14th Workshop of the LHC Higgs Cross Section Working Group

DMWG Report on 2HDM activities

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Why consider "less simplified models" like 2HDM?

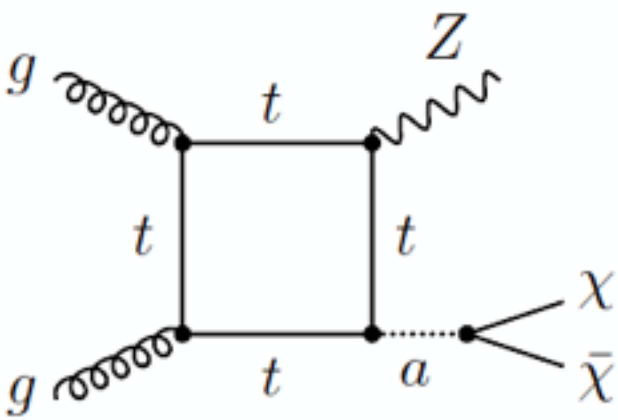
ATLAS EXPERIMENT

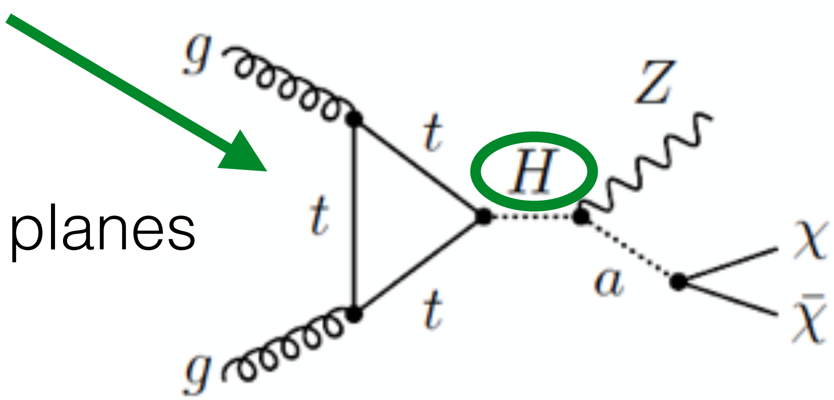
Effective field theory (EFT): $\frac{m_q}{\Lambda^3}\bar{\chi}\chi\bar{q}q$ → **Simplified models**: $g_\chi\bar{\chi}\chi S + \frac{g_q y_q}{\sqrt{2}}\bar{q}qS$ → **Consistent simplified models**: $g_\chi\bar{\chi}\chi s + Y_q\bar{q}Hq + \mu s|H|^2$

- Simplified Models used as benchmarks for several signatures (more details here)
  - not gauge invariant ⇒ unitarity violating amplitudes
- 2HDM are well-motivated extension of SM
  - Add in extra (pseudo-)scalar to couple to (SM singlet) DM
- Many signatures relevant!
  - Mono-Z and mono-h always weaker in Simplified Models, now very relevant due to possible resonant production!

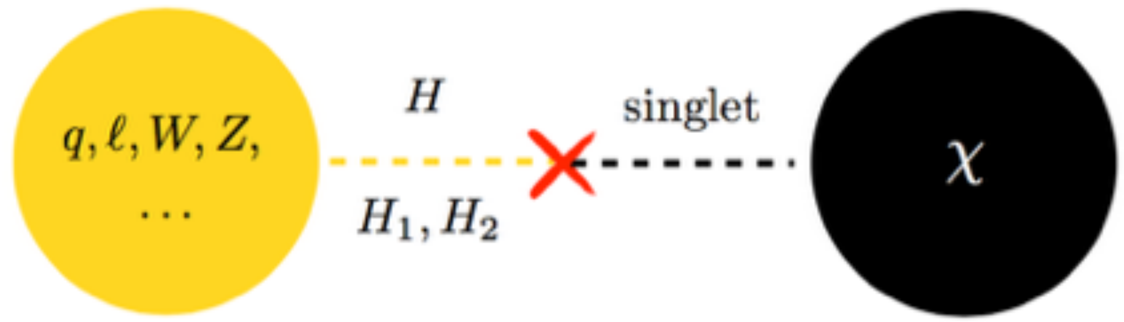
→ *compare, confront, combine different search strategies*

- Sufficiently complete, but simplified enough to define grid planes in parameter space
  - Can be relatively easily reused/recast by theorists





The Model



$$\mathcal{L} \supset -\bar{Q}Y_u\tilde{H}_2 d_R + \bar{Q}Y_d H_1 u_R - ib_P P H_1^\dagger H_2 - iy_\chi P\bar{\chi}\gamma_5\chi + \text{h.c.}$$

sketch from U. Haisch

Particle Content

- CP-even bosons: h, H
- CP-odd bosons: A, a
- Charged bosons: $H^\pm$
- Dirac DM χ

- Spin-0 models with fermionic DM can be made $SU(2)_L \times U(1)_Y$ invariant by introducing a **new dark Higgs** that couples to visible scalar sector
- If scalar sector minimal, SM Higgs is mediator → Higgs constraints are severe
- Higgs constraints can be avoided in extensions with **2 Higgs doublets** (assuming decoupling or alignment limit)
  - Add **pseudo-scalar mediator** to couple to DM
- Impose softly broken Z(2) symmetry to avoid FCNCs
- Focus mostly on Yukawa structure of type-II
  - Signatures largely independent of type*, but more or less prominent

Model	up-type	down-type	leptons
Type I	H_2	H_2	H_2
Type II	H_2	H_1	H_1
Type III (X)	H_2	H_2	H_1
Type IV (Y)	H_2	H_1	H_2

*holds true for gluon-fusion initial states

Model Parameters

- Parameter space can be reduced by constraints/assumptions
- **Assumptions**
  - Lightest CP-even boson (h) is SM Higgs
    - **Choose M_h = 125 GeV, v = 246 GeV**
  - Alignment limit:
    - **Choose $\cos(\beta - \alpha) = 0$**
    - Otherwise, $\tan(\beta)$ affected by constraints from Higgs coupling measurements

parameters

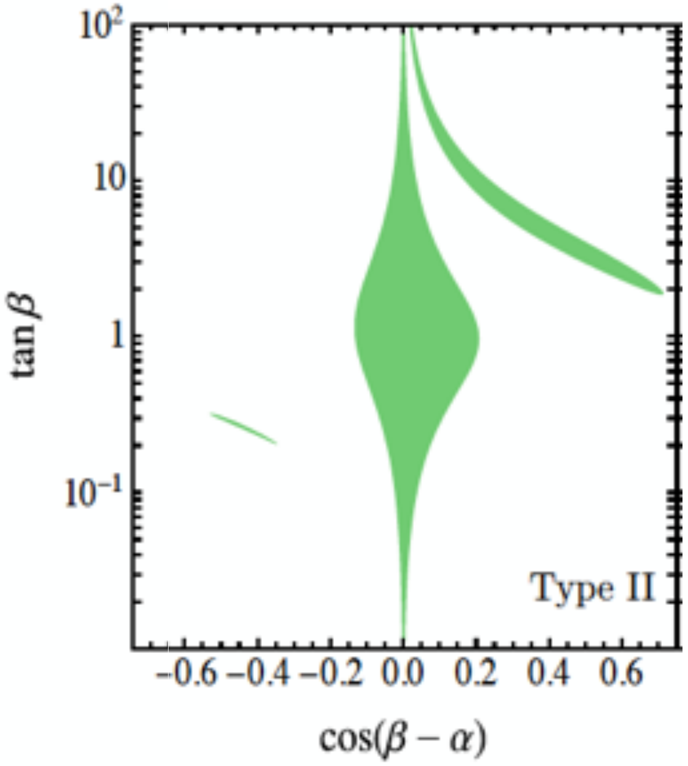
v, M_h, $\cos(\beta - \alpha)$

M_a, M_A, M_H, $M_{H^\pm}$

$\tan(\beta)$, $\cos(\theta)$

λ_3, λ_{P1}, λ_{P2}, λ_P

M_χ, y_χ



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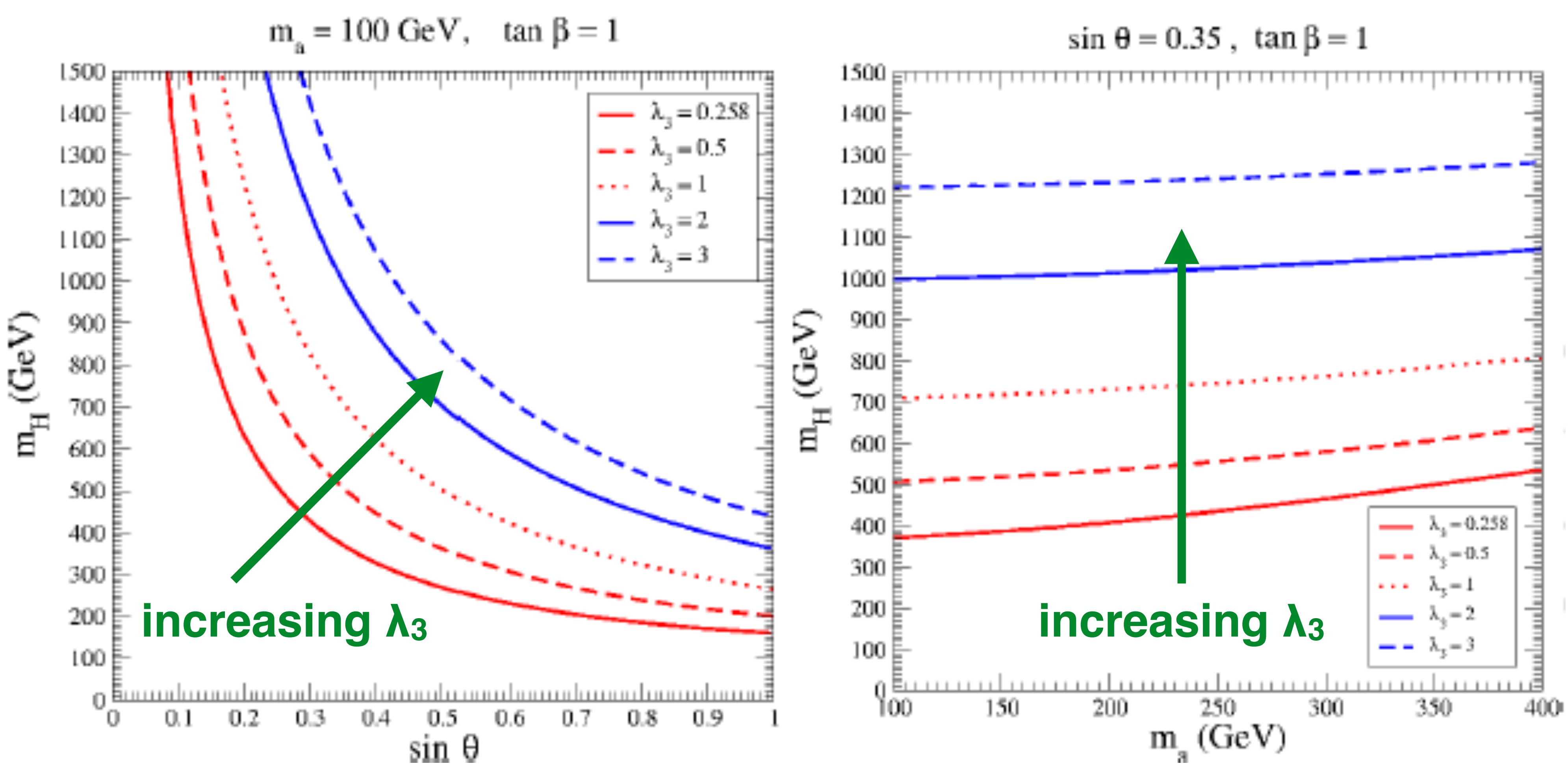
    - **Choose $\cos(\beta - \alpha) = 0$**
    - Otherwise, $\tan(\beta)$ affected by constraints from Higgs coupling measurements
  - Mass splittings between M_a, M_A, M_H, $M_{H^\pm}$ constrained by electroweak precision measurements
    → circumvented in case of $M_H = M_{H^\pm}$ and $\cos(\beta - \alpha)=0$
    - **Choose $M_A = M_H = M_{H^\pm}$** (also to simplify life - for now!)

