EXPLORING THE INFLUENCE OF VECTOR-LIKE QUARKS (VLQS) IN RARE B-DECAYS

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OVERVIEW

Standard Model and its Limitations

Rare B-Physics and its significance in probing New Physics

Physics Beyond Standard Model

Vector Like Quarks (VLQs)

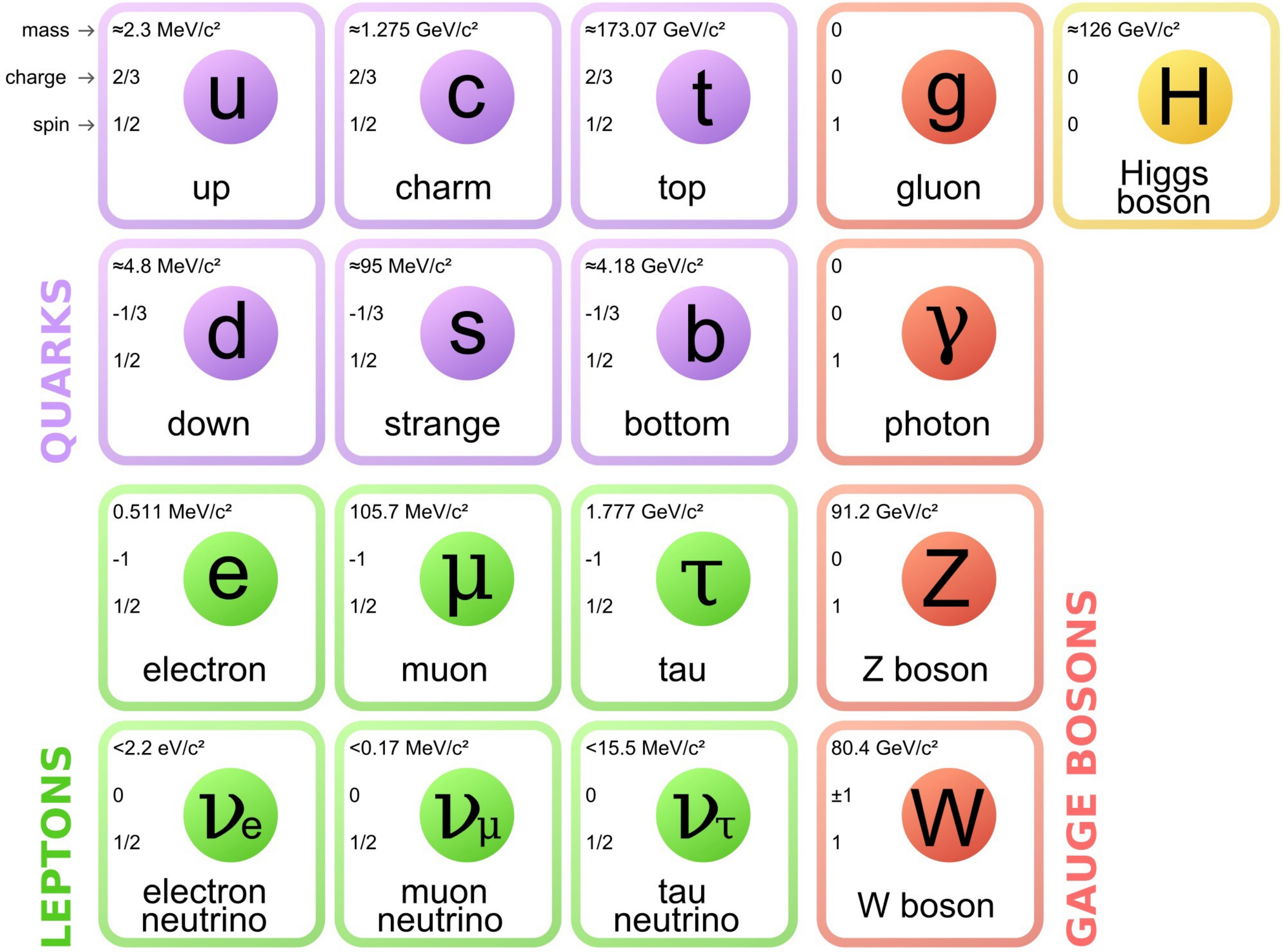
Impacts of VLQs in B-decays

Conclusion

STANDARD MODEL AND ITS LIMITATIONS

- The Standard Model is not actually a model. It is an incredibly successful theory that provides our best description of the subatomic particles and the fundamental forces that drive their interactions.
- The SM successfully unifies the electromagnetic and weak forces into the electroweak force, providing a comprehensive framework for understanding particle interactions.
- SM doesn't provide explanation for

1. Dark Matter and Dark Energy
2. Neutrino Masses
3. Baryogenesis
4. Matter-antimatter Asymmetry
5. Hierarchy problem
6. Flavor Physics puzzles



