Overview of Flavour Physics

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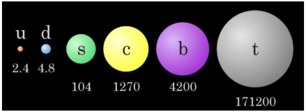
Horizons in Particle Accelerators & Laboratory-based Quantum sensors

Motivation

- Despite its tremendous success, SM can be regarded as a low-energy effective theory of a more fundamental theory
- No direct evidence of NP either in Energy frontier or Intensity frontier
- There are a few open issues, which can not be addressed in the SM
    - Existence of Dark Matter $\Rightarrow$ New weakly interacting particles
    - Non-zero neutrino masses $\Rightarrow$ Right-handed (sterile) neutrinos
    - Observed Baryon Asymmetry of the Universe $\Rightarrow$ Additional CP violating interactions
- It is obvious that SM must be extended.
- So the question is How to go beyond the SM and What is the underlying fundamental theory ?
- Hopefully, Flavour Physics will provide us some light in this direction

Importance of Flavour Physics

- Flavour Physics encompasses many of the open questions of the Standard Model
- Why there are 3-generations of quarks with hierarchical masses



- What determines the hierarchical structure of the CKM matrix

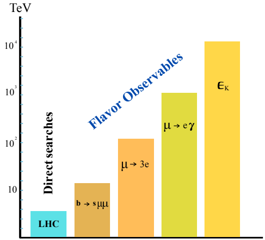
$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1-\frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

- The CKM paradigm explains CP violation but it is really not sufficient to explain the matter-antimatter asymmetry of the Universe.
- Most importantly, Flavour Physics serves as a tool to discover New Physics beyond the SM.

New Physics Prospects with Flavour

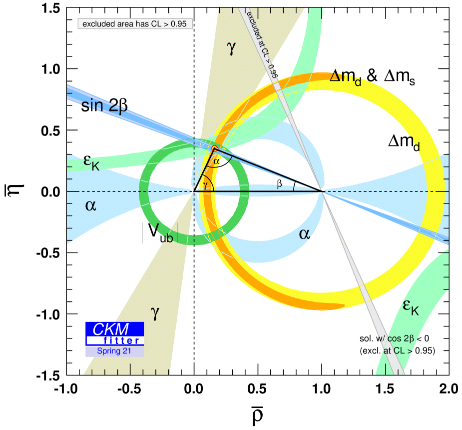
- Searches for NP signature can be performed in two ways
- The first one is through direct production of New Particles at colliders
- The second method exploits the presence of Virtual states in the decays of SM particles
- Flavour observables are quite sensitive to high energy scales through virtual effects.

- Flavour Physics can probe NP at much higher scale than the direct searches at Colliders

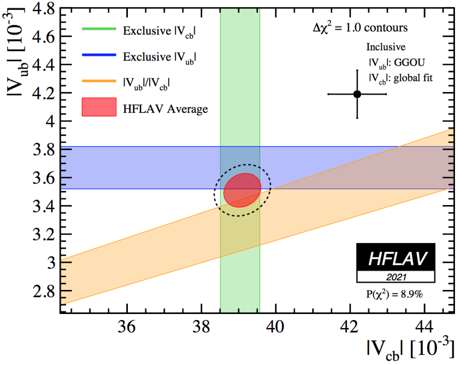


CKM Unitarity Triangle

SM analysis shows very good overall consistency, but still it allows NP $\sim 10\%$

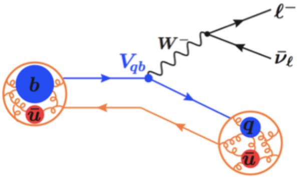


Long-standing Issue Exclusive vs. Inclusive: $|V_{ub}|$ & $|V_{cb}|$



2.8σ discrepancy between Exclusive vs. Inclusive $|V_{cb}|$ and 1.5σ between $|V_{ub}|$

Long-standing Issue Exclusive vs. Inclusive: $|V_{ub}|$ & $|V_{cb}|$



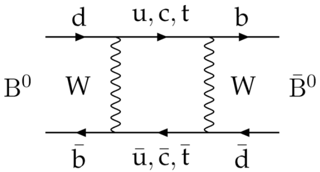
- $|V_{qb}|$ determined from semileptonic B decays:

$$d\Gamma \propto G_F^2 |V_{qb}|^2 |L_\mu \langle X \bar{q} \gamma^\mu P_L b | B \rangle|^2$$

  - $|V_{cb}|$: Exclusive $(D\ell\nu, D^*\ell\nu)$: $(39.09 \pm 0.069) \times 10^{-3}$
    Inclusive $(X_c\ell\nu)$: $(42.16 \pm 0.50).10^{-3}$ $(2.8\ \sigma)$

  - $|V_{ub}|$: Exclusive $(\pi\ell\nu)$: $(3.73 \pm 0.14) \times 10^{-3}$
    Inclusive $(X_u\ell\nu)$: $(4.19 \pm 0.17 \pm 0.18) \times 10^{-3}$ $(1.5\ \sigma)$

Mixing in Neutral Mesons



- Neutral mesons (K, D, B, B_s) are created as flavour eigenstates of strong interaction. They can mix through weak interactions
  - The time evolution is obtained by

$$i\frac{\partial}{\partial t}\begin{pmatrix} P^0(t) \\ \bar{P}^0(t) \end{pmatrix} = \left[\begin{pmatrix} M_{11} & M_{12} \\ M_{12}^* & M_{22} \end{pmatrix} - \frac{i}{2}\begin{pmatrix} \Gamma_{11} & \Gamma_{12} \\ \Gamma_{12}^* & \Gamma_{22} \end{pmatrix}\right]\begin{pmatrix} P^0(t) \\ \bar{P}^0(t) \end{pmatrix}$$

  - The physical eigenstates are P_L and P_H:

$$|P_{L,H}\rangle = p|P^0\rangle \mp q|\bar{P}^0\rangle, \qquad |P_{L,H}(t)\rangle = e^{-i(m_{L,H} - i\Gamma_{L,H}/2)t}|P_{L,H}(t=0)\rangle$$

  - The mass and lifetime differences of P_L and P_H :

$$x = \frac{\Delta m}{\Gamma} = \frac{m_H - m_L}{\Gamma}, \qquad y = \frac{\Delta\Gamma}{2\Gamma} = \frac{\Gamma_H - \Gamma_L}{2\Gamma}, \qquad \text{with} \quad \Gamma = \frac{\Gamma_L + \Gamma_H}{2}$$

CP Violation in Mixing

- This kind of CP violation is the one that was first discovered in the kaon system in the 1960s, and in the B system.
- Let's concentrate on the B system, and consider the final CP state f, which can come from either B^0 and $\bar{B}^0$, such that

$$\Gamma(B^0(t) \to f) = |A_f|^2 e^{-\Gamma t} \left[\frac{1+|\lambda|^2}{2} + \frac{1-|\lambda|^2}{2} \cos \Delta M t - Im(\lambda) \sin \Delta M t \right]$$

$$\Gamma(\overline{B^0}(t) \to f) = |A_f|^2 e^{-\Gamma t} \left[\frac{1+|\lambda|^2}{2} - \frac{1-|\lambda|^2}{2} \cos \Delta M t + Im(\lambda) \sin \Delta M t \right]$$

