Polarizations of $B \to VV$ in QCD factorization

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Based on collaborations with M.Beneke and J.Rohrer

第十届全国粒子物理学术会议April 2008

Motivation

$B \to VV$ decays share the roles of $B \to PP$, PV decays in

- the determination of CKM matrix elements, especially the angles(phases):
  - $\sin 2\beta$ and $\cos 2\beta$ from $B \to J/\Psi K^*$;
  - $\sin 2\alpha$ from $B \to \rho\rho$;

- new physics search
  - direct search for the unexpected large branching ratios of rare decays in the SM;
  - more new physics sensitive observables in $B \to VV$:
    polarizations, phases (phase diffences) of helicity amplitudes

Plan of talk

1. Helicity amplitudes of $B \to VV$
2. Current experimental status
3. QCD factorization formula for $B \to VV$
4. Phenomenologies of $B \to VV$
   - Tree-dominated decays ($B \to \rho\rho$)
   - Penguin-dominated decays ($B \to \phi K^*$ and ρK^*)
5. Summary

Based on the works collaborated with M.Beneke and J. Rohrer

– *"Branching fractions, polarization and asymmetries of $B \to VV$ decays"*, Nucl. Phys. B774, 64-101, 2007;

– *"Enhanced electroweak penguin amplitude in $B \to VV$ decays"*, Phys. Rev. Lett. 96, 141801, 2006.

Helicity amplitudes of $B \to VV$

General decay amplitude of $B(p_B) \to V_1(p_1, \eta^*) V_2(p_2, \epsilon^*)$

$$\mathcal{A}\,(B \to V_1 V_2) = i\,\eta^{*\mu}\epsilon^{*\nu}\left(S_1 g_{\mu\nu} - S_2 \frac{p_{B\mu}p_{B\nu}}{m_B^2} + i S_3 \varepsilon_{\mu\nu\rho\sigma}\frac{p_1^\rho p_2^\sigma}{p_1 \cdot p_2}\right)$$

With definite helicity,

$$\mathcal{A}_0 \;=\; \mathcal{A}(B \to V_1(p_1, \eta_0^*) V_2(p_2, \epsilon_0^*)) \;=\; \frac{i m_B^2}{2 m_1 m_2}\left(S_1 - \frac{S_2}{2}\right),$$

$$\mathcal{A}_\pm \;=\; \mathcal{A}(B \to V_1(p_1, \eta_\pm^*) V_2(p_2, \epsilon_\pm^*)) \;=\; i\,(S_1 \mp S_3)\,.$$

Or we can define transversity amplitudes

$$\mathcal{A}_{\parallel,\perp} \;=\; \left(\mathcal{A}_+ \pm \mathcal{A}_-\right)/\sqrt{2}\,.$$

$\mathcal{A}_0$, $\mathcal{A}_\parallel$ are CP-even, and $\mathcal{A}_\perp$ is CP-odd.

$\Rightarrow$ 6 flavor-tagged helicity amplitudes, total 10 independent observables;

Definitions of observables

- flavor-tagged definitions

$$f^B_{L,\parallel,\perp} = \frac{\left|\mathcal{A}_{0,\parallel,\perp}\right|^2}{|\mathcal{A}_0|^2 + \left|\mathcal{A}_\parallel\right|^2 + |\mathcal{A}_\perp|^2}, \qquad \phi^B_{\parallel,\perp} = \arg\frac{\mathcal{A}_{\parallel,\perp}}{\mathcal{A}_0},$$

$$f^{\bar{B}}_{L,\parallel,\perp} = \frac{\left|\bar{\mathcal{A}}_{0,\parallel,\perp}\right|^2}{|\bar{\mathcal{A}}_0|^2 + \left|\bar{\mathcal{A}}_\parallel\right|^2 + |\bar{\mathcal{A}}_\perp|^2}, \qquad \phi^{\bar{B}}_{\parallel,\perp} = \arg\frac{\bar{\mathcal{A}}_{\parallel,\perp}}{\bar{\mathcal{A}}_0},$$

- flavor-averaged quantities and asymmetries

$$f_h = \frac{1}{2}\left(f^{\bar{B}}_h + f^B_h\right), \qquad A^h_{\rm CP} = \frac{f^{\bar{B}}_h - f^B_h}{f^{\bar{B}}_h + f^B_h}$$

$$\begin{aligned} \phi_h &\equiv \phi^{\bar{B}}_h - \Delta\phi_h \pmod{2\pi} \\ &\equiv \phi^B_h + \Delta\phi_h \pmod{2\pi}, \qquad -\frac{\pi}{2} \le \Delta\phi_h < \frac{\pi}{2} \end{aligned}$$

$h = L, \parallel, \perp$

- In absence of CP violation, $A^h_{\rm CP} = 0$ and $\delta\phi_h = 0$.

