CP3 Origins

Cosmology & Particle Physics

SDU

A Radiatively induced Elementary Goldstone Higgs

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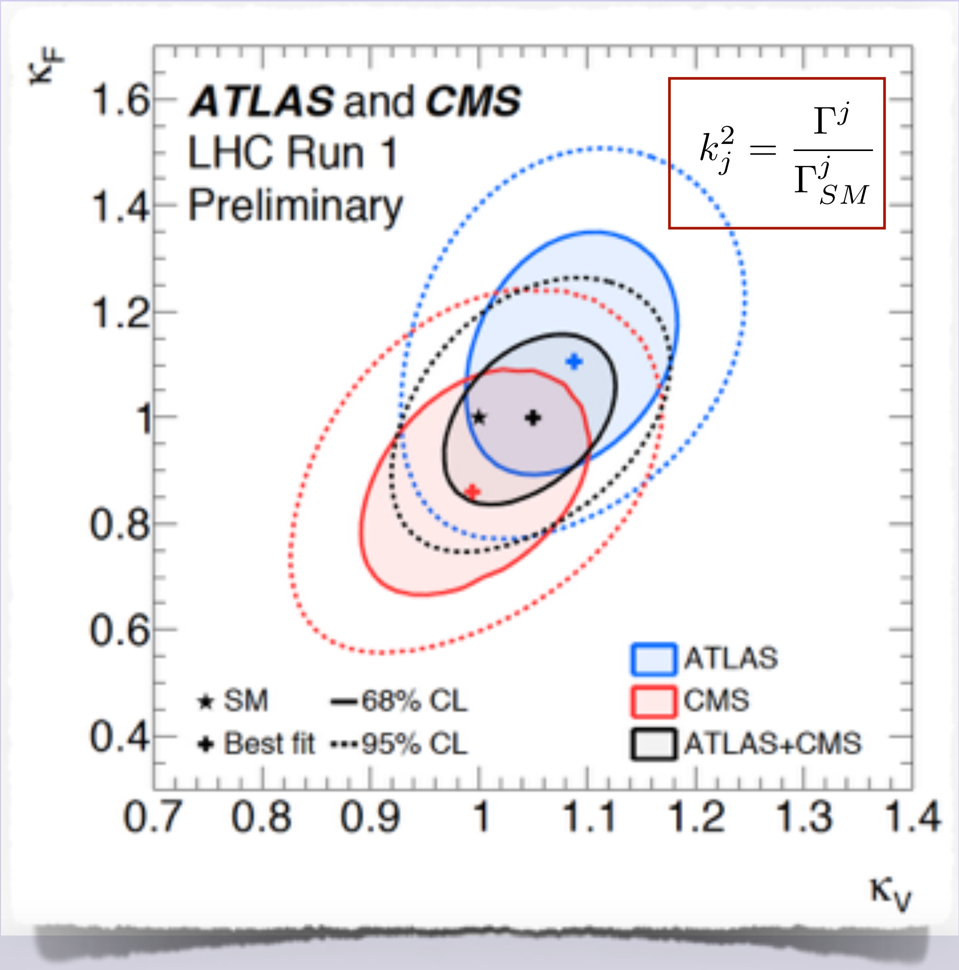
Invisibles Workshop 2016
Padova 12-16 September 2016

invisibles

neutrinos, dark matter & dark energy physics

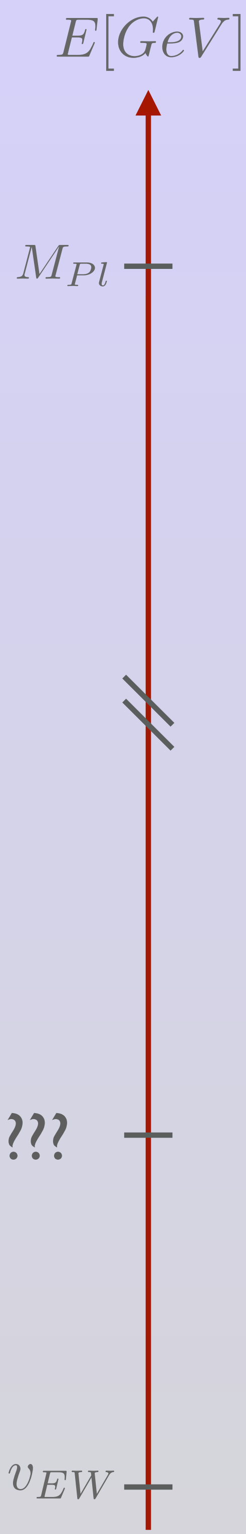
The Standard Model



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

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

Open problems (theory)

