Composite Leptoquarks and Anomalies in B-meson Decays

Marco Nardecchia

DAMTP and Cavendish Laboratory,
University of Cambridge

9 April 2015, Portorož

Outline

- (No) Introduction
- EW Naturalness & Anomalies
- Composite Leptoquarks
- Conclusions

(No) introduction

- See talks by A. Crivellin, R. Zwicky, S. Jaeger, W. Altmannshofer, G. Hiller, A. Vicente,… and references therein

- Anomalies

1) Tensions in the LHCb data coming from $B \to K^* \mu^+ \mu^-$

2) Hint of violation of lepton universality in R_K

(No) introduction

- See talks by A. Crivellin, R. Zwicky, S. Jaeger, W. Altmannshofer, G. Hiller, A. Vicente,… and references therein

- Anomalies

1) Tensions in the LHCb data coming from $B \to K^* \mu^+ \mu^-$

2) Hint of violation of lepton universality in R_K

- A possible solution (SM)….

Long distance QCD

Statistical fluctuation

(No) introduction

- See talks by A. Crivellin, R. Zwicky, S. Jaeger, W. Altmannshofer, G. Hiller, A. Vicente,… and references therein

- Anomalies

1) Tensions in the LHCb data coming from $B \to K^* \mu^+ \mu^-$

2) Hint of violation of lepton universality in R_K

- A possible solution (SM)….

Long distance QCD

Statistical fluctuation

- If New Physics

1) Simple and economic interpretation at the EFT level, NP in the muon sector

2) Quite large effects in C_9^μ, C_{10}^μ

(No) introduction

- See talks by A. Crivellin, R. Zwicky, S. Jaeger, W. Altmannshofer, G. Hiller, A. Vicente,… and references therein

- Anomalies

1) Tensions in the LHCb data coming from $B \to K^* \mu^+ \mu^-$

2) Hint of violation of lepton universality in R_K

- A possible solution (SM)….

Long distance QCD

Statistical fluctuation

- If New Physics

1) Simple and economic interpretation at the EFT level, NP in the muon sector

2) Quite large effects in C_9^μ, C_{10}^μ

- New Physics at the LHC motived by Naturalness problem of the EW scale

(No) introduction

- See talks by A. Crivellin, R. Zwicky, S. Jaeger, W. Altmannshofer, G. Hiller, A. Vicente,… and references therein

- Anomalies

1) Tensions in the LHCb data coming from $B \to K^* \mu^+ \mu^-$

2) Hint of violation of lepton universality in R_K

- A possible solution (SM)….

Long distance QCD

Statistical fluctuation

- If New Physics

1) Simple and economic interpretation at the EFT level, NP in the muon sector

2) Quite large effects in C_9^μ, C_{10}^μ

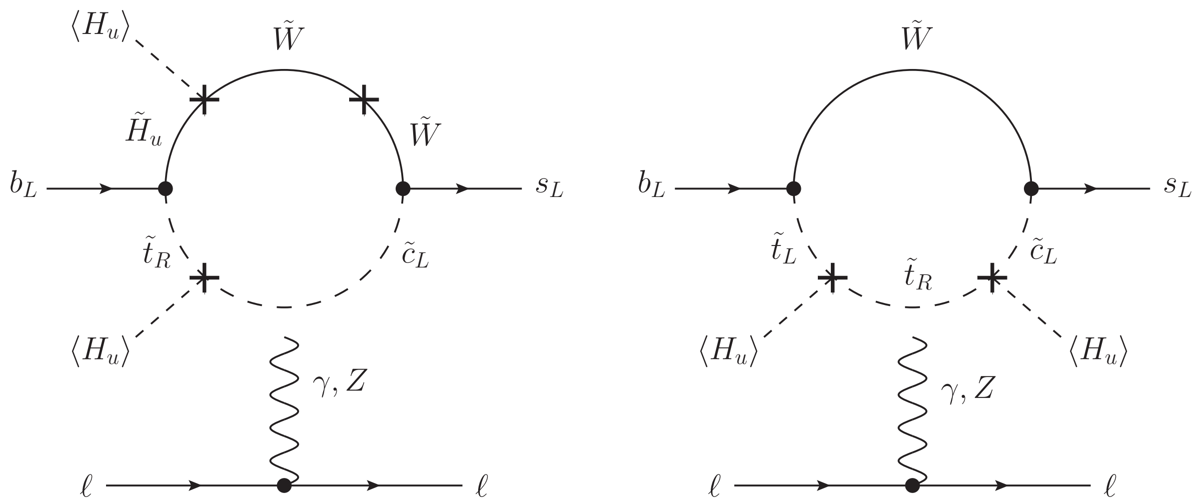
- New Physics at the LHC motived by Naturalness problem of the EW scale

Which is the interpretation of these anomalies in the context of SUSY and Composite Higgs?

MSSM

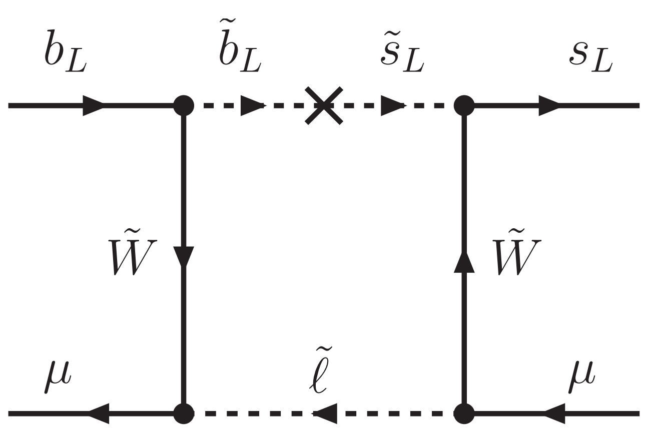
Altmannshofer, Straub
arXiv:1308.1501, arXiv:1411.3161

- $B \to K^* \mu^+ \mu^-$



- Large effects possible in C_{10}^Z
- Better than SM but worse than NP in C_9^μ
- Lepton universal

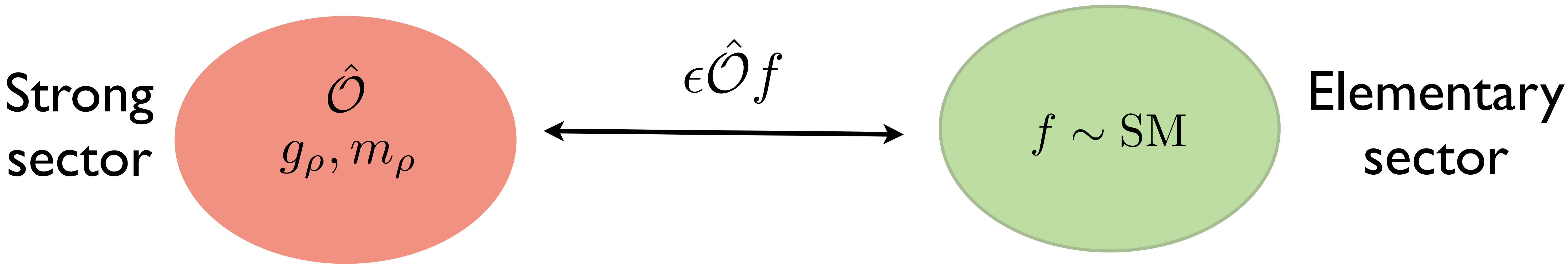
- R_K



- Lepton universality is broken by slepton masses $m_{\tilde{e}} \gg m_{\tilde{\mu}}$
- Box diagrams are numerically small, very light particles in the loop
- Direct searches (LHC+LEP) give strong constraints, probably no holes left (but a careful analysis is required)

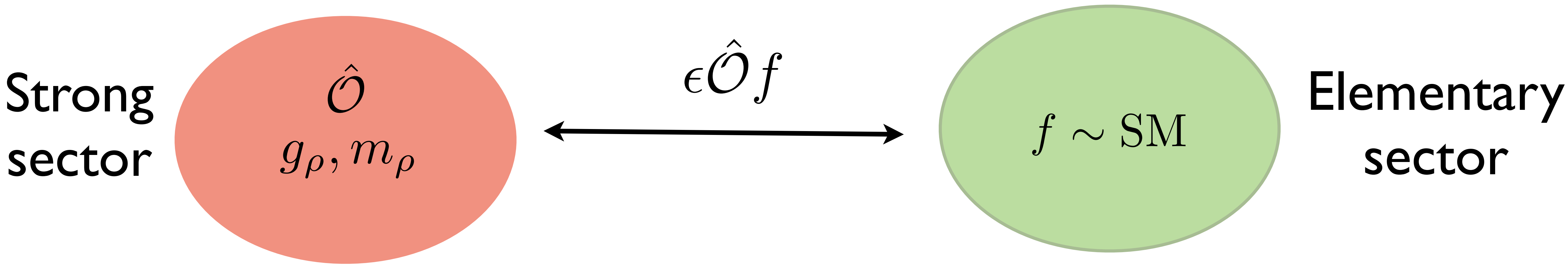
The LHCb results suggest an extensions of the MSSM

