Electroweak phase transition with two Higgs doublets near the alignment limit

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Based on **1712.08430**

In collaboration with

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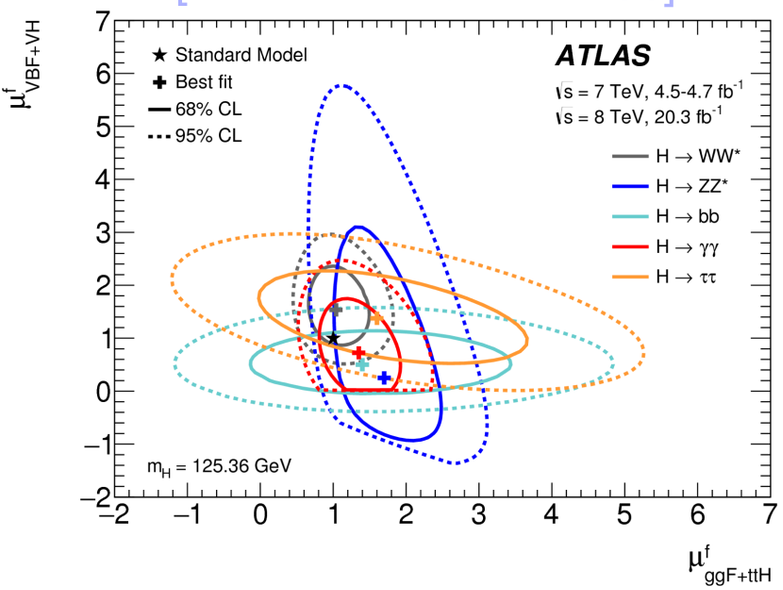
IAS Program on High Energy Physics
Hong Kong, January 22nd, 2018

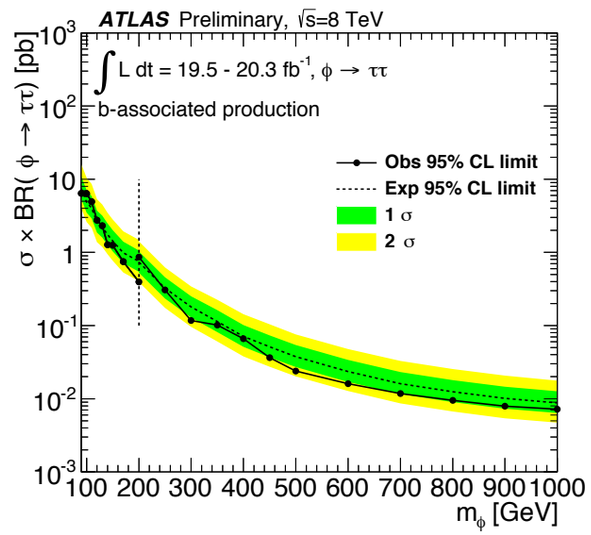
HKUST JOCKEY CLUB
INSTITUTE FOR ADVANCED STUDY

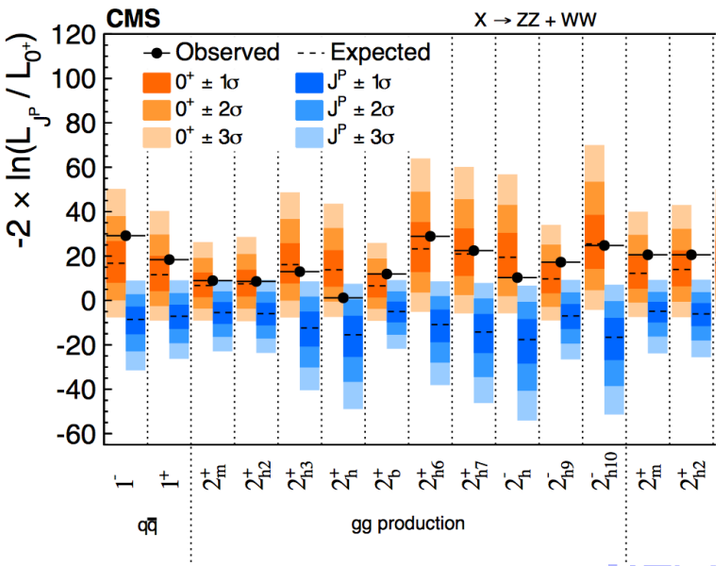
Motivations

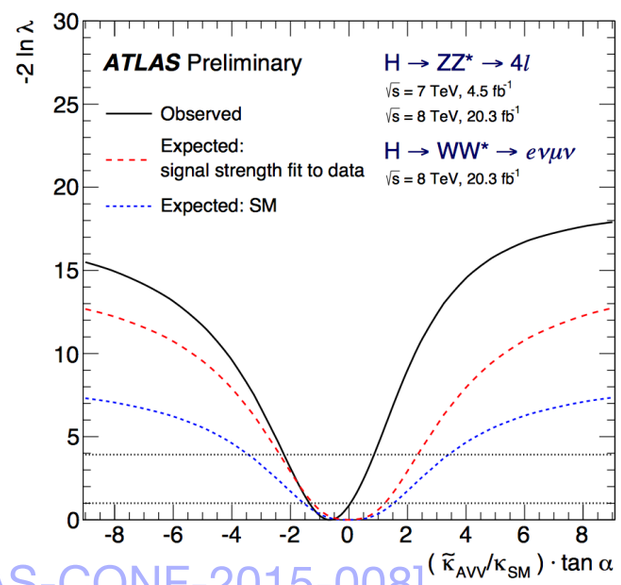
[ATLAS-HIGG-2014-06]



[ATLAS-2014-049]







[CMS-HIG-14-018] [ATLAS-CONF-2015-008]

So far in very good agreement with the SM

$$\eta \in [5.8, 6.6] \times 10^{-10}$$

$$\Omega_{\rm DM} h^2 = 0.1186(20)$$

$$|\Delta m_{21}| \approx 0.1 \text{ eV}$$

$$|\theta_{QCD}| \lesssim 10^{-10}$$

$$\ldots$$

Series of observations requiring new physics (or large fine tuning)

A connection to the Higgs sector can be found for all these observations

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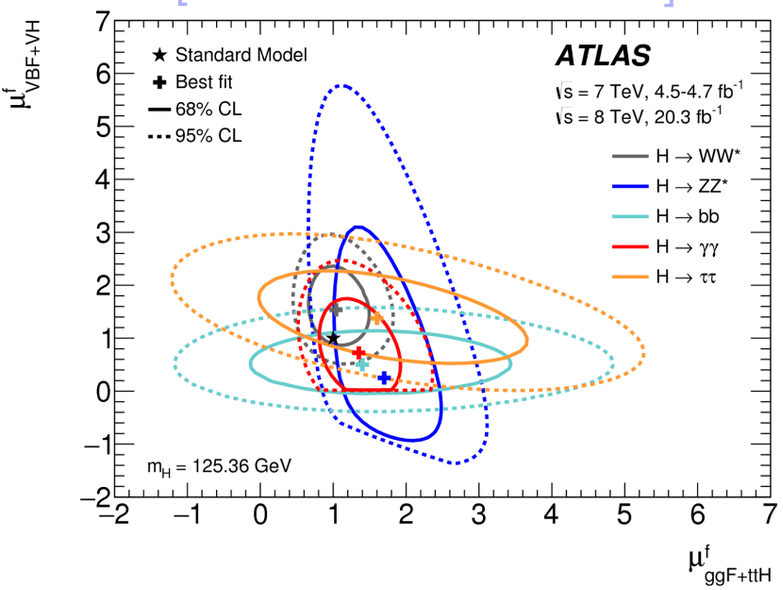

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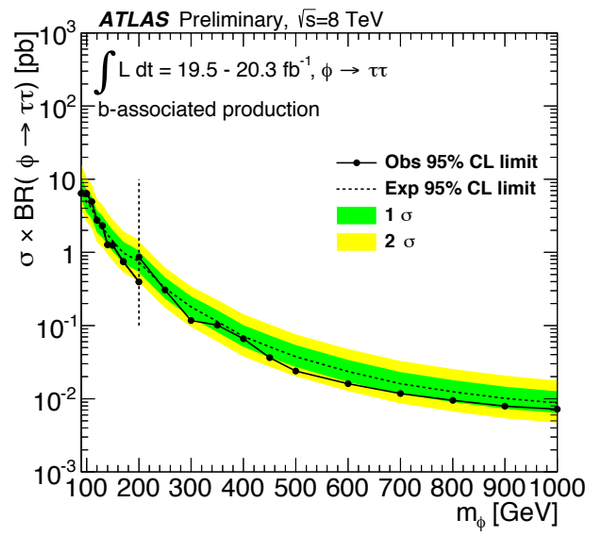

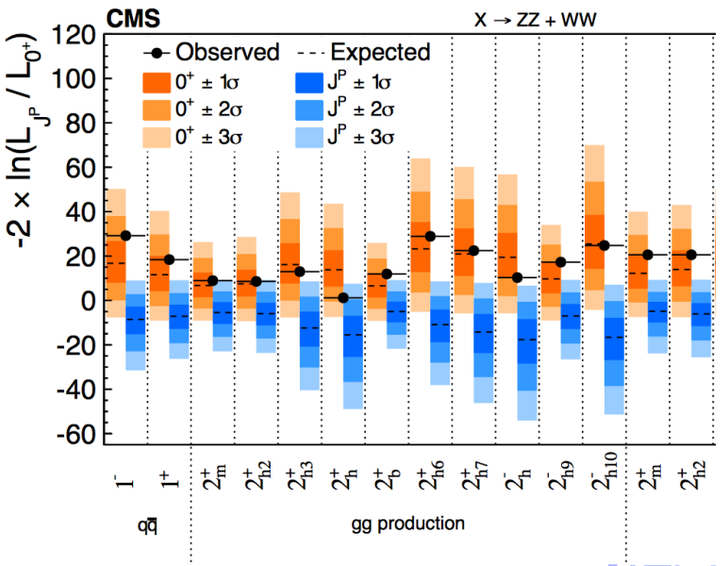

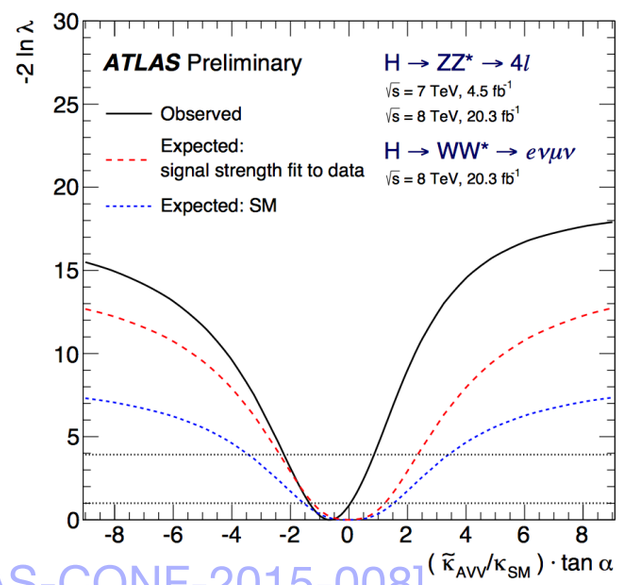

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Electroweak baryogenesis

Testable in colliders and in the sky, several handles

- Require a first-order phase transition: nucleation of expending bubbles of true vacuum ➜ presence of extra degrees of freedom testable at colliders
- Diffusion of chiral species through the bubble wall, asymmetry generated due to CP-violating interactions ➜ electric dipole moments as important probe
- Chiral asymmetry changed to baryon asymmetry in the symmetric vacuum by the electroweak sphaleron
- Enforcing sphaleron rate suppression inside the bubbles to prevent washout of the asymmetry in the true vacuum: $\xi \equiv v_c/T_c \gtrsim 1$, termed "strong first-order phase transition" (SFOPT) ➜ restriction of model parameter space
- Bubbles expend and eventually collide ➜ stochastic gravitational waves possibly observable in space-based interferometers

Here we look for parameter space regions that leads to a SFOPT
and look at the associated LHC phenomenology

Two-Higgs-doublet models

- The SM EWSB sector contains one Higgs doublet but there is no reason for such minimality. Simple extension: an additional Higgs doublet → (Φ_1, Φ_2).

- Omitting the possibility of CP violation in the Higgs sector, the physical spectrum consists of 5 states: 2 CP-even h, H, a CP-odd A and a pair of charged states $H^\pm$.

$$\Phi_i = \frac{1}{\sqrt{2}} \begin{pmatrix} \sqrt{2}\phi_i^+ \\ v_i + \phi_i + i\eta_i \end{pmatrix} \qquad \begin{aligned} v_1 &= v\cos\beta \\ v_2 &= v\sin\beta \end{aligned} \qquad \begin{pmatrix} H \\ h \end{pmatrix} = \begin{pmatrix} c_\alpha & s_\alpha \\ -s_\alpha & c_\alpha \end{pmatrix} \begin{pmatrix} \sqrt{2}\mathrm{Re}\Phi_1^0 - v_1 \\ \sqrt{2}\mathrm{Re}\Phi_2^0 - v_2 \end{pmatrix}$$

Both h and H can be identified with the SM-like state: here we consider h-125.

- The general 2HDM has large tree-level flavor changing neutral currents: forbid them by imposing a $\mathbb{Z}_2$-symmetry: $\Phi_1 \to \Phi_1,\ \Phi_2 \to -\Phi_2$ (natural flavour violation)

$$\mathcal{V}_0 = m_{11}^2 \Phi_1^\dagger \Phi_1 + m_{22}^2 \Phi_2^\dagger \Phi_2 - [m_{12}^2 \Phi_1^\dagger \Phi_2 + \mathrm{h.c.}] + \frac{1}{2}\lambda_1 (\Phi_1^\dagger \Phi_1)^2 + \frac{1}{2}\lambda_2 (\Phi_2^\dagger \Phi_2)^2 + \lambda_3 (\Phi_1^\dagger \Phi_1)(\Phi_2^\dagger \Phi_2)$$
$$+ \lambda_4 (\Phi_1^\dagger \Phi_2)(\Phi_2^\dagger \Phi_1) + \left\{ \frac{1}{2}\lambda_5 (\Phi_1^\dagger \Phi_2)^2 + \mathrm{h.c.} \right\}$$

The alignment limit

- Higgs basis: the vev v≃246 GeV resides entirely in one of the two doublets:

$$\begin{pmatrix} H_1 \\ H_2 \end{pmatrix} \equiv \begin{pmatrix} c_\beta & s_\beta \\ -s_\beta & c_\beta \end{pmatrix} \begin{pmatrix} \Phi_1 \\ \Phi_2 \end{pmatrix} \qquad H_1 = \frac{1}{\sqrt{2}} \begin{pmatrix} \sqrt{2}G^+ \\ v + h_1 + iG^0 \end{pmatrix}, \; H_2 = \frac{1}{\sqrt{2}} \begin{pmatrix} \sqrt{2}H^+ \\ h_2 + iA \end{pmatrix}$$

$$\begin{aligned} \mathcal{V}_0 =& Y_1 H_1^\dagger H_1 + Y_2 H_2^\dagger H_2 + Y_3[H_1^\dagger H_2 + \text{h.c.}] + \frac{1}{2} Z_1 (H_1^\dagger H_1)^2 + \frac{1}{2} Z_2 (H_2^\dagger H_2)^2 + Z_3 (H_1^\dagger H_1)(H_2^\dagger H_2) \\ &+ Z_4 (H_1^\dagger H_2)(H_2^\dagger H_1) + \left\{ \frac{1}{2} Z_5 (H_1^\dagger H_2)^2 + \left[Z_6 (H_1^\dagger H_1) + Z_7 (H_2^\dagger H_2) \right] H_1^\dagger H_2 + \text{h.c.} \right\} \end{aligned}$$

- The CP-even mass matrix and eigenstates are:

$$\mathcal{M}_H^2 = \begin{pmatrix} Z_1 v^2 & Z_6 v^2 \\ Z_6 v^2 & m_A^2 + Z_5 v^2 \end{pmatrix} \qquad \begin{aligned} H &= h_1 c_{\beta-\alpha} - h_2 s_{\beta-\alpha} \\ h &= h_1 s_{\beta-\alpha} + h_2 c_{\beta-\alpha} \end{aligned}$$

⇨ A SM-like state is obtained if one of the two mass eigenstates is aligned with the direction of the vev: the alignment limit

Here $s_{\beta-\alpha} \geq 0.99$

[JB, Gunion, Haber, Jiang, Kraml '15 '16]

<u>Alignment in the h-125 scenario:</u>

$$c_{\beta-\alpha} = \frac{-Z_6 v^2}{\sqrt{(m_H^2 - m_h^2)(m_H^2 - Z_1 v^2)}} \simeq 0 \quad \Rightarrow \begin{cases} m_H^2 \gg v^2 \text{: Decoupling limit} \\ |Z_6| \ll 1 \text{: Alignment w/o decoupling} \end{cases}$$

