Extended Higgs Sector 2HDM+a Models

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Behalf of the Extended Higgs Sector Combination

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Outline

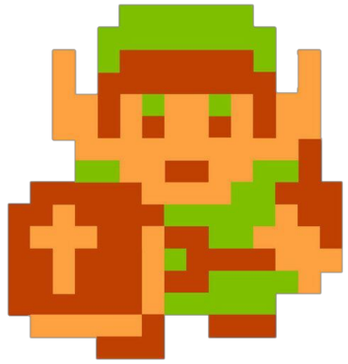
- The **Pseudoscalar Two Higgs Doublet Model** (2HDM+a) is a next generation DM model:
  - Represents the simplest, theoretically consistent extension of a DM simplified pseudoscalar model.
  - Contains a rich parameter space and novel detection signatures.
- Phenomenological studies of the model as well as recommendations for 2HDM+a parameter scans are documented in the DMWG White Paper.
- The recent DM Summary paper reinterpreted previous DM searches to present the first set of collider limits for this model.
- Looking forward the Extended Higgs Sector Combination looks to utilize the full Run 2 data, explore new channels, and perform statistical combinations.

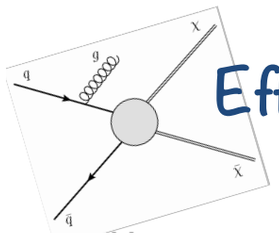
Combination Talks Friday!

Evolution of Dark Matter Models

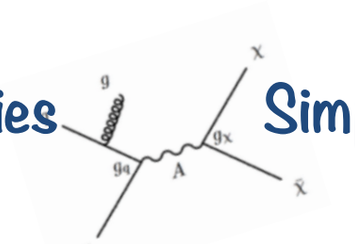
Figure by Arely Cortes

Theoretical Framework

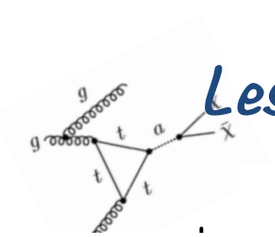




Effective Field Theories



Simplified models



Less simplified models

Operators in the Lagrangian made from DM and SM fields

EFTs have energy scale, Λ. Only valid for momentum transfers well below Λ.

Introduces spin-0 or spin-1 mediators

Describes DM production kinematics with a minimal number of free parameters

Not a complete theory

I.e. Super Symmetry or 2HDM+a

Gauge Invariant, Renormalizable

Larger number of free parameters leading to rich phenomenology

2HDM+a Model

- The 2HDM+a model is produced by mixing a DM coupled pseudoscalar, P, with the CP-odd Higgs from Two Higgs Doublet Model (Type-II).

$$\mathcal{L}_\chi = -iy_\chi P\bar{\chi}\gamma_5\chi$$

$$V_P = \frac{1}{2}m_P^2P^2 + P\left(ib_P H_1^\dagger H_2 + \text{h.c.}\right) + P^2\left(\lambda_{P1}H_1^\dagger H_1 + \lambda_{P2}H_2^\dagger H_2\right)$$

Mass Eigenstates

CP-even: H, h

CP-odd: A, a

Charged: H±

Alignment Limit

- Work in the alignment limit, cos(β -α) = 0.
- Light scalar, h, associated with SM Higgs, 125 GeV.
- Electroweak VEV, $v = \sqrt{v_1^2 + v_2^2} = 246\ \text{GeV}$.
- Heavy scalar, H, does not couple to vector bosons pairs.

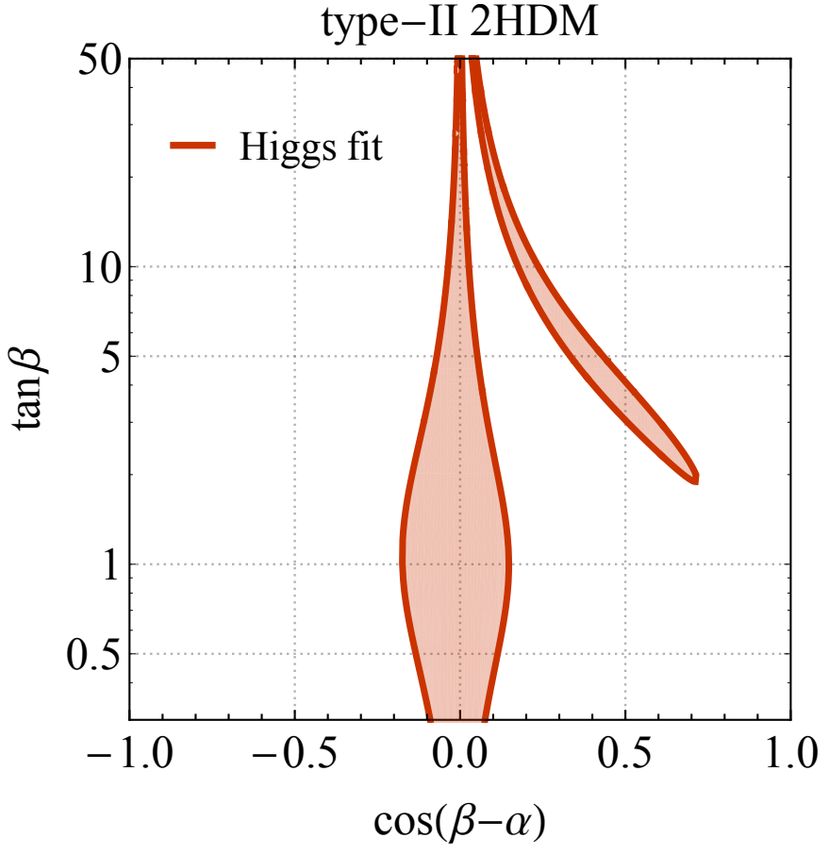
$\cos(\beta-\alpha)$

HW^+W^- ZAh $W^\pm H^\mp h$

HZZ Zah

} **∅ couplings**

***For CP symmetric 2HDM, A also has no tree-level coupling to ZZ or WW.**



2HDM+a Parameters

2HDM+a model has 14 parameters:

$$\left\{ \begin{array}{c} v,\, M_h,\, M_A,\, M_H,\, M_{H^\pm},\, M_a,\, m_\chi \\ \cos(\beta-\alpha),\, \tan\beta,\, \sin\theta, \\ y_\chi,\, \lambda_3,\, \lambda_{P1},\, \lambda_{P_2} \end{array} \right\}$$

- **Alignment limit fixes v, M_h, and cos(β -α) values.**
- **Vacuum stability and unitarity constrain quartic couplings, λ_3, λ_{1p} , λ_{2p} = 3.**
- **Choose DM coupling, y_χ = 1.**
- **EW precision measurements constrain mass splitting. Set M_A=M_H=$M_{H^\pm}$.**

Reduces to 5 free parameters:

Free Parameters

M_A=M_H=$M_{H^\pm}$: mass of heavy pseudoscalar A, heavy scalar H, and charged scalar, $H^\pm$.