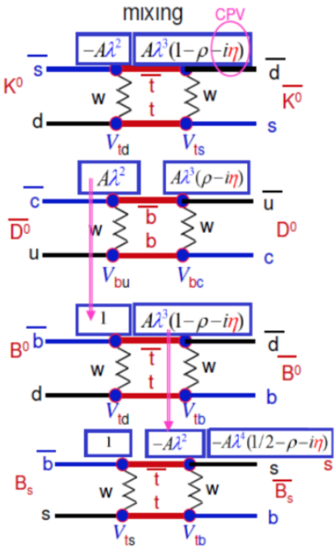
- Thus, one obtains

$$\mathcal{A}_{CP}(t) = \frac{\Gamma(B^0(t) \to f) - \Gamma(\overline{B^0}(t) \to f)}{\Gamma(B^0(t) \to f) + \Gamma(\overline{B^0}(t) \to f)} = A_{CP}^{dir} \cos(\Delta M t) + A_{CP}^{mix} \sin(\Delta M t)$$

where

$$A_{CP}^{dir}(f) = \frac{1-|\lambda|^2}{1+|\lambda|^2}, \quad A_{CP}^{mix}(f) = \frac{-2Im(\lambda)}{1+|\lambda|^2}, \quad \lambda = (q/p)(\bar{A}_f/A_f).$$

CP Violation in mixing



slow mixing, small CPV

CPV discovery

KM hypothesis

super slow mixing, very small CPV

long distance diagrams can come into play

good place to look for non-SM CPV,

but SM "background" not well predicted

large mixing, large CPV

good place to test SM CPV

super fast mixing, small CPV

good place to look for non-SM CPV

Mixing and CPV in Neutral Meson system

- The most general effective Hamiltonians for $\Delta F = 2$ processes (with $q_1 q_2 = sd, uc, bq$ for $M = K, D, B_q$)

$$\mathcal{H}_{\rm eff} = \sum_{i=5}^{5} C_i Q_i^{q_1 q_2} + \sum_{i=1}^{3} \tilde{C}_i \tilde{Q}_i^{q_1 q_2}$$

Q_i are the dim-6 operators having the form (e.g. for $B_d - \bar{B}_d$ system)

$$Q_1 = (\bar{d}_L^\alpha \gamma_\mu b_L^\alpha)(\bar{d}_L^\beta \gamma^\mu b_L^\beta), \quad Q_2 = (\bar{d}_R^\alpha b_L^\alpha)(\bar{d}_R^\beta b_L^\beta), \quad Q_3 = (\bar{d}_R^\alpha b_L^\beta)(\bar{d}_R^\beta b_L^\alpha)$$

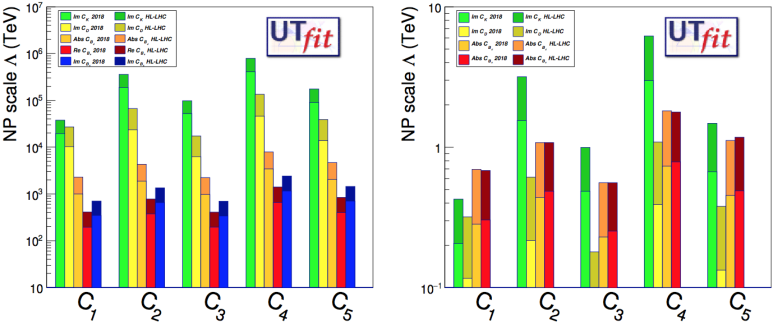
$$Q_4 = (\bar{d}_R^\alpha b_L^\alpha)(\bar{d}_L^\beta b_R^\beta), \quad Q_5 = (\bar{d}_R^\alpha b_L^\beta)(\bar{d}_L^\beta b_R^\alpha), \text{ and } \tilde{Q}_{1,2,3} \xleftrightarrow{L \leftrightarrow R} Q_{1,2,3}$$

- The Wilson coefficients at the NP scale are generally characterised as

$$C_i(\Lambda) = \frac{F_i L_i}{\Lambda^2} ,$$

- For NP contributing to $M - \overline{M}$ mixing at tree level with $\mathcal{O}(1)$ coupling to SM fermions the flavor and loop factors are: $F_i = L_i = 1$
- For NP effects at loop level: $F_i = V_{tq_1} V_{tq_2}^*$ and $L_i = g_2^2$, g_2 is the weak coupling strength

Present and Future (HL-LHC) constraints on NP scale

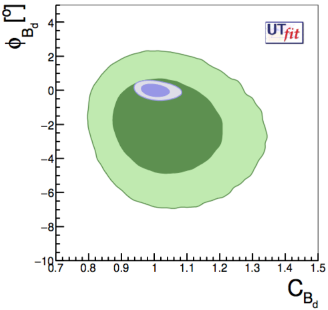


Present (lighter) and future (darker) constraints on NP scale from $\Delta F = 2$ processes. Left panel for NP coupling at tree level, while Right panel for NP coupling at 1-loop level

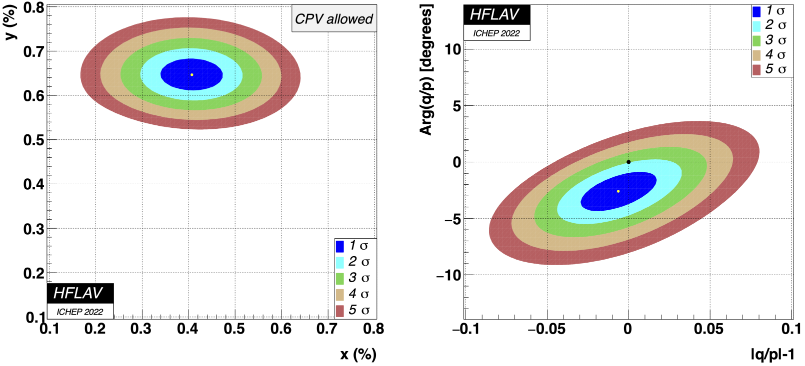
- The contribution of NP to $\Delta F = 2$ transition can be parameterized in a model independent way as

$$C_{B_q} e^{i\phi_{B_q}} = \frac{\langle B_q | \mathcal{H}^{\rm SM+NP} | \bar{B}_q \rangle}{\langle B_q | \mathcal{H}^{\rm SM} | \bar{B}_q \rangle}$$

- SM point corresponds to $C_{B_q} = 1$ and $\phi_{B_q} = 0$. Present (green) and future (blue) constraints on NP contributions to $B_q - \bar{B}_q$ mixing



Mixing in Charmed Meson



Mixing in Charm meson is firmly established

CP violation in charm decays

- CP Violation in charm decays has been found almost 20 years after it has been found in B decays.
- CP violation stems mainly from interference of tree and penguin diagrams
- Size of penguin diagrams in B decays is determined mainly by $m_t/m_W > 1$, while in charm decays the size of penguin operator is determined by $m_b/m_W \ll 1$
- Also in charm decays, GIM mechanism is extremely effective, and hence, penguin operators are not relevant in charm decays.
- Direct CP violation charm decays has been first discovered in the combination of CP asymmetries by LHCb (1903.08726):

$$\Delta a_{CP}^{\mathrm{dir}} = a_{CP}^{\mathrm{dir}}(D^0 \to K^+K^-) - a_{CP}^{\mathrm{dir}}(D^0 \to \pi^+\pi^-) = (-0.161 \pm 0.028)\%.$$

Direct CP violation in charm decays

- Direct CP asymmetries in $D \to h^- h^+$ process

$$A_{CP}(D^0 \to h^- h^+) = \frac{\Gamma(D^0 \to h^- h^+) - \Gamma(\overline{D}^0 \to h^- h^+)}{\Gamma(D^0 \to h^- h^+) + \Gamma(\overline{D}^0 \to h^- h^+)}$$

