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Fundamental Models for partially composite Higgs and fermions

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Intro

Protection against possible new thresholds

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, but...)
- Models with physics at the TeV scale fits into the category (at least at 2 loops)

Naturalness scorecard

SUSY

- ...
- Ok, you know the story

Compositeness

- Custodial symmetry
- LR symmetry
- Light top partners
- Precision tests (?)
- Flavor (??)
- Higgs mass a bit large
- No fundamental description

QCD: fundamental and natural

- 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 old technicolor theories

I use the ‘vintage’ name TC (techni-color) instead of ultra-color, hyper-color etc..

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)

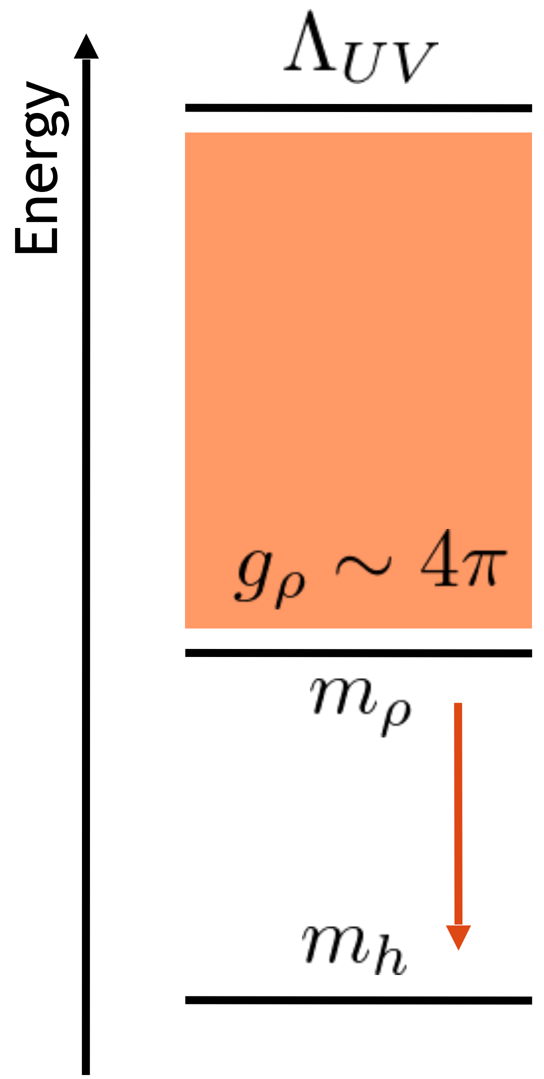
Can we realize a composite Higgs sector? (let's try)

Composite Higgs

What is it?

(or, how we want it look like)

The compositeness "paradigm"



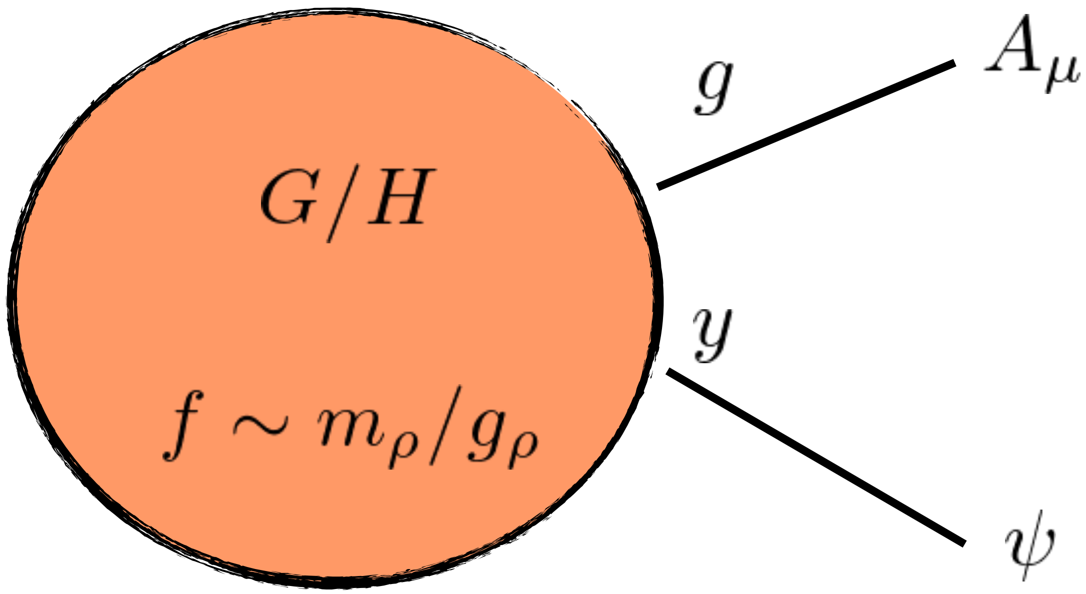
"Easy" piece:
Large separation between the UV and IR scale achieved via a QCD-like dynamics

"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

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 '05
Giudice, Grojean, Pomarol Rattazzi, '07

