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(Fundamental) Composite Models at the TeV scale

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w/ Francesco Sannino, Alessandro Strumia, Elena Vigiani (arXiv:1607.01659)

Intro

After the dream...

Information | References (44) | Citations (466) | Files | Plots

Search for resonances decaying to photon pairs in 3.2 fb^{-1} of pp collisions at $\sqrt{s}$ = 13 TeV with the ATLAS detector

The ATLAS collaboration

Dec 15, 2015

ATLAS-CONF-2015-081
Experiment: CERN-LHC-ATLAS

Abstract
This note describes a search for new resonances decaying to two photons, with invariant mass larger than 200 GeV. The search is optimized for scalars such as those expected, for example, in models with an extended Higgs sector. The dataset consists of 3.2 fb^{-1} of pp collisions at $\sqrt{s}$ = 13 TeV recorded with the ATLAS detector at the Large Hadron Collider. The data are consistent with the expected background in most of the mass range. The most significant deviation in the observed diphoton invariant mass spectrum is found around 750 GeV, with a global significance of about 2 standard deviations. A limit is reported on the fiducial production cross section of a narrow scalar boson times its decay branching ratio into two photons, for masses ranging from 200 GeV to 1.7 TeV.

let's go back to real life

Same old story

Thresholds rather than quadratic divergences

If a scalar is coupled to a particle of mass M

$$\text{tuning} \equiv \Delta \sim \frac{y^2 M^2}{16\pi^2 m_h^2}$$

- MPlanck will induce such corrections (Yes, very likely...)
- Models with physics at the TeV scale fits into the category (at least at 2 loops)

An example of a natural theory

QCD is a wonderland

- Accidentally light quarks explain pions
- Theory is well defined (even non perturbatively: lattice)
- Pion mass can be computed (ratios)
- Phenomenology dictated by symmetries (and their breaking)

Can we take inspiration from QCD to “solve” hierarchy problem?

I will discuss new applications of technicolor TC theories

Generic features of TC

In a model with vector-like fermions and gauge fields:

- Chiral symmetry (if fermions are light)
- Species symmetry $Q_i \to e^{is_i} Q_i$
- If SU(N) and SO(N) a TC baryon number

Can we do DM models? (not in this talk, sorry)

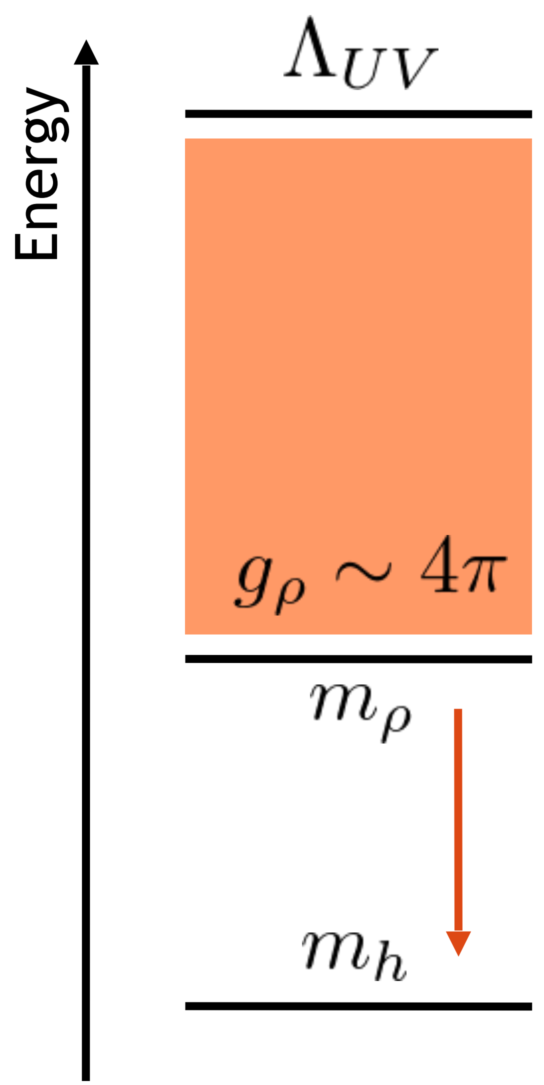
Can we realize a composite Higgs sector? (let's try)

Composite Higgs

What is it?

(or, how we want it look like)

The compositeness “paradigm”



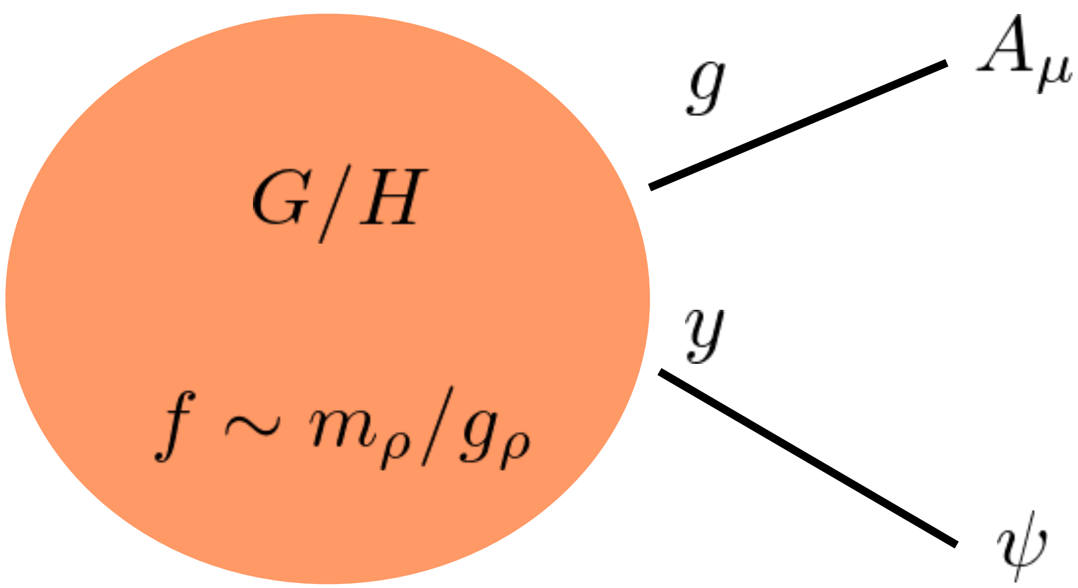
“Easy” piece:
Large separation between the UV and IR scale achieved via a QCD-like dynamics

“Difficult” piece:
Achieve a realistic light Higgs from the strong sector and be consistent with precision data

At the end of this talk both pieces will appear very difficult...

Composite Higgs models

In presence of an approximate global symmetry the Higgs could be a pseudo-GB



Higgs (and W/Z goldstones) are part of the strong sector

The external fields are the SM quarks and (transverse) gauge bosons

The couplings to the SM sector break the shift symmetry and generate a potential at 1-loop.

- Generate EWSB radiatively and achieve a Higgs boson of 125 GeV
- Consistency with precision data (& rich phenomenology in direct searches)

Georgi Kaplan '80s; Agashe,Contino, Pomarol

Minimal Composite Higgs

Agashe, Contino, Pomarol

In the minimal scenario the symmetry is SO(5)/SO(4)

