THE DYNAMICAL COMPOSITE HIGGS

Gero von Gersdorff

São Paulo, 27/11/2015

Based on work with E. Pontón and R. Rosenfeld
(and work in progress with S.Fichet)

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

INTRODUCTION

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- Electroweak Symmetry Breaking is far from understood!
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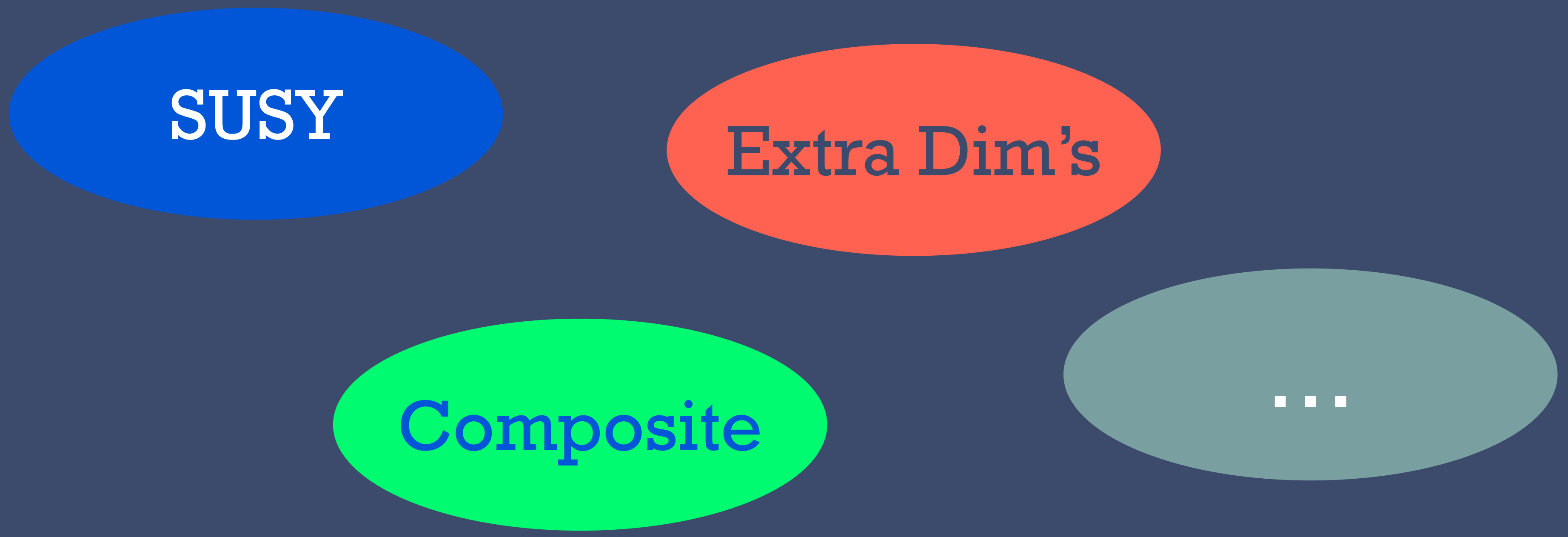

The Composite Higgs

- If the Higgs is a "meson", why don't we see the higher excitations? (why $m_{res} >> m_h$? "Little Hierarchy")
- Higgs as the pNGB of a spontaneously broken global symmetry:
  — SU(3) ➜ $SU(2)_L$ x U(1)
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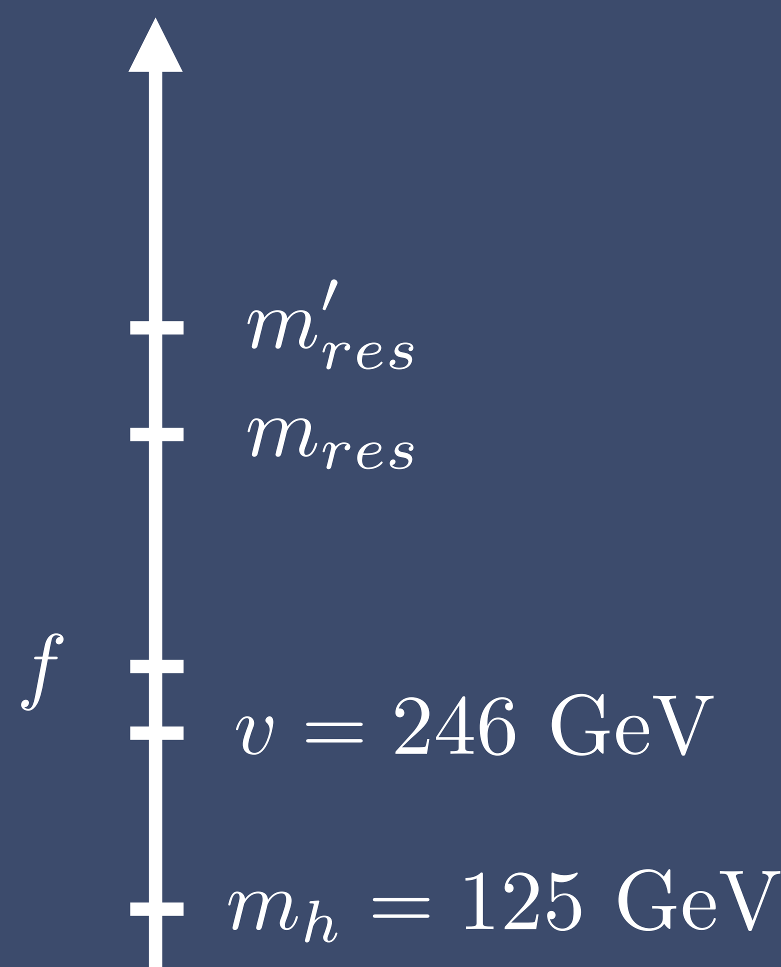
$$m_{res} = g_* f \qquad m_h = \frac{g_*^2}{4\pi} v$$



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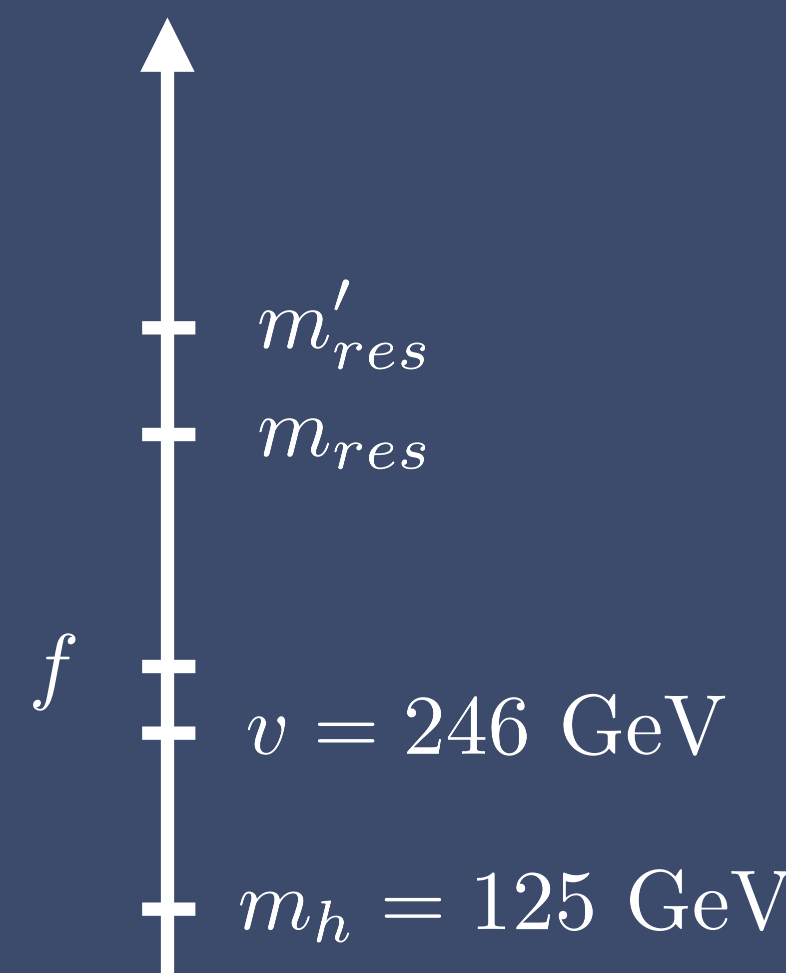
$$f > 600 \text{ GeV}$$



