Turning every stone at the LHC: diverse signatures with the 2HDM+a model

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Introduction

Intense activity in model-independent DM searches at the LHC

First EFT then simplified models (DMSIMP)

Going towards UV completion by making models more realistic

Various models on the market, see talk by Felix Kahlhoefer yesterday

For scalar mediators, take into account mixing with SM Higgs LHC measurements ~rule out model with single Higgs doublet

Investigate models with two Higgs doublets and a pseudoscalar mediator (2HDM+a)

Benchmark model proposed https://arxiv.org/abs/1701.07427

The LHC DM working group (theory+experiment) is producing a white paper to be used as a blueprint for LHC searches

ATLAS+CMS+theory working together to explore parameter space

Today: review signatures of benchmark model based on existing literature, preliminary draft of LHC DM working group (LHCDMWG), and some dedicated work for this talk (GP)

Collider DM searches

From full theories to EFT and back

SUSY
UED
little Higgs

Effective field theory (EFT)

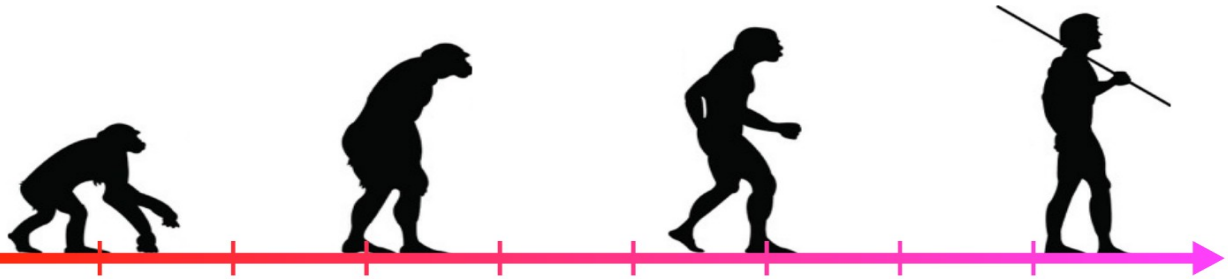
$$\frac{m_q}{\Lambda^3}\,\bar{\chi}\chi\bar{q}q$$

Simplified models

$$g_\chi\bar{\chi}\chi S + \frac{g_q y_q}{\sqrt{2}}\,\bar{q}qS$$

Consistent simplified models

$$g_\chi\bar{\chi}\chi s + Y_q\bar{q}Hq + \mu s|H|^2$$



Pre-LHC LHC

(Extended from a slide by U- Haisch)

….. but SUSY DM searches very active and exciting field throughout, see talk by. E.Rossi and K.R. Schmidt-Holberg earlier this morning

The 2HDM+a model

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

Canonical 2HDM model with additional pseudoscalar singlet interacting with DM.

$\text{States}: h, H, A, H^\pm, a$ — One additional Higgs pseudoscalar

$\text{Angles}: \alpha, \beta, \theta$ — One additional mixing angle

DM sector: m_χ, y_χ — Mass and coupling of DM particle

Relevant point for DM phenomenology: pseudoscalars A and a result from the mixing of mediator and 2HDM pseudoscalar with angle θ

By convention:

A couples to DM with strength sinθ, a couples to DM with strength cosθ

Parameter Reduction

Model with 14 parameters

LHC DM working group: fix parameters based on SM constraints, consistency of theory and LHC Run 2 detectability

- Type II 2HDM
- h is particle discovered at the LHC
- $\sin(\beta-\alpha)=1$: Decoupling limit
- $\lambda_P=\lambda_1=\lambda_2=3$: quadrilinear couplings: boundedness of potential, and tuning for signatures
- Assume $M_H=M_A=M_{H+}$: EWK precision constraints
- DM coupling $y_\chi=1$

Free parameters:

$$m_a,\ m_A,\ \tan\beta,\ \sin\theta,\ m_\chi$$

M_χ kept fixed at 10 GeV in most studies

Traversal of signatures

Original paper arXiV:1701.07427 already includes a rather detailed examination of the LHC signatures, based on experimental analyses available at the time

An additional signature proposed in arXiV:1712.03874

The draft of the LHC DM working group white paper includes large amount of signature studies on 2HDM+pseudoscalar, from many different groups, mostly at parton level, as well as material on 2HDM+ scalar and comparisons with DD and ID. Draft at:

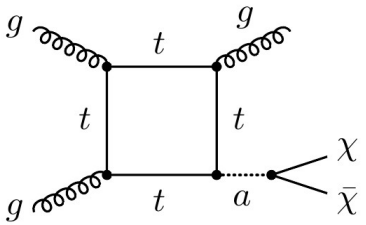
https://github.com/LHC-DMWG/DMWG-2HDM-whitepaper/tree/DMWG_edited

I'll try in the following to provide a unified view of the expected parameter space coverage with full LHC luminosity, based on above material and on additional particle-level studies

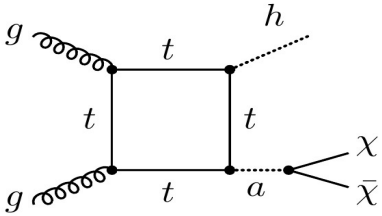
DMSIMP

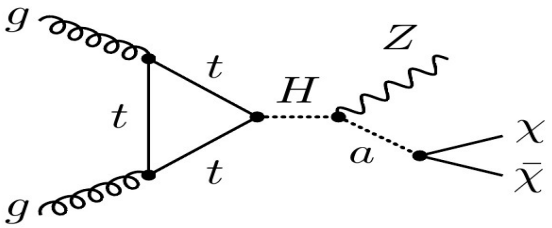
additional for 2HDM

Signature



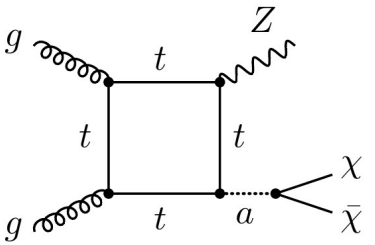
monojet

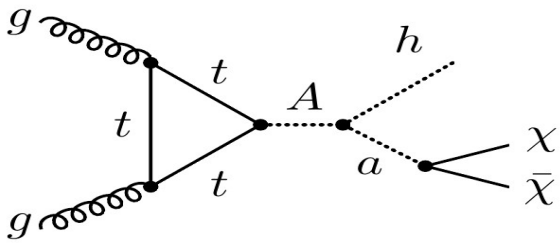




h+DM

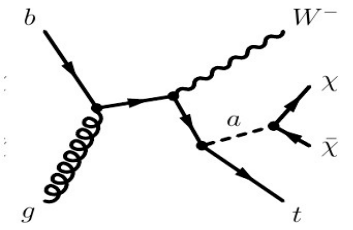
On-shell H decay

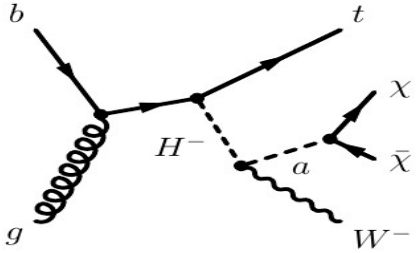




Z+DM

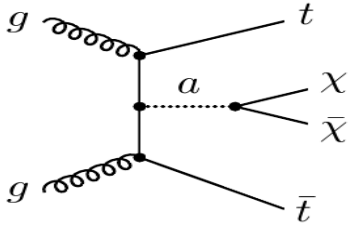
On-shell A decay

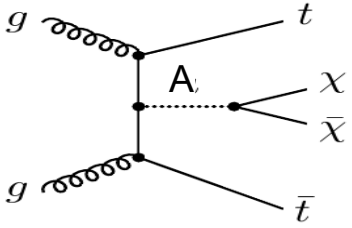




tW+DM

On-shell H+ decay

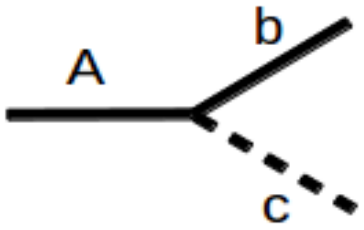




tt+DM

Resonant decays of heavy Higgses

Decay of a heavy particle into a visible particle and an invisible one: transverse momenta of visible, invisible, and transverse mass of visible distributed as a Jacobian, with end point:



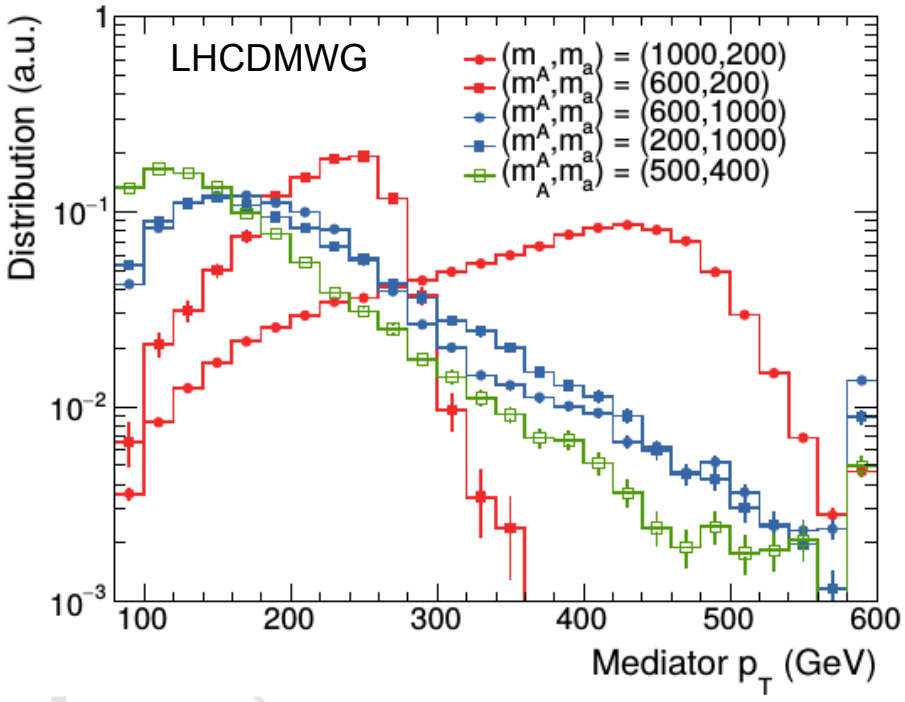
$$E_T^{\mathrm{miss},max} \approx \frac{\sqrt{\left(M_{A/H}^2 - M_a^2 - M_{h/Z}^2\right)^2 - 4M_a^2 M_{h/Z}^2}}{2M_{A/H}}.$$

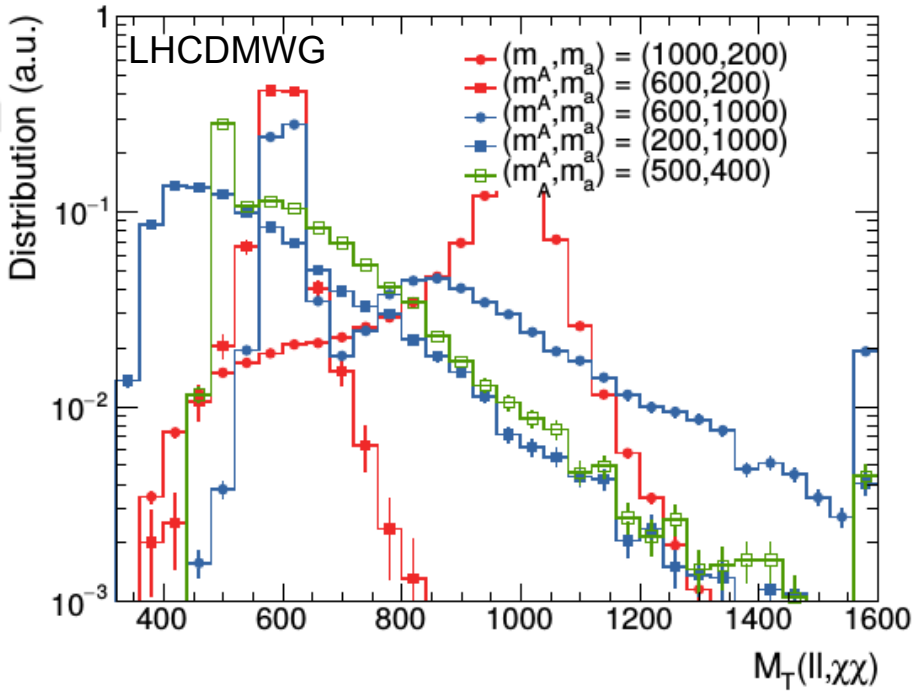
Signal can be separated from background by fitting the shape of E_T^{miss}, or $P_T(h/Z)$, or $M_T(h/Z,E_T^{miss})$

Information on the mass-difference $M_{A/H} - M_a$ can be obtained from the observed spectra

Kinematic distributions

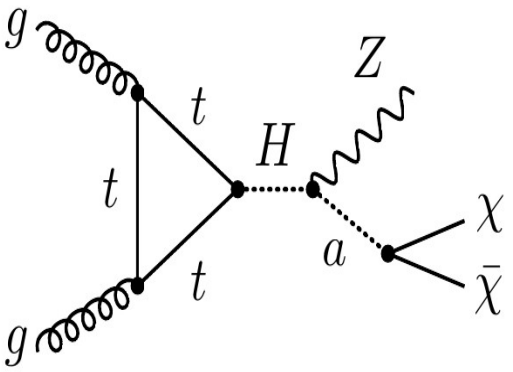
Parton level Z+DM: $H \rightarrow Z\, a,\ a \rightarrow \chi\chi$





$$M_T^2 = m_1^2 + m_2^2 + 2\left(E_{T,1}E_{T,2} - \vec{p}_{T,1}\cdot\vec{p}_{T,2}\right)$$

LHCDMWG proposal: main plane for comparison is (M_S, m_a) for different S=H,A,H+, highlighting the dependence of the experimental reach from 2-body decay kinematics



H decay: Z+DM

Two decay modes considered:

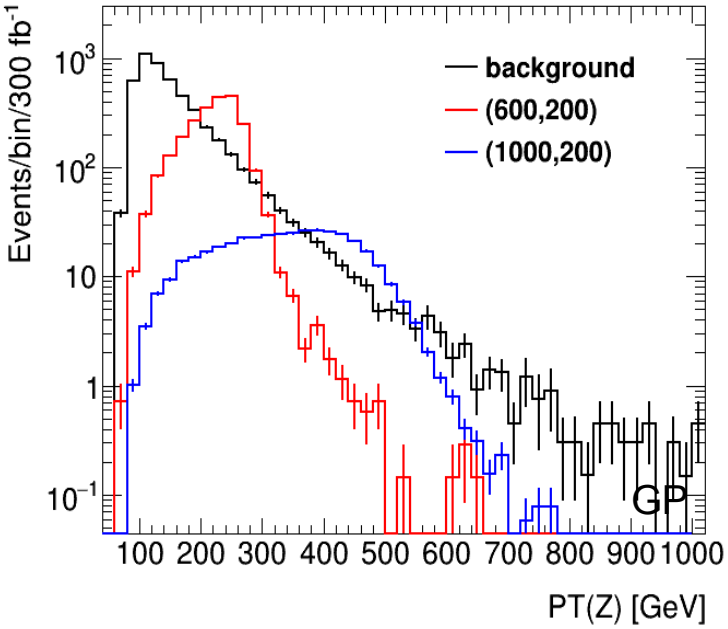
Z → leptons

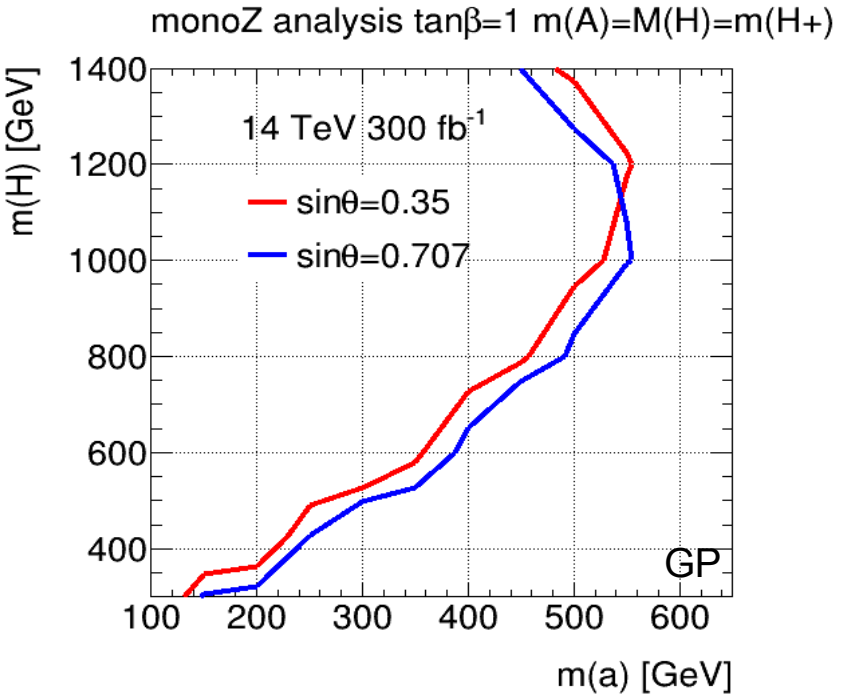
Z → hadrons

For Z → ll: shape fit on $P_T(Z)$ show smeared particle-level study

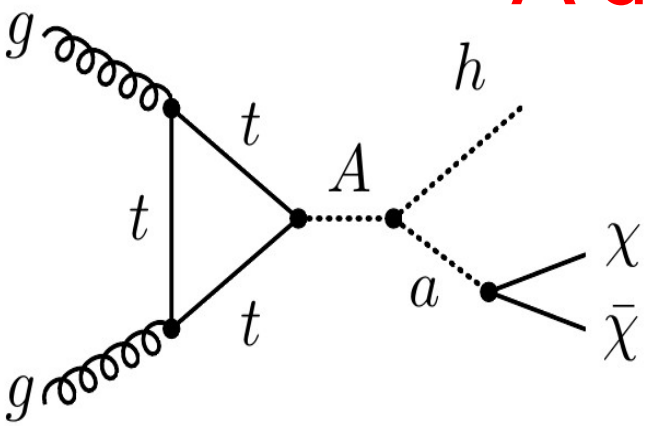
Similar sensitivity for sinθ 0.35 and 0.7

Preliminary





A decay: h+DM



Three possible h decays to consider:

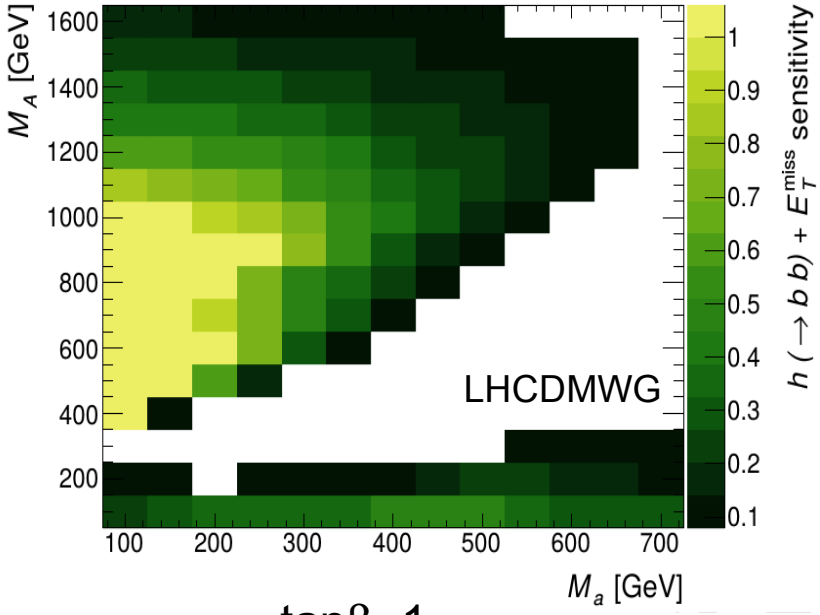
h → bb BR: 0.58

h → γγ BR: 0.00227

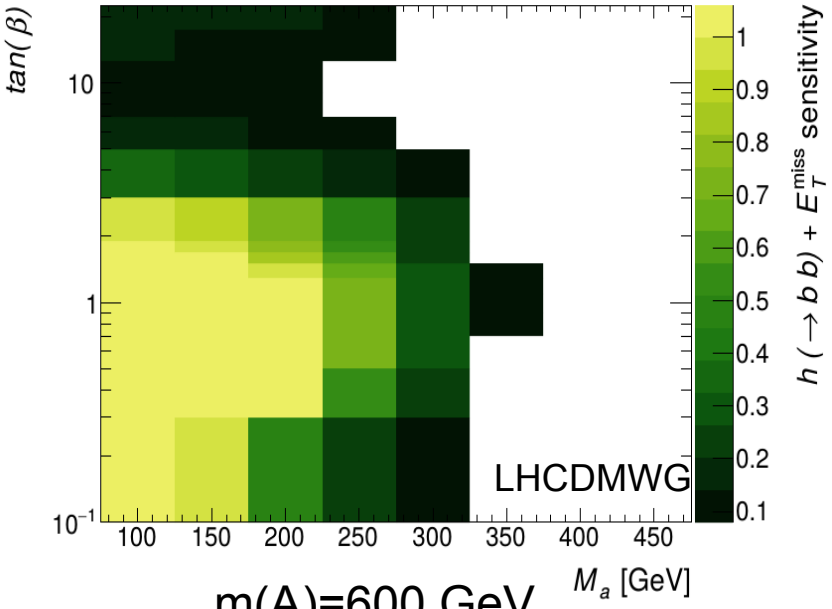
h → WW* → llνν BR: 0.214*0.047 (e,μ)

no mass peak

From LHCDMWG h → bb reach in for sinth=0.35 parton level, 13 TeV 40 fb^{-1}



tanβ=1



m(A)=600 GeV

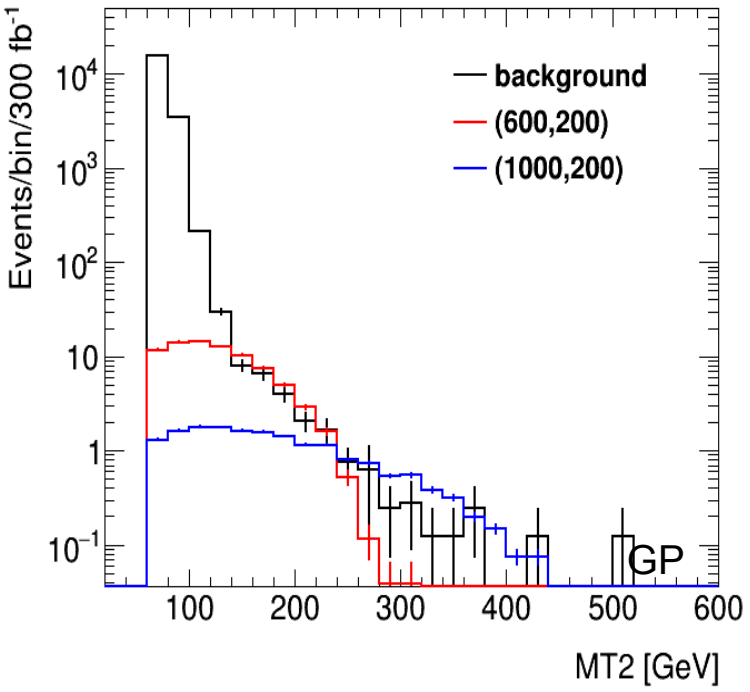
A decay: h+DM (2)

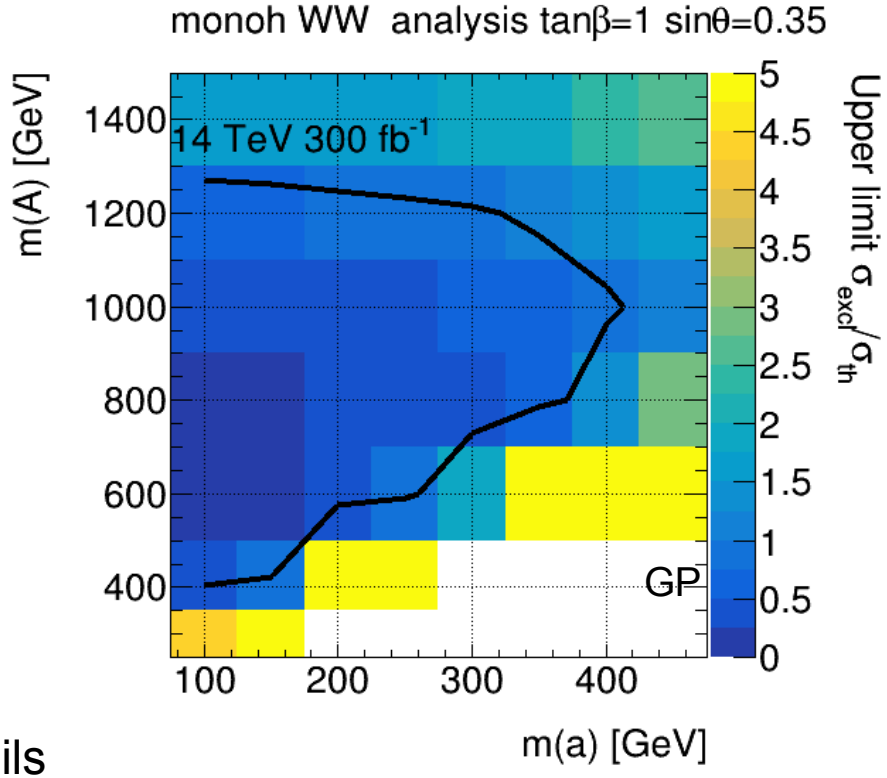
Use decay chain $h \rightarrow WW^* \rightarrow ll\nu\nu$

