Charmless two-body B decays at LHCb

Thomas Latham

(on behalf of the LHCb Collaboration)

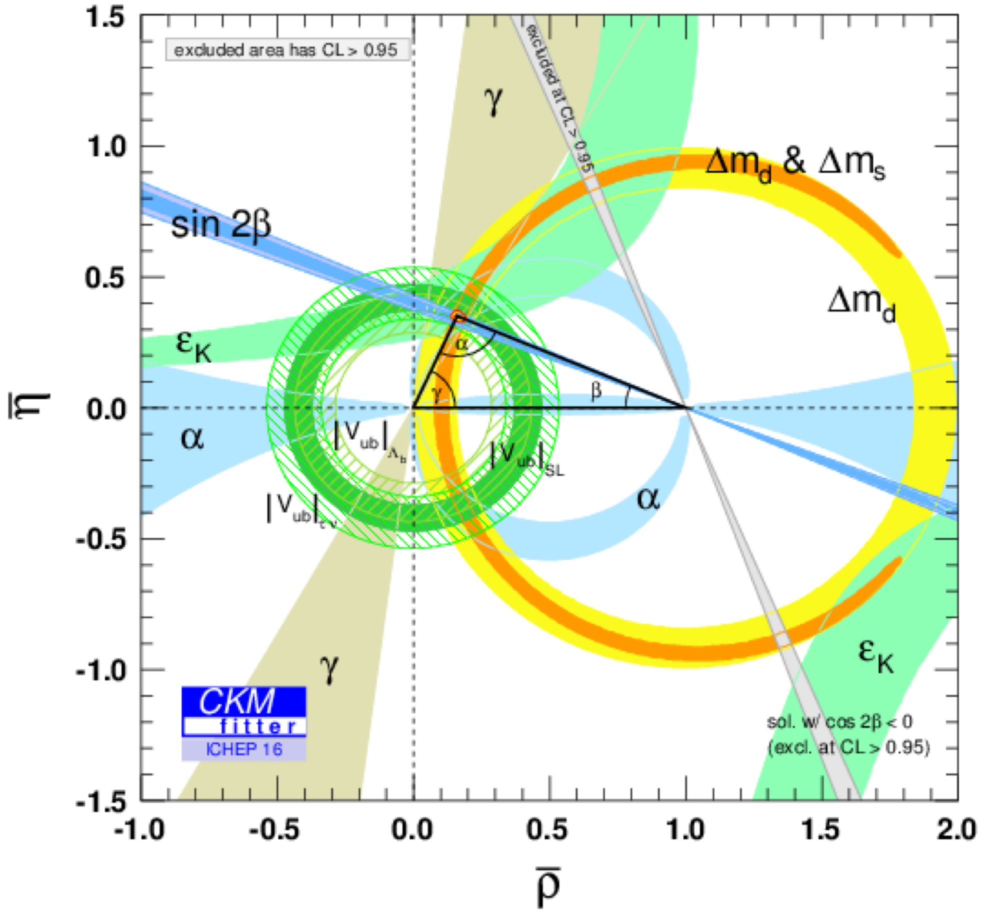
7th May 2018

Overview

- Introduction
- Recent results from LHCb
  - Measurements of time-dependent and time-integrated CP asymmetries in $B^0_{(s)} \rightarrow h^+h^-$ decays
    - LHCb-PAPER-2018-006 (in preparation)
  - First observation of the decay $B^0 \rightarrow p\bar{p}$
    - Phys. Rev. Lett. 119 (2017) 232001
- Concluding remarks

CKM mechanism and CP violation

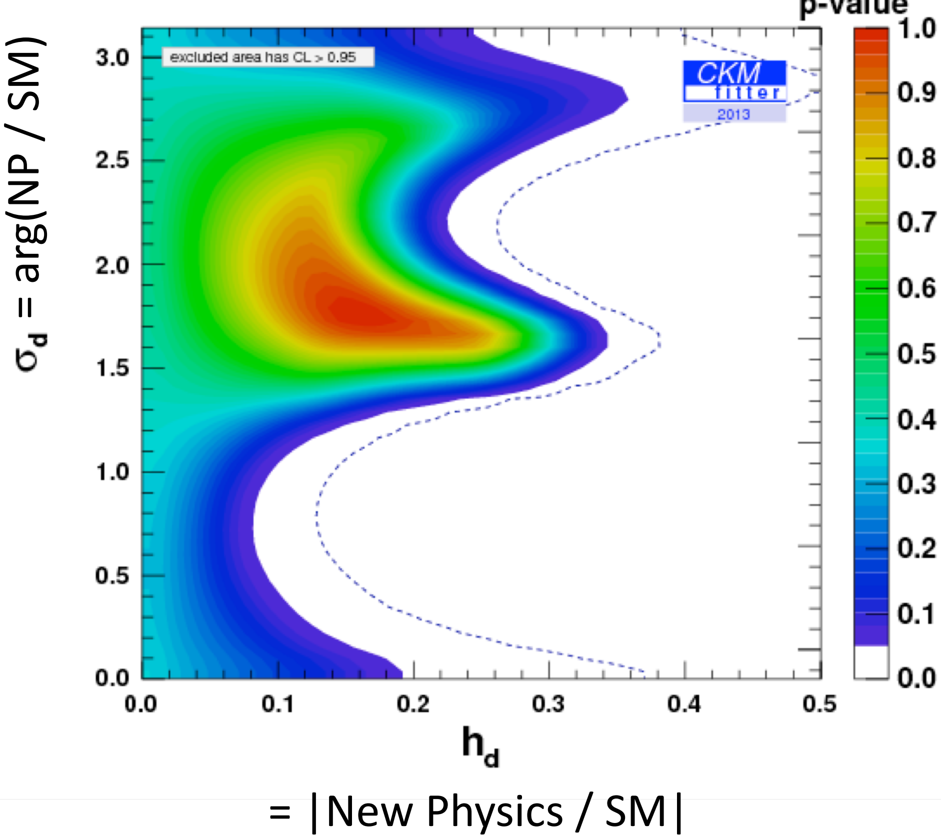
- CKM mechanism agrees well with experiment
- But still plenty of room for new physics
- Vital to measure CP violating observables in as many different decay processes as possible
- Look for disagreements



CKM mechanism and CP violation

- CKM mechanism agrees well with experiment
- But still plenty of room for new physics
- Vital to measure CP violating observables in as many different decay processes as possible
- Look for disagreements

Allowed new physics contributions in B^0 mixing

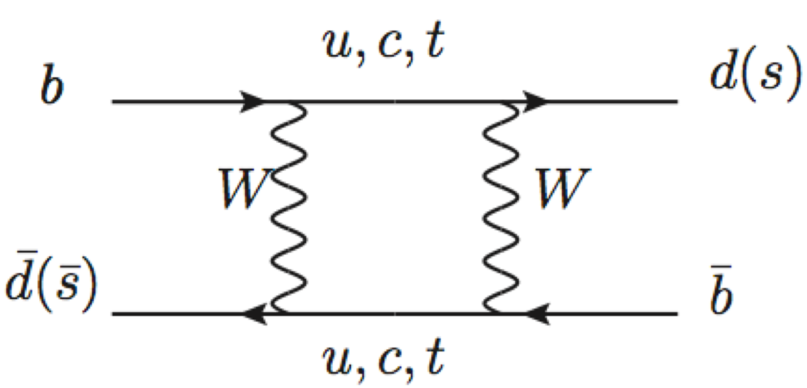


Manifestations of CPV

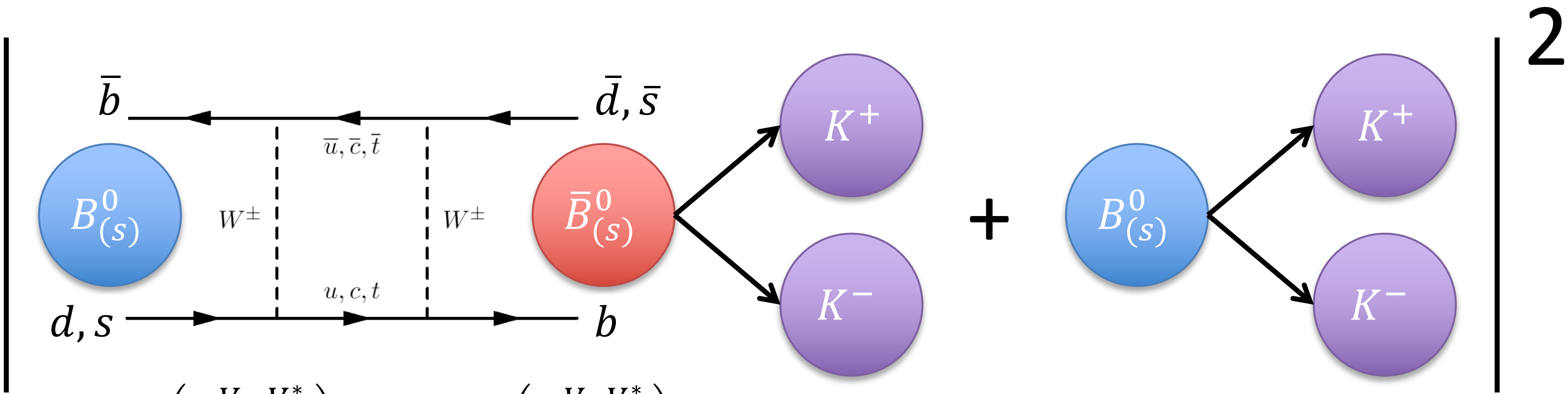
- **CPV in decay** $|\bar{A}_{\bar{f}}/A_f| \neq 1$
  - The ratio of the amplitudes for the decay of b and $\bar{b}$ hadrons to CP-conjugate final states is not of unit magnitude
  - Only form of CPV possible for B^+ mesons and b-baryons
- **Mixing-induced CPV** $\arg(\lambda_f) + \arg(\lambda_{\bar{f}}) \neq 0$
  - The ratio of the amplitudes for decays with and without mixing is not real
  - Investigated for both B^0 and B_s^0 decays
  - Requires time-dependent analyses (more on this later)
- **CPV in mixing** $|q/p| \neq 1$
  - Expected to be small for the B meson system
  - Will not discuss this further today (although LHCb has made important measurements in last couple of years)

[Phys. Rev. Lett. 114 (2015) 041601]

[Phys. Rev. Lett. 117 (2016) 061803]



$B^0_{(s)} \sim \bar{B}^0_{(s)}$ mixing



$$\beta = \arg\left(-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right) \quad \beta_s = \arg\left(-\frac{V_{ts}V_{tb}^*}{V_{cs}V_{cb}^*}\right)$$

- Neutral B mesons exhibit mixing through box diagram
- Decays to *CP* eigenstates allow to probe the mixing phase through the interference between decays with and without mixing
- Make comparison of direct and indirect determinations, as well as direct determinations in different decays, to probe possible new physics contributions

Time-dependent asymmetries

- The time-dependent CP asymmetry is given by:

$$A_{CP}(t) = \frac{\Gamma[\bar{B}^0_{d,s}(t) \to f] - \Gamma[B^0_{d,s}(t) \to f]}{\Gamma[\bar{B}^0_{d,s}(t) \to f] + \Gamma[B^0_{d,s}(t) \to f]} = \frac{-C_f \cos(\Delta m_{d,s}\, t) + S_f \sin(\Delta m_{d,s}\, t)}{\cosh(\frac{\Delta\Gamma_{d,s}}{2} t) + A_f^{\Delta\Gamma_{d,s}} \sinh(\frac{\Delta\Gamma_{d,s}}{2} t)}$$

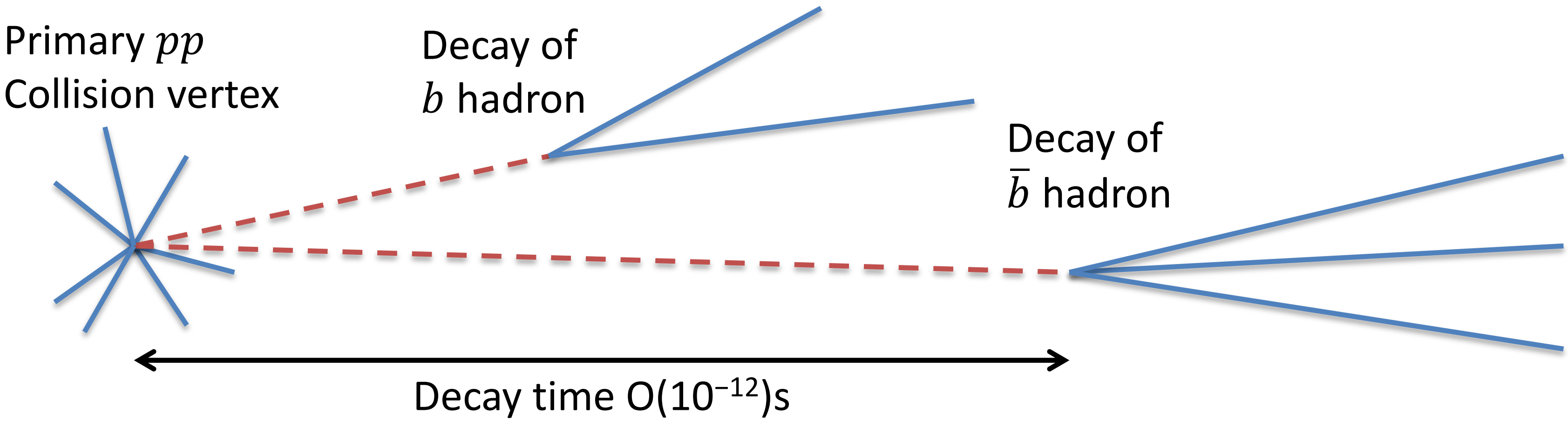
$$C_f = \frac{1 - |\lambda_f|^2}{1 + |\lambda_f|^2} \qquad S_f = \frac{2\mathrm{Im}\lambda_f}{1 + |\lambda_f|^2} \qquad A_f^{\Delta\Gamma_{d,s}} = \frac{2\mathrm{Re}\lambda_f}{1 + |\lambda_f|^2}$$