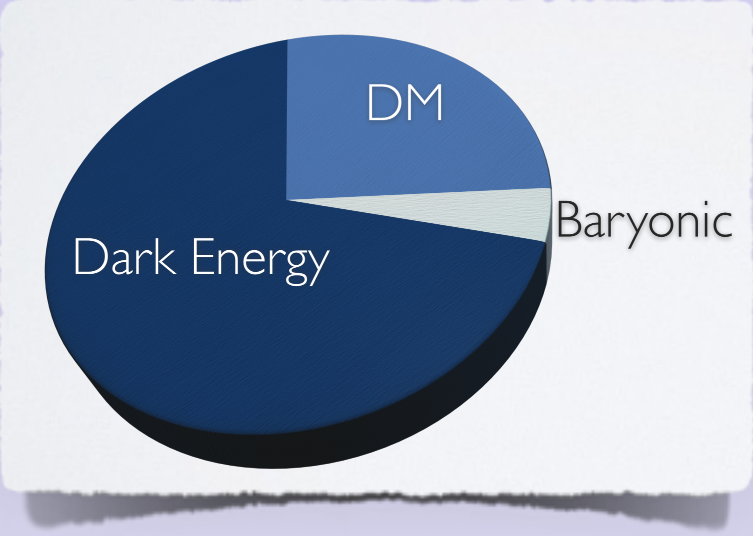


- Lack of dynamical motivation for the ***origin of SSB***

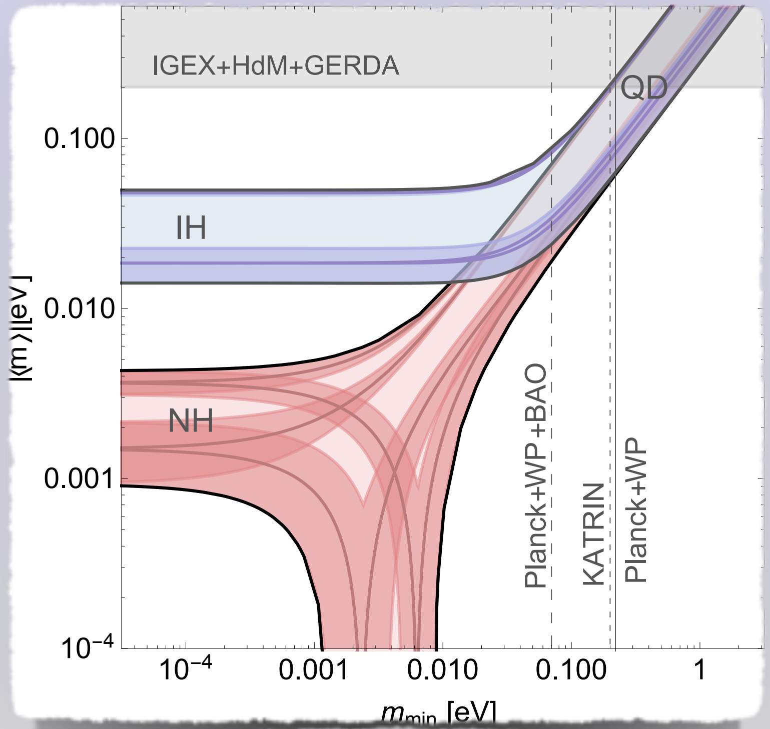
- ***Hierarchy problem***: Why is the SU(2)× U(1) breaking scale so much smaller than the unification scale? (Absence of mechanisms establishing the EW scale against quantum corrections)

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



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



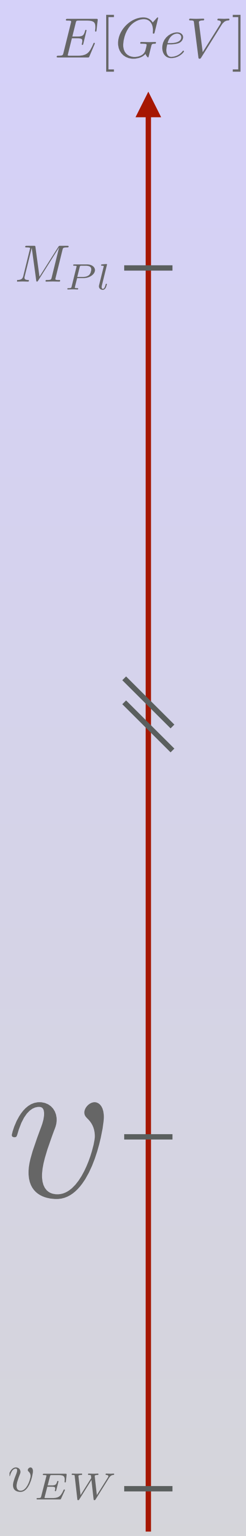
From Nature…

Ginkgoes are the only surviving species of Ginkgophyta and are undoubtedly the most ancient seeding plants. In the Jurassic and Cretaceous, similar plants grew on all emerged land, but they later disappeared gradually, except for this large tree that Darwin called "a living fossil".

The majestic ginkgo was brought to Padova in 1750. It is a male specimen, on which female branches were inserted for teaching purposes in the late 1800s.

Elementary Goldstone Higgs

H. Gertov, AM , E. Molinaro, F. Sannino Phys. Rev. D 92, 095003 (2015)
T. Alanne, H. Gertov, F. Sannino, K. Tuominen Phys. Rev. D 91, 095021 (2015)
T. Alanne, H. Gertov, AM, F. Sannino arXiv:1608.07442



- 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.
- We extend the Higgs sector symmetry
- The physical Higgs emerges as pNGB (idea used by many others!).
- Once the SM gauge and fermion sectors are embedded in the larger symmetry 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

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

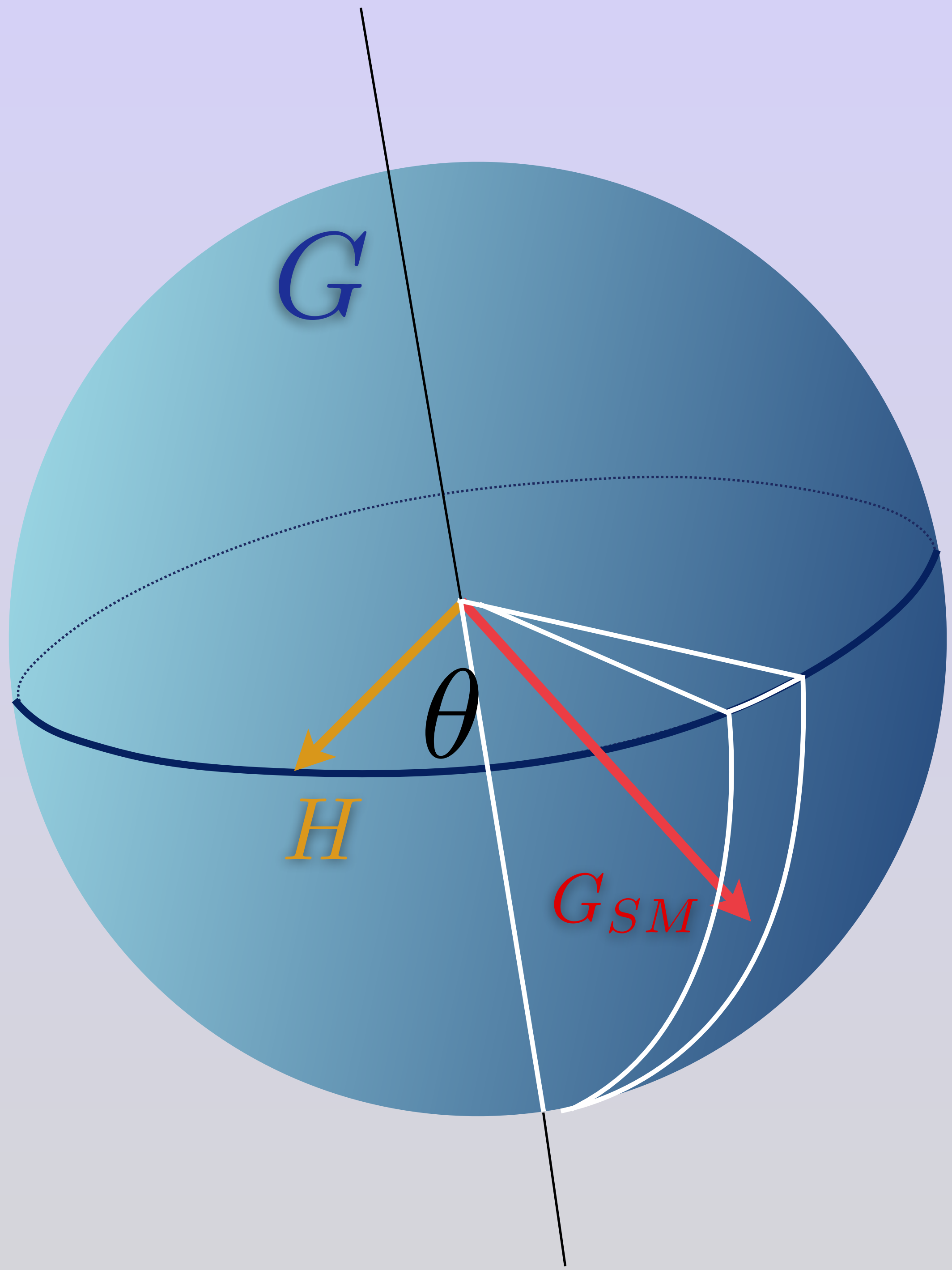
interesting possibility both for (ultra) minimal Technicolor models and the composite GB Higgs scenarios, and for constructing UV completions of Little Higgs models