M_a: mass of pseudoscalar mediator ($M_a < M_A$)

sinθ: mixing angle between **a** and **A,** both couple to DM.

tanβ: ratio of VEVs of Higgs doublets

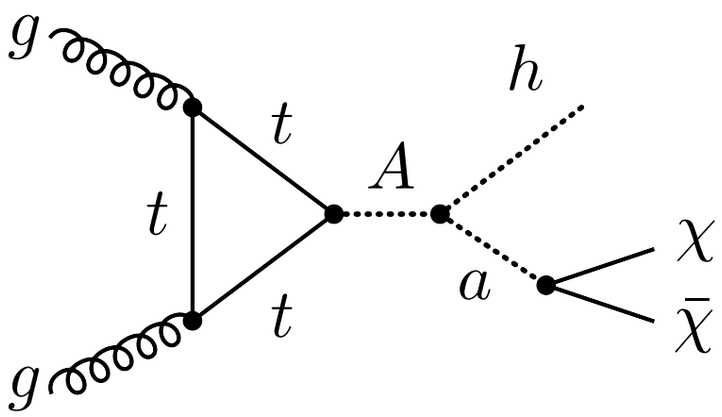
M_χ: DM mass

Signatures

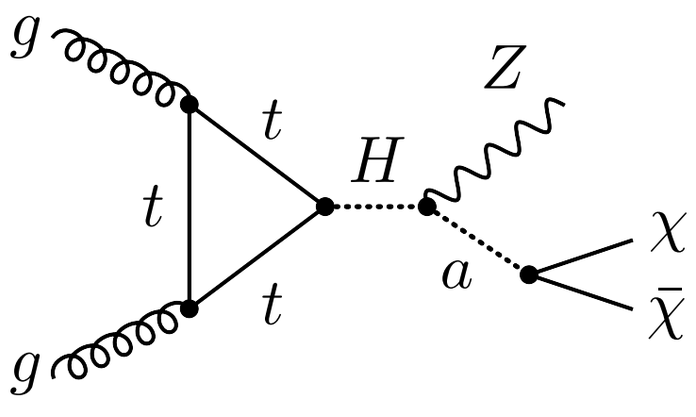
Signatures with resonantly produced A/H/H± are enhanced. Can be more sensitivity than traditional DM search channels, ie Mono-Jet.

