2HDM+a mono-h studies at ATLAS: Summary and Vacuum Stability

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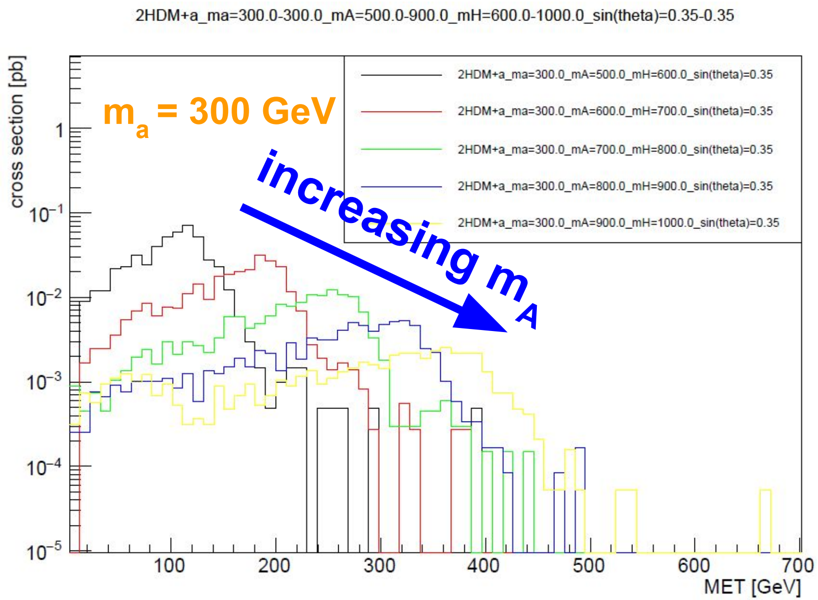
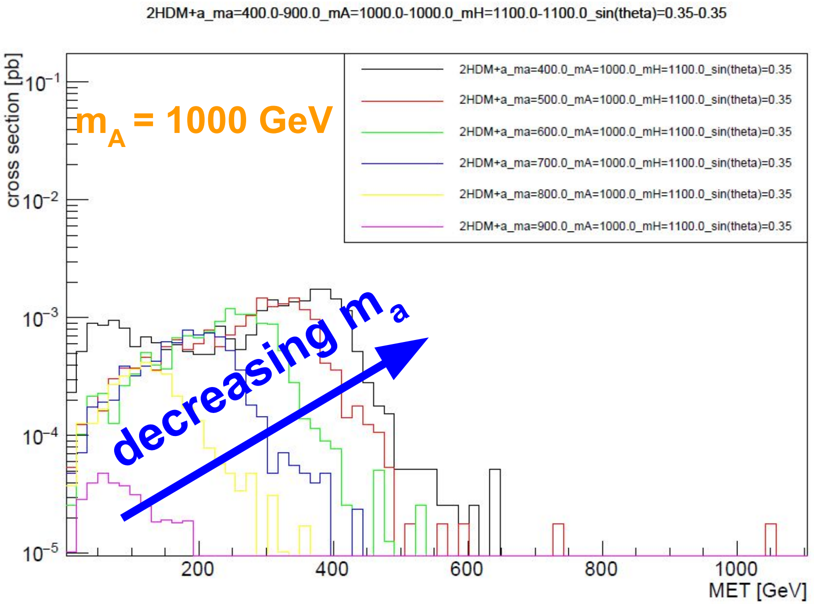
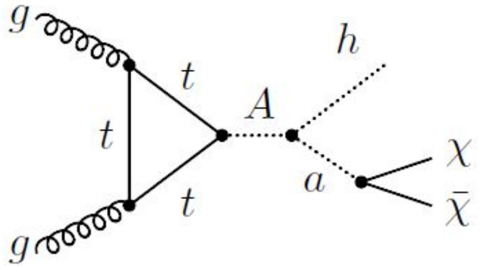
Signal Kinematics: Mediator Masses



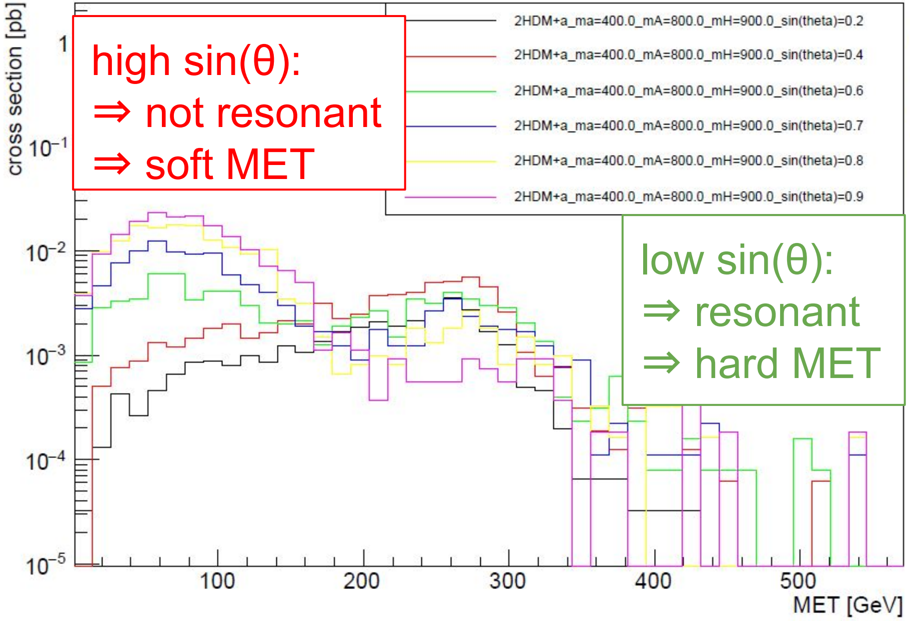


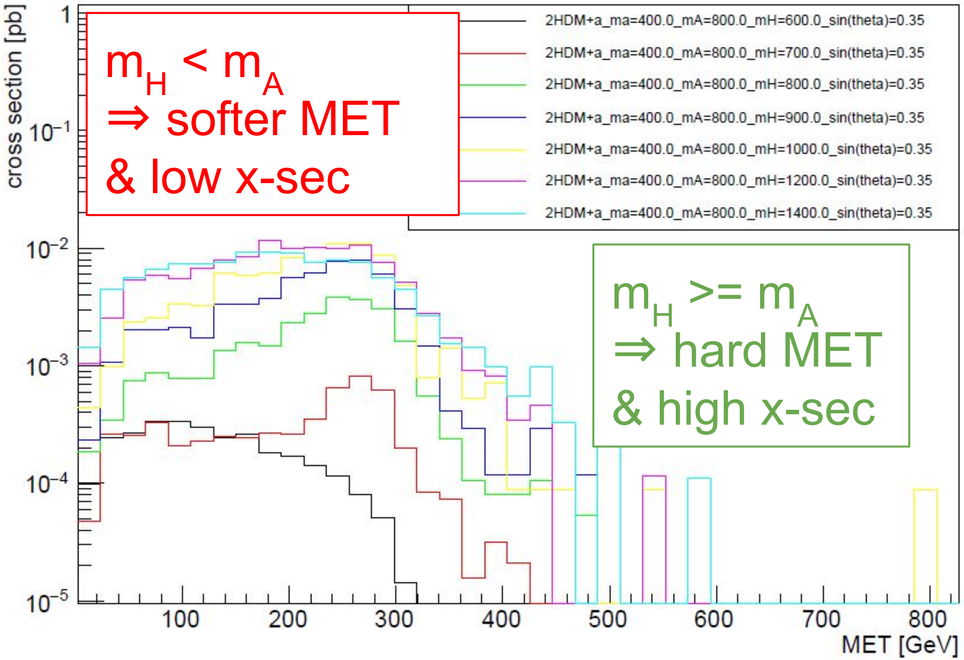


- goal: benchmark with wide variety of signatures
- m_a and m_A dominant effect on signal shape
  - ⇒ make signal grid a mass grid

more detailed slides

$\sin(\theta) = 0.35$ and $m_H - m_A = 100$ GeV ⇒ Jacobian Peak for hard MET

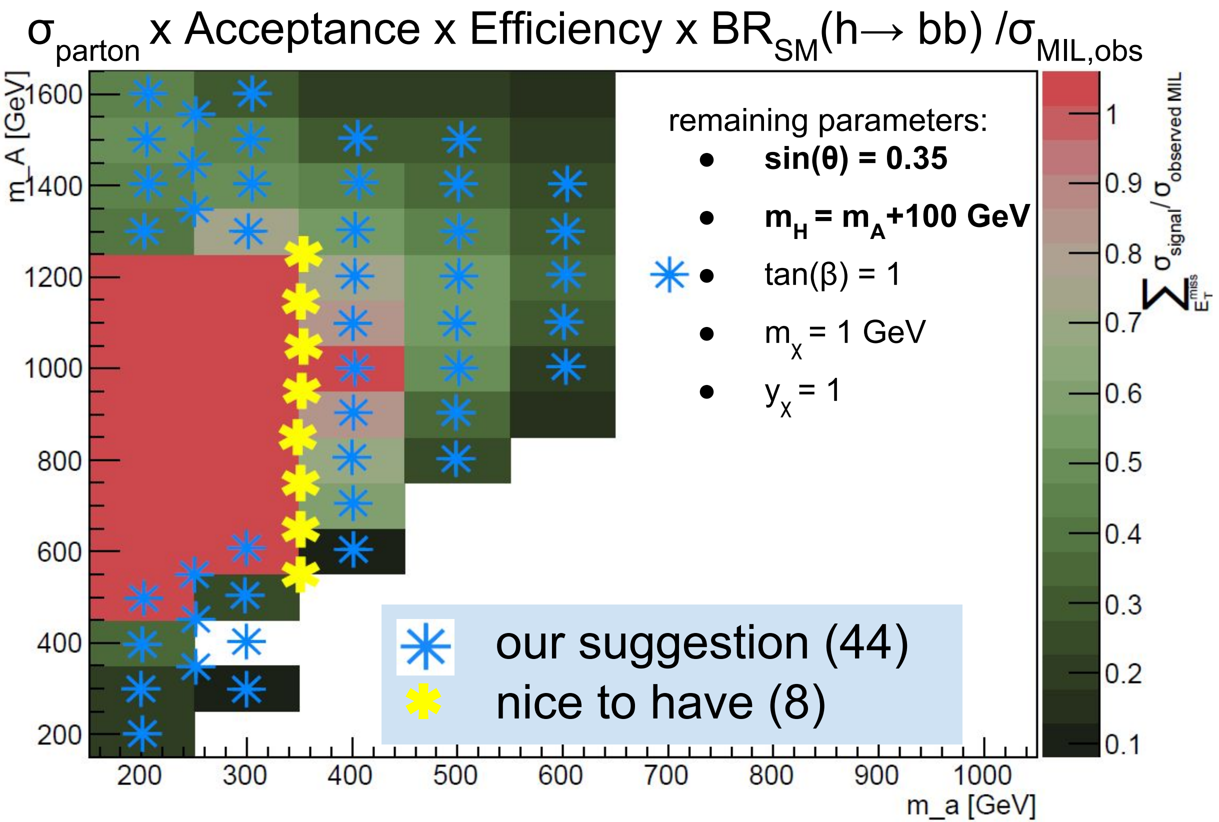




$$\Gamma(A \to \chi\chi) \propto \sin^2\theta \qquad \Gamma(a \to \chi\chi) \propto \cos^2\theta$$
$$\Gamma(A \to ff) \propto \cos^2\theta \qquad \Gamma(a \to ff) \propto \sin^2\theta$$
$$\Gamma(A \to ah) \propto \sin\theta\cos\theta$$

$$g_{Aah} = \frac{1}{M_A v}\Big[M_h^2 - 2M_H^2 - M_A^2 + 4M_{H^\pm}^2 - M_a^2 - 2\lambda_3 v^2 + 2\left(\lambda_{P1}\cos^2\beta + \lambda_{P2}\sin^2\beta\right)v^2\Big]\sin\theta\cos\theta\,,$$

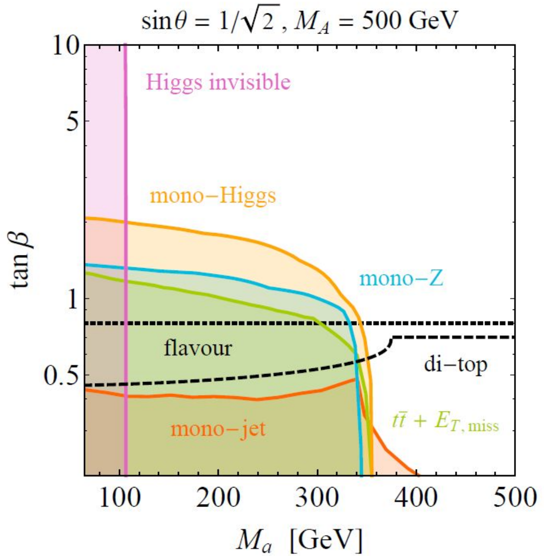
Grid proposal for generating MC

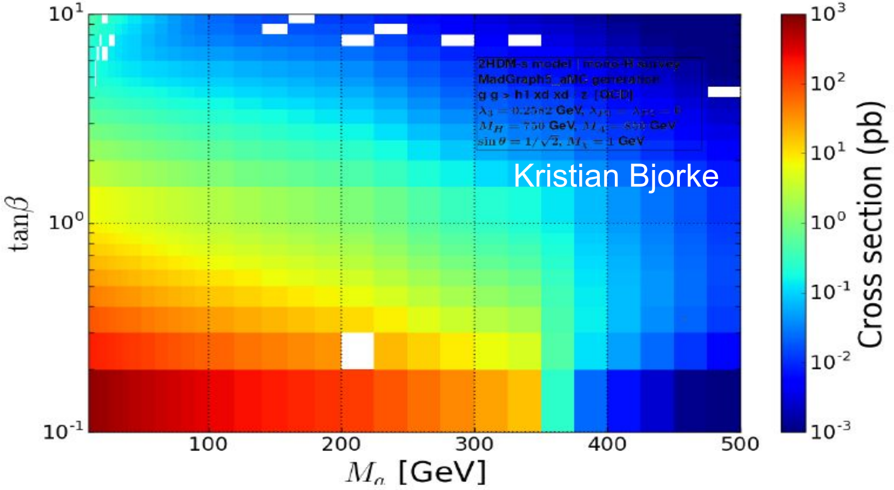


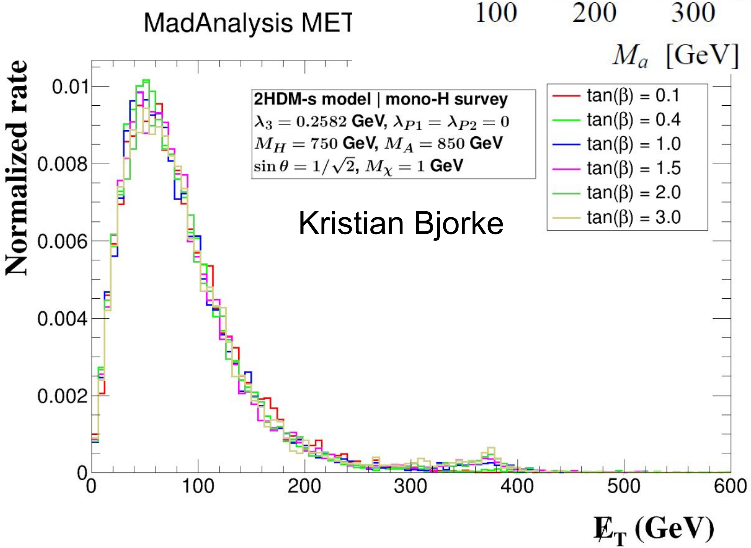
- mass grid to generate MC:
  - large variety of h+MET signal shapes
- $m_H \sim m_A \Rightarrow$ interesting for Z+MET(see Koji's Talk)
  - similar signal shape variety
  - exact value of m_H-m_A less important for Z+MET
- plot tan(β) vs. m_a:
  - take a slice in $m_A(m_H)$
  - rescale in tan(β) (> 0.8)
  - in line with usual 2HDM limit plots

Benchmark 3, 4

- nice complementarity of many search channels:
    - h+MET
    - Z+MET
    - jet+MET
    - tt+MET
    - Di-top resonance
- generate MC (also for mono-h)
    - enable comparison to all channels



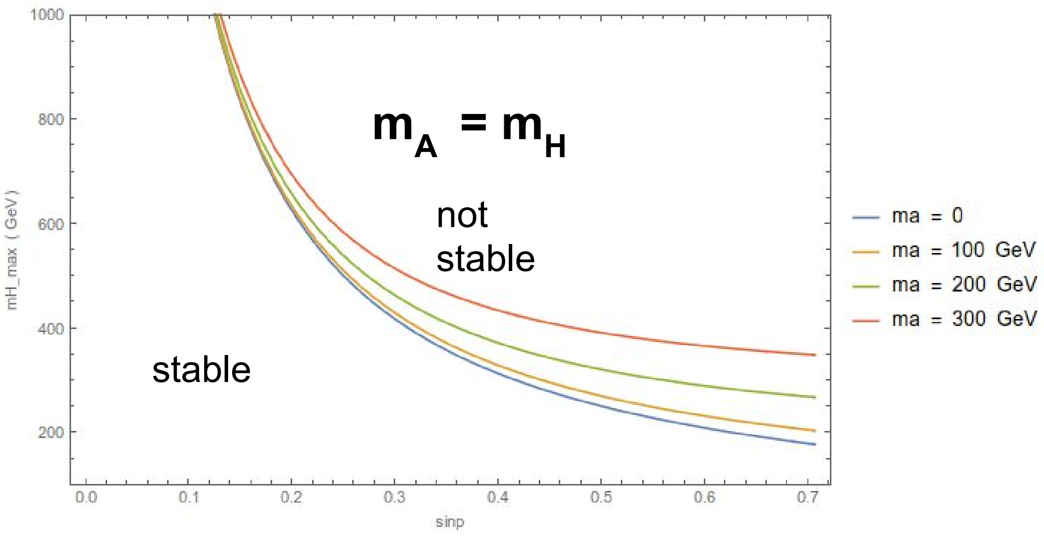




The Problem of Vacuum Stability

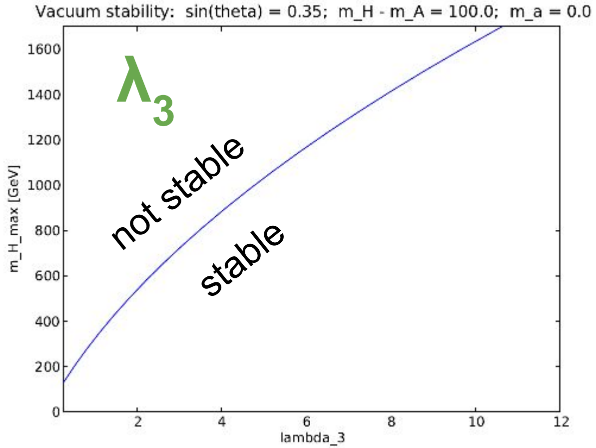
- Jose Miguel No pointed out:
  - $\lambda_3 = 0$ with $m_H = m_{H+-}$ gives unstable vacuum
    ⇒ unphysical!
  - recommendation: $\lambda_3 = (m_h/v)^2 \sim 0.258$
  - even with this choice of λ_3: still no stable vacuum
- affects both BM3 and m_a vs. m_A grid proposal!

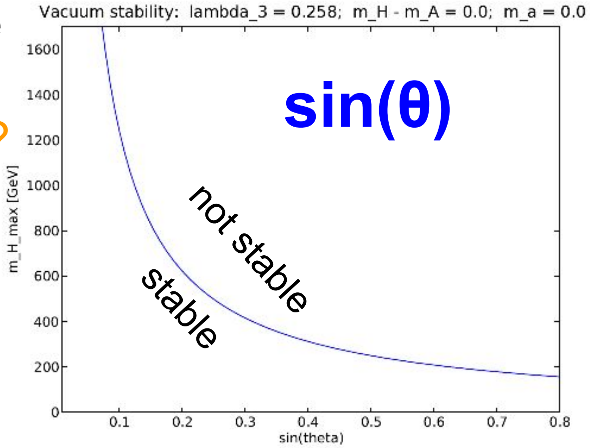
plot by Jose Miguel No:

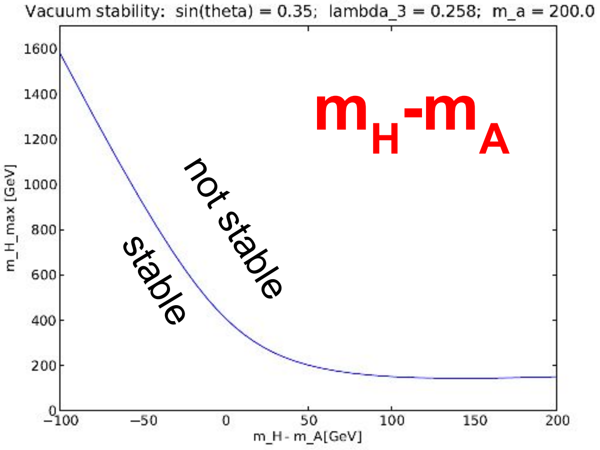


Different Approaches

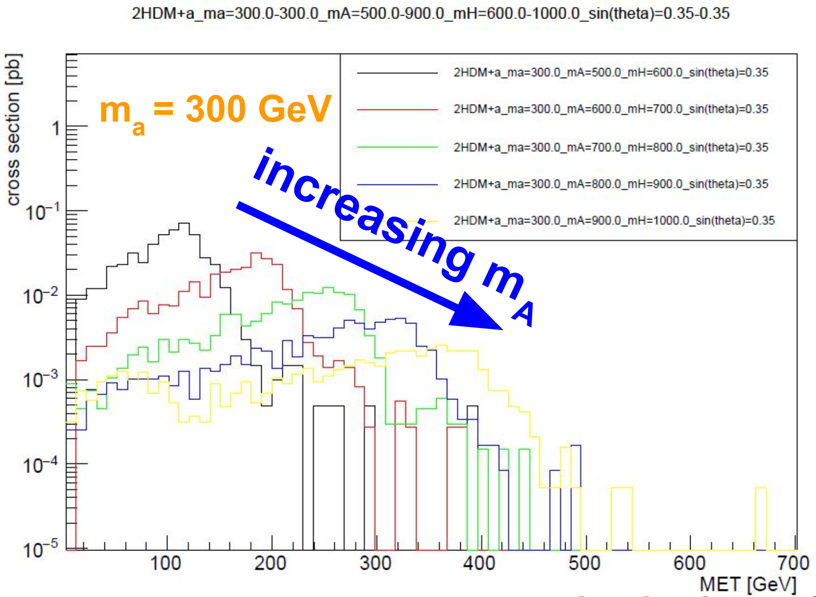
- even with $\lambda_3 = (m_h/v)^2$, we still get no stable vacuum
- ways to get stable vacuum:
  1. m_H-m_A lower
     → quickly lose signal xsec
     ⇒ avoid if possible
  2. sin(θ) lower
     → quickly lose signal xsec
     ⇒ avoid if possible
  3. λ_3 larger
     → effect on signal?

