Status of Composite Higgs

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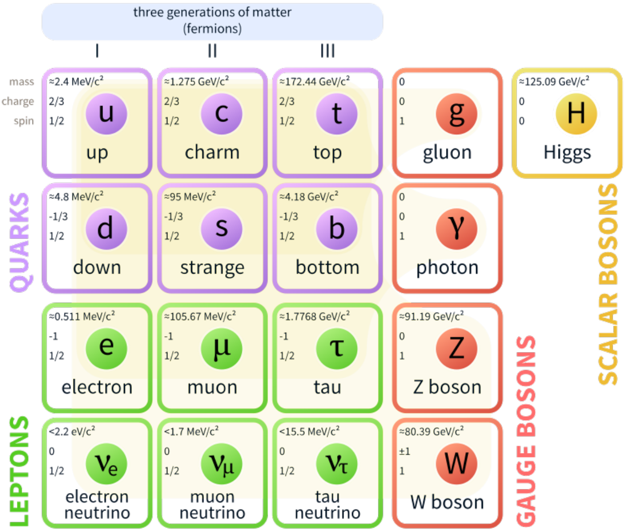
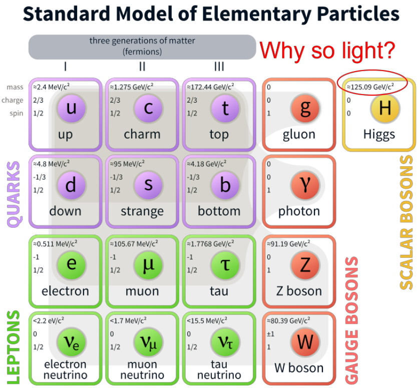
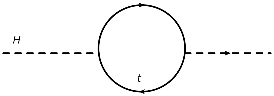
Standard Model of Elementary Particles



Hierarchy problem



- Higgs mass is a relevant operator quadratically sensitive to the UV physics



- Hiearachy problem, need some mechanism to protect Higgs mass.

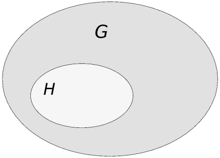
Symmetry to protect the Higgs mass

What if there is a symmetry which forbids $m^2 H^2$ of the lagrangian, i.e. is the system invariant under larger symmetry in the limit $m^2 \to 0$?

- In supersymmetry the Higgs mass is related to the fermion superpartner mass$\Rightarrow$ chiral symmetry protection.
- In Composite Higgs models Higgs boson is a Goldstone boson $\Rightarrow$shift symmetry protects the Higgs mass.

Higgs as a PNGB(Georgi-Kaplan)

- Composite sector is invariant under the global group G, which is broken spontaneously to its subgroup H, as a result we have Goldstone bosons along G/H generators



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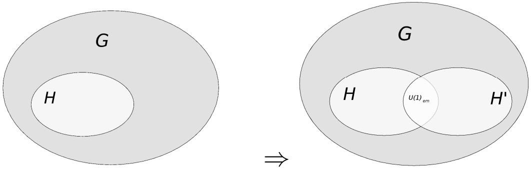

however the gauged subgroup H' which contains SM interactions is misaligned with the subgroup H. The misalignment between subgroups H and H' breaks $G \to U(1)_{em}$.

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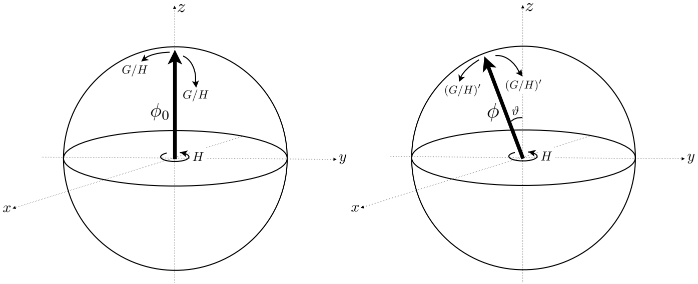

