CP violation results from time-dependent analysis of $B_{d,s} \rightarrow h^+h^-$ decays

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On behalf of LHCb collaboration

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Outline

- Introduction
- Measurement of time-dependent CP violation in $B^0 \rightarrow \pi^+\pi^-$ and $B_s \rightarrow K^+K^-$ decays at LHCb
  - LHCb-CONF-2016-018
    - 1 fb^{-1} @ 7 TeV and 2 fb^{-1} @ 8 TeV
  - Event selection
  - Experimental decay rates
  - Flavour tagging calibration
  - Decay time resolution
- Results and conclusions

CPV observable

- Observables are the time-dependent asymmetries of the $B^0 \rightarrow \pi^+\pi^-$ and $B_s \rightarrow K^+K^-$

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

CPV from mixing/decay interference

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

CPV in the decay

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

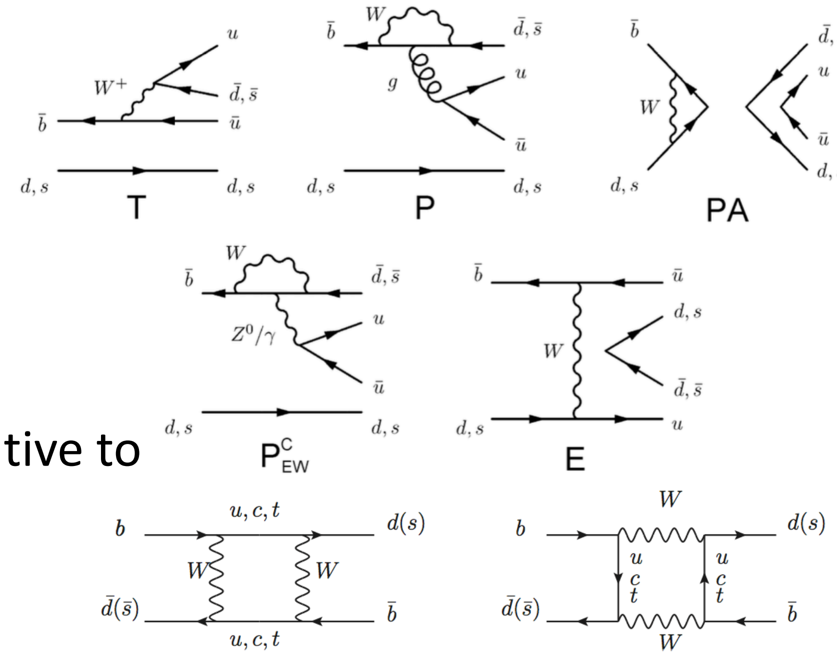
$$\left|C_f\right|^2 + \left|S_f\right|^2 + \left|A_f^{\Delta\Gamma}\right|^2 = 1$$

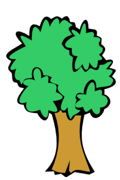
$$\lambda_f = \frac{q}{p}\frac{\bar{A}_f}{A_f}$$

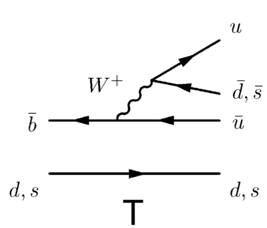
- q/p is related to the neutral B mixing
- $A_f/\bar{A}_f$ is the ratio between the CP conjugate decay amplitudes

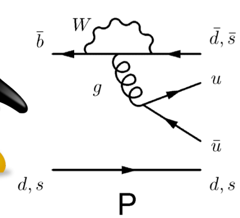
Motivation

- A rich set of physics processes participates to the $B^0 \rightarrow \pi^+\pi^-$ and $B_s \rightarrow K^+K^-$ decays
  - Tree and penguin decay topologies
  - Neutral B-mixing
- Time dependent CPV observables are sensitive to CKM angle γ and $-2\beta_s$
  - presence of loop diagrams introduce hadronic uncertainties
  - presence of loop diagrams makes the CPV observables sensitive to New Physics contribution
  - opportunity to compare results with the CKM phases determined from decays dominated by tree-level topologies









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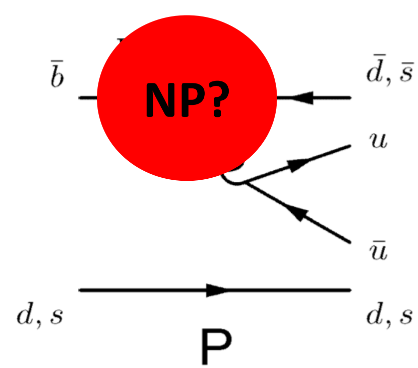
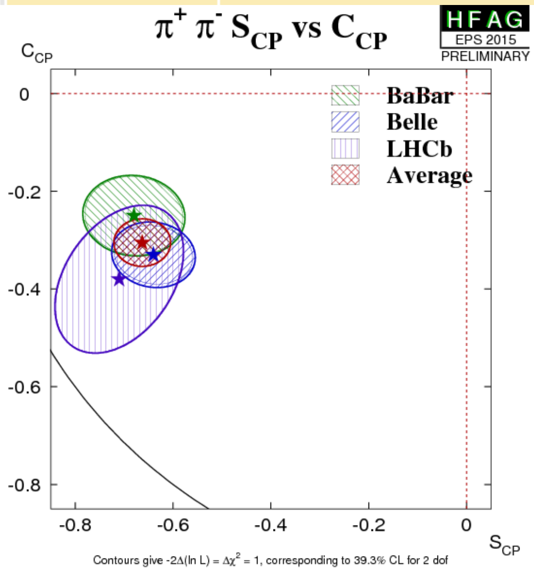


Current status

Experiment	S_{CP} ($\pi^+\pi^-$)	C_{CP} ($\pi^+\pi^-$)	Correlation	Reference
BaBar N(BB)=467M	−0.68 ± 0.10 ± 0.03	−0.25 ± 0.08 ± 0.02	−0.06 (stat)	PRD 87 (2013) 052009
Belle N(BB)=772M	−0.64 ± 0.08 ± 0.03	−0.33 ± 0.06 ± 0.03	−0.10 (stat)	PRD 88 (2013) 092003
LHCb $\int L dt$=1.0 fb^{-1}	−0.71 ± 0.13 ± 0.02	−0.38 ± 0.15 ± 0.02	0.38 (stat)	JHEP 1310 (2013) 183
Average	−0.66 ± 0.06	−0.31 ± 0.05	0.00	HFAG correlated average χ^2 = 0.9/4 dof (CL=0.92 ⇒ 0.1σ)



- $C_{\pi\pi}$ and $S_{\pi\pi}$ are well constrained by B-factories and LHCb
  - All three experiments are in good agreement
- C_{KK} and S_{KK} are measured only by LHCb using 1 fb^{-1} @ 7 TeV
  - No measurement is available for A_{KK}

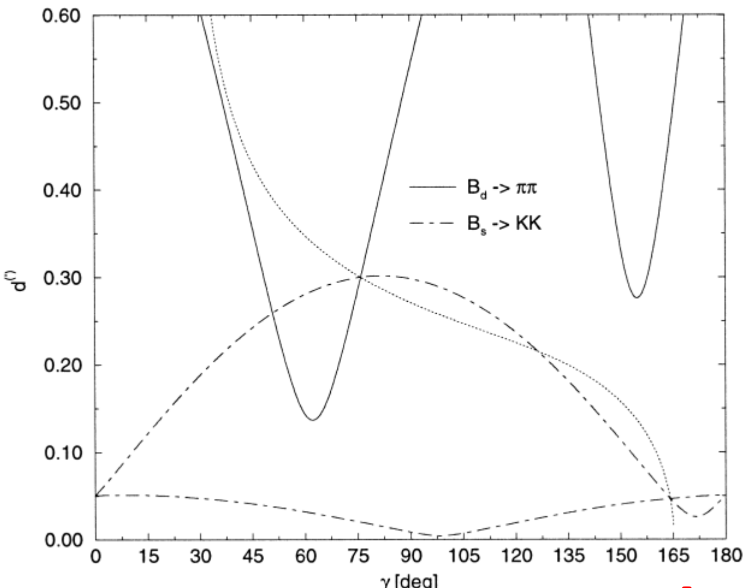
JHEP 1310 (2013) 183

$$C_{KK} = 0.14 \pm 0.11\,(\text{stat}) \pm 0.03\,(\text{syst}),$$
$$S_{KK} = 0.30 \pm 0.12\,(\text{stat}) \pm 0.04\,(\text{syst}),$$

