Direct and mixing-induced CP violation in charmless two-body B decays in LHCb

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INFN-Bologna/CERN

Heavy Quarks and Leptons 2012
Prague
12 June 2012

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.

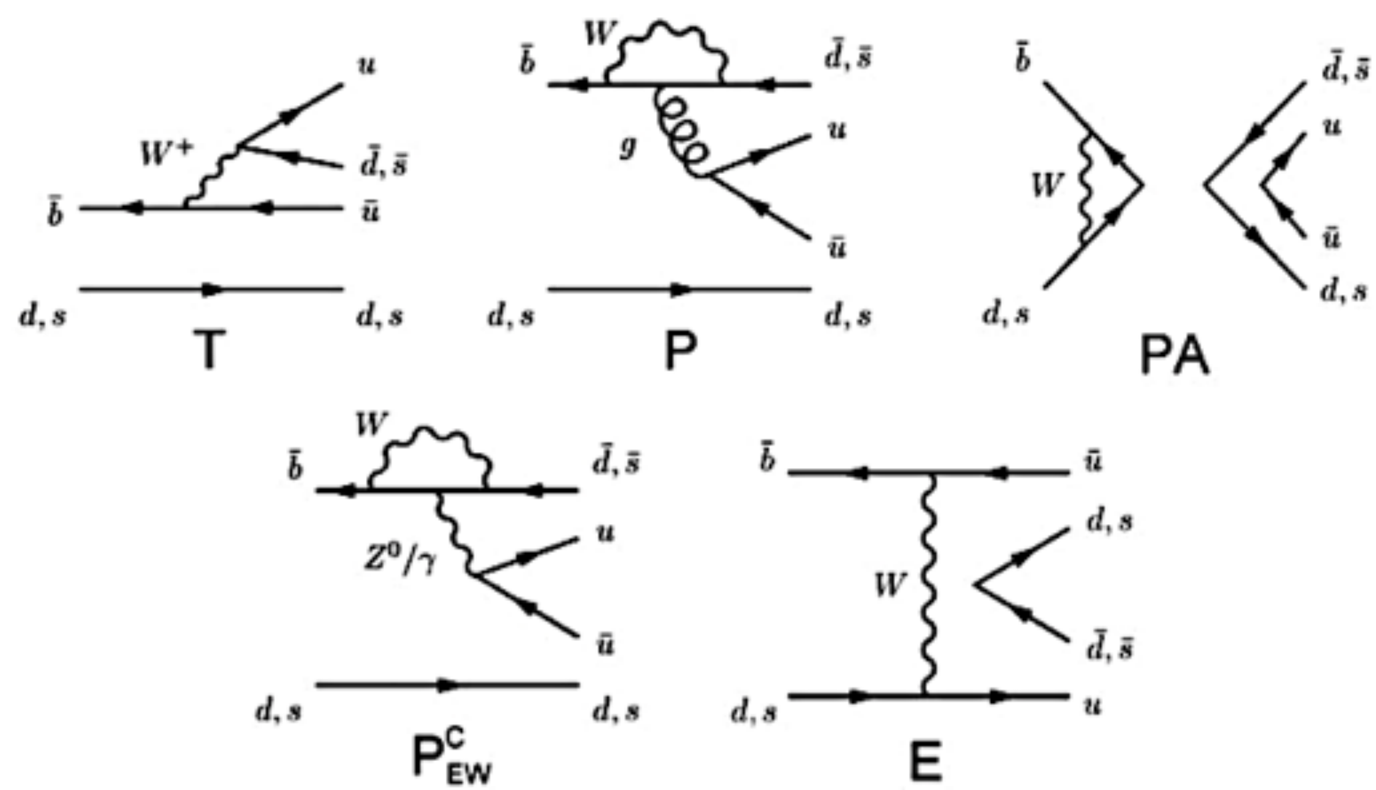
Contribution to $K\pi$-puzzle.

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}

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

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

We define the observables:

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

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

Notice the "difference" in the sign of K and π!

Results before LHCb:

	$A_{CP}(B^0 \to K\pi)$	$A_{CP}(B_s^0 \to \pi K)$
BaBar	$-0.107 \pm 0.016^{+0.006}_{-0.004}$	-
Belle	$-0.094 \pm 0.018 \pm 0.008$	-
CLEO	$-0.04 \pm 0.16 \pm 0.02$	-
CDF	$-0.086 \pm 0.023 \pm 0.009$	$0.39 \pm 0.15 \pm 0.08$
HFAG 2010	$-0.098^{+0.012}_{-0.011}$	0.39 ± 0.17

Time-integrated Analysis Steps

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.

Variable	$A_{CP}(B^0 \to K\pi)$	$A_{CP}(B_s^0 \to K\pi)$
Track quality χ^2/ndf	< 3	< 3
Track p_T [GeV/c]	> 1.1	> 1.2
Track d_{IP} [mm]	> 0.15	> 0.20
$\max(p_T^K, p_T^\pi)$ [GeV/c]	> 2.8	> 3.0
$\max(d_{IP}^K, d_{IP}^\pi)$ [mm]	> 0.3	> 0.4
d_{CA} [mm]	< 0.08	< 0.08
p_T^B [GeV/c]	> 2.2	> 2.4
d_{IP}^B [mm]	< 0.06	< 0.06
$t_{\pi\pi}$ [ps]	> 0.9	> 1.5

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

Exclusive event samples selected under ππ, Kπ, KK, pK, pπ daughter mass hypothesis.

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 in fact "raw" asymmetries (depend on the *B* production asymmetries and detection asymmetries).

Time Integrated Asymmetries Extraction

We introduce correction A_Δ to the measured asymmetries:

$$A_{CP} = A^{\mathrm{raw}} - A_\Delta \,,$$

where

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

Corrections:

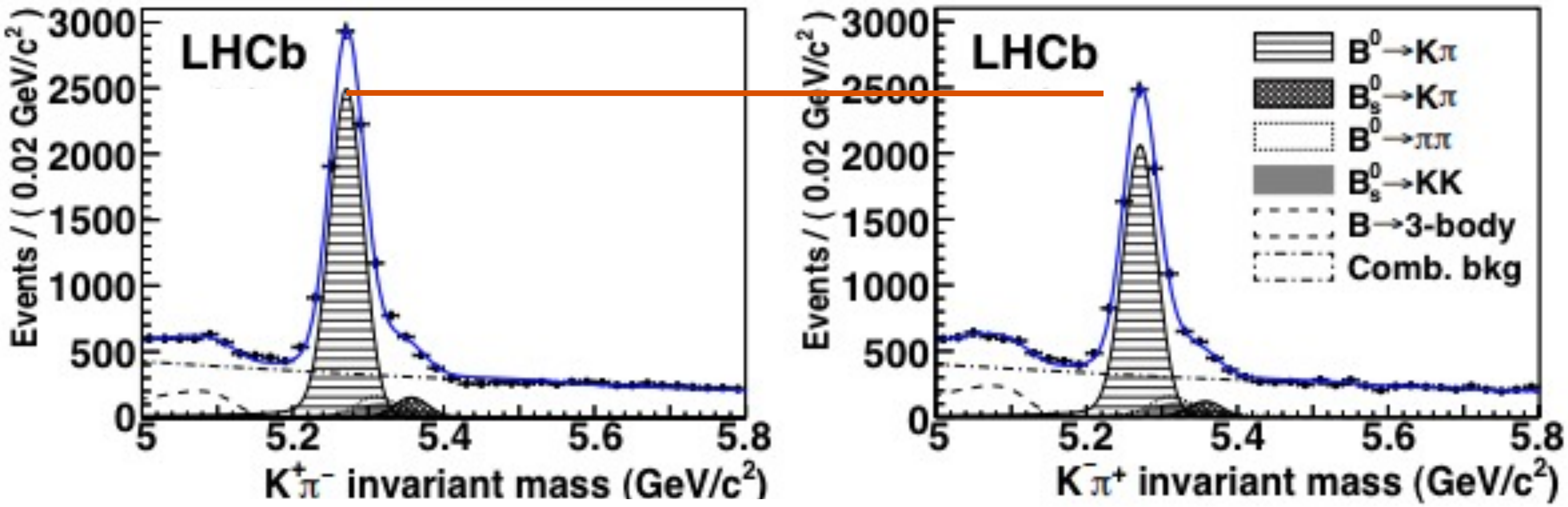
Detection asymmetry part: estimated from the tagged and untagged decays of $D \to hh$, $\zeta=+1$ for B_d and $\zeta=-1$ for B_s.