$$|C_f|^2 + |S_f|^2 + |A_f^{\Delta\Gamma}|^2 = 1$$

$$\lambda_f = \frac{q}{p}\frac{\bar{A}_f}{A_f}$$

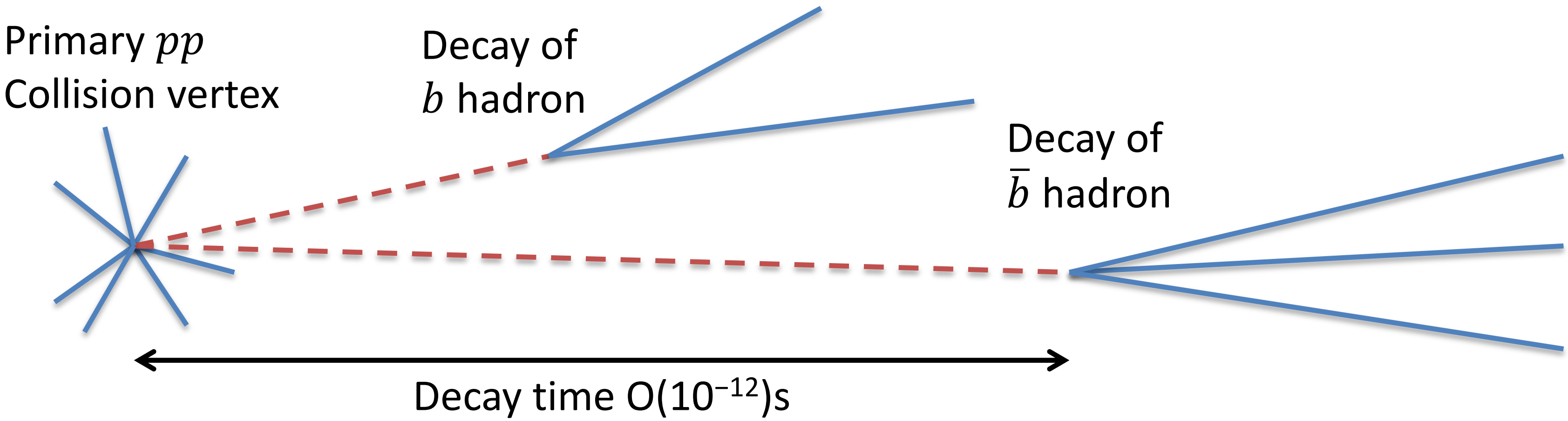
- $\frac{\bar{A}_f}{A_f}$ is the ratio of decay amplitudes
- $\frac{q}{p}$ is related to the neutral B mixing

Time dependent analysis

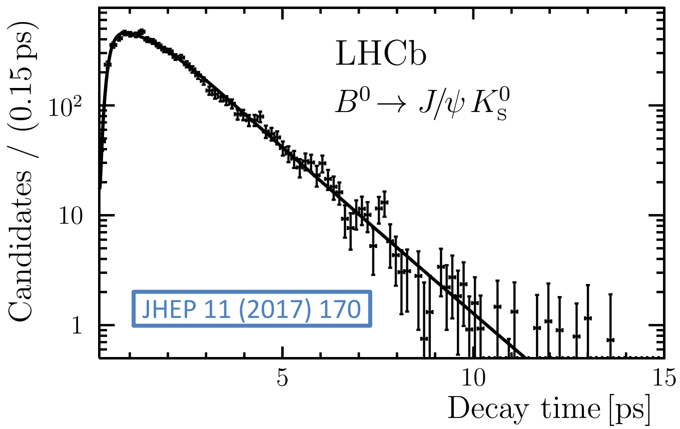


- Vertex measurements by LHCb VELO allow decay times of particles to be precisely determined
- Need also to tag the flavour of the signal at production
- Putting these two pieces of information together, can measure decay rates as a function of the decay time
- Hence allows mixing-induced CPV to be probed

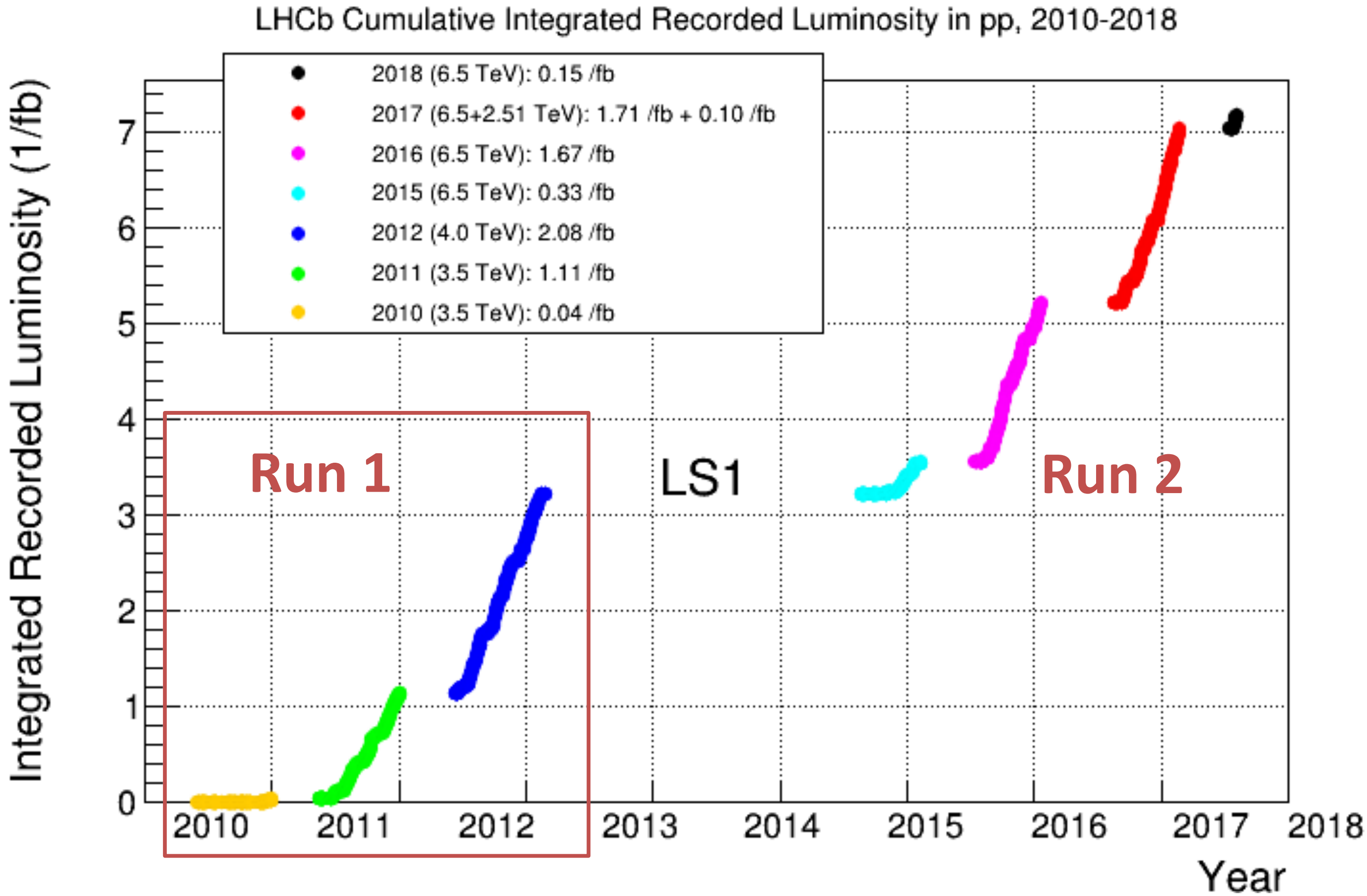
Time dependent analysis



- Need also to account for effects of:
  - Decay time acceptance (due to trigger and selection requirements)
  - Experimental resolution on the measurement of the decay time
  - Rate of mis-tagging the flavour



Data Sample



2011 + 2012 data set (3 fb^{-1}) used in analyses discussed today

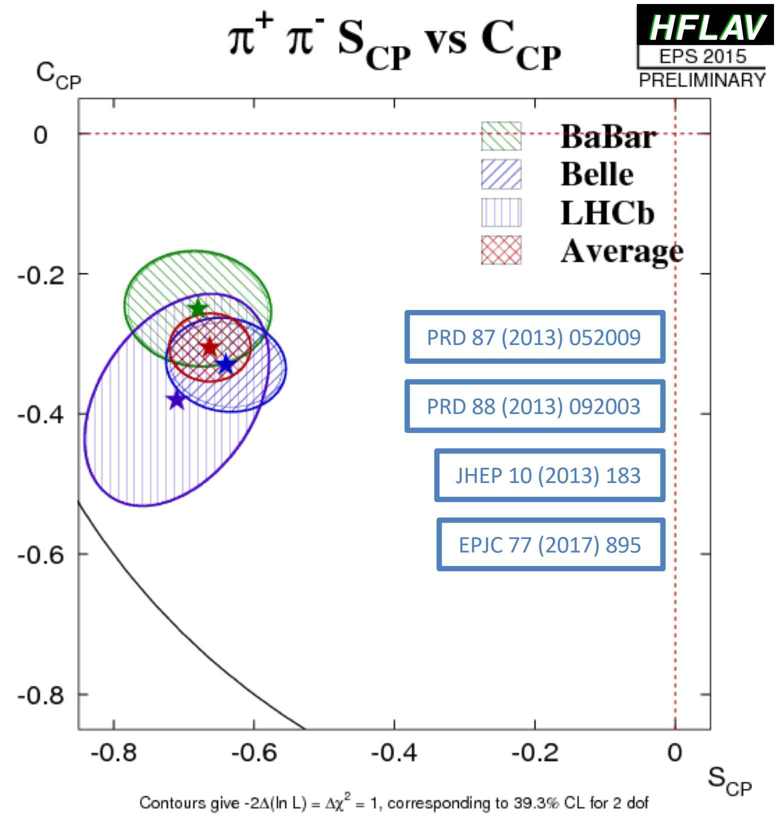
Measurements of CP asymmetries in $B^0_{(s)} \to h^+ h'^-$ decays

LHCb-PAPER-2018-006

in preparation

Previous experimental status

- Measurements of $C_{\pi\pi}$ and $S_{\pi\pi}$ in good agreement between B-factories and LHCb
- C_{KK} and S_{KK} are measured only by LHCb
  - No measurement yet of $A^{\Delta\Gamma}_{KK}$
- A_{CP} values in $B \to K\pi$ modes in good agreement between experiments – LHCb already leading the precision



PRD 87 (2013) 052009

PRD 88 (2013) 092003

JHEP 10 (2013) 183

EPJC 77 (2017) 895

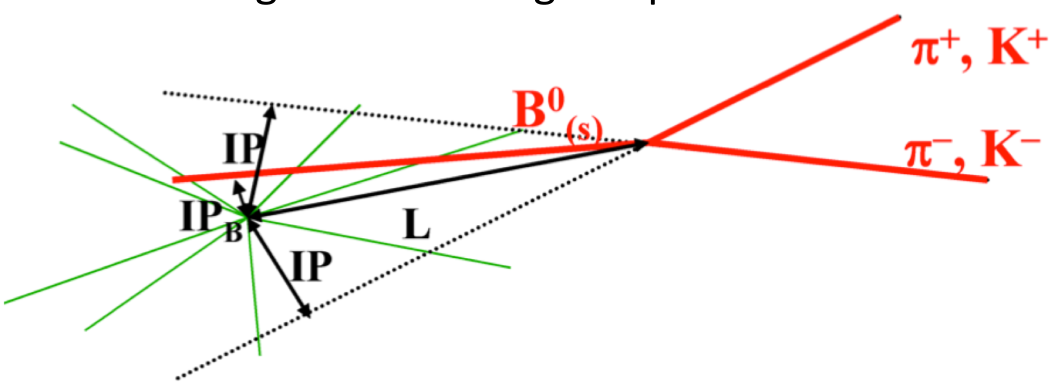
Experiment	$A_{CP}^{B^0}$	$A_{CP}^{B_s^0}$
BaBar	$-0.107 \pm 0.016 \,^{+\,0.006}_{-\,0.004}$	—
Belle	$-0.069 \pm 0.014 \pm 0.007$	—
CDF	$-0.083 \pm 0.013 \pm 0.004$	$0.22 \pm 0.07 \pm 0.02$
LHCb	$-0.080 \pm 0.007 \pm 0.003$	$0.27 \pm 0.04 \pm 0.01$
HFLAV Avg.	-0.082 ± 0.006	0.26 ± 0.04

PRD 87 (2013) 052009 | PRD 87 (2013) 031103 | PRL 113 (2014) 242001

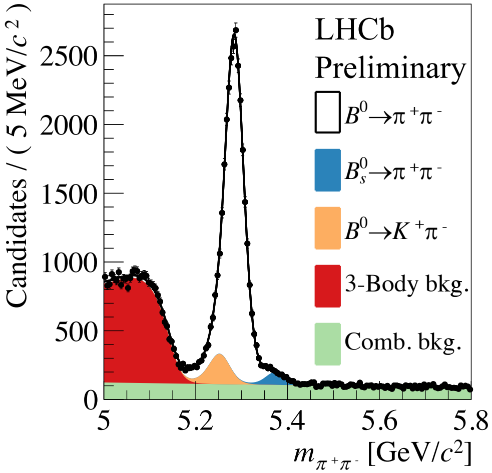
PRL 110 (2013) 221601 | EPJC 77 (2017) 895

