CP violation in the b system at LHCb

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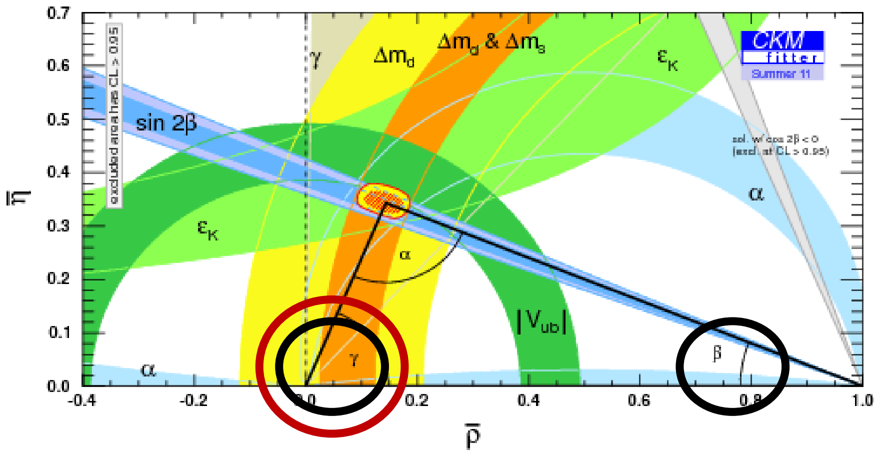
On behalf of the LHCb collaboration

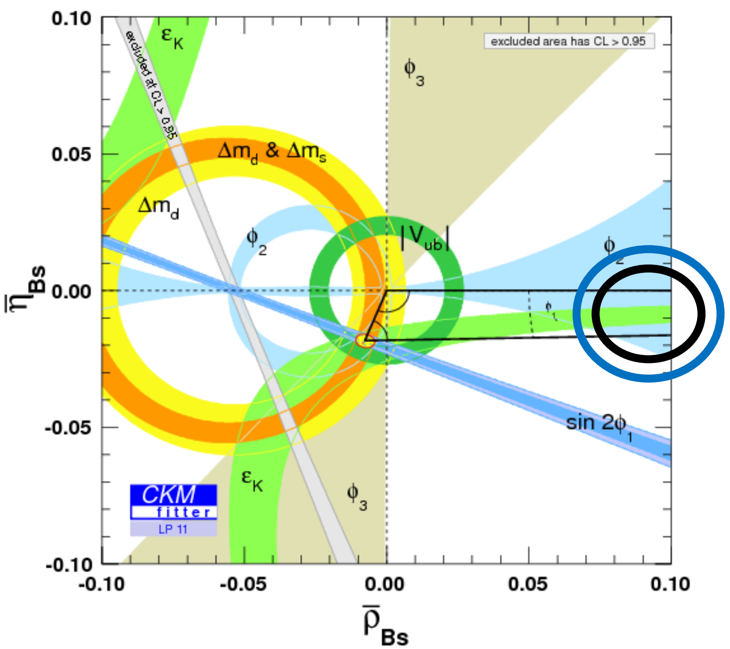
Only source of CP violation in SM:

$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

$$V_{ub}^* V_{ud} + V_{cb}^* V_{cd} + V_{tb}^* V_{td} = 0$$



$$V_{ub}^* V_{us} + V_{cb}^* V_{cs} + V_{tb}^* V_{ts} = 0$$



in this talk:

- $B \to D\, h$: CP violation in decay
- $B_s \to J/\Psi\, \Phi$ ($B_s \to J/\Psi\, \pi\pi$): CP violation in interference of decay and mixing
- $B \to h^+ h^-$: CP violation in decay and in interference of decay and mixing

CP violation in decay in $B^{\pm} \rightarrow D\ h^{\pm}$

LHCb-PAPER-2012-001,
submitted to Phys. Lett. B, arXiv:1203.3662

CP violation in $B^{\pm} \to D\, h^{\pm}$

CKM angle γ not yet precisely measured:

- indirect constraints from CKMFitter(summer 2011): $\gamma = (67.1^{+4.6}_{-3.7})^{\circ}$

Measurement of CP violation in $B^{\pm} \to Dh^{\pm}$:

- first important step towards γ from trees measurement
- no large New Physics contribution in tree-level transitions

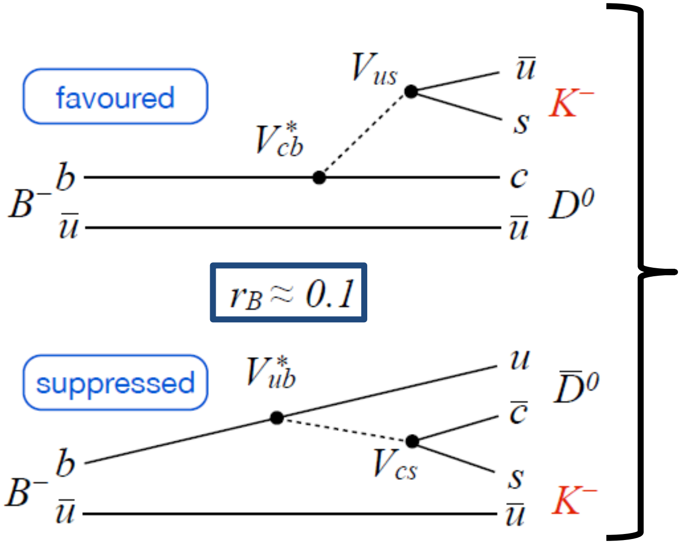
$$\gamma = \arg\left(-\frac{V_{ud}V_{ub}^{*}}{V_{cd}V_{cb}^{*}}\right)$$

GLW mode

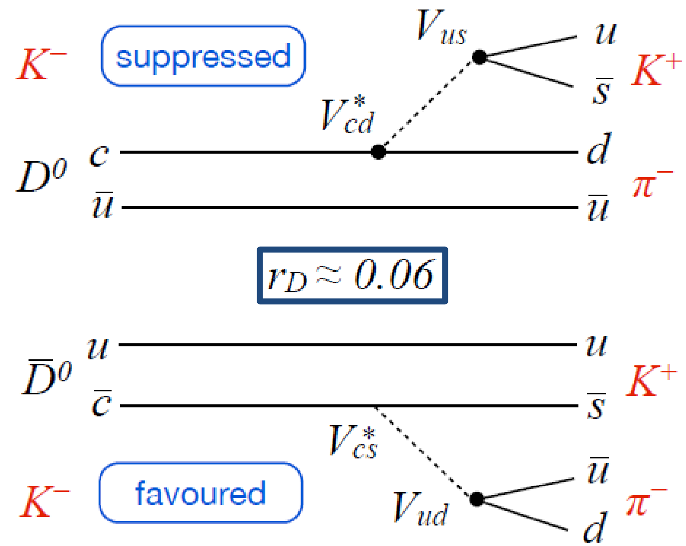
Phys. Lett. B253 (1991) 483
Phys. Lett. B265 (1991) 172

ADS mode

Phys. Rev. Lett. 78 (1997) 3257
Phys. Rev. D63 (2001) 036005



$D^0/\bar{D}^0 \to K^+K^-$
$\to \pi^+\pi^-$
CP eigenstates



r_B, r_D: relative amplitudes
$\delta_B\ \delta_D$: strong phases

larger interference in ADS mode → better sensitivity to γ

CP violation in $B^{\pm} \to D\,h^{\pm}$

Physics observables:

GLW mode:

Ratio of partial widths: $\frac{<\Gamma(B^{\pm}\to[\pi\pi]_D h^{\pm}),\ \Gamma(B^{\pm}\to[KK]_D h^{\pm})>}{\Gamma(B^{\pm}\to D_f h^{\pm})} \to R_{CP+}$

CP asymmetries: $\frac{\Gamma(B^{-}\to D_{CP} h^{-}) - \Gamma(B^{+}\to D_{CP} h^{+})}{\Gamma(B^{-}\to D_{CP} h^{-}) + \Gamma(B^{+}\to D_{CP} h^{+})} \to A_{CP+}$

ADS mode:

Ratio of partial widths: $\frac{\Gamma(B^{\pm}\to D_{ADS} h^{\pm})}{\Gamma(B^{\pm}\to D_f h^{\pm})} \to R_{ADS}$

CP asymmetries: $\frac{\Gamma(B^{-}\to D_{ADS} h^{-}) - \Gamma(B^{+}\to D_{ADS} h^{+})}{\Gamma(B^{-}\to D_{ADS} h^{-}) + \Gamma(B^{+}\to D_{ADS} h^{+})} \to A_{ADS}$

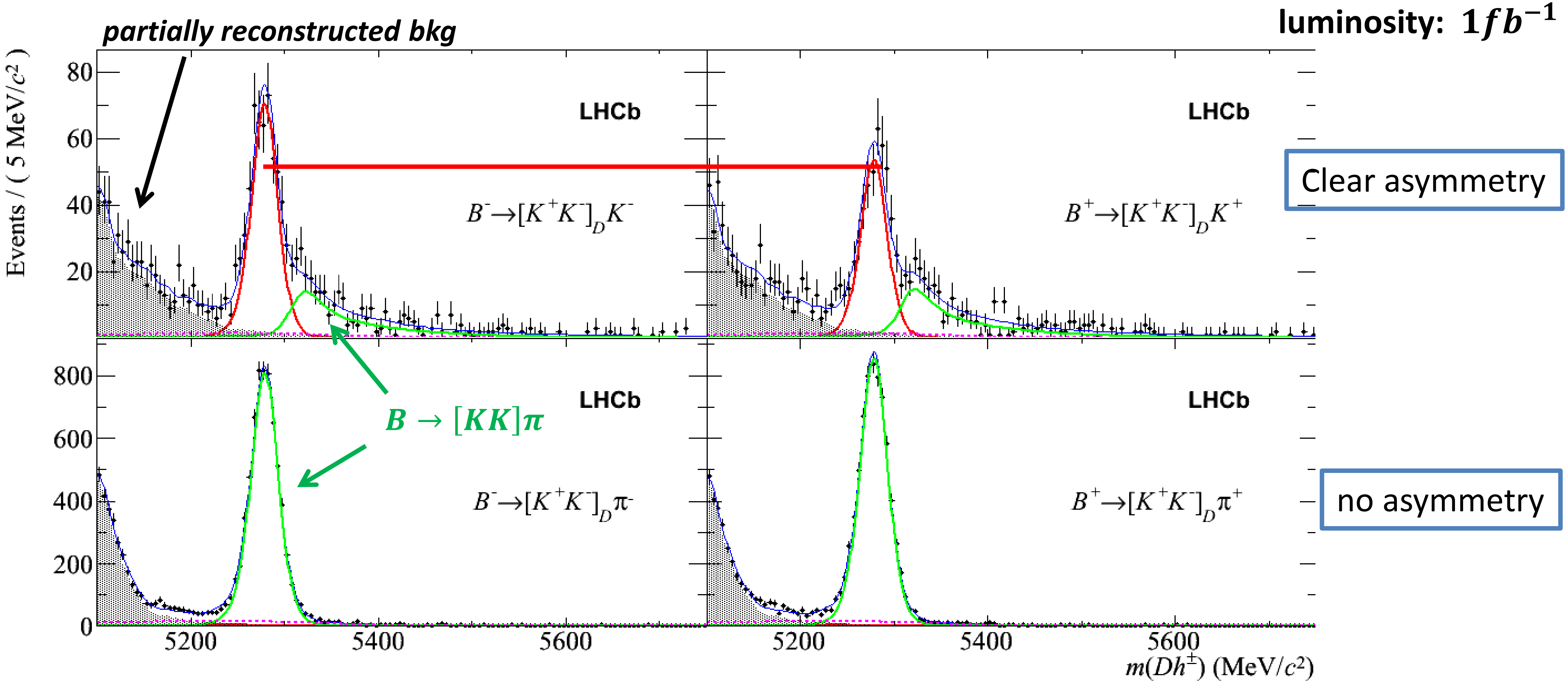
observables depend on $\gamma, r_B, r_D, \delta_B, \delta_D$

Analysis Strategy:

- Reconstructed all possible combinations $B^{\pm} \to D[h^{\pm}h^{\pm}]h^{\pm}$
- particle ID to distinguish final states
- Simultaneous fit to ADS and GLW modes

