Search for the decay $B^0 \to K^*(892)\tau^+\tau^-$

as a test for Lepton Flavour Universality in quark transitions

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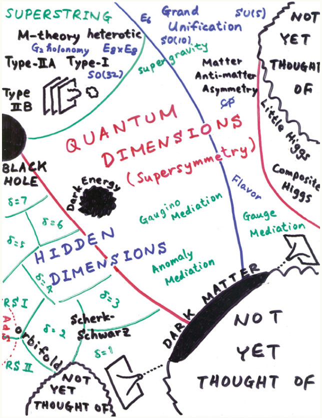
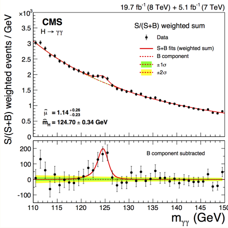
The quest for new physics

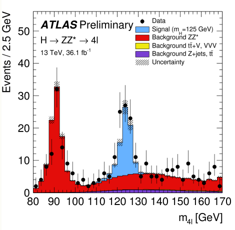
By the discovery of the Brout-Englert-Higgs boson in 2012, the SM of particle physics was completed.. Yet leaving many unanswered questions !



dailygalaxy.com



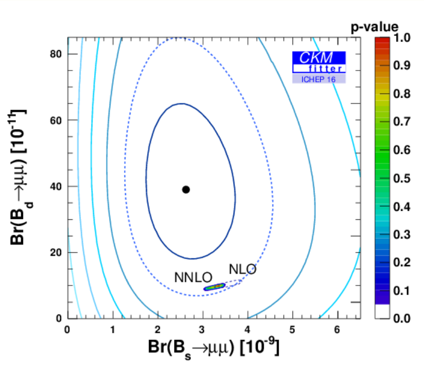
arXiv:1207.7235



ATLAS-CONF-2017-032

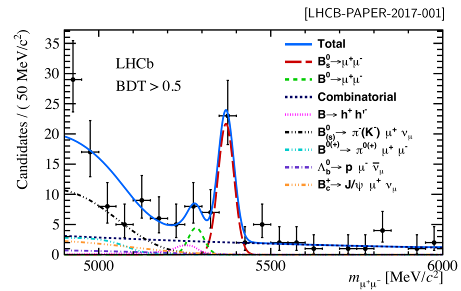
$B_s \to \mu\mu$

The heavily suppressed (in the SM) decay $B_s \to \mu\mu$ was first seen by a joint effort between CMS and LHCb in 2015.



CKM-fitter

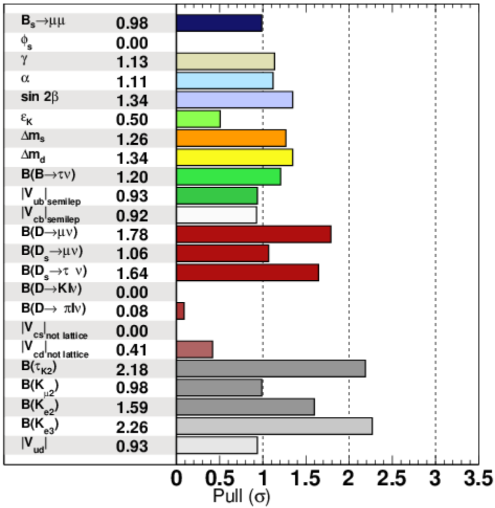
Later in 2017 LHCb measurement was made with 7.8σ significance !



arXiv:1703.05747

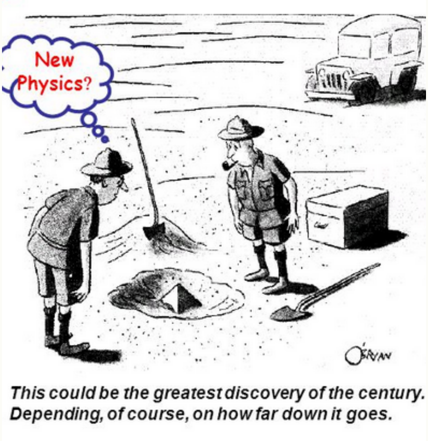
Precision measurements

Various parameters sensitive to NP from heavy flavour physics, the pull is estimated from the SM global fit
Results show consistency with the SM in general ..



(CKM Fitter group)

It is not as dark as it seems ! or is it ??



SLAC DOE Rev. 2006

Few years ago, some hints from B-factories and the LHCb started showing tension between beauty physics and the SM

Lepton Universality in the SM

If we examined the lepton coupling to the Z and $W^{\pm}$ via measurement of the branching fractions $\mathcal{B}$ of the leptonic decays of the Z produced in ee collisions for any two of the three families, it has been measured to be close to unity (i.e. ~ 1).

