Composite Leptoquarks with Partial Compositeness

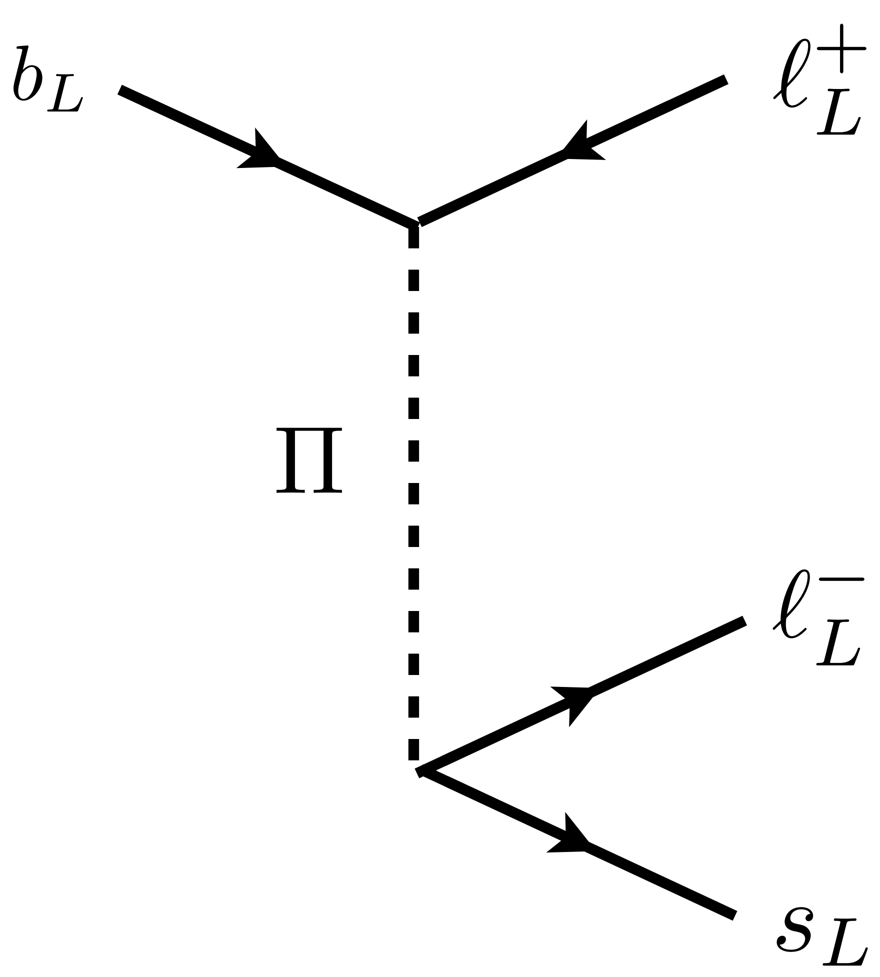
Marco Nardecchia

DAMTP and Cavendish Laboratory,
University of Cambridge

ZPW2015, The Flavour of New Physics, Zurich

Outline

Based on 1412.5942 in collaboration with
Ben Gripaios and Sophie Renner



- Explaining the anomalies in semileptonic B-meson decays, in the context of a Composite Higgs model with an extra PNGB

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

- Flavour Violation regulated by the mechanism of partial compositeness

Outline

- Anomalies in B decays
- Theoretical Framework
- Fit to the B meson anomalies
- Predictions
- Conclusions

Anomalies

[Several talks yesterday]

1) $B \to K^* \mu^+ \mu^-$ angular observables

2) Various branching ratios are low compared to the SM predictions

Decay	obs.	q^2 bin	SM pred.	measurement		pull
$\bar{B}^0 \to \bar{K}^{*0}\mu^+\mu^-$	$10^7\ \frac{d\text{BR}}{dq^2}$	$[16, 19.25]$	0.47 ± 0.05	0.31 ± 0.07	CDF	$+1.9$
$\bar{B}^0 \to \bar{K}^{*0}\mu^+\mu^-$	A_{FB}	$[2, 4.3]$	-0.04 ± 0.03	-0.20 ± 0.08	LHCb	$+1.9$
$\bar{B}^0 \to \bar{K}^{*0}\mu^+\mu^-$	F_L	$[2, 4.3]$	0.79 ± 0.03	0.26 ± 0.19	ATLAS	$+2.7$
$\bar{B}^0 \to \bar{K}^{*0}\mu^+\mu^-$	S_5	$[2, 4.3]$	-0.16 ± 0.03	0.12 ± 0.14	LHCb	-2.0
$\bar{B}^- \to \bar{K}^{*-}\mu^+\mu^-$	$10^7\ \frac{d\text{BR}}{dq^2}$	$[4, 6]$	0.50 ± 0.08	0.26 ± 0.10	LHCb	$+1.9$
$\bar{B}^- \to \bar{K}^{*-}\mu^+\mu^-$	$10^7\ \frac{d\text{BR}}{dq^2}$	$[15, 19]$	0.59 ± 0.06	0.40 ± 0.08	LHCb	$+1.8$
$\bar{B}^0 \to \bar{K}^{0}\mu^+\mu^-$	$10^8\ \frac{d\text{BR}}{dq^2}$	$[0.1, 2]$	2.71 ± 0.53	1.26 ± 0.56	LHCb	$+1.9$
$\bar{B}^0 \to \bar{K}^{0}\mu^+\mu^-$	$10^8\ \frac{d\text{BR}}{dq^2}$	$[16, 23]$	0.93 ± 0.10	0.37 ± 0.22	CDF	$+2.3$
$B_s \to \phi\mu^+\mu^-$	$10^7\ \frac{d\text{BR}}{dq^2}$	$[1, 6]$	0.39 ± 0.06	0.23 ± 0.05	LHCb	$+2.0$