Results GLW mode

luminosity: $1fb^{-1}$

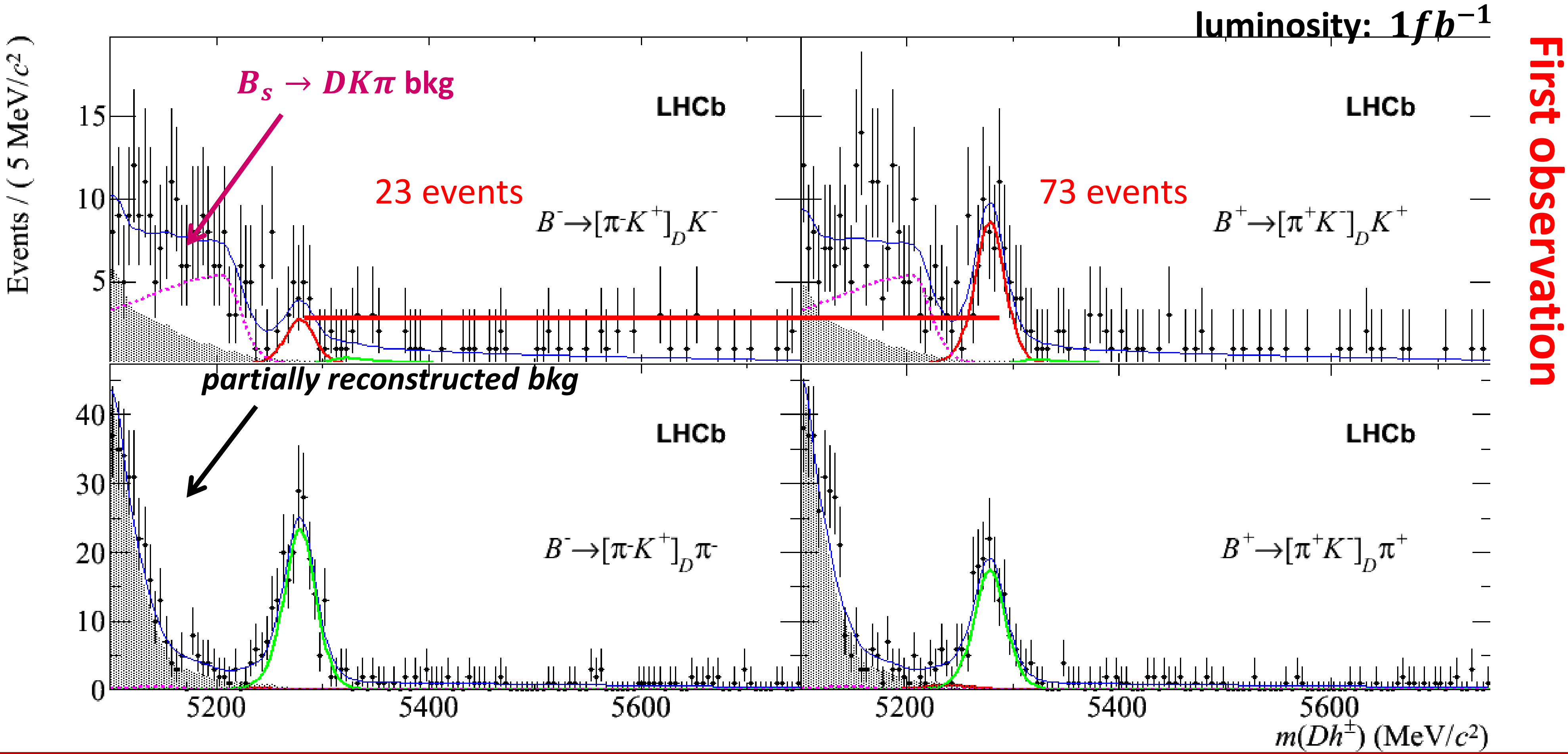


$$R_{CP+} = 1.007 \pm 0.038 \pm 0.012$$

$$A_{CP+} = 0.145 \pm 0.032 \pm 0.010$$

Largest systematics: particle identification, det./prod. asymmetries

Results ADS mode

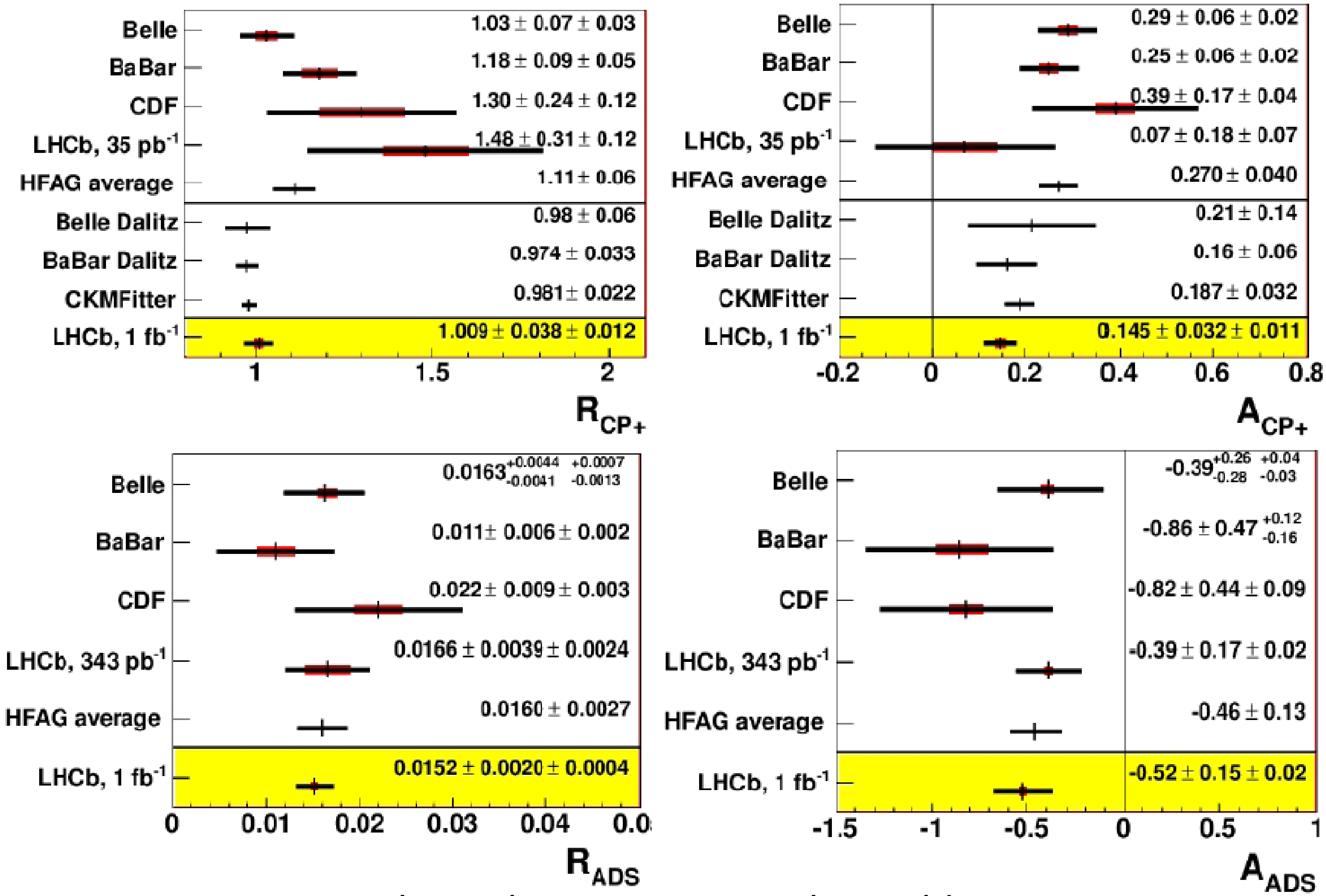


$$R_{ADS(K)} = 0.0152 \pm 0.0020 \pm 0.0004 \quad R_{ADS(\pi)} = 0.00410 \pm 0.00025 \pm 0.00005$$

$$A_{ADS(K)} = -0.52 \pm 0.15 \pm 0.02 \ \ (4\,\sigma) \quad A_{ADS(\pi)} = 0.143 \pm 0.062 \pm 0.011 \ \ (2.4\,\sigma)$$

Largest systematics: background shape, det./prod. asymmetrie

Comparison



LHCb results consistent with world average

Most precise measurements in ADS mode

Observables depend on $\gamma \rightarrow$ large step towards γ-measurement

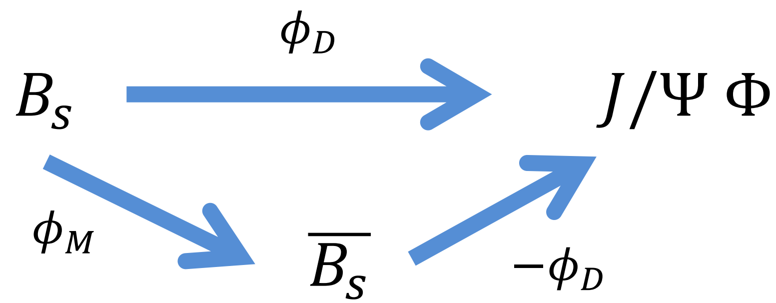
CP violation in $B_s \to J/\Psi\ \Phi$

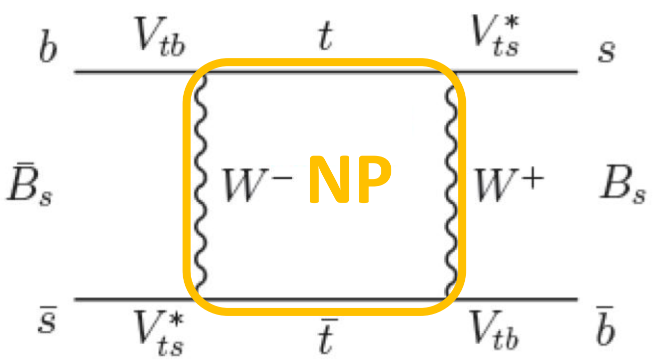
LHCb-CONF-2012-002

$0.37 fb^{-1}$ published in PRL, arXiv:1112.3183

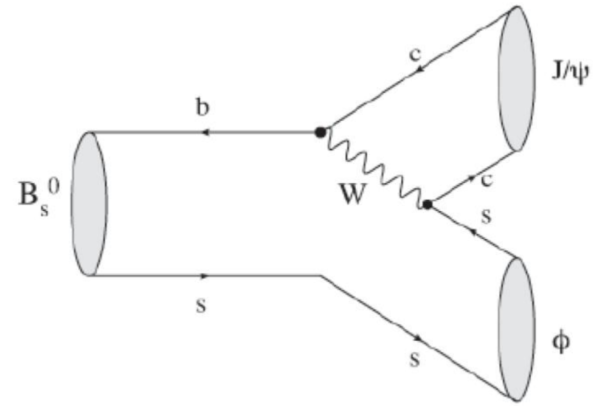
CP violation in $B_s \to J/\Psi\ \Phi$

Interference between mixing and decay:
$\to$ CP violating phase $\phi_s = \phi_M - 2\,\phi_D$





$$\phi_s = -2\arg[-\frac{V_{ts}V_{tb}^*}{V_{cs}V_{cb}^*}]$$



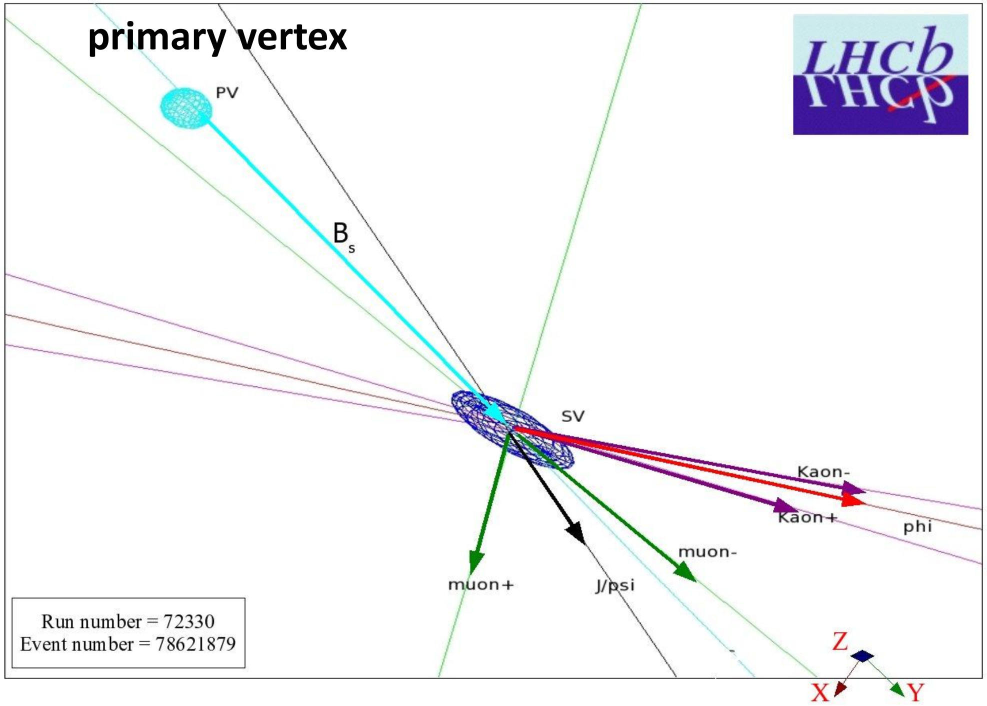
New Physics: $\phi_s = \phi_s^{SM} + \phi_s^{NP}$