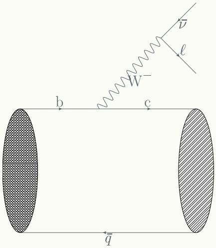
$$\mathcal{B}(Z \to e^+e^-) = (3.363 \pm 0.004)\% \qquad \mathcal{B}(W^+ \to e^+\nu) = (10.75 \pm 0.13)\%$$
$$\mathcal{B}(Z \to \mu^+\mu^-) = (3.366 \pm 0.007)\% \qquad \mathcal{B}(W^+ \to \mu^+\nu) = (10.57 \pm 0.15)\%$$
$$\mathcal{B}(Z \to \tau^+\tau^-) = (3.370 \pm 0.008)\% \qquad \mathcal{B}(W^+ \to \tau^+\nu) = (11.25 \pm 0.20)\%$$

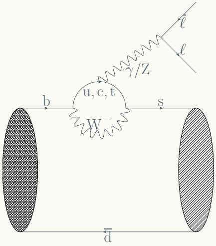
PDG 2016[1]

[1]The $W \to \tau\nu$ is $\sim 1\sigma$ higher than the other due to the chirality and D- functions
The SM prediction is 10.75 %

Lepton universality in quark transitions

Quark transitions in beauty and charmed hadrons decays offer an additional test for the Lepton Flavour Universality (LFU). By the FCCC in the $b \to c$ transition and FCNC penguins in $b \to s$ transition.



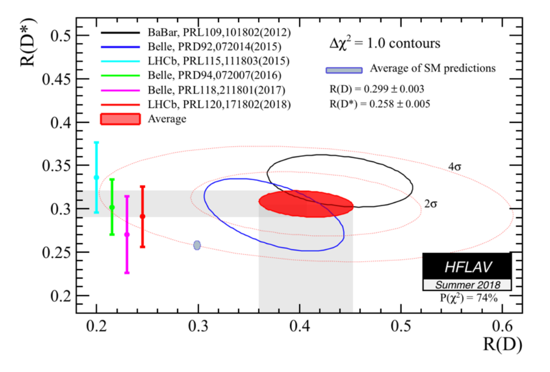


Hints of LFU violation

Tests for LFU using the B meson decays involving the quark transitions $b \to c\ \mu\nu$ and $b \to c\ \tau\nu$, via the observables

$$R_{D^{(*)}} \equiv \frac{\mathcal{B}(\bar{B} \to D^{(*)}\tau^-\bar{\nu})}{\mathcal{B}(\bar{B} \to D^{(*)}\ell^-\bar{\nu})},$$

has reported an average of $\sim 4\sigma$ deviation from Standard Model predictions.



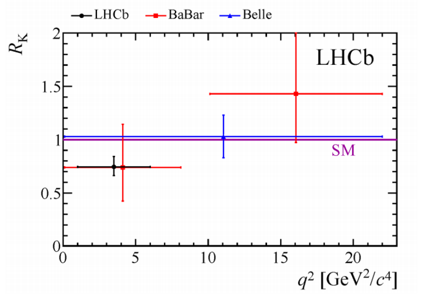
Heavy Flavour Averaging Group (CERN- 2018)

Hints of LFU violation

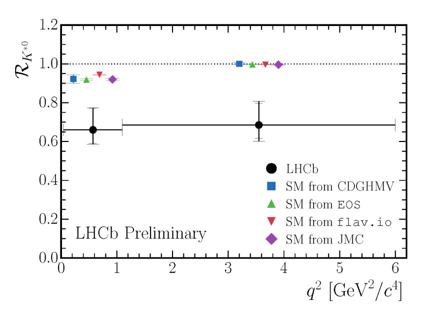
LHCb measurements of the observables:

$$R_{K^{(*)}} \equiv \frac{\mathcal{B}(\bar{B} \to K^{(*)} \mu\mu)}{\mathcal{B}(\bar{B} \to K^{(*)} ee)},$$

that involve the quark transitions, $b \to s\ ee$ and $b \to s\ \mu\mu$.



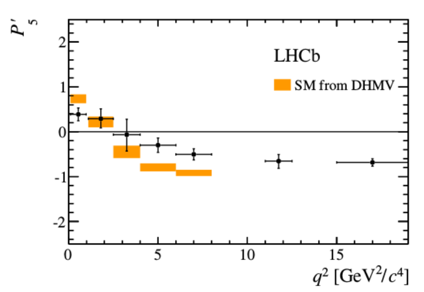
arXiv:1406.6482



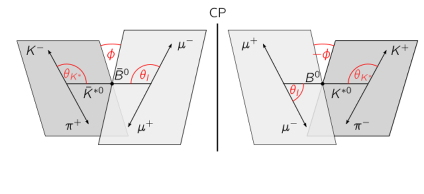
arXiv:1705.05802

Shows SM deviation of $2.2 - 2.4\sigma$ at low and $\sim 2.6\sigma$ at central q^2 for R_{K^*}
R_K has shown a $\sim 2.5\sigma$ deviation from SM prediction from LHCb measurements
.

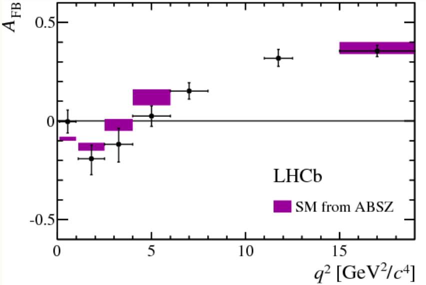
Clean observables, with small hadronic uncertainty.