STANDARD MODEL

- Gauge Symmetry $SU(3)_c \times SU(2)_L \times U(1)_Y$. $\xrightarrow[\text{Higgs Mechanism}]{\text{Symmetry Breaking}}$ $SU(3)_c \times U(1)_Y$

- SM Lagragian,

$$\mathcal{L}_{SM} = \mathcal{L}_{Kinetic+guage} + \mathcal{L}_{Higgs} + \mathcal{L}_{Yukawa}$$

flavor physics

- After Symmetry Breaking

$$\mathcal{L}_{yukawa} = -(\bar{\Psi}_L \Phi^c Y_u u_R + \bar{u}_R \Phi^{c\dagger} Y_u^* \Psi_L) - (\bar{\Psi}_L \, \Phi Y_d d_R + \bar{d}_R \Phi^\dagger Y_d^* \Psi_L)$$
$$= -\frac{vY_u}{\sqrt{2}}(\bar{u}_L u_R + \bar{u}_R u_L) - \frac{vY_d}{\sqrt{2}}(\bar{d}_L d_R + \bar{d}_R d_L)$$

Flavor(weak) eigenstates

$$\Psi^u = \begin{pmatrix} u \\ c \\ t \end{pmatrix}, \quad \Psi^d = \begin{pmatrix} d \\ s \\ b \end{pmatrix},$$

- Fermion Mass term

$$-\bar{\Psi}_L^u \widehat{M}_1 \Psi_R^u - \bar{\Psi}_R^u \widehat{M}_1^\dagger \Psi_L^u - \bar{\Psi}_L^d \widehat{M}_2 \Psi_R^d - \bar{\Psi}_R^d \widehat{M}_2^\dagger \Psi_L^d$$

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

$$\Psi^u \to A_1 \Psi^u \; with \; A_1^\dagger A_1 = 1$$
$$\Psi^d \to A_2 \Psi^d \; with \; A_2^\dagger A_2 = 1$$

- Transform Mass Matrices

$$A_1^\dagger \widehat{M}_1 A_1 = \frac{v}{\sqrt{2}} A_1^\dagger \widehat{Y}_u A_1 = \begin{pmatrix} m_u & & \\ & m_c & \\ & & m_t \end{pmatrix}$$

$$A_2^\dagger \widehat{M}_2 A_2 = \frac{v}{\sqrt{2}} A_2^\dagger \widehat{Y}_d A_2 = \begin{pmatrix} m_d & & \\ & m_s & \\ & & m_b \end{pmatrix}$$

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

$V_{CKM} = A_1^{\dagger} A_2$

$V^{\dagger} V = A_2^{\dagger} A_1 A_1^{\dagger} A_2 = \mathbf{1}$

- CKM-Matrix allows non-diagonal couplings of the charged currents.

$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

- No flavor changing neutral currents (FCNC) in the standard model at tree-level.(require Loop process)
- Charged current Interaction is the only flavor changing process in SM.

$$\mathcal{L}_{cc} = \frac{g}{2\sqrt{2}} \sum_{i=1}^{3} \bar{u}_i \gamma^{\mu} (1 - \gamma_5)\, W_{\mu}^{-} d_i$$

$$\mathcal{L}_{Nc} = \frac{g}{2\sqrt{2}} \sum_{i=1}^{3} \bar{u}_i \gamma^{\mu} (a + b\gamma_5)\, Z_{\mu} u_i$$

RARE B DECAYS

Q: What is a rare decay of a B meson ?

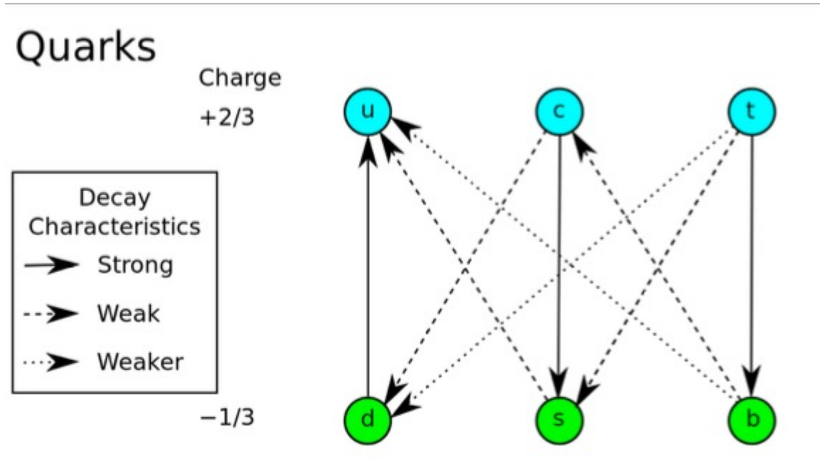
Ans 1: A decay that is suppressed.

- **Loop-level decays mediated by weak interaction** (Flavour 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) ?

No FCNC at first order, but possible as higher order corrections!

