CP Violation in Charmless 3-body B decays

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$B^{\pm} \to h^{+}h^{-}h^{\pm}$ **LHCb Brazilian Group**

Outline

- **Theory and Techniques**
- **The LHCb Detector**
- $B^{\pm} \to h^+ h^- h^{\pm}$ **decays.** ($h = K, \pi$)
- $B^{\pm} \to p\bar{p}h^{\pm}$ **decays.**

Theory and Techniques

Introduction

- CP Violation (Sakharov, Baryogenesys)
- Discovered 1964 (neutral kaons)
- Standard Model CPV (CKM matrix)
- SM CPV (insufficient, Universe)
- CKM matrix: D (small or null), B (measurable)
- 3-body decays are interesting (signatures in Dalitz Plot)

Conditions for Direct CP Violation

- **In charged B decays, we have multiple amplitudes :**

$$\mathcal{A}(B \to f) = |A_1|e^{i(\delta_1+\phi_1)} + |A_2|e^{i(\delta_2+\phi_2)} + |A_3|e^{i(\delta_3+\phi_3)} + \ldots$$

- **Strong phases (δ_i) are invariant under CP Transformation:** $\delta_i \to \delta_i$
- **Weak phases (ϕ_i) change sign under CP Transformation:** $\phi_i \to -\phi_i$

$$\bar{\mathcal{A}}(\bar{B} \to \bar{f}) = |\bar{A}_1|e^{i(\delta_1-\phi_1)} + |\bar{A}_2|e^{i(\delta_2-\phi_2)} + |\bar{A}_3|e^{i(\delta_3-\phi_3)} + \ldots$$

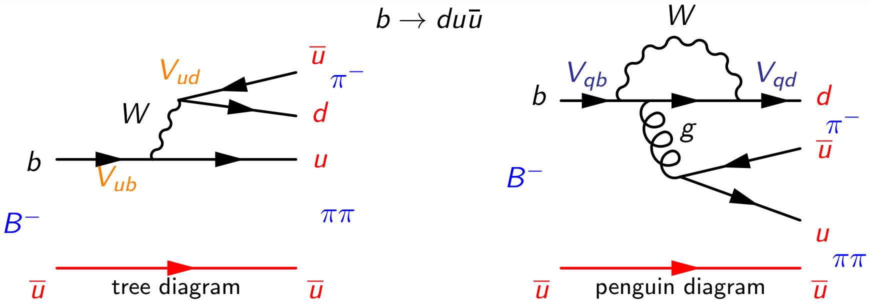
- **The Asymmetry can be calculated as:**

$$\mathcal{A}_{CP}(B \to f) = \frac{|\bar{\mathcal{A}}|^2 - |\mathcal{A}|^2}{|\bar{\mathcal{A}}|^2 + |\mathcal{A}|^2} \propto \sum_{ij} \sin(\delta_i - \delta_j)\sin(\phi_i - \phi_j)$$

- **Conditions for Direct CP Violation:**

1) **At least two amplitudes.**
2) **Non-zero weak phase difference,** $\phi_i - \phi_j \neq 0$
3) **Non-zero strong phase difference,** $\delta_i - \delta_j \neq 0$

BSS Model for the $B^{\pm} \to \pi^{+}\pi^{-}\pi^{\pm}$decay



1) At least two amplitudes. Tree x Pengin

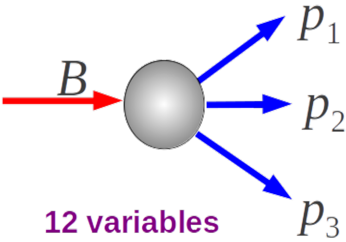
- In both diagrams: Initial State: B meson, Final State: $\pi\pi\pi$
- BSS model: b is considered as free. $\bar{u}$ is considered an espectator (quark level)

2) Non-zero week phase difference: **CKM**: $\mathcal{A}^T \propto VubVud$, $\mathcal{A}^P \propto VqbVqd, q = u, c, t$.

3) Non-zero strong phase difference: (penguin: q on its mass shell (u, c for b decays)).

Source of $\delta_i - \delta_j \neq 0$ are Short Distance Effects.!!!

Dalitz Plot



12 variables

$$E_B = \sum_i E_i$$

1 constraint

$$\vec{p}_B = \sum_i \vec{p}_i$$

3 constraints

$$E_i = \vec{p}_i^{\,2} + m_i^2$$

3 constraints

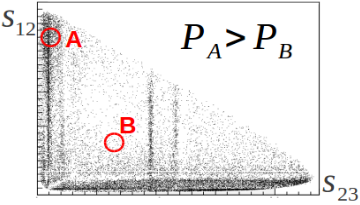
If p1, p2, p3 pseudoscalars

3 constraints

12 variables – 10 constraints = 2 variables:

$$s_{12} = (p_1 + p_2)^2,\ s_{23} = (p_2 + p_3)^2$$

Dalitz Plot

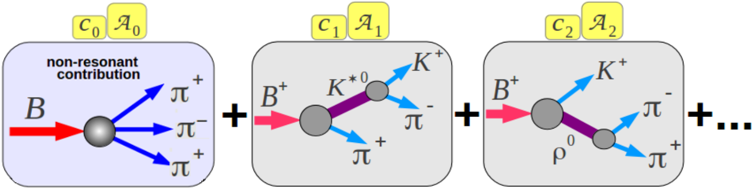


Probability Density Function: $\mathcal{P}(s_{12}, s_{23})$

$$\mathcal{P} = |\mathcal{A}|^2$$

Amplitud: $\mathcal{A}(s_{12}, s_{23})$

Example: $B^+ \to K^+\pi^-\pi^+$:



Isobar Model: the decay amplitude is a coherent sum of a non-resonant amplitude plus resonant amplitudes:

$$\mathcal{A}(s_{12}, s_{23}) = c_{nr}\mathcal{A}_{NR}(s_{12}, s_{23}) + \sum_k c_k \mathcal{A}_k(s_{12}, s_{23})$$

Amplitude Analysis

$$\mathcal{A}(s_{12}, s_{23}) = c_{nr}\mathcal{A}_{NR}(s_{12}, s_{23}) + \sum_k c_k \mathcal{A}_k(s_{12}, s_{23})$$

$$\mathcal{A}_k = F^B(s_{12}, s_{23})F^R(s_{12}, s_{23})BW(s_{12}, s_{23})\mathcal{M}(s_{12}, s_{23})$$

Fitting the model to data (DP plane) we obtain the complex coefficients c_{nr}, c_k wich tell us the contribution of ressonances.

Asymmetry : In order to consider asymmetry we define a contribution for the particle and the antiparticle:

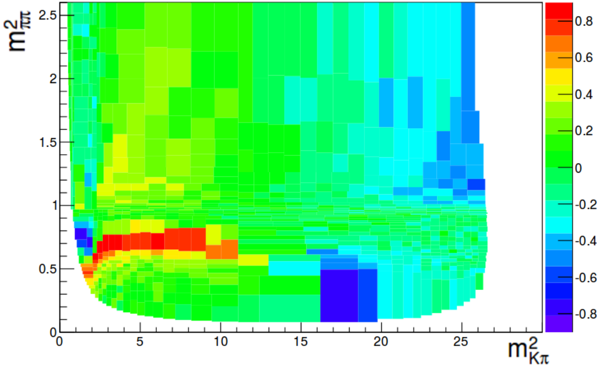
$$\mathcal{A}(s_{12}, s_{23}) = \underbrace{\sum_j c_j \mathcal{A}_j(s_{12}, s_{23})}_{B^{+} sample} + \underbrace{\sum_j \bar{c}_j \bar{\mathcal{A}}_j(s_{12}, s_{23})}_{B^{-} sample} , \quad \mathcal{A}_j(s_{12}, s_{23}) = \bar{\mathcal{A}}_j(s_{12}, s_{23})$$

c_j and $\bar{c}_j$ contains weak and strong phases.

$$A_{CP} = \frac{|\bar{c}_j|^2 - |c_j|^2}{|\bar{c}_j|^2 + |c_j|^2}$$

Asymmetry Map from Mirandizing Method

Phys.Rev.D 86,036005(2012).
I.Bediaga, J.Miranda, A.C.dosReis, I.I.Bigi, A.Gomes, J.M.Otalora Goicochea, and A.Veiga.

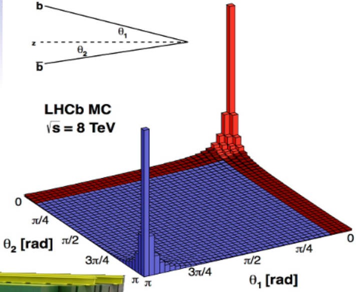


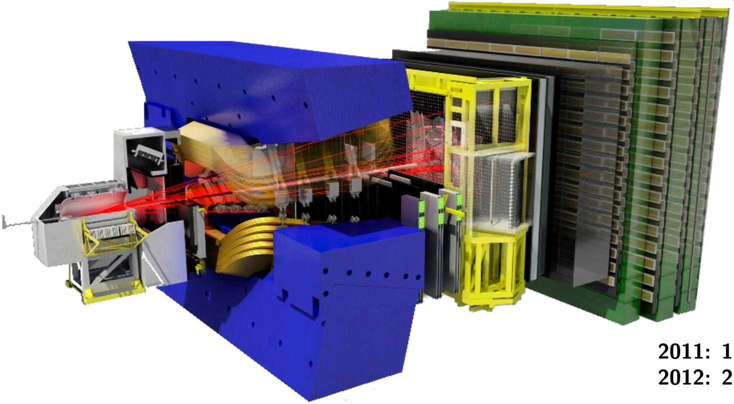
- Histogram performed by an adaptive binning algorithm.
- Each bin contains the same number of events.
- The asymmetry was calculated from the evens inside the bin.
- The vertical color scale tell us the asymmetry value.

