PROBING NEW PHYSICS: VECTOR LIKE QUARKS IN RARE B-DECAYS

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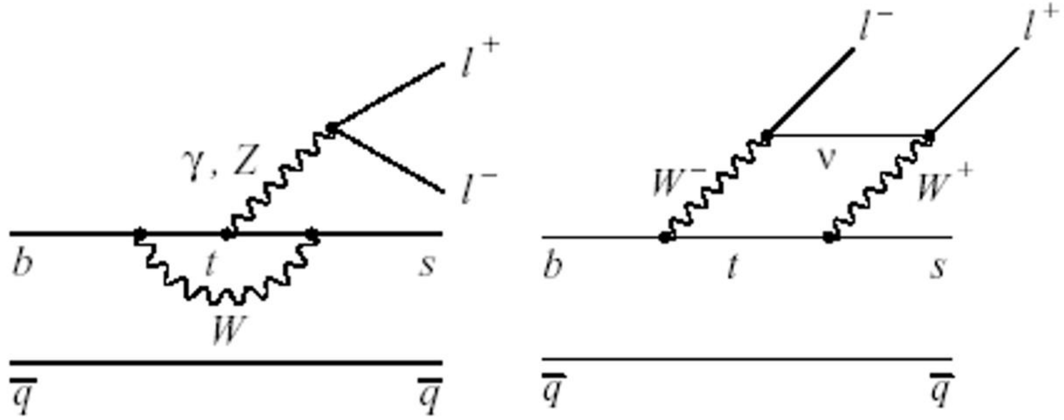

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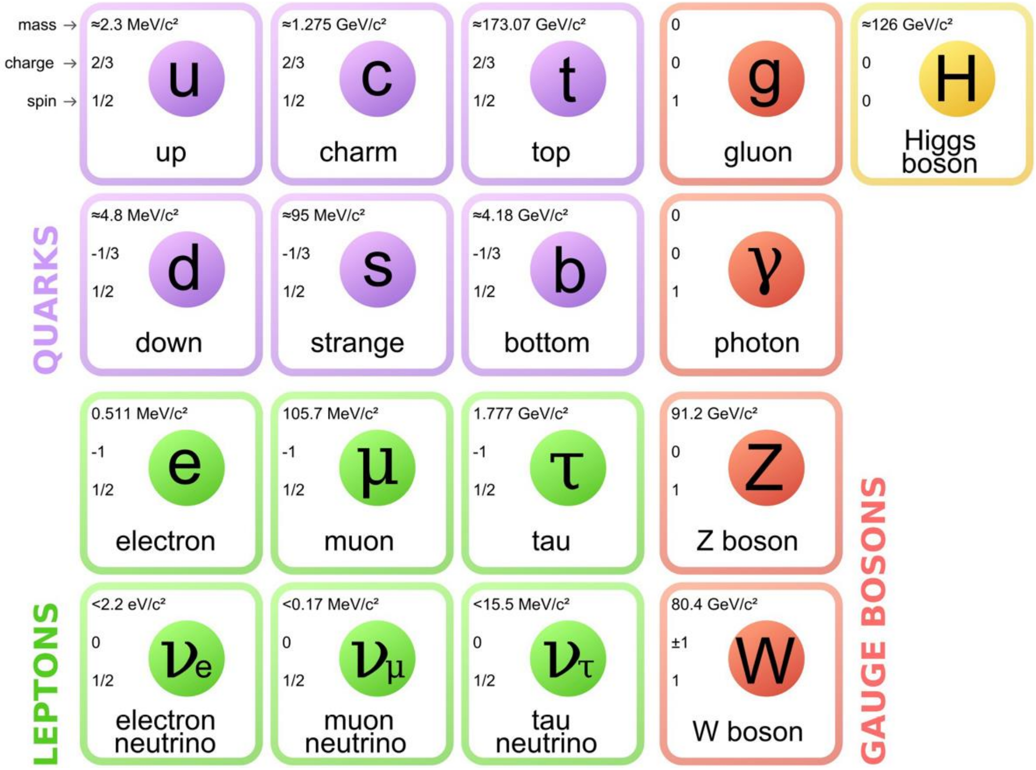
OVERVIEW

- Motivation
- Standard Model
- Rare B-Decays
- Physics Beyond Standard Model
- Rare B-Decays in VQM
- Results & Conclusion
- References

MOTIVATION

- Rare B-decays are highly suppressed in the SM -- sensitive probes of New Physics (NP)
- Anomalies in Rare 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 beyond Standard Model.

STANDARD MODEL AND ITS LIMITATIONS



- SM doesn't provide explanation for

1. Dark Matter and Dark Energy
2. Neutrino Masses
3. Matter-antimatter Asymmetry
4. Cannot explain observed lepton flavor universality violation (LFUV)
5. Fails to explain B-anomalies
6. Flavor Physics puzzles

STANDARD MODEL

- Standard Model Lagrangian, . $\mathcal{L}_{SM} = \mathcal{L}_{K+G} + \mathcal{L}_H + \mathcal{L}_Y$
- After Symmetry Breaking, Fermion Mass term is

$$-\overline{\psi_L^u}\,\widehat{M_1}\,\psi_R^u - \overline{\psi_R^u}\,\widehat{M_1^\dagger}\,\psi_L^u - \overline{\psi_L^d}\,\widehat{M_2}\,\psi_R^d - \overline{\psi_R^d}\,\widehat{M_2^\dagger}\,\psi_L^d .$$

Where, $\widehat{M_1} = \frac{v}{\sqrt{2}}\widehat{Y_u}$, $\widehat{M_2} = \frac{v}{\sqrt{2}}\widehat{Y_d}$

- Rotation to Mass Eigenstates, $\psi^u = A_1\psi^u$ and $\psi^d = A_2\psi^d$ with $A_1^\dagger A_1 = A_2^\dagger A_2 = 1$
- Hence Mass Matrices are diagonalized, $A_1^\dagger \widehat{M_1} A_1 = \begin{pmatrix} m_u & & \\ & m_c & \\ & & m_t \end{pmatrix}$

STANDARD MODEL

- CKM-Matrix is a unitary matrix, it connects the weak eigenstates with the mass eigenstates.

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

- CKM-Matrix allows non-diagonal couplings of the charged currents.
- $\mathrm{V_{CKM}} = \mathrm{A_1^\dagger A_2}$, $\quad \mathrm{V_{CKM}}^\dagger \mathrm{V_{CKM}} = \mathbb{I}$
- The unitarity of the CKM matrix assures the absence of elementary FCNC vertices. Hence, No flavor changing neutral currents (FCNC) in the standard model at tree-level, (require Loop process).

RARE B-DECAYS

- Loop-level decays mediated by weak interaction. (Flavor Changing Neutral Currents)
- Transition strongly suppressed: (loops, CKM elements, sometimes GIM mechanism)

Q: How are rare decays of B mesons connected to NP (New Physics) ?

- FCNCs are forbidden at tree level due to GIM mechanism, but occur at loop level in the penguin and box diagrams, transitions like b $\rightarrow$ s and s$\rightarrow$ d are possible and they are perfect for indirect discovery: even small contributions have large effects on rare decays.
- The rare radiative decays like $B \rightarrow X_s\gamma$ and semi-leptonic decays $B \rightarrow X_s l^+ l^-$, more specifically $B \rightarrow K\, \upsilon\bar{\upsilon}$ are sensitive probes of new Physics.
- In the SM at the one-loop level they can be described by a set of basic effective vertices.
- Effective Hamiltonian

$$\mathcal{H}_{eff} = \frac{G_F}{\sqrt{2}} \sum_i V_{CKM}^i \, C_i O_i$$

EFFECTIVE VERTICES

- Using the Feynman rules, we can get effective vertices for a particular process, eventually leading to Wilson coefficients.

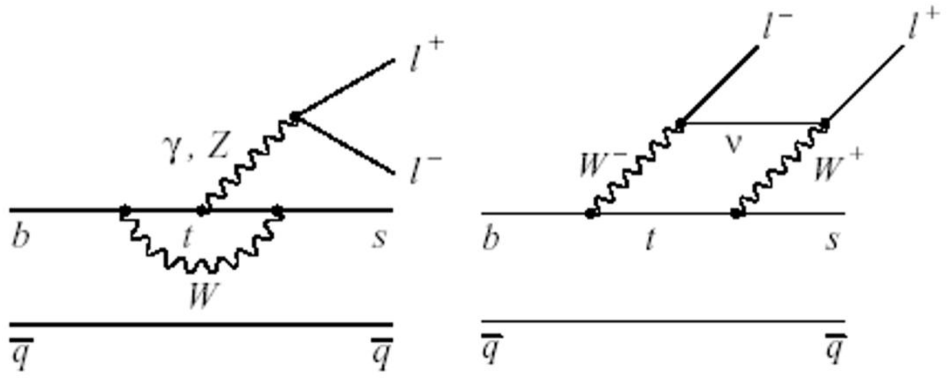
$$\bar{s}\, Zb = i\lambda_i \frac{G_F}{\sqrt{2}} \frac{e}{2\pi^2} M_Z^2 \frac{\cos\theta_W}{\sin\theta_W} C_0(x_i)\bar{s}\gamma^\mu(1-\gamma^5)b$$

Where, λ_i=$V_{is}^{*}V_{ib}$

- Wilson Coefficient for $B \to X_s l^+ l^-$, are related to functions like $C_0(x_i)$, top quark is dominant x_t= $\frac{m_t^2}{M_W^2}$.
- $C_7 = -\frac{1}{2} D'_0(x_i)$
- $C_9 = \frac{(Y_0(x_i) - 4sin^2\theta_W Z_0(x_i))}{sin^2\theta_W}$
- $C_{10} = -\frac{Y_0(x_i)}{sin^2\theta_W}$

$Y_0(x_i)$= $C_0(x_i)$- $B_0(x_i)$

$Z_0(x_i)$= $C_0(x_i)$- 1/4$D_0(x_i)$



PHYSICS BEYOND STANDARD MODEL

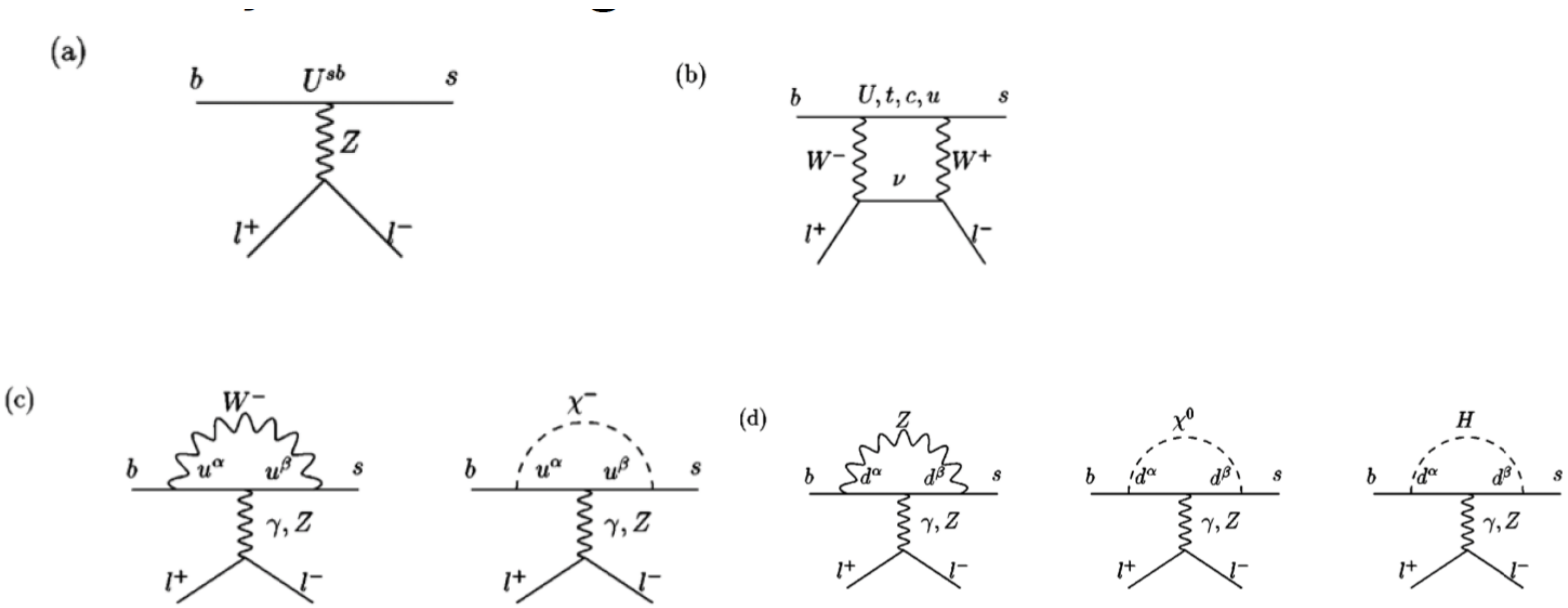
- **VECTOR LIKE QUARKS**

One New Physics Scenario is augmenting the Standard Model with additional down-type Vector Like Quarks, which leads to a non-unitary extended quark mixing matrix.

