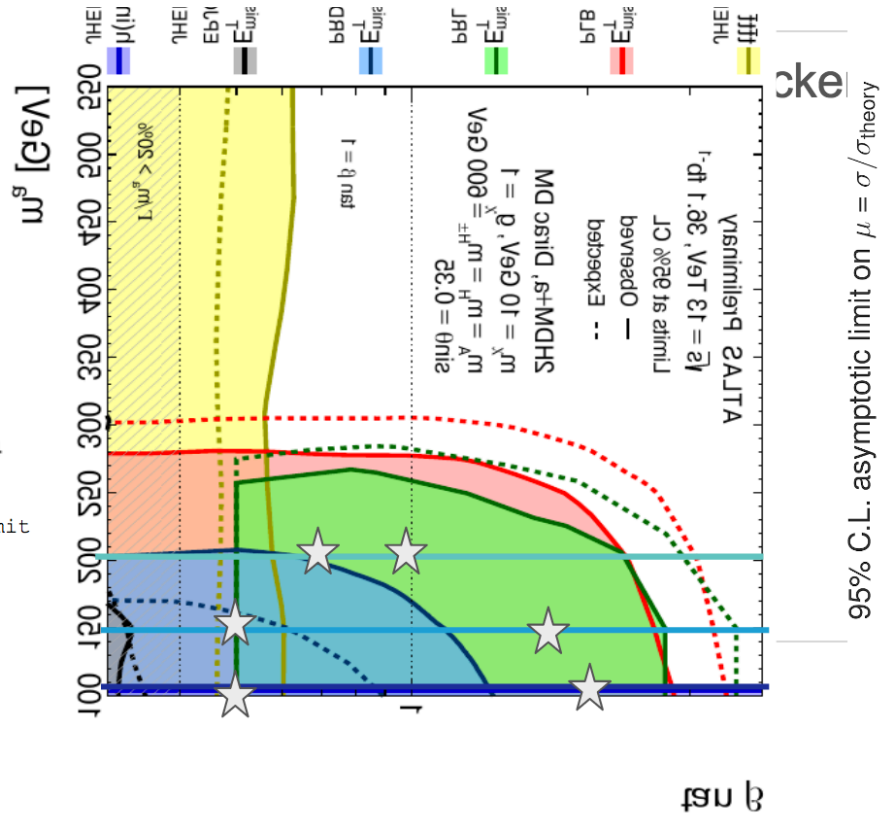

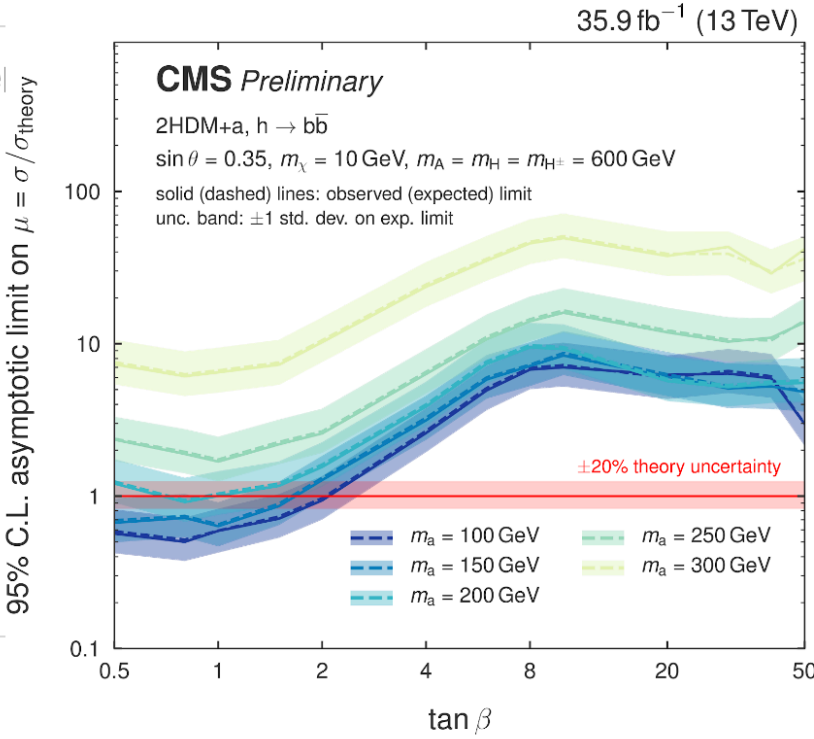

Comparison artwork: Philipp Gadow

MONO-H(BB) EXCLUSION DIFFERENCES