LHCb Experiment

The LHCb Detector

- Single-arm forward spectrometer ($2 < \eta < 5$),
- Designed to study particles containing b and c quarks
- Includes a High precision tracking system
- Ring Imaging Cherenkov Detectors (charged hadrons)
- Calorimeter System (photons, electrons and hadrons)
- Muon System, interleaved layers of iron and MWPC (muons)





2011: 1 fb^{-1}, $\sqrt{s} = 7$ TeV
2012: 2 fb^{-1}, $\sqrt{s} = 8$ TeV

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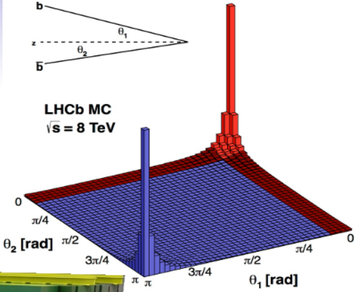

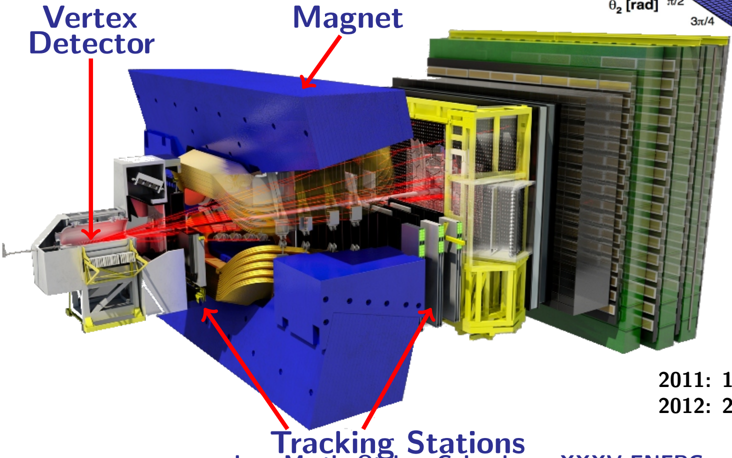

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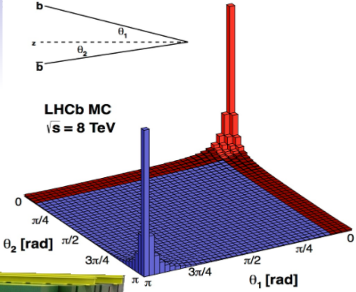

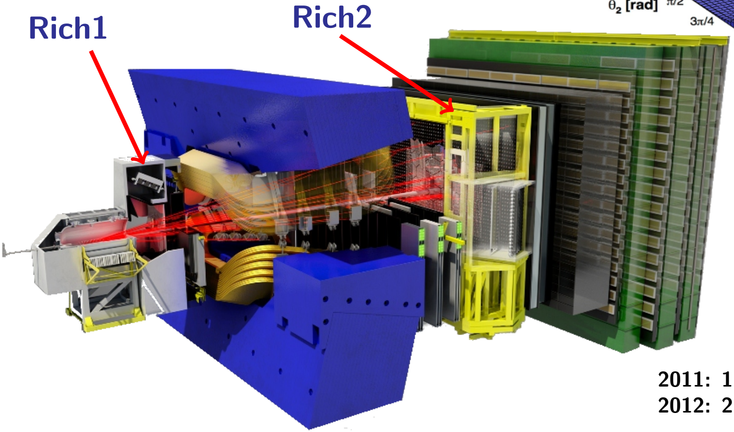

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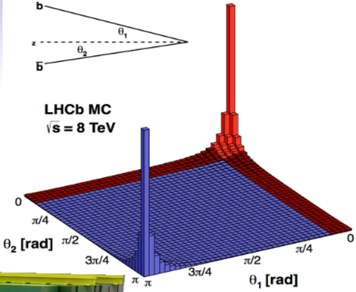

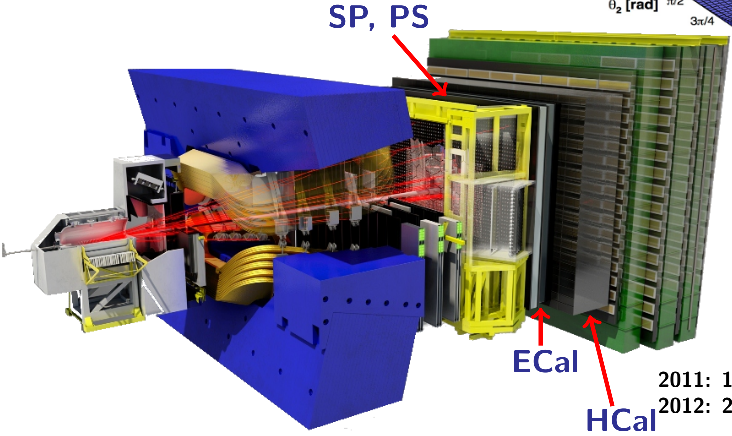

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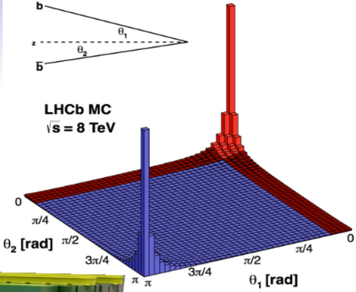

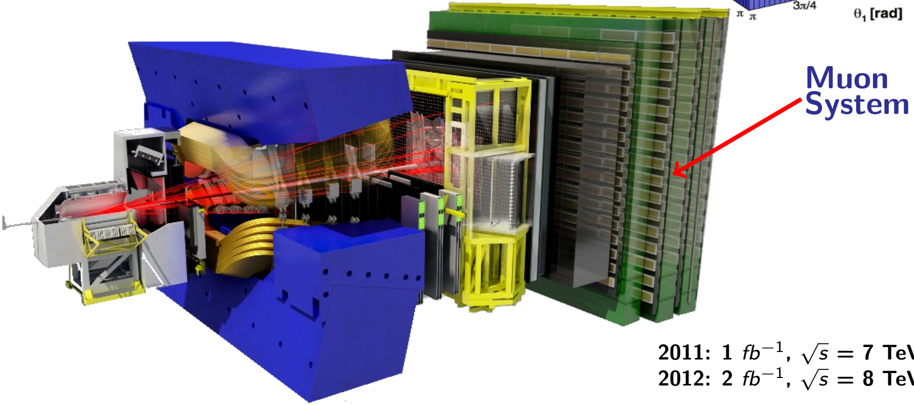

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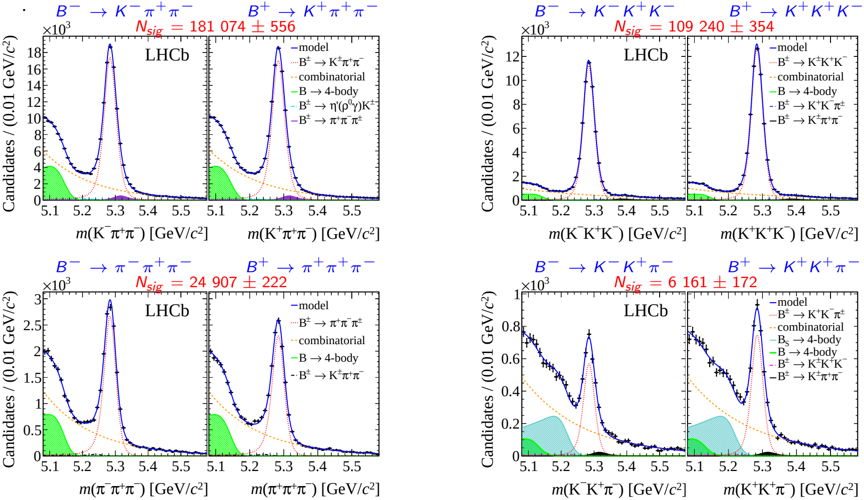
$B^{\pm} \to h^{+}h^{-}h^{\pm}$ decays.

Inclusive CP asymmetry [arXiv:1408.5373]

Measurement of the raw CP asymmetry from simultaneous mass fit to B^+ and B^- candidates:

$$\mathcal{A}_{raw} = \frac{N_{B^-} - N_{B^+}}{N_{B^-} + N_{B^+}}$$



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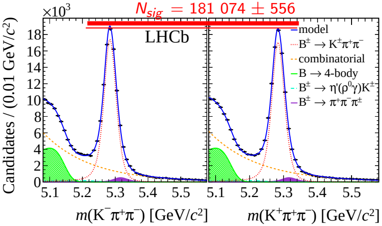
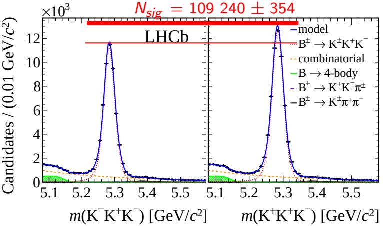
$B^- \to K^-\pi^+\pi^-$ $B^+ \to K^+\pi^+\pi^-$

$N_{sig} = 181\,074 \pm 556$



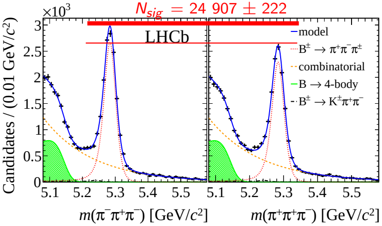
$B^- \to K^-K^+K^-$ $B^+ \to K^+K^+K^-$

$N_{sig} = 109\,240 \pm 354$



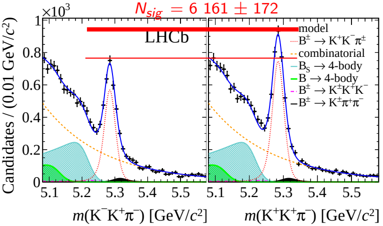
$B^- \to \pi^-\pi^+\pi^-$ $B^+ \to \pi^+\pi^+\pi^-$

$N_{sig} = 24\,907 \pm 222$



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

$N_{sig} = 6\,161 \pm 172$



Inclusive CP asymmetry [arXiv:1408.5373]

- The raw asymmetry has to be corrected for the B-meson production asymmetry and the detector asymmetry :

$$\mathcal{A}_{raw} \approx \mathcal{A}_{CP} + \mathcal{A}_P + \mathcal{A}_D^{h'}$$

- Decays divided into two categories depending on the flavour of the unpaired hadron:

$B^{\pm} \to h^+ h^- K^{\pm}$ $\quad \mathcal{A}_{CP} = \mathcal{A}_{raw} - \mathcal{A}_P(B^{\pm}) - \mathcal{A}_D(K^{\pm})$

$B^{\pm} \to h^+ h^- \pi^{\pm}$ $\quad \mathcal{A}_{CP} = \mathcal{A}_{raw} - \mathcal{A}_P(B^{\pm}) - \mathcal{A}_D(\pi^{\pm})$

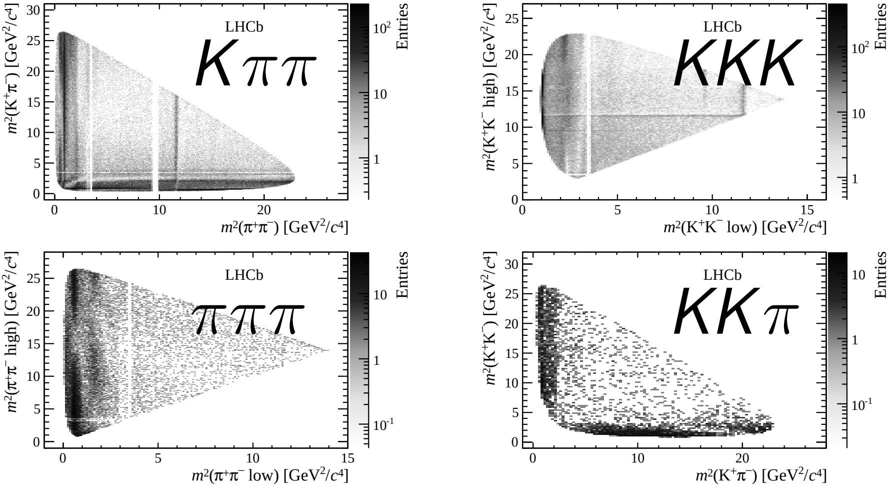
  - $\mathcal{A}_P(B)$ from $B \to J/\psi(\mu\mu)K$ studies and using $\mathcal{A}_D(K) = (-0.126 \pm 0.018)\%$ [PRL 108 (2012) 201601]
  - $\mathcal{A}_D(\pi) = (0.00 \pm 0.25)\%$ from studies of prompt D^* decays [PLB 713 (2012) 186]