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Restrictions on the Coset, MCHM

- PNGB boson multiplet should contain the Higgs boson $SU(2)_L$ doublet and the unbroken coset must contain the SM gauge group

$$SU(2)_L \times U(1)_Y \in \mathcal{H}$$

- Symmetry breaking better respect the custodial symmetry in order to pass the constraints from the EW precision tests ($\Delta\rho$)

$$SU(2)_L \times SU(2)_R \in \mathcal{H}$$

- the minimal coset is (**MCHM**)

$$SO(5)/SO(4) \qquad SO(4) = \frac{SU(2)_L \times SU(2)_R}{Z_2}$$

We have exactly four PNGB corresponding to the components of the one complex $SU(2)$ doublet

First tuning

- We need some explicit breaking of the Goldstone symmetry to generate the Higgs potential.
- The Goldstone boson symmetry fixes the potential of the Higgs boson to have the following form:

$$V \sim A \sin^2 \frac{h}{f} + B \sin^4 \frac{h}{f} + ...$$

- The natural value of the Higgs vev is $\boxed{< h > \sim f}$
- At the same time no resonances still discovered at LHC around $4\pi f$ $\sim$TeV

Higgs interactions

- The most generic lagrangian for the PNGB in the case of a nonlinearly realized symmetry breaking can be constructed using the CCWZ formalism

$$U(\Pi) = e^{i\Pi/f}, \quad \Pi = \Pi^{\hat{a}} T^{\hat{a}}$$

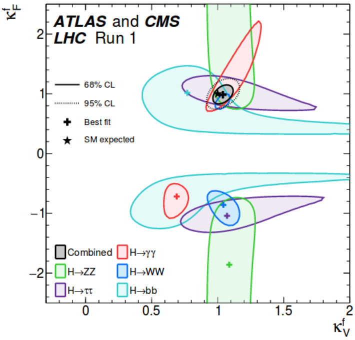
- The kinetic terms for the Goldstone boson Higgs will fix its interactions with the gauge bosons

$$\frac{f^2}{4} Tr(D_\mu U)^\dagger D^\mu U = \frac{1}{2}(\partial_\mu h)^2 + \frac{f^2}{4}\left(g^2 W_\mu^+ W_\mu^- + \frac{g^2}{2c_W^2} Z_\mu^2\right) \sin^2\left(\theta + \frac{h}{f}\right)$$

the ratio $\boxed{\dfrac{g_{hvv}^{\text{Composite Higgs}}}{g_{hvv}^{SM}} = cos(\theta) = \sqrt{1 - \dfrac{v_{SM}^2}{f^2}} = \sqrt{1-\xi}}$

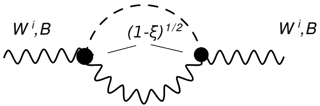
Bounds from Higgs couplings

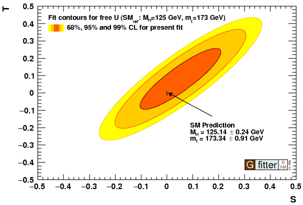
- Higgs couplings EW gauge bosons are modified
- These modifications can be tested at LHC, hWW, hZZ couplings (k_V) parameter



$$k_v \in [0.9, 1.15] \Rightarrow f \gtrsim 550\,GeV$$

Bounds on Higgs couplings from EW precision





$$S_{IR} = \frac{1}{12\pi}\left[\log\frac{m_h^2}{m_Z^2} + (1-k_v^2)\log\frac{\Lambda^2}{m_h^2}\right]$$

$$T_{IR} = \frac{-3}{16\pi\cos^2\theta_W}\left[\log\frac{m_h^2}{m_Z^2} + (1-k_v^2)\log\frac{\Lambda^2}{m_h^2}\right]$$

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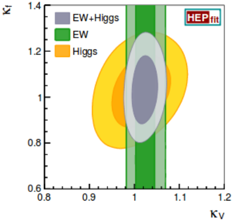

