Final state interaction effect on CP asymmetry in charmless three-body B decays

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arXiv:1307.8164 [hep-ph]

”Implications of LHCb measurements and future prospects”
CERN, Oct 14-16, 2013

Outline

- Experimental facts:
  $B^\pm \to K^\pm\pi^+\pi^-$, $B \to KKK$, $B \to \pi\pi\pi$, $B \to \pi KK$, $K\pi \to K\pi$, $\pi\pi \to \pi\pi$
- CPT constraint and FSI
- Pattern of CP violation in $B^\pm \to K^\pm\pi^+\pi^-$ and $B^\pm \to K^\pm K^+K^-$
- Why no CP violation in $B^\pm \to K^\pm p\bar{p}$?
- Conclusion and Outlook

Where are the events?
Low two-body mass region in $B^{\pm} \to K^{\pm}\pi^{+}\pi^{-}$!
(Supports the 2+1 decay process dominance.)

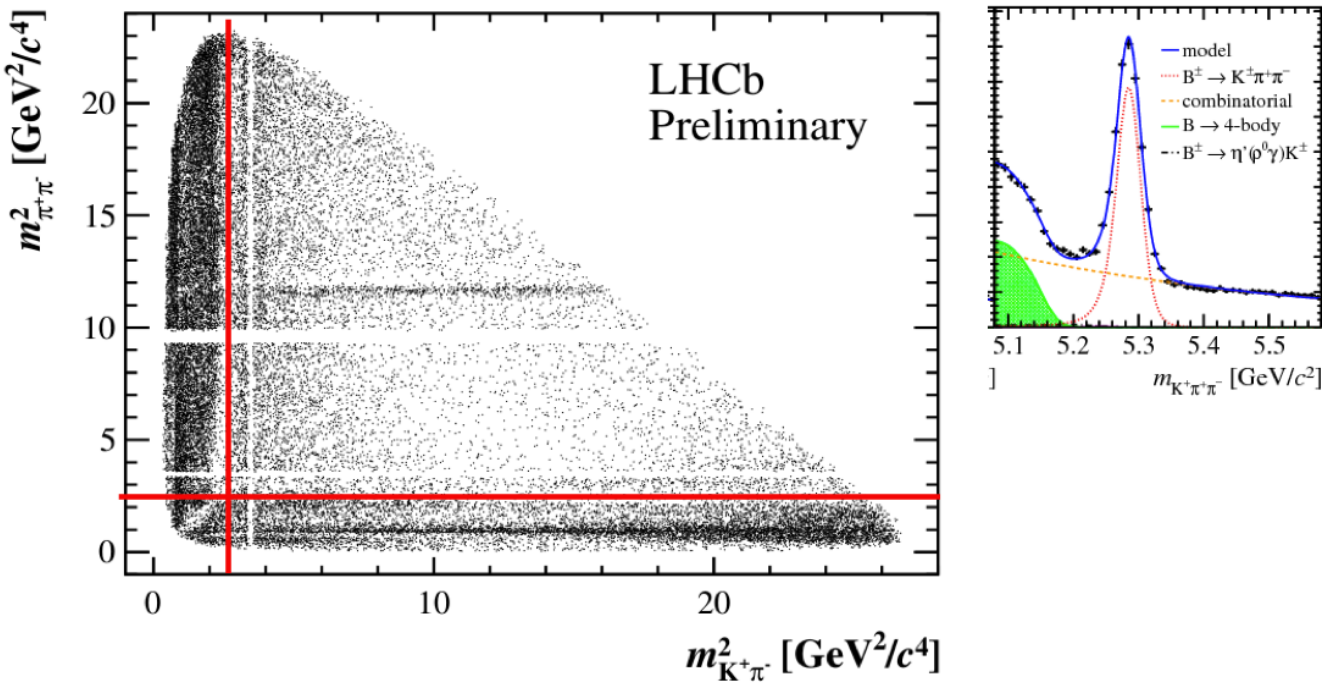


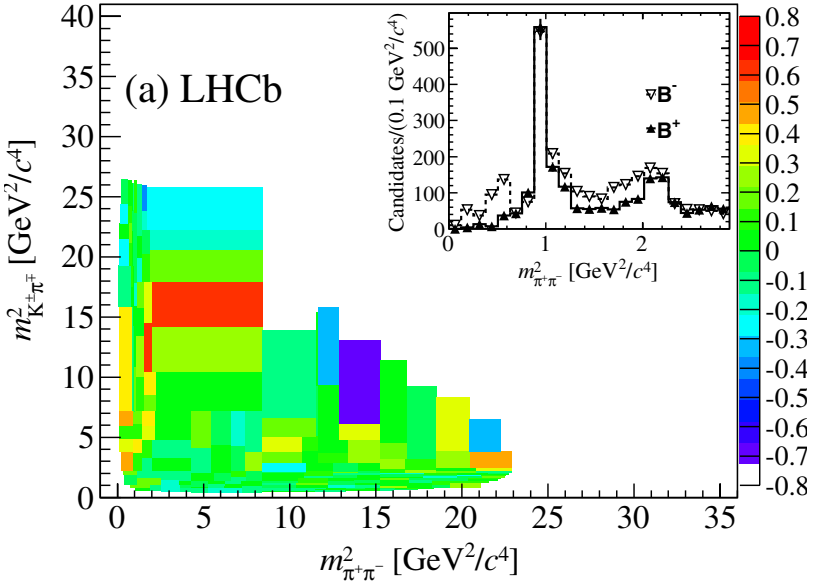
Figure : LHCb-CONF-2012-018.

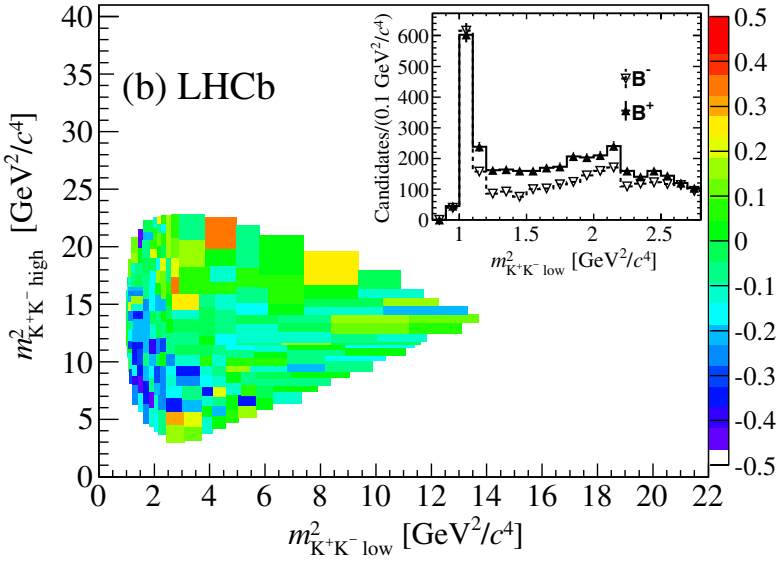
Low two-body mass region dominance (except charmonium):
$B^{\pm} \to K^{\pm}K^{+}K^{-}$, $B^{\pm} \to \pi^{\pm}\pi^{+}\pi^{-}$, $B^{\pm} \to \pi^{\pm}K^{+}K^{-}$, $B^{\pm} \to K^{\mp}p\bar{p}$!!!!!

Asymmetry in the Dalitz Plot: $B^{\pm} \to K^{\pm}\pi^{+}\pi^{-}$ and $B^{\pm} \to K^{\pm}K^{+}K^{-}$

Aaij et al. LHCb Coll. PRL111,101801(2013)

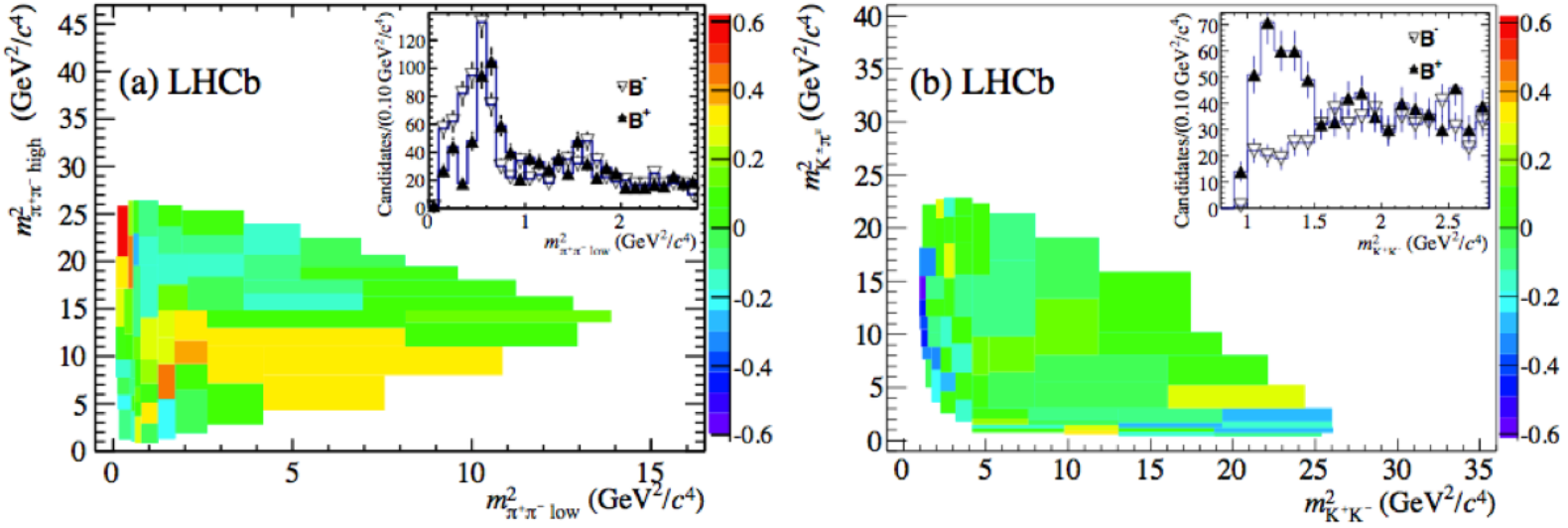
$B^{\pm}$ three-body decay populates low-mass region of the meson pair!