Definitions of observables (Belle)

- Time dependent observables:

$$\Gamma(\bar{B}^0(B^0)(t) \to V_1 V_2) = e^{-\Gamma_B t} \sum_{\lambda \le \sigma} (\Lambda_{\lambda\sigma} \pm \Sigma_{\lambda\sigma} \cos(\Delta m_B t) \mp \rho_{\lambda\sigma} \sin(\Delta m_B t))g_\lambda g_\sigma \,,$$

with

$$\Lambda_{\lambda\lambda} = \frac{1}{2}(|A_\lambda|^2 + |\bar{A}_\lambda|^2)\,, \qquad \Sigma_{\lambda\lambda} = \frac{1}{2}(|A_\lambda|^2 - |\bar{A}_\lambda|^2)\,,$$

$$\Lambda_{\perp i} = -\mathrm{Im}(A_\perp A_i^* - \bar{A}_\perp \bar{A}_i^*)\,, \qquad \Lambda_{\parallel 0} = \mathrm{Re}(A_\parallel A_0^* + \bar{A}_\parallel \bar{A}_0^*)\,,$$

$$\Sigma_{\perp i} = -\mathrm{Im}(A_\perp A_i^* + \bar{A}_\perp \bar{A}_i^*)\,, \qquad \Sigma_{\parallel 0} = \mathrm{Re}(A_\parallel A_0^* - \bar{A}_\parallel \bar{A}_0^*)\,,$$

$$\rho_{\perp i} = \mathrm{Re}\left(\frac{q}{p}(A_\perp^* \bar{A}_i + A_i^* \bar{A}_\perp)\right)\,, \qquad \rho_{\perp\perp} = \mathrm{Im}\left(\frac{q}{p} A_\perp^* \bar{A}_\perp\right)\,,$$

$$\rho_{\parallel 0} = -\mathrm{Im}\left(\frac{q}{p}(A_\parallel^* \bar{A}_0 + A_0^* \bar{A}_\parallel)\right)\,, \qquad \rho_{ii} = -\mathrm{Im}\left(\frac{q}{p} A_i^* \bar{A}_i\right)\,,$$

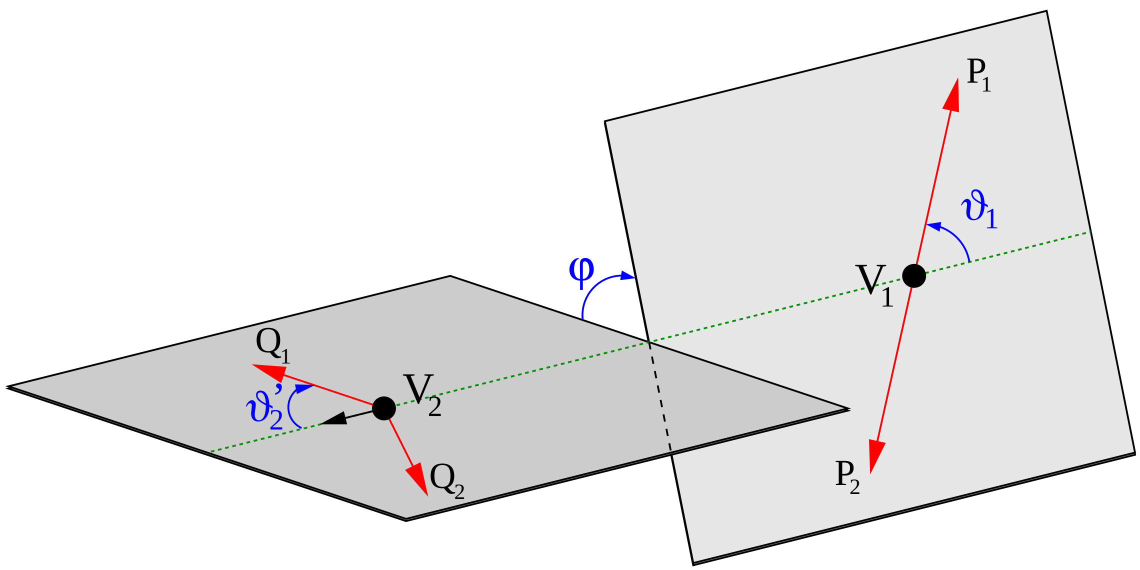
where $i = 0, \parallel$. These 18 observables can have connections with the observables used by BaBar collaborations if one uses relevant normalization and neglects the small CP asymmetries.

$$\frac{d\Gamma(B \to V_1 V_2 \to (P_1 P_2)(Q_1 Q_2))}{d\cos\vartheta_1 d\cos\vartheta_2 d\varphi}$$

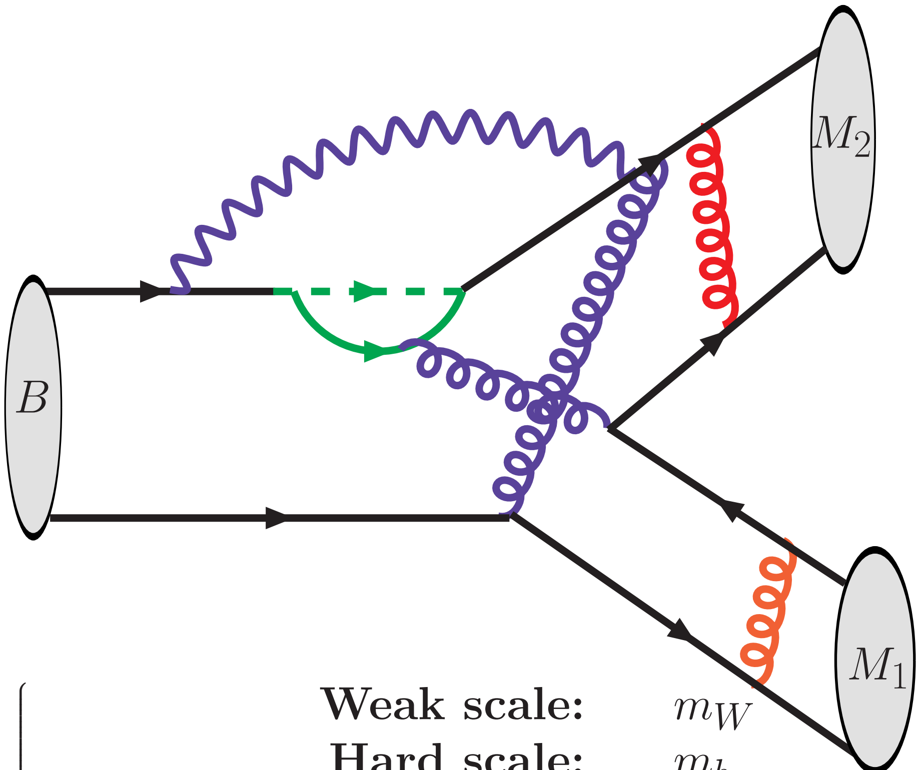
$$\propto \; |\mathcal{A}_0|^2 \cos^2\vartheta_1 \cos^2\vartheta_2 + \frac{1}{4}\sin^2\vartheta_1 \sin^2\vartheta_2 \left(\left|\mathcal{A}_+\right|^2 + |\mathcal{A}_-|^2\right)$$