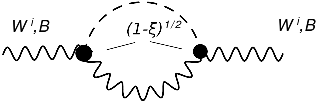

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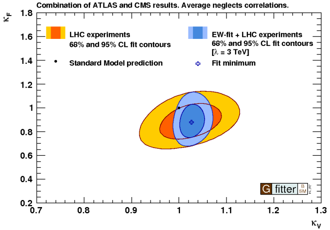
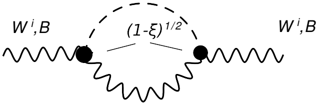
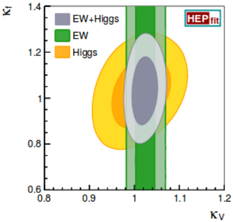
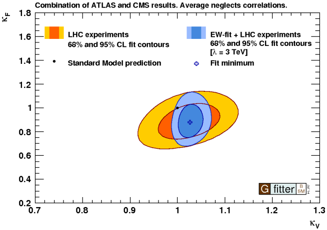


$k_V \in [0.98, 1.13]$ at 95% $\Rightarrow f \gtrsim 1.2$ TeV

Bounds on Higgs couplings from EW precision







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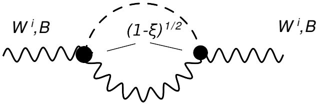
There is unavoidable tuning $\sim \frac{v^2}{f^2} \sim 0.04$

Bounds on Higgs couplings from EW precision



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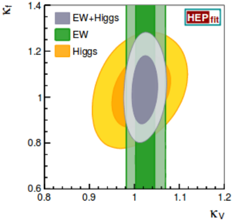
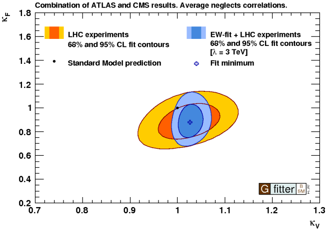




$k_V \in [0.98, 1.13]$ at 95% $\Rightarrow f \gtrsim 1.2$ TeV

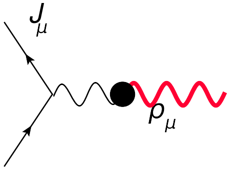
There is unavoidable tuning $\sim \frac{v^2}{f^2} \sim 0.04$

Up to possible cancellations reducing the strength of the EW constraints.

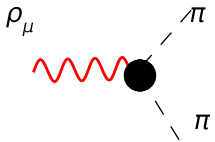
Vector-like resonances

- By analogy with QCD we expect to have new composite vector-like resonances ρ, which appear as multiplets of the unbroken subgroup, i.e. singlet , triplets of $SU(2)_L, SU(2)_R$ etc.
- ρ couplings to SM fields, **model independent couplings**

$$\mathcal{L} \sim -\frac{1}{g_\rho^2}\rho_{\mu\nu}\rho^{\mu\nu} + \frac{m_\rho^2}{2g_\rho^2}\left(\hat{\rho}_\mu - iU^\dagger D_\mu U\right)^2$$



$\sim \frac{g^2}{g_\rho}$



$\sim \frac{m_\rho^2 E}{g_\rho f^2}$

S parameter from vector resonances

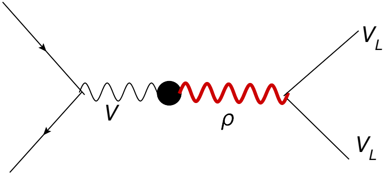
- Virtual ρ exchange will contribute to the EW precision parameters

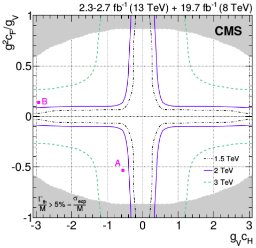
$\Rightarrow$

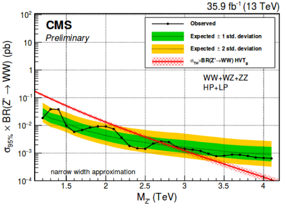
$$\Delta S \sim \frac{4\pi v}{m_\rho^2}, \quad m_\rho \gtrsim 2\,TeV$$