[Altmannshofer, Straub 1411.3161]

• Main sources of uncertainty: form factors, non-factorisable contributions from the hadronic weak Hamiltonian.

Anomalies

[Several talks yesterday]

1) $B \to K^* \mu^+ \mu^-$ angular observables

2) Various branching ratios are low compared to the SM predictions

Decay	obs.	q^2 bin	SM pred.	measurement		pull
$\bar{B}^0 \to \bar{K}^{*0} \mu^+ \mu^-$	$10^7 \frac{d\text{BR}}{dq^2}$	$[16, 19.25]$	0.47 ± 0.05	0.31 ± 0.07	CDF	$+1.9$
$\bar{B}^0 \to \bar{K}^{*0} \mu^+ \mu^-$	A_{FB}	$[2, 4.3]$	-0.04 ± 0.03	-0.20 ± 0.08	LHCb	$+1.9$
$\bar{B}^0 \to \bar{K}^{*0} \mu^+ \mu^-$	F_L	$[2, 4.3]$	0.79 ± 0.03	0.26 ± 0.19	ATLAS	$+2.7$
$\bar{B}^0 \to \bar{K}^{*0} \mu^+ \mu^-$	S_5	$[2, 4.3]$	-0.16 ± 0.03	0.12 ± 0.14	LHCb	-2.0
$\bar{B}^- \to \bar{K}^{*-} \mu^+ \mu^-$	$10^7 \frac{d\text{BR}}{dq^2}$	$[4, 6]$	0.50 ± 0.08	0.26 ± 0.10	LHCb	$+1.9$
$\bar{B}^- \to \bar{K}^{*-} \mu^+ \mu^-$	$10^7 \frac{d\text{BR}}{dq^2}$	$[15, 19]$	0.59 ± 0.06	0.40 ± 0.08	LHCb	$+1.8$
$\bar{B}^0 \to \bar{K}^0 \mu^+ \mu^-$	$10^8 \frac{d\text{BR}}{dq^2}$	$[0.1, 2]$	2.71 ± 0.53	1.26 ± 0.56	LHCb	$+1.9$
$\bar{B}^0 \to \bar{K}^0 \mu^+ \mu^-$	$10^8 \frac{d\text{BR}}{dq^2}$	$[16, 23]$	0.93 ± 0.10	0.37 ± 0.22	CDF	$+2.3$
$B_s \to \phi \mu^+ \mu^-$	$10^7 \frac{d\text{BR}}{dq^2}$	$[1, 6]$	0.39 ± 0.06	0.23 ± 0.05	LHCb	$+2.0$

[Altmannshofer, Straub 1411.3161]

• Main sources of uncertainty: form factors, non-factorisable contributions from the hadronic weak Hamiltonian.

3) Hint of violation of lepton-flavour universality

[arXiv:0709.4174]

$$R_K = \frac{\text{BR}(B \to K \mu^+ \mu^-)_{[1,6]}}{\text{BR}(B \to K e^+ e^-)_{[1,6]}} = 0.745^{+0.090}_{-0.074} \pm 0.036$$

$$R_K^{SM} = 1.0003 \pm 0.0001$$

Theoretically very clean!

