Building a viable Asymptoticaly Safe SM

Steven Abel (Durham IPPP)

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- Motivation; hierarchy versus triviality
- Asymptotically safe 4D QFTs
- Tetrad model for the ASSM
- Radiative symmetry breaking
- Relevant operators

Hierarchy versus triviality

The triviality problem:

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Scalars lead to Landau poles:

 \Rightarrow the theory is UV incomplete

But trying to UV complete it results in the hierarchy problem

QCD is (unlike SUSY) a UV complete theory. Why?

- 1. *There is no hierarchy problem:* quark masses are protected by chiral symmetry *problem:* quark masses are protected by chira
- 2. *There is no triviality problem:* QCD is **asymptotically free**

QCD is (unlike SUSY) a UV complete theory. Why?

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- 2. *There is no triviality problem:* QCD is **asymptotically free**

But, we do not care about running masses because they do not change the Gaussian UV fixed point. We simply measure them and let them run. Or equivalently, relevant operators are anyway effectively zero in the UV. *So we don't even need the chiral symmetry: point 1 becomes irrelevant in this case.*

The Basic idea

Gastmans et al '78 Weinberg '79 Peskin Reuter, Wetterich Gawedski, Kupiainen Kawai et al, de Calan et al ', Litim Morris

Weinberg used this as a basis for his proposal of UV complete theories

Categorise the possible content of a theory as folows:

Irrelevant operators: would disrupt the fixed point - therefore asymptotically safe theories have to emanate precisely from UV fixed point where they are assumed zero (exactly renormalizable trajectory)

Marginal operators: can be involved in determining the UV fixed point where they become *exactly* marginal. Or can be marginally relevant (asymptotically free) or irrelevant.

Relevant operators: become "irrelevant" in the UV but may determine the IR fixed point.

Dangerously irrelevant operators: grow in both the UV and IR (common in e.g. SUSY)

Harmless relevant operators: shrink in both the UV and IR

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Note relevant or marginally relevant operators still have "infinities" at the FP - just as quark masses, they still run at the FP just like any other relevant operator: but being relevant they do not affect the FP. (By definition they become unimportant at in the UV.)

U.V. v. I.R. F.P.

Caswell-Banks-Zaks fixed point:

Take QCD with $SU(N_C)$ and N_F fermions but very large numbers of colours+flavours

$$
\partial_t \alpha = -B\alpha^2 + C\alpha^3 \qquad \qquad B \propto \epsilon = \frac{N_F}{N_C} - \frac{11}{2}
$$

2

Turns out C>0, B>0: theory has *stable* IR fixed point at $\alpha = B/C$ and *unstable* one in UV $\alpha = 0$

Cartoon of a would-be Interacting UV FP:

Again would have …

$$
\partial_t \alpha = -B\alpha^2 + C\alpha^3
$$

But requires C<0, B<0, this theory has *stable* IR fixed point at $\alpha = 0$ and *unstable* UV one at $\alpha = B/C$

Real situation requires several couplings to realise

Litim & Sannino '14 $\frac{1}{2}$ (*Sannino*²_{*IA*}) fermions *Qⁱ* (*i* = 1*, ··· , N^F*) in the fundamental representation, and an *N^F* ⇥ *N^F* complex

Need to add scalars and Yukawa couplings:

$$
\mathcal{L} = -\frac{1}{2} \text{Tr} F^{\mu\nu} F_{\mu\nu} + \text{Tr} (\overline{Q} i \not{D} Q) + y \text{Tr} (\overline{Q} H Q) + \text{Tr} (\partial_{\mu} H^{\dagger} \partial^{\mu} H) - u \text{Tr} [(H^{\dagger} H)^{2}] - v (\text{Tr} [H^{\dagger} H])^{2},
$$

 $\mathcal{F}\mathcal{F}$ indices the trace over $\mathcal{F}\mathcal{F}$ indices. The model has four counters four co μ by constants given by the gauge coupling μ , and the quartic scalar coupling μ , and the quartic scalar coupling μ Initially have $U(N_F)_L \times U(N_F)_R$ flavour symmetry *H* is an $N_F \times N_F$ scalar

