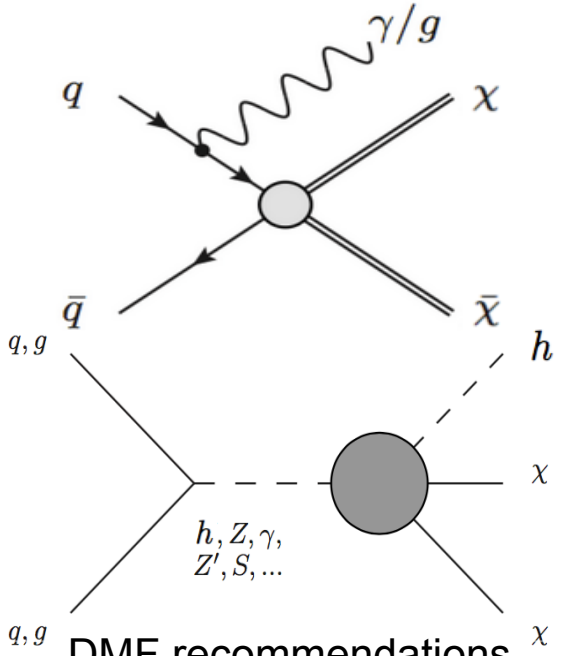
SENSITIVITY STUDIES OF THE 2HDM+A MODEL AT ATLAS

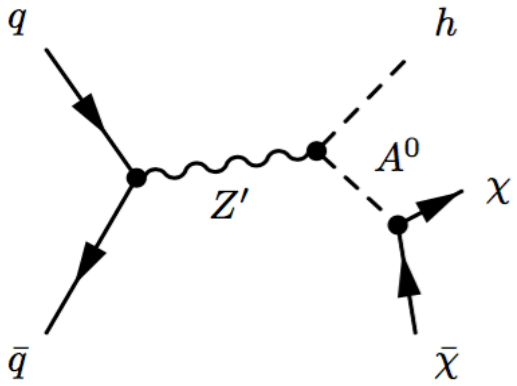
LHC DM WG meeting
28.04.2017

Oleg Brandt
on behalf of ATLAS



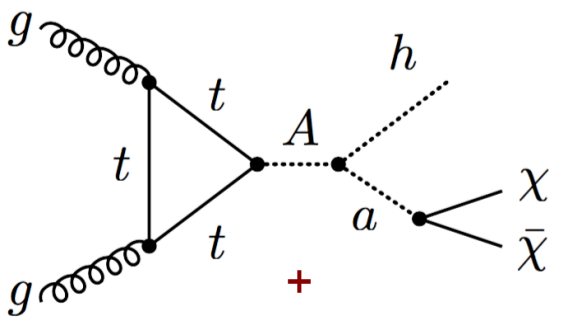
DMF recommendations
arXiv:1507.00966

1) Effective field theory



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

2) Simplified models



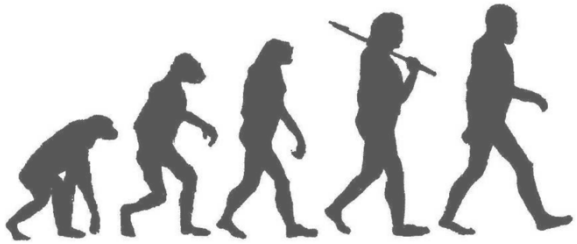
\+

many other signatures

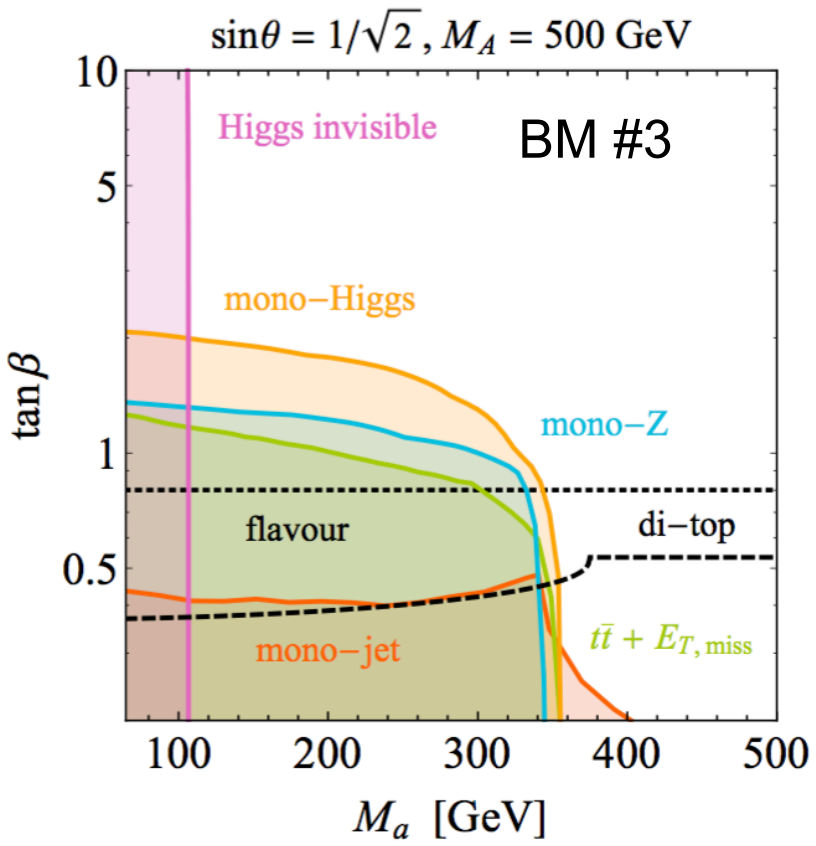
2HDM+a model
arXiv:1701.07427

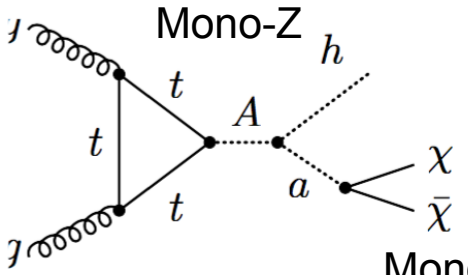
3) Simplified, consistent, & UV-complete models

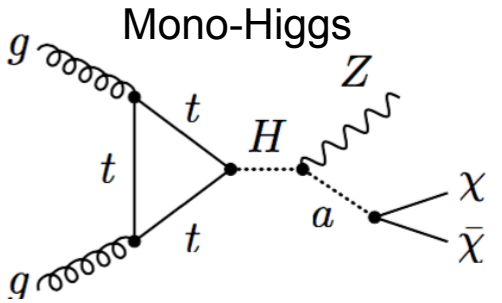
Richer kinematics + phenomenology

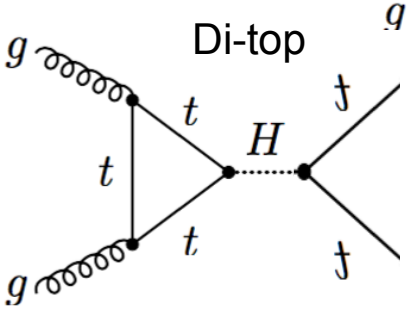


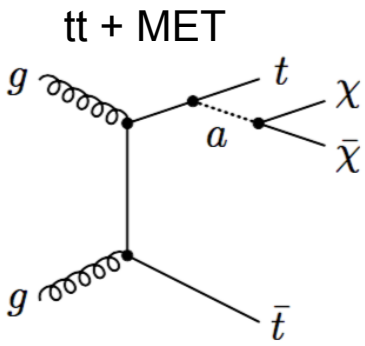
- **Diverse palette of signatures:**

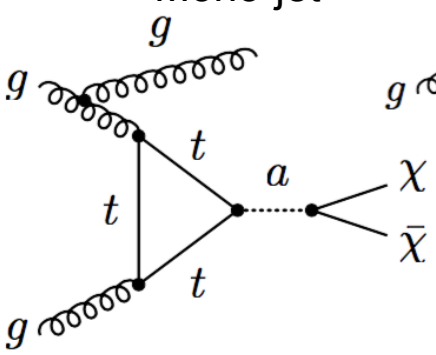












- **The interplay is experimentally exciting!**
- **Today's talk:**
  - ATLAS study of model pheno + status
  - First proposal for signal grid (ATLAS)

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

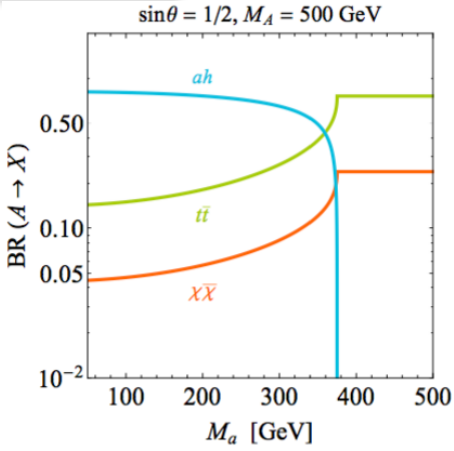
- *4 affect MET shape:*
  - m_a
  - m_A
  - m_H

  } *kinematics & channels*

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

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

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

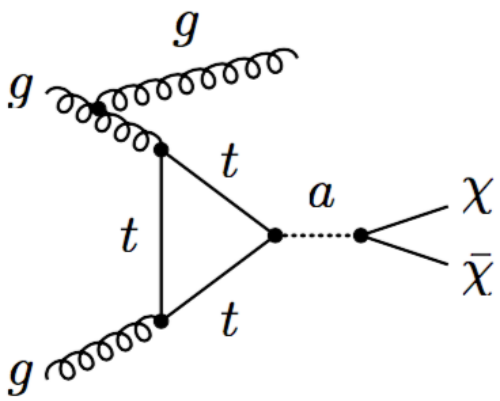


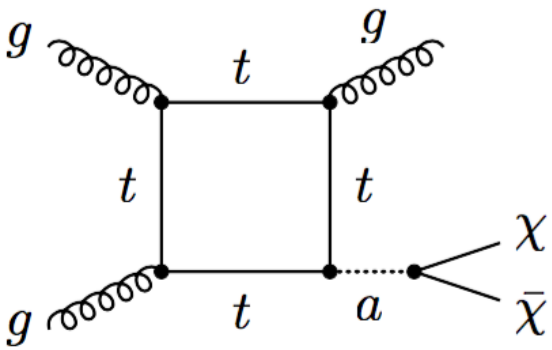
[1] can change shapes if u/d-type couplings process-relevant
[2] statement true if decay mediator on-shell

General software status

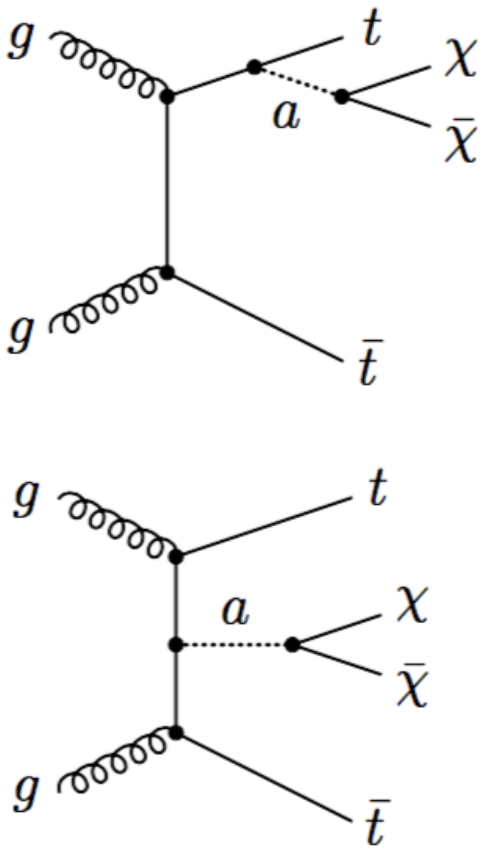
- UFO implemented
  - Most signatures now work at LO and NLO
    - Jet + MET works, checking g g > xd xd j [QCD]
    - HF + MET works at LO, NLO needs more work (Uli looking into this)
    - Z + MET works
    - h + MET generally works (some excluded phase space not stable)
      - 2-dim scan with 50 points / 10k each ~ 1 day on 500 cores
- Many thanks to the authors for their help!
  - (especially Uli for technical details!)

- 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}?



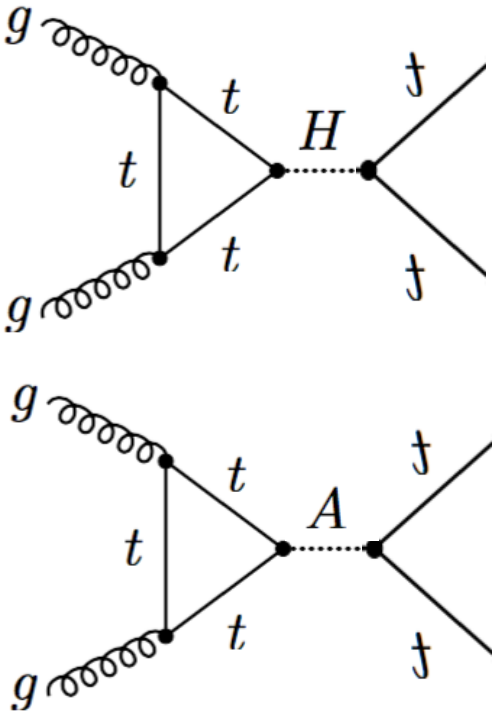


- Syntax:
  - p p > xd xd t t
  - p p > xd xd b b
- Status:
  - Madgraph setup working at LO
    - 4 and 5 flavour scheme (FS)
  - NLO setup fails (UFO issue, Uli looking into this)
- Next steps:
  - Quantify difference 4 vs 5 FS
  - Systematically study model at particle level
- General:
  - Driving the sensitivity for 2HDM+a for:
    - tanβ < 0.5
    - High m_a
  - Define grid using resonant (other) signatures
    - Check complementarity?



$tt/bb/\tau\tau$ RESONANCES

- Syntax:
  - p p > t t [QCD]
- Status:
  - Madgraph working
  - Model extends “normal” type-II 2HDM Models
    - type-II 2HDM already used in searches
- Next steps:
  - Model SM/2HDM+a interference using a 2HDM:
    - Production mode same in 2HDM & 2HDM+a
    - Decay width differs between 2HDM & 2HDM+a
      - Small effect (tt decay dominant in BM #3)
    - Study in more detail at particle level
      - Rescale existing benchmark samples
- General:
  - Define grid using resonant (other) signatures
    - Check complementarity?



W + E_T^{MISS}

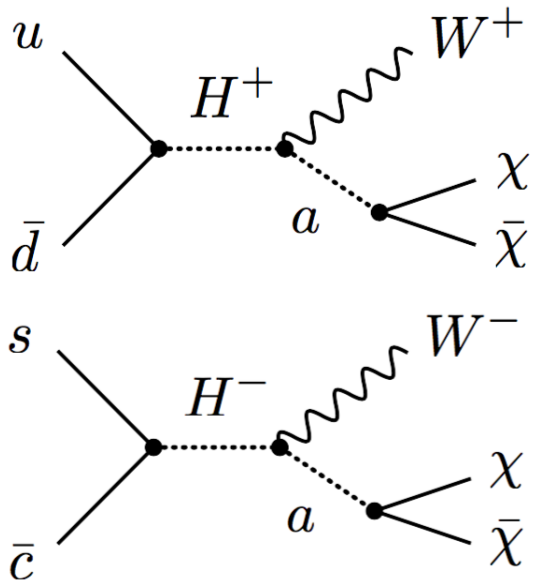
- Syntax:
  - p p > xd xd w
- Status:
  - UFO being prepared
- Next steps:
  - Plug & play
- General:
  - **Always there, but low Xsec:**

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

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

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

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

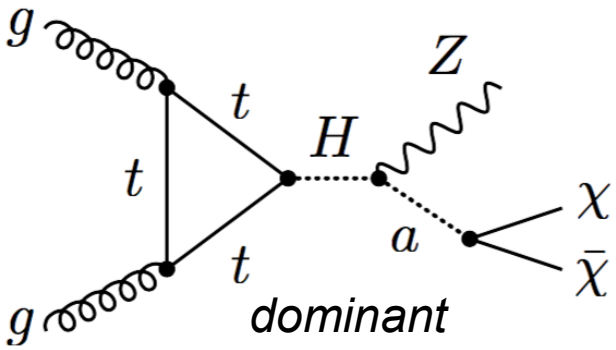


  - Still want this UFO to motivate W+MET?
    - Model gives interesting kinematic distributions…
  - Change in kinematics and xsec with u/d type couplings?

