

Misura dei parametri di violazione della
simmetria CP nei decadimenti

$$B_s^0 \rightarrow J/\psi K^+ K^- \text{ e } B_s^0 \rightarrow J/\psi \pi^+ \pi^-$$

a LHCb

Piera Muzzetto

a nome della collaborazione LHCb

Università degli studi di Cagliari e INFN

IFAE 2019 - Napoli



Materia?



Antimateria?



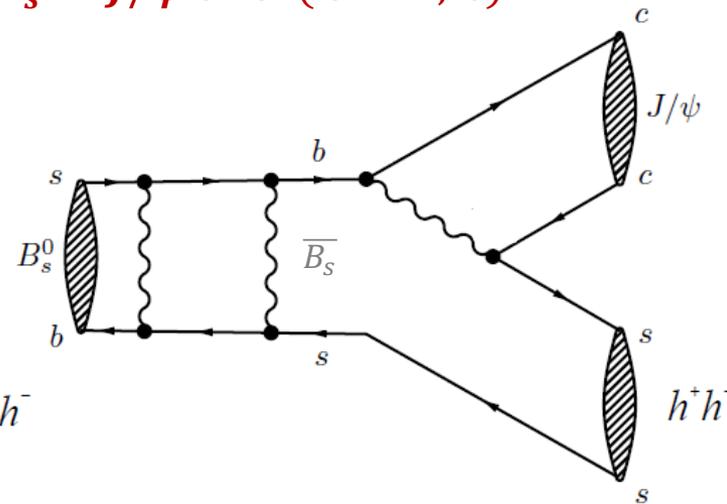
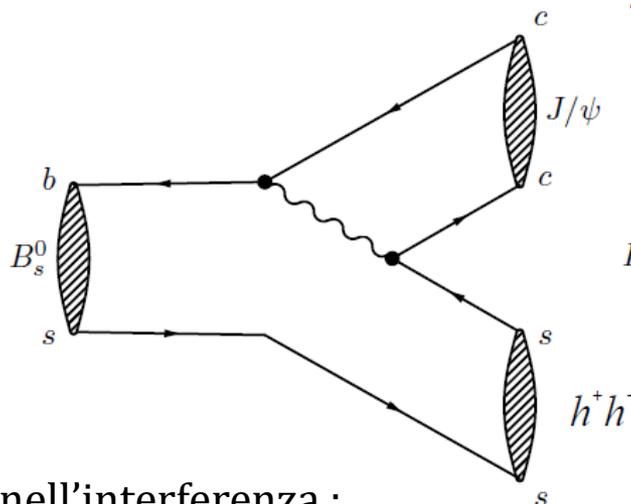
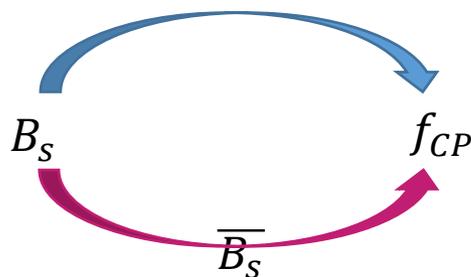
Evidente asimmetria ⇒ **Violazione di CP**

Violazione di CP nell'interferenza fra decadimento diretto e con mescolamento

⇒

Canali maggiormente studiati:

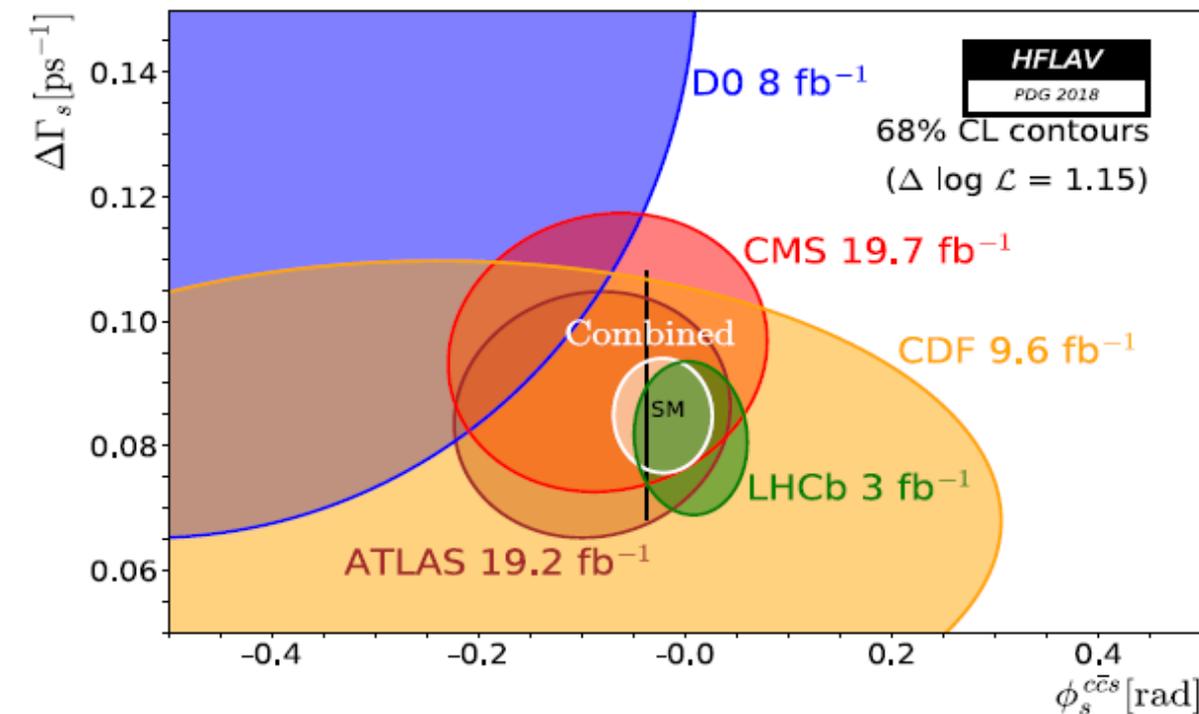
$$B_s^0 \rightarrow J/\psi h^+ h^- (h = K, \pi)$$



Fase di violazione di CP nell'interferenza :

$$\phi_s^{MS} = -2\beta_s = -2 \arg \left(-\frac{V_{cb} V_{cs}^*}{V_{tb} V_{ts}^*} \right)$$

Trascurando i contributi al decadimento di ordine superiore



Canali usati a LHCb

- $B_s^0 \rightarrow \psi(2s)\phi$
- $B_s^0 \rightarrow D_s D_s$
- $B_s^0 \rightarrow J/\psi K^- K^+$
- $B_s^0 \rightarrow J/\psi \pi^+ \pi^-$

Valore MS [CKM Fitter 2018]:

$$\phi_s^{MS} = -0.03686_{-0.00068}^{+0.00096} \text{ rad}$$

Stato dell'arte pre Moriond 2019 [HFLAV 2018]:

$$\phi_s = -0.021 \pm 0.031 \text{ rad}$$

$$\Delta\Gamma_s = 0.088 \pm 0.006 \text{ ps}^{-1}$$

Novità: aggiornamento analisi di ϕ_s in LHCb

dati utilizzati: **2015/2016** luminosità integrata di **1.9 fb⁻¹**

$$B_s \rightarrow J/\psi K^+ K^-$$

Canale d'oro per la misura di ϕ_s :

- maggior statistica \Rightarrow **molto sensibile ad effetti di nuova fisica;**
- stato finale **combinazione di autostati di CP:**

$$|B_L\rangle \propto p|B\rangle + q|\bar{B}\rangle \sim \text{CP pari}$$

$$|B_H\rangle \propto p|B\rangle - q|\bar{B}\rangle \sim \text{CP dispari}$$



molte variabili di interesse

$$\Delta\Gamma_s = \Gamma_L - \Gamma_H$$

$$\Gamma_s = (\Gamma_L + \Gamma_H)/2$$

- misura di $|\lambda| = \eta \frac{q}{p} \frac{\bar{A}_f}{A_f}$ (Violazione di CP diretta)

$$B_s \rightarrow J/\psi \pi^+ \pi^-$$

- Diversi contributi risonanti con stato finale **principalmente CP dispari**
- permette la misura, mediante un'analisi d'ampiezza, di Γ_H e $|\lambda|$

