Unearthing B anomalies through rare K decays

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RKF 2019

31 May 2019

Flavour physics is one of the best probes of BSM physics

There are several indications pointing towards the possible existence of NP

Anomalies in the decay of the B meson were reported through the measurements of the $b \to sll$ transitions in the form of foll. ratio:

Hiller, Kruger
0310219

LFU violations??

2.5σ

$$R_K = 0.846 \; {}^{+0.060}_{-0.054}\,(\text{stat.}) \; {}^{+0.016}_{-0.014}\,(\text{syst.})$$

$R_K^{SM} = 1.003$

T. Humair talk Moriond EW 2019
R. Oldeman talk Moriond QCD 2019

Also, the measurement of RK*

$$R_{K^*}[0.045, 1.1] \equiv \frac{Br\,(B \to K^* \mu^+ \mu^-)}{Br\,(B \to K^* e^+ e^-)} = 0.52^{+0.36}_{-0.26} \pm 0.05 \;\text{(Belle)},$$

$$R_{K^*}[1.1, 6] = 0.96^{+0.45}_{-0.29} \pm 0.11 \;\text{(Belle)}.$$

M. Prim
Moriond EW '19

$R_{K^*}^{SM} \simeq 0.93$ for low q^2 while $R_{K^*}^{SM} = 1$ elsewhere

Things are looking GOOD!!

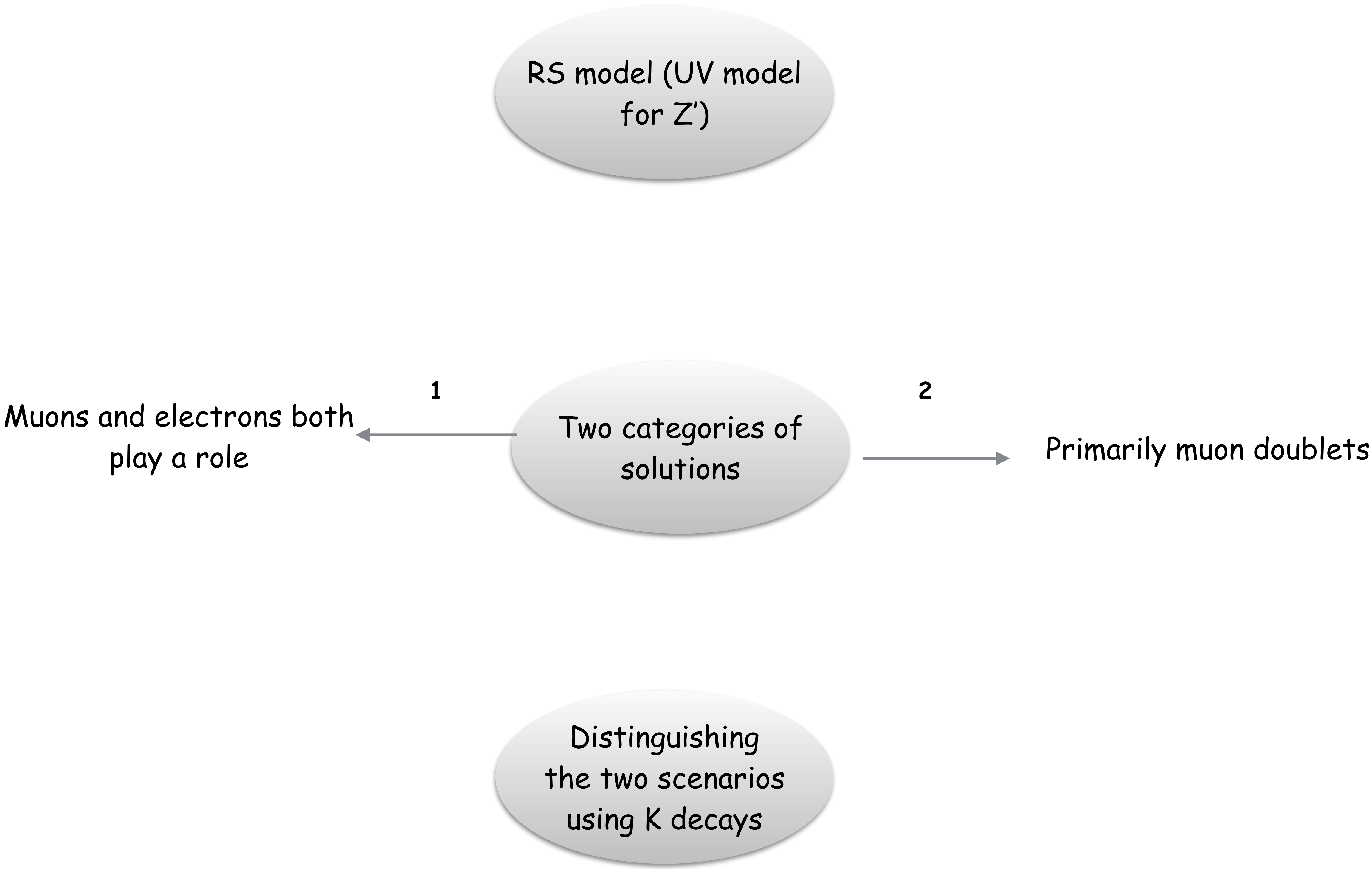
Motivated by the P_5' anomaly, it is not uncommon to consider NP purely in the muon sector

However, this will not necessarily constitute the holy grail for our analysis, leaving the door open for electrons as well

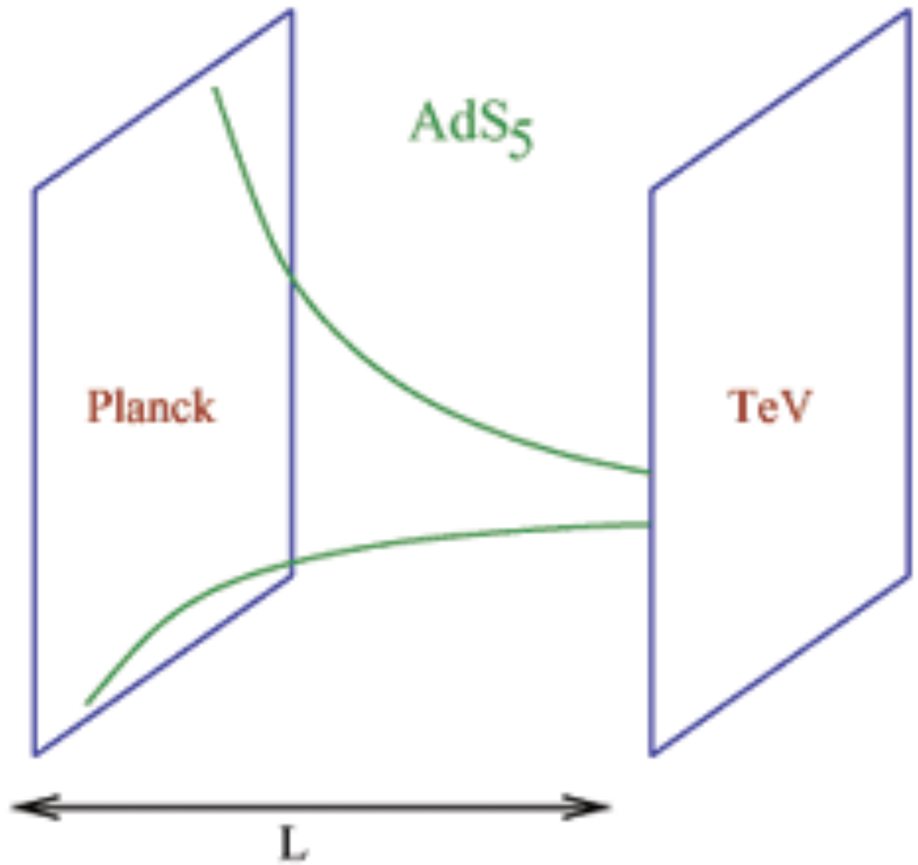
Several models of leptoquarks, additional Z', composite dynamics etc. have been put forth as a possible explanation to these anomalies

As a model building exercise, we focus on custodial models of RS and correlate the currently observed anomalies to observables in Kaon sector.