3.7σ from SM

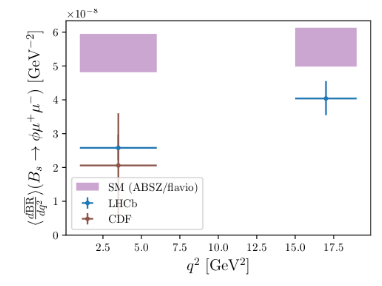


arXiv:1512.04442



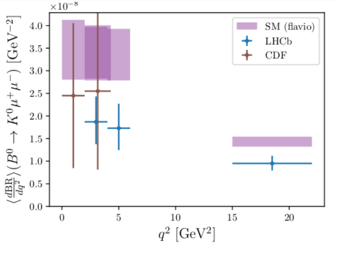
Differential branching fractions

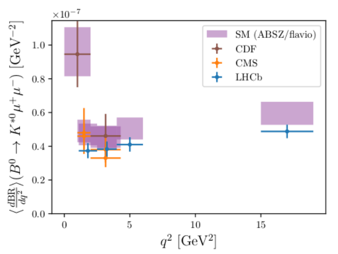
The angular analysis was preformed on $B_s \to \phi(K^+K^-)\mu^+\mu^-$, as it has similar helicity states expansion as $B \to K^*\mu^+\mu^-$, the angular observables tuned to be consistent with SM, but the dif. BR was found to be $> 3\sigma$ less than the SM prediction.



arXiv:1506.08777

Similar deviation could be seen in other BR involving $b \to s\mu\mu$.

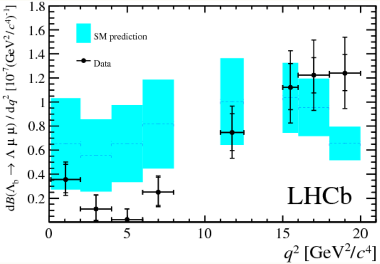




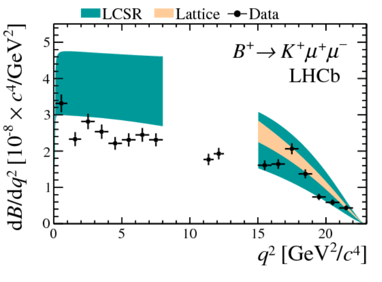
Plots by D. Straub - `flav.io`

Differential branching fractions

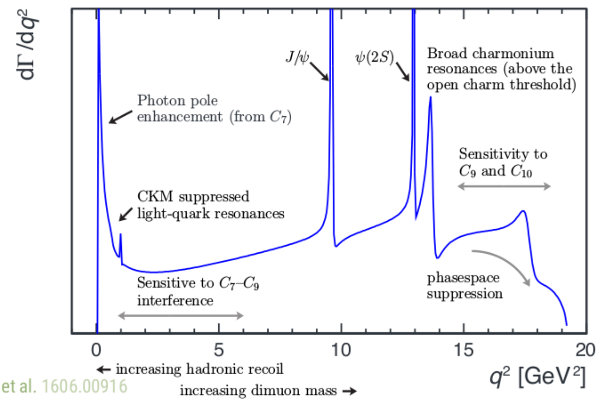
More discrepancies can be seen in other decays involving $b \to s\mu\mu$ transitions branching fractions, suggesting that the μ is the source of the LFU anomalies not the e.



arXiv:1503.07138

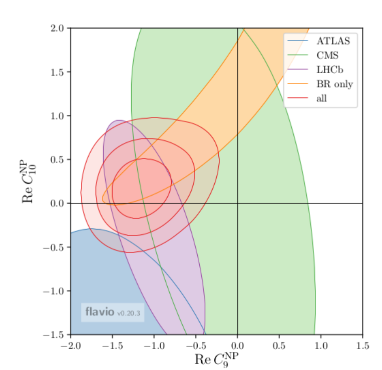


One could argue that such discrepancies come from hadronic uncertainties or that we are missing something in qcd processes beyond form factors.. but this is apparently not the case.

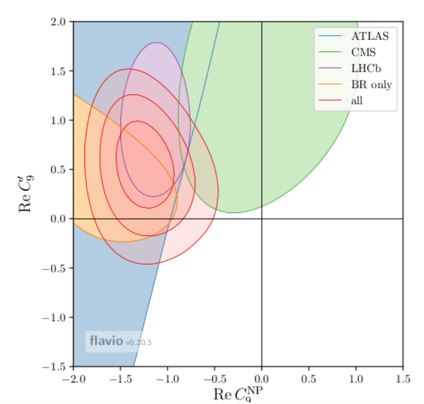


Blake et al. 1606.00916

Global fits for $b \to s\ell\ell$



5σ

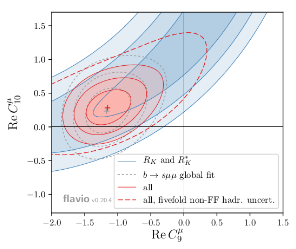


5.3σ

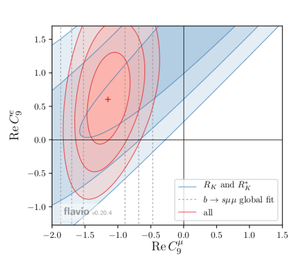
When we combine all of these effects in terms of Wilson coefficients, and pull them from SM by:

