CP violation in charmless hadronic B decays at LHCb

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(Centro Brasileiro de Pesquisas Físicas, Brazil)

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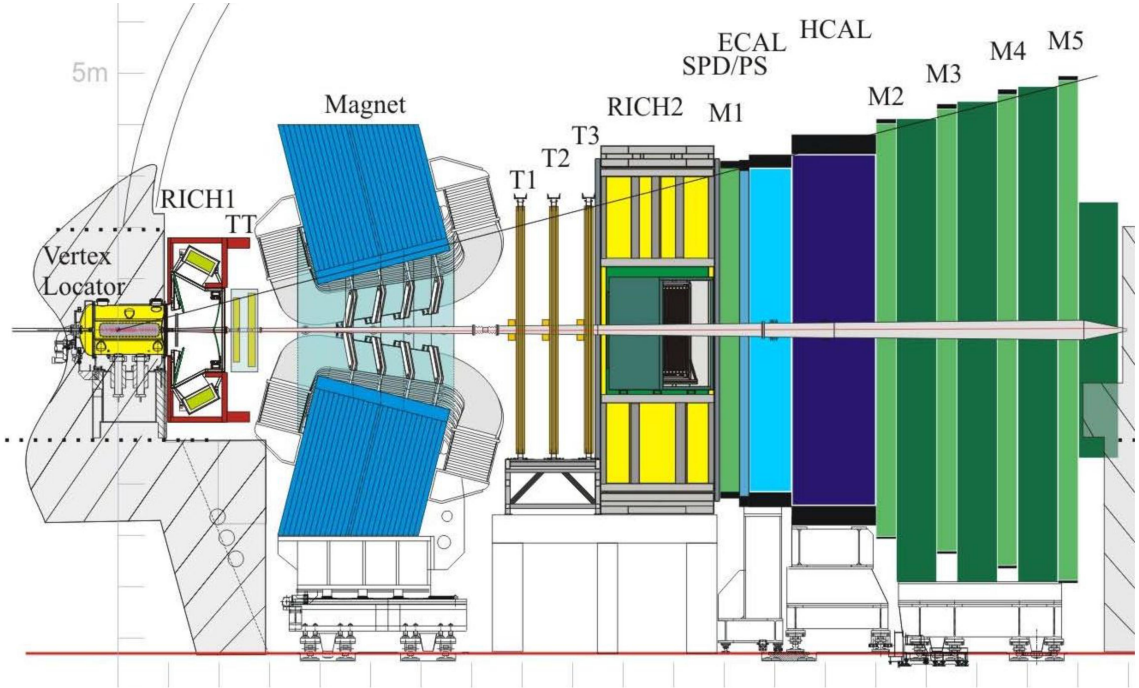
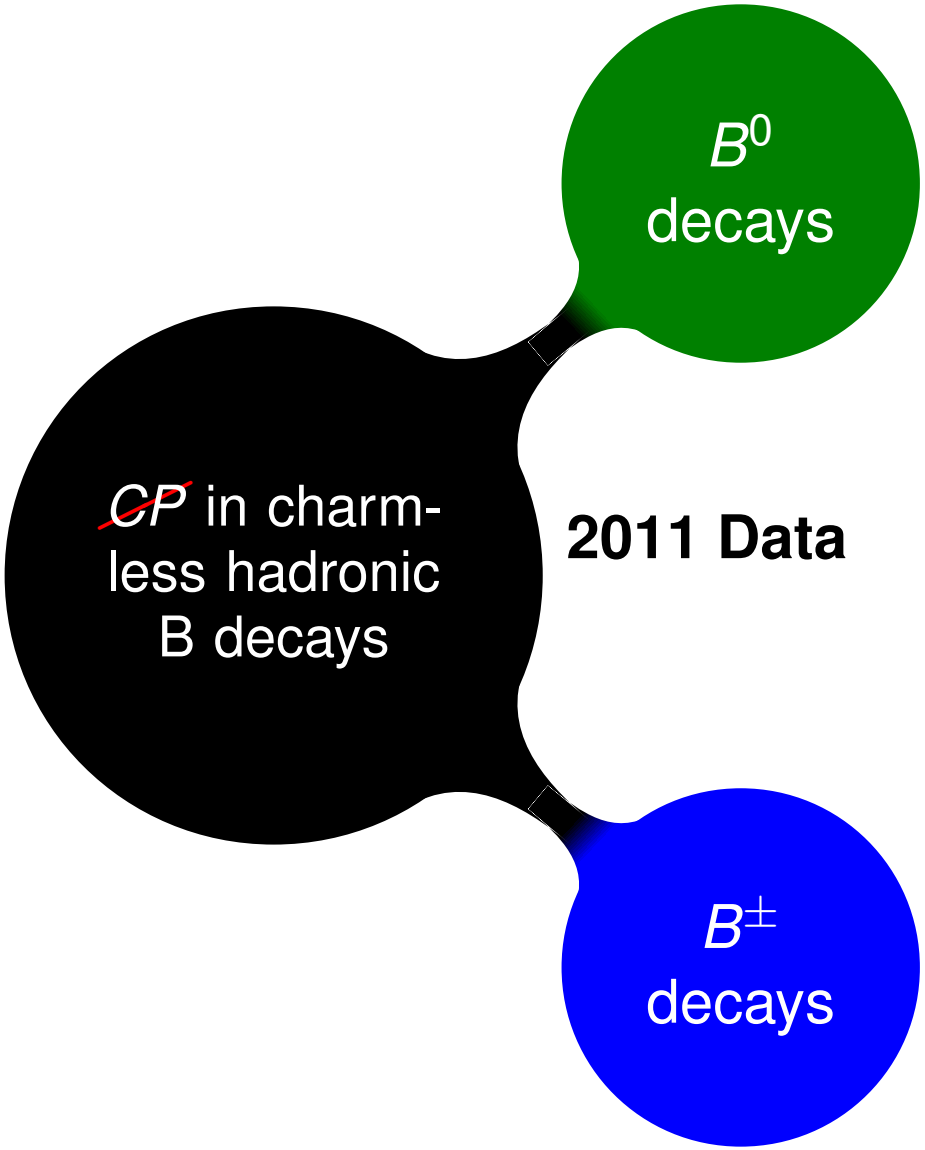
LHCb detector



- Integrated luminosity: 37 pb^{-1} (2010), **1.0 fb^{-1} (2011)**, 2 fb^{-1} (2012)
- Efficient trigger for many B-decay topologies
- Excellent particle identification for $\pi - K$ separation in a wide momentum range
- Good decay-time resolution in particular to resolve fast B_S oscillations
- Good mass resolution to efficiently suppress background

Outline



2011 Data

LHCb-PAPER-2013-007 NEW!

$\not{CP}$ phase in $B_s^0 \to \phi\phi$

PRL 108, 201601 (2012)

$\mathcal{A}_{CP}\ (B^0 \to hh)$

$$\mathcal{A}_{CP} = \frac{\Gamma(B^- \to f) - \Gamma(B^+ \to \bar{f})}{\Gamma(B^- \to f) + \Gamma(B^+ \to \bar{f})}$$

LHCb-CONF-2012-028

$\mathcal{A}_{CP}\ (B^\pm \to K^+K^-\pi^\pm)$

$\mathcal{A}_{CP}\ (B^\pm \to \pi^\pm\pi^+\pi^-)$

LHCb-CONF-2012-018

$\mathcal{A}_{CP}\ (B^\pm \to K^\pm\pi^+\pi^-)$

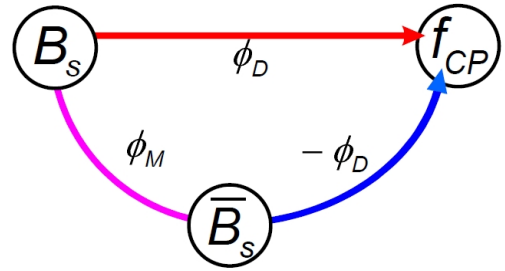
$\mathcal{A}_{CP}\ (B^\pm \to K^\pm K^+K^-)$

Notation: CP violation $\equiv \not{CP} \equiv \mathcal{A}_{CP}$

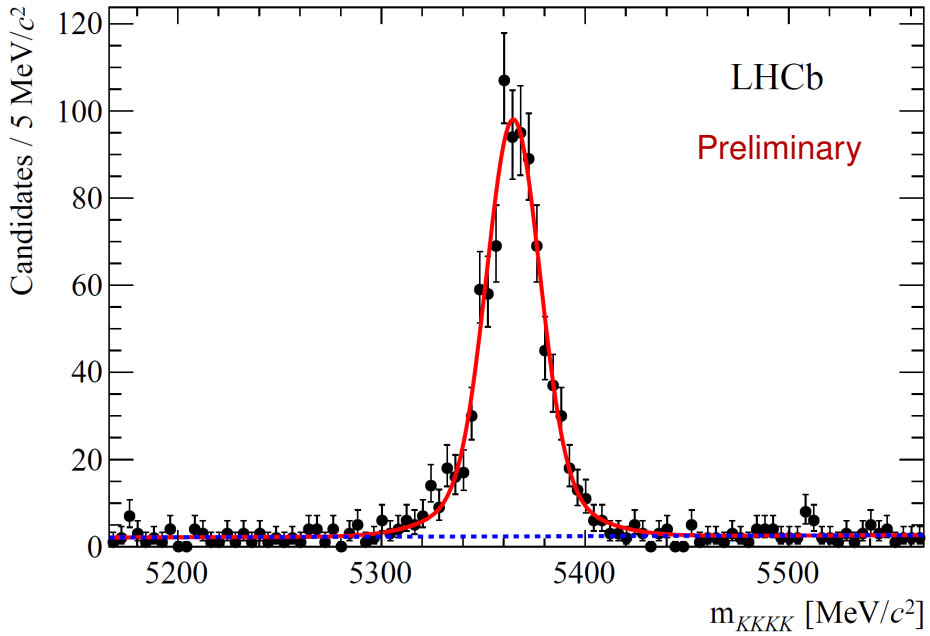
$B_s^0 \to \phi\phi$

LHCb-PAPER-2013-007 (in preparation)

- Proceeds via a gluonic $b \to s\bar{s}s$ hadronic penguin
- Forbidden at tree level in Standard Model
- SM expectation of ϕ_S is zero
- Excellent probe of new heavy particles entering the penguin quantum loops
- 880 ± 31 events observed in KKKK final state [1.0 fb^{-1} data]
- Results presented based on time-dependent tagged angular analysis



Interference of mixing & decay:
~~*CP*~~ phase $\phi_S = \phi_M + 2\phi_D$

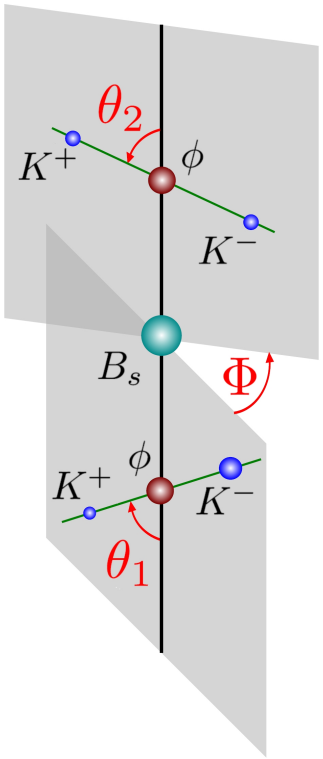


$B_s^0 \to \phi\phi$

LHCb-PAPER-2013-007 (in preparation)

Analysis method

- Final state a mixture of CP-even and CP-odd eigenstates $\to$ full angular analysis in helicity basis is employed
- Unbinned maximum likelihood fit is performed to the decay time, **t**, and the three angles in helicity bases, $\Omega = \{cos\theta_1, cos\theta_2, \Phi\}$
- Time resolution accounted for with single Gaussian convolution (39.7 fs resolution from simulation)
- Use of opposite side and same side flavour tagging (see Bruno and Alberto slides)

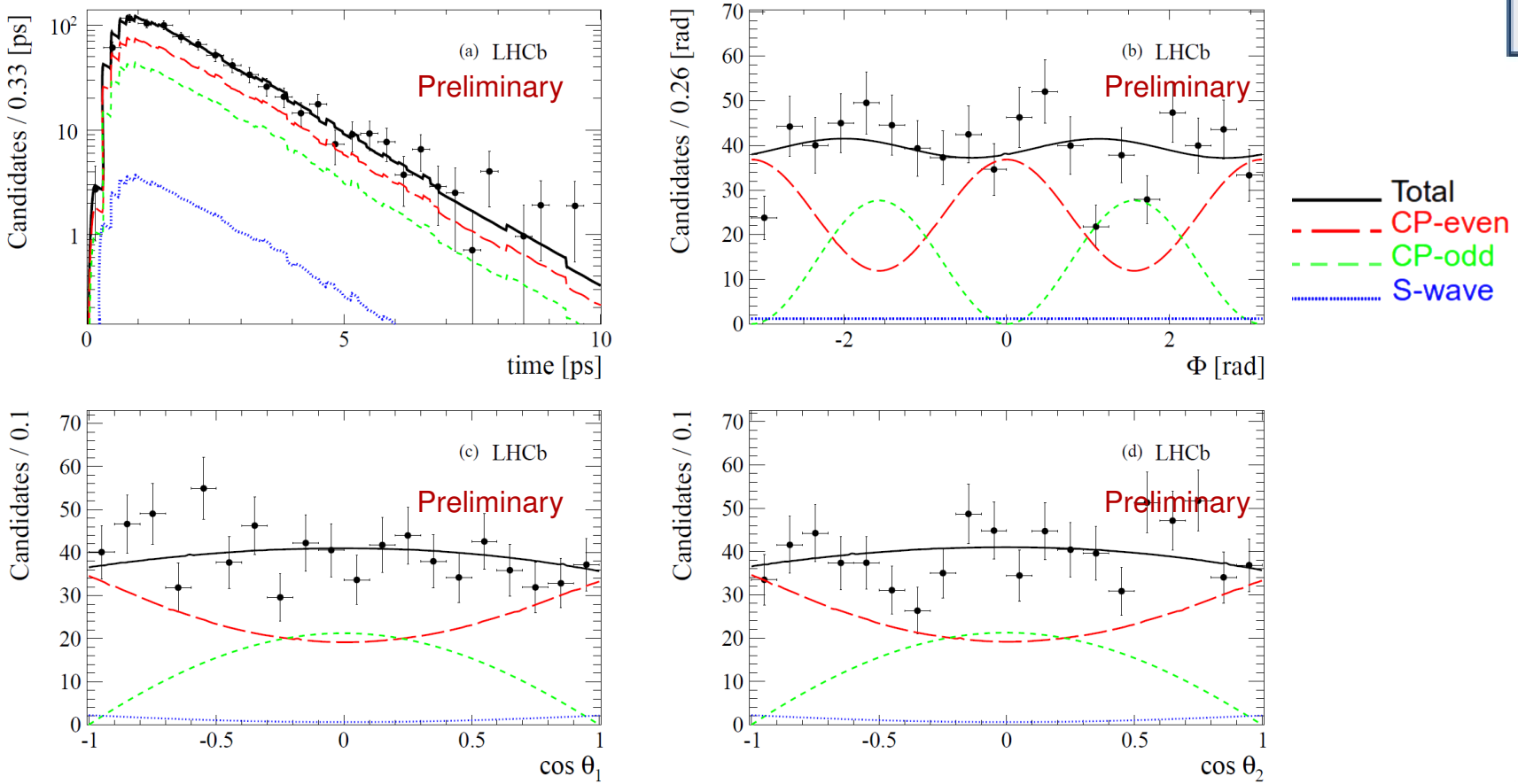


Acceptances

- Magnetic field causes low p_T kaons to be swept out of detector acceptance $\to$ causes efficiency drop as cos $\theta_i \to \pm 1$
- Due to KKKK final state, time biasing criteria are unavoidable to select from background, e.g. impact parameter of kaon tracks w.r.t. PV
- These angular and time acceptances are taken from simulation

$B_s^0 \to \phi\phi$

LHCb-PAPER-2013-007 (in preparation)



- Γ_S and $\Delta\Gamma_S$ are constrained to $B_S \to J/\psi\,\phi$ measured values

  $\Gamma_S = 0.663 \pm 0.008\,\mathrm{ps}^{-1}$ and $\Delta\Gamma_S = 0.100 \pm 0.017\,\mathrm{ps}^{-1}$ [LHCb-PAPER-2013-002]

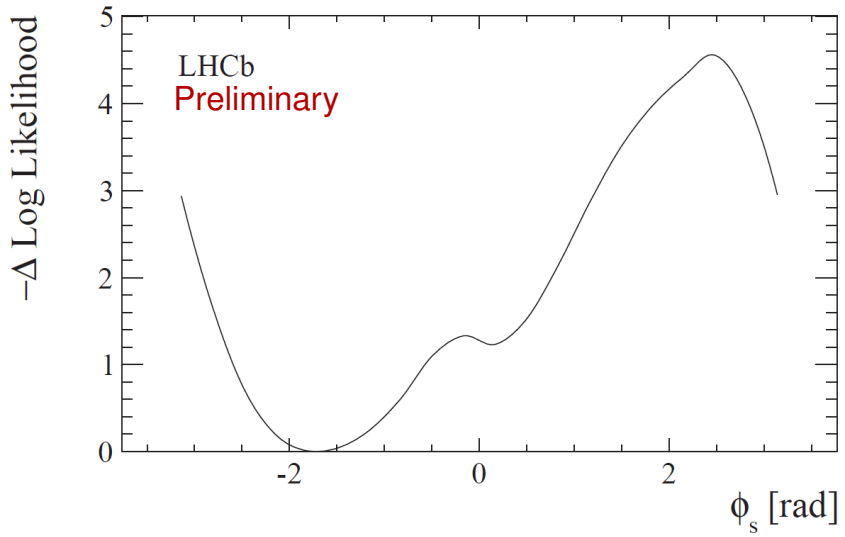
- B_S oscillation frequency constrained to the value of $17.73 \pm 0.05\,\mathrm{ps}^{-1}$

  [LHCb-CONF-2011-050]

$B_s^0 \to \phi\phi$

LHCb-PAPER-2013-007 (in preparation)

- Small dataset → Feldman Cousins (pseudo-experiments) are used to provide the correct coverage.
- Preliminary **A interval of [-2.46, -0.76] rad at 68% C.L. is obtained for ϕ_S**
- Preliminary The p-value of the SM hypothesis is 16%.



- The dominant systematic uncertainties arise from:
  - the description of the decay time acceptance;
  - the knowledge of the S-wave contamination from $B_S^0 \to f_0\phi$ and $B_S^0 \to f_0 f_0$

- **First time-dependent tagged analysis of ~~CP~~ in the interference between mixing and decay for the $B_s^0 \to \phi\phi$.**

$B^0 \to hh$

PRL 108, 201601 (2012)

Previous results

- $\mathcal{A}_{CP}(B^0 \to K\pi) = -0.097 \pm 0.012$ **[PDG]**
- $\mathcal{A}_{CP}(B^0_S \to K\pi) = 0.39 \pm 0.17$ **[PDG]** CDF(PRL**106**(2011)181802)

no evidence of ~~CP~~ in B^0_S

Analysis

- Very efficient hadronic trigger $\to$ one high p_T track
- $B^0_S \to K\pi \sim 14\times$ lower decay rate and $\sim 4\times$ lower production than $B^0 \to K\pi$. Applied a tighter selection for B^0_S.
- Magnet field polarity reversion $\to$ minimizes instrumental charge asymmetry
- Inclusive hh selection under $\pi\pi$ mass hypothesis within $4.7 - 5.9\,\mathrm{GeV}/c^2$
- Unbinned maximum likelihood fit:

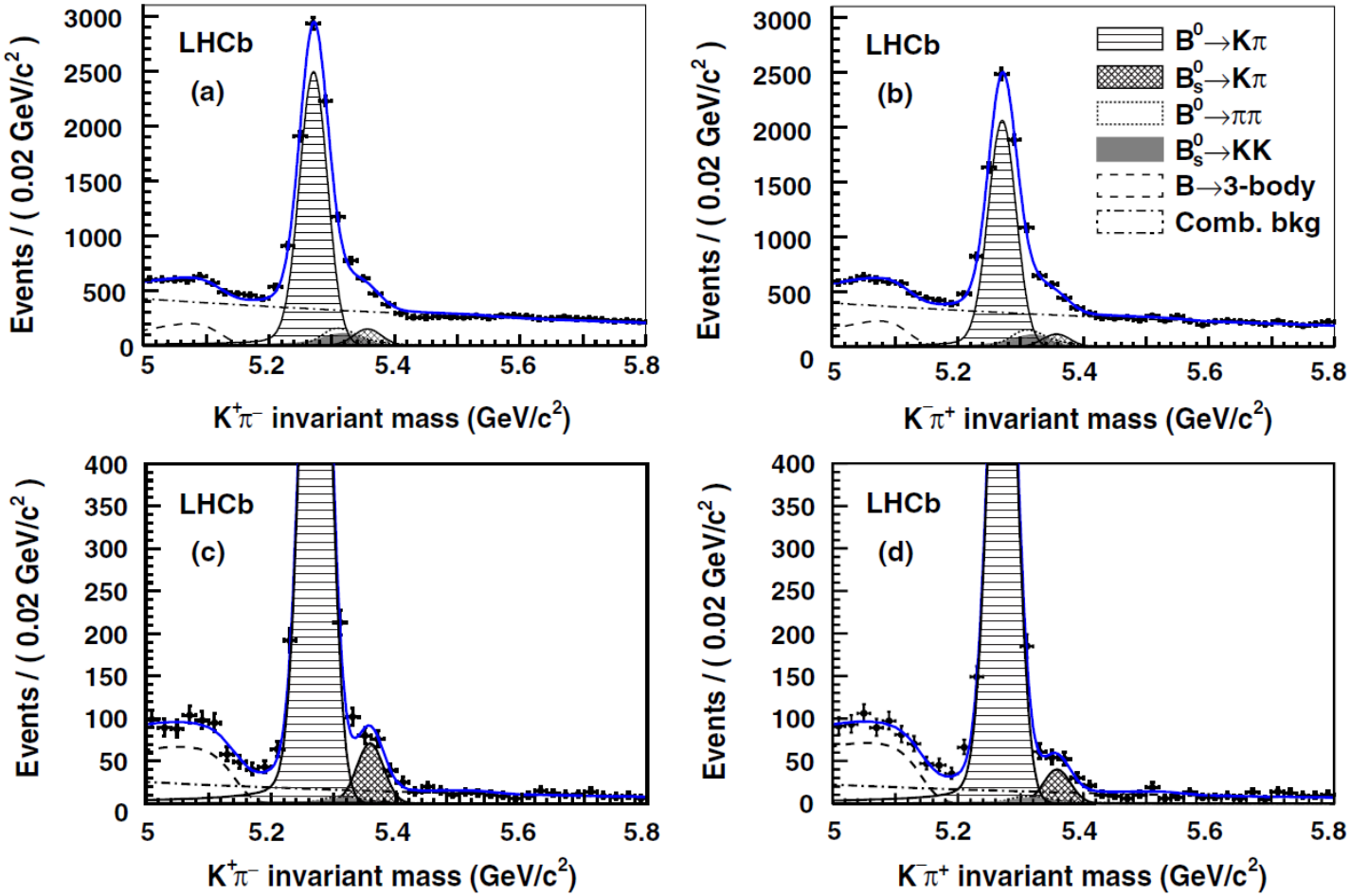
$$N(B^0 \to K\pi) = 13250 \pm 150 \qquad N(B^0_S \to K\pi) = 314 \pm 27$$

- $\mathcal{A}_{CP} = \mathcal{A}_{CP}^{RAW} \pm \mathcal{A}_D(K\pi) - k_{d(s)}\mathcal{A}_P(B^0_{(S)})$
  - instrumental asymmetry ($\mathcal{A}_D$) from D^*
  - production asymmetry ($\mathcal{A}_P$) from $B^0 \to J/\psi\, K^{*0}$
  - $k_{d(s)}$ describes dilution of $\mathcal{A}_P$ due to $B^0_{(s)} - \bar{B}^0{}_{(s)}$ mixing

$$\begin{aligned} \mathcal{A}_D &= -0.010 \pm 0.02 \\ \mathcal{A}_P &= +0.010 \pm 0.013 \\ k_d &= +0.303 \pm 0.005 \\ k_s &= -0.033 \pm 0.003 \end{aligned}$$

$B^0 \to hh$

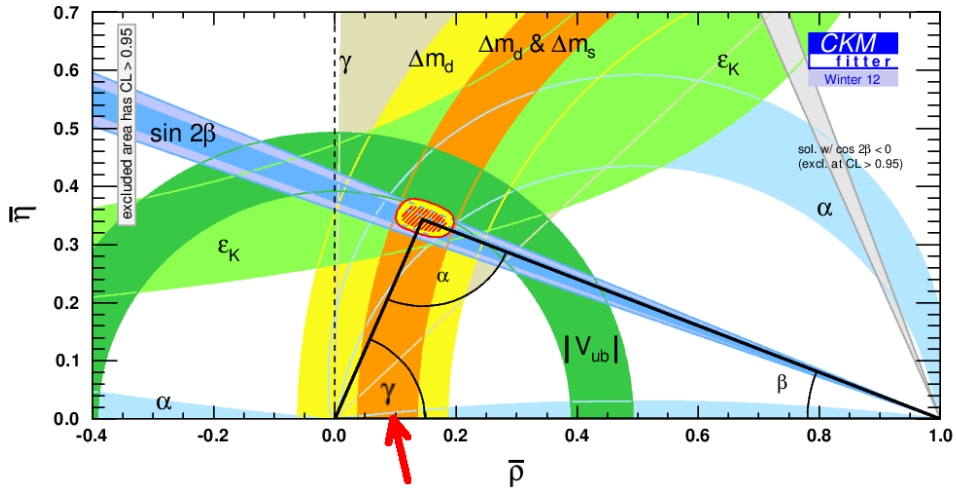
PRL 108, 201601 (2012)



- **First evidence for ~~*CP*~~ in B_S.**
- $\mathcal{A}_{CP}(B_S^0 \to K\pi) = 0.27 \pm 0.08(\text{stat}) \pm 0.02(\text{syst})$, **3.3σ**
- $\mathcal{A}_{CP}(B^0 \to K\pi) = -0.088 \pm 0.011(\text{stat}) \pm 0.008(\text{syst})$, **$> 6\sigma$**

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

LHCb-CONF-2012-018 and LHCb-CONF-2012-028



- $B^{\pm} \to h^{\pm} h^{+} h^{-}$ gives access to γ angle of the unitary triangle (see Alberto slides)
- $\gamma = arg\left(-\frac{V_{ud} V_{ub}^{*}}{V_{cd} V_{cb}^{*}}\right)$

- Two groups of two decays with:
  - similar physics (see backup slide for the diagrams)
    - $B^{\pm} \to K^{\pm} K^{+} K^{-}$ and $B^{\pm} \to K^{\pm} \pi^{+} \pi^{-}$

      $\to \gamma$ in tree diagram $\propto \lambda^4$ and penguin diagram $\propto \lambda^2$ $\quad (\lambda \equiv sin\theta_C \equiv |V_{us}| \approx 0.22)$
    - $B^{\pm} \to K^{+} K^{-} \pi^{\pm}$ and $B^{\pm} \to \pi^{\pm} \pi^{+} \pi^{-}$

      $\to \gamma$ in tree diagram $\propto \lambda^3$ and penguin diagram $\propto \lambda^3$
  - CPT connection (related final state through scattering $KK \to \pi\pi$)
  - similar statistics
  - same selection except for particle ID and background vetoes
  - similar challenges (both use $B^{\pm} \to J/\psi\, K^{\pm}$ as control channel)

    $\mathcal{A}_{CP}^{RAW}(J/\psi\, K) - \mathcal{A}_{CP}(J/\psi\, K) = B^{-}/B^{+}$ production and K instrumental asymmetries

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

LHCb-CONF-2012-018 and LHCb-CONF-2012-028

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

$$\mathcal{A}_{CP}(hhK) = \mathcal{A}_{CP}^{RAW}(hhK) - \mathcal{A}_{CP}^{RAW}(J/\psi K) + \mathcal{A}_{CP}(J/\psi K)$$

B^{+}/B^{-} production and instrumental asymmetries

physical ~~CP~~ (from PDG)

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

$$\mathcal{A}_{CP}(hh\pi) = {}^{ACC}\mathcal{A}_{CP}^{RAW}(hh\pi) - \mathcal{A}_{CP}^{RAW}(J/\psi K) + A_{I}^{K} - A_{I}^{\pi} + \mathcal{A}_{CP}(J/\psi K)$$

B^{+}/B^{-} production and instrumental asymmetries

$\mathcal{A}_{CP}^{RAW}(J/\psi K)$ [Extracted from LHCb-CONF-2012-018]

A_{I}^{K} [Extracted from a large sample of $D^{0} \to K\pi$ and $D^{0} \to KK$. - LHCb:PRL 108, (2012) 201601]

A_{I}^{π} [Extracted from a large D^{*} sample. - LHCb: PLB713,(2012) 186]

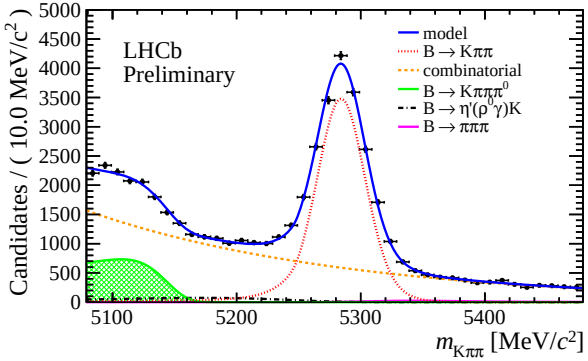
raw asymmetry corrected by the acceptance

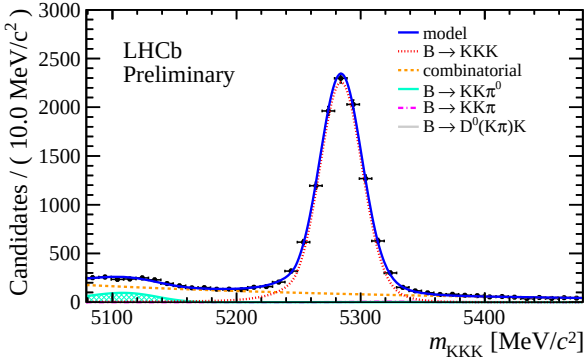
physical ~~CP~~ (from PDG)

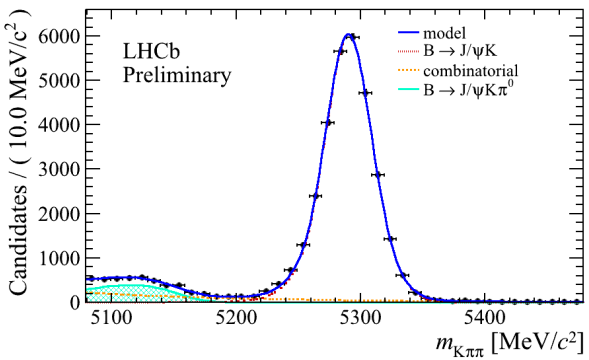
$\mathcal{A}_{CP}(J/\psi K) = (1 \pm 7) \times 10^{-3}$ [PDG]

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

LHCb-CONF-2012-018 and LHCb-CONF-2012-028



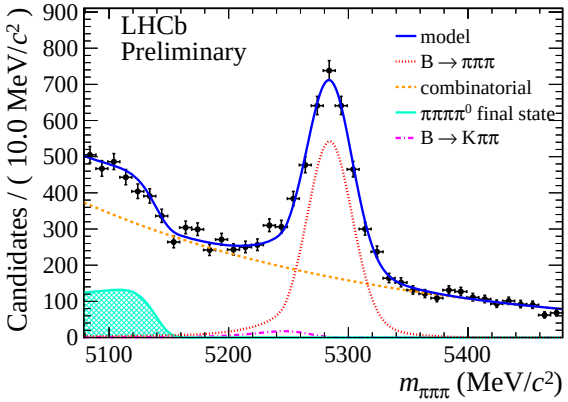


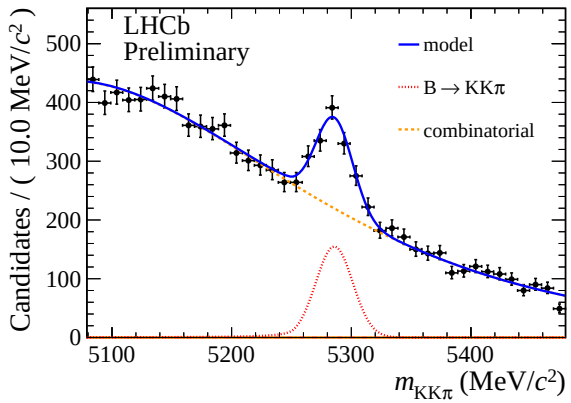


LHCb-CONF-2012-018

Preliminary ▸ $\mathcal{A}_{CP}(K\pi\pi) = +0.034 \pm 0.009(\text{stat}) \pm 0.004(\text{syst}) \pm 0.007(\text{J}/\psi\ \text{K})$, 2.8σ

Preliminary ▸ $\mathcal{A}_{CP}(KKK) = -0.046 \pm 0.009(\text{stat}) \pm 0.005(\text{syst}) \pm 0.007(\text{J}/\psi\ \text{K})$, 3.7σ





LHCb-CONF-2012-028

Preliminary ▸ $\mathcal{A}_{CP}(\pi\pi\pi) = +0.120 \pm 0.020(\text{stat}) \pm 0.019(\text{syst}) \pm 0.007(\text{J}/\psi\ \text{K})$, 4.2σ

Preliminary ▸ $\mathcal{A}_{CP}(KK\pi) = -0.153 \pm 0.046(\text{stat}) \pm 0.019(\text{syst}) \pm 0.007(\text{J}/\psi\ \text{K})$, 3.0σ

About the plots: Fits of B^- samples of all the four decays and the control channel.

Inspecting the phase space

How to get fish that we do not know?

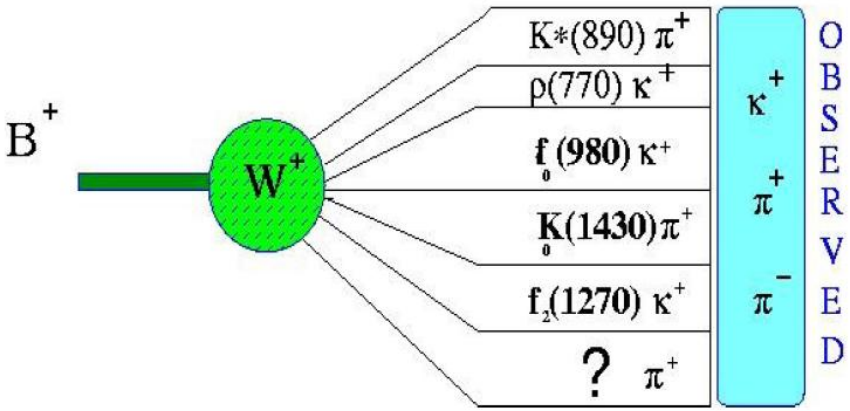
Fishing net. Attacking a large space with an idea of the kind of fish expected there.

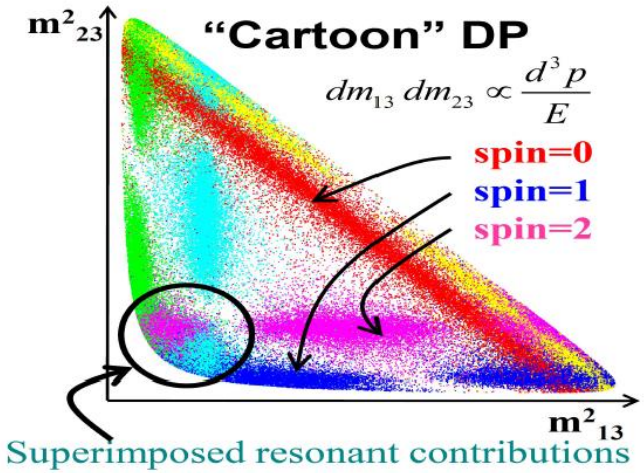
Inspecting the phase space

How to get fish that we do not know?

Fishing net. Attacking a large space with an idea of the kind of fish expected there.

Search for ~~*CP*~~ in three body decays

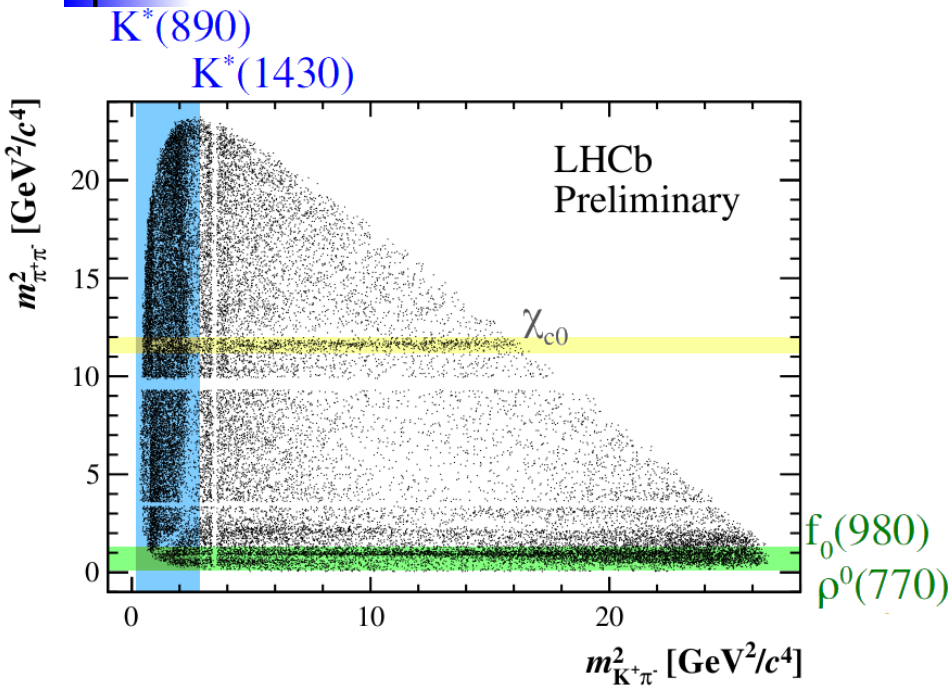




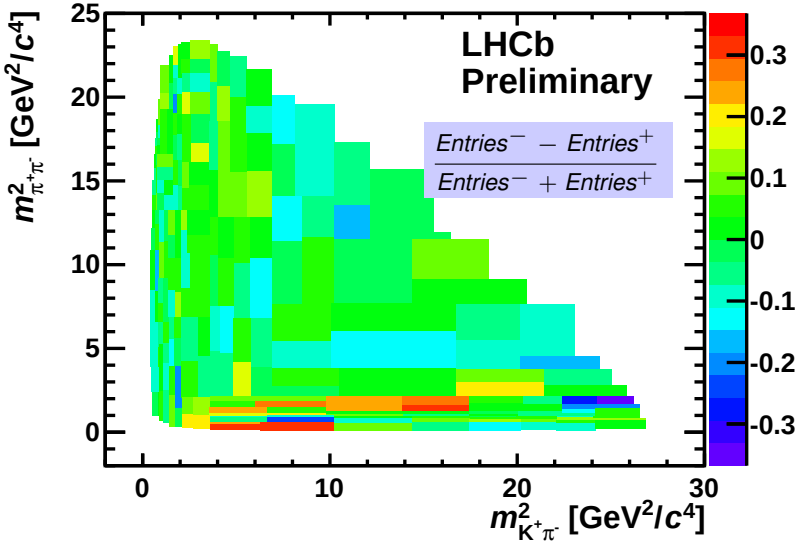
- Each intermediary state is included in a coherent sum for the total decay.
- Resonance interference (parallel or crossing) → probe for ~~*CP*~~

~~CP~~ in phase space: $B^{\pm} \to K^{\pm}\pi^{+}\pi^{-}$

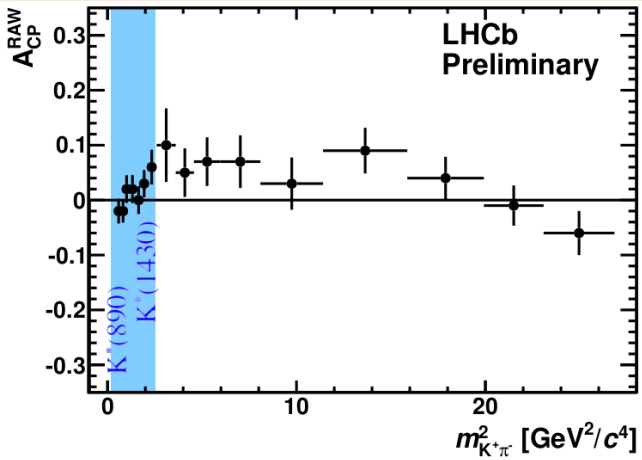
LHCb-CONF-2012-018

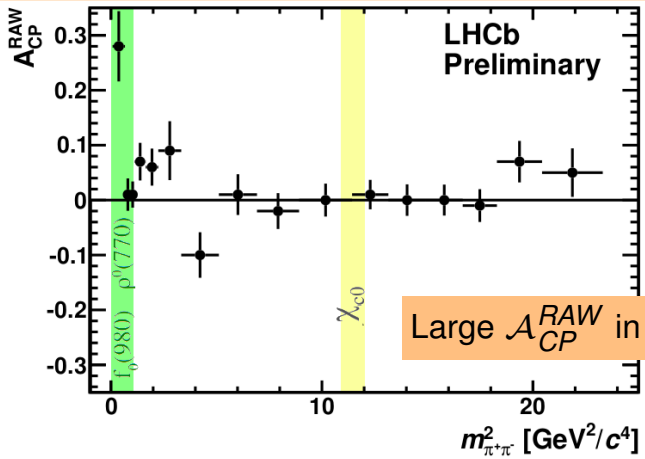


Illustrative view 1: entries asymmetry



Illustrative view 2: the mass projections are divided into bins with sufficient events to perform a simplified mass fit



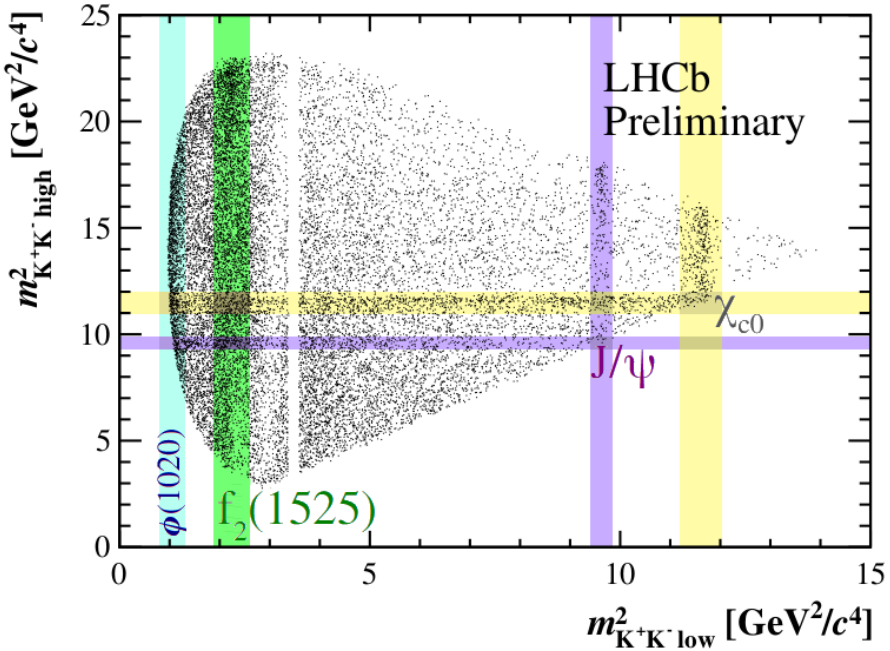


Consistent with the B-factories.

Large $\mathcal{A}_{CP}^{RAW}$ in the region of ρ^0 and f_0.

~~CP~~ in phase space: $B^{\pm} \to K^{\pm}K^{+}K^{-}$

LHCb-CONF-2012-018



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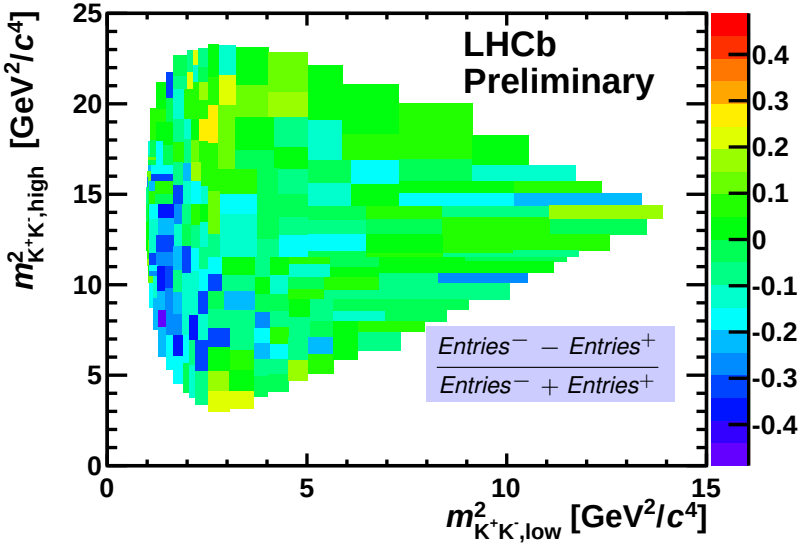
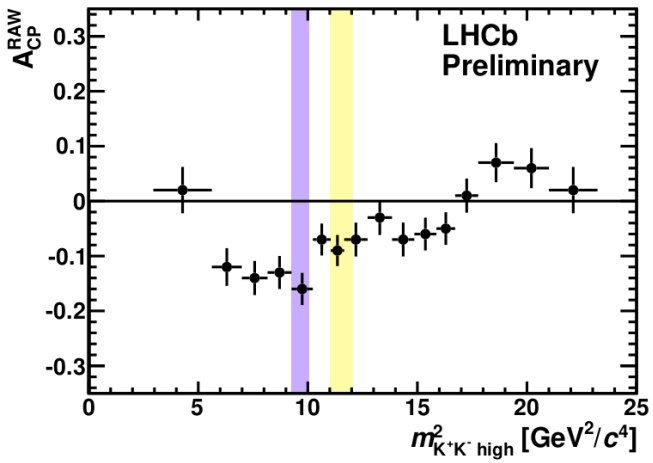
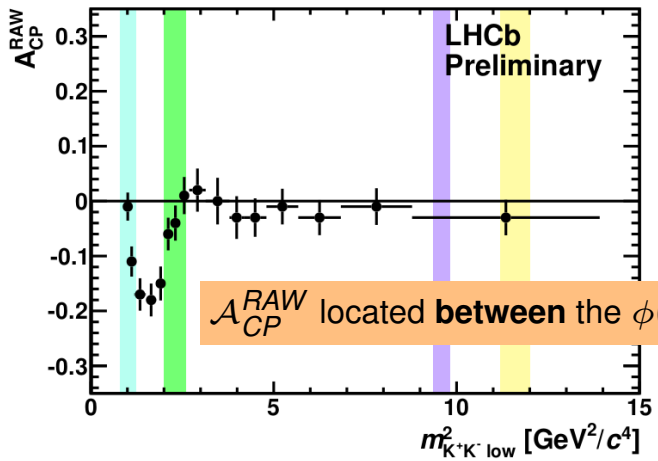


Illustrative view 2: the mass projections are divided into bins with sufficient events to perform a simplified mass fit





$\mathcal{A}_{CP}^{RAW}$ located **between** the $\phi(1020)$ and $f_2(1525)$.

~~CP~~ in phase space: $B^{\pm} \to K^{+}K^{-}\pi^{\pm}$

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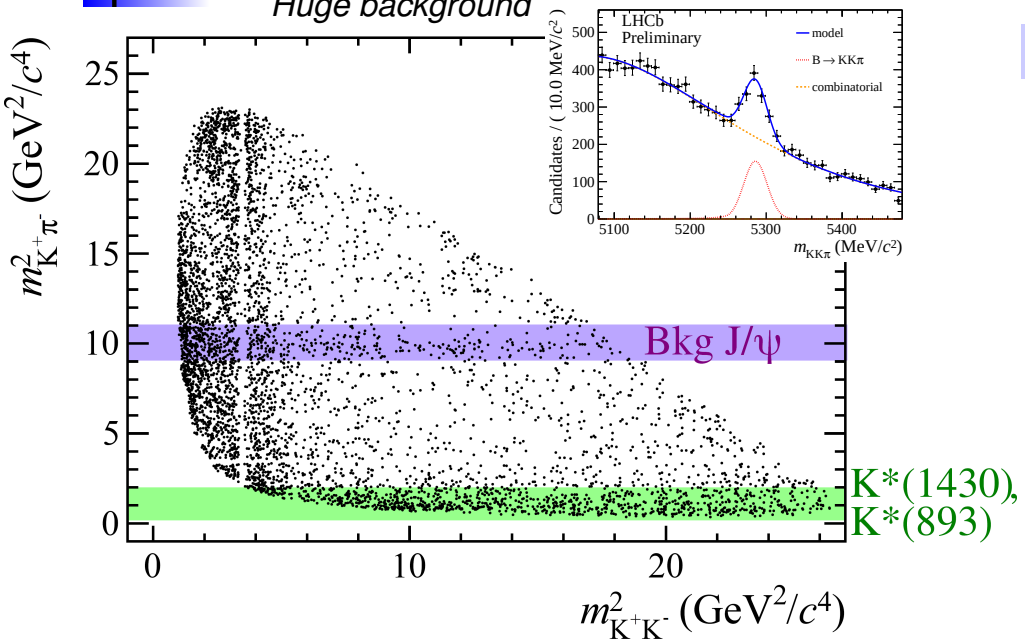
Huge background



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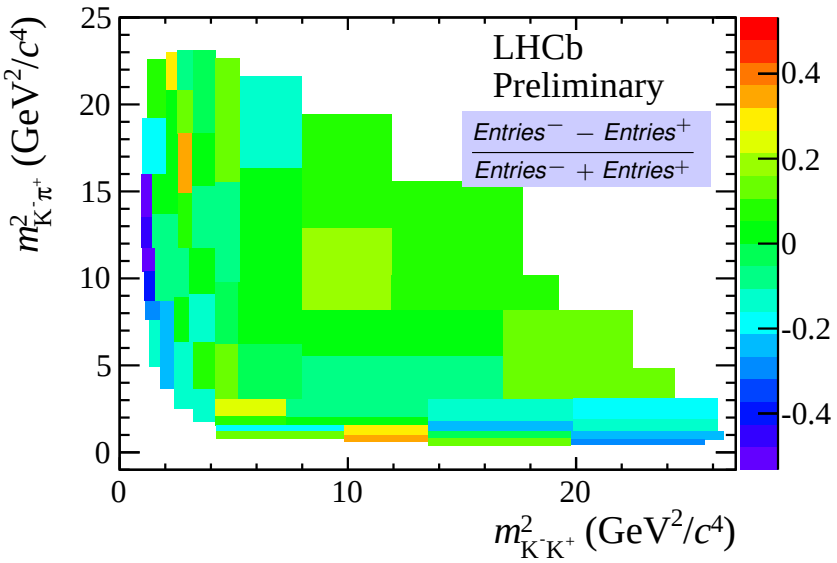
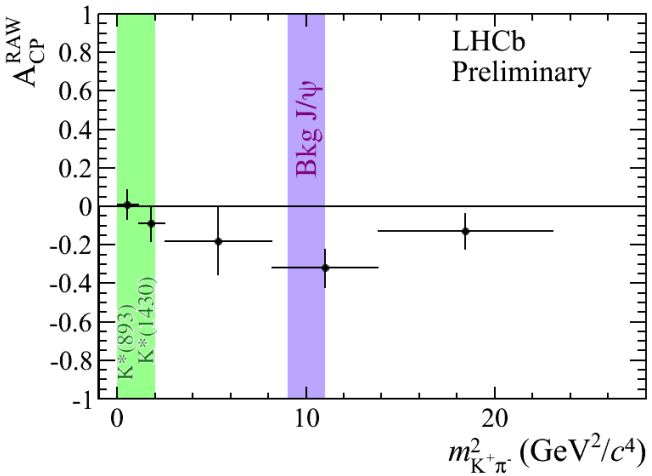
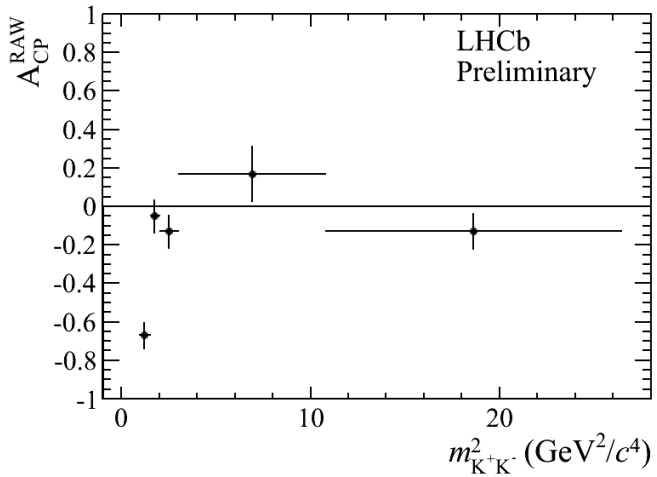


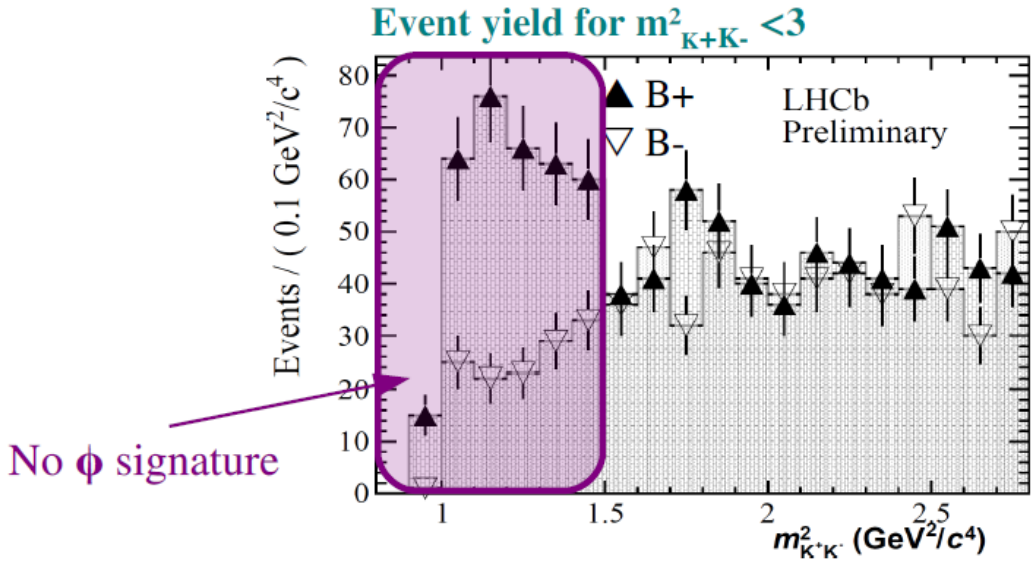
Illustrative view 2: the mass projections are divided into bins with sufficient events to perform a simplified mass fit



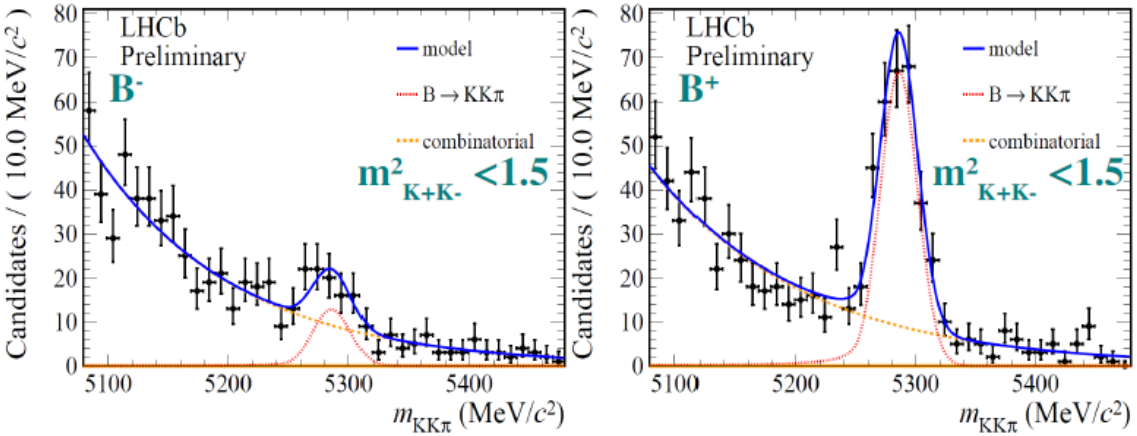


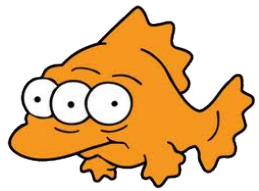
Zoom in the large ~~CP~~ region: $B^{\pm} \to K^{+}K^{-}\pi^{\pm}$

LHCb-CONF-2012-028



- **Very large ~~CP~~ in a region of the phase space not associated to a resonance.**

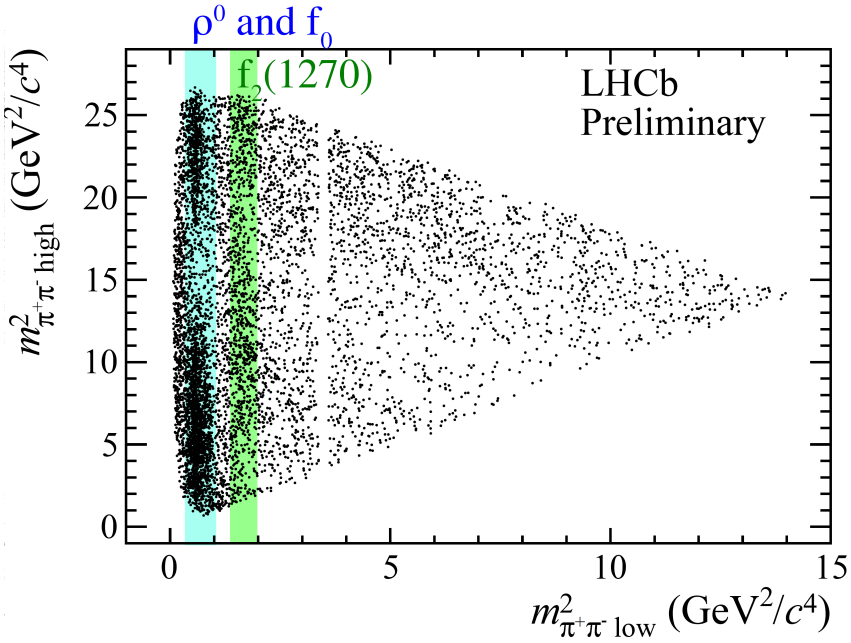




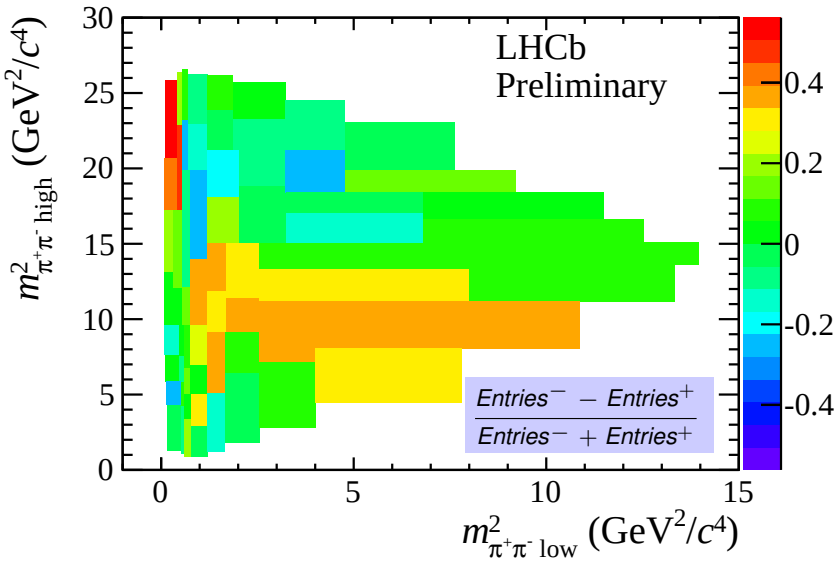
$$\mathcal{A}_{CP}(K^+K^-\pi^\pm region) = -0.671 \pm 0.067_{(stat)} \pm 0.028_{(syst)} \pm 0.007_{(J/\psi K^\pm)} \qquad 9.2\sigma$$

~~CP~~ in phase space: $B^{\pm} \to \pi^{\pm}\pi^{+}\pi^{-}$

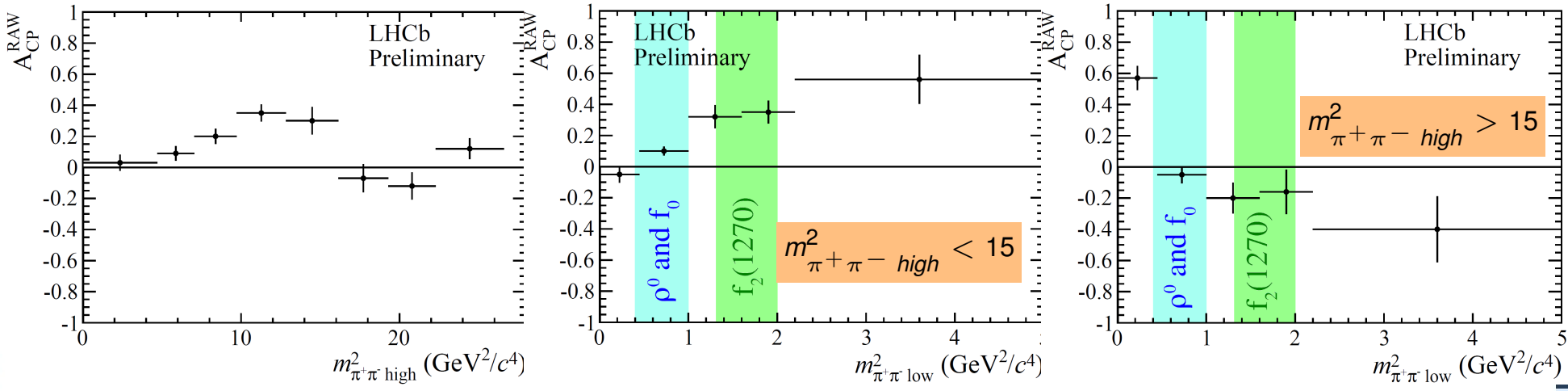
LHCb-CONF-2012-028



Illustrative view 1: entries asymmetry

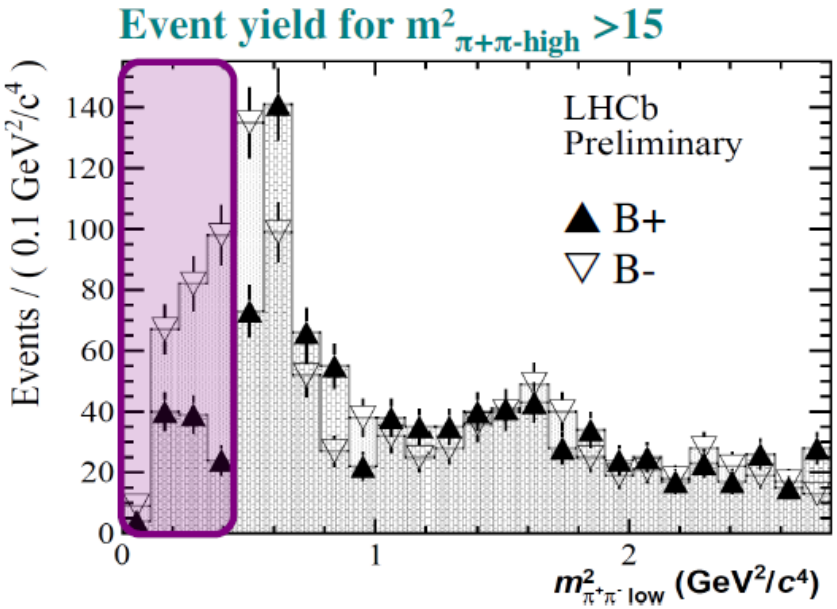


Illustrative view 2: the mass projections are divided into bins with sufficient events to perform a simplified mass fit

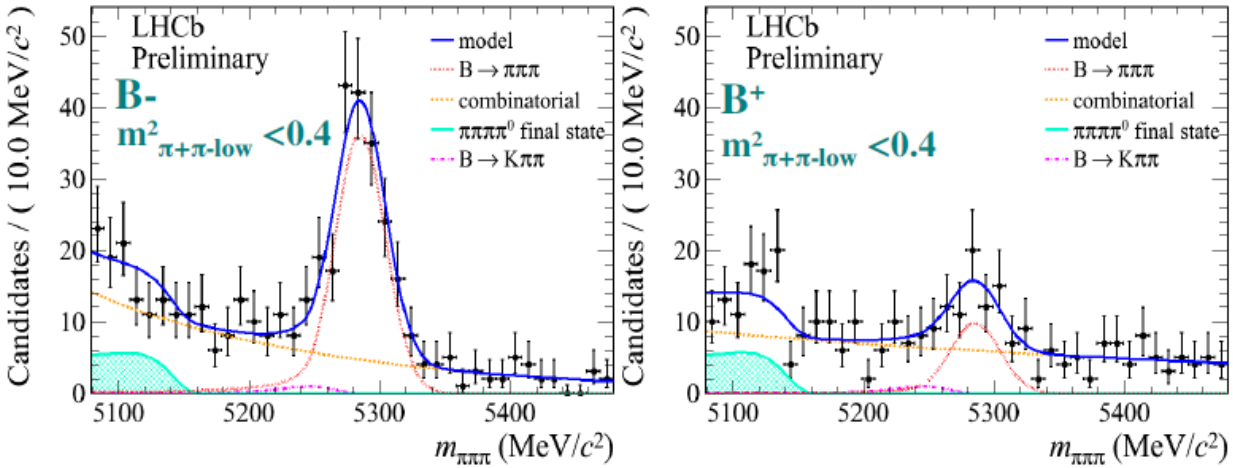


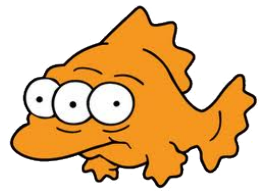
Zoom in the large ~~CP~~ region: $B^{\pm} \to \pi^{\pm}\pi^{+}\pi^{-}$

LHCb-CONF-2012-028



- **Very large positive ~~CP~~ in a region of the phase space not associated to a resonance.**





$$\mathcal{A}_{CP}(\pi^{\pm}\pi^{+}\pi^{-}\ region) = +0.622 \pm 0.075_{(\mathrm{stat})} \pm 0.032_{(\mathrm{syst})} \pm 0.007_{(J/\psi K^{\pm})} \qquad 7.6\sigma$$

Conclusions

- **A first measurement of ϕ_S using the time-dependent tagged analysis of ~~CP~~ in hadronic $B_s^0 \to \phi\phi$ decays yields a 68% C.L. of $[-2.46, -0.76]$rad.**

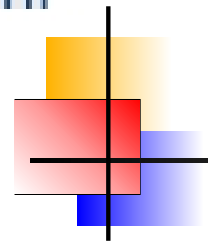
- **First evidence of direct ~~CP~~ in $B_S^0 \to K^-\pi^+$ and precision at $B^0 \to K^+\pi^-$**
  $\mathcal{A}_{CP}(B^0 \to K\pi) = -0.088 \pm 0.01_{(\text{stat})} \pm 0.008_{(\text{syst})}$, $[> 6\sigma]$
  $\mathcal{A}_{CP}(B_S^0 \to K\pi) = +0.27 \pm 0.08_{(\text{stat})} \pm 0.02_{(\text{syst})}$, $[3.3\sigma]$

- **Evidence of direct ~~CP~~ in $B^\pm \to K^\pm\pi^+\pi^-$ and $B^\pm \to K^\pm K^+ K^-$**
  $\mathcal{A}_{CP}(K\pi\pi) = +0.034 \pm 0.009_{(\text{stat})} \pm 0.004_{(\text{syst})} \pm 0.007_{(J/\psi\ K)}$, $[2.8\sigma]$
  $\mathcal{A}_{CP}(KKK) = -0.046 \pm 0.009_{(\text{stat})} \pm 0.005_{(\text{syst})} \pm 0.007_{(J/\psi\ K)}$, $[3.7\sigma]$

- **Evidence of direct ~~CP~~ in $B^\pm \to K^+K^-\pi^\pm$ and $B^\pm \to \pi^\pm\pi^+\pi^-$**
  $\mathcal{A}_{CP}(\pi\pi\pi) = +0.120 \pm 0.020_{(\text{stat})} \pm 0.019_{(\text{syst})} \pm 0.007_{(J/\psi\ K)}$, $[4.2\sigma]$
  $\mathcal{A}_{CP}(KK\pi) = -0.153 \pm 0.046_{(\text{stat})} \pm 0.019_{(\text{syst})} \pm 0.007_{(J/\psi\ K)}$, $[3.0\sigma]$

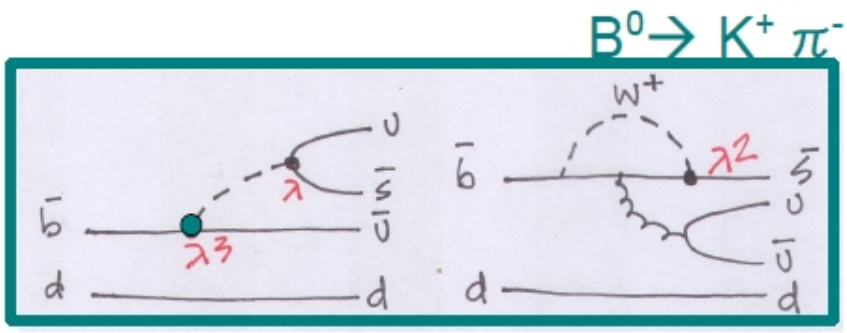
- **Large ~~CP~~ in regions of dalitz plot in charmless 3-body B-decays**
  $\mathcal{A}_{CP}(KK\pi\ \textit{region}) = -0.671 \pm 0.067_{(\text{stat})} \pm 0.028_{(\text{syst})} \pm 0.007_{(J/\psi\ K)}$, $[9.2\sigma]$
  $\mathcal{A}_{CP}(\pi\pi\pi\ \textit{region}) = +0.622 \pm 0.075_{(\text{stat})} \pm 0.032_{(\text{syst})} \pm 0.007_{(J/\psi\ K)}$, $[7.6\sigma]$

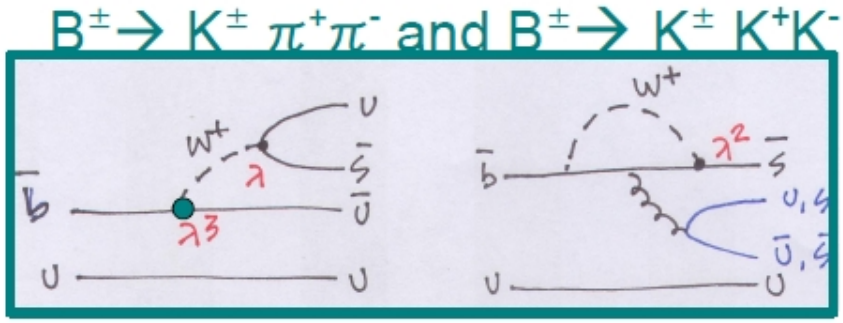
- **All measurements use only 1.0 fb^{-1} of data (2011). Additional 2 fb^{-1} from 2012 is being analyzed now.**

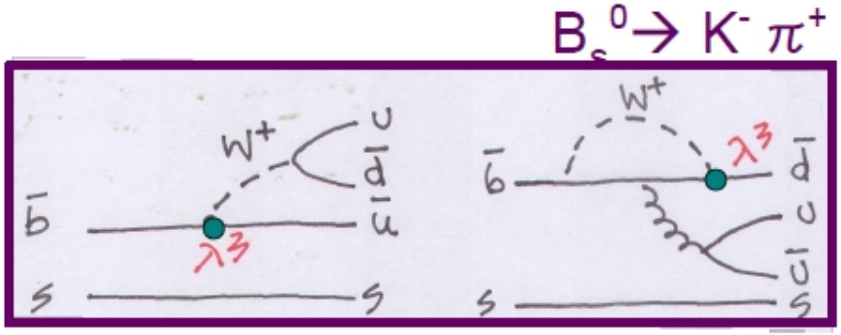


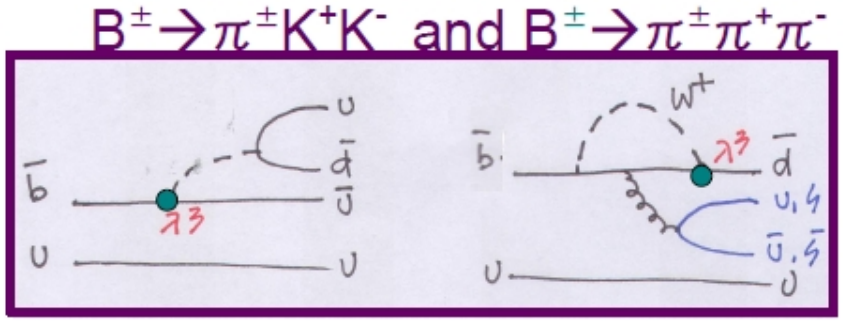
BACKUP SLIDES

$B^{\pm} \to h^{\pm} h^{+} h^{-}$ and $B^{0} \to hh$ diagrams









Extracted from J. Miranda presentation at CKM2012.