The Elementary Goldstone Higgs

Works in collaboration with
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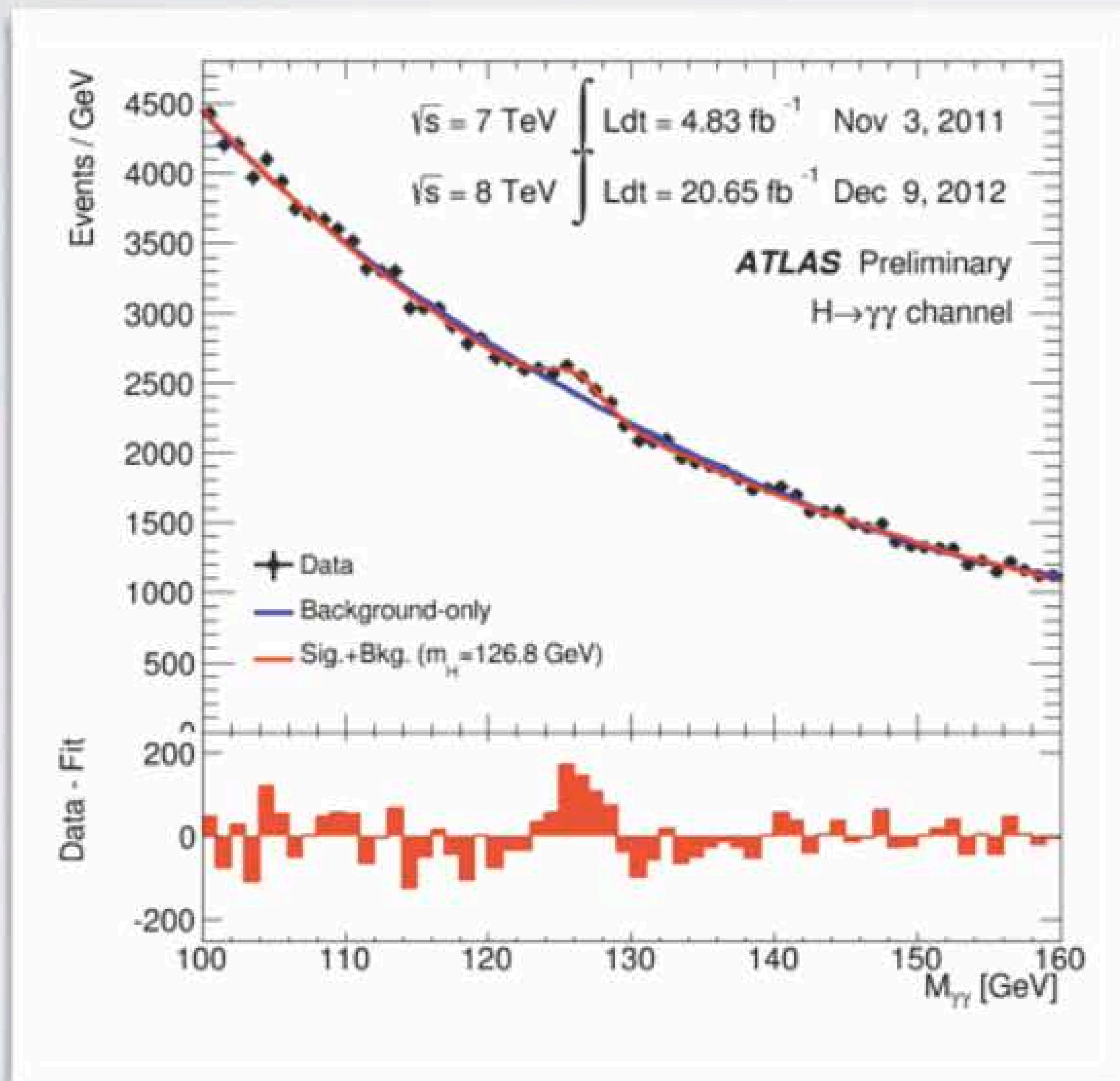
IPMU, 25 November 2015

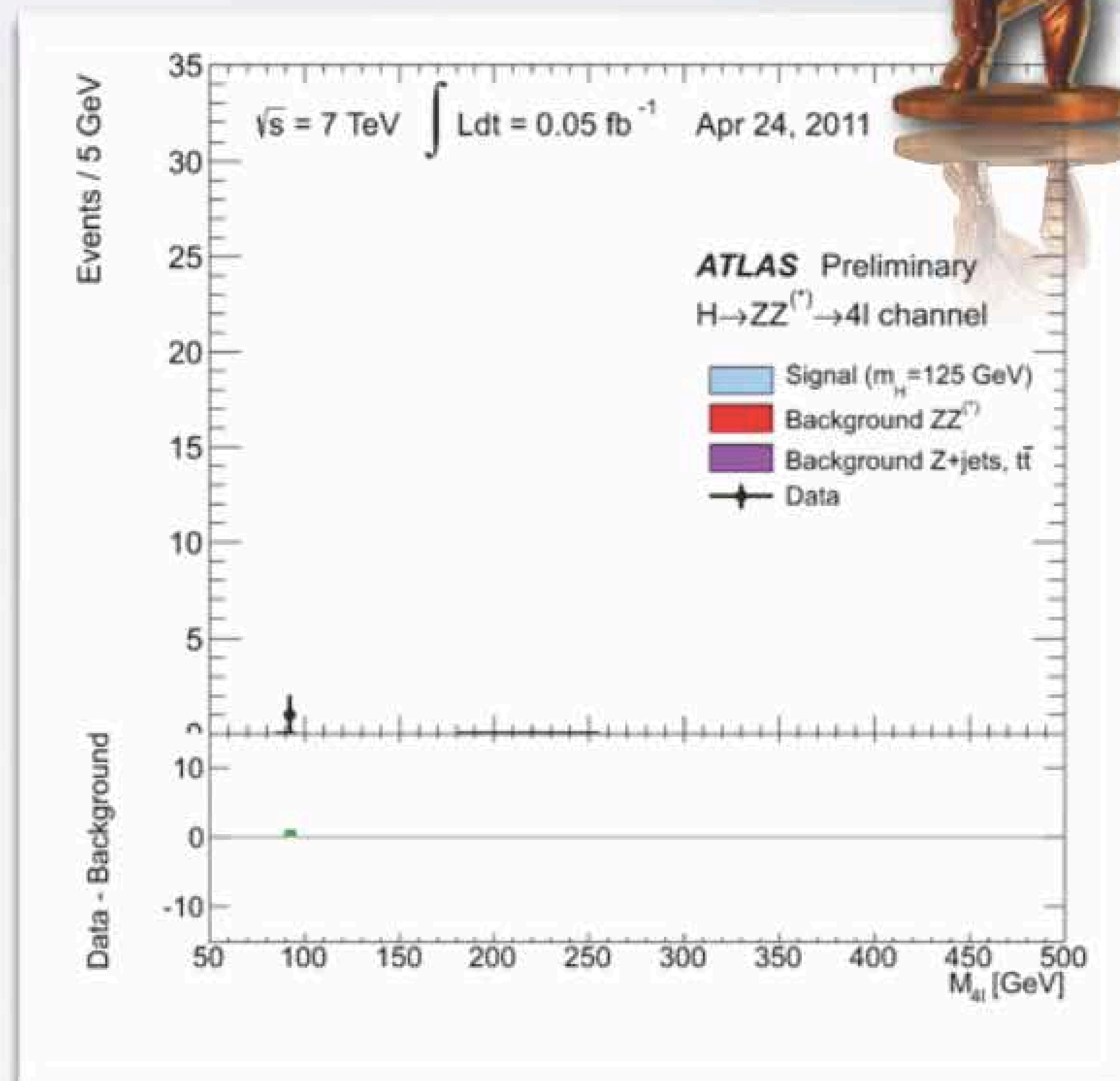
CP³ Origins
Cosmology & Particle Physics

UNIVERSITY OF SOUTHERN DENMARK

The discovery of the Higgs

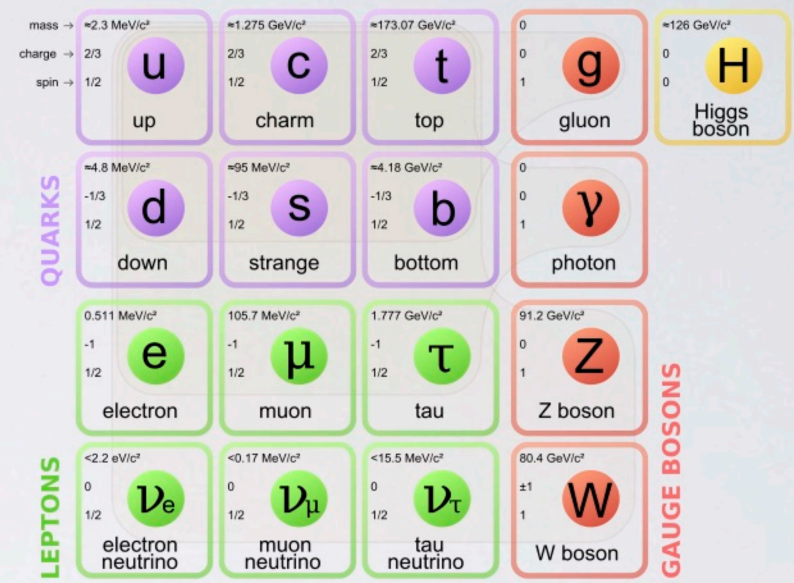
On the 4th of July 2012

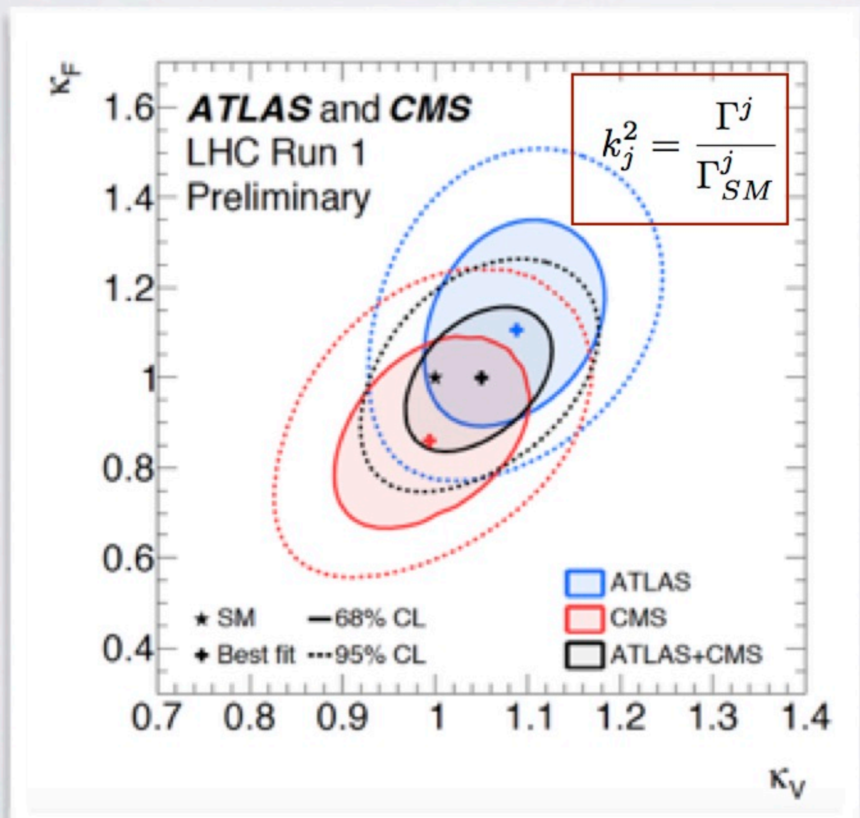


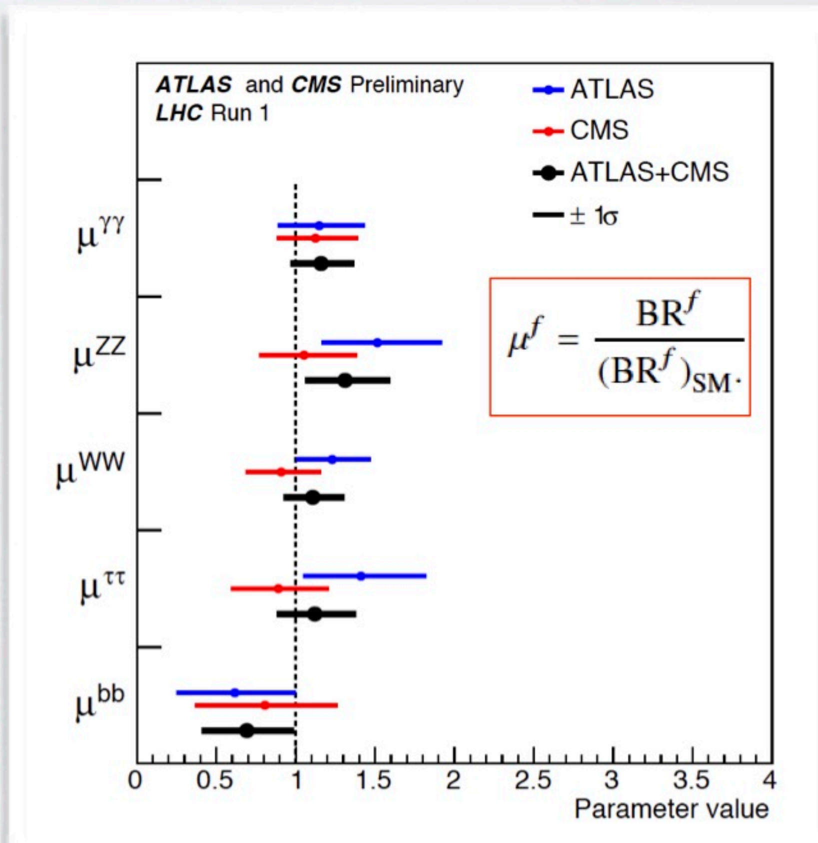


The Standard Model

- 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)







