

# **Global analysis of charmless B decays into two vector mesons in SCET**

王超

IHEP, CAS

In collaboration with 周四红, 李营, 吕才典

HFCPV 2017, 武汉

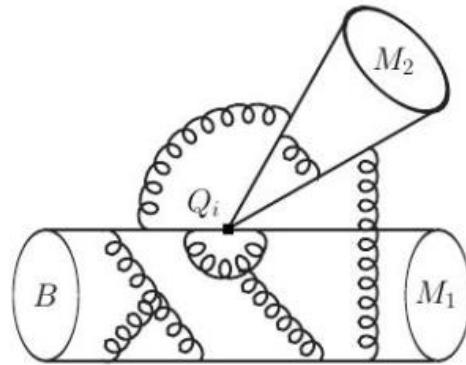
based on Phys. Rev. D 96, 073004 (2017)

# Outline

- Motivation
- Factorization formulas for  $B \rightarrow V V$  in SCET
- Numerical analysis
- Summary

# Two body non-leptonic decay

- Six-quark interaction,



- three scales

$$m_b, \sqrt{m_b \Lambda_{QCD}}, \Lambda_{QCD}$$

Dynamical approaches based on QCD:

- QCDF

Beneke, Buchalla, Neubert, Sachrajda NPB 2000;  
Beneke, Neubert NPB, 2003

- PQCD

Keum, Li, Sanda PRD 2001;  
Lu, Ukai, Yang PRD 2001

- SCET

Bauer, Fleming, Pirjol, Stewart PRD 2001;  
Beneke, Feldmann PLB 2003

# Two body non-leptonic decay

## SCET

- $B \rightarrow M_1 M_2$  Factorization

Bauer, Pirjol, Rothstein, Stewart PRD 2004;  
Williamson, Zupan PRD 2006

- Numerical estimate

$B \rightarrow \pi\pi, B \rightarrow K\pi, B \rightarrow KK$

Bauer, Rothstein, Stewart PRD 2006

Charmless  $B_{(s)} \rightarrow PP$  involving  $\eta, \eta'$   
Williamson, Zupan PRD 2006

Charmless  $B_{(s)} \rightarrow VP$

Wang, Wang, Yang, Lu PRD 2008

$B \rightarrow VV$

- QCDF

Cheng, Yang PRD 2008;  
Cheng, Chua PRD 2009

- PQCD

Zou, Ali, Lu, Liu, Li PRD 2015

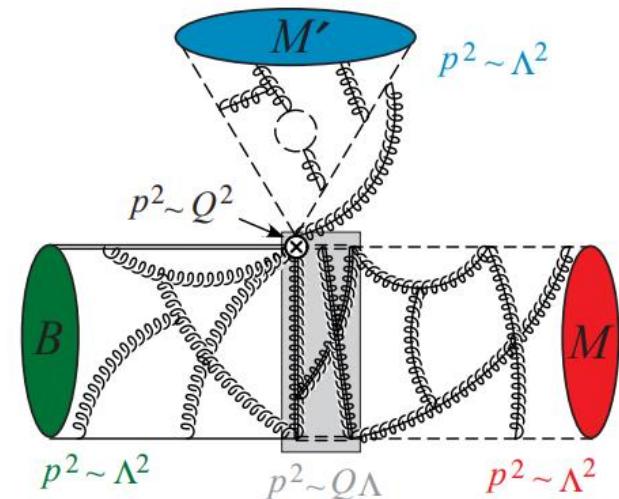
# QCD $\rightarrow$ SCET<sub>I</sub>

- Integrating out scale  $\mathcal{O}(m_b^2)$

$$\begin{aligned}
 & (\bar{u}b)_{V-A}(\bar{d}u)_{V-A} \\
 \Rightarrow & [\bar{u}_{n,\omega_1} \not{P}_L b_v] [\bar{d}_{\bar{n},\omega_2} \not{P}_L u_{\bar{n},\omega_3}] \sim \mathcal{O}(\lambda^0) \\
 \frac{-2}{m_b} & [\bar{u}_{n,\omega_1} ig \not{\beta}_{n,\omega_4}^\perp P_L b_v] [\bar{d}_{\bar{n},\omega_2} \not{P}_L u_{\bar{n},\omega_3}] \sim \mathcal{O}(\lambda^1)
 \end{aligned}$$

$$\lambda = \sqrt{\Lambda_{QCD}/m_b} \quad \bar{u}_{n,\omega} = [\bar{\xi}_n^{(u)} W_n]$$

$$Q_{if}^{(0,1)} = \tilde{Q}_{if}^n Q_{if}^{\bar{n}}. \quad \langle V_L | Q_{if}^{\bar{n}} | 0 \rangle = m_B f_V \phi_{V_L}.$$



- $\langle MM' | O_i | B \rangle = T(\mu) \otimes \phi_{M'}(\mu) \otimes \zeta^{B \rightarrow M}$   
 $+ T_J(\mu, z) \otimes \phi_{M'}(\mu) \otimes \zeta_J^{B \rightarrow M}(z)$

# SCET<sub>I</sub> → SCET<sub>II</sub>

- Integrating out scale  $\mathcal{O}(m_b \Lambda_{QCD})$

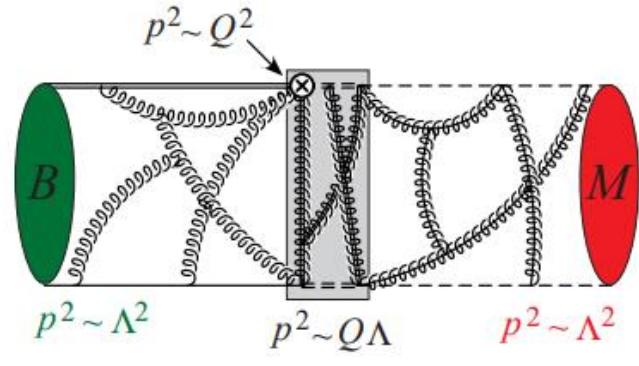
$$T_1 = \int d^4y d^4y' T[\tilde{Q}_{if}^{(0)}(0), i\mathcal{L}_{\xi_n q}^{(1)}(y), i\mathcal{L}_{\xi_n \xi_n}^{(1)}(y') + i\mathcal{L}_{cg}^{(1)}(y')] + \int d^4y T[\tilde{Q}_{if}^{(0)}(0), i\mathcal{L}_{\xi_n q}^{(1,2)}(y)],$$

$$T_2 = \int d^4y T[\tilde{Q}_{if}^{(1)}(0), i\mathcal{L}_{\xi_n q}^{(1)}(y)],$$

$$\lambda = \Lambda_{QCD}/m_b$$

$$\langle V_L | T_1 | B \rangle = m_B \zeta^{BV_L}. \quad \langle V_L | T_2 | B \rangle = m_B \zeta_J^{BV_L}.$$

$$\zeta_J(z) = \phi_{M_2}(x) \otimes J(z, x, k_+) \otimes \phi_B(k_+).$$



$$\alpha_s(\sqrt{\Lambda m_b}) > \alpha_s(m_b)$$

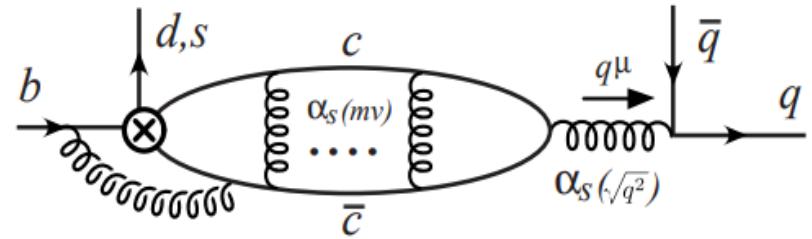
- Instead we treat both  $\zeta$  and  $\zeta_J$  as nonperturbative parameters
- $Q_{if}^{0,1}$  have scalar bilinears, give vanishing contributions to  $B \rightarrow V_T V_T$

# Charming penguin

- source of strong phase
- $B \rightarrow V_T V_T$
- Naive analysis:

$$\mathcal{A}^0 : \mathcal{A}^- : \mathcal{A}^+ = 1 : \frac{\Lambda_{QCD}}{m_b} : \left( \frac{\Lambda_{QCD}}{m_b} \right)^2,$$

Violated by the charming penguin contribution



On-shell charm quarks

- $\mathcal{A}_{||} = \frac{G_F}{\sqrt{2}} m_B^2 \lambda_c^{(f)} A_{cc||}^{V_1 V_2},$   
 $\mathcal{A}_\perp = \frac{G_F}{\sqrt{2}} m_B^2 \lambda_c^{(f)} A_{cc\perp}^{V_1 V_2}.$

Beneke et al. EPJC 2009 !

# Factorization formulas and observables

- $B \rightarrow V_L V_L$

$$\begin{aligned}\mathcal{A}_L = \frac{G_F}{\sqrt{2}} m_B^2 &\times \left\{ f_{V_1} \zeta_J^{BV_2} \int du \phi_{V_1}(u) T_{1J}(u) \right. \\ &+ f_{V_1} T_{1\zeta} \zeta^{BV_2} + (1 \leftrightarrow 2) + \lambda_c^{(f)} A_{ccL}^{V_1 V_2} \left. \right\}\end{aligned}$$

- $B \rightarrow VP$

$$\begin{aligned}\mathcal{A}_{PV} = \frac{G_F}{\sqrt{2}} m_B^2 &\left\{ f_P \zeta_J^{BV} \int du \phi_P(u) T_{PJ}(u) \right. \\ &+ f_P \zeta_{Jg}^{BV} \int du \phi_P(u) T_{1Jg}(u) \\ &+ f_P (T_P \zeta^{BV} + T_{Pg} \zeta_g^{BV}) + \lambda_c^{(f)} A_{cc(g)}^{PV} \\ &\left. + (P \leftrightarrow V) \right\} + \text{chiral enhanced penguins}\end{aligned}$$

# Factorization formulas and observables

- For explicit decay channels, hard kernel flavor relevant

$$\begin{aligned} T_1 = & \ c_1^f BM_2 \delta_u M_1 \Lambda^f + (c_2^f \pm c_3^f) BM_2 \Lambda^f \text{Tr}[\delta_u M_1] \\ & + c_4^f BM_2 M_1 \Lambda^f + (c_5^f \pm c_6^f) BM_2 \Lambda^f \text{Tr}[M_1], \end{aligned}$$

$$T_{1J} = T_1(c_i^f \rightarrow b_i^f),$$

$$A_{cc}^{M_1 M_2} = BM_2 M_1 \Lambda^f A_{cc}^{+ -}$$

Wang, Wang, Yang, Lu PRD 2008

# Factorization formulas and observables

- unpolarized

$$\Gamma = \frac{|\mathbf{p}|}{8\pi m_B^2} (|\mathcal{A}_L|^2 + |\mathcal{A}_{||}|^2 + |\mathcal{A}_{\perp}|^2), \quad A_{CP} = \frac{\sum_h (|\bar{\mathcal{A}}_h|^2 - |\mathcal{A}_h|^2)}{\sum_h (|\bar{\mathcal{A}}_h|^2 + |\mathcal{A}_h|^2)},$$

- polarized

$$f_{L,||,\perp} = \frac{|\mathcal{A}_{L,||,\perp}|^2}{|\mathcal{A}_L|^2 + |\mathcal{A}_{||}|^2 + |\mathcal{A}_{\perp}|^2},$$

$$\phi_{||,\perp} = \text{Arg} \frac{\mathcal{A}_{||,\perp}}{\mathcal{A}_L}.$$

$$A_{CP}^0 = \frac{\bar{f}_L - f_L}{\bar{f}_L + f_L}, \quad A_{CP}^{\perp} = \frac{\bar{f}_{\perp} - f_{\perp}}{\bar{f}_{\perp} + f_{\perp}},$$

$$\Delta\phi_{||} = \frac{\bar{\phi}_{||} - \phi_{||}}{2}, \quad \Delta\phi_{\perp} = \frac{\bar{\phi}_{\perp} - \phi_{\perp}}{2},$$

# Numerical results

- 8 input real parameters under  $SU(3)$  symmetry
  - $\zeta, \zeta_J, A_{ccL}, A_{cc\parallel}, A_{cc\perp}$ .
- 35 observables of  $B^{\pm/0} \rightarrow VV$  with statistical significance no less than  $3\sigma$

$$\begin{aligned}\zeta &= (33.3 \pm 1.6) \times 10^{-2}, & \zeta_J &= (1.6 \pm 1.0) \times 10^{-2}, \\ |A_{ccL}| &= (38.1 \pm 1.1) \times 10^{-4}, & \arg[A_{ccL}] &= -0.29 \pm 0.11, \\ |A_{cc\parallel}| &= (18.8 \pm 0.8) \times 10^{-4}, & \arg[A_{cc\parallel}] &= 1.98 \pm 0.18, \\ |A_{cc\perp}| &= (17.1 \pm 0.7) \times 10^{-4}, & \arg[A_{cc\perp}] &= 2.11 \pm 0.18,\end{aligned}$$

with  $\chi^2/\text{d.o.f.} = 67.1/(35 - 8) = 2.5$

# Numerical results

- $B \rightarrow P P$  and  $B \rightarrow P V$

$$A_0^{B \rightarrow V} = \zeta + \zeta_J = 0.349 \pm 0.019.$$

$$\zeta \sim \zeta_J \Rightarrow C \sim T$$

- $B \rightarrow V_L V_L$

$$\zeta \gg \zeta_J \Rightarrow C \ll T$$

Color-suppressed contribution  
is indeed suppressed

“ $\pi\pi$ ” puzzle

Theoretically:  $Br(B^0 \rightarrow \pi^0 \pi^0) < Br(B^0 \rightarrow \pi^0 \rho^0) < Br(B^0 \rightarrow \rho^0 \rho^0)$

Experimentally: inverse order

Consistent with LCSR

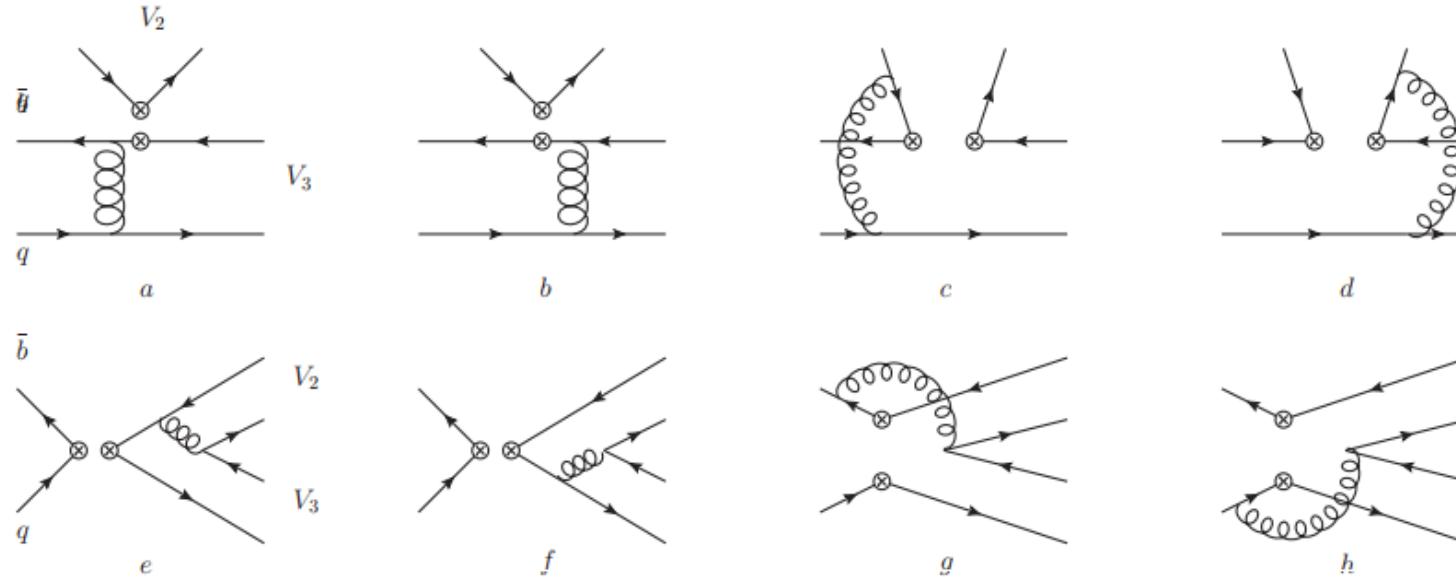
Bharucha, Straub, Zwicky JHEP 2016

- $|A_{cc\parallel}| \approx |A_{cc\perp}|$

The positive helicity amplitude  
Of charming penguin is negligible

| Modes   | $Br(10^{-6})$      | $f_L(\%)$        | $f_{\perp} (\%)$     | $\phi_{\parallel}(\text{rad})$              | $\phi_{\perp}(\text{rad})$              |
|---|--------------------|------------------|----------------------|---|---|
| $\overline{B}^0 \rightarrow \overline{K}^{*0} \phi$     | $9.14 \pm 3.14$    | $51.0 \pm 16.4$  | $22.2 \pm 9.9$       | $2.41 \pm 0.62$                             | $2.54 \pm 0.62$                         |
| <i>Exp</i>  | $10.0 \pm 0.5$     | $49.7 \pm 1.7$   | $22.4 \pm 1.5$       | $2.43 \pm 0.11$                             | $2.53 \pm 0.09$                         |
| $B^- \rightarrow K^{*-} \phi$                           | $9.86 \pm 3.39$    | $51.0 \pm 16.4$  | $22.2 \pm 9.9$       | $2.41 \pm 0.62$                             | $2.54 \pm 0.62$                         |
| <i>Exp</i>  | $10.0 \pm 2.0$     | $50 \pm 5$       | $20 \pm 5$           | $2.34 \pm 0.18$                             | $2.58 \pm 0.17$                         |
| $\overline{B}_s^0 \rightarrow \phi\phi$                 | $19.0 \pm 6.5$     | $51.0 \pm 16.4$  | $22.2 \pm 9.9$       | $2.41 \pm 0.62$                             | $2.54 \pm 0.62$                         |
| <i>Exp</i>  | $19.3 \pm 3.1$     | $36.2 \pm 1.4$   | $30.9 \pm 1.5$       | $2.55 \pm 0.11$                             | $2.67 \pm 0.23$                         |
| $\overline{B}_s^0 \rightarrow K^{*0} \phi$              | $0.56 \pm 0.19$    | $54.6 \pm 15.0$  | $20.5 \pm 9.1$       | $2.37 \pm 0.59$                             | $2.50 \pm 0.59$                         |
| <i>Exp</i>  | $1.13 \pm 0.30$    | $51 \pm 17$      | $28 \pm 11$          | $1.75 \pm 0.58 \pm 0.30$                    |   |
| $\overline{B}_s^0 \rightarrow K^{*0} \overline{K}^{*0}$ | $8.60 \pm 3.07$    | $44.9 \pm 18.3$  | $24.9 \pm 11.1$      | $2.47 \pm 0.67$                             | $2.60 \pm 0.67$                         |
| <i>Exp</i>  | $28 \pm 7$         | $31 \pm 13$      | $38 \pm 11$          |   |   |
|   | $A_{CP}^{dir}(\%)$ | $A_{CP}^0(\%)$   | $A_{CP}^{\perp}(\%)$ | $\Delta\phi_{\parallel}(10^{-2}\text{rad})$ | $\Delta\phi_{\perp}(10^{-2}\text{rad})$ |
| $\overline{B}^0 \rightarrow \overline{K}^{*0} \phi$     | $-0.39 \pm 0.44$   | $-0.38 \pm 0.45$ | $0.39 \pm 0.44$      | $-0.85 \pm 0.35$                            | $-0.85 \pm 0.35$                        |
| <i>Exp</i>  | $0 \pm 4$          | $-0.7 \pm 3.0$   | $-2 \pm 6$           | $5 \pm 5$                                   | $8 \pm 5$                               |
| $B^- \rightarrow K^{*-} \phi$                           | $-0.39 \pm 0.44$   | $-0.38 \pm 0.45$ | $0.39 \pm 0.44$      | $-0.85 \pm 0.35$                            | $-0.85 \pm 0.35$                        |
| <i>Exp</i>  | $-1 \pm 8$         | $17 \pm 11$      | $22 \pm 25$          | $7 \pm 21$                                  | $19 \pm 21$                             |
| $\overline{B}_s^0 \rightarrow \phi\phi$                 | $-0.39 \pm 0.44$   | $-0.38 \pm 0.45$ | $0.39 \pm 0.44$      | $-0.85 \pm 0.35$                            | $-0.85 \pm 0.35$                        |
| $\overline{B}_s^0 \rightarrow K^{*0} \phi$              | $6.61 \pm 7.56$    | $5.48 \pm 6.70$  | $-6.61 \pm 7.56$     | $14.6 \pm 5.3$                              | $14.6 \pm 5.3$                          |
| $\overline{B}_s^0 \rightarrow K^{*0} \overline{K}^{*0}$ | $-0.56 \pm 0.61$   | $-0.68 \pm 0.77$ | $0.56 \pm 0.61$      | $-1.17 \pm 0.60$                            | $-1.17 \pm 0.60$                        |

# LO Feynman diagrams



LO SCET: a-d (real) + charming penguin

PQCD: a-h, hard gluon

QCDF: a'-b', c-d , fit e-h

# Branch ratios

| Channel                                       | Exp.            | SCET            | PQCD                   | QCDF                   |
|---|-----------------|-----------------|------------------------|------------------------|
| $\bar{B}^0 \rightarrow \rho^0 \rho^0$         | $0.97 \pm 0.24$ | $1.00 \pm 0.29$ | $0.27^{+0.12}_{-0.10}$ | $0.9^{+1.9}_{-0.45}$   |
| $\bar{B}^0 \rightarrow \rho^0 \omega$         | $< 1.6$         | $0.59 \pm 0.19$ | $0.40^{+0.17}_{-0.14}$ | $0.08^{+0.36}_{-0.02}$ |
| $\bar{B}_s^0 \rightarrow K^{*0} \bar{K}^{*0}$ | $28 \pm 7$      | $8.6 \pm 3.0$   | $5.4^{+3.0}_{-2.4}$    | $6.6^{+2.2}_{-2.2}$    |

$B^0 \rightarrow \rho^0 \rho^0$ : PQCD, large cancellations in the hard-scattering emission diagrams and the annihilation ones.

$B^0 \rightarrow \rho^0 \omega$  : in QCDF the color-suppressed diagrams canceled .

$B_s \rightarrow K^{*0} K^{*0}$ : experiment.

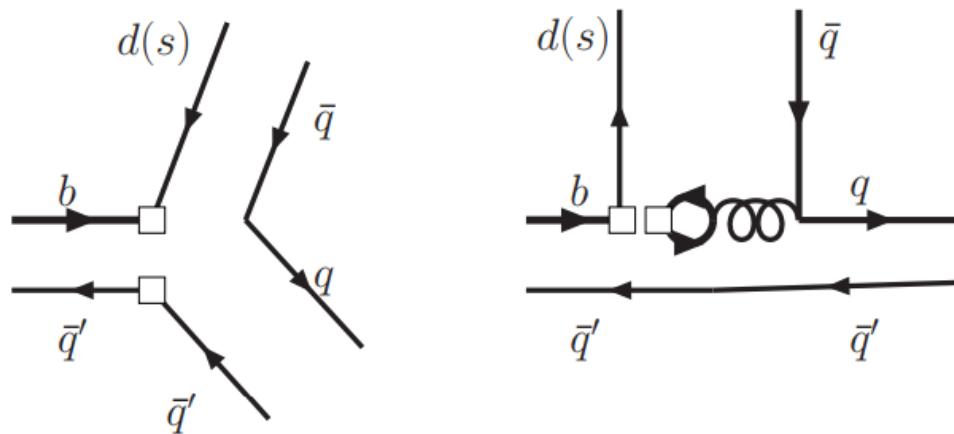
# Polarization fraction

- $f_L \sim 0.5$

QCDF: NLO effects, penguin annihilation

PQCD: annihilation diagrams especially  $(S+P)(S-P)$

SCET: charming penguins



Same topologies in flavor space, however, different power counting  $\rightarrow$  different  $f_L$ .

# Direct CP asymmetry

- QCDF and PQCD hard-scattering and annihilation diagrams  
PQCD:  $(S+P)(S-P)$  annihilation  $\propto V_{tb}V_{tD}^*$
- SCET Charming penguin  $\propto V_{cb}V_{cD}^*$

| Channel                               | Exp.       | SCET            | PQCD                   | QCDF             |
|---------------------------------------|------------|-----------------|------------------------|------------------|
| $B^- \rightarrow \rho^- \rho^0$       | $-5 \pm 5$ | 0               | $0.05^{+0.06}_{-0.03}$ | 0.06             |
| $\bar{B}^0 \rightarrow \rho^0 \rho^0$ |            | $19.5 \pm 23.5$ | $70.7^{+4.8}_{-9.6}$   | $30^{+22}_{-31}$ |
| $\bar{B}^0 \rightarrow \rho^0 \omega$ |            | $8.6 \pm 10.1$  | $59.4^{+13.4}_{-11.8}$ | $3^{+51}_{-76}$  |

Different CKM matrix elements affect CP asymmetry sizably; test PQCD and SCET

# Summary

- (1)  $\zeta_J^V \ll \zeta^V$ , differs from  $B \rightarrow PP(V)$  cases  $\zeta_J^P \simeq \zeta^P$ .
- (2) giving all observables for the 28 decay modes,  
including  $Br$ ,  $f_{L,\parallel,\perp}$ ,  $\phi_{\parallel,\perp}$ ,  $A_{CP}$ ,  $A_{CP}^{0,\perp}$ ,  $\Delta\phi_{\parallel,\perp}$
- (3) charming penguins  $A_{cc(L,\parallel,\perp)}$   $\Rightarrow$  large  $f_{\parallel,\perp}$ .  
 $\Rightarrow A_{CP}$
- (4) high-precision study to discriminate QCDF, PQCD and SCET.

*Thanks !*