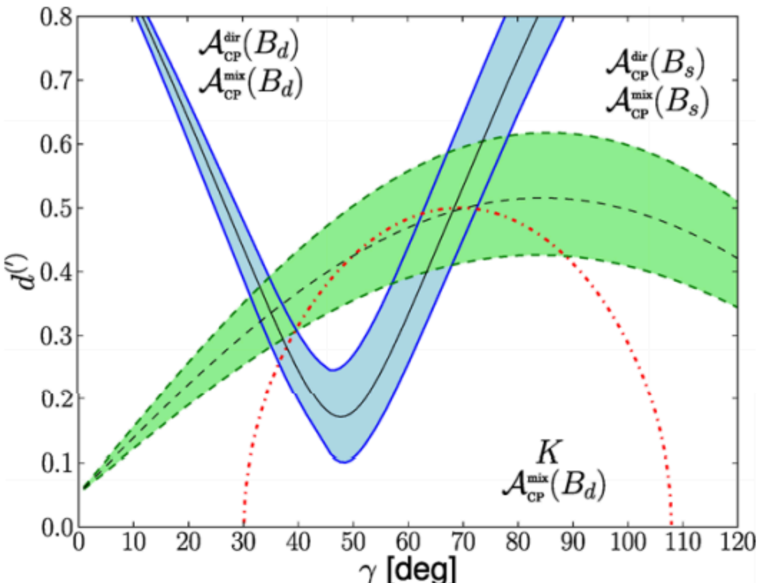
How to exploit B→hh decays

- First proposal to use TD CP asymmetries of B→hh decays dates back to 1999
  - Use U-spin symmetry to constraint QCD uncertainties
  - Use external inputs of ϕ_d

Phys. Lett. B459 (1999) 306



Phys. J. C71 (2011) 1532



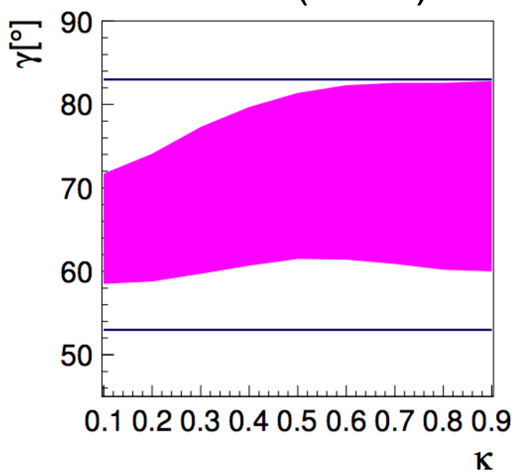
$A_{dir} = -C_f$; $A_{mix} = S_f$

How to exploit B→hh decays

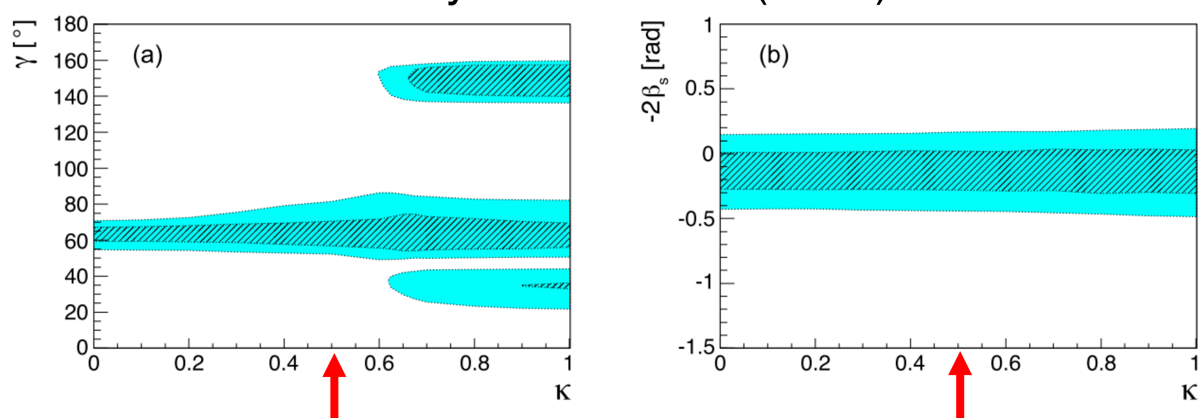
- Main issue is to reduce uncertainties coming from strong phases and amplitudes
  - Use also isospin symmetry to further constraint hadronic uncertainties
  - Combined analysis of $B^{0,\pm} \rightarrow \pi^{0,\pm}\pi^{0,\pm}$ and $B_s \rightarrow K^+K^-$

κ = allowed level of non factorizable U-spin breaking

JHEP 10 (2012) 029



Phys. Lett. B741 (2015) 1



$$\gamma = (63.5^{+7.2}_{-6.7})^\circ, \qquad -2\beta_s = -0.12^{+0.14}_{-0.16}\ \text{rad.}$$

Up to 50% non factorisable U-spin breaking effects

- New strategies are being developed to reduce the usage of U-spin symmetry → arXiv:1608.00901v1

Measurement of time-dependent CP asymmetries in $B^0 \to \pi^+\pi^-$ and $B_s \to K^+K^-$ decays

Event selection (I)

- Event selection is separated in two steps
  - First → Particle identification
    - Separate the two final states
    - Reduce amount of cross contamination from other B→hh modes to ~10% of the signal

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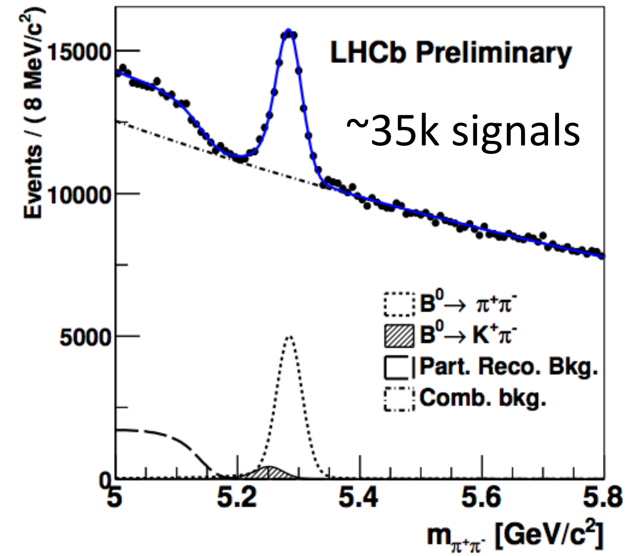
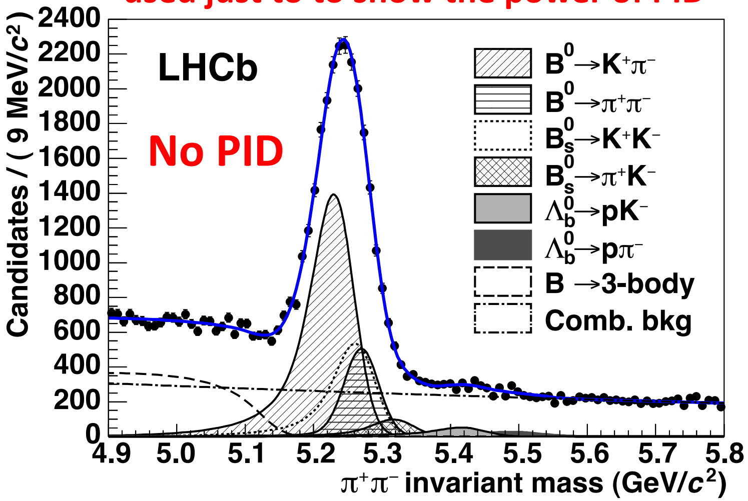


Plot from an old LHCb paper used just to to show the power of PID



JHEP 10 (2012) 37

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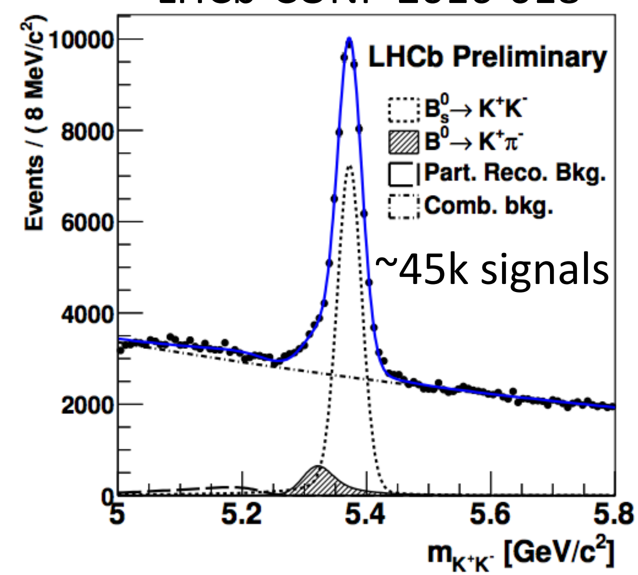

