Benchmarks on Double Higgs production for Singlet Extension

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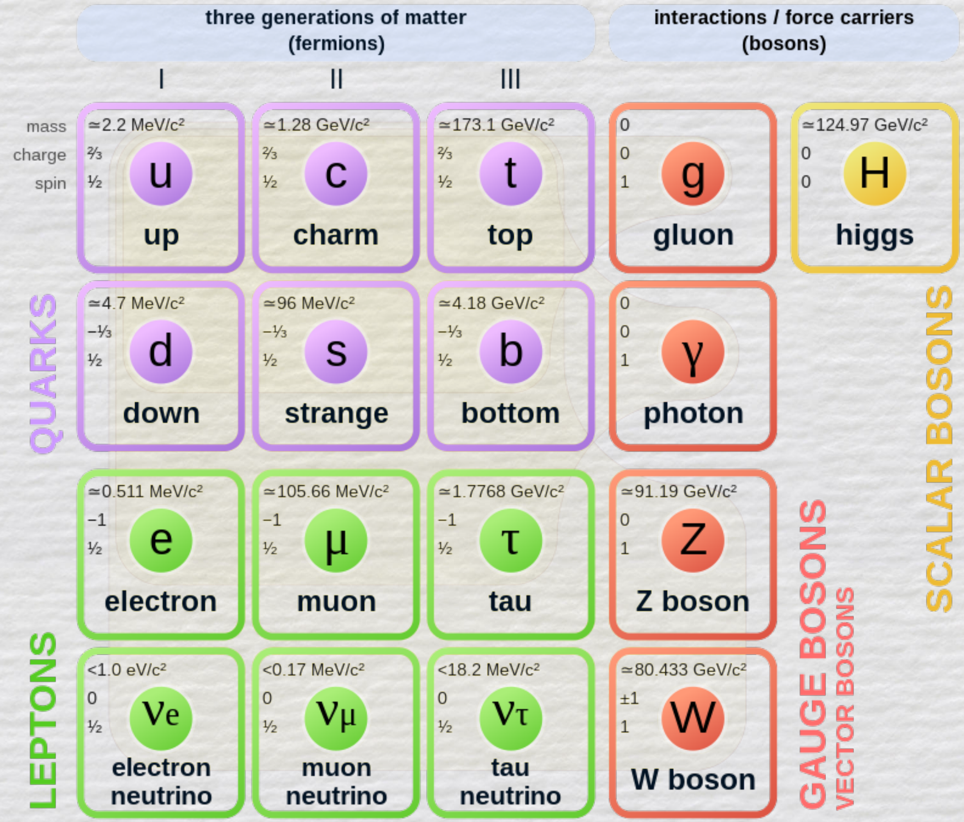
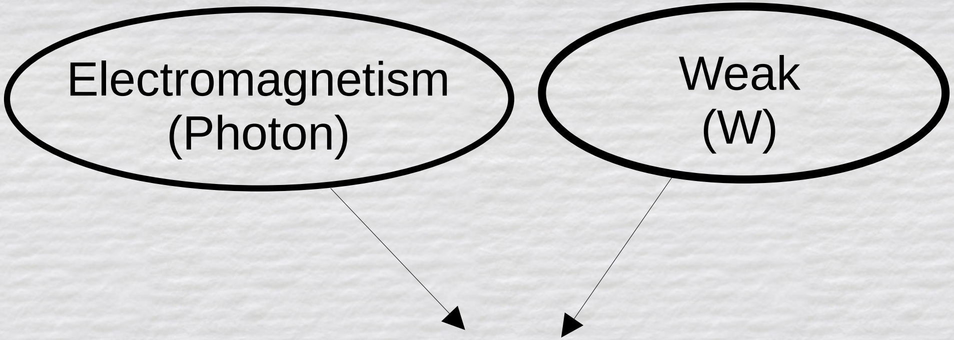
Going Beyond The Standard Model of Elementary Particles





Unification

- Help in further understanding of EW phase transition
- Accuracy for double Higgs production
- Possible DM candidate?

