New Physics Models for the B Decay Anomalies

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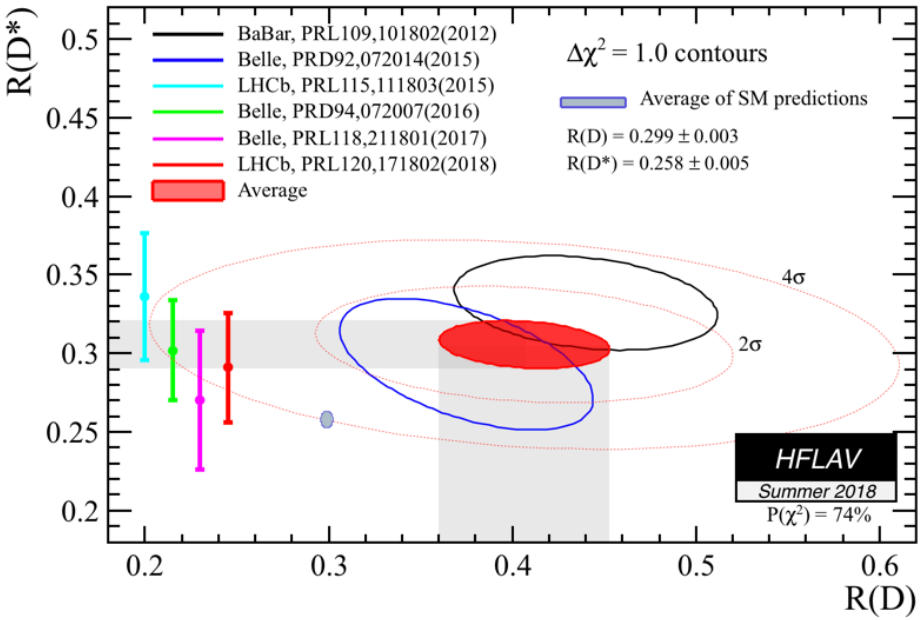
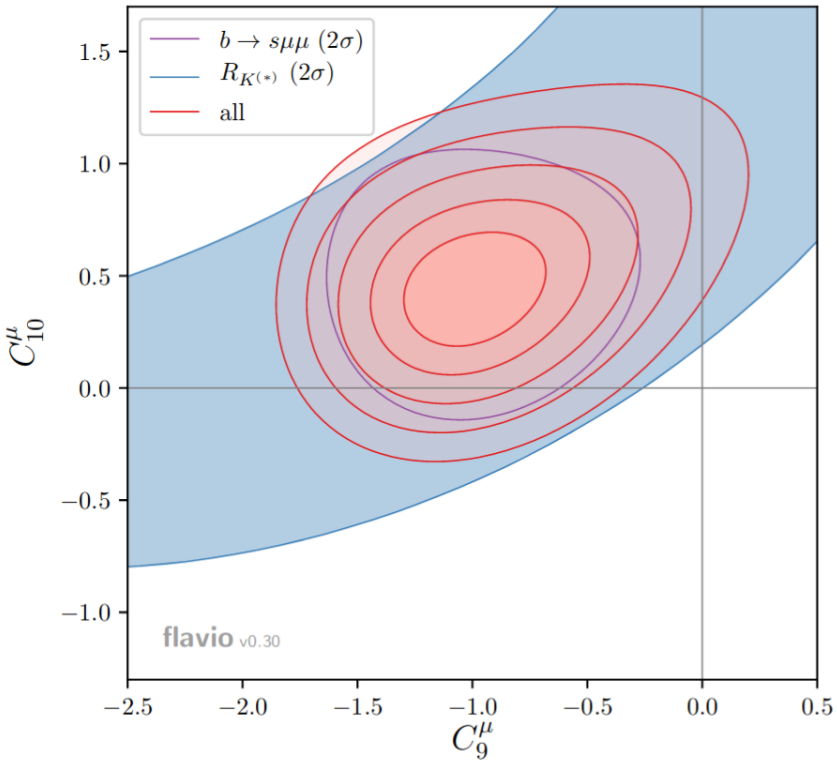
Implications of LHCb measurements and future prospects
October 17–19, 2018

Hints for Lepton Flavour Universality Violation



Straub, CKM'18



- 3.8σ anomaly in $b \to c\tau\nu$ in combined fit
- various *consistent* $2-3\sigma$ deviations in $b \to s\mu^+\mu^-$ transitions leading to $> 5\sigma$ tension in global fits

Lepton Flavour Universality Violation?!

The weirdest of all anomalies. . .

Who ordered that?

New Physics in $b \to c\tau\nu$

Model-independent description by effective four-fermion operators

$$\mathcal{L}_{\text{eff}}^{b\to c\tau\nu} = -\frac{4G_F}{\sqrt{2}} V_{cb} \sum_j C_j \mathcal{O}_j$$

$$\mathcal{O}_{V_{L,R}} = (\bar{c}\gamma^\mu P_{L,R} b)(\bar{\tau}\gamma_\mu P_L \nu)$$
$$\mathcal{O}_{S_{L,R}} = (\bar{c} P_{L,R} b)(\bar{\tau} P_L \nu)$$
$$\mathcal{O}_T = (\bar{c}\sigma^{\mu\nu} P_L b)(\bar{\tau}\sigma_{\mu\nu} P_L \nu)$$

