Overview of UV completions of effective models explaining B-physics anomalies

Werner Porod

(Uni. Würzburg)

28 Aug. 2019

Overview

Why extending the SM?

Most of the data can be explained (extremely well) by the SM, but

- Flavour
  - hierarchy of fermion masses, in particular ν
  - mixing pattern: small mixing for q versus large mixing for ν
- anomalies
  - $(g-2)_\mu$
  - b-physics:

$$R_{D^{(*)}} = \frac{\Gamma(\bar{B} \to D^{(*)}\tau\bar{\nu})}{\Gamma(\bar{B} \to D^{(*)}l\bar{\nu})} \; (l = e, \mu) \qquad , \; R_{K^{(*)}} = \frac{\Gamma(\bar{B} \to \bar{K}^{(*)}\mu^+\mu^-)}{\Gamma(\bar{B} \to \bar{K}^{(*)}e^+e^-)}$$

  - ...
- Cosmology
  - Dark matter
  - Baryon asymmetry of the Universe

Flavour as probe of new physics

Flavour physics is sensitive to virtual effects of heavy new physics.

Flavour-changing neutral current (FCNC) interactions probe scales up to 100 TeV and above, because in the Standard Model several suppression factors mount up:

- electroweak loop
- small CKM elements, e.g. $|V_{ts}| = 0.04$, $|V_{td}| = 0.01$
- Glashow-Iliopoulos-Maiani (GIM) suppression

$$\propto \frac{m_c^2 - m_u^2}{m_W^2} \,, \quad \frac{m_s^2 - m_d^2}{m_W^2} \,,$$

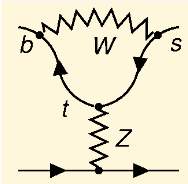
  in K and D decays
- helicity suppression

$$\propto \frac{m_b}{m_W}$$

  in radiative and leptonic B decays.

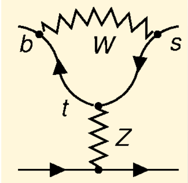
Decays governed by $b \to s l^+ l^- (l = e, \mu)$:

- $B \to K l^+ l^-$
- $B \to K^* l^+ l^-$
- $B \to \phi l^+ l^-$



Decays governed by $b \to s l^+ l^- (l = e, \mu)$:

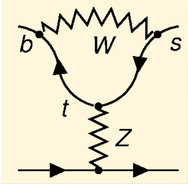
- $B \to K l^+ l^-$
- $B \to K^* l^+ l^-$
- $B \to \phi l^+ l^-$



- $B \to K^* \mu^+ \mu^-$ permits the measurement of angular observables, defined in terms of angles within and between the $K^* \to K\pi$ and $\mu^+\mu^-$ decay planes. One of those, called P_5' deviates from the SM prediction by more than 3σ in the LHCb experiment.

Decays governed by $b \to s l^+ l^- (l = e, \mu)$:

- $B \to K l^+ l^-$
- $B \to K^* l^+ l^-$
- $B \to \phi l^+ l^-$



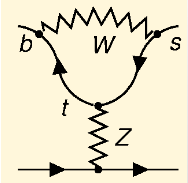
- $B \to K^* \mu^+ \mu^-$ permits the measurement of angular observables, defined in terms of angles within and between the $K^* \to K\pi$ and $\mu^+\mu^-$ decay planes. One of those, called P_5' deviates from the SM prediction by more than 3σ in the LHCb experiment.
- The LHCb data for ratios

$$\frac{BR(B \to K \mu^+ \mu^-)}{BR(B \to K e^+ e^-)} \text{ and } \frac{BR(B \to K^* \mu^+ \mu^-)}{BR(B \to K^* e^+ e^-)}$$

are too small by $2.3 - 2.6\sigma$ in some bins of the lepton invariant mass q^2

Decays governed by $b \to s l^+ l^- (l = e, \mu)$:

- $B \to K l^+ l^-$
- $B \to K^* l^+ l^-$
- $B \to \phi l^+ l^-$



- $B \to K^* \mu^+ \mu^-$ permits the measurement of angular observables, defined in terms of angles within and between the $K^* \to K\pi$ and $\mu^+\mu^-$ decay planes. One of those, called P_5' deviates from the SM prediction by more than 3σ in the LHCb experiment.
- The LHCb data for ratios

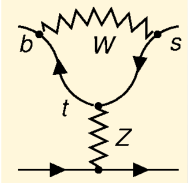
$$\frac{BR(B \to K\mu^+\mu^-)}{BR(B \to K e^+ e^-)} \text{ and } \frac{BR(B \to K^*\mu^+\mu^-)}{BR(B \to K^* e^+ e^-)}$$

are too small by $2.3 - 2.6\sigma$ in some bins of the lepton invariant mass q^2

- $BR(B \to \phi\mu^+\mu^-)$ measurement about 2.2σ below SM prediction

Decays governed by $b \to s l^+ l^- (l = e, \mu)$:

- $B \to K l^+ l^-$
- $B \to K^* l^+ l^-$
- $B \to \phi l^+ l^-$



- $B \to K^* \mu^+ \mu^-$ permits the measurement of angular observables, defined in terms of angles within and between the $K^* \to K\pi$ and $\mu^+\mu^-$ decay planes. One of those, called P_5' deviates from the SM prediction by more than 3σ in the LHCb experiment.
- The LHCb data for ratios

$$\frac{BR(B \to K\mu^+\mu^-)}{BR(B \to K e^+ e^-)} \text{ and } \frac{BR(B \to K^*\mu^+\mu^-)}{BR(B \to K^* e^+ e^-)}$$

  are too small by $2.3 - 2.6\sigma$ in some bins of the lepton invariant mass q^2
- $BR(B \to \phi\mu^+\mu^-)$ measurement about 2.2σ below SM prediction
- G. D'Amico et al., arXiv:1704.05438: include updates Moriond 2019, R_K by LHCb and R_{K^*} by Belle, despite shift in direction of SM, conclusions are unchanged

