Towards a coherent picture of diphoton and flavour anomalies *

Dario Buttazzo

Physik-Institut - Universität Zürich

Heavy Flavour, Quo Vadis? – Islay, July 14th, 2016

* based on arXiv:1604.03940 in collaboration with A. Greljo, G. Isidori, D. Marzocca

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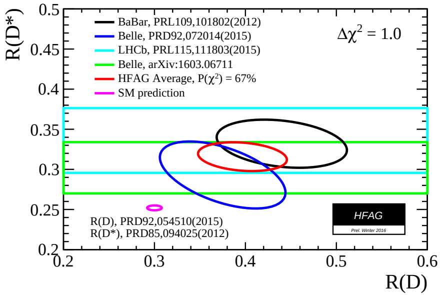
Motivation 1(a): LFU in charged currents

- ◇ Violation of lepton flavour universality in $b \to c$ decays:

$$R_{D^{(*)}} = \frac{\mathcal{B}(B \to D^{(*)}\tau\bar{\nu})}{\mathcal{B}(B \to D^{(*)}\ell\bar{\nu})}$$



- ◇ $\sim 4\sigma$ excess over the SM prediction
- ◇ Good agreement between 3 different experiments
- ◇ $\sim 15\%$ enhancement of tree-level LL amplitude $(\bar{b}_L\gamma_\mu c_L)(\bar{\tau}_L\gamma_\mu\nu_\tau)$

Motivation 1(b): LFU in neutral currents

- μ/e universality in $b \to s$ transitions

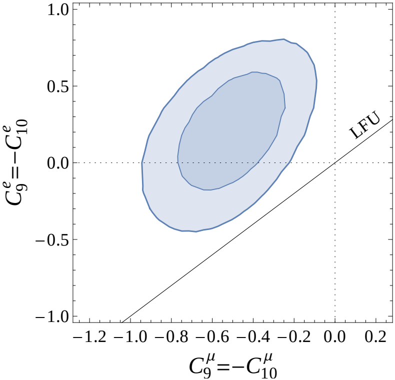
$$R_K = \left.\frac{\mathcal{B}(B \to K\mu^+\mu^-)}{\mathcal{B}(B \to Ke^+e^-)}\right|_{q^2\in[1,6]\,\mathrm{GeV}} = 0.745^{+0.090}_{-0.074} \pm 0.036$$

LHCb 1406.6482

- $B \to K^*\mu^+\mu^-$ angular distribution (P_5')

LHCb-PAPER-2015-051

Altmannshofer and Straub, 1411.3161



- Combined fit: $\sim 3.9\sigma$ over the SM prediction
- $\sim 15\%$ contribution to the LL operator $(\bar{b}_L\gamma_\mu s_L)(\bar{\mu}_L\gamma_\mu\mu_L)$

Motivation 1: LFU in B decays

- Dynamical assumption: New Physics in Left-handed currents.
- Flavour structure: coupling to third generation.
  (approximate $\mathrm{U}(2)^5$ symmetry)

Specific realisations involve heavy vectors:

- ◇ Vector triplets — Greljo, Isidori, Marzocca 1506.01705
- ◇ Vector leptoquarks — Barbieri, Isidori, Pattori, Senia 1512.01560

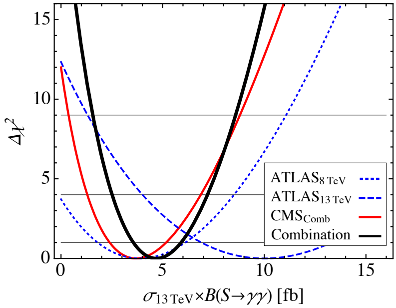
▶ see also Martin's talk

Find a UV completion for this class of models

Motivation 2: the diphoton excess

- Searches for resonances in $pp \to \gamma\gamma$ at the LHC: excess of events at $750\,\mathrm{GeV}$ in both ATLAS and CMS

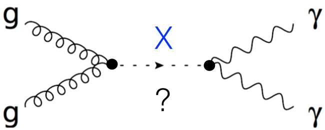
- For narrow resonance, local significance 3.6σ (ATLAS) and 3.4σ (CMS).



- Data consistent with a (pseudo)-scalar particle $gg \to X \to \gamma\gamma$.

$$\sigma_{13\,\mathrm{TeV}}(pp \to \eta) \times \mathcal{B}(\eta \to \gamma\gamma) = 4.7^{+1.2}_{-1.1}\,\mathrm{fb}$$

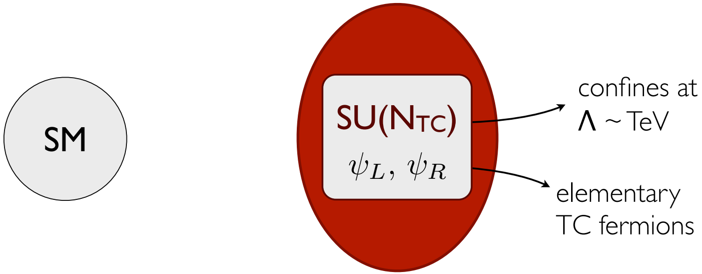
see e.g. B, Greljo, Marzocca 1512.04929



Is there a way to fit all these anomalies
in a single, coherent picture?

