CKM Mumbai - 30 November 2016

Mixing induced CP violation in B_d decays

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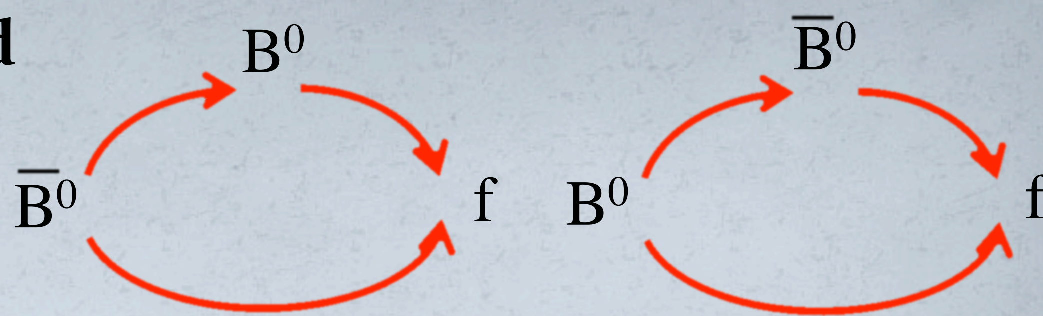
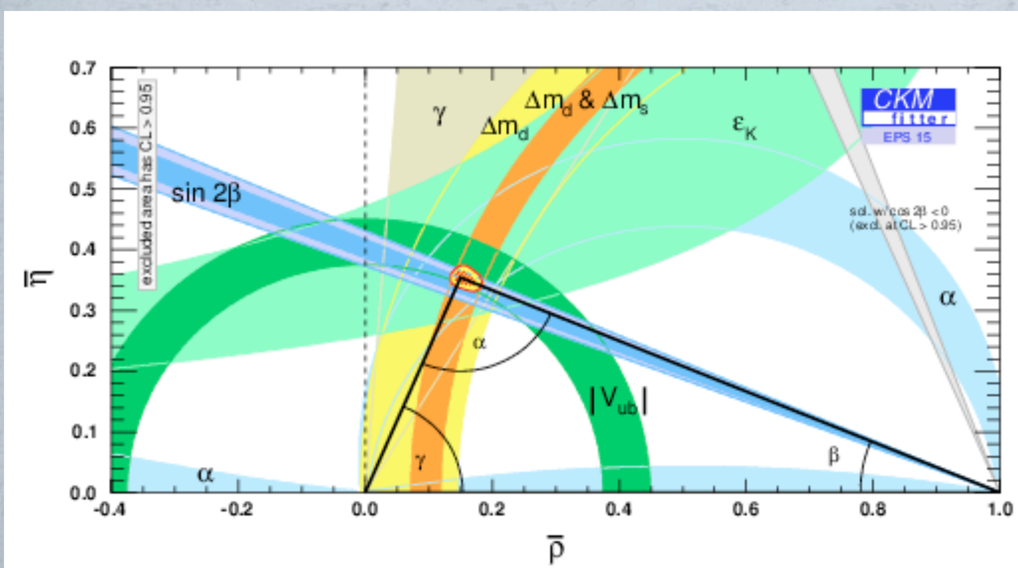
On behalf of the LHCb Collaboration

- **Large CPV is expected in interference between B^0 decays with or w/o mixing.**



- **Measurements of CP phase provide constraints to SM parameters and probe for BSM physics**



$$\beta \equiv \arg[-(V_{cd}V_{cb}^*)/(V_{td}V_{tb}^*)]$$

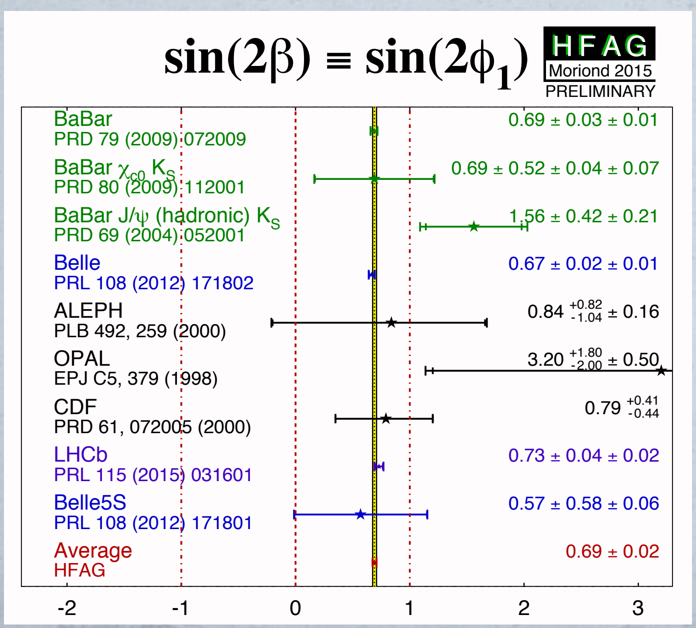
- $\beta = (21.9 \pm 0.7)^\circ$ **wa**
- $\beta^{SM} = (24.3\ ^{+1.3}_{-1.4})^\circ$

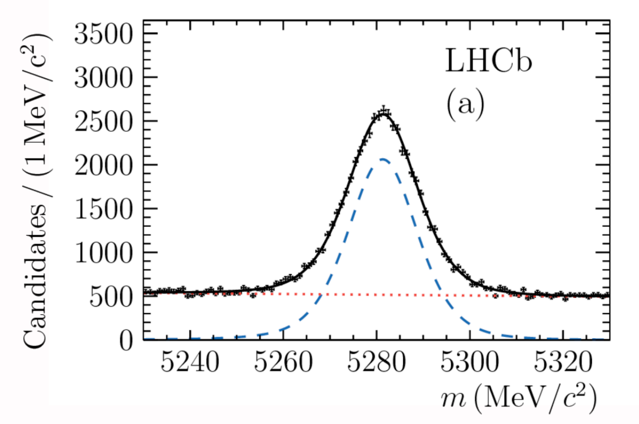
  CKMFitter, all meas. except β

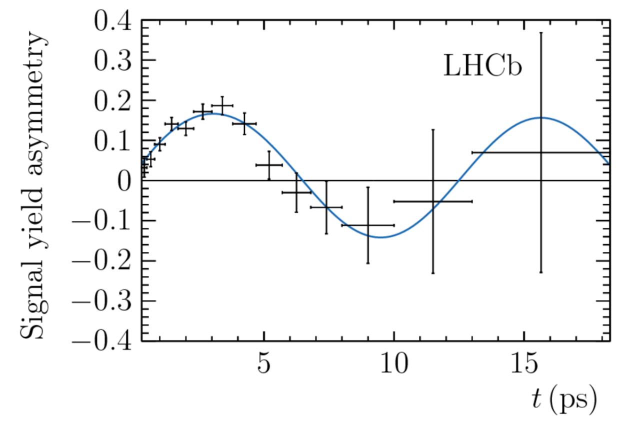
$B^0 \rightarrow J/\psi K_S$

- **Dominated by tree $b \rightarrow c\bar{c}s$ transition in SM $S = \sin(2\beta)$**