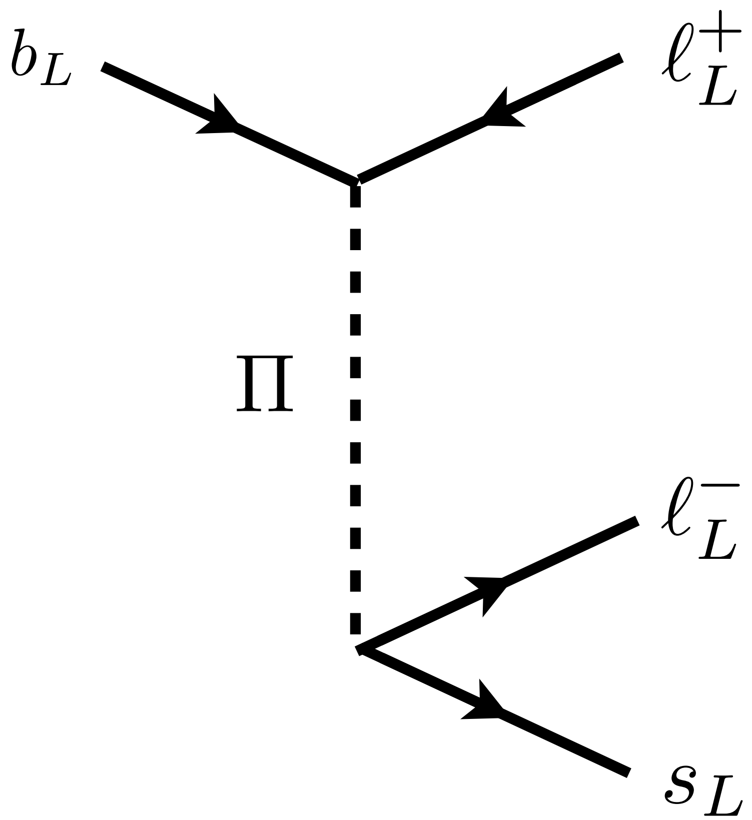
New Physics interpretation

[Various groups]

- Minimal option: New Physics (NP) in the muon sector only.
- Short distance effects from NP are expected to generate a chiral currents
- Best fit is obtained for the current $(\bar{b}_L \gamma_\alpha s_L)(\overline{\mu}_L \gamma^\alpha \mu_L)$ $\quad C_9^{\mu,NP} = -C_{10}^{\mu,NP}$

New Physics interpretation

- Minimal option: New Physics (NP) in the muon sector only. [Various groups]
- Short distance effects from NP are expected to generate a chiral currents
- Best fit is obtained for the current $(\bar{b}_L \gamma_\alpha s_L)(\overline{\mu}_L \gamma^\alpha \mu_L)$ $\quad C_9^{\mu,NP} = -C_{10}^{\mu,NP}$
- An explicit model [Hiller, Schmaltz arXiv:1408.1627]



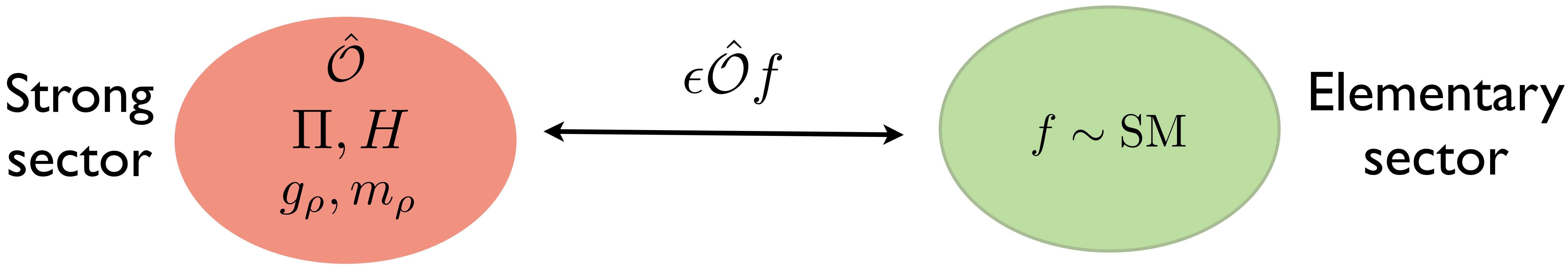
- Quantum numbers of the new states, uniquely determined by the structure of the current

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

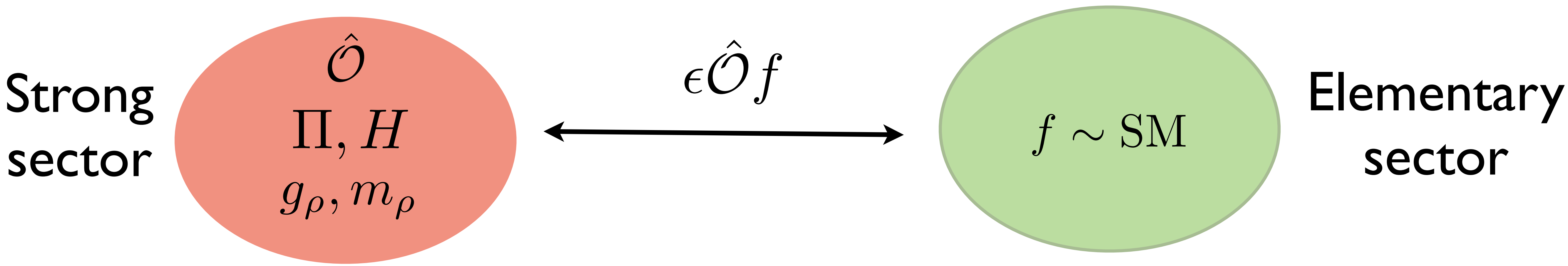
$$\lambda_{ij}\, \overline{q}^c_{Lj} i\tau_2 \tau_a \ell_{Li}\, \Pi$$

