Right-handed currents in the B meson system

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Outline

⊗ Consistency of the present experimental results with the general scheme of weak interactions and CP violation in the SM is nontrivial:

- Discrepancy between $\sin 2\beta_{J/\psi K_S}$ and $\sin 2\beta_{\phi K_S}$?
- Large Br($B \to \tau\nu$)?
- Polarization puzzle in $B \to VV$?
- And more ...

Left-Right models

∗ General left-right model (LRM) with group $SU(2)_L \times SU(2)_R \times U(1)$ has the following features:

- Covariant derivative for the fermions $f_{L,R}$:

$$D^\mu f_{L,R} = \partial^\mu f_{L,R} + i g_{L,R} W^{\mu a}_{L,R} T^a_{L,R} f_{L,R} + i g_1 B^\mu S f_{L,R}$$

- Unbroken $U(1)$ (Electric Charge):

$$Q = T^3_L + T^3_R + S$$

- Quark & Lepton fields (T_L, T_R, S):

$$\begin{aligned} q'_L &= \begin{pmatrix} u' \\ d' \end{pmatrix}_L \sim (\frac{1}{2}, 0, \frac{1}{6}), \quad q'_R = \begin{pmatrix} u' \\ d' \end{pmatrix}_R \sim (0, \frac{1}{2}, \frac{1}{6}), \\ l'_L &= \begin{pmatrix} \nu' \\ e' \end{pmatrix}_L \sim (\frac{1}{2}, 0, -\frac{1}{2}), \quad l'_R = \begin{pmatrix} \nu' \\ e' \end{pmatrix}_R \sim (0, \frac{1}{2}, -\frac{1}{2}) \end{aligned}$$

- Higgs VEVs (simplest case):

$$\langle \Phi \rangle = \begin{pmatrix} k & 0 \\ 0 & k' \end{pmatrix}, \quad \langle \chi_L \rangle = \begin{pmatrix} 0 \\ v_L \end{pmatrix}, \quad \langle \chi_R \rangle = \begin{pmatrix} 0 \\ v_R \end{pmatrix}$$

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- Higgs couplings induce $W_L - W_R$ mixing leading to mass eigenstates:

$$\begin{pmatrix} W^+ \\ W'^+ \end{pmatrix} = \begin{pmatrix} \cos\xi & e^{-i\alpha_\circ}\sin\xi \\ -\sin\xi & e^{-i\alpha_\circ}\cos\xi \end{pmatrix} \begin{pmatrix} W_L^+ \\ W_R^+ \end{pmatrix}$$

where

$$\zeta_g \equiv \frac{g_R^2 M_W^2}{g_L^2 M_{W'}^2} \geq \xi_g \equiv \frac{g_R}{g_L}\xi$$

- Charged interaction Lagrangian:

$$\begin{aligned} L_{CC} \quad = \quad & -\frac{1}{\sqrt{2}}\overline{P}\gamma^\mu \Big\{[V^L g_L c_\xi L + V^R g_R s_\xi^+ R] W_\mu^+ + [-V^L g_L s_\xi L + V^R g_R c_\xi^+ R] W_\mu'^+ \\ & +[(V^L M_P g_L c_\xi - V^R M_N g_R s_\xi^+) L + (-V^L M_N g_L c_\xi + V^R M_P g_R s_\xi^+) R] \frac{\varphi_\mu^+}{M_W} \\ & +[-(V^L M_P g_L s_\xi + V^R M_N g_R c_\xi^+) L + (V^L M_N g_L s_\xi + V^R M_P g_R c_\xi^+) R] \frac{\varphi_\mu'^+}{M_{W'}} \Big\} N \\ & + H.C. + \ldots, \end{aligned}$$

- Lower bound on $M_{W'}$ can be obtained from the limits on deviations of muon decay parameters:

$$\zeta_g < 0.034 \qquad \text{or} \qquad M_{W'} > (g_R/g_L) \times 440\ \text{GeV}$$

(C.A. Gagliardi, R.E. Tribble, and N.J. Williams, Phys. Rev. D **72** 073002 (2005))

