CP3 Origins
Cosmology & Particle Physics

University of Southern Denmark

The Elementary Goldstone Higgs

Works in collaboration with
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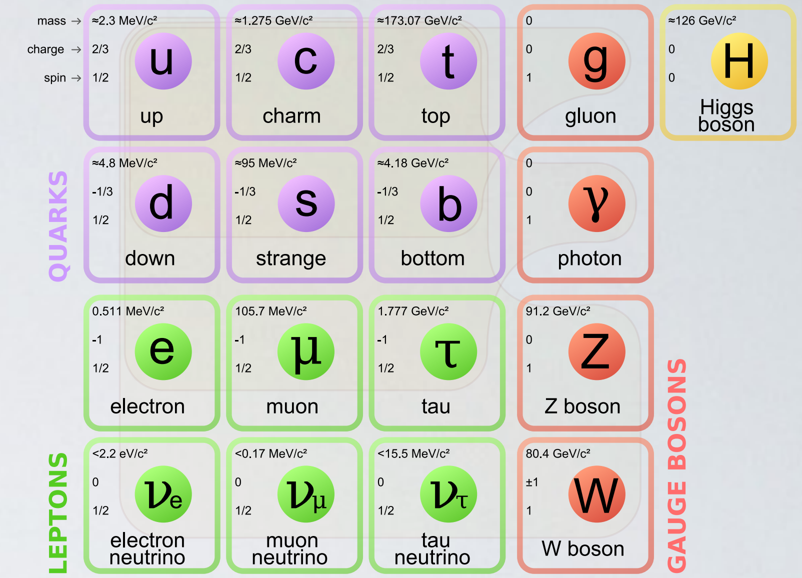
Rencontres de Moriond 50 since 1966

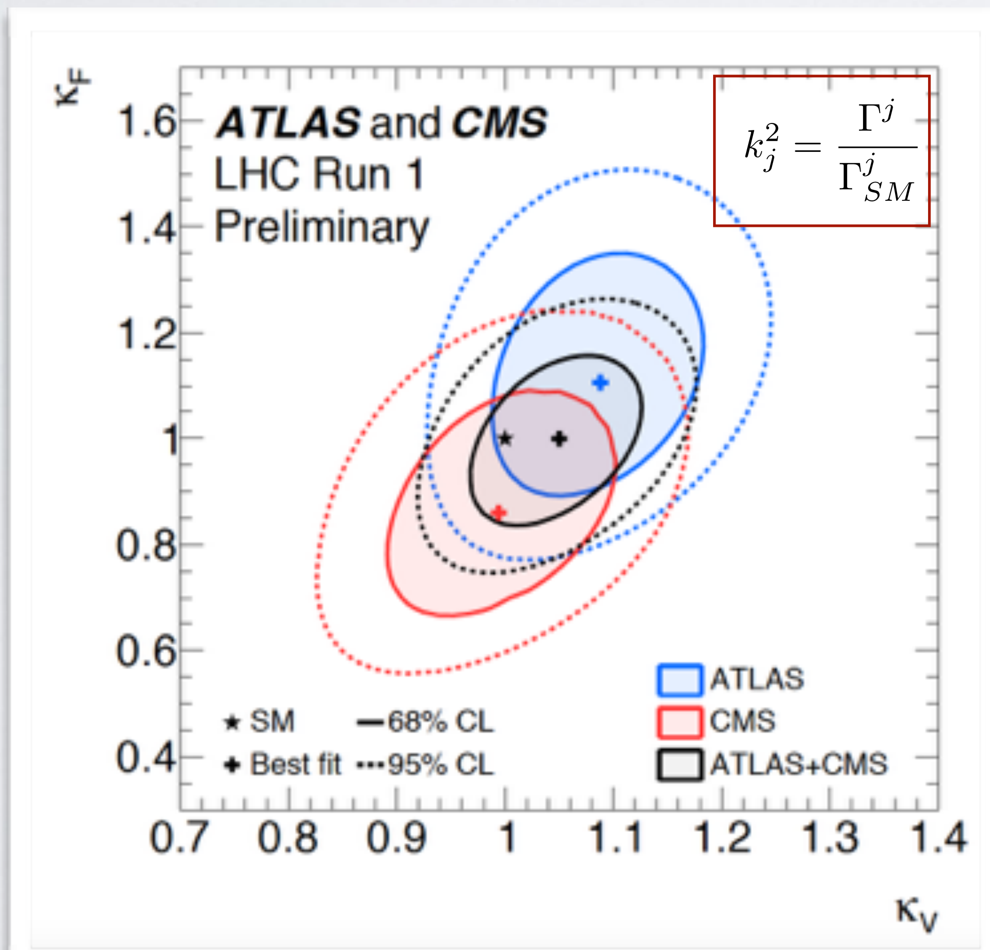
Aurora Meroni

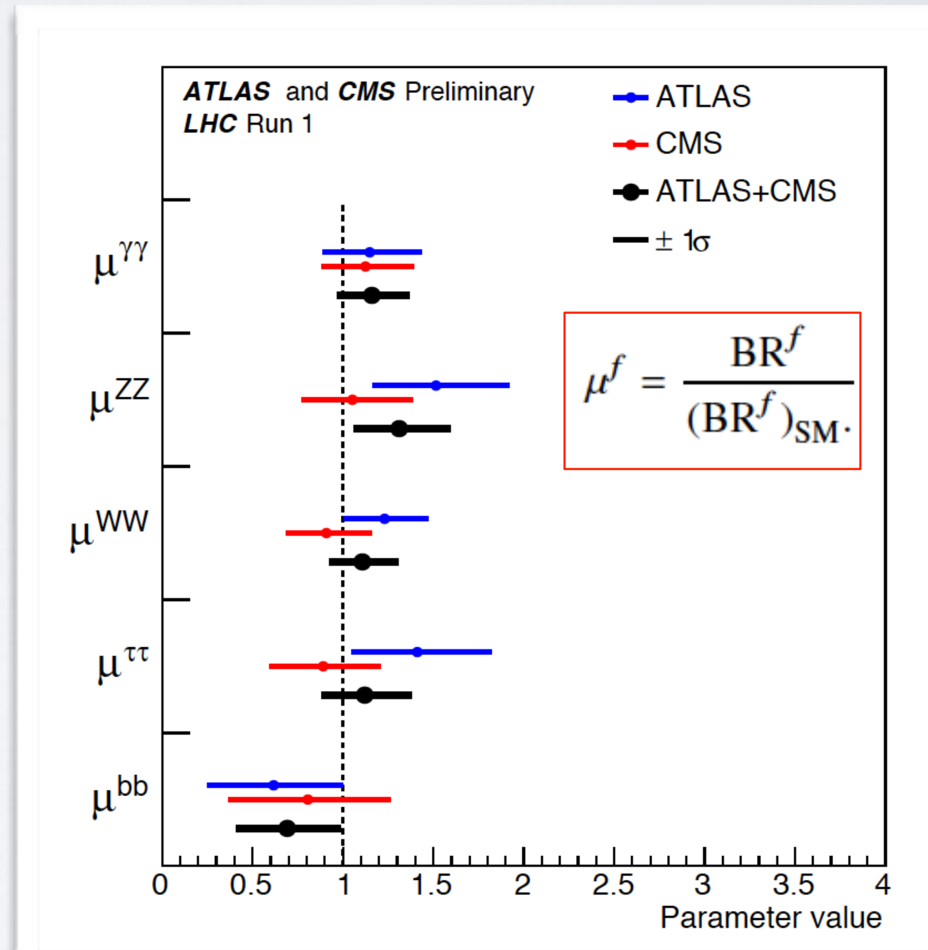
51st Recontres des Moriond EW
La Thuile 2016

The Standard Model



- Unification of strong and electroweak interactions SU(3) x SU(2) x U(1)
- Higgs sector exhibits even larger chiral symmetry SU(2) xSU(2)~SO(4)
- interactions: gauge, Yukawas and self-interactions
- precision obtained is at the level of 10% in the best channels (WW and ZZ)