- A prominent test of direct CPV in charm is the observable,

$$\Delta A_{CP} = A_{CP}(K^- K^+) - A_{CP}(\pi^- \pi^+)$$

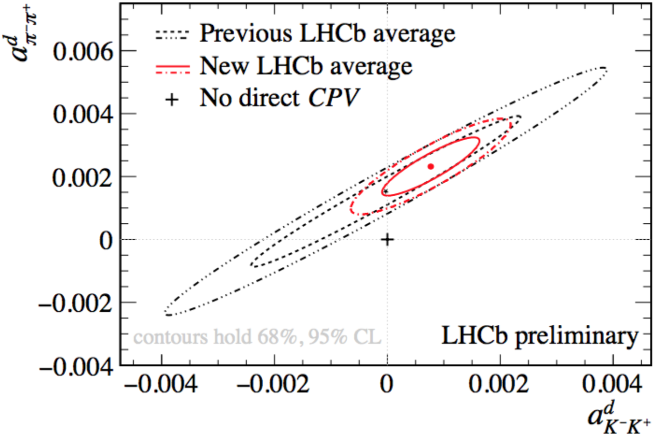
- Direct CPV in $D \to K^- K^+$ has recently measured by LHCb with 5.7 fb^{-1} data set

$$a_{CP}^{\mathrm{dir}}(D^0 \to K^+ K^-) = (7.7 \pm 5.7) \times 10^{-4}$$

- Combination of the measurement of CPV in KK mode with the difference between KK and $\pi\pi$ leads to the first evidence of CPV in $\pi\pi$ mode (3.8σ)

$$a_{CP}^{\mathrm{dir}}(D^0 \to \pi^+ \pi^-) = (23.2 \pm 6.1) \times 10^{-4}$$

Direct CP violation in charm decays



Lepton Flavour Universality a key ingredient of SM

- In the SM, the couplings of the gauge bosons to leptons are independent of the lepton flavour
- Equal couplings of the W and Z bosons to electrons, muons and taus
- Yukawa sector breaks the universality in two ways $\mathcal{L}_{SM} \supset Y^E_{ij} \overline{L}^i_L E^j_R H + \mathrm{h.c}$
  In the mass terms $m_e \neq m_\mu \neq m_\tau$ and in Higgs interactions (negligible for flavour physics)
- LFU is enforced in the SM by construction and any violation of it would be a clear sign of physics beyond the SM.
- Over the years, LFU violation has been searched in several other system $(Z \to \ell\ell,\ \ W \to \ell\nu,\ \ J/\psi \to \ell\ell,\ \pi \to \ell\nu,\ K \to (\pi)\ell\nu,\ \cdots)$
- These measurements provide very strong limit on lepton non-universality in the EW sector.

Quick Recap of Recent Anomalies in B-sector

- However, in last few years there are several measurements, which do not agree with the SM predictions.
- These deviations are not statistically significant enough to claim the discovery of NP. At the same time, they are not weak enough to be completely ignored.
- They may be considered as smoking-gun signals of possible NP.
- Some of these are:
  - $R_{D^{(*)}}$ Anomaly ($b \to c\ell\nu$): NP in charged currents
  - $R_{K^{(*)}}$ Anomaly (Hint for Lepton Flavour Non-Universality)
  - Deviations in $b \to s\mu\mu$: P_5', BR($B \to K^{(*)}\mu\mu$), $B_s \to \phi\mu\mu$ (NP in FCNC transitions)
- These anomalies may guide us how to probe or go beyond the SM

Recent anomalies in the B sector

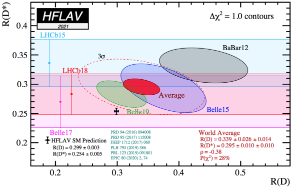
1. $R_{D^{(*)}}$

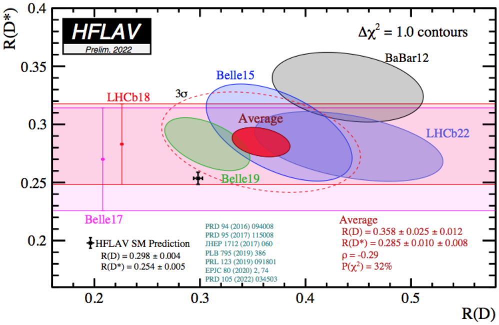
$$R_{D^{(*)}} = \frac{\mathrm{Br}\left(\bar{B} \to D^{(*)}\tau\bar{\nu}_\tau\right)}{\mathrm{Br}\left(\bar{B} \to D^{(*)}\ell\bar{\nu}_\ell\right)}, \qquad R_{D^{(*)}}^{\mathrm{Expt}} > R_{D^{(*)}}^{\mathrm{SM}}$$

$$R_D^{\mathrm{WA}} = 0.339 \pm 0.026 \pm 0.014\,, \qquad R_{D^*}^{\mathrm{Expt}} = 0.295 \pm 0.010 \pm 0.010$$

$$R_D^{\mathrm{SM}} = 0.299 \pm 0.003\,, \qquad R_{D^*}^{\mathrm{SM}} = 0.258 \pm 0.005\,.$$

R_D and R_{D^*} exceed SM predictions by 1.4σ and 2.8σ respectively. Considering $R_D - R_{D^*}$ correlation of -0.38, the resulting discrepancy is 3.3σ between Expt and SM results.

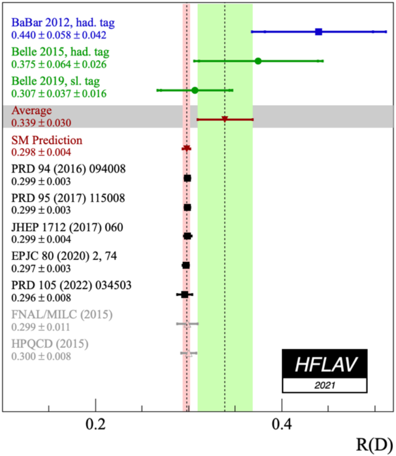


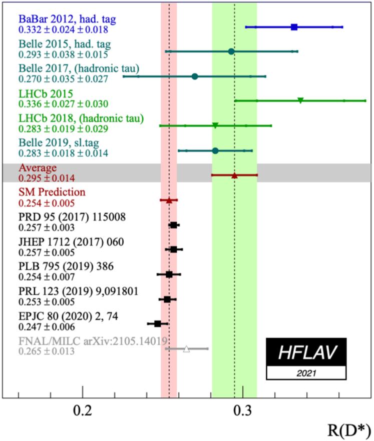


$R_D = 0.441 \pm 0.060 \pm 0.066, \quad R_{D^*} = 0.281 \pm 0.018 \pm 0.024, \quad \rho = -0.43$

New measurement gives 3.2σ discrepancy with SM. Overall agreement between measurements

Summary of R_D & R_{D^*} from various Measurements





- About 3σ deviation from SM prediction, seen in 3 different expts with different tagging methods (hadronic and semileptonic).
- Measurements are consistent with e/μ universality $R_D^{\mathrm{Exp}} = 0.995(45)$, $R_{D^*}^{\mathrm{Expt}} = 1.04(5)$
- In addition Belle also has measured

$$P_\tau^{D^*}|^{\mathrm{Expt}} = -0.38 \pm 0.51^{+0.21}_{-0.16}, \quad (\mathrm{SM}: -0.497 \pm 0.01)$$
$$F_L^{D^*}|^{\mathrm{Expt}} = 0.60 \pm 0.08 \pm 0.04, \quad (\mathrm{SM}: 0.46 \pm 0.04) \quad (1.6\sigma \text{ discrepancy})$$

- LHCb result on $R_{J/\psi}$

$$R_{J/\psi} = \frac{BR(B_c \to J/\psi\tau\nu)}{BR(B_c \to J/\psi\mu\nu)} = 0.71 \pm 0.17 \pm 0.18$$

has about 2σ deviation from its SM value $R_{J/\psi} = 0.283 \pm 0.048$.