- W' mass limit can be lowered to approximately 400 GeV by taking the following forms of V^R (ΔM_K yields no severe constrant on $M_{W'}$):

$$V_I^R = \begin{pmatrix} e^{i\omega} & 0 & 0 \\ 0 & c_R e^{i\alpha_1} & s_R e^{i\alpha_2} \\ 0 & -s_R e^{i\alpha_3} & c_R e^{i\alpha_4} \end{pmatrix}, \quad V_{II}^R = \begin{pmatrix} 0 & e^{i\omega} & 0 \\ c_R e^{i\alpha_1} & 0 & s_R e^{i\alpha_2} \\ -s_R e^{i\alpha_3} & 0 & c_R e^{i\alpha_4} \end{pmatrix}$$

where c_R (s_R) $\equiv \cos\theta_R$ ($\sin\theta_R$) ($0^\circ \leq \theta_R \leq 90^\circ$).

(P. Langacker and S.U. Sanker, Phys. Rev. D **40** 1569 (1989))

- Four-Fermion interaction for $b \to c(u)$ semileptonic decays:

$$\mathcal{H}_{eff} = 2\sqrt{2} G_F V_{qb}^L \left[(\bar{q}_L \gamma_\mu b_L) + \xi_q (\bar{q}_R \gamma_\mu b_R) \right] (\bar{\ell}_L \gamma_\mu \nu_L) \,,$$

where $\xi_q \equiv \xi(g_R V_{qb}^R)/(g_L V_{qb}^L)$ and $q = u, c$.

- Total decay rate of $B \to l\nu X_c$:

$$\Gamma(b \to cl\nu) \simeq \frac{G_F^2 m_b^5 |V_{cb}^L|^2}{192\pi^3} \left[(1 + r_c^2 \xi_g^2) f(x) - r_c \xi_g h(x) \right]$$

where $x \equiv m_c/m_b$, $f(x) \sim 1 + O(x^2)$, and $h(x) \sim 4x + O(x^3)$.

- Following approximate bound can be obtained by the comparison of $|V_{cb}|_{incl}$ and $|V_{cb}|_{excl}$:

$$\xi_c \approx 0.14 \pm 0.18$$

(M.B. Voloshin, Mod. Phys. Lett. A **12**, 1823 (1997))

- $|V^R_{ub}|$ could be as large as λ for the following types of V^R:

$$\begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & 1 & 0 \end{pmatrix}, \quad \begin{pmatrix} 0 & 1 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & 1 \end{pmatrix}, \quad \begin{pmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ 1 & 0 & 0 \end{pmatrix}$$

(T.G. Rizzo, Phys. Rev. D **58** 114014 (1998))

- In the LRM,

$$|V_{ub}|_{incl} \simeq |V_{ub}| + O(\xi_g^2) \sim O(\lambda^4) \quad (\lambda \simeq 0.22)$$

- 2008 HFAG averages of the selected theoretical methods for $|V_{ub}|_{incl}$:

$$|V_{ub}|_{incl} \times 10^3 = \begin{cases} 4.48 \pm 0.16 \, ^{+\,0.25}_{-\,0.26} & \text{(DGE)} \\ 3.78 \pm 0.13 \pm 0.24 & \text{(AC)} \\ 4.09 \pm 0.20 & \text{(Our average)} \end{cases},$$

(Compared to the recent average $(4.11 \pm 0.28) \times 10^{-3}$:
M. Antonelli, et al., Phys. Rept. **494** 197 (2010))

- Recently obtained value of $|V_{ub}|_{excl}$ from $B \to \pi e \nu$ is smaller than those of $|V_{ub}|_{incl}$:

$$|V_{ub}|^{LCSR}_{excl} = (3.5 \pm 0.4 \pm 0.2 \pm 0.1) \times 10^{-3}$$

- In the LRM, we can roughly estimate the mixing parameter ξ_u from the mismatch between the values of $|V_{ub}|_{incl}$ and $|V_{ub}|_{excl}$:

$$\begin{aligned} |V_{ub}|^{\pi e \nu}_{excl} &= |V^L_{ub}||1+\xi_u| \simeq |V_{ub}|_{incl}|1+\xi_u| \\ \Rightarrow \mathrm{Re}(\xi_u) &= -(0.14 \pm 0.12) \end{aligned}$$