Minimal Composite Higgs

Agashe,Contino, Pomarol

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

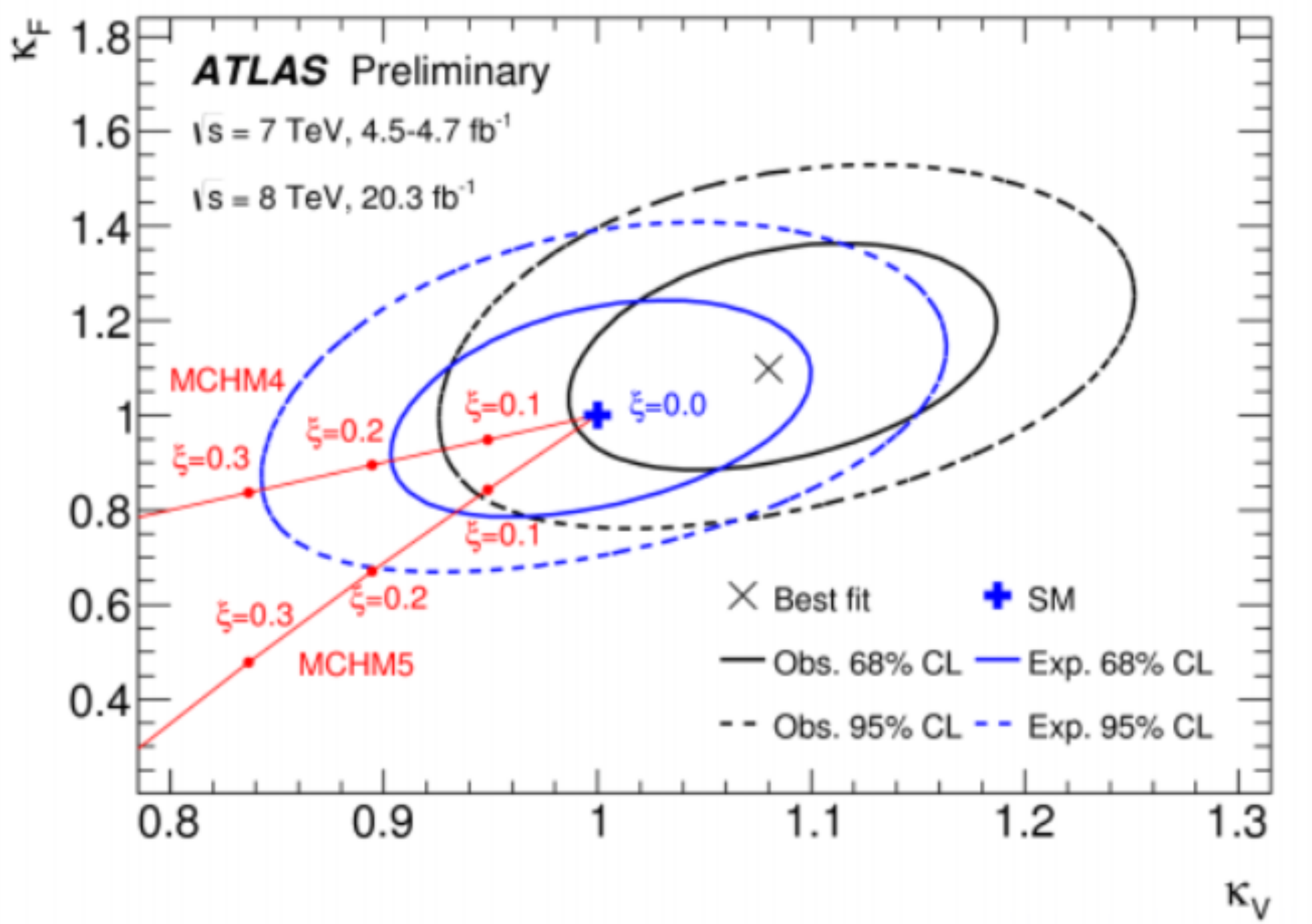
- Strong sector is SO(4) invariant, resonances in SO(4) multiplets
- Higgs is a bidoublet, custodial symmetry
- Deviation in Higgs couplings due to pNGB nature

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

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

Deviations 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 is light
- Need to look for colored fermionic top-partners

Agashe, Da Rold, Contino, Pomarol '06
...
Panico Wulzer
De Curtis, Redi, Tesi
Matsedonskyi Panico Wulzer
Marzocca Serone Shu
Pomarol Riva
...