Quiver diagram for this model:

play ² Ilaaft like gauglings flow could in principle be four dimensional $\frac{1}{2}$ can choose the coupling⁸ how could in principle Four 't Hooft-like couplings - flow could in principle be four dimensional

$$
\alpha_g = \frac{g^2 N_C}{(4\pi)^2}, \quad \alpha_y = \frac{y^2 N_C}{(4\pi)^2}, \quad \alpha_h = \frac{u N_F}{(4\pi)^2}, \quad \alpha_v = \frac{v N_F^2}{(4\pi)^2}
$$

we duivan by the Vulcave we find 1D treigeteries but driven by the Yukawa we find 1D trajectories…

$$
\beta_g = \alpha_g^2 \left[\frac{4}{3} \epsilon + \left(25 + \frac{26}{3} \epsilon \right) \alpha_g \left[-2 \left(\frac{11}{2} + \epsilon \right)^2 \alpha_g \right] \right]
$$
\n
$$
\beta_y = \alpha_y \left[\left(13 + 2\epsilon \right) \alpha_y - 6 \alpha_g \right]
$$

Along the critical-curve/exact-trajectory can parameterise the flow in terms of Figure 1: The renormalisation group flow of the marginal coupling from the marginal couplings from the UV fixed point and α Along the critical-curve/exact-trajectory can parameterise the flow in terms of $\alpha_g(t)$ $\alpha_g(t)$
L

values of the renormalisation time *t* = ln *µ/µ*⁰ by [3, 60] 1 **1** $\frac{1}{2}$ **W** $\frac{11}{2}$ $\frac{11}{2}$ $\frac{1}{2}$ $\frac{1}{2}$ $\frac{1}{2}$ $\frac{1}{2}$ $\frac{1}{2}$ $\frac{1}{2}$ $\frac{1}{2}$ $\frac{1}{2}$ P_0 and F_1 as the small value of N_F is 11 . S_{C} is set of solutions, the initial gauge coupling N_C and 2 $\alpha_g^* = 0.4561 \epsilon$, where $\epsilon = \frac{N}{N_c}$ *N^F N^C* At the fixed point it is arbitrarily weakly coupled, $\alpha_g^* = 0.4561 \epsilon$, where $\epsilon = \frac{N_F}{N_G} - \frac{11}{2}$ $\frac{1}{2}$

^y = 0*.*2105 ✏ + 0*.*5082 ✏² + *O*(✏³)

Tetrad Model for the ASSM…

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Tetrad Model - focus on breaking SU(Nc) to SU(3) colour with new scalars … \bigcirc

Oles, Rechenberger, Scherer, Zamben
Pelaggi, Plascencia, Salvio, Sannino, Felaggi, Frascencia, Sarvio, Sannino, Telaggi, Frascencia, Sarvio, Sannino, Sumbov, Monnaro, Sannino, Wang, Mann, Meffe, Sannino, Steele, Wang, Zhang, c.f. Gies, Jaeckel, Wetterich '04; Bond, Litim; Bond, Hiller, Kowalska, Litim; Gies, Rechenberger, Scherer, Zambelli; $\frac{1}{6}$ $\rm I$

$SU(N_S) =$ $SU(N_C - 4)_S \oplus SU(2)_S$ $SU(N_C)$ $SU(2)_L\otimes SU(n_g)_L$ $SU(2)_r \otimes SU(n_g)_r$	spin
$\square \supset (\square, \square)$ Q_{ai}	1/2
\bigcap ia	1/2
H^i_\cdot (\Box, \Box) \square \sqsupset	$\overline{0}$
$\tilde{\Box}=\tilde{\Box}_{N_C-4}\oplus \tilde{\Box}_2$ $S_{a,\ell=1N_S}$	$\overline{0}$
$\Box = \Box_{N_C-4} \oplus \Box_2$	1/2
$\ddot{\Box} = \ddot{\Box} N_C - 4 \oplus \ddot{\Box} 2$ (\Box, \Box) \square	1/2

 $SU(2)_R = [SU(2)_r \otimes SU(2)_S]_{\rm diag}$ $S(z)_R = [SU(2)_r \otimes SU(2)_S]_{disc}$

