The Elementary Goldstone Higgs

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Work in collaboration with
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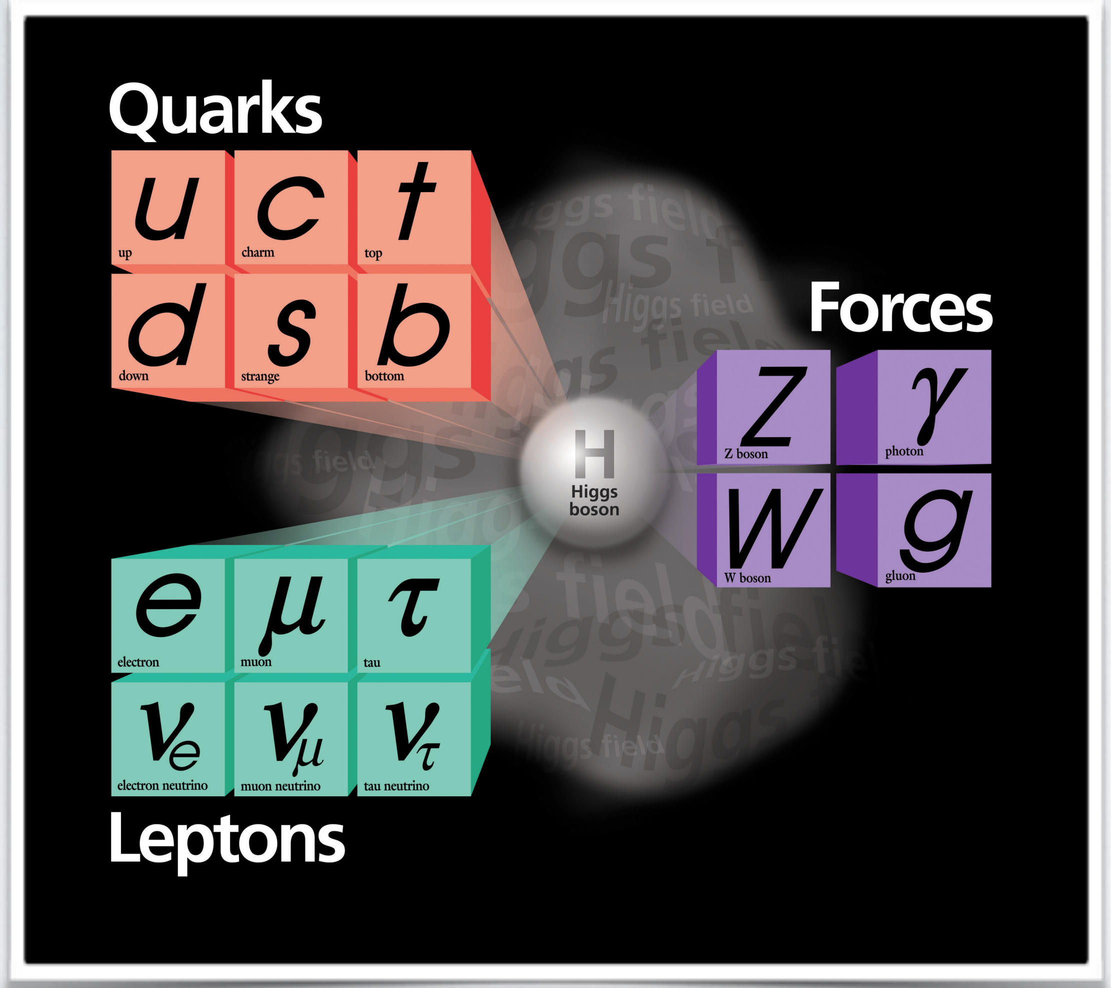
CP3 Origins
Cosmology & Particle Physics

