Probing New Physics: The Role of Vector-Like Quarks in Rare B-Decays

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Motivation

- Rare B-decays are highly suppressed in the SM $\Rightarrow$ sensitive probes of New Physics (NP)
- Anomalies in B-decays have been observed,and by studying Rare B-decays in the presence of vector-like quarks, we aim to understand their impact on the observed experimental results and test the validity of this theoretical extension.
- Vector-Like Quarks (VLQs) are promising BSM candidate.

Contents

Rare B-Decays

- A rare B decay is a decay that does not proceed by the dominant $b \to c$ transition. The decays either involve $b \to u$ transitions, loop $b \to s$ transitions or transitions with W-exchange.

> CKM matrix plays a crucial role in the suppression due to the Glashow-Iliopoulos-Maiani (GIM) mechanism, which ensures that FCNC processes are forbidden at tree level and only occur via higher-order processes with a small probability.

Rare B-Decays

- The FCNC processes $b \to sZ$ test the predictions of the SM and examine its limits.

Effective Field Theory (EFT) used to study low-energy consequences ($E << M_W$, like B-decays)

$$\mathcal{H}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum_i C_i(\mu)\mathcal{O}_i(\mu)$$

- O_i are fermion Operators
- C_i are Wilson Coefficients

Rare B-decays

Many experimental data available, each sensitive to one or more Wilson coefficient,

- Inclusive decays:

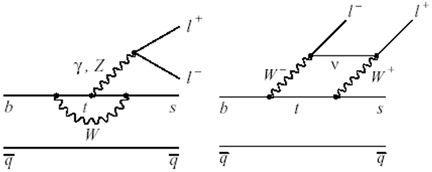
$$B \to X_s\gamma \quad (C_7)$$

$$B \to X_s\ell^+\ell^- \quad (C_7, C_9, C_{10})$$

- Exclusive decays:

$$B_s \to \mu^+\mu^- \quad (C_{10})$$

$$B \to K\ell^+\ell^- \quad (C_7, C_9, C_{10})$$



Vector Quark Model

The minimal extension of the SM in this direction can be obtained by adding a vector-like isosinglet quark.

In Vector-like Quark Model (VQM), adding an extra isosinglet pair of quarks, U and D, to the SM. The Dirac mass terms of VLQs,

$$m_U(\bar{U}_L U_R + \bar{U}_R U_L) + m_D(\bar{D}_L D_R + \bar{D}_R D_L)$$

The left and right components of the VLQs are $SU(2)_L$ singlets, leading to non-unitarity CKM with a new parameter,

$$U^{\alpha\beta} \equiv \sum_{i=1}^{3} A_L^{qi\alpha *} A_L^{qi\beta} = \delta_{\alpha\beta} - A_L^{q\alpha 4} A_L^{q\beta 4*} = \begin{matrix} (V^\dagger V)^{\alpha\beta}, & \text{down-type} \\ (VV^\dagger)^{\alpha\beta}, & \text{up-type} \end{matrix}$$

- $U^{\alpha\beta}$ would signal new physics and the presence of FCNC at the tree level, which can substantially modify the predictions of SM for the FCNC processes.
- VLQ Introduce new FCNCs via modified Z couplings

$B \to X_s l^+ l^-$ in the VQM

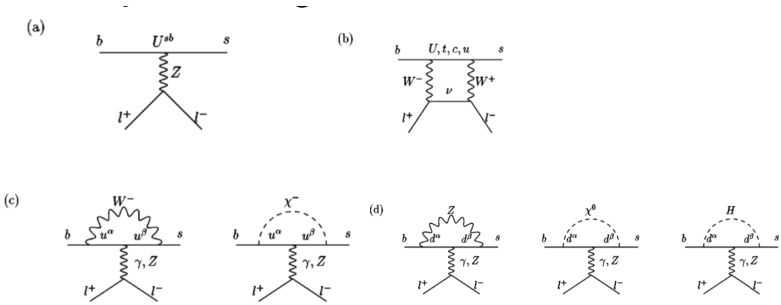


Figure: The Feynmann diagrams for $B \to X_s l^+ l^-$ in the VQM.

