Studies of CP violation in charmless B decays

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Two-body decays

Motivation

Why do we want to study these decays?

Sensitive to New physics contributions

Loop level determination of weak phase γ and mixing phases ϕ_s, ϕ_d.

Test U-spin symmetry ($d \longleftrightarrow s$).

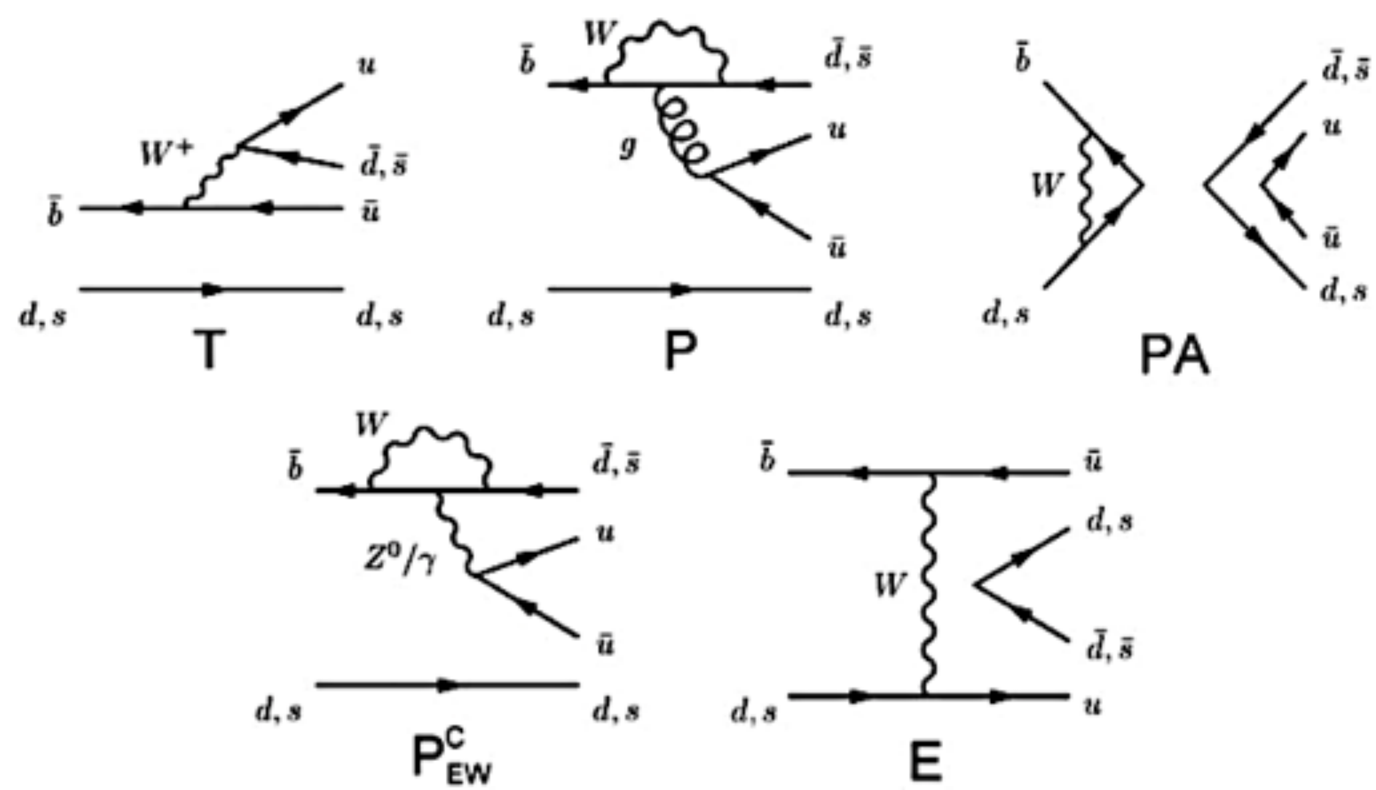
Contribution to $K\pi$-puzzle.

What channels can we use?

$B_d \to K\pi$*, $B_d \to \pi\pi$*, $B_d \to KK$, $B_d \to pK$,
$B_s \to \pi K$*, $B_s \to \pi\pi$, $B_s \to KK$*, $B_s \to pK$,
$B_s \to \phi\phi$*,
$\Lambda_b \to p\pi$, $\Lambda_b \to pK$ etc.

What information can we get?
Branching Ratios
Time-integrated *CP* asymmetries (A_{cp})*
Time-dependent *CP* asymmetries (A_{dir}, A_{mix})*
Effective lifetime*
Triple decay asymmetries and polarization amplitudes*

Example of diagrams contributing to the amplitudes of charmless B-decays to two charged mesons: Tree, Penguin, Penguin Annihilation, Exchange.



* In this talk

$\mathcal{L}$=0.35 fb^{-1}

$B_d \to K\pi$, $B_s \to \pi K$ Time-integrated *CP* asymmetries

Phys. Rev. Lett. 108 (2012), arXiv:1202.6251

We define the observables:

$$A_{CP}(B^0 \to K\pi) = \frac{\Gamma(\bar{B}^0 \to K^-\pi^+) - \Gamma(B^0 \to K^+\pi^-)}{\Gamma(\bar{B}^0 \to K^-\pi^+) + \Gamma(B^0 \to K^+\pi^-)}$$
$$A_{CP}(B_s^0 \to \pi K) = \frac{\Gamma(\bar{B}_s^0 \to \pi^-K^+) - \Gamma(B_s^0 \to \pi^+K^-)}{\Gamma(\bar{B}_s^0 \to \pi^-K^+) + \Gamma(B_s^0 \to \pi^+K^-)}.$$

Event selection is tuned to have better sensitivities for the *CP* violation variables.

All the events are reconstructed under the same daughter hypothesis. Afterwards the PID selection is applied.

PID calibration is performed on data using $D^* \to D^0(K\pi)\pi$ and $\Lambda_b \to p\pi$ decays.

Maximum Likelihood fit is performed simultaneously to all the samples (additional samples are fixing the cross-feed backgrounds contributions under the signal peaks).

The extracted A_{cp} are "raw" asymmetries, we correct it by A_Δ:

$$A_\Delta(B^0_{(s)} \to K\pi) = \zeta_{d(s)} A_D(K\pi) + \kappa_{d(s)} A_P(B^0_{(s)} \to K\pi)$$

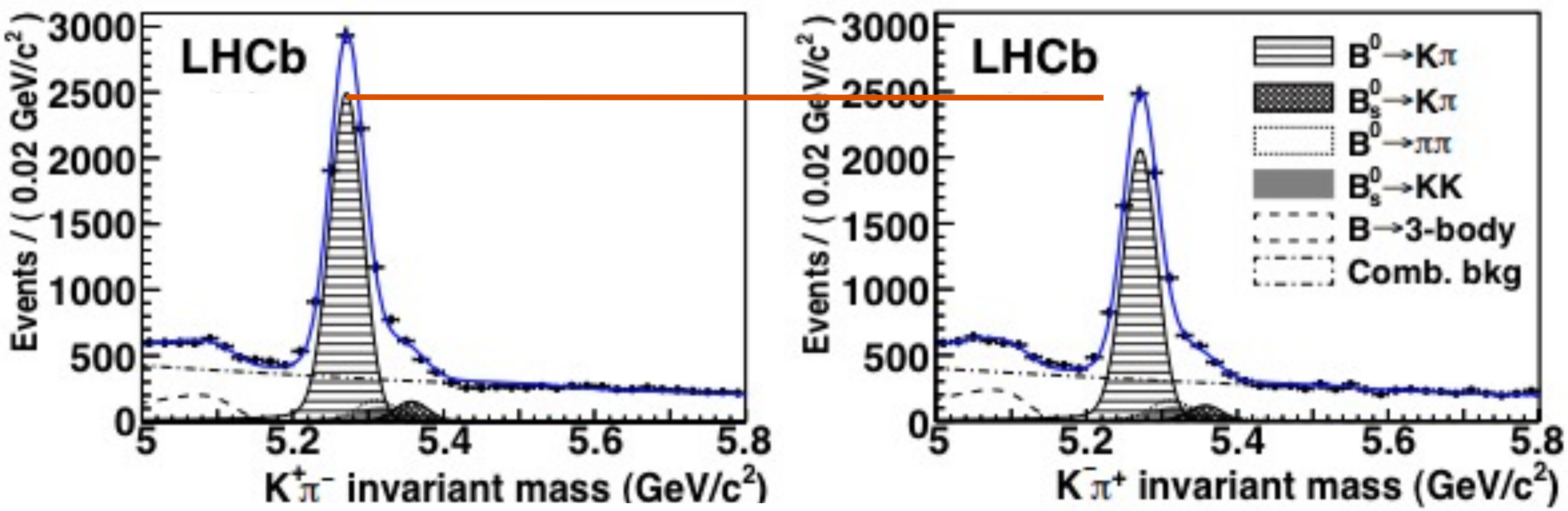
Detection asymmetry part, A_D: estimated from the tagged and untagged decays of $D \to hh$, ζ=+1 for B_d and ζ=-1 for B_s.

Production asymmetry part, A_P: estimated from the $B^0 \to J/\Psi K^*$ decays. κ is the factor that accounts for the neutral B oscillations.

$B_d \to K\pi$ Time Integrated Asymmetries

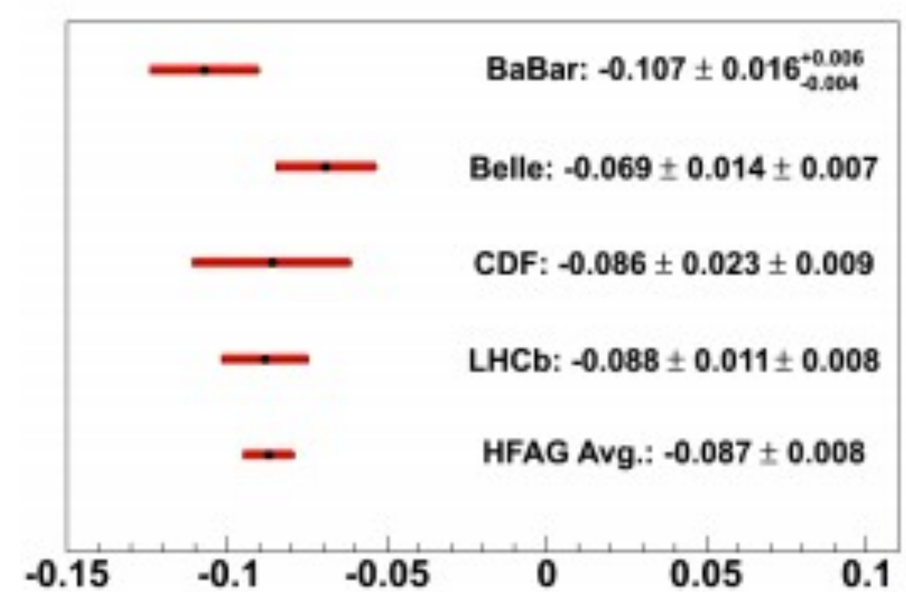
The asymmetry in the *B* and $\overline{B}$ decays can be seen by eye.

$N_{B_d \to K\pi} = 13250 \pm 150$

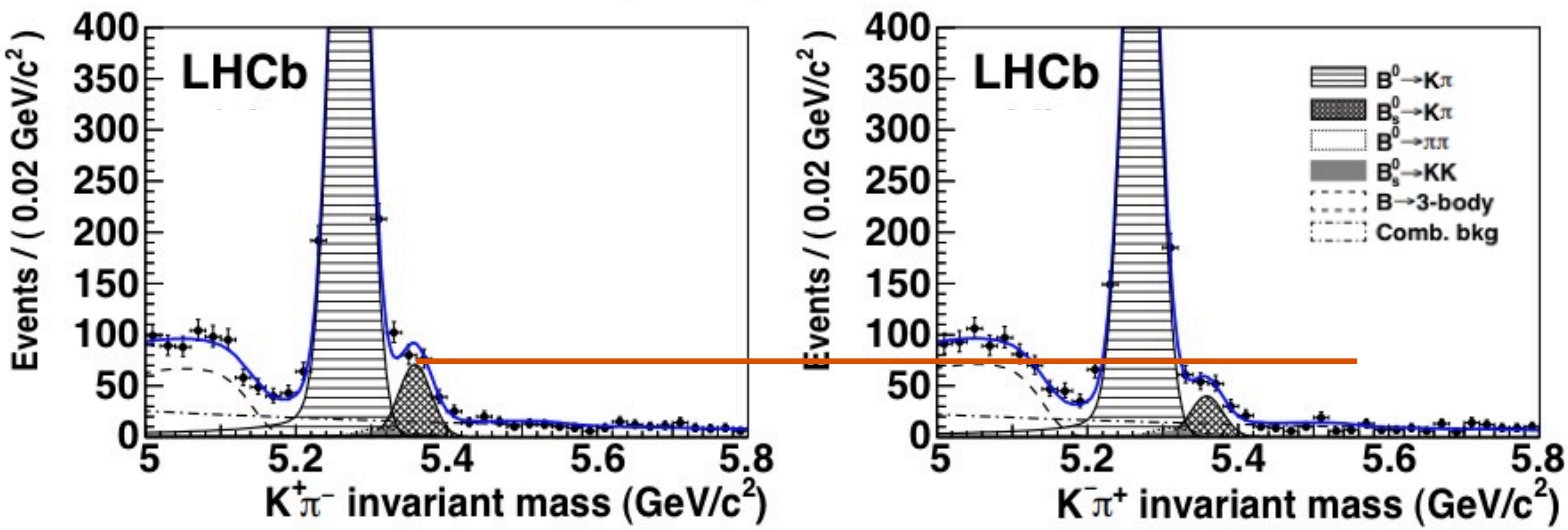


$$A_{CP}(B^0 \to K\pi) = -0.088 \pm 0.011\,(\mathrm{stat}) \pm 0.008\,(\mathrm{syst})$$

- Worlds' most precise measurement
- First observation of the *CP* violation at a hadron collider (>6σ)



$N_{B_s \to \pi K} = 314 \pm 27$



$$A_{CP}(B_s^0 \to K\pi) = 0.27 \pm 0.08\,(\text{stat}) \pm 0.02\,(\text{syst}).$$

- Worlds' most precise measurement
- First evidence of *CP* violation in B_s decays (3.3σ)

In agreement with CDF result: $A_{CP}\left(B_s \to \pi K\right) = 0.39 \pm 0.15 \pm 0.08$

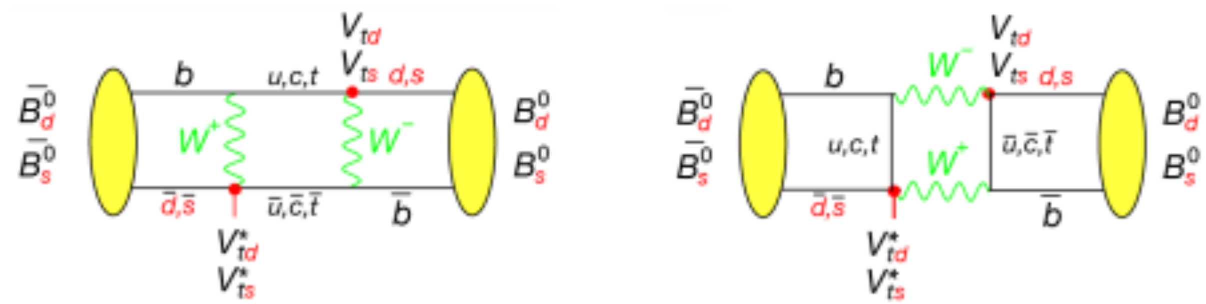
Preliminary

$\mathcal{L}$=0.67 fb^{-1}

$B_d \to \pi\pi$, $B_s \to KK$ Time-dependent *CP* asymmetries

CERN-LHCb-CONF-2012-007

Formalism for time-dependence



If we consider the *f* to be a *CP* eigenstate:

$$A_{CP}(t) = \frac{\Gamma(\bar{B} \to f_{CP}) - \Gamma(B \to f_{CP})}{\Gamma(\bar{B} \to f_{CP}) + \Gamma(B \to f_{CP})}$$

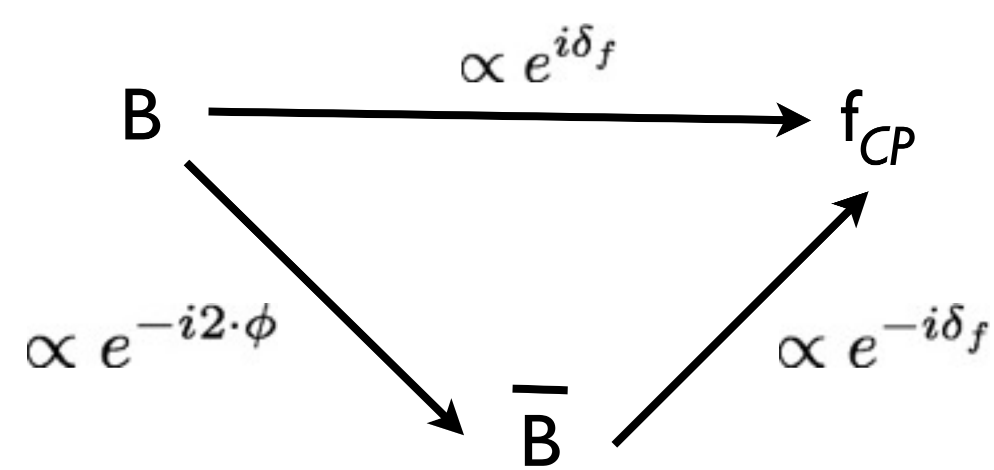
which can be recalculated to

$$A_{CP}(t) = \frac{A_{\rm dir}\cos(\Delta m t) + A_{\rm mix}\sin(\Delta m t)}{\cosh(\frac{\Delta\Gamma}{2}t) - A_{\Delta}\sinh(\frac{\Delta\Gamma}{2}t)}$$

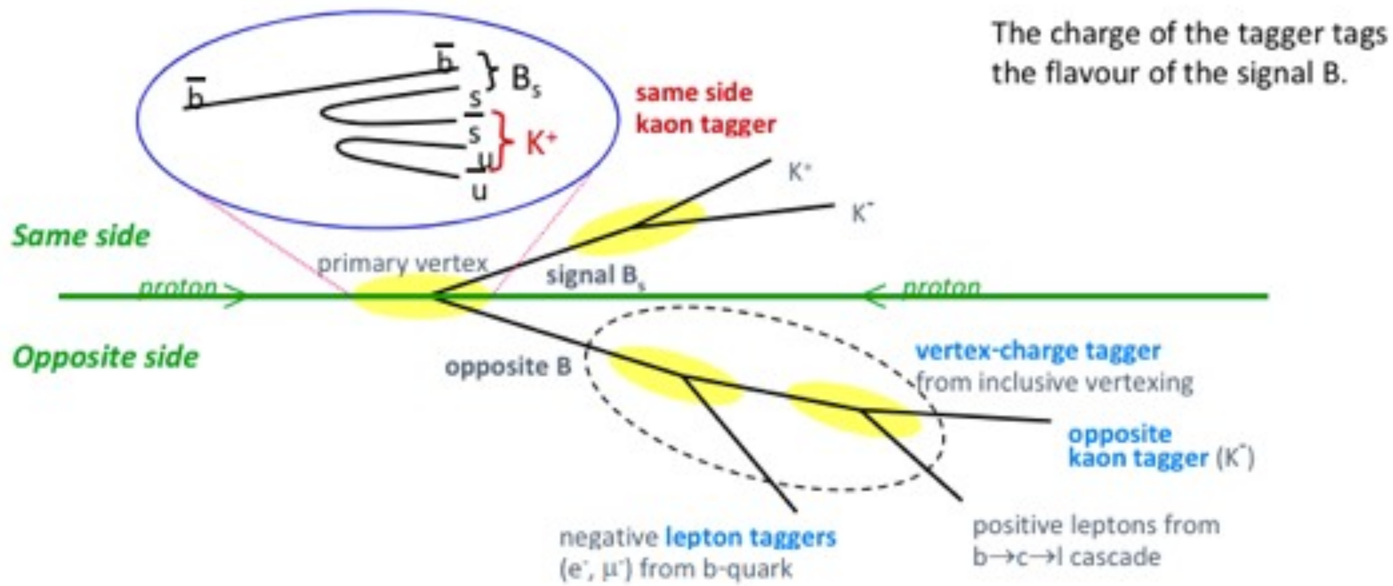
$A_{\rm dir}$: direct CPV from decay.

$A_{\rm mix}$: mixing CPV in the decay.

$A_{\rm dir}^2 + A_{\rm mix}^2 + A_{\Delta}^2 = 1$



arXiv:1202.4979v2
Eur. Phys. J. 72 (2012), 2022.



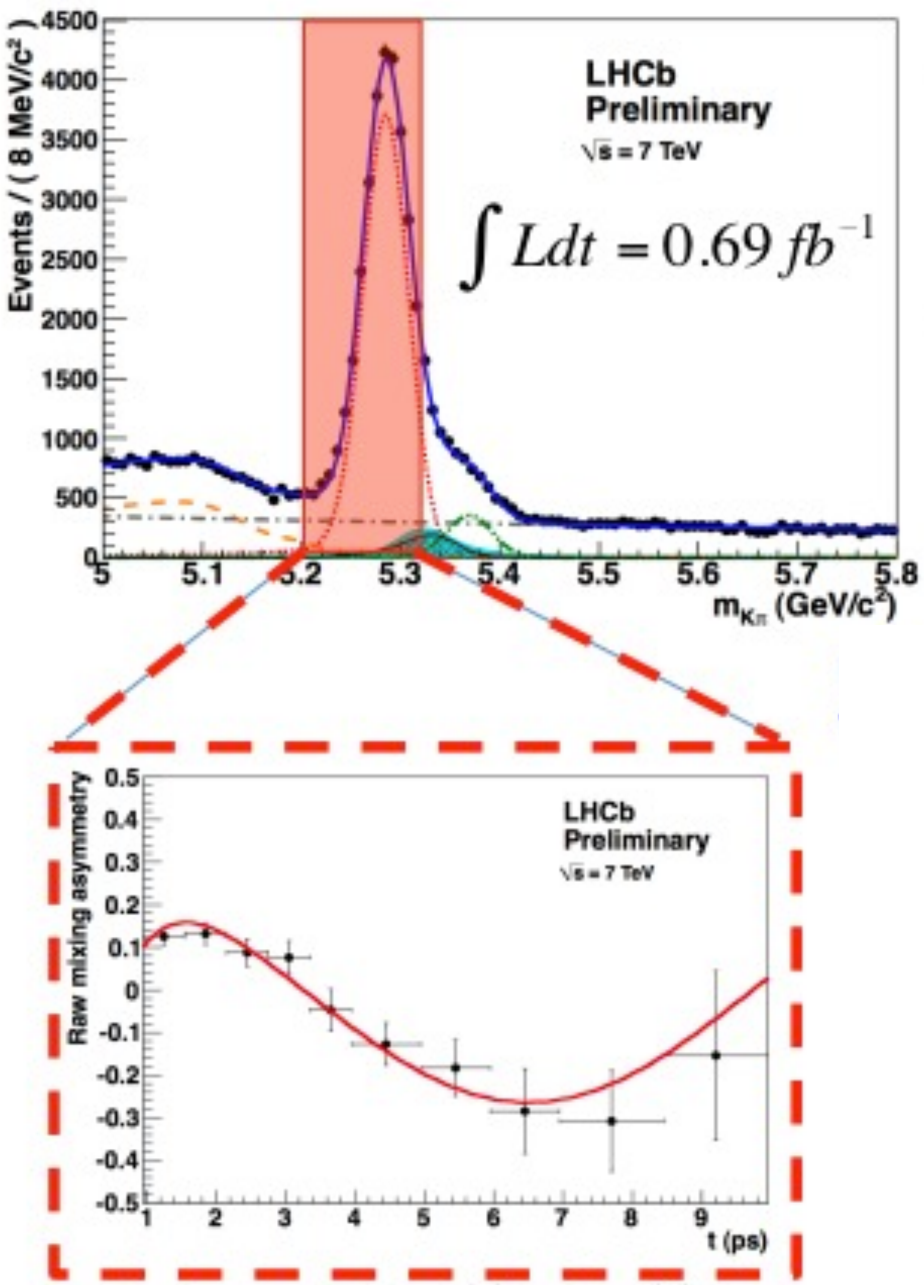
In this talk we use opposite side taggers:
Exploit the decay products of the other b hadron: lepton (e or μ); kaon; overall charge of secondary vertex.

When more than one tagger is available per event, these probabilities are combined into a single probability and a single decision per event.

In this analysis, we use the $B_d \to K\pi$ decays in order to extract performance of tagging. From the 2D ML (mass X time) fit:

OS tagging power: $\varepsilon_{eff}=\varepsilon_{tag}(1-2\omega)^2=(2.3\pm0.1)\%$

$B_d \to K\pi$



$$A(t)=\frac{\Gamma_{unmix}(t)-\Gamma_{mix}(t)}{\Gamma_{unmix}(t)+\Gamma_{mix}(t)}$$

N_{sig}~5.4k events

ω_{mistag} likelihood is taken from the $B_d \to K\pi$ channel

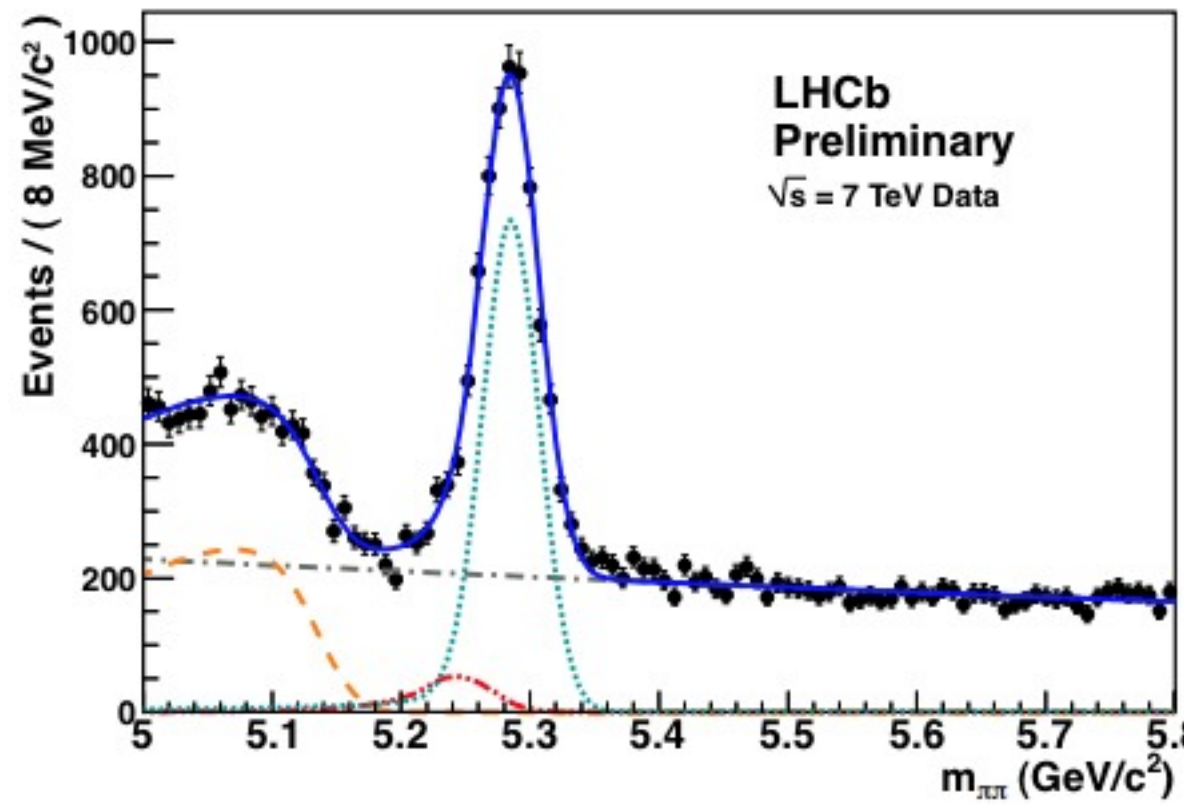
Results:

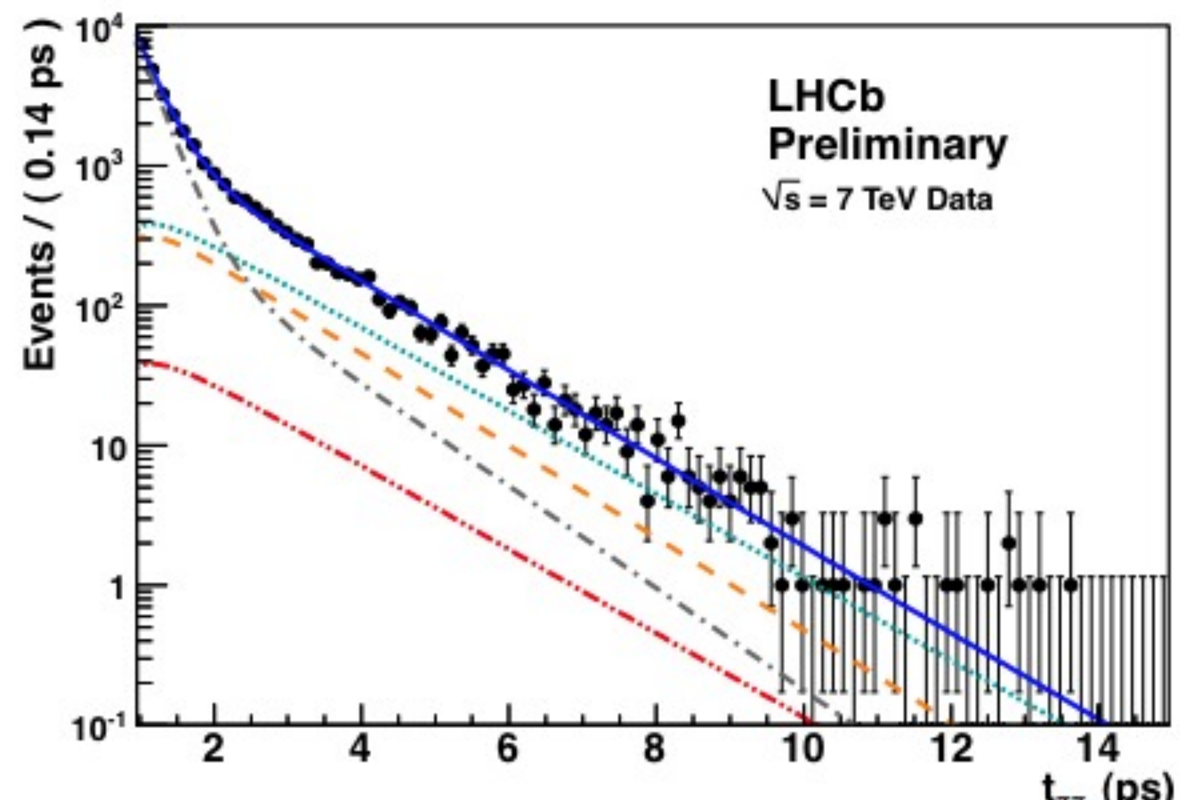
$$A^{\rm dir}_{\pi\pi} = 0.11 \pm 0.21 \pm 0.03$$

$$A^{\rm mix}_{\pi\pi} = -0.56 \pm 0.17 \pm 0.03$$

$$\rho(A^{\rm dir}_{\pi\pi}, A^{\rm mix}_{\pi\pi}) = -0.34$$

The first evidence of mixing induced CP violation at an hadron collider(3.2σ)





Full fit

$B_d \to \pi\pi$ signal

$B \to 3h$ bkg

$B_d \to K\pi$ bkg

comb bkg

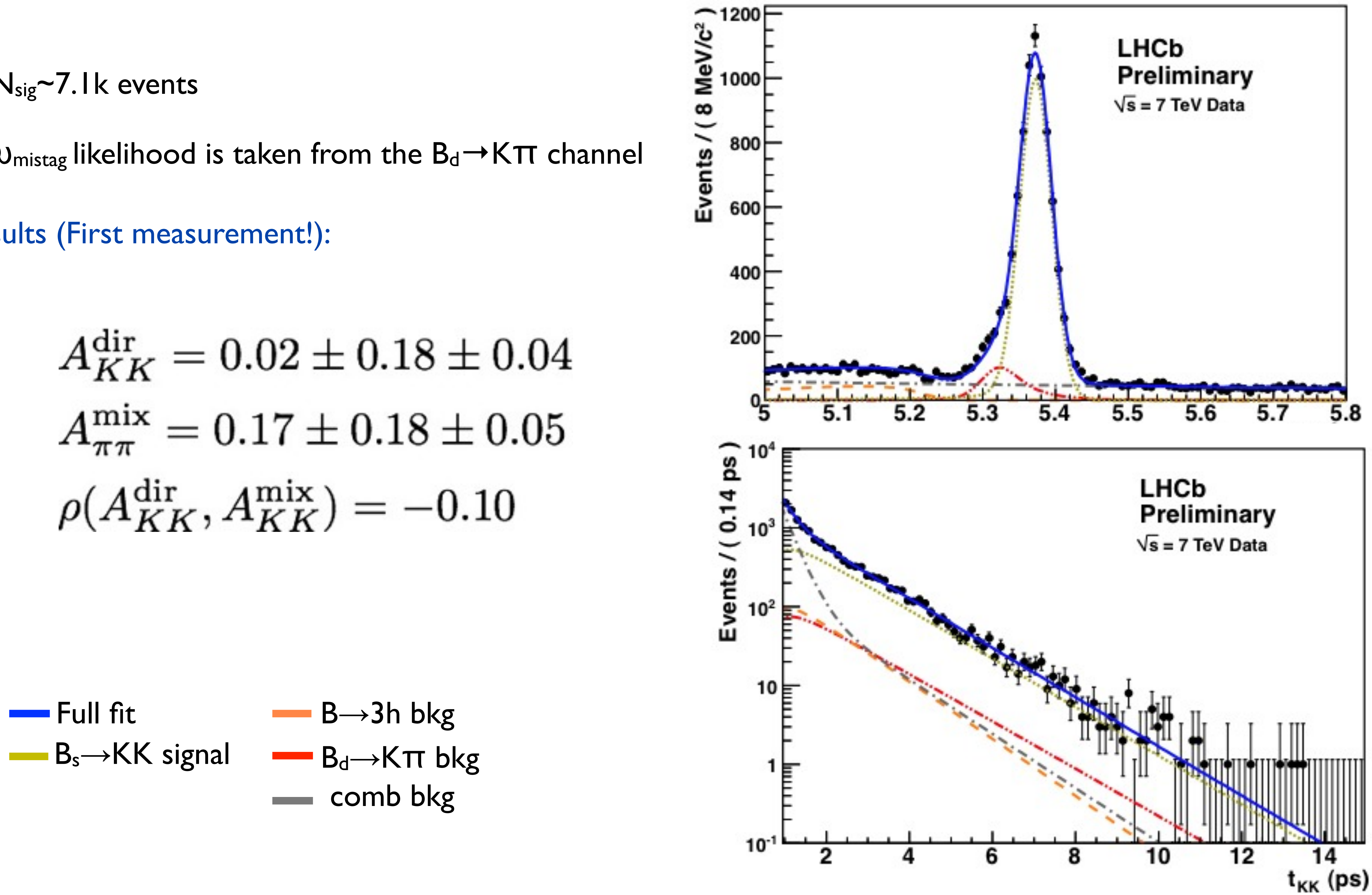
$B_s \to KK$ Time-Dependent Asymmetry

N_{sig}~7.1k events

ω_{mistag} likelihood is taken from the $B_d \to K\pi$ channel

Results (First measurement!):

$$A_{KK}^{\rm dir} = 0.02 \pm 0.18 \pm 0.04$$
$$A_{\pi\pi}^{\rm mix} = 0.17 \pm 0.18 \pm 0.05$$
$$\rho(A_{KK}^{\rm dir}, A_{KK}^{\rm mix}) = -0.10$$



Our results:

$B_d \to \pi^+\pi^-$

$A_{dir} = 0.11 \pm 0.21 \pm 0.03$

$A_{mix} = -0.56 \pm 0.23 \pm 0.03$

$B_s \to K^+K^-$

$A_{dir} = 0.02 \pm 0.18 \pm 0.04$

$A_{mix} = 0.17 \pm 0.18 \pm 0.05$

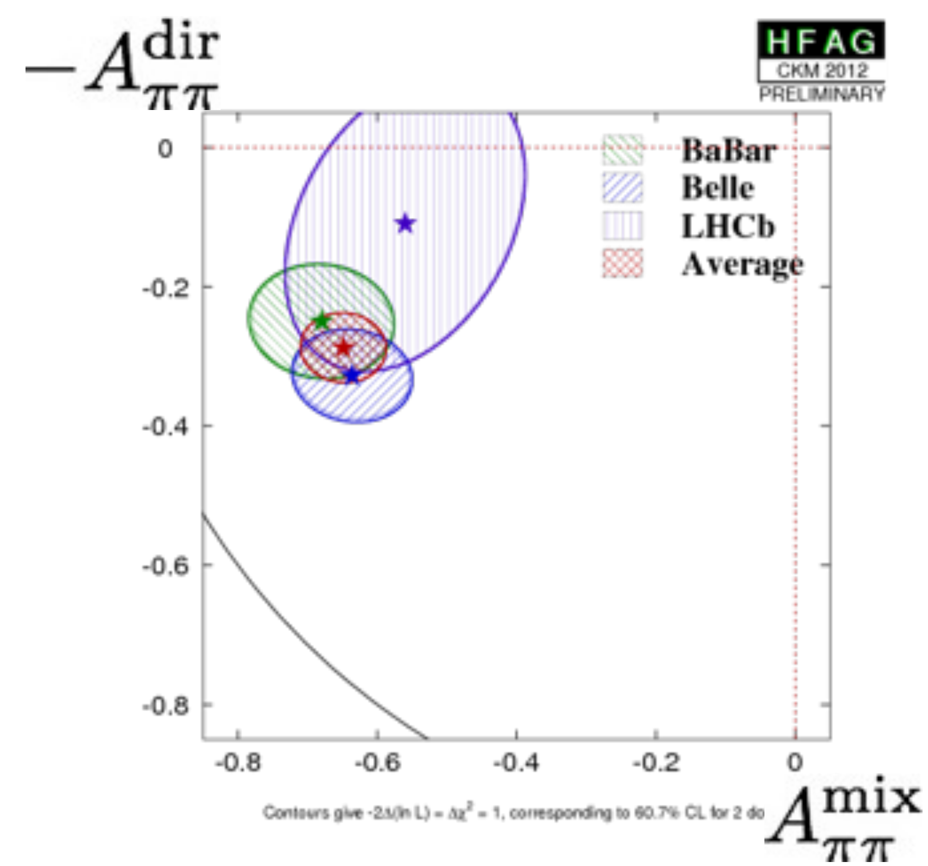
	$A^{dir}_{\pi\pi}$	$A^{mix}_{\pi\pi}$
BaBar	0.25±0.08±0.02	−0.68±0.10±0.03
Belle	0.33±0.06±0.03	−0.64±0.08±0.03

← NEW CKM'2012

U-spin symmetry implies:

$A_{dir}(B_d \to \pi\pi) \sim A_{CP}(B_s \to \pi K) = 0.27 \pm 0.08 \pm 0.02$

$A_{dir}(B_s \to KK) \sim A_{CP}(B_d \to K\pi) = -0.088 \pm 0.011 \pm 0.008$



New HFAG world averages for $B_d \to \pi^+\pi^-$:

$A_{dir} = -0.29 \pm 0.05$

$A_{mix} = -0.65 \pm 0.06$

$\mathcal{L}$=1.0 fb^{-1}

$B_s \to KK$ Effective Lifetime Measurement

Phys. Lett. B716 (2012) 393, arXiv:1207.5993

The untagged decay time distribution can be written as:

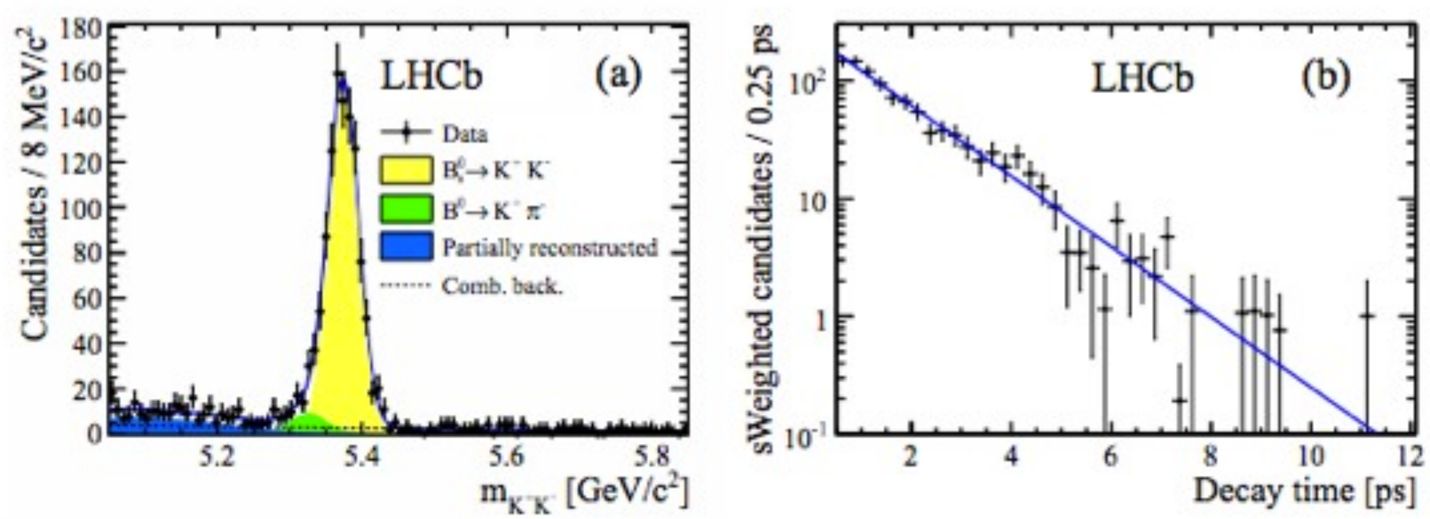
$$\Gamma(t) \;\propto\; (1-\mathcal{A}_{\Delta\Gamma_s})\, e^{-\Gamma_L t} + (1+\mathcal{A}_{\Delta\Gamma_s})\, e^{-\Gamma_H t}\,.$$

In this case, fitting the decay time with a single exponential gives an effective lifetime defined as:

$$\tau_{KK} = \tau_{B_s^0}\frac{1}{1-y_s^2}\left[\frac{1+2\mathcal{A}_{\Delta\Gamma_s}y_s+y_s^2}{1+\mathcal{A}_{\Delta\Gamma_s}y_s}\right] \text{, with } \quad y_s \equiv \frac{\Delta\Gamma_s}{2\Gamma_s}$$

Analysis steps:

- two consecutive Neural Network NeuroBayes® selections applied:
    1. based on the kinematic variables
    2. the kinematic information is combined with the PID
- only events with τ>0.5 ps are considered
- mass fit is used to extract sWeights for the signal decay time distribution



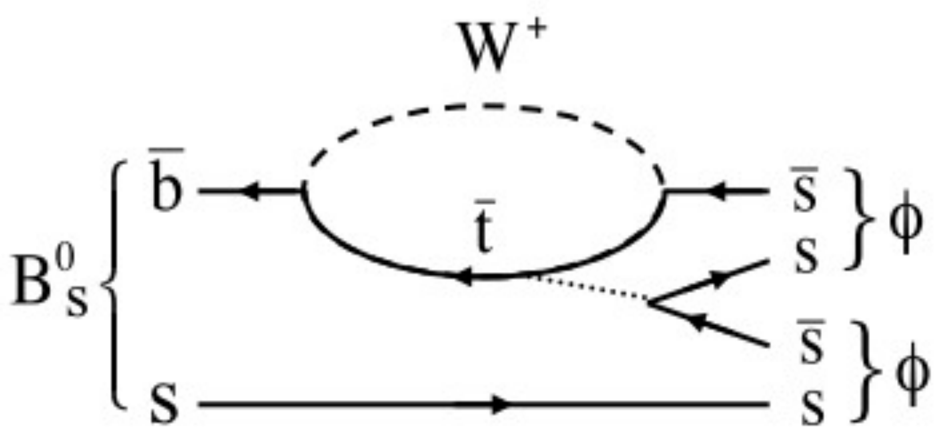
$$\tau_{KK} = 1.455 \pm 0.046(\text{stat.}) \pm 0.006(\text{syst.})\text{ps}$$

Which can be compared to the SM predictions: $\tau_{KK}^{\text{SM}} = 1.40 \pm 0.02\ \text{ps}$

$\mathcal{L}$=1.0 fb^{-1}

$B_s \rightarrow \phi\phi$ Triple Decay Asymmetries and Polarization Amplitudes

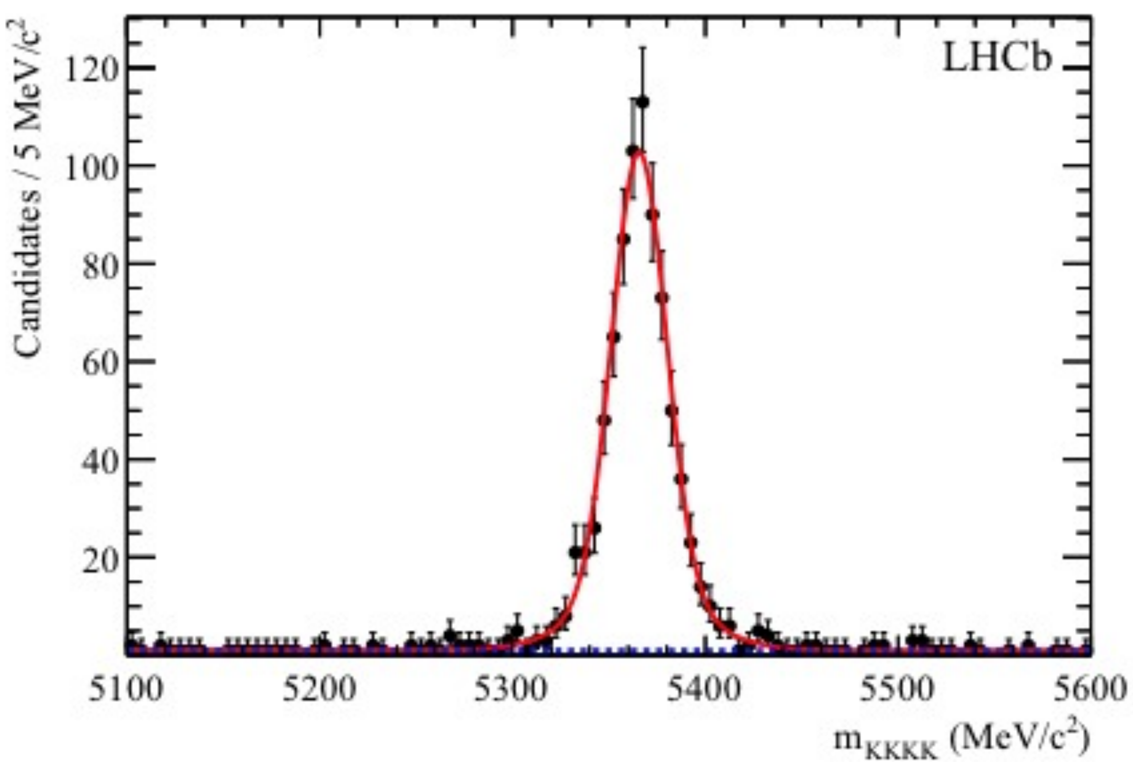
Phys. Lett. B713 (2012) 369-377, arXiv:1204.2813



$b \rightarrow q\bar{q}s$ penguin transitions are sensitive to new physics in decay amplitude
$B_s \rightarrow \phi\phi$ is a Golden mode for probing CP violating weak phase ϕ_s in hadronic Bs decays

The cut based selection is applied to obtain 801±29 events with very high purity.

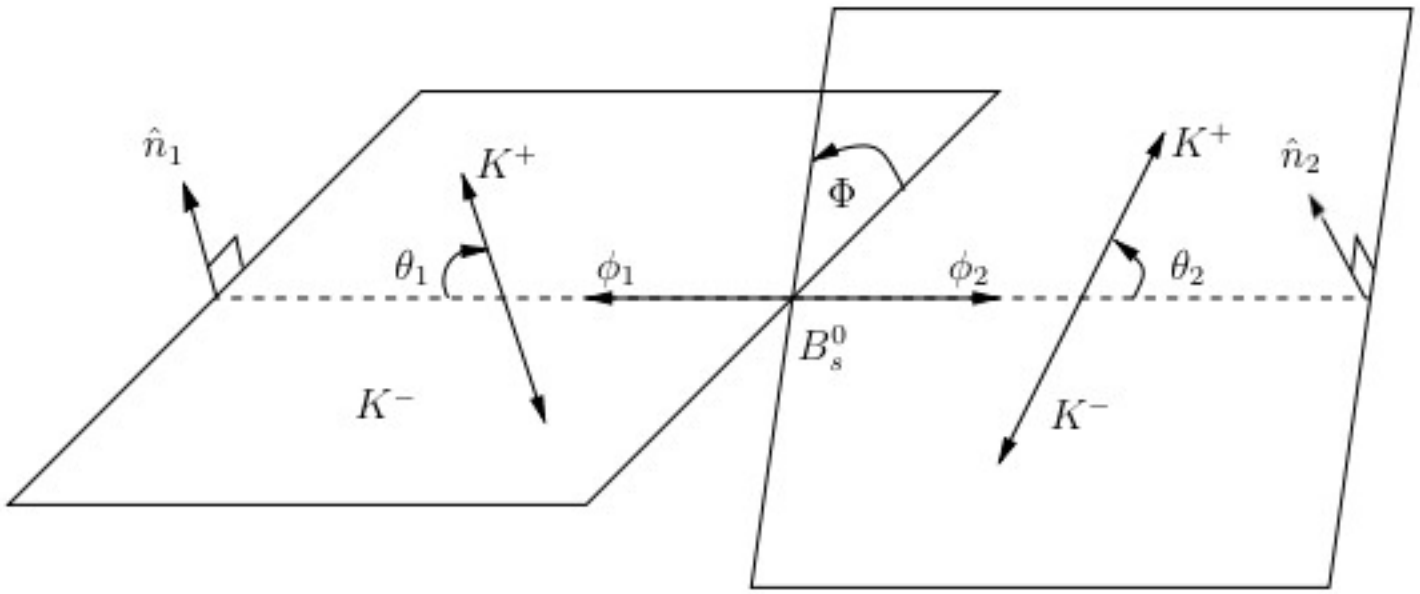
S-wave component in the KK mass distribution is found negligible.



With the help of CPT theorem look for T violation equivalent to CP violation.

Look at observables in P→VV decays:

$$U = \sin(2\Phi)/2$$
$$V = sign(\cos\theta_1 \cos\theta_2)\sin\Phi$$



which correspond to the T-odd triple product:

$$\sin\Phi = (\hat{n}_1 \times \hat{n}_2) \cdot \hat{p}_1\,,$$
$$\sin(2\Phi)/2 = (\hat{n}_1 \cdot \hat{n}_2)(\hat{n}_1 \times \hat{n}_2) \cdot \hat{p}_1\,,$$

We can search for the *CP* violation effects by studying:

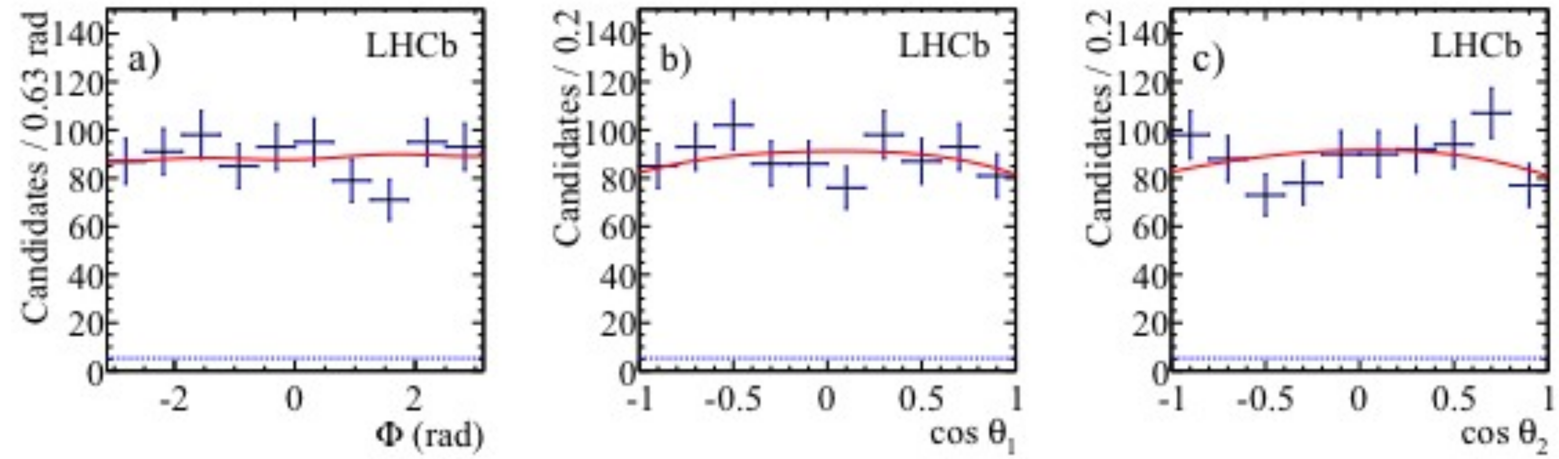
$$A_U = \frac{N_+ - N_-}{N_+ - N_-} \qquad A_V = \frac{M_+ - M_-}{M_+ - M_-}$$

where "+" terms corresponds to positive variable value and "-" term to negative.
A_u~f_4 A_v~f_6, which means that the difference of A_u or A_v from 0 indicates the deviation from SM.

We perform an unbinned maximum likelihood fit to the reconstructed mass and helicity angle distributions.

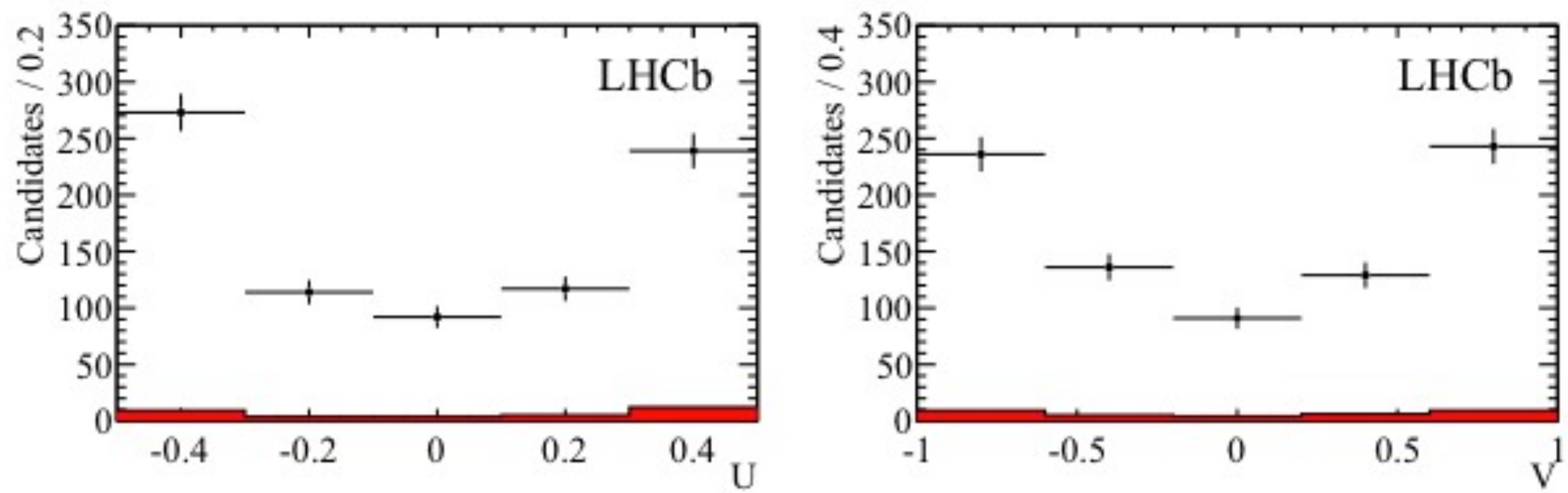
With lifetime constrained from $B_s \to J/\psi\phi$:

$$|A_0|^2 = 0.365 \pm 0.022\,(\text{stat}) \pm 0.012\,(\text{syst})$$
$$|A_\perp|^2 = 0.291 \pm 0.024\,(\text{stat}) \pm 0.010\,(\text{syst})$$
$$\cos(\delta_\parallel) = -0.844 \pm 0.068\,(\text{stat}) \pm 0.029\,(\text{syst})$$



Simultaneous fits are performed to the mass distributions for each of the two partitions corresponding to each observable individually.

$$A_U = -0.055 \pm 0.036\,(\text{stat}) \pm 0.018\,(\text{syst})$$
$$A_V = 0.010 \pm 0.036\,(\text{stat}) \pm 0.018\,(\text{syst})$$



$5286.6 < M(K^+K^-K^+K^-) < 5446.6\ \text{MeV}/c^2$

The future plans also include the time-dependent analysis of this mode.

Summary for two-body decays

LHCb have already provided several results in the field:

Time integrated $B \to K\pi$:

- $B_d \to K\pi$: world's best (6σ) significance of the direct *CP* asymmetry.
- $B_s \to \pi K$: first evidence of direct *CP* asymmetry (3σ).

Time dependent $B \to \pi\pi/KK$:

- $B_d \to \pi\pi$: measurement favors BaBar results.
- $B_s \to KK$: first ever measurement in this channel

Effective Lifetime measurement $B_s \to KK$:

- measurement is compatible and close in precision to the SM predictions.

Triple decay and polarization amplitudes $B_s \to \phi\phi$:

- the results are in good agreement with previous results by CDF and have better precision

Three-body decays

$\mathcal{L}$=1.0 fb^{-1}

$B_u \rightarrow K\pi\pi$, $B_u \rightarrow KKK$, $B_u \rightarrow \pi\pi\pi$ Time-integrated *CP* asymmetries

CERN-LHCb-CONF-2012-028
CERN-LHCb-CONF-2012-018

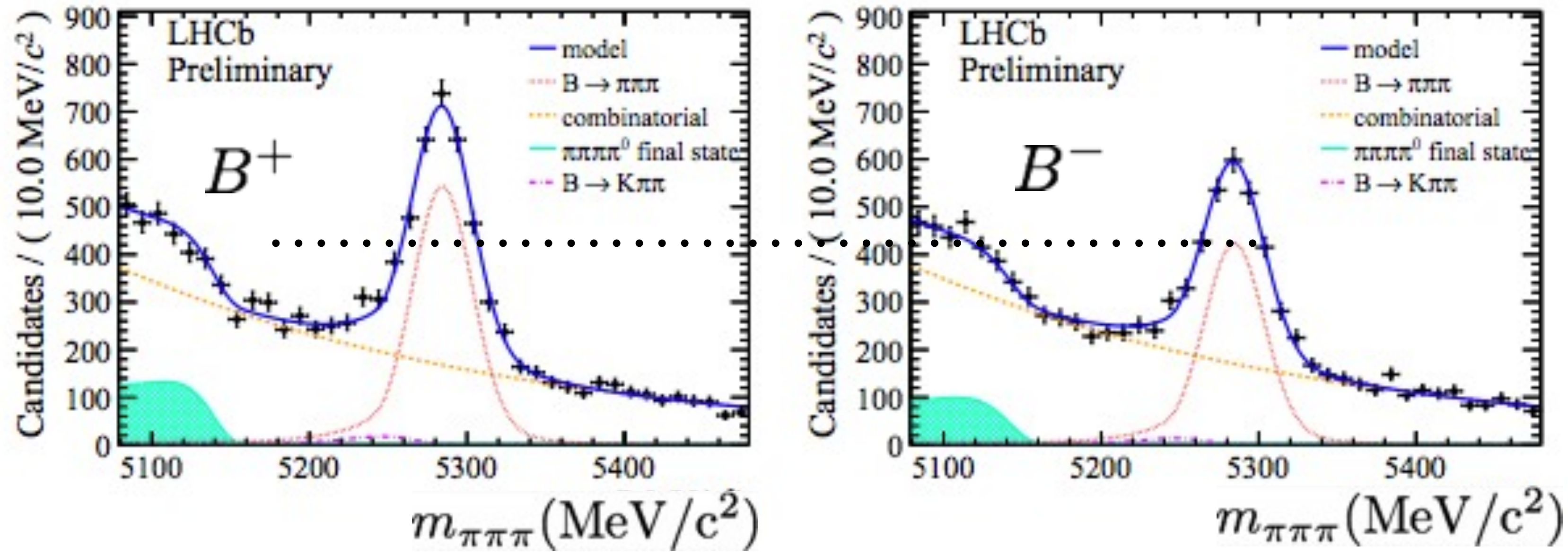
$B^{\pm} \to \pi^{\pm}\pi^{+}\pi^{-}$

The modes are sensitive to the NP effects and can be studied in Dalitz plain

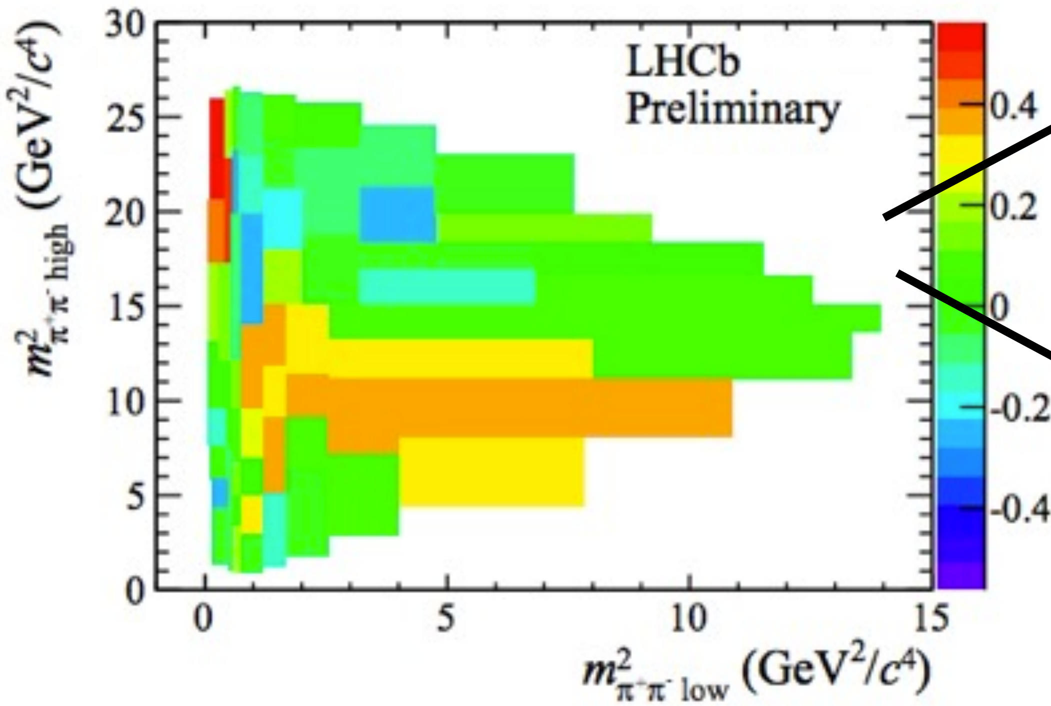
N_{sig}~5k events

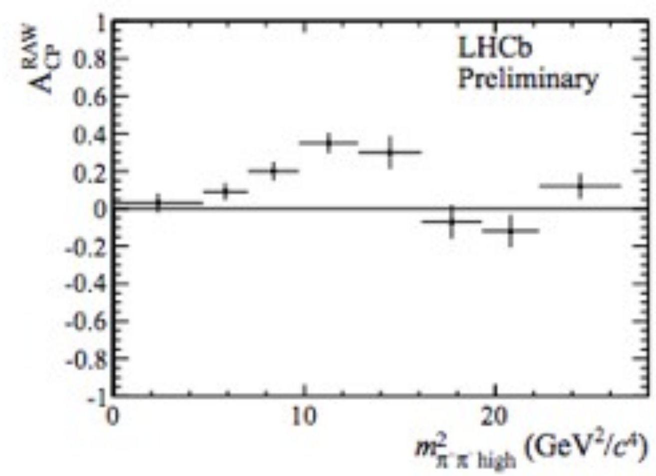
The measured asymmetry is A_{raw} and is to be corrected (like in 2-body case).

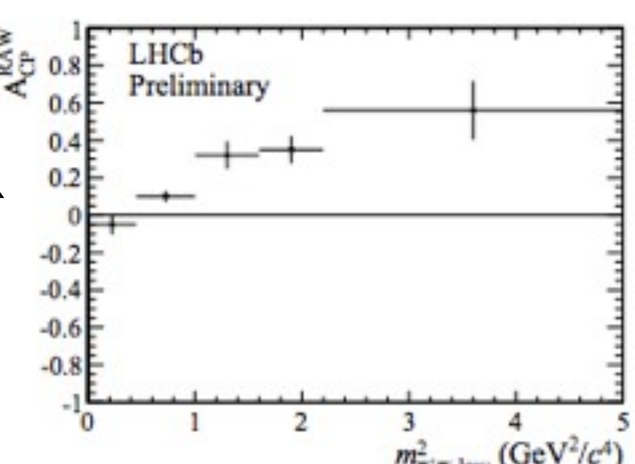
Where asymmetry comes from?



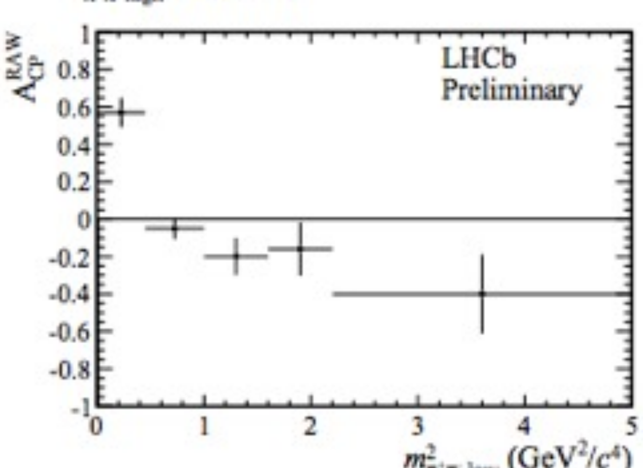
Cutting mass in signal region and making equal population binning:







$m^2_{\pi^+\pi^-\mathrm{high}} < 15\ \mathrm{GeV}^2/c^4$



$m^2_{\pi^+\pi^-\mathrm{high}} > 15\ \mathrm{GeV}^2/c^4$

The similar analyses yield:

Significance of 4.2σ:

$$A_{CP}(B^{\pm} \to \pi^{\pm}\pi^{+}\pi^{-}) = +0.120 \pm 0.020(\mathrm{stat}) \pm 0.019(\mathrm{syst}) \pm 0.007(J/\psi\, K^{\pm})$$

Significance of 3.0σ:

$$A_{CP}(B^{\pm} \to K^{+}K^{-}\pi^{\pm}) = -0.153 \pm 0.046(\mathrm{stat}) \pm 0.019(\mathrm{syst}) \pm 0.007(J/\psi\, K^{\pm})$$

Significance of 2.8σ:

$$A_{CP}(B^{\pm} \to K^{\pm}\pi^{+}\pi^{-}) = +0.034 \pm 0.009(\mathrm{stat}) \pm 0.004(\mathrm{syst}) \pm 0.007(J/\psi\, K^{\pm})$$

Significance of 3.7σ:

$$A_{CP}(B^{\pm} \to K^{\pm}K^{+}K^{-}) = -0.046 \pm 0.009(\mathrm{stat}) \pm 0.005(\mathrm{syst}) \pm 0.007(J/\psi K^{\pm}),$$

Features:

CPV not uniform in the Dalitz plot,

large CPV in the low KK and ππ invariant mass regions

no evidence of large CPV elsewhere

$\mathcal{L}$=1.0 fb^{-1}

$B_{d(s)} \rightarrow K_s hh$ branching ratios

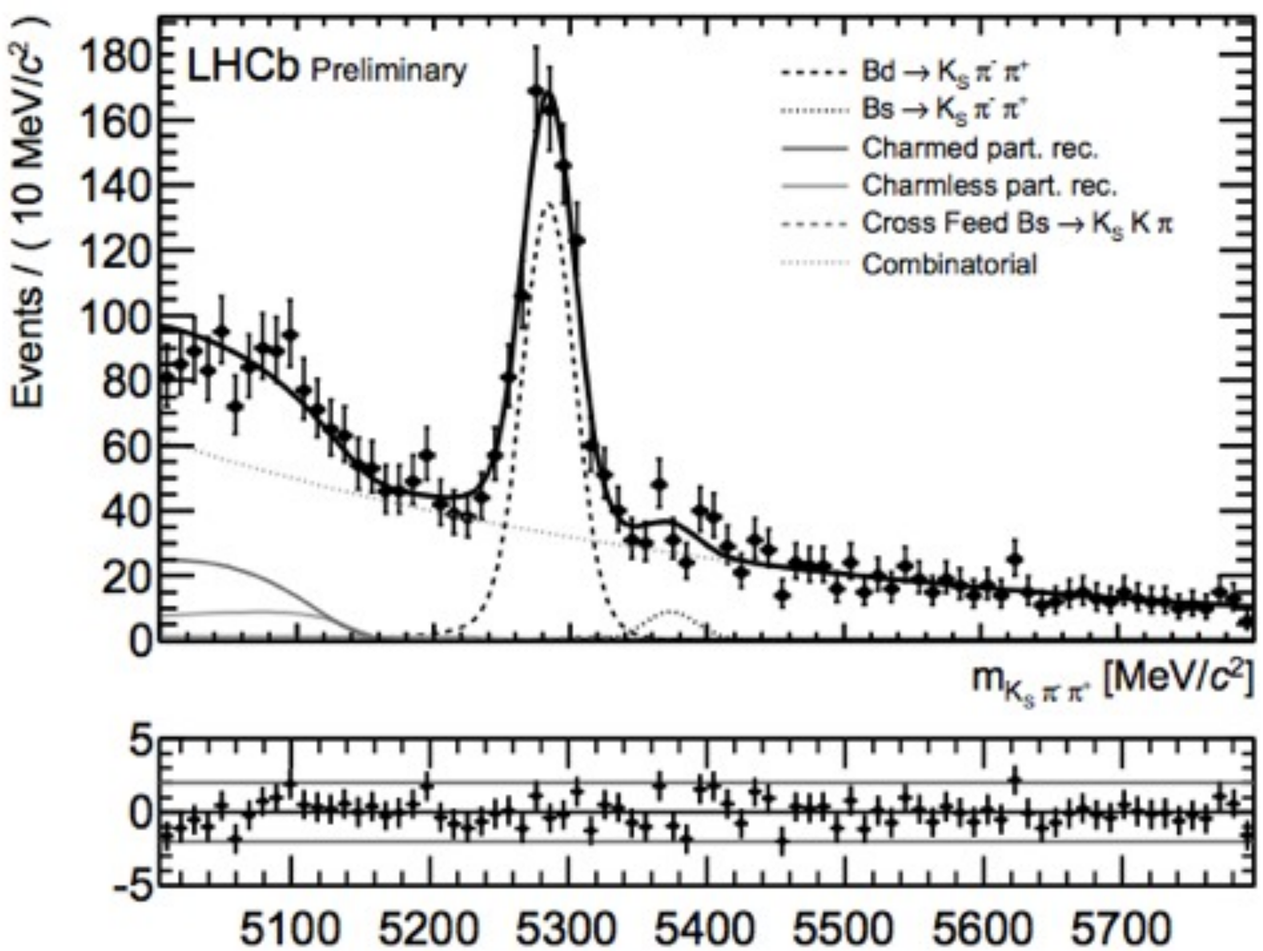
CERN-LHCb-CONF-2012-023

PDG:

Decay mode	Branching fraction (10^{-6}) BaBar	Belle	World average
$B^0 \to K^0\pi^+\pi^-$	50.2 ± 2.3	47.5 ± 4.4	49.6 ± 2.0
$B^0 \to K^0 K^{\pm}\pi^{\mp}$	6.4 ± 1.2	< 18	6.4 ± 1.2
$B^0 \to K^0 K^+ K^-$	23.8 ± 2.6*	28.3 ± 5.2	24.7 ± 2.3

- Search for the three unobserved modes $B_s^0 \to K_S\pi\pi$, $B_s^0 \to K_S K\pi$ and $B_s^0 \to K_S KK$
- Measurement of the branching fractions (BF) relative to the well-established BF of $B^0 \to K_S\pi\pi$ from B-factories
- Potentially, very sensitive to γ angle
- The time-dependent analyses is possible with more statistics

* PDG did not include yet new results from BaBar, arXiv:1201.5897.



$$\frac{\mathcal{B}(B_d^0 \to K_S K \pi)}{\mathcal{B}(B_d^0 \to K_S \pi\pi)} = 0.117 \pm 0.018 \text{ (stat.) } \pm 0.018 \text{ (syst.)}$$

$$\frac{\mathcal{B}(B_d^0 \to K_S K K)}{\mathcal{B}(B_d^0 \to K_S \pi\pi)} = 0.53 \pm 0.04 \text{ (stat.) } \pm 0.04 \text{ (syst.)}$$

$$\frac{\mathcal{B}(B_s^0 \to K_S \pi\pi)}{\mathcal{B}(B_d^0 \to K_S \pi\pi)} = 0.24 \pm 0.06 \text{ (stat.) } \pm 0.04 \text{ (syst.)}$$

$$\frac{\mathcal{B}(B_s^0 \to K_S K \pi)}{\mathcal{B}(B_d^0 \to K_S \pi\pi)} = 1.96 \pm 0.15 \text{ (stat.) } \pm 0.20 \text{ (syst.)}$$

$$\frac{\mathcal{B}(B_s^0 \to K_S K K)}{\mathcal{B}(B_d^0 \to K_S \pi\pi)} = 0.084 \pm 0.031 \text{ (stat.) } \pm 0.019 \text{ (syst.)}$$

- The observation of $B^0 \to K_S K \pi$ by BaBar is confirmed
- The $B^0 \to K_S K K$ result is compatible with the B-factory
- First evidence of the decay $B_s \to K_S \pi\pi$.
- Hint of the $B_s \to K_S K K$.

Summary for three-body decays

LHCb have already provided several results in the field:

Time integrated Bu→hhh:

several first observations of CP violation. Study of asymmetries in localized regions.

Branching ratios measurements for $B_{(s)} \to K_s hh$:

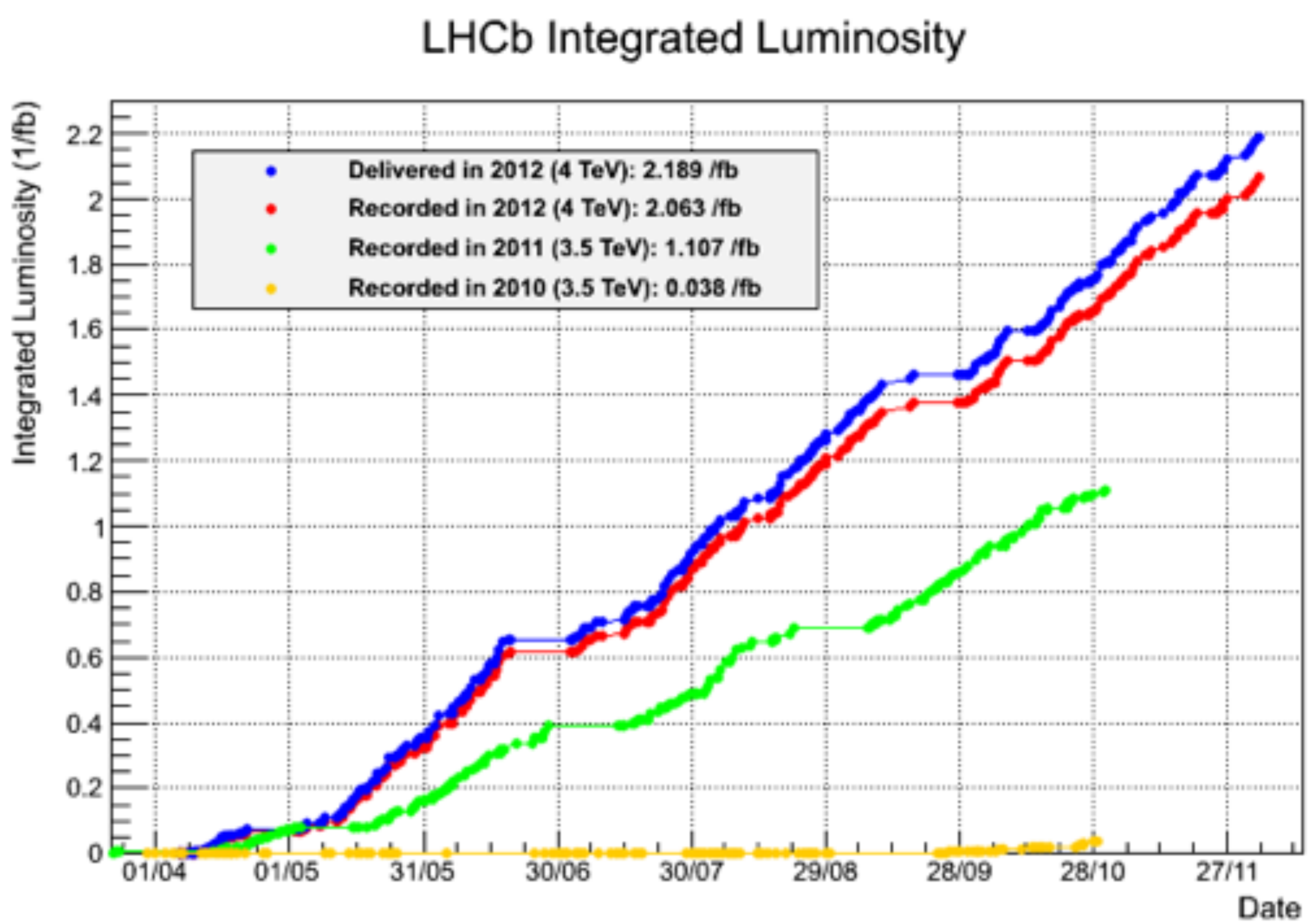
several first observations are made. Good prospects for future analyses

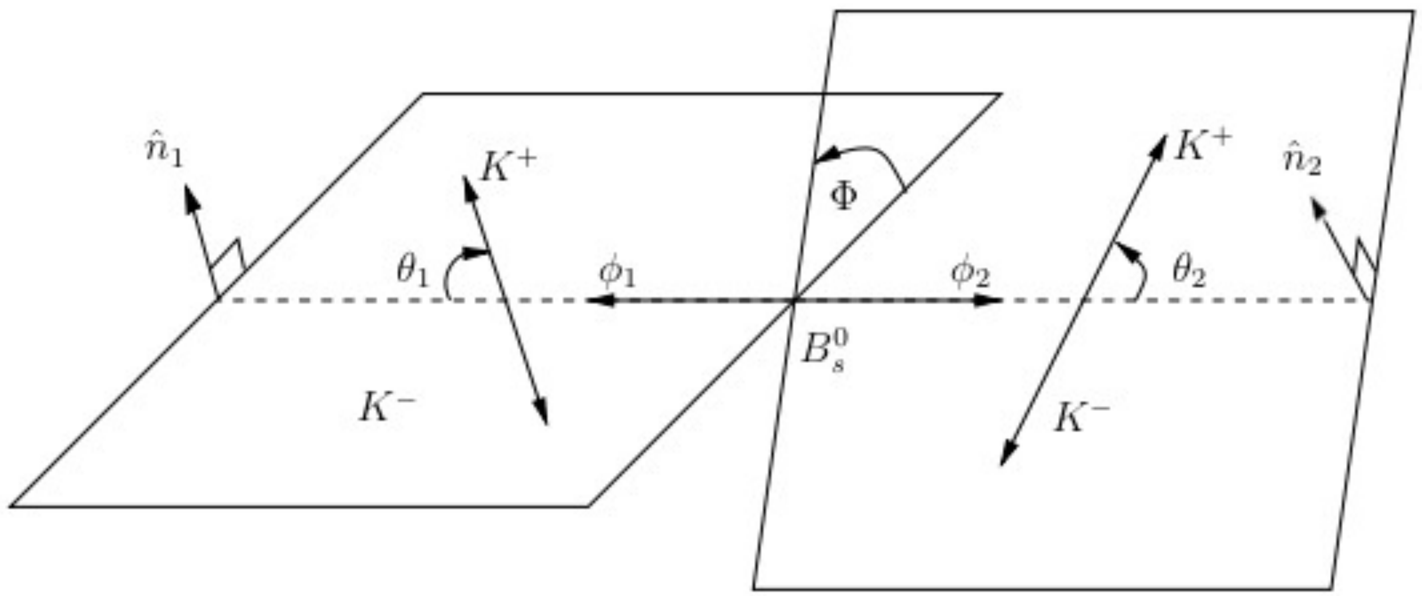
Final Summary

LHCb have already provided several results in the field using 2011 dataset

The performance of detector allowed to produce important analyses with good prospects for the 2012 run.

Looking forward for the data of the 2012 run, where we already have ~2.0 fb^{-1}





The time-dependent differential decay rate for the $B_s \to \phi\phi$ mode can be written as

$$\frac{d^4\Gamma}{d\cos\theta_1 d\cos\theta_2 d\Phi dt} \propto \sum_{i=1}^{6} K_i(t) f_i(\theta_1, \theta_2, \Phi)$$

where

$$\begin{aligned}
f_1(\theta_1,\theta_2,\Phi) &= 4\cos^2\theta_1\cos^2\theta_2\,,\\
f_2(\theta_1,\theta_2,\Phi) &= \sin^2\theta_1\sin^2\theta_2(1+\cos 2\Phi)\,,\\
f_3(\theta_1,\theta_2,\Phi) &= \sin^2\theta_1\sin^2\theta_2(1-\cos 2\Phi)\,,\\
f_4(\theta_1,\theta_2,\Phi) &= -2\sin^2\theta_1\sin^2\theta_2\sin 2\Phi\,,\\
f_5(\theta_1,\theta_2,\Phi) &= \sqrt{2}\sin 2\theta_1\sin 2\theta_2\cos\Phi\,,\\
f_6(\theta_1,\theta_2,\Phi) &= -\sqrt{2}\sin 2\theta_1\sin 2\theta_2\sin\Phi\,.
\end{aligned}$$

In case of validity of SM:

$$\begin{aligned}
K_1 &= |A_0|^2/\Gamma_{\mathrm{L}}\,,\\
K_2 &= |A_\parallel|^2/\Gamma_{\mathrm{L}}\,,\\
K_3 &= |A_\perp|^2/\Gamma_{\mathrm{H}}\,,\\
K_4 &= 0\,,\\
K_5 &= |A_0||A_\parallel|\cos(\delta_\parallel)/\Gamma_{\mathrm{L}}\,,\\
K_6 &= 0\,,
\end{aligned}$$