DIAS
Danish Institute for Advanced Study

The Standard Model



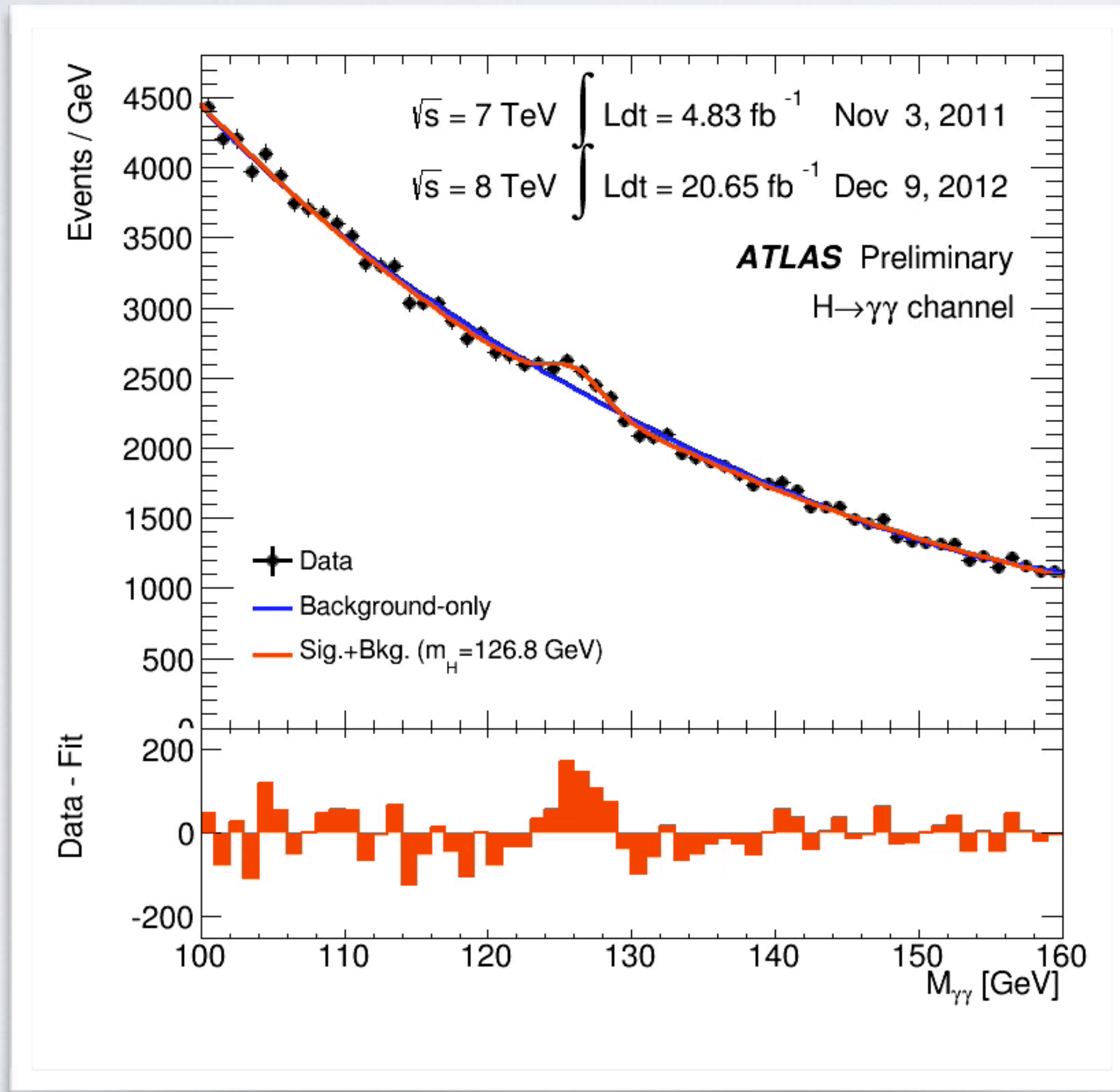
$SU_c(3) \times SU_L(2) \times U_Y(1)$

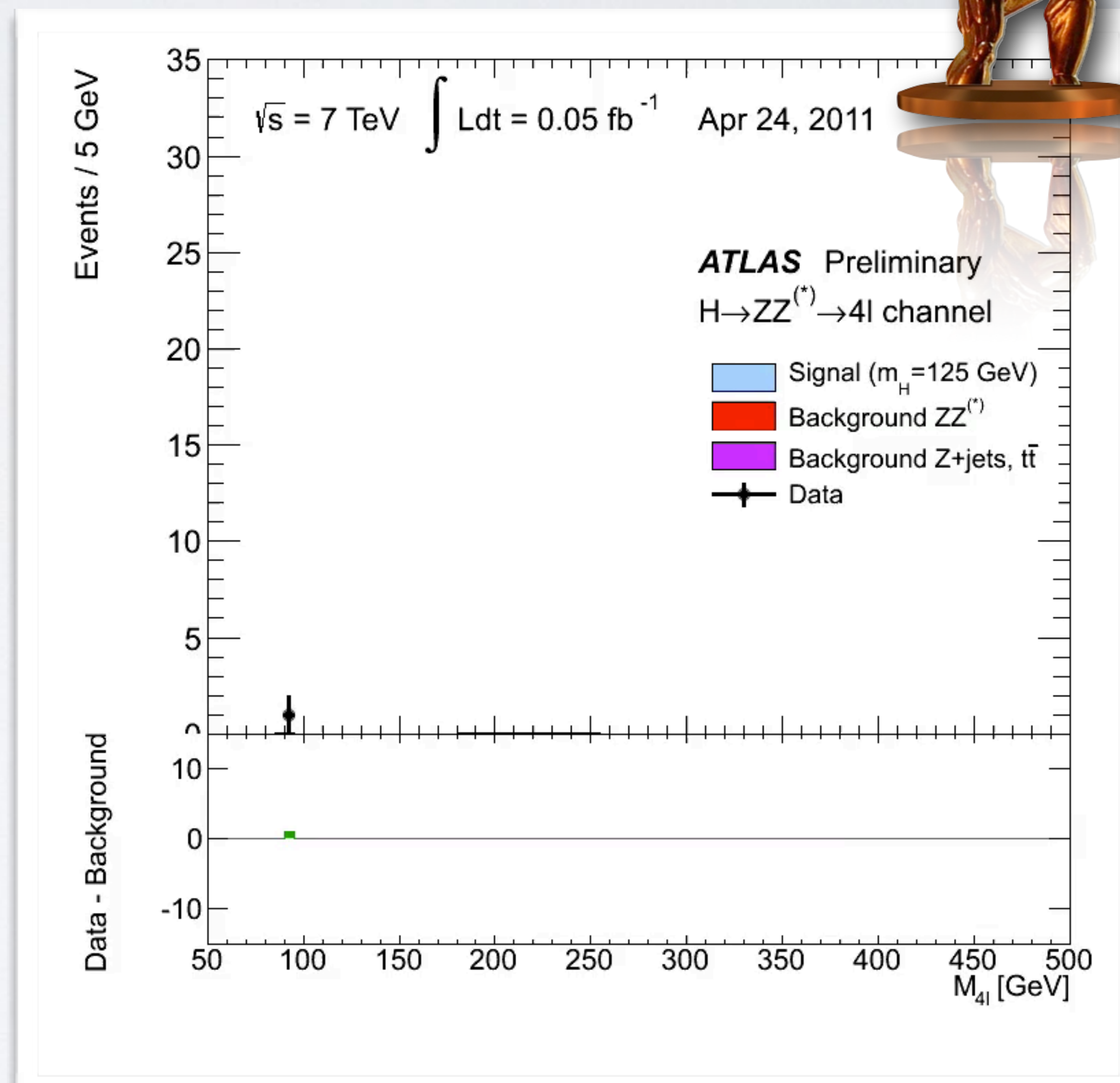
Why do we have mass?

The Higgs was predicted in 1964

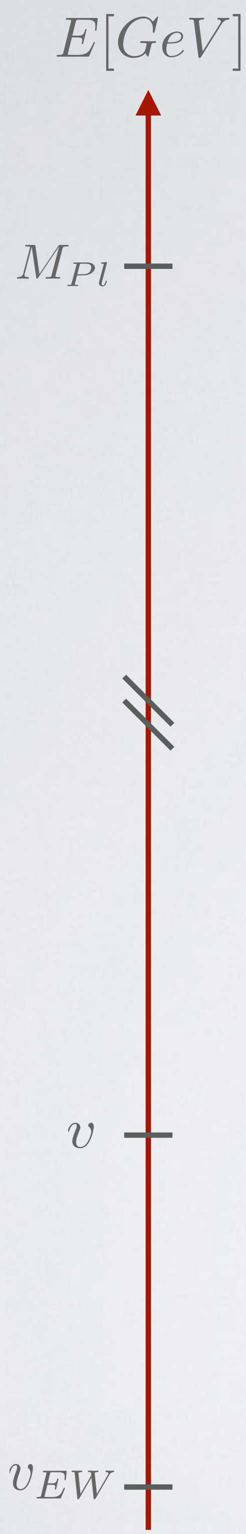
The discovery of the Higgs

On the 4th of July 2012





The EGH paradigm



H. Gertov, A. Meroni, E. Molinaro, F. Sannino Phys. Rev. D 92, 095003 (2015)
T. Alanne, H. Gertov, F. Sannino, K. Tuominen Phys. Rev. D 91, 095021 (2015)




- A different paradigm where the Higgs sector symmetry is larger.
- The physical Higgs emerges as a pNGB.
- Different paradigm: allows to disentangle the vacuum expectation of the *elementary* Higgs sector from the EW scale.
- C*alculable* radiative corrections induce the proper breaking of the EW symmetry and naturally aligns the vacuum in the pNGB Higgs direction.
- The EW scale is only radiatively induced and it is order of magnitudes smaller than the scale of the Higgs sector in isolation.

The EGH model

The symmetry is enlarged to SU(4)

Antisymmetric, breaking to Sp(4)

Symmetric, breaking to SO(4)

The scalar sector consists of 12 real fields expressed as

$$M = \left[\frac{\sigma + i\Theta}{2} + \sqrt{2}(i\Pi^i + \tilde{\Pi}^i)X^i\right]E$$

The most general renormalizable Lagrangian

$$
\begin{aligned}
V_M \;\; &= \;\; \frac{1}{2} m_M^2 \mathrm{Tr}[M^\dagger M] + (c_M \mathrm{Pf}(M) + \mathrm{h.c.}) + \frac{\lambda}{4} \mathrm{Tr}[M^\dagger M]^2 \\
& + \lambda_1 \mathrm{Tr}[M^\dagger M M^\dagger M] - 2 \left(\lambda_2 \mathrm{Pf}(M)^2 + \mathrm{h.c.} \right) \\
& + \left(\frac{\lambda_3}{2} \mathrm{Tr}[M^\dagger M] \mathrm{Pf}(M) + \mathrm{h.c.} \right)
\end{aligned}
$$

The vacuum, v, is in the σ direction with the value

$$
v^2 \;\; = \;\; \frac{c_{MR} - m_M^2}{\lambda + \lambda_1 - \lambda_{2R} - \lambda_{3R}}
$$

in the case where all the couplings are real

Vacuum Allignment

The vacuum used is a superposition of two vacua

$$\Sigma_\theta = \cos\theta\,\Sigma_B + \sin\theta\,\Sigma_H$$

Electroweak vacuum

$$\Sigma_B = \begin{pmatrix} i\sigma_2 & 0 \\ 0 & -i\sigma_2 \end{pmatrix}$$

Technicolor vacuum

$$\Sigma_H = \begin{pmatrix} 0 & 1 \\ -1 & 0 \end{pmatrix}$$

Spectrum

The spectrum at tree-level for real couplings are

$$m_\sigma^2 = 2(c_M - m_M^2)$$

$$m_\Theta^2 = \frac{c_M(2\lambda + 2\lambda_1 + 2\lambda_{2R} - \lambda_{3R}) - m_M^2(4\lambda_{2R} + \lambda_{3R})}{\lambda + \lambda_1 - \lambda_{2R} - \lambda_{3R}}$$

$$m_{\tilde{\Pi}}^2 = \frac{c_{MR}(2\lambda + 4\lambda_1 - \lambda_{3R}) - m_M^2(2\lambda_1 + 2\lambda_{2R} + \lambda_{3R})}{\lambda + \lambda_1 - \lambda_{2R} - \lambda_{3R}}$$

$$m_\Pi^2 = 0$$

Electroweak Interactions

The electroweak interactions appear in the kinetic term of the Lagrangian

$$\mathscr{L}_{\rm kin} = \frac{1}{2}{\rm Tr}\left[D_\mu M^\dagger D^\mu M\right]$$

where

$$\begin{aligned} D_\mu M &= \partial_\mu M - i\left(G_\mu M + M G_\mu^{\rm T}\right) \\ G_\mu &= g W_\mu^i T_L^i + g' B_\mu T_R^3 \end{aligned}$$

which gives the masses

$$\begin{aligned} m_W^2 &= \tfrac{1}{4} g^2 v^2 \sin^2\theta \\ m_Z^2 &= \tfrac{1}{4}(g^2 + g'^2) v^2 \sin^2\theta \\ m_A^2 &= 0 \end{aligned}$$