parameters
v, M_h, $\cos(\beta - \alpha)$
M_a, M_A, M_H, $M_{H^\pm}$
$\tan(\beta)$, $\cos(\theta)$
λ_3, λ_{P1}, λ_{P2}, λ_P
M_χ, y_χ

Model Parameters

- **Assumptions (continued)**
  - Vacuum stability, perturbativity and unitary constrains affect quartic couplings
    - In particular: boundedness from below requires $\lambda_3 \geq M_h^2/v^2 = 0.258$
      → allowed param space increases with λ_3



Model Parameters

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  - Vacuum stability, perturbativity and unitary constrains affect quartic couplings
    - In particular: boundedness from below requires $\lambda_3 \geq M_h^2/v^2 = 0.258$
      → allowed param space increases with λ_3
      - **But:**
        g_{aAh} decreases with increasing λ_3 except if $\lambda_3 \approx \lambda_{P1} \approx \lambda_{P2}$
        → g_{aAh} important for mono-h signatures!
      - **On the other hand:**
        $\Gamma(H \to aa)$ enhanced with λ_3, therefore $BR(H \to Za)$ reduced
        → mono-Z most sensitive for small $\lambda_{P1} \approx \lambda_{P2}$ or sufficient splitting

→ **Choose $\lambda_3 = \lambda_{P1} = \lambda_{P2} = 3$**
(not ideal for mono-Z, but compromise between mono-h and mono-Z)

Summary of Model

ATLAS EXPERIMENT

$v, M_h, \cos(\beta-\alpha)$	$\longleftrightarrow$	fixed by Higgs measurements,
$M_{H^\pm}$,	$\longleftrightarrow$	constrained by flavour observables,
$\sin(\theta)\,, M_H$ or M_A	$\longleftrightarrow$	constrained by EWPM,
$\lambda_3, \lambda_{P1}, \lambda_{P2}\,, \lambda_P$	$\longleftrightarrow$	constrained by stability, perturbativity and unitarity

- Additional parameters for DM: mass M_χ and coupling y_χ
  - **Choose y_χ = 1**

Free parameters

M_a: mass of mediator a

M_A: mass of heavy pseudo scalar A

sin(θ): mixing angle between a and A

tan(β): ratio of VEVs of Higgs doublets

M_χ: DM mass

→

Parameter Scans

2D scan of **M_a-M_A**

2D scan of **M_a-tan(β)**

2 1D scans in **sin(θ)**

1D scan of **M_χ**

Alternative: Scalar Mediator

- Similar model: add scalar mediator to 2HDM
  → differently affected by limits from direct and indirect DM searches
  - Direct detection: scalar model much more constrained by spin-independent bounds, due to existing tree level contributions
    (pseudoscalar model: only loop-level contributions)
  - Indirect detection: bounds more stringent for pseudoscalar model
    (DM annihilation is s-wave) than for scalar model (DM annihilation is p-wave)
- Similar topologies at LHC, different production rates
  - cross section for gluon-fusion of scalar particle generally smaller than that of pseudoscalar

    ⇒ mono-Z larger in scalar model:

    pp→A→sZ (scalar model) vs.
    pp→H→aZ (pseudoscalar model)
    with $\sigma(pp \to A) > \sigma(pp \to H)$

Particle Content

- CP-even boson: h
- CP-odd boson: A
- neutral scalars: S_1, S_2
- Charged bosons: $H^{\pm}$
- Dirac DM χ