The model

- A new strongly-interacting sector, with vector-like fermions ψ, and a confined gauge group $\mathrm{SU}(N_{TC})$
- Approximate global symmetry $\mathrm{SU}(N_F)_L \times \mathrm{SU}(N_F)_R \times \mathrm{U}(1)$



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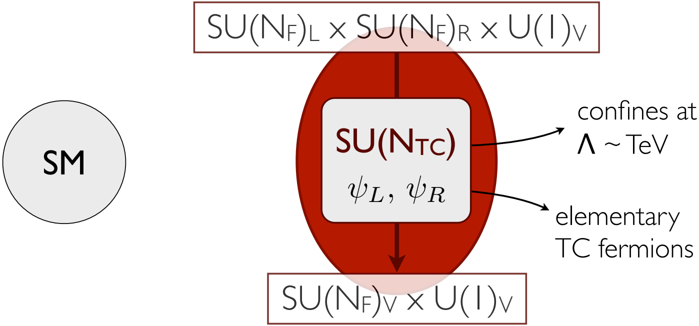

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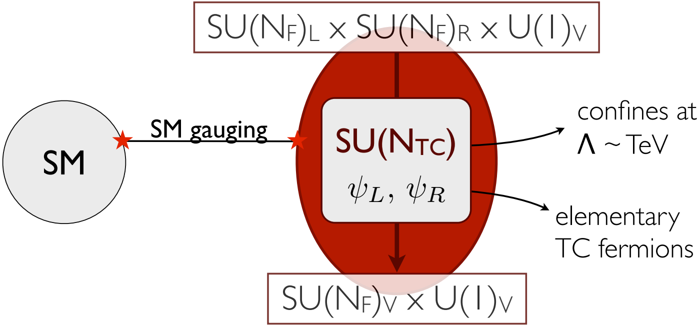

pNGB: $\eta, \pi^{\pm}, \pi^{0}, \cdots$

★ $pp \to \eta \to \gamma\gamma$

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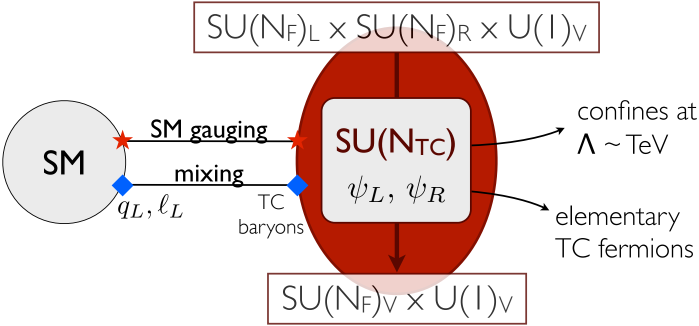


pNGB: $\eta, \pi^{\pm}, \pi^0, \cdots$

★ $pp \to \eta \to \gamma\gamma$

Vector mesons: $\rho^{\pm}, \rho^0, \omega, \cdots$

◆ $R_{D^{(*)}}, R_K$

Greljo, Isidori, Marzocca 1506.01705

Pseudo Nambu-Goldstone bosons

The theory condenses at a scale f:

$$\langle \psi_i \psi_j \rangle = -f^2 B_0 \delta_{ij}$$

$SU(N_F)_L \times \mathrm{SU}(N_F)_R \longrightarrow \mathrm{SU}(N_F)_V$: $N_F^2 - 1$ Goldstone bosons.

The global symmetry $\mathrm{SU}(N_F)_V$ is explicitly broken by the mass terms $\mathcal{M}$ and by SM gauge interactions D_μ.

$$\mathcal{L}_{\chi_{\mathrm{PT}}} = \frac{f^2}{4}\left(\mathrm{Tr}\left[(D_\mu\Sigma)^\dagger(D^\mu\Sigma)\right] + 2B_0(\mathrm{Tr}[\mathcal{M}\Sigma] + \mathrm{Tr}[\mathcal{M}^\dagger\Sigma^\dagger])\right)$$

$\Sigma = \exp\left(\frac{2i}{f} t^a \pi^a\right)$ is the pNGB matrix;
$\mathcal{M} = \mathrm{diag}(m_{\psi_i})$ is the TC-quark mass matrix;
$B_0 \approx 20 \times f$ in QCD

Example: for $\psi \sim (\mathbf{1}, \mathbf{2}, Y)$, $\quad |\pi^a\rangle = \frac{1}{\sqrt{2}}|\bar{L}\sigma^a L\rangle, \quad m_\pi = 2B_0 m_L$.

Chiral anomaly

Coupling to SM gauge fields through anomaly. For a singlet η:

$$\mathcal{L}_{\rm WZW} \supset -\frac{\eta}{16\pi^2 f}\left(g_1^2 A^\eta_{BB} B_{\mu\nu}\widetilde{B}^{\mu\nu} + g_2^2 A^\eta_{WW} W^i_{\mu\nu}\widetilde{W}^{\mu\nu}_i + g_3^2 A^\eta_{GG} G^A_{\mu\nu}\widetilde{G}^{\mu\nu}_A\right)$$

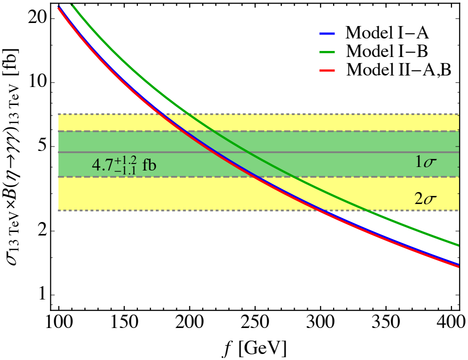
$$A^\eta_{gg} = 2N_{\rm TC}{\rm Tr}[t_\eta T^a T^a], \quad A^\eta_{WW} = 2N_{\rm TC}{\rm Tr}[t_\eta \tau^i \tau^i], \quad A^\eta_{BB} = 2N_{\rm TC}{\rm Tr}[t_\eta Y^2].$$

(no coupling to gluons for a non-singlet neutral state, e.g. π^0)

Decay widths:

$$\Gamma_{\eta\to\gamma\gamma} = \frac{\alpha^2}{64\pi^3} A^\eta_{\gamma\gamma}\frac{m_\eta^3}{f^2},$$

$$\Gamma_{\eta\to gg} = \frac{\alpha_s^2}{64\pi^3} A^\eta_{gg}\frac{m_\eta^3}{f^2}.$$