- VLQ-- A spin 1/2 fermion, color triplet (fundamental rep of SU(3)) and have higher masses than the Standard Model quarks, which makes them more difficult to detect at detectors.
- The same SM quantum numbers for L and R chiralities, and they are SU(2) singlet, leading to a non-unitary CKM matrix with a new parameter.
- $U^{\alpha\beta} = \sum_{i=u,c,t} A^{\alpha 4}\ A^{\beta 4*} \neq 0, For\ \alpha \neq \beta$

$U^{\alpha\beta}$ 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.

RARE B-DECAYS IN VQM



RARE B-DECAYS 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.

$$\mathcal{H}_{eff} = \frac{G_F}{\sqrt{2}} \sum_i V^i_{CKM} \, (C_L O_L + C_R O_R)$$

where $O_L = \frac{e^2}{16\pi^2} \gamma_\mu \bar{s}(\gamma_\mu P_L) b \bar{\nu}(1-\gamma_5)\nu$ and $O_R = \frac{e^2}{16\pi^2} \gamma_\mu \bar{s}(\gamma_\mu P_R) b \bar{\nu}(1-\gamma_5)\nu$

- Using the results coming from effective Hamiltonian, while considering extra generation of quark (VLQ), we have calculated the effective vertices for the one-loop level calculations of, $B \to$ K $\nu\bar{\nu}$.
- Branching Ratio $B \to K\nu\bar{\nu}$, including the additional diagrams (tree-level and Higgs loops) using form factors from LCSR,
- $f(k) = \frac{0.162}{1-SB(\frac{M_B}{5.41})^2} + \frac{0.173}{(1-SB(\frac{M_B}{5.41})^2)^2}$. , $\lambda = SB^2 + (\frac{m_k}{M_B})^4 + 1 - 2\left(SB(\frac{m_k}{M_B})^2 + (\frac{m_k}{M_B})^2 + SB\right)$
- SB varies from [0,0.82]; we get the Total branching ratio by integrating over SB,

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

- Here X' contains the New Physics parameter U_{sb},
- $X' = X_{SM} + \frac{U_{sb}}{V_{ts}^8 V_{tb}} \begin{Bmatrix} \frac{\pi}{\alpha} sin^2\theta_W + \frac{1}{48}\frac{M_D^2}{M_W^2} sin^2\theta_W \left((\frac{-2}{\epsilon} - \frac{1}{2} + \frac{x_1^2 \log(x_1)}{(1-x_1)^2} + \frac{x_1}{(1-x_1)}) + (\frac{-2}{\epsilon} - \frac{1}{2} + \frac{x_2^2 \log(x_2)}{(1-x_2)^2} + \frac{x_2}{(1-x_2)}) \right) \\ +(\frac{\frac{-1}{2}+\frac{1}{3}sin^2\theta_W}{16}) \frac{M_D^2}{M_W^2} \left((\frac{1}{\epsilon} + \frac{3}{4} - \frac{x_1^2 \log(x_1)}{2(1-x_1)^2} - \frac{1}{2(1-x_1)}) + (\frac{1}{\epsilon} + \frac{3}{4} - \frac{x_2^2 \log(x_2)}{2(1-x_2)^2} - \frac{1}{2(1-x_2)}) \right) \end{Bmatrix}$