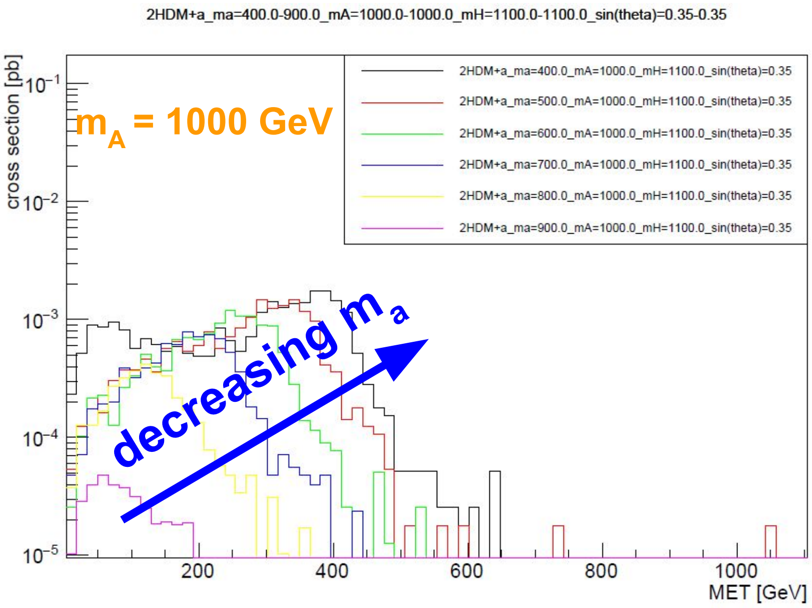






Reminder: $\lambda_3 = 0$, $m_H = m_A + 100$ GeV



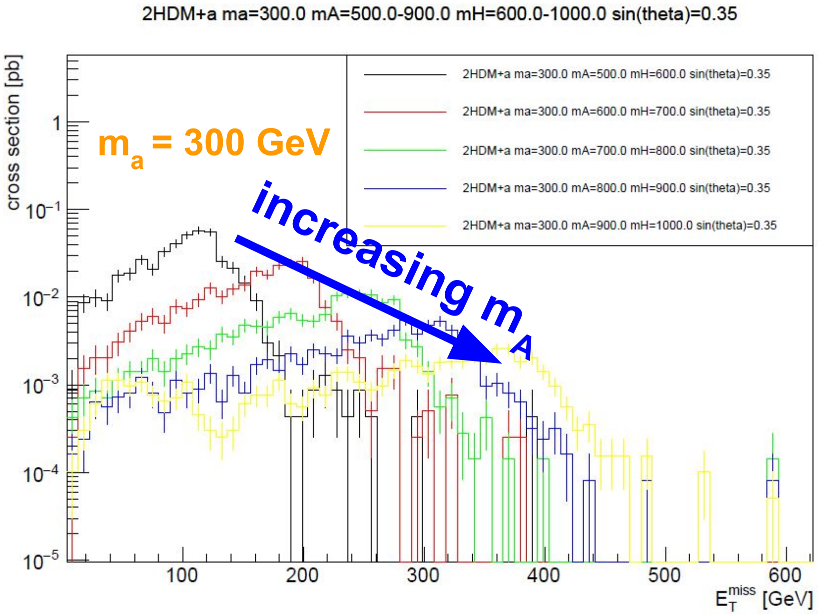


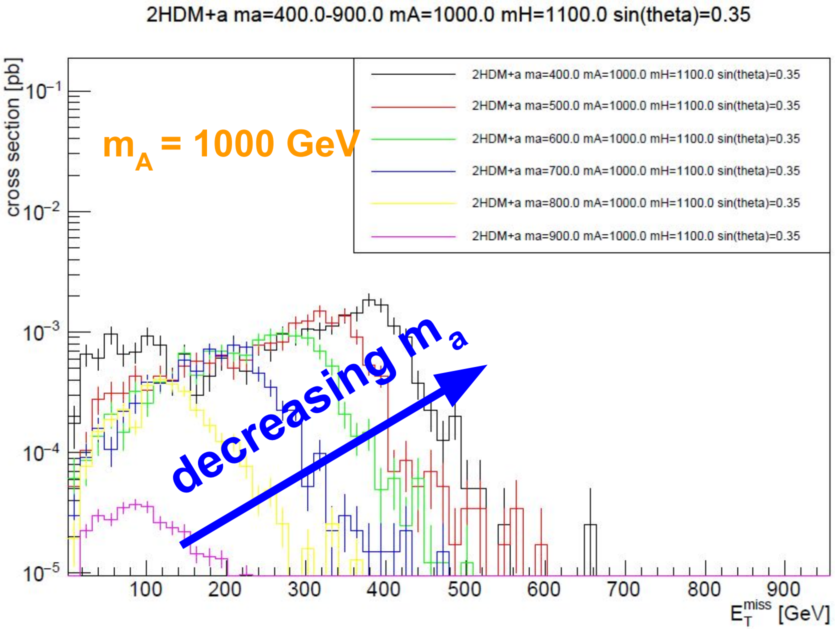
⇒ varied signal kinematics

⇒ measurable x-secs

⇒ clear trends when changing m_a & m_A

$\lambda_3 = (m_h/v)^2$, $m_H = m_A + 100$ GeV





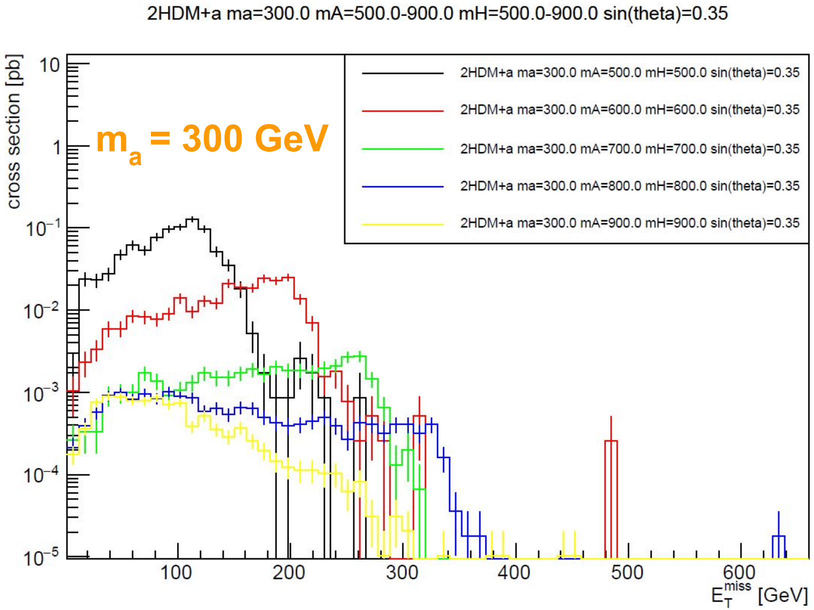
⇒ general picture unchanged

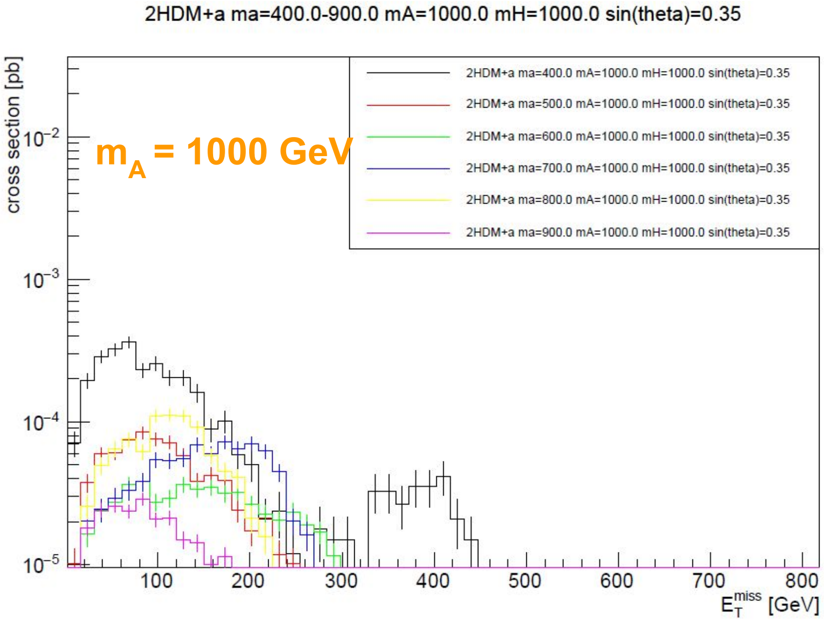
⇒ but no vacuum stability

softly-Z_2-breaking parameter in 2HDM Lagrangian

⇒ $\lambda_3 = (m_h/v)^2$ equivalent to choice of $(m_{12})^2 = m_A^2 \tan(\beta)/(1+\tan(\beta))^2$ in ATLAS 2HDM benchmark recommendations

$\lambda_3 = 6$, $m_A = m_H$



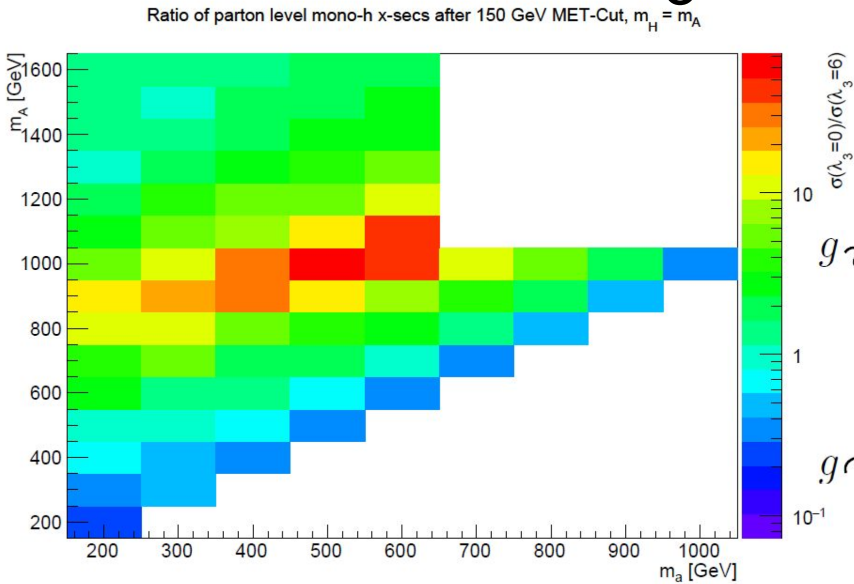


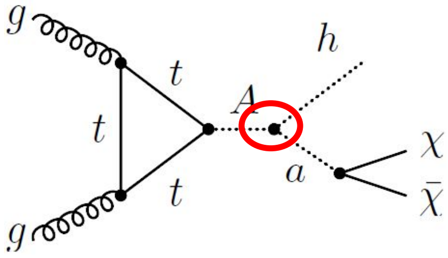
the vacuum is stable, but:

⇒ reduced variety of signatures with detectable xsecs

⇒ Complex, non-intuitive mass dependence

$\lambda_3 = 6, m_A = m_H$





possible solution:

$\lambda_{P1} = \lambda_{P2} = \lambda_3 = 3, 2\pi, 3\pi, \ldots$

- g_{Aah} unchanged (compared to $\lambda_{P1} = \lambda_{P2} = \lambda_3 = 0$)
- makes (large part of) mass grid stable
- changes g_{haa}
  - problem?

$$g_{Aah} = \frac{1}{M_A v}\left[M_h^2 - 2M_H^2 - M_A^2 + 4M_{H\pm}^2 - M_a^2 - 2\lambda_3 v^2 + 2\left(\lambda_{P1}\cos^2\beta + \lambda_{P2}\sin^2\beta\right)v^2\right]\sin\theta\cos\theta\,, \quad (4.12)$$

← does not affect Z+MET b.c. simpler A-a-Z vertex

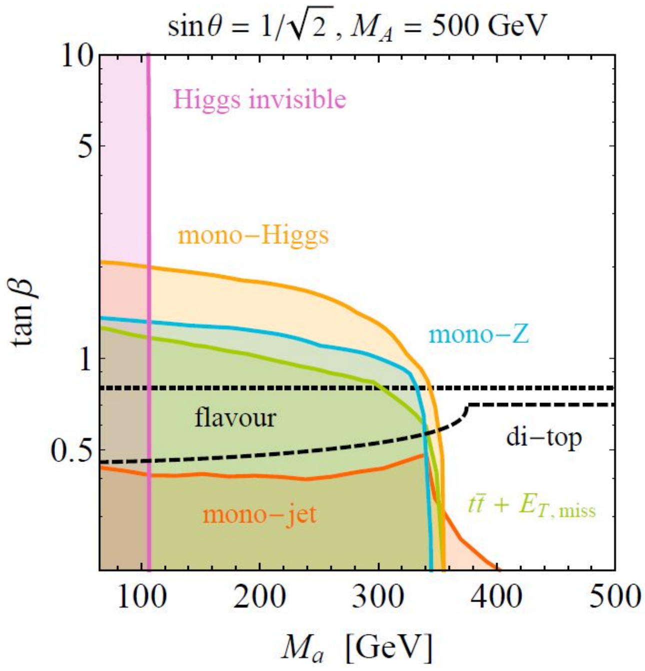
⇒ Complex, non-intuitive mass dependence

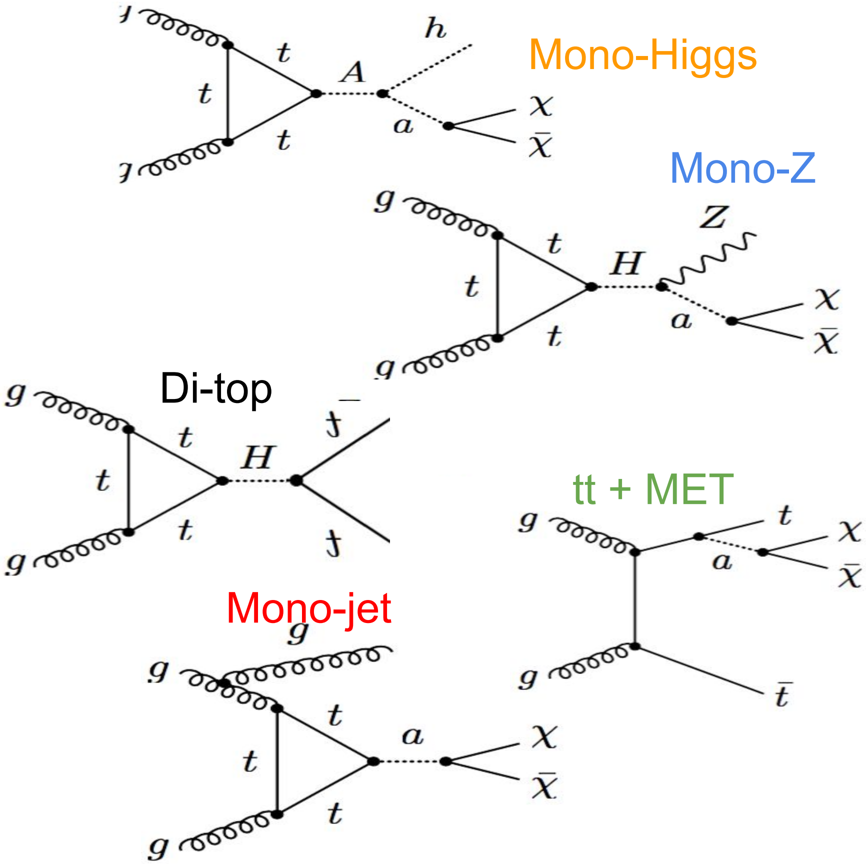
Summary

- m_a - m_A grid for producing diverse signal kinematics
  - high complementary with Z + MET since m_H - m_A fixed
  - reweight fixed m_A slice in tan(β) for plotting m_a vs. tan(β)
- generate points in m_a - tan(β) plane of BM3
  - for complementarity with all other search channels
  - reweight for high values of tan(β)
- lack of vacuum stability:
  - less important than diversity of signatures
  - not fixed by just $\lambda_3 = 0.2582 = (m_h/v)^2$
    - this choice of λ_3 would be equivalent to the recommendation for m_{12} in existing ATLAS 2HDM benchmarks
    - h+MET signal kinematics dependence on λ_3 is complex
  - $\lambda_{P1} = \lambda_{P2} = \lambda_3$ (= 3, 2π , 3π, ...) as simple solution?

Backup

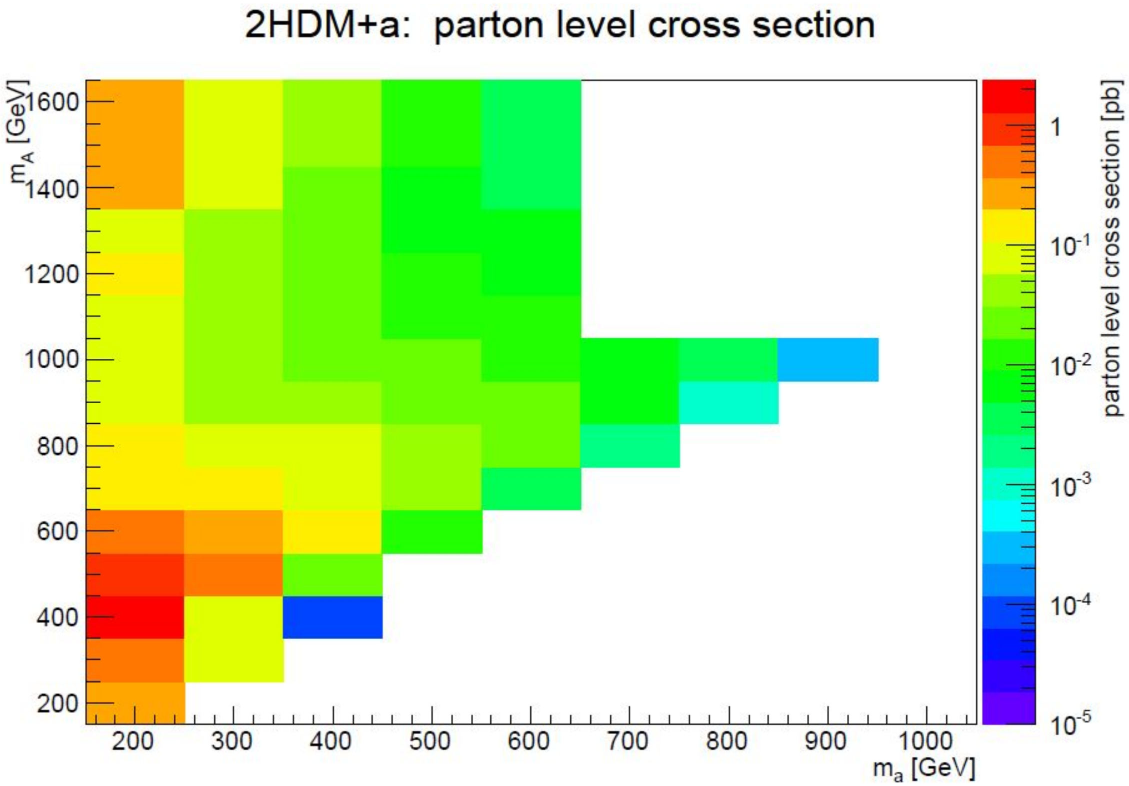
2HDM+a: Diverse palette of signatures





The interplay is experimentally exciting!