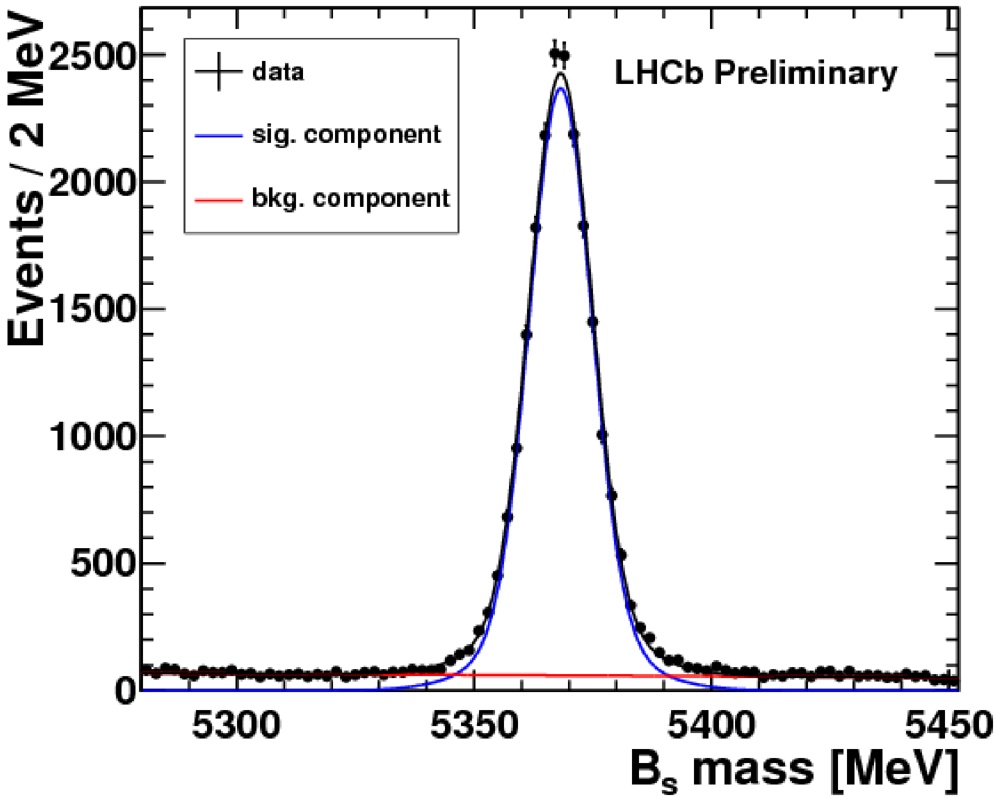
tree-level transition dominant
(penguin contribution $\sim 10^{-4} - 10^{-3}$)

ϕ_s in Standard Model well predicted and small: -0.036 ± 0.002 rad

[J.Charles et al., Phys. Rev. ***D84*** *(2011) 033005]*

$B_s \to J/\Psi\ \Phi$ at LHCb





- luminosity: $1 fb^{-1}$
- Selection based on simple kinematic cuts
- Cut on decay time $t > 0.3$ ps to suppress prompt background
- Very clean signal with ≈ 21200 signal candidates

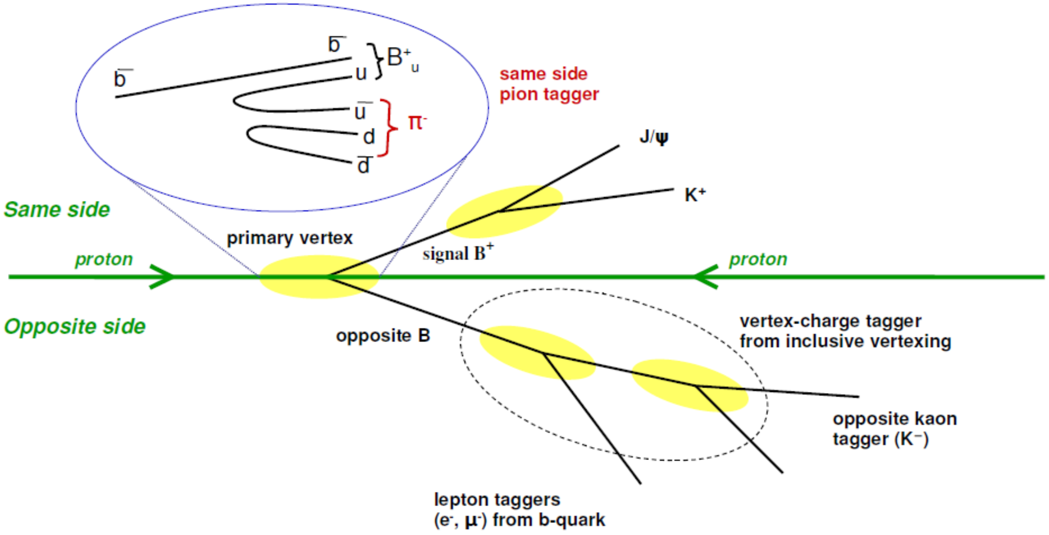
Tagging and decay time resolution

Time dependent CP measurement → need good flavor tagging and time resolution

Tag B production flavor:

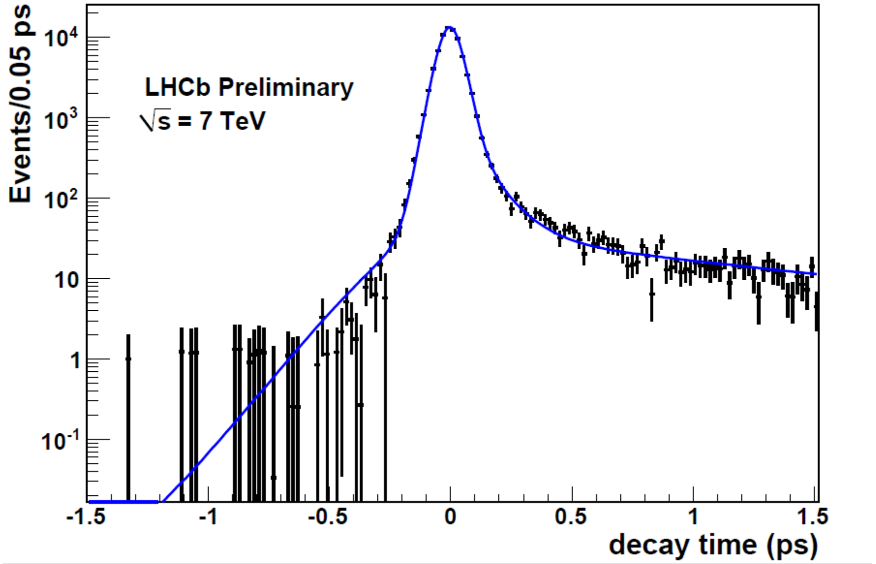
- tagger calibration with $B^+ \to J/\Psi\ K^+$
- tagging efficiency: 33%
- wrong tag probability: 36.8%

$$\boldsymbol{\varepsilon D^2 = 2.3\%}$$



Proper time resolution:

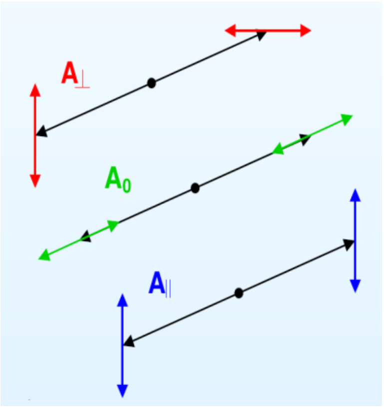
- measured with prompt J/Ψ decaying at t=0
- effective resolution: 45 fs



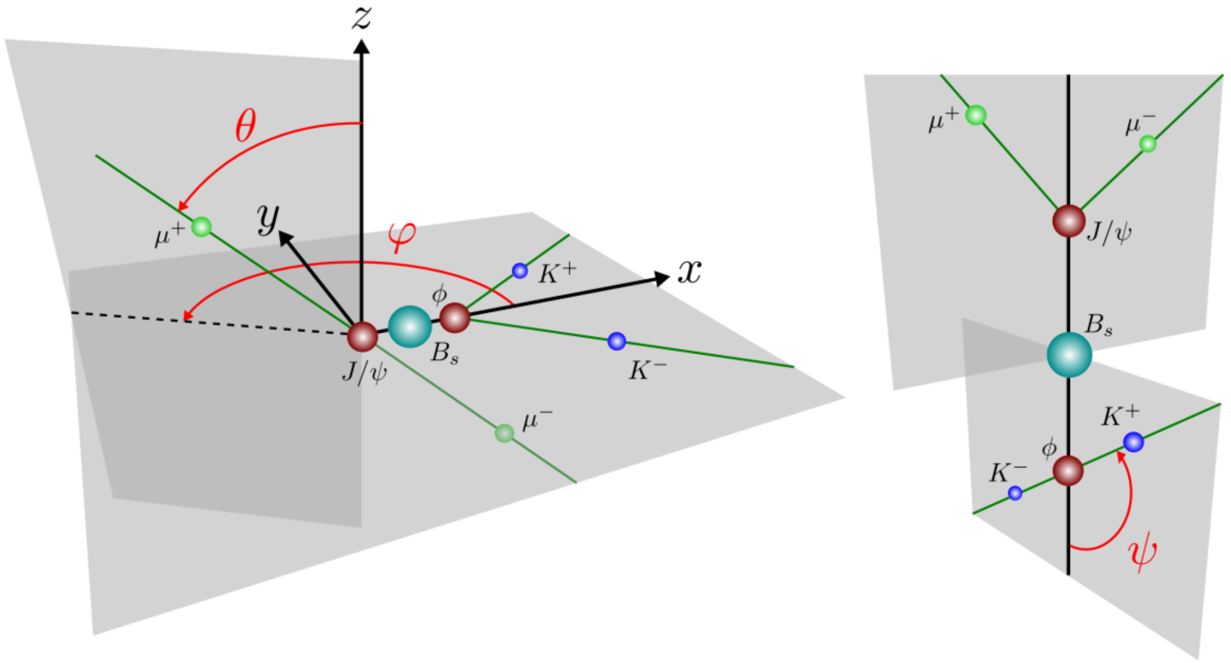
Separation of CP eigenstates

P -> VV decay:
final state is mixture of CP even and CP odd eigenstates

Described by three polarization amplitudes: $A_\perp$ (CP-odd)
A_0 , $A_\parallel$ (CP-even)

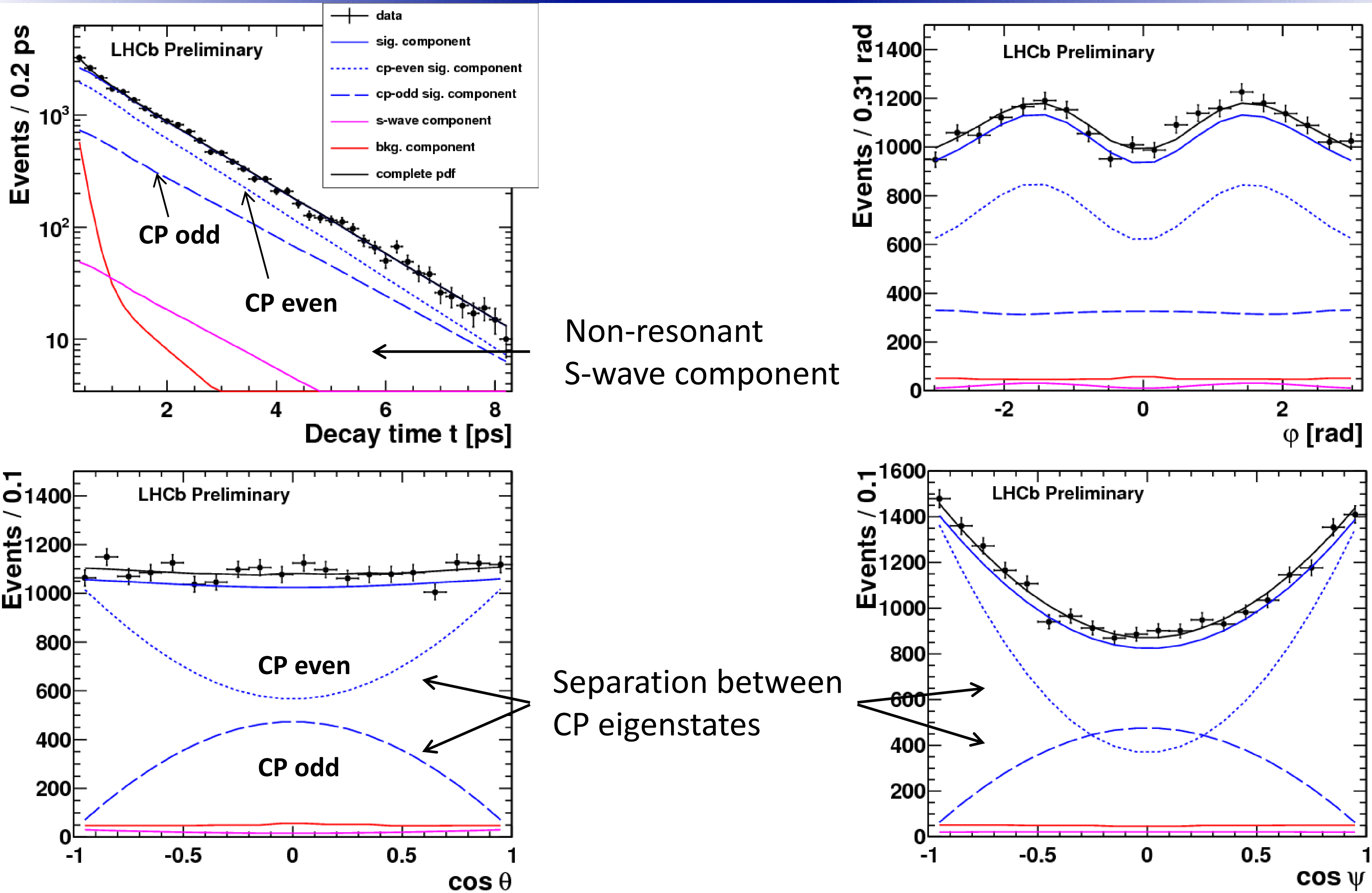


Final states described by three transversity angles: $\Omega = \{\varphi,\ \theta,\ \psi\}$