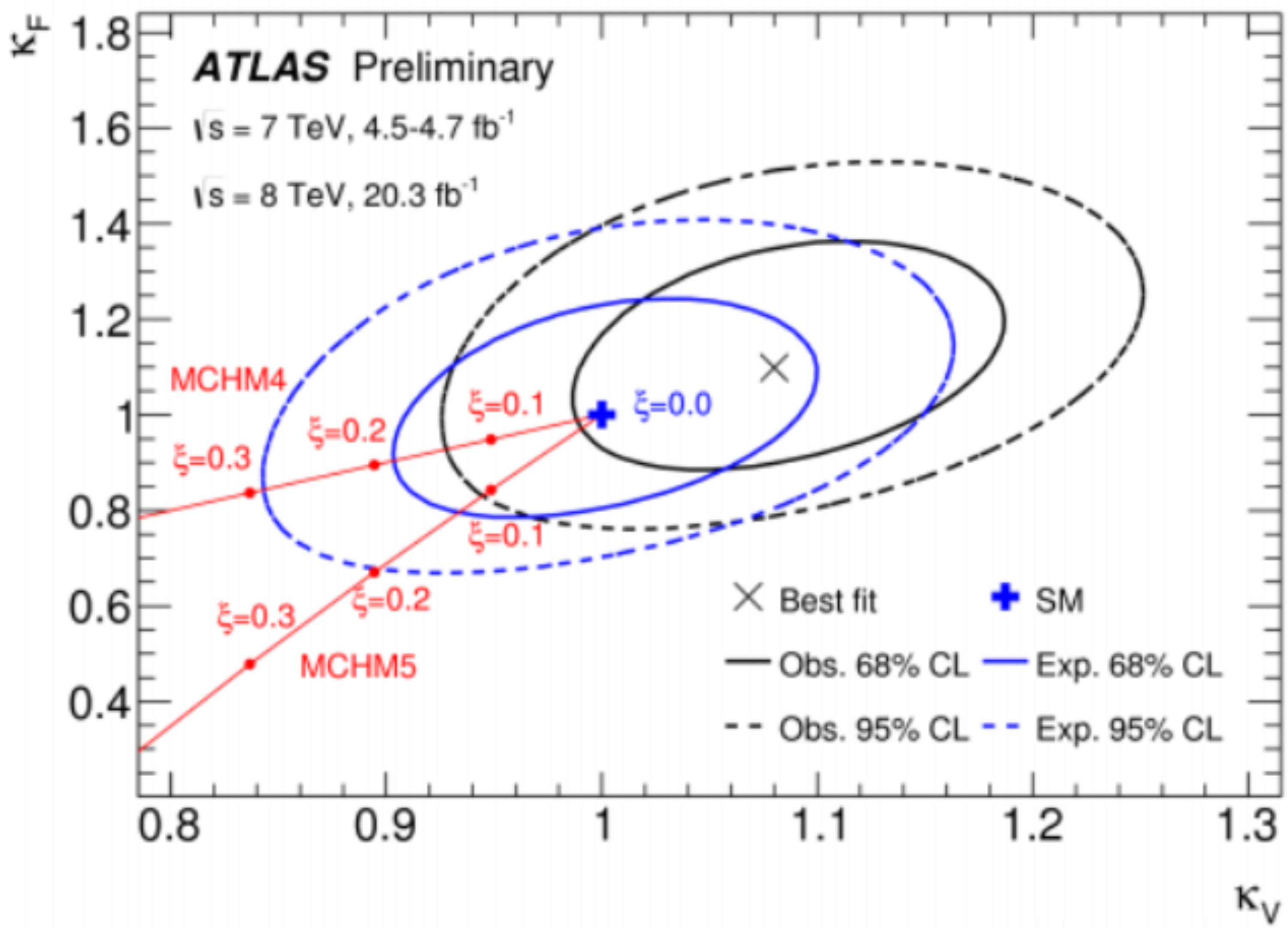
- Strong sector is SO(4) invariant, resonances in SO(4) multiplets
- Higgs is a bidoublet, custodial symmetry
- Deviation in Higgs couplings due to pNGB nature

$$U = \exp\left(i\sqrt{2}\frac{\pi^a}{f}T^a\right)$$

$$\frac{f^2}{4}\mathrm{Tr}[(D_\mu U)^2] \supset +\frac{1}{2}m_V^2 V^2\left(1+2\sqrt{1-\frac{v^2}{f^2}}\frac{h}{v}+\cdots\right)$$

Deviation in Higgs couplings

Coupling to vectors are model independent



$$k_V = \sqrt{1-\xi}, \quad \xi = v^2/f^2 \qquad\qquad f \gtrsim 700\ GeV$$

Fermion masses?

Higgs is a pNGB, how we generate Yukawa couplings?

$$\mathcal{L} = y_Q f Q \mathcal{B}_Q + \ldots$$

Kaplan 1992

- Partial Compositeness, through linear mixing
- B is a composite fermion, a baryon, top partner
- All flavor transitions are controlled by y
- In general more than one CKM matrix

$$y_f \sim \frac{y_Q y_U}{g_\rho}$$

Higgs mass and Tuning

In effective Composite Higgs model, the potential is computed as an expansion in y

$$m_h^2 \simeq b\,\frac{N_c y_t^2 v^2}{2\pi^2}\frac{m_\psi^2}{f^2}, \qquad \Delta \simeq \frac{m_\Psi^2}{m_t^2} = \frac{f^2}{v^2}\frac{m_\Psi^2}{y_t^2 f^2}$$

- 125 GeV requires light composite fermions
- Tuning is minimized when the overall scale $m\Psi$ is light
- Need to look for colored fermionic top-partners