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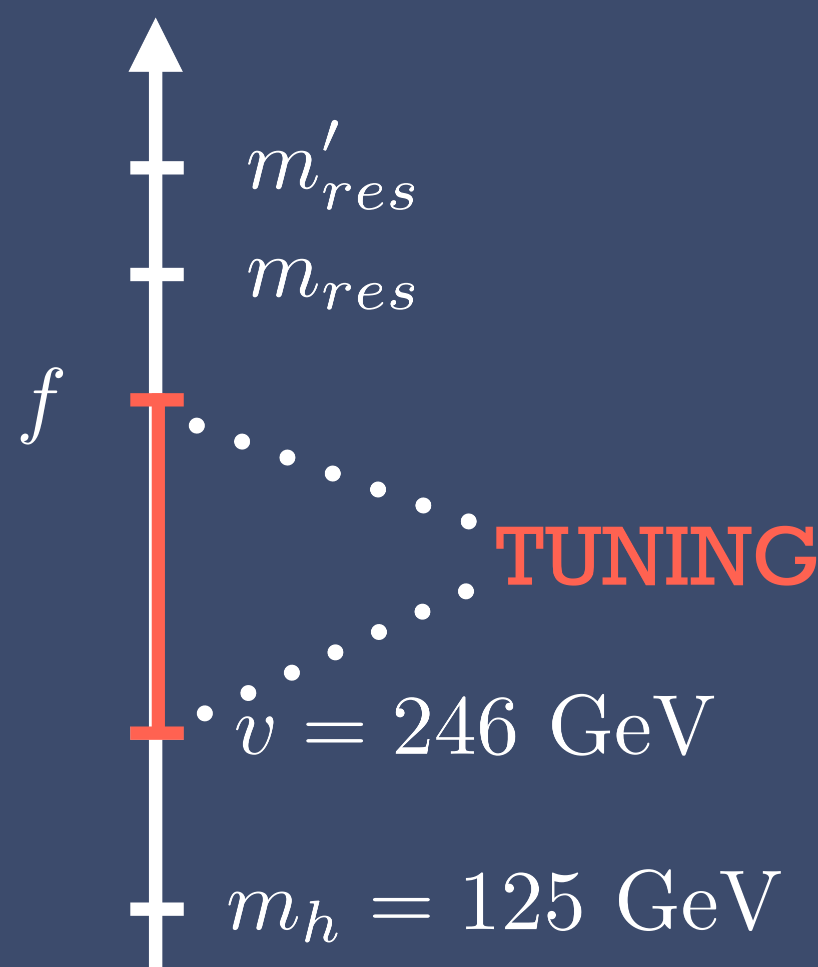

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Open Questions

- Can one have an SO(5) global symmetry?
  - Renormalizable (gauge) theories typically have larger (accidental) global symmetry groups (breaking patterns classified in Peskin 1980)
- What is the UV theory (the constituents of the CH)?
  - Can it be made out of Standard Model fermions?
- What is the dynamics causing the global symmetry breaking?
  - Is there an SO(5) "Higgs boson"?

Open Questions

- In this talk, I will present a model that
  - Possesses just SO(5) global symmetry
  - Accomplishes SO(5) as well as EW breaking dynamically
  - Features a CH made out of an (extended) top sector
  - Has SO(5) Higgs particle whose self coupling is predicted
  - Has few parameters and is compatible with all constraints

  This model is largely inspired by the seminal paper: "Minimal Dynamical Symmetry Breaking of the Standard Model", Bardeen, Hill, Lindner '90

MINIMAL DYNAMICAL EWSB
(IT DOESN'T WORK)

The Top Condensation Mechanism

- EWSB triggered from 4-fermion (NJL) interaction:

$$\mathcal{L} = G\left(\bar{q}_L t_R\right)^2$$

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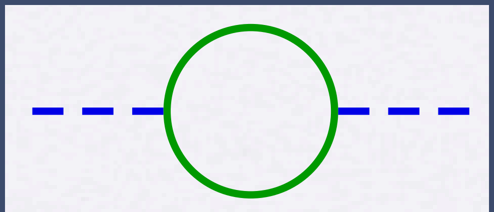
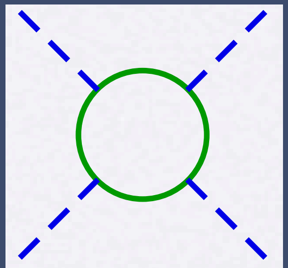
- Radiative correction make Higgs dynamical:

$$\mathcal{L} = \frac{1}{G_c\Lambda^2}\log\frac{\Lambda}{\mu}\,|DH|^2 - \left(\frac{1}{G} - \frac{1}{G_c}\right)|H|^2 - H(\bar{q}_L t_R) - \frac{1}{G_c\Lambda^2}\log\frac{\Lambda}{\mu}|H|^4$$





$$G_c = \frac{8\pi^2}{N_c\Lambda^2}$$

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- EWSB occurs for $G > G_c$
- The ratio of top and Higgs mass is fixed: $m_h = 2\ m_t$

$$G_c = \frac{8\pi^2}{N_c\Lambda^2}$$

Top Condensation: Beyond Large N_C

- Equivalently, consider beta functions

$$16\pi^2\beta_{y_t^2} = 2N_c\, y_t^4 + 3\, y_t^4$$

$$16\pi^2\beta_\lambda = 4N_c\, y_t^2\lambda - 2N_c\, y_t^4 + 24\lambda^2$$

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- Including scalar loops, IR fixed point ➜ $m_h = 1.3\, m_t$
- Including gauge loops, nonlinear relation between m_h and m_t

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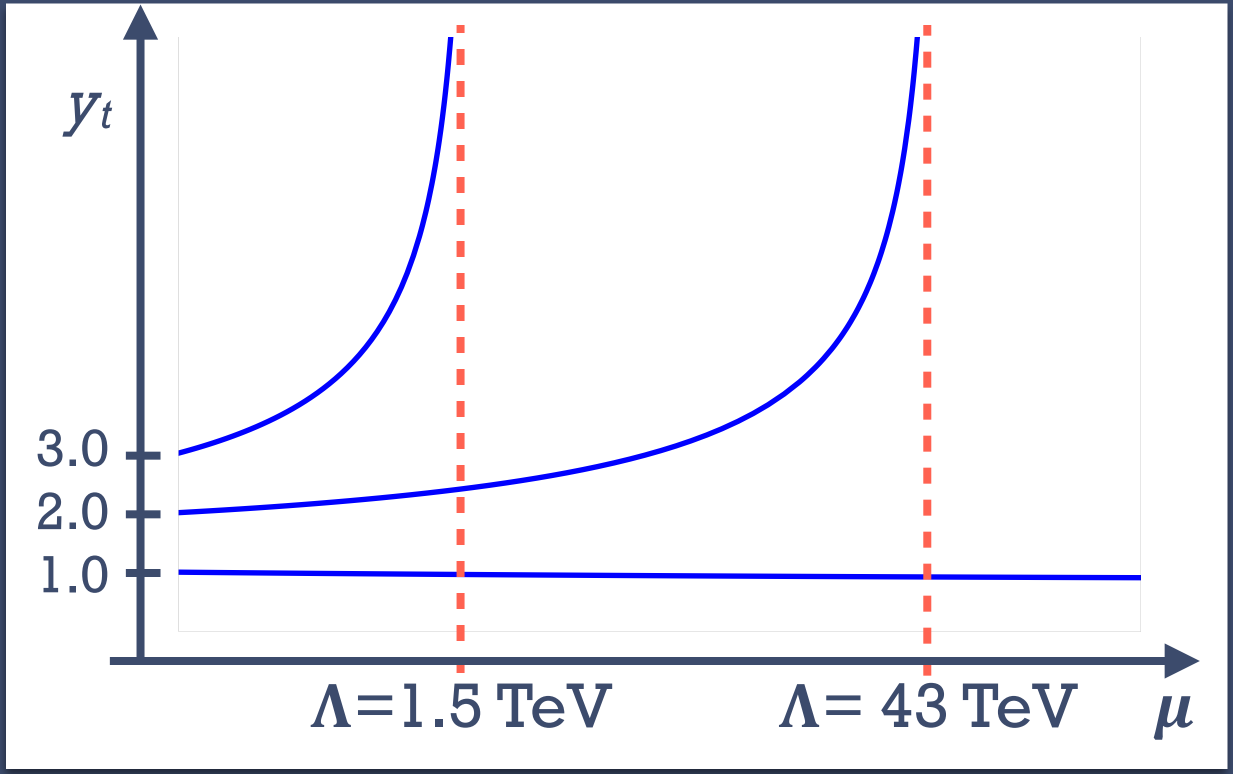
- Compositeness scale are Landau Poles for Yukawas
- Physical Yukawa ~ 1 is too small
- Top Seesaw: Enlarge top sector