→ Statistical separation of CP eigenstates

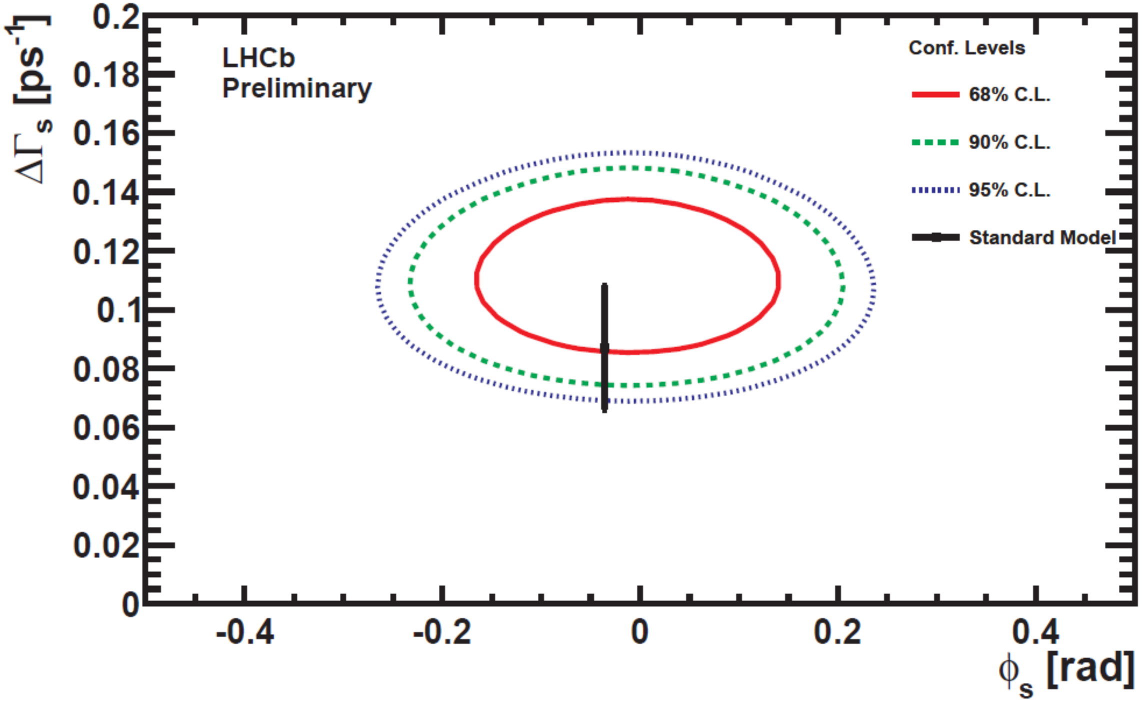
Separation of CP eigenstates



$B_s \to J/\Psi\ \Phi$ results

ϕ_s − $\Delta\Gamma_s$ contour plot:

(statistical uncertainties only)



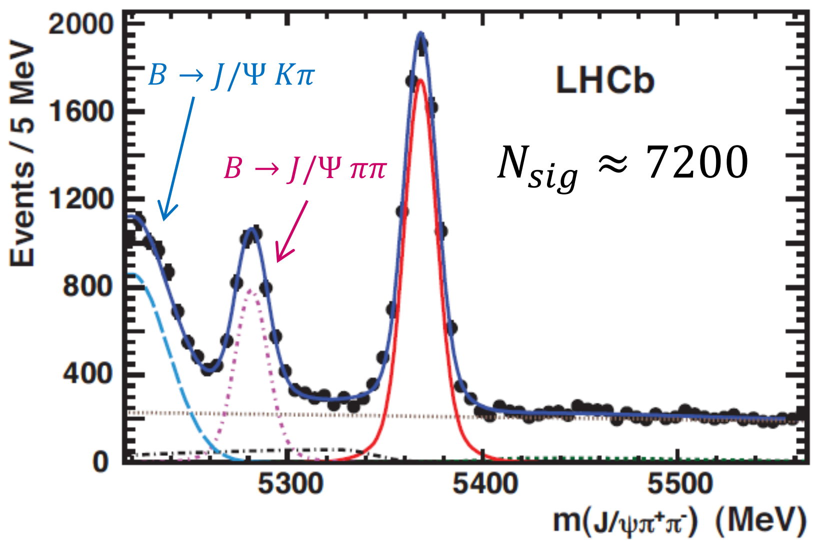
$$\phi_s = -0.001 \pm 0.101 \pm 0.027\ rad$$
$$\Delta\Gamma_s = 0.116 \pm 0.018 \pm 0.006\ ps^{-1}$$
$$\Gamma_s = 0.6580 \pm 0.0054 \pm 0.0066\ ps^{-1}$$

Largest systematics: direct CPV in mixing/decay, angular acceptances

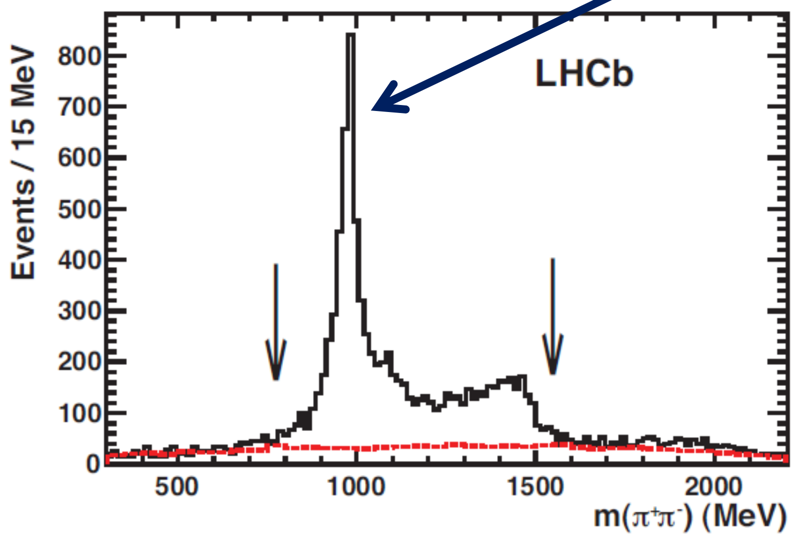
ϕ_s from $B_s \to J/\Psi\ \pi\pi$

BR smaller than $B_s \to J/\Psi\ \Phi$

But: pure CP odd eigenstate $\to$ no angular analysis necessary



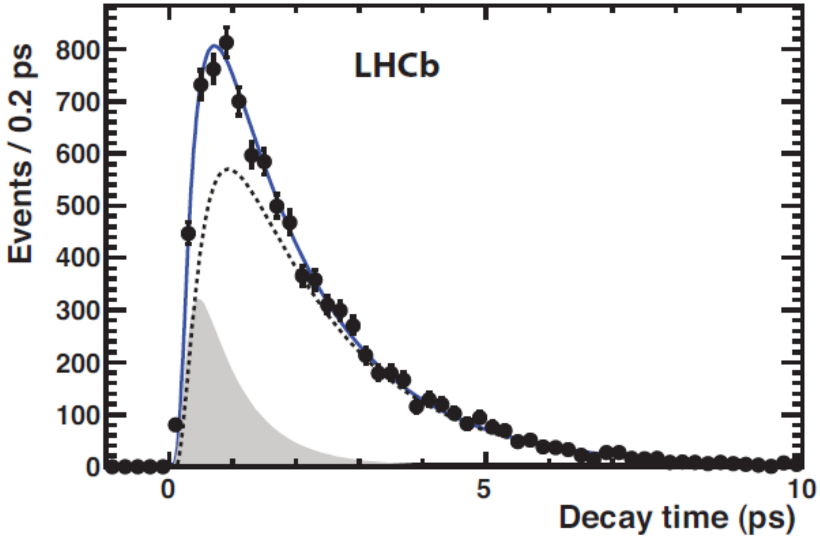
including $f_0(980)$



+ $f_0(1370)$
+ non-resonant

showed to be pure CP-odd

LHCb-PAPER-2012-005



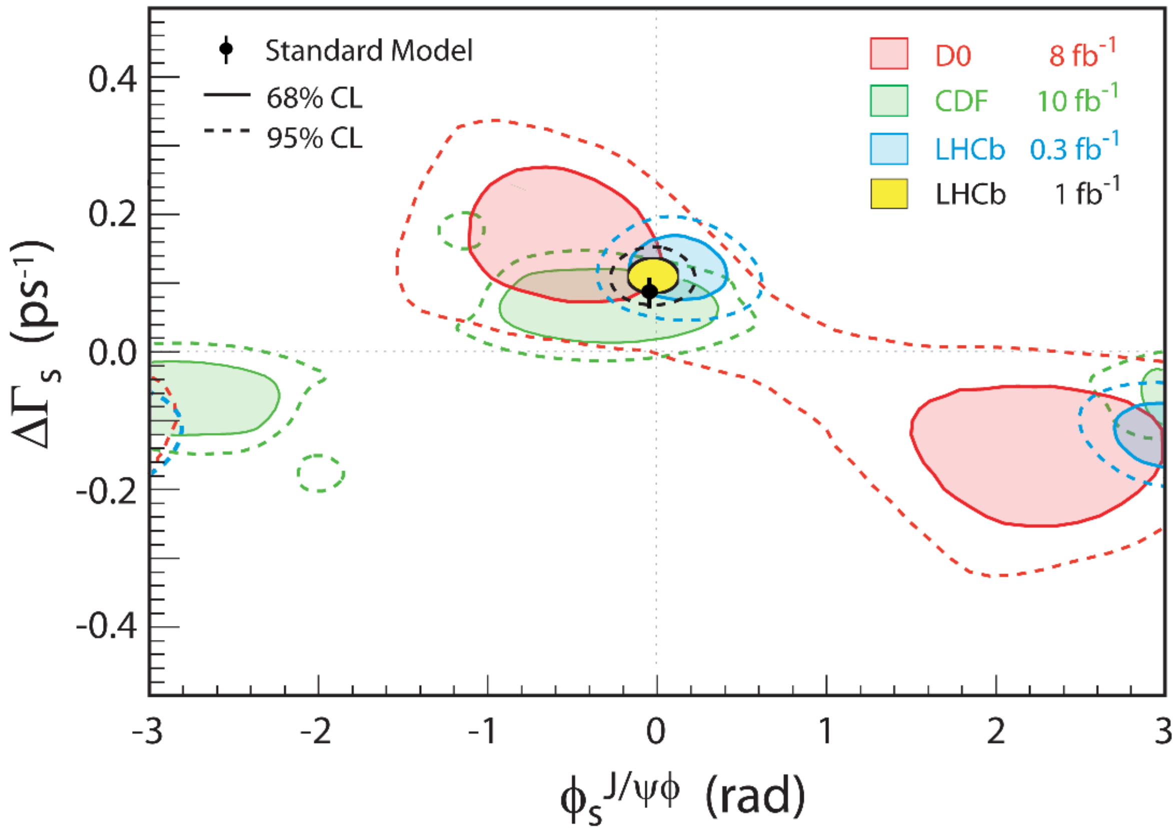
- Γ_s and $\Delta\Gamma_s$ from $B_s \to J/\Psi\ \Phi$ analysis

$$\phi_s = -0.002 \pm 0.17 \pm 0.02\ rad$$

Combined solution

Combination of $B_s \to J/\Psi\ \Phi$ and $B_s \to J/\Psi\ \pi\pi$ results:

$$\phi_s = -0.002 \pm 0.083 \pm 0.027\ rad$$



Also resolved two-fold ambiguity: $\Delta\Gamma_s > 0$

LHCb-PAPER-2011-028
submitted to PRL, arXiv:1202.4717

➢ **Result in very good agreement with SM**

Time dependent CP violation in $\mathrm{B} \rightarrow hh$

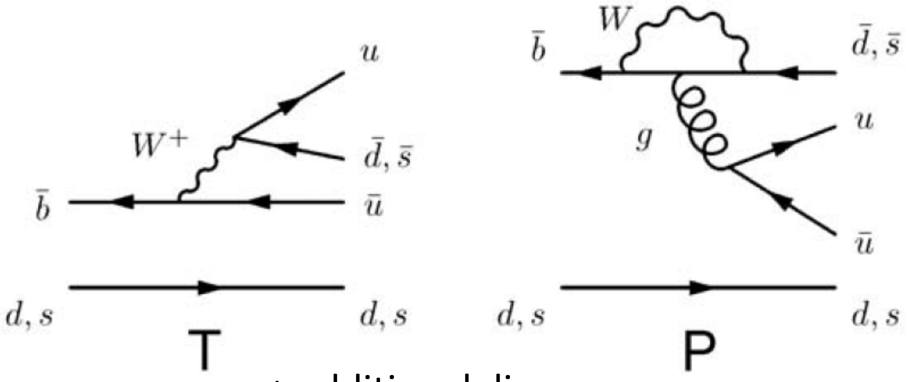
LHCb-CONF-2012-007

Time dependent CPV in B → hh'