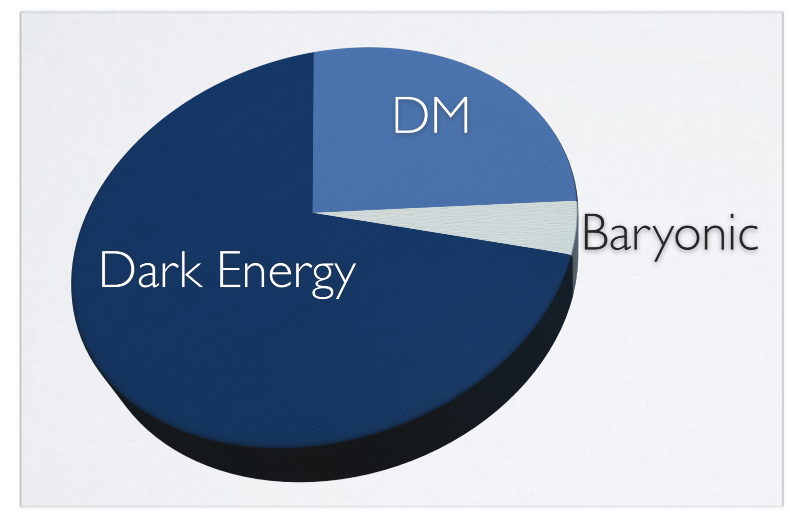


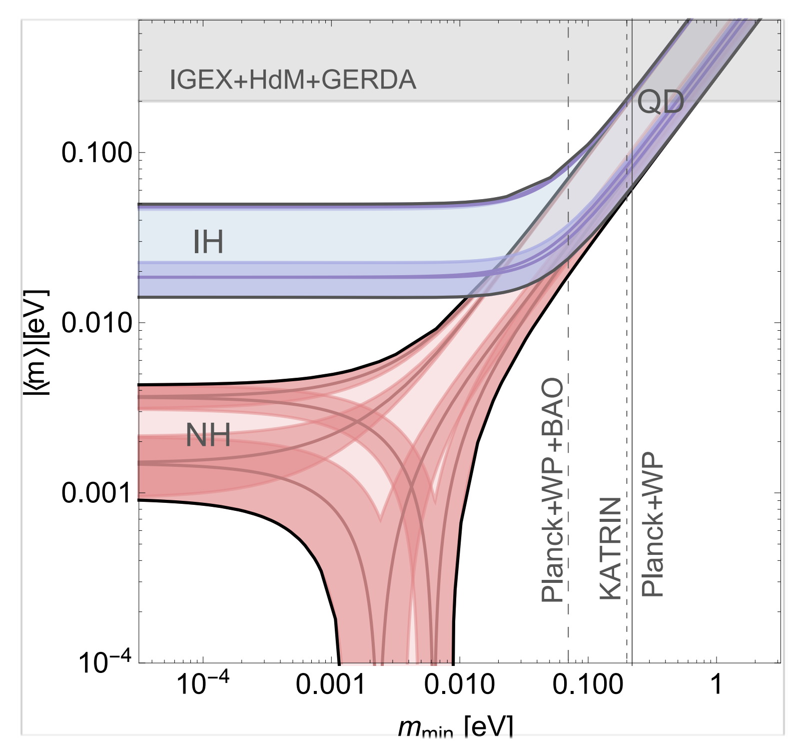
presented at LHCP-2015, 15th September 2015 [ATALS-CONF-2015-044; CMS-PAS-HIG-15-002]

Open problems & unknowns (pheno)

- Explanation of ***matter-antimatter*** asymmetry
- ***Elusive sector***: neutrinos and DM (BSM physics!)
  - absolute value of neutrino masses, Hierarchy (normal or inverted) , CP-phases: δ, and Majorana phases
  - Connection between non zero neutrino masses and ***symmetries*** for the lepton mixing
  - ***Nature*** of massive neutrinos ($2\beta 0\nu$): Dirac or Majorana

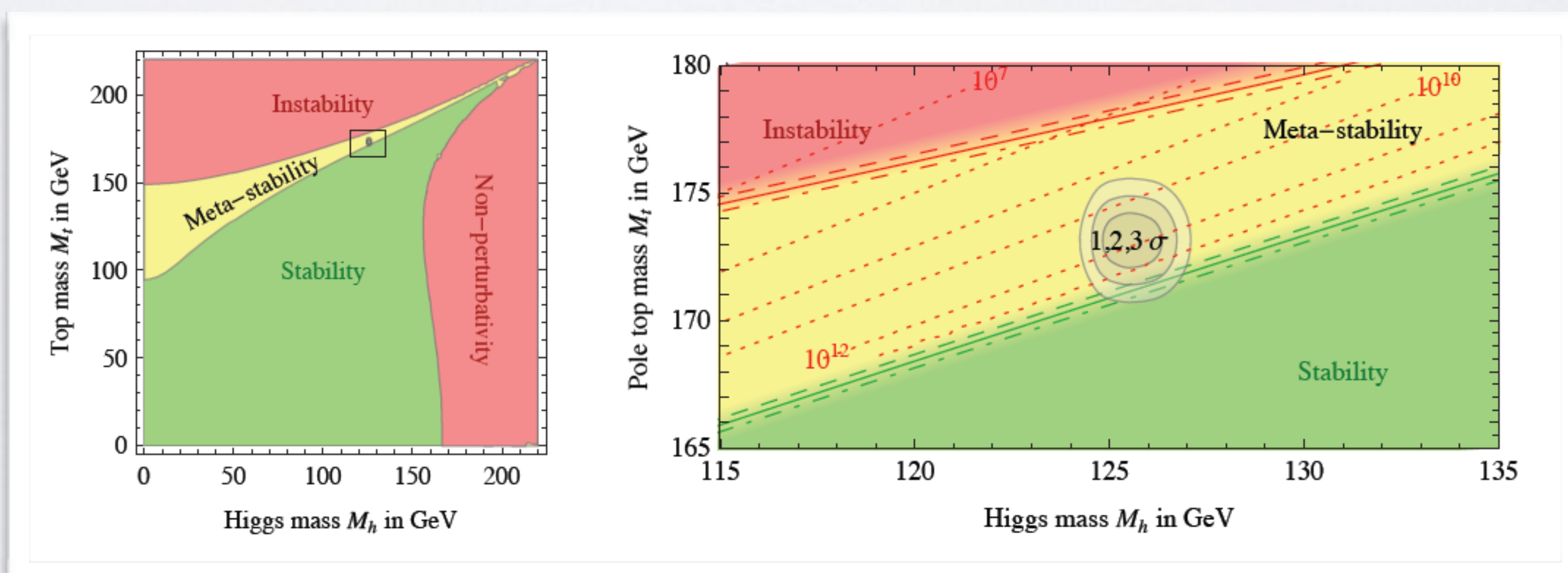
$$|<m>| = \left|\sum_{j}^{light} (U_{ej}^{PMNS})^2 m_j\right|$$





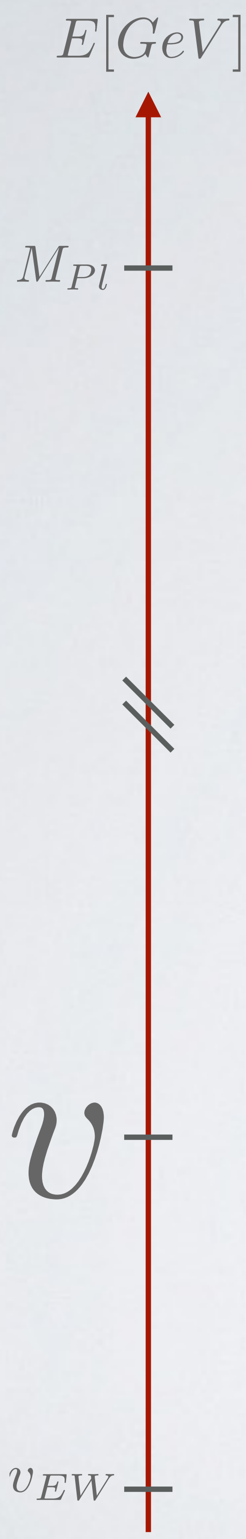
Open problems (theory)

- ***Hierarchy problem***: Why is the SU(2)× U(1) breaking scale so much smaller than the unification scale? (Absence of mechanisms establishing the EW scale against quantum corrections)
- Lack of dynamical motivation for the ***origin of SSB***
- ***Flavour puzzle***: Why does Nature repeat Herself?
- The absence of absolute ***vacuum stability***



G. Degrassi et al., 1205.6497

Elementary Goldstone Higgs



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

- We extend the Higgs sector symmetry
- The physical Higgs emerges as pNGB.
- We explore a different paradigm, that is the one that 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 present realization is, by construction, UV complete and under perturbative control.

