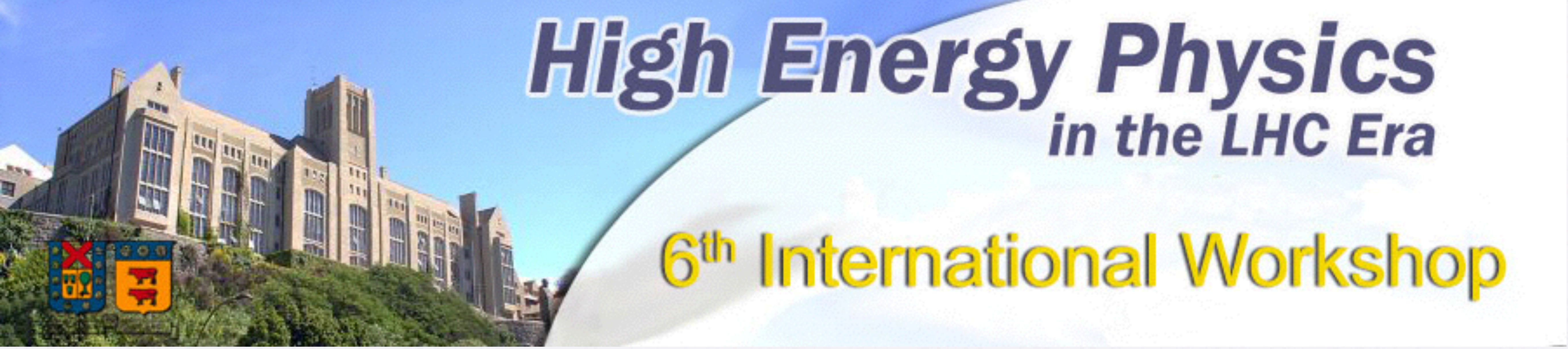

The Dynamical Composite Higgs

Based on Gersdorff, EP, Rosenfeld, 1502.07347

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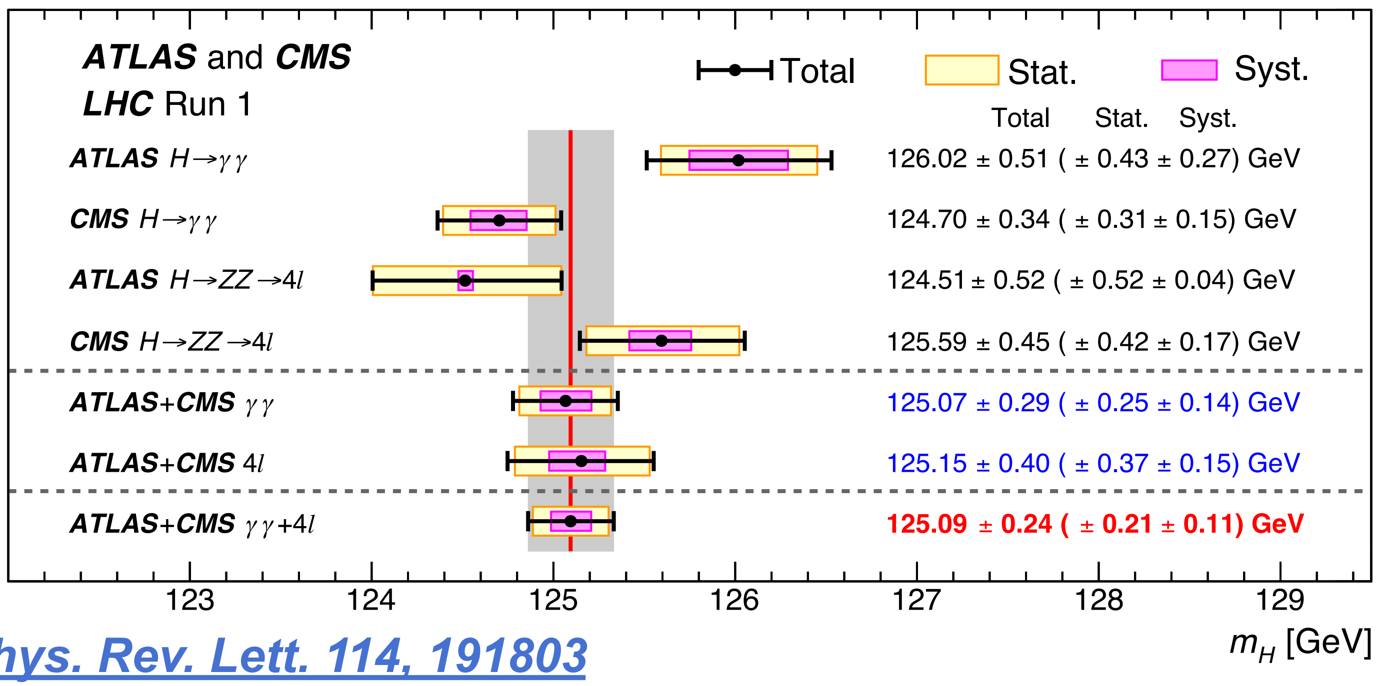
ICTP SAIFR International Centre for Theoretical Physics South American Institute for Fundamental Research

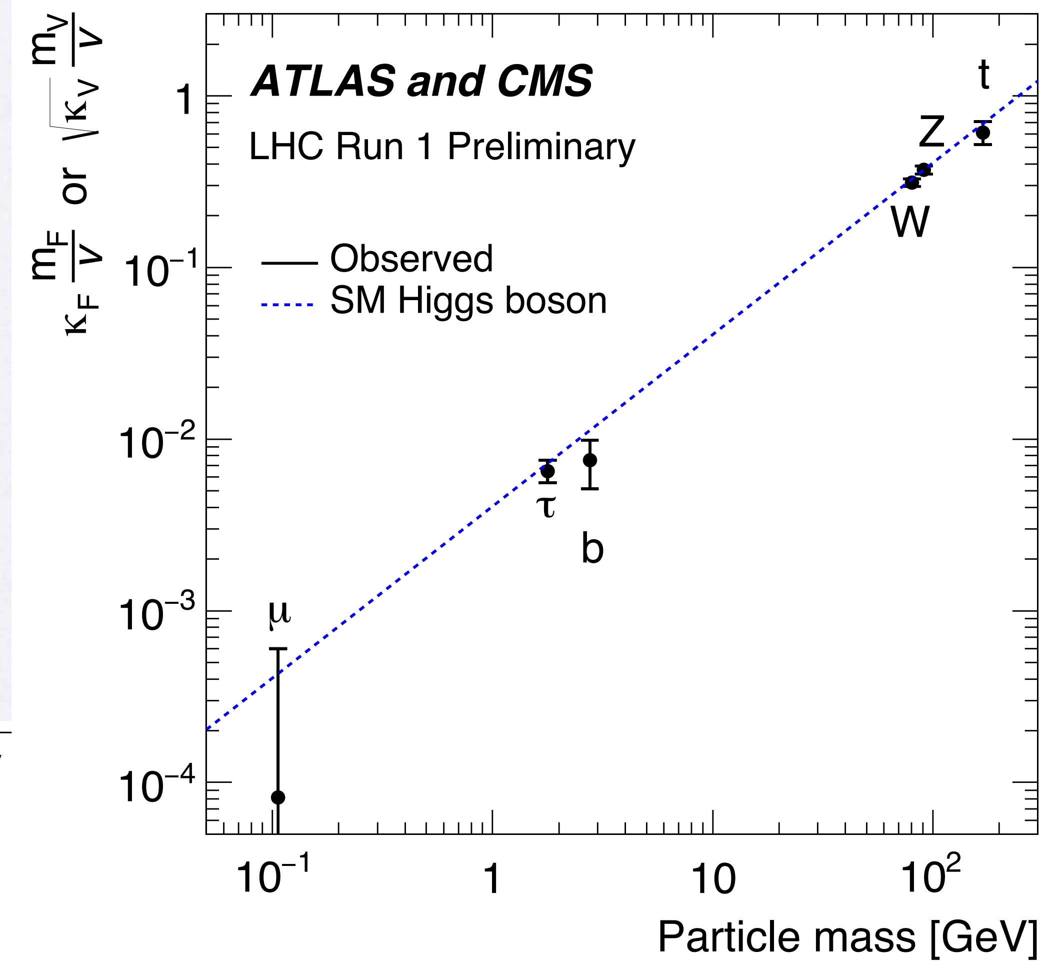
unesp UNIVERSIDADE ESTADUAL PAULISTA "JÚLIO DE MESQUITA FILHO"