Evaluate reach based on smeared particle level simulation

Shape fit on the M_{T2} variable built with 2 leptons and E_T^{miss}

Preliminary



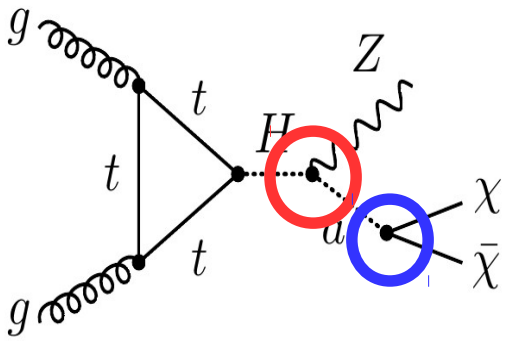


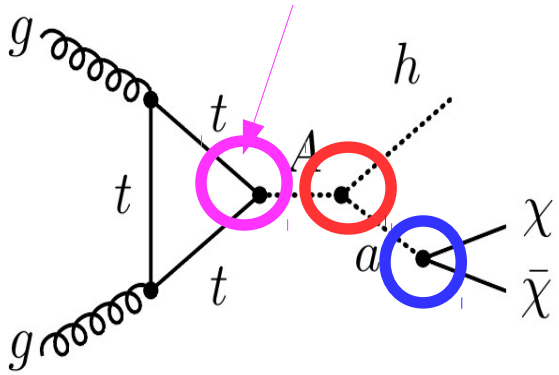
Background dominated by WW tails

Study being documented

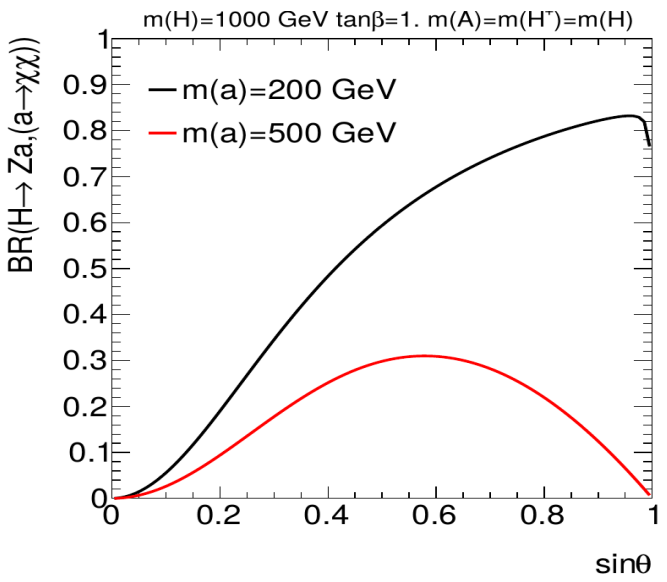
Sinθ dependence: DM+Z and DM+h resonant

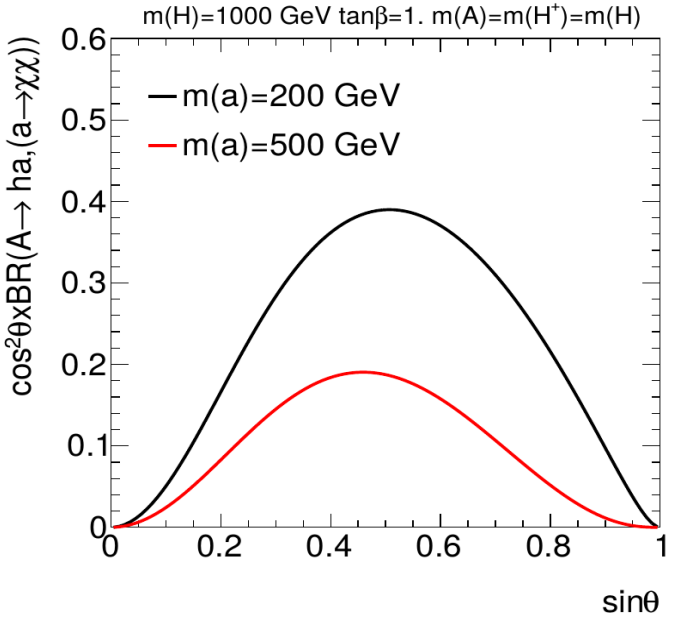
A production vertex proportional to $\cos\theta^2$





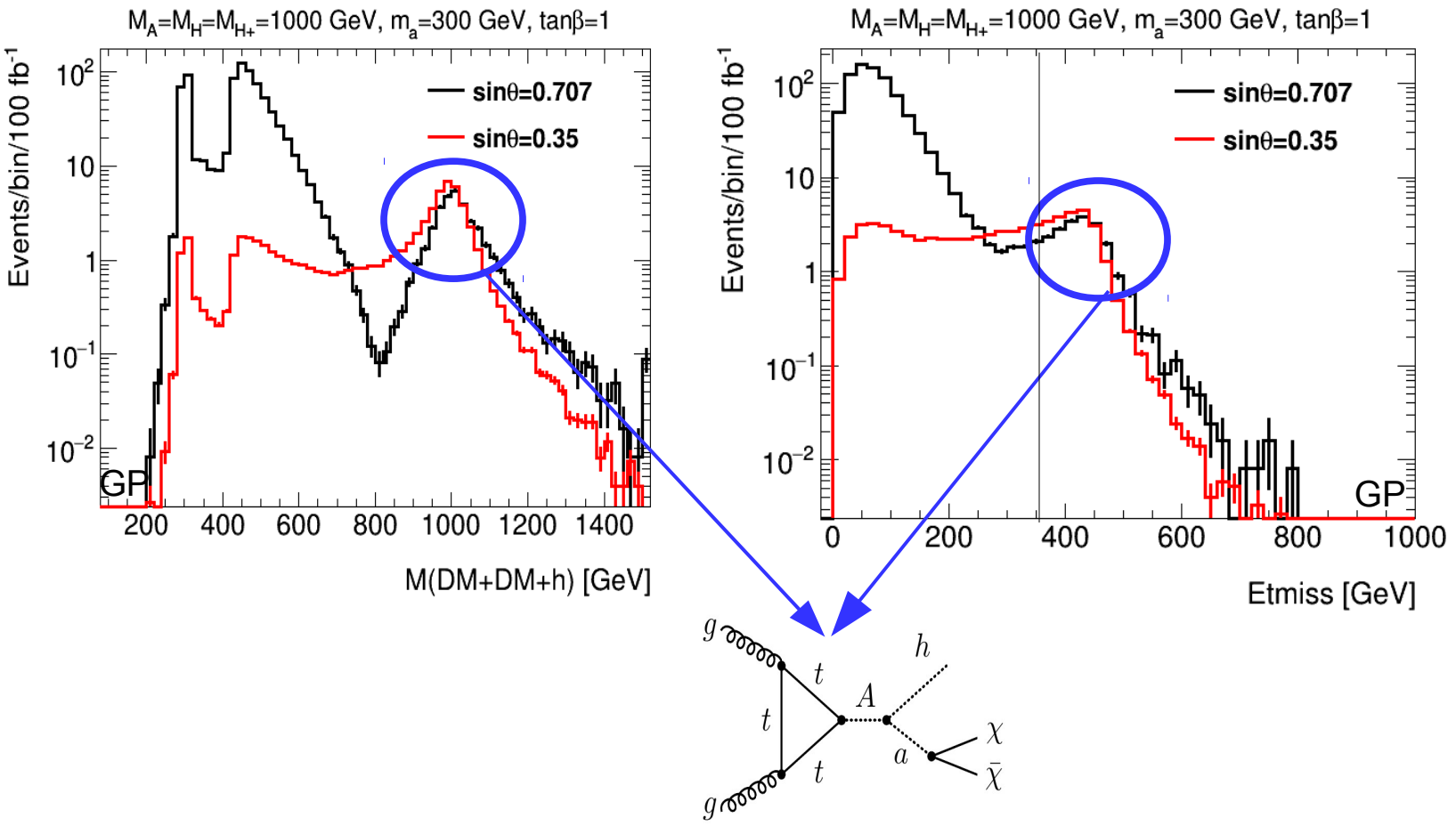
For tanβ=1 BR(a → χχ) only depends from θ if channel a → tt open





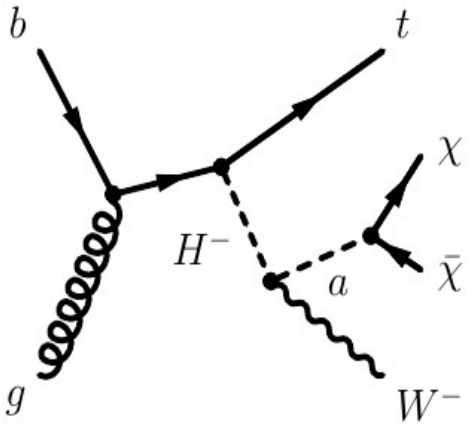
But resonant diagrams are not the full story....

h+DM: Non-resonant contibutions vs sinθ



For h → bb analysis, sensitivity dominated by region with E_T^{miss}>350 GeV, no acceptance for 'softer' contributions

H^+ decay: tW+DM



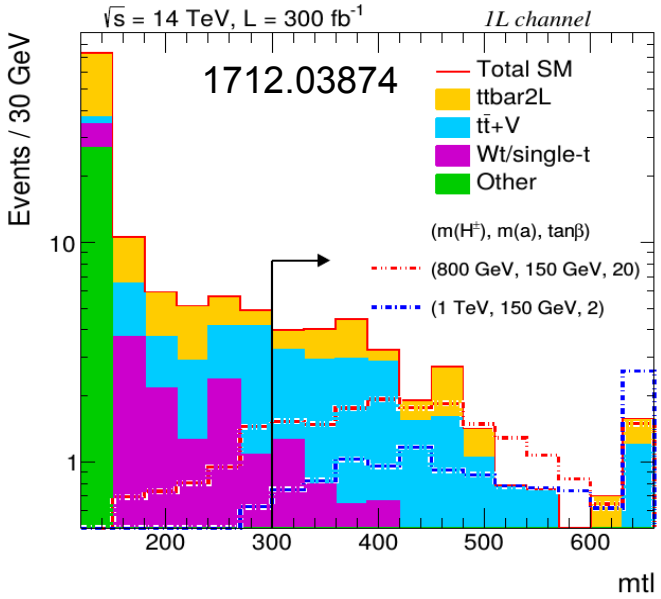
Channel proposed in https://arxiv.org/abs/1712.03874
(see also talk by P.Pani in open session)

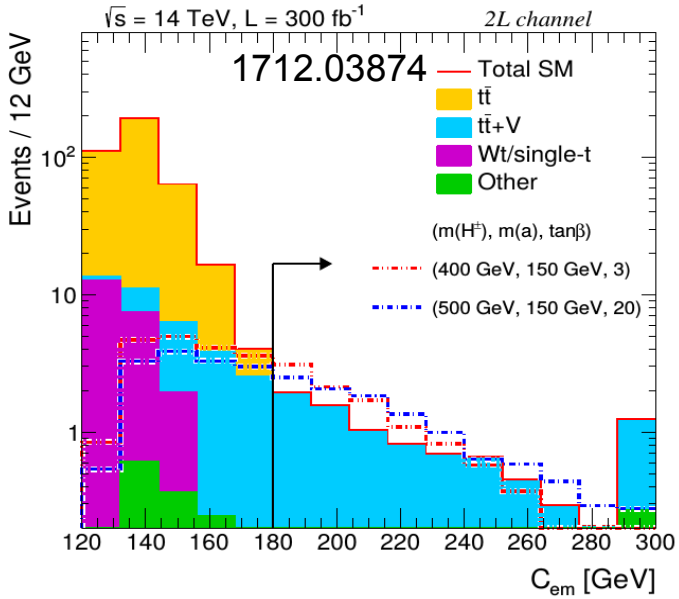
Two final states:

1 lepton + 3 jets (1b) + Etmiss

2 leptons + 1 b-jet + Etmiss

Dominant backgrounds: tt, ttZ ($Z \rightarrow \nu\nu$)





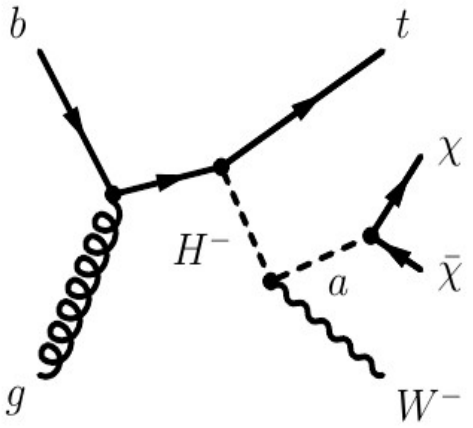
Key discriminants: 1l: transverse mass lepton, E_T^{miss}

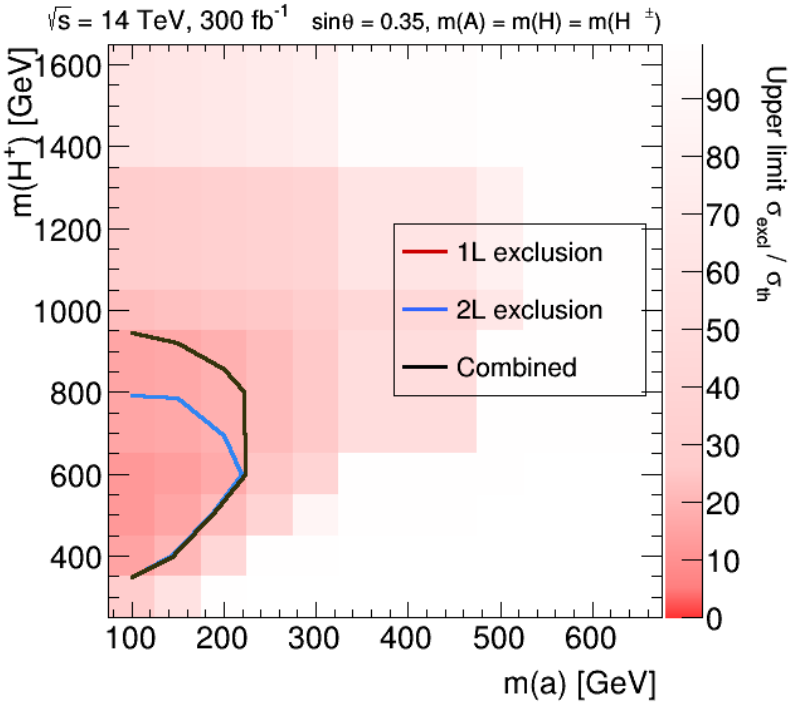
2l: $M_{T2}+0.2*E_T^{miss}$

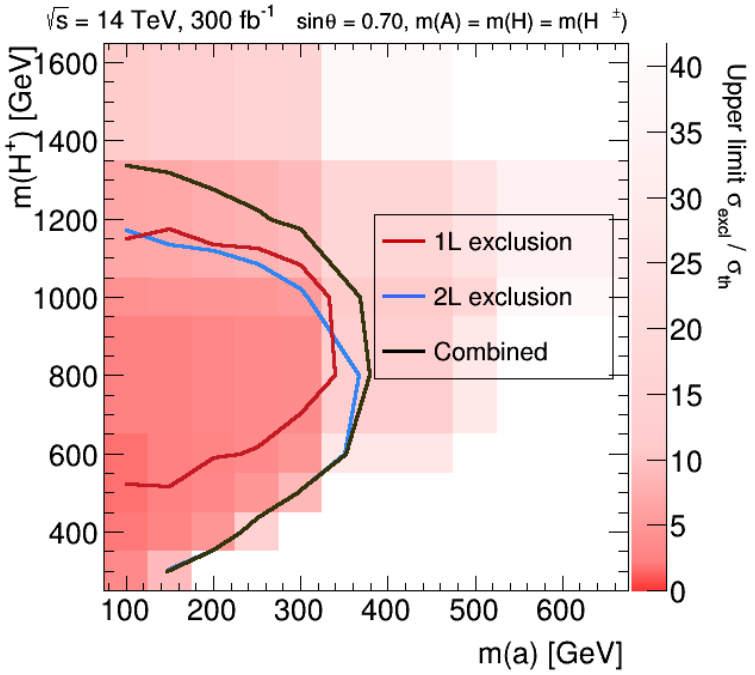
H+ decay: tW+DM (2)

Two-lepton final state dominates at low m_{H+} because of softer kinematic requirements.

Observe strong sinθ dependence

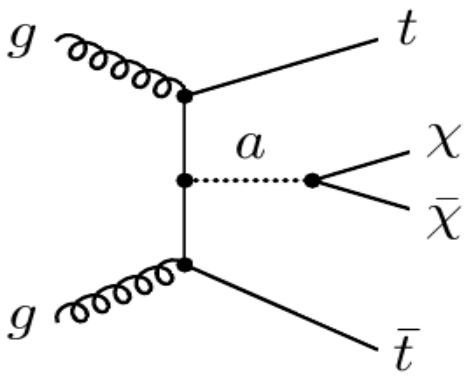


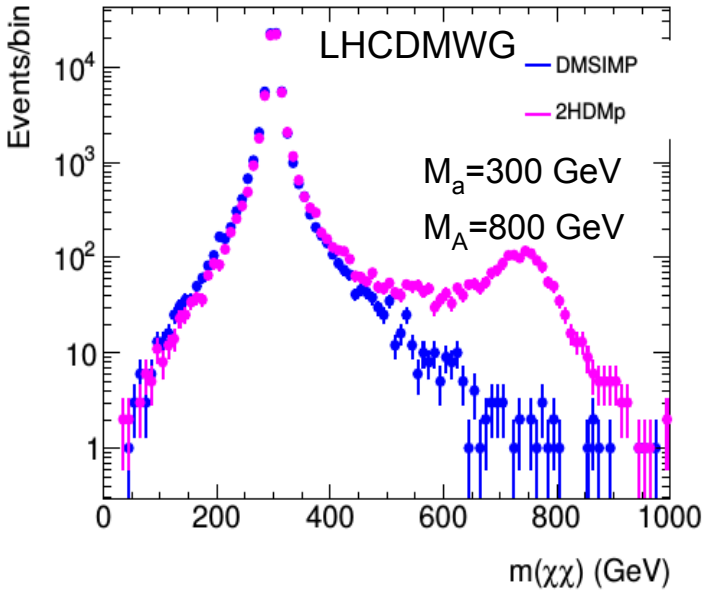




New plots based on analysis in https://arxiv.org/abs/1712.03874

tt+DM signatures





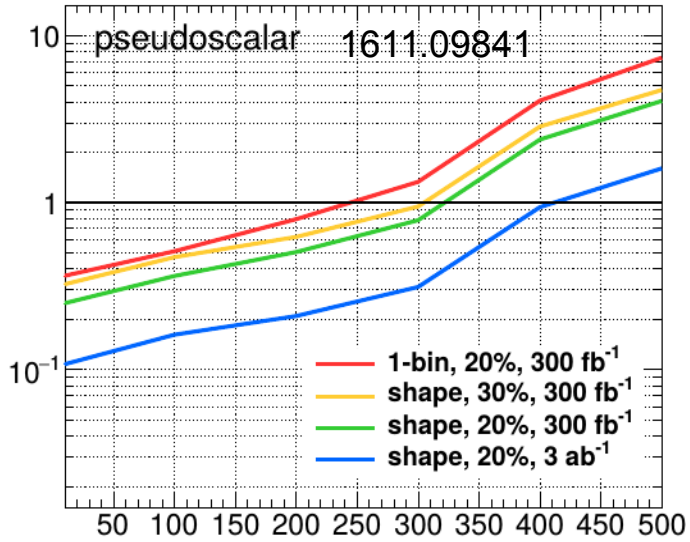
No new decay diagram involved wrt simplified model, but both a and A may decay into DM

Implications:

a) can recast avaible DM+tt results

b) for each (m(a), m(A)) configuration need to take into account also A decay by rescaling of acceptances

$$Acc_{2HDM}(m(A), M(a)) = \frac{\sigma_a \times Acc_{DMSIMP}(m(a)) + \sigma_A \times Acc_{DMSIMP}(m(A))}{\sigma_a + \sigma_A}$$