$$- \cos\vartheta_1 \sin\vartheta_1 \cos\vartheta_2 \sin\vartheta_2 \left[\mathrm{Re}\left(e^{-i\varphi}\mathcal{A}_0\mathcal{A}_+^*\right) + \mathrm{Re}\left(e^{+i\varphi}\mathcal{A}_0\mathcal{A}_-^*\right)\right]$$

$$+ \frac{1}{2}\sin^2\vartheta_1 \sin^2\vartheta_2 \,\mathrm{Re}\left(e^{2i\varphi}\mathcal{A}_+\mathcal{A}_-^*\right),$$



Picture of B non-leptonic two-body decays



Weak scale:	m_W
Hard scale:	m_b
Hard-collinear scale:	$\sqrt{m_b \Lambda_{\rm QCD}}$
Soft (or collinear) scale:	$\Lambda_{\rm QCD}$

– Basic idea: to separate the contribution from different scales;

– Separation of m_W and m_b scale by the weak Hamiltonian

$$\mathcal{H}_{eff} = \sum_i C_i(\mu) Q_i(\mu)$$

– Separation of m_b and lower scales

$$\langle M_1 M_2 | Q_i(\mu) | \bar{B} \rangle = ?$$

Tree operators:

$$Q_1^u = (\bar{u}_\alpha b_\alpha)_{V-A}(\bar{q}_\beta u_\beta)_{V-A} \quad Q_1^c = (\bar{c}_\alpha b_\alpha)_{V-A}(\bar{q}_\beta c_\beta)_{V-A}$$
$$Q_2^u = (\bar{u}_\alpha b_\beta)_{V-A}(\bar{q}_\beta u_\alpha)_{V-A} \quad Q_2^c = (\bar{c}_\alpha b_\beta)_{V-A}(\bar{q}_\beta c_\alpha)_{V-A}$$

QCD penguin operators:

$$Q_3 = (\bar{q}_\alpha b_\alpha)_{V-A}\sum_{q'}(\bar{q}'_\beta q'_\beta)_{V-A} \quad Q_4 = (\bar{q}_\beta b_\alpha)_{V-A}\sum_{q'}(\bar{q}'_\alpha q'_\beta)_{V-A}$$
$$Q_5 = (\bar{q}_\alpha b_\alpha)_{V-A}\sum_{q'}(\bar{q}'_\beta q'_\beta)_{V+A} \quad Q_6 = (\bar{q}_\beta b_\alpha)_{V-A}\sum_{q'}(\bar{q}'_\alpha q'_\beta)_{V+A}$$

EW penguin operators:

$$Q_7 = \tfrac{3}{2}(\bar{q}_\alpha b_\alpha)_{V-A}\sum_{q'} e_{q'}(\bar{q}'_\beta q'_\beta)_{V+A} \quad Q_8 = \tfrac{3}{2}(\bar{q}_\beta b_\alpha)_{V-A}\sum_{q'} e_{q'}(\bar{q}'_\alpha q'_\beta)_{V+A}$$
$$Q_9 = \tfrac{3}{2}(\bar{q}_\alpha b_\alpha)_{V-A}\sum_{q'} e_{q'}(\bar{q}'_\beta q'_\beta)_{V-A} \quad Q_{10} = \tfrac{3}{2}(\bar{q}_\beta b_\alpha)_{V-A}\sum_{q'} e_{q'}(\bar{q}'_\alpha q'_\beta)_{V-A}$$

Dipole operators:

$$Q_{7\gamma} = -\tfrac{e}{8\pi^2} m_b \bar{q}_\alpha \sigma^{\mu\nu}(1+\gamma_5) b_\alpha F_{\mu\nu} \quad Q_{8G} = -\tfrac{g}{8\pi^2} m_b \bar{q}_\alpha \sigma^{\mu\nu} t^a_{\alpha\beta}(1+\gamma_5) b_\beta G^a_{\mu\nu}$$