Composite Higgs

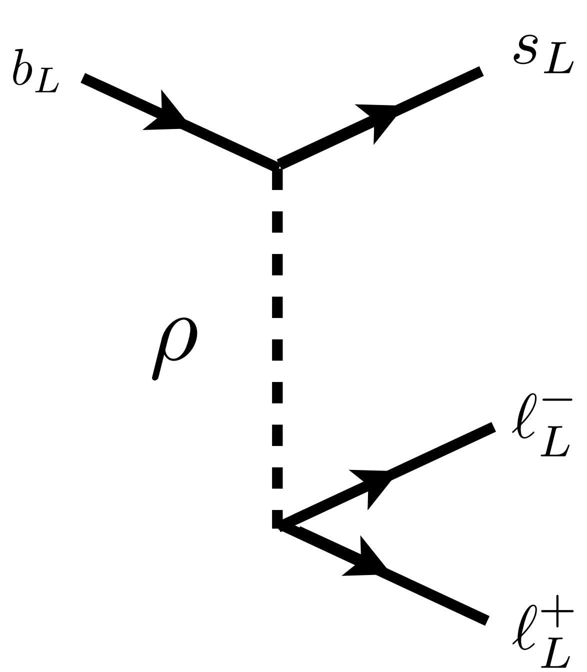


- The Higgs is a pseudo Goldstone boson

Composite Higgs

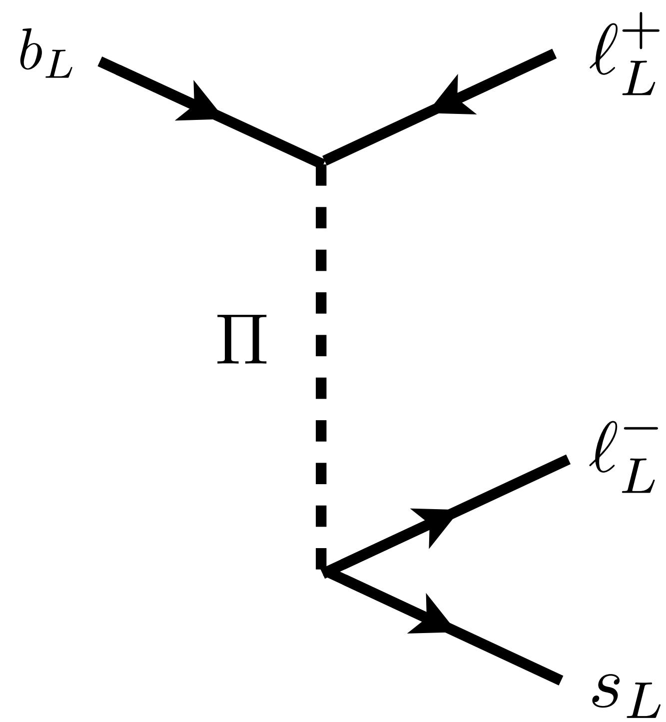


- The Higgs is a pseudo Goldstone boson
- Possible contributions to semileptonic B decays



- Spin-1 Vector exchange

Niehoff, Stangl, Straub
1503.03865

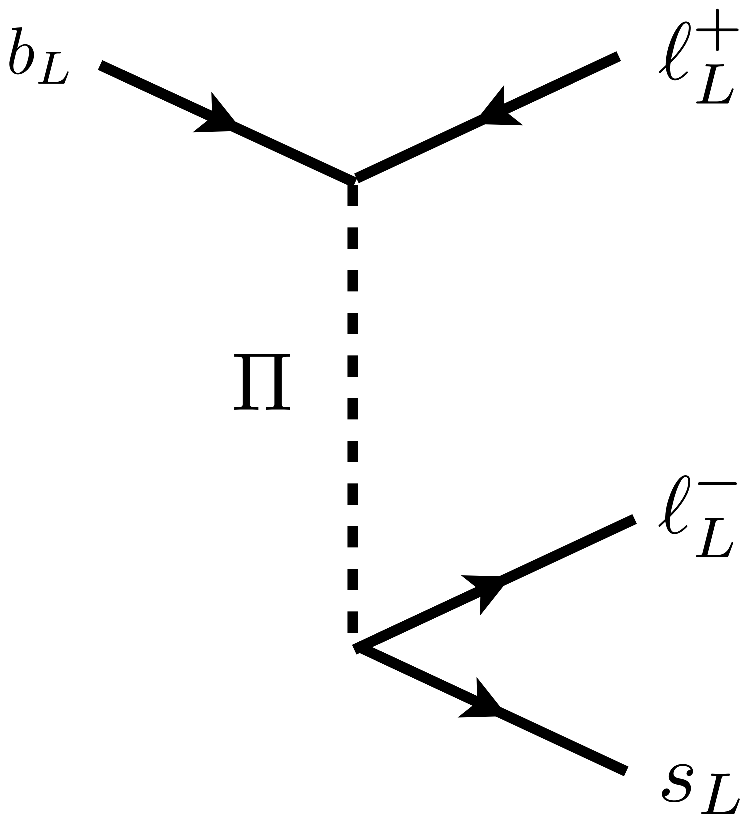


- Scalar leptoquark

Based on 1412.5942, JHEP,
Ben Gripaios and Sophie Renner

Leptoquarks

- A leptoquark interpretation Hiller, Schmaltz 1408.1627



- Quantum number of the new states, uniquely determined by the the Left-Left structure

$$\Pi \sim (\overline{\mathbf{3}}, \mathbf{3}, 1/3)$$

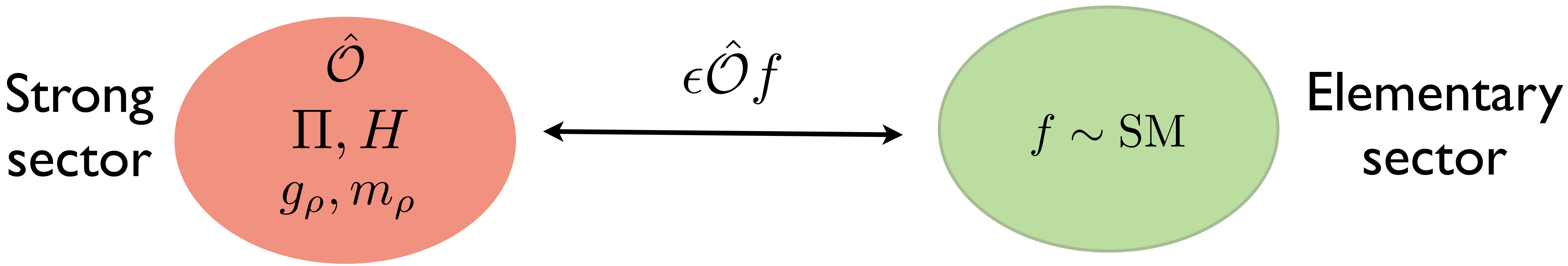
$$\lambda_{ij}\, \overline{q}^c_{Lj} i\tau_2 \tau_a \ell_{Li}\, \Pi$$

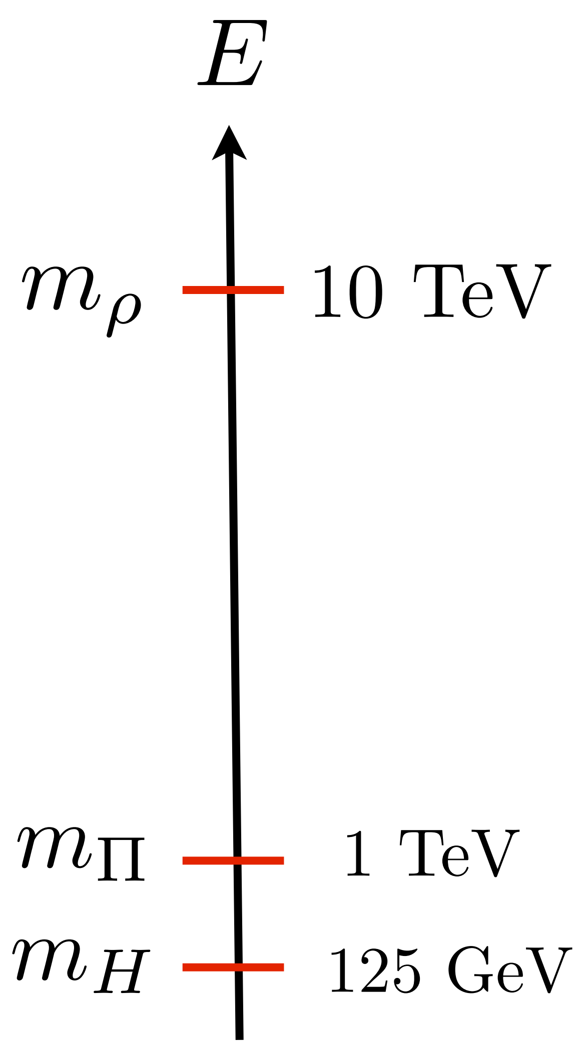
- Anomalies are fitted when $\sqrt{|\lambda^*_{s\mu}\lambda_{b\mu}|} \simeq M/(48\,\mathrm{TeV})$