Event selection

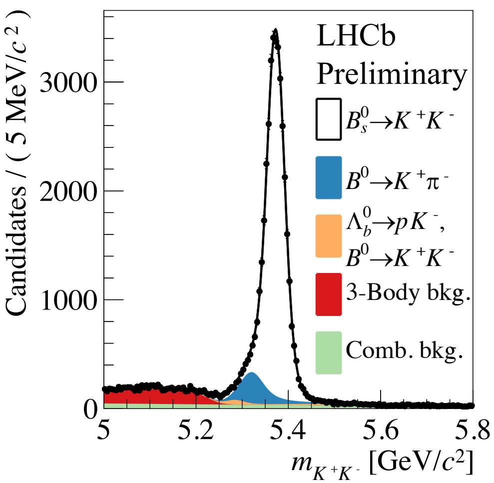
- Particle identification
  - Separate the various final states
  - Reduce amount of cross contamination from other $B \to h^+h^-$ modes to ~10% of the signal
- A multivariate Boosted Decision Tree classifier is used to remove combinatorial background
  - Use kinematical and topological variables
  - Signal training sample from simulation
  - Background training sample from data sidebands



$\sim$29k $B^0 \to \pi^+\pi^-$ signal decays



$\sim$37k $B_s^0 \to K^+K^-$ signal decays



Experimental decay rates

$$f(t,\xi,\eta,\delta_t) = K^{-1}\left\{\left[(1-A_{\rm P})\,\Omega_{\rm sig}(\xi,\eta) + (1+A_{\rm P})\,\bar{\Omega}_{\rm sig}(\xi,\eta)\right] I_+(t,\delta_t) + \left[(1-A_{\rm P})\,\Omega_{\rm sig}(\xi,\eta) - (1+A_{\rm P})\,\bar{\Omega}_{\rm sig}(\xi,\eta)\right] I_-(t,\delta_t)\right\},$$

t = decay time
ξ = B flavour
η = predicted mistag probability
δ_t = decay time error

$$I_+(t,\delta_t) = \left\{e^{-\Gamma t'}\left[\cosh\left(\frac{\Delta\Gamma}{2}t'\right) + A_f^{\Delta\Gamma}\sinh\left(\frac{\Delta\Gamma}{2}t'\right)\right]\right\} \otimes R(t-t'|\delta_t)\cdot g(\delta_t)\cdot\varepsilon_{\rm acc}(t),$$

$$I_-(t,\delta_t) = \left\{e^{-\Gamma t'}\left[C_f\cos(\Delta m t') - S_f\sin(\Delta m t')\right]\right\} \otimes R(t-t'|\delta_t)\cdot g(\delta_t)\cdot\varepsilon_{\rm acc}(t).$$

- CP violation coefficients determined from unbinned maximum likelihood fits
  - Fit variables:
    - B-candidate invariant mass
    - Decay time and associated per-event error
    - Per-event mistag probability
  - Simultaneous fit to $\pi^+\pi^-$, K^+K^- and $K^+\pi^-$ spectra

- Crucial experimental ingredients
  - Determination of any production asymmetry
    - Detection asymmetries also important for flavour-specific modes
  - Determination of the flavour of signal B at production (flavour tagging)
  - Determination of the decay time resolution and acceptance

Production asymmetry

$$f(t,\xi,\eta,\delta_t) = K^{-1}\{[(1-A_\mathrm{P})\Omega_\mathrm{sig}(\xi,\eta)+(1+A_\mathrm{P})\bar{\Omega}_\mathrm{sig}(\xi,\eta)]I_+(t,\delta_t)+ [(1-A_\mathrm{P})\Omega_\mathrm{sig}(\xi,\eta)-(1+A_\mathrm{P})\bar{\Omega}_\mathrm{sig}(\xi,\eta)]I_-(t,\delta_t)\},$$

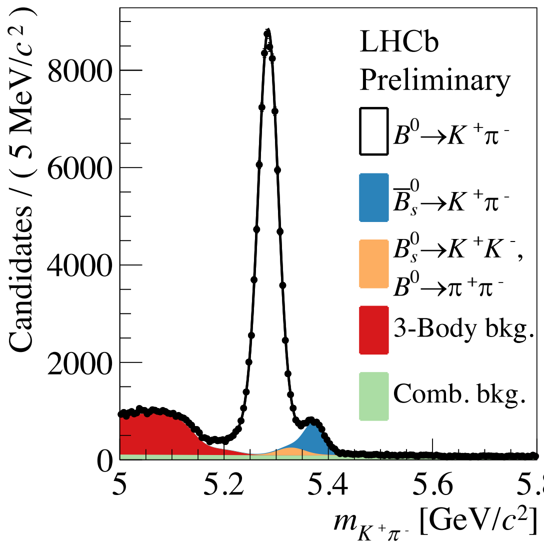
$$I_+(t,\delta_t) = \left\{e^{-\Gamma t'}\left[\cosh\left(\frac{\Delta\Gamma}{2}t'\right)+A_f^{\Delta\Gamma}\sinh\left(\frac{\Delta\Gamma}{2}t'\right)\right]\right\}\otimes R(t-t'|\delta_t)\cdot g(\delta_t)\cdot\varepsilon_\mathrm{acc}(t),$$

$$I_-(t,\delta_t) = \left\{e^{-\Gamma t'}[C_f\cos(\Delta m t')-S_f\sin(\Delta m t')]\right\}\otimes R(t-t'|\delta_t)\cdot g(\delta_t)\cdot\varepsilon_\mathrm{acc}(t).$$

- A_P: production asymmetry
  - determined from time-dependent asymmetries of $B^0\rightarrow K^+\pi^-$ and $B_s^0\rightarrow K^-\pi^+$ decays:

$A_P(B^0) = (0.19 \pm 0.60)\%$

$A_P(B_s^0) = (2.4 \pm 2.1)\%$

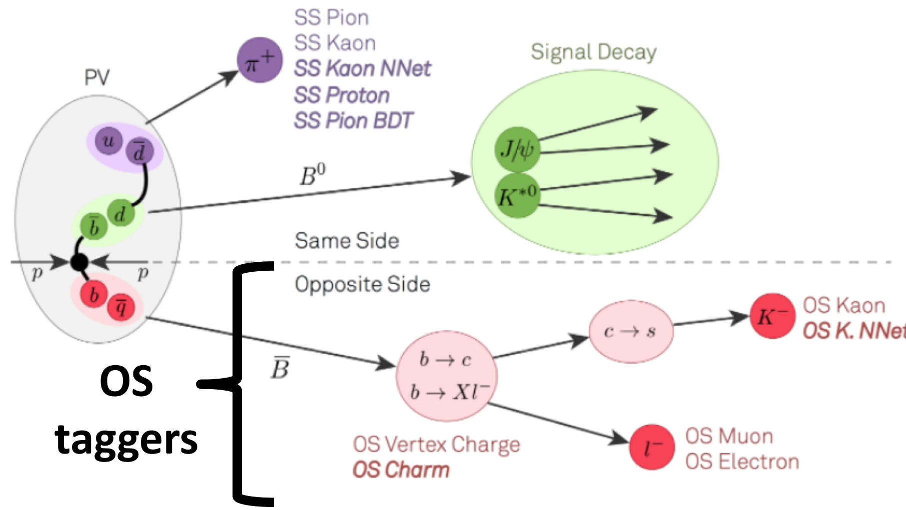


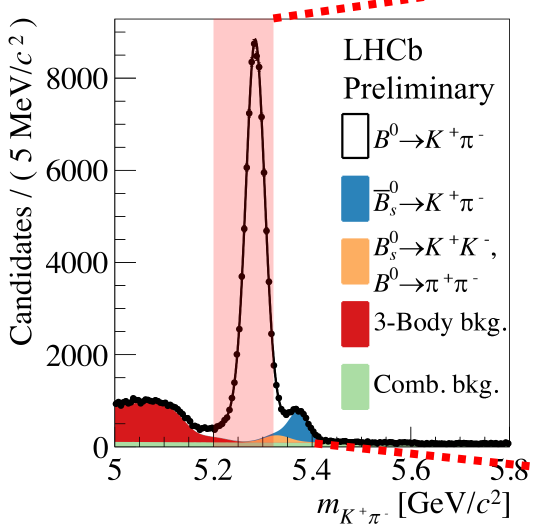
~94k $B^0\rightarrow K^+\pi^-$ and ~7k $B_s^0\rightarrow K^-\pi^+$ signal decays

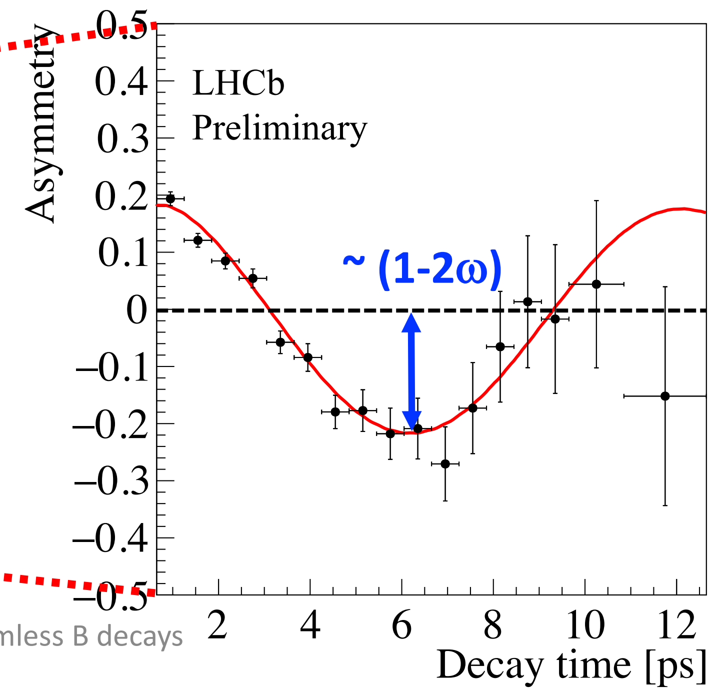
Flavour tagging

LHCb-PAPER-2018-006

- Analysis uses both **Opposite Side** (OS) and **Same Side** (SS) taggers:
  - information is used on a per-event basis:
    $\omega = p_0 + p_1(\eta - \hat{\eta})$
- Calibration
  - Use time-dependent asymmetry of control modes in data for calibration
  - $B^0 \to K^+\pi^-$ shown for OS taggers







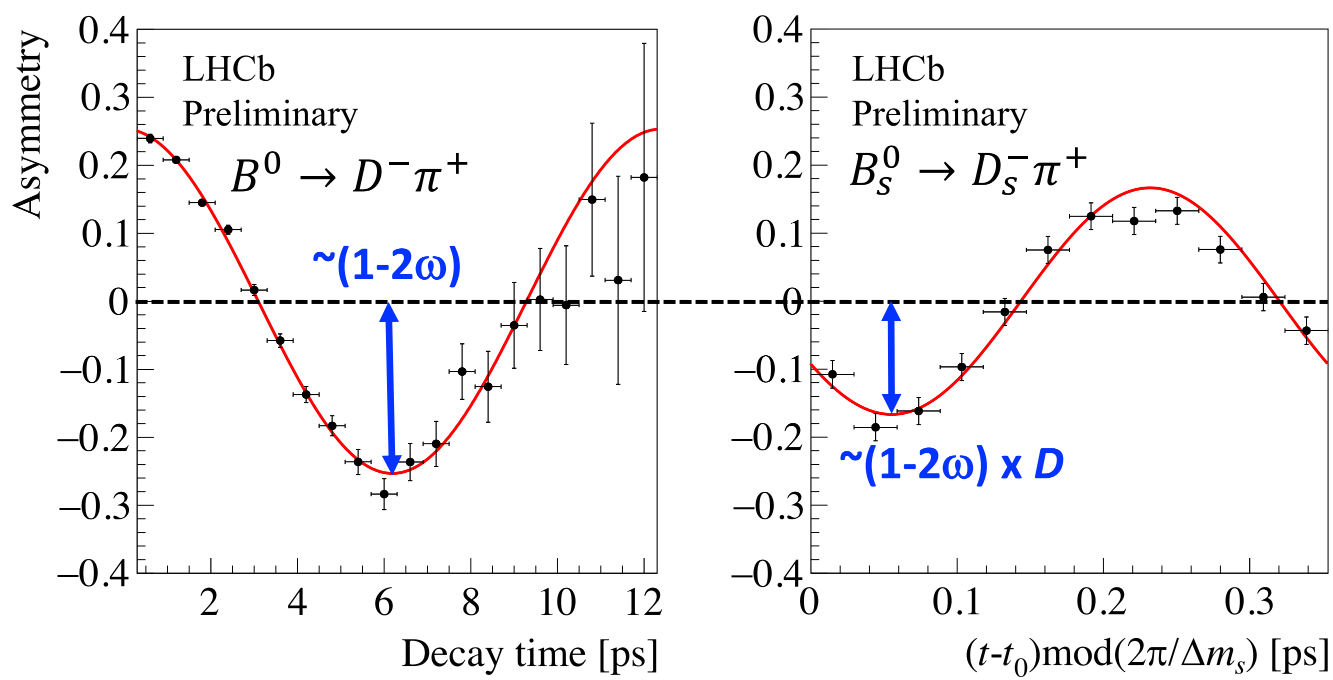
Decay time resolution

- Decay time resolution introduces a dilution of oscillation amplitudes $D = \exp(-\frac{1}{2}\Delta m^2\,\sigma_t^2)$
- Dilution from σ_t is negligible for B^0 due to small Δm_d
- Resolution determined on per-event basis: decay time error δ_t computed in reconstruction
- Calibration of this quantity is performed on data, measuring simultaneously the time-dependent asymmetries of $B^0 \to D^-\pi^+$ and $B_s^0 \to D_s^-\pi^+$ decays

$$\sigma_t = q_0 + q_1(\delta t - 30\text{fs})$$

LHCb Preliminary

$$q_0 = (46.1 \pm 4.1)\text{fs}$$
$$q_1 = 0.81 \pm 0.38$$



Decay time acceptance

$$f\left(t,\xi,\eta,\,\delta_t\right)=K^{-1}\left\{\left[\left(1-A_{\mathrm{P}}\right)\Omega_{\mathrm{sig}}\left(\xi,\eta\right)+\left(1+A_{\mathrm{P}}\right)\bar{\Omega}_{\mathrm{sig}}\left(\xi,\eta\right)\right]I_{+}\left(t,\,\delta_t\right)+\left[\left(1-A_{\mathrm{P}}\right)\Omega_{\mathrm{sig}}\left(\xi,\eta\right)-\left(1+A_{\mathrm{P}}\right)\bar{\Omega}_{\mathrm{sig}}\left(\xi,\eta\right)\right]I_{-}\left(t,\,\delta_t\right)\right\},$$