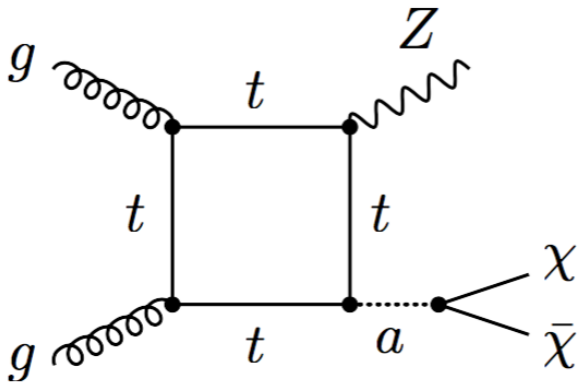
$Z + E_T^{MISS}$

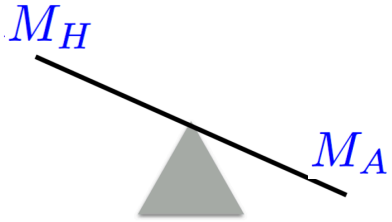
- Syntax:
  - p p > xd xd z [QCD]
- Status:
  - Madgraph working
    - M_a < 10 GeV unstable (for m_χ = 1 GeV)
      - Not relevant given h→inv
  - Systematic studies ongoing (next slides)
- Next steps:
  - Conclude studies
  - Converge on a grid
- General:
  - **Can be resonantly enhanced**
    - → driving sensitivity for 2HDM+a
  - **Z + E_T^{miss} dominant** over h + E_T^{miss} if

$$M_A > M_H, M_a$$
$$(M_{H^\pm} \simeq M_A)$$

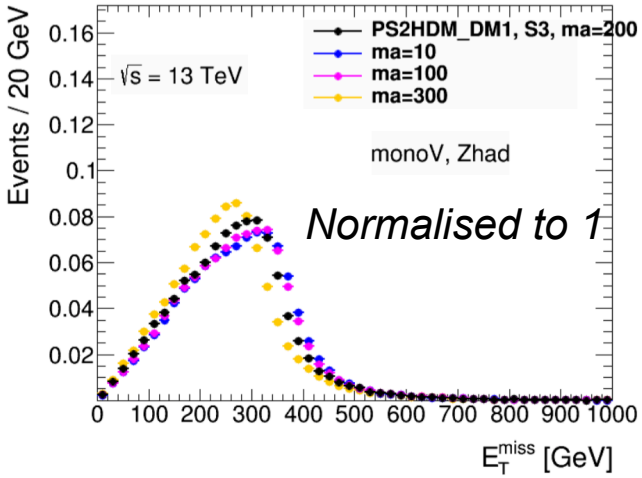


dominant

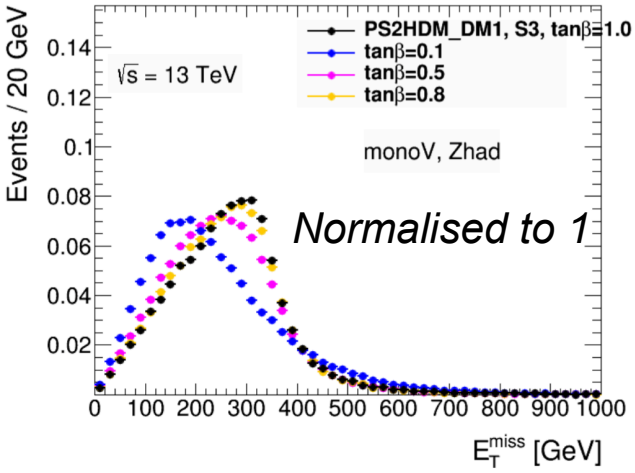


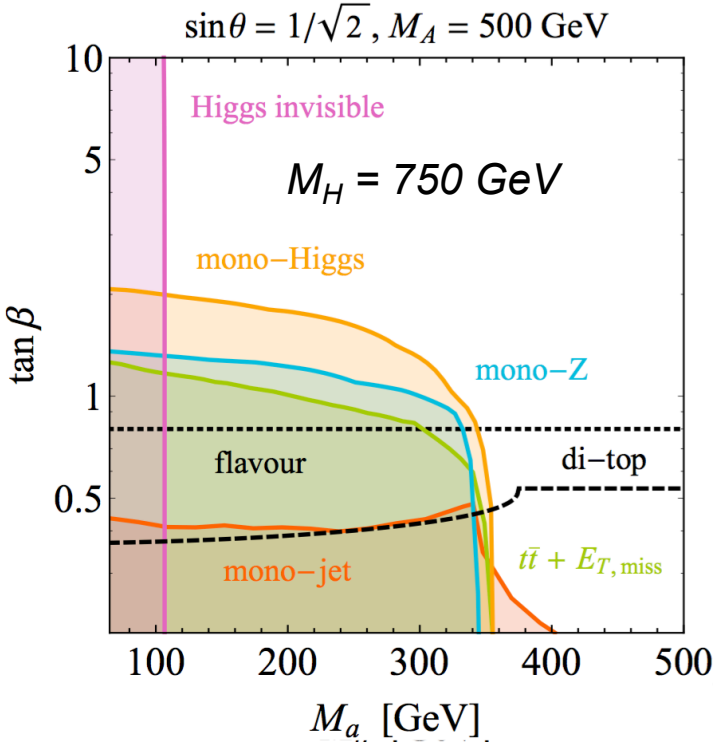


- **Most studies start from BM #3** (provides most signatures)
  - Explore model parameters one by one
    - **Weak dependence on M_a**



    - **Some dependence on tanβ**



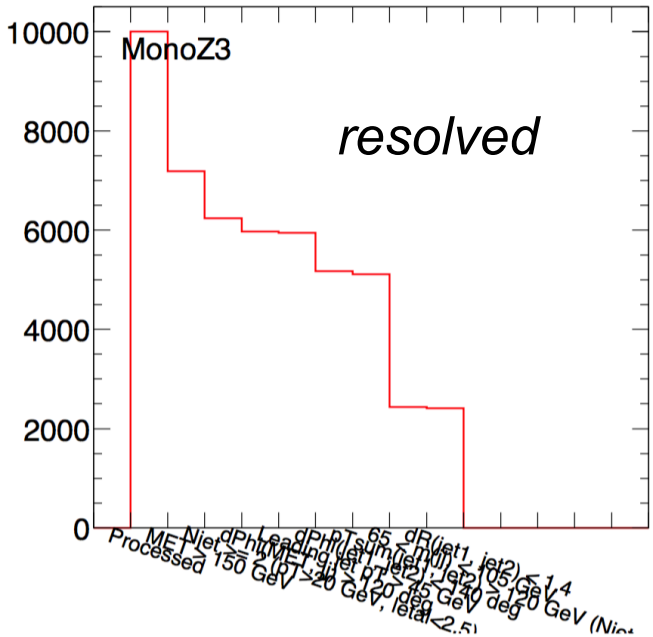


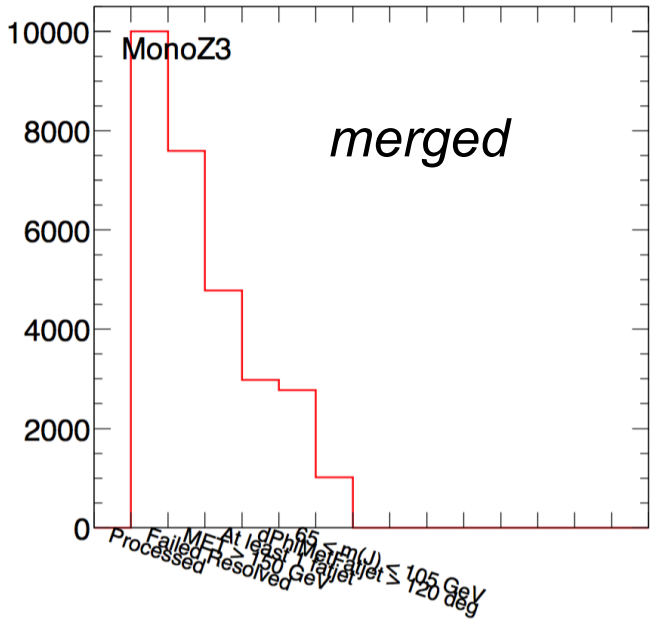
$Z \rightarrow \ell\ell$ channels favoured for small $M_a - M_H$ splitting due to lower E_T^{miss} cut:

$$M_H \gtrsim M_a + \sqrt{M_Z^2 + (E_{T,\mathrm{miss}}^{\mathrm{cut}})^2}$$

- Check **contribution of resolved vs. merged** analyses
  - (merged is CPU-intensive)
  - Mimic analysis-like cut flow:
    - try M_H = 1, 1.5, 2 TeV (1 TeV shown)

Guidance on good choices of parameters welcome!
e.g. M_H < 1.2 TeV, tanβ > 0.3





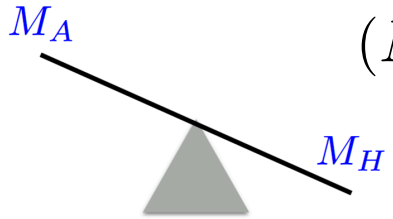
selections motivated by PLB 763 (2016) 251

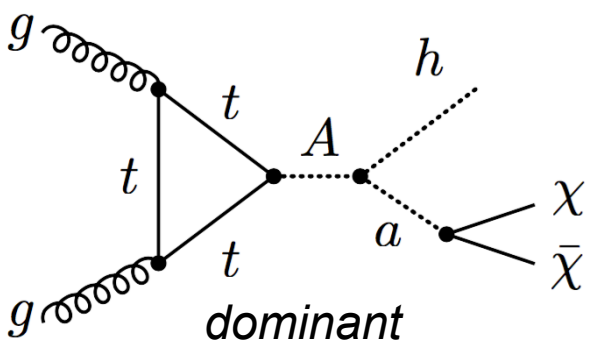
  - Efficiencies for resolved (~25%) and merged (~15%) remain similar
    - Non-resonant production contributes for high m_H
      - To enhance, increase m_A coherently and $m_A > m_H$
    - No dependence on M_a = 10, 20, 50, 200 GeV (expected, not shown)

h + E_T^{MISS}

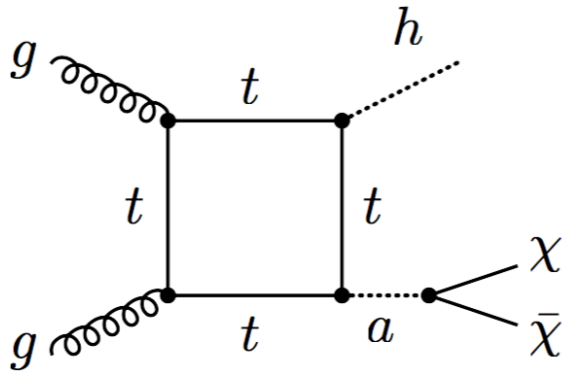
- Syntax:
  - g g > xd xd h1 [QCD]
- Status:
  - Madgraph working
  - Systematic studies ongoing (next slides)
  - Preliminary grid proposal (next slides)
- Next steps:
  - Converge on a grid
- General:
  - **Can be resonantly enhanced**
    - → driving sensitivity for 2HDM+a
  - **h + E_T^{miss} dominant** over Z + E_T^{miss} if

$$M_H > M_A, M_a$$
$$(M_{H^\pm} \simeq M_H)$$





dominant



h(yy) + MET channel favoured for small M_a – M_A splitting due to lower MET cut:

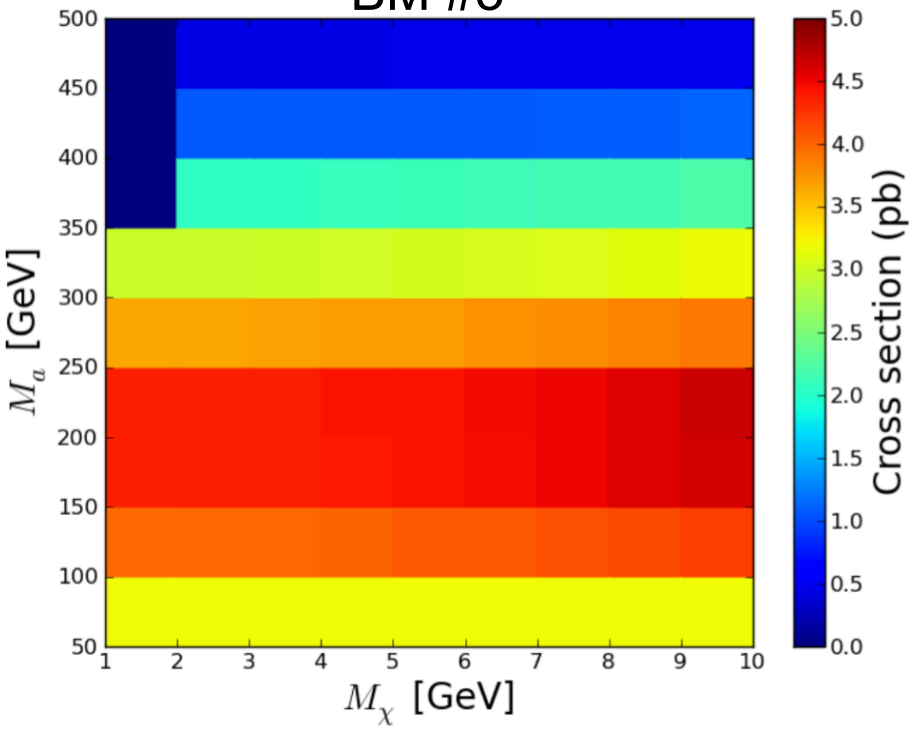
$$M_A \gtrsim M_a + \sqrt{M_h^2 + (E_{T,\mathrm{miss}}^{\mathrm{cut}})^2}$$

h + E_T^{MISS} : PARAMETER SCAN

- Confirm that parameters **only change total xsec:**
  - y_χ
  - $0.4 < \tan\beta < 1$
    - For higher $\tan\beta$ bb production
  - m_χ
    - as long as m_A on-shell

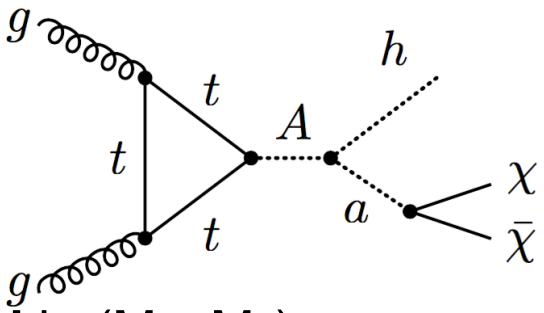
Grid proposal for other 4 parameters

BM #3



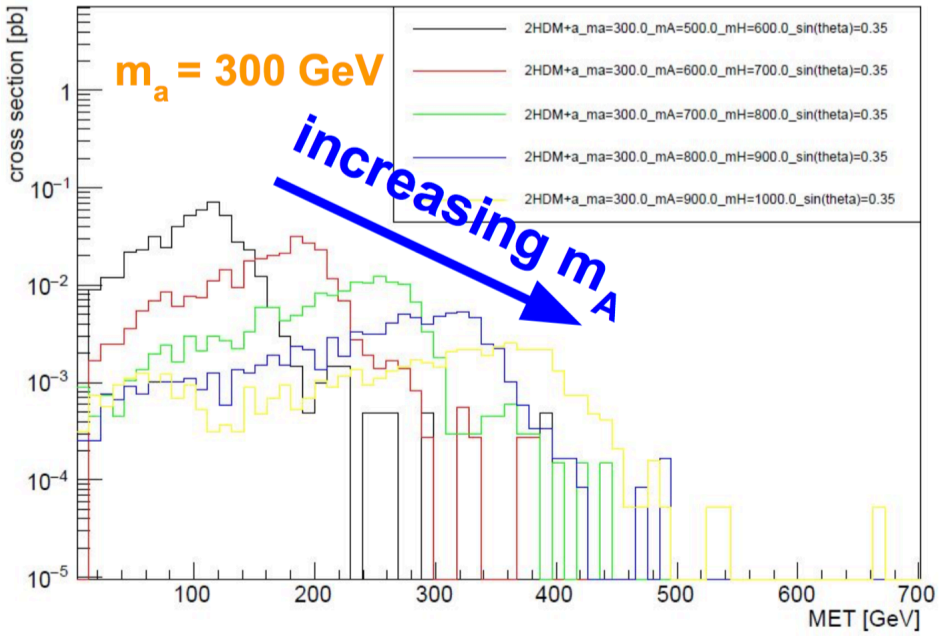
h + E_T^{MISS} : MAIN GRID FROM KINEMATICS

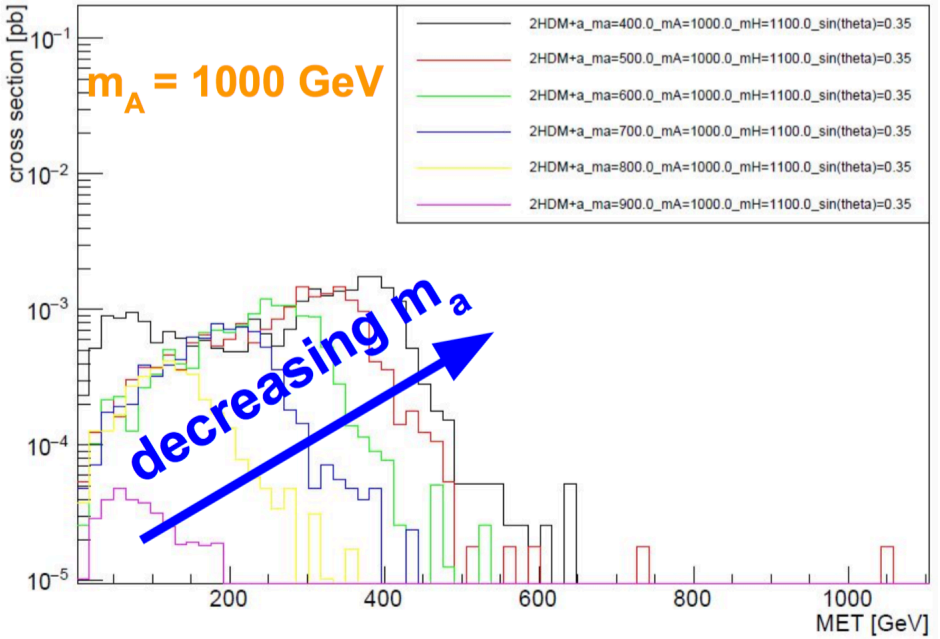
- **Dominant effect** on signal shape **from mediator masses M_A, M_a**



  - Make **2dim signal grid** in (M_A, M_a)

sinθ = 0.35, M_H = M_A + 100 GeV



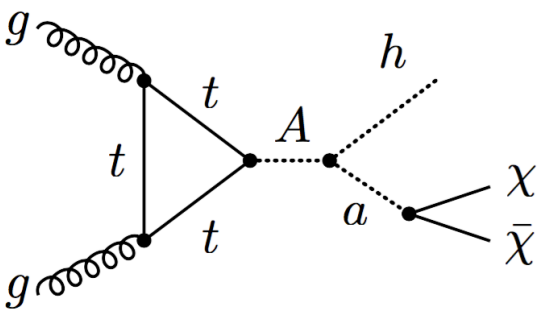


  - Subdominant effects from sinθ and M_H
    - → see next slides

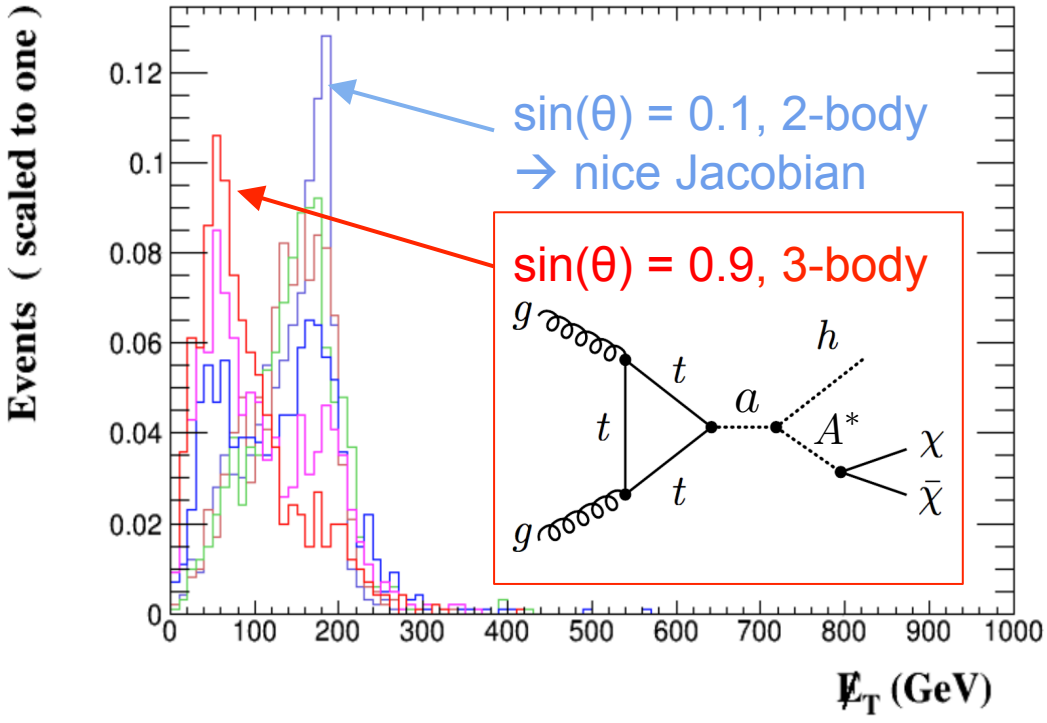
h + E_T^{MISS} : SECONDARY SCAN IN SINθ?