Dobrescu et al '97/'98



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Invariant under SO(5) x $U(1)_X$

- Choice $G = G'$, invariant under $U(5)_L$ x $U(1)_R$
  ➜ more scalar states, (2HDM) Dobresci,Cheng + Gu '14
- Take only G supercritical ➜ minimal model GG, Ponton, Rosenfeld '15

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- The composite scalar $\Phi = \left(\bar{S}_R F_L + \bar{F}_L S_R\right)$ is a 5_0 of SO(5)
- 5 real d.o.f: pNGB Higgs + one SM singlet, the radial mode

Flowing to the IR

- Again Rewrite 4-fermion interaction

$$\frac{G}{2}\left(\bar{S}_R F_L + \bar{F}_L S_R\right)^2 = -\frac{1}{2G}\Phi^2 - \Phi\left(\bar{S}_R F_L + \bar{F}_L S_R\right)$$

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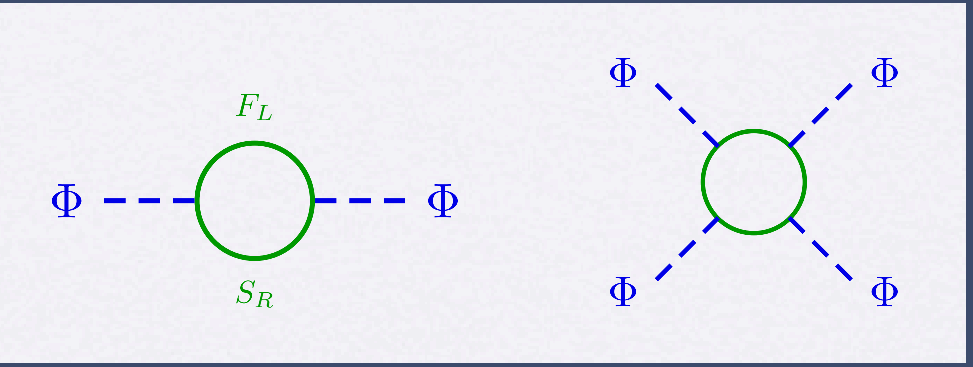

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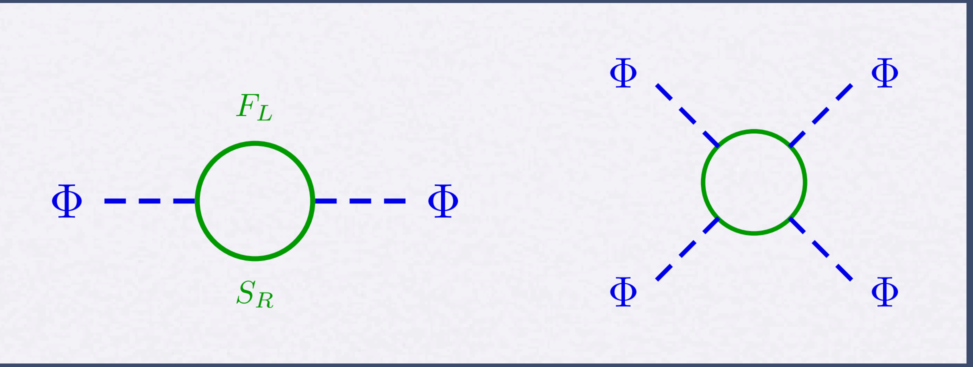

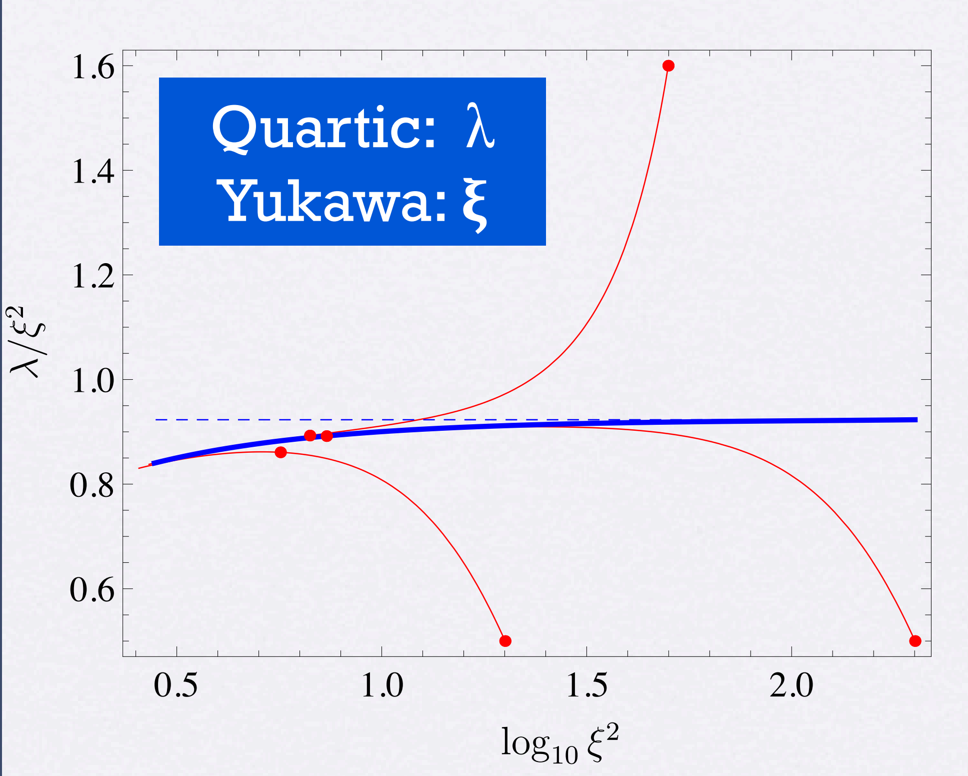

- Due to the presence of the IR fixed point, the quartic λ and hence the mass of the radial mode become a prediction of the model

$$m_{\mathcal{H}}^2 = \frac{24}{13}\, m_S^2$$

The Full Top Sector

- Weakly gauge $SU(2) \times U(1)_Y$ subgroup of $SO(5) \times U(1)_X$
- Hypercharge embedded as $Y = Q_X + T_{R3}$
- Need to have chiral field content of the SM: $(q_L = 2_{1/6}) + (t_R = 1_{2/3})$
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$Q_{L1} + Q_{L2} + S_L + S_R + Q_{R2} + t_R$

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Extended Model:
$Q_{L1} + Q_{L2} + S_L + S_R + Q_{R1} + Q_{R2} + q_L + t_R$

The full Top Sector

- Complete multiplets have mass mixings with incomplete ones[1)]

$$\mathcal{L}_{mix}^{min} = -\mu'_{QQ}\, \bar{Q}_L^2 Q_R^2 - \mu_{tS}\, \bar{S}_L t_R$$

$$\mathcal{L}_{mix}^{ext} = \mathcal{L}_{mix}^{min} - \mu_{QQ}\, \bar{Q}_L^1 Q_R^1 - \mu_{qQ}\, \bar{q}_L Q_R^1$$

[1)] One additional parameter $\mu_{SS}\, \bar{S}_L S_R$: equivalent to a tadpole $\mathcal{L} = \tau \Phi_5$

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$2_{\frac{7}{6}}$	$m'^2_Q = \mu'^2_{QQ}$

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Top Quark:

$$m_t^2 = \frac{\sin^2(\frac{v}{f})}{2} m_S^2 \times c_R^2\, s_R^2 \times s_L^2$$

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SPIN-1 SECTOR

Wakamatsu + Weise '88
GG, Ponton, Rosenfeld '15

- Spin-1 states are also obtained from 4-fermion interactions:

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SPECTRUM:

$SO(4)$	$m_\rho^2 = \frac{g_\rho^2 f_\rho^2}{2}$
$\frac{SO(5)}{SO(4)}$	$m_a^2 = \frac{m_\rho^2}{r_v}$

$$r_v = \frac{f^2}{\hat{f}^2} < 1$$

PARAMETER SPACE

- Free parameters of the model:
  - Couplings: $\xi, \ g_\rho$
  - SB scales: $f, \ \hat{f}$
  - Mass mixings: $\mu'_{QQ}, \ \mu_{tS}, \ (\mu_{QQ}, \ \mu_{qQ})$

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- EWSB (fixing correct values for v and m_h) removes 2 parameters
  ➜ Spectrum alone fixes the parameters of the model
- Predictions: m_ϕ, couplings, EW mass splittings

pNGB Potential

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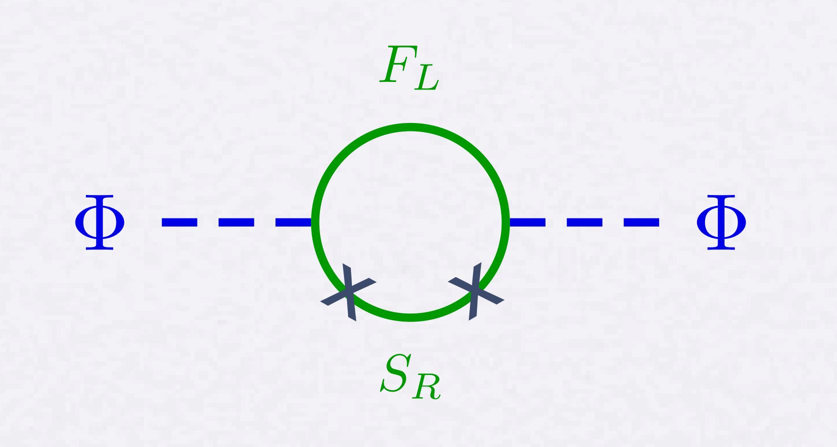

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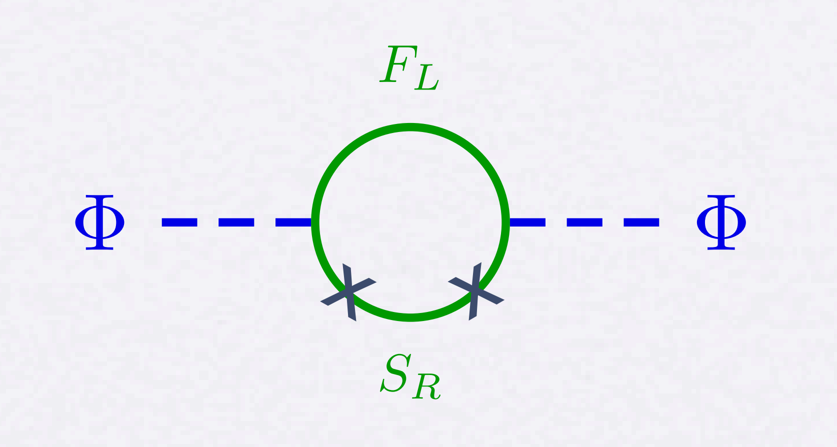
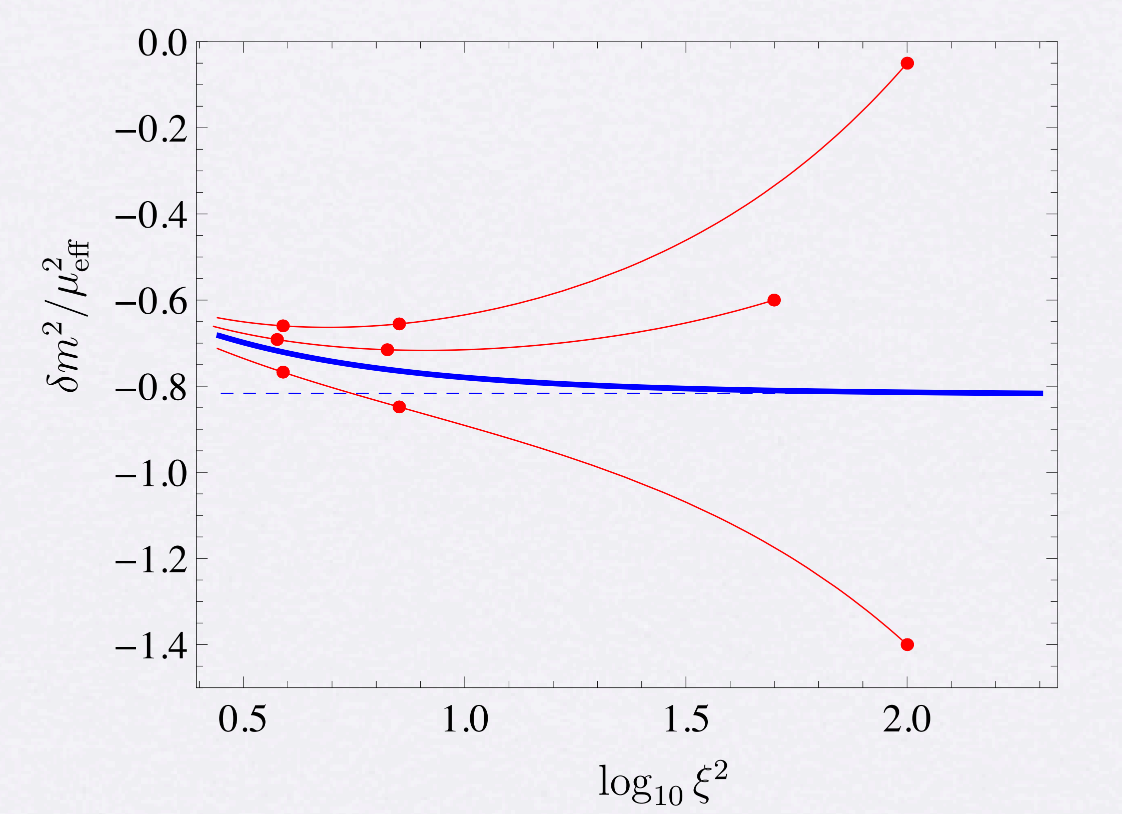


- New ~~SO~~(5) Counterterm δm^2 !
- However, IR fixed point!

