Benchmarks on Double Higgs production for Singlet Extension

Miguel Angel Soto Alcaraz
Collaborating with: I. Lewis; M. Sullivan; J. Scoot

Particle Physics on the plains
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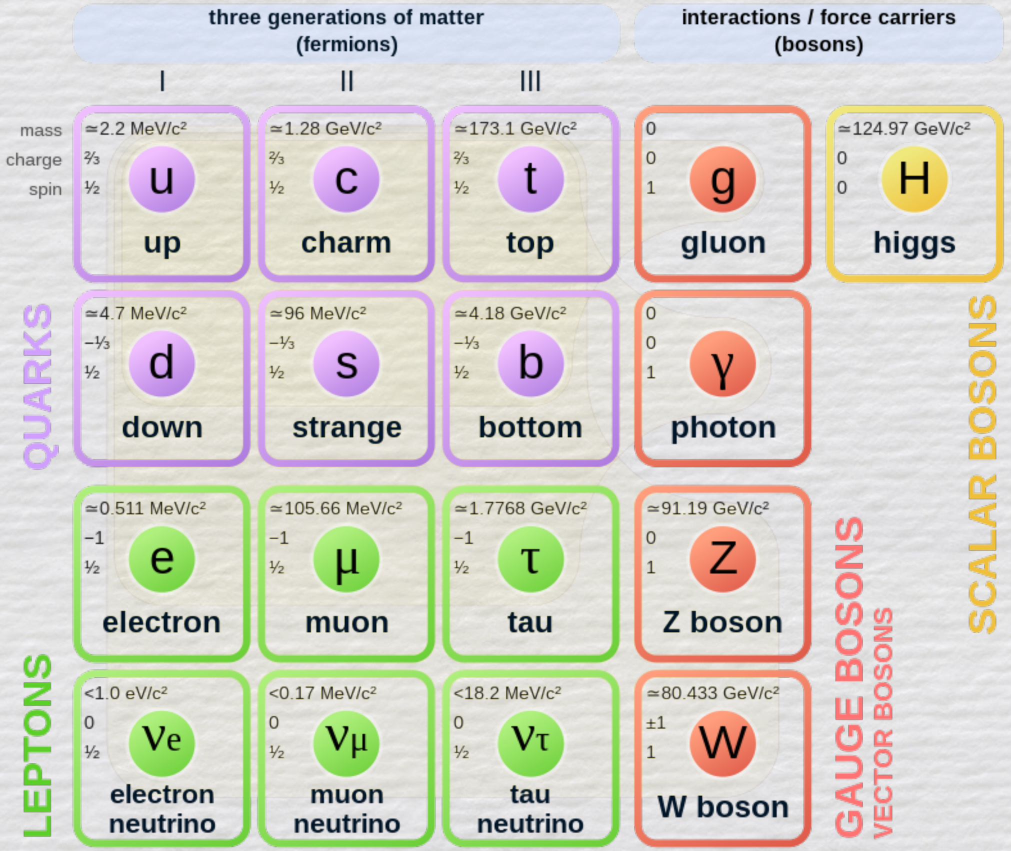
Going beyond the Standard Model of Elementary Particles



- Many open questions:
  - Dark Matter?
  - Neutrino masses?
  - Baryon asymmetry?

Help in further understanding of EW phase transition

Model Extension

- 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, with neutral component having a vev of

$$< \phi_0 >= \frac{v}{\sqrt{2}} = v_{\mathrm{EW}} = 246 \mathrm{GeV}$$

- EWSB at the minimum of potential

$$0 = \frac{v}{2}\left(-2\mu^2 + 2\lambda v^2 + a_1 x + a_2 x^2\right)$$

$$0 = x\left(b_2 + b_3 x + b_4 x^2 + \frac{a_2 v^2}{2}\right) + b_1 + \frac{a_1 v^2}{4}$$