Fitting the diphoton signal

$f \approx (70 \div 80\,{\rm GeV}) \times N_{\rm TC}$

(assuming $gg \to \eta \to gg, \gamma\gamma, VV$)

Coupling to SM fermions

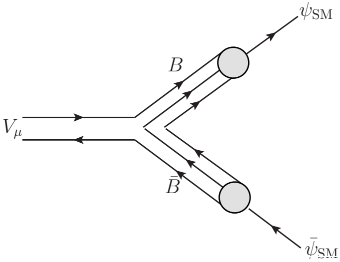
Assumption

The **3rd generation** of SM fermions couple to the composite sector through mixing with a suitable set of TC baryons.

$$\mathcal{L}_{\rm mix} \supset \kappa_q \bar{q}_L B_q + \kappa_\ell \bar{\ell}_L B_\ell$$

$$\mathcal{L}_\omega = g_\rho \, (a_q^\omega \; \bar{B}_q \gamma^\mu B_q + a_\ell^\omega \; \bar{B}_\ell \gamma^\mu B_\ell) \, \omega_\mu$$

$$\longrightarrow (g_q \, \bar{q}_L \gamma_\mu q_L + g_\ell \, \bar{\ell}_L \gamma_\mu \ell_L) \omega_\mu$$

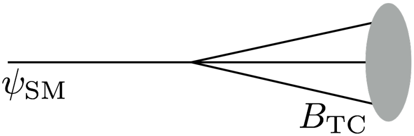


The couplings of vector mesons to different TC-baryons are not universal (depend on the flavour structure of the baryons and mesons)

Partial compositeness

- The mixing between SM fermions and TC baryons arises from four-fermion operators in the UV

$$\mathcal{L}_{4f} = \frac{1}{\Lambda_\ell^2}\bar{\ell}_L^c L_L \bar{L}_L^c L_L + \frac{1}{\Lambda_q^2}\bar{q}_L^c L_L \bar{Q}_L^c Q_L$$



- Example of UV completion: heavy scalars

$$\mathcal{L}_{\rm UV} = y_\phi \bar{\ell}_L^c L_L \phi + z_\phi \bar{L}_L^c L_L \phi^* + y_\chi \bar{q}_L^c L_L \chi + z_\chi \bar{Q}_L^c Q_L \chi^* + \text{h.c.}$$

Kaplan 1991

- Large mixing: the scale $\Lambda_{\ell,q}$ can not be too high, $M_{\phi,\chi} \gtrsim \Lambda_{\rm TC}$

An explicit example: minimal model – $\mathrm{SU}(5)$

- coupling to quarks & gg anomaly $\Rightarrow$ coloured TC-fermions
- coupling to doublets q_L, ℓ_L $\Rightarrow$ at least a $\mathrm{SU}(2)_L$-doublet TC-quark

Minimal field content: $\{Q \sim (\mathbf{3}, \mathbf{1}, Y_Q),\ L \sim (\mathbf{1}, \mathbf{2}, Y_L)\} \sim \mathbf{5} + \bar{\mathbf{5}}$

$$\mathrm{SU}(5)_L \times \mathrm{SU}(5)_R \to \mathrm{SU}(5)_V : \qquad \text{24 pNGB}$$

	Flavour structure	$\mathcal{G}_{\mathrm{SM}}$ irrep	pNGB Mass m_π^2
$\mathcal{V}$	$(\bar{Q}Q)$	$(\mathbf{8}, \mathbf{1}, 0)$	$2B_0 m_Q$
U	$(\bar{L}Q)$	$(\mathbf{3}, \mathbf{2}, Y_Q - Y_L)$	$B_0(m_L + m_Q)$
π	$(\bar{L}L)$	$(\mathbf{1}, \mathbf{3}, 0)$	$2B_0 m_L$
η	$3(\bar{L}L) - 2(\bar{Q}Q)$	$(\mathbf{1}, \mathbf{1}, 0)$	$\frac{2}{5}B_0(3m_L + 2m_Q)$

Plus gauge corrections $\Delta m^2 \simeq \frac{3\Lambda^2}{16\pi^2} \sum_i g_i^2 C_2^{(i)}(\pi^a) \approx (0.1 \div 0.3\, m_\rho)^2$

An explicit example: minimal model – $\mathrm{SU}(5)$

$N_{\rm TC}=3$: two choices of $Y_{Q,L}$ that give baryons with quantum n. of q,ℓ

$$|\bar B_\ell(B_\ell)\rangle_{(\mathbf{1},\mathbf{2},\pm 1/2)} \propto |LLL\rangle, \qquad |\bar B_q\rangle_{(\bar{\mathbf{3}},\mathbf{2},-1/6)} \propto |QQL\rangle,$$

for $\{Y_Q,Y_L\}=\{-\frac{1}{6},\frac{1}{6}\}$ or $\{Y_Q,Y_L\}=\{0,-\frac{1}{6}\}$.
No other mixing with SM states possible.

$$A^\eta_{BB}=-2\sqrt{\frac{3}{5}}N_{TC}\left(Y_L^2-Y_Q^2\right), \quad A^\eta_{WW}=-\frac{1}{2}\sqrt{\frac{3}{5}}N_{TC}, \quad A^\eta_{gg}=\sqrt{\frac{3}{5}}N_{TC}.$$

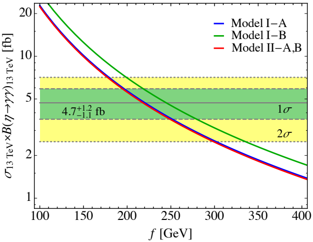
Assuming only decays through anomalies: $f=71\,(79)\times N_{\rm TC}$ GeV.

