Charmless *B* decays

(Review of LHCb results on CP violation measurements)

- Physics motivation: Why charmless decays?
- LHCb detector
- Direct CPV measurements: $B^0 \to K^+\pi^-$, $B^0_s \to K^-\pi^+$ [PRL 110, 221601 (2013)]
  $B^\pm \to K^\pm\pi^+\pi^-$, $K^\pm K^+K^-$, $\pi^\pm K^+K^-$, $\pi^\pm\pi^+\pi^-$ [Preliminary LHCb-PAPER-2014-044]
- Mixing-induced CPV measurements: $B^0 \to \pi^+\pi^-$, $B^0_s \to K^+K^-$ [JHEP 10 (2013) 183]
  $B^0_s \to \phi\phi$ [arXiv:1407.2222]
- Summary

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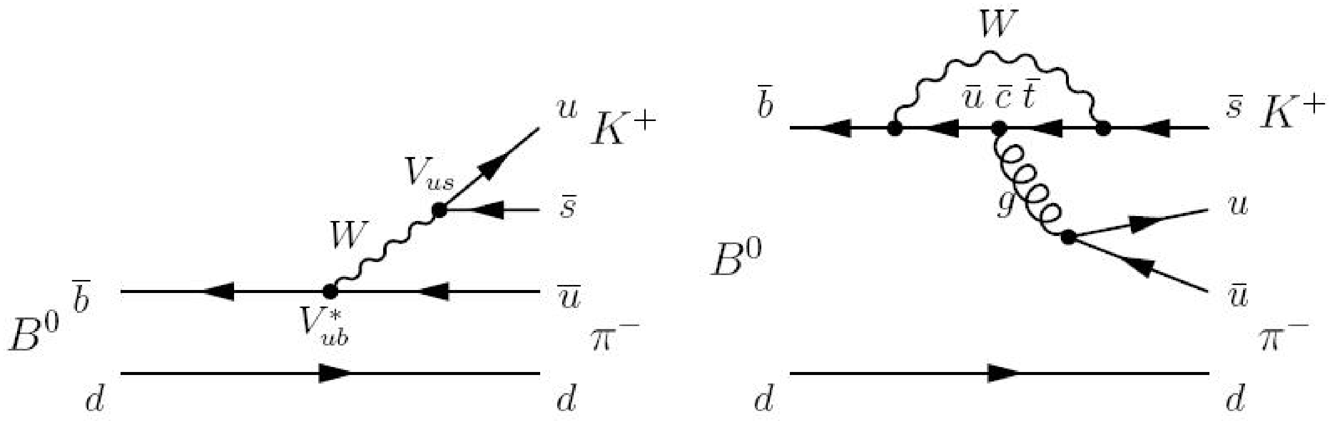
Physics motivation: Why charmless decays?

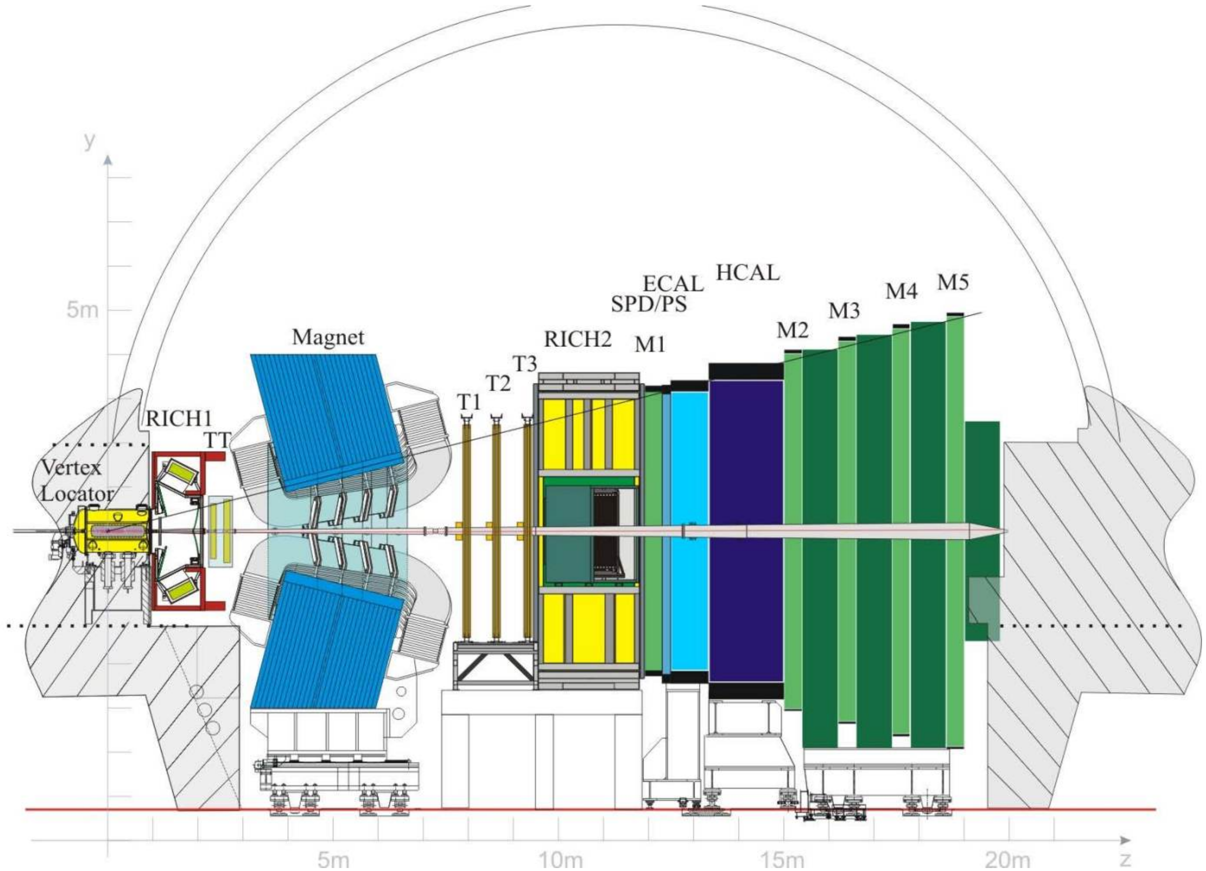
- Charmless decays have several great features:

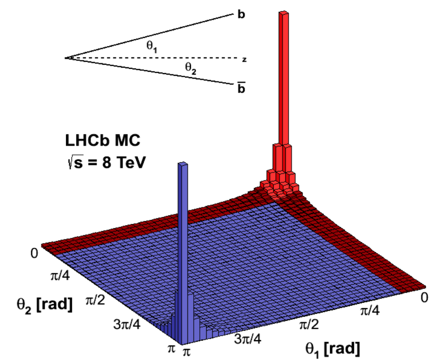


Feynman tree (a) and penguin (b) diagrams for the $B_d^0 \to K^+\pi^-$ decay

- Contributions from tree and penguin diagrams.
- Potential for direct CP violation.
- Sensitive to CKM angles.
- Possible contributions from new heavy particles (new physics) in the loop.
- Can search for signs of new physics such as enhanced branching fractions, anomalous CP asymmetries or polarizations.

LHCb detector: An excellent place to study *B* decays



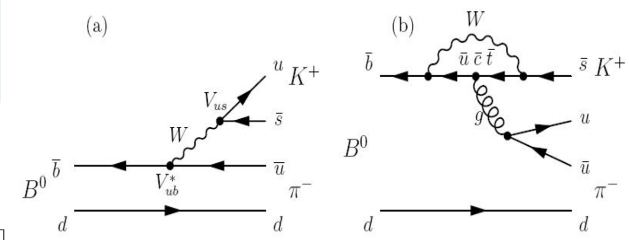


- LHCb is a single-arm forward spectrometer.
- $2 < \eta < 5$ coverage.
- Luminosities: 1.0 fb^{-1} (2011 run pp @ 7 TeV) and 2.0 fb^{-1} (2012 run pp @ 8 TeV).

- Tracking and vertexing (courtesy of T stations and Vertex Locator).
- Particle identification (courtesy of the RICH detectors – separates $K^{\pm}$, $\pi^{\pm}$, p).
- Ability to reverse magnet polarity.
- Efficient triggers (can trigger using calorimeter and muon systems at hardware level).
- **For LHCb performance during Run I: See talk of G. Graziani earlier.**

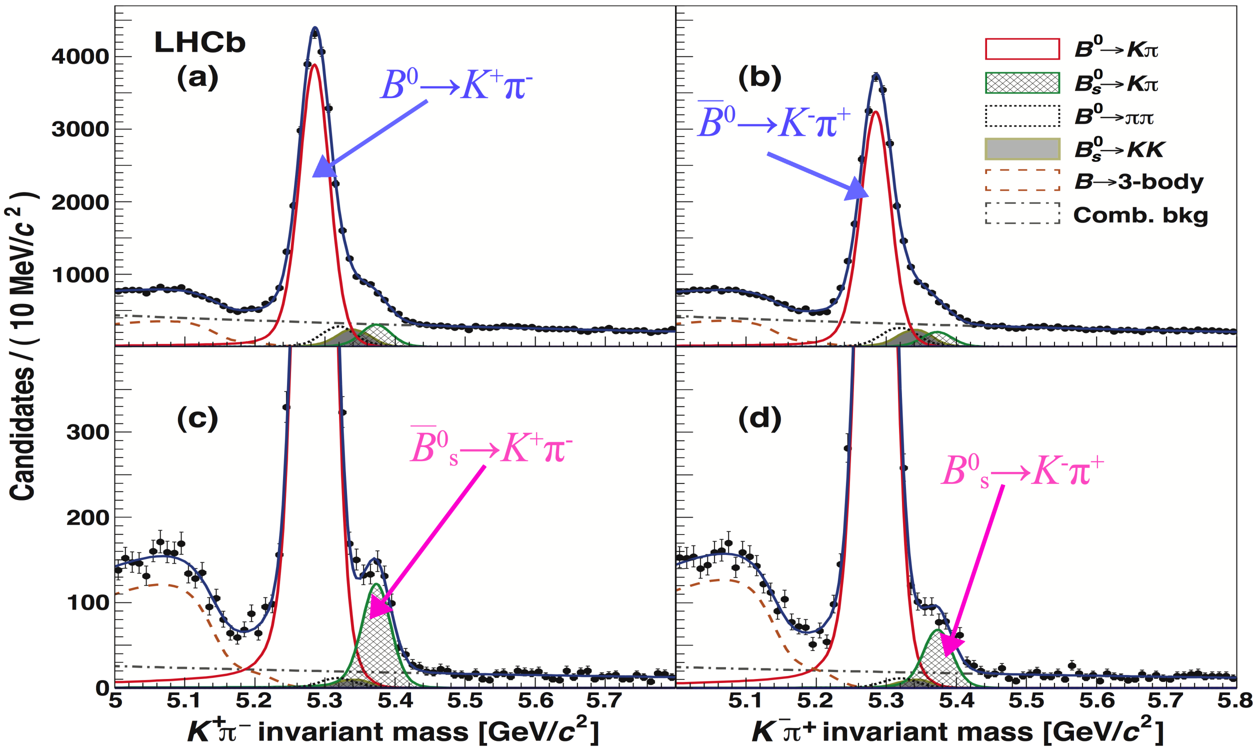
Direct CPV measurement in $B^0 \to K^+\pi^-$, $B^0_s \to K^-\pi^+$

- direct $\mathcal{A}_{CP} = \dfrac{|\bar{A}|^2 - |A|^2}{|\bar{A}|^2 + |A|^2} \propto |A_T||A_P| \sin(\varphi_T - \varphi_P)\sin(\delta_T - \delta_P)$



Feynman tree (a) and penguin (b) diagrams for the $B^0_d \to K^+\pi^-$ decay

- Using 1/fb (2011) @ $\sqrt{s}$ = 7 TeV.



- $\mathcal{A}_{CP}(B^0)$ = $-0.080 \pm 0.007 \pm 0.003$ (most precise measurement, 10.5σ)
- $\mathcal{A}_{CP}(B^0_s)$ = $-0.27 \pm 0.04 \pm 0.01$ (first observation of CPV in B^0_s decays, 6.5σ)

PRL 110, 221601 (2013)

- $\Delta_{K\pi} = \dfrac{\mathcal{A}_{CP}(B^0)}{\mathcal{A}_{CP}(B^0_s)} + \dfrac{\mathcal{B}(B^0_s)\cdot\tau_{B^0}}{\mathcal{B}(B^0)\cdot\tau_{B^0_s}} = -0.02 \pm 0.05 \pm 0.04 \equiv 0$ [U-spin symmetry of SM Lipkin PLB 621 (2005) 126]

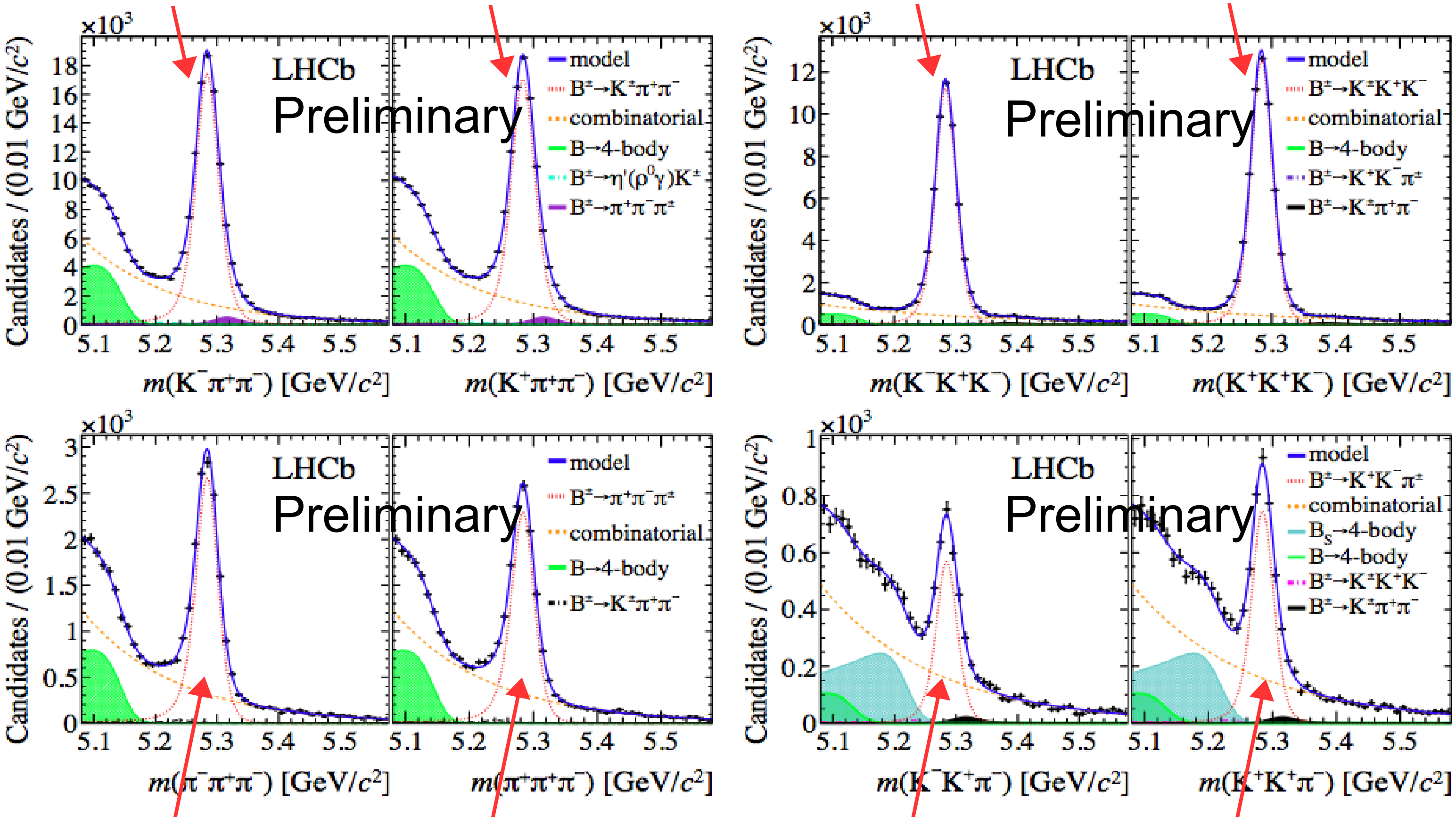
CP violation measurement in $B^{\pm}\to K^{\pm}\pi^{+}\pi^{-}$, $B^{+}\to K^{\pm}K^{+}K^{-}$, $B^{\pm}\to K^{+}K^{-}\pi^{\pm}$ and $B^{\pm}\to\pi^{+}\pi^{-}\pi^{\pm}$

- Motivated by the large CP violation observed in two-body charmless decays.
- Dominated by quasi two-body processes involving intermediate resonant states.
- Rich interference pattern makes them favourable for investigation of CP asymmetries that are localized in the phase space.
- Possible sources of strong phases:
  - Short distance processes (quark level):
    - Where the gluon involved in the loop is timelike (on-shell), that is momentum transfer $q^2 > 4m^2_i$, where $i = u$ or c quark present in the loop.
  - Long distance processes (hadron-hadron interactions):
    - Interference between intermediate states.
    - Final state $KK\leftrightarrow\pi\pi$ rescattering.
- Previous analysis for the first measurement of direct CPV on these decays done using 1 fb^{-1} : [PRL 111 (2013) 101810]
  [PRL 112 (2014) 011801]
- Next slides, will present update using 3 fb^{-1} (full Run I data), now with better selection (with improved particle identification and suppression of combinatorial background). → Allowing investigation of CP asymmetry in the phase space.

CP violation measurement in the phase-space of $B^{\pm}\to$ (charged three-body)

- $(N+\overline{N}) = 181069 \pm 404\ (stat.)$
- $(N+\overline{N}) = 109240 \pm 354\ (stat.)$

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



(Penguin dominated)

(Tree dominated)

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

- $(N+\overline{N}) = 24907 \pm 222\ (stat.)$
- $(N+\overline{N}) = 6161 \pm 172\ (stat.)$

CP violation measurement in the phase-space of $B^{\pm} \to$ (charged three-body)

- Raw asymmetry from fitted yields: $\mathcal{A}_{raw} = [N_{B^-} - \overline{N}_{B^+}] / [N_{B^-} + \overline{N}_{B^+}]$
  for small asymmetries, $\mathcal{A}_{raw} \approx \mathcal{A}_{CP} - \mathcal{A}_{P}(B^{\pm}) - \mathcal{A}_{D}(h^{\pm})$

- Raw asymmetry has to be corrected for detector asymmetry ($\mathcal{A}_{D}(K^{\pm})$ or $\mathcal{A}_{D}(\pi^{\pm})$) and production asymmetry ($\mathcal{A}_{P}(B^{\pm})$) to extract CP asymmetry $\mathcal{A}_{CP}$:

  $\mathcal{A}_{CP} = \mathcal{A}_{raw} - \mathcal{A}_{P}(B^{\pm}) - \mathcal{A}_{D}(K^{\pm}) = \mathcal{A}_{raw} - \mathcal{A}_{\Delta}$ [for $B^{\pm} \to K^{\pm}hh$]

  $\mathcal{A}_{CP} = \mathcal{A}_{raw} - \mathcal{A}_{P}(B^{\pm}) - \mathcal{A}_{D}(\pi^{\pm}) = \mathcal{A}_{raw} - \mathcal{A}_{\Delta} + \mathcal{A}_{D}(K^{\pm}) - \mathcal{A}_{D}(\pi^{\pm})$ [for $B^{\pm} \to \pi^{\pm}hh$]

  where $\mathcal{A}_{\Delta} = \mathcal{A}_{raw}(B^{\pm} \to J/\psi K^{\pm}) - \mathcal{A}_{CP}(B^{\pm} \to J/\psi K^{\pm})$

  - $\mathcal{A}_{\Delta}$ using $B^{\pm} \to J/\psi K^{\pm}$ control sample.
  - $\mathcal{A}_{D}(\pi^{\pm}) = (0.00 \pm 0.25)\%$ from studies of prompt $D^{\pm}$ decays [PLB 713 (2012) 186].
  - $\mathcal{A}_{D}(K^{\pm}) = (-1.26 \pm 0.18)\%$ [using $D^{*+} \to D^0(K^-\pi^+\pi^-\pi^+)\pi^+$, with same method in PLB 713 (2012) 186].

- Acceptance correction for non-uniform efficiencies across the Dalitz plot, from simulated data.

- **Inclusive CP asymmetry (PRELIMINARY) :**

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

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

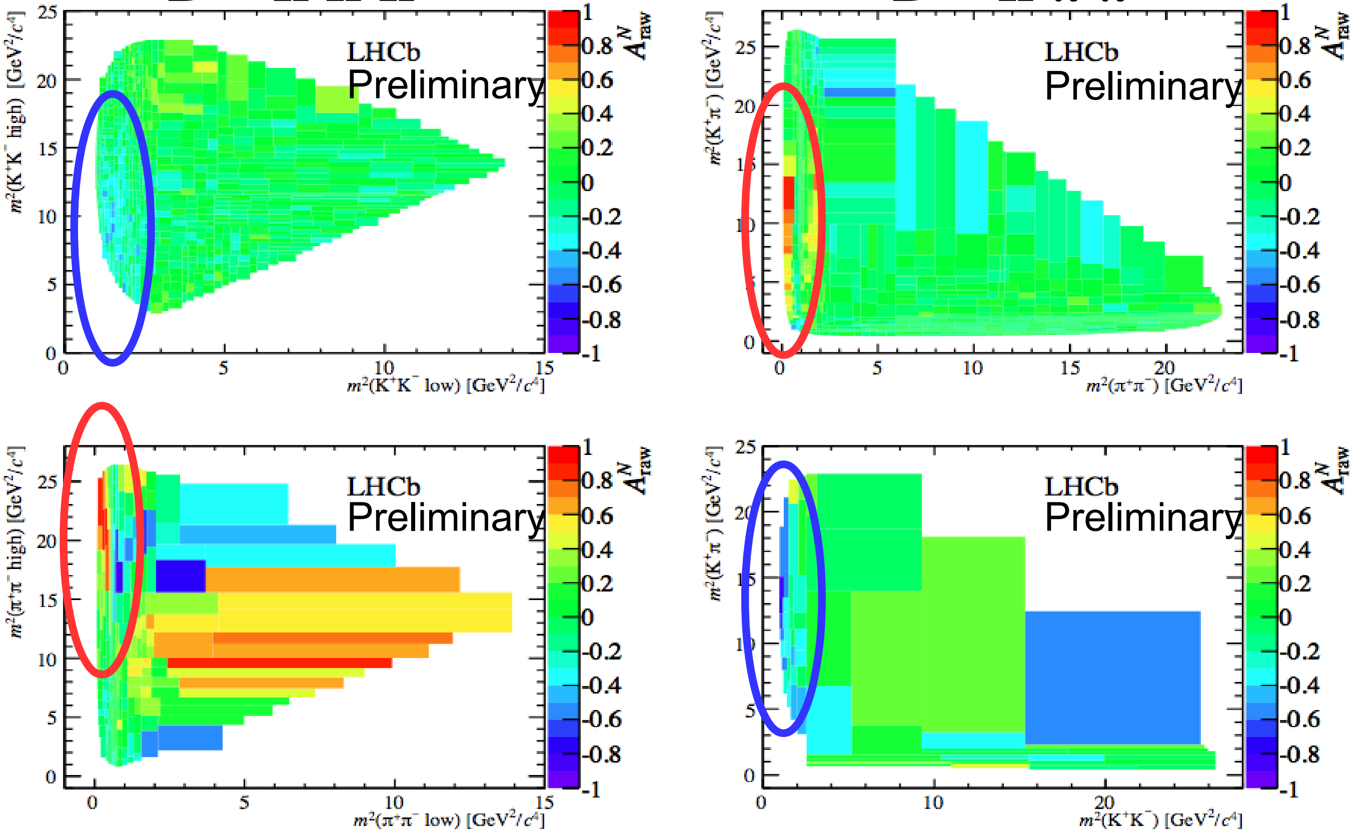
  $\mathcal{A}_{CP}(B^{\pm} \to \pi^{\pm}\pi^{+}\pi^{-}) = +0.058 \pm 0.008\ (stat) \pm 0.009\ (syst) \pm 0.007\ (\mathcal{A}_{CP}(J/\psi K))$ **[4.2σ]**

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

CP violation measurement in the local regions of Dalitz plot of $B^{\pm}\rightarrow$ (charged three-body)

- Adaptive binning is used to keep total events in each bin approximately constant.
- Backgrounds are subtracted via *sPlot* technique and corrected for efficiencies.
- Observed large local raw asymmetries in certain regions of the phase space.

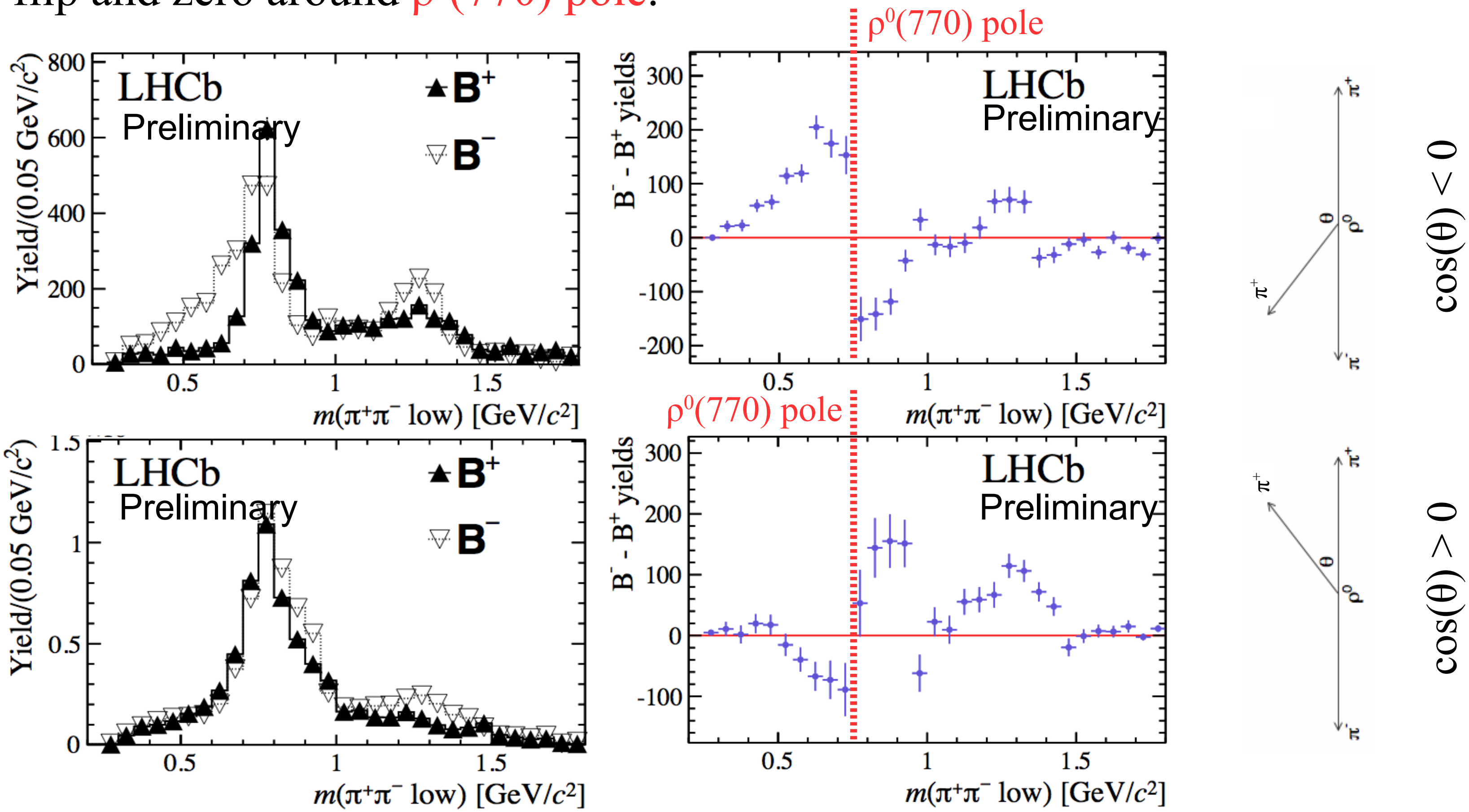
$B^{\pm}\rightarrow K^{\pm}K^{+}K^{-}$ $\qquad$ $B^{\pm}\rightarrow K^{\pm}\pi^{+}\pi^{-}$



$B^{\pm}\rightarrow\pi^{\pm}\pi^{+}\pi^{-}$ $\qquad$ $B^{\pm}\rightarrow\pi^{\pm}K^{+}K^{-}$

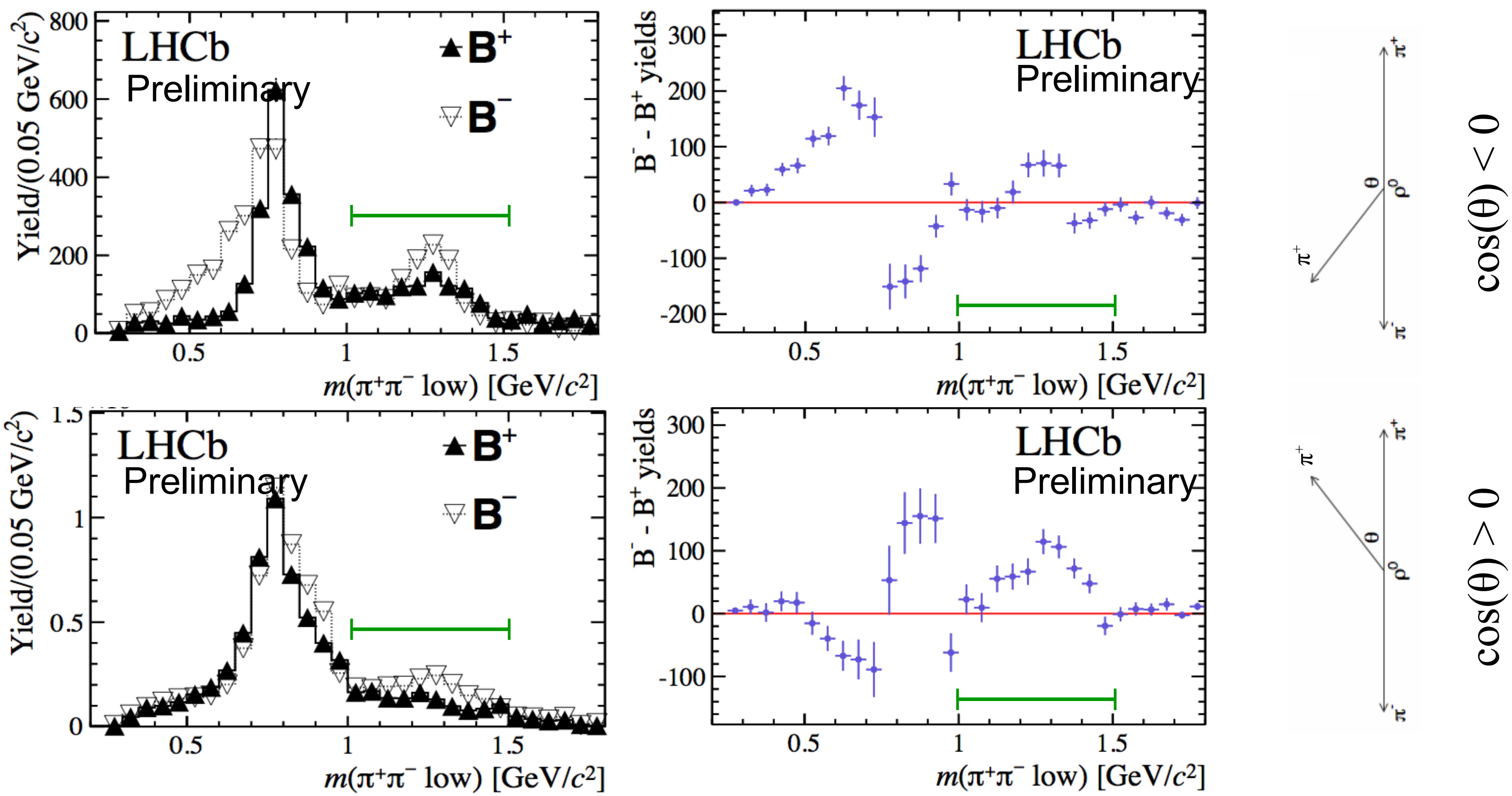
Interference effects in the CP asymmetry of $B^{\pm} \to$ (charged three-body)

- Project onto $m_{\pi\pi}$ the $B^{\pm} \to \pi^{\pm}\pi^{+}\pi^{-}$ Dalitz plot (zoomed into the region with large asymmetry), splitted according to the sign of the cos(θ). θ is the angle between the momenta of unpaired hadron and the resonant daughter with the same-sign charge.
- Sign-flip and zero around ρ⁰(770) pole.



Rescattering effects in the CP asymmetry of $B^{\pm} \rightarrow$ (charged three-body)

- Observed large charge asymmetries in the rescattering region ($1 < m_{\pi\pi} < 1.5$ GeV/c^2) of $B^{\pm} \rightarrow \pi^{\pm}\pi^{+}\pi^{-}$.
- The same is observed for the other 3 decays. [Projections in the back-up slides]



Rescattering effects in the CP asymmetry of $B^{\pm} \longrightarrow$ (charged three-body)

- For all the $B^{\pm} \rightarrow$(charged three-body), measured the charge asymmetry in the scattering region : $1 < (m_{\pi\pi}$ or $m_{KK}) < 1.5$ GeV/c^2.

- **Charge asymmetry in the rescattering regions (PRELIMINARY):**

$$\left.\begin{aligned}
\mathcal{A}_{CP}(B^{\pm} \rightarrow K^{\pm}\pi^{+}\pi^{-}) &= +0.121 \pm 0.012\ (stat) \pm 0.017\ (syst) \pm 0.007\ (\mathcal{A}_{CP}(J/\psi K)) \\
\mathcal{A}_{CP}(B^{\pm} \rightarrow K^{\pm}K^{+}K^{-}) &= -0.221 \pm 0.011\ (stat) \pm 0.004\ (syst) \pm 0.007\ (\mathcal{A}_{CP}(J/\psi K)) \\
\mathcal{A}_{CP}(B^{\pm} \rightarrow \pi^{\pm}\pi^{+}\pi^{-}) &= +0.172 \pm 0.021\ (stat) \pm 0.015\ (syst) \pm 0.007\ (\mathcal{A}_{CP}(J/\psi K)) \\
\mathcal{A}_{CP}(B^{\pm} \rightarrow \pi^{\pm}K^{+}K^{-}) &= -0.328 \pm 0.028\ (stat) \pm 0.029\ (syst) \pm 0.007\ (\mathcal{A}_{CP}(J/\psi K))
\end{aligned}\right\} > 5\sigma$$

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- **CPT** : the sum of the partial width of a family of final states related by strong rescattering should be the same for particles and antiparticles. → positive and negative asymmetries.

- [Projections from Dalitz plot to $m_{\pi\pi}$ or m_{KK} for the other three decays are in the back-up slides.]
- [Invariant mass fits to events with m_{hh} in the rescattering region are in the back-up slides]

Mixing-induced CP violation in $B^0 \to \pi^+\pi^-$ and $B^0_s \to K^+K^-$

- Decays to CP-eigenstates. Need time-dependent measurements to observe CP violation.

  time-dependent $\mathcal{A}_{CP}(t) = \dfrac{\Gamma_{\overline{B}\to f}(\mathrm{t}) - \Gamma_{B\to f}(\mathrm{t})}{\Gamma_{\overline{B}\to f}(\mathrm{t}) + \Gamma_{B\to f}(\mathrm{t})} = \dfrac{-C_f \cos(\Delta m\, t) + S_f \sin(\Delta m\, t)}{\cosh((\Delta\Gamma/2)\, t) + D_f \sinh((\Delta\Gamma/2)\, t)}$

  C_f represents the asymmetry in the decay amplitudes.
  S_f represents the mixing-induced CP asymmetry.
  $D^2_f = 1 - C^2_f - S^2_f$

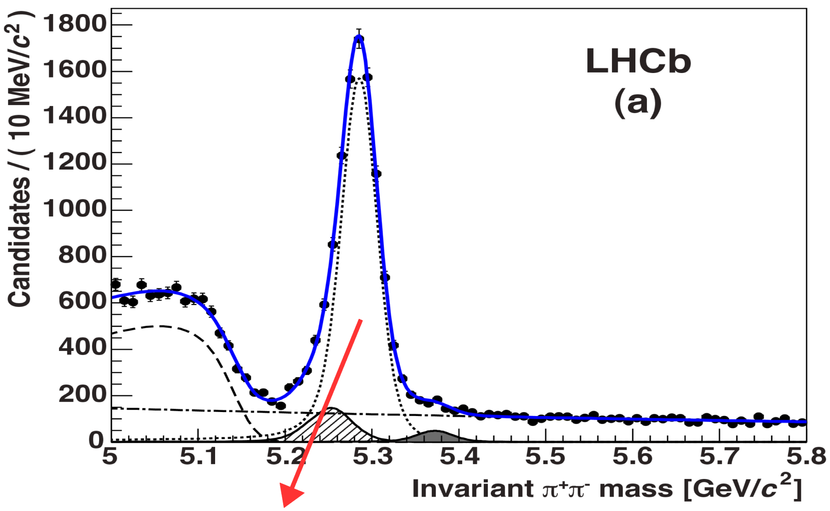
- 2D fits on invariant mass and tagged decay time to extract CP observables C_f and S_f.

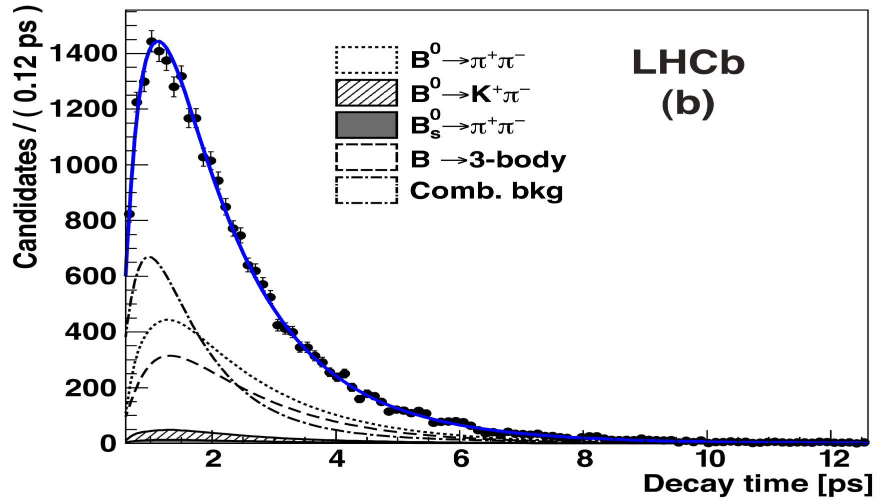
- The $C_{\pi\pi}$ and C_{KK} give access to the angle γ of the CKM unitarity triangle.
  The $S_{\pi\pi}$ and S_{KK} give access to γ and B^0 (for $S_{\pi\pi}$) and B^0_s (for S_{KK}) mixing phases.
  [PLB 459 (1999) 306, EPJ C52 (2007) 267, JHEP 1210 (2012) 029]

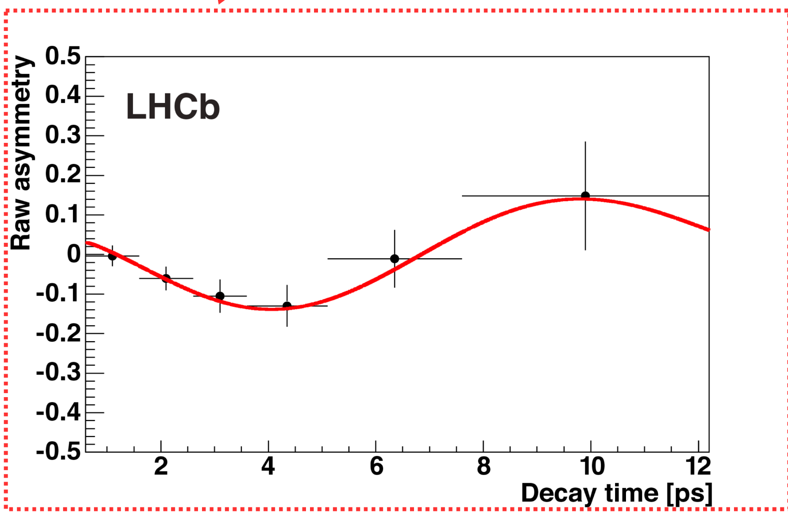
- Interpretation of C_f and S_f is not trivial because of the presence of hadronic quantities in the equation.

Mixing-induced CP violation in $B^0 \to \pi^+\pi^-$

- Using 1/fb (2011) @ $\sqrt{s}$ = 7 TeV. N_{events} ~ **9000** of $B^0 \to \pi^+\pi^-$ events.

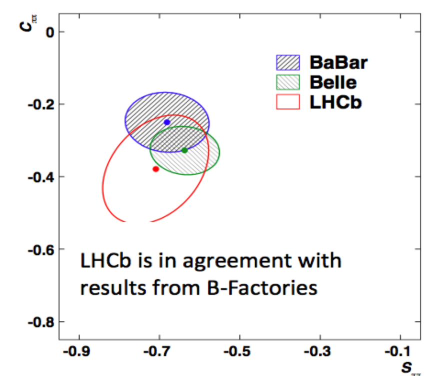






- $C_{\pi\pi}$ = -0.38 ± 0.15 ± 0.02
- $S_{\pi\pi}$ = -0.71 ± 0.13 ± 0.02

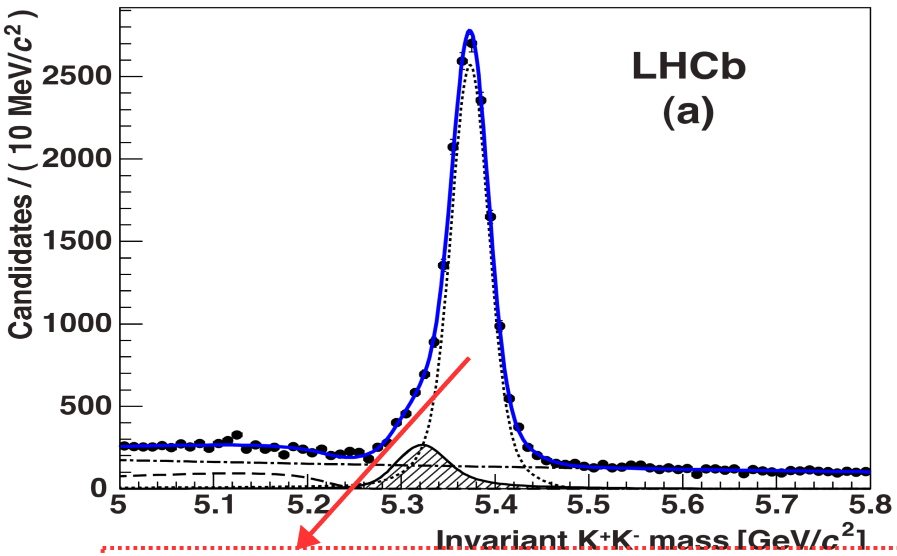
  $\rho(C_{\pi\pi}, S_{\pi\pi}) = 0.38$
- Significance of $(C_{\pi\pi}, S_{\pi\pi})$ to differ from (0,0) is 5.6σ.

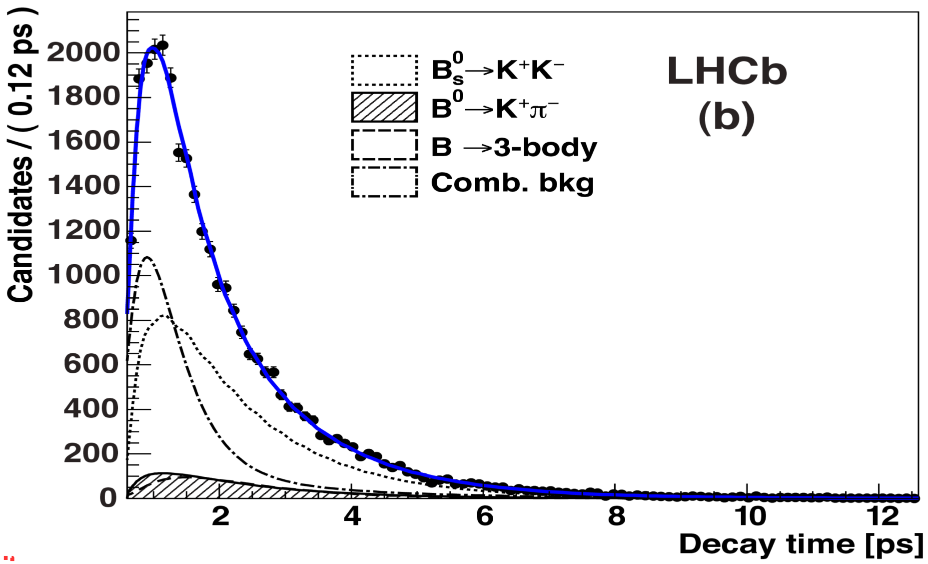


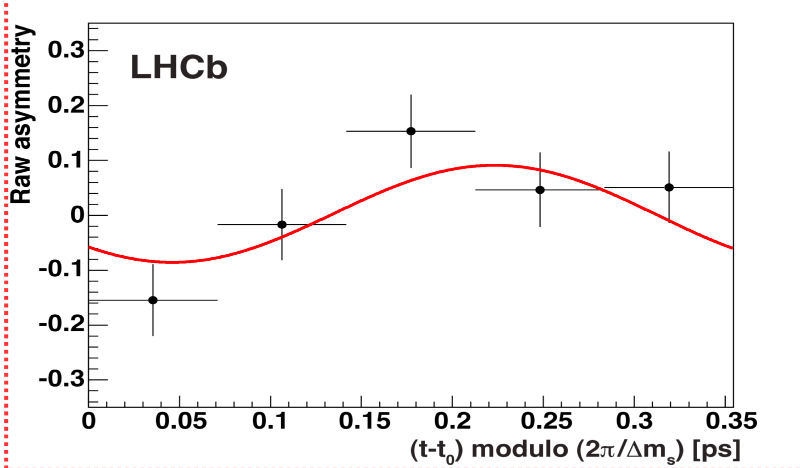
JHEP 10 (2013) 183

Mixing-induced CP violation in $B^0_s \to K^+K^-$

- Using 1/fb (2011) @ $\sqrt{s}$ = 7 TeV. N_{events} ~ **15000** of $B^0_s \to K^+K^-$ events.





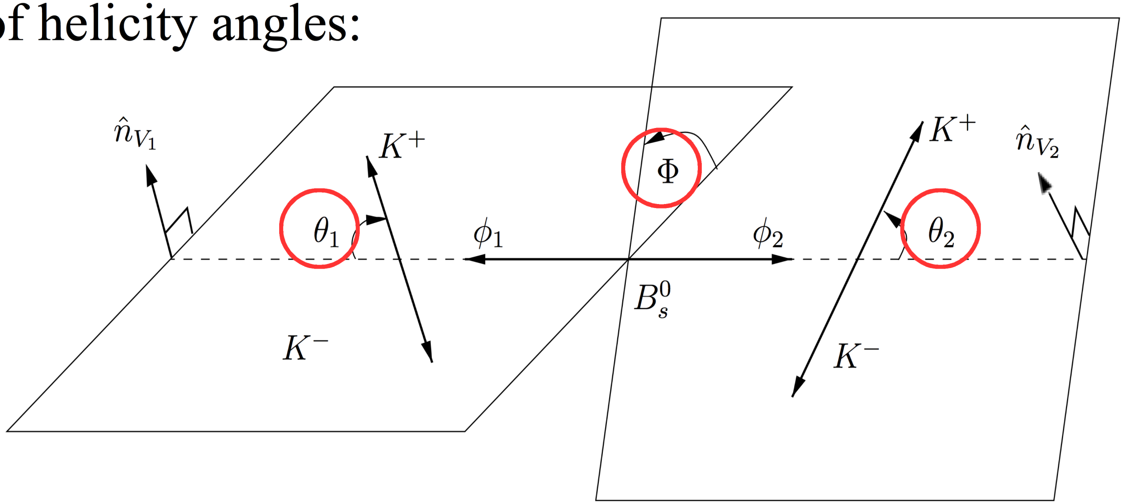


- $C_{KK} = 0.14 \pm 0.11 \pm 0.03$
- $S_{KK} = 0.30 \pm 0.12 \pm 0.04$
  $\rho(C_{KK}, S_{KK}) = 0.02$
- Significance of (C_{KK}, S_{KK}) to differ from (0,0) is 2.7σ.

JHEP 10 (2013) 183

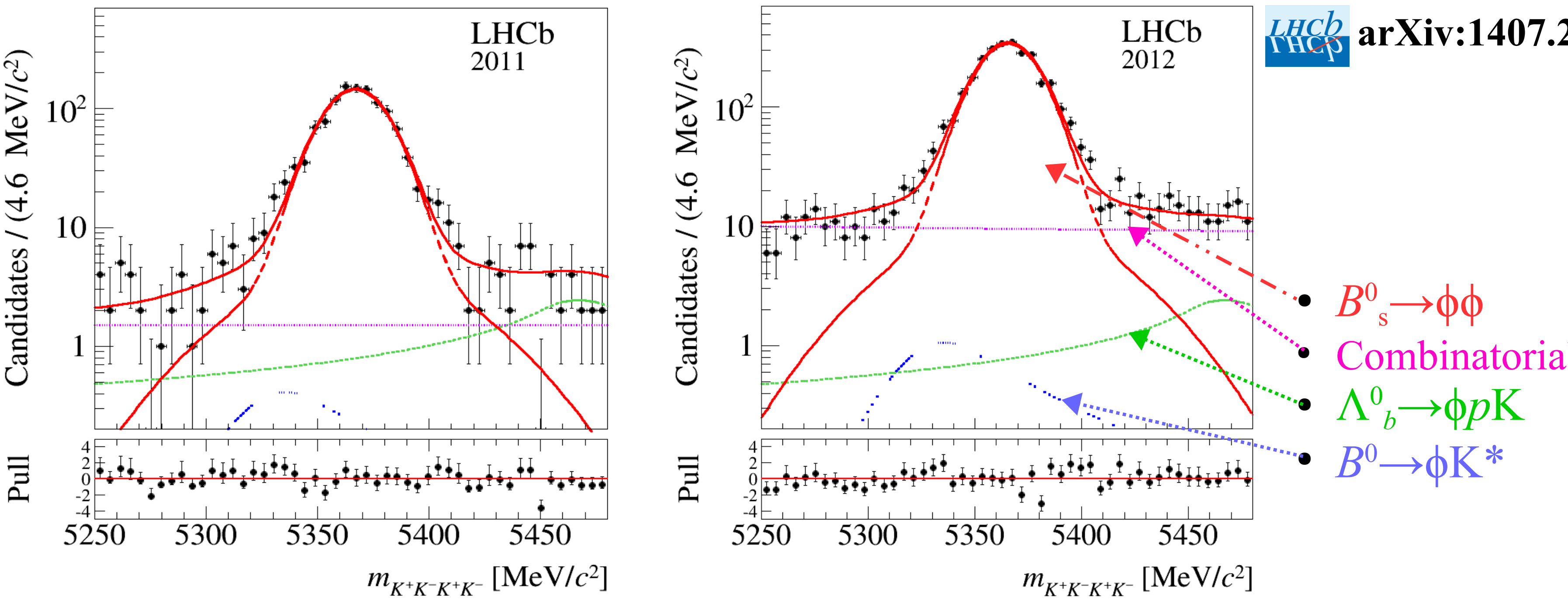
Mixing-induced CP violation in $B^0_s \to \phi\phi$

- Decay forbidden at the tree level in the SM and proceeds via gluonic penguin loop. → *provides excellent probe for new heavy particles entering the loop.*
- $B^0_s \to \phi\phi$ is a pseudoscalar to two vectors. Need angular analysis to disentangle the CP eigenstates.
- Total amplitude is a coherent sum of *P*-, *S*-, and double *S*-wave processes, and is accounted for during fitting by making use of different functions of the helicity angles associated with these terms. (*S*- and double *S*-wave included since ϕ resonance is close to $f_0(980)$.)
- Definition of helicity angles:



Mixing-induced CP violation in $B^0_s \to \phi\phi$

- Using 1/fb (@ √s = 7 TeV) and 2/fb (@ √s = 8 TeV).
- Unbinned maximum likelihood fit to mass, time and angles.
- $\phi \to K^+K^-$ candidate is required to be within 25 MeV/c² of the known ϕ mass.



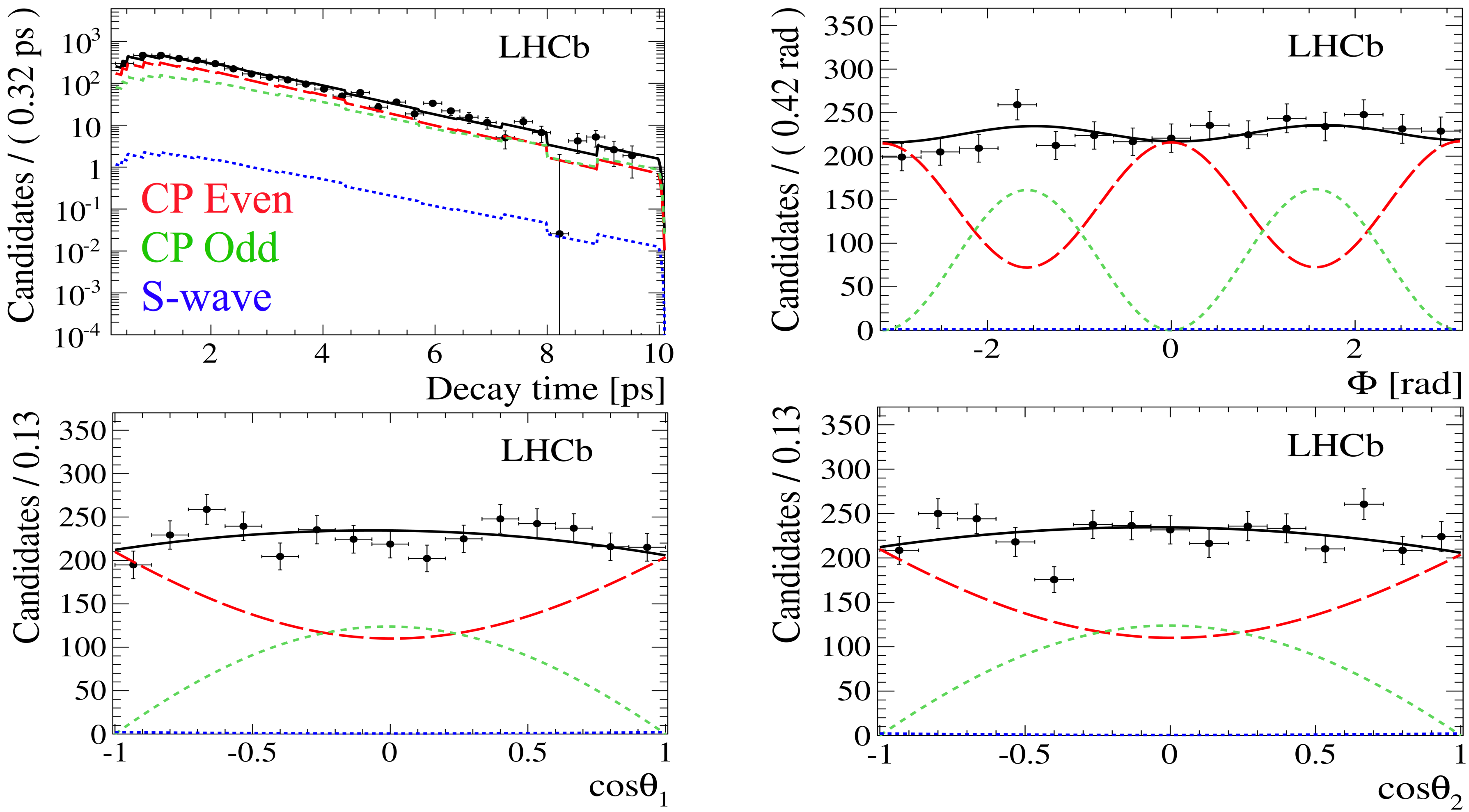
arXiv:1407.2222

- $N_{events} \sim 4000$ of $B^0_s \to \phi(K^+K^-)\phi(K^+K^-)$ events.
- Combinatorial background is flat and small.
- Very small contributions from mis-ID of $\pi \to K$ of $B^0 \to \phi K^*$ and $p \to K$ of $\Lambda^0_b \to \phi pK$.

Mixing-induced CP violation in $B^0_s \to \phi\phi$

- Projections of the fit.

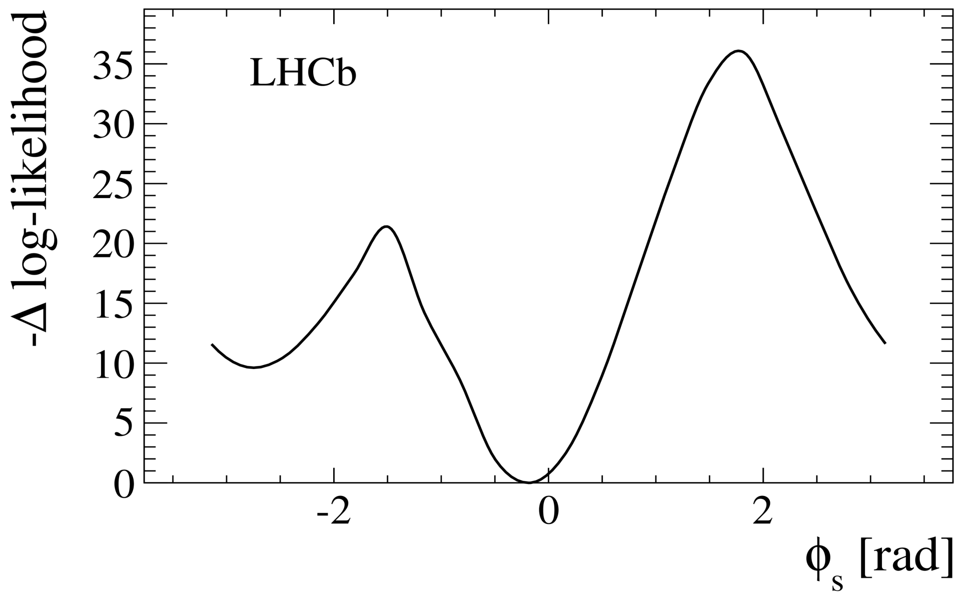
arXiv:1407.2222



Mixing-induced CP violation in $B^0_s \to \phi\phi$

- $\phi_s = (-0.17 \pm 0.15 \pm 0.03)$ rad
- $|\lambda| = 1.04 \pm 0.07 \pm 0.03$
- $|A_0|^2 = 0.364 \pm 0.012 \pm 0.009$
- $|A_\perp|^2 = 0.305 \pm 0.013 \pm 0.005$

arXiv:1407.2222



- Results consistent with no CP violation as expected in the Standard Model.
- A_S and A_{SS} are consistent with zero.
- Main systematic uncertainties from angular and decay time acceptance.
- Uncertainties due to Γ_s, $\Delta\Gamma_s$, Δm_s and tagging included in the statistical uncertainty.

Summary

- Charmless B decays are a good probe to search for new physics.
- Most precise measurement of direct CP violation in $B^0 \to K^+\pi^-$ (10.5σ) and first observation of direct CP violation in B^0_s observed in $B^0_s \to \pi^+ K^-$ (6.5σ).
- Measured CP asymmetries in charged three-body decay of $B^\pm$. CP asymmetries not uniform in phase space. $KK \leftrightarrow \pi\pi$ rescattering is apparent. Interference effects seem important around the $\rho^0(770)$ resonance.
- Measurement of $C_{\pi\pi}$ and $S_{\pi\pi}$ (in good agreement with measurements from B factories) with significance of 5.6σ that it is away from (0,0). First measurement of C_{KK} and S_{KK}.
- Precise measurement of the CPV phase in $B^0_s \to \phi\phi$.
  - No evidence yet of non-zero phase (SM predictions small)
- More LHCb results not shown today:

$B^0_{(s)} \to K^0_S h^+ h^{(\prime)-}$	[JHEP 10 (2013) 143]
$\Lambda^0_b, \Xi^0_b \to K^0_S p h^-$	[JHEP 04 (2014) 087]
$B^\pm \to p\bar{p}h^\pm$	[arXiv:1407.5907]
$B^0 \to \phi K^{*0}$	[JHEP 05 (2014) 069]
$B^0_s \to K^{*\pm} K^\mp$	[arXiv:1407.7704]

BACK-UP SLIDES

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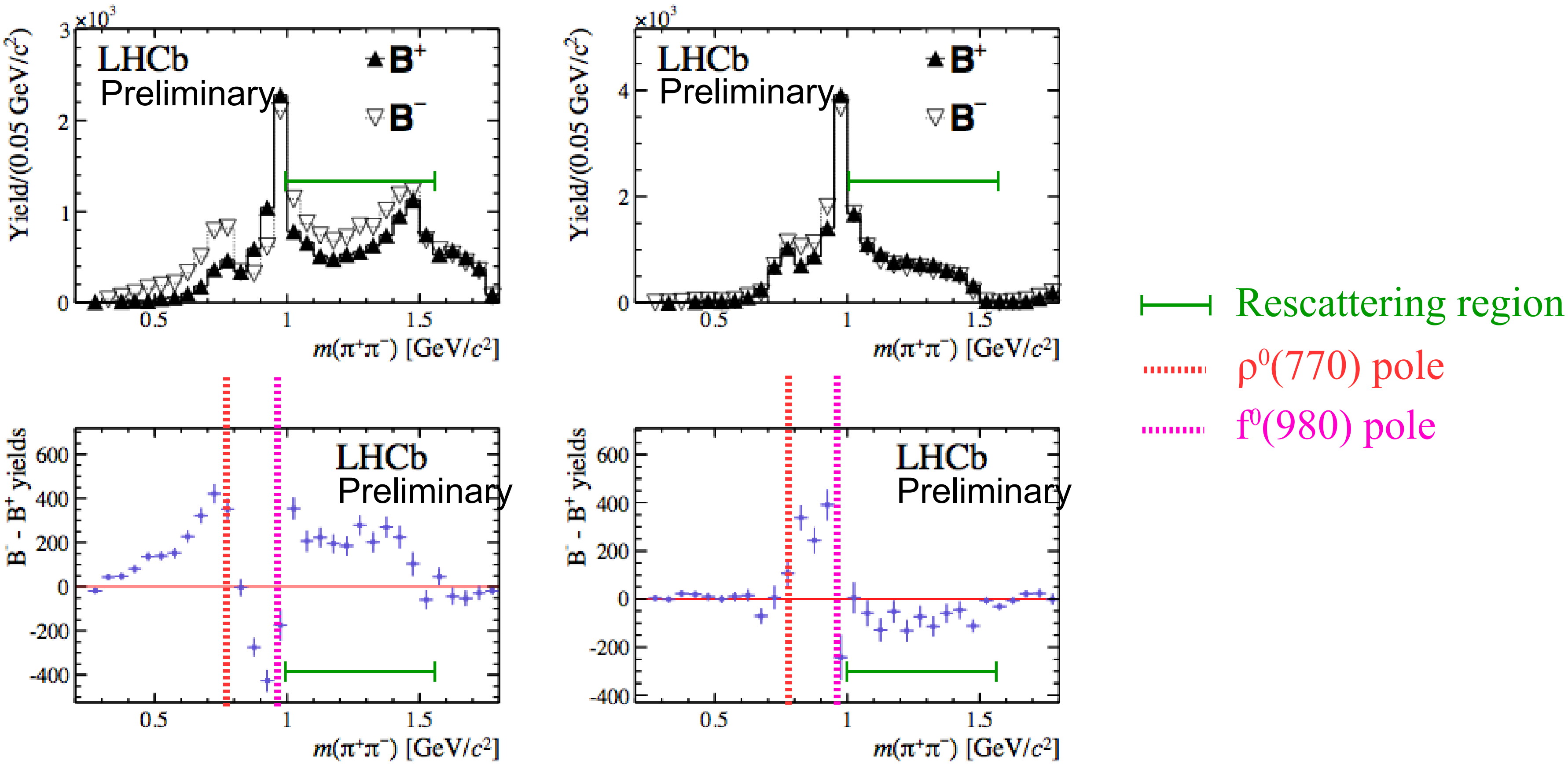
Interference effects in the CP asymmetry of $B^{\pm} \rightarrow$ (charged three-body)

- Project onto $m_{\pi\pi}$ the $B^{\pm} \rightarrow K^{\pm}\pi^{+}\pi^{-}$ Dalitz plot (zoomed into the region with large asymmetry), splitted according to the sign of the cos(θ).



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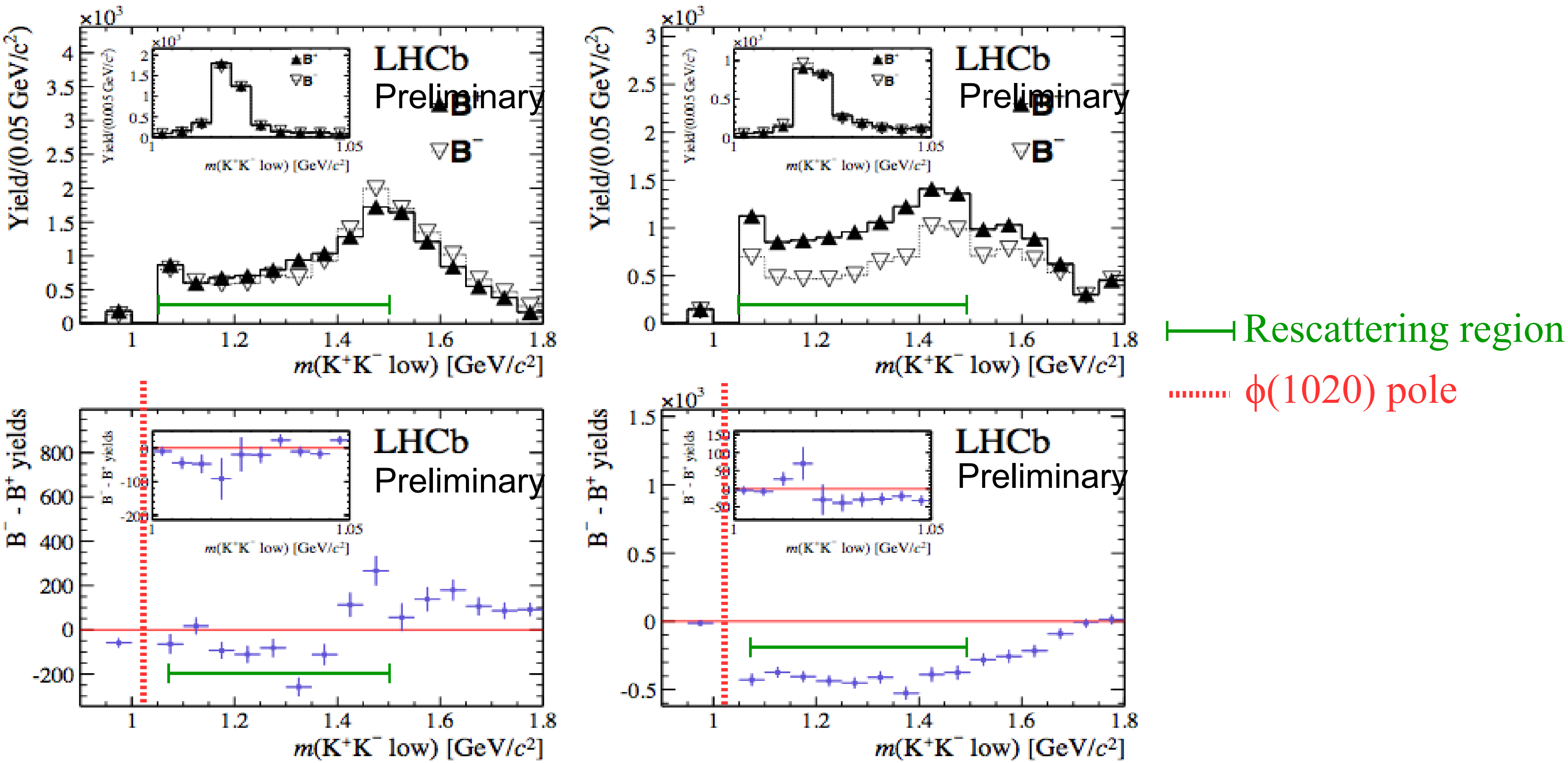
cos(θ) < 0 **cos(θ) > 0**

Interference effects in the CP asymmetry of $B^{\pm}\to$ (charged three-body)

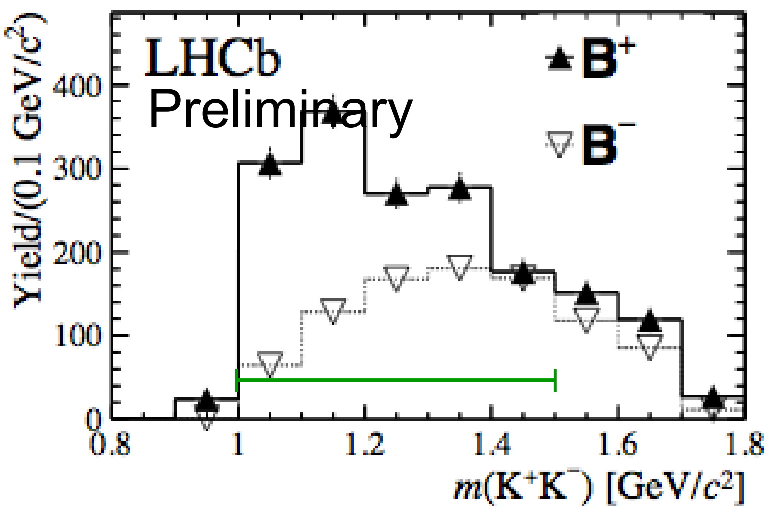
- Project onto m_{KK} the $B^{\pm}\to K^{\pm}K^{+}K^{-}$ Dalitz plot (zoomed into the region with large asymmetry), splitted according to the sign of the cos(θ).

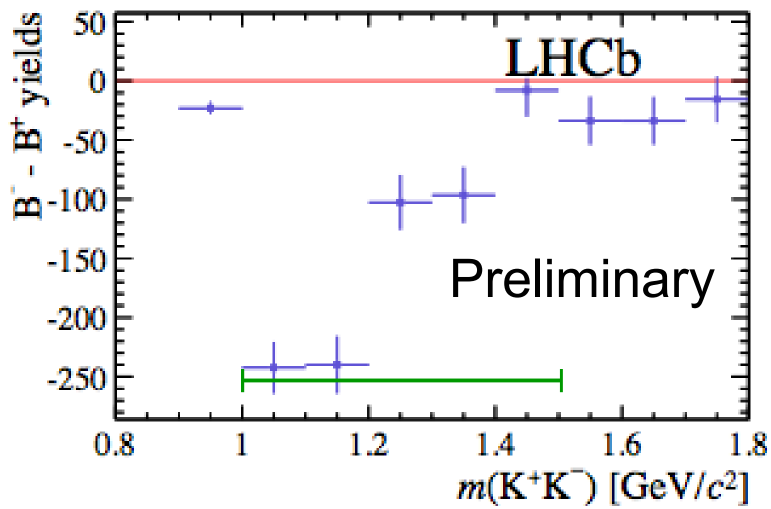


cos(θ) < 0 **cos(θ) > 0**

Interference effects in the CP asymmetry of $B^{\pm} \longrightarrow$ (charged three-body)

- Project onto m_{KK} the $B^{\pm} \rightarrow \pi^{\pm} K^{+} K^{-}$ Dalitz plot (zoomed into the region with large asymmetry).

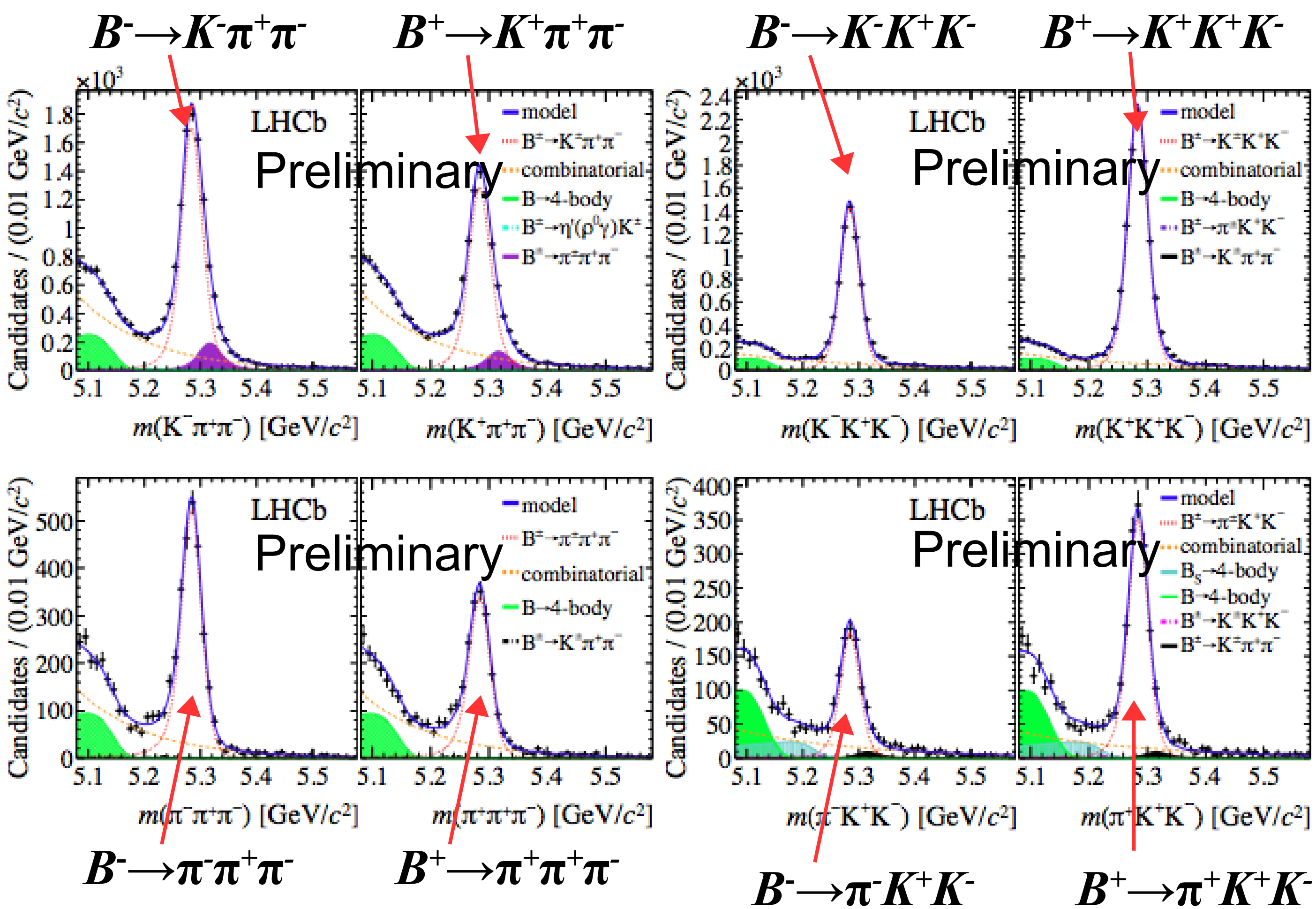




Rescattering region

Interference effects in the CP asymmetry of $B^{\pm} \rightarrow$ (charged three-body)

- Invariant mass fit for events with m_{hh} in the rescattering region ($1 < (m_{\pi\pi}$ or $m_{KK}) < 1.5$ GeV/c^2).



(Penguin dominated)

(Tree dominated)