- Acceptance correction to take into account non uniformity of efficiencies and raw asymmetries in the phase space

$$A_{CP}(B^{\pm} \to K^{\pm}\pi^+\pi^-) = +0.025 \pm 0.004\,(\text{stat}) \pm 0.004\,(\text{syst}) \pm 0.007(J/\psi\, K^{\pm}) \quad 2.8\sigma$$
$$A_{CP}(B^{\pm} \to K^{\pm}K^+K^-) = -0.036 \pm 0.004\,(\text{stat}) \pm 0.002\,(\text{syst}) \pm 0.007(J/\psi\, K^{\pm}) \quad 4.3\sigma$$
$$A_{CP}(B^{\pm} \to \pi^{\pm}\pi^+\pi^-) = +0.058 \pm 0.008\,(\text{stat}) \pm 0.009\,(\text{syst}) \pm 0.007(J/\psi\, K^{\pm}) \quad 4.2\sigma$$
$$A_{CP}(B^{\pm} \to \pi^{\pm}K^+K^-) = -0.123 \pm 0.017\,(\text{stat}) \pm 0.012\,(\text{syst}) \pm 0.007(J/\psi\, K^{\pm}) \quad 5.6\sigma$$

Dalitz Plot [arXiv:1408.5373]

Dalitz plots in the signal region with bkg: $\pm 34\ MeV/c^2$ (hhh and hhK), $\pm 17\ MeV/c^2$ (πKK)



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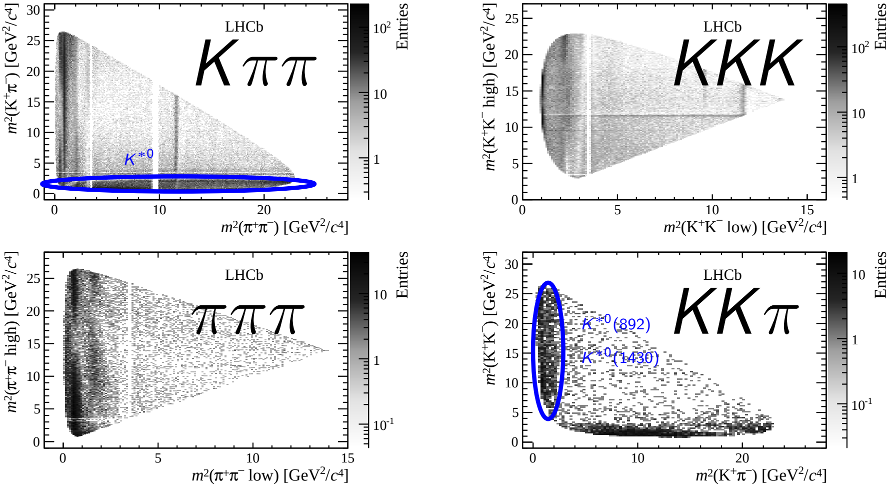

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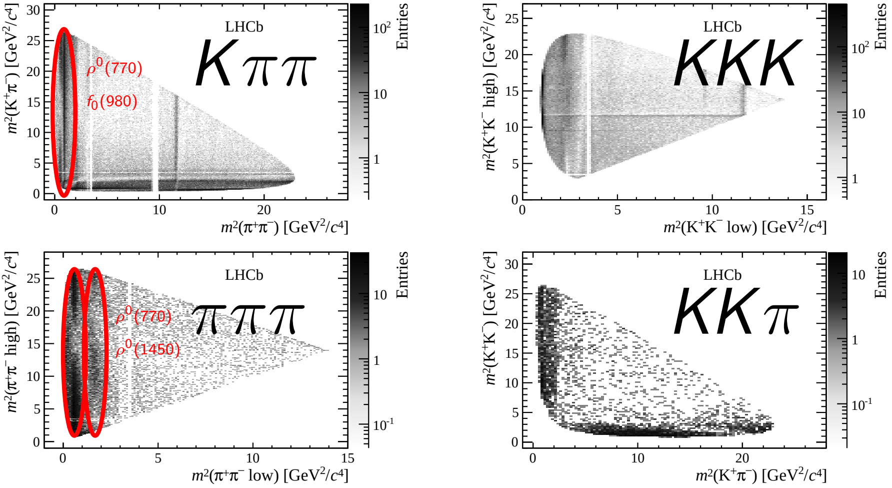

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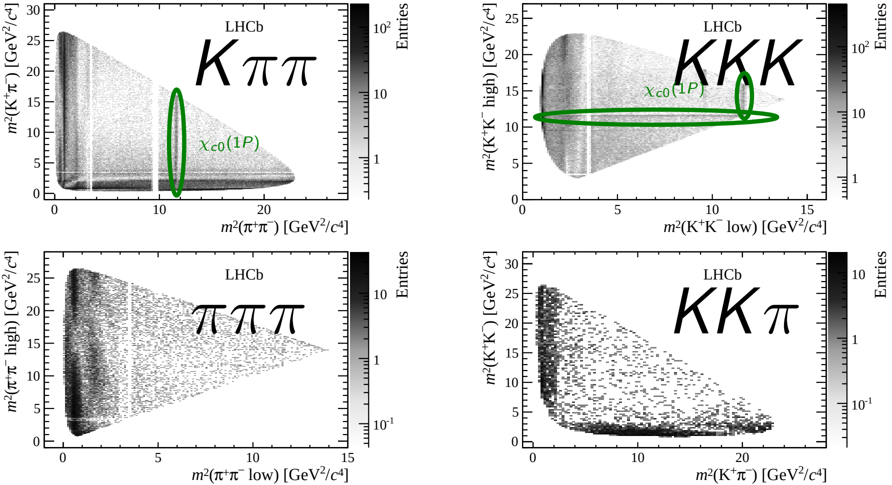

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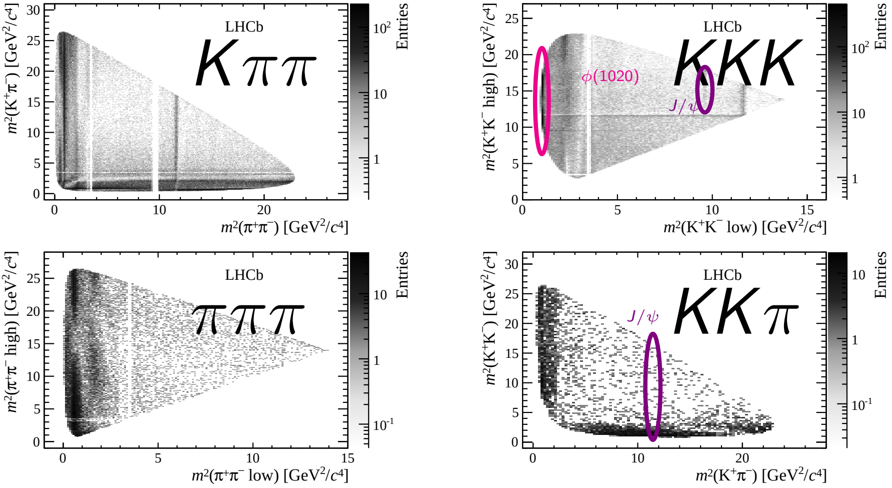
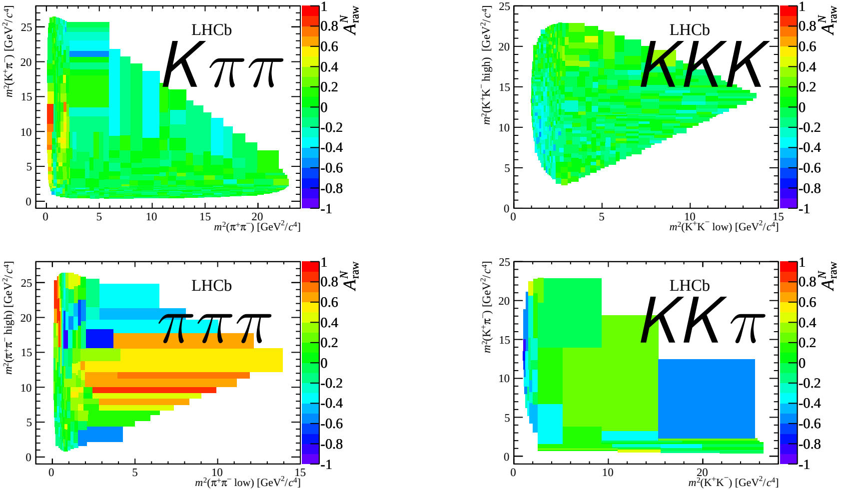


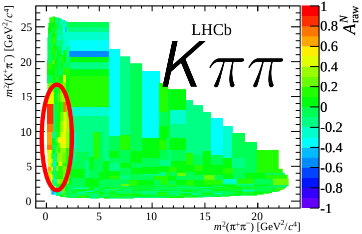
CP asymmetries in the phase space [arXiv:1408.5373]

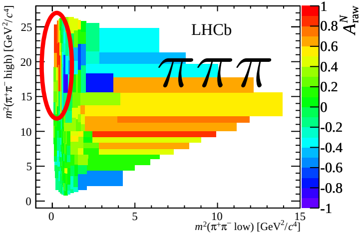
- Also background subtracted (SPlot) and efficiency corrected



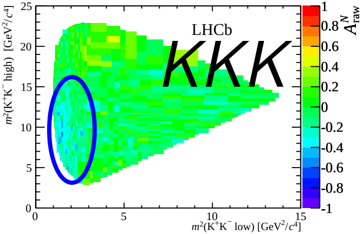
CP asymmetries in the phase space [arXiv:1408.5373]