Exercise: recast results on simplified model presented in https://arxiv.org/abs/1611.09841

tt+DM signatures

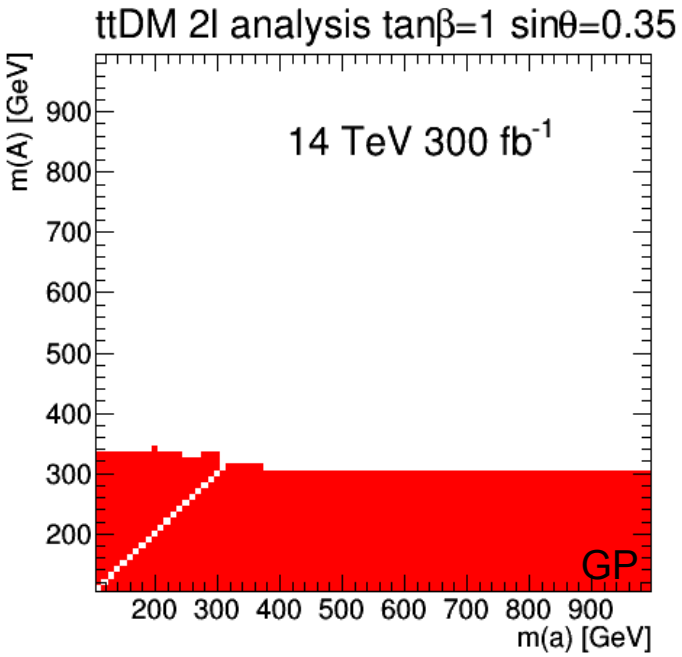
Recasting results at tanβ=1

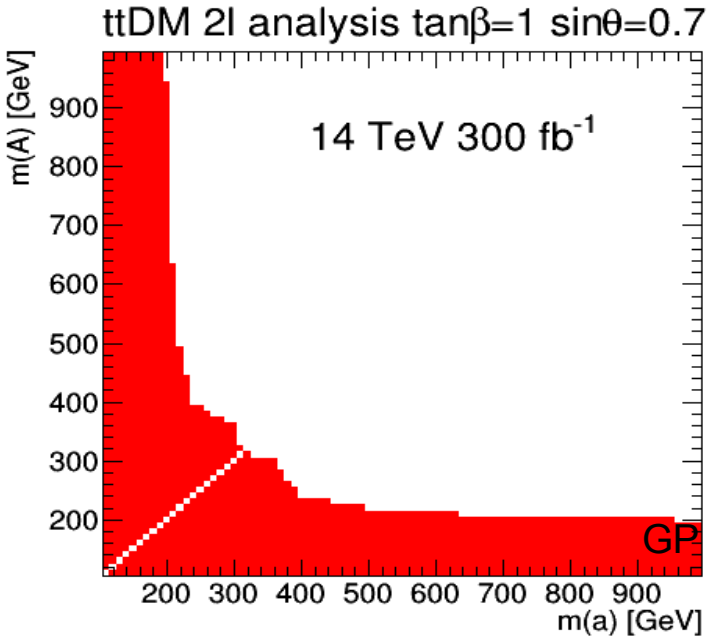
For sinθ = 0.35 sensitivity only from DM production through A

For sinθ=0.7 symmetric contribution of a and A

Complements for m(A)~m(a) sensitivity of resonant decays

Complementary coverage to X+DM for m(A)<m(a)





tanβ dependence

Studies from https://arxiv.org/abs/1701.07427

Left plot: M_A=750 GeV, right plot M_H=750 GeV: no M_A=M_H=M_{H+} condition

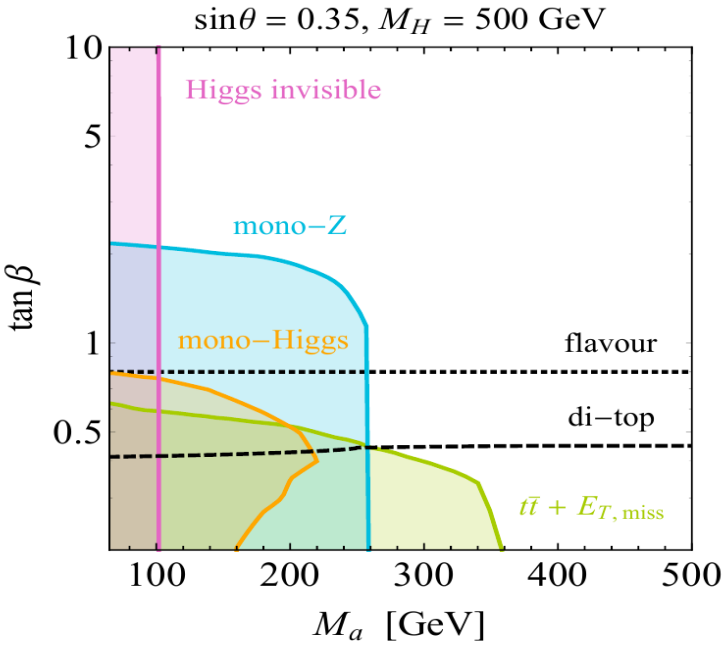
Assume 13 TeV 40 fb^{-1} for mono signatures and 300 fb^{-1} for ttDM

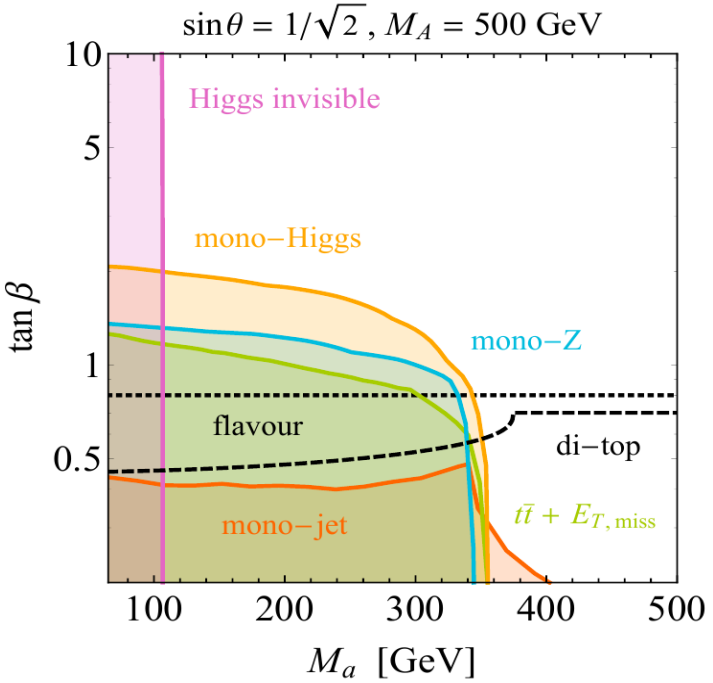
Production cross-section dominated by couplings to top

Type II 2HDM: production cross-section goes as $\cot\beta^2$

Reach in tanβ < 5 even at high luminosity

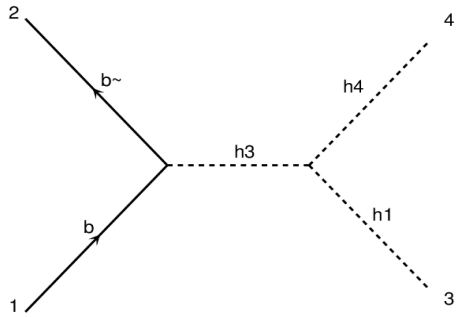
Cutoff in m(a) sensitivity determined by opening of decays: H → aa, a → ttb

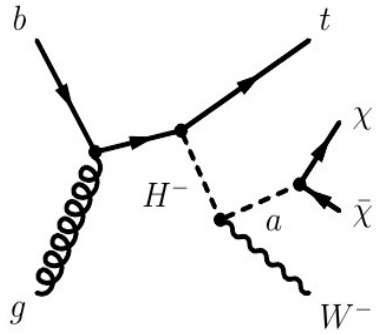




Covering the high tanβ region

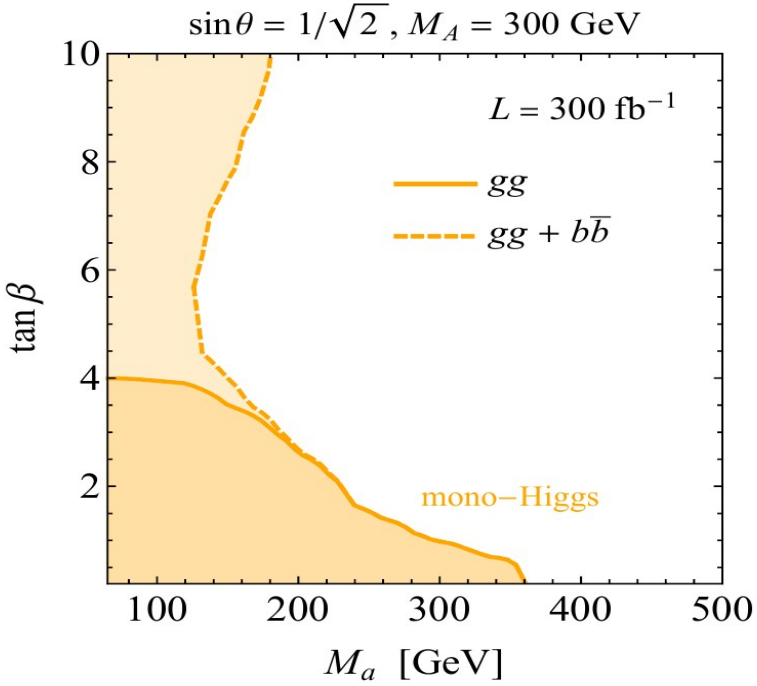
Consider processes with b-quarks in initial state

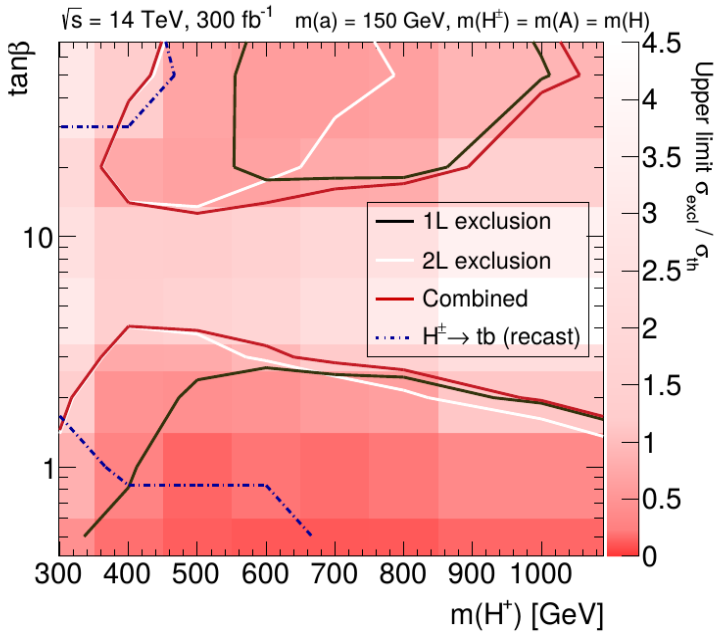




From https://arxiv.org/abs/1701.07427

From https://arxiv.org/abs/1712.03874





Possible contribution also from bbDM, but experimentally difficult channel

Additional signatures

In 2HDM+a models several more signatures conceivable, which may result in interesting LHC searches. Examples:

Consider ttA and ttZ production + cascade to a like in DM+h & DM+Z

pp → ttH → ttaZ → ttZ+DM

pp → ttA → ttah → tth+DM

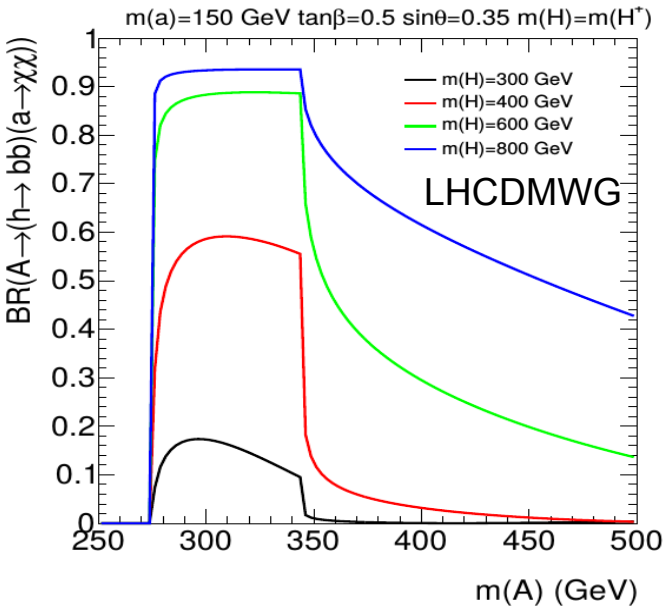
Low cross-section signatures, may be useful at high lumi in difficult regions

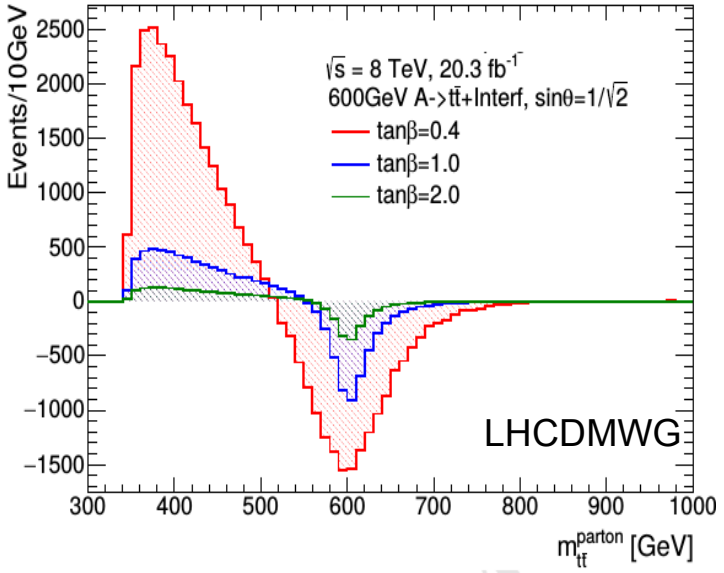
For m(higgs)> 2* m(t) a/A may decay into tt: peaks in tt invariant mass.

Need correct treatment of interference with SM

pp → A/a/H → tt

pp → ttA/a → tttt



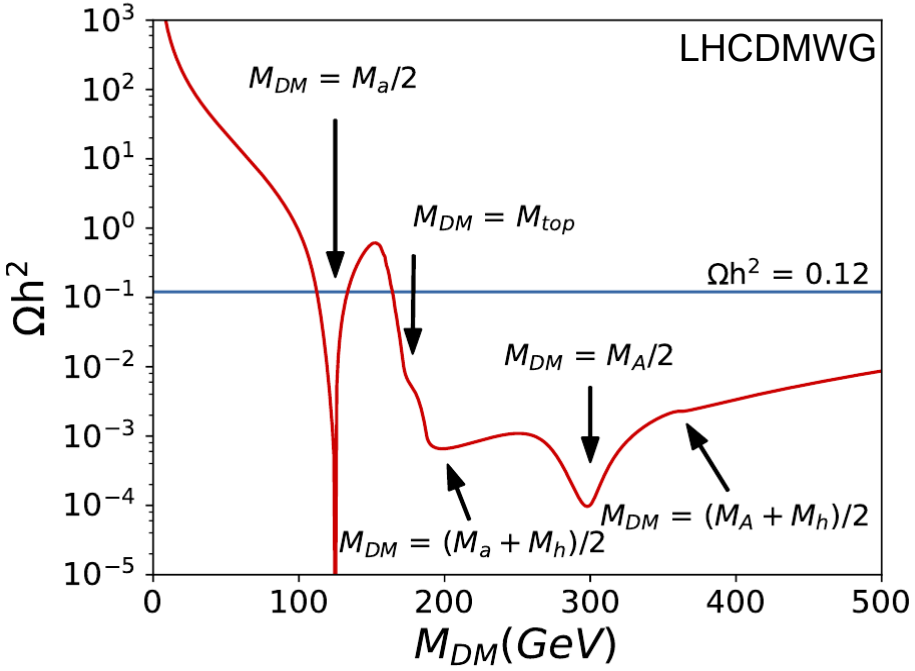


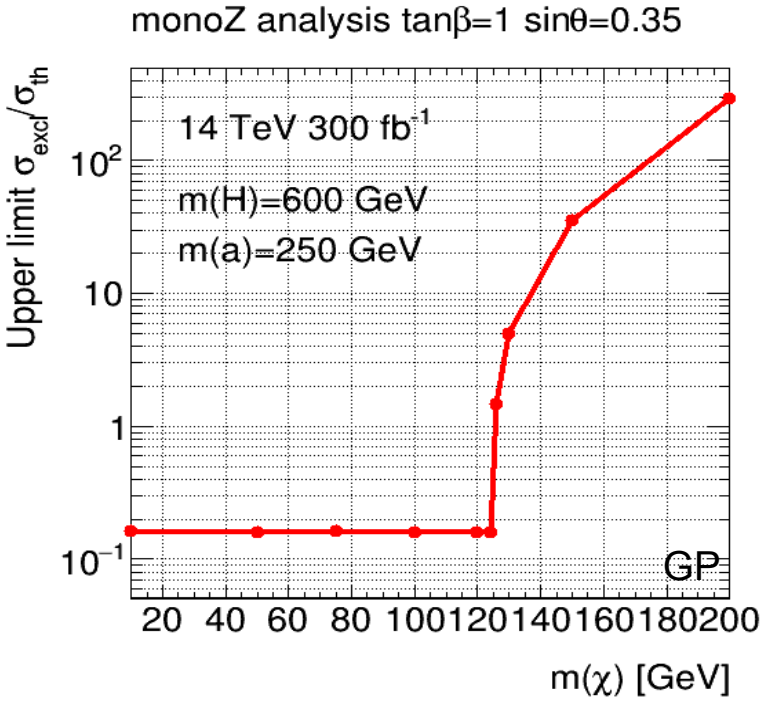
Dependence on m_χ

All studies performed for m(χ)=10 GeV

If model only includes new bosons and χ, relic density measurements require m(χ)>100 GeV

Sensitivity drops quickly when m(χ)>2*m(a) and/or m(χ)>2*m(A) (depending on signature, relative mass hierarchy and sinθ)





Conclusions

One of the directions of DM studies @ Colliders is the evolution of simplified models towards realistic models

2HDM+a model chosen as a benchmark to evaluate LHC potential

The presence of a hierarchy of Higgs particles boosts the sensitivity of known signatures, and provides new ways for looking for DM at the LHC

