Constraints on Z’ solutions to the flavor anomalies with trans-Planckian asymptotic safety

Daniele Rizzo

Based on

arXiv:2209.07971

in collaboration with

A. Chikkaballi, K. Kowalska, W. Kotlarski & E. Sessolo

Asymptotic Safety meets Particle Physics and Friends

Albert Einstein Hall, DESY, Hamburg

December 14th 2022

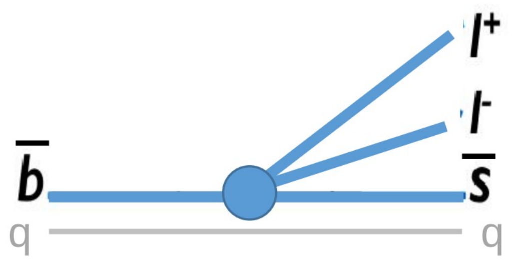
NARODOWE CENTRUM NAUKI

NATIONAL CENTRE FOR NUCLEAR RESEARCH ŚWIERK

Lepton anomalies in b → s transition

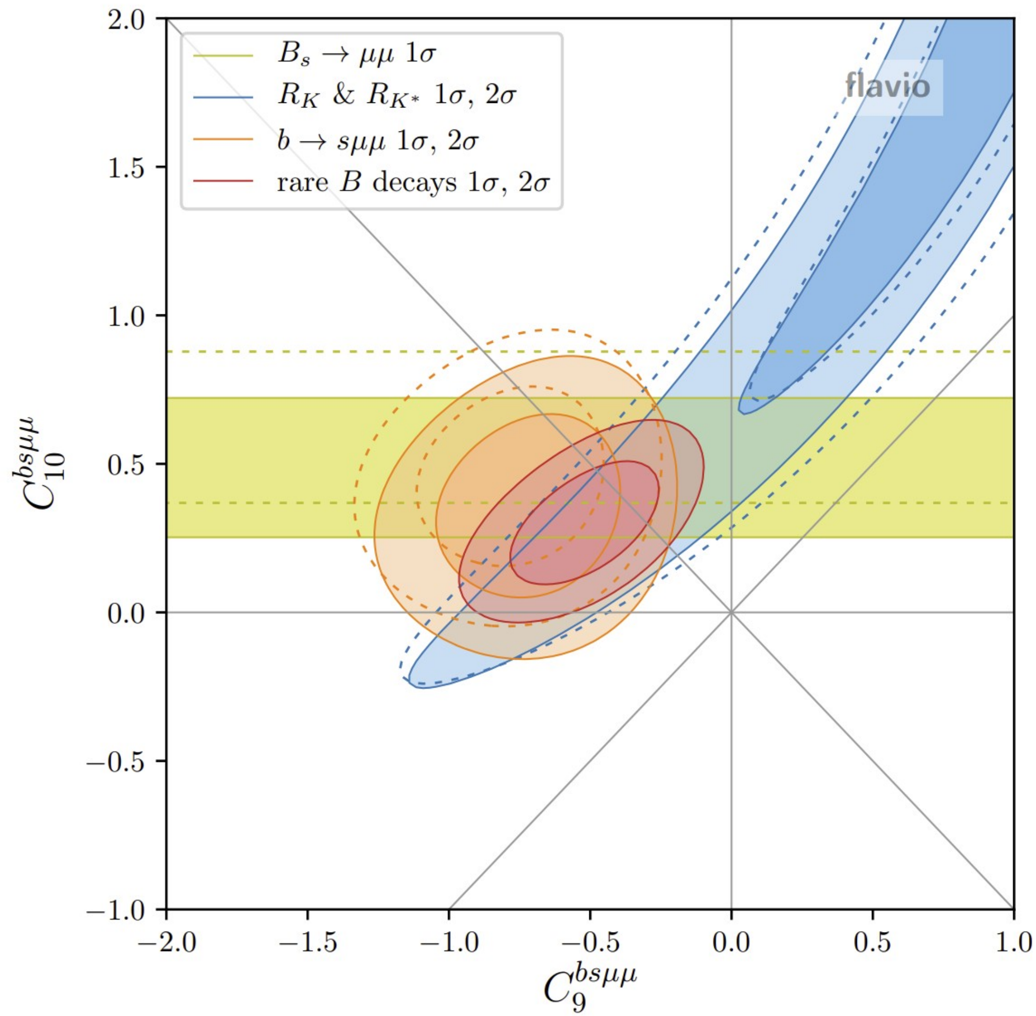
$$\mathcal{H}_{eff} = \frac{G_F}{\sqrt{2}} V_{tb} V_{tx}^* \sum_i C_i O_i$$

$$C_i = C_i^{SM} + C_i^{NP}$$



$$-1.03 \leq C^{\mu}_{9,\mathrm{NP}} \leq -0.43$$

$$-0.53 \leq C^{\mu}_{9,\mathrm{NP}} \left(= -C^{\mu}_{10,\mathrm{NP}}\right) \leq -0.25$$



Altmannshofer, Stangl arXiv: 2103.13370

daniele.rizzo@ncbj.gov.pl
Daniele Rizzo

Minimal Z' models for flavor anomalies

Effective Hamiltonian

$$\mathcal{H}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum_{i,l} (C_i^l O_i^l + C_i'^l O_i'^l) + \text{H.c.}\,,$$

Operator relevant for b-s transition

$$O_9^{(\prime)\mu} = \frac{\alpha_{\text{em}}}{4\pi} \left(\bar{s}\gamma^\rho P_{L(R)} b\right) \left(\bar{\mu}\gamma_\rho \mu\right),$$
$$O_{10}^{(\prime)\mu} = \frac{\alpha_{\text{em}}}{4\pi} \left(\bar{s}\gamma^\rho P_{L(R)} b\right) \left(\bar{\mu}\gamma_\rho \gamma_5 \mu\right),$$

daniele.rizzo@ncbj.gov.pl
Daniele Rizzo

Minimal Z’ models for flavor anomalies

Effective Hamiltonian

$$\mathcal{H}_{\rm eff} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum_{i,l} (C_i^l O_i^l + C_i'^l O_i'^l) + \text{H.c.}\,,$$

Operator relevant for b-s transition

$$O_9^{(\prime)\mu} = \frac{\alpha_{\rm em}}{4\pi} \left(\bar{s}\gamma^\rho P_{L(R)} b\right) \left(\bar{\mu}\gamma_\rho \mu\right),$$
$$O_{10}^{(\prime)\mu} = \frac{\alpha_{\rm em}}{4\pi} \left(\bar{s}\gamma^\rho P_{L(R)} b\right) \left(\bar{\mu}\gamma_\rho \gamma_5 \mu\right),$$

Lagrangian parametrizing lepton flavor universality violating couplings of Z’ to the b-s current and the muons

$$\mathcal{L} \supset Z'_\rho \left[\left(g_L^{sb}\, \bar{s}\gamma^\rho P_L\, b + g_R^{sb}\, \bar{s}\gamma^\rho P_R\, b + \text{H.c.} \right) + g_L^{\mu\mu}\, \bar{\mu}\gamma^\rho P_L\, \mu + g_R^{\mu\mu}\, \bar{\mu}\gamma^\rho P_R\, \mu \right],$$

daniele.rizzo@ncbj.gov.pl
Daniele Rizzo

Minimal Z’ models for flavor anomalies

Effective Hamiltonian

$$\mathcal{H}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum_{i,l} (C_i^l O_i^l + C_i'^l O_i'^l) + \text{H.c.}\,,$$

Operator relevant for b-s transition

$$O_9^{(\prime)\mu} = \frac{\alpha_{\text{em}}}{4\pi} \left(\bar{s}\gamma^\rho P_{L(R)} b\right) \left(\bar{\mu}\gamma_\rho \mu\right),$$
$$O_{10}^{(\prime)\mu} = \frac{\alpha_{\text{em}}}{4\pi} \left(\bar{s}\gamma^\rho P_{L(R)} b\right) \left(\bar{\mu}\gamma_\rho \gamma_5 \mu\right),$$

Lagrangian parametrizing lepton flavor universality violating couplings of Z’ to the b-s current and the muons

$$\mathcal{L} \supset Z'_\rho \left[\left(g_L^{sb}\, \bar{s}\gamma^\rho P_L\, b + g_R^{sb}\, \bar{s}\gamma^\rho P_R\, b + \text{H.c.} \right) + g_L^{\mu\mu}\, \bar{\mu}\gamma^\rho P_L\, \mu + g_R^{\mu\mu}\, \bar{\mu}\gamma^\rho P_R\, \mu \right],$$

Wilson coefficients relevant for b-s transition

$$C_{9,\text{NP}}^{\mu} = -2\, \frac{g_L^{sb} g_V^{\mu\mu}}{V_{tb} V_{ts}^*} \left(\frac{\Lambda_v}{m_{Z'}} \right)^2, \qquad C_{10,\text{NP}}^{\mu} = -2\, \frac{g_L^{sb} g_A^{\mu\mu}}{V_{tb} V_{ts}^*} \left(\frac{\Lambda_v}{m_{Z'}} \right)^2,$$

daniele.rizzo@ncbj.gov.pl
Daniele Rizzo

Theories with two U(1) group factors

Lagrangian of a fermion charged under both $\mathrm{U}(1)_Y \times \mathrm{U}(1)_X$

$$\mathcal{L} \supset -\frac{1}{4} B_{\mu\nu} B^{\mu\nu} - \frac{1}{4} X_{\mu\nu} X^{\mu\nu} - \frac{\epsilon}{2} B_{\mu\nu} X^{\mu\nu} + i \bar{f} \left(\partial^\mu - i g_Y Q_Y \tilde{B}^\mu - i g_X Q_X \tilde{X}^\mu \right) \gamma_\mu f \, ,$$

daniele.rizzo@ncbj.gov.pl
Daniele Rizzo

Theories with two U(1) group factors

Lagrangian of a fermion charged under both $\mathrm{U}(1)_Y \times \mathrm{U}(1)_X$

$$\mathcal{L} \supset -\frac{1}{4}B_{\mu\nu}B^{\mu\nu} - \frac{1}{4}X_{\mu\nu}X^{\mu\nu} - \frac{\epsilon}{2}B_{\mu\nu}X^{\mu\nu} + i\bar{f}\left(\partial^\mu - ig_Y Q_Y \tilde{B}^\mu - ig_X Q_X \tilde{X}^\mu\right)\gamma_\mu f \,,$$

U(1) Gauge couplings in physical basis

$$(Q_Y\, Q_X)\begin{pmatrix} g_Y & 0 \\ 0 & g_X \end{pmatrix}\begin{pmatrix} \tilde{B}^\mu \\ \tilde{X}^\mu \end{pmatrix} \quad \rightarrow \quad (Q_Y\, Q_X)\begin{pmatrix} g_V & g_\epsilon \\ 0 & g_D \end{pmatrix}\begin{pmatrix} V^\mu \\ D^\mu \end{pmatrix}$$