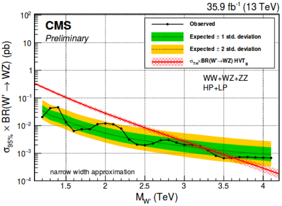
for the full calculation including the loops of the heavy resonances *1511.00592,1511.08235*

Bounds on vector bosons.





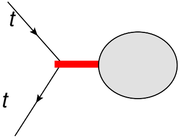




The bounds are strong for the not so large values of $g_\rho \lesssim 3$

Fermion masses: bilinears like in technicolor *Dimopoulos, Susskind 79*

- Usual technicolor generation of the fermion masses



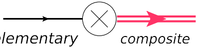
$$\frac{\lambda_t}{\Lambda_{UV}^{d-1}} \bar{q}_L O_s t_R \Rightarrow$$

$$m_t \sim \left(\frac{m_*}{\Lambda_{UV}}\right)^{d-1} \lambda_t v \Rightarrow$$

- $\Lambda_{UV} \gtrsim 10\, TeV$ for $d = 3$,**problematic for flavor physics**
- Constraints are partially evaded in the walking, conformal models $d \to 1$ (*Luty,Okui*). $d \to 1$ under pressure by bootstrap methods which relate the anomalous dimension of the fermions mass operator to the Higgs mass operator *(Rattazzi,Rychkov, Tonni, Vichi)*
- Use bilinears only for the light quarks (*Pomarol,Panico)*

Fermions: Partial compositeness *(Kaplan)*

- SM fermions mix only linearly with composite fermions



$$\Delta\mathcal{L} = \frac{\lambda_{t_L}}{\Lambda_{uv}^{d_L-5/2}}\bar{q}_L O^L + \frac{\lambda_{t_R}}{\Lambda_{UV}^{d_R-5/2}} t_R O_R$$

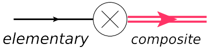
- At the TeV scale

$$\lambda_{t_L} \sim \lambda_{t_L}(\Lambda_{UV})\left(\frac{m_*}{\Lambda_{UV}}\right)^{d_L-5/2} \quad \lambda_{t_R} \sim \lambda_{t_R}(\Lambda_{UV})\left(\frac{m_*}{\Lambda_{UV}}\right)^{d_L-5/2}$$

- No problem with top mass generation, since we can have fermionic operators with the anomalous dimension $\sim 5/2$ without spoiling the Higgs mass hierarchy problem.

Fermions: Partial compositeness & 5D dual models

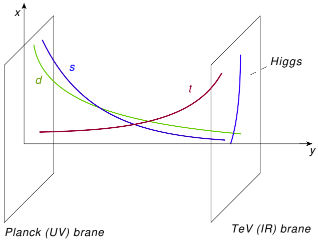
SM fermions mix only linearly with composite fermions



$$s_{L,R} \sim \left(\frac{\Lambda}{\Lambda_{UV}}\right)^{d_{L,R}-5/2},$$

$$m \sim \left(\frac{\Lambda}{\Lambda_{UV}}\right)^{d_L+d_R-5}$$

5D-Randall-Sundrum picture

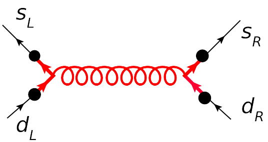


$$s_{L,R} \Leftrightarrow f(\text{IR brane})$$

Elementary-Composite mixing corresponds to the wave-function at the IR brane.

Flavor violation in partial compositeness/color octet vectors

- Models based on the partial compositeness necessary contain color octet vector resonance -ρ- composite/KK gluon
- Flavor bounds are strong $M_{KK} \gtrsim 15$ TeV *(Csaki et al;Agashe et al...)*



- Looks hopeless for the LHC, however with some "mild tuning" the bound can be relaxed.