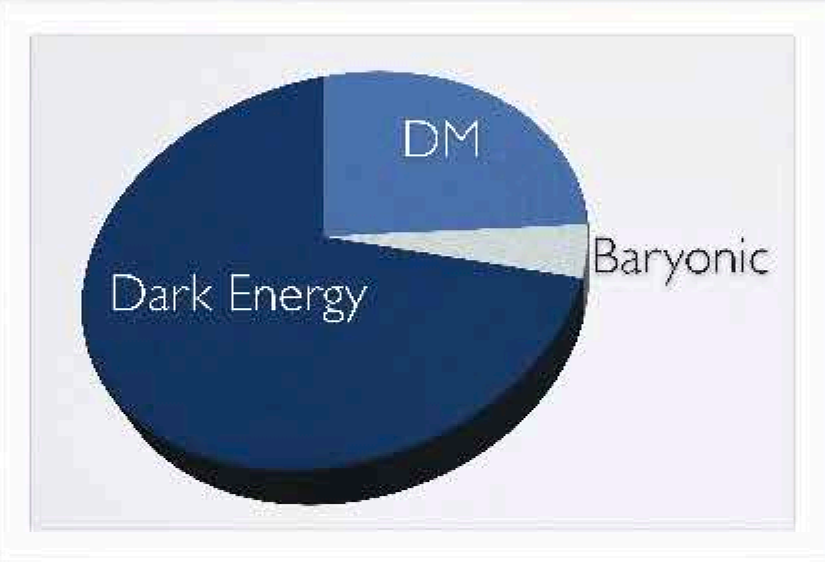
presented at LHCP-2015, 15th September 2015 [ATALS-CONF-2015-044; CMS-PAS-HIG-15-002]

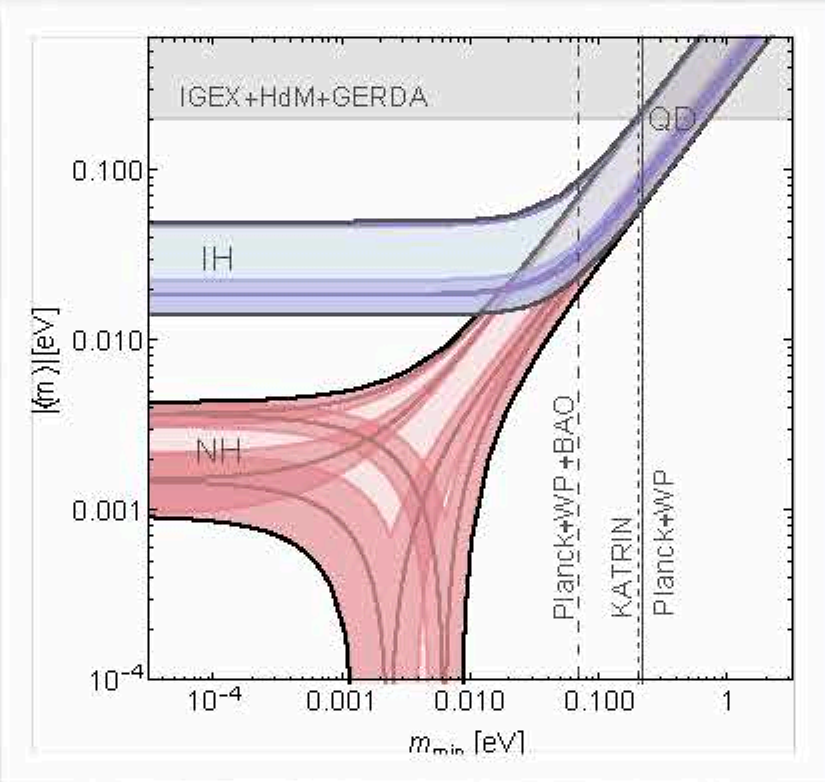
open problems & unknowns (pheno)

- Explanation of ***matter-antimatter*** asymmetry
- ***Elusive sector***: neutrinos and DM (BSM physics!)
  - ***Nature*** of massive neutrinos ($2\beta0\nu$): Dirac or Majorana

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

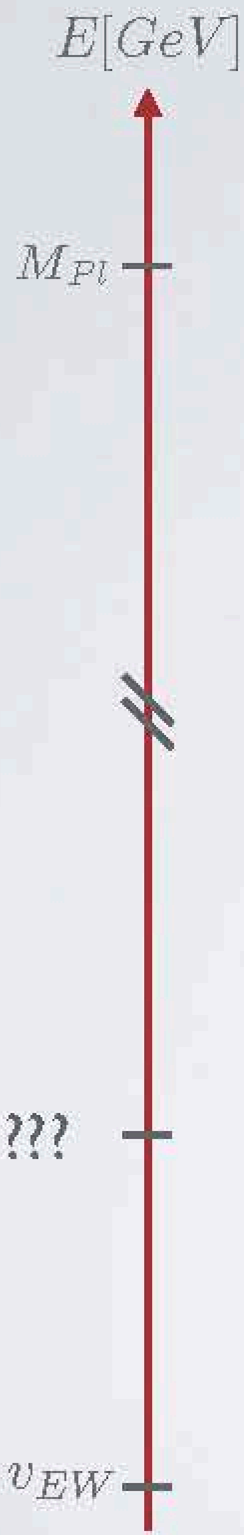
  - absolute value of neutrino masses, Hierarchy (normal or inverted) , CP-phases: δ, and Majorana phases
  - Connection between non zero neutrino masses and ***symmetries*** for the lepton mixing



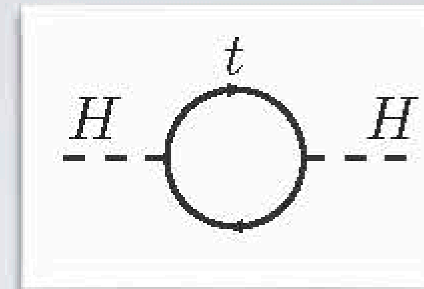


A. M. Eur.Phys.J.Plus 130 (2015) 11, 232

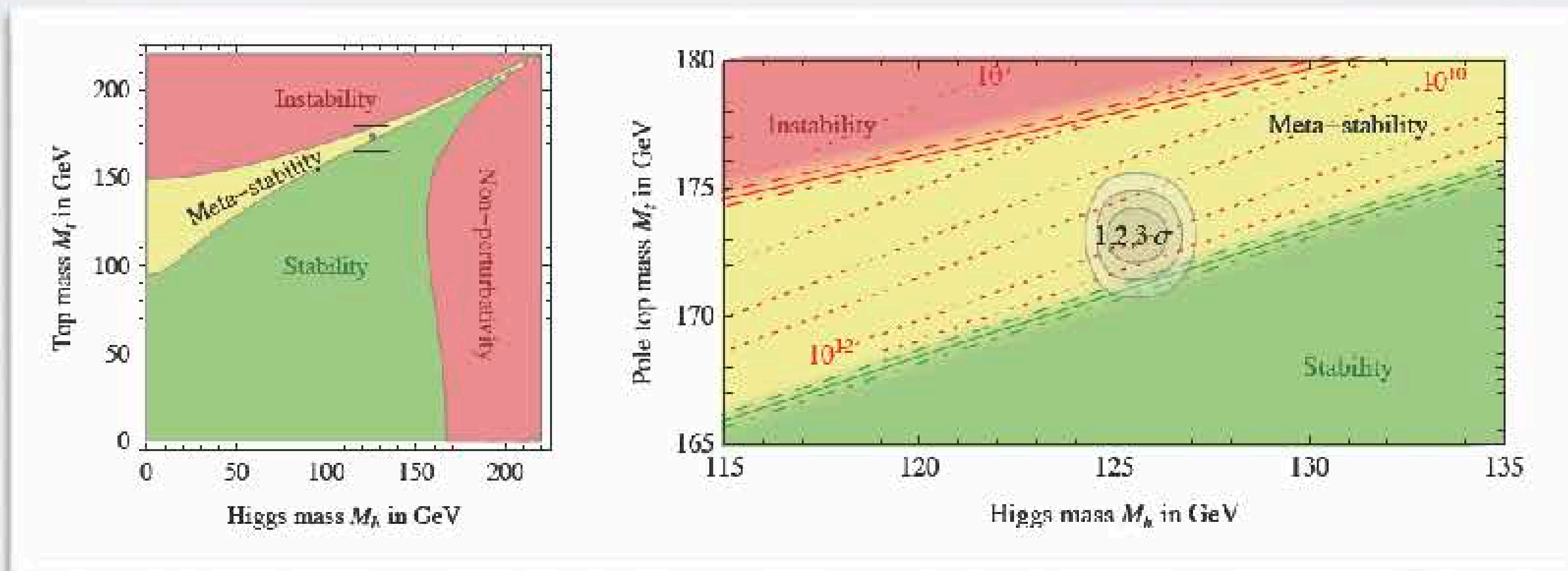
open problems (theory)



- ***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)



- The absence of absolute ***vacuum stability***



G. Degrassi et al., 1205.6497

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

- ***Flavour puzzle***: Why does Nature repeat Herself?

Atlas for model building

of course not complete ...

Atlas for model building

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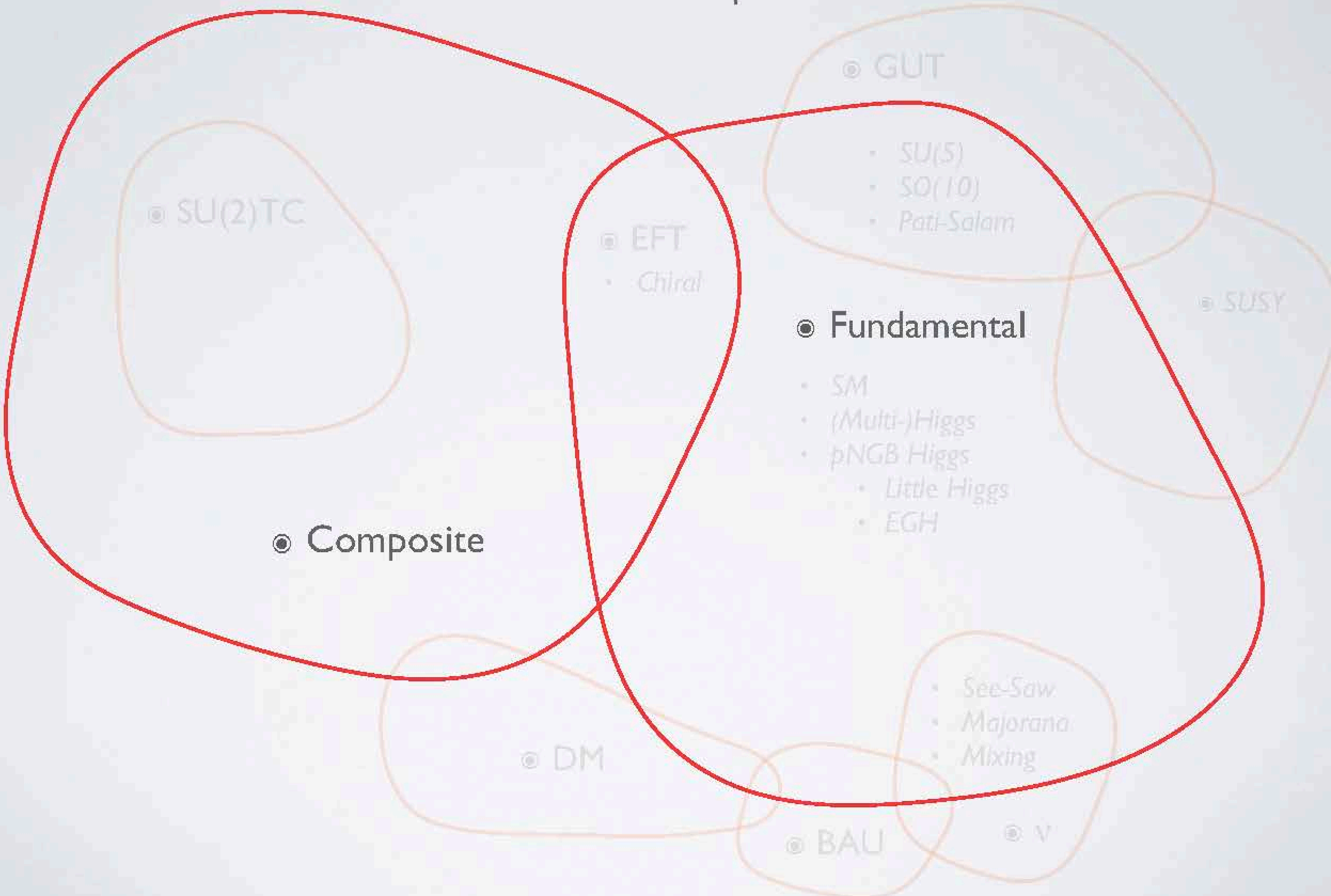
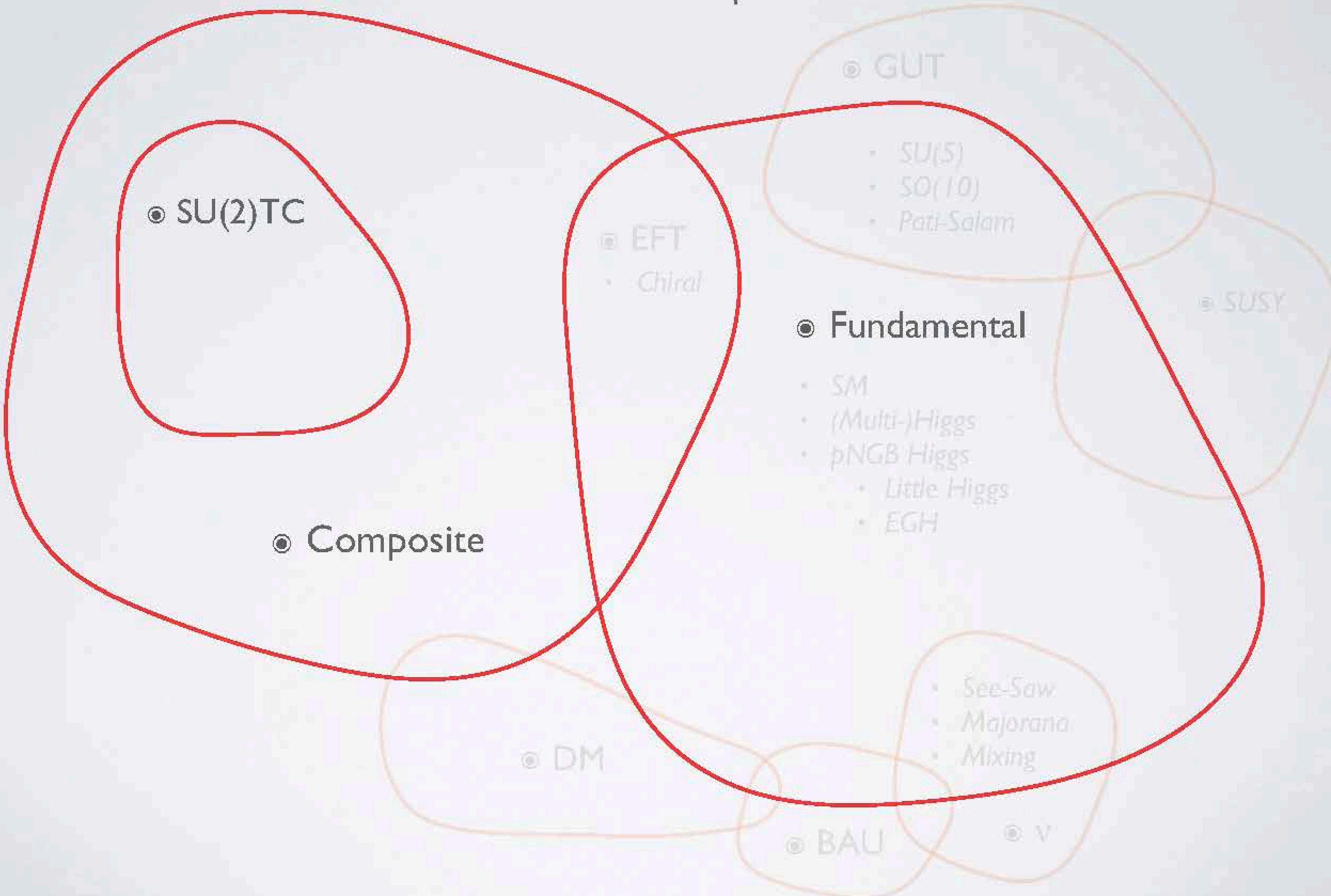


