

New directions in B-anomalies model building

Admir Greljo

20 September 2018, CKM





 The largest coherent set of discrepancies between Theory and Experiment today







New directions in B-anomalies model building - Admir Greljo, Johannes Gutenberg-Universität Mainz onowing the general sumprised radiatization of this approach we can describe both models in which the new vec gauge extension of the SM and simplified Lagrangian reads simplified \mathbb{E}_{μ} and \mathbb{E}_{μ} simplified Elagrangian reals and verators segmenting that our the is a fermion current transforming as a Standarthan built in terms of SN $W'^{a} \mathcal{L} J^{a}_{\mu} = -\frac{1}{2} \mathcal{D} \mathcal{V}^{a}_{\nu} D^{\mu} \mathcal{V}^{a}_{\nu} D^{\mu} \mathcal{V}^{a}_{\nu}$ $= \mathcal{V}_{\mu}^{a\nu} \mathcal{V}, \mathcal{D}_{\mu} \mathcal{V}, \mathcal{J}_{\mu} \mathcal{V}, \mathcal{J}, \mathcal{J$ on fields: where $T^a = g_q \lambda_{ij}^q \left(\overline{Q}_L^i \gamma_F I_i W_e \right)$ for $\mathcal{G}_L^i \mathcal{G}_L^i \mathcal{G}_L$ are Hermitian Bavintegantices ant aby no perators and then proceed an efine Q_L^i anators of dientics of a k6 twe loptain difference is a pierse in the flat wn-type quarks and charged-lepton2. Are di Teheale ffectsive lag pangiane vor symmetry, upden which the light generations on that is the start 2qespectively, and all other fermions are saidlets we further assume that in list s responsible for the effective interactions cial EA above was electrower as d generationBSMonestruicationthatentienthatentiatenal 18, 24, feimiEqs) 41, This boomd s in Eq. (5) $\operatorname{sign} \mathbb{R}_{ij}^{\ell \ell} = \delta_{i3}\delta_{3j}$. The corrections to this third are expected to be generation of subleading priate $U(2)_q \times U(2)_\ell$ breaking spurions $\frac{g_{\ell}}{2}$ of \mathcal{G}_{ℓ} and \mathcal{G}_{ℓ} be a redefinition of subleading prime \mathcal{G}_{ℓ} by the second of subleading \mathcal{G}_{ℓ} by the second \mathcal{G}_{ℓ} by the second \mathcal{G}_{ℓ} by the second ikawa couplings for the SM light fermi Φns_V^2 e quark case, the leading $U(2)_q$ breaking spurion is a doublet, whose flavor str This term induces an unphysical generative deviation of the flavor str uously connected to the CKM matrial Sallon we have the solution.

B-anomalies model building - Admir Greljo, Johannes Gutenberg-Universität Mainz

 $\frac{1}{115} \frac{2}{20} \frac{1}{2} \frac$ d Leghofe extransio Doth models in

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UV2V sine alls where the bass should be to be to be the state of the bass should be bass should be bass should be the bass shou serse during the service of the base role have the service of the

darfontekpelegd(Ad))) the The provide the second of the beh in the LQ or QQ

The share of the named on arks and leptons nd seneration no as Compasite Higgs mo MS CONTRACTING TO THE PILLO CONTRACTUOMS OF the tashanis be water find to specify and the anter preserve sty SM anarks Marina Heller Reperience and D. V. - μ dμ V. + 9 King natrix Heller Reperience Alost notable constroints ecators and then proceed and Aletailailedis Desidei abort Dilateo (Chine Contractor States and BUGRING DOR SCHOOL fective sense and starting on the sense is the sense of t Alg fermions). In this when the E-allemanes Professional and the second se to the property of the proper

Challenges for Model Builders?