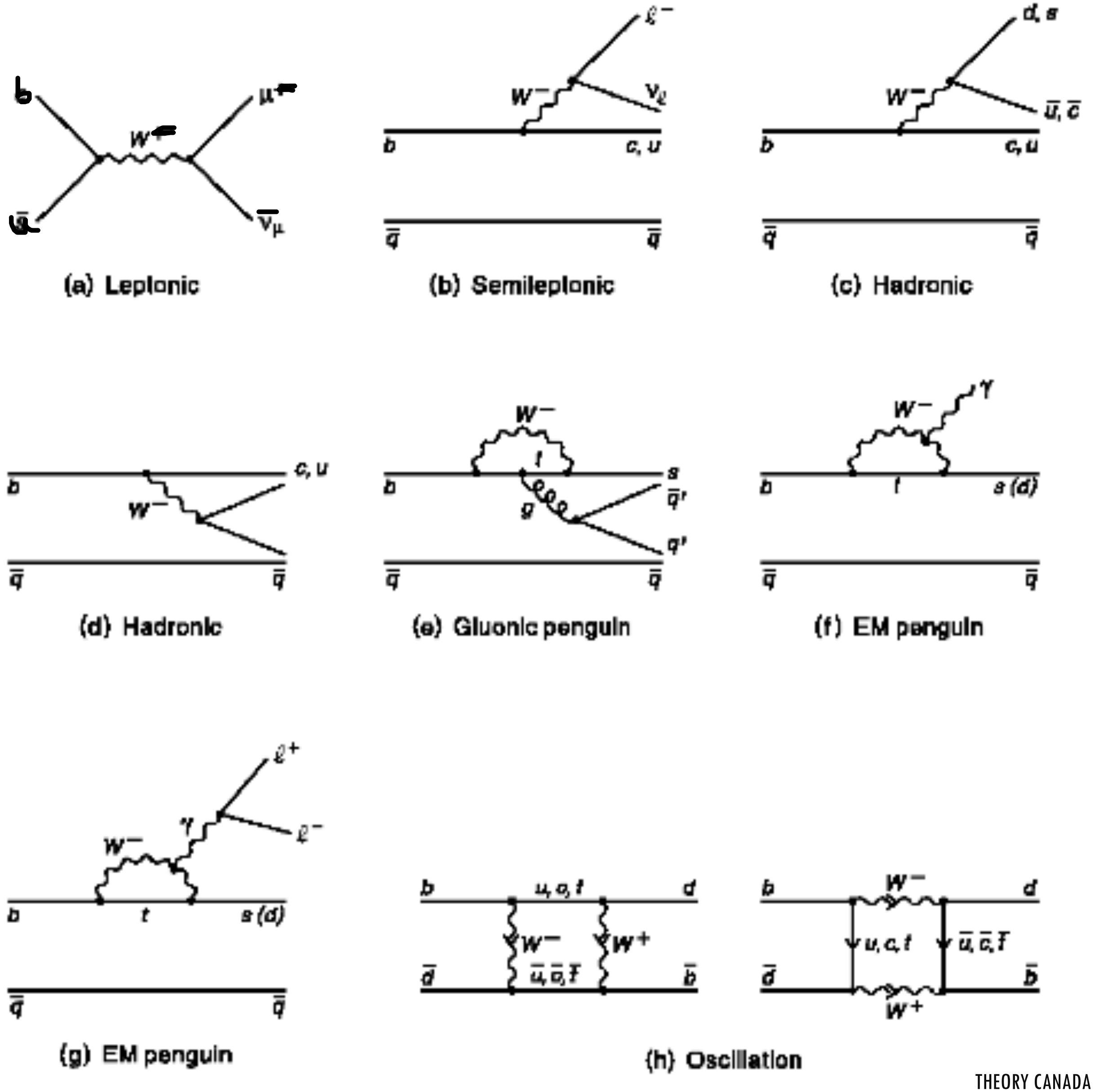
Perfect for indirect discovery: even small contributions have large effects on rare decays



Q: So which transitions give rise to rare decays ?

Ans 1: Decays that involve a jump in generations.
Ans 2: b→u decays
jumping generations is highly suppressed

FEYNMAN DIAGRAMS OF B-DECAY



PHYSICS BEYOND STANDARD MODEL

- GIM Mechanism ------- NP

Glashow Iliopoulus Maiani Mechanism, suppresses FCNC due to cancellation of weak amplitudes with opposite signs.

- Vector Quark Model (VQM)-------Extension of SM

1. CKM matrix is non-Unitary
2. FCNC at Tree level ($Zs\bar{b}$)

- The rare radiative decays like $B \to X_s\gamma$ and $B \to X_s l^+ l^-$ are sensitive probes of new Physics.
- B ⟶ Xsγ constrains the parameters of the VQM, since vectorlike down-type quark contributions to b ⟶ sγ just occur at loop level as the case of the SM,
- The constraints on zsb, the tree level FCNC coupling for b ⟶ sZ, from B ⟶ Xsγ are less restrictive compared to those from processes governed by b ⟶ sl^+l^- transition.