- Just two, non-vanishing leptoquark coupling

- Scale of New Physics not predicted

Theoretical Framework





- Being PGB, Higgs and Leptoquarks are lighter than the other resonances coming from the strong sector

- SM fermion masses are generated by the mechanism of partial compositeness

$$|SM\rangle = \cos\epsilon |f\rangle + \sin\epsilon |\mathcal{O}\rangle$$

- BSM Flavour violation regulated by the same mechanism

- Naturalness (…)

Leptoquarks as PNGB

- Partial compositeness requires the presence of coloured composite state, plausible to expect coloured PNGB Gripaios 0910.1789

- Depending on the quantum numbers of the PNGB, diquark and leptoquark couplings are expected Gripaios, Giudice, Sundrum 1105.3189

- Colour gauge group can be part of the symmetries of the strong sector (in analogously to the EW group)

- Coset structure $(\mathbf{1},\mathbf{2},1/2)+(\overline{\mathbf{3}},\mathbf{3},1/3)+(\mathbf{3},\mathbf{3},-1/3)$

$$SO(5)\to SU(2)_H\times SU(2)_R \qquad H\sim(\mathbf{2},\mathbf{2})$$

$$SO(9)\to SU(4)\times SU(2)_\Pi \qquad (\Pi+\Pi^\dagger)\sim(\mathbf{6},\mathbf{3})$$

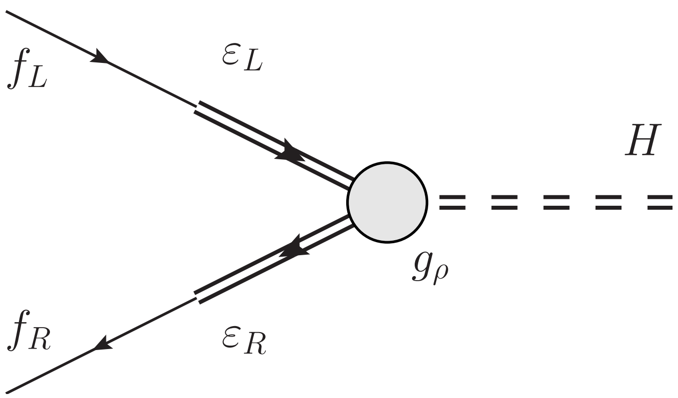
- SM embedding

$$\begin{array}{rcl} SU(3)_C\times U(1)_\psi & \supset & SU(4) \\ SU(2)_L & = & (SU(2)_H\times SU(2)_\Pi)_D \\ T_Y & = & -\frac{1}{2}T_\psi+T_{3R} \end{array}$$

- Mass term generated by the colour gauge interactions $m_\Pi^2\sim\dfrac{\alpha_s}{4\pi}m_\rho^2$

Partial Compositeness in CH models

- Yukawa sector:



$$\mathcal{L}_{\rm elem} = i\overline{f}\gamma^\mu D_\mu f$$

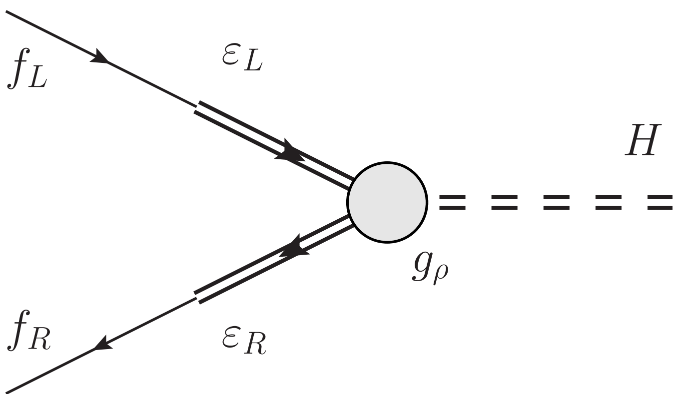
$$\mathcal{L}_{\rm comp} = \mathcal{L}_{\rm comp}(g_\rho, m_\rho, H)$$

$$\mathcal{L}_{\rm mix} = \epsilon_L\, f_L \mathcal{O}_L + \epsilon_L\, f_R \mathcal{O}_R + h.c.$$

$$Y^{ij} = c_{ij}\, \epsilon_L^i \epsilon_R^j\, g_\rho \longrightarrow Y^{ij} \sim \epsilon_L^i \epsilon_R^j g_\rho$$

Partial Compositeness in CH models

- Yukawa sector:



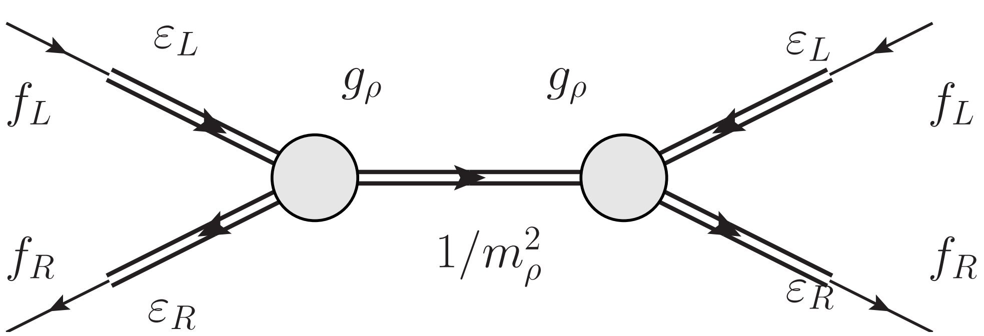
$$\mathcal{L}_{\rm elem} = i\bar{f}\gamma^\mu D_\mu f$$

$$\mathcal{L}_{\rm comp} = \mathcal{L}_{\rm comp}(g_\rho, m_\rho, H)$$

$$\mathcal{L}_{\rm mix} = \epsilon_L\, f_L \mathcal{O}_L + \epsilon_L\, f_R \mathcal{O}_R + h.c.$$

$$Y^{ij} = c_{ij}\, \epsilon_L^i \epsilon_R^j\, g_\rho \longrightarrow Y^{ij} \sim \epsilon_L^i \epsilon_R^j g_\rho$$

- Flavor violation beyond the CKM one is generated:

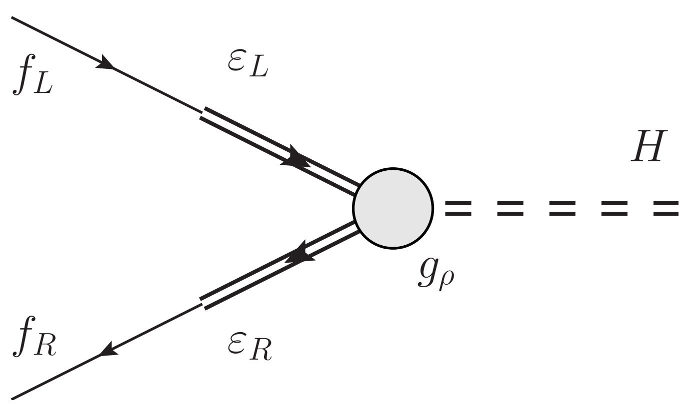


$$\sim \frac{g_\rho^2}{m_\rho^2}\epsilon_L^i \epsilon_R^i \epsilon_L^j \epsilon_R^j$$

FV related to the SM one but not in a Minimal FV way

Partial Compositeness in CH models

- Yukawa sector:



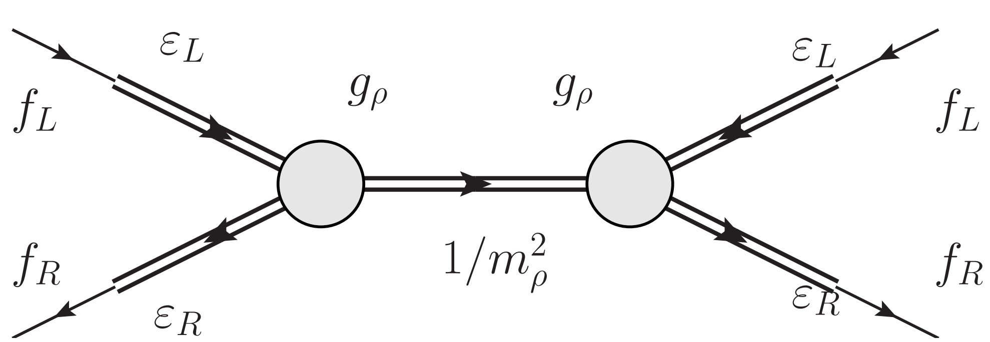
$$\mathcal{L}_{\text{elem}} = i\overline{f}\gamma^\mu D_\mu f$$

$$\mathcal{L}_{\text{comp}} = \mathcal{L}_{\text{comp}}(g_\rho, m_\rho, H)$$

$$\mathcal{L}_{\text{mix}} = \epsilon_L \, f_L \mathcal{O}_L + \epsilon_L \, f_R \mathcal{O}_R + h.c.$$

$$Y^{ij} = c_{ij} \, \epsilon_L^i \epsilon_R^j \, g_\rho \longrightarrow Y^{ij} \sim \epsilon_L^i \epsilon_R^j g_\rho$$