Potential beyond tree-level

$$V(h_1,h_2,T) = V_0(h_1,h_2) + V_{\rm CW}(h_1,h_2) + V_{\rm CT}(h_1,h_2) + V_{\rm th}(h_1,h_2,T) + V_{\rm daisy}(h_1,h_2,T)$$

- One-loop at zero temperature:

$$V_{\rm CW}(h_1,h_2) = \sum_i (-1)^{2s_i} n_i \frac{\hat{m}_i^4(h_1,h_2)}{64\pi^2}\left[\ln\left(\frac{\hat{m}_i^2(h_1,h_2)}{Q^2}\right) - C_i\right]$$ [Coleman, Weinberg '73]

- Finite parts fixed such that there is no shift in vevs and mass matrices from tree-level to loop-level

- One-loop at finite temperature:

$$V_{\rm th}(h_1,h_2,T) = \frac{T^4}{2\pi^2}\sum_i n_i J_{B,F}\left(\frac{m_i^2(h_1,h_2)}{T^2}\right)$$ [Dolan, Jackiw '74]

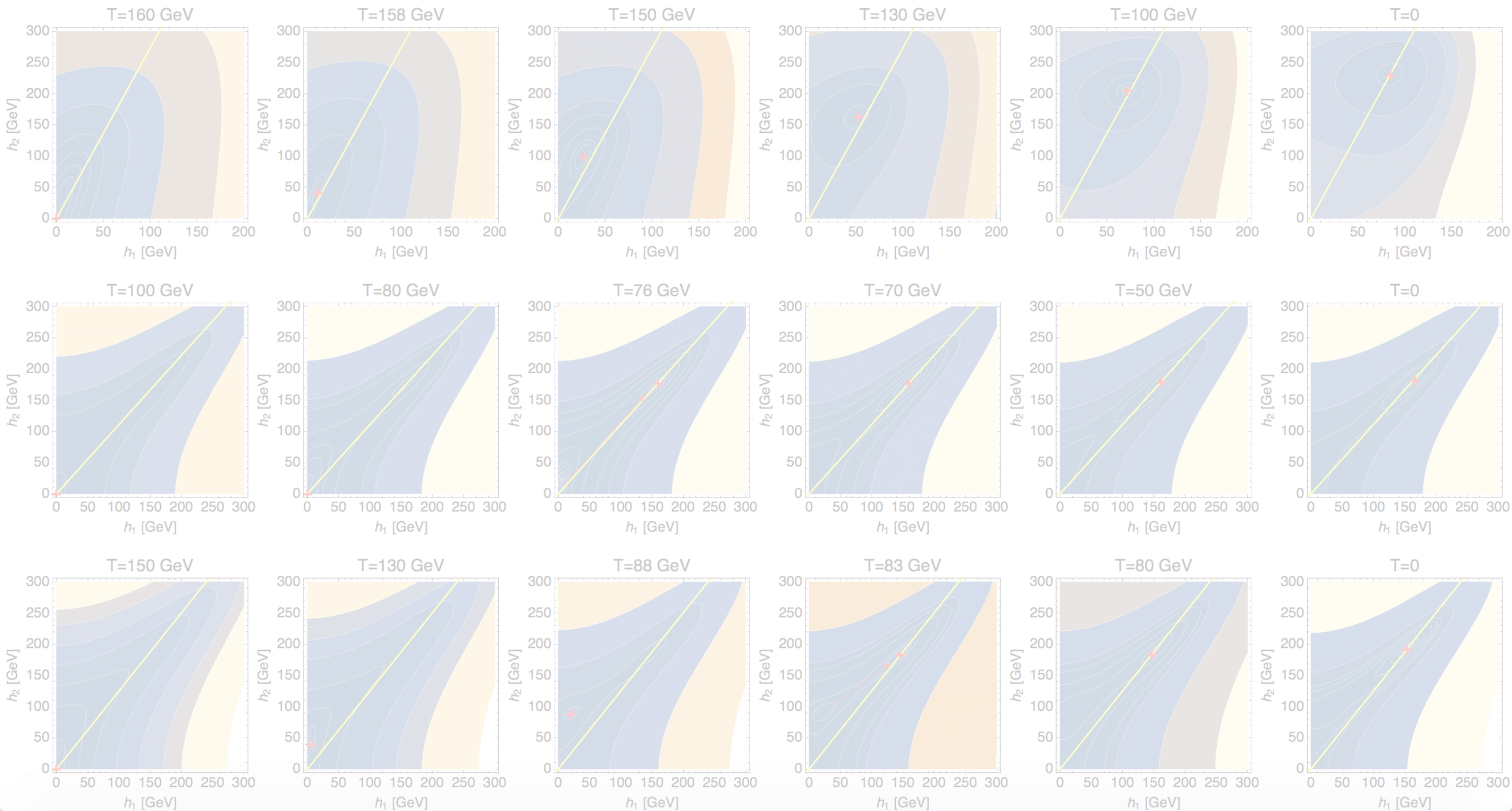
$$J_{B,F}(y) = \mp\sum_{l=1}^{\infty}\frac{(\pm 1)^l y}{l^2}K_2(\sqrt{y}l)$$ [Anderson, Halle '92]

- Dominant thermal corrections:

$$V_{\rm daisy}(h_1,h_2,T) = -\frac{T}{12\pi}\sum_i n_i\left[\left(M_i^2(h_1,h_2,T)\right)^{\frac{3}{2}} - \left(m_i^2(h_1,h_2)\right)^{\frac{3}{2}}\right]$$

[Carrington '92; Arnold, Espinosa '93; Delaunay, Grojean, Wells '07]

Vacuum histories



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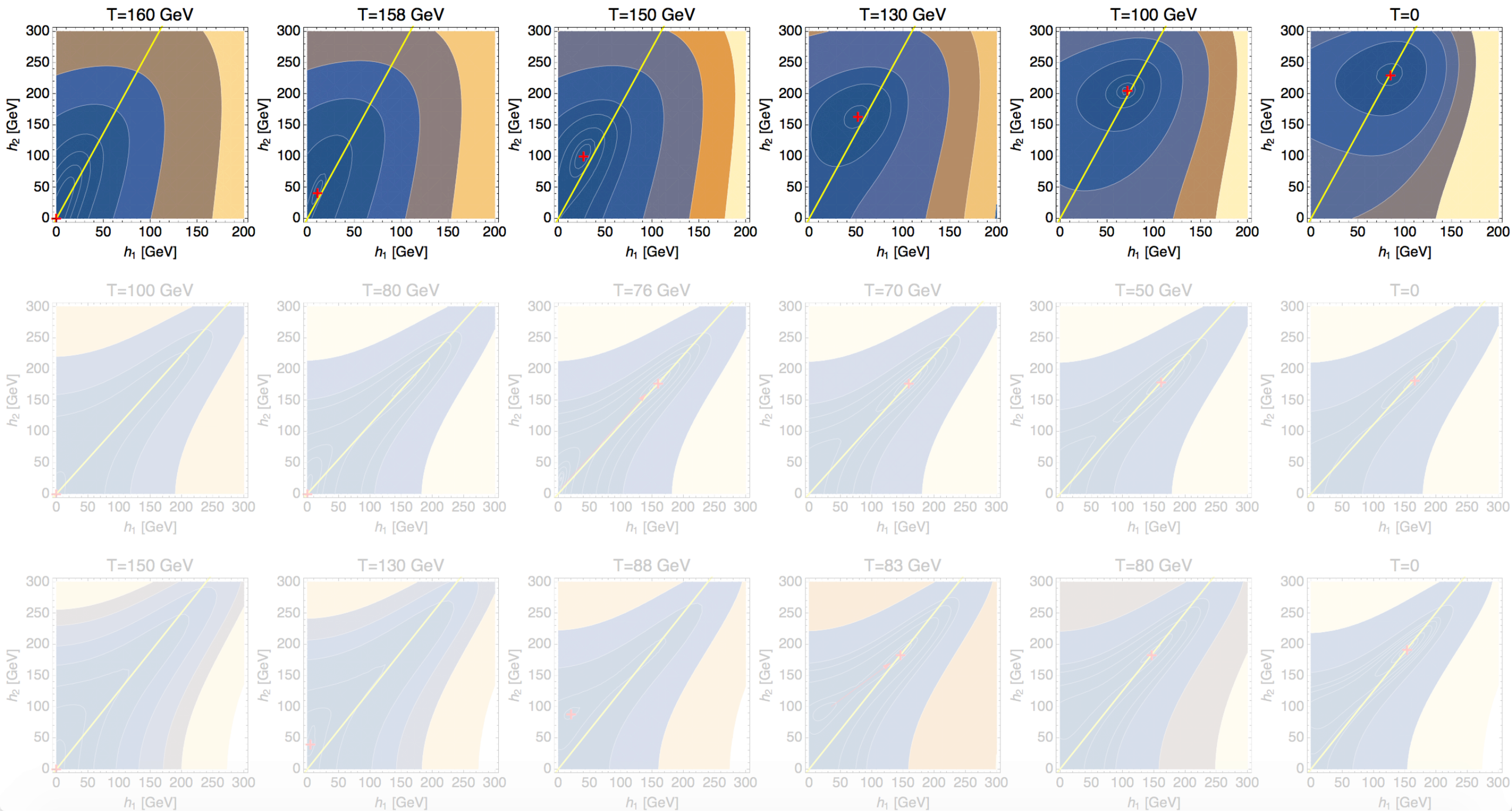

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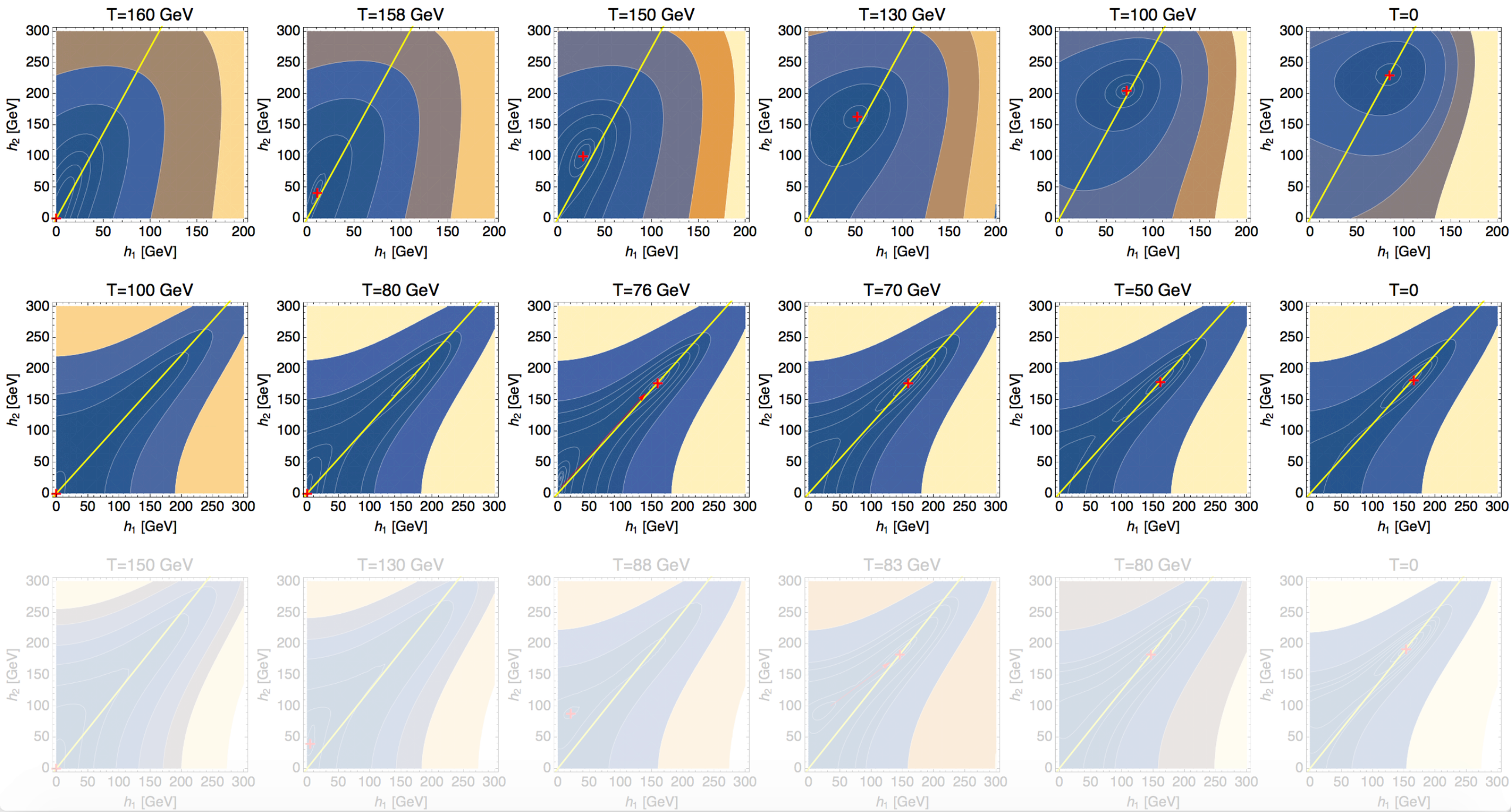

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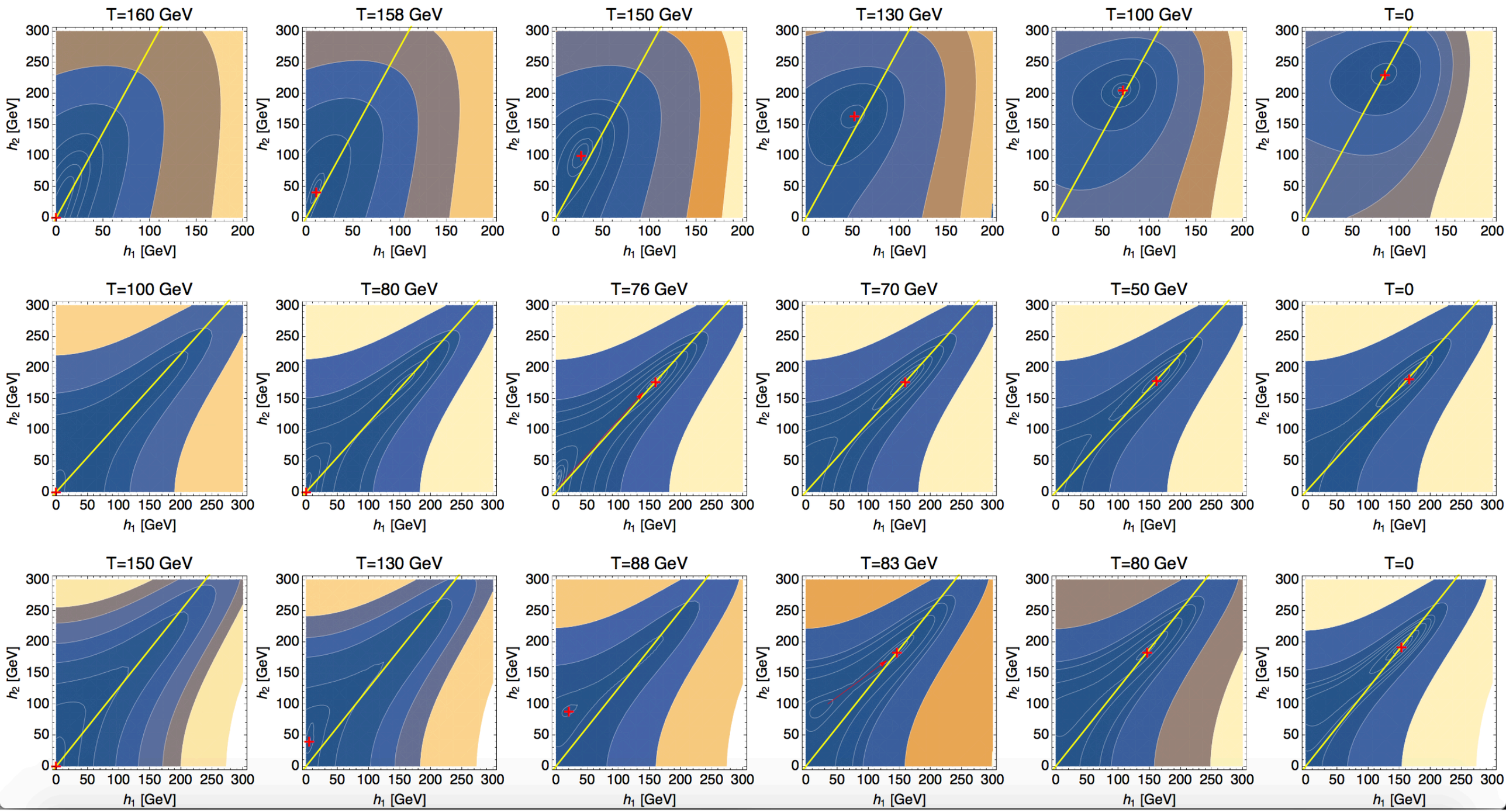