Electrons or muons or both?


RS model (UV model for Z')
1
Muons and electrons both play a role
Two categories of solutions
2
Primarily muon doublets
Distinguishing the two scenarios using K decays

Randall Sundrum Model Randall, Sundrum '99



S_1/Z_2 compactified

$$ds^2 = e^{-2ky}\eta_{\mu\nu}dx^\mu dx^\nu + dy^2$$

- Geometry can determine the coupling of the fermions to the Higgs and new physics states #win
- Its a model of flavour #win

Elements of the framework 1.: Gauge bosons in RS

The bulk gauge symmetry is: $SU(2)_L \times SU(2)_R \times U(1)_X$

Broken by boundary conditions to SM gauge group on the UV brane

$$W^a_{L\mu}(+,+) \quad B_\mu(+,+) \quad W^a_{R\mu}(-,+) \quad Z_{X,\mu}(-,+)$$

On the IR brane, vev breaks the custodial symmetry to

$$SU(2)_L \times SU(2)_R \to SU(2)_V$$

T parameter safe

vev mixes the zero modes and the higher KK excitations

$$\begin{aligned}
Z_{SM} &= Z^{(0)} - \frac{M_Z^2}{M_{KK}^2}\left(-\sqrt{2kR\pi}(Z^{(1)}) + \sqrt{2kR\pi}\cos\phi\cos\psi\ Z^{'}\right) \\
Z_H &= \cos\zeta\ (Z^{(1)}) + \sin\zeta\ (Z^{'}) \\
Z_X &= -\sin\zeta\ (Z^{(1)}) + \cos\zeta\ (Z^{'})
\end{aligned}$$

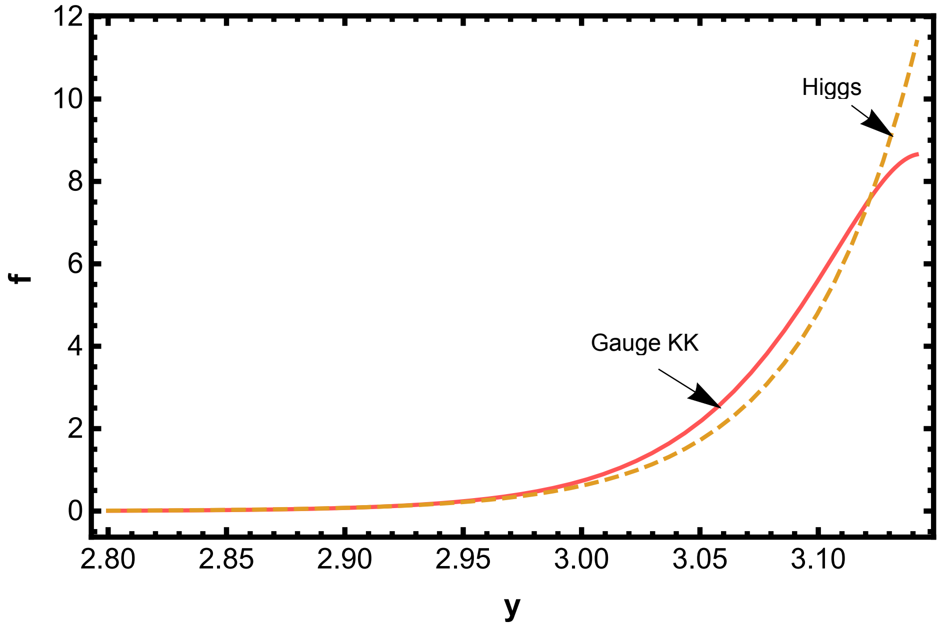
KK excitations of the corresponding bulk gauge fields lead to a tower of states: We consider the lowest scale with mass $M_{KK} = 3$ TeV

In the mass basis there are three neutral states with similar mass contributing to the $Z', Z_X, A^{(1)}$ FCNC

They have a similar wave function profile which is peaked near the IR brane: Origin of non-universal couplings

Obtained by solving the bulk equations of motion in AdS space

$$[z_n^2 \frac{d^2}{dz_n^2} + z_n \frac{d}{dz_n} + (z_n^2 - 1)](e^{-\sigma} f^{(n)}(y)) = 0$$



Elements of the framework 2.:

Fermions in RS

The quark and leptons transform
as bi-doublets.

$$\zeta \equiv \begin{bmatrix} \xi_L^u(-,+) & v^u(+,+) \\ \chi_L^d(-+) & v^d(+,+) \end{bmatrix}$$

The charged lepton and down type singlets transform as (1,3) under the custodial symmetry

Dimensionless
O(1) parameter

We consider fermion field with a bulk mass parametrised as: $m_\Psi = ck$

The choice of `c' can in general be different for the doublet and singlet fields

They play the same role as the FN charges in Froggatt-Nielsen Models

Solving the bulk equations of motion for the SM fermions we get

Zero mode for the Z_2 even field say $f_L^{(0)}$ satisfies

Localized profiles!!