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

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

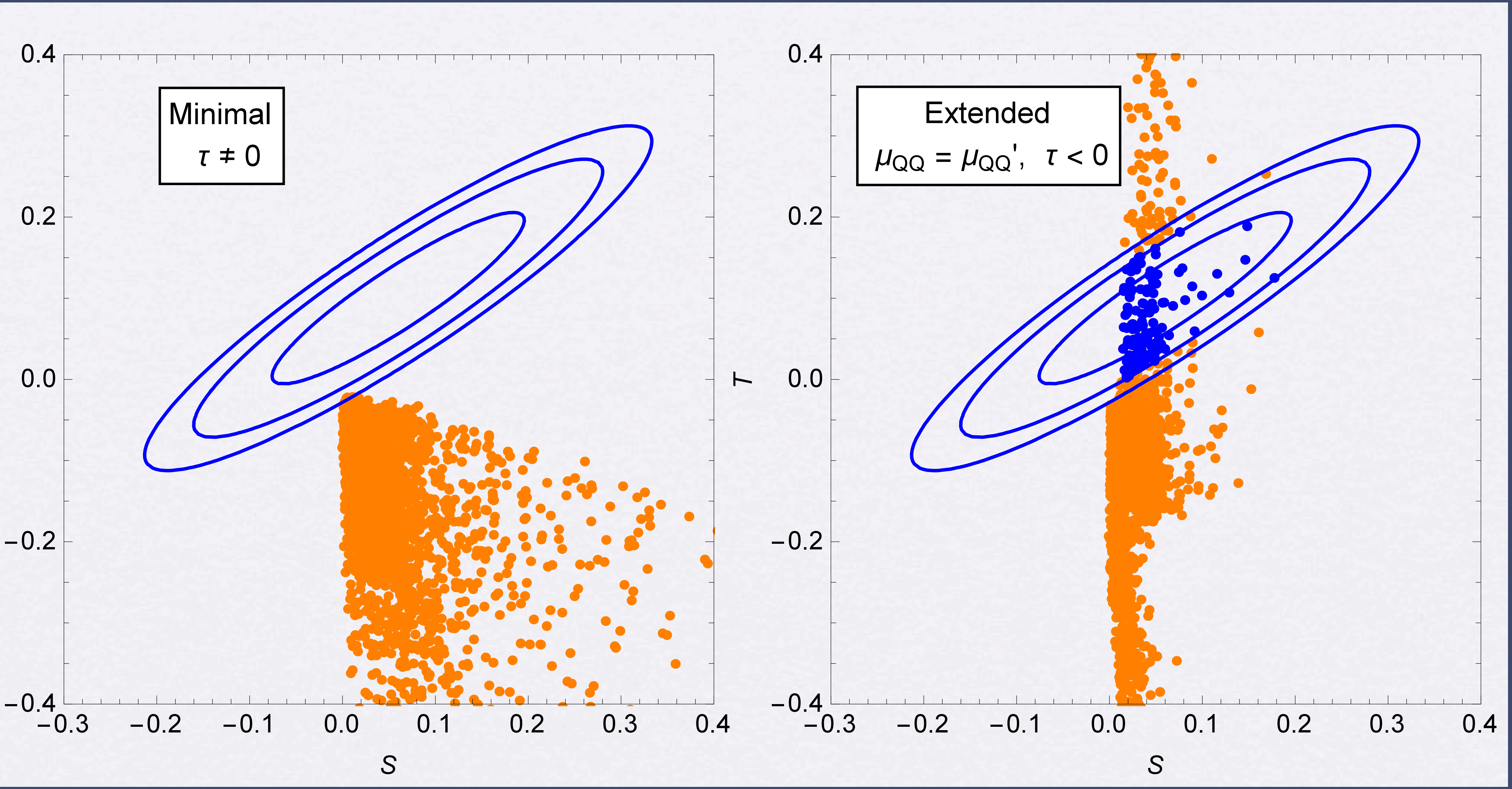
- pNGB Higgs potential is fully calculable!



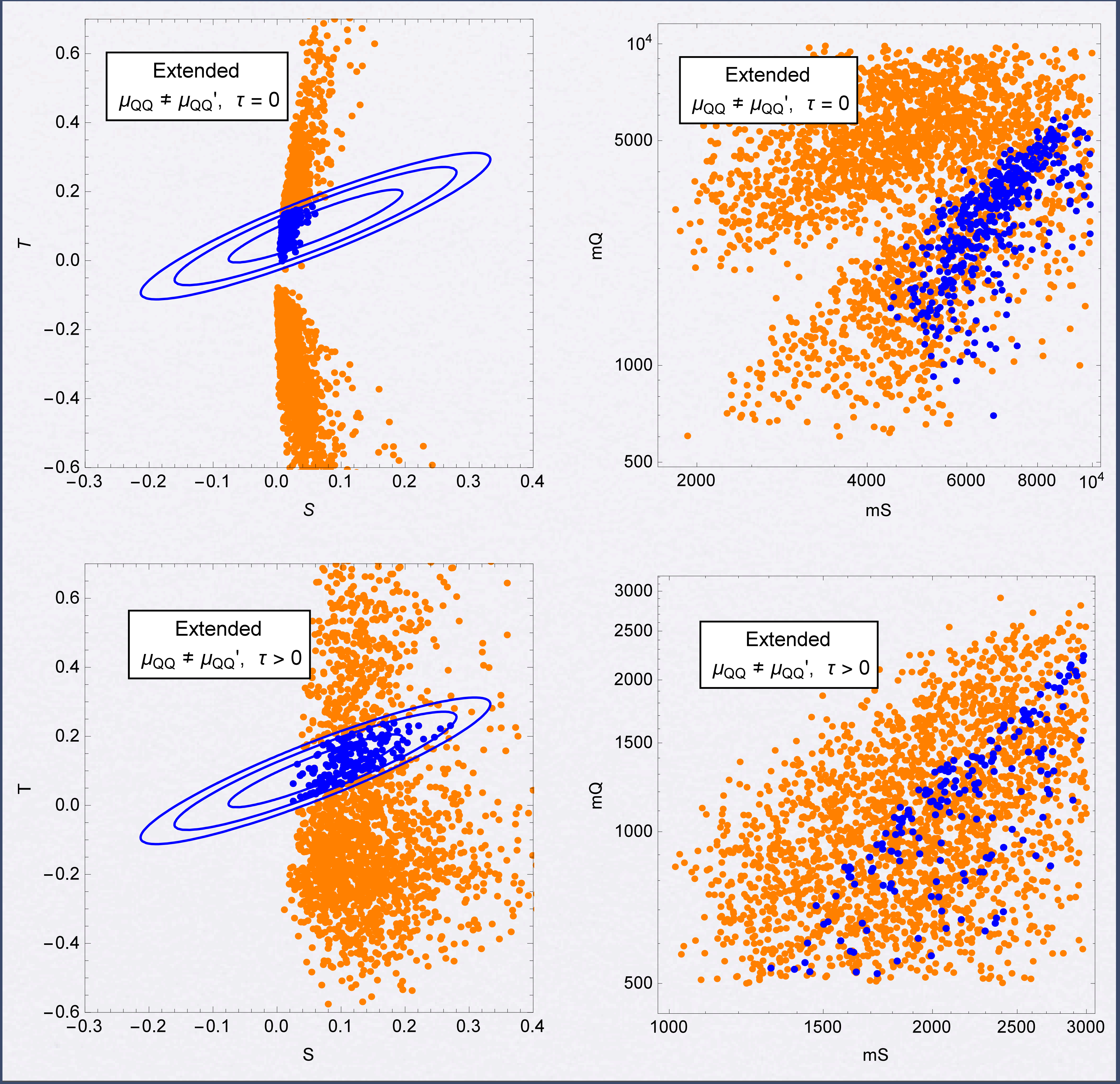
PHENOMENOLOGY

SCANS

- Perform scans over parameter space, fixing m_t, m_h, v
- Test against EWPT (S and T parameters)



Scans



Extended
$\mu_{QQ} \neq \mu_{QQ}'$, $\tau = 0$
T
S
mQ
mS
Extended
$\mu_{QQ} \neq \mu_{QQ}'$, $\tau = 0$
Extended
$\mu_{QQ} \neq \mu_{QQ}'$, $\tau > 0$
T
S
Extended
$\mu_{QQ} \neq \mu_{QQ}'$, $\tau > 0$
mQ
mS