$$\text{pull} = \sqrt{\chi^2_{SM} - \chi^2_{\text{best fit}}}$$

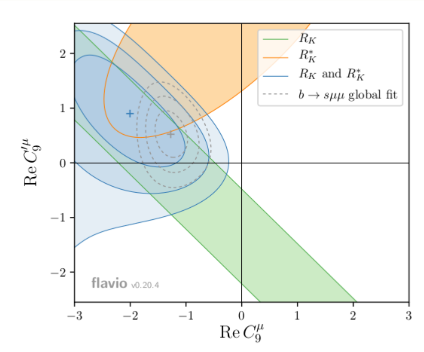
Fits C^{μ} VS C^{e}



C_0^{μ}, C_{10}^{μ}

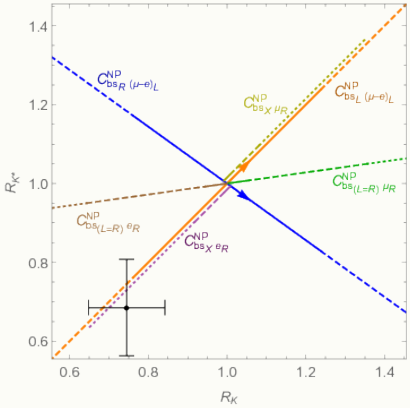


C_9^{μ}, C_9^{e}



RH currents not favoured by data..

General scheme for NP Wilson coefficients



Carmona & Goertz arXiv:1503.07138

- For LH chiral theories, electron currents does not not contribute;
- If both RH and LH fermions couple to the NP we expect significant contribution from the electron.

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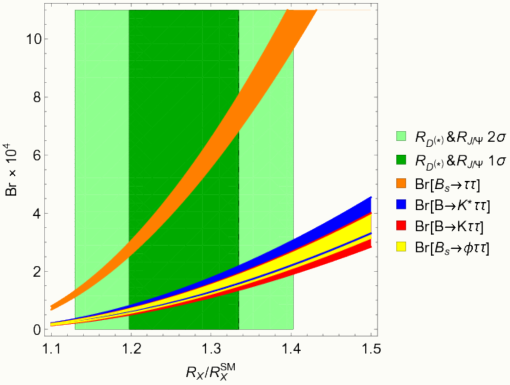
- Z' or composite Higgs models are also viable candidates (A. Carmona and F. Goertz).
- An observable similar to $R_{K^{(*)}}$ needs to be measured for $B \to K\tau\tau$.

The search for the decay $B \to K^* \tau^+ \tau^-$

Extrapolating from $R_{D^{(*)}}$ anomalies, Capdevila *et al* arXiv:1712.01919 predicted enhancement of the BR with τ's up to 10^3



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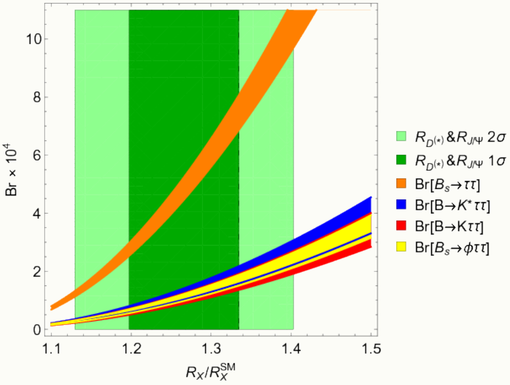
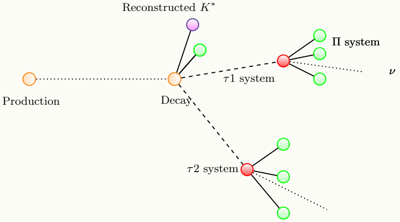
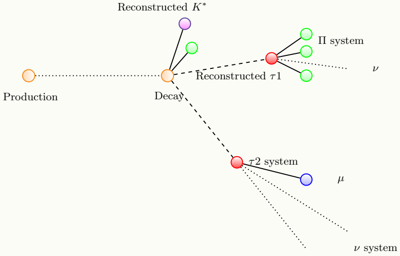


We expect enhancement of $\sim 10^{+3}$ of the SM for $B \to K^* \tau^+ \tau^-$ BR..

The search for the decay $B \to K^* \tau^+ \tau^-$

Nevertheless, the search for this decay is challenging due to its complex topology, particularly in hadronic machines...





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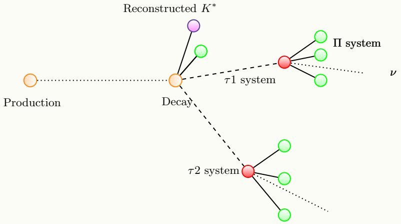
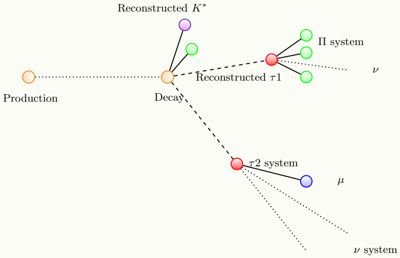


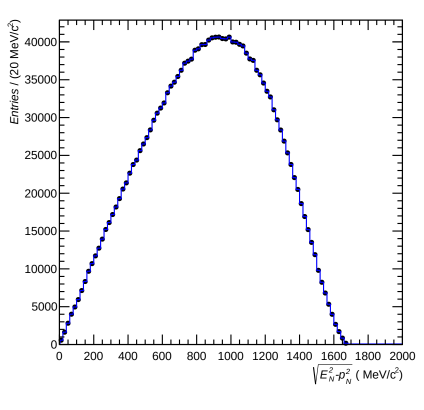


Considering both τ final states we could reconstruct $\sim 5\%$ of these decays..