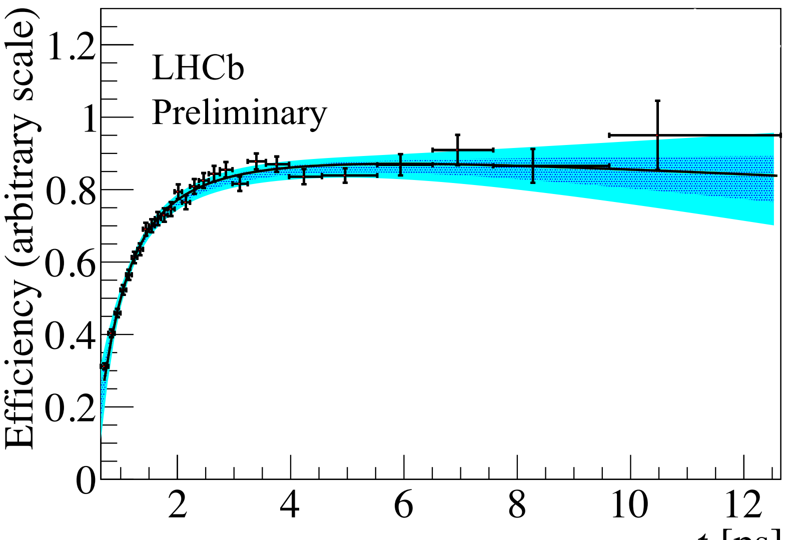
$$I_{+}\left(t,\,\delta_t\right)=\left\{e^{-\Gamma t'}\left[\cosh\left(\frac{\Delta\Gamma}{2}t'\right)+A_f^{\Delta\Gamma}\sinh\left(\frac{\Delta\Gamma}{2}t'\right)\right]\right\}\otimes R\left(t-t'|\delta_t\right)\cdot g\left(\delta_t\right)\cdot\varepsilon_{\mathrm{acc}}\left(t\right),$$

$$I_{-}\left(t,\,\delta_t\right)=\left\{e^{-\Gamma t'}\left[C_f\cos\left(\Delta m t'\right)-S_f\sin\left(\Delta m t'\right)\right]\right\}\otimes R\left(t-t'|\delta_t\right)\cdot g\left(\delta_t\right)\,\varepsilon_{\mathrm{acc}}\left(t\right).$$

- $\varepsilon_{\mathrm{acc}}(t)$ is the decay time acceptance
- Introduced by selection requirements
- Parameterised using empirical function:

$$\varepsilon_{acc}(t)\propto\left[d_0-\mathrm{erf}\left(d_1 t^{d_2}\right)\right](1-d_3 t)$$

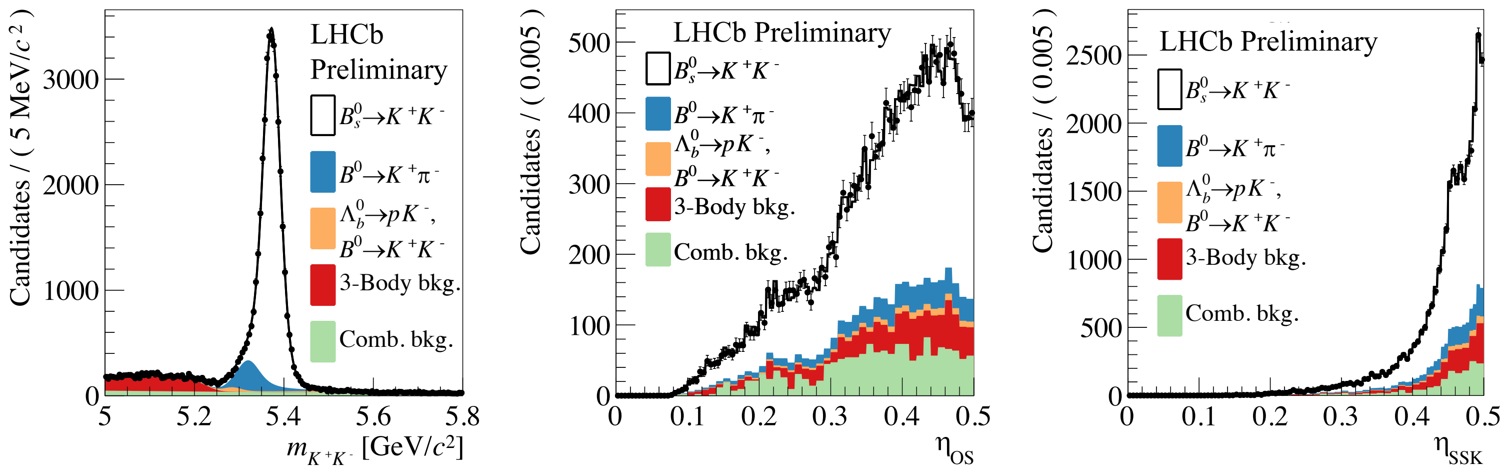
- Parameters determined from $B^0\to K^+\pi^-$ data and corrected for other final states based on simulation

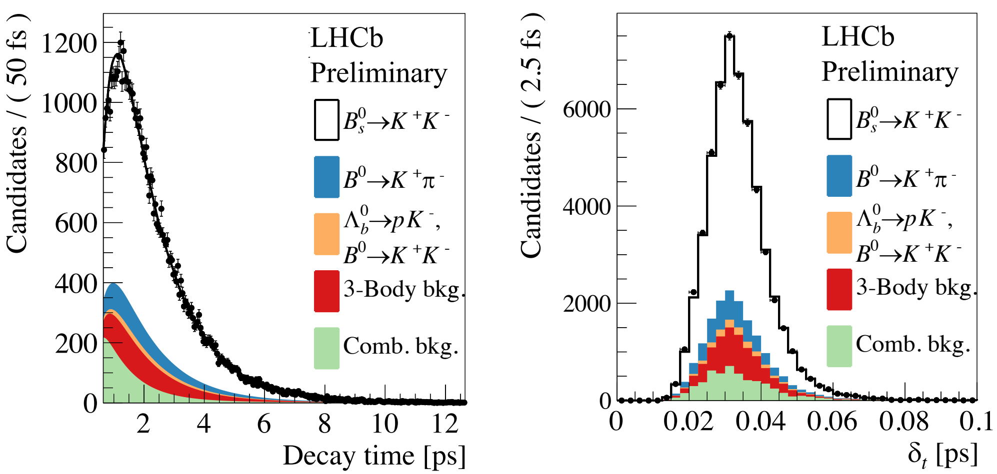


LHCb-PAPER-2018-006

Result of the simultaneous fit

K^+K^- spectrum





Fixed parameters

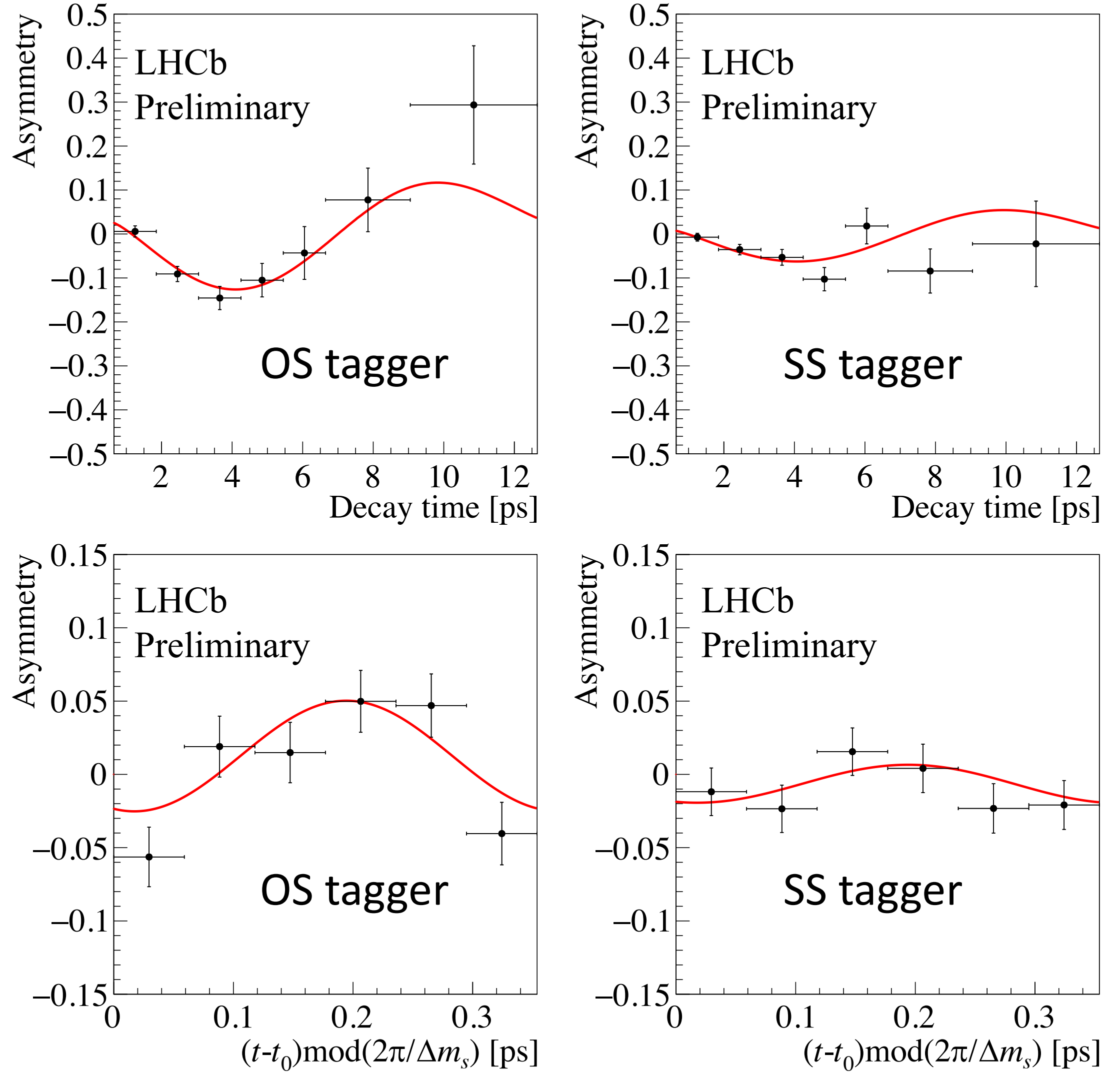
Parameter	Value
Δm_d	$0.5065 \pm 0.0019\ \text{ps}^{-1}$
Γ_d	$0.6579 \pm 0.0017\ \text{ps}^{-1}$
$\Delta\Gamma_d$	0
Δm_s	$17.757 \pm 0.021\ \text{ps}^{-1}$
Γ_s	$0.6654 \pm 0.0022\ \text{ps}^{-1}$
$\Delta\Gamma_s$	$0.083 \pm 0.007\ \text{ps}^{-1}$
$\rho(\Gamma_s, \Delta\Gamma_s)$	-0.292