Asymmetry in the Dalitz Plot: $B^{\pm} \to \pi^{\pm}\pi^{+}\pi^{-}$ and $B^{\pm} \to \pi^{\pm}K^{+}K^{-}$

- $B^{\pm}$ three-body decay populates low-mass region of the meson pair!
- $\pi\pi \to KK$ $s-$wave inelastic scattering appreciable for $M_{\pi\pi} < 1.6$ GeV (D. H. Cohen et al., Phys. Rev. D **22**, 2595 (1980)).

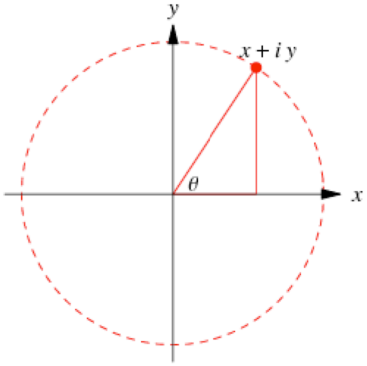


From "Charmless three-body B decays" talk by Irina NASTEVA

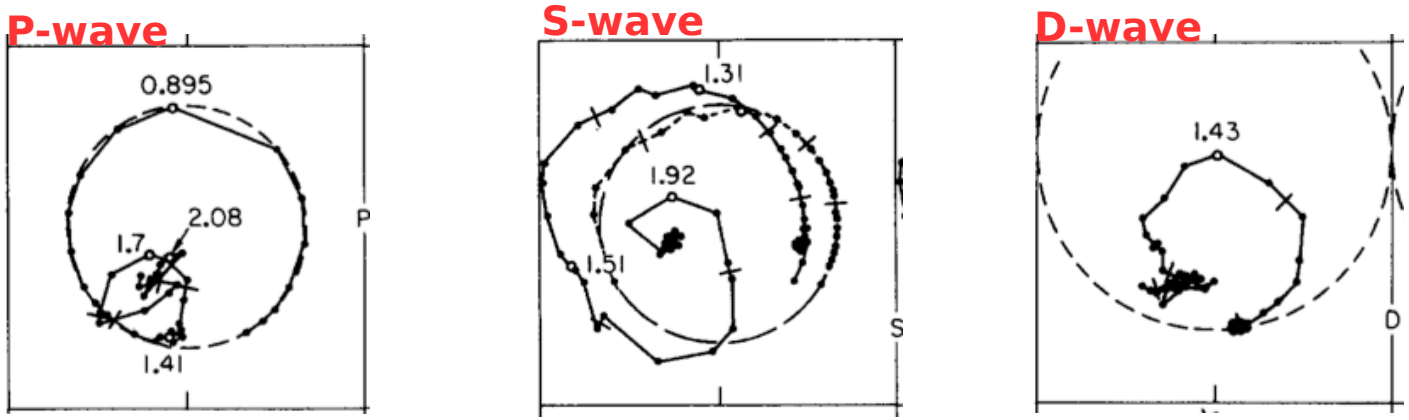
$K^+\pi^- \to K^+\pi^-$ scattering

Inelasticity: $\eta = 1 \Rightarrow$ 100% of hh → hh
$\eta = 0 \Rightarrow$ 0% –> hh

Argand plot.



LASS collaboration $K^+\pi^- \to K^+\pi^-$ (1988) Nuclear Physics B296 (1988) 493–526



No deviation from the unitary circle ($\eta = 1$) up to 1.6 GeV.