The Top Mass

The Yukawa interactions in the Lagrangian is

$$\mathscr{L}_{\rm Yuk}^{\rm top} \;=\; y_t (Q t^c)^\dagger_\alpha {\rm Tr}[P_\alpha M] + {\rm h.c.}$$

which gives the mass of the top

$$m_{\rm top} \;=\; \frac{y_t}{\sqrt{2}} v \sin\theta$$

To have the correct observed masses:

$$v_{ew} \;=\; v \sin\theta$$

Explicit breaking of SU(4) to Sp(4)

SU(4) is broken minimally to Sp(4) in a way which gives mass to Π_5

$$V_{\rm br} \;=\; \frac{1}{8}\mu_M^2 \,{\rm Tr}\left[E_A M\right] {\rm Tr}\left[E_A M\right]^*$$

where

$$E_A \;=\; \begin{pmatrix} i\sigma_2 & 0 \\ 0 & i\sigma_2 \end{pmatrix}$$

and gives the mass term to Π_5 and $\tilde{\Pi}_5$

$$V_{\rm br} \;=\; \frac{1}{2}\mu_M^2 \left[(\Pi_5)^2 + (\tilde{\Pi}_5)^2\right]$$

The One-loop corrections

The 6 couplings are expressed in terms of the masses and the vacuum

$$\begin{pmatrix} m_M \\ c_{MR} \\ \lambda \\ \lambda_1 \\ \lambda_{2R} \\ \lambda_{3R} \end{pmatrix} \longleftrightarrow \begin{pmatrix} M_\sigma \\ M_\Theta \\ M_{\tilde{\Pi}} \\ v \\ \tilde{\lambda} \\ \lambda_{2R} \end{pmatrix}$$

$$\begin{aligned} M_{\tilde{\Pi}}^2 &= M_\Theta^2 + 2v\lambda_f \\ \lambda_f &= \lambda_1 - \lambda_{2R} \\ \tilde{\lambda} &= \lambda + 4\lambda_1 \end{aligned}$$

The Coleman-Weinberg potential:

$$\delta V(\Phi) = \frac{1}{64\pi^2}\mathrm{Str}\left[\mathcal{M}_0^4(\Phi)\log\frac{\mathcal{M}_0^2(\Phi)}{\mu_0^2} - C\right] + V_{GB}$$

$$C_{\mathrm{scalar}} = \frac{3}{2} \qquad C_{\mathrm{EW}} = \frac{5}{6} \qquad C_{\mathrm{top}} = \frac{3}{2}$$

The Physical Higgs

The physical Higgs is a superposition of σ and Π_4

$$\begin{pmatrix} \sigma \\ \Pi_4 \end{pmatrix} = \begin{pmatrix} \cos\alpha & -\sin\alpha \\ \sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} h \\ H \end{pmatrix}$$

The observed Higgs boson with the mass

$$m_h = 125.03^{+0.26}_{-0.27}\ \mathrm{GeV}$$

is mostly the Π_4 and hence are the lightest of the two Higgs bosons

Constraints on the Parameter Space

The potential must be minimised with respect to θ

$$\left.\frac{\partial \delta V}{\partial \theta}\right|_v = 0 \qquad \left.\frac{\partial^2 \delta V}{\partial \theta^2}\right|_v > 0$$

The top and the electroweak bosons must have the correct masses

$$v_{ew} = v \sin\theta = 246 \text{ GeV}$$

The observable constraints on the self couplings

$$c_V = c_f = \sin(\theta + \alpha)$$

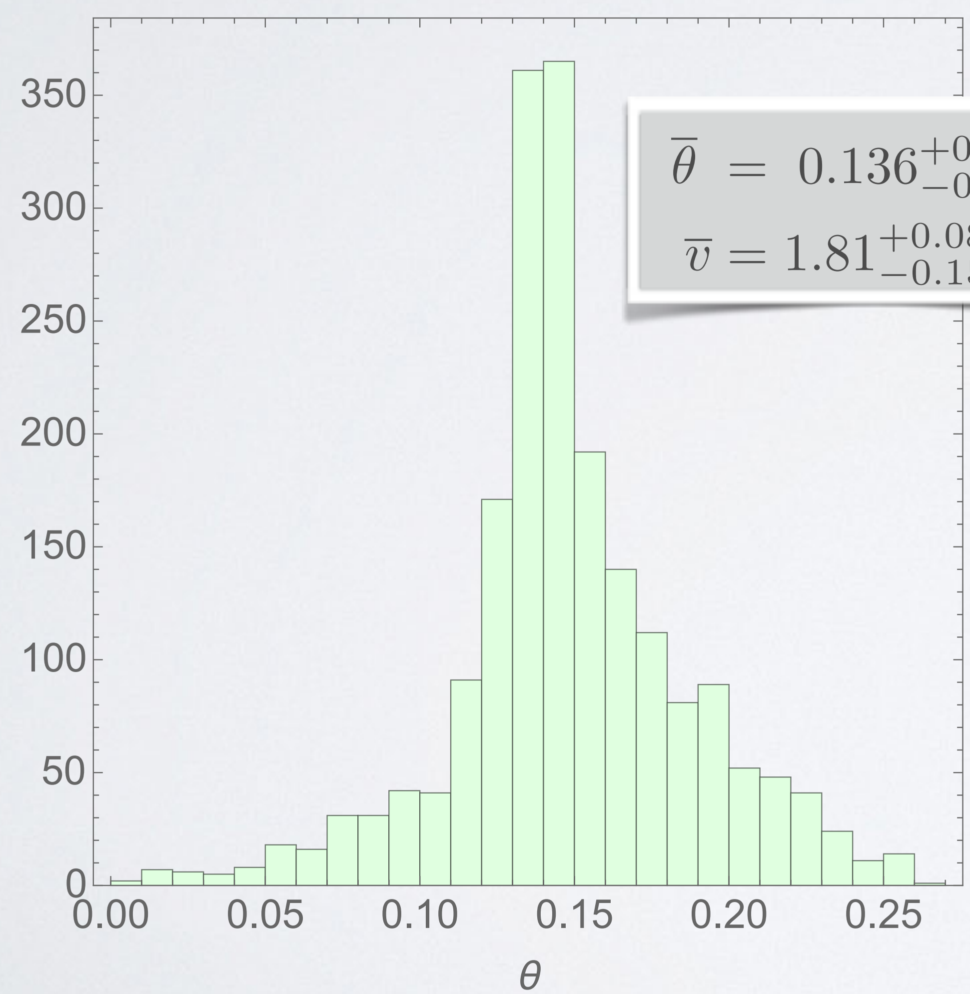
$$c_V = 1.01^{+0.07}_{-0.07} \quad \text{and} \quad c_f = 0.89^{+0.14}_{-0.13}$$

One Common Scalar mass

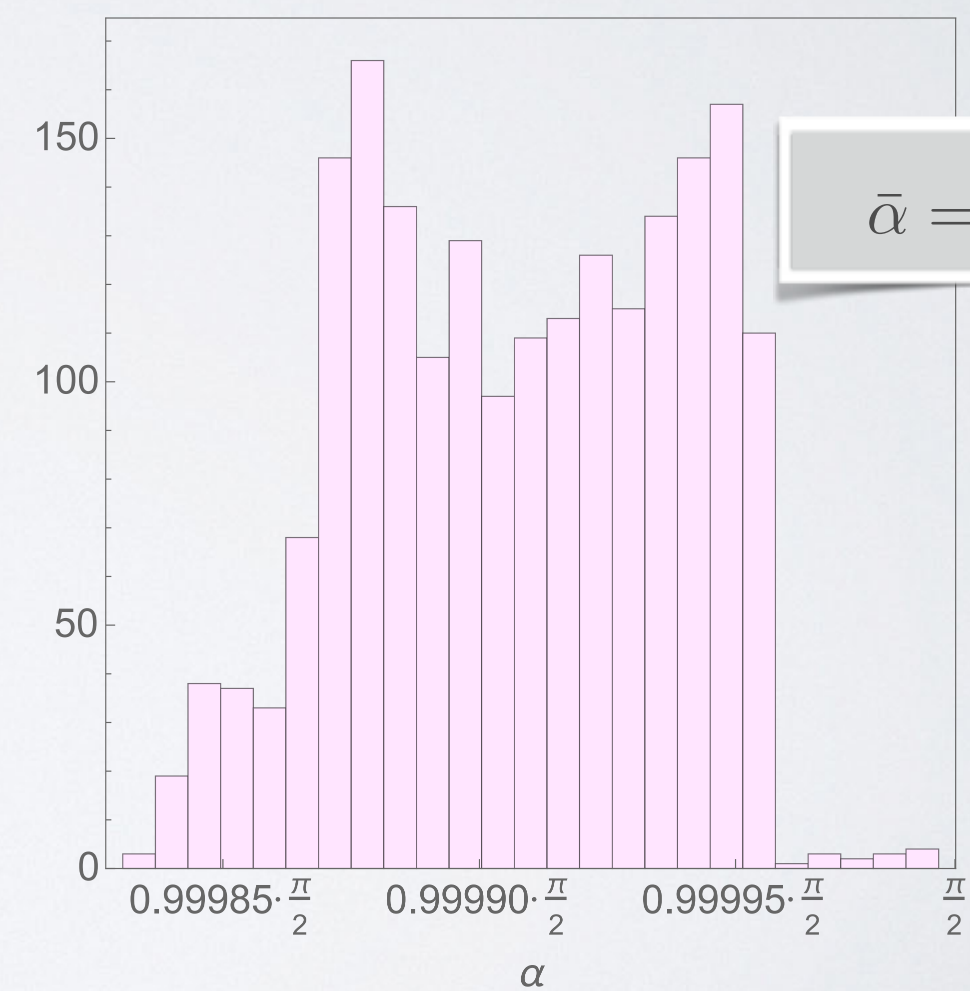
The free parameters in this case:

$$v, \quad \theta, \quad \mu_M, \quad \tilde{\lambda}, \quad M_S$$

$$m_h \leq \mu_M \leq 1 \text{ TeV}$$
$$m_h \leq M_S \leq 5 \text{ TeV}$$

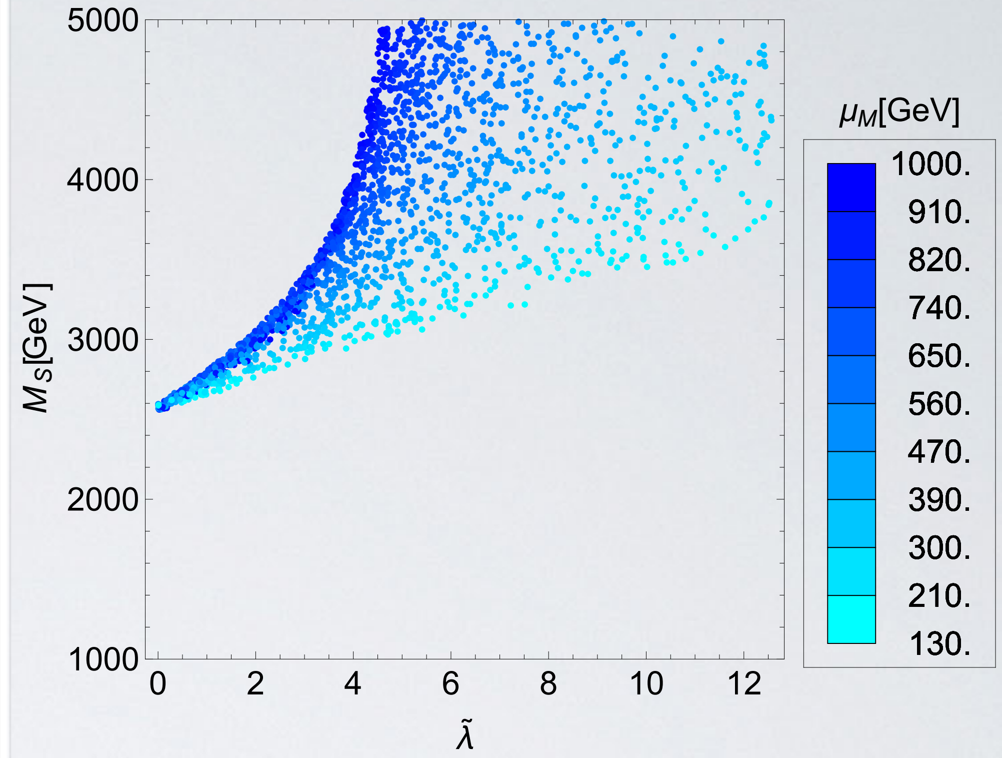


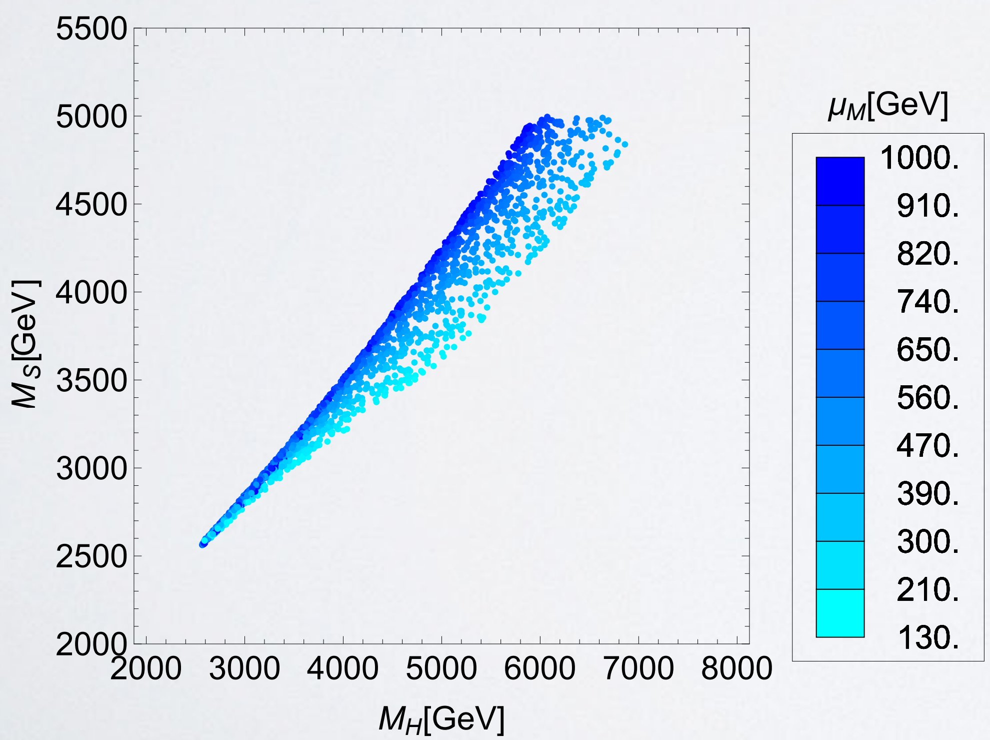
$$\bar{\theta} = 0.136^{+0.006}_{-0.012}$$
$$\bar{v} = 1.81^{+0.08}_{-0.15} \text{TeV}$$