$B \to X_s l^+ l^-$ in the VQM

In the VQM, the tree level FCNC diagram (1a) gives

$$A_{1(a)} = U_{sb}(-1 + 2\sin^2\theta_W)$$

Fig (1 d)shows penguin diagrams via Z, χ^0, H^0, amplitude is proportional to U_{sb}. $\sum_{\delta=1}^{4} U^{\alpha\delta} U^{\delta\beta} = U^{\alpha\beta}$.

$$C_i = C_i(SM) + C_i(NP)$$

The coupling in $b \to sZ$ changes the values of the Wilson coefficients C_9 and C_{10} at tree-level.

$$C_9^{total} = C_9^{eff} - \frac{\pi}{\alpha}\frac{U_{sb}}{V_{ts}^* V_{tb}}(4\sin^2\theta_W - 1), \qquad C_{10}^{total} = C_{10} - \frac{\pi}{\alpha}\frac{U_{sb}}{V_{ts}^* V_{tb}}$$

arXiv:hep-ph/0105049

$B \to K\nu\bar{\nu}$ in VQM

Vector-like quark (VLQ) models significantly alter the decay $B \to K\nu\bar{\nu}$ through non unitarity of CKM matrix and penguin diagram contributions, modifying the effective Wilson coefficient C_L.

$$\mathcal{H}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} \sum_i V^i_{CKM}(C_L\mathcal{O}_L + C_R\mathcal{O}_R)$$

$$\mathcal{O}_L = \frac{e^2}{16\pi^2}\bar{s}\gamma_\mu P_L b\bar{\nu}(1-\gamma_5)\nu$$

and $C_L = \frac{X'}{\sin^2\theta_W}$.

$$
\begin{aligned}
C_{10}^{NP} = C_{10,\mathrm{SM}} &- \frac{U_{sb}}{\lambda_t}\frac{\pi}{\alpha} - \frac{U_{sb}}{\lambda_t}\frac{M_D^2}{M_W^2}\left\{\frac{1}{48}\left[\left(\frac{-2}{\epsilon} - \frac{1}{2} + \frac{x_1^2 \log x_1}{(1-x_1)^2} + \frac{x_1}{1-x_1}\right)\right.\right. \\
&+ \left.\left(\frac{-2}{\epsilon} - \frac{1}{2} + \frac{x_2^2 \log x_2}{(1-x_2)^2} + \frac{x_2}{1-x_2}\right)\right] \\
&+ \left(\frac{\frac{-1}{2} + \frac{1}{3}\sin^2\theta_W}{16\sin^2\theta_W}\right)\left[\left(\frac{1}{\epsilon} + \frac{3}{4} - \frac{x_1^2 \log x_1}{2(1-x_1)^2} - \frac{1}{2(1-x_1)}\right)\right. \\
&+ \left.\left.\left(\frac{1}{\epsilon} + \frac{3}{4} - \frac{x_2^2 \log x_2}{2(1-x_2)^2} - \frac{1}{2(1-x_2)}\right)\right]\right\}
\end{aligned}
$$

$B \to K\nu\bar{\nu}$ in VQM

The branching ratio of $B \to K\nu\bar{\nu}$ with the contribution of vector-like quarks using form factor from LCSR,

$$\frac{dB(B \to K\nu\bar{\nu})}{dSB} = \frac{G_F^2 \alpha^2 M_B^5}{256\pi^5 \sin^4\theta_W} X'^2 \tau_B |V_{ts}^* V_{tb}|^2 \lambda^{\frac{3}{2}} f^2(K),$$

By using the fit parameters, and SB varing from [0,0.82]; we get the Total branching ratio,

$$\int \lambda^{\frac{3}{2}} f^2(K) dSB = 0.0719497$$

$$BR(B \to K\nu\bar{\nu}) = \frac{G_F^2 \alpha^2 M_B^5}{256\pi^5 \sin^4\theta_W} X'^2 \tau_B |V_{ts}^* V_{tb}|^2 \int \lambda^{\frac{3}{2}} f^2(K) dSB,$$