Mass Grid: Parton level x-secs



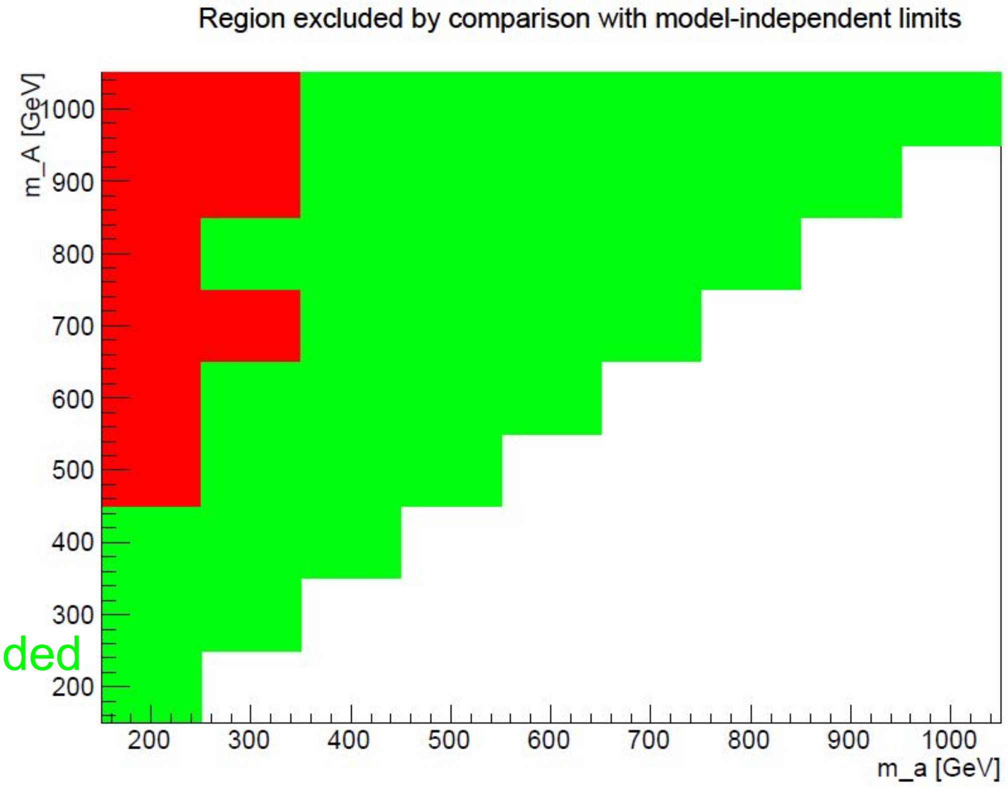
remaining parameters:

- **$\sin(\theta) = 0.35$**
- **$m_H = m_A + 100$ GeV $= m_{H+-}$**
- $\tan(\beta) = 1$
- $m_\chi = 1$ GeV
- $y_\chi = 1$

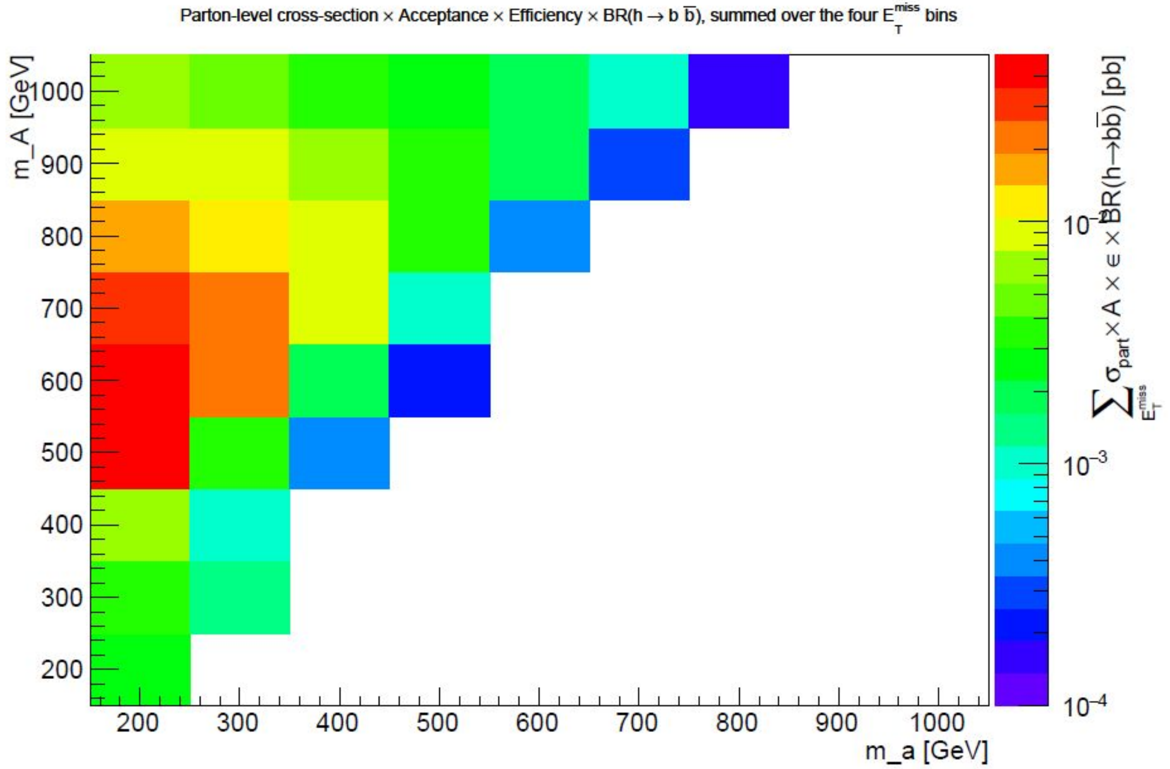
Backup: Exclusion Region

excluded

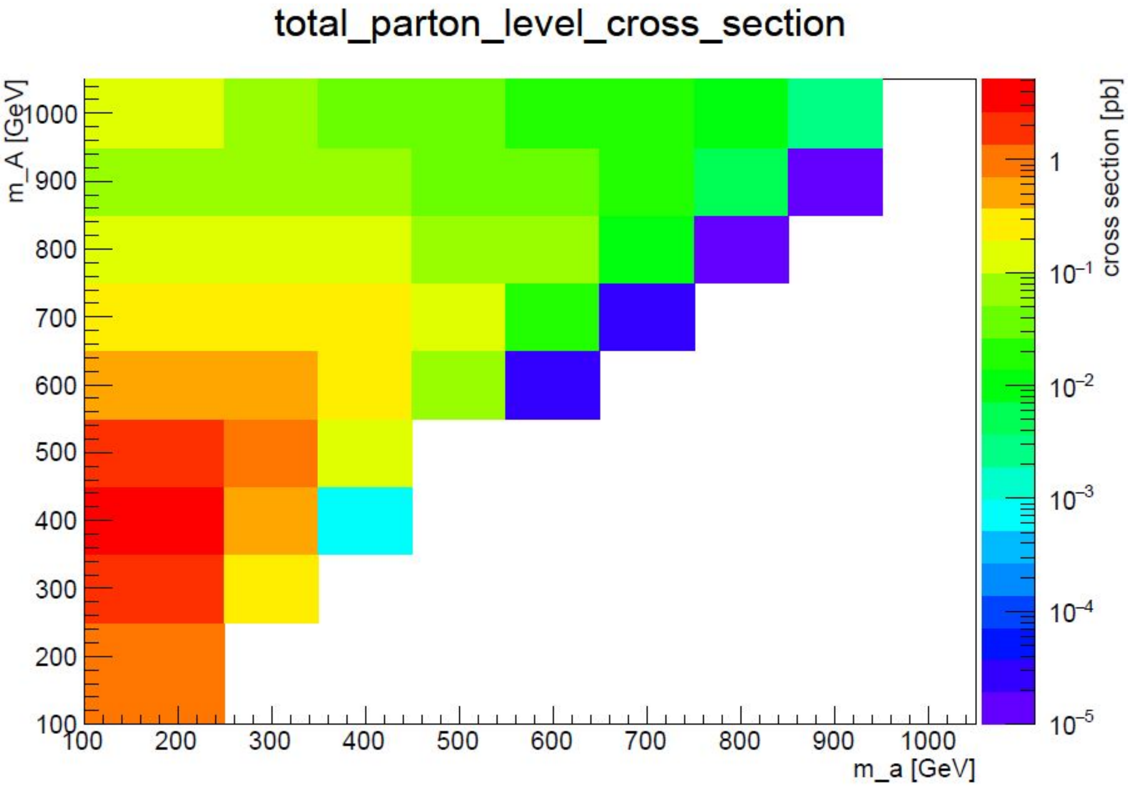
scanned, not excluded



Backup: Cross-Section

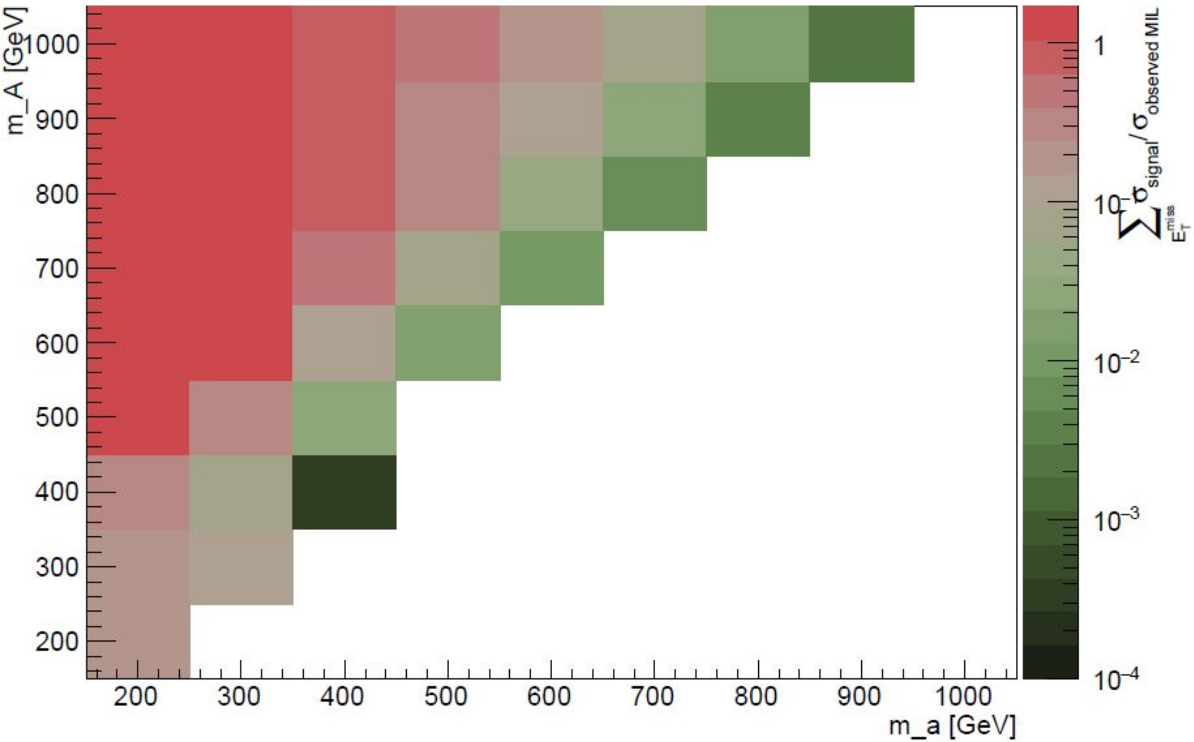


Backup: Parton-Level Cross-Section



Estimating mono-h→ bb Sensitivity

σ_{parton} x Acceptance x Efficiency x BR_{SM}(h→ bb) /$\sigma_{MIL,obs}$



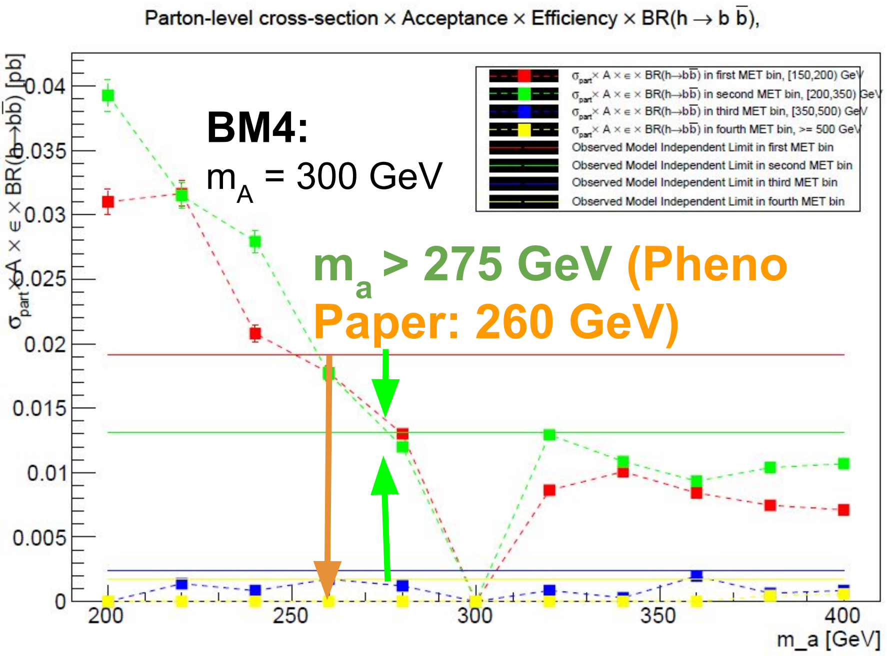
1. simulate parton-level x-sec
2. bin into 4 MET bins
3. fold (bin-by-bin) with Acceptance x Efficiency
4. multiply with SM h→bb branching ratio
5. divide (bin-by-bin) by observed upper limit on σ(h(→bb) + MET)
6. sum over 4 MET bins

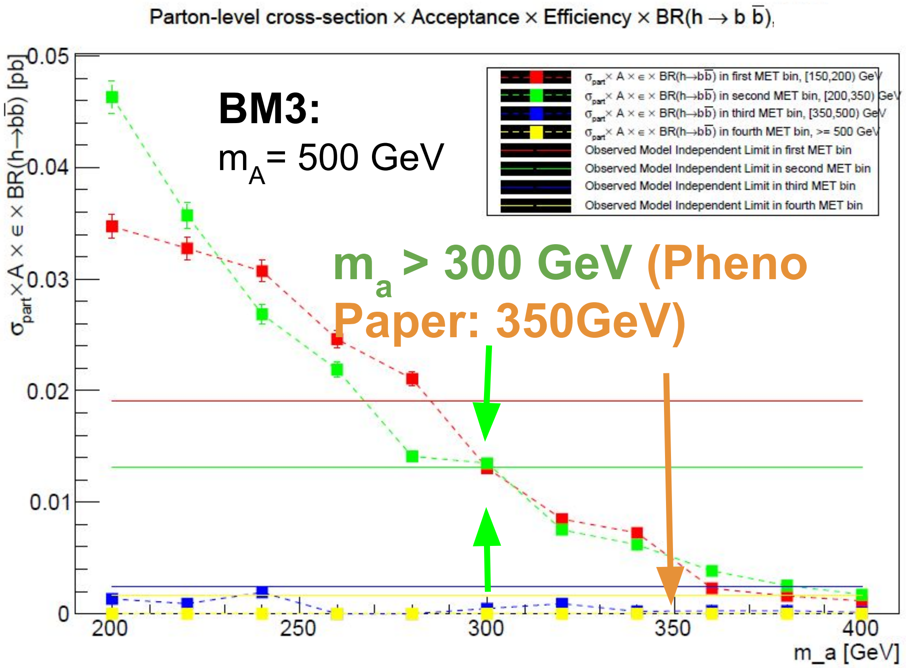
Range in E_T^{miss}/GeV	$\sigma^{obs}_{vis,h+DM}$ [fb]	$\sigma^{exp}_{vis,h+DM}$ [fb]	$\mathcal{A} \times \varepsilon$ %
[150, 200)	19.1	$18.3^{+7.2}_{-5.1}$	15
[200, 350)	13.1	$10.5^{+4.1}_{-2.9}$	35
[350, 500)	2.4	$1.7^{+0.7}_{-0.5}$	40
[500, ∞)	1.7	$1.8^{+0.7}_{-0.5}$	55

Cross-Check: Benchmarks 3 and 4

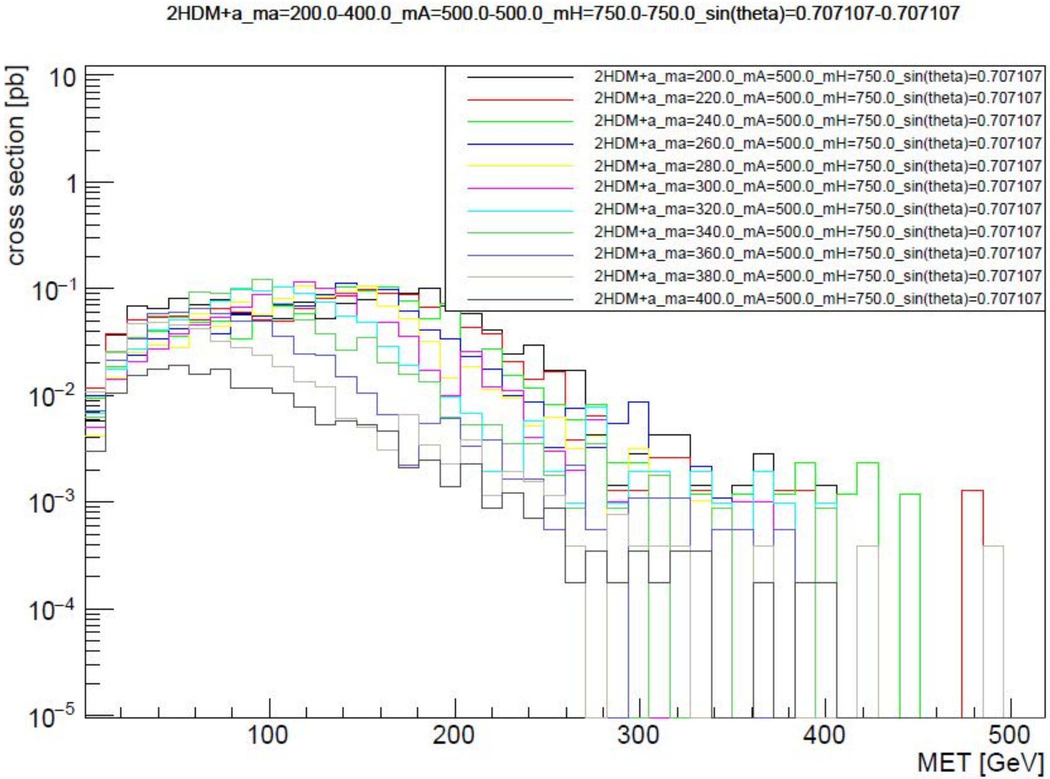
- scan m_a along $\tan(\beta) = 1$ for Benchmarks 3 and 4
- compare to MILs (L = 36.5 fb^{-1} for mono-h → bb)
  - ⇒ similar to pheno paper expectation (there: L = 40 fb^{-1} for mono-h → γγ)

- m_H = 750 GeV
- $\sin(\theta)$ = 1/sqrt(2)

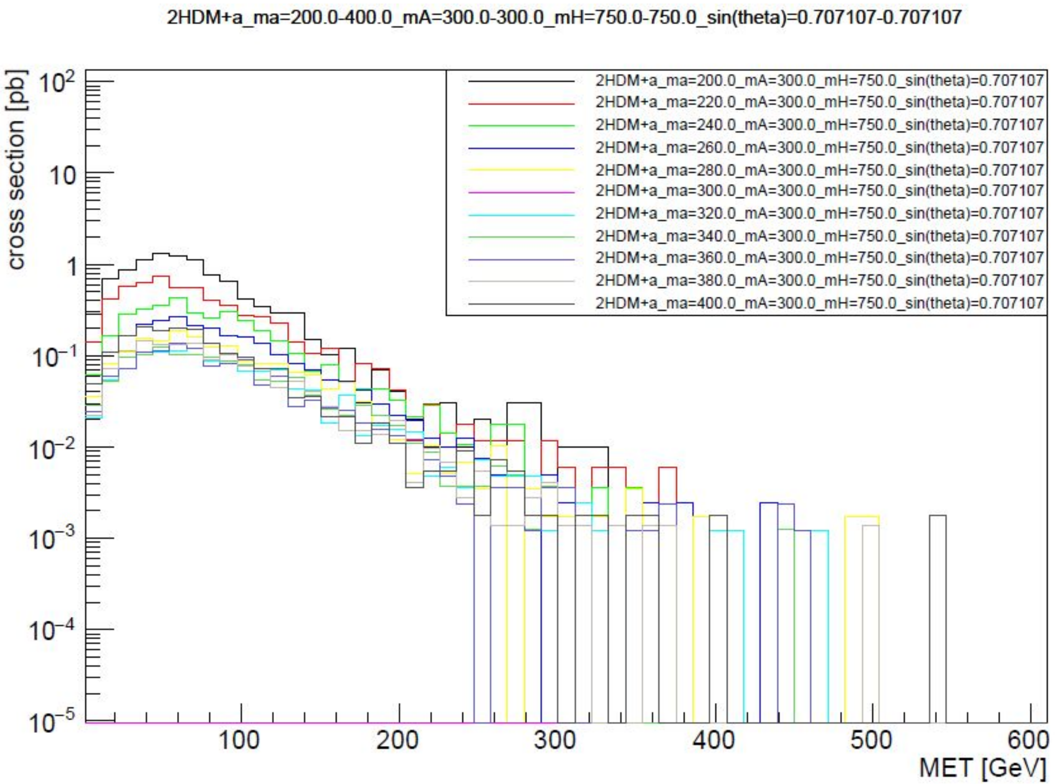




Backup: MET(m_a) in BM3

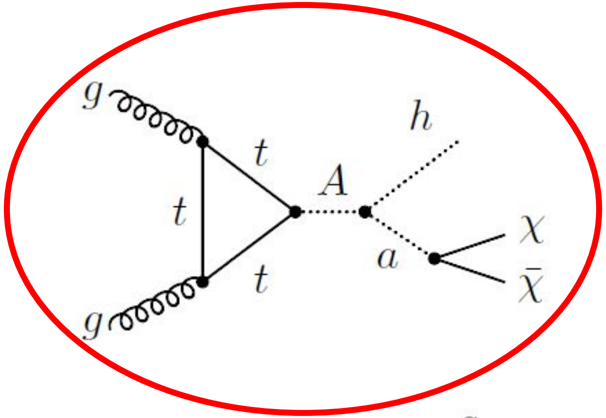


Backup: MET(m_a) in BM4



2HDM+a Parameters

- 2HDM + pseudoscalar DM-mediators a, A
- **14** parameters in total
  - 7 fixed by symmetry, EW-precision measurements, observed higgs properties,...
- **7** free parameters:



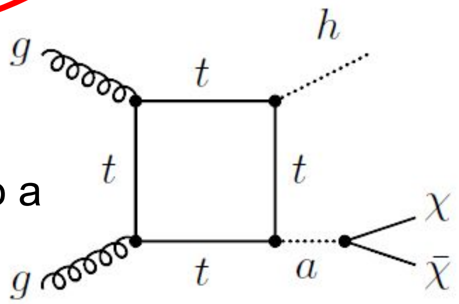
dominant contribution

Change kinematics:

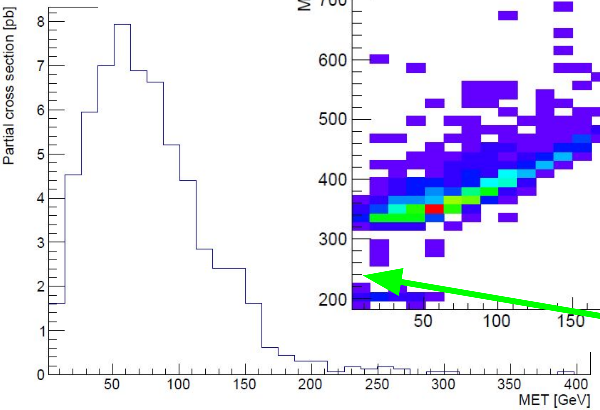
- m_a,m_A : DM mediator masses
- sin(θ) : a-A mixing angle
- $m_{H:}$ heavy neutral scalar mass

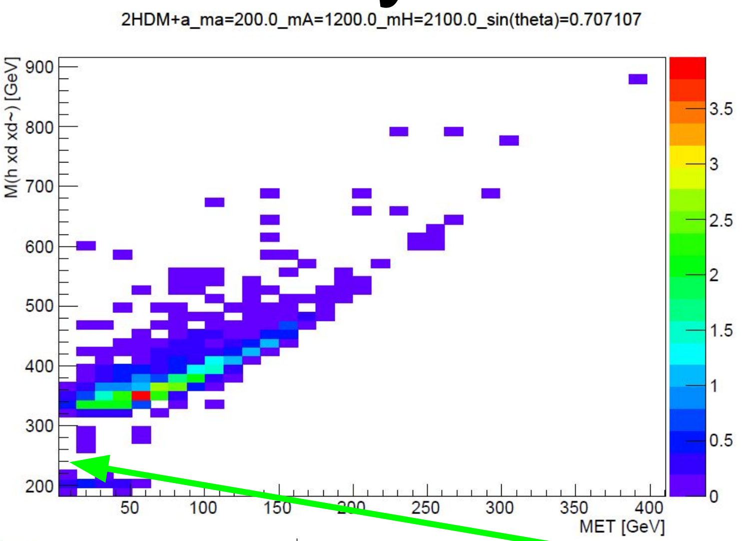
Change (only)cross-section:

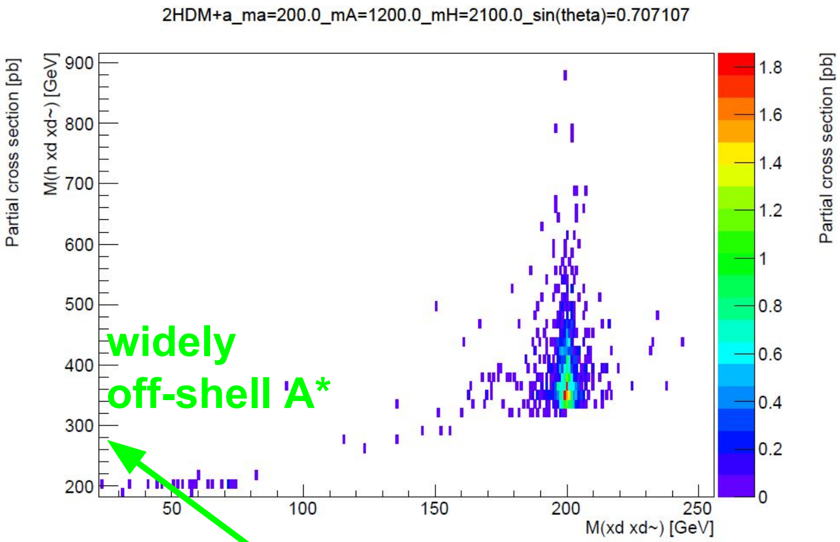
- y_χ: DM Yukawa-coupling to a and A
- tan(β): ratio of vacuum expectation values
- m_χ : DM particle mass



Why no hard MET?







problem:

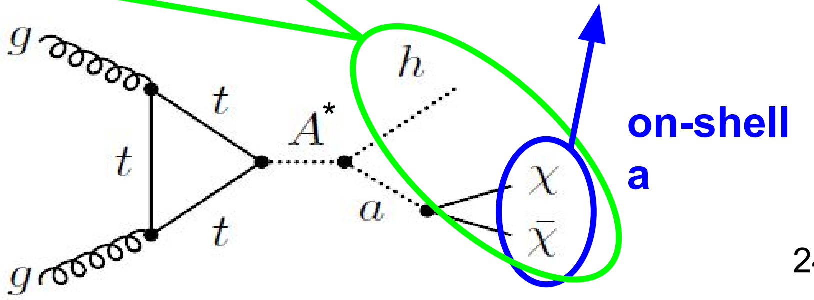
soft MET ⇐⇒ A not resonant

want:

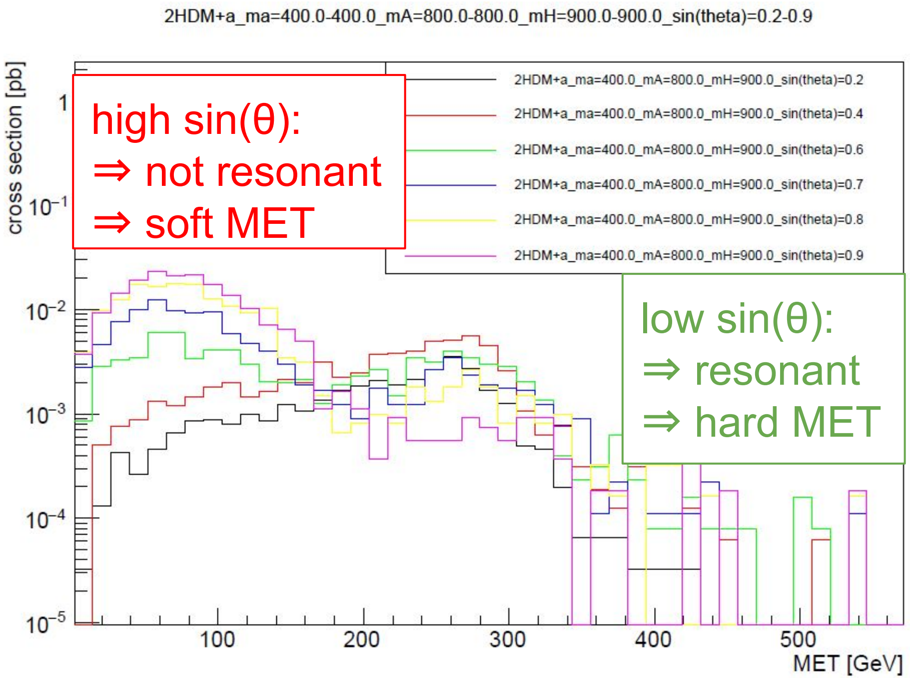
hard MET ⇐⇒ A resonant

→ Q: how to ensure resonant A decay?

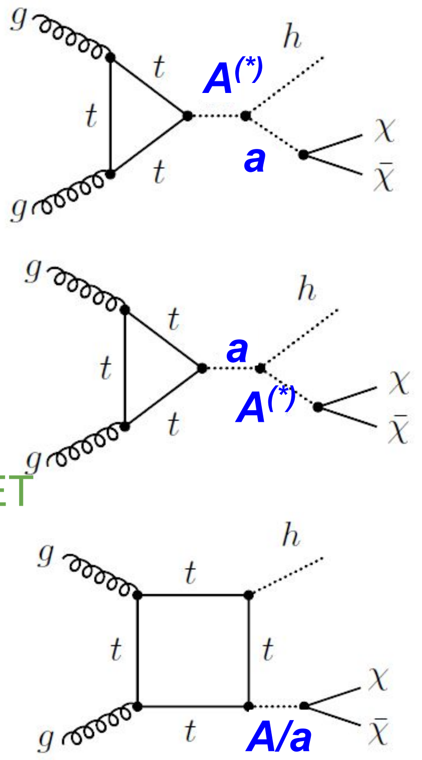
→A: **sin(θ) and m_H**



How to hard MET: sin(θ)



- sin(θ): a-A mixing parameter
- influences couplings to:
  - DM fermion
  - 2HDM bosons
  - SM fermions
  - SM bosons
- changes width of A:
  - wide ⇒ soft MET
  - narrow ⇒ hard MET



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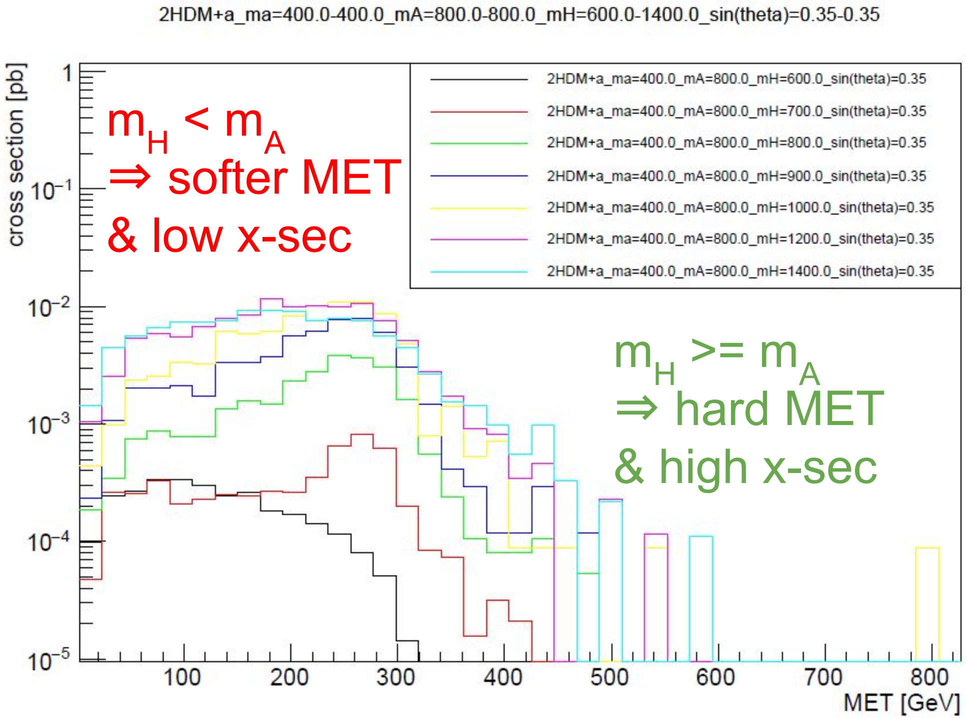
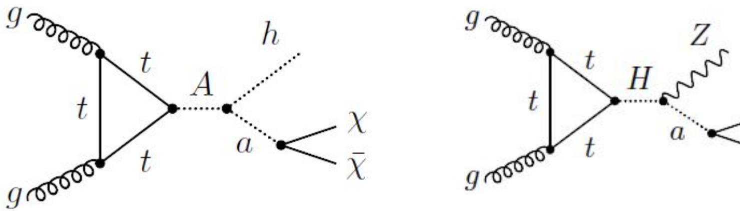
$$\Gamma(A \to ff) \propto \cos^2\theta \qquad \Gamma(a \to ff) \propto \sin^2\theta$$
$$\Gamma(A \to ah) \propto \sin\theta\cos\theta$$

How to hard MET: m_H



m_H : mass of heavy scalar H

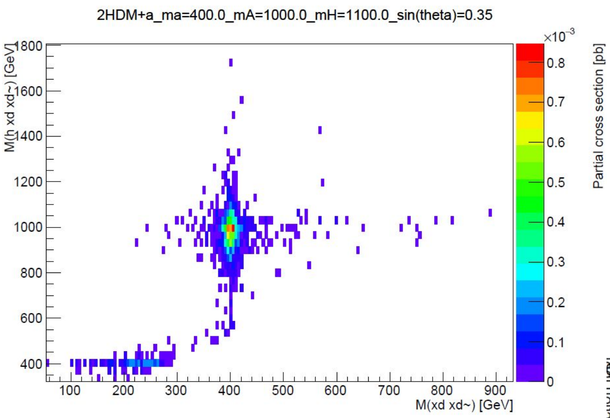
- strength of a-A-h coupling
- gg→H→ Z +DM competes for phase space



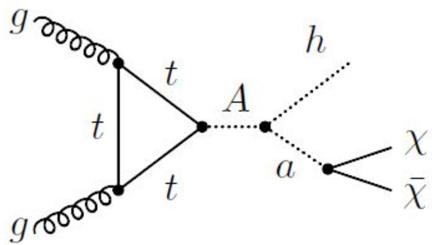
$$\Gamma(A \to ah) = \frac{1}{16\pi} \frac{\lambda^{1/2}(M_A, M_a, M_h)}{M_A} g_{Aah}^2$$

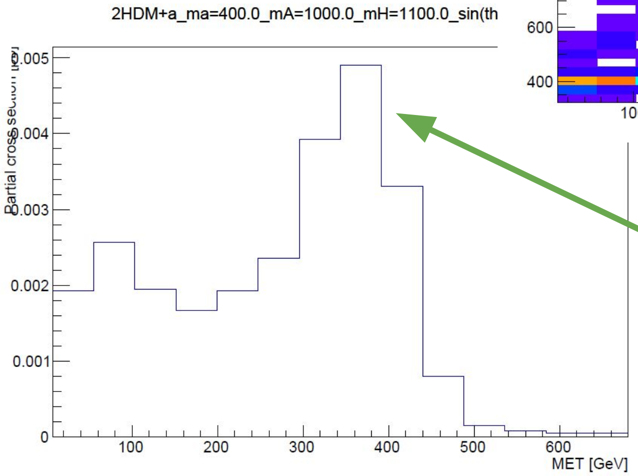
$$g_{Aah} = \frac{1}{M_A v}\left[M_h^2 - 2M_H^2 - M_A^2 + 4M_{H^\pm}^2 - M_a^2 - 2\lambda_3 v^2 + 2\left(\lambda_{P1}\cos^2\beta + \lambda_{P2}\sin^2\beta\right)v^2\right]\sin\theta\cos\theta\,,$$

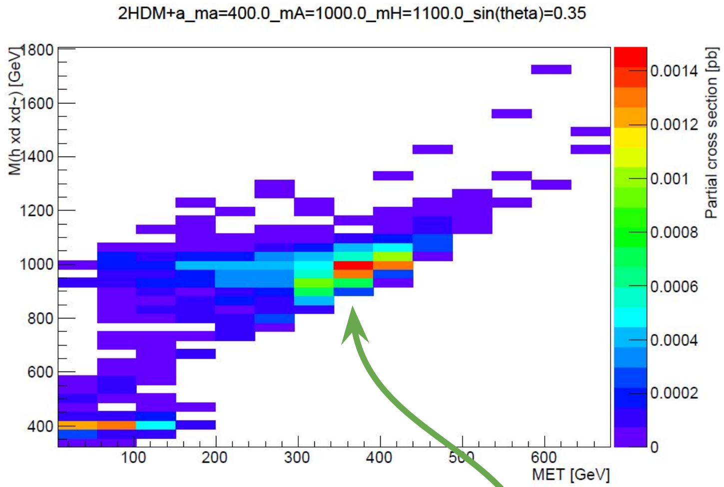
low sin(θ) & $m_H \sim m_A \Rightarrow$ hard MET



resonant A → a h dominates



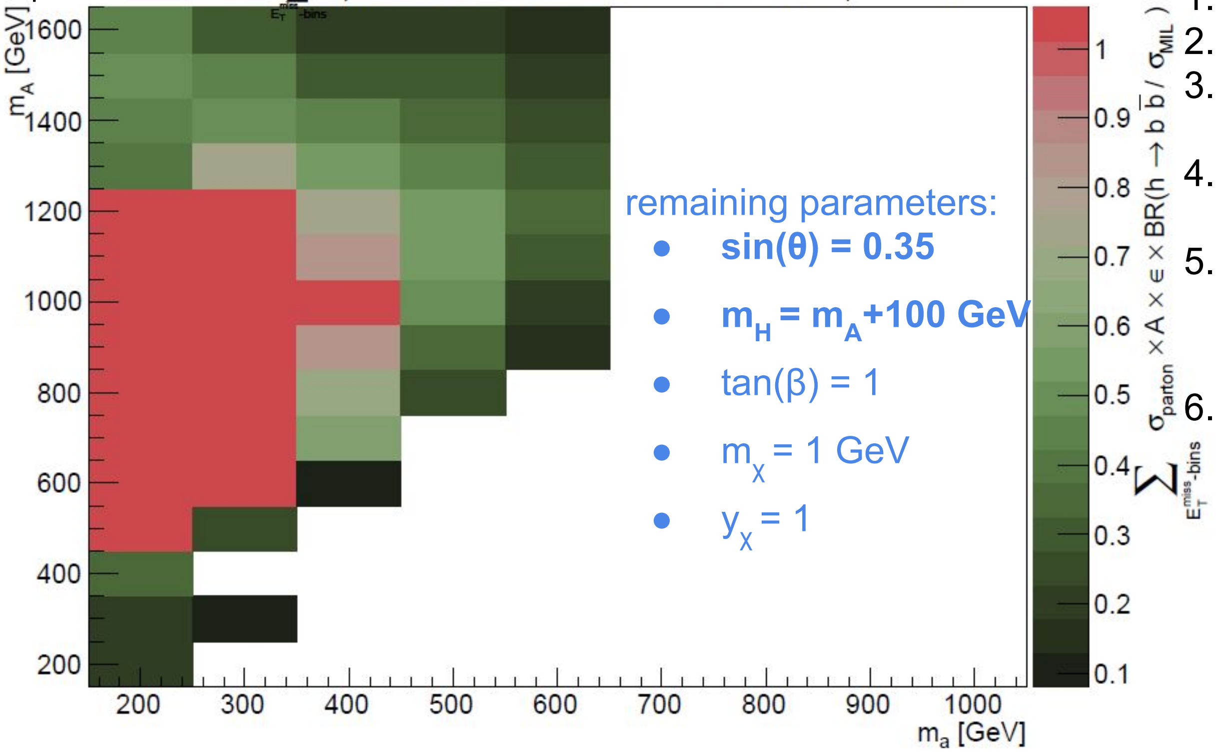




this results in a Jacobian Peak at high MET

Estimate Signal Sensitivity

σ_{parton} x Acceptance x Efficiency x $BR_{SM}(h \rightarrow bb) / \sigma_{MIL,obs}$



remaining parameters:

- **sin(θ) = 0.35**
- **$m_H = m_A$+100 GeV**
- tan(β) = 1
- m_χ = 1 GeV
- y_χ = 1

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The Problem of Vacuum Stability

- Jose No pointed out:
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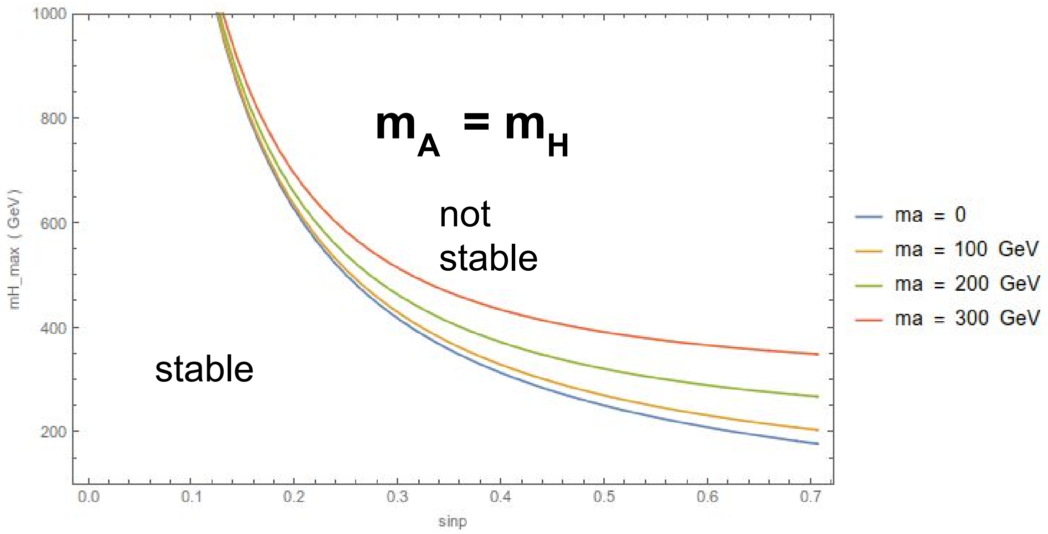
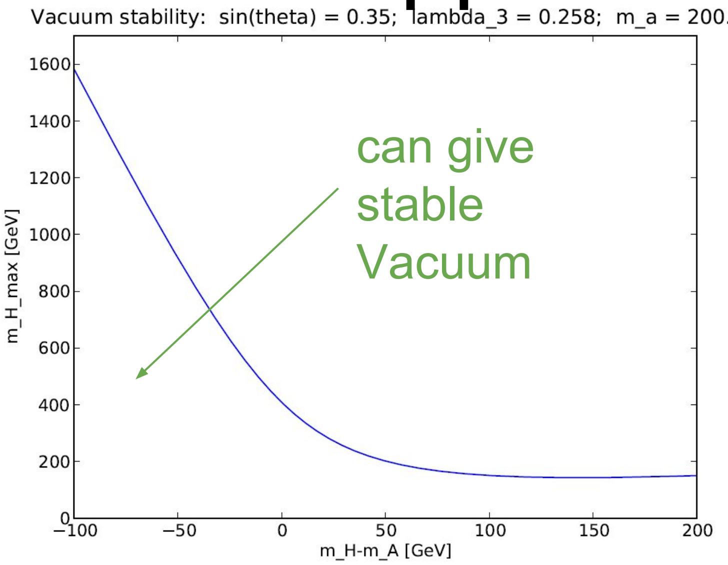
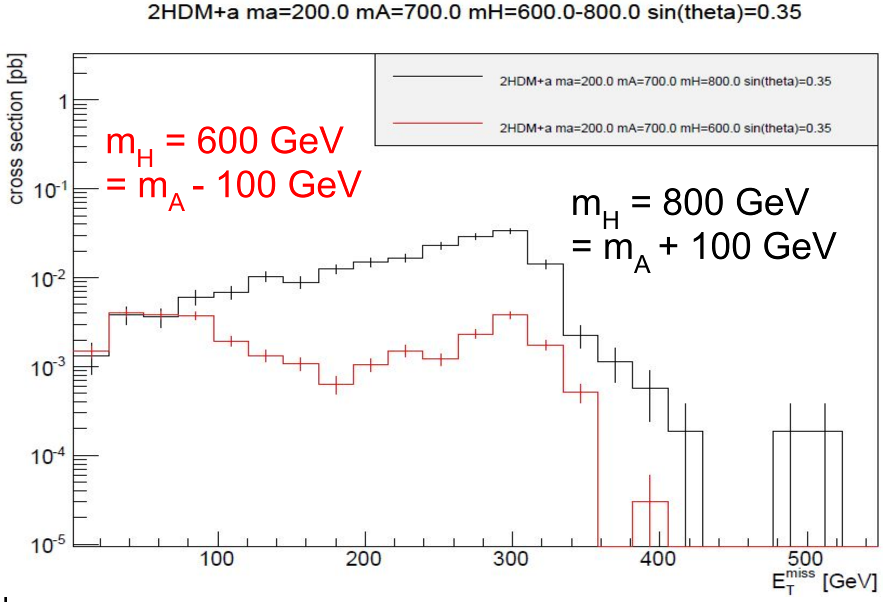
  - recommendation: lambda_3 = $(m_h/v)^2 \sim 0.258$
  - even with this choice of lambda_3, still no stable vacuum b.c. :
    - m_H too high (esp. $m_H > m_A$)
    - sin(theta) too high
- affects both BM3 and mono-h(bb) proposal!