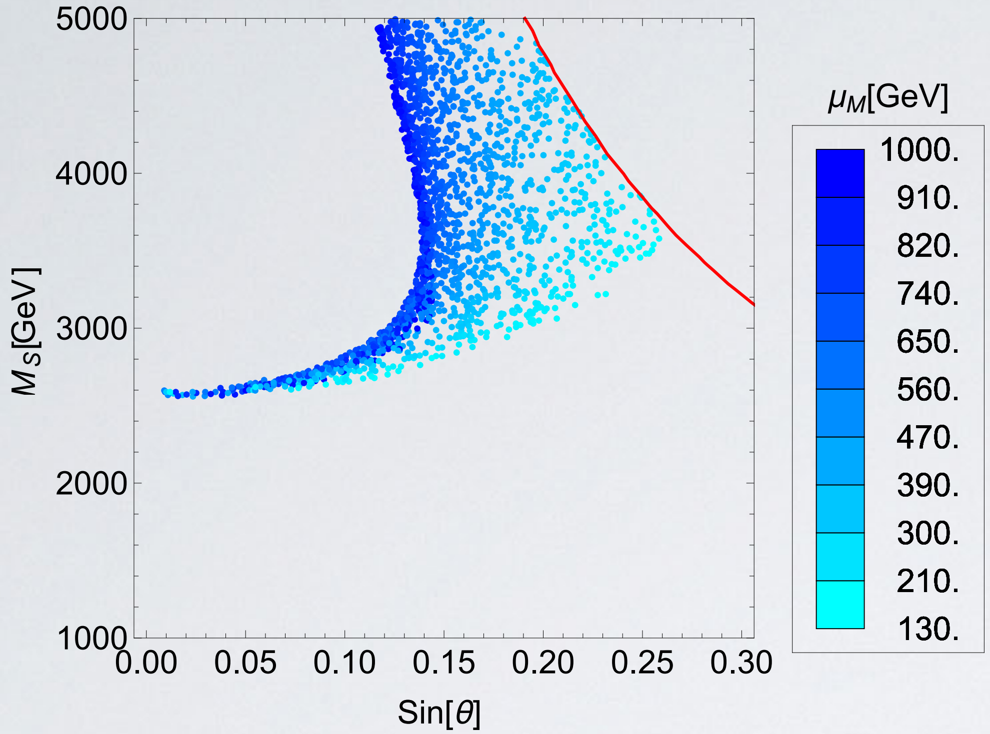
$$\bar{\alpha} = 1.57$$

The minimum mass:
$M_S \approx 2600$





Correlation between
M_S and M_H

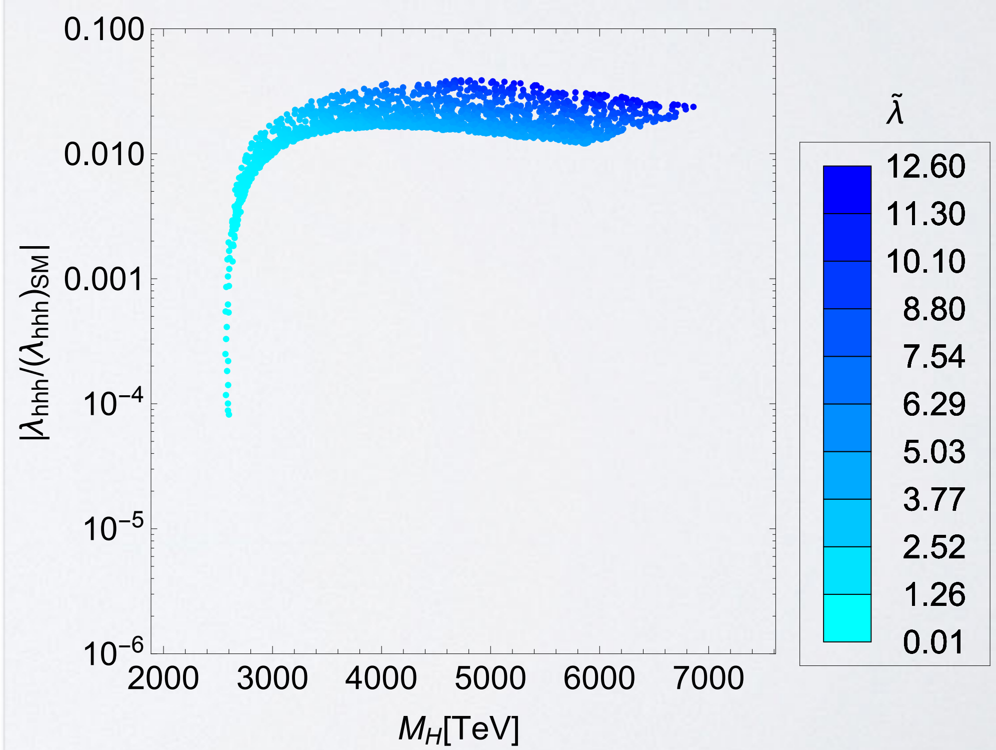


$$(\text{for } M_S \approx 2600, K \approx 90)$$

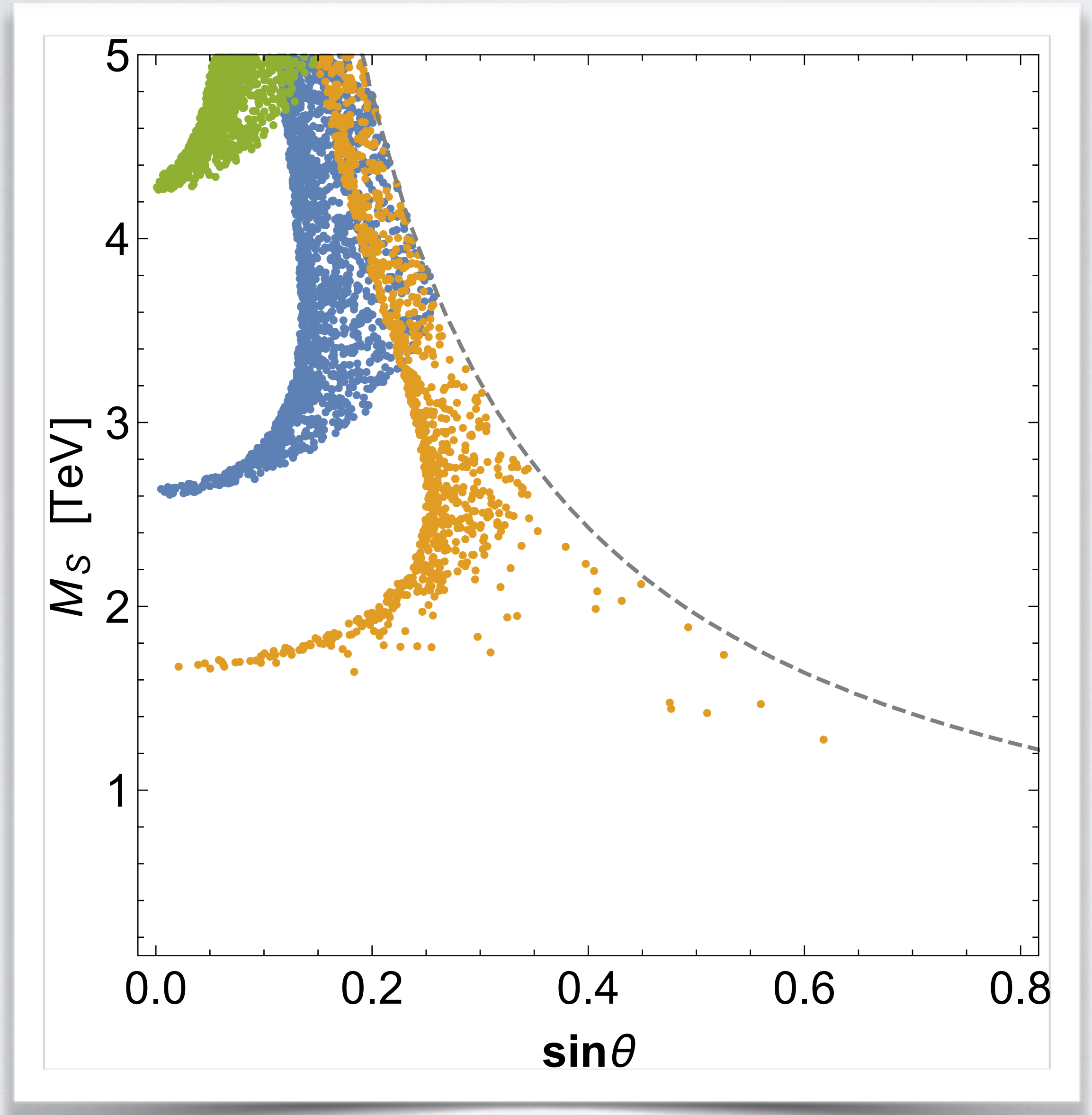
$$\tilde{\lambda} \approx K \sin^2\theta \quad \text{for} \quad \sin\theta \lesssim 0.1$$

$$\frac{\lambda_{hhh}}{\lambda_{hhh}^{SM}} = v_{EW} \frac{M_S^2 \cos\alpha}{v m_h^2}$$