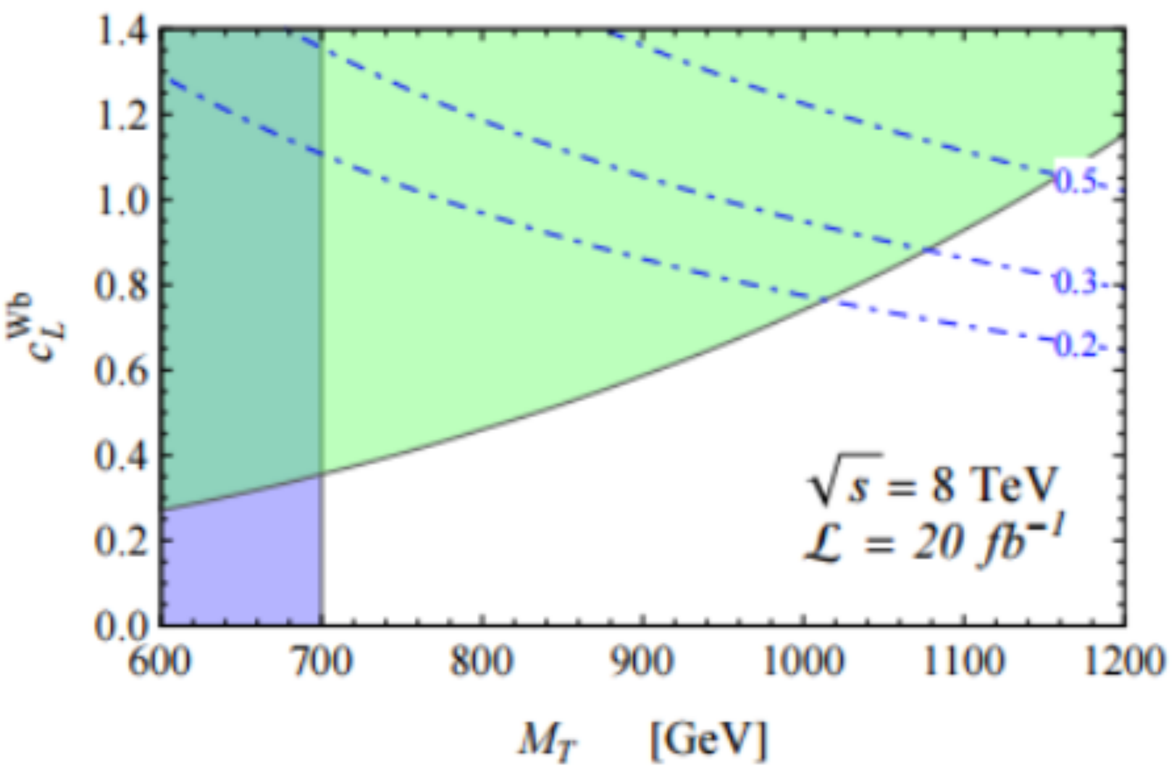
The search for Top partners

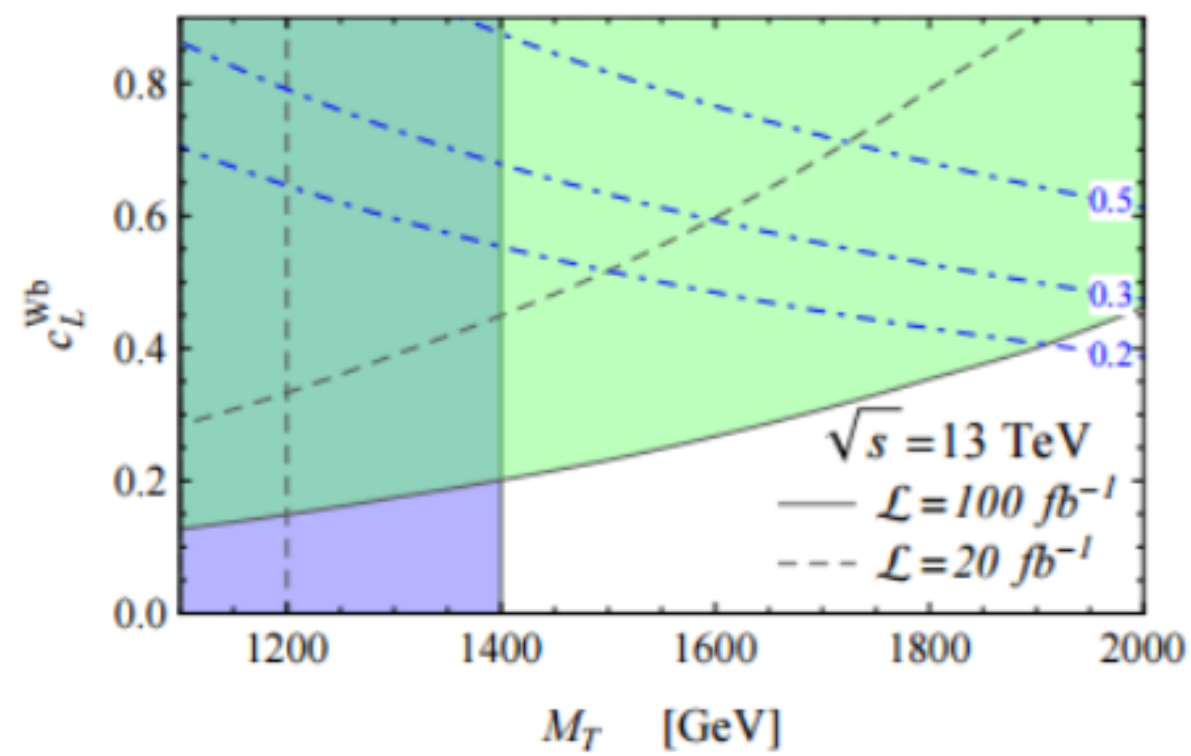
Production modes

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

Decay modes

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



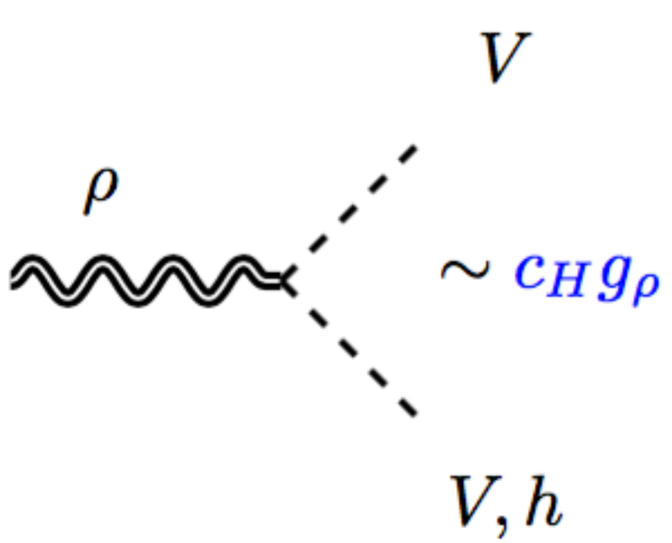


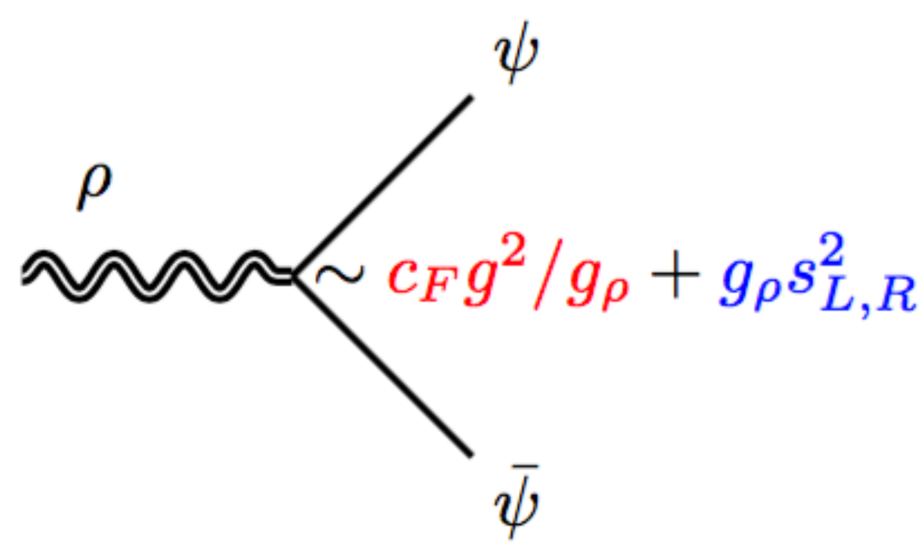
Matsedonskyi, Panico, Wulzer

Electroweak Spin-1 resonances

In models with custodial symmetry $3 \oplus 1_{\pm} \oplus 1_0$ of SU(2) U(1)

They couple strongly with the composite Higgs and weakly to light fermions via W/Z mizing

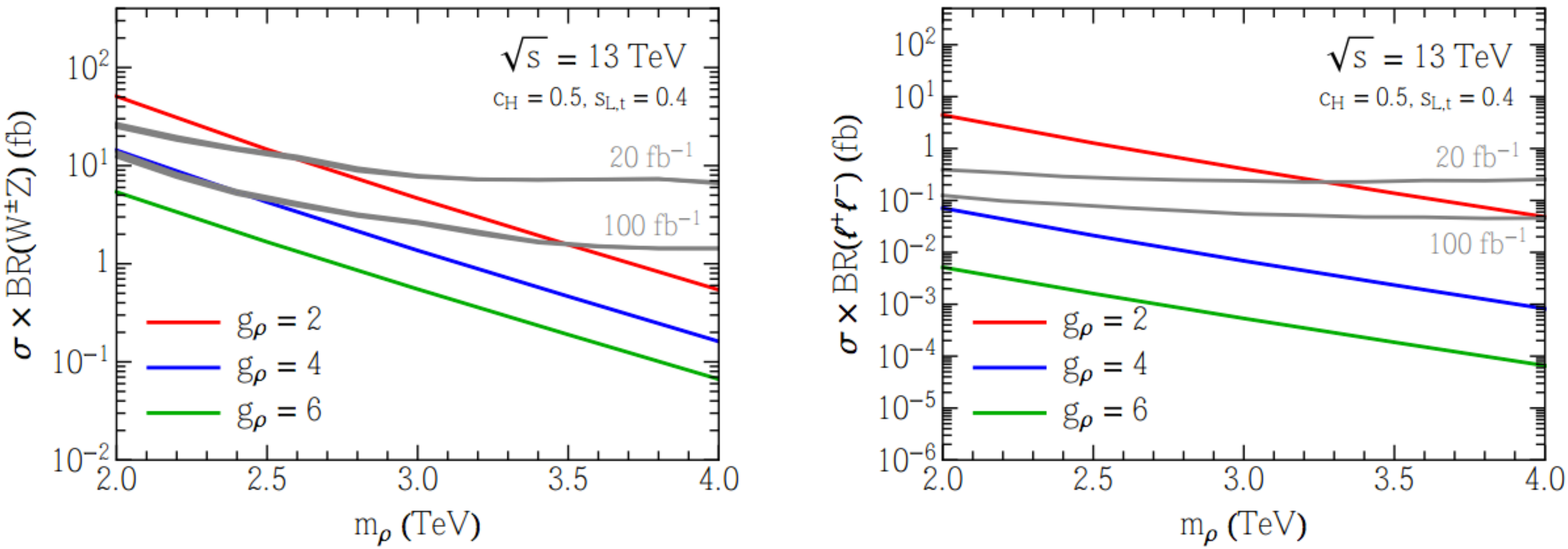




Strong coupling to diboson — Weak coupling to light fermions