Polarization in $B \to VV$

Polarization:

$$V(\epsilon_0^*) \sim v_\uparrow \bar{u}_\downarrow + v_\downarrow \bar{u}_\uparrow, \quad V(\epsilon_+^*) \sim v_\uparrow \bar{u}_\uparrow, \quad V(\epsilon_-^*) \sim v_\downarrow \bar{u}_\downarrow$$

approximately,

$$u_R(p) \sim u_\uparrow(p), \quad u_L(p) \sim u_\downarrow(p), \quad v_L(p) \sim v_\uparrow(p), \quad v_R(p) \sim v_\downarrow(p)$$

each helicity flip costs the suppression $m/2E$.

$$\Rightarrow |\bar{A}_0| : |\bar{A}_-| : |\bar{A}_+| \sim 1 : \frac{\Lambda}{m_B} : \frac{\Lambda^2}{m_B^2}$$

$$f_L = 1 - \mathcal{O}(m_V^2/m_B^2), \qquad f_\perp \simeq f_\parallel \simeq \mathcal{O}(m_V^2/m_B^2)$$

Tree-dominated processes

- $B \to \rho\rho, \omega\rho$;
- $1 - f_L = \mathcal{O}(\Lambda^2/m_b^2)$ about few percent;

Decay Modes	P.F.	Belle	BaBar	HFAG
$B^+ \to \rho^0\rho^+$	f_L	$0.95 \pm 0.11 \pm 0.02$	$0.905 \pm 0.042^{+0.023}_{-0.027}$	$0.912^{+0.044}_{-0.045}$
$B^0 \to \rho^0\rho^0$	f_L	$0.70 \pm 0.14 \pm 0.05$		0.70 ± 0.15
$B^0 \to \rho^+\rho^-$	f_L	$0.941^{+0.034}_{-0.040} \pm 0.030$	$0.992 \pm 0.024^{+0.026}_{-0.013}$	$0.978^{+0.025}_{-0.022}$
$B^0 \to K^{*0}\bar{K}^{*0}$	f_L		$0.80^{+0.10}_{-0.12} \pm 0.06$	$0.80^{+0.12}_{-0.13}$
$B^+ \to \omega\rho^+$	f_L		$0.82 \pm 0.11 \pm 0.02$	0.82 ± 0.11

- Obtain $\sin 2\alpha$ from the time-dependent measurements of $B \to \rho\rho$;

Penguin-dominated processes

- Case 1: $B \to \phi K^*$
  $1 - f_L = \mathcal{O}(1)$ about a half $\Rightarrow$ (polarization puzzles);

Decay Modes	P.F.	Belle	BaBar	HFAG
$B^+ \to \phi K^{*+}$	f_L	$0.52 \pm 0.08 \pm 0.03$	$0.46 \pm 0.12 \pm 0.03$	0.50 ± 0.07
	$f_\perp$	$0.19 \pm 0.08 \pm 0.02$		0.19 ± 0.08
	$\phi_\parallel$	$2.10 \pm 0.28 \pm 0.04$		2.10 ± 0.31
	$\phi_\perp$	$2.31 \pm 0.30 \pm 0.07$		2.31 ± 0.31
$B^0 \to \phi K^{*0}$	f_L	$0.45 \pm 0.05 \pm 0.02$	$0.506 \pm 0.040 \pm 0.015$	0.491 ± 0.032
	$f_\perp$	$0.31^{+0.06}_{-0.05} \pm 0.02$	$0.227 \pm 0.038 \pm 0.013$	0.252 ± 0.031
	$\phi_\parallel$	$2.40^{+0.28}_{-0.24} \pm 0.07$	$2.31 \pm 0.14 \pm 0.08$	$2.37^{+0.14}_{-0.13}$
	$\phi_\perp$	$2.51 \pm 0.25 \pm 0.06$	$2.24 \pm 0.15 \pm 0.09$	2.36 ± 0.14

Penguin-dominated processes

- Case 2: $B \to \rho K^*$
  - * $1 - f_L = \mathcal{O}(\Lambda^2/m_b^2)$ for $B^+ \to \rho^0 K^{*+}$
  - * $1 - f_L = \mathcal{O}(1)$ for $B^+ \to \rho^+ K^{*0}$ and $B^0 \to \rho^0 K^{*0}$
  - * Even more puzzling than $B \to \phi K^*$!

Decay Modes	P.F.	Belle	BaBar	HFAG
$B^+ \to \rho^0 K^{*+}$	f_L		$0.96^{+0.04}_{-0.15} \pm 0.04$	$0.96^{+0.06}_{-0.16}$
$B^+ \to \rho^+ K^{*0}$	f_L	$0.43 \pm 0.11^{+0.05}_{-0.02}$	$0.52 \pm 0.10 \pm 0.04$	0.48 ± 0.08
$B^0 \to K^{*0} \rho^0$	f_L		$0.57 \pm 0.09 \pm 0.08$	0.57 ± 0.12

Polarization puzzles

- $B \to \phi K^*$: enhanced penguin amplitude with negative-helicity
  - * new physics effects (scalar and tensor current-current coupling)

    Kagan, 2004;Das and Yang, 2004
  - * large charming penguin *C.W.Bauer et al, 2003*
  - * final state interactions *H.Y.Cheng, 2004*
  - * smaller A_0, larger A_1 and V *H.N.Li et al, 2004*
  - * large annihilation effects

    Kagan, 2004; Beneke, Rohrer and Yang, 2006
- $B \to \rho K^*$:
  - * Expected to follow the same pattern of $B \to \phi K^*$;
  - * $1 - f_L = \mathcal{O}(\Lambda^2/m_b^2)$ for $B^+ \to \rho^0 K^{*+}$
  - * $1 - f_L = \mathcal{O}(1)$ for $B^+ \to \rho^+ K^{*0}$ and $B^0 \to \rho^0 K^{*0}$
  - * Large electroweak penguin in negative-helicity amplitude or new physics?