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)

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

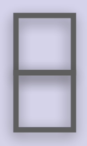
Description valid also for TC
Peskin Nucl. Physics B175 (1980) 197
Preskill Nucl. Physics B 177 (1981) 21-59

The EGH model

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

How do I break it?

5 Goldstone Bosons — broken generators

6-dim irrep 

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

vacuum alignment

$\Pi_1 \,, \Pi_2 \,, \Pi_3$ — 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

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

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
Sannino, Cacciapaglia, 2014

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

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

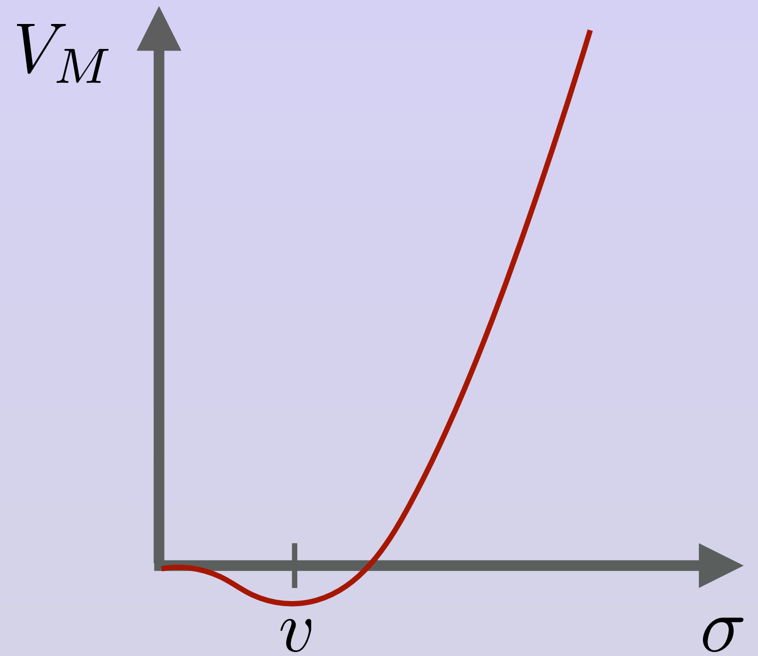
SCALARS + DARK MATTER

Tree-Level Scalar potential

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

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

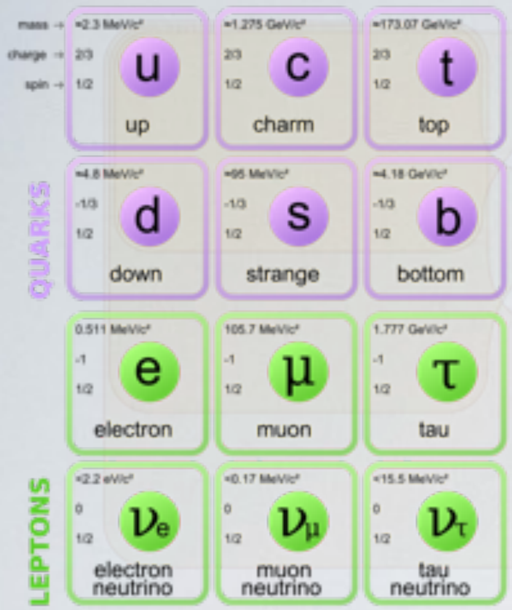
$$\text{with} \quad E_A = \begin{pmatrix} i\,\sigma_2 & 0 \\ 0 & i\,\sigma_2 \end{pmatrix}$$



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

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

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



Yukawa Interactions

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

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

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

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

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

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

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

Neutrinos as easily incorporated!

Electroweak Gauge Bosons

The electroweak interactions appear in the kinetic term of the Lagrangian

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

where

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

which gives the masses

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

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

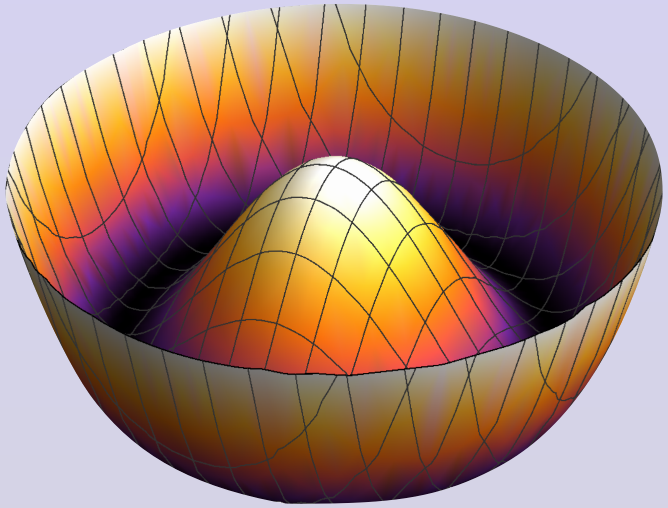
Parameters, Constraints and Minimization

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

Higgs boson mass

$$m_h = 125.09 \pm 0.21(stat.) \pm 0.11(syst.)$$

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



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

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

About one-loop corrections and vev alignment…

Theories in which the gauge group is only a part of the original global symmetry can undergo a vacuum (mis)alignment phenomenon via quantum corrections.

$$V_1(\varphi) = \frac{1}{64\pi^2}\mathrm{Str}\left[\Lambda^4\left(\log\Lambda^2 - \frac{1}{2}\right) + 2\mathcal{M}^2(\varphi)\Lambda^2 + \mathcal{M}^4(\varphi)\left(\log\frac{\mathcal{M}^2(\varphi)}{\Lambda^2} - \frac{1}{2}\right)\right] + \text{c.t.}$$

arXiv:1608.07442

Vacuum alignment with(out) elementary scalars

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University of Southern Denmark, Campusvej 55, DK-5230 Odense M, Denmark.