Production rate is model-independent $\sim g^2/g_\rho^4$

Electroweak Spin-1 resonances



(w/ Matthew Low and Liantao Wang)

- Large branching to dibosons
- Also dilepton are important
- 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)

(see also Barbieri, Greco, Rattazzi, Wulzer)

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?

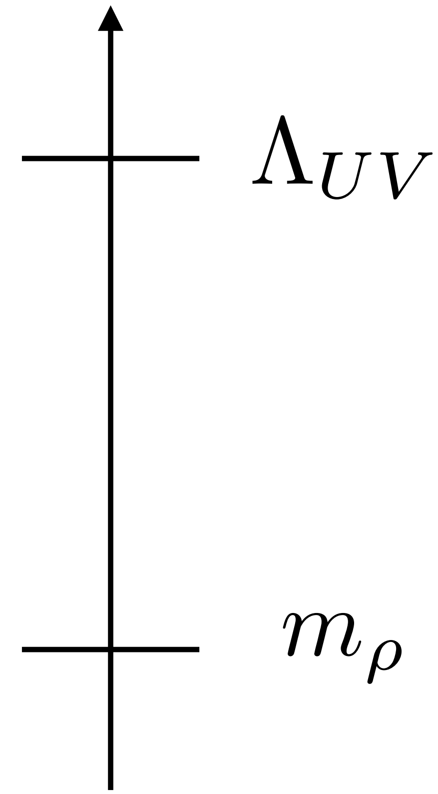
Fundamental Partial Compositeness

Sannino, Strumia, Tesi, Vigiani (arXiv:1607.01659)

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
- Large separation of scales

Ferretti Karateev; Ferretti '16
Vecchi '15

What is $\mathcal{O}_q$?