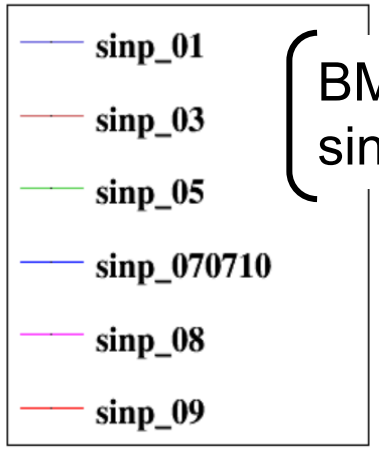
- Sinθ: a, A mixing angle

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



- Change balance between high-MET peak & low-MET bulk
- → **main scan:** pick low **sinθ = 0.35** value giving **hard MET**



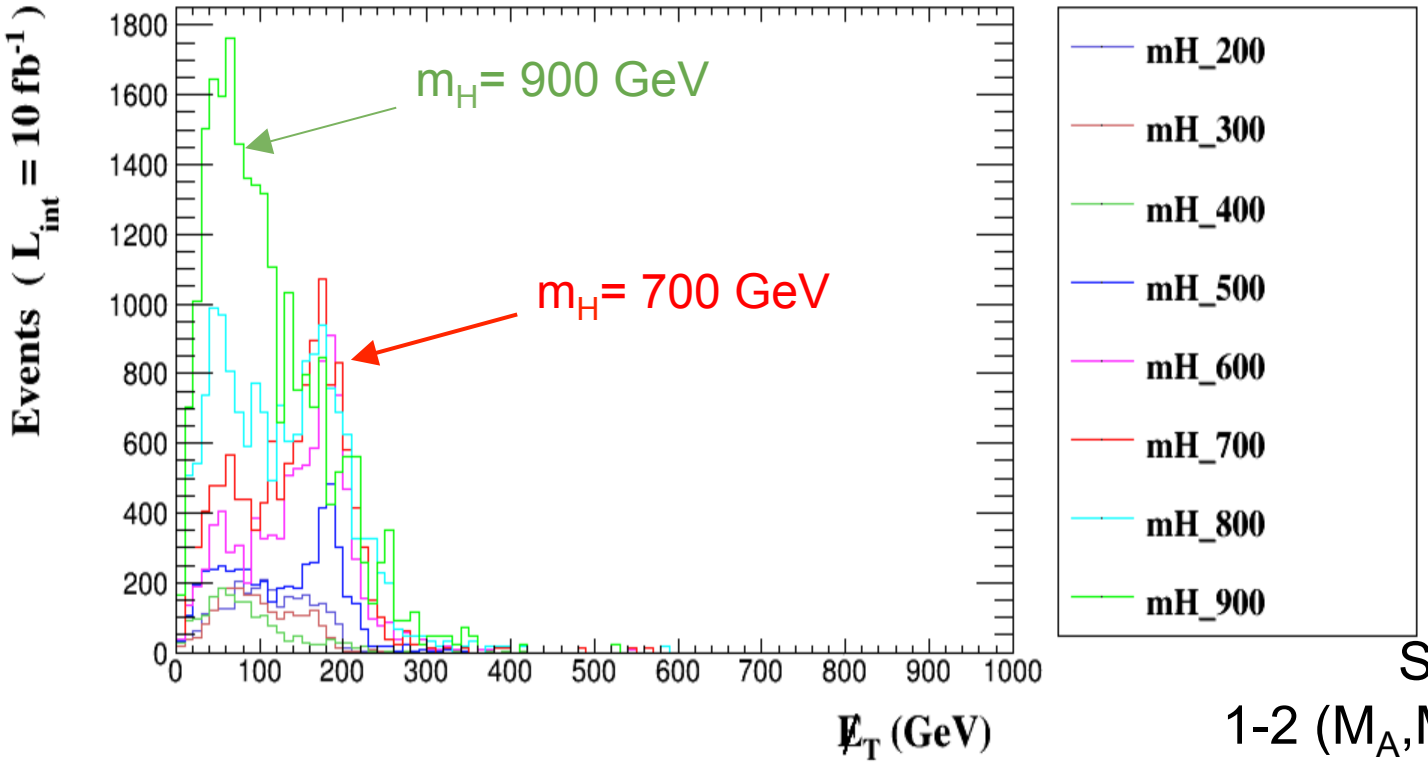


BM #3 uses sinθ = 1/√2

Scan sinθ for 1-2 (M_A,M_a) points?
3dim scan not realistic because of CPU: N^{dim}

h + E_T^{MISS} : SECONDARY SCAN IN M_H?

- **M_H: heavy scalar mass**
  - Not part of diagrams, but determines couplings
  - Change balance between high-MET peak & low-MET bulk
  - → **main scan:** pick **$M_H = M_A + 100$ GeV** value giving **hard MET**
    - Scalar couplings small → widths narrow → on-shell A decay dominant
    - M_H and M_A close → complementarity between Z+MET and h+MET



Scan M_H for 1-2 (M_A,M_a) points?

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

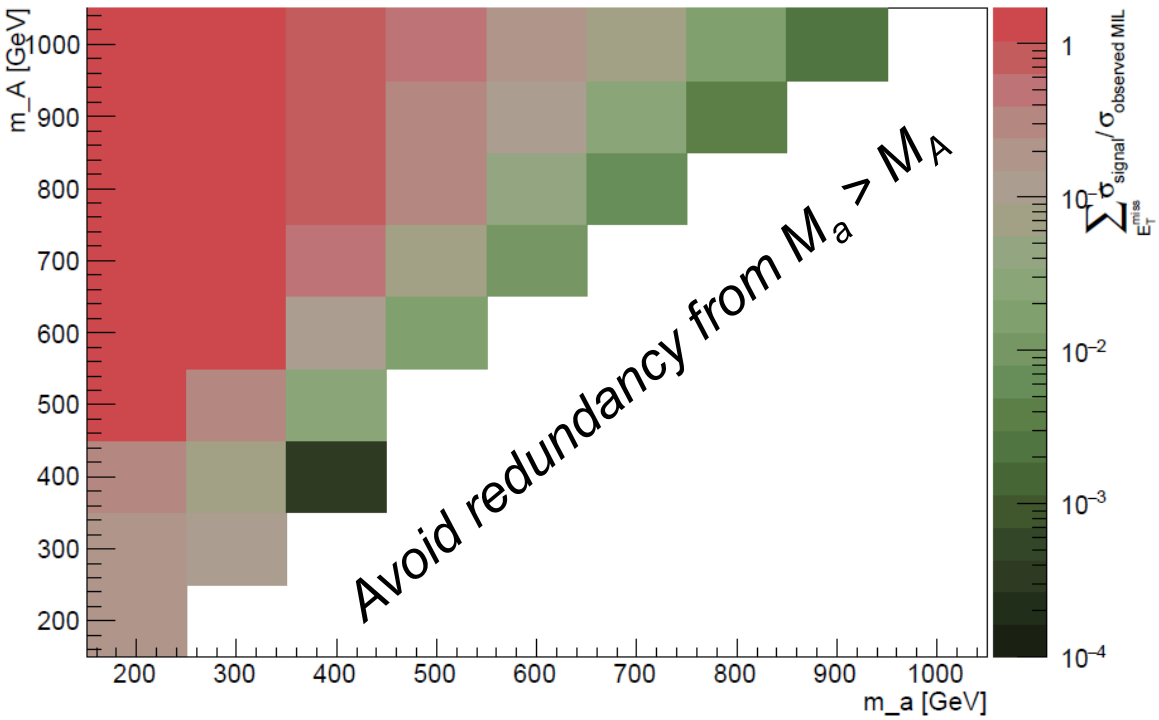
- **Use limits on visible cross-section**
  - "Model-independent" limits

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 $\sigma^{obs}_{vis,h+DM}$
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



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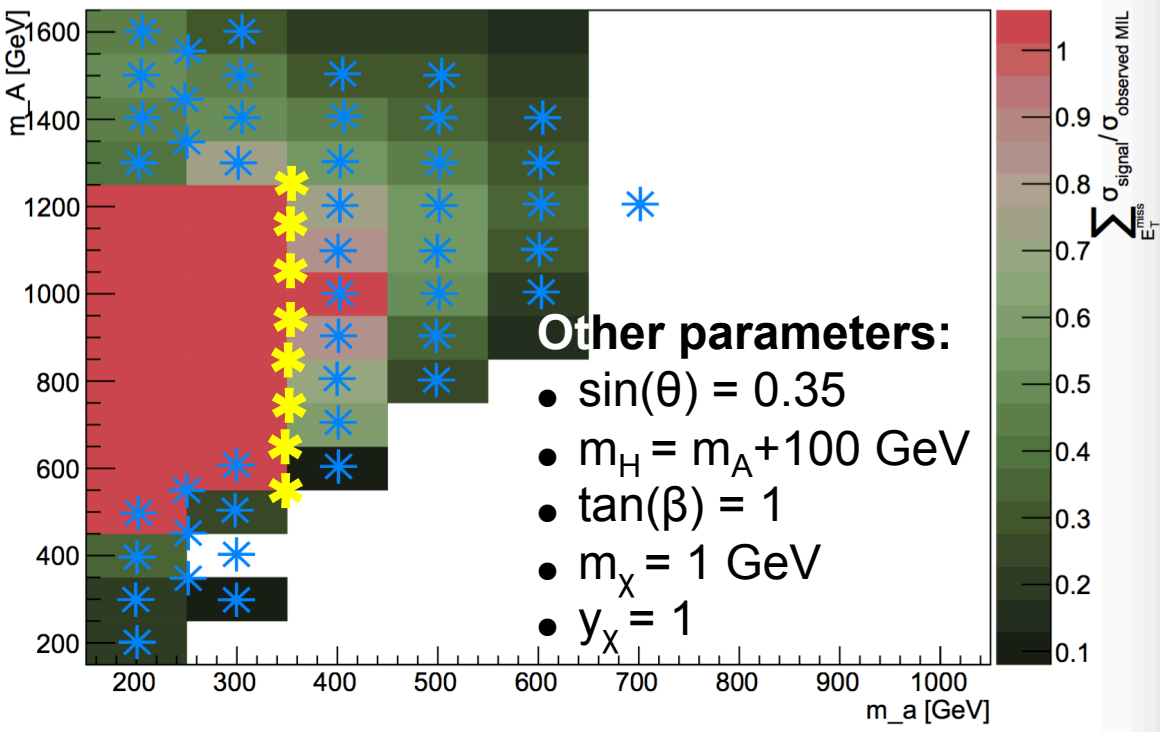
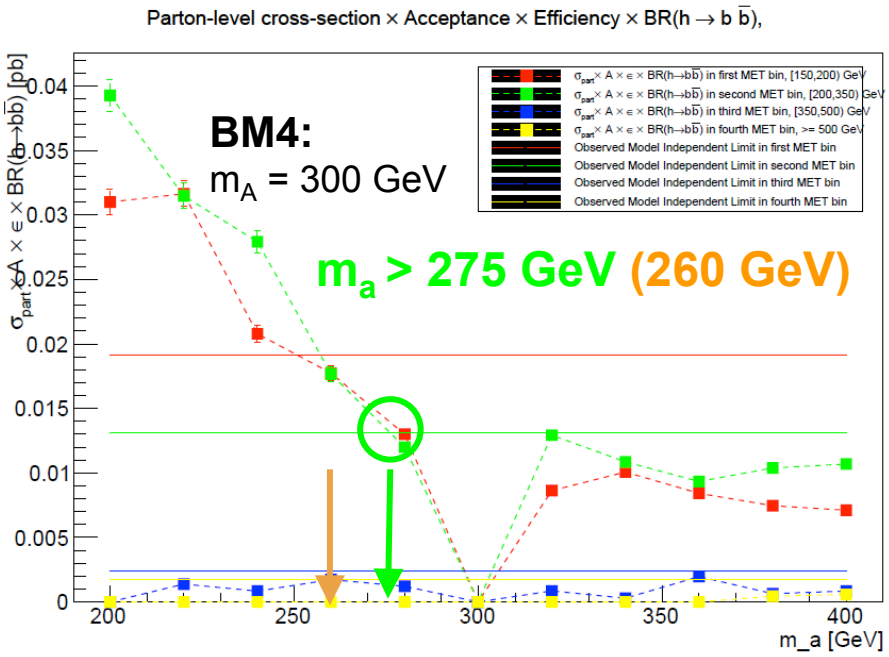
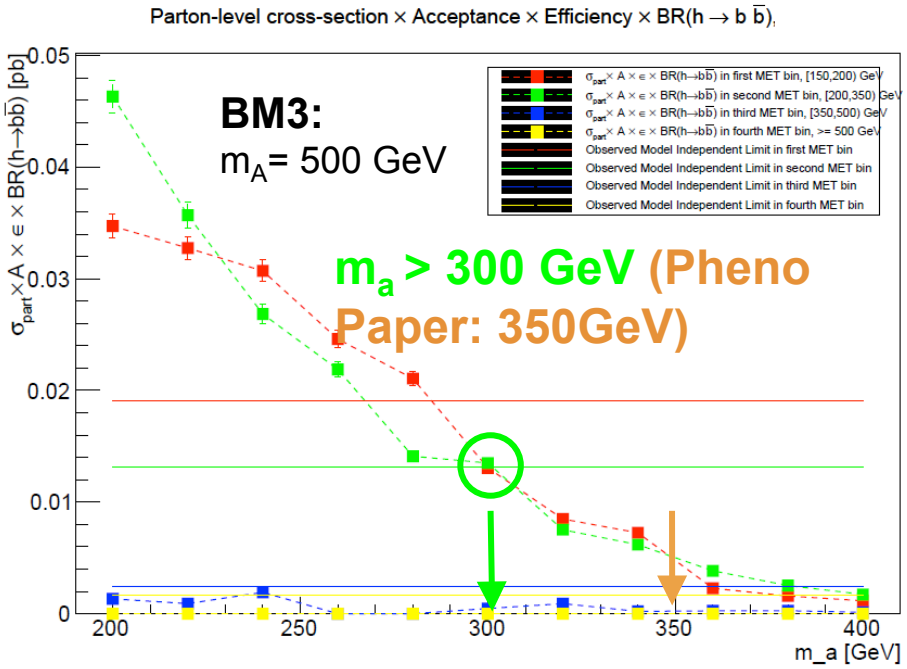


our suggestion (44)
nice to have (8)

$h(bb) + E_T^{MISS}$: CROSS-CHECKS

- **Scan M_a along $\tan\beta = 1$** for Benchmarks #3 and #4
  - Compare to **MILs** (L = 36.5 fb^{-1} from h(bb)+MET, conservative)
  - similar to **pheno paper expectation** (L = 40 fb^{-1} from h(γγ)+MET)