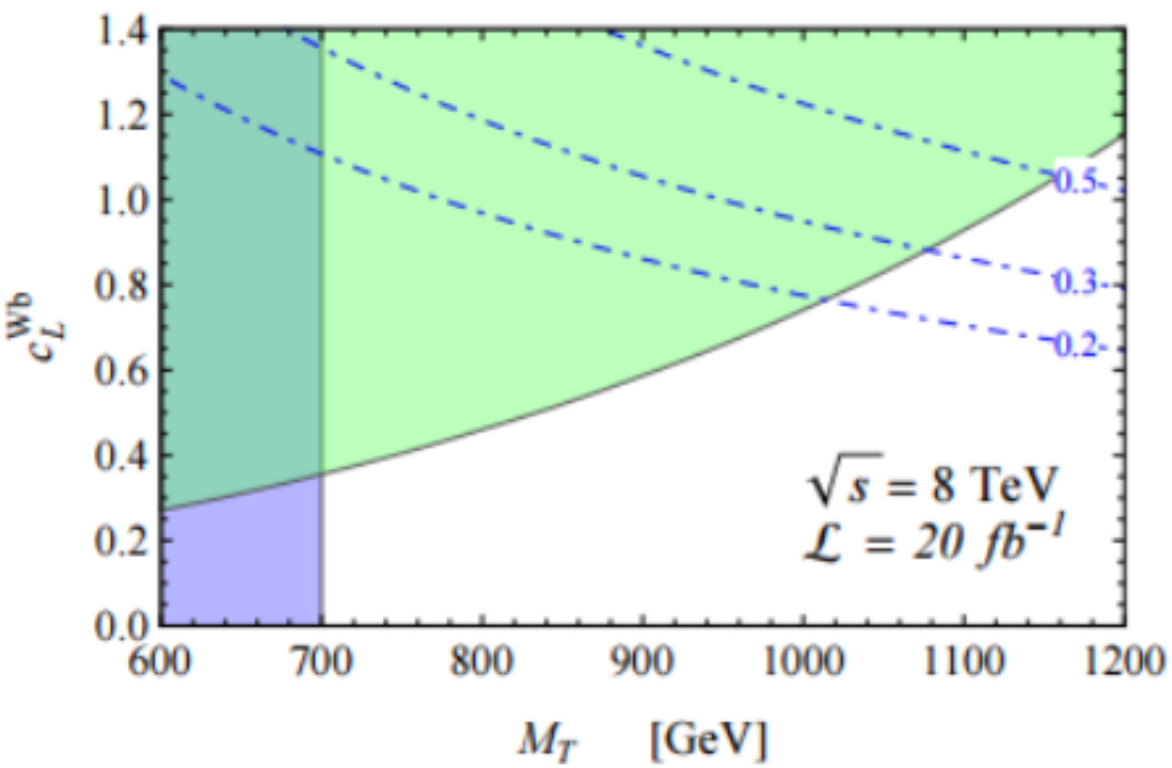
The search for Top partners

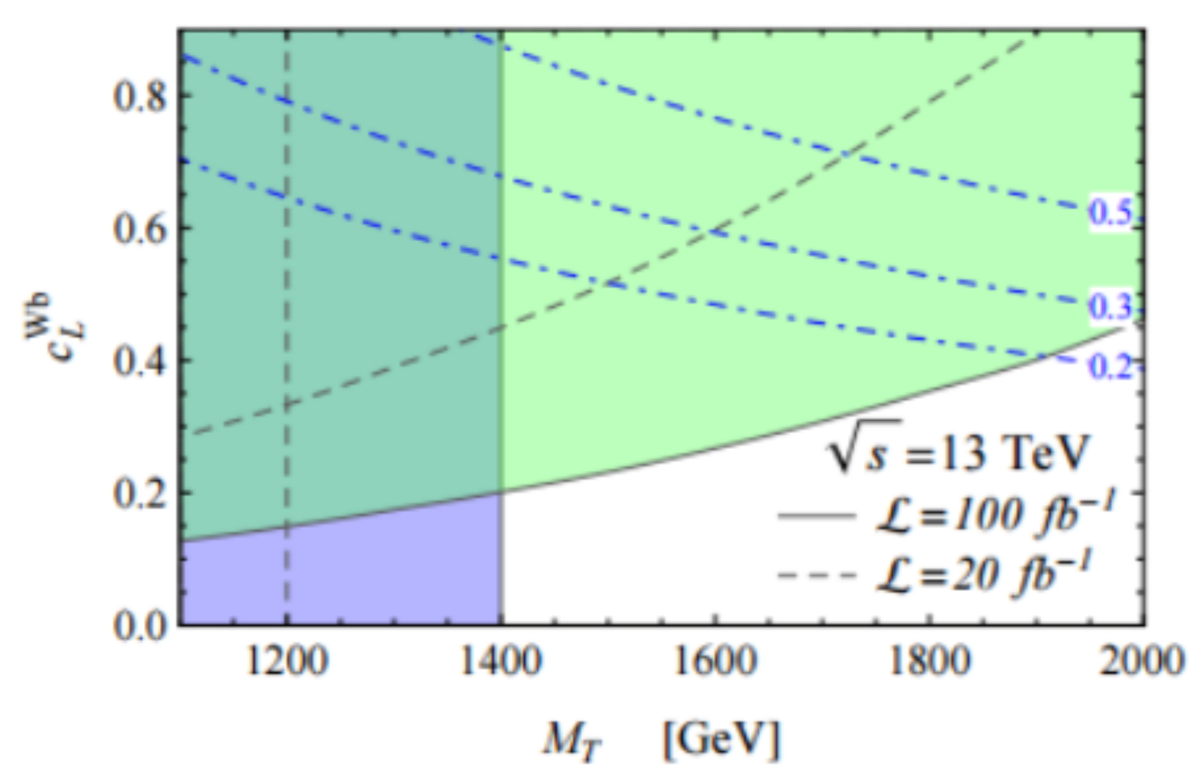
Production modes

- QCD, pair production
- $Wb(t)$ fusion, single production

Decay modes

- Depend on the EW charges
- $T \to th, W_L b, Z_L t \; (W_L t)$



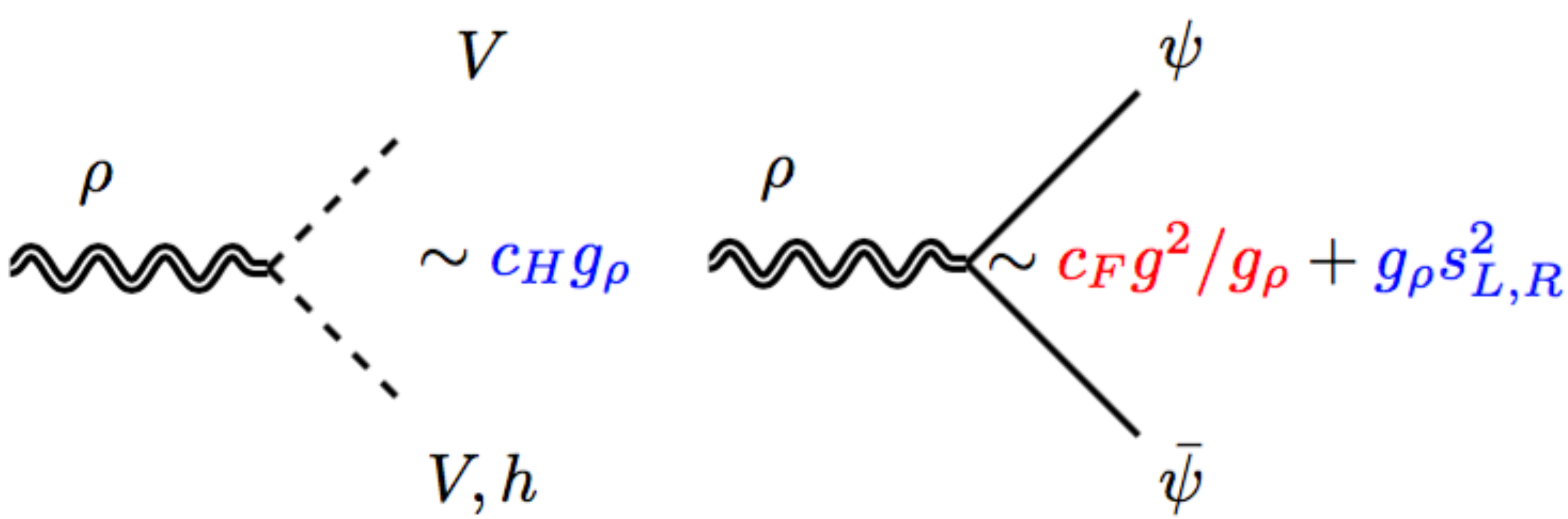


Matsedonskyi, Panico, Wulzer

Electroweak Spin-1 resonances

In SO(5)/SO(4) model we expect

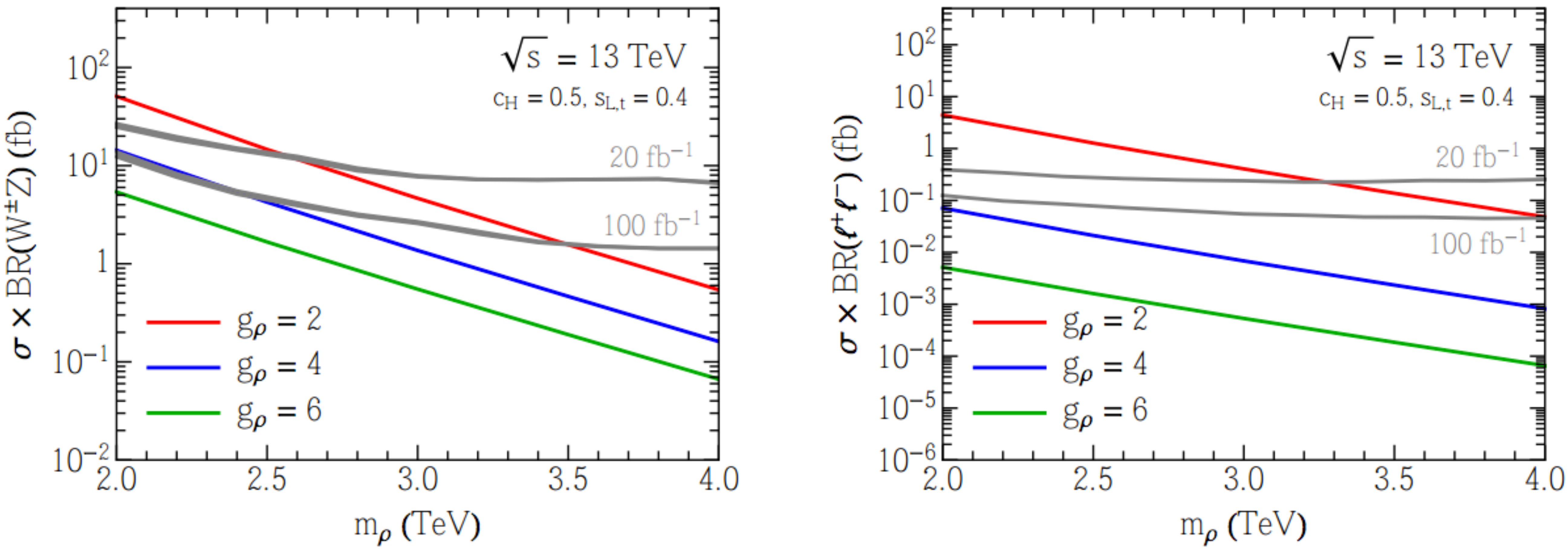
spin-1 resonances: $3 \oplus 1_{\pm} \oplus 1_0$ of SU(2) U(1)



Strong coupling to diboson — Weak coupling to light fermions

$\boxed{\textbf{Production rate} \text{ is model-independent} \sim g^2/g_\rho^4}$

Electroweak Spin-1 resonances



(w/ Matthew Low and Liantao Wang)

- Large branching to dibosons
- Production rate suppressed at large grho

Partial summary

Composite Higgs is a motivated scenario:

- Higgs coupling deviations
- New resonances and new effects in precision data
- Symmetry arguments allow to treat a strong sector
- Offers a scenario for Twin Higgs (w/ Matthew Low and Liantao Wang)

The problem is that Composite Higgs is not QCD

- Symmetries are postulated and difficult to argue they are accidental
- No fundamental description (what are the constituents?)
- How to generate fermion masses?