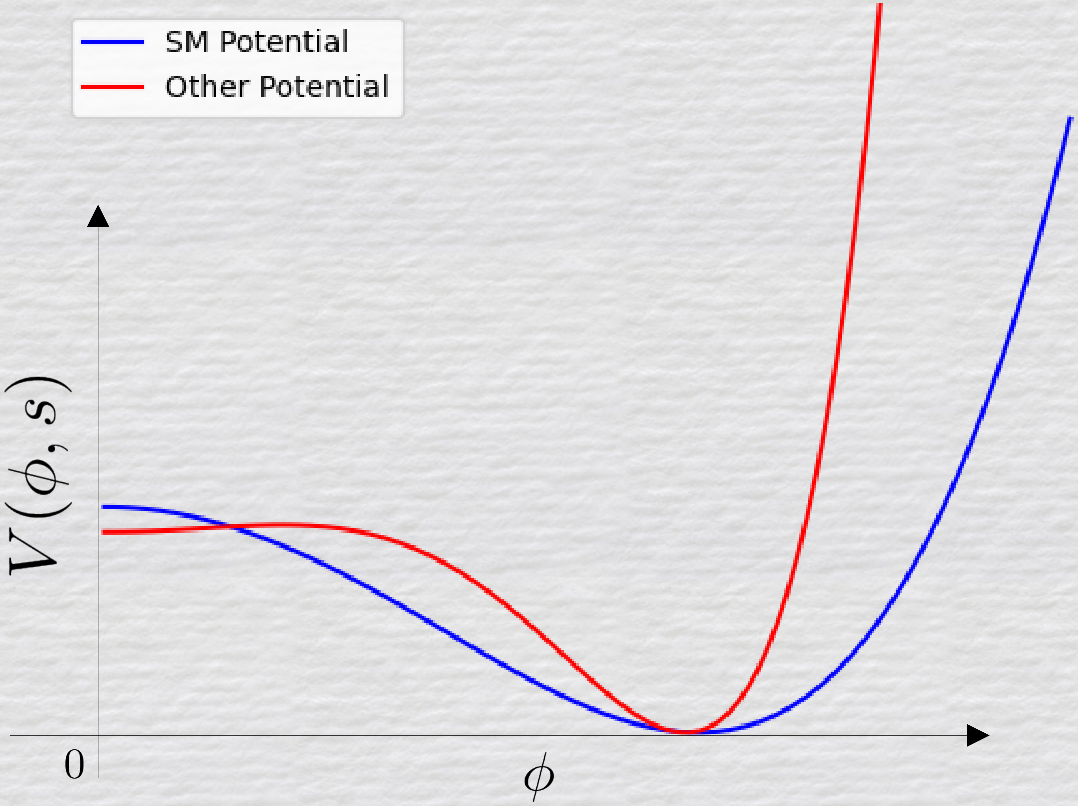
Model Extension

All interactions embedded into the Lagrangian

$$\mathcal{L}_{\text{SM}}$$

The extension must hold the already known Global minimum

$$\mathcal{L}_{\text{new}} = \mathcal{L}_{\text{SM}} + V(H,S)$$

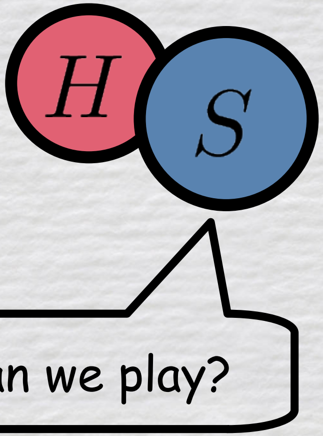


Model Extension

$$H = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ \phi_0 + v \end{pmatrix}$$

- The simplest extension is the addition of a gauge real singlet $S = s + x$

$$V(H,S) = -\mu^2 H^\dagger H + \lambda \left(H^\dagger H\right)^2 + \frac{a_1}{2} H^\dagger H S + \frac{a_2}{2} H^\dagger H S^2 + b_1 S + \frac{b_2}{2} S^2 + \frac{b_3}{3} S^3 + \frac{b_4}{4} S^4.$$



- Only coupling to Higgs doublet H.
- Real minimums only

$$(v_{EW}, 0), \quad (v_\pm, x_\pm), \quad (0, x_{1,2,3})$$

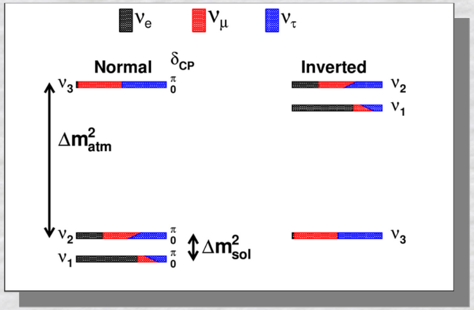
- Scan to see where is global

C.-Y. Chen, S. Dawson, and I. M. Lewis
arXiv:1410.5488

No Z_2 symmetry
More freedom in parameters

- Manipulate to get rid of as many constants, like

$$\mu^2 = \lambda v_{\mathrm{EW}}^2, \quad b_1 = -\frac{v_{\mathrm{EW}}^2}{4} a_1 \quad \text{from} \quad V(v_{\mathrm{EW}}, 0)$$



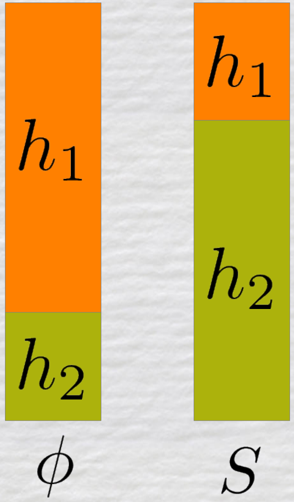
- Further manipulation. Transform to the mass eigenstates

$$V_m(h_1, h_2) \quad \Rightarrow \begin{pmatrix} h_1 \\ h_2 \end{pmatrix} = R(\theta) \begin{pmatrix} \phi \\ s \end{pmatrix}$$

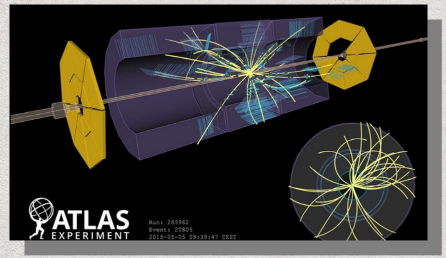
- Similar as neutrinos having flavor and mass eigenstates