- 10% enhancement of the tau SM amplitude $\Rightarrow$ LUV in $b \to c\tau\nu$ as

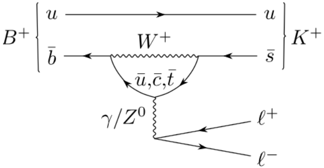
$$\Lambda \simeq 3 \text{ TeV (Tree level NP)} \qquad \frac{V_{cb}}{v^2} \text{ vs. } \frac{1}{\Lambda^2}$$

2 $R_{K^{(*)}}$

- Sizable discrepancies ($> 2\sigma$) reported by the LHCb and Belle Collaborations in the ratio $R_{K^{(*)}}$ (FCNC transitions, loop and CKM suppressed in SM)

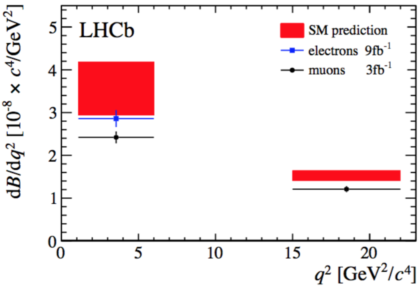
$$R_{K^{(*)}} = \frac{\mathrm{Br}(B \to K^{(*)}\mu\mu)}{\mathrm{Br}(B \to K^{(*)}ee)}, \qquad R_{K^{(*)}}^{\mathrm{Expt}} < R_{K^{(*)}}^{\mathrm{SM}}$$

LNU observable	SM prediction	Expt. value	Deviation
$R_{K^+}\vert_{q^2\in[1.1,6.0]}$	1.0003 ± 0.0001	$0.846^{+0.044}_{-0.041}$ (LHCb)	3.1σ
$R_{K_S}\vert_{q^2\in[1.1,6.0]}$		$0.66^{+0.20+0.02}_{-0.14-0.04}$ (LHCb)	2σ
$R_{K^*}\vert_{q^2\in[0.045,1.1]}$	0.92 ± 0.02	$0.660^{+0.110}_{-0.070} \pm 0.024$ (LHCb)	2.2σ
$R_{K^{*0}}\vert_{q^2\in[1.1,6.0]}$	1.00 ± 0.01	$0.685^{+0.113}_{-0.007} \pm 0.047$ (LHCb)	2.4σ
$R_{K^{*+}}\vert_{q^2\in[1.1,6.0]}$		$0.70^{+0.18+0.03}_{-0.13-0.04}$ (LHCb)	2σ



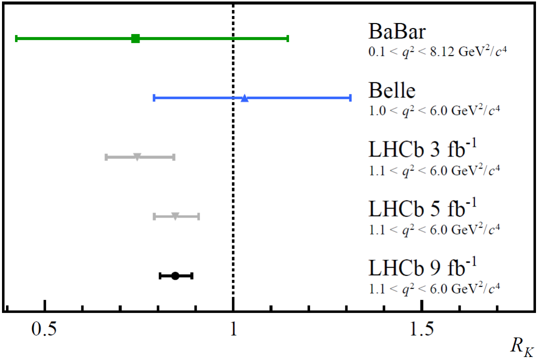
Branching Ratios

- The differential Branching fraction (JHEP 06, 135 (2014))
$$\frac{d\mathrm{Br}}{dq^2}(B^\pm \to K^\pm e^+ e^-) = \left(28.6^{+1.5}_{-1.4} \pm 1.3\right) \times 10^{-9}\ \mathrm{GeV}^{-2}$$
in $(1.1 < q^2 < 6.0\mathrm{GeV}^2)$.
- Branching fraction of the electron mode is consistent with the SM prediction



Summary of R_K measurement

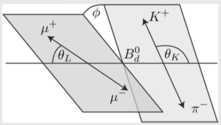
- $R_K = 0.846^{+0.044}_{-0.041}$ which shows 3.1σ deviation from SM (LHCb Collab. 2103.11769)



Dynamics for $B^0 \to K^{*0}\mu^+\mu^-$

The decay distribution of $B^0 \to K^{*0}(\to K\pi)\ell\ell$ described by 3 angles $(\theta_l, \theta_K, \phi)$ and q^2

$$\frac{1}{d(\Gamma+\bar{\Gamma})/dq^2}\frac{d^4(\Gamma+\bar{\Gamma})}{dq^2 d\vec{\Omega}} = \frac{9}{32\pi}\Big[\frac{3}{4}(1-F_L)\sin^2\theta_K + F_L\cos^2\theta_K$$
$$+\frac{1}{4}(1-F_L)\sin^2\theta_K\cos 2\theta_l - F_L\cos^2\theta_K\cos 2\theta_l$$
$$+ S_3\sin^2\theta_K\sin^2\theta_l\cos 2\phi + S_4\sin 2\theta_K\sin 2\theta_l\cos\phi$$
$$+ S_5\sin 2\theta_K\sin\theta_l\cos\phi + \frac{4}{3}A_{FB}\sin^2\theta_K\cos\theta_l$$
$$+ S_7\sin 2\theta_K\sin\theta_l\sin\phi + S_8\sin 2\theta_K\sin 2\theta_l\sin\phi$$
$$+ S_9\sin^2\theta_K\sin^2\theta_l\sin 2\phi\Big]$$

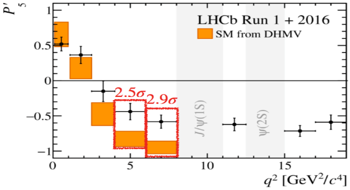


$\vec{\Omega} =$ $(\cos\theta_l, \cos\theta_k, \phi)$

$$P'_{4,5,8} = \frac{S_{4,5,8}}{\sqrt{F_L(1-F_L)}}, \qquad P'_6 = \frac{S_7}{\sqrt{F_L(1-F_L)}}$$

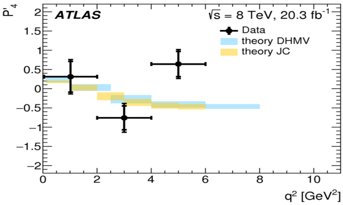
FFI observables in $B \to K^* \ell\ell$

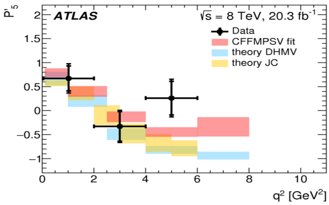
3. $P'_{4,5}$



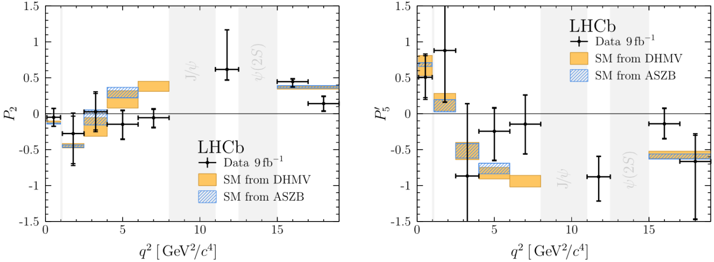
LHCb: PRL **125**, 011802 (2020)

ATLAS Resuls show $\sim 2.7\sigma$ deviation





FFI Observables in $B^{*+} \to K^{*+}\mu^+\mu^-$

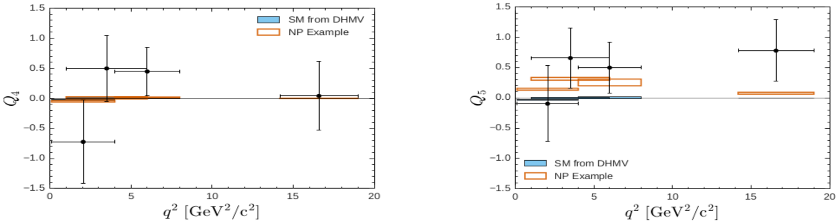


P_2 in [6-8] GeV^2 bin shows 3.0σ deviation from its SM value, whereas P_5' broadly agrees with the deviation observed in $B^0 \to K^{*0}\mu^+\mu^-$.