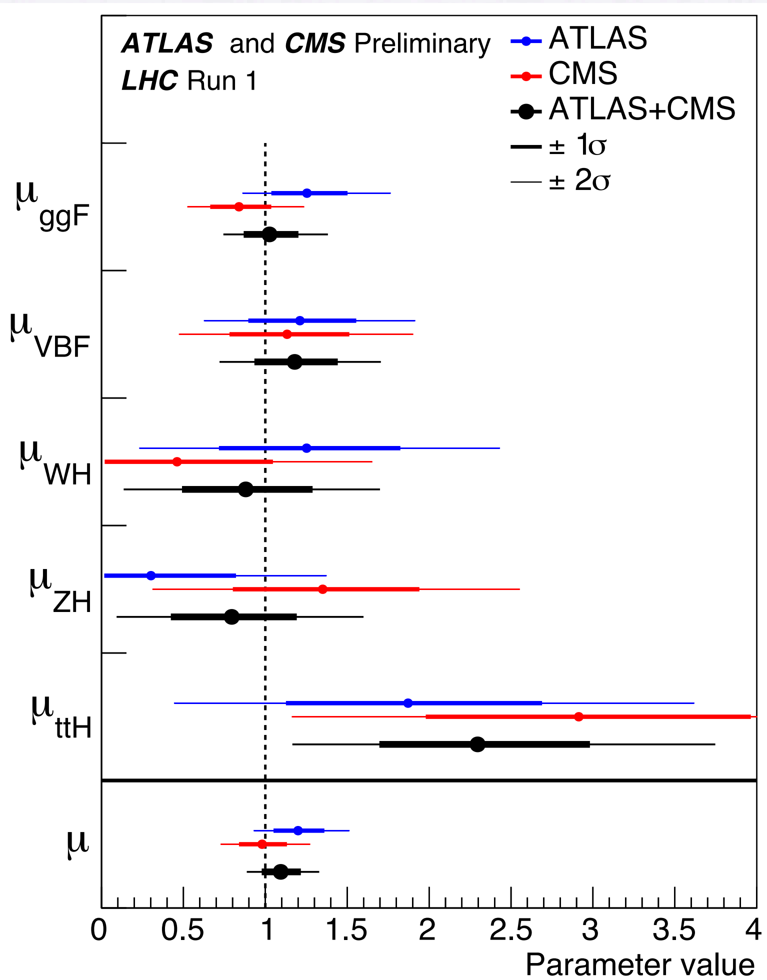
After the Higgs Boson Discovery…

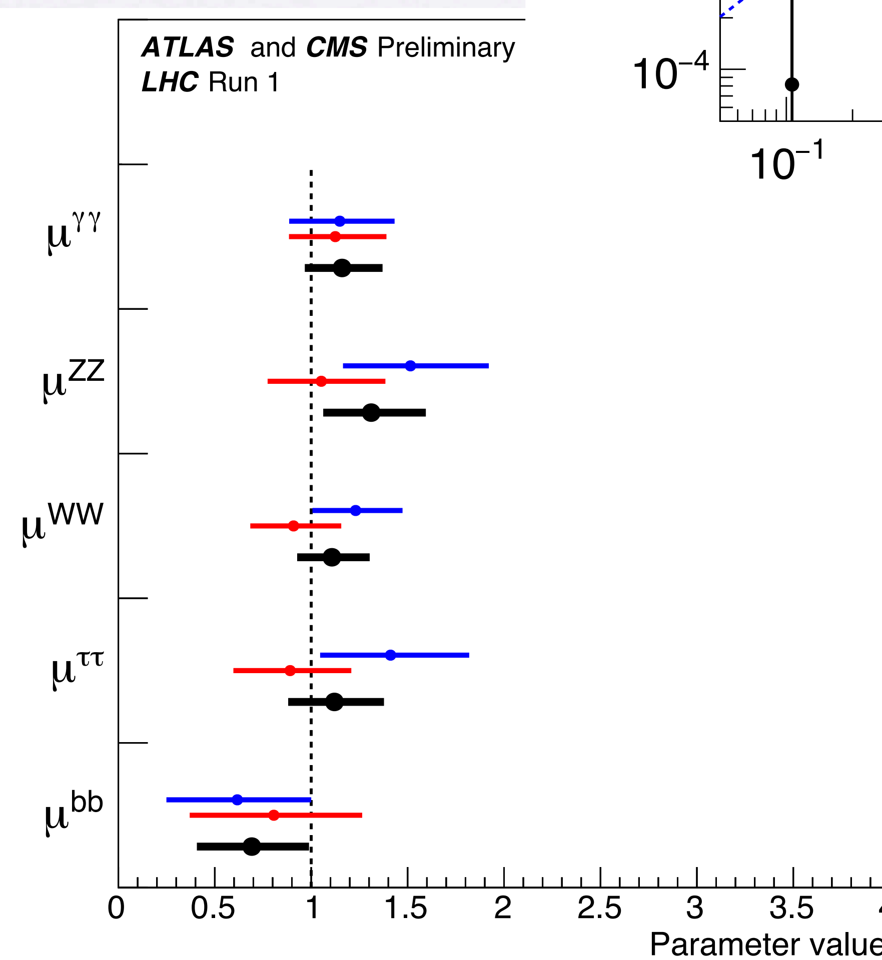
Towards Precision Measurements



Phys. Rev. Lett. 114, 191803

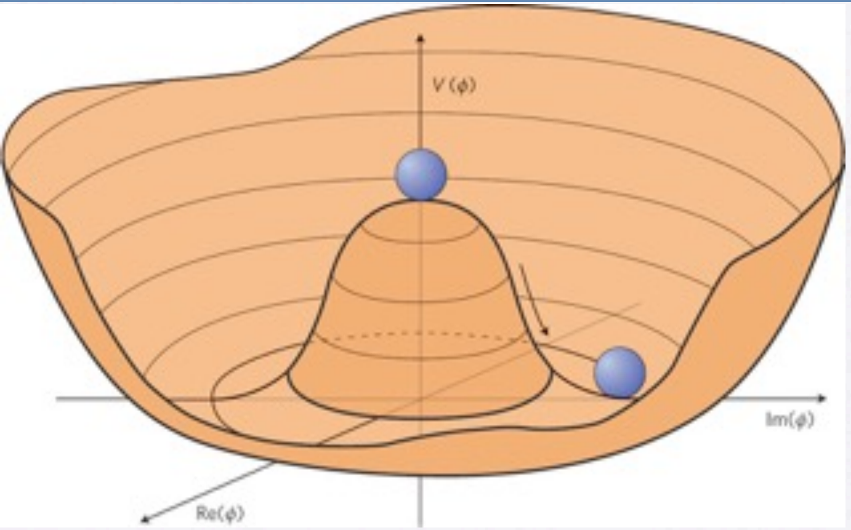






ATLAS-CONF-2015-044

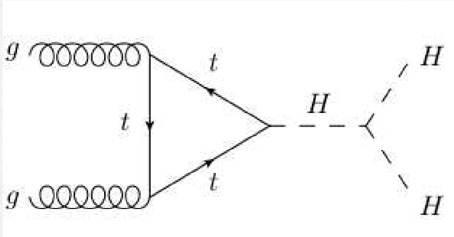
Unfinished Business



- **Higgs width** $< 5.4 \times \Gamma_{\mathrm{SM}}$ (from off-shell, $ZZ \to 4l$) CMS-HIG-14-002

  (better from fits to rates, with some assumptions)

- **Higgs self-interactions: trilinear, (quartic)**



- **Couplings to lighter fermions**

  (may never know if the electron mass really is connected to the 125 GeV Higgs)

Higgs Precision Measurements

Why bother measuring the Higgs properties as precisely as possible?

- Deviations from SM expectations would signal new physics
- More fundamentally: test point-like nature of the Higgs boson

Contrast to a particle like the electron:

e^- Compton wavelength ~ 400 fm $\gg$ 10^{-3} fm $\sim$ scales probed so far

$\longrightarrow$ This is a pretty darn point-like particle.

For the Higgs boson, our current resolution is of order its mass:

Is the Higgs like the "electron", or rather like the "proton"?

Time-honored history for progress in particle physics!

Composite Higgs?

If the Higgs is a composite state, the underlying dynamics may be the key to an understanding of EWSB as a dynamical outcome of the theory!