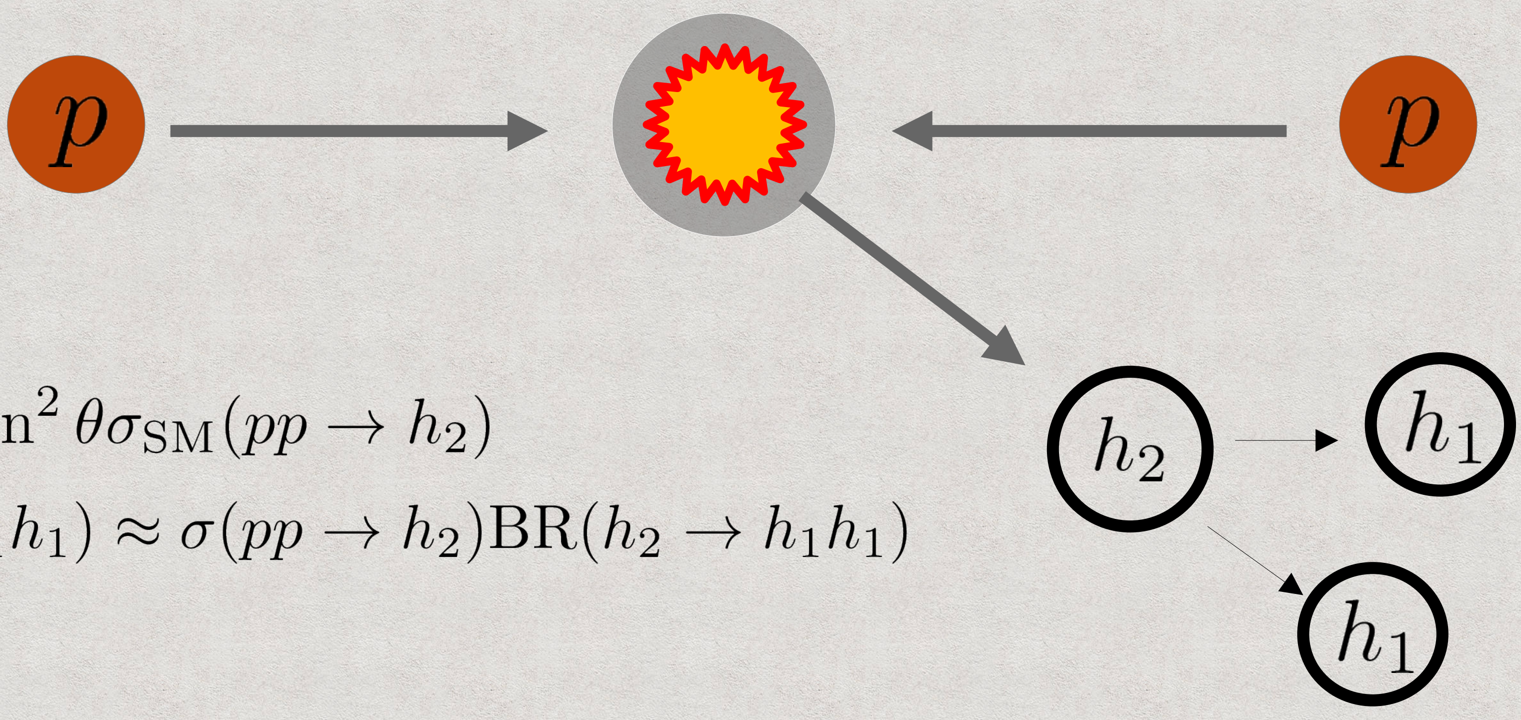
- Leaving total of 4 free parameters

$$a_2, b_3, b_4, m_2, \theta$$



PRODUCTION





$$\sigma(pp \to h_2) = \sin^2\theta \sigma_{\mathrm{SM}}(pp \to h_2)$$

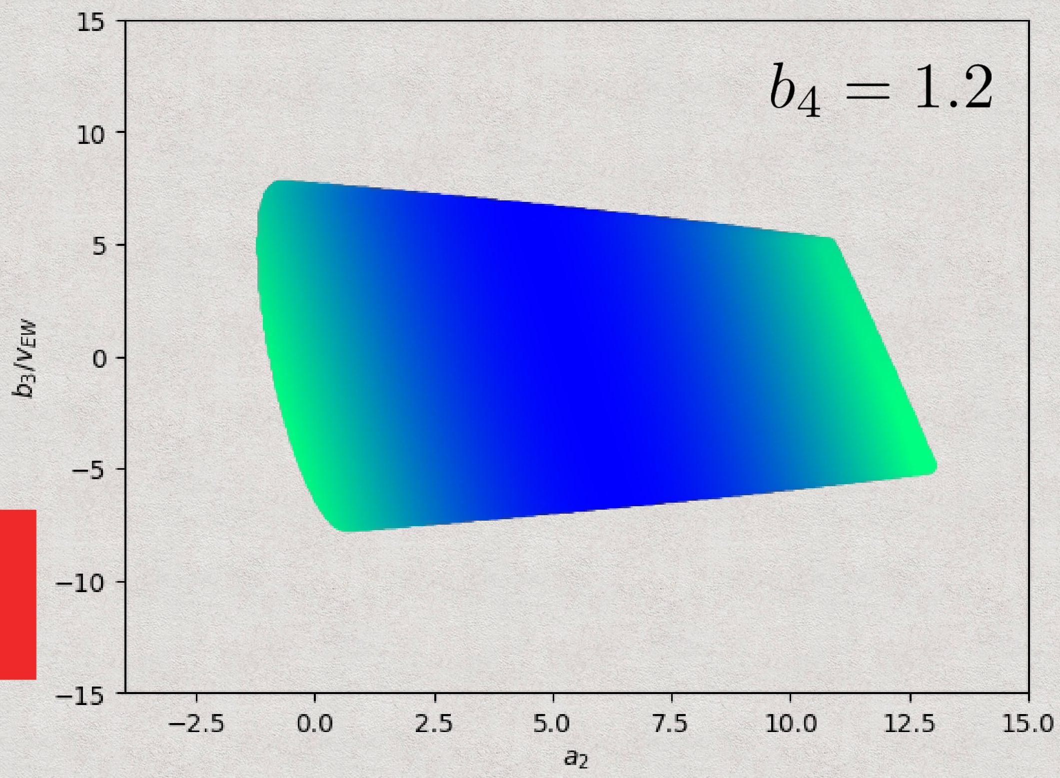
$$\sigma(pp \to h_2 \to h_1 h_1) \approx \sigma(pp \to h_2) \mathrm{BR}(h_2 \to h_1 h_1)$$

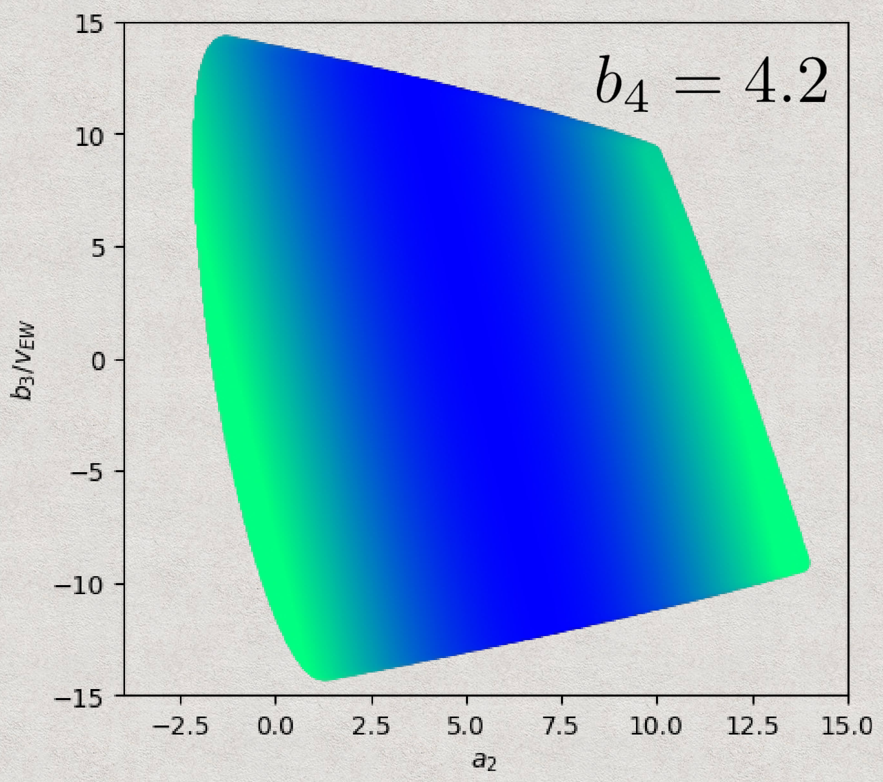
Combine to obtain:

$$\frac{\sigma(pp \to h_2 \to h_1 h_1)}{\sigma_{\mathrm{SM}}(pp \to h_2)} \approx \sin^2\theta \mathrm{BR}(h_2 \to h_1 h_1)$$

