The Elementary Goldstone Higgs

Works in collaboration with
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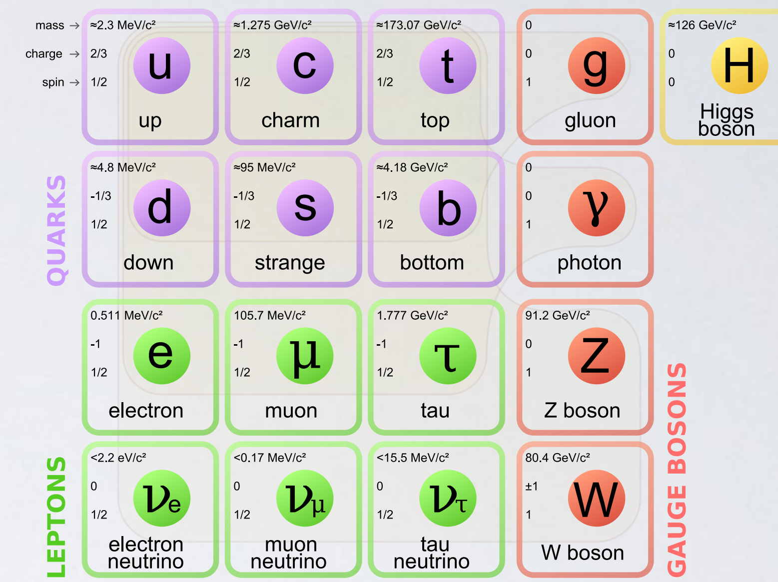
SCALARS, 6 December 2015

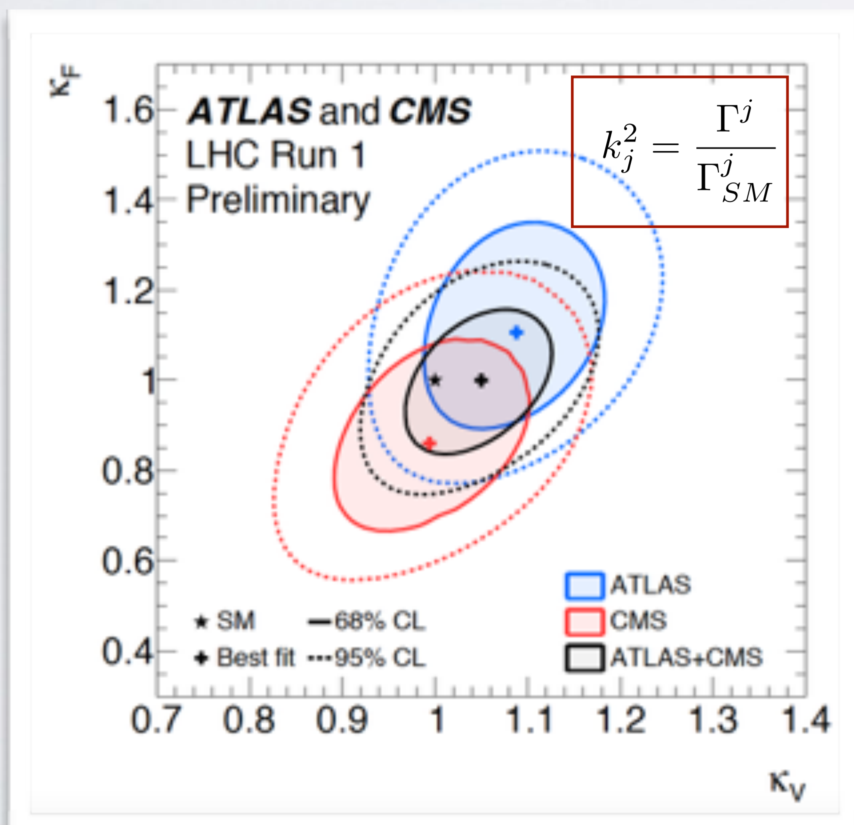
CP3 Origins
Cosmology & Particle Physics

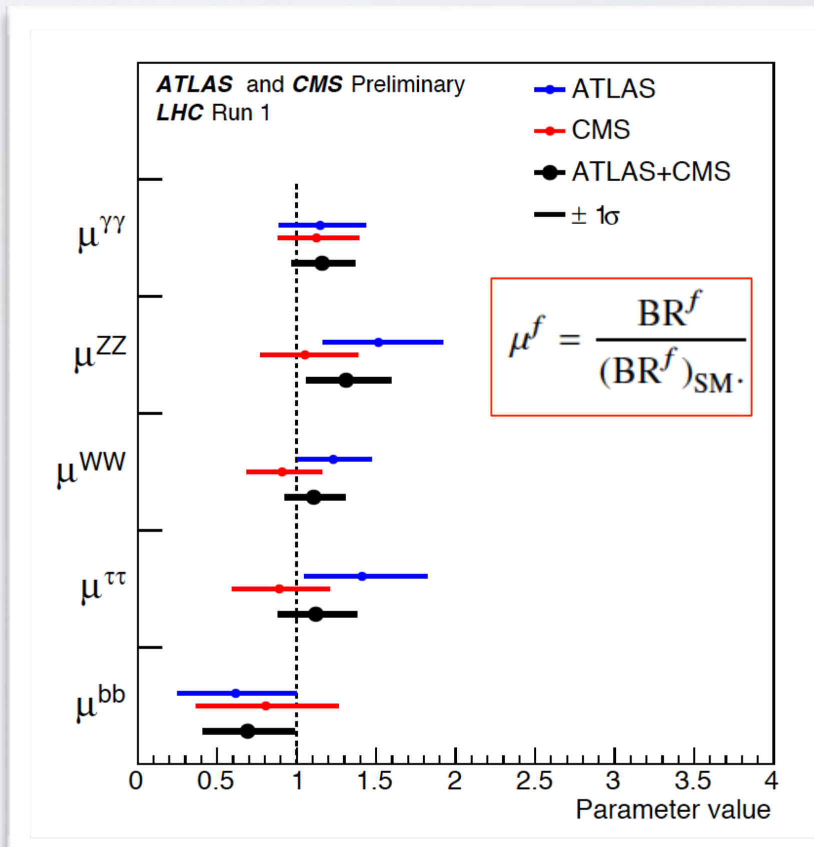
University of Southern Denmark

The Standard Model

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





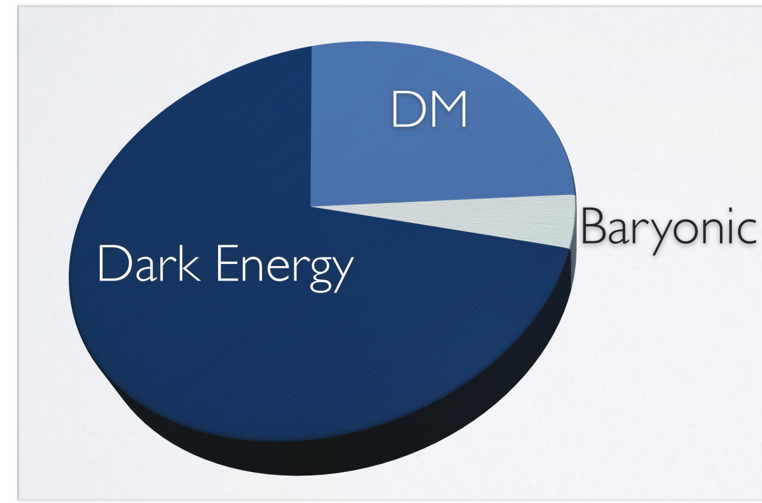


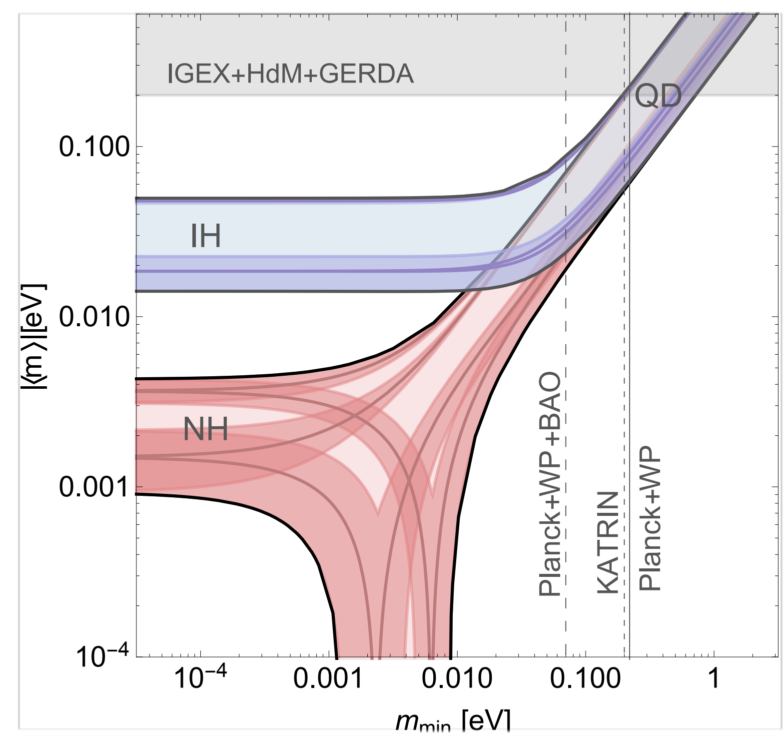
presented at LHCP-2015, 15th September 2015 [ATALS-CONF-2015-044; CMS-PAS-HIG-15-002]

Open problems & unknowns (pheno)

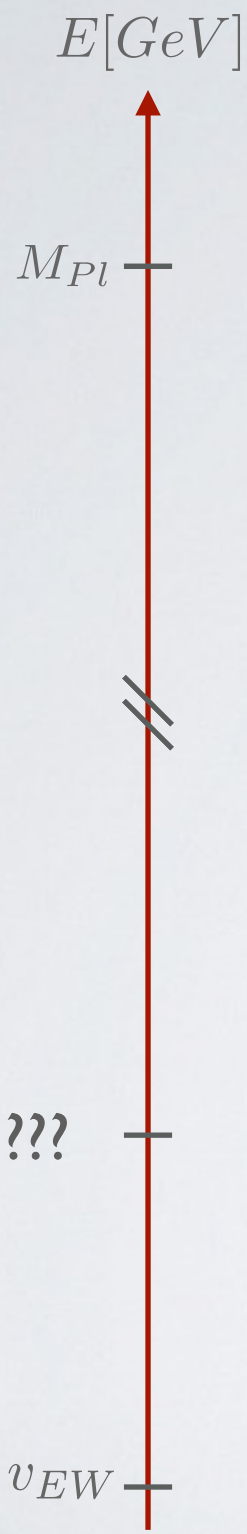
- Explanation of ***matter-antimatter*** asymmetry
- ***Elusive sector***: neutrinos and DM (BSM physics!)
    - absolute value of neutrino masses, Hierarchy (normal or inverted) , CP-phases: δ, and Majorana phases
    - Connection between non zero neutrino masses and ***symmetries*** for the lepton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

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

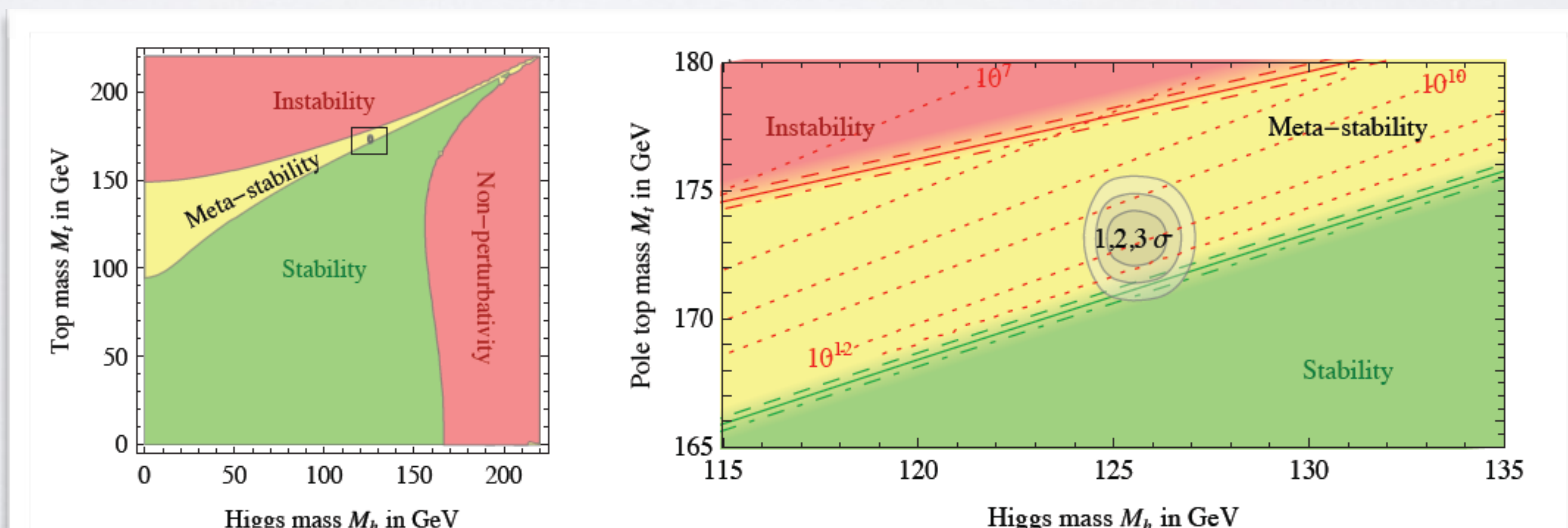




Open problems (theory)



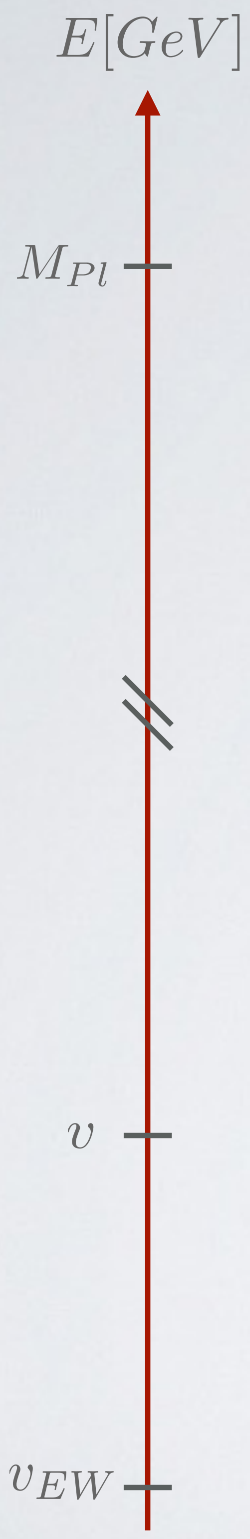
- ***Hierarchy problem***: Why is the SU(2)× U(1) breaking scale so much smaller than the unification scale? (Absence of mechanisms establishing the EW scale against quantum corrections)
- Lack of dynamical motivation for the ***origin of SSB***
- ***Flavour puzzle***: Why does Nature repeat Herself?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



G. Degrassi et al., 1205.6497

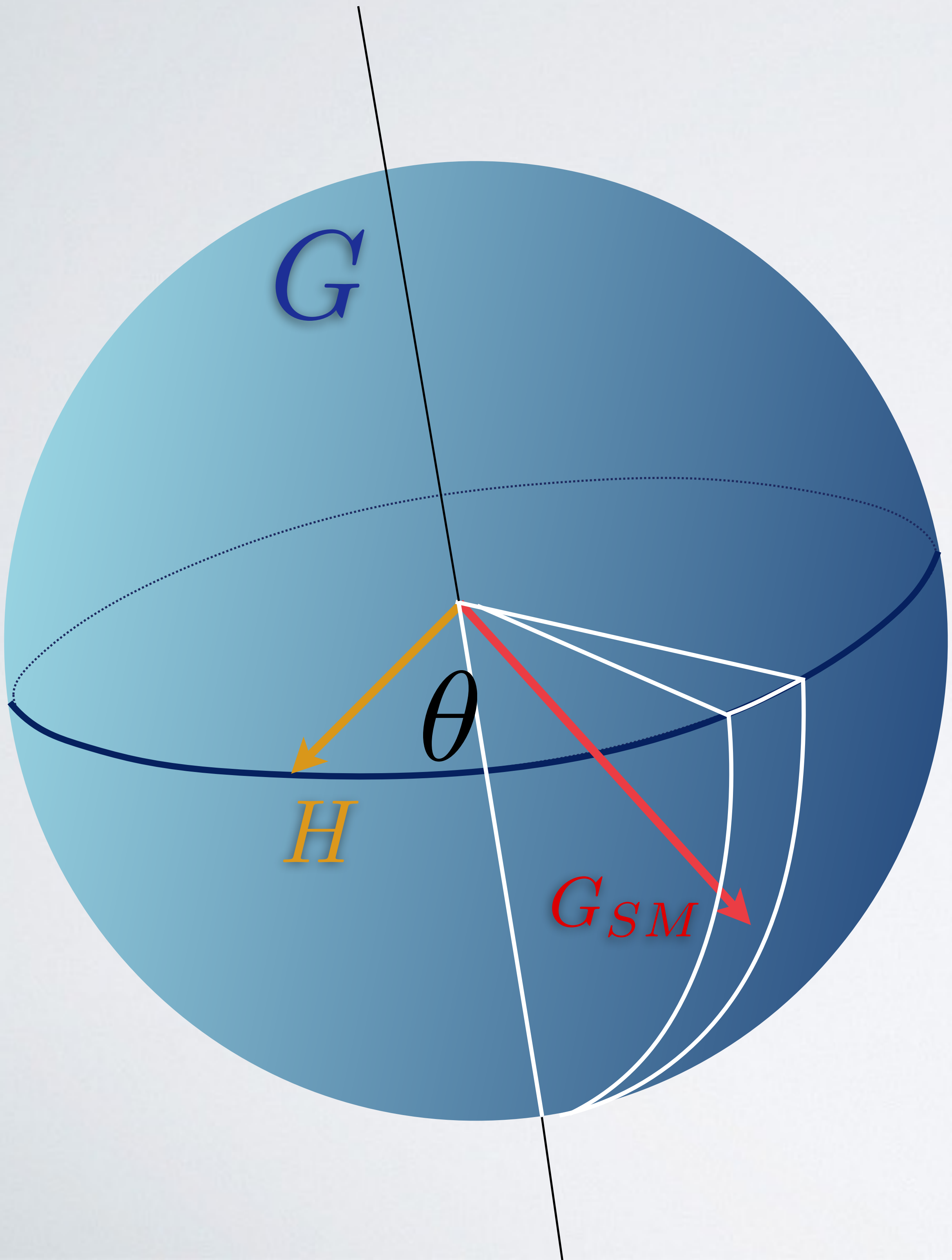
Elementary Goldstone Higgs

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 a pseudo Nambu Goldstone Boson (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.
- *Calculable* 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.

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 $SU(4)/Sp(4)$.

$\theta = 0$

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

$\theta = \pi/2$

- 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

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

T_a 10 generators of Sp(4)

X_a 5 broken generators of SU(4)

How do I break it?

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

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

Vacuum Alignment

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

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

The vacuum used is a superposition of two vacua

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

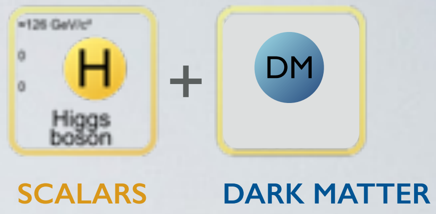
Electroweak vacuum

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

Technicolor vacuum

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

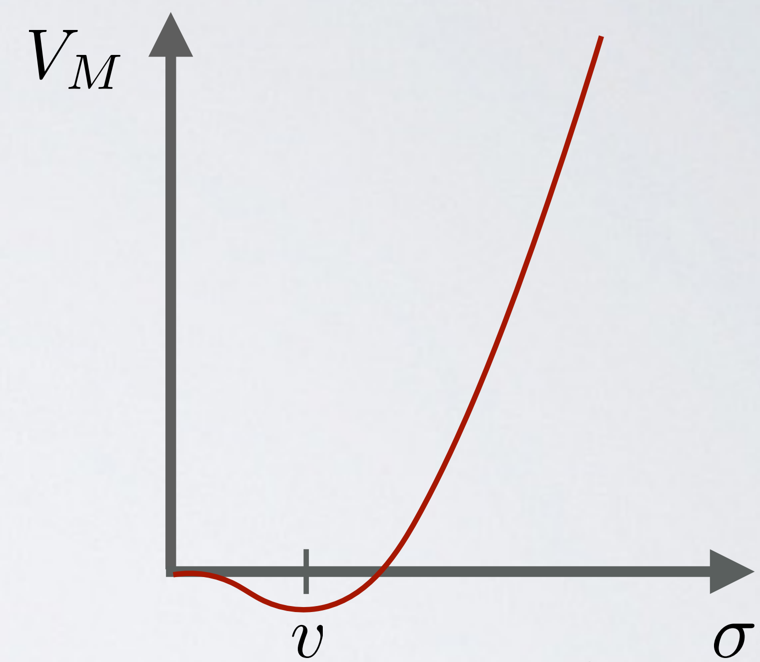
Tree-Level Scalar potential



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

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

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

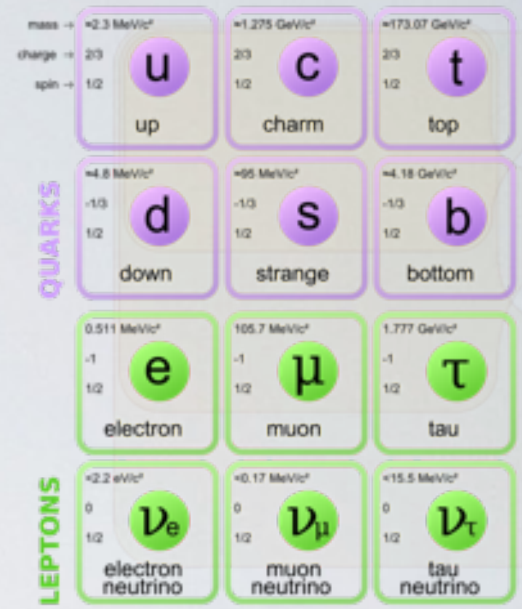


$$\langle \sigma^2 \rangle \equiv v^2 = \frac{c_M - m_M^2}{4\,\lambda_{11}}$$

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

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

Yukawa Interactions



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

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

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

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

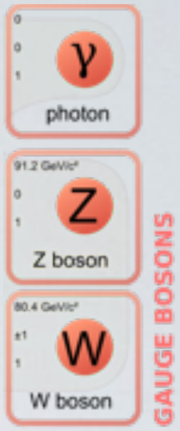
$$\begin{aligned} -\mathcal{L}^{\mathrm{Y}}_{q,\ell,\nu} &= \frac{Y^u_{ij}}{\sqrt{2}} \left(\mathbf{Q}^T_i P_a \mathbf{Q}_j\right)^\dagger Tr\left[P_a M\right] + \frac{Y^d_{ij}}{\sqrt{2}} \left(\mathbf{Q}^T_i \overline{P}_a \mathbf{Q}_j\right)^\dagger Tr\left[\overline{P}_a M\right] \\ &+ \frac{Y^\nu_{\alpha\beta}}{\sqrt{2}}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

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

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

Neutrinos as easily incorporated!

Electroweak Gauge Bosons



The electroweak interactions appear in the kinetic term of the Lagrangian

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

where

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

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:

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

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

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

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

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

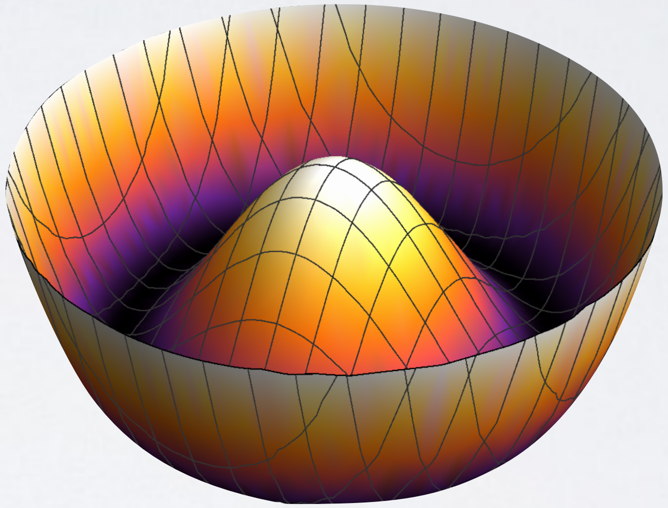
Parameters, Constraints and Minimization

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

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

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

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

What fixes θ ?

- Gauge and top corrections
- Explicit breaking of global symmetry

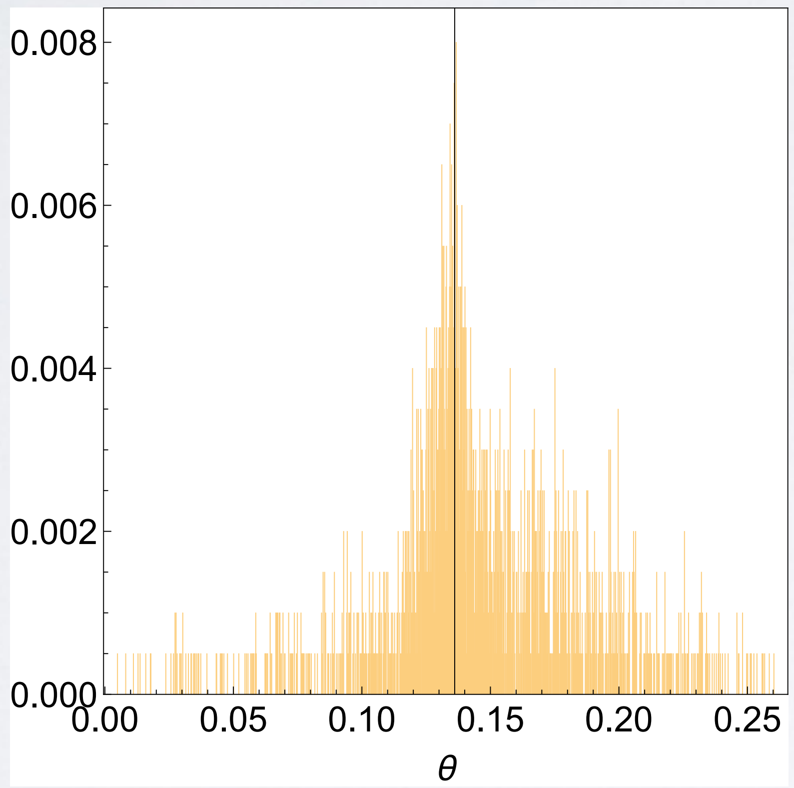
- CW analysis to determine vacuum expectation value
- Couplings close to SM values

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

Small θ via radiative corrections

in the minimal scenario

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



Assuming perturbativity of $\tilde{\lambda}$

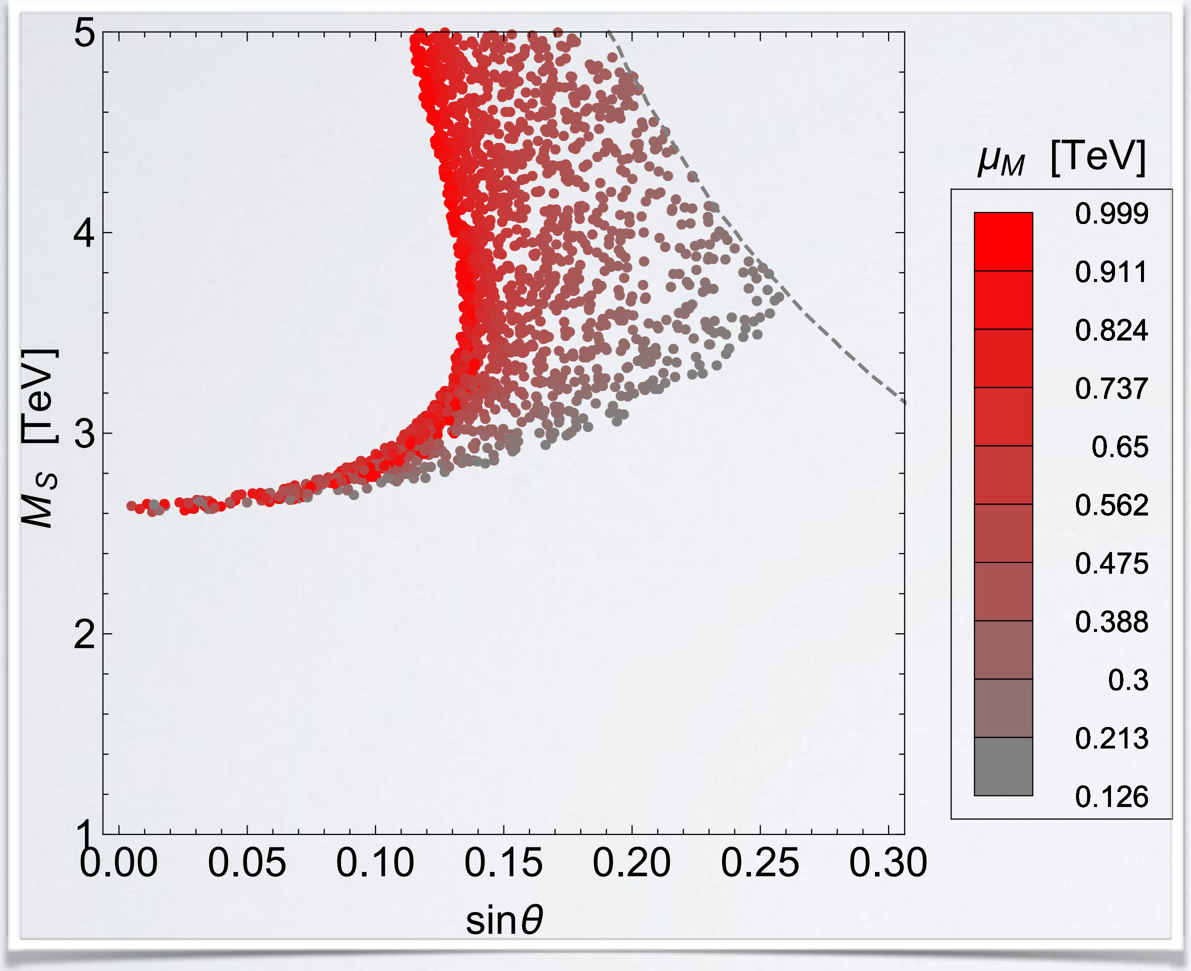
$$\bar{\theta} = 0.136^{+0.006}_{-0.012}\,,$$

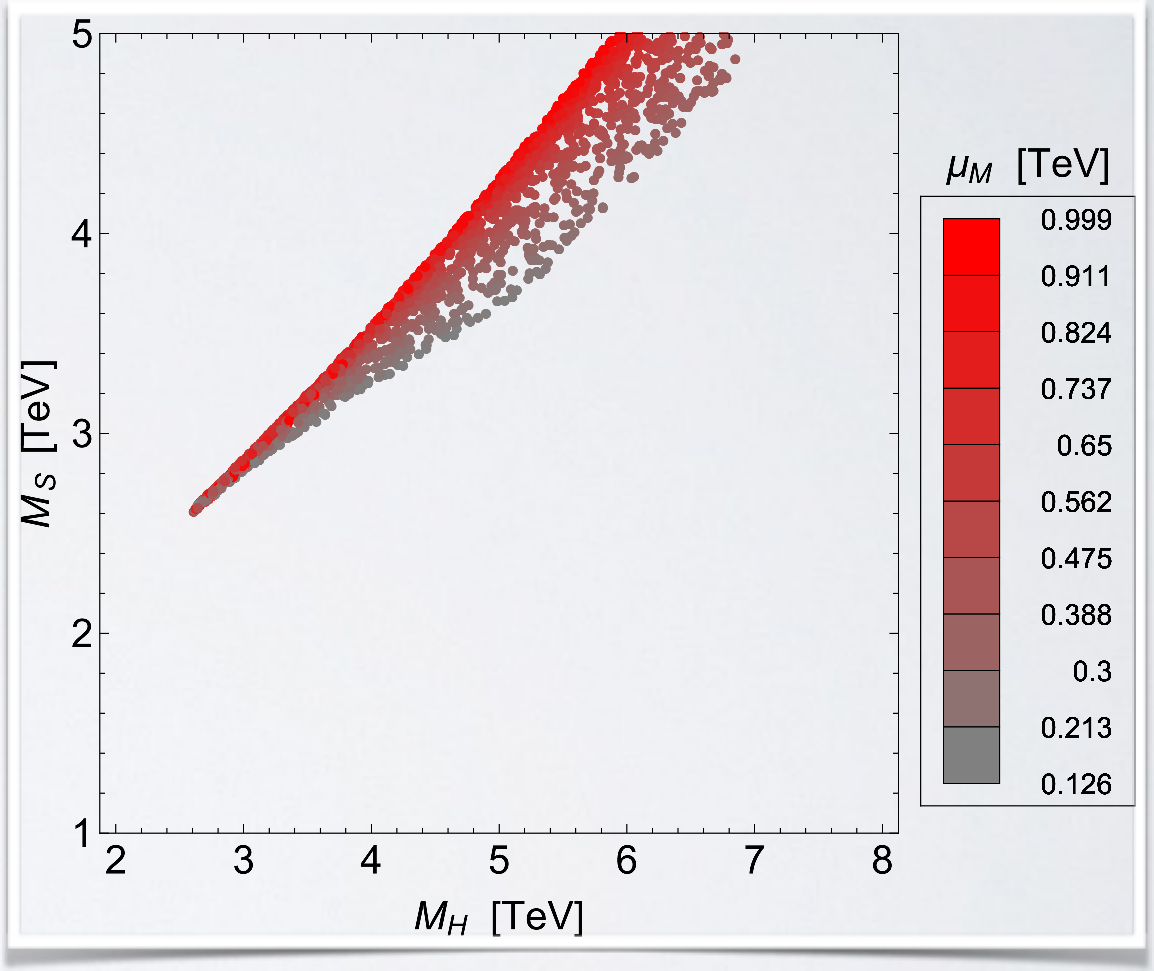
$$\bar{v} = 1.81^{+0.08}_{-0.15}\ \mathrm{TeV}$$