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

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

$$\mathcal{B} \sim \psi\psi\psi$$

- dim=9/2, requires very large anomalous dimensions -2
- need non trivial dynamics (only lattice can tell, not found in QCDpt)
- Generated by what?

Composite fermions likely not baryons

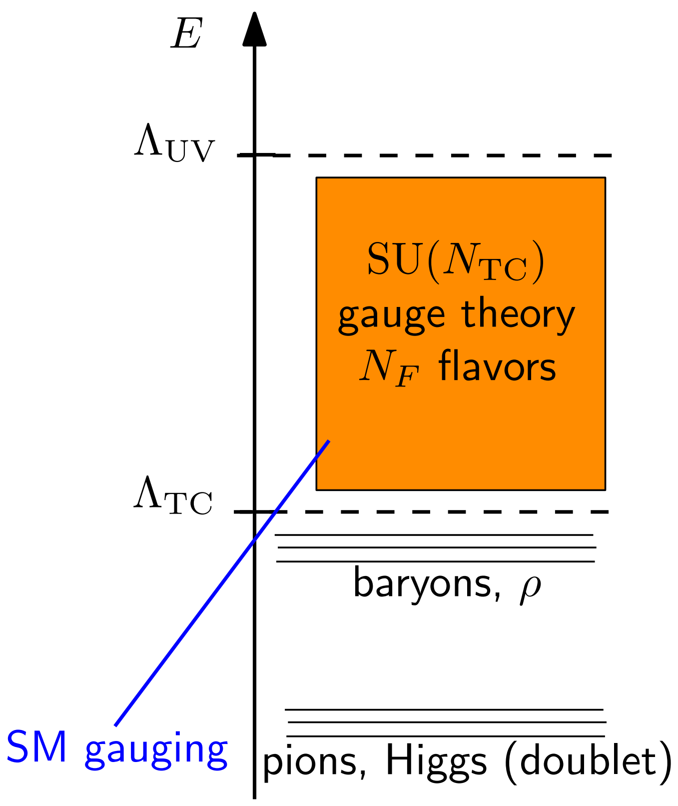
Other considerations

- Baryons are heavy $m_{\mathcal{B}}/m_\rho \sim N$ Witten
- Data requires 'light' top partners
- Top partners are more like 'mesons' Caracciolo Parolini Serone
- Ferretti proposed also trilinear $\mathcal{B} \sim \chi\psi\psi$
- what about? $\mathcal{B} \sim \psi\phi$

The realization — Columbus' egg

Generate all the fermion masses

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



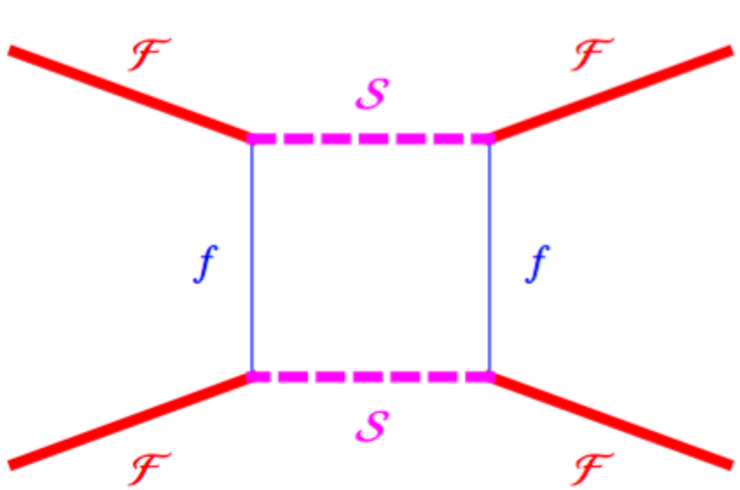
$$\Delta\mathcal{L} = f\mathcal{F}\mathcal{S}^* + h.c., \qquad f = Q, U, D, L, E$$

engineering dimension already 5/2

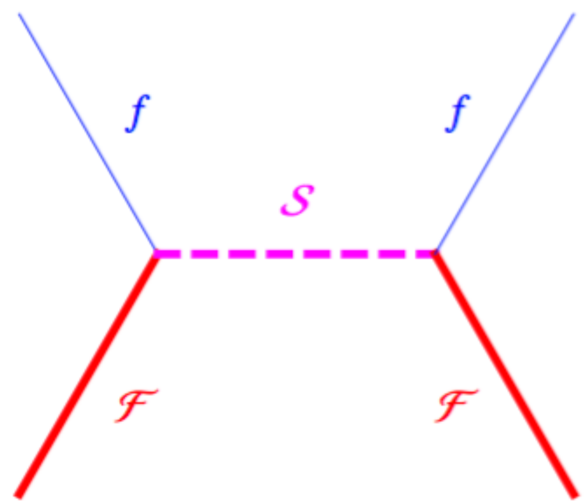
Here TC does not break the EW symmetry!