World Averages from Heavy Flavour Averaging Group

Result of the simultaneous fit

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

$B_s^0 \to K^+K^-$



CPV results

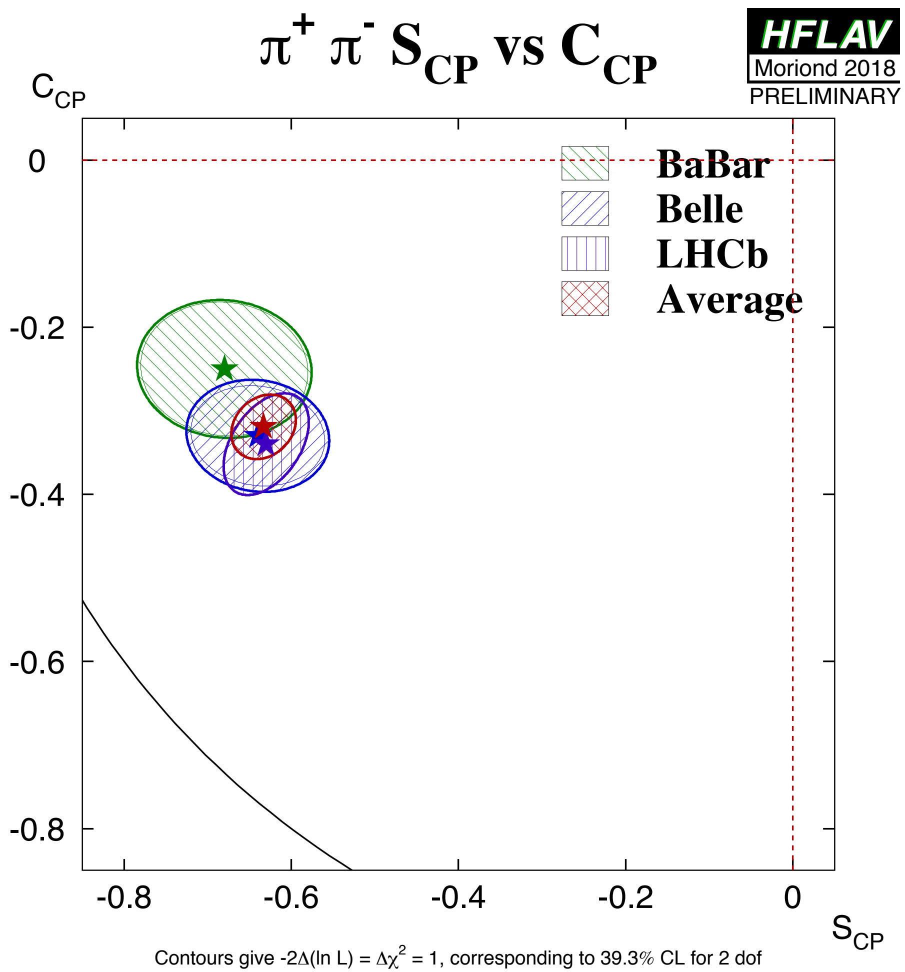
LHCb Preliminary

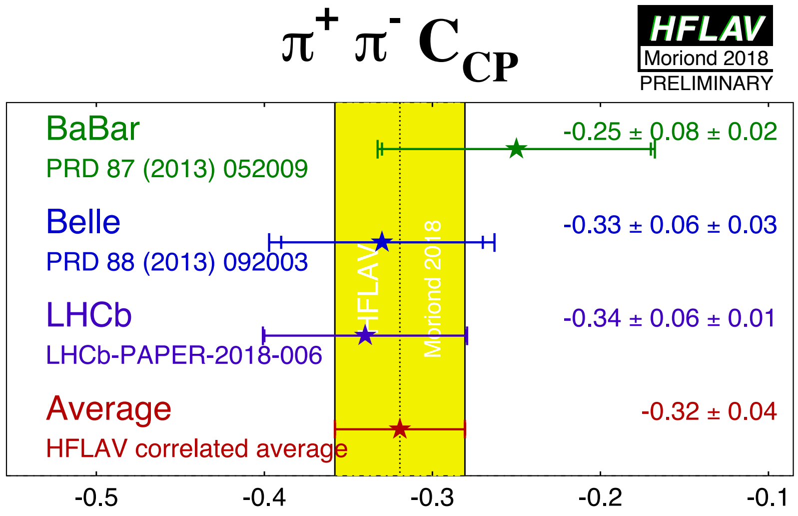
$$
\begin{aligned}
C_{\pi^+\pi^-} &= -0.34 \pm 0.06 \pm 0.01, \\
S_{\pi^+\pi^-} &= -0.63 \pm 0.05 \pm 0.01, \\
C_{K^+K^-} &= 0.20 \pm 0.06 \pm 0.02, \\
S_{K^+K^-} &= 0.18 \pm 0.06 \pm 0.02, \\
A^{\Delta\Gamma}_{K^+K^-} &= -0.79 \pm 0.07 \pm 0.10, \\
A^{B^0}_{CP} &= -0.084 \pm 0.004 \pm 0.003, \\
A^{B^0_s}_{CP} &= 0.213 \pm 0.015 \pm 0.007,
\end{aligned}
$$

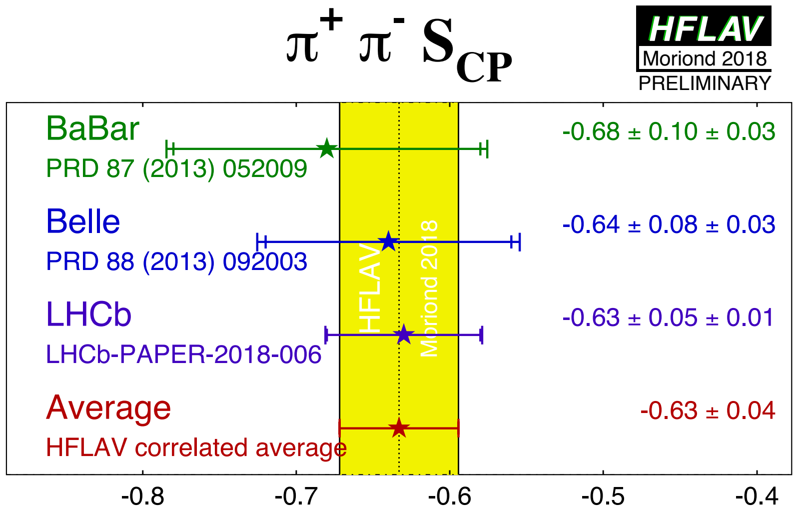
- Significant improvement ($\sim 2\times$ better precision) wrt previous results
- Most precise measurements from a single experiment
- First determination of $A^{\Delta\Gamma}_{KK}$
- Significance for $(C_{K^+K^-}, S_{K^+K^-}, A^{\Delta\Gamma}_{K^+K^-})$ to differ from $(0,0,-1)$ is determined to be 4σ
  - Strongest evidence of time-dependent CPV in B^0_s system to date

Comparison with other experiments

Courtesy of the Heavy Flavour Averaging Group







First observation of $B^0 \to p\bar{p}$

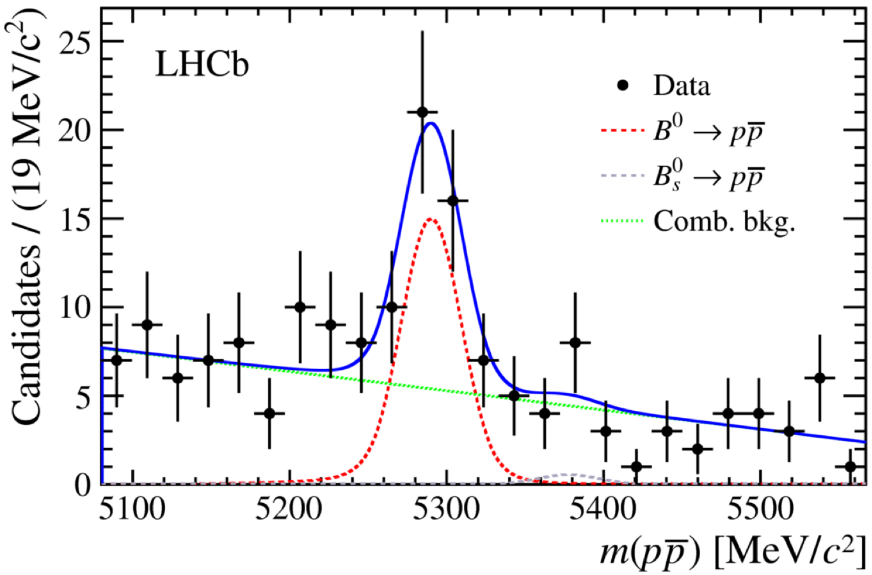
Phys. Rev. Lett. 119 (2017) 232001

Search for $B^0 \to p\bar{p}$

- Decay not seen at B factories, first evidence came from LHCb analysis of 2011 data [JHEP 10 (2013) 005]
- Central value determined there ($\sim 10^{-8}$) was much smaller than most theoretical calculations at the time
- More recent theoretical work has been able to accommodate the small BF of this mode, see e.g. [Phys. Rev. D 91 (2015) 077501, Phys. Rev. D 91 (2015) 036003]
- Important to improve knowledge of such rare hadronic decays

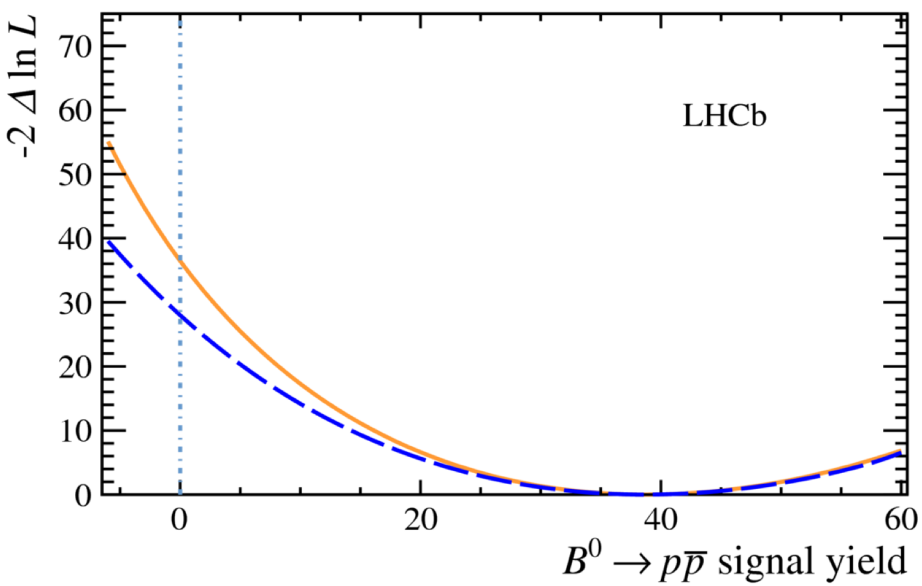
Phys. Rev. Lett. 119 (2017) 232001

First observation of $B^0 \to p\bar{p}$



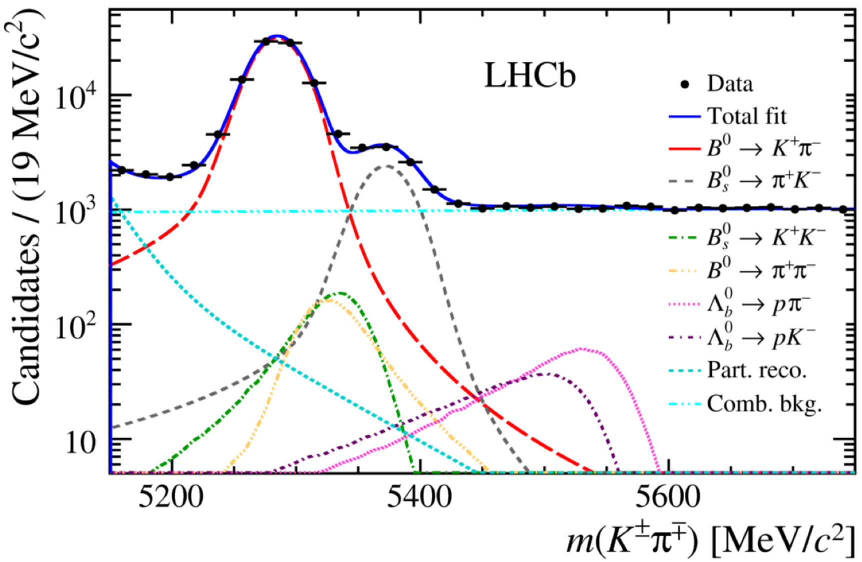
- Clear B^0 signal peak, with yield of 39 ± 8
- No significant signal from corresponding B_s^0 decay: 2 ± 4

- Significance of $B^0 \to p\bar{p}$ determined to be 5.3σ including effect of systematic uncertainties
- Constitutes first observation of the decay!



Branching fraction of $B^0 \to p\bar{p}$

- Branching fractions determined relative to $B^0 \to K^+\pi^-$ decay
  - Very clean sample of ~89k signal candidates



- Rarest hadronic B decay ever observed!

$$\mathcal{B}(B^0 \to p\bar{p}) = (1.25 \pm 0.27 \pm 0.18)\times 10^{-8}$$

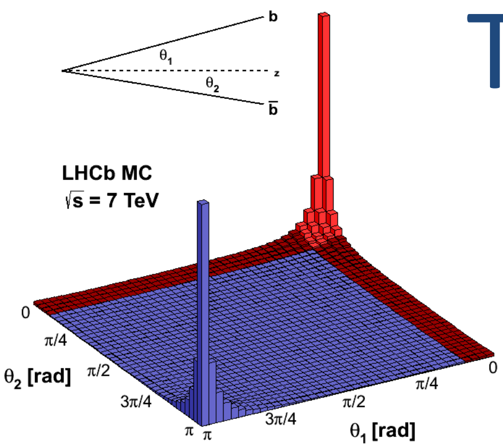
$$\mathcal{B}(B_s^0 \to p\bar{p}) < 1.5\times 10^{-8} \text{ at 90\% CL}$$

Concluding remarks

- Highly sophisticated analyses of CP violation in charmless B decays
  - See also analyses of $B_s^0 \to \phi\phi$ and $B_s^0 \to K^{*0}\overline{K}^{*0}$ presented by G. Cowan
- Most precise measurements of CP violation parameters in the decays:
  - $B^0 \to \pi^+\pi^-$
  - $B^0 \to K^+\pi^-$
  - $B_s^0 \to K^-\pi^+$
  - $B_s^0 \to K^+K^-$
- Recently, several first observations of baryonic decays of B mesons have been made, including:
  - The rarest hadronic B meson decay yet observed: $B^0 \to p\bar{p}$
- Updates to include full Run 1 + Run 2 samples will further improve the precision – expect $\sim 3\times$ Run 1 integrated luminosity
- Looking further forward, the LHCb upgrade(s) will provide unprecedented samples of these decays
- Excellent prospects for making precision tests of the Standard Model explanation of CP violation