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

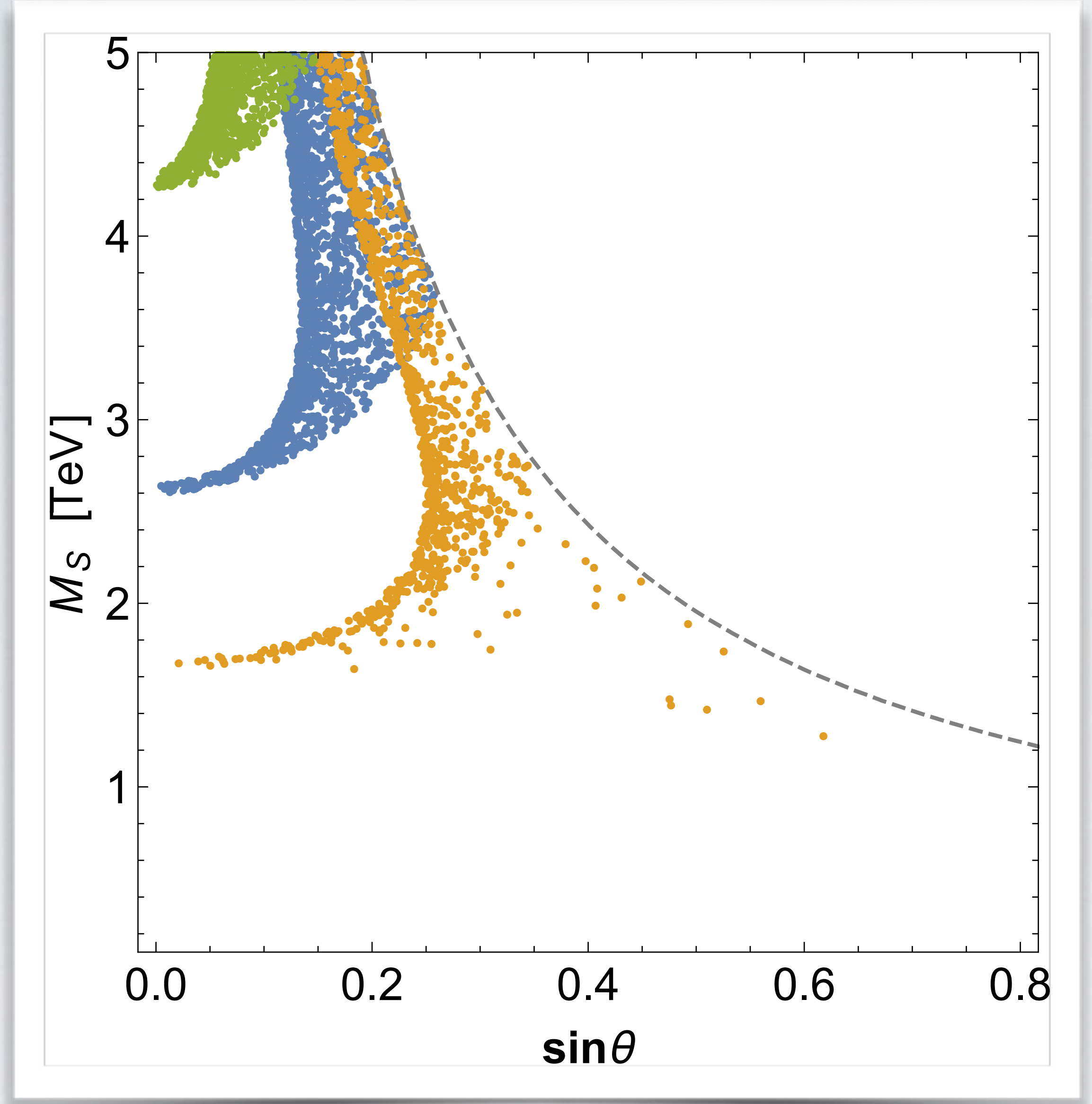
The minimal scenario

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





The Higgs mass as a constraint

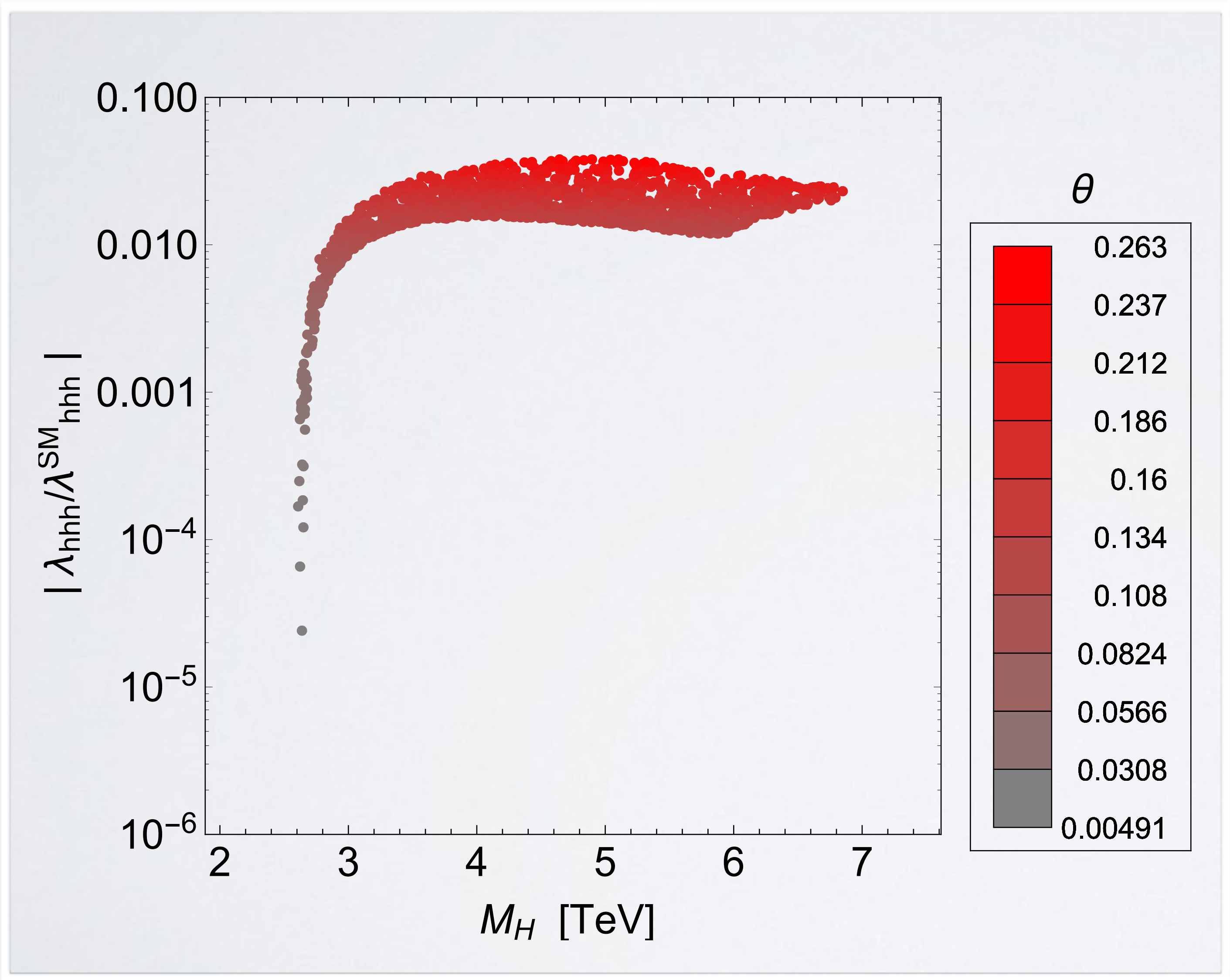


$$m_h = 125.7 \pm 0.4 \text{ GeV}$$

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

small θ and small self-coupling

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



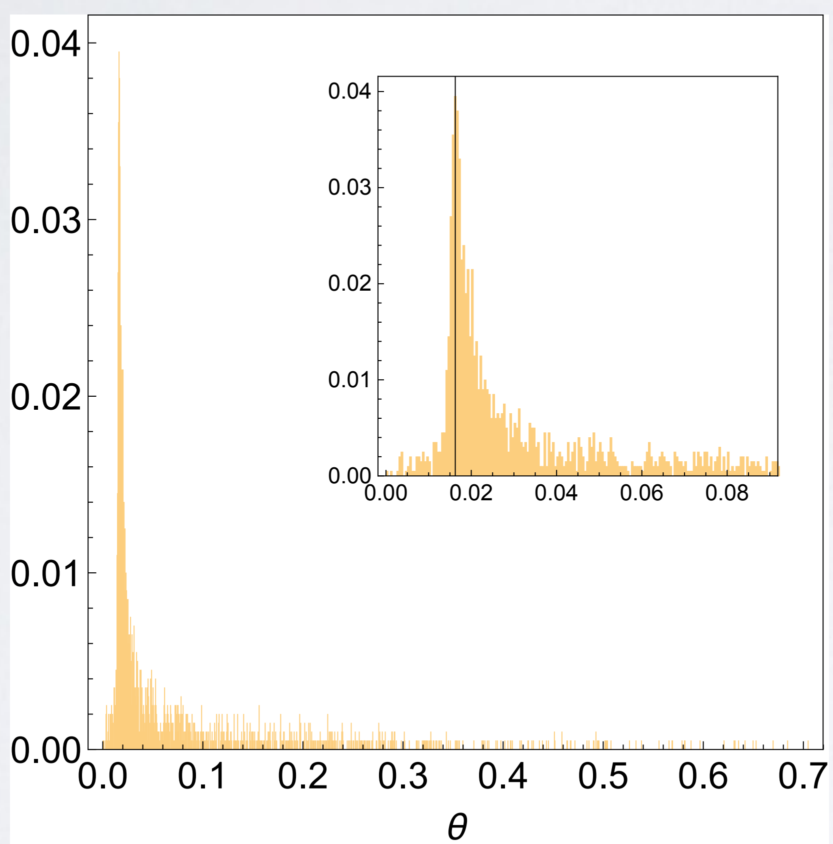
$$\frac{\lambda_{HHH}}{\lambda^{SM}_{hhh}} = v_{\mathrm{EW}}\,\frac{M_S^2\cos\alpha}{v\,m_h^2}$$

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

σ field and other scalars

non minimal scenario

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



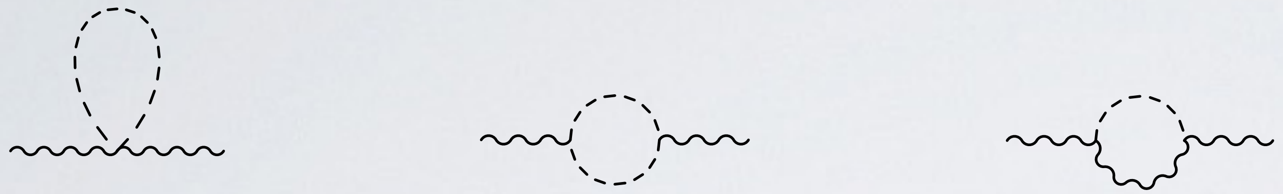
Assuming perturbativity of $\tilde{\lambda}$