The realization

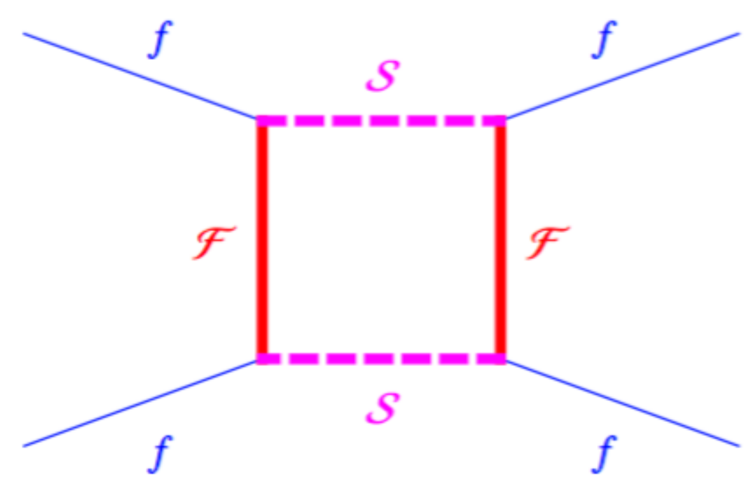
$$\Delta\mathcal{L} = f\mathcal{F}\mathcal{S}^* + h.c., \qquad f = Q, U, D, L, E$$



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



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

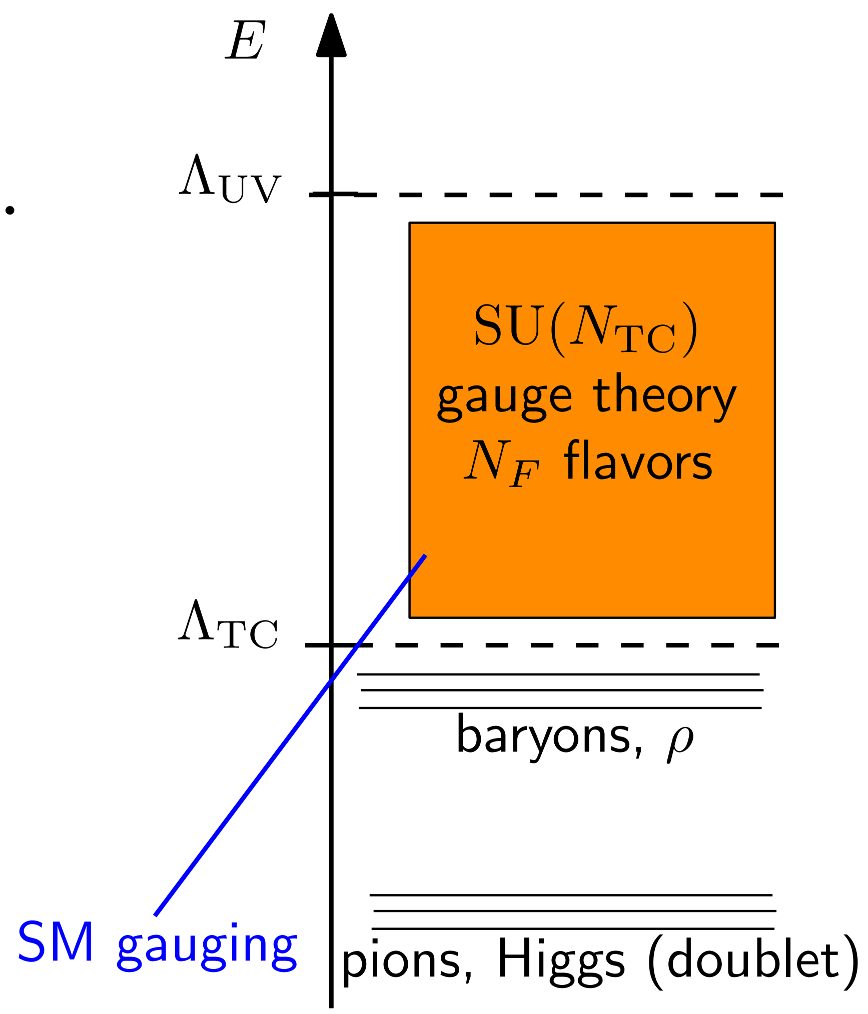


Flavour violations
f^4

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

The realization

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



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

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

Accidental Symmetries

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

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

- Symmetries of kinetic terms
- TCfermions need to be light, *a posteriori* 1-loop smaller than Λ_{TC}
- Negligible potential for scalars
- Unbroken TC-baryon number in SU(N)

Condensation and chiral symmetry breaking

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 need TC scalars to be friendly with us

- <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

no time to discuss them here,
I will focus on the 'conservative' case

Custodial symmetry

Data require an approximate custodial symmetry in the strong sector

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

	SU(N)	SO(N)	Sp(N)
$\mathcal{F}$	$\mathcal{F}_L + \mathcal{F}_{E^c} + \mathcal{F}_N$	$\mathcal{F}_L + \mathcal{F}_{L^c} + \mathcal{F}_N$	$\mathcal{F}_{2_0} + \mathcal{F}_{1_{1/2}} + \mathcal{F}_{1_{-1/2}}$
G/H	$SU(4)_L \times SU(4)_R \to SU(4)$	$\mathrm{SU}(5) \to \mathrm{SO}(5)$	$\mathrm{SU}(4) \to \mathrm{Sp}(4)$
π	$2(2,2) + (1,1) + (3,1) + (1,3)$	$(3,3) + (2,2) + (1,1)$	$(2,2) + (1,1)$

- 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

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

- Minimize the bound with a composite tR (large yU from running)
- Protection is possible invoking a LR symmetry Q = (2,2)
- 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

