Predictions for flavorful Z' models from asymptotic safety

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Based on work in collaboration with
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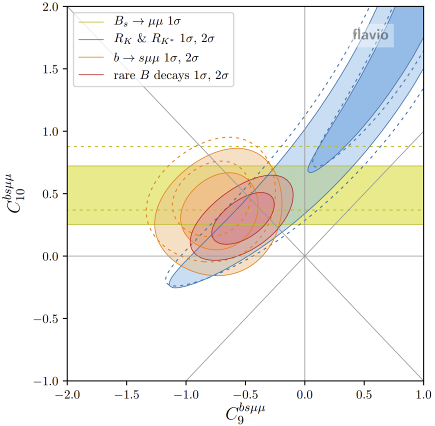
Lepton flavour universality violation in $b \to s$ transition



Altmannshofer, Stangl arXiv: 2103.13370

- Scalar leptoquark
- Vector leptoquark
- $U(1)_X$

Minimal Z' models for flavor anomalies

Lagrangian parametrizing LFUV couplings of Z' to the b-s current and the muons

$$\mathcal{L} \supset Z'_\alpha \left(\Delta_L^{sb}\, \bar{s}_L \gamma^\alpha\, b_L \, + \Delta_R^{sb}\, \bar{s}_R \gamma^\alpha\, b_R + \text{ H.c.} \right) + Z'_\alpha \left(\Delta_L^{\mu\mu}\, \bar{\mu}_L \gamma^\alpha \mu_L + \Delta_R^{\mu\mu}\, \bar{\mu}_R \gamma^\alpha \mu_R + \text{H.c.} \right) .$$

$$C^\mu_{9,\text{NP}} = -2\frac{\Delta_L^{sb}\Delta_9^{\mu\mu}}{V_{tb}V^*_{ts}}\left(\frac{\Lambda_v}{m_{Z'}}\right)^2, \quad C'^\mu_{9,\text{NP}} = -2\frac{\Delta_R^{sb}\Delta_9^{\mu\mu}}{V_{tb}V^*_{ts}}\left(\frac{\Lambda_v}{m_{Z'}}\right)^2,$$

$$C^\mu_{10,\text{NP}} = -2\frac{\Delta_L^{sb}\Delta_{10}^{\mu\mu}}{V_{tb}V^*_{ts}}\left(\frac{\Lambda_v}{m_{Z'}}\right)^2, \quad C'^\mu_{10,\text{NP}} = -2\frac{\Delta_R^{sb}\Delta_{10}^{\mu\mu}}{V_{tb}V^*_{ts}}\left(\frac{\Lambda_v}{m_{Z'}}\right)^2 .$$

$$\Delta_9^{\mu\mu} \equiv (\Delta_R^{\mu\mu} + \Delta_L^{\mu\mu})/2 \qquad , \qquad \Delta_{10}^{\mu\mu} \equiv (\Delta_R^{\mu\mu} - \Delta_L^{\mu\mu})/2$$

Minimal Z' models for flavor anomalies

NP particle content

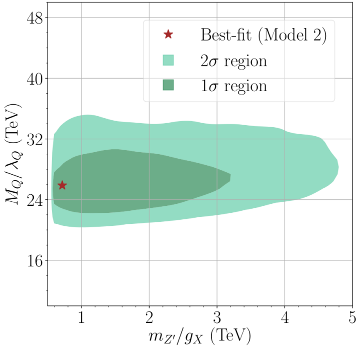
Q : (**3**,**2**,1/6,-1)
Q' : ($\bar{\mathbf{3}}$,**2**,-1/6,1)
S : (**1**,**1**,0,-1)

VL quarks terms in the Lagrangian

$$\mathcal{L} \supset \left(-Y_{Q,i}\, S\, Q'\, q_i + \text{H.c.}\right) - M_Q Q' Q\,.$$

$$\Delta_L^{sb} \approx -\frac{g_X\, Y_{Q,2} Y_{Q,3} v_S^2}{2M_Q^2 + \left(Y_{Q,2}^2 + Y_{Q,3}^2\right) v_S^2}\,,$$

$$\Delta_R^{sb} \approx 0\,.$$



Kowalska, Kumar, Sessolo,
arXiv: 1903.10932

VL leptons with an $U(1)_X$ charge

NP particle content

L : ($\mathbf{1}$,$\mathbf{2}$,-1/2,Q_X)
L' : ($\mathbf{1}$,$\bar{2}$,-1/2,-Q_X)