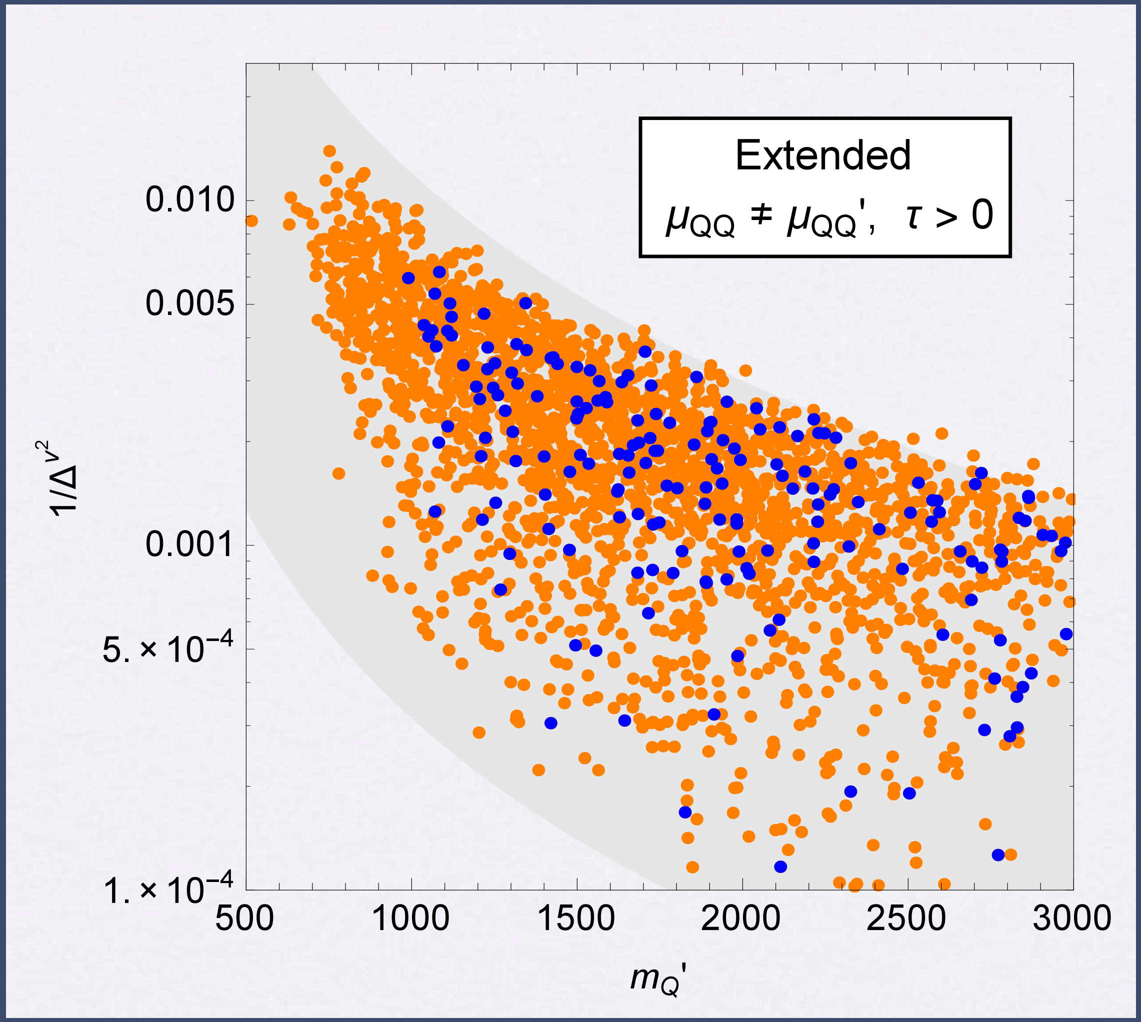
Scans

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

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

- Combining EWSB, top mass and EWPT constraints is very restrictive
- Certain mass hierarchies can be identified

Fine Tuning?



- Fine tuning ~1%, mainly due to $\delta m^2 = r_* \mu_{eff}^2$ $(\mu_{eff}^2 = 2\mu_{tS}^2 - \mu_{QQ}^2 - \mu_{QQ}'^2)$
- Enhanced symmetry for $$\mu_{QQ} = \mu'_{QQ} = \mu_{tS}$$

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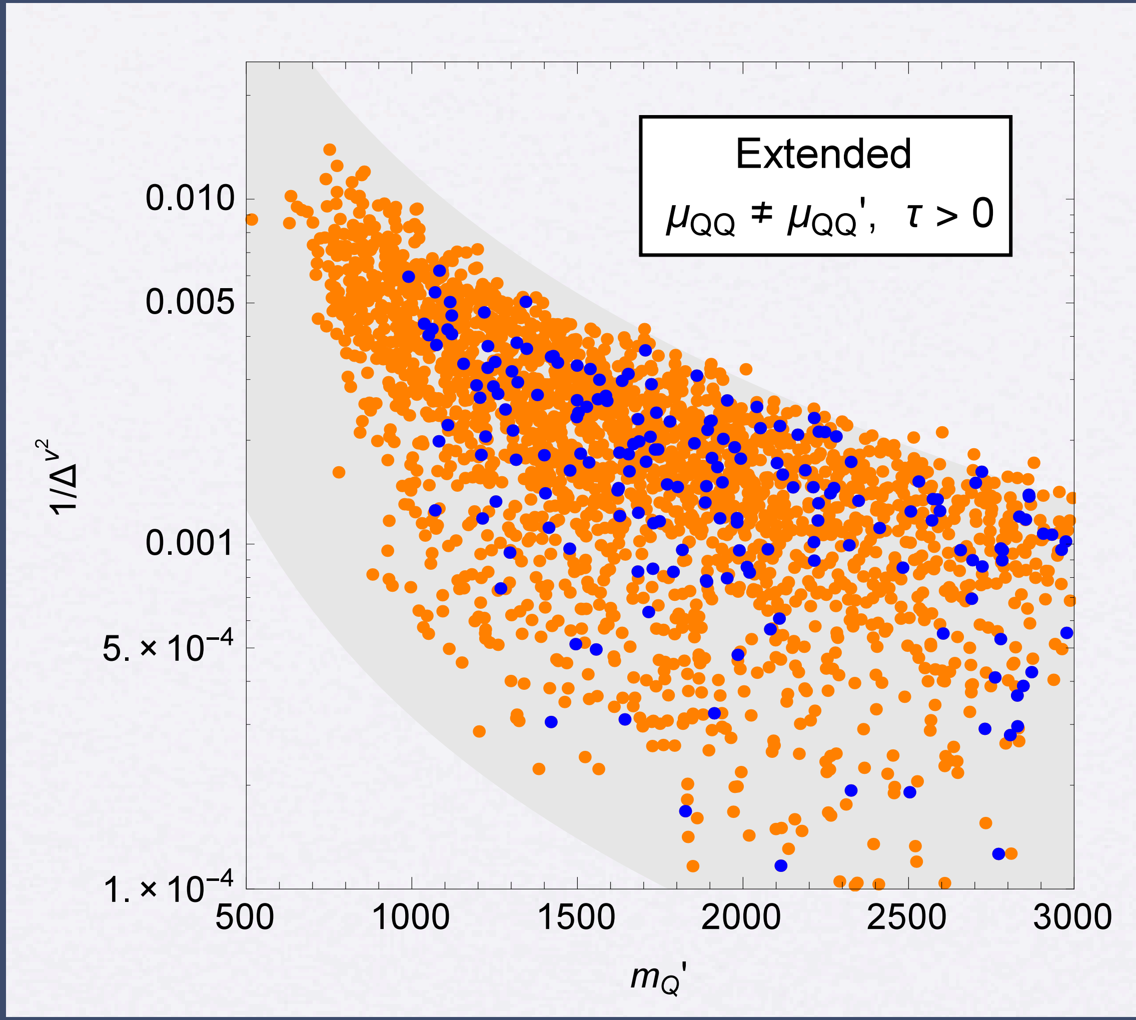