CP Asymmetry: $$A_{CP}(t) = \frac{\Gamma_{\bar{B}\to f}(t) - \Gamma_{B\to f}(t)}{\Gamma_{\bar{B}\to f}(t) + \Gamma_{B\to f}(t)} = \frac{A_f^{dir}\cos(\Delta m t) + A_f^{mix}\sin(\Delta m t)}{\cosh\left(\frac{\Delta\Gamma}{2}t\right) - A_f^{\Delta\Gamma}\sinh\left(\frac{\Delta\Gamma}{2}t\right)}$$

with: $$\left(A_f^{dir}\right)^2 + \left(A_f^{mix}\right)^2 + \left(A_f^{\Delta\Gamma}\right)^2 = 1$$

- asymmetries are related to CKM angles γ, β, β_s
- $B \to hh$ via tree and penguin processes



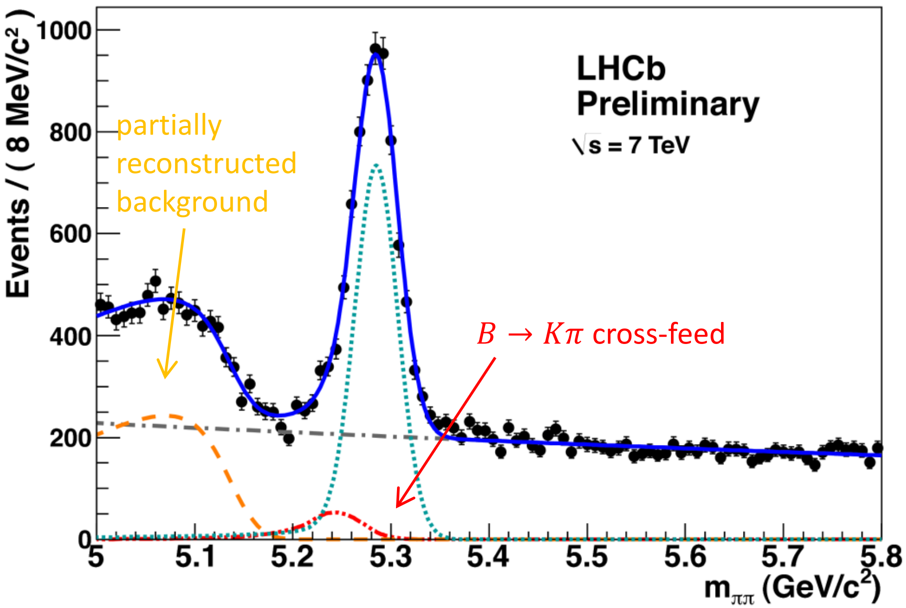
+ additional diagrams

New Physics dominantly in loop processes
-> complementary approach to γ measurement in $B \to Dh$

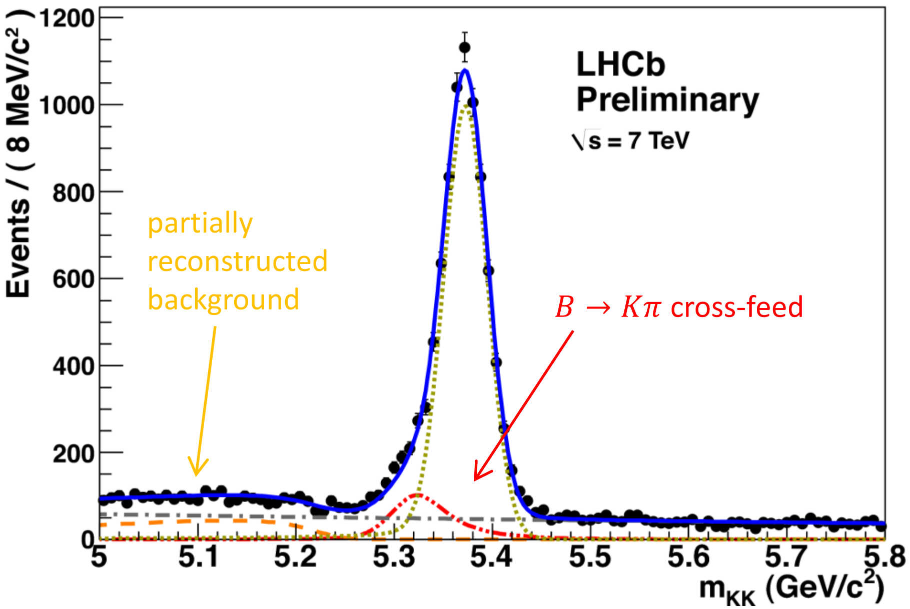
Analysis strategy

- luminosity: $0.69 fb^{-1}$
- Simple kinematic cuts to select candidates,
  particle identification to distinguish different modes ($\pi\pi$, KK, $K\pi$)
- Use $B \to K\,\pi$ for calibrating tagging efficiency and mistag probability
- Maximum likelihood fit to get time dependent asymmetries in $B \to KK$ and $B \to \pi\pi$

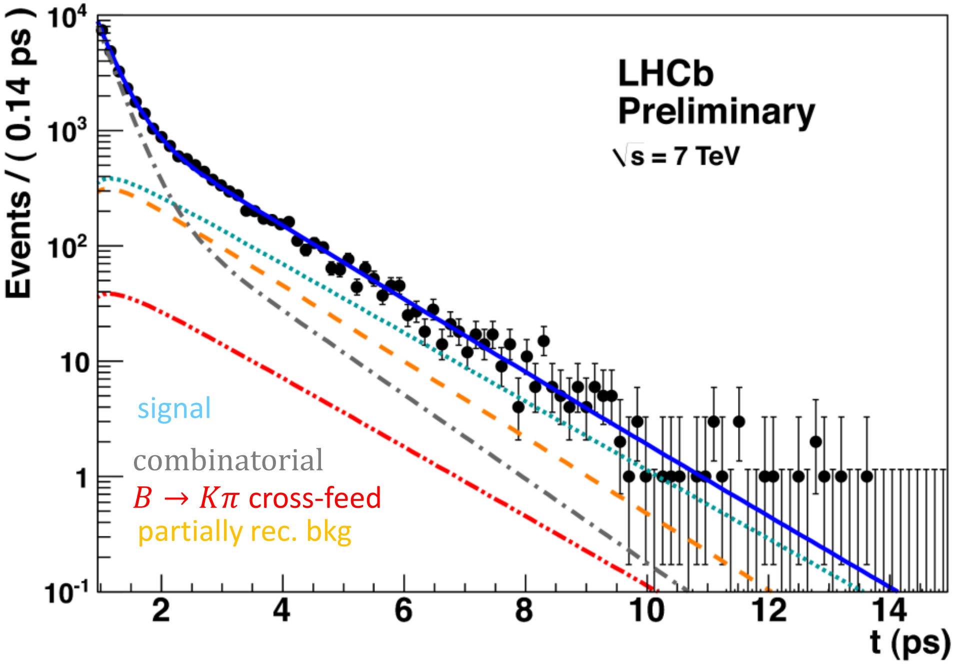
$B^0 \to \pi\pi$

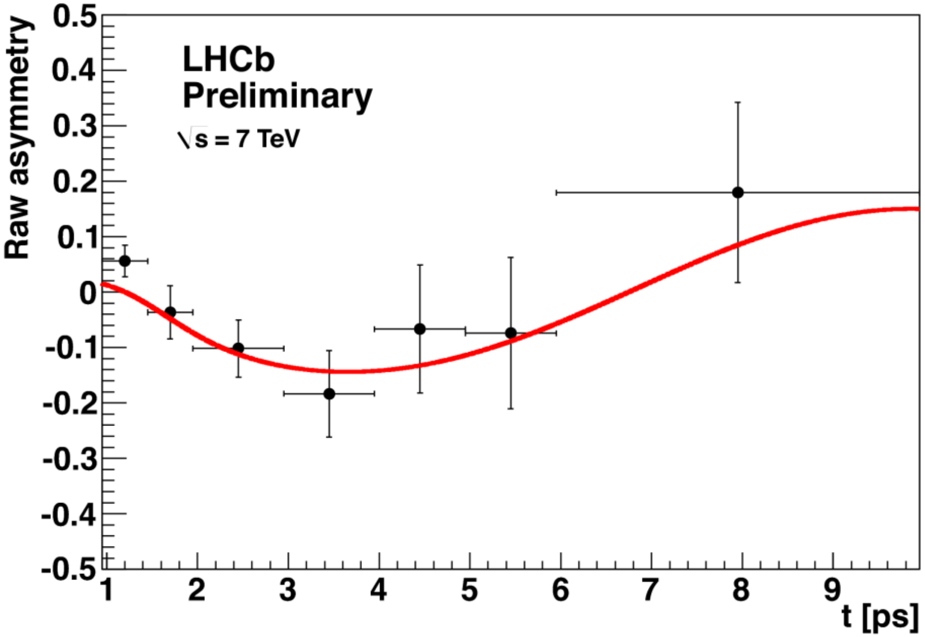


$B_s \to KK$



$B^0 \to \pi^+\pi^-$ result

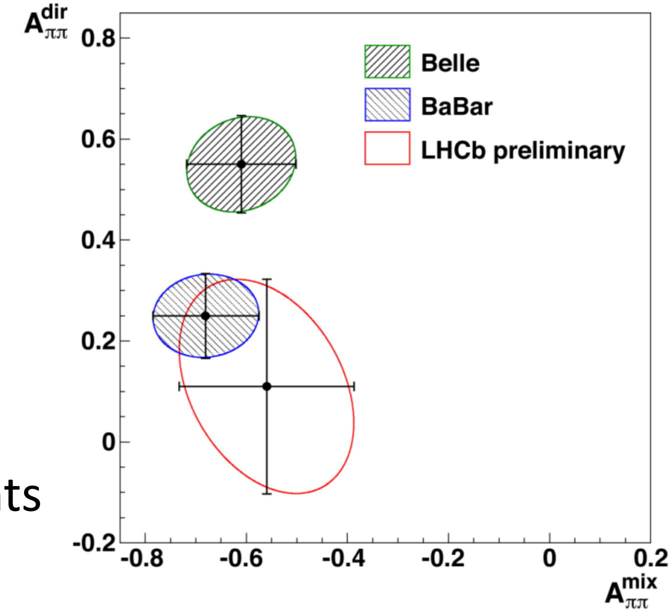




$$A_{\pi\pi}^{dir} = 0.11 \pm 0.21 \pm 0.03$$

$$A_{\pi\pi}^{mix} = -0.56 \pm 0.17 \pm 0.03 \quad (3.2\,\sigma)$$

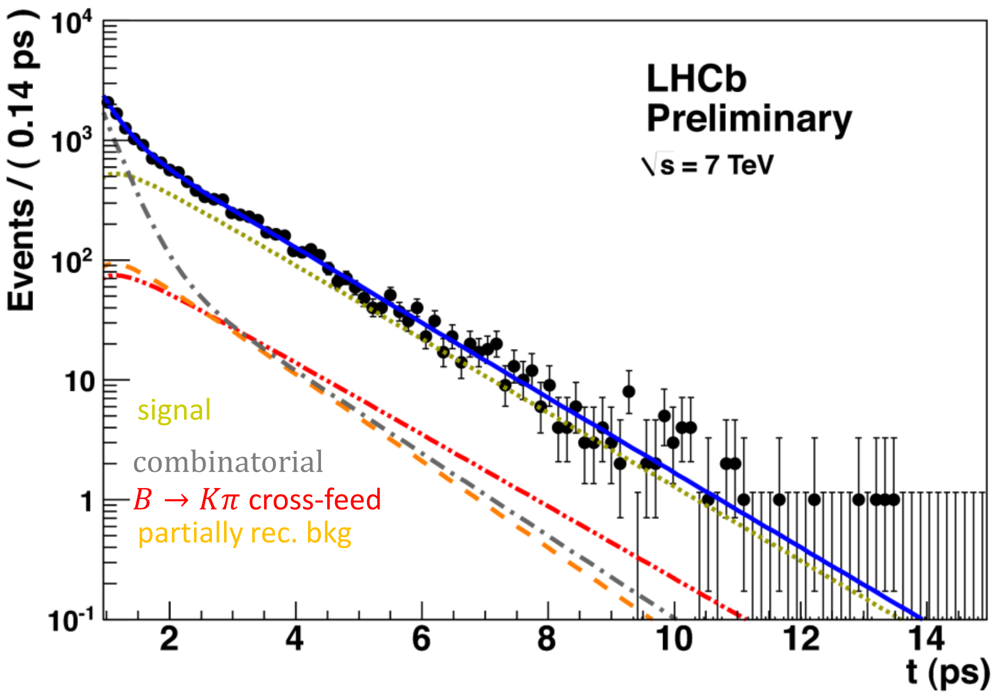
$$corr\left(A_{\pi\pi}^{dir}, A_{\pi\pi}^{mix}\right) = -0.34$$