Fundamental Composite Higgs

Again on partial compositeness

While it is quite easy to write theories with a Higgs made of fermions...

... generating fermion masses requires a coupling
to a composite operator with dimension 5/2

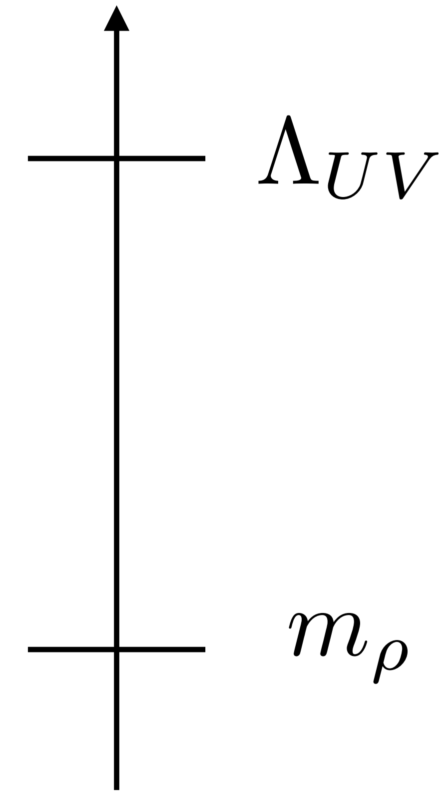
$$\mathcal{L} = y_Q Q \mathcal{O}_q + \ldots$$

- This will help to separate fermion masses and scale of flavor violation
- If a true baryon dim=9/2, requires very large anomalous dimensions -2
- Only lattice can eventually tell if -2 is possible, in QCDpt is small

What we want for partial compositeness

$$\mathcal{L} = y_Q Q \mathcal{O}_q + \ldots$$

$$y_f \simeq \sqrt{N}\frac{y_Q y_U}{4\pi}\left(\frac{m_\rho}{\Lambda_{UV}}\right)^{d_Q+d_U-5}$$

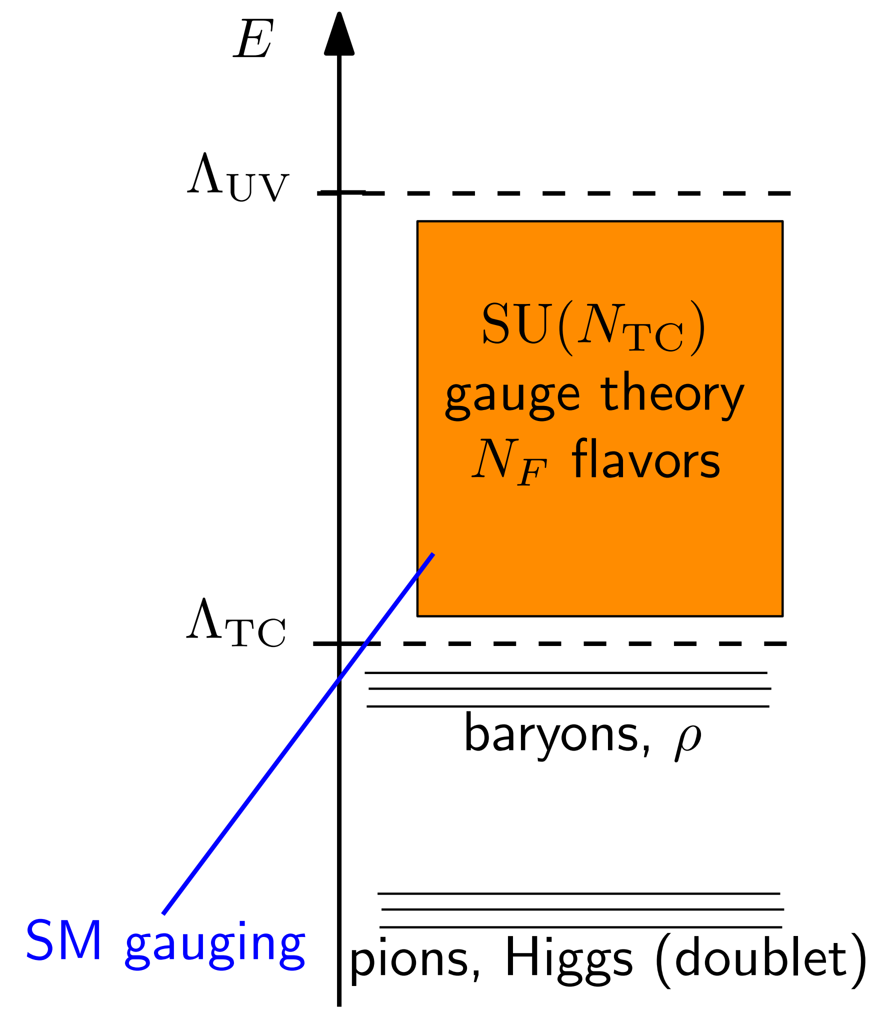


- LambdaUV is the scale where flavor is generated
- Operators with dimension close to 5/2 do the job
- If we stick to fermions then $O_q \sim \mathcal{F}\mathcal{F}\mathcal{F}$
- For fermions need to use irrelevant operators difficult to include leptons
- Generated by what?
- Maybe the story is more trivial...

Ferretti Karateev; Ferretti '16
Vecchi '15

The realization — Columbus' egg

- SM without the Higgs
- New TC gauge interactions
- New TC-fermions (vector-like)
- New TC-scalars
- New Yukawa Interactions



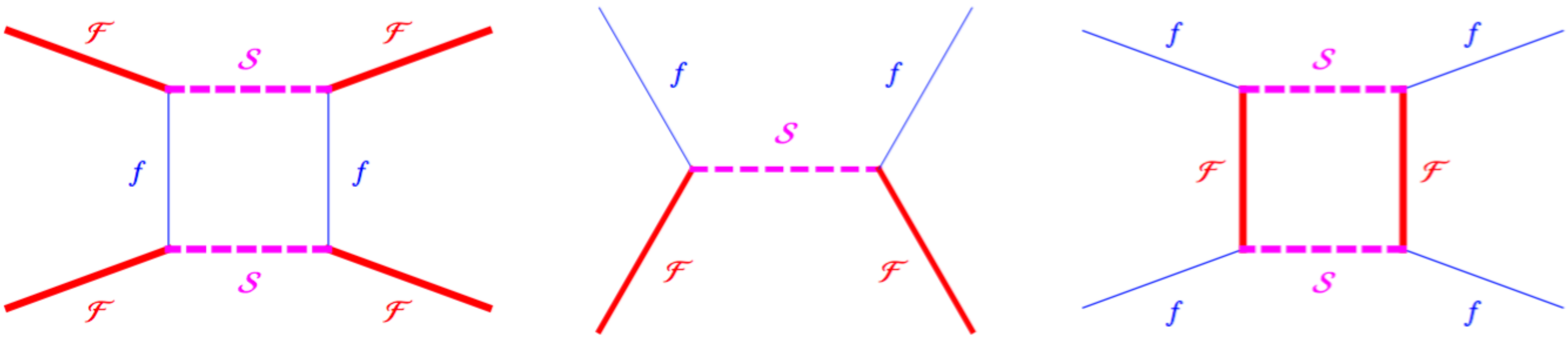
$$\Delta\mathcal{L} = f\mathcal{F}\mathcal{S}^* + h.c., \qquad f = Q, U, D, L, E$$

engineering dimension already 5/2

TC scalar were used in old TC
where TC breaks EW (and no Higgs)
Dobrescu Simmmons

The realization

$$\Delta\mathcal{L} = f\mathcal{F}\mathcal{S}^* + h.c., \qquad f = Q, U, D, L, E$$