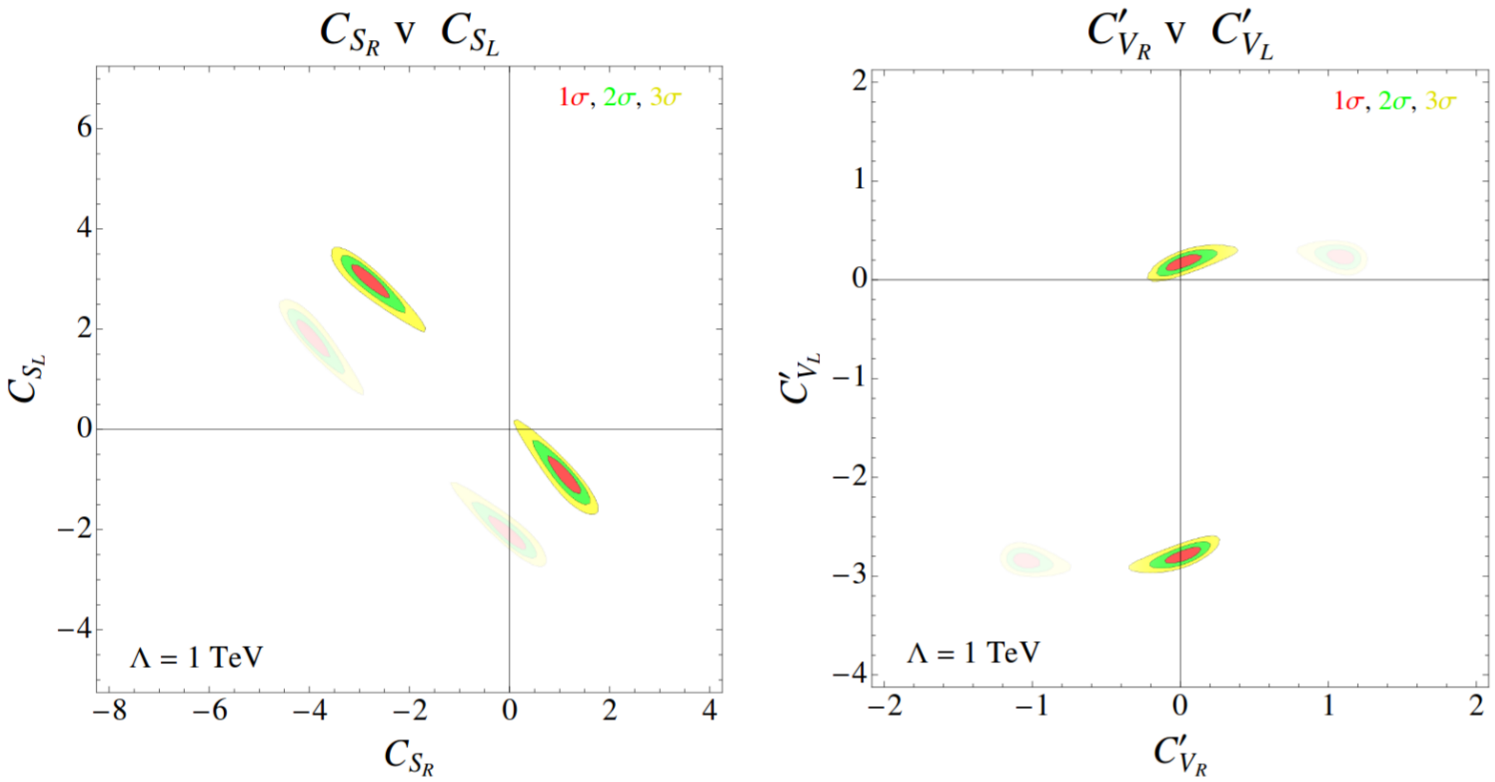
SM: tree-level $W^\pm$ exchange $\succ$ $C_{V_L} = 1$, $C_{j\neq V_L} = 0$

Popular BSM scenarios:

- charged Higgs contributions $\succ$ $\delta C_{S_{L,R}} \neq 0$
- new charged vector boson W' $\succ$ $\delta C_{V_{L,R}} \neq 0$
- (scalar or vector) leptoquark $\succ$ $\delta C_j \neq 0$ (depending on model)

Global Fit of Wilson Coefficients

Freytsis, Ligeti, Ruderman (2015)
see also Bardhan et al. (2016); Cai et al. (2017); Angelescu et al. (2018)



➢ **good fit for** $\delta C_{S_R} \simeq -\delta C_{S_L} \neq 0$ **or** $\delta C_{V_L} \neq 0$
but rather large NP contribution required

Constraints on NP Explanations

Scalar models ($\delta C_{S_R} \simeq -\delta C_{S_L} \neq 0$)

- large $B_c \to \tau\nu$ decay rate, in tension with B_c lifetime

  Alonso, Grinstein, Camalich (2016)

- issues with differential q^2 distribution in $B \to D\tau\nu$

  Celis, Jung, Li, Pich (2016)

Vector models ($\delta C_{V_L} \neq 0$)

- tension with $\tau \to \mu\nu\bar{\nu}$ and $Z \to \ell\bar{\ell}$ Feruglio, Paradisi, Pattori (2016)

Generally: watch out for $SU(2)_L$ symmetry

- strong constraints from $b\bar{b} \to \tau\bar{\tau}$ at ATLAS and CMS

  Faroughy, Greljo, Kamenik (2016)

- large impact on $B_s \to \tau^+\tau^-$, $B \to K\tau^+\tau^-$, $B \to K^{(*)}\nu\bar{\nu}$ etc.

  Crivellin, Müller, Ota (2017)

- contributions to $\Upsilon \to \tau^+\tau^-$ and $\psi \to \tau^+\tau^-$ Aloni et al. (2017)

➢ **full BSM resolution of $R(D^{(*)})$ anomaly challenging**

Light Right-Handed Neutrinos?