Event selection (II)

- A multivariate Boosted Decision Tree classifier is used to remove combinatorial background
  - aiming at best S/sqrt(S+B)
  - Use kinematical and topological variables
  - Parameterise signal from MC
  - Background from sideband

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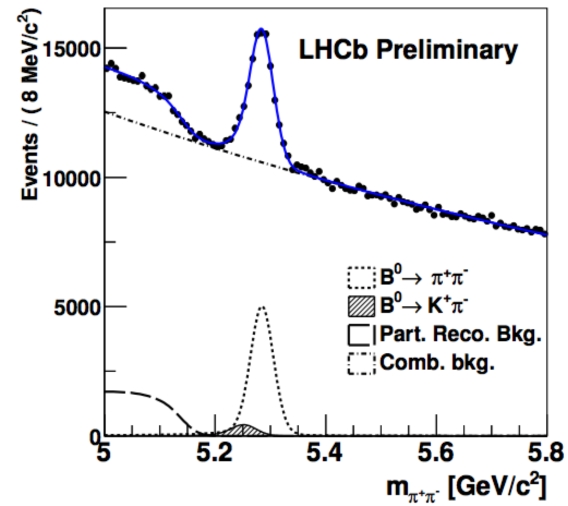

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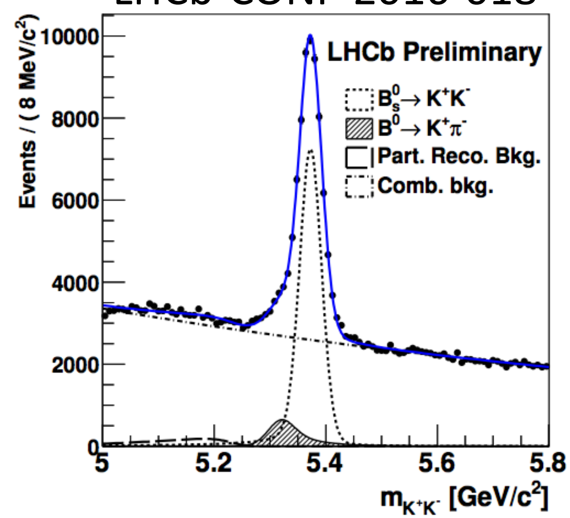

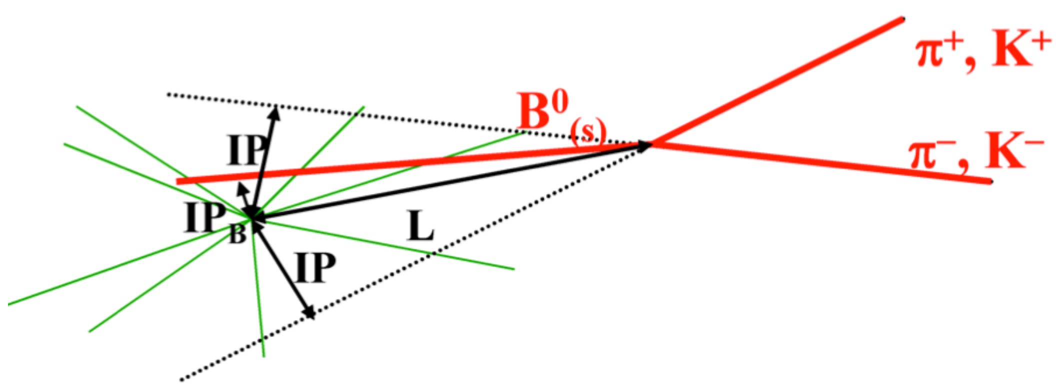

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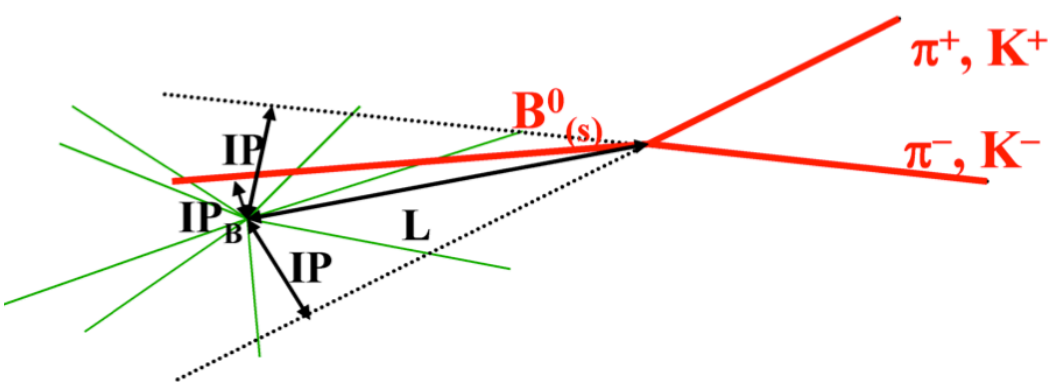
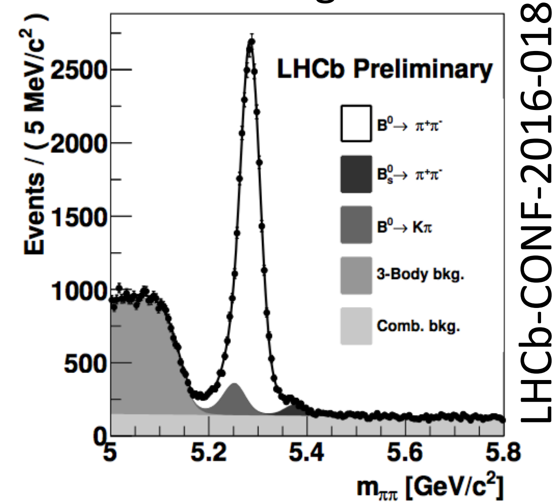
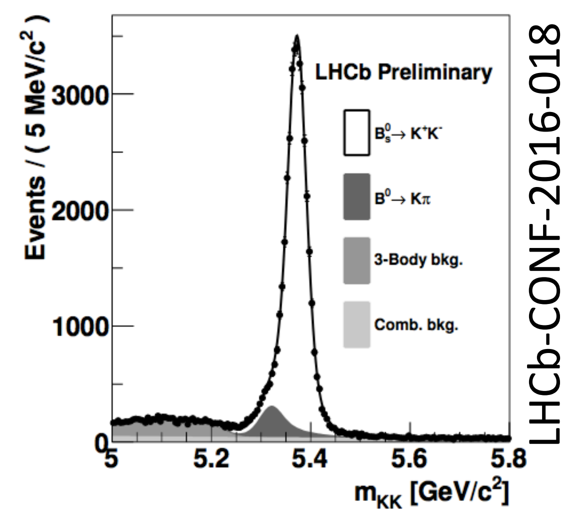


~28k signals



~36k signals



Determination of time-dependent asymmetries

- CP violation coefficients are determined from unbinned maximum likelihood fits to
  - Mass, decay time, per-event mistag probability, per-event decay time error
  - Simultaneous fit to $\pi^+\pi^-$, K^+K^- and $K^+\pi^-$ spectra
- Crucial ingredients, both diluting the amplitude of time-dependent asymmetries
  - Determination of the flavour of the B at the production (flavour tagging)
  - Determination of the decay time resolution
    - fundamental for $B_s \rightarrow K^+K^-$ decay due to fast oscillation