Higgs potential
$\mathcal{F}^4 \sim H^2$

SM fermion masses
$ff\mathcal{F}\mathcal{F} \sim ffH$

Flavour violations
f^4

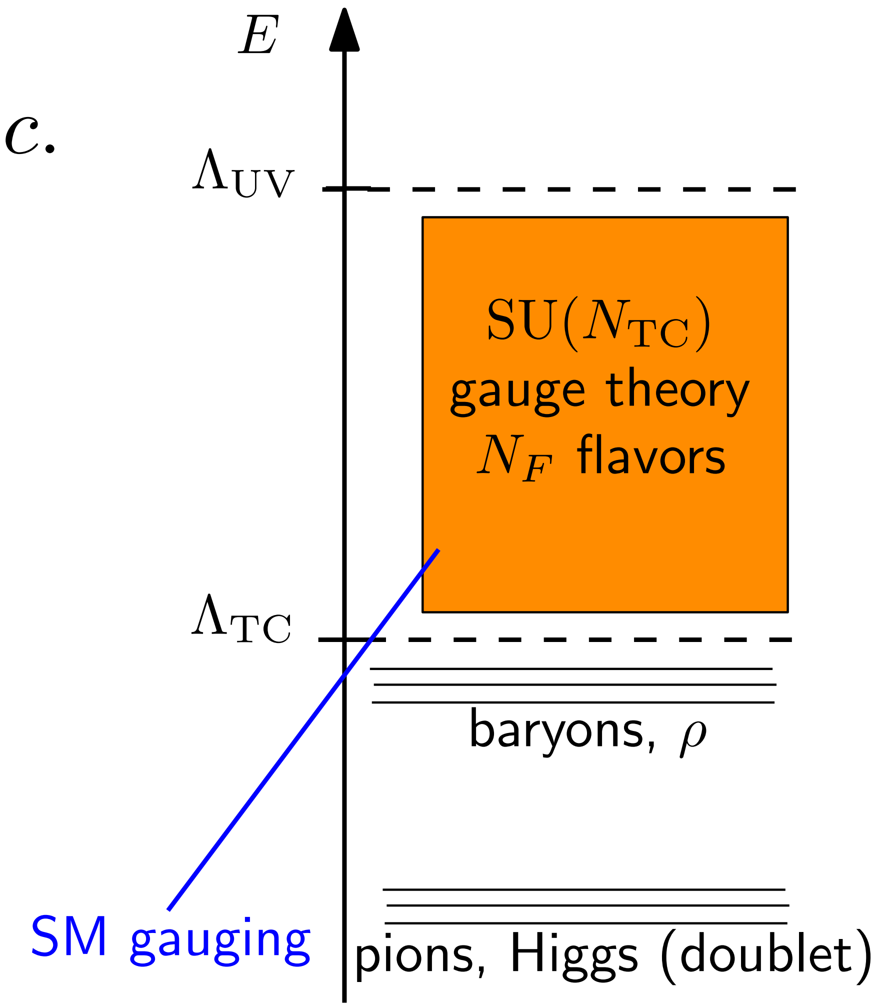
We mainly focus on the scenario where $\mathcal{F}\mathcal{F}^c \sim H$

We make use of $\quad \Lambda_{\rm TC} \sim m_\rho \sim g_\rho f \sim g_{\rm TC} f \sim \dfrac{4\pi}{\sqrt{N}} f \cdots$

The realization

$$\mathcal{L} = \mathcal{L}_{SM,H=0} + \bar{\mathcal{F}}_i D\mathcal{F}_i + m_i \mathcal{F}_i^c \mathcal{F}_i + yQ\mathcal{F}\mathcal{S} + h.c.$$

confinement **symmetry breaking**



$$\mathcal{L} = \mathcal{L}_{SM,H=0} + f^2(D\mathcal{U})^2 + \Lambda f^2 m\mathcal{U} + V(U,y) + yQ\mathcal{U}U + h.c.$$

$$\mathcal{F}\mathcal{F}^c = \Lambda f^2 \mathcal{U} = \Lambda f^2 + i\Lambda f H + \cdots$$

Accidental Symmetries

The TC interactions (similarly to QCD) leave some accidental global symmetries

Fields	Gauge	Global symmetry of fermions			Global, scalars	
	$\mathrm{SU}(N)_{\mathrm{TC}}$	$\mathrm{SU}(N_F)_L$	$\mathrm{SU}(N_F)_R$	$\mathrm{U}(1)_V$	$\mathrm{SU}(N_S)$	$\mathrm{U}(1)_S$
$\mathcal{F}$	N	N_F	1	$+1$	1	0
$\mathcal{F}^c$	$\bar{N}$	1	$\bar{N}_F$	-1	1	0
$\mathcal{S}$	N	1	1	0	N_S	1
	$\mathrm{SO}(N)_{\mathrm{TC}}$		$\mathrm{SU}(N_F)$		$\mathrm{O}(N_S)$	
$\mathcal{F}$	N		N_F		1	
$\mathcal{S}$	N		1		N_S	
	$\mathrm{Sp}(N)_{\mathrm{TC}}$		$\mathrm{SU}(N_F)$		$\mathrm{Sp}(2N_S)$	
$\mathcal{F}$	N		N_F		1	
$\mathcal{S}$	N		1		$2N_S$	

- Symmetries of kinetic terms
- Unbroken TC-baryon number in SU(N)

Condensation and chiral symmetry breaking

Upon confinement we can have these patterns of symmetry breaking

Gauge group	Fermion bilinear condensate	Intact scalar symmetries
$\mathrm{SU}(N)_{\mathrm{TC}}$	$\mathrm{SU}(N_F)_L \otimes \mathrm{SU}(N_F)_R \to \mathrm{SU}(N_F)$	$\mathrm{U}(N_S)$
$\mathrm{SO}(N)_{\mathrm{TC}}$	$\mathrm{SU}(N_F) \to \mathrm{SO}(N_F)$	$\mathrm{O}(N_S)$
$\mathrm{Sp}(N)_{\mathrm{TC}}$	$\mathrm{SU}(N_F) \to \mathrm{Sp}(N_F)$	$\mathrm{Sp}(2N_S)$

- We assume confinement if $\beta_{\mathrm{TC}} < \dfrac{1}{3}\beta_{\mathrm{TC}}^{gauge}$

Issues with TC scalar (not discussed here)

- <S> and <SS> not fixed by theory. Lattice?
- They can break TC, and give and elementary GB Higgs
- They can also break G and give pNGB Higgs

Custodial symmetry

Data require an approximate custodial symmetry in the strong sector

$$\frac{\hat{T}}{f^2}(H^\dagger D_\mu H)^2, \text{w/o custodial } \hat{T} \simeq \frac{v^2}{f^2} \sim 10^{-3}$$

$G_{\rm TC}$	$\mathrm{SU}(N)_{\rm TC}$	$\mathrm{SO}(N)_{\rm TC}$	$\mathrm{Sp}(N)_{\rm TC}$
$\mathcal{F}$	$\mathcal{F}_L \oplus \mathcal{F}_{E^c} \oplus \mathcal{F}_N$	$\mathcal{F}_L \oplus \mathcal{F}_{L^c} \oplus \mathcal{F}_N$	$2_0 \oplus 1_{1/2} \oplus 1_{-1/2}$
$G_{\rm gl} \to H_{\rm gl}$	$\mathrm{SU}(4)_L \otimes \mathrm{SU}(4)_R \to \mathrm{SU}(4)$	$\mathrm{SU}(5) \to \mathrm{SO}(5)$	$\mathrm{SU}(4) \to \mathrm{Sp}(4)$
TCπ	$2(2,2) \oplus 1 \oplus 3_L \oplus 3_R$	$(1,1) \oplus (2,2) \oplus (3,3)$	$(2,2) \oplus (1,1)$
$\mathcal{S}$	$\mathcal{S}_L \oplus \mathcal{S}_{E^c} \oplus \mathcal{S}_N$	$\mathcal{S}_L \oplus \mathcal{S}_N$	$\mathcal{S}_L \oplus \mathcal{S}_N$
$G_{\rm gl} \to H_{\rm gl}$	$\mathrm{SU}(4) \to \mathrm{SU}(2)_L \otimes \mathrm{SU}(2)_R$	$\mathrm{SO}(5) \to \mathrm{SO}(4)$	$\mathrm{Sp}(6) \to \mathrm{Sp}(4) \otimes \mathrm{Sp}(2)$
if $\langle \mathcal{S}\mathcal{S} \rangle \propto$	$\mathrm{diag}\,(0,0,1,1)$	$\mathrm{diag}\,(0,0,0,0,1)$	$\varepsilon \otimes \mathrm{diag}\,(0,0,1)$
TCπ	$2 \times (2,2) \oplus (1,1)$	$(2,2)$	$2(2,2)$

- Presence of one (2,2) is ok
- In SU(N) need alignment between two (2,2)
- Yukawas can be a source of breaking (they generate the potential)