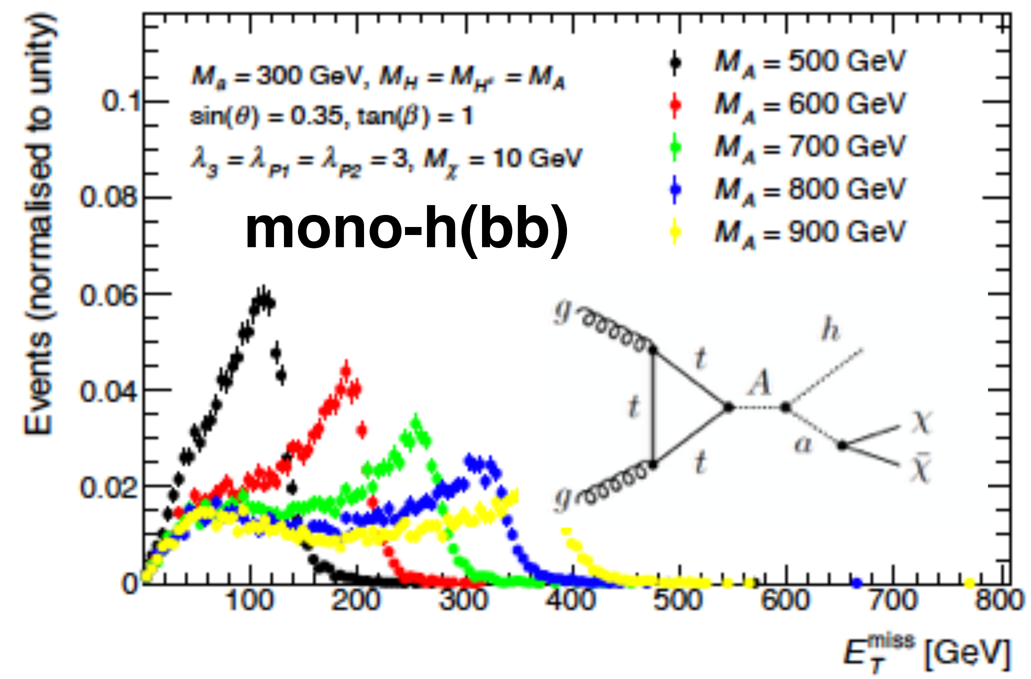
Parameter Scans

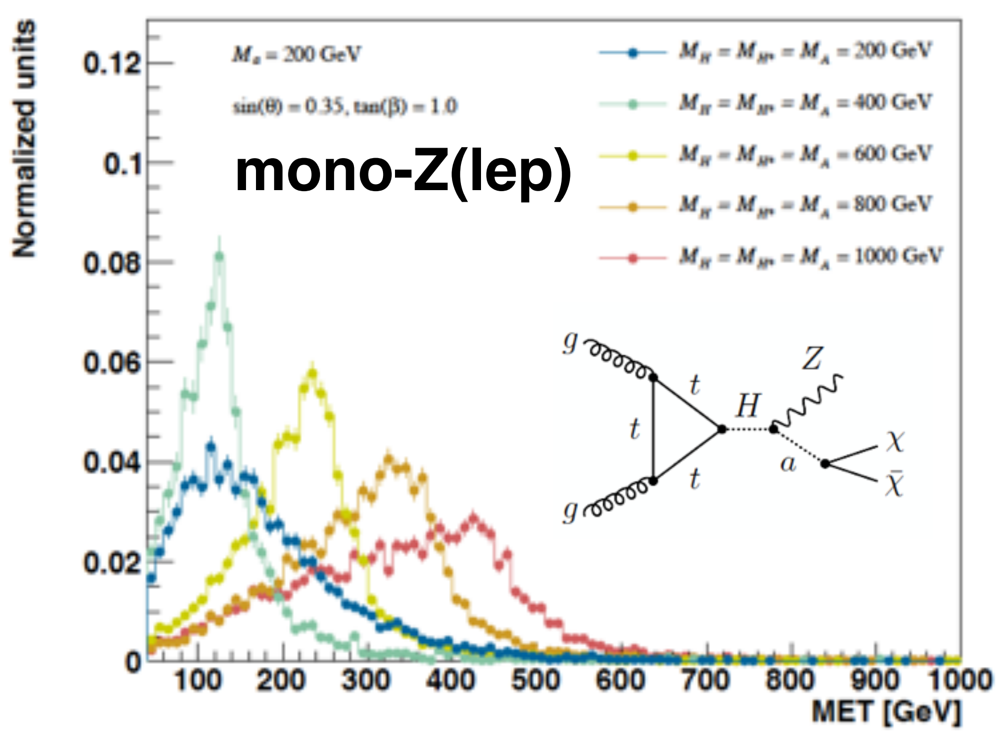
2D Scan in M_a-M_A

Fixed parameters: tan(β) = 1.0, sin(θ) = 0.35, M_χ = 10 GeV

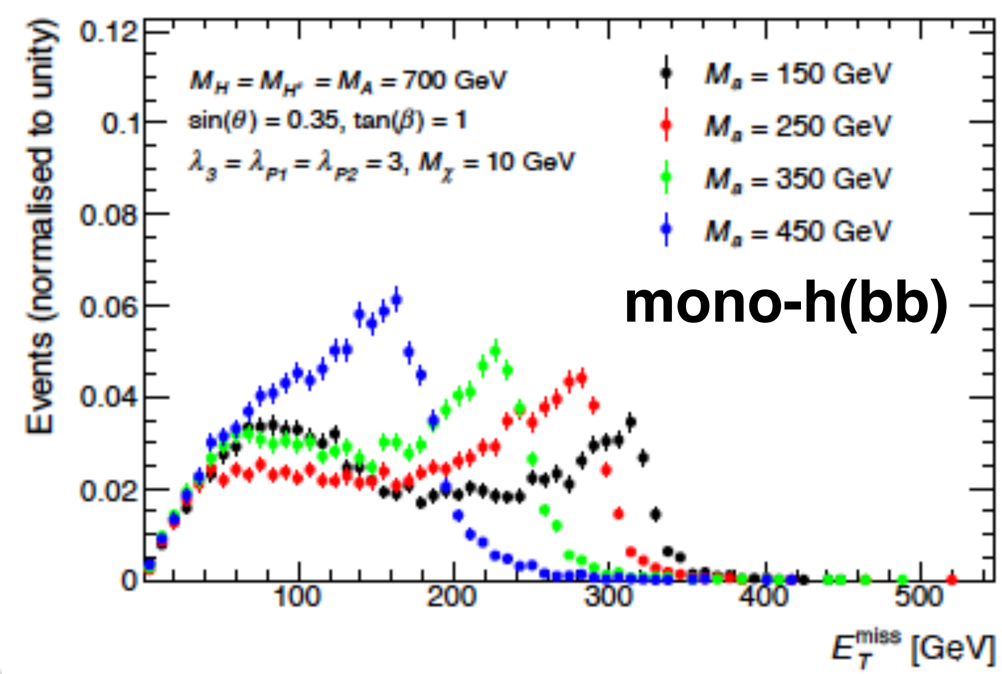
- **Motivation**: highlight complementarity of mono-h and mono-Z
- E_T^{miss} shape depends crucially on | M_A – M_a| (mono-h) / | M_H – M_a| (mono-Z)
  - Jacobian peak for resonant production

$$E_T^{miss,max} \approx \frac{\sqrt{(M_A^2 - M_a^2 - M_h^2)^2 - 4M_a^2 M_h^2}}{2M_A}$$





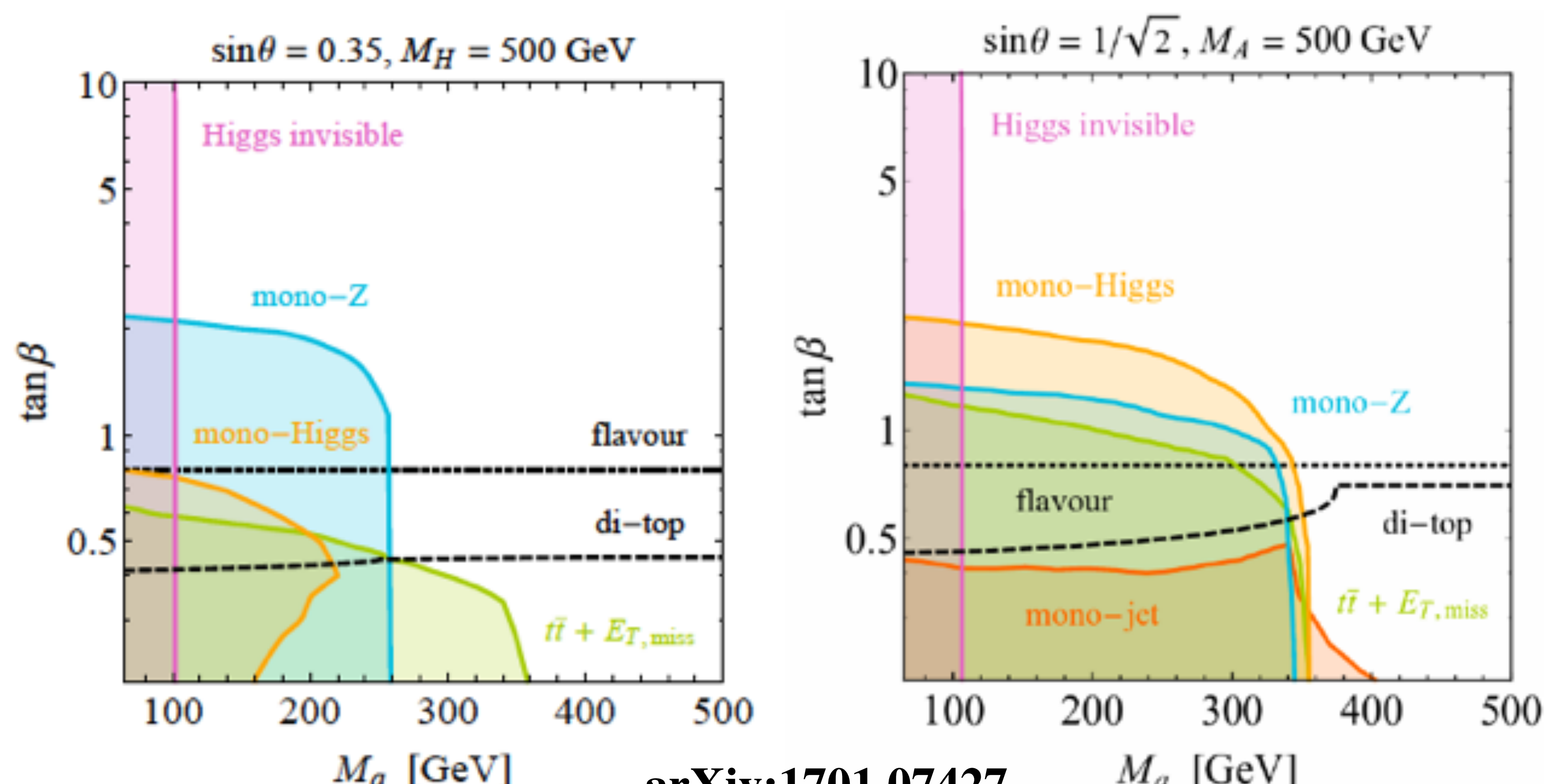
$$E_T^{miss,max} \approx \frac{\sqrt{\left(M_H^2 - M_a^2 - M_Z^2\right)^2 - 4M_a^2 M_Z^2}}{2M_H}.$$



2D Scan in M_a- tan(β)

Fixed parameters: M_A = 600 GeV, sin(θ) = 0.35, M_χ = 10 GeV

- **Motivation**:
  - Highlight complementarity between all signatures
  - Parameterisation commonly used for constraints on 2HDMs
- DM+tt and mono-jet mostly sensitive for tan(β) < 0.4
- Caveat: perturbative top Yukawa requires tan(β) > 0.4
  - Still include results in M_a – tan(β) plot but shade area with tan(β) < 0.4



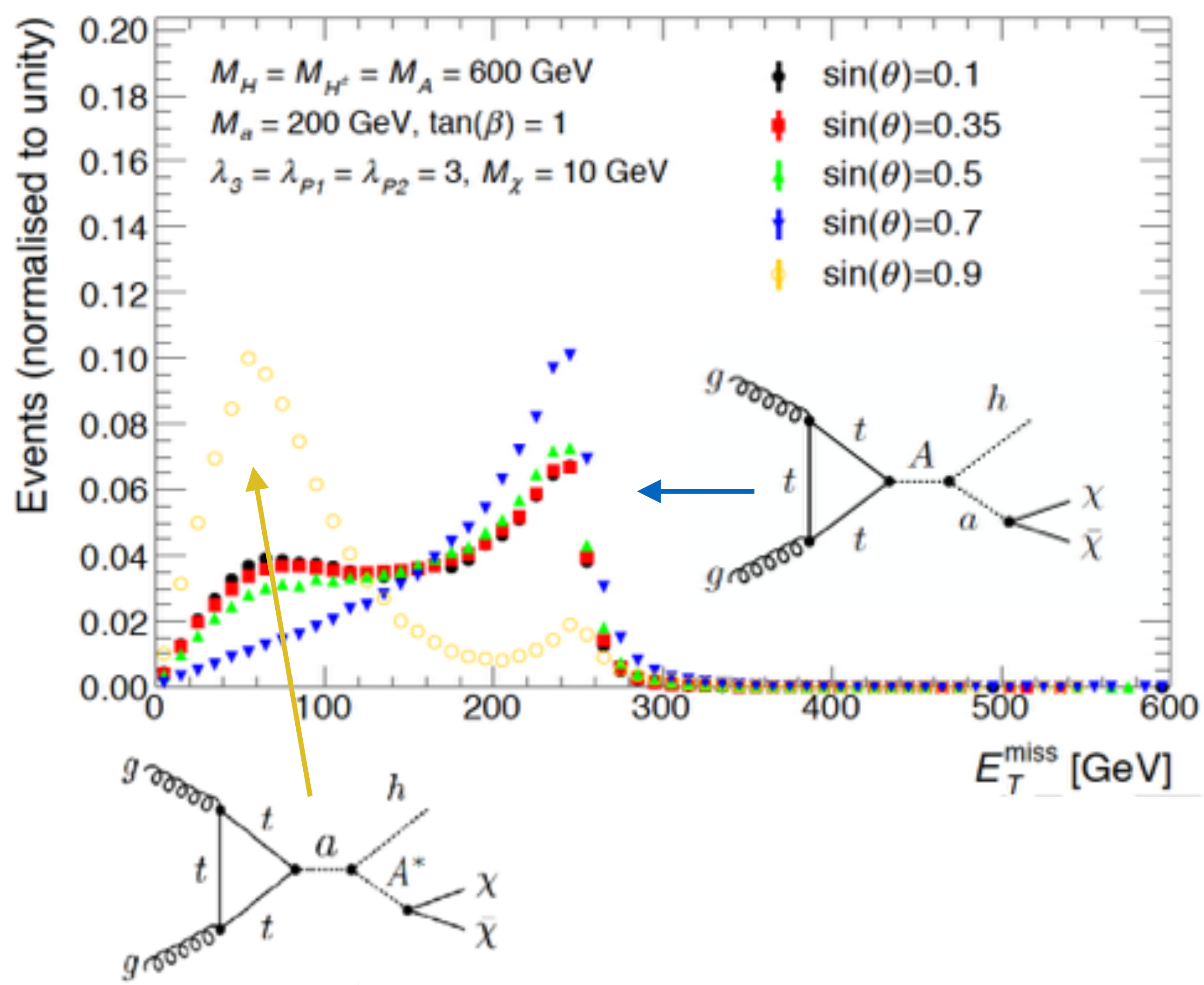
arXiv:1701.07427

Two 1D Scans in sin(θ)