- For $\mathrm{Re}(\xi_u) = -0.14$, the branching fraction for semileptonic $B \to \rho \ell \nu$ decays can be enhanced by 17% while the branching fraction for radiative leptonic $B \to \gamma \ell \nu$ decays can be reduced by 18%.
  (C.-H. Chen and S.-h. Nam, Phys. Lett. **B666** 462 (2008))

Leptonic $b \to u$ transitions

- In 2006 (& 2007), the BELLE and BABAR collaborations have found first evidence for the purely leptonic $B^- \to \tau^- \bar{\nu}$ decays:

$$Br(B^- \to \tau^- \bar{\nu}_\tau) = \begin{cases} (1.79\,{}^{+0.56}_{-0.49}\,{}^{+0.46}_{-0.51}) \times 10^{-4} & \text{(BELLE)} \\ (1.2 \pm 0.4 \pm 0.3 \pm 0.2) \times 10^{-4} & \text{(BABAR)} \end{cases}$$

- Our estimate (in 2008) of the branching fraction was:

$$\begin{aligned} Br(B^- \to \tau^- \bar{\nu}_\tau) &= Br(B^- \to \tau^- \bar{\nu}_\tau)^{SM} |1 - \xi_u|^2 \\ &= (1.38 \pm 0.31) \times 10^{-4} |1 - \xi_u|^2 \\ &= (1.78 \pm 0.53) \times 10^{-4} \end{aligned}$$

- Current experimental result (by UTfit Collaboration) is

$$Br(B^- \to \tau^- \bar{\nu}_\tau) = (1.73 \pm 0.34) \times 10^{-4}$$

$\Longrightarrow$ agrees very well with our earlier prediction!

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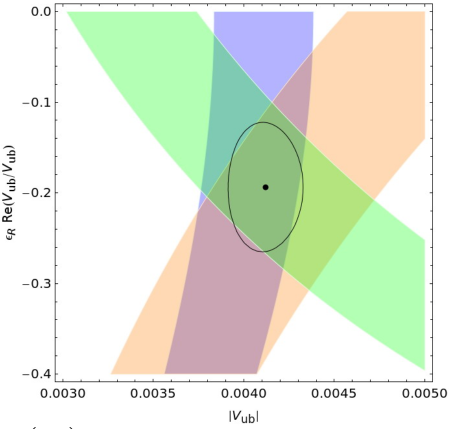

Constraints on $|V_{ub}|$ and $\epsilon_R \, \mathrm{Re}\left(\frac{\tilde{V}_{ub}}{V_{ub}}\right)$ from d $B \to \pi \ell \nu$ (green), $B \to X_u \ell \nu$ (blue), and $B \to \tau \nu$ (orange). The bands denote the $\pm 1\sigma$ intervals of the various experimental constraints (Buras, Gemmler, Isidori, arXiv:1007.1993).

- Effective Hamiltonian for $\Delta B = 1$ and $\Delta S = 1$ transition in the LRM:

$$\mathcal{H}_{eff} = \frac{G_F}{\sqrt{2}} \left[\sum_{\substack{i=1,2,11,12 \\ q=u,c}} \lambda_q^{LL} C_i^q O_i^q - \lambda_t^{LL} \left(\sum_{i=3}^{10} C_i O_i + C_7^\gamma O_7^\gamma + C_8^G O_8^G \right) \right] + (C_i O_i \to C_i' O_i')$$