What will be measured

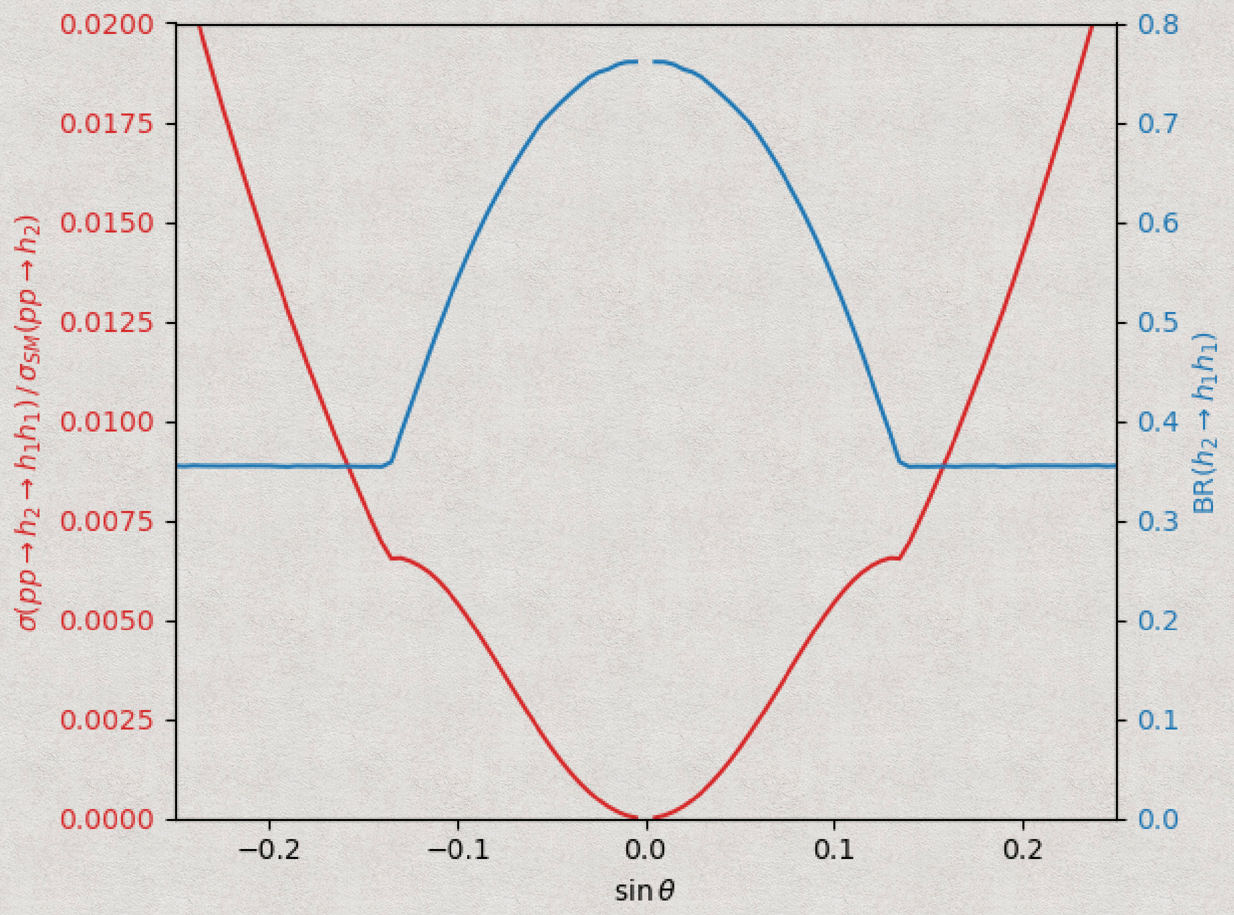
Valid a2 and b3 regions for $m_2 = 800, \sin\theta = 0.14$





For given angle and mass, max area with $b_4 = 4.2$ → Bounded from above by perturbative unitarity.

Now make scan for other parameters



- Same behaviour for all masses
- In λ_{211}, first there is dominance by a_2 and then by $\sin\theta$

$$V \supset \frac{\lambda_{211}}{2!} h_2 h_1^2$$

$$\lambda_{211} = \sin\theta \left[-\frac{2m_1^2 + m_2^2}{v_{\text{ew}}} \cos^2\theta - a_2 v_{\text{ew}} \left(-3\cos^2\theta\right) + b_3 \sin 2\theta \right]$$

