Recent Flavour anomalies and their Implications on Invisible sector

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Jan 23, 2025

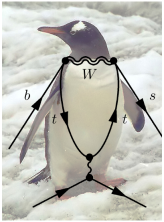
Motivation

- 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

Possible ways to search for New Physics

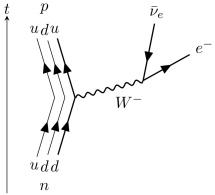
- Searches for NP signature can be performed in two ways
- The first one is through direct production of new particles in colliders.
- The second method exploits the presence of virtual states in the decays of SM particles.

- Due to QM, the intermediate states can be much heavier than the initial and final particles and can affect the decay rate as well as the angular distributions.



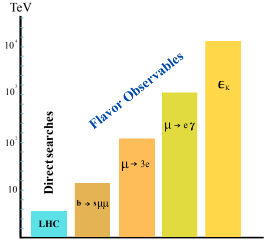
Possible ways to search for New Physics

- The most familiar example is the beta decay process that probes physics at the W boson scale.



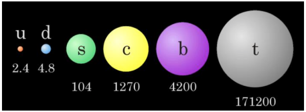
- Flavour observables are quite sensitive to high energy scales through virtual effects

- Mismatch between expt results with SM predictions hints towards existence of NP.
- Flavour physics can probe NP at much higher scale than the direct searches at coliders



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



- Why the Quark and Lepton mixing matrices are so different
- Most importantly, Flavour Physics serves as a tool to discover New Physics beyond the SM.
- Three Pillars of Flavour Physics:
    - The CKM mixing matrix and the Unitarity Triangle
    - Neutral Meson Mixing ($M^0 - \overline{M^0}$)
    - Rare decays: Flavour Changing Neutral Current transitions ($b \to s, d$)

Key Ingredient of Flavour Physics

- The unitary CKM matrix $V_{\rm CKM}$ relates the weak eigenstates of d-type quarks to the corresponding mass eigenstates

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

- In the standard parametrization, $V_{\rm CKM}$ is:

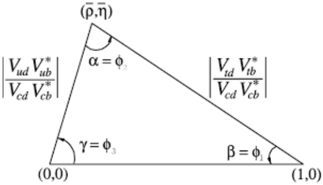
$$\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{\rm CP}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{\rm CP}} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

- Jarlskog Invariace: $J = {\rm Im}(V_{us}V_{cb}V_{ub}^*V_{cs}^*) = \mathcal{O}(10^{-5})$
- The CKM paradigm explains CP violation but it is really not sufficient to explain the matter-antimatter asymmetry of the Universe.

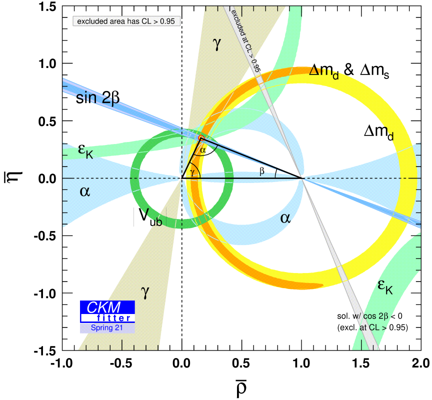
CKM Unitarity Triangle

- The unitarity condition of CKM matrix:

$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$$



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



Precise determination of the apex of the UT is essential to test the SM

Results from B Sector

- CP violation in B system is established, CKM Mechanism is the source of CPV $\Rightarrow$ Kobayashi and Maskawa got the Nobel Prize in 2008.
- Data from B factories are impressive agreement with SM prediction.
- $\mathcal{O}(20\%)$ NP contributions to most loop-level processes (FCNC) are still allowed
- No clear signal of New Physics, but there are several tensions at the level of $(3-4)\sigma$
- Next-generation flavour experiments will improve the sensitivity by almost one order
- Overall, the NP sensitivity extends to
  - TeV region for SM-like flavour violation
  - (10-100) TeV in less constrained cases

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, e.g.,
  $\mathcal{L}_{SM} \supset Y^E_{ij} \overline{L}^i_L E^j_R H + \mathrm{h.c} \implies m_e \neq m_\mu \neq m_\tau$
- 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
  - 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)
  - $R_{K^{(*)}}$ Anomaly (Dissolved with the recent data)
- These anomalies may guide us how to probe or go beyond the SM

Recent anomalies in the B sector

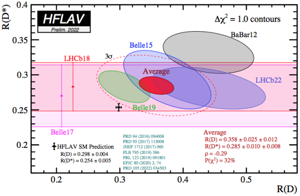
1. $R_{D^{(*)}}$

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

$$R_D^{\mathrm{WA}} = 0.441 \pm 0.060 \pm 0.066\,, \qquad R_{D^*}^{\mathrm{WA}} = 0.281 \pm 0.018 \pm 0.024$$

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

R_D and R_{D^*} exceed SM predictions by 1.4σ and 2.8σ. With $\rho = -0.43$, the discrepancy is 3.2σ between Expt and SM results.



- 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 $R_D^{\rm Exp} = 0.995(45)$, $R_{D^*}^{\rm Expt} = 1.04(5)$
- In addition Belle also has measured

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

- 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

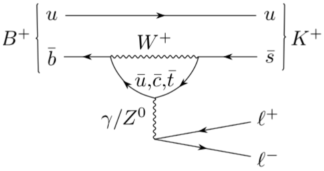
$$\Lambda \simeq 3 \text{ TeV (Tree level NP)} \qquad \frac{V_{cb}}{v^2} \text{ vs. } \frac{1}{\Lambda^2}$$

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

- Analogously, one can define the LFU observables in FCNC transitions $b \to s\ell\ell$, which loop and CKM suppressed in SM

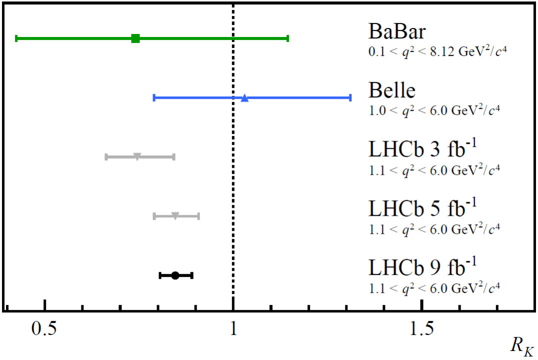
$$R_{K^{(*)}} = \frac{\mathrm{Br}(B \to K^{(*)}\mu\mu)}{\mathrm{Br}(B \to K^{(*)}ee)}$$

- SM expectation is $R_{K^{(*)}} \simeq 1$
- Has been the center of attraction ever since the first measurement of R_K by LHCb in 2014.