$$(\lambda_{hhh}^{SM} = 3m_h^2/v_{EW})$$



The Dependence of the Higgs Mass



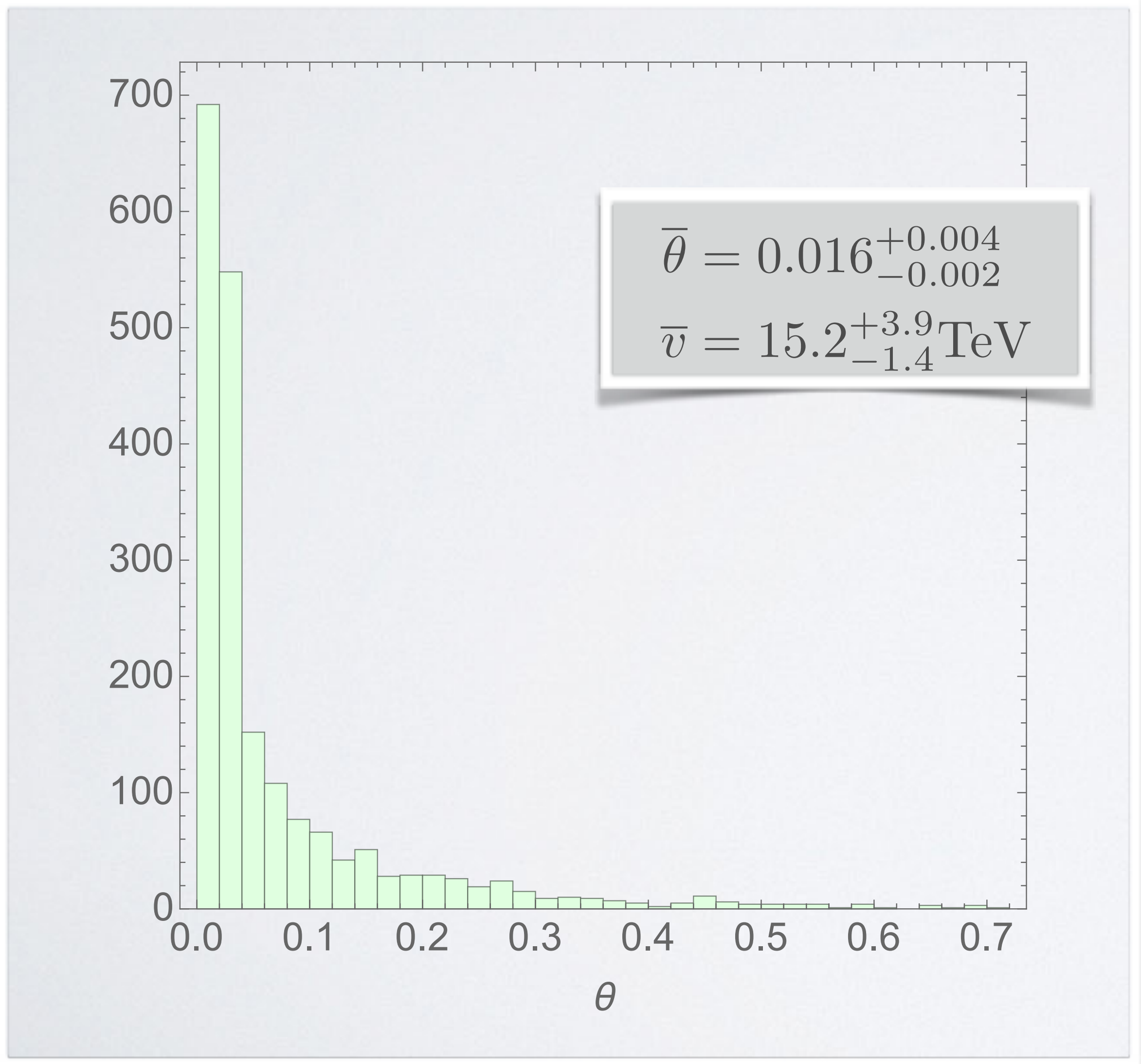
- The observed Higgs mass
- 10 % less than the observed Higgs mass
- 10 % more than the observed Higgs mass

The Mass of the σ Different

The free parameters in this case:

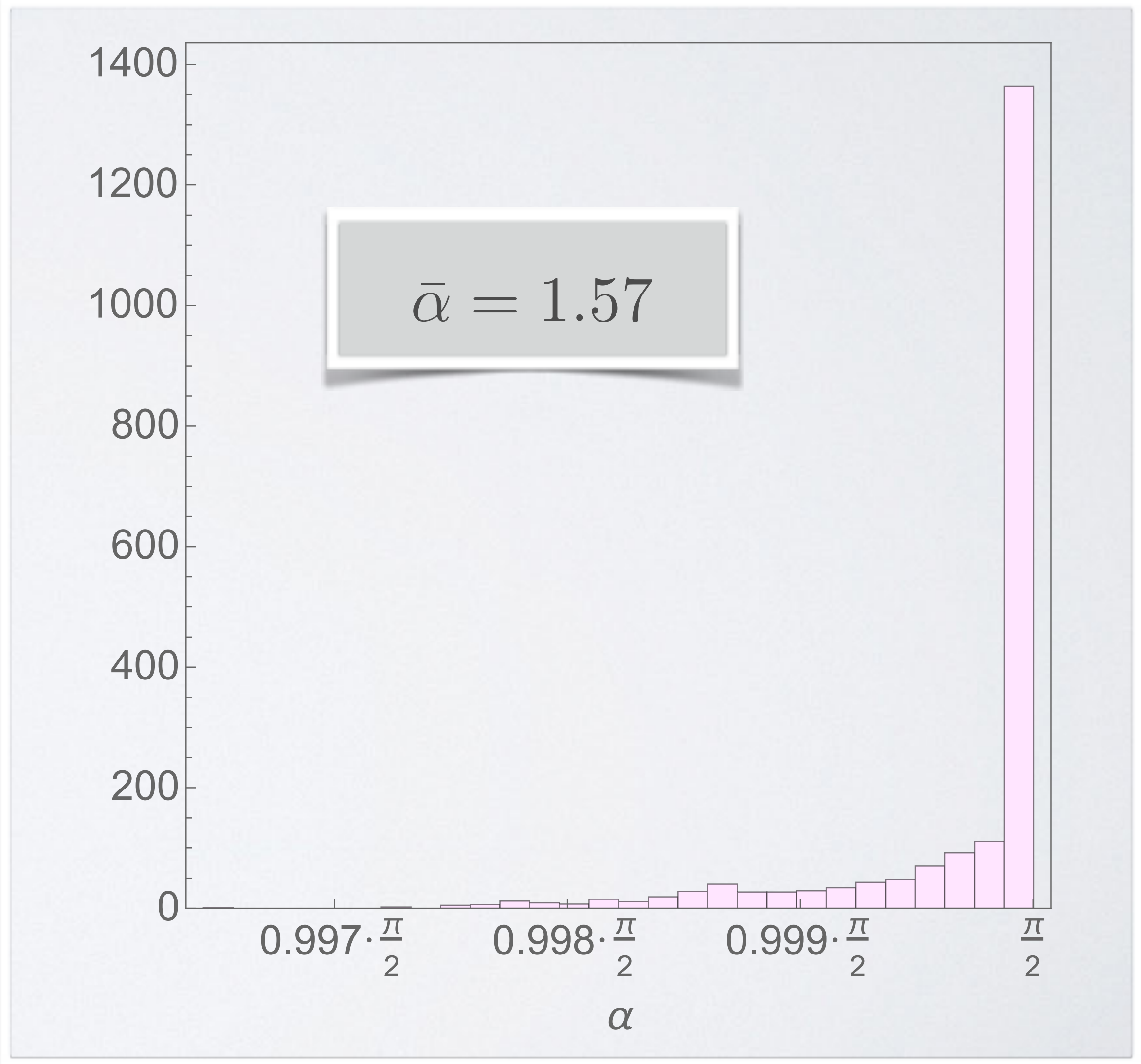
$$v, \quad \theta, \quad \mu_M, \quad \tilde{\lambda}, \quad M_S, \quad M_\sigma$$

$$m_h \leq \mu_M \leq 1 \text{ TeV}$$
$$m_h \leq M_S, M_\sigma \leq 5 \text{ TeV}$$