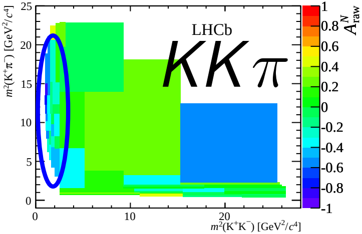
Large asymmetries at low $m^2_{\pi\pi}$





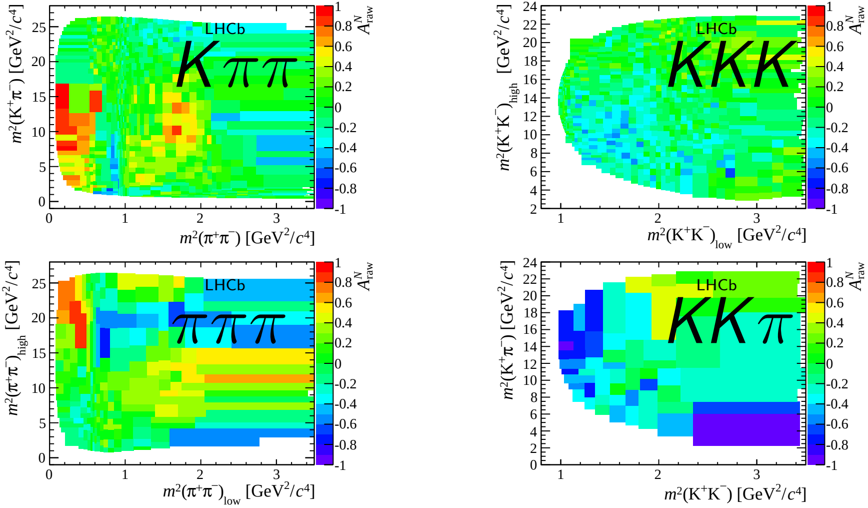
Large asymmetries at low m^2_{KK}





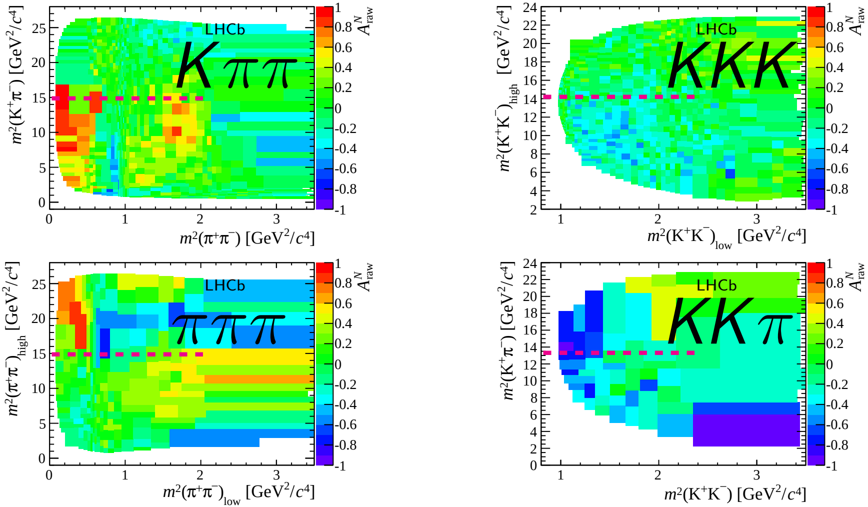
Interference

- Zoom at low mass region. Asymmetry is more evident.

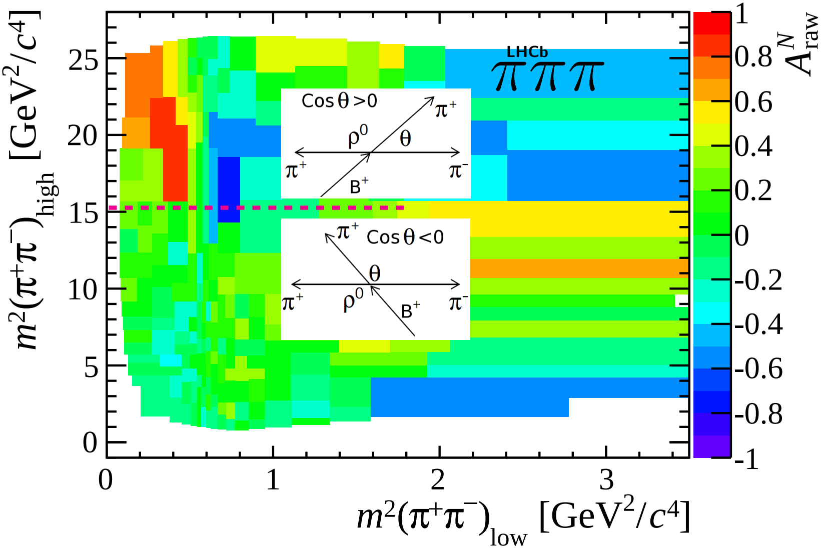


Interference

- The behavior of all channels change at midle of the vertical range



Interference: $B^{\pm} \to \pi^+\pi^-\pi^{\pm}$



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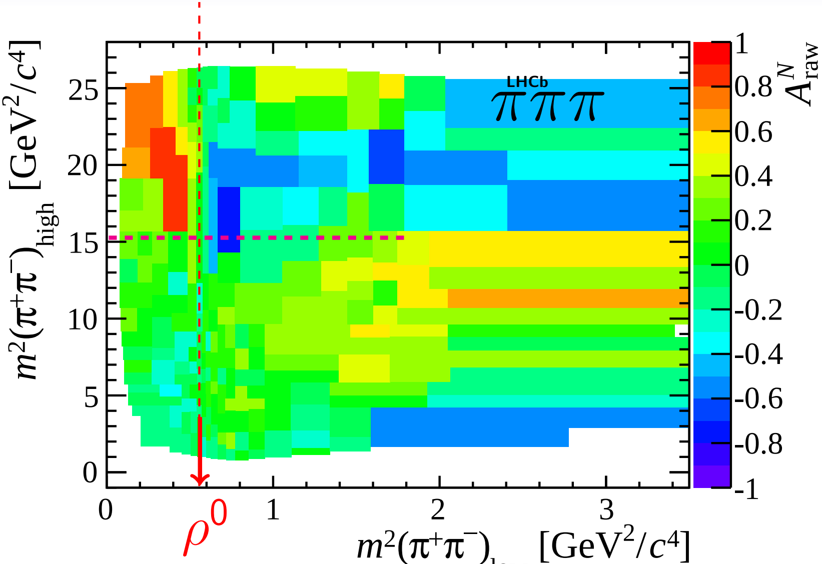

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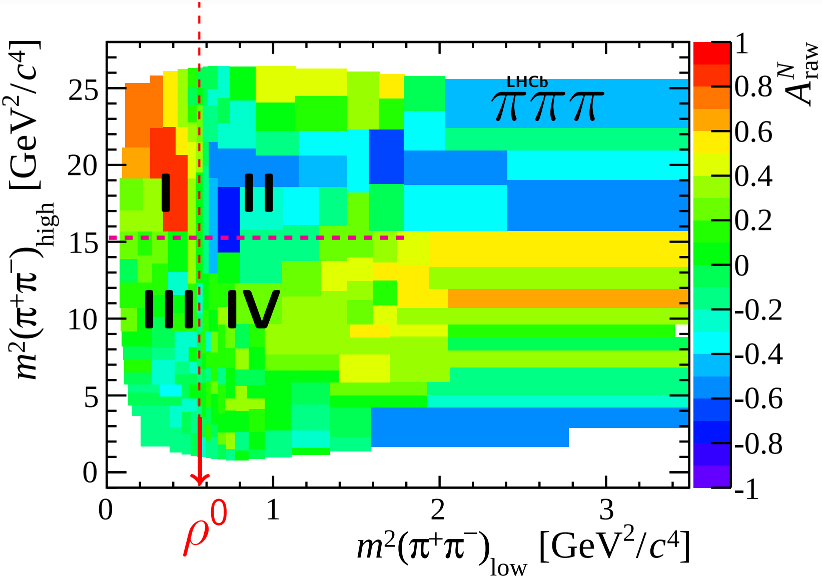
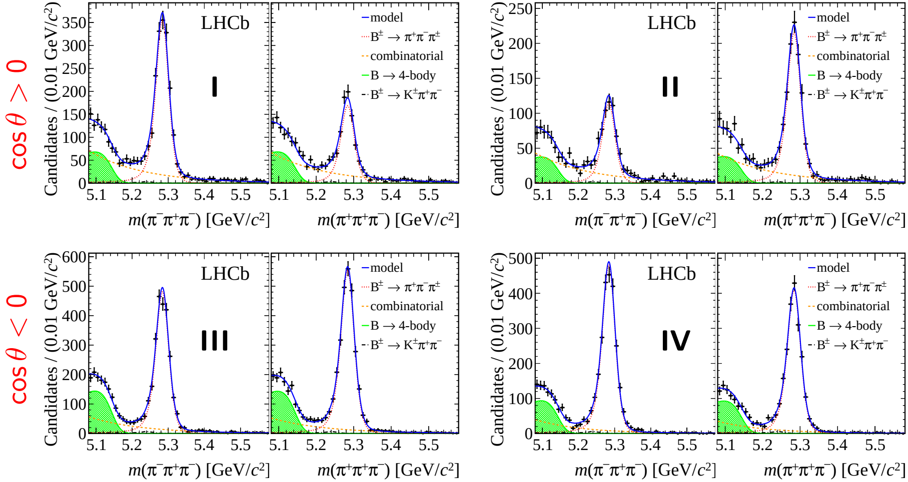
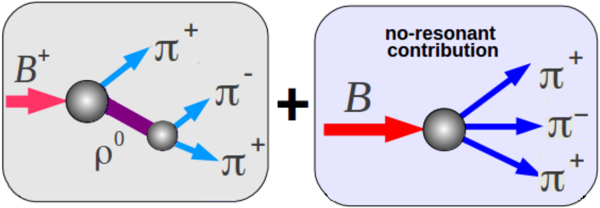


Interference: $B^\pm \to \pi^+\pi^-\pi^\pm$

$0.47 < m_{\pi\pi\,low}\,GeV/c^2 < 0.77$ $\quad$ $0.77 < m_{\pi\pi\,low}\,GeV/c^2 < 0.92$



Interference: $B^{\pm} \to \pi^+\pi^-\pi^{\pm}$ (Simple Isobar Model)



$$B^+: \quad \mathcal{A}_+ = A_+^{\rho} e^{i\Phi_+^{\rho}} F_{\rho}^{BW} \cos\theta + A_+^{nr} e^{i\Phi_+^{nr}} F_{nr}$$

$$B^-: \quad \mathcal{A}_- = A_-^{\rho} e^{i\Phi_-^{\rho}} F_{\rho}^{BW} \cos\theta + A_-^{nr} e^{i\Phi_-^{nr}} F_{nr}$$

The phase (Φ) contains the weak (ϕ) and strong (δ) phases.

$$F_{\rho}^{BW} = \frac{1}{m_{\rho}^2 - s - i m_{\rho}\Gamma_{\rho}(s)} \qquad F_{nr} = 1$$

Interference: $B^{\pm} \to \pi^{+}\pi^{-}\pi^{\pm}$ (Simple Isobar Model)

- Diference of magnitudes (Short Distance Effect)

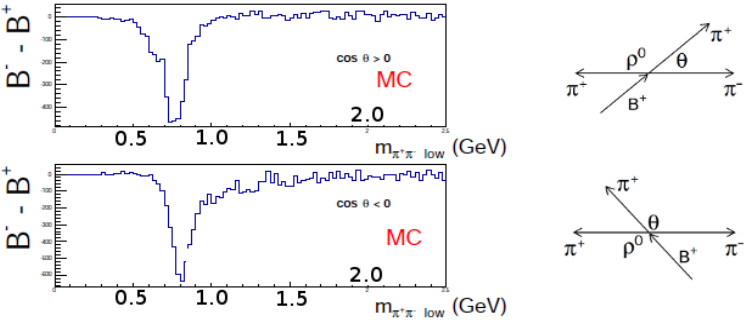
$$
\begin{aligned}
\Delta|\mathcal{A}_{+}|^2 = |\mathcal{A}_{+}|^2 - |\mathcal{A}_{-}|^2 = {} & [(A^{\rho}_{+})^2 - (A^{\rho}_{-})^2]\,|F^{BW}_{\rho}|^2 \cos^2\theta + [(A^{nr}_{+})^2 - (A^{nr}_{+})^2]|F_{nr}|^2 + \\
& 2\cos\theta |F^{BW}_{\rho}|^2 |F_{nr}| \{ \\
& (m^2_{\rho} - s)\,[A^{\rho}_{+}A^{nr}_{+}\cos(\Phi^{\rho}_{+} - \Phi^{nr}_{+}) - A^{\rho}_{-}A^{nr}_{-}\cos(\Phi^{\rho}_{-} - \Phi^{nr}_{-})] - \\
& m_{\rho}\Gamma_{\rho}\,[A^{\rho}_{+}A^{nr}_{+}\sin(\Phi^{\rho}_{+} - \Phi^{nr}_{+}) - A^{\rho}_{-}A^{nr}_{-}\sin(\Phi^{\rho}_{-} - \Phi^{nr}_{-})]\}
\end{aligned}
$$

- Real part of the BW (Long Distance Effect)
- Imag part of the BW (Long Distance Effect)

Interference: $B^{\pm} \to \pi^{+}\pi^{-}\pi^{\pm}$ (Simple Isobar Model)

Monte Carlo simulation for the short distance term:

$$\mathcal{A}_{CP} \propto [(A_{+}^{\rho})^2 - (A_{-}^{\rho})^2]|F_{\rho}^{BW}|^2 \cos^2\theta + \ldots$$
$$-2(m_{\rho}^2 - s)|F_{\rho}^{BW}|^2|F_{nr}|^2 \cos\theta \ldots$$
$$+2m_{\rho}\Gamma_{\rho}|F_{\rho}^{BW}|^2|F_{nr}|^2 \cos\theta \ldots$$



- If it were the dominant term, we should see a peak at the ρ mass.
- The peak should has the same sign for $\cos\theta > 0$ and for $\cos\theta < 0$

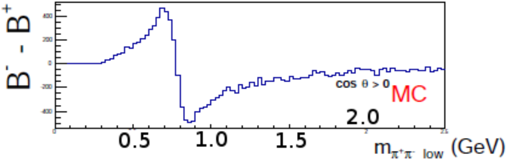
Interference: $B^{\pm} \to \pi^+\pi^-\pi^{\pm}$ (Simple Isobar Model)

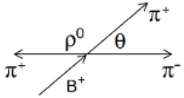
Monte Carlo simulation for the long distance term (Re BW):

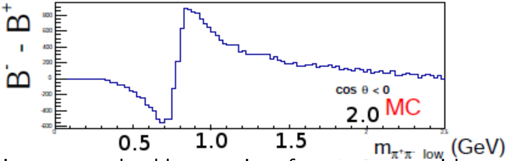
$$\mathcal{A}_{CP} \propto [(A^{\rho}_{+})^2 - (A^{\rho}_{-})^2]|F^{BW}_{\rho}|^2 \cos^2\theta + \dots$$

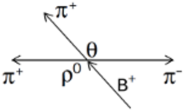
$$-2(m^2_{\rho} - s)|F^{BW}_{\rho}|^2|F_{nr}|^2 \cos\theta \dots$$

$$+2m_{\rho}\Gamma_{\rho}|F^{BW}_{\rho}|^2|F_{nr}|^2 \cos\theta \dots$$







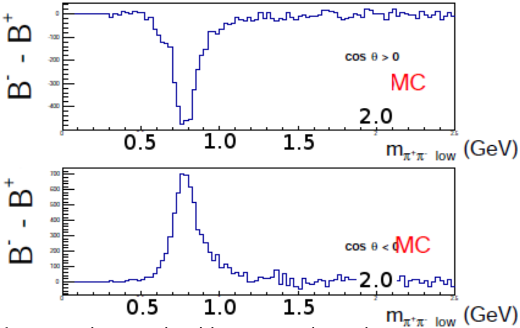


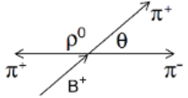
- In this case, we should see an interferent pattern with asymmetry zero at the ρ mass.
- For $\cos\theta > 0$ the asymmetry is $(+)$ below the ρ mass and (-) above.
- For $\cos\theta < 0$ the behaviour is oposite.

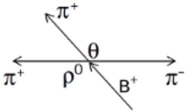
Interference: $B^{\pm} \to \pi^+\pi^-\pi^{\pm}$ (Simple Isobar Model)

Monte Carlo simulation for the long distance term (Im BW):

$$\mathcal{A}_{CP} \propto [(A_+^{\rho})^2 - (A_-^{\rho})^2]|F_{\rho}^{BW}|^2 \cos^2\theta + \ldots$$
$$-2(m_{\rho}^2 - s)|F_{\rho}^{BW}|^2|F_{nr}|^2 \cos\theta \ldots$$
$$+2m_{\rho}\Gamma_{\rho}|F_{\rho}^{BW}|^2|F_{nr}|^2 \cos\theta \ldots$$

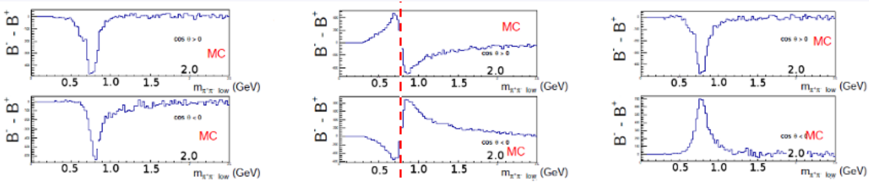




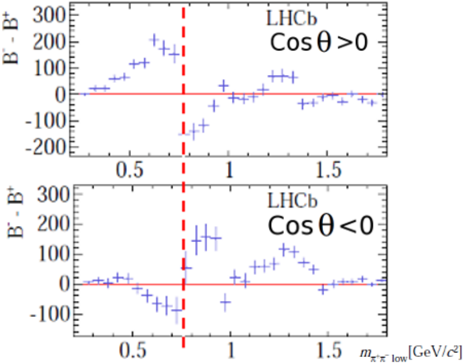


- In this case, also we should see a peak at the ρ mass.
- But the peak has oposite sign for $\cos\theta > 0$ and $\cos\theta < 0$.

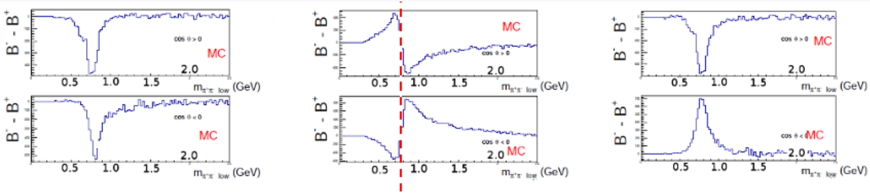
Interference: $B^{\pm} \to \pi^{+}\pi^{-}\pi^{\pm}$ (Simple Isobar Model)



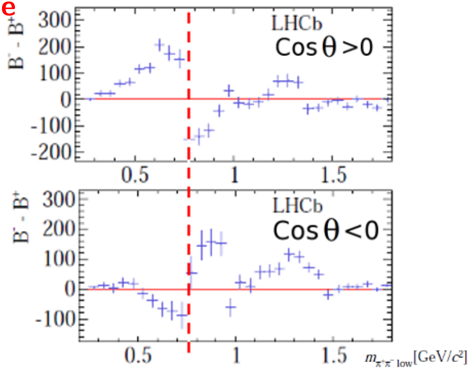
Long distance term (Re BW))



Interference: $B^{\pm} \to \pi^{+}\pi^{-}\pi^{\pm}$ (Simple Isobar Model)



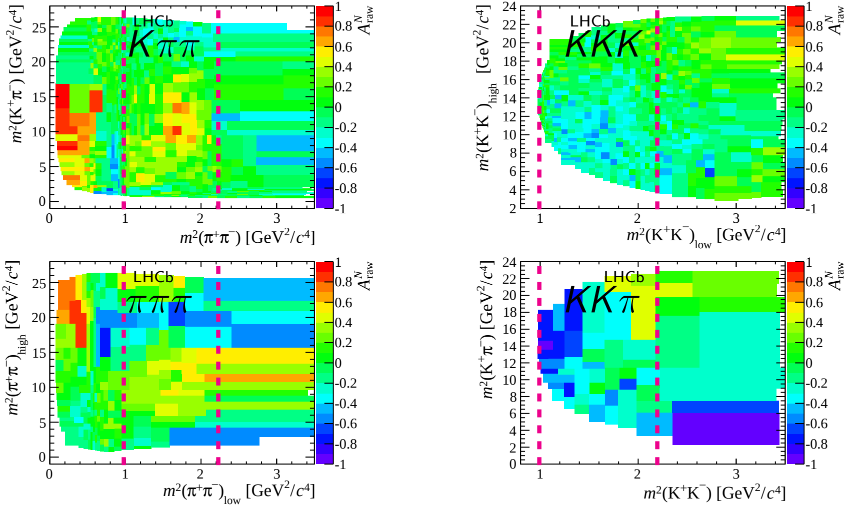
Long-distance effects play an important role generating strong phase.



Rescattering $\pi\pi \to KK$

Large asymmetries: $1 < m_{\pi\pi} < 1.5$

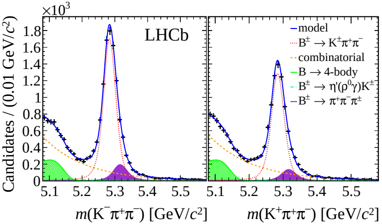
Large asymmetries: $1 < m_{KK} < 1.5$



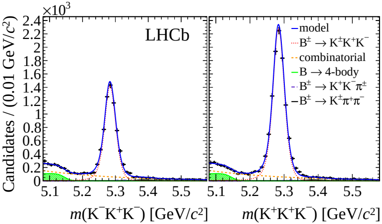
Rescattering $\pi\pi \to KK$

Invariant masses with $\pi\pi$ and KK in the **"rescattering region"**: $(1.0 - 1.5) GeV/c^2$

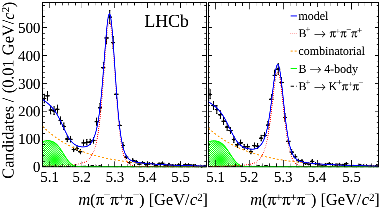
$\mathcal{A}_{CP}(K\pi\pi) = +0.121 \pm 0.012 \pm 0.017 \pm 0.007$



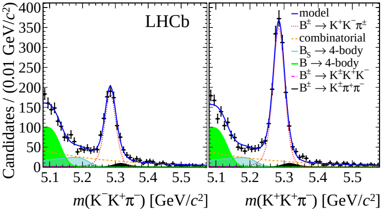
$\mathcal{A}_{CP}(KKK) = -0.211 \pm 0.011 \pm 0.004 \pm 0.007$



$\mathcal{A}_{CP}(\pi\pi\pi) = +0.172 \pm 0.021 \pm 0.015 \pm 0.007$



$\mathcal{A}_{CP}(\pi KK) = -0.328 \pm 0.028 \pm 0.029 \pm 0.007$



All the asymmetries have more than 5σ of significance

Scattering and CPT constraint

High local asymmetries not obviously associated to resonances.

positive for $K^{\pm}$ $\pi^+\pi^-$ **negative** for $K^{\pm}$ K^+K^-

positive for $\pi^+\pi^-$ $\pi^{\pm}$ **negative** for $K^+K^-\pi^{\pm}$

$$\sum_{f_\alpha^{(i)} \in F_i} \Gamma(P \to f_\alpha^{(i)}) = \sum_{\bar{f}_\alpha^{(i)} \in \bar{F}_i} \Gamma(\bar{P} \to \bar{f}_\alpha^{(i)})$$

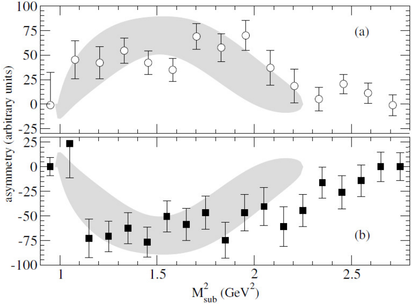
(Bigi & Sanda 2nd edition pp 57) all f_α in F_i connected via strong interactions

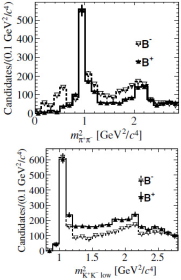
for two modes $\pi\pi$ and KK: $\Gamma(A^+_{\pi\pi}) + \Gamma(A^+_{KK}) = \Gamma(A^-_{\pi\pi}) + \Gamma(A^-_{KK})$, then:

$$\Delta\Gamma_{\pi\pi} = -\Delta\Gamma_{KK}$$

I.Bediaga, T.Frederico, O.Lourenço, Phys.Rev.D 89,094013 (2014)

$\Delta\Gamma_{KK} = (sin\gamma)\sqrt{1-\eta^2}cos(\delta_{KK} + \delta_{\pi\pi} + \Phi)F(M^2_{KK})$ (Inelasticity and Unitarity)

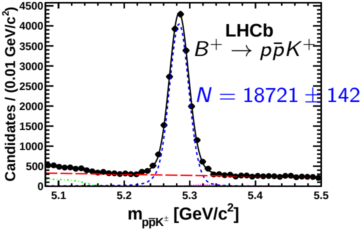


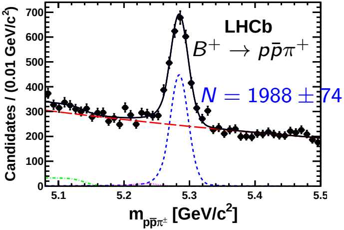


$B^{\pm} \to p\bar{p}h^{\pm}$ decays.

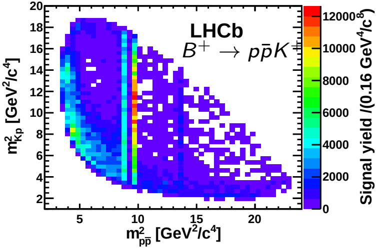
$B^\pm \to p\bar{p}h^\pm$ decays

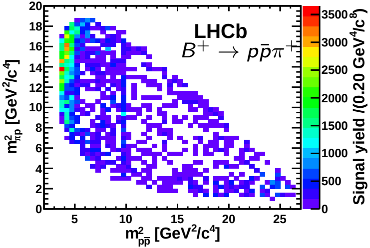
- Yields extracted with an unbinned maximum likelihood fit





- Background subtracted Dalitz distributions using sPlot technique

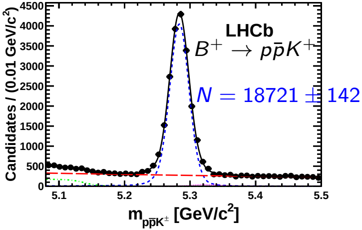


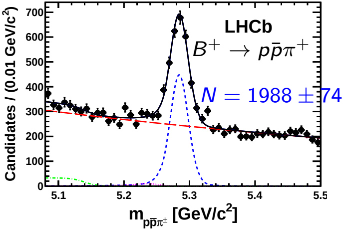


- **At low $m^2_{p\bar{p}}$ invariant mass the behaviour is differently distributed in the two modes**
- **Charmonium bands clearly visible: $J\psi$, $\psi(2S)$ and η_c**
- **At low m^2_{pk} invariant mass we see $\Lambda(1520)$**

$B^{\pm} \to p\bar{p}h^{\pm}$ decays

- Yields extracted with an unbinned maximum likelihood fit





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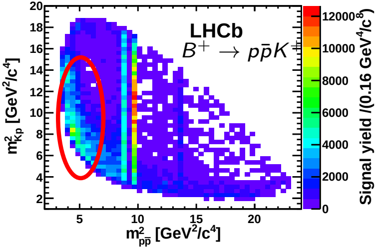

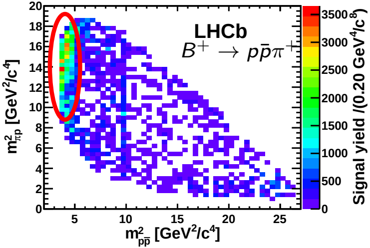

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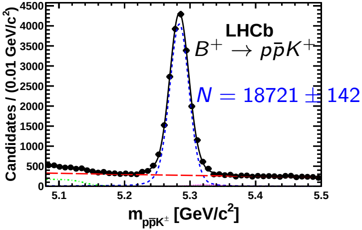

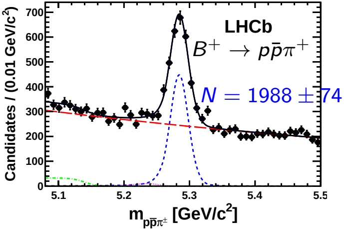

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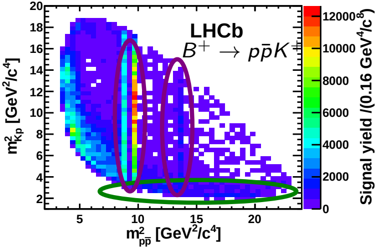

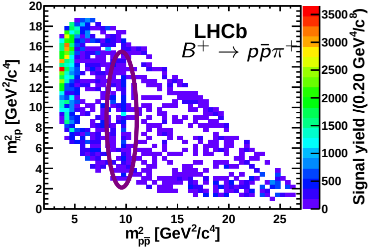

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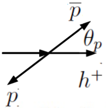
$B^\pm \to p\bar{p}h^\pm$ decays: Dynamics

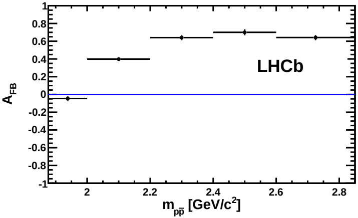
- Measurement of the forward-backward asymmetry



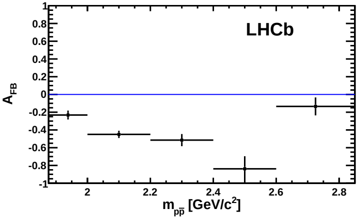
$$\mathcal{A}_{FB} = \frac{N(\cos\theta_p > 0) - N(\cos\theta_p < 0)}{N(\cos\theta_p > 0) + N(\cos\theta_p < 0)}$$

- Variation of the A_{FB} as a function of $m_{p\bar{p}}$

$B^+ \to p\bar{p}K^+$



$B^+ \to p\bar{p}\pi^+$

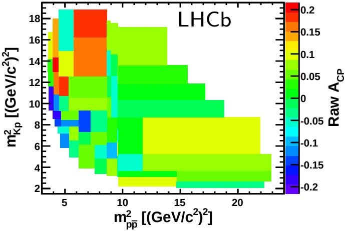


- Opposite behaviour for the two decay modes

$$\mathcal{A}_{FB}(p\bar{p}K^+, m_{p\bar{p}} < 2.85 GeV/c^2) = 0.495 \pm 0.012(stat) \pm 0.007(syst)$$
$$\mathcal{A}_{FB}(p\bar{p}\pi^+, m_{p\bar{p}} < 2.85 GeV/c^2) = -0.409 \pm 0.033(stat) \pm 0.006(syst)$$

$B^{\pm} \to p\bar{p}h^{\pm}$ decays: CP asymmetries

- Variation of A_{CP} as a function of the Dalitz-plot variables only for $B^{\pm} \to p\bar{p}K^{\pm}$
- Adaptive binning analysis



$B^{\pm} \to p\bar{p}h^{\pm}$ decays: CP asymmetries

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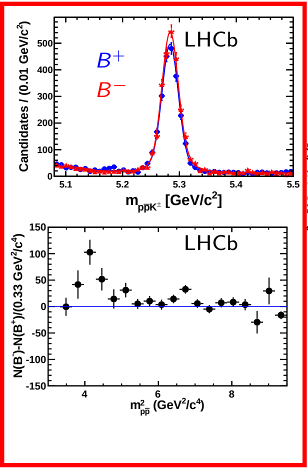
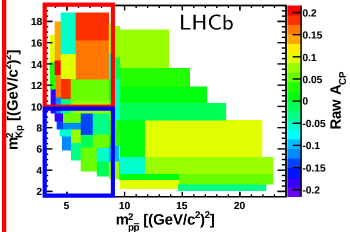
$m^2_{Kp} > 10\ GeV^2/c^4$



Clear sign-flip pattern at low $m^2_{p\bar{p}}$



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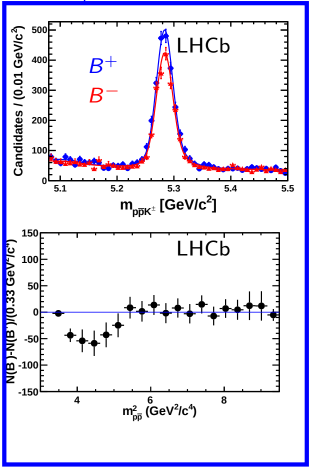


$B^{\pm} \to p\bar{p}h^{\pm}$ decays: CP asymmetries

- The raw CP is corrected for production and detection asymmetries as in $B^{\pm} \to h^+h^-h^{\pm}$decays.

$B^{\pm} \to p\bar{p}K^{\pm}$ $\quad \mathcal{A}_{CP} = \mathcal{A}_{raw} - \mathcal{A}_P(B^{\pm}) - \mathcal{A}_D(K^{\pm})$

$B^{\pm} \to p\bar{p}\pi^{\pm}$ $\quad \mathcal{A}_{CP} = \mathcal{A}_{raw} - \mathcal{A}_P(B^{\pm}) - \mathcal{A}_D(\pi^{\pm})$

First evidence of CPV in baryonic B decays

Mode/region	A_{CP}	
$\eta_c(\to p\bar{p})K^{\pm}$	0.040±0.034 (stat)±0.004 (syst)	
$\psi(2S)(\to p\bar{p})K^{\pm}$	0.092±0.058 (stat)±0.004 (syst)	
$p\bar{p}K^{\pm}$, $m_{p\bar{p}} < 2.85\,\mathrm{GeV}/c^2$	0.021±0.020 (stat)±0.004 (syst)	
$p\bar{p}K^{\pm}$, $m_{p\bar{p}} < 2.85\,\mathrm{GeV}/c^2$, $m^2_{Kp} < 10\,\mathrm{GeV}^2/c^4$	-0.036±0.023 (stat)±0.004 (syst)	
$p\bar{p}K^{\pm}$, $m_{p\bar{p}} < 2.85\,\mathrm{GeV}/c^2$, $m^2_{Kp} > 10\,\mathrm{GeV}^2/c^4$	0.096±0.024 (stat)±0.004 (syst)	4σ
$p\bar{p}K^{\pm}$, $m^2_{p\bar{p}} < 6\,\mathrm{GeV}^2/c^4$, $m^2_{Kp} < 10\,\mathrm{GeV}^2/c^4$	-0.066±0.026 (stat)±0.004 (syst)	
$p\bar{p}K^{\pm}$, $m^2_{p\bar{p}} < 6\,\mathrm{GeV}^2/c^4$, $m^2_{Kp} > 10\,\mathrm{GeV}^2/c^4$	0.087±0.026 (stat)±0.004 (syst)	3.5σ
$p\bar{p}\pi^{\pm}$, $m_{p\bar{p}} < 2.85\,\mathrm{GeV}/c^2$	-0.041±0.039 (stat)±0.005 (syst)	

- Systematics uncertainties dominated by the uncertainty on the $\mathcal{A}_{CP}(J/\psi K)$ measurement

$B^{\pm} \to p\bar{p}h^{\pm}$ decays: B.F. measurements

- Branching fraction of $B^{+} \to \bar{\Lambda}(1520)(K^{+}\bar{p})p$ relative to $B^{+} \to J/\psi(p\bar{p})K^{+}$

$$\frac{\mathcal{B}(B^{+} \to \bar{\Lambda}(1520)(K^{+}\bar{p})p)}{\mathcal{B}(B^{+} \to J/\psi(p\bar{p})K^{+})} = \frac{N_{\Lambda \to Kp}}{N_{J/\psi \to p\bar{p}}} \times \frac{\epsilon^{gen}_{J/\psi \to p\bar{p}}}{\epsilon^{gen}_{\Lambda \to Kp}} \times \frac{\epsilon^{sel}_{J/\psi \to p\bar{p}}}{\epsilon^{sel}_{\Lambda \to Kp}}$$

- Similar equation for the ratio $B^{+} \to p\bar{p}\pi^{+}$ to $B^{+} \to J/\psi(p\bar{p})\pi^{+}$
- Resonant modes extracted with a 2D fit to $p\bar{p}h^{+}$ and $p\bar{p}/K^{+}\bar{p}$

$$\frac{\mathcal{B}(B^{+} \to \bar{\Lambda}(1520)(K^{+}\bar{p})p)}{\mathcal{B}(B^{+} \to J/\psi(p\bar{p})K^{+})} = 0.033 \pm 0.005(stat) \pm 0.007(syst)$$
$$\frac{\mathcal{B}(B^{+} \to p\bar{p}\pi^{+}), m_{p\bar{p}} < 2.85 GeV/c^{2}}{\mathcal{B}(B^{+} \to J/\psi(p\bar{p})\pi^{+})} = 12.0 \pm 1.2(stat) \pm 0.3(syst)$$

- Using
  - $\mathcal{B}(B^{+} \to J/\psi K^{+}) = (1.016 \pm 0.033) \times 10^{-3}$ [PDG]
  - $\mathcal{B}(J/\psi \to p\bar{p}) = (2.17 \pm 0.07) \times 10^{-3}$ [PDG]
  - $\mathcal{B}(\Lambda(1520) \to K^{+}\bar{p}) = 0.234 \pm 0.016$ [Eur.Phys.J. A47(2011)133]

$$\mathcal{B}(B^{+} \to \bar{\Lambda}(1520)(K^{+}\bar{p})p) = (3.15 \pm 0.48(stat) \pm 0.07(syst) \pm 0.26(BF)) \times 10^{-7}$$
$$\mathcal{B}(B^{+} \to p\bar{p}\pi^{+}, m_{p\bar{p}} < 2.85 GeV/c^{2}) = (1.07 \pm 0.11(stat) \pm 0.03(syst) \pm 0.11(BF)) \times 10^{-6}$$

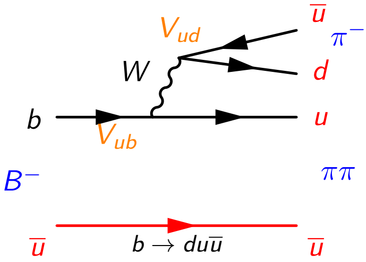
Summary

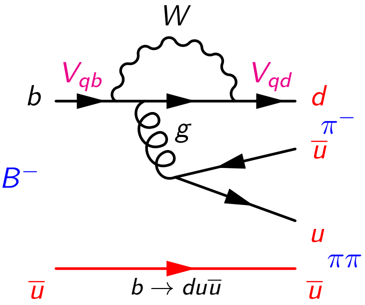
- **New results with the full LHCb data set ($3fb^{-1}$)**
- $B^{\pm} \to h^{+}h^{-}h^{\pm}$**decays**
  - **Evidence of global direct CP violation**
  - **High localised CP asymmetries across the Dalitz plot**
  - **Long-distance effects play an important role in generating a strong phase difference:**
    - **Interference between resonances.**
    - **Rescattering.**
- $B^{\pm} \to p\bar{p}h^{\pm}$**decays**
  - **Large forward-backward asymmetries**
  - **First evidence CP violation in decays involving baryons**
  - **Sign-flip of CP asymmetry probably generated by interference of long-distance $p\bar{p}$ waves**
- **Next Step: Amplitude Analyses.**

BackUp Slides

BSS Model for the $B^{\pm} \to \pi^{+}\pi^{-}\pi^{\pm}$ decay

$b \to d u \bar{u}$





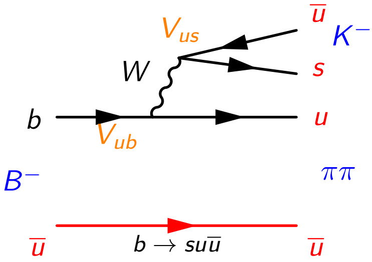
- Strangeness = 0
- Penguin: $q = u, c, t$
- Tree Dominant.
- Different week phase (CKM mechanism).
- Different strong phase (for u and c in the penguin).

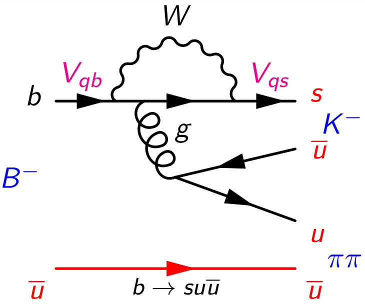
$$\begin{bmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{bmatrix} \quad (1)$$

$$\begin{bmatrix} 1-\frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{\lambda^2}{2} & A\lambda^2 \\ A[\lambda^3(1-\rho-i\eta)] & -A\lambda^2 & 1 \end{bmatrix}, \quad (2)$$

BSS Model for $B^{\pm} \to K^{\pm}\pi^{+}\pi^{-}$ & $B^{\pm} \to K^{\pm}K^{+}K^{-}$ decays

$b \to s u \bar{u}$





- Strangeness $= 1$
- Penguin: $q = u, c, t$
- Penguin Dominant.
- CPV expected from interference between tree and penguin diagrams

$$\begin{bmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{bmatrix} \quad (3)$$

$$\begin{bmatrix} 1-\frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{\lambda^2}{2} & A\lambda^2 \\ A[\lambda^3(1-\rho-i\eta)] & -A\lambda^2 & 1 \end{bmatrix}, \quad (4)$$

Amplitude Analysis

Problems in the usual Isobar Model:

- **Many** broad states (**scalars**) squeezed in a **narrow mass window**
- For D mesons the **Non-Resonant amplitude** A_0^{NR} is assumed to be **constant** (**due to the small phase space**), but this is not the case for B meson decays.
- High Non-Resonant contribution in B meson decays.
- In Isobar Model, hard to disentangle the Non-Resonant and broad structures in the S-Wave.