The EGH model

$$SO(6) \sim SU(4) \ \rightarrow \ Sp(4) \sim SO(5)$$

interesting possibility both for (ultra) minimal Technicolor models and the composite GB Higgs scenarios, and for constructing UV completions of Little Higgs models

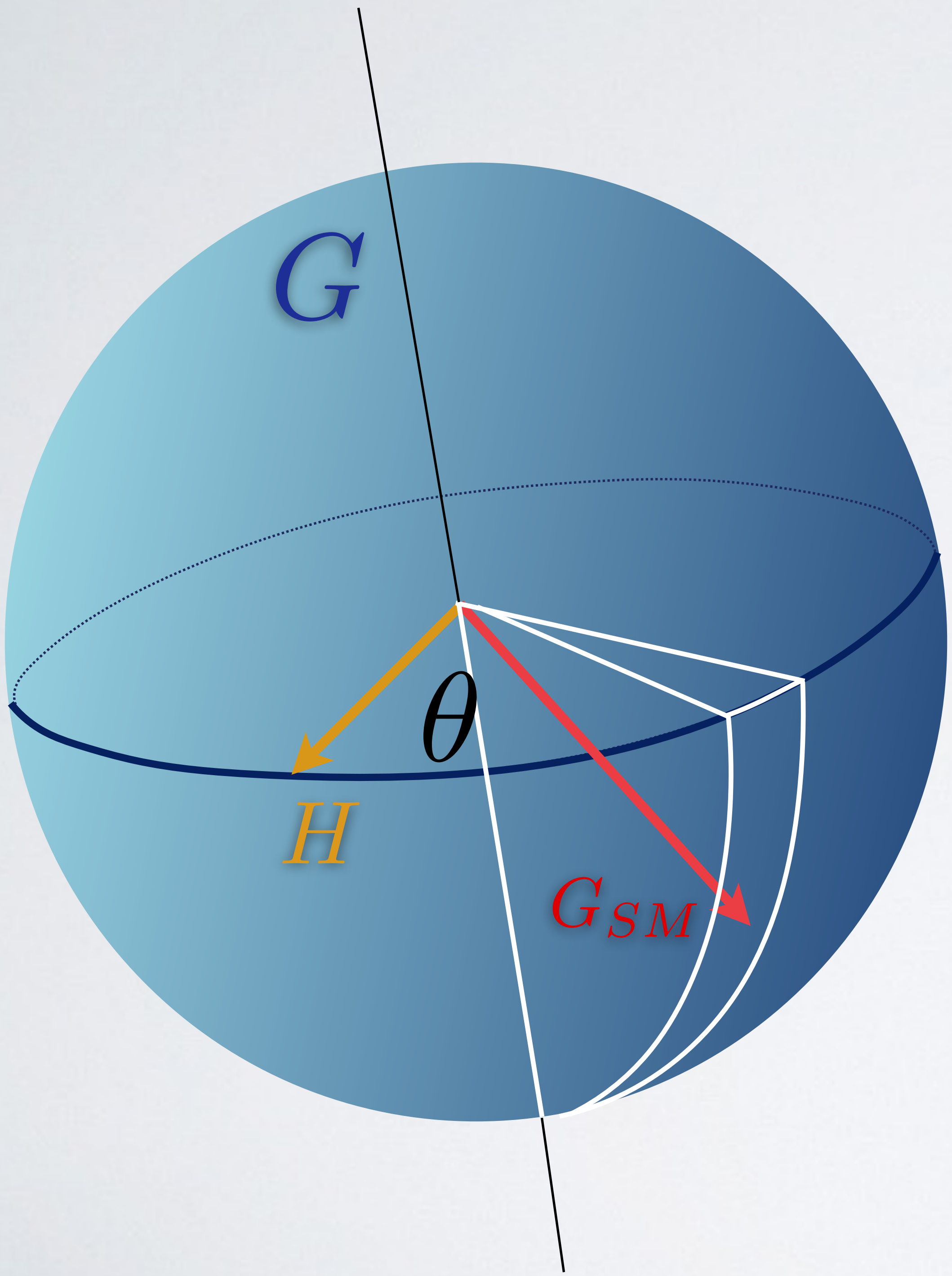
T. Appelquist, P. S. Rodrigues da Silva and F. Sannino, [hep-ph/9906555]
Z. -y. Duan, P. S. Rodrigues da Silva and F. Sannino, [hep-ph/0001303]
T.A. Ryttov and F. Sannino, [arXiv:0809.0713 [hep-ph]]
E. Katz, A. E. Nelson and D. G. E. Walker, [hep-ph/0504252]
B. Gripaios, A. Pomarol, F. Riva and J. Serra [arXiv:0902.1483 [hep-ph]]
J. Galloway, J.A. Evans, M.A. Luty and R.A. Tacchi [arXiv:1001.1361 [hep-ph]]
J. Barnard, T. Gherghetta and T. S. Ray, arXiv:1311.6562 [hep-ph]
G. Ferretti and D. Karateev, arXiv:1312.5330 [hep-ph]
P. Batra and Z. Chacko [arXiv:0710.0333 [hep-ph]]

T_a 10 generators of Sp(4)

X_a 5 broken generators of SU(4)

How do I break it?

Alignment of the vacuum



- We study **G = SU(4)** and **H = Sp(4)**
- The Higgs arises as one of the 5 Goldstone bosons belonging to the coset $SU(4)/Sp(4)$.

θ = 0

- EW gauge group does not break
- Higgs is a Goldstone boson

θ = π/2

- EW breaks completely
- Higgs is a massive excitation

Description valid also for TC

Peskin Nucl. Physics B175 (1980) 197

Preskill Nucl. Physics B 177 (1981) 21-59

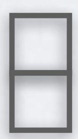
The EGH model

$$SO(6) \sim SU(4) \;\rightarrow\; Sp(4) \sim SO(5)$$

6-dim irrep (pseudo-real) of SU(4) : $M^{[i,j]}$

5 Goldstone Bosons

broken generators



$$M = \left[\frac{1}{2}\left(\sigma + i\,\Theta\right) + \sqrt{2}\left(\Pi_i + i\,\tilde{\Pi}_i\right) X^i_\theta\right] E_\theta$$

vacuum alignment

Π_1, Π_2, Π_3 Longitudinal polarizations of the W and Z bosons

Π_4 EGH (at tree-level)

the radiative corrections generate a mass term for the Higgs boson, which arises as a linear combination of the σ and Π_4 fields around the vacuum.

Π_5 DM candidate

Vacuum Alignment

Both for fundamental & composite
Appelquist, Sannino, 98, 99
Ryttov, Sannino, 2008
Katz, Nelson Walker, 2005
Gripaios, Pomarol, Riva, Serra, 2009
Galloway, Evans, Luty, Tacchi, 2010
Sannino, Cacciapaglia, 2014

$$\langle M \rangle = \frac{v}{2} E_\theta$$

The vacuum used is a superposition of two vacua

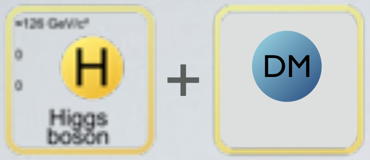
$$E_\theta = \cos\theta \, E_B + \sin\theta \, E_H = -E_\theta^T$$

Electroweak vacuum

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

Technicolor vacuum

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



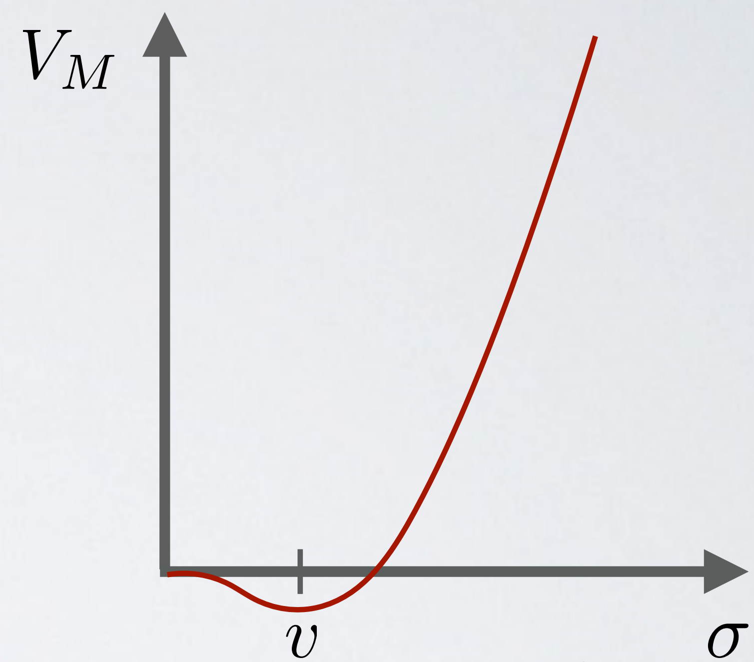
SCALARS + DARK MATTER

Tree-Level Scalar potential

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

$$V_{DM} = \frac{\mu_M^2}{8} Tr\left[E_A M\right] Tr\left[E_A M\right]^* = \frac{1}{2}\mu_M^2 \left(\Pi_5^2 + \tilde{\Pi}_5^2\right) ,$$