Experimental decay rates for signals

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

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

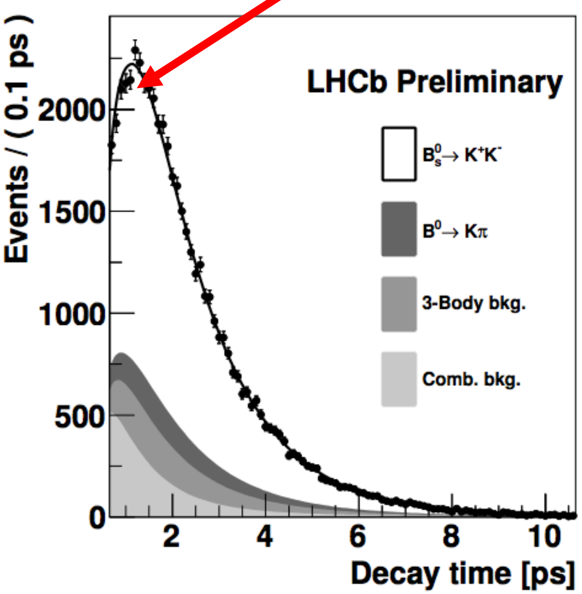
$$\begin{aligned}
I_{+}\left(t,\,\delta_t\right) &= \left\{e^{-\Gamma t'}\left[\cosh\left(\frac{\Delta\Gamma}{2}t'\right)+A_f^{\Delta\Gamma}\sinh\left(\frac{\Delta\Gamma}{2}t'\right)\right]\right\}\otimes \\
&\quad R\left(t-t'|\delta_t\right)\cdot g\left(\delta_t\right)\cdot\varepsilon_{\mathrm{acc}}\left(t\right), \\
I_{-}\left(t,\,\delta_t\right) &= \left\{e^{-\Gamma t'}\left[C_f\cos\left(\Delta m t'\right)-S_f\sin\left(\Delta m t'\right)\right]\right\}\otimes \\
&\quad R\left(t-t'|\delta_t\right)\cdot g\left(\delta_t\right)\cdot\varepsilon_{\mathrm{acc}}\left(t\right).
\end{aligned}$$

Experimental decay rates for signals

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

$$\begin{aligned} I_+(t,\delta_t) &= \left\{e^{-\Gamma t'}\left[\cosh\left(\frac{\Delta\Gamma}{2}t'\right) + A_f^{\Delta\Gamma}\sinh\left(\frac{\Delta\Gamma}{2}t'\right)\right]\right\} \otimes \\ &\quad R(t-t'|\delta_t)\cdot g(\delta_t)\cdot \varepsilon_\mathrm{acc}(t), \\ I_-(t,\delta_t) &= \left\{e^{-\Gamma t'}\left[C_f\cos(\Delta m t') - S_f\sin(\Delta m t')\right]\right\} \otimes \\ &\quad R(t-t'|\delta_t)\cdot g(\delta_t)\ \varepsilon_\mathrm{acc}(t). \end{aligned}$$

  - $\varepsilon_{acc}(t)$ = decay time acceptance
  - Introduced by selection requirements
  - Studied from simulation



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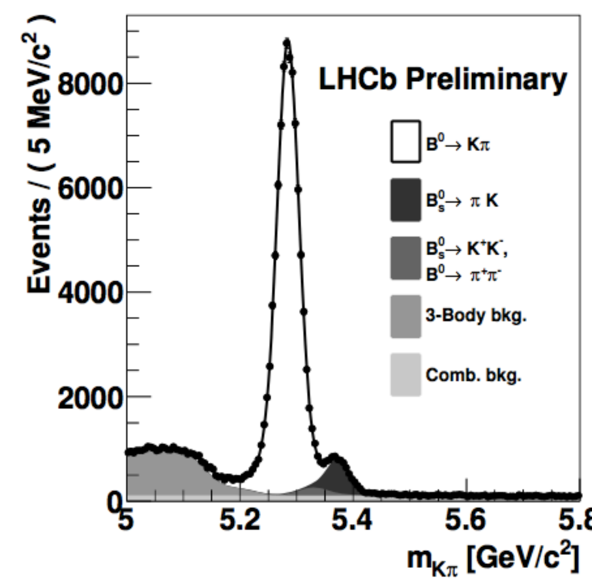
Experimental decay rates for signals

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

$$\begin{aligned} I_+(t,\delta_t) &= \left\{e^{-\Gamma t'}\left[\cosh\left(\frac{\Delta\Gamma}{2}t'\right) + A_f^{\Delta\Gamma}\sinh\left(\frac{\Delta\Gamma}{2}t'\right)\right]\right\} \otimes \\ &\quad R(t-t'|\delta_t)\cdot g(\delta_t)\,\varepsilon_\mathrm{acc}(t), \\ I_-(t,\delta_t) &= \left\{e^{-\Gamma t'}\left[C_f\cos(\Delta m t') - S_f\sin(\Delta m t')\right]\right\} \otimes \\ &\quad R(t-t'|\delta_t)\cdot g(\delta_t)\cdot\varepsilon_\mathrm{acc}(t). \end{aligned}$$

- $\Omega(\eta,\xi)$ = flavour tagging
- $R(t,\delta t)$ = decay time resolution
- A_P = production asymmetry Determined from time-dependent asymmetries of untagged $B^0 \to K\pi$ and $B_s \to \pi K$ decays



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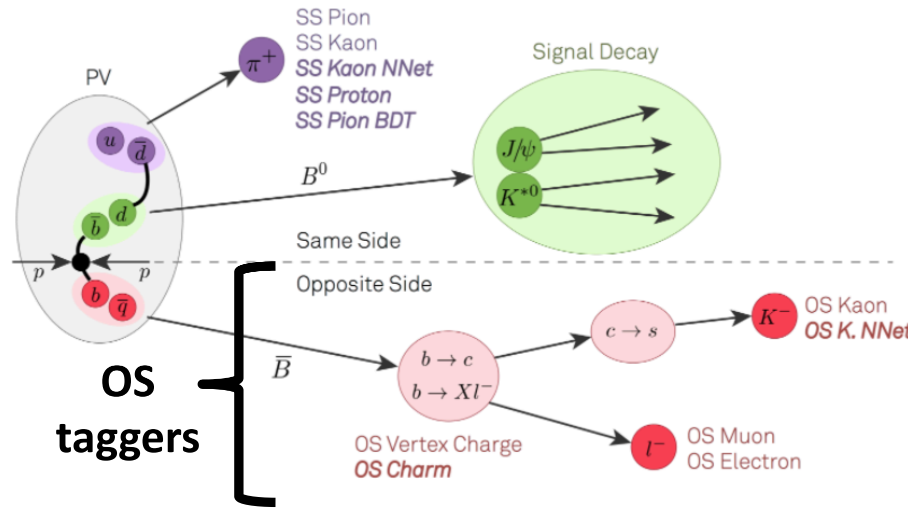
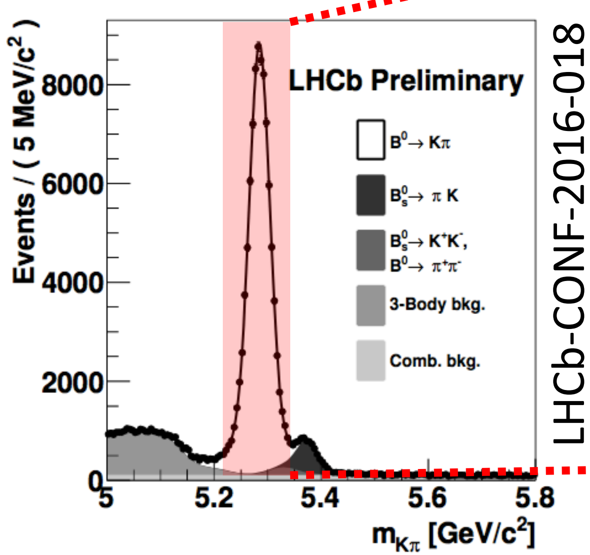
Flavour tagging

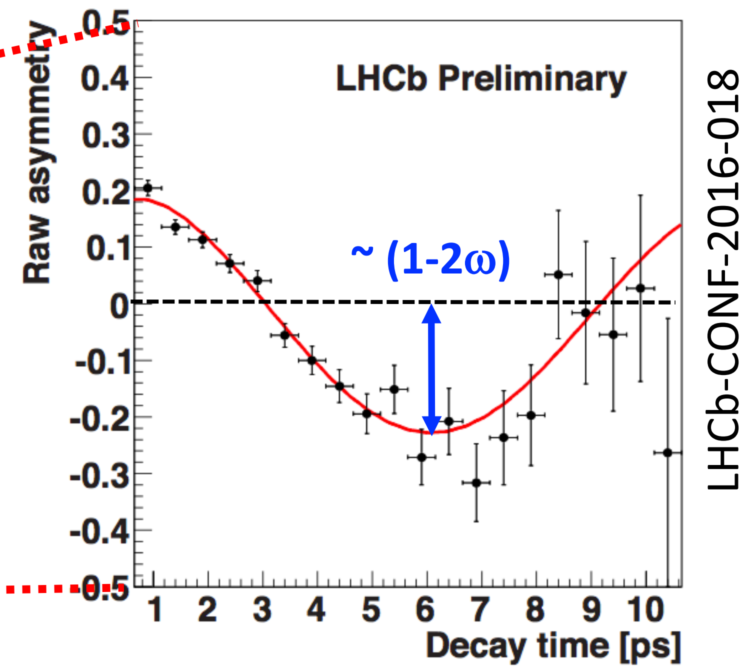
- In this analysis only **Opposite Side** (OS) taggers are used:
  - information is used on a per-event basis

$$\omega = p_0 + p_1(\eta - \eta)$$

- Calibration
  - Use time-dependent asymmetry of $B^0 \rightarrow K^+\pi^-$ for calibration







Decay time resolution (I)

- Decay time resolution introduce a dilution factor in the oscillation amplitudes
  - Determined on per-event basis calibrating the decay time error δ_t computed in reconstruction

$$D = \exp(-0.5\, \Delta m^2\, \sigma_t^2)$$

Δm is the oscillation frequency of the B meson
σ_t is the width of the decay time resolution

$$\sigma_t = q_0 + q_1(\delta_t - 30\ \mathrm{fs})$$

Relation between δ_t and σ_t is studied on MC

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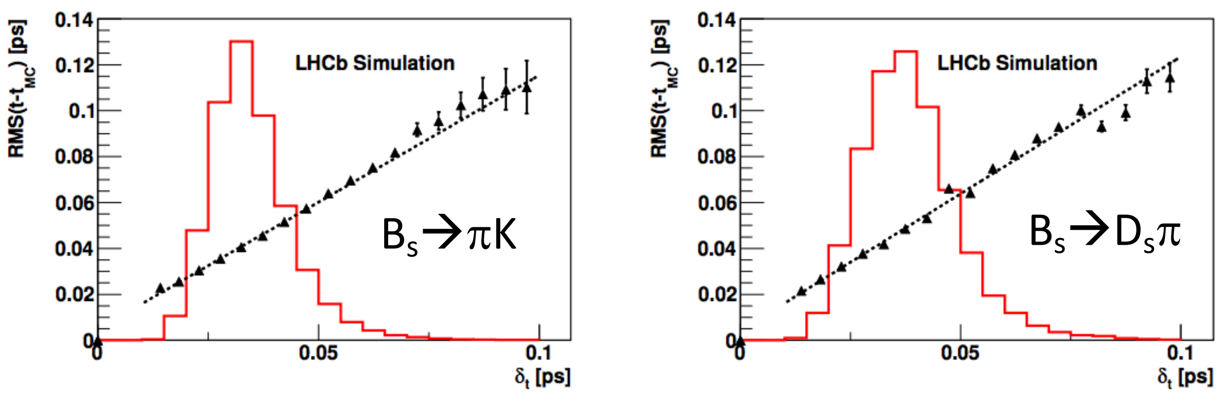


Calibration curve is very similar between $B_s \to \pi K$ and $B_s \to D_s\pi$ in simulation

Decay time resolution (II)

- Calibration on data is performed measuring simultaneously the time-dependent asymmetries of $B^0 \to D^-\pi^+$ and $B_s \to D_s\pi$ decays

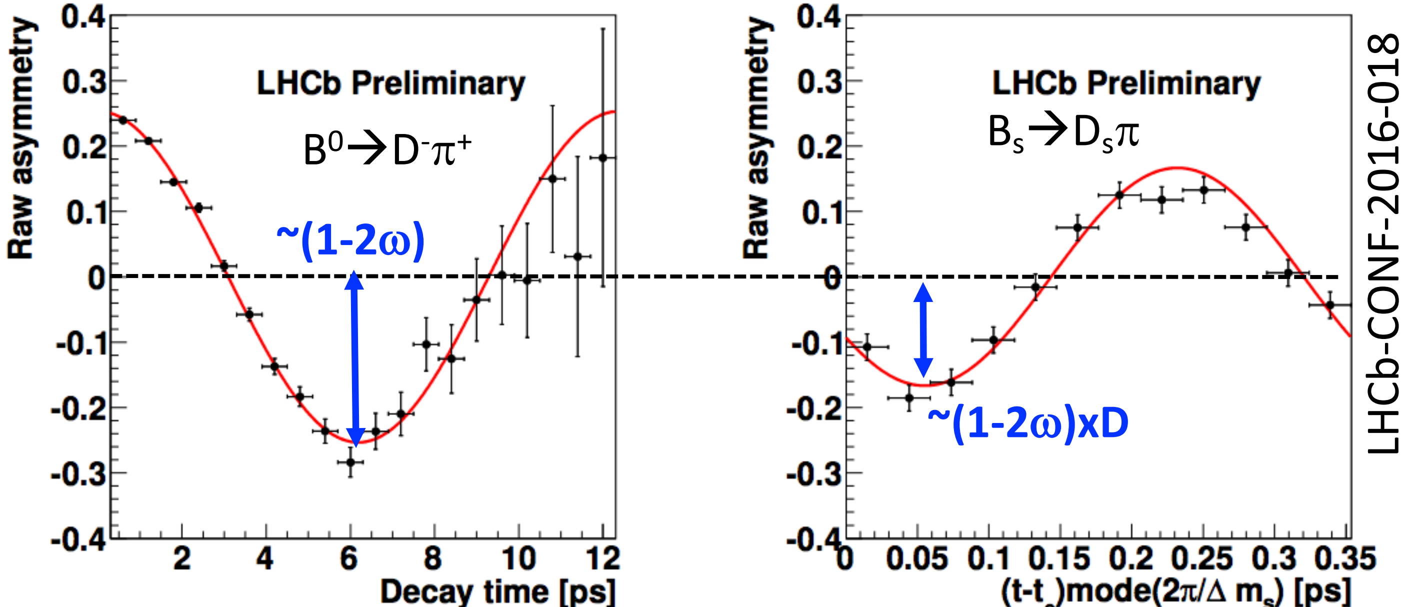
$$D = \exp(-0.5\,\Delta m^2\,\sigma_t^2)$$

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

LHCb Preliminary

$q_0 = 46.1 \pm 4.1$ fs

$q_1 = 0.81 \pm 0.38$



Dilution from σ_t negligible for $B^0 \to$ small Δm_d

Result of the simultaneous fit

$\pi^+\pi^-$ spectrum

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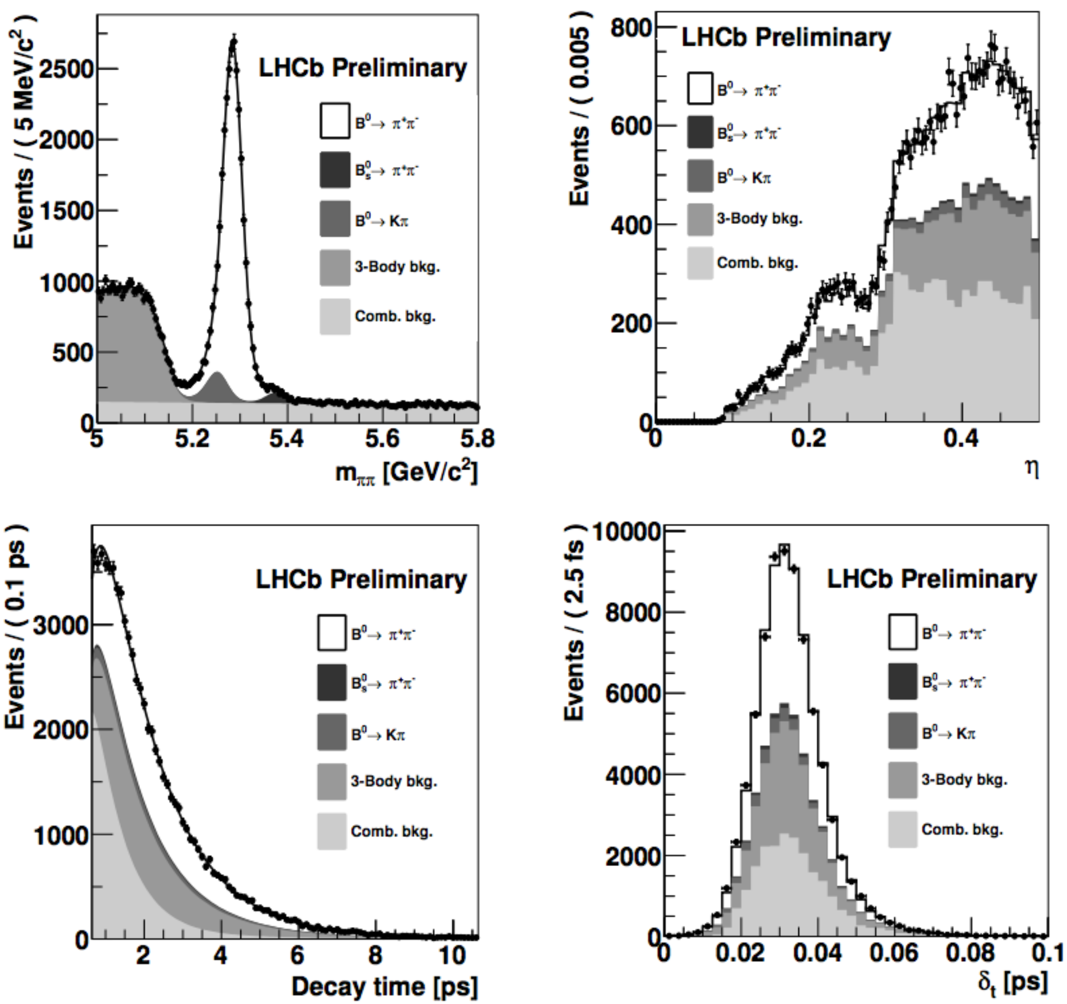


Fixed parameters

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

Averages from Heavy Flavour Averaging Group

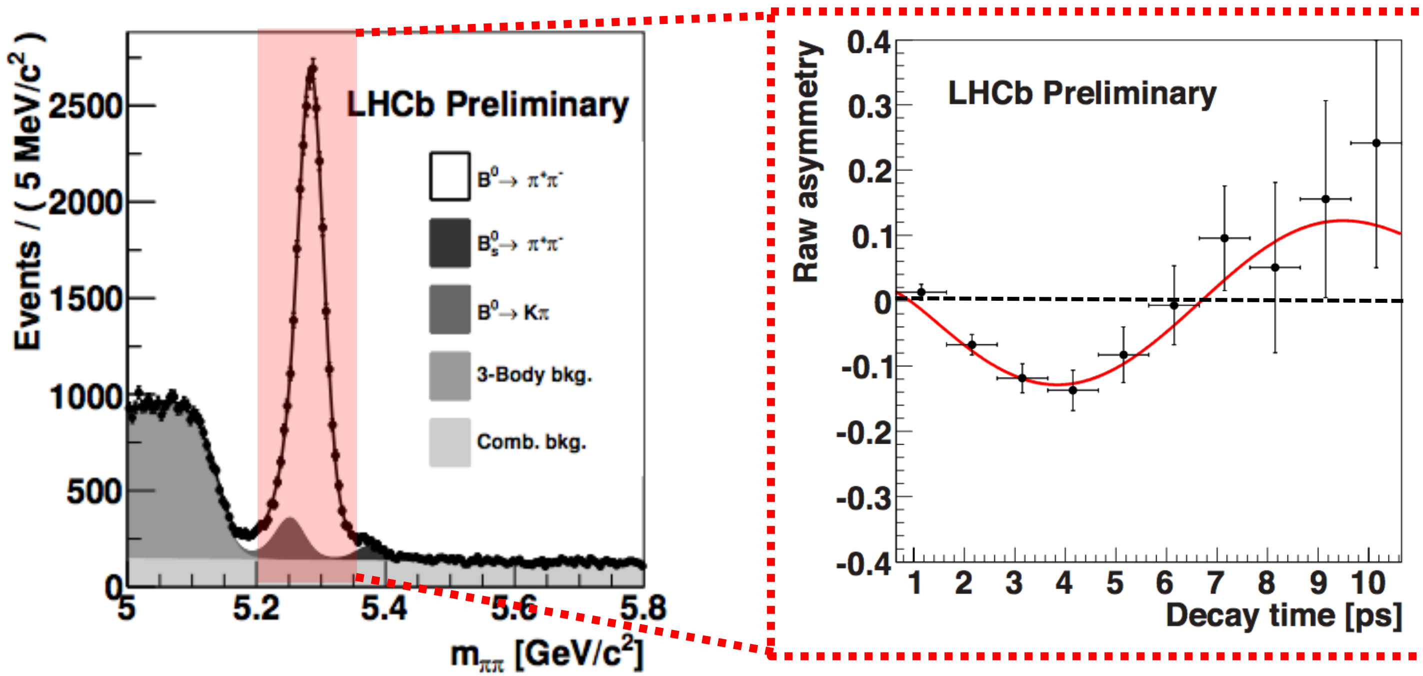
Results of the simultaneous fit

$\pi^+\pi^-$ spectrum

(LHCb Preliminary)

$$\boxed{\begin{aligned} C_{\pi^+\pi^-} &= -0.243 \pm 0.069, \\ S_{\pi^+\pi^-} &= -0.681 \pm 0.060, \end{aligned}}$$

statistical error only



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Result of the simultaneous fit

K^+K^- spectrum

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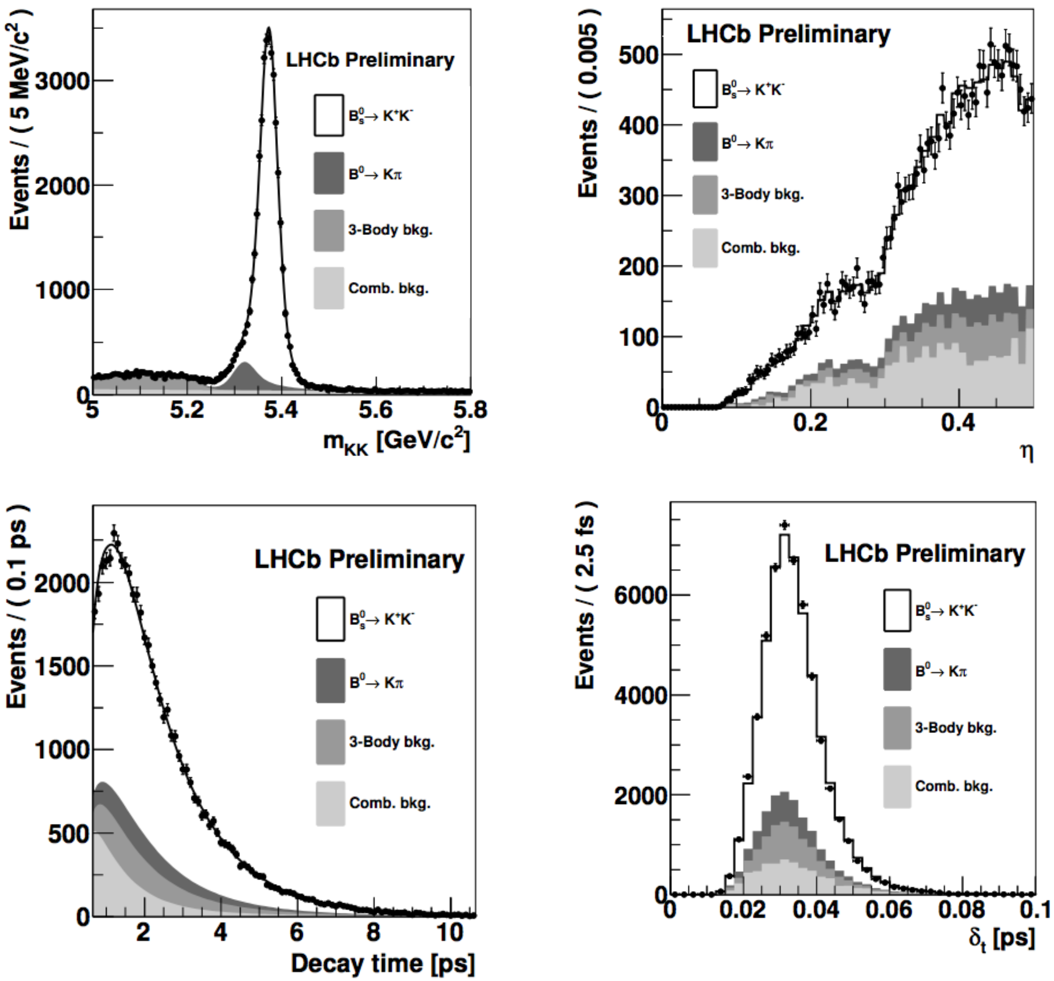

Fixed parameters

Parameter	Value
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Δm_s	$17.757 \pm 0.021\ \ \mathrm{ps}^{-1}$
Γ_s	$0.6654 \pm 0.0022\,\mathrm{ps}^{-1}$
$\Delta\Gamma_s$	$0.083 \pm 0.007\ \ \mathrm{ps}^{-1}$
$\rho(\Gamma_s, \Delta\Gamma_s)$	$-\,0.292$

Averages from Heavy Flavour Averaging Group

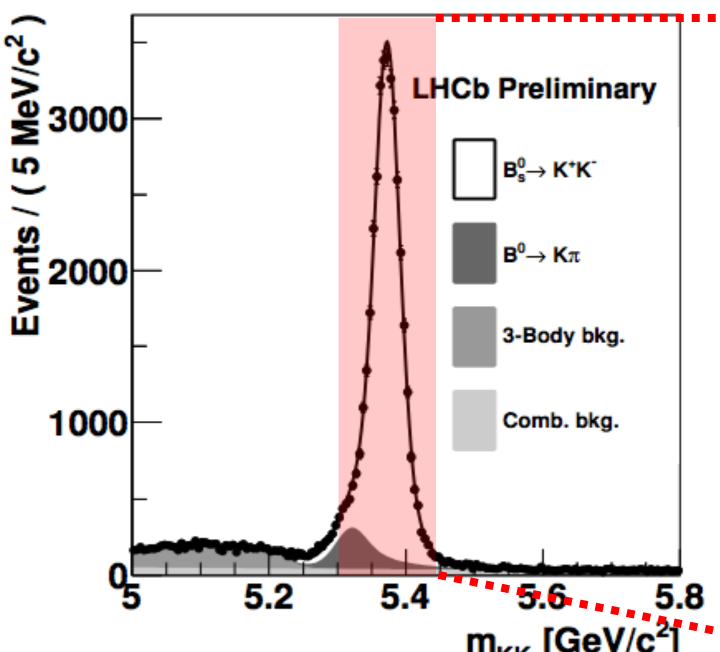
Result of the simultaneous fit

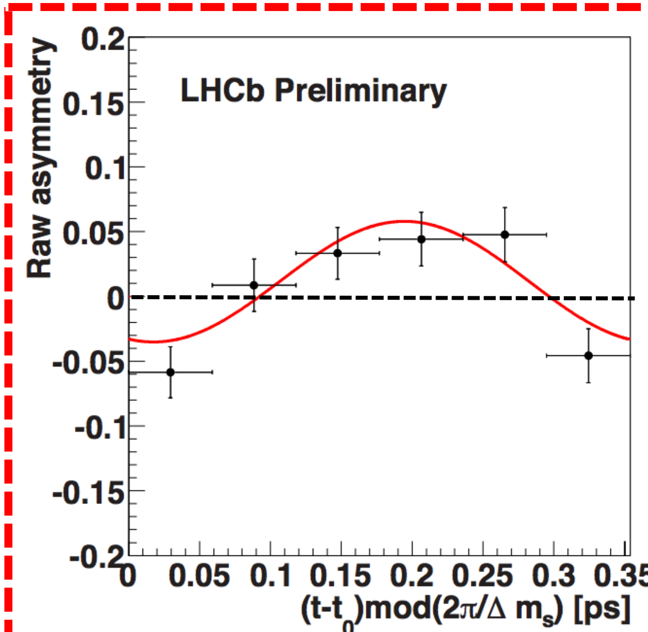
K^+K^- spectrum

(LHCb Preliminary)

$$\begin{aligned} C_{K^+K^-} &= 0.236 \pm 0.062, \\ S_{K^+K^-} &= 0.216 \pm 0.062, \\ A^{\Delta\Gamma}_{K^+K^-} &= -0.751 \pm 0.075. \end{aligned}$$

statistical error only





LHCb-CONF-2016-018

Systematic uncertainties

LHCb Preliminary - LHCb-CONF-2016-018

Parameter	$C_{\pi^+\pi^-}$	$S_{\pi^+\pi^-}$	$C_{K^+K^-}$	$S_{K^+K^-}$	$A^{\Delta\Gamma}_{K^+K^-}$
Time acceptance	0.001	0.001	0.003	0.003	0.093
Time resolution calibration	0.000	0.000	0.016	0.017	0.012
Time resolution model	0.000	0.000	0.007	0.008	0.000
Time error distribution	0.002	0.002	0.002	0.002	0.019
Input parameters: $\Gamma_{d,s}$, $\Delta\Gamma_{d,s}$, $\Delta m_{d,s}$	0.001	0.001	0.001	0.003	0.046
Tagging calibration	0.002	0.003	0.002	0.003	0.000
Cross-feed bkg. time model	0.003	0.002	0.001	0.001	0.021
Comb. and 3-body bkg. time model	0.001	0.001	0.000	0.000	0.001
Mass model	0.003	0.003	0.006	0.005	0.010
Total	0.005	0.005	0.019	0.020	0.109

Final results

LHCb Preliminary - LHCb-CONF-2016-018

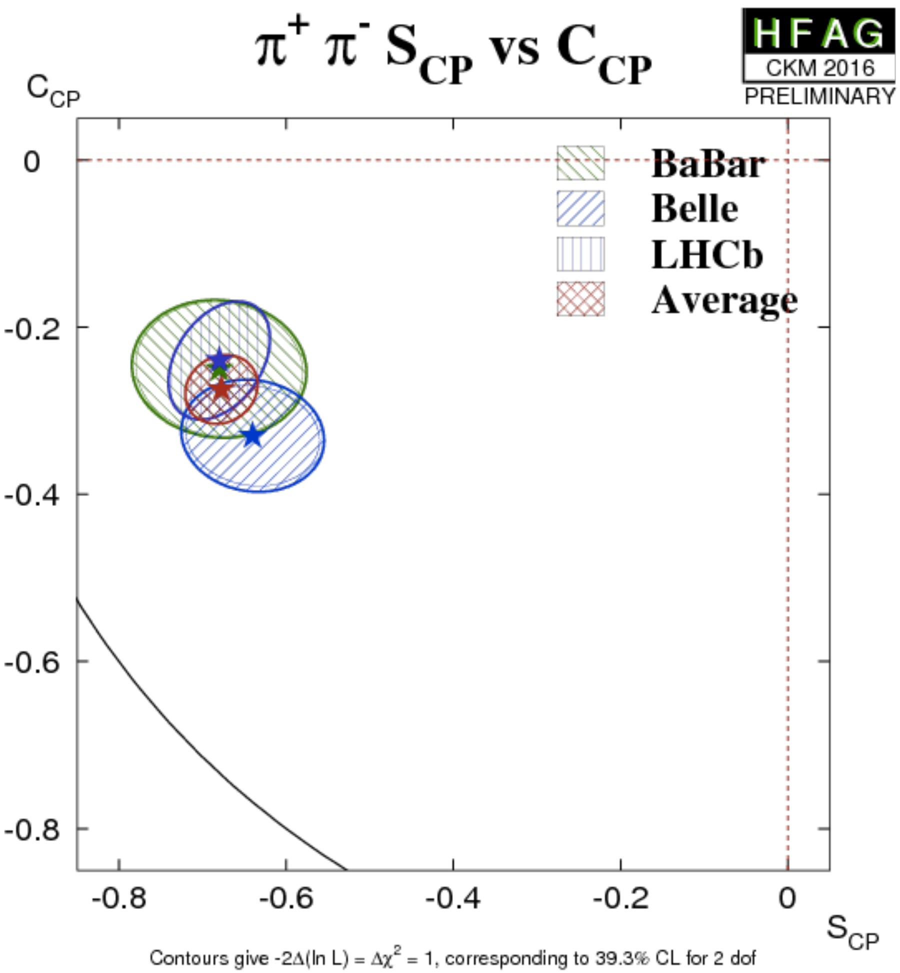
$$
\begin{aligned}
C_{\pi^+\pi^-} &= -0.24 \pm 0.07 \pm 0.01, \\
S_{\pi^+\pi^-} &= -0.68 \pm 0.06 \pm 0.01, \\
C_{K^+K^-} &= 0.24 \pm 0.06 \pm 0.02, \\
S_{K^+K^-} &= 0.22 \pm 0.06 \pm 0.02, \\
A^{\Delta\Gamma}_{K^+K^-} &= -0.75 \pm 0.07 \pm 0.11.
\end{aligned}
$$