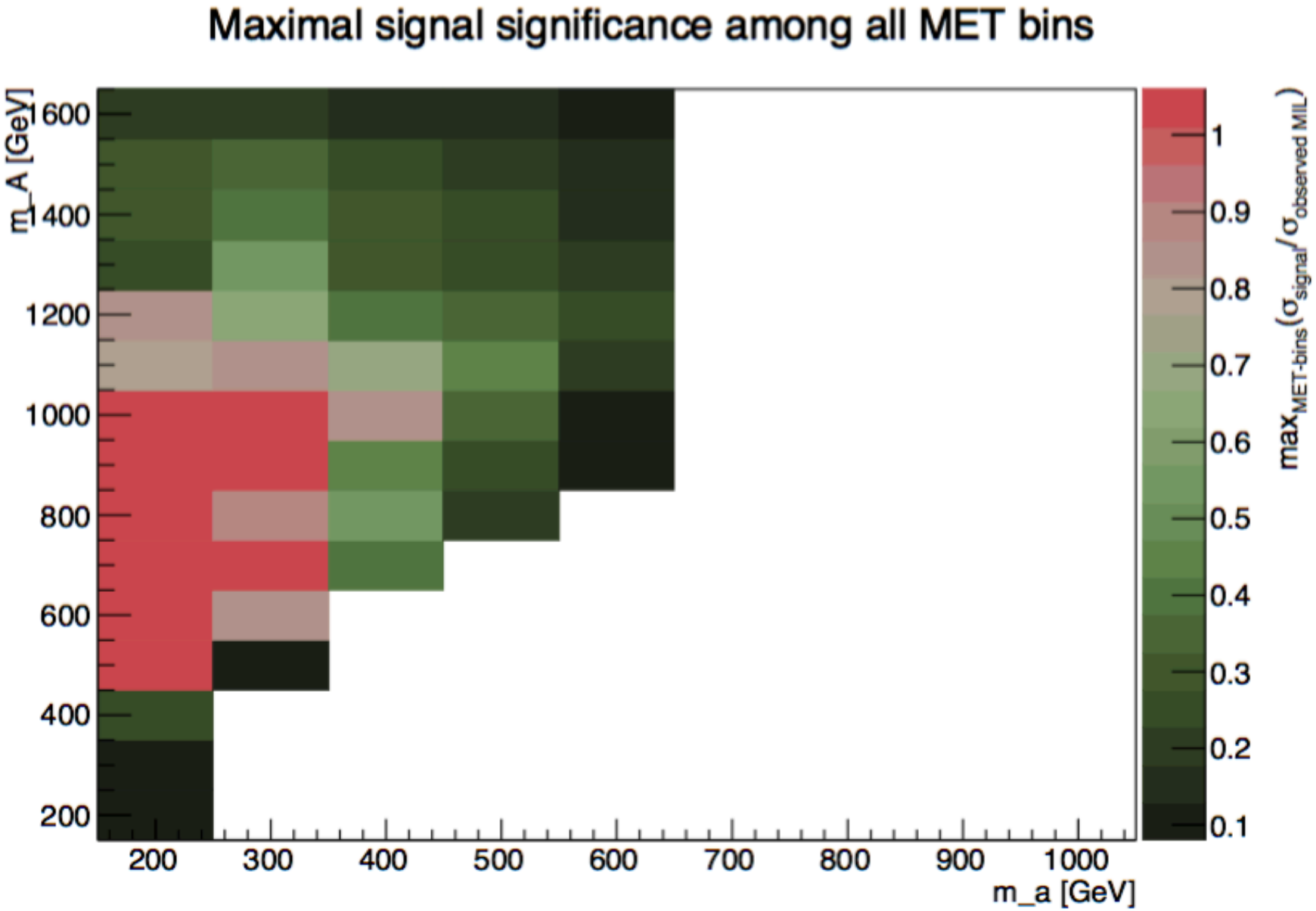




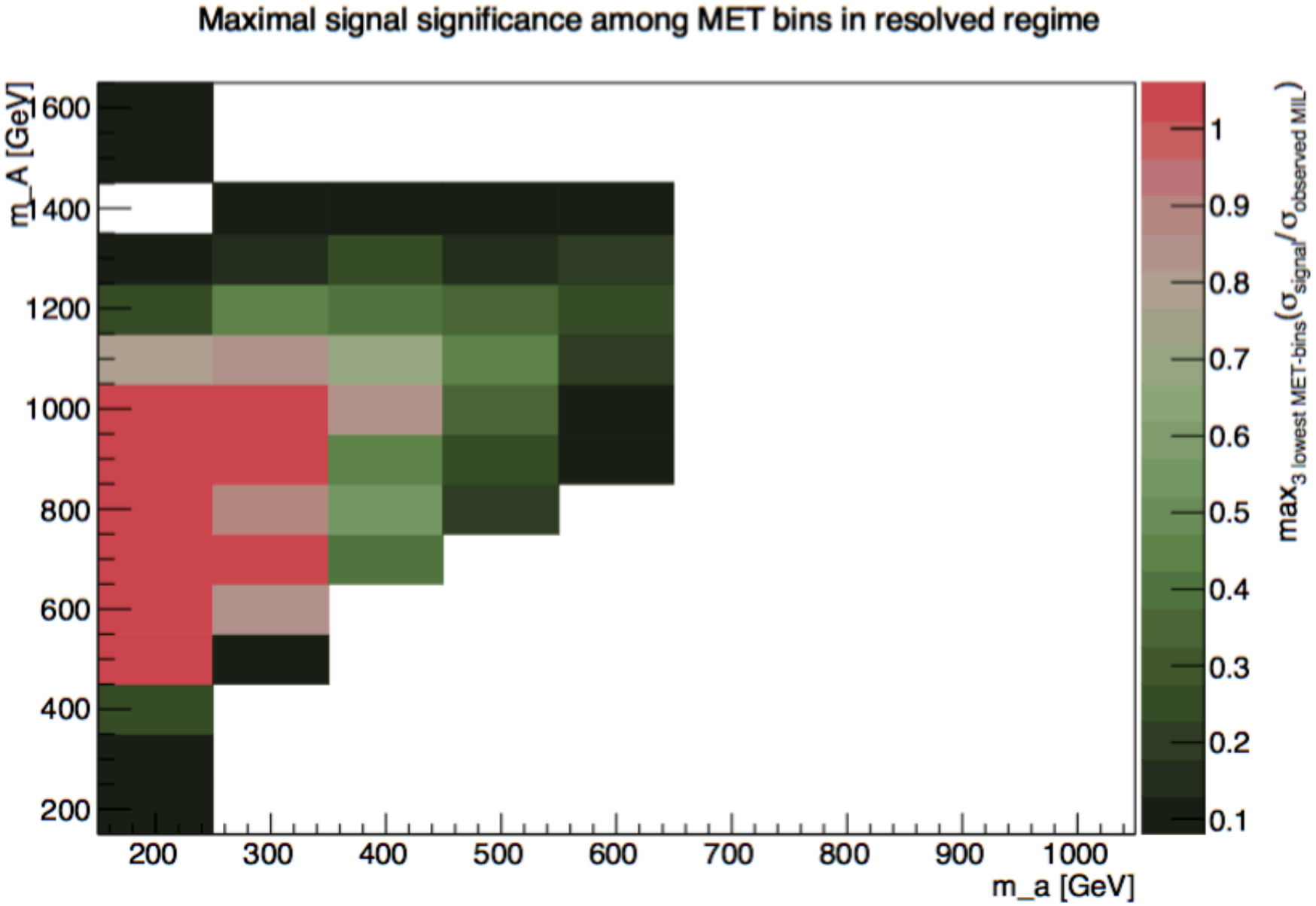
SUMMARY + OUTLOOK

- **2HDM+a:**
  - simplified, consistent, UV-complete model
  - **Rich phenomenology:**
    - Interesting complementarity between signatures
    - Resonant production of DM + distinct SM signatures
- 2HDM+a **extensively studied at ATLAS**
  - Madgraph UFO tested & works for most signatures
  - **Z + MET:**
    - Parameter scans in progress
  - **h + MET:**
    - Parameter scans in relevant variables:
      - (M_A, M_a) in 2dim, 1-dim scans in $\sin\theta$, M_H
    - First grid proposal
      - Based on “model-independent” visible xsec limits
- **Next steps:**
  - Converge on grid definition

Backup


Maximal signal significance among all MET bins
m_A [GeV]
200
400
600
800
1000
1200
1400
1600
m_a [GeV]
200
300
400
500
600
700
800
900
1000
max MET-bins (σ signal / σ observed MIL)
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1

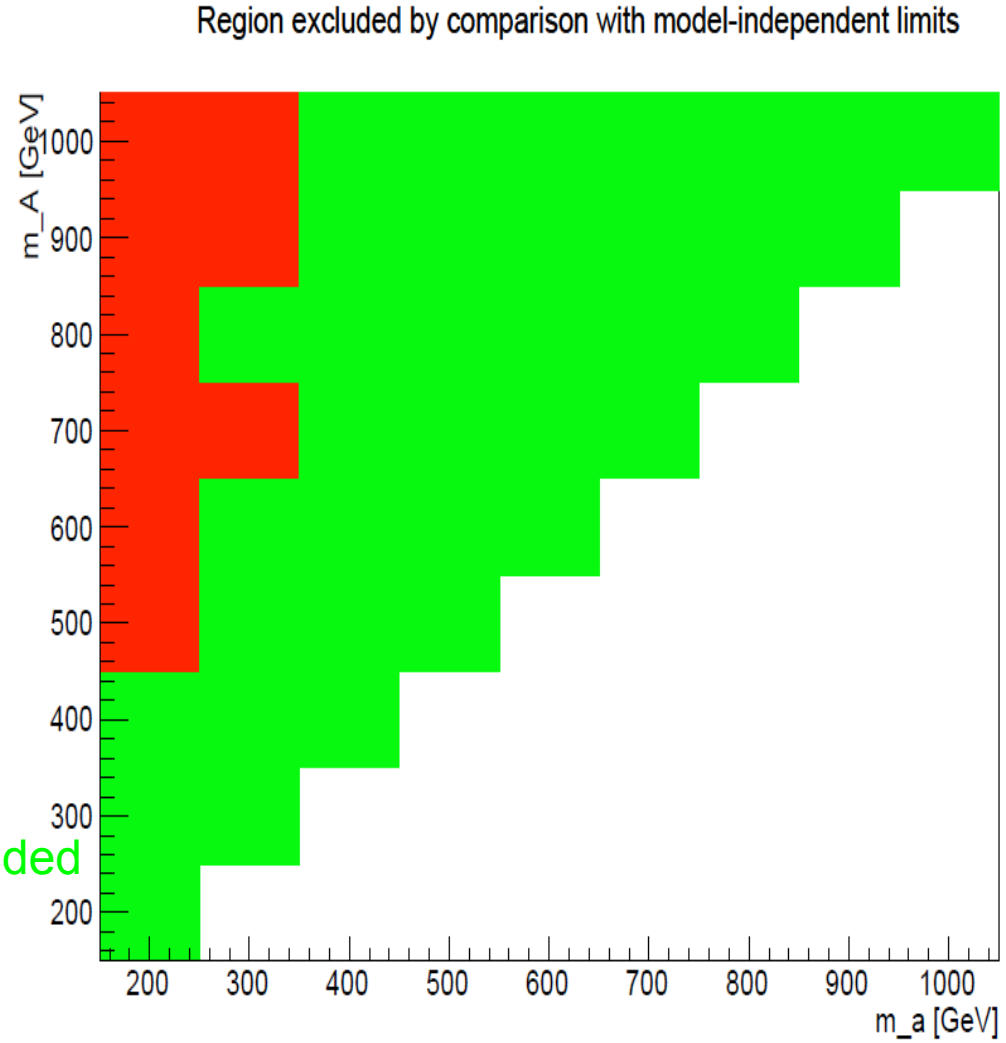
$h(bb) + E_T^{MISS}$: RESOLVED ONLY



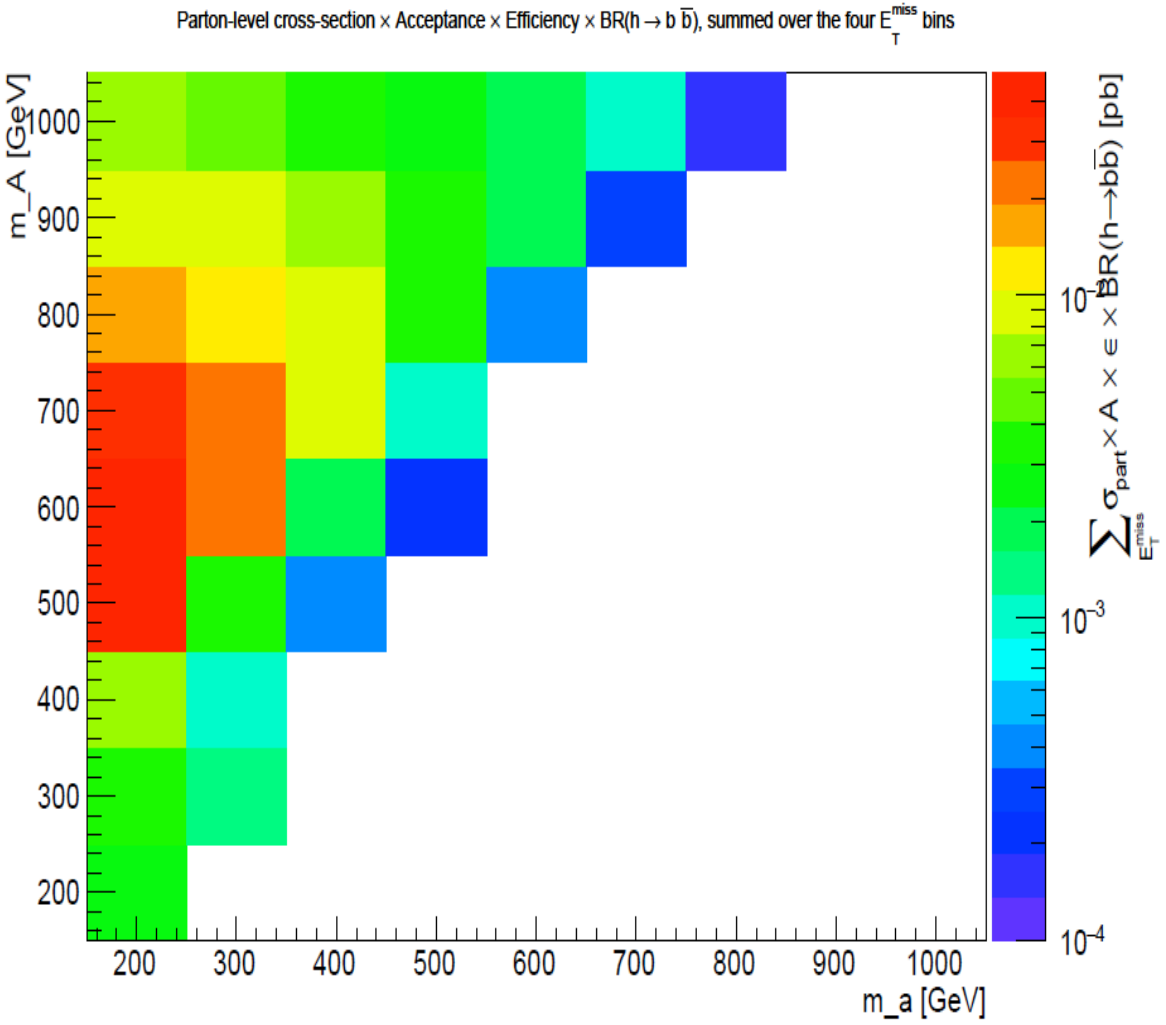
Backup: Exclusion Region

excluded

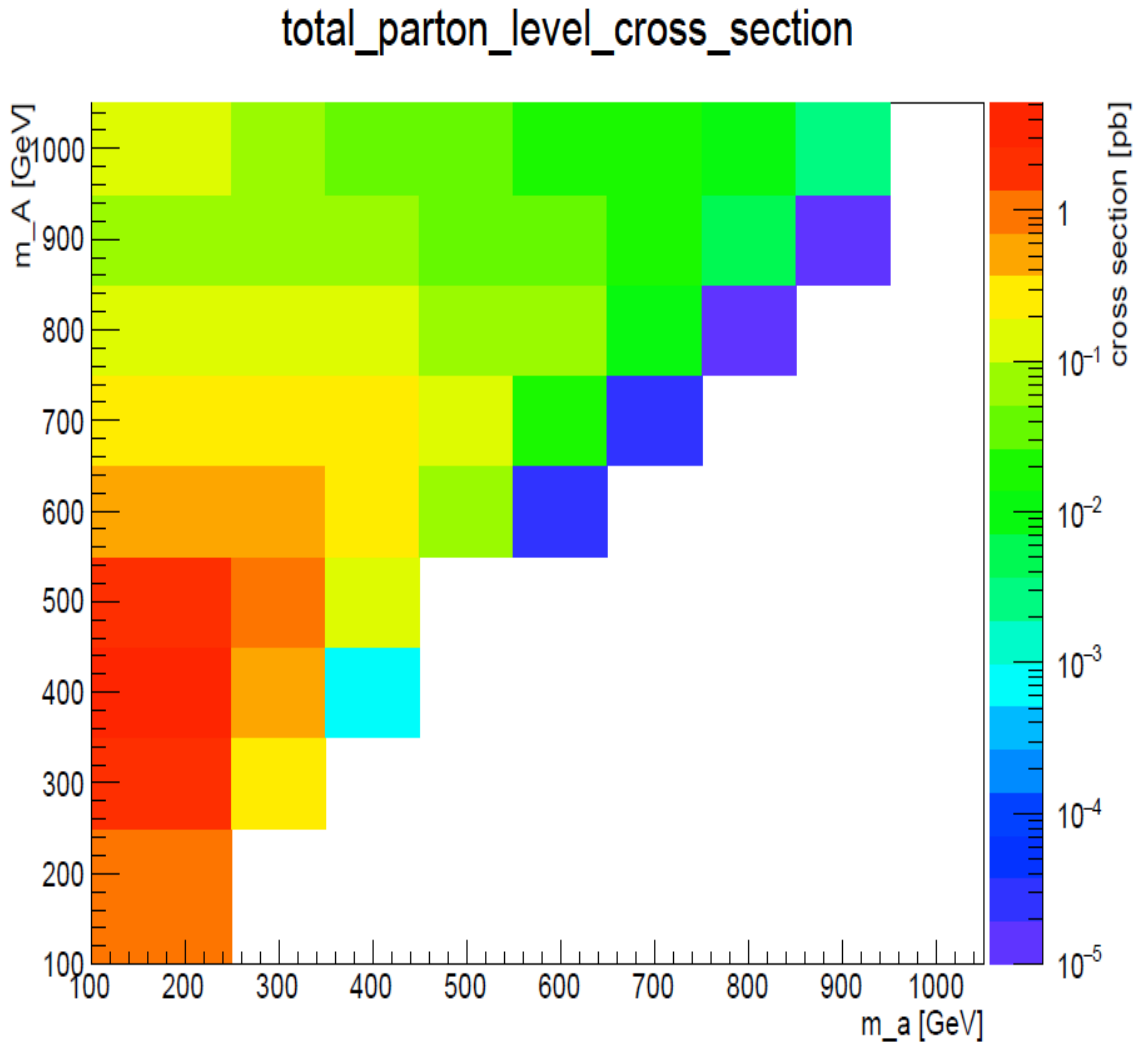
scanned, not excluded



Backup: Cross-Section

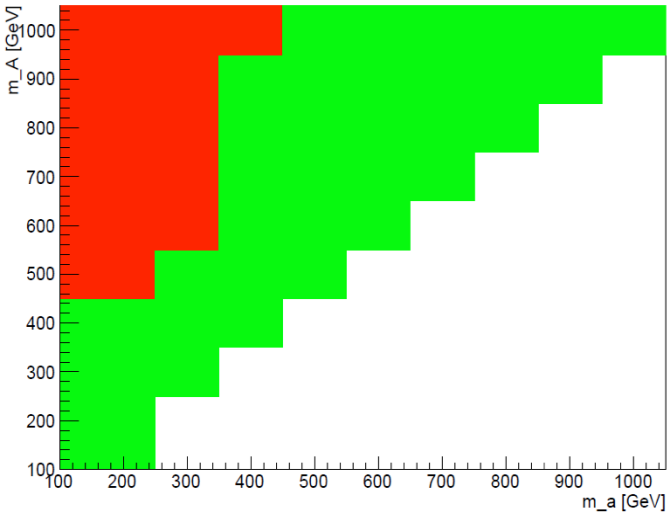


Backup: Parton-Level Cross-Section

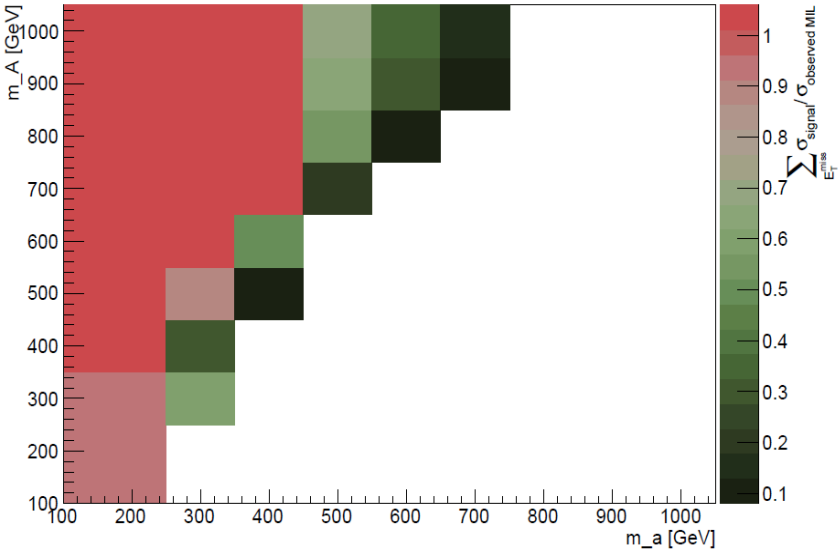


Scan: $m_H = m_A + 300$ GeV

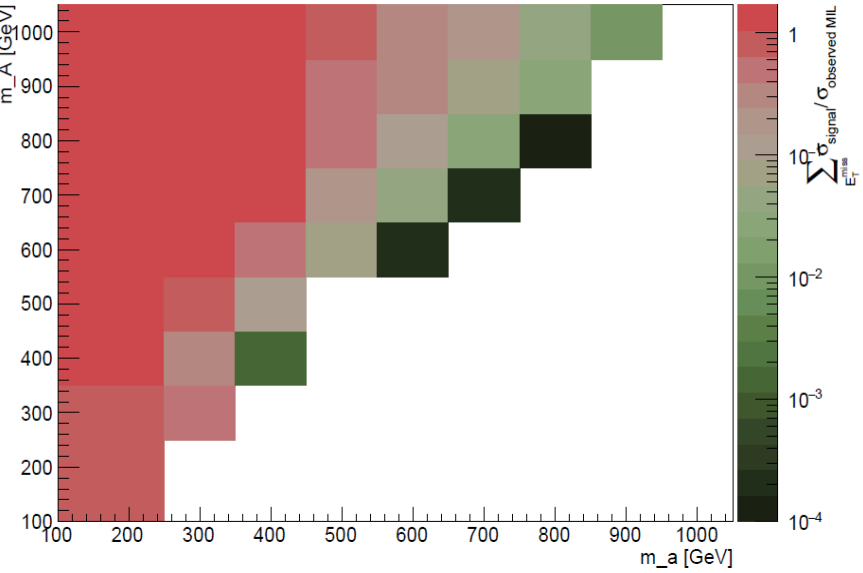
Region excluded by comparison with model-independent limits



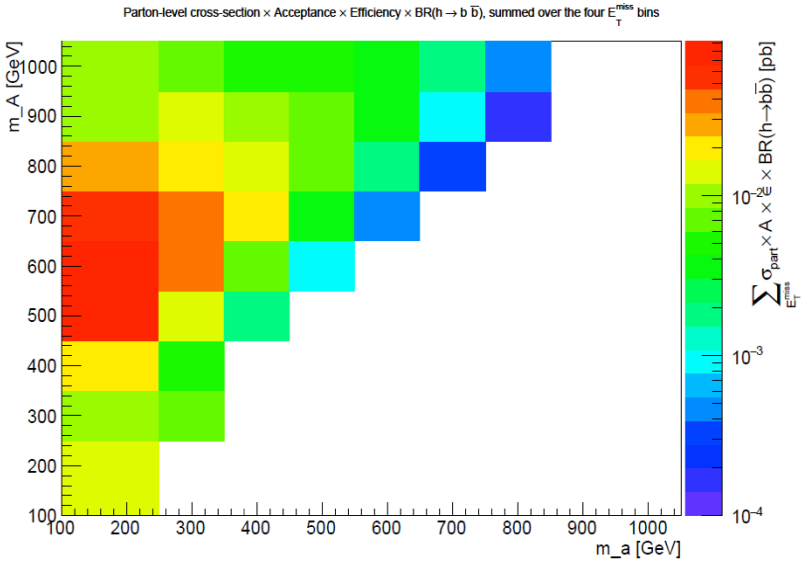
Signal significance (relative to MILs), summed over the four E_T^{miss} bins



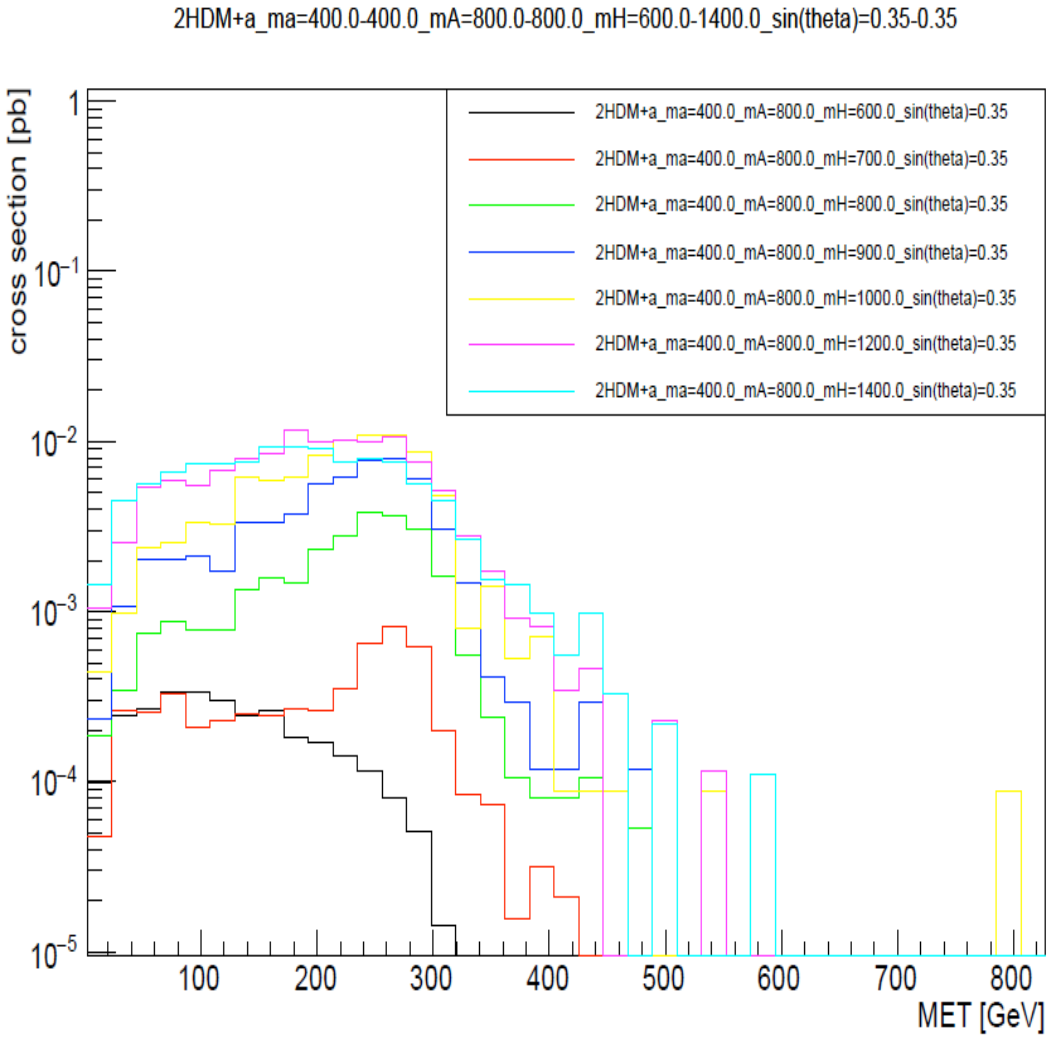
Signal significance (relative to MILs), summed over the four E_T^{miss} bins



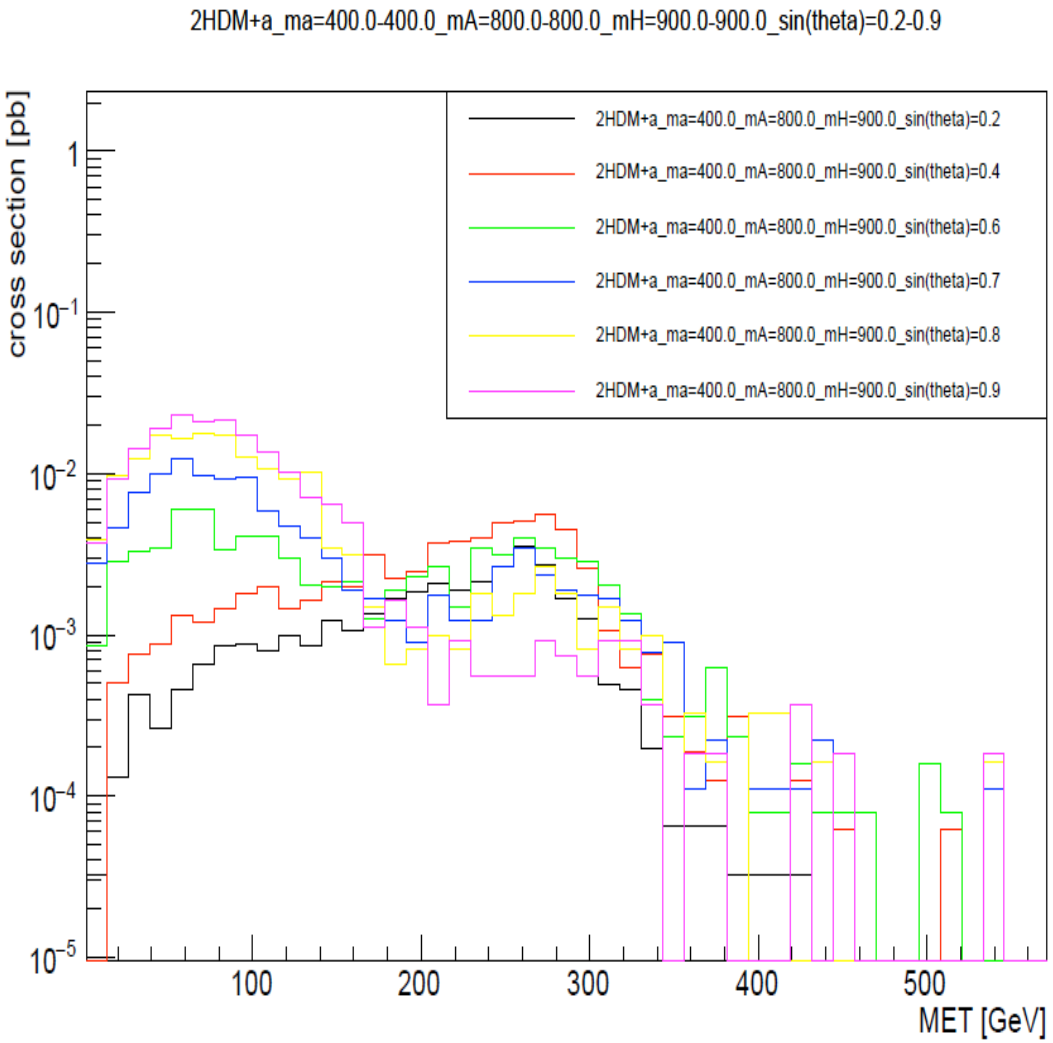
Parton-level cross-section × Acceptance × Efficiency × BR($h \to b\bar{b}$), summed over the four E_T^{miss} bins



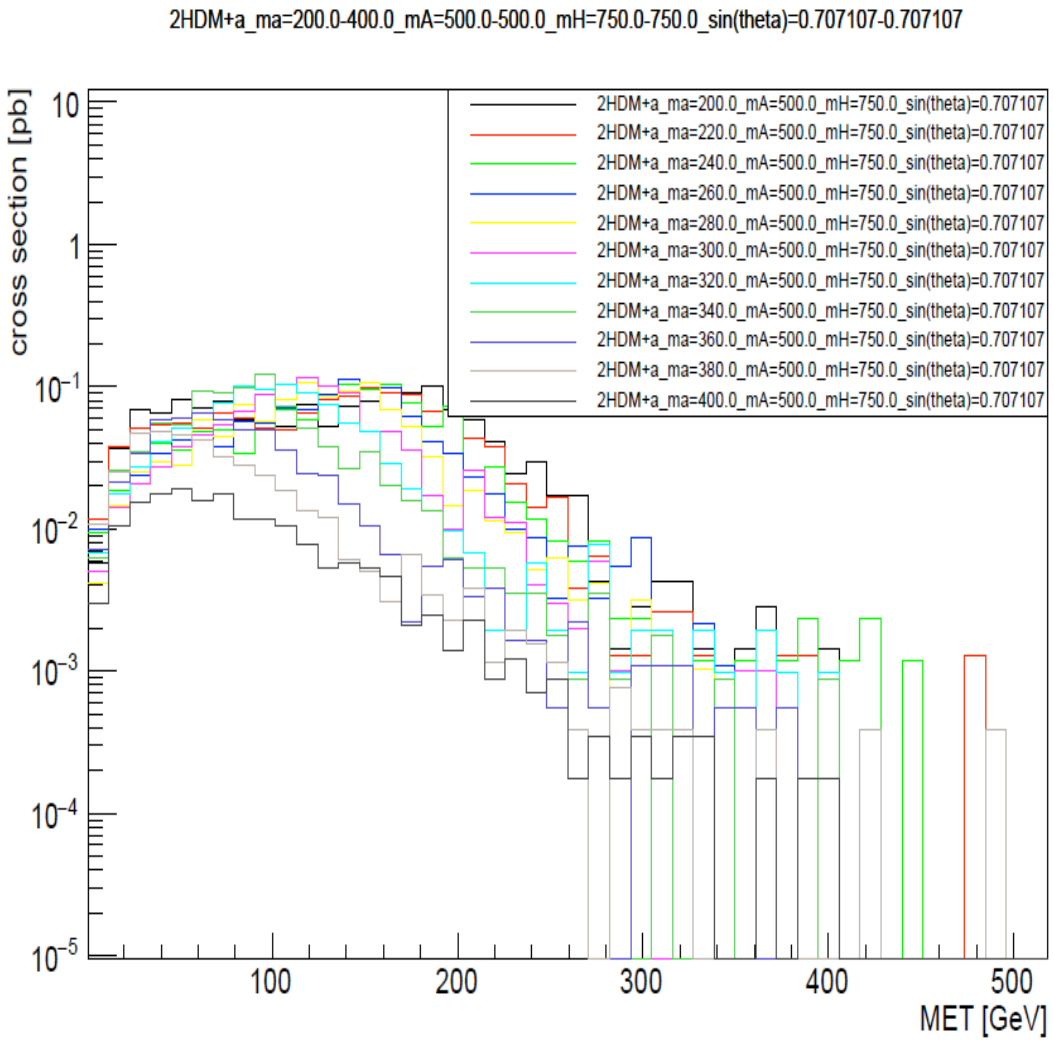
Backup: m_H scan



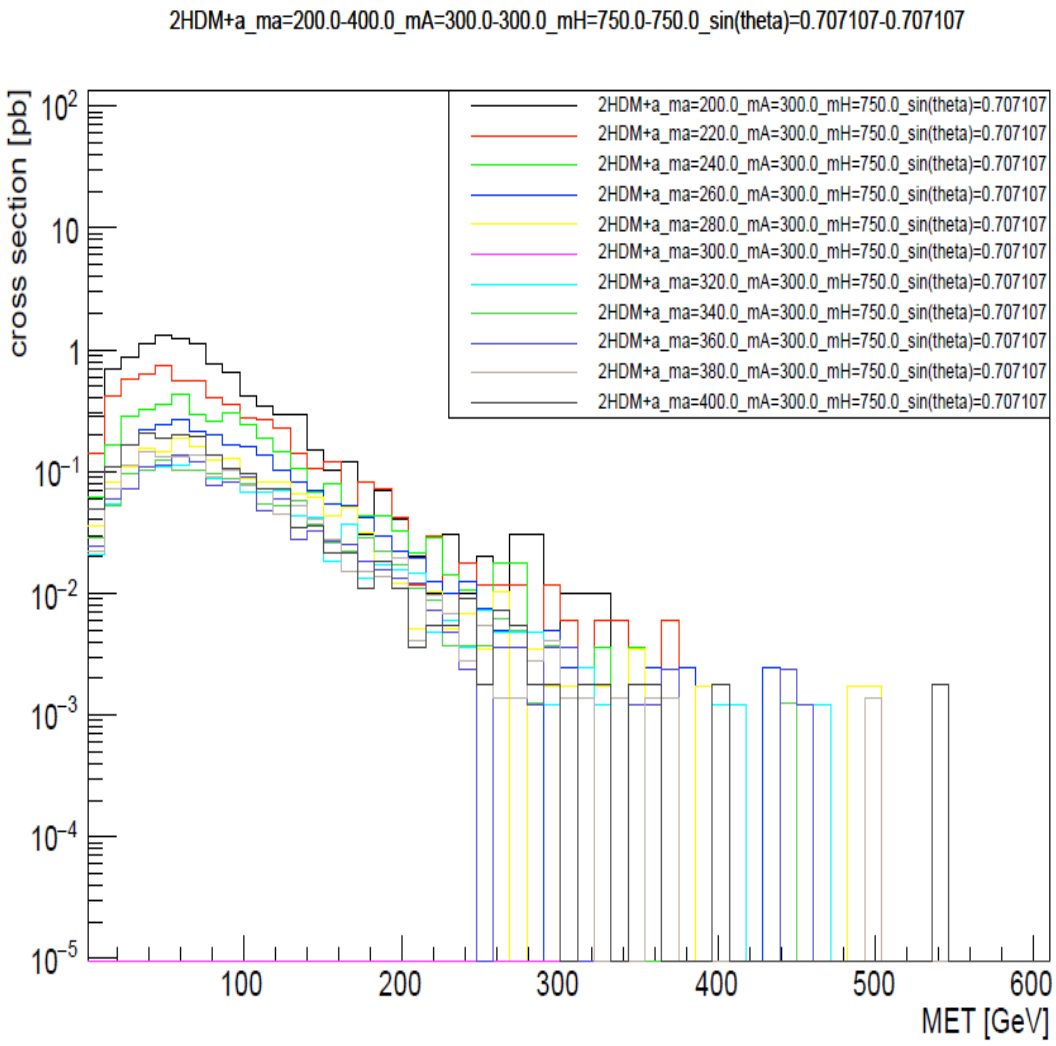
sin(θ)