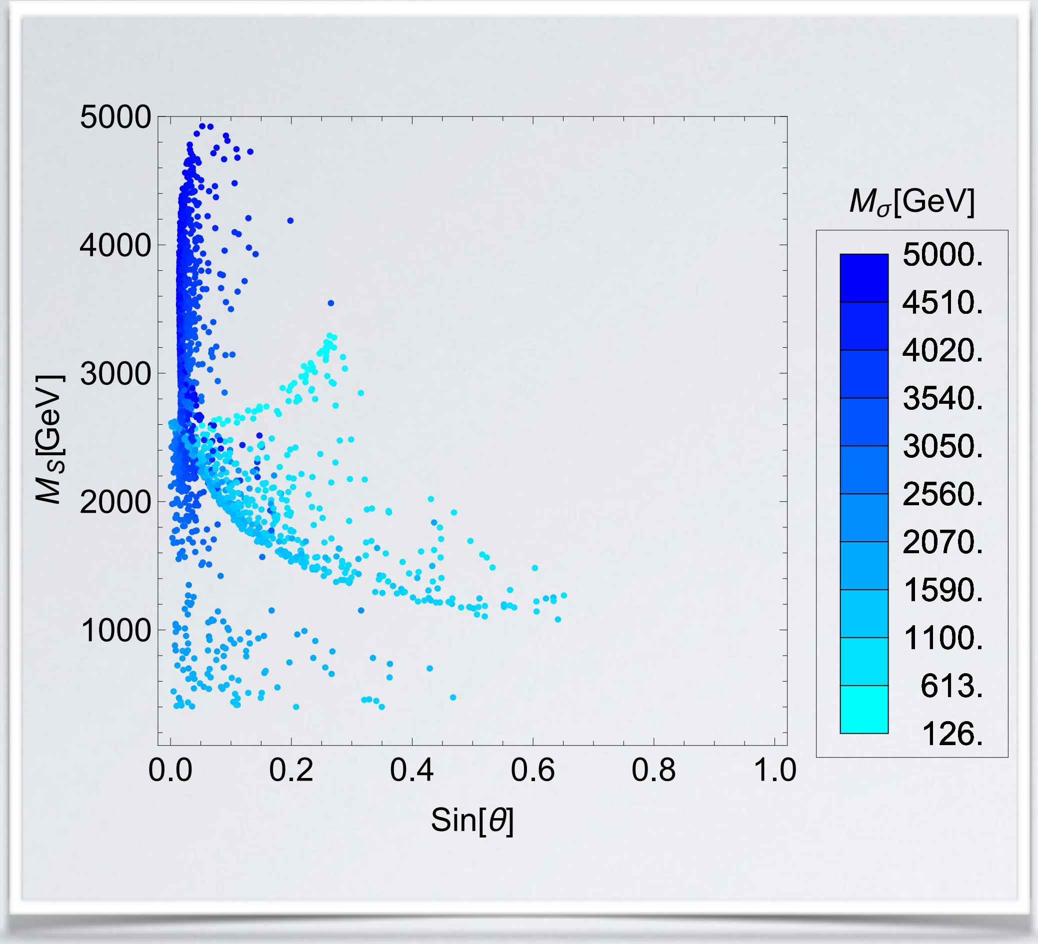


$\bar{\theta} = 0.016^{+0.004}_{-0.002}$

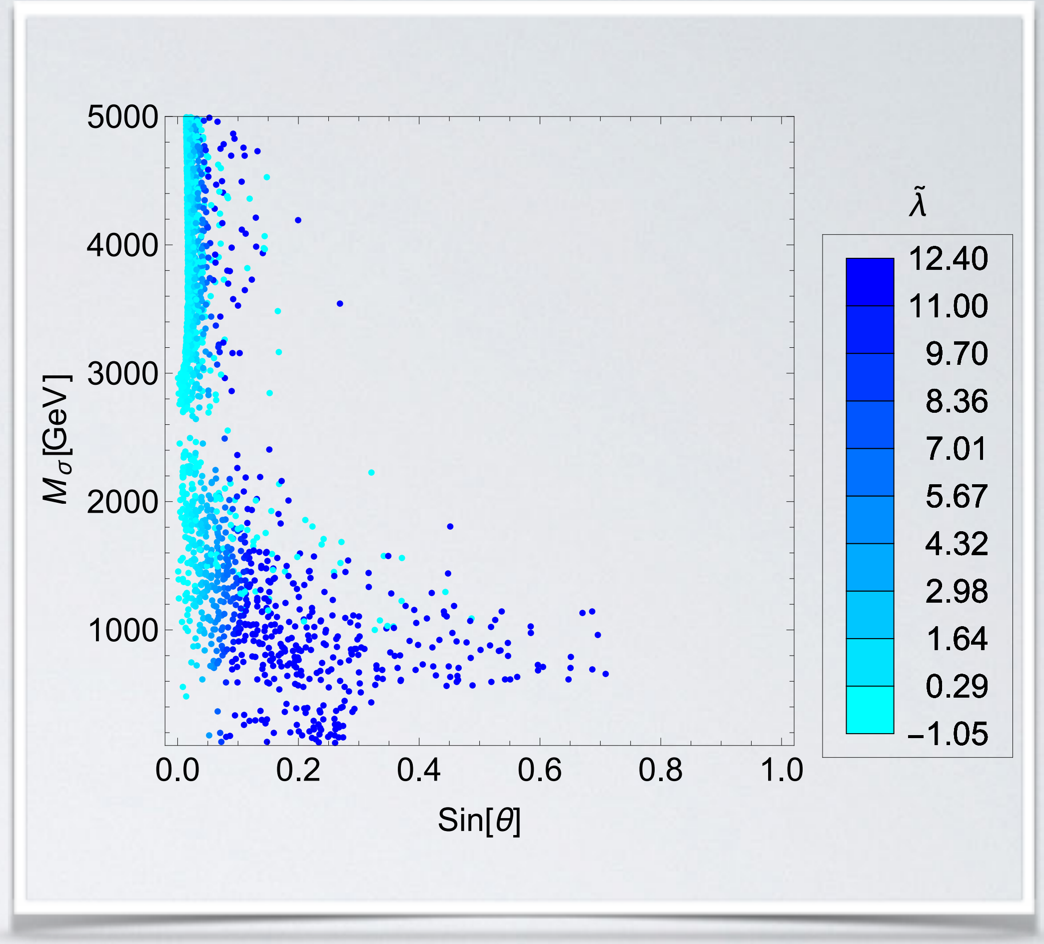
$\bar{v} = 15.2^{+3.9}_{-1.4}\text{TeV}$