Summary of R_K measurement pre-Dec, 22

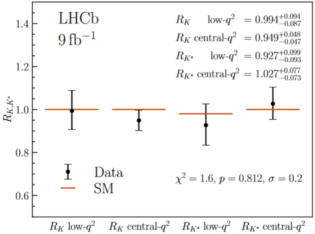
- $R_K = 0.846^{+0.044}_{-0.041}$ which shows 3.1σ deviation from SM (LHCb Collab. 2103.11769)



Latest LHCb result on R_K measurement [arXiv: 2212.09152, arXiv: 2212.09153]

- In Dec, 22 LHCb released a reanalysis of $R_{K^{(*)}}$ measurements including expt. systematics and a tighter selection for electrons
- LHCb has decreed that the reanalysis supplants previous results
- The four measurements of $R_{K^{(*)}}$ actually compatible with SM

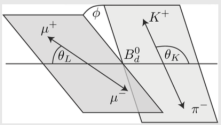
$$R_{K_{[0.1,1.1]}} = 0.994^{+0.090}_{-0.082}\ (\mathrm{stat})^{+0.029}_{-0.027}\ (\mathrm{syst}),$$
$$R_{K^*_{[0.1,1.1]}} = 0.927^{+0.093}_{-0.087}\ (\mathrm{stat})^{+0.036}_{-0.035}\ (\mathrm{syst}),$$
$$R_{K_{[1.1,6]}} = 0.949^{+0.042}_{-0.041}\ (\mathrm{stat})^{+0.022}_{-0.022}\ (\mathrm{syst}),$$
$$R_{K^*_{[1.1,6]}} = 1.027^{+0.072}_{-0.068}\ (\mathrm{stat})^{+0.027}_{-0.026}\ (\mathrm{syst}).$$



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

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

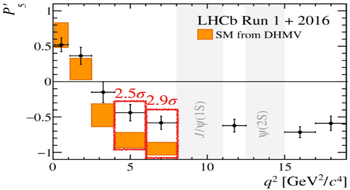


$\vec{\Omega} =$
$(\cos\theta_l, \cos\theta_k, \phi)$

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

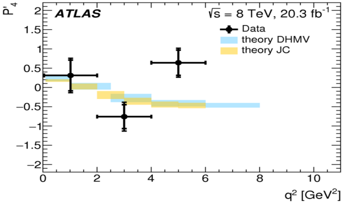
FFI observables in $B^0 \to K^{*0}\ell\ell$

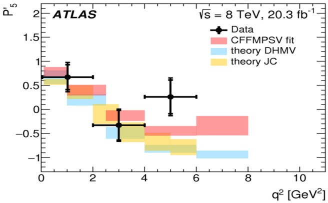
3. $P'_{4,5}$



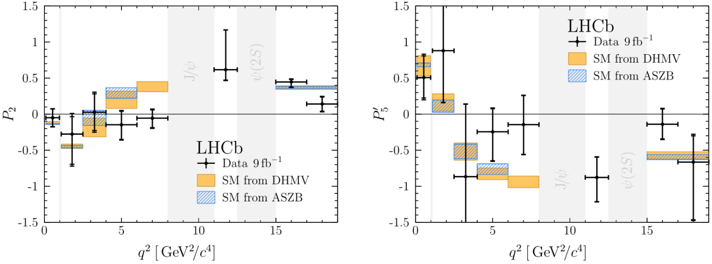
LHCb: PRL **125**, 011802 (2020)

ATLAS Results show $\sim 2.7\sigma$ deviation





FFI Observables in $B^{*+} \to K^{*+}\mu^+\mu^-$ PRL 126, 161802 (2021)

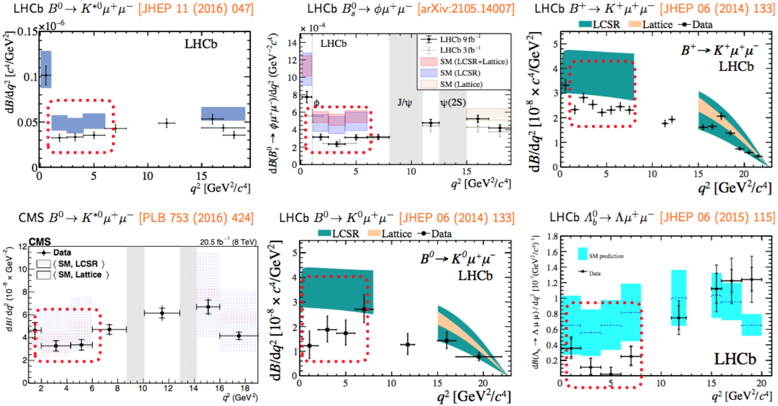


- 3σ deviation for P_2 in [6-8] GeV^2 bin, while P'_5 broadly agrees with the deviation observed in $B^0 \to K^{*0}\mu^+\mu^-$.
- Considering 20% deficit in SM muon channel

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

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

Differential decay rates of $b \to s\mu^+\mu^-$ deacy modes



- Data consistently below SM predictions, particularly at low-q^2 region
- Tension at the level of (1-3)σ, sizable hadronic theory uncertainties

Anomalies in $b \to s\nu\bar{\nu}$ transition (2311.14647)

- Recently Belle II reported the BR for $B^+ \to K^+\nu\bar{\nu}$ using 362 fb^{-1} data with Hadronic and Inclusive Tagging

$$\mathcal{B}(B^+ \to K^+\nu\bar{\nu}) = (2.3 \pm 0.5(\mathrm{stat})^{+0.5}_{-0.4}(\mathrm{syst})) \times 10^{-5}$$

which has 2.7σ deviation with the SM result.