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

daniele.rizzo@ncbj.gov.pl
Daniele Rizzo

Minimal Z’ models for flavor anomalies

Particle content

$$S : (\mathbf{1}, \mathbf{1}, 0, Q_S)$$

$$Q : (\mathbf{3}, \mathbf{2}, 1/6, Q_S) \qquad Q' : (\bar{\mathbf{3}}, \bar{\mathbf{2}}, -1/6, -Q_S)$$

daniele.rizzo@ncbj.gov.pl Daniele Rizzo

Minimal Z' models for flavor anomalies

Particle content

$$S : (\mathbf{1}, \mathbf{1}, 0, Q_S)$$

$$Q : (\mathbf{3}, \mathbf{2}, 1/6, Q_S) \qquad Q' : (\bar{\mathbf{3}}, \bar{\mathbf{2}}, -1/6, -Q_S)$$

Interaction

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

daniele.rizzo@ncbj.gov.pl Daniele Rizzo

Minimal Z' models for flavor anomalies

Particle content

$$S : (\mathbf{1}, \mathbf{1}, 0, Q_S)$$

$$Q : (\mathbf{3}, \mathbf{2}, 1/6, Q_S) \qquad Q' : (\bar{\mathbf{3}}, \bar{\mathbf{2}}, -1/6, -Q_S)$$

Interaction

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

Couplings in WET

$$g_L^{sb} \approx \pm g_X Q_S \frac{\sqrt{2}\, m_Q\, \lambda_{Q,2}\, \lambda_{Q,3}\, v_S^2}{\left(2m_Q^2 + \lambda_{Q,2}^2\, v_S^2\right)\sqrt{2\, m_Q^2 + \left(\lambda_{D,2}^2 + \lambda_{D,3}^2\right) v_S^2}}\,,$$

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

daniele.rizzo@ncbj.gov.pl

Daniele Rizzo

Minimal Z’ models for flavor anomalies

Particle content

$$S : (\mathbf{1}, \mathbf{1}, 0, Q_S)$$

$$Q : (\mathbf{3}, \mathbf{2}, 1/6, Q_S) \qquad Q' : (\bar{\mathbf{3}}, \bar{\mathbf{2}}, -1/6, -Q_S)$$

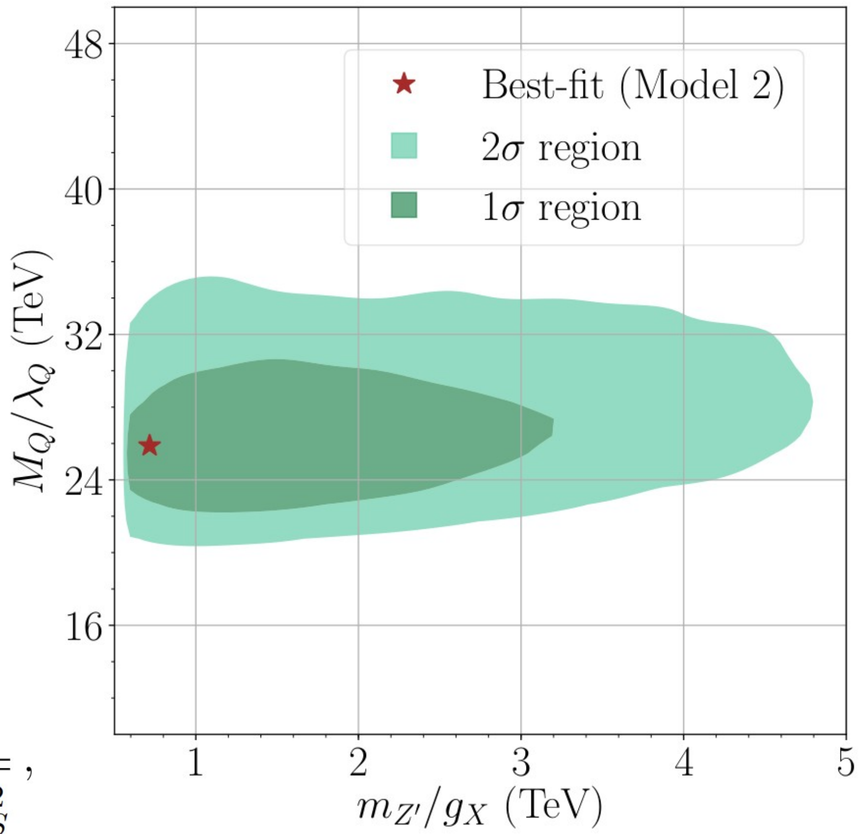
Interaction

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

Couplings in WET

$$g_L^{sb} \approx \pm g_X Q_S \frac{\sqrt{2}\, m_Q\, \lambda_{Q,2}\, \lambda_{Q,3}\, v_S^2}{(2m_Q^2 + \lambda_{Q,2}^2\, v_S^2)\sqrt{2\, m_Q^2 + (\lambda_{D,2}^2 + \lambda_{D,3}^2)\, v_S^2}}\,,$$

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



Kowalska, Kumar, Sessolo.
arXiv: 1903.10932

daniele.rizzo@ncbj.gov.pl Daniele Rizzo

Couplings through mixing: VL leptons with a U(1)’ charge

Particle content $L : (\mathbf{1}, \mathbf{2}, -1/2, Q_L)$ $L' : (\mathbf{1}, \bar{\mathbf{2}}, 1/2, -Q_L)$.

daniele.rizzo@ncbj.gov.pl Daniele Rizzo

Couplings through mixing:
VL leptons with a U(1)' charge

Particle content

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

$$S : (\mathbf{1}, \mathbf{1}, 0, Q_S)$$

Interaction

$$\mathcal{L} \supset \lambda_{L,i} S^{(*)} L' l_i + m_L L' L + \mathrm{H.c.}\,,$$

daniele.rizzo@ncbj.gov.pl

Daniele Rizzo

Couplings through mixing: VL leptons with a U(1)' charge

Particle content

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

$$S : (\mathbf{1}, \mathbf{1}, 0, Q_S)$$

Interaction

$$\mathcal{L} \supset \lambda_{L,i} S^{(*)} L' l_i + m_L L' L + \mathrm{H.c.}\,,$$

Couplings in WET

$$g_L^{\mu\mu} \approx g_X\, Q_L\, \frac{\lambda_{L,2}^2 v_S^2}{2m_L^2 + \lambda_{L,2}^2 v_S^2}\,, \qquad g_R^{\mu\mu} \approx 0\,,$$

daniele.rizzo@ncbj.gov.pl
Daniele Rizzo

Couplings through mixing: VL leptons with a U(1)' charge

Particle content

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

$$S:(\mathbf{1},\mathbf{1},0,Q_S)$$

Interaction

$$\mathcal{L} \supset \lambda_{L,i} S^{(*)} L' l_i + m_L L' L + \mathrm{H.c.}\,,$$

Couplings in WET

$$g_L^{\mu\mu} \approx g_X\, Q_L\, \frac{\lambda_{L,2}^2 v_S^2}{2m_L^2 + \lambda_{L,2}^2 v_S^2}\,, \qquad g_R^{\mu\mu} \approx 0\,,$$

Wilson coefficients

$$C_9^\mu = -C_{10}^\mu \approx \mp \frac{Q_L}{Q_S}\frac{\Lambda_v^2}{V_{tb}V_{ts}^*}\left[\frac{\sqrt{2}\, m_Q\, \lambda_{Q,2}\, \lambda_{Q,3}}{(2m_Q^2 + \lambda_{Q,2}^2\, v_S^2)\sqrt{2\, m_Q^2 + (\lambda_{Q,2}^2 + \lambda_{Q,3}^2)\, v_S^2}}\right]\left(\frac{\lambda_{L,2}^2 v_S^2}{2m_L^2 + \lambda_{L,2}^2 v_S^2}\right).$$

daniele.rizzo@ncbj.gov.pl Daniele Rizzo

Direct lepton couplings: L_\mu-L_\tau symmetry

Particle content

$$l_1 : (\mathbf{1}, \mathbf{2}, -1/2, 0) \qquad e_R : (\mathbf{1}, \mathbf{1}, 1, 0)$$

$$l_2 : (\mathbf{1}, \mathbf{2}, -1/2, 1) \qquad \mu_R : (\mathbf{1}, \mathbf{1}, 1, -1)$$

$$l_3 : (\mathbf{1}, \mathbf{2}, -1/2, -1) \qquad \tau_R : (\mathbf{1}, \mathbf{1}, 1, 1)\,.$$

daniele.rizzo@ncbj.gov.pl
Daniele Rizzo

Direct lepton couplings: L_\mu-L_\tau symmetry

Particle content

$$l_1 : (\mathbf{1}, \mathbf{2}, -1/2, 0) \qquad e_R : (\mathbf{1}, \mathbf{1}, 1, 0)$$
$$l_2 : (\mathbf{1}, \mathbf{2}, -1/2, 1) \qquad \mu_R : (\mathbf{1}, \mathbf{1}, 1, -1)$$
$$l_3 : (\mathbf{1}, \mathbf{2}, -1/2, -1) \qquad \tau_R : (\mathbf{1}, \mathbf{1}, 1, 1)\,.$$

Couplings in WET $g_V^{\mu\mu} = g_X \qquad g_A^{\mu\mu} = 0\,.$

daniele.rizzo@ncbj.gov.pl
Daniele Rizzo

Direct lepton couplings: L_\mu-L_\tau symmetry

Particle content

$$l_1 : (\mathbf{1}, \mathbf{2}, -1/2, 0) \qquad e_R : (\mathbf{1}, \mathbf{1}, 1, 0)$$
$$l_2 : (\mathbf{1}, \mathbf{2}, -1/2, 1) \qquad \mu_R : (\mathbf{1}, \mathbf{1}, 1, -1)$$
$$l_3 : (\mathbf{1}, \mathbf{2}, -1/2, -1) \qquad \tau_R : (\mathbf{1}, \mathbf{1}, 1, 1)\,.$$