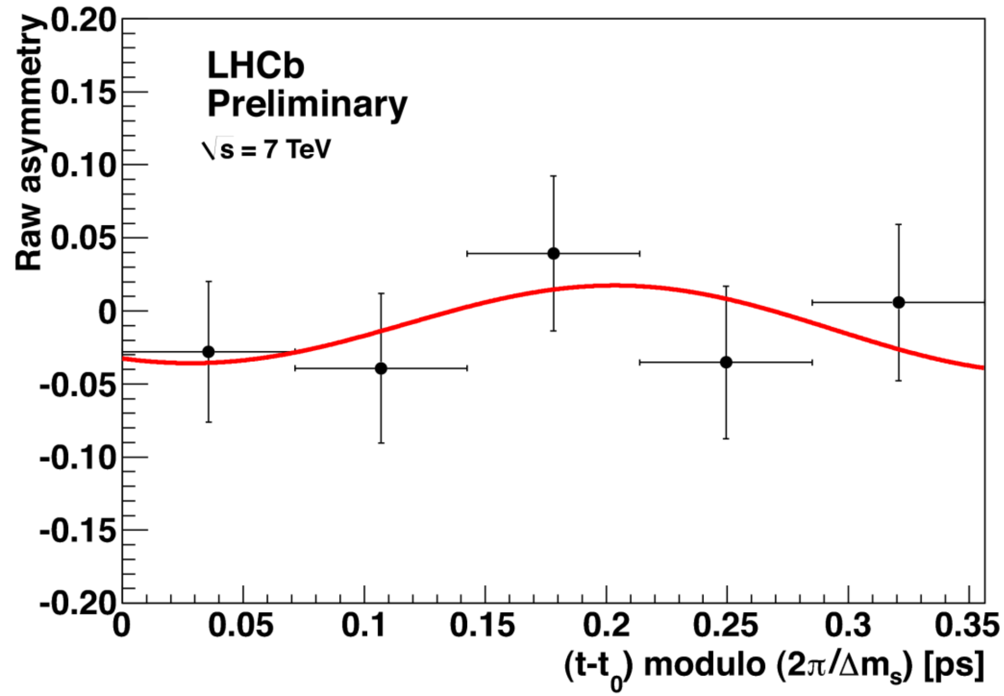


- ➢ Results in good agreement with previous measurements

Largest systematics: external input of Δm_d

$B_s \to K^+K^-$ result





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

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

$$corr\left(A_{KK}^{dir}, A_{KK}^{mix}\right) = -0.10$$

- First measurement of time dependent CP asymmetry in $B_s \to K^+K^-$

Largest systematics: external input of Δm_s, decay time acceptance

Summary

- LHCb successfully performed new CP measurements with data of last year

- Combined measurement of CP asymmetry in $B \to Dh$ GLW and ADS mode
  $\rightarrow$ important step towards precise γ measurement

- CP violation in $B_s \to J/\Psi\ \Phi$
  $\rightarrow$ results in agreement with SM prediction, room for NP gets smaller

- Time dependent CP asymmetries in B->hh
  $\rightarrow$ first measurement in $B_s \to KK$

Prospects:

- all shown analysis still statistical limited $\rightarrow$ improvement with 2012 data
- γ measurement: other interesting channels (e.g. $B \to DK^*$)
  $\rightarrow$ on track for combined γ measurement
- ϕ_s in $B_s \to J/\Psi\ \Phi$: plan to publish results with $1fb^{-1}$ dataset

Backup

$B \to Dh$ observables

$$R^f_{K/\pi} = \frac{\Gamma(B^- \to [f]_D K^-) + \Gamma(B^+ \to [f]_D K^+)}{\Gamma(B^- \to [f]_D \pi^-) + \Gamma(B^+ \to [f]_D \pi^+)}$$

$$A^f_h = \frac{\Gamma(B^- \to [f]_D h^-) - \Gamma(B^+ \to [f]_D h^+)}{\Gamma(B^- \to [f]_D h^-) + \Gamma(B^+ \to [f]_D h^+)}$$

$$R^\pm_h = \frac{\Gamma(B^\pm \to [\pi^\pm K^\mp]_D h^\pm)}{\Gamma(B^\pm \to [K^\pm \pi^\mp]_D h^\pm)}$$

$$R_{CP+} = \frac{< R^{KK}_{K/\pi}, R^{\pi\pi}_{K/\pi} >}{R^{K\pi}_{K/\pi}}$$

$$A_{CP+} = < A^{KK}_K, A^{\pi\pi}_K >$$

$$R_{ADS(h)} = \frac{R^-_h + R^+_h}{2}$$

$$A_{ADS(h)} = \frac{R^-_h - R^+_h}{R^-_h + R^+_h}$$

$$R_{CP+} = 1 + r_B^2 + 2 r_B \cos\delta_B \cos\gamma$$

$$R_{ADS} = \frac{r_B^2 + r_D^2 + 2 r_B r_D \cos(\delta_B + \delta_D)\cos\gamma}{1 + (r_B r_D)^2 + 2 r_B r_D \cos(\delta_B - \delta_D)\cos\gamma}$$

$$A_{CP+} = \frac{2 r_B \sin\delta_B \sin\gamma}{1 + r_B^2 + 2 r_B \cos\delta_B \cos\gamma}$$

$$A_{ADS} = \frac{2 r_B r_D \sin(\delta_B + \delta_D)\sin\gamma}{r_B^2 + r_D^2 + 2 r_B r_D \cos(\delta_B + \delta_D)\cos\gamma}$$

r_B, r_D: relative magnitude of suppressed amplitude, δ_B δ_D: strong phases

$B \to Dh$ event yields

Table 1: Corrected event yields.

$B^\pm$ mode	D mode	B^-	B^+
$DK^\pm$	$K^\pm\pi^\mp$	3170 ± 83	3142 ± 83
	$K^\pm K^\mp$	592 ± 40	439 ± 30
	$\pi^\pm\pi^\mp$	180 ± 22	137 ± 16
	$\pi^\pm K^\mp$	23 ± 7	73 ± 11
$D\pi^\pm$	$K^\pm\pi^\mp$	40767 ± 310	40774 ± 310
	$K^\pm K^\mp$	6539 ± 129	6804 ± 135
	$\pi^\pm\pi^\mp$	1969 ± 69	1973 ± 69
	$\pi^\pm K^\mp$	191 ± 16	143 ± 14

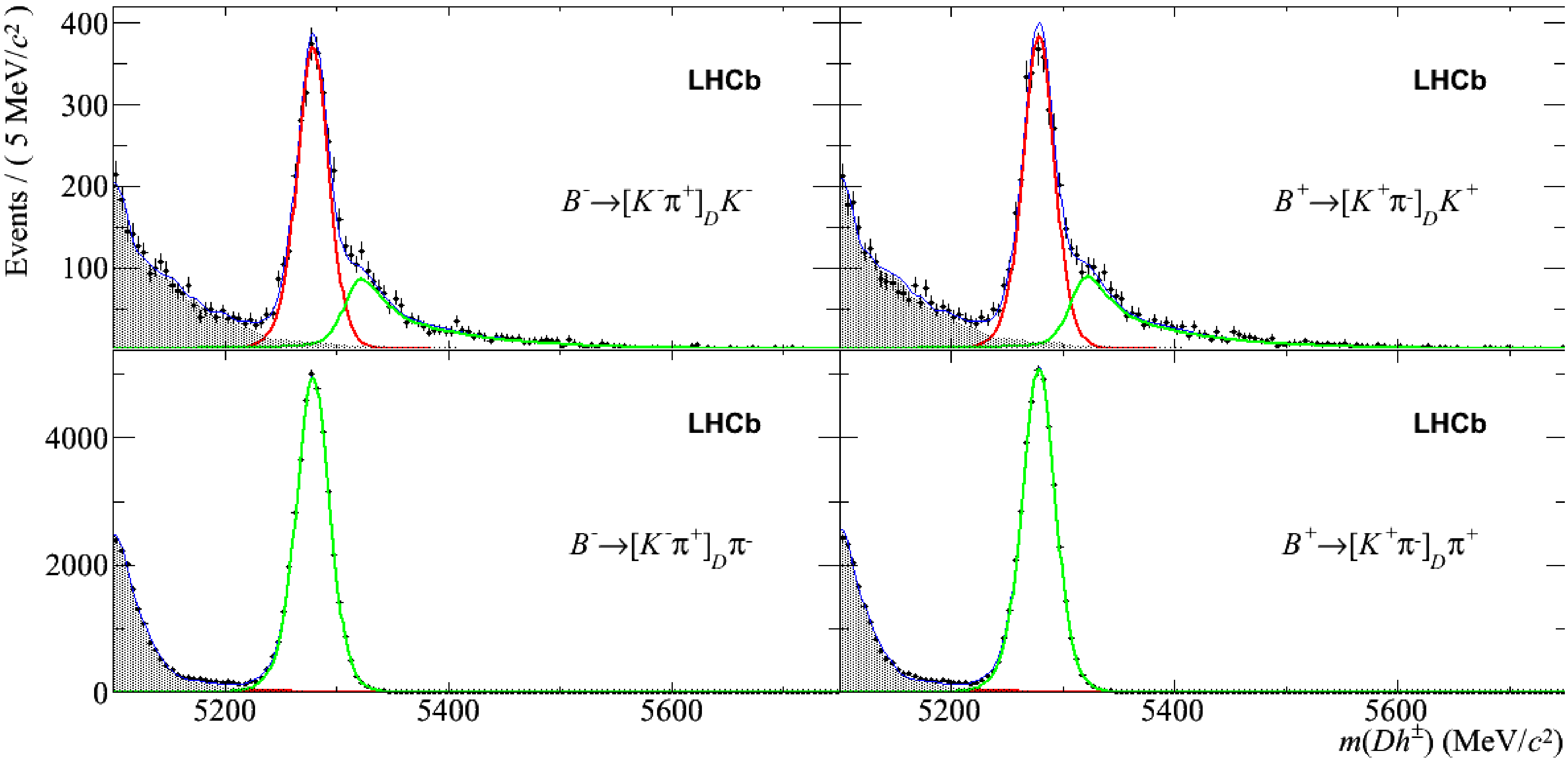
Systematics:

$\times 10^{-3}$	PID	PDFs	Sim	$A_{\text{instr.}}$	Total
$R^{K\pi}_{K/\pi}$	1.4	0.9	0.8	0	1.8
$R^{KK}_{K/\pi}$	1.3	0.8	0.9	0	1.8
$R^{\pi\pi}_{K/\pi}$	1.3	0.6	0.8	0	1.7
$A^{K\pi}_{\pi}$	0	1.0	0	9.4	9.5
$A^{K\pi}_{K}$	0.2	4.1	0	16.9	17.4
A^{KK}_{K}	1.6	1.3	0.5	9.5	9.7
$A^{\pi\pi}_{K}$	1.9	2.3	0	9.0	9.5
A^{KK}_{π}	0.1	6.6	0	9.5	11.6
$A^{\pi\pi}_{\pi}$	0.1	0.4	0	9.9	9.9
R^-_K	0.2	0.4	0	0.1	0.4
R^+_K	0.4	0.5	0	0.1	0.7
R^-_π	0.01	0.03	0	0.07	0.08
R^+_π	0.01	0.03	0	0.07	0.07