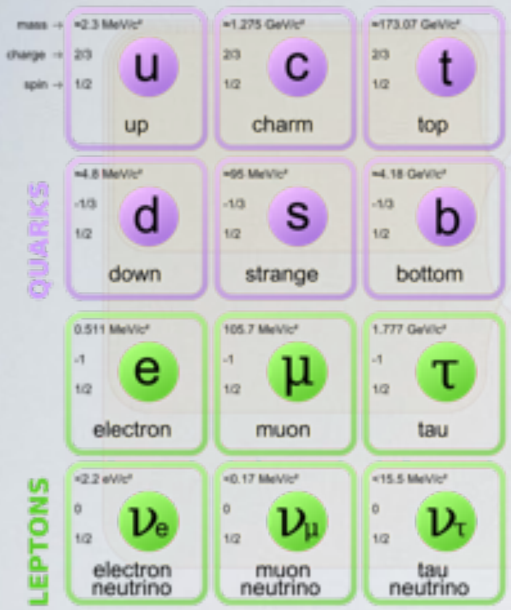
$$\text{with} \quad E_A = \begin{pmatrix} i\,\sigma_2 & 0 \\ 0 & i\,\sigma_2 \end{pmatrix}$$



$$\langle \sigma^2 \rangle \equiv v^2 = \frac{c_M - m_M^2}{4\,\lambda_{11}}$$

$$V = V_M + V_{DM}$$

$$m_\sigma^2 \equiv M_\sigma^2 \,, \quad m_\Theta^2 \equiv M_\Theta^2 \,, \quad m_{\tilde{\Pi}_i}^2 \equiv M_\Theta^2 + 2\lambda_f v^2 \quad m_{\tilde{\Pi}_5}^2 \equiv M_\Theta^2 + 2\lambda_f v^2 + \mu_M^2$$



Yukawa Interactions

Operators that explicitly break the *SU*(4) global symmetry

$$\mathcal{L}_q^{\mathrm{Y}} + \mathcal{L}_\ell^{\mathrm{Y}} + \mathcal{L}_\nu^{\mathrm{Y+Majorana}}$$

- $\mathbf{L}_\alpha = \left(L, \quad \tilde{\nu}, \quad \tilde{\ell}\right)^T_{\alpha L} \sim \mathbf{4}, \qquad \mathbf{Q}_i = \left(Q, \quad \tilde{q}^u, \quad \tilde{q}^d\right)^T_{i\,L} \sim \mathbf{4}$

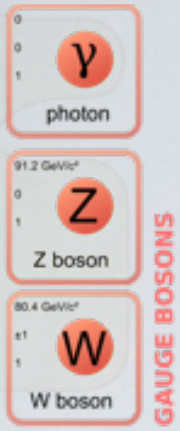
$$m_F = y_F \frac{v \sin\theta}{\sqrt{2}}$$

$$\begin{aligned} -\mathcal{L}^{\mathrm{Y}}_{q,\ell,\nu} &= \frac{Y^u_{ij}}{\sqrt{2}} \left(\mathbf{Q}_i^T P_a \mathbf{Q}_j\right)^\dagger Tr\left[P_a M\right] + \frac{Y^d_{ij}}{\sqrt{2}} \left(\mathbf{Q}_i^T \overline{P}_a \mathbf{Q}_j\right)^\dagger Tr\left[\overline{P}_a M\right] \\ &+ \frac{Y^\nu_{\alpha\beta}}{\sqrt{2}} \left(\mathbf{L}_\alpha^T P_a \mathbf{L}_\beta\right)^\dagger Tr\left[P_a M\right] + \frac{Y^\ell_{\alpha\beta}}{\sqrt{2}} \left(\mathbf{L}_\alpha^T \overline{P}_a \mathbf{L}_\beta\right)^\dagger Tr\left[\overline{P}_a M\right] \\ &+ \frac{1}{2} \left(M_R\right)_{jk} \overline{\nu}_{jR} \left(\nu_{kR}\right)^c + \mathrm{h.c.} \end{aligned}$$

$$P_1 = \frac{1}{\sqrt{2}} \begin{pmatrix} \mathbf{0_2} & \tau_3 \\ -\tau_3 & \mathbf{0_2} \end{pmatrix}, \quad P_2 = \frac{1}{\sqrt{2}} \begin{pmatrix} \mathbf{0_2} & \tau^- \\ -\tau^+ & \mathbf{0_2} \end{pmatrix},$$

$$\overline{P}_1 = \frac{1}{\sqrt{2}} \begin{pmatrix} \mathbf{0_2} & \tau^+ \\ -\tau^- & \mathbf{0_2} \end{pmatrix}, \quad \overline{P}_2 = \frac{1}{\sqrt{2}} \begin{pmatrix} \mathbf{0_2} & \overline{\tau}_3 \\ -\overline{\tau}_3 & \mathbf{0_2} \end{pmatrix}$$

Neutrinos as easily incorporated!



Electroweak Gauge Bosons

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

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

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

Quantum Corrections

The Renormalized Coleman-Weinberg potential at 1-loop:

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

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

$$\delta V(\sigma,\Pi_4) \;=\; \delta V_{\rm EW}(\sigma,\Pi_4) \;+\; \delta V_{\rm top}(\sigma,\Pi_4) \;+\; \delta V_{\rm sc}(\sigma,\Pi_4)$$

$$\delta V_{\rm EW}(\sigma,\Pi_4) \;=\; \frac{3}{1024\pi^2}\,\phi^4\left[2g^4\left(\log\frac{g^2\,\phi^2}{4\mu_0^2}-\frac{5}{6}\right)+(g^2+g'^2)^2\left(\log\frac{(g^2+g'^2)\,\phi^2}{4\mu_0^2}-\frac{5}{6}\right)\right], \tag{1}$$

$$\delta V_{\rm top}(\sigma,\Pi_4) \;=\; -\,\frac{3}{64\pi^2}\,\phi^4 y_t^4\left(\log\frac{y_t^2\,\phi^2}{2\mu_0^2}-\frac{3}{2}\right) \tag{2}$$

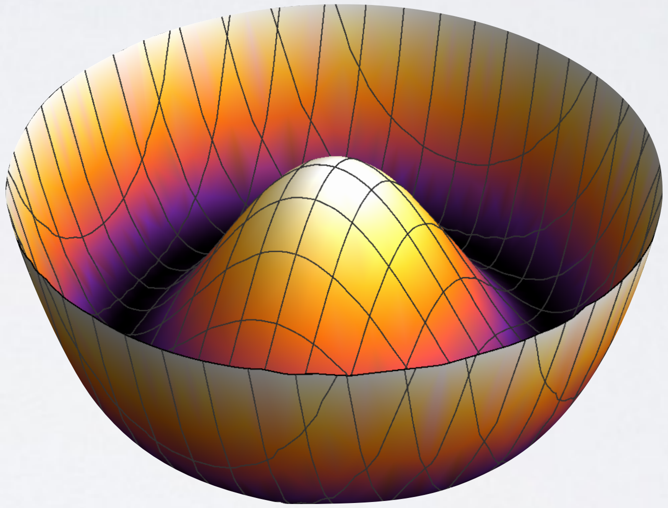
Parameters, Constraints and Minimization