- Flavor violation beyond the CKM one is generated:



$$\sim \frac{g_\rho^2}{m_\rho^2} \epsilon_L^i \epsilon_R^i \epsilon_L^j \epsilon_R^j$$

FV related to the SM one but not in a Minimal FV way

- Focus on Leptoquark resonance

Mixing parameters

- Mixing parameters are related to values of fermion masses and mixing

$$(Y_u)_{ij} \sim g_\rho \epsilon_i^q \epsilon_j^u \qquad (Y_d)_{ij} \sim g_\rho \epsilon_i^q \epsilon_j^d \qquad (Y_e)_{ij} \sim g_\rho \epsilon_i^\ell \epsilon_j^e,$$

- In the quarks sector everything is fixed up to 2 parameters, (g_ρ, ϵ_3^q)

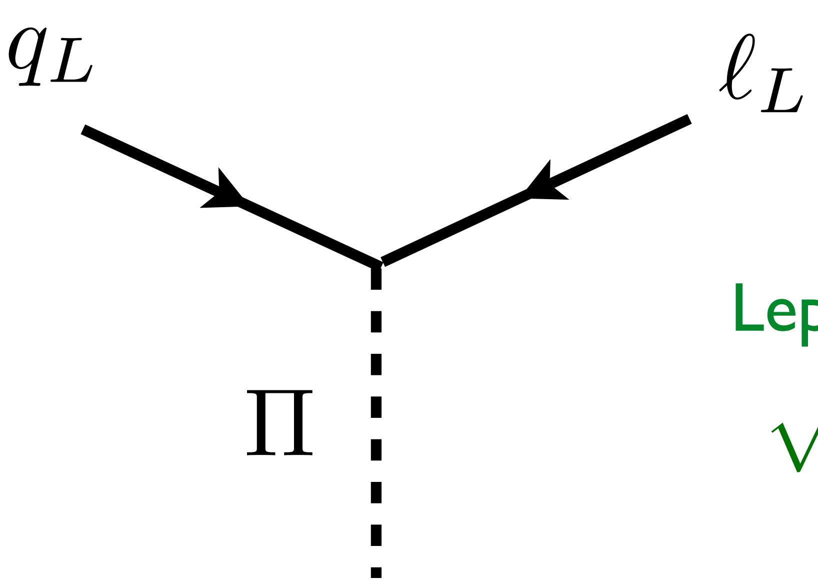
- In the lepton sector parameters cannot be univocally connected to physical inputs, due to our ignorance on neutrino masses, will assume that left and right mixing have similar size

Mixing Parameter	Value
$\epsilon_1^q = \lambda^3 \epsilon_3^q$	$1.15 \times 10^{-2}\, \epsilon_3^q$
$\epsilon_2^q = \lambda^2 \epsilon_3^q$	$5.11 \times 10^{-2}\, \epsilon_3^q$
$\epsilon_1^u = \frac{m_u}{v g_\rho} \frac{1}{\lambda^3 \epsilon_3^q}$	$5.48 \times 10^{-4}/(g_\rho \epsilon_3^q)$
$\epsilon_2^u = \frac{m_c}{v g_\rho} \frac{1}{\lambda^2 \epsilon_3^q}$	$5.96 \times 10^{-2}/(g_\rho \epsilon_3^q)$
$\epsilon_3^u = \frac{m_t}{v g_\rho} \frac{1}{\epsilon_3^q}$	$0.866/(g_\rho \epsilon_3^q)$
$\epsilon_1^d = \frac{m_d}{v g_\rho} \frac{1}{\lambda^3 \epsilon_3^q}$	$1.24 \times 10^{-3}/(g_\rho \epsilon_3^q)$
$\epsilon_2^d = \frac{m_s}{v g_\rho} \frac{1}{\lambda^2 \epsilon_3^q}$	$5.29 \times 10^{-3}/(g_\rho \epsilon_3^q)$
$\epsilon_3^d = \frac{m_b}{v g_\rho} \frac{1}{\epsilon_3^q}$	$1.40 \times 10^{-2}(g_\rho \epsilon_3^q)$
$\epsilon_1^\ell = \epsilon_1^e = \left(\frac{m_e}{g_\rho v}\right)^{1/2}$	$1.67 \times 10^{-3}/g_\rho^{1/2}$
$\epsilon_2^\ell = \epsilon_2^e = \left(\frac{m_\mu}{g_\rho v}\right)^{1/2}$	$2.43 \times 10^{-2}/g_\rho^{1/2}$
$\epsilon_3^\ell = \epsilon_3^e = \left(\frac{m_\tau}{g_\rho v}\right)^{1/2}$	$0.101/g_\rho^{1/2}$

Flavour Violation & Leptoquarks

- Comment later about the flavour physics associated with m_ρ
- Relevant Lagrangian

$$\mathcal{L} = \mathcal{L}_{SM} + (D^\mu \Pi)^\dagger D_\mu \Pi - M^2 \Pi^\dagger \Pi + \lambda_{ij}\, \overline{q}^c_{Lj} i\tau_2 \tau_a \ell_{Li}\, \Pi + \text{ h.c.}$$



Quarks →

Leptons $\sqrt{Y_\ell}$ ↓

$\lambda_{ij}/(c_{ij} g_\rho^{1/2} \epsilon_3^q)$	$j=1$	$j=2$	$j=3$
$i=1$	1.92×10^{-5}	8.53×10^{-5}	1.67×10^{-3}
$i=2$	2.80×10^{-4}	1.24×10^{-3}	2.43×10^{-2}
$i=3$	1.16×10^{-3}	5.16×10^{-3}	0.101

- c are O(1) parameters
- Only 3 fundamental parameters reduced to a single combination in all the flavour observable!

$$(g_\rho, \epsilon_3^q, M) \longrightarrow \sqrt{g_\rho}\epsilon_3^q/M$$

Fit to the anomalies

- The analysis of $b \to s\mu^+\mu^-$ observable gives

$$C_9^{NP\mu} = -C_{10}^{NP\mu} \in [-0.84, -0.12] \quad (\text{at } 2\sigma)$$

Altmannshofer, Straub 1411.3161

- In our framework gives

$$C_9^{\mu NP} = -C_{10}^{\mu NP} = \left[\frac{4G_F e^2 (V_{ts}^* V_{tb})}{16\sqrt{2}\pi^2}\right]^{-1} \frac{\lambda_{22}^* \lambda_{23}}{2M^2} = -0.49\, c_{22}^* c_{23} (\epsilon_3^q)^2 \left(\frac{M}{\text{TeV}}\right)^{-2} \left(\frac{g_\rho}{4\pi}\right)$$

$$\text{Re}(c_{22}^* c_{23}) \in [0.24, 1.71] \left(\frac{4\pi}{g_\rho}\right) \left(\frac{1}{\epsilon_3^q}\right)^2 \left(\frac{M}{\text{TeV}}\right)^2 \quad (\text{at } 2\sigma)$$