- Combining this with previous data gives the new world average:

$$\mathcal{B}(B^+ \to K^+\nu\bar{\nu}) = (1.3 \pm 0.4) \times 10^{-5}$$

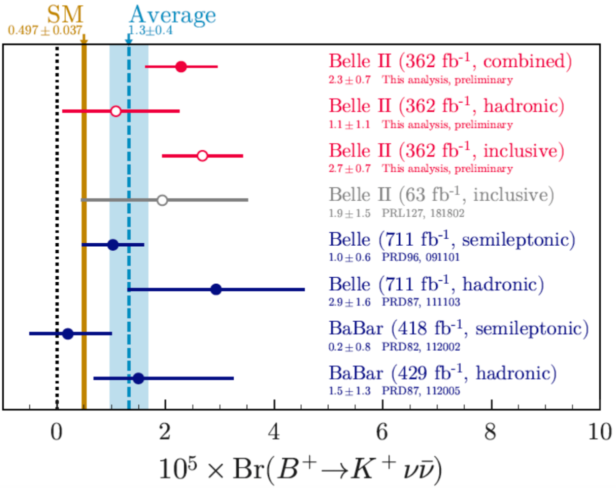
- Precise SM prediction, does not suffer much from hadronic uncertainties

$$\mathcal{B}(B^+ \to K^+\nu\bar{\nu}) = (5.58 \pm 0.37) \times 10^{-6} \quad (\mathrm{HPQCD\ Collab})$$

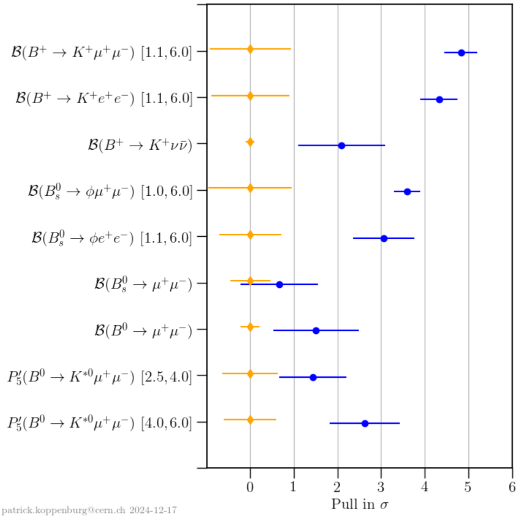
including the long distance contributions $(0.61 \pm 0.06) \times 10^{-6}$.

- Attractive scenarios: Additional decay channels with undetected final states, e.g., sterile neutrinos, dark matter, long-lived particles
- Light sterile neutrinos are well motivated and occur numerous minimal extension of SM

Summary of $B \to K\nu\bar{\nu}$ Measurements



List of Anomalies in Flavour sector



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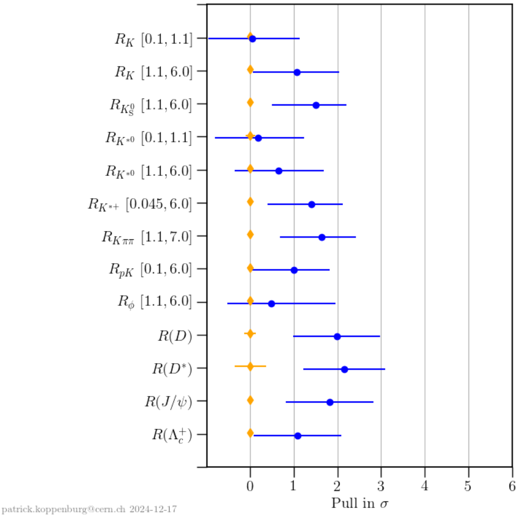


How to address the Anomalies in b sector

- 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

- In order to explain these deviations, one can perform a model-independent analysis by considering the relevant effective Hamiltonian
- Additional NP contributions are often assumed to be real, as there have been no signs of CP violation in these processes.
- Under these assumptions, a specific scenario of NP is defined by adding NP contributions to some of the Wilson coefficients

$$C_i = C_i^{\mathrm{SM}} + C_i^{\mathrm{NP}}$$

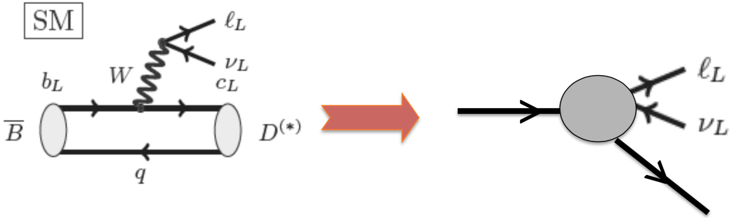
Effective Field Theory Approach for $b \to c\tau^- \bar{\nu}_\tau$

- The effective Hamiltonian responsible for the CC $b \to c\tau\bar{\nu}_l$ quark level transitions is

$$\mathcal{H}_{\rm eff}^{\rm CC} = \frac{4G_F}{\sqrt{2}} V_{cb}\Big[\Big(\delta_{l\tau} + C^l_{V_L}\Big)\mathcal{O}^l_{V_L} + C^l_{V_R}\mathcal{O}^l_{V_R} + C^l_{S_L}\mathcal{O}^l_{S_L} + C^l_{S_R}\mathcal{O}^l_{S_R} + C^l_T\mathcal{O}^l_T\Big]$$