QCD factorization formula for $B \to VV$

Kagan, 2004; M.Beneke, J.Rohrer and DY, 2005

$$\langle V_{1,h} V_{2,h} | Q_i | \bar{B} \rangle = F^{B\to V_1,h} T_i^{I,h} * f_{V_2}^h \Phi_{V_2}^h + (V_1 \leftrightarrow V_2) + T_i^{II,h} * f_B \Phi_B * f_{V_1} \Phi_{V_1} * f_{V_2}^h \Phi_{V_2}^h + \mathcal{O}(1/m_b)\,.$$

where $h = 0, \mp$, and in terms of α-convention in [Beneke& Neubert, 2003]

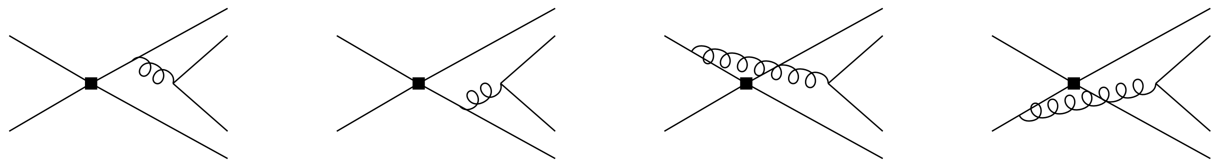
$$\mathcal{A}_h(\bar{B} \to V_1 V_2) \sim A^h \sum_i \alpha_i^h (V_1 V_2)$$

$$\begin{cases} A^0 \sim A_0^{B\to V_1} \sim \left(\frac{\Lambda}{m_b}\right)^{3/2} \\ A^- \sim \frac{m_2}{m_B}\left((1+\frac{m_1}{m_B})A_1^{B\to V_1} + (1-\frac{m_1}{m_B})V^{B\to V_1}\right) \sim \left(\frac{\Lambda}{m_b}\right)^{5/2} \\ A^- \sim \frac{m_2}{m_B}\left((1+\frac{m_1}{m_B})A_1^{B\to V_1} - (1-\frac{m_1}{m_B})V^{B\to V_1}\right) \sim \left(\frac{\Lambda}{m_b}\right)^{7/2} \end{cases}$$

- Positive helicity amplitude is highly suppressed and cannot be calculated in same way.

$$\Rightarrow f_{\|} = f_{\perp}\,, \phi_{\|} = \phi_{\perp}.$$

Penguin weak annihilations



$$X_A \sim \ln \frac{m_B}{\Lambda_A}(1+\rho_A e^{i\phi_A}),\ X_A^2,\ X_L \sim \frac{m_B}{\Lambda_L}(1+\rho_L e^{i\phi_L});$$

$$P^h = A^h_{V_1 V_2}\left[\alpha_4^h + \beta_3^h\right],$$

$$\begin{cases} \alpha_4^c(\pi\bar{K}) + \beta_3^c(\pi\bar{K}) = & -0.09 - \{0.02\,[-0.01, 0.05]\}, \\ \alpha_4^{c0}(\rho\bar{K}^*) + \beta_3^{c0}(\rho\bar{K}^*) = & -0.03 - \{0.00\,[-0.00, 0.00]\}, \\ \alpha_4^{c-}(\rho\bar{K}^*) + \beta_3^{c-}(\rho\bar{K}^*) = & -0.05 - \{0.03\,[-0.04, 0.10]\}. \end{cases}$$

$$\frac{P^-}{P^0} \simeq \frac{A^-_{\rho K^*}}{A^0_{\rho K^*}}\frac{\alpha_4^{c-} + \beta_3^{c-}}{\alpha_4^{c,0}} \simeq \frac{0.05 + [-0.04, 0.10]}{0.12}, \quad \text{with } \frac{A^-_{\rho K^*}}{A^0_{\rho K^*}} \simeq \frac{1}{4}.$$

Negative-helicity penguin amplitude can be (but need not) be enhanced by the penguin annihilation!

Enhanced EW penguin in $B \to VV$

$$\mathcal{H}_{\text{eff}} = \frac{G_F}{\sqrt{2}} \sum_{p=u,c} \lambda_p^{(D)} \sum_{a=\mp} C_{7\gamma}^a Q_{7\gamma}^a + \ldots,$$

$$Q_{7\gamma}^{\mp} = -\frac{e\bar{m}_b}{8\pi^2} \bar{D}\sigma_{\mu\nu}(1 \pm \gamma_5) F^{\mu\nu} b \quad \lambda_p^{(D)} = V_{pD}^* V_{pb}.$$

introduces the additional EW penguin amplitude for the decays to the neutral vector meson (ρ^0,ω, ϕ),

The resulted amplitudes for different helicities

$$|\Delta P_0^{EW}| : |\Delta P_-^{EW}| \sim 1 : m_b/\Lambda$$

(Here we neglect the contribution from $Q_{7\gamma}^+$.)