NEW PHYSICS PARAMETERS

- For numerical results we first constraint the phase space of the New Physics parameter by using $Bs \rightarrow \mu^+\mu^-$ and $B\rightarrow X_s\ \mu^+\mu^-$.
- Modified Branching Ratio: $BR^{NP}(Bs \rightarrow \mu^+\mu^-\ ) = BR^{SM}\left|1+\frac{C_{10}^{NP}}{C_{10}^{SM}}\right|^2$, with New Physics Parameters r_{sb} and θ_{sb},
- $r_{sb} = \left|\frac{U_{sb}}{V_{tb}V_{ts}^*}\right|, \theta_{sb} = arg\left|\frac{U_{sb}}{V_{tb}V_{ts}^*}\right|$
- Using the C_{10}^{NP},
- $$C_{10}^{NP}=C_{10}^{SM} - \frac{U_{sb}}{V_{ts}^8 V_{tb}}\left\{\begin{array}{c} \frac{\pi}{\alpha}+\frac{1}{48}\frac{M_D^2}{M_W^2}\left(\left(\frac{-2}{\epsilon}-\frac{1}{2}+\frac{x_1^2\log(x_1)}{(1-x_1)^2}+\frac{x_1}{(1-x_1)}\right)+\left(\frac{-2}{\epsilon}-\frac{1}{2}+\frac{x_2^2\log(x_2)}{(1-x_2)^2}+\frac{x_2}{(1-x_2)}\right)\right) \\ +\left(\frac{\frac{-1}{2}+\frac{1}{3}sin^2\theta_W}{16sin^2\theta_W}\right)\frac{M_D^2}{M_W^2}\left(\left(\frac{1}{\epsilon}+\frac{3}{4}-\frac{x_1^2\log(x_1)}{2(1-x_1)^2}-\frac{1}{2(1-x_1)}\right)+\left(\frac{1}{\epsilon}+\frac{3}{4}-\frac{x_2^2\log(x_2)}{2(1-x_2)^2}-\frac{1}{2(1-x_2)}\right)\right)\end{array}\right\}$$