Tetrad Model - focus on breaking SU(Nc) to SU(3) colour with new scalars ...
c.f. Gies, Jaeckel, Wett
Litim: Bond Hiller Ko *q*² `² *···* α *IVIOUCI* $\overline{}$ *s* on breaking c) t $\overline{\mathbf{S}}$ \overline{y} ill \overline{N} \bullet Terrait Mouel – Toeus on breaking $SO(13C)$ to $SO(3)$ colour with fiew searars \bullet ...
c.f. Gies, Jaeckel, We \bullet $\frac{1}{2}$ sU(Nc) to $\frac{1}{2}$ ϵ $\mathbf{u} \mathbf{v}$ \overline{t} 3) colour with nev
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c.f. Gies, Jaeckel, Wetterich '04; Bond, Litim; Bond, Hiller, Kowalska, Litim; chenberger, Scheren ones, iv
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Smirne i, Pl 2 ψ˜1 $\mathbf{1}$ Oles, Rechenberger, Scherer, Zambern,
Pelaggi, Plascencia, Salvio, Sannino,
Smirnov: Molinaro, Sannino, Wano: $Zhang,$ [−] ¹ \overline{a} er, I
er, 9
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inin relaggi, Piascencia, Salvio, Sannino, Telaggi, Piascencia, Salvio, Sannino, **v**
Gi_t
m;
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elli: Sumbov, Monnaro, Sannino, Wang, Mann, Meffe, Sannino, Steele, Wang, Zhang, Table 2. Gies, Rechenberger, Scherer, Zambelli; Felaggi Plascencia Salvio Sannino $\frac{1}{6}$ $\rm I$

 $SU(2)_R$ $= [SU(2)_r \otimes SU(2)_r]$ $SU(2)_R = [SU(2)_r \otimes SU(2)_S]$ ϵ $\overline{}$ $\frac{2}{\pi}$ $SU(2)_R = [SU(2)_r \otimes SU(2)_S]_{\rm diag}$ $S(z)_R = [SU(2)_r \otimes SU(2)_S]_{disc}$

Extension of Pati-Salam - breaks to SU(3) if we choose Γ is the Γ models. Note that the Γ models that the first the f Γ Algusion of I ali-Saiani - bicans to SO(. Ey xtension of Pati-Salam - breaks to $SU(3)$ if $N_S = N_C - 2$ $\frac{1}{2}$ $\frac{1}{2}$ Extension of Pati-Salam - breaks to SU(3) if we choose $N_S = N_C - 2$

$$
\frac{q_j^{\ell}}{N_C} \frac{\|\mathbf{1}\|\|\mathbf{1}\|\|\mathbf{1}\|\|\mathbf{1}\|\|\mathbf{1}\|\|\mathbf{1}\|\|\mathbf{1}\|\|\mathbf{1}\|\|\mathbf{1}\|\mathbf{1}\|\|\mathbf{1}\|\mathbf{1}\|\mathbf{1}\|\mathbf{1}\|\mathbf{1}\|\mathbf{1}\|\mathbf{1}\|\mathbf{1}\|\mathbf{1}\|\mathbf{1}\|\mathbf{1}\|\mathbf{1}\|\mathbf{1}\|\mathbf{1}\|\mathbf{1}\|\mathbf{1}\|\mathbf{1}\|\mathbf{1}\|\mathbf{1}\|\mathbf{1}\|\mathbf{1}\|\mathbf{1}\|\mathbf{1}\|\mathbf{1}\|\mathbf{1}\|\mathbf{1}\|\mathbf{1}\|\mathbf{1}\|\mathbf{1}\|\mathbf{1}\|\mathbf{1}\|\mathbf{1}\|\mathbf{1}\|\mathbf{1}\|\mathbf{1}\|\mathbf{1}\|\mathbf{1}\|\mathbf{1}\|\mathbf{1}\|\mathbf{1}\|\mathbf{1}\|\mathbf{1}\|\mathbf{1}\|\mathbf{1}\|\mathbf{1}\|\mathbf{1}\|\mathbf{1}\|\mathbf{1}\|\mathbf{1}\|\mathbf{1}\|\mathbf{1}\|\mathbf{1}\|\mathbf{1}\|\mathbf{1}\|\mathbf{1}\|\mathbf{1}\|\mathbf{1}\|\mathbf{1}\|\mathbf{1}\|\mathbf{1}\|\mathbf{1}\|\mathbf{1}\|\mathbf{1}\|\mathbf{1}\|\mathbf{1}\|\mathbf{1}\|\mathbf{1}\|\mathbf{1}\|\mathbf{1}\|\mathbf{1}\|\mathbf{1}\|\mathbf{1}\|\mathbf{1}\|\mathbf{1}\|\mathbf{1}\|\mathbf{1}\|\mathbf{1}\|\mathbf{1}\|\mathbf{1}\|\mathbf{1}\|\mathbf{1}\|\mathbf{1}\|\mathbf{1}\|\mathbf{1}\|\mathbf{1}\|\mathbf{1}\|\mathbf{1}\|\mathbf{1}\|\mathbf{1}\|\mathbf{1}\|\mathbf{1}\|\mathbf{1}\|\mathbf{1}\|\mathbf{1}\|\mathbf{1}\|\mathbf{1}\|\mathbf{1}\|\mathbf{1}\|\mathbf{1}\|\mathbf{1}\|\mathbf{1}\|\mathbf{1}\|\mathbf{1}\|\mathbf{1}\|\mathbf{1}\|\mathbf{1}\|\mathbf{1}\|\mathbf{1}\|\mathbf{1}\|\mathbf{1}\|\mathbf{1}\|\mathbf{1}\|\mathbf
$$