Flavour universality

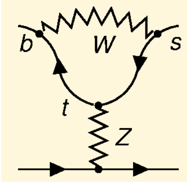
Effective Hamiltonian

$$H = -\frac{4G_F V_{tb} V_{ts}^*}{\sqrt{2}} \sum_{l=e,\mu,\tau} \left[C_9^{ll} O_9^{ll} + C_{10}^{ll} O_{10}^{ll} + C_9'^{\,ll} O_9'^{\,ll} + C_{10}'^{\,ll} O_{10}'^{\,ll} \right] + \ldots$$

We need in particular

$$O_9^{ll} = \frac{\alpha}{4\pi} \bar{s}_L \gamma^\mu b_L \, \bar{l} \gamma_\mu l \quad \text{and} \quad O_{10}^{ll} = \frac{\alpha}{4\pi} \bar{s}_L \gamma^\mu b_L \, \bar{l} \gamma_\mu \gamma_5 l$$

Wilson coefficients C_9^{ll} and C_{10}^{ll} from the Z-penguin diagram and other diagrams



In the SM

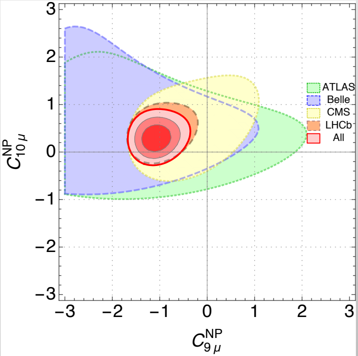
$$C_{9,10}^{ll} \equiv C_{9,10}^{ee} = C_{9,10}^{\mu\mu} = C_{9,10}^{\tau\tau}$$

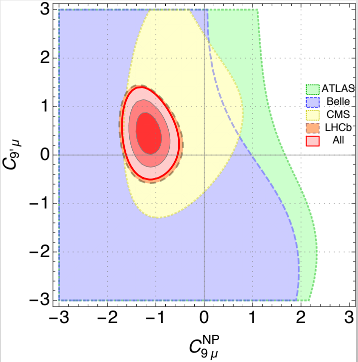
Flavour universality of the weak interaction!

Global fits to all relevant observables (including those which comply with the SM prediction) point consistently to new physics with

$$C_9^{\mu\mu,NP} \simeq -\frac{1}{4} C_9^{\mu\mu,SM}$$

and also potential NP contributions to $C_{10}^{\mu\mu}$ and/or $C_9'^{\mu\mu}$





B. Capdevila, A. Crivellin, S. Descotes-Genon, J. Matias and J. Virto, arXiv:1704.05340 update by F. Straub in Moriond 2019

- Methodology: In a global fit of the Wilson coefficients to all data one performs a likelihood test, comparing the likelihood of the best-fit point to that of the SM scenario.
- Result: For scenarios in which new physics contributions are assumed to be only in $C_{9,10}^{\mu\mu}$ (and possibly in the coefficients $C'_{9,10}{}^{\mu\mu}$), the statistical significance of the new-physics hypothesis ranges between 5.0σ and 5.7σ. The sign and magnitude of the deviation is consistent in all observables, and observables insensitive to $C_{9,10}^{\mu\mu}$ are measured SM-like.

  (B. Capdevila, A. Crivellin, S. Descotes-Genon, J. Matias and J. Virto, arXiv:1704.05340)

Explanation within the SM

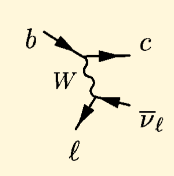
The predictions for $B_s \to \phi\mu^+\mu^-$ and P_5' involve hadronic physics, one needs non-perturbative methods

1. to constrain the contributions from $(c, \bar{c})$ resonances which convert to $\mu^+\mu^-$ via a virtual photon.
2. to calculate the $B_s \to \phi$ and $B_s \to K^*$ form factors

$\Rightarrow$ underestimated theory uncertainties can fake new physics in C_9^{ll}

Decays governed by $b \to c l \bar{\nu}$:

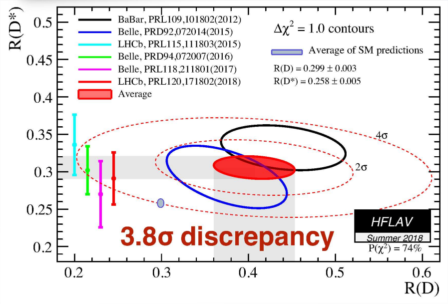
- $B \to D \tau \bar{\nu}$
- $B \to D^* \tau \bar{\nu}$
- $B \to J/\psi\, \tau \bar{\nu}$



$$R_D = \frac{BR(B \to D \tau \bar{\nu})}{BR(B \to D \mu \bar{\nu})}\,,\quad R_{D^*} = \frac{BR(B \to D^* \tau \bar{\nu})}{BR(B \to D^* \mu \bar{\nu})}\,,\quad R_{J/\psi} = \frac{BR(B \to J/\psi\, \tau \bar{\nu})}{BR(B \to J/\psi\, \mu \bar{\nu})}\,,$$

are all measured to be larger than the SM prediction.
The SM is very robust!

The R(D) and R(D*) puzzles



$$R(D) \equiv \frac{\mathcal{B}(\bar{B} \to D^+\tau^-\bar{\nu}_\tau)}{\mathcal{B}(\bar{B} \to D^+\ell^-\bar{\nu}_\ell)}$$

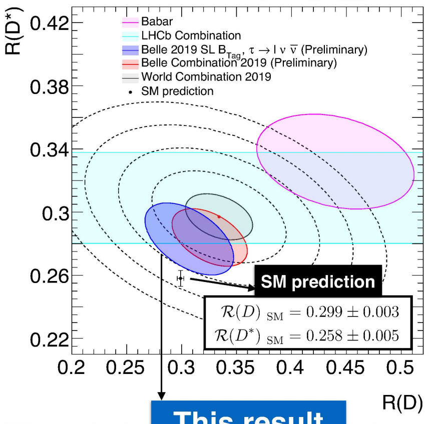
$$R(D^*) \equiv \frac{\mathcal{B}(\bar{B} \to D^{*+}\tau^-\bar{\nu}_\tau)}{\mathcal{B}(\bar{B} \to D^{*+}\ell^-\bar{\nu}_\ell)}$$

where $\ell = e,\mu$

Experiment	Tag method	τ mode	R(D)	R(D*)
Babar '12	Hadronic	ν ν	**0.440 ± 0.058 ± 0.042**	0.332 ± 0.024 ± 0.018
Belle '15	Hadronic	ν ν	**0.375 ± 0.064 ± 0.026**	0.293 ± 0.038 ± 0.015
LHCb '15	-	ν ν	-	0.336 ± 0.027 ± 0.030
Belle '16	**Semileptonic**	ν ν	-	0.302 ± 0.030 ± 0.011
Belle '17	Hadronic	π ν, ρ ν	-	0.270 ± 0.035 ± 0.027
LHCb '18	-	π π π	-	0.291 ± 0.019 ± 0.029
Average	-	-	**0.407 ± 0.039 ± 0.024**	0.306 ± 0.013 ± 0.007
SM			**0.299 ± 0.003**	0.258 ± 0.005