- The possible minimums for (v, x) are

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

- Only real minimums interested
- One by construction and the other analytically

FREE PARAMETERS

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

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

- 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

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

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

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

- Partial width at tree level decay is given by

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

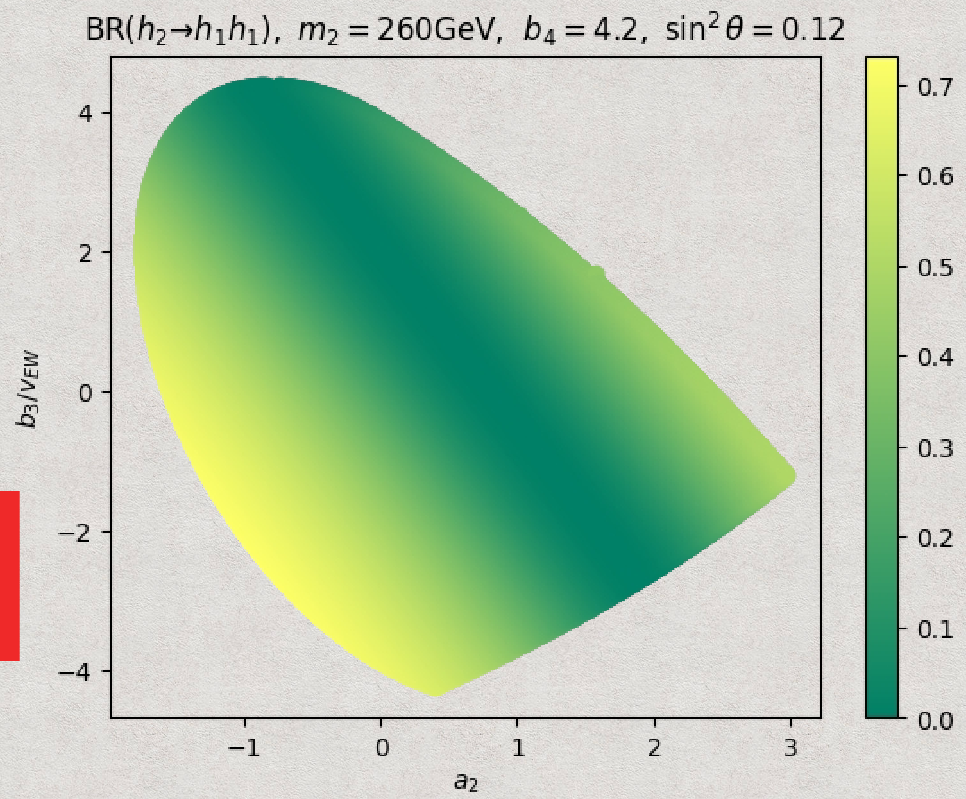
- From the scattering $h_2 h_2 \to h_2 h_2$, perturbative unitarity is used

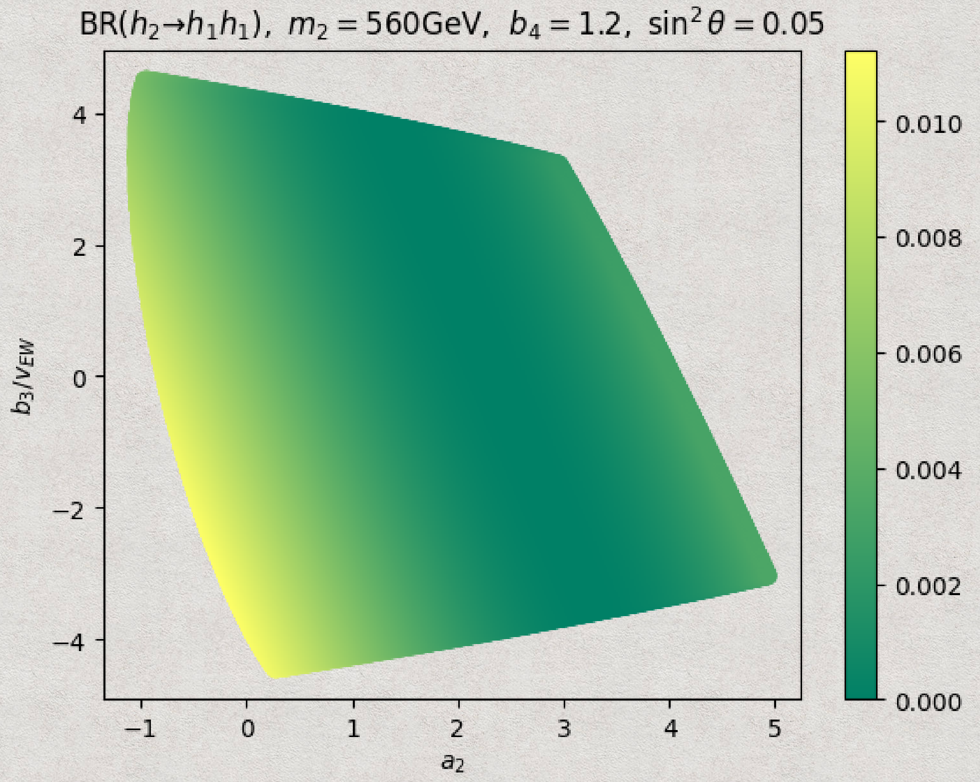
$$\mathcal{M} = 16\pi \sum_i (2i+1) a_i P_i(\cos\theta), \qquad \lambda_{2222} = 6b_4 + \mathcal{O}(\theta^2)$$