Weak breaking must then occur along the H-Higgs directions: uki
| $\mathbf n$ nust then occur along the H-Higgs direct:

$$
H = \left(\begin{array}{cccc} \left(\begin{array}{cccc}h_u^0 & h_d^- \\ h_u^+ & h_d^0 \end{array}\right)_{11} & \left(\begin{array}{cccc}h_u^0 & h_d^- \\ h_u^+ & h_d^0 \end{array}\right)_{12} & \left(\begin{array}{cccc}h_u^0 & h_d^- \\ h_u^+ & h_d^0 \end{array}\right)_{13} & \cdots \\ \left(\begin{array}{cccc}h_u^0 & h_d^- \\ h_u^+ & h_d^0 \end{array}\right)_{21} & \left(\begin{array}{cccc}h_u^0 & h_d^- \\ h_u^+ & h_d^0 \end{array}\right)_{22} & \left(\begin{array}{cccc}h_u^0 & h_d^- \\ h_u^+ & h_d^0 \end{array}\right)_{23} & \cdots \\ \left(\begin{array}{cccc}h_u^0 & h_d^- \\ h_u^+ & h_d^0 \end{array}\right)_{31} & \left(\begin{array}{cccc}h_u^0 & h_d^- \\ h_u^+ & h_d^0 \end{array}\right)_{32} & \left(\begin{array}{cccc}h_u^0 & h_d^- \\ h_u^+ & h_d^0 \end{array}\right)_{33} & \cdots \\ \vdots & \vdots & \vdots & \vdots \\ \end{array}\right)
$$

Assignment implies 9 pairs of Higgses one for each Yukawa coupling we are assuming flavour degeneracy in all the couplings of α . One coupling instead for example, α \bullet Assignment implies 9 pairs of Higgses one for each Yukawa coupling

Explicit embedding looks like P-S with $SU(N_C) \times SU(2)_L \times SU(2)_R \longrightarrow SU(3)_c \times SU(2)_L \times U(1)_Y$ icit embedding iooks like \sim \sim \sim \mathfrak{S} \mathfrak{S} \cdot (\cdot 1)

$$
Q = \begin{pmatrix} q_1 & \ell_1 & \cdots & \left(\frac{\Psi_1}{2}\right) \cdots \\ q_2 & \ell_2 & \cdots & \left(\frac{\Psi_1}{2}\right) \cdots \\ q_3 & \ell_3 & \cdots & \left(\frac{\Psi_1}{2}\right) \cdots \\ \vdots & \vdots & \ddots & \vdots \end{pmatrix} \right\} N_F \; ; \quad \tilde{Q} = \begin{pmatrix} \left(\begin{array}{c} u^c \\ d^c \end{array}\right) & \left(\begin{array}{c} \nu^c_e \\ e^c \end{array}\right) & \cdots & \left(\begin{array}{c} \tilde{\Psi}_{-\frac{1}{2}} \\ \tilde{\Psi}_{\frac{1}{2}} \\ \tilde{\Psi}_{-\frac{1}{2}} \\ \vdots \end{array}\right) \cdots \\ \left(\begin{array}{c} \Psi_2 \\ \Psi_1 \\ \vdots \end{array}\right) & \cdots & \left(\begin{array}{c} \Psi_1 \\ \Psi_2 \\ \vdots \end{array}\right) & \cdots \end{pmatrix} \begin{pmatrix} \nu^c \\ e^c \\ \mu^c \end{pmatrix} & \left(\begin{array}{c} \nu^c_\mu \\ \mu^c \\ \mu^c \end{array}\right) & \cdots & \left(\begin{array}{c} \tilde{\Psi}_{-\frac{1}{2}} \\ \tilde{\Psi}_{\frac{1}{2}} \\ \tilde{\Psi}_{\frac{1}{2}} \\ \vdots \end{array}\right) \cdots \end{pmatrix}
$$