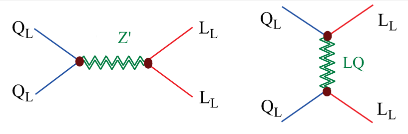
Conclusion / Preliminary R(D$^{(*)}$) averages

- **Most precise measurement** of R(D) and R(D*) to date
- First **R(D)** measurement performed with a **semileptonic tag**
- Results **compatible with SM** expectation within **1.2σ**
- **R(D) - R(D*) Belle average** is now within **2σ** of the SM prediction
- **R(D) - R(D*) exp. world average** tension with SM expectation **decreases from 3.8σ to 3.1σ**



$$\mathcal{R}(D) = 0.307 \pm 0.037 \pm 0.016$$
$$\mathcal{R}(D^*) = 0.283 \pm 0.018 \pm 0.014$$

B-physics anomalies: `simplified models' + roads to UV completions

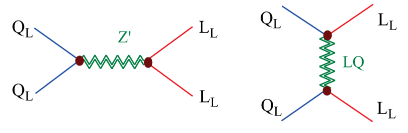


Roads to UV completions

Non-perturbative TeV-scale dynamics (non-renormalizable models)

Perturbative TeV-scale dynamics (renormalizable models)

B-physics anomalies: `simplified models' + roads to UV completions



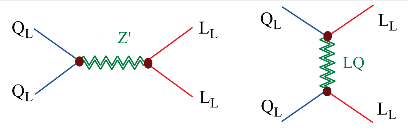
Roads to UV completions

Non-perturbative TeV-scale dynamics (non-renormalizable models)

- Scalar LQ as PNG: Gripaios, '10; Gripaios, Nardecchia, Renner, '14 . . .
- Vector LQ (or W',Z') as technifermion resonances: Barbieri et al. '15; Buttazzo et al. '16; Barbieri et al. '17 . . .
- W', Z' as Kaluza-Klein excitations (e.g. from warped extra dim.): Megias, Quiros, Salas '17; Megias, Panico, Pujolas, Quiros '17 . . .

Perturbative TeV-scale dynamics (renormalizable models)

B-physics anomalies: 'simplified models' + roads to UV completions



Roads to UV completions

Non-perturbative TeV-scale dynamics (non-renormalizable models)

- Scalar LQ as PNG: Gripaios, '10; Gripaios, Nardecchia, Renner, '14 ...
- Vector LQ (or W',Z') as technifermion resonances: Barbieri et al. '15; Buttazzo et al. '16; Barbieri et al. '17 ...
- W', Z' as Kaluza-Klein excitations (e.g. from warped extra dim.): Megias, Quiros, Salas '17; Megias, Panico, Pujolas, Quiros '17 ...

Perturbative TeV-scale dynamics (renormalizable models)

- Renormalizable models with scalar mediators (LQ, but also RPV-SUSY): Hiller, Schmaltz, '14; Becirevic et al. '16; Fajfer et al. '15-'17; Dorsner et al. '17; Crivellin, Müller, Ota '17; Altmannshofer, Dev, Soni, '17 ...
- Gauge models: Cline, Camalich '17; Calibbi, Crivellin, Li, '17; Assad, Fornal, Grinstein, '17; Di Luzio, Greljo, Nardecchia, '17 ...

not all leptoquarks can do the job: G. D'Amico et al.,arXiv:1704.05438

scalar leptoquarks

Lepto-Quark	coupling structure	potential explanation
$S_3 \sim (\bar{3}, 3, 1/3)$	$y\, QL\, S_3 + y'\, QQ\, S_3^\dagger +$ h.c.	x
$R_2 \sim (3, 2, 7/6)$	$y\, UL\, R_2 + y'\, QE\, R_2^\dagger +$ h.c.	x
$\tilde{R}_2 \sim (3, 2, 1/6)$	$y\, DL\, \tilde{R}_2 +$ h.c.	
$\tilde{S}_1 \sim (\bar{3}, 1, 4/3)$	$y\, DE\, \tilde{S}_1 + y'\, UU\, \tilde{S}_1^\dagger +$ h.c.	x

vector leptoquarks

Lepto-Quark	coupling structure	potential explanation
$U_3 \sim (3, 3, 2/3)$	$\bar{Q}\gamma_\mu L\, U_3^\mu +$ h.c.	x
$V_2 \sim (\bar{3}, 2, 5/6)$	$y\, \bar{D}\gamma_\mu L\, V_2^\mu + y'\, \bar{Q}\gamma_\mu E\, V_2^\mu + y''\, \bar{Q}\gamma_\mu U\, V_2^{\dagger\mu} +$ h.c.	
$U_1 \sim (\bar{3}, 1, 2/3)$	$y\, \bar{Q}\gamma_\mu L\, U_1^\mu + y_2\, \bar{D}\gamma_\mu E\, U_1^\mu +$ h.c.	x

C. W. Murphy, arXiv:1512.06976: U_1 is very promising
D. Buttazzo, A. Greljo, G. Isidori, D. Marzocca,
arXiv:1706.07808: U_1 or $S_1 + S_3$ very promising

for details on leptoquark phenomenolgy:
I. Doršner, S. Fajfer, A. Greljo, J. F. Kamenik and N. Košnik, arXiv:1603.04993

U_1 appears naturally in $SU(4)$, but non-observation of $K_L \to e\mu$ implies $m_{U_1} \gtrsim 10^6$ GeV in the simplest models.