Effect on Rare B-Decays

- There is an experimental discrepancy in the result of branching ratio $B \to K\nu\bar{\nu}$ with the Standard Model from Belle-II
- For numerical results we first constraint the phase space of the New Physics parameter by using $B_s \to \mu^+\mu^-$.

$$\mathrm{BR}^{\mathrm{NP}}(B_s \to \mu^+\mu^-) = \mathrm{BR}^{\mathrm{SM}} \left| 1 + \frac{C_{10}^{\mathrm{NP}}}{C_{10}^{\mathrm{SM}}} \right|^2$$

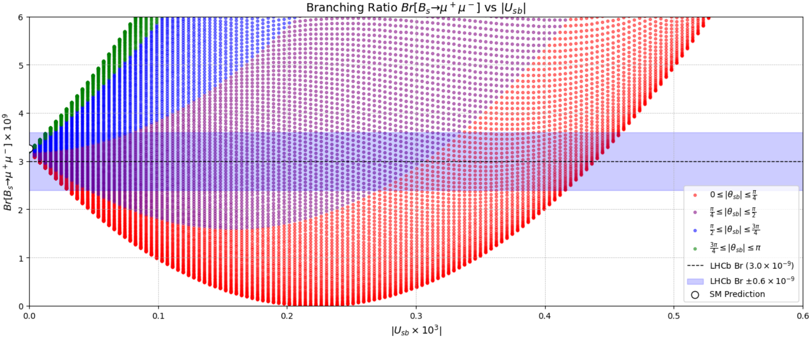
- Z-like exchange from VLQs modifies branching ratios, with New Physics parameters

$$U_{sb} = |U_{sb}|\, e^{i\theta_{sb}}$$

$$r_{sb} = \left| \frac{U_{sb}}{V_{tb}V_{ts}^*} \right|, \quad \theta_{sb} = arg \left| \frac{U_{sb}}{V_{tb}V_{ts}^*} \right|$$

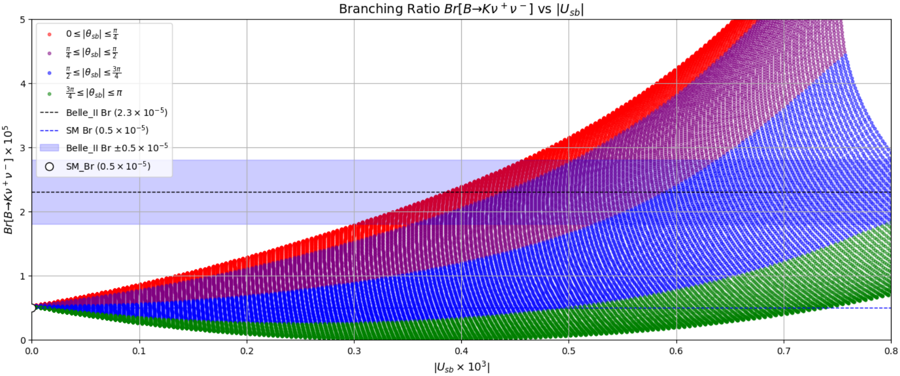
Numerical Analysis

The Standard Model Prediction $\mathrm{BR}(B_s \to \mu^+\mu^-) = (3.23 \pm 0.27) \times 10^{-9}$
Belle-II Result $\mathrm{BR}(B_s \to \mu^+\mu^-) = (3.0 \pm 0.6) \times 10^{-9}$



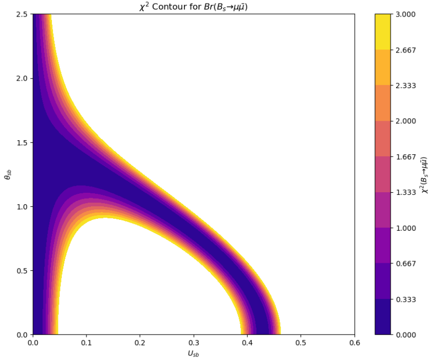
Numerical Analysis

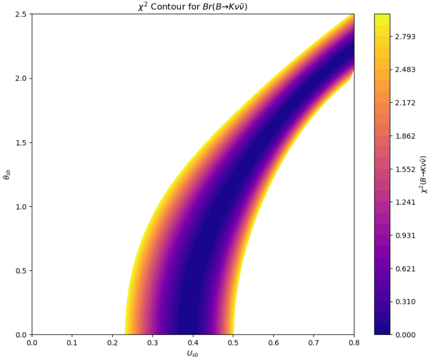
The Standard Model Prediction BR$(B \to K\nu\bar{\nu}) = (0.5 \pm 0.27) \times 10^{-5}$
The Experimental Result BR$(B \to K\nu\bar{\nu}) = (2.3 \pm 0.5) \times 10^{-5}$