We systematically elucidate differences and similarities of the vacuum alignment issue in composite and renormalizable elementary extensions of the Standard Model featuring a pseudo-Goldstone Higgs. We also provide general conditions for the stability of the vacuum in the elementary framework, thereby extending previous studies of the vacuum alignment.

Preprint: CP^3*-Origins-2016-037 DNRF90*

I. INTRODUCTION

Theories in which the gauge group is only a part of the original global symmetry can undergo a vacuum (mis)alignment phenomenon via quantum corrections. In two pioneering papers in the context of technicolor, Peskin [1] and Preskill [2] rec-

II. REVIEW OF THE VACUUM ALIGNMENT IN COMPOSITE SCENARIOS

Let us consider underlying composite framework with global chiral-symmetry-breaking pattern $\mathrm{SO}(N) \to \mathrm{SO}(N-1)$. The corresponding coset space is parameterized by

Quantum Corrections

The Renormalized Coleman-Weinberg potential at 1-loop:

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

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

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

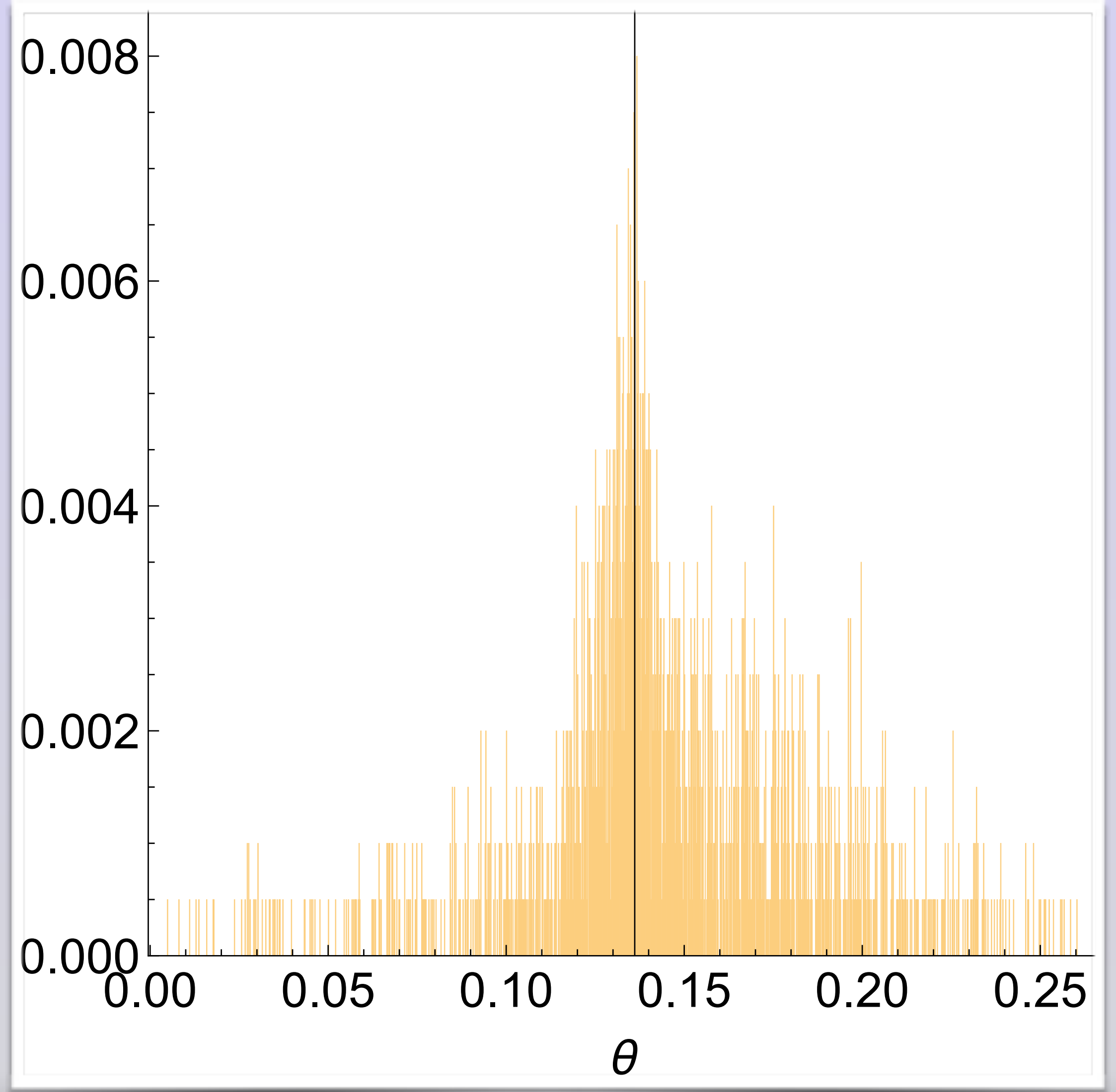
$$\delta V_{\mathrm{EW}}(\sigma,\Pi_4) = \frac{3}{1024\pi^2}\,\phi^4\left[2g^4\left(\log\frac{g^2\,\phi^2}{4\mu_0^2} - \frac{5}{6}\right) + (g^2+g'^2)^2\left(\log\frac{(g^2+g'^2)\,\phi^2}{4\mu_0^2} - \frac{5}{6}\right)\right], \tag{1}$$

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

Small θ via radiative corrections

in the minimal scenario

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



Assuming perturbativity of $\tilde{\lambda}$

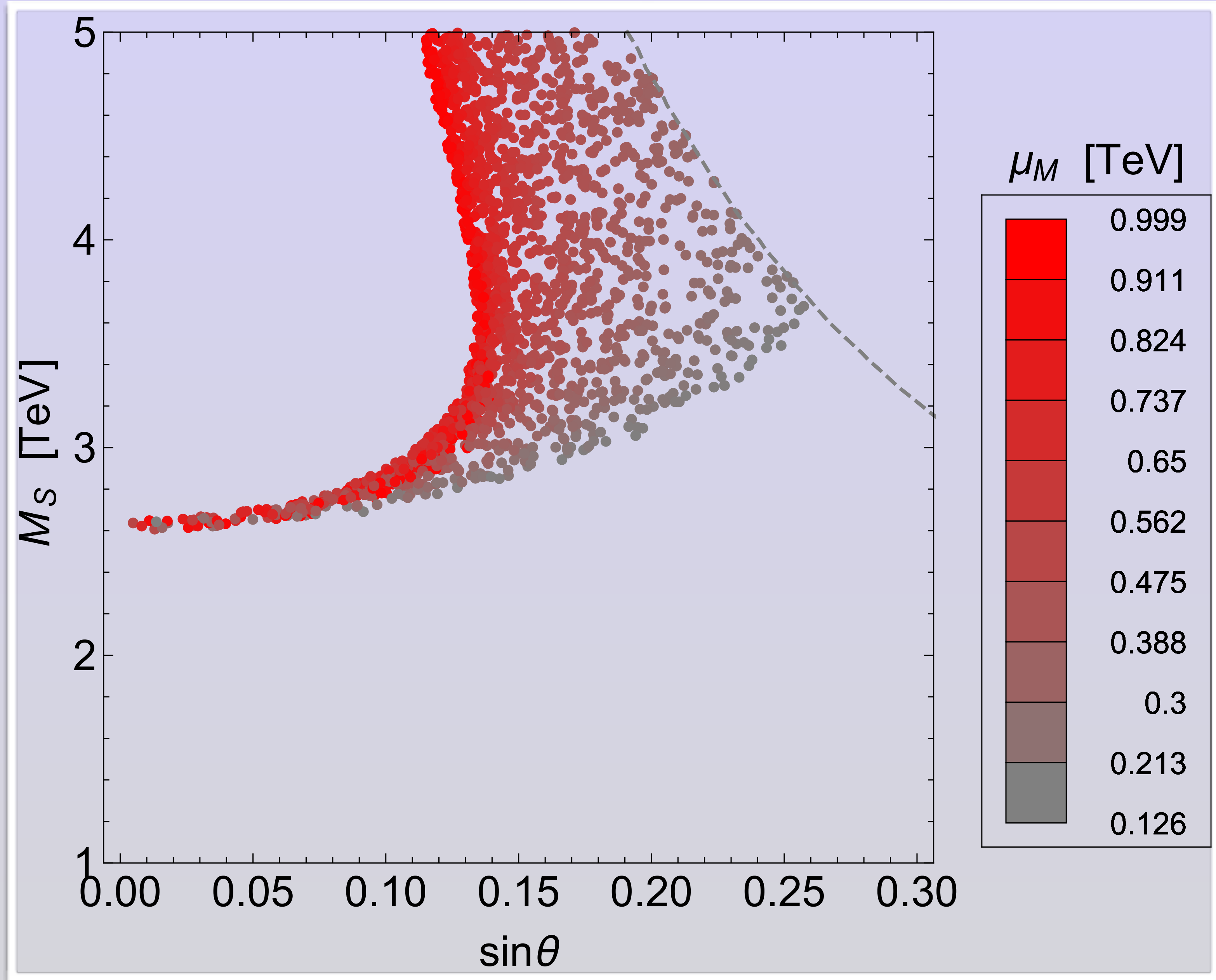
$$\overline{\theta} = 0.136^{+0.006}_{-0.012}\,,$$

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

- Higgs mostly pNGB
- $v_{ew} = v\sin\theta = 246\ \mathrm{GeV}$
- In composite scenarios θ is not small (it can be smaller due to the addition of ad-hoc operators)

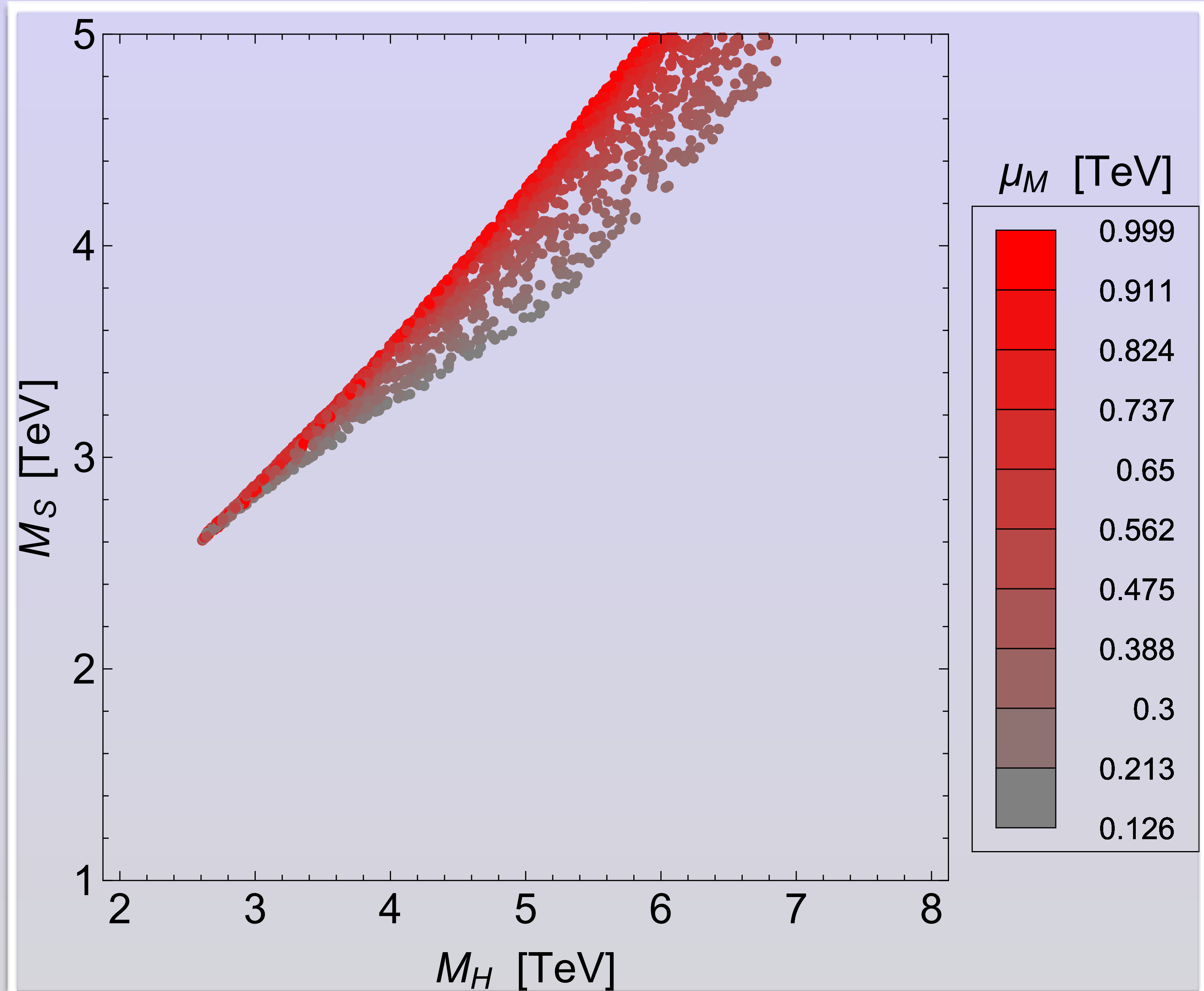
The minimal scenario

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

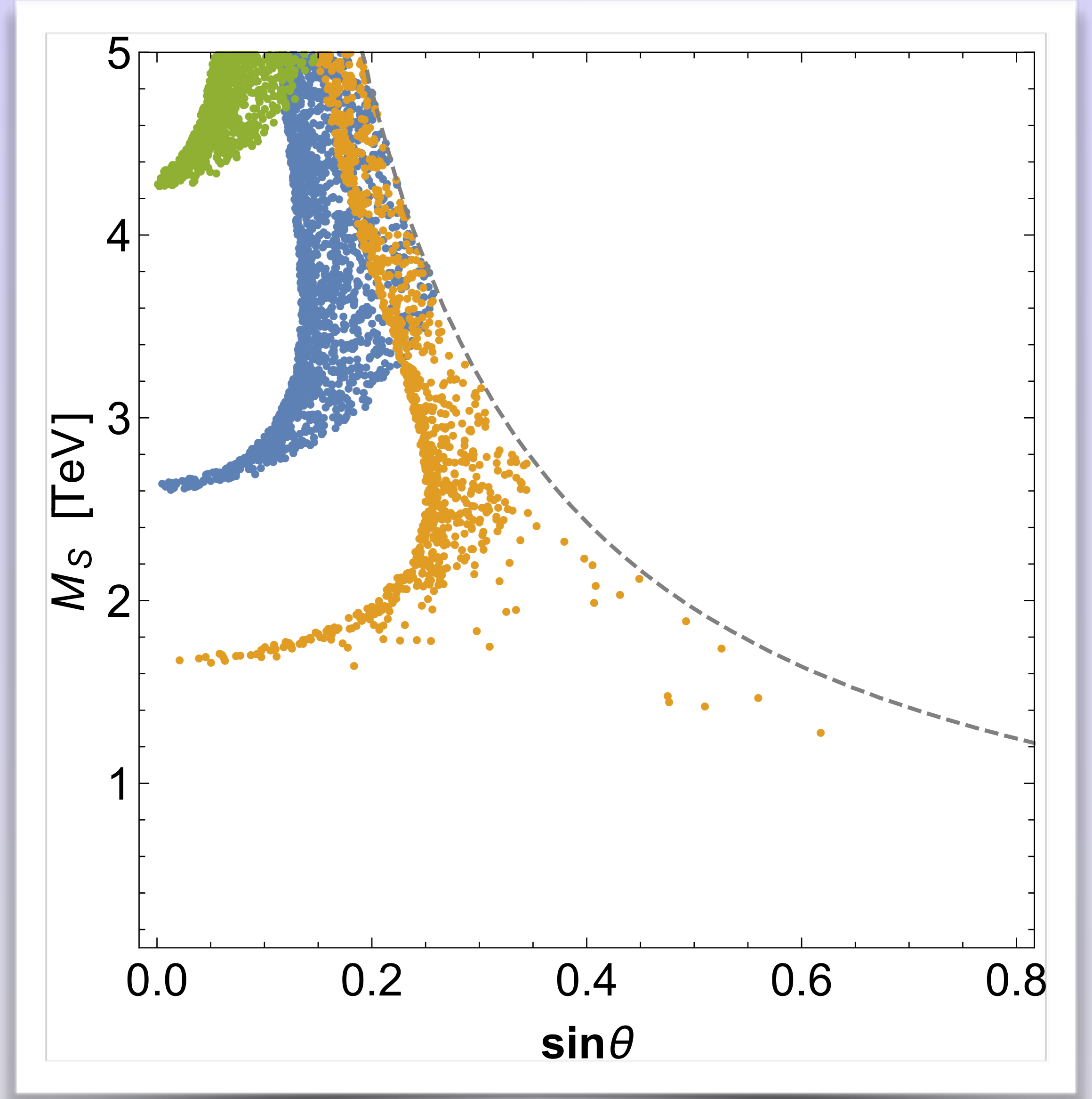


The minimal scenario

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



The Higgs mass as a constraint

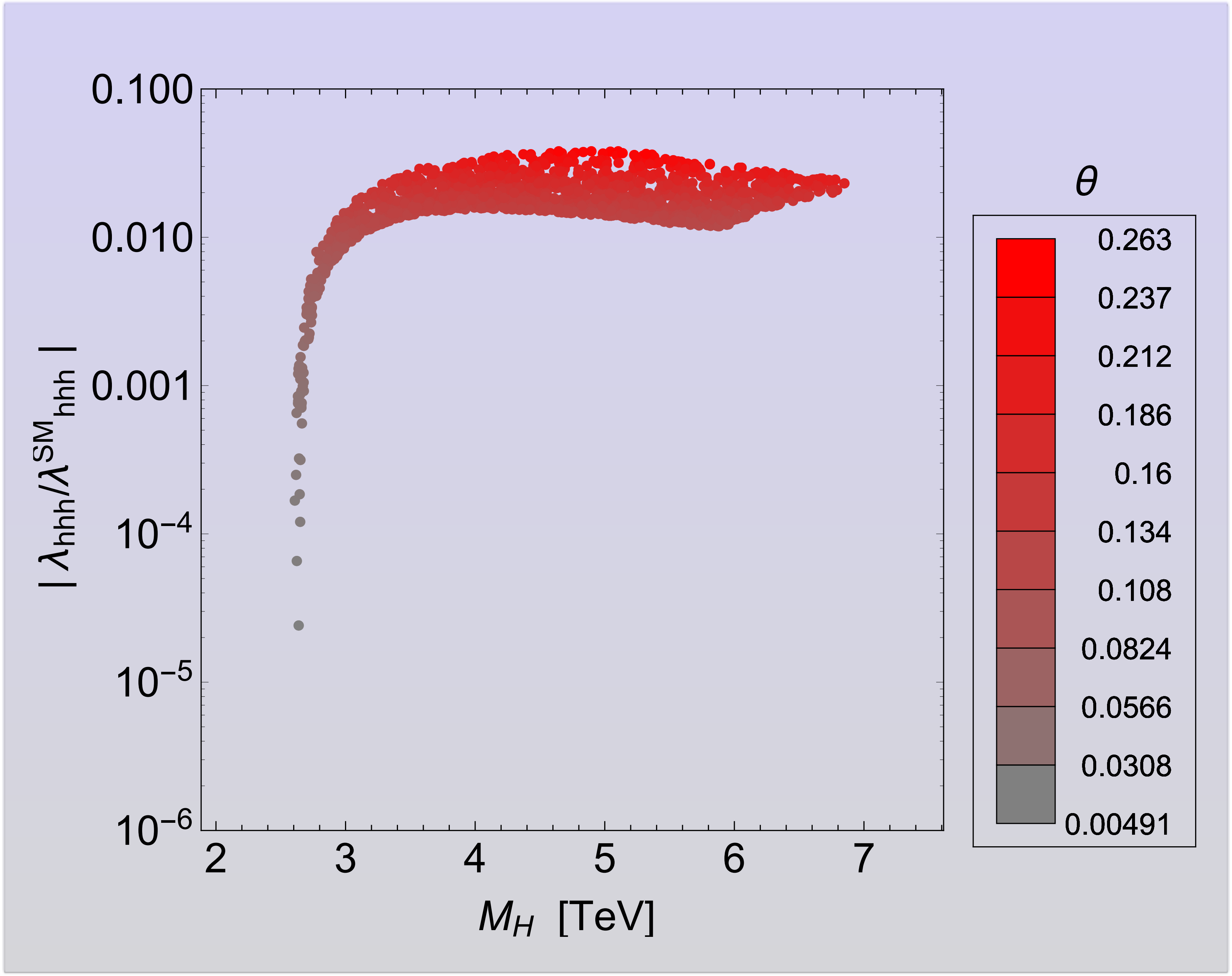


$$m_h = 125.09 \pm 0.21(stat.) \pm 0.11(syst.)$$

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

small θ and small self-coupling

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



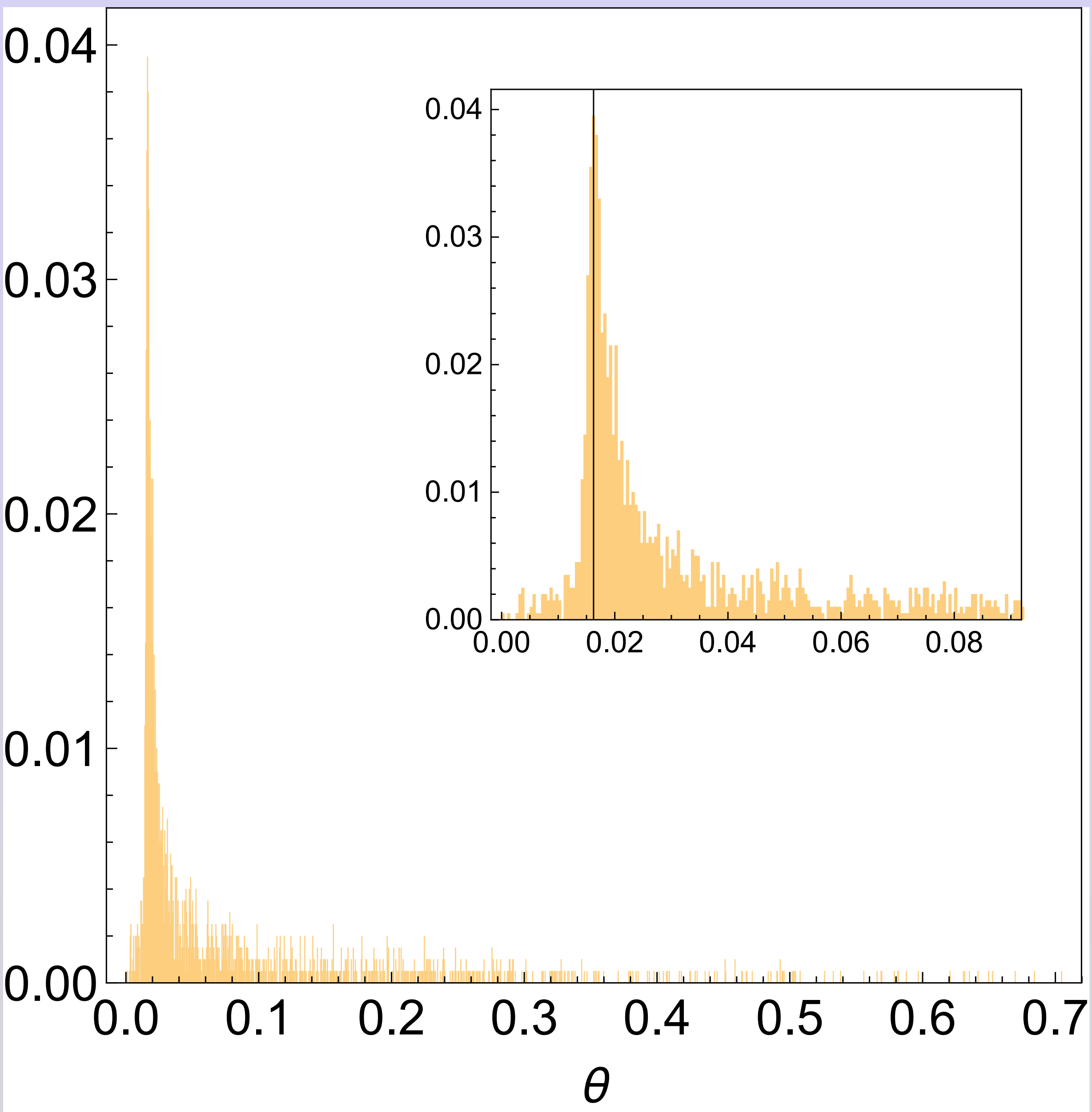
$$\frac{\lambda_{HHH}}{\lambda^{SM}_{hhh}} = v_{\rm EW}\,\frac{M_S^2\cos\alpha}{v\,m_h^2}$$