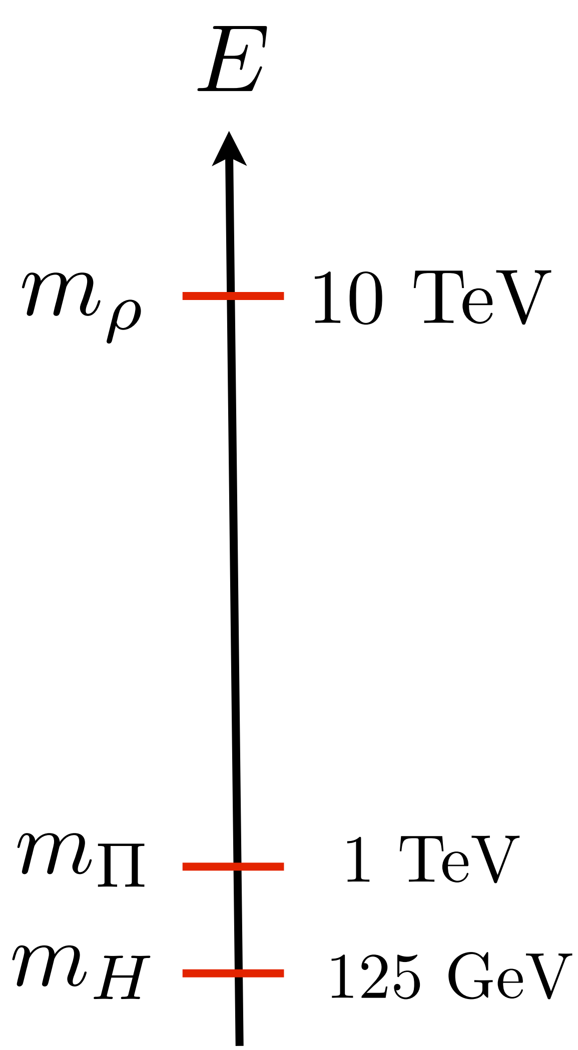
- Anomalies are fitted when $\dfrac{|\lambda^*_{s\mu}\lambda_{b\mu}|}{M^2} \simeq \dfrac{1}{(48\ \mathrm{TeV})^2}$
- Scale of New Physics not predicted $\quad 700\ \mathrm{GeV} \lesssim M \lesssim 48\ \mathrm{TeV}$

Theoretical Framework



Theoretical Framework





- Being PGBs, 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 states, 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 analogy to the EW group)

Leptoquarks as PNGB

- Partial compositeness requires the presence of coloured composite states, 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 analogy to the EW group)

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

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

Agashe, Contino, Pomarol hep-ph/0412089

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

- SM embedding

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

Leptoquarks as PNGB

- Partial compositeness requires the presence of coloured composite states, 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 analogy to the EW group)

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

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

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

Agashe, Contino, Pomarol hep-ph/0412089

- SM embedding

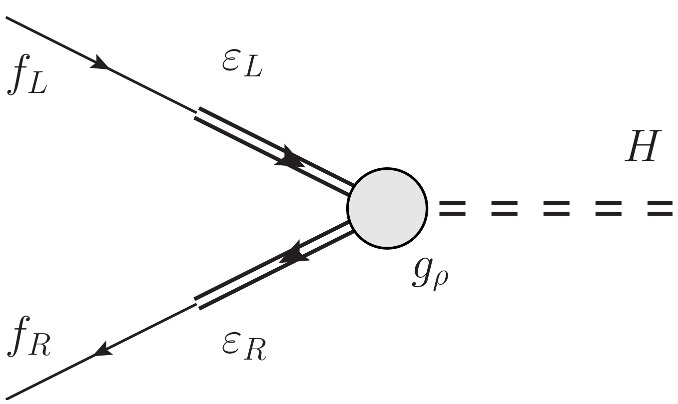
$$\begin{aligned} SU(3)_C \times U(1)_\psi &\supset SU(4) \\ SU(2)_L &= (SU(2)_H \times SU(2)_\Pi)_D \\ T_Y &= -\tfrac{1}{2} T_\psi + T_{3R} \end{aligned}$$

- 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:

D. B. Kaplan (1991)



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

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

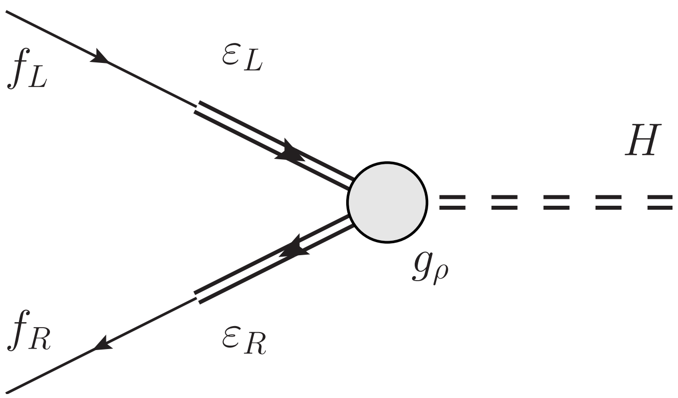
$$\mathcal{L}_{\rm mix} = \epsilon_L\, f_L \mathcal{O}_L + \epsilon_L\, f_R \mathcal{O}_R + h.c.$$

$$Y^{ij} = c_{ij}\,\epsilon^i_L \epsilon^j_R\, g_\rho \longrightarrow Y^{ij} \sim \epsilon^i_L \epsilon^j_R g_\rho$$

Partial Compositeness in CH models

- Yukawa sector:

D. B. Kaplan (1991)



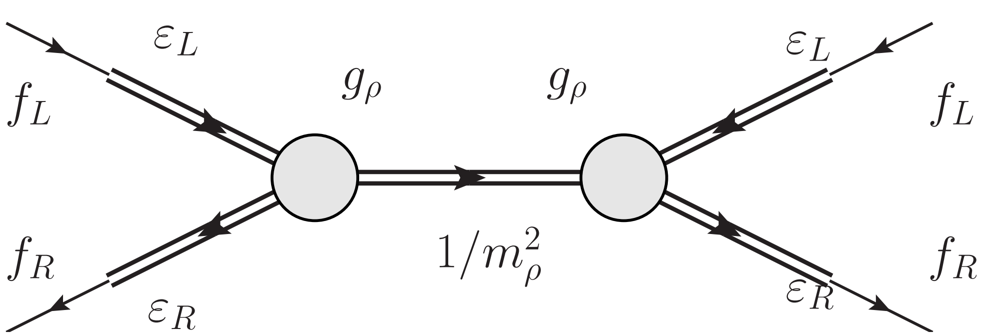
$$\mathcal{L}_{\rm elem} = i\bar{f}\gamma^\mu D_\mu f$$

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

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

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

- Flavour violation beyond the SM one is generated:



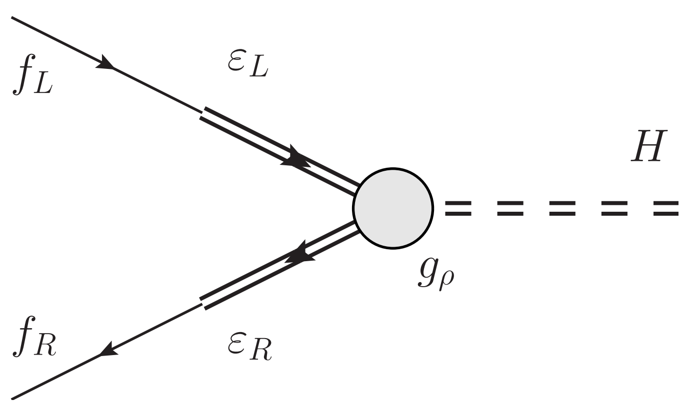
$$\sim \frac{g_\rho^2}{m_\rho^2} \epsilon_L^i \epsilon_R^i \epsilon_L^j \epsilon_R^j$$

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

Partial Compositeness in CH models

- Yukawa sector:

D. B. Kaplan (1991)



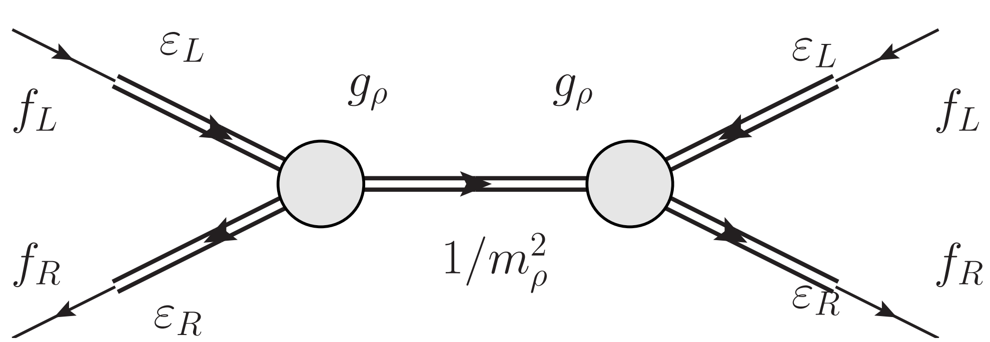
$$\mathcal{L}_{\rm elem} = i\bar{f}\gamma^\mu D_\mu f$$