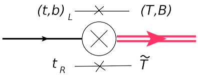
Higgs potential from top quark loops

- Top coupling to the strong sector explicitly breaks the shift symmetry ⇒.
- The V_{CW} will be generated for the Higgs field leading to the spontaneous symmetry breaking and the Higgs mass.
- These contributions are calculable in the extra-dimensional models as well as the effective theories based on the symmetries of the action.
- We can relate the Higgs mass to the masses of the composite resonances.

MCHM 5 model

- Minimal model based on the $SO(5)/SO(4)$ coset where composite fermions appear as a multiplet of **5**
- SM mass generation

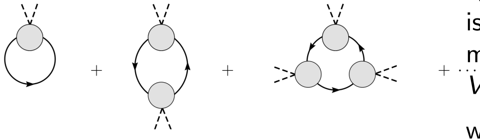
$$\mathbf{5}: \quad \mathcal{Q} = \frac{1}{\sqrt{2}} \begin{pmatrix} T_{2/3} & X_{5/3} \\ B_{-1/3} & X_{2/3} \end{pmatrix} \oplus \tilde{\mathbf{T}}_{\mathbf{2/3}}$$



$$\Delta\mathcal{L} = \lambda_L^t \bar{q}_L P_q U(\pi)\mathcal{Q} + \lambda_R^T \bar{t}_R P_t U(\pi)\mathcal{Q} + M_1 \bar{\mathcal{Q}}_1 \mathcal{Q}_1 + M_4 \bar{\mathcal{Q}}_4 \mathcal{Q}_4$$

$$m_t \sim \frac{\lambda_L^t \lambda_R^t v}{f M_*}$$

Higgs potential



Quadratic divergence of the top quark loop is cut at the scale of the top partner masses,

$V(h) = \alpha \sin^2 \frac{h}{f} + \beta \sin^4 \frac{h}{f}$

where $\alpha \sim \frac{3\lambda_{L,R}^2 M_*^2}{16\pi^2}$, $\beta \sim \frac{3\lambda^4}{16\pi^2}$

- We need to tune $\alpha \ll \beta$ to be small, otherwise $< h > \sim f$, additional tuning compared to the $\frac{v^2}{f^2}$
- $m_H^2 \sim \frac{\beta}{f^2} \sin^2 \frac{h}{f} \sim \frac{m_t^2 M_*^2}{16\pi^2 f^2}$

Light Higgs prefers light top parnters

Light top partners for light Higgs

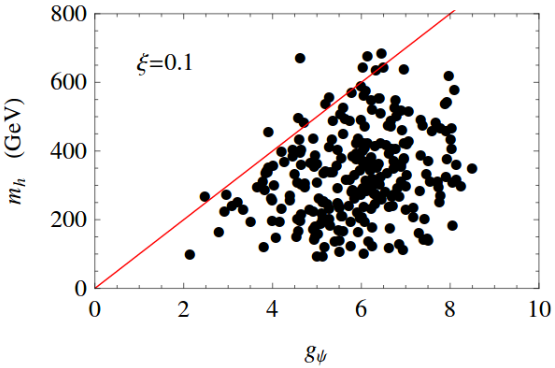
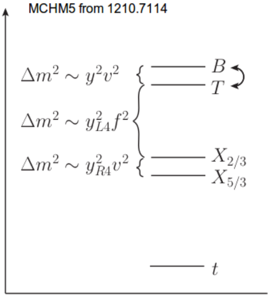


Figure : $g_\psi \equiv \frac{M_*}{f}$, from *Panico,Redi,Tesi,Wulzer 1210.7114*

Fermion spectrum

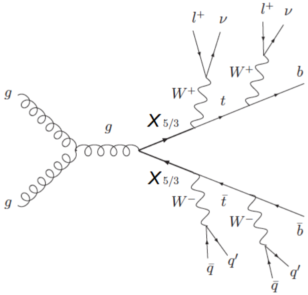
- We need light composite fermions in order to have Higgs light.
- This fields are charged under QCD, can be produced in strong interactions at LHC.
- Composite resonances should come as the multiplets of the unbroken subgroup SO(4).
- The lightest component of the multiplet is the state which does not mix with the SM fields. In the case of the model based on the 5-plet -$X_{5/3}$ field.