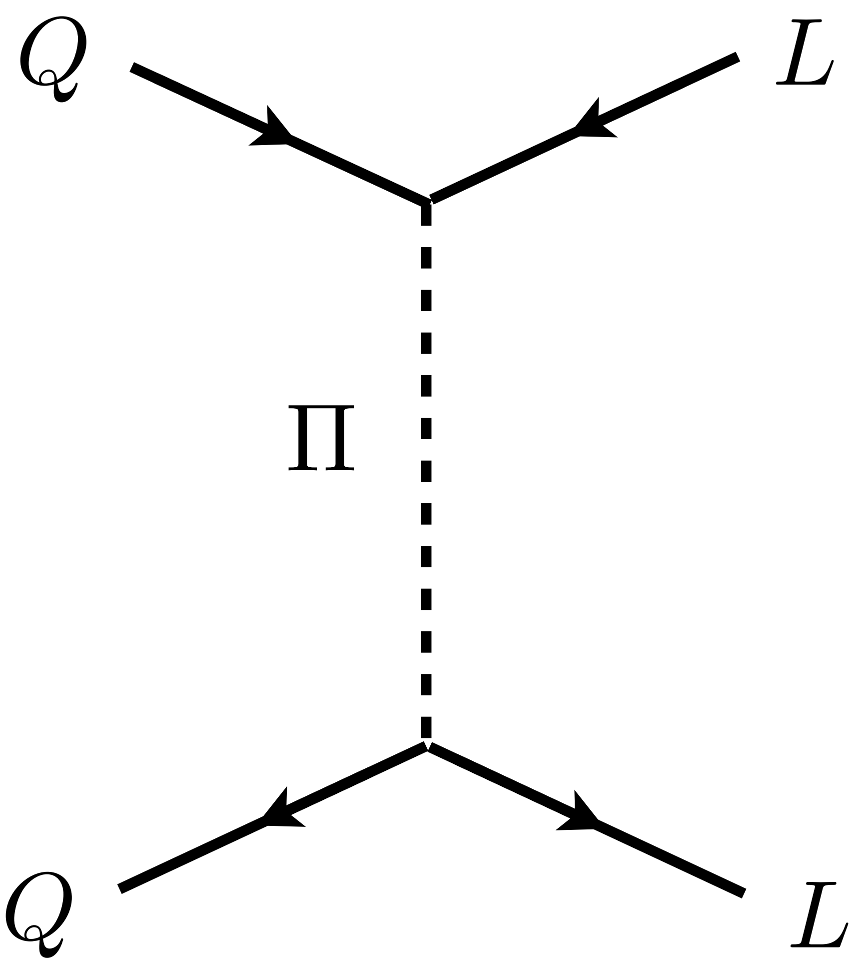
- Due to the partial compositeness structure, negligible contribution to observables involving electrons like $\text{BR}(B \to K e^+ e^-)$. R_K is easily accommodated.

- 3 immediate implications

1) the composite sector is genuinely strong interacting, $g_\rho \sim 4\pi$
2) that left-handed quark doublet should be largely composite, $\epsilon_3^q \sim 1$
3) the mass of the leptoquark states should be low, $M \lesssim 1$ TeV

Flavour violation at the tree level

- Integrating away the leptoquarks fields we get



$$\mathcal{L}_{LQ}^{eff} = \sum_{ij\ell k} \frac{\lambda_{ij}(\lambda_{\ell k})^*}{2M^2} \Big[2\left(\bar{d}_L\gamma^\mu d_L\right)_{kj}\left(\bar{e}_L\gamma_\mu e_L\right)_{\ell i} + 2\left(\bar{u}'_L\gamma^\mu u'_L\right)_{kj}\left(\bar{\nu}_L\gamma_\mu \nu_L\right)_{\ell i} + \left(\bar{d}_L\gamma^\mu d_L\right)_{kj}\left(\bar{\nu}_L\gamma_\mu \nu_L\right)_{\ell i} + \left(\bar{u}'_L\gamma^\mu u'_L\right)_{kj}\left(\bar{e}_L\gamma_\mu e_L\right)_{\ell i} + \left(\bar{u}'_L\gamma^\mu d_L\right)_{kj}\left(\bar{e}_L\gamma_\mu \nu_L\right)_{\ell i} + \left(\bar{d}_L\gamma^\mu u'_L\right)_{kj}\left(\bar{\nu}_L\gamma_\mu e_L\right)_{\ell i}\Big],$$

$$u_L'^j = V_{CKM}^{\dagger jk} u_L^k$$

- "Vertical" correlations induced by SM gauge invariance
- "Horizontal" correlations induced by partial compositeness

Predictions

- We expect large effects coming from third families of leptons

Lepton $\sqrt{Y_\ell}$ ↓

$\lambda_{ij}/(c_{ij} g_\rho^{1/2} \epsilon_3^q)$	$j=1$	$j=2$	$j=3$
$i=1$	1.92×10^{-5}	8.53×10^{-5}	1.67×10^{-3}
$i=2$	2.80×10^{-4}	1.24×10^{-3}	2.43×10^{-2}
$i=3$	1.16×10^{-3}	5.16×10^{-3}	0.101

- Decay channels with taus are difficult to be reconstructed $b \longrightarrow s\tau^+\tau^-$

- More interesting are channels with tau neutrinos in the final state

$$R_K^{*\nu\nu} \equiv \frac{\mathcal{B}(B \to K^* \nu\overline{\nu})}{\mathcal{B}(B \to K^* \nu\overline{\nu})_{SM}} < 3.7,$$

$$R_K^{\nu\nu} \equiv \frac{\mathcal{B}(B \to K \nu\overline{\nu})}{\mathcal{B}(B \to K \nu\overline{\nu})_{SM}} < 4.0.$$

Buras et al. arXiv:1409.4557

- Considering just $B \longrightarrow K^* \overline{\nu}_\mu \nu_\mu$ gives $\Delta R_K^{(*)\nu\nu} < \text{ few } \%$

- Including $\mathrm{BR}(B \longrightarrow K \nu_\tau \overline{\nu}_\tau)$, large deviation $\Delta R_K^{(*)\nu\nu} \sim 50\%$

Testable at Belle II

See 1002.5012

Predictions

- Rare Kaon decay

Hurt et al 0807.5039
NA62 1411.0109

$$\mathcal{B}(K^+ \to \pi^+ \nu\nu) = 8.6(9) \times 10^{-11}[1 + 0.96\delta C_{\nu\bar{\nu}} + 0.24(\delta C_{\nu\bar{\nu}})^2]$$

Present bound $\delta C_{\nu\bar{\nu}} \in [-6.3, 2.3]$ NA62 expected sensitivity $\delta C_{\nu\bar{\nu}} \in [-0.2, 0.2]$

Composite leptoquark prediction

$$\delta C_{\nu\bar{\nu}} = 0.62 \ \mathrm{Re}(c_{31} c_{32}^*) \left(\frac{g_\rho}{4\pi}\right) (\epsilon_3^q)^2 \left(\frac{M}{\mathrm{TeV}}\right)^{-2}$$

- Radiative decay $\mu \longrightarrow e\gamma$

$$|c_{23}^* c_{13}| < 1.4 \left(\frac{4\pi}{g_\rho}\right) \left(\frac{M}{\mathrm{TeV}}\right)^2 \left(\frac{1}{\epsilon_3^q}\right)^2$$

- Meson mixing ΔM_{B_s}

$$|c_{33} c_{23}^*| < 4.2 \left(\frac{4\pi}{g_\rho}\right)^2 \left(\frac{M}{\mathrm{TeV}}\right)^2 \left(\frac{1}{\epsilon_3^q}\right)^4$$