LHCb: PRL 126, 161802 (2021)

4 $Q_{4,5}$

- $Q_i = P_i'^{\mu} - P_i'^{e}$ Belle: PRL **118**, 111801 (2017)



- Considering 20% deficit in SM muon channel $\Rightarrow$ LUV in $b \to s\ell\ell$

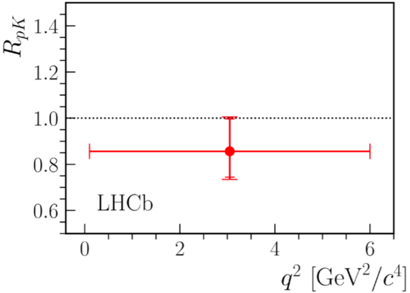
$$\Lambda \simeq 30 \text{ TeV (Tree level NP)} \qquad \frac{V_{ts}}{(4\pi)^2 v^2} \text{ vs. } \frac{1}{\Lambda^2}$$

$$\Lambda \simeq 3 \text{ TeV (One -- loop NP)} \qquad \frac{V_{ts}}{(4\pi)^2 v^2} \text{ vs. } \frac{1}{(4\pi)^2 \Lambda^2}$$

R_{pK} : $\Lambda_b \to \Lambda(1520)\ell^+\ell^-$

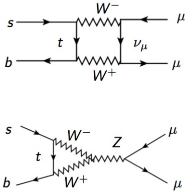
$$R_{pK}^{-1} = \frac{\mathcal{B}(\Lambda_b^0 \to pK^- e^+e^-)}{\mathcal{B}(\Lambda_b^0 \to pK^- J/\psi(\to e^+e^-))} \Bigg/ \frac{\mathcal{B}(\Lambda_b^0 \to pK^- \mu^+\mu^-)}{\mathcal{B}(\Lambda_b^0 \to pK^- J/\psi(\to \mu^+\mu^-))}$$

$R_{pK} = 0.86^{+0.14}_{-0.11} \pm 0.05$ Consistent with SM JHEP 40 (2020)



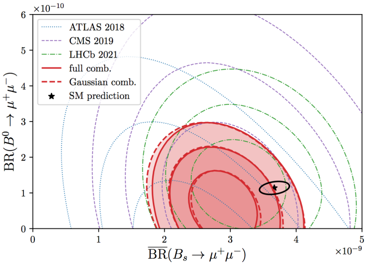
$B_s \to \mu^+\mu^-$ (2103.13370)

The rare decay $B_s \to \mu^+\mu^-$ is mediated through quark level transition $b \to s\mu\mu$ and highly suppressed in the SM (loop suppressed, CKM suppressed, helicity suppressed and theoretically very clean)



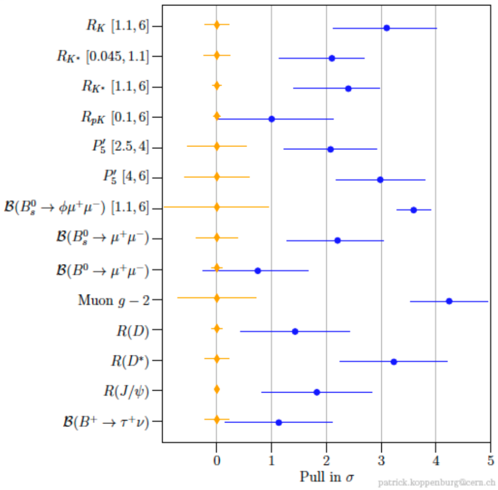
$$\mathrm{Br}(B_s \to \mu\mu) = (2.93 \pm 0.35) \times 10^{-9}$$
$$\mathrm{Br}(B_d \to \mu\mu) = (0.56 \pm 0.70) \times 10^{-10},$$

$$\mathrm{Br}(B_s \to \mu\mu)|_{SM} = (3.67 \pm 0.15) \times 10^{-9}$$
$$\mathrm{Br}(B_d \to \mu\mu)|_{SM} = (1.14 \pm 0.12) \times 10^{-10}$$



2.3σ discrepancy with SM

List of Anomalies in Flavour sector



Summary of Observed Anomalies in B decays

Decay Processes	$b \to c \ell \bar{\nu}_\ell$	$b \to s \ell^+ \ell^-$
Observables	$R_D, R_{D^*}, R_{J/\psi}, F_L^{D^*}, P_\tau^{D^*}$	$R_K, R_{K^*}, P_5', \mathcal{B}$
SM	Tree level CKM favored	One-loop (FCNC process) GIM suppressed
LFU violation	τ vs. e/μ	μ vs. e
Caveats	τ reconstruction difficult	e reconstruction difficult at LHCb
Advantages	Well-understood theory	Solid theory for $R_{K^{(*)}}$, Some caveats for P_5' and $\mathcal{B}$

- Lots of reasons to be excited !

  Two different sets of anomalies of very different taste
- All combined, the most compelling hints for physics BSM seen so far.

How to address the Anomalies in b sector

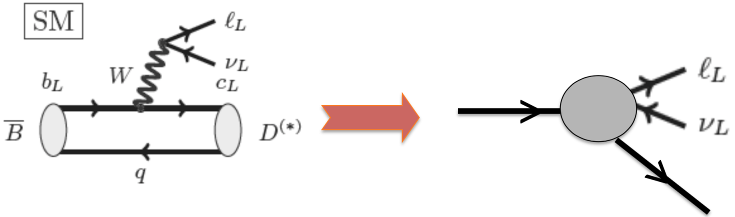
- As seen, the NP scales are quite different for the CC $b \to c\ell\nu$ and NC $b \to s\ell\ell$ transitions if the effect of NP is considered at tree level for both the processes. So tree level contribution with single mediator like W' for $b \to c$ and Z' for $b \to s$ will not work.
- However, if NP contributions arise at tree level for CC and at loop-level for NC, then the scale could be same for both processes
- First step: To construct effective Lagrangian which might explain experimental data
- Next, to find the new particles which can mimic effective Lagrangian
- Need to check all other low energy flavour constraints, electroweak observables, including direct searches for NP at LHC
- Construct the consistent model for NP of your choice !