VL leptons terms in the Lagrangian

$$\mathcal{L} \supset (Y_{L,i}\, S\, L'\, l + \mathrm{H.c.}) + M_L L' L\,.$$

$$\Delta_L^{\mu\mu} \approx g_X\, Q_X \frac{Y_{L,2}^2 v_S^2}{2M_L^2 + Y_{L,2}^2 v_S^2}\,, \qquad \Delta_R^{\mu\mu} \approx 0\,.$$

NP contribution to C_9

$$C_9^{\mu\mu} \approx Q_X \frac{2\Lambda_v^2}{V_{tb}V_{ts}^*} \left(\frac{Y_{Q,2}Y_{Q,3}}{2M_Q^2 + \left(Y_{Q,2}^2 + Y_{Q,3}^2\right) v_S^2} \right) \left(\frac{Y_{L,2}^2 v_S^2}{2M_L^2 + Y_{L,2}^2 v_S^2} \right).$$

$L_\mu - L_\tau$ symmetry

SM leptons

$$\begin{aligned} l_1 &: (1,2,-1/2,0) & e_R &: (1,1,1,0) \\ l_2 &: (1,2,-1/2,1) & \mu_R &: (1,1,1,-1) \\ l_3 &: (1,2,-1/2,-1) & \tau_R &: (1,1,1,1) \end{aligned}$$

$$\Delta_9^{\mu\mu} \approx g_X \qquad \Delta_{10}^{\mu\mu} \approx 0\,.$$

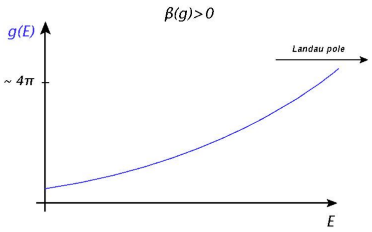
NP contribution to C_9

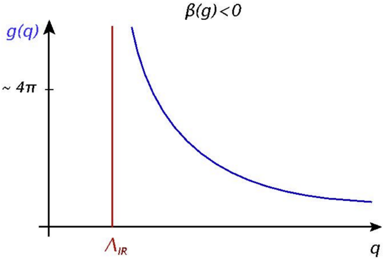
$$C_{9,\mathrm{NP}}^{\mu} \approx \frac{2\Lambda_v^2}{V_{tb}V_{ts}^*}\,\frac{Y_{Q,2}Y_{Q,3}}{2M_Q^2 + \left(Y_{Q,2}^2 + Y_{Q,3}^2\right)v_S^2}\,.$$

Landau pole & asymptotic freedom

Running CC up to 1-loop

$$g(\Lambda) = \frac{g_{\rm obs}}{1 - \beta\, g_{\rm obs} \ln \Lambda/m}\,, \qquad \Lambda_{\rm Landau} = m \exp\left\{\frac{1}{\beta\, g_{\rm obs}}\right\}$$





Quantum gravity corrections to the β-functions

Since gravitons couple to energy-momentum through a CC with dimension $[M_P]^{-1}$, dimensional analysis implies that gravity corrects the β-functions linearly.