$$e^{-\sigma}\left(\partial_y - 2\sigma'\right) f_L^{(0)} = 0$$

Using orthonormality

$$f_L^{(0)} = N e^{k0.5(y-\pi R)}$$

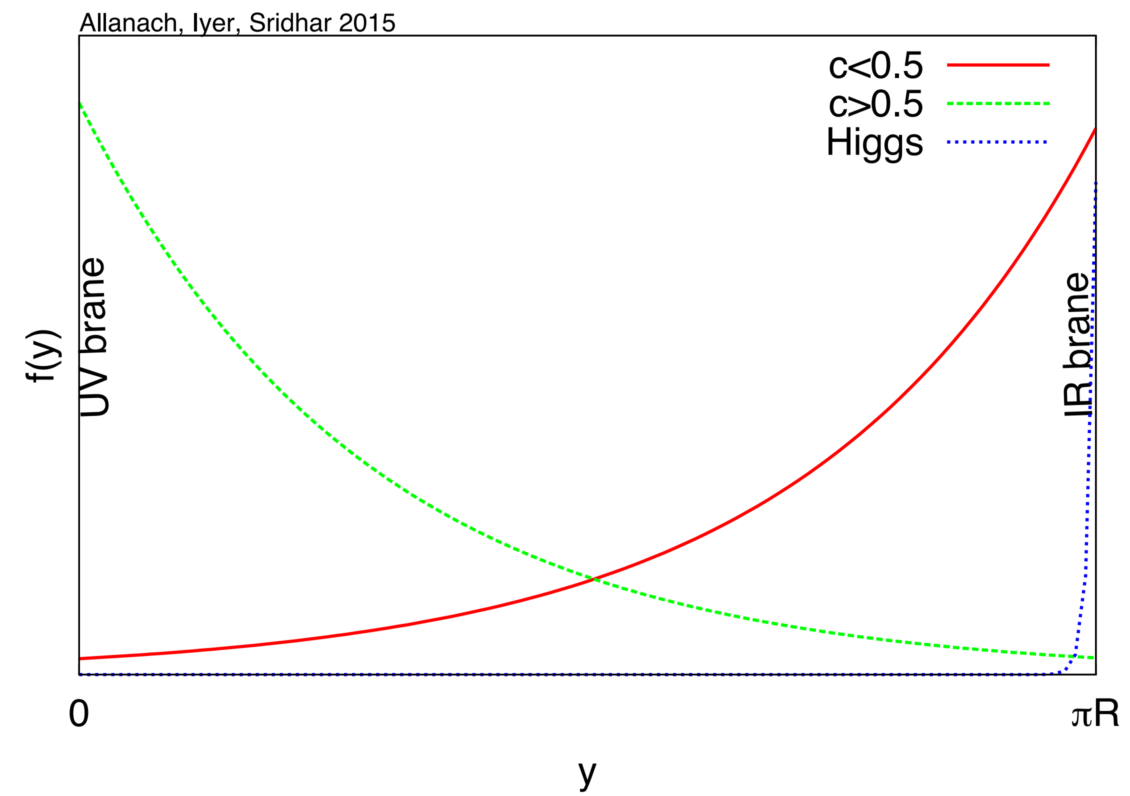
field re-definitions

Introducing a bulk mass term $m_{1/2} = c\sigma' = ck$ modifies the solution to

$$f_L^{(0)} = N e^{(0.5-c)\sigma(y)}$$

These bulk masses control the localisation of the fermion zero mode (SM fermions) in the bulk

$$Y^{(4)} = Y^{(5)} \int_0^{\pi R} dy \; f_0^{(0)}(b,y) f_{1/2}^{(0)}(c_L,y) f_{1/2}^{(0)}(c_R,y)$$



The choices are governed by the proximity to the Higgs field and hence a relatively larger effective Yukawa coupling

Except for the third generation doublet and top singlet, other fields are away from the IR brane

Elements of the framework 3.: Non-universal couplings

Consider vector of fermions in flavour basis

$$\eta^T = \left[f^{(1)}, f^{(2)}, f^{(3)}\right]$$

Rotating to mass basis

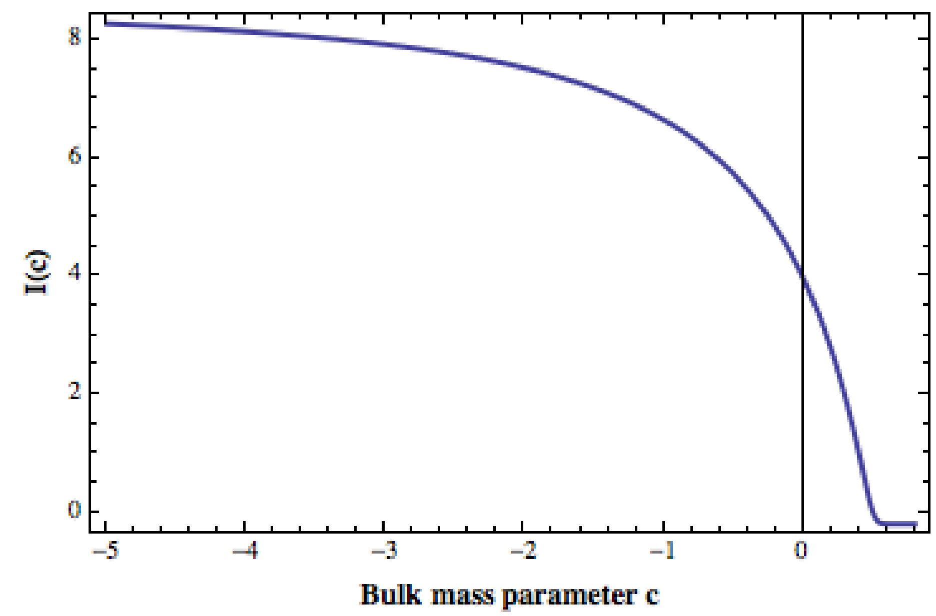
$$\eta_M = D\ \eta$$

D is a 3 x 3 unitary matrix

The coupling matrix in the mass basis is given as

$$a^{ij}_{L,R} = \tilde{g}\ \eta^T_{L,R} D^\dagger_{L,R} \begin{bmatrix} I_{f_1} & 0 & 0 \\ 0 & I_{f_2} & 0 \\ 0 & 0 & I_{f_3} \end{bmatrix} D_{L,R}\eta_{L,R}$$

$$I(c) = \frac{1}{\pi R}\int_0^{\pi R} dy e^{\sigma(y)} (f_i^{(0)}(y,c))^2 \xi^{(1)}(y)_{Z^{(1)},Z'}$$



The off-diagonal couplings can be simply read off as:

$$a^{12} = \tilde{g}\left(D^*_{21}D_{22}(I(2)-I(1)) + D^*_{31}D_{32}(I(3)-I(1))\right)$$
$$a^{23} = \tilde{g}\left(D^*_{12}D_{13}(I(1)-I(2)) + D^*_{32}D_{33}(I(3)-I(2))\right)$$
$$a^{13} = \tilde{g}\left(D^*_{21}D_{23}(I(2)-I(1)) + D^*_{31}D_{33}(I(3)-I(1))\right)$$

$\Delta F = 2$ constraints

The additional contributions can be parametrised into the following effective lagrangian

$$\mathcal{L}_{eff} = \mathcal{L}_{SM} + \frac{c_1}{\Lambda^2}(\bar{s}_L \gamma^\mu d_L)^2 + \frac{c_2}{\Lambda^2}(\bar{b}_L \gamma^\mu d_L)^2 + \frac{c_3}{\Lambda^2}(\bar{b}_L \gamma^\mu s_L)^2$$

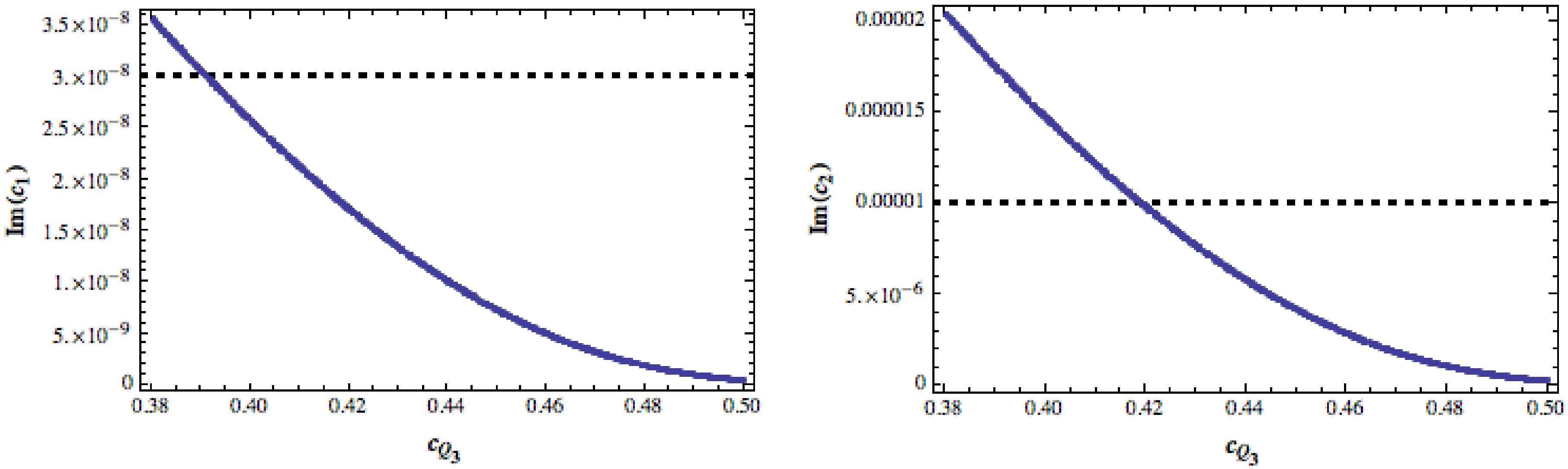


Figure 2: The Wilson co-efficient c_i as a function of c_{Q_3} for $s \to d$ and $b \to d$ transitions.