[Buttazzo, AG, Isidori, Marzocca] Single mediator? 1706.07808 B' soptoquárk **ector** 0.04 0.02 Vreak ion of the scer nplest ector lepton fiar and long (3) hour bier of the strike the vector leptoquark \bar{U}_{μ} , imposing $|\beta_{s\mu,s\tau}|$ -0.06 $\frac{1}{3} \int_{-0.06 - 0.04 - 0.02}^{-0.04 - 0.02} \int_{\pi}^{0.04} \Delta^{0.06} \chi^2 \leq 2.3 \ (1\sigma), \ 6.0 \ (2\sigma), \ \text{and} \ 11.6$ $\pm \ln \frac{1}{\alpha} = \ln \frac{1}{\alpha} + \ln \frac{1}{\alpha} + \ln \frac{1}{\alpha} = \ln \frac{1}{\alpha} + \ln$ • Tree-level $U_{1,\mu\nu}^{\dagger}U_{\bullet}^{\text{Expanding SU(2)}} M_{\mu\nu}^{2}U_{\bullet}^{\dagger}M_{\mu\nu}^{2}U_{\bullet}^{2}U_{\bullet}^{\dagger}M_{\mu\nu}^{2}U_{\bullet}^{2}U_{\bullet}^{2}U_{\bullet}^{\dagger}M_{\mu\nu}^{2}U_{\bullet}^{2}U_$ where $C_{U\mu} = v^2 |g_U^{B*2}/(2M_U^2)^{B} \to 0.$ Note τ $i \neq c \neq j \neq 0$ satisfies our structure and in

[1706.07808]1708.08450, 1709.00692, 1712.01368, 1712.06844, 1801.07256, 1802.04274, 1805.09328, 1805.03209, 1806.07403, 1807.02068, 1807.10745, 1808.00942, 1808.05511, 1808.07492, 1808.08179, ...] Only a selection



Direction



A cake by [Buttazzo], 2017



'74 Pati-Salam

- Pati-Salam quark-lepton unification $\mathbf{4} = \mathbf{3}_{q} + \mathbf{1}_{\ell}$
- Resolves another open problem of the SM charge quantisation
- Low-scale Pati-Salam
 No proton decay
 - ✗ Flavour ≥ 1000 TeV [1801.02895]

A cake by [Buttazzo], 2017



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Consistent model with Pati-Salam LQ at the TeV scale? A cake by [Buttazzo], 2017



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Establishing links (The big picture)

Consistent model with Pati-Salam LQ at the TeV scale?

- [Talk by Isidori] Charge
- Hierarchy

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- Flavour problem
 Neutrino masses
 - **B-anomalies**

[This talk]

- Massive vector crave an UV completion
- Simplified mediator model approach is incomplete!
- I want a model to be
 Complete (but simple),
 Renormalizable,
 Calculable (perturbatively)
- **'Proper**' low-energy model to check the stability of the B-anomalies solution

Consistent model with Pati-Salam LQ at the TeV scale?

'4321' model

Extended gauge symmetry $G \equiv SU(4) \times SU(3)' \times SU(2)_L \times U(1)'$

		Field	d conte	nt		
	Field	SU(4)	SU(3)'	$SU(2)_L$	U(1)'	
Fermions	$q_L^{\prime i}$	1	3	2	1/6	
	$u_R'^i$	1	3	1	2/3	
	$d_R'^i$	1	3	1	-1/3	
	$\ell_L'^i$	1	1	2	-1/2	i='
	$e_R^{\prime i}$	1	1	1	-1	
	Ψ^i_L	4	1	2	0	
	Ψ^i_R	4	1	2	0	4
Scalars	Н	1	1	2	1/2	[]
	Ω_1	$\overline{4}$	1	1	-1/2	
	Ω_3	$\overline{4}$	3	1	1/6	[
	Ω_{15}	15	1	1	0	

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i=1,2,3

4321 Model for B-anomalies [Di Luzio, AG, Nardecchia] 1708.08450

Phenomenology

[Di Luzio, Fuentes-Martin, AG, Nardecchia, Renner] 1808.00942

Model structure from [Georgi, Nakai], 1606.05865 [Diaz, Schmaltz, Zhong], 1706.05033

~TeV

'4321' model

Extended gauge symmetry $G \equiv SU(4) \times SU(3)' \times SU(2)_L \times U(1)'$ $\int SSB: \langle \Omega_3 \rangle > \langle \Omega_1 \rangle \gg \langle \Omega_{15} \rangle \gg \langle H \rangle$

Scalars:

 $\Omega_1 = (\overline{4}, 1, 1, -1/2)$

 $\Omega_3 = (\overline{4}, 3, 1, 1/6)$

 $\langle \Omega_3 \rangle = \begin{pmatrix} \overline{\sqrt{2}} & 0 & 0 \\ 0 & \frac{v_3}{\sqrt{2}} & 0 \\ 0 & 0 & \frac{v_3}{\sqrt{2}} \end{pmatrix}, \quad \langle \Omega_1 \rangle = \begin{pmatrix} 0 \\ 0 \\ 0 \\ v_1 \end{pmatrix}$

$$G_{\rm SM} \equiv SU(3)_c \times SU(2)_L \times U(1)_Y$$

Embedding: $SU(3)_4 \times U(1)_4 \subset SU(4)$ and $SU(3)_c = (SU(3)_4 \times SU(3)')_{\text{diag}}$ $U(1)_Y = (U(1)_4 \times U(1)')_{\text{diag}}$

Gauge couplings: $g_s = \frac{g_4 g_3}{\sqrt{g_4^2 + g_3^2}} \quad g_Y = \frac{g_4 g_1}{\sqrt{g_4^2 + \frac{2}{3}g_1^2}}$

*One free coupling constant

~TeV

V_{EW}







A vector-like
$$(\mathbf{4}, 1, \mathbf{2}, 0)$$

fermion rep. $\Psi_{L,R} = (Q'_{L,R}, L'_{L,R})^T$

$$-\overline{q}_L' \lambda_q \,\Omega_3^T \Psi_R - \overline{\ell}_L' \,\lambda_\ell \,\Omega_1^T \Psi_R$$

- $\langle \Omega_3 \rangle$ mixes the would-be SM state q'_L with $Q'_L \subset \Psi_L$
- $\langle \Omega_1 \rangle$ mixes the would-be SM state ℓ'_L with $L'_L \subset \Psi_L$.



• How to get large flavour violation to be mediated only by the LQ?



Cabibbo mechanism for LQ



Cabibbo mechanism for LQ

Without loss of generality
$\mathcal{L}_{\rm SM-like} = -\overline{q}'_L V^{\dagger} Y_u d_R H - \overline{q}'_L Y_d d_R H - \ell'_L Y_e e_R H + \text{h.c.},$
$\mathcal{L}_{\text{mix}} = -\overline{q}'_L \lambda_q \Psi_R \Omega_3 - \overline{\ell}'_L \lambda_\ell \Psi_R \Omega_1 - \overline{\Psi}_L (\hat{M} + \lambda_{15} \Omega_{15}) \Psi_R + \text{h.c.}$
Assumptions
$\lambda_q = \lambda_q \equiv \operatorname{diag}\left(\lambda_{12}^4, \lambda_{12}^4, \lambda_3^4\right) , \qquad ($
$\begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 \end{pmatrix} $
2 $\lambda_{\ell} = \lambda_{\ell} W' \equiv \operatorname{diag}\left(\lambda_{1}^{\epsilon}, \lambda_{2}^{\epsilon}, \lambda_{3}^{\epsilon}\right) \begin{bmatrix} 0 \cos \theta_{LQ} - \sin \theta_{LQ} \\ 0 & \cdot & 0 \end{bmatrix}$
$\left(\begin{array}{c} 0 \sin \theta_{LQ} & \cos \theta_{LQ} \end{array} \right)$
$\lambda_{15} \propto M \propto 1$, *a hat means diagonal



- No tree-level Z', g' FCNC for down quarks
- Strong suppression of treelevel FCNC for up quarks

$$\mathcal{G}_Q \equiv U(2)_{q'+\Psi} \times U(1)_{q'_3+\Psi_3}$$
$$\lambda_\ell \to 0$$

'4321' model

• Redefine



 $\Psi_L = (Q'_L, L'_L)^T = (Q_L, WL_L)^T$

*same for the right-handed

- No tree-level Z' FCNC for leptons $\lambda_q \to 0$ $\mathcal{G}_L = U(1)_{\ell'_1 + \tilde{\Psi}_1} \times U(1)_{\ell'_2 + \tilde{\Psi}_2} \times U(1)_{\ell'_3 + \tilde{\Psi}_3}$
- Only LQ interaction feels W matrix!

$$i\overline{\Psi}_L \gamma^{\mu} D_{\mu} \Psi_L \supset \frac{g_4}{\sqrt{2}} U_{\mu} \overline{Q}_L \gamma^{\mu} \begin{pmatrix} 1 & 0 & 0\\ 0 & \cos \theta_{LQ} & \sin \theta_{LQ}\\ 0 & -\sin \theta_{LQ} & \cos \theta_{LQ} \end{pmatrix} L_L.$$

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			chie Derner
	21	AG, Naldec	land and a
			1808.00942

Calculable, so calculate!