$\pi^+\pi^- \to \pi^+\pi^-$ scattering

CERN-Munich collaboration $\pi^+\pi^- \to \pi^+\pi^-$ (1973) Nuclear Physics B64 (1973) 134–162.

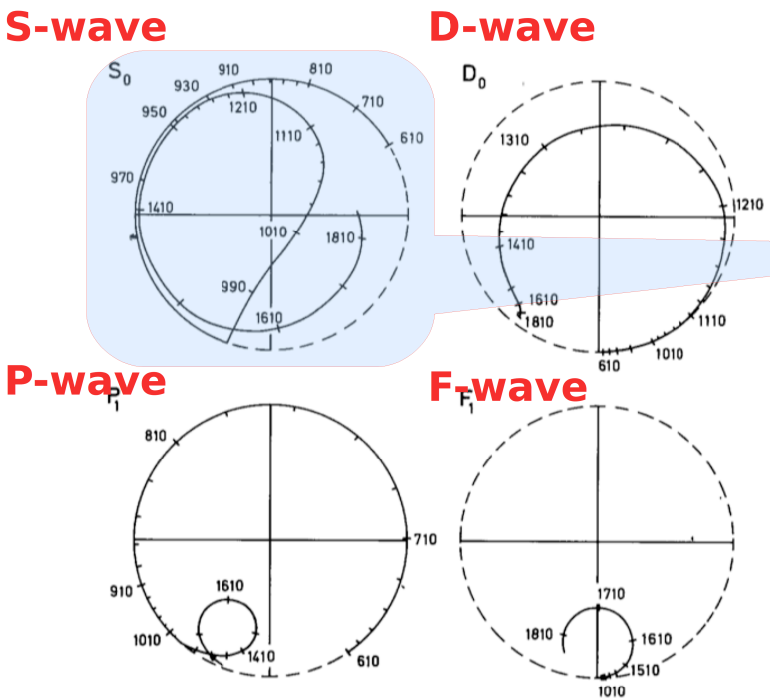


Fig. 6. Argand diagrams (Im T_l^I *versus* Re T_l^I) for the partial wave amplitudes from the energy-dependent fit. Numbers indicate the $\pi\pi$ energy.

Cohen, D et al PRD 22 (1980) 2595

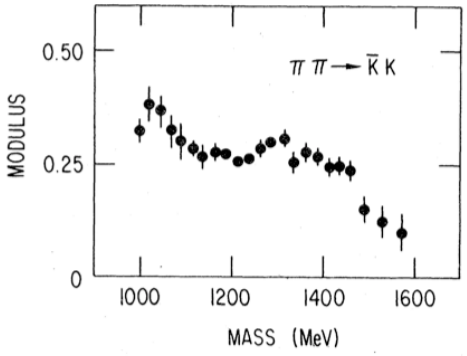


FIG. 27. Modulus of the $\pi\pi \to \bar{K}K$ scattering amplitude $|T(\pi\pi \quad \bar{K}K)|$ from solution I(b).

Strongly coupled channels:

$$\pi^+\pi^- \to K^+K^-$$

Large deviation from the unitary circle ($\eta = 1$) in s-wave up to about 1.6GeV !

CPT invariance constraint and decay

R. E. Marshak, Riazuddin, and C. P. Ryan, *Theory of Weak Interactions in Particle Physics* (Wiley-Interscience, 1969).

- $\mathcal{C}PT\,|h\rangle = \eta\langle\bar{h}|$, ($\bar{h}$ is the charge conjugate state and η is a phase)
- The weak and strong Hamiltonians conserve CPT:
  $(\mathcal{C}PT)^{-1}\,H_w\,\mathcal{C}PT = H_w \quad \text{and} \quad (\mathcal{C}PT)^{-1}\,H_s\,\mathcal{C}PT = H_s$
- Weak decay amplitude: $\langle\lambda_{out}|H_w|h\rangle$, λ_{out} with FSI from the strong interaction.
- CPT constraint: $\langle\lambda_{out}|H_w|h\rangle = \langle\lambda_{out}|(\mathcal{C}PT)^{-1}H_w\mathcal{C}PT|h\rangle = \eta_h\eta_\lambda\langle\bar{\lambda}_{in}|H_w|\bar{h}\rangle^*$.

