Spectator Scattering and Annihilation Corrections in $B \to MM$ Decays

✓ Chang Qin (常钦)

Institute of Particle and Nuclear Physics

Henan Normal University

Collaborators: 孙俊峰, 杨悦玲, 李晓楠, 胡晓会

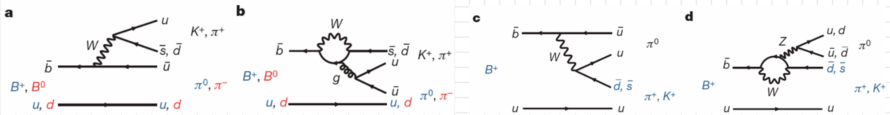
Refs: Phys.Rev. D90 (2014) 5, 054019; Phys. Lett. B740 (2015) 56; Phys. Lett. B743 (2015) 444

July, 2015. 兰州

Outline

1. Preliminary and Motivation

1.1 πK CP Puzzle



The SM expects $\Delta A \equiv \mathrm{A}_{CP}(B^- \to \pi^0 K^-) - \mathrm{A}_{CP}(\bar{B}^0 \to \pi^+ K^-) \approx 0\%$

HFAG: $\Delta A = (4.0 \pm 2.1)\,\% - (-8.2 \pm 0.6)\,\% = (12.2 \pm 2.2)\,\% \quad 5.5\sigma$

Theoretical Predictions:

$$\mathrm{A}_{CP}(B^- \to \pi^0 K^-) = -15.0\%\,, \ -3.6\%\ (\mathrm{QCDF});\ (-1^{+3}_{-5})\%\,,\ (2.2 \pm 2.0)\%\ (\mathrm{pQCD})$$

$$\mathrm{A}_{CP}(\bar{B}^0 \to \pi^+ K^-) = -16.1\%\,, \ -4.1\%\ (\mathrm{QCDF});\ (-9^{+6}_{-8})\%\,,\ (-6.5 \pm 3.1)\% \quad (\mathrm{pQCD})$$

Refs.: D. S. Du, H. J. Gong, J. F. Sun, D. S. Yang and G. H. Zhu, Phys. Rev. D **65** (2002) 074001; M. Beneke and M. Neubert, Nucl. Phys. B **651** (2003) 225; H. N. Li, S. Mishima and A. I. Sanda, Phys. Rev. D **72** (2005) 114005; W. Bai, M. Liu, Y. Y. Fan, W. F. Wang, S. Cheng and Z. J. Xiao Chin. Phys. C38 (2014) 033101. .

1.2 $\pi\pi$ Puzzle

"$\pi\pi$ puzzle" is reflected by

$$R_{+-}^{\pi\pi} \equiv 2\left[\frac{\mathcal{B}(B^- \to \pi^-\pi^0)}{\mathcal{B}(\bar{B}^0 \to \pi^+\pi^-)}\right]\frac{\tau_{B^0}}{\tau_{B^+}}\,, \qquad R_{00}^{\pi\pi} \equiv 2\left[\frac{\mathcal{B}(\bar{B}^0 \to \pi^0\pi^0)}{\mathcal{B}(\bar{B}^0 \to \pi^+\pi^-)}\right],$$

HFAG: $R_{+-}^{\pi\pi}$(Exp.) $= 1.99 \pm 0.15$ $R_{00}^{\pi\pi}$(Exp.) $= 0.75 \pm 0.09$

$$\begin{aligned} \text{The amplitudes} \quad \sqrt{2}A(B^- \to \pi^-\pi^0) &= -[T + C + P_{ew}e^{i\phi_2}] \\ A(\bar{B}^0 \to \pi^+\pi^-) &= -[T + Pe^{i\phi_2}] \\ \sqrt{2}A(\bar{B}^0 \to \pi^0\pi^0) &= -[C + (P_{ew} - P)e^{i\phi_2}] \end{aligned}$$

$$\begin{aligned} \text{SM generally expect} \quad & \mathcal{B}(B^- \to \pi^-\pi^0) \lesssim \mathcal{B}(\bar{B}^0 \to \pi^+\pi^-) \Longrightarrow R_{+-}^{\pi\pi} \sim 2 \\ & \mathcal{B}(\bar{B}^0 \to \pi^0\pi^0) \sim \mathcal{O}(\lambda^2)\mathcal{B}(\bar{B}^0 \to \pi^+\pi^-) \Longrightarrow R_{00}^{\pi\pi} \sim \mathcal{O}(\lambda^2) \\ \text{Theoretical Predictions :} \quad & R_{+-}^{\pi\pi} = 1.82\,, 1.91\,, \quad R_{00}^{\pi\pi} = 0.27\,, 0.22 \quad \text{QCDF (S4, NNLO)} \\ & R_{+-}^{\pi\pi} = 0.93\,, 1.15\,, \quad R_{00}^{\pi\pi} = 0.03\,, 0.09 \quad \text{pQCD (+NLO)} \end{aligned}$$

Refs.: M. Beneke and M. Neubert, Nucl. Phys. B **651** (2003) 225; M. Beneke, T. Huber and X. Q. Li, Nucl. Phys. B **832** (2010) 109; X. N. Li and S. Mishima, Phys. Rev. D73 (2006) 114014.

1.3 Pure annihilation $\bar{B}_s^0 \to \pi^+\pi^-$ and $\bar{B}_d^0 \to K^+K^-$ decays

The evidence of pure annihilation decays $\bar{B}_s^0 \to \pi^+\pi^-$ and $\bar{B}_d^0 \to K^+K^-$ are firstly reported by CDF, and soon confirmed by LHCb.

$$\mathcal{B}(\bar{B}_s^0 \to \pi^+\pi^-) = (0.73 \pm 0.14) \times 10^{-6}, \quad 5.2\sigma \quad HFAG$$
$$\mathcal{B}(\bar{B}_d^0 \to K^+K^-) = (0.12 \pm 0.05) \times 10^{-6}, \quad 2.4\sigma \quad HFAG$$

Theoretically, the pure annihilation non-leptonic B meson decays are expected much rare with a branching fractions at the level 10^{-7} or less due to the fact that the annihilation corrections are formally Λ_{QCD}/m_b power suppressed.

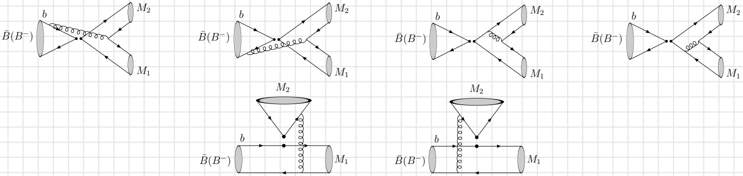
pQCD predictions: Z. J. Xiao, W. F. Wang and Y. Y. Fan, Phys. Rev. D 85 (2012) 094003

$$\mathcal{B}(\bar{B}_s^0 \to \pi^+\pi^-) = (5.10^{+1.96+0.25+1.05+0.29}_{-1.68-0.19-0.83-0.20}) \times 10^{-7};$$
$$\mathcal{B}(\bar{B}_d^0 \to K^+K^-) = (1.56^{+0.44+0.23+0.22+0.13}_{-0.42-0.22-0.19-0.09}) \times 10^{-7}$$

QCDF predictions: H. Y. Cheng and C. K. Chua, Phys. Rev. D80 (2009) 114008; D80 (2009) 114026

	QCDF		Experiment	Difference
$\mathcal{B}(\bar{B}_d^0 \to K^+K^-) =$	$(0.10^{+0.03+0.03}_{-0.02-0.03}) \times 10^{-6}$	$\Longleftrightarrow$	$(0.12 \pm 0.05) \times 10^{-6}$	$< 1\sigma$
$\mathcal{B}(\bar{B}_s^0 \to \pi^+\pi^-) =$	$(0.26^{+0.00+0.10}_{-0.00-0.09}) \times 10^{-6}$	$\Longleftrightarrow$	$(0.73 \pm 0.14) \times 10^{-6}$	3.4σ

1.4 End-point divergency



Regulation Scheme (parameterization) :

$$\int_0^1 \frac{dx}{x} \to X_A\,, \qquad \int_0^1 dx\,\frac{\ln x}{x} \to -\frac{1}{2}(X_A)^2\,,$$

$$X_A^{i,f} = (1 + \rho e^{i\phi}) \ln \frac{m_b}{\Lambda_h}$$

Traditional scenarios S4

$$\rho_d^{PP} = 1\,, \quad \phi_d^{PP} = -55^\circ$$

which are universal for above topologies of $B \to PP$ decay modes.

1.5 Implications of recent measurements

Guo-Huai Zhu, Phys. Lett. B 702 (2011) 408;
Kai Wang and Guo-Huai Zhu, Phys. Rev. D 88 (2013) 014043.

Brief summary of the "new" treatment:

- X_A^i is possibly non-universal for $B_{u,d}$ and B_s decays, but X_A^f is universal, *i. e.*, flavor asymmetry-breaking effects should be considered carefully.
- $X_A^i \neq X_A^f$ is possible due to gluon emission from the initial and final state quarks, respectively.

Aims of our work:

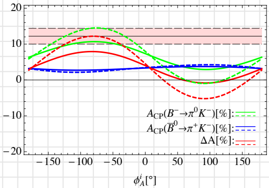
- Testing such "new" treatment.
- Fitting the annihilation and spectator corrections
- Evaluating its effects on the puzzles in B decays.

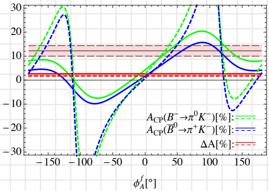
2. HSS and Anni. in $B_{u,d,s} \to PP$ decays

2.1 Solutions to πK CP Puzzle

$$\begin{aligned}\sqrt{2}\,\mathcal{A}_{B^- \to \pi^0 K^-} &= \sum_{p=u,c} V_{pb} V_{ps}^* \Big\{ A_{\pi K} \big[\delta_{pu} \left(\alpha_1 + \boldsymbol{\beta_2} \right) + \alpha_4^p + \alpha_{4,\mathrm{EW}}^p + \boldsymbol{\beta_3^p} + \beta_{3,\mathrm{EW}}^p \big] \\ &\quad + A_{K^- \pi^0} \Big[\delta_{pu}\, \boldsymbol{\alpha_2} + \frac{3}{2} \alpha_{3,\mathrm{EW}}^p \Big] \Big\}, \\ \mathcal{A}_{\bar{B}^0 \to \pi^+ K^-} &= \sum_{p=u,c} V_{pb} V_{ps}^* A_{\pi K} \Big[\delta_{pu}\, \alpha_1 + \alpha_4^p + \alpha_{4,\mathrm{EW}}^p + \boldsymbol{\beta_3^p} - \frac{1}{2} \beta_{3,\mathrm{EW}}^p \Big],\end{aligned}$$

Two direct ways: $\boldsymbol{\alpha_2}$ (HSS) and/or $\alpha_{3,\mathrm{EW}}^p$;

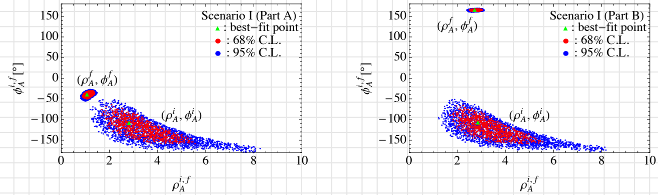




Possible solutions: $\phi_A^i \sim -100°(\rho_A^i \gtrsim 2)$,
$\phi_A^f \sim -60°\ (\rho_A^f \sim 1)$ or $\phi_A^f \sim 130°\ (\rho_A^f \sim 2)$

Fitting results based on the method of weighted least squares :

Combining constraints from $B_{u,d} \to \pi K$ and KK decays.



$\chi^2_{min} = 2.47$ and $\chi^2_{min} = 2.46$, respectively.

Table: Numerical results of annihilation parameters in scenario I with the assumption $X_H = X_A^i$

	ρ_A^i	$\phi_A^i [°]$	ρ_A^f	$\phi_A^f [°]$
Part A	$2.82^{+2.73}_{-1.15}$	-108^{+44}_{-50}	$1.07^{+0.30}_{-0.20}$	-40^{+10}_{-11}
Part B	$2.86^{+2.68}_{-1.20}$	-108^{+42}_{-51}	$2.72^{+0.30}_{-0.22}$	166^{+3}_{-4}

$X_A^i \neq X_A^f$ is required.

Table: The CP-averaged branching ratios (in units of 10^{-6}).

Decay Mode	Exp. data	scenario I	scenario II	S4
$B^- \to \pi^- \bar{K}^0$	23.79 ± 0.75	$20.53^{+1.52+4.28}_{-0.65-3.87}$	$21.54^{+1.60+4.40}_{-0.68-3.99}$	20.3
$B^- \to \pi^0 K^-$	$12.94^{+0.52}_{-0.51}$	$11.29^{+0.88+2.14}_{-0.45-1.96}$	$11.78^{+0.92+2.20}_{-0.47-2.01}$	11.7
$\bar{B}^0 \to \pi^+ K^-$	$19.57^{+0.53}_{-0.52}$	$17.54^{+1.34+3.61}_{-0.65-3.27}$	$18.51^{+1.41+3.73}_{-0.67-3.38}$	18.4
$\bar{B}^0 \to \pi^0 \bar{K}^0$	9.93 ± 0.49	$8.05^{+0.60+1.84}_{-0.27-1.65}$	$8.60^{+0.65+1.90}_{-0.29-1.72}$	8.0
$B^- \to K^- K^0$	1.19 ± 0.18	$1.45^{+0.13+0.32}_{-0.09-0.29}$	$1.51^{+0.13+0.32}_{-0.09-0.29}$	1.46
$\bar{B}^0 \to K^- K^+$	0.12 ± 0.05	$0.13^{+0.01+0.02}_{-0.01-0.02}$	$0.15^{+0.02+0.02}_{-0.01-0.02}$	0.07
$\bar{B}^0 \to K^0 \bar{K}^0$	1.21 ± 0.16	$1.22^{+0.11+0.27}_{-0.08-0.24}$	$1.32^{+0.12+0.27}_{-0.08-0.25}$	1.58
$B^- \to \pi^- \pi^0$	$5.48^{+0.35}_{-0.34}$	$5.20^{+0.64+1.11}_{-0.47-1.00}$	$5.59^{+0.68+1.15}_{-0.51-1.04}$	5.1
$\bar{B}^0 \to \pi^+ \pi^-$	5.10 ± 0.19	$5.88^{+0.66+1.66}_{-0.49-1.45}$	$5.74^{+0.64+1.63}_{-0.47-1.42}$	5.2
$\bar{B}^0 \to \pi^0 \pi^0$	$1.91^{+0.22}_{-0.23}$	$1.67^{+0.22+0.25}_{-0.19-0.23}$	$2.13^{+0.29+0.32}_{-0.24-0.29}$	0.7
$R^{\pi\pi}_{+-}$	1.99 ± 0.15	$1.64^{+0.06+0.13}_{-0.06-0.11}$	$1.80^{+0.07+0.17}_{-0.07-0.13}$	1.82
$R^{\pi\pi}_{00}$	0.75 ± 0.09	$0.57^{+0.06+0.16}_{-0.06-0.12}$	$0.74^{+0.08+0.22}_{-0.08-0.17}$	0.27

Table: The direct CP asymmetries (in units of 10^{-2})

Decay Mode	Exp. data	scenario I	scenario II	S4
$B^- \to \pi^- \bar{K}^0$	-1.5 ± 1.9	$-0.05^{+0.00+0.13}_{-0.00-0.15}$	$-0.17^{+0.01+0.14}_{-0.01-0.15}$	0.3
$B^- \to \pi^0 K^-$	4.0 ± 2.1	$3.2^{+0.2+0.6}_{-0.2-0.6}$	$2.5^{+0.1+0.6}_{-0.1-0.6}$	-3.6
$\bar{B}^0 \to \pi^+ K^-$	-8.2 ± 0.6	$-7.7^{+0.4+0.9}_{-0.4-0.9}$	$-9.1^{+0.4+0.9}_{-0.5-0.9}$	-4.1
$\bar{B}^0 \to \pi^0 \bar{K}^0$	-1 ± 10	$-10.3^{+0.6+0.9}_{-0.6-1.0}$	$-10.6^{+0.6+0.9}_{-0.6-0.9}$	0.8
ΔA_{CP}	12.2 ± 2.2	$10.9^{+0.6+0.9}_{-0.5-0.8}$	$11.6^{+0.6+0.9}_{-0.6-0.8}$	0.5
$B^- \to K^- K^0$	3.9 ± 14.1	$-0.6^{+0.0+3.2}_{-0.0-2.9}$	$2.0^{+0.1+3.4}_{-0.1-3.0}$	-4.3
$\bar{B}^0 \to K^- K^+$	—	0^{+0+0}_{-0-0}	0^{+0+0}_{-0-0}	—
$\bar{B}^0 \to K^0 \bar{K}^0$	-6 ± 26	-17^{+1+2}_{-1-2}	-16^{+1+2}_{-1-2}	-11.5
$B^- \to \pi^- \pi^0$	2.6 ± 3.9	$-1.1^{+0.1+0.1}_{-0.1-0.1}$	$-1.2^{+0.1+0.1}_{-0.1-0.1}$	-0.02
$\bar{B}^0 \to \pi^+ \pi^-$	29 ± 5	19^{+1+4}_{-1-4}	24^{+2+5}_{-2-4}	10.3
$\bar{B}^0 \to \pi^0 \pi^0$	43 ± 24	46^{+3+6}_{+3-6}	38^{+2+6}_{-2-6}	-19.0

Table: The mixing-induced CP asymmetries (in units of 10^{-2}) .

Decay Mode	Exp. data	scenario I	scenario II
$\bar{B}^0 \to \pi^0 \bar{K}^0$	57 ± 17	78^{+3+1}_{-3-1}	79^{+3+1}_{-3-1}
$\bar{B}^0 \to K^- K^+$	—	-86^{+6+0}_{-5-0}	-86^{+6+0}_{-5-0}
$\bar{B}^0 \to K^0 \bar{K}^0$	-108 ± 49	-10^{+1+0}_{-1-0}	-11^{+1+0}_{-1-0}
$\bar{B}^0 \to \pi^+ \pi^-$	-65 ± 6	-59^{+11+2}_{-10-3}	-60^{+10+2}_{-10-2}
$\bar{B}^0 \to \pi^0 \pi^0$	—	77^{+6+1}_{-8-2}	77^{+7+1}_{-9-2}

With the new treatment for annihilation corrections, scenario I presents good theoretical results for not only $B \to \pi K$ but also $B \to \pi\pi$ decays.
However, annihilation should be helpless for $R_{00}^{\pi\pi}$ puzzle due to $\mathcal{A}^{anni}_{\bar{B}^0 \to \pi^+\pi^-} \simeq \mathcal{A}^{anni}_{\bar{B}^0 \to \pi^0\pi^0}$.

$$\begin{aligned}
\mathcal{A}_{\bar{B}^0 \to \pi^+\pi^-} = & \sum_{p=u,c} V_{pb} V^*_{pd} A_{\pi\pi} \Big[\delta_{pu} \left(\alpha_1 + \beta_1 \right) + \alpha_4^p + \alpha^p_{4,\mathrm{EW}} + \beta_3^p + 2\, \beta_4^p \\
& - \frac{1}{2} \left(\beta^p_{3,\mathrm{EW}} - \beta^p_{4,\mathrm{EW}} \right) \Big] , \\
-\mathcal{A}_{\bar{B}^0 \to \pi^0\pi^0} = & \sum_{p=u,c} V_{pb} V^*_{pd} A_{\pi\pi} \Big[\delta_{pu} \left(\alpha_2 - \beta_1 \right) - \alpha_4^p + \frac{3}{2} \alpha^p_{3,\mathrm{EW}} + \frac{1}{2} \alpha^p_{4,\mathrm{EW}} - \beta_3^p - 2\, \beta_4^p \\
& + \frac{1}{2} \left(\beta^p_{3,\mathrm{EW}} - \beta^p_{4,\mathrm{EW}} \right) \Big] .
\end{aligned}$$

2.2 Solutions to both πK and $\pi\pi$ puzzles.

Within QCDF framework, besides of X_H, the first inverse moment of the B meson distribution amplitude, λ_B, which is used to parameterize integral of the B-meson distribution amplitude

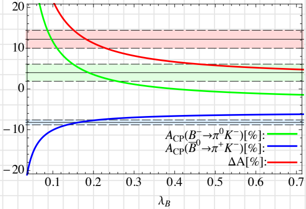
$$\int_0^1 \frac{d\xi}{\xi}\, \Phi_B(\xi) \equiv \frac{m_B}{\lambda_B}\,,$$

is another important parameter. $\lambda_B = 0.2\, GeV$ is used in scenario I.

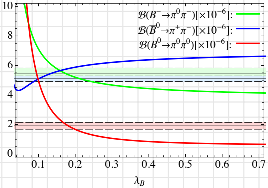
The value of λ_B

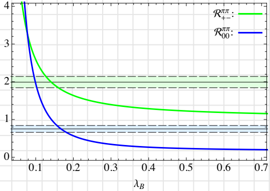
- The study of hadronic B decays favors a relative small value of λ_B
  $350 \pm 150\, MeV$ ($200\, MeV$ in S2) Beneke *et. al.*, Nucl. Phys. B **675** (2003) 333
  $200^{+250}_{-0}\, MeV$ Beneke *et. al.*, Nucl. Phys. B **774** (2007) 64
  $300 \pm 100\, MeV$ H. Y. Cheng and C. K. Chua, Phys. Rev. D **80** (2009) 114008
  $200\, MeV$ Zhu, *et. al.*, Phys. Lett. B 702 (2011) 408; Phys. Rev. D 88 (2013) 014043
- QCD sum rule
  $460 \pm 110\, MeV$ at the scale $1GeV$, Braun, *et. al.*, Phys. Rev. D **69** (2004) 034014
- Experimental analysis of $B^+ \to l\bar{\nu}_l\gamma$ decay by BABAR collaboration
  $\lambda_B > 300MeV$ at $90\% C.L.$ BABAR, Phys. Rev. D **80** (2009) 111105
  $\lambda_B > 115MeV$, An improved analysis is performed by Beneke, Eur. Phys. J. C**71** (2011) 1818

Its effect on πK puzzle:



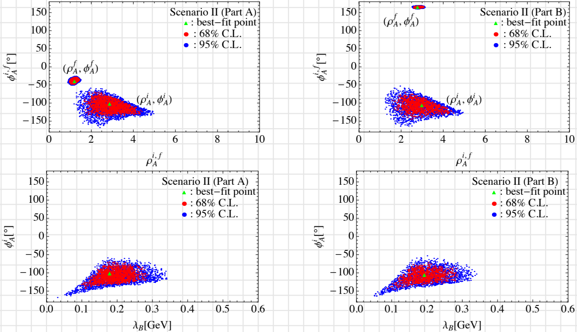
Its effect on $\pi\pi$ puzzle:





Phenomenally, $\lambda_B \sim 0.2\,GeV$ is required for resolving πK and $\pi\pi$ puzzles.

With available experimental data of $B_{u,d} \to \pi\pi\,,\pi K$ and KK decays



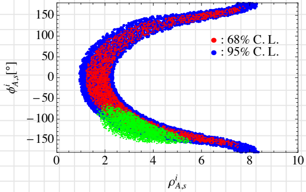
The best-fit points of part A and B correspond to $\chi^2_{min} = 3.66$ and $\chi^2_{min} = 3.67$, respectively.

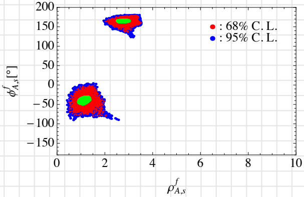
Table: Numerical results of annihilation parameters and λ_B in scenario II.

	ρ_A^i	$\phi_A^i[^\circ]$	ρ_A^f	$\phi_A^f[^\circ]$	$\lambda_B[GeV]$
Part A	$2.88^{+1.52}_{-1.30}$	-103^{+33}_{-40}	$1.21^{+0.22}_{-0.25}$	-40^{+12}_{-8}	$0.18^{+0.11}_{-0.08}$
Part B	$2.98^{+1.50}_{-1.40}$	-106^{+35}_{-39}	$2.78^{+0.29}_{-0.18}$	165^{+4}_{-3}	$0.19^{+0.09}_{-0.10}$

2.3 Test the flavor dependence of $X_A^{i,f}$ on initial states

Fitting results in B_s decays ($B_s \to \pi\pi\,, \pi K$ and KK)





- X_A^f in B_s decays are similar to the ones in $B_{u,d}$ decays
- A relative large ρ^i is required by not only "πK and $\pi\pi$ puzzles" but also $\mathcal{B}(B_s \to \pi^+\pi^-)$
- $X^i_{A,s} = X^i_{A,(u,d)}$ is also allowed.

i. e., the possible flavor symmetry breaking effects of building blocks A_k^i are concealed by large theoretical uncertainties;
and thus, $X_A^{i,f}$ are still universal for $B_{u,d,s} \to PP$ decays.

A Global Fit in $B_{u,d,s} \to PP$ decays. $N_{obs} = 28$, $N_{dof} = 5$

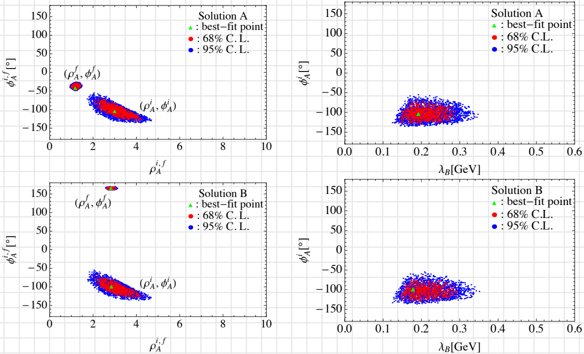


Table: Numerical results

	ρ_A^i	$\phi_A^i[°]$	ρ_A^f	$\phi_A^f[°]$	$\lambda_B[GeV]$
Part A	$3.00^{+1.25}_{-0.96}$	-104^{+36}_{-26}	$1.18^{+0.24}_{-0.20}$	-42^{+13}_{-5}	$0.19^{+0.10}_{-0.04}$
Part B	$2.85^{+1.48}_{-0.79}$	-100^{+33}_{-28}	$2.83^{+0.21}_{-0.21}$	165^{+3}_{-4}	$0.18^{+0.12}_{-0.03}$

Table: The CP-averaged branching ratios (in units of 10^{-6}) .

Decay Mode	Exp. data	this work	Cheng
$\bar{B}_s \to \pi^- K^+$	5.4 ± 0.6	$5.1^{+0.6+3.2}_{-0.4-2.4}$	$5.3^{+0.4+0.4}_{-0.8-0.5}$
$\bar{B}_s \to \pi^0 K^0$	—	$1.87^{+0.24+0.30}_{-0.19-0.28}$	$1.7^{+2.5+1.2}_{-0.8-0.5}$
$\bar{B}_s \to \pi^+ \pi^-$	0.73 ± 0.14	$0.62^{+0.05+0.10}_{-0.02-0.09}$	$0.26^{+0.00+0.10}_{-0.00-0.09}$
$\bar{B}_s \to \pi^0 \pi^0$	—	$0.31^{+0.02+0.01}_{-0.01-1.66}$	$0.13^{+0.0+0.05}_{-0.0-0.05}$
$\bar{B}_s \to K^+ K^-$	24.5 ± 1.8	$19.2^{+1.4+6.0}_{-0.6-5.0}$	$25.2^{+12.7+12.5}_{-7.2-9.1}$
$\bar{B}_s \to K^0 \bar{K}^0$	< 66	$20.1^{+1.5+6.6}_{-0.6-5.4}$	$26.1^{+13.5+12.9}_{-8.1-9.4}$

Table: The direct CP asymmetries (in units of 10^{-2})

Decay Mode	Exp. data	this work	Cheng
$\bar{B}_s \to \pi^- K^+$	26 ± 4	33^{+2+15}_{-2-9}	$20.7^{+5.0+3.9}_{-3.0-8.8}$
$\bar{B}_s \to \pi^0 K^0$	—	47^{+2+8}_{-2-9}	$36.3^{+17.4+26.6}_{-18.2-24.3}$
$\bar{B}_s \to \pi^+ \pi^-$	—	0^{+0+0}_{-0-0}	0
$\bar{B}_s \to \pi^0 \pi^0$	—	0^{+0+0}_{-0-0}	0
$\bar{B}_s \to K^+ K^-$	-14 ± 11	$-12.3^{+0.6+0.4}_{-0.6-0.4}$	$-7.7^{+1.6+4.0}_{-1.2-5.1}$
$\bar{B}_s \to K^0 \bar{K}^0$	—	$0.53^{+0.03+0.11}_{-0.03-0.14}$	$0.40^{+0.04+0.10}_{-0.04-0.04}$

Table: The mixing-induced CP asymmetries (in units of 10^{-2})

Decay Mode	Exp. data	this work	Cheng
$\bar{B}_s \to \pi^0 K^0$	—	$-9.3^{+13.7+6.8}_{-14.5-7.0}$	8^{+29+23}_{-27-26}
$\bar{B}_s \to \pi^+ \pi^-$	—	$16.4^{+0.9+0.0}_{-0.9-0.0}$	15^{+0+0}_{-0-0}
$\bar{B}_s \to \pi^0 \pi^0$	—	$16.4^{+0.9+0.0}_{-0.9-0.0}$	15^{+0+0}_{-0-0}
$\bar{B}_s \to K^+ K^-$	30 ± 13	$17.6^{+0.9+4.6}_{-0.9-5.8}$	22^{+4+5}_{-5-3}
$\bar{B}_s \to K^0 \bar{K}^0$	—	$0.53^{+0.03+0.02}_{-0.03-0.02}$	$0.4^{+0+0.2}_{-0-0.2}$

2.4 Brief Summary

- The significant hard spectator corrections is demanded for resolving both "πK" and "$\pi\pi$ puzzles".
  Moreover, a relative large X_A^i is required by $\mathcal{B}(\bar{B}_s \to \pi^+\pi^-)$
- $X_A^{i,f}$ are still universal for $B_{u,d,s} \to PP$ decays.
- $X_H(\rho_H, \phi_H) = X_A^i(\rho_A^i, \phi_A^i)$ is allowed, but $X_A^i \neq X_A^f$.

  numerically $(\rho_A^i, \phi_A^i) \sim (2.9, -103°)$; $(\rho_A^f, \phi_A^f) \sim (1.2, -40°)$ or $(2.8, 165°)$; $\lambda_B \sim 0.2GeV$
- The "new" treatment provides better theoretical results of $B_{u,d,s} \to \pi\pi\,, \pi K$ and KK decays than the traditional one.

3. Further test in $B_{u,d,s} \to PV$ Decays and preliminary result in $B \to VV$ Decays

3.1 $B_{u,d} \to PV$ Decays

Decay modes:

penguin-dominated $b \to s\bar{q}q$ $(q = u, d)$ transition: $B \to \pi K^*$, ρK

tree-dominated $b \to s\bar{q}q$ transition: $B \to \pi\rho$

penguin-dominated $b \to s\bar{s}s$ transition: $B \to \phi K$

penguin- and annihilation-dominated $b \to s\bar{s}s$ transition: $B \to KK^*$

$N_{obs} = 35\ (49)$

Free parameters:

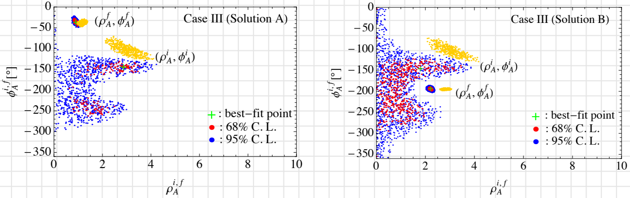
Generally, $N_{dof} = 7$: $X_H(\rho_H, \phi_H)$, $X_A^{i,f}(\rho_A^{i,f}, \phi_A^{i,f})$ and λ_B

Detailed analyses (Case I and II) in $B_{u,d,s} \to PV$ decays present that:

(1) $X_H = X_A^i$ is allowed, but $X_H \neq X_A^f$;

(2) No further constraint on the space of λ_B is found. So, $\lambda_B = 0.2 GeV$ (PP) is used as input.

The most simplified scenario: $N_{dof} = 4$: $X_A^{i,f}(\rho_A^{i,f}, \phi_A^{i,f})$



Caption: The best-fit points of Solutions A and B correspond to $\chi^2_{\rm min} = 23$ and 26;
The fitted results for $B \to PP$ decays at 68% C.L. are indicated by yellow points.

Findings:

- The main conclusions in $B \to PV$ decays are similar to the ones in $B \to PP$ decays, such as: $X_A^i \neq X_A^f$
- Numerically, $(\rho^i_{A,H}, \phi^i_{A,H}[^\circ]) = (2.87^{+0.66}_{-1.95}, -145^{+14}_{-21})$, $(\rho_A^f, \phi_A^f[^\circ]) = (0.91^{+0.12}_{-0.13}, -37^{+10}_{-9})$
- Exactly, The spaces of $(\rho_A^{i,f}, \phi_A^{i,f})$ for $B \to PV$ decays are separated from the spaces of $B \to PP$ decays, i.e., X_A for $B \to PP$ and PV decays should be introduced and treated individually.

Table: Branching ratios (10^{-6}) and direct CP asymmetries (10^{-2}).

Decay modes	Branching fractions			Direct CP asymmetries		
	Exp.	Case III	S4	Exp.	Case III	S4
$B^- \to \pi^- \bar{K}^{*0}$	10.5 ± 0.8	$8.7^{+0.4+1.3}_{-0.5-1.2}$	8.4	-4.2 ± 4.1	$0.47^{+0.02+0.11}_{-0.02-0.13}$	0.8
$B^- \to \pi^0 K^{*-}$	8.8 ± 1.2	$5.4^{+0.3+0.7}_{-0.3-0.7}$	6.5	-39 ± 12	$0.4^{+0.0+4.0}_{-0.0-4.7}$	-6.5
$\bar{B}^0 \to \pi^+ K^{*-}$	8.4 ± 0.8	$7.5^{+0.4+1.1}_{-0.5-1.0}$	8.1	-23 ± 6	-26^{+1+1}_{-1-1}	-12.1
$\bar{B}^0 \to \pi^0 \bar{K}^{*0}$	3.3 ± 0.6	$2.9^{+0.1+0.5}_{-0.2-0.5}$	2.5	-15 ± 13	-21^{+1+6}_{-1-6}	1.0
$B^- \to \bar{K}^0 \rho^-$	$9.4^{+1.9}_{-3.2}$	$7.9^{+0.4+1.3}_{-0.5-1.1}$	9.7	21^{+31}_{-28}	$1.3^{+0.1+0.1}_{-0.1-0.1}$	0.8
$B^- \to K^- \rho^0$	$3.74^{+0.49}_{-0.45}$	$3.41^{+0.19+0.63}_{-0.21-0.57}$	4.3	37 ± 11	26^{+1+5}_{-1-5}	31.7
$\bar{B}^0 \to K^- \rho^+$	7.0 ± 0.9	$9.0^{+0.5+1.4}_{-0.5-1.3}$	10.1	20 ± 11	27^{+1+3}_{-1-3}	20
$\bar{B}^0 \to \bar{K}^0 \rho^0$	4.7 ± 0.7	$5.5^{+0.3+0.8}_{-0.3-0.7}$	6.2	6 ± 20	15^{+1+3}_{-1-3}	-2.8
$B^- \to \pi^- \rho^0$	$8.3^{+1.2}_{-1.3}$	$6.8^{+0.6+1.2}_{-0.6-1.1}$	12.3	18^{+9}_{-17}	$-6.7^{+0.2+3.2}_{-0.2-3.7}$	-11.0
$B^- \to \pi^0 \rho^-$	$10.9^{+1.4}_{-1.5}$	$10.9^{+0.8+2.7}_{-0.8-2.4}$	10.3	2 ± 11	$8.2^{+0.2+1.6}_{-0.3-1.5}$	9.9
$\bar{B}^0 \to \pi^\pm \rho^\mp$	23.0 ± 2.3	$26.7^{+2.1+5.1}_{-2.2-4.5}$	23.6	—	—	—
$\bar{B}^0 \to \pi^0 \rho^0$	2.0 ± 0.5	$1.2^{+0.1+0.5}_{-0.1-0.5}$	1.1	-27 ± 24	$-3.9^{+0.1+5.0}_{-0.1-5.1}$	10.7
$B^- \to K^- \phi$	8.8 ± 0.5	$9.9^{+0.5+1.6}_{-0.6-1.5}$	11.6	4.1 ± 2.0	$0.72^{+0.02+0.14}_{-0.03-0.16}$	0.7
$\bar{B}^0 \to \bar{K}^0 \phi$	$7.3^{+0.7}_{-0.6}$	$9.3^{+0.4+1.5}_{-0.5-1.4}$	10.5	-1 ± 14	$1.2^{+0.0+0.1}_{-0.0-0.1}$	0.8
$B^- \to K^- K^{*0}$	< 1.1	$0.58^{+0.03+0.09}_{-0.04-0.09}$	0.66	—	$-10.6^{+0.3+3.0}_{-0.4-2.6}$	-9.6
$B^- \to K^{*-} K^0$	—	$0.46^{+0.02+0.08}_{-0.03-0.07}$	0.55	—	$-23.0^{+0.6+2.1}_{-0.8-2.2}$	-21.1
$\bar{B}^0 \to K^\pm K^{*\mp}$	< 0.4	$0.11^{+0.01+0.01}_{-0.01-0.01}$	0.15	—	—	—
$\bar{B}^0 \to K^{(*)0} \bar{K}^{*0}$	< 1.9	$0.96^{+0.05+0.13}_{-0.06-0.11}$	1.10	—	—	—

Table: The mixing-induced CP asymmetries (10^{-2}).

Decay modes	Exp.	Case III	S4
$\bar{B}^0 \to \bar{K}^0 \rho^0$	54^{+18}_{-21}	63^{+2+3}_{-2-2}	—
$\bar{B}^0 \to \pi^0 \rho^0$	-23 ± 34	-29^{+5+3}_{-7-5}	—
$\bar{B}^0 \to \bar{K}^0 \phi$	74^{+11}_{-13}	72^{+2+0}_{-2-0}	—

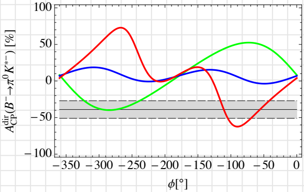
Table: The CP asymmetry parameters (10^{-2}).

	$\bar{B}^0 \to \pi^+ \rho^- + $ c.c.			$\bar{B}^0 \to K^+ K^{*-} + $ c.c.			$\bar{B}^0 \to K^0 \bar{K}^{*0} + $ c.c.		
	Exp.	Case III	S4	Exp.	Case III	S4	Exp.	Case III	S4
C	-3 ± 6	$4.6^{+0.2+0.8}_{-0.2-0.9}$	5	—	0^{+0+0}_{-0-0}	—	—	$13.0^{+0.5+0.6}_{-0.4-0.7}$	—
S	6 ± 7	$-3.6^{+5.0+1.6}_{-6.8-1.6}$	9	—	12^{+5+0}_{-7-0}	—	—	$4.2^{+0.2+0.7}_{-0.1-0.7}$	—
ΔC	27 ± 6	33^{+1+14}_{-1-15}	0	—	0^{+0+0}_{-0-0}	—	—	$-15.3^{+0.1+9.1}_{-0.1-8.7}$	—
ΔS	1 ± 8	$-1.8^{+0.2+0.9}_{-0.3-0.8}$	-3	—	0^{+0+0}_{-0-0}	—	—	$-25.0^{+0.3+6.4}_{-0.2-5.7}$	—
A_{CP}	-11 ± 3	$-11.8^{+0.4+1.5}_{-0.3-1.7}$	-8	—	0^{+0+0}_{-0-0}	—	—	$-10.7^{+0.3+2.2}_{-0.4-2.1}$	—

A new problem: $\pi^0 K^{*-}$ CP puzzle

Exp. : $A_{CP}^{dir}(B^- \to \pi^0 K^{*-}) = (-39 \pm 12)\%$ BABAR [arXiv:1501.00705]

CaseIII: $A_{CP}^{dir}(B^- \to \pi^0 K^{*-}) = (0.4^{+0.0+4.0}_{-0.0-4.7})\%$, $\sim 3\sigma$ difference



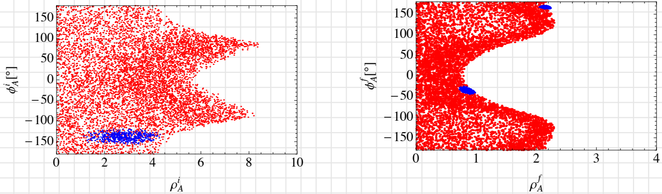
green: ϕ_H, blue: ϕ_A^i and red: ϕ_A^f.

Recalling just mentioned findings, we would like to point out that: a relatively large HSS corrections with $\rho_H \sim 3$ and $\phi_H \sim -140°$ is required to enhance α_2 contributions in resolving the "$\pi\pi$" and "πK" puzzles, but clearly leads to a wrong sign for $A_{CP}^{dir}(B^- \to \pi^0 K^{*-})$ when confronted with BABAR data.

H. Cheng, C. Chiang and A. Kuo, Phys. Rev. D **91** (2015) 1, 014011.
Thanks prof. Cheng for his helpful comments.

3.2 $B_s \to PV$ Decays

Fitting result at 68% C.L.:



blue: $B_{u,d}$ red: B_s.

Due to the large theoretical uncertainties and only few available experimental data with large errors, the spaces of both (ρ_A^i, ϕ_A^i) and (ρ_A^f, ϕ_A^f) in B_s decays are hardly to be well restricted for now.

Table: The CP-averaged branching fractions (10^{-6}).

Decay Modes	Class	This work	Cheng	S4	FS
$\bar{B}_s \to \pi^- K^{*+}$	T	$6.8^{+0.6+3.6}_{-0.6-2.8}$	$7.8^{+0.4+0.5}_{-0.7-0.7}$	6.8	7.92 ± 1.02
$\bar{B}_s \to \pi^0 K^{*0}$	C	$1.4^{+0.1+0.2}_{-0.1-0.2}$	$0.89^{+0.80+0.84}_{-0.34-0.35}$	0.33	3.07 ± 1.20
$\bar{B}_s \to K^+ \rho^-$	T	$16.0^{+1.3+9.4}_{-1.3-7.2}$	$14.7^{+1.4+0.9}_{-1.9-1.3}$	19.8	14.63 ± 1.46
$\bar{B}_s \to K^0 \rho^0$	C	$1.4^{+0.1+0.2}_{-0.1-0.2}$	$1.9^{+2.9+1.4}_{-0.9-0.6}$	0.68	0.56 ± 0.24
$\bar{B}_s \to \pi^0 \phi$	C, P_{EW}	$0.20^{+0.01+0.05}_{-0.02-0.04}$	$0.12^{+0.02+0.04}_{-0.01-0.02}$	0.12	1.94 ± 1.14
$\bar{B}_s \to K^0 \phi$	P	$0.45^{+0.02+0.07}_{-0.03-0.07}$	$0.6^{+0.5+0.4}_{-0.2-0.3}$	0.46	0.41 ± 0.07
$\bar{B}_s \to \pi^0 \rho^0$	WA	$0.017^{+0.001+0.001}_{-0.001-0.001}$	$0.02^{+0.00+0.01}_{-0.00-0.01}$	0.017	—
$\bar{B}_s \to \pi^\pm \rho^\mp$	WA	$0.034^{+0.002+0.002}_{-0.002-0.002}$	$0.04^{+0.00+0.02}_{-0.00-0.02}$	0.029	—
$\bar{B}_s \to K^\pm K^{*\mp}$	P	$17.3^{+0.7+3.1}_{-1.1-2.7}$	$21.6^{+10.0+12.9}_{-5.7-9.3}$	22.7	16.01 ± 1.25
$\bar{B}_s \to \bar{K}^{(*)0} K^{*0}$	P	$17.3^{+0.7+3.1}_{-1.1-2.7}$	$20.6^{+10.9+12.8}_{-6.4-9.3}$	22.2	15.65 ± 1.22

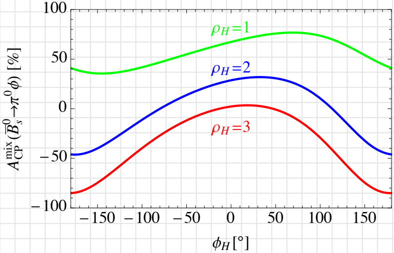
Table: The CP asymmetry parameters (10^{-2})

CP asymmetry parameters	$\bar{B}_s \to K^\pm K^{*\mp}$		$\bar{B}_s \to \pi^\pm \rho^\mp$	$\bar{B}_s \to \bar{K}^{(*)0} K^{*0}$
	This work	Cheng	This work	This work
C	-4^{+0+2}_{-0-2}	-8^{+4+15}_{-4-14}	0	$-0.44^{+0.01+0.06}_{-0.02-0.04}$
S	-9^{+0+6}_{-0-6}	-5^{+1+13}_{-1-9}	-74^{+2+0}_{-2-0}	$-0.1^{+0.0+0.0}_{-0.0-0.0}$
ΔC	8^{+1+14}_{-2-14}	-3^{+12+46}_{-14-49}	0	18^{+0+12}_{-0-14}
ΔS	28^{+1+8}_{-1-8}	33^{+9+30}_{-10-48}	0	37^{+0+6}_{-0-6}
A_{CP}	24^{+1+1}_{-1-2}	19^{+3+14}_{-4-11}	0	$-0.4^{+0.0+0.1}_{-0.0-0.1}$

Table: The direct and mixing-induced CP asymmetries (10^{-2})

Decay Modes	This work	Cheng	S4	FS
$A_{CP}^{dir}(\bar{B}_s \to \pi^- K^{*+})$	-28^{+1+6}_{-1-9}	$-24.0^{+1.2+7.7}_{-1.5-3.9}$	-22.0	-13.6 ± 5.3
$A_{CP}^{dir}(\bar{B}_s \to K^+ \rho^-)$	$11.5^{+0.3+4.8}_{-0.5-2.8}$	$11.7^{+3.5+10.1}_{-2.1-11.6}$	6.2	12.0 ± 2.7
$A_{CP}^{dir}(\bar{B}_s \to \pi^0 K^{*0})$	-64^{+2+6}_{-1-6}	$-26.3^{+10.8+42.2}_{-10.9-36.7}$	15.4	-42.3 ± 15.8
$A_{CP}^{dir}(\bar{B}_s \to \rho^0 K^0)$	$51.8^{+1.4+2.7}_{-1.8-3.0}$	$28.9^{+14.6+25.0}_{-14.5-23.7}$	11.6	-12.4 ± 45.3
$A_{CP}^{mix}(\bar{B}_s \to \rho^0 K^0)$	43^{+7+2}_{-4-2}	29^{+23+16}_{-24-21}	—	-34.8 ± 28.5
$A_{CP}^{dir}(\bar{B}_s \to \pi^0 \phi)$	66^{+1+3}_{-2-5}	$82.2^{+10.9+9.0}_{-14.0-55.3}$	24.8	7.3 ± 20.1
$A_{CP}^{mix}(\bar{B}_s \to \pi^0 \phi)$	-73^{+1+7}_{-1-7}	40^{+4+32}_{-10-53}	—	43.9 ± 17.1
$A_{CP}^{dir}(\bar{B}_s \to K^0 \phi)$	$-2.85^{+0.08+0.75}_{-0.12-0.73}$	$-3.2^{+1.2+0.6}_{-1.4-1.3}$	-7.4	0
$A_{CP}^{mix}(\bar{B}_s \to K^0 \phi)$	-70^{+2+0}_{-2-0}	-69^{+1+1}_{-1-1}	—	-69.2 ± 0.0
$A_{CP}^{dir}(\bar{B}_s \to \pi^0 \rho^0)$	0	0	—	—
$A_{CP}^{mix}(\bar{B}_s \to \pi^0 \rho^0)$	-74^{+2+0}_{-2-0}	-65^{+3+0}_{-3-0}	—	—

The dependence of $A_{CP}^{mix}(\bar{B}_s \to \pi^0\phi)$ on ϕ_H.



$$\mathcal{A}(\bar{B}_s \to \pi^0\phi) \propto V_{ub}V_{us}^*\alpha_2 + V_{tb}V_{ts}^*\frac{3}{2}\alpha_{3,EW}^p$$

It is a very important decay mode due to the fact that:

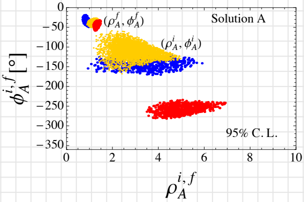
- It is irrelevant to the interference induced by anni. corrections (at QCD NLO).
- Very sensitive to HSS corrections, and play an important role to judge the two direct ways through α_2 or $\alpha_{3,EW}$ respectively to resolve the so-called "πK and $\pi\pi$ puzzles".

3.3 Preliminary result in $B \to VV$ Decays

yellow: PP; blue: PV;

red: VV ($B \to \rho K^*$,$K^* \bar{K}^*$,ϕK^*; $N_{obs.} = 36$, $N_{dof} = 4$).

One of solutions, for instance,



Note: such solution is disfavored by $\mathcal{B}(B \to \rho^0 \rho^0)$.

Findings and Comments:

(1) The corrections (end-point) of HSS and Anni. in $B \to PP$, PV and VV decays are similar, especially for X_A^f, which may be explained by the similarity of the final light mesons' DAs. (Thanks prof. H.-N. Li for the explanation in pQCD.)

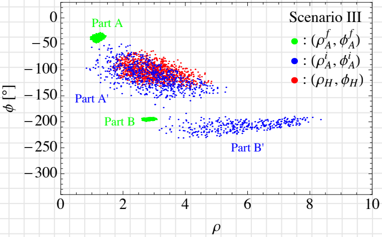
(2) The "new" treatment (Zhu and Wang) is supported by data.

(3) The puzzles, πK (or πK^*) and $\pi\pi$ (or $\rho\rho$) puzzles, are still there.

Thanks

河南師範大學
HENAN NORMAL UNIVERSITY

Thank you!


Scenario III
● : (ρ_A^f, ϕ_A^f)
● : (ρ_A^i, ϕ_A^i)
● : (ρ_H, ϕ_H)
Part A
Part A'
Part B
Part B'
ϕ [°]
0
−50
−100
−150
−200
−250
−300
ρ
0
2
4
6
8
10