- The corresponding dimension-six effective operators are given as

$$\begin{aligned}
\mathcal{O}^l_{V_L} &= (\bar{c}_L\gamma^\mu b_L)(\bar{\tau}_L\gamma_\mu\nu_{lL})\,, & \mathcal{O}^l_{V_R} &= (\bar{c}_R\gamma^\mu b_R)(\bar{\tau}_L\gamma_\mu\nu_{lL})\,,\\
\mathcal{O}^l_{S_L} &= (\bar{c}_R b_L)(\bar{\tau}_R\nu_{lL})\,, & \mathcal{O}^l_{S_R} &= (\bar{c}_L b_R)(\bar{\tau}_R\nu_{lL})\,,\\
\mathcal{O}^l_T &= (\bar{c}_R\sigma^{\mu\nu} b_L)(\bar{\tau}_R\sigma_{\mu\nu}\nu_{lL})
\end{aligned}$$



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%	
$\chi^2_{\rm min}$/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

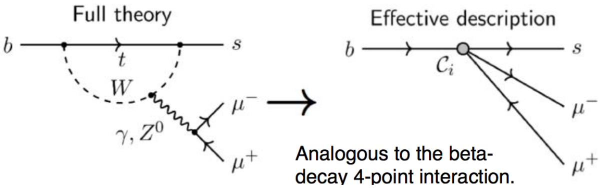
Bottom line

- $\mathcal{O}_{V_L}$ 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 operators

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

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



Effective Lagrangian for $b \to s\ell^-\ell^+$

- The effective Hamiltonian mediating the NC leptonic/semileptonic $b \to s\ell^+\ell^-$

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

where $\mathcal{O}_i$'s are the dimension-six operators:

$$\mathcal{O}_7^{(\prime)} = \frac{\alpha_{\rm em}}{4\pi} \left[\bar{s}\sigma_{\mu\nu}\big(m_s P_{L(R)} + m_b P_{R(L)}\big) b \right] F^{\mu\nu},$$

$$\mathcal{O}_9^{(\prime)} = \frac{\alpha_{\rm em}}{4\pi} \big(\bar{s}\gamma^\mu P_{L(R)} b\big)\big(\bar{\ell}\gamma_\mu \ell\big) , \qquad \mathcal{O}_{10}^{(\prime)} = \frac{\alpha_{\rm em}}{4\pi} \big(\bar{s}\gamma^\mu P_{L(R)} b\big)\big(\bar{\ell}\gamma_\mu \gamma_5 \ell\big) ,$$

$$\mathcal{O}_S^{(\prime)} = \frac{\alpha_{\rm em}}{4\pi} \big(\bar{s} P_{L(R)} b\big)\big(\bar{\ell}\ell\big) , \qquad \mathcal{O}_P^{(\prime)} = \frac{\alpha_{\rm em}}{4\pi} \big(\bar{s} P_{L(R)} b\big)\big(\bar{\ell}\gamma_5 \ell\big) ,$$

- The primed as well as (pseudo)scalar operators are absent in the SM and can be generated only in the BSM theories.

Grobal-fit Results (1D)

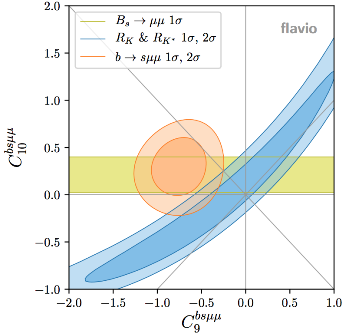
- Good fits obtained along the direction $C_{9\mu}^{\rm NP} = -C_{10\mu}^{\rm NP}$, arises naturally in models obeying $SU(2)_L$ invariance

	All				LFUV			
1D Hyp.	Best fit	$1\ \sigma/2\ \sigma$	$\mathrm{Pull}_{\mathrm{SM}}$	p-value	Best fit	$1\ \sigma/\ 2\ \sigma$	$\mathrm{Pull}_{\mathrm{SM}}$	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

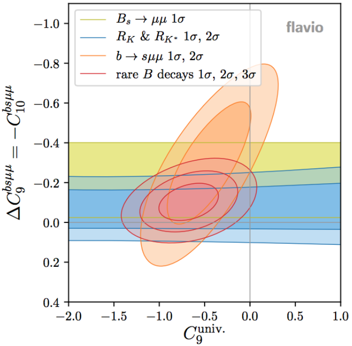
Status of New Physics with updated data [arXiv: 2212.10497]

- The updated results are fully compatible with SM predictions, no longer provide evidence of a μ/e universality violation
- The global fit results in $(C_9^{bs\mu\mu}, C_{10}^{bs\mu\mu})$, assuming no NP in the electron channel



- Slight tension between the best-fit regions preferred by LFU ratios and the $b \to s\mu\mu$ observables
- This tension can be resolved in the presence of LFU NP, which contributes only to $b \to s\mu\mu$ but not R_{K^*}
- Case-I: $(C_9^{\rm univ}, \Delta C_9^{bs\mu\mu} = -C_{10}^{bs\mu\mu})$, where $C_9^{bs\mu\mu} = C_9^{\rm univ.} + \Delta C_9^{bs\mu\mu}$ and $C_9^{bsee} = C_9^{\rm univ}$
- The best-fit values are

$$C_9^{\rm univ.} = -0.64 \pm 0.22$$
$$\Delta C_9^{bs\mu\mu} = -C_{10}^{bs\mu\mu} = -0.11 \pm 0.06$$



Gauged $L_\mu - L_\tau$ Model with Scalar LQ $S_1(\bar{3}, 1, 1/3)$

- The SM has accidental $U(1)$ global symmetries like B and L no. conservation
- However, they become anomalous if promoted into a local one
- The anomaly free situation can be obtained if instead of considering B and L separately, some combinations between them, e.g., $B - L$, $L_e - L_\mu$, $L_e - L_\tau$ or $L_\mu - L_\tau$
- For the anomaly cancellation of local $B - L$ models, one requires 3 RHNs with appropriate $B - L$ charges
- However, for $L_\alpha - L_\beta$ anomaly cancellation does not require any extra chiral fermionic degrees of freedom.
- $U(1))_{L_\mu - L_\tau}$ is less constrained, as the extra Z' does not couple to electrons and quarks, $\Rightarrow$ free from any constraints from lepton and hadron colliders