Fixed parameters: tan(β) = 1, M_χ = 10 GeV

Scan 1: M_a = 200 GeV, M_A = 600 GeV
Scan 2: M_a = 350 GeV, M_A = 1000 GeV

- **Motivation**:
  - Interplay between resonant and non-resonant production (mono-h and mono-Z)
    - 2-body (where a Jacobian peak occurs) and off-shell/3-body production

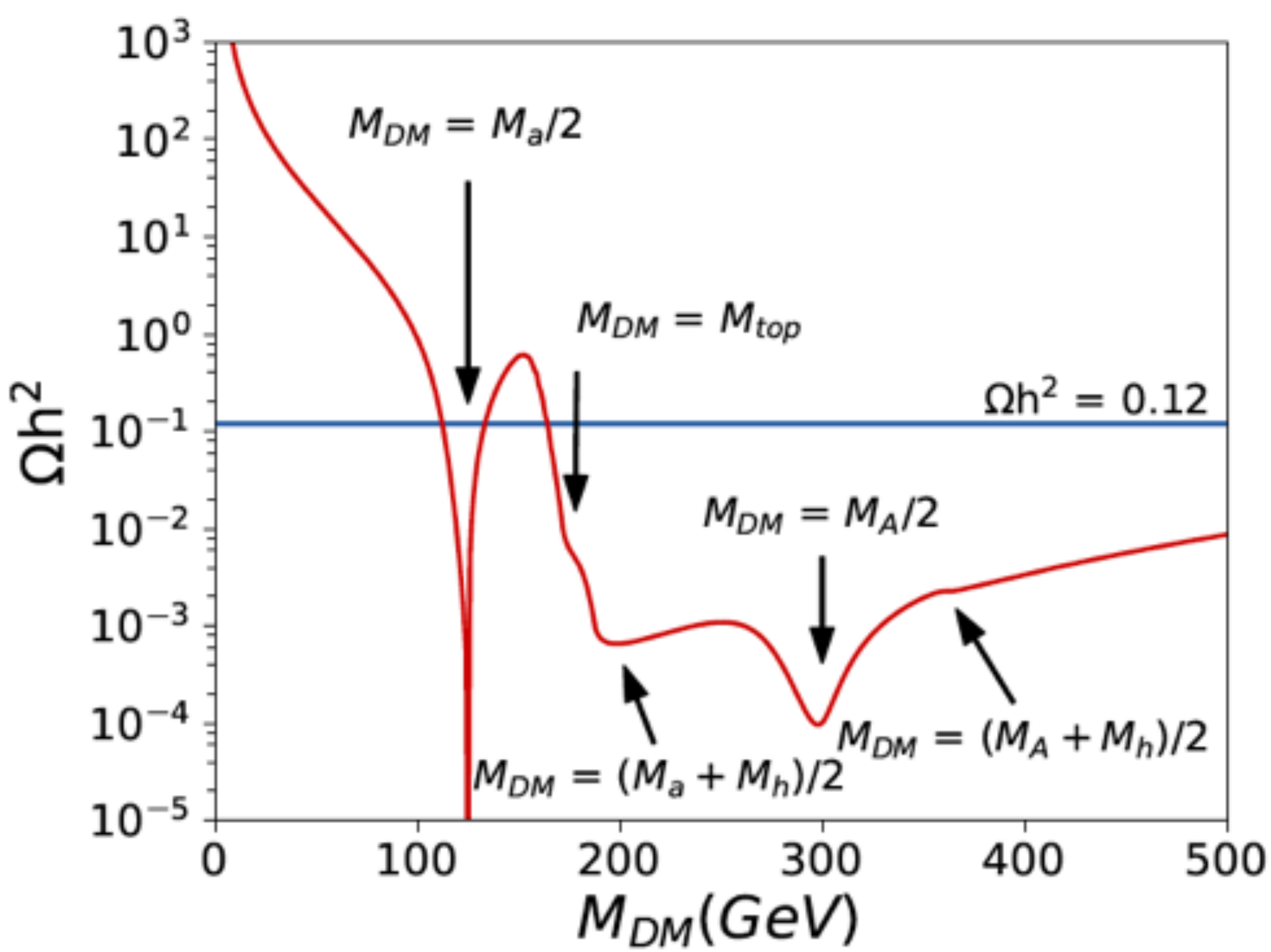


  - DM+tt and DM+bb more sensitive at higher sin(θ)
    - Choice of tan(β) = 1.0 not optimal for DM+tt and DM+bb → set tan(β) different from1.0 in 1D scans for these signatures

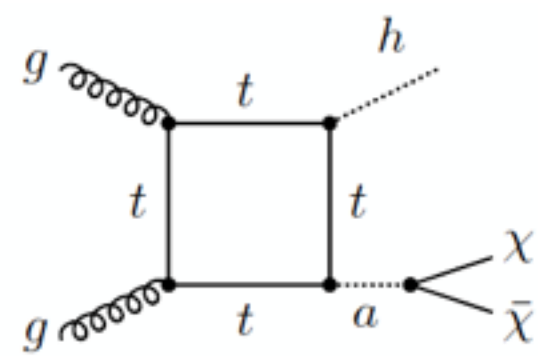
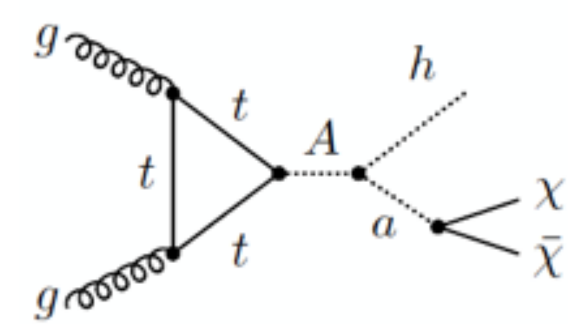
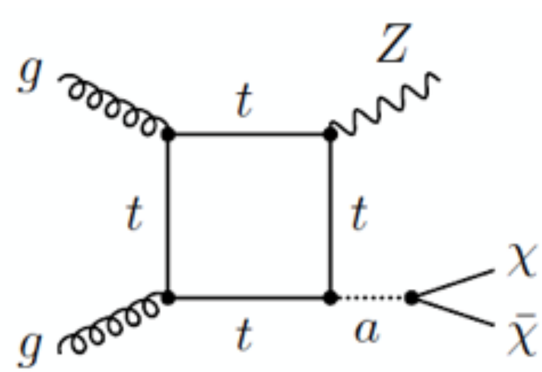
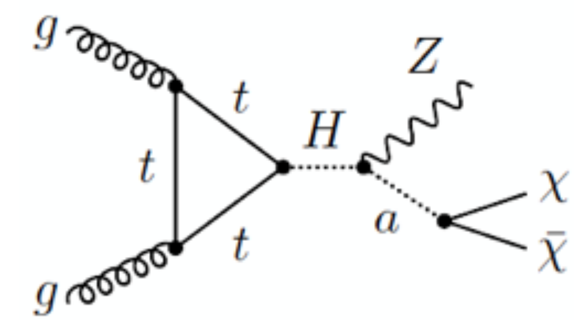
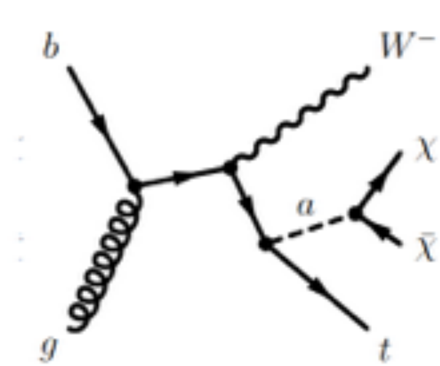
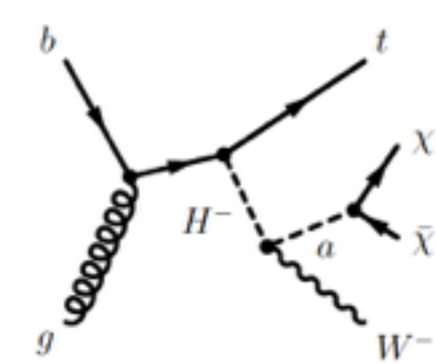
1D scan in M_χ

Fixed parameters: M_a = 250 GeV, M_A = 600 GeV, tan(β) = 1, sin(θ) = 0.35

- **Motivation**: study signature-specific dependence on M_χ, relevant for relic density constraints
  - Interesting for future studies: higher values of M_χ preferred by relic density
    - Currently focus on lower M_χ to have sufficiently high cross sections

