CPV Measurements at LHCb

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on behalf of LHCb collaboration

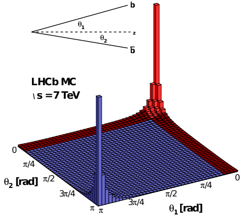
XLth International Meeting on Fundamental Physics

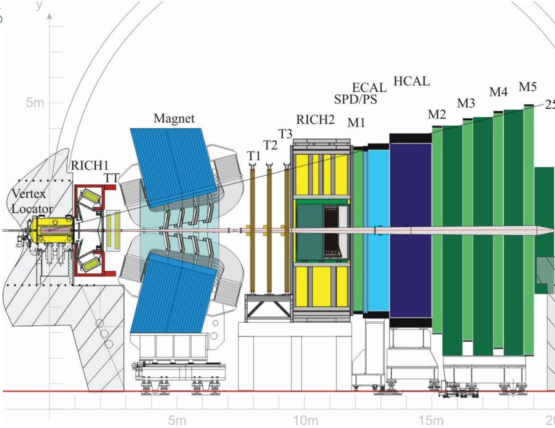
Benasque, May 25 - June 02, 2012

Universitat de Barcelona

1. LHCb
2. CPV in beauty
   - CPV in $B^{\pm} \to DK^{\pm}$
   - A_{CP} in $B^0 \to K^*\gamma$
   - CPV phase ϕ_s from $B_s^0 \to J/\psi X$
   - CPV in $B \to hh$
3. CPV in charm
   - $D^0 \to \pi^+\pi^-$ and $D^0 \to K^+K^-$
   - Search for CP violation in $D^+ \to K^+K^-\pi^+$

- Designed for CP violation and rare decays of heavy mesons
- Single arm forward spectrometer, $b\bar{b}$ pair production correlated, 40 % in the acceptance.
- Unique kinematic region (among the LHC experiments): high rapidity ($2 < \eta < 5$) and able to access low p_T
- Excellent momentum resolution and PID
- Huge amount of $b\bar{b}$ and $c\bar{c}$ produced in the LHCb Acc: $\sigma(b\bar{b})_{LHCb} = 75.3 \pm 5.4 \pm 13.0\,\mu$b $\sigma(c\bar{c})_{LHCb} = 1742 \pm 267\,\mu$b

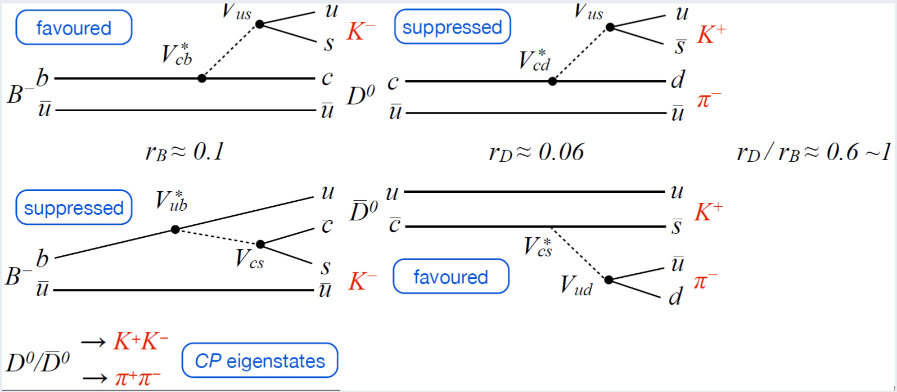




beautiful CPV

- CPV in $B^{\pm} \to DK^{\pm}$
- A_{CP} in $B^0 \to K^* \gamma$
- CPV phase ϕ_s from $B_s^0 \to J/\psi X$
- CPV in $B \to hh$

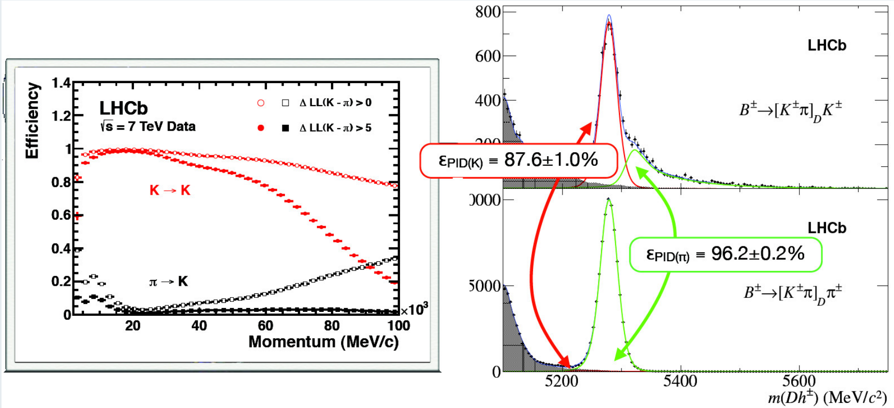
- CPV in $B^{\pm} \to DK^{\pm}$: PLB 712 (2012) 203-212



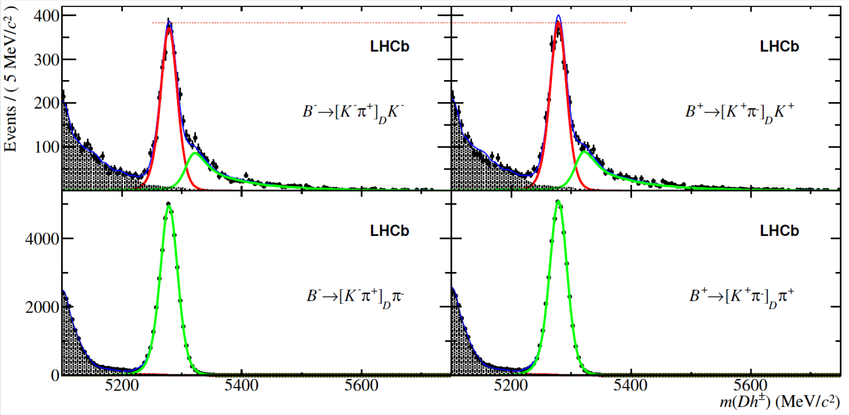
CP modes: $B^- \to DK^-$ and $D \to KK, \pi\pi$
ADS modes: $B^- \to DK^-$ and $D \to K^+\pi^-$ [PRL 78 (1997) 3257]
Favoured mode: $B^- \to DK^-$ and $D \to K^-\pi^+$ (favoured)

1^{st} simultaneous anlysis of $B^\pm \to D_{CP}h^\pm$ and $B^\pm \to D_{ADS}h^\pm$ $\Leftarrow$ motivated by the future extraction of γ.
Gives access to 7 ratios (not discussed here) and 6 A_{CP}

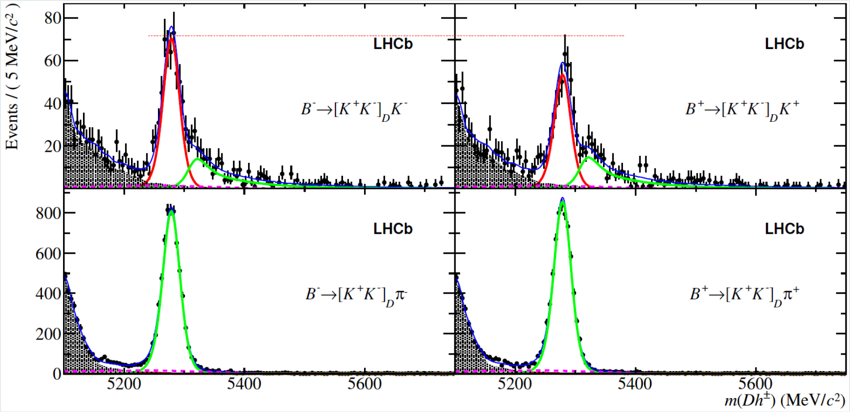
Observation of CPV in $B^\pm \to DK^\pm$

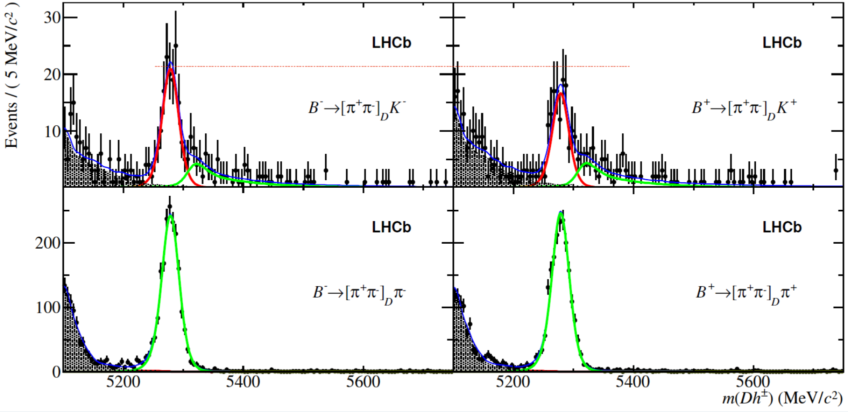


- Key point, the PID: thanks to our RICHs !
- Cross feed (double misID in ADS mode): Vetoed in a swap mass hypothesis method → cross feed rate: 6×10^{-5}


Events / (5 MeV/c²)
400
300
200
100
LHCb
B⁻→[K⁻π⁺]_D K⁻
LHCb
B⁺→[K⁺π⁻]_D K⁺
4000
2000
0
LHCb
B⁻→[K⁻π⁺]_D π⁻
LHCb
B⁺→[K⁺π⁻]_D π⁺
5200
5400
5600
5200
5400
5600
m(Dh±) (MeV/c²)

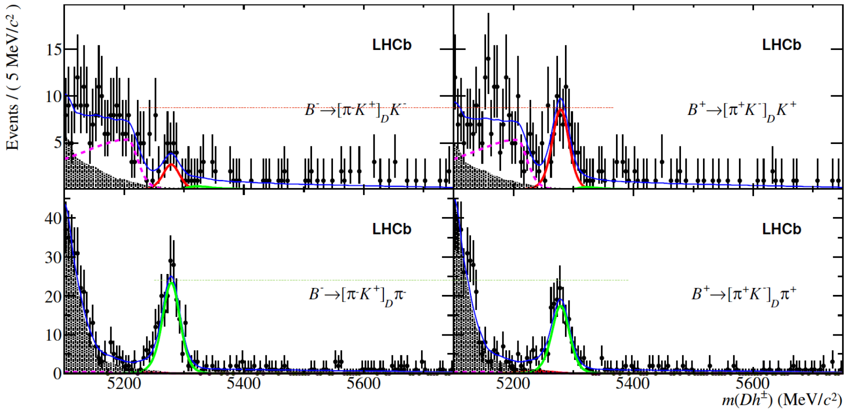
KK mode


Events / (5 MeV/c^2)
LHCb
$B^- \to [K^+K^-]_D K^-$
LHCb
$B^+ \to [K^+K^-]_D K^+$
LHCb
$B^- \to [K^+K^-]_D \pi^-$
LHCb
$B^+ \to [K^+K^-]_D \pi^+$
$m(Dh^\pm)$ (MeV/c^2)



- $A(B^- \to [K^+K^-]_D K^-) \& A(B^- \to [\pi^+\pi^-]_D K^-)$

$\Rightarrow A_{CP+} = (14.5 \pm 3.2 \pm 1.0)\,\% \; : \; 4.5\sigma$



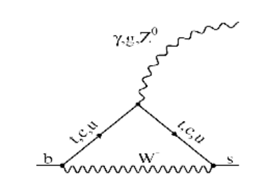
First Observation of $B^\pm \to [\pi^\pm K]_D K^\pm$ in the ADS mode (10σ):
$\mathcal{B}(B^\pm \to [\pi^\pm K]_D K^\pm) \approx (2.2 \pm 0.3) \times 10^{-7}$

$A_{ADS(\pi)} = (14.3 \pm 6.2 \pm 1.1)\%$: 2.4σ and $A_{ADS(K)} = (-52 \pm 15 \pm 2)\%$: 4.0σ

$A_{ADS(K)} \& A_{CP+} \Rightarrow CPV@5.8\sigma$

- A_{CP} in $B^0 \to K^*\gamma$: LHCb-CONF-2012-004

- Study the $b \to s\gamma$ transition. NP can arise in new particles contributing to the loop.
- Small value predicted by the SM: $A_{CP}^{\mathrm{SM}} = -0.0061 \pm 0.0043$
- Measurement by BaBar [PRL 103, 211802 (2009)]: $A_{CP}^{\mathrm{BaBar}} = -0.0016 \pm 0.0022 \pm 0.007$ Stat. limited.



The raw A_{CP} measured in data:

$A_{CP} = A_{CP}^{raw} - A_D(K\pi) - \kappa A_P$

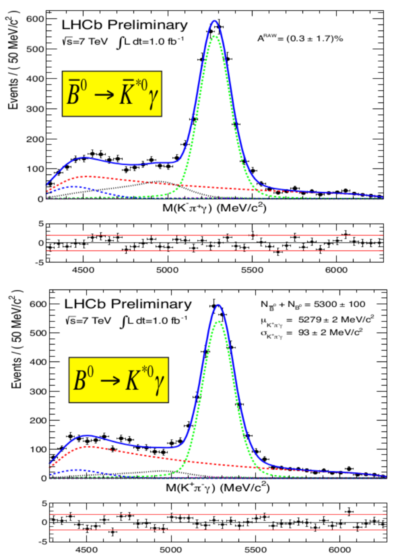
- $A_D(K\pi)$ and A_P: Detection and B^0 production asymmetry (from control channels)
- κ: dilution factor due to B^0 oscillation

Measurement done on $\int \mathcal{L} = 1.0\,\text{fb}^{-1}$

Total yield: $N_{B^0} + N_{\overline{B}^0} = 5300 \pm 100$

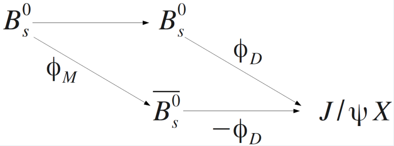
$A_{CP} = -0.008 \pm 0.017(\text{stat.}) \pm 0.009(\text{syst.})$

Systematic dominated by background model, $b\overline{b}$ production asymmetry in pp collisions and $(K^+\pi^-)/(K^-\pi^+)$ detection asymmetry



- CPV phase ϕ_s from $B_s^0 \to J/\psi X$: arXiv:1204.5675, arXiv:1112.3183, LHCb-CONF-2012-002

CPV phase ϕ_s from $B_s \to J/\psi X$



- Measure relative phase difference:

  $\phi_s = \phi_M - 2\phi_D$

- In SM, normal conventions and ignoring penguins:

  $\phi_D \sim 0$

  $\phi_s^{\mathrm{SM}} = \phi_M$

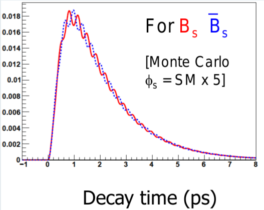
  predicated to be small (~ -0.04) and predominantly determined by arg(V_{ts}) [$\phi_s = -2\arg(\mathrm{V_{ts}V_{tb}^*/V_{cs}V_{cb}^*})$]

- New Physics can add large phases: $\phi_s = \phi_s^{\mathrm{SM}} + \phi_s^{\mathrm{NP}}$
- $B_s \to J/\psi\Phi$ and $B_s \to J/\psi\pi\pi$: very clean decays
- But requires time-dependent, flavour tagged, angular analysis

- differential decay rate for $B_s \to f_{\rm odd}$:

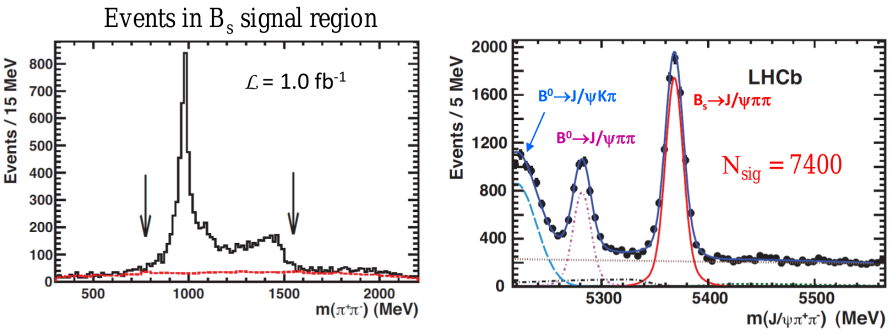
$$\Gamma(B_s^0 \to f_{\rm odd}) = \frac{\mathcal{N}}{2} e^{-\Gamma_s t} \left\{ e^{\Delta\Gamma_s t/2}(1+\cos\phi_s) + e^{-\Delta\Gamma_s t/2}(1-\cos\phi_s) - \sin(\phi_s)\sin(\Delta m_s t) \right\},$$

$$\Gamma(\overline{B}_s^0 \to f_{\rm odd}) = \frac{\mathcal{N}}{2} e^{-\Gamma_s t} \left\{ e^{\Delta\Gamma_s t/2}(1+\cos\phi_s) + e^{-\Delta\Gamma_s t/2}(1-\cos\phi_s) + \sin(\phi_s)\sin(\Delta m_s t) \right\}.$$



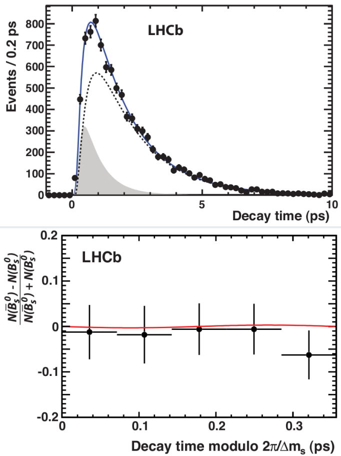
- Signal is sinusoidal time distribution:
  - Amplitude proportional to $\sin(\phi_s)$
  - Opposite sign for B and $\bar{B} \Rightarrow$ must Tag (using opposite side: $\epsilon_{\rm tag} \sim 33\,\%$)
  - Diluted by wrong tagging probability ($\omega_{\rm tag} \sim 36.8\,\%$)
  - Diluted by detector resolution (σ_t)
- What we measure: $\sin(\phi_s) \times D(\sigma_t) \times (1-\omega_{\rm tag}) \times \sin(\Delta m_s t)$

- LHCb updated ϕ_s measurement with $1.0\,\text{fb}^{-1}$.
- $m(\pi\pi)$ [775,1550] MeV. The statistics is doubled with respect to the events only in $f_0(980)$ peak region. 7421 ± 105 events.
- Boosted Decision Tree selection is used.

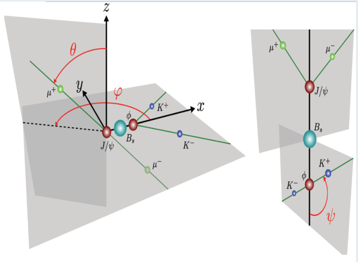


- Simultaneously fit tagged and untagged events
- $\Delta\Gamma_s$ and Γ_s constrained to LHCb's measurements in $J/\psi\phi$.
- $\Delta m_s = 17.63 \pm 0.11 \pm 0.02\,\text{ps}^{-1}$ constrained to LHCb's measurements in $B_s \to D_s(3)\pi$, [PLB 709 (2012) 177]

$$\phi_s^{J/\psi\pi\pi} = -0.019^{+0.173}_{-0.174}(\text{stat.})^{+0.004}_{-0.003}(\text{syst.})\text{rad}$$

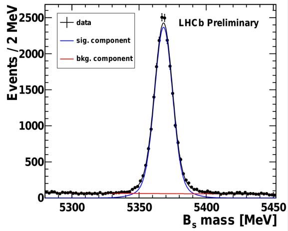


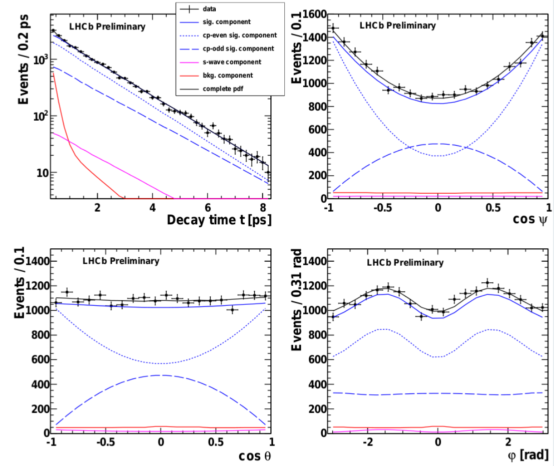
- Decay to CP-odd and CP-even final states, $\to$ need analysis of decay angle distribution



Transversity angles $\Omega = \{\theta, \phi, \psi\}$

- but much larger BR: $J/\psi\phi / J/\psi\pi\pi \sim 5$
- Differential cross section is "very rich":
  - 3 P-wave amplitudes of KK system $(A_\perp, A_0, A_\parallel)$
  - 1 S-wave amplitude (A_S)
  - 10 terms with all interferences $\Gamma_s, \Delta\Gamma_s, \Delta m_s, \phi_s, |A_0|^2, |A_\perp|^2, \delta_\parallel, \delta_\perp, |A_S|^2, \delta_S$
- ... but fundamentally for ϕ_s we still measure: $\sin(\phi_s) \times D(\sigma_t) \times (1 - \omega_{\text{tag}}) \times \sin(\Delta m_s t)$
- and because we separate the terms, we measure the lifetimes of Heavy and Light eigenstates separately: $\Delta\Gamma_s$ and Γ_s





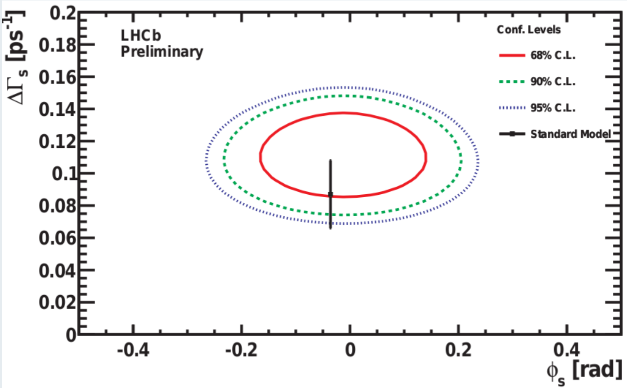
- Simple selection with kinematic cuts
- Most background removed by decay time cut $t > 0.3\,\mathrm{ps}$
- Clean signal
- Approx. 21200 signal events

- Maximum likelihood fit to signal + background time, angle and mass distributions.
- Constrain Δm_s to $17.63 \pm 0.11\,\text{ps}$

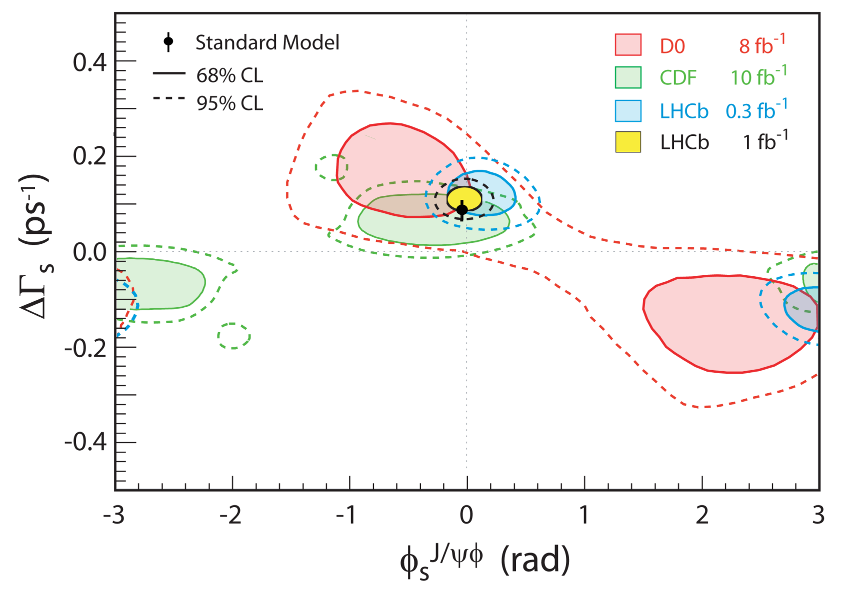
Parameter	Value	Stat.	Syst.
$\Gamma_s\,[\text{ps}^{-1}]$	0.6580	0.0054	0.0066
$\Delta\Gamma_s\,[\text{ps}^{-1}]$	0.116	0.018	0.006
$\lvert A_\perp(0)\rvert^2$	0.246	0.010	0.013
$\lvert A_0(0)\rvert^2$	0.523	0.007	0.024
F_S	0.022	0.012	0.007
$\delta_\perp\,[\text{rad}]$	2.90	0.36	0.07
$\delta_\perp\,[\text{rad}]$	[2.81, 3.47]		0.13
$\delta_s\,[\text{rad}]$	2.90	0.36	0.08
$\phi_s\,[\text{rad}]$	-0.001	0.202	0.027

- ϕ_s uncorrelated with other quantities

	Γ_s	$\Delta\Gamma_s$	$\lvert A_\perp\rvert^2$	$\lvert A_0\rvert^2$	ϕ_s
Γ_s	1.00	-0.38	0.39	0.20	-0.01
$\Delta\Gamma_s$		1.00	-0.67	0.63	-0.01
$\lvert A_\perp(0)\rvert^2$			1.00	-0.53	-0.01
$\lvert A_0(0)\rvert^2$				1.00	-0.02
ϕ_s					1.00



$$
\begin{aligned}
\Gamma_s &= 0.6580 \pm 0.0054(\text{stat.}) \pm 0.0066(\text{syst.})\,\text{ps}^{-1} \\
\Delta\Gamma_s &= 0.116 \pm 0.018(\text{stat.}) \pm 0.006(\text{syst.})\,\text{ps}^{-1} \\
\phi_s &= -0.001 \pm 0.101(\text{stat.}) \pm 0.027(\text{syst.})\,\text{rad}
\end{aligned}
$$


Standard Model
68% CL
95% CL
D0 8 fb^{-1}
CDF 10 fb^{-1}
LHCb 0.3 fb^{-1}
LHCb 1 fb^{-1}
0.4
0.2
0.0
-0.2
-0.4
$\Delta\Gamma_s$ (ps^{-1})
-3
-2
-1
0
1
2
3
$\phi_s^{J/\psi\phi}$ (rad)

ϕ_s: $B_s^0 \to J/\psi\phi$ and $B_s^0 \to J/\psi\pi\pi$

- Used a simultaneous fit to both datasets, taking all common parameters and correlations into account
- Used largest syst. error.

$$\phi_s = -0.002 \pm 0.083(\text{stat.}) \pm 0.027(\text{syst.})\,\text{rad}$$

- CPV in $B \to hh$: PLB 707 (2012), arXiv:1202.6251, LHCb-CONF-2012-007, LHCb-PAPER-2011-029

Direct CP asymmetry in $B_{d,s} \to K\pi$: LHCb-PAPER-2011-029

- Interference of tree and loop diagrams.
- Potentially sensitive to new physics.

Time dependent CP violation in $B \to hh$: LHCb-CONF-2012-007

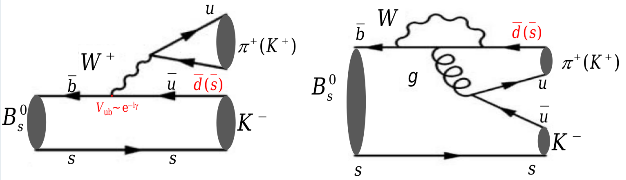
- Sensitive to β, β_s and γ.
- First measurement for $B_s^0 \to KK$.

$B_s^0 \to KK$ effective lifetime: LHCb [PLB 707 (2012)] , LHCb-CONF-2012-001

- Sensitive to $\Delta\Gamma_s$ and ϕ_s.
- Two measurements: 2010 and 2011 datasets.

Interference of tree and loop diagrams.

- Potentially sensitive to new physics.
- A_{CP} in $B_d^0 \to K\pi$ is established.
- Consider B_s^0 system: 14 times lower decay rate, 4 times lower production rate.

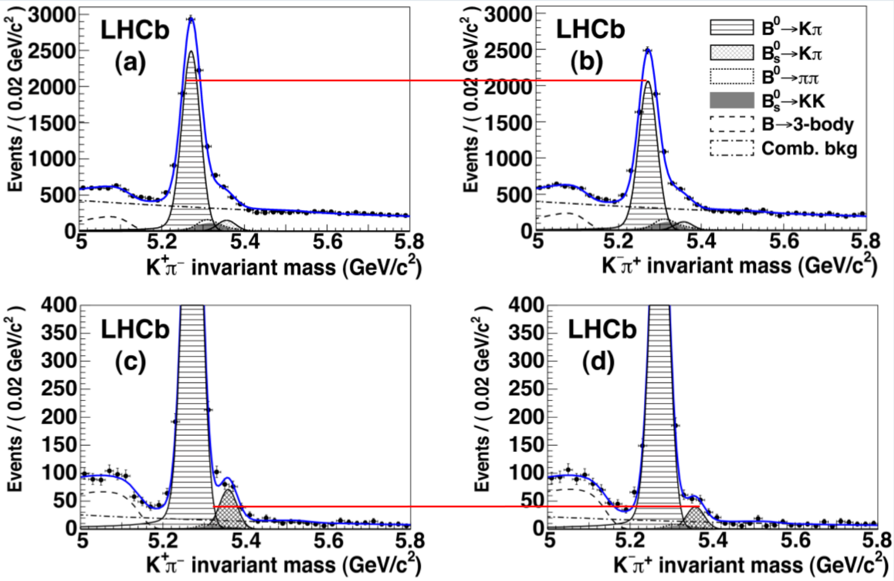


Direct A_{CP} defined as: $A_{CP} = \frac{\Gamma(\overline{B}_{(s)} \to \bar{f}_{(s)}) - \Gamma(B_{(s)} \to f_{(s)})}{\Gamma(\overline{B}_{(s)} \to \bar{f}_{(s)}) + \Gamma(B_{(s)} \to f_{(s)})}$

The raw A_{CP} measured in data: $A_{CP} = A_{CP}^{raw} - A_D(K\pi) - \kappa A_P$

- $A_D(K\pi)$: Instrumental asymmetry studied with D^* and D^0 decays.
- A_P: B^0 production asymmetry studied with $B^0 \to J/\psi(\mu\mu)K^*(K\pi)$
- κ: dilution factor due to B^0 oscillation

$B_{d,s} \to K\pi$: mass distributions



Results with $\int \mathcal{L} = 0.35\,\mathrm{pb}^{-1}$:

$$A_{CP}(B_d^0 \to K\pi) = (-8.8 \pm 1.1(\text{stat.}) \pm 0.8(\text{syst.}))\,\%$$
$$A_{CP}(B_s^0 \to K\pi) = (27 \pm 8(\text{stat.}) \pm 2(\text{syst.}))\,\%$$

$A_{CP}(B_d^0 \to K\pi)$

- The most precise measurement available to date
- good agreement with the current world average from HFAG: $-0.098^{+0.012}_{-0.011}$
- Deviation from 0 exceeds 6 s (sum in quadrature stat + syst)
- Systematic uncertainty most important contribution from instrumental and production asymmetry

$A_{CP}(B_s^0 \to K\pi)$: 3.3σ significance !

- First evidence of CP violation in the decays of B_s^0 mesons
- In agreement with CDF result: 0.39 ± 0.15 (stat) ± 0.08 (syst) [PRL 106, 181802 (2011)]
- Systematic uncertainty most important contribution from modelling of the signal and background components in the maximum likelihood fit

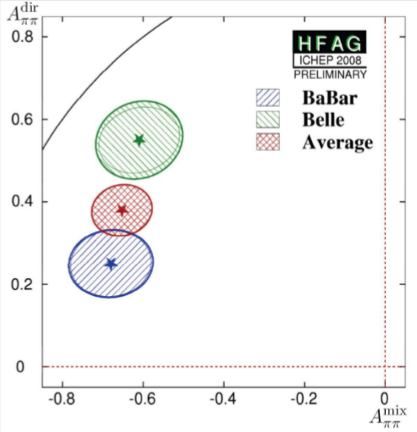
R. Fleischer PLB459 (1999) 306

$$A_{CP}(t) = \frac{\Gamma_{\bar{B}\to f}(t) - \Gamma_{B\to f}(t)}{\Gamma_{\bar{B}\to f}(t) + \Gamma_{B\to f}(t)} = \frac{\mathcal{A}^{dir}\cos(\Delta M t) + \mathcal{A}^{mix}\sin(\Delta M t)}{\cosh(\frac{\Delta\Gamma}{2}t) - \mathcal{A}^{\Delta\Gamma}\sinh(\frac{\Delta\Gamma}{2}t)}$$

with the constraint that: $(\mathcal{A}_f^{dir})^2 + (\mathcal{A}_f^{mix})^2 + (\mathcal{A}_f^{\Delta\Gamma})^2 = 1$

- Only the measurement $B_d^0 \to \pi\pi$ available (No $B_s^0 \to KK$)
- Not in good agreement

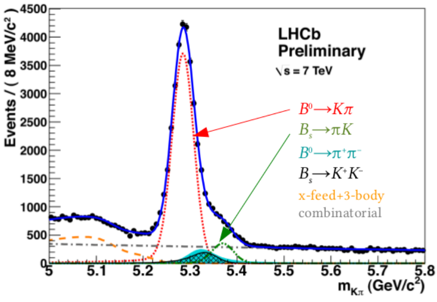
$\to$ a third measurement is necessary

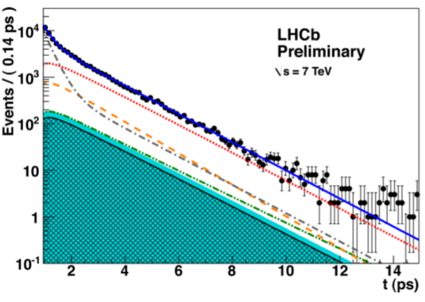


Experiment	$A_{\pi\pi}^{dir}$	$A_{\pi\pi}^{mix}$	$\rho(A_{\pi\pi}^{dir}, A_{\pi\pi}^{mix})$
BABAR	$0.25 \pm 0.08 \pm 0.02$	$-0.68 \pm 0.10 \pm 0.03$	0.06
Belle	$0.55 \pm 0.08 \pm 0.05$	$-0.61 \pm 0.10 \pm 0.04$	0.15
HFAG average	0.38 ± 0.06	-0.65 ± 0.07	0.08

Analysis strategy

- Integrated luminosity : $0.69\,\mathrm{fb}^{-1}$
- Events selection:
  Common kinematic cuts for $B \to K\pi$, $B \to \pi\pi$, $Bs \to KK$,
  PID cuts to distinguish the different final states
- Decay time resolution: Form $B \to J/\psi X$: $50\,\mathrm{fs}$
- Decay time acceptance from MC
- Flavour tagging:
  Use Opposite side (OS) tagging
  Use $B \to K\pi$ to calibrate efficiency and mistag rate

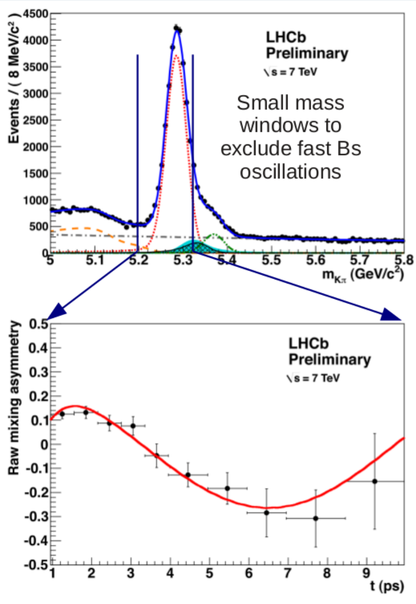




- Very small contribution from Λ_b negected
- Input form other LHCb measurements

Input parameters	LHCb results	
parameter	value	reference
Δm_s	$17.63 \pm 0.11 \pm 0.02$ ps^{-1}	arXiv:1112.4311
Γ_s	$0.657 \pm 0.009 \pm 0.008$ ps^{-1}	arXiv:1112.3183
$\Delta\Gamma_s$	$0.123 \pm 0.029 \pm 0.011$ ps^{-1}	arXiv:1112.3183

Time dependent $B \to K\pi$ fit (2/2)



- 5 tagging categories
- $\sim 4.5\,\%$ efficiency
- No large difference between B and $\bar{B}$ observed

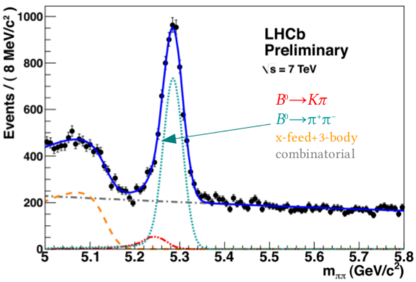
Production Asymmetry → Propagated Gaussian term in $\pi\pi$ and KK

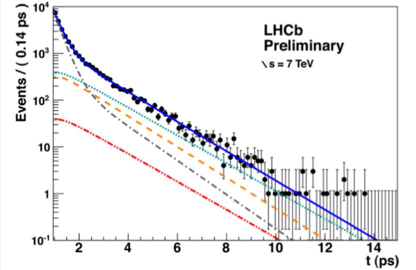
- $A_P(B_d^0) = -0.015 \pm 0.013$
- $A_P(B_s^0) = -0.03 \pm 0.06$

B_d^0 parameters:

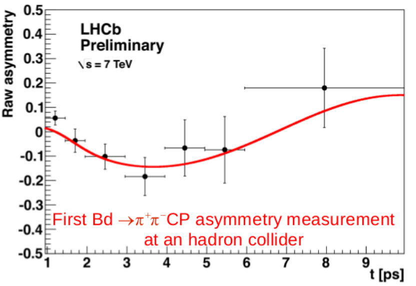
- $\Delta m_d = (0.484 \pm 0.019)\,\mathrm{ps}^{-1}$
- $\tau(B_d^0) = (1.509 \pm 0.011)\,\mathrm{ps}$

Time dependent $B_d^0 \to \pi\pi$ fit





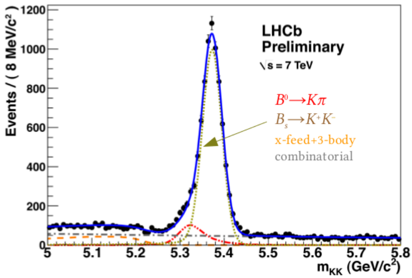
Input parameters		LHCb results
parameter	value	reference
Δm_d	$0.499 \pm 0.032 \pm 0.003\ \mathrm{ps}^{-1}$	LHCb-CONF-2011-010

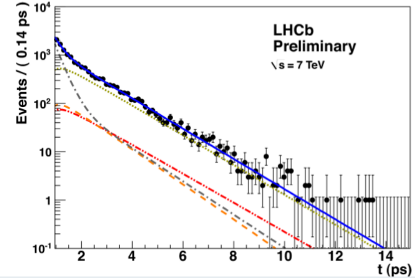


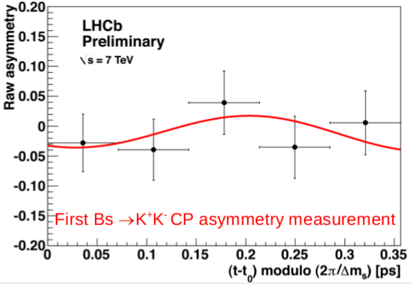
$$\mathcal{A}_{\pi\pi}^{dir} = 0.11 \pm 0.21 \pm 0.03$$
$$\mathcal{A}_{\pi\pi}^{mix} = -0.56 \pm 0.17 \pm 0.03$$
$$\rho(\mathcal{A}_{\pi\pi}^{dr}, \mathcal{A}_{\pi\pi}^{mix}) = -0.34$$

$\tau(B_d^0) = (1.497 \pm 0.025)\,\mathrm{ps}$

in agreement with World Awarage



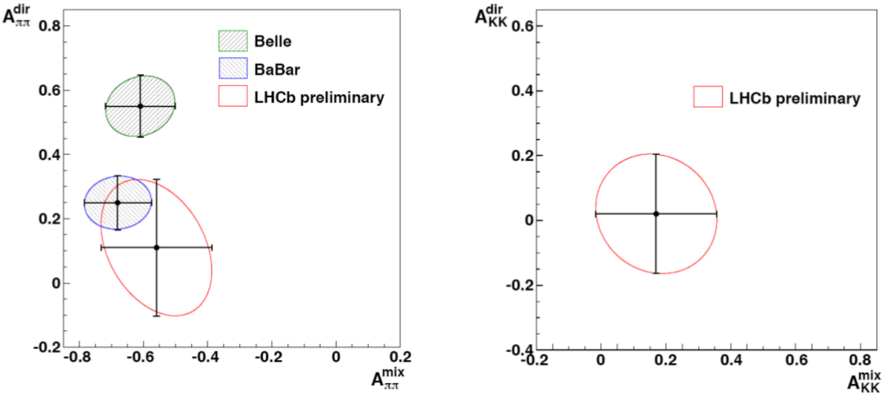




Input parameters		LHCb results
parameter	value	reference
Δm_s	$17.63 \pm 0.11 \pm 0.02\ \text{ps}^{-1}$	arXiv:1112.4311
Γ_s	$0.657 \pm 0.009 \pm 0.008\ \text{ps}^{-1}$	arXiv:1112.3183

$$\mathcal{A}_{KK}^{dir} = 0.02 \pm 0.18 \pm 0.04$$
$$\mathcal{A}_{KK}^{mix} = 0.17 \pm 0.18 \pm 0.05$$
$$\rho(\mathcal{A}_{KK}^{dr}, \mathcal{A}_{KK}^{mix}) = -0.10$$
$$\Delta\Gamma_s = (0.076 \pm 0.019)\,\text{ps}^{-1}$$

in agreement with LHCb-PAPER-2011-021



- $\mathcal{A}^{dir}$ favours BaBar result
- $\mathcal{A}^{mix}$ compatible with world avarage

Assuming U-symmetry and neglecting penguin contributions (small):
$\mathcal{A}^{dir}_{KK} \approx \mathcal{A}_{CP}(B^0 \to K\pi) = -0.088 \pm 0.011 \pm 0.008$
[LHCb-PAPER-2011-029]
SM prediction assuming U-symmetry: $\mathcal{A}^{mix}_{KK} \simeq 0.15$

Largest systematic contribution is due to the errors on the input parameters in all results

The untagged decay time distribution:

$$\Gamma(t) \propto (1-\mathcal{A}_{\Delta\Gamma_s})e^{-\Delta_L t} + (1+\mathcal{A}_{\Delta\Gamma_s})e^{-\Delta_H t}$$

$$\mathcal{A}_{\Delta\Gamma_s} = -2\mathrm{Re}(\lambda/(1+|\lambda|^2) \qquad \lambda = (\mathrm{q/p})(\bar{\mathrm{A}}/\mathrm{A}) \qquad \text{No CPV} \to \lambda = 1$$

$B_s^0 \to KK$ effective lifetime:

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

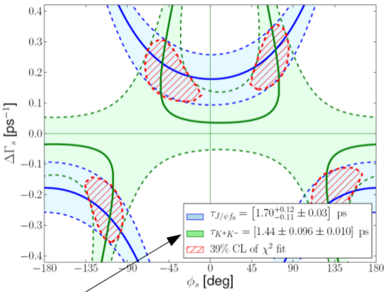
$y_s = \Delta\Gamma_s/2\Gamma_s$ and $\tau_{B_s^0} = 2/(\Gamma_H+\Gamma_L) = \Gamma_s^{-1}$

Alternative way to extract Γ_s and ϕ_s
New Measurements from 2011 data $\int\mathcal{L} = 1.0\,\mathrm{fb}^{-1}$:

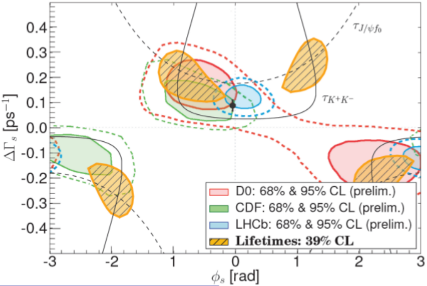
- $\tau_{KK} = 1.468 \pm 0.046(\mathrm{stat.}) \pm 0.006(\mathrm{syst.})\,\mathrm{ps}$ [LHCb-CONF-2012-001]

Fleischer, Knegjens, [arXiv:1109.5115]

Using effective lifetimes to constrain of $\Delta\Gamma$s and ϕs



Including direct measurements



$$\tau_{K^+K^-} = [1.44 \pm 0.096(\text{stat}) \pm 0.010(\text{syst})]\ \text{ps}$$ LHCb [PLB 707 (2012)]

$$\tau_{J/\psi f_0} = [1.70^{+0.12}_{-0.11}(\text{stat}) \pm 0.03(\text{syst})]\ \text{ps}$$ CDF [PRD84:052012, 2011]

charming CPV

- $D^0 \to \pi^+\pi^-$ and $D^0 \to K^+K^-$
- Search for CP violation in $D^+ \to K^+K^-\pi^+$

CPV in charm

- 3 modes of observing CP violation:
  - in the mixing: rates of $D^0 \to \overline{D}^0$ and $\overline{D}^0 \to D^0$ differ,
  - in the decay: amplitudes for a process and its conjugate differ,
  - in the interference between mixing and decay diagrams.
- In the SM, indirect CP violation in charm is expected to be very small and universal between CP eigenstates $O(10^{-4})$
- Direct CP violation expected small as well
  - Negligible in Cabibbo-favoured (CF) modes (SM tree dominates everything)
  - In singly-Cabibbo-suppressed (SCS) modes: up to $O(10^{-3})$ plausible, and few $\times 10^{-3}$ possible
- Till some months ago it was usually said that any enhancement bringing CP asymmetries in charm to O(%) would have been a sign of NP...

- $D^0 \to \pi^+\pi^-$ and $D^0 \to K^+K^-$: arXiv:1112.0938

Time-integrated asymmetries

- Looking for the time-dependent CP asymmetry defined as:

$$A_{CP}(f;t) \equiv \frac{\Gamma(D^0(t) \to f) - \Gamma(\overline{D}^0(t) \to f)}{\Gamma(D^0(t) \to f) + \Gamma(\overline{D}^0(t) \to f)},$$

where $f = K^+K^-$ or $\pi^+\pi^-$.

- The asymmetry has a time dependence due to mixing. but the time-integrated asymmetry is measured:

$$A_{CP}(f) = a^{\mathrm{dir}}_{CP}(f) + \frac{\langle t \rangle}{\tau} a^{\mathrm{ind}}_{CP},$$

- The flavour of the initial state (D^0 or $\overline{D}^0$) is tagged by requiring a $D^{*+} \to D^0\pi_s^+$ decay, with the flavour determined by the charge of the slow pion (π_s^+)

$$\Delta A_{CP} \equiv A_{CP}(K^+K^-) - A_{CP}(\pi^+\pi^-) = [a_{CP}^{\text{dir}}(K^+K^-) - a_{CP}^{\text{dir}}(\pi^+\pi^-)] + \frac{\Delta\langle t\rangle}{\tau} a_{CP}^{\text{ind}},$$

- $\Delta\langle t\rangle \to 0$, $\Delta A_{CP} =$ difference between the two direct CP asymmetry.
- if time-acceptance is $\neq$ for KK and $\pi\pi$ $\to$ remaining contribution from indirect CPV.

To 1$^{\text{st}}$ order the *raw* asymmetries are:

$$A_{raw}(f) = A_{CP}(f) + A_D(f) + A_D(\pi^+) + A_P(D^{*+}),\ D = \text{Detection},\ P = \text{Production}$$

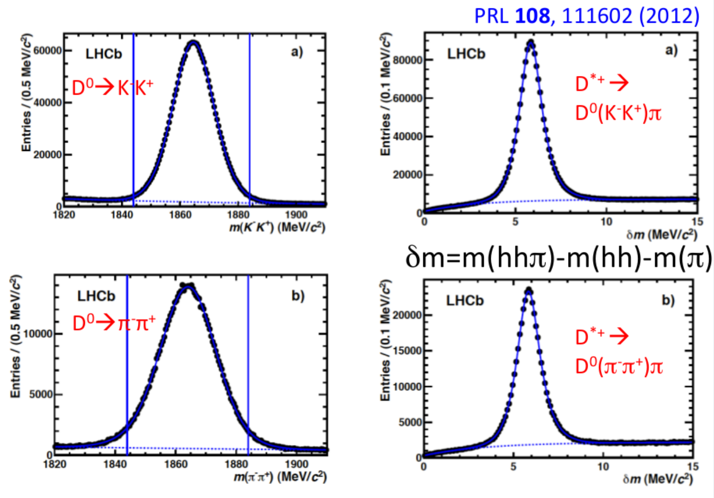
- $A_D(\pi^+)$ and $A_P(D^{*+})$ are indepentent of $f \to$, cancel in ΔA_{CP}
- $A_D(K^+K^-) = A_D(\pi^+\pi^-)$, final states are self-conjugate

$$\Delta A_{CP} \equiv A_{CP}(K^+K^-) - A_{CP}(\pi^+\pi^-) = A_{raw}(K^+K^-) - A_{raw}(\pi^+\pi^-)$$

$D^0 \to \pi^+\pi^-$ and $D^0 \to K^+K^-$ signal yields

Total signal yield with $\int \mathcal{L} = 0.62\,\mathrm{fb}^{-1}$ with 60 % (40 %) Mag ↑(↓):

- 1.4M $D^0 \to K^+K^-$ tagged
- 0.4M $D^0 \to \pi^+\pi^-$ tagged



ΔA_{CP} measurement at LHCb

- LHCb uses 1D unbinned max. likelihood fits ofr δm.
- In order to take into account kinematic differences of reconstructed decay (related to KK and $\pi\pi$ masses), fits are performed in kinematic (η, p_T) bins of D^{*+} and π_s^+. (In total 216 subsamples of data)
- a ΔA_{CP} is determined in each bin.
- Consistency for ΔA_{CP} amongst kinematic bins: $chi^2/\mathrm{ndf} = 211/215$ (χ^2 prob. 56 %)

weight average:

$$\Delta A_{CP} = [-0.82 \pm 0.21(\mathrm{stat.})]\,\%$$

systematics

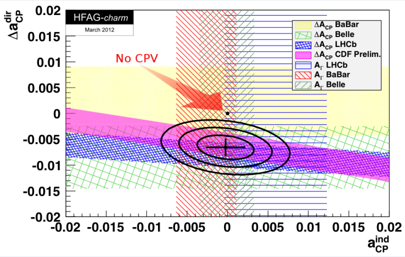
Fiducial cuts	0.01 %
Peaking background asymmetry cuts	0.04 %
Fit procedure	0.08 %
Multiple candidates	0.06 %
Kinematic binning	0.02 %
Total Syst.	0.11 %

several of the systematic uncertainties have a statistical component ($\searrow$ with stat.)

final result:

$$\Delta A_{CP} = [-0.82 \pm 0.21(\text{stat.}) \pm 0.11(\text{syst.})]\,\%$$

$\Rightarrow 3.5\sigma$ deviation from zero.