Couplings in WET $\quad g_V^{\mu\mu} = g_X \qquad g_A^{\mu\mu} = 0\,.$

Wilson coefficients

$$C_9^\mu \approx \mp \frac{1}{Q_S}\,\frac{2\Lambda_v^2}{V_{tb}V_{ts}^*}\,\frac{\sqrt{2}\,m_Q\,\lambda_{Q,2}\,\lambda_{Q,3}}{\left(2m_Q^2 + \lambda_{Q,2}^2\,v_S^2\right)\sqrt{2\,m_Q^2 + \left(\lambda_{Q,2}^2 + \lambda_{Q,3}^2\right)v_S^2}}\,, \qquad C_{10}^\mu = 0\,.$$

daniele.rizzo@ncbj.gov.pl Daniele Rizzo

Quantum Gravity contributions to the Running of the Coupling Constants

daniele.rizzo@ncbj.gov.pl
Daniele Rizzo

Quantum Gravity contributions to the Running of the Coupling Constants

Renormalization Group Equations in the Sub-Planckian regime

$$\beta_g = \beta_g^{\mathrm{SM+NP}}$$

$$\beta_y = \beta_y^{\mathrm{SM+NP}}$$

daniele.rizzo@ncbj.gov.pl

Daniele Rizzo

Quantum Gravity contributions to the Running of the Coupling Constants

Renormalization Group Equations in the Sub-Planckian regime

$$\beta_g = \beta_g^{\mathrm{SM+NP}}$$

$$\beta_y = \beta_y^{\mathrm{SM+NP}}$$

Renormalization Group Equations in the Trans-Planckian regime

$$\beta_g = \beta_g^{\mathrm{SM+NP}} - g\, f_g$$

$$\beta_y = \beta_y^{\mathrm{SM+NP}} - y\, f_y$$

daniele.rizzo@ncbj.gov.pl

Daniele Rizzo

Quantum Gravity contributions to the Running of the Coupling Constants

Renormalization Group Equations in the Sub-Planckian regime

$$\beta_g = \beta_g^{\mathrm{SM+NP}}$$

$$\beta_y = \beta_y^{\mathrm{SM+NP}}$$

Renormalization Group Equations in the Trans-Planckian regime

$$\beta_g = \beta_g^{\mathrm{SM+NP}} - g\, f_g$$

$$\beta_y = \beta_y^{\mathrm{SM+NP}} - y\, f_y$$

Stability Matrix

$$M_k^i \equiv \left[\frac{\partial \beta^i(g)}{\partial g^k}\right]_{g=g^*}$$

Linearization Coupling Constant

$$g_i(t) = g_i^* + \sum_m A_m\, V_{mi}\, e^{\lambda_m t}$$

daniele.rizzo@ncbj.gov.pl
Daniele Rizzo

Fixed Point Analysis

$$\text{SM}: \quad g_3\,,\ g_2\,,\ g_Y\,,\ y_t\,,\ y_b\,,\ V_{33}\,,$$
$$\text{NP}: \quad g_D,\ g_\epsilon,\ \lambda_{Q,2},\ \lambda_{Q,3},\ \lambda_{L,2}\,,$$

daniele.rizzo@ncbj.gov.pl

Daniele Rizzo

Fixed Point Analysis

$$\text{SM}: \quad g_3\,,\; g_2\,,\; g_Y\,,\; y_t\,,\; y_b\,,\; V_{33}\,,$$
$$\text{NP}: \quad g_D,\; g_\epsilon,\; \lambda_{Q,2},\; \lambda_{Q,3},\; \lambda_{L,2}\,,$$

Gauge couplings

$$g_Y^* = 4\pi\sqrt{\frac{f_g}{\widetilde{Q}_Y}}\,, \quad g_D^* = 4\pi\sqrt{\frac{f_g\widetilde{Q}_Y}{\widetilde{Q}_Y\widetilde{Q}_X - \widetilde{Q}_{YX}^2}}\,, \quad g_\epsilon^* = -4\pi\widetilde{Q}_{YX}\sqrt{\frac{f_g}{\widetilde{Q}_Y^2\widetilde{Q}_X - \widetilde{Q}_Y\widetilde{Q}_{YX}^2}}\,,$$

daniele.rizzo@ncbj.gov.pl

Daniele Rizzo

Fixed Point Analysis

$$\text{SM}: \quad g_3\,,\; g_2\,,\; g_Y\,,\; y_t\,,\; y_b\,,\; V_{33}\,,$$
$$\text{NP}: \quad g_D,\; g_\epsilon,\; \lambda_{Q,2},\; \lambda_{Q,3},\; \lambda_{L,2}\,,$$

Gauge couplings

$$g_Y^* = 4\pi\sqrt{\frac{f_g}{\widetilde{Q}_Y}}\,, \quad g_D^* = 4\pi\sqrt{\frac{f_g\widetilde{Q}_Y}{\widetilde{Q}_Y\widetilde{Q}_X - \widetilde{Q}_{YX}^2}}\,, \quad g_\epsilon^* = -4\pi\widetilde{Q}_{YX}\sqrt{\frac{f_g}{\widetilde{Q}_Y^2\widetilde{Q}_X - \widetilde{Q}_Y\widetilde{Q}_{YX}^2}}\,,$$

$$\begin{aligned}
\widetilde{Q}_Y &= \frac{2}{3}\sum_i d(R_{i3})d(R_{i2})Q_{Yi}^2 + \frac{1}{3}\sum_j d(R_{j3})d(R_{j2})Q_{Yj}^2 \\
\widetilde{Q}_X &= \frac{2}{3}\sum_i d(R_{i3})d(R_{i2})Q_{Xi}^2 + \frac{1}{3}\sum_j d(R_{j3})d(R_{j2})Q_{Xj}^2 \\
\widetilde{Q}_{YX} &= \frac{2}{3}\sum_i d(R_{i3})d(R_{i2})Q_{Yi}Q_{Xi} + \frac{1}{3}\sum_j d(R_{j3})d(R_{j2})Q_{Yj}Q_{Xj}
\end{aligned}$$

daniele.rizzo@ncbj.gov.pl

Daniele Rizzo

Fixed Point Analysis

$$\text{SM}: \quad g_3\,,\ g_2\,,\ g_Y\,,\ y_t\,,\ y_b\,,\ V_{33}\,,$$
$$\text{NP}: \quad g_D,\ g_\epsilon,\ \lambda_{Q,2},\ \lambda_{Q,3},\ \lambda_{L,2}\,,$$

Gauge couplings

$$g_Y^* = 4\pi\sqrt{\frac{f_g}{\widetilde{Q}_Y}}\,, \quad g_D^* = 4\pi\sqrt{\frac{f_g\widetilde{Q}_Y}{\widetilde{Q}_Y\widetilde{Q}_X - \widetilde{Q}_{YX}^2}}\,, \quad g_\epsilon^* = -4\pi\widetilde{Q}_{YX}\sqrt{\frac{f_g}{\widetilde{Q}_Y^2\widetilde{Q}_X - \widetilde{Q}_Y\widetilde{Q}_{YX}^2}}\,,$$

$$\begin{aligned}
\widetilde{Q}_Y &= \frac{2}{3}\sum_i d(R_{i3})d(R_{i2})Q_{Yi}^2 + \frac{1}{3}\sum_j d(R_{j3})d(R_{j2})Q_{Yj}^2 \\
\widetilde{Q}_X &= \frac{2}{3}\sum_i d(R_{i3})d(R_{i2})Q_{Xi}^2 + \frac{1}{3}\sum_j d(R_{j3})d(R_{j2})Q_{Xj}^2 \\
\widetilde{Q}_{YX} &= \frac{2}{3}\sum_i d(R_{i3})d(R_{i2})Q_{Yi}Q_{Xi} + \frac{1}{3}\sum_j d(R_{j3})d(R_{j2})Q_{Yj}Q_{Xj}
\end{aligned}$$

Model	Sec. reference	Fermion charges	$\widetilde{Q}_{YX}$
1A	Sec. 2.3	$Q_{\text{SM}} = 0,\ Q_L = Q_S$	0
1B	Sec. 2.3	$Q_{\text{SM}} = 0,\ Q_L = -Q_S$	$8/3\,Q_S$
2	Sec. 2.2	$Q_\mu = 1,\ Q_\tau = -1$	$4/3\,Q_S$

daniele.rizzo@ncbj.gov.pl

Daniele Rizzo

Fixed Point Analysis

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

NP: $g_D,\ g_\epsilon,\ \lambda_{Q,2},\ \lambda_{Q,3},\ \lambda_{L,2}\,,$

Gauge couplings

$$g_Y^* = 4\pi\sqrt{\frac{f_g}{\widetilde{Q}_Y}}\,,\quad g_D^* = 4\pi\sqrt{\frac{f_g\widetilde{Q}_Y}{\widetilde{Q}_Y\widetilde{Q}_X - \widetilde{Q}_{YX}^2}}\,,\quad g_\epsilon^* = -4\pi\widetilde{Q}_{YX}\sqrt{\frac{f_g}{\widetilde{Q}_Y^2\widetilde{Q}_X - \widetilde{Q}_Y\widetilde{Q}_{YX}^2}}\,,$$

$$\begin{aligned}
\widetilde{Q}_Y &= \frac{2}{3}\sum_i d(R_{i3})d(R_{i2})Q_{Yi}^2 + \frac{1}{3}\sum_j d(R_{j3})d(R_{j2})Q_{Yj}^2 \\
\widetilde{Q}_X &= \frac{2}{3}\sum_i d(R_{i3})d(R_{i2})Q_{Xi}^2 + \frac{1}{3}\sum_j d(R_{j3})d(R_{j2})Q_{Xj}^2 \\
\widetilde{Q}_{YX} &= \frac{2}{3}\sum_i d(R_{i3})d(R_{i2})Q_{Yi}Q_{Xi} + \frac{1}{3}\sum_j d(R_{j3})d(R_{j2})Q_{Yj}Q_{Xj}
\end{aligned}$$

Model	Sec. reference	Fermion charges	$\widetilde{Q}_{YX}$
1A	Sec. 2.3	$Q_{\rm SM}=0,\ Q_L=Q_S$	0
1B	Sec. 2.3	$Q_{\rm SM}=0,\ Q_L=-Q_S$	$8/3\,Q_S$
2	Sec. 2.2	$Q_\mu=1,\ Q_\tau=-1$	$4/3\,Q_S$

$$y_t^* = F_t\left(f_g, f_y\right)$$

daniele.rizzo@ncbj.gov.pl

Daniele Rizzo

Fixed Point Analysis

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

NP: $g_D,\ g_\epsilon,\ \lambda_{Q,2},\ \lambda_{Q,3},\ \lambda_{L,2}\,,$

Gauge couplings

$$g_Y^* = 4\pi\sqrt{\frac{f_g}{\widetilde{Q}_Y}}\,,\quad g_D^* = 4\pi\sqrt{\frac{f_g\widetilde{Q}_Y}{\widetilde{Q}_Y\widetilde{Q}_X - \widetilde{Q}_{YX}^2}}\,,\quad g_\epsilon^* = -4\pi\widetilde{Q}_{YX}\sqrt{\frac{f_g}{\widetilde{Q}_Y^2\widetilde{Q}_X - \widetilde{Q}_Y\widetilde{Q}_{YX}^2}}\,,$$

$$\begin{aligned}
\widetilde{Q}_Y &= \frac{2}{3}\sum_i d(R_{i3})d(R_{i2})Q_{Yi}^2 + \frac{1}{3}\sum_j d(R_{j3})d(R_{j2})Q_{Yj}^2\\
\widetilde{Q}_X &= \frac{2}{3}\sum_i d(R_{i3})d(R_{i2})Q_{Xi}^2 + \frac{1}{3}\sum_j d(R_{j3})d(R_{j2})Q_{Xj}^2\\
\widetilde{Q}_{YX} &= \frac{2}{3}\sum_i d(R_{i3})d(R_{i2})Q_{Yi}Q_{Xi} + \frac{1}{3}\sum_j d(R_{j3})d(R_{j2})Q_{Yj}Q_{Xj}
\end{aligned}$$