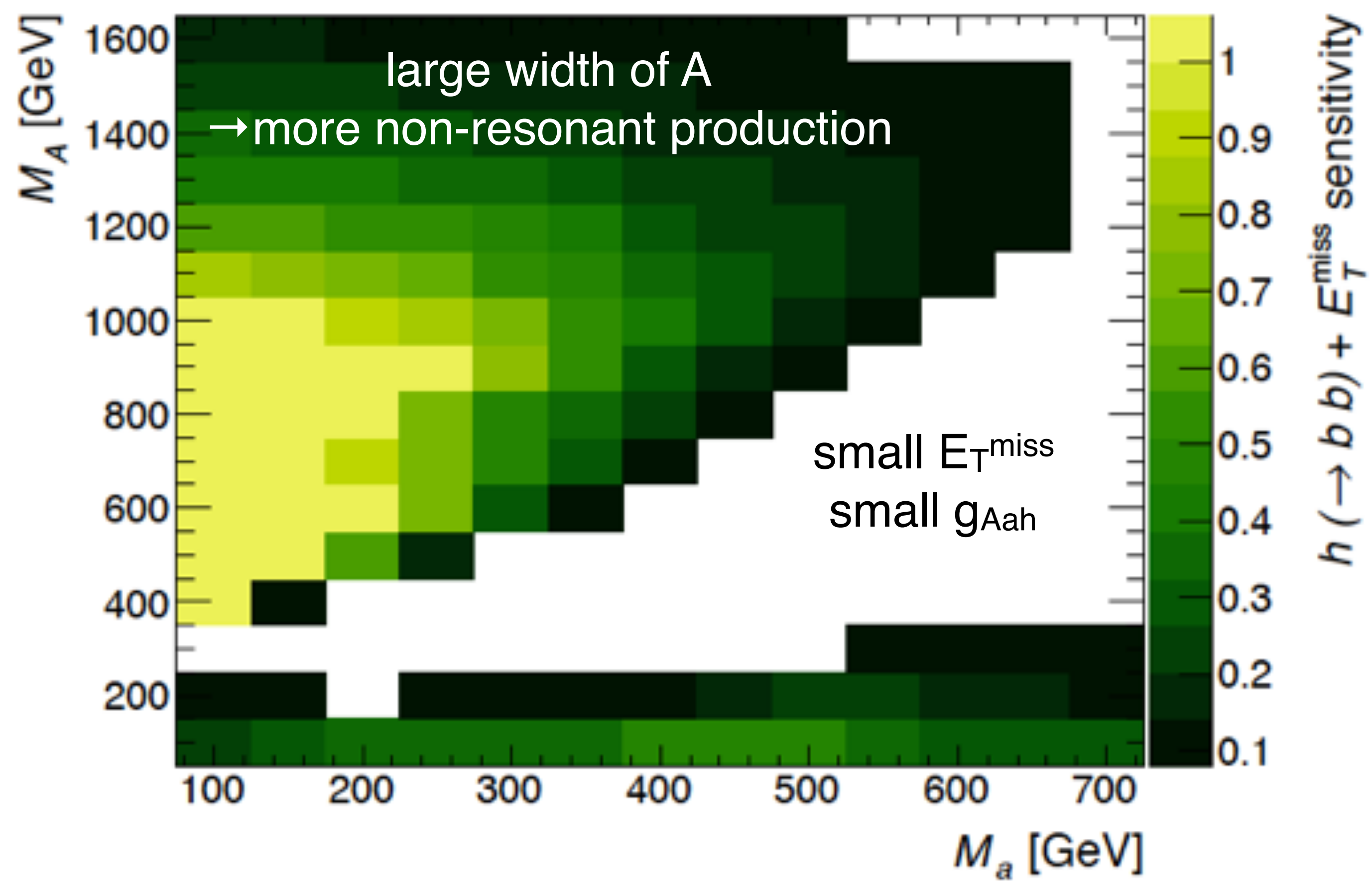


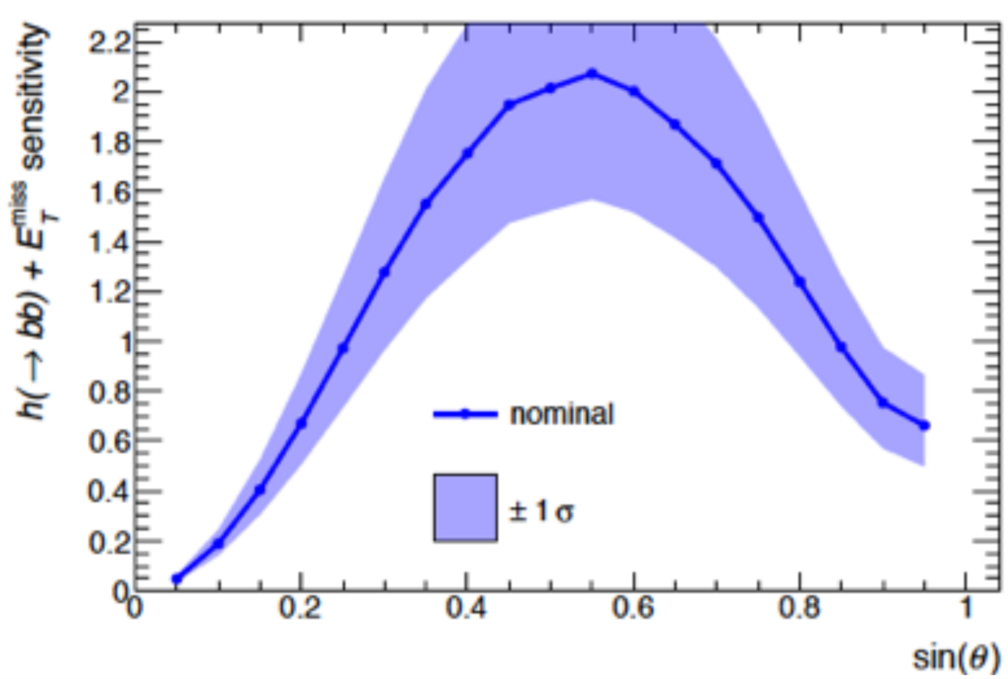
Signatures profiting from possible resonant production

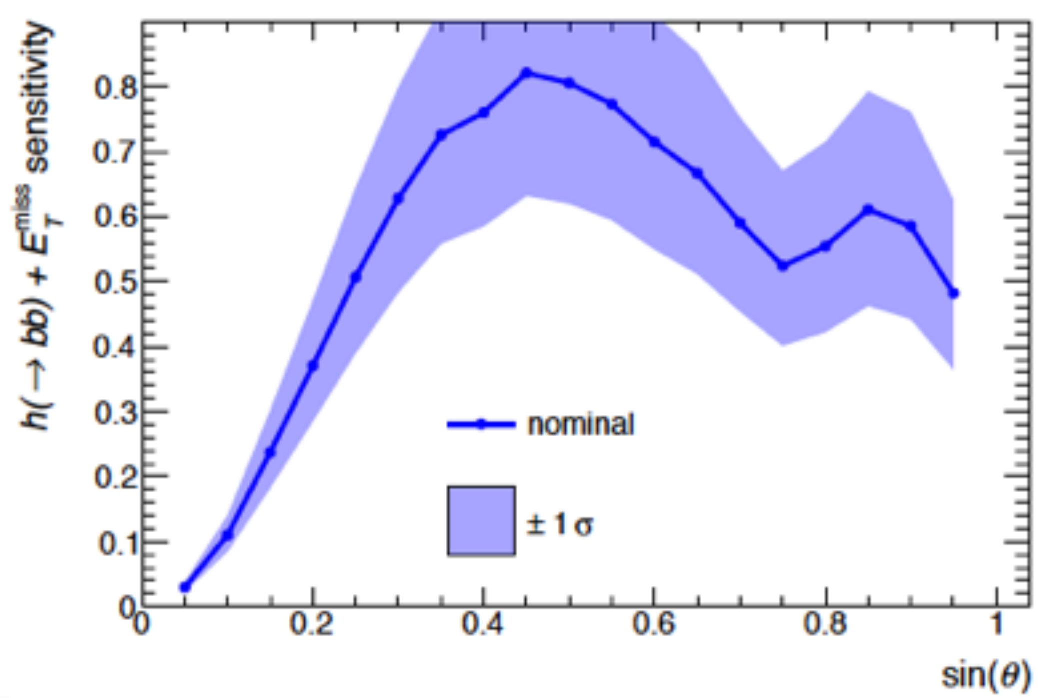
	Non-resonant production/ also present in simplified model	Resonant production/ new in 2HDM!
mono-h(bb)		
mono-Z (lep and had)		
DM+t(W)		

Mono-h

- M_A, M_a change Jacobian peak in E_T^{miss} → higher E_T^{miss} for higher M_A, lower M_a
- decay widths of A and a depend on M_H → affects ratio of resonant/non-resonant production
- mixing of a and A ($\sin(\theta)$) affects E_T^{miss}
  - low $\sin(\theta)$: resonant production dominant
  - $\sin(\theta) > 0.7$: 3-body (offshell) gives broad low-E_T^{miss} peak