CONSTRIANTS ON NEW PHYSICS PARAMETERS

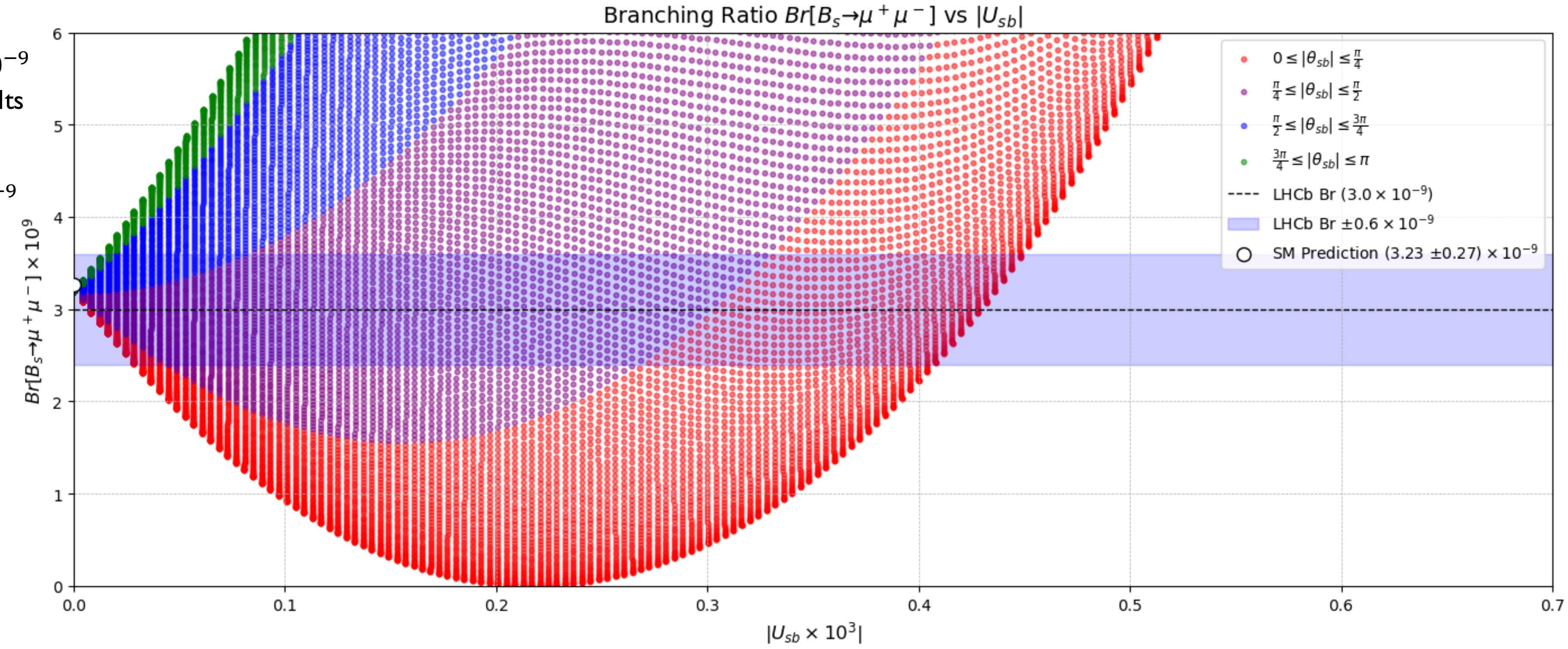
The Standard Model

$BR(Bs \rightarrow \mu^+\mu^-)$
$= (3.23 \pm 0.27) \times 10^{-9}$

The experimental results from LHCb

$BR(Bs \rightarrow \mu^+\mu^-)$
$= (3.0 \pm 0.6) \times 10^{-9}$

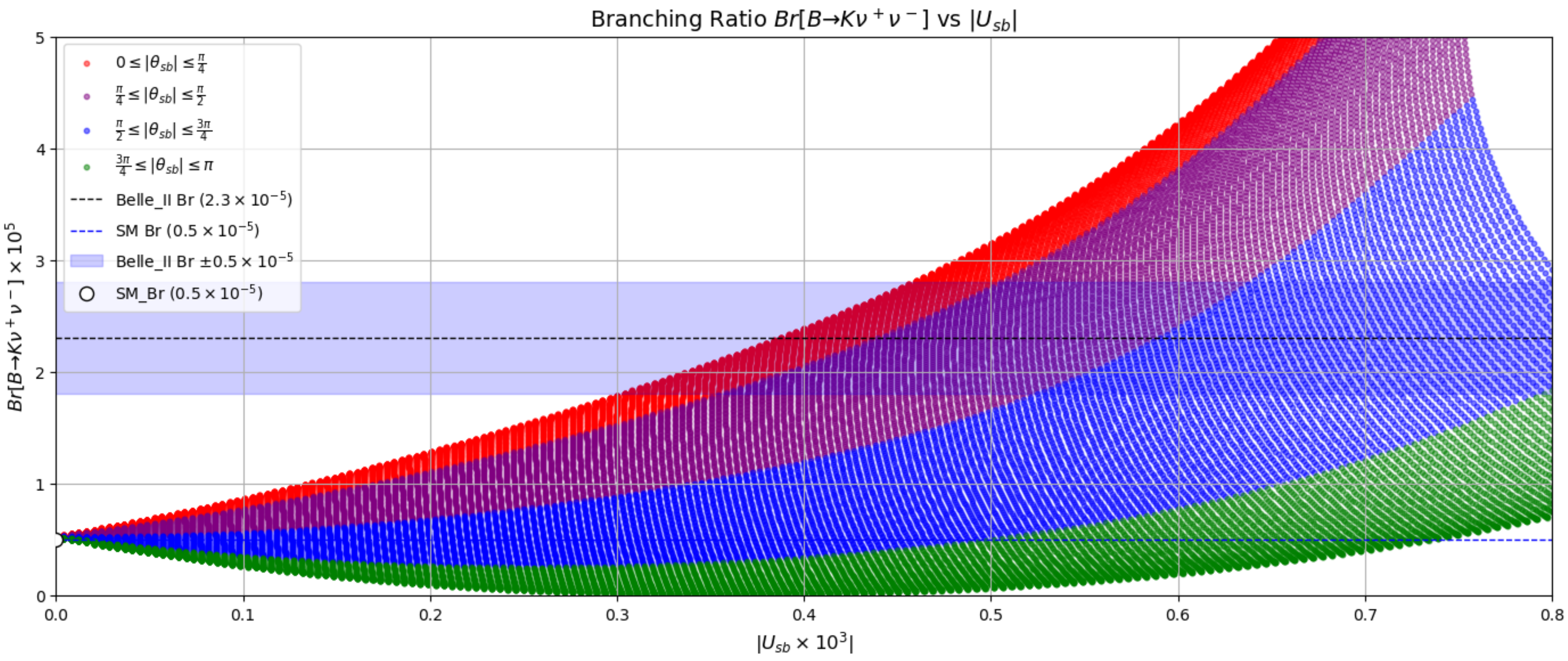
$U_{sb} = |U_{sb}|e^{i\theta_{sb}}$



BRANCHING RATIO ENHANCEMENT

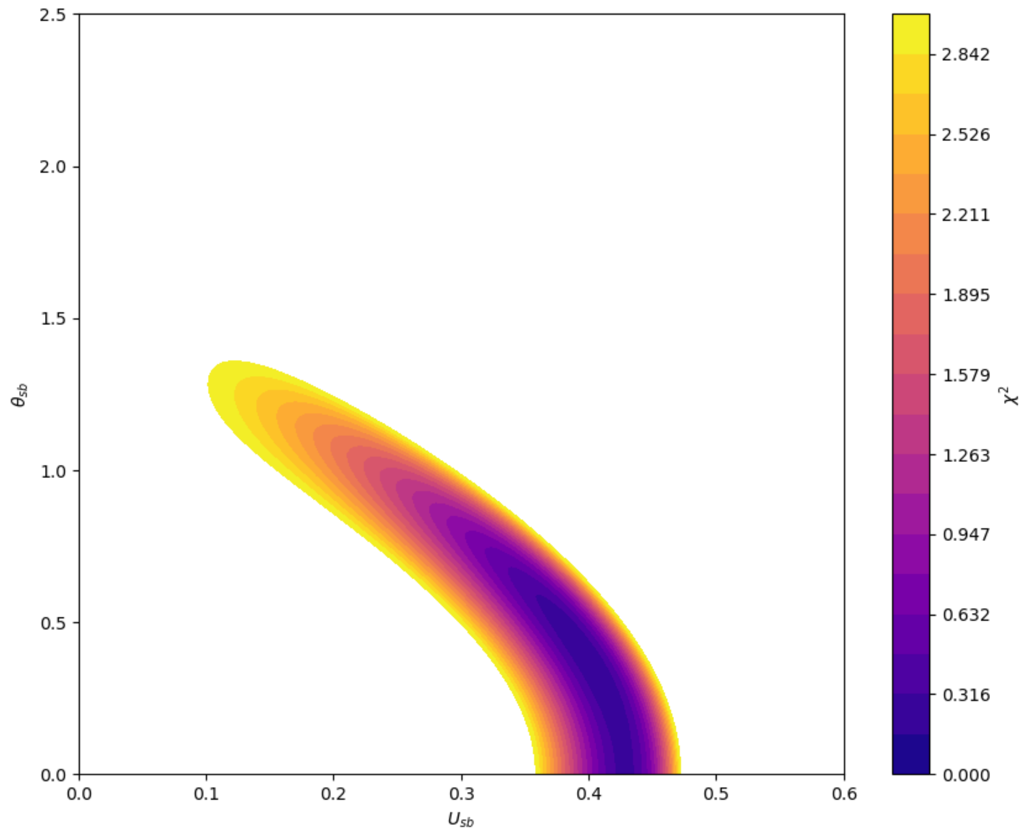
The Standard Model
$BR(B \rightarrow K\,\nu\nu) = (0.5) \times 10^{-5}$
Whereas the experimental results from Belle-II
$BR(B \rightarrow K\,\nu\nu)$
$= (2.3 \pm 0.7) \times 10^{-5}$
Which lies 2.7σ above Standard Model.

Addition of Vector like quarks has enhanced the Branching ratio $BR(B \rightarrow K\,\nu\nu)$.



CHI-SQUARED ANALYSIS

The Numerical Evaluation and χ^2 plots gives significant enhancement in the Branching ratio of $B \to K\upsilon\bar{\upsilon}$ indicating that Vector Like Quark Model is promising New Physics candidate Beyond Standard Model.



CONCLUSION

- Rare B decays continue to be valuable probes of physics beyond the SM.
- The presence of VLQ has expanded the phase space of $Bs \to \mu^+\mu^-$ for M_D <1.5 TeV.
- One cannot neglect the effect when the VLQ mass is much heavier than the EW scale. When $M_D/M_W \sim 10$, may expect about 10% corrections to the Wilson coefficients.
- Numerical results validate theoretical expectations and VLQs provide viable explanations for observed tensions in $B \to K\upsilon\bar{\upsilon}$, 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.
- Future data from LHCb and Belle-II will further test these models

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Thank You!