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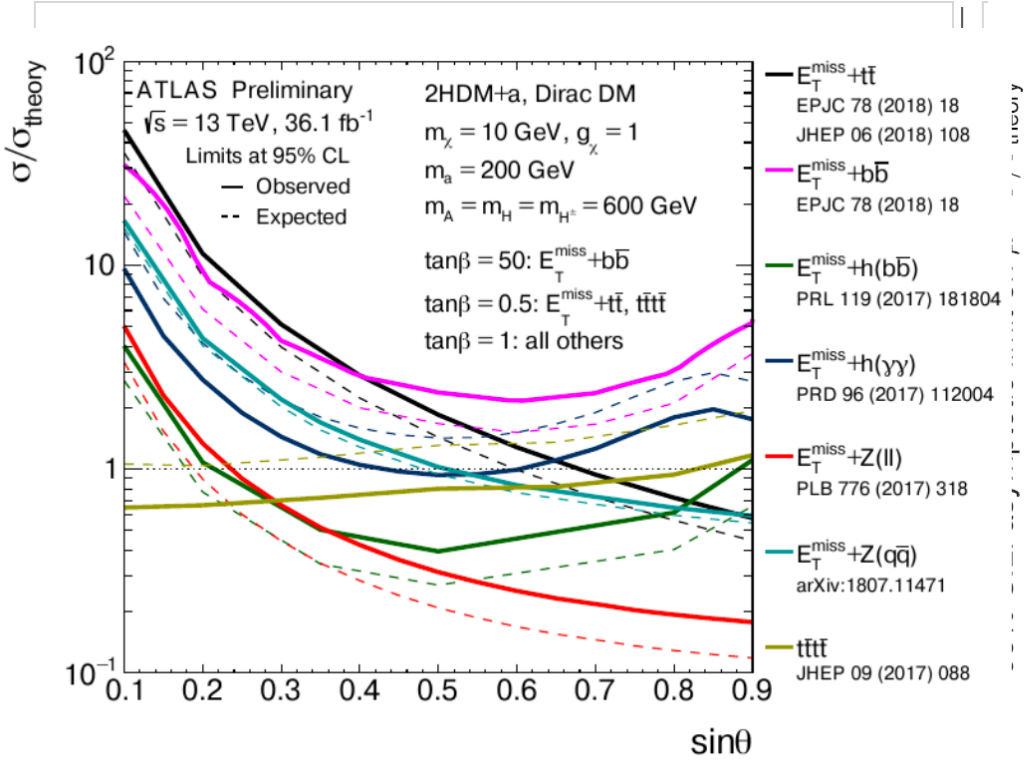
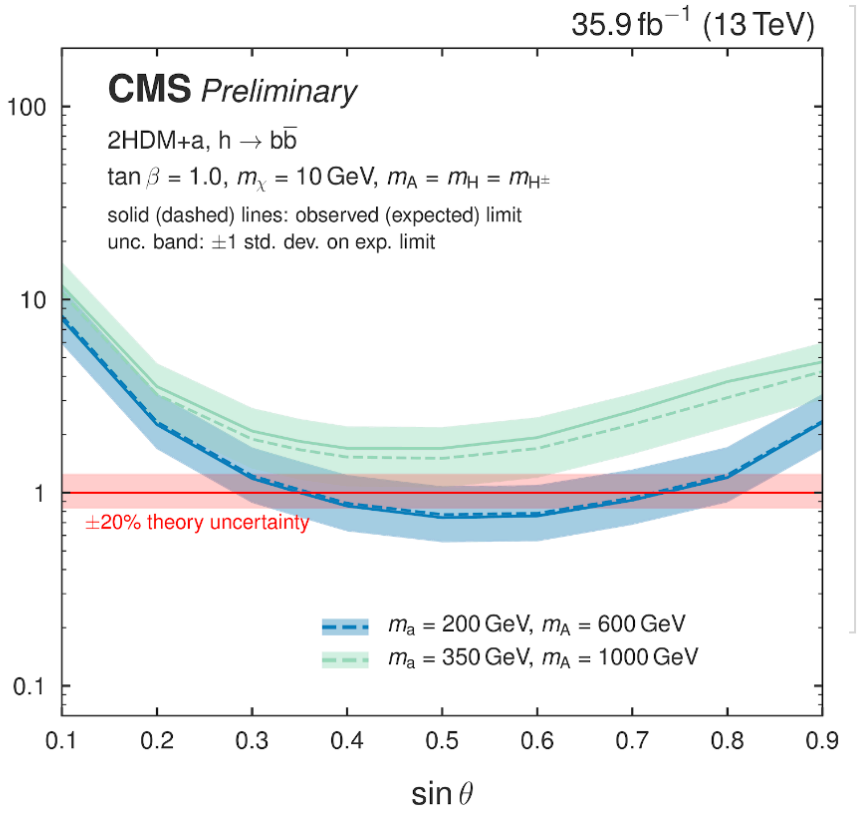