The representative coefficient in QCDF

$$\Delta\alpha_{3,\mathrm{EW}}^{p\mp}(V_1V_2) = \mp\frac{2\alpha_{\mathrm{em}}}{3\pi}C_{7\gamma,\mathrm{eff}}^{\mp}R_{\mp}\frac{m_B\bar{m}_b}{m_{V_2}^2}$$

with $R_- = 1$ in the heavy quark limit. Numerically, we have

$$\Delta\alpha_{3,\mathrm{EW}}^{p-}(K^*\rho) \approx 0.02\,,$$

meanwhile the uncorrected EW penguin and leading QCD penguin

$$\alpha_{3,\mathrm{EW}}^{p-}(K^*\rho) = C_7 + C_9 + \frac{C_8 + C_{10}}{N_c} + \ldots \approx -0.01\,,$$

$$\hat{\alpha}_4^{c-}(\rho K^*) = C_4 + \frac{C_3}{N_c} + \ldots \approx -0.055\,.$$

Effectively,

$$|\Delta\alpha_{3,\mathrm{EW}}^{c-}(K^*V_2)| = \frac{2\alpha_{\mathrm{em}}}{3\pi}R_-\frac{m_B^2}{m_{V_2}^2}\left(\frac{\Gamma(B\to K^*\gamma)}{\frac{G_F^2|V_{ts}^*V_{tb}|^2}{8\pi^3}\frac{\alpha_{\mathrm{em}}}{4\pi}m_B^5T_1^{K^*}(0)^2}\right)^{1/2}$$

with $T_1^{K^*}(0) \approx 0.28$, we get

$$|\Delta\alpha_{3,\mathrm{EW}}^{c-}(K^*\rho)| = 0.023\,.$$

Tree-dominated decays

$$\mathrm{BrAv}(B \to \rho^- \rho^0) = \left|\frac{V_{ub}}{3.53 \cdot 10^{-3}}\right|^2 \times \left|\frac{A_0^{B\to\rho}(0)}{0.30}\right|^2 \times \left(18.8^{+0.4+3.2}_{-0.4-3.9}\right) \cdot 10^{-6}$$

	BrAv / 10^{-6}		A_{CP} / percent	
	Theory	Experiment	Theory	Experiment
$B^- \to \rho^- \rho^0$	$18.8^{+0.4+3.2}_{-0.4-3.9}$	18.2 ± 3.0	0^{+0+0}_{-0-0}	-8 ± 13
$\bar{B}^0 \to \rho^+ \rho^-$	$23.6^{+1.7+3.9}_{-1.9-3.6}$	$23.1^{+3.2}_{-3.3}$	-1^{+0+4}_{-0-8}	$+11 \pm 13$
$\bar{B}^0 \to \rho^0 \rho^0$	$0.9^{+0.6+1.9}_{-0.3-0.9}$	1.07 ± 0.38	$+28^{+5+53}_{-7-29}$	n/a
$B^- \to \omega \rho^-$	$12.8^{+1.1+2.0}_{-1.3-2.4}$	$10.6^{+2.6}_{-2.3}$	-8^{+3+5}_{-2-8}	$+4 \pm 18$
$\bar{B}^0 \to \omega \rho^0$	$0.2^{+0.1+0.3}_{-0.1-0.1}$	< 1.5	no prediction	n/a
$\bar{B}^0 \to \omega \omega$	$0.9^{+0.5+1.5}_{-0.3-0.9}$	< 4.0	-29^{+9+25}_{-6-44}	n/a

	f_L / percent		$A^0_{\rm CP}$ / percent
	Theory	Experiment	Theory
$B^- \to \rho^-\rho^0$	$95.9^{+0.2+3.4}_{-0.3-5.9}$	$91.2^{+4.4}_{-4.5}$	-0^{+0+0}_{-0-0}
$\bar{B}^0 \to \rho^+\rho^-$	$91.3^{+0.4+5.6}_{-0.3-6.4}$	96.8 ± 2.3	-2^{+0+4}_{-0-2}
$\bar{B}^0 \to \rho^0\rho^0$	90^{+3+8}_{-4-56}	87 ± 14	-8^{+2+59}_{-1-28}
$B^- \to \omega\rho^-$	$93.7^{+1.1+4.7}_{-1.0-8.1}$	82 ± 11	-2^{+1+7}_{-0-6}
$\bar{B}^0 \to \omega\rho^0$	49^{+11+47}_{-11-23}	n/a	$+35^{+25+47}_{-15-84}$
$\bar{B}^0 \to \omega\omega$	93^{+2+5}_{-4-22}	n/a	$+6^{+1+14}_{-1-24}$

Strategies in penguin-dominated decays

- QCDF loses predictive power in penguin annihilations with transverse polarization;
- Use information from experiments as much as we can;
  - Strategy 1: fit only the penguin annihilation from $B \to \phi K^*$ measurements;
  - Strategy 2: fit the whole penguin amplitude from $B \to \phi K^*$;
  - Trust the predictions for other topological amplitudes using QCDF;
  - Constrained X_A:

$$\varrho_A = 0.5 \pm 0.2_{\text{exp.}} \qquad \varphi_A = (-43 \pm 19_{\text{exp.}})^\circ,$$