Atlas for model building

of course not complete …



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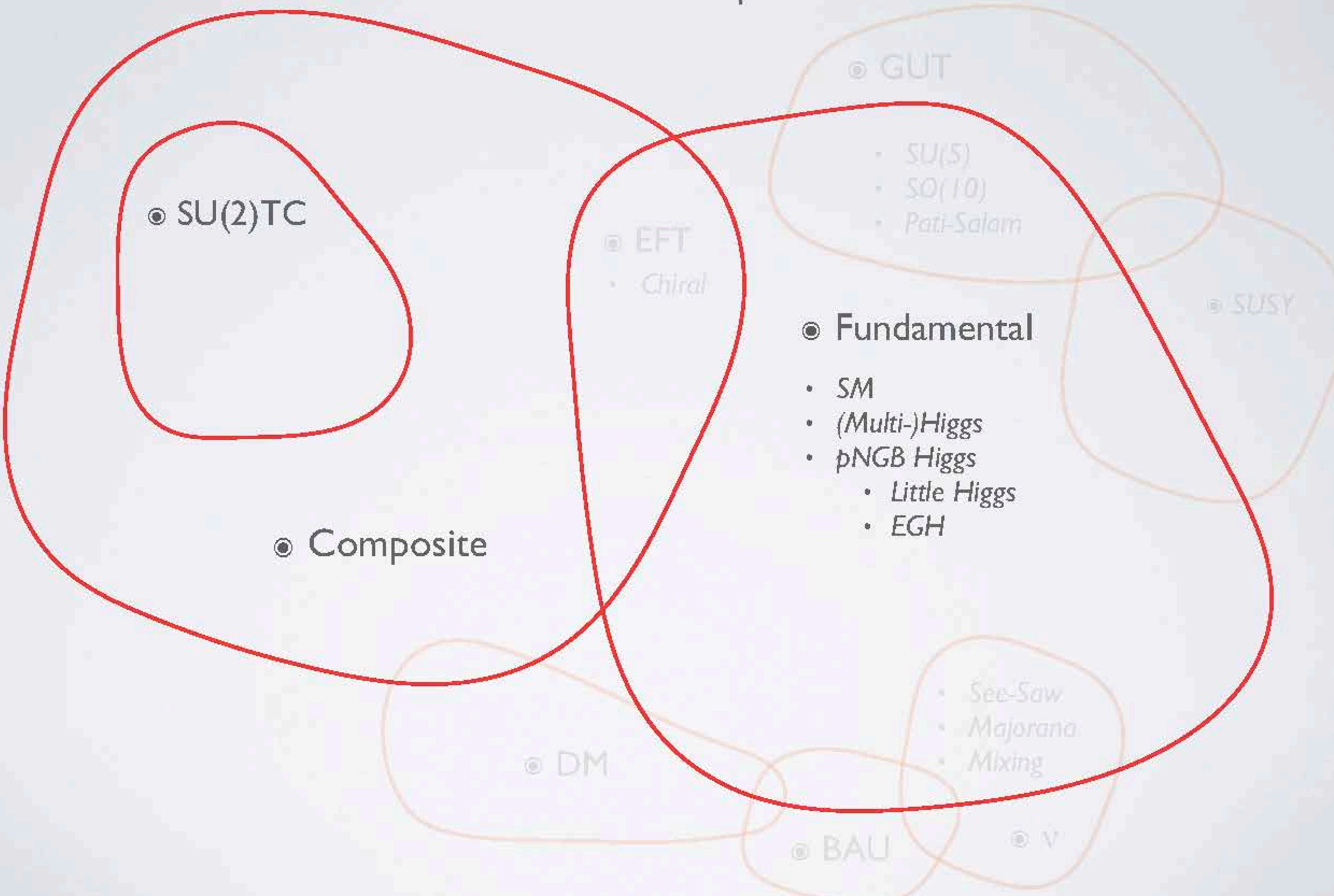

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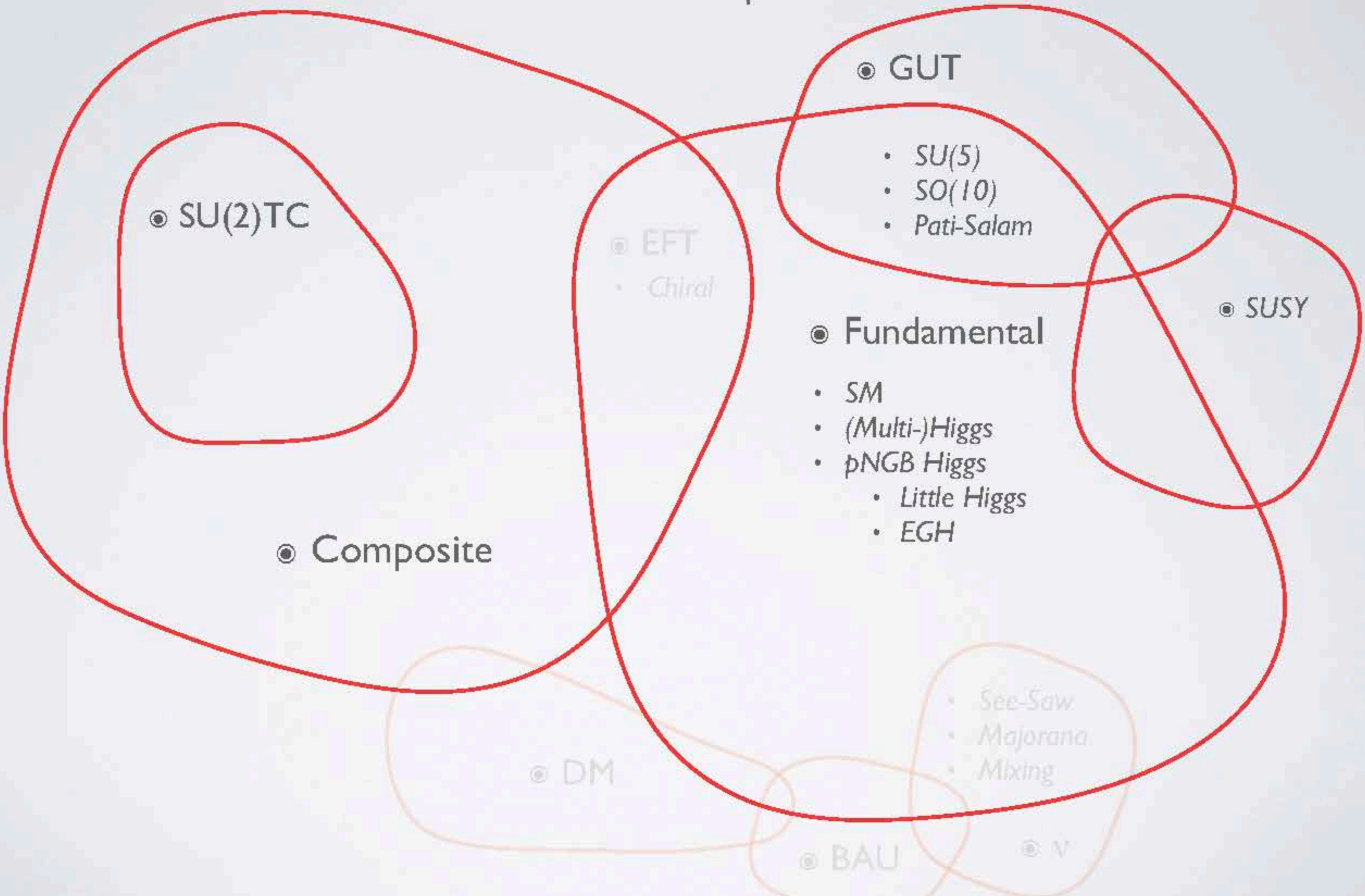

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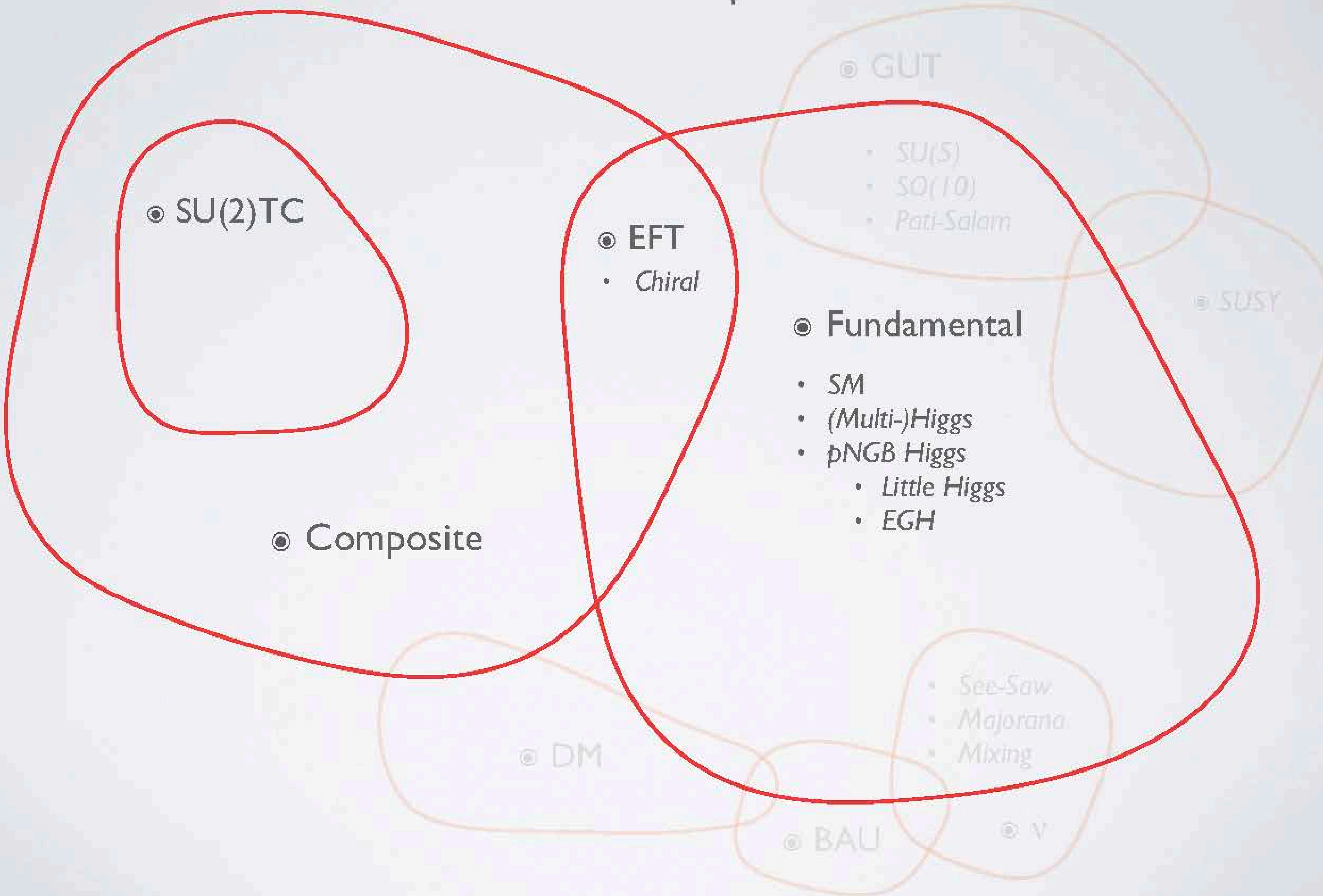