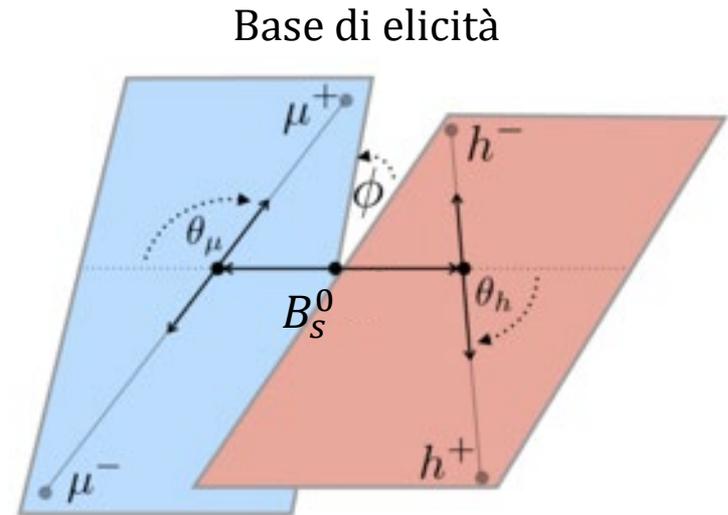
NB: diagrammi di ordine superiore trascurabili \Rightarrow confronto con valore MS molto preciso

Sperimentalmente **per determinare ϕ_s** occorre:

- separare gli stati di CP \Rightarrow analisi angolare
- un'analisi dipendente dal tempo
- conoscere il sapore del B_s

\Downarrow

Studio del tasso di decadimento differenziale dipendente dal tempo:



$$\frac{d\Gamma}{dt dm_{hh} d\Omega} \sim \sum_{k=1}^{10} f(\Omega, m_{hh}) \underset{\text{efficienza}}{\epsilon}(t, \Omega) (1 - 2\omega) \overset{B_s \text{ o } \bar{B}_s}{\uparrow} h_k(t|B_s) \oplus \underset{\text{risoluzione}}{G}(t, \sigma_t)$$

$$h_k(t) = \frac{3}{4\pi} e^{-\Gamma_s t} \left\{ \mathbf{a}_k \cosh \frac{\Delta\Gamma t}{2} + \mathbf{b}_k \sinh \frac{\Delta\Gamma t}{2} + \mathbf{c}_k \cos(\Delta m t) + \mathbf{d}_k \sin(\Delta m t) \right\}$$

ϕ_s e λ all'interno dei coefficienti

Selezione dei candidati

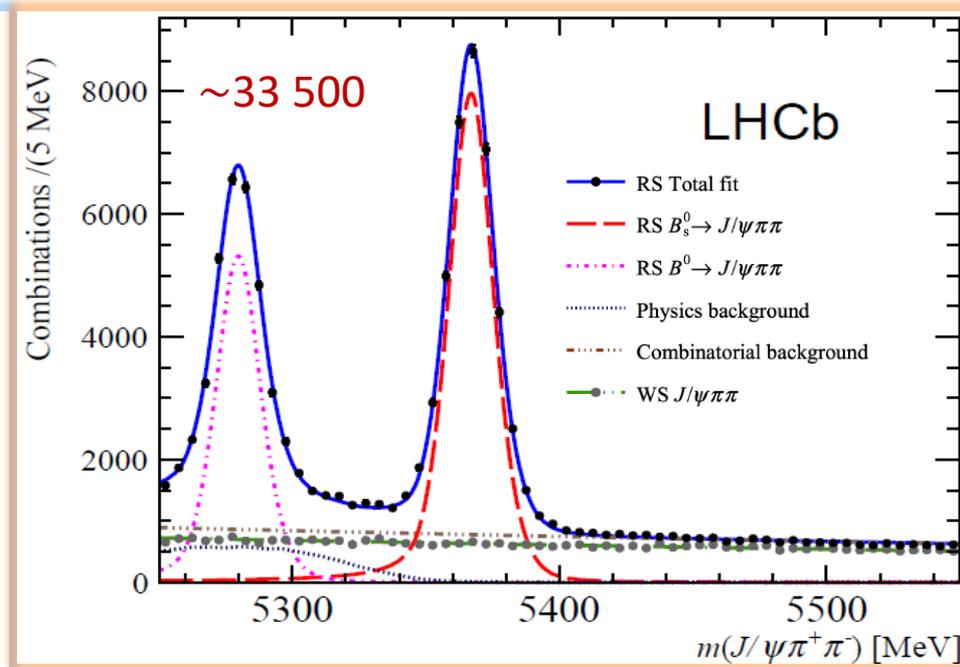