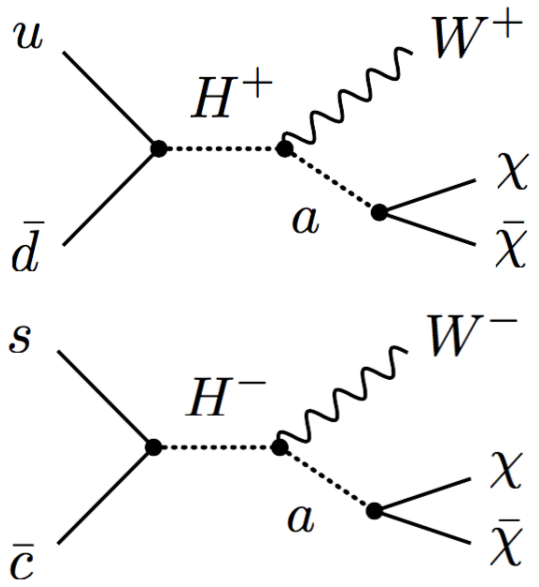
- General:
  - **Always there, but low Xsec:**

$$\sigma(pp \to H^+) = 0.2 - 1\,\text{fb}$$

$$M_{H^+} = 750 - 500\,\text{GeV}$$

$$\sigma(pp \to A) = 0.3 - 3.1\,\text{pb}$$

$$M_A = 750 - 500\,\text{GeV}$$



  - Still want this UFO to motivate W+MET?
    - Model gives interesting kinematic distributions…
  - Change in kinematics and xsec with u/d type couplings?

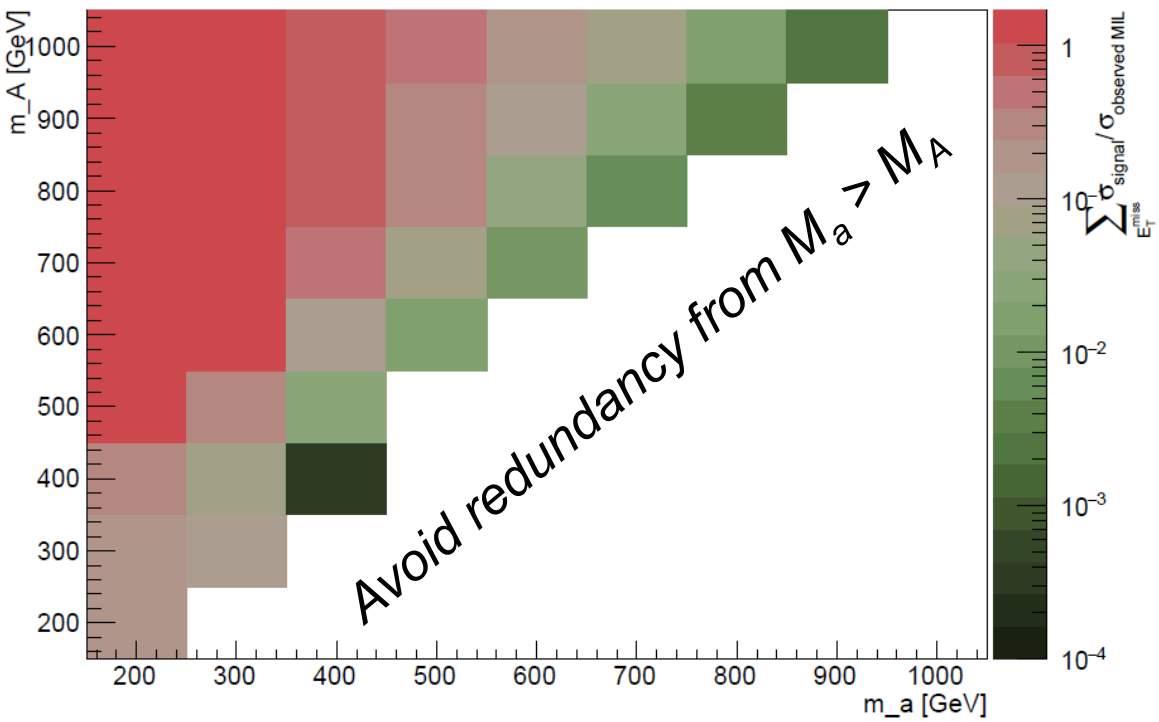
- **Use limits on visible cross-section**
  - "Model-independent" limits