Model	Sec. reference	Fermion charges	$\widetilde{Q}_{YX}$
1A	Sec. 2.3	$Q_{\rm SM}=0,\ Q_L=Q_S$	0
1B	Sec. 2.3	$Q_{\rm SM}=0,\ Q_L=-Q_S$	$8/3\,Q_S$
2	Sec. 2.2	$Q_\mu=1,\ Q_\tau=-1$	$4/3\,Q_S$

$$y_t^* = F_t\left(f_g, f_y\right)$$

$$\mathrm{FP}_{M,a}:\quad \lambda_{Q,2}^* \neq 0,\ \lambda_{Q,3}^* = 0\,,\qquad \mathrm{FP}_{M,b}:\quad \lambda_{Q,2}^* = 0,\ \lambda_{Q,3}^* \neq 0\,,$$

daniele.rizzo@ncbj.gov.pl

Daniele Rizzo

Fixed Point Analysis

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

NP: $g_D,\; g_\epsilon,\; \lambda_{Q,2},\; \lambda_{Q,3},\; \lambda_{L,2}\,,$

Model	Sec. reference	Fermion charges	$\widetilde{Q}_{YX}$
1A	Sec. 2.3	$Q_{\rm SM}=0,\, Q_L=Q_S$	0
1B	Sec. 2.3	$Q_{\rm SM}=0,\, Q_L=-Q_S$	$8/3\,Q_S$
2	Sec. 2.2	$Q_\mu=1,\, Q_\tau=-1$	$4/3\,Q_S$

$$g_Y^* = 4\pi\sqrt{\frac{f_g}{\widetilde{Q}_Y}}\,,\quad g_D^* = 4\pi\sqrt{\frac{f_g\widetilde{Q}_Y}{\widetilde{Q}_Y\widetilde{Q}_X-\widetilde{Q}_{YX}^2}}\,,\quad g_\epsilon^* = -4\pi\widetilde{Q}_{YX}\sqrt{\frac{f_g}{\widetilde{Q}_Y^2\widetilde{Q}_X-\widetilde{Q}_Y\widetilde{Q}_{YX}^2}}\,,$$

	f_g	f_y	g_Y^*	g_D^*	g_ϵ^*	y_t^*	$\lambda_{Q,3}^*$	$\lambda_{Q,2}^*$	$\lambda_{L,2}^*$
$\mathrm{FP}_{1\mathrm{A},a}$	0.012	0.0025	0.498	0.418	0	0.406	0	0.072	0.648
$\mathrm{FP}_{1\mathrm{A},b}$	0.012	0.0029	0.498	0.418	0	0.424	0.200	0	0.610
$\mathrm{FP}_{1\mathrm{B},a}$	0.012	0.0026	0.498	0.436	0.151	0.417	0	0.163	0.586
$\mathrm{FP}_{1\mathrm{B},b}$	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	–

daniele.rizzo@ncbj.gov.pl

Daniele Rizzo

Predictions

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

NP: $g_D,\ g_\epsilon,\ \lambda_{Q,2},\ \lambda_{Q,3},\ \lambda_{L,2}\,,$

Couplings at the FP

	f_g	f_y	g_Y^*	g_D^*	g_ϵ^*	y_t^*	$\lambda_{Q,3}^*$	$\lambda_{Q,2}^*$	$\lambda_{L,2}^*$
$\mathrm{FP}_{1\mathrm{A},a}$	0.012	0.0025	0.498	0.418	0	0.406	0	0.072	0.648
$\mathrm{FP}_{1\mathrm{A},b}$	0.012	0.0029	0.498	0.418	0	0.424	0.200	0	0.610
$\mathrm{FP}_{1\mathrm{B},a}$	0.012	0.0026	0.498	0.436	0.151	0.417	0	0.163	0.586
$\mathrm{FP}_{1\mathrm{B},b}$	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	–

Couplings at 2 TeV

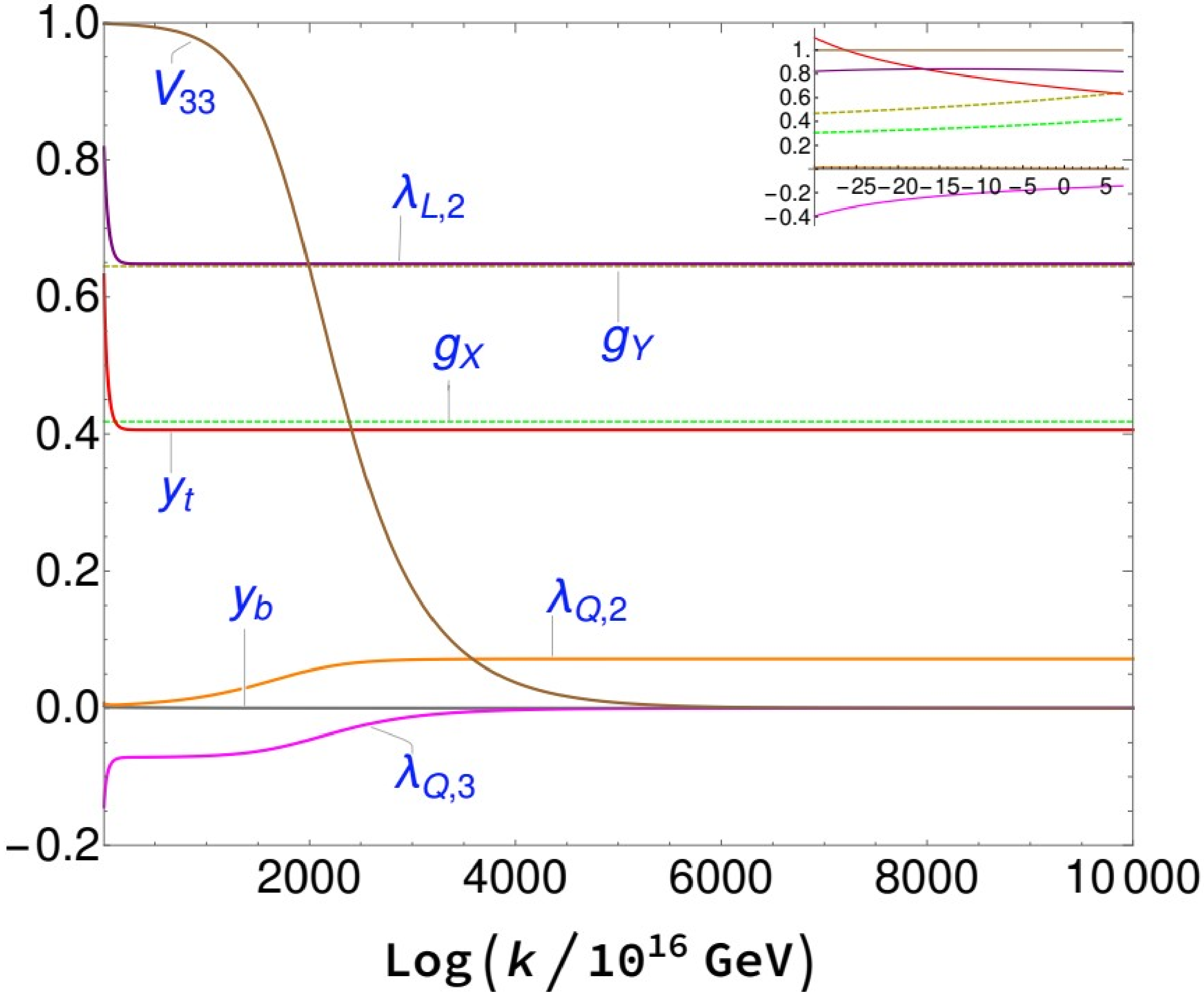
	$g_Y(k_0)$	$g_D(k_0)$	$g_\epsilon(k_0)$	$y_t(k_0)$	$\lambda_{Q,3}(k_0)$	$\lambda_{Q,2}(k_0)$	$\lambda_{L,2}(k_0)$
$\mathrm{FP}_{1\mathrm{A},a}$	0.364	0.305	0	1.08	-0.381	0.016	0.823
$\mathrm{FP}_{1\mathrm{A},b}$	0.364	0.305	0	1.09	0.034	0.803	0.606
$\mathrm{FP}_{1\mathrm{B},a}$	0.363	0.318	0.110	1.05	-0.612	0.296	0.652
$\mathrm{FP}_{1\mathrm{B},b}$	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	–

daniele.rizzo@ncbj.gov.pl

Daniele Rizzo

Predictions

$$\text{SM}: \quad g_3\,,\; g_2\,,\; g_Y\,,\; y_t\,,\; y_b\,,\; V_{33}\,,$$
$$\text{NP}: \quad g_D,\; g_\epsilon,\; \lambda_{Q,2},\; \lambda_{Q,3},\; \lambda_{L,2}\,,$$



daniele.rizzo@ncbj.gov.pl

Daniele Rizzo

Experimental constraints: Kinetic Mixing

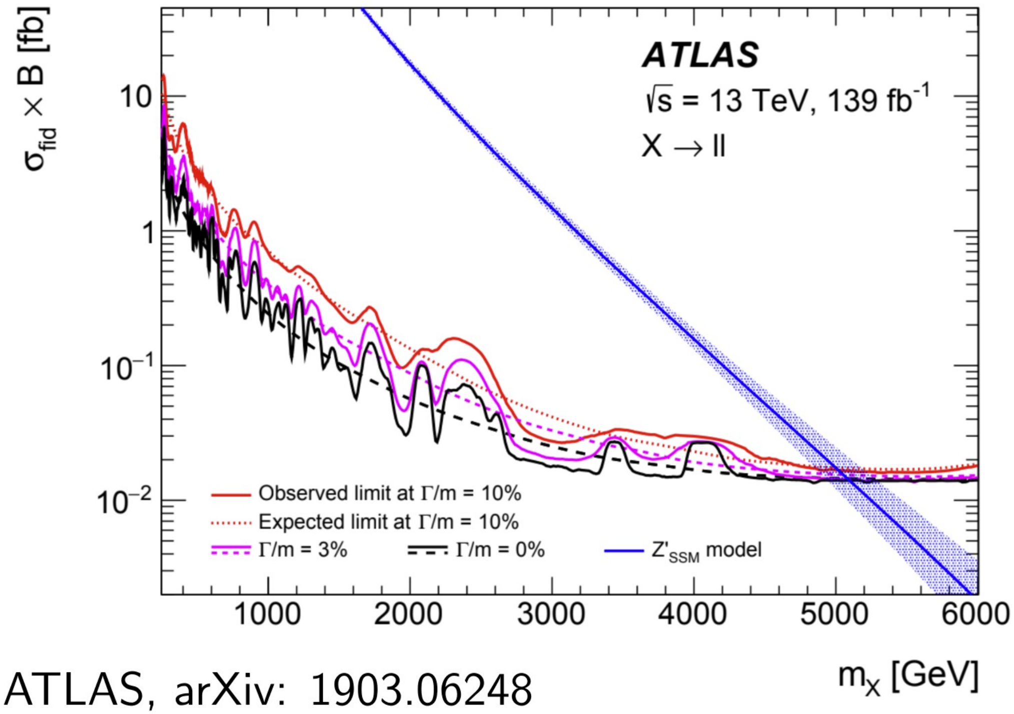
$$\epsilon = \frac{g_\epsilon}{\sqrt{g_\epsilon^2 + g_V^2}} \,.$$

daniele.rizzo@ncbj.gov.pl
Daniele Rizzo

Experimental constraints: Kinetic Mixing

$$\epsilon = \frac{g_\epsilon}{\sqrt{g_\epsilon^2 + g_V^2}} \,.$$

$$pp > X > l^+ l^-$$



ATLAS, arXiv: 1903.06248

daniele.rizzo@ncbj.gov.pl

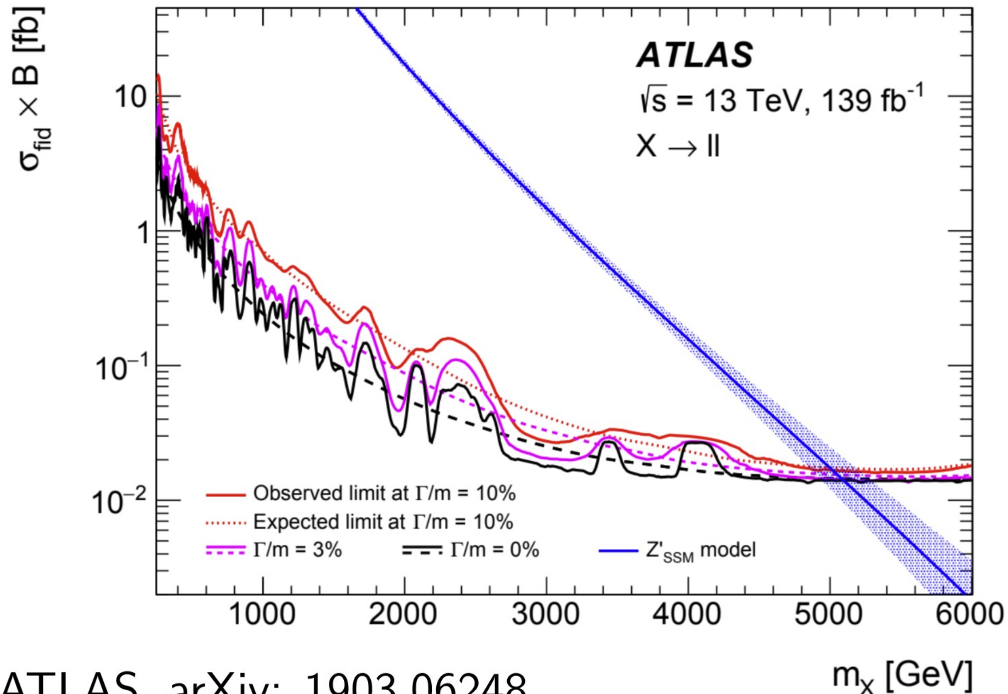
Daniele Rizzo

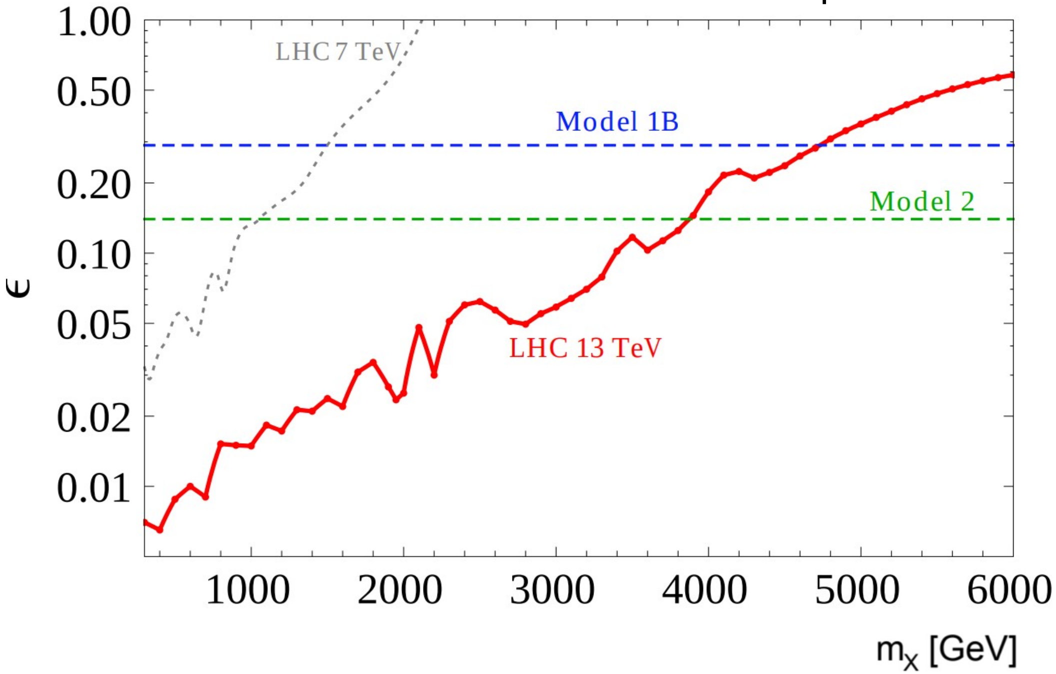
Experimental constraints: Kinetic Mixing

$$\epsilon = \frac{g_\epsilon}{\sqrt{g_\epsilon^2 + g_V^2}}\,.$$

$$pp > X > l^+ l^-$$

Simulations performed with MadGraph





ATLAS, arXiv: 1903.06248

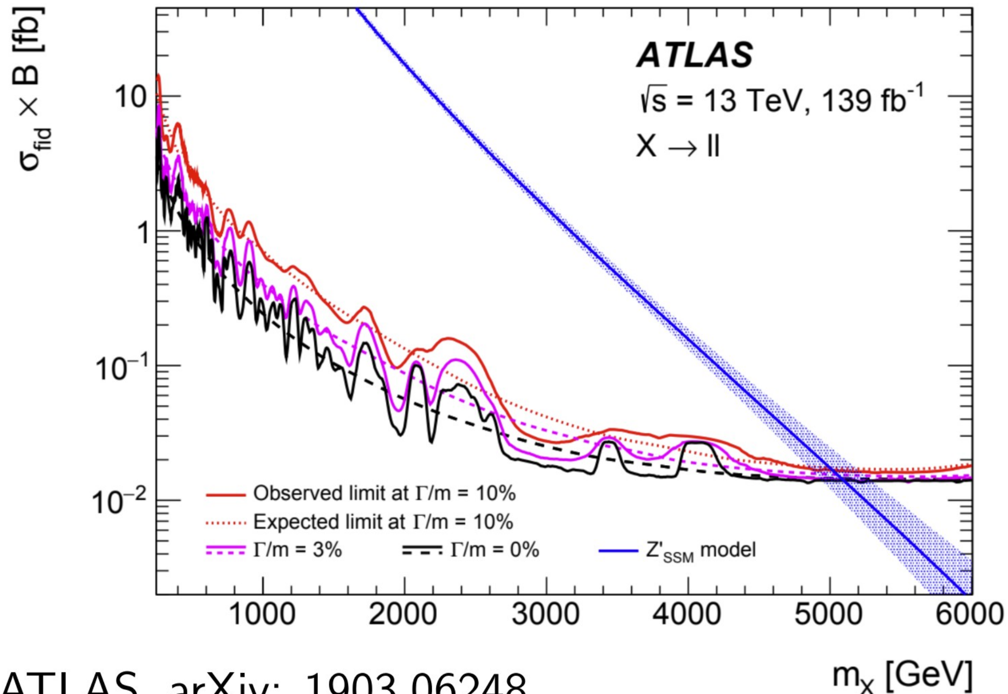
daniele.rizzo@ncbj.gov.pl
Daniele Rizzo

Experimental constraints: Kinetic Mixing

$$\epsilon = \frac{g_\epsilon}{\sqrt{g_\epsilon^2 + g_V^2}} \, .$$

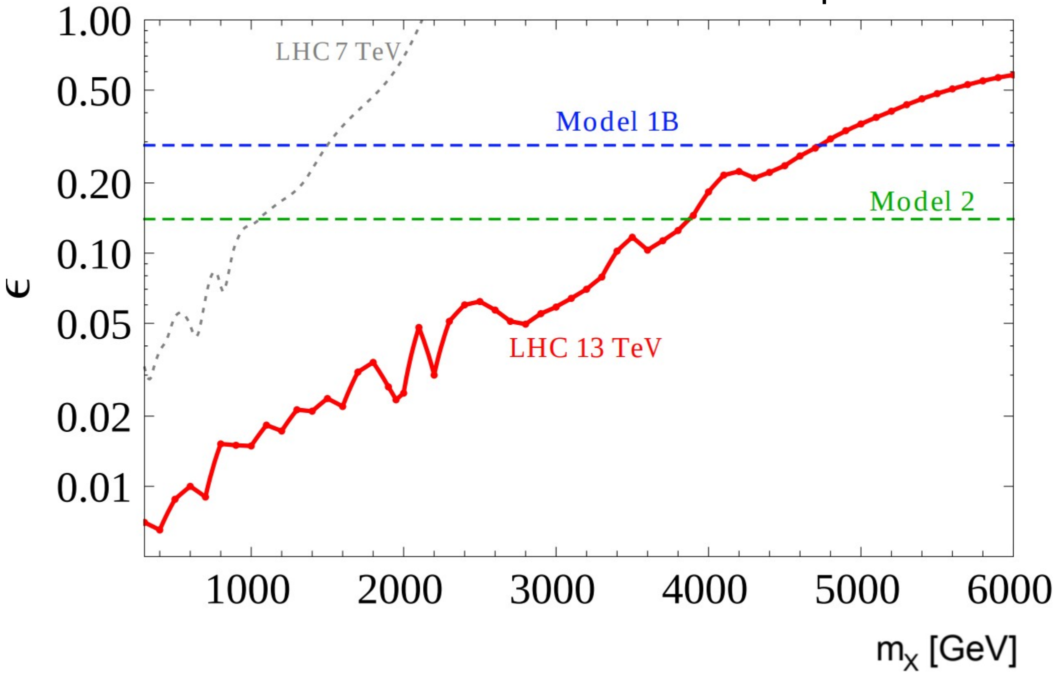
$$\text{Model 1B:} \quad m_{Z'} \gtrsim 4.7\,\text{TeV}\,,$$
$$\text{Model 2:} \quad m_{Z'} \gtrsim 3.9\,\text{TeV}\,,$$