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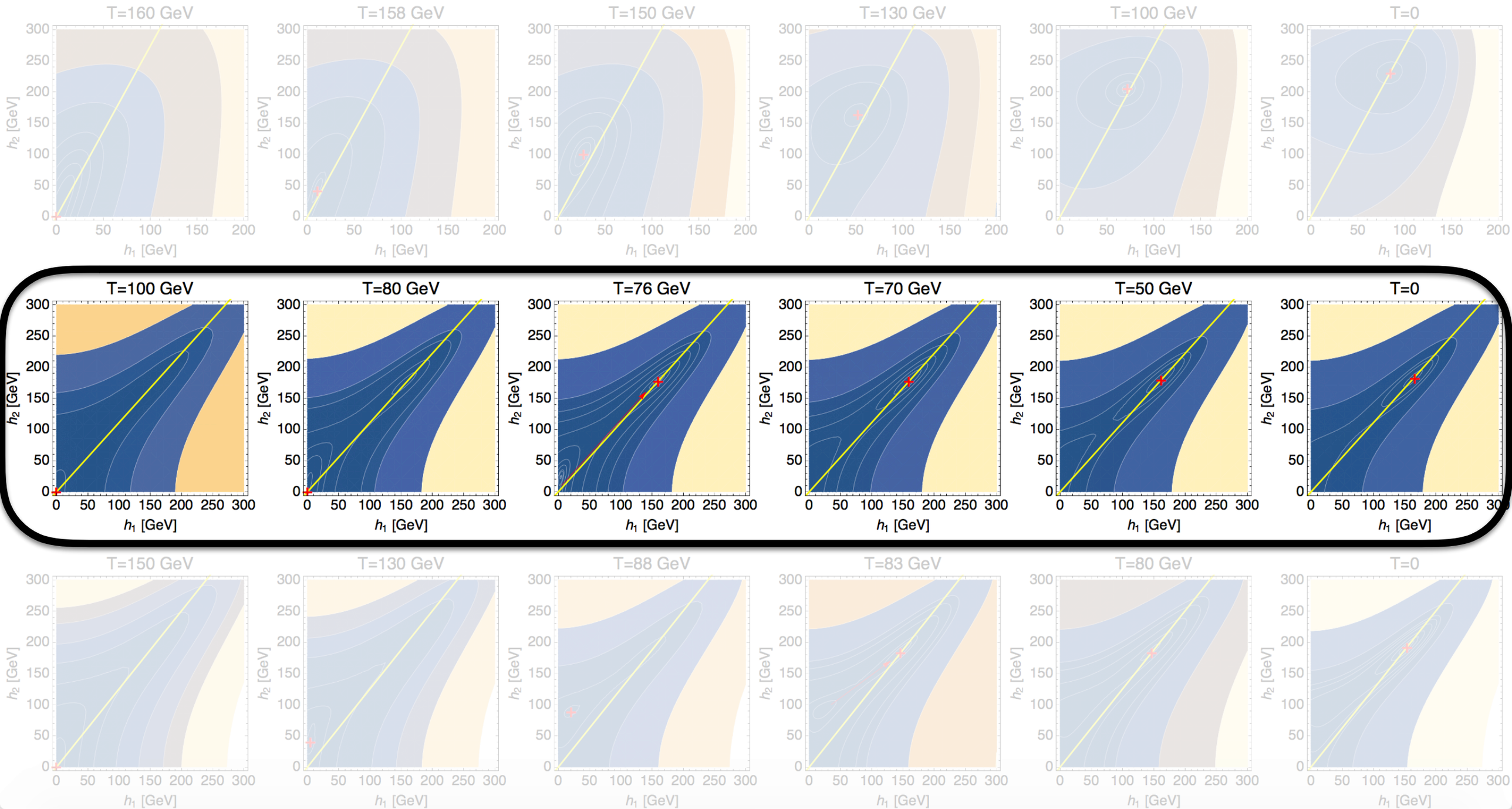
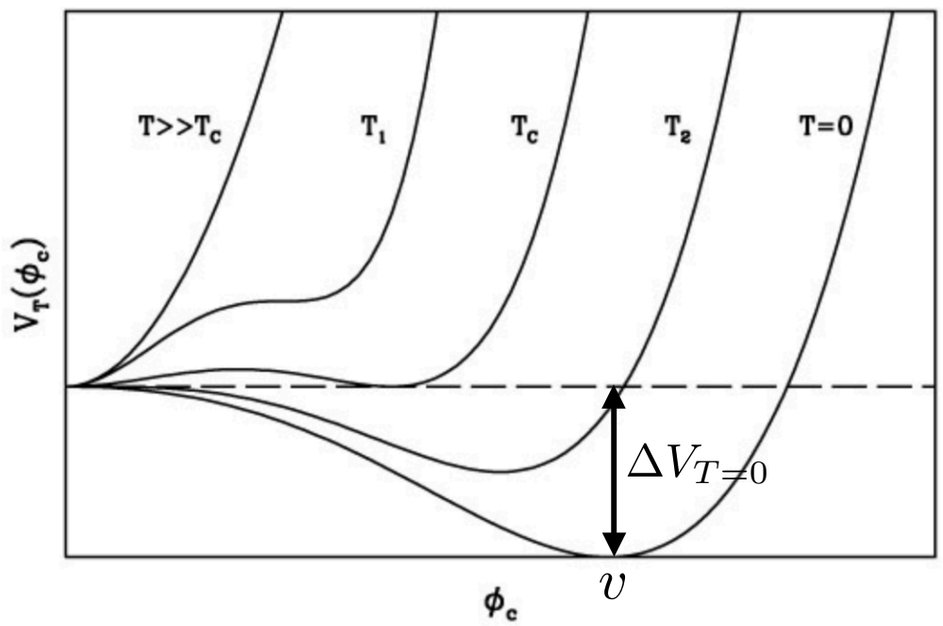
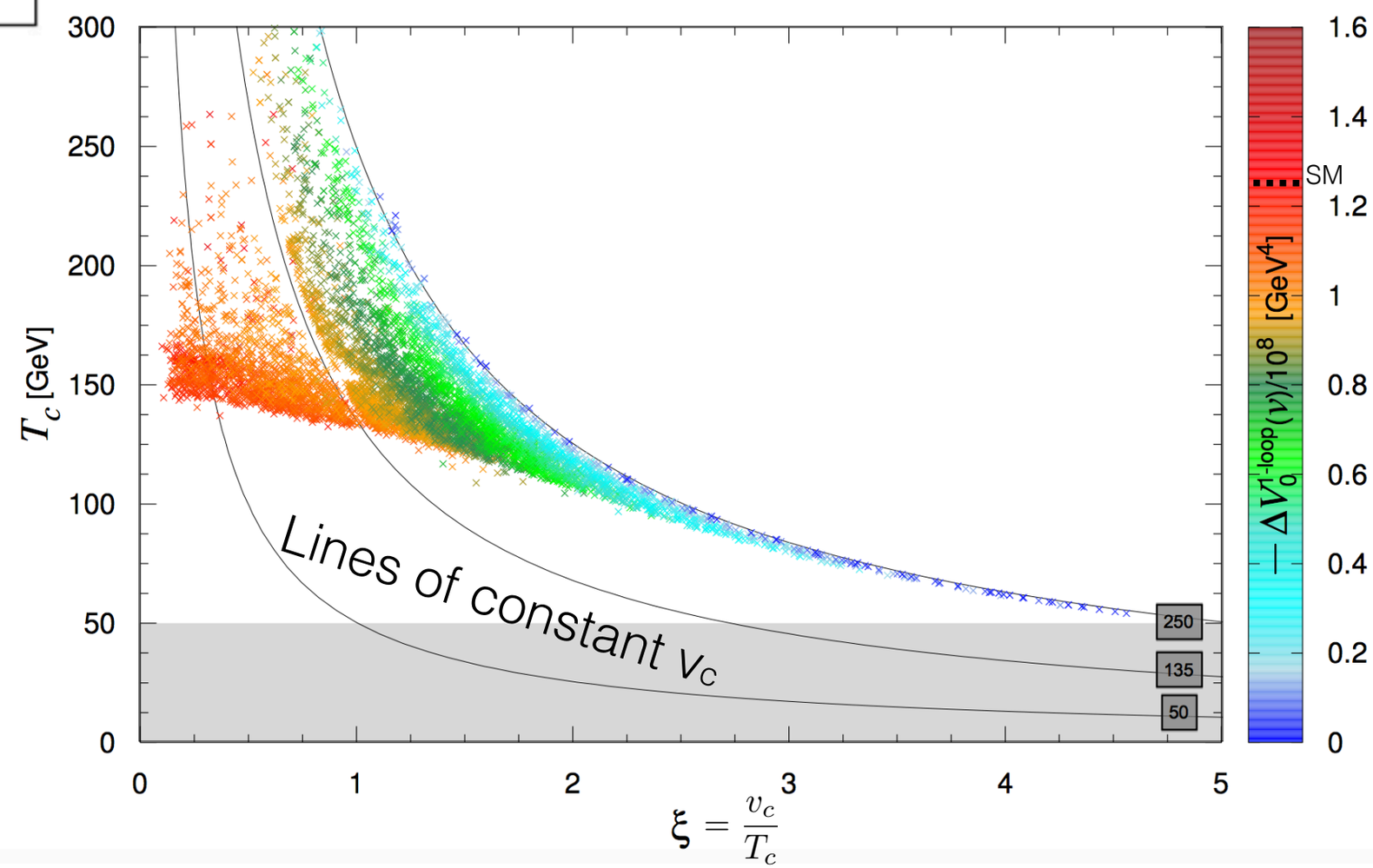


Zero temperature potential and critical parameters



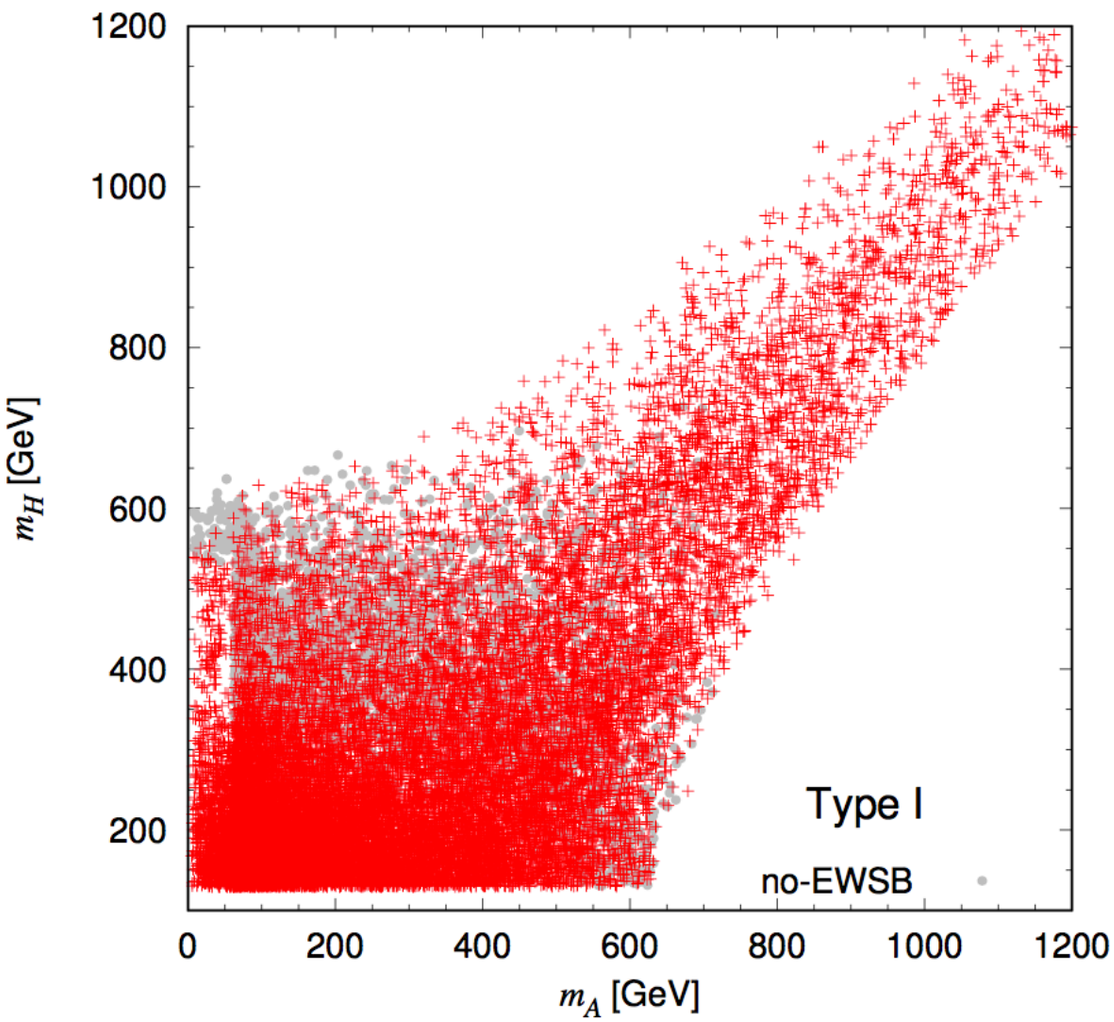
- Expectation: $v_c \sim v$ and small T_c for small potential depth at zero temperature
- In the SM: driven by the h-125 mass, but in presence of additional (light) scalars, can expect sizeable modifications [Harman, Huber '16; Dorsh, Huber, Mimasu, No '17]

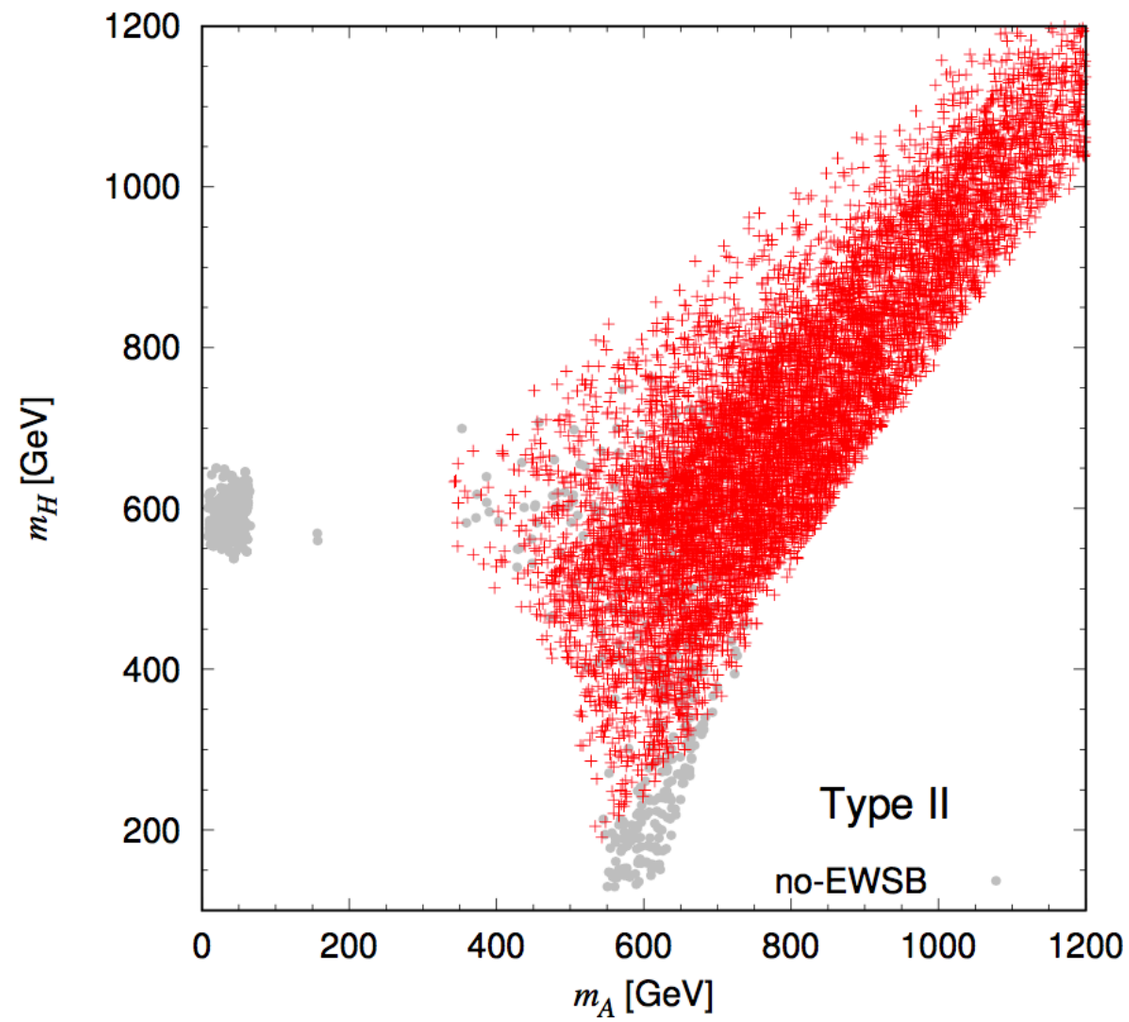


- Details of the PT largely independent of the Yukawa structure
- Critical vev largely driven by the potential depth at 0T
- Critical temperature on the other hand shows small correlation with depth