Effective Field Theory Approach for $b \to c\tau^-\bar{\nu}_\tau$

- Most of the EFT analyses assume that NP is present mainly in $b \to c\tau^-\bar{\nu}_\tau$ transitions
- As there are no signs of LU violation, for electron and muon in $b \to c\ell\bar{\nu}_\ell$ decays

$$R_D^{\mu/e} = \frac{Br(B \to D\mu\nu)}{Br(B \to De\nu)} = 0.995(45)$$

$$R_{D*}^{\mu/e} = \frac{Br(B \to D^*\mu\nu)}{Br(B \to D^*e\nu)} = 1.04(5)$$



EFT for $b \to c\tau^-\bar{\nu}_\tau$

NP contributions to $b \to c\tau\nu$ (over complete set of operators)(1506.08896)

$$\mathcal{H} = \frac{4G_F}{\sqrt{2}} V_{cb}\mathcal{O}_{V_L} + \frac{1}{\Lambda^2}\sum_i C_i^{(\prime,\prime\prime)}\mathcal{O}_i^{(\prime,\prime\prime)}$$

	Operator	Fierz identity	Allowed Current	$\delta\mathcal{L}_{\rm int}$
$\mathcal{O}_{V_L}$	$(\bar{c}\gamma_\mu P_L b)(\bar{\tau}\gamma^\mu P_L \nu)$		$(\mathbf{1},\mathbf{3})_0$	$(g_q \bar{q}_L \boldsymbol{\tau}\gamma^\mu q_L + g_\ell \bar{\ell}_L \boldsymbol{\tau}\gamma^\mu \ell_L)W'_\mu$
$\mathcal{O}_{V_R}$	$(\bar{c}\gamma_\mu P_R b)(\bar{\tau}\gamma^\mu P_L \nu)$			
$\mathcal{O}_{S_R}$	$(\bar{c}P_R b)(\bar{\tau}P_L \nu)$		$\rangle(\mathbf{1},\mathbf{2})_{1/2}$	$(\lambda_d \bar{q}_L d_R \phi + \lambda_u \bar{q}_L u_R i\tau_2 \phi^\dagger + \lambda_\ell \bar{\ell}_L e_R \phi)$
$\mathcal{O}_{S_L}$	$(\bar{c}P_L b)(\bar{\tau}P_L \nu)$			
$\mathcal{O}_T$	$(\bar{c}\sigma^{\mu\nu} P_L b)(\bar{\tau}\sigma_{\mu\nu} P_L \nu)$			
$\mathcal{O}'_{V_L}$	$(\bar{\tau}\gamma_\mu P_L b)(\bar{c}\gamma^\mu P_L \nu)$	$\longleftrightarrow \quad \mathcal{O}_{V_L}\langle$	$(\mathbf{3},\mathbf{3})_{2/3}$	$\lambda\, \bar{q}_L \boldsymbol{\tau}\gamma_\mu \ell_L \boldsymbol{U}^\mu$
$\mathcal{O}'_{V_R}$	$(\bar{\tau}\gamma_\mu P_R b)(\bar{c}\gamma^\mu P_L \nu)$	$\longleftrightarrow \quad -2\mathcal{O}_{S_R}$	$\rangle(\mathbf{3},\mathbf{1})_{2/3}$	$(\lambda\, \bar{q}_L \gamma_\mu \ell_L + \tilde{\lambda}\, \bar{d}_R \gamma_\mu e_R)U^\mu$
$\mathcal{O}'_{S_R}$	$(\bar{\tau}P_R b)(\bar{c}P_L \nu)$	$\longleftrightarrow \quad -\frac{1}{2}\mathcal{O}_{V_R}$		
$\mathcal{O}'_{S_L}$	$(\bar{\tau}P_L b)(\bar{c}P_L \nu)$	$\longleftrightarrow \quad -\frac{1}{2}\mathcal{O}_{S_L} - \frac{1}{8}\mathcal{O}_T$	$(\mathbf{3},\mathbf{2})_{7/6}$	$(\lambda\, \bar{u}_R \ell_L + \tilde{\lambda}\, \bar{q}_L i\tau_2 e_R)R$
$\mathcal{O}'_T$	$(\bar{\tau}\sigma^{\mu\nu} P_L b)(\bar{c}\sigma_{\mu\nu} P_L \nu)$	$\longleftrightarrow \quad -6\mathcal{O}_{S_L} + \frac{1}{2}\mathcal{O}_T$		
$\mathcal{O}''_{V_L}$	$(\bar{\tau}\gamma_\mu P_L c^c)(\bar{b}^c\gamma^\mu P_L \nu)$	$\longleftrightarrow \quad -\mathcal{O}_{V_R}$		
$\mathcal{O}''_{V_R}$	$(\bar{\tau}\gamma_\mu P_R c^c)(\bar{b}^c\gamma^\mu P_L \nu)$	$\longleftrightarrow \quad -2\mathcal{O}_{S_R}$	$(\bar{\mathbf{3}},\mathbf{2})_{5/3}$	$(\lambda\, \bar{d}_R^c \gamma_\mu \ell_L + \tilde{\lambda}\, \bar{q}_L^c \gamma_\mu e_R)V^\mu$
$\mathcal{O}''_{S_R}$	$(\bar{\tau}P_R c^c)(\bar{b}^c P_L \nu)$	$\longleftrightarrow \quad \frac{1}{2}\mathcal{O}_{V_L}\langle$	$(\bar{\mathbf{3}},\mathbf{3})_{1/3}$	$\lambda\, \bar{q}_L^c i\tau_2 \boldsymbol{\tau}\ell_L \boldsymbol{S}$
$\mathcal{O}''_{S_L}$	$(\bar{\tau}P_L c^c)(\bar{b}^c P_L \nu)$	$\longleftrightarrow \quad -\frac{1}{2}\mathcal{O}_{S_L} + \frac{1}{8}\mathcal{O}_T$	$\rangle(\bar{\mathbf{3}},\mathbf{1})_{1/3}$	$(\lambda\, \bar{q}_L^c i\tau_2 \ell_L + \tilde{\lambda}\, \bar{u}_R^c e_R)S$
$\mathcal{O}''_T$	$(\bar{\tau}\sigma^{\mu\nu} P_L c^c)(\bar{b}^c\sigma_{\mu\nu} P_L \nu)$	$\longleftrightarrow \quad -6\mathcal{O}_{S_L} - \frac{1}{2}\mathcal{O}_T$		

Global Fit to NP Couplings

- Global fits are performed by various groups including the measurements on R_D, R_{D^*}, q^2 deferential distribution, $F_L^{D^*}$, $\mathcal{B}(B_c \to \tau\nu)$.
  1903.10486,1910.09269, 2002.05726, 2002.07272, 2004.10208 $\cdots$
  In addition to global minima there are are also local minima.

	Min 1b	Min 2b	Min 1b	Min 2b
$\mathcal{B}(B_c \to \tau\nu)$	10%		30%	
$\chi^2_{\rm min}/\text{d.o.f.}$	37.6/54	42.1/54	37.6 /54	42.0/54
C_{V_L}	$0.14^{+0.14}_{-0.12}$	$0.41^{+0.05}_{-0.05}$	$0.14^{+0.14}_{-0.14}$	$0.40^{+0.06}_{-0.07}$
C_{S_R}	$0.09^{+0.14}_{-0.52}$	$-1.15^{+0.18}_{-0.09}$	$0.09^{+0.33}_{-0.56}$	$-1.34^{+0.57}_{-0.08}$
C_{S_L}	$-0.09^{+0.52}_{-0.11}$	$-0.34^{+0.13}_{-0.19}$	$-0.09^{+0.68}_{-0.21}$	$-0.18^{+0.13}_{-0.57}$
C_T	$0.02^{+0.05}_{-0.05}$	$0.12^{+0.04}_{-0.04}$	$0.02^{+0.05}_{-0.05}$	$0.11^{+0.03}_{-0.04}$

1904.09311

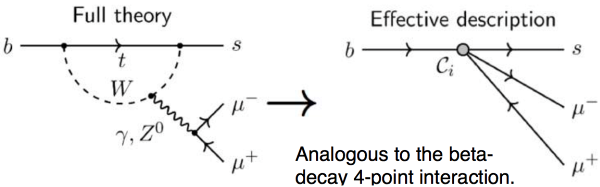
Bottom line

- $\mathcal{O}_{V_L}$ has the same Lorentz structure as SM hence R_D and R_{D^*} proportional to $(1+C_{V_L})^2$: Preferred scenario
- $\mathcal{O}_{V_R}$: $R_D \propto (1+C_{V_R})^2$ whereas $R_{D^*} \propto (1-C_{V_R})^2$, hence not possible to find a common solution to both R_D and R_{D^*}.
- $\mathcal{O}_{S_L}$ and $\mathcal{O}_{S_R}$ predict large branching ratio for $B_c \to \tau\nu$, hence constrained by B_c lifetime.
- Large value of tensor operator predicts small $F_L^{D^*}$ but provides a decent description to data. However, such operators not easily generated by NP theories at EW scale. In some cases they appear due to RG evolution from EW scale to b quark scale, with strong correlation with scalar opeartors