$$\mathcal{A}(t) \equiv \frac{\Gamma(\bar{B}^0(t) \rightarrow J/\psi K_S^0) - \Gamma(B^0(t) \rightarrow J/\psi K_S^0)}{\Gamma(\bar{B}^0(t) \rightarrow J/\psi K_S^0) + \Gamma(B^0(t) \rightarrow J/\psi K_S^0)} = S\sin(\Delta m t) - C\cos(\Delta m t)$$







- **LHCb with RUN I data（3 fb^{-1}）**

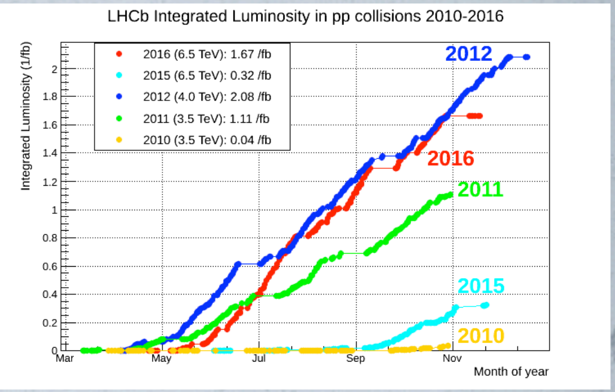
  41 560 ± 270 candidates

$$S = 0.731 \pm 0.035(\text{stat}) \pm 0.020(\text{syst}),$$
$$C = -0.038 \pm 0.032(\text{stat}) \pm 0.005(\text{syst})$$

$\rho(S,C) = 0.483$ PRL 115 (2015) 031601

$B^0 \rightarrow J/\psi\, K_S$ prospects

- $2fb^{-1}$ (2015+2016) at 13 TeV already on tape → more than double data yield



PRL 115 (2015) 031601

systematics

Origin	σ_S		σ_C	
Background tagging asymmetry	0.0179	(2.5%)	0.0015	(4.5%)
Tagging calibration	0.0062	(0.9%)	0.0024	(7.2%)
$\Delta\Gamma$	0.0047	(0.6%)	—	
Fraction of wrong PV component	0.0021	(0.3%)	0.0011	(3.3%)
z-scale	0.0012	(0.2%)	0.0023	(7.0%)
Δm	—		0.0034	(10.3%)
Upper decay time acceptance	—		0.0012	(3.6%)
Correlation between mass and decay time	—		—	
Decay time resolution calibration	—		—	
Decay time resolution offset	—		—	
Low decay time acceptance	—		—	
Production asymmetry	—		—	
Sum	0.020	(2.7%)	0.005	(15.2%)

- **Small systematic uncertainties, will decrease with increasing data samples.**
  - **Currently dominated by background tagging asymmetry.**

- **Higher tagging power available from new algorithms**
- **Control of penguing contributions from measurementts in other channels**

$B^0_s \to J/\psi\, K_S$

- **Under approximated SU(3) symmetry allow to control size of penguin amplitudes in $B^0 \to J/\psi\, K_S$**
- **LHCb with 3 fb^{-1}**

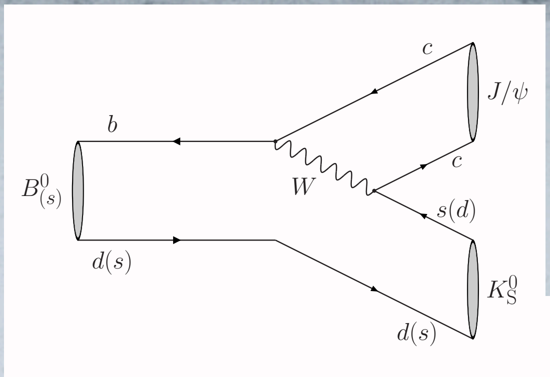
  908 ± 36 signal candidates

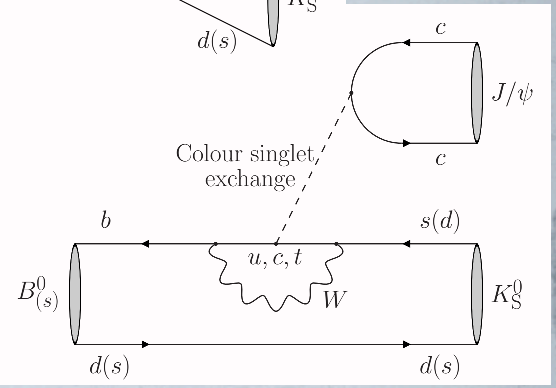
$$\mathcal{B}(B^0_s \to J/\psi\, K^0_S)/\mathcal{B}(B^0 \to J/\psi\, K^0_S)$$
$$0.0431 \pm 0.0017\,(\text{stat}) \pm 0.0012\,(\text{syst}) \pm 0.0025\,(f_s/f_d)$$