Particle Content of $L_\mu - L_\tau$ model (RM et al, PRD 105, 015033)

	Field	$SU(3)_C \times SU(2)_L \times U(1)_Y$	$U(1)_{L_\mu - L_\tau}$	Z_2
Fermions	$Q_L \equiv (u, d)_L^T$	$(\mathbf{3}, \mathbf{2}, 1/6)$	0	$+$
	u_R	$(\mathbf{3}, \mathbf{1}, 2/3)$	0	$+$
	d_R	$(\mathbf{3}, \mathbf{1}, -1/3)$	0	$+$
	$\ell_L \equiv e_L, \mu_L, \tau_L$	$(\mathbf{1}, \mathbf{2}, -1/2)$	$0, 1, -1$	$+$
	$\ell_R \equiv e_R, \mu_R, \tau_R$	$(\mathbf{1}, \mathbf{1}, -1)$	$0, 1, -1$	$+$
	N_e, N_μ, N_τ	$(\mathbf{1}, \mathbf{1}, 0)$	$0, 1, -1$	$-$
Scalars	H	$(\mathbf{1}, \mathbf{2}, 1/2)$	0	$+$
	η	$(\mathbf{1}, \mathbf{2}, 1/2)$	0	$-$
	ϕ_2	$(\mathbf{1}, \mathbf{1}, 0)$	2	$+$
	S_1	$(\bar{\mathbf{3}}, \mathbf{1}, 1/3)$	-1	$-$
Gauge bosons	$W_\mu^i \ (i = 1, 2, 3)$	$(\mathbf{1}, \mathbf{3}, 0)$	0	$+$
	B_μ	$(\mathbf{1}, \mathbf{1}, 0)$	0	$+$
	V_μ	$(\mathbf{1}, \mathbf{1}, 0)$	0	$+$

Table: Fields and their charges of the proposed $U(1)_{L_\mu - L_\tau}$ model.

Lagrangian of the Model

The Lagrangian of the present model can be written as

$$
\begin{aligned}
\mathcal{L}_G &= -\frac{1}{4}\left(\hat{\mathbf{W}}_{\mu\nu}\hat{\mathbf{W}}^{\mu\nu} + \hat{B}_{\mu\nu}\hat{B}^{\mu\nu} + \hat{V}_{\mu\nu}\hat{V}^{\mu\nu} + 2\sin\chi\hat{B}_{\mu\nu}\hat{V}^{\mu\nu}\right), \\
\mathcal{L}_f &= -\frac{1}{2}M_{ee}\overline{N_e^c}N_e - \frac{f_\mu}{2}\left(\overline{N_\mu^c}N_\mu\phi_2^\dagger + \mathrm{h.c.}\right) - \frac{f_\tau}{2}\left(\overline{N_\tau^c}N_\tau\phi_2 + \mathrm{h.c.}\right) \\
&\quad -\frac{1}{2}M_{\mu\tau}(\overline{N_\mu^c}N_\tau + \overline{N_\tau^c}N_\mu) - \sum_{l=e,\mu,\tau}(Y_{ll}(\overline{\ell_L})_l\tilde{\eta}N_{lR} + \mathrm{h.c}) \\
&\quad - \sum_{q=d,s,b}(y_{qR}\,\overline{d^c_{qR}}S_1 N_\mu + \mathrm{h.c.}), \\
\mathcal{L}_{G-f} &= -g_{\mu\tau}\overline{\mu}\gamma^\mu\mu\hat{V}_\mu + g_{\mu\tau}\overline{\tau}\gamma^\mu\tau\hat{V}_\mu - g_{\mu\tau}\overline{\nu_\mu}\gamma^\mu(1-\gamma^5)\nu_\mu\hat{V}_\mu \\
&\quad + g_{\mu\tau}\overline{\nu_\tau}\gamma^\mu(1-\gamma^5)\nu_\tau\hat{V}_\mu - g_{\mu\tau}\overline{N_\mu}\hat{V}_\mu\gamma^\mu\gamma^5 N_\mu + g_{\mu\tau}\overline{N_\tau}\hat{V}_\mu\gamma^\mu\gamma^5 N_\tau, \\
\mathcal{L}_S &= \left|\left(i\partial_\mu - \frac{g}{2}\boldsymbol{\tau}^a\cdot\hat{\mathbf{W}}_\mu^a - \frac{g'}{2}\hat{B}_\mu\right)\eta\right|^2 + \left|\left(i\partial_\mu - \frac{g'}{3}\hat{B}_\mu + g_{\mu\tau}\hat{V}_\mu\right)S_1\right|^2 \\
&\quad + \left|\left(i\partial_\mu - 2g_{\mu\tau}\hat{V}_\mu\right)\phi_2\right|^2 - V(H,\eta,\phi_2,S_1).
\end{aligned}
$$

Scalar potential

- The scalar potential V is expressed as

$$
\begin{aligned}
V(H,\eta,\phi_2,S_1) = {} & V(H) + \mu_\eta^2\eta^\dagger\eta + \lambda_{H\eta}(H^\dagger H)(\eta^\dagger\eta) + \lambda_\eta(\eta^\dagger\eta)^2 \\
& + \lambda'_{H\eta}(H^\dagger\eta)(\eta^\dagger H) + \frac{\lambda''_{H\eta}}{2}\left[(H^\dagger\eta)^2 + \mathrm{h.c.}\right] + \mu_\phi^2(\phi_2^\dagger\phi_2) + \lambda_\phi(\phi_2^\dagger\phi_2)^2 \\
& + \mu_S^2({S_1}^\dagger S_1) + \lambda_S({S_1}^\dagger S_1)^2 + \left[\lambda_{H\phi}(\phi_2^\dagger\phi_2) + \lambda_{HS}(S_1^\dagger S_1)\right](H^\dagger H) \\
& + \lambda_{S\phi}(\phi_2^\dagger\phi_2)({S_1}^\dagger S_1) + \lambda_{\eta\phi}(\phi_2^\dagger\phi_2)(\eta^\dagger\eta) + \lambda_{S\eta}({S_1}^\dagger S_1)(\eta^\dagger\eta).
\end{aligned}
$$