Effective Field Theory Approach for $b \to s\ell\ell$

- Compared to $b \to c\ell\nu_\ell$, $b \to s\ell\ell$ transitions are richer due to large no of observables
- The effective Hamiltonian describing $b \to s\ell^+\ell^-$ process

$$\mathcal{H}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \left[\sum_{i=1}^{6} C_i(\mu)\mathcal{O}_i + \sum_{i=7,9,10,S,P} \left(C_i(\mu)\mathcal{O}_i + C_i'(\mu)\mathcal{O}_i' \right) \right].$$



Analogous to the beta-decay 4-point interaction.

Grobal-fit Results (1D)

- Good fits obtained along the direction $C_{9\mu}^{\rm NP} = -C_{10\mu}^{\rm NP}$, arises naturally in models obeying $SU(2)_L$ invariance

	All				LFUV			
1D Hyp.	Best fit	$1\,\sigma/2\,\sigma$	$\mathrm{Pull}_{\rm SM}$	p-value	Best fit	$1\,\sigma/\ 2\,\sigma$	$\mathrm{Pull}_{\rm SM}$	p-value
$\mathcal{C}_{9\mu}^{\rm NP}$	-1.06	$[-1.20,-0.91]$ $[-1.34,-0.76]$	7.0	39.5 %	-0.82	$[-1.06,-0.60]$ $[-1.32,-0.39]$	4.0	36.0 %
$\mathcal{C}_{9\mu}^{\rm NP} = -\mathcal{C}_{10\mu}^{\rm NP}$	-0.44	$[-0.52,-0.37]$ $[-0.60,-0.29]$	6.2	22.8 %	-0.37	$[-0.46,-0.29]$ $[-0.55,-0.21]$	4.6	68.0 %
$\mathcal{C}_{9\mu}^{\rm NP} = -\mathcal{C}_{9'\mu}$	-1.11	$[-1.25,-0.96]$ $[-1.39,-0.80]$	6.5	28.0 %	-1.61	$[-2.13,-0.96]$ $[-2.54,-0.41]$	3.0	9.3 %
$\mathcal{C}_{9\mu}^{\rm NP} = -3\mathcal{C}_{9e}^{\rm NP}$	-0.89	$[-1.03,-0.75]$ $[-1.17,-0.62]$	6.7	32.2 %	-0.61	$[-0.78,-0.44]$ $[-0.97,-0.29]$	4.0	36.0 %

Best fit values for new WCs: 2104.08921

Grobal-fit Results: 2D & 6D

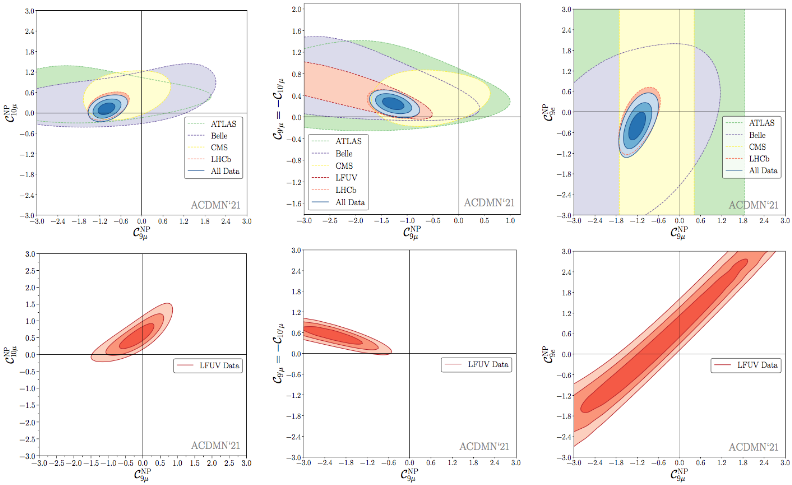
	All			LFUV		
2D Hyp.	Best fit	$\mathrm{Pull}_{\mathrm{SM}}$	p-value	Best fit	$\mathrm{Pull}_{\mathrm{SM}}$	p-value
$(\mathcal{C}_{9\mu}^{\mathrm{NP}}, \mathcal{C}_{10\mu}^{\mathrm{NP}})$	$(-1.00, +0.11)$	6.8	39.4 %	$(-0.12, +0.54)$	4.3	65.6 %
$(\mathcal{C}_{9\mu}^{\mathrm{NP}}, \mathcal{C}_{7'})$	$(-1.06, +0.00)$	6.7	37.8 %	$(-0.82, -0.03)$	3.7	32.6 %
$(\mathcal{C}_{9\mu}^{\mathrm{NP}}, \mathcal{C}_{9'\mu})$	$(-1.22, +0.56)$	7.2	49.8 %	$(-1.80, +1.12)$	4.1	53.6 %
$(\mathcal{C}_{9\mu}^{\mathrm{NP}}, \mathcal{C}_{10'\mu})$	$(-1.26, -0.35)$	7.4	55.9 %	$(-1.82, -0.59)$	4.7	84.1 %
$(\mathcal{C}_{9\mu}^{\mathrm{NP}}, \mathcal{C}_{9e}^{\mathrm{NP}})$	$(-1.20, -0.41)$	6.9	41.7 %	$(-0.73, +0.08)$	3.6	30.3 %

	$\mathcal{C}_7^{\mathrm{NP}}$	$\mathcal{C}_{9\mu}^{\mathrm{NP}}$	$\mathcal{C}_{10\mu}^{\mathrm{NP}}$	$\mathcal{C}_{7'}$	$\mathcal{C}_{9'\mu}$	$\mathcal{C}_{10'\mu}$
Best fit	+0.01	-1.21	+0.15	+0.01	+0.37	-0.21
1 σ	$[-0.02, +0.04]$	$[-1.38, -1.01]$	$[+0.00, +0.34]$	$[-0.02, +0.03]$	$[-0.12, +0.80]$	$[-0.42, +0.02]$
2 σ	$[-0.04, +0.06]$	$[-1.52, -0.83]$	$[-0.11, +0.49]$	$[-0.03, +0.05]$	$[-0.51, +1.12]$	$[-0.60, 0.23]$

Pull 6.6 σ

Best fit values for new WCs: 2104.08921

Grobal-fit Results: 2D

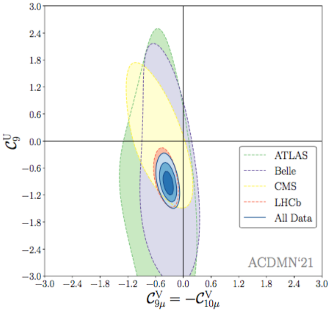


New Physics Contribution to both μ and e channels

- In addition to LFUV NP contribution to C_9^μ, one can also have LFU NP contributions:

$$C_i^e = C_i^U \qquad C_{i\mu} = C_i^U + C_i^V \qquad (i = 9^{(\prime)}, 10^{(\prime)})$$