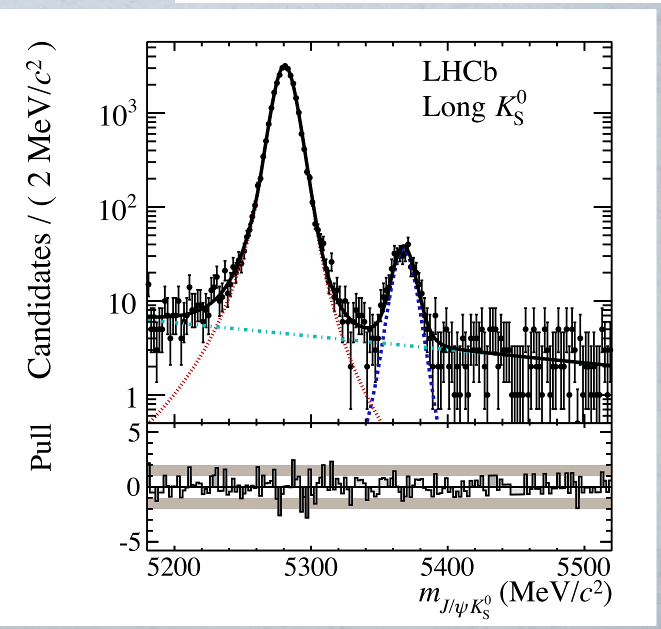
- **Tagged time-dependent analysis**

$$C_{\text{dir}} = -0.28 \pm 0.41\,(\text{stat}) \pm 0.08\,(\text{syst})$$
$$S_{\text{mix}} = -0.08 \pm 0.40\,(\text{stat}) \pm 0.08\,(\text{syst})$$

- **Precision not yet sufficient to derive constraints on $\Delta\phi_d$**
- **Good prospects for RUN II**





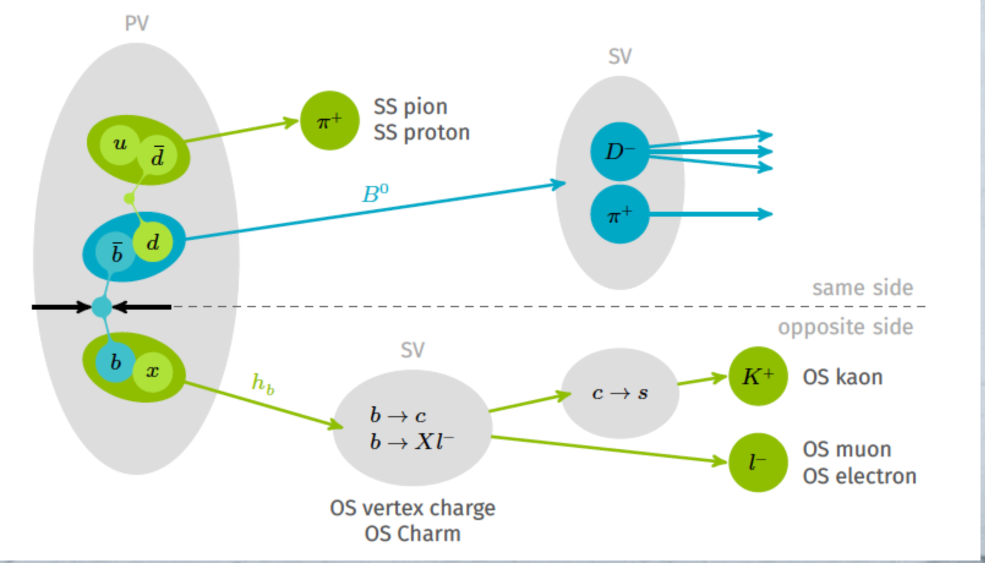


Flavour tagging at LHCb

- **Determines B^0 signal flavour at production, using information from the rest of the event**
- Sensitivity $\sigma^{stat} \sim 1 / \sqrt{\varepsilon(1-2\omega)^2 N}$ ε tagging efficiency
  ω wrong tag rate
- **Many algorithms combined**
- **Recently added/retuned: OS charm, SS pion, SS proton taggers**

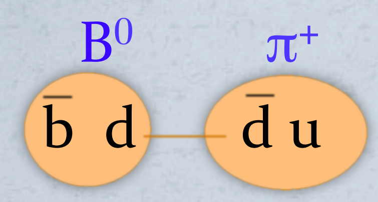
Same Side

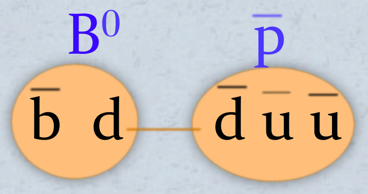
Opposite Side



Same Side B^0 flavour tagging

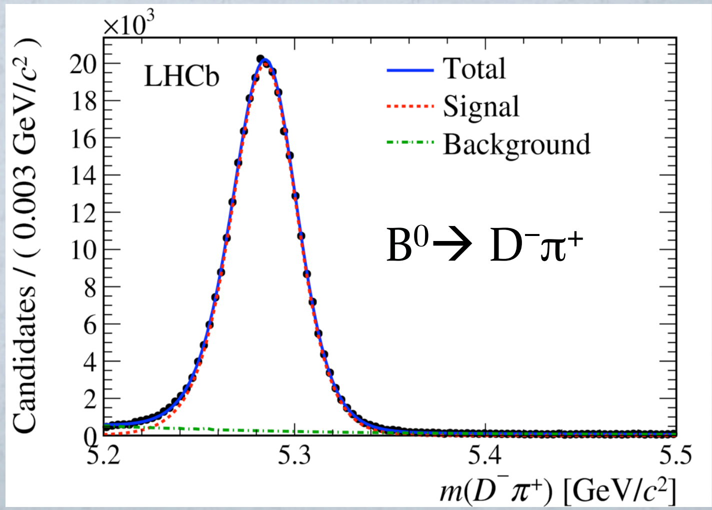
- **Exploit correlation of signal B flavour with charge of pions (protons) from the hadronization process**





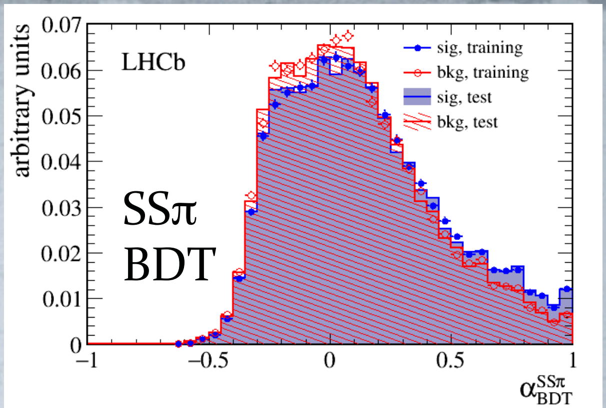
or decays of excited states, eg. $B^{**+} \rightarrow B^0 \pi^+$

- **Tagging algorithms tuned and calibrated on data using flavour specific B^0 decay modes**