- Wilson Coefficients ($\mu = 1.5$ GeV):

$$\begin{aligned}
C_1^q &= -0.443, & C_1^{q\prime} &= C_1^q \zeta_g \lambda_q^{RR} / \lambda_q^{LL} \\
C_2^q &= 1.224, & C_2^{q\prime} &= C_2^q \zeta_g \lambda_q^{RR} / \lambda_q^{LL} \\
C_3 = 0.023, \quad C_4 &= -0.045, & C_5 = 0.012, \quad C_6 &= -0.064 \\
C_7 = 0.008\alpha, \quad C_8 &= 0.064\alpha, & C_9 = -1.403\alpha, \quad C_{10} &= 0.482\alpha \\
C_7^\gamma &= -0.385 - 17.07 A^{tb}, & C_7^{\gamma\prime} &= -17.07 A^{ts*} \\
C_8^G &= -0.175 - 7.506 A^{tb}, & C_8^{G\prime} &= -7.506 A^{ts*} \\
C_{11}^{u\prime} &= 0.623 A^{us*}, & C_{12}^{u\prime} &= 0.881 A^{us*}.
\end{aligned}$$

where

$$\lambda_q^{AB} \equiv V_{qs}^{A*} V_{qb}^{B}, \qquad A^{tD} = \xi_g \frac{V_{tD}^R}{V_{tD}^L} e^{i\alpha_\circ} \ (D = b, s)$$

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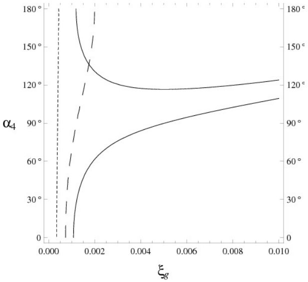
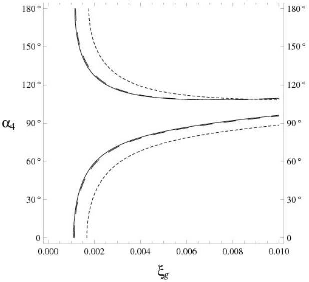
- Recent measurements of the $b \to s\gamma$ decay rate have indirectly limited new physics contributions to a few percent.
- Contour plot corresponding to $|\delta^{s\gamma}_{LRM}| \leq 0.1$ for $\sin\theta_R = 0.04$ (solid line), 0.24 (dashed line), and 0.75 (dotted line) respectively, where $\delta^{s\gamma}_{LRM} = (|C^{\gamma}_7|^2_{LRM} - |C^{\gamma}_7|^2_{SM})/|C^{\gamma}_7|^2_{SM}$. The left region of the contour is allowed:

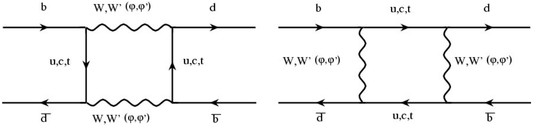


Type I (V^R_I)



Type II (V^R_{II})

- Effective Hamiltonian in the $B\bar{B}$ system is obtained from the box diagrams:



$H_{eff}^{B\bar{B}} = H_{eff}^{SM} + H_{eff}^{RR} + H_{eff}^{LR}$:

$$H_{eff}^{SM} = \frac{G_F^2 M_W^2}{4\pi^2} (\lambda_t^{LL})^2 S(x_t^2) (\bar{d}_L \gamma_\mu b_L)^2$$

$$H_{eff}^{LR} = \frac{G_F^2 M_W^2}{2\pi^2} \{ [\lambda_c^{LR} \lambda_t^{RL} x_c x_t \zeta_g A_1(x_t^2, \zeta) + \lambda_t^{LR} \lambda_t^{RL} x_t^2 \zeta_g A_2(x_t^2, \zeta)] (\bar{d}_L b_R)(\bar{d}_R b_L)$$
$$+ \lambda_t^{LL} \lambda_t^{RL} x_b \xi_g^- [x_t^3 A_3(x_t^2)(\bar{d}_L \gamma_\mu b_L)(\bar{d}_R \gamma_\mu b_R) + x_t A_4(x_t^2)(\bar{d}_L b_R)(\bar{d}_R b_L)] \}$$

where $\xi_g^\pm \equiv e^{\pm \alpha_\circ} \xi_g$, and $x_i \equiv m_i / M_W$ $(i = u, c, t)$