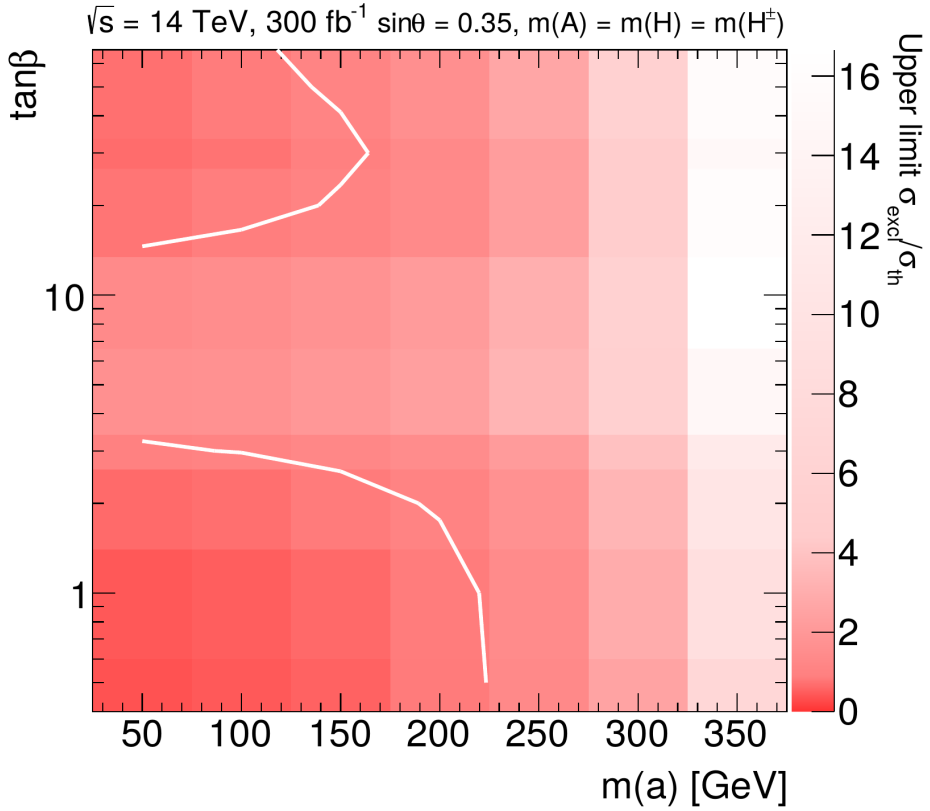
A significant part of the parameter space of the model is very likely covered by existing searches

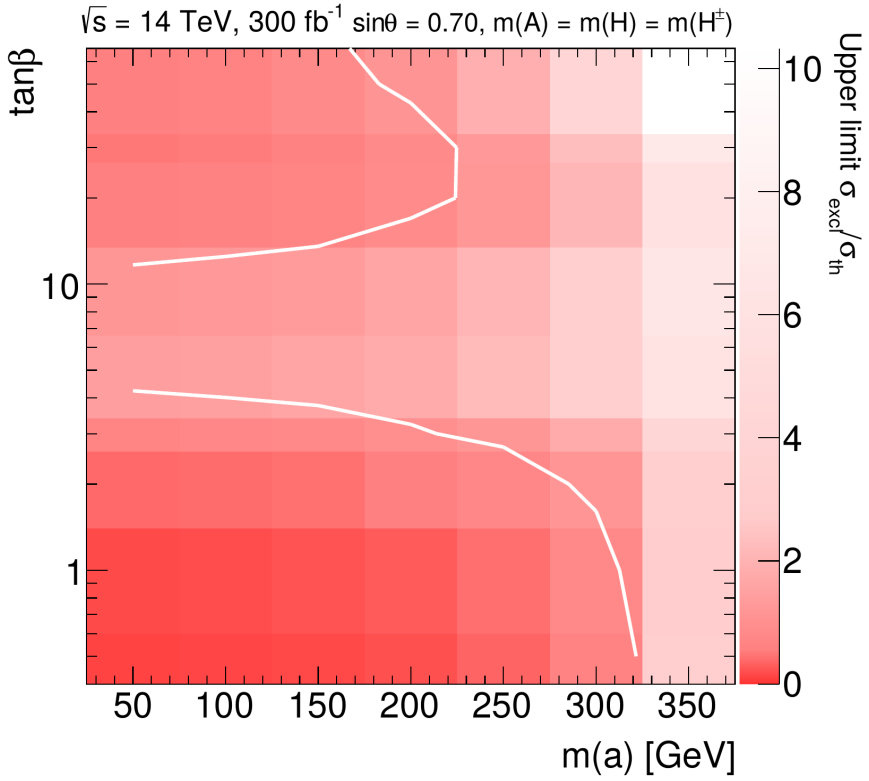
Very promising coverage with higher statistics

Concentrated work by the LHCDMWG aimed at providing a solid intellectual framework for a dedicated search campaign based on the LHC data from Run2 and Run3

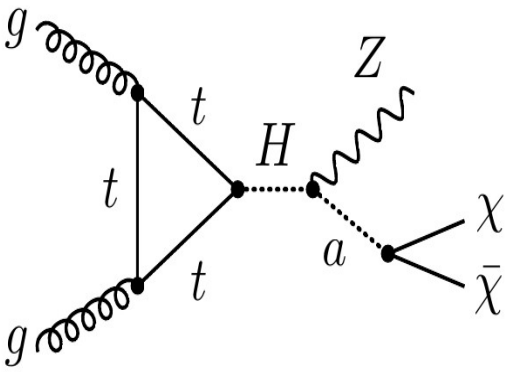
Backup material

m(a)-tanβ plane for pp → H^+t





Two-lepton analysis – m(A)=500 GeV



H decay: Z+DM

Two decay modes considered:

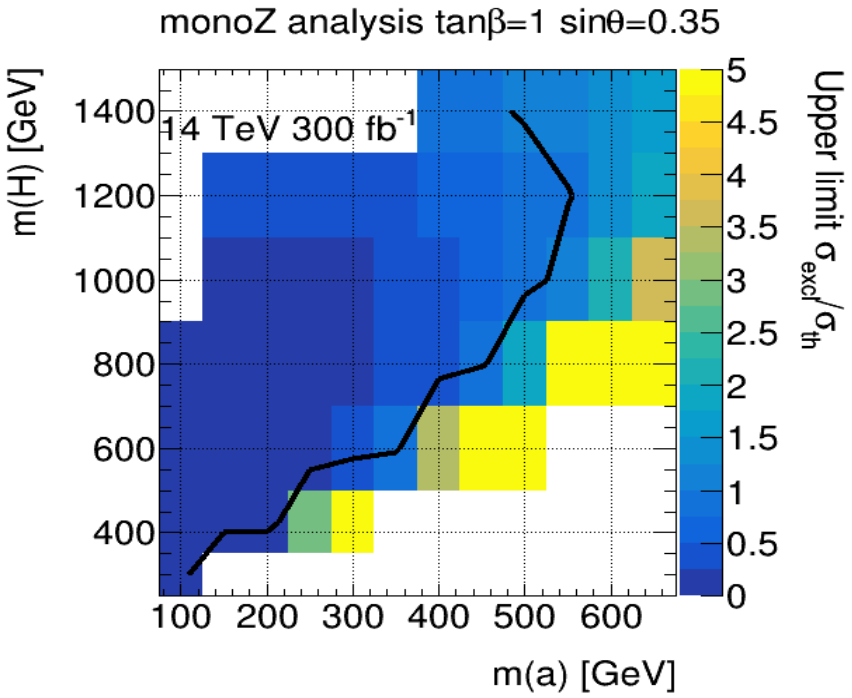
Z → leptons

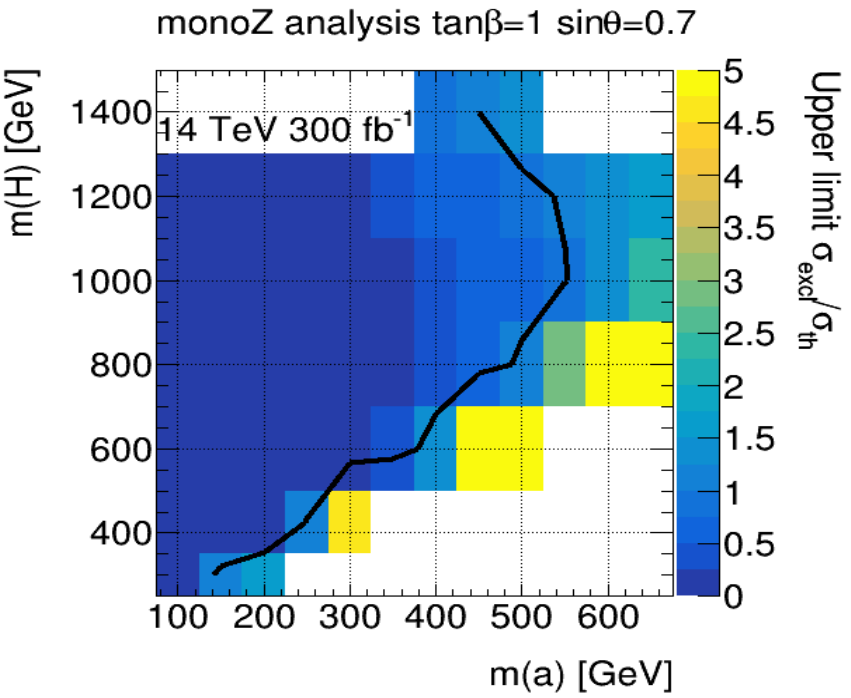
Z → hadrons

For Z → ll: shape fit on $P_T(Z)$

Sensitivity very similar for sinθ 0.35 and 0.7 when m(a)>2*m(t)

sinθ=0.7 much more sensitive for m(a)<2*m(t)





Monojets