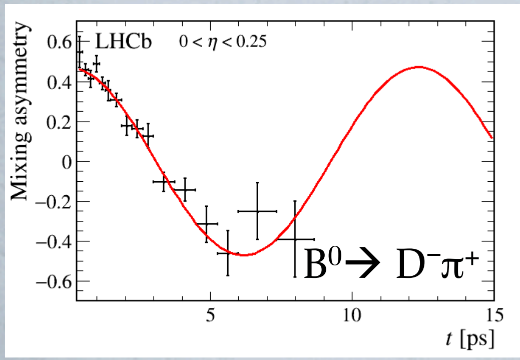
arXiv:1610.06019

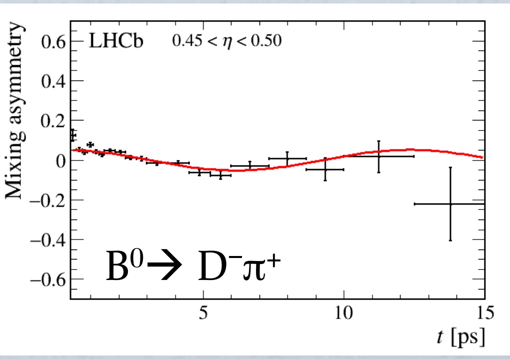
- Select pions (protons) from primary vertex and train a BDT to separate right tag/wrong tag candidates

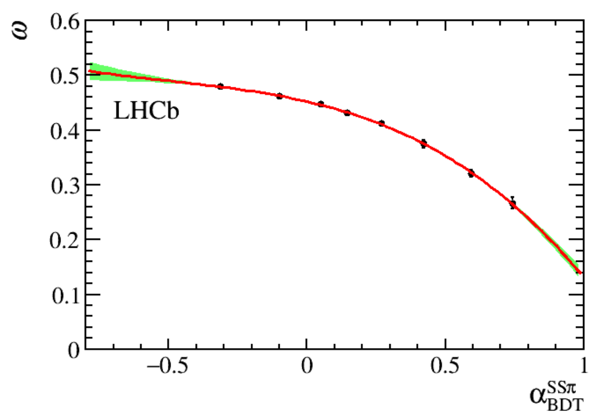


- **Convert the BDT output into a mistag probability associated to that particle with a time-dependent analysis of flavour oscillations**

$$A(t) = \frac{N^{unmix}(t) - N^{mix}(t)}{N^{unmix}(t) + N^{mix}(t)} = (1-2\omega)\cos(\Delta m\, t)$$

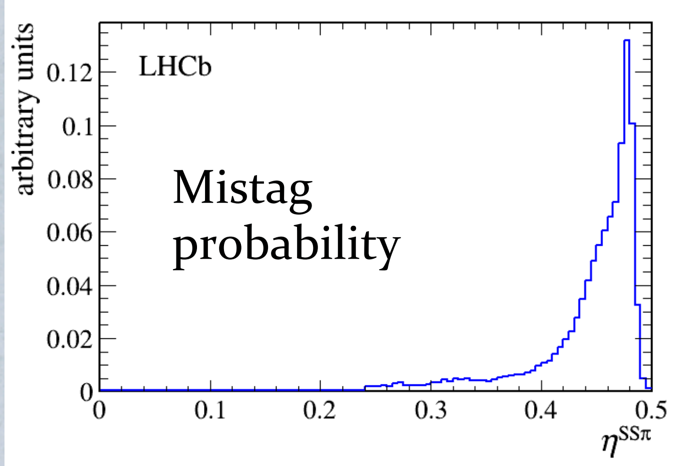


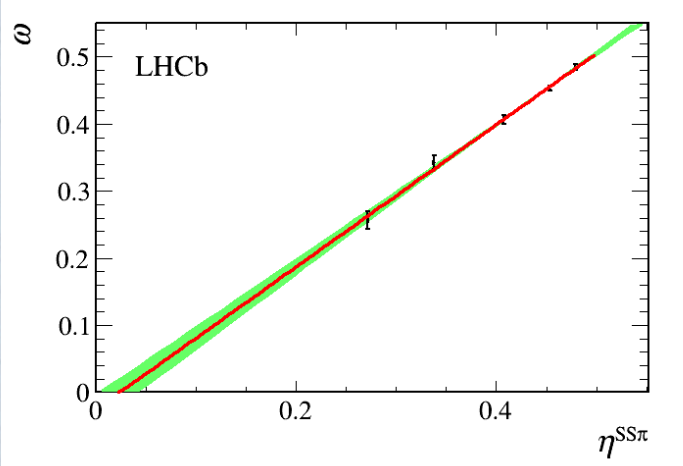




arXiv:1610.06019

- **Mistag calibration checked on control samples**
  - **Assume linear relation between true and predicted mistag**

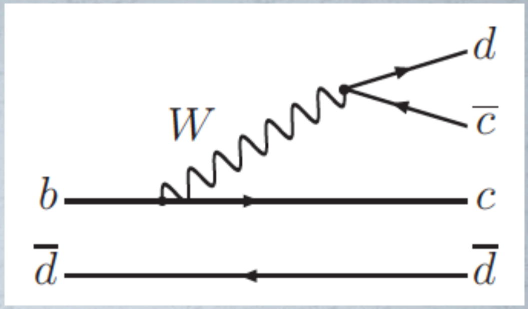


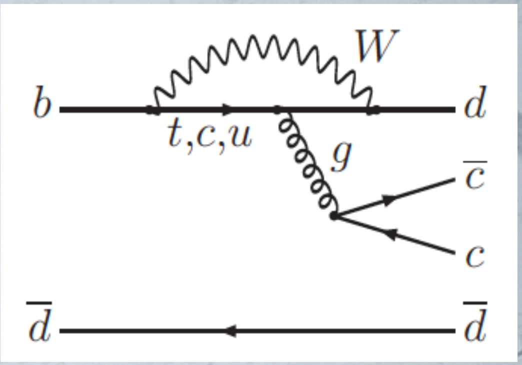


arXiv:1610.06019

- **SS pion tagger gives +60% in tagging power wrt SS algorithm used for RUNI $B^0 \to J/\psi K_S$ analysis.**
- **SS proton provides an additional +25%**
- **Final performance depends on the kinematic properties of the selected B^0 decays.**

$B^0 \rightarrow D^+D^-$





- **Measure sin(2β) from dominant, tree level, $b \rightarrow c\bar{c}d$ transition**
- **Sensitivity to higher order contributions provide constraints to possible additional CP phases.**
- **Time-dependent decay rate**