Distortions in Z couplings

Q doublet is strongly mixed via yQ to the composite state B

$$\delta Z_{b_L b_L} = \frac{y_t^2}{y_U^2}\frac{v^2}{f^2} \sim 2\ 10^{-3}$$

- Protection is possible invoking a LR symmetry
- Structurally difficult in SU(N) and Sp(N) models
- SO(N) gauge theories allows for a LR symmetry in Q couplings

A broad characterization

- TC asymptotically free and confining

$$N \gtrsim \frac{3(4N_F + N_S)}{44} \qquad \mathrm{SU}(N)_{\mathrm{TC}}$$

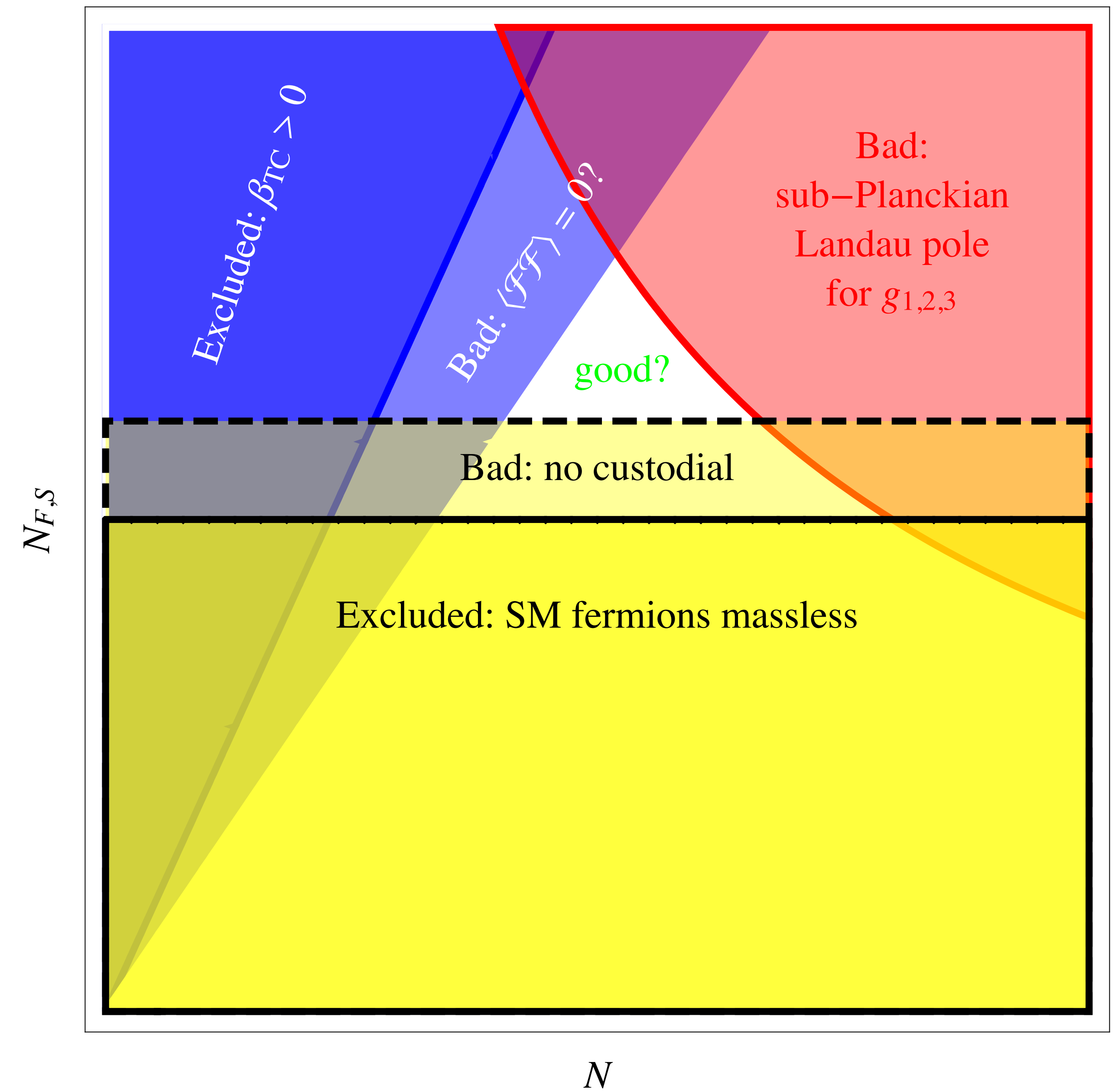
$$N \gtrsim \frac{3(4N_F + N_S)}{44} + 2 \qquad \mathrm{SO}(N)_{\mathrm{TC}}$$

$$N \gtrsim \frac{3(2N_F + N_S)}{22} - 2 \qquad \mathrm{Sp}(N)_{\mathrm{TC}}$$

- No landau poles for SM

$$b_3 \lesssim 1.9, \quad b_2 \lesssim 5.3, \quad b_3 \lesssim 10$$

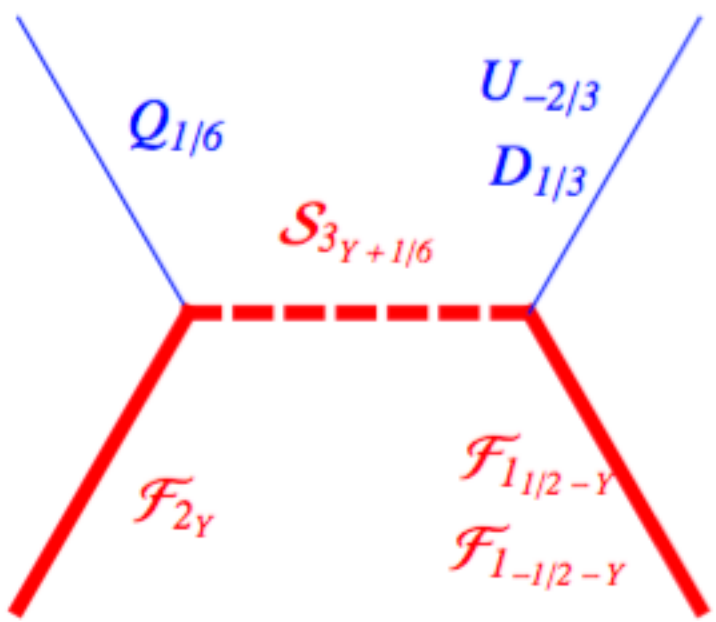
- All SM fermions get mass
- Higgs custodially protected (Zbb?)



Difficult to realize these conditions in concrete models but...

How to find these models?

Look for a minimal square root of SM fermion quantum numbers preserving B and L numbers



$$\mathscr{L}_Y \sim (Q\mathcal{F}\mathcal{S}_q^* + Q_R\mathcal{F}^c\mathcal{S}_q) + (L\mathcal{F}\mathcal{S}_\ell^* + L_R\mathcal{F}^c\mathcal{S}_\ell)$$

A model with SU(5) fragments and Y=-1/2

name	spin	generations	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$	G_{TC}
$\mathcal{F}_N$	$1/2$	N_{gF}	1	1	0	N
$\mathcal{F}_N^c$	$1/2$	N_{gF}	1	1	0	$\bar{N}$
$\mathcal{F}_L$	$1/2$	N_{gF}	1	2	$-1/2$	N
$\mathcal{F}_L^c$	$1/2$	N_{gF}	1	2	$+1/2$	$\bar{N}$
$\mathcal{F}_{E^c}$	$1/2$	N_{gF}	1	1	-1	N
$\mathcal{F}_{E^c}^c$	$1/2$	N_{gF}	1	1	$+1$	$\bar{N}$
$\mathcal{S}_{E^c}$	0	N_{gS}	1	1	-1	N
$\mathcal{S}_{D^c}$	0	N_{gS}	3	1	$-1/3$	N

$$\mathscr{L}_Y = y_L \, L\mathcal{F}_L\mathcal{S}_{E^c}^* + y_E \, E\mathcal{F}_N^c\mathcal{S}_{E^c} + (y_D \, D\mathcal{F}_N^c + y_U \, U\mathcal{F}_{E^c}^c)\mathcal{S}_{D^c} + y_Q \, Q\mathcal{F}_L\mathcal{S}_{D^c}^* + \text{h.c.}$$

- TC-baryon number conserved
- No F-S-S interaction possible
- New TC-fermions (vector-like)