plot by Jose No:



Approach 1: smaller $m_H - m_A$

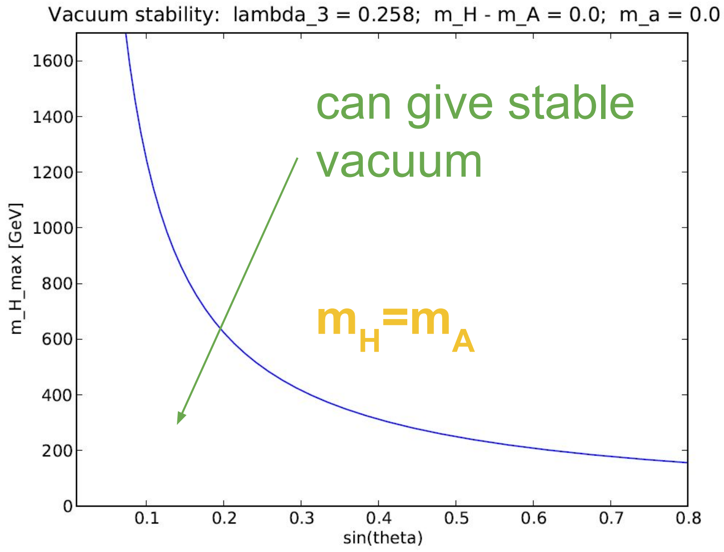


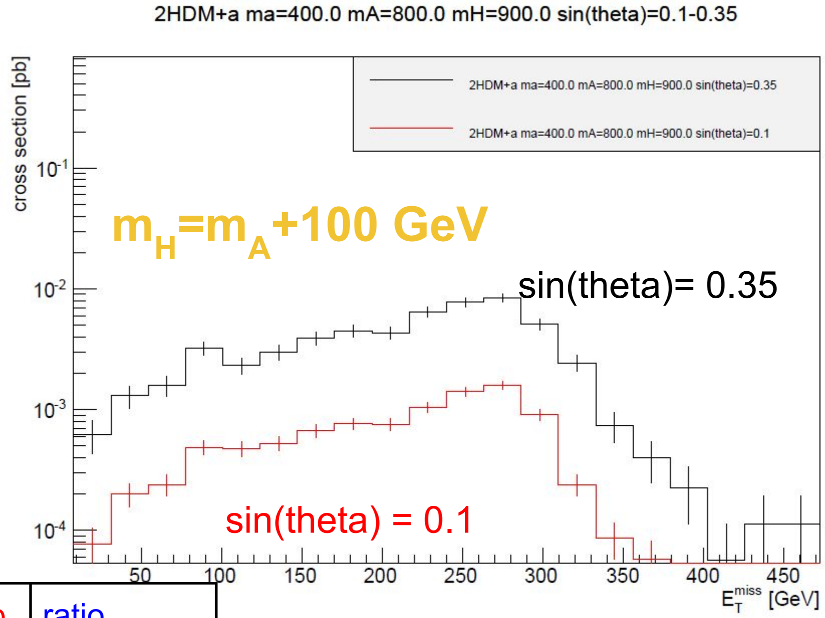


m_a/GeV	m_A/GeV	x-sec(m_H=m_A+ 100 GeV)/pb	x-sec(m_H=m_A -100 GeV)/pb	ratio
200	700	0.1895	0.03026	6.26
300	400	0.1040	0.004672	22.26
400	600	0.1295	0.002987	43.34

greatly reduces mono-h (bb) signal

Approach 2: smaller sin(theta)

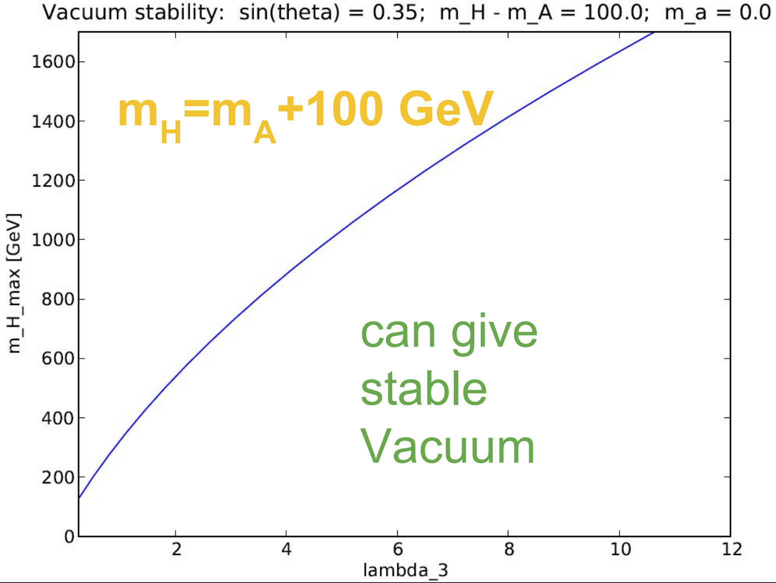


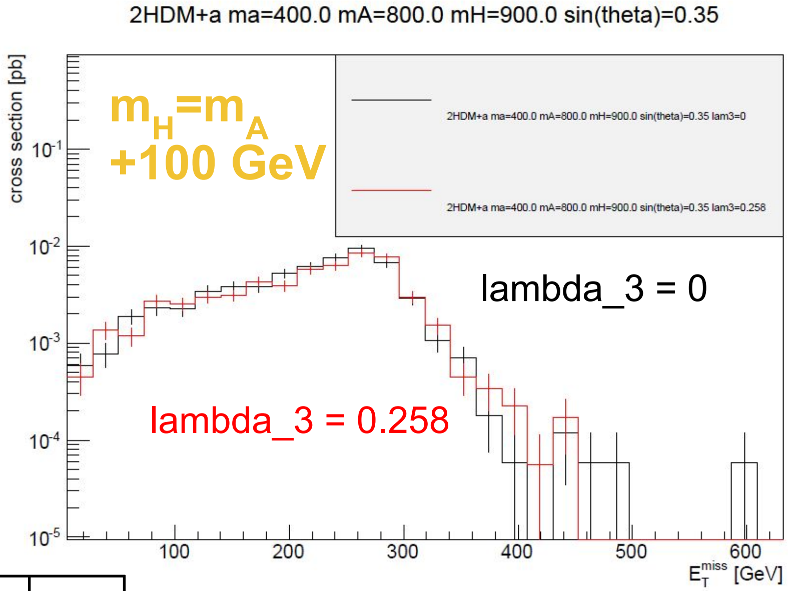


m_a/GeV	m_A/GeV	x-sec(sin(theta)=0.35)/pb	x-sec(sin(theta)=0.1)/pb	ratio
300	500	0.4322	0.0546	7.92
400	800	0.05644	0.00955	5.91
500	1300	0.008539	0.00131	6.51

substantially reduces mono-h (bb) signal (even without $m_A = m_H$)

Approach 3: larger lambda_3 (I)

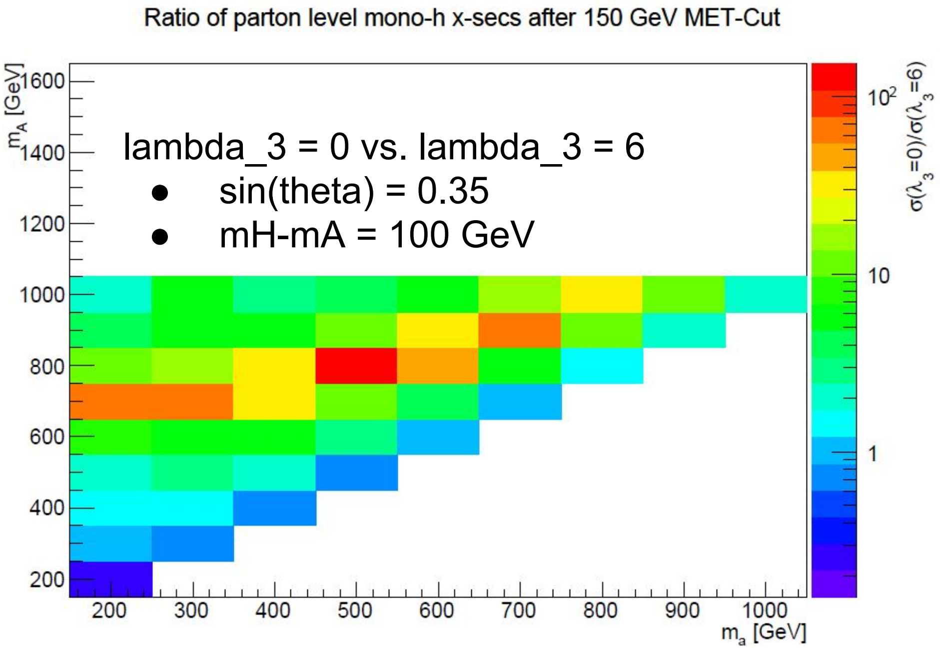




m_a/GeV	m_A/GeV	x-sec(lambda_3 = 0)/pb	x-sec(lambda_3 = 0.258)/pb	ratio
300	500	0.4928	0.4322	1.14
400	800	0.05917	0.056444	1.05
500	1300	0.008661	0.008539	1.01

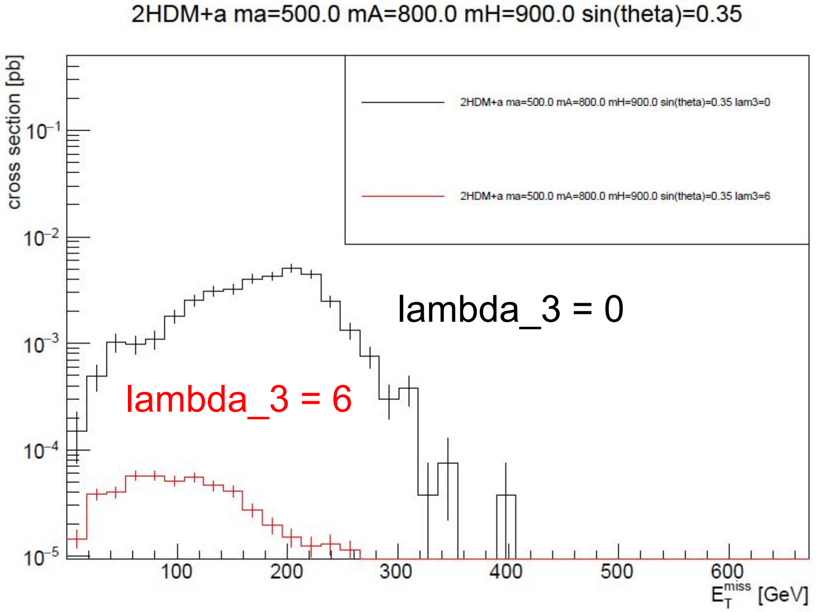
almost identical signal

Approach 3: larger lambda_3 (II)



lambda_3 = 0 vs. lambda_3 = 6

- sin(theta) = 0.35
- mH-mA = 100 GeV

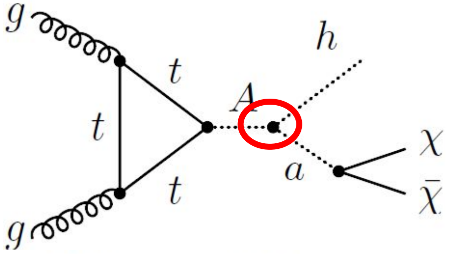


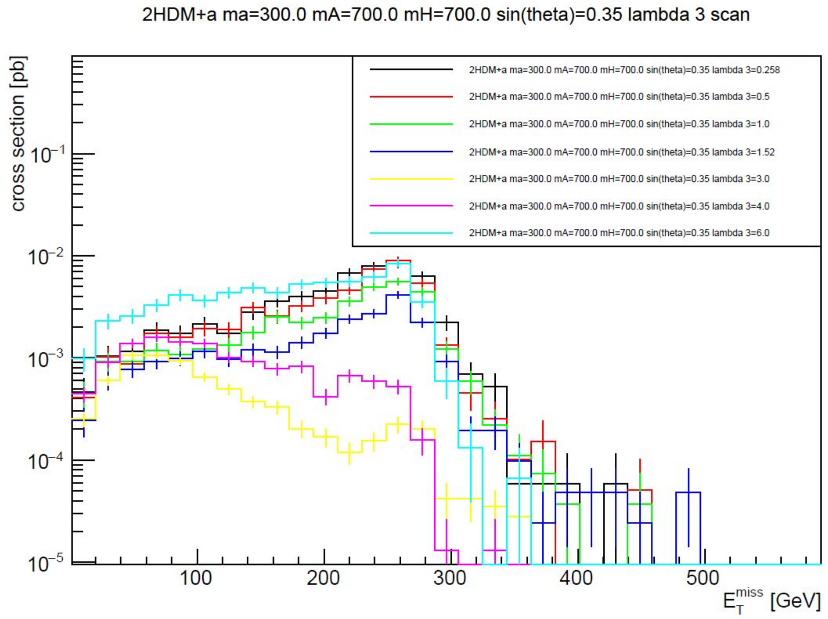
~~almost identical signal~~

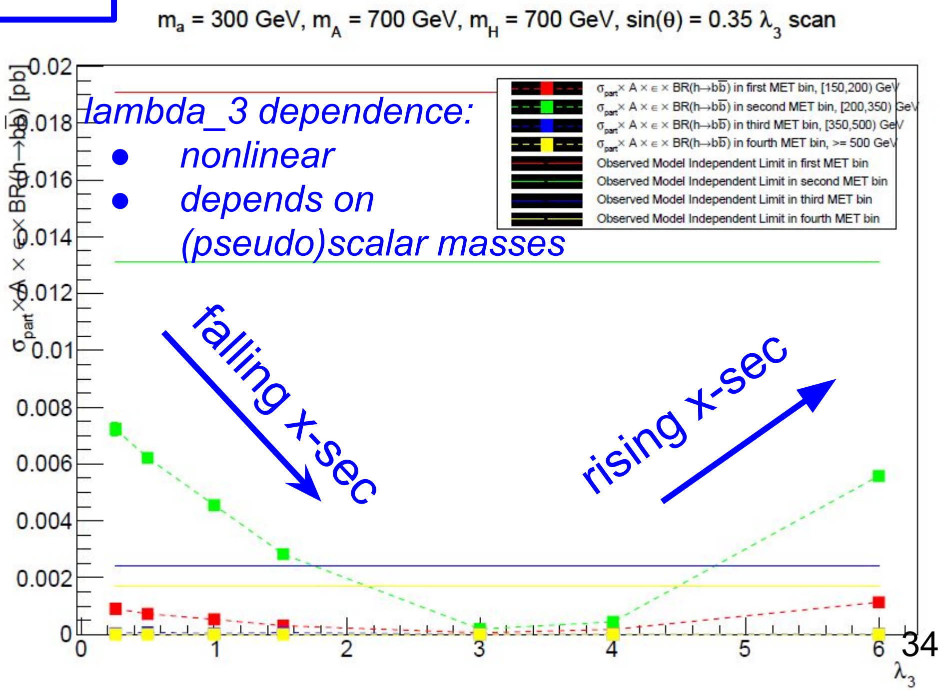
- does not hold for arb. large lambda_3
- signal x-sec can be much smaller
- depends on pseudoscalar masses

lambda_3 dependence

$$g_{Aah} = \frac{1}{M_A v}\left[M_h^2 - 2M_H^2 - M_A^2 + 4M_{H\pm}^2 - M_a^2 - 2\lambda_3 v^2 + 2\left(\lambda_{P1}\cos^2\beta + \lambda_{P2}\sin^2\beta\right)v^2\right]\sin\theta\cos\theta\,, \quad (4.12)$$







Vacuum Stability: Quartic Couplings (alignment limit)

$$v^2\lambda_1 = m_h^2 - \frac{t_\beta\,(m_{12}^2 - m_H^2 s_\beta c_\beta)}{c_\beta^2}\,,$$

$$v^2\lambda_2 = m_h^2 - \frac{(m_{12}^2 - m_H^2 s_\beta c_\beta)}{t_\beta s_\beta^2}\,,$$

$$v^2\lambda_3 = m_h^2 + 2m_{H^\pm}^2 - 2m_H^2 - \frac{(m_{12}^2 - m_H^2 s_\beta c_\beta)}{s_\beta c_\beta}\,,$$

$$v^2\lambda_4 = m_A^2 - 2m_{H^\pm}^2 + m_H^2 + \frac{(m_{12}^2 - m_H^2 s_\beta c_\beta)}{s_\beta c_\beta}\,,$$

$$v^2\lambda_5 = m_H^2 - m_A^2 + \frac{(m_{12}^2 - m_H^2 s_\beta c_\beta)}{s_\beta c_\beta}\,. \qquad (2.10)$$

[arXiv:1604.01406v2 [hep-ph]]

here A is 'our' A_0
(no mixing, no DM-mediator)

→ but 'our' A is mixed from A_0 and a_0 (= P in 2HDM+a paper):

⇒ replace $(m_A)^2$ with $(\cos(\theta)m_A)^2 + (\sin(\theta)m_a)^2$

Vacuum Stability: equations

$$\lambda_1 > 0\,, \quad \lambda_2 > 0\,, \quad \lambda_3 > -\sqrt{\lambda_1\lambda_2}\,, \quad \lambda_3 + \lambda_4 - |\lambda_5| > -\sqrt{\lambda_1\lambda_2}\,. \qquad (3.1)$$

arXiv:1604.01406v2 [hep-ph]

with $\mathbf{m_H = m_{H+-}}$ and in the **alignment limit**,

$\lambda_3 >= (m_h/v)^2$ *gives that* $\lambda_{1,2} > 0$ *for any* $tan(\beta)$,

so only the last equation is relevant. It can be shown (using the relations in (2.10) in linked paper/ on slide 10) that with such a λ_3,

$sqrt(\lambda_1\, \lambda_2) >= \lambda_3$ *for any* $tan(\beta)$.