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

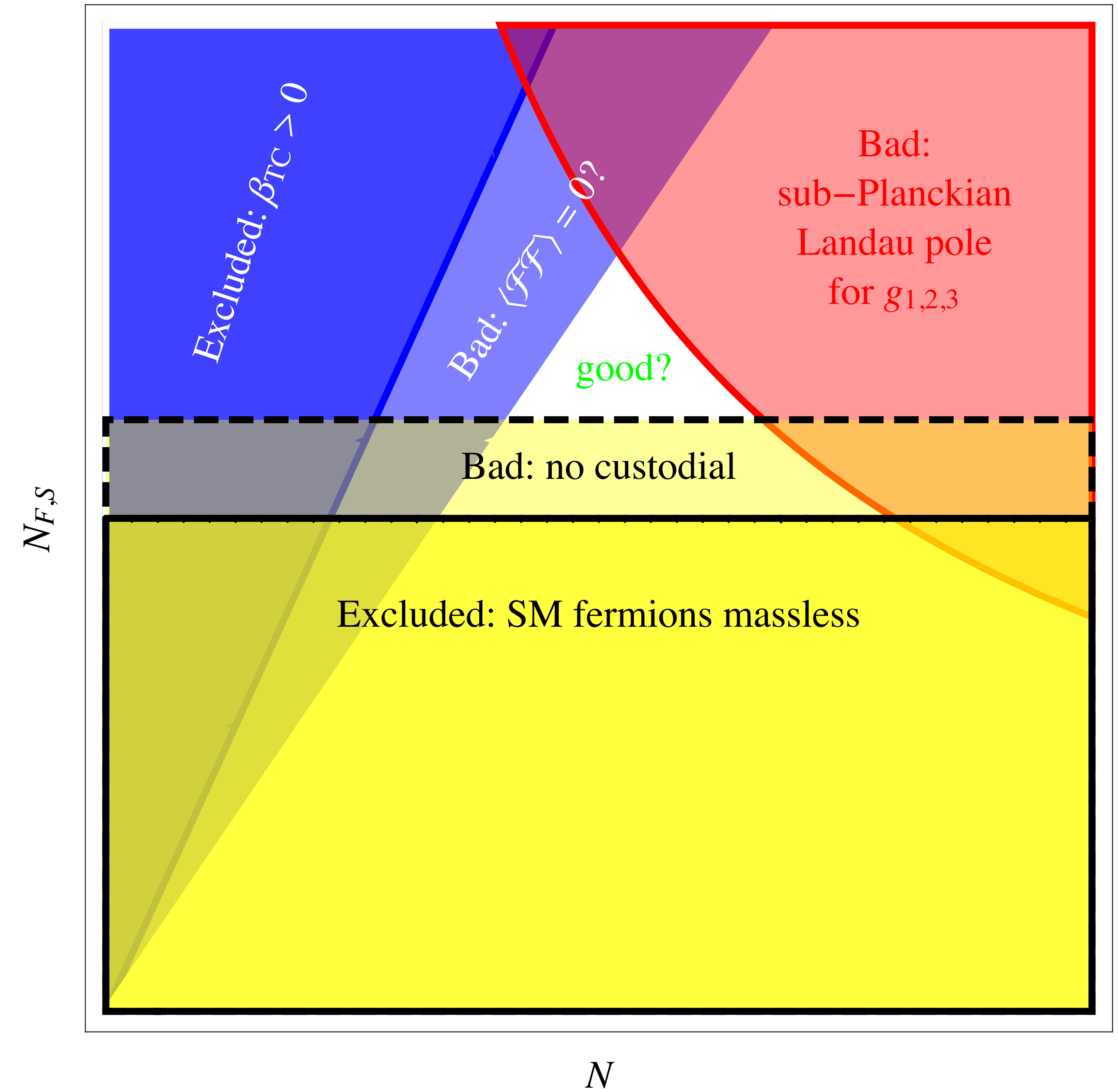
$$N \gtrsim \frac{3(4N_F + N_S)}{44} + 2 \qquad SO(N)_{TC}$$

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

- No landau poles for SM

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

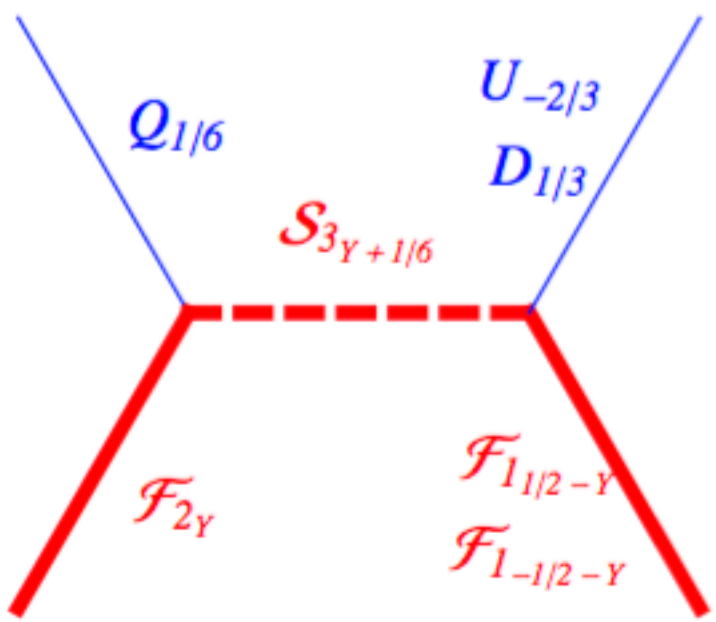
- All SM fermions get mass
- Higgs custodially protected (Zbb?)



Non trivial requirements, but...

How to find these models?

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



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

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
- TCscalars in 3 families

$$N_{g_F} = 1, N_{g_S} = 3$$

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

Symmetry breaking is $SU(4)_L \times SU(4)_R \to SU(4)$

- TC-pions are in the 15 of SU(4)