Greljo, Shakya, Robinson, Zupan (2018)
Asadi, Buckley, Shih (2018)

Recent suggestion: right-handed W' + light right-handed neutrinos

- naturally present in left-right symmetric models
- $SU(2)_L$-related constraints avoided ➢ $1/|V_{cb}|$ enhancement possible
- ν_R mass affects differential distributions
- no interference with SM ➢ low NP scale required

Model variants (addressing also $b \to s\mu\mu$)

- leptoquarks with right-handed neutrinos

Azatov, Barducci, Ghosh, Marzocca, Ubaldi (2018)

- custodial RS model

Carena, Megias, Quiros, Wagner (2018)

New Physics in $b \to s\mu\mu$ (and ee, $\tau\tau$)

Effective Hamiltonian

$$\mathcal{H}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{tb}^* V_{ts} \frac{e^2}{16\pi^2} \sum_i (C_i \mathcal{O}_i + C_i' \mathcal{O}_i') + h.c.$$

Good global fit solutions:

Altmannshofer, Stangl, Straub (2017)
Capdevila, Crivellin, Descotes-Genon, Matias, Virto (2017)

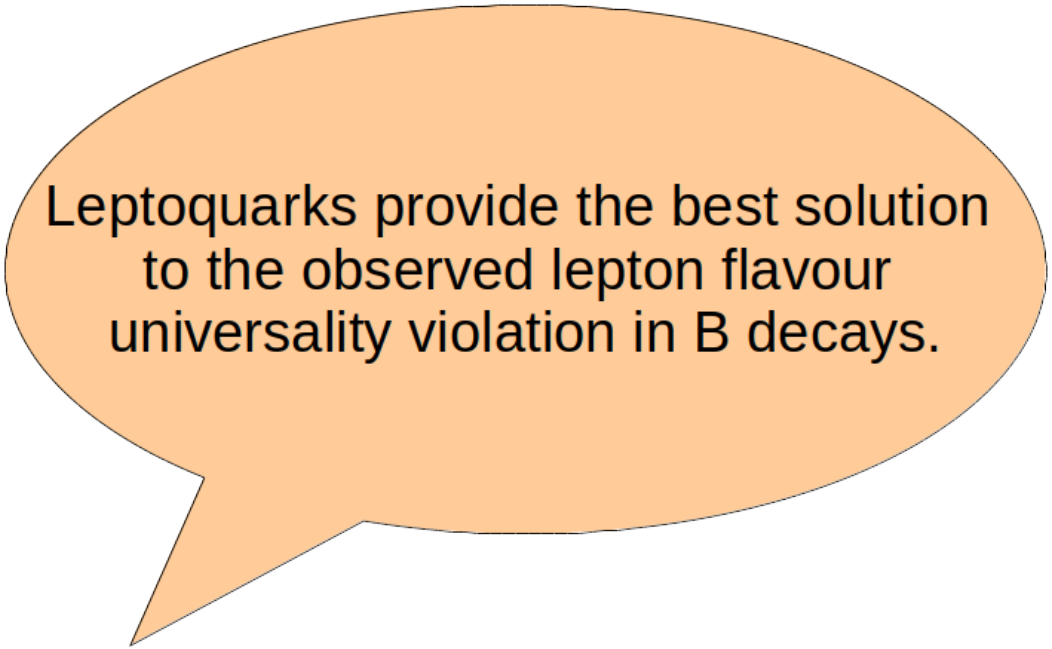
- $C_9^{\text{NP}} \sim -1.2$ ➢ LH quark current, muon vector current
- $C_9^{\text{NP}} = -C_{10}^{\text{NP}} \sim -0.7$ ➢ LH quark and lepton currents

The usual suspects

- new heavy neutral gauge boson Z'
- or again some leptoquark?

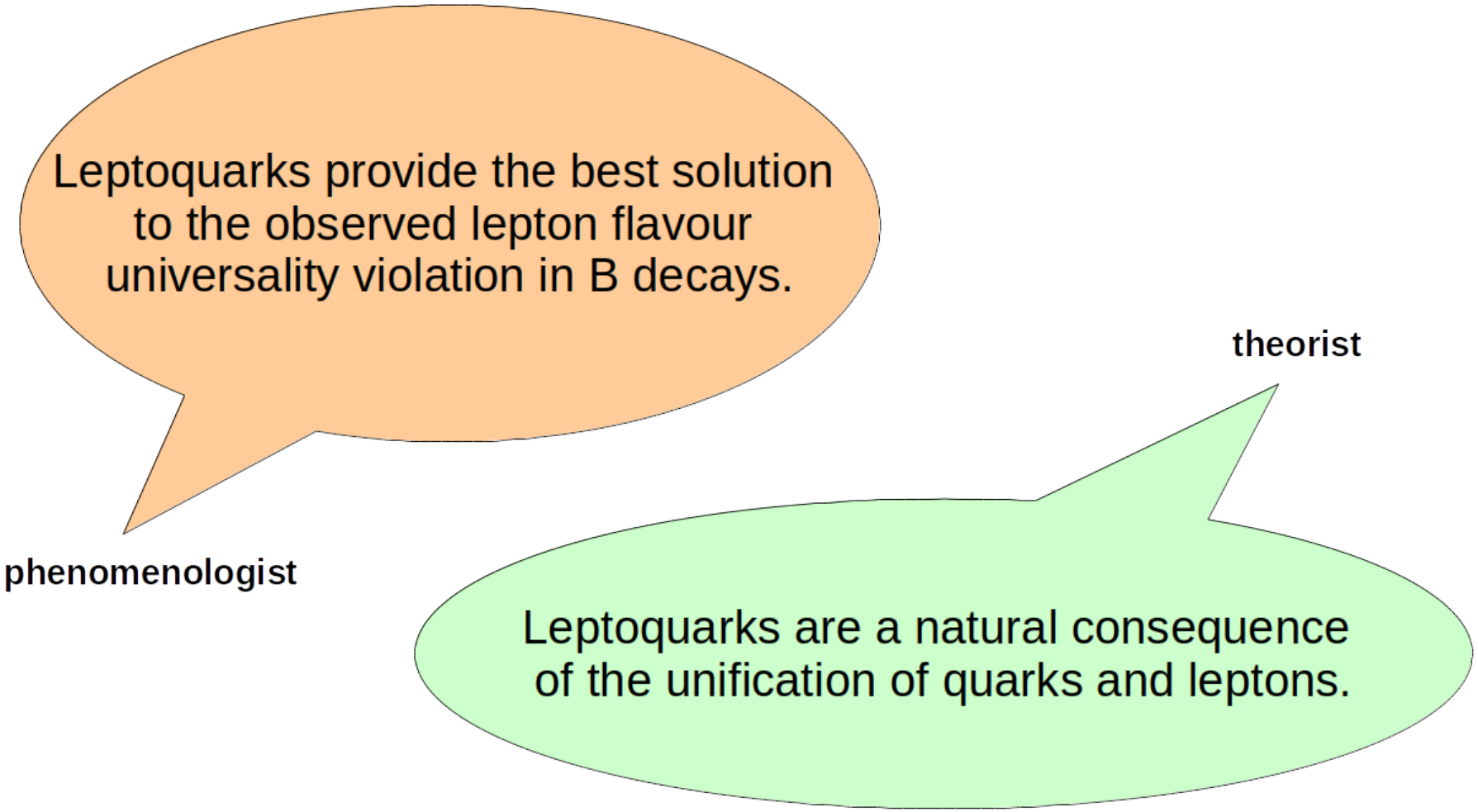
Altmannshofer, Straub (2013); Hiller, Schmaltz (2014)
Altmannshofer et al. (2014); Altmannshofer, Carena, Crivellin (2016)
D'Amico et al. (2017); Di Chiara et al. (2017)
Becirevic et al. (2018); Fajfer et al. (2018) ...