Some proposals on how to save this

- $SU(4) \times SU(3) \times SU_L(2) \times U(1)$, where $SU(3)_C$ emerges from the diagonal part of $SU(3) \times SU(3)' \subset SU(4)$ + extra vector-like fermions
  L. Di Luzio, A. Greljo, and M. Nardecchia, arXiv:1708.08450;
  C. Cornella, J. Fuentes-Martin and G. Isidori, arXiv:1903.11517.
- $SU(4) \times SU_L(2) \times SU(2)_R \times U(1)_{PQ}$ + extra-like fermions + textures
  L. Calibbi, A. Crivellin, and T. Li, arXiv:1709.00692.
- 3-site $SU(4) \times SU_L(2) \times SU(2)_R$ + extra-like fermions + link fields
  M. Bordone, C. Cornella, J. Fuentes-Martin, and G. Isidori, arXiv:1712.01368.
- $SU(4) \times SU_L(2) \times SU(2)_R$ + Randall-Sundrum
  M. Blanke and A. Crivellin, arXiv:1801.07256.
- $SU(4)_L \times SU(4)_R \times SU_L(2) \times U(1)$+ extra-like fermions (automatic)
  B. Fornal, S. A. Gadam and B. Grinstein, arXiv:1812.01603

two problems

- contributions of the scalar sector to observables ignored
- usually a rather specific Ansatz for the flavor structure which is not RGE invariant

$SU(4)\times SU(2)_L\times U(1)_R$ as an example†

possible origin*:

$$SO(10)\to SU(4)\times SU(2)_L\times U(1)_R \text{ via } 45_H+126_H$$

Particle content: gauge bosons

	$SU(4)\times SU(2)_L\times U(1)_R$	$SU(3)_C\times SU(2)_L\times U(1)_Y$
$A_\mu=\begin{pmatrix} G_\mu & U_{1\mu} \\ U^*_{1,\mu} & B'_\mu \end{pmatrix}$	$(15,1,0)$	G_μ $(8,1,0)$ $U_{1,\mu}$ $(3,1,2/3)$ B'_μ $(1,1,0)$
W_μ	$(1,3,0)$	$(1,3,0)$
B_μ	$(1,1,0)$	$(1,1,0)$

Linear combination of B and B' gives B_Y, the orthognal one a Z' after symmetry breaking

$$m_{U_1}\simeq m_{Z'}$$

† model based on A.D. Smirnov, hep-ph/9503239, P. Fileviez Perez, M.B. Wise arXiv:13076213
* S. Bertolini, L. Di Luzio and M. Malinsky, arXiv:1202.0807 breaking without tachyons

Scalars

	G_{421}	G_{321}	G_{31}
$\chi = \begin{pmatrix} \bar{S}_1^\dagger \\ \chi^0 \end{pmatrix}$	$(4, 1, 1/2)$	$\bar{S}_1^\dagger$ $(3, 1, 2/3)$ χ^0 $(1, 1, 0)$	$(3, 1, 2/3)$ $(1, 0)$
H	$(1, 2, 1/2)$	$(1, 2, 1/2)$	H_1^+ $(1, 1)$ H_1^0 $(1, 0)$
$\Phi = \begin{pmatrix} G & R_2 \\ \tilde{R}_2^\dagger & H2 \end{pmatrix}$	$(15, 2, 1/2)$	R_2 $(3, 2, 7/6)$ $\tilde{R}_2^\dagger$ $(\bar{3}, 2, -1/6)$ G $(8, 2, 1/2)$ H_2 $(1, 2, 1/2)$	$R_2^{5/3}$ $(3, 5/3)$ $R_2^{2/3}$ $(3, 2/3)$ $\tilde{R}_2^{-1/3\,\dagger}$ $(\bar{3}, 1/3)$ $\tilde{R}_2^{2/3\,\dagger}$ $(\bar{3}, -2/3)$ G^+ $(8, 1)$ G^0 $(8, 0)$ H_2^+ $(1, 1)$ H_2^0 $(1, 0)$

$$G_{421} = SU(4) \times SU(2)_L \times U(1)_R \;,\; G_{321} = SU(3)_C \times SU(2)_L \times U(1)_Y \;,\; G_{31} = SU(3)_C \times U(1)_{em}$$

$$\langle \chi \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v_\chi \end{pmatrix}, \qquad \langle H \rangle = \frac{1}{\sqrt{2}} \begin{bmatrix} 0 \\ v_1 \end{bmatrix}, \; \langle \Phi \rangle = \frac{1}{2\sqrt{6}} \begin{pmatrix} \not{1} & 0 \\ 0 & -3 \end{pmatrix} \otimes \begin{bmatrix} 0 \\ v_2 \end{bmatrix},$$

Scalar potential

$$
\begin{aligned}
V = {} & m_H^2|H|^2 + m_\chi^2|\chi|^2 + m_\Phi^2 \mathrm{Tr}(|\Phi|^2) + \lambda_1|H|^2|\chi|^2 \\
& + \lambda_2|H|^2\mathrm{Tr}(|\Phi|^2) + \lambda_3|\chi|^2\mathrm{Tr}(|\Phi|^2) + (\lambda_4 H_i^\dagger \chi^\dagger \Phi^i \chi + \mathrm{h.c.}) \\
& + \lambda_5 H_i^\dagger \mathrm{Tr}(\Phi_j^\dagger \Phi^i) H^j + \lambda_6 \chi^\dagger \Phi^i \Phi_i^\dagger \chi + \lambda_7|H|^4 + \lambda_8|\chi|^4 \\
& + \lambda_9 \mathrm{Tr}(|\Phi|^4) + \lambda_{10}(\mathrm{Tr}|\Phi|^2)^2 + \Big(\lambda_{11} H_i^\dagger\, \mathrm{Tr}(\Phi^i\, \Phi^j) H_j^\dagger \\
& + \lambda_{12} H_i^\dagger\, \mathrm{Tr}(\Phi^i\, \Phi^j\, \Phi_j^\dagger) + \lambda_{13} H_i^\dagger\, \mathrm{Tr}(\Phi^i\, \Phi_j^\dagger\, \Phi^j) + \mathrm{h.c.}\Big) \\
& + \lambda_{14}\chi^\dagger|\Phi|^2\chi + \lambda_{15}\mathrm{Tr}(\Phi_i^\dagger\, \Phi^j\, \Phi_j^\dagger\, \Phi^i) \\
& + \lambda_{16}\mathrm{Tr}(\Phi_i^\dagger\, \Phi^j)\, \mathrm{Tr}(\Phi_j^\dagger\, \Phi^i) + \lambda_{17}\mathrm{Tr}(\Phi_i^\dagger\, \Phi_j^\dagger)\, \mathrm{Tr}(\Phi^i\, \Phi^j) \\
& + \lambda_{18}\mathrm{Tr}(\Phi_i^\dagger\, \Phi_j^\dagger\, \Phi^i\, \Phi^j) + \lambda_{19}\mathrm{Tr}(\Phi_i^\dagger\, \Phi_j^\dagger\, \Phi^j\, \Phi^i)
\end{aligned}
$$