Resonance Enhanced

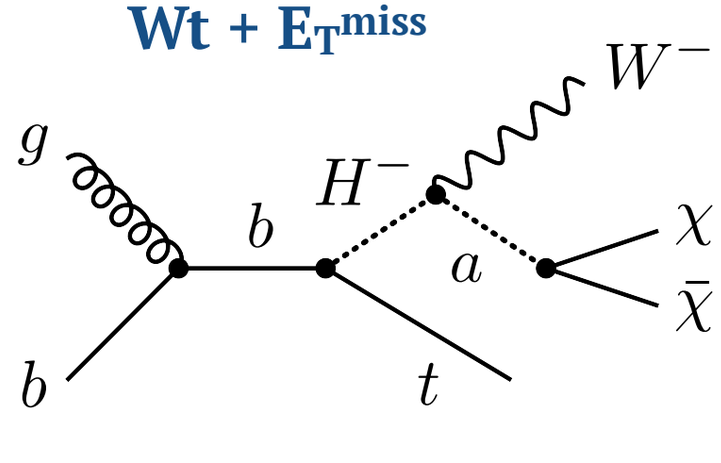
h + E_T^{miss}



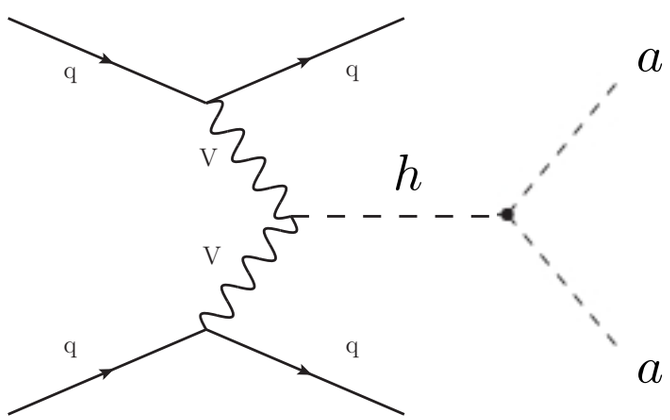
Z + E_T^{miss}



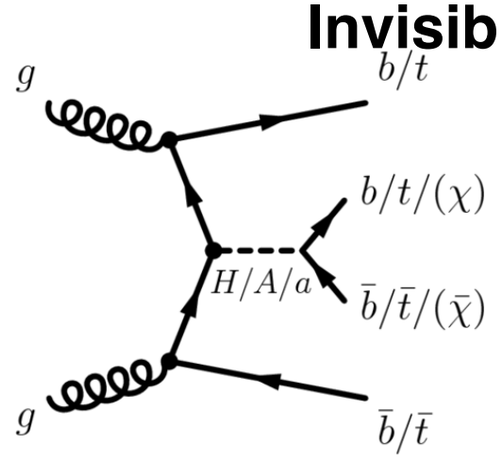
Wt + E_T^{miss}



Higgs Decay

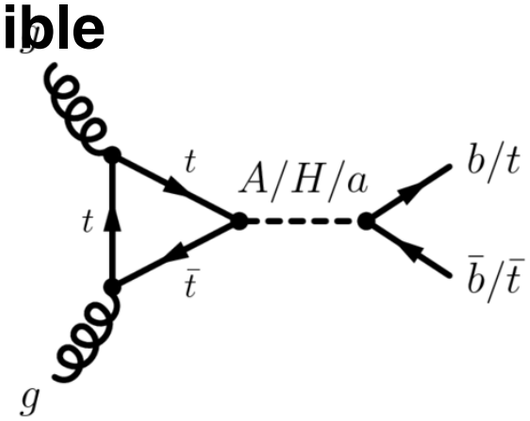


Invisible / Visible



bb + E_T^{miss}

4-top



tt + E_T^{miss}

Multi-b

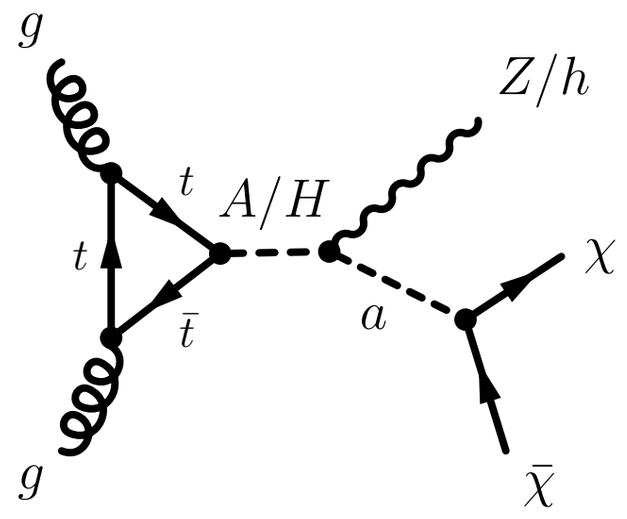
bb **tt**

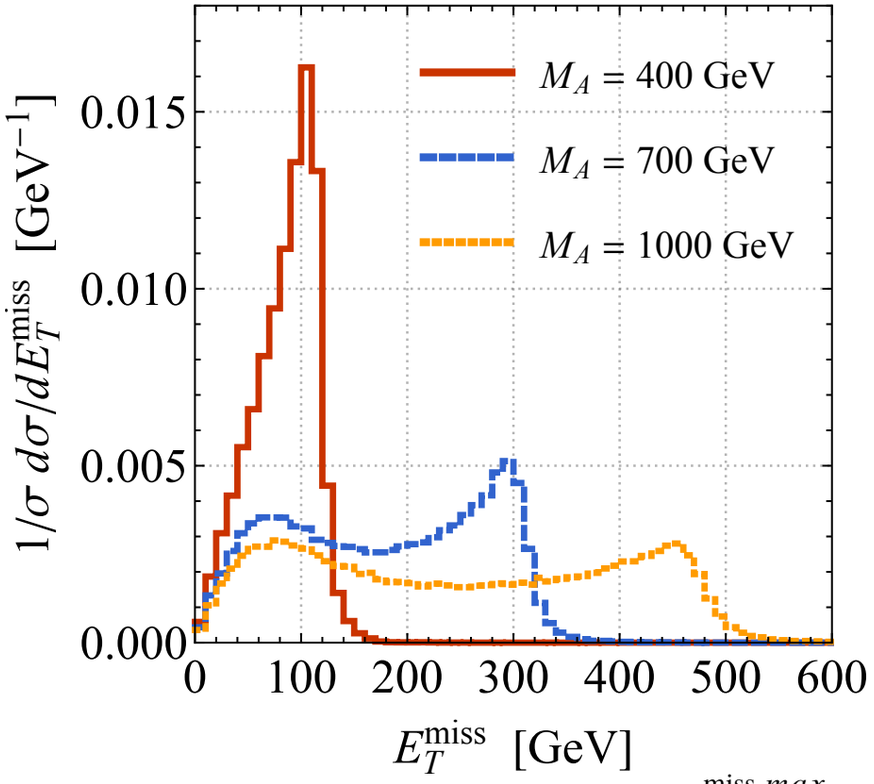
Jet + E_T^{miss}

2HDM+a Kinematics

Kinematics of resonance enhanced signatures are **distinct** from Simplified models:

- Two body decay leads to E_T^{miss} distributions with a *Jacobian* peak. Location depends on: ($M_{H/A/H\pm}$ - M_a)
- Transverse mass observable , M_T, useful to discriminate signal from background. Or M_{T2} for 2L Wt+E_T^{miss}





$$E_T^{miss,max} \approx \frac{\sqrt{\left(m_A{}^2 - m_a{}^2 - m_h^2\right)^2 - 4m_a{}^2 m_h^2}}{2m_A}$$

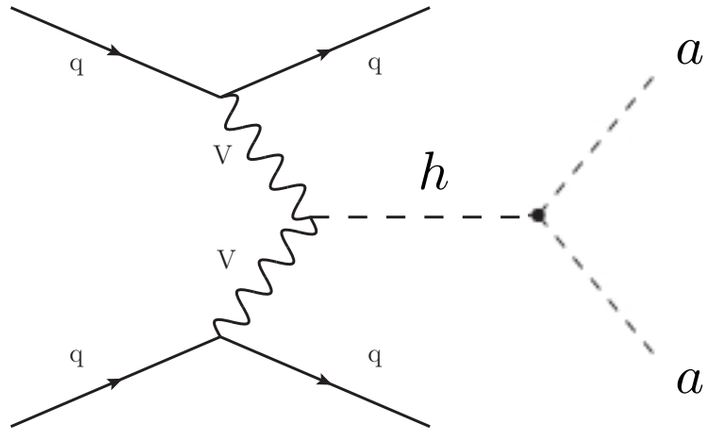
- bb+E_T^{miss} and tt+E_T^{miss} kinematics are similar to those for simplified pseudo-scalar model.
- For ditop production kinematics are similar to 2HDM models. Interference with SM ditop production leads to a peak-dip distribution in m_{tt}.

Talk by Lluïsa-Maria Mir

Higgs Decay

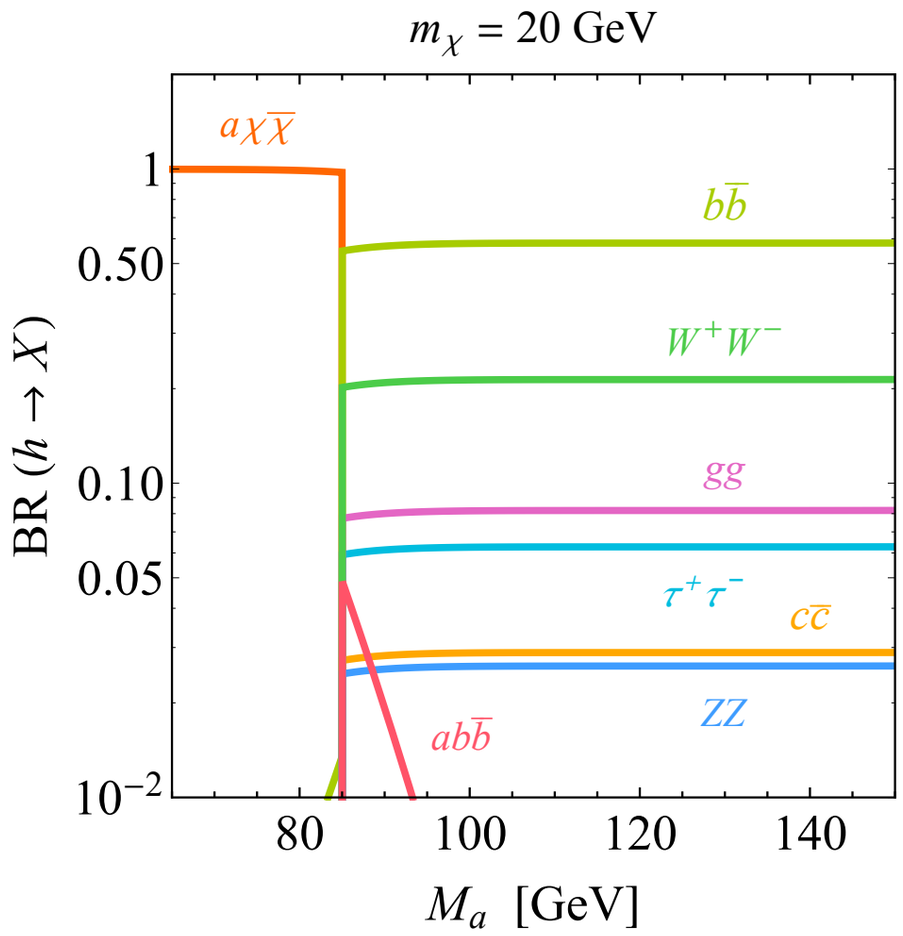
For light mediator masses, M_a, SM Higgs measurements effectively probe the 2HDM+a model.

h->aa (even in alignment limit). Most restrictive when considering one of the a's off-shell.



Invisible Higgs Decay

- For M_a < 125 GeV Higgs can decay to DM:
  h → aχχ →χχ χχ.
- Reinterpret limits on Invisible Higgs BF. Current constraints from Run 1 (23%), but new Invisible Higgs combination planned for Run2.



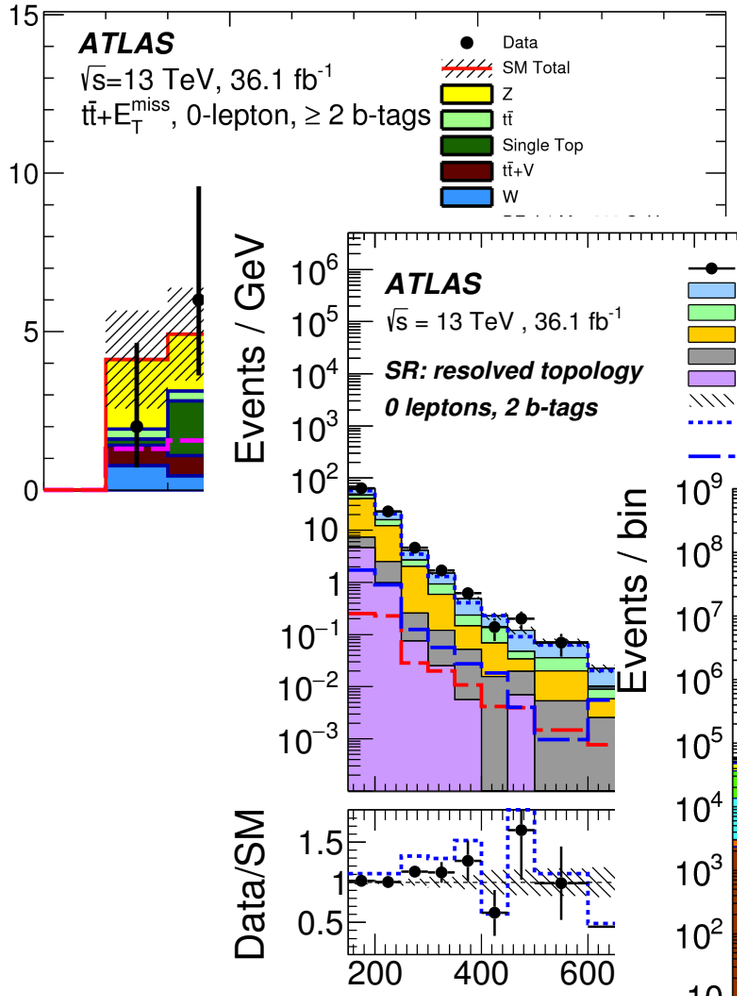
Visible / Mixed Higgs Decay

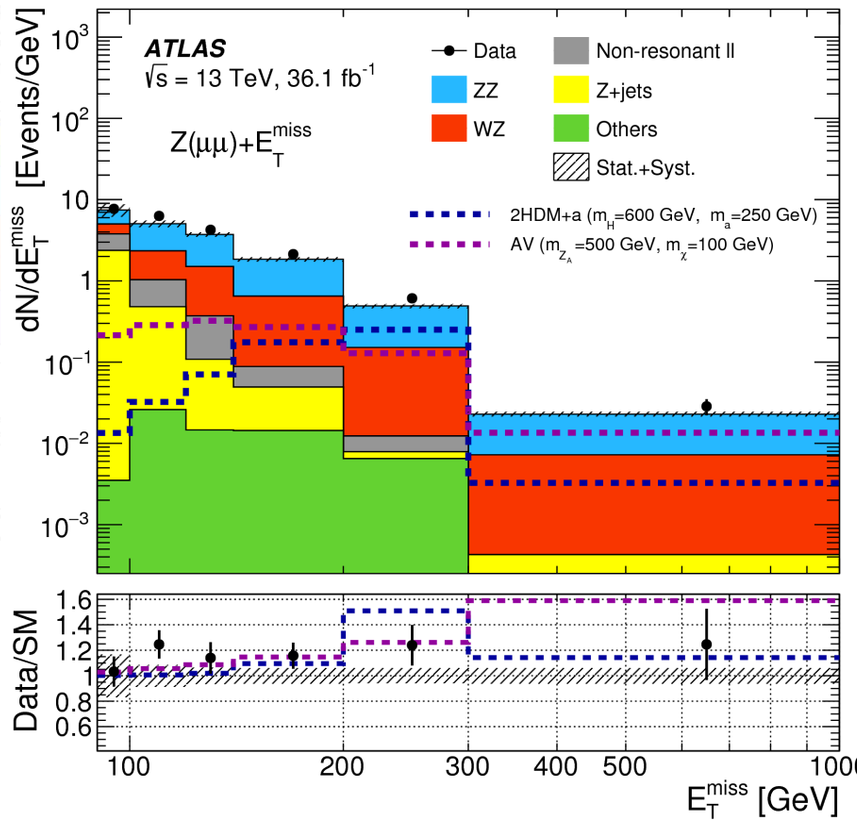
- For large tanβ, or when M_χ is too large to allow h->aχχ, there can also be h → abb decays, leading to bb χχ or 4b final states.