A model with Y=-1/2

$$\mathscr{L}_Y = y_L\ L\mathcal{F}_L\mathcal{S}^*_{E^c} + y_E\ E\mathcal{F}^c_N\mathcal{S}_{E^c} + (y_D\ D\mathcal{F}^c_N + y_U\ U\mathcal{F}^c_{E^c})\mathcal{S}_{D^c} + y_Q\ Q\mathcal{F}_L\mathcal{S}^*_{D^c} + \text{h.c.}$$

- TC-pions are

$$\mathrm{TC}\pi = 2\times(1,1)_0 \oplus (1,3)_0 \oplus [(1,1)_1 \oplus 2\times(1,2)_{-1/2} + \text{h.c.}] \qquad \text{under } G_{\mathrm{SM}}$$

- Unbroken TC-baryon number

$\mathcal{F}_N^3$ possible DM (need to explore this more)

- Other hadron states are composite fermions, vectors (and higher spin)

At low energy the phenomenology is the same as discussed in the introduction

Other possibilities

- <u>Model with Y=1/2</u>

  $$(\mathcal{F}_{L^c} \oplus \mathcal{F}_E \oplus \mathcal{F}_N) \oplus 3 \times (\mathcal{S}_N \oplus \mathcal{S}_{U^c}).$$

  $$\mathscr{L}_Y = y_L\ L\mathcal{F}_{L^c}\mathcal{S}_N^* + y_E\ E\mathcal{F}_E^c\mathcal{S}_N + (y_D\ D\mathcal{F}_E^c + y_U\ U\mathcal{F}_N^c)\mathcal{S}_{U^c} + y_Q\ Q\mathcal{F}_{L^c}\mathcal{S}_{U^c}^* + \text{h.c.}$$

  Allowed for SU(3), TC-baryon number broken by S^3

- <u>Model with Y=0</u>

  $$(\mathcal{F}_{2_0} \oplus \mathcal{F}_{1_{\pm 1}}) \oplus 3 \times (\mathcal{S}_{3_{1/6}} + \mathcal{S}_{1_1})$$

  Allowed for Sp(2)–Sp(14), TC-baryon unstable

Higgs potential

Computable in a chiral expansion $\mathcal{F}\mathcal{F} = f^2 \Lambda \mathcal{U}$

- TC-fermion masses (contribution neglected in effective theories)
- SM gauge interactions
- Yukawa interactions

$$
\begin{aligned}
-M_h^2 &\sim c_m \left(\sum_i m_{\mathcal{F}_i} \right) \Lambda_{\mathrm{TC}} + \left(c_g \frac{3(3g_2^2 + g_Y^2)}{64\pi^2} - c_y N_c \frac{y_t^2}{16\pi^2} \right) \Lambda_{\mathrm{TC}}^2 \,, \\
\lambda_H &\sim \frac{c_y N_c y_Q^2 y_U^2}{12(4\pi)^2} - \frac{c_g g_{\mathrm{TC}}^2 (3g_2^2 + g_Y^2)}{16(4\pi)^2} \sim \frac{y_t^2}{N} \,,
\end{aligned}
$$

Flavour sector

Spurionic structure similar to SM (but richer)

Coupling	Flavor symmetry of SM fermions					Flavor of TC-scalars	
	U(3)$_L$	U(3)$_E$	U(3)$_Q$	U(3)$_U$	U(3)$_D$	U(3)$_{\mathcal{S}_{E^c}}$	U(3)$_{\mathcal{S}_{D^c}}$
y_L	3	1	1	1	1	3	1
y_E	1	3	1	1	1	$\bar{3}$	1
y_Q	1	1	3	1	1	1	3
y_U	1	1	1	3	1	1	$\bar{3}$
y_D	1	1	1	1	3	1	$\bar{3}$
$m^2_{\mathcal{S}_E}$	1	1	1	1	1	$3 \otimes \bar{3}$	1
$m^2_{\mathcal{S}_D}$	1	1	1	1	1	1	$3 \otimes \bar{3}$
λ_E	1	1	1	1	1	$(3 \otimes \bar{3})^2$	1
$\lambda_{D,D'}$	1	1	1	1	1	1	$(3 \otimes \bar{3})^2$
λ_{ED}	1	1	1	1	1	$3 \otimes \bar{3}$	$3 \otimes \bar{3}$

3 matrices in y, 2 in mS (and scalar potential)

only CKM in the SM...

Flavour bounds - dipoles

- Dipole operators give strong bounds (partial compositeness not enough)

$$d_{LE} \sim y_L y_E^T$$

10^4 above the bound

- Need to require flavor blind masses for TC scalars, then

$$d_{LE} \sim \frac{g_{\rm SM}}{g_{\rm TC}} \frac{v}{\Lambda_{\rm TC}^2} y_L \cdot X \cdot y_E^T \qquad \text{with} \qquad X = \frac{(y_L^\dagger y_L)}{g_{\rm TC}^2}, \frac{(y_E^\dagger y_E)^T}{g_{\rm TC}^2}$$

$$\Lambda_{\rm TC} \sim {\rm TeV}$$

Analogous estimates for neutron dipole moment

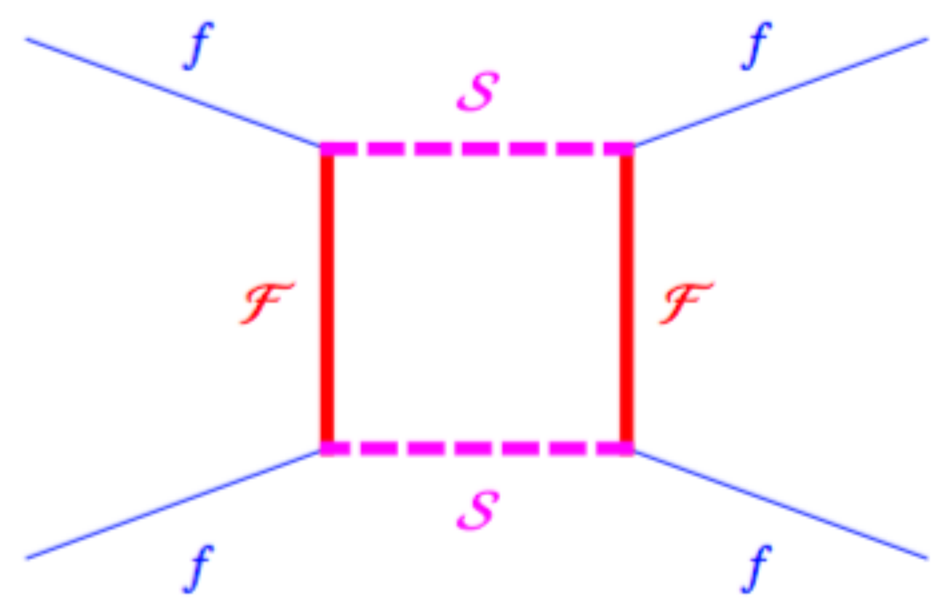
- Quark sector can contribute to dLE

$$d_{LE} \propto (y_L y_E^T) T$$

$$\mathrm{Im}\, T = \frac{1}{g_{\rm TC}^{12}} \mathrm{Im}\ \mathrm{Tr}[(y_Q^\dagger y_Q)^2 (y_U^\dagger y_U)^{T2} (y_Q^\dagger y_Q)(y_U^\dagger y_U)^T] \sim \frac{y_t^4 y_c^2 V_{cb} V_{ub} V_{us}}{g_{\rm TC}^6}.$$

Flavour bounds - $\Delta F = 2$

$$\sim \frac{(y_f^\dagger y_f)_{ij}(y_{f'}^\dagger y_{f'})_{i'j'}}{g_{\rm TC}^2 m_{\mathcal{S}}^2}(\bar f_i \gamma_\mu f'_{j'})(\bar f'_{i'}\gamma_\mu f_j) \qquad \text{for any } f, f' = \{L, E, Q, U, D\}.$$



- Kaon mixing $|\Lambda| > 3 \times 10^5\,\mathrm{TeV}$

  $\Lambda \gtrsim \Lambda_{\rm TC}/\sqrt{y_s y_d} \sim 10^4 \Lambda_{\rm TC}$

- B system under control

Other directions?