Why this Sudden Fuzz about Leptoquarks?



phenomenologist

Why this Sudden Fuzz about Leptoquarks?

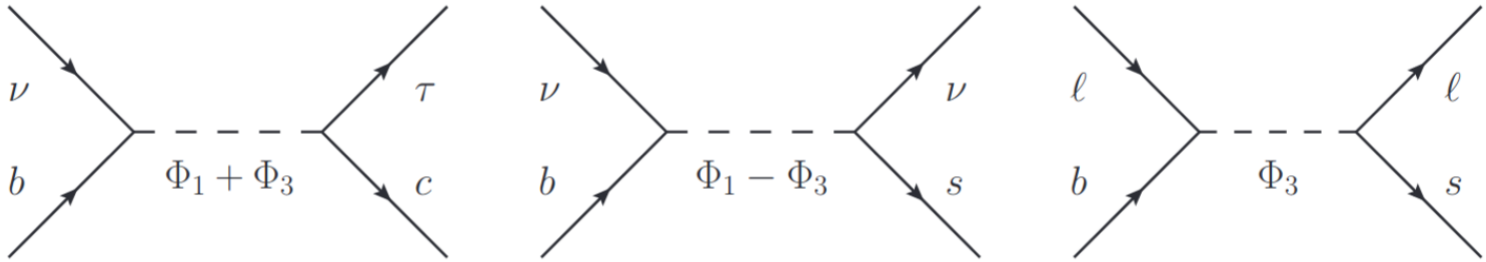


Maybe not as weird as we thought. . .

Status of Scalar Leptoquarks

Crivellin, Müller, Ota (2017)

- no single scalar leptoquark provides simultaneous solution to the B anomalies
- successful model with two scalar leptoquarks – $SU(2)_L$ singlet and triplet – of equal mass and equal coupling strengths



Possible UV-completion: Marzocca (2018)
composite Higgs model with LQs as pseudo-Goldstone bosons of spont. broken global symmetry $SU(10)_L \times SU(10)_R \to SU(10)_D$

- **Alternative model:** scalar leptoquarks from $SU(5)$ GUT

Becirevic, Dorsner, Fajfer, Faroughy, Kosnik, Sumensari (2018)

The $SU(2)_L$-Singlet Vector Leptoquark

Alonso, Grinstein, M. Camalich (2015)
Calibbi, Crivellin, Ota (2015)
Fajfer, Kosnik (2015)
Barbieri, Isidori, Pattori, Senia (2016)
Buttazzo, Greljo, Isidori, Marzocca (2017)
Angelescu, Becirevic, Faroughy, Sumensari (2018)

Most promising 1-particle solution: $SU(2)_L$-singlet vector leptoquark

- ➢ evades stringent constraints from B_s mixing and $b \to s\nu\bar{\nu}$
- ➢ B_c life-time under control
- ➢ beware of loop effects! Crivellin, Greub, Saturnino, Müller (2018)

Model building challenges

- identify UV origin of such vector LQ ➢ gauge symmetry?
- generate flavour non-universal LQ couplings
- avoid re-introduction of constraints due to additional particles present in UV-complete model

Back to the 70s: Pati-Salam

Recall: Pati-Salam (PS) model — Pati, Salam (1974)

- unification of quarks and leptons by introducing lepton number as fourth colour
- gauge group $G_{\text{PS}} = SU(4) \times SU(2)_L \times SU(2)_R$

  ➢ $SU(4)$ contains $SU(2)_L$-singlet vector leptoquark in addition to gluons and $B - L$ gauge boson

Simplest realisation

- LQ couplings are gauge couplings ➢ flavour-universal
- $m_{\text{LQ}} > \mathcal{O}(10^3\,\text{TeV})$ from $K_L \to \mu e$ and $K \to \pi \mu e$

➢ extend model to achieve flavour-dependent couplings and lower LQ mass to TeV scale

Recent Model-Building Efforts

quite some activity in this model-building challenge:

Barbieri, Murphy, Senia (2016)
Di Luzio, Greljo, Nardecchia (2017)
Calibbi, Crivellin, Li (2017)
Bordone, Cornella, Fuentes-Martin, Isidori (2017)
MB, Crivellin (2018)
Greljo, Stefanek (2018)
Heeck, Teresi (2018)
Balaji, Foot, Schmidt (2018)

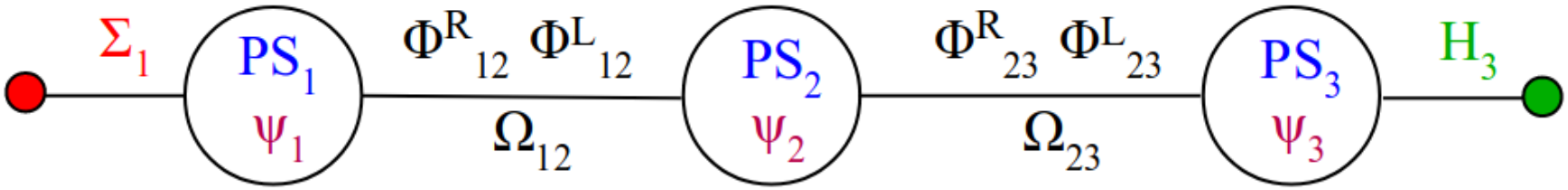
...

This talk: two examples

- three-site model with PS^3 symmetry
  Bordone, Cornella, Fuentes-Martin, Isidori (2017)
- Pati-Salam in Randall-Sundrum background MB, Crivellin (2018)

The PS^3 Model

Bordone, Cornella, Fuentes-Martin, Isidori (2017)
model sketch from Isidori, CKM'18



High-scale [$\sim 10^3$ TeV]
"vertical" breaking

$PS_1 \to SM_1$

link fields

$PS_i \times PS_j \to PS_{i+j}$

$SM \ (\to QED)$

Low-scale "vertical" Breaking [EWSB]

$SM_3 \to QED_3$

Key Features of PS^3

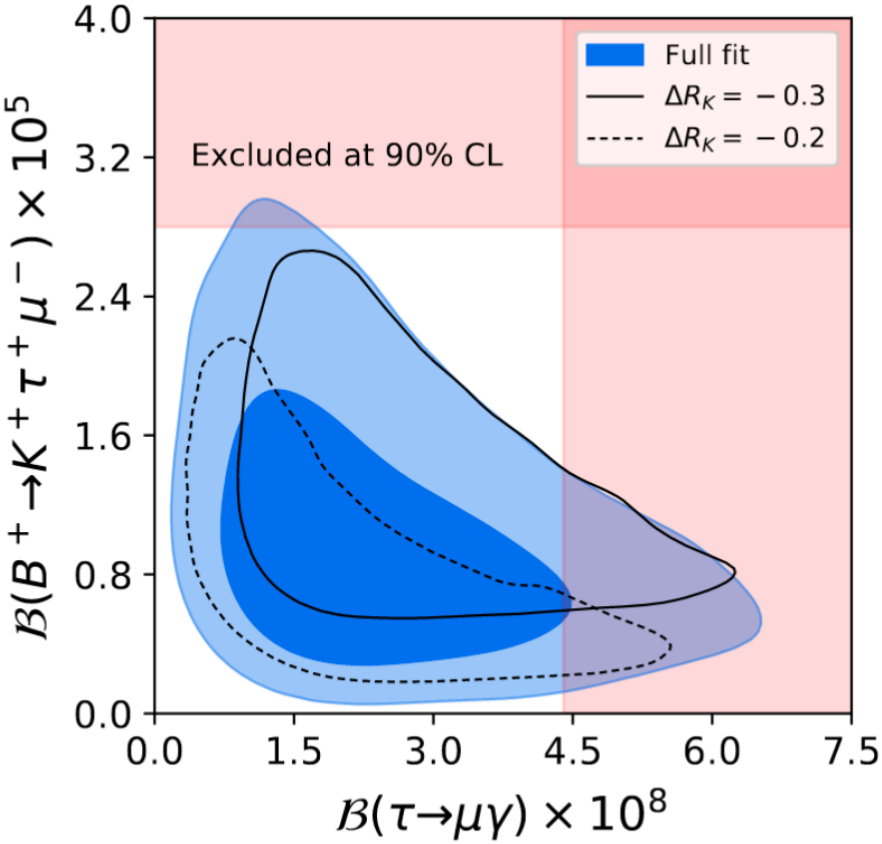
Bordone, Cornella, Fuentes-Martin, Isidori (2017), (2018)

common to all PS-type models

- TeV-scale LQ, colour-octet vector and Z'
- decent fit to low-energy data
- large $\tau \to \mu$ LFV effects

specific to PS^3

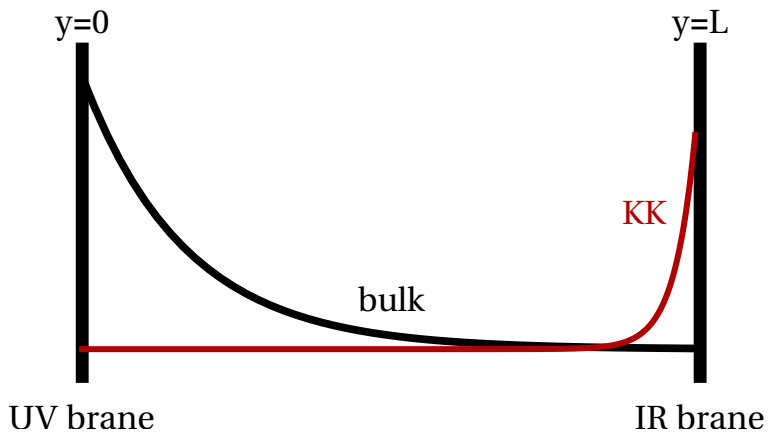
- hierarchical symmetry breaking pattern relates flavour-dependent LQ couplings to Yukawa hierarchies
- LQ coupling also to right-handed fermions



Pati-Salam in the Randall-Sundrum Background

Model in a nutshell: MB, Crivellin (2018)

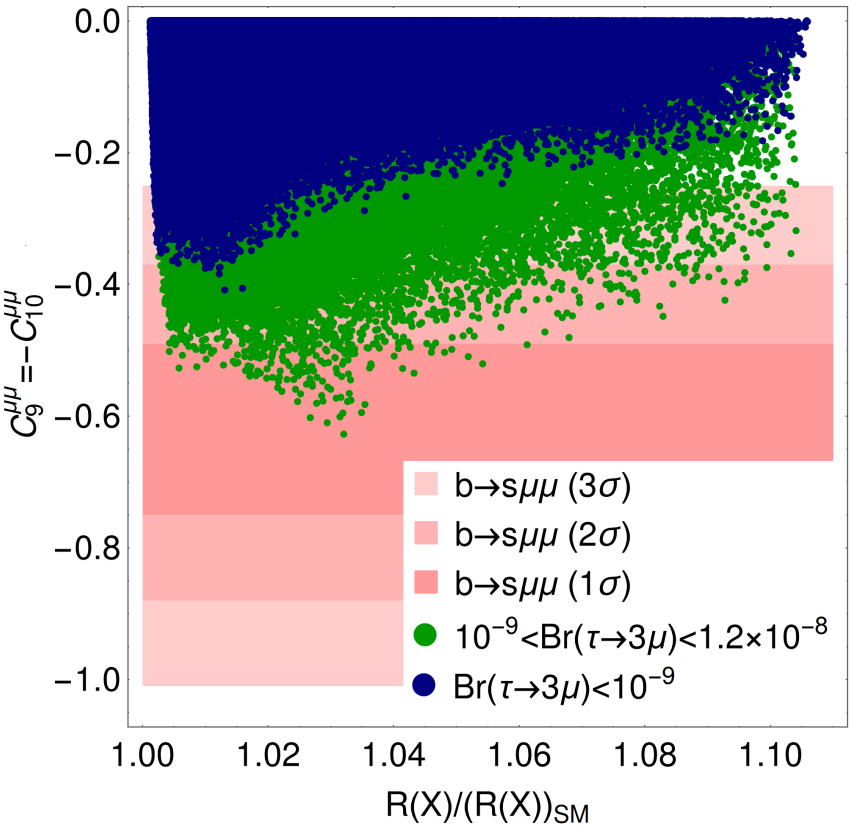
- embed PS gauge symmetry in 5D warped model described by Randall-Sundrum metric



- symmetry breaking by boundary conditions to SM gauge group, instead of sophisticated Higgs sector
  - ➢ massless zero modes for SM particles only
  - ➢ TeV-scale KK resonances for all degrees of freedom of G_{PS}, incl. LQ
  - ➢ flavor-dependent couplings from localisation of SM fermions in 5D bulk

Key Features of Warped PS

MB, Crivellin (2018)



- less parametric freedom due to geometric origin of symmetry breaking ➢ predictive
- full resolution of $b \to s\mu\mu$ anomaly
- noticeable improvement in $b \to c\tau\nu$, supported by W' contribution in addition to LQ
- CPV in $D - \bar{D}$ mixing on the verge of discovery
- observable rate for $\tau \to 3\mu$

Conclusions

Are the B decay anomalies opening the window towards the unification of quarks and leptons?

Backup slides

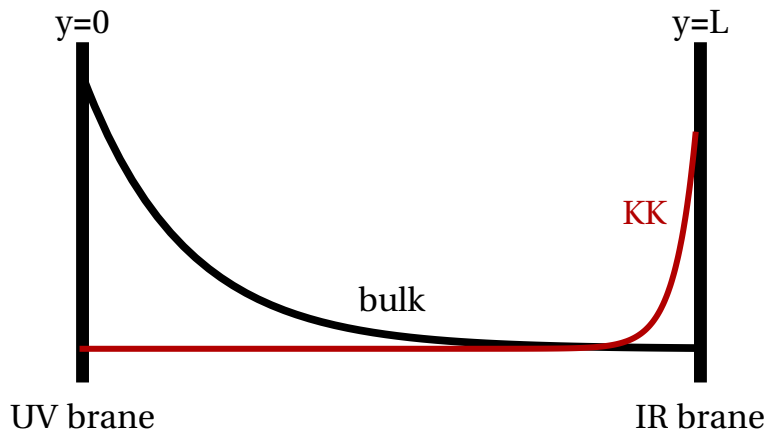
Pati-Salam in the Randall-Sundrum background

Idea: MB, Crivellin (2018)
embed Pati-Salam model into the 5D Randall-Sundrum space-time

$$ds^2 = e^{-2ky}\eta_{\mu\nu}dx^\mu dx^\nu - dy^2 \qquad 0 \leq y \leq L$$

Randall, Sundrum (1999)

- extra space-time coordinate y
  confined to interval $0 \leq y \leq L$,
  and warped by e^{-2ky} factor
- 4D Kaluza-Klein (KK) decomposition
  - towers of massive KK modes localized near IR brane
  - massless zero modes depending on boundary conditions
    ➢ identified with SM particles



Gauge symmetry breaking pattern

Two step symmetry breaking pattern

1. Pati-Salam gauge symmetry in the 5D bulk, broken by boundary conditions on the UV brane

$$SU(4) \times SU(2)_L \times SU(2)_R \to SU(3)_c \times SU(2)_L \times U(1)_Y$$

2. SM Higgs confined to the **UV** brane induces EW symmetry breaking

$$SU(2)_L \times U(1)_Y \to U(1)_{\text{em}}$$

- Higgs decoupled from KK modes at IR brane
- stringent EW precision constraints are evaded
- Yukawa couplings need to respect SM gauge symmetry only
- *but:* usual RS solution to gauge and flavour hierarchy problems lost

Fermion sector

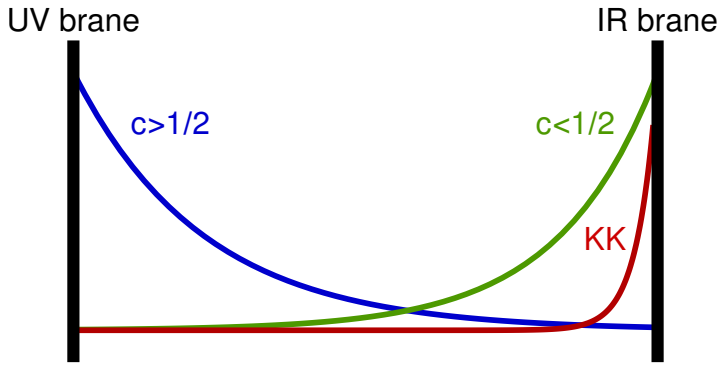
- fermions as 5D bulk fields in complete PS representations

$$\begin{pmatrix} u_L^1 & u_L^2 & u_L^3 & \nu_L \\ d_L^1 & d_L^2 & d_L^3 & \ell_L \end{pmatrix} \sim (4,2,1) \qquad \begin{pmatrix} u_R^1 & u_R^2 & u_R^3 & \nu_R \\ d_R^1 & d_R^2 & d_R^3 & \ell_R \end{pmatrix} \sim (4,1,2)$$

  ➢ massless zero modes correspond to SM fermions

- zero mode localization along extra dimension y depends exponentially on 5D bulk mass parameter $c = m_{5D}/k$

  ➢ non-universal couplings to KK modes



B anomalies require

- hierarchical localization of LH fermions: $c_{L1} > c_{L2} > c_{L3}$
- RH fermions localized at UV brane

The 4D composite dual

AdS/CFT correspondence: dual 4D composite model

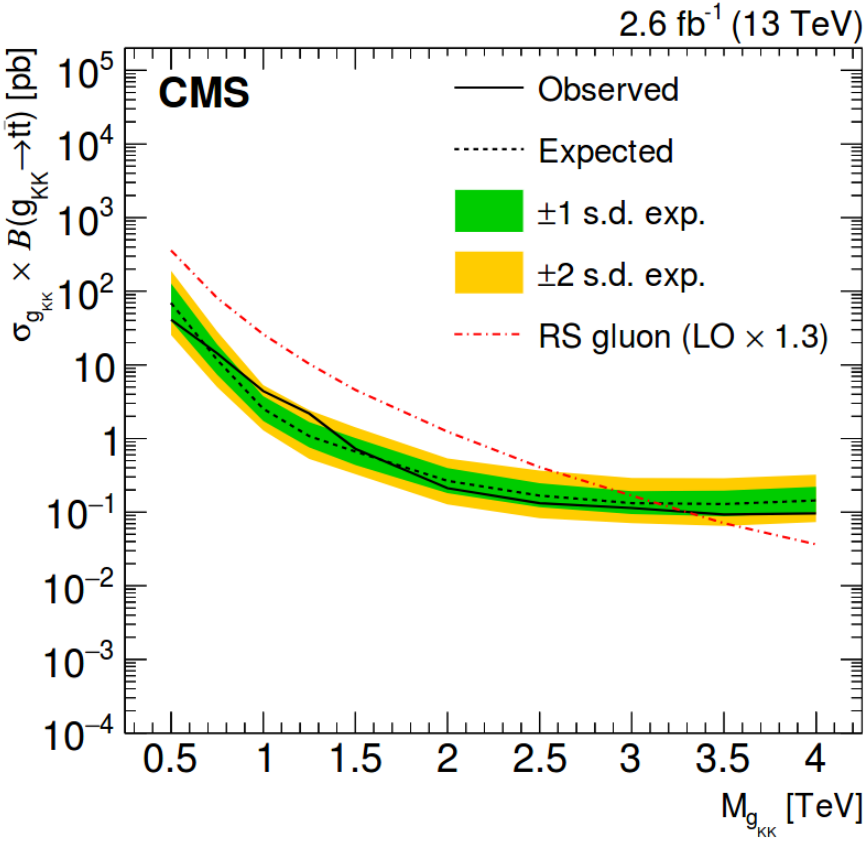
- elementary sector with SM gauge group
- *elementary* Higgs field
- conposite sector with Pati-Salam global symmetry
- left-handed fermions partially composite – linear mixing of SM fermions with composite resonances: $0 \sim s_1^{q,\ell} \ll s_2^{q,\ell} \ll s_3^{q,\ell} \sim 1/\sqrt{2}$
- right-handed fermions (mostly) elementary

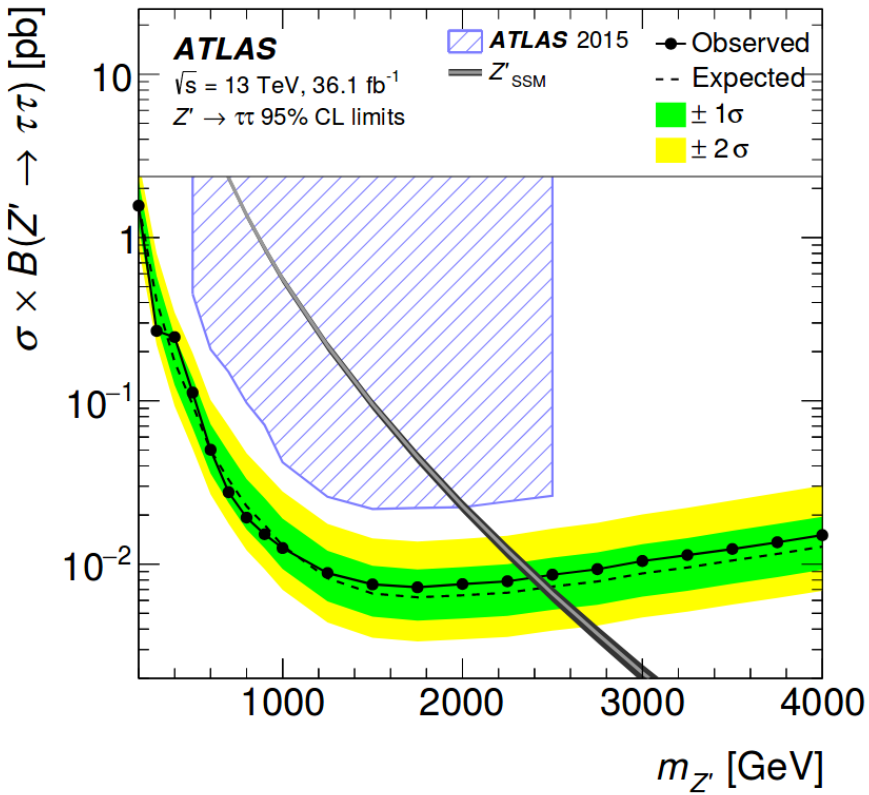
Simplified model: keep only SM fields + lowest-lying KK modes

- common mass scale M_{KK} for all new particles
- massive vector resonances for entire PS gauge group
- massive vectorlike fermions that mix with SM fermions

LHC constraints

strongest constraints from searches for $t\bar{t}$ and $\tau\bar{\tau}$ resonances





➢ for our model: $M_{\mathrm{KK}} \geq 3\,\mathrm{TeV}$

Flavour alignment

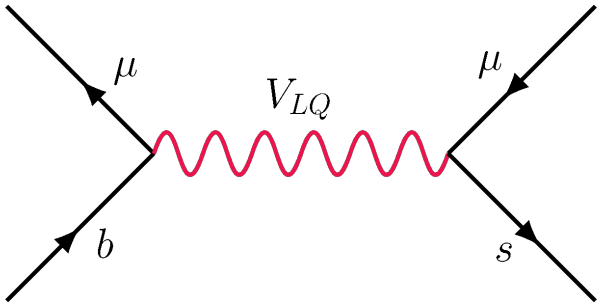
- generically, KK modes of gluons, $B-L$ gauge boson and W_L^3 mediate tree level FCNCs
  - ➢ reintroduces problematic contributions to meson mixings and $b \to s\nu\bar{\nu}$
- avoided by imposing flavour alignment between elementary-composite mixing (=5D bulk masses) and Y_d
  - ➢ no tree level FCNCs in the down sector
  - ➢ relevant tree level contribution to $D^0 - \bar{D}^0$ mixing (CKM)
- resulting leptoquark coupling matrix

$$\Gamma^{LQ,L}_{d_i\ell_j} = \frac{ig_s^*}{\sqrt{2}} \begin{pmatrix} 0 & 0 & 0 \\ 0 & s_2^q s_2^\ell c_\ell & s_2^q s_2^\ell s_\ell \\ 0 & -s_3^q s_3^\ell s_\ell & s_3^q s_3^\ell 2c_\ell \end{pmatrix}_{ij}$$

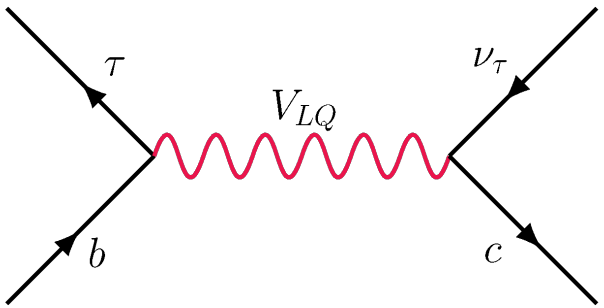
$u_i\nu_j$ coupling includes additional CKM rotation

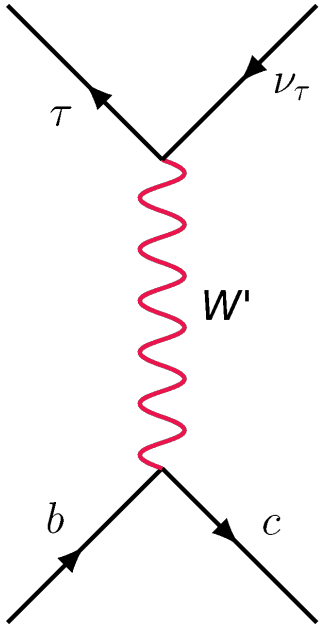
Important tree level effects

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



$b \to c\tau\nu$





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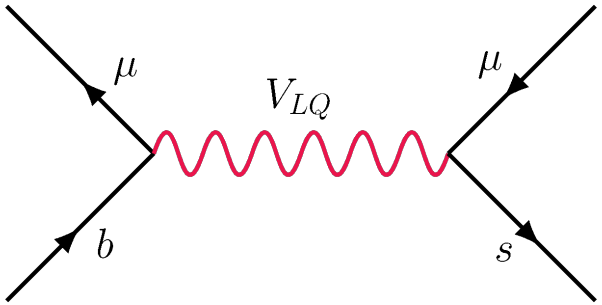

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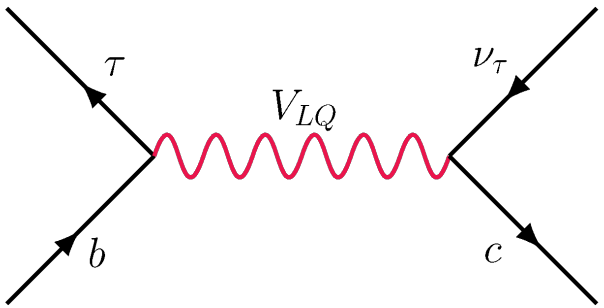

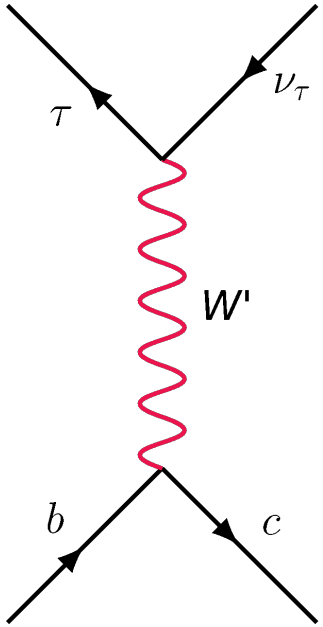

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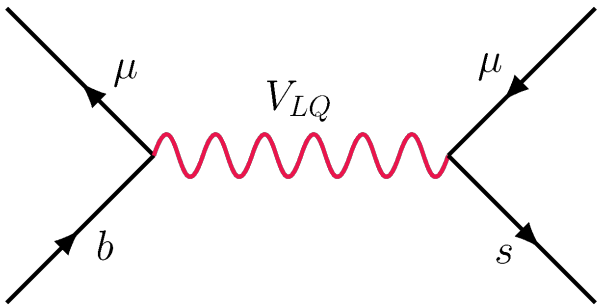
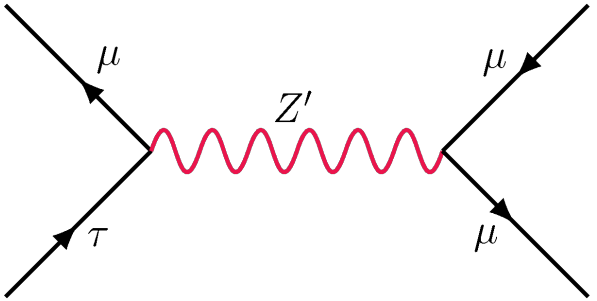


$\tau \to 3\mu$



$b \to c\tau\nu$