- SSB occurs when the scalars get their VEVs: $\langle\phi_2\rangle = \frac{v_2}{\sqrt{2}}$, $\langle H\rangle = \frac{v}{\sqrt{2}}$, $SU(2)_L \times U(1)_Y \times U(1)_{L_\mu - L_\tau} \Longrightarrow SU(2)_L \times U(1)_Y \Longrightarrow U(1)_{em}$
- We have $\mu_\eta^2, \mu_S^2 > 0$ and the masses of the SLQ and inert doublet η are

$$
\begin{aligned}
M_{S_1}^2 &= 2\mu_S^2 + \lambda_{HS}v^2 + \lambda_{S\phi}v_2^2\ , \\
M_{\eta_c}^2 &= \mu_\eta^2 + \lambda_{H\eta}v^2/2 + \lambda_{\eta\phi}v_2^2/2, \\
M_{\eta_{r,i}}^2 &= \mu_\eta^2 + \left(\lambda_{H\eta} + \lambda'_{H\eta} \pm \lambda''_{H\eta}\right)v^2/2 + \lambda_{\eta\phi}v_2^2/2.
\end{aligned}
$$

Gauge mixing

- For the mixing of $U(1)_Y$ and $U(1)_{L_\mu - L_\tau}$ gauge bosons, we consider the $GL(2,R)$ transformation

$$\begin{pmatrix} \bar{B}_\mu \\ \bar{V}_\mu \end{pmatrix} = \begin{pmatrix} 1 & \sin\chi \\ 0 & \cos\chi \end{pmatrix} \begin{pmatrix} \hat{B}_\mu \\ \hat{V}_\mu \end{pmatrix}.$$

- Thus, the mass matrix of gauge fields in the basis $\left(W_\mu^3, \bar{B}_\mu, \bar{V}_\mu\right)$ as

$$M_G^2 = \begin{pmatrix} \frac{1}{8}g^2 v^2 & -\frac{1}{8}gg' v^2 & \frac{1}{8}gg' \tan\chi v^2 \\ -\frac{1}{8}gg' v^2 & \frac{1}{8}g'^2 v^2 & -\frac{1}{8}g'^2 \tan\chi v^2 \\ \frac{1}{8}gg' \tan\chi v^2 & -\frac{1}{8}g'^2 \tan\chi v^2 & 2g_{\mu\tau}^2 \sec\chi^2 v^2 \end{pmatrix}.$$

- Diagonalization of M_G^2 gives the masses of the physical gauge bosons

$$M_Z^2 = M_{Z_{SM}}^2 \cos\alpha^2 - \delta M^2 \sin 2\alpha + M_{\bar{V}}^2 \sin\alpha^2,$$
$$M_{Z'}^2 = M_{Z_{SM}}^2 \sin\alpha^2 + \delta M^2 \sin 2\alpha + M_{\bar{V}}^2 \cos\alpha^2,$$
$$\alpha = \frac{1}{2}\tan^{-1}\left[\frac{2\,\delta M^2}{M_{\bar{V}}^2 - M_{Z_{SM}}^2}\right].$$

Scalar and Fermion mixing

- The CP-even scalars h and h_2 as well as the heavy fermion states N_μ and N_τ mix with the mixing matrices given as

$$M_H^2 = \begin{pmatrix} 2\lambda_H v^2 & \lambda_{H\phi} v v_2 \\ \lambda_{H\phi} v v_2 & 2\lambda_\phi v_2^2 \end{pmatrix}, \quad M_N = \begin{pmatrix} \frac{1}{\sqrt{2}} f_\mu v_2 & M_{\mu\tau} \\ M_{\mu\tau} & \frac{1}{\sqrt{2}} f_\tau v_2 \end{pmatrix}.$$

One can diagonalize the above mass matrices using a 2×2 rotation matrix

$$U_\zeta^T M_H^2 U_\zeta = \mathrm{diag}\ [M_{H_1}^2, M_{H_2}^2], \qquad U_\beta^T M_N U_\beta = \mathrm{diag}\ [M_-, M_+],$$

with $\zeta = \frac{1}{2} \tan^{-1} \left(\frac{\lambda_{H\phi} v v_2}{\lambda_\phi v_2^2 - \lambda_H v^2} \right)$, $\beta = \frac{1}{2} \tan^{-1} \left(\frac{2M_{\mu\tau}}{(f_\tau - f_\mu)(v_2/\sqrt{2})} \right)$.

- The lightest fermion mass eigenstate N_- considered as probable DM candidate, and M_{H_1} as the SM Higgs

M_{S_1}	M_+	M_{H_1}	M_{H_2}	$\sin\beta$	$\sin\zeta$	χ	$\alpha \times 10^4$
1200	500	125	500	$1/2$	$10^{-3} - 10^{-2}$	10^{-3}	$4.83 - 4.85$

Table: Values of the model parameters used in the analysis (masses are in GeV).