	(Y_Q,Y_L)	$R_{Z\gamma}$	R_{ZZ}	R_{WW}
A:	$(-\frac{1}{6},\frac{1}{6})$	6.7	11	37
B:	$(0,-\frac{1}{6})$	5.0	9.1	34

Experimental bounds:

$R_{Z\gamma}\lesssim 5.6$, $R_{ZZ}\lesssim 11$, $R_{WW}\lesssim 36$.

(see e.g. B, Greljo, Marzocca 1512.04929)



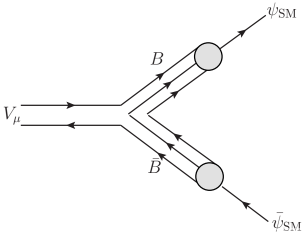
Vector resonances

$$|\rho^a\rangle_{(\mathbf{1},\mathbf{3},0)} = \frac{1}{\sqrt{2}}|\bar{L}\sigma^a L\rangle, \quad |\omega\rangle_{(\mathbf{1},\mathbf{1},0)} = \frac{1}{\sqrt{2}}|\bar{L}L\rangle, \quad |\phi\rangle_{(\mathbf{1},\mathbf{1},0)} = \frac{1}{\sqrt{3}}|\bar{Q}Q\rangle.$$

(+ coloured states)
Mass of vector mesons: $m^2_{V_{ij}} = c_0^2(4\pi f)^2 + c_1^2 B_0(m_i + m_j)$. $\quad (c_{0,1} \lesssim 1)$

$$\mathcal{L}_\omega = g_\rho \ (a_q^\omega \ \bar{B}_q\gamma^\mu B_q + a_\ell^\omega \ \bar{B}_\ell\gamma^\mu B_\ell) \ \omega_\mu$$

- ◇ ρ and ω ($\bar{L}L$) couple to both B_q and B_ℓ, $a^\rho_{q,\ell} \approx 2a^\omega_{q,\ell} \approx \mathcal{O}(1)$.
- ◇ ϕ ($\bar{Q}Q$) can couple via connected diagrams only to B_q, $a_\ell^\phi \ll 1$, $a_q^\phi \approx \sqrt{2/3}\, a_q^\rho$.



- ▶ Assuming similar coupling g_ρ for vector mesons and pNGB with the same flavour composition (e.g. ρ and π), $g_\eta \approx g_\rho/\sqrt{15}$.

  $\Gamma_{tt} \approx (3.3 \text{ GeV}) \times \frac{m_\eta^2}{m_B^2} \left|g_{\eta BB}\kappa_t^2\right|^2 \quad \Rightarrow \quad \mathcal{B}(\eta \to t\bar{t}) \lesssim 19\%.$

Another example: two doublets – $\mathrm{SU}(8)$

Next-to-minimal field content: $\{Q \sim (\mathbf{3}, \mathbf{2}, Y_Q),\ L \sim (\mathbf{1}, \mathbf{2}, Y_L)\}$

$\mathrm{SU}(8)_L \times \mathrm{SU}(8)_R \to \mathrm{SU}(8)_V$: 63 pnGB

	Flavour structure	$\mathcal{G}_{\rm SM}$ irrep	pNGB Mass m_π^2
$\mathcal{V}, \tilde{\mathcal{V}}, \rho'$	$(\bar{Q}Q)$	$(\mathbf{8}, \mathbf{1}, 0), (\mathbf{8}, \mathbf{3}, 0), (\mathbf{1}, \mathbf{3}, 0)$	$2B_0 m_Q$
$\mathcal{U}, \tilde{\mathcal{U}}$	$(\bar{L}Q)$	$(\mathbf{3}, \mathbf{3}, \Delta Y), (\mathbf{3}, \mathbf{1}, \Delta Y)$	$B_0(m_L + m_Q)$
π	$(\bar{L}L)$	$(\mathbf{1}, \mathbf{3}, 0)$	$2B_0 m_L$
η	$3(\bar{L}L) - (\bar{Q}Q)$	$(\mathbf{1}, \mathbf{1}, 0)$	$\frac{1}{2}B_0(3m_L + m_Q)$

Many choices of $Y_{Q,L}$ that give baryons with quantum numbers of q, ℓ, but only two reproduce the $\gamma\gamma$ signal: $\{Y_Q, Y_L\} = \{\frac{1}{2}, -\frac{1}{6}\}$, or $\{\frac{1}{6}, -\frac{1}{2}\}$.

$$A:\quad |B_\ell\rangle_{(\mathbf{1},\mathbf{2},-1/2)} \propto |LLL\rangle, \quad |B_q\rangle_{(\bar{\mathbf{3}},\mathbf{2},+1/6)} \propto |QLL\rangle,$$
$$B:\quad |\bar{B}_\ell\rangle_{(\mathbf{1},\mathbf{2},+1/2)} \propto |QQQ\rangle, \quad |\bar{B}_q\rangle_{(\bar{\mathbf{3}},\mathbf{2},-1/6)} \propto |QQL\rangle.$$

	$R_{Z\gamma}$	R_{ZZ}	R_{WW}
A, B	0.6	0.09	0

In both cases $f = 70\ N_{\rm TC}$ GeV.

Composite Higgs

A composite Higgs can be included in the Goldstone spectrum:

◇ Custodial symmetry requires $H \sim (\mathbf{2}, \mathbf{2})$ under $\mathrm{SU}(2)_L \times \mathrm{SU}(2)_R$

$$L \sim (\mathbf{N}, \mathbf{2}, \mathbf{1}), \ R = (N, E) \sim (\mathbf{N}, \mathbf{1}, \mathbf{2}) \quad \Rightarrow \quad H = (\bar{L}R)$$

- ▶ Flavour group $\mathrm{SU}(4) \times \mathrm{SU}(4) \to \mathrm{SU}(4)$: two complex Higgs doublets $H = (H_u, H_d) = (\bar{L}N, \bar{L}E) \sim \mathbf{4}$.