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

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

Valid a2 and b3 for some values of free parameters





For given angle and mass, max area with $b_4 = 4.2$

PRODUCTION

- Results must agree with

$$\mathrm{BR}(h_1 \to f_{\mathrm{SM}}) = \mathrm{BR}_{SM}(h_1 \to f_{\mathrm{SM}})$$

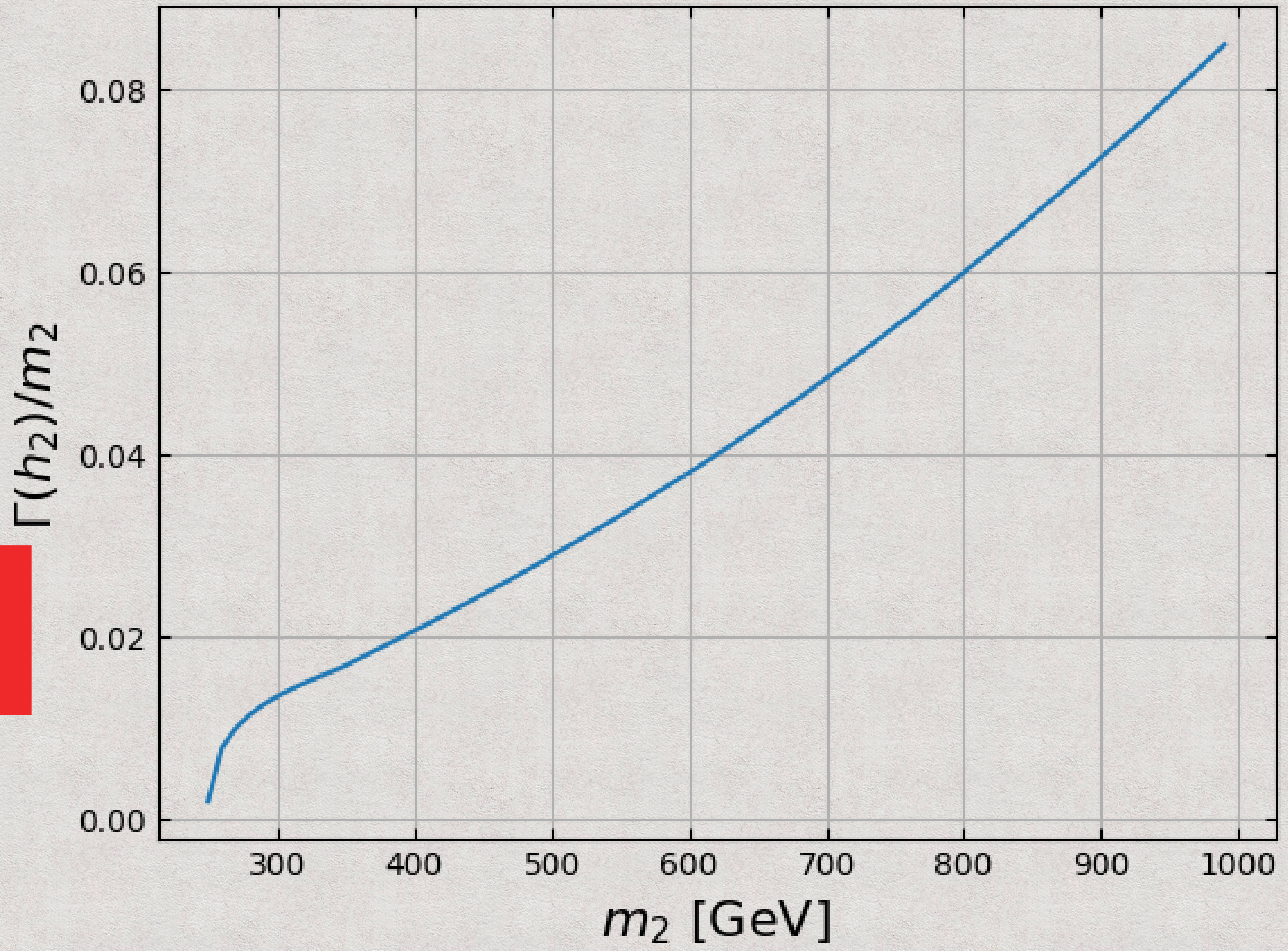
- While BR are suppressed by a factor of $\sin^2\theta$

$$\Gamma(h_2 \to f_{\mathrm{SM}}) = \sin^2\theta\Gamma_{\mathrm{SM}}(h_2 \to f_{\mathrm{SM}})$$