The effective di-neutrino mass

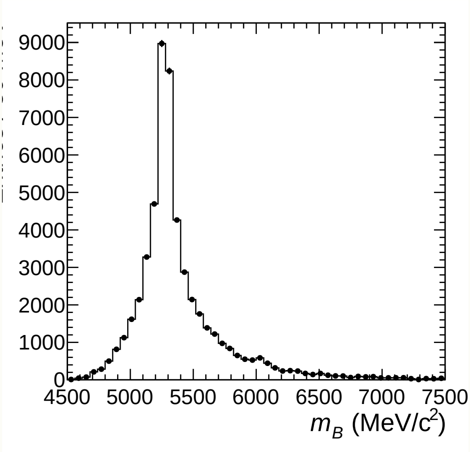
The internal degrees of freedom for the 2 neutrinos in the $\tau \to \mu\nu\bar{\nu}$ cannot be constraint from the decay topology, using the TRUTH MC we can plot the distribution for this parameter:

$$m_N = \sqrt{2p_\nu p_{\bar{\nu}}(1 - \cos\theta_{\nu\bar{\nu}})}$$



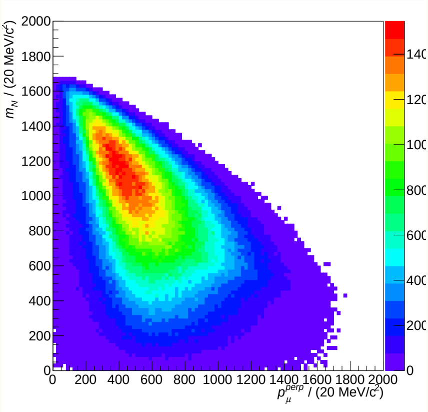
Testing the solution of TRUTH sample

The reconstruction equations using the mean of m_N as a fixed value was tested on TRUTH MC:



Search for correlation

A 2-D histogram between $p_\mu^\perp$ and m_N was constructed from TRUTH events to study the possibility of correlating the 2 variables, as seen in the figure, possible anti-correlation is observed. The correlation factor is found to be $r = -0.503$.

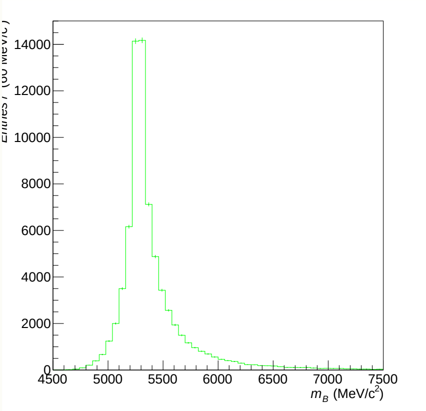


The correlation is stronger for low $p_\mu^\perp$ events. While for the large $p_\mu^\perp$ values it is less prominent.

Testing the solution with linear model on TRUTH

The solution with the linear model for m_N was tested on TRUTH simulation, and the left-tail of the B-mass histogram was fit by a Gaussian :

	value (MeV)	Err ($\pm$ MeV)
mean	5306.26	68.71
RMS	147.72	84.78



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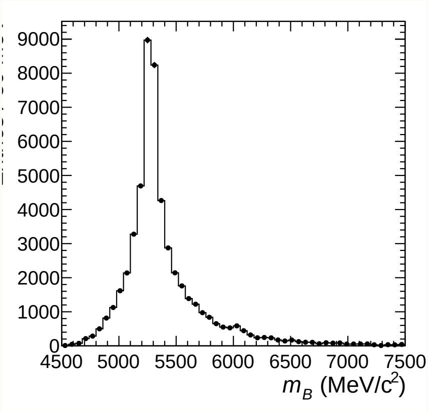
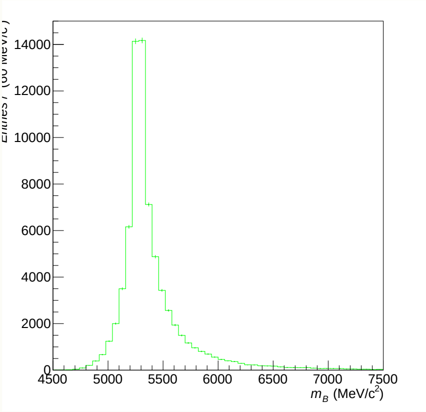


before

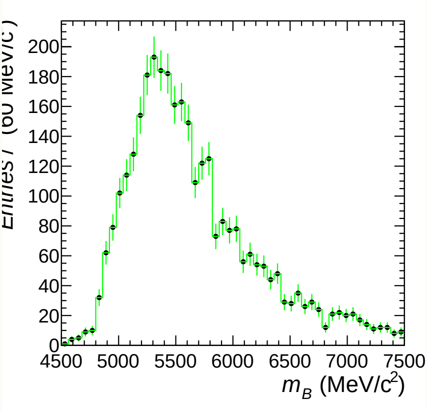


after

Testing the solution with linear model on REC

The solution with the linear model for m_N was tested on REC simulation, and the left-tail of the B-mass histogram was fit by a Gaussian :

	value (MeV)	Err ($\pm$ MeV)
mean	5381.28	95.05
RMS	282.92	63.75



Efficiency evaluation

The reconstructibility and stripping efficiencies $\varepsilon_{\text{Rec}} \cdot \varepsilon_{\text{Strip}} = N_{REC}/N_{TRUTH}$ of the 3pi 3pi and 3pimu decays are

