Frontiers of Fundamental Physics 14

CP violation effects in multibody B decays

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on behalf of the LHCb collaboration

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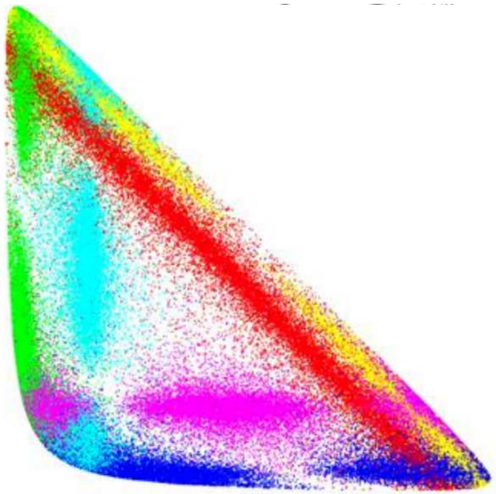
18 July 2014

Outline

1. Motivation
2. LHCb Detector
3. $B^{\pm} \to K^{\pm}K^{+}K^{-}$ and $B^{\pm} \to K^{\pm}\pi^{+}\pi^{-}$ (penguin dominated)
4. $B^{\pm} \to \pi^{\pm}K^{+}K^{-}$ and $B^{\pm} \to \pi^{\pm}\pi^{+}\pi^{-}$ (tree dominated)
5. $B^{\pm} \to K^{\pm}p\bar{p}$ and $B^{\pm} \to \pi^{\pm}p\bar{p}$
6. Summary



Toy MC Dalitz plot (DP)

Dalitz plot contains all kinematic and dynamic information of decay

Amplitude analysis one of the most powerful techniques

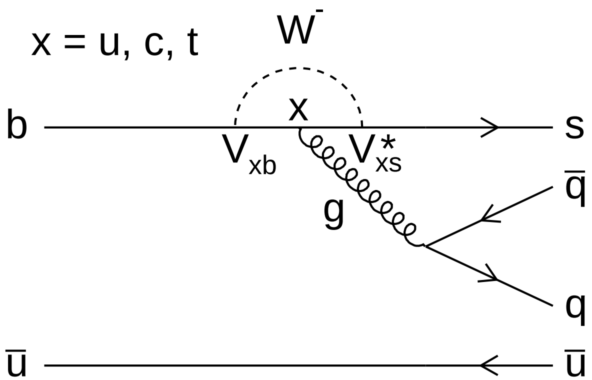
Extract amplitude-level information rather than amplitude-squared information

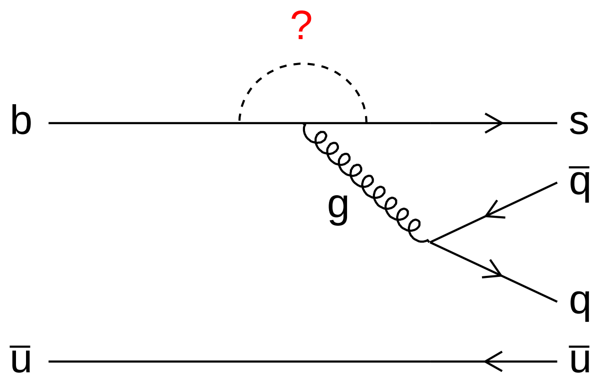
Interference between intermediate states allows measurement of relative magnitudes and phases

Motivation

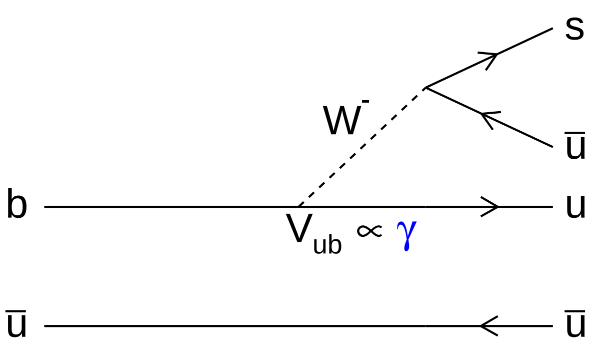
Charmless $B \to 3h$ decay channels provide a rich environment for physics observables

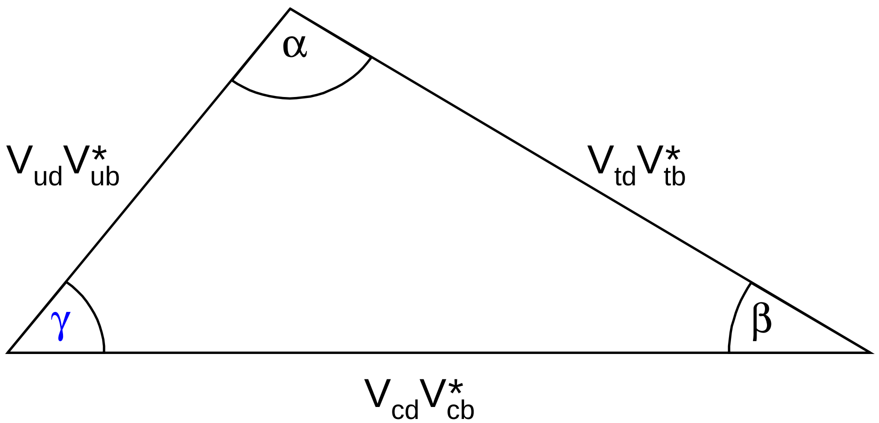
Unknown heavy particle in the loop could carry a new CP violating phase





Tree sensitive to $\gamma = \phi_3 \equiv -\arg\left(\frac{V_{ud}V^*_{ub}}{V_{cd}V^*_{cb}}\right)$





Motivation

In charged B decays, presence of multiple amplitudes may lead to direct CP violation

$A(B \to f) = \sum_i |A_i| e^{i(\delta_i + \phi_i)}$

$\bar{A}(\bar{B} \to \bar{f}) = \sum_i |\bar{A}_i| e^{i(\delta_i - \phi_i)}$

Strong phase (δ) invariant under CP, while weak phase (ϕ) changes sign under CP

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

3 conditions required for direct CP violation

- At least 2 amplitudes
- Non-zero strong phase difference, $\delta_i - \delta_j \neq 0$
- Non-zero weak phase difference, $\phi_i - \phi_j \neq 0$

Source of weak phase differences come from different CKM phases of each amplitude

Motivation

Direct CP violation more complicated in $B \to 3h$ decay channels compared to 2-body decays

There are at least 4 possible sources of strong phase

1. Short-distance contributions (quark level)

BSS mechanism, PRL **43** 242 (1979)

Penguin diagram (b) contains 3 quark generations in loop

If gluon in penguin is timelike (on-shell)

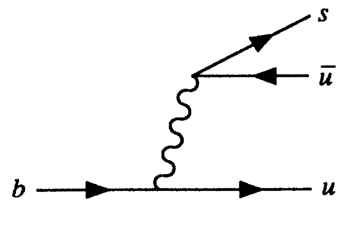
Momentum transfer $q^2 > 4m_i^2$ where $i = u, c$

Particle rescattering (c) generates a phase difference

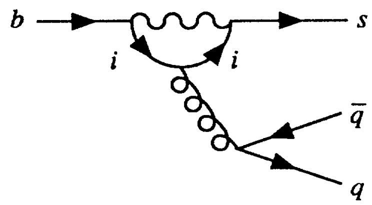
Tree contribution (a) carries different strong phase

CP violation in 2-body processes caused by this effect

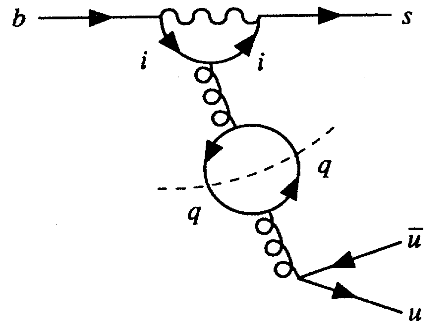
eg. $B^0 \to K^+\pi^-$



(a)



(b)



(c)

Motivation

Remaining sources unique to multibody decays

Long-distance contributions ($q\bar{q}$ level)

2. Breit-Wigner phase

   Represents intermediate resonance states

$$F_R^{\mathrm{BW}}(s) = \frac{1}{m_R^2 - s - i m_R \Gamma_R(s)}$$

   Phase varies across the Dalitz plot

3. Relative CP-even phase in the isobar model

$$A(B \to f) = \sum_i |A_i| e^{i(\delta_i + \phi_i)}$$
$$\bar{A}(\bar{B} \to \bar{f}) = \sum_i |\bar{A}_i| e^{i(\delta_i - \phi_i)}$$

   Related to final state interactions between different resonances

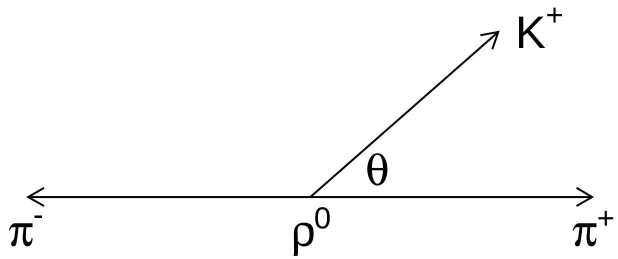
Motivation

Each source of strong phase leaves a unique signature in the Dalitz plot

Illustrate with series of examples

Consider $B^{\pm} \to K^{\pm}\pi^{+}\pi^{-}$ with only 2 isobars

$B^{\pm} \to K^{\pm}\rho^{0}$ and non-resonant (NR) component



ρ lineshape a Breit-Wigner, F_{ρ}^{BW}

ρ^{0} is a vector resonance, so angular distribution follows $\cos\theta$

$$A_{+} = a_{+}^{\rho} e^{i\delta_{+}^{\rho}} F_{\rho}^{\mathrm{BW}} \cos\theta + a_{+}^{\mathrm{NR}} e^{i\delta_{+}^{\mathrm{NR}}} F^{\mathrm{NR}}$$

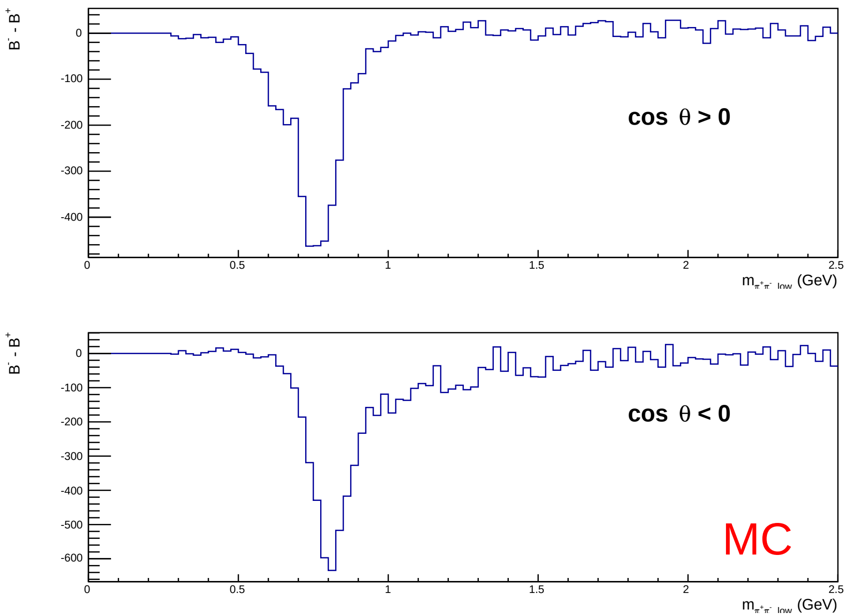
$$A_{-} = a_{-}^{\rho} e^{i\delta_{-}^{\rho}} F_{\rho}^{\mathrm{BW}} \cos\theta + a_{-}^{\mathrm{NR}} e^{i\delta_{-}^{\mathrm{NR}}} F^{\mathrm{NR}}$$

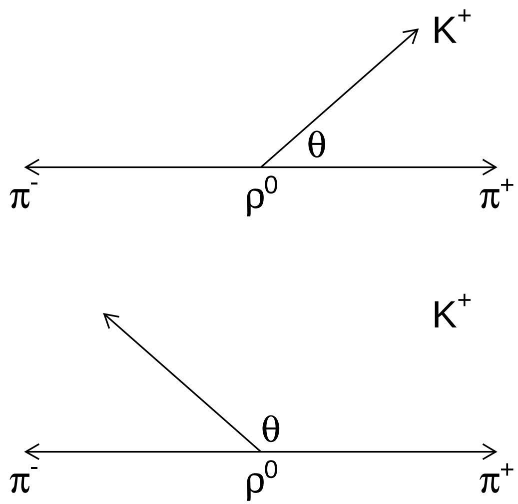
$$\begin{aligned}
\mathcal{A}_{CP} &\propto |A_{-}|^2 - |A_{+}|^2 \\
&\propto [(a_{-}^{\rho})^2 - (a_{+}^{\rho})^2]|F_{\rho}^{\mathrm{BW}}|^2 \cos^2\theta + \ldots \\
&\quad -2(m_{\rho}^2 - s)|F_{\rho}^{\mathrm{BW}}|^2|F^{\mathrm{NR}}|^2 \cos\theta \ldots \\
&\quad +2m_{\rho}\Gamma_{\rho}|F_{\rho}^{\mathrm{BW}}|^2|F^{\mathrm{NR}}|^2 \cos\theta \ldots
\end{aligned}$$

Motivation

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

Only depends on ρ resonance, maximum difference at ρ pole, quadratic in helicity



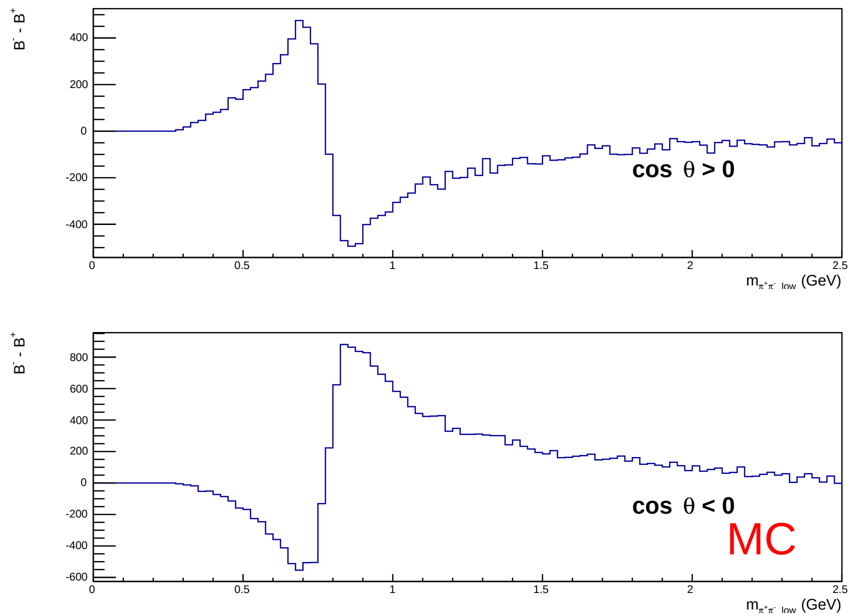


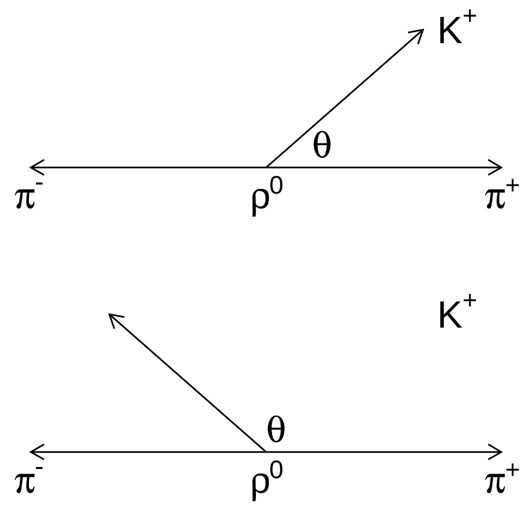
Only short-distance effects can create $a_+^\rho \neq a_-^\rho$

Motivation

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

Interference term from real part of Breit-Wigner, zero at ρ pole, linear in helicity



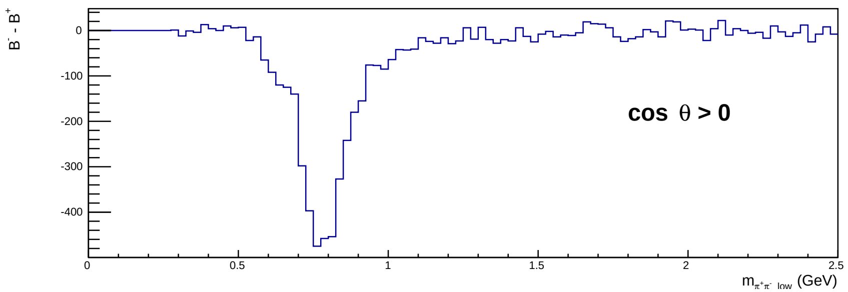


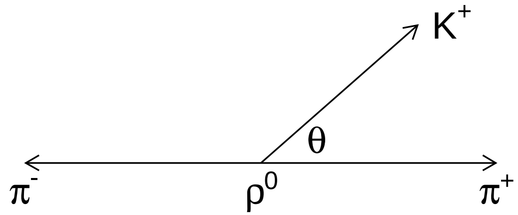
Caused by long distance effects from final state interactions

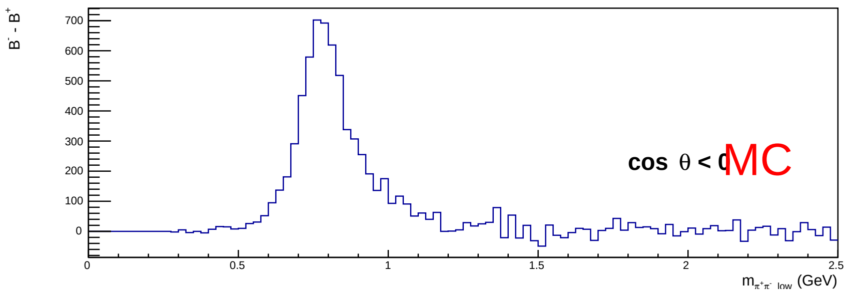
Motivation

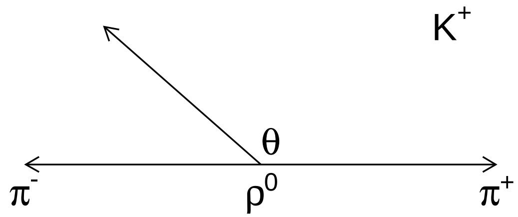
$$\mathcal{A}_{CP} \propto [(a_-^\rho)^2 - (a_+^\rho)^2]|F_\rho^{\mathrm{BW}}|^2\cos^2\theta + \ldots$$
$$-2(m_\rho^2 - s)|F_\rho^{\mathrm{BW}}|^2|F^{\mathrm{NR}}|^2\cos\theta\ldots$$
$$+2m_\rho\Gamma_\rho|F_\rho^{\mathrm{BW}}|^2|F^{\mathrm{NR}}|^2\cos\theta\ldots$$

Interference term from imaginary part of Breit-Wigner, maximum at ρ pole, linear in helicity









Caused by long distance effects from Breit-Wigner phase and final state interactions

Motivation

Last source of strong phase

4. Final state $KK \leftrightarrow \pi\pi$ rescattering

Can occur between decay channels with the same flavour quantum numbers

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

CPT conservation constrains hadron rescattering

For given quantum numbers, sum of partial widths equal for charge-conjugate decays

$KK \leftrightarrow \pi\pi$ rescattering generates a strong phase

Look into rescattering region

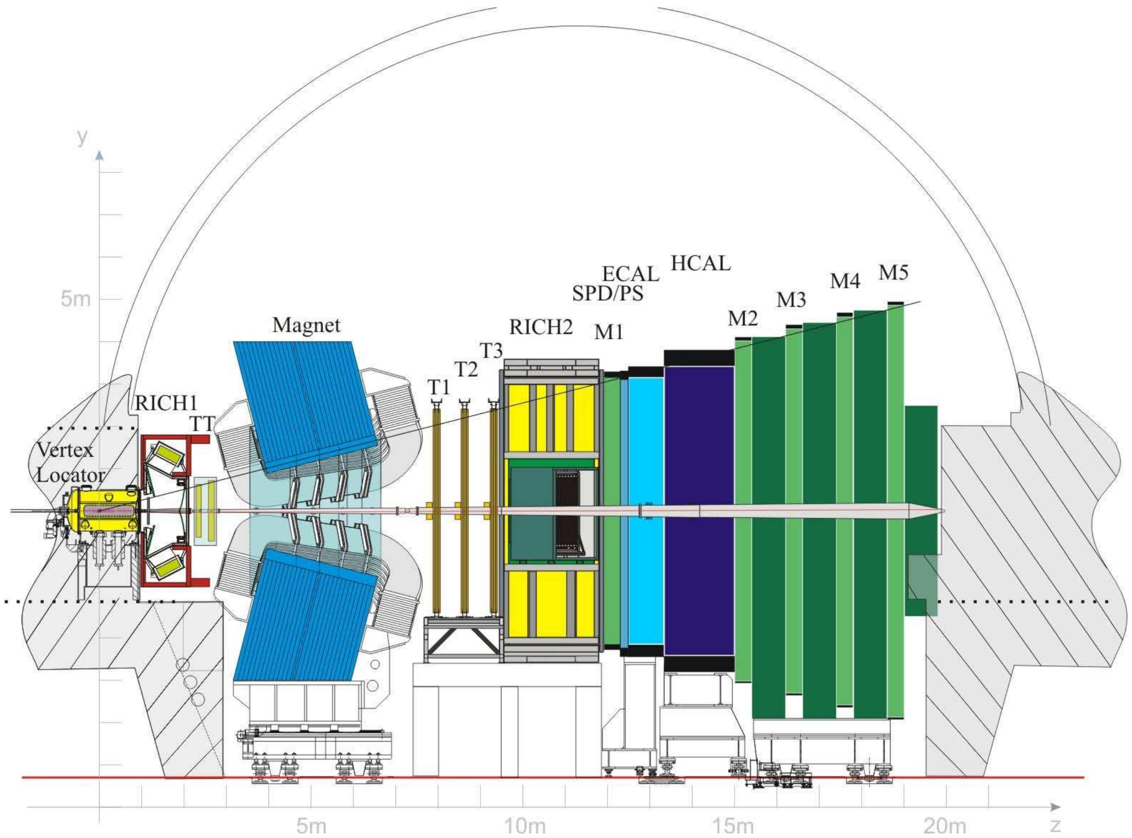
If rescattering phase in one decay channel generates direct CP violation in this region,

Rescattering phase should generate opposite sign direct CP violation in partner decay channel

LHCb Detector

pp collisions

- b quark tends to foward/backward direction



Data set: 1 fb^{-1} @ 7 TeV and 2 fb^{-1} @ 8 TeV

Forward spectrometer

Vertex Locater (VeLo)
- Precision tracking

Tracker Turicensis (TT)
- Tracking, p measurement

Ring Imaging Cherenkov (RICH)
- Particle identification

Electromagnetic Calorimeter (ECAL)
- e, γ ID

Hadronic Calorimeter (HCL)
- Hadronic showers

Muon Detector

Magnet polarity reversal

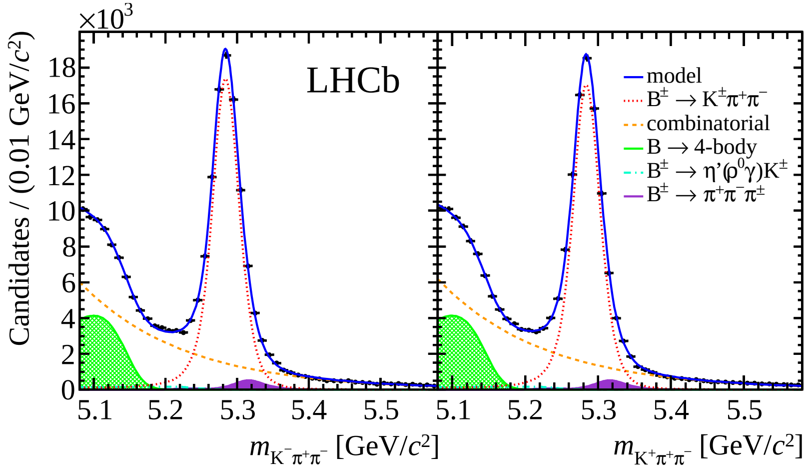
$B^{\pm} \to K^{\pm}h^{+}h^{-}, \pi^{\pm}h^{+}h^{-}$

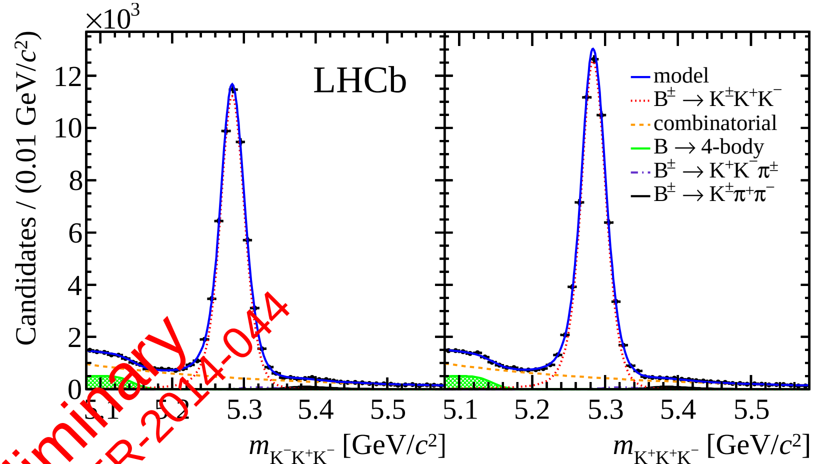
$B^{-} \to K^{-}\pi^{+}\pi^{-}$ $\quad$ $B^{+} \to K^{+}\pi^{+}\pi^{-}$

$N_{\mathrm{Sig}} = 181069 \pm 404$ (stat)

$B^{-} \to K^{-}K^{+}K^{-}$ $\quad$ $B^{+} \to K^{+}K^{+}K^{-}$

$N_{\mathrm{Sig}} = 109240 \pm 354$ (stat)





Penguin

Preliminary
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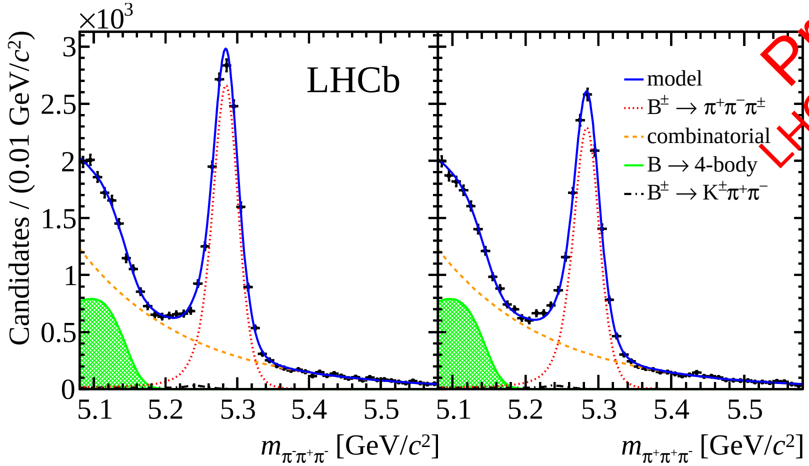

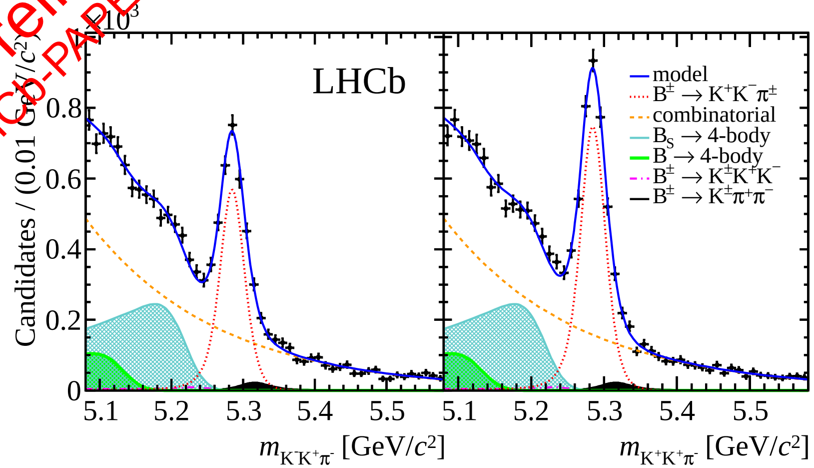

Tree

$B^{-} \to \pi^{-}\pi^{+}\pi^{-}$ $\quad$ $B^{+} \to \pi^{+}\pi^{+}\pi^{-}$

$N_{\mathrm{Sig}} = 24907 \pm 222$ (stat)

$B^{-} \to \pi^{-}K^{+}K^{-}$ $\quad$ $B^{+} \to \pi^{+}K^{+}K^{-}$

$N_{\mathrm{Sig}} = 6161 \pm 172$ (stat)

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

Global direct CP asymmetry

$$\mathcal{A}_{CP}^{\mathrm{Raw}} = \frac{N_{B^-} - N_{B^+}}{N_{B^-} + N_{B^+}}$$

Correct for $B^{\pm}$ production asymmetry and unpaired hadron (eg. $B^{\pm} \to K^{\pm}\pi^{+}\pi^{-}$) detection asymmetry

$$\mathcal{A}_{CP} = \mathcal{A}_{CP}^{\mathrm{Raw}} - \mathcal{A}_{P} - \mathcal{A}_{D}^{h}$$

$\mathcal{A}_{P}$ and $\mathcal{A}_{D}^{K}$ from $B^{\pm} \to J/\psi[\mu^{+}\mu^{-}]K^{\pm}$, PRL **108** 201601 (2012)

$\mathcal{A}_{D}^{\pi}$ from prompt D^{+} studies, PLB **713** 186 (2012)

$$\mathcal{A}_{CP}(B^{\pm} \to K^{\pm}\pi^{+}\pi^{-}) = +0.025 \pm 0.004\ (\mathrm{stat}) \pm 0.004\ (\mathrm{syst}) \pm 0.007\ (J/\psi K^{\pm}) \quad (2.8\sigma)$$

$$\mathcal{A}_{CP}(B^{\pm} \to K^{\pm}K^{+}K^{-}) = -0.036 \pm 0.004\ (\mathrm{stat}) \pm 0.002\ (\mathrm{syst}) \pm 0.007\ (J/\psi K^{\pm}) \quad (4.3\sigma)$$

$$\mathcal{A}_{CP}(B^{\pm} \to \pi^{\pm}\pi^{+}\pi^{-}) = +0.058 \pm 0.008\ (\mathrm{stat}) \pm 0.009\ (\mathrm{syst}) \pm 0.007\ (J/\psi K^{\pm}) \quad (4.2\sigma)$$

$$\mathcal{A}_{CP}(B^{\pm} \to \pi^{\pm}K^{+}K^{-}) = -0.123 \pm 0.017\ (\mathrm{stat}) \pm 0.012\ (\mathrm{syst}) \pm 0.007\ (J/\psi K^{\pm}) \quad (5.6\sigma)$$

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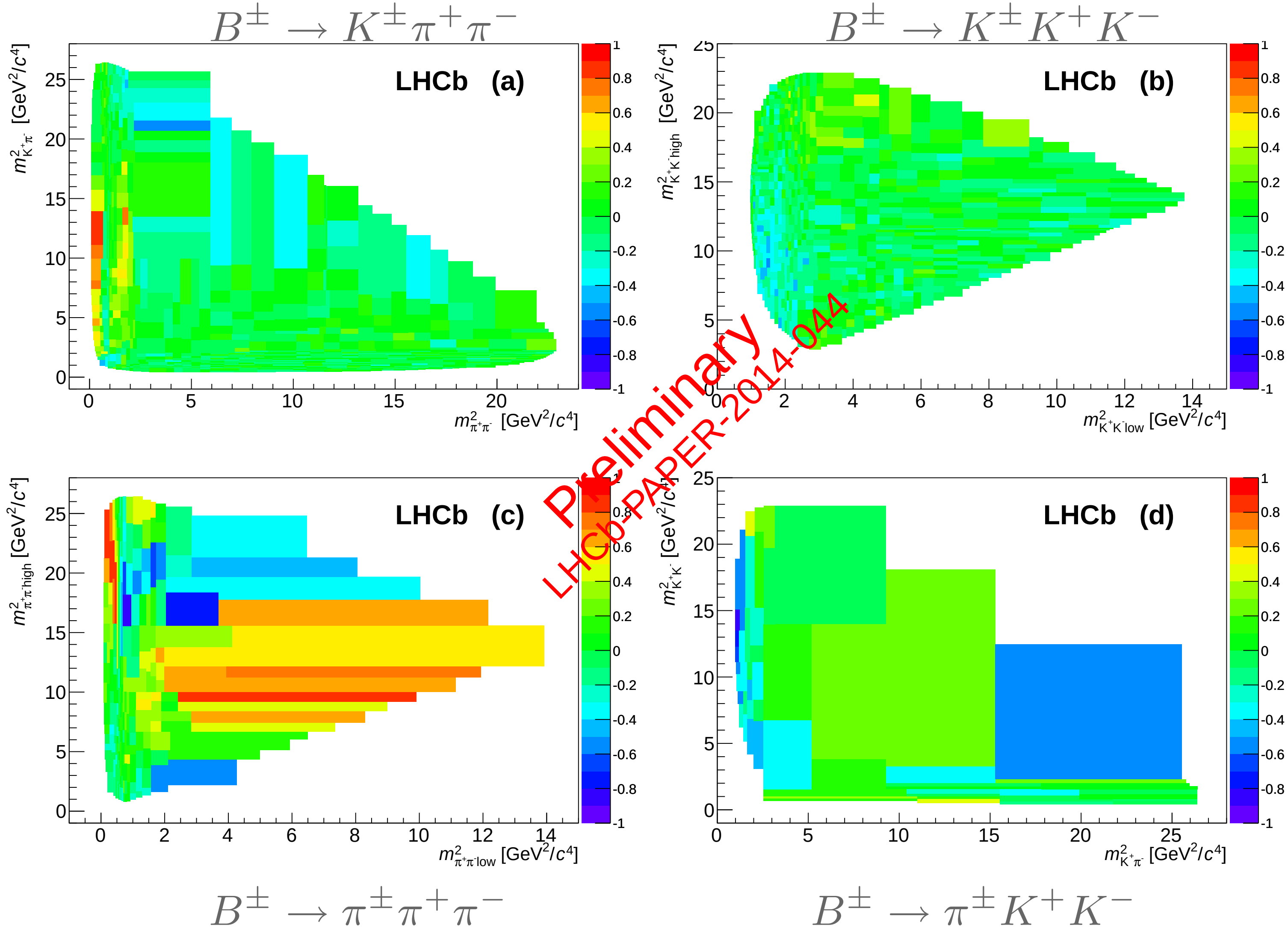
$B^{\pm} \to K^{\pm}h^{+}h^{-}, \pi^{\pm}h^{+}h^{-}$

Dalitz plot background subtracted and effiency corrected with $\sim (N_{B+} + N_{B-})$ in each bin

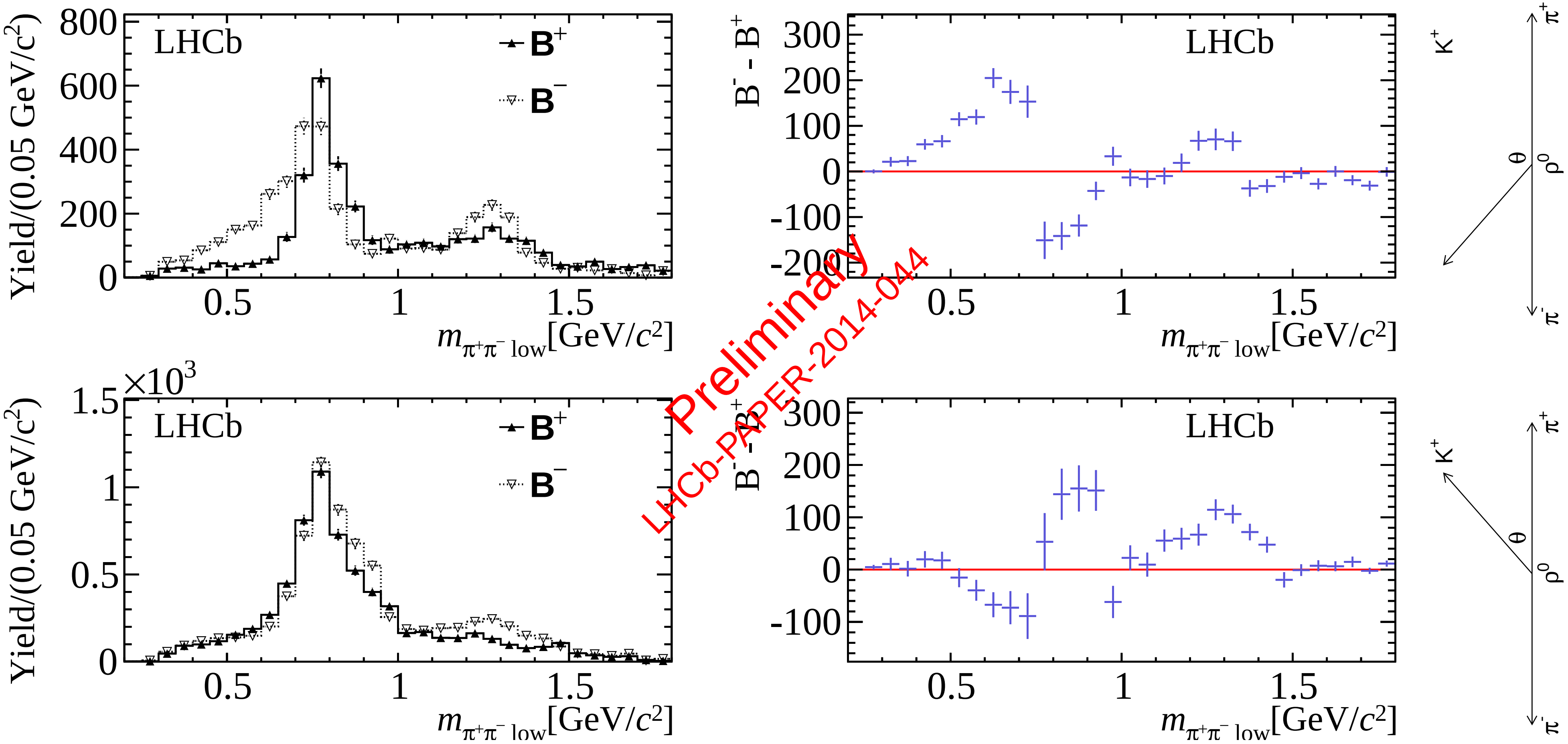


Penguin

Tree

CP Asymmetry by Interference

Project onto $m_{\pi\pi}$ of $B^{\pm} \to \pi^{\pm}\pi^{+}\pi^{-}$

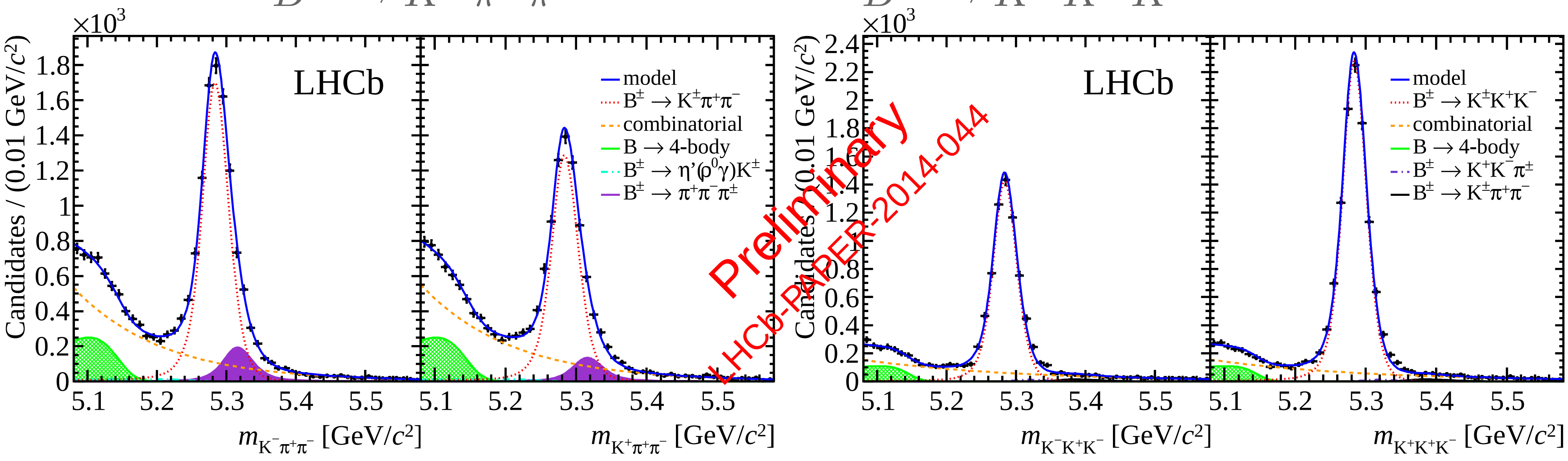


Sign-flip and zero around ρ^0 pole, CP asymmetry may be dominated by real part of Breit-Wigner

CP Asymmetry by Rescattering

$\pi\pi \leftrightarrow KK$ rescattering region: $1.0 - 1.5\ \mathrm{GeV}/c^2$

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



$$\mathcal{A}_{CP}(B^\pm \to K^\pm\pi^+\pi^-) = +0.121 \pm 0.012\ (\mathrm{stat}) \pm 0.017\ (\mathrm{syst}) \pm 0.007\ (J/\psi K^\pm)$$

$$\mathcal{A}_{CP}(B^\pm \to K^\pm K^+ K^-) = -0.211 \pm 0.011\ (\mathrm{stat}) \pm 0.004\ (\mathrm{syst}) \pm 0.007\ (J/\psi K^\pm)$$

Clear opposite sign CP asymmetry in $KK/\pi\pi$ - related channels

$KK \leftrightarrow \pi\pi$ rescattering would require this by CPT conservation

$B^{\pm} \to K^{\pm}p\bar{p}$ and $B^{\pm} \to \pi^{\pm}p\bar{p}$

Another new preliminary result based on full data set

$B^{\pm} \to K^{\pm}p\bar{p}$ penguin dominated

$B^{\pm} \to \pi^{\pm}p\bar{p}$ tree dominated

Similar physics to non-baryonic 3-body charmless decays

$p\bar{p} \leftrightarrow h^{+}h^{-}$ rescattering expected to be smaller than $KK \leftrightarrow \pi\pi$ rescattering

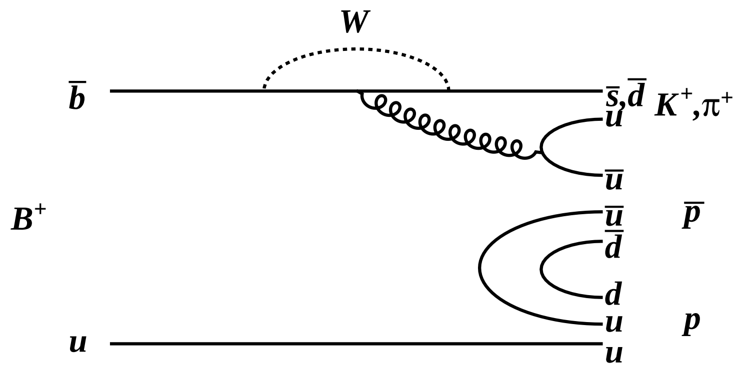
- CP asymmetry could be less pronounced

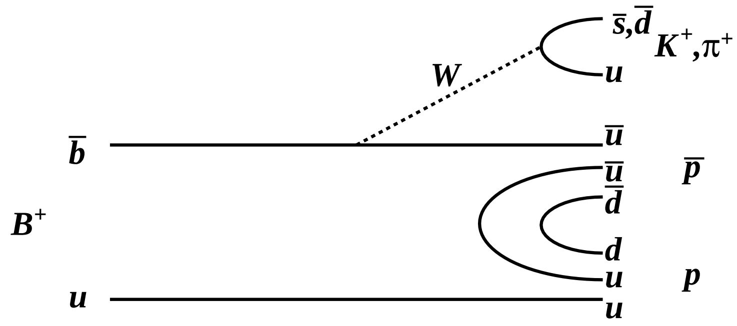
Threshold enhancement in low $m_{p\bar{p}}$ typical in $B \to p\bar{p}X$ decays

- Need to better understand dynamics of these decays

Previous publication based on 1 fb^{-1}

- No evidence of CP violation
- PRD **88** 052015 (2013)

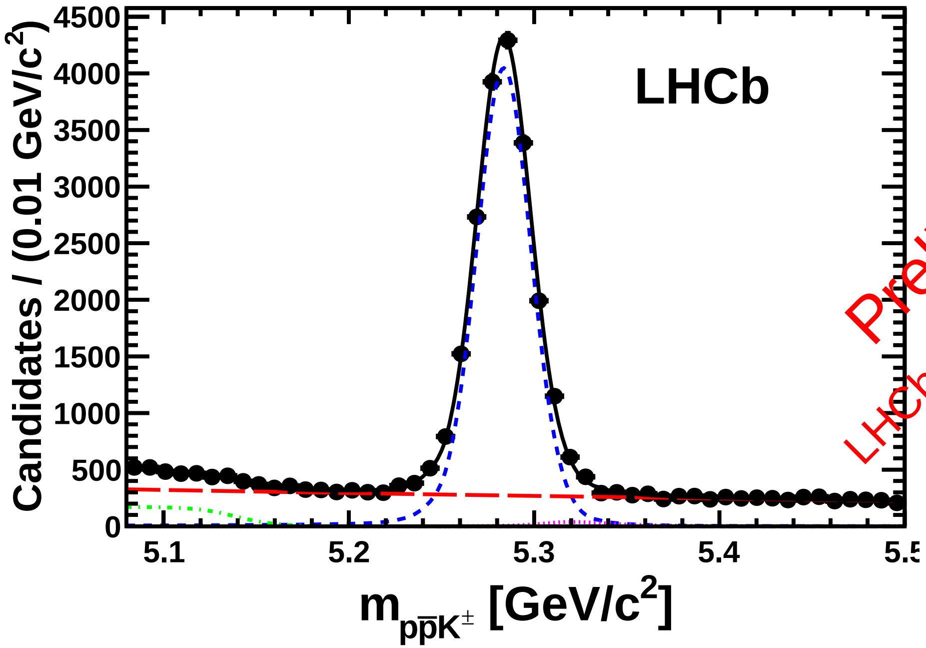




Signal Yield

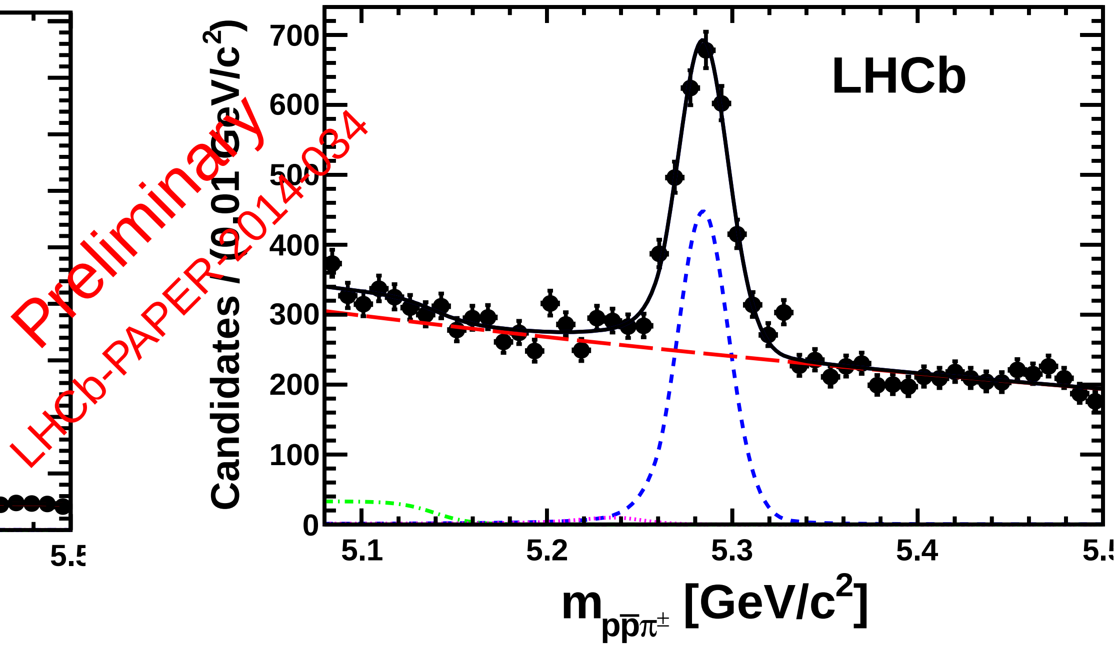
$B^{\pm} \to K^{\pm} p\bar{p}$

$N_{\mathrm{Sig}} = 18721 \pm 142\ (\mathrm{stat})$



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

$N_{\mathrm{Sig}} = 1988 \pm 74\ (\mathrm{stat})$



Blue: Signal

Red: Combinatorial

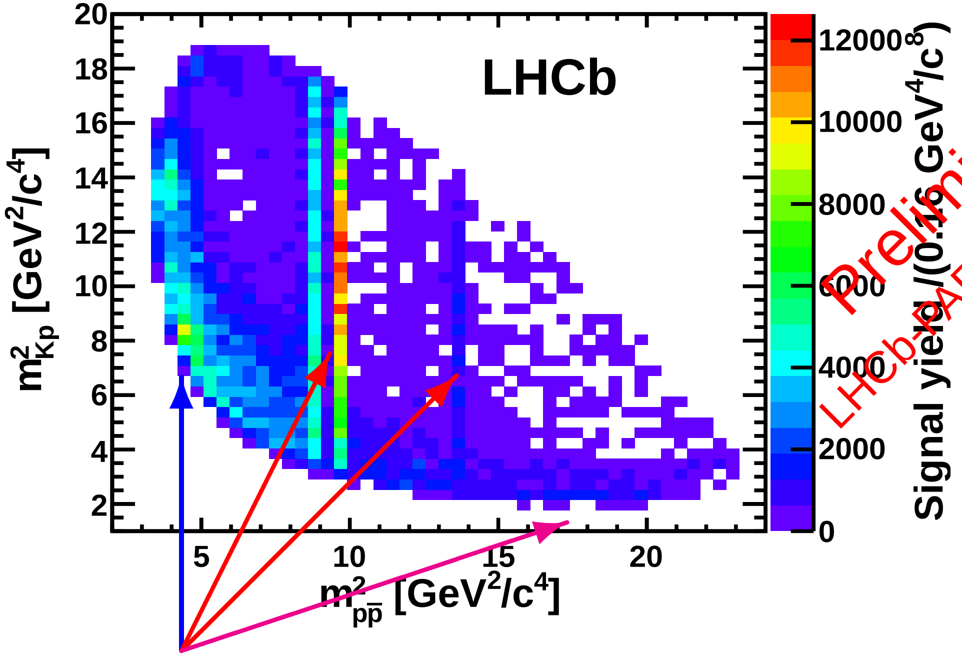
Green: Partially reconstrcuted

Purple: Cross-feed

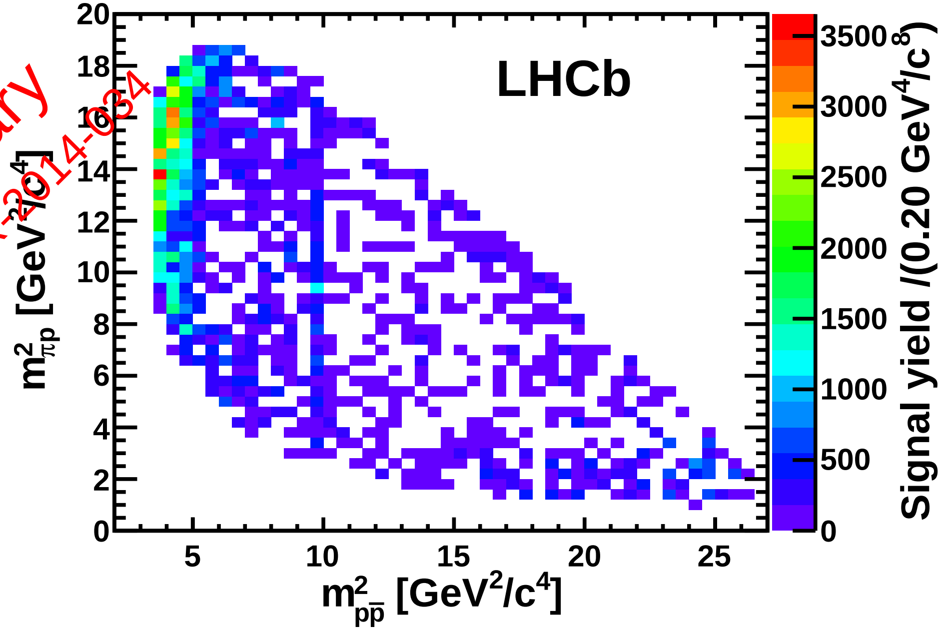
Dalitz Plot

Background subtracted and efficiency corrected using calibrated MC

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



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



Low $m_{p\bar{p}}$ threshold enhancement

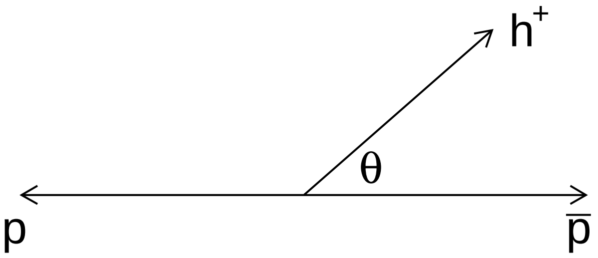
Charmonimum resonances

Define $m_{p\bar{p}} < 2.85$ GeV$/c^2$ as charmless region

$\Lambda(1520) \to pK$

Forward-Backward Asymmetry

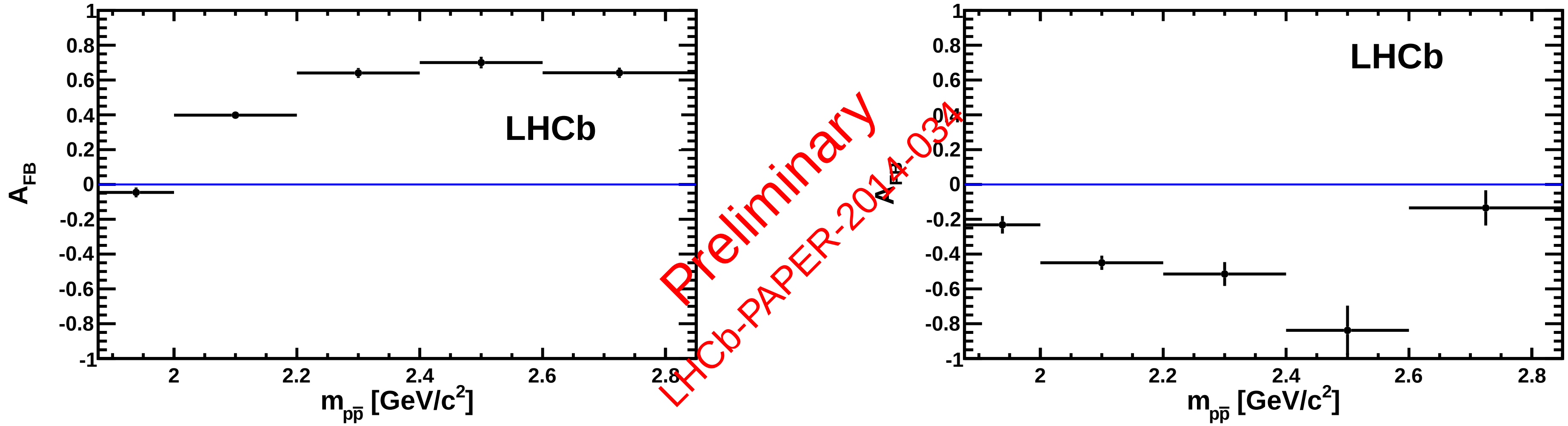
$$A_{\mathrm{FB}} = \frac{N(\cos\theta > 0) - N(\cos\theta < 0)}{N(\cos\theta > 0) + N(\cos\theta < 0)}$$



Meausure forward-backward asymmetry in bins of $m_{p\bar{p}}$

Gives hint on $p\bar{p}$ waves that might contribute

$B^{\pm} \to K^{\pm} p\bar{p}$ $B^{\pm} \to \pi^{\pm} p\bar{p}$



$$A_{\mathrm{FB}}^{p\bar{p}K}(m_{p\bar{p}} < 2.85\ \mathrm{GeV}/c^2) = +0.495 \pm 0.012\ (\mathrm{stat}) \pm 0.007\ (\mathrm{syst})$$

$$A_{\mathrm{FB}}^{p\bar{p}\pi}(m_{p\bar{p}} < 2.85\ \mathrm{GeV}/c^2) = -0.409 \pm 0.033\ (\mathrm{stat}) \pm 0.006\ (\mathrm{syst})$$

Large asymmetries indicate dominance of non-resonant $p\bar{p}$ scattering, J Phys G **34** 283 (2007)

Direct CP Asymmetry

Measure $\mathcal{A}_{CP}$ in Dalitz plot bins

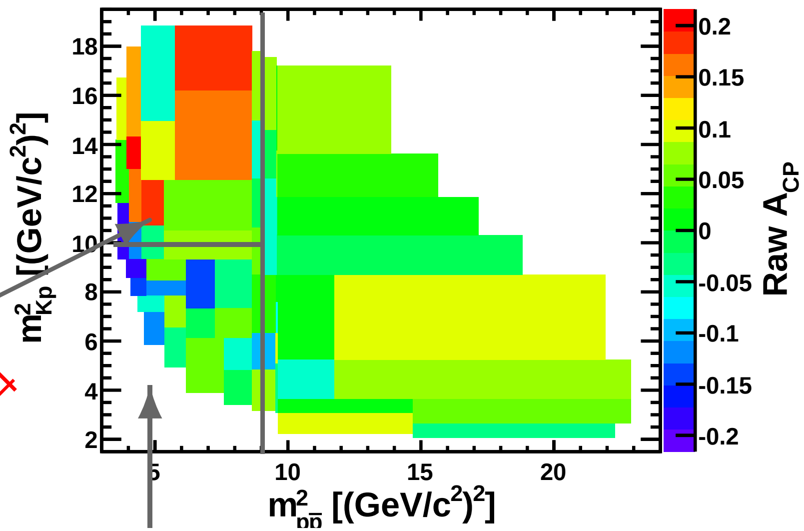
- Same number of events in each bin

$$\mathcal{A}_{CP}(m_{p\bar{p}} < 2.85\ \mathrm{GeV}/c^2, m^2_{Kp} > 10\ \mathrm{GeV}^2/\mathrm{c}^4)$$
$$= +0.096 \pm 0.024\ (\mathrm{stat}) \pm 0.004\ (\mathrm{syst}) \quad (4.0\sigma)$$

First evidence of CP violation in any B decay

- involving baryons

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



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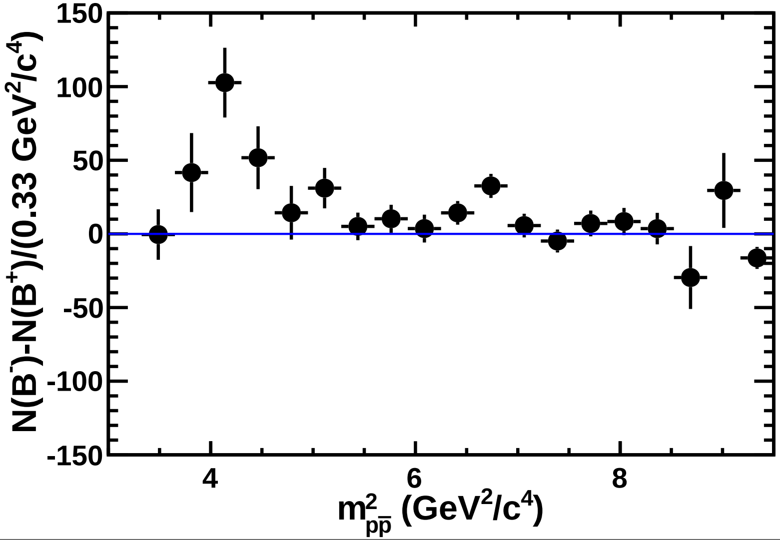

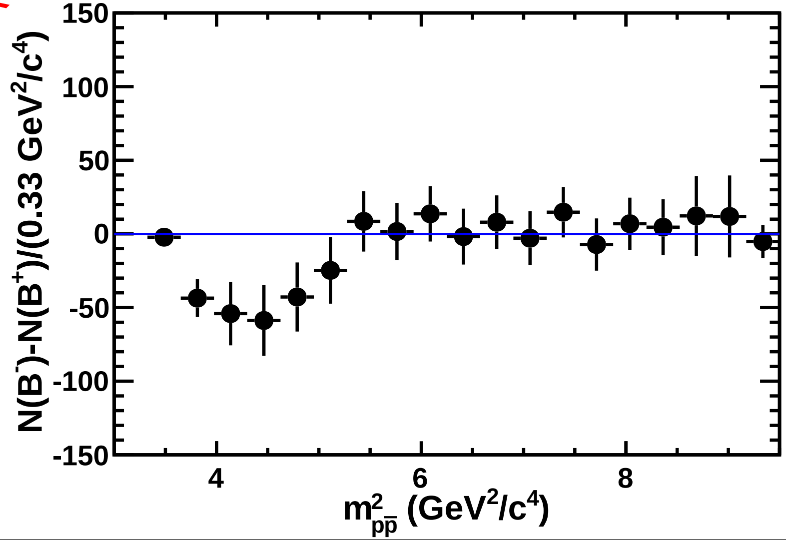

Summary

New preliminary results with the full LHCb data set

$B^\pm \to K^\pm h^+ h^-$ and $B^\pm \to \pi^\pm h^+ h^-$

- Evidence of global direct CP violation
- Large localised CP asymmetries across the Dalitz plot
- Long-distance effects play an important role in generating a strong phase

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

- Large forward-backward asymmetries indicate dominance of non-resonant $p\bar{p}$ scattering
- First evidence CP violation in decays involving baryons
- Sign-flip of CP asymmetry probably generated by interference of long-distance $p\bar{p}$ waves

Look forward to amplitude analyses on all these channels

Backup