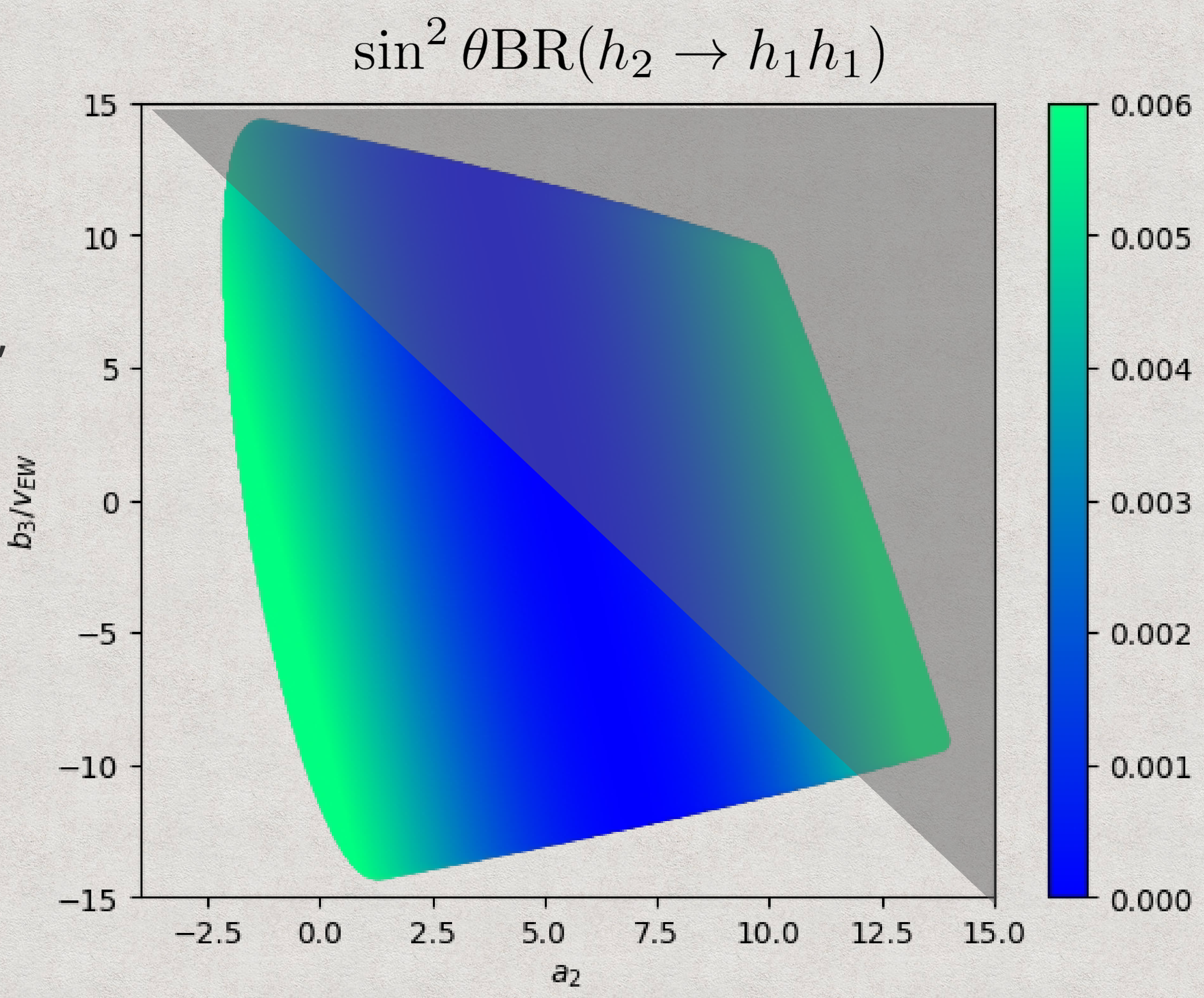
- Narrow width approximation

$$\Gamma(h_2) \leq 0.1 m_2$$

- Entering the Multi-Tev region, the narrow width approximation starts taking effect.

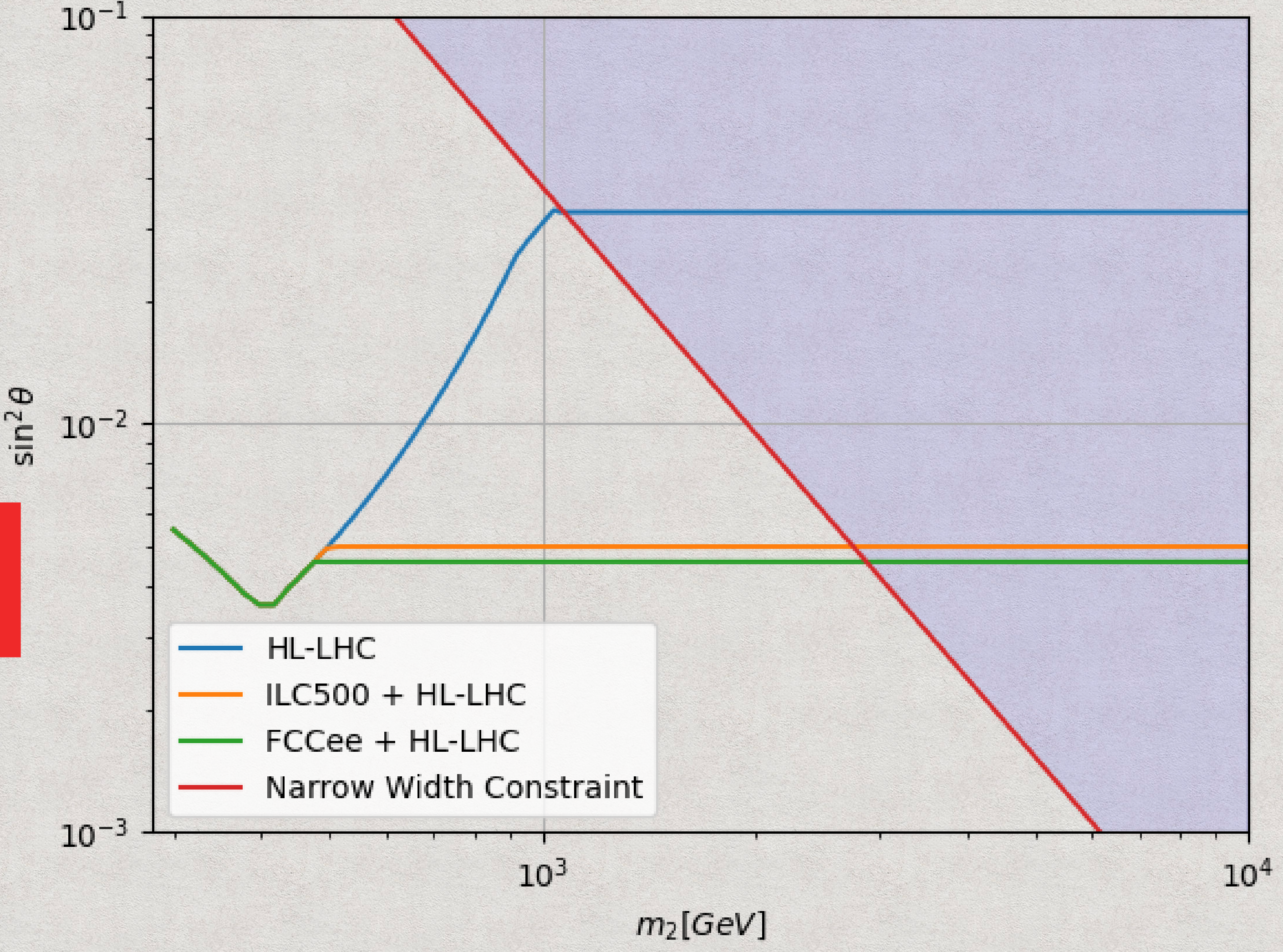
- Constraint in mixing angle:

$$\sin^2\theta \lesssim \frac{0.2\pi v_{\rm ew}^2}{m_2^2}$$



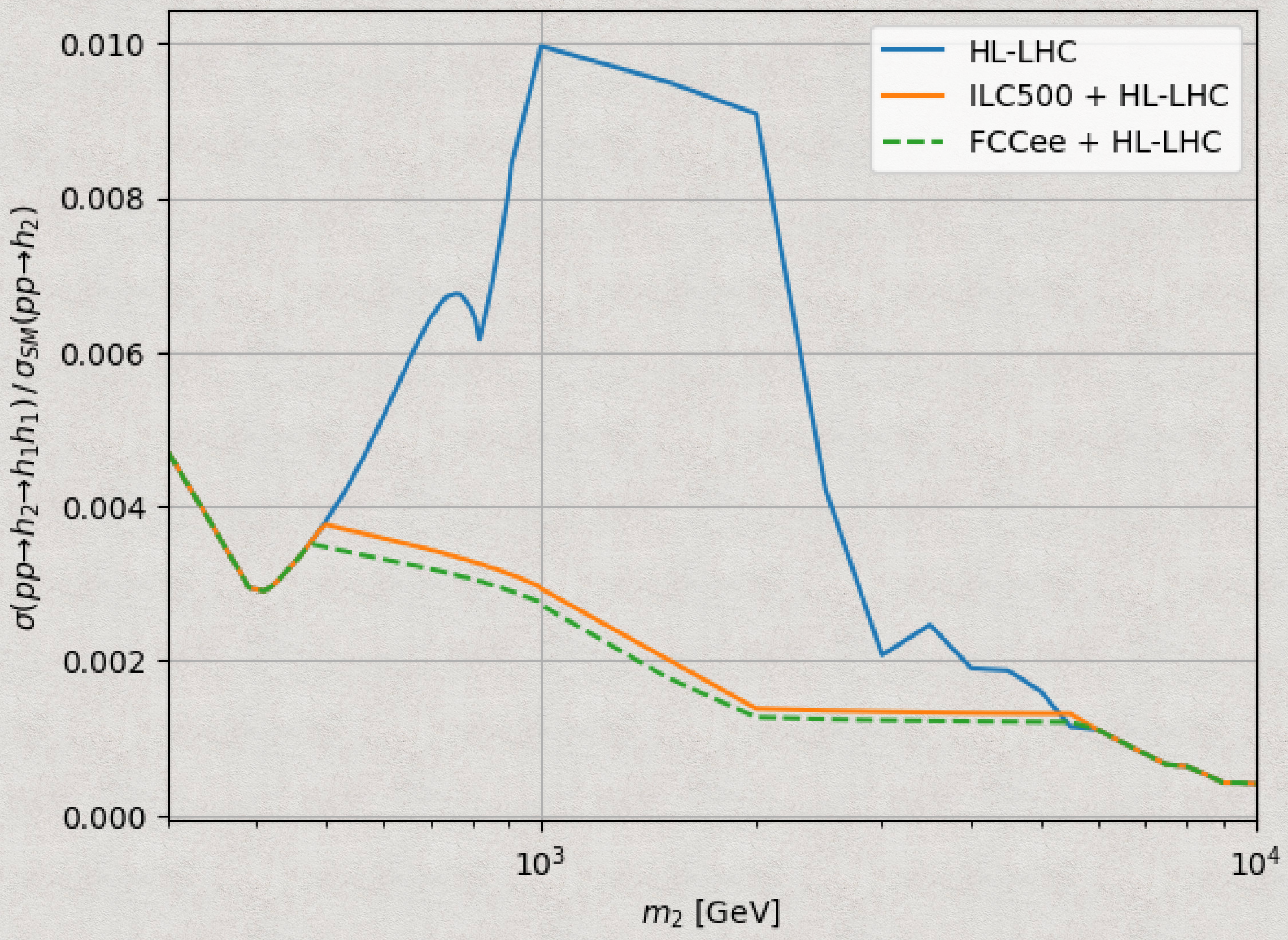
Colliders benchmarks

arXiv:1910.11775



- Entering high energy region.
- After some point, the approximations takes over

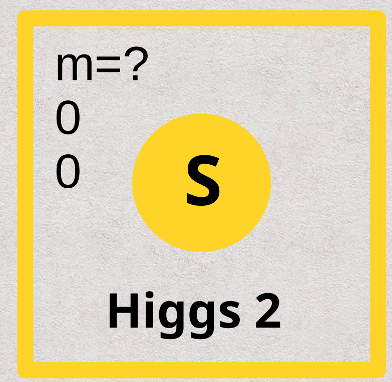
$$\sin^2\theta \lesssim \frac{0.2\pi v_{\mathrm{ew}}^2}{m_2^2}$$