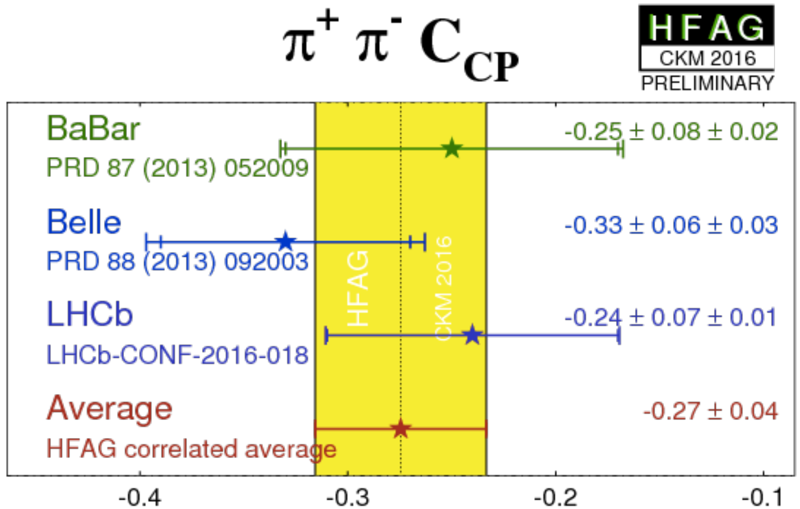
Statistical Correlation	$C_{\pi^+\pi^-}$	$S_{\pi^+\pi^-}$	$C_{K^+K^-}$	$S_{K^+K^-}$	$A^{\Delta\Gamma}_{K^+K^-}$
$C_{\pi^+\pi^-}$	1.000	0.376	−0.009	−0.011	0.000
$S_{\pi^+\pi^-}$	−	1.000	−0.055	−0.013	0.000
$C_{K^+K^-}$	−	−	1.000	−0.005	0.035
$S_{K^+K^-}$	−	−	−	1.000	0.037
$A^{\Delta\Gamma}_{K^+K^-}$	−	−	−	−	1.000

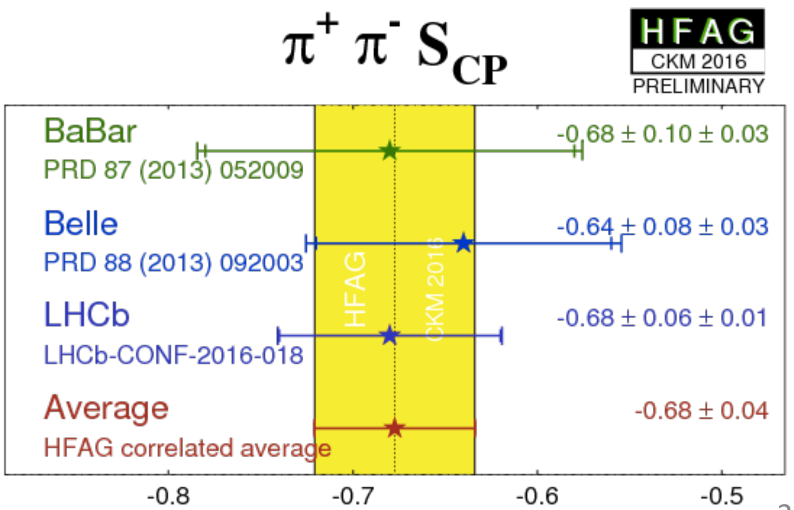
- Significant improvement with respect to previous result
  - Results are in agreement with ~ x 2 better precision
- Most precise determination of $S_{\pi\pi}$
- First determination of $A^{\Delta\Gamma}_{KK}$
- Naïve determination of CPV significance
  - Neglecting correlations and summing in quadrature statistical and systematic uncertainties
  - (C_{KK}, S_{KK}, A_{KK}) is 5.3σ from (0, 0, 1)
  - (C_{KK}, S_{KK}) is 4.9σ from (0, 0)
  - C_{KK} and S_{KK} are 3.6σ and 3.3σ from 0, respectively

Final results

By courtesy of the Heavy Flavour Averaging Group





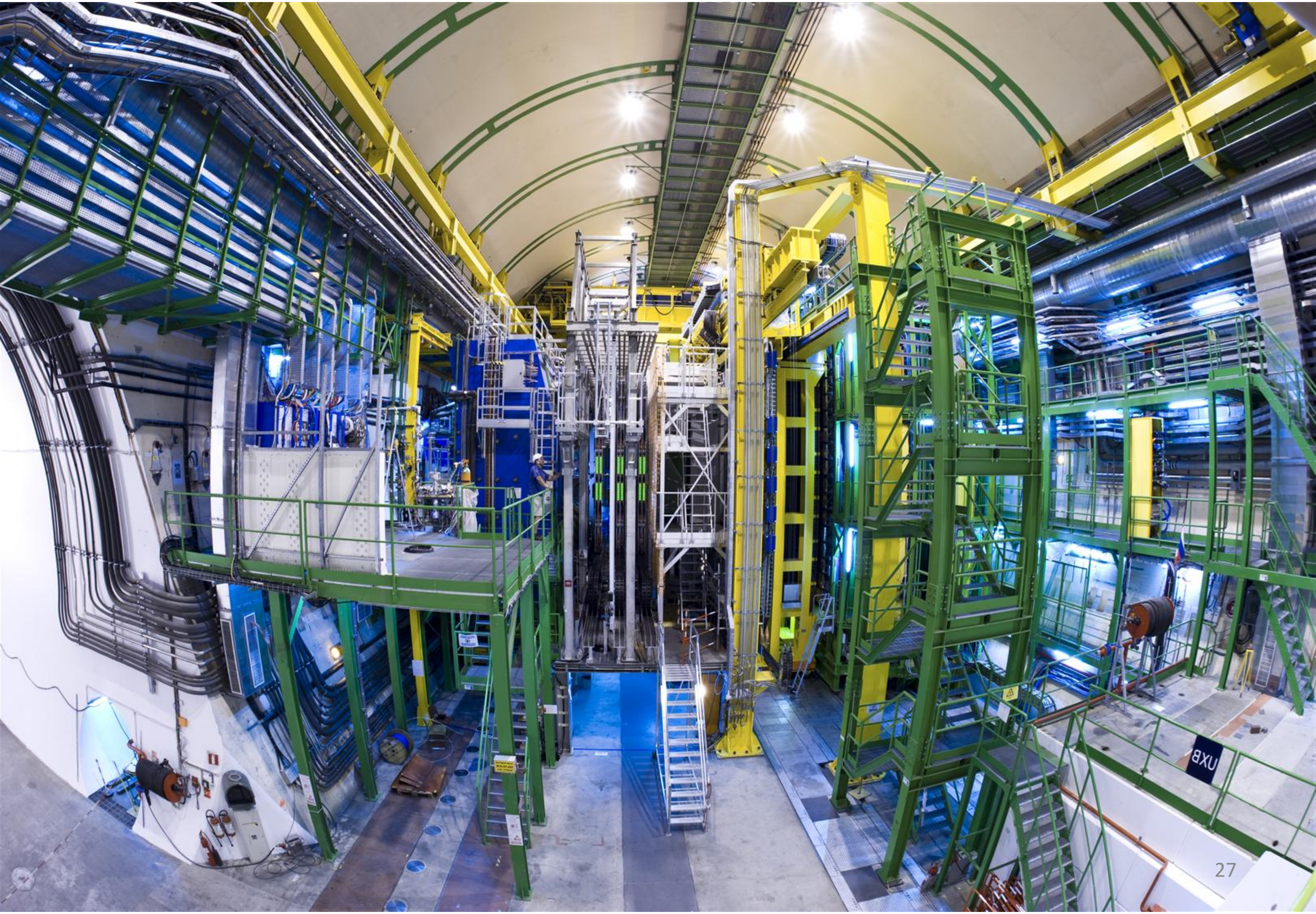


Conclusions

- The measurement of time-dependent CP violation with $B^0 \rightarrow \pi^+\pi^-$ and $B_s \rightarrow K^+K^-$ have been presented
  - The full Run1 sample of LHCb has been used
    - 1 fb^{-1} @ 7 TeV and 2 fb^{-1} @ 8 TeV
    - Significant improvement with respect to previous measurement
  - Only OS taggers have been used
    - Update including SS taggers will follow shortly
  - Best measurement of $S_{\pi\pi}$ from a single experiment
  - With a naïve determination of CPV significance
    - First evidence of CPV in the decay and in the mixing/decay interference in $B_s \rightarrow K^+K^-$
    - First observation of CPV in the $B_s \rightarrow K^+K^-$ decay
    - More accurate determination of significance is needed

Backup

The LHCb detector



The LHCb detector