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

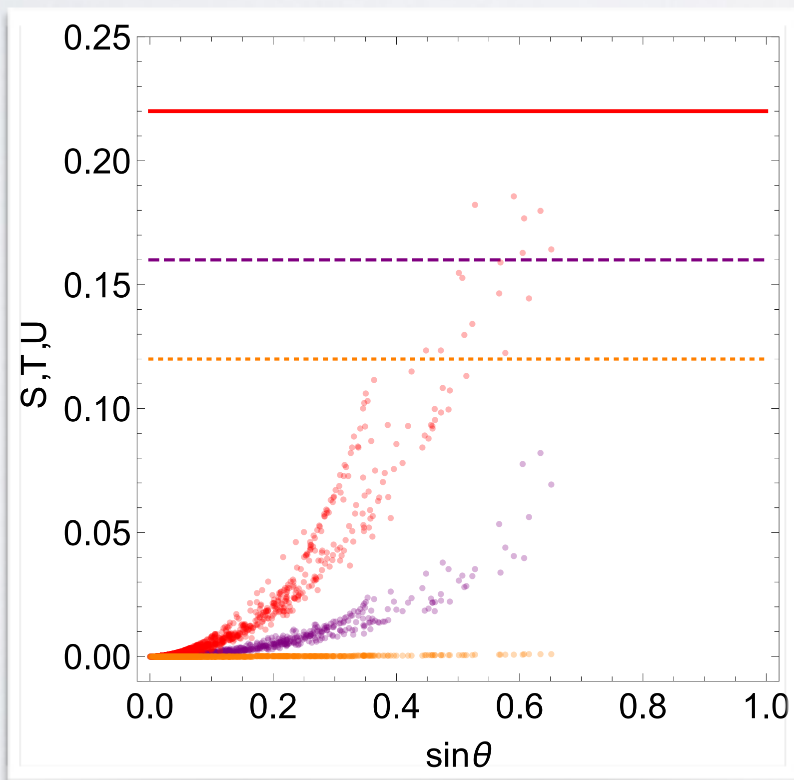
$$\bar{f} = 15.2^{+3.9}_{-1.4}\ \mathrm{TeV}$$

Testing the model

Oblique parameters S T U



- T and U are very suppressed
- S depends in the most generic case on the masses of extra massive scalars



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

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

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

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 spectrum in TeV range
  - Yukawa sector

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

- We need to test models! We need good observables in order to test them in the next collider generation:
  - trilinear coupling
  - …

Thanks

for the attention