'4321' model





'4321' model

- Peculiar high-p_T signatures
- Dominant decays of new fermions are | > 3



• Exotic multi-lepton & multi-jet signatures





Old idea, see e.g. [Bečirević, Fajfer, Košnik, Sumensari] 1608.08501



Direction II

'SU(2)_L was a blessing, but also a curse'

Idea: Decorrelate R(D^(*)) from FCNC limits









Simplified mediator model

[Marzocca et al], 1807.10745



Simplified mediator model

[Marzocca et al], 1807.10745

4321 Completion of the Vector LQ + RHN solution from 1807.10745

• Field content

 $b \to s \mu \bar{\mu}$ $b \to c \tau \bar{\nu}_{\tau}$





j=1,	2,3	SH-like fermions		
Field	SU(4)	SU(3)'	$SU(2)_L$	$\overline{U(1)'}$
$q_L^{\prime i}$	1	3	2	1/6
$u_R^{\prime i}$	1	3	1	2/3
$d_R^{\prime i}$	1	3	1	-1/3
$\ell_L^{\prime i}$	1	1	2	-1/2
$e_R^{\prime i}$	1	1	1	-1
Vr'	I	I	1	0
Light-sterile neutring				

- 4321 > 321 breaking from 1708.08450
- Yukawa

$$\mathcal{L}_{Y} \supset -\overline{q}'_{L} Y_{d} H d'_{R} - \overline{q}'_{L} Y_{u} \tilde{H} u'_{R} - \overline{\ell}'_{L} Y_{e} H e'_{R} \quad (9)$$
$$- \overline{q}'_{L} \lambda_{q} \Omega_{3}^{T} \Psi_{R} - \overline{\ell}'_{L} \lambda_{\ell} \Omega_{1}^{T} \Psi_{R} - \overline{\Psi}_{L} M \Psi_{R} + \text{h.c.}$$

- $\overline{\Psi}_{\underline{\lambda}}^{\mu} \lambda_{\underline{\lambda}} \underbrace{\mathfrak{R}}_{\underline{\lambda}}^{\mu} \underbrace{\mathfrak{R}}_{\underline{\lambda}}^{\mu} \overline{\Psi}_{\underline{\lambda}}^{\mu} \lambda_{\underline{\lambda}} \underbrace{\mathfrak{R}}_{\underline{\lambda}}^{\mu} \underbrace{\mathcal{R}}_{\underline{\lambda}}^{\mu} \overline{\Psi}_{\underline{\lambda}}^{\mu} \underbrace{\mathcal{R}}_{\underline{\lambda}}^{\mu} \underbrace{\mathcal{R}}_{\underline{\lambda}}^$
- Anomalies

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[AG, Marzocca],

TBD



[LHCb please stop this madness]

Backup slides





Matter content

	Field	$SU(3)_c$	$SU(2)_L$	$SU(2)_V$	U(1)'		
		SM-like chiral fermions					
	$q_L^{\prime i}$	3	2	1	1/6		
	$\ell_L'^i$	1	2	1	-1/2		
	$u_R'^i$	3	1	1	2/3		
	$d_R'^i$	3	1	1	-1/3		
	$e_R'^i$	1	1	1	-1		
	$ u_R'^i $	1	1	1	0		
	$Q_{L,R}'$	3	1	2	1/6		
	$L'_{L,R}$	1	1	2	-1/2		
	i	Scalars					
	H	1	2	1	1/2		
	H_V	1	1	2	1/2		

$$\mathcal{L} \supset \mathcal{L}_{\text{Yuk}}^{\text{SM}} - \lambda_d^i \bar{Q}'_L H_V d_R'^i - \lambda_u^i \bar{Q}'_L \tilde{H}_V u_R'^i - \lambda_e^i \bar{L}'_L H_V e_R'^i - \lambda_\nu^i \bar{L}'_L \tilde{H}_V \nu_R'^i - M_Q \bar{Q}'_L Q_R' - M_L \bar{L}'_L L_R' + \text{h.c.}_{30}$$

[AG, Robinson, Shakya, Zupan] 1804.04642



:) FV **Z'** couplings uncorrelated!



1706.05033