The effective Hamiltonian for $s \to d\nu\bar{\nu}$ transitions is given in the SM as follows

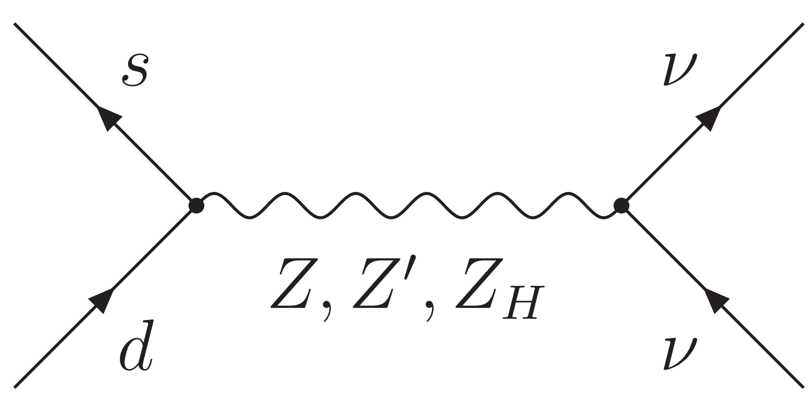
$$[\mathcal{H}_{\text{eff}}^{\nu\bar{\nu}}]_{\text{SM}}^{K} = g_{\text{SM}}^2 \sum_{\ell=e,\mu,\tau} \left[\lambda_c^{(K)} X_{\text{NNL}}^{\ell}(x_c) + \lambda_t^{(K)} X(x_t)\right] (\bar{s}d)_{V-A} (\bar{\nu}_\ell \nu_\ell)_{V-A} + h.c.\,,$$

There are additional contributions in RS

$$\mathcal{L}_{\text{FCNC}}(Z) = -\left[\mathcal{L}_L(Z) + \mathcal{L}_R(Z)\right]\,,$$

$$\mathcal{L}_L(Z) = \Delta_L^{sd}(Z)\,(\bar{s}_L \gamma_\mu d_L)\,Z^\mu\,,$$

$$\mathcal{L}_R(Z) = \Delta_R^{sd}(Z)\,(\bar{s}_R \gamma_\mu d_R)\,Z^\mu\,,$$



After some re-arrangement the RS contribution can be written as

$$[\mathcal{H}_{\rm eff}^{\nu\bar\nu}]^K = g_{\rm SM}^2 \sum_{\ell=e,\mu,\tau} \left[\lambda_c^{(K)} X_{\rm NNL}^{\ell}(x_c) + \lambda_t^{(K)} X_K^{V-A}\right] (\bar s d)_{V-A} (\bar\nu_\ell \nu_\ell)_{V-A}$$

$$+ g_{\rm SM}^2 \sum_{\ell=e,\mu,\tau} \left[\lambda_t^{(K)} X_K^{V}\right] (\bar s d)_{V} (\bar\nu_\ell \nu_\ell)_{V-A} + h.c.\,.$$

Not in SM

In a un-correlated scenario, one can exploit coupling of right handed quarks to the neutral gauge boson

Relatively larger enhancement is possible especially with right handed currents

Blanke, Buras, Duling Gemler, Gori

We are now in a position to understand the contributions to b-sll transitions

The effective operator contributing to this process is given as

$$\mathcal{L} \supset \frac{V_{tb}^* V_{ts} G_F \alpha}{\sqrt{2}\pi} \sum_i C_i \mathcal{O}_i$$

$$\begin{aligned} \mathcal{O}_9 &= (\bar{s}_L \gamma^\mu b_L)(\bar{l}\gamma_\mu l) \qquad \mathcal{O}_{9'} = (\bar{s}_R \gamma^\mu b_R)(\bar{l}\gamma_\mu l) \\ \mathcal{O}_{10} &= (\bar{s}_L \gamma^\mu b_L)(\bar{l}\gamma_\mu \gamma^5 l) \quad \mathcal{O}_{10'} = (\bar{s}_R \gamma^\mu b_R)(\bar{l}\gamma_\mu \gamma^5 l) \end{aligned}$$

The couplings α^{ij} are related to the FV co-eff a^{ij} defined earlier

The tree level contributions to b-sll is simply

$$\mathcal{L}_{NP} \subset \sum_{X=Z_{SM},Z_H,Z_X,\gamma^{(1)}} X_\mu \left[\alpha_L^{bs}(X)(\bar{s}_L\gamma^\mu b_L) + \alpha_R^{bs}(X)(\bar{s}_R\gamma^\mu b_R) + \bar{l}\left(\alpha_V^l(X)\gamma^\mu - \alpha_A^l(X)\gamma^\mu\gamma^5\right) l\right]$$

Using this the WC are simply

$$\begin{aligned} \Delta C_9 &= -\frac{\sqrt{2}\pi}{M_X^2 G_F \alpha}\alpha_L^{bs}(X)\alpha_V^l(X), \qquad \Delta C_9' = -\frac{\sqrt{2}\pi}{M_X^2 G_F \alpha}\alpha_R^{bs}(X)\alpha_V^l(X) \\ \Delta C_{10} &= \frac{\sqrt{2}\pi}{M_X^2 G_F \alpha}\alpha_L^{bs}(X)\alpha_A^l(X), \quad \Delta C_{10}' = \frac{\sqrt{2}\pi}{M_X^2 G_F \alpha}\alpha_R^{bs}(X)\alpha_A^l(X) \end{aligned}$$

We consider two scenarios as a solution to the observed anomalies in neutral current sector

Non-universality in muon singlets. Lepton doublets universal but non-negligible

Scenario A: The muon singlets are closer to the gauge KK states (couple more). The lepton doublets are universal and relatively away.

Unorthodox scenario as there are contributions to the WC from the lepton doublets as well

These are largely due to ensure fits to the muon mass with O(1) Parameters.