Mass spectra

- Experimental constraints depend on the Yukawa structure: Type-I and Type-II here





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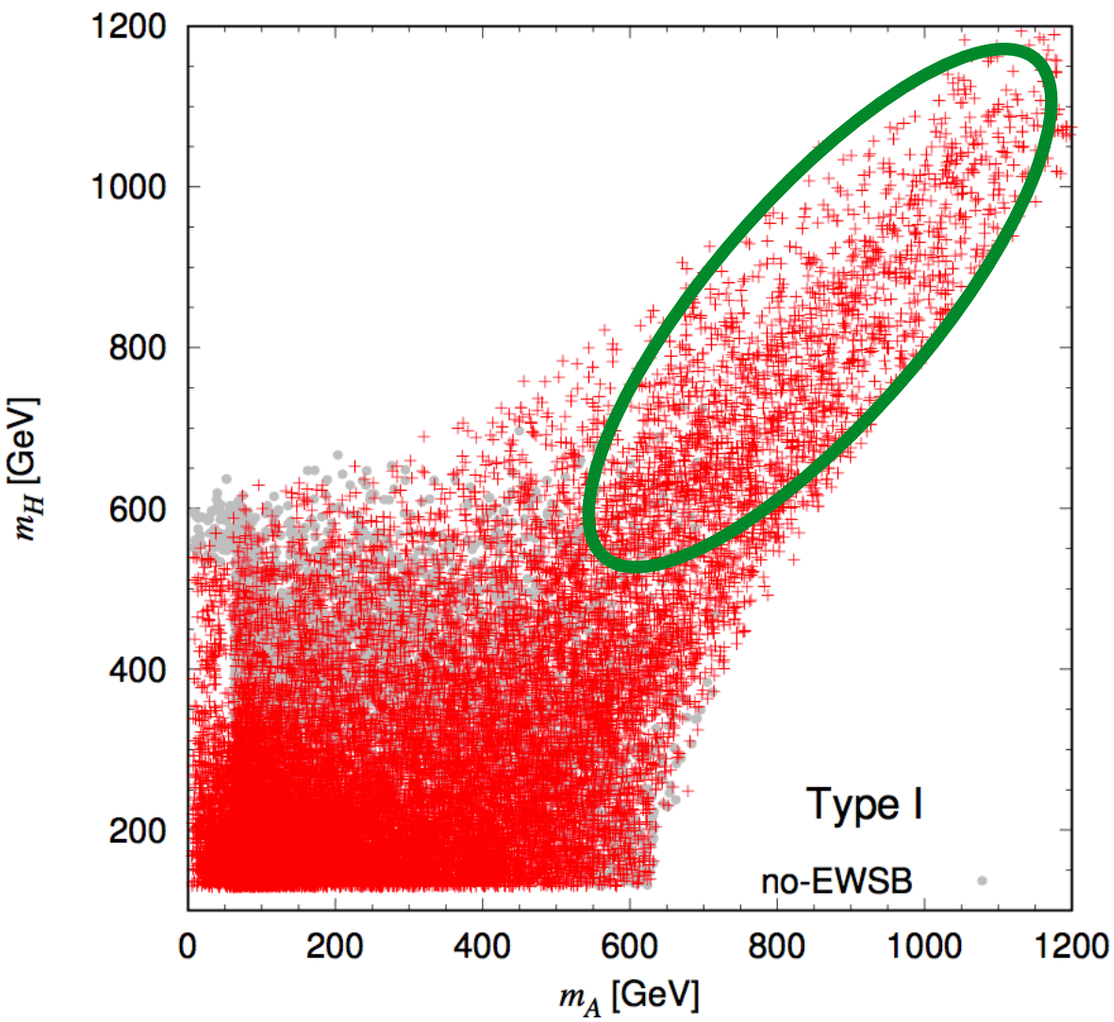

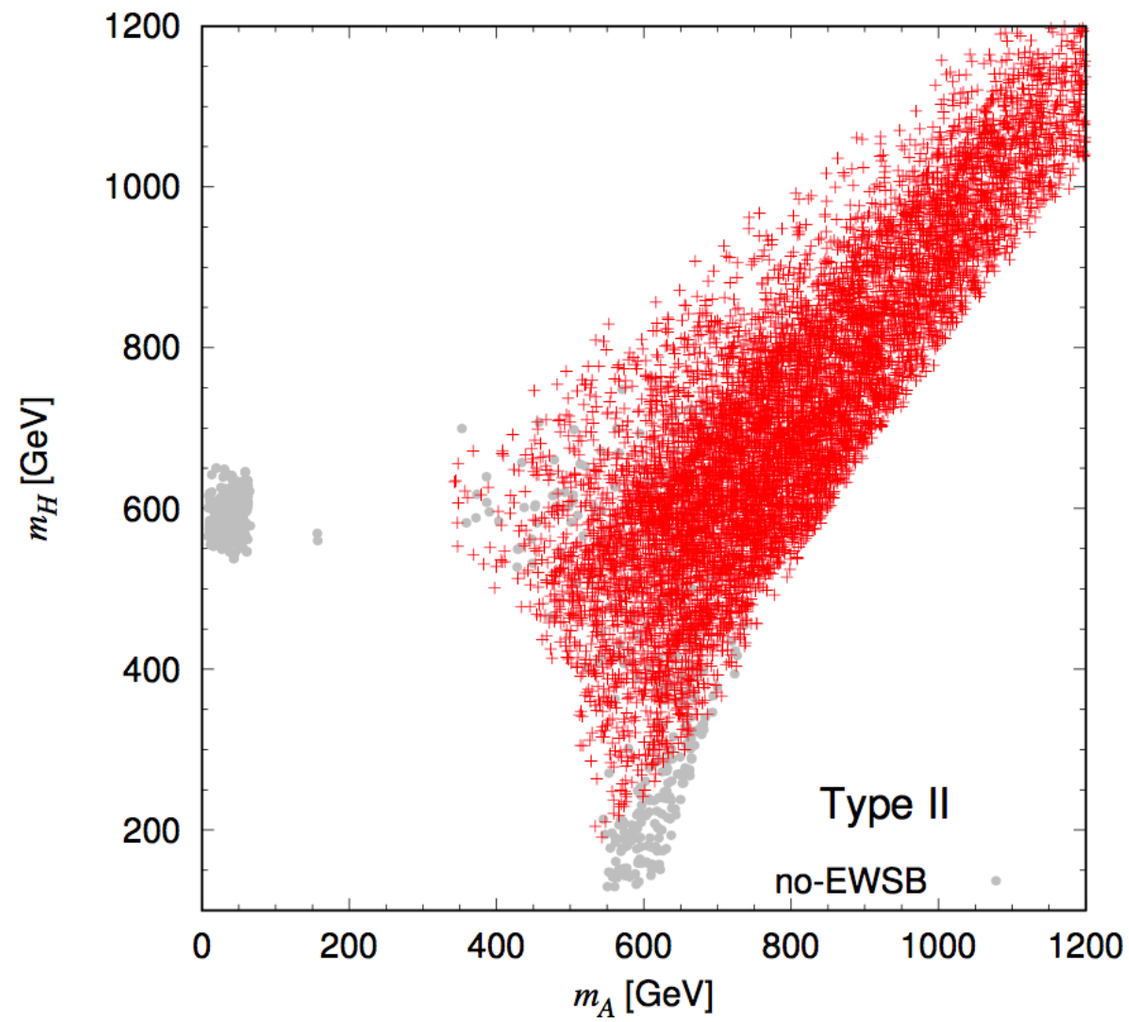

Degeneracy:
T parameter
+ decoupling

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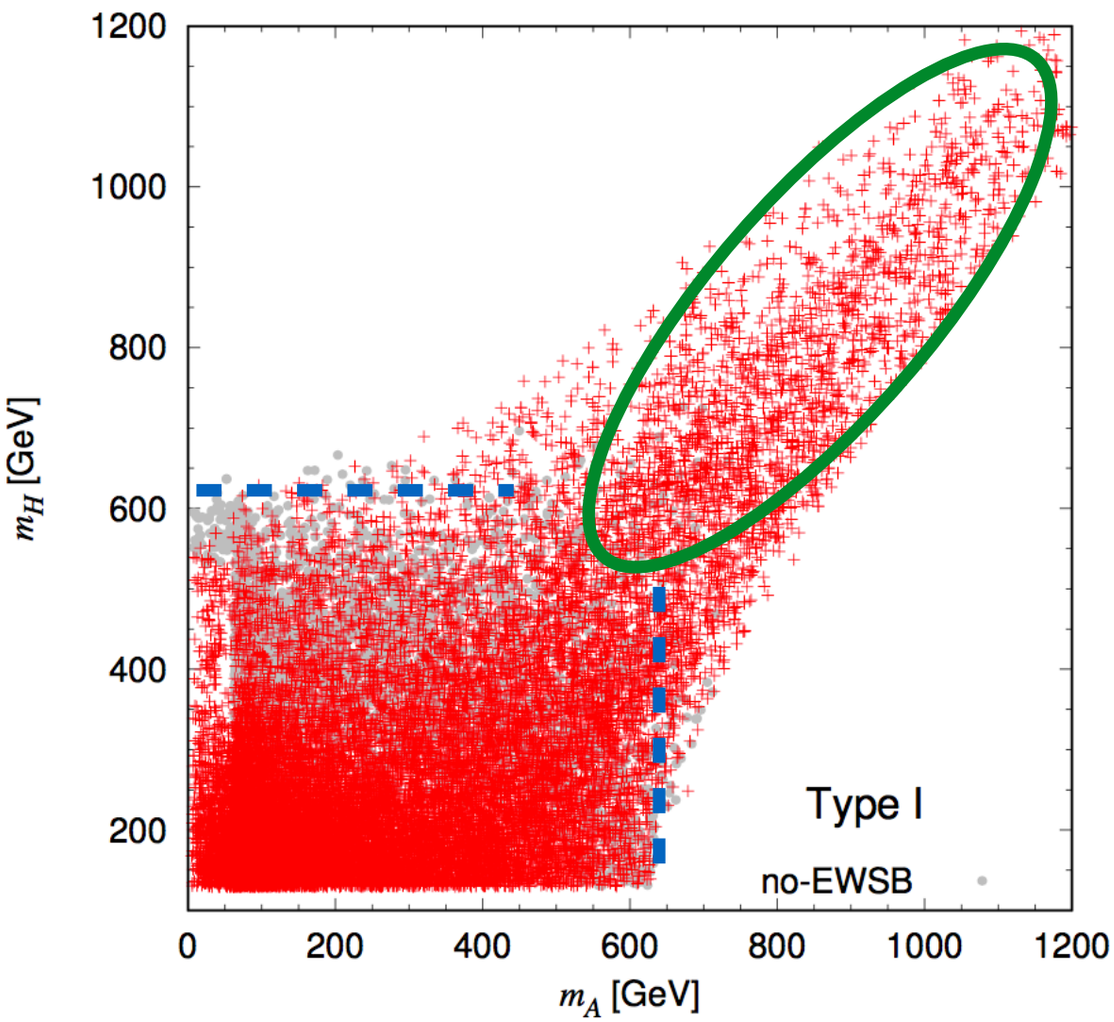

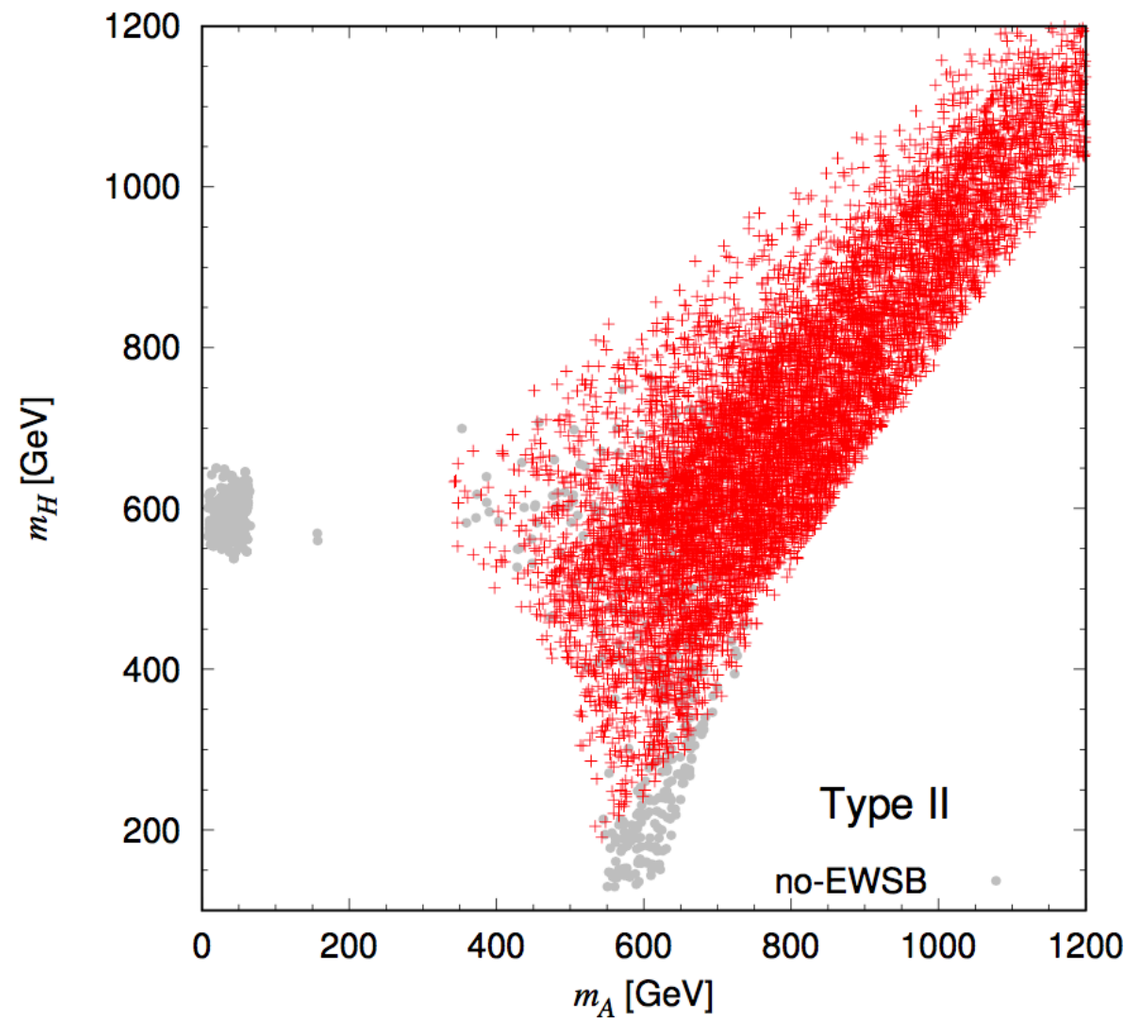

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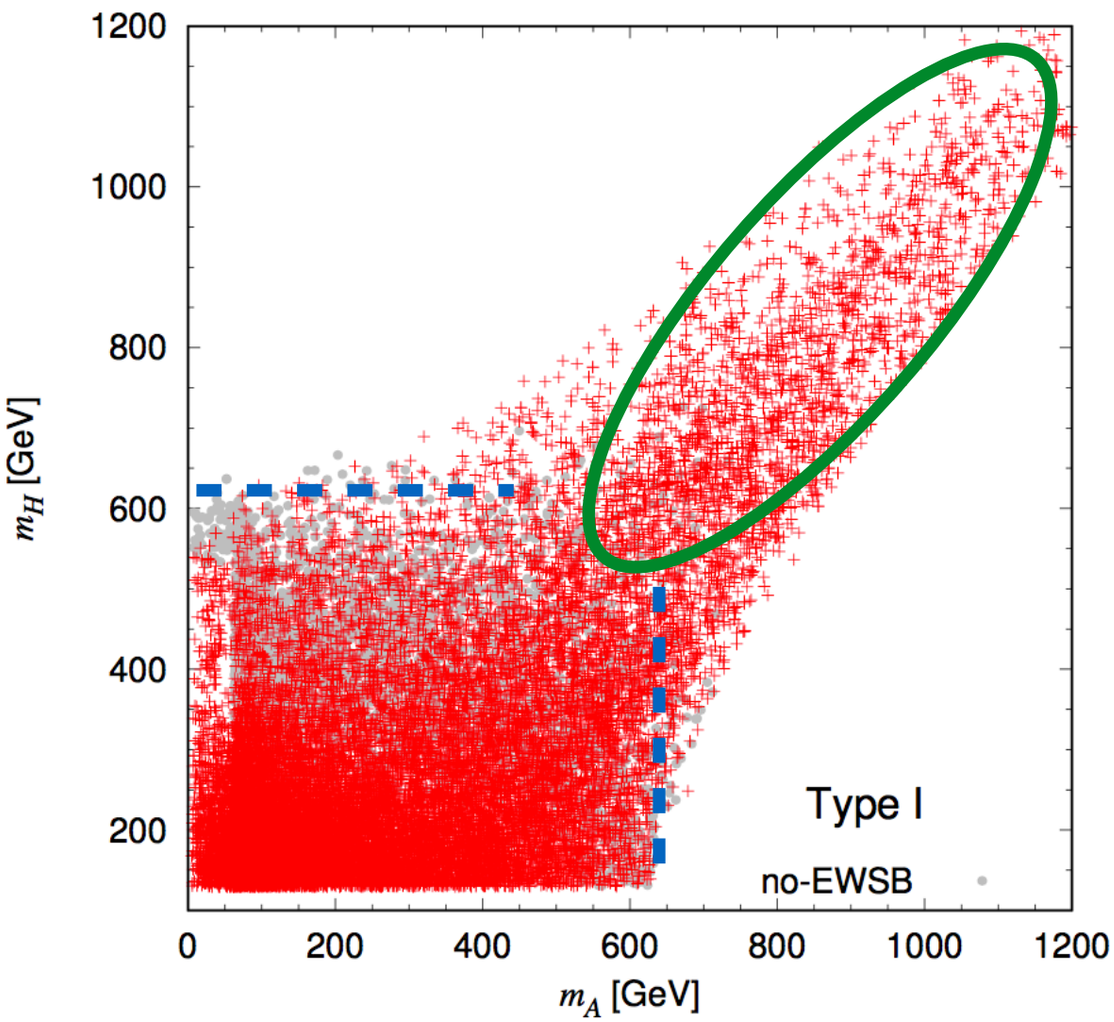

