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Flavour anomalies and model building

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Anomalies after Moriond '19

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Anomalies have never been better

[cit. Gino Isidori]

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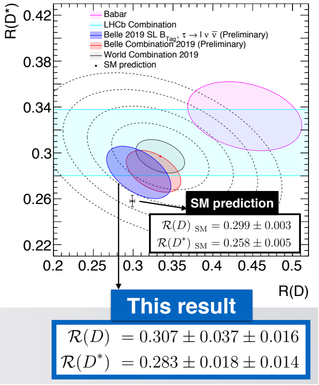
[cit. Gino Isidori]

- Update of R_{K^*} from Belle still with large errors.

- New Belle results lower the combined discrepancy of $R_{D^{(*)}}$ with the SM.

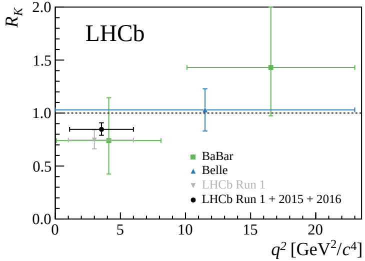
- New LHCb result on R_K confirms the 2.5σ tension.

$R_{D^{(*)}}$



- The Belle result is still preliminary: we still wait for final results and correlations
- The discrepancy reduces from 3.7σ to 3.1σ
- Is this change bad or unexpected? No!
  - The size of the “old" deviation was too big to be compared to a tree-level SM process
  - The decrease shifts the NP scale up, helps to avoid tight constraints and provides a better combination with $R_{K^{(*)}}$

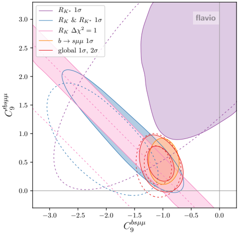
$b \to s\ell^+\ell^-$



- New measurement of LHCb confirms a 2.5σ tension in R_K
- Other experiment still don't have a high significance such to confirm or reject the anomaly

- Update of global fits show still interesting scenarios
- Given that R_K now is closer to the SM than R_{K^*}, new scenarios with non-SM like operators are viable

$\rightarrow$ Sebastien's talk



[1903.10434]

What now?

- After the analyses of 2019 we still don't see a clear sign of New Physics.
- Data will (eventually) lead us to a clear conclusion:
  - LHCb still has a large amount of data to be analysed for $b \to s\ell\ell$
  - Update of $R_{K^{(*)}}$ most likely to be ready in one year time
  - An update for R_{D^*} from LHCb is also due
  - New observables like $R(\Lambda_c)$ should be (soon) released
  - Belle2 is taking data

We need to keep looking

Combined explanation $R_{D^{(*)}}$-$R_{K^{(*)}}$

- The FCNC and CC anomalies can be considered as a coherent pattern of anomalies
- The NP must couple mainly to third generation of quarks and leptons
- A non-trivial flavour structure is needed to suppress coupling with 1st and 2nd generation
- $R_{D^{(*)}}$ feeds $b \to s\ell\ell$ [Crivellin, Greub, Müller, Saturnino, '18]

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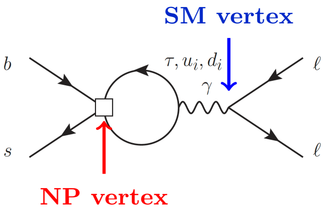


- If we assume any NP which generates a $bc\tau\nu$ interaction, gauge invariance generates $bs\tau\tau$ coupling
- Via loop effects we generate effectively $bs\ell\ell$ coupling universal for $\ell = \mu, e$
- A fit to $b \to s\ell\ell$ data must take in account such contributions

$$C_9^{bs\mu\mu} = \Delta C_9^{bs\mu\mu} + C_9^{\text{univ}}$$
$$C_9^{bsee} = C_9^{bs\tau\tau} = C_9^{\text{univ}}$$

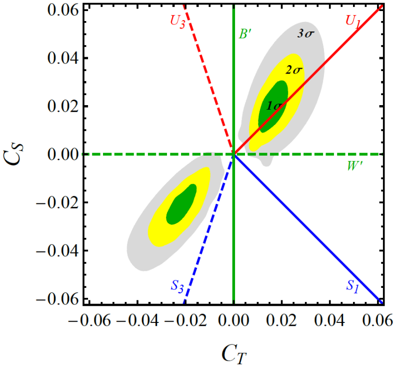
Single particle solution [Buttazzo,Grejlo,Isidori,Marzocca, JHEP 1711 (2017)]