The fit in this case is 4D scenario with C9, C10 for both electron and muon contributing

Scenario B: The lepton singlets now have near universal coupling and smaller coupling to the gauge KK states. The muon doublets are now closer to the KK states and hence larger coupling

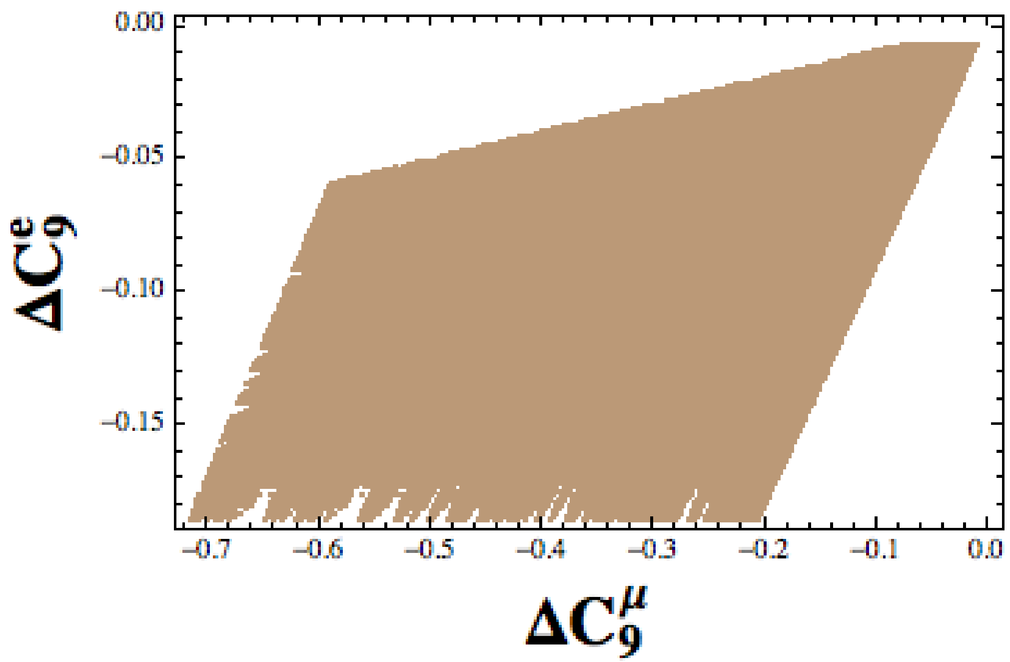
The fits to muon mass is better with O(1) Parameters.

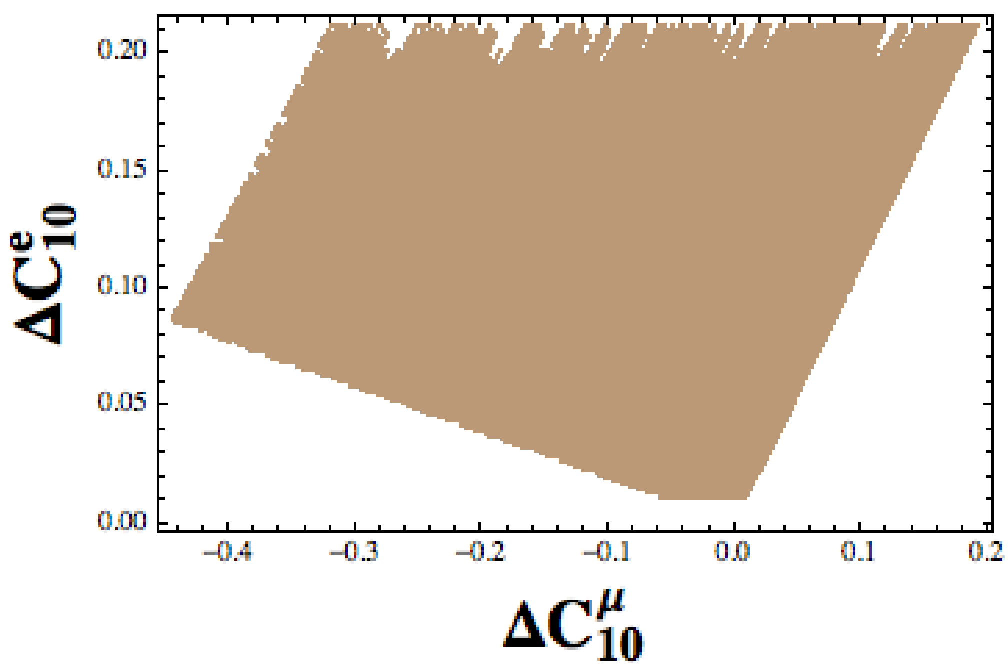
Non-universality in muon doublets

Mainly C9 and C10 for the muon contribute with a possibility of C9=-C10

Scenario A:

G. D'Ambrosio, A. I
Eur.Phys.J. C78 (2018) no.6, 448 .





The following ranges were used in the scan:

$$c_{\mu_R} \in [0.4, 0.5] \quad c_{Q_3} \in [0.4, 0.5] \quad c_L \in [0.5, 0.55]$$

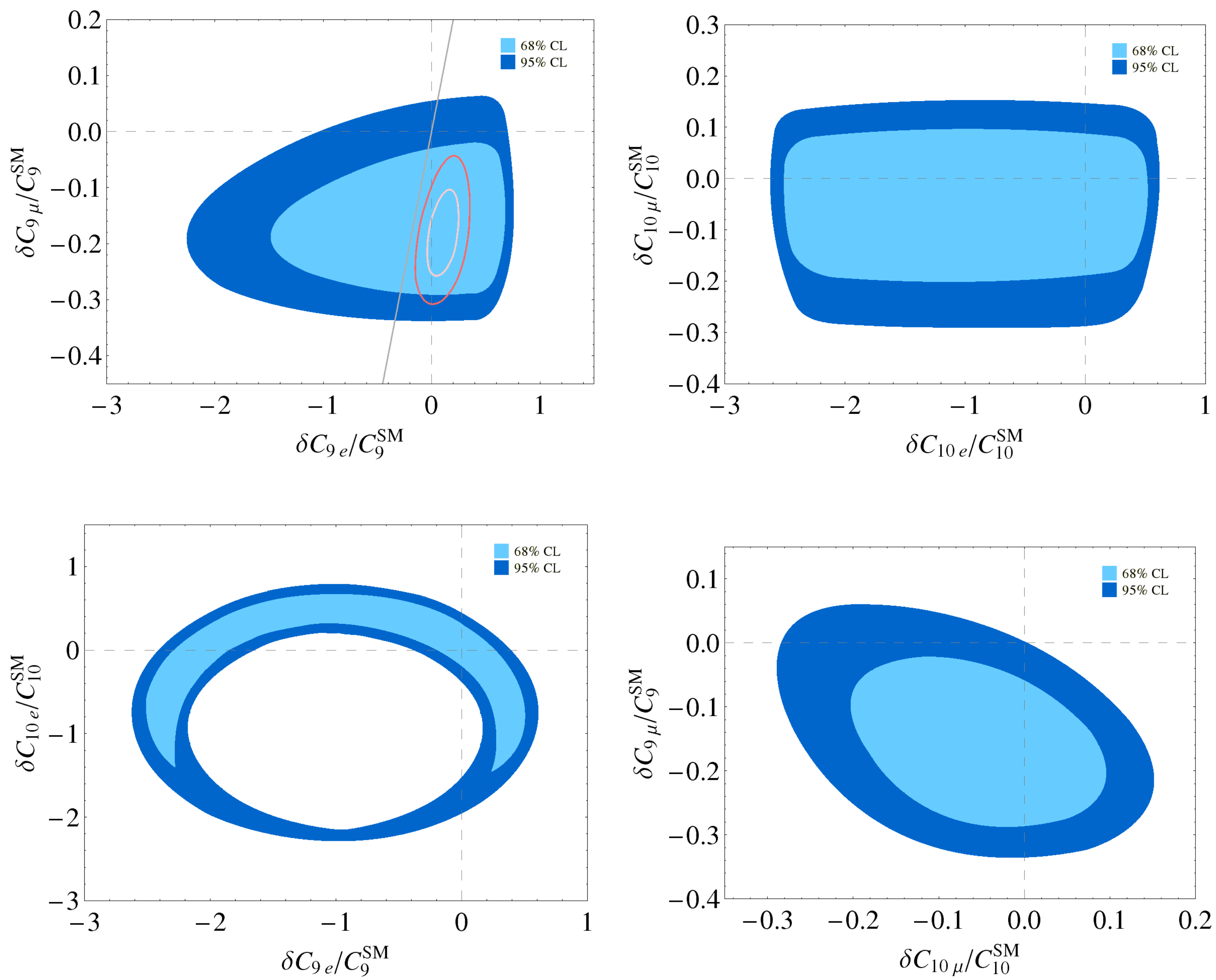
The Z- mu mu coupling is not a problem as the singlets are also embedded in custodial representations!