$\mathcal{C}^{\rm V}_{9\mu} = -\mathcal{C}^{\rm V}_{10\mu}$ $\mathcal{C}^{\rm U}_{9}$	-0.30 -0.92	$[-0.39, -0.21]$ $[-1.10, -0.72]$	$[-0.47, -0.13]$ $[-1.27, -0.51]$	7.3	53.8 %



Specific NP models for $b \to s\mu\mu$ and $b \to c\tau\nu$

1. $b \to s\mu\mu$
   - Loop level:
     - Z' + vector-like quarks
     - Leptoquarks
     - 2HDM
   - Tree-level mediators:
     - Charged and colored: Scalar or vector Leptoquarks
     - Neutral vectors: Z': Interesting phenomenological implications
2. $b \to c\tau\nu$
   - Charged Scalars, Charged Gauge Boson (W')
   - Colored Bosons (Leptoquarks) $\Rightarrow$ Upon Fierz transformation can provide Scalar/Vector/Tensor operators

Leptoquarks

- Leptoquarks are color triplet bosons that couple to quarks and leptons:

LQ	SM rep	Spin	F=3B+S	Proton decay	$R_{K^{(*)}}$	$R_{D^{(*)}}$
S_1	$(\bar{3}, 1, +1/3)$	0	-2	Yes	Yes	Yes
$\overline{S}_1$	$(\bar{3}, 1, -2/3)$	0	-2	Yes	No	No
$\tilde{S}_1$	$(\bar{3}, 1, +4/3)$	0	-2	Yes	No	No
S_3	$(\bar{3}, 3, +1/3)$	0	-2	Yes	Yes	No
R_2	$(3, 2, +7/6)$	0	0	No	Yes	Yes
$\tilde{R}_2$	$(3, 2, +1/6)$	0	0	No	No	No
U_1	$(3, 1, +2/3)$	1	0	No	Yes	Yes
$\overline{U}_1$	$(3, 1, -1/3)$	1	0	No	No	No
$\tilde{U}_1$	$(3, 1, +5/3)$	1	0	No	No	No
U_3	$(3, 3, +2/3)$	1	0	No	Yes	No
V_2	$(\bar{3}, 2, +5/6)$	1	-2	Yes	Yes	No
$\tilde{V}_2$	$(\bar{3}, 2, -1/6)$	1	-2	Yes	Yes	No

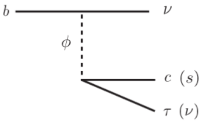
Single Scalar Leptoquark $S_1(3,1,-1/3) \equiv \phi$: 1511.01900

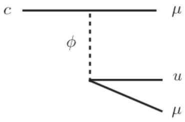
- Leptoquark can couple to $(L_L Q_L)$ and $e_R u_R$
- An additional discrete symmetry has to be imposed (with L_L and ϕ have opposite parity) to avoid proton decay
- The interaction Lagrangian

$$\begin{aligned}\mathcal{L} \supset\ & \bar{Q}^c \lambda^L i\tau_2 L \phi^* + \bar{u}_R^c \lambda^R e_R \phi^* + \text{H.c.} \qquad \text{(weak basis)} \\ =\ & \bar{u}_L^c \lambda^L_{\mu e} e_L \phi^* - \bar{d}_L^c \lambda^L_{d\nu} \nu_L \phi^* + \bar{u}_R^c \lambda^R_{\mu e} e_R \phi^* + \text{H.c.} \qquad \text{(mass basis)}\end{aligned}$$

- ϕ mediates semileptonic B-meson decays at tree level

$$\mathcal{L}_{\text{eff}} = \frac{1}{2M_\phi^2}\left[-\lambda^{L*}_{u_i l_j}\lambda^L_{b\nu_k}\bar{u}^i_L\gamma^\mu b_L \bar{\ell}^j_L \gamma^\mu \nu_k + \lambda^{R*}_{u_i l_j}\lambda^L_{b\nu_k}\left(\bar{u}^i_R b_L \bar{\ell}^j_R \nu_k - \text{Tensor term}\right)\right]$$





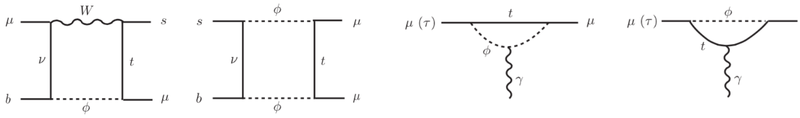
- For a TeV scale LQ, the fit to expt. data on $R_{D^{(*)}}$ gives

$$\lambda^{L*}_{c\tau}\lambda^{L}_{b\nu_\tau} \approx 0.35\left(\frac{M_\phi}{1\ \mathrm{TeV}}\right)^2 , \qquad \lambda^{R*}_{c\tau}\lambda^{L}_{b\nu_\tau} \approx -0.03\left(\frac{M_\phi}{1\ \mathrm{TeV}}\right)^2 .$$

- The model also gives tree level FCNC $B \to K\nu\nu$ and $D^0 \to \mu\mu$ (consistent with the present upper bound for suitable choice of couplings)
- The $b \to s\mu\mu$ transition occurs at one-loop level:

$$C^{\mu}_{LL} = \frac{m_t^2}{8\pi\alpha M_\phi^2}|\lambda^{L}_{t\mu}|^2 - \frac{1}{64\pi\alpha}\frac{\sqrt{2}}{G_F M_\phi^2}\frac{(\lambda_L\lambda^{L\dagger})_{bs}}{V_{tb}V^*_{ts}}(\lambda_L\lambda^{L\dagger})_{\mu\mu} \Rightarrow (-1.5 < C^{\mu}_{LL} < -0.7).$$

- The model also explains $(g-2)_\mu$, and $\tau \to \mu\gamma$
- Cons: Discrete symmetry is adhoc, Not UV complete, etc..



Vector LQ $U_1^\mu(3,1,2/3)$: 1609.04367, 2004.09464,1511.06024, $\cdots$

- Vector LQ $U_1^\mu(3,1,2/3)$ with $Y=2/3$ and $F=0$ can mediate $b\to s\ell\ell$ and $b\to c\ell\nu$
- The int. Lagrangian of U_1^μ LQs with the SM fermion bilinear in int basis

$$\mathcal{L}=\left(\lambda_{1L}^{ij}\bar{Q}_{iL}\gamma^\mu L_{jL}+\lambda_{1R}^{ij}\bar{d}_{iR}\gamma^\mu l_{jR}\right)U_{1\mu},$$

- Down type quark fields are rotated into the mass basis by the V_{CKM}
- Fierz transformation gives new WC to the $b\to c\tau\bar{\nu}$,

$$C_{V_1}=\frac{1}{2\sqrt{2}G_F V_{cb}}\sum_{k=1}^{3}V_{k3}\left[\frac{\lambda_{1L}^{2l}\lambda_{1L}^{k3*}}{M^2_{U_1^{2/3}}}\right],$$

- The new WC for $b\to s\ell\ell$

$$C_9^{NP}=-C_{10}^{NP}=\frac{\pi}{\sqrt{2}G_F V_{tb}V_{ts}^*\alpha}\left[\frac{\lambda_{1L}^{2l}\lambda_{1L}^{k3*}}{M^2_{U_1^{2/3}}}\right]$$

Summary

- Current anomalies $R_{K^{(*)}}$ and $R_{D^{(*)}}$ in semileptonic B meson decays hint towards the violation of Lepton Flavour Universality.
- They have huge impact on model building and also in the searches new particle like Leptoquarks and Z'.
- Building a viable model which accommodates the observed B anomalies and consistent with all other measured flavor observables is difficult.
- Models with leptoquarks seem to address the anomalies along with some additional assumptions
- But they do not provide a clear picture of an UV complete model.

Thank you for your attention!