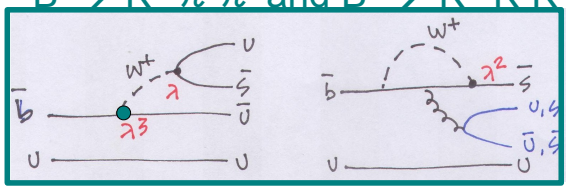
$$\langle\lambda_{out}|H_w|h\rangle = \eta_h\eta_\lambda\sum_{\bar{\lambda}'} S_{\bar{\lambda}',\bar{\lambda}}\langle\bar{\lambda}'_{out}|H_w|\bar{h}\rangle^*, \qquad S_{\bar{\lambda}',\bar{\lambda}} = \langle\bar{\lambda}'_{out}|\bar{\lambda}_{in}\rangle$$

- $\Gamma_h = \Gamma_{\bar{h}}$: identical particle and antiparticle life-times.

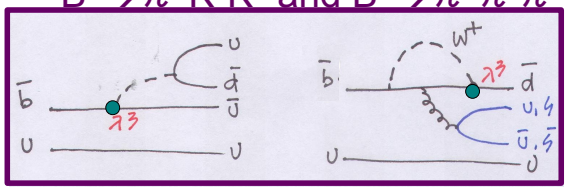
CP violation

CPT, Tree and Penguin amplitudes.

$B^{\pm} \to K^{\pm}\, \pi^{+}\pi^{-}$ and $B^{\pm} \to K^{\pm}\, K^{+}K^{-}$



$B^{\pm} \to \pi^{\pm} K^{+}K^{-}$ and $B^{\pm} \to \pi^{\pm}\pi^{+}\pi^{-}$



- Decay amplitude can be written in two pieces as [Bander, Silverman, Soni, PRL 43, 242 (1979)] $\mathcal{A}^{\pm} = [a^{T}\, e^{i(\,\delta^{T} \pm \gamma)} + a^{P}\, e^{i\,\delta^{P}}]$,
- General way [PDG - 12. CP Violation in Meson Decays]:

$$\mathcal{A}^{\pm} = A + e^{\pm i\gamma}\, B\,,$$

  where A and B are complex amplitudes invariant for CP, carrying strong FSI
- CP transformation changes the sign of the weak phase γ.

Coupled-Channel decay, CPT, FSI and CP asymmetry

- $\mathcal{A}^- = \langle \lambda_{out} | H_w | h \rangle = A_\lambda + e^{-i\gamma} B_\lambda \,, \qquad \mathcal{A}^+ = \langle \overline{\lambda}_{out} | H_w | \overline{h} \rangle = A_\lambda + e^{i\gamma} B_\lambda$
- **CPT and FSI:** $\mathcal{A}^\pm = A_\lambda + e^{\pm i\gamma} B_\lambda = \eta_h \eta_\lambda \sum_{\lambda'} S_{\lambda',\lambda} \left(A_{\lambda'} + e^{\mp i\gamma} B_{\lambda'} \right)^*$
- S-matrix and strong scattering amplitude: $S_{\lambda',\lambda} = \delta_{\lambda',\lambda} + i\, t_{\lambda',\lambda} \qquad (\lambda = \alpha, \beta)$
- **Perturbative treatment of FSI:** $A_\lambda = A_{0\lambda} + \delta A_\lambda$ **and** $B_\lambda = B_{0\lambda} + \delta B_\lambda$

L. Wolfenstein, Phys. Rev. D 43 (1991) 151

I. Bigi, A. I. Sanda, ”CP Violation”, 2nd Edition, Publisher: Cambridge University Press, 2009-05-25, ISBN: 052184794X

Coupled-Channel decay, CPT, FSI and CP asymmetry: LO in strong interaction

- **Leading order in $t_{\lambda',\lambda}$:**
  - $\mathcal{A}^{\pm}_{LO} = A_{0\lambda} + e^{\pm\imath\gamma} B_{0\lambda} + \imath \sum_{\lambda'} t_{\lambda',\lambda} \left(A_{0\lambda'} + e^{\pm\imath\gamma} B_{0\lambda'}\right)$

$$A_{0\lambda} = \eta_h \eta_\lambda A^*_{0\lambda} \quad \text{and} \quad B_{0\lambda} = \eta_h \eta_\lambda B^*_{0\lambda}.$$

- **The CPT constraint for two-channels:**
  - $\Gamma(A^+_\alpha) + \Gamma(A^+_\beta) = \Gamma(A^-_\alpha) + \Gamma(A^-_\beta)$ is still valid in LO!

$$\text{if Imag}\left[B_{0\alpha}\, A^*_{0\alpha}\right] = -\text{Imag}\left[B_{0\beta}\, A^*_{0\beta}\right]$$

- CP asymmetry: $\Delta\Gamma_\lambda = \Gamma\left(h \to \lambda\right) - \Gamma\left(\overline{h} \to \overline{\lambda}\right)$
- Two-channels α and β coupled by the strong interaction: $\Delta\Gamma_\alpha = -\Delta\Gamma_\beta$,

Inelasticity and CP violation

- Unitarity and symmetry of the S-matrix ($S_{\alpha,\beta} = S_{\beta,\alpha}$)

$$S = \begin{bmatrix} \eta e^{2\imath\delta_\alpha} & \imath\sqrt{1-\eta^2}\, e^{\imath(\delta_\alpha+\delta_\beta)} \\ \imath\sqrt{1-\eta^2}\, e^{\imath(\delta_\alpha+\delta_\beta)} & \eta e^{2\imath\delta_\beta} \end{bmatrix}$$

- Asymmetry: $$\Delta\Gamma_\alpha = 4(\sin\gamma)\left(\zeta_0 + \sqrt{1-\eta^2}\,\zeta_1\right)$$

$$\zeta_0 = \text{Imag}\left[B^*_{0\alpha} A_{0\alpha}(1 + i(t_{\alpha\alpha} - t^*_{\alpha\alpha}))\right]$$

$$\zeta_1 = \text{Real}\left[B^*_{0\alpha}\, A_{0\beta}\, e^{i(\delta_\alpha+\delta_\beta)} - B^*_{0\beta}\, A_{0\alpha}\, e^{-i(\delta_\alpha+\delta_\beta)}\right]$$

Born terms = partonic level [Bander, Silverman, Soni, PRL 43, 242 (1979)]

"Compound " CP asymmetry [Cheng, Chua, and Soni, PRD71, 014030 (2005)]

- If the phases of $B_{0\alpha}$ and $A_{0\alpha}$ are equal $\Rightarrow \zeta_0 = 0$!

Estimate of $\Delta\Gamma_{KK(\pi\pi)}$ in $B^{\pm} \to K^{\pm}K^{+}K^{-}$ $(B^{\pm} \to K^{\pm}\pi^{+}\pi^{-})$.

- $s-$wave scattering $\pi\pi \to \pi\pi$ and KK (I=0)
- Channels $\alpha \equiv K^{+}K^{-}$ and $\beta \equiv \pi^{+}\pi^{-}$
  - $$\Delta\Gamma_{KK} = \int dM^2_{KK'} \left(\frac{\partial^2}{\partial M^2_{KK'} \partial M^2_{KK}} \Gamma_{B^- \to K^- K^+ K^-} - \frac{\partial^2}{\partial M^2_{KK'} \partial M^2_{KK}} \Gamma_{B^+ \to K^+ K^+ K^-} \right)$$
- 2+1 decay mechanism ($K^{\pm}$ = spectator)
  - $$\Delta\Gamma_{KK} \propto (\sin\gamma)\sqrt{1-\eta^2}\,\cos\left(\delta_{KK} + \delta_{\pi\pi} + \Phi\right) F(M^2_{KK})$$
- Phase-space factor: $F(M^2_{KK}) = (M^2_{K^+K^-})_{max} - (M^2_{K^+K^-})_{min}$

Theo. vs. Exp. for $\Delta\Gamma_{\pi\pi(KK)}$ in $B^{\pm} \to K^{\pm}\pi^{+}\pi^{-}$ and $B^{\pm} \to K^{\pm}K^{+}K^{-}$

- $\Phi << \delta_{KK} + \delta_{\pi\pi}$ and $\delta_{KK} \approx \delta_{\pi\pi}$
- $s-$wave I=0 $\delta_{\pi\pi}$ and η from Pelaez and Ynduráin PRD71,074016(05)
- Fit the absolute normalization

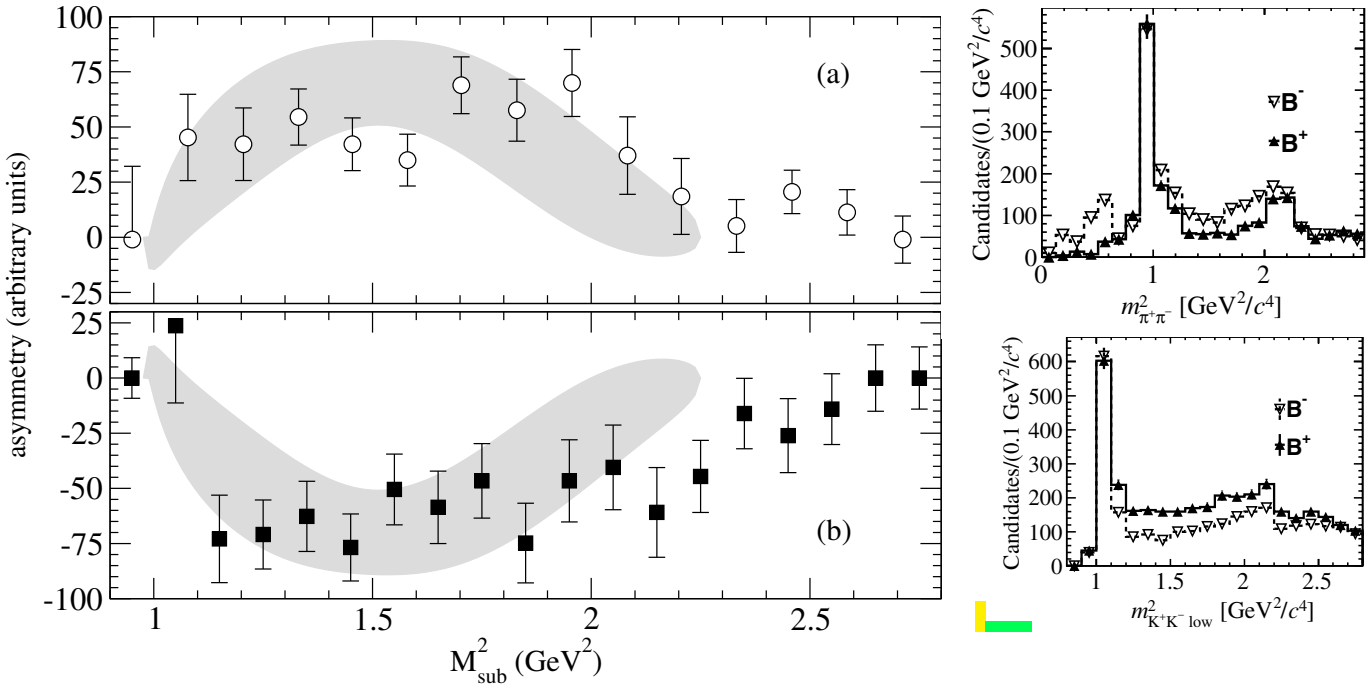


Figure : Theo. estimate (grey band) as a function of the subsystem mass compared to experimental data of (a) the asymmetry of $B^{\pm} \to K^{\pm}\pi^{+}\pi^{-}$ decay (circles), and of (b) the asymmetry of $B^{\pm} \to K^{\pm}K^{+}K^{-}$ decay (squares). Exp. data from R. Aaij *et al.* (LHCb Coll.) PRL111,101801(2013).

No CP violation in $B^{\pm} \to K^{\pm} p\bar{p}$

R. Aaij et al. (LHCb Collaboration) PRD88, 052015 (2013)

STUDIES OF THE DECAYS $B^+ \to p\bar{p}h^+ \ldots$ PHYSICAL REVIEW D **88,** 052015 (2013)

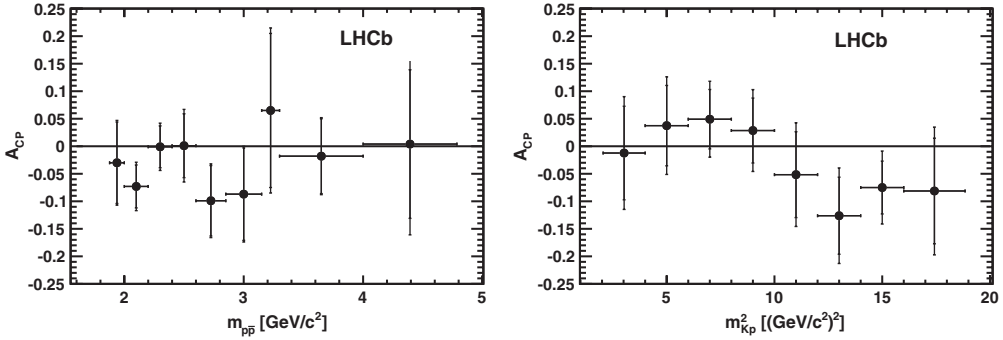


FIG. 7. Distribution of A_{CP} for the Dalitz-plot projections on $m_{p\bar{p}}$ and m^2_{Kp} for $B^{\pm} \to p\bar{p}K^{\pm}$ events. In the $m_{p\bar{p}}$ projection (left), the bin $[2.85, 3.15]$ GeV$/c^2$ contains only the value of the charmless $p\bar{p}K^{\pm}$ after subtraction of the $\eta_c - J/\psi$ contribution. The m^2_{Kp} projection (right) has been obtained after removing the charmonia bands.

- Why? FSI?

No CP violation in $B^{\pm} \to K^{\pm} p\bar{p}$: competing decay channels

Branching ratios for pp annihilation at rest into three narrow mesons.

Claude Amsler Reviews of Modern Physics, Vol. 70, No. 4, October 1998

Two body final states

$\pi^+\pi^-$	3.33	$\pm$	0.17	10^{-3}
$\pi^+\pi^-$	3.07	$\pm$	0.13	10^{-3}
$\omega\eta$	1.51	$\pm$	0.12	10^{-2}
	1.63	$\pm$	0.12	10^{-2}
$\omega\eta'$	0.78	$\pm$	0.08	10^{-2}
$\omega\omega$	3.32	$\pm$	0.34	10^{-2}
$\omega\eta$	1.51	$\pm$	0.12	10^{-2}
	1.63	$\pm$	0.12	10^{-2}
$\omega\eta'$	0.78	$\pm$	0.08	10^{-2}
$\omega\omega$	3.32	$\pm$	0.34	10^{-2}
K^+K^-	1.01	$\pm$	0.05	10^{-3}
K^+K^-	0.99	$\pm$	0.05	10^{-3}

Three body final states

$\pi^+\pi^-\pi^0$	$\pi^+\pi^-(\pi^0)$	6.9	$\pm$	0.4	10^{-2}
$\pi^0\eta\eta$	6γ	2.0	$\pm$	0.4	10^{-3}
$\pi^0\pi^0\omega$	7γ	2.00	$\pm$	0.21	10^{-2}
	$\pi^+\pi^-6\gamma$	2.57	$\pm$	0.17	10^{-2}
$\pi^+\pi^-\omega$	$2\pi^+2\pi^-(\pi^0)$	6.6	$\pm$	0.6	10^{-2}
$\omega\eta\pi^0$	7γ	6.8	$\pm$	0.5	10^{-3}
$\pi^0\pi^0\eta$	6γ	6.7	$\pm$	1.2	10^{-3}
	$\pi^+\pi^-6\gamma$	6.50	$\pm$	0.72	10^{-3}
$\pi^+\pi^-\eta$	$\pi^+\pi^-2\gamma$	1.63	$\pm$	0.12	10^{-2}
	$\pi^+\pi^-6\gamma$	1.33	$\pm$	0.16	10^{-2}
$\pi^{\pm}K^{\mp}K_S$	$\pi^+\pi^-\pi^{\pm}K^{\mp}$	2.73	$\pm$	0.10	10^{-3}
$\pi^{\pm}K^{\mp}K_L$	$\pi^{\pm}K^{\mp}(K_L)$	2.91	$\pm$	0.34	10^{-3}
$\omega K_S K_S$	$3\pi^+3\pi^-(\pi^0)$	1.17	$\pm$	0.07	10^{-3}
ωK^+K^-	$K^+K^-\pi^+\pi^-(\pi^0)$	2.30	$\pm$	0.13	10^{-3}

Many channels with similar magnitude!

No CP violation in $B^{\pm} \to K^{\pm} p\bar{p}$

- many channels for $p\bar{p}$ at rest with similar branching ratios
- CPT constraint and FSI:
  - $$\Delta\Gamma_{\lambda} \sim 4(\sin\gamma)\,\mathrm{Imag}\left[i \sum_{\lambda' \neq \lambda} B^{*}_{0\lambda} t_{\lambda',\lambda} A_{0\lambda'} - i \sum_{\lambda' \neq \lambda} B^{*}_{0\lambda'} t^{*}_{\lambda',\lambda} A_{0\lambda} \right] \sim 0$$
- Coherent sum of similar amplitudes with varying phases: vanishing result!

Conclusion and Outlook

Conclusion

- Constraint of CPT invariance + FSI
- Assumption that CP violation is due to the interference of two CP-conserving amplitudes separated by a CP-noninvariant weak phase.
- CP violation in three-body charmless $B^{\pm}$ decays is driven by the relevance of the $\pi\pi \to KK$ scattering!
- No CP violation in $B^{\pm} \to p\bar{p}\, h^{\pm}$ resulting from the coherent sum of several terms!

Outlook

- Normalization of the asymmetries (partonic amplitudes);
- Higher partial waves and isospins;
- Three-body rescattering? ($D \to KK\pi$)†

† $D^{\pm} \to K^{\mp}\pi^{\pm}\pi^{\pm}$
Magalhães, Robilotta, Guimarães, TF, de Paula, Bediaga, dos Reis, Maekawa, Zarnauskas, PRD84 (2011) 094001.