- Based on $U(2)^n$ flavour symmetry
- No contradiction between LFU anomalies and constraints from EWPT, flavour observables or hight-p_T data
- Possible one particle solution:

	Singlet	Triplet
Scalar LQ:	S_1	S_3
Vector LQ:	U_1	U_3
Colorless vector:	B'	W'

- The most promising single-mediator solution is the vector leptoquark $U_\mu \sim (3,1)_{2/3}$

UV completion needed



A UV completion for $U_\mu \sim (3,1)_{2/3}$

Two possibilities:

- Mediator of a composite state of a new strongly interacting sector
- Massive gauge boson of a spontaneously broken gauge theory

[Di Luzio,Grejlo,Nardecchia; Blanke,Crivellin; Di Luzio,Fuentes-Martín,Grejlo,Nardecchia,Renner]

The natural choice: Pati-Salam group $\Rightarrow$ PS $\equiv SU(4) \times SU(2)_L \times SU(2)_R$

[Pati,Salam, Phys. Rev. D 10 (1974) 275]

- Quarks and leptons are part of the **same multiplet** of $SU(4) \Rightarrow$ lepton are seen as the **4th colour**
- No proton decay

$$\Psi_L = \begin{pmatrix} Q_L^\alpha \\ Q_L^\beta \\ Q_L^\gamma \\ L_L \end{pmatrix}$$

Main problems:

- the LQ coupling with the heavy and light generations is **flavour blind**
- tights constrains in processes as $K_L \to \mu e \Rightarrow$ LQ mass $\sim 100\,\text{TeV}$

The "4321" model

$$SU(4) \times SU(3)' \times SU(2)_L \times U(1)'$$

$$SU(3)_c \times SU(2)_L \times U(1)_Y$$

At low energies we have:

- the SM
- the LQ U_1 with a mass $\mathcal{O}(1\,\text{TeV})$
- inevitably a massive color octect G' and a Z' with masses of $\mathcal{O}(1\,\text{TeV})$

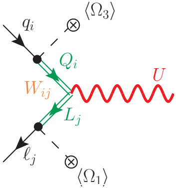
The PS leptoquark introduces always new states

The original "4321"

[Di Luzio, Greljo,Nardecchia, '17]

[Di Luzio, Fuentes-Martín, Greljo, Nardecchia, Renner, '18]

- The SM particles are charged only under the 321 component
- New vector-like are charged under the $SU(4)$
- The mixing between the vector-like and the SM fields induces effective SM-U_1 couplings

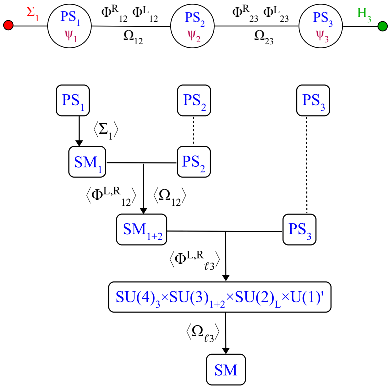


- The effective interactions between the SM fields and U_1 are mainly left-handed
- Using the freedom on the vector-like couplings it's possible to have a good fit to low energy data and avoid most of the constraints

Main Idea: at high energies the 3 families are charged under 3 independent gauge groups

$$\mathbf{PS^3 = PS_1 \times PS_2 \times PS_3}$$

- The breaking controls the hierarchy of the Yukawa couplings
- Low energy pheno is governed by the $\mathcal{O}$(**TeV**) **breaking only**
- At low scale we recover the SM + 1 LQ + 1 Z' and a coloron
- The LQ couples to both LH and RH fermions



A three-site model

[MB, Cornella, Fuentes-Martín, Isidori, '17, '18]