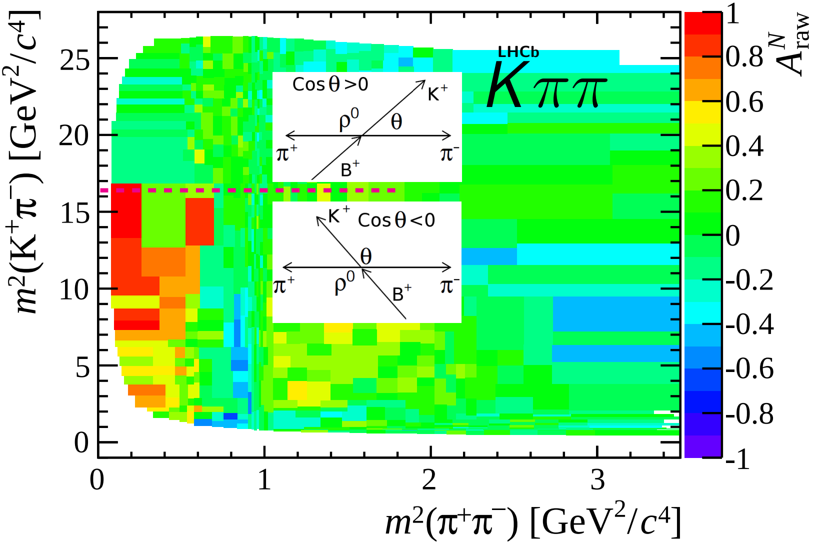
The Partial Wave Analysis:

- This method was developed by **E791 collaboration**. **PRD 73, 032004 (2006)**

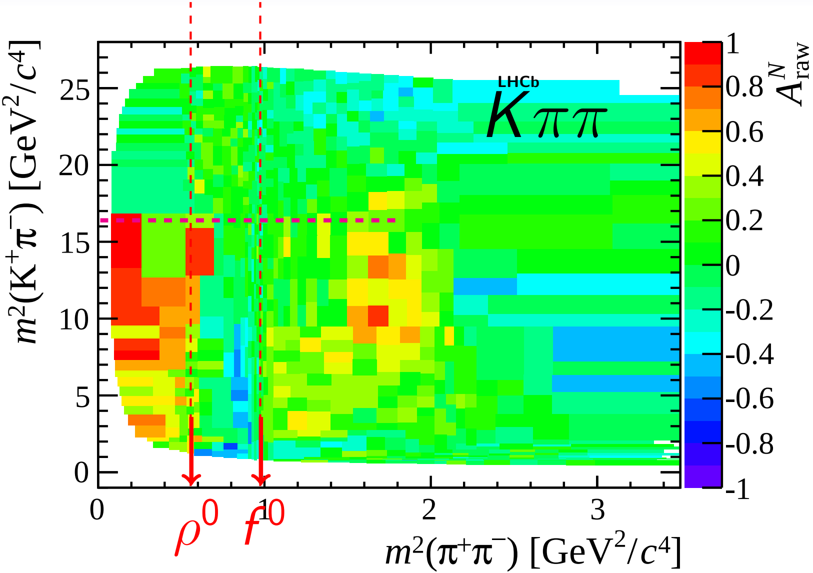
$$\mathcal{A} = \underbrace{S - Wave}_{a_0(s_i)e^{i\phi_0(s_i)}} + \underbrace{P - Wave + D - Wave}_{\text{Isobar Model}} +$$

- The real functions $a_0(s_i)$ and $\phi_0(s_i)$ are **extracted directly from data**.
- **The measurement is inclusive**: convolution of elastic, inelastic scattering, mixed isospin, FSI, etc...
- **Accuracy** depends on the features of **P-(or D-waves)** - an **interferometry analysis**.

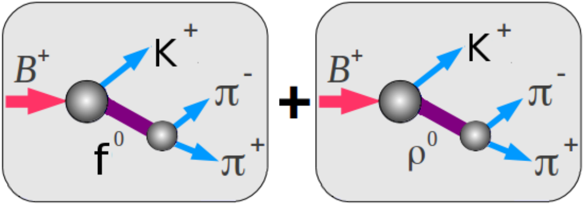
Interference: $B^\pm \to K^\pm\pi^+\pi^-$



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



Interference: $B^{\pm} \to K^{\pm}\pi^{+}\pi^{-}$ (Simple Isobar Model)



B positive $\mathcal{M}_{+} = a^{\rho}_{+} e^{i\delta^{\rho}_{+}} F^{\rm BW}_{\rho} \cos\theta + a^{f}_{+} e^{i\delta^{f}_{+}} F^{\rm BW}_{f}$

B negative $\mathcal{M}_{-} = a^{\rho}_{-} e^{i\delta^{\rho}_{-}} F^{\rm BW}_{\rho} \cos\theta + a^{f}_{-} e^{i\delta^{f}_{-}} F^{\rm BW}_{f}$

$$F^{\rm BW}_{R}(s) = \frac{1}{m^2_R - s - i m_R \Gamma_R(s)}$$ $R = \rho, f$

Interference: $B^\pm \to K^\pm \pi^+ \pi^-$ (Simple Isobar Model)

$$
\begin{aligned}
|\Delta\mathcal{M}|^2 &= |\mathcal{M}_+|^2 - |\mathcal{M}_-|^2 \\
&= [(a_+^\rho)^2 - (a_-^\rho)^2]|F_\rho^{\rm BW}|^2\cos^2\theta + [(a_+^f)^2 - (a_-^f)^2]|F_f^{\rm BW}|^2 + 2\cos\theta|F_\rho^{\rm BW}|^2|F_f^{\rm BW}|^2 \times \\
&\quad \{[(m_\rho^2 - s)(m_f^2 - s) - m_\rho\Gamma_\rho m_f\Gamma_f][a_+^\rho a_+^f\cos(\delta_+^\rho - \delta_+^f) - a_-^\rho a_-^f\cos(\delta_-^\rho - \delta_-^f)] \\
&\quad -[m_\rho\Gamma_\rho(m_f^2 - s) - m_f\Gamma_f(m_\rho^2 - s))[a_+^\rho a_+^f\sin(\delta_+^\rho - \delta_+^f) - a_-^\rho a_-^f\sin(\delta_-^\rho - \delta_-^f)]\}
\end{aligned}
$$

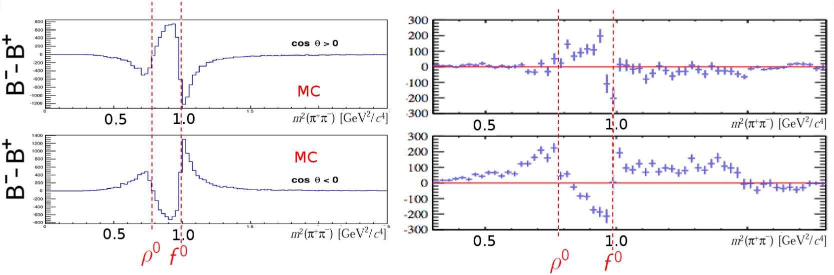
$$
[(a_+^\rho)^2 - (a_-^\rho)^2]|F_\rho^{\rm BW}|^2\cos^2\theta + [(a_+^{nr})^2 - (a_-^{nr})^2]|F^{\rm NR}|^2
$$

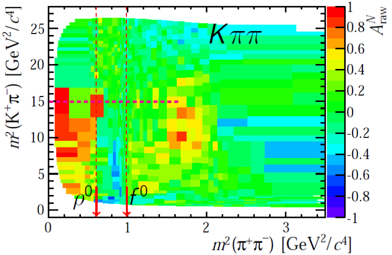
$$
2\cos\theta|F_\rho^{\rm BW}|^2|F^{\rm NR}|^2 \begin{cases} (m_\rho^2 - s)(m_f^2 - s) - m_\rho\Gamma_\rho m_f\Gamma_f \\ m_\rho\Gamma_\rho(m_f^2 - s) - m_f\Gamma_f(m_\rho^2 - s) \end{cases}
$$

Long distance interference: Real part of Dalitz CP asymmetry (first term)

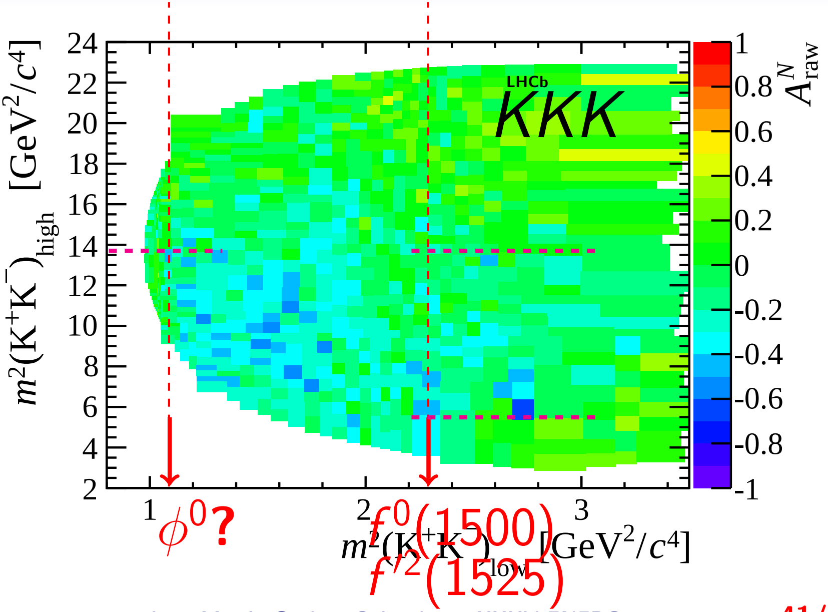
Long distance interference: Imaginary part of Dalitz CP asymmetry (second term)

Interference: $B^{\pm} \to K^{\pm}\pi^{+}\pi^{-}$ (Simple Isobar Model)





Interference: $B^{\pm} \to K^{\pm}K^{+}K^{-}$



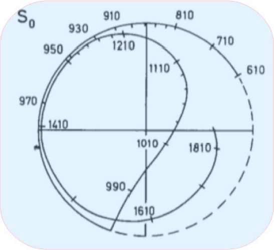
Scattering and CPT constraint

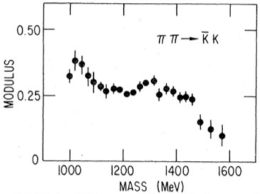
- **Scattering:**

CERN-Munich collab: $\pi^+\pi^- \to \pi^+\pi^-$ **scattering** Nuclear Physics B64 (1973) 134-162

Strongly coupled channels: $\pi^+\pi^- \to K^+K^-$ PRD 22 (1980) 2595

S-wave





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

.

- **CPT constraint**:

High local asymmetries not obviously associated to resonances.

positive for $K^\pm \; \pi^+\pi^-$ **negative** for $K^\pm \; K^+K^-$

positive for $\pi^+\pi^- \; \pi^\pm$ **negative** for $K^+K^-\pi^\pm$

$$\sum_{f_\alpha^{(i)} \in F_i} \Gamma(P \to f_\alpha^{(i)}) = \sum_{\bar{f}_\alpha^{(i)} \in \bar{F}_i} \Gamma(\bar{P} \to \bar{f}_\alpha^{(i)})$$

(Bigi & Sanda 2nd edition pp 57)
all f_α in F_i connected via strong interactions

for two channels α and β: $\Gamma(A^+_\alpha) + \Gamma(A^+_\beta) = \Gamma(A^-_\alpha) + \Gamma(A^-_\beta)$, then: $\Delta\Gamma_\alpha = -\Delta\Gamma_\beta$