Year	Experiment	Results	$\Delta\langle t\rangle/\tau$	$\overline{\langle t\rangle}/\tau$
2007	Belle	$A_\Gamma = (0.01 \pm 0.30\ (stat.) \pm 0.15\ (syst.))\%$	-	-
2008	BaBar	$A_\Gamma = (0.26 \pm 0.36\ (stat.) \pm 0.08\ (syst.))\%$	-	-
2011	LHCb	$A_\Gamma = (-0.59 \pm 0.59\ (stat.) \pm 0.21\ (syst.))\%$	-	-
2008	BaBar	$A_{CP}(KK) = (0.00 \pm 0.34\ (stat.) \pm 0.13\ (syst.))\%$ $A_{CP}(\pi\pi) = (-0.24 \pm 0.52\ (stat.) \pm 0.22\ (syst.))\%$	0.00	1.00
2008	Belle	$\Delta A_{CP} = (-0.86 \pm 0.60\ (stat.) \pm 0.07\ (syst.))\%$	0.00	1.00
2011	LHCb	$\Delta A_{CP} = (-0.82 \pm 0.21\ (stat.) \pm 0.11\ (syst.))\%$	0.10	2.08
2012	CDF Prelim.	$\Delta A_{CP} = (-0.62 \pm 0.21\ (stat.) \pm 0.10\ (syst.))\%$	0.25	2.58
	Fit Result	**Agreement with no CP violation** **$CL = 6.1\text{x}10^{-5}$**		

Data is consistent with no CPV at 0.006 % CL,

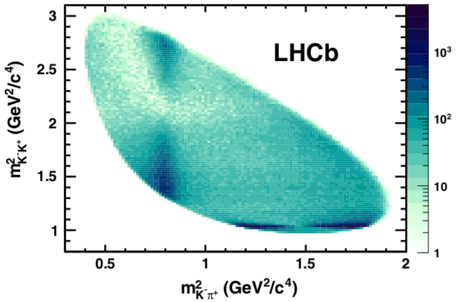
$$\Delta a_{CP}^{dir} = (-0.656 \pm 0.154)\,\%,$$

$$a_{CP}^{ind} = (-0.025 \pm 0.231)\,\%.$$

- Search for CP violation in $D^+ \to K^+K^-\pi^+$: PRD 84 (2011) 112008

Search for CP violation in $D^+ \to K^+ K^- \pi^+$

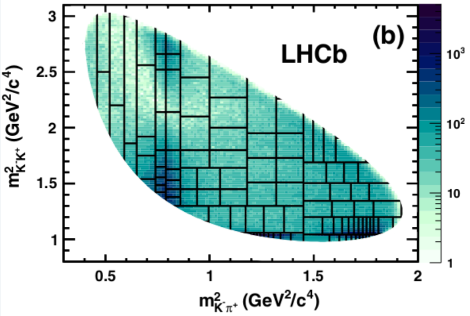
- Phys. Rev. D 84, 112008 (2011)
- Model-independent search for direct CPV in three body decays.
- Look for CPV in SCS decay $D^+ \to K^+ K^- \pi^+$.
- Search for local asymmetries across Dalitz space
- Model-independent method based on binning Dalitz plot and comparing corresponding bins.



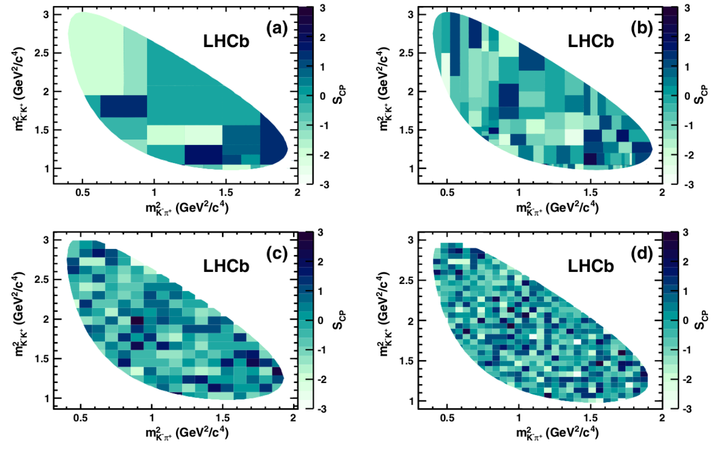
- Bin Dalitz space and compare bins between D^+ and D^- Dalitz space.
- Based on the Miranda method (PRD 80:096006, 2009)

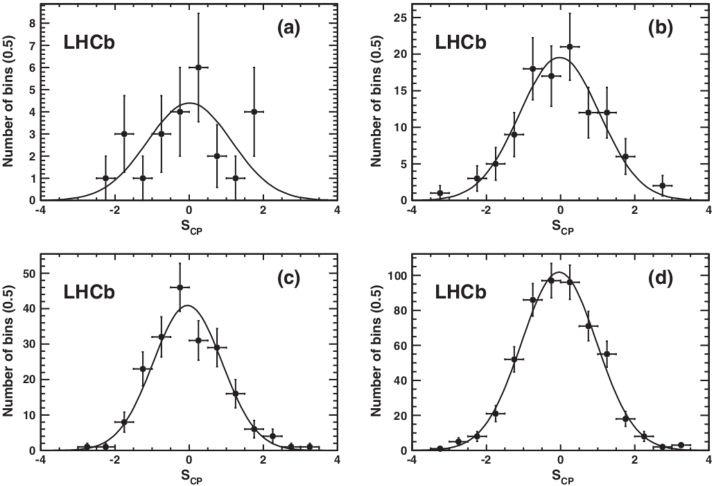
$$S_{CP} = \frac{N^i(D^+) - \alpha N^i(D^-)}{\sqrt{N^i(D^+) - \alpha^2 N^i(D^-)}}, \qquad \alpha = \frac{N_{\text{tot}}(D^+)}{N_{\text{tot}}(D^-)}$$

- α normalise away overall asymmetry, but also mrevoes production and detection effects
- Plotting S_{CP} for all bins, if NO CPV $\to$ Gaussian with $\mu = 0$ and $\sigma = 1$
- Calculate $\chi^2 = \sum_i (S^i_{CP})^2$ and p-values under NO CPV assumption.
- Use CF ($D_s^+ \to K^+K^-\pi^+$) where NO CPV expected to check for A_{Det}



- Sevral binning tested





- All consistent with no CPV. Binning shown agrees with hypothesis of NO CPV (with p-value of 10.6 %)
- Carried out on $35\,\mathrm{pb}^{-1} \to$ update on full 2011 data set in progress

CPV in beauty

- CPV in $B^{\pm} \to DK^{\pm}$:
  Direct CPV @ 5.8σ, 1^{st} obs. of the ADS mode.
- A_{CP} in $B^0 \to K^*\gamma$:
  In agreement with SM expectation
- CPV phase ϕ_s from $B_s^0 \to J/\psi X$:
  World's most precise measurement of $\phi_s = -0.002 \pm 0.083 \pm 0.027$ rad., first direct obs. for a non-zero $\Delta\Gamma_s$.
- CPV in $B \to hh$:
  First evidence of CPV in the decays of B_s mesons. First measurement of $B \to KK$. $A_{\pi\pi}^{dir}$ favours BaBar results.

CPV in charm

- $D^0 \to \pi^+\pi^-$ and $D^0 \to K^+K^-$:
  First evidence of CPV in the charm sector (3.5σ).
- Search for CP violation in $D^+ \to K^+K^-\pi^+$:
  No evidence of CPV.