Backup Slides

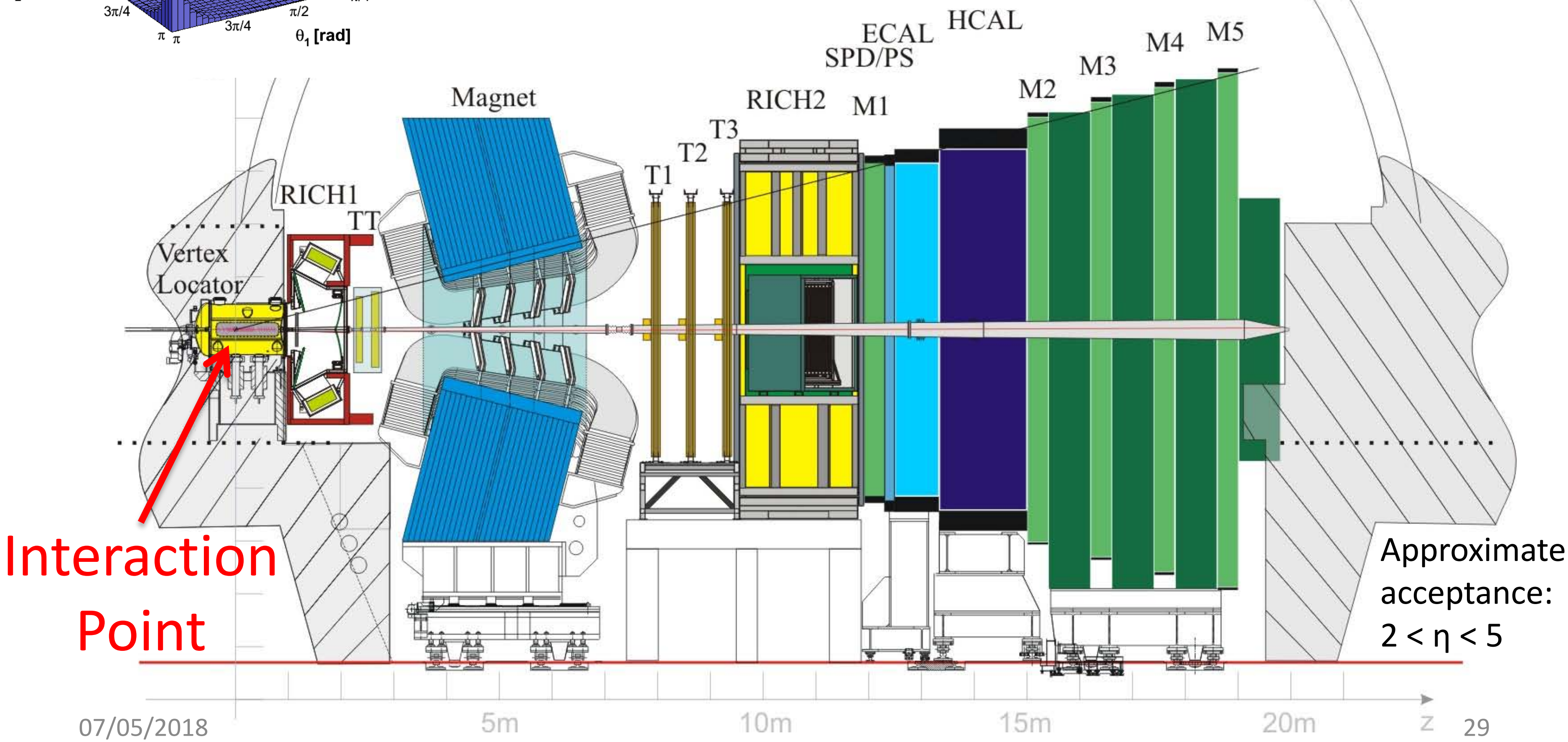
The LHCb detector



LHCb σ(pp → H_b X) @ 7 TeV = (72.0 ± 0.3 ± 6.8) μb

LHCb σ(pp → H_b X) @ 13 TeV = (154.3 ± 1.5 ± 14.3) μb

[Phys. Rev. Lett. 118 (2017) 052002]



Time-dependent decay rates

- For an initially pure flavour eigenstate, time evolution proceeds according to:

$$\frac{d\Gamma[B^0_{d,s}(t) \to f]}{dt} \propto e^{-\Gamma t}\Big[\left(|A_f|^2 + |\bar{A}_f|^2\right)\cosh\left(\tfrac{\Delta\Gamma_{d,s}}{2}t\right) + \left(|A_f|^2 - |\bar{A}_f|^2\right)\cos(\Delta m_{d,s}\,t)$$
$$+2\mathrm{Re}\left(\tfrac{q}{p}A_f^*\bar{A}_f\right)\sinh\left(\tfrac{\Delta\Gamma_{d,s}}{2}t\right) - 2\mathrm{Im}\left(\tfrac{q}{p}A_f^*\bar{A}_f\right)\sin(\Delta m_{d,s}\,t)\Big]$$

$$\frac{d\Gamma[\bar{B}^0_{d,s}(t) \to f]}{dt} \propto e^{-\Gamma t}\Big[\left(|A_f|^2 + |\bar{A}_f|^2\right)\cosh\left(\tfrac{\Delta\Gamma_{d,s}}{2}t\right) - \left(|A_f|^2 - |\bar{A}_f|^2\right)\cos(\Delta m_{d,s}\,t)$$
$$+2\mathrm{Re}\left(\tfrac{q}{p}A_f^*\bar{A}_f\right)\sinh\left(\tfrac{\Delta\Gamma_{d,s}}{2}t\right) + 2\mathrm{Im}\left(\tfrac{q}{p}A_f^*\bar{A}_f\right)\sin(\Delta m_{d,s}\,t)\Big]$$

- The time-dependent CP asymmetry is therefore:

$$A_{CP}(t) = \frac{\Gamma[\bar{B}^0_{d,s}(t) \to f] - \Gamma[B^0_{d,s}(t) \to f]}{\Gamma[\bar{B}^0_{d,s}(t) \to f] + \Gamma[B^0_{d,s}(t) \to f]} = \frac{-C_f\cos(\Delta m_{d,s}\,t) + S_f\sin(\Delta m_{d,s}\,t)}{\cosh\left(\tfrac{\Delta\Gamma_{d,s}}{2}t\right) + A_f^{\Delta\Gamma_{d,s}}\sinh\left(\tfrac{\Delta\Gamma_{d,s}}{2}t\right)}$$

$$C_f = \frac{1-|\lambda_f|^2}{1+|\lambda_f|^2}$$

$$S_f = \frac{2\mathrm{Im}\lambda_f}{1+|\lambda_f|^2}$$

$$A_f^{\Delta\Gamma_{d,s}} = \frac{2\mathrm{Re}\lambda_f}{1+|\lambda_f|^2}$$

$$\lambda_f = \frac{q}{p}\frac{\bar{A}_f}{A_f}$$

- $|C_f|^2 + |S_f|^2 + |A_f^{\Delta\Gamma}|^2 = 1$
- $\frac{q}{p}$ is related to the neutral B mixing
- $\frac{\bar{A}_f}{A_f}$ is the ratio of decay amplitudes

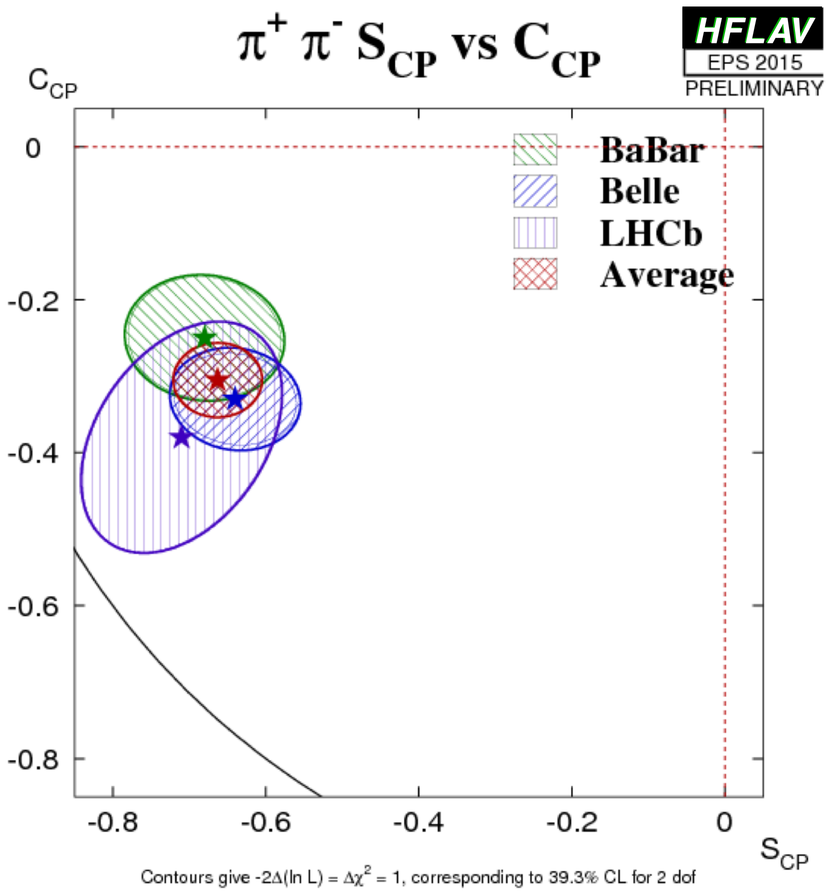
Previous experimental status

Reference	Experiment	$C_{\pi^+\pi^-}$	$S_{\pi^+\pi^-}$	$\rho(C_{\pi^+\pi^-}, S_{\pi^+\pi^-})$
PRD 87 (2013) 052009	BaBar	$-0.25 \pm 0.08 \pm 0.02$	$-0.68 \pm 0.10 \pm 0.03$	-0.06
PRD 88 (2013) 092003	Belle	$-0.33 \pm 0.06 \pm 0.03$	$-0.64 \pm 0.08 \pm 0.03$	-0.10
JHEP 10 (2013) 183	LHCb	$-0.38 \pm 0.15 \pm 0.02$	$-0.71 \pm 0.13 \pm 0.02$	0.38
EPJC 77 (2017) 895	HFLAV Avg.	-0.31 ± 0.05	-0.66 ± 0.06	0.00
		$C_{K^+K^-}$	$S_{K^+K^-}$	$\rho(C_{K^+K^-}, S_{K^+K^-})$
JHEP 10 (2013) 183	LHCb	$0.14 \pm 0.11 \pm 0.03$	$0.30 \pm 0.12 \pm 0.04$	0.02

Reference	Experiment	$A_{CP}^{B^0}$	$A_{CP}^{B_s^0}$
PRD 87 (2013) 052009	BaBar	$-0.107 \pm 0.016 \, ^{+\,0.006}_{-\,0.004}$	—
PRD 87 (2013) 031103	Belle	$-0.069 \pm 0.014 \pm 0.007$	—
PRL 113 (2014) 242001	CDF	$-0.083 \pm 0.013 \pm 0.004$	$0.22 \pm 0.07 \pm 0.02$
PRL 110 (2013) 221601	LHCb	$-0.080 \pm 0.007 \pm 0.003$	$0.27 \pm 0.04 \pm 0.01$
EPJC 77 (2017) 895	HFLAV Avg.	-0.082 ± 0.006	0.26 ± 0.04

Previous experimental status

- Measurements of $C_{\pi\pi}$ and $S_{\pi\pi}$ in good agreement between B-factories and LHCb
- C_{KK} and S_{KK} are measured only by LHCb (using 1 fb^{-1} @ 7 TeV)
  - No measurement yet of $A_{KK}^{\Delta\Gamma}$



Experimental decay rates – flavour specific decays

$$f_{\rm FS}\left(t,\,\delta_t,\,\psi,\,\vec{\xi},\,\vec{\eta}\right) = K_{\rm FS}\left(1-\psi A_{CP}\right)\left(1-\psi A_{\rm F}\right)\times \left\{\left[(1-A_{\rm P})\Omega_{\rm sig}(\vec{\xi},\vec{\eta})+(1+A_{\rm P})\bar{\Omega}_{\rm sig}(\vec{\xi},\vec{\eta})\right]H_+\left(t,\,\delta_t\right)+ \psi\left[(1-A_{\rm P})\Omega_{\rm sig}(\vec{\xi},\vec{\eta})-(1+A_{\rm P})\bar{\Omega}_{\rm sig}(\vec{\xi},\vec{\eta})\right]H_-\left(t,\,\delta_t\right)\right\},$$

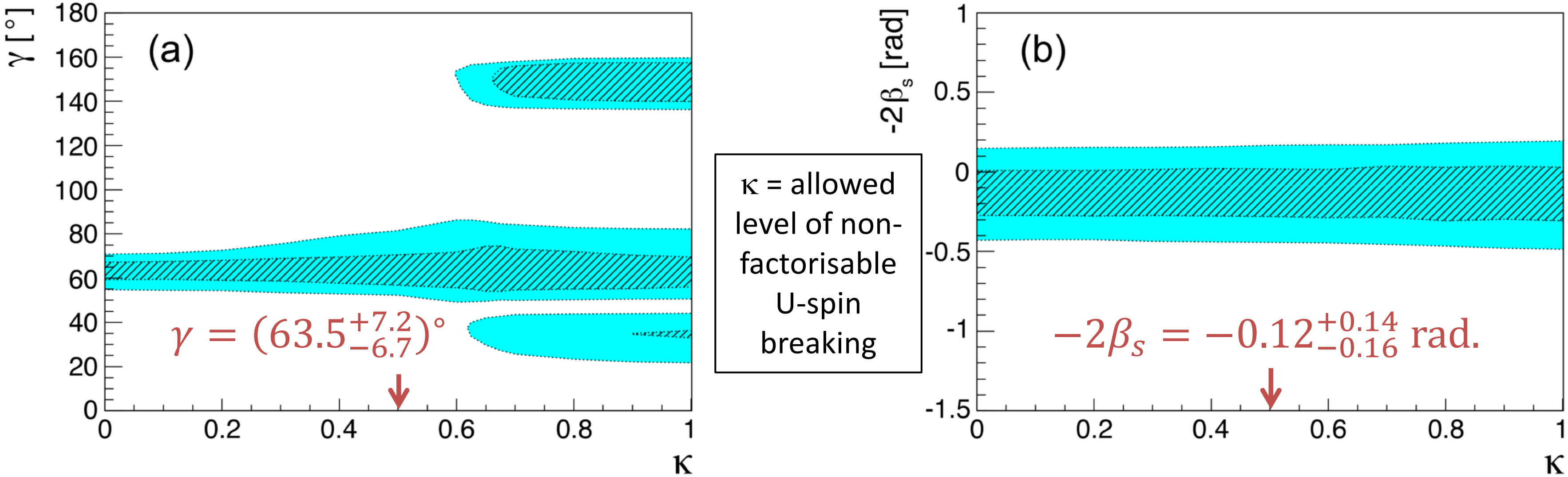
$$H_+\left(t,\,\delta_t\right) = \left[e^{-\Gamma_{d,s}t'}\cosh\left(\frac{\Delta\Gamma_{d,s}}{2}t'\right)\right]\otimes R\left(t-t'|\delta_t\right)\,g_{\rm sig}\left(\delta_t\right)\,\varepsilon_{\rm sig}\left(t\right),$$

$$H_-\left(t,\,\delta_t\right) = \left[e^{-\Gamma_{d,s}t'}\cos\left(\Delta m_{d,s}t'\right)\right]\otimes R\left(t-t'|\delta_t\right)\,g_{\rm sig}\left(\delta_t\right)\,\varepsilon_{\rm sig}\left(t\right),$$