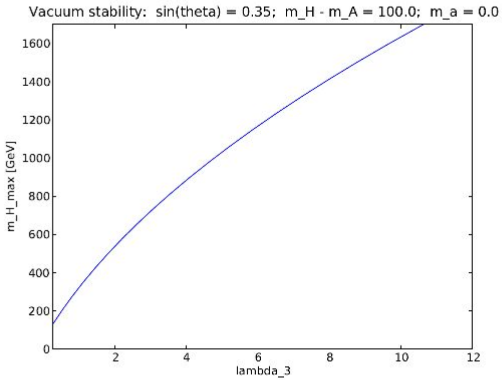
Using this, the last ineq. in (3.1) is fulfilled in all cases where

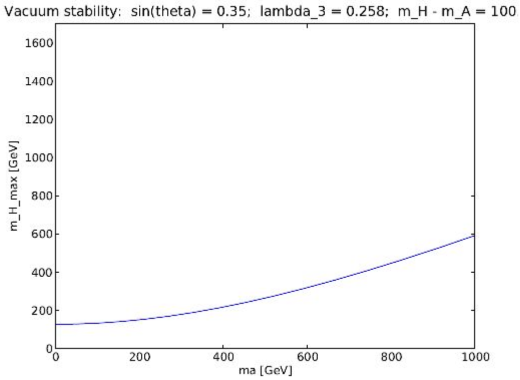
$2\lambda_3 + \lambda_4 - |\lambda_5| > 0$, which after inserting (2.10) gives

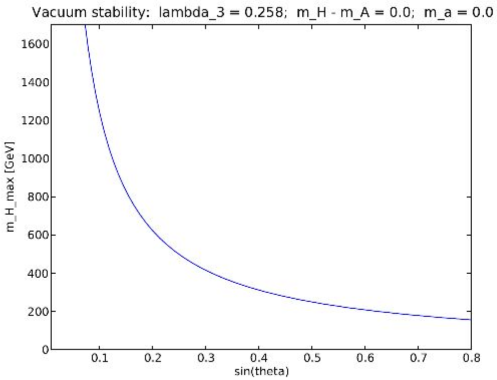
$$v^2\lambda_3 > m^2_H - (cos(\theta)m_A)^2 - (sin(\theta)m_a)^2$$

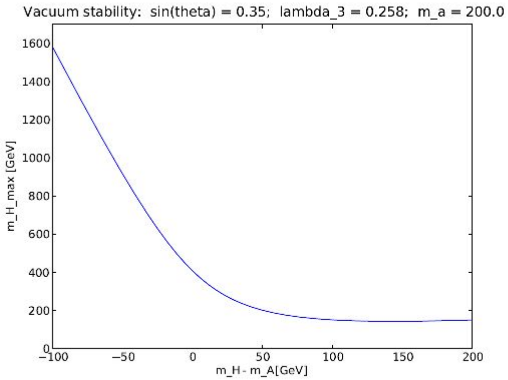
which can then be solved for $m_{H,max}$ $(v,\lambda_3,m_a,sin(\theta),m_H-m_A)$

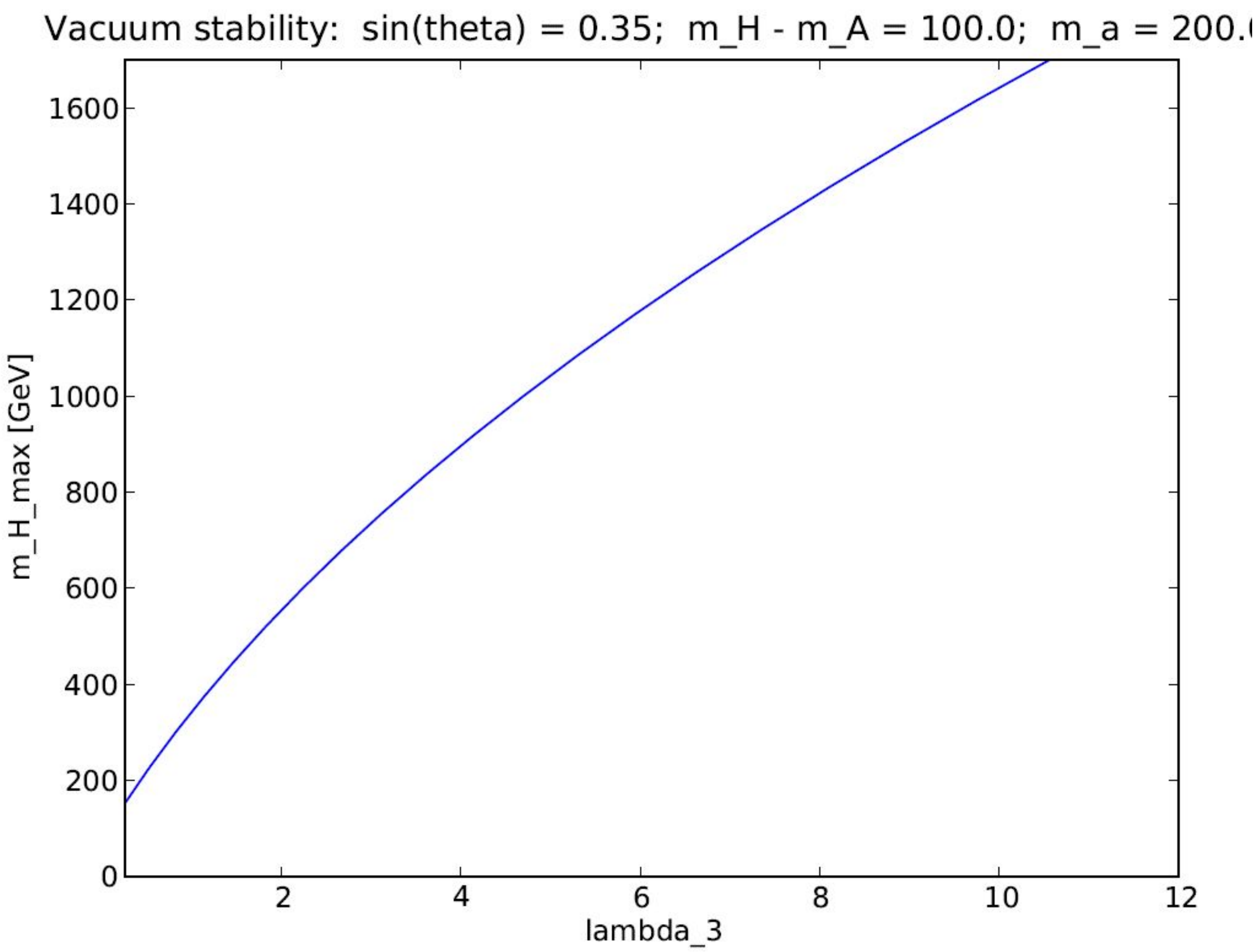
Vacuum Stability: dependencies

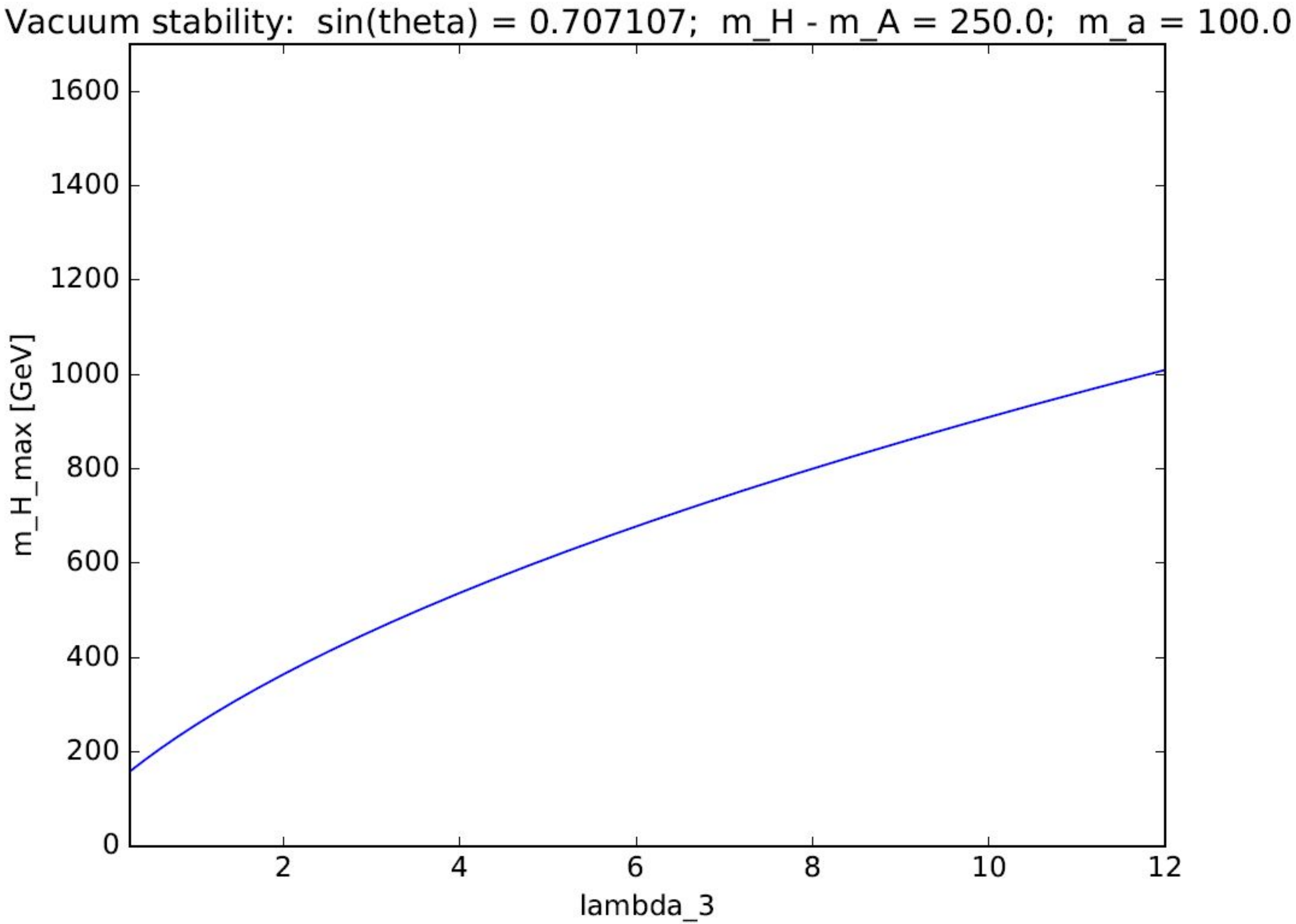




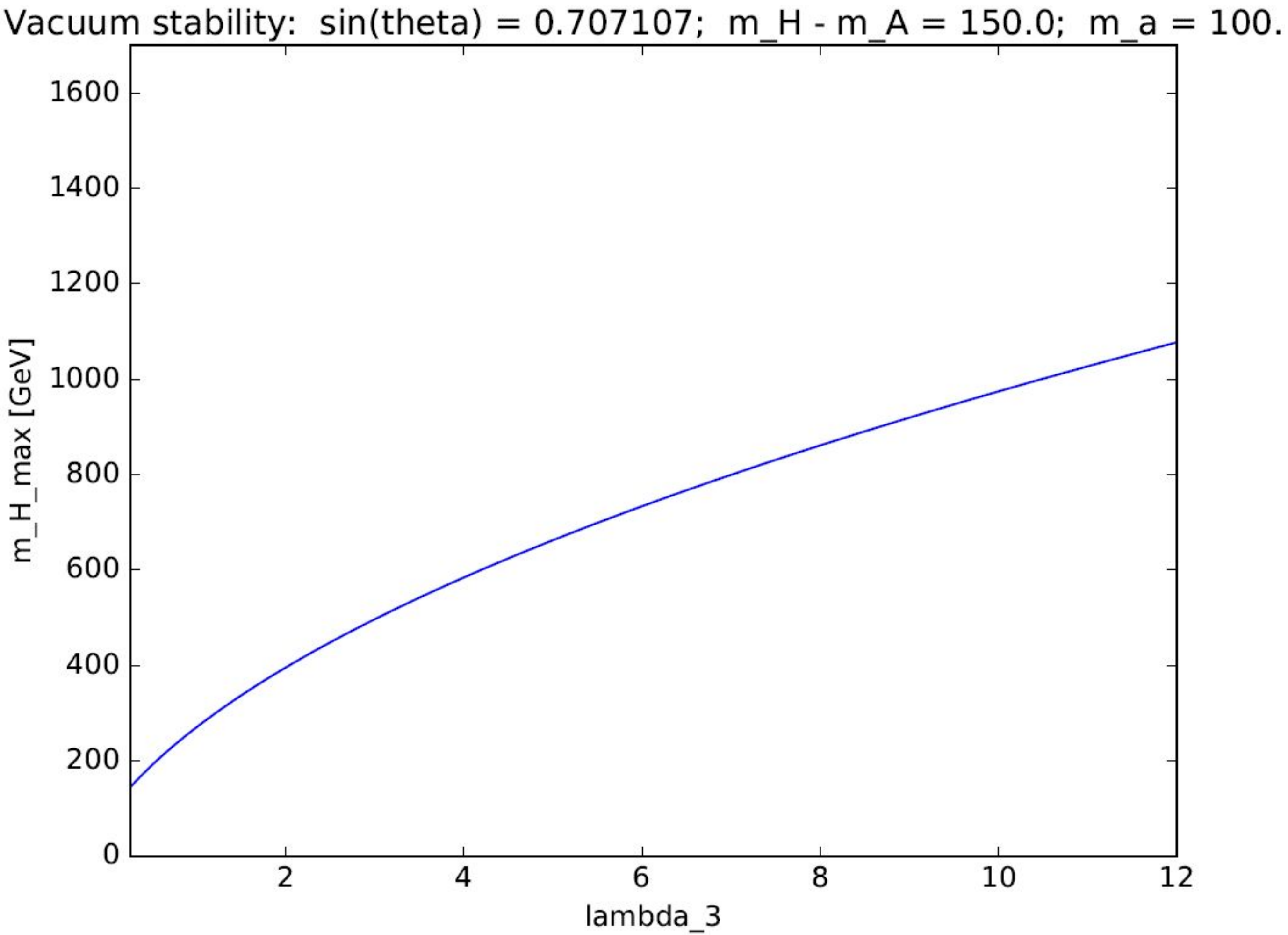





Vacuum stability: sin(theta) = 0.35; m_H - m_A = 100.0; m_a = 200.
m_H_max [GeV]
lambda_3
0
200
400
600
800
1000
1200
1400
1600
2
4
6
8
10
12

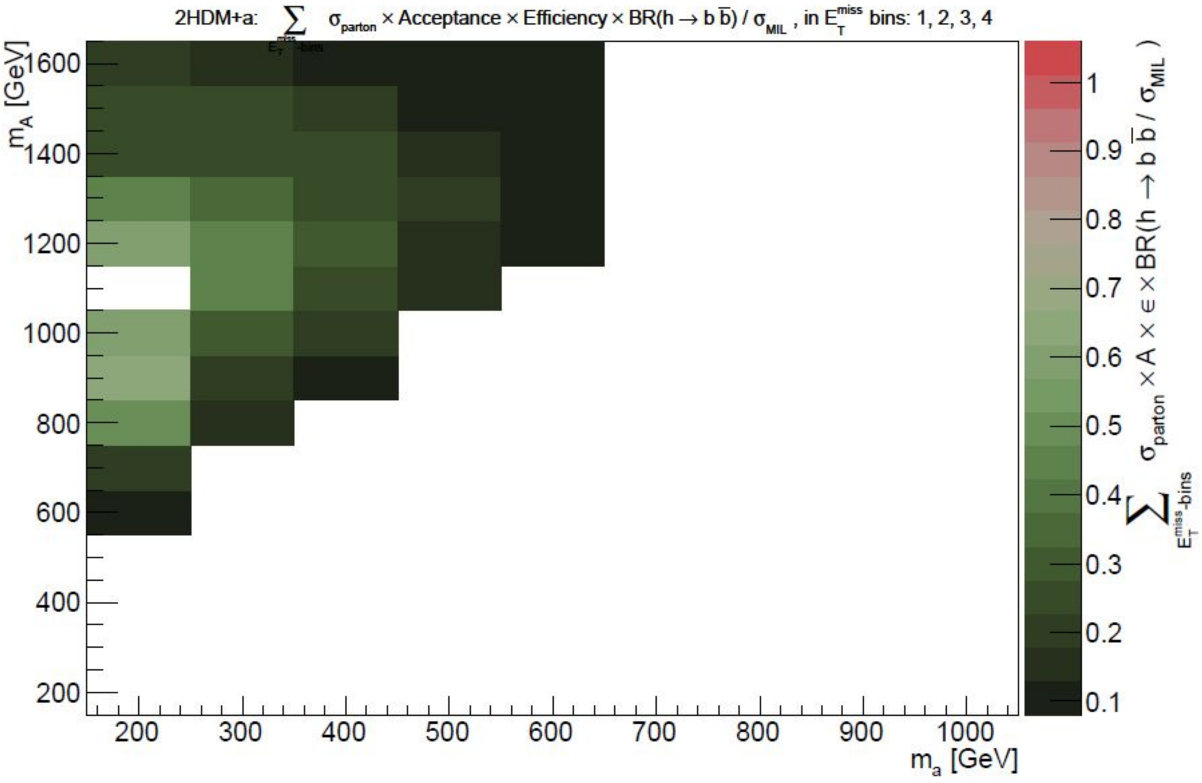


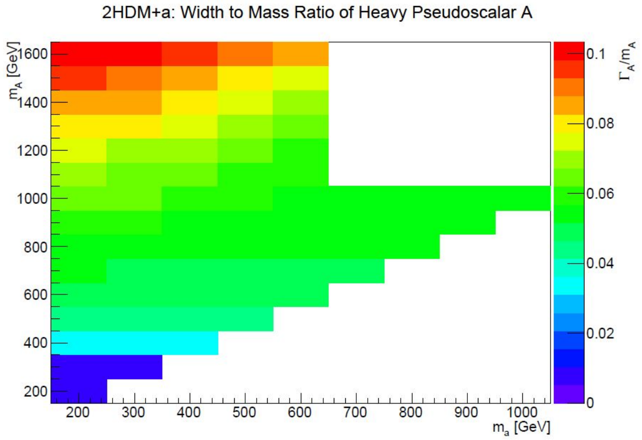
Vacuum stability: sin(theta) = 0.707107; m_H - m_A = 250.0; m_a = 100.0
m_H_max [GeV]
lambda_3
0
200
400
600
800
1000
1200
1400
1600
2
4
6
8
10
12



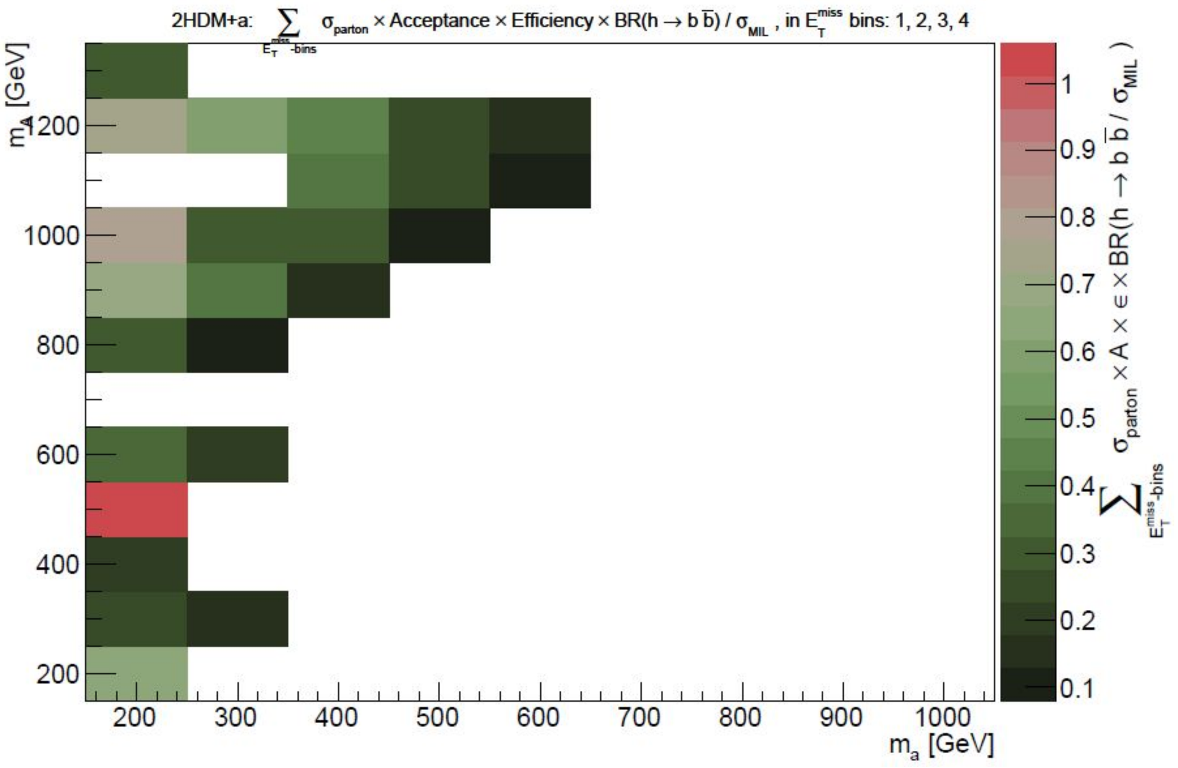
Vacuum stability: sin(theta) = 0.707107; m_H - m_A = 150.0; m_a = 100.
m_H_max [GeV]
lambda_3
0
200
400
600
800
1000
1200
1400
1600
2
4
6
8
10
12

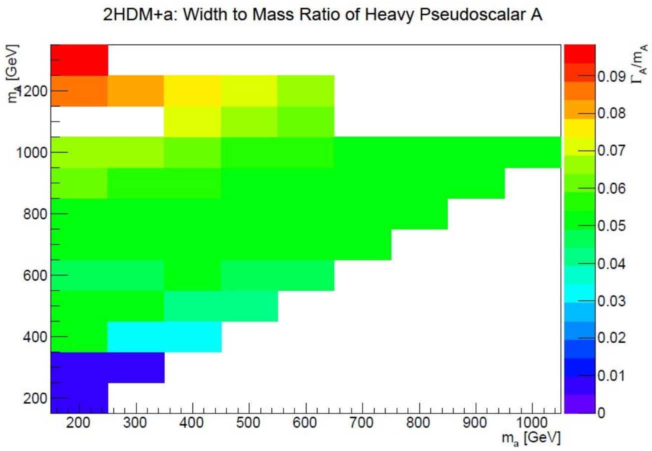
Scan with $m_H = m_A$ - 100 GeV, λ_3=0.258