Decay mode	$\varepsilon_{\text{Rec}} \cdot \varepsilon_{\text{Strip}}(\%)$	uncertainty $\pm(\%)$ (95% CL)
3pi3pi	0.86	0.07
3pimu	0.03	0.04

Moreover, the reconstruction method efficiencies for both decays are

Decay mode	$\varepsilon_{\text{Meth}}(\%)$	uncertainty $\pm(\%)$ (95% CL)
3pi3pi	18.20	0.41
3pimu	19.86	0.46

SU(2) × U(1) LQ Model

New vector Leptoquark is based on extending the SM symmetry by a group similar to the EW group, i.e.

$$\textit{pre GUT} \longrightarrow SU(3)_c \times SU(2)_{\mathrm{LQ}} \times SU(2)_W \times U(1)_X \longrightarrow SU(3)_c \times SU(2)_W \times U(1)_Y$$

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- The model is chiral, coupling only to left-handed currents.
- Introducing an $SU(2)$ triplet V_μ^a and a $U(1)$ C_μ gauge bosons with coupling constants g_{LQ} and g'_{LQ}, respectively.
- After the SSB, three bosons acquire mass and one is left massless we identify as the B_μ boson associated with the weak hypercharge Y.

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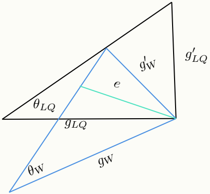
New vector Leptoquark is based on extending the SM symmetry by a group similar to the EW group, i.e.

$$pre\ GUT \longrightarrow SU(3)_c \times SU(2)_{\mathrm{LQ}} \times SU(2)_W \times U(1)_X \longrightarrow SU(3)_c \times SU(2)_W \times U(1)_Y$$

- The model is chiral, coupling only to left-handed currents.
- Introducing an $SU(2)$ triplet V_μ^a and a $U(1)$ C_μ gauge bosons with coupling constants g_{LQ} and g'_{LQ}, respectively.
- After the SSB, three bosons acquire mass and one is left massless we identify as the B_μ boson associated with the weak hypercharge Y.
- The scale of the SSB of this model is expected to be $\Lambda_{LQ} \sim$ TeV.

The Model

There is an immediate constraint on this model for the mixing angle of V_μ^3 and C_μ from the weak mixing angle and the EM fine structure constant, at Λ_{EW}:



$$(g'_{LQ})^2 = 4\pi\alpha_{EM} \frac{1}{\cos^2\theta_W \sin^2\theta_{LQ}}$$

For natural g'_{LQ}, one expects $\theta_{LQ} \approx 18.65$ deg.
Implying that $M_U = 1.05\, M_V$

The Lagrangian

The gauge leptoquark lagrangian is given by:

$$\begin{aligned}\mathcal{L}_{LQ} = &-\frac{1}{4}\left(V^a_{\mu\nu}V_a^{\mu\nu} + C_{\mu\nu}C^{\mu\nu}\right) - ig_{LQ}\left[\bar{LQ}_{U_L}\frac{\sigma^a}{2}\not{V}_a LQ_{U_L}\right] \\ &- ig_{LQ}\left[\bar{LQ}_{D_L}\frac{\sigma^a}{2}\not{V}_a LQ_{D_L}\right] - ig'_{LQ}\left[\bar{LQ}_{U(D)_L}(IX)\not{C} LQ_{U(D)_L}\right] \\ &- ig'_{LQ}X\left[\bar{U(D)}_R\not{C}U(D)_R + \bar{E}_R\not{C}E_R\right].\end{aligned}$$

With:

$$LQ_{U_L} := \left\{\begin{pmatrix}u_L\\ \nu_e\end{pmatrix};\begin{pmatrix}c_L\\ \nu_\mu\end{pmatrix};\begin{pmatrix}t_L\\ \nu_\tau\end{pmatrix}\right\},\ LQ_{D_L} := \left\{\begin{pmatrix}d_L\\ e_L\end{pmatrix};\begin{pmatrix}s_L\\ \mu_L\end{pmatrix};\begin{pmatrix}b_L\\ \tau_L\end{pmatrix}\right\},$$

$$U_R := \{u_R, c_R, t_R\},\ D_R := \{d_R, s_R, b_R\},\ E_R := \{e_R, \mu_R, \tau_R\}.$$

The first family - in red- does not couple to the leptoquarks

Flavour mixing

The LQ flavour mixing matrices are given by

$$\mathcal{U}^u_{LQ} = \begin{pmatrix} \mathcal{U}_{u\nu_e} & \mathcal{U}_{u\nu_\mu} & \mathcal{U}_{u\nu_\tau} \\ \mathcal{U}_{c\nu_e} & \mathcal{U}_{c\nu_\mu} & \mathcal{U}_{c\nu_\tau} \\ \mathcal{U}_{t\nu_e} & \mathcal{U}_{t\nu_\mu} & \mathcal{U}_{t\nu_\tau} \end{pmatrix}$$

$$\mathcal{U}^d_{LQ} = \begin{pmatrix} \mathcal{U}_{de} & \mathcal{U}_{d\mu} & \mathcal{U}_{d\tau} \\ \mathcal{U}_{se} & \mathcal{U}_{s\mu} & \mathcal{U}_{s\tau} \\ \mathcal{U}_{be} & \mathcal{U}_{b\mu} & \mathcal{U}_{b\tau} \end{pmatrix}$$