In this talk I will focus on ``model-building" aspects, more than the phenomenology of such constructions…

Composite Higgs

BSM: Standard Model + Strongly coupled sector

Strong dynamics

New fermions (and scalars, if SUSY)

Sufficiently large global symmetry G

($SU(3)_C \times SU(2)_L \times U(1)_Y \subset G$)

Dynamically generated scale Λ

⋮

Set of resonances

Composite Higgs

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$G \to \mathcal{H}$

Set of resonances

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Set of resonances

- $SU(2)_L \times U(1)_Y \not\subset \mathcal{H}$ → ``Technicolor'', no need of Higgs (ruled out)

Composite Higgs

BSM: Standard Model + Strongly coupled sector

Strong dynamics

New fermions (and scalars, if SUSY)

Sufficiently large global symmetry G

($SU(3)_C \times SU(2)_L \times U(1)_Y \subset G$)

Dynamically generated scale Λ → $G \to \mathcal{H}$

Set of resonances

Mass gap: Higgs as a pNGB

- $SU(2)_L \times U(1)_Y \not\subset \mathcal{H}$ → ``Technicolor", no need of Higgs (ruled out)
- $SU(2)_L \times U(1)_Y \subset \mathcal{H}$ → SM group unbroken at Λ

Amongst resonances: state with Higgs quantum numbers

Symmetries

Can entertain a number of symmetry breaking patterns:

G	$\mathcal{H}$	N_G	NGBs rep.$[\mathcal{H}]$ = rep.$[\mathrm{SU}(2)\times\mathrm{SU}(2)]$
SO(5)	SO(4)	4	$\mathbf{4} = (\mathbf{2},\mathbf{2})$
SO(6)	SO(5)	5	$\mathbf{5} = (\mathbf{1},\mathbf{1}) + (\mathbf{2},\mathbf{2})$
SO(6)	SO(4) × SO(2)	8	$\mathbf{4}_{+\mathbf{2}} + \bar{\mathbf{4}}_{-\mathbf{2}} = 2\times(\mathbf{2},\mathbf{2})$
SO(7)	SO(6)	6	$\mathbf{6} = 2\times(\mathbf{1},\mathbf{1}) + (\mathbf{2},\mathbf{2})$
SO(7)	G_2	7	$\mathbf{7} = (\mathbf{1},\mathbf{3}) + (\mathbf{2},\mathbf{2})$
SO(7)	SO(5) × SO(2)	10	$\mathbf{10}_{\mathbf{0}} = (\mathbf{3},\mathbf{1}) + (\mathbf{1},\mathbf{3}) + (\mathbf{2},\mathbf{2})$
SO(7)	$[\mathrm{SO}(3)]^3$	12	$(\mathbf{2},\mathbf{2},\mathbf{3}) = 3\times(\mathbf{2},\mathbf{2})$
Sp(6)	Sp(4) × SU(2)	8	$(\mathbf{4},\mathbf{2}) = 2\times(\mathbf{2},\mathbf{2}), (\mathbf{2},\mathbf{2}) + 2\times(\mathbf{2},\mathbf{1})$
SU(5)	SU(4) × U(1)	8	$\mathbf{4}_{-5} + \bar{\mathbf{4}}_{+\mathbf{5}} = 2\times(\mathbf{2},\mathbf{2})$
SU(5)	SO(5)	14	$\mathbf{14} = (\mathbf{3},\mathbf{3}) + (\mathbf{2},\mathbf{2}) + (\mathbf{1},\mathbf{1})$
SO(9)	SO(8)	8	$\mathbf{8} = (\mathbf{2},\mathbf{2})_1 + (\mathbf{2},\mathbf{2})_{-1}$

Modified from Mrazek et. al 2011

Focus has been on the study of the low-energy consequences that follow from assuming the corresponding symmetry

Microscopic Realizations?

What sort of new physics could lead to the desired symmetry breaking pattern?

Such UV questions have received comparatively little attention (for good reasons)

- If anything, we are only starting to explore the low-energy side of such phenomena

  The EFT approach is bound to be the most relevant tool, probably for a while

- We have very few tools to analyze the physics of strongly-coupled theories

  One options is to appeal to SUSY, e.g.

  Kitano, Luty & Nakal, 1206.4053

  Caracciolo, Francesco, Parolini & Serone, 1211.7290

  Parolini, 1405.4875

  Here we look for non-SUSY UV completions (à la Nambu-Jona-Lasinio)

Largely inspired by the seminal work of Bardeen, Hill and Lindner (1989)

Our work: ``pNGB Top condensation''

(Gersdorff, EP, Rosenfeld, 2015)

See also:
(Cheng, Dobrescu & Jiayin, 2013)
(Cheng & Jiayin, 2014)

The MCHM

(i.e. Minimal Composite Higgs Model)

Agashe, Contino, Pomarol '04;

Focus on the minimal group, $G = SO(5) \times U(1)_X$ **, which**

- contains the SM group: $SU(2)_L \times U(1)_Y$
- contains 4 (p)NGB's that can be identified with a Higgs doublet
- contains custodial symmetry $SU(2)_L \times SU(2)_R \sim SO(4) = \mathcal{H}$

Pattern of symmetry breaking (EW sector):

Gauge: $SU(2)_L \times U(1)_Y \longrightarrow U(1)_Q$

$$\cap$$

Global: $SO(5) \xrightarrow[E \sim f]{} SU(2)_L \times SU(2)_R \xrightarrow[E \sim v]{} SU(2)_{L+R}$ custodial

Our (modest) Goal

Exhibit a UV completion to the SO(5)/SO(4) symmetry breaking pattern, such that

- The Higgs constituents are identified…
- as well as the interactions that hold them together.

As we will see, the resulting model has itself a cutoff and needs to be UV completed:

- This would happen at a scale parametrically above the weak scale…
- … about which we know essentially nothing: it may be that ``technicolor-like" constructions can be revived and applied at this higher scale

  We have provided a simple, renormalizable, UV completion, but we emphasize that it is wise to remain agnostic about the physics at that scale.

The Top Sector

$$G_{\text{strong}} \times G_{\text{QCD}} \times \left[SO(5) \times U(1)_X \subset SU(5) \times U(1)_X\right]^{\text{approx.}}_{\text{global}}$$

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Optional strong dynamics, operational (somewhat) above scales of interest

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QCD or perhaps an extension (e.g. top-color)

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$$SU(2)_L \times U(1)_Y \subset SO(5) \times U(1)_X$$

``Composite sector'': vector-like $\mathbf{5} \oplus \mathbf{1}$

$$F_L = \begin{pmatrix} T_L \\ B_L \\ \chi_L \\ T'_L \\ S_L \end{pmatrix} \quad F_R = \begin{pmatrix} T_R \\ B_R \\ \chi_R \\ T'_R \\ S_R \end{pmatrix} \quad S'_L \;\; S'_R$$

``Elementary sector''

$$q_L \qquad t_R$$

The Top Sector

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``**Elementary sector**''

$q_L \qquad t_R$

$$F = \begin{pmatrix} T \\ B \\ \chi \\ T' \\ S \end{pmatrix}$$

$\}$ Quantum numbers of the LH (t, b) in the SM

S'

The Top Sector

$$G_{\rm strong} \times G_{\rm QCD} \times [SO(5) \times U(1)_X \subset SU(5) \times U(1)_X]^{\rm approx.\ global}$$

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$$q_L \qquad t_R$$

$$F = \begin{pmatrix} T \\ B \\ \chi \\ T' \\ S \end{pmatrix}$$

$\left.\begin{matrix} T \\ B \end{matrix}\right\}$ **Quantum numbers of the LH (t, b) in the SM**

$\left.\begin{matrix} \chi \\ T' \end{matrix}\right\}$ $SU(2)_L$ **doublet with exotic Y = 7/6** $\quad (Q = T^3_L + T^3_R + X)$

S'

The Top Sector

$$G_{\rm strong} \times G_{\rm QCD} \times [SO(5) \times U(1)_X \subset SU(5) \times U(1)_X]^{\rm approx.\ global}$$

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QCD or perhaps an extension (e.g. top-color)

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``**Composite sector**": vector-like $\mathbf{5} \oplus \mathbf{1}$

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``**Elementary sector**"

$$q_L \qquad t_R$$

$$F = \begin{pmatrix} T \\ B \\ \chi \\ T' \\ S \end{pmatrix}$$

- T, B: Quantum numbers of the LH (t, b) in the SM
- χ, T': $SU(2)_L$ doublet with exotic Y = 7/6 $\quad (Q = T^3_L + T^3_R + X)$
- $S \longrightarrow SU(2)_L$ singlet with Q = 2/3
- $S' \longrightarrow SU(2)_L$ singlet with Q = 2/3

(S and S'): Quantum numbers of the RH t in the SM

The Top Sector

$$G_{\text{strong}} \times G_{\text{QCD}} \times [SO(5) \times U(1)_X \subset SU(5) \times U(1)_X]^{\text{approx. global}}$$

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$$F_L = \begin{pmatrix} T_L \\ B_L \\ \chi_L \\ T'_L \\ S_L \end{pmatrix} \quad F_R = \begin{pmatrix} T_R \\ B_R \\ \chi_R \\ T'_R \\ S_R \end{pmatrix} \qquad S'_L \quad S'_R$$

``Elementary sector''

$$q_L \qquad t_R$$

After all is said and done:

The observed top and bottom are linear combinations of the previous states (sharing the appropriate quantum numbers)

Simplified Limits

The ``composite sector" fills SU(5) multiplets [We will see shortly how this is reduced to SO(5)]