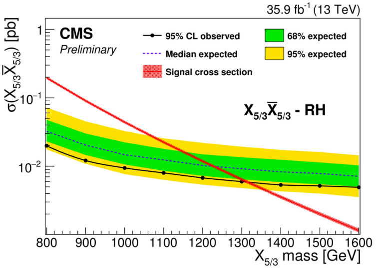


Bounds on 5/3 field

- top parners are charged under QCD SU(3)
- are pair produced

$$pp \to XX, \quad X \to tW$$



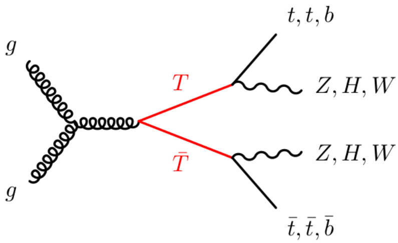


$m_{5/3} \gtrsim 1.3$ **TeV**

Bounds on 2/3 field

- top parners are charged under QCD SU(3)
- are pair produced

$$pp \to TT, \quad T \to tZ, tH, bW$$



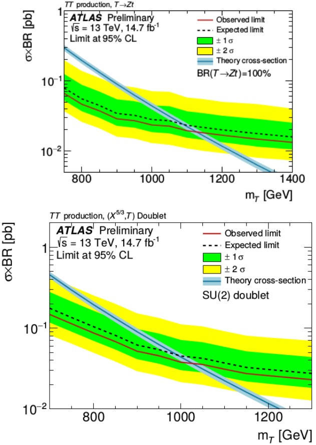
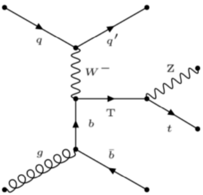


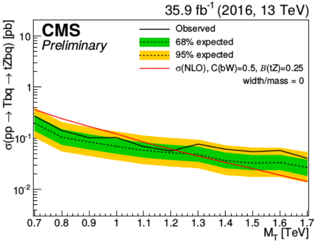
Figure : *ATLAS-CONF-2016-101*

$$m_{5/3} \gtrsim 1.1\, TeV$$

Single top partner production

Composite fermions mix strongly with the third generation quarks.

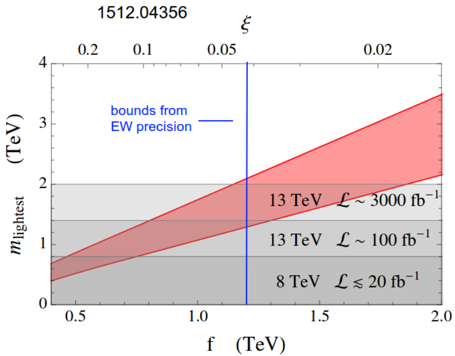




$m_T \gtrsim 1.2$ **TeV**

Bounds on the compositeness

- So far the bounds from the Higgs couplings/EWPT are stronger than direct searches
- Direct searches will become competitive at HL-LHC
- Tuning becomes worse with higher masses of the composite resonance

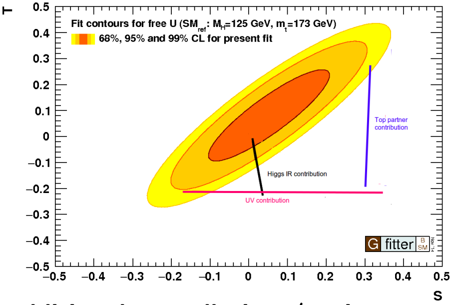


Are there ways to relax the constraints on the compositeness ?