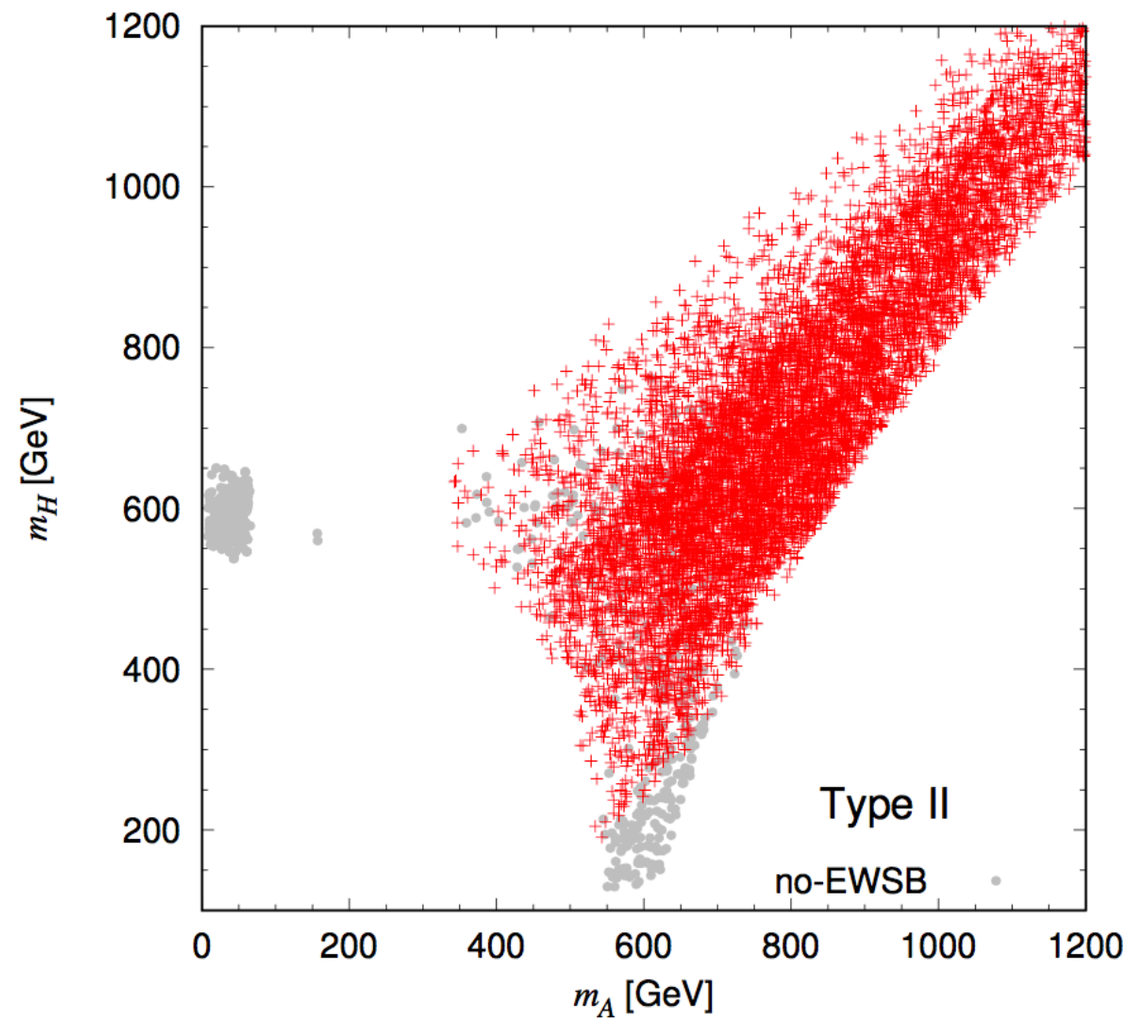

Degeneracy: T parameter + decoupling

Perturbativity limit

Type-I offers a very wide range of possibilities

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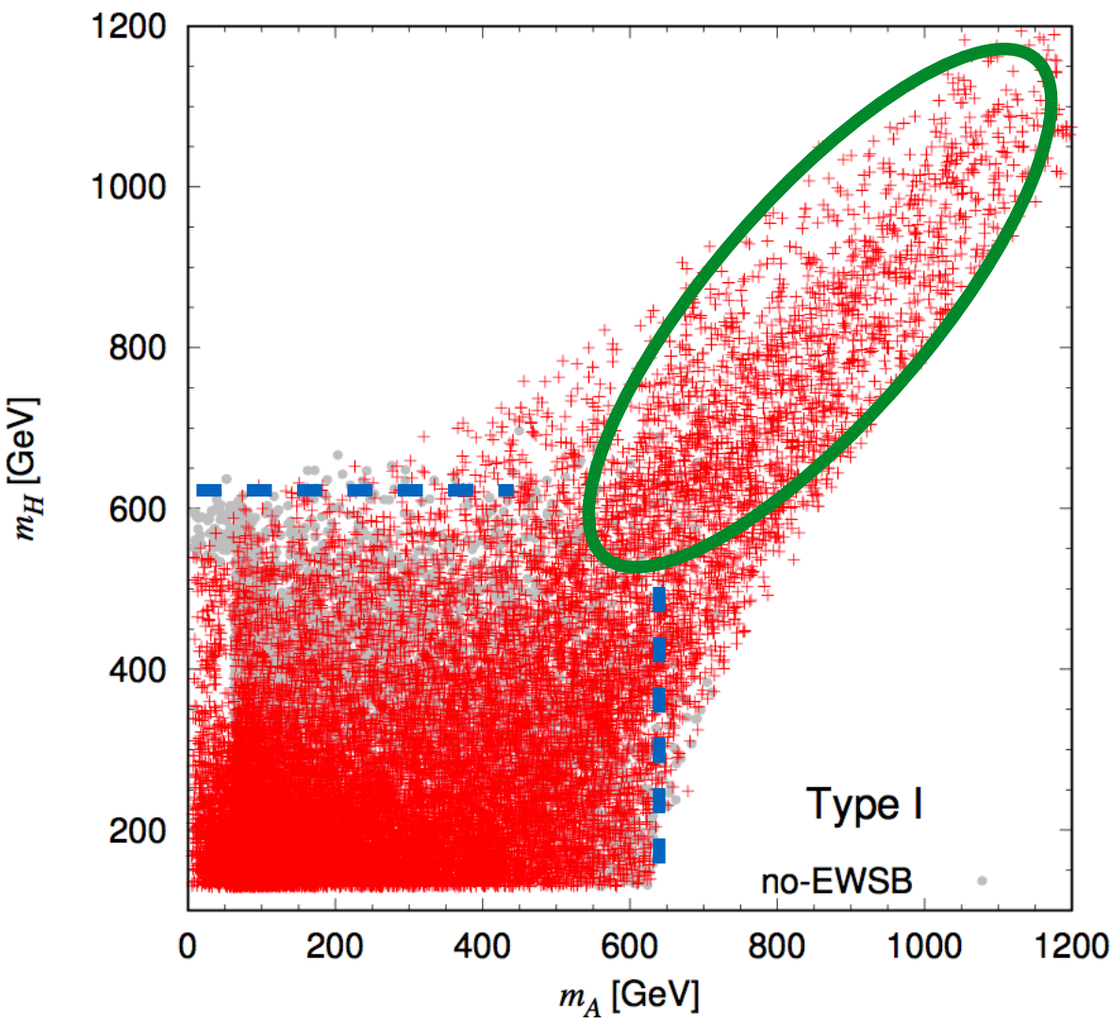

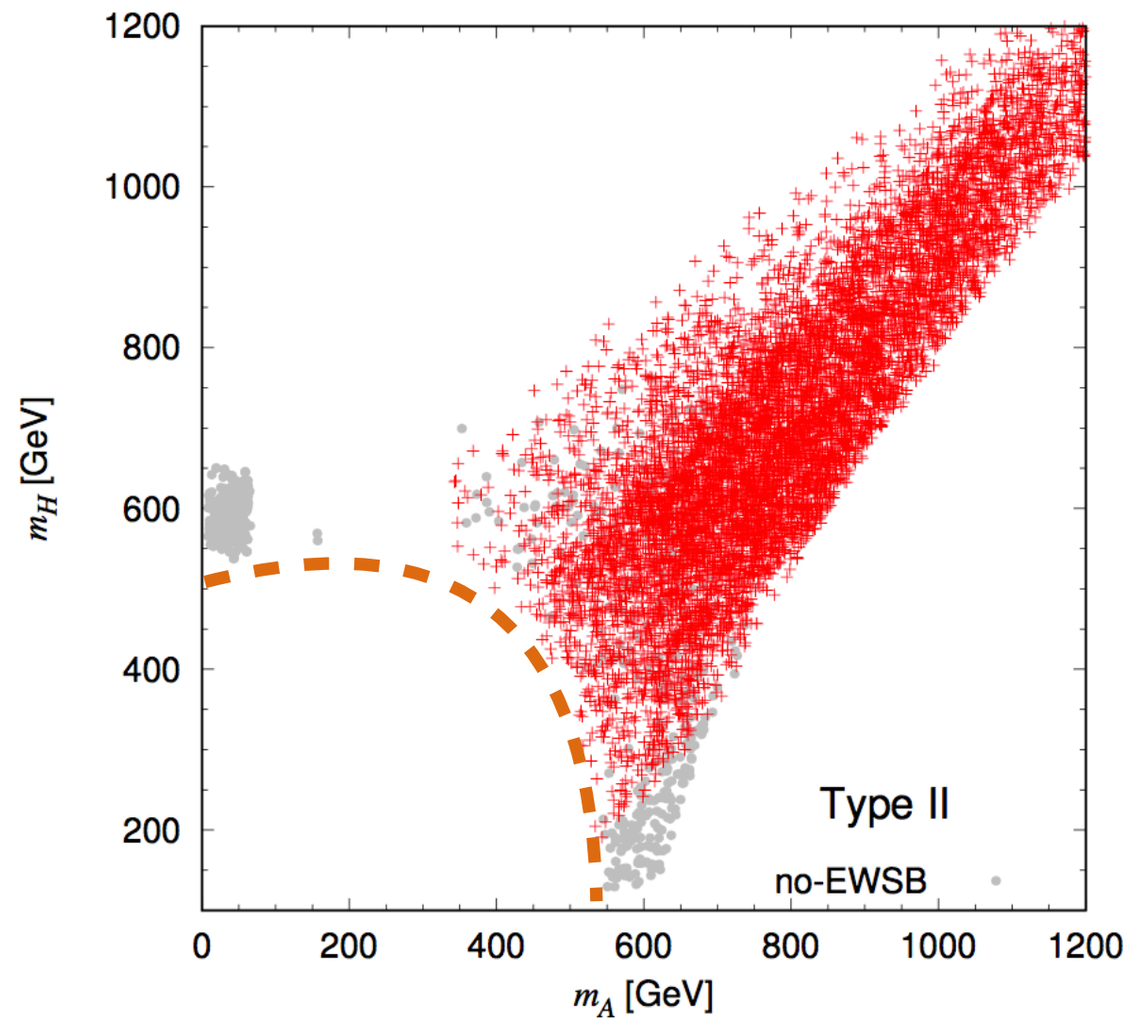

$m_{H^\pm} \gtrsim 580$ GeV $(B \to X_s \gamma)$

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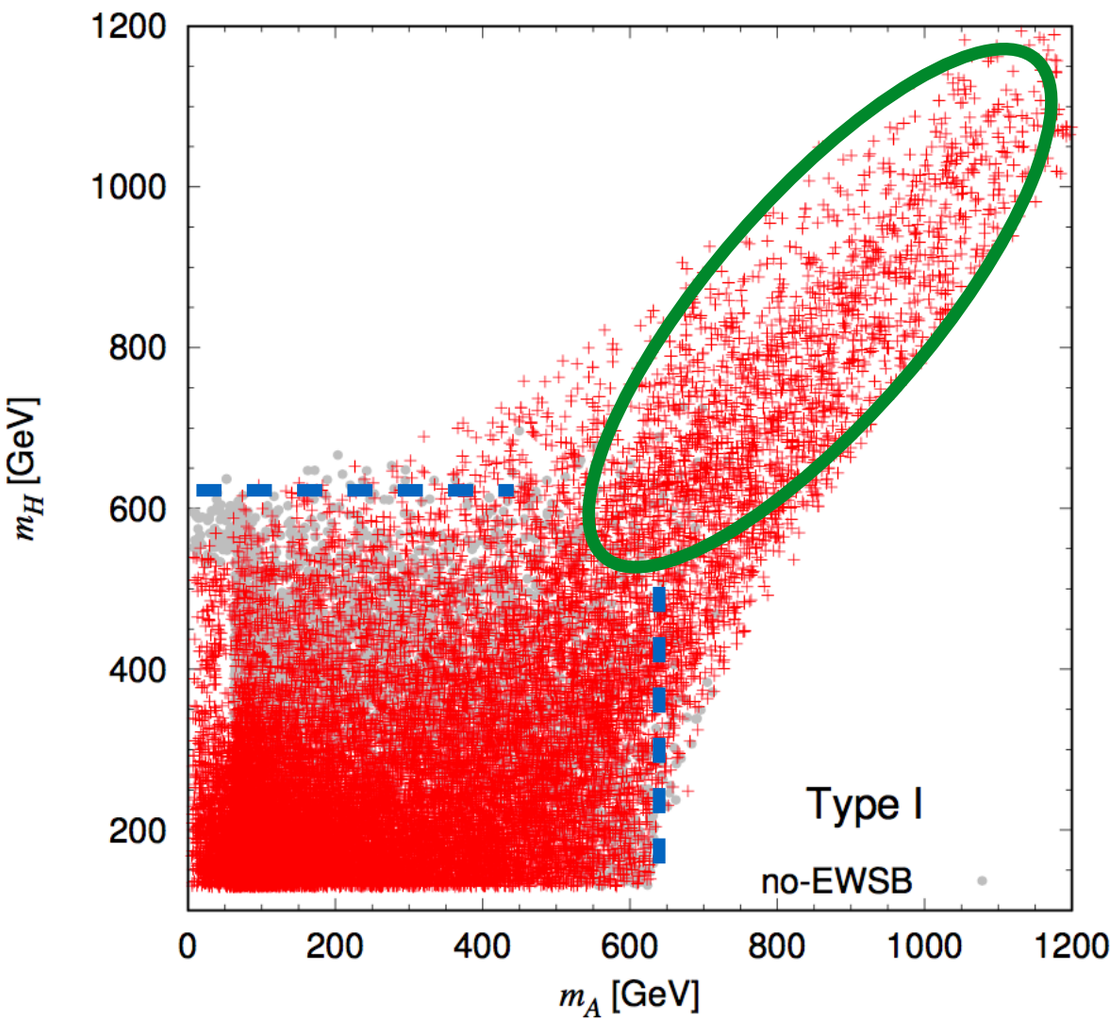