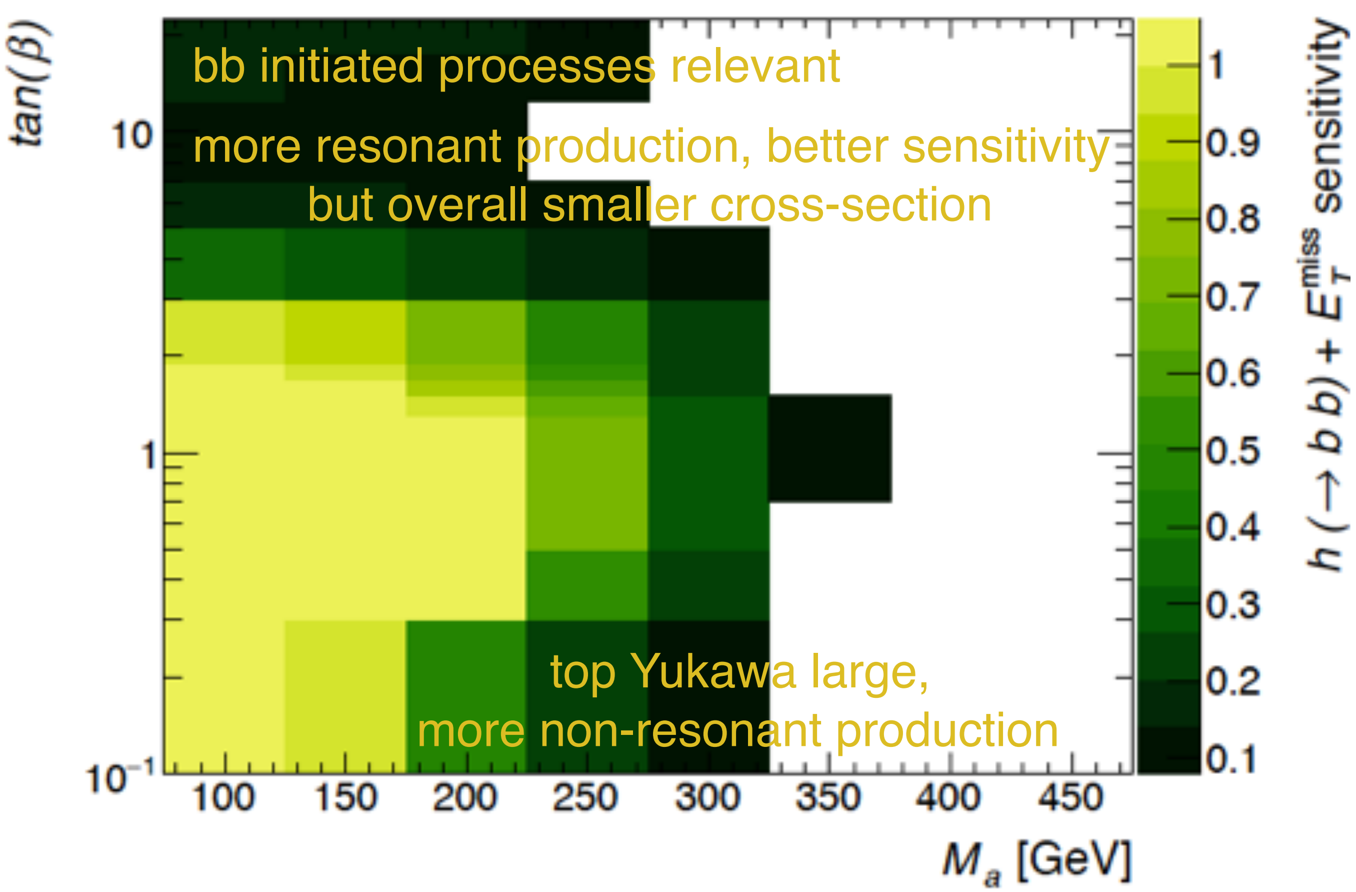


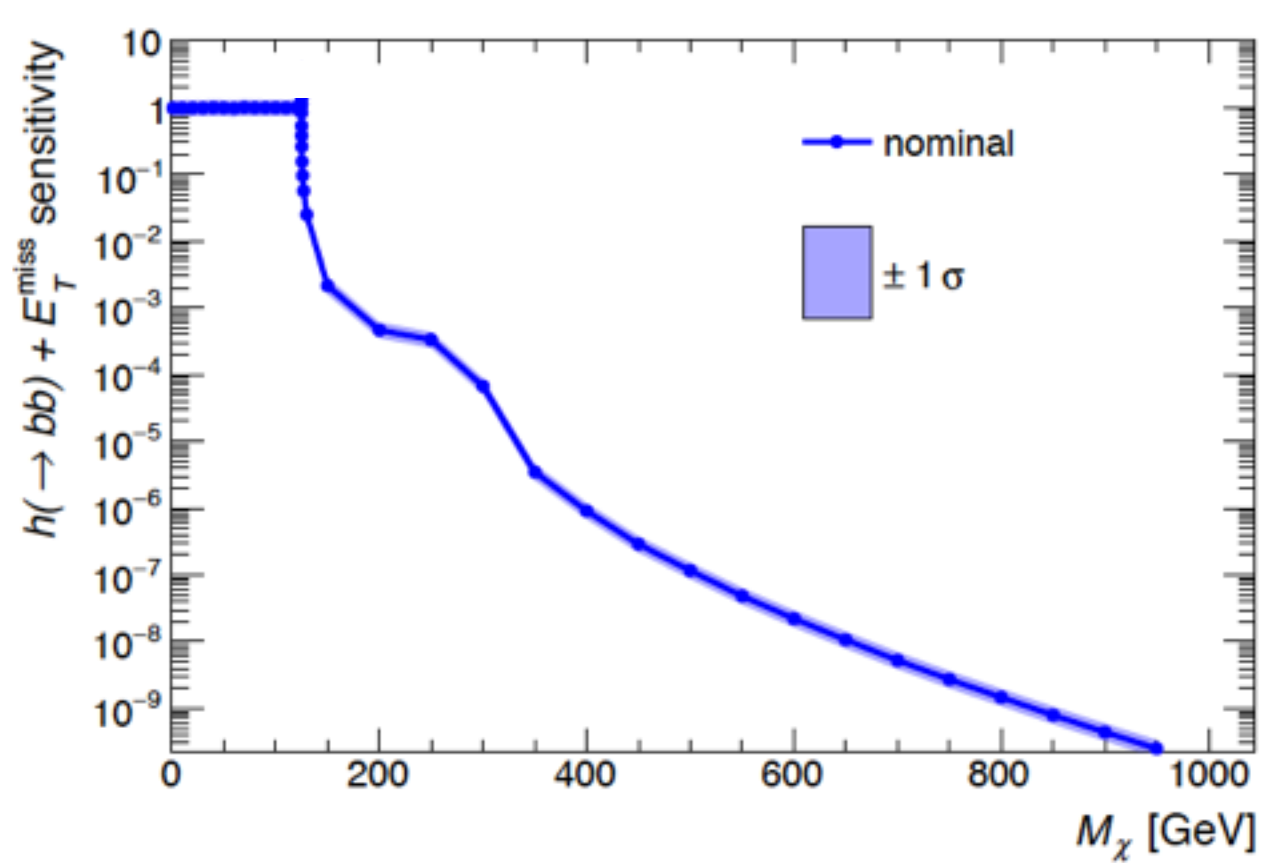




Mono-h

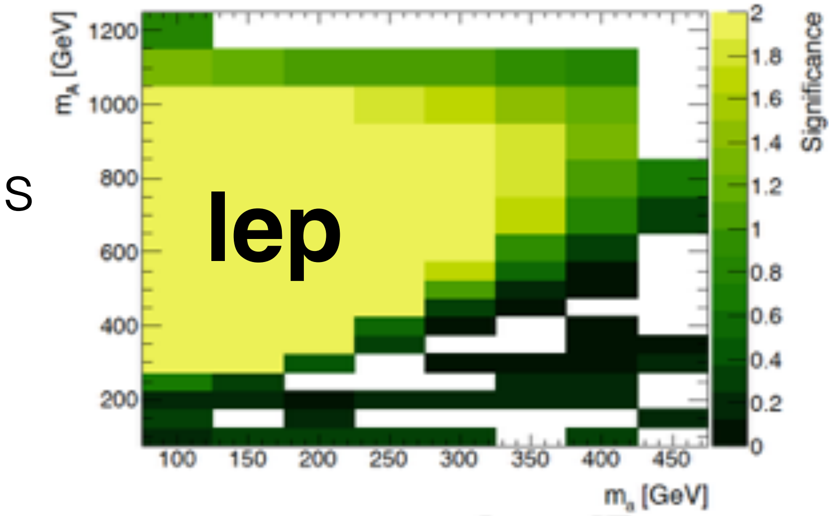
- At high tan(β), bb initial state gets relevant - everywhere else gluon fusion dominates
- tan(β) only varies E_T^{miss} in cases where resonant production is possible
  - Small tan(β): top Yukawa large → non-resonant production dominant
- M_χ changes cross-section and E_T^{miss}, depending on the mass hierarchy of A, a, H, h