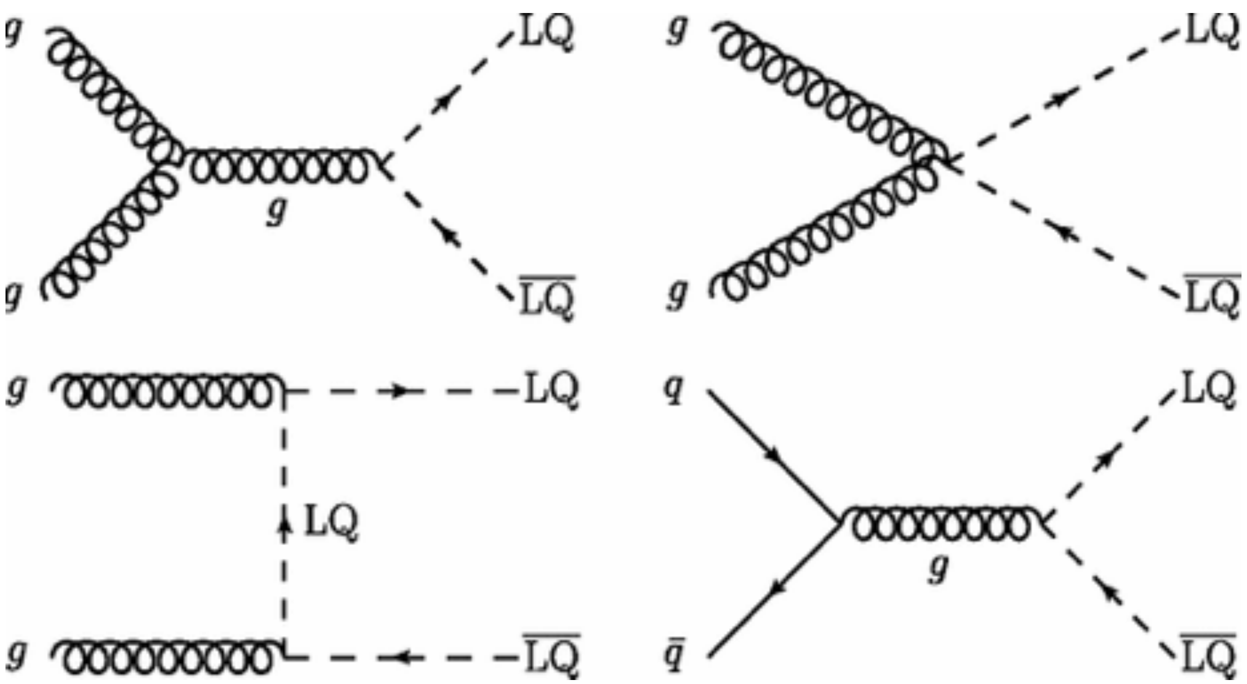
Constraints

Decay	(ij)(kl)*	$\lvert\lambda_{ij}\lambda^*_{kl}\rvert / \left(\frac{M}{\text{TeV}}\right)^2$	$\lvert c_{ij}c^*_{kl}\rvert \left(\frac{g_\rho}{4\pi}\right)(\epsilon_3^q)^2 / \left(\frac{M}{\text{TeV}}\right)^2$
$K_S \to e^+e^-$	$(12)(11)^*$	< 1.0	$< 4.9 \times 10^7$
$K_L \to e^+e^-$	$(12)(11)^*$	$< 2.7 \times 10^{-3}$	$< 1.3 \times 10^5$
$\dagger\ K_S \to \mu^+\mu^-$	$(22)(21)^*$	$< 5.1 \times 10^{-3}$	$< 1.2 \times 10^3$
$K_L \to \mu^+\mu^-$	$(22)(21)^*$	$< 3.6 \times 10^{-5}$	< 8.3
$K^+ \to \pi^+e^+e^-$	$(11)(12)^*$	$< 6.7 \times 10^{-4}$	$< 3.3 \times 10^4$
$K_L \to \pi^0e^+e^-$	$(11)(12)^*$	$< 1.6 \times 10^{-4}$	$< 7.8 \times 10^3$
$K^+ \to \pi^+\mu^+\mu^-$	$(21)(22)^*$	$< 5.3 \times 10^{-3}$	$< 1.2 \times 10^3$
$K_L \to \pi^0\nu\bar{\nu}$	$(31)(32)^*$	$< 3.2 \times 10^{-3}$	< 42.5
$\dagger\ B_d \to \mu^+\mu^-$	$(21)(23)^*$	$< 3.9 \times 10^{-3}$	< 46.0
$B_d \to \tau^+\tau^-$	$(31)(33)^*$	< 0.67	$< 4.6 \times 10^2$
$\dagger\ B^+ \to \pi^+e^+e^-$	$(11)(13)^*$	$< 2.8 \times 10^{-4}$	$< 6.9 \times 10^2$
$\dagger\ B^+ \to \pi^+\mu^+\mu^-$	$(21)(23)^*$	$< 2.3 \times 10^{-4}$	< 2.7

- With a breaking of lepton universality is generically associated a breaking of the lepton flavour. [Glashow, Guadagnoli, Lane, 1411.0565]

- In our framework, all the LFV decays are below the current experimental sensitivity

LHC



- Production via strong interaction

- Decay to fermions of the third family

$$\Pi_{4/3} \to \overline{\tau}\ \overline{b}, \quad M > 720 \text{ GeV}$$
$$\Pi_{1/3} \to \overline{\tau}\ \overline{t} \text{ or } \Pi_{1/3} \to \overline{\nu_\tau}\ \overline{b}, \quad M > 410 \text{ GeV}$$
$$\Pi_{-2/3} \to \overline{\nu_\tau}\ \overline{t}. \quad M > 640 \text{ GeV}$$

- Stop and sbottom + dedicated leptoquark searches

[ATLAS arXiv:1407.0583]
[CMS arXiv:1408.0806]
[CMS-PAS-EXO-13-010]

$$M > 720 \text{ GeV}$$

Naturalness

- From the B-meson decays anomalies we get $M \sim \ 1 \ \mathrm{TeV}, \ g_\rho \sim 4\pi$

- We can infer the scale of the strong sector from $M \sim \frac{\alpha_s}{4\pi} m_\rho^2 \longrightarrow \quad m_\rho \sim 10 \ \mathrm{TeV}$

- Flavour physics is (almost) fine in the quark sector, but we need a departure from flavour anarchy in the lepton sector   See Rattazzi, etal. arXiv:1205.5803

- Higgs potential $V(H) \sim \frac{3}{4\pi^2} (\epsilon_3^{q,u})^2 m_\rho^4 \, \overline{V} \left(\frac{g_\rho H}{m_\rho} \right)$

  natural value $v \sim f = \frac{m_\rho}{g_\rho} \sim 1 \ \mathrm{TeV}$ EW tuning $\xi \equiv \frac{v^2}{f^2} = \mathrm{few}\%$

- In general, a larger tuning is required to obtain a light physical Higgs

Conclusions

• Current anomalies in B decays can be explained in the context of a composite Higgs model featuring an additional (light) leptoquark as pseudo-Goldstone boson.

• Considering the present sensitivity and the future prospects, indirect effects could show up in various observables:

$$\mathrm{BR}(B \to K^{(*)}\nu\overline{\nu}),\ \mathrm{BR}(K^+ \to \pi^+\nu\overline{\nu}),\ \mathrm{BR}(\mu \to e\gamma)$$

• Composite leptoquarks could be within the reach of LHC13

• The scale of the composite sector is expected to be at $m_\rho \sim 10\ \mathrm{TeV}$, tuning is below the *per cent* level

Backup

Fits

Coeff.	best fit	1σ	2σ	$\chi^2_{\rm b.f.} - \chi^2_{\rm SM}$
$C_7^{\rm NP}$	-0.05	$[-0.08, -0.02]$	$[-0.11, 0.01]$	3.2
C_7'	-0.05	$[-0.14, 0.04]$	$[-0.22, 0.13]$	0.3
$C_9^{\rm NP}$	-1.31	$[-1.65, -0.95]$	$[-1.98, -0.58]$	12.9
C_9'	0.26	$[-0.02, 0.53]$	$[-0.29, 0.81]$	0.9
$C_{10}^{\rm NP}$	0.60	$[0.32, 0.90]$	$[0.06, 1.23]$	5.1
C_{10}'	-0.18	$[-0.40, 0.03]$	$[-0.62, 0.24]$	0.7
$C_9^{\rm NP} = C_{10}^{\rm NP}$	-0.09	$[-0.36, 0.20]$	$[-0.61, 0.53]$	0.1
$C_9^{\rm NP} = -C_{10}^{\rm NP}$	-0.55	$[-0.74, -0.36]$	$[-0.95, -0.19]$	9.7
$C_9' = C_{10}'$	-0.06	$[-0.36, 0.24]$	$[-0.67, 0.52]$	0.
$C_9' = -C_{10}'$	0.13	$[-0.00, 0.25]$	$[-0.13, 0.38]$	0.9

$$\mathcal{O}_7^{(\prime)} = \frac{e}{16\pi^2} m_b \left(\bar{s}\sigma_{\alpha\beta}P_{R(L)}b\right) F^{\alpha\beta} ,$$
$$\mathcal{O}_9^{\ell(\prime)} = \frac{\alpha_{\rm em}}{4\pi} \left(\bar{s}\gamma_\alpha P_{L(R)}b\right)\left(\bar{\ell}\gamma^\alpha\ell\right) ,$$
$$\mathcal{O}_{10}^{\ell(\prime)} = \frac{\alpha_{\rm em}}{4\pi} \left(\bar{s}\gamma_\alpha P_{L(R)}b\right)\left(\bar{\ell}\gamma^\alpha\gamma_5\ell\right).$$

[Fits by various groups,
Gosh, MN, Renner,1408.4097,
Hurth, el al.,1410.4545,
Altmannshofer, Straub, 1411.3161]

- Assuming only one source of NP at high scale, data prefers effects in the muon sector
- If only one Wilson coefficient is allowed to be non vanishing, various groups agree that NP in $\mathcal{O}_9^\mu$ is preferred by the data. $C_9^{\mu,NP} \approx -1$
- Short distance effects from New Physics are expected to have a chiral structure

$$\begin{matrix} \bar{\ell}\gamma^\alpha\ell \\ \bar{\ell}\gamma^\alpha\gamma_5\ell \end{matrix} \longrightarrow \begin{matrix} \bar{\ell}_L\gamma^\alpha\ell_L \\ \bar{\ell}_R\gamma^\alpha\ell_R \end{matrix}$$

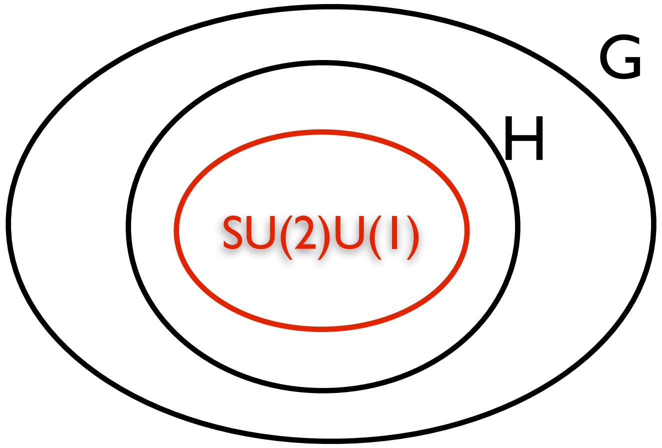
Best Fit with
Left-Left currents

$$C_9^{\mu,NP} = -C_{10}^{\mu,NP}$$

Composite Higgs

Georgi, Kaplan (1984)
Agashe, Contino, Pomarol hep-ph/0412089
Contino, 1005.4269
Bellazzini, Csaki, Serra 1401.2457