ψ = B flavour (determined by final state)
t = decay time
ξ = B flavour tag
η = predicted mistag probability
δ_t = decay time error

Phys. Lett. B741 (2015) 1

Constraints on CKM parameters

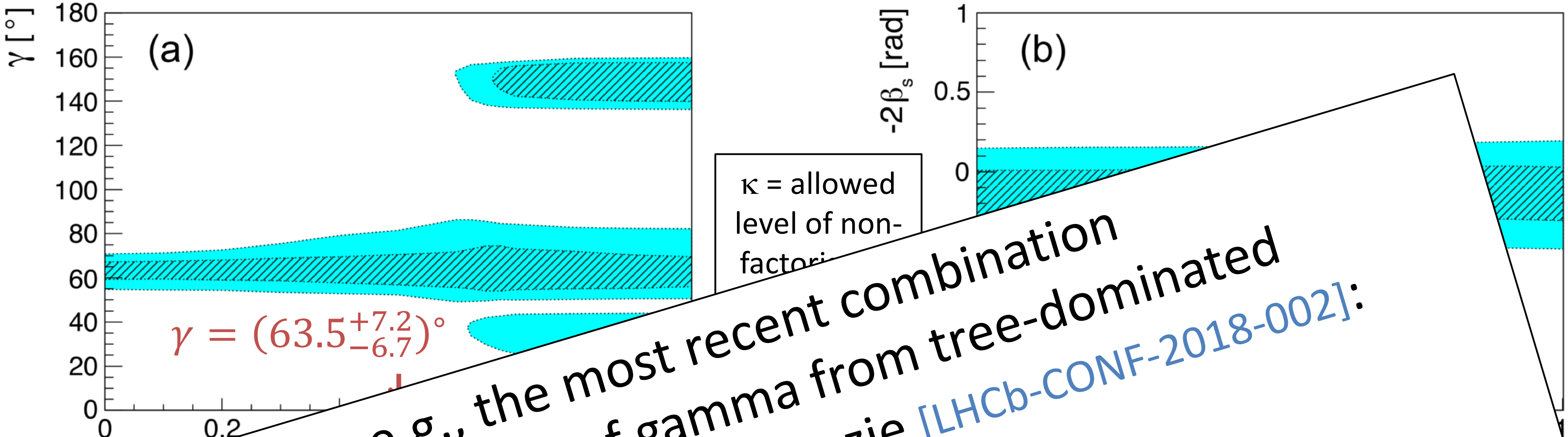


- Recent LHCb paper uses methodology from [JHEP 10 (2012) 029]
- Combine information from $B^0 \to \pi^+\pi^-$, $B_s^0 \to K^+K^-$, $B^+ \to \pi^+\pi^0$, and $B^0 \to \pi^0\pi^0$ decays
- Use flavour symmetries (isospin and U-spin) to constrain uncertainties from hadronic parameters (strong phases, etc.)
- Very little effect of U-spin breaking on extraction of $-2\beta_s$ but further improvements in extraction of γ using this method are potentially limited by understanding of U-spin breaking
- New strategies are being developed to reduce the dependence on U-spin symmetry

[PRD 94 (2016) 113014]

Phys. Lett. B741 (2015) 1

Constraints on CKM parameters



$\gamma = (63.5^{+7.2}_{-6.7})^\circ$

Compare with, e.g., the most recent combination of LHCb measurements of gamma from tree-dominated decays presented earlier by M. Kenzie [LHCb-CONF-2018-002]:

$$\gamma = (74.0^{+5.0}_{-5.8})^\circ$$

The two measurements are compatible within current precision

…ecays

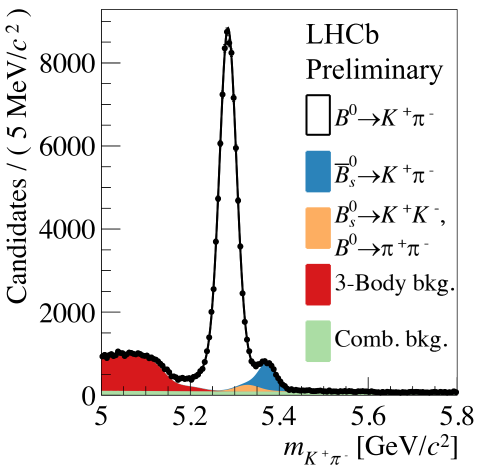
…n hadronic

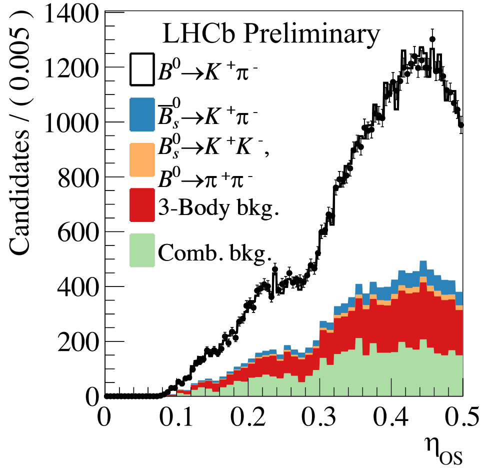
- …of $-2\beta_s$ but further improvements in …otentially limited by understanding of U-spin breaking
- …eveloped to reduce the dependence on U-spin symmetry

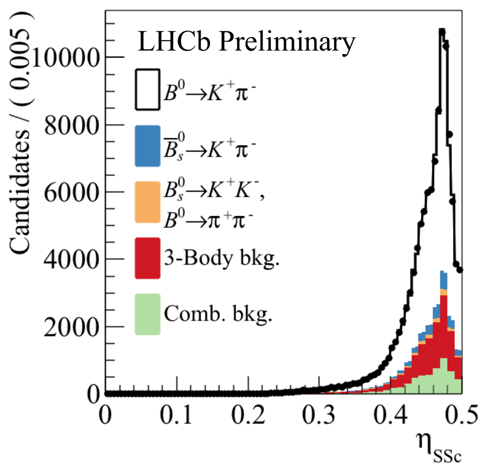
[PRD 94 (2016) 113014]

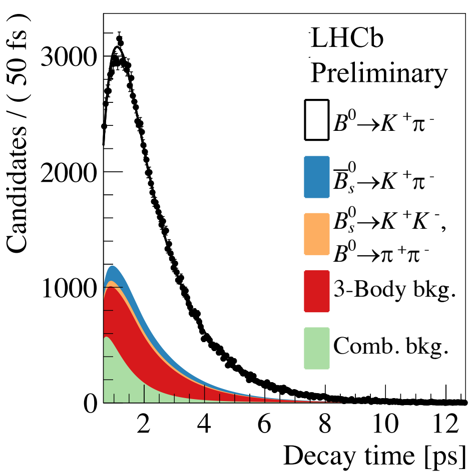
Result of the simultaneous fit

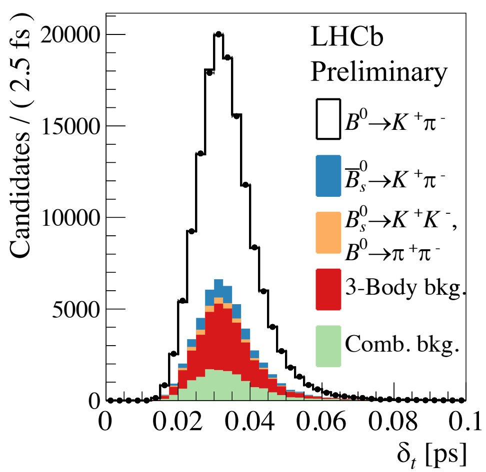
$K^+\pi^-$ spectrum











Fixed parameters

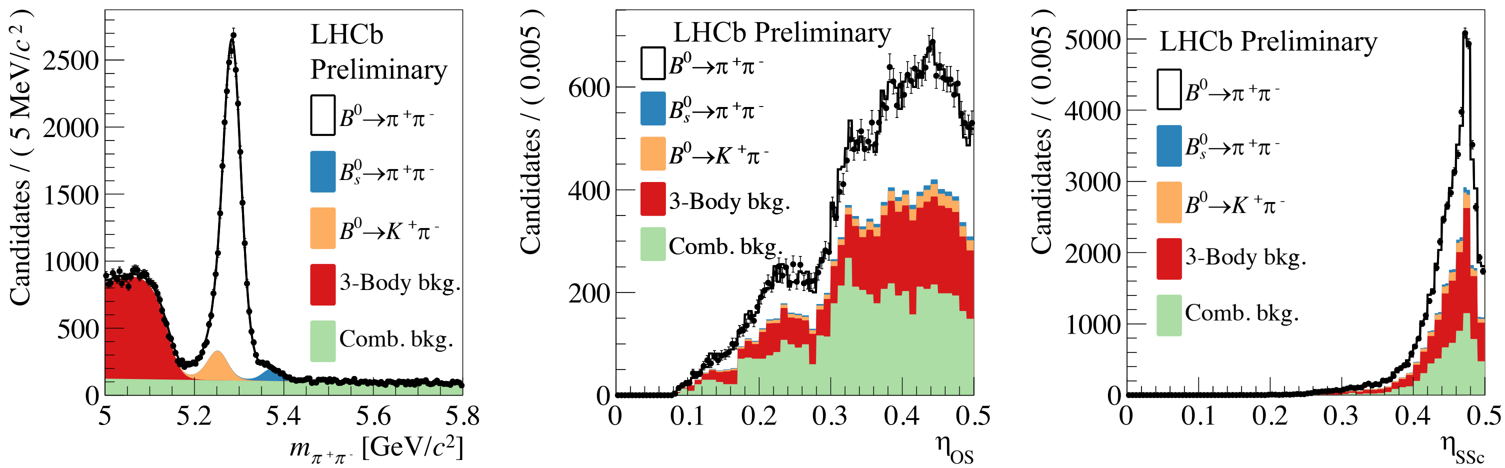
Parameter	Value
Δm_d	$0.5065 \pm 0.0019\ \text{ps}^{-1}$
Γ_d	$0.6579 \pm 0.0017\ \text{ps}^{-1}$
$\Delta\Gamma_d$	0
Δm_s	$17.757 \pm 0.021\ \text{ps}^{-1}$
Γ_s	$0.6654 \pm 0.0022\ \text{ps}^{-1}$
$\Delta\Gamma_s$	$0.083 \pm 0.007\ \text{ps}^{-1}$
$\rho(\Gamma_s, \Delta\Gamma_s)$	-0.292

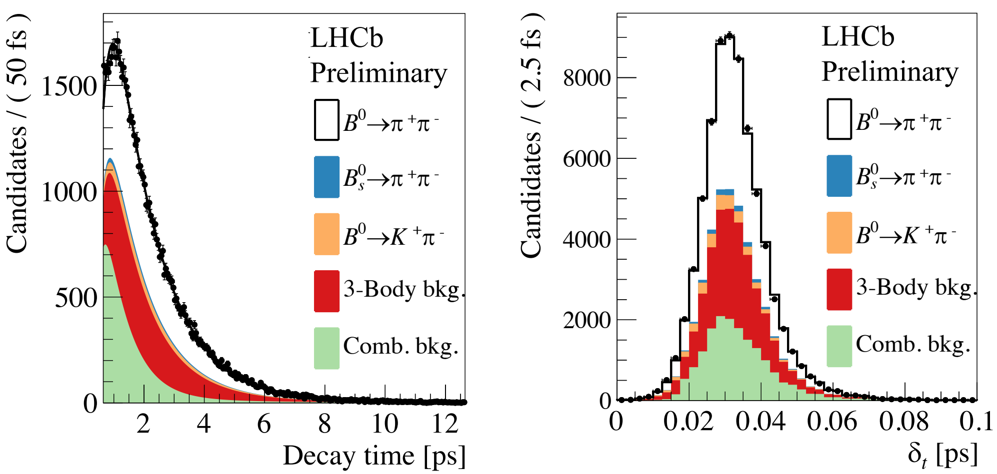
World Averages from
Heavy Flavour Averaging Group

LHCb-PAPER-2018-006

Result of the simultaneous fit

$\pi^+\pi^-$ spectrum





Fixed parameters

Parameter	Value
Δm_d	$0.5065 \pm 0.0019\ \mathrm{ps}^{-1}$
Γ_d	$0.6579 \pm 0.0017\ \mathrm{ps}^{-1}$
$\Delta\Gamma_d$	0
Δm_s	$17.757 \pm 0.021\ \mathrm{ps}^{-1}$
Γ_s	$0.6654 \pm 0.0022\ \mathrm{ps}^{-1}$
$\Delta\Gamma_s$	$0.083 \pm 0.007\ \mathrm{ps}^{-1}$
$\rho(\Gamma_s, \Delta\Gamma_s)$	-0.292