Dark Matter Relic Abundance

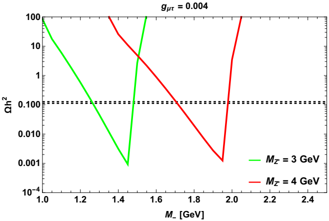
- The relic density of the light DM (N_-) is computed via freeze-out mechanism through the following decay channels:

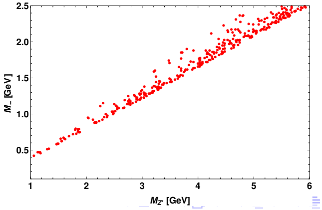
$$N_-\overline{N}_- \rightarrow \mu\overline{\mu},\ \tau\overline{\tau},\ \nu_\mu\overline{\nu}_\mu,\ \nu_\tau\overline{\nu}_\tau \ \ (s \text{ channel } Z' \text{ and } \eta \text{ portal})$$
$$\rightarrow d\overline{d},\ s\overline{s} \ \ (t \text{ channel } SLQ(S_1) \text{ portal})$$

- DM relic density is computed by

$$\Omega h^2 = \frac{2.14\times 10^9 \mathrm{GeV}^{-1}}{g*^{1/2}\, M_{Pl}}\frac{1}{J(x_f)}, \qquad J(x_f) = \int_{x_f}^{\infty}\frac{\langle\sigma v\rangle(x)}{x^2}dx.$$

where $x = M_-/T$ and x_f is the freeze out parameter.





Detection prospects

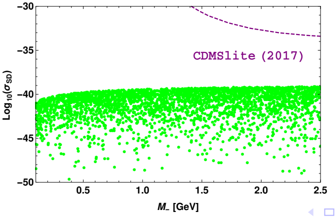
- SLQ portal spin-dependent (SD) cross section can arise from the effective interaction

$$\mathcal{L}_{\rm eff}^{\rm SD} \simeq \frac{y_{qR}^2 \cos^2\beta}{4(M_{S_1}^2 - M_-^2)} (\overline{N}_- \gamma^\mu \gamma^5 N_-)(\overline{q}\gamma_\mu \gamma^5 q)\,,$$

and the computed cross section is given as

$$\sigma_{\rm SD} = \frac{\mu_r^2}{\pi} \frac{\cos^4\beta}{(M_{S_1}^2 - M_-^2)^2} \left[y_{dR}^2 \Delta_d + y_{sR}^2 \Delta_s\right]^2 J_n(J_n+1).$$

- The WIMP-nucleon cross section via (Z, Z') portal and (H_1, H_2) portal is found to be very small and insensitive to direct detection experiments.



Constraints from Flavour sector

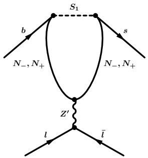
- Model parameters of LQ and Z' couplings can be constrained using $R_{K^{(*)}}$ and $\mathrm{Br}(B \to X_s \gamma)$.
- The effective Hamiltonian mediating $b \to s l^+ l^-$ is

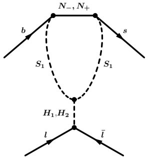
$$\mathcal{H}_{\rm eff} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \left[\sum_{i=1}^{6} C_i(\mu) O_i + \sum_{i=7,9,10} \Big(C_i(\mu) O_i + C_i'(\mu) O_i' \Big) \right],$$

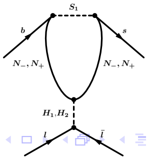
$$O_7^{(\prime)} = \frac{e}{16\pi^2} \Big[\bar{s}\sigma_{\mu\nu} \left(m_s P_{L(R)} + m_b P_{R(L)} \right) b \Big] F^{\mu\nu},$$

$$O_9^{(\prime)} = \frac{\alpha_{\rm em}}{4\pi} (\bar{s}\gamma^\mu P_{L(R)} b)(\bar{l}\gamma_\mu l), \qquad O_{10}^{(\prime)} = \frac{\alpha_{\rm em}}{4\pi} (\bar{s}\gamma^\mu P_{L(R)} b)(\bar{l}\gamma_\mu \gamma_5 l),$$

- Following one loop diagrams provide non-zero contribution to the rare $b \to sll$ processes (2nd and 3rd diagrams $\propto m_q M_\pm / M_{S_1}^2$)







- Z' exchange penguin diagram gives the transition amplitude of $b \to sll$ process

$$\mathcal{M} = \frac{1}{2^5\pi^2}\frac{y_{qR}^2 g_{\mu\tau}^2}{(q^2 - M_{Z'}^2)}\mathcal{V}_{sb}(\chi_-, \chi_+)\Big[\bar{u}(p_B)\gamma^\mu(1+\gamma_5)u(p_K)\Big]\Big[\bar{v}(p_2)\gamma_\mu u(p_1)\Big],$$

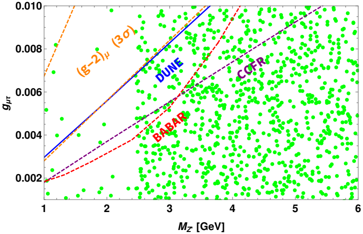
which provides additional primed Wilson coefficient

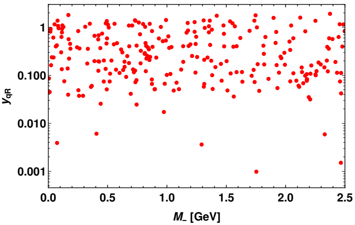
$$C_9'^{\rm NP} = \frac{\sqrt{2}}{2^4\pi G_F \alpha_{\rm em} V_{tb}V_{ts}^*}\frac{y_{qR}^2 g_{\mu\tau}^2}{(q^2 - {M_{Z'}}^2)}\mathcal{V}_{sb}\left(\chi_-, \chi_+\right) ,$$

$\mathcal{V}_{sb}\left(\chi_-, \chi_+\right)$ is the loop function and $\chi_\pm = M_\pm^2/M_{S_1}^2$.