with $|H|^2 = H_i^\dagger H^i$, $|\chi|^2 = \chi^\dagger\chi$, $|\Phi|^2 = \Phi_i^\dagger\Phi^i$; $i, j \ldots SU(2)$ indices.
After $SU(4)$ breaking, one has a sum-rule among the $SU(2)_L$ doubets

$$
m_G^2 + 2m_{H'}^2 \sin^2\beta = \frac{3}{2}(m_{R_2}^2 + m_{\tilde{R}_2}^2)\,,
$$

After $SU(2)_L$ breaking

$$
\tilde{R}_2^{2/3}, R_2^{2/3} \to R'_{1,2}
$$

Fermions

	$SU(4)\times SU(2)_L\times U(1)_R$	$SU(3)_C\times SU(2)_L\times U(1)_Y$
$F_L=\begin{pmatrix}Q\\L\end{pmatrix}$	$(4,2,0)$	Q $(3,2,1/6)$ L $(1,2,-1/2)$
$f_u^c=\begin{pmatrix}u^c & \nu^c\end{pmatrix}$	$(\bar 4,1,-1/2)$	u^c $(\bar 3,1,-2/3)$ ν^c $(1,1,0)$
$f_d^c=\begin{pmatrix}d^c & e^c\end{pmatrix}$	$(\bar 4,1,1/2)$	d^c $(\bar 3,1,1/3)$ e^c $(1,1,1)$
N	$(1,1,0)$	$(1,1,0)$

$$-\mathcal{L}_Y = f_u^c Y_1 H F_L + f_u^c Y_2 \Phi F_L + f_d^c Y_3 H^\dagger F_L + f_d^c Y_4 \Phi^\dagger F_L + f_u^c Y_5 \chi N + \frac{1}{2} N\mu N + \text{h.c.}$$

Mass matrices:

$$U_u^\dagger \hat{M}_u V_u = \frac{v_1}{\sqrt{2}} Y_1 + \frac{v_2}{2\sqrt{6}} Y_2, \quad U_d^\dagger \hat{M}_d V_d = \frac{v_1}{\sqrt{2}} Y_3 + \frac{v_2}{2\sqrt{6}} Y_4$$

$$U_\nu^\dagger \hat{M}_\nu U_\nu^* = \begin{pmatrix} 0 & \frac{v_1}{\sqrt{2}} Y_1 - \frac{3v_2}{2\sqrt{6}} Y_2 & 0 \\ \frac{v_1}{\sqrt{2}} Y_1^T - \frac{3v_2}{2\sqrt{6}} Y_2^T & 0 & \frac{v_\chi}{\sqrt{2}} Y_5 \\ 0 & \frac{v_\chi}{\sqrt{2}} Y_5^T & \mu \end{pmatrix}, \quad \hat{M}_e = \frac{v_1}{\sqrt{2}} Y_3 - \frac{3v_2}{2\sqrt{6}} Y_4$$

Numerical input

In the following, if not stated otherwise

$$V_u = V_d(\phi_{12}, \phi_{13}, \phi_{23}) V_{CKM}^\dagger \ , \ U_d = V_d^* \ , \ U_u = V_u^*$$

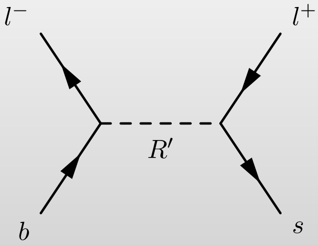
Numerical input values	
Y_2	diag$(10^{-8}, 10^{-7}, 10^{-5})$
Y_5	diag$(10^{-2}, 5 \cdot 10^{-2}, 10^{-1})$
$\phi_{12},\ \phi_{13},\ \phi_{23}$	$\pi/2,\ 0,\ \pi/4$
v_χ	$4 \cdot 10^6$ GeV
$m_A,\ m_{R_1'}$	$2 \cdot 10^5$ GeV, 900 GeV
$\tan\beta$	50

μ calculated from known neutrino masses and U_{PMNS}

U_1 contribution to $K_L \to e\mu \Rightarrow v_\chi > 10^6$

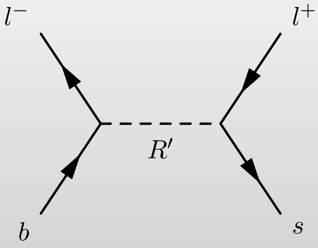
$\Rightarrow$ tiny mixing between R_1' and R_2' $\Rightarrow$ cannot explain $R_{D,D^*,J/\psi}$