- Maximum production rates constraints

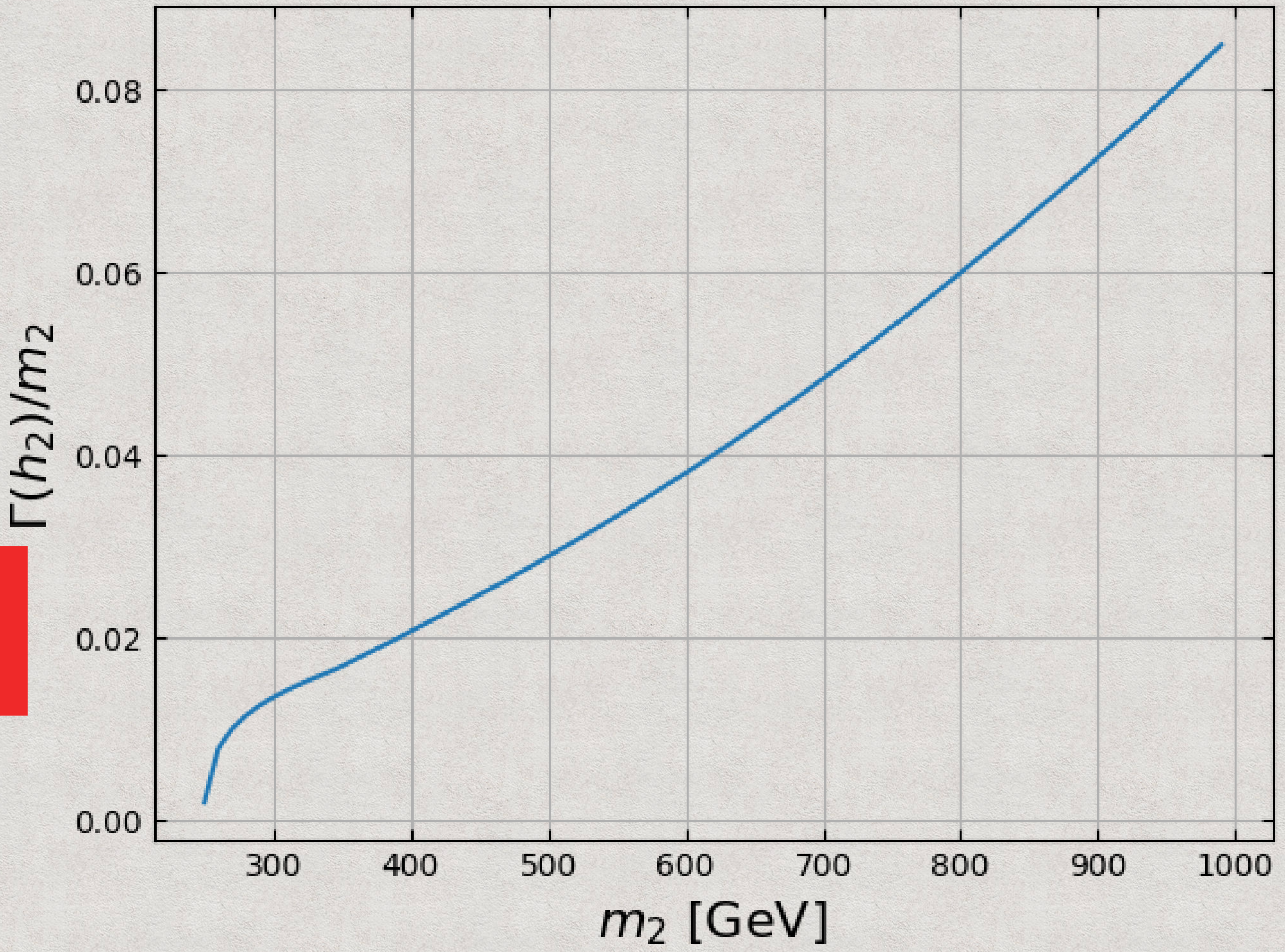
$$\sin^2\theta \mathrm{BR}(h_2 \to h_1 h_1)$$

- **Finale:**
- Add real gauge singlet to model
- Identify free parameters and make scan
- Maximize production rate



Coming soon…?

¡Muchas Gracias!



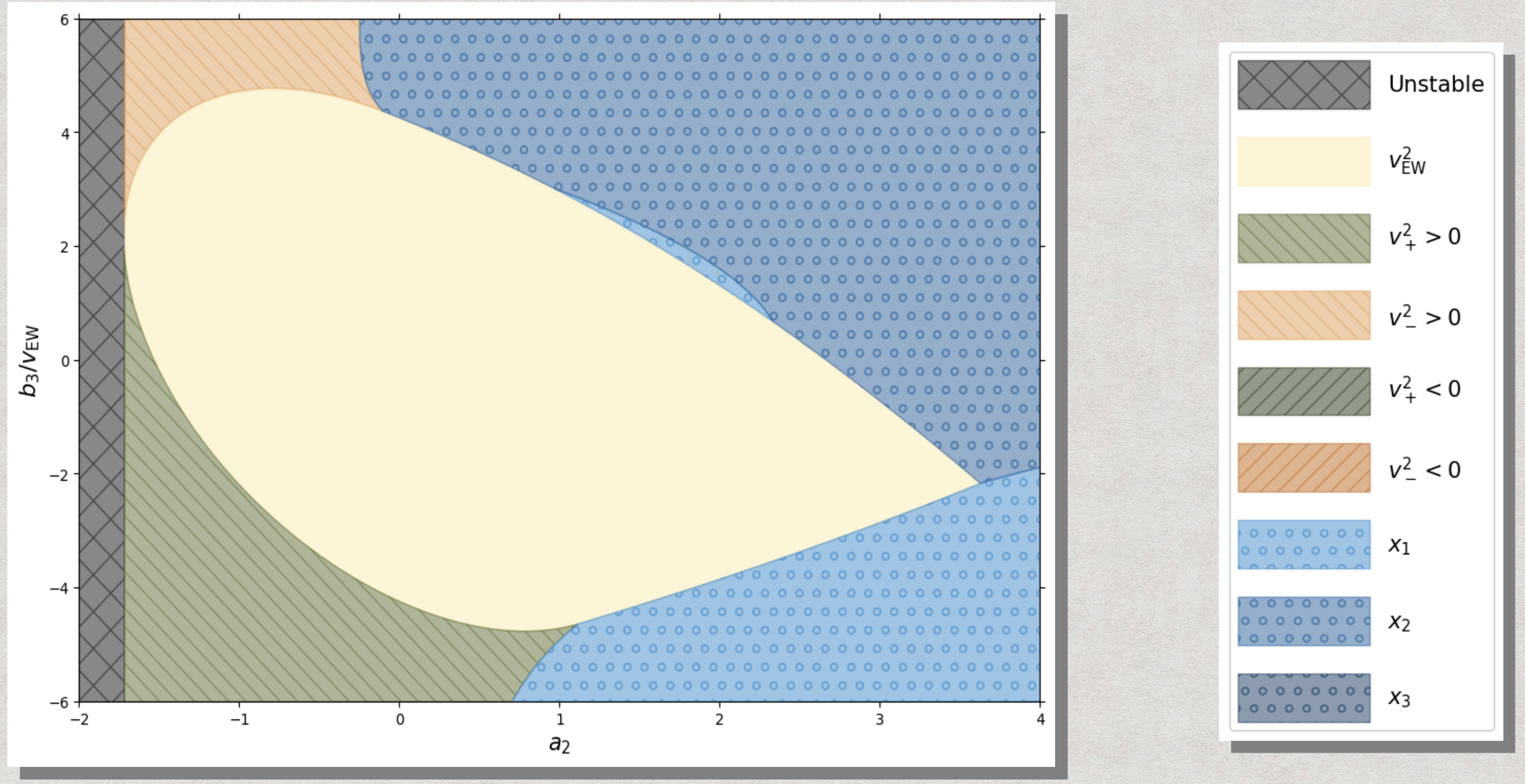
Ratio between maximum width and mass, sticking to the previous constraints.