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

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

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

- Flavour violation beyond the SM 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 Yukawas but not in a Minimal FV way

- Focus on leptoquark resonance

Parameters

- Yukawas are given by $(Y_u)_{ij} \sim g_\rho \epsilon_i^q \epsilon_j^u$ $\quad (Y_d)_{ij} \sim g_\rho \epsilon_i^q \epsilon_j^d$ $\quad (Y_e)_{ij} \sim g_\rho \epsilon_i^\ell \epsilon_j^e,$
- Parameters $\epsilon_i^q, \epsilon_i^u, \epsilon_i^d, \epsilon_i^\ell, \epsilon_i^e, g_\rho$ $\quad 3 \times 5 + 1 = 16$
- Physical input $m_i^u, m_i^d, m_i^\ell, V_{CKM}$ $\quad 3+3+3+2 = 11$ relations
- We will assume that left (ϵ_i^ℓ) and right (ϵ_i^e) mixings have similar size $\quad 3$ relations
- Everything is fixed up to 2 parameters,

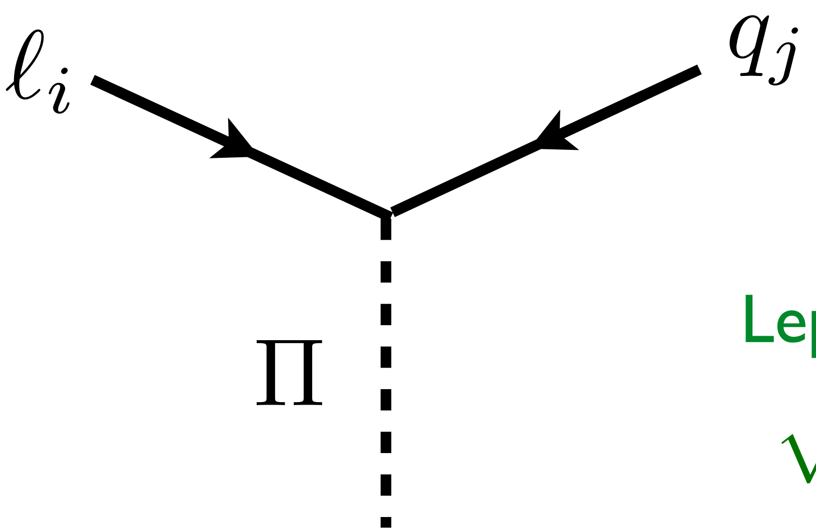
$$(g_\rho, \epsilon_3^q)$$

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

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



$$g_\rho \epsilon^\ell_i \epsilon^q_j \times c_{ij}$$

Quarks $\lambda^3 \quad : \quad \lambda^2 \quad : \quad 1$

Leptons $\sqrt{Y_\ell}$

$\lambda_{ij}/(c_{ij} g_\rho^{1/2} \epsilon^q_3)$	$j=1$	$j=2$	$j=3$
$i=1$	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, predictions are O(1)
- Only 3 fundamental parameters reduced to a single combination in all the flavour observable!

$$(g_\rho, \epsilon^q_3, M) \to \sqrt{g_\rho} \epsilon^q_3 / M$$

Fit to the anomalies

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

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

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

- 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 rather light $M \lesssim 1$ TeV

Fit to the anomalies

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

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

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

- 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 rather light $M \lesssim 1$ TeV

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

Predictions

- We expect large effects coming from the third family 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 $b \to s\tau^+\tau^-$

Predictions

- We expect large effects coming from the third family 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 $b \longrightarrow s\tau^+\tau^-$

- Channels with tau neutrinos in the final state are more interesting

arXiv:1409.4557
and
Girrbach's talk

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

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

- Considering just $B \longrightarrow K^*\overline{\nu}_\mu\nu_\mu$ gives

$$\Delta R_K^{(*)\nu\nu} < \text{ few } \%$$

Predictions

- We expect large effects coming from the third family 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 $b \to s\tau^+\tau^-$

- Channels with tau neutrinos in the final state are more interesting

arXiv:1409.4557
and
Girrbach's talk

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

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

- Considering just $B \to K^* \overline{\nu}_\mu \nu_\mu$ gives

$$\Delta R_K^{(*)\nu\nu} < \text{ few } \%$$

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

Testable at Belle II

See 1002.5012

Predictions

- Rare Kaon decay

arXiv:
0807.5039
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 $\delta C_{\nu\bar{\nu}} = 0.62 \; \mathrm{Re}(c_{31} c_{32}^*) \left(\frac{g_\rho}{4\pi}\right) (\epsilon_3^q)^2 \left(\frac{M}{\mathrm{TeV}}\right)^{-2}$

Predictions

arXiv:
0807.5039
1411.0109

- Rare Kaon decay

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

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 $\mu \longrightarrow e\gamma$