- The $B^0 \bar{B}^0$ mixing matrix element in the LRM can be written as

$$M_{12} = M_{12}^{SM} + M_{12}^{LR} = M_{12}^{SM} \left(1 + r_{LR}^q\right), \quad r_{LR}^q = \frac{< \bar{B}_q^0 | H_{eff}^{LR} | B_q^0 >}{< \bar{B}_q^0 | H_{eff}^{SM} | B_q^0 >}$$

$B\bar{B}$ mixing

- In the case of V_I^R, $r_{LR}^d \sim 0$ and

$$
\begin{aligned}
r_{LR}^s \approx & \left\{ -2.77 \left(\frac{1-\zeta_g-(4.92-19.7\zeta_g)\ln(1/\zeta_g)}{1-5.47\zeta_g} \right) \zeta_g s_R^2 e^{i(\alpha_2-\alpha_3)} \right. \\
& +153 \left(\frac{1-5.02\zeta_g-(0.498-1.99\zeta_g)\ln(1/\zeta_g)}{1-9.94\zeta_g+28.9\zeta_g^2} \right) \zeta_g s_R c_R e^{i(-\alpha_3+\alpha_4)} \\
& \left. +1.72\xi_g s_R e^{-i\alpha_3} \right\}
\end{aligned}
$$

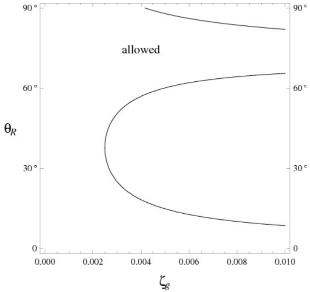
- In the case of V_{II}^R, $r_{LR}^s \sim 0$ and

$$
\begin{aligned}
r_{LR}^d \approx & \left\{ 16.9 \left(\frac{1-\zeta_g-(4.92-19.7\zeta_g)\ln(1/\zeta_g)}{1-5.47\zeta_g} \right) \zeta_g s_R^2 e^{i(-2\beta+\alpha_2-\alpha_3)} \right. \\
& -783 \left(\frac{1-5.02\zeta_g-(0.498-1.99\zeta_g)\ln(1/\zeta_g)}{1-9.94\zeta_g+28.9\zeta_g^2} \right) \zeta_g s_R c_R e^{i(-\beta-\alpha_3+\alpha_4)} \\
& \left. -8.78\xi_g s_R e^{i(-\beta-\alpha_3)} \right\}
\end{aligned}
$$

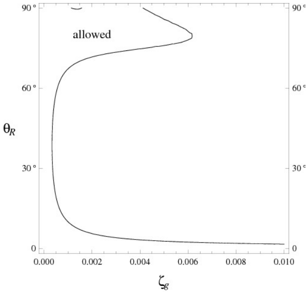
(S.-h. Nam, Phys. Rev. D **66** 055008 (2002))

$B\bar{B}$ mixing

- Contour plot corresponding to $0.7 < |1 + r_{LR}| < 1.3$ for $\zeta_g = 2\xi_g$ and $\alpha_{2,3,4} = 120^\circ$:



$B_s\bar{B}_s\ (V_I^R)$



$B_d\bar{B}_d\ (V_{II}^R)$

$\sin 2\beta$ in LRM

- For neutral B mesons decays, CP asymmetry can be expressed by the parametrization invariant quantity λ:

$$\lambda \equiv -\left(\frac{q}{p}\right)_B \frac{\mathcal{A}(\bar{B}^0 \to \bar{f})}{\mathcal{A}(B^0 \to f)}, \qquad \left(\frac{q}{p}\right)_B \simeq \frac{M_{12}^*}{|M_{12}|},$$

- In the SM, the CP angle β is simply the imaginary part of λ:

$$\sin 2\beta = \mathrm{Im}\lambda(B \to J/\psi K_S) \simeq \mathrm{Im}\lambda(B \to \phi K_S)$$