β-functions of the theory

$$\beta_g = \beta_g^{SM+NP} \qquad \beta_y = \beta_y^{SM+NP}$$

β-functions in the Trans-planckian regime

$$\beta_g = \beta_g^{SM+NP} - f_g\, g \qquad \beta_y = \beta_y^{SM+NP} - f_y\, y$$

Relevant and irrelevant directions of the RG flow

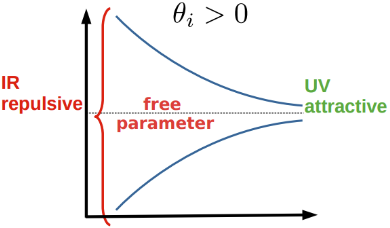
Fixed point

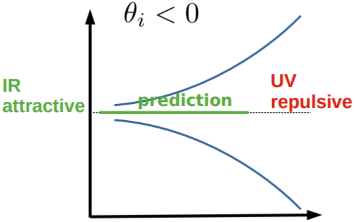
$$\{g^*, y^*\} \qquad \beta_g(g^*, y^*) = \beta_y(g^*, y^*) = 0$$

Stability matrix

$$\{\alpha\} = \{g, y\} \qquad M_{ij} = \left.\frac{\partial \beta_i}{\partial \alpha_j}\right|_{\{\alpha^*\}}$$

Relevant and irrelevant directions of the RG flow





Relevant couplings are free parameters of the theory

Irrelevant couplings provide predictions

Source: Kamila Kowalska

Fixed point

CC relevant for flavour anomalies

SM : $g_3\,,\ g_2\,,\ g_Y\,,\ y_t\,,\ y_b\,,\ V_{33}\,,$

BSM: $g_D,\ g_\epsilon,\ Y_{Q,2},\ Y_{Q,3},\ Y_{L,2}.$

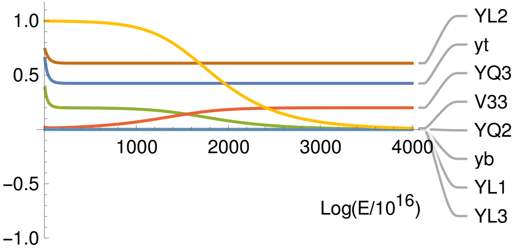
CC fixed point

$$g_3^* = g_2^* = 0$$

$$y_b^* = V_{33}^* = 0$$

	f_g	f_y	g_Y^*	g_D^*	g_ϵ^*	y_t^*	$Y_{Q,3}^*$	$Y_{Q,2}^*$	$Y_{L,2}^*$
$\mathrm{FP}_{1\mathrm{A},\mathrm{a}}$	0.012	0.0025	0.498	0.418	0	0.406	0	0.072	0.648
$\mathrm{FP}_{1\mathrm{A},\mathrm{b}}$	0.012	0.0029	0.498	0.418	0	0.424	0.200	0	0.610
$\mathrm{FP}_{1\mathrm{B},\mathrm{a}}$	0.012	0.0026	0.498	0.436	0.151	0.417	0	0.163	0.586
$\mathrm{FP}_{1\mathrm{B},\mathrm{b}}$	0.012	0.0034	0.498	0.436	0.151	0.452	0.264	0	0.547
$\mathrm{FP}_{2,a}$	0.010	0.0018	0.479	0.366	0.069	0.356	0	0.302	–
$\mathrm{FP}_{2,b}$	0.010	0.0037	0.479	0.366	0.069	0.453	0.379	0	–

Running standard model couplings



	$g_Y(Q_0)$	$g_D(Q_0)$	$g_\epsilon(Q_0)$	$y_t(Q_0)$	$Y_{Q,3}(Q_0)$	$Y_{Q,2}(Q_0)$	$Y_{L,2}(Q_0)$
$\mathrm{FP}_{1A,a}$	0.364	0.305	0	1.08	-0.381	0.016	0.823
$\mathrm{FP}_{1A,b}$	0.364	0.305	0	1.09	0.034	0.803	0.606
$\mathrm{FP}_{1B,a}$	0.363	0.318	0.110	1.05	-0.612	0.296	0.652
$\mathrm{FP}_{1B,b}$	0.363	0.318	0.110	1.08	0.004	0.874	0.499
$\mathrm{FP}_{2,a}$	0.363	0.277	0.052	1.03	-0.700	0.638	–
$\mathrm{FP}_{2,b}$	0.363	0.277	0.052	1.10	0.040	0.988	–