Evading the constraints on the Higgs couplings

- LHC constraints on k_V are still weak, the main constraint comes from the EWPT
- Corrections to the S,T observables from the modified Higgs couplings can be compensated by UV contributions or the top/top partner loops

1306.4655,1308.2676 .



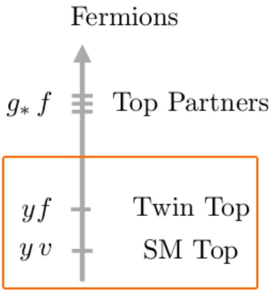
of course we have to pay price of additional cancellations/tuning...

Evading the bounds on top partners/Twin Higgs models

(Chacko,Harnik, Goh 05)

- LHC bounds can be evaded if the top partners are color neutral
- There is an elementary twin sector related by Z_2 parity .
- Z_2 and the Goldstone symmetry suppress the contribution of the composite resonances to the Higgs mass *1411.2974 ,1411.3310 ,1501.05310 ,1501.07803,1501.07890...*

1501.07803



$$\delta m_h^2|_{IR}^{1-loop} \simeq \frac{3y_t^4}{8\pi^2} v^2 \left(\log \frac{m_*^2}{m_t^2} + \log \frac{m_*^2}{\tilde{m}_t^2} \right)$$

from *1501.07803*

Low energy constraints on Twin Higgs

- Flavor bounds as bad as in CH scenario $M_* \gtrsim 20 - 30$ TeV, $f \gtrsim 2 - 3$ TeV *1512.03427*
- In order to satisfy EW precision we need to rely on the cancellations between IR and, top-top partner and UV contributions *1702.00797*, we need $\xi \lesssim$ few % to avoid tuning $\Rightarrow f \gtrsim 1.5$ TeV...
- **improvement compared to CH not so strong, however can make new physics undiscoverable at LHC.**

CH and B physics anomalies

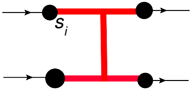
$$R_K = \frac{\Gamma(B \to K\mu^+\mu^-)}{\Gamma(B \to Ke^+e^-)}$$

$$\Delta C_9^\mu \sim \Delta C_{10}^\mu = -0.64$$

$$O_9^l = (\bar{s}\gamma_\mu P_L b)(l\gamma^\mu l)$$

$$O_{10}^l = (\bar{s}\gamma_\mu P_L b)(l\gamma^\mu \gamma_5 l)$$

- Attempts to explain these anomalies in CH 1412.1791,1503.03865,1608.02362
- four fermion operators are generated by the exchange of the composite resonances.



$$C_{9,10} \propto \frac{g_*^2}{M^2} s_b s_s s_\mu^2 \sim -0.24 (s_b^L)^2 \left(\frac{g_\rho}{4\pi}\right)^2 \times \left(\frac{(s_\mu^l)^2 4\pi v}{m_\mu}\right) \times \left(\frac{TeV}{m_*}\right)^2$$

- other low energy (for example ϵ_K) constraints can be satisfied either by some extra tuning
- tuning can be partially reduced by considering more complicated coset $\frac{SO(9)\times SO(5)}{SU(4)\times SU(2)_\Pi \times SU(2)\times SU(2)}$, where four fermion operators are generated by the PGB leptoquarks 1412.1791

Summary

- Composite Higgs models present an interesting solution to the hierarchy problem
- Lead to interesting phenomenology at LHC
- Partial explanation of the origin of flavor.
- Both low energy experiments and LHC are strongly constraining the allowed parameter space of the models, Twin Higgs a possibility to avoid some of them.
- Topics not discussed but which are an active field of research:
  - Non-minimal cosets, we have other Goldstone bosons, possible DM candidates...
  - Use of lattice data to understand better the dynamics behind the CH models.
  - ⋮