Mrazek et al. 1105.5403
Ferretti 1404.7137, 1604.06467

◇ Radiative corrections from SM top can modify the Higgs mass and generate a potential for H

$$m_h^2 = B_0(m_L + m_R) - \Delta_{\mathrm{loop}}$$

◇ SM Yukawa couplings can be generated by partial compositeness, from the same mixing with TC-baryons

Interlude: a $\mathrm{U}(2)^5$ flavour symmetry

An approximate symmetry of the SM quark Yukawa couplings:

Under $\mathrm{U}(2)_q \times \mathrm{U}(2)_u \times \mathrm{U}(2)_d$, the 3rd generation quarks transform as a singlets, while the first two as doublets,

$$q_L = \begin{pmatrix} \boldsymbol{q_L} \\ q_L^3 \end{pmatrix}, \qquad u_R = \begin{pmatrix} \boldsymbol{u_R} \\ t_R \end{pmatrix}, \qquad d_R = \begin{pmatrix} \boldsymbol{d_R} \\ b_R \end{pmatrix}.$$

If extended to the lepton sector, $\mathrm{U}(2)^5$.

Weakly broken by the spurions $\mathbf{V}_q \sim \mathbf{2}_q$ and $\mathbf{V}_\ell \sim \mathbf{2}_\ell$, plus light fermion masses (e.g. $\Delta y_u \sim (\mathbf{2}_q, \mathbf{2}_u)$).

Barbieri et al. 1105.2296
Barbieri, B, Sala, Straub 1203.4218

Vector resonances and flavour

I. The interactions between heavy vectors and SM fermions arise only from mixing between SM fermions and techni-baryons.

II. The mixing respects an approximate $\mathrm{U}(2)^5$ flavor symmetry: sizable mixing only with 3rd generation.

III. The leading corrections to the exact $\mathrm{U}(2)^5$ limit are obtained from the $\mathrm{U}(2)_{q_L}$ and $\mathrm{U}(2)_{\ell_L}$ spurion doublets.

$$B_\ell \to \kappa_\ell \chi_i^\ell \ell_L^i\,, \quad (\ell \leftrightarrow q), \qquad \chi_i^{\ell(q)} = \left(\varepsilon_1^{\ell(q)}, \varepsilon_2^{\ell(q)}, 1\right).$$

In the down-quark mass basis, $(\varepsilon_1^q,\, \varepsilon_2^q) = \xi\,(V_{td}, V_{ts})$ ($\xi = 0$: exact alignment).

Coupling to vector mesons

$$\mathcal{L}_\omega \supset g_\rho \left[a_q^\omega \;\kappa_q^2\; \lambda_{ij}^q \;\left(\bar{q}_L^i \gamma^\mu q_L^j\right) + a_\ell^\omega \;\kappa_\ell^2\; \lambda_{ij}^\ell \;\left(\bar{\ell}_L^i \gamma^\mu \ell_L^j\right)\right]\omega_\mu,$$

with $\lambda_{ij}^{\ell(q)} \equiv \chi_i^{\ell(q)*}\chi_j^{\ell(q)}$.

Flavour symmetry: $\lambda_{\mu\mu}^\ell = |\lambda_{\tau\mu}^\ell|^2,\ \lambda_{s\mu}^{\ell q} = \lambda_{bs}^{q*}\lambda_{\tau\mu}^\ell,\ \lambda_{s\tau}^{\ell q} = \lambda_{bs}^{q*},\ \lambda_{b\mu}^{\ell q} = \lambda_{\tau\mu}^\ell.$

Example: a colorless triplet ρ

$$|\rho^a\rangle = \frac{1}{\sqrt{2}}(\bar{L}\sigma^a L) \sim (\mathbf{1},\mathbf{3},0)$$

$\mathrm{SU}(2)_L$-triplet current:

$$J^a_\mu = g_q \lambda_q^{ij}\left(\bar{q}^i_L \gamma_\mu \tau^a q^j_L\right) + g_\ell \lambda_\ell^{ij}\left(\bar{\ell}^i_L \gamma_\mu \tau^a \ell^j_L\right),$$

$$\mathcal{L}_\rho \supset \rho^a_\mu J^a_\mu \quad \longrightarrow \quad \mathcal{L}_{4f}^{(\rho)} = -\frac{1}{2m_\rho^2} J^a_\mu J^\mu_a$$

$$\Delta\mathcal{L}_{\mathrm{c.c.}} = -\frac{g_q g_\ell}{2m_\rho^2}(V\lambda^q)_{ij}\lambda^\ell_{ab}\left(\bar{u}^i_L\gamma_\mu d^j_L\right)\left(\bar{\ell}^a_L\gamma_\mu\nu^b_L\right) + \mathrm{h.c.},$$

$$\Delta\mathcal{L}_{\mathrm{FCNC}} = -\frac{g_q g_\ell \lambda^\ell_{ab}}{4m_\rho^2}\left[\lambda^q_{ij}\left(\bar{d}^i_L\gamma_\mu d^j_L\right) - (V\lambda^q V^\dagger)_{ij}\left(\bar{u}^i_L\gamma_\mu u^j_L\right)\right]\left[\left(\bar{\ell}^a_L\gamma_\mu\ell^b_L\right) - \left(\bar{\nu}^a_L\gamma_\mu\nu^b_L\right)\right],$$

$$\Delta\mathcal{L}_{\Delta F=2} = -\frac{g_q^2}{8m_\rho^2}\left[(\lambda^q_{ij})^2\left(\bar{d}^i_L\gamma_\mu d^j_L\right)^2 + (V\lambda^q V^\dagger)^2_{ij}\left(\bar{u}^i_L\gamma_\mu u^j_L\right)^2\right],$$

$$\Delta\mathcal{L}_{\mathrm{LFV}} = -\frac{g_\ell^2}{8m_\rho^2}\lambda^\ell_{ab}\lambda^\ell_{cd}(\bar{\ell}^a_L\gamma_\mu\ell^b_L)(\bar{\ell}^c_L\gamma_\mu\ell^d_L),$$

$$\Delta\mathcal{L}_{\mathrm{LFU}} = -\frac{1}{2m_\rho^2}\left[-\frac{g_\ell^2}{2}\lambda^\ell_{ab}\lambda^\ell_{cd} + g_\ell^2\lambda^\ell_{ad}\lambda^\ell_{cb}\right](\bar{\ell}^a_L\gamma_\mu\ell^b_L)(\bar{\nu}^c_L\gamma_\mu\nu^d_L).$$

Low-energy data fit

◇ Input data – ρ_μ and ω_μ.