- Leading to a total width of

$$\Gamma(h_2) = \Gamma(h_2 \to h_1 h_1) + \Gamma(h_2 \to f_{\mathrm{SM}})$$

- With $\Gamma(h_2 \to f_{\mathrm{SM}})_{\mathrm{SM}}$ being the SM Higgs decay with mass m_2



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

- Due to last constraint, a narrow width approximation can be used

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

- Due to mixing with Higgs, couplings to SM fermions and gauge bosson proportional to $\sin\theta$

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

- Maximization of production

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

- Current constraints given by ATLAS $\sin^2\theta \leq 0.12$

- Future Collider benchmarks so far given by:

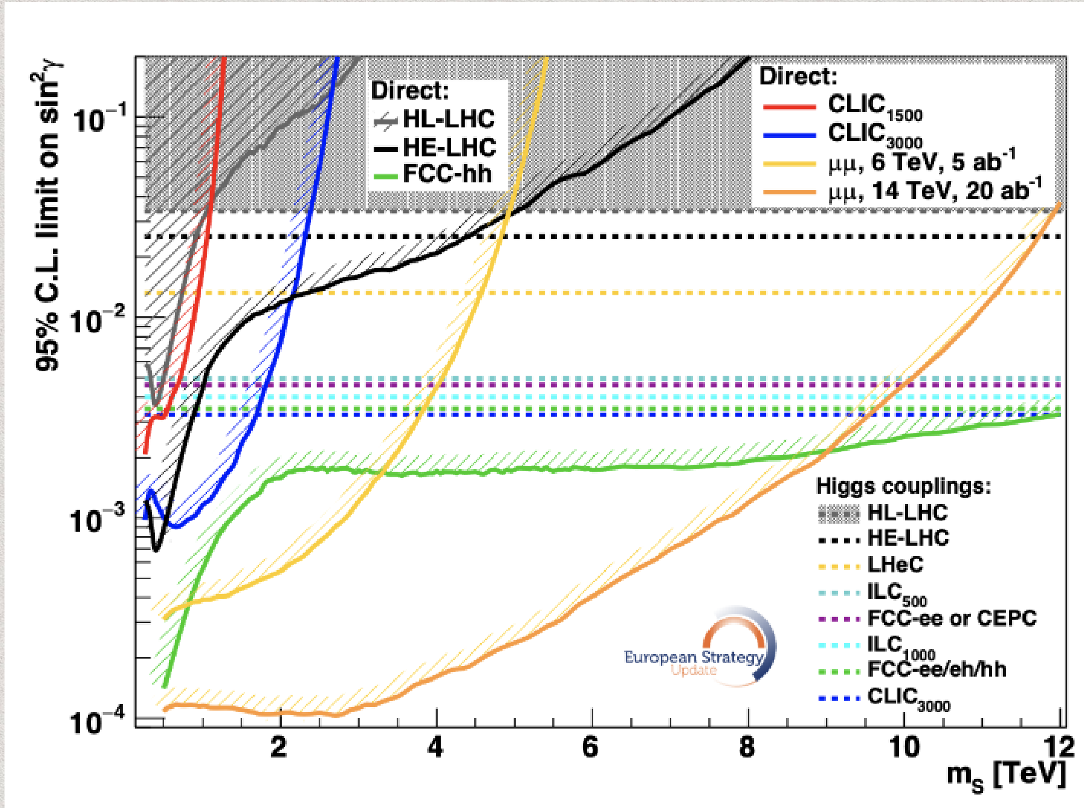
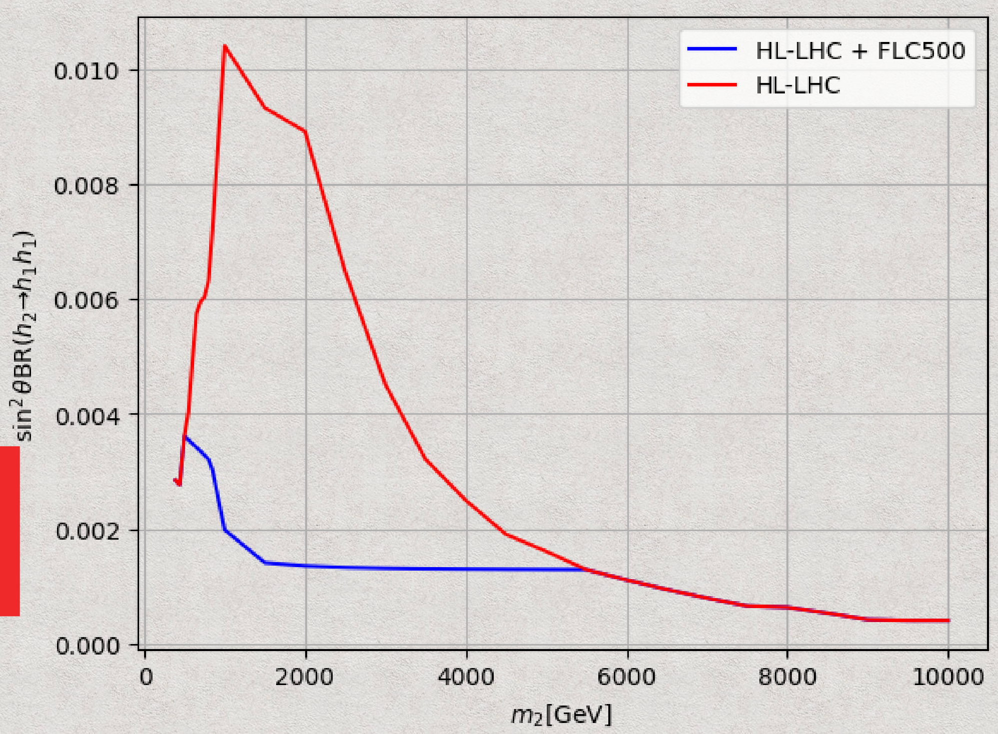
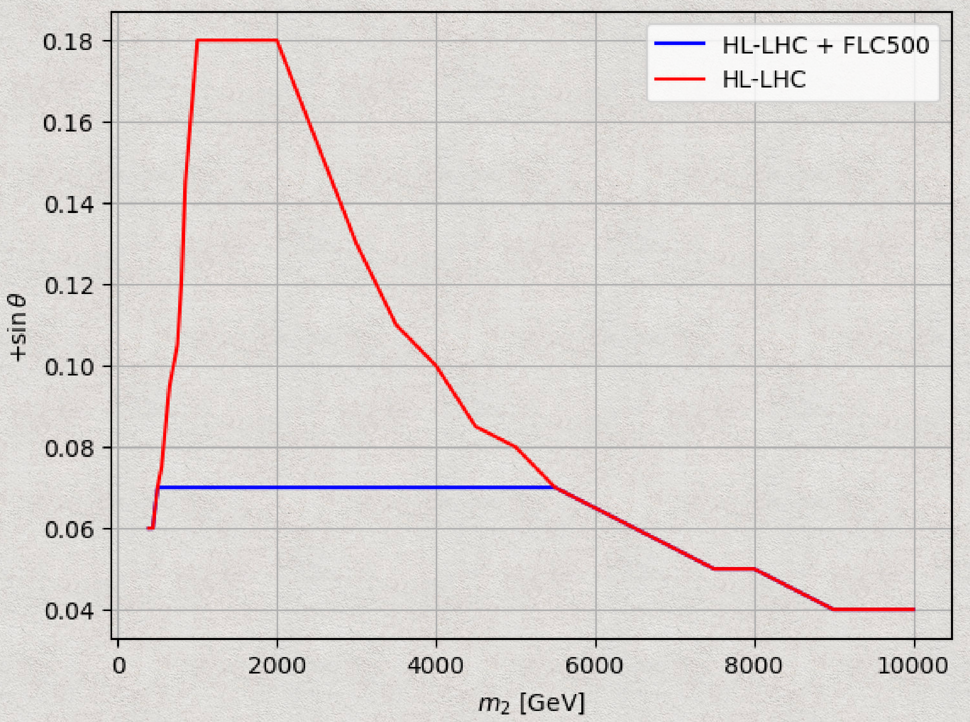


Figure taken from: arXiv:1910.11775 [hep-ex].

Benchmarks for some future colliders





- **Finale:**
- Add real gauge singlet to model
- Identify free parameters and make scan
- Maximize production rate
- **What's next?**
- Use new data to apply further constraints to $\sin\theta$

Coming soon...?