- $B \to J/\psi K_S$ decay is governed by the tree-level contribution. In the LRM:

$$\mathcal{A}(B \to J/\psi K_s)_I \simeq \frac{G_F}{\sqrt{2}} \lambda_c^{LL} \left\{1 + 25(c_R s_R \zeta_g e^{-i(\alpha_2 - \alpha_1)} - 2 s_R \xi_g e^{-i\alpha_2})\right\} X^{(BK_s, J/\psi)}$$

$$\mathcal{A}(B \to J/\psi K_s)_{II} \simeq \frac{G_F}{\sqrt{2}} \lambda_c^{LL} \left\{1 - 50 s_R \xi_g e^{-i\alpha_2}\right\} X^{(BK_s, J/\psi)}$$

where $X^{(BK_s, J/\psi)} \equiv < J/\psi | \bar{c}\gamma_\mu c | 0 >< K_s | \bar{s}\gamma^\mu b | B^\circ >$

(S.-h. Nam, Phys. Rev. D **68** 115006 (2003))

- Transition amplitude for $B \to \phi K$ in the LRM:

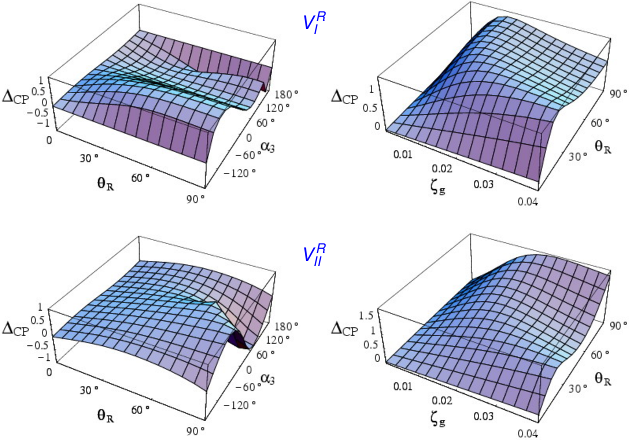
$$\mathcal{A}(B \to \phi K)_I \simeq -\frac{G_F}{\sqrt{2}}\Big[\Big\{1.77 - 0.027 e^{-i(\gamma+\varphi)} + 16.2\zeta_g c_R s_R e^{i(\alpha_4-\alpha_3)} -13.1\xi_g(c_R e^{i\alpha_4} + 24.0 s_R e^{-i\alpha_3})\Big\}10^{-3} X^{(BK,\phi)} + \Big\{3.32 - 0.031 e^{-i(\gamma+\varphi)} + 18.9\zeta_g c_R s_R e^{i(\alpha_4-\alpha_3)} -16.4\xi_g(c_R e^{i\alpha_4} + 24.7 s_R e^{-i\alpha_3})\Big\}10^{-1} X^{(B,K\phi)}\Big]$$

$$\mathcal{A}(B \to \phi K)_{II} \simeq -\frac{G_F}{\sqrt{2}}\Big[\Big\{1.77 - 0.027 e^{-i(\gamma+\varphi)} - 13.1\xi_g c_R e^{i\alpha_4}\Big\}10^{-3} X^{(BK,\phi)} + \Big\{3.32 - 0.031 e^{-i(\gamma+\varphi)} - 16.4\xi_g c_R e^{i\alpha_4}\Big\}10^{-1} X^{(B,K\phi)}\Big]$$

where $\gamma = 60^\circ$, φ=87° (CP-even phase), and

$$X^{(BK,\phi)} \equiv < \phi|\bar{s}\gamma_\mu s|0 >< K|\bar{s}\gamma^\mu b|B >,$$
$$X^{(B,K\phi)} \equiv \pm < K\phi|\bar{s}\gamma_\mu(1(\pm\gamma_5))d|0 >< 0|\bar{d}\gamma^\mu\gamma_5 b|B >$$

∗ Plots of the *CP* asymmetry difference $\Delta_{CP} \equiv \mathrm{Im}\lambda(B \to J/\psi K_S) - \mathrm{Im}\lambda(B \to \phi K_S)$:



Summary

- In the LRM , the W' contributions to $B^0\bar{B}^0$ mixing and CP asymmetry in B^0 decays are highly dependent upon the phases in the mass mixing matrices $V^{L,R}$.
- Admixture of a right-handed $b \to c(u)$ current could give a significantly different contributions to the inclusive and exclusive rates of the semileptonic decays of the B mesons.
- In hadronic B decays, different CP even phases arise from the annihilation contributions as well as the loop corrections of the current-current operators.
- The mixing angle ξ_g receives strong constraint from $b \to s\gamma$ especially in the manifest LRM.
- Right-handed currents cannot significantly contribute to ΔM_{B_d} and ΔM_{B_s} simultaneously.
- If there is a large discrepancy between $\sin 2\beta_{J/\psi K_S}$ and $\sin 2\beta_{\phi K_S}$, the manifest LRM is disfavored.

Back up

Polarization fraction for $B \to VV$ modes

- The decay $B \to V_1 V_2$ is described by the amplitude

$$\mathcal{A}(B \to V_1 V_2) = \mathcal{A}_0\, \varepsilon_1^* \cdot \varepsilon_2^* + \mathcal{A}_1\, (\varepsilon_1^* \cdot p_2)(\varepsilon_2^* \cdot p_1) + i\mathcal{A}_2\, \epsilon^{\alpha\beta\gamma\delta} \varepsilon_{1\alpha}^* \varepsilon_{2\beta}^* p_{1\gamma} p_{2\delta}$$

- The three helicity amplitudes can be rewritten in the transversity basis as:

$$\mathcal{A}_L = -x\mathcal{A}_0 - m_1 m_2 (x^2 - 1)\mathcal{A}_1, \qquad \mathcal{A}_{\parallel} = -\sqrt{2}\mathcal{A}_0$$
$$\mathcal{A}_{\perp} = -\sqrt{2} m_1 m_2 \sqrt{x^2 - 1}\mathcal{A}_2, \qquad x \equiv \frac{p_1 \cdot p_2}{m_1 m_2}$$

- In the LRM ,

$$\mathcal{A}(B \to V_1 V_2) = \frac{G_F}{\sqrt{2}} \sum_{q=u,c} \lambda_q^{LL} \left[C_{\pm}^{I} X_{\pm}^{(BV_1, V_2)} + C_{\pm}^{A} X_{\pm}^{(B, V_1 V_2)} \right]$$

$$\Rightarrow |\mathcal{A}(B \to V_1 V_2)|^2 = |\mathcal{A}_L|^2 + |\mathcal{A}_{\perp}|^2 + |\mathcal{A}_{\parallel}|^2$$

Polarization Fraction for the ϕK^* channel

- In the helicity basis,

$$
\begin{aligned}
\mathcal{A}_0 &= \frac{G_F}{\sqrt{2}} \sum_{q=u,c} \lambda_q^{LL} \left[f_2 m_2 (m_B + m_1) \left(c_-^I - c_+^I \right) A_1(m_2^2) - f_B m_B^2 \left(c_-^A + c_+^A \right) V_1(m_B^2) \right] \\
\mathcal{A}_1 &= \frac{G_F}{\sqrt{2}} \sum_{q=u,c} \lambda_q^{LL} \left[-\frac{2 f_2 m_2}{m_B + m_1} \left(c_-^I - c_+^I \right) A_2(m_2^2) + f_B \left(c_-^A + c_+^A \right) V_2(m_B^2) \right] \\
\mathcal{A}_2 &= \frac{G_F}{\sqrt{2}} \sum_{q=u,c} \lambda_q^{LL} \left[-\frac{2 f_2 m_2}{m_B + m_1} \left(c_-^I + c_+^I \right) V(m_2^2) + f_B \left(c_-^A - c_+^A \right) A(m_B^2) \right]
\end{aligned}
$$

$\Rightarrow$ Right-handed contribution can enhance $\mathcal{A}_\perp$ and $\mathcal{A}_\parallel$.

- Illustration of the behavior of Γ_L/Γ for the ϕK^* channel by varying θ_R: