Mass-degenerate NMSSM Higgs bosons and the effects of quantum interference

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KIAS, Seoul

SUSY2018, Barcelona

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****with Biswaranjan Das, Poulose Poulose and Stefano Moretti***

CONTENTS

THE MINIMAL SUPERSYMMETRIC SM

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Defined by the superpotential

$$W_{\rm MSSM} = h_u\, \widehat{Q}\cdot\widehat{H}_u\, \widehat{U}^c_R \;+\; h_d\, \widehat{H}_d\cdot\widehat{Q}\, \widehat{D}^c_R \;+\; h_e\, \widehat{H}_d\cdot\widehat{L}\, \widehat{E}^c_R \;+\; \mu\widehat{H}_u\cdot\widehat{H}_d$$

with two complex Higgs doublet fields

$$H^0_d = \begin{pmatrix} \frac{1}{\sqrt{2}}(v_d + H_{dR} + iH_{dI}) \\ H^-_d \end{pmatrix},\; H^0_u = e^{i\phi_u}\begin{pmatrix} H^+_u \\ \frac{1}{\sqrt{2}}(v_u + H_{uR} + iH_{uI}) \end{pmatrix}$$

Physical Higgs states:

Scalars h and H,

pseudoscalar A, a H± pair

$$\mathcal{M}^2_0 = \left(\begin{array}{c|c} \mathcal{M}^2_S & 0 \\ \hline 0 & \mathcal{M}^2_P \end{array}\right)$$

Tree-level masses of the neutral scalars:

$$M^2_{h,H} = \frac{1}{2}\left[M^2_A + M^2_Z \mp \sqrt{(M^2_A + M^2_Z)^2 - 4M^2_A M^2_Z \cos^2 2\beta}\right]$$

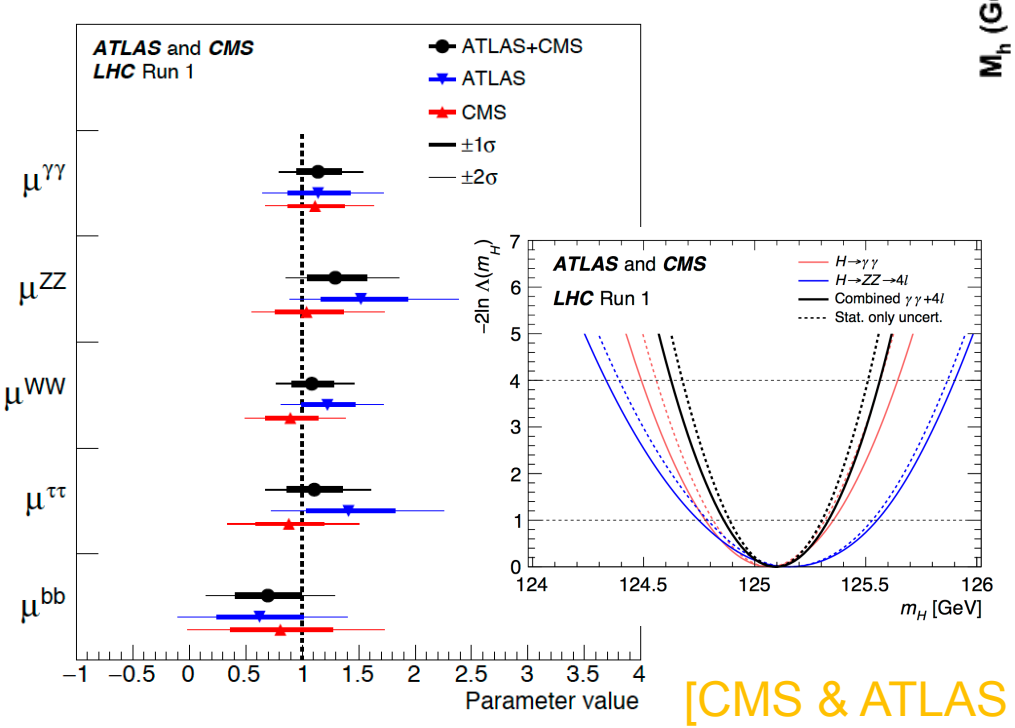
$$\boxed{M^2_h \leq \min(M^2_Z,\, M^2_A)\cdot\cos^2 2\beta}$$

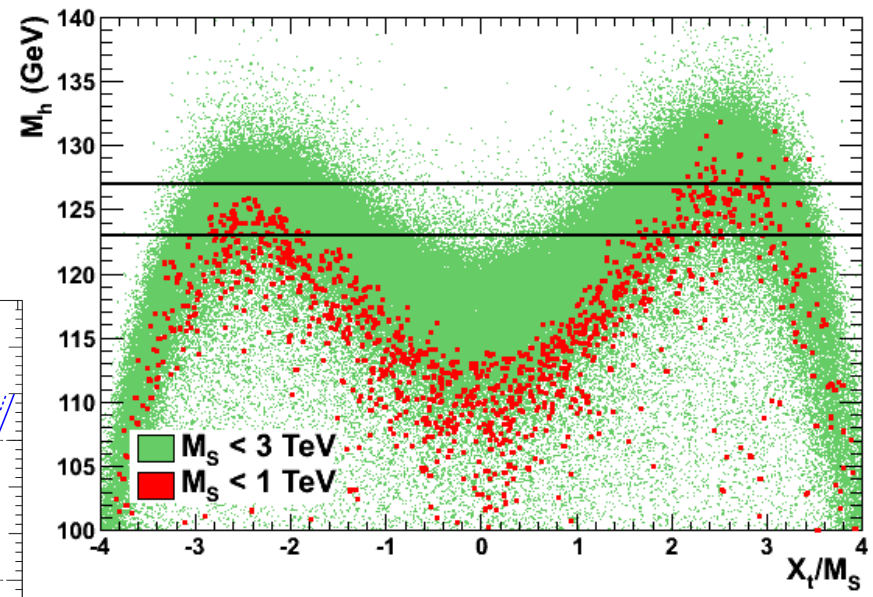
LIGHTEST HIGGS BOSON MASS

The mass of h receives higher order corrections, mainly from the (s)top sector

$$\Delta M_h^2 \propto \ln \frac{M_{\rm SUSY}^2}{M_t^2} + \frac{X_t^2}{M_{\rm SUSY}^2}\left(1 - \frac{X_t^2}{12 M_{\rm SUSY}^2}\right) \Leftarrow X_t = A_t - \mu \cot\beta$$

`H_{obs}' observed at the LHC:





[A. Arbey *et al.*, 1112.3028]

[CMS & ATLAS Colls., 1606.02266]

HEAVIER HIGGS BOSONS

To identify h with H_{obs}

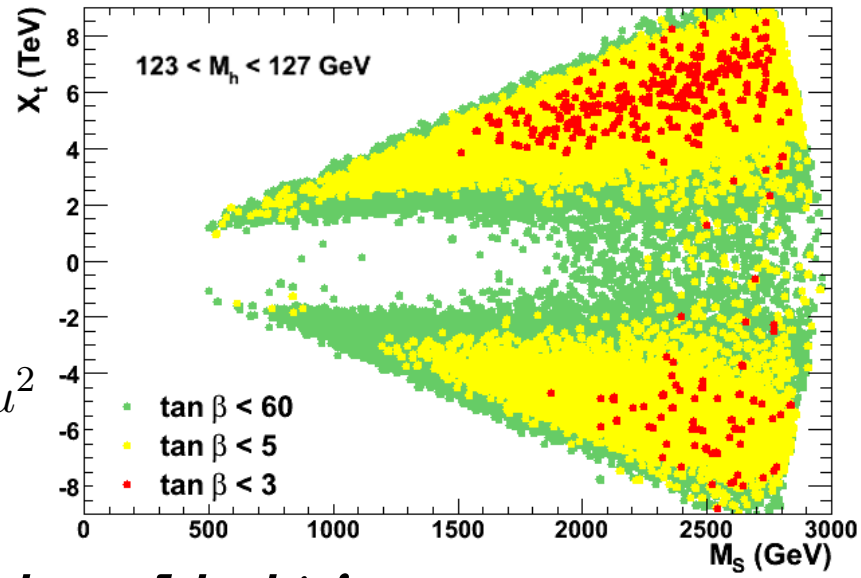
- ***Enhance SUSY corrections***

  But M_S and X_t too large

  ➡ ***fine-tuning problem redux***

$$\frac{M_Z^2}{2} = \frac{m_{H_d}^2 + \Sigma_d^d - (m_{H_u}^2 + \Sigma_u^u)\tan^2\beta}{\tan^2\beta - 1} - \mu^2$$

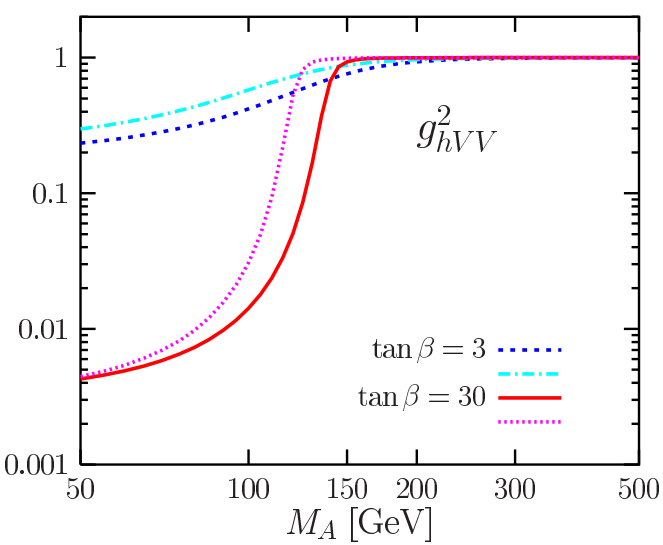
[A. Arbey *et al.*, 1112.3028]