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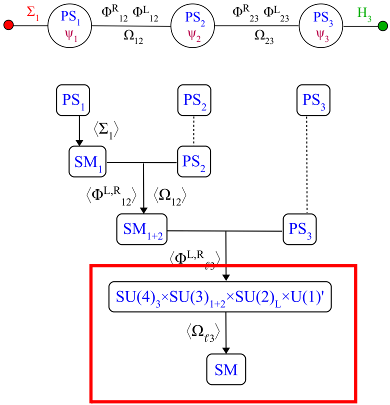
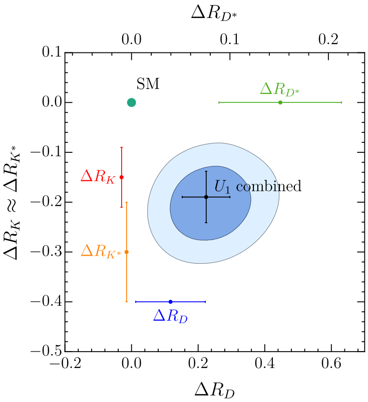
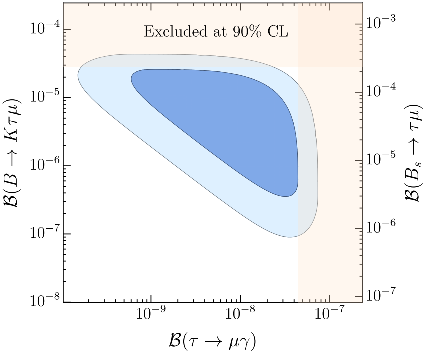


Fit to low energy data

[MB, Cornella, Fuentes-Martín, Isidori, '17, '18]
[Cornella, Fuentes-Martín, Isidori, '19]





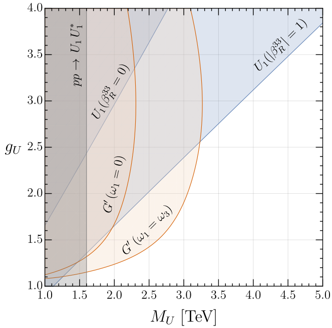
- Good fit to low energy data within the 1σ region
- RH currents help to ease the tension with $R_{D^{(*)}}$ and rise the NP scale

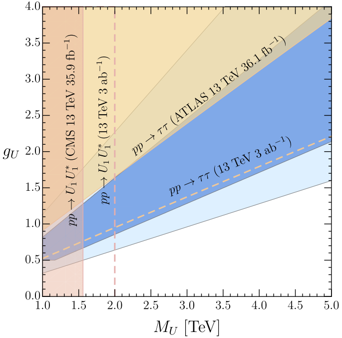
- RH currents generate interesting contributions in B_s decays
- LFV processes are a smoking gun of this model

High-p_T constraints on PS models

[Baker, Fuentes-Martín,Isidori,König]

- The most stringent bound on U_1 comes from $pp \to \tau\tau$
- The bound on Z' are weaker
- Bounds on G' come from $pp \to \bar{t}t$ but it becomes weaker as the width increases
- The relation between M_U and $M_{G'}$ in PS[3] helps to create combined exclusion limits





$g_U \sim 3 \;\Rightarrow\; M_U \geqslant 3.8\,\text{GeV}$

Scalar solutions

With scalars LQ, we need at least **two** mediators

- Composite scenario: $S_1 + S_3$ [D.Marzocca]
  - Strong dynamics not known
  - B_s mixing + EWPT create tension with $R_{D^{(*)}}$
  - Need to enforce some couplings to be zero to avoid proton decay

- GUT inspired scenarios: $S_3 + R_2$ [Bečiveríc, Doršner, Fajfer, Faroughy,Košnik,Sumensari]
  - Predicts interesting LFV signals
  - No explicit realisation so far which avoids proton decay

What is still to be done?

Model	$R_{K^{(*)}}$	$R_{D^{(*)}}$	$R_{K^{(*)}}$ & $R_{D^{(*)}}$
S_1	✗*	✓	✗*
R_2	✗*	✓	✗
$\widetilde{R}_2$	✗	✗	✗
S_3	✓	✗	✗
U_1	✓	✓	✓
U_3	✓	✗	✗

- Colourless solution $W' + Z'$: tension with high-p_T searches with $\tau_L \tau_L$ or $b_L b_L$ final states [Greljo,Isidori,Marzocca,'15]

- Solutions with right-handed neutrino are motivated and help to ease the tension with $b \to c\tau\nu$ data but they are most likely to be excluded from high-p_T

[Greljo, Camalich,Ruiz-Álvarez,'18]

It seems like there is not much space left...

What are we looking for?

...but data can help us!

If the anomalies are trues, NP **must** appear somewhere else.

A full dedicated flavour physics program run by LHCb, Belle II but also experiments like NA62 is needed to

- determine the flavour structure of the NP sector;
- different correlations among low energy observable can help to distinguish the possible models.

Only with such programs will we be able to determine what type of NP is realised in nature.