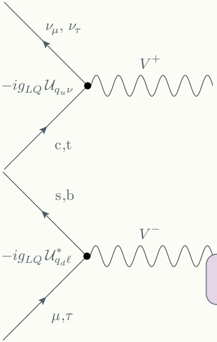
Where the terms in green are the largest, in blue are smaller, and the ones in red are of $\sim \lambda^4$ or less.

$$\lambda \sim \mathcal{O}(10^{-1})$$

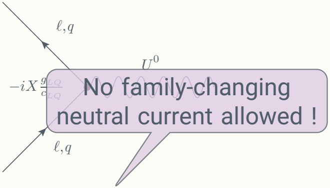
The exact determination of the values of such mixings need to be determined from experimental fits..

Feynman Rules

There are charged and neutral currents:



$$\mathcal{L}_{cc} = -g_{LQ} j_\mu^{dCC} V^{-\mu}$$



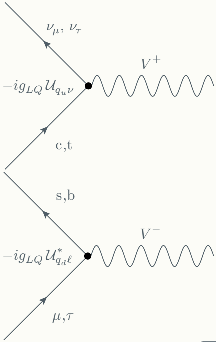
The charged Leptoquark currents :

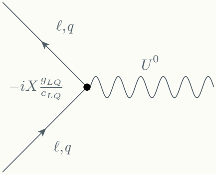
$$j_\mu^{dCC} = \bar{\ell}\gamma_\mu\omega_L q_d \qquad j_\mu^{uCC} = \bar{\nu}\gamma_\mu\omega_L q_u$$

The neutral Leptoquark currents :

$$j_\mu^{NC} = X_\ell\bar{\ell}\gamma_\mu\ell + X_\nu\bar{\nu}\gamma_\mu\nu + X_q\bar{q}\gamma_\mu q.$$

There are charged and neutral currents:





$$\mathcal{L}_{nc} = -g'_{LQ} j_\mu^{NC} U^\mu$$

The charged Leptoquark currents :

$$j_\mu^{dCC} = \bar{\ell}\gamma_\mu\omega_L q_d \qquad j_\mu^{uCC} = \bar{\nu}\gamma_\mu\omega_L q_u$$

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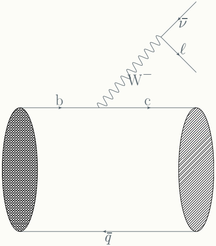
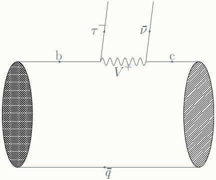
$$j_\mu^{NC} = X_\ell\bar{\ell}\gamma_\mu\ell + X_\nu\bar{\nu}\gamma_\mu\nu + X_q\bar{q}\gamma_\mu q.$$

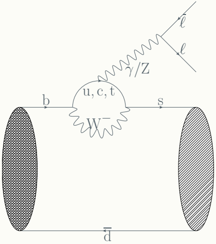
Phenomenology of the model

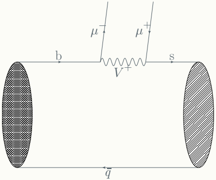
$\bar{B} \to D\ell\bar{\nu}$ decays





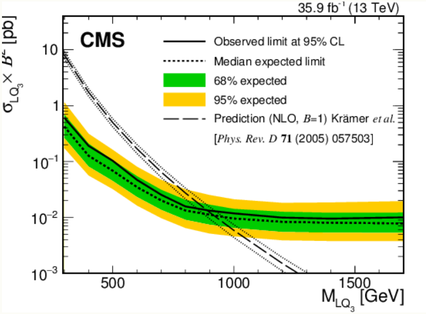
$\bar{B} \to K\ell\bar{\ell}$ decays



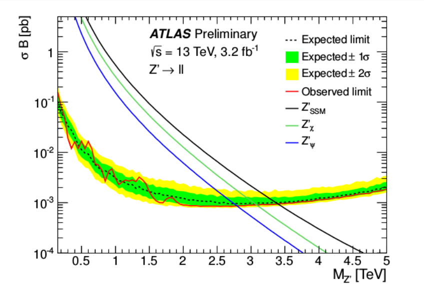


The transition $b \to s\mu\mu$ is suppressed by a factor of $\sim 10^{-4}$ although it is at tree-level in this model due to Flavour-mixing.