However, we must keep in mind that $SO(5) \subset SU(5)$ is only an approximate symmetry:

a) Broken (explicitly) by the SM weak gauge interactions

b) The ``elementary sector" does not fill SU(5), nor SO(5), multiplets

c) Only the (gauged) SM symmetry must be preserved

$\longrightarrow$ Global symmetry can be (softly) broken by mass terms

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c) Only the (gauged) SM symmetry must be preserved

$\longrightarrow$ **Global symmetry can be (softly) broken by mass terms**

$$Q^1 = \begin{pmatrix} T \\ B \end{pmatrix} \qquad Q^2 = \begin{pmatrix} \chi \\ T' \end{pmatrix}$$

$$\mathcal{L}^{mass}_{\text{Fermion}} = \overbrace{-\mu_{QQ}\,\bar{Q}^1_L Q^1_R - \mu'_{QQ}\,\bar{Q}^2_L Q^2_R - \mu_{SS}\bar{S}_L S_R}^{\mathbf{5}} \overbrace{-\mu_1 \bar{S}'_L S'_R}^{\mathbf{1}} + \text{h.c.}$$

$$-\mu_{51}\bar{S}_L S'_R - \mu'_{51}\bar{S}'_L S_R + \text{h.c.}$$

$$\underbrace{-\mu_{tS}\bar{S}_L t_R - \mu'_{tS}\bar{S}'_L t_R - \mu_{qQ}\,\bar{q}_L Q^1_R + \text{h.c.}}_{\text{Mixing between composite and elementary sectors}}$$

5-1 mixing

Mixing between composite and elementary sectors

Simplified Limits

$$\mathcal{L}^{mass}_{\rm Fermion} \;=\; -\,\mu_{QQ}\,\bar{Q}^1_L Q^1_R - \mu'_{QQ}\,\bar{Q}^2_L Q^2_R - \mu_{SS}\bar{S}_L S_R - \mu_1 \bar{S}'_L S'_R + \text{h.c.}$$
$$-\mu_{51}\bar{S}_L S'_R - \mu'_{51}\bar{S}'_L S_R + \text{h.c.}$$
$$-\mu_{tS}\bar{S}_L t_R - \mu'_{tS}\bar{S}'_L t_R - \mu_{qQ}\,\bar{q}_L Q^1_R + \text{h.c.}$$

For simplicity, we can decouple some states without changing the underlying mechanism:

1) **``<u>Extended" Model</u>:** $\mu'_{51} \to \infty$ **to decouple** (S'_L, S_R)

Light states: $F_L + (Q^1_R, Q^2_R) + S_R + (q_L, t_R)$

(relabel $\mu_{51} \to \mu_{SS}$ and $S'_R \to S_R$)

2) **``<u>Minimal" Model</u>: also** $\mu_{qQ} \to \infty$ **to decouple** (q_L, Q^1_R)

Light states: $F_L + Q^1_R + S_R + t_R$

Both limits share an approximate $SO(5)_L \subset SU(5)_L$**, which is the central player**

From SU(5) to SO(5)

The SU(5) symmetry can be naturally reduced to SO(5) by 4-fermion operators

Minimal field content:

(Gersdorff, EP, Rosenfeld, 2015)

$$F_L \to 5 \text{ of } SO(5), \; Q_X = 2/3$$

$$S_R \to 1 \text{ of } SO(5), \; Q_X = 2/3$$

$$\mathcal{L}_F = i\bar{F}_L \not{\partial} F_L + i\bar{S}_R \not{\partial} S_R$$

⟵ no mass terms allowed

$$+ \frac{G_S}{2}\left(\bar{S}_R F_L + \bar{F}_L S_R\right)^2 - \frac{G'_S}{2}\left(\bar{S}_R F_L - \bar{F}_L S_R\right)^2$$

Two SO(5) structures: if $G_S = G'_S$ $\longrightarrow$ $2G_S|\bar{S}_R F_L^i|^2$ is $SU(5)$ invariant

The symmetry breaking pattern of interest is

not crucial here

$$SO(5)_L \times U(1)_X \to SO(4)_L \times U(1)_X$$

Nambu-Jona-Lasinio: Review

Nambu & Jona-Lasinio, 1961
Nambu, 1988
Miranski et. al., 1989
Bardeen, Hill and Lindner, 1989

$$\mathcal{L}_F = i\bar{F}_L \not{\partial} F_L + i\bar{S}_R \not{\partial} S_R$$

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Upshot:

- **4-fermion theory: effective theory with a cutoff** $\Lambda \sim G_S^{-1/2}$
- **If strength above a certain critical value,** $G_S \Lambda^2 \gtrsim \mathcal{O}(8\pi^2)$ **, a non-vanishing condensate arises:** $\langle \bar{F}_L S_R \rangle \neq 0$ ⟶ **breaking of the global SO(5)**

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$$\mathcal{L}_F = i\bar{F}_L \not{\partial} F_L + i\bar{S}_R \not{\partial} S_R \qquad \longleftarrow \text{ no mass terms allowed}$$

$$+ \frac{G_S}{2}\left(\bar{S}_R F_L + \bar{F}_L S_R\right)^2 - \frac{G'_S}{2}\left(\bar{S}_R F_L - \bar{F}_L S_R\right)^2$$

Upshot:

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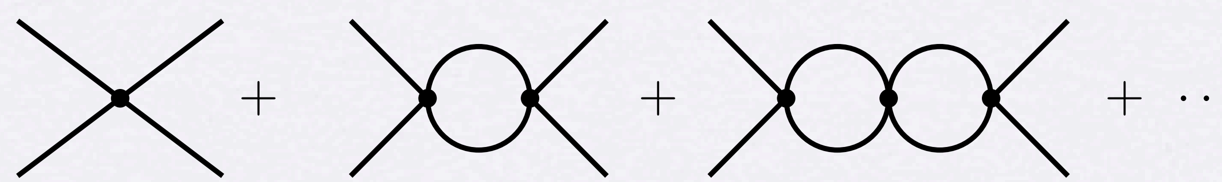
- **Goldstone modes, as well as a heavy mode, can be identified from**

$$\langle \bar{F}_L S_R(x) \bar{S}_R F_L(y) \rangle =$$



(becomes exact in the large N_c **, i.e. planar limit: study a ``gap equation")**

- **We will assume that only** G_S **(and not** G'_S**) is *super-critical***

Nambu-Jona-Lasinio: Review

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$$\mathcal{L}_F = i\bar{F}_L \partial\!\!\!/ F_L + i\bar{S}_R \partial\!\!\!/ S_R$$

← no mass terms allowed

$$+ \frac{G_S}{2}\left(\bar{S}_R F_L + \bar{F}_L S_R\right)^2 - \frac{G'_S}{2}\left(\bar{S}_R F_L - \bar{F}_L S_R\right)^2$$

To understand the NJL mechanism, it is easier and physically more transparent to use a trick: rewrite the Lagrangian with the help of an auxiliary scalar field Φ

$$\mathcal{L}_F = i\bar{F}_L \partial\!\!\!/ F_L + i\bar{S}_R \partial\!\!\!/ S_R$$
$$- \frac{1}{2G_S}\Phi^2 - \Phi(\bar{S}_R F_L + \text{h.c.})$$

From the EOM, can think of Φ as the fermion bilinear $\sim \bar{F}_L S_R$

Nambu-Jona-Lasinio: Review

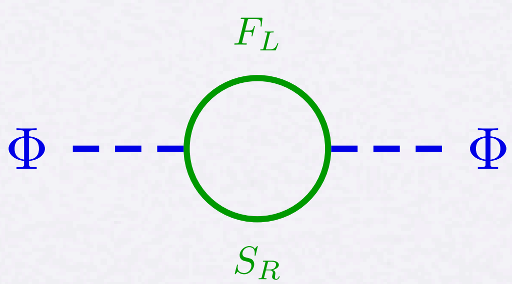
$$\mathcal{L}_F = i\bar{F}_L \partial\!\!\!/ F_L + i\bar{S}_R \partial\!\!\!/ S_R - \frac{1}{2G_S}\Phi^2 - \Phi(\bar{S}_R F_L + \text{h.c.})$$

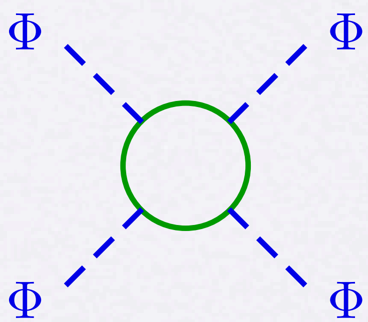
Nambu-Jona-Lasinio: Review

$$\mathcal{L}_F = i\bar{F}_L \not\partial F_L + i\bar{S}_R \not\partial S_R$$
$$+ \frac{1}{2}(\partial_\mu \Phi)^2 - \frac{1}{4}\lambda\left(\Phi^2 - \hat{f}^2\right)^2 - \xi\,\Phi\,(\bar{S}_R F_L + \text{h.c.})$$

Fermion loops induce:

- **kinetic term for Φ**
- ***negative* mass squared**
- **quartic self-interactions**