Kinetic mixing constraint

Kinetic terms in the Lagrangian

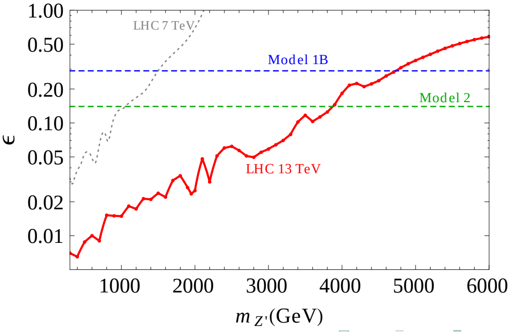
$$\mathcal{L} \supset -\frac{1}{4}W^i_{\mu\nu}W^{i\mu\nu} - \frac{1}{4}B_{\mu\nu}B^{\mu\nu} - \frac{1}{4}X_{\mu\nu}X^{\mu\nu} - \frac{1}{2}\epsilon B_{\mu\nu}X^{\mu\nu}$$

Kinetic mixing parametrization

$$\epsilon = \frac{g_\epsilon}{\sqrt{g_y^2 + g_\epsilon^2}}$$

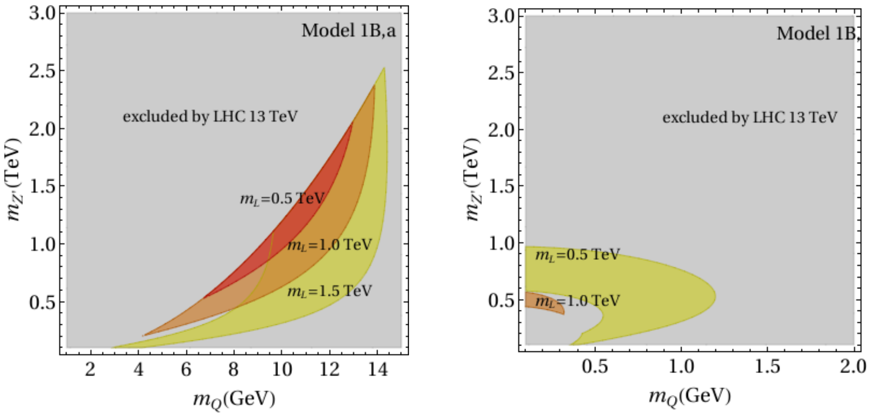
Jaeckel, Jankowiak, Spannowsky arXiv:1212.3620

p p > Z' > $l^+ l^-$



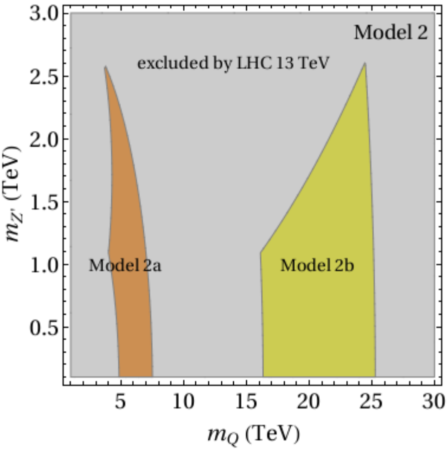
Kinetic mixing constraint (model 1B)

$m_{Z'} > 3.9$ TeV LHC 13 TEV



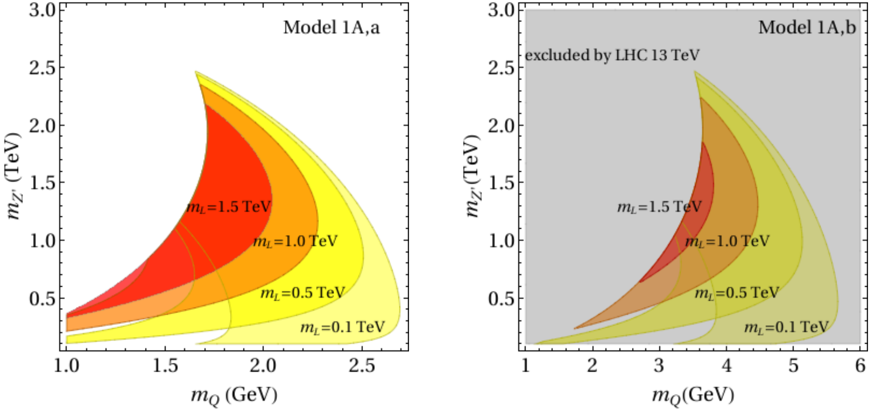
Kinetic mixing constraint (model 2)