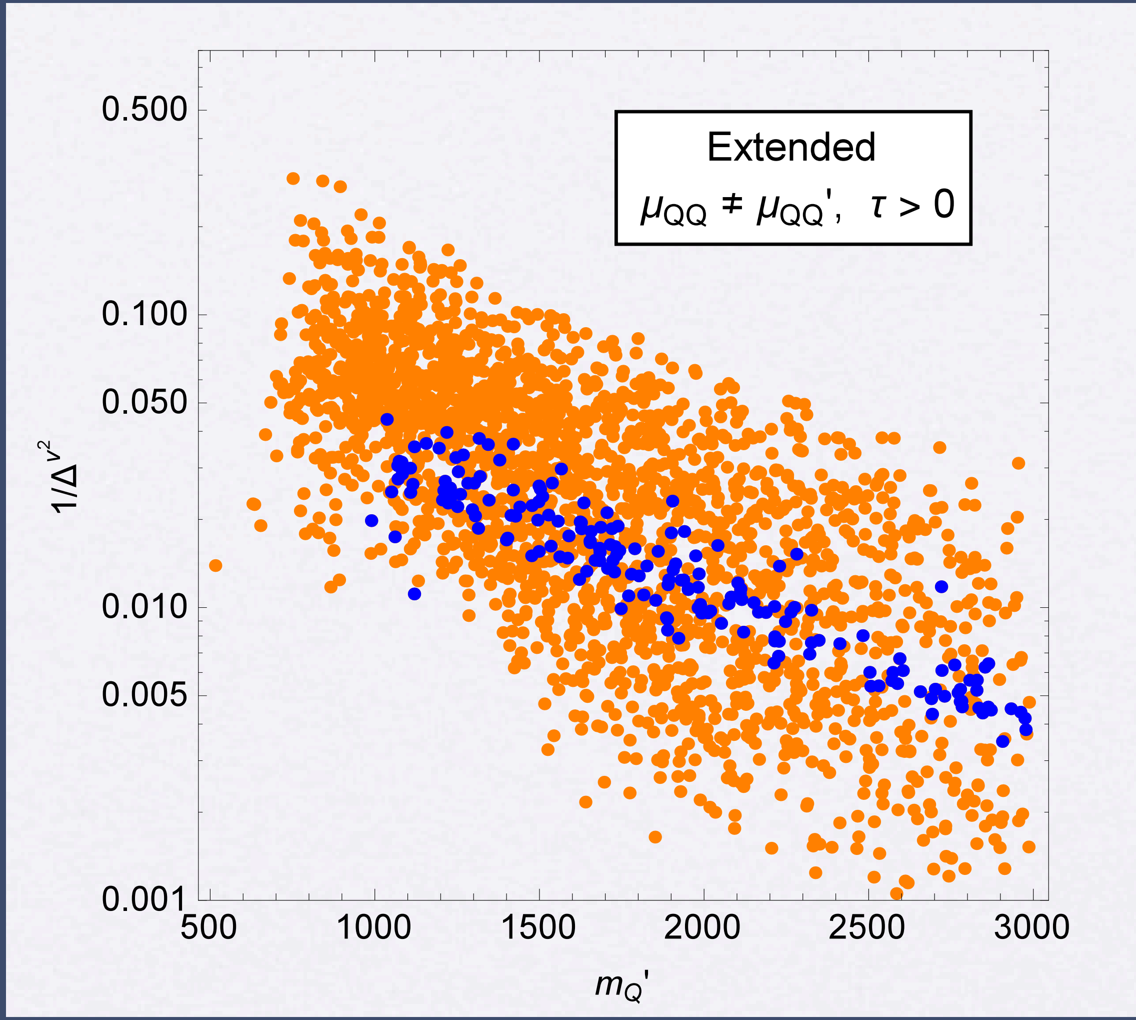

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- Enhanced symmetry for

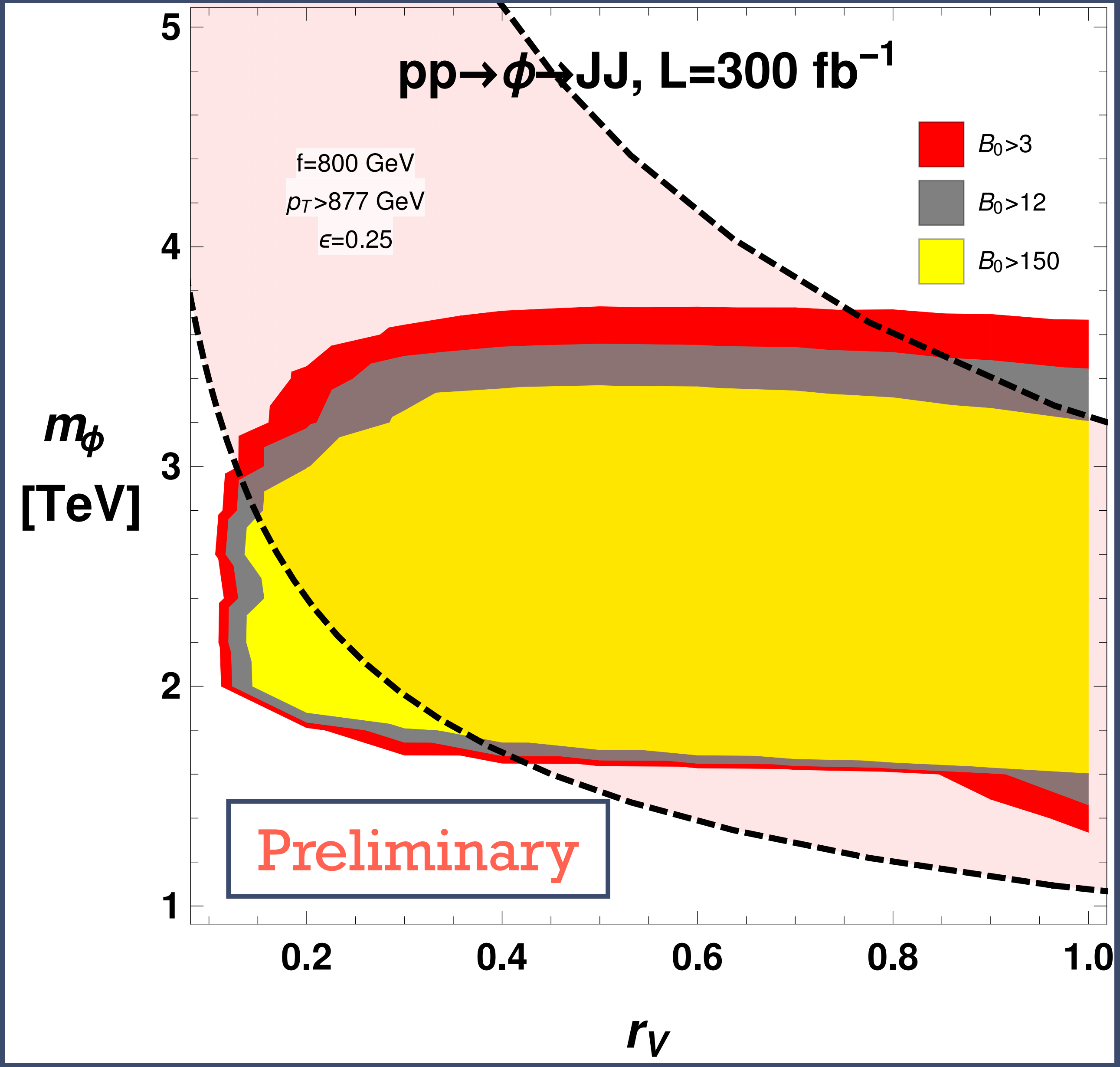
  $\mu_{QQ} = \mu_{QQ}' = \mu_{tS}$

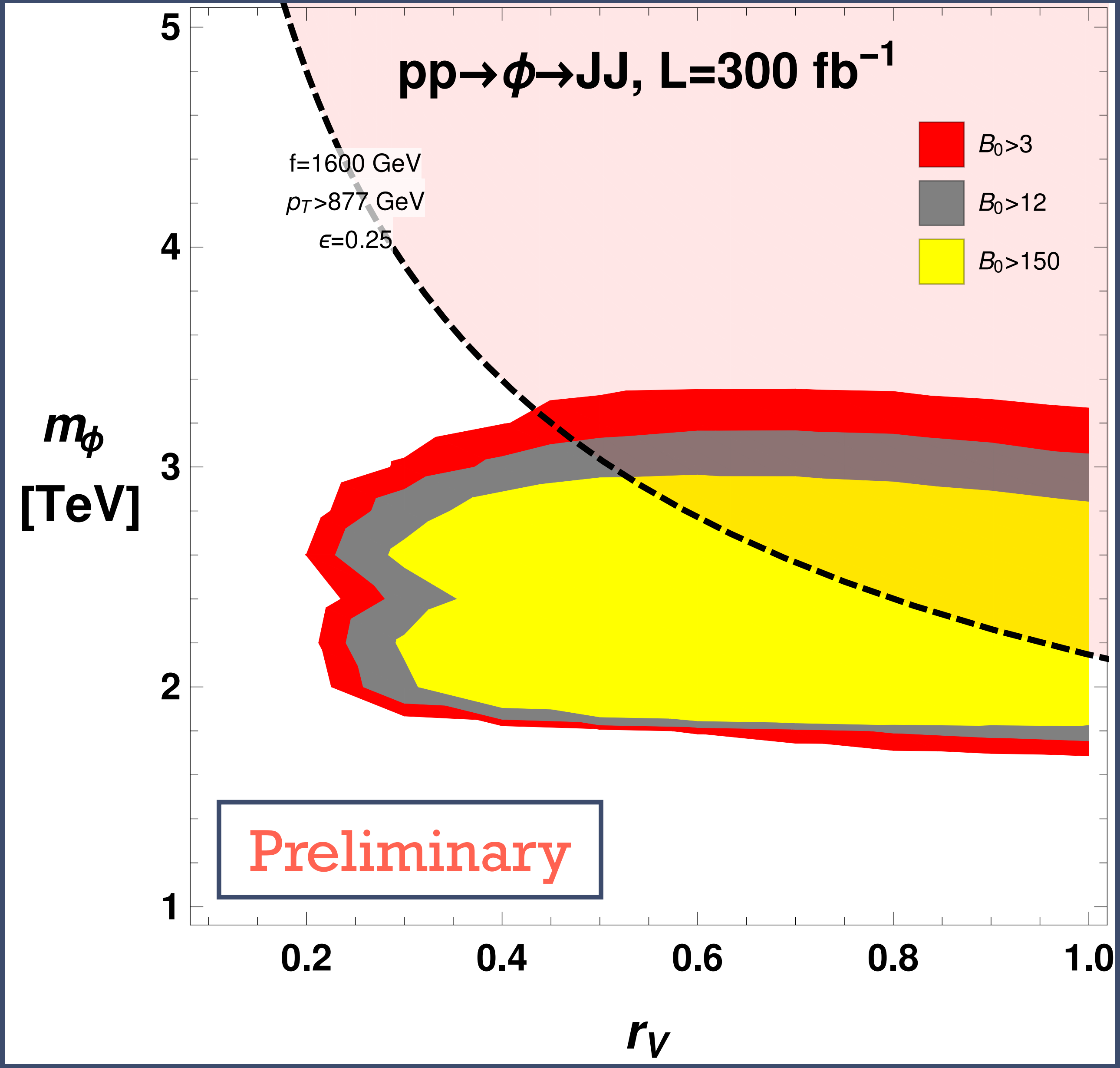
- Fine tuning, keeping μ_{eff} fixed ~ 5%
- Can also be improved by going to less minimal top sectors