Example ontributions of R' to different processes

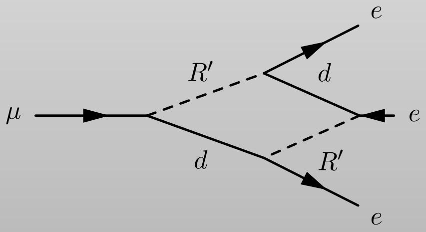


- the needed one

Example ontributions of R' to different processes

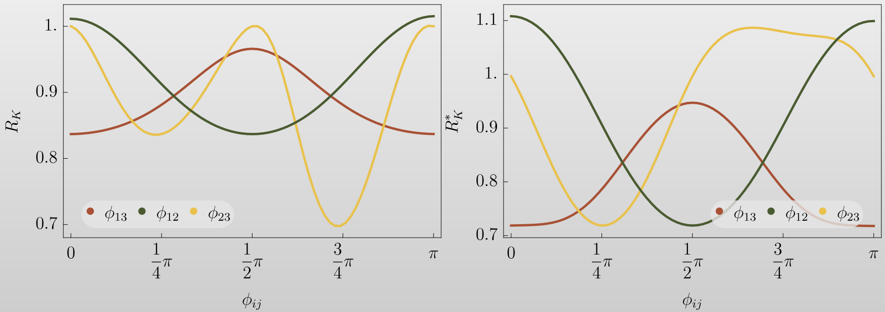


- the needed one



- but also this exists

Explanation of R_K and R_{K^*}

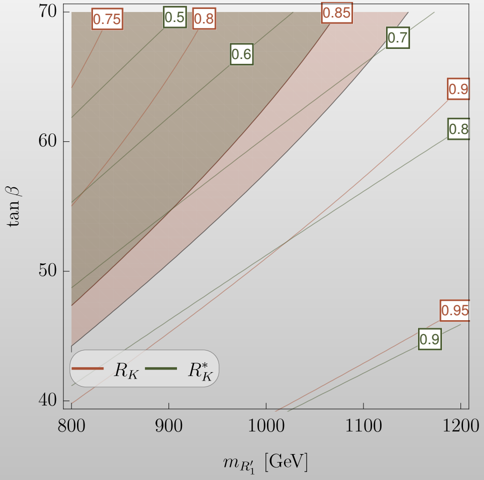


other parameters as in table shown before, in particular

$$(\phi_{12},\ \phi_{13},\ \phi_{23}) = (\pi/2,\ 0,\ \pi/4)$$

T. Faber, M. Hudec, M. Malinský, P. Meinzinger, W.P. and F. Staub, arXiv:1808.05511

Explanation of R_K and R_{K^*}

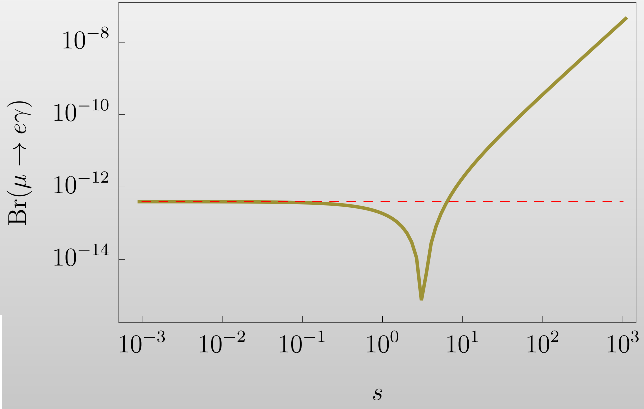


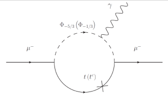
other parameters as in table shown before, in particular

$$(\phi_{12},\ \phi_{13},\ \phi_{23}) = (\pi/2,\ 0,\ \pi/4)$$

T. Faber, M. Hudec, M. Malinský, P. Meinzinger, W.P. and F. Staub, arXiv:1808.05511

Constraints: $\mu \to e\gamma$



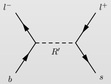


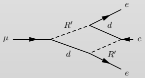
other parameters as in table shown before, in particular

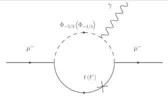
$$m_{R_1'} = 900\text{ GeV} \quad , \quad Y_2 = \text{diag}(10^{-8}, 10^{-7}, 10^{-5}) \to sY_2$$

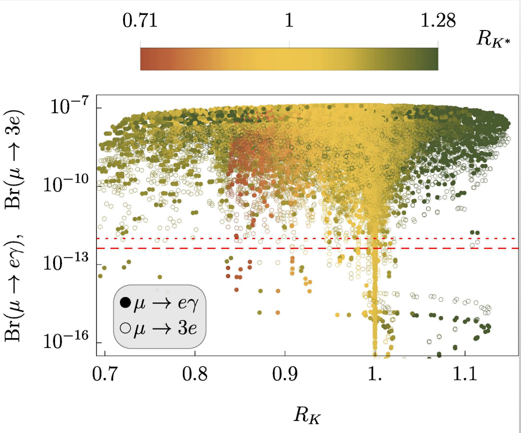
T. Faber, M. Hudec, M. Malinský, P. Meinzinger, W.P. and F. Staub, arXiv:1808.05511

Constraints: $\mu \to e\gamma$, $\mu \to 3e$









scan over $\phi_{12}, \phi_{12}, \phi_{12}$, other parameters as in table before

T. Faber, M. Hudec, M. Malinský, P. Meinzinger, W.P. and F. Staub, arXiv:1808.05511

Additional constraints

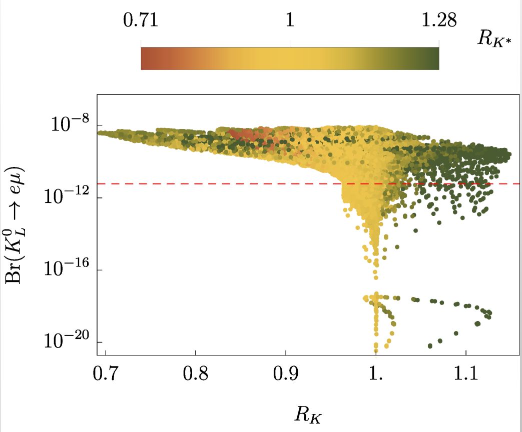
Once BR($\mu \to e\gamma$)and BR($\mu \to 3e$) are consistent with data, then the usual suspects do not give anything further

- $\tau \to l\gamma, \tau \to 3l$
- $\Delta M_{B_d}, \Delta M_{B_s}$
- $B_{s,d} \to \mu^+\mu^-$
- $B \to X_s \nu\bar{\nu}$

However

- BR($B \to X_s e\mu$) close to experimental limit

Scalar contributions to $K_L \to e\mu$



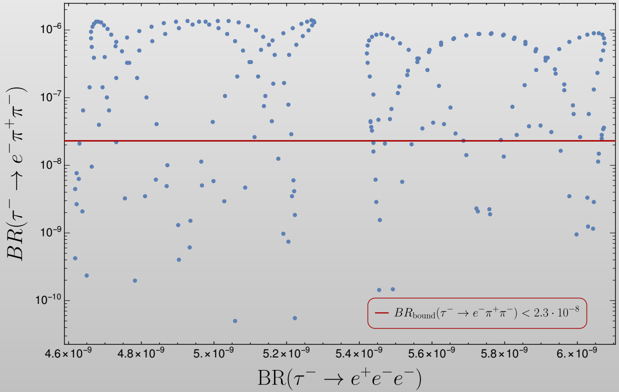
scan over ϕ_{12}, ϕ_{12}, ϕ_{12} , other parameters as in table before

T. Faber, M. Hudec, M. Malinský, P. Meinzinger, W.P. and F. Staub, arXiv:1808.05511

End of the story?