$$
N_S=N_C-2
$$

$$
q = \begin{pmatrix} \begin{pmatrix} \psi_0 & \psi_1 \\ \psi_{-1} & \psi_0 \end{pmatrix} \begin{pmatrix} \psi_1 \\ \psi_{-1} \\ \psi_2 \\ \psi_{-1} \end{pmatrix} & \cdots & \begin{pmatrix} \psi_1 \\ \psi_2 \\ \psi_{-1} \\ \psi_{-1} \end{pmatrix} \\ \begin{pmatrix} \psi_0 & \psi_1 \\ \psi_{-1} \\ \psi_0 \end{pmatrix} \begin{pmatrix} \psi_1 \\ \psi_2 \\ \psi_{-1} \\ \psi_{-1} \end{pmatrix} & \cdots & \begin{pmatrix} \psi_1 \\ \psi_2 \\ \psi_{-1} \\ \psi_{-1} \end{pmatrix} \\ \begin{pmatrix} \psi_0 & \psi_1 \\ \psi_{-1} \\ \psi_{-1} \end{pmatrix} \begin{pmatrix} \psi_1 \\ \psi_2 \\ \psi_{-1} \\ \psi_{-1} \end{pmatrix} & \cdots & \begin{pmatrix} \psi_1 \\ \psi_2 \\ \psi_{-1} \\ \psi_{-1} \end{pmatrix} \\ \vdots & \vdots & \vdots & \vdots \end{pmatrix} \end{pmatrix} \begin{pmatrix} \tilde{\psi}_1 \\ \tilde{\psi}_2 \\ \tilde{\psi}_1 \\ \tilde{\psi}_2 \end{pmatrix} \begin{pmatrix} \tilde{\psi}_2 \\ \tilde{\psi}_1 \\ \tilde{\psi}_2 \\ \tilde{\psi}_1 \end{pmatrix} \begin{pmatrix} \tilde{\psi}_2 \\ \tilde{\psi}_1 \\ \tilde{\psi}_2 \end{pmatrix} & \cdots & \begin{pmatrix} \tilde{\psi}_2 \\ \tilde{\psi}_1 \\ \tilde{\psi}_2 \\ \tilde{\psi}_1 \end{pmatrix} \\ \vdots & \vdots & \vdots & \vdots \end{pmatrix}
$$

 N_C \mathbf{A}^T

Explicit embedding looks like P-S with $SU(N_C) \times SU(2)_L \times SU(2)_R \longrightarrow SU(3)_c \times SU(2)_L \times U(1)_Y$ \bigcirc icit embedding iooks like \mathfrak{S} \mathfrak{S} \sim \sim \sim \cdot (\cdot 1)

 \mathbf{A}^T

$$
Q = \begin{pmatrix} q_1 & \ell_1 & \cdots & \left(\frac{\Psi_1}{\Psi_{-\frac{1}{2}}} \right) \cdots \\ q_2 & \ell_2 & \cdots & \left(\frac{\Psi_2}{\Psi_{-\frac{1}{2}}} \right) \cdots \\ q_3 & \ell_3 & \cdots & \left(\frac{\Psi_3}{\Psi_{-\frac{1}{2}}} \right) \cdots \\ \vdots & \vdots & \vdots & \vdots \end{pmatrix} \begin{pmatrix} \sqrt{v} & \ell_1 & \ell_2 & \ell_3 \\ \ell_2 & \ell_3 & \cdots & \left(\frac{\Psi_1}{\Psi_{-\frac{1}{2}}} \right) \cdots \\ \ell_3 & \ell_3 & \cdots & \left(\frac{\Psi_1}{\Psi_{-\frac{1}{2}}} \right) \cdots \\ \vdots & \vdots & \vdots & \vdots \end{pmatrix} \begin{pmatrix} \sqrt{v} & \ell_1 & \ell_2 & \ell_3 \\ \ell_1 & \ell_2 & \ell_3 & \cdots & \left(\frac{\Psi_1}{\Psi_{-\frac{1}{2}}} \right) \cdots \\ \ell_1 & \ell_2 & \ell_1 & \ell_1 \\ \ell_1 & \ell_2 & \ell_2 & \cdots & \left(\frac{\Psi_1}{\Psi_{-\frac{1}{2}}} \right) \cdots \\ \vdots & \vdots & \vdots & \vdots \end{pmatrix}
$$
\n
$$
= \begin{pmatrix} \left(\frac{\psi_0}{\psi_0} & \psi_1 \right) & \left(\frac{\psi_1}{\psi_1} \right) &
$$