2HDM+a_ma=400.0-400.0_mA=800.0-800.0_mH=900.0-900.0_sin(theta)=0.2-0.9
cross section [pb]
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
100
200
300
400
500
MET [GeV]
2HDM+a_ma=400.0_mA=800.0_mH=900.0_sin(theta)=0.2
2HDM+a_ma=400.0_mA=800.0_mH=900.0_sin(theta)=0.4
2HDM+a_ma=400.0_mA=800.0_mH=900.0_sin(theta)=0.6
2HDM+a_ma=400.0_mA=800.0_mH=900.0_sin(theta)=0.7
2HDM+a_ma=400.0_mA=800.0_mH=900.0_sin(theta)=0.8
2HDM+a_ma=400.0_mA=800.0_mH=900.0_sin(theta)=0.9

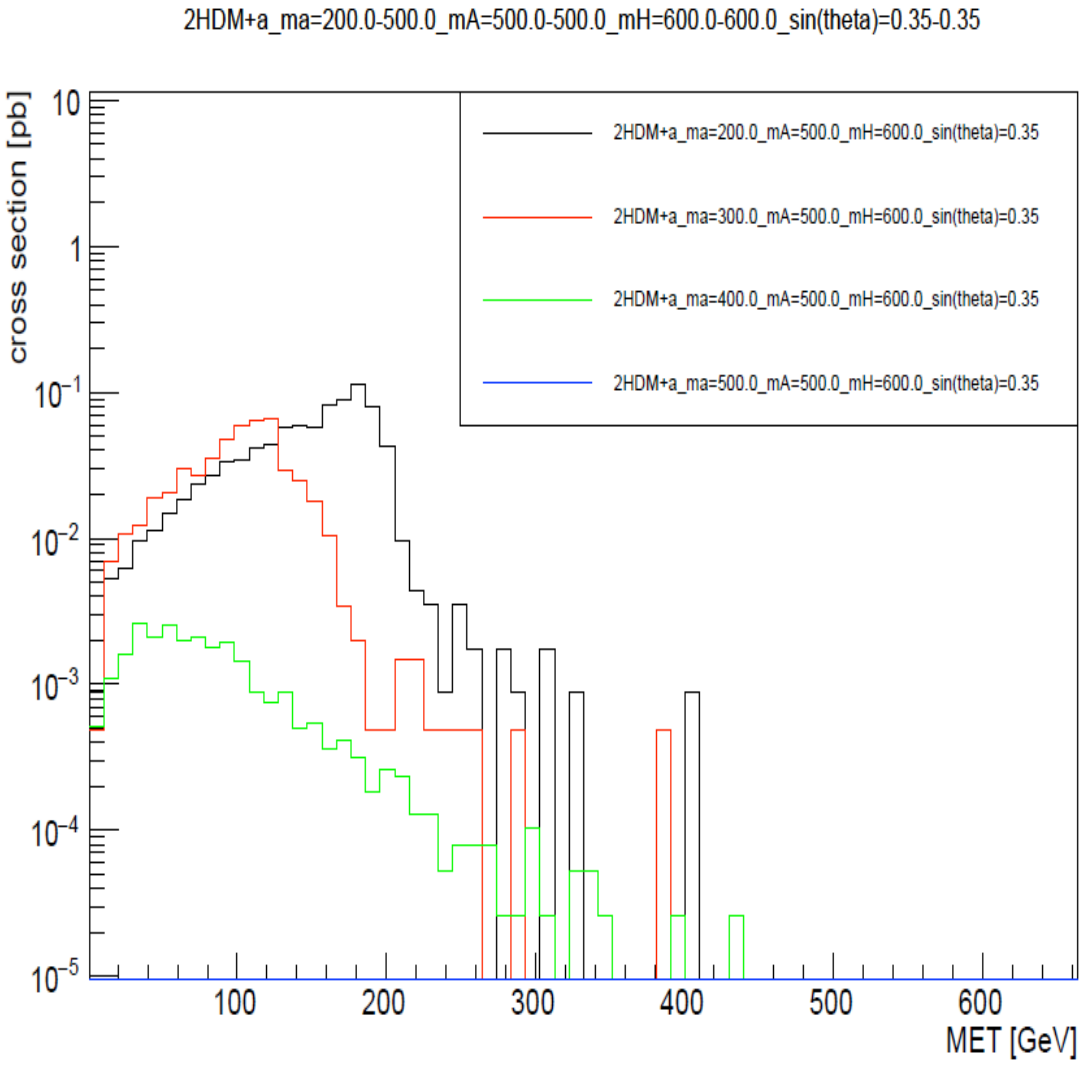
MET(m_a) in BM3


2HDM+a_ma=200.0-400.0_mA=500.0-500.0_mH=750.0-750.0_sin(theta)=0.707107-0.707107
cross section [pb]
10
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
100
200
300
400
500
MET [GeV]
2HDM+a_ma=200.0_mA=500.0_mH=750.0_sin(theta)=0.707107
2HDM+a_ma=220.0_mA=500.0_mH=750.0_sin(theta)=0.707107
2HDM+a_ma=240.0_mA=500.0_mH=750.0_sin(theta)=0.707107
2HDM+a_ma=260.0_mA=500.0_mH=750.0_sin(theta)=0.707107
2HDM+a_ma=280.0_mA=500.0_mH=750.0_sin(theta)=0.707107
2HDM+a_ma=300.0_mA=500.0_mH=750.0_sin(theta)=0.707107
2HDM+a_ma=320.0_mA=500.0_mH=750.0_sin(theta)=0.707107
2HDM+a_ma=340.0_mA=500.0_mH=750.0_sin(theta)=0.707107
2HDM+a_ma=360.0_mA=500.0_mH=750.0_sin(theta)=0.707107
2HDM+a_ma=380.0_mA=500.0_mH=750.0_sin(theta)=0.707107
2HDM+a_ma=400.0_mA=500.0_mH=750.0_sin(theta)=0.707107

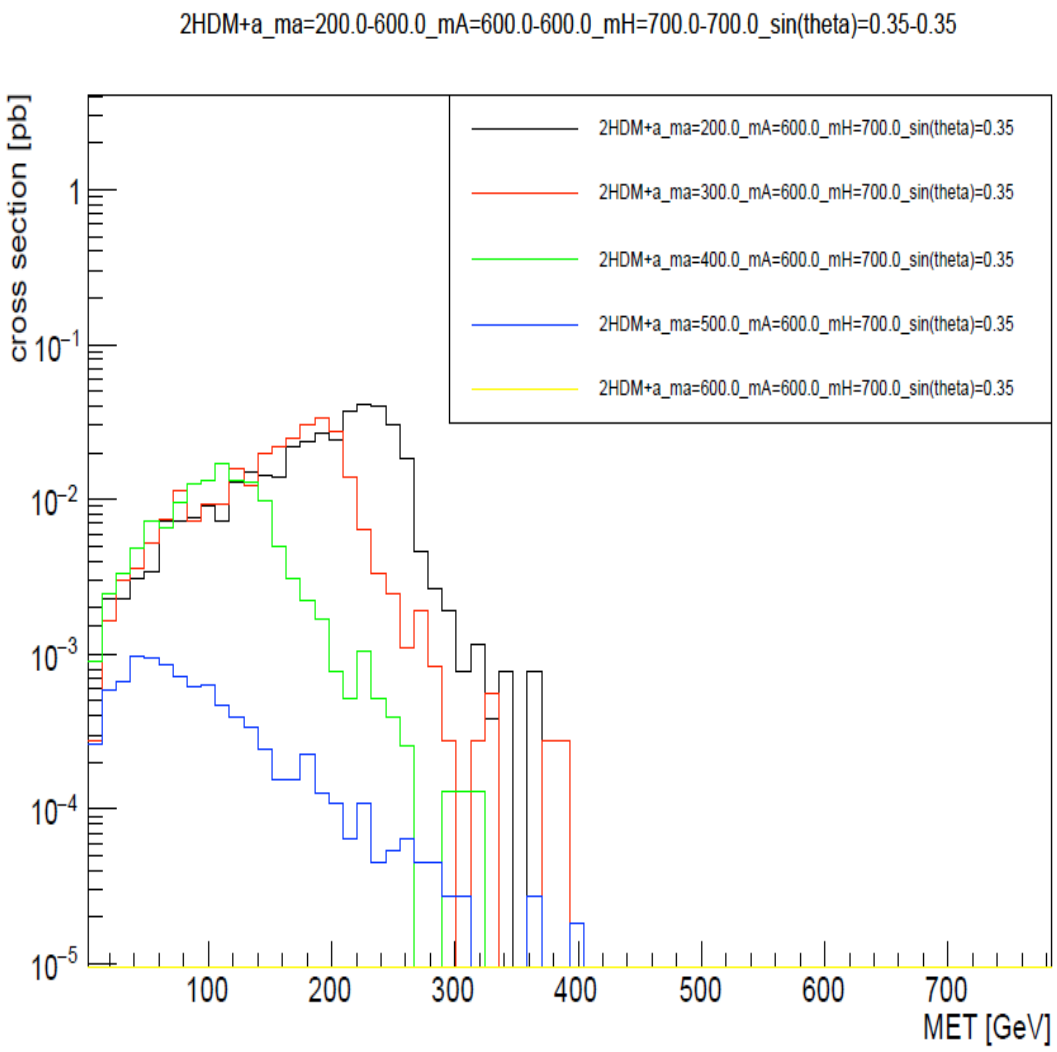
MET(m_a) in BM4


2HDM+a_ma=200.0-400.0_mA=300.0-300.0_mH=750.0-750.0_sin(theta)=0.707107-0.707107
cross section [pb]
MET [GeV]
2HDM+a_ma=200.0_mA=300.0_mH=750.0_sin(theta)=0.707107
2HDM+a_ma=220.0_mA=300.0_mH=750.0_sin(theta)=0.707107
2HDM+a_ma=240.0_mA=300.0_mH=750.0_sin(theta)=0.707107
2HDM+a_ma=260.0_mA=300.0_mH=750.0_sin(theta)=0.707107
2HDM+a_ma=280.0_mA=300.0_mH=750.0_sin(theta)=0.707107
2HDM+a_ma=300.0_mA=300.0_mH=750.0_sin(theta)=0.707107
2HDM+a_ma=320.0_mA=300.0_mH=750.0_sin(theta)=0.707107
2HDM+a_ma=340.0_mA=300.0_mH=750.0_sin(theta)=0.707107
2HDM+a_ma=360.0_mA=300.0_mH=750.0_sin(theta)=0.707107
2HDM+a_ma=380.0_mA=300.0_mH=750.0_sin(theta)=0.707107
2HDM+a_ma=400.0_mA=300.0_mH=750.0_sin(theta)=0.707107