Fair to use then

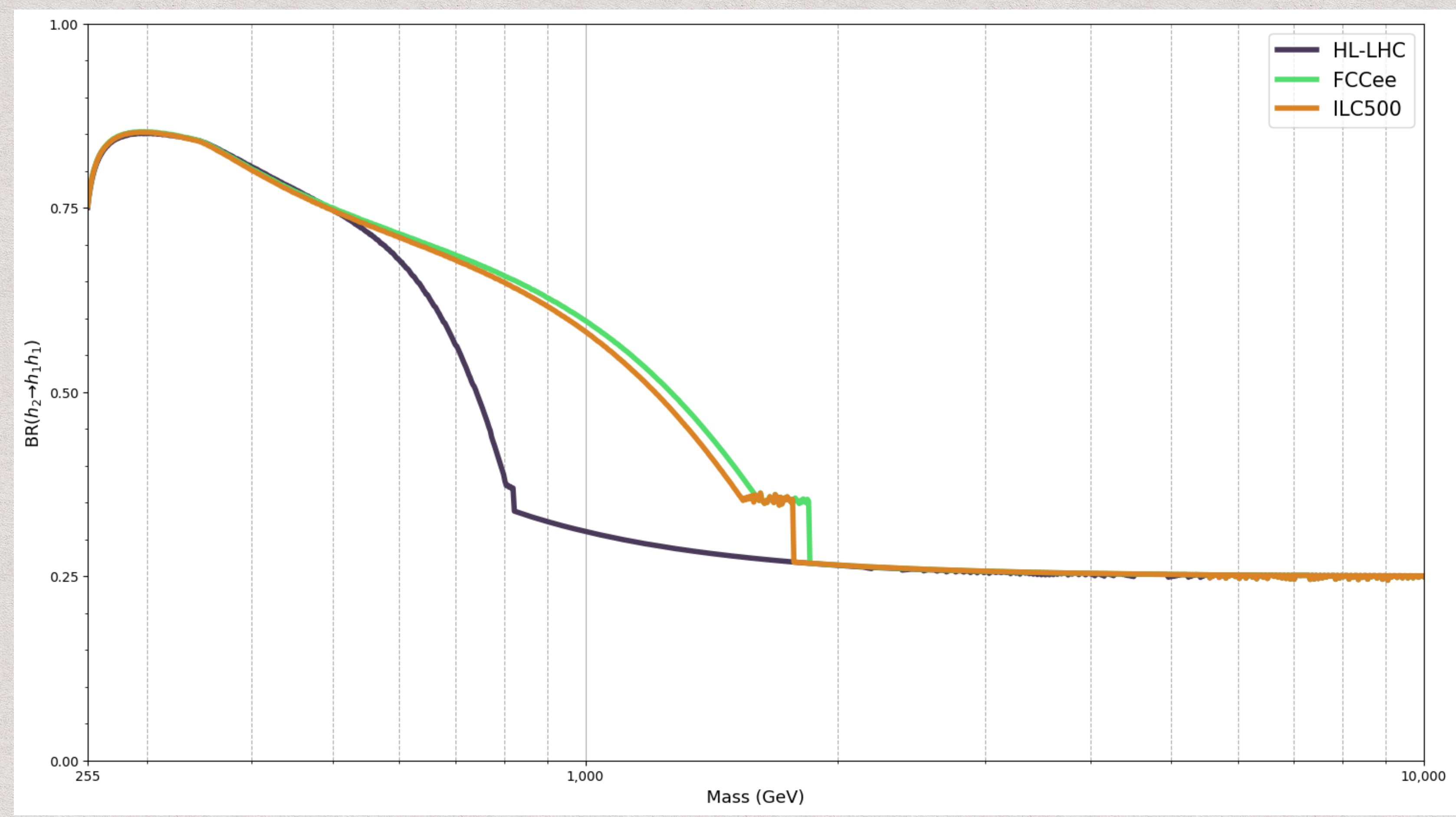
$$\Gamma(h_2) \leq 0.1 m_2$$

Allowing to do Narrow width approximation

$$m_2 = 280\text{GeV}, \quad \sin\theta = 0.30$$



- Branching Ratios



By Jacob Scott

FREE PARAMETERS

- From $(v, x) = (v_{EW}, 0)$, it is found

$$\mu^2 = \lambda v_{\rm EW}^2, \quad b_1 = -\frac{v_{\rm EW}^2}{4} a_1$$

- Rewrite in terms of the mass eigenstates. If $U = (h\, S)$

$$V_m = \frac{1}{2} U M^2 U^T \quad \Rightarrow \begin{pmatrix} h_1 \\ h_2 \end{pmatrix} = R(\theta)^T U^T,$$

- The next constraints can be found

$$a_1 = \frac{m_1^2 - m_2^2}{v_{\rm EW}} \sin 2\theta, \quad \lambda = \frac{m_1^2 \cos^2\theta + m_2^2 \sin^2\theta}{2 v_{\rm EW}}.$$

$$b_2 = m_1^2 \sin^2\theta + m_2^2 \cos^2\theta - \frac{a_2 v_{\rm EW}^2}{2},$$

- Partial width at tree level decay is given by

$$\Gamma(h_2 \to h_1 h_1) = \frac{\lambda_{211}^2}{32\pi m_2}\sqrt{1-\frac{4m_1^2}{m_2}}, \quad \Rightarrow \quad m_2 \geq 2m_1$$

- From the scattering $h_2 h_2 \to h_2 h_2$, perturbative unitarity is used

$$\mathcal{M} = 16\pi \sum_i (2i+1) a_i P_i(\cos\theta), \qquad \lambda_{2222} = 6b_4 + \mathcal{O}(\theta^2)$$

- With restriction of $|a_0| \leq 1/2$

$$a_0 = \frac{3b_4}{8\pi}, \quad \Rightarrow \quad b_4 \leq 4.2$$

More Constraints

- Vacuum Stability yields

$$V^{(4)} = 4\lambda\phi_0^4 + 2a_2\phi_0^2 s^2 + b_4 s^4 > 0 \Rightarrow a_2 \geq -2\sqrt{\lambda b_4}.$$

- The following couplings terms will be used

$$V \supset \frac{\lambda_{211}}{2} h_2 h_1^2 + \frac{\lambda_{2222}}{4!} h_2^4$$

- First for h_2 decay, and the second for limit in b_4