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

Higgs boson mass

$$m_h = 125.7 \pm 0.4 \text{ GeV}$$

$$\begin{pmatrix} \sigma \\ \Pi_4 \end{pmatrix} = \begin{pmatrix} \cos\alpha & -\sin\alpha \\ \sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} H_1 \\ H_2 \end{pmatrix}$$



electroweak bosons masses

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

Higgs couplings with fermions and vector bosons

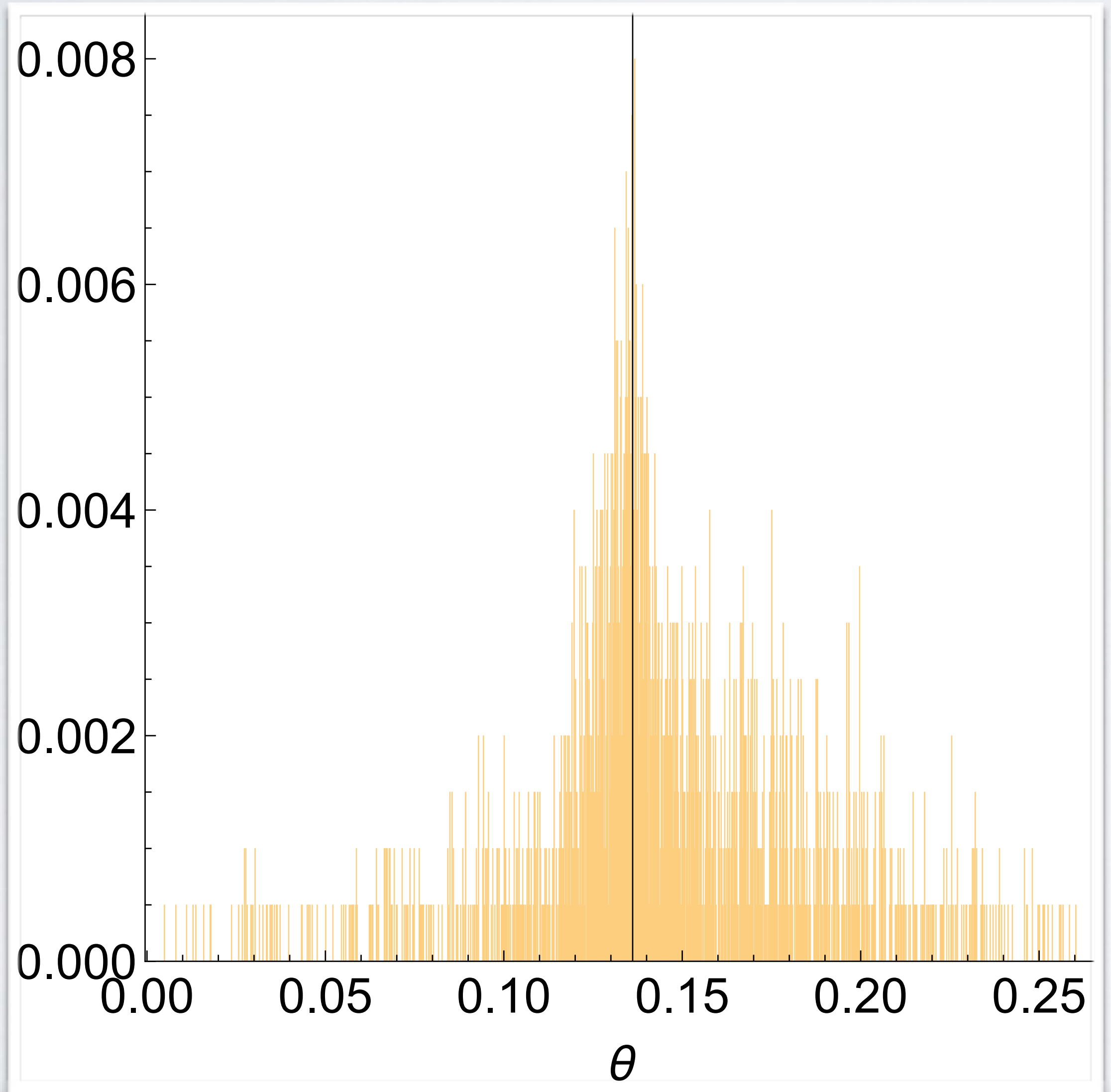
$$c_V = 1.01^{+0.07}_{-0.07} \qquad c_f = 0.89^{+0.14}_{-0.13}$$

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

Small θ via radiative corrections

in the minimal scenario

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



Assuming perturbativity of $\tilde{\lambda}$

$$\bar{\theta} = 0.136^{+0.006}_{-0.012}\,,$$

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

In composite scenarios θ is not small (it can be smaller due to the addition of ad-hoc operators)

What fixes θ ?

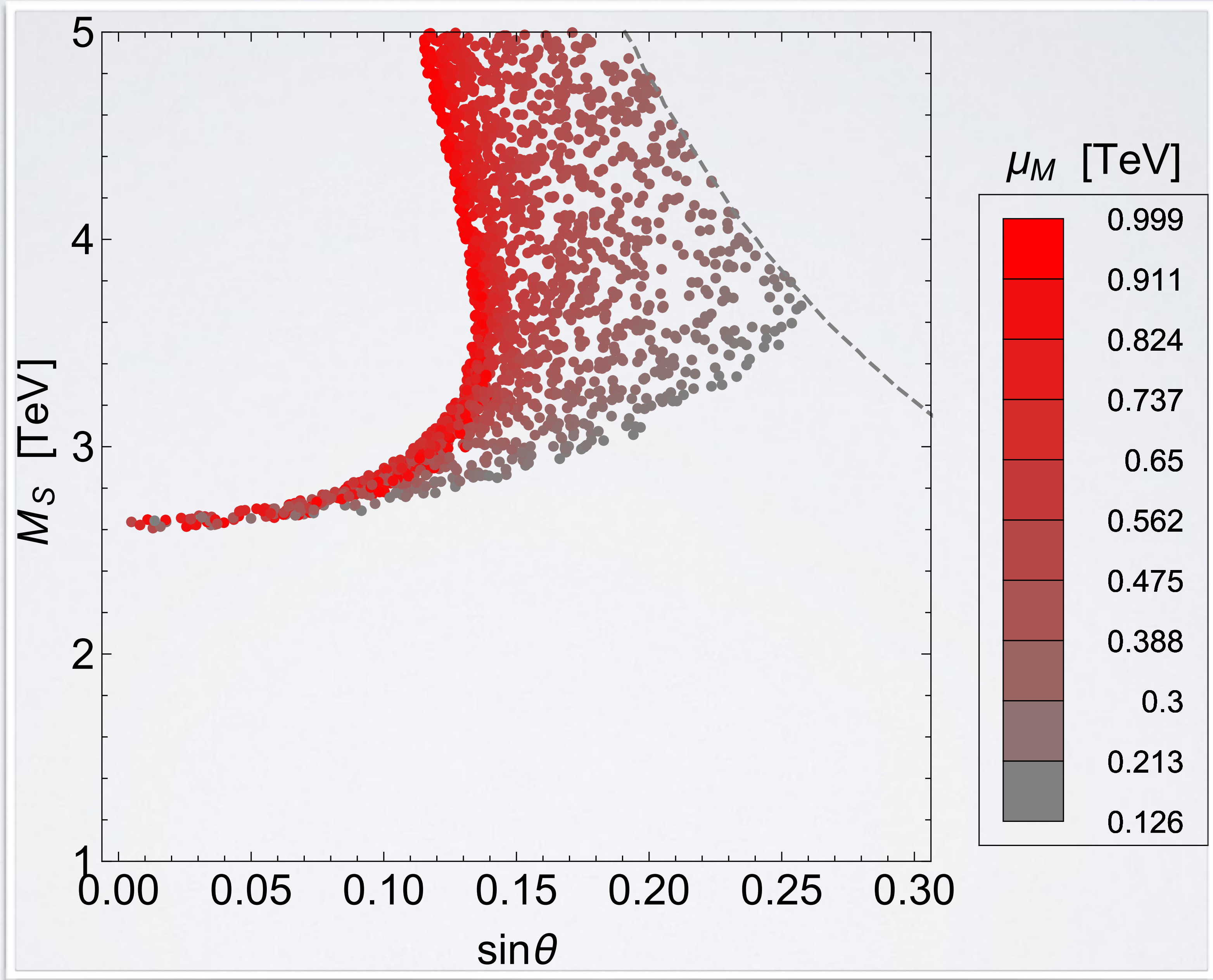
- Gauge and top corrections
- Explicit breaking of global symmetry

- CW analysis to determine vacuum expectation value
- Couplings close to SM values