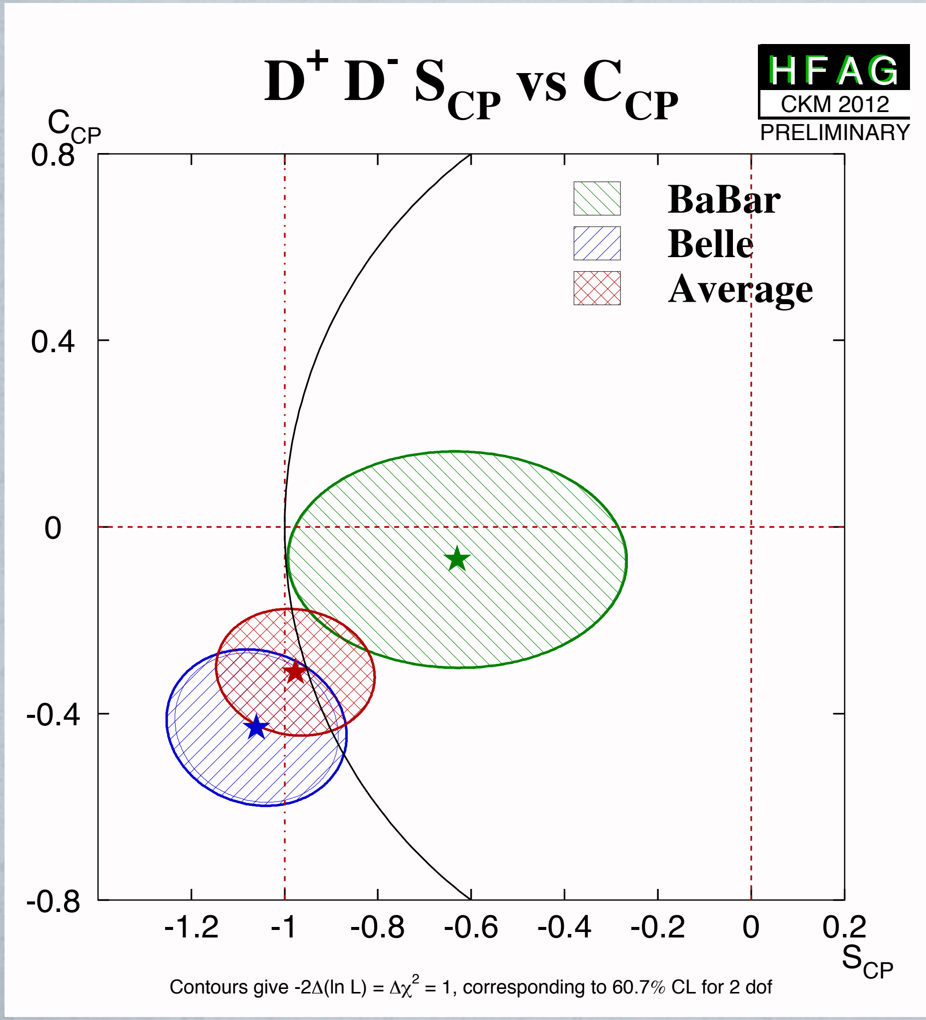
$$\frac{\mathrm{d}\Gamma(t,d)}{\mathrm{d}t} \propto \mathrm{e}^{-t/\tau}\Big(1 - d\,S\sin(\Delta m t) + d\,C\cos(\Delta m t)\Big)$$

$$S/\sqrt{1-C^2} = -\sin(\phi_d + \Delta\phi).$$

d = ± 1
B^0 flavour at production

- **SM, at tree level:** $\phi_d = 2\beta$ $C = 0$

$B^0 \rightarrow D^+D^-$ previous results



BaBar PRD 79 (2009) 032002

N(BB) = 467 M

$S = -0.63 \pm 0.36 \pm 0.05$

$C = -0.07 \pm 0.23 \pm 0.03$

Belle PRD 85 (2012) 091106

N(BB) = 772M

$S = -1.06\ ^{+0.21}_{-0.14} \pm 0.08$

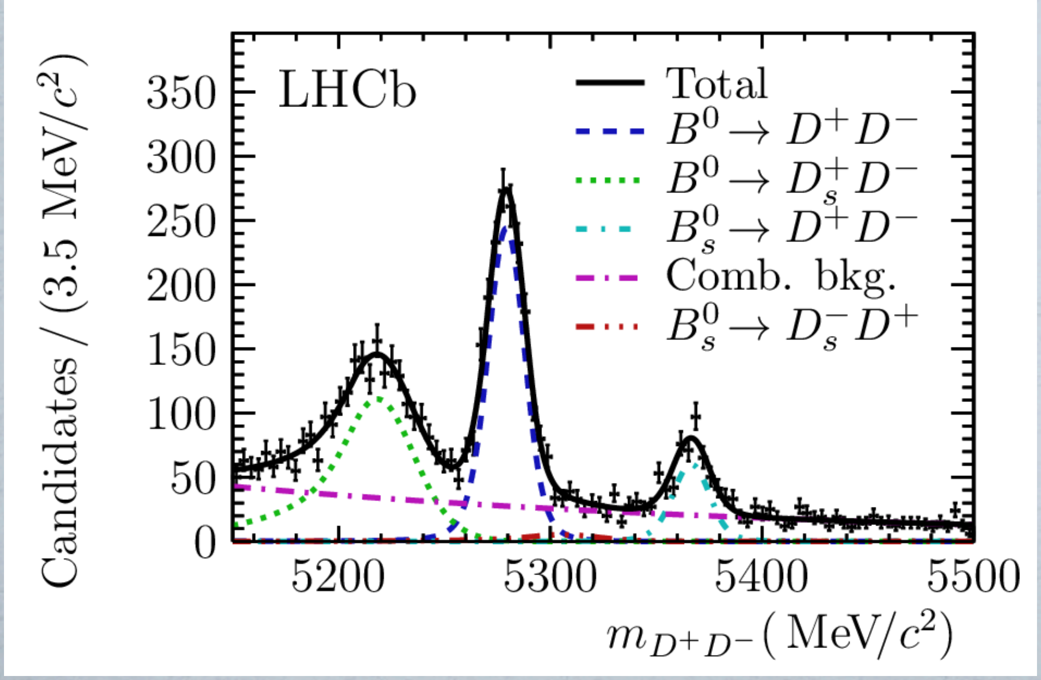
$C = -0.43 \pm 0.16 \pm 0.05$

- **Not yet a constraint to additional SM phases.**

- $B^0 \rightarrow D^+ D^- \rightarrow (K^-\pi^+\pi^+)(K^+\pi^-\pi^-)$

  $\rightarrow (K^-K^+\pi^+)(K^+\pi^-\pi^-)$, $(K^-\pi^+\pi^+)(K^+K^-\pi^-)$

  - **Two BDTs used to suppress combinatorial background.**
  - **Requirements on decay time significance of each D to suppress contamination of $B \rightarrow D\,K\pi\pi$ and $B \rightarrow D\,KK\pi$ decays**



RUN I data (3 fb^{-1})

1610 ± 50 signal candidates

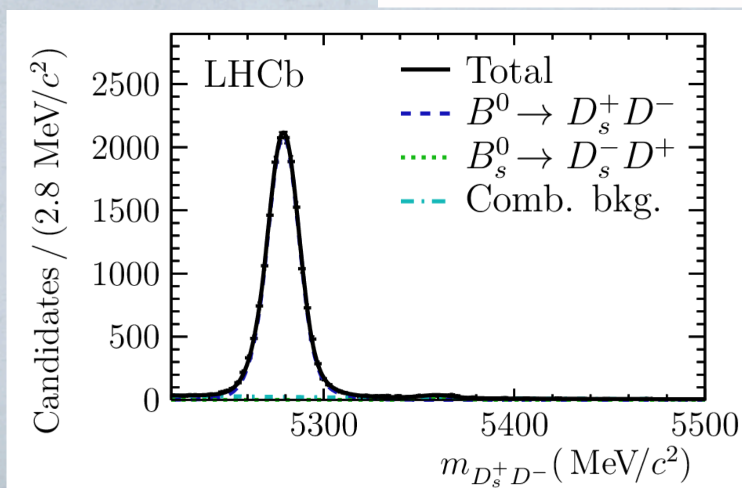
arXiv:1610.06620

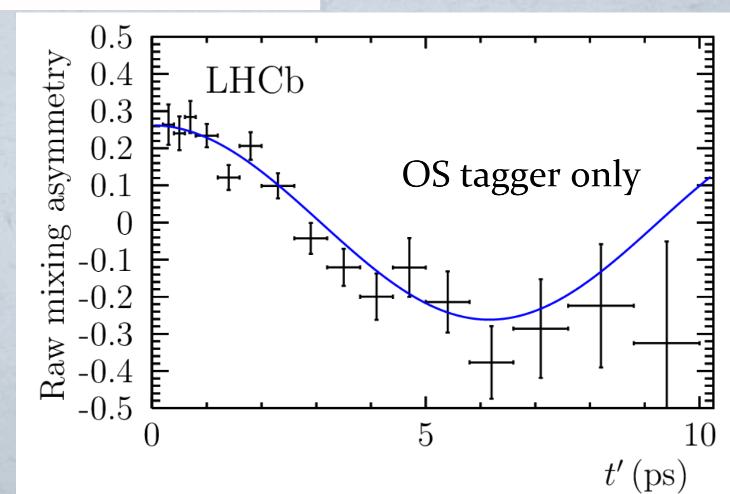
$B^0 \to D_s^+ D^-$ as control channel

- **Mistag probability calibrated on $B^0 \to D_s^+ D^-$ decays.**
- **Similar selection as signal, to minimize kinematic differences**

  16 736 ± 134 **signal candidates**
- **Decay-time fit to B^0 flavour oscillations to calibrate all taggers**

$B^0 \to D_s^+(K^+K^-\pi^+)D^-(K^+\pi^-\pi^-)$



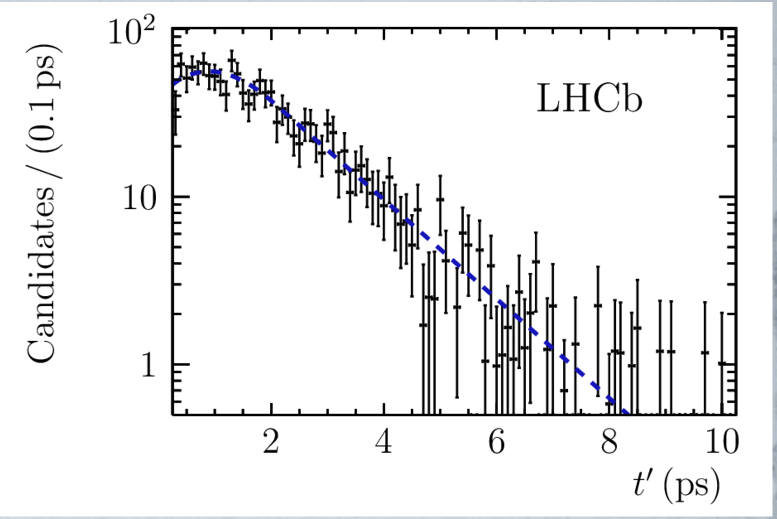


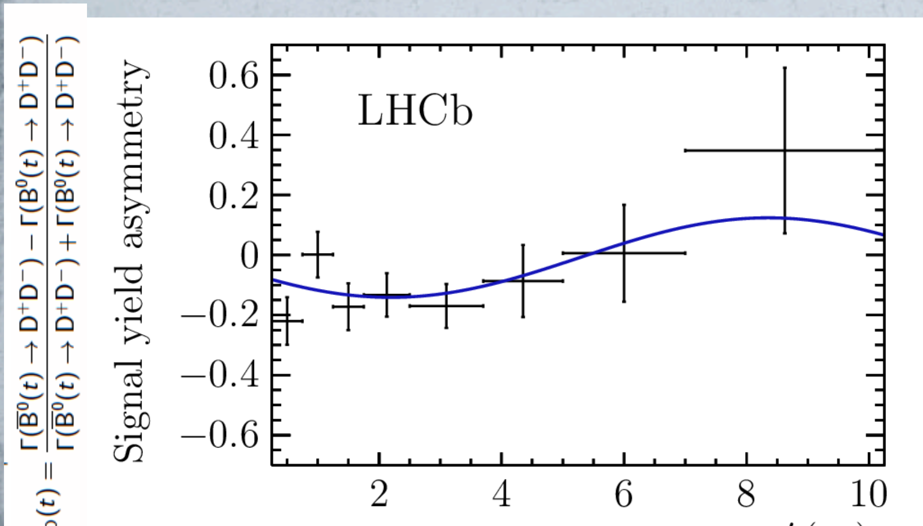
arXiv:1610.06620

$B^0 \rightarrow D^+D^-$ decay-time fit

$$\frac{d\Gamma(t,d)}{dt} \propto e^{-t/\tau}\left(1 - d\,S\sin(\Delta m t) + d\,C\cos(\Delta m t)\right)$$

- **Convoluted with a decay-time resolution derived from simulation (~50 ps) and time acceptance with free parameters**





arXiv:1610.06620

- $\varepsilon(1-2\omega)^2 = 8.1 \pm 0.6\ \%$

  $\varepsilon = 87.6 \pm 0.8\ \%$ $\omega = 34.8 \pm 0.6\%$

- **High tagging power due to improved algorithms and high p_T of selected B^0**

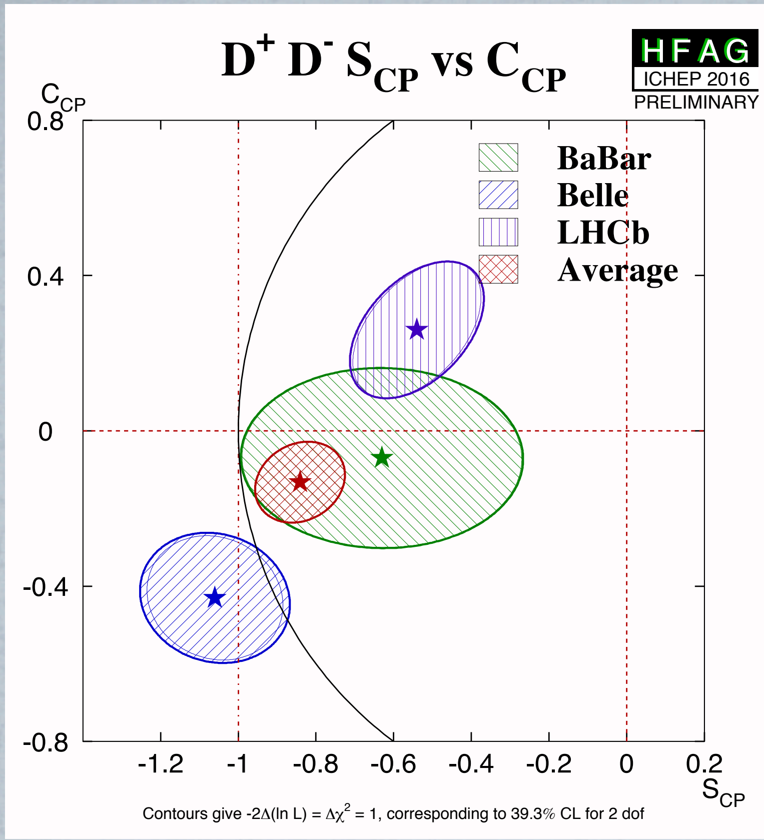
arXiv:1610.06620

$$S = -0.54\,^{+0.17}_{-0.16}\,(\text{stat}) \pm 0.05\,(\text{syst})$$
$$C = 0.26\,^{+0.18}_{-0.17}\,(\text{stat}) \pm 0.02\,(\text{syst})$$

Exclude CP symmetry conservation by 4σ

- Stat. correlation coeff. $\rho = 0.48$, larger than at B factories.
- **Main systematic from residual 2% $B^0 \rightarrow D^+ K^+ K^- \pi^-$ background (assumed with maximal CP violation, opposite to signal).**
- **This result constrains the phase shift due to higher-order SM corrections to**

$$\Delta\phi = -0.16\,^{+0.19}_{-0.21}\ \text{rad}$$



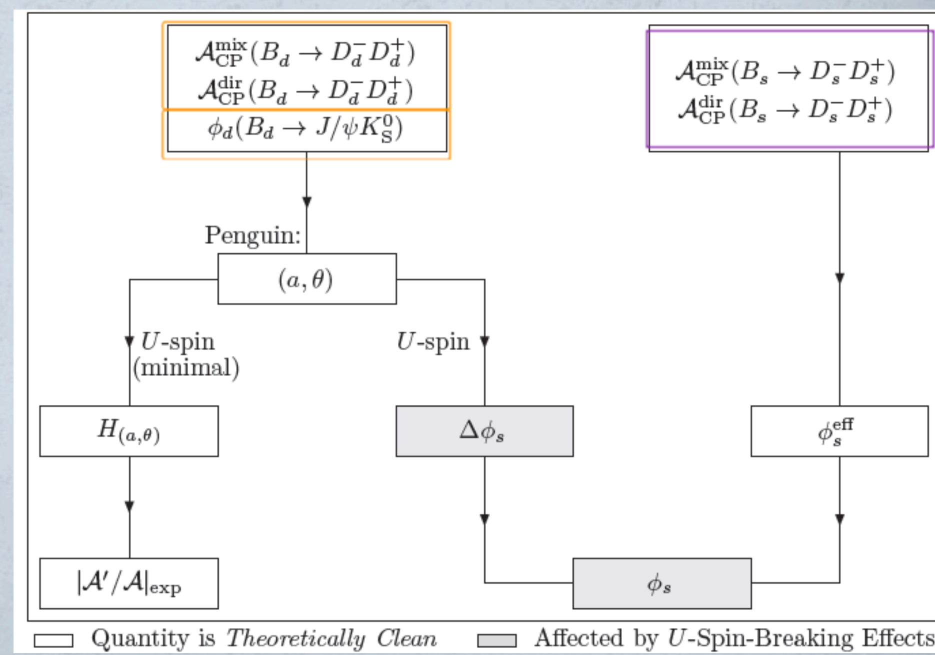
- SU(3) symmetry relates $\Delta\phi_d$ to $\Delta\phi_s$ $B^0 \rightarrow D^+ D^-$ controls size of penguin contributions to $B^0_s \rightarrow D_s^+ D_s^-$

  Bel et al. arXiv:1505.01361,

  Jung and Schacht arXiv:1410.8396

  Gronau et al. arXiv:0805.4601

→ see S. Akar's talk



- LHCb result compatible with BaBar one.
- Comparison with Belle hampered by non-Gaussian uncertainties

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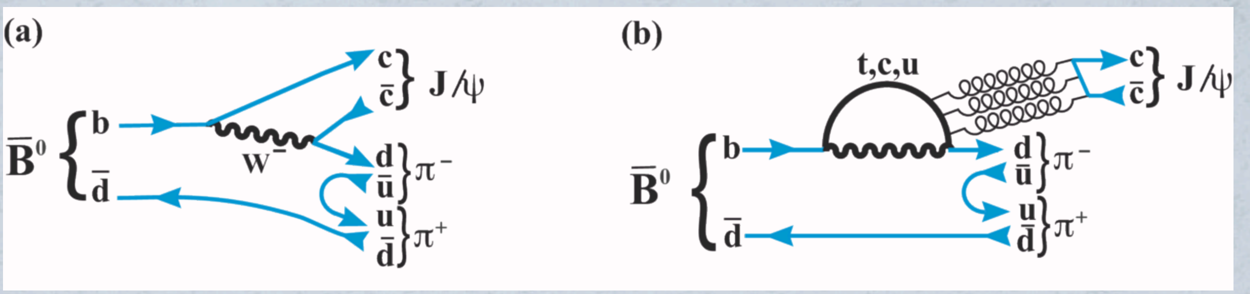
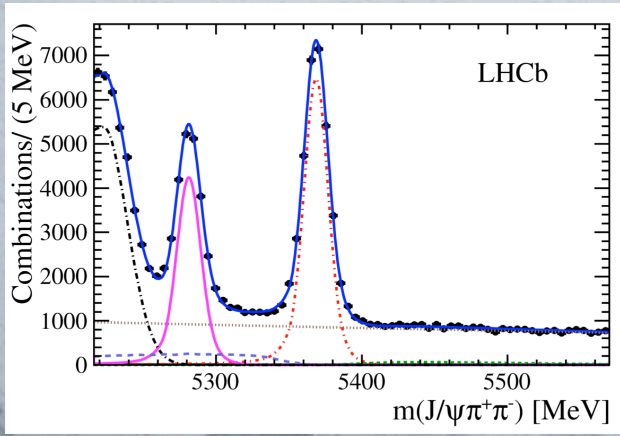
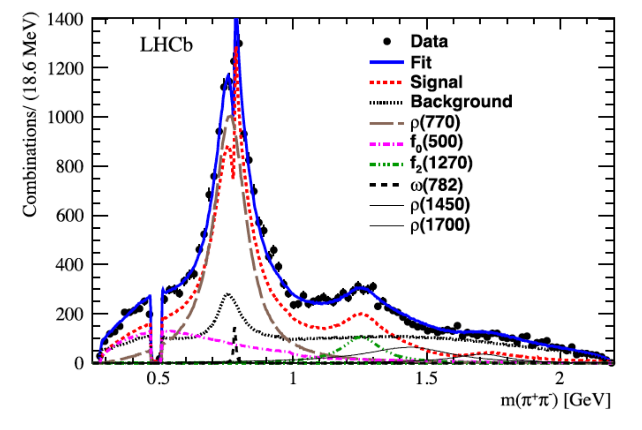
$B^0 \to J/\psi\ \pi^+\pi^-$

- **Penguin contributions are predicted to be enhanced in $B^0 \to J/\psi\ \pi^+\pi^-$ wrt to $B^0 \to J/\psi K_S$**



- **Six resonances considered in the $B^0 \to J/\pi^+\pi^-$ final state as in a previous amplitude analysis** Phys Rev. D 90 (2014) 012203





Largest rate(~66%) for $B^0 \to J/\psi\rho^0(770)$

- **Time-dependent measurement, in each resonant final state**
  - Assume equal CP parameters for the three transversity states of $B^0 \rightarrow J/\psi\rho^0(770)$ and a common CP parameter for all other resonances

$$\alpha_{CP}^i = \frac{1-|\lambda_i|}{1+|\lambda_i|}$$

$2\beta_i^{\rm eff}$ (°)		$\alpha_{CP}^i (\times 10^{-3})$	
ρ	$41.7 \pm 9.6^{+2.8}_{-6.3}$	ρ	$-32 \pm 28^{+9}_{-7}$
other − ρ	$3.6 \pm 3.6^{+0.9}_{-0.8}$	other	$-1 \pm 25^{+7}_{-14}$

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- **Difference wrt to $B^0 \rightarrow J/\psi K_S$**

$$\Delta 2\beta_f = 2\beta^{J/\psi\rho} - 2\beta^{J/\psi K_S^0} = (-0.9 \pm 9.7^{+2.8}_{-6.3})^\circ$$

- Approximated SU(3) symmetry relates penguin contribution in $B^0 \rightarrow J/\psi\rho^0$ and $B^0_s \rightarrow J/\psi\phi$ decays. Can limit the size of penguin contributions in $B^0_s \rightarrow J/\psi\phi$ to

$$\delta_P = (0.05 \pm 0.56)^\circ$$

Conclusion

- **Several mixing-induced CPV measurements in B^0 decays at LHCb with RUN I data**
- **Charmonium:**

  $B^0 \rightarrow J/\psi\, K_S$, $B^0 \rightarrow J/\psi\, \pi^+\pi^-$, $B^0 \rightarrow J/\psi\, K^+\pi^-$
- **Open charm:**

  $B^0 \rightarrow D^+ D^-$, $B^0 \rightarrow D^+ \pi^-$ (see A. Birnkraut's talk)

- **Exciting prospects with new RUN II data and improved analysis techniques.**
- **Higher trigger efficiency for hadronic modes will also come with LHCb Upgrade**

backup

Table 8
Comparison of S_f and C_f between different measurements.

Experiment	f	S_f	C_f
LHCb	$\overset{(-)}{B}{}^0 \to J/\psi\rho^0$	$-0.66^{+0.13+0.09}_{-0.12-0.03}$	$-0.063 \pm 0.056^{+0.019}_{-0.014}$
Belle [33]	$\overset{(-)}{B}{}^0 \to J/\psi\pi^0$	$-0.65 \pm 0.21 \pm 0.05$	$-0.08 \pm 0.16 \pm 0.05$
BaBar [34]	$\overset{(-)}{B}{}^0 \to J/\psi\pi^0$	$-1.23 \pm 0.21 \pm 0.04$	$-0.20 \pm 0.19 \pm 0.03$

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