The c values for the lepton doublets are chosen such that to ensure an extension into 5D leptonic MFV.

This is a 4D fit to b-s ll data.

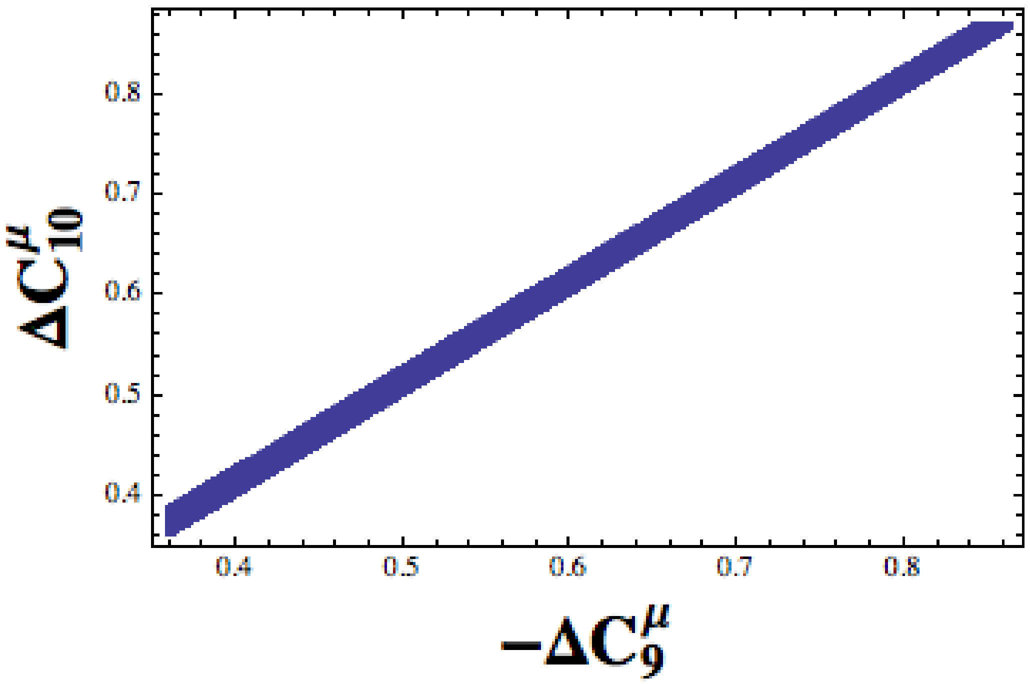
A model independent fit along these lines was performed in Hurth, Mahmoudi, Neshatpour 1603.00865

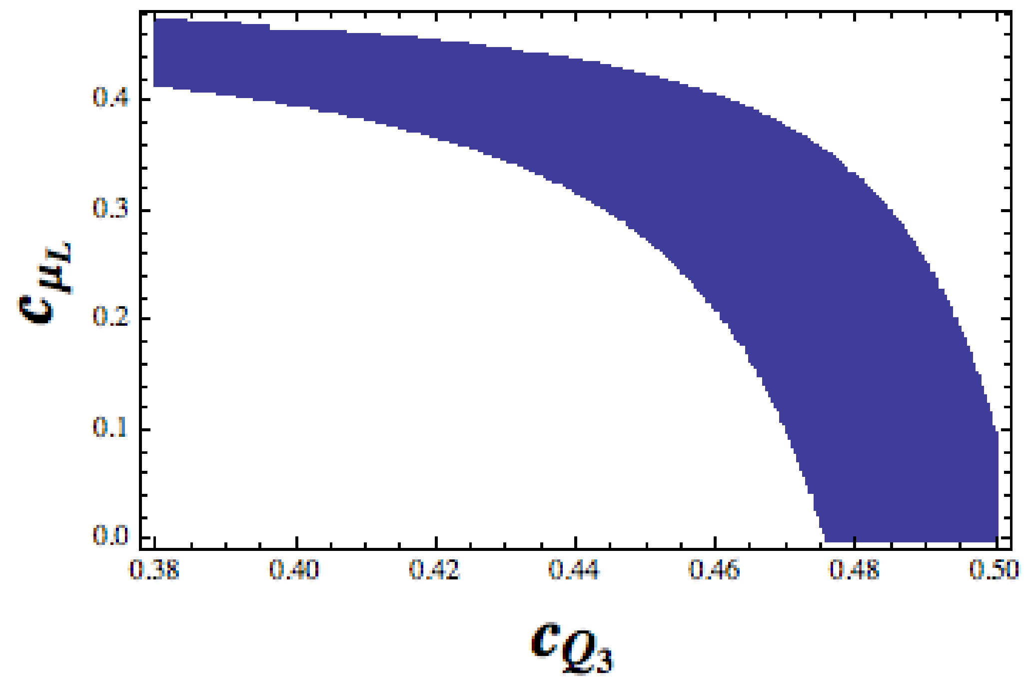
It was shown to relax the allowed ranges on the WC required to fit the data.



Scenario B:

G. D'Ambrosio, A. I
Eur.Phys.J. C78 (2018) no.6, 448 .





$$c_{\mu_R} \in [0.5, 0.6] \quad c_{Q_3} \in [0.4, 0.5] \quad c_{L_2} \in [0, 0.5]$$

The Z- mu mu coupling is not a problem as the doublets are also embedded in custodial representations!

From B anomalies to rare Kaon decays

Rare Kaon decays are likely to constitute the next probe for NP

The SM expectation is

$$\mathcal{B}(K^+ \to \pi^+ \nu\bar{\nu}) = 8.3 \pm 0.3 \pm 0.3 \times 10^{-11} \quad \mathcal{B}(K_L \to \pi^0 \nu\bar{\nu}) = 2.9 \pm 0.2 \pm 0.0 \times 10^{-11}$$

The current experimental bound is

$$\mathcal{B}(K^+ \to \pi^+ \nu\bar{\nu}) = 17.3^{+11.5}_{-10.5} \times 10^{-11} \quad \mathcal{B}(K_L \to \pi^0 \nu\bar{\nu}) \leq 2.6 \times 10^{-8} \quad (90\% \text{ C.L.})$$

Scenario A:

G. D'Ambrosio, A. I
Eur.Phys.J. C78 (2018) no.6, 448

The effective lagrangian for $s \to d\nu\nu$ transitions is given as

$$\mathcal{L} = \frac{4G_F\alpha}{2\sqrt{2}\pi} V_{ts}^* V_{td} C_{ds,l} \left(\bar{s}_L \gamma_\mu d_L\right) \left(\bar{\nu}_l \gamma^\mu \nu_l\right)$$

Neutrino couplings are determined by the lepton doublet parameters!