Parameters: $\epsilon_{q,\ell} = \frac{g_{q,\ell} m_W}{g m_\rho}, \lambda^q_{bs}, \lambda^\ell_{\tau\mu}$.

	Obs. $\mathcal{O}_i$	Prediction $\mathcal{O}_i(x_\alpha)$	Experimental value
$b \to c\tau\nu$	R_0	$\epsilon_\ell \epsilon_q$	0.13 ± 0.03
$b \to s\mu\mu$	ΔC_9^μ	$-(\pi/\alpha_{\rm em})\, \lambda^\ell_{\mu\mu}(\epsilon_\ell\epsilon_q + \epsilon^0_\ell\epsilon^0_q)\, \lambda^q_{bs}/\lvert V^*_{tb}V_{ts}\rvert$	-0.58 ± 0.16
B_s mix	$\Delta R^{\Delta F=2}_{B_s}$	$\left(\epsilon_q^2 + (\epsilon_q^0)^2\right)\lvert\lambda^q_{bs}\rvert^2 \,(\lvert V^*_{tb}V_{ts}\rvert^2 R^{\rm loop}_{\rm SM})^{-1}$	-0.10 ± 0.07
$b \to c\ell\nu$	$\Delta R^{\mu e}_{b\to c}$	$2\epsilon_\ell\epsilon_q\lambda^\ell_{\mu\mu}$	< 0.01
$\tau \to \ell\nu\nu$	$R_{\tau\to\mu/e}$	$\left\lvert 1 + \epsilon_\ell^2\lambda^\ell_{\mu\mu} + \frac{(\epsilon^0_\ell)^2 - \epsilon_\ell^2}{2}\lvert\lambda^\ell_{\tau\mu}\rvert^2 \right\rvert^2 + \left\lvert \frac{\epsilon_\ell^2 + (\epsilon^0_\ell)^2}{2}\lambda^\ell_{\tau\mu}\right\rvert^2$	1.0040 ± 0.0032
$\tau \to 3\mu$	$\Lambda^{-2}_{\tau\mu}$	$(G_F/\sqrt{2})\left(\epsilon_\ell^2 + (\epsilon^0_\ell)^2\right)\lambda^\ell_{\mu\mu}\lambda^\ell_h\tau\mu$	$< 4.1 \times 10^{-9}\ {\rm GeV}^{-2}$
D mix	Λ^{-2}_{uc}	$(G_F/\sqrt{2})\left(\epsilon_q^2 + (\epsilon^0_q)^2\right)\lvert V_{ub}V^*_{cb}\rvert^2$	$< 5.6 \times 10^{-14}\ {\rm GeV}^{-2}$
$b \to s\nu\nu$	$R_{K^{(*)}\nu}$	$\frac{2}{3} + \frac{1}{3}\left\lvert 1 + \frac{\pi}{\alpha_{\rm em}}(\epsilon_\ell\epsilon_q - \epsilon^0_\ell\epsilon^0_q)\frac{\lambda^q_{bs}}{\lvert V^*_{tb}V_{ts}\rvert C^{\rm SM}_\nu}\right\rvert^2$	< 2.6

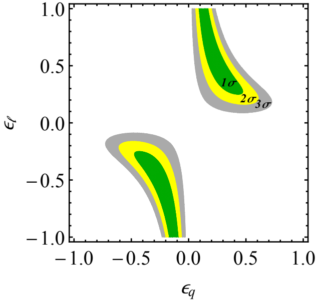
◇ Color octet contribution to meson mixing: $(\epsilon^0_q)^2 \to -2\epsilon^2_O/3$

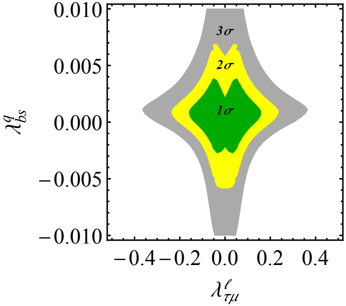
$\mathcal{L} \supset \frac{g_O}{2}\lambda^q_{ij}\mathcal{V}^A\bar{q}^i_L\gamma_\mu T^A q^j_L$

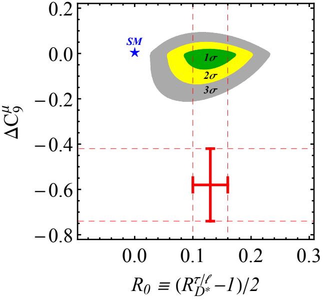
◇ Leptoquarks – in the extended $\mathrm{SU}(8)$ model – can also contribute

see also Barbieri, Isidori, Pattori, Senia 1512.01560

Low-energy fit: results







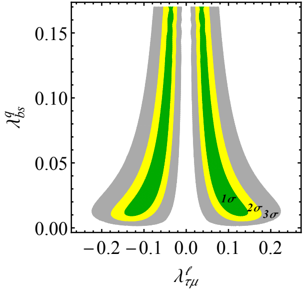
- Fit driven by $R_0(D^*) = \epsilon_q \epsilon_\ell$.
- Small values of $\lambda^q_{bs} \ll V_{ts}$.
- Good fit to $b \to c\tau\nu$. Somewhat smaller $b \to s\mu\mu$ due to B_s mixing and $\tau \to \mu/e$ constraints.