  - $\hat{\alpha}_4^{c-} = \alpha_4^{c-} + \beta_3$ from data:

$$\begin{aligned} \bar{\mathcal{A}}_- &= A_{K^*\phi}\lambda_c^{(s)} P_-^{K^*\phi}, \\ P_-^{K^*\phi} &= (-0.084 \pm 0.008(\text{exp})^{+0.008}_{-0.009}(\text{th})) \\ &\quad + i\,(0.021 \pm 0.015(\text{exp})^{+0.003}_{-0.002}(\text{th})), \end{aligned}$$

with α_3^{c-} from QCDF

$$\hat{\alpha}_4^{c-} = (-0.08 \pm 0.02) + i\,(0.03 \pm 0.02).$$

Observable		Theory			Experiment
		default	constrained X_A	$\hat{\alpha}_4^{c-}$ from data	
BrAv $/10^{-6}$	ϕK^{*-}	$10.1^{+0.5+12.2}_{-0.5-7.1}$	$10.1^{+0.5+7.2}_{-0.5-4.8}$	$10.4^{+0.5+5.2}_{-0.5-3.9}$	9.7 ± 1.5
	$\phi \bar{K}^{*0}$	$9.3^{+0.5+11.4}_{-0.5-6.5}$	$9.3^{+0.5+6.7}_{-0.5-4.5}$	$9.6^{+0.5+4.7}_{-0.5-3.6}$	9.50 ± 0.90
$A_{\rm CP}/\%$	ϕK^{*-}	0^{+0+2}_{-0-1}	0^{+0+0}_{-0-0}	0^{+0+3}_{-0-2}	5 ± 11
	$\phi \bar{K}^{*0}$	1^{+0+1}_{-0-0}	1^{+0+0}_{-0-0}	1^{+0+2}_{-0-1}	0.0 ± 7.0
$f_L/\%$	ϕK^{*-}	45^{+0+58}_{-0-36}	45^{+0+35}_{-0-31}	44^{+0+23}_{-0-23}	50.0 ± 7.0
	$\phi \bar{K}^{*0}$	44^{+0+59}_{-0-36}	44^{+0+35}_{-0-31}	43^{+0+23}_{-0-23}	49.0 ± 4.0
$A^0_{\rm CP}/\%$	ϕK^{*-}	-1^{+0+2}_{-0-1}	-1^{+0+1}_{-0-1}	-1^{+0+2}_{-0-2}	n/a
	$\phi \bar{K}^{*0}$	0^{+0+1}_{-0-1}	0^{+0+1}_{-0-0}	0^{+0+1}_{-0-2}	1.0 ± 8.0
$(f_\parallel - f_\perp)/\%$	ϕK^{*-}	0^{+0+2}_{-0-2}	0^{+0+2}_{-0-2}	0^{+0+2}_{-0-2}	12^{+17}_{-17}
	$\phi \bar{K}^{*0}$	0^{+0+2}_{-0-2}	0^{+0+2}_{-0-2}	0^{+0+2}_{-0-2}	$-3.0^{+8.9}_{-7.2}$
$(A^\parallel_{\rm CP} - A^\perp_{\rm CP})/\%$	ϕK^{*-}	0^{+0+0}_{-0-0}	0^{+0+0}_{-0-0}	0^{+0+0}_{-0-0}	n/a
	$\phi \bar{K}^{*0}$	0^{+0+0}_{-0-0}	0^{+0+0}_{-0-0}	0^{+0+0}_{-0-0}	32^{+36}_{-36}
$\phi_\parallel/^\circ$	ϕK^{*-}	-41^{+0+84}_{-0-53}	-41^{+0+35}_{-0-30}	-40^{+0+21}_{-0-21}	-60 ± 16
	$\phi \bar{K}^{*0}$	-42^{+0+87}_{-0-54}	-42^{+0+35}_{-0-30}	-42^{+0+21}_{-0-21}	-42^{+10}_{-9}
$\Delta\phi_\parallel/^\circ$	ϕK^{*-}	0^{+0+0}_{-0-1}	0^{+0+0}_{-0-0}	0^{+0+0}_{-0-0}	n/a
	$\phi \bar{K}^{*0}$	0^{+0+0}_{-0-0}	0^{+0+0}_{-0-0}	0^{+0+0}_{-0-1}	2 ± 10
$(\phi_\parallel - \phi_\perp)/^\circ$	ϕK^{*-}	0^{+0+1}_{-0-1}	0^{+0+1}_{-0-1}	0^{+0+1}_{-0-1}	-12^{+24}_{-24}
	$\phi \bar{K}^{*0}$	0^{+0+1}_{-0-1}	0^{+0+1}_{-0-1}	0^{+0+1}_{-0-1}	-6^{+14}_{-13}
$(\Delta\phi_\parallel - \Delta\phi_\perp)/^\circ$	ϕK^{*-}	0^{+0+0}_{-0-0}	0^{+0+0}_{-0-0}	0^{+0+0}_{-0-0}	n/a
	$\phi \bar{K}^{*0}$	0^{+0+0}_{-0-0}	0^{+0+0}_{-0-0}	0^{+0+0}_{-0-0}	0^{+15}_{-15}