When the induced kinetic term becomes sizeable (Yukawa coupling $\xi \ll \infty$), we can think of Φ as a proper, dynamical degree of freedom, corresponding to a fermion bound state. This requires a gap between the bound state mass and the cutoff Λ . The Yukawa interaction induces a dynamical mass for (S_L, S_R)

Nambu-Jona-Lasinio: Review

$$\mathcal{L}_F = i\bar{F}_L \not{\partial} F_L + i\bar{S}_R \not{\partial} S_R$$
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(Quasi) IR Fixed points:

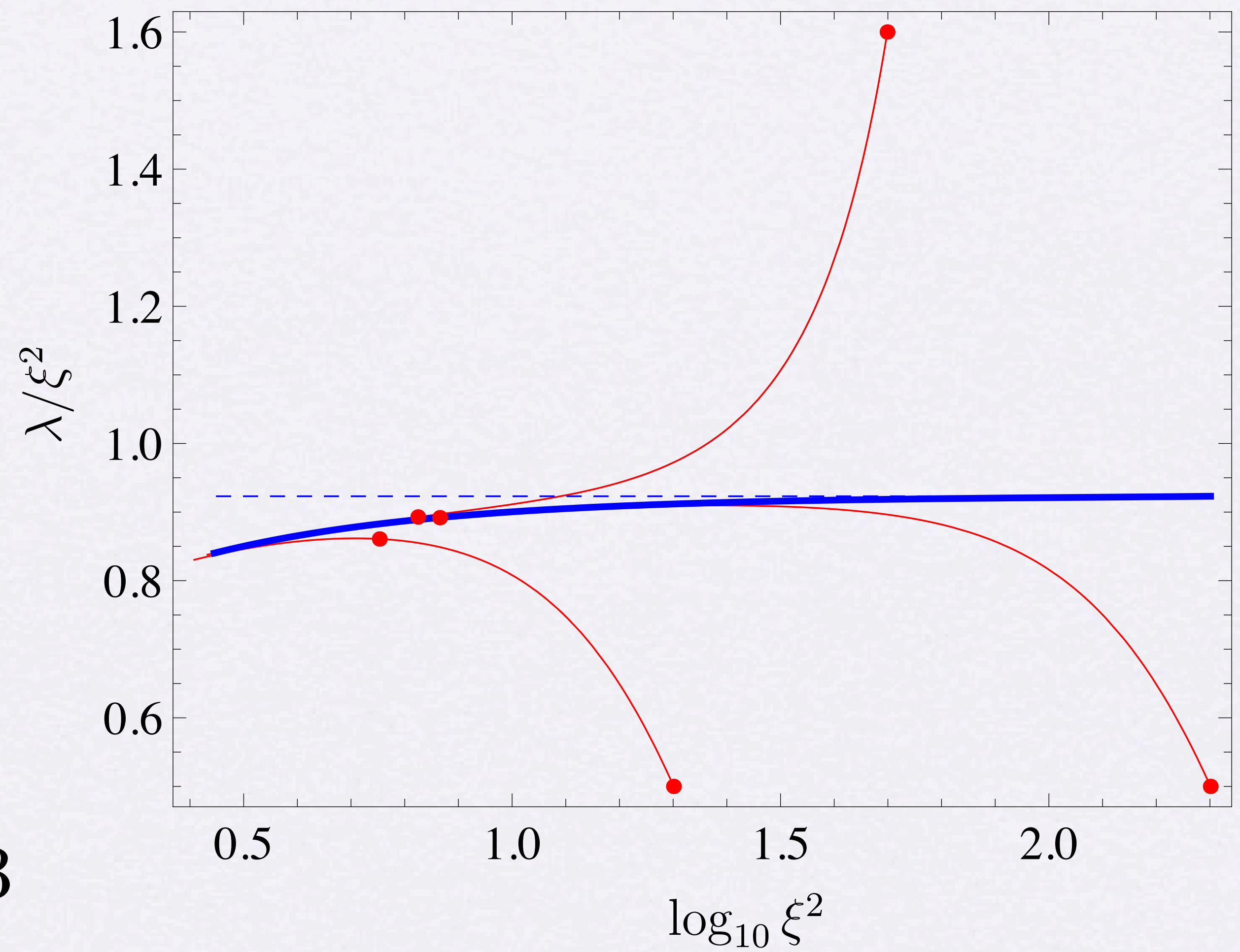
For SO(N) symmetry and N_c colors:

$$16\pi^2\beta_{\xi^2} = (4N_c + N + 5)\xi^4$$
$$16\pi^2\beta_\lambda = 2(N+8)\lambda^2 - 8N_c\xi^4 + 8N_c\xi^2\lambda$$

imply $\lambda = a_*\xi^2$ **hence:**

$$m_{\mathcal{H}}^2 = 2a_* m_S^2$$

For $N = 5$ **and** $N_c = 3:$ $a_* = 12/13$



pNGB Top Condensation

The $SO(5) \to SO(4)$ breaking generates 4 NGB's:

$$\Phi = \begin{pmatrix} H^{0*} \\ -H^- \\ H^+ \\ H^0 \\ \hat{f} \end{pmatrix} = \langle \mathcal{H} \rangle \, U \begin{pmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 1 \end{pmatrix} \qquad U = e^{\sqrt{2} i \, h^{\hat{a}} T^{\hat{a}} / f}$$

May think of the NGB's as composite states of the ``top sector" described above.

At loop level, the small terms that break the SO(5) can lead to vacuum misalignment:

$$\langle H^0 \rangle = \frac{1}{\sqrt{2}} \hat{f} \sin(\langle h^{\hat{4}} \rangle / f) \qquad \langle \Phi_5 \rangle = \hat{f} \cos(\langle h^{\hat{4}} \rangle / f)$$

To what extent is EWSB an outcome of the dynamics?

Need to compute the Coleman-Weinberg potential...

The Spin-1 Sector

As already mentioned, a subroup $SU(2)_L \times U(1)_Y \supset SO(5) \times U(1)_X$ is (weakly) gauged, so as to embed the SM gauge interactions.

It is also possible to describe massive spin-1 resonances, that might arise from the underlying strong dynamics.

Such composite spin-1 fields can arise from the ``vector channel" 4-fermion interactions:

$$\mathcal{L}_V = -\frac{G_\rho}{2}(J^{A\,\mu})^2 - \frac{G_X}{2}(J^{X\,\mu})^2$$

involving the conserved currents

$$J^{A\,\mu} = (\bar{Q}_L, \bar{S}_L)\, T^A \gamma^\mu \begin{pmatrix} Q_L \\ S_L \end{pmatrix}, \qquad J^{X\,\mu} = q_X(\bar{Q}_L\gamma^\mu Q_L + \bar{S}_L\gamma^\mu S_L + \bar{S}_R\gamma^\mu S_R$$

The Spin-1 Sector

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The analysis proceeds in complete analogy to the analysis of the ``scalar channels":

- Rewrite 4-fermion interactions in terms of auxiliary spin-1 fields
- These become dynamical due to quantum effects, thus describing the corresponding (composite) bound states

Note: the corresponding gauge symmetry can be made explicit using the *Hidden Local Symmetry* formalism

Bando et. al., 1988

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- **Upshot:**

Massive spin-1 resonances with masses m_ρ , m_a and m_X (coupling $\sim g_\rho$)

Light spin-1 resonances that get mass only after EWSB

⟶ identified with the SM gauge fields

Electroweak Symmetry Breaking

Tree-level potential for pNGB's vanishes, but is generated at 1-loop from

- **Spin-1 sector: gauging of SM subgroup** ⟶ **proportional to** g, g'
- **Spin-1/2 sector: SO(5) soft breaking terms** $\mu_{tS}, \mu_{QQ}, \mu'_{QQ}$

Calculability?

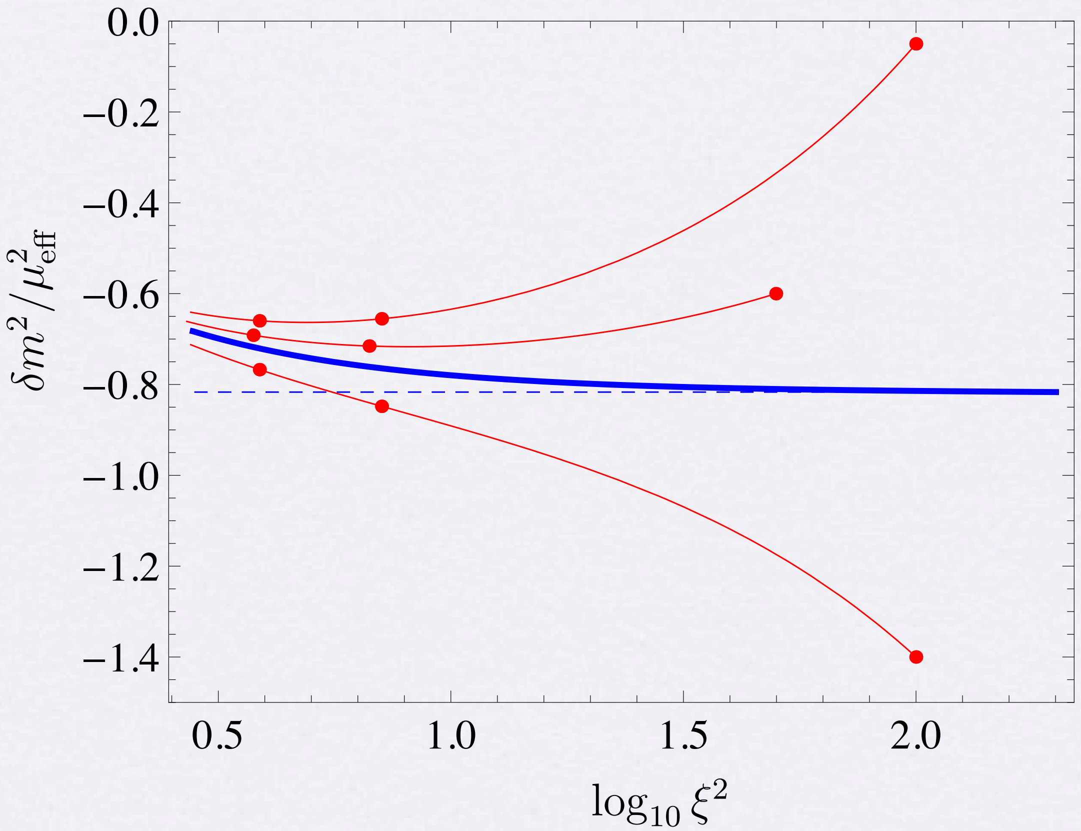
- **Spin-1 contributions are *super-soft*, cutoff at** m_ρ
- **Spin-1/2 contributions are only *soft*: logarithmically divergent**

However:

Counterterm for Higgs mass δm^2 **displays an IR quasi-fixed point**

$$\delta m^2 = -r_* \mu_{\rm eff}^2$$

$$\mu_{\rm eff}^2 \equiv 2\mu_{tS}^2 - \mu_{QQ}^2 - \mu_{QQ}'^2$$

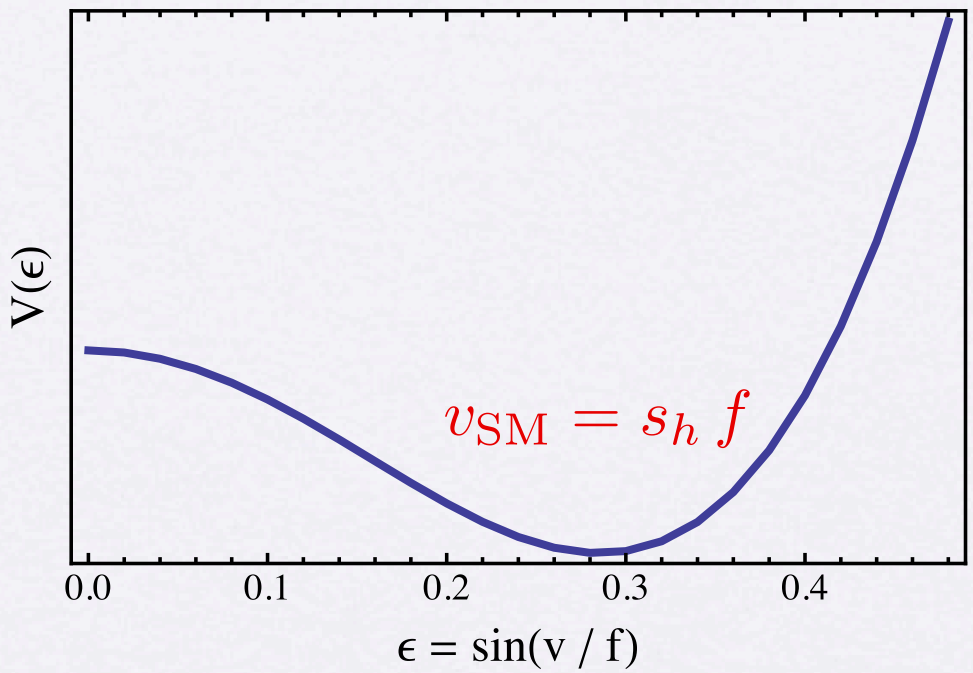


Electroweak Symmetry Breaking

Upshot: Coleman-Weinberg potential is effectively super-soft!

$$V \;=\; -\frac{\alpha}{2}s_h^2 + \frac{\beta}{4}s_h^4 + \mathcal{O}(s_h^6)$$

- **Gauge interactions:**
  prefer ``vacuum alignment" (no EWSB)
- **Yukawa interactions (dominated by top):**
  can induce EWSB



Parameter space:

$$\xi, g_\rho \qquad \hat{f}, f \qquad \mu_{QQ}, \mu'_{QQ}, \mu_{tS}, \mu_{qQ}$$

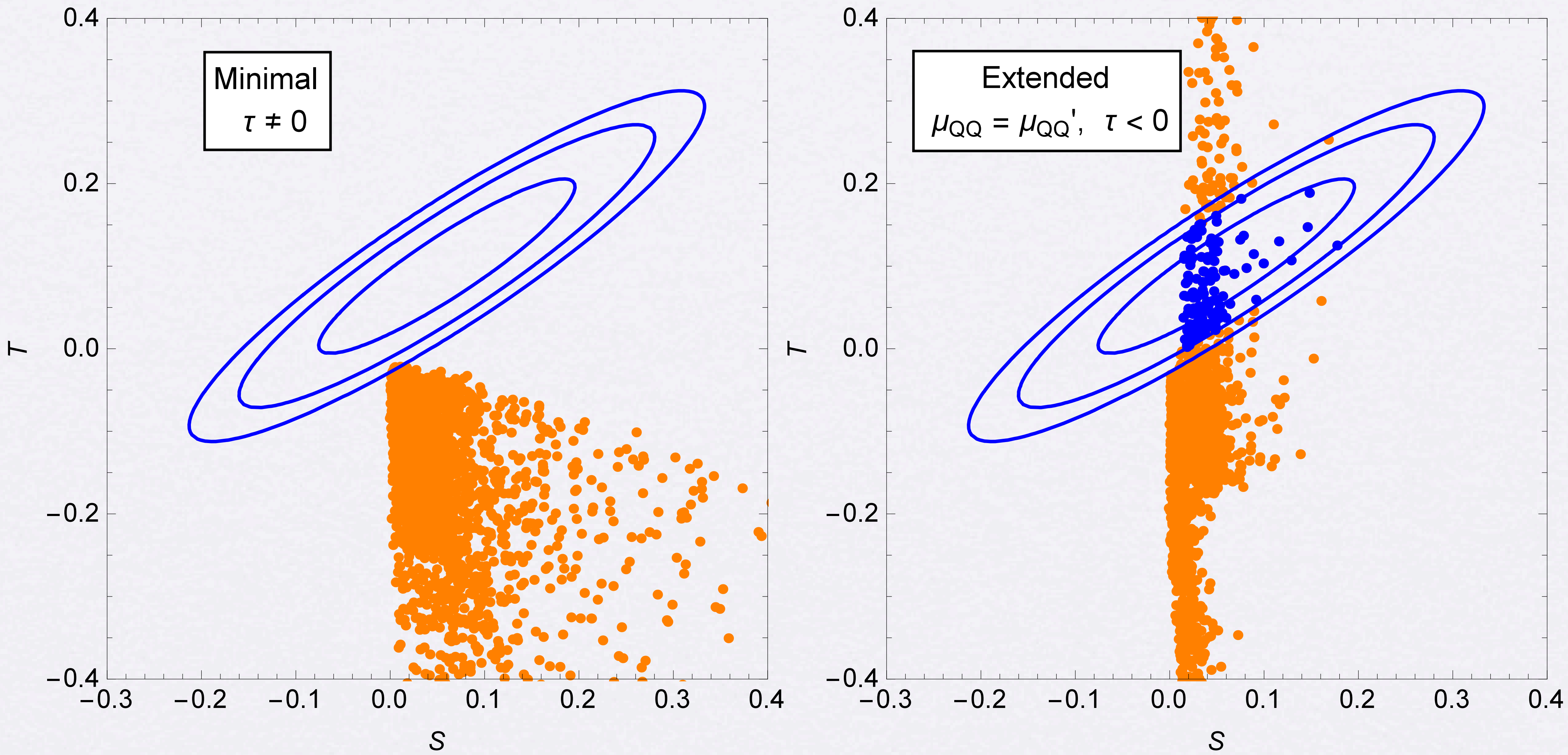
masses: $m_S, m_Q, m'_Q, m_\rho, m_a, m_t$

Mixing angles: $s_R = \dfrac{\mu_{tS}}{m_S}\,, \qquad s_L = \dfrac{\mu_{qQ}}{m_Q}$

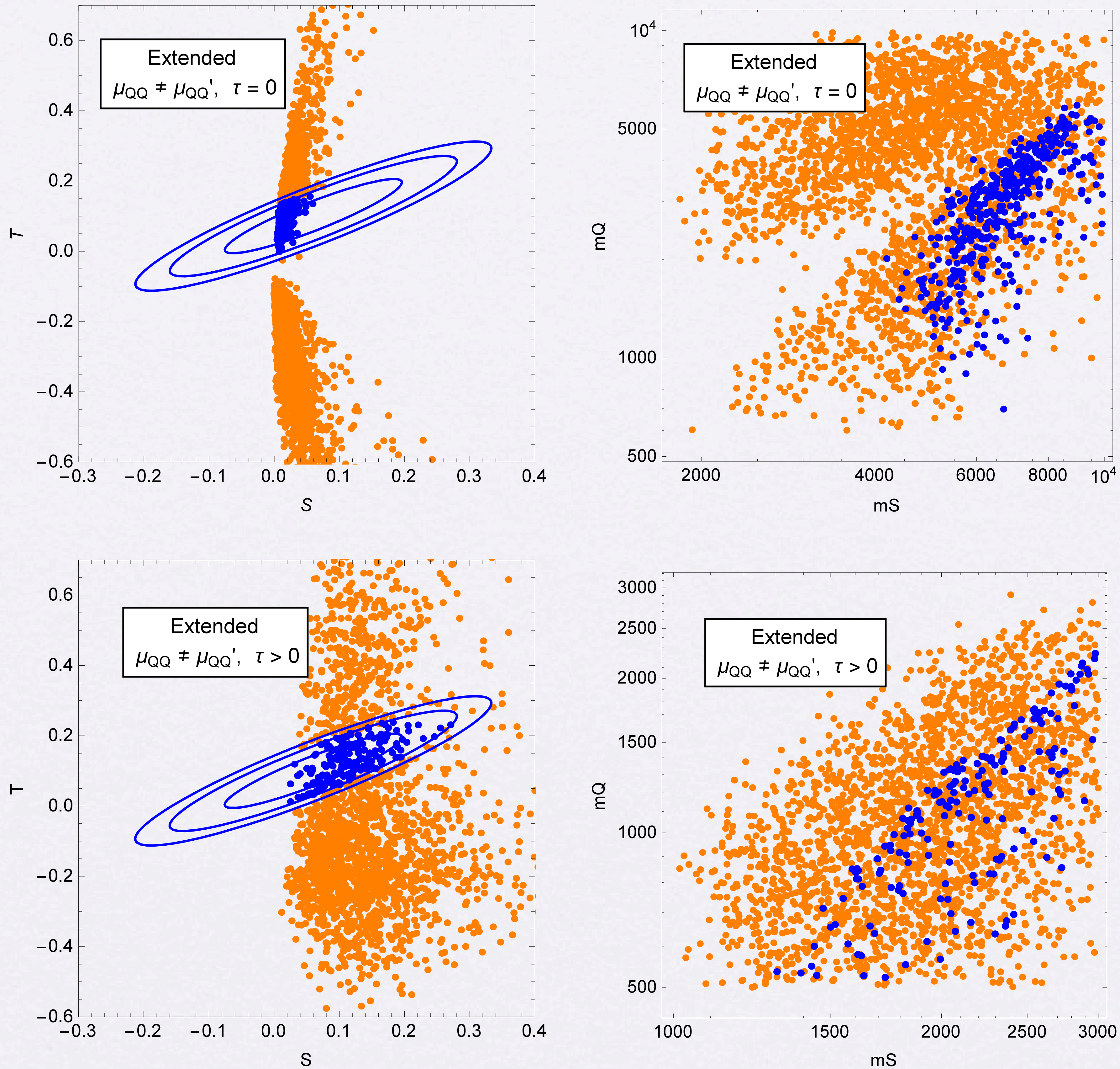
Electroweak Symmetry Breaking

Look for regions of parameter space with EWSB and correct top and Higgs masses

Then test for general agreement with EW precision measurements (oblique)



Spectrum features



Phenomenology: Brief Remarks

- Fermionic resonances, some with exotic charges

  Characteristic of SO(5)/SO(4) constructions

Contino & Servant, 2008
Mrazek & Wulzer, 2009
Dissertori et. al., 2010

- The radial mode $\mathcal{H}$ (whose mass is predicted in terms of the singlet fermion mass)

  Smoking gun of the present microscopic scenario!

- With Gersdorff, Fichet, and Rosenfeld, currently evaluating the LHC discovery potential.

  Preliminary results based on $pp \to \mathcal{H} \to VV \to JJ$ indicate a reach of around 3 TeV at the high-luminosity LHC...

  (crucial effect of light generations)

Summary

- Higgs compositeness: a fundamental question to be settled experimentally

  Models of Higgs compositeness a necessary ingredient

- While not as urgent, microscopic UV completions can put EFT studies on more solid ground

- In this talk, we presented a first step that exhibits explicitly both the Higgs constituents and the interactions that hold them together

- Can build a further (renormalizable) UV completion that leads to the required 4-fermion interactions, in the desired region of parameter space (see 1502.07340)

- It will be interesting to use such an explicit construction to ask phenomenological questions, such as
  - When could deviations be expected to first show up
  - How would the top content of the Higgs first be manifested
  - What would it take to establish such a picture

The answers to such questions may carry more general lessons

Thank you!

Backup Slides

Fermion Spectrum

The fermion mass spectrum (``extended model") is determined by:

- **The spontaneous breaking of** $SO(5) \to SO(4)$ **:** $\xi \hat{f}$
- **(Soft) explicit SO(5) breaking terms:** μ_i
- **EW symmetry breaking (misalignment):** $s_h = \sin(h/f)$

$$\mathcal{L}_{2/3} = -\begin{pmatrix}\bar{S}_L & \bar{Q}_L^{2,2} & \bar{Q}_L^{1,1} & \bar{q}_L\end{pmatrix} \begin{pmatrix} \xi \hat{f} c_h & 0 & \mu_{tS} & 0 \\ \xi \hat{f} \frac{s_h}{\sqrt{2}} & \mu'_{QQ} & 0 & 0 \\ \xi \hat{f} \frac{s_h}{\sqrt{2}} & 0 & 0 & \mu_{QQ} \\ 0 & 0 & 0 & \mu_{qQ} \end{pmatrix} \begin{pmatrix} S_R \\ Q_R^{2,2} \\ t_R \\ Q_R^{1,1} \end{pmatrix} + \text{h.c.} \,,$$

``Heavy" states:

$$m_S^2 \approx \xi^2 \hat{f}^2 + \mu_{tS}^2 \qquad m'^2_Q \approx \mu'^2_{QQ} \qquad m_Q^2 = \mu_{QQ}^2 + \mu_{qQ}^2$$

``Light" top quark: $m_t^2 \approx \frac{s_v^2}{2} \frac{\xi^2 \hat{f}^2 \, \mu_{tS}^2 \mu_{qQ}^2}{m_S^2 m_Q^2}$ **(and massless bottom)**

Spectrum features

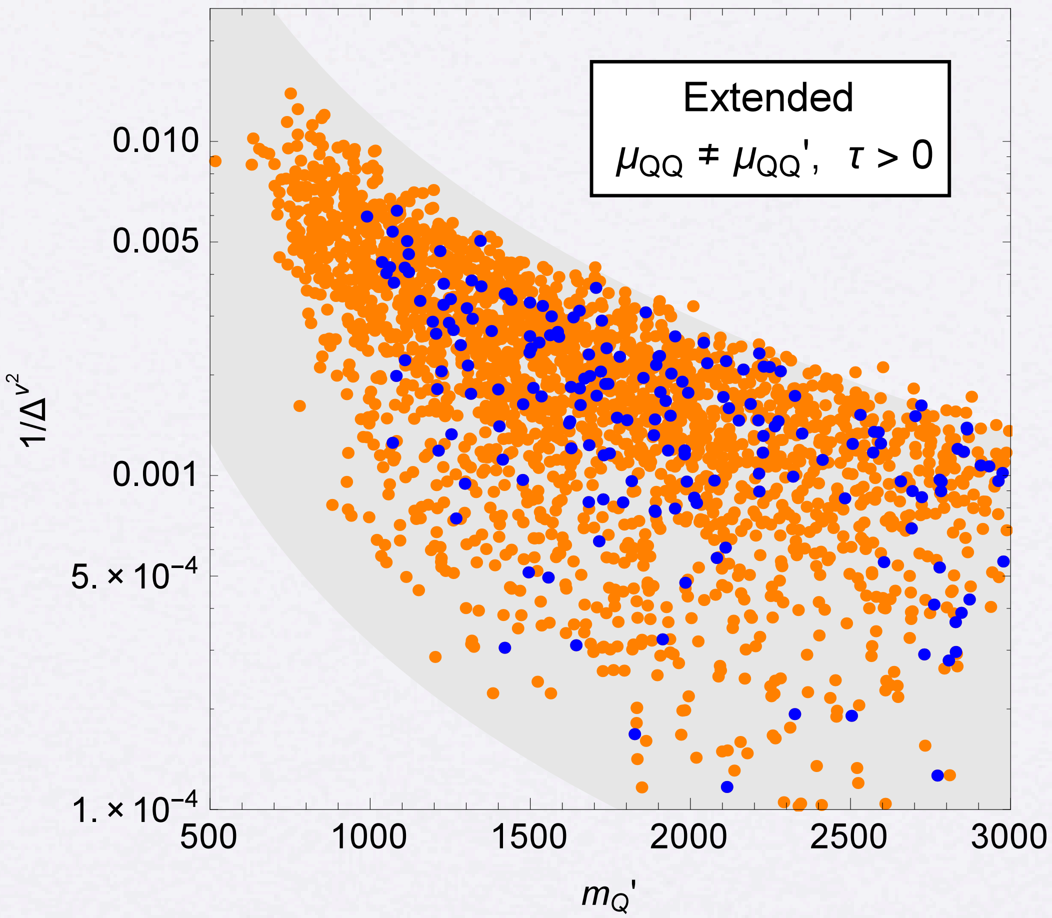
Model			m_h	EWPT	Spectrum	Remarks
Minimal		$\tau = 0$	too light			
		$\tau \neq 0$	$\checkmark$	$\times$		
Extended	$\mu_{QQ} = \mu'_{QQ}$	$\tau = 0$	too light			
		$\tau > 0$	$\checkmark$	$\times$		$\epsilon \ll 1$
		$\tau < 0$	$\checkmark$	$\checkmark$	$m_{\mathcal{H}} < m_S < m'_Q < m_Q$	$\epsilon \gtrsim 1$
	$\mu_{QQ} \neq \mu'_{QQ}$	$\tau = 0$	$\checkmark$	$\checkmark$	$m_Q < m'_Q, m_S$	$\epsilon \ll 1$
		$\tau > 0$	$\checkmark$	$\checkmark$	$m_Q < m'_Q, m_S$	$\epsilon \ll 1$
		$\tau < 0$	$\checkmark$	$\checkmark$		

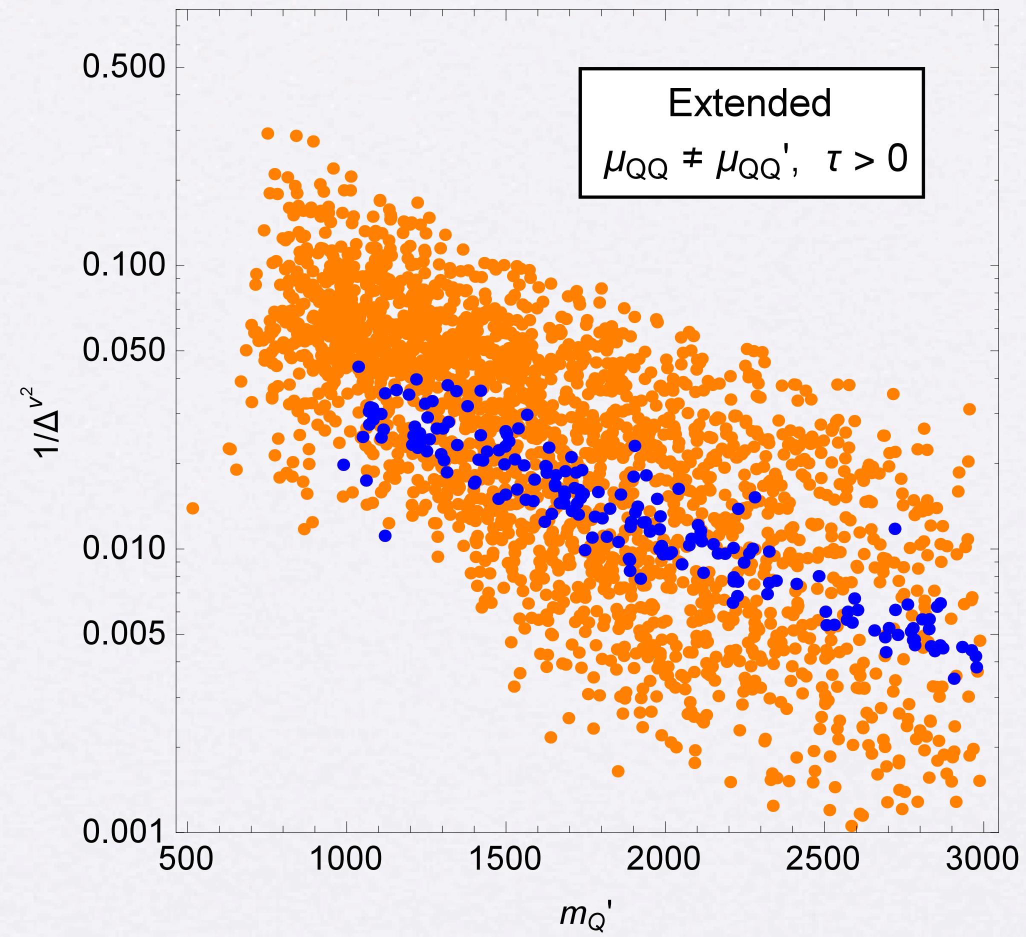
$$\epsilon \equiv \frac{\mu_{\rm eff}^2}{2\mu_{tS}^2}$$

The recently measured Higgs mass of ~125 GeV, as well as precision measurements, impose significant restrictions on the parameter space.

Sometimes, certain mass hierarchies between heavy vector-like fermions and the heavy scalar (radial mode) are singled-out.

Naturalness





$$\Delta^M \equiv \max_P \Delta_P^M \, , \qquad \Delta_P^M \equiv \left| \frac{\partial \log M}{\partial \log P} \right|$$

$$P \in \{\hat{f}, f_\rho, \xi, g_\rho, \mu_{tS}, \mu_{QQ}, \mu_{QQ'}, \tau\}$$

Analytic estimate:

$$\frac{\Delta \alpha_{\mu_{tS}}}{\alpha} \approx \frac{4 r_* \mu_{tS}^2}{r_v m_h^2}$$

A Renormalizable UV Model

Consider a $SU(N_c) \times SU(N_c)$ **gauge theory, spontaneously broken to the diagonal**

(as in top-color models)

<u>Field content</u>: SM quarks and any new vector-like states charged under first $SU(N_c)$**, hence no anomalies. Diagonal unbroken subgroup identified with QCD** $N_c = 3$

- **Focus on** $F_L^i (i = 1, \ldots 5)$ **and** S_R **of the main part of the talk.**
- **Add a (neutral) real scalar** $\Xi^i (i = 1, \ldots 5)$ **with mass of the same order as the broken gauge bosons (this scalar may itself be a composite state)**

In unitary gauge:

$$\mathcal{L}_{\rm UV} \supset -\frac{1}{2} M_\Xi^2 \, \Xi^2 + y \, (\bar{S}_R \, \Xi^i F_L^i + \text{h.c.}) + \frac{1}{2} \, M_G^2 G_\mu G^\mu + \frac{1}{2} \, \hat{g} \, G_\mu^A (\bar{S}_R \gamma^\mu \lambda^A S_R + \bar{F}_{L,i} \gamma^\mu \lambda^A F_L^i) \ ,$$

Integrating out the heavy fields:

$$\mathcal{L} \supset \frac{y^2}{2 M_\Xi^2} \, (\bar{S}_R F_L^i + \text{h.c.})^2 - \frac{\hat{g}^2}{8 M_G^2} (\bar{S}_R \gamma^\mu \lambda^A S_R + \bar{F}_{L,i} \gamma^\mu \lambda^A F_L^i)^2$$

A Renormalizable UV Model

$$\mathcal{L} \supset \frac{y^2}{2M_\Xi^2}(\bar{S}_R F_L^i + \text{h.c.})^2 - \frac{\hat{g}^2}{8M_G^2}(\bar{S}_R \gamma^\mu \lambda^A S_R + \bar{F}_{L,i}\gamma^\mu \lambda^A F_L^i)^2$$

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After Fierz rearrangement, this leads to the ``scalar channel" 4-fermion int's, with

$$G_S = \frac{\hat{g}^2}{2M_G^2} + \frac{y^2}{M_\Xi^2}, \qquad G'_S = \frac{\hat{g}^2}{2M_G^2}$$

One naturally obtains $G_S > G'_S$: one super-critical, the other sub-critical.

At the same time, one finds the required ``vector channel" 4-fermion interactions