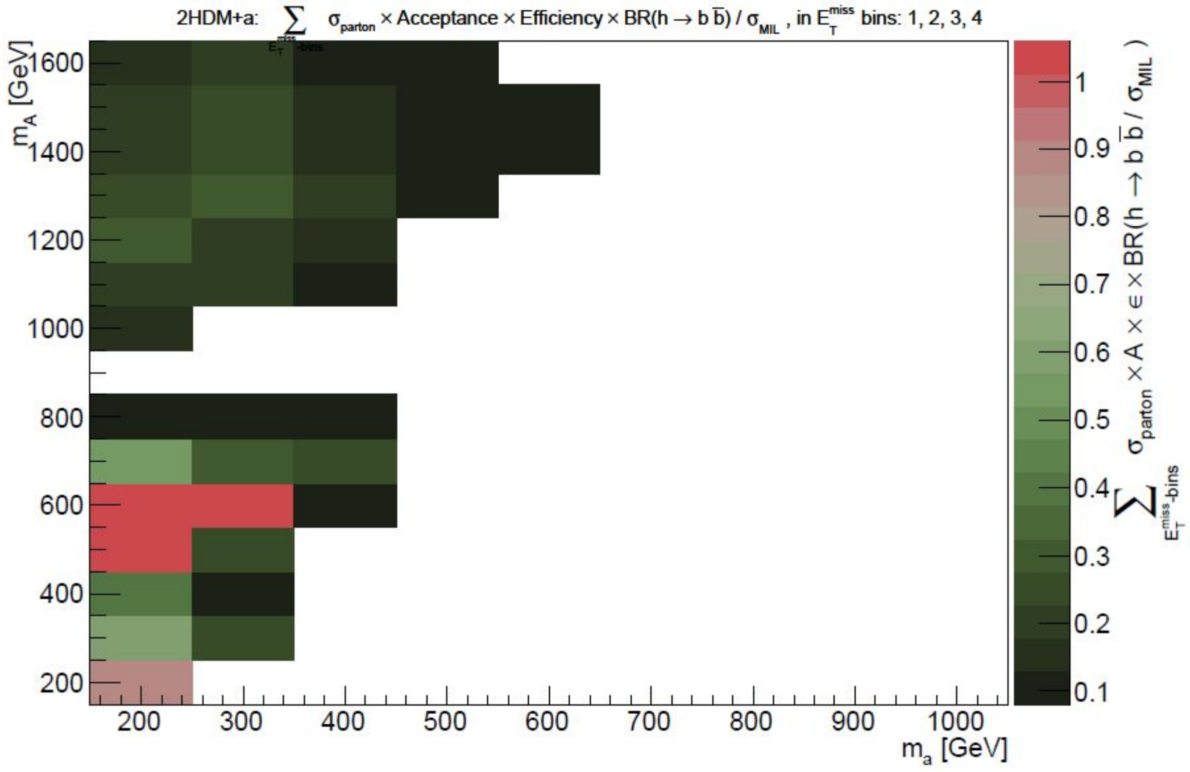


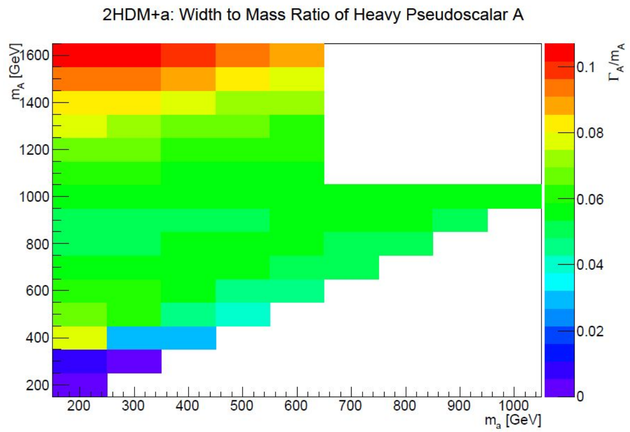
Scan with $m_H = m_A + 100$ GeV, λ_3=6



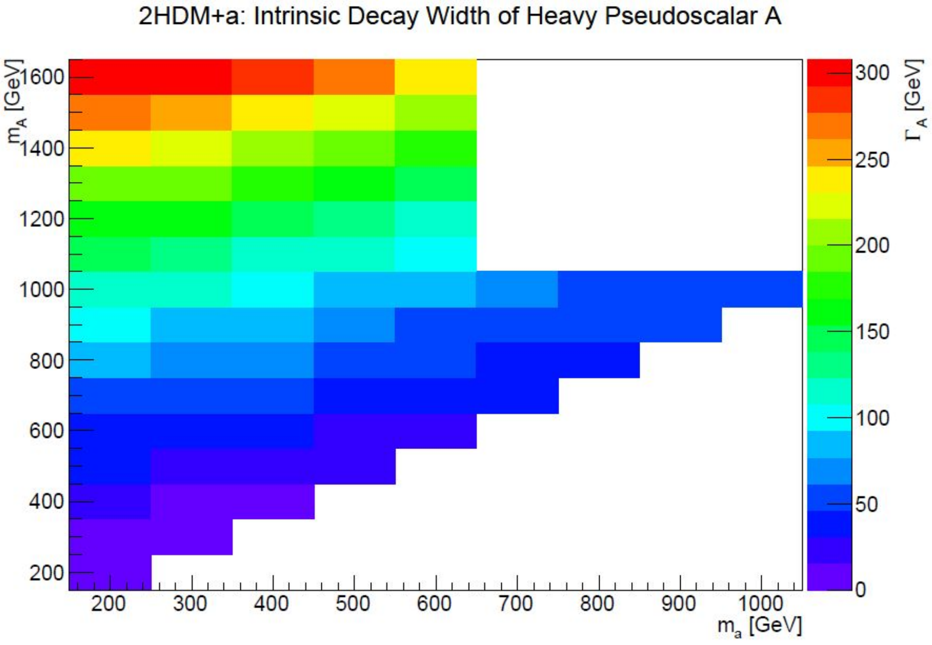


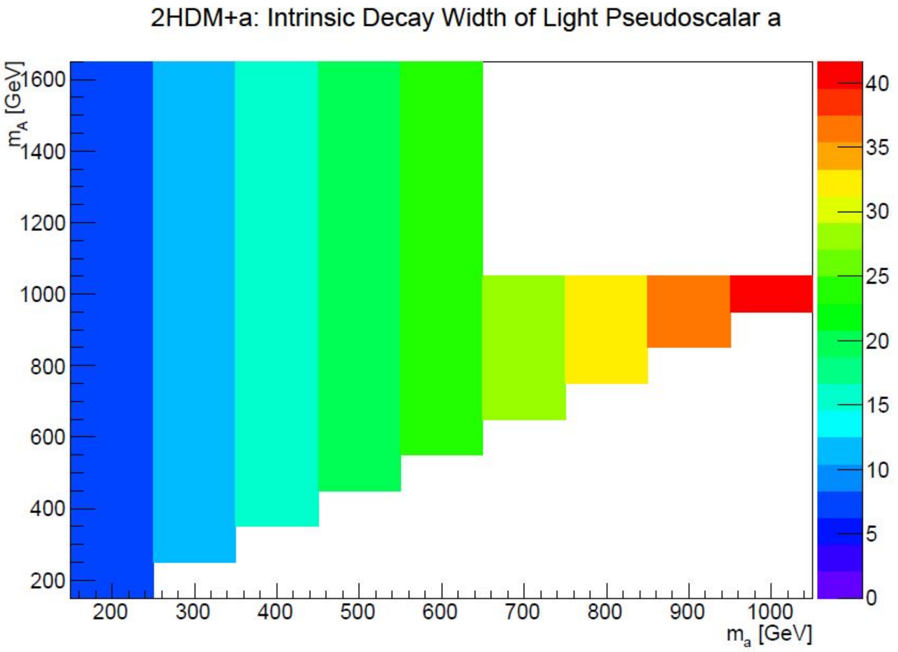
Scan with $m_H = m_A$ GeV, λ_3=6





Pseudoscalar Widths

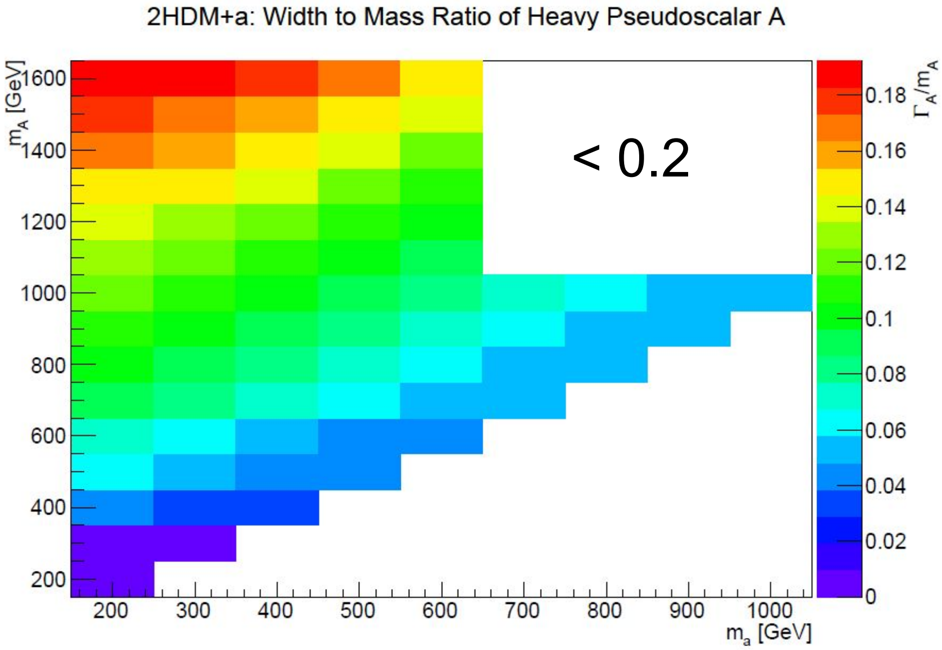


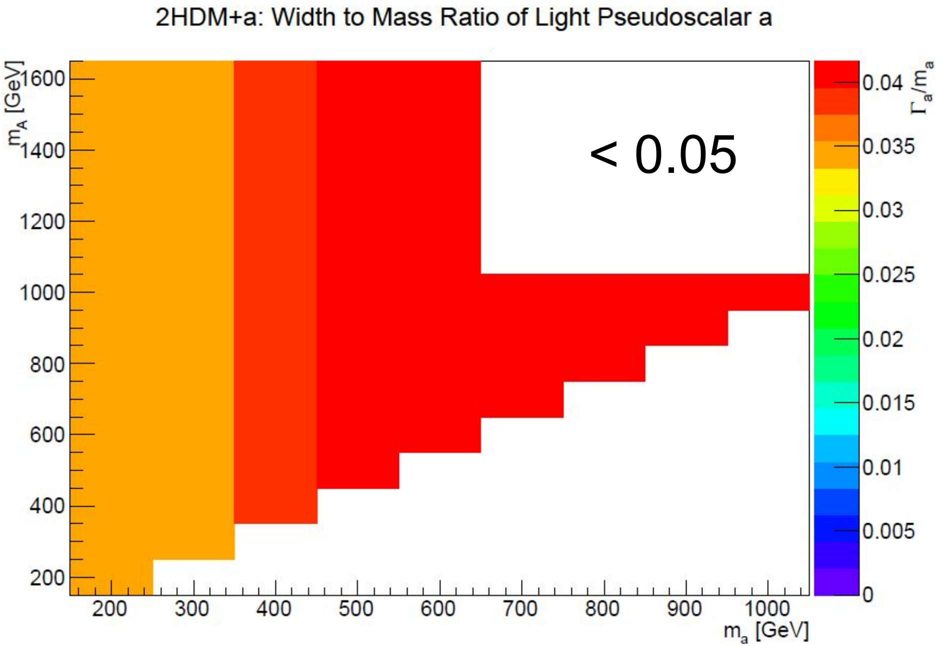


- width of a is always small
- width of A can get large → too large?

- mH = mA + 100 GeV
- sin(theta) = 0.35

Width/Mass Ratio

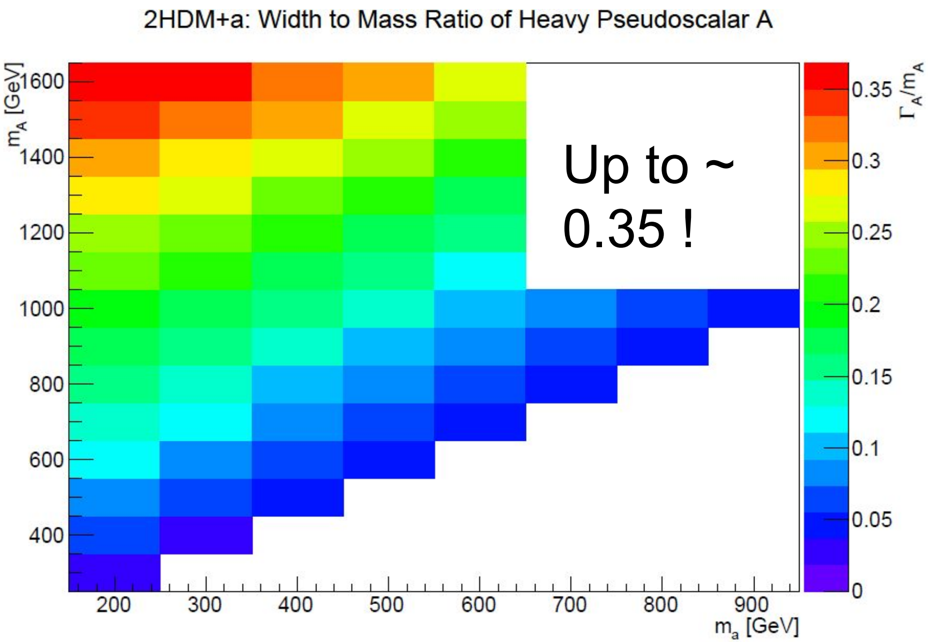


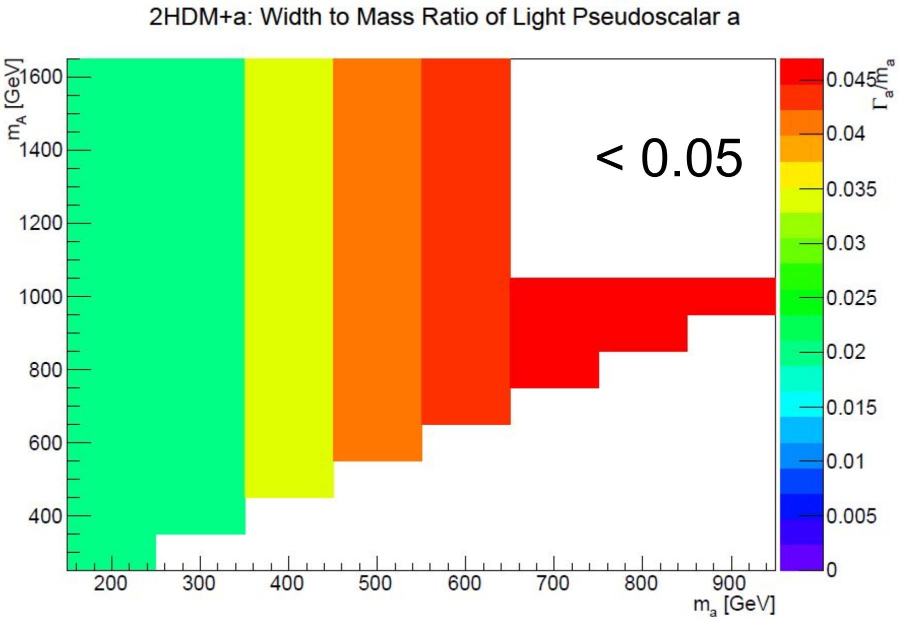


- width of a is always small
- width of A can get large → too large?
  - paper: widths <~ m/3 for Benchmarks
  - → up to m/5 should be ok

- mH = mA + 100 GeV
- sin(theta) = 0.35

Width/Mass at sin(theta) = 1/sqrt(2)

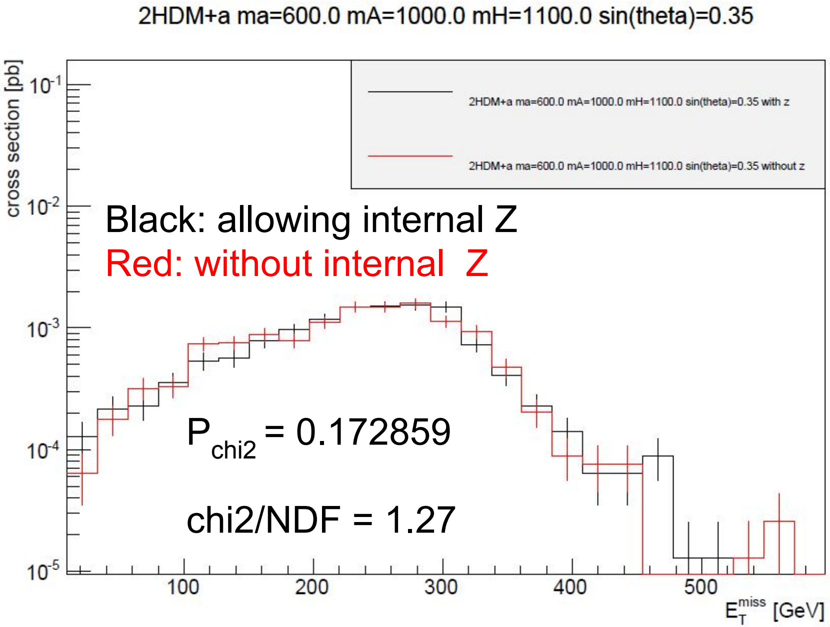


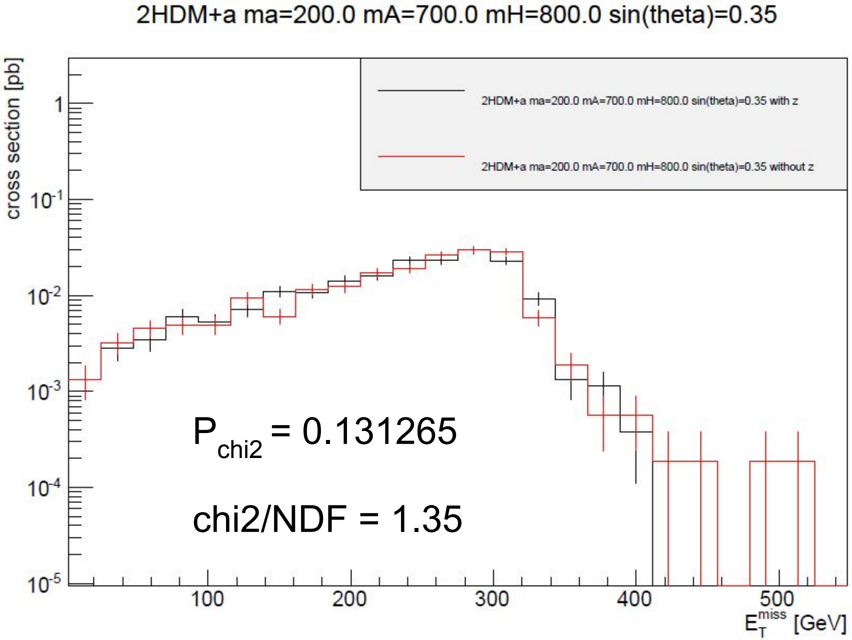


- width of a stays small
- width of A can get large → too large?
  - paper: widths <~ m3 for Benchmarks
  - ⇒ the very top left is a bit of a problem

- mH = mA + 100 GeV
- *sin(theta) = 1/sqrt(2)*

“/z” vs no “/z”: Cross-check

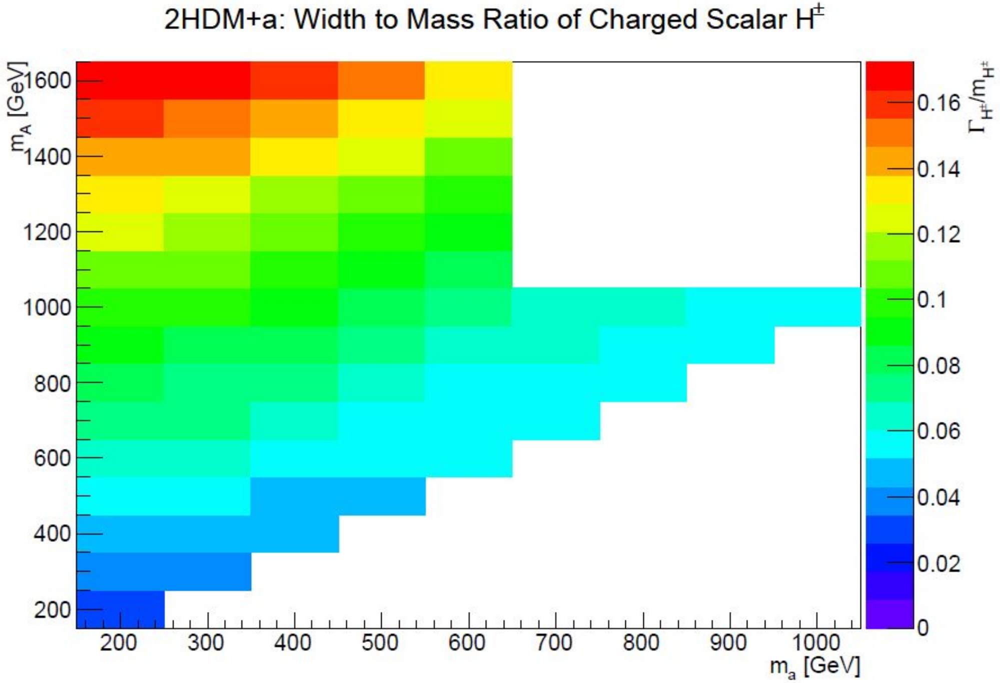


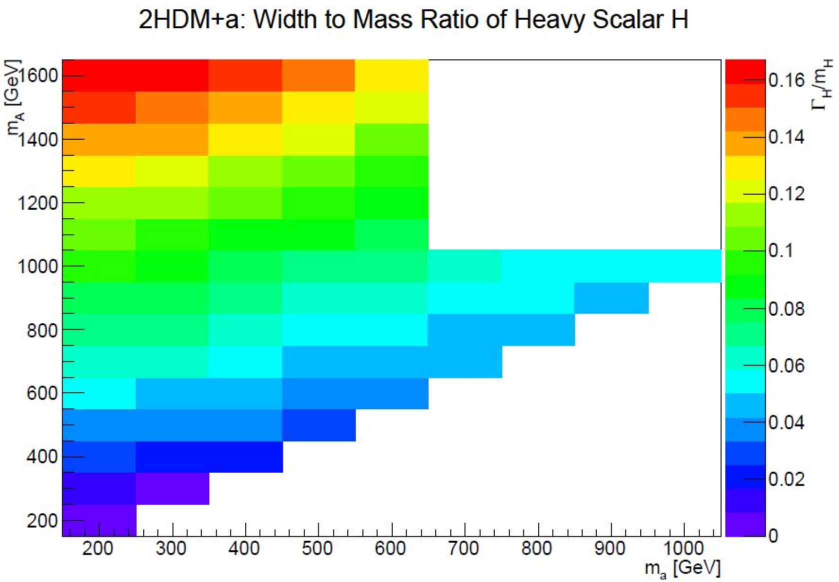


- Event generation in mono-h excluding internal z lines (generate g g > h1 xd xd~ \z [QCD]) is a lot faster
- Can break gauge invariance ⇒ cross-check needed
- Checked standalone with 1000 events each
- ⇒ no striking difference, will verify with larger sample