Analyses

- h(bb) + E_T^{miss}
- h(γγ) + E_T^{miss}
- h(ττ) + E_T^{miss}
- Z(ll) + E_T^{miss}
- Wt + E_T^{miss}
- tj+ E_T^{miss}
- bb + E_T^{miss}
- tt + E_T^{miss}
- bb
- tt
- Multi-b-jets
- 4-top

★New channels





★Resolved and merged analyses for multi-jet final sates.

★0L, 1L, and 2L analyses for tt, tt + E_T^{miss}, tj+ E_T^{miss} , Wt + E_T^{miss}.

For Full Run-2

Re-optimize Selection cuts

Utilize MET Significance

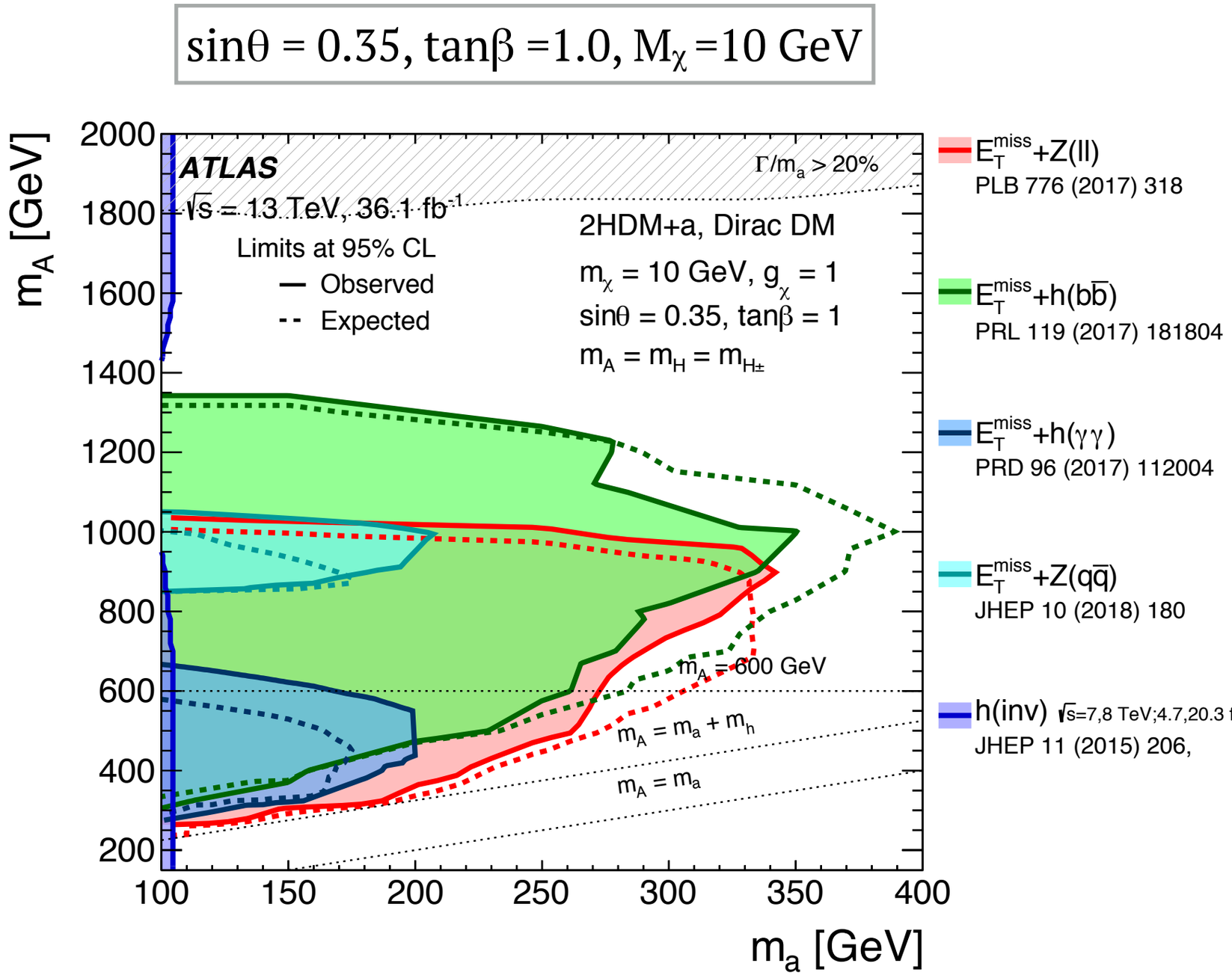
Improve Background estimates

2HDM+a specific discriminating variables, BDTs …

M_A-M_a Scan

Benchmark Parameter scans chosen to highlight properties of the model and complementarity of signatures.