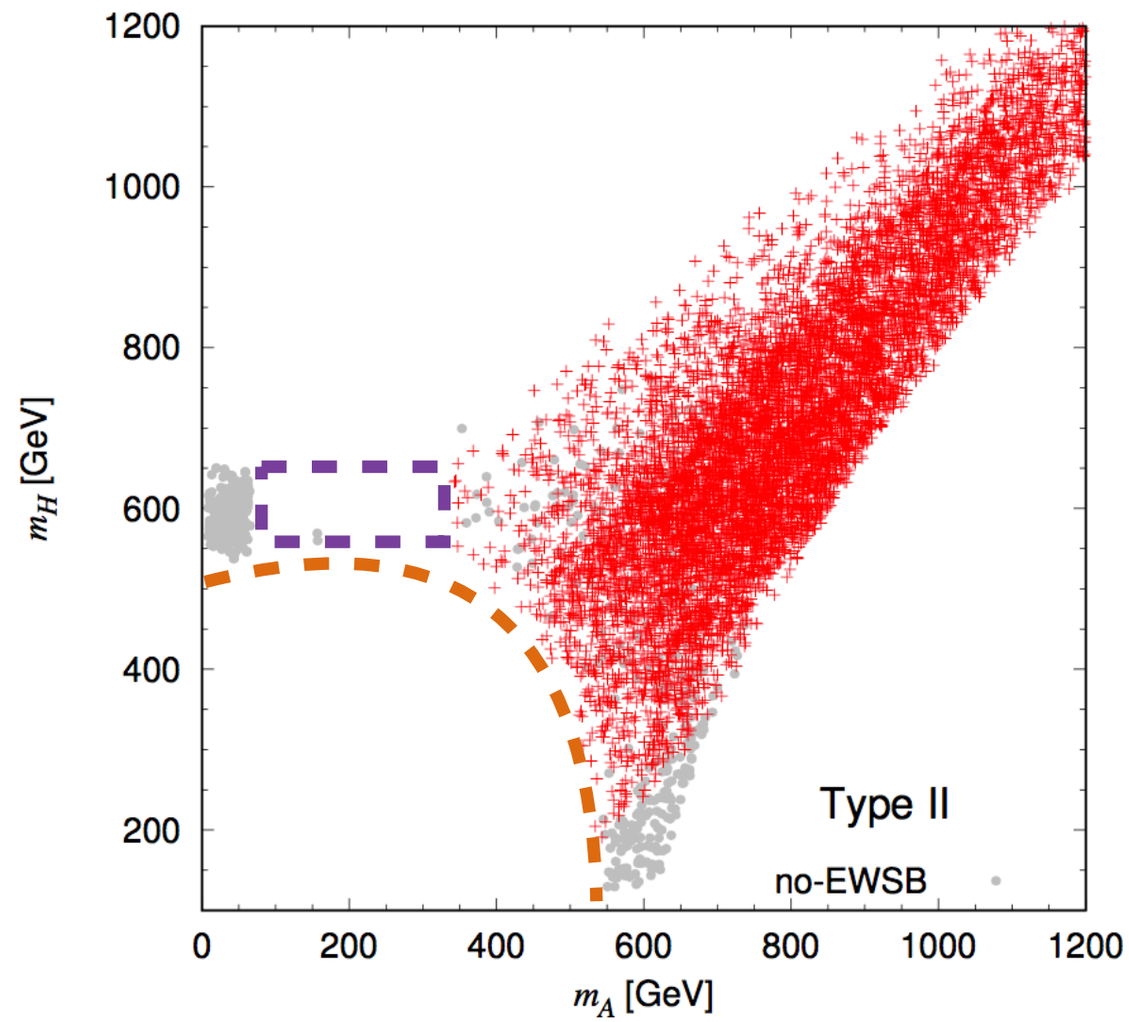

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$H/A \to \tau\tau$, $A \to Zh$

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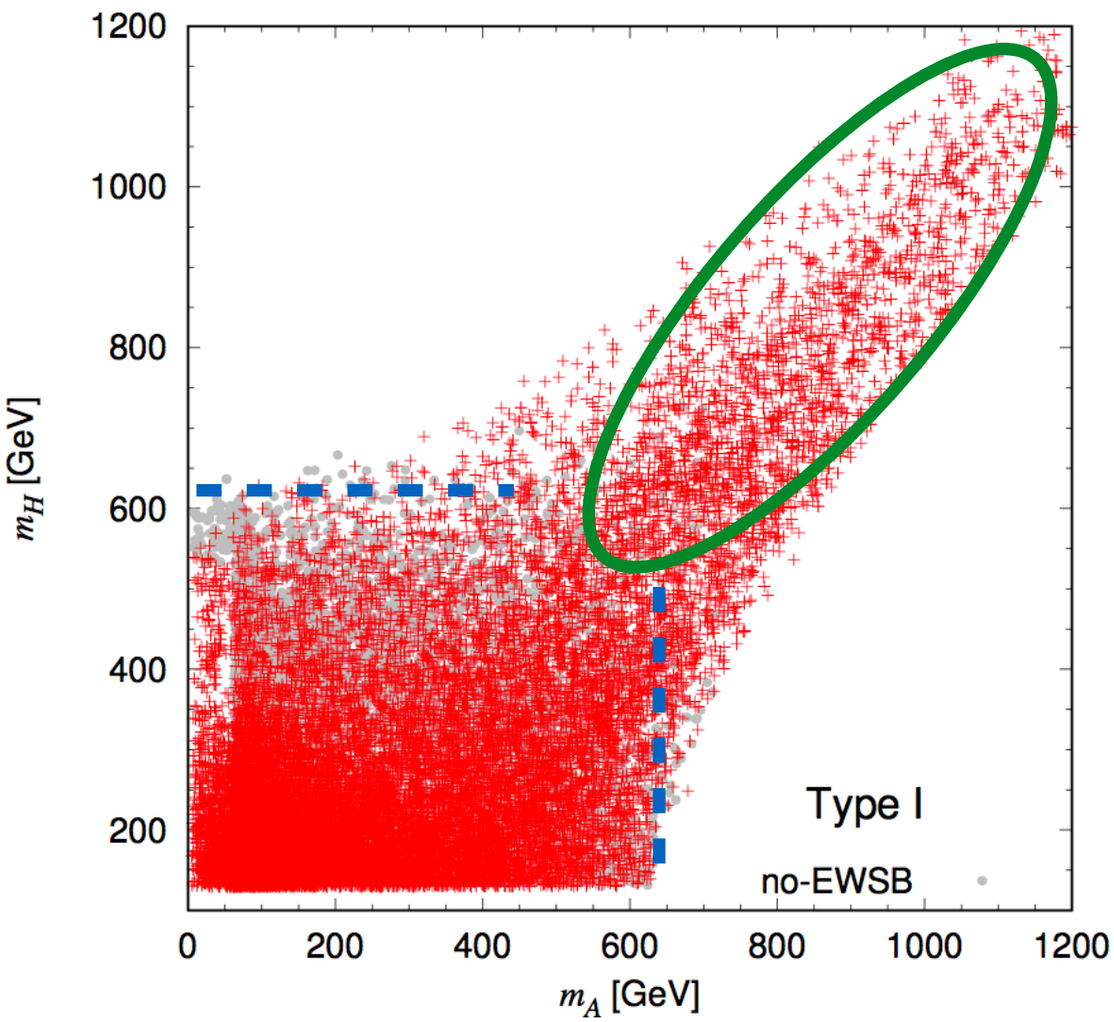

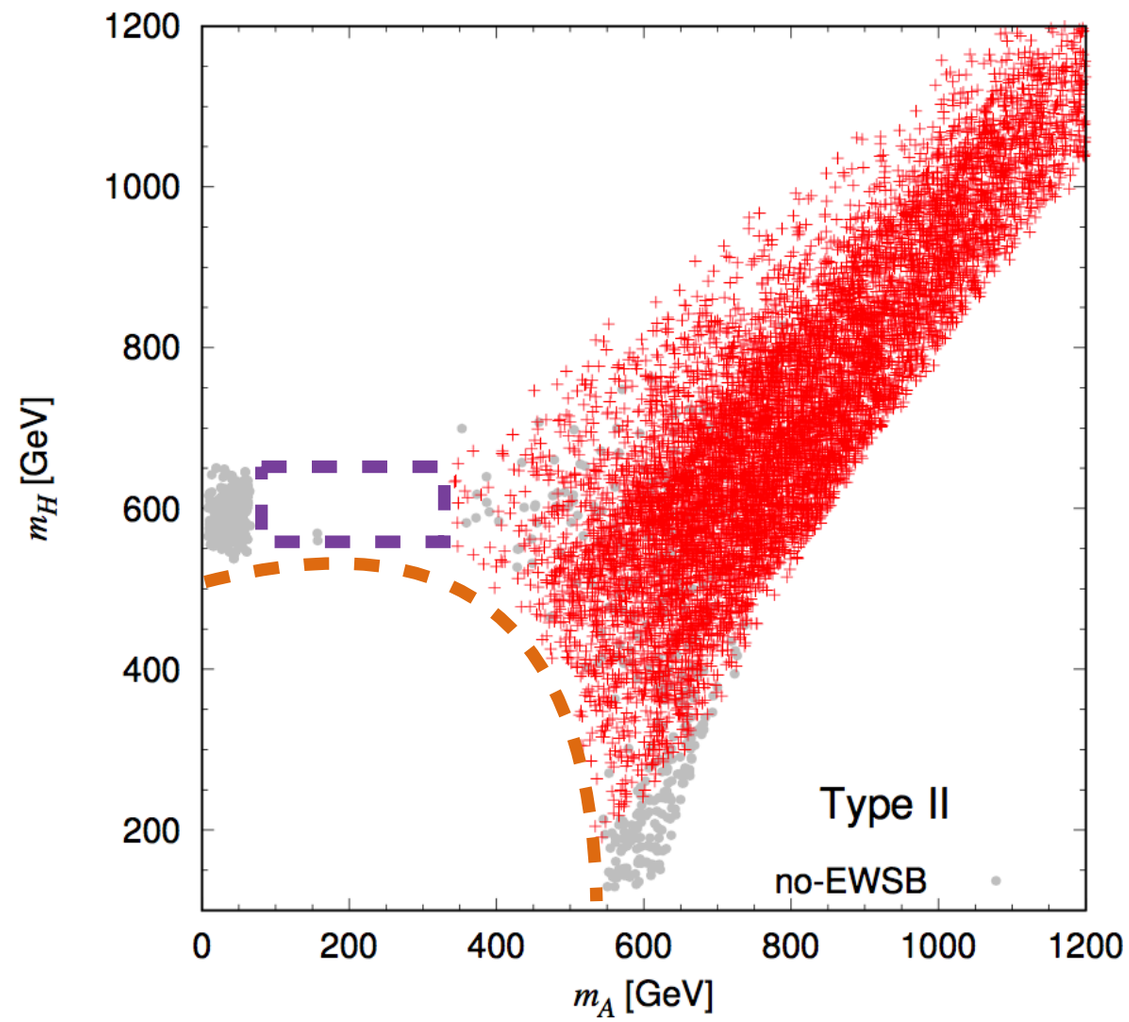

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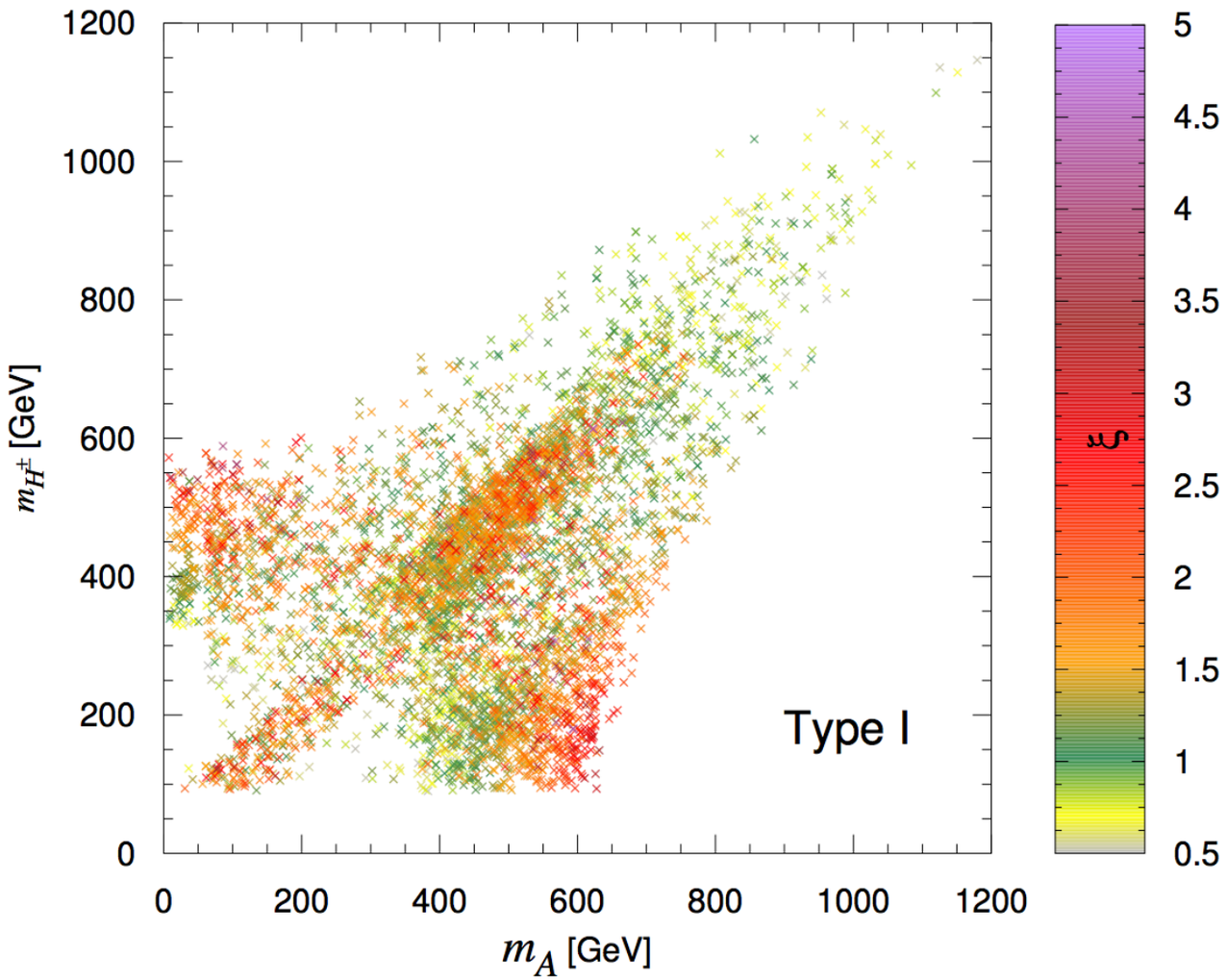
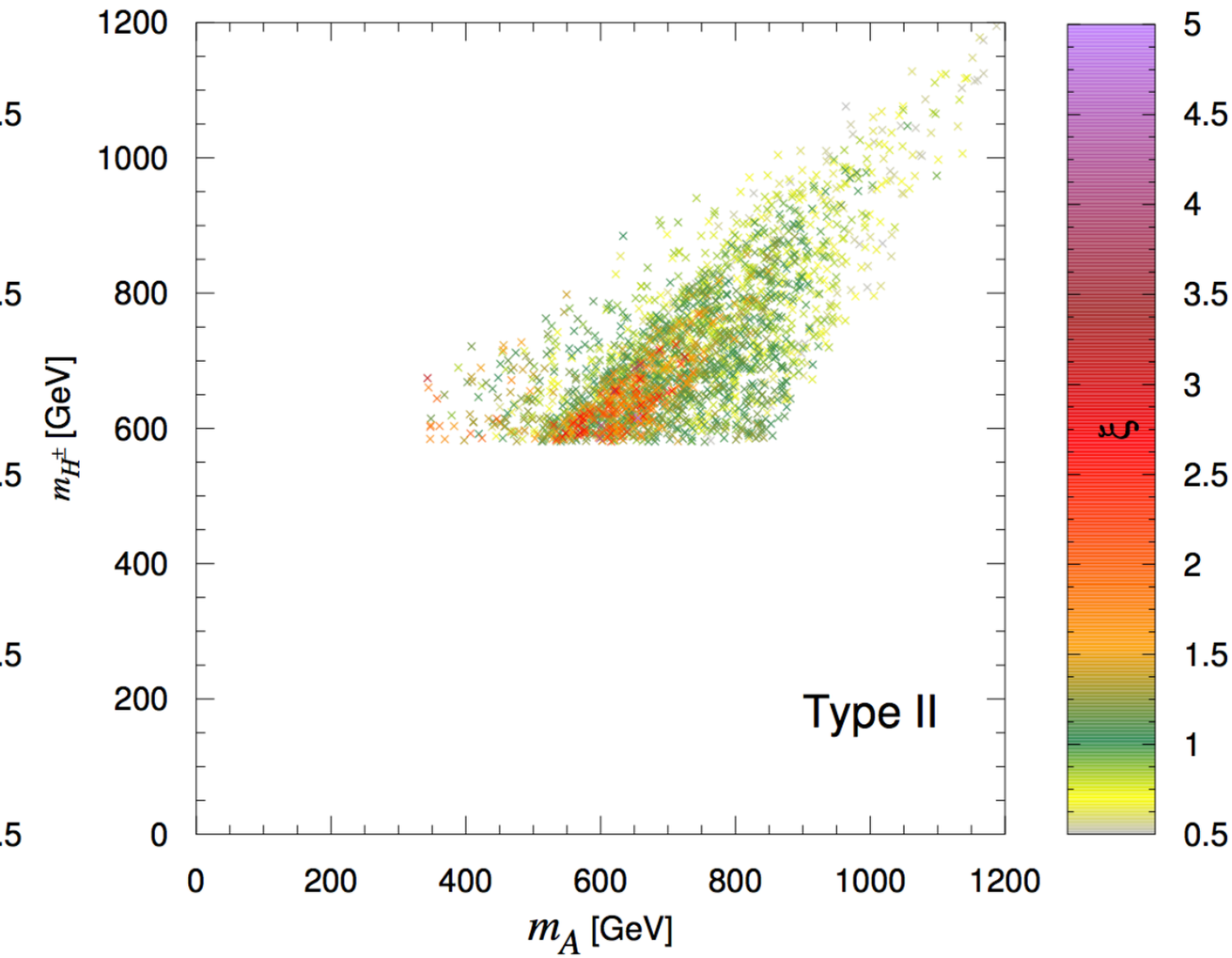
$H/A \to \tau\tau \ , \ A \to Zh$