$m_{Z'} > 4.8$ TeV LHC 13 TEV



Tests on model 1A

$Y_{Q2} = 0.016$ $\quad$ $Y_{Q2} = 0.803$



Conclusions

1. Despite Standard Model gives often good predictions on physical quantity, it is not a UV completed theory. The introduction of a Z' boson is able to give UV completion.
2. The parameters space of models with a Z' are very wide. Asymptotic safety was used as a tool to reduce the parameters space of such models. To do so, the only assumption we made was the presence of a fixed point in the deep UV.
3. The flow of the coupling constants gave us predictions for the new physics, which we tested with searches for kinetic mixing at LHC, using the 13 TeV run.
4. All but one scenarios were this way excluded, because of a too high value for the kinetic mixing.
5. New tests on the scenario 1A,a must be performed, using other LHC bounds. Stay tuned.

Thanks for the attention.

Trans-Planckian RGEs Gauge couplings Model 1A

$$\frac{dg_3}{dt} = -\frac{17}{3}\frac{g_3^3}{16\pi^2} - f_g g_3\,,$$
$$\frac{dg_2}{dt} = -\frac{1}{2}\frac{g_2^3}{16\pi^2} - f_g g_2\,,$$
$$\frac{dg_Y}{dt} = \frac{139}{18}\frac{g_Y^3}{16\pi^2} - f_g g_Y\,,$$
$$\frac{dg_D}{dt} = \frac{1}{16\pi^2}\left(11 g_D^2 + \frac{139}{18} g_\epsilon^2\right) g_D - f_g g_D\,,$$
$$\frac{dg_\epsilon}{dt} = \frac{1}{16\pi^2}\left(11 g_D^2 g_\epsilon + \frac{139}{9} g_Y^2 g_\epsilon + \frac{139}{18} g_\epsilon^3\right) - f_g g_\epsilon\,.$$

Trans-Planckian RGEs Gauge couplings Model 1B

$$\frac{dg_3}{dt} = -\frac{17}{3}\frac{g_3^3}{16\pi^2} - f_g g_3\,,$$
$$\frac{dg_2}{dt} = -\frac{1}{2}\frac{g_2^3}{16\pi^2} - f_g g_2\,,$$
$$\frac{dg_Y}{dt} = \frac{139}{18}\frac{g_Y^3}{16\pi^2} - f_g g_Y\,,$$
$$\frac{dg_D}{dt} = \frac{1}{16\pi^2}\left(11 g_D^2 + \frac{139}{18} g_\epsilon^2 - \frac{16}{3} g_D g_\epsilon\right) g_D - f_g g_D\,,$$
$$\frac{dg_\epsilon}{dt} = \frac{1}{16\pi^2}\left(11 g_D^2 g_\epsilon + \frac{139}{9} g_Y^2 g_\epsilon + \frac{139}{18} g_\epsilon^3 - \frac{16}{3} g_D g_Y^2 - \frac{16}{3} g_D g_\epsilon^2\right) - f_g g_\epsilon\,.$$

Trans-Planckian RGEs Gauge couplings $L_\mu - L_\tau$ model

$$\frac{dg_3}{dt} = -\frac{17}{3}\frac{g_3^3}{16\pi^2} - f_g g_3 ,$$

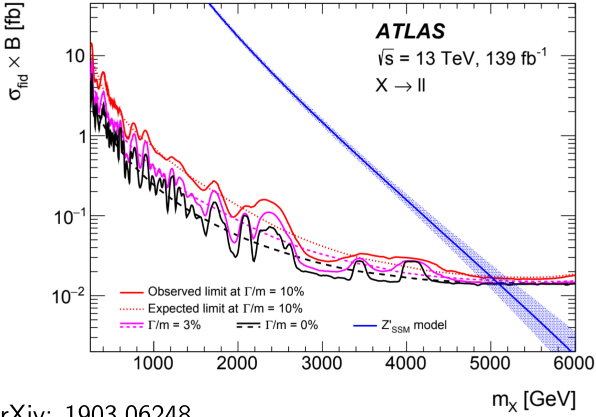
$$\frac{dg_2}{dt} = -\frac{7}{6}\frac{g_2^3}{16\pi^2} - f_g g_2 ,$$