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

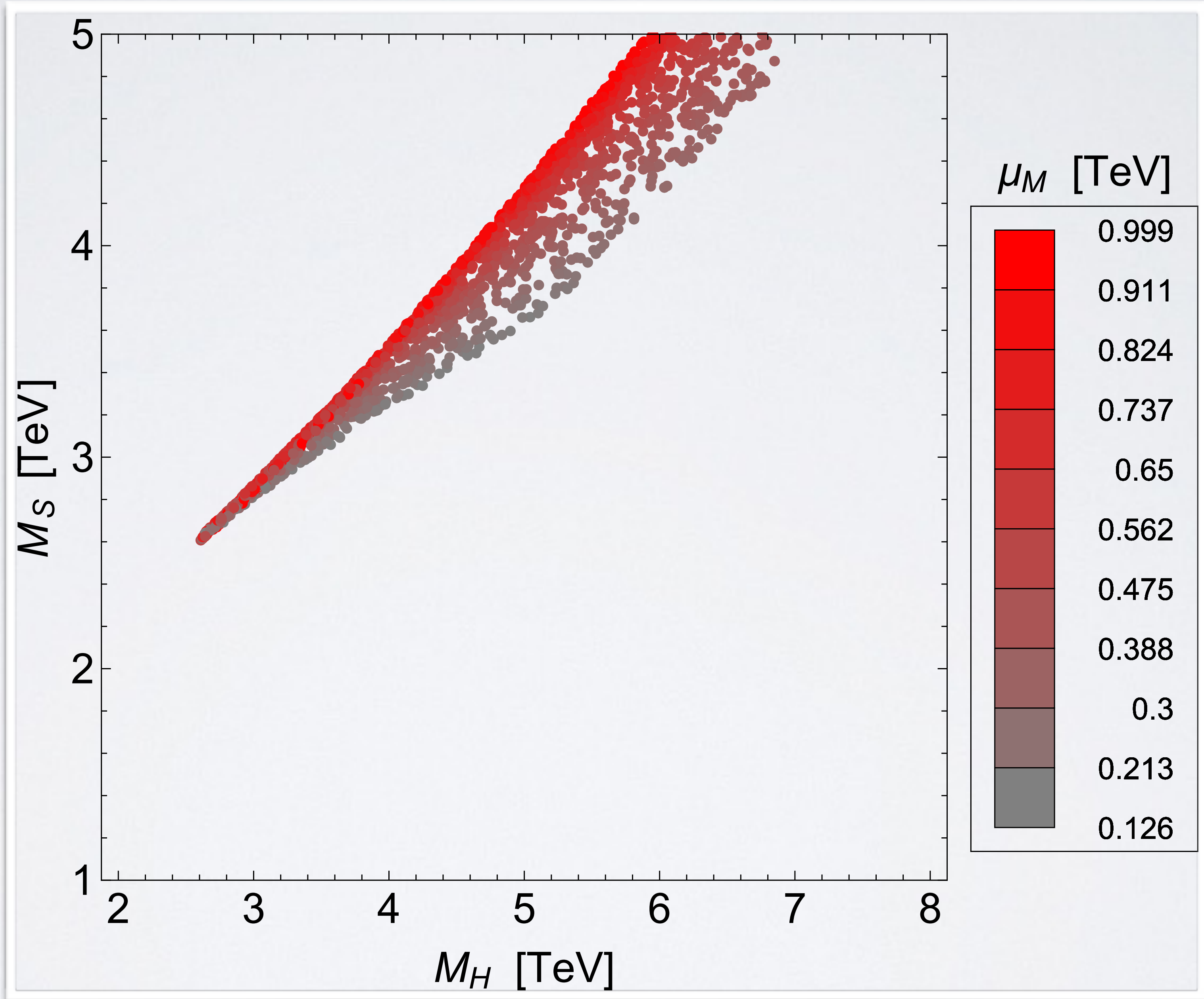
The minimal scenario

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

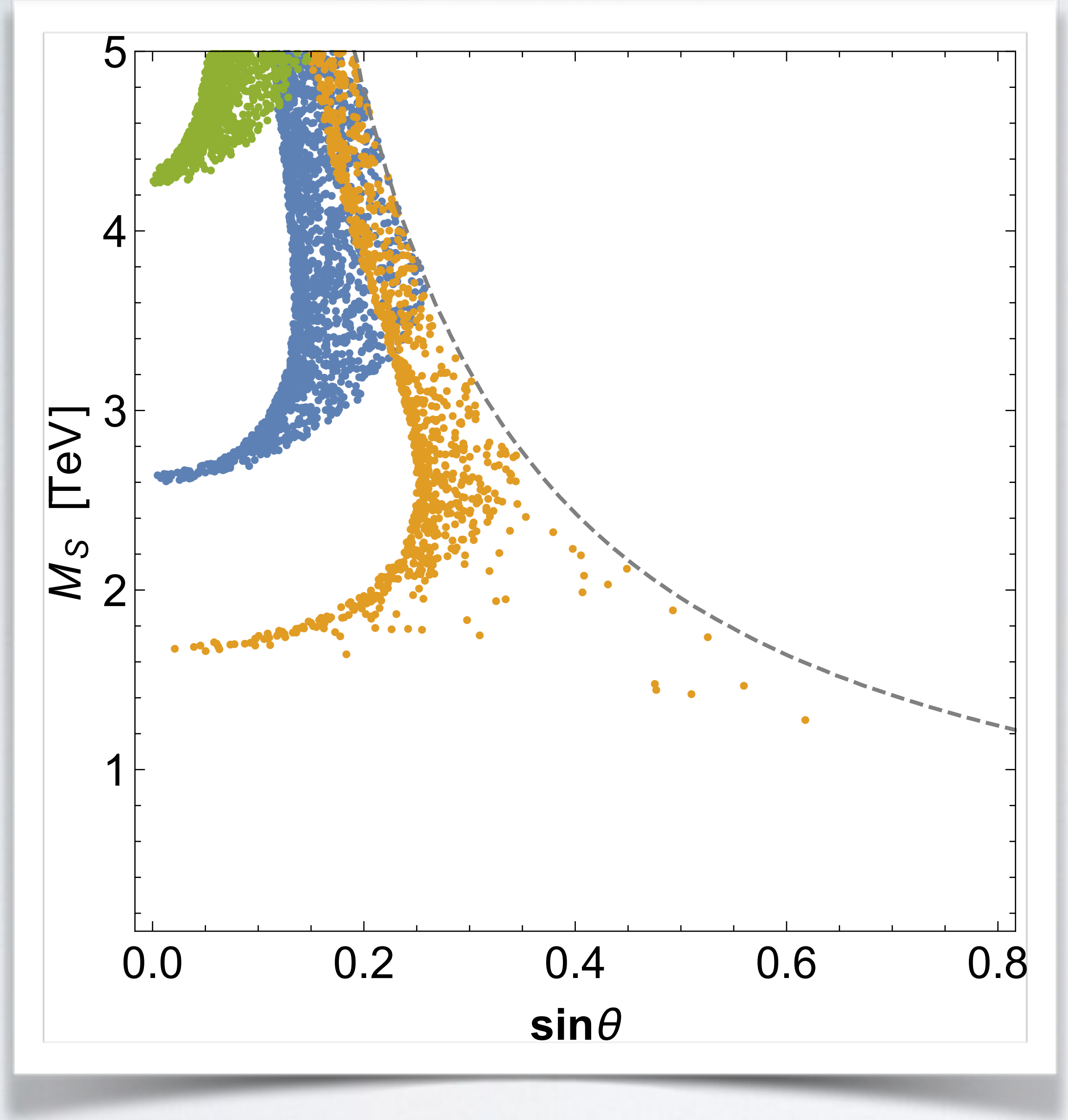


The minimal scenario

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



The Higgs mass as a constraint

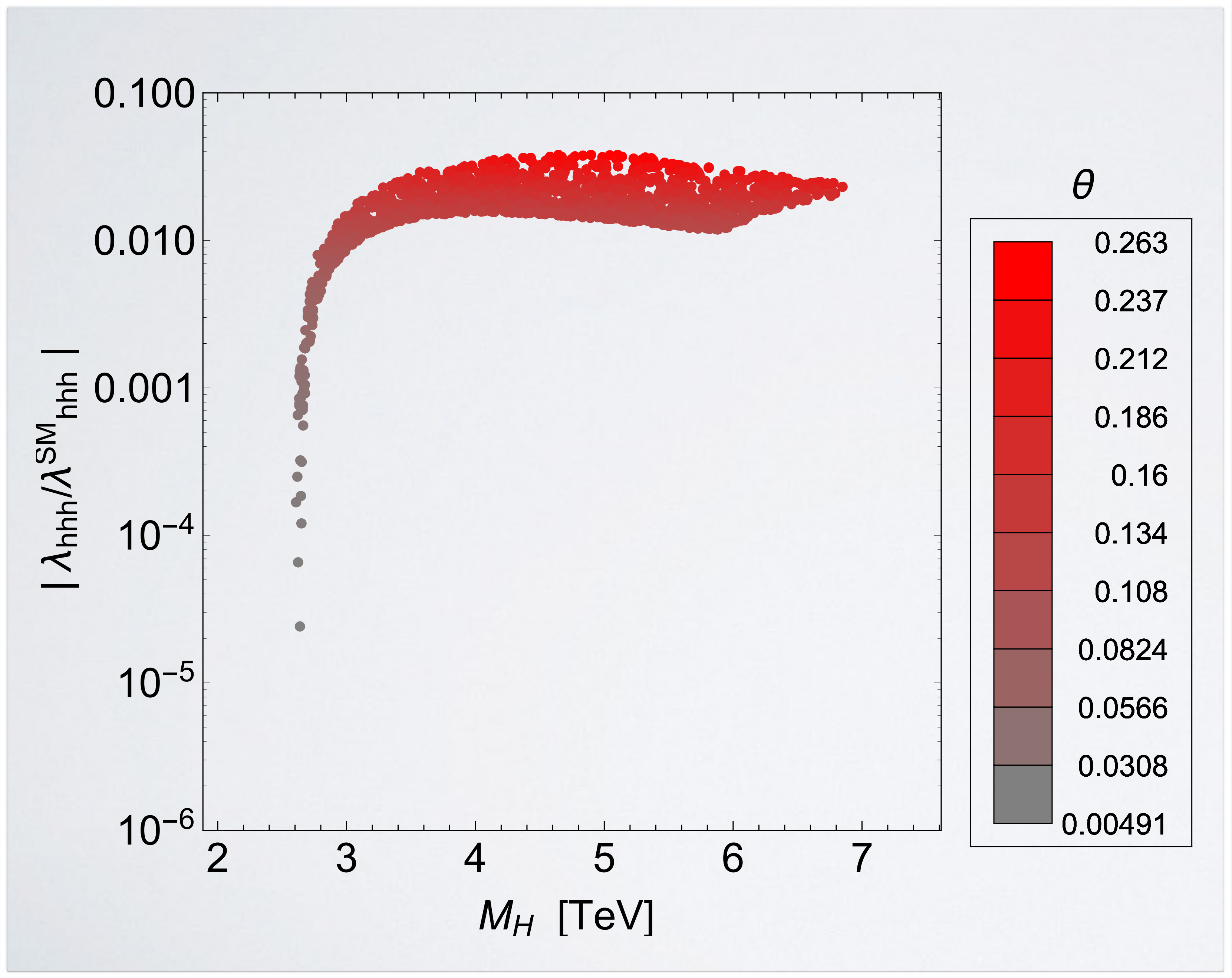


$$m_h = 125.7 \pm 0.4 \text{ GeV}$$

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

small θ and small self-coupling

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



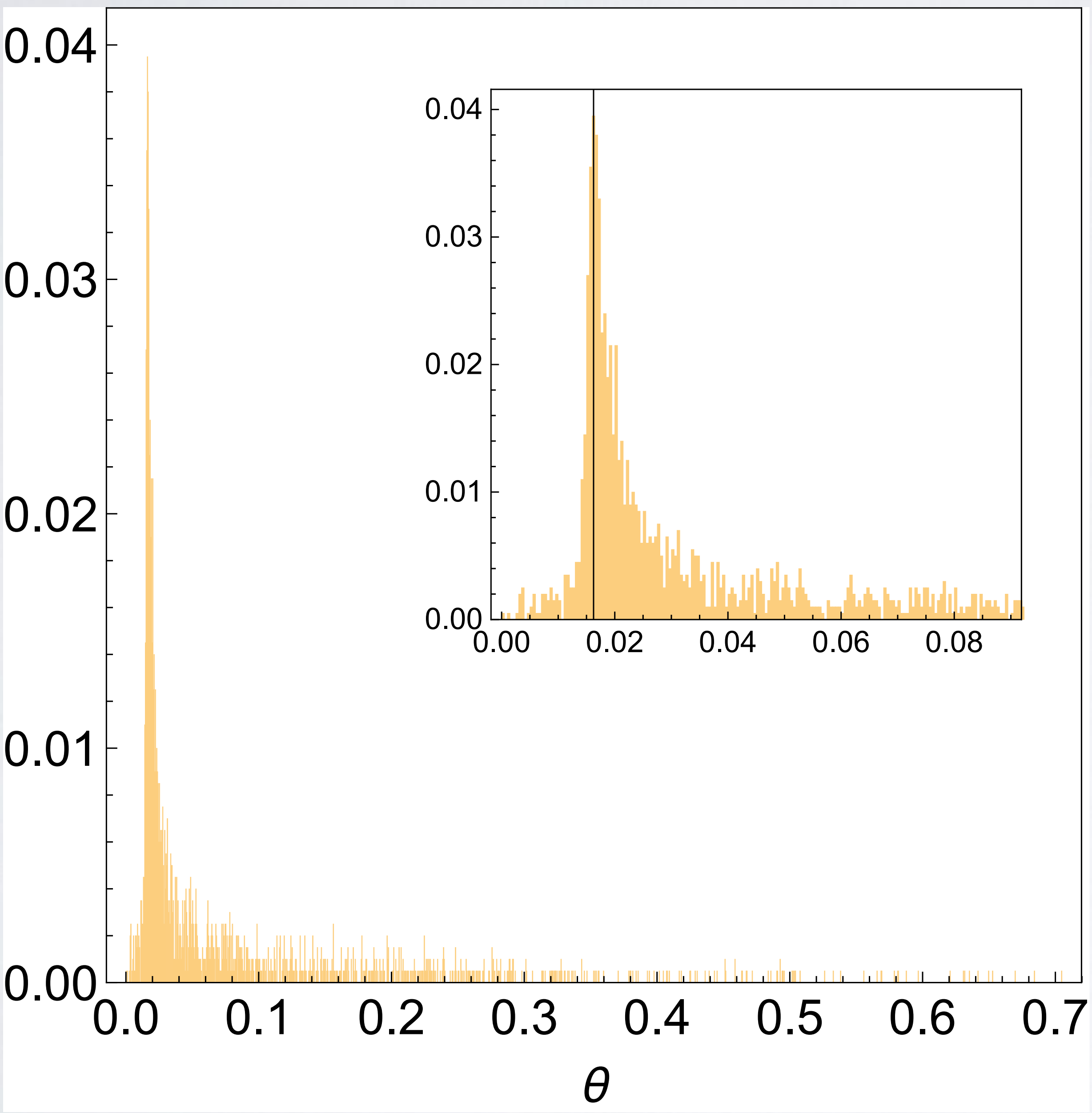
$$\frac{\lambda_{HHH}}{\lambda^{SM}_{hhh}} = v_{\rm EW}\,\frac{M_S^2\cos\alpha}{v\,m_h^2}$$

$$(\lambda^{\rm SM}_{hhh} = 3\,m_h^2/v_{\rm EW})$$

σ field and other scalars

non minimal scenario

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



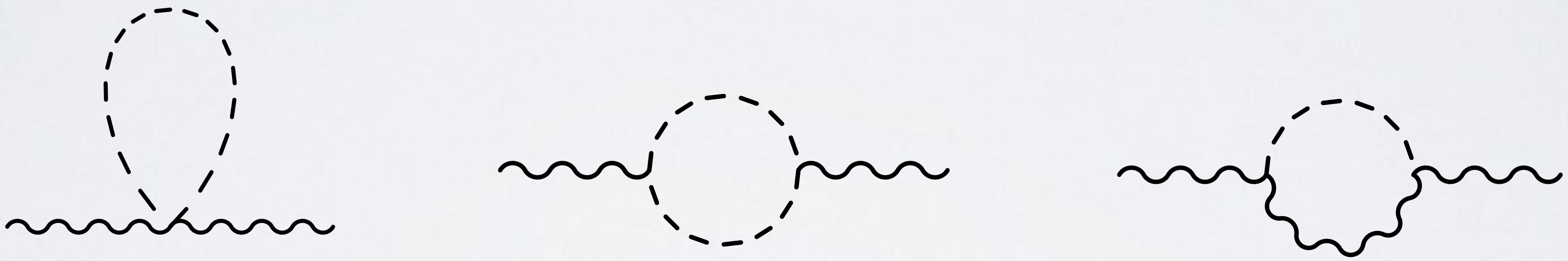
Assuming perturbativity of $\tilde{\lambda}$

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

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

EW Test of the model

$$M = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 & -S^* + i\tilde{S}^* & \Pi_0^* + i\tilde{\Pi}_0 & \Pi^+ - i\tilde{\Pi}^+ \\ S^* - i\tilde{S}^* & 0 & -\Pi^- + i\tilde{\Pi}^- & \Pi_0 - i\tilde{\Pi}_0 \\ -\Pi_0^* - i\tilde{\Pi}_0 & \Pi^- - i\tilde{\Pi}^- & 0 & S - i\tilde{S} \\ -\Pi^+ + i\tilde{\Pi}^+ & -\Pi_0 + i\tilde{\Pi}_0 & -S + i\tilde{S} & 0 \end{pmatrix}$$