- As only $C_9'^{\rm NP}$ involves, $B_s \to \mu\mu(\tau\tau)$ won't play any role in constraining the new parameters.
- Absence of $Z'\mu\tau$ coupling $\Rightarrow$ LFV decays like $B \to K^{(*)}\mu\tau$, $\tau \to \mu\gamma$ and $\tau \to 3\mu$ are not allowed

- Thus, using R_K/R_{K^*} and $\mathrm{Br}(B \to X_s\gamma)$ observables, the $g_{\mu\tau}$, $M_{Z'}$ and the y_{qR}, M_- allowed regions are shown below





- The allowed range of all the four new parameters consistent with flavor phenomenology

Parameters	y_{qR}	$g_{\mu\tau}$	M_- (GeV)	$M_{Z'}$ (GeV)
Allowed range	$0 - 2.0$	$0 - 0.01$	$0 - 2.5$	$1 - 6$

Table: The allowed regions of y_{qR}, $g_{\mu\tau}$, M_- and $M_{Z'}$ parameters.

Footprints on $b \to s + \not{E}$ decay modes

- In SM, $b \to s+$ missing energy can be described by the $b \to s\nu\bar{\nu}$
- The effective Hamiltonian in SM

$$\mathcal{H}_{eff} = \frac{-4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \left(C_L^\nu \mathcal{O}_L^\nu + C_R^\nu \mathcal{O}_R^\nu \right) + h.c.,$$

where

$$\mathcal{O}_L^\nu = \frac{\alpha_{\rm em}}{4\pi} \left(\bar{s}_R \gamma_\mu b_L \right) \left(\bar{\nu} \gamma^\mu \left(1 - \gamma_5\right) \nu \right), \quad \mathcal{O}_R^\nu = \frac{\alpha_{\rm em}}{4\pi} \left(\bar{s}_L \gamma_\mu b_R \right) \left(\bar{\nu} \gamma^\mu \left(1 - \gamma_5\right) \nu \right),$$

$$C_L^\nu = -X(x_t)/\sin^2\theta_w \,, \qquad X(x_t) = X_0(x_t) + \frac{\alpha_s}{4\pi} X_1(x_t),$$

- The branching ratios of $B_{(s)} \to K^*(\phi)\nu\bar{\nu}$ and their corresponding experimental limits are

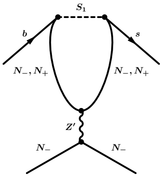
Decay process	BR in the SM	Experimental limit
$B^0 \to K^0 \nu_l \bar{\nu}_l$	$(4.53 \pm 0.267) \times 10^{-6}$	$<2.6 \times 10^{-5}$
$B^+ \to K^+ \nu_l \bar{\nu}_l$	$(4.9 \pm 0.288) \times 10^{-6}$	$<1.6 \times 10^{-5}$
$B^0 \to K^{*0} \nu_l \bar{\nu}_l$	$(9.48 \pm 0.752) \times 10^{-6}$	$<1.8 \times 10^{-5}$
$B^+ \to K^{*+} \nu_l \bar{\nu}_l$	$(1.03 \pm 0.06) \times 10^{-5}$	$<4.0 \times 10^{-5}$
$B_s \to \phi \nu_l \bar{\nu}_l$	$(1.2 \pm 0.07) \times 10^{-5}$	$<5.4 \times 10^{-3}$

- In this model, the additional process involved is

$$b \to s + \text{missing energy} = b \to s\nu\nu + b \to sN_-N_-$$

Footprints on $b \to s + \not{E}$ decay modes

- The relevant one-loop diagram for $b \to s N_- N_-$ is



- Thus, e.g., the amplitude of $B \to K N_- N_-$ process from the Z' exchanging diagram is

$$\mathcal{M} = C^{\rm NP}(q^2)[\bar{u}(p_B)\gamma^\mu(1+\gamma_5)u(p_K))][\bar{v}(p_2)\gamma_\mu u(p_1))]$$

where

$$C^{\rm NP}(q^2) = \frac{1}{2^5\pi^2}\frac{y_{qR}^2 g_{\mu\tau}^2 \cos 2\beta \cos\alpha \sec\chi}{q^2 - M_{Z'}^2}\mathcal{V}_{sb}(\chi_-, \chi_+)\,,$$

Predicted Results for $b \to s + \not{E}$ decay modes

- We use two sets of benchmark values of new parameters, allowed by both the DM and flavor phenomenology

Benchmark	y_{qR}	$g_{\mu\tau}$	M_- (GeV)	$M_{Z'}$ (GeV)
Benchmark-I	2.0	0.002	1.7	4
Benchmark-II	2.0	0.008	1.8	4.8

Table: Benchmark values of y_{qR}, M_-, $g_{\mu\tau}$ and $M_{Z'}$ parameters used in our analysis.

Predicted Results for $b \to s+ \not{E}$ decay modes

- For Benchmark-I, there is a singularity at $q^2 = M_{Z'}^2$, i.e., $q^2 = 16\ \mathrm{GeV}^2$. To avoid it, we use the cuts at $(M_{Z'} - 0.002)^2 \leq q^2 \leq (M_{Z'} + 0.002)^2$ GeV^2.

$\mathrm{Br}(b \to s\not{E})$	Benchmark-I	Benchmark-II	Experimental Limit
$\mathrm{Br}(B^0 \to K^0\not{E})$	0.645×10^{-5}	0.457×10^{-5}	$< 2.6 \times 10^{-5}$
$\mathrm{Br}(B^+ \to K^+\not{E})$	0.697×10^{-5}	0.516×10^{-5}	$< 1.6 \times 10^{-5}$
$\mathrm{Br}(B^0 \to K^{*0}\not{E})$	1.271×10^{-5}	0.981×10^{-5}	$< 1.8 \times 10^{-5}$
$\mathrm{Br}(B^+ \to K^{*+}\not{E})$	1.381×10^{-5}	1.066×10^{-5}	$< 4.0 \times 10^{-5}$
$\mathrm{Br}(B_s \to \phi\not{E})$	1.618×10^{-5}	1.24×10^{-5}	$< 5.4 \times 10^{-3}$

Table: The predicted branching ratios of $b \to s\not{E}$ processes for two different benchmark values of new parameters.

Summary

- Current anomalies in the Flavor sector provide an ideal platform to look for New Physics.
- 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.

Thank you for your attention!