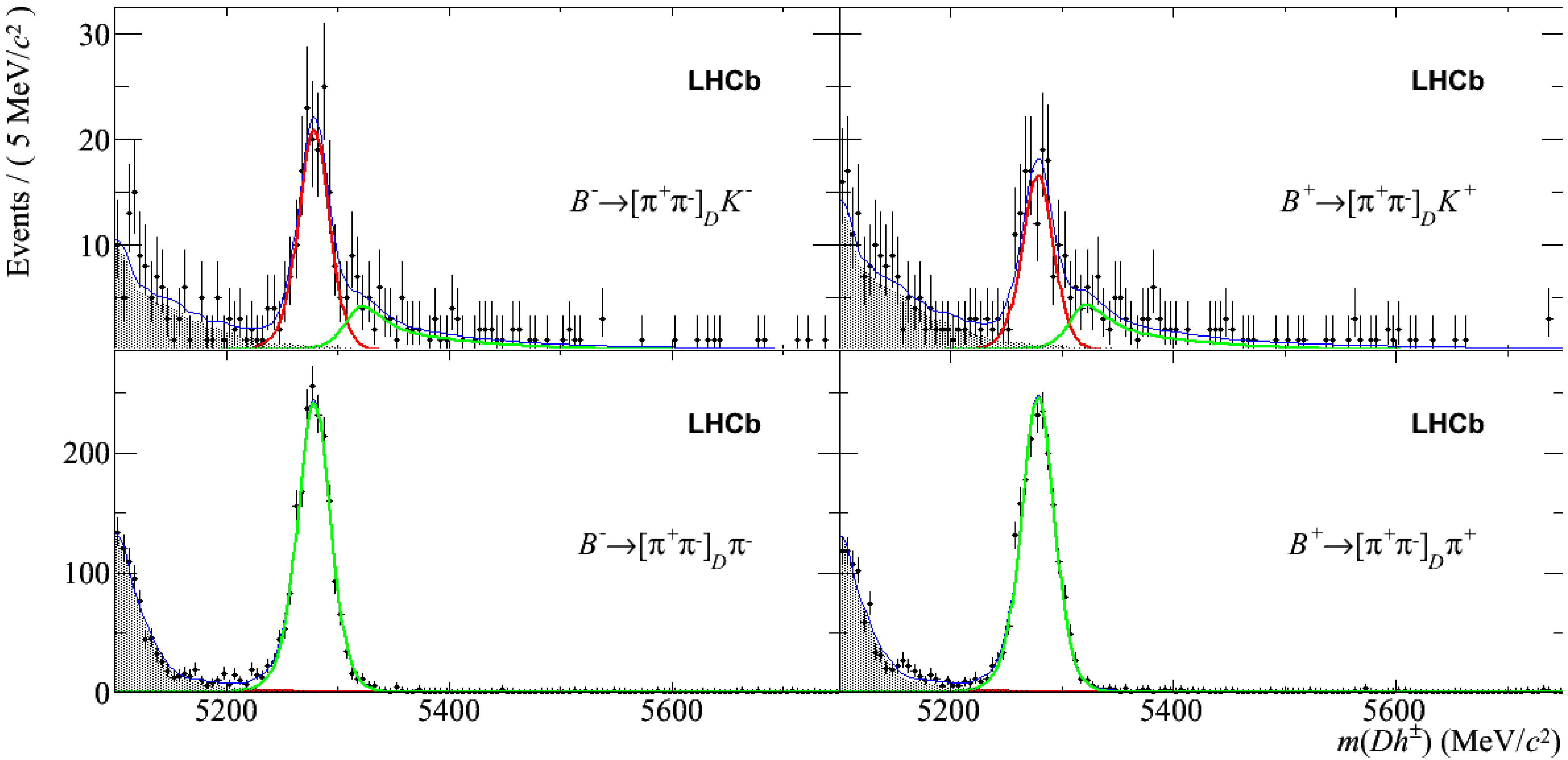
$B \to Dh$ results

$$
\begin{aligned}
R^{K\pi}_{K/\pi} &= 0.0774 \pm 0.0012 \pm 0.0018 \\
R^{KK}_{K/\pi} &= 0.0773 \pm 0.0030 \pm 0.0018 \\
R^{\pi\pi}_{K/\pi} &= 0.0803 \pm 0.0056 \pm 0.0017 \\
A^{K\pi}_{\pi} &= -0.0001 \pm 0.0036 \pm 0.0095 \\
A^{K\pi}_{K} &= 0.0044 \pm 0.0144 \pm 0.0174 \\
A^{KK}_{K} &= 0.148 \pm 0.037 \pm 0.010 \\
A^{\pi\pi}_{K} &= 0.135 \pm 0.066 \pm 0.010 \\
A^{KK}_{\pi} &= -0.020 \pm 0.009 \pm 0.012 \\
A^{\pi\pi}_{\pi} &= -0.001 \pm 0.017 \pm 0.010 \\
R^{-}_{K} &= 0.0073 \pm 0.0023 \pm 0.0004 \\
R^{+}_{K} &= 0.0232 \pm 0.0034 \pm 0.0007 \\
R^{-}_{\pi} &= 0.00469 \pm 0.00038 \pm 0.00008 \\
R^{+}_{\pi} &= 0.00352 \pm 0.00033 \pm 0.00007.
\end{aligned}
$$

$B \to Dh$ favoured mode

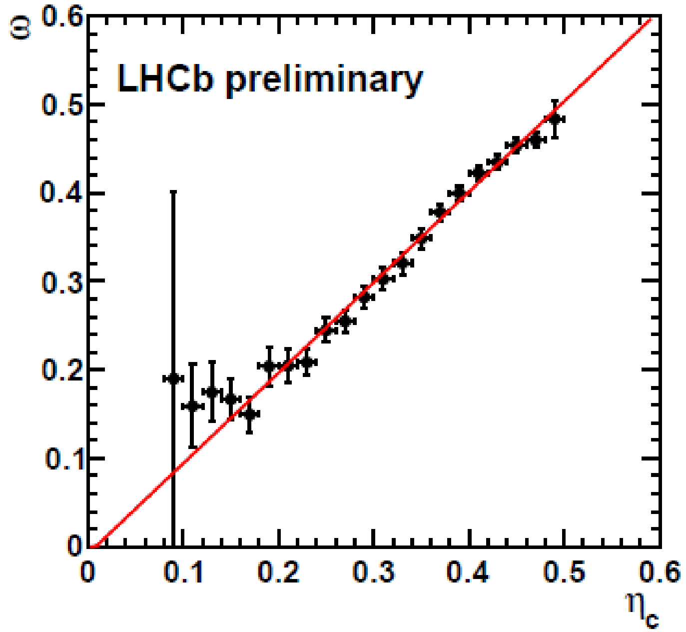


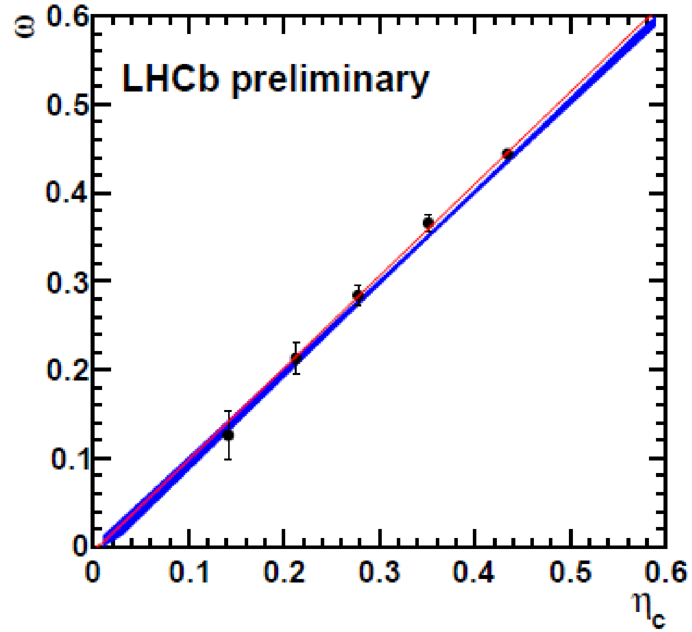
$B \to D[\pi\pi]h$ CP mode

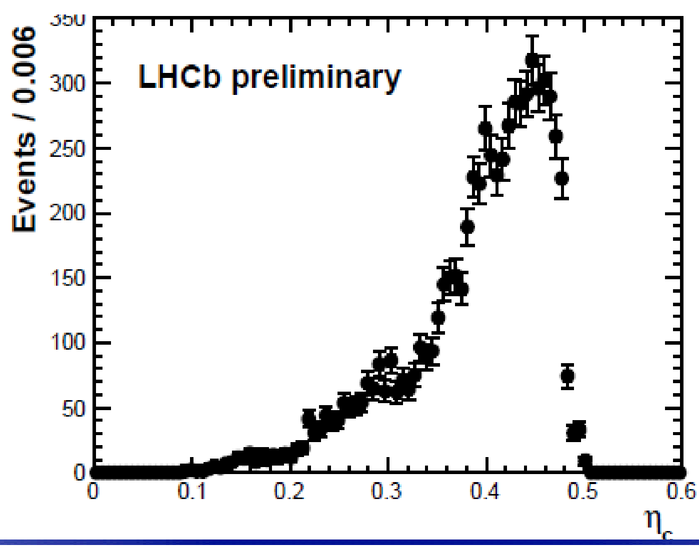


$B_s \rightarrow J/\Psi\ \Phi$ tagging calibration

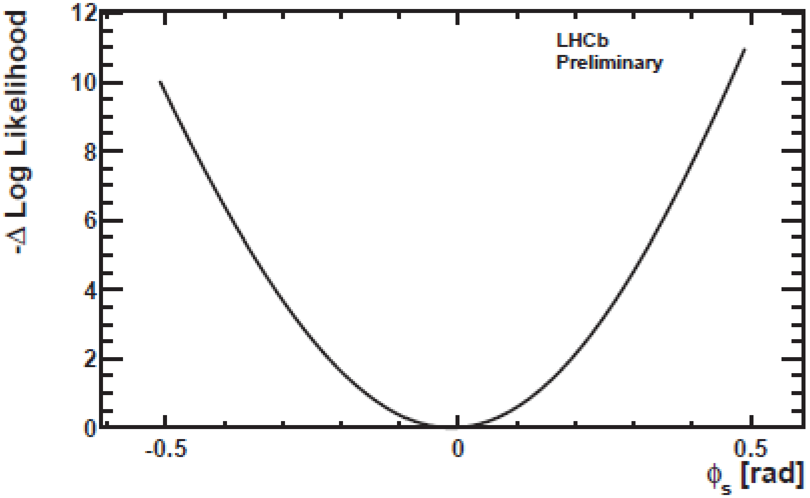
p_0	p_1	$\langle \eta_c \rangle$
$0.392 \pm 0.002 \pm 0.009$	$1.035 \pm 0.021 \pm 0.012$	0.391

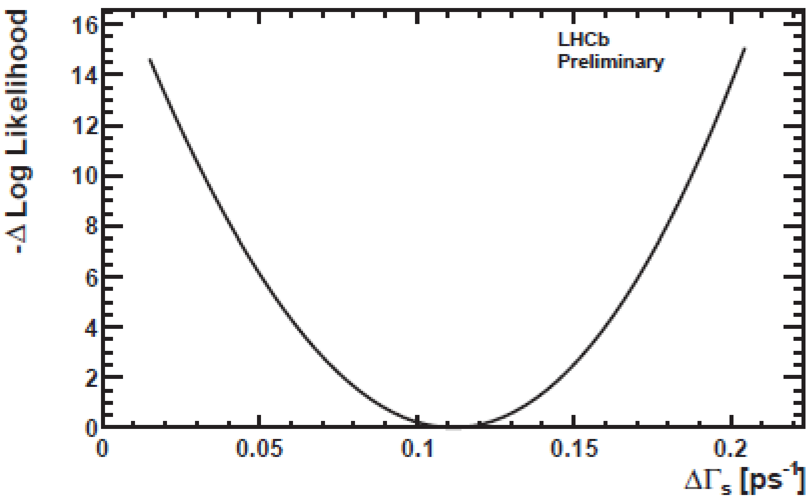




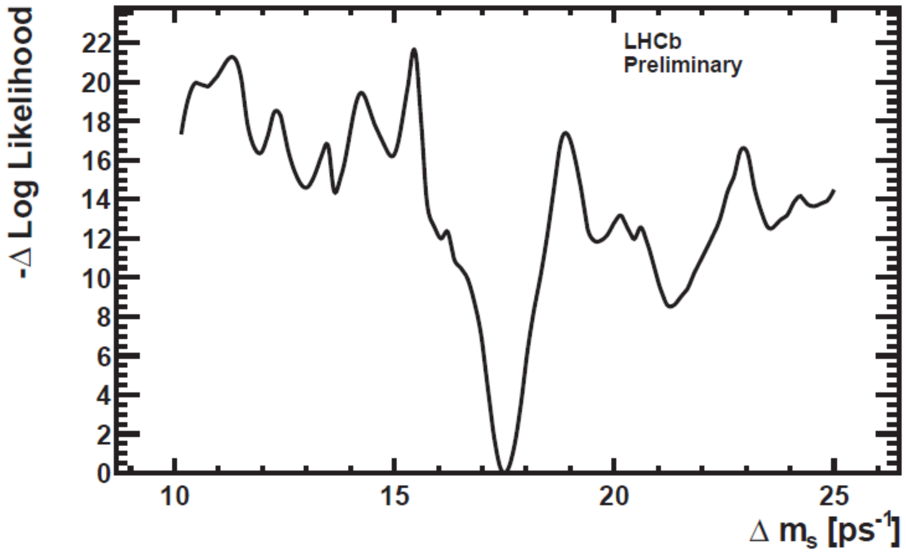


$B_s \to J/\Psi\ \Phi$ likelihood scans





LLH scan for floating Δm_s:



$B_s \to J/\Psi\ \Phi$ numerical results

Parameter	Value	Stat.	Syst.
Γ_s [ps^{-1}]	0.6580	0.0054	0.0066
$\Delta\Gamma_s$ [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
$\delta_\perp$ [rad]	2.90	0.36	0.07
$\delta_\parallel$ [rad]	[2.81, 3.47]		0.13
δ_s [rad]	2.90	0.36	0.08
ϕ_s [rad]	-0.001	0.101	0.027

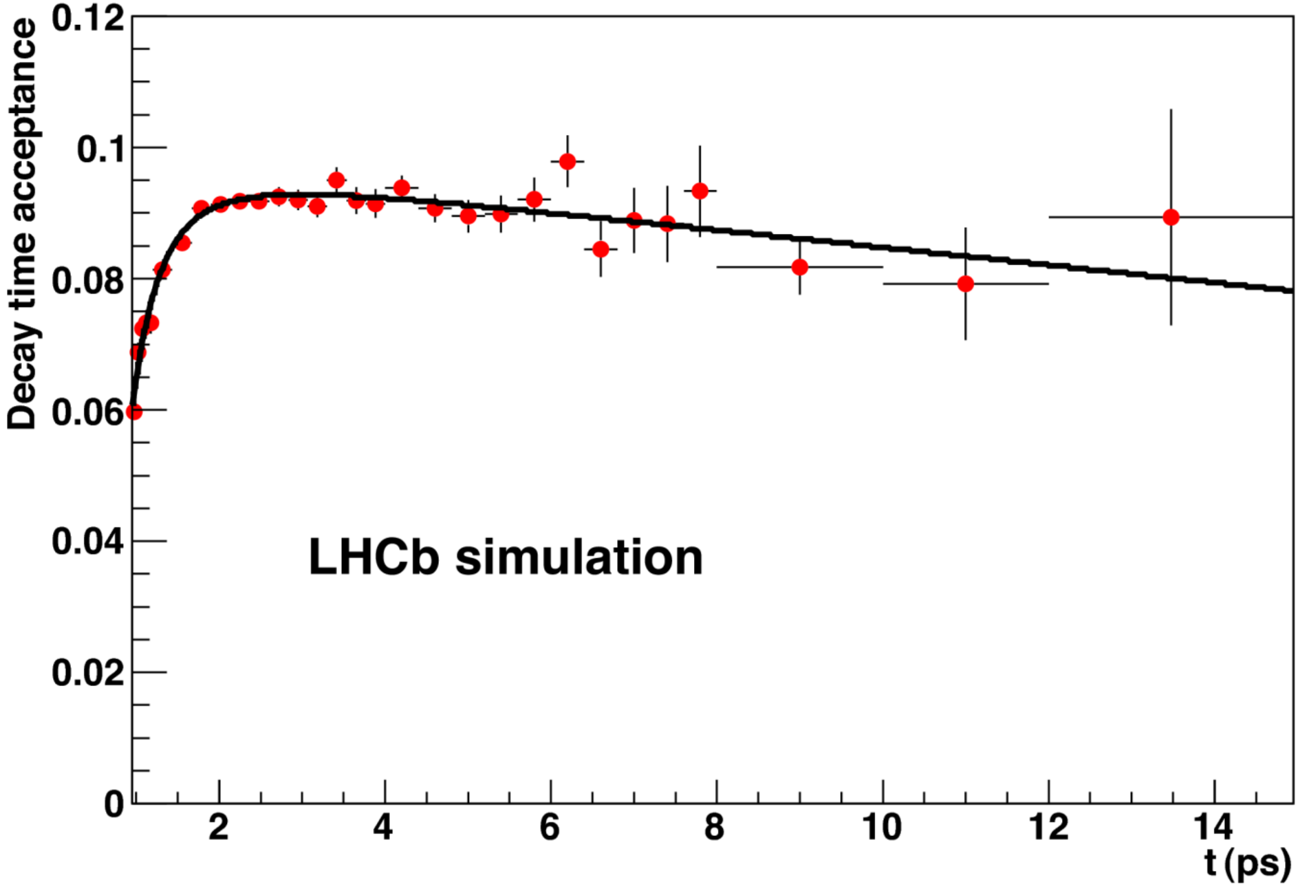
Correlations:

	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

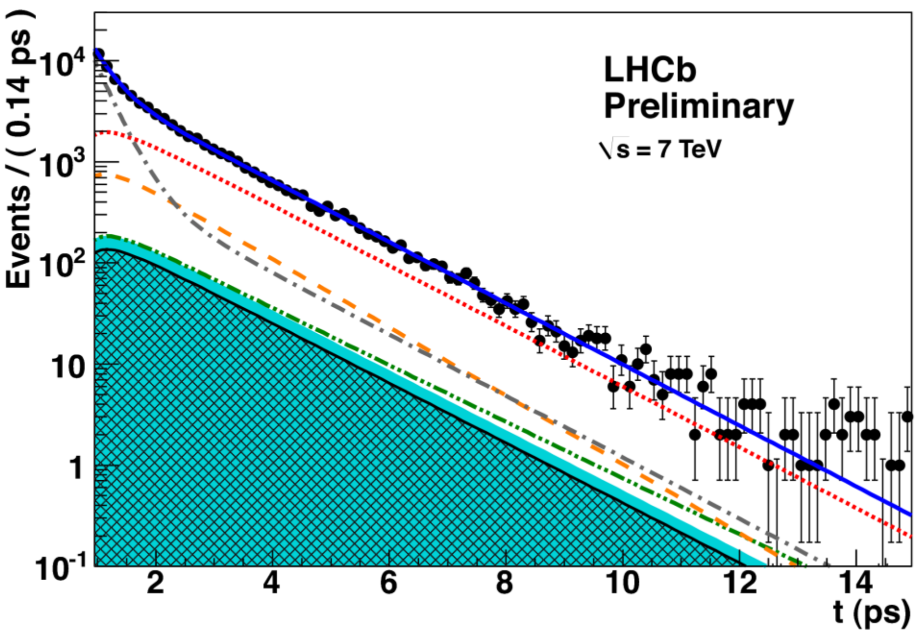
Systematic uncertainties:

Source	Γ_s [ps^{-1}]	$\Delta\Gamma_s$ [ps^{-1}]	$A_\perp^2$	A_0^2	F_S	$\delta_\parallel$ [rad]	$\delta_\perp$ [rad]	δ_s [rad]	ϕ_s [rad]
Description of background	0.0010	0.004	-	0.002	0.005	0.04	0.04	0.06	0.011
Angular acceptances	0.0018	0.002	0.012	0.024	0.005	0.12	0.06	0.05	0.012
t acceptance model	0.0062	0.002	0.001	0.001	-	-	-	-	-
z and momentum scale	0.0009	-	-	-	-	-	-	-	-
Production asymmetry (± 10%)	0.0002	0.002	-	-	-	-	-	-	0.008
CPV mixing & decay (± 5%)	0.0003	0.002	-	-	-	-	-	-	0.020
Fit bias	-	0.001	0.003	-	0.001	0.02	0.02	0.01	0.005
Quadratic sum	0.0066	0.006	0.013	0.024	0.007	0.13	0.07	0.08	0.027

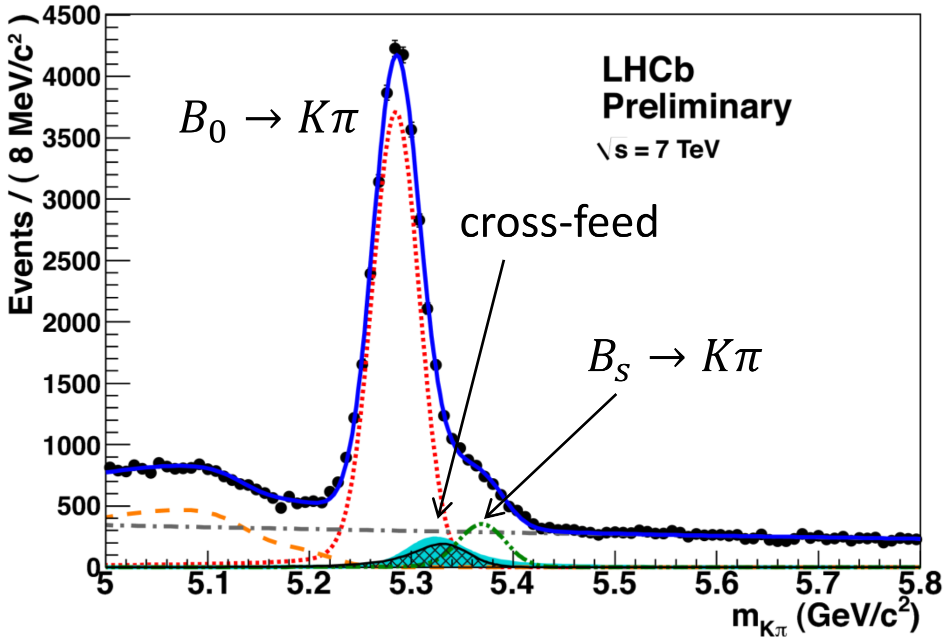
$B \to KK$ decay time acceptance



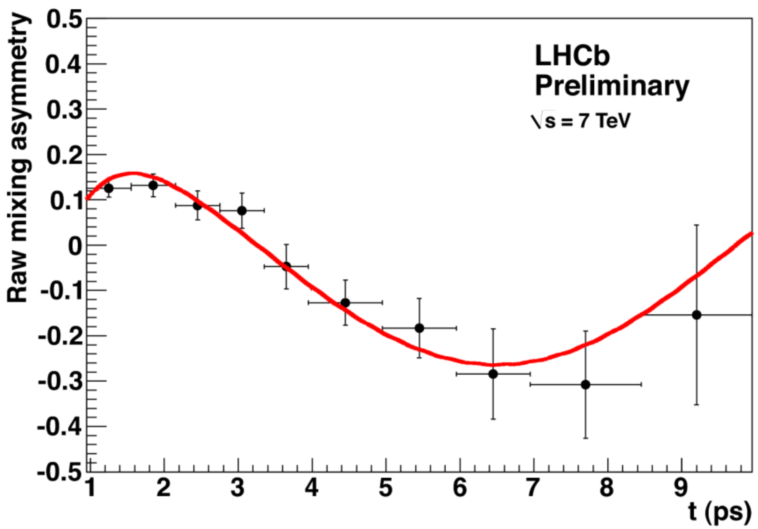
$B \to K\pi$ fit



LHCb
Preliminary
√s = 7 TeV
Events / (0.14 ps)
t (ps)



LHCb
Preliminary
√s = 7 TeV
$B_0 \to K\pi$
cross-feed
$B_s \to K\pi$
Events / (8 MeV/c²)
$m_{K\pi}$ (GeV/c²)



LHCb
Preliminary
√s = 7 TeV
Raw mixing asymmetry
t (ps)

$B \to hh$ systematic uncertainties

Systematic uncertainty	$A^{dir}_{\pi\pi}$	$A^{mix}_{\pi\pi}$	A^{dir}_{KK}	A^{mix}_{KK}
Tagging efficiencies	0.001	0.001	0.002	0.001
Mistag rates	0.001	0.008	0.002	0.004
Different average tagging efficiencies	0.007	0.001	0.009	0.005
Decay time resolution width	negligible	negligible	0.018	0.029
Decay time resolution bias	0.001	negligible	0.007	0.004
Decay time resolution model	negligible	negligible	0.002	0.007
Decay time acceptance	0.006	0.003	0.019	0.030
Input quantities Δm_d and Δm_s	0.026	0.018	0.023	0.031
Input quantity Γ_s	–	–	0.004	0.006
Combinatorial decay time model	0.007	0.008	0.009	0.005
Cross-feed decay time model	0.007	negligible	0.001	0.001
Signal mass lineshape model	negligible	0.009	0.008	0.005
Signal mass final state radiation	0.002	0.009	0.009	0.006
Combinatorial mass lineshape model	negligible	0.001	0.001	negligible
Cross-feed mass lineshape (smearing)	0.001	0.001	0.001	0.001
Cross-feed mass lineshape (shift)	negligible	0.002	0.001	0.001
Particle identification	0.001	0.006	0.002	0.001
Total	0.029	0.026	0.040	0.054