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

Predictions

- Rare Kaon decay

arXiv:
0807.5039
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

Model independent constraints
Davidson, Bailey, Campbell hep-ph/9309310

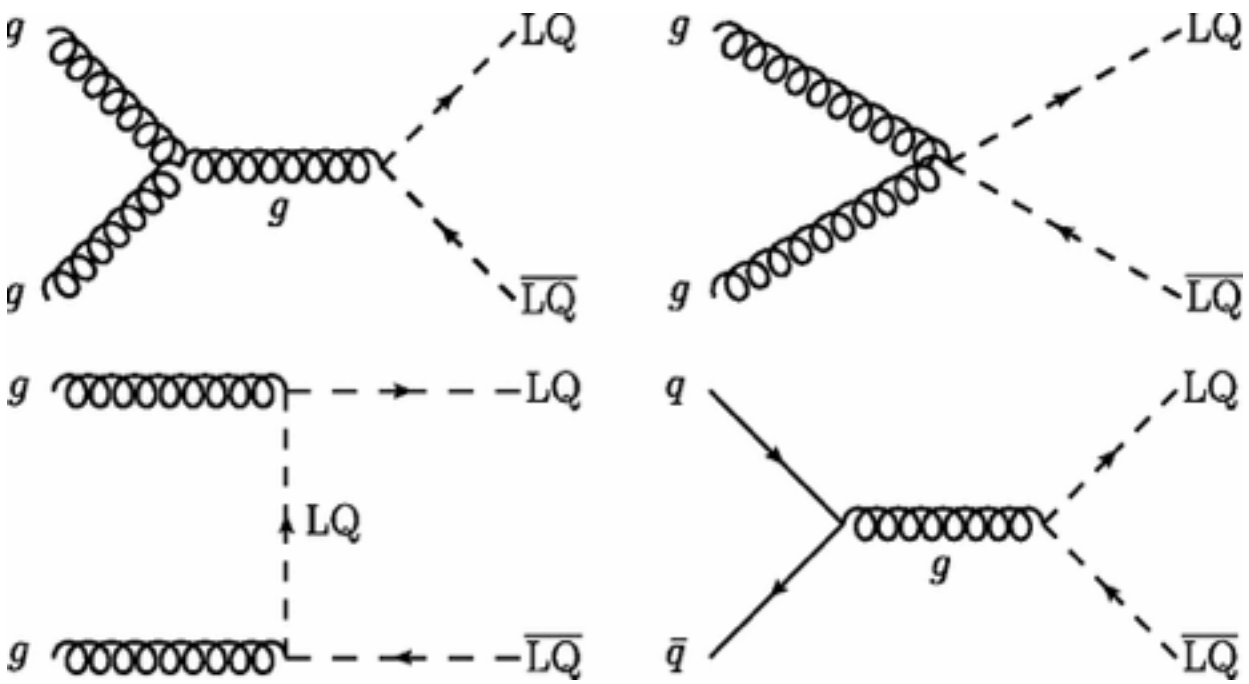
Decay	(ij)(kl)*	$\lvert\lambda_{ij}\lambda^*_{kl}\rvert / \left(\frac{M}{\mathrm{TeV}}\right)^2$	$\lvert c_{ij}c^*_{kl}\rvert \left(\frac{g_\rho}{4\pi}\right)(\epsilon^q_3)^2 / \left(\frac{M}{\mathrm{TeV}}\right)^2$
$K_S \to e^+e^-$	$(12)(11)^*$	< 1.0	$< 4.9 \times 10^7$
$K_L \to e^+e^-$	$(12)(11)^*$	$< 2.7 \times 10^{-3}$	$< 1.3 \times 10^5$
$\dagger\ K_S \to \mu^+\mu^-$	$(22)(21)^*$	$< 5.1 \times 10^{-3}$	$< 1.2 \times 10^3$
$K_L \to \mu^+\mu^-$	$(22)(21)^*$	$< 3.6 \times 10^{-5}$	< 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

$M = 1$ TeV

- A breaking of the lepton universality is generally associated to a breaking of the lepton flavour. [See Glashow, Guadagnoli, Lane arXiv: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:

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

• 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

Quark sector

$$m_\rho = 10 \text{ TeV} \qquad g_\rho = 4\pi$$

Operator $\Delta F = 2$	$\text{Re}(c) \times (4\pi/g_\rho)^2$	$\text{Im}(c) \times (4\pi/g_\rho)^2$	Observables
$(\bar{s}_L \gamma^\mu d_L)^2$	$6 \times 10^2 \left(\frac{\epsilon_3^u}{\epsilon_3^q}\right)^2$	$2 \left(\frac{\epsilon_3^u}{\epsilon_3^q}\right)^2$	$\Delta m_K;\ \epsilon_K$ [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	"
$(\bar{c}_L \gamma^\mu u_L)^2$	$4 \times 10^2 \left(\frac{\epsilon_3^u}{\epsilon_3^q}\right)^2$	$70 \left(\frac{\epsilon_3^u}{\epsilon_3^q}\right)^2$	$\Delta m_D;\ \|q/p\|, \phi_D$ [44][45]
$(\bar{c}_L u_R)^2$	30	6	"
$(\bar{c}_R u_L)(\bar{c}_L u_R)$	3×10^2	50	"
$(\bar{b}_L \gamma^\mu d_L)^2$	$5 \left(\frac{\epsilon_3^u}{\epsilon_3^q}\right)^2$	$2 \left(\frac{\epsilon_3^u}{\epsilon_3^q}\right)^2$	$\Delta m_{B_d};\ S_{\psi K_S}$ [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 $\Delta F = 1$	**$\text{Re}(c)$**	**$\text{Im}(c)$**	**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	$K \to 2\pi;\ \epsilon'/\epsilon$ [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 $\Delta F = 0$	**$\text{Re}(c)$**	**$\text{Im}(c)$**	**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

$m_\rho = 10\ \mathrm{TeV} \quad g_\rho = 4\pi$

Leptonic Operator	$\mathrm{Re}(c)$	$\mathrm{Im}(c)$	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]

New Physics (Model Independent)

- Model independent analysis via a low-energy effective Hamiltonian

$$\mathcal{H}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} \left(V_{ts}^* V_{tb}\right) \sum_i C_i^\ell(\mu)\, \mathcal{O}_i^\ell(\mu)$$

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

$$\begin{aligned}
C_7^{SM} &= -0.319, \\
C_9^{SM} &= 4.23, \\
C_{10}^{SM} &= -4.41.
\end{aligned}$$

SM gives lepton flavour universal contribution

- Data suggest New Physics in the muon sector only. [Various groups]

- Short distance effects from NP are expected to have a chiral structure

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

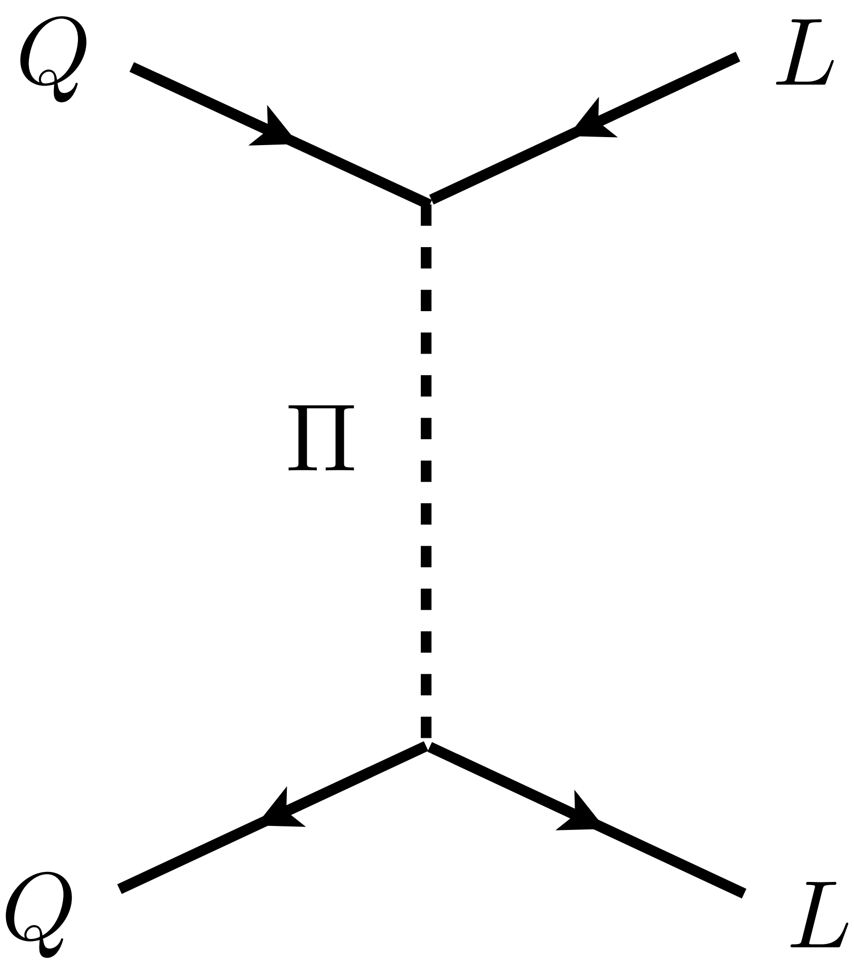
Best Fit with Left-Left currents

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

- Look for the current $(\bar{b}_L \gamma_\alpha s_L)(\overline{\mu}_L \gamma^\alpha \mu_L)$

Flavour violation at the tree level

- We integrate away the leptoquark fields, then we get



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

$$u'^{j}_L = V^{\dagger jk}_{CKM} u^k_L$$

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