$$\frac{dg_Y}{dt} = \frac{127}{18}\frac{g_Y^3}{16\pi^2} - f_g g_Y ,$$

$$\frac{dg_D}{dt} = \frac{1}{16\pi^2}\left(\frac{37}{3}g_D^2 - \frac{8}{3}g_D g_\epsilon + \frac{127}{18}g_\epsilon^2\right) g_D - f_g g_D ,$$

$$\frac{dg_\epsilon}{dt} = \frac{1}{16\pi^2}\left(\frac{37}{3}g_D^2 g_\epsilon - \frac{8}{3}g_D g_\epsilon^2 - \frac{8}{3}g_D g_Y^2 + \frac{127}{18}g_\epsilon^3 + \frac{127}{9}g_\epsilon g_Y^2\right) - f_g g_\epsilon ,$$

Cross-section as function of $m_{Z'}$



ATLAS, arXiv: 1903.06248

Kinetic mixing in term of gauge couplings

$$\mathcal{L} \supset -\frac{1}{4}B_{\mu\nu}B^{\mu\nu} - \frac{1}{4}X_{\mu\nu}X^{\mu\nu} - \frac{}{2}B_{\mu\nu}X^{\mu\nu} + i\bar{\psi}\left(\partial^\mu - ig_1 Q_1 B^\mu - ig_X Q_X X^\mu\right)\gamma_\mu\psi$$

$$\begin{pmatrix} B^\mu \\ X^\mu \end{pmatrix} = \begin{pmatrix} 1/\sqrt{2(1-\epsilon)} & -1/\sqrt{2(1+\epsilon)} \\ 1/\sqrt{2(1-\epsilon)} & 1/\sqrt{2(1+\epsilon)} \end{pmatrix} \begin{pmatrix} V_1^\mu \\ V_X^\mu \end{pmatrix}$$

$$i\bar{\psi}\,\mathcal{V}^\mu\gamma_\mu\psi \qquad \rightarrow \qquad \mathcal{V}^\mu = (Q_1\ Q_X)\begin{pmatrix} g_{11} & g_{1X} \\ g_{X1} & g_{XX} \end{pmatrix}\begin{pmatrix} V_1^\mu \\ V_X^\mu \end{pmatrix}$$

$$\begin{pmatrix} g_{11} & g_{1X} \\ g_{X1} & g_{XX} \end{pmatrix} = \begin{pmatrix} g_1/\sqrt{2(1-\epsilon)} & -g_1/\sqrt{2(1+\epsilon)} \\ g_X/\sqrt{2(1-\epsilon)} & g_X/\sqrt{2(1+\epsilon)} \end{pmatrix}$$

Kinetic mixing in term of gauge couplings

$$g_{11} g_{XX} = -g_{1X} g_{X1}$$

$$\widetilde{\mathcal{G}} = \begin{pmatrix} g_Y & g_\epsilon \\ 0 & g_D \end{pmatrix}$$

$$\begin{aligned} g_Y^2 + g_\epsilon^2 &= g_{11}^2 + g_{1X}^2 \\ g_D g_\epsilon &= g_{11} g_{X1} + g_{1X} g_{XX} \\ g_D^2 &= g_{X1}^2 + g_{XX}^2 \,. \end{aligned}$$

$$g_1 = g_Y \,, \quad g_D = \frac{g_X}{\sqrt{1-\epsilon^2}} \,, \quad g_\epsilon = -\frac{\epsilon g_Y}{\sqrt{1-\epsilon^2}}$$