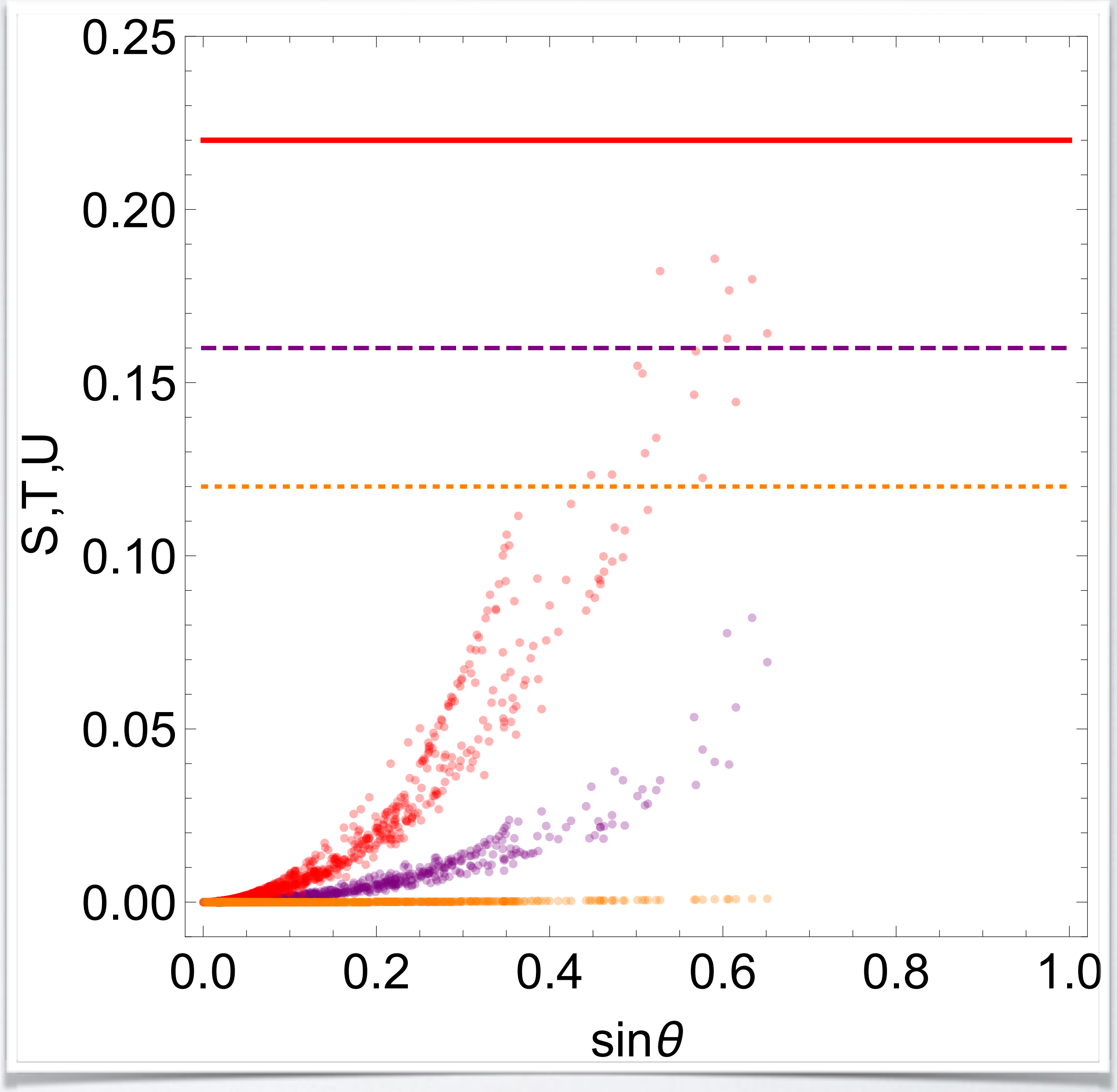


Oblique parameters S T U

Oblique Parameters

- T and U are very suppressed: dependence on $\cos(\theta+\alpha)$

- S depends in the most generic case on the masses of extra massive scalars: dependence on $\cos(\theta+\alpha)$ and $\sin\theta$



Conclusions and Outlook

- Radiatively induced Higgs model, like EGH, are valid alternative:
  - the observed Higgs emerges as a pNGB with its mass arising via radiative corrections.
  - massive scalar spectrum in TeV range
  - Yukawa sector (computable)
  - DM candidate

- T and U very well protected.
- S is suppressed by higher massive states and *sin*θ!

- Tests for the next collider generation:
  - trilinear coupling
  - scalar spectrum

- possible GUT extension (*Pati-Salam*) [arXiv:1511.01910]

Thanks

for the attention

Back-up

Oblique parameters

$$S = \frac{\cos^2(\theta+\alpha)}{72\pi}\left(\frac{-5m_H^4+22m_H^2m_Z^2-5m_Z^4}{\left(m_H^2-m_Z^2\right)^2}+\frac{5m_h^4-22m_h^2m_Z^2+5m_Z^4}{\left(m_h^2-m_Z^2\right)^2}\right.$$
$$\left.-\frac{6m_h^4\left(m_h^2-3m_Z^2\right)\log\left(\frac{m_h^2}{m_Z^2}\right)}{\left(m_h^2-m_Z^2\right)^3}+\frac{6m_H^4\left(m_H^2-3m_Z^2\right)\log\left(\frac{m_H^2}{m_Z^2}\right)}{\left(m_H^2-m_Z^2\right)^3}\right)$$
$$+\frac{\sin^2\theta}{72\,\pi}\left(-\frac{6\left(M_\Theta^6-3M_\Theta^4M_{\tilde\Pi}^2\right)\log\left(\frac{M_{\tilde\Pi}^2}{M_\Theta^2}\right)}{\left(M_\Theta^2-M_{\tilde\Pi}^2\right)^3}+\frac{-5M_\Theta^4+22M_\Theta^2M_{\tilde\Pi}^2-5M_{\tilde\Pi}^4}{\left(M_\Theta^2-M_{\tilde\Pi}^2\right)^2}\right),$$

$$U = -\frac{\cos^2(\theta+\alpha)}{12\pi}\left(2\left(m_W^2-m_Z^2\right)\left(\frac{m_h^2\left(m_h^4-m_W^2m_Z^2\right)}{\left(m_h^2-m_W^2\right)^2\left(m_h^2-m_Z^2\right)^2}-\frac{m_H^2\left(m_H^4-m_W^2m_Z^2\right)}{\left(m_H^2-m_W^2\right)^2\left(m_H^2-m_Z^2\right)^2}\right)\right.$$
$$+\frac{m_W^4\left(m_W^2-3m_h^2\right)\log\left(\frac{m_h^2}{m_W^2}\right)}{\left(m_h^2-m_W^2\right)^3}+\frac{m_Z^4\left(m_Z^2-3m_h^2\right)\log\left(\frac{m_h^2}{m_Z^2}\right)}{\left(m_Z^2-m_h^2\right)^3}$$
$$\left.+\frac{m_W^4\left(m_W^2-3m_H^2\right)\log\left(\frac{m_H^2}{m_W^2}\right)}{\left(m_W^2-m_H^2\right)^3}+\frac{m_Z^4\left(m_Z^2-3m_H^2\right)\log\left(\frac{m_H^2}{m_Z^2}\right)}{\left(m_H^2-m_Z^2\right)^3}\right).$$

$$T = \frac{\cos^2(\theta+\alpha)}{16\pi}\left(\frac{\log\left(\frac{m_H^2}{m_h^2}\right)}{c_W^2}-\frac{\left(4m_h^2+m_Z^2\right)\log\left(\frac{m_h^2}{m_Z^2}\right)}{c_W^2s_W^2\left(m_h^2-m_Z^2\right)}+\frac{\left(4m_H^2+m_Z^2\right)\log\left(\frac{m_H^2}{m_Z^2}\right)}{c_W^2s_W^2\left(m_H^2-m_W^2\right)}\right.$$
$$\left.+\frac{\left(4m_h^2+m_W^2\right)\log\left(\frac{m_h^2}{m_W^2}\right)}{s_W^2\left(m_Z^2-m_W^2\right)}-\frac{\left(4m_H^2+m_W^2\right)\log\left(\frac{m_H^2}{m_W^2}\right)}{c_W^2\left(m_h^2-s_W^2\right)}\right),$$