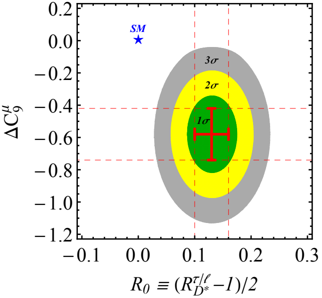
Only contribution from ρ_μ and ω_μ

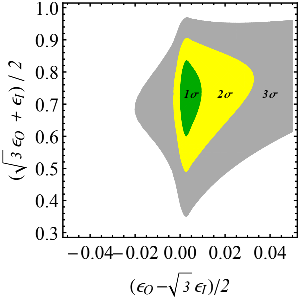
Low-energy fit: results

Including QQ and LL mesons

- ◇ Excellent fit to $b \to c\tau\nu$ and $b \to s\mu\mu$
- ◇ Size of λ^q_{bs} as expected
- ◇ Somewhat tuned cancellation in B_s mixing





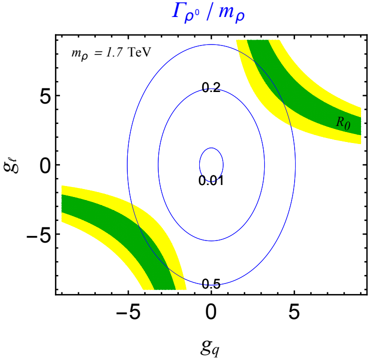


LHC phenomenology: ρ mesons

Due to large coupling, vector mesons decay mainly into 3rd gen. fermions.

$$\Gamma_{\rho^0\to\tau^+\tau^-\,(\nu_\tau\bar\nu_\tau)} = \frac{g_\ell^2}{96\pi} m_\rho\,, \qquad \Gamma_{\rho^0\to b\bar b\,(t\bar t)} = \frac{g_q^2}{32\pi} m_\rho.$$

- ρ is expected to be a broad resonance



Decays to pairs of pNGB through TC interaction can also be sizable:

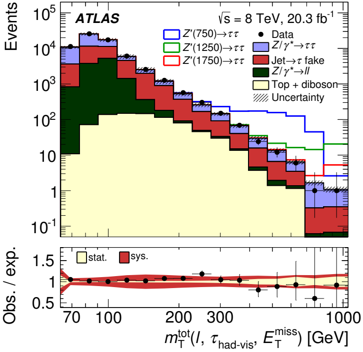
$$\Gamma_{\rho\to\pi\pi} = \frac{g_{\rho\pi\pi}^2}{192\pi} m_\rho \left(1 - \frac{4m_\pi^2}{m_\rho^2}\right)\,,$$

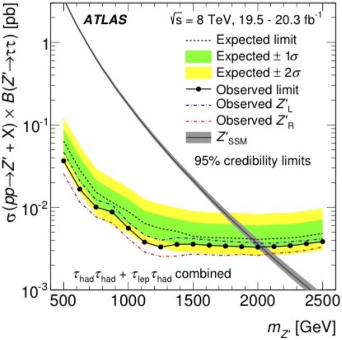
$$\left(\mathcal{L} = \frac{g_{\rho\pi\pi}}{2}\epsilon_{abc}\rho^a_\mu \pi^b \partial_\mu \pi^c\right)$$

- Main production channel: $b\bar b \to \rho^0$ single production.
  For $g_q = 5$, $m_\rho = 1.7\,\mathrm{TeV}$, one finds $\sigma_{b\bar b}/\sigma_{u\bar u} \approx 7$.

LHC phenomenology: $\rho^0 \to \tau\tau$

ATLAS search for Z' decaying into $\tau^+\tau^-$, 1502.07177

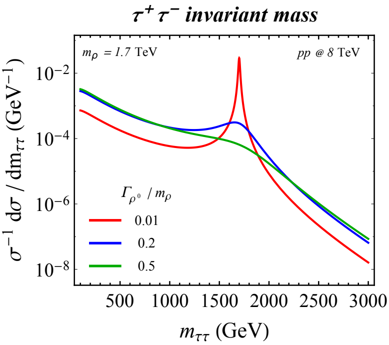


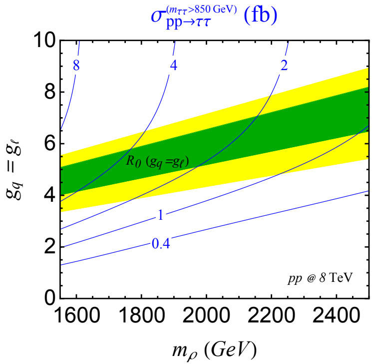


- ◇ For large masses (above $\sim$ 1.5 TeV), basically one bin in total transverse mass: $m^T_{\rm tot} > 850\,\mathrm{GeV}$.
- ◇ 95% C.L. exclusion above 1.5 TeV: $\sigma < 4\,\mathrm{fb}$ $(7\,\mathrm{fb})$ for a narrow width (20% width).