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

$$A_\Delta(B_d \to K\pi) = (-0.7 \pm 0.6)\%$$
$$A_\Delta(B_s \to \pi K) = (1.0 \pm 0.2)\%$$

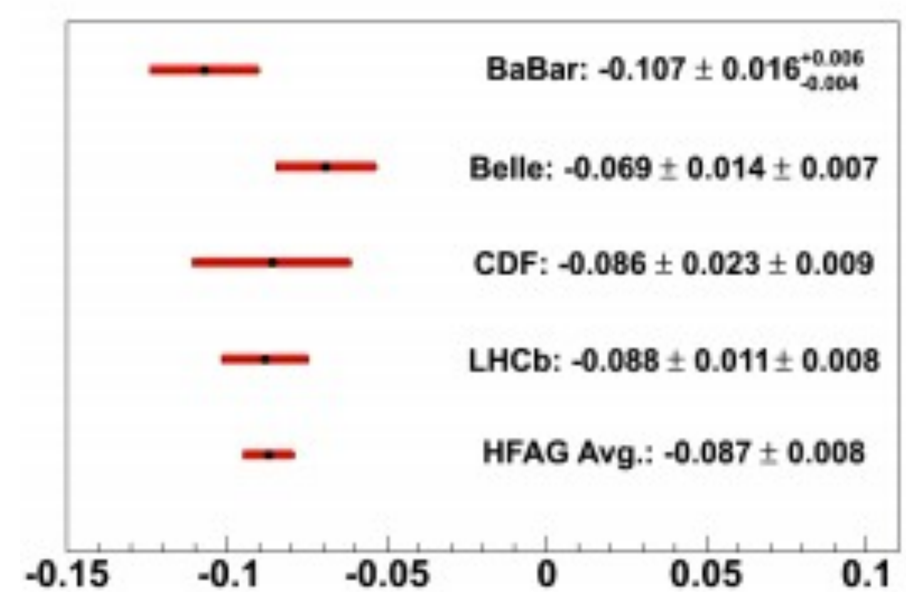
The asymmetry in the *B* and $\overline{B}$ decays can be seen by eye.

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



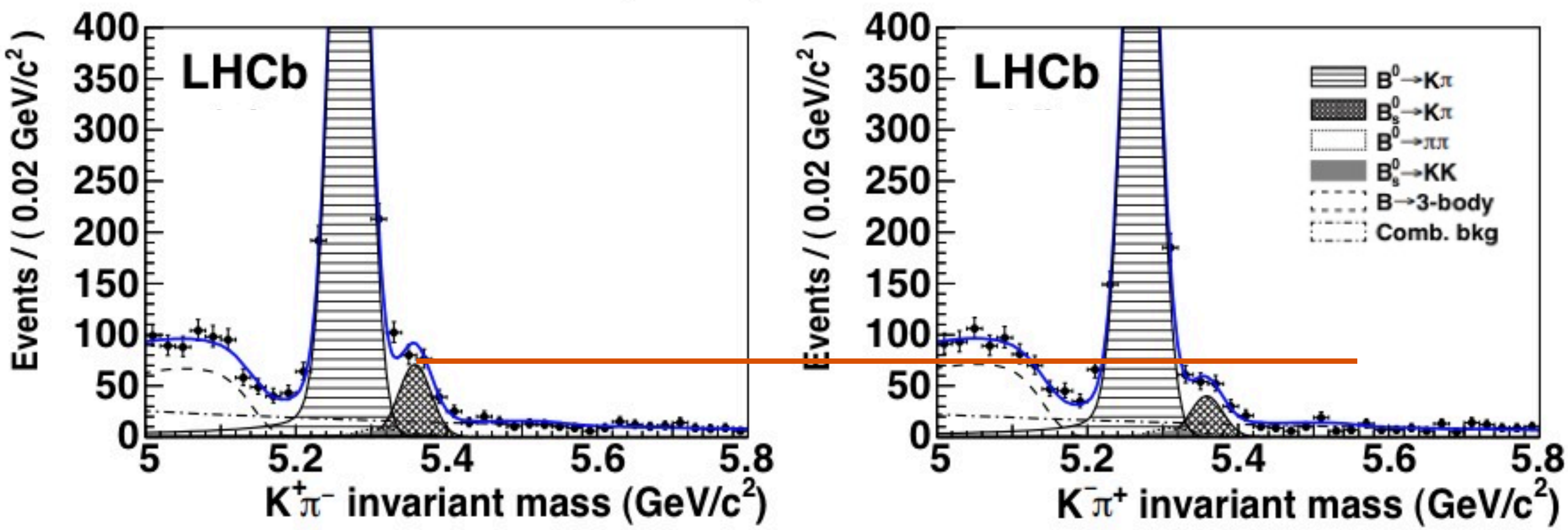
$$A_{CP}(B^0 \to K\pi) = -0.088 \pm 0.011\,(\text{stat}) \pm 0.008\,(\text{syst})$$

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



$B_s \to \pi K$ Time Integrated Asymmetries

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



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

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

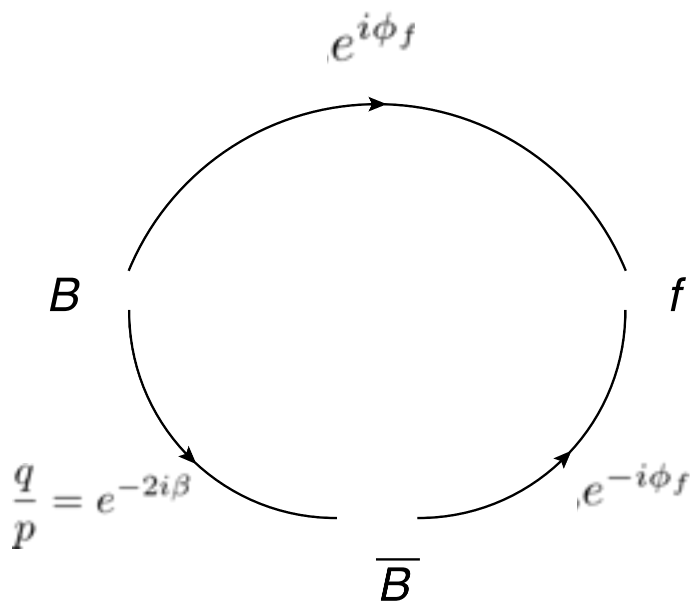
In agreement with CDF result: $A_{CP}(B_s \to \pi K) = 0.39 \pm 0.15 \pm 0.08$

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



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

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

A_{dir} : direct CPV from decay.

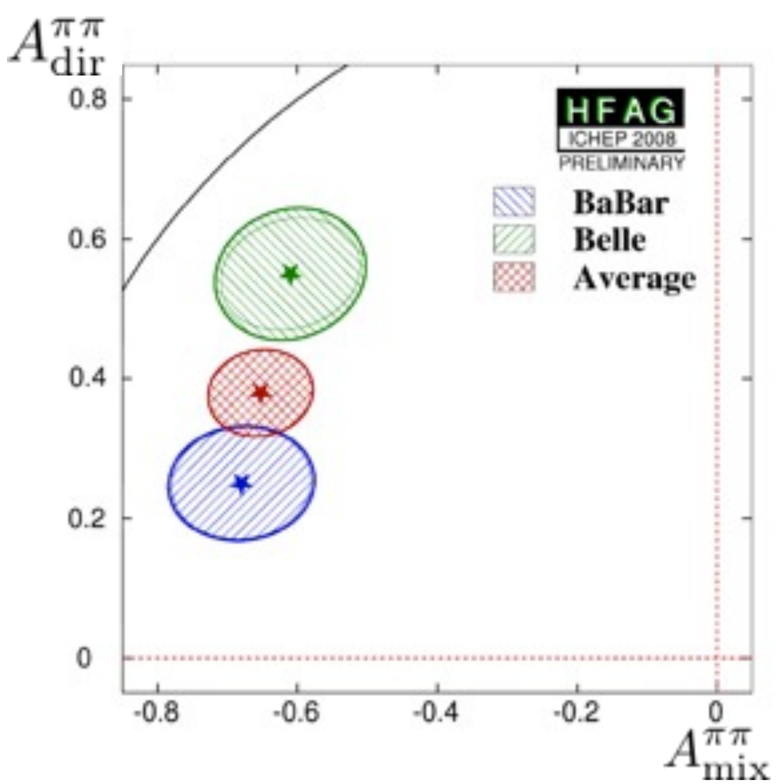
A_{mix}: mixing CPV in the decay.

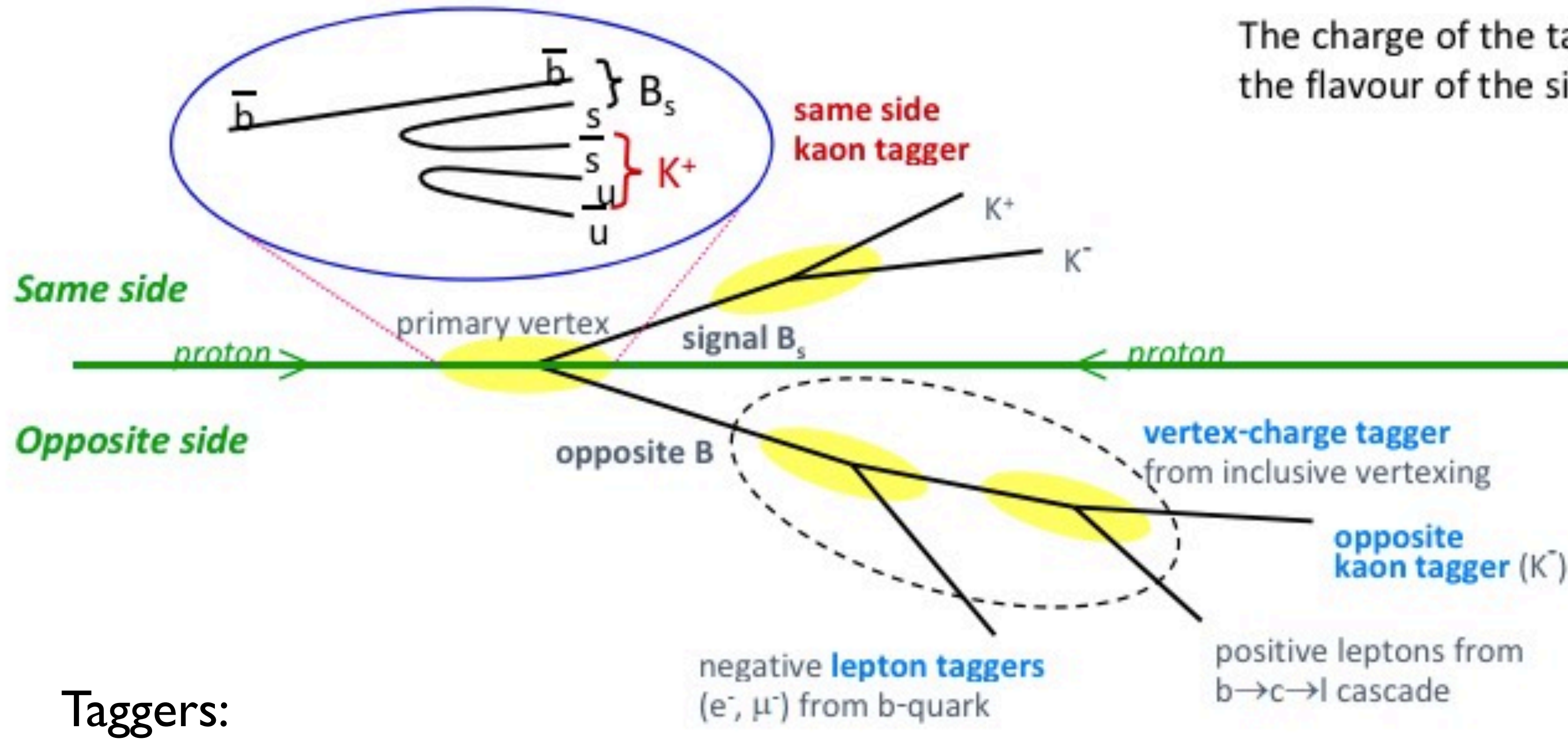
$$A^2_{\text{dir}} + A^2_{\text{mix}} + A^2_{\Delta} = 1$$

Situation before LHCb:

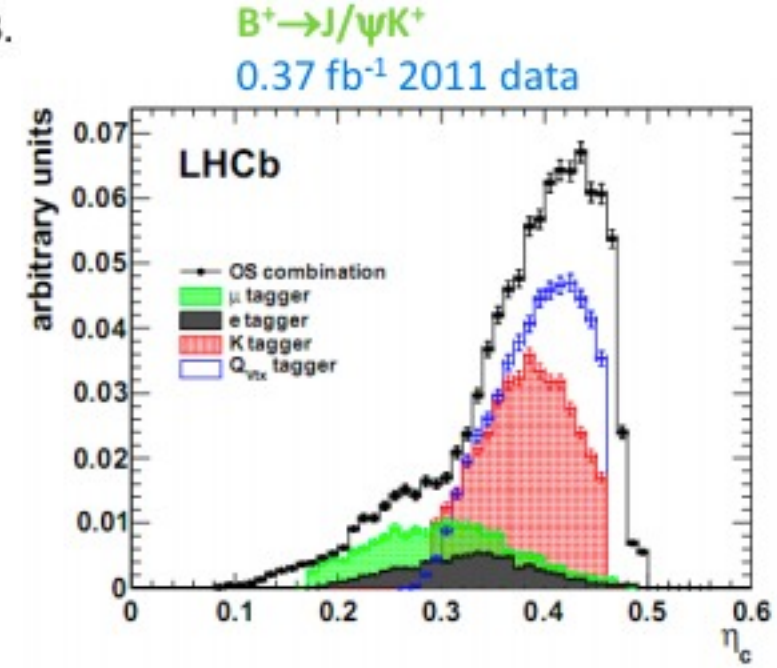
$B_d \to \pi\pi$: BaBar and Belle have measured A_{dir} and A_{mix}. The agreement is good for A_{mix}.

$B_s \to KK$: No measurement has been performed yet.





The charge of the tagger tags the flavour of the signal B.



Taggers:

Opposite side taggers: Exploit the decay products of the other b hadron: lepton (e or μ); kaon; overall charge of secondary vertex.

Same side taggers: π (for B_d or B_u) or K (for B_s) produced at the fragmentation process of the signal B.

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

We characterize tagging performance by mistag rate, ω_{mistag}, and tagging efficiency, ε_{tag}.
In this talk only Opposite side taggers are used.

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

The $B_d \to K\pi$ decay:

- flavor specific final state
- copious
- same decay dynamics as channels under study.

Thus, we use it to calibrate the tagging performance for this analysis.

Selection stays the same as in time-integrated case.

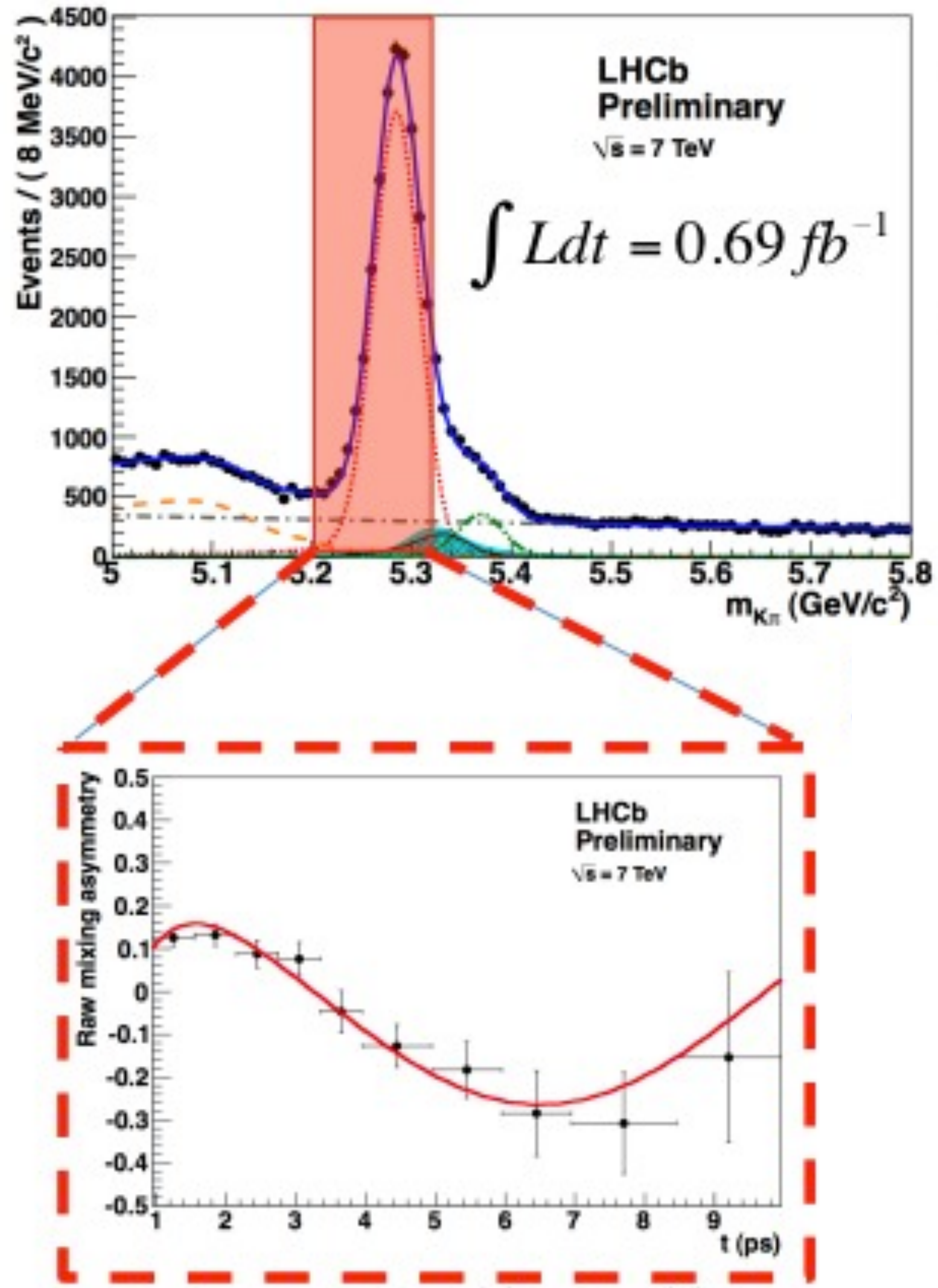
2D Maximum likelihood fit to mass and decay time used to extract the performance of the tagger combinations.

OS tagging power: $\varepsilon_{eff} = \varepsilon_{tag}(1-2\omega)^2 = (2.3 \pm 0.1)\%$

We are also able to measure:

$\Delta m_d = (0.484 \pm 0.019)\ ps^{-1}$
$\tau(B^0) = (1.509 \pm 0.011)\ ps$
(only statistical errors)

Which is in agreement with world averages



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

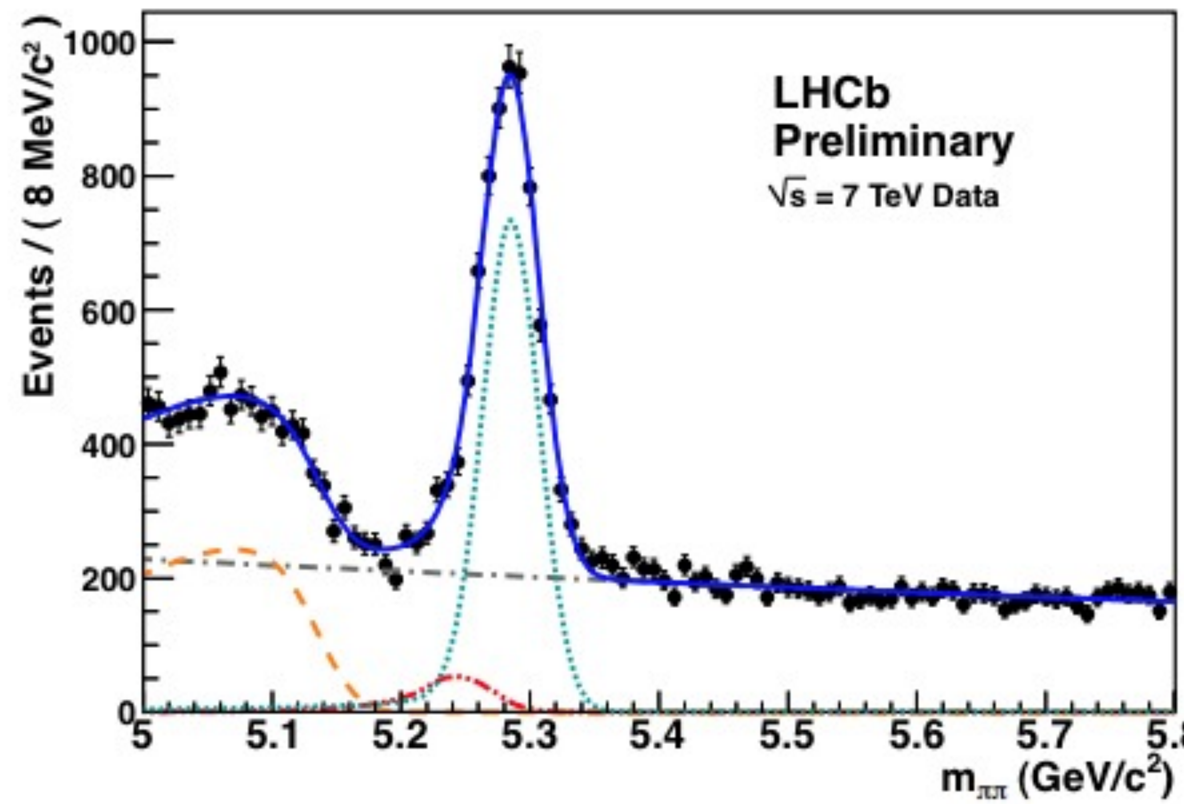
N_{sig}~5.4k events

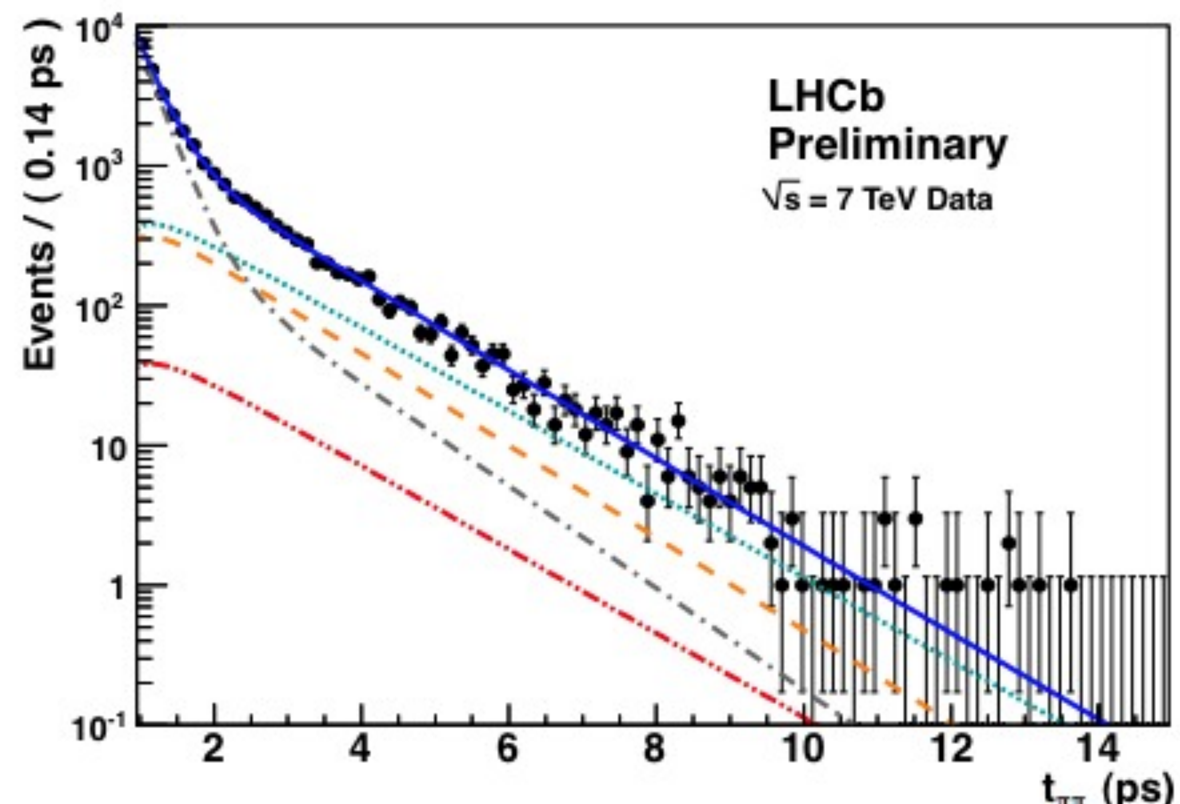
ω_{mistag} likelihood is taken from the $B_d \to K\pi$ channel

Results:

$$A^{dir}_{\pi\pi} = 0.11 \pm 0.21 \pm 0.03$$
$$A^{mix}_{\pi\pi} = -0.56 \pm 0.17 \pm 0.03$$
$$\rho(A^{dir}_{\pi\pi},\, A^{mix}_{\pi\pi}) = -0.34.$$

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

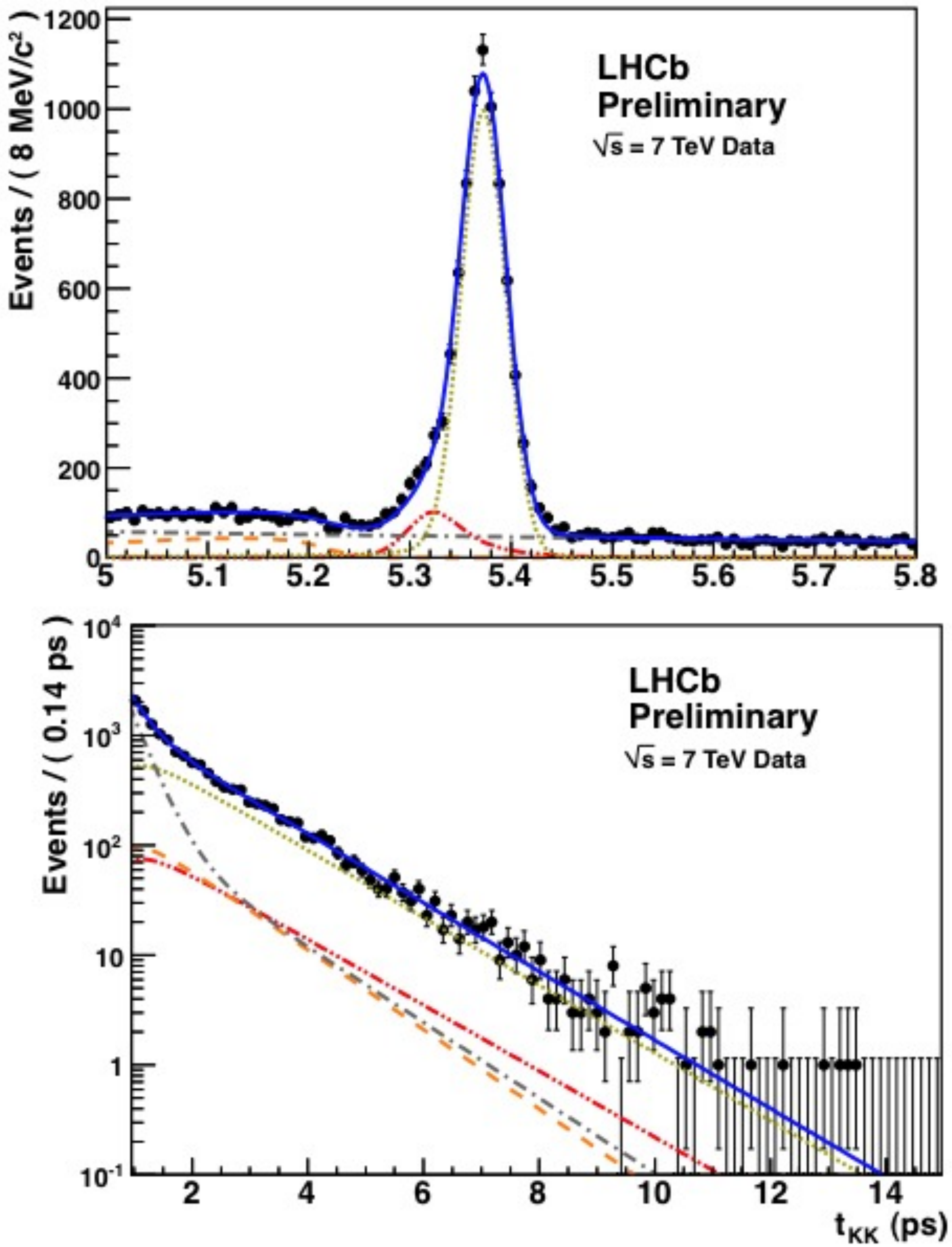
N_{sig}~7.1k events

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

Results (First measurement!):

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

- Full fit
- $B_s \to KK$ signal
- $B \to 3h$ bkg
- $B_d \to K\pi$ bkg
- comb bkg



Our results:

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

A_{dir} = 0.11±0.21±0.03
A_{mix} = -0.56±0.23±0.03

$B_s \to K^+K^-$

A_{dir} = 0.02±0.18±0.04
A_{mix} = 0.17±0.18±0.05

Old HFAG world averages:

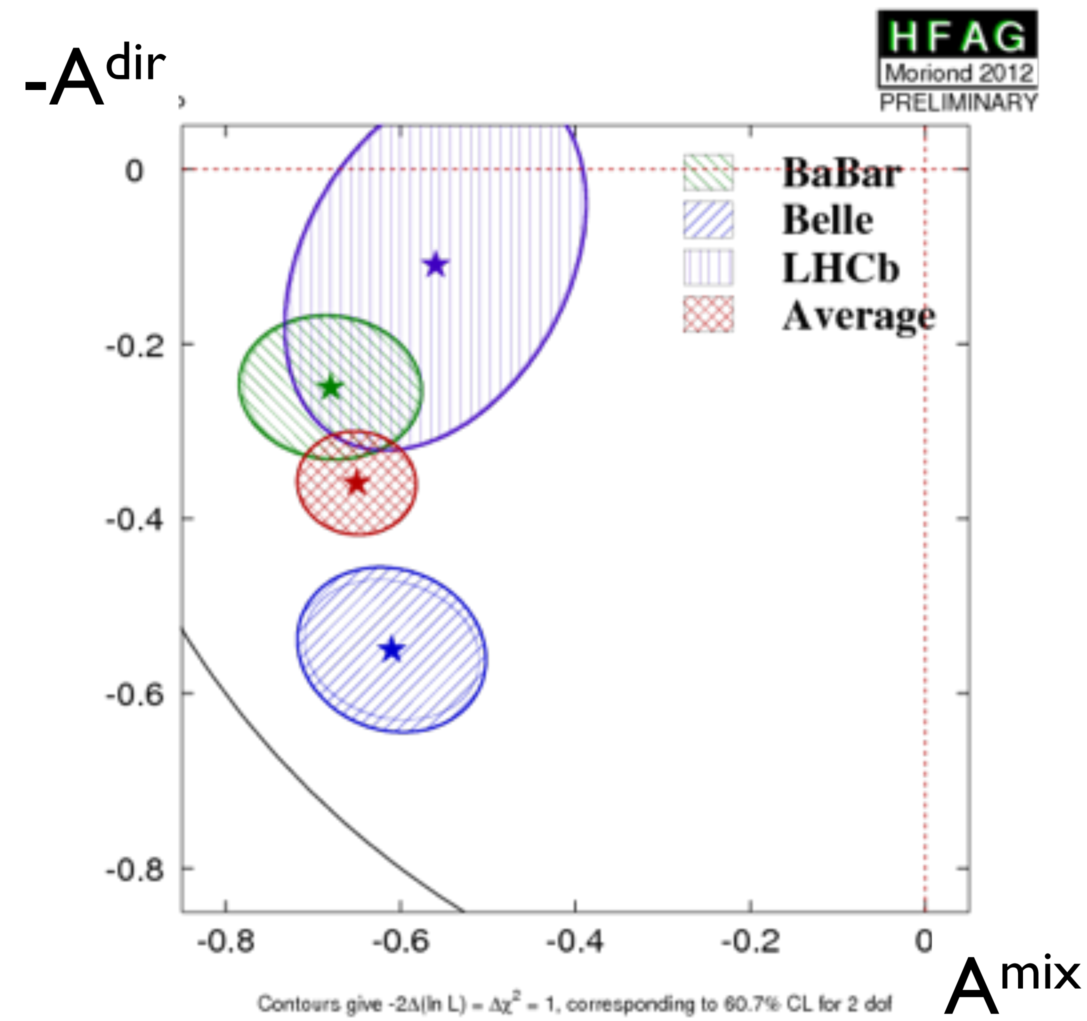
	$\mathcal{A}^{dir}_{\pi^+\pi^-}$	$\mathcal{A}^{mix}_{\pi^+\pi^-}$
BaBar	$0.25 \pm 0.08 \pm 0.02$	$-0.68 \pm 0.10 \pm 0.03$
Belle	$0.55 \pm 0.08 \pm 0.05$	$-0.61 \pm 0.10 \pm 0.04$
Average	0.38 ± 0.06	-0.65 ± 0.07

U-spin symmetry implies:

$A_{dir}(B_d \to \pi\pi) \sim A_{CP}(B_s \to \pi K)$=0.27±0.08±0.02
$A_{dir}(B_s \to KK) \sim A_{CP}(B_d \to K\pi)$=-0.088±0.011±0.008

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

A_{dir} = 0.36 ± 0.06
A_{mix} = -0.65 ± 0.07

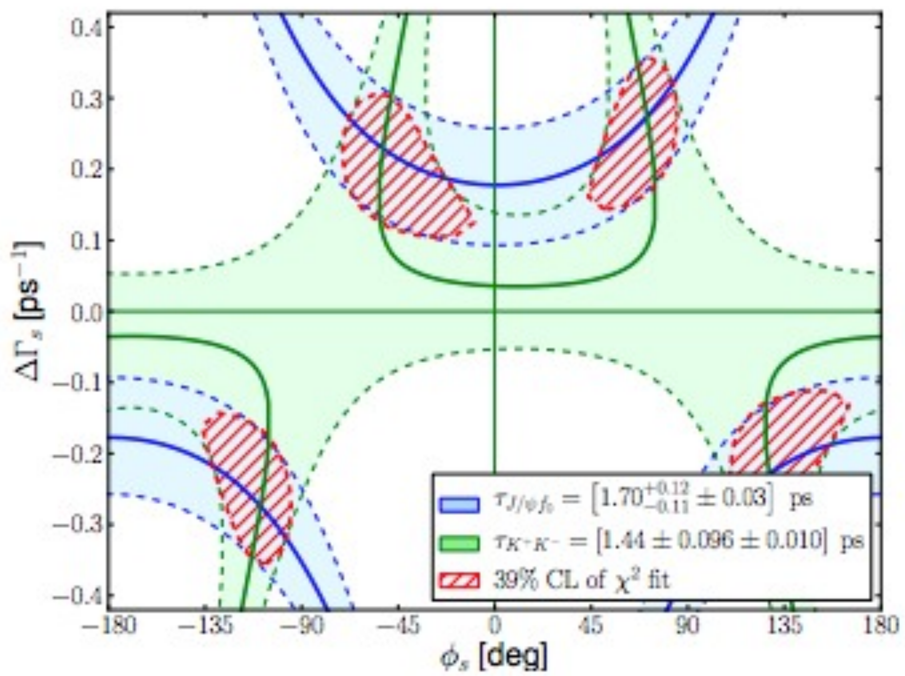


Preliminary

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

$B_s \rightarrow KK$ Effective Lifetime Measurement

CERN-LHCb-CONF-2012-001



Comparison between *CP* even and *CP* odd lifetimes is useful to constrain the *CP* violation parameters

Fleischer, Knegjens arXiv:1109.5115

The untagged decay time distribution can be written as:

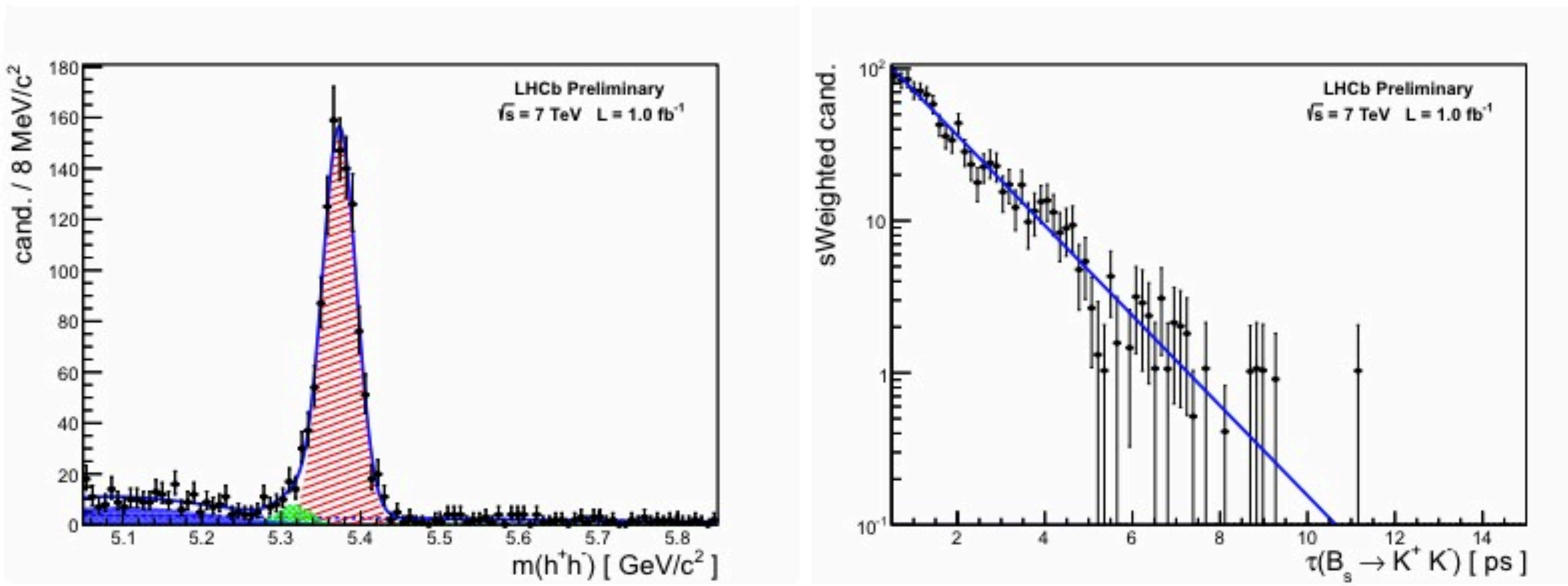
$$\Gamma(t) \;\propto\; (1 - \mathcal{A}_{\Delta\Gamma_s})\, e^{-\Gamma_L t} + (1 + \mathcal{A}_{\Delta\Gamma_s})\, e^{-\Gamma_H t}\,.$$

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

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

with $y_s \equiv \dfrac{\Delta\Gamma_s}{2\Gamma_s}$, 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



$$\tau_{KK} = 1.468 \pm 0.046 \text{ (stat.)} \pm 0.006 \text{ (syst.) ps},$$

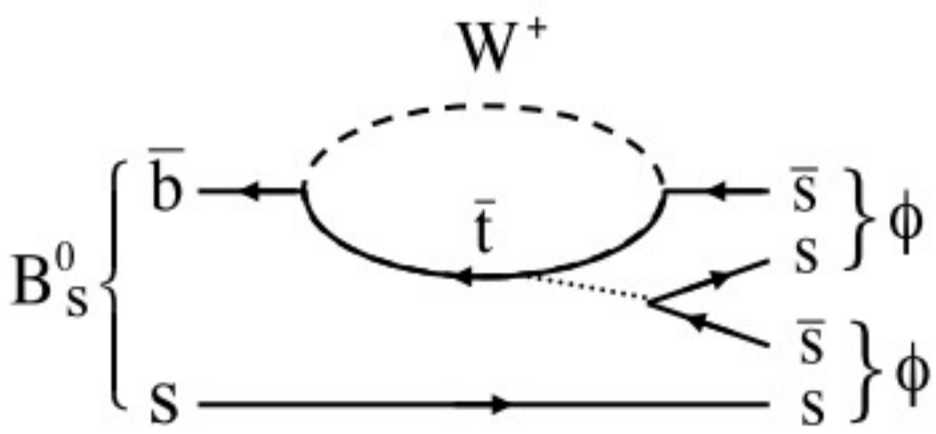
Which can be compared to the SM predictions:

$$\tau_{KK}^{SM} = (1.390 \pm 0.032) \text{ ps}.$$

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

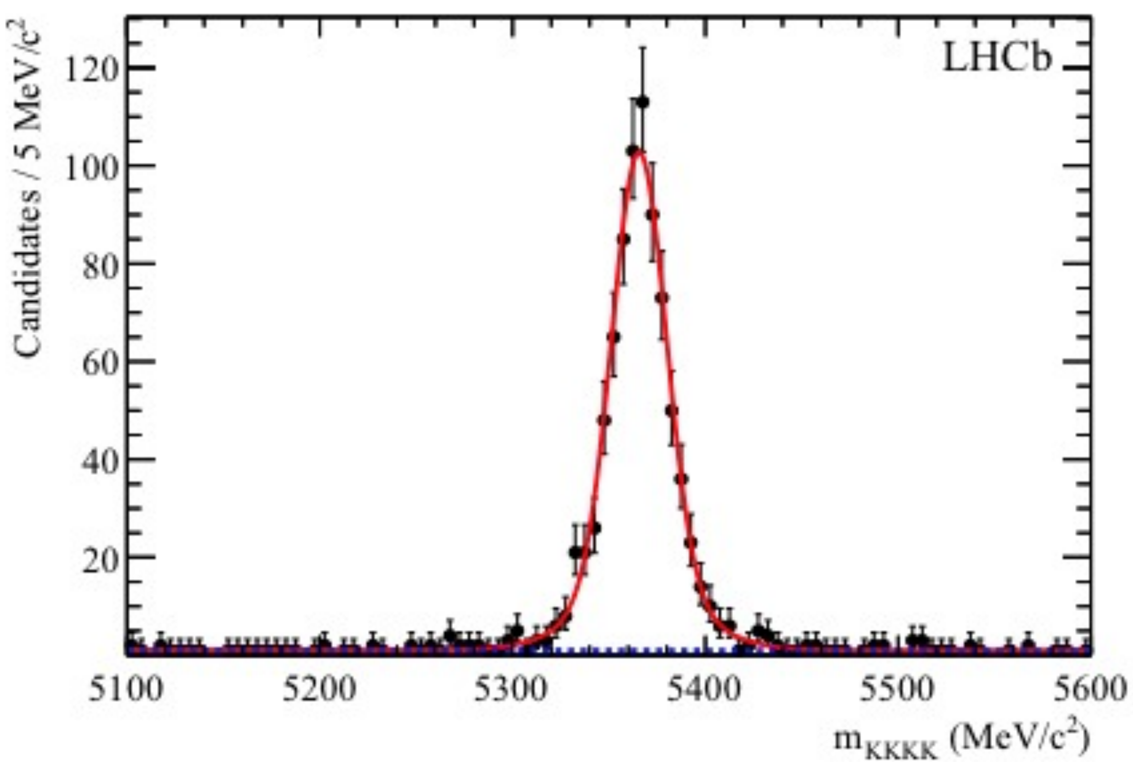
$B_s \to \phi\phi$ Triple Decay Asymmetries and Polarization Amplitudes

LHCb-PAPER-2012-004, arXiv:1204.2813,
accepted to Phys. Lett. B



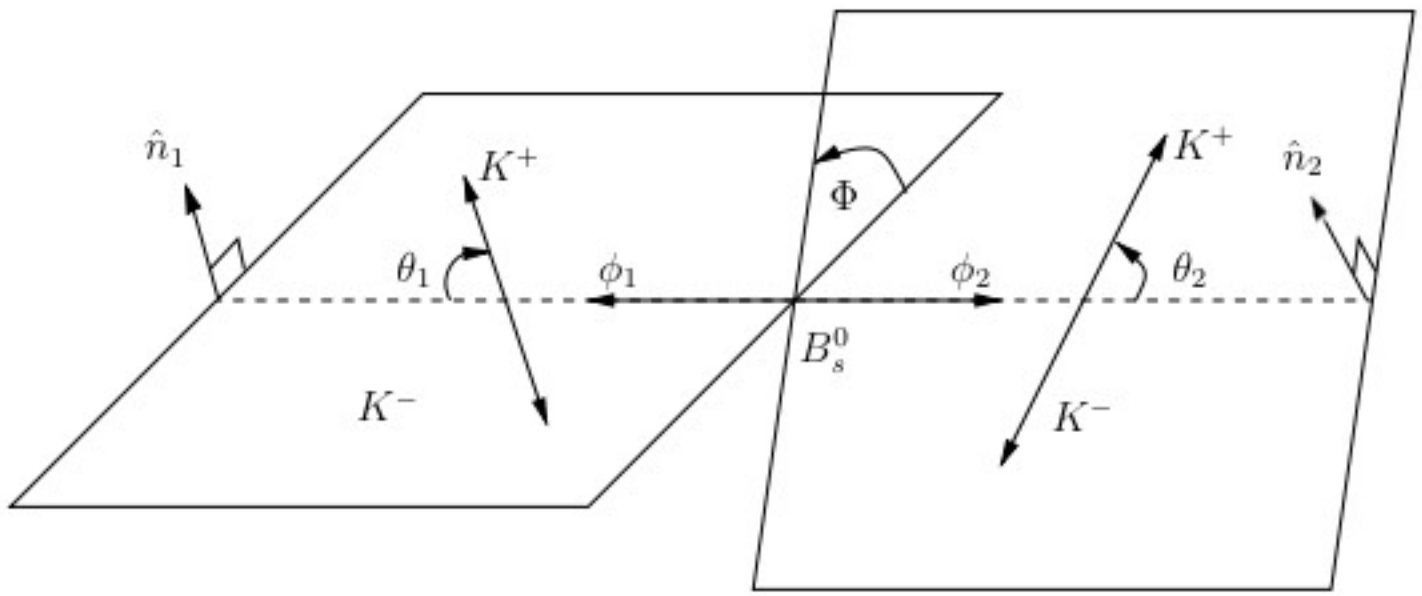
b→q$\bar{q}$ s penguin transitions are sensitive to new physics in decay amplitude
Bs→ϕϕ is a Golden mode for probing CP violating weak phase ϕs in hadronic Bs decays

Variable	Value
Track χ^2/ndf	$<$ 5
Track p_T	$>$ 500 MeV/c
Track IP χ^2	$>$ 21
$\Delta \ln \mathcal{L}_{K\pi}$	$>$ 0
$\|M_\phi - M_\phi^{PDG}\|$	$<$ 12 MeV/c^2
${p_T}^{\phi 1}$, ${p_T}^{\phi 2}$	$>$ 900 MeV/c
${p_T}^{\phi 1} \cdot {p_T}^{\phi 2}$	$>$ 2 GeV^2/c^2
ϕ vertex χ^2/ndf	$<$ 24
B^0_s vertex χ^2/ndf	$<$ 7.5
B^0_s vertex separation χ^2	$>$ 270
B^0_s IP χ^2	$<$ 15



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.



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

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

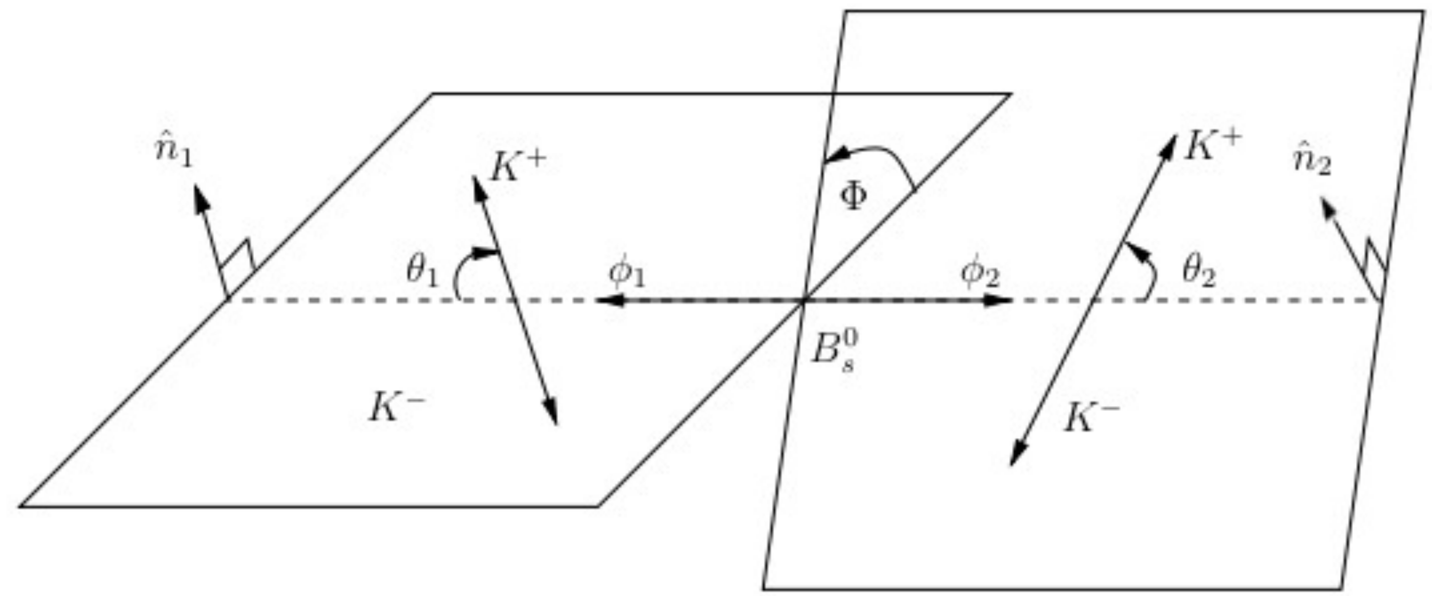
In case of validity of SM:

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

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:

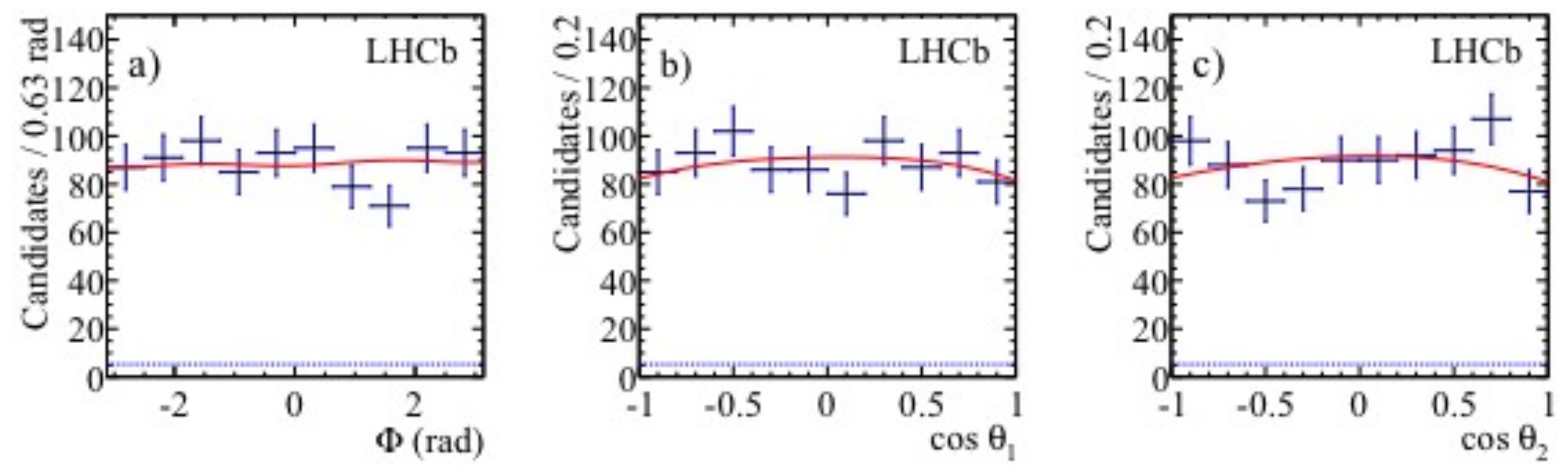
$$A_U = \frac{N_+ - N_-}{N_+ - N_-} \qquad A_V = \frac{M_+ - M_-}{M_+ - M_-}$$

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.

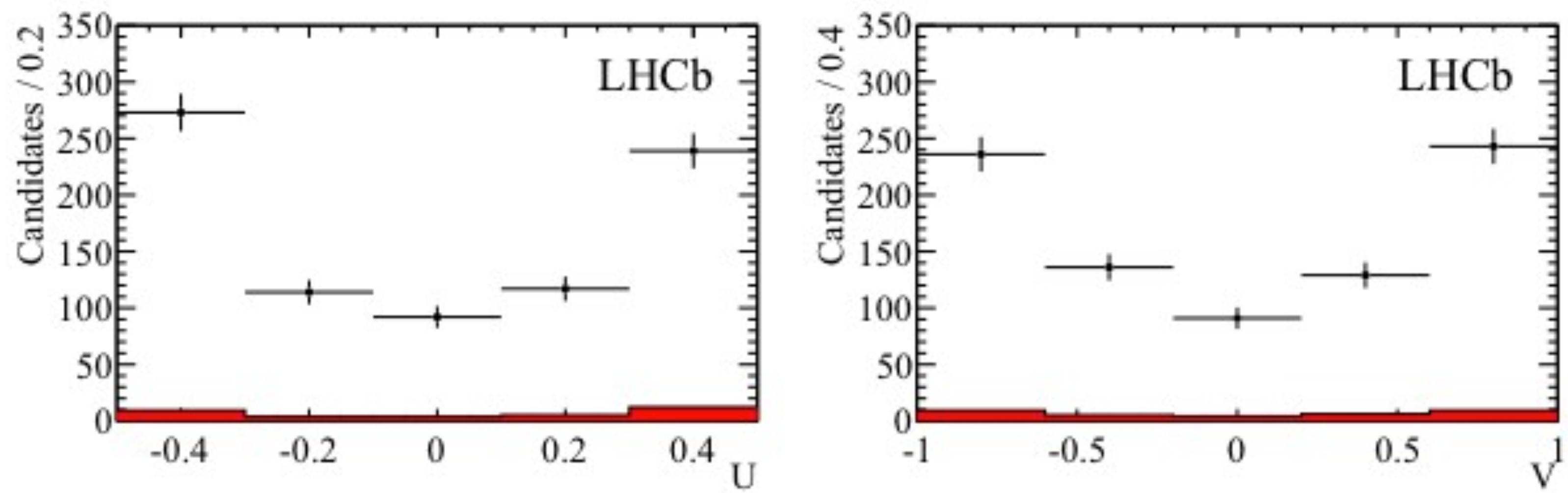
With lifetime constrained from $B_s \to J/\psi\phi$:

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



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

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



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

Summary

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

Looking forward for the data of the 2012 run, where we expect to collect ~1.5 fb^{-1}