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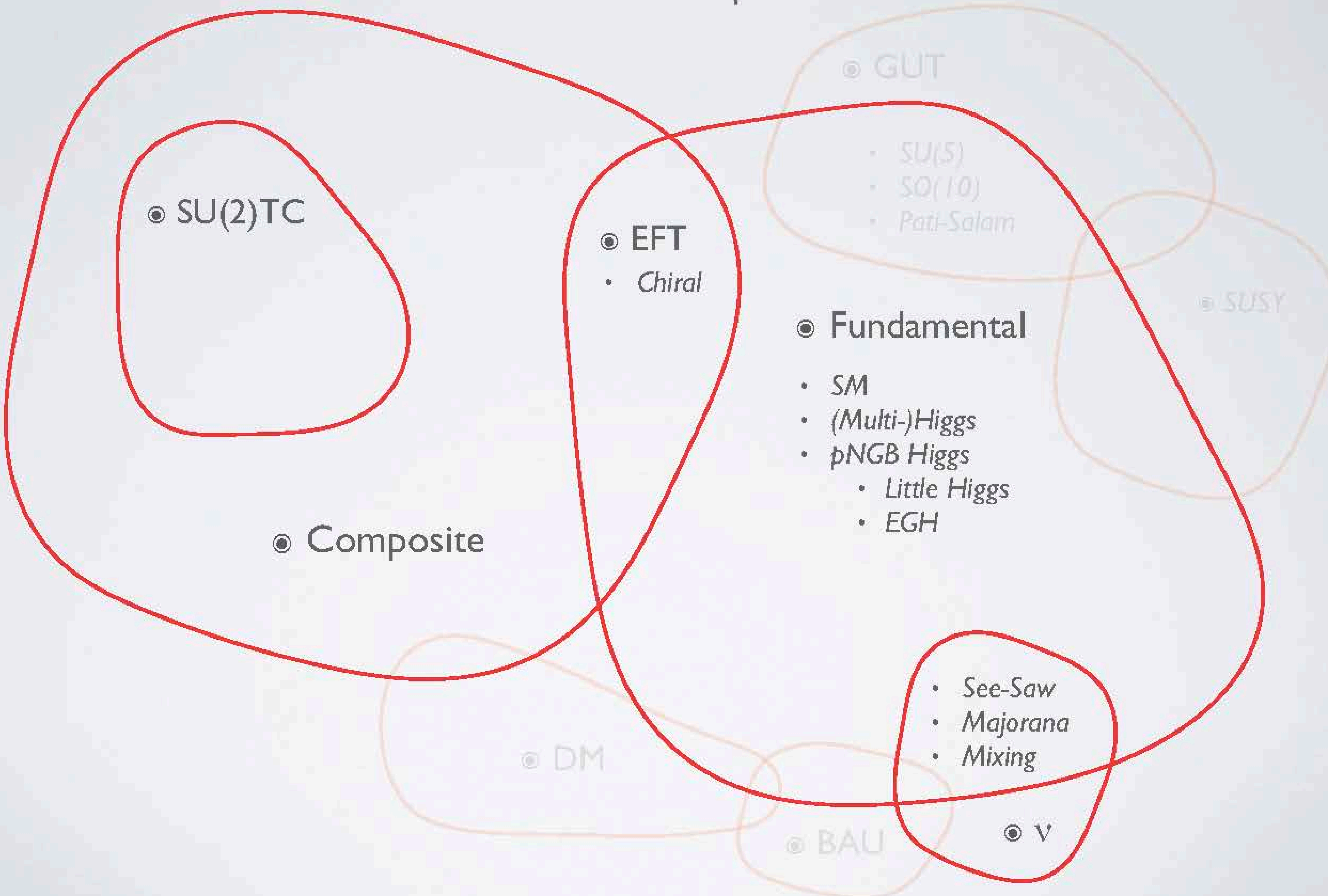

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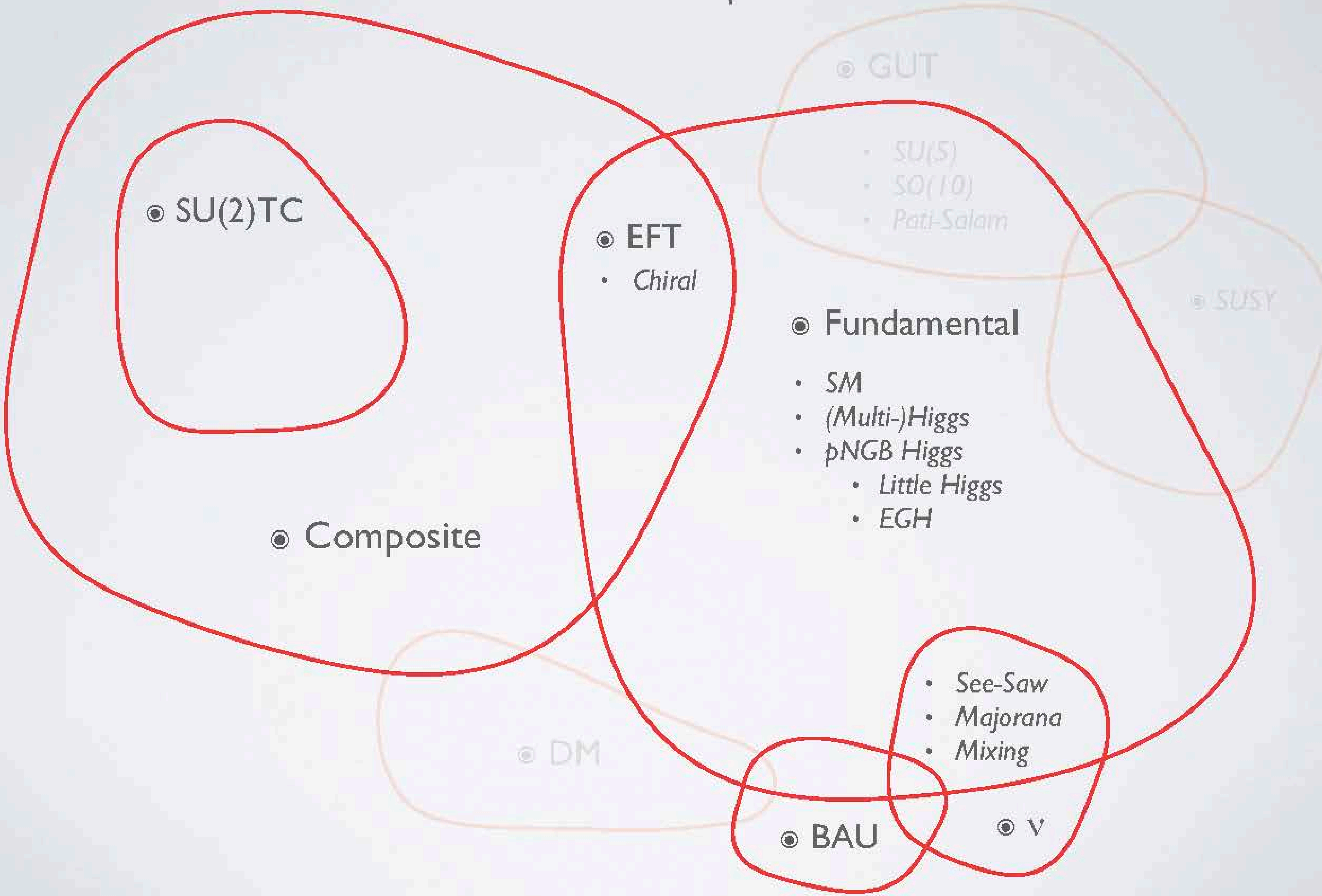

Atlas for model building

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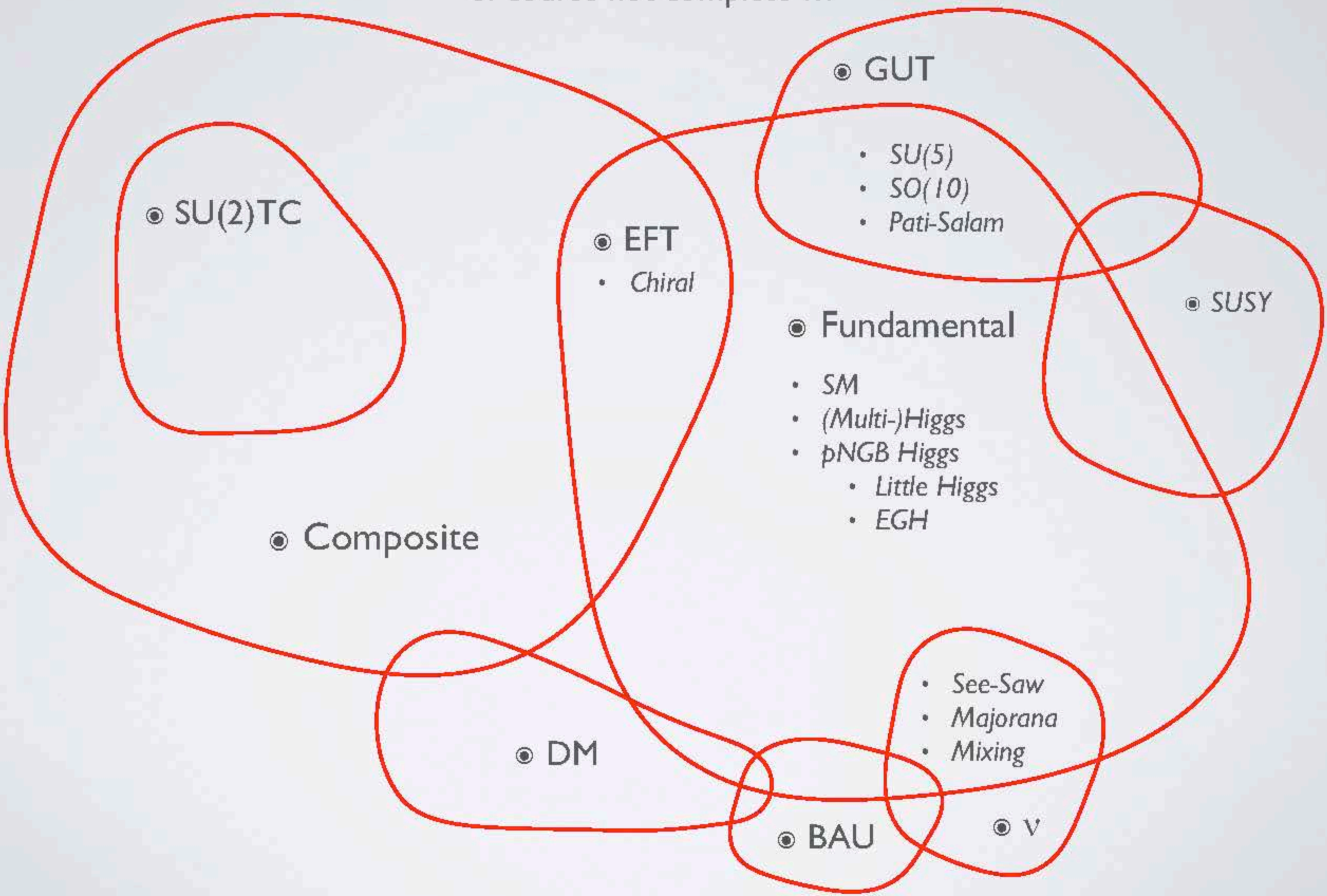
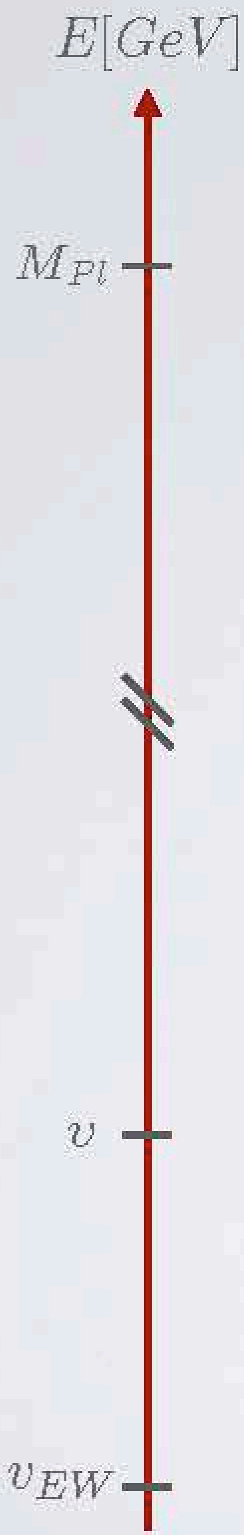


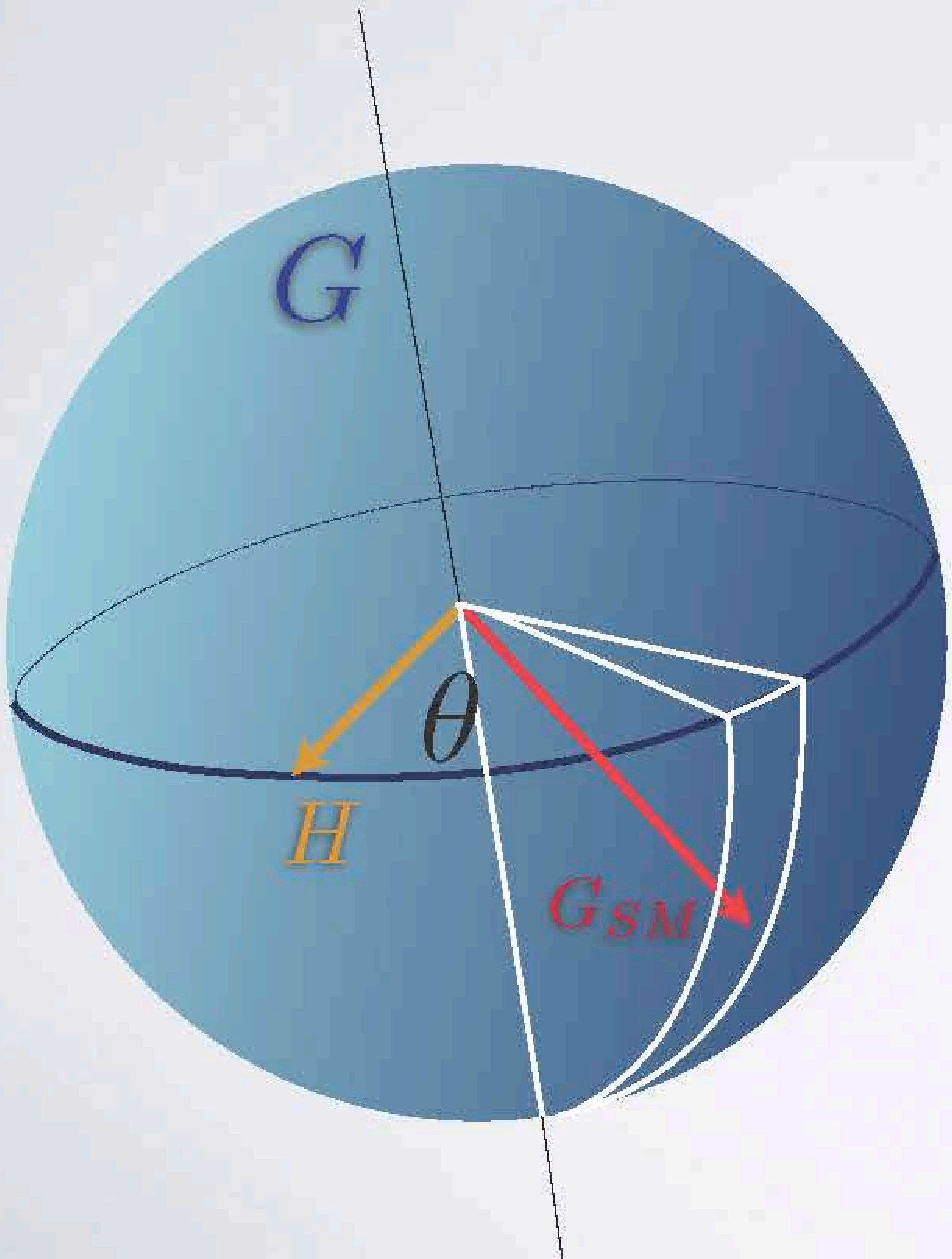
Elementary Goldstone Higgs



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 explore a different paradigm where the Higgs sector symmetry is larger
- 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.

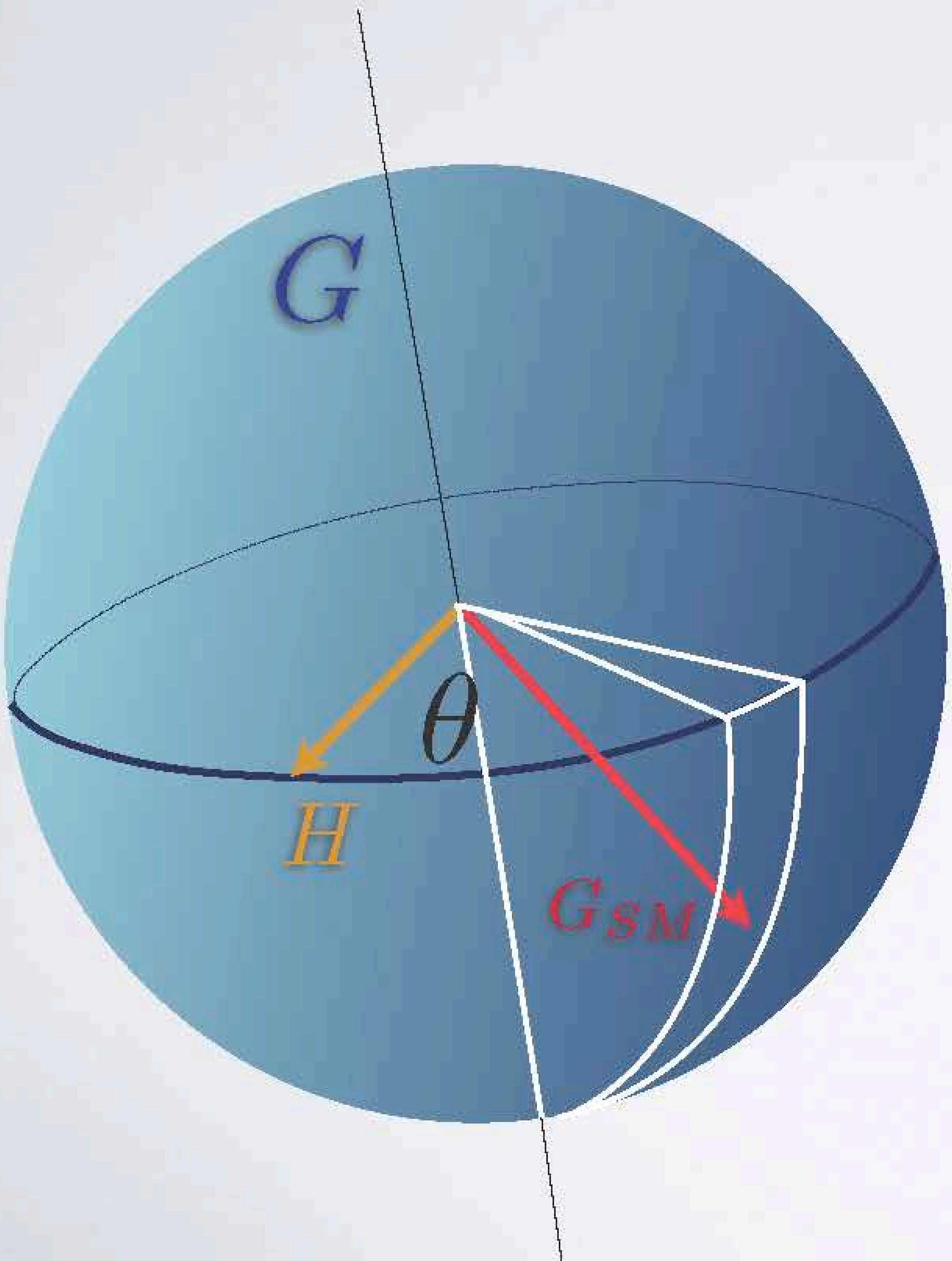
Alignment of the vacuum



- We study **G = SU(4)** and **H = Sp(4)**
- The angle θ describes the orientation of the vacuum alignment of the theory and the amount of breaking of the SM gauge group
- The Higgs arises as one of the 5 Goldstone bosons belonging to the coset $SU(4)/Sp(4)$.
- The 1-loop corrections are responsible of the value of θ

Similar description can be found in
Peskin Nucl. Pays. B 175 (1980) 197-233
Preskill Nucl Phys. B177 (1981) 21-59

Alignment of the vacuum



$\theta = 0$

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

$\theta = \pi/2$

- EW breaks completely
- Higgs is a massive excitation

Realization

Sannino, Cacciapaglia JHEP 1404 (2014) 111

- Scalar Sector is composite
- extra SU(2) gauge + 2 Dirac fermions
- 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!

The EGH model

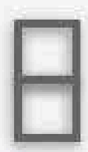
$$SO(6) \sim SU(4) \;\rightarrow\; Sp(4) \sim SO(5)$$

T_a 10 generators of Sp(4)

X_a 5 broken generators of SU(4)

How do I break it?

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



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

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

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

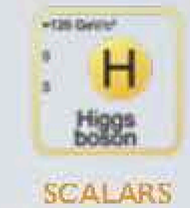
Electroweak vacuum

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

Technicolor vacuum

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

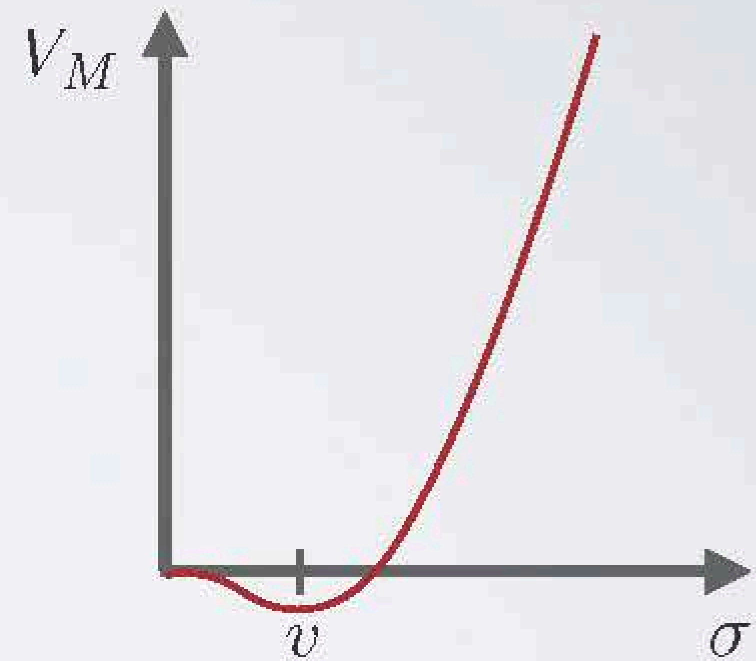
Scalar Tree-Level Spectrum I



+ …

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

$$Pf(M) = \frac{1}{8} \epsilon_{ijkl} M_{ij} M_{kl}$$



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

$$\mathcal{M}^2(\Phi)\big|_{\sigma=f} \equiv \partial_{\phi_i}\partial_{\phi_j} V_M\big|_{\sigma=f} \,,$$

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

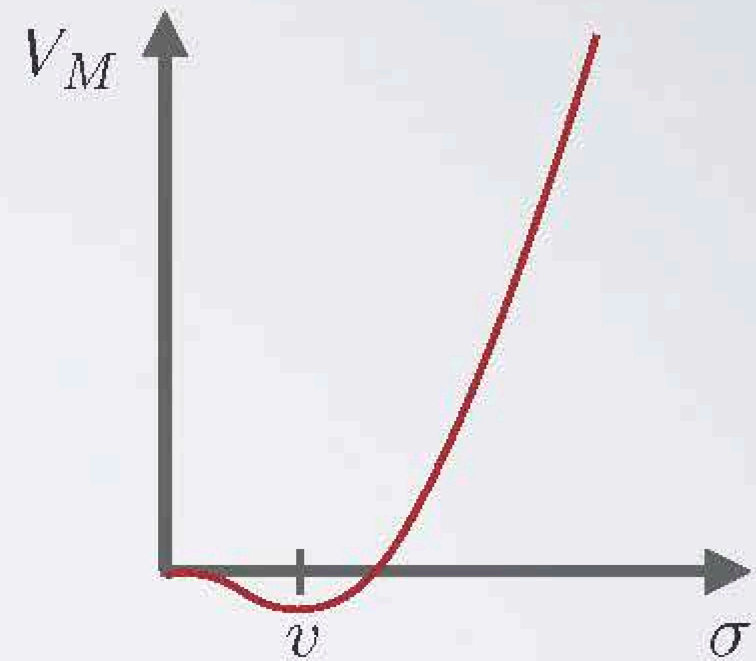
Scalar Tree-Level Spectrum II

SCALARS + DARK MATTER

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

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

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



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

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

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

Electroweak Gauge Bosons

The electroweak interactions appear in the kinetic term of the Lagrangian

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

where

$$D_\mu M = \partial_\mu M - i\left(G_\mu M + M G_\mu^{\text{T}}\right)$$

$$G_\mu = g W_\mu^i T_L^i + g' B_\mu T_R^3$$

which gives the masses

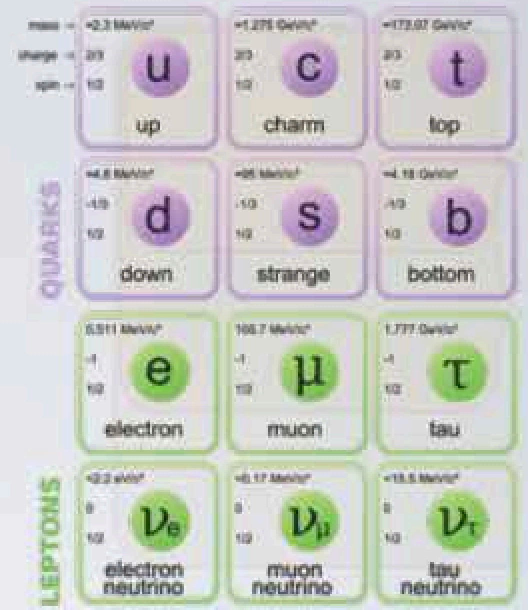
$$m_W^2 = \tfrac{1}{4} g^2 v^2 \sin^2\theta$$

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

$$m_A^2 = 0$$

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

Yukawa Interactions



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

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

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

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

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

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

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

Neutrinos

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

- $\mathbf{L}_\alpha = \left(L, \quad \tilde{\nu}, \quad \tilde{\ell}\right)^T_{\alpha L} \sim \mathbf{4}$

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

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

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

$$
-\mathcal{L}^{\mathrm{lep}} = Y^\ell_{\alpha\beta} \frac{f \sin\theta}{\sqrt{2}} \, \overline{\ell}_{\alpha L} \ell_{\beta R} + Y^\nu_{\alpha j} \frac{f \sin\theta}{\sqrt{2}} \, \overline{\nu}_{\alpha L} \nu_{jR} + \frac{1}{2} (M_R)_{jk} \, \overline{\nu}_{jR} \, (\nu_{kR})^c
$$

$$
m_\nu = -m_D \, M_R^{-1} \, m_D^T \quad \text{and} \quad m_D = Y^\nu \frac{f \sin\theta}{\sqrt{2}} = Y^\nu \frac{v_{\mathrm{EW}}}{\sqrt{2}}
$$

Quantum Corrections

The Renormalized Coleman-Weinberg potential at 1-loop:

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

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

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

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

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

What fixes θ ?

- Gauge and top corrections
- Explicit breaking of global symmetry

  - minimization of the (tree-level)+CW to determine vet
  - constraints: couplings close to SM values

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

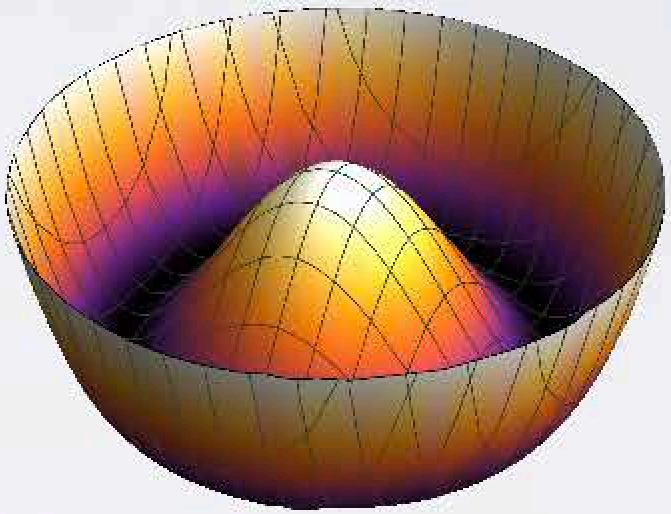
Parameters, Constraints and Minimization

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

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

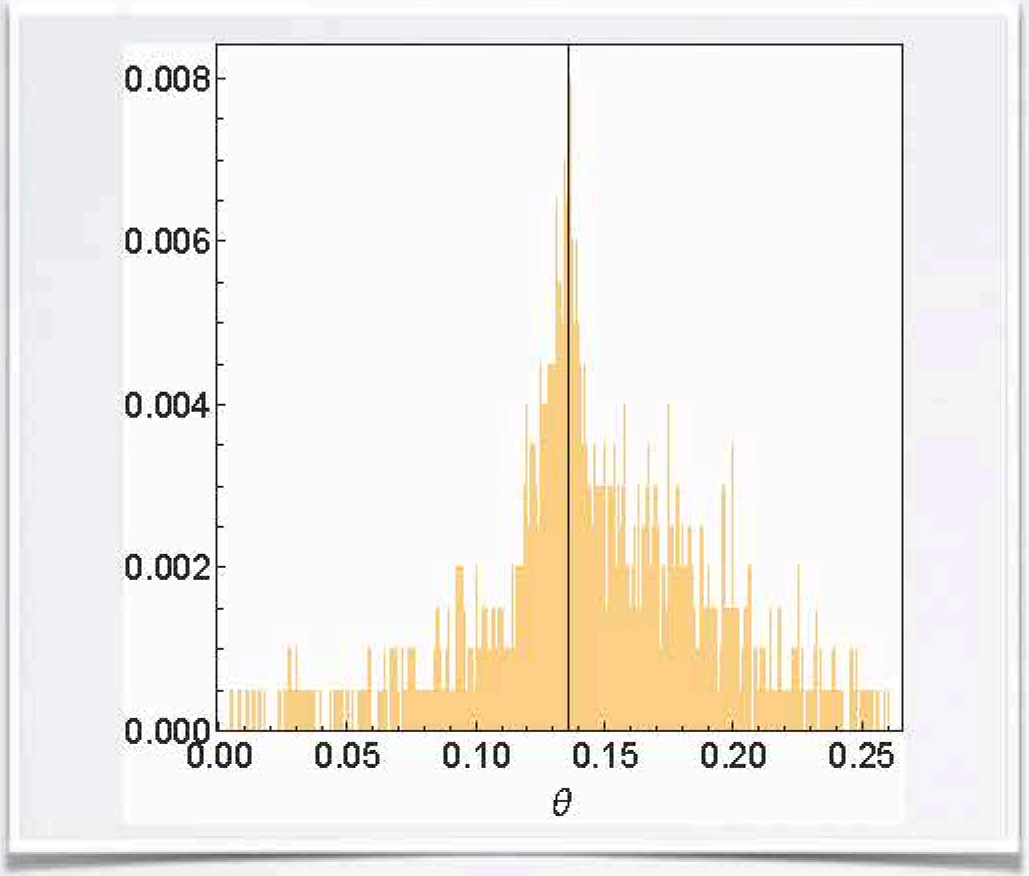
$$c_V = 1.01^{+0.07}_{-0.07} \qquad c_f = 0.89^{+0.14}_{-0.13}$$

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

Small θ via radiative corrections

in the minimal scenario

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



Assuming perturbativity of $\tilde{\lambda}$

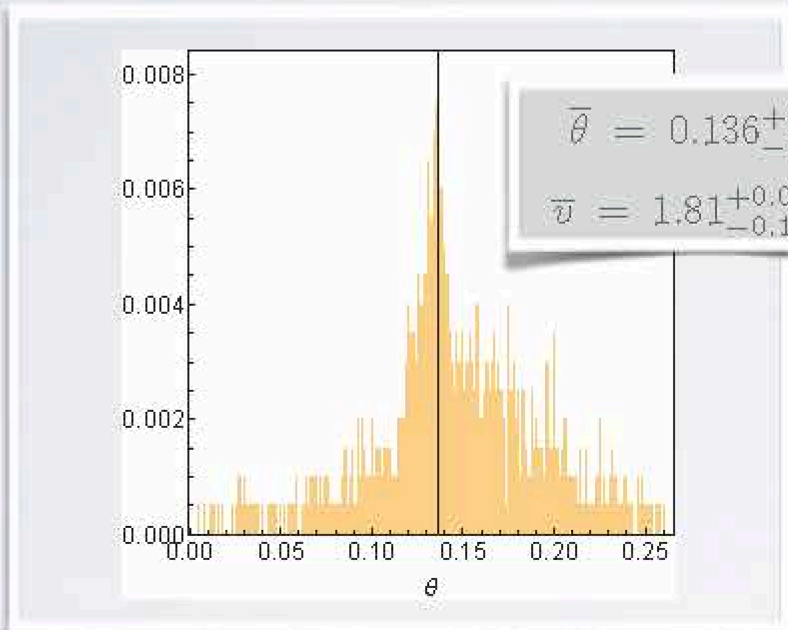
$$\overline{\theta} = 0.136^{+0.006}_{-0.012}\,,$$

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

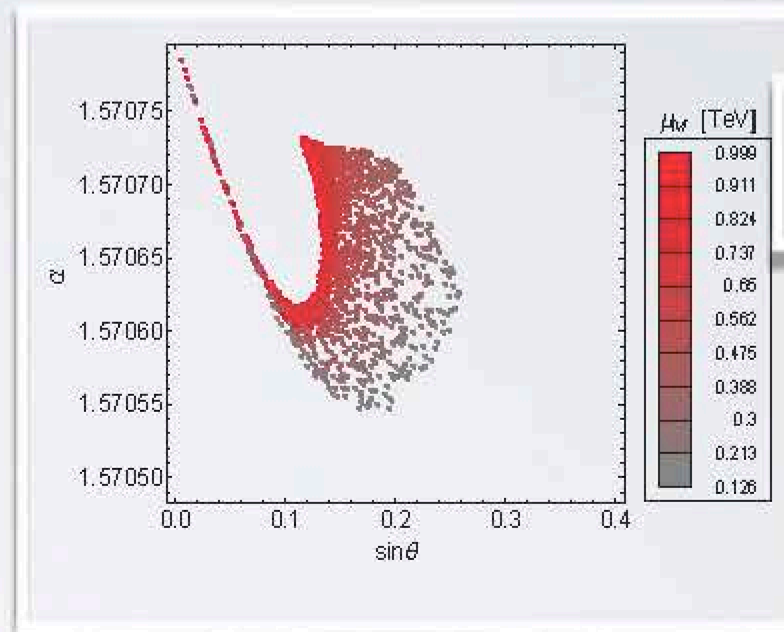
In composite scenarios θ is not small (it can be smaller due to the addition of ad-hoc operators)

The minimal scenario

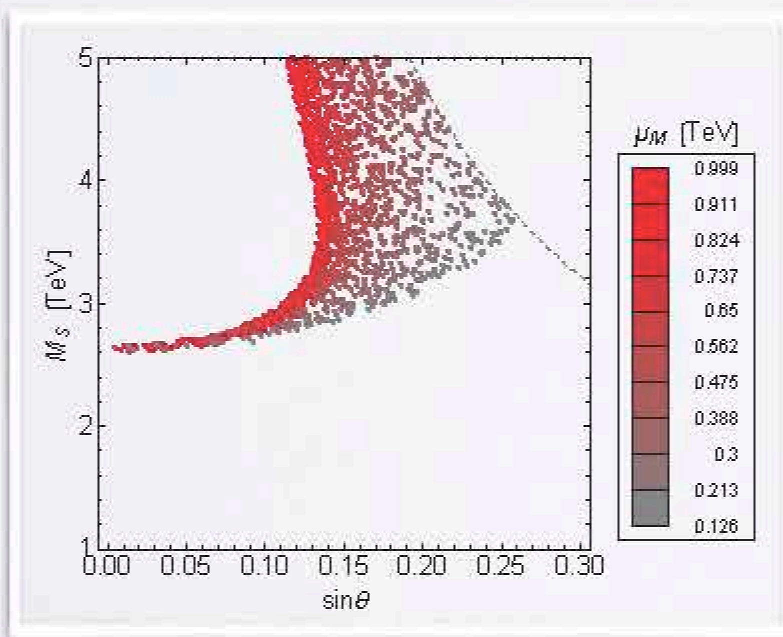
$$v\,,\quad \theta\,,\quad M_S\quad \mu_M\,,\quad \tilde{\lambda}$$

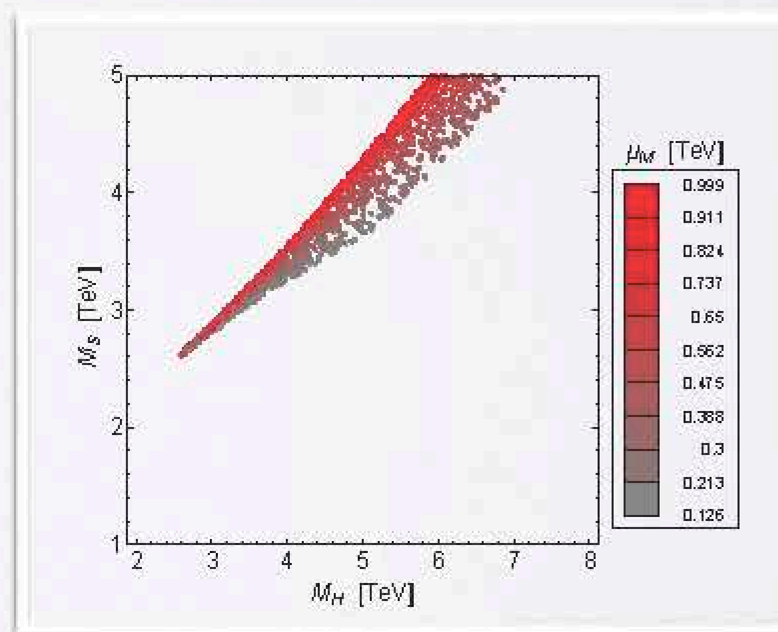


$$\overline{\theta}\;=\;0.136^{+0.006}_{-0.012}\,,$$
$$\overline{v}\;=\;1.81^{+0.08}_{-0.15}\;\mathrm{TeV}$$



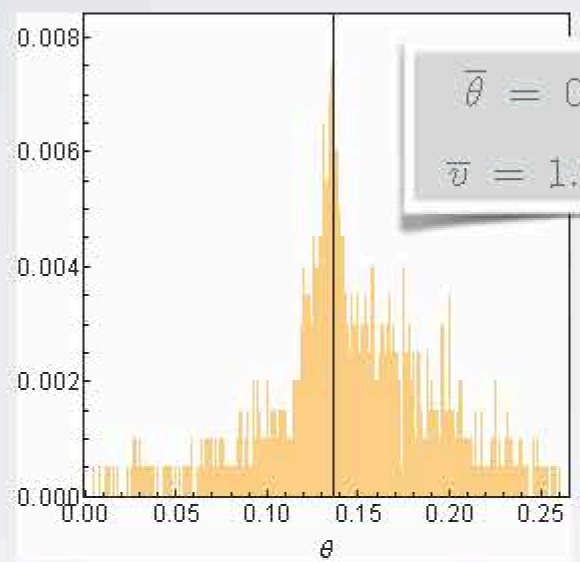
$$\overline{\alpha} = 1.57$$





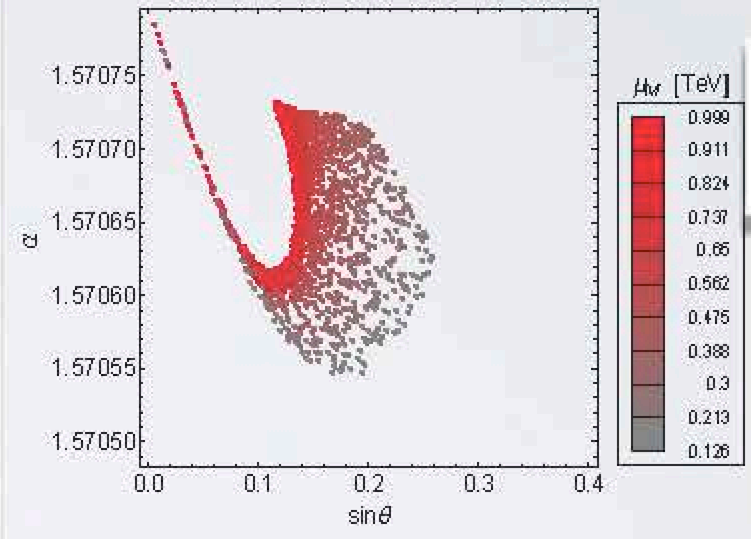
The minimal scenario

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

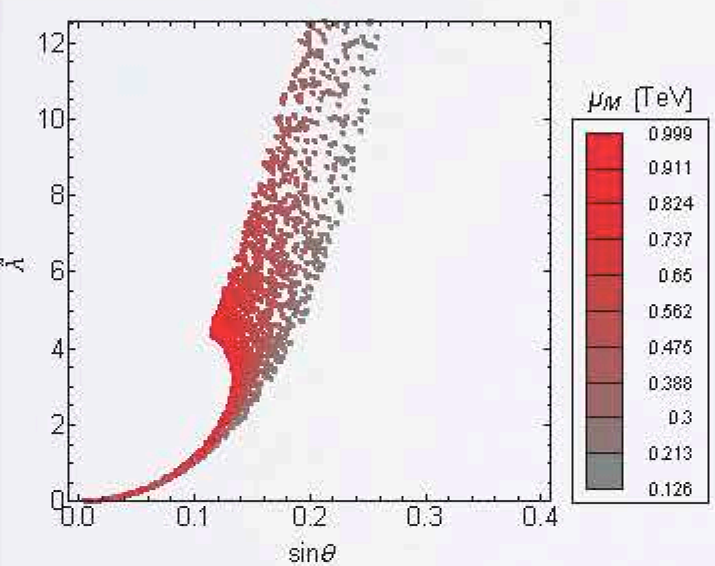


$\overline{\theta} = 0.136^{+0.006}_{-0.012}\,,$

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



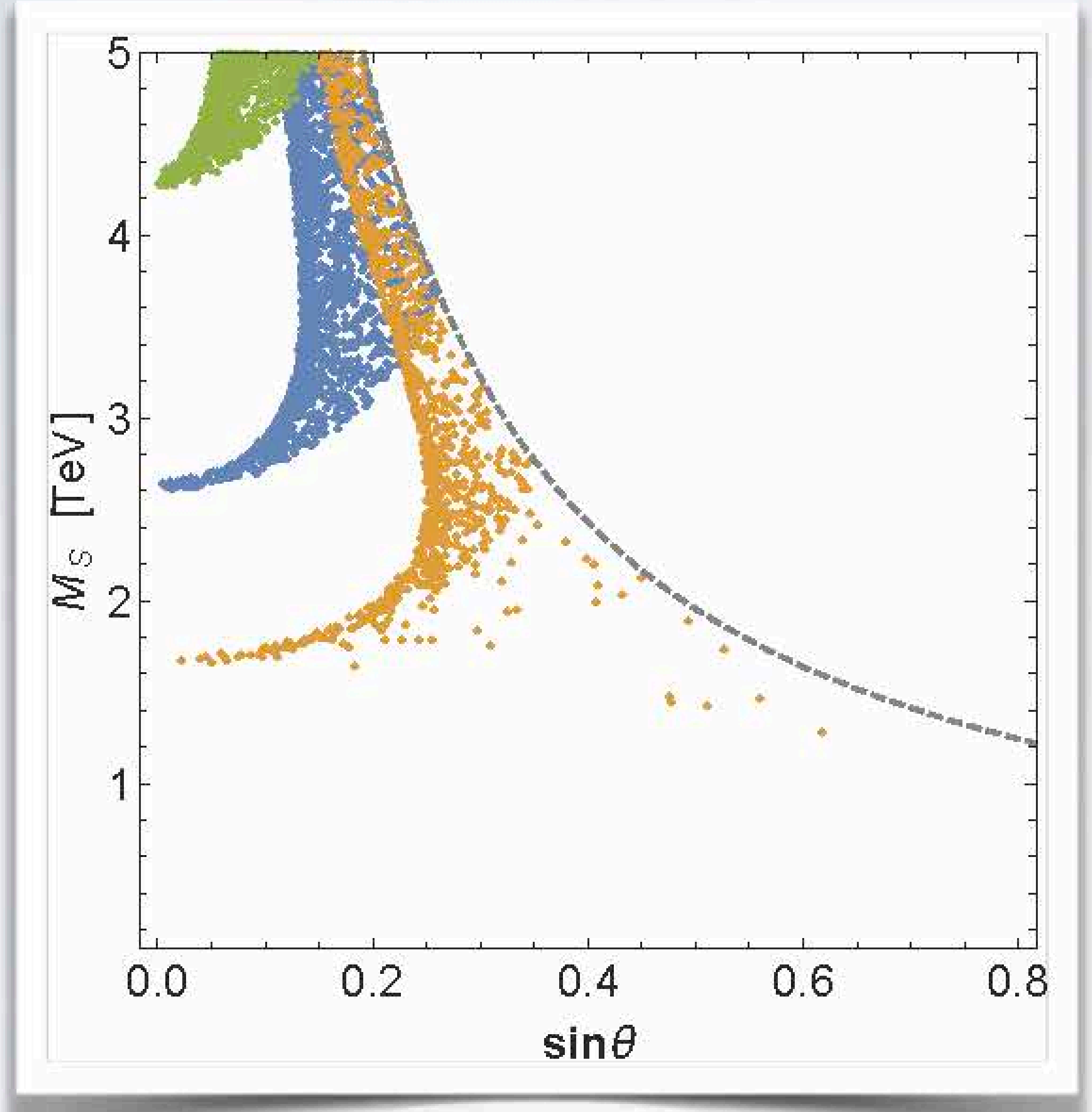
$\overline{\alpha} = 1.57$



(for $M_S \approx 2.6$ GeV, $K \approx 90$)

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

The Higgs as a constraint



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

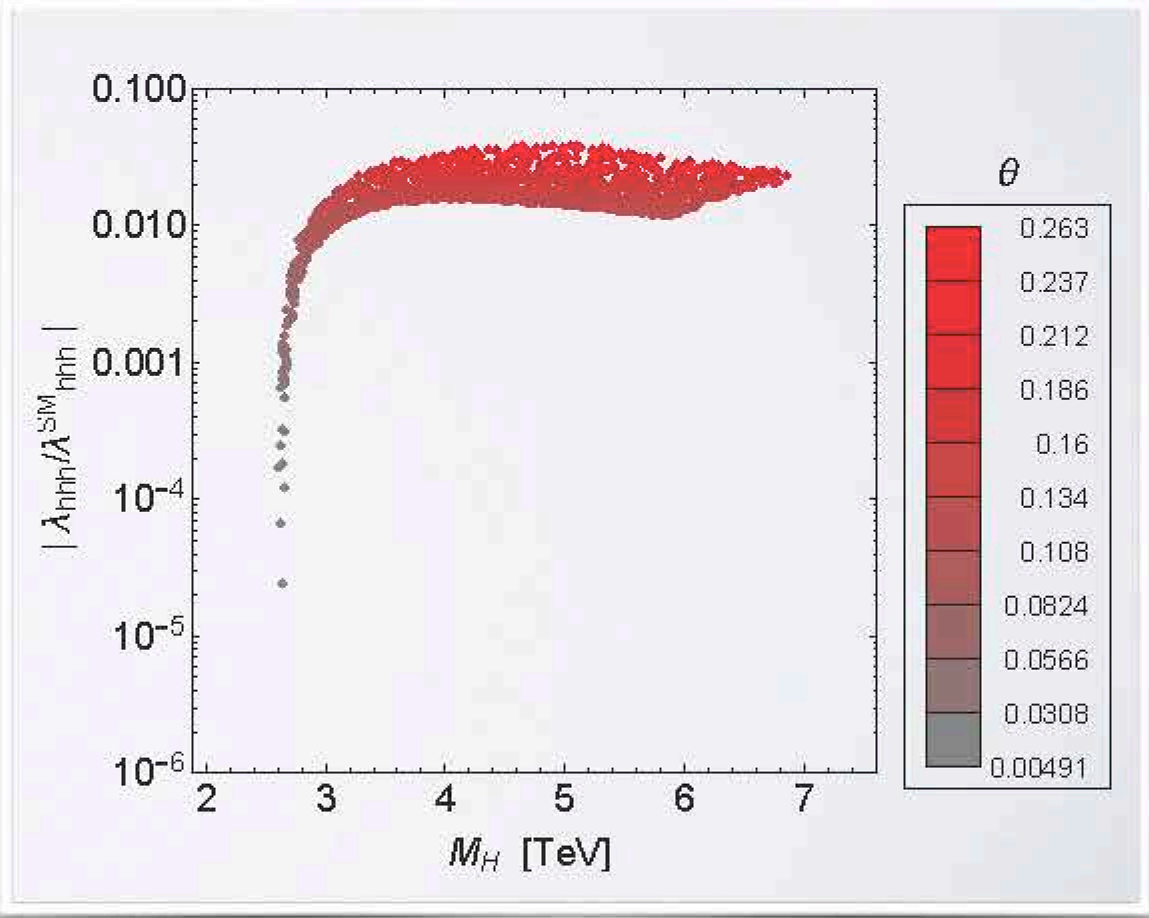
Higgs mass respectively at 10% less/ more than the observed Higgs mass (yellow/green points respectively). We show as well the results using the exact 3σ uncertainty on the Higgs mass (blue points). The dashed line corresponds to the perturbative limit on the coupling.

small θ and small self-coupling

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

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

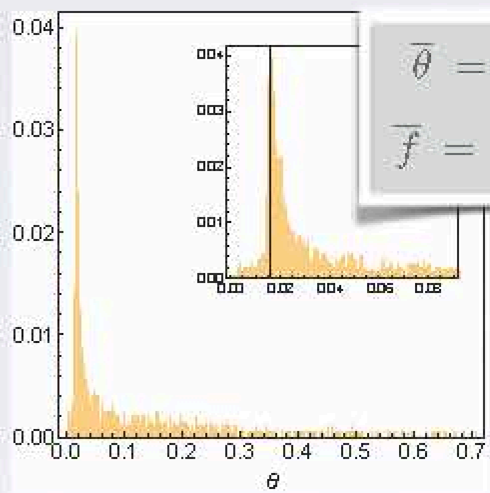
$$(\lambda^{\rm SM}_{hhh} = 3\, m_h^2/v_{\rm EW})$$