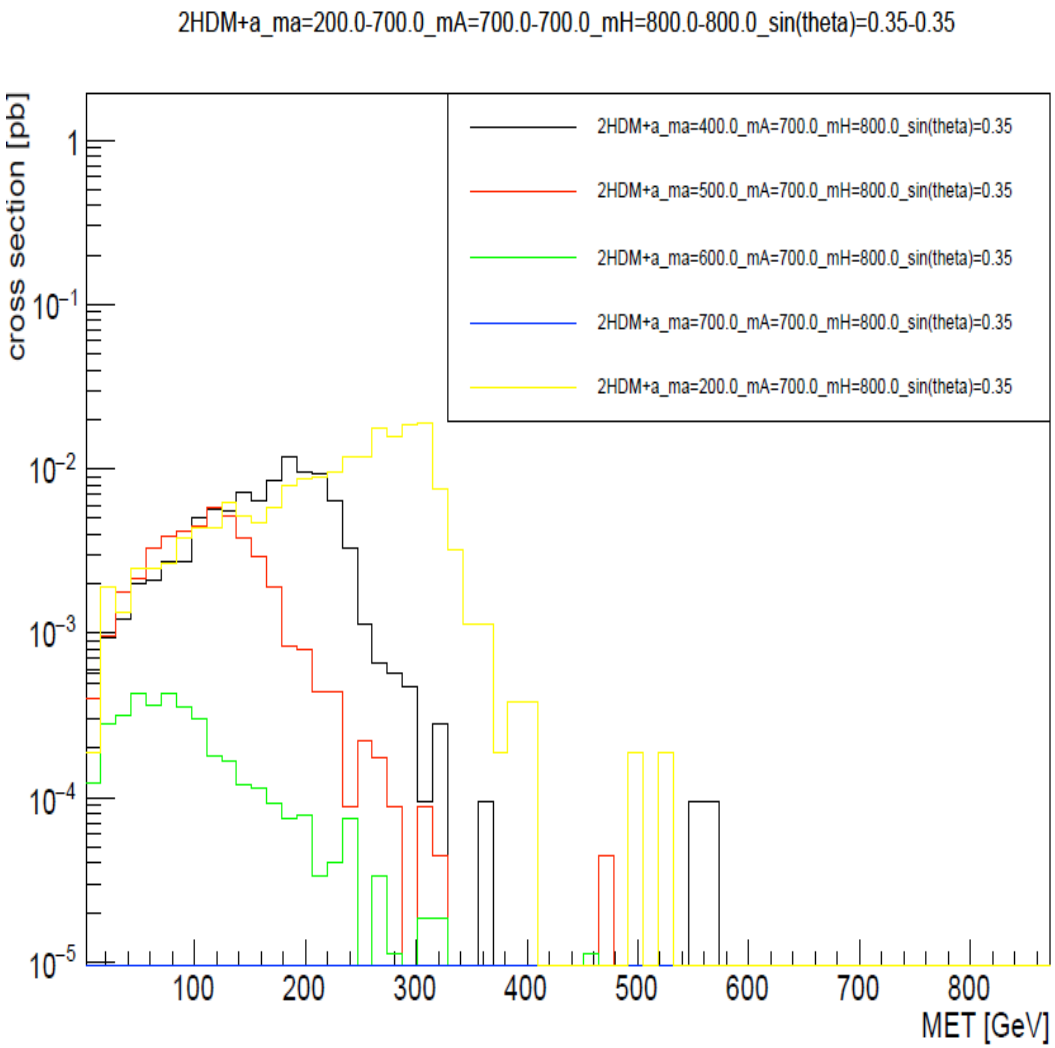
MET Variation with m_a : m_A = 500 GeV



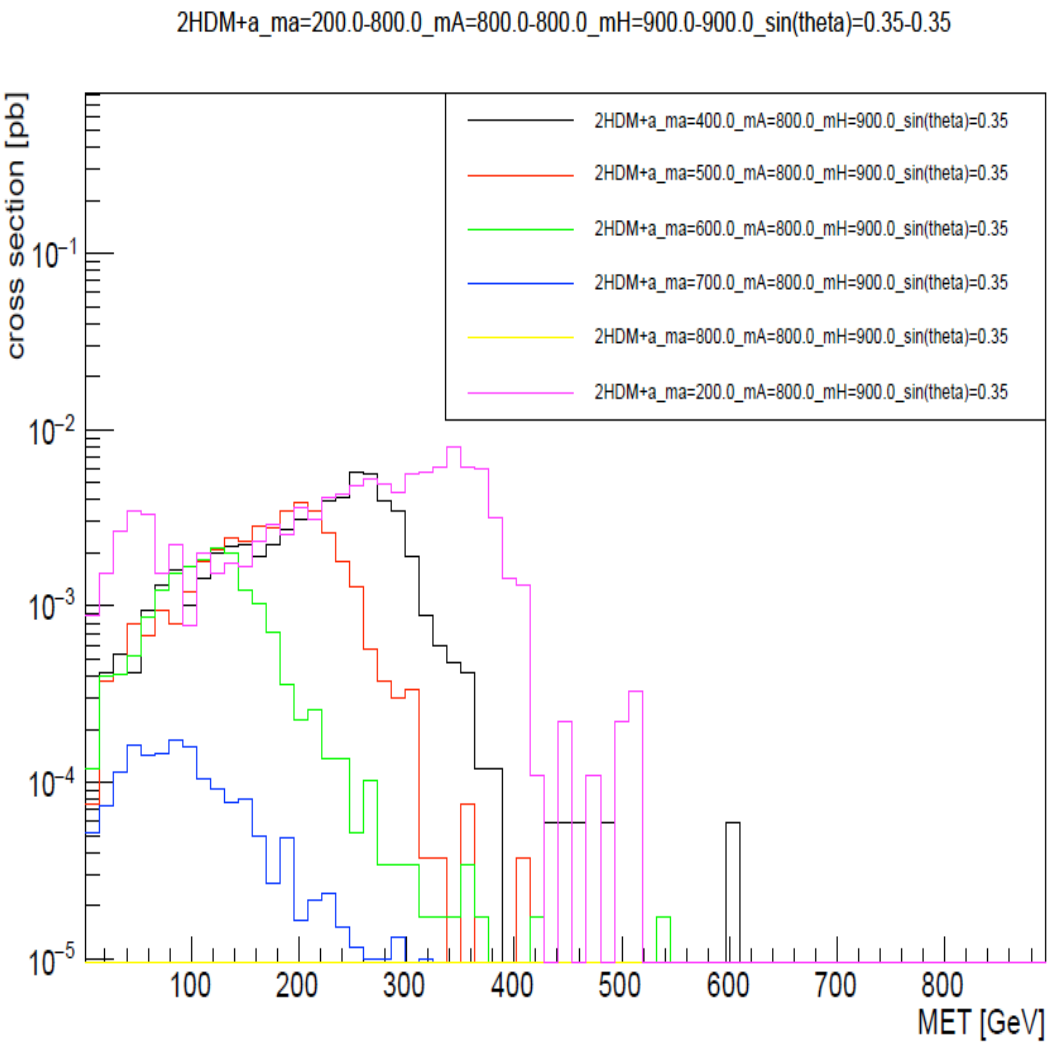
MET Variation with m_a : m_A = 600 GeV



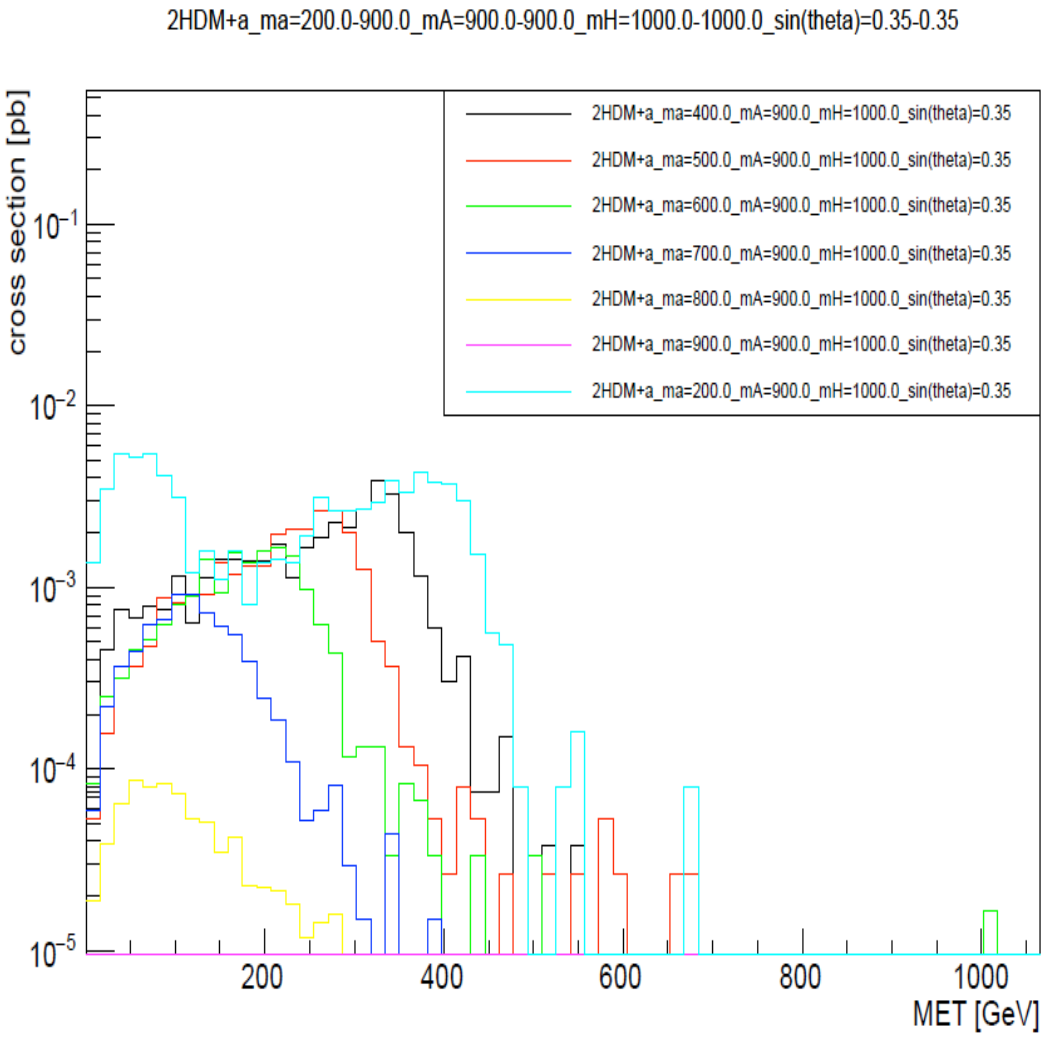
MET Variation with m_a : m_A = 700 GeV



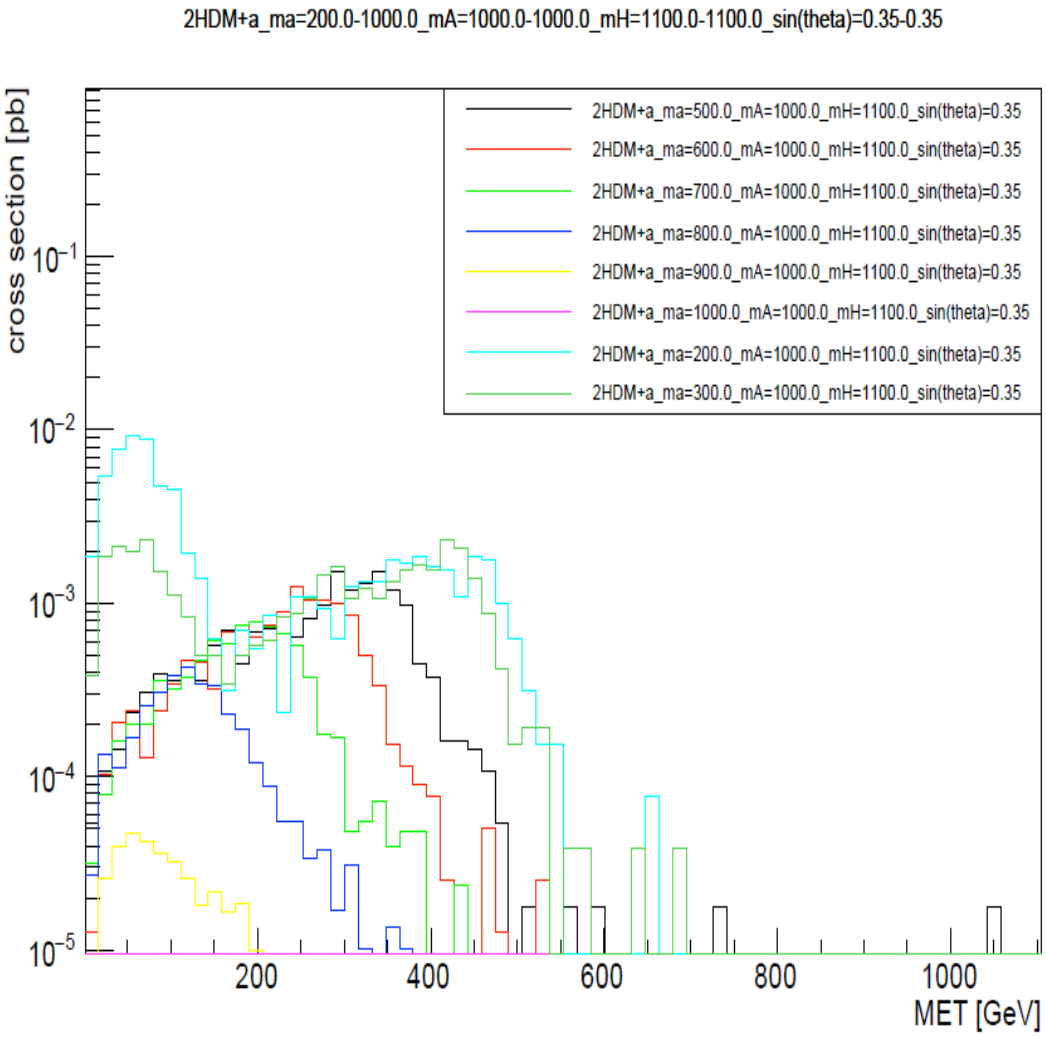
MET Variation with m_a : m_A = 800 GeV



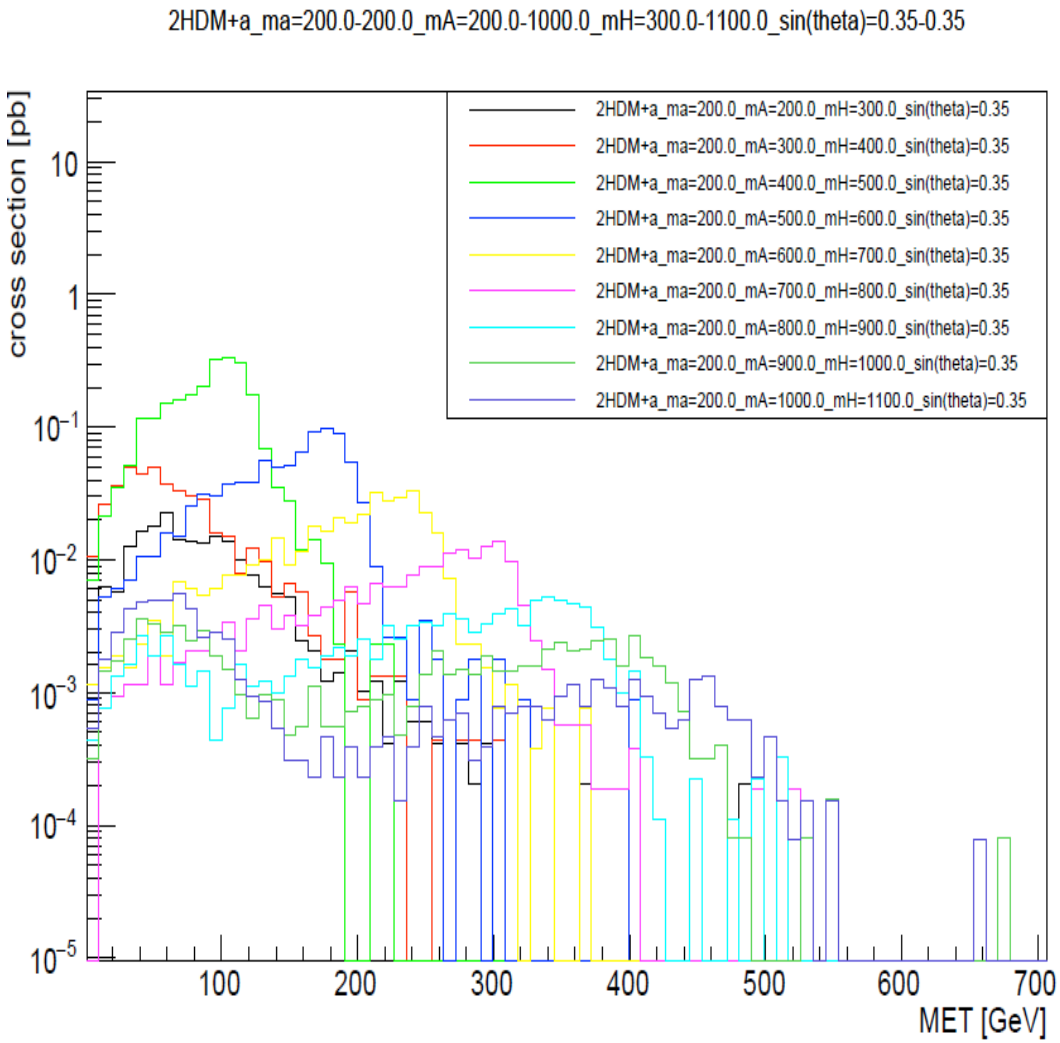
MET Variation with m_a : m_A = 900 GeV



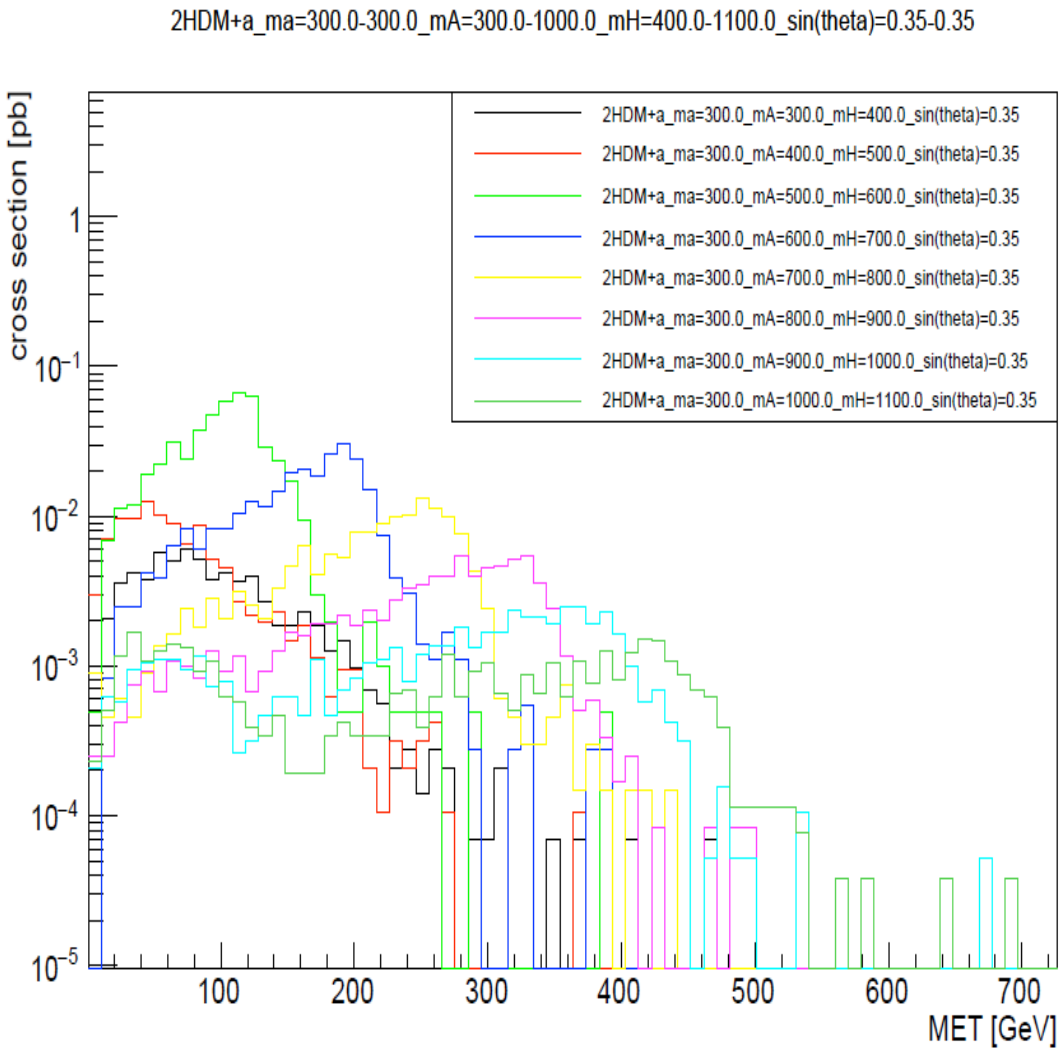
MET Variation with m_a : m_A = 1000 GeV



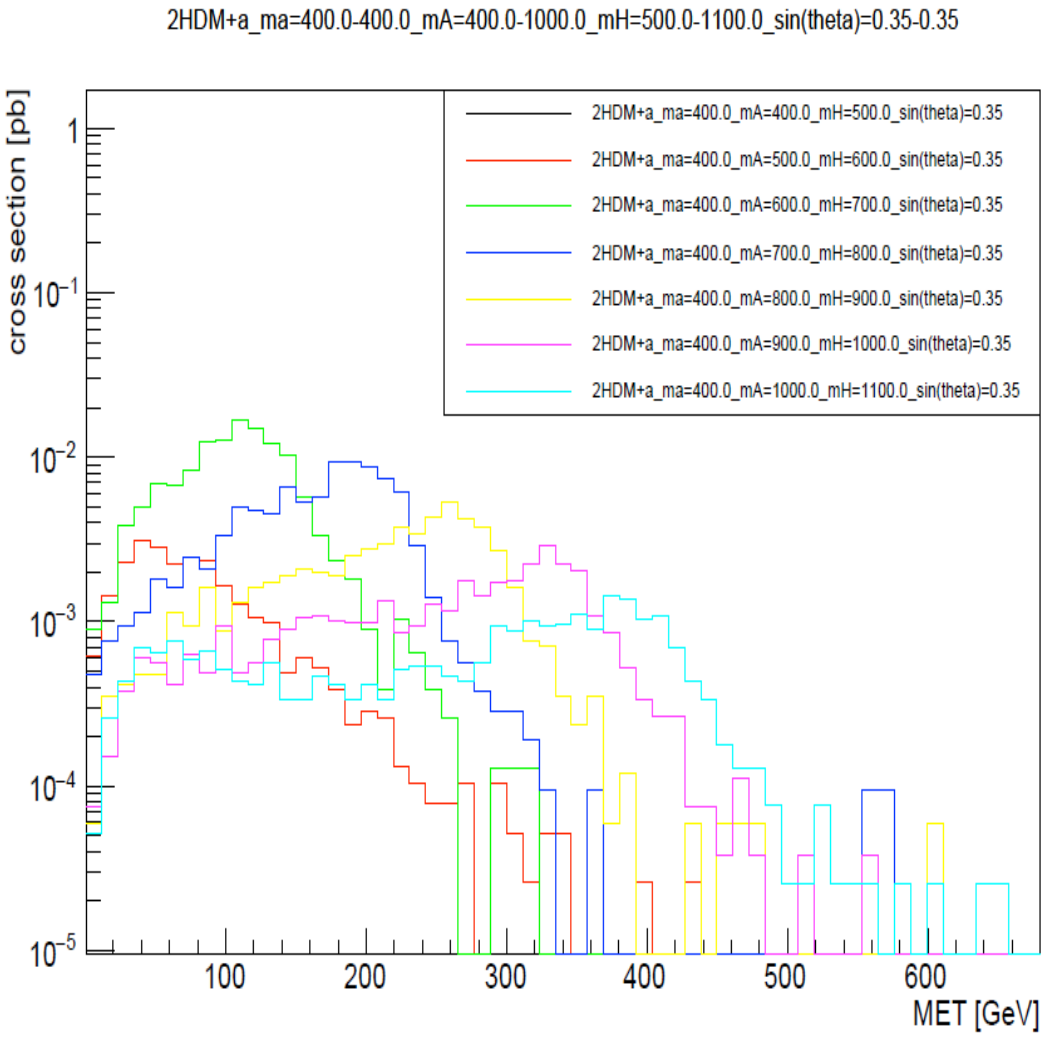
MET Variation with m_A : m_a = 200 GeV



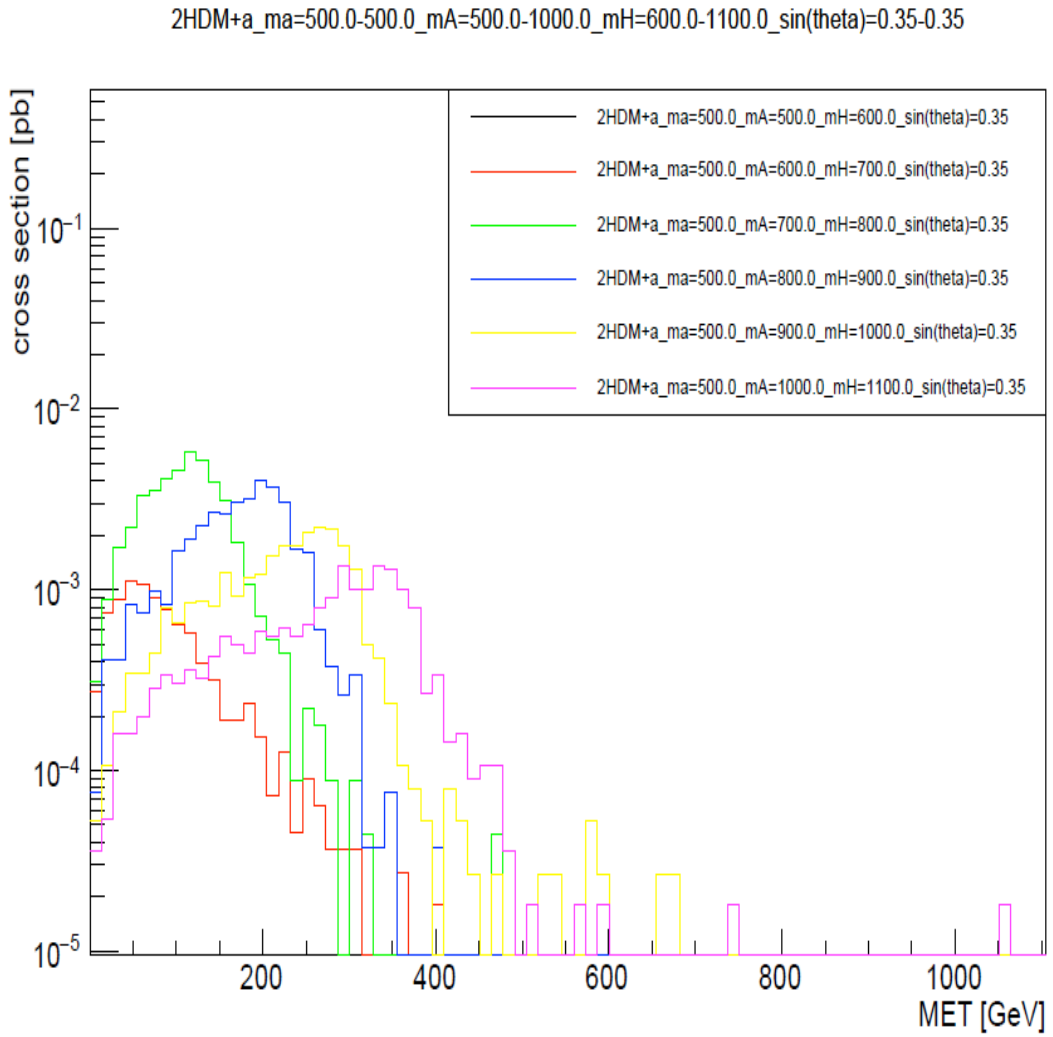
MET Variation with m_A : m_a = 300 GeV



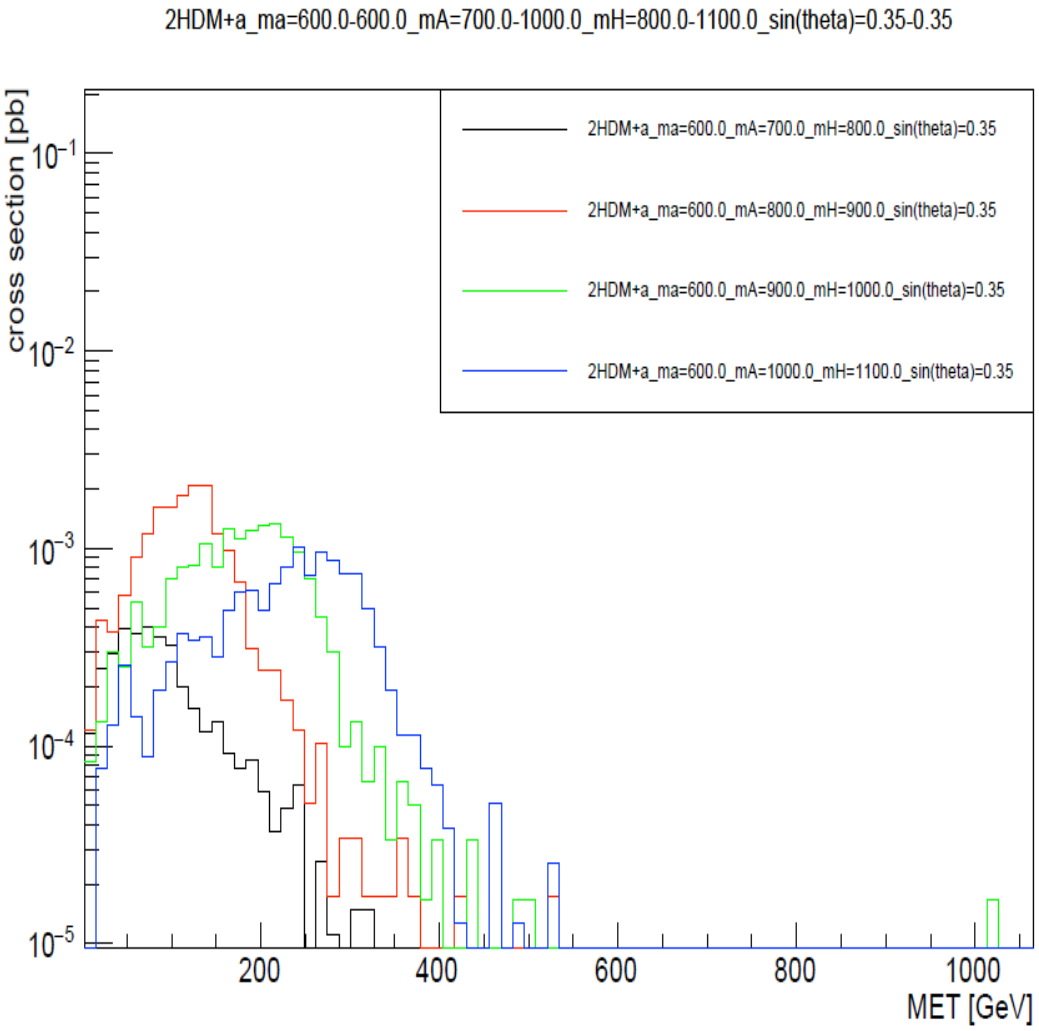
MET Variation with m_A : m_a = 400 GeV



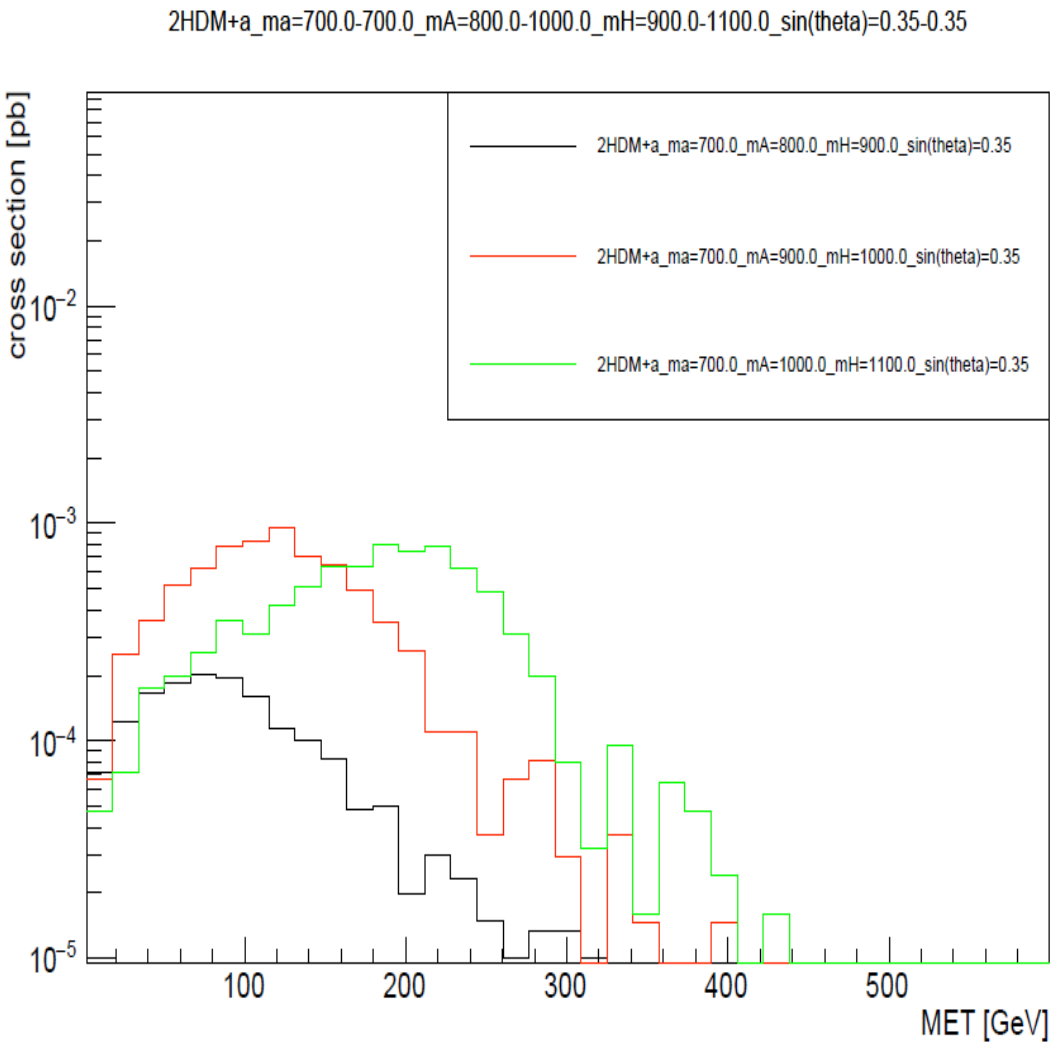
MET Variation with $m_A : m_a = 500$ GeV



MET Variation with $m_A : m_a = 600$ GeV



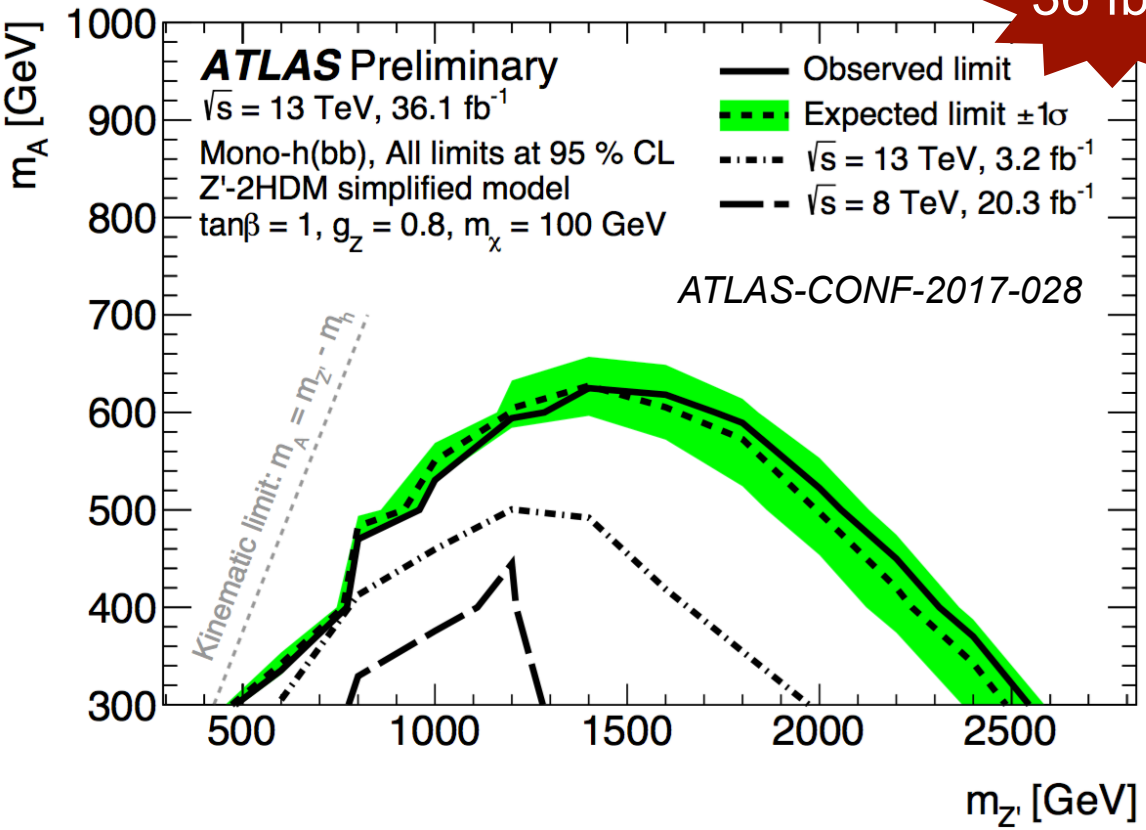
MET Variation with $m_A : m_a = 700$ GeV



- **Results for Z'-2HDM model:**
  - Large portion of parameter space excluded