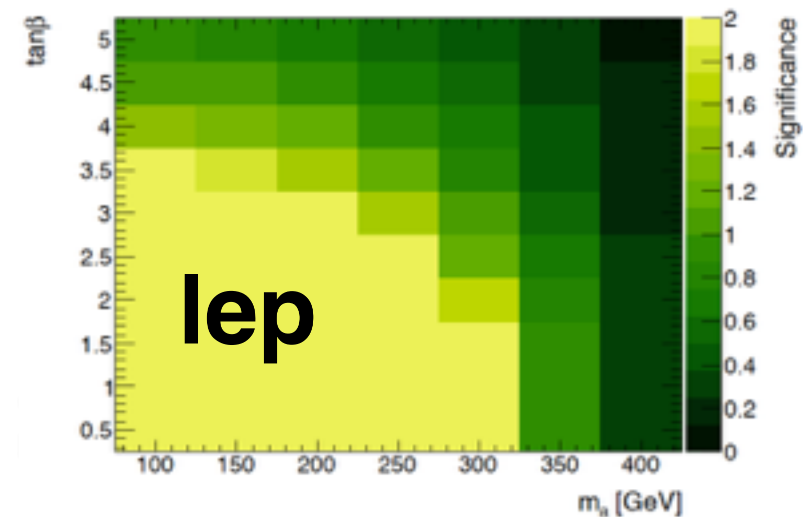


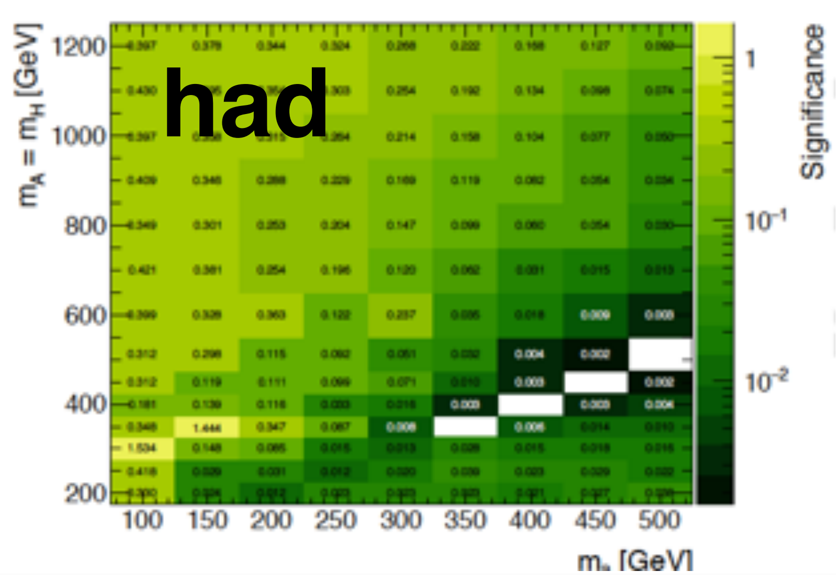


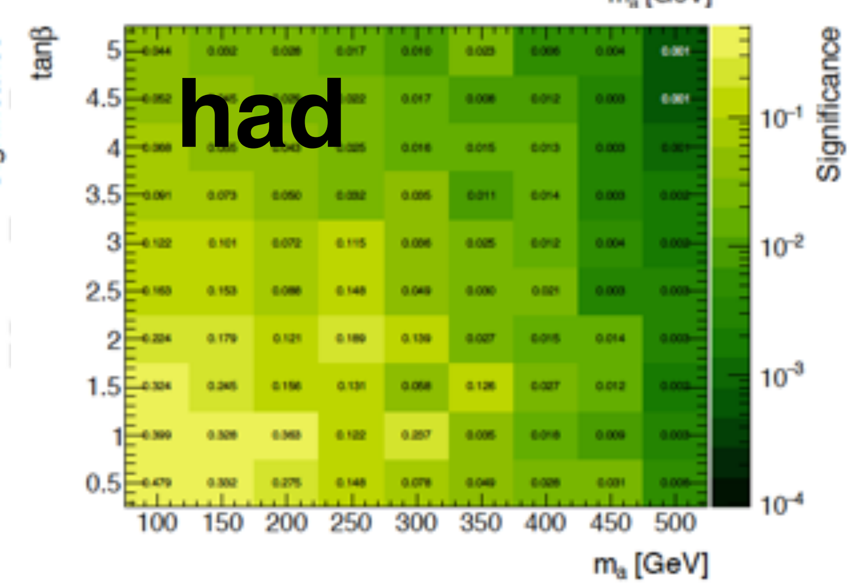
Mono-Z

- Resonant process H→aZ gives Jacobian peak in E_T^{miss}
  - Peak depends on M_H and M_a, broader for higher masses
  - Suppressed for diagonal ($M_a \approx M_A$)
- For $M_a < M_A$, DM dominantly from on-shell a,
  for $M_a > M_A$ mostly H $\rightarrow \chi\chi$
- If $|M_a - M_A| < M_Z$, non-resonant production dominant
  → sensitivity decreases
- For M_a < 350 GeV cross section increases with $\sin(\theta)$,
  for M_a > 350GeV, a → tt accessible
  ⇒ cross section decreases for high $\sin(\theta)$
- Most sensitive for lower tan(β)



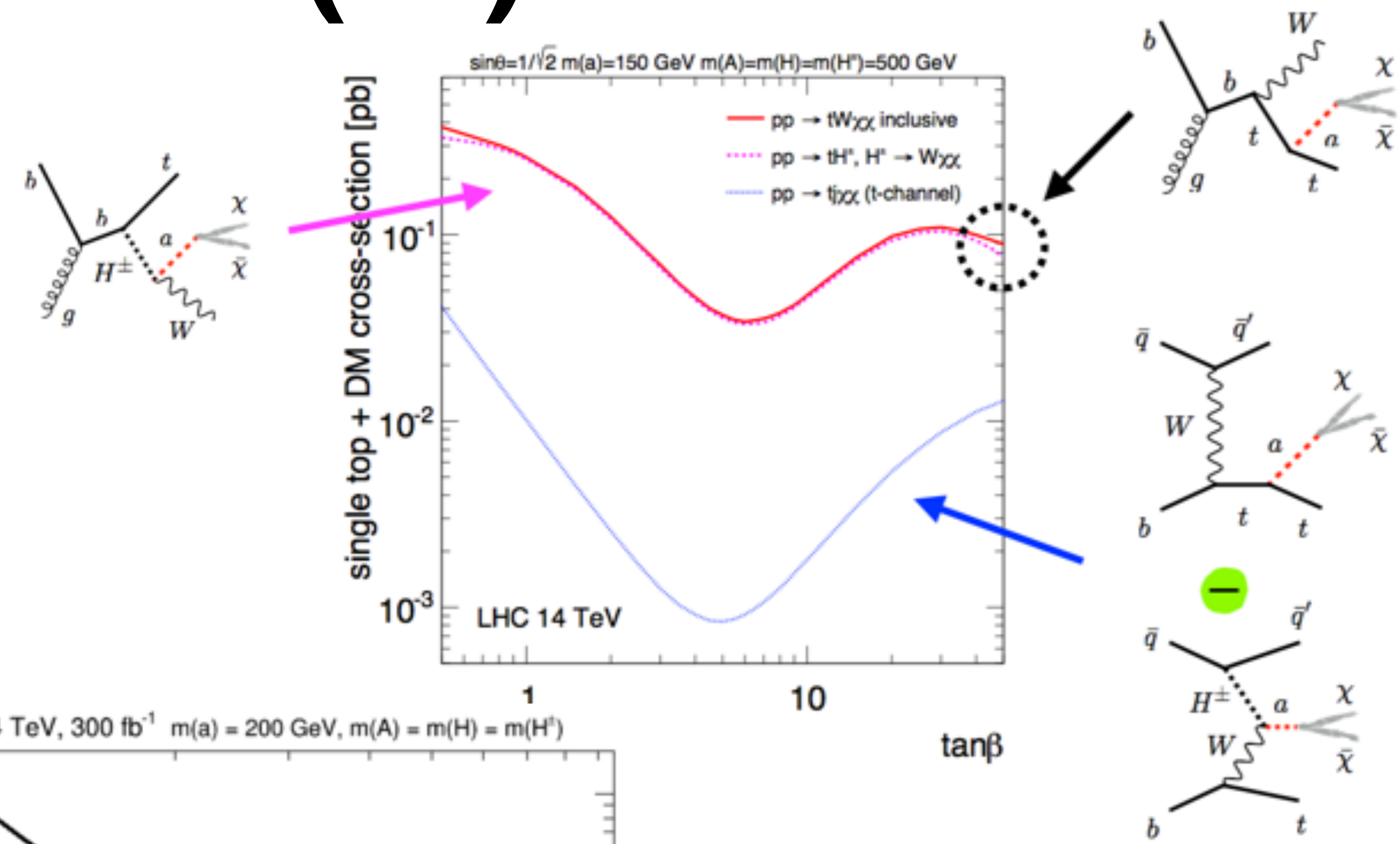


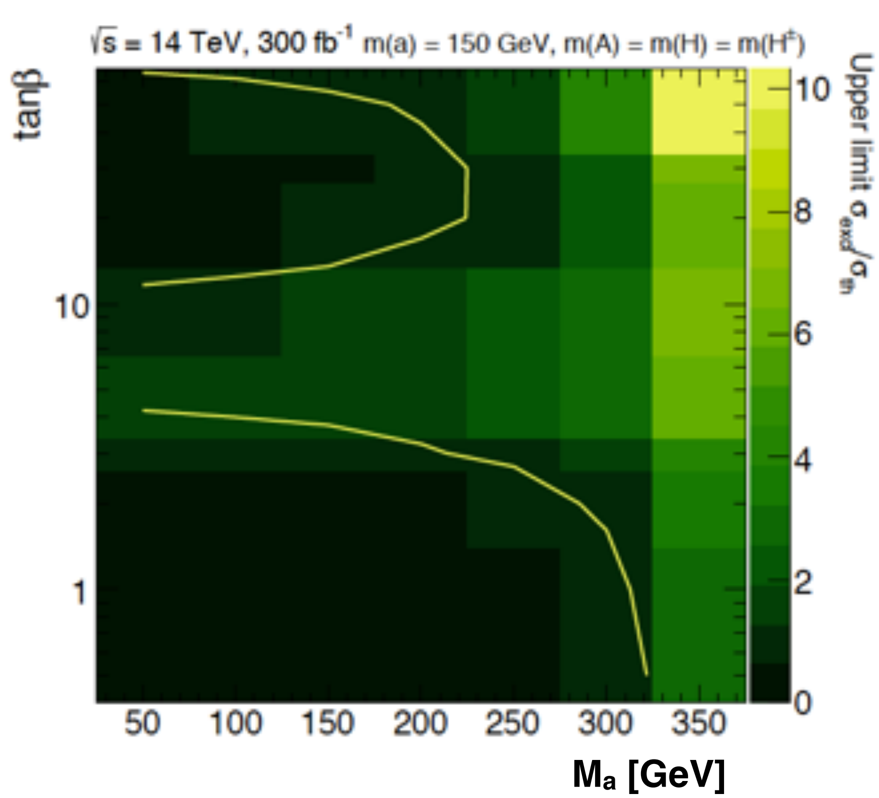


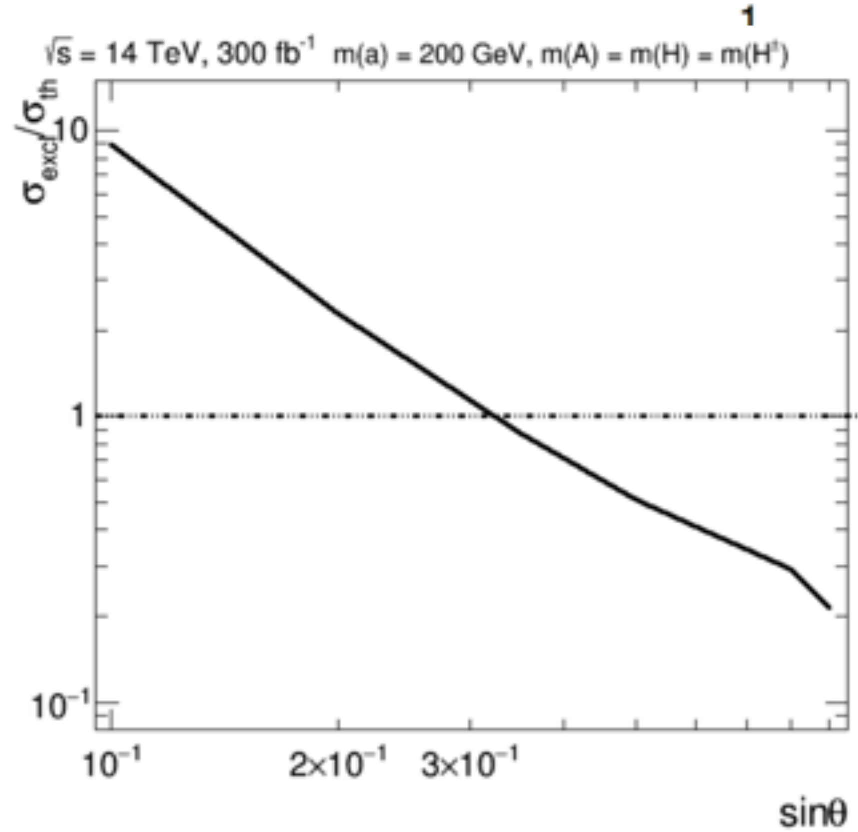


DM+t(W)

- When $H^\pm \to W^\pm a$ possible, $H^\pm$ is produced on-shell
  - cross section of $pp \to tW\chi\chi$ one order of magnitude larger than in Simplified Model