χ^2 Analysis and Constraints

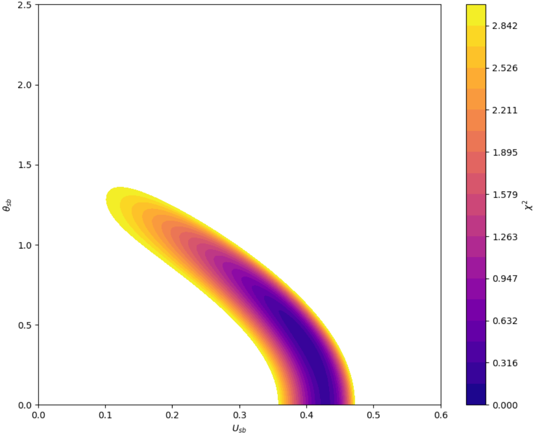
Improved fit to $B_s \to \mu^+\mu^-$ by $\sim 20\%$ for ($M_D < 1.5$ TeV)





Total χ^2 Analysis

- NP contributions from VLQs improve fits to observed data



Conclusion

- Rare B decays continue to be valuable probes of Physics beyond the SM.
- Rare decays provide powerful, indirect constraints.
- The presence of VLQ has expanded the phase space of $B_s \to \mu^+\mu^-$ and $B \to K\nu^+\nu^-$ for $M_D < 1.5 TeV$.
- VLQs provide viable explanations for observed tensions in $B \to K\nu^+\nu^-$, and large enhancement is possible which can explain the B-Anomalies.
- This model can modify angular observables, and other characteristics of the rare B-decay processes.
- Extensions: CP violation, global flavor fits, precision in $B \to K^{(*)}\nu\bar{\nu}$, angular observables.

Thank You!

Questions?

References

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Back UP

Back Up

$B \to K\nu\bar{\nu}$ in VQM

There is an experimental discrepancy in the result of branching rat$B \to K\nu\bar{\nu}$ with the standard model model model by 3σ, we have calculated the branching ratio of $B \to K\nu\bar{\nu}$ with the contribution of vector-like quarks,

$$\frac{dB(B \to K\nu\bar{\nu})}{dSB} = \frac{G_F^2 \alpha^2 M_B^5}{256\pi^5 \sin^4\theta_W} X'^2 \tau_B |V_{ts}^* V_{tb}|^2 \lambda^{\frac{3}{2}} f^2(K),$$

where we used the LCSR form factors,

$$f_K(q^2) = \frac{r_1}{1-(\frac{q}{m_1})^2} + \frac{r_2}{(1-(\frac{q}{m_1})^2)^2}$$

By using the fit parameters, we have

$$f(K) = \frac{0.162}{1 - SB(\frac{M_B}{5.41})^2} + \frac{0.173}{(1 - SB(\frac{M_B}{5.41})^2)^2}$$

$$\lambda = SB^2 + (\frac{m_k}{M_B})^4 + 1 - 2\left(SB(\frac{m_k}{M_B})^2 + (\frac{m_k}{M_B})^2 + SB\right)$$

SB varies from [0,0.82]; we get the Total branching ratio by integrating over SB,

$$\int \lambda^{\frac{3}{2}} f^2(K) dSB = 0.0719497$$

$$BR(B \to K\nu\bar{\nu}) = \frac{G_F^2 \alpha^2 M_B^5}{256\pi^5 \sin^4\theta_W} X'^2 \tau_B |V_{ts}^* V_{tb}|^2 \int \lambda^{\frac{3}{2}} f^2(K) dSB,$$

The X' here includes the contribution of standard Model as well as Vector like quarks (NP parameter).