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

σ field and other scalars

non minimal scenario

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



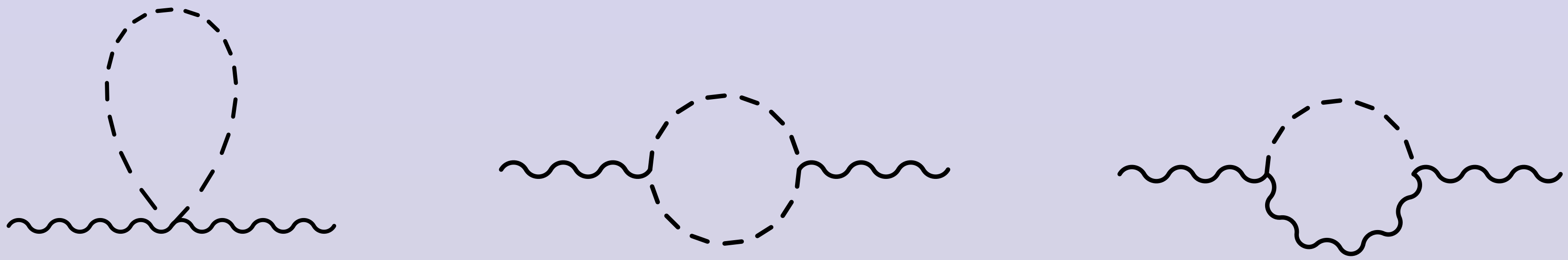
Assuming perturbativity of $\tilde{\lambda}$

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

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

EW Test of the model

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

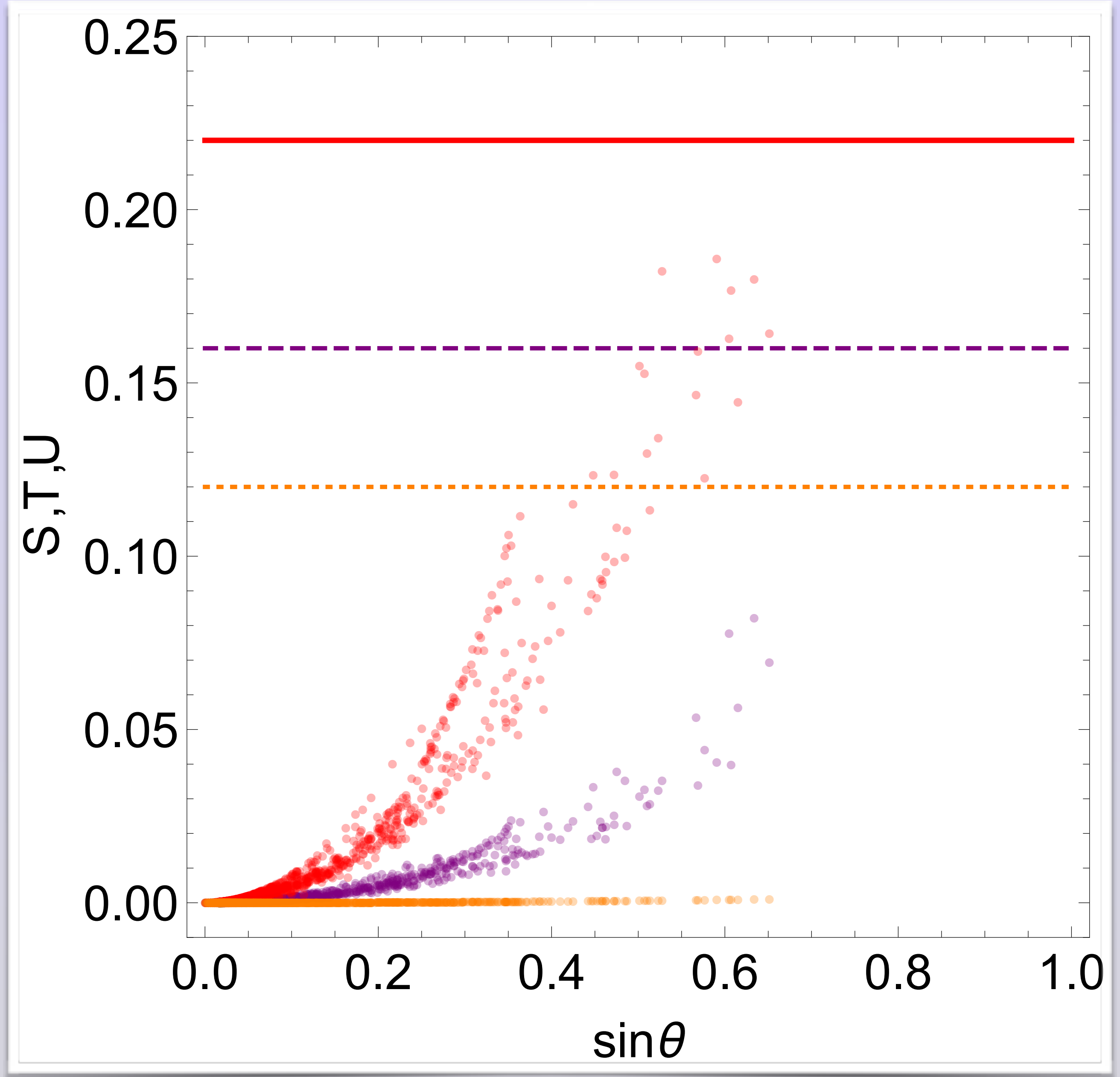


Oblique parameters S T U

Oblique Parameters

- T and U are very suppressed: dependence on cos(θ+α)

- S depends in the most generic case on the masses of extra massive scalars: dependence on cos(θ+α) and sinθ



Conclusions

- 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

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

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

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

Realization

- Scalar Sector is composite
- extra SU(2) gauge + 2 Dirac fermions (Sannino, Cacciapaglia JHEP 1404 (2014) 111)
- Fermion masses: difficult
- GUT more involved
- Hierarchy problem addressed
- light Higgs mass
- Top quark contributions prefer the Higgs as a massive scalar (need of extra operators for pNGB)

- Scalar sector is elementary
- Renormalisable potential
- Perturbative computations
- Fermion masses: straightforward
- Precision tests
- Interesting GUT scenarios
- Postpone hierarchy problem
- Top quark contributions prefer the Higgs as a GB

Different mass spectrum!