World Averages from Heavy Flavour Averaging Group

LHCb-PAPER-2018-006

Statistical correlations

	$C_{\pi^+\pi^-}$	$S_{\pi^+\pi^-}$	$C_{K^+K^-}$	$S_{K^+K^-}$	$A^{\Delta\Gamma}_{K^+K^-}$	$A^{B^0}_{CP}$	$A^{B^0_s}_{CP}$
$C_{\pi^+\pi^-}$	1.000	0.448	−0.006	−0.009	0.000	−0.009	0.003
$S_{\pi^+\pi^-}$	0.448	1.000	−0.040	−0.006	0.000	0.008	0.000
$C_{K^+K^-}$	−0.006	−0.040	1.000	−0.014	0.025	0.006	0.001
$S_{K^+K^-}$	−0.009	−0.006	−0.014	1.000	0.028	−0.003	0.000
$A^{\Delta\Gamma}_{K^+K^-}$	0.000	0.000	0.025	0.028	1.000	0.001	0.000
$A^{B^0}_{CP}$	−0.009	0.008	0.006	−0.003	0.001	1.000	0.043
$A^{B^0_s}_{CP}$	0.003	0.000	0.001	0.000	0.000	0.043	1.000

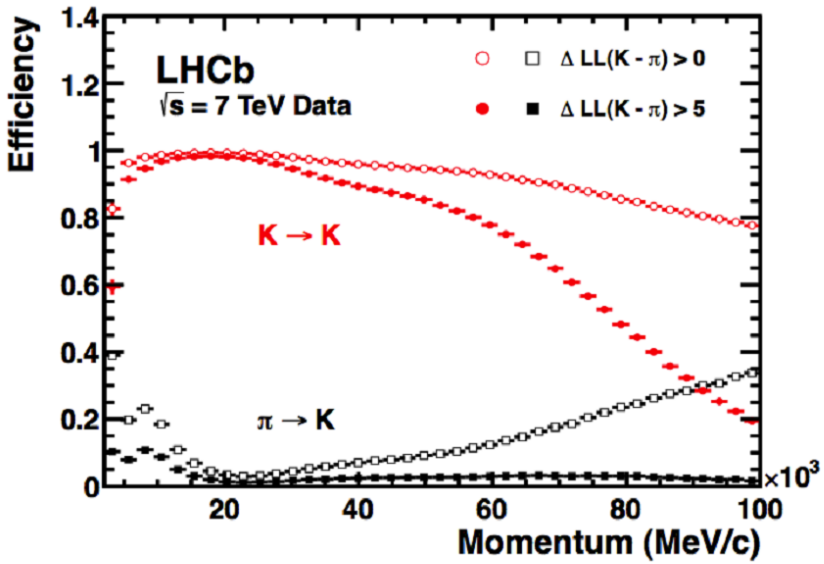
Systematic uncertainties

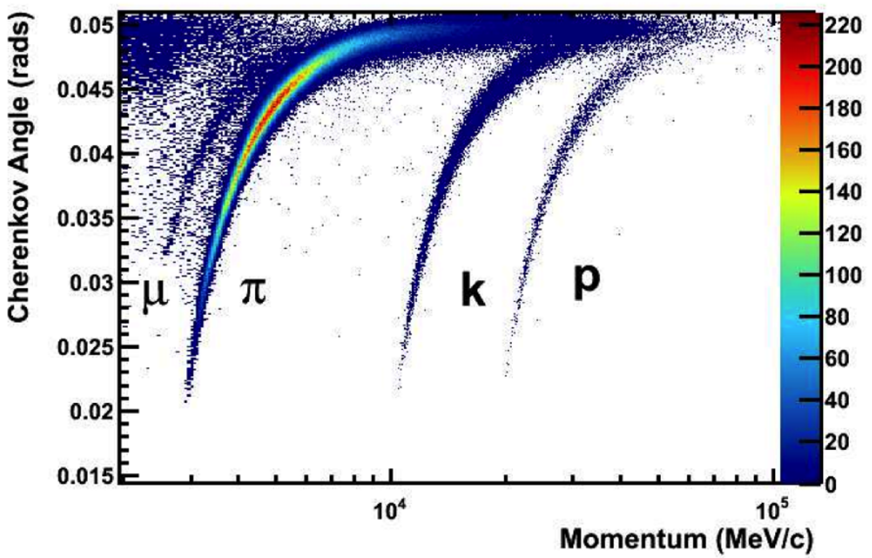
Source of uncertainty	$C_{\pi^+\pi^-}$	$S_{\pi^+\pi^-}$	$C_{K^+K^-}$	$S_{K^+K^-}$	$A^{\Delta\Gamma}_{K^+K^-}$	$A^{B^0}_{CP}$	$A^{B^0_s}_{CP}$
Time-dependent efficiency	0.0011	0.0004	0.0020	0.0017	0.0778	0.0004	0.0002
Time-resolution calibration	0.0014	0.0013	0.0108	0.0119	0.0051	0.0001	0.0001
Time-resolution model	0.0001	0.0005	0.0002	0.0002	0.0003	negligible	negligible
Input parameters	0.0025	0.0024	0.0092	0.0107	0.0480	negligible	0.0001
OS-tagging calibration	0.0018	0.0021	0.0018	0.0019	0.0001	negligible	negligible
SSK-tagging calibration	n/a	n/a	0.0061	0.0086	0.0004	n/a	n/a
SSc-tagging calibration	0.0015	0.0017	n/a	n/a	n/a	negligible	negligible
Cross-feed time model	0.0075	0.0059	0.0022	0.0024	0.0003	0.0001	0.0001
Three-body bkg.	0.0070	0.0056	0.0044	0.0043	0.0304	0.0008	0.0043
Comb.-bkg. time model	0.0016	0.0016	0.0004	0.0002	0.0019	0.0001	0.0005
Signal mass model (reso.)	0.0027	0.0025	0.0015	0.0015	0.0023	0.0001	0.0041
Signal mass model (tails)	0.0007	0.0008	0.0013	0.0013	0.0016	negligible	0.0003
Comb.-bkg. mass model	0.0001	0.0003	0.0002	0.0002	0.0016	negligible	0.0001
PID asymmetry	n/a	n/a	n/a	n/a	n/a	0.0025	0.0025
Detection asymmetry	n/a	n/a	n/a	n/a	n/a	0.0014	0.0014
Total	0.0115	0.0095	0.0165	0.0191	0.0966	0.0030	0.0066

Kaon/pion separation

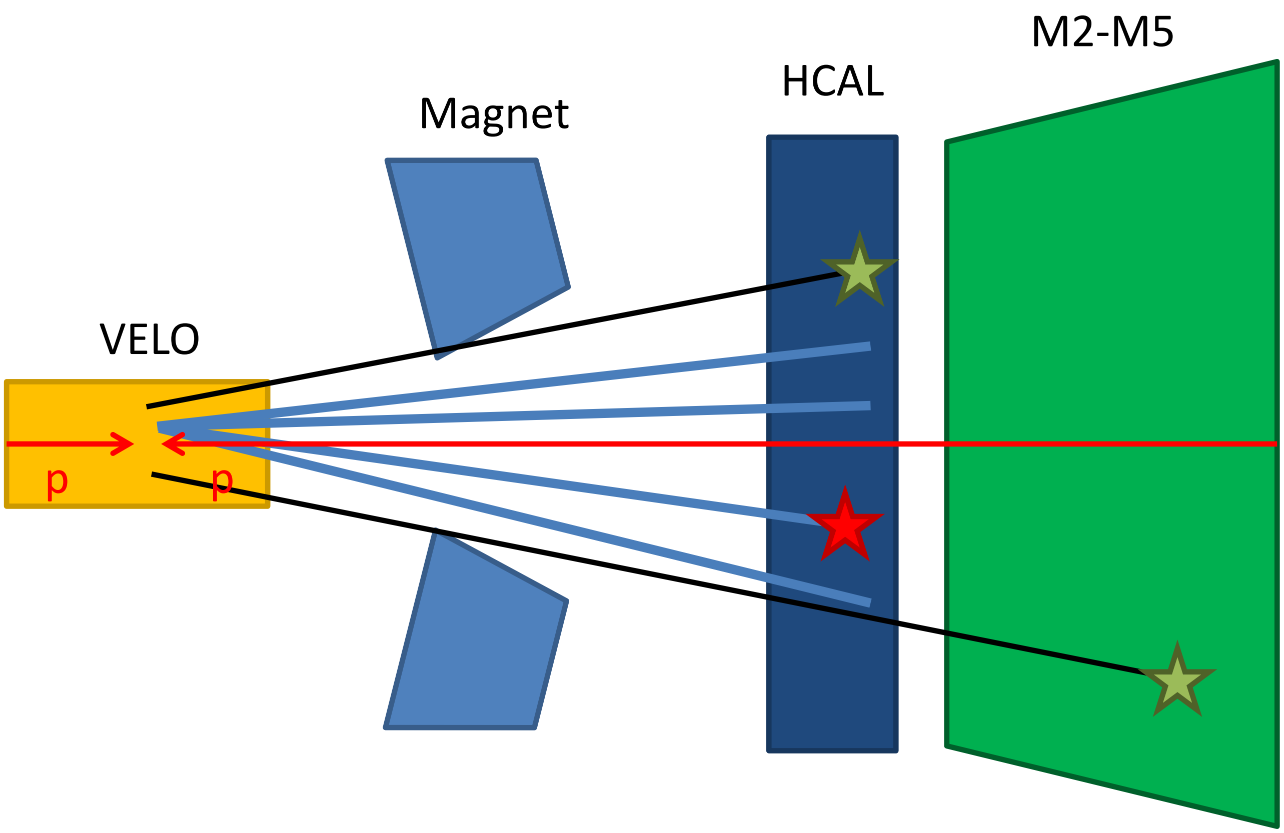
- Most particle identification information comes from the Ring Imaging Cherenkov detectors.
- Different radiators provide separation over a wide momentum range.

$$\cos\theta = \frac{1}{\beta n}$$





Trigger categories



Trigger On Signal

- Particle from the signal decay fires a trigger line.
- Triggered by HCAL deposits.

Trigger Independent of Signal

- Particle from the rest of the event fires a trigger line.
- Triggered mostly by HCAL deposits or muons.

- Trigger Efficiencies:
  - ~30% efficient for multi-body hadronic
  - ~90% efficient for di-muons

Eur. Phys. J. C73 (2013) 2373

Table 16: Statistical sensitivities of the LHCb upgrade to key observables. For each observable the current sensitivity is compared to that which will be achieved by LHCb before the upgrade, and that which will be achieved with $50\,\mathrm{fb}^{-1}$ by the upgraded experiment. Systematic uncertainties are expected to be non-negligible for the most precisely measured quantities. Note that the current sensitivities do not include new results presented at ICHEP 2012 or CKM2012.

Type	Observable	Current precision	LHCb 2018	**Upgrade** ($50\,\mathrm{fb}^{-1}$)	Theory uncertainty
B_s^0 mixing	$2\beta_s$ ($B_s^0 \to J/\psi\,\phi$)	0.10 [138]	0.025	0.008	~ 0.003
	$2\beta_s$ ($B_s^0 \to J/\psi\, f_0(980)$)	0.17 [214]	0.045	0.014	~ 0.01
	a_{sl}^s	6.4×10^{-3} [43]	0.6×10^{-3}	0.2×10^{-3}	0.03×10^{-3}
Gluonic penguins	$2\beta_s^{\mathrm{eff}}(B_s^0 \to \phi\phi)$	–	0.17	0.03	0.02
	$2\beta_s^{\mathrm{eff}}(B_s^0 \to K^{*0}\bar{K}^{*0})$	–	0.13	0.02	< 0.02
	$2\beta^{\mathrm{eff}}(B^0 \to \phi K_S^0)$	0.17 [43]	0.30	0.05	0.02
Right-handed currents	$2\beta_s^{\mathrm{eff}}(B_s^0 \to \phi\gamma)$	–	0.09	0.02	< 0.01
	$\tau^{\mathrm{eff}}(B_s^0 \to \phi\gamma)/\tau_{B_s^0}$	–	5 %	1 %	0.2 %
Electroweak penguins	$S_3(B^0 \to K^{*0}\mu^+\mu^-; 1 < q^2 < 6\,\mathrm{GeV}^2/c^4)$	0.08 [67]	0.025	0.008	0.02
	$s_0\, A_{\mathrm{FB}}(B^0 \to K^{*0}\mu^+\mu^-)$	25 % [67]	6 %	2 %	7 %
	$A_{\mathrm{I}}(K\mu^+\mu^-; 1 < q^2 < 6\,\mathrm{GeV}^2/c^4)$	0.25 [76]	0.08	0.025	~ 0.02
	$\mathcal{B}(B^+ \to \pi^+\mu^+\mu^-)/\mathcal{B}(B^+ \to K^+\mu^+\mu^-)$	25 % [85]	8 %	2.5 %	~ 10 %
Higgs penguins	$\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	1.5×10^{-9} [13]	0.5×10^{-9}	0.15×10^{-9}	0.3×10^{-9}
	$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	–	~ 100 %	~ 35 %	~ 5 %
Unitarity triangle angles	γ ($B \to D^{(*)}K^{(*)}$)	~ 10–$12°$ [244, 258]	4°	0.9°	negligible
	γ ($B_s^0 \to D_s K$)	–	11°	2.0°	negligible
	β ($B^0 \to J/\psi\, K_S^0$)	0.8° [43]	0.6°	0.2°	negligible
Charm CP violation	A_Γ	2.3×10^{-3} [43]	0.40×10^{-3}	0.07×10^{-3}	–
	$\Delta\mathcal{A}_{CP}$	2.1×10^{-3} [18]	0.65×10^{-3}	0.12×10^{-3}	–