$$pp > X > l^+ l^-$$



ATLAS, arXiv: 1903.06248

Simulations performed with MadGraph

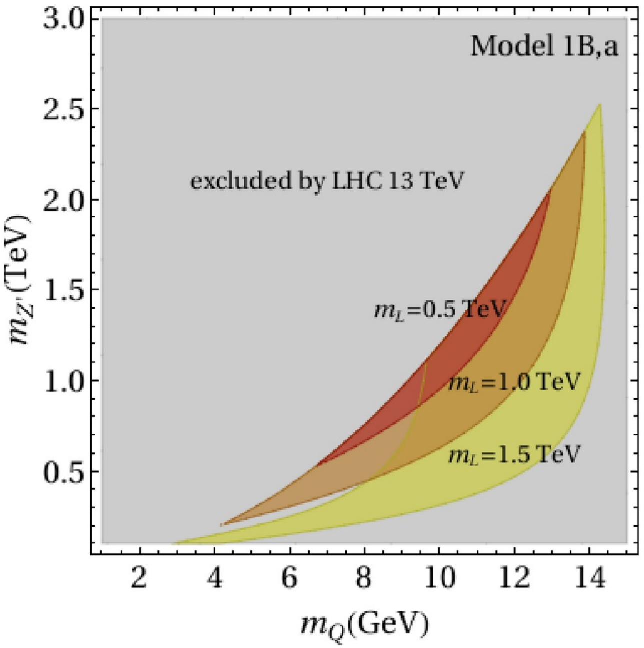


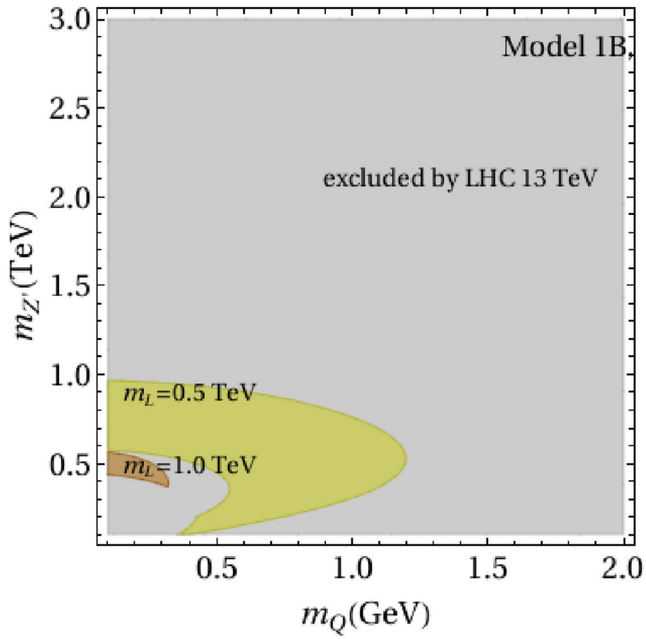
daniele.rizzo@ncbj.gov.pl

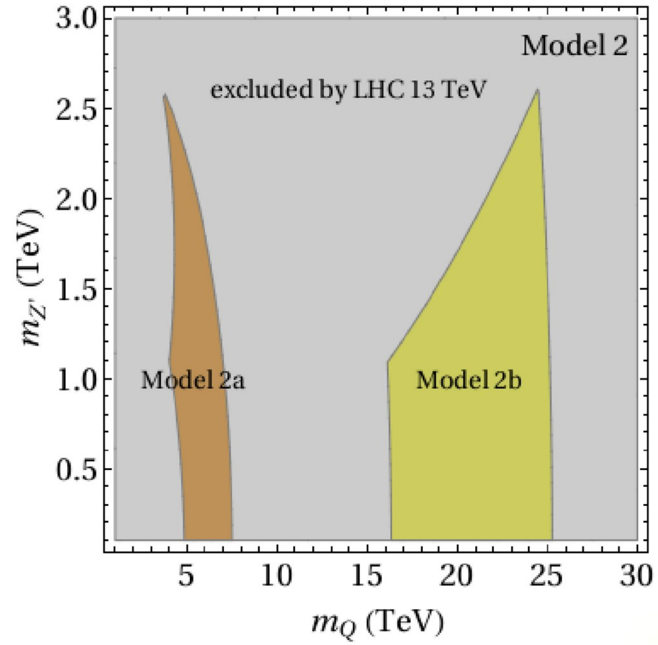
Daniele Rizzo

Experimental constraints: Kinetic Mixing & Wilson Coefficients

$$m_{Z'} \gtrsim 4.7\,\mathrm{TeV}\,, \qquad m_{Z'} \gtrsim 3.9\,\mathrm{TeV}\,,$$

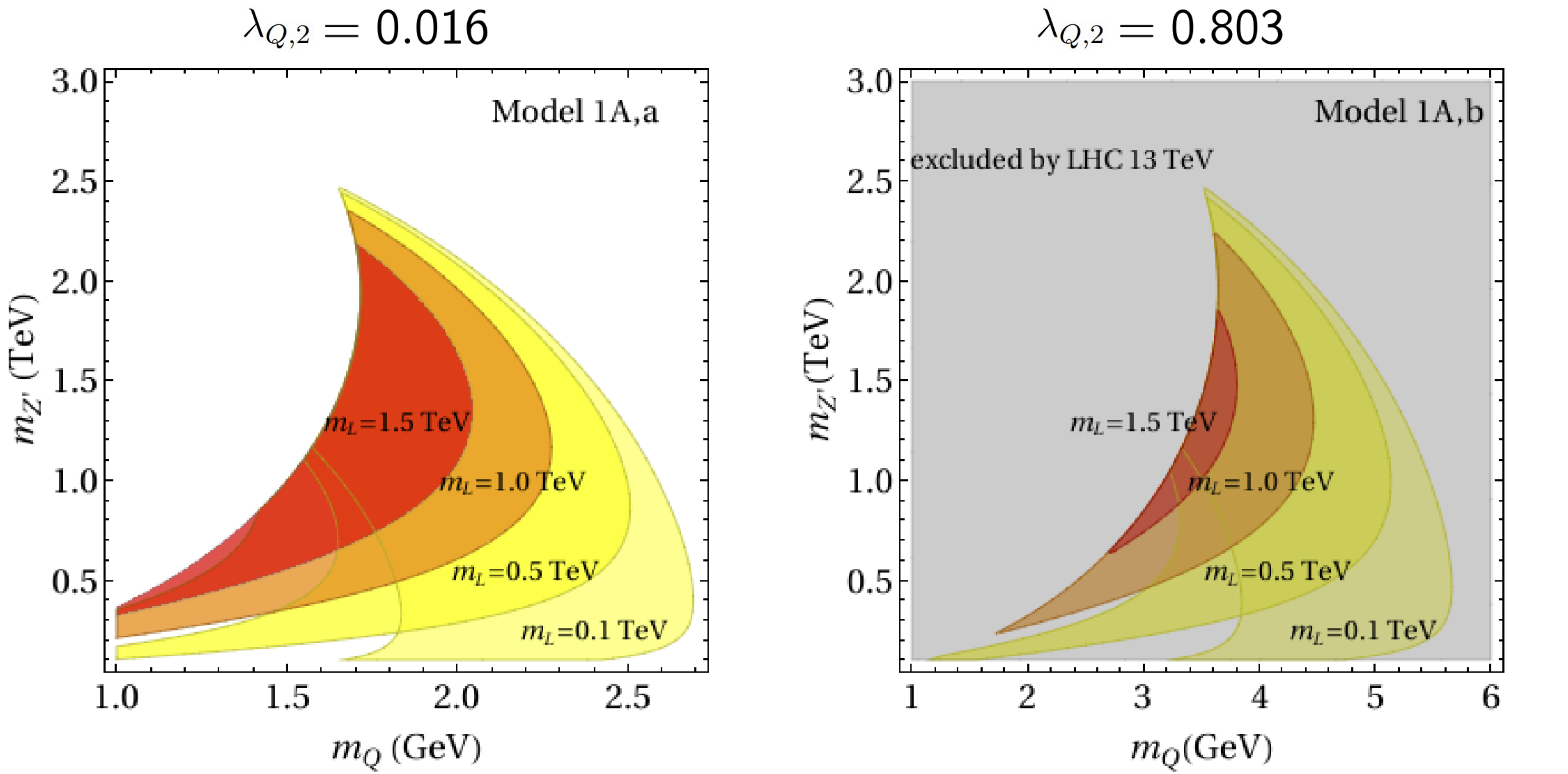






daniele.rizzo@ncbj.gov.pl
Daniele Rizzo

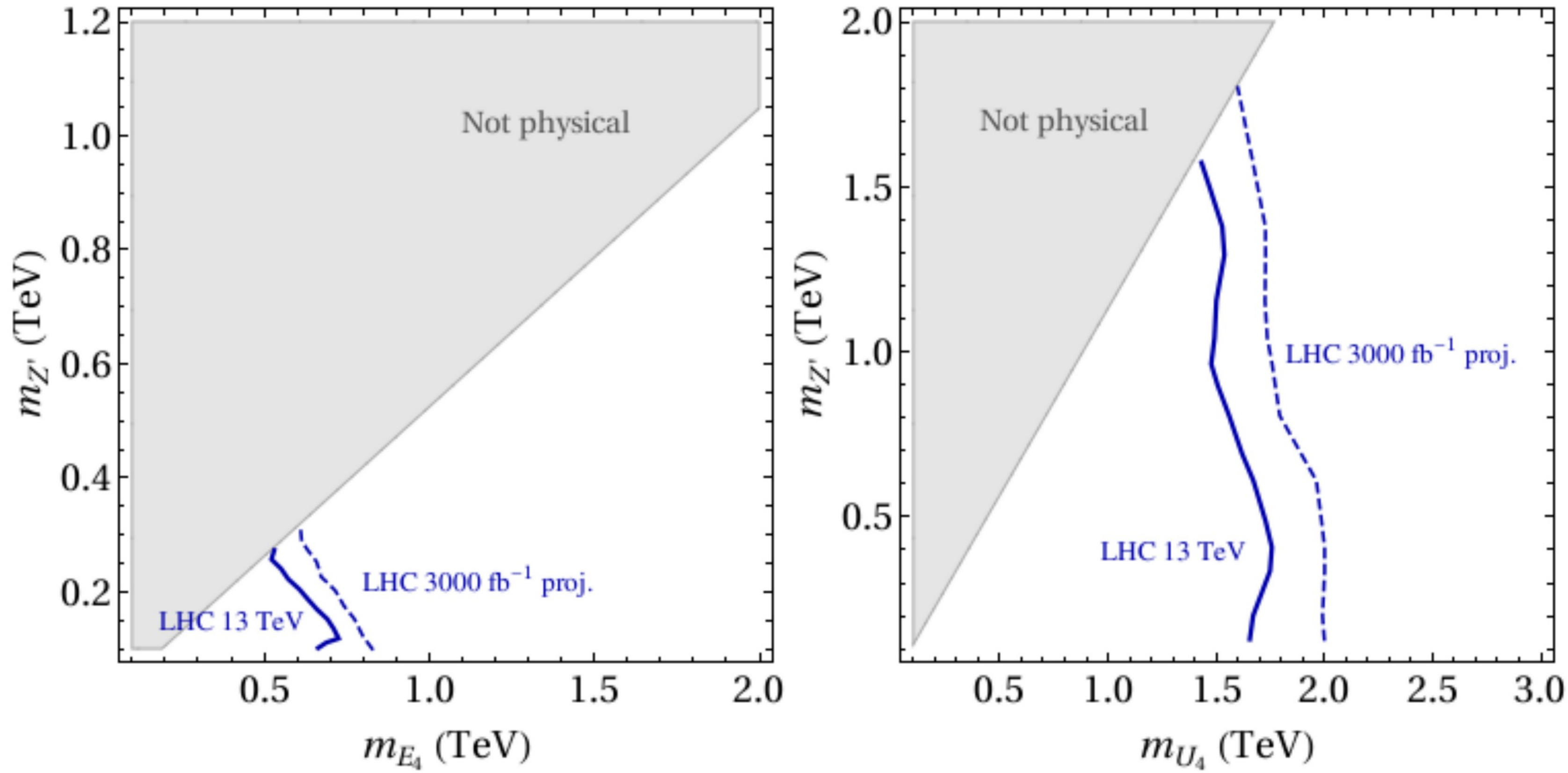
Experimental constraints:
Kinetic Mixing & Wilson Coefficients