Of course not, because

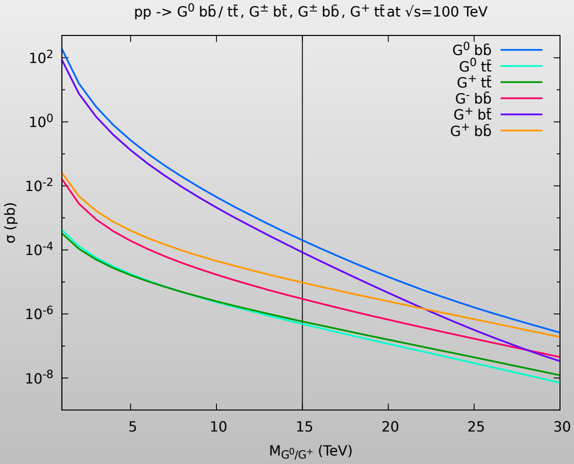
- giving up the restriction $U_d = V_d^*$ und $U_u = V_u^*$: tiny regions in parameter space with an explanation of $R_K^{(*)}$ consistent with K_L decays



T. Faber et al.,arXiv:1812.07592

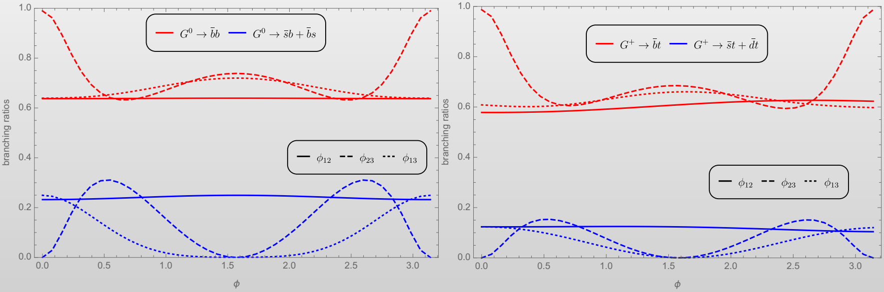
- additional vector-like $SU(2)_L$ leptons gives consistent explanation for $R_K^{(*)}$ while satisfying also the K_L decays, need at least two additional generations

Scalar gluon production



T. Faber et al.,arXiv:1812.07592

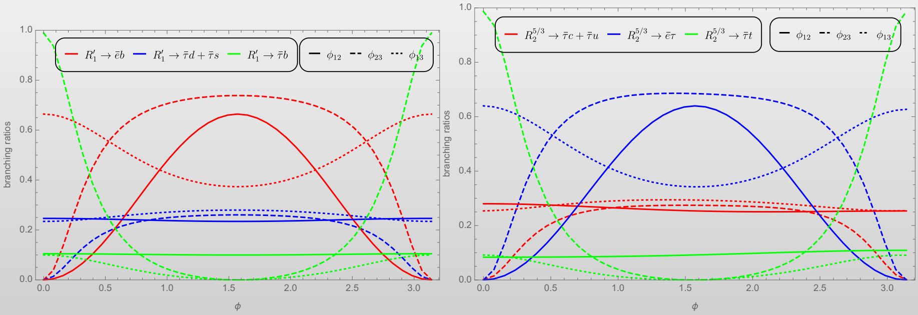
Scalar gluon decays



scan over $\phi_{12}, \phi_{12}, \phi_{12}$, other parameters as in table before
in the region where $R_K^{(*)}$ can be explained + consistency with other data

$$BR(G^0 \to b\bar{b}) \simeq 0.7 - 0.75\,,$$
$$BR(G^0 \to b\bar{d} + d\bar{b}) + BR(G^0 \to b\bar{s} + s\bar{b}) \simeq 0.15\,,$$
$$BR(G^+ \to t\bar{b}) \simeq 0.65 - 0.73\,.$$

Leptoquark decays



scan over $\phi_{12}, \phi_{12}, \phi_{12}$, other parameters as in table before
in the region where $R_K^{(*)}$ can be explained + consistency with other data

$$\text{BR}(R_2^{+2/3} \to e^+ b) \simeq \text{BR}(R_2^{+2/3} \to \tau^+ b) \simeq \frac{m_b^2}{2m_\tau^2} \left(\text{BR}(R_2^{+2/3} \to \tau^+ d) + \text{BR}(R_2^{+2/3} \to \tau^+ s) \right)$$

$$\text{BR}(R_2^{+5/3} \to t e^+) \simeq \text{BR}(R_2^{+5/3} \to t\tau^+) \simeq \frac{m_b^2}{2m_\tau^2} \left(\text{BR}(R_2^{+5/3} \to u\tau^+) + \text{BR}(R_2^{+5/3} \to c\tau^+) \right)$$