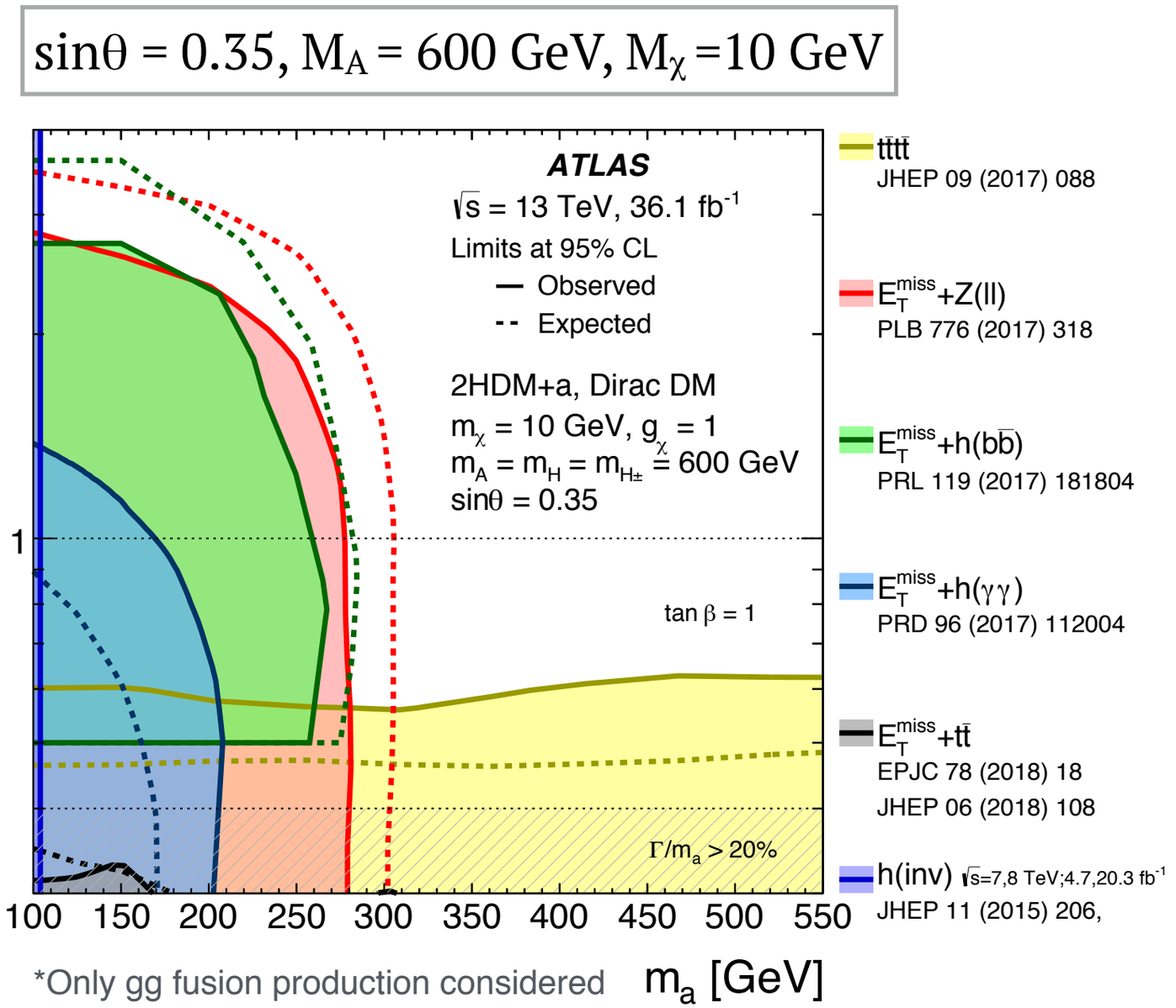
- M_A-M_a scan highlights impact of the Jacobian peak.
- a->tt decay, reduces sensitivity for M_a > 350 GeV.
- H(inv) sets hard lower bound on m_a.
- Introduce new signatures: Wt + MET, H(ττ)+MET, tt+MET.
- Perform statistical combinations on channels of *comparable* reach



tanβ Scan

For Type-2 2HDM, low values of tanβ increase coupling to top quarks while high values increase coupling to bottom quarks.

- Highlight sensitivity to high and low tanβ for top and b-quark signatures, respectively.
- New signatures:
  bb, bbbb,
  tt, Wt + MET.
- Include contributions from bb-induced production for Mono-H and Mono-Z channels.
- New benchmark with higher value of sinθ[1]



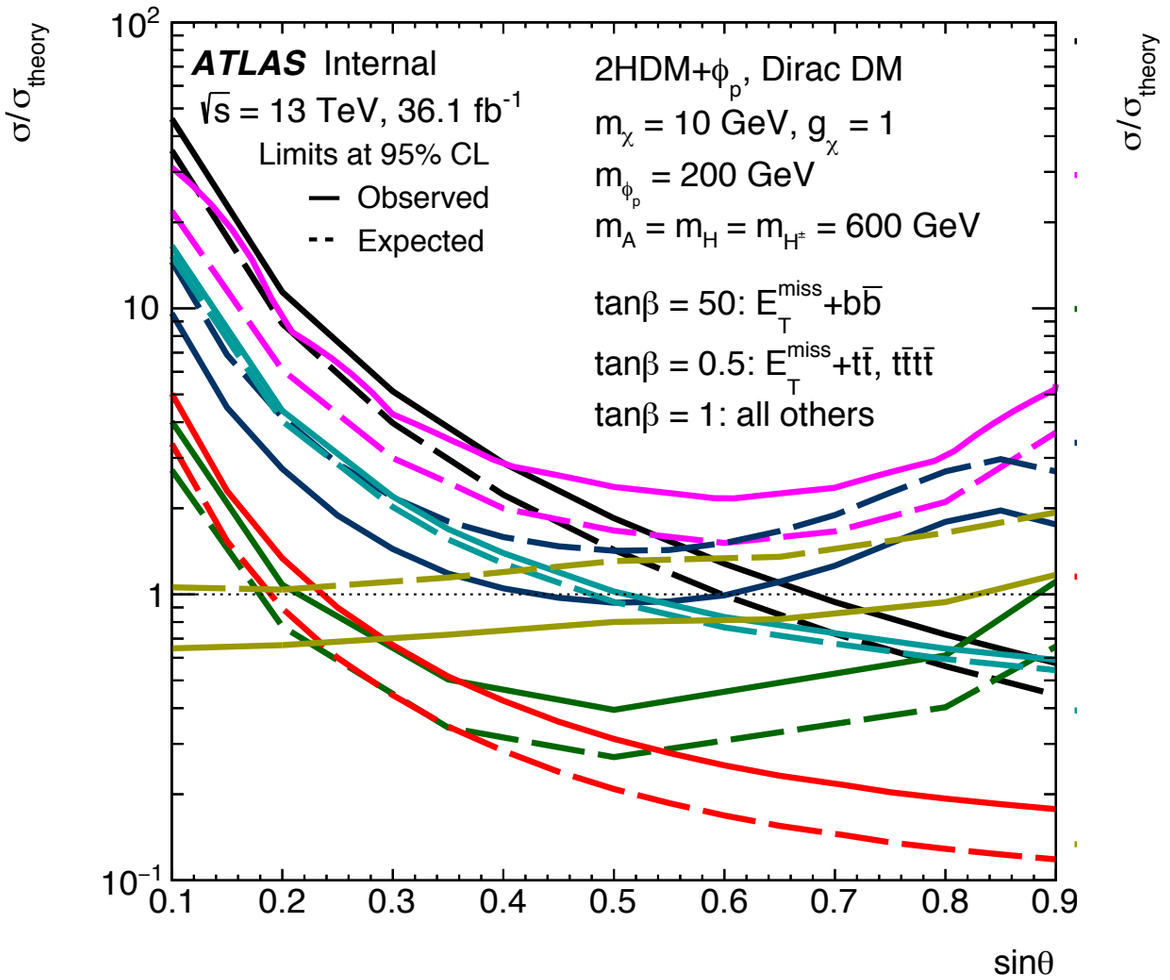
[1] Larger value of sinθ corresponds to tighter constraint on M_H $M_{H\pm}$ splitting, and vacuum instability for O(M_A=1TeV).

sinθ Scans

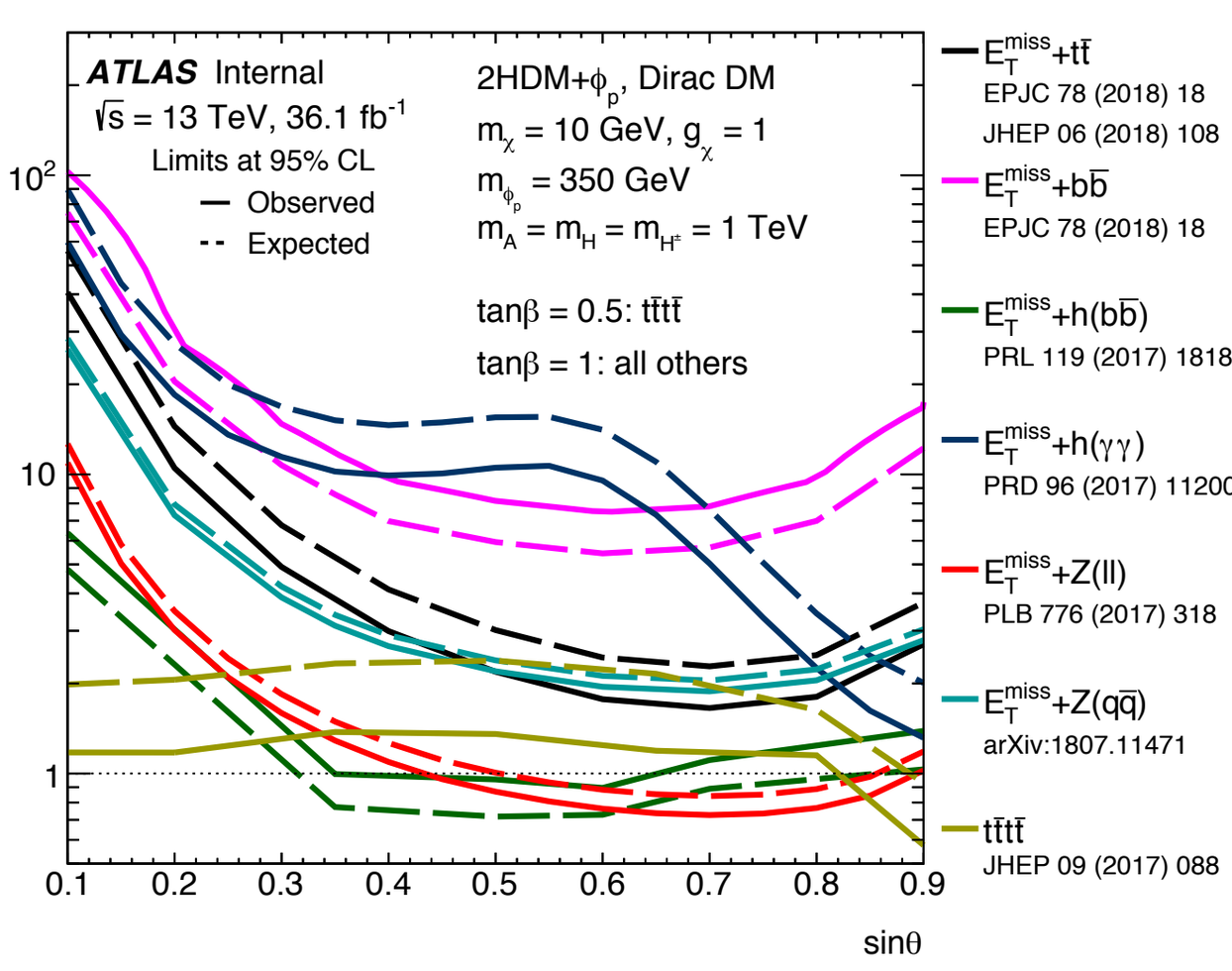
sinθ controls whether a decays preferentially to χχ or, if kinematically accessible, tt.

- Two 1D scans are chosen to highlight how sinθ dependence differs whether a is above or below the tt threshold.

M_H= 600 GeV, m_a = 200 GeV, tanβ = 1.0, mχ = 10 GeV



M_H= 1000 GeV, m_a = 350 GeV, tanβ = 1.0, mχ = 10 GeV



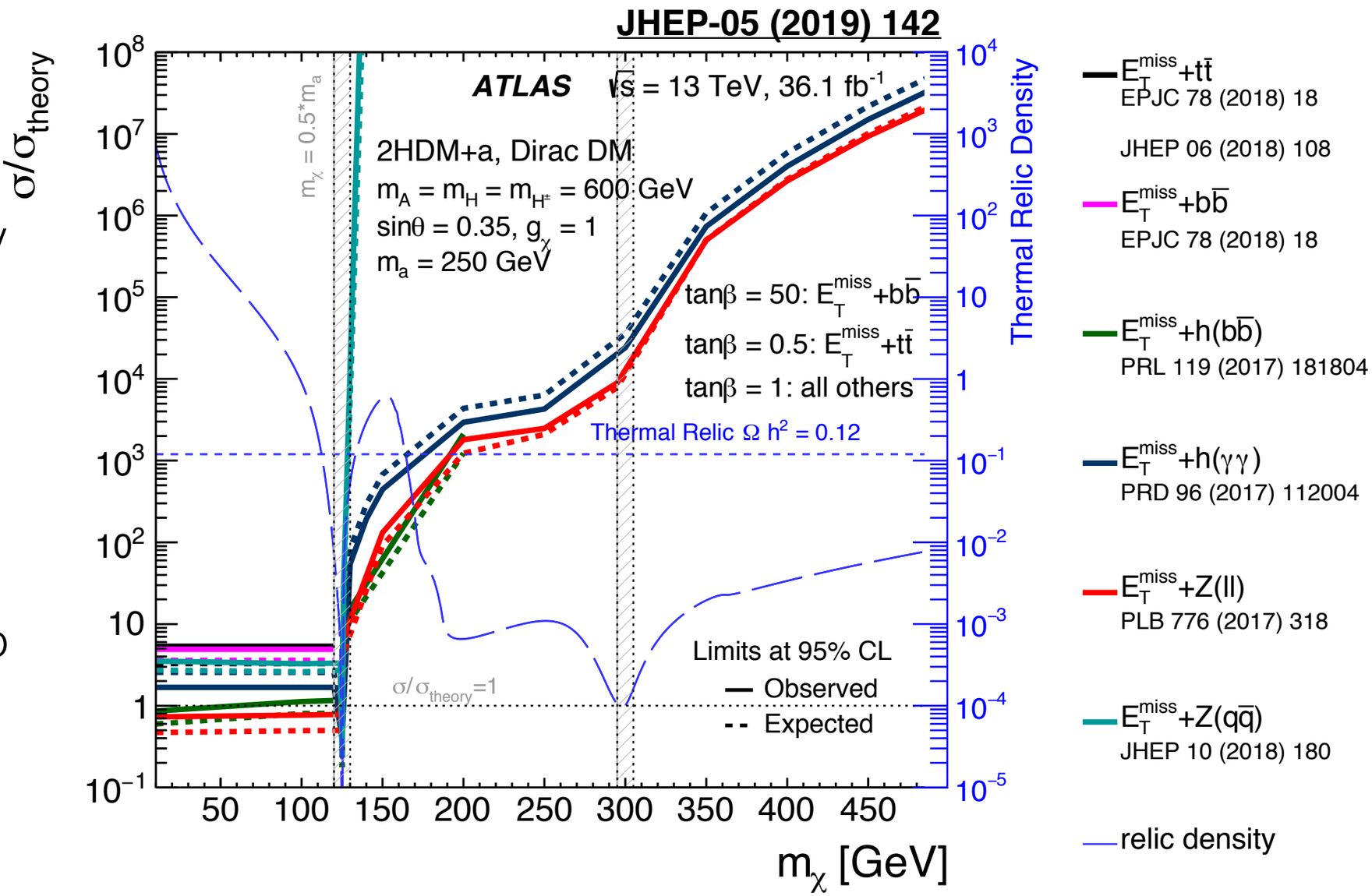
- h + E_T^{miss}, has complicated sinθ behavior. Resonance and non-resonance Feynman diagrams have different sinθ dependence, altering E_T^{miss} shape.