 q

Little q's required (by chiral symmetry) to remove the extra $SU(2)$ doublets: (Nc-4) uncharged under SU(2)R

And the couplings that do this are as follows:

Y and Y˜ Yukawa couplings are responsible for giving masses to the unwanted degrees of freedom in the Note expect relatively light (TeV scale) q-states looking like "higgsinos" And the couplings that do this are as follows: f_{Ω} f_{Ω} $\overline{\text{)}\text{W}}$

 N^2 N^2 N^2 N^2 N^2 N^2 N^2 For later use define rescaled c'pgs: $\alpha_g = \frac{N_C g^2}{(4\pi)^2}$; $\alpha_y = \frac{N_C y^2}{(4\pi)^2}$; $\alpha_{\tilde{y}} = \frac{N_C \tilde{y}^2}{(4\pi)^2}$; $\alpha_Y = \frac{N_C Y^2}{(4\pi)^2}$; $\alpha_{\tilde{Y}} = \frac{N_C \tilde{Y}^2}{(4\pi)^2}$; $\frac{(10)}{N^2}$ $\frac{(10)}{N}$ $\frac{(10)}{N^2}$ $\frac{(10)}{N^2}$ λ in λ $\alpha_{u_1} \;=\; \frac{N_F^2 u_1}{(4\pi)^2} \, ; \; \alpha_{u_2} = \frac{N_F u_2}{(4\pi)^2} \, ; \; \alpha_{v_1} = \frac{N_C^2 v_1}{(4\pi)^2} \, ; \; \alpha_{w_1} = \frac{N_C^2 w_1}{(4\pi)^2} \, ; \; \alpha_{w_2} = \frac{N_C w_2}{(4\pi)^2}$ In case you're suffering from "expectation versus reality syndrome" …

In case you're suffering from "expectation versus reality syndrome" …

 $\frac{1}{2}$ to see (et least some of) what we did. to see far reast some or what we did. A quiver diagram is useful to see (at least some of) what we did:

Before:

 T that respects that respectively that respectively in addition to the gauging for the gaug After: (hence the name Tetrad)

As this model is based on LS, the same UVFP applies (see later). But what about AS for \bigcirc **the SU(2)xSU(2) electroweak gauge groups?**

These see a large number of flavours (Nf (small f) of order order Nc)?

This gives UVFP behaviour with a fixed point at 't Hooft couple ~ 1 … if Nf >>16: \bigcirc

> Palanques Mestre, Pascual; Gracey; Holdom; Shrock; Antipin, Pica, Sannino

∂ As this model is based on LS, the same UVFP applies (see later). But what about AS for the SU(2)xSU(2) electroweak gauge groups? A a this model is hosed on LS, the same UV/ED englise (see later). But what about AS far As this mouth is bastu on the, the same O v F1 applies (see fact). But what about AS for $f(x) = \text{tr}(x) - \text{er}(x)$ bectrowed and $f(x)$ and $f(x)$ and $f(x)$ are number of $f(x)$ $\overline{\mathbf{S}}$ for $\overline{101}$

These see a large number of flavours (Nf (small f) of order order Nc)? *N*_{pere see a large pumber of flavours (Nf (small f) of order order No)?} $\frac{1}{2}$ can be organised in terms of $\frac{1}{2}$ These see a large number of flavours (Nf (small f) of order order Nc)? from scalar and quark loops are simply additive in the resummation, with the number of

*N^f g*0² his gives UVFP behaviour with a fixed point at 't Hooft couple ~ 1 ... if Nf $>>16$: This gives UVFP behaviour with a fixed point at 't Hooft couple ~ 1 ... if Nf \gg 16: \bigcirc

Palanques Mestre, Pascual; Gracey; Holdom; with que vielence, *g alcohans*, *g*_{*CICC</sup>₂)}, <i>g*_{CICC}₂), *g*_{CICC}₂, *g*_{*C*}₂, *g*^{*C*}_{*C*}*C*_{*C*}^{*C*}_{*C*}^{*C*}_{*C*}^{*C*}_{*C*}^{*C*}_{*C*}^{*C*}_{*C*}^{*C*}_{*C*}^{*C*}_{*C*}^{*C*}_{*C*}^{*C*}_{*C*}^{*C*}_{*C*}^{*C*}</sub> Δ *Fhrock*; *Antipin*, *Pica*, *Sannino*

Resum first terms gives

3 4 ↵˜ ↵˜² =1+ *H*(˜↵) *N^f* ⁺ *^O*(*^N* ² *^f*) *,* (27) where the additional terms, suppressed by at least a factor of 1*/N*² as the class shown on the first line of figure 3. From figure 2 it is clear that contributions from scalar and quark loops are simply additive in the resummation, with the number of *SU*(2)*L/R* quark doublets being 3*N/*2, and scalar doublets being 3*N^F /*4 for *SU*(2)*^L* and 3*N^F /*4 + *N/*4 for *SU*(2)*R*, in the SM embedding we are considering. Therefore setting *N^F* ⇡ 21*/*4, *SU*(2)*^L* has *N^f* ⇡ 87*N/*16 while *SU*(2)*^R* has *N^f* ⇡ 91*N/*16. The important point about the function *H*(˜↵) is that it has a *negative* logarithmic sin-↵˜⁰ = 3 ² *.* (28) Thus one can always find a solution to ↵˜(˜↵) = 0 at ˜↵⇤ somewhat below this value. For Thus one can always find a solution to ↵˜(˜↵) = 0 at ˜↵⇤ somewhat below this value. For values of *N^f* & 5, ˜↵ runs in the UV rapidly to a value ˜↵⇤ that is in fact exponentially close to 3*/*2 [1, 9]. Indeed the form of the singularity is *^H*(˜↵) = ¹ ⁴ log *[|]*³ 2˜↵*[|]* + constant , (29) ² *Ce*4*N^f* , for some constant *C*. For even modest *N^f* (note that for *N* = 10 one has *N^f* ⇠ 50) the exponential term is completely negligible. Thus one can always find a solution to ↵˜(˜↵) = 0 at ˜↵⇤ somewhat below this value. For values of *N^f* & 5, ˜↵ runs in the UV rapidly to a value ˜↵⇤ that is in fact exponentially close to 3*/*2 [1, 9]. Indeed the form of the singularity is so one has ˜↵⇤ = 3 ² *Ce*4*N^f* , for some constant *C*. For even modest *N^f* (note that for *N* = 10 one has *N^f* ⇠ 50) the exponential term is completely negligible.

values of *N*^f \sim N^4 runs in the UV rapidly to a value \sim N^4 that is in fact exponentially close \sim

Overall the picture is …

Can show by power counting that the two kinds of UVFP decouple.

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- **In the Veneziano limit the corrections to the weak FP go like epsilon. Can neglect everything but SU(2) gauge couplings when determining the SU(2) fixed points.**
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i.e.

- **Can show by power counting that the two kinds of UVFP decouple.** ↵*g*(*t*) ¹ *.* (24) \mathbf{y} when \mathbf{y}
- **he weak FP oo l** In the Veneziano limit the corrections to the weak FP go like epsilon. Can neglect ke ensilan. Can neglect \bigcirc everything but SU(2) gauge couplings when determining the SU(2) fixed points.
- **i.e.**

Conversely for the SU(Nc) fixed point …

- Suppose that the classically relevant operators are negligible. (compared to the scales we are about to generate.)
- Then Coleman-Weinberg radiative symmetry breaking is induced along the flow.
- First look at Yukawas:

• This in turn induces a flow in the quartic couplings driving them negative: we essentially have Gildener-Weinberg breaking of the extended PS symmetry.

 $10²$

— t

15

5

 $10¹⁰$

 100

-5

• Note that the H mass-squareds are all positive at this scale.

 -0.2

 $\frac{200}{100}$

 -0.2

 -0.4

 -0.6

 $\frac{-100-t}{200}$

• This in turn induces a flow in the quartic couplings driving them negative: we essentially have Gildener-Weinberg breaking of the extended PS symmetry. negative and form a minimum radiative and form a minimum radiatively form and the second of DC sympatively rally have Ghueller wennely breaking of the extended FS symb

 $\left\vert -0.10\right\vert$

• Note that the H mass-squareds are all positive at this scale.