- Supersymmetric version (models will be conventionally natural)

  SUSY will require doubling the TC scalar

  $$\mathscr{L}_Y \sim (Q\mathcal{F}\mathcal{S}_q^* + Q_R\mathcal{F}^c\mathcal{S}_q) \longrightarrow \quad \mathcal{S}_q^* \to \mathcal{S}_q'$$

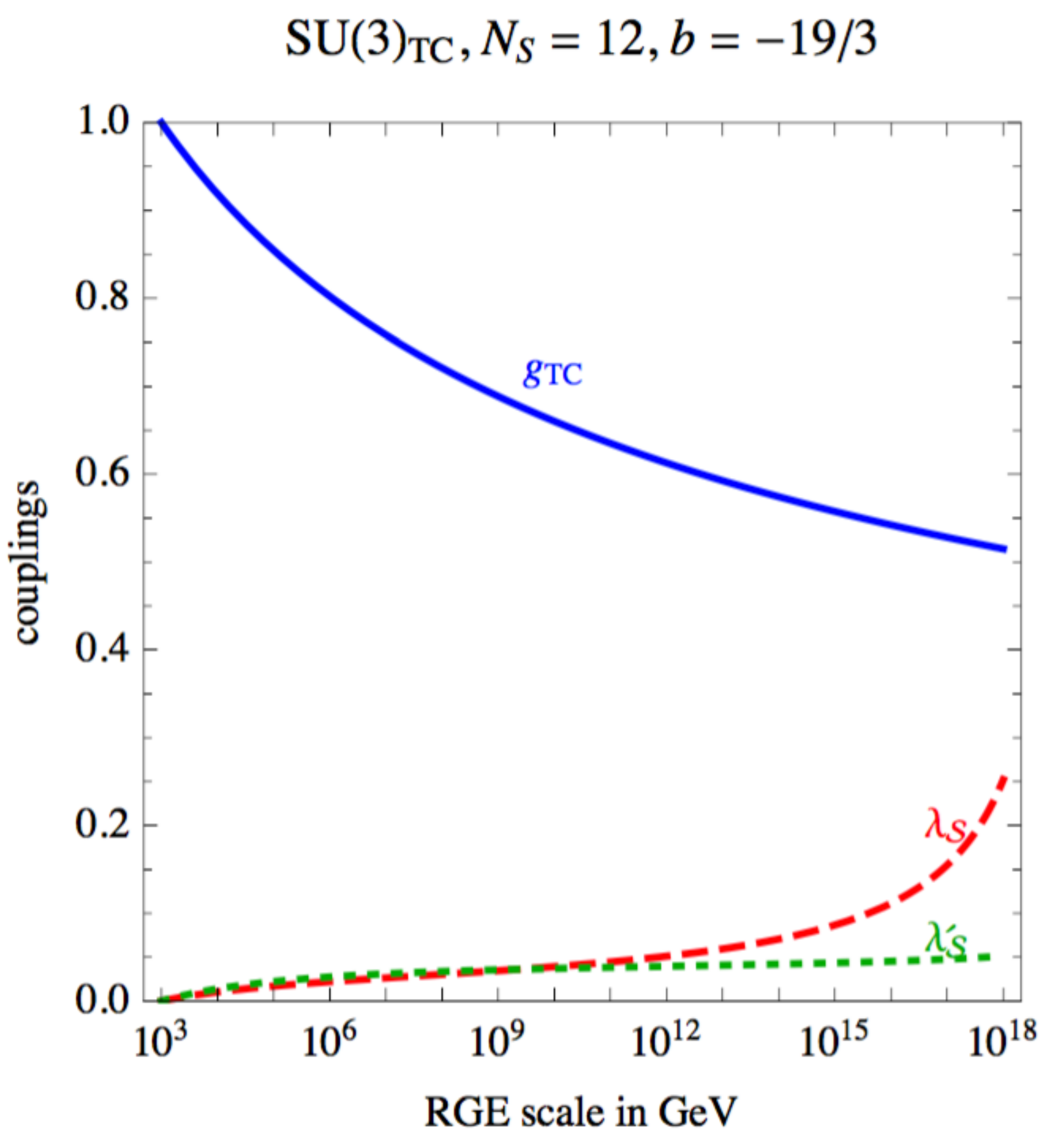
  Landau poles close, cannot work for all fermions

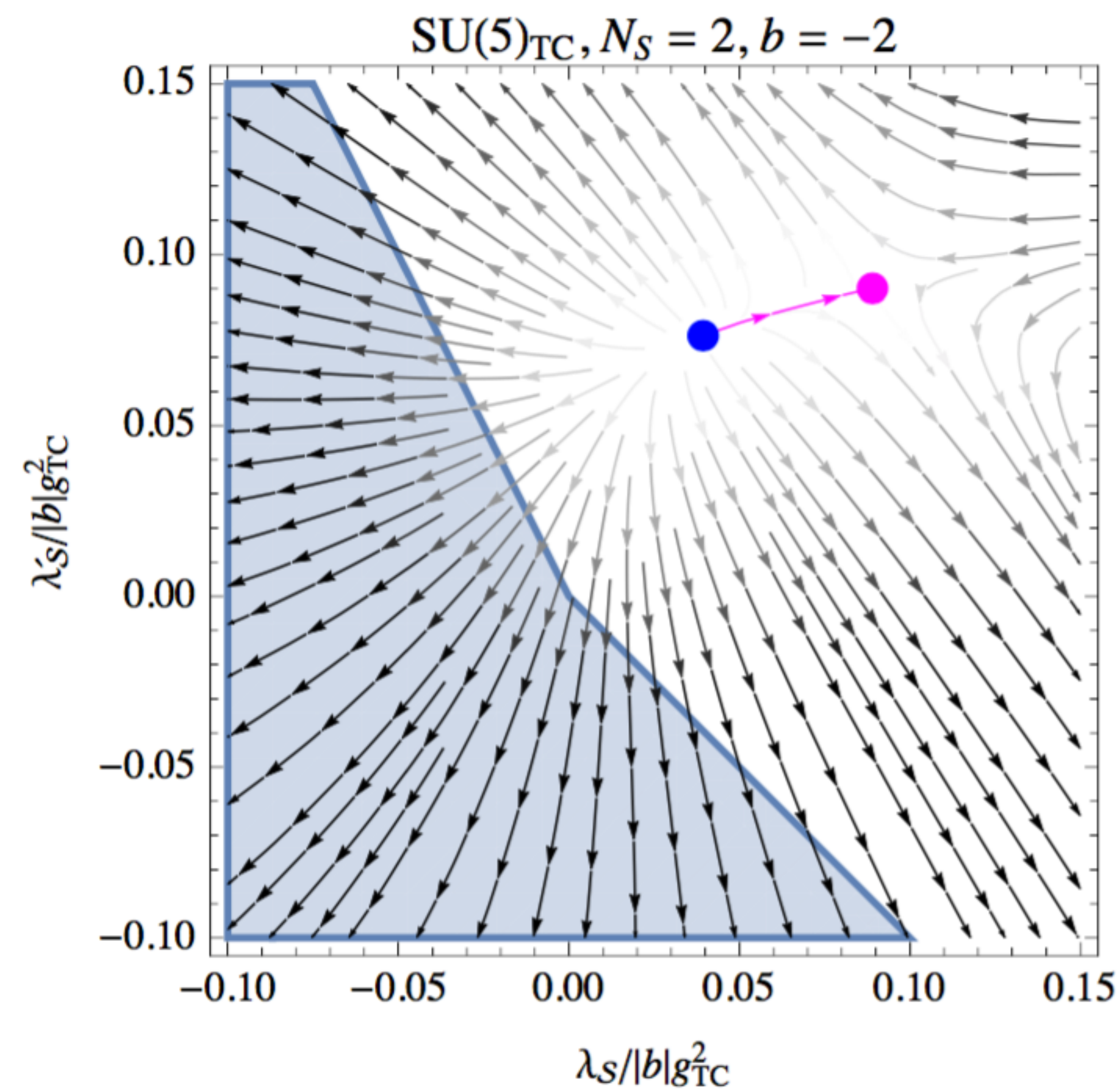
- Explore DM and lepton sector in explicit realizations

Conclusions

- Composite Higgs has been discussed mostly in effective approaches
- Motivated phenomenology for LHC
- Need to understand if plausible UV model exists
- TC with fermion and scalar might be a first step
- Or, just, the low energy description of something more fundamental
- First example of a complete coupling of the Higgs to all fermions
- Accidental symmetries of the SM are unmatched (not a surprise!)

TCscalar quartic couplings





- IR (pseudo) fixed points with positive quartic found