Direct searches



3rd gen LQ searches $M_{LQ} > 0.8$TeV



Z'-like bosons searches $M_{Z'} > 3.4$TeV

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

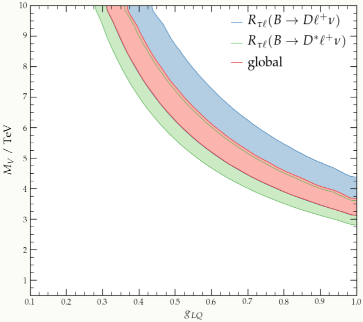
The Wilson coefficients from the transition $b \to c\ell\nu$ modified by this model are computed and found to be :

$$C_{VL}^{\tau\nu_\tau} = \beta \frac{\mathcal{U}_{b\tau}\mathcal{U}^*_{c\nu_\tau}}{\mathcal{V}^*_{cb}} \qquad C_{VL}^{\tau\nu_\mu} = \beta \frac{\mathcal{U}_{b\tau}\mathcal{U}^*_{c\nu_\mu}}{\mathcal{V}^*_{cb}}$$

$$C_{VL}^{\mu\nu_\tau} = \beta \frac{\mathcal{U}_{b\mu}\mathcal{U}^*_{c\nu_\tau}}{\mathcal{V}^*_{cb}} \qquad C_{VL}^{\mu\nu_\mu} = \beta \frac{\mathcal{U}_{b\mu}\mathcal{U}^*_{c\nu_\mu}}{\mathcal{V}^*_{cb}}$$

with

$$\beta = \left(\frac{g_{LQ}}{g_W}\right)^2 \left(\frac{M_W}{M_V}\right)^2$$



The global fit from experimental data with $\pm 1\sigma$ shows a Mass of 3.5 TeV consistent with natural coupling $g_{LQ} \approx 1$

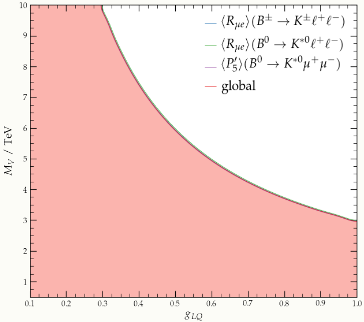
Constraints from $R_{K^{(*)}}$ and P_5'

The Wilson coefficients from the transition $b \to s\ell\ell$ modified by this model,

$$C_9^{\tau\tau} = \beta \frac{\mathcal{U}_{b\tau}\mathcal{U}^*_{s\tau}}{\mathcal{V}^*_{tb}\mathcal{V}_{ts}} \qquad C_9^{\mu\mu} = \beta \frac{\mathcal{U}_{b\mu}\mathcal{U}^*_{s\mu}}{\mathcal{V}^*_{tb}\mathcal{V}_{ts}}$$

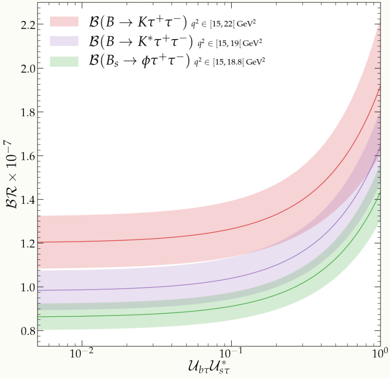
$$C_{10}^{\tau\tau} = -C_9^{\tau\tau}$$

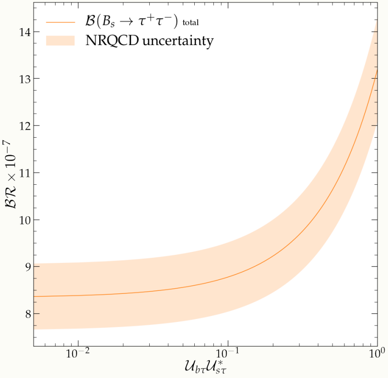
$$C_{10}^{\mu\mu} = -C_9^{\mu\mu}$$



In order to explain both anomalies, we require that the mixing satisfy $\dfrac{\mathcal{U}_{b\tau}\,\mathcal{U}^*_{c\nu_\mu}}{\mathcal{U}_{b\mu}\mathcal{U}^*_{s\mu}} \sim 10^2$.

Predictions for $b \to s\tau\tau$





Enhancement of the branching fractions for the decays involving $b\tau\tau$ as a function of the LQ flavour mixing., for $M_V \sim 1$ TeV and natural coupling.

What to expect ?

The expected number of B's that are produced at the LHCb and decaying into $K^*\tau\tau$ with $\tau \to 3\pi\nu$ and $\tau \to \mu\nu\bar{\nu}$

- 3 fb^{-1}(Run I) and 5 fb^{-1}(Run II).

$$\mathcal{N} = \int \mathscr{L} dt \cdot \sigma_{b\bar{b}} \cdot 2f_{b\to B} \cdot 2\mathcal{B}_{B\to K^*\tau\tau}\mathcal{B}_{\tau\to 3\pi\nu}\mathcal{B}_{\tau\to\mu\nu\bar{\nu}}\,\varepsilon_{Sel}$$

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- 250μb^{-1} 13 TeV

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- $\sim 40\%$

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- 250μb^{-1} 13 TeV
- $\sim 40\%$
- $\sim 10^{-7}$(SM) $\sim 10^{-5}$(NP) $\cdot 0.1 \cdot 0.17$

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- $= \varepsilon_{\text{Acc}} \cdot \varepsilon_{\text{Rec}} \cdot \varepsilon_{\text{Meth}} \cdot \varepsilon_{\text{Trig}} \cdot \varepsilon_{\text{Strip}} \cdot \approx 10^{-6} - 10^{-5}$

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- $= \varepsilon_{\text{Acc}} . \varepsilon_{\text{Rec}} . \varepsilon_{\text{Meth}} . \varepsilon_{\text{Trig}} . \varepsilon_{\text{Strip}} . \approx 10^{-6} - 10^{-5}$
- We get $\mathcal{N} \approx$ 2(SM) – 200(NP) events Run II of LHCb