- The Higgs is a pseudo Goldstone boson
- Pattern of symmetry breaking:



$$\underset{f > v}{G \longrightarrow H}$$

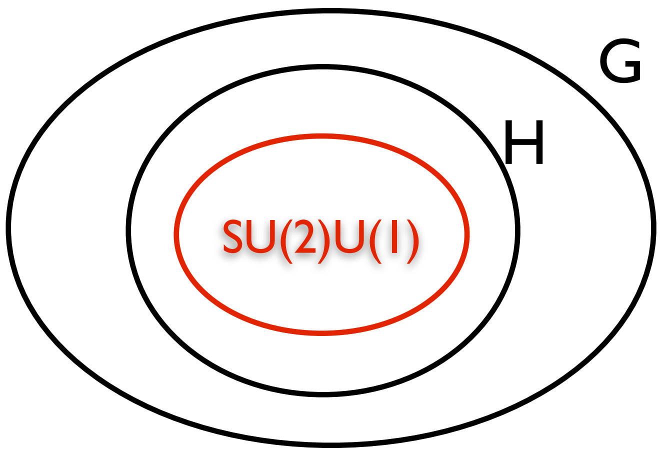
by strong interactions g_ρ, m_ρ

Composite Higgs

- The Higgs is a pseudo Goldstone boson

Georgi, Kaplan (1984)
Agashe, Contino, Pomarol hep-ph/0412089
Contino, 1005.4269
Bellazzini, Csaki, Serra 1401.2457

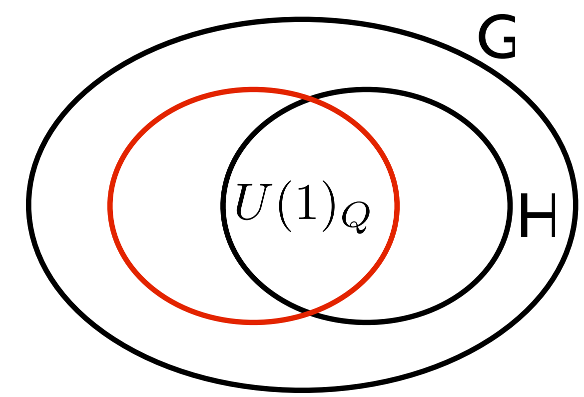
- Pattern of symmetry breaking:



$$G \underset{f > v}{\longrightarrow} H$$

by strong interactions g_ρ, m_ρ

Comparing with TC

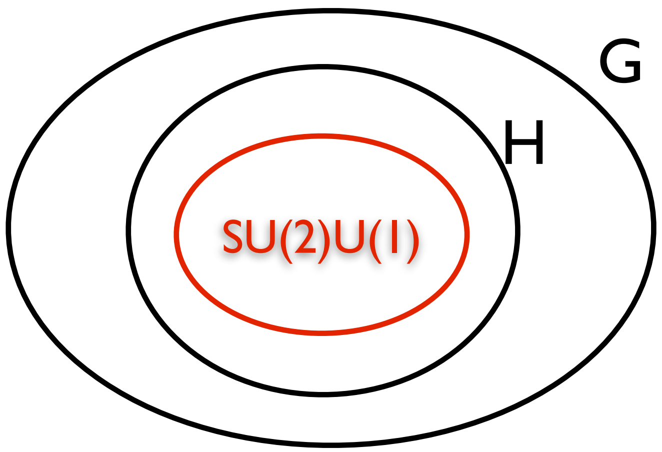


Composite Higgs

- The Higgs is a pseudo Goldstone boson

Georgi, Kaplan (1984)
Agashe, Contino, Pomarol hep-ph/0412089
Contino, 1005.4269
Bellazzini, Csaki, Serra 1401.2457

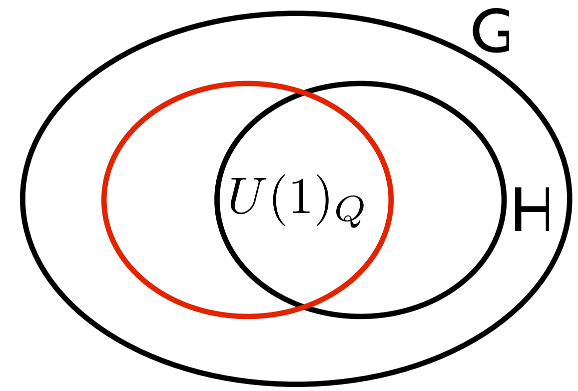
- Pattern of symmetry breaking:



$$G \to H$$
$$f > v$$

by strong interactions g_ρ, m_ρ

Comparing with TC



- Explicit breaking of G due to the Yukawa sector and an effective potential for H is generated:

1. EW symmetry is broken
2. Higgs mass is generated

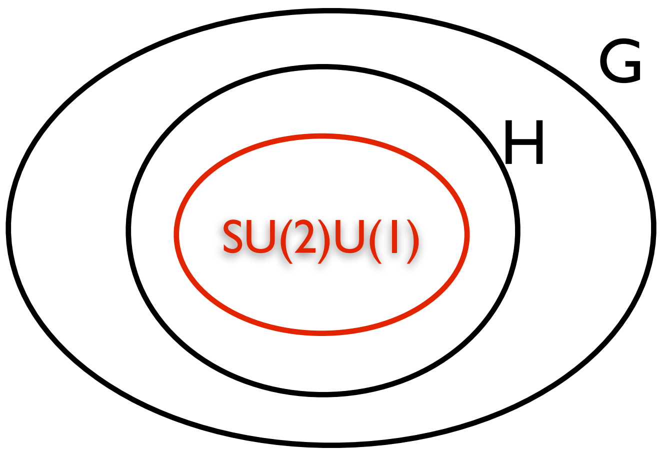
$$V(H) \sim \frac{m_\rho^4}{g_\rho^2} \times \frac{y_{L,R}^2}{16\pi^2} \times \hat{V}(H/f)$$

Composite Higgs

- The Higgs is a pseudo Goldstone boson

Georgi, Kaplan (1984)
Agashe, Contino, Pomarol hep-ph/0412089
Contino, 1005.4269
Bellazzini, Csaki, Serra 1401.2457

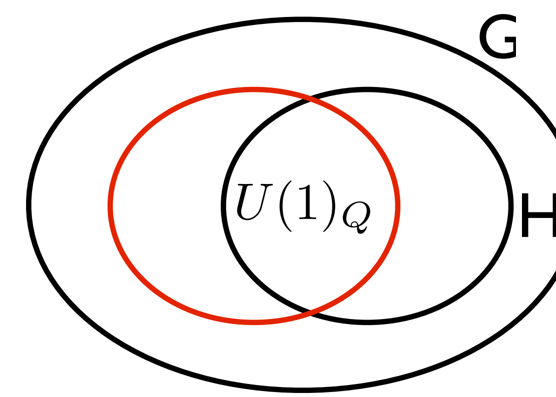
- Pattern of symmetry breaking:



$$G \longrightarrow H$$
$$f > v$$

by strong interactions g_ρ, m_ρ

Comparing with TC



- Explicit breaking of G due to the Yukawa sector and an effective potential for H is generated:

  1. EW symmetry is broken
  2. Higgs mass is generated

$$V(H) \sim \frac{m_\rho^4}{g_\rho^2} \times \frac{y_{L,R}^2}{16\pi^2} \times \hat{V}(H/f)$$

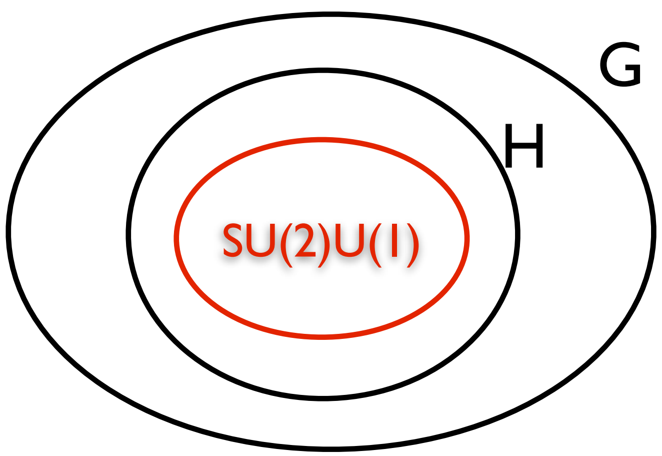
- EW tuning is characterised by $\xi \equiv \dfrac{v^2}{f^2}$