width/mass of H and H^{+-}

⇒ very similar to A

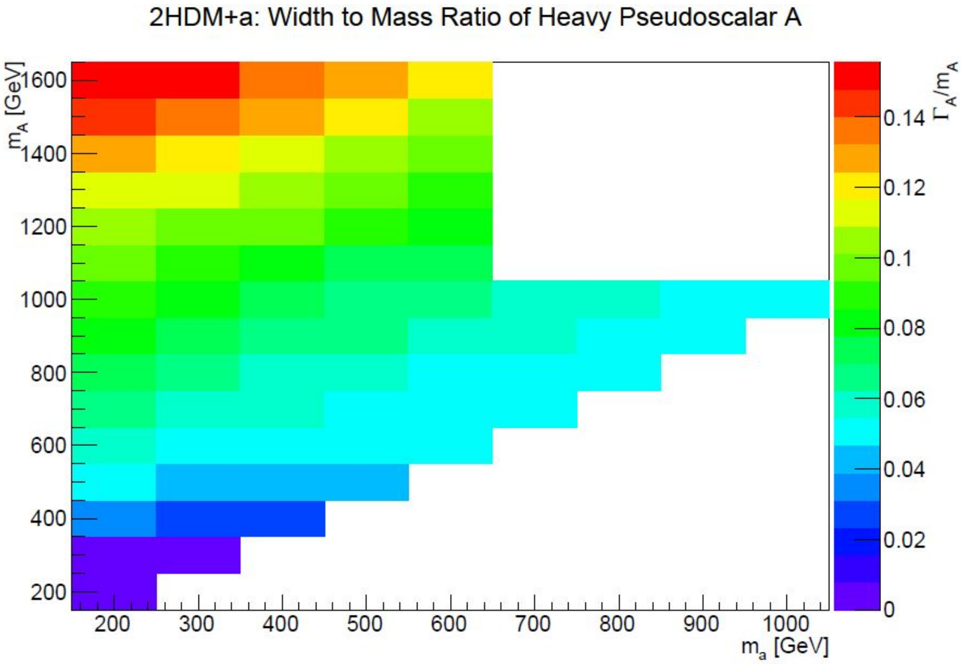


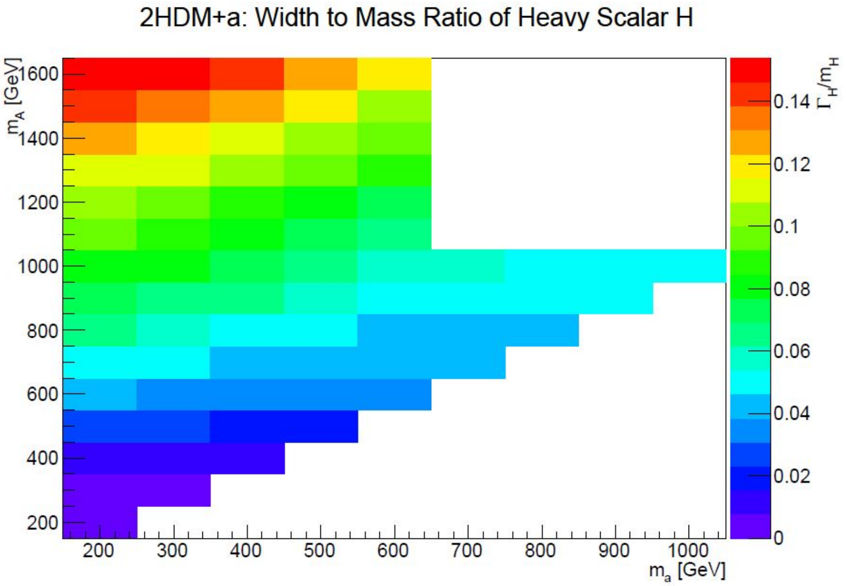


- mH = mA + 100 GeV
- sin(theta) = 0.35

For smaller m_H

⇒ no big changes compared to $m_A = m_H + 100$ GeV

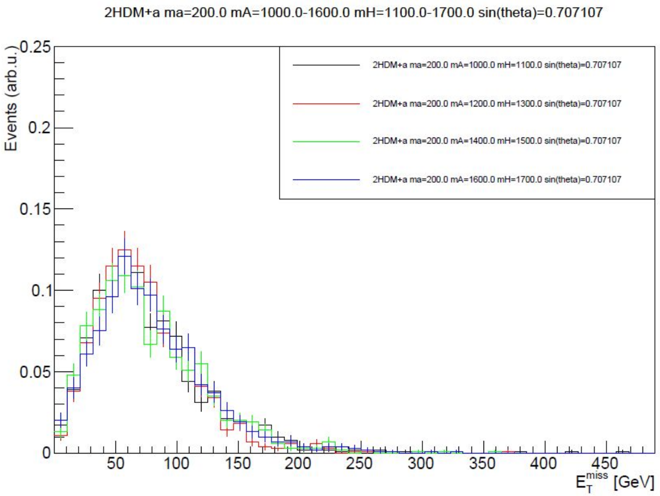


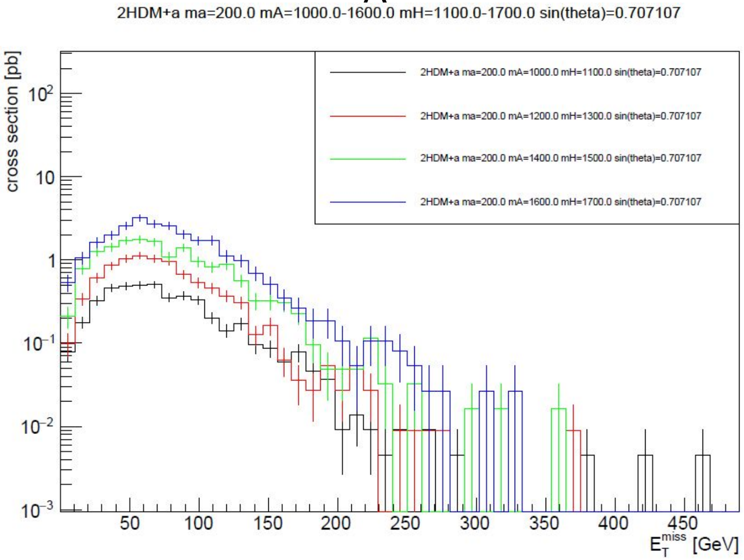


- mH = mA GeV
- sin(theta) = 0.35

Backup: m_A signal degeneracy for sin(theta) = 1/sqrt(2)

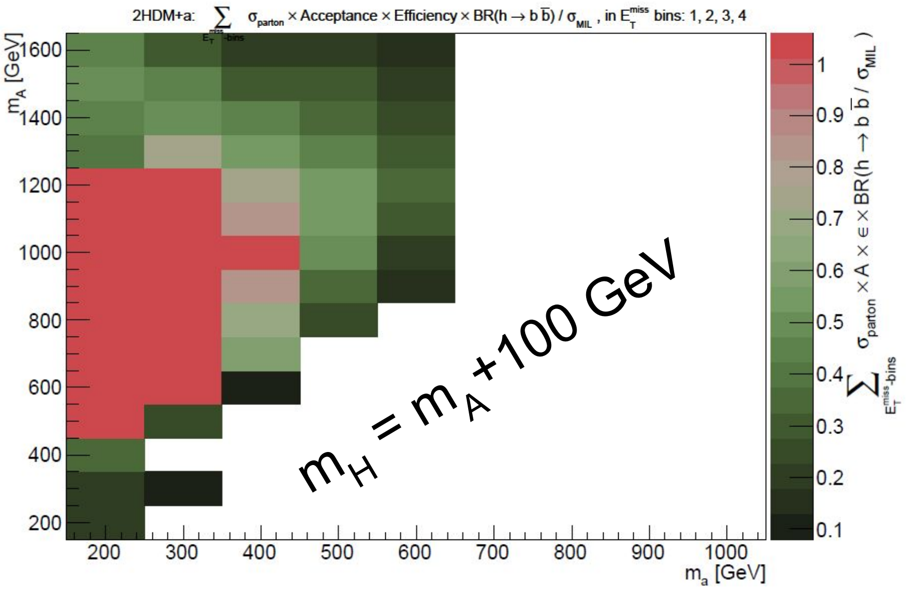
- only minor signal shape changes from changing m_A ($\gg m_a$)for sin(theta) = 1/sqrt(2)
- dominant effect is cross-section increase
- $\rightarrow$ exclusion largely independent of m_A in this region

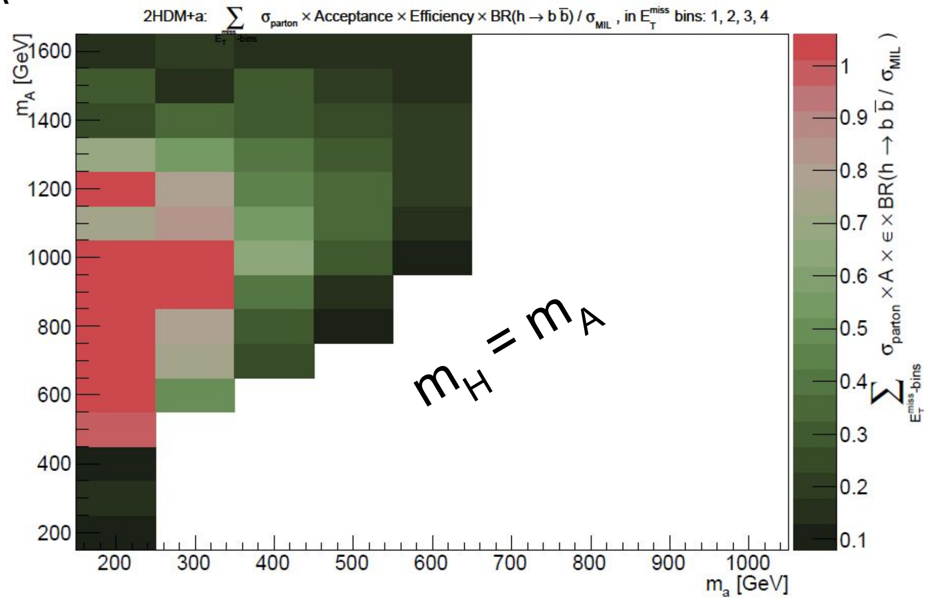




$m_H = m_A$+100 GeV vs. $m_H = m_A$

- less sensitive to $m_H = m_A$ scenario (reduced cross-section)
- would mono-Z benefit much from $m_H = m_A$?
    - ⇒ if not, stick to $m_H = m_A$ +100 GeV

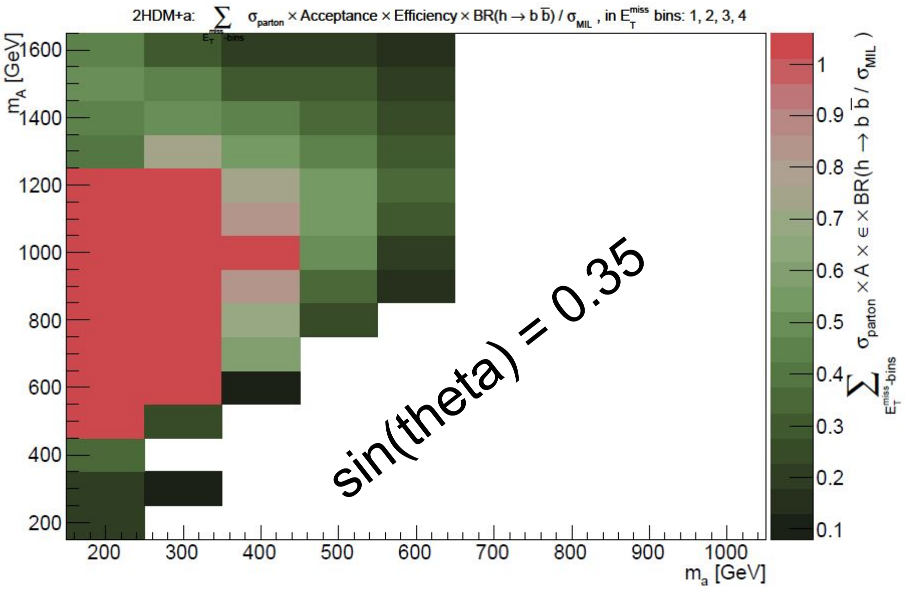


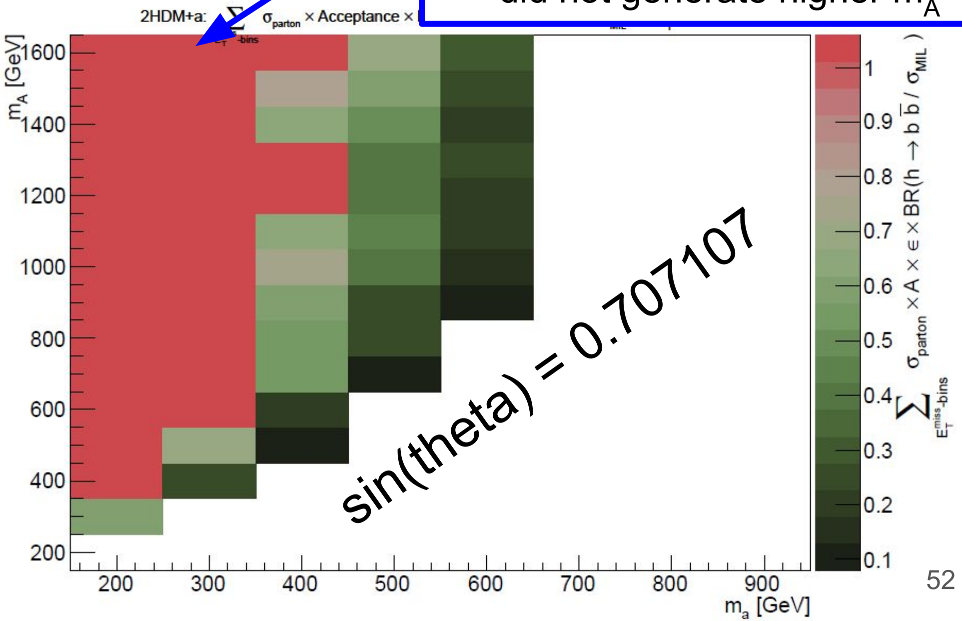


sin(theta) = 0.35 vs sin(theta)=1/sqrt(2)

- large significance gain for high-m_A,low-m_a region
  - low-MET, but high x-sec signal
- ⇒ sin(theta) .lhe-reweighting of interest here

Width of A ~ m_A/3. for m_A >= 1.5 TeV
⇒ cannot rely on Auto-Calc. Widths
⇒ did not generate higher m_A

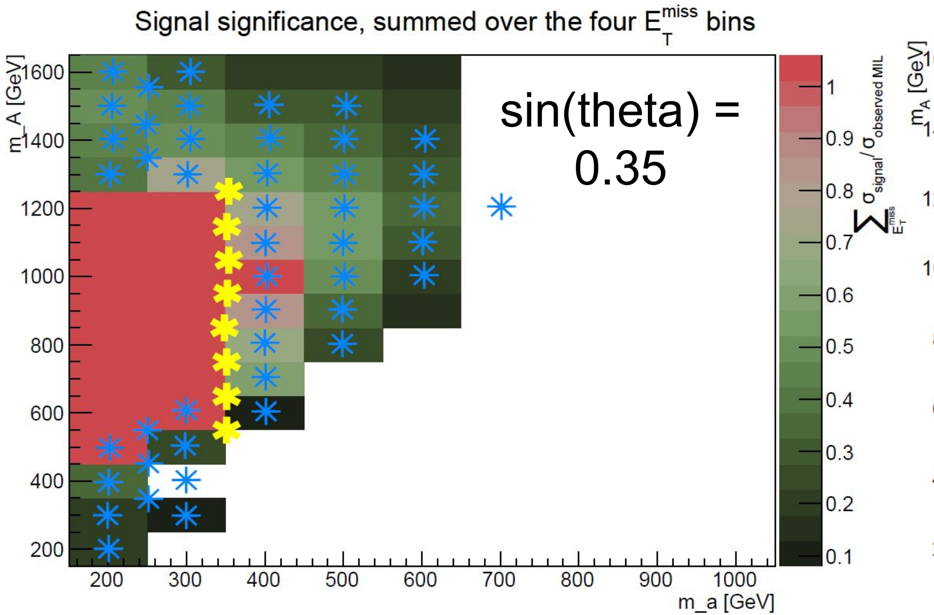


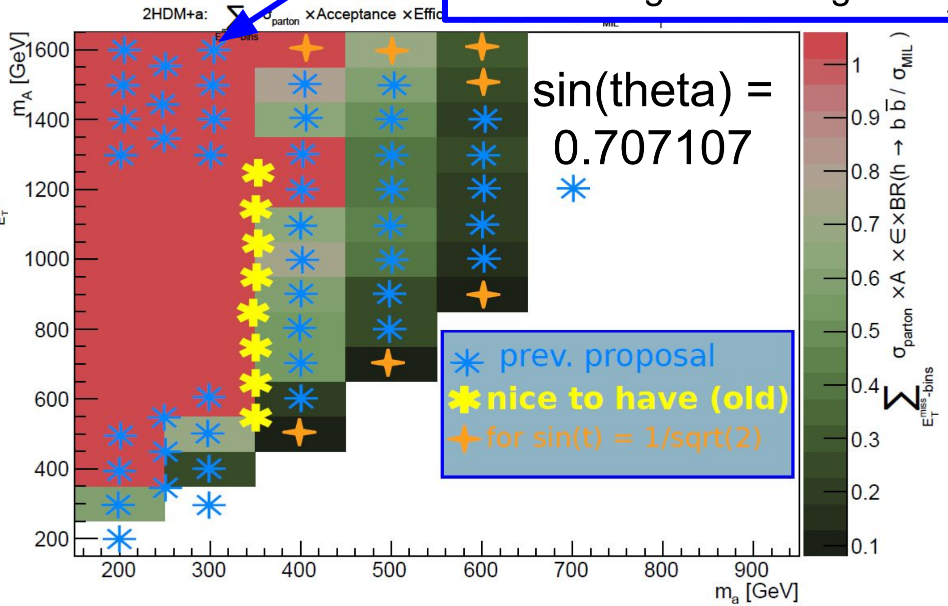


sin(theta) = 0.35 vs sin(theta)=1/sqrt(2)

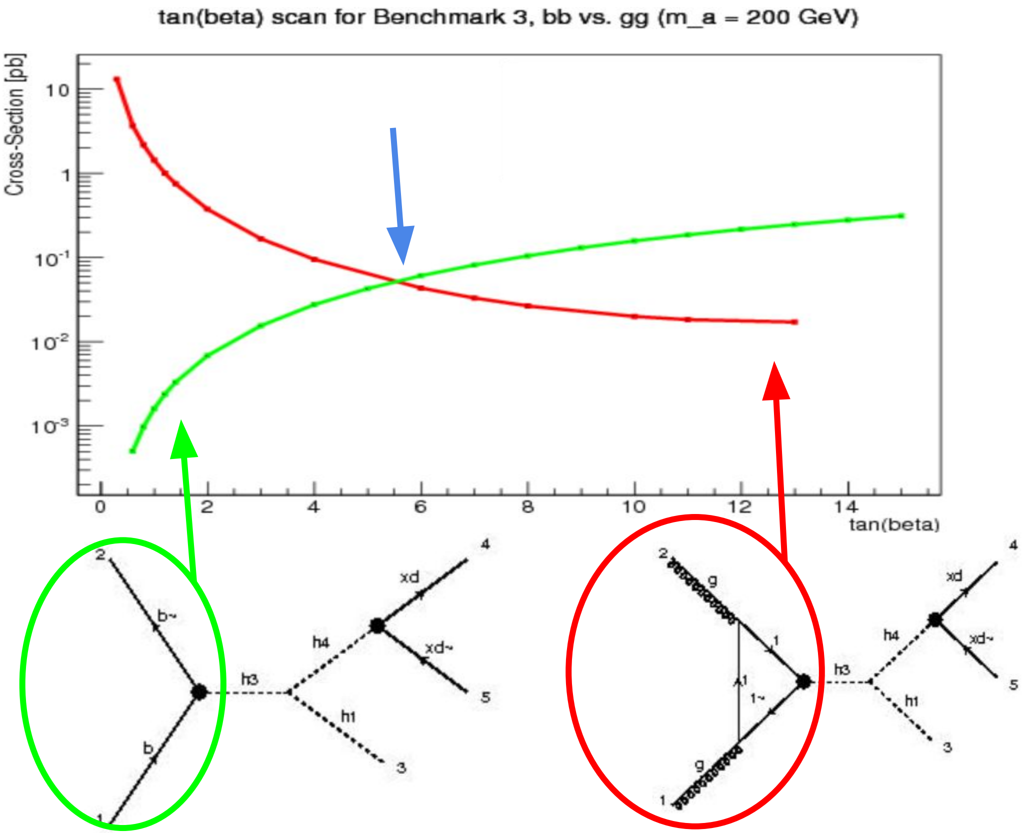
- large significance gain for high-m_A,low-m_a region
  - low-MET, but high x-sec signal
- ⇒ sin(theta) .lhe-reweighting of interest here

Width of A ~ m_A/3. for m_A >= 1.5 TeV
⇒ cannot rely on Auto-Calc. Widths
⇒ did not generate higher m_A





High tan(beta): production via bb?



- Comparing production channels: 'b b > …' and 'g g > …'
  - type II Yukawa-sector
  - gluon fusion dominant up to tan(beta) ~ 5