    - Stronger sensitivity than mono-h($\gamma\gamma$) for $p_{T,h} \gtrsim 150$ GeV
    - Complementarity for $p_{T,h} \lesssim 150$GeV

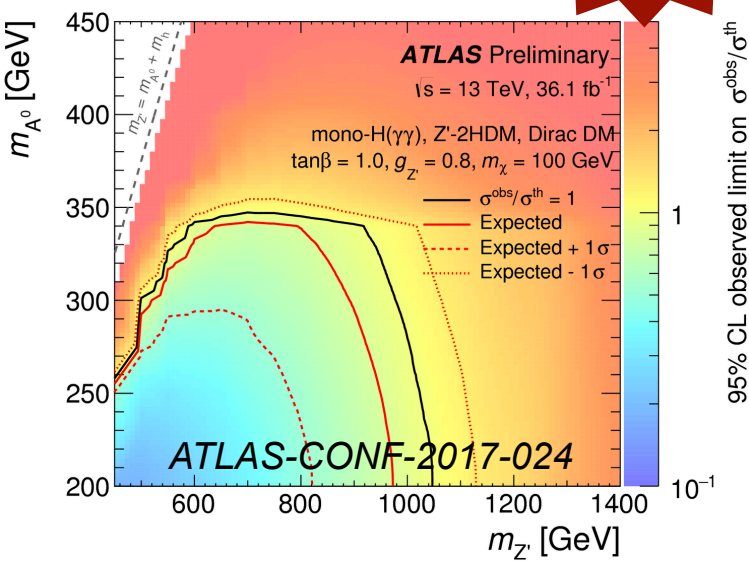
mono-h(bb)

36 fb^{-1}!



mono-h($\gamma\gamma$)

36 fb^{-1}!



HIGGS(*bb*) + E_T^{MISS}: "MODEL-INDEPENDENT" LIMITS

- **Limits on h+DM events with minimal model dependence**
  - Assume SM-like Higgs boson ($m_h \approx 125$ GeV, BR(h→bb) ≈ 58%)
  - Assume back-to-back topology of Higgs and E_T^{miss}
- **Set limits on visible cross section:**

$$\sigma_{\text{vis},h+\text{DM}} \equiv \sigma_{h+\text{DM}} \times BR(h \rightarrow b\bar{b}) \times \mathcal{A} \times \varepsilon$$

- $\mathcal{A} \times \varepsilon$ probability to reconstructed in same E_T^{miss} bin as generated and to pass all selections except b-tagging and $m_{h,reco}$ (measurement-specific)
  - $\sigma_{h+\text{DM}}$ at **parton level** → can compare with $\int_{E_T^{\text{miss}}\ \text{bin}} \mathrm{d}\sigma/\mathrm{d}E_T^{\text{miss}}$

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

Weakest limit from a range of Z'-2HDM models