LHC phenomenology: $\rho^0 \to \tau\tau$

Recast the exclusion approximating $m^T_{\rm tot} \approx m_{\tau\tau}$:





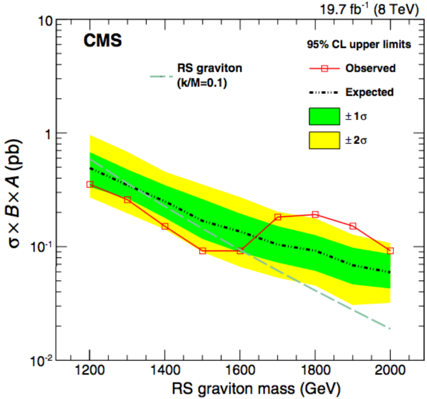
Cross-section $\sigma(pp \to \rho \to \tau\tau)$, for $m_{\tau\tau} > 850\,\mathrm{GeV}$

ATLAS bound: $\sigma \gtrsim 4 \div 7\,\mathrm{fb}$. The relevant region above $\sim 1.5\,\mathrm{TeV}$ still allowed, but will be probed soon!

LHC phenomenology: $\rho^0 \to b\bar{b}$

Large coupling to t, b: $\rho \to bb$ is another relevant channel.

CMS search for heavy resonances $pp \to X \to jj/jb/bb$, 1501.4198.

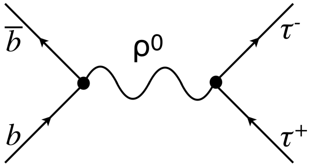


- At present, limits not comparable with $\tau\tau$ channel, if $g_q \approx g_\ell$.
- If $g_q \gtrsim g_\ell$, it could also become an interesting channel soon!
- (ATLAS results similar)

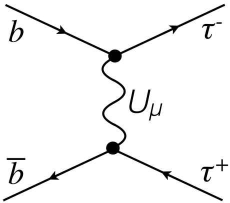
LHC phenomenology: Leptoquarks

The signal in $pp \to \tau\tau$ (and $pp \to bb$) is a rather generic prediction in this framework, whatever the specific realisation.

Flavour anomalies at low p_T	$\Rightarrow$	High p_T signatures at LHC



- The exchange of ρ in the s-channel gives a signal in the high-mass tails of $\tau\tau$ distribution.



- The exchange of Leptoquarks in the t-channel gives a very similar signature in $\tau\tau$.

Summary

- There are several intriguing experimental hints of new phenomena, both at low and high p_T:
  - Lepton flavour universality violation in B decays,
  - Diphoton resonance at LHC.
- They can be described by a single coherent picture, involving a new strongly interacting sector and vectorlike confinement:
  - Singlet pNGB $pp \to \eta \to \gamma\gamma$
  - Flavour effects due to exchange of vector resonances ρ, ω, ...
- $U(2)$ flavour symmetry: couplings mostly to 3rd generation, a specific pattern of flavour violation in light generations.
- A generic prediction: new resonances should be seen soon in $\tau\tau$, bb final states at the LHC!

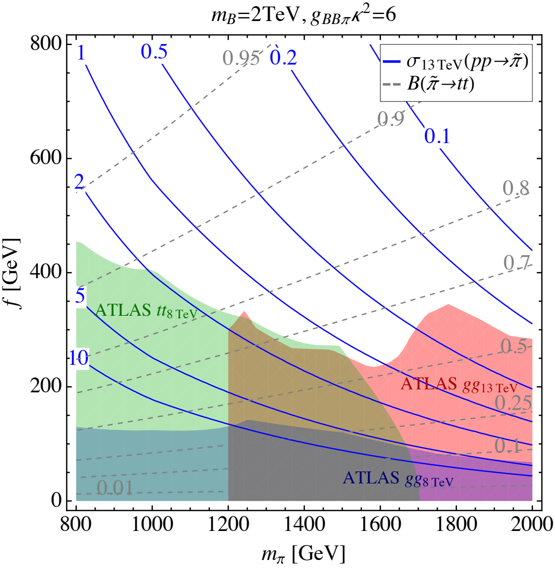
A few comments

- ⋄ The models presented here are a sketch: many different realisations are possible: more states, different symmetry groups, . . .
- ⋄ Many predictions qualitative, due to strong interactions.
- ⋄ Many experimental searches not optimized for this scenario.
- ⋄ Higgs should really be included in the picture: if new physics at the TeV, should be natural.
- ⋄ Is the embedding in $\mathrm{SU}(5)$ of the minimal scenario accidental?
- ⋄ Diphoton resonance not really compelling (slightly larger f, different coset, can decay in other channels,. . .)

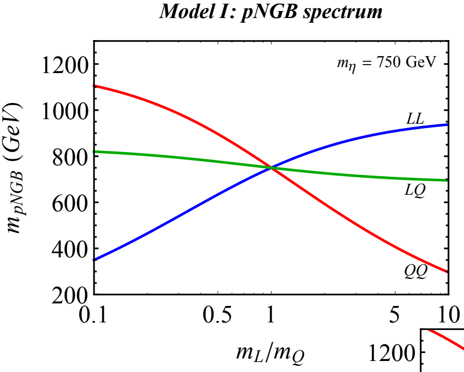
Thank you!

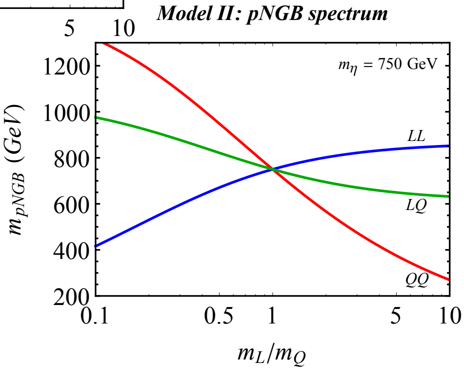
Backup

Bounds on color octets



Mass of TC-fermions





Other models w/ flavour and diphoton

- Scalar singlet + Scalar leptoquark in the loop to enhance production + VL fermions in the loop to enhance diphoton BR

$$\mathcal{L} \supset \kappa_\phi S \phi^* \phi + \kappa_\psi S \bar{\psi} \psi$$

Bauer and Neubert 1512.06828

- Diphoton resonance as a flavon + VL quarks

Bonilla et al. 1602.08092