BrAv $/10^{-6}$	Theory		Experiment
	default	$\hat{\alpha}_4^{c-}$ from data	
$B^- \to K^{*-}\phi$	$10.1^{+0.5+12.2}_{-0.5-7.1}$	$10.4^{+0.5+5.2}_{-0.5-3.9}$	9.7 ± 1.5
$\bar{B}^0 \to \bar{K}^{*0}\phi$	$9.3^{+0.5+11.4}_{-0.5-6.5}$	$9.6^{+0.5+4.7}_{-0.5-3.6}$	9.50 ± 0.90
$B^- \to K^{*-}\omega$	$2.4^{+0.8+2.9}_{-0.7-1.3}$	$2.3^{+0.8+1.4}_{-0.7-0.7}$	< 3.4
$\bar{B}^0 \to \bar{K}^{*0}\omega$	$2.0^{+0.1+3.1}_{-0.1-1.4}$	$1.9^{+0.1+1.5}_{-0.1-0.7}$	< 4.2
$B^- \to \bar{K}^{*0}\rho^-$	$5.9^{+0.3+6.9}_{-0.3-3.7}$	$5.8^{+0.3+3.1}_{-0.3-1.9}$	9.2 ± 1.5
$B^- \to K^{*-}\rho^0$	$4.5^{+1.5+3.0}_{-1.3-1.4}$	$4.5^{+1.5+1.8}_{-1.3-1.0}$	< 6.1
$\bar{B}^0 \to K^{*-}\rho^+$	$5.5^{+1.7+5.7}_{-1.5-2.9}$	$5.4^{+1.7+2.6}_{-1.5-1.5}$	n/a
$\bar{B}^0 \to \bar{K}^{*0}\rho^0$	$2.4^{+0.2+3.5}_{-0.1-2.0}$	$2.3^{+0.2+1.1}_{-0.1-0.8}$	5.6 ± 1.6
$\bar{B}_s \to \phi\phi$	$21.8^{+1.1+30.4}_{-1.1-17.0}$	$19.5^{+1.0+13.1}_{-1.0-8.0}$	$14.0^{+8.0}_{-7.0}$

f_L / percent	Theory		Experiment
	default	$\hat{\alpha}_4^{c-}$ from data	
$B^- \to K^{*-}\phi$	45^{+0+58}_{-0-36}	44^{+0+23}_{-0-23}	50.0 ± 7.0
$\bar{B}^0 \to \bar{K}^{*0}\phi$	44^{+0+59}_{-0-36}	43^{+0+23}_{-0-23}	49.0 ± 4.0
$B^- \to K^{*-}\omega$	$53^{+8\ +57}_{-11-39}$	$56^{+8\ +22}_{-11-19}$	n/a
$\bar{B}^0 \to \bar{K}^{*0}\omega$	40^{+4+77}_{-3-43}	43^{+4+38}_{-3-32}	n/a
$B^- \to \bar{K}^{*0}\rho^-$	56^{+0+48}_{-0-30}	57^{+0+21}_{-0-18}	48.0 ± 8.0
$B^- \to K^{*-}\rho^0$	84^{+2+16}_{-3-25}	85^{+2+9}_{-3-11}	96^{+6}_{-16}
$\bar{B}^0 \to K^{*-}\rho^+$	61^{+5+38}_{-7-28}	62^{+5+17}_{-6-15}	n/a
$\bar{B}^0 \to \bar{K}^{*0}\rho^0$	22^{+3+53}_{-3-14}	22^{+3+21}_{-3-13}	57 ± 12

More on $B \to \rho K^*$ system

$$
\begin{aligned}
A_h(\rho^- \bar{K}^{*0}) &= P_h \\
\sqrt{2}A_h(\rho^0 K^{*-}) &= [P_h + P_h^{EW}] + e^{-i\gamma}[T_h + C_h] \\
A_h(\rho^+ K^{*-}) &= P_h + e^{-i\gamma}T_h \\
-\sqrt{2}A_h(\rho^0 \bar{K}^{*0}) &= [P_h - P_h^{EW}] + e^{-i\gamma}[-C_h]
\end{aligned}
$$

and define $x_h = X_h/P_h$ $(h = 0, -1)$.

$$
\begin{array}{cccc}
 & \bar{\Gamma}_-(\rho^- \bar{K}^{*0}) : & \sqrt{2}\bar{\Gamma}_-(\rho^0 K^{*-}) : & \sqrt{2}\bar{\Gamma}_-(\rho^0 \bar{K}^{*0}) \\
\sim & 1 : & |1 + p_-^{EW}|^2 : & |1 - p_-^{EW}|^2
\end{array}
$$

	$B^- \to K^{*-}\rho^0$			$\bar{B}^0 \to \bar{K}^{*0}\rho^0$		
	incl.	excl.	exp.	incl.	excl.	exp.
BrAv $/10^{-6}$	4.5	5.4	< 6.1	2.4	1.4	5.6 ± 1.6
f_L / %	84	70	96^{+6}_{-16}	22	37	57 ± 12
$A_{\rm CP}$ / %	16	14	20^{+32}_{-29}	-15	-24	9 ± 19

- QCDF predicts $f_L(\rho^0 K^{*-}) > f_L(\rho^- \bar{K}^{*0}) > f_L(\rho^0 \bar{K}^{*0})$. It is against current measurements.

Conclusions and perspective

- QCD factorization loses predictive power for penguin-dominated $B \to VV$ decays;
- Penguin weak annihilation could be an answer to polarization puzzle of $B \to \phi K^*$;
- Enhanced electroweak penguin with negative-helicity could explain the polarization puzzles in $B^+ \to \rho^+ K^{*0}$ and $B^+ \to \rho^0 K^{*+}$, but not for polarization of $B^0 \to \rho^0 K^{*0}$;
- Polarization puzzles of $B \to \rho K^*$ are challenging for new physics model building;
- New measurements on polarizations in $B \to AV$ and TV will shed more light on research of chirality structure of interaction, but QCD effects are still crucial;

THANKS!