- ***Maximise tree-level mass***

$$\tan\beta \gg 1$$

➡ ***Decoupling limit!***



$$M_{H^\pm} \overset{M_A \gg M_Z}{\longrightarrow} M_A\left[1 + \frac{M_W^2}{2M_A^2}\right]$$

$$M_H \overset{M_A \gg M_Z}{\longrightarrow} M_A\left[1 + \frac{M_Z^2 \sin^2 2\beta + \epsilon\cos^2\beta}{2M_A^2}\right]$$

➡ $$\boxed{M_H \simeq M_{H^\pm} \simeq M_A}$$

[A. Djouadi, hep-ph/0503173]

THE (Z_3-INVARIANT) NEXT-TO-MSSM

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`μ-problem' of the MSSM: add a singlet superfield

$$W_{\rm NMSSM} = \text{MSSM Yukawa terms} + \lambda \widehat{S}\widehat{H}_u \cdot \widehat{H}_d + \frac{\kappa}{3}\widehat{S}^3$$

$$S^0 = \frac{e^{i\phi_s}}{\sqrt{2}}(v_s + S_R + iS_I)$$

EWSB ➡ $\mu_{\rm eff} \equiv \lambda \left\langle \hat{S} \right\rangle = \lambda v_s$

$$\begin{aligned} V_0 = & \left|\lambda\left(H_u^+ H_d^- - H_u^0 H_d^0\right) + \kappa S^2\right|^2 \\ & + \left(m_{H_u}^2 + |\mu + \lambda S|^2\right)\left(\left|H_u^0\right|^2 + \left|H_u^+\right|^2\right) + \left(m_{H_d}^2 + |\mu + \lambda S|^2\right)\left(\left|H_d^0\right|^2 + \left|H_d^-\right|^2\right) \\ & + \frac{g^2}{4}\left(\left|H_u^0\right|^2 + \left|H_u^+\right|^2 - \left|H_d^0\right|^2 - \left|H_d^-\right|^2\right)^2 + \frac{g_2^2}{2}\left|H_u^+ H_d^{0*} + H_u^0 H_d^{-*}\right|^2 \\ & + m_S^2 |S|^2 + \left(\lambda A_\lambda \left(H_u^+ H_d^- - H_u^0 H_d^0\right) S + \frac{1}{3}\kappa A_\kappa S^3 + \text{h.c.}\right), \end{aligned}$$

- ***5 neutral Higgs bosons: h, h_s, H and a_s, A***
- ***Possible enhancement in the tree-level mass of h***

$$M_h^2 \leq M_Z^2 \cos^2 2\beta + \frac{\lambda^2 v^2 \sin^2 2\beta}{2} - \frac{\lambda^2 v^2}{2\kappa^2}\left[\lambda - \sin 2\beta\left(\kappa + \frac{A_\lambda}{\sqrt{2} v_s}\right)\right]^2$$

NMSSM HIGGS MASS SPECTRUM

Masses of the two lightest scalars are given by (for large-ish tanβ - H, A decoupled)

$$M^2_{h,h_s} \approx \frac{1}{2}\left\{M_Z^2 + 4(\kappa v_s)^2 + \kappa v_s A_\kappa \mp \sqrt{\left[M_Z^2 - 4(\kappa v_s)^2 - \kappa v_s A_\kappa\right]^2 + 4\lambda^2 v^2 \left[2\lambda v_s - (A_\lambda + \kappa v_s)\sin 2\beta\right]^2}\right\}$$

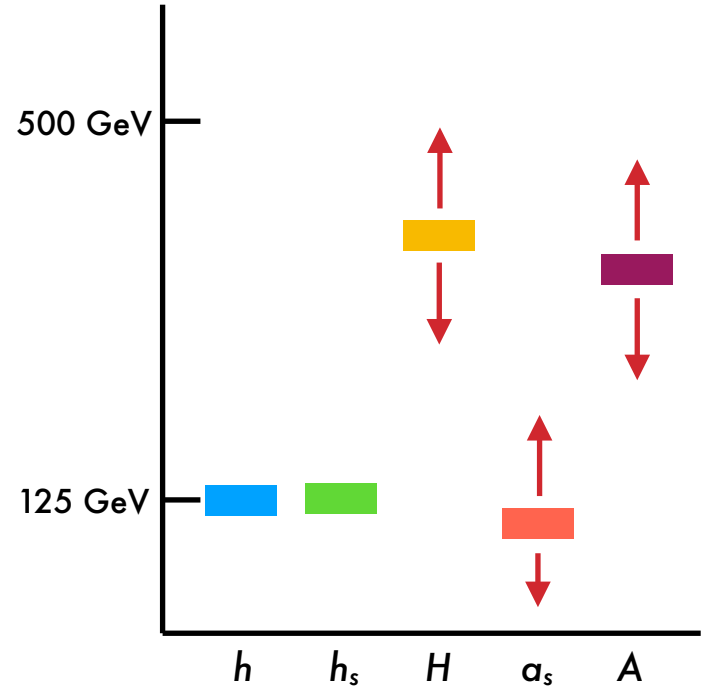
$$v \equiv \sqrt{v_u^2 + v_d^2} \simeq 174$$

λ~0.5, tanβ~2 ➡ large mixing, which can lead to

$$M_{h,h_s} \simeq 125\,\text{GeV}$$

Mass of the additional singlet-like pseudoscalar

$$M^2_{a_s} \simeq \lambda(A_\lambda + 4\kappa v_s)\frac{v^2 \sin 2\beta}{2 v_s} - 3\kappa v_s A_\kappa$$



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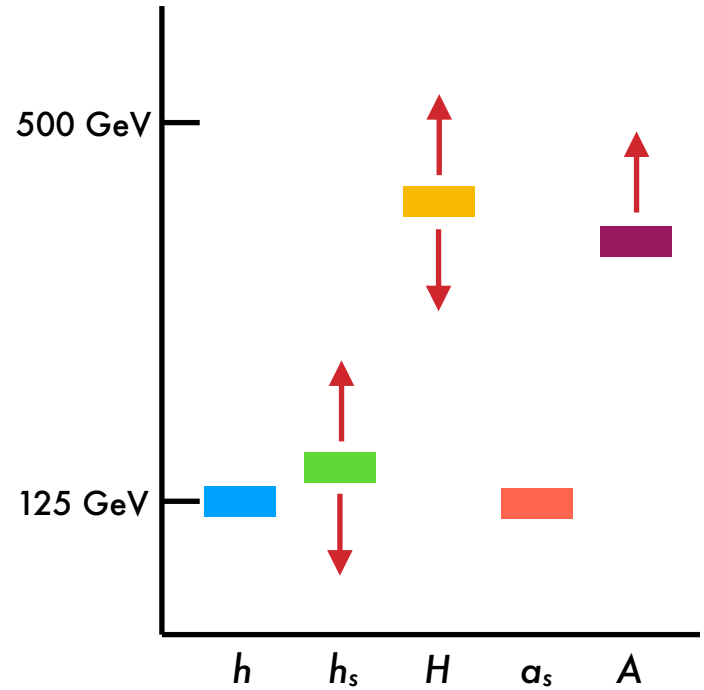

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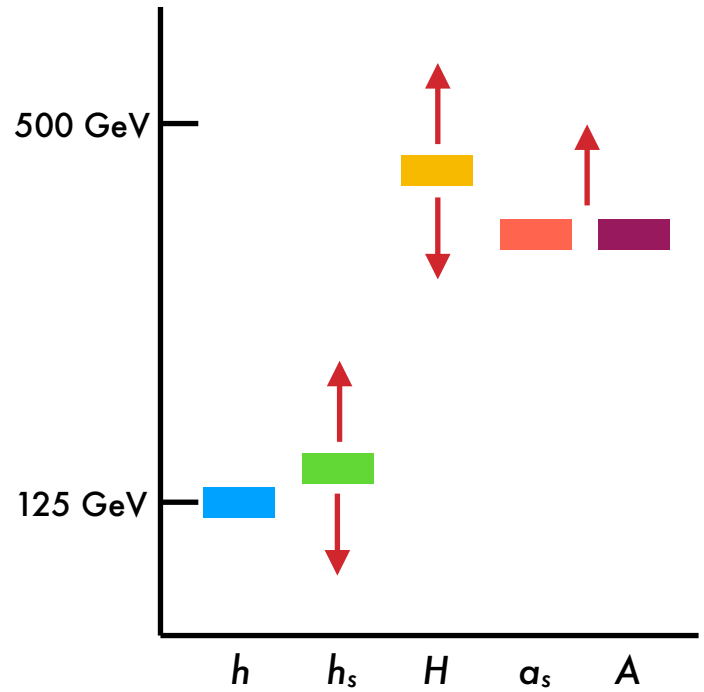

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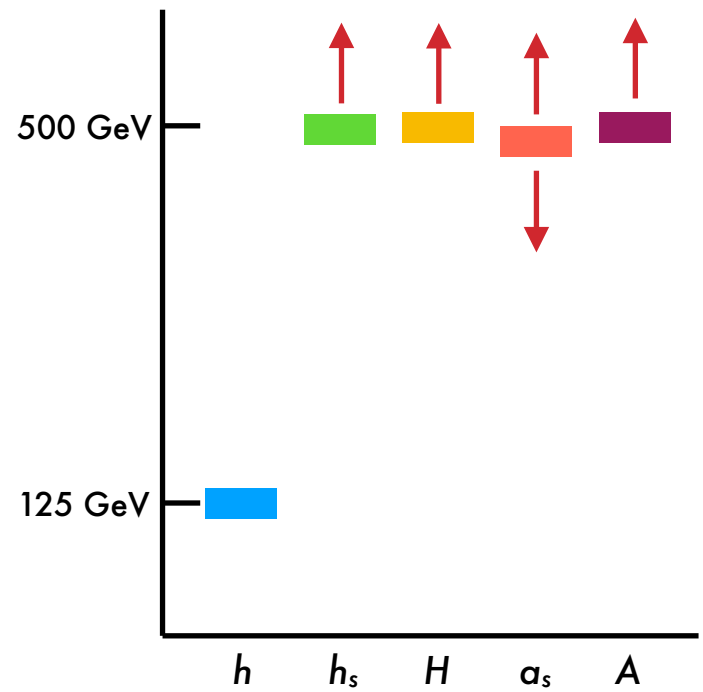


DI-PHOTON PAIR NEAR 125 GEV

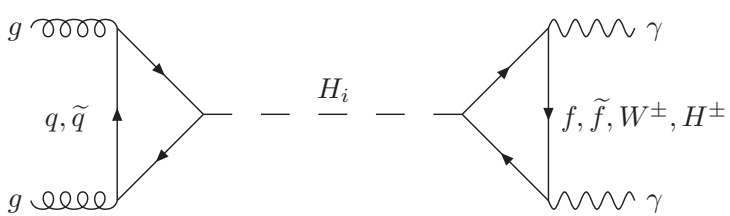
Quantum interference from loop effects, e.g,

$$\Im\mathrm{m}\hat{\Pi}_{ij}^{HH}(s) = \frac{v^2}{16\pi} \sum_{k\geq l=1-5} \frac{S_{ij;kl}}{1+\delta_{kl}} g_{H_iH_kH_l} g_{H_jH_kH_l}\ \lambda^{1/2}\Big(1,\kappa_{H_k},\kappa_{H_l}\Big)\ \Theta\Big(s-(m_{H_k}+m_{H_{H_l}})^2\Big)$$

[J. Ellis, J. S. Lee, A. Pilaftsis, 0404167]

Warrants taking the full propagator into account

$$D(\hat{s}) = \hat{s}\begin{pmatrix} \hat{s}-M_{H_1}^2+i\Im\mathrm{m}\widehat{\Pi}_{11}(\hat{s}) & & \\ & \hat{s}-M_{H_2}^2+i\Im\mathrm{m}\widehat{\Pi}_{22}(\hat{s}) & \\ & & \hat{s}-M_{H_3}^2+i\Im\mathrm{m}\widehat{\Pi}_{33}(\hat{s}) \end{pmatrix}^{-1}$$



$$\frac{d\sigma_{pp}^{\gamma\gamma}}{d\sqrt{\hat{s}}} = \int_\tau^1 \frac{2\sqrt{\hat{s}}}{s}\frac{dx_1}{x_1}\frac{g(x_1)g(\hat{s}/sx_1)}{1024\pi\hat{s}^3} \sum_{i,j=1-5}\Big\{\sum_{\lambda=\pm}|\mathcal{M}_{P_i\lambda}|^2\,|D_{ij}(\hat{s})|^2\sum_{\sigma=\pm}|\mathcal{M}_{D_j\sigma}|^2\Big\}$$

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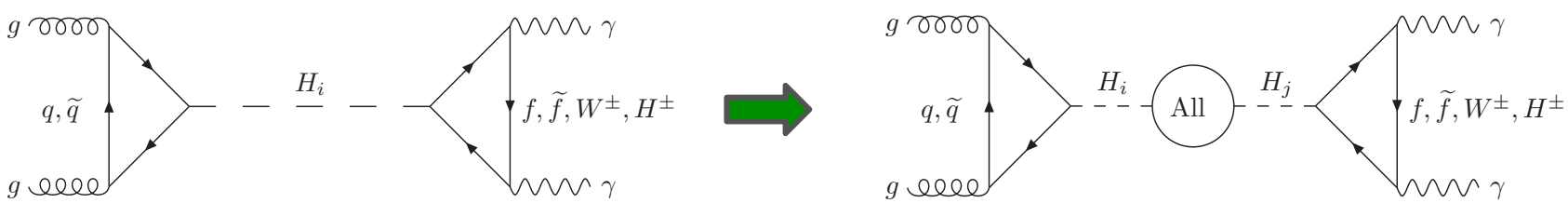


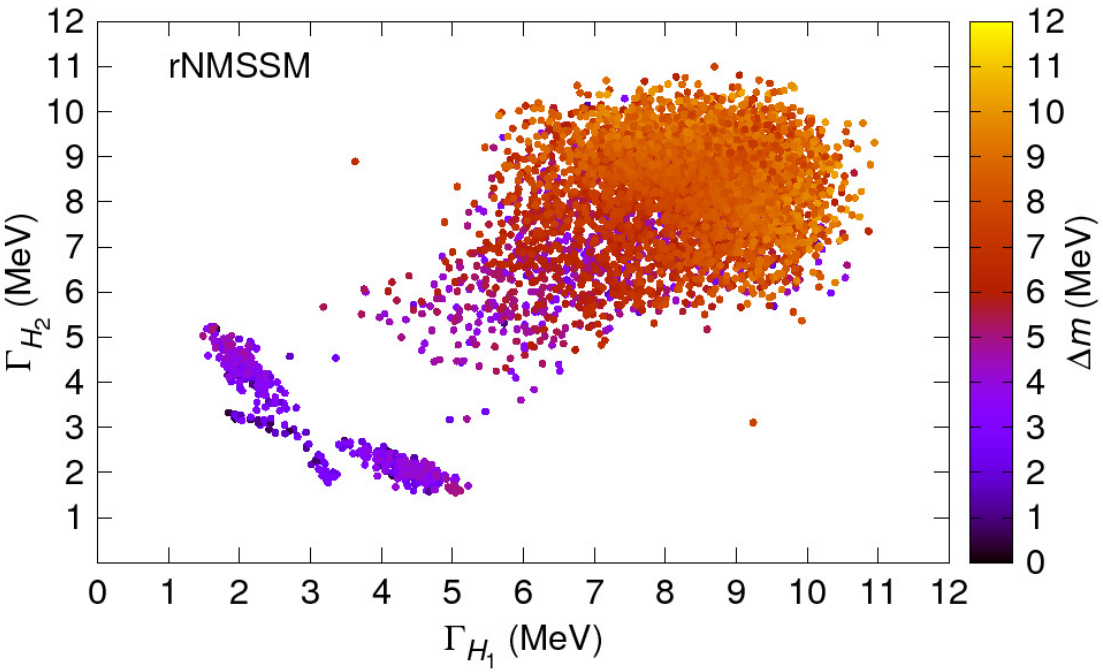
$$\frac{d\sigma_{pp\to yy}}{d\sqrt{\hat{s}}} = \int_\tau^1 \frac{2\sqrt{\hat{s}}}{s} \frac{dx_1}{x_1} \frac{g(x_1)g(\hat{\tau}x_1)}{1024\pi\hat{s}} \mathcal{A}_{gg\to yy}^2$$

PARAMETER SPACE SCANS

[B. Das, P. Poulose, S. Moretti, SM, 1704.02941]

$$M_0 \equiv M_{Q_{1,2,3}} = M_{U_{1,2,3}} = M_{D_{1,2,3}} = M_{L_{1,2,3}} = M_{E_{1,2,3}}$$

$$M_{1/2} \equiv 2M_1 = M_2 = \frac{1}{3}M_3 \qquad A_0 \equiv A_{\tilde{t}} = A_{\tilde{b}} = A_{\tilde{\tau}}$$



Parameter	Scanned range
M_0 (GeV)	800 – 2000
$M_{1/2}$ (GeV)	100 – 500
A_0 (GeV)	−3000 – 0
$\tan\beta$	2 – 8
λ	0.58 – 0.7
κ	0.3 – 0.6
$\mu_{\rm eff}$ (GeV)	100 – 200
A_λ (GeV)	200 – 1000
A_κ (GeV)	−300 – 0

Mass spectrum generator: NMSSMCalc

EXPERIMENTAL CONSTRAINTS

KIAS KOREA INSTITUTE FOR ADVANCED STUDY

Width estimate from H_{obs}* ⟶ WW and ZZ: < 13 MeV

[CMS Collaboration, 1605.02329]

Limit from fits to signal rates: Γ_{obs} < 41 MeV

[CMS-PAS-Higgs-16-033]

LHC measurements of the fiducial cross section for H_{obs} ⟶ di-photon: $43.2 \pm 14.9 \pm 4.9\,\mathrm{fb}$ [ATLAS-CONF-2016-067]

$69^{+18}_{-22}\,\mathrm{fb}$ [CMS-PAS-Higgs-16-020]

Exclusion limits on non-SM Higgs bosons from LEP, Tevatron and LHC using HiggsBounds-v4.1

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Define

Case 1: $\sum_{i=1-5}\sum_{\lambda,\sigma=\pm}\left|\mathcal{M}_{P_i\lambda}\frac{1}{\hat{s}-m^2_{H_i}+i\Im\mathrm{m}\hat{\Pi}_{ii}(\hat{s})}\mathcal{M}_{D_i\sigma}\right|^2$

Case 2: $\left|\sum_{i=1-5}\sum_{\lambda,\sigma=\pm}\mathcal{M}_{P_i\lambda}D_{ii}\mathcal{M}_{D_i\sigma}\right|^2$ ⟶ $\mathcal{A}^2_{gg\to yy}$

Case 3: $\left|\sum_{i,j=1-5}\sum_{\lambda,\sigma=\pm}\mathcal{M}_{P_i\lambda}D_{ij}\mathcal{M}_{D_j\sigma}\right|^2$

IMPACT ON CROSS SECTION

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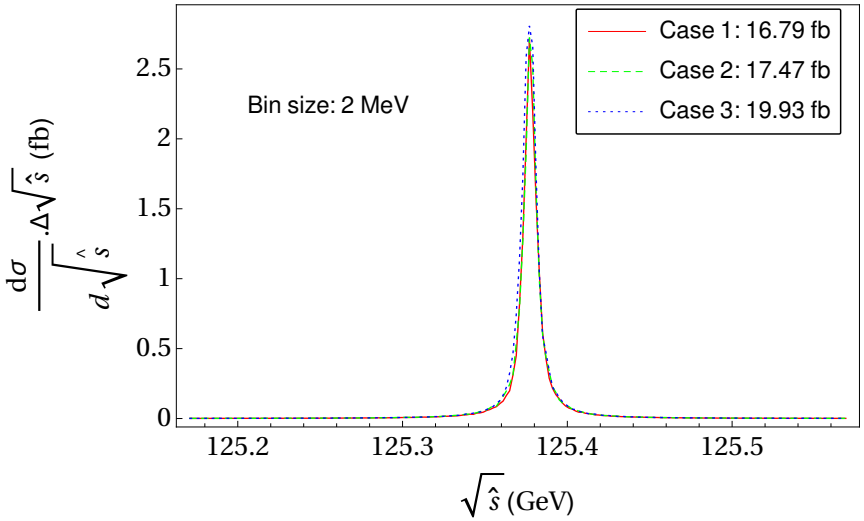
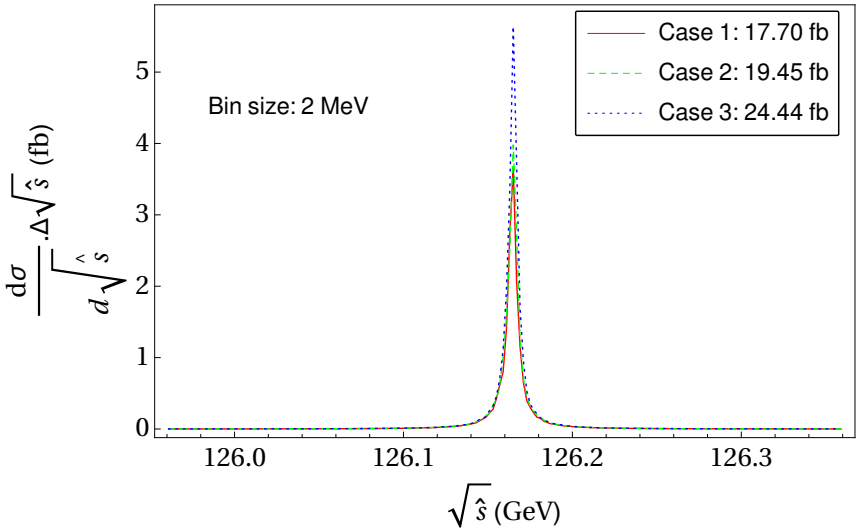
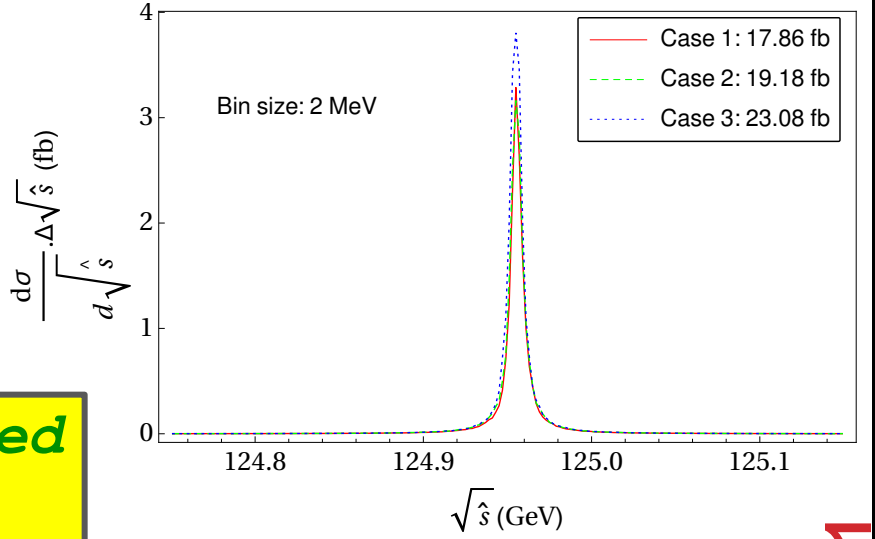
Benchmark points from scans

BP	m_{H_1} (GeV)	m_{H_2} (GeV)	Δm_H (MeV)	Γ_{H_1} (MeV)	Γ_{H_2} (MeV)
1	125.3688	125.3782	9.4	10.7	9.7
2	124.9498	124.9562	6.4	10.1	9.1
3	126.1641	126.1667	2.6	10.1	9.3







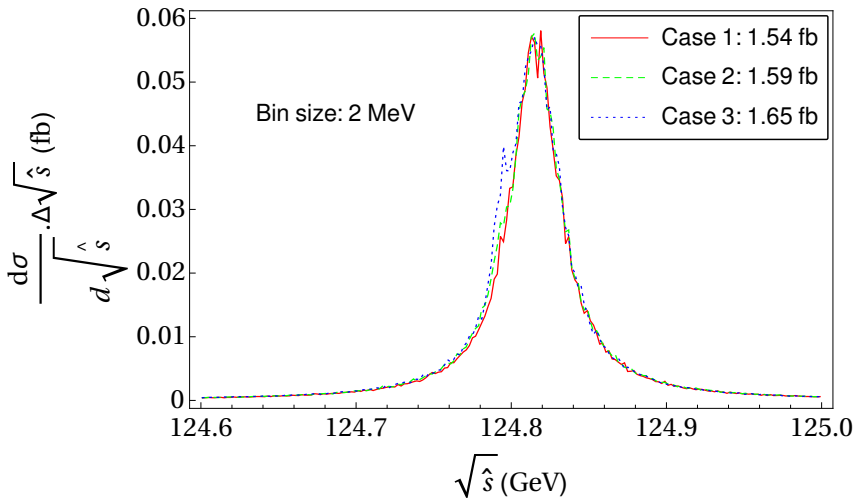
(NNLO) Cross section enhanced by ~40% for Γ_1, Γ_2 >> Δm

DETECTABILITY AT THE LHC

~~$\Gamma_{h_{obs}} < 13$ MeV~~

TP	m_{H_1} (GeV)	m_{H_2} (GeV)	Δm_H (MeV)	Γ_{H_1} (MeV)	Γ_{H_2} (MeV)	$\sigma_{pp}^{\gamma\gamma}$ (fb) Case 1	Case 2	Case 3
1	124.7928	124.8158	2.3	10.8	38.3	1.54	1.59	1.65
2	123.8696	124.1991	329.5	400.2	73.5	0.118	0.128	0.153
3	123.4590	123.7876	328.6	704.9	39.2	0.362	0.485	0.527

Two small peaks



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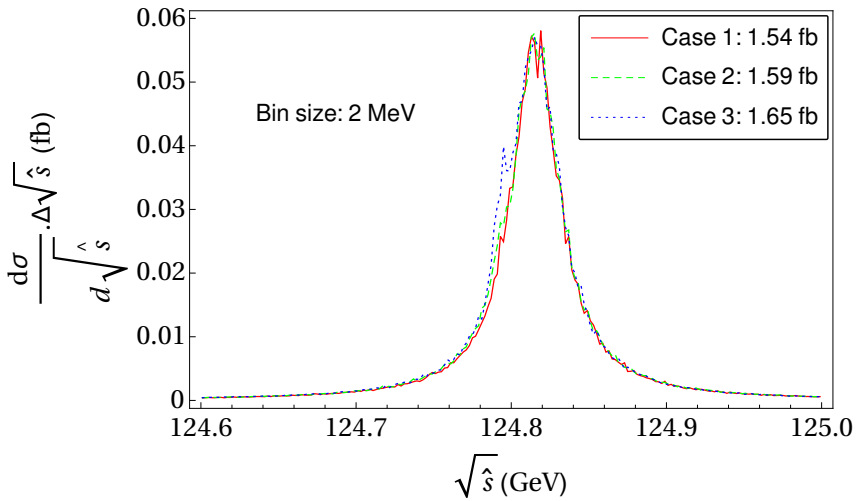
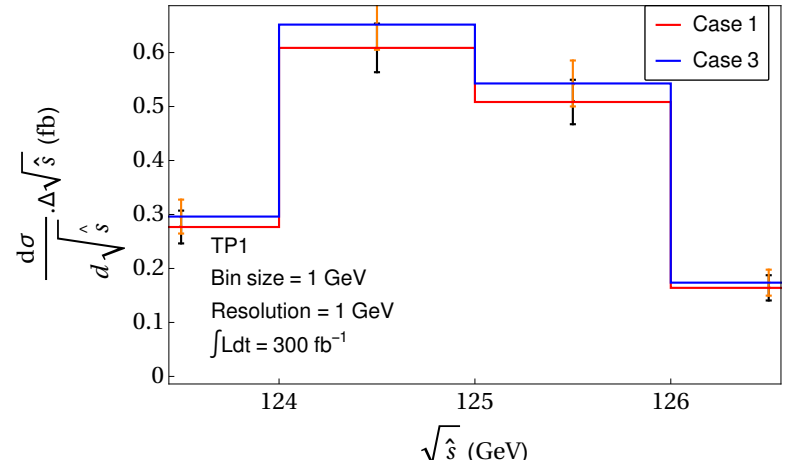
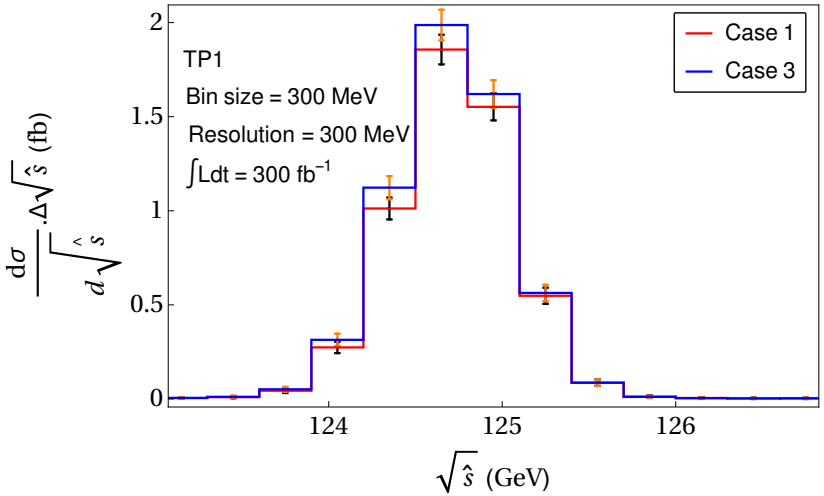
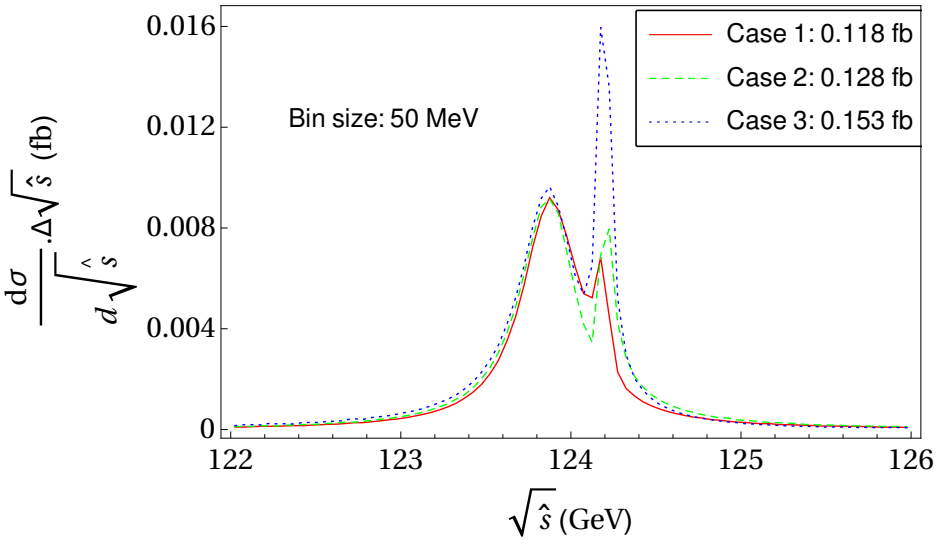


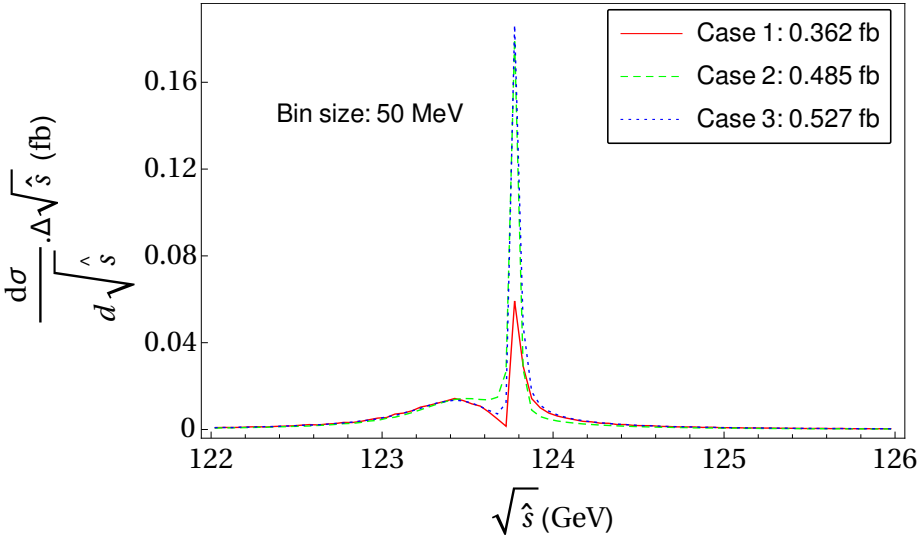


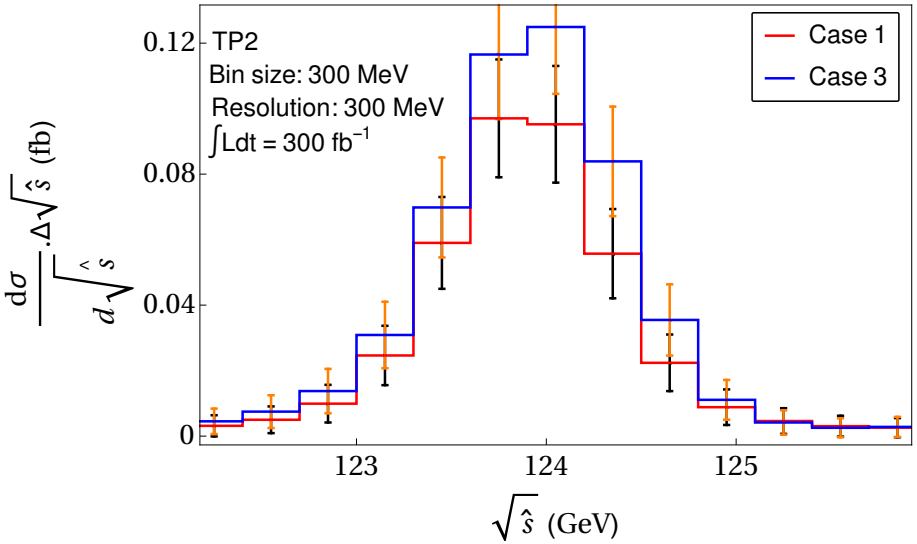


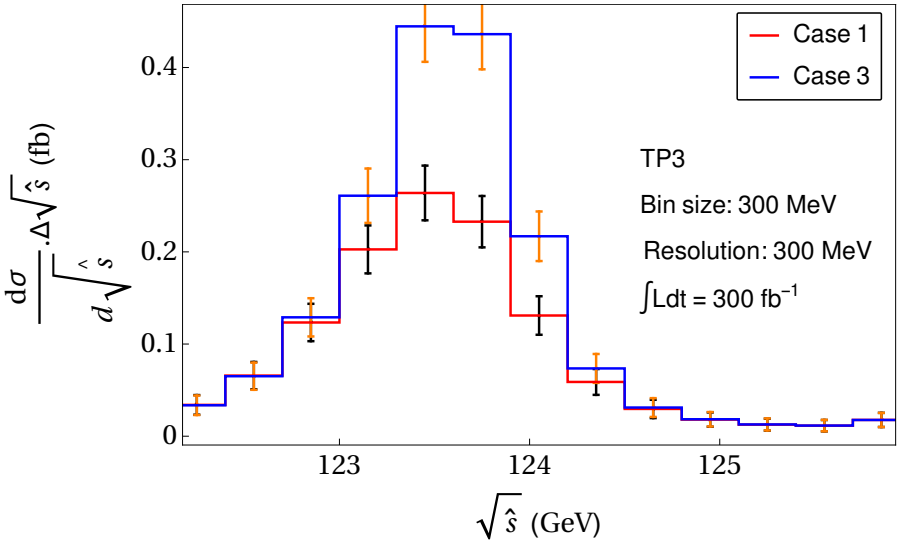
Convolute with a Gaussian of width equal to bin size

WIDER WIDTHS?









Mutually distinguishable distribution shapes

HEAVY h_s AND a_s IN THE NMSSM

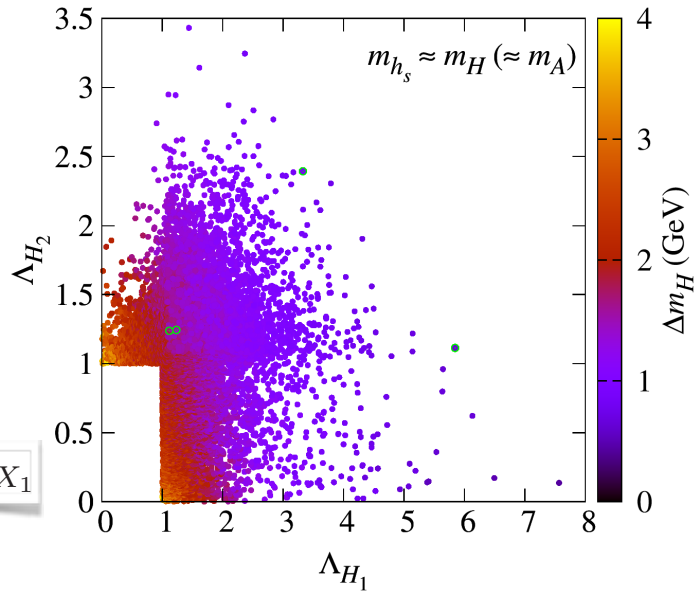
[B. Das, P. Poulose, S. Moretti, SM, 1804.10393]

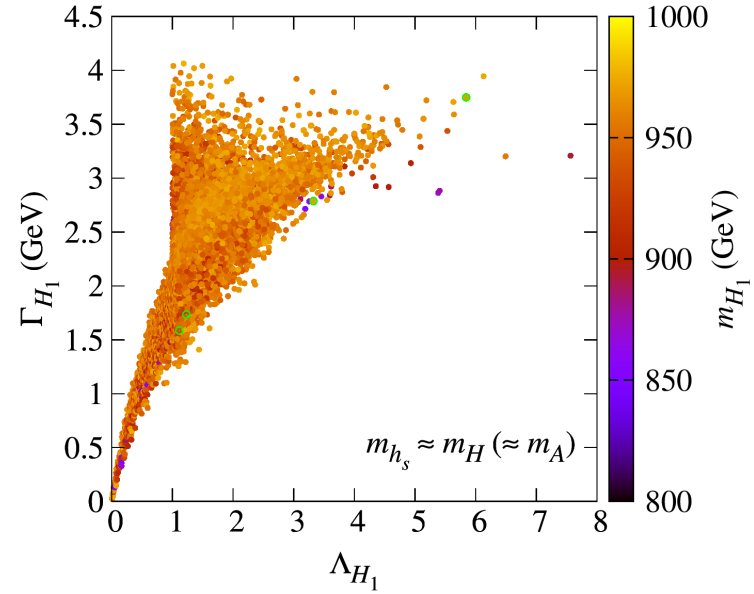
scenario-1:

$$m_{h_s} \approx m_H$$

$$\Lambda_{X_i} = \frac{\Gamma_{X_i}}{\Delta m_X}$$

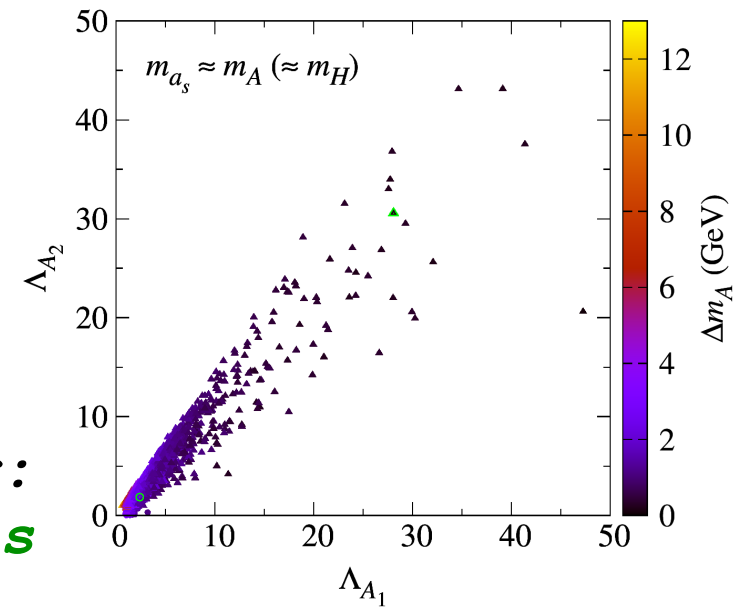
$$\Delta m_X = m_{X_2} - m_{X_1}$$

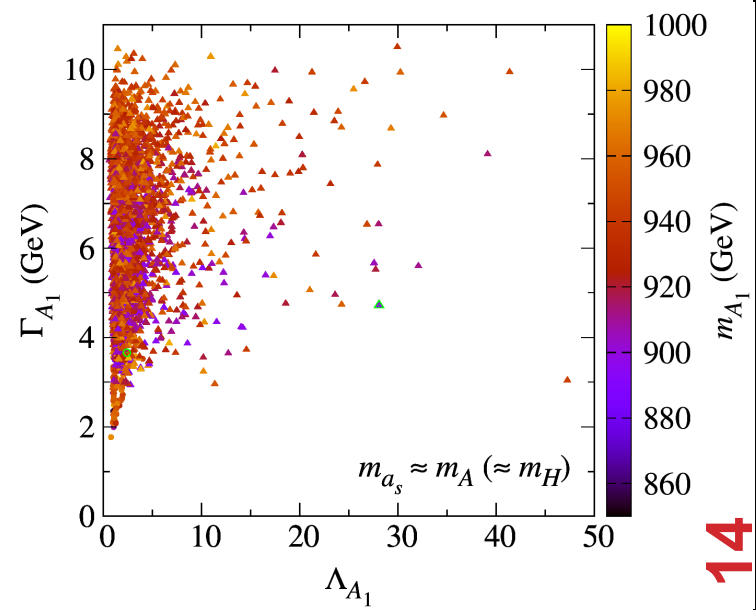




scenario-2:

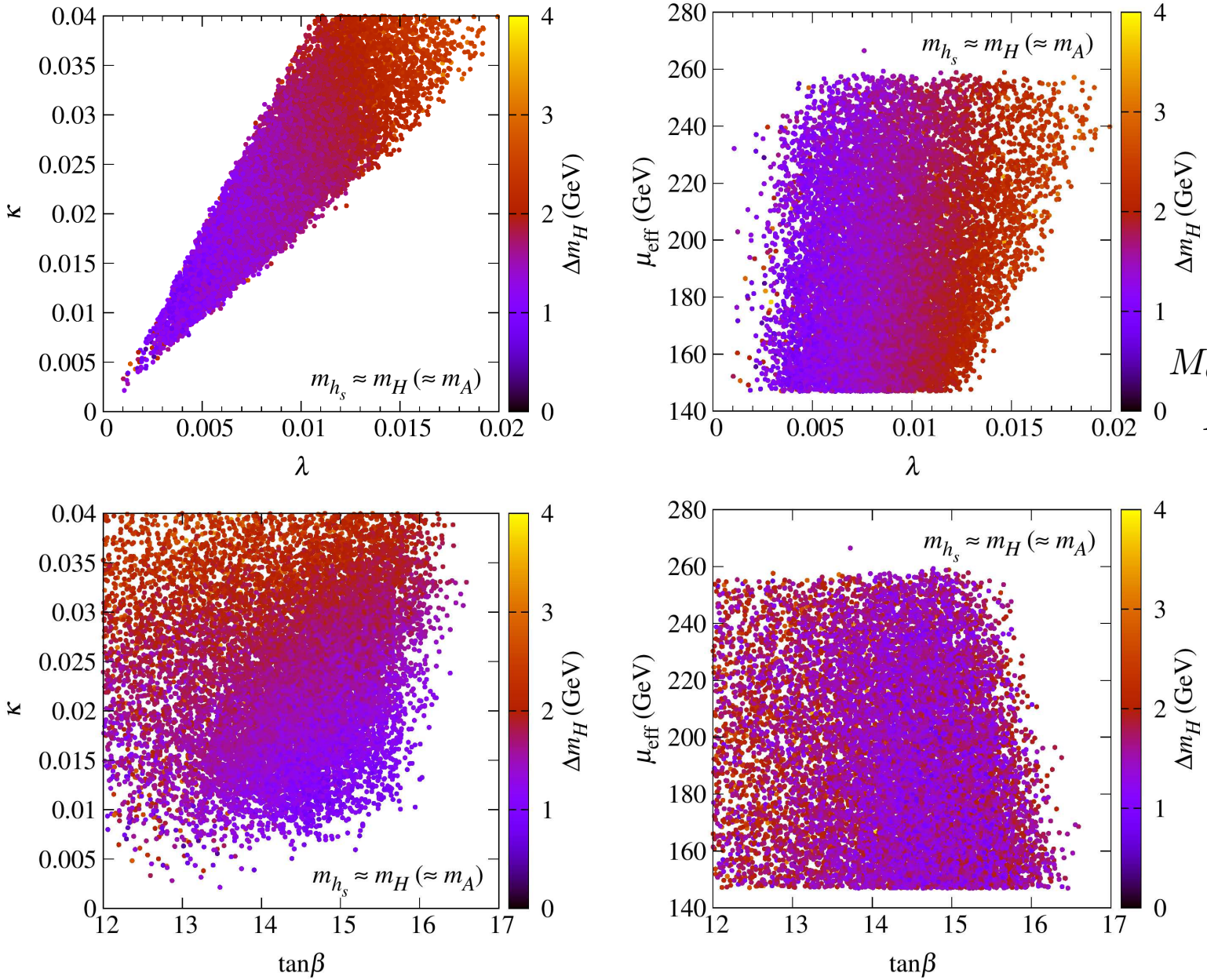
$$m_{a_s} \approx m_A$$





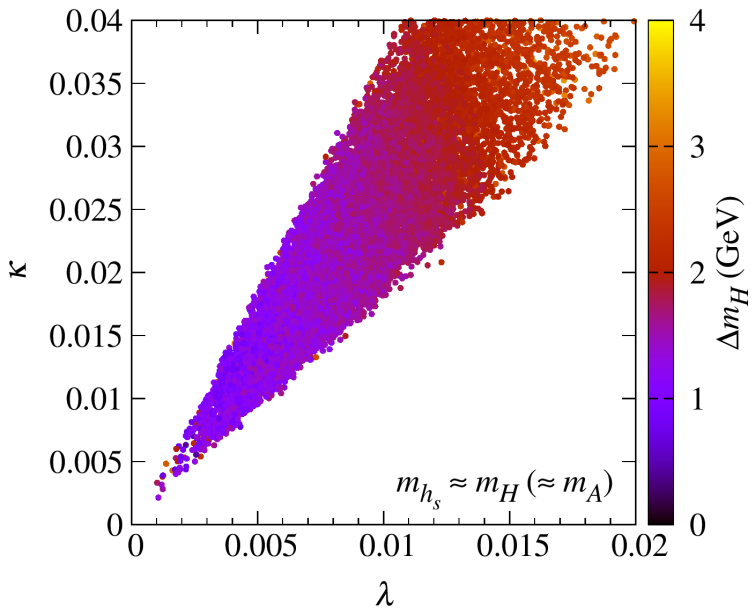
Mass spectrum generator:
NMSSMTools

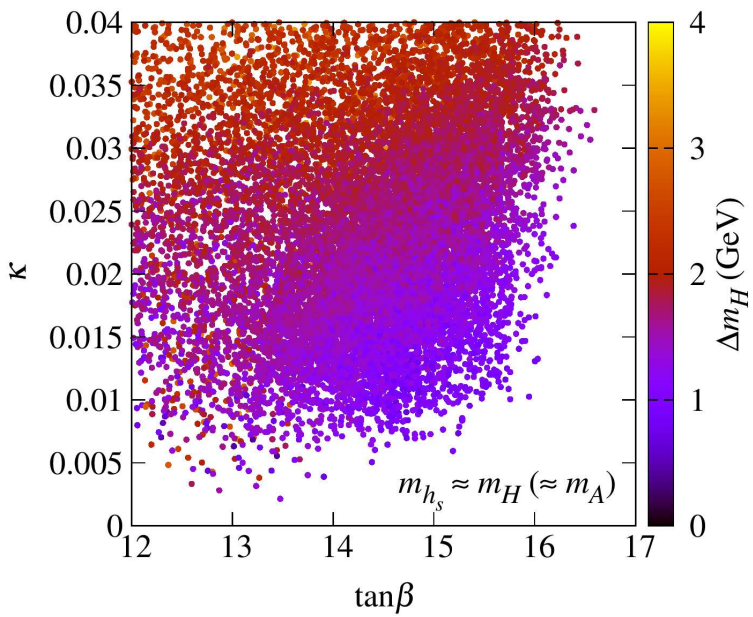
PARAMETER CORRELATIONS: $m_{h_s} \approx m_H$

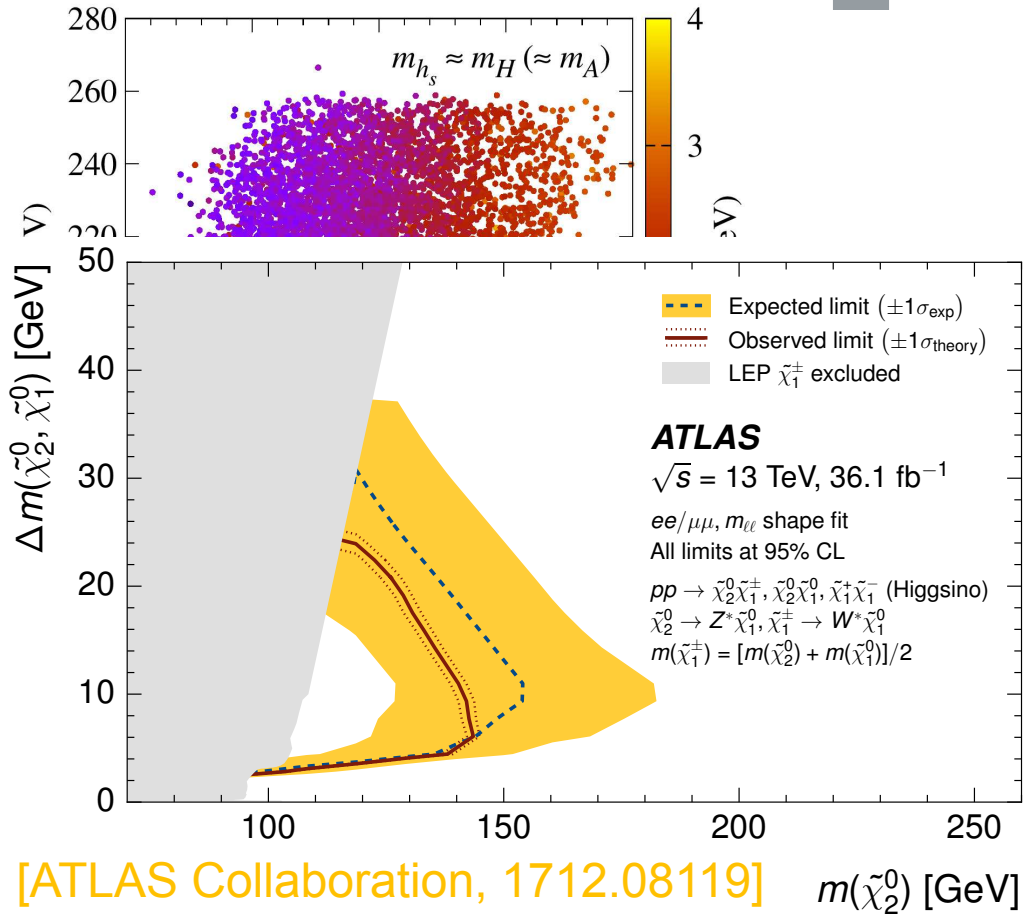


$$M_{Q,U,D} = 3\,\text{TeV}$$
$$M_{L,E} = 2\,\text{TeV}$$
$$M_2 = 1\,\text{TeV}$$

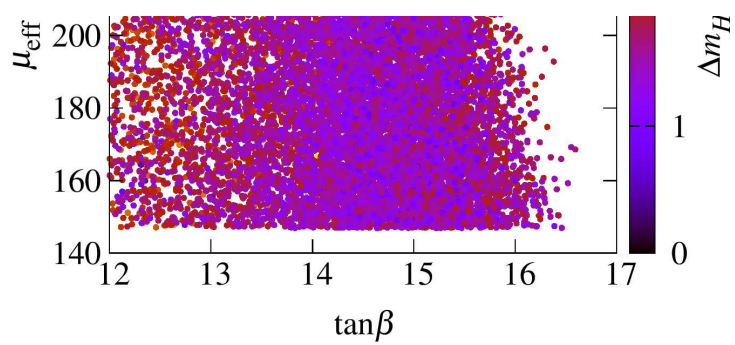
PARAMETER CORRELATIONS: $m_{h_s} \approx m_H$



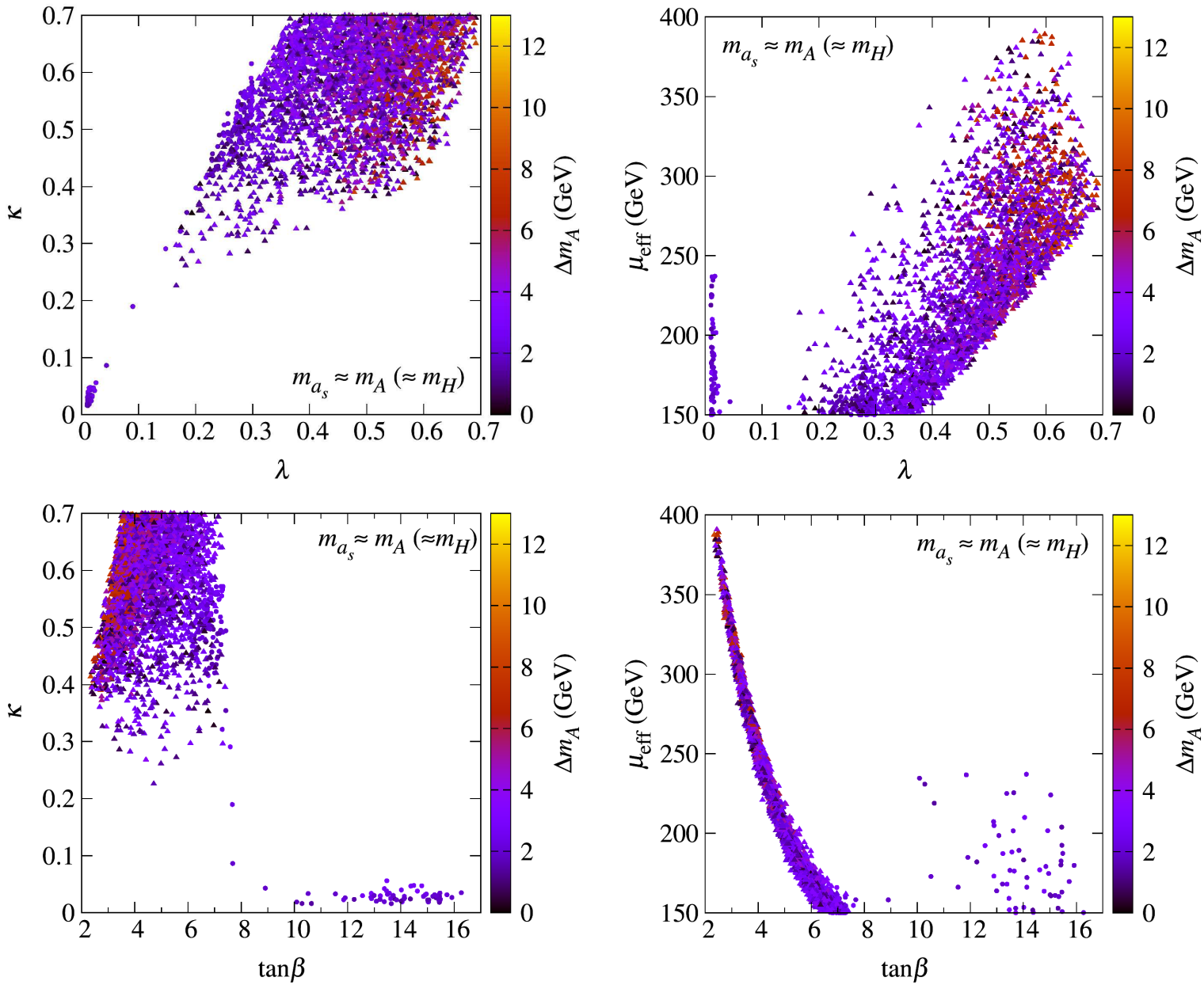




[ATLAS Collaboration, 1712.08119]



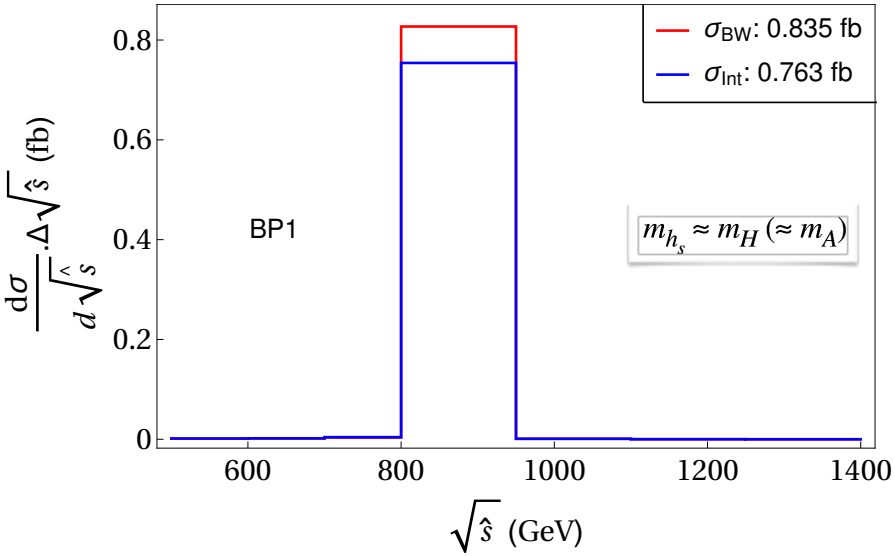
PARAMETER CORRELATIONS: $m_{a_s} \approx m_A$



$m_{h_s} > m_h$

$m_{h_s} < m_h$

DI-TAU CHANNEL AT THE LHC

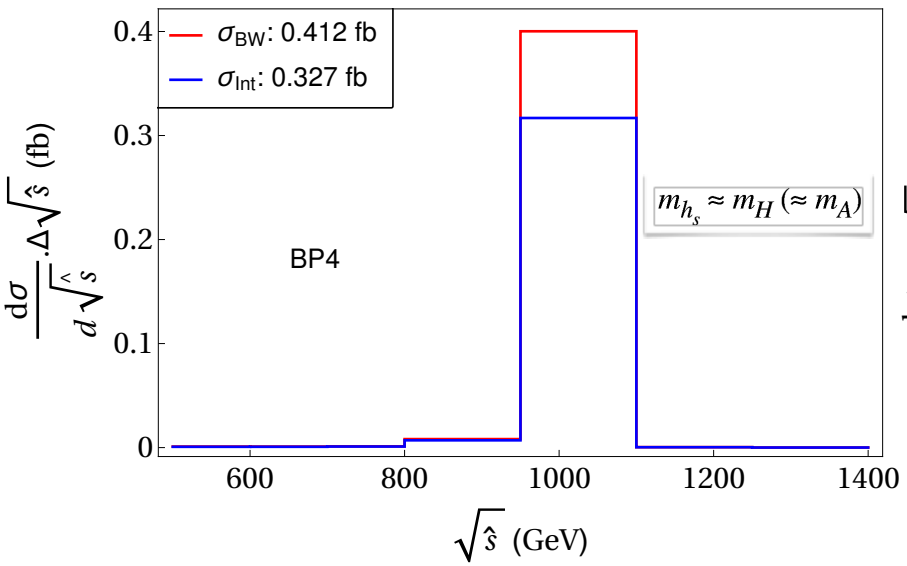


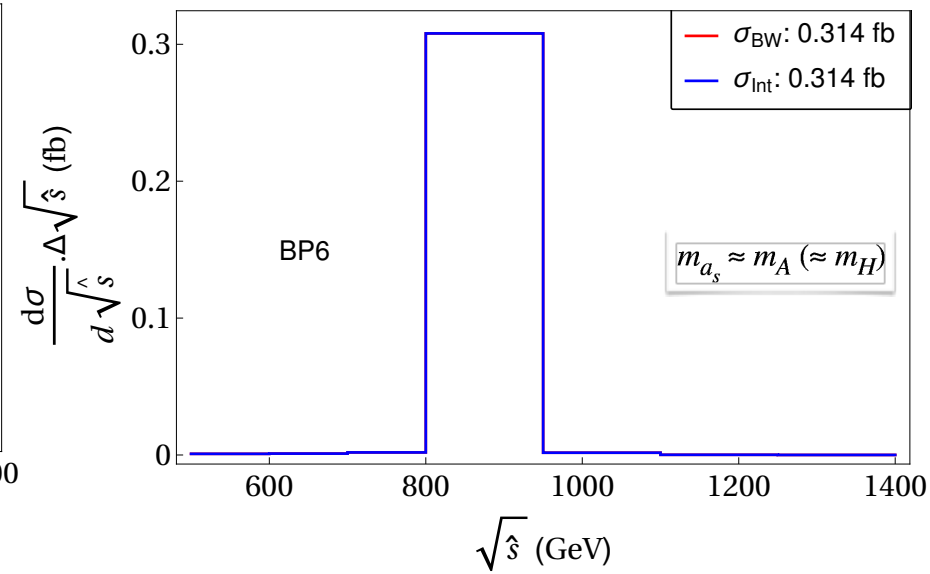
$$\mathrm{BR}(H_i \to \gamma\gamma) \lesssim 10^{-5}$$

$\mathrm{BR}(H_i \to \tau^+\tau^-)$ ***can reach ~10%***

But experimental resolution for $H_i \to \tau^+\tau^-$ ***only ~15-20% of the*** H_i ***mass***

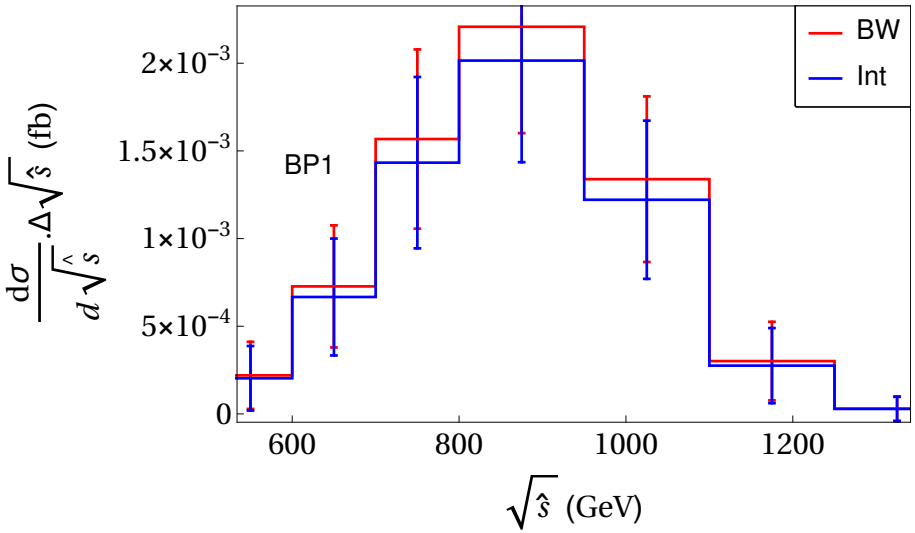
[L. Bianchini *et al.*, 1603.05910]

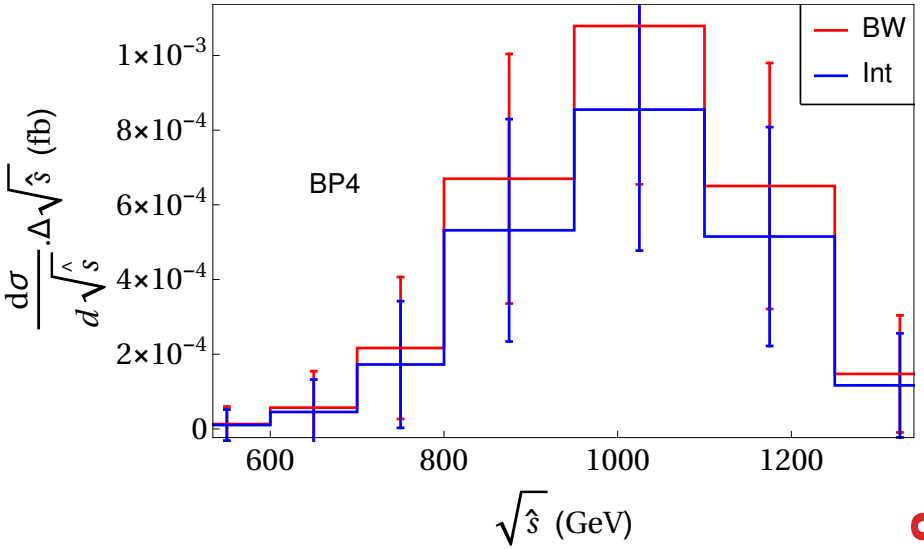




ESTABLISHING SIGNATURE

BP	1	4	6
$\tan\beta$	13.84	15.84	5.65
λ	0.0034	0.0041	0.3948
κ	0.0068	0.0141	0.6197
$\mu_{\rm eff}$ (GeV)	217.73	15.26	172.92
m_{H_1} (GeV)	866.05	973.01	107.13
m_{H_2} (GeV)	867.47	973.85	900.11
m_{A_1} (GeV)	698.06	626.84	896.46
m_{A_2} (GeV)	867.31	973.61	896.63
Δm_X (GeV)	1.42	0.84	0.170
Γ_{H_1} (GeV)	1.59	2.79	
Γ_{H_2} (GeV)	1.76	2.01	4.84
Γ_{A_1} (GeV)			5.14
Γ_{A_2} (GeV)	3.39	4.82	4.72
BR(H_1)	0.1032	0.1059	0.0915
BR(H_2)	0.1025	0.1051	0.0122
BR(A_1)	0.0861	0.0019	10^{-7}
BR(A_2)	0.1015	0.1051	0.0126
σ_{NWA} (fb)	0.715	0.381	0.343
$\sigma_{\rm BW}$ (fb)	0.835	0.412	0.314
$\Delta\sigma_1$ (%)	+16.9	+8.2	+17.2
$\sigma_{\rm Int}$ (fb)	0.763	0.327	0.314
$\Delta\sigma_2$ (%)	−8.6	20.6	0





CONCLUSIONS

- *In the NMSSM, multiple Higgs bosons could be contributing to the observed ~125 GeV signal*
- *Important to disentangle them - signature not only of new physics but also of non-minimal SUSY*
- *Quantum interference effects could be the key*
- *Narrow width of the signal - necessary to improve mass resolution of the photon pair*
- *The new (pseudo)scalar of the NMSSM and the heavy MSSM-like (pseudo)scalar can also be mass-degenerate, and can thus mutually interfere*
- *Di-photon rate too low; poor mass resolution of the tau pair again an obstacle*

KIAS KOREA INSTITUTE FOR ADVANCED STUDY

THANK YOU!

감사합니다!