VECTOR LIKE QUARKS (VLQS)

1. A spin 1/2 fermion
2. Same SM quantum numbers for L and R chiralities, SU(2) singlet
3. color triplet (fundamental rep of $SU(3)_C$
4. Higher masses than Standard Model quarks, which makes them more difficult to detect.

Standard Model

1. Yukawa Coupling:

i,j=1,2,3 $$-f_d^{ij}\bar{\psi}_L^i d_R^j \phi - f_u^{ij}\bar{\psi}_L^i u_R^j \tilde{\phi} + \text{H.c.},$$

2. Spontaneous Symmetry Breaking

$$-\bar{\Psi}_L^u \widehat{M}_1 \Psi_R^u - \bar{\Psi}_R^u \widehat{M}_1^\dagger \Psi_L^u - \bar{\Psi}_L^d \widehat{M}_2 \Psi_R^d \text{-} \bar{\Psi}_R^d \widehat{M}_2^\dagger \Psi_L^d$$

3. Rotation from weak to mass eigenstates

$$\Psi^u \to A_1 \Psi^u \,, \Psi^d \to A_2 \Psi^d$$

$$\left.\begin{aligned} A_1^\dagger \widehat{M}_1 A_1 &= \frac{v}{\sqrt{2}} A_1^\dagger \widehat{Y}_u A_1 \\ A_2^\dagger \widehat{M}_2 A_2 &= \frac{v}{\sqrt{2}} A_2^\dagger \widehat{Y}_d A_2 \end{aligned}\right\} \text{Diagonal}$$

4. CKM Matrix

$$V^\dagger{}_{CKM} V_{CKM} = A_2^\dagger A_1 A_1^\dagger A_2 = \mathbf{1}$$

5. **No FCNC** at tree-level

Vector Like Quarks

1. Yukawa Coupling $$-f_d^{ij}\bar{\psi}_L^i d_R^j \phi - f_u^{ij}\bar{\psi}_L^i u_R^j \tilde{\phi} + \text{H.c.},$$

Additionally $$-f_d^{i4}\bar{\psi}_L^i D_R \phi - f_u^{i4}\bar{\psi}_L^i U_R \tilde{\phi} + \text{H.c.},$$

2. Spontaneous Symmetry Breaking

$$\bar{d}_L^\alpha M_d^{\alpha\beta} d_R^\beta + \bar{u}_L^\alpha M_u^{\alpha\beta} u_R^\beta + \text{H.c.},$$

where Md and Mu are 4x4 mass matrices and α, β =1 . . . 4 cover ordinary and vectorlike quarks.

3. Rotation from weak to Mass eigenstates

$$u_{L,R}^\alpha \equiv A^{\alpha\beta} u_{L,R}^{\beta\prime} \,,\, d_{L,R}^\alpha \equiv A^{\alpha\beta} d_{L,R}^{\beta\prime}$$

Where $A_L^{d\dagger} M_d A_R^d$, $A_L^{u\dagger} M_u A_R^u$ are diagonal.

4. CKM Matrix

$$U^{\alpha\beta} \equiv \sum_{i=1}^{3} V^{\alpha i} V^{\beta i*} = \sum_{i=1}^{3} V_{CKM}^{i\alpha*} V_{CKM}^{i\beta} = \delta_{\alpha\beta} - A^{\alpha 4} A^{4\beta}$$

5. In VQM, transformations lead to intergenerational mixing among quarks not only in the charged current sector but also in the neutral current interactions.

In this model, the gauge structure of the SM remains intact except for an additional pair of iso-singlet quarks, U and D, the Dirac mass terms of vector- like quarks, i.e.,
$m_U(\overline{U_L}U_R + \overline{U_R}U_L)+m_D(\overline{D_L}D_R + \overline{D_R}D_L)$
are invariant under electroweak gauge symmetry.

The charge current interaction term

$$J_{CC}^{W}{}^{\mu}=\sum_{i=1}^{3} I\frac{g}{\sqrt{2}}\bar{u}_L^i\gamma^\mu d_L^i W_\mu^+ + \mathrm{H.c.},$$

Transform to

$$J_{CC}^{W}{}^{\mu}=\sum_{\alpha,\beta=1}^{4} I\frac{g}{\sqrt{2}}\bar{u}_L'^{\alpha}V^{\alpha\beta}\gamma^\mu d_L'^{\beta}W_\mu^+ + \mathrm{H.c.},$$