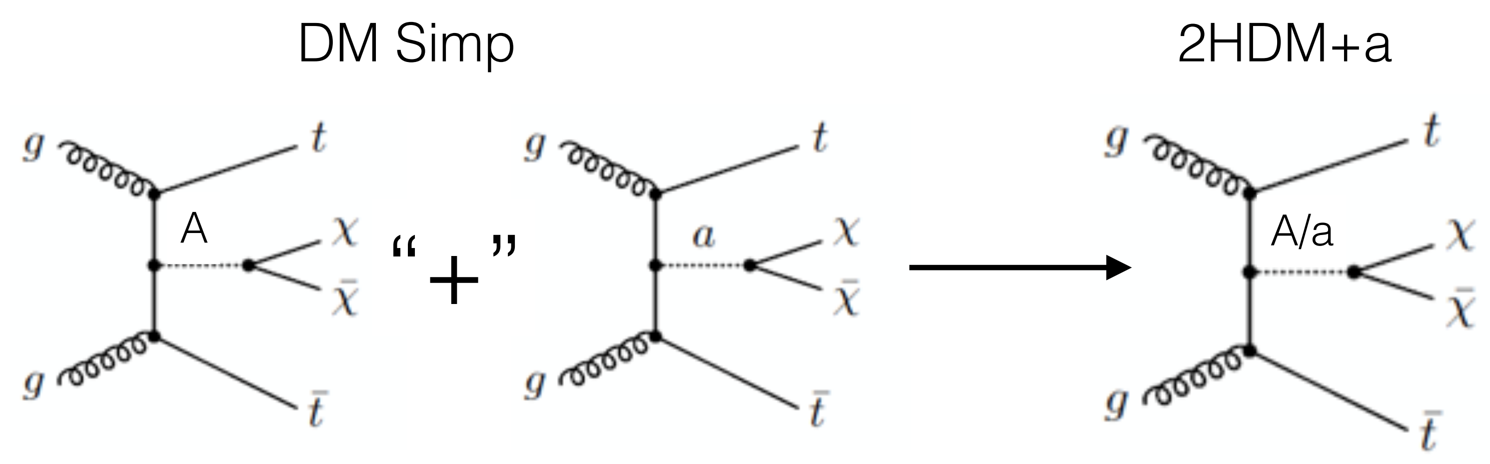


- sensitivity reach in M_a - $\tan(\beta)$ is comparable to mono-h results

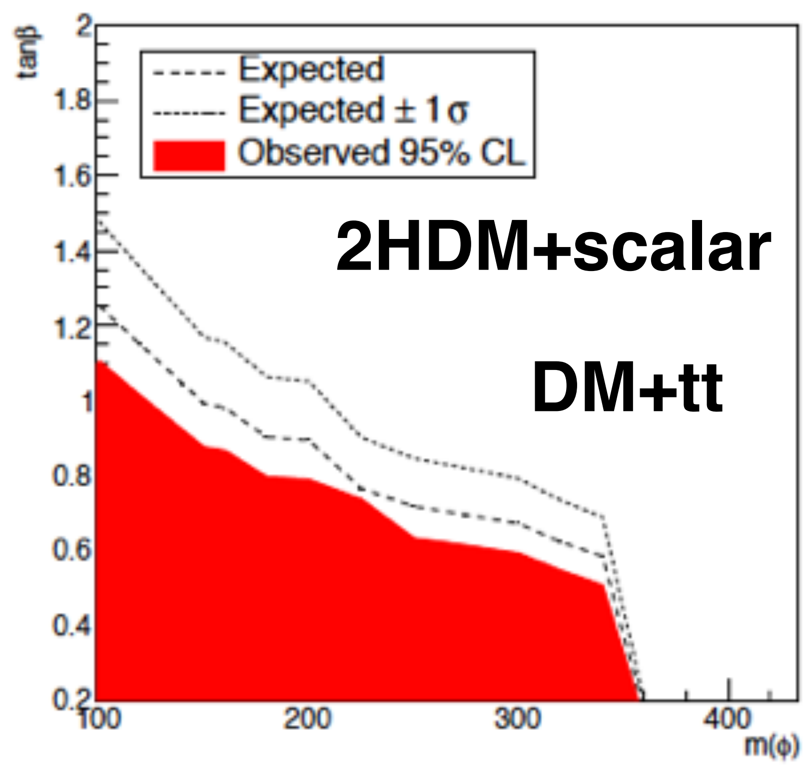
Signatures without resonant production modes

DM + heavy flavour

- Signal samples: rescaling possible from Simplified Model

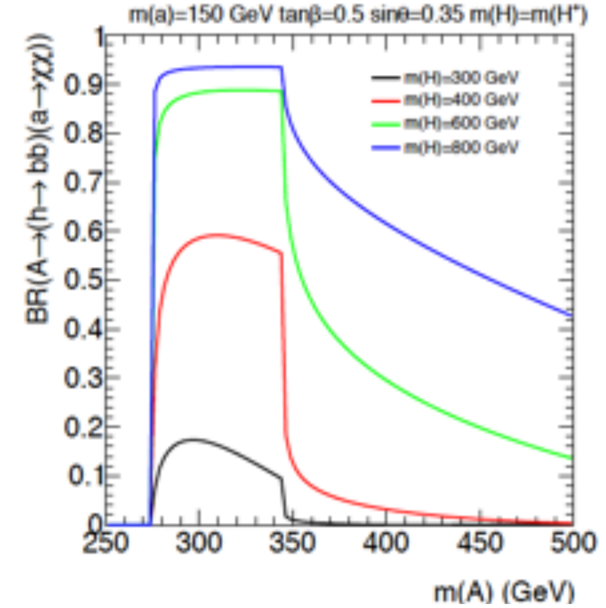


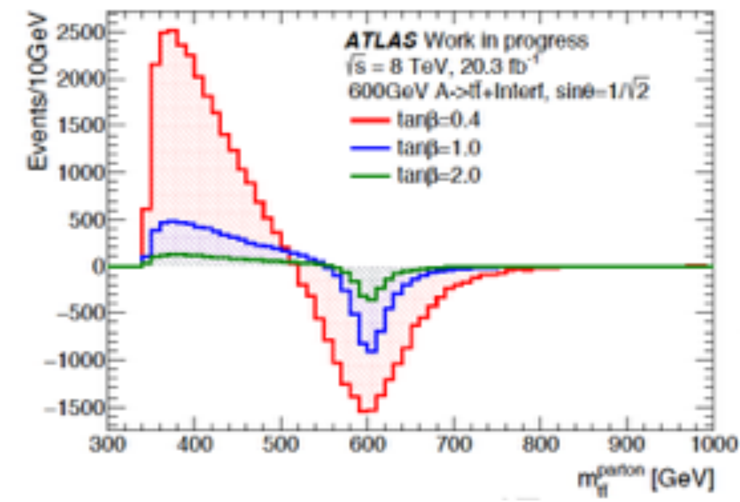
- small tan(β): couplings of A and a to down-type quarks are heavily suppressed irrespectively of the Yukawa assignment
  → DM+bb needs high tan(β)
- Kinematics don't depend on tan(β) or sin(θ)
- E_T^{miss} and leading and trailing top quark p_T distributions get harder with increasing M_a
  - For $M_A < M_a$ same trend with M_A
- Usually a → $\chi\,\chi$ is dominant, but depends on tan(β)
- Interesting bounds also on model with scalar mediator

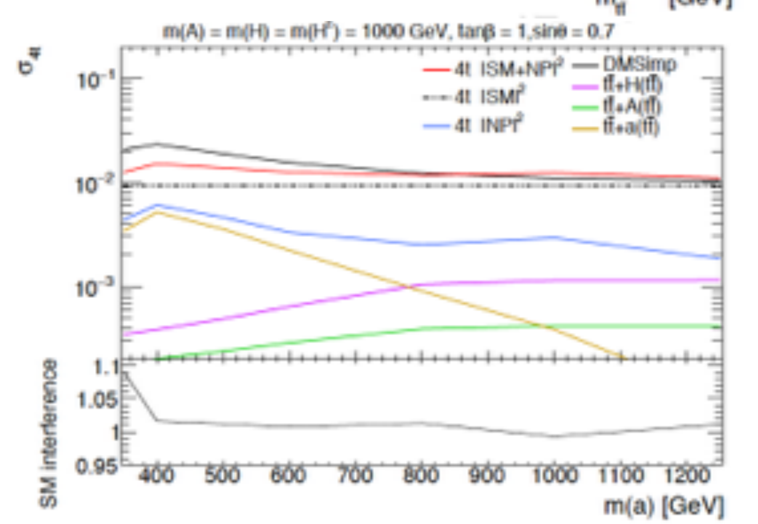


Other signatures

- **(DM+) tth / (DM+) ttZ**:
  - can have sizeable contribution, importance depends on model parameters
  - further studies needed to understand interplay and complementarity wrt other signatures
- **ttbar resonance**:
  - interference effects between signal and SM tt distort signal shape
  - recent analysis: (pseudo-)scalar masses of 500 - 650GeV probed in a minimal 2HDM → similar range possible for 2HDM+a
- **4 tops**:
  - rare but increasingly important signature
  - interesting complementarity with DM + tt







Conclusions and Outlook

- **Taking the step from Simplified Models for DM production to 2HDM-like extensions allows for**
  - consistent theoretical framework
  - rich phenomenology
  - interesting interplay between signatures due to possible resonant production
- **Constraints and model assumptions allow to reduce free parameters**
  - Proposed following scans: M_a-M_A, M_a-tan(β), sin(θ), M_χ
  - Presented results from different signatures
- **Results and studies summarised in DMWG white paper (work in progress!)**

- **Future possibilities**
  - Relax assumption on mass hierarchy → affects possible collider signatures
  - Include di-boson searches → give up alignment limit
  - Comparison with direct and indirect DM searches

Points of contact with efforts of HXSWG

- **What are the main differences between the models we are using?**
  - HXSWG (based on https://arxiv.org/pdf/1610.07922.pdf):
    - different 2HDM scenarios → no DM
    - inert 2HDM → one of the Higgses is DM, different phenomenology
    - Largest overlap: 2HDM and SM singlet → DM would be spin-0
      - For us: fermionic DM
    - NMSSM scenarios → possible overlap

- **Which aspects of our model would be most interesting for you and where could we collaborate?**
  - Comments and discussion very welcome!
    - Contact: lhc-dmwg-contributors@cern.ch