Some examples

S_1 $(\bar{3},1,1/3)$ and/or S_3 $(\bar{3},3,1/3)$

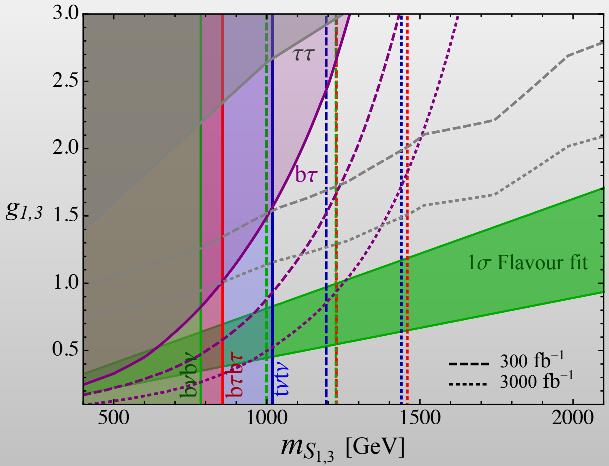
- B. Gripaios, arXiv:0910.1789: choose global symmetry such that $SU(4) \in G$ and $SU(3)_C \times U(1)_{B-L} \in H \Rightarrow G/H$ has leptoquarks as PNGB
  $SO(11)/SO(10)$ has just H and S_1 as PNGB
- $SU(10)_L \times SU(10)_R \times U(1)_{HB}/SU(10)_D \times U(1)_{HB}$, D. Marzocca, arXiv:1803.10972:
  has S_1, S_3, R_2 and T_2 $(\bar{3},2,5/6)$ among the PNGB
  proton stability: via $F_\pm = 3B \pm L \Rightarrow$ interesting collider phenomenology
- $SO(13)/SO(6) \times SU(2)^3$, L. Da Rold and F. Lamagna, arXiv:1812.08678:
  has S_3, R_2 and $\tilde{R}_2$ among the PNGB
  proton stability: need a Z_2 and set certain Yukawa couplings to zero by hand

U_1

- $SU(4) \times SO(5) \times U(1)_X/SU(4) \times SO(4) \times U(1)_X$ R. Barbieri, C. W. Murphy and F. Senia, arXiv:1611.04930 ; R. Barbieri and A. Tesi, arXiv:1712.06844:
  approximate $U(2)^5$ symmetry for first two SM generations, additional Dirac-fermions, which partly mix SM-fields
- $SU(N_F)_L \times SU(N_F)_R \times U(1)_V/SU(N_F)_V \times U(1)_V$ D. Buttazzo, A. Greljo, G. Isidori and D. Marzocca, arXiv:1604.03940:
  include also the U_3, approximate $U(2)^5$ symmetry for first two SM generations

PNGB leptoquarks do not couple to a pair of SM-fermions

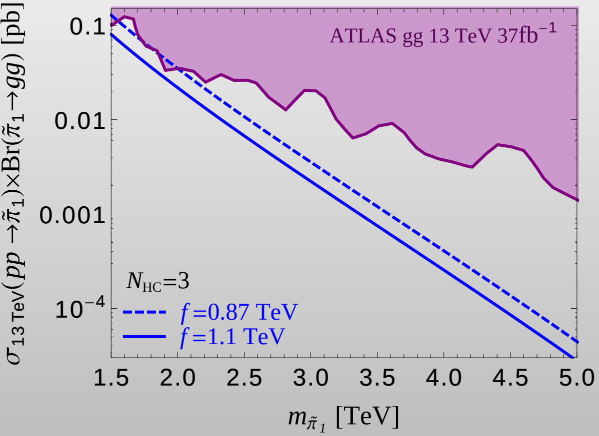
S_1, S_3



Present and future expected exclusion limits at 95% CL; vertical lines from pair-production modes; purple from single production in the $b\tau$ channel; gray from the off-shell $\tau\tau$ tail.
D. Marzocca, arXiv:1803.10972

Scalar gluons

$\tilde{\pi}_1 \to gg$, $\tilde{\pi}_3 \to \gamma V$ ($V = Z, W^{\pm}$)



D. Marzocca, arXiv:1803.10972

$\tilde{R}_2, T_2$

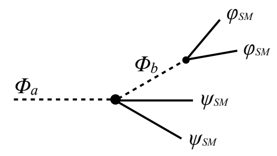
$$r_{\frac{2}{3}}\,,\, r_{-\frac{1}{3}} \qquad t_{-\frac{1}{3}}\,,\, t_{-\frac{4}{3}}$$

$F_\pm$ symmetry forbids couplings to two fermions

$$\Rightarrow \mathcal{L}^{\text{eff}}_{\text{LQ}} \supset \frac{i g_3}{\sqrt{2} f} \sin\frac{\theta}{2}\, \bar{t}^c_L \nu_\tau r^\dagger_{\frac{2}{3}} \tilde{\eta}_R - \frac{i(g_1 - g_3)}{2\sqrt{2} f} \sin\frac{\theta}{2}\, \bar{b}^c_L \nu_\tau r^\dagger_{-\frac{1}{3}} \tilde{\eta}_R + h.c.$$
$$+ \frac{i g_3}{\sqrt{2} f} \sin\frac{\theta}{2}\, \bar{b}^c_L \tau_L t^\dagger_{-\frac{4}{3}} \tilde{\eta}_T + \frac{i(g_1 + g_3)}{2\sqrt{2} f} \sin\frac{\theta}{2}\, \bar{b}^c_L \nu_\tau t^\dagger_{-\frac{1}{3}} \tilde{\eta}_T + h.c.\,.$$

$$\tilde{\eta}_{R,T} = \eta_1 \pm \frac{1}{\sqrt{2}}\eta_2 \mp \frac{1}{\sqrt{30}}\eta_3$$

η_i being gauge singlet PNGB decaying into $gg, \gamma\gamma, \gamma Z, ZZ, W^+W^-$



- If

$$R_{D^{(*)}} = \frac{\Gamma(\bar{B} \to D^{(*)}\tau\bar{\nu})}{\Gamma(\bar{B} \to D^{(*)}l\bar{\nu})}\ (l = e, \mu) \qquad , \ R_{K^{(*)}} = \frac{\Gamma(\bar{B} \to \bar{K}^{(*)}\mu^+\mu^-)}{\Gamma(\bar{B} \to \bar{K}^{(*)}e^+e^-)}$$

  get confirmed, then clear sign of new physics
- Could be explained via leptoquarks, in particular the vector U_1 $(\bar{3}, 1, 2/3)$ or S_1 $(\bar{3}, 1, 1/3)$ + S_3 $(\bar{3}, 3, 1/3)$
- U_1 part of $SU(4)$ but constrained by K_L decays
- Mechanisms to get a smaller mass
  - extended gauge groups such as $SU(4) \times SU(3) \times SU(2) \times U(1)$
  - extra vector-like fermions
  - combination with Randall-Sundrum
  - strong dynamics
- S_1 $(\bar{3}, 1, 1/3)$ + S_3 $(\bar{3}, 3, 1/3)$ as PNGB
- in all cases: significant constraints from low energy data from different sectors and also from LHC searches