Looking for the SO(5) Higgs at the LHC

- Analysis for the channel:
  $pp \rightarrow \phi \rightarrow VV \rightarrow JJ$
- Shape analysis

GG, Fichet, Ponton, Rosenfeld w.i.p.





Conclusions

- The Dynamical Composite Higgs is (class of) models addressing various issues usually not considered
  - SO(5) global symmetry
  - Dynamical breaking of SO(5) (via NJL / 4-fermion)
  - Constituents of the Higgs (Extended top sector)
  - An SO(5) "Higgs" boson

- Fully calculable pNGB Higgs radiative potential
  - Allows for correct Higgs, Z and top mass
- Various IR fixed points (radial mode quartic coupling, GB mass)
- EWPT (oblique) can be satisfied
- The radial mode could potentially be identified at the LHC13

BACKUP

Enhanced Symmetry

	Q	Q	S	S	Q	Q	q	t
SO(5) x U(1)	5			1	-		-	-
SU(2)	2	2	1	1	2	2	2	1

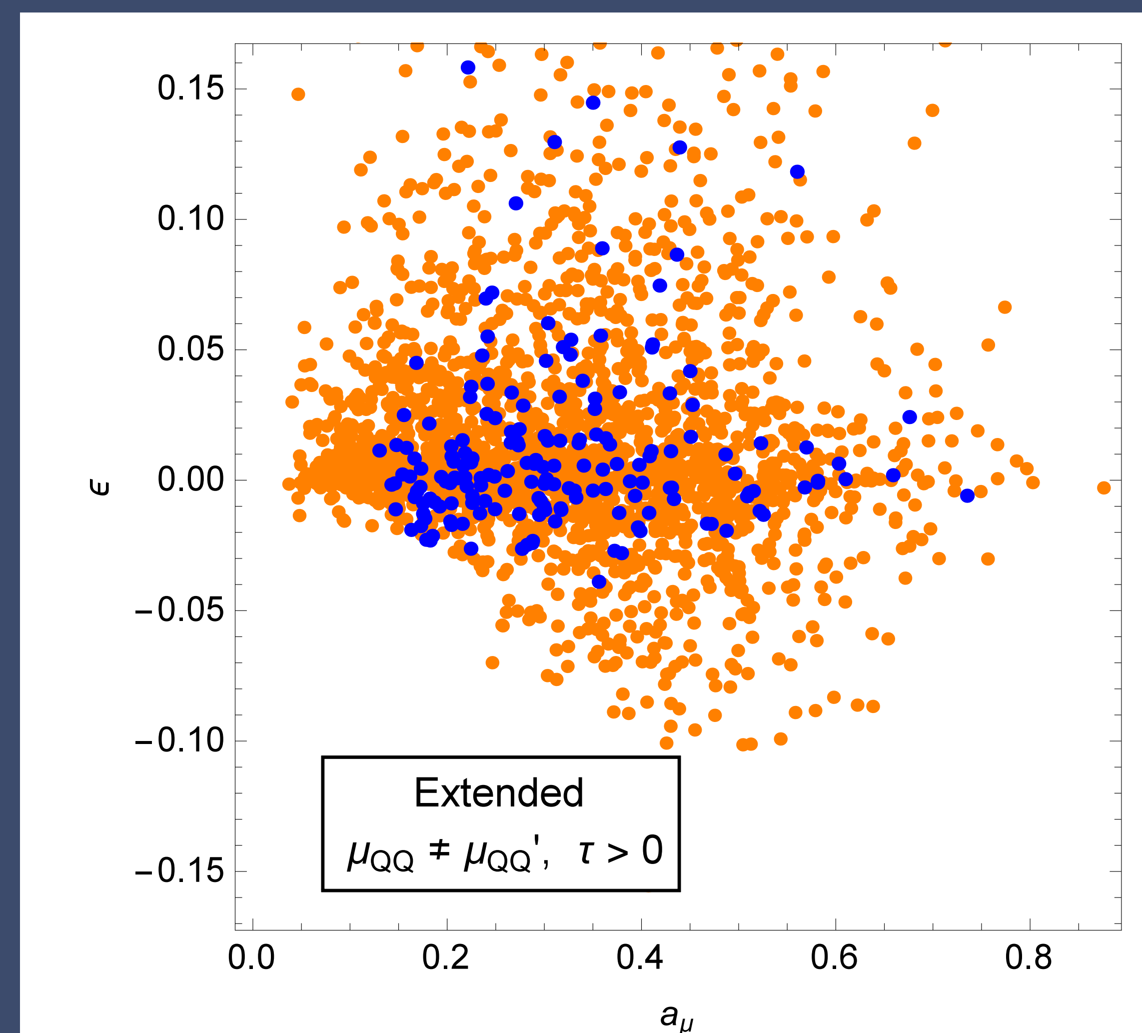
- **Mass Lagrangians**

$$\mathcal{L}_{mix}^{min} = -\mu'_{QQ}\,\bar{Q}_L^2 Q_R^2 - \mu_{tS}\,\bar{S}_L t_R$$

$$\mathcal{L}_{mix}^{ext} = -\mu_{QQ}\,\bar{Q}_L^1 Q_R^1 - \mu_{qQ}\,\bar{q}_L Q_R^1$$

- **For** $\mu_{QQ} = \mu'_{QQ} = \mu_{tS}$ **unify** $Q_{R1} + Q_{R2} + t_R \rightarrow F_R$
- **Only q_L remains "incomplete"**

$$a_\mu = \frac{\mu'_{QQ} - \mu_{QQ}}{\mu'_{QQ} + \mu_{QQ}} \qquad \epsilon = \frac{\mu_{eff}^2}{2\mu_{tS}^2}$$



The Full Lagrangian

$$\mathcal{L} = i(\bar{\mathcal{Q}}_L, \bar{\mathcal{S}}_L) \not{D} \begin{pmatrix} \mathcal{Q}_L \\ \mathcal{S}_L \end{pmatrix} + i\bar{\mathcal{S}}_R \not{D} \mathcal{S}_R + \frac{1}{2}(\nabla_\mu \mathcal{H})^2 - \frac{1}{4}\lambda \left(\mathcal{H}^2 - \hat{f}^2 \right)^2 - \xi \, \mathcal{H} \, \bar{\mathcal{S}}\mathcal{S}$$
$$+ \frac{1}{4} f_\rho^2 \left(\mathcal{A}_\mu^A - i[U_5^\dagger D_\mu^{SM} U_5]^A \right)^2 + \frac{1}{4} f_X^2 \left(\mathcal{A}_\mu^X - i \, U_1^\dagger D_\mu^{SM} U_1 \right)^2$$
$$- \frac{1}{4g_\rho^2} (\mathcal{F}_{\mu\nu}^V)^2 - \frac{1}{4g_X^2} (\mathcal{F}_{\mu\nu}^X)^2 - \frac{1}{4g_0^2} (w_{\mu\nu}^a)^2 - \frac{1}{4g_0'^2} (b_{\mu\nu})^2 \;,$$

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)

Field content: 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:

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

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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