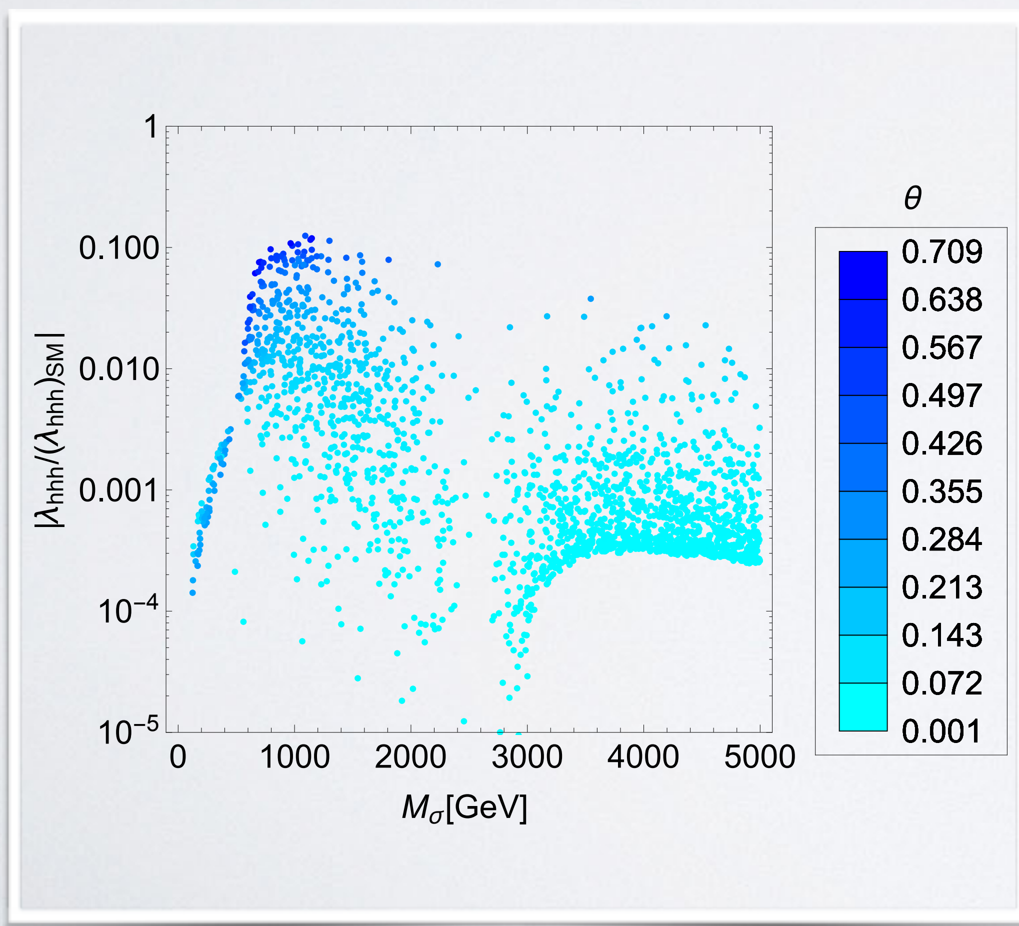
$\bar{\alpha} = 1.57$



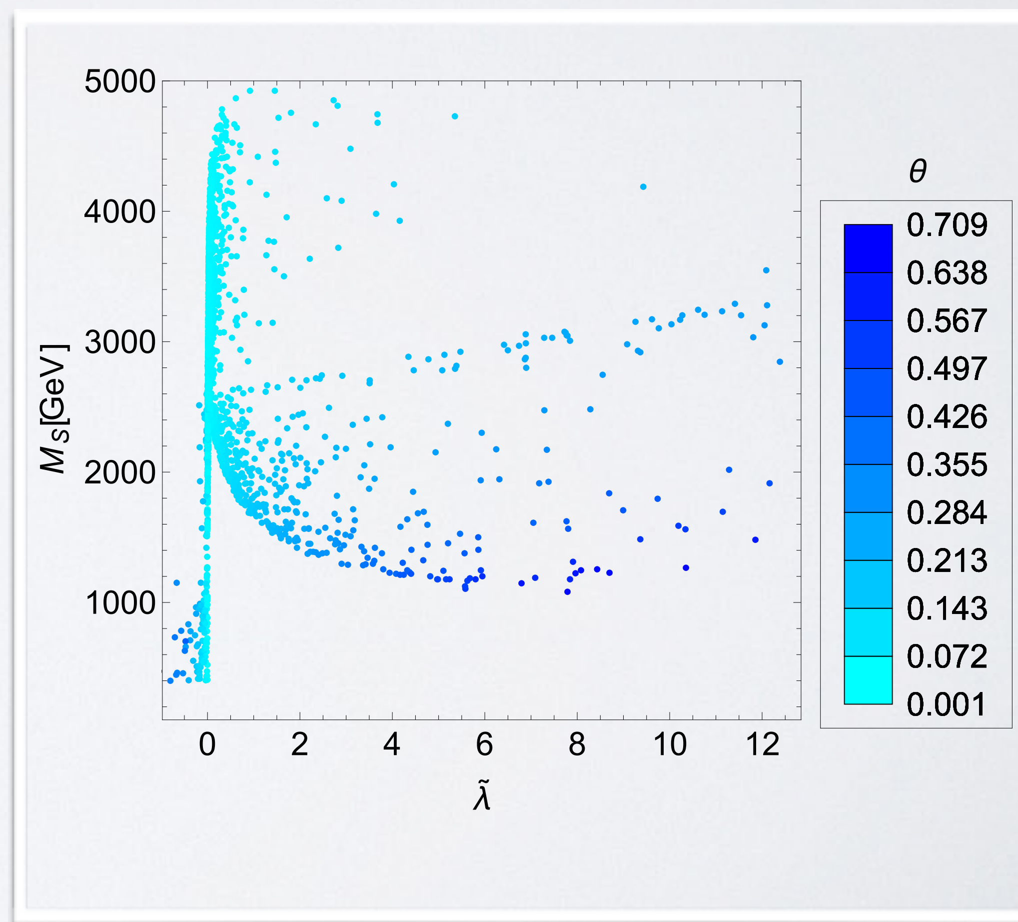
M_S[GeV]
Sin[θ]
M_σ[GeV]
5000. 4510. 4020. 3540. 3050. 2560. 2070. 1590. 1100. 613. 126.



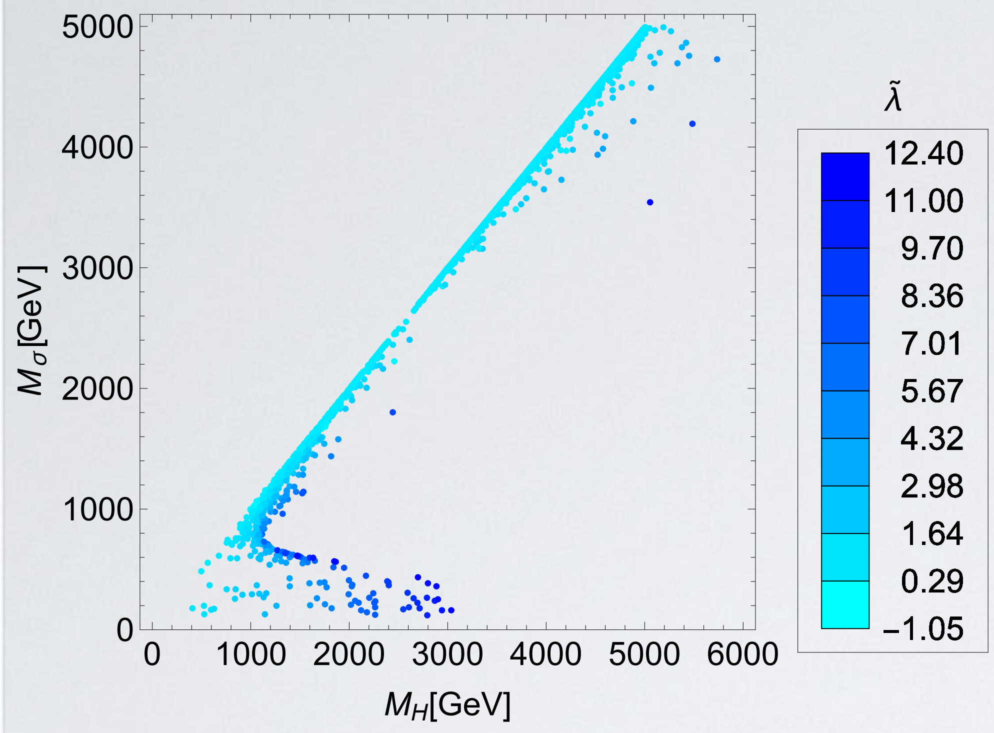
M_σ[GeV]
Sin[θ]
$\tilde{\lambda}$
12.40 11.00 9.70 8.36 7.01 5.67 4.32 2.98 1.64 0.29 −1.05



$|\lambda_{hhh}/(\lambda_{hhh})_{SM}|$
M_σ[GeV]
θ
0.709 0.638 0.567 0.497 0.426 0.355 0.284 0.213 0.143 0.072 0.001

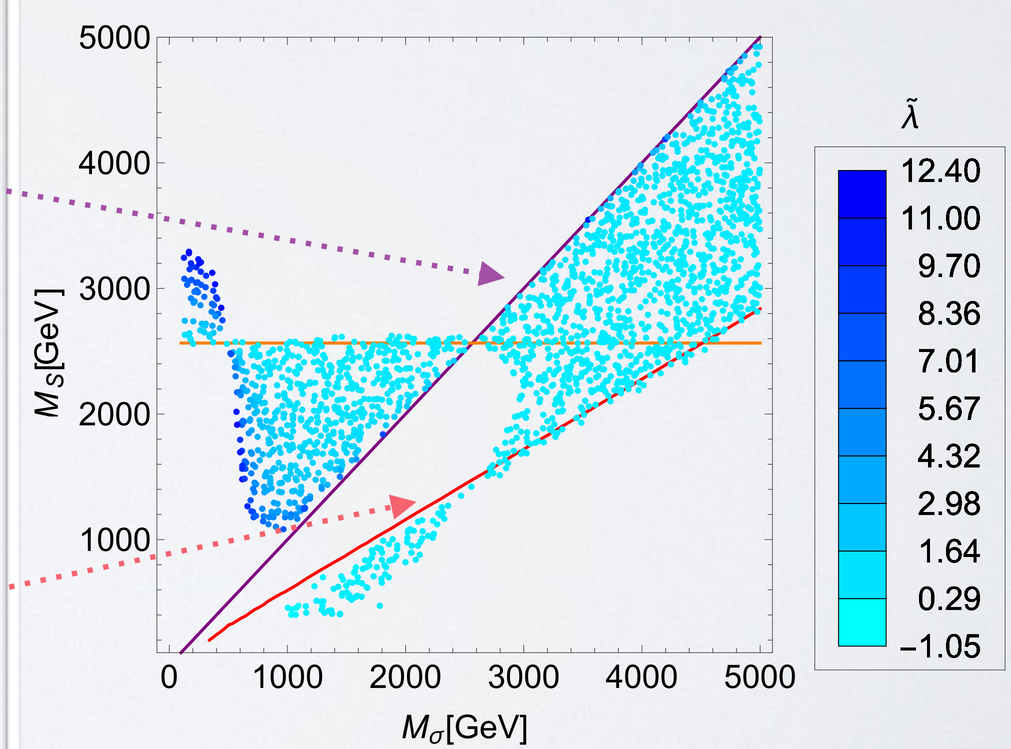


M_S[GeV]
$\tilde{\lambda}$
θ
0.709 0.638 0.567 0.497 0.426 0.355 0.284 0.213 0.143 0.072 0.001



Linear dependence between M_σ and M_H

$$M_\sigma = M_S$$



$$\lambda \approx 0 \qquad M_S^4 \approx \frac{M_\sigma^4\left(\log\left[\frac{m_t^2}{M_\sigma^2}\right]-1\right)}{6\left(\log\left[\frac{m_t^2}{M_\sigma^2}\right]-1\right)}$$

Conclusion

- The elementary Higgs sector of the SM is enhanced to an SU(4) symmetry which breaks spontaneously to Sp(4)
- The embedding of the electroweak gauge sector is parametrised by an angle
- The observed Higgs emerges as a pNGB with its mass arising via radiative corrections.
- The preferred EW vacuum alignment point to an energy scale almost 60 times higher than the SM electroweak scale. Due to the perturbative nature of the theory the new scalars remain in the few TeV energy range.