where

$$V^{\alpha\beta}=\sum_{i=1}^{3}(A_L^{u\dagger})^{\alpha i}(A_L^{d})^{i\beta},$$

Neutral current coupled to z boson transforms as

$$J_{NC}^{Z}{}^{\mu}=I\frac{g}{\cos\theta_w}\left(I_w^q\sum_{i=1}^{3}\sum_{\alpha,\beta=1}^{4}\bar{q}'^{\alpha}_L\gamma^\mu q_L'^{\beta}(A_L^{q\dagger})^{\alpha i}A_L^{qi\beta}\right.$$
$$-Q_q\sin^2\theta_w\sum_{\delta=1}^{4}\sum_{\alpha,\beta=1}^{4}\bar{q}_L'^{\alpha}\gamma^\mu q_L'^{\beta}(A_L^{q\dagger})^{\alpha\delta}A_L^{q\delta\beta}$$
$$\left.+\bar{q}_R'^{\alpha}\gamma^\mu q_R'^{\beta}(A_R^{q\dagger})^{\alpha\delta}A_R^{q\delta\beta}\right)$$

$$=I\frac{g}{\cos\theta_w}\sum_{\alpha,\beta=1}^{4}(I_w^q U^{\alpha\beta}\bar{q}_L'^{\alpha}\gamma^\mu q_L'^{\beta}$$
$$-Q_q\sin^2\theta_w\delta^{\alpha\beta}\bar{q}'^{\alpha}\gamma^\mu q'^{\beta}),$$

IMPACT OF VLQS IN B-PHYSICS

- Tree level FCNC's in the Z sector. ----- Non-unitary of CKM Matrix
- Extra Quark in Loop
- Non-unitarity parameters $U^{\alpha\beta}(\alpha \neq \beta)$ appear at the one-loop level FCNC's as multiplicative factors for terms which are independent of the internal quark mass.

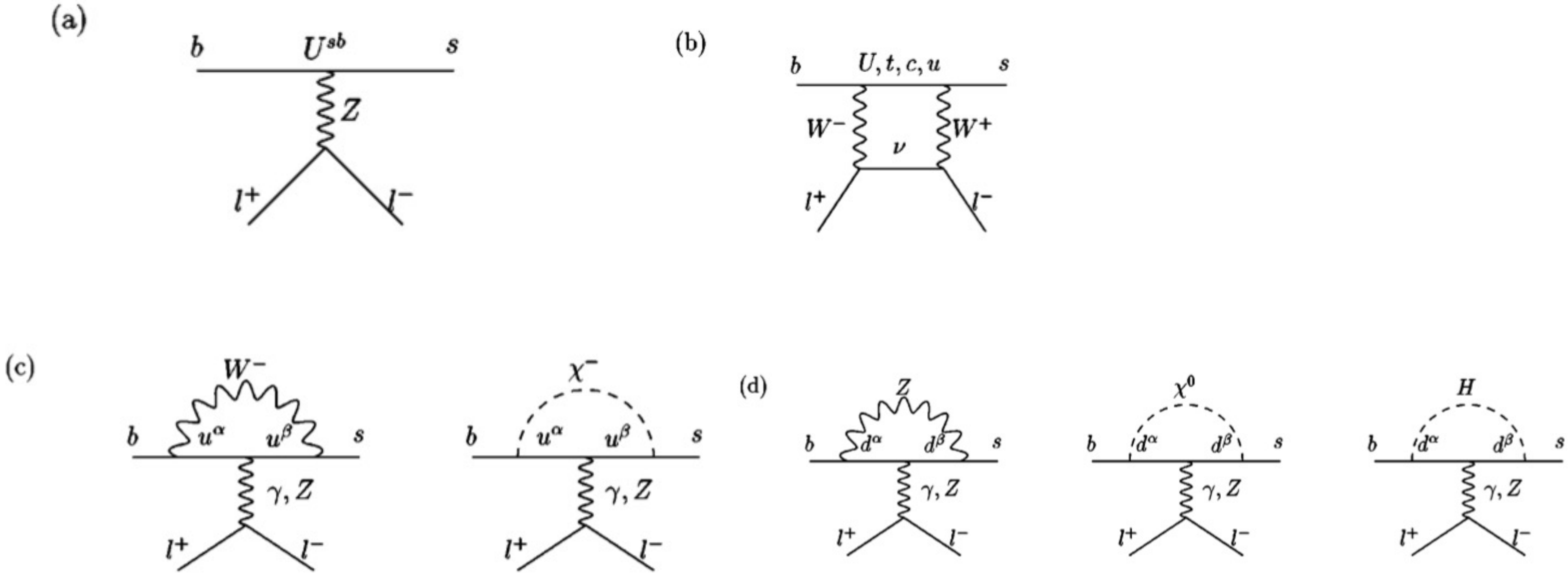
$$U^{\alpha\beta} = \sum_{i=1}^{3} (A_L^{qi\alpha})^* A_L^{qi\beta} = \delta^{\alpha\beta} - (A_L^{q4\alpha})^* A_L^{q4\beta}$$

$$= \begin{cases} (V^\dagger V)^{\alpha\beta}, & q \equiv \text{down-type} \\ (VV^\dagger)^{\alpha\beta}, & q \equiv \text{up-type}. \end{cases}$$