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

- 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

- Model with Y=1/2 $SU(4)_L \times SU(4)_R \to SU(4)$

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

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

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

- Model with Y=0

$$SU(4) \to Sp(4)$$

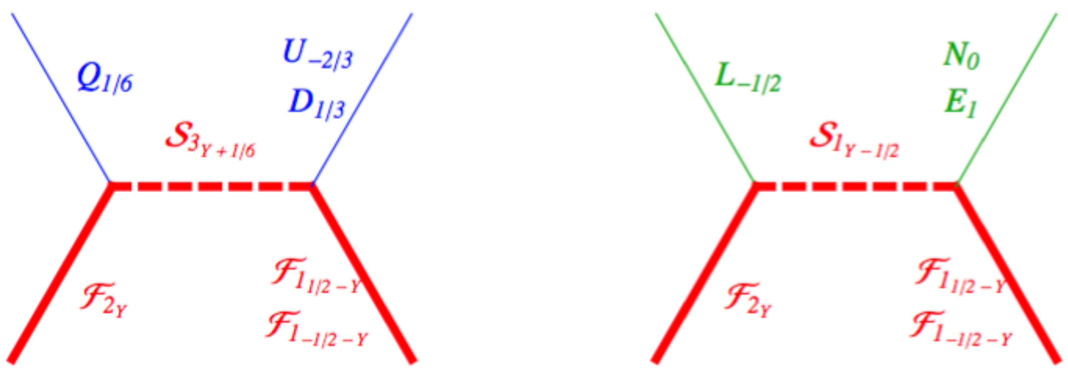
$$(\mathcal{F}_{2_0} \oplus \mathcal{F}_{1_{\pm 1}}) \oplus 3 \times (\mathcal{S}_{3_{1/6}} + \mathcal{S}_{1_1})$$

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

New pheno from a fundamental perspective?

Lepto-quarks generically expected at scale Λ_{TC}

- Depending on the charge of fundamental fermions and fields
- In our construction they originate exchanging a TCfermion



$$\frac{y_Q y_L^T}{g_{\mathrm{TC}}} \times \bar{Q}\gamma_\mu L$$

- Present also without breaking L and/or B numbers
- Usually forgotten in composite models
- Large BR to heavy quarks and leptons
- Limits comparable to top partner searches, m > TeV

New pheno from a fundamental perspective?

Many pNGBs expected heavier than Higgs by f/v

- Triplet can decay to Zgammma, WZ, Wgamma (anomaly)
- Challenging for LHC, many EW charged scalars (need to asses LHC reach)
- Generically we don't expect colored pNGB

Most minimal fundamental model is SU(4)/Sp(4) = SO(6)/SO(5)

- Singlet pGB is CP-odd, sizeable tt and bb and gamma gamma
- Usually all the pions are unstable

Higgs potential in fundamental models

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 (number of invariants depend on the gauge groups)

$$M_h^2 \sim c_m \left(\sum_i m_{\mathcal{F}_i} \right) \Lambda_{\rm TC} + \left(c_g \frac{3(3g_2^2 + g_Y^2)}{64\pi^2} - c_y N_c \frac{y_t^2}{16\pi^2} \right) \Lambda_{\rm TC}^2$$

$$\lambda_H \sim \frac{c_y N_c y_Q^2 y_U^2}{12(4\pi)^2} - \frac{c_g g_{\rm TC}^2 (3g_2^2 + g_Y^2)}{16(4\pi)^2} \sim \frac{y_t^2}{N} ,$$

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...

here, TCscalars carry flavor

Leptons are not composite...

- 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

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

Analogous estimates for neutron dipole moment

- The same operator structures also contribute to unseen $\mu \to e\gamma$

We need to assume TCscalars are flavor blind

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

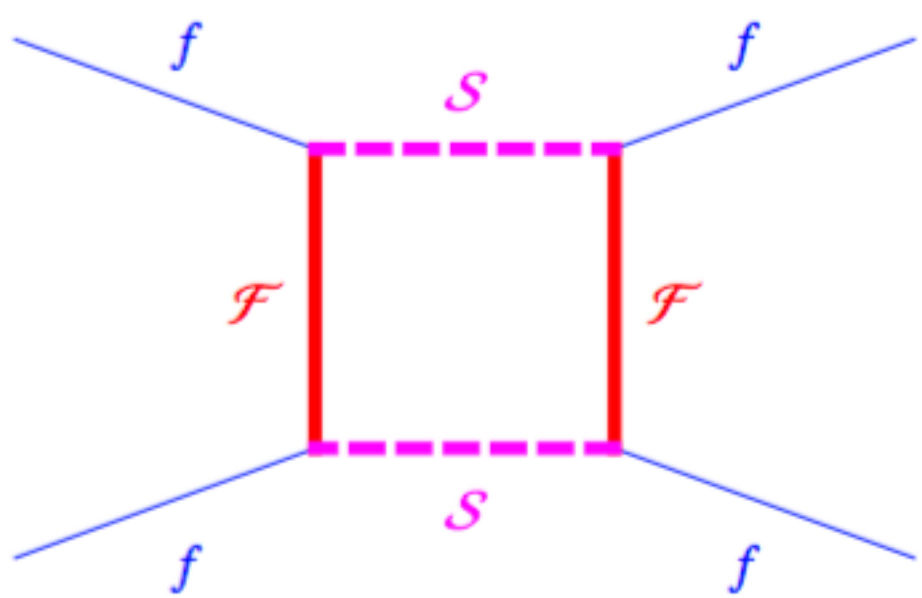
Flavour bounds - $\Delta F = 2$

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

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

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

- B system under control



The model looks like a 'moderate anarchy'

Other directions?

- Supersymmetric version (models will be "natural" in the common sense)

  SUSY will require doubling the TC scalar

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

  Landau poles close, cannot work for all fermions

  Caracciolo Parolini Serone
  Marzocca Parolini Serone

- Explore DM and lepton sector in explicit realizations

  In models with stable TC-baryons

  Antipini, Redi, Strumia, Vigiani

- A fundamental twin Higgs?

  Need to have a chiral composite topR

Conclusions

- Composite Higgs is a motivated EFT
- Rich phenomenology at LHC
- Composite Higgs needs fundamental scalars (like it or not...)
- First example of a complete coupling of the Higgs to all fermions
- Accidental symmetries of the SM are unmatched (not a surprise!)