Type-II has much more restricted spectra

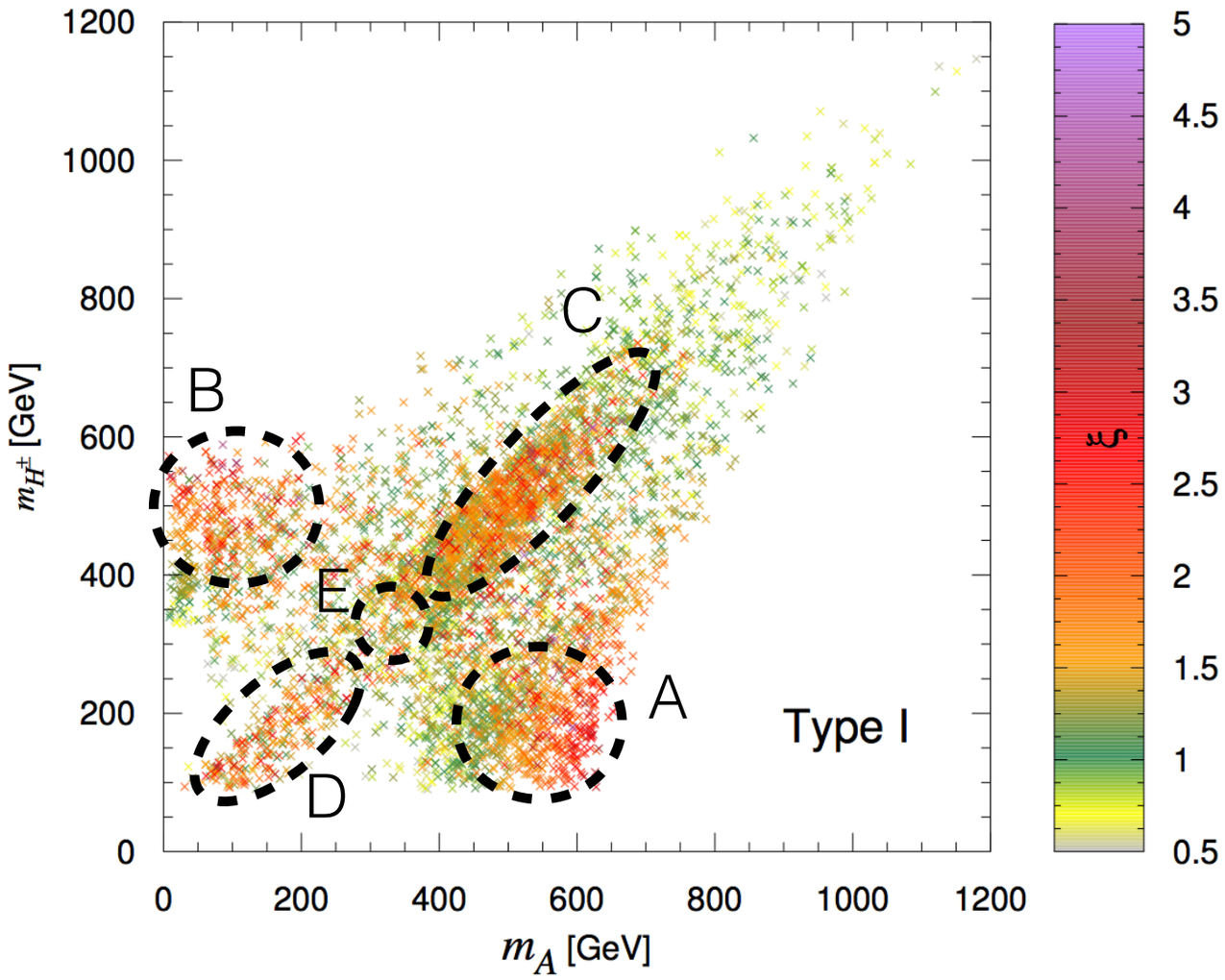
Mass maps

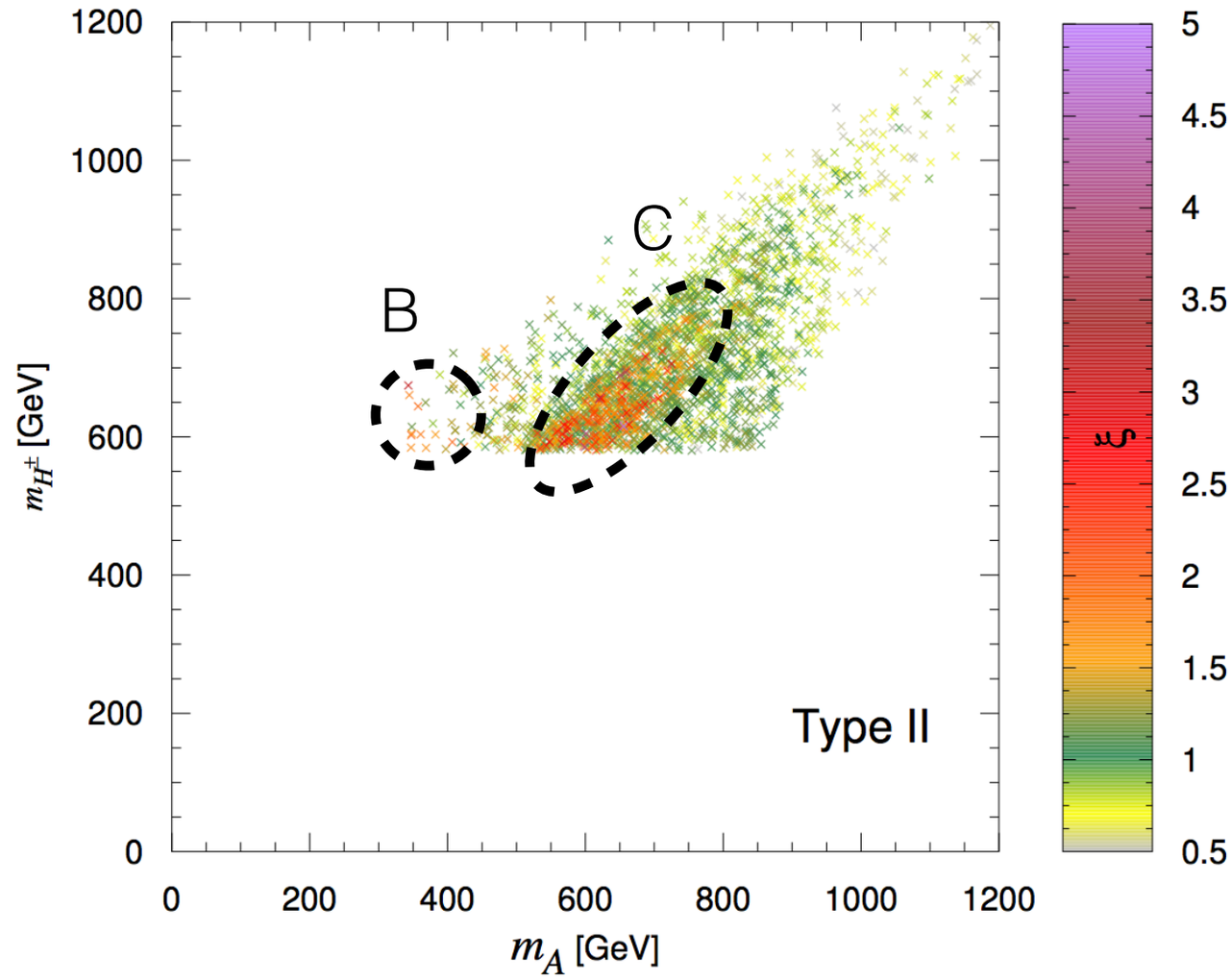




Sce.	m_H [GeV]	m_A [GeV]	$m_{H^\pm}$ [GeV]	Type	Main H/A decays
A	130 – 300	400 – 600	100 – 300	I	$A \to W^- H^+ (60\%), ZH (25\%)$
B	400 – 600	10 – 200	400 – 600	I, II	$H \to ZA (50 - 75\%)$
C	130 – 200	450 – 800	450 – 800	I, II	$A \to ZH (\sim 100\%)$
D	400 – 600	10 – 250	100 – 250	I	$H \to W^- H^+ (60\%), ZA (25\%)$
E	300 – 350	300 – 350	300 – 350	I	$A \to Zh (\sim 100\%)$, $H \to W^+ W^- (\gtrsim 40\%)$

Mass maps





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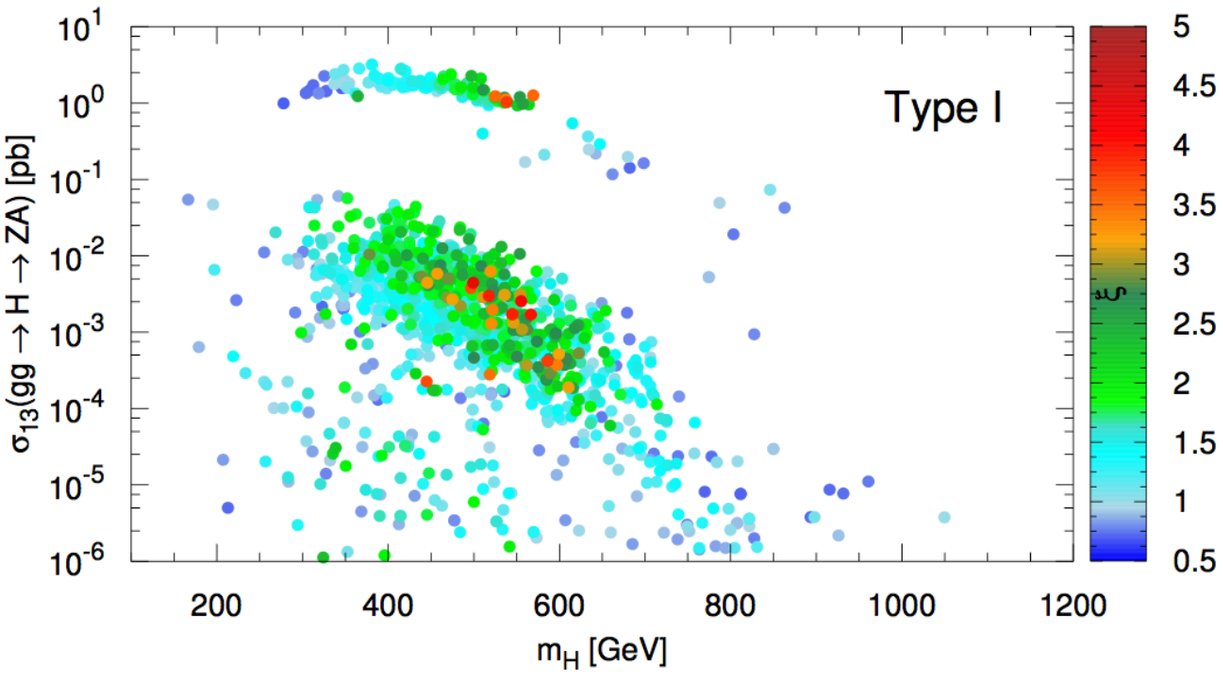
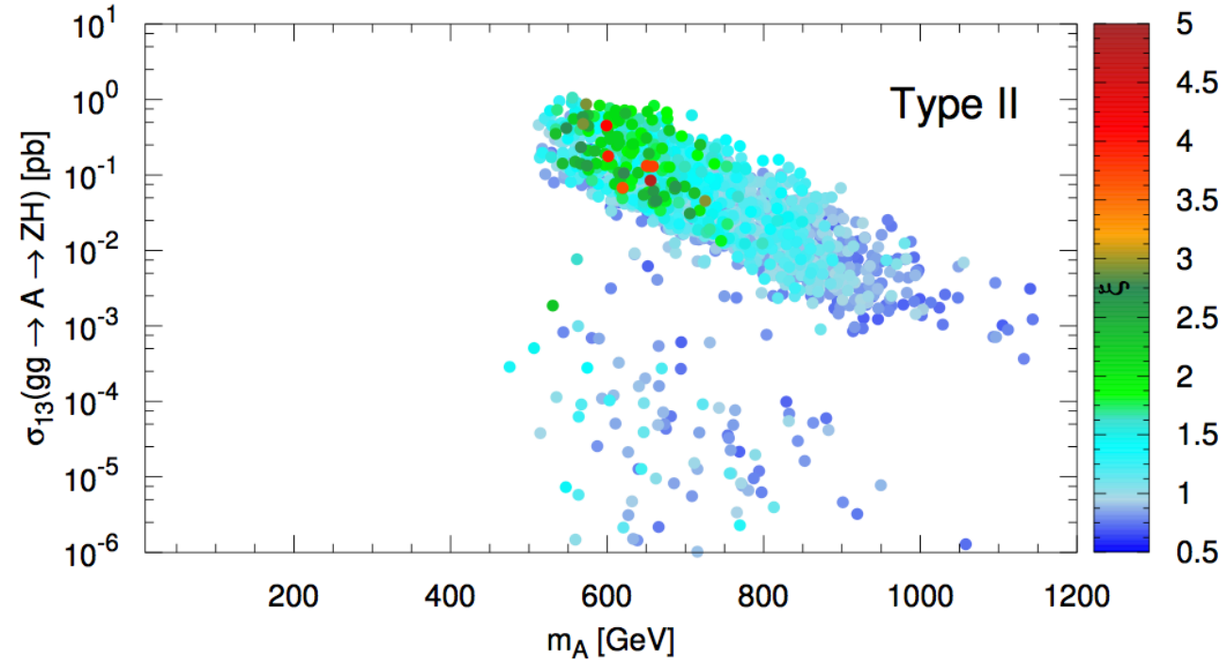
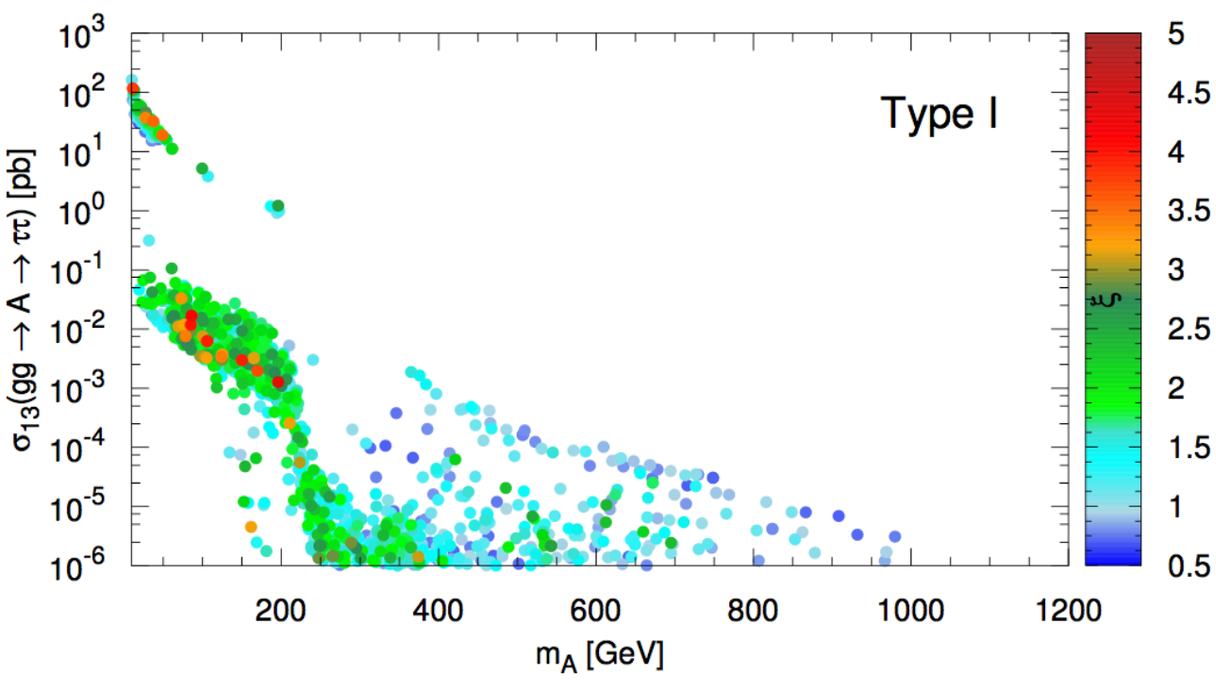
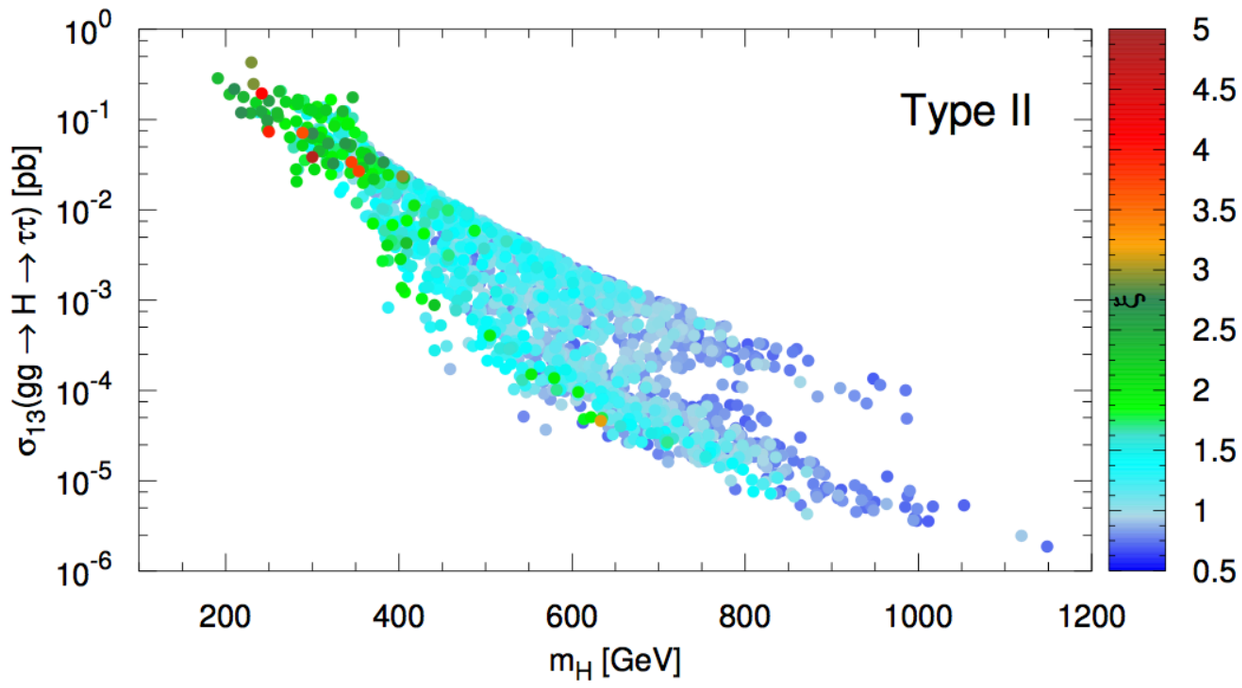
E	300 – 350	300 – 350	300 – 350	I	$A \to Zh(\sim 100\%)$, $H \to W^+W^- (\gtrsim 40\%)$