Organize relevant operators in terms of the $U(N_F) \times U(N_F)$ **flavour symmetry** that we break with the mass-squareds (closed under RG): Organize relevant onerators in terms of the $U(N_F) \times U(N_F)$ flavour symmetry.

$$
H = \frac{(h_0 + ip_0)}{\sqrt{2N_F}} \mathbb{1}_{N_F \times N_F} + (h_a + ip_a)T_a
$$

$$
\mathcal{L}_{Soft} = -m_{h_0}^2 \text{Tr}\left[H^{\dagger}H\right] - \sum_{a=1}^{N_F^2 - 1} \Delta_a^2 \text{Tr}\left[HT^a\right] \text{Tr}\left[H^{\dagger}T^a\right]
$$

<u>Then solve Callan Symanzik eqn for them as usual =></u> cross-terms in the potential, α _h2 a_n² a^{*h*}2 a_n² a^{*h*}2 aⁿ² a^{*h*}2 aⁿ² 0*h*² *a*, arise from the Tr(*H†* Then solve Callan Sumanzik ean for them as usual => *Then solve Calan Symanzik eqn for them as usual =>*

Non-trivial simple example…

Consider case where the trace component has a slightly smaller mass-squared: $m = 1$ simple suitable structure is generator in the simple suitable suitable structure is generator diagonal and universal consider the where the trace component has a sughtly sinance mass square

<u>Non-trivial simple example...</u> diative symmetry breaking. Consider the case of a slightly positive 20 minutes of a slightly positive 20 minutes

After some work find the following answer in terms of two RG invariants, one for each independent (non-predicted) relevant operator (where $v = (1 - 1/NF^2)$): each independent (non-predicted) relevant operator (w

$$
m_0^2 = \tilde{m}_*^2 \left(\frac{\alpha_g^*}{\alpha_g} - 1\right)^{-\frac{3f_{m_0}}{4\epsilon}} - \Delta_*^2 \nu \left(\frac{\alpha_g^*}{\alpha_g} - 1\right)^{-\frac{3f_{\Delta}}{4\epsilon}},
$$

$$
m_{a=1...N_F^2-1}^2 = \tilde{m}_*^2 \left(\frac{\alpha_g^*}{\alpha_g} - 1\right)^{-\frac{3f_{m_0}}{4\epsilon}} + \Delta_*^2 (1 - \nu) \left(\frac{\alpha_g^*}{\alpha_g} - 1\right)^{-\frac{3f_{\Delta}}{4\epsilon}}
$$

$$
f_{m_0} > f_{\Delta}
$$

 Dies away quickly *in the IR*
 Dies away slowly *in the IR*

Starting values get relatively closer in UV (note the masses are all shrinking in absolute

$$
\alpha_{g,min} \ \stackrel{\epsilon \rightarrow 0}{\longrightarrow} \ \ \frac{1}{2} \alpha_g^*
$$

$$
m_{0,min}^2 \sim -\tilde{m}_{*}^2
$$

<u>Generally in IR find flavour bierarchies grow …</u> $N = 1$ in the IR. Simple flavour hierarchies can the IR. Simple flavour hierarchies can the intervals of the IR. Simple flavour hierarchies can the IR. Simple flavour hierarchies can the intervals of the intervals of the α f⇒ α f⇒ α

$$
V \to \sum_{n>1} \Delta_n^2 \left[\text{Tr}_n \left(h^2 + p^2 \right) - n \left(\left(\text{Tr}_n h \right)^2 + \left(\text{Tr}_n p \right)^2 \right) \right]
$$

where Tr_n is the trace over the SU(n) sub-matrix \overline{v} , Tr_n is the trace over th e SU(n) sub-matrix

Summary

- Adapted perturbative asymptotically safe QFTs (gauge-Yukawa theories)
- A minimal embedding of the SM within this set-up straightforward within an extended PS structure
- Radiative symmetry breaking can be driven by Coleman-Weinberg or running massterms
- Overall now has the "feel of" other RG systems with large numbers of degrees of freedom in the UV: simpler dual way to understand this type of theory?
- It would be very nice to have a better lattice handle on large Nf UV fixed points