σ field and other scalars

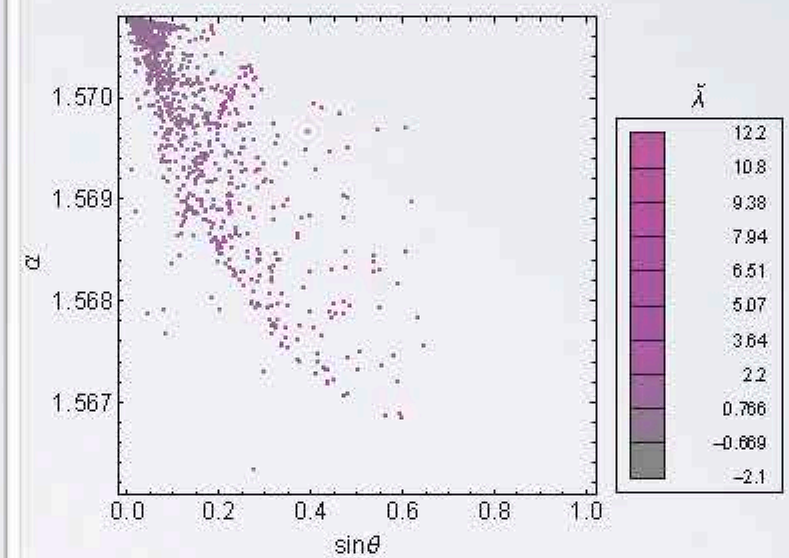
non minimal scenario

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

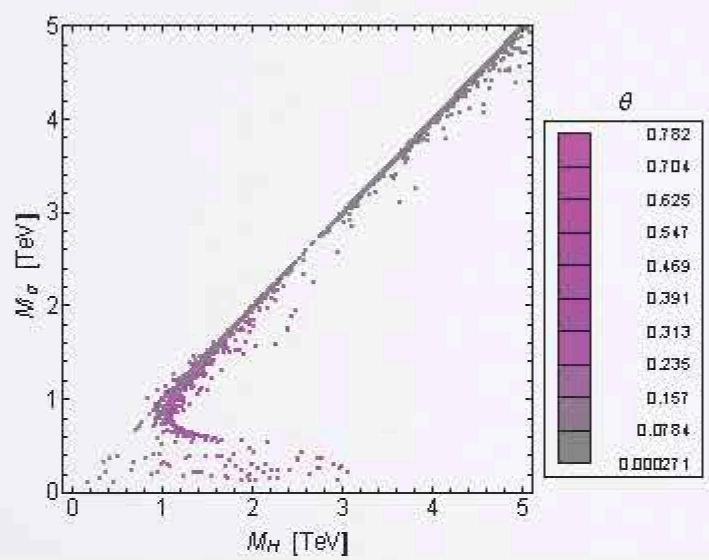


$\overline{\theta} = 0.016^{+0.004}_{-0.002}$

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



$\overline{\alpha} = 1.57$

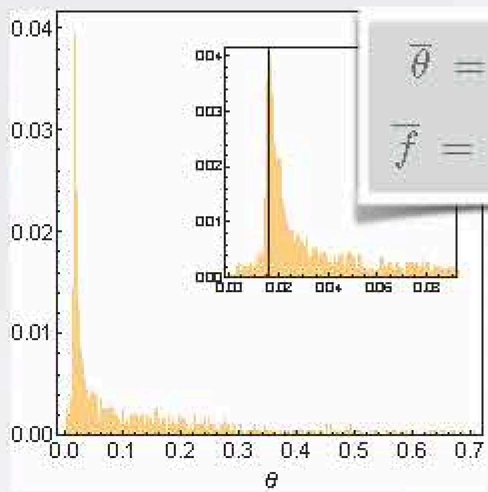


The mass of the second Higgs boson is depending linearly on M_σ

σ field and other scalars

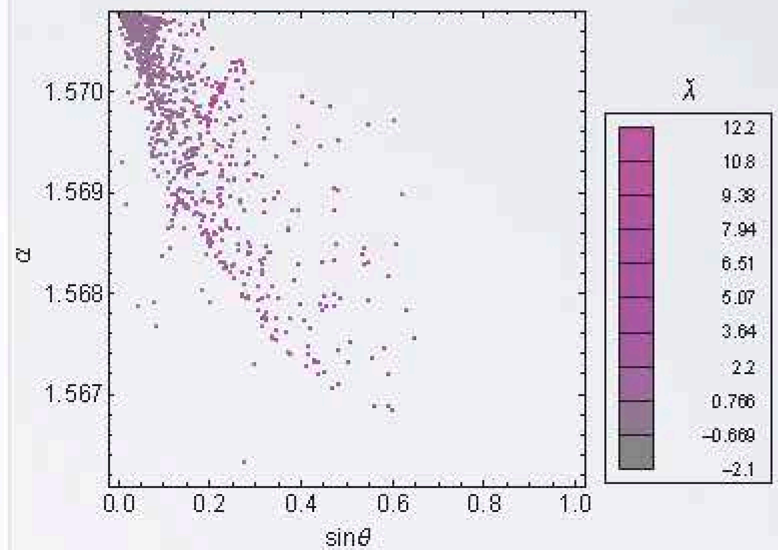
non minimal scenario

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



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

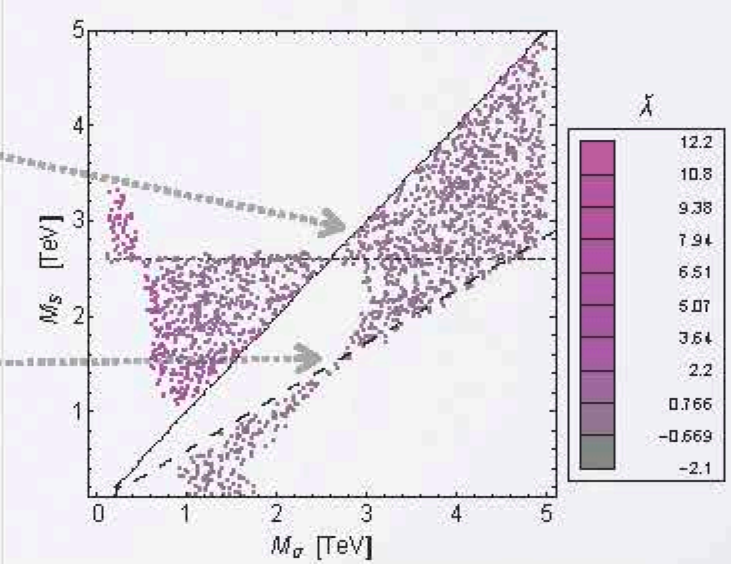
$$\overline{f} = 15.2^{+3.9}_{-1.4}\ \text{TeV}$$



$$\overline{\alpha} = 1.57$$

$$M_\sigma = M_S$$

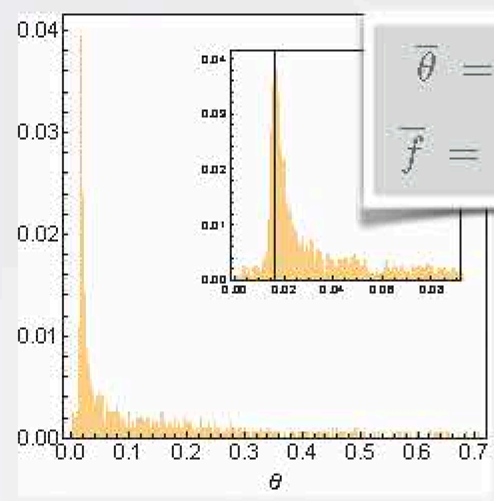
$$\lambda \approx 0 \qquad M_S^4 \approx \frac{M_\sigma^4\left(\log\left[\frac{m_t^2}{M_\sigma^2}\right]-1\right)}{6\left(\log\left[\frac{m_t^2}{M_\sigma^2}\right]+1\right)}$$



σ field and other scalars

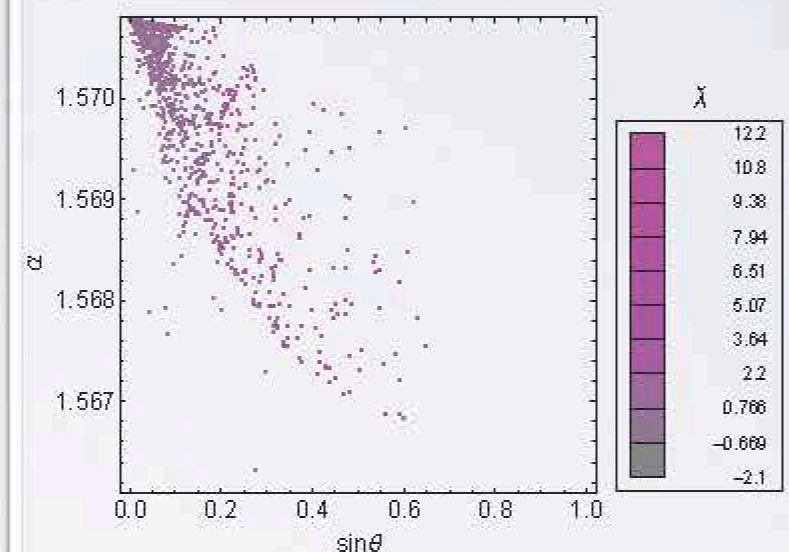
non minimal scenario

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

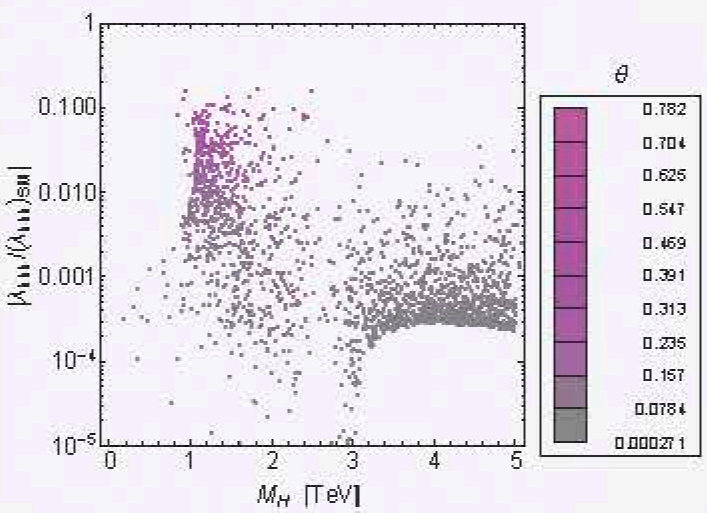


$$\overline{\theta} = 0.016^{+0.004}_{-0.002}$$

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

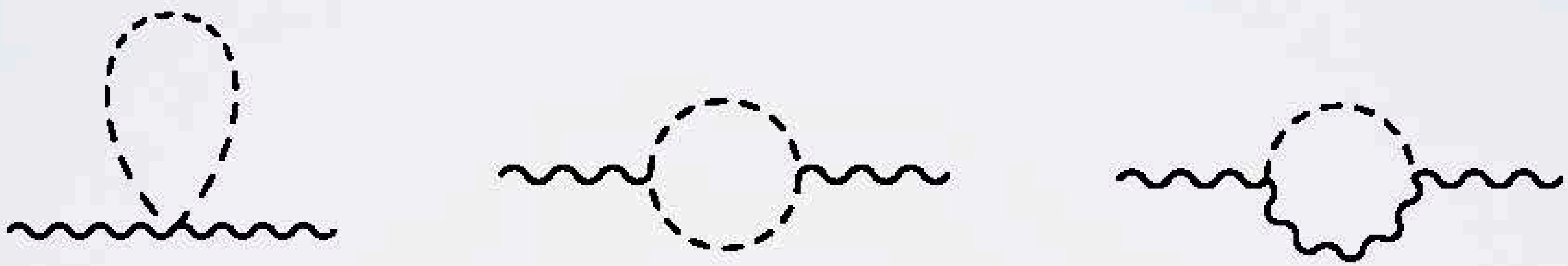


$$\overline{\alpha} = 1.57$$



EW Test of the model

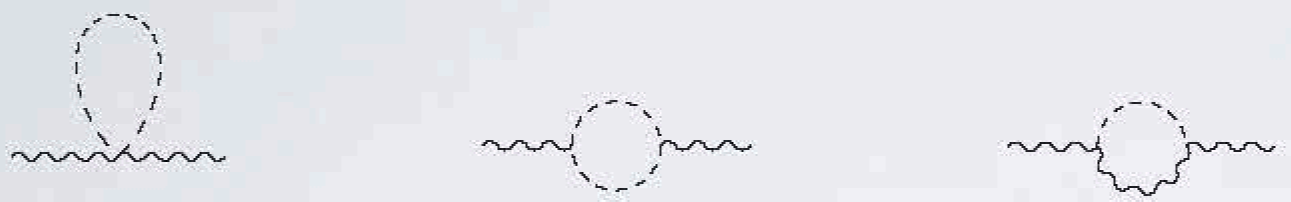
$$M = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 & -S^* + i\tilde{S}^* & \Pi_0^* + i\tilde{\Pi}_0 & \Pi^+ - i\tilde{\Pi}^+ \\ S^* - i\tilde{S}^* & 0 & -\Pi^- + i\tilde{\Pi}^- & \Pi_0 - i\tilde{\Pi}_0 \\ -\Pi_0^* - i\tilde{\Pi}_0 & \Pi^- - i\tilde{\Pi}^- & 0 & S - i\tilde{S} \\ -\Pi^+ + i\tilde{\Pi}^+ & -\Pi_0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



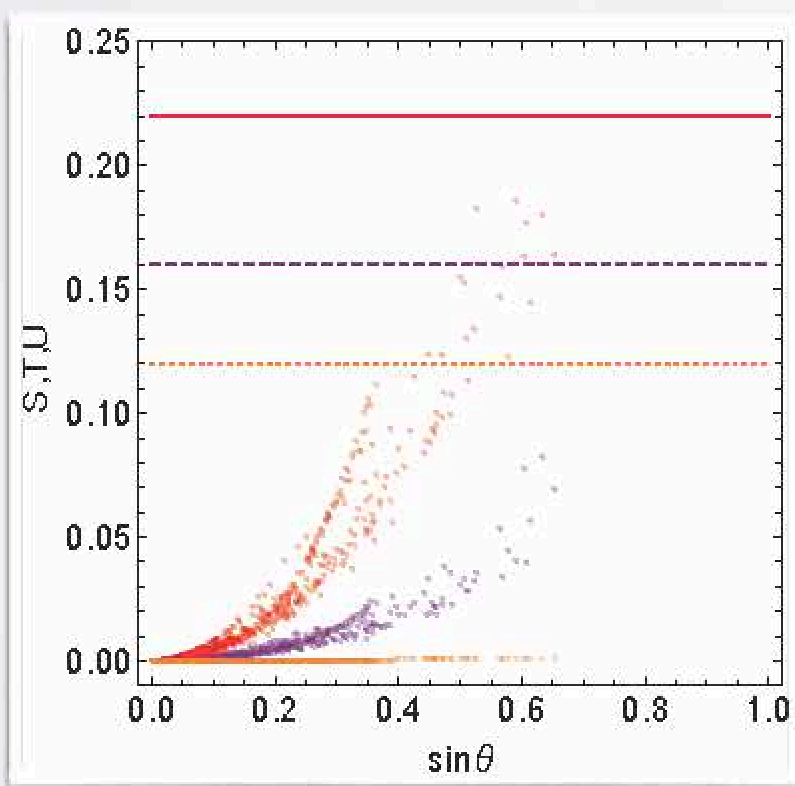
Oblique parameters S T U

Tests of 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



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

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

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

Conclusions

- The elementary scalar sector of the SM is enhanced to an SU(4) symmetry that breaks spontaneously to Sp(4)
- The embedding of the electroweak gauge sector is parametrised by an angle, θ
- The observed Higgs emerges as a pNGB with its mass arising via radiative corrections.
- resulting θ such that $v \sim 60\ v_{EW}$
- Due to the perturbative nature of the theory the new scalars remain in the few TeV energy range.

Outlook

- Radiatively induced Higgs model, like EGH, are valid alternative in order to solve hierarchy problem (or postpone it) and explain the light Higgs mass
- We need to test models! We need good observables in order to test them in the next collider generations:
    - trilinear coupling
    - …

Thanks

for the attention