daniele.rizzo@ncbj.gov.pl
Daniele Rizzo

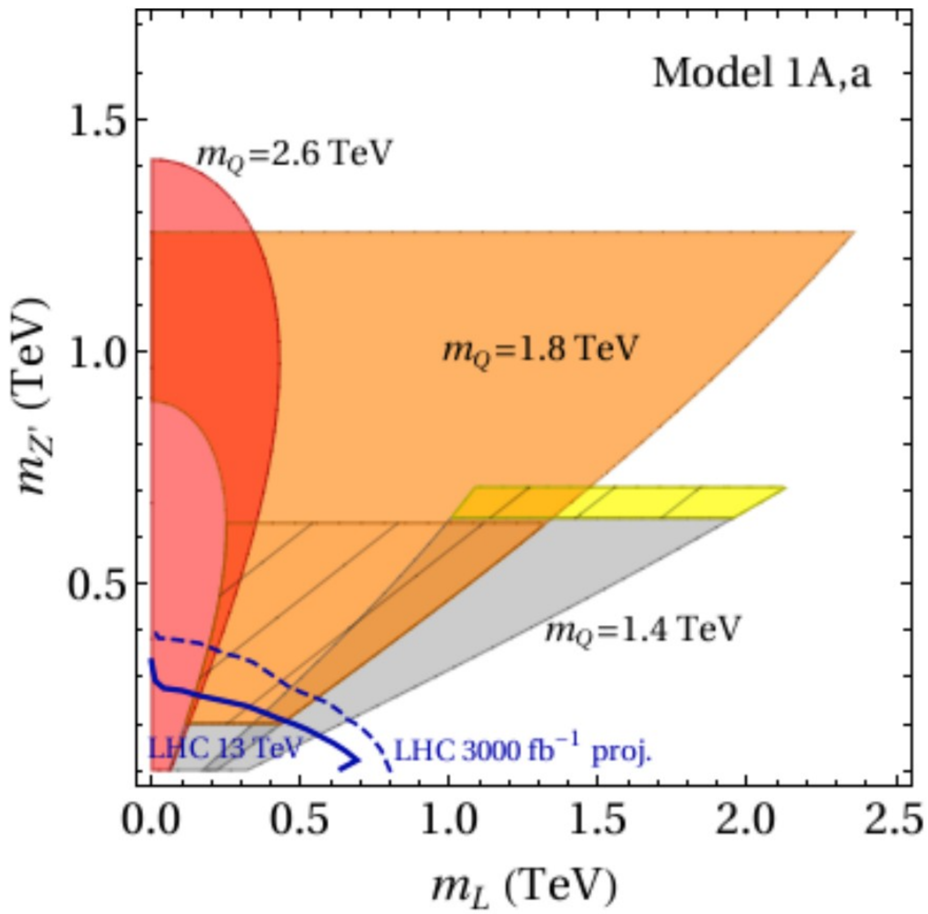
Experimental constraints: Production of VL fermions and Z’

SARAH → SPheno → Herwig → CheckMATE



daniele.rizzo@ncbj.gov.pl
Daniele Rizzo

Experimental constraints: Production of VL fermions and Z’



daniele.rizzo@ncbj.gov.pl

Daniele Rizzo

Conclusions

- Models with Z’ and VL fermions are able to explain flavor anomalies. However, the parameters space of such models is very wide.

- Asymptotic safety was used as a framework to constrain the parameters space. To do so, the only assumption was the presence of an interactive fixed point.

- The flow of the coupling constants gave us predictions for the new physics.

- Using already existing searches at 13 TeV at the LHC we were able to constrain even more the parameter space of the models. Some of them were this way excluded while one particular model can actually be tested with the new searches at 3000 1/fb at the LHC.

daniele.rizzo@ncbj.gov.pl
Daniele Rizzo

Thanks for the attention!

daniele.rizzo@ncbj.gov.pl
Daniele Rizzo

Quantum Gravity contributions to the Running of the Coupling Constants

Einstein-Hilbert Gravity

$$S_{\rm EH} = \frac{1}{16\pi G_N}\int d^4x\sqrt{g}\,(-R(g)+2\Lambda)$$

Fixed Point

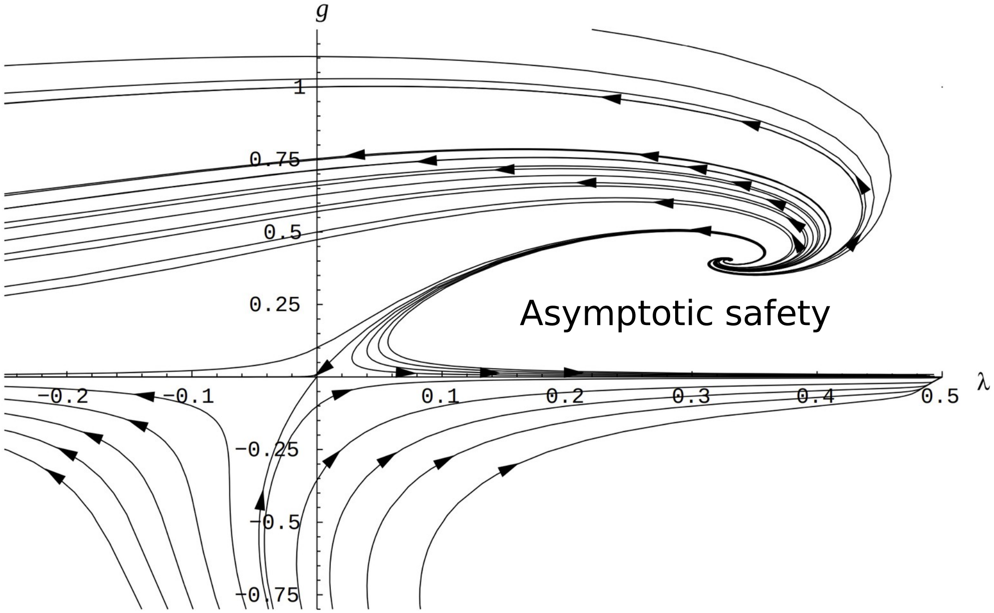
$$\beta_g \equiv \frac{dg}{d\ln k} = 0 \qquad \beta_\lambda \equiv \frac{d\lambda}{d\ln k} = 0$$

Gaussian Fixed Point

$$g = 0 \qquad \lambda = 0$$

Interactive Fixed Point

$$g = g^* \qquad \lambda = \lambda^*$$



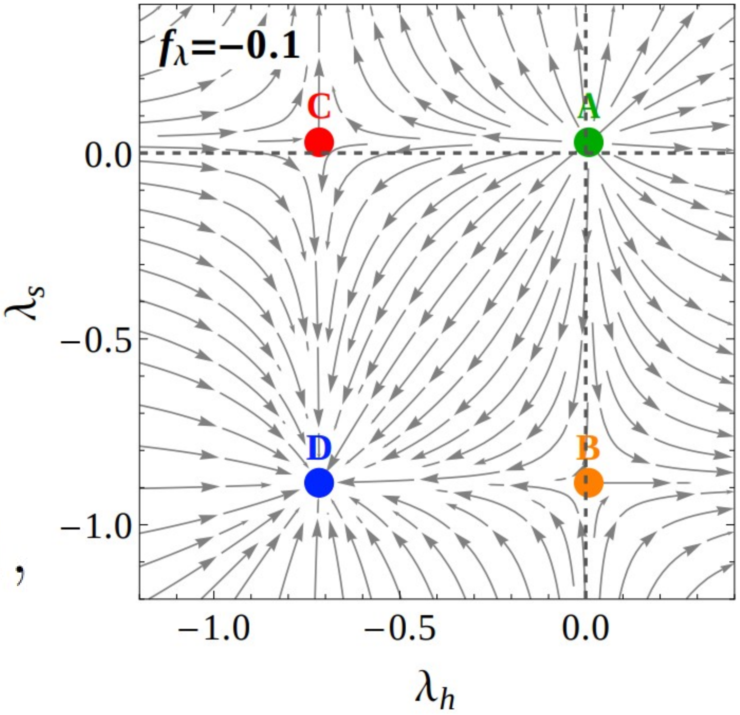
Reuter, Saueressig, hep-th/0110054

daniele.rizzo@ncbj.gov.pl
Daniele Rizzo

Scalar Sector

$$V\left(|h|^2, |S|^2\right) = -\mu_h^2 h^\dagger h + \lambda_h \left(h^\dagger h\right)^2 + \mu_S^2\, S^\dagger S + \lambda_S \left(S^\dagger S\right)^2 + \lambda_{hS} \left(S^\dagger S\right)\left(h^\dagger h\right)$$

	λ_h^*	λ_S^*	λ_{hS}^*	θ_h	θ_S	θ_{hS}
$\mathrm{FP_A}$	>0	>0	$\approx 0^+$	$-$	$-$	$-$
$\mathrm{FP_B}$	>0	<0	$\approx 0^+$	$-$	$+$	$-$
$\mathrm{FP_C}$	<0	>0	$\approx 0^+$	$+$	$-$	$-$
$\mathrm{FP_D}$	<0	<0	>0	$+$	$+$	$-$



$$\lambda_S(173\,\mathrm{GeV}) = 0.18\,, \quad \lambda_{hS}(173\,\mathrm{GeV}) = 0.1\,,$$

$$m_{H_2} = \sqrt{\lambda_h v_h^2 + \lambda_S v_S^2 + \sqrt{\lambda_h^2 v_h^4 + \lambda_{hS}^2 v_h^2 v_S^2 - 2\lambda_h \lambda_S v_h^2 v_S^2 + \lambda_S^2 v_S^4}}\,.$$

daniele.rizzo@ncbj.gov.pl
Daniele Rizzo

Experimental constraints: Scalar Sector

$$V\left(|h|^2, |S|^2\right) = -\mu_h^2 h^\dagger h + \lambda_h \left(h^\dagger h\right)^2 + \mu_S^2 S^\dagger S + \lambda_S \left(S^\dagger S\right)^2 + \lambda_{hS} \left(S^\dagger S\right)\left(h^\dagger h\right)$$

$$m_H^2 = \begin{pmatrix} -\mu_h^2 + 3\lambda_h v_h^2 + \frac{1}{2}\lambda_{hS} v_S^2 & \lambda_{hS} v_S v_h \\ \lambda_{hS} v_S v_h & \mu_S^2 + 3\lambda_S v_S^2 + \frac{1}{2}\lambda_{hS} v_h^2 \end{pmatrix}$$

$$\sin\alpha_H = \frac{\lambda_{hS}\, v_h\, v_S}{2\sqrt{\lambda_h^2 v_h^4 + \lambda_{hS}^2 v_h^2 v_S^2 - 2\lambda_h \lambda_S v_h^2 v_S^2 + \lambda_S^2 v_S^4}} < 0.2$$