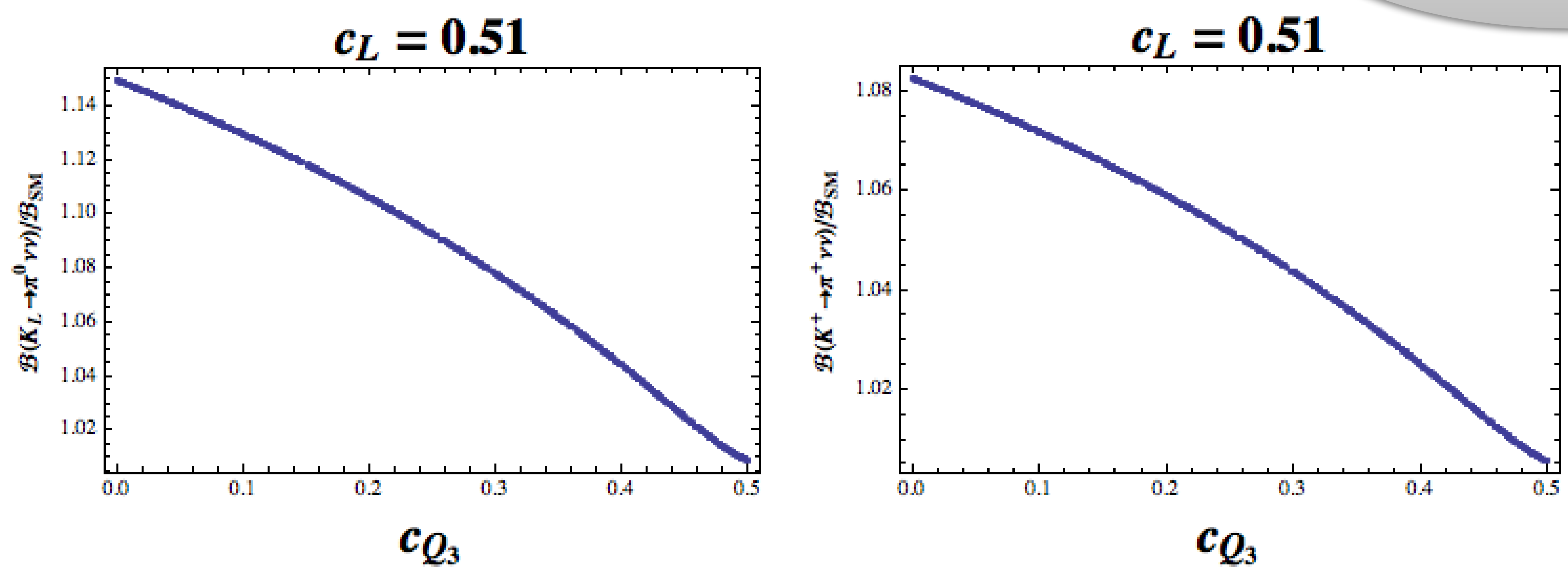
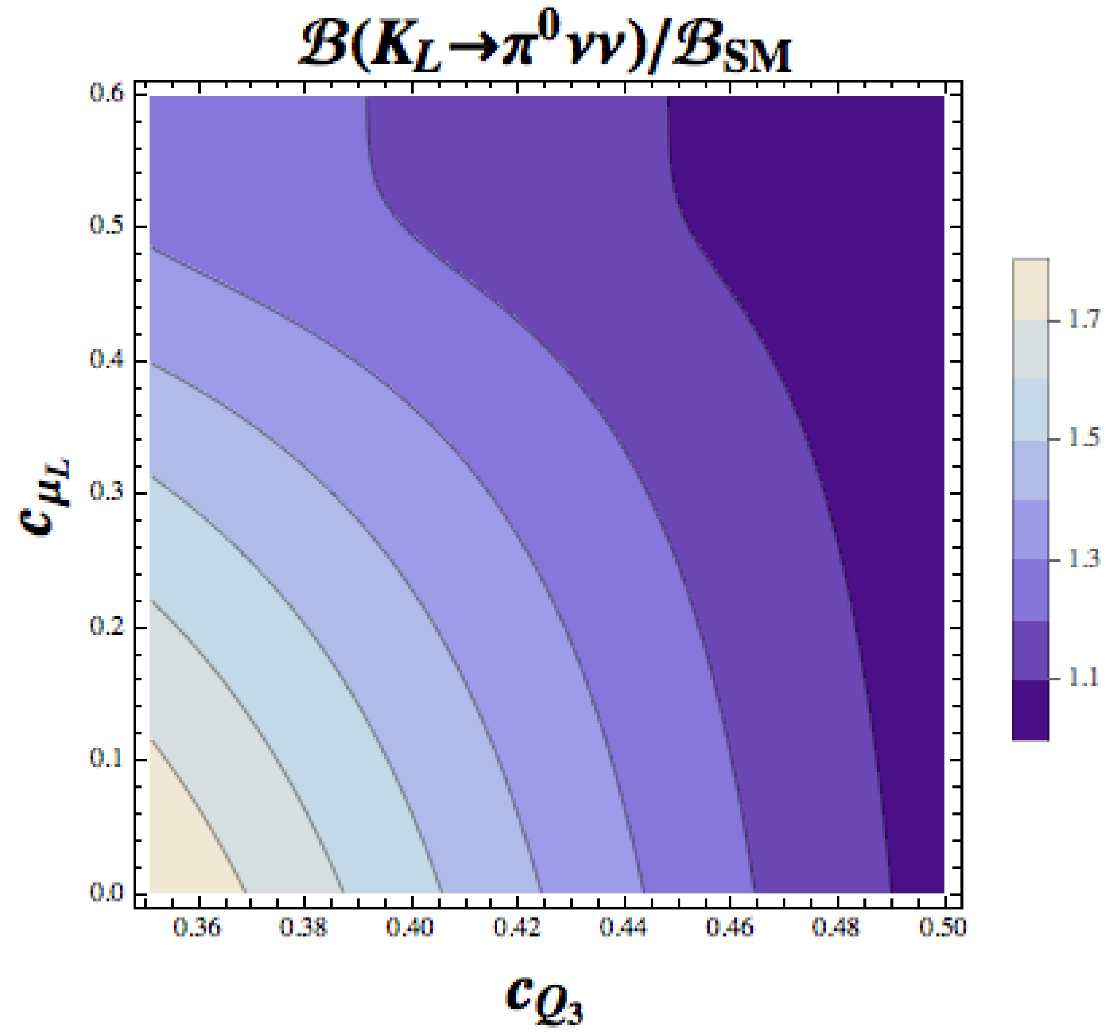