Composite Higgs

Georgi, Kaplan (1984)
Agashe, Contino, Pomarol hep-ph/0412089
Contino, 1005.4269
Bellazzini, Csaki, Serra 1401.2457

- The Higgs is a pseudo Goldstone boson

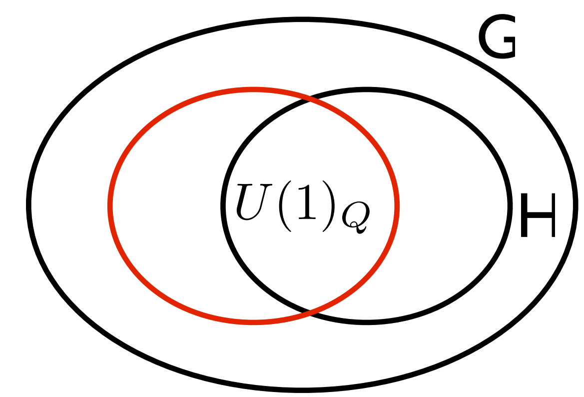
- Pattern of symmetry breaking:



$$G \underset{f > v}{\longrightarrow} H$$

by strong interactions g_ρ, m_ρ

Comparing with TC



- Explicit breaking of G due to the Yukawa sector and an effective potential for H is generated:

    1. EW symmetry is broken
    2. Higgs mass is generated

$$V(H) \sim \frac{m_\rho^4}{g_\rho^2} \times \frac{y_{L,R}^2}{16\pi^2} \times \hat{V}(H/f)$$

- EW tuning is characterised by $\xi \equiv \frac{v^2}{f^2}$

- Minimal realisation

    1. H contains EW group and the custodial symmetry $H = SO(4)$
    2. G/H contains only one Higgs doublet $G/H = SO(5)/SO(4)$

Parameters (quark sector)

- Yukawas are given by

$$(Y_u)_{ij} \sim g_\rho \epsilon_i^q \epsilon_j^u \qquad\qquad (Y_d)_{ij} \sim g_\rho \epsilon_i^q \epsilon_j^d$$

- And diagonalized by

$$(L_u^\dagger Y_u R_u)_{ij} = g_\rho \epsilon_i^u \epsilon_i^q \delta_{ij} \equiv y_i^u \delta_{ij}\,, \qquad (L_d^\dagger Y_d R_d)_{ij} = g_\rho \epsilon_i^d \epsilon_i^q \delta_{ij} \equiv y_i^d \delta_{ij}\,,$$

$$(L_u)_{ij} \sim (L_d)_{ij} \sim \min\left(\frac{\epsilon_i^q}{\epsilon_j^q}, \frac{\epsilon_j^q}{\epsilon_i^q}\right)\,, \qquad (R_{u,d})_{ij} \sim \min\left(\frac{\epsilon_i^{u,d}}{\epsilon_j^{u,d}}, \frac{\epsilon_j^{u,d}}{\epsilon_i^{u,d}}\right)$$

- Link with the CKM $\quad V_{CKM} = L_d^\dagger L_u \sim L_{u,d}$

$$\frac{\epsilon_1^q}{\epsilon_2^q} \sim \lambda \qquad \frac{\epsilon_2^q}{\epsilon_3^q} \sim \lambda^2 \qquad \frac{\epsilon_1^q}{\epsilon_3^q} \sim \lambda^3$$

- Everything is fixed up to 2 parameters $\quad g_\rho, \epsilon_i^q, \epsilon_i^u, \epsilon_i^d \qquad 1+3+3+3=10$

$$m_i^u, m_i^d, V_{CKM} \qquad 3+3+2=8$$

(g_ρ, ϵ_3^q) in what follows

Quark sector

$m_\rho = 10$ TeV $g_\rho = 4\pi$

Operator $\Delta F = 2$	$\mathrm{Re}(c) \times (4\pi/g_\rho)^2$	$\mathrm{Im}(c) \times (4\pi/g_\rho)^2$	Observables
$(\bar{s}_L\gamma^\mu d_L)^2$	$6 \times 10^2 \left(\frac{\epsilon_3^u}{\epsilon_3^q}\right)^2$	$2 \left(\frac{\epsilon_3^u}{\epsilon_3^q}\right)^2$	Δm_K; ϵ_K [44][45]
$(\bar{s}_R d_L)^2$	500	2	"
$(\bar{s}_R d_L)(\bar{s}_L d_R)$	2×10^2	0.6	"
$(\bar{c}_L\gamma^\mu u_L)^2$	$4 \times 10^2 \left(\frac{\epsilon_3^u}{\epsilon_3^q}\right)^2$	$70 \left(\frac{\epsilon_3^u}{\epsilon_3^q}\right)^2$	Δm_D; $\lvert q/p\rvert, \phi_D$ [44][45]
$(\bar{c}_L u_R)^2$	30	6	"
$(\bar{c}_R u_L)(\bar{c}_L u_R)$	3×10^2	50	"
$(\bar{b}_L\gamma^\mu d_L)^2$	$5 \left(\frac{\epsilon_3^u}{\epsilon_3^q}\right)^2$	$2 \left(\frac{\epsilon_3^u}{\epsilon_3^q}\right)^2$	Δm_{B_d}; $S_{\psi K_S}$ [44][45]
$(\bar{b}_R d_L)^2$	80	30	"
$(\bar{b}_R d_L)(\bar{b}_L d_R)$	3×10^2	80	"
$(\bar{b}_L\gamma^\mu s_L)^2$	$6 \left(\frac{\epsilon_3^u}{\epsilon_3^q}\right)^2$		Δm_{B_s} [44][45]
$(\bar{b}_R s_L)^2$	1×10^2		"
$(\bar{b}_R s_L)(\bar{b}_L s_R)$	3×10^2		"
Operator $\Delta F = 1$	**$\mathrm{Re}(c)$**	**$\mathrm{Im}(c)$**	**Observables**
$\overline{s_R}\sigma^{\mu\nu} e F_{\mu\nu} b_L$	1		$B \to X_s$ [46]
$\overline{s_L}\sigma^{\mu\nu} e F_{\mu\nu} b_R$	2	9	"
$\overline{s_R}\sigma^{\mu\nu} g_s G_{\mu\nu} d_L$	-	0.4	$K \to 2\pi$; ϵ'/ϵ [47]
$\overline{s_L}\sigma^{\mu\nu} g_s G_{\mu\nu} d_R$	-	0.4	"
$\bar{s}_L\gamma^\mu b_L\, H^\dagger i \overleftrightarrow{D}_\mu H$	$30 \left(\frac{g_\rho}{4\pi}\right)^2 (\epsilon_3^u)^2$		$B_s \to \mu^+\mu^-$ [48]
$\bar{s}_L\gamma^\mu b_L\, H^\dagger i \overleftrightarrow{D}_\mu H$	$6 \left(\frac{g_\rho}{4\pi}\right)^2 (\epsilon_3^u)^2$	$10 \left(\frac{g_\rho}{4\pi}\right)^2 (\epsilon_3^u)^2$	$B \to X_s \ell^+\ell^-$ [46]
Operator $\Delta F = 0$	**$\mathrm{Re}(c)$**	**$\mathrm{Im}(c)$**	**Observables**
$\bar{d}\sigma^{\mu\nu} e F_{\mu\nu} d_{L,R}$	-	3×10^{-2}	neutron EDM [49][50]
$\bar{u}\sigma^{\mu\nu} e F_{\mu\nu} u_{L,R}$	-	0.3	"
$\bar{d}\sigma^{\mu\nu} g_s G_{\mu\nu} d_{L,R}$	-	4×10^{-2}	"
$\bar{u}\sigma^{\mu\nu} g_s G_{\mu\nu} u_{L,R}$	-	0.2	"
$\bar{b}_L\gamma^\mu b_L\, H^\dagger i \overleftrightarrow{D}_\mu H$	$5 \left(\frac{g_\rho}{4\pi}\right)^2 (\epsilon_3^u)^2$		$Z \to b\bar{b}$ [51]

- Close to the current sensitivity

- Not excluded, given the uncertainties

Lepton sector

$m_\rho = 10$ TeV $\quad g_\rho = 4\pi$

Leptonic Operator	Re(c)	Im(c)	Observables
$\bar{e}\sigma^{\mu\nu}eF_{\mu\nu}e_{L,R}$	-	5×10^{-2}	electron EDM [52]
$\overline{\mu}\sigma^{\mu\nu}eF_{\mu\nu}e_{L,R}$	4×10^{-3}		$\mu\to e\gamma$ [53]
$\bar{e}\gamma^\mu\mu_{L,R}\,H^\dagger i\overleftrightarrow{D}_\mu H$	$1.5\left(\frac{g_\rho}{4\pi}\right)\frac{\epsilon_3^e}{\epsilon_3^\ell}$		$\mu(Au)\to e(Au)$ [54]