$$m_{H_2} \approx 2.02\, m_{Z'}\,. \qquad \sin\alpha_H \approx \frac{20\,\mathrm{GeV}}{m_{Z'}}.$$

daniele.rizzo@ncbj.gov.pl
Daniele Rizzo

RGEs Model 1B

$$\frac{dy_t}{dt} = \frac{1}{16\pi^2}\left[3y_b^2 + \frac{9}{2}y_t^2 - \frac{17}{12}g_Y^2 - \frac{17}{12}g_\epsilon^2 - \frac{9}{4}g_2^2 - 8g_3^2 - \frac{3}{2}{V_{33}}^2 y_b^2 \right.$$
$$\left. + \frac{1}{2}{V_{32}}^2(\lambda_{Q,2})^2 + V_{32}V_{33}\lambda_{Q,3}\lambda_{Q,2} + \frac{1}{2}{V_{33}}^2(\lambda_{Q,3})^2\right] y_t - f_y y_t$$

$$\frac{dy_b}{dt} = \frac{1}{16\pi^2}\left[\frac{9}{2}y_b^2 + 3y_t^2 - \frac{5}{12}g_Y^2 - \frac{5}{12}g_\epsilon^2 - \frac{9}{4}g_2^2 - 8g_3^2 - \frac{3}{2}{V_{33}}^2 y_t^2 + \frac{1}{2}(\lambda_{Q,3})^2\right] y_b - f_y y_b$$

$$\frac{d\lambda_{Q,2}}{dt} = \frac{1}{16\pi^2}\left\{\left[7(\lambda_{Q,2})^2 + \frac{13}{2}(\lambda_{Q,3})^2 + 2(\lambda_{L,2})^2 + \frac{1}{2}y_t^2{V_{32}}^2 - \frac{9}{2}g_2^2 - 8g_3^2 \right.\right.$$
$$\left.\left. - \frac{1}{6}g_Y^2 - \frac{1}{6}g_\epsilon^2 - 3g_D^2 + g_D g_\epsilon\right]\lambda_{Q,2} + 2y_t^2 V_{32}V_{33}\lambda_{Q,3}\right\} - f_y\lambda_{Q,2}$$

$$\frac{d\lambda_{Q,3}}{dt} = \frac{1}{16\pi^2}\left\{\left[\frac{15}{2}(\lambda_{Q,2})^2 + 7(\lambda_{Q,3})^2 + 2(\lambda_{L,2})^2 + \frac{1}{2}y_b^2 + \frac{1}{2}y_t^2{V_{33}}^2 - \frac{9}{2}g_2^2 - 8g_3^2 \right.\right.$$
$$\left.\left. - \frac{1}{6}g_Y^2 - \frac{1}{6}g_\epsilon^2 - 3g_D^2 + g_D g_\epsilon\right]\lambda_{Q,3} - y_t^2 V_{32}V_{33}\lambda_{Q,2}\right\} - f_y\lambda_{Q,3}$$

$$\frac{d\lambda_{L,2}}{dt} = \frac{1}{16\pi^2}\left[6(\lambda_{Q,2})^2 + 6(\lambda_{Q,3})^2 + 3(\lambda_{L,2})^2 - \frac{9}{2}g_2^2 - \frac{3}{2}g_Y^2 - \frac{3}{2}g_\epsilon^2 - 3g_D^2 \right.$$
$$\left. + 3g_D g_\epsilon\right]\lambda_{L,2} - f_y\lambda_{L,2}$$

$$\frac{d|V_{33}|}{dt} = \frac{V_{23}}{16\pi^2}\left[-\frac{3}{2}V_{23}V_{33}y_b^2 + \frac{1}{2}\left(V_{22}V_{32}(\lambda_{Q,2})^2 \right.\right.$$
$$\left.\left. + V_{22}V_{33}\lambda_{Q,2}\lambda_{Q,3} + V_{23}V_{32}\lambda_{Q,2}\lambda_{Q,3} + V_{23}V_{33}(\lambda_{Q,3})^2\right)\right]$$
$$- \frac{V_{32}}{16\pi^2}\left[\frac{3}{2}V_{32}V_{33}y_t^2 - \frac{1}{2}\lambda_{Q,2}\lambda_{Q,3}\right]$$

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

$$\frac{d\lambda_h}{dt} = \frac{1}{16\pi^2}\left[\frac{3}{8}(g_Y^2 + g_\epsilon^2)^2 + \frac{3}{4}(g_Y^2 + g_\epsilon^2)g_2^2 + \frac{9}{8}g_2^4 - 3g_Y^2\lambda_h - 3g_\epsilon^2\lambda_h - 9g_2^2\lambda_h \right.$$
$$\left. + 24\lambda_h^2 + \lambda_{hS}^2 + 12y_b^2\lambda_h + 12y_t^2\lambda_h - 6y_b^4 - 6y_t^4)\right] - f_\lambda\lambda_h$$

$$\frac{d\lambda_S}{dt} = \frac{1}{16\pi^2}\left[6g_D^4 g_Y^2/(g_Y^2 + g_\epsilon^2) + 2\lambda_{hS}^2 - 12g_D^2\lambda_S + 20\lambda_S^2 + 8(\lambda_{L,2})^2\lambda_S - 4(\lambda_{L,2})^4 \right.$$
$$\left. + 24(\lambda_{Q,2})^2\lambda_S + 24(\lambda_{Q,3})^2\lambda_S - 12\left((\lambda_{Q,2})^2 + (\lambda_{Q,3})^2\right)^2\right] - f_\lambda\lambda_S$$

$$\frac{d\lambda_{hS}}{dt} = \frac{1}{16\pi^2}\left[-\frac{3}{2}g_Y^2\lambda_{hS} - \frac{9}{2}g_2^2\lambda_{hS} - 6g_D^2\lambda_{hS} + 12\lambda_h\lambda_{hS} + 4\lambda_{hS}^2 + 8\lambda_{hS}\lambda_S \right.$$
$$+ 4(\lambda_{L,2})^2\lambda_{hS} + 12(\lambda_{Q,2})^2\lambda_{hS} + 12(\lambda_{Q,3})^2\lambda_{hS} + 6y_b^2\lambda_{hS} + 6y_t^2\lambda_{hS}$$
$$- 12y_b^2(\lambda_{Q,3})^2 - 12y_t^2{V_{32}}^2(\lambda_{Q,2})^2 - 12y_t^2{V_{33}}^2(\lambda_{Q,3})^2$$
$$\left. - 12y_t^2 V_{32}V_{33}\lambda_{Q,2}\lambda_{Q,3}\right] - f_\lambda\lambda_{hS}\,.$$

daniele.rizzo@ncbj.gov.pl
Daniele Rizzo

Example:
Gauge Sector U(1)' extension

Beta functions equations

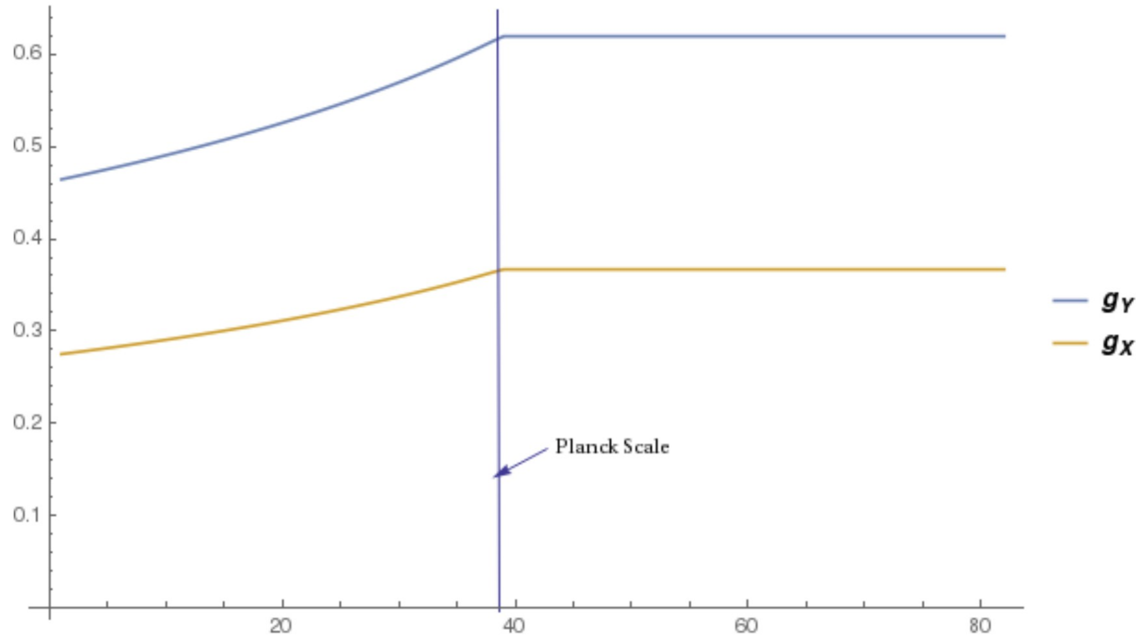
$$\frac{dg_3}{dt} = -\frac{17}{3}\frac{g_3^3}{16\pi^2} - f_g g_3 \,,$$

$$\frac{dg_2}{dt} = -\frac{1}{2}\frac{g_2^3}{16\pi^2} - f_g g_2 \,,$$

$$\frac{dg_Y}{dt} = \frac{139}{18}\frac{g_Y^3}{16\pi^2} - f_g g_Y \,,$$

$$\frac{dg_D}{dt} = \frac{1}{16\pi^2}\left(11 g_D^2 + \frac{139}{18} g_\epsilon^2\right) g_D - f_g g_D \,,$$

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



Plot from A. Chikkaballi's talk at DESY

daniele.rizzo@ncbj.gov.pl
Daniele Rizzo

Example:
Gauge Sector U(1)’ extension

Beta functions equations

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

$$\frac{dg_2}{dt} = -\frac{1}{2}\frac{g_2^3}{16\pi^2} - f_g g_2 \,,$$

$$\frac{dg_Y}{dt} = \frac{139}{18}\frac{g_Y^3}{16\pi^2} - f_g g_Y \,,$$

$$\frac{dg_D}{dt} = \frac{1}{16\pi^2}\left(11 g_D^2 + \frac{139}{18} g_\epsilon^2\right) g_D - f_g g_D \,,$$

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

Eigenvectors

$$\begin{pmatrix} 0. & 0. & 0. & 0. & 1. \\ 0. & 0. & 0. & 1. & 0. \\ 1. & 0. & 0. & 0. & 0. \\ 0. & 1. & 0. & 0. & 0. \\ 0. & 0. & 1. & 0. & 0. \end{pmatrix}$$

Linearized CC at the FP

```
gy[t] == 0.644314
g2[t] == 1. A4 e^(-0.0121806 t)
g3[t] == 1. A5 e^(-0.0121806 t)
gϵ[t] == 0
gd[t] == 0.418165
```

Eigenvalues

{0.0243612, 0.0243612, 0.0243612, -0.0121806, -0.0121806}

Values FP

g_Y^*	0.498
g_D^*	0.418
g_ϵ^*	0

daniele.rizzo@ncbj.gov.pl

Daniele Rizzo