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 $\sigma^{obs}_{vis,h+DM}$
6. sum over 4 MET bins

ATLAS-CONF-2017-028

Range in E_T^{miss}/GeV	$\sigma^{obs}_{vis,h+DM}$ [fb]	$\sigma^{exp}_{vis,h+DM}$ [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



$h(bb) + E_T^{MISS}$: SENSITIVITY ESTIMATE

- **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 $\sigma^{obs}_{vis,h+DM}$
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ATLAS-CONF-2017-028

Range in E_T^{miss}/GeV	$\sigma^{obs}_{vis,h+DM}$ [fb]	$\sigma^{exp}_{vis,h+DM}$ [fb]	$\mathcal{A} \times \varepsilon$ %
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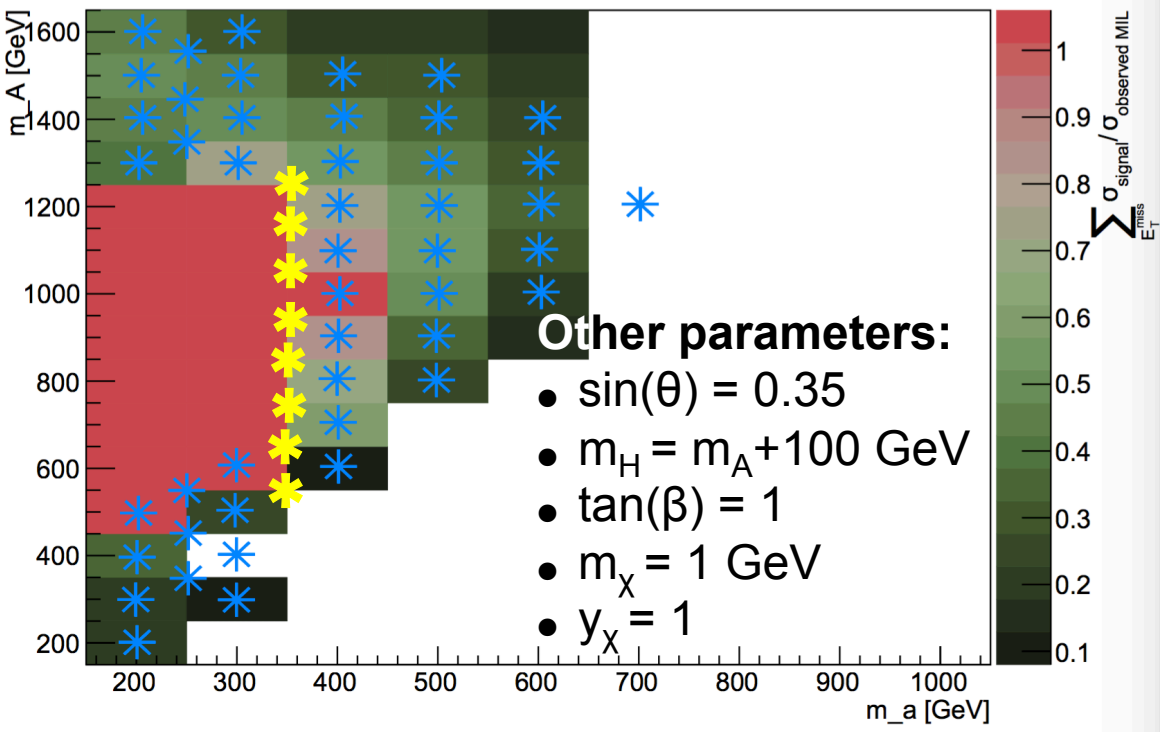

our suggestion (44)
nice to have (8)

- Syntax:
  - p p > xd xd j [QCD]
    - (checking g g > xd xd j [QCD])
- Status:
  - Some signal-points generated in private setup,
  - ATLAS setup working
- Next steps:
  - Systematically study model at particle level
  - Re-interpret limits
    - Test rescaling existing benchmark samples
- General:
  - Typically, not dominating sensitivity for 2HDM+a
  - 2HDM+a parameter grid definition should be driven by resonant (other) signatures
    - → check complementarity with jet + E_t^{miss}?