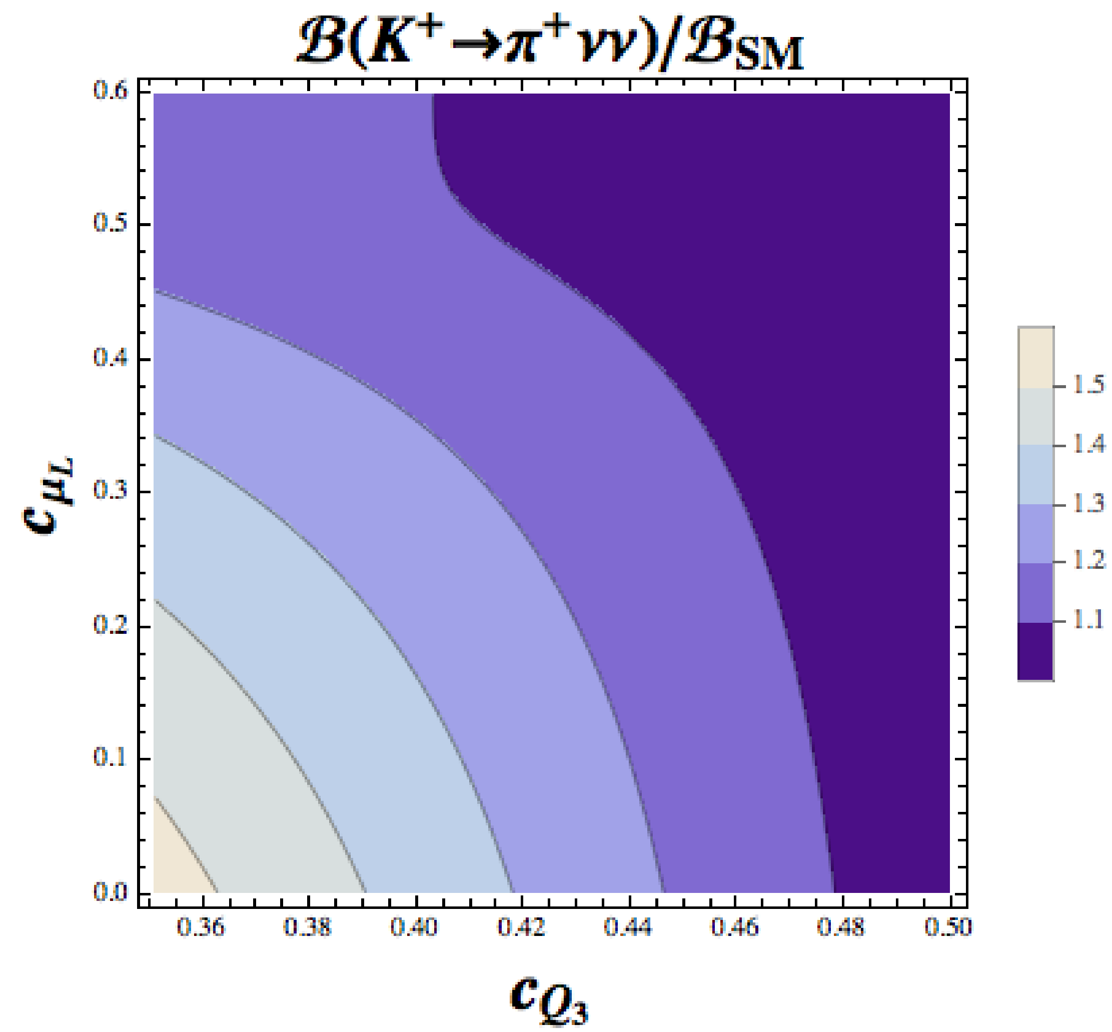
Figure 6: Scenario **A**: Plots depicting the excess over the SM expectation for the K decays modes. The c parameters for the doublets is universal and chosen to be $c_L = 0.51$.

Due to universality of lepton doublets, the contributions cannot be enhanced beyond a point!

Scenario B:

G. D'Ambrosio, A. I
Eur.Phys.J. C78 (2018) no.6, 448 .





The larger contributions in this case are primarily due c_{L_3} is free compared to Scenario A.

What about charged current transitions?

$$\mathcal{L}_{b\to cl\nu} \subset \frac{4G_f}{\sqrt{2}} V_{cb}\left[C_\tau(\bar{c}\gamma^\nu P_L b)(\bar{\tau}\gamma_\nu(U\nu)) + C_\mu(\bar{c}\gamma^\nu P_L b)(\bar{\mu}\gamma_\nu(U\nu))\right]$$

There is a reported excess in the measurement of the following ratio

$$R(D^*) = \frac{\mathcal{B}(\bar{B}\to D^*\tau^-\bar{\nu}_\tau)}{\mathcal{B}(\bar{B}\to D^* l^-\bar{\nu}_l)} \text{ where } l = \mu, e$$

$$R_D^{\rm exp} = 0.403 \pm 0.047, \quad R_{D^*}^{\rm exp} = 0.310 \pm 0.017$$

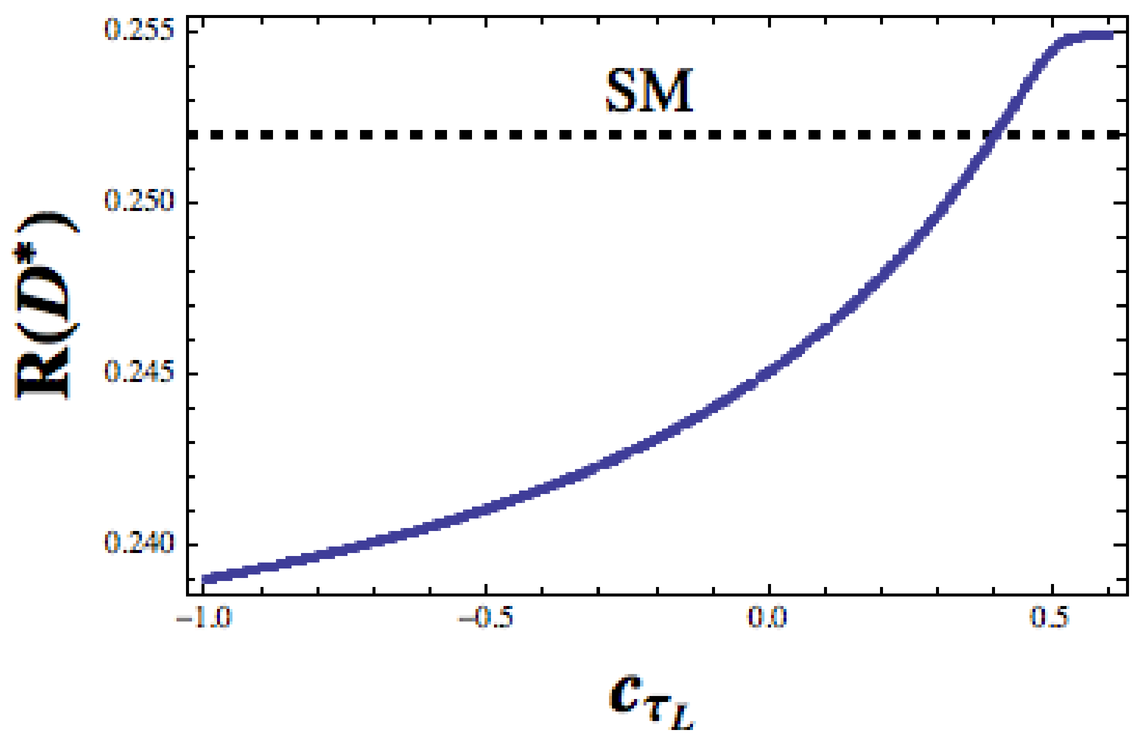
While the SM expectation is

$$R_D^{\rm SM} = 0.300 \pm 0.011, \quad R_{D^*}^{\rm SM} = 0.254 \pm 0.004$$

Like the neutral states, the charged states also mix through the vev

$$
\begin{aligned}
W^{\pm}_{SM} &= W^{(0)\pm} - \frac{m_W^2}{M_{KK}^2}\sqrt{2kR\pi}W^{(1)\pm} \\
W^{\pm}_{H} &= \cos\chi\ (W^{\pm(1)}) + \sin\chi\ (W^{\pm'}) \\
W^{\pm}_{X} &= -\sin\chi\ (W^{\pm(1)}) + \cos\chi\ (W^{\pm'})
\end{aligned}
$$

$$
R(D^*) = 2R(D^*)|_{SM}\frac{|1+\alpha_\tau|^2}{1+|1+\alpha_\mu|^2}
$$



Increasing the compositeness of the tau does not help!! At best consistent with the SM.

Electrons or muons or both?

The verdict is yet to be out on the nature of the anomalies (if they are confirmed)

Maybe some hints can be seen in the future and upcoming analyses

K physics (D'Ambrosio, Iyer et al.) or direct searches (Conventi, D'Ambrosio, Iyer, Mangano, Rossi)