Cross-sections at LHC Run-II

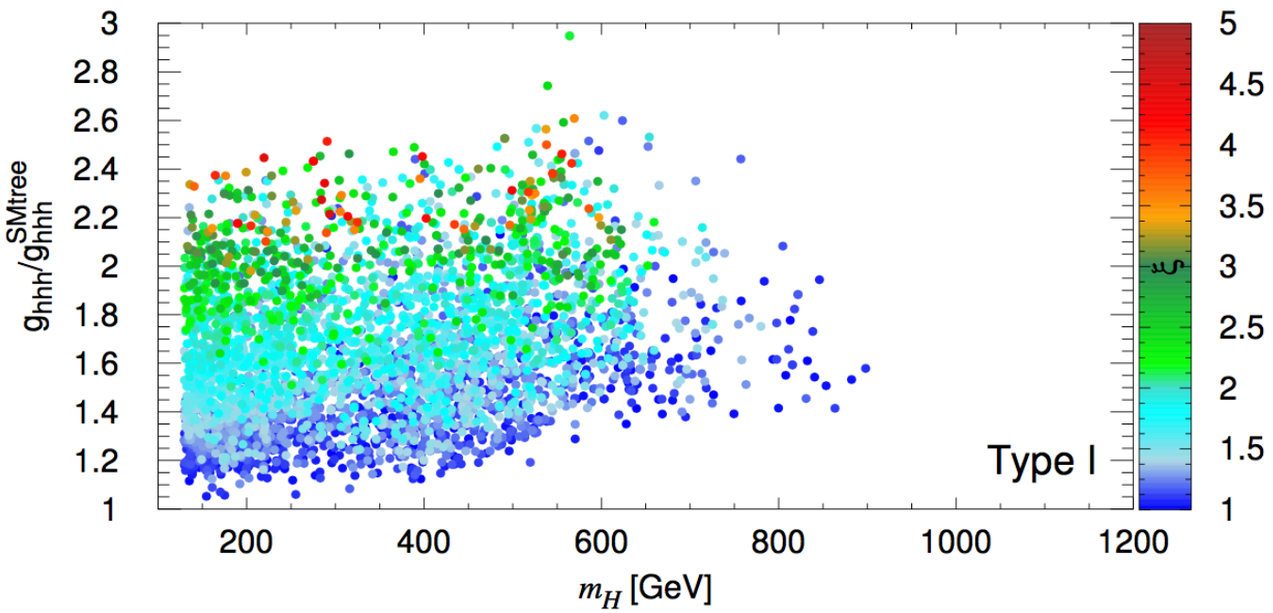


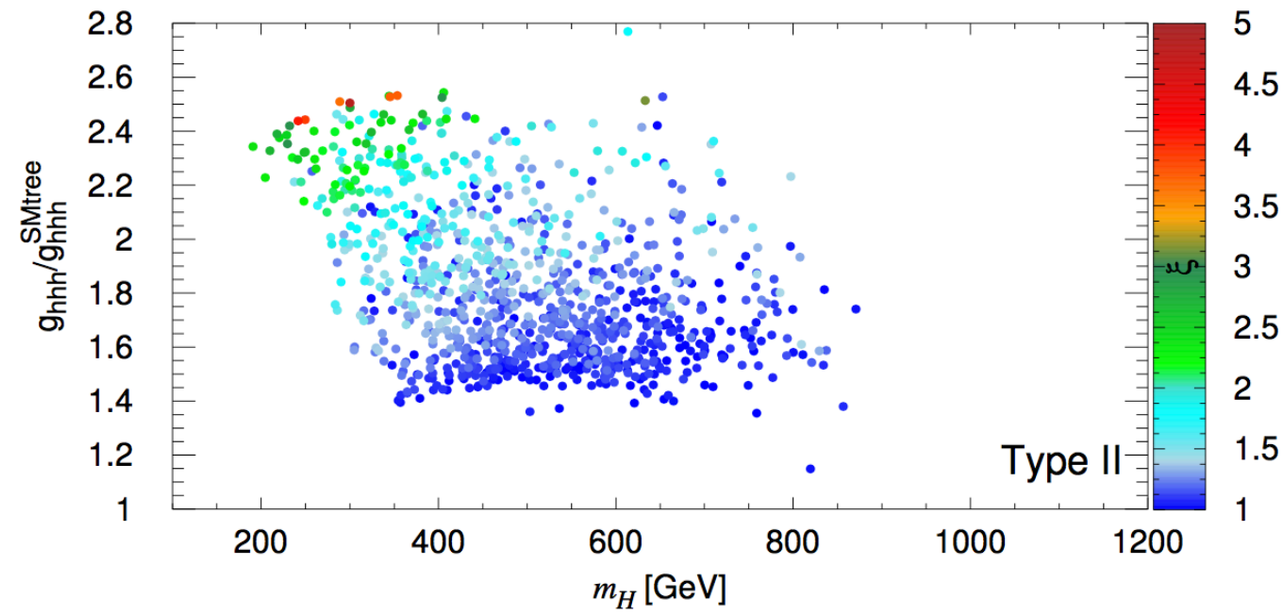






Trilinear Higgs coupling



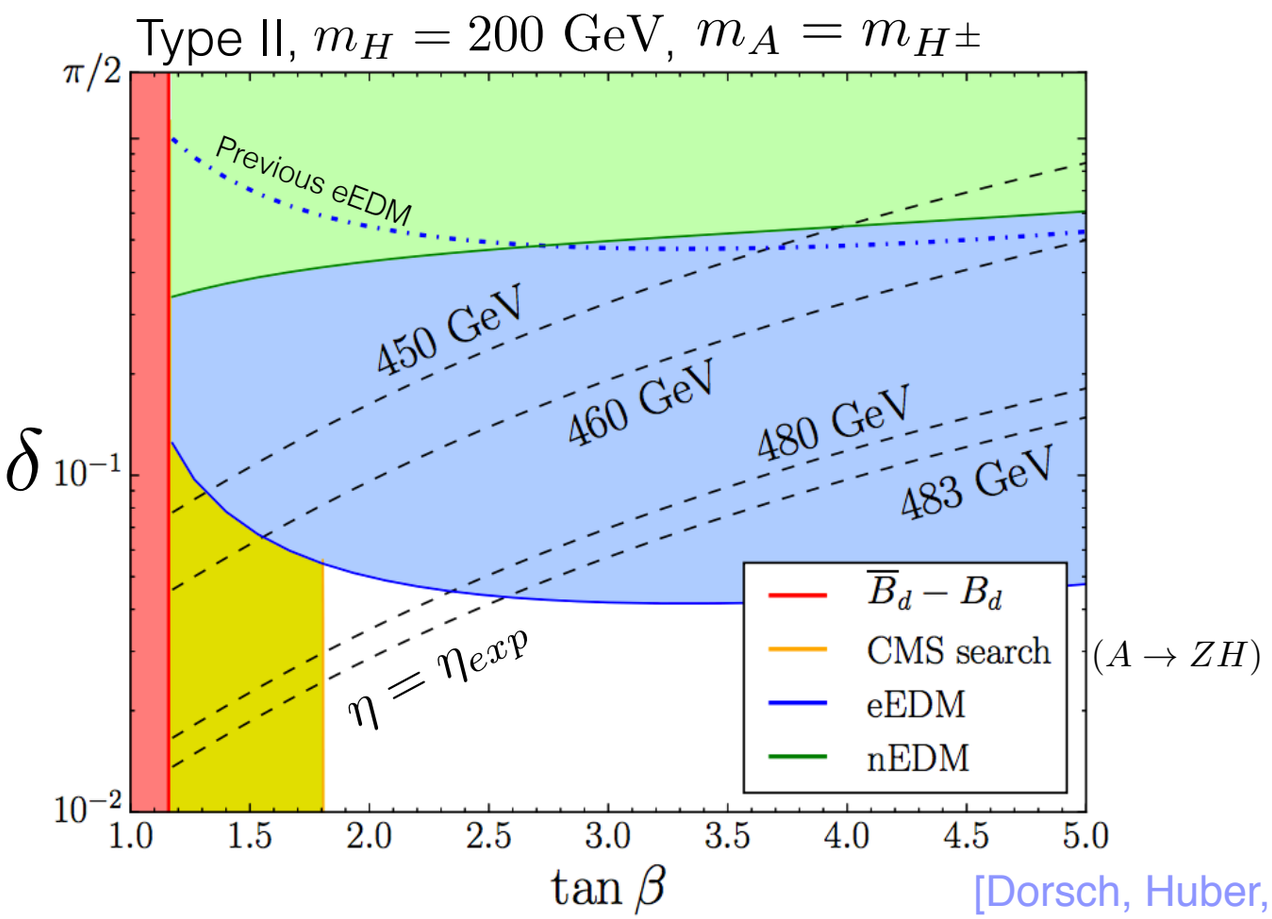


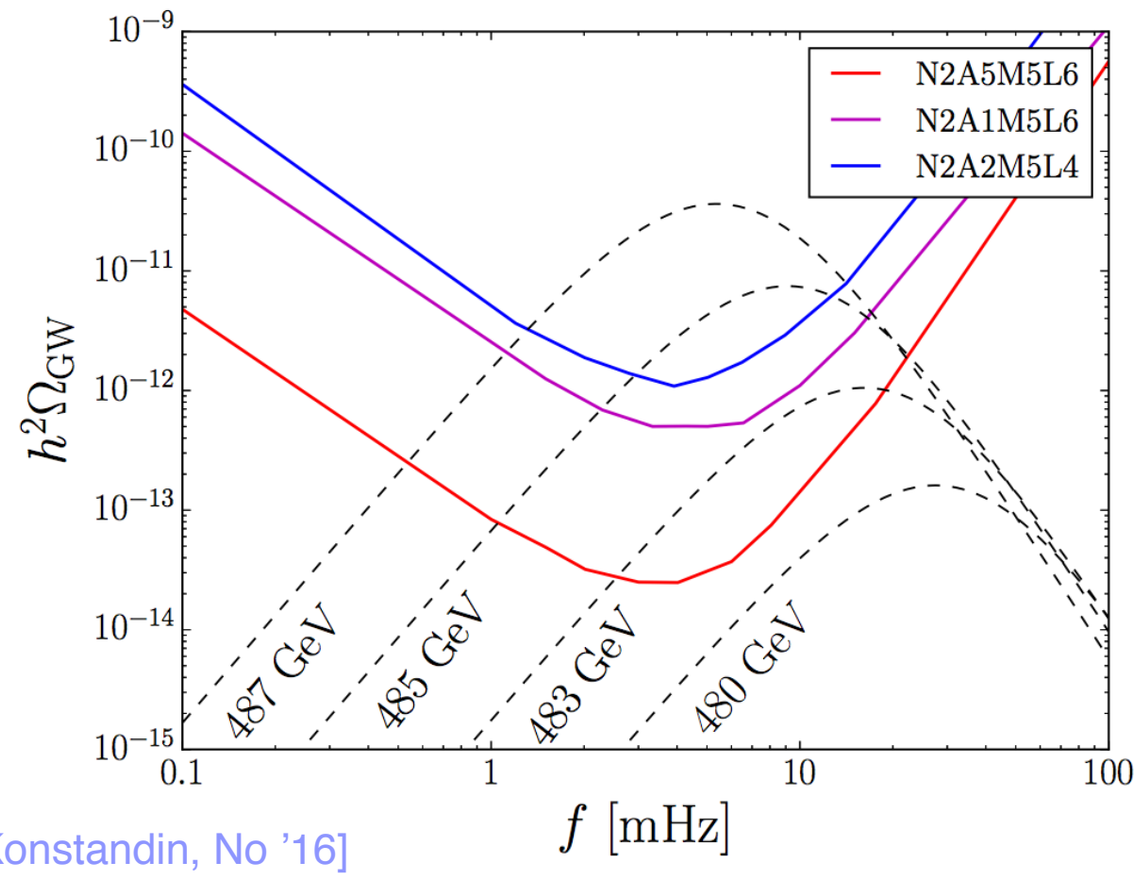
Requiring ξ>1 leads to enhancement of the trilinear Higgs coupling relative to SM

Coupling enhancement largely correlated with the size of ξ

Baryon asymmetry

- The softly-broken $\mathbb{Z}_2$ symmetric 2HDM potential has one free CP violating phase:





[Dorsch, Huber, Konstandin, No '16]

- eEDM and direct searches are fully complementary

- Additional tests within LISA: bubble collisions generate sound waves in the plasma: main source of gravitational waves [Hindmarsh, Huber, Rammukainen, Weir '13, '15]

Conclusions

While the properties of the 125 GeV state appear more and more SM-like, the alignment limit of the 2HDM is singled out.

Strong complementarity between collider searches, flavour observables and cosmological quantities.

SFOPT leads to characteristic mass spectra with distinct signatures at colliders, In particular Higgs-to-Higgs decays but not only

Precision determination of the trilinear Higgs coupling is a probe of such scenarios