DM mass Scan

Limits on M_χ are compared to relic density calculations made with MadDM.

$\sin\theta = 0.35, \tan\beta = 1.0, M_A = 600$ GeV, $M_a = 250$ GeV

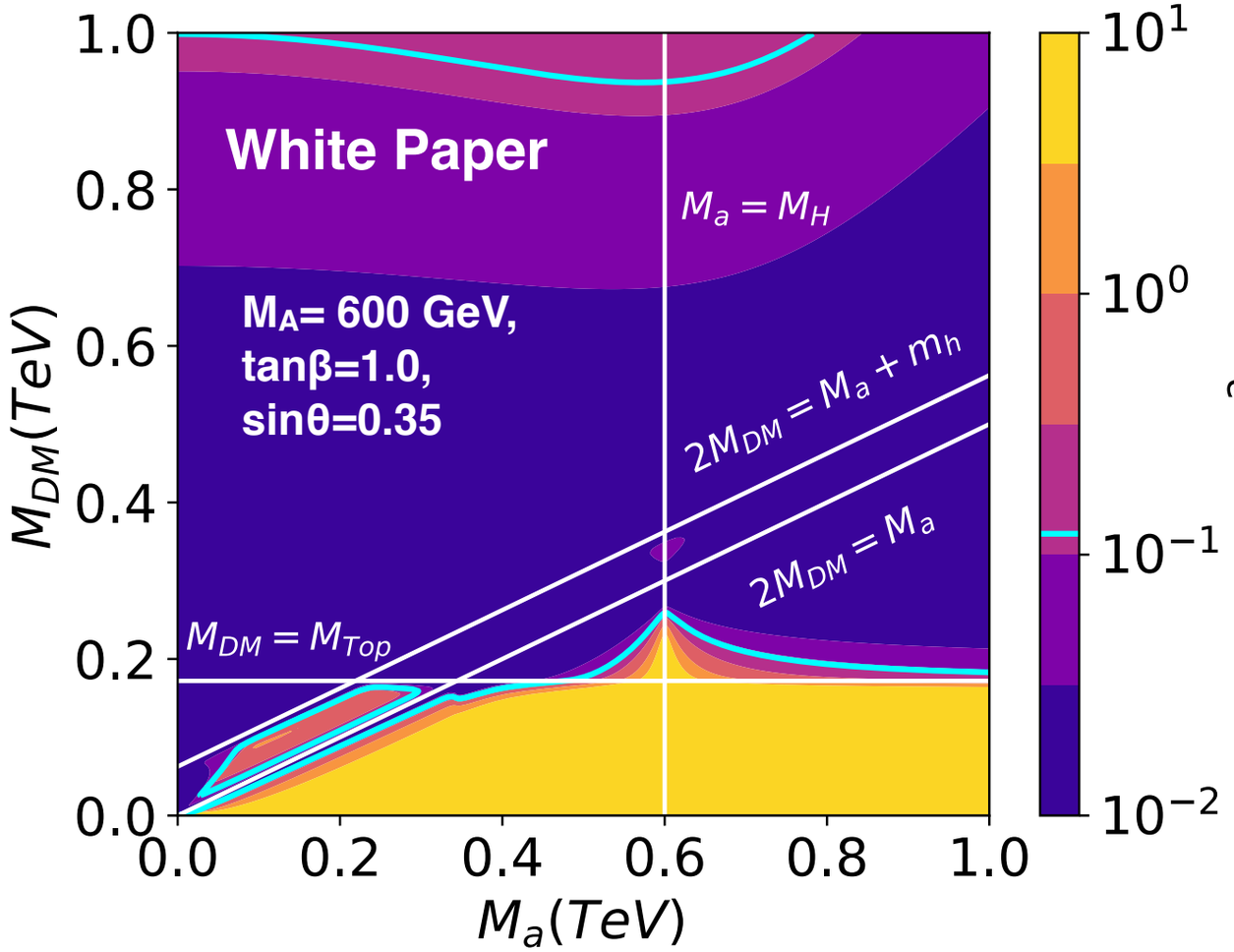
- For $M_\chi < M_a/2 (< M_t)$ model is largely independent of M_χ.
- Sensitivity falls off sharply for off-shell M_χ.
- Relic density is depleted by resonant enhancement $\chi\chi$-> a/A->SM for $m_\chi = 1/2 * m_{a/A}$
- For $m_\chi > m_t$ annihilation to fermions becomes favored leading to an under-abundance of DM.



DM mass Scan

For future benchmark, consider 2D scan of M_a : $M\chi$:

- Relic density plateau for $M\chi = M_{top}$.
- Highlight regions of correct, relic density only explorable by non-MET searches, ie 4-top.
- Invisible Higgs dependence on $M\chi$.
- Minimal additional points required, since for, $M\chi < M_a/2$, DM mass has negligible impact on cross section or kinematics.



Summary

- 2HDM+a introduces a new, theoretically consistent, model of DM.
- Model has 5 free parameters, use 1D and 2D Benchmark scans to highlight features of the parameter space.
- First limits have been made reinterpreting 2015+2016 searches.
- Introducing new channels, in particular Wt + E_T^{miss} and visible final states.
- Expect improved sensitivity from full Run 2 dataset, optimized searches, and statistical combination.