- FCNC in mass eigen state

$$J_{NC}^{Z\ \mu} = I \frac{g}{cos\theta_w} \sum_{\alpha,\beta=1}^{4} (I_w^q U^{\alpha\beta} \bar{q}'^{\alpha}_L \gamma^\mu q'^{\beta}_L - Q_q sin^2\theta_w \delta^{\alpha\beta} \bar{q}'^{\alpha}_L \gamma^\mu q'^{\beta}_L)$$

THE FEYNMANN DIAGRAMS



arXiv:hep-ph/0105049

RARE B DECAYS $B \to X_s l^+ l^-$ IN THE VQM

- Effective Lagrangian for $B \to X_s l^+ l^-$ can be written as

$$L_{\text{eff}} = \frac{G_F}{\sqrt{2}} (A \bar{s} L_\mu b \bar{l} L^\mu l + B \bar{s} L_\mu b \bar{l} R^\mu l + 2 m_b C \bar{s} T_\mu b \bar{l} \gamma^\mu l),$$

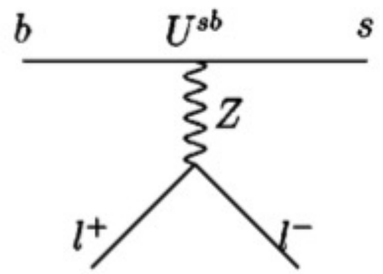
Where,

$$L_\mu = \gamma_\mu (1 - \gamma_5), \quad R_\mu = \gamma_\mu (1 + \gamma_5),$$

$$T_\mu = i \sigma_{\mu\nu} (1 + \gamma_5) q^\nu / q^2.$$

- In the VQM, the tree level FCNC diagram of Fig. 1a leads to the results

$$A^{\text{SD}}_{1(a)} = U^{sb}(-1 + 2 \sin^2 \theta_W), \quad B^{\text{SD}}_{1(a)} = U^{sb}(2 \sin^2 \theta_W) \qquad \text{(a)}$$

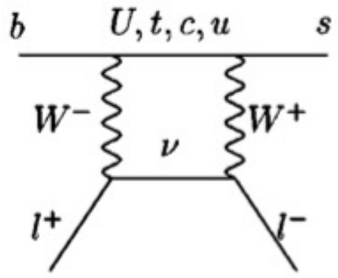


- From Fig. 1b, the box diagram contributes A^{SD} only,

$$A^{\text{SD}}_{1(b)} = -\frac{\alpha}{\pi \sin^2 \theta_W} \sum_{\beta=1}^{4} V^*_{\beta s} V_{\beta b} B_0(x_\beta). \qquad \text{(b)}$$

Where effective vertex function $B_0(x)$

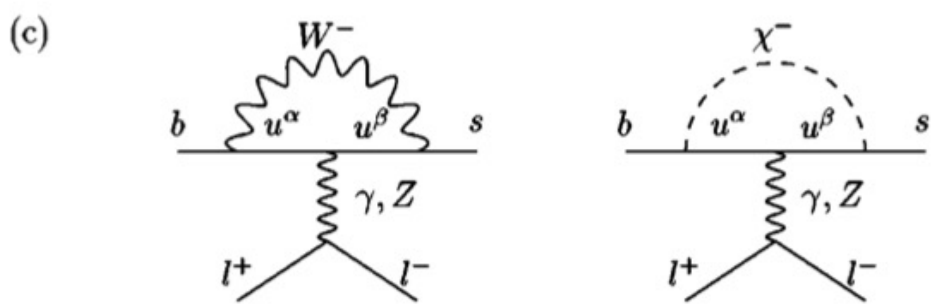
$$B_0(x) = \frac{1}{4} \left[1 + \frac{x}{1-x} + \frac{x \ln x}{(1-x)^2} \right].$$



- Photon and Z penguin diagrams (Fig 1c and 1d) also contribute to A and B

$$A^{SD}_{1(c)} = -\frac{\alpha}{\pi}\sum_{\beta=1}^{4} V^*_{\beta s}V_{\beta b}\left[\frac{1}{4}D_0(x_\beta) \quad + \left(1-\frac{1}{2\sin^2\theta_W}\right)C_0(x_\beta)\right],$$

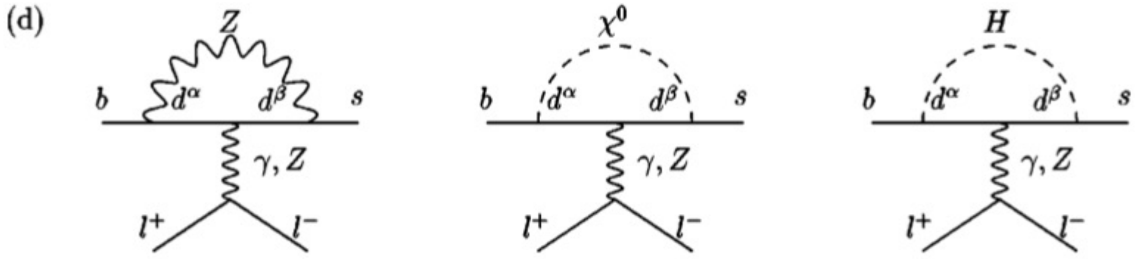
$$B^{SD}_{1(c)} = -\frac{\alpha}{\pi}\sum_{\beta=1}^{4} V^*_{\beta s}V_{\beta b}\left[\frac{1}{4}D_0(x_\beta)+C_0(x_\beta)\right],$$



Effective photon and Z vertex functions are

$$C_0(x) = \frac{x}{8}\left[\frac{x-6}{x-1}+\frac{3x+2}{(x-1)^2}\ln x\right].$$

$$D_0(x) = -\frac{4}{9}\ln x + \frac{-19x^3+25x^2}{36(x-1)^3} + \frac{x^2(5x^2-2x-6)}{18(x-1)^4}\ln x,$$



- Fig. 1d shows penguin diagrams via z, χ^0, H are subleading as compared to tree level FCNC contribution.

$$\sum_{\delta=1}^{4} U^{\alpha\delta}U^{\delta\beta} = U^{\alpha\beta}$$

- SD part of Coefficient A and B:

$$A^{SD}=A^{SD}_{1(a)}+A^{SD}_{1(b)}+A^{SD}_{1(c)},$$

$$B^{SD}=B^{SD}_{1(a)}+B^{SD}_{1(c)}.$$

- Coefficient C in Lagrangian is given as

$$C=\frac{\alpha}{\pi}\sum_{\beta=1}^{4} V^*_{\beta s}V_{\beta b}\frac{1}{4}D'_0(x_\beta),$$

Where,

$$D'_0(x)=-\frac{8x^3+5x^2-7x}{12(1-x)^3}+\frac{x^2(2-3x)}{2(1-x)^4}\ln x.$$

- The LD contributions enter A and B coefficients through charm-quark loop ($c\bar{c}$ continuum) and the intermediate resonances ψ and ψ':

$$A^{LD}=B^{LD}=\frac{\alpha}{2\pi}V^*_{cs}V_{cb}[3C_1+C_2](\tau^{\text{cont}}+\tau^{\text{res}}).$$

$$O_1=\bar{s}L^\mu b\bar{c}L_\mu c,\quad O_2=\bar{c}L^\mu b\bar{s}L_\mu c.$$

- C_1 and C_2 are the Wilson coefficients of the current-current operators O_1 and O_2, respectively.

$$\tau^{\text{cont}}=-g\left(\frac{m_c}{m_b},z\right),$$

$$\tau^{\text{res}}=\frac{16\pi^2}{9}\left(\frac{f^2_\psi(q^2)/m^2_\psi}{m^2_\psi-q^2-im_\psi\Gamma_\psi}+(\psi\to\psi')\right).$$

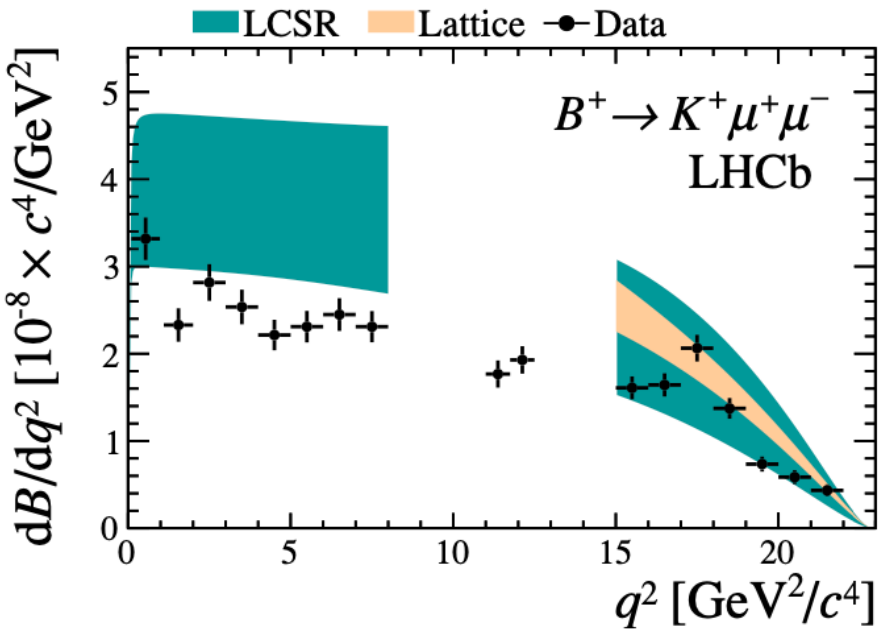
RESULTS:

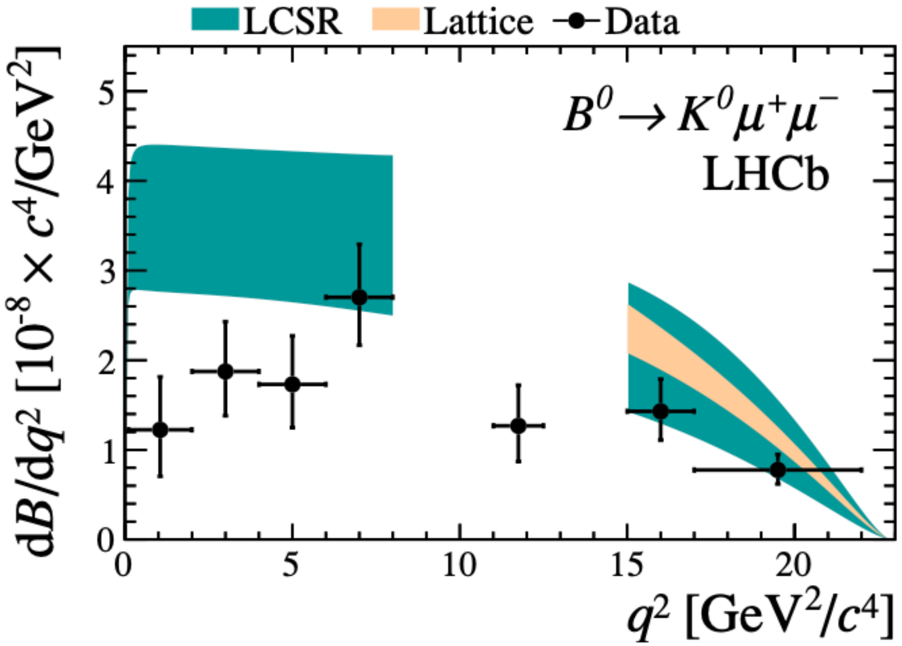
By inserting the coefficients, A $=A^{SD}+A^{LD}$, B $=B^{SD}$ and C into effective Lagrangian, we can calculate various observables. The differential decay rate for the process, approximated as the free quark decay $b\to sl^+l^-$ can be written as

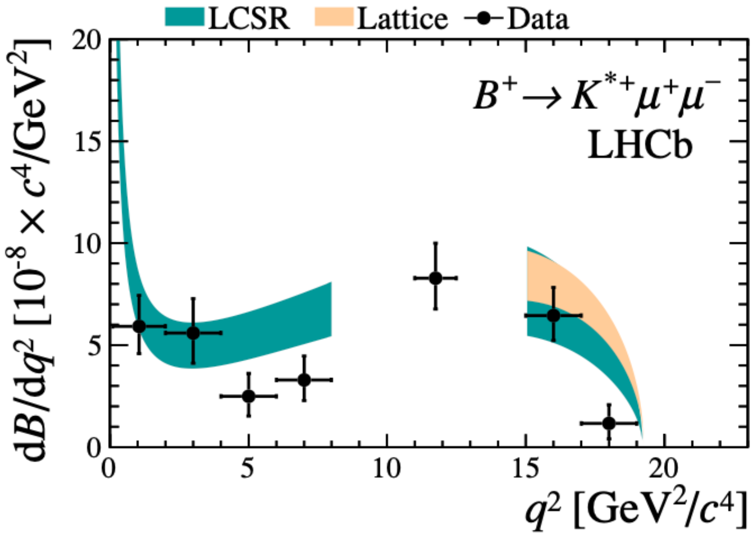
$$\frac{1}{BR(B\to X_ce\bar{\nu}_e)}\frac{dBR(B\to X_sl^+l^-)}{dz}=\frac{2(1-z)^2}{f(m_c/m_b)|V_{cb}|^2}((|A|^2+|B|^2)(1+2z)\ +2|C|^2(1+2/z)+6\Re[(A+B)^*C]),$$

EXPERIMENTAL RESULT

- Differential branching fraction results for the B+ → K^{+}μ+μ−, B_0 → K_0μ+μ− and B+ → K^{*+}μ+μ− decays.
- The uncertainties shown on the data points are the quadratic sum of the statistical and systematic uncertainties.
- The shaded regions illustrate the theoretical predictions and their uncertainties from light cone sum rule and lattice QCD calculations.
- The branching fraction measurements all have lower values than the SM predictions which gives the hint to New Physics.







Aaij R et al. (LHCb) 2014 JHEP 06 133

CONCLUSION

- Rare B decays continue to be valuable probes of physics beyond the SM.
- The VLQ model extends the SM by introducing additional quarks that transform under the fundamental representations of the electroweak gauge group. These additional quarks possess both left- and right-handed chiralities, unlike the SM quarks, which only exhibit left-handed chirality.
- Their presence can modify the branching ratios, angular observables, and other characteristics of the rare B-decay processes.
- Experimental measurements of rare B-decays offer a way to test the predictions of the VLQ model and explore the influence of VLQs on these decays.
- By comparing experimental data with theoretical predictions incorporating VLQs, researchers can evaluate the viability of the VLQ model and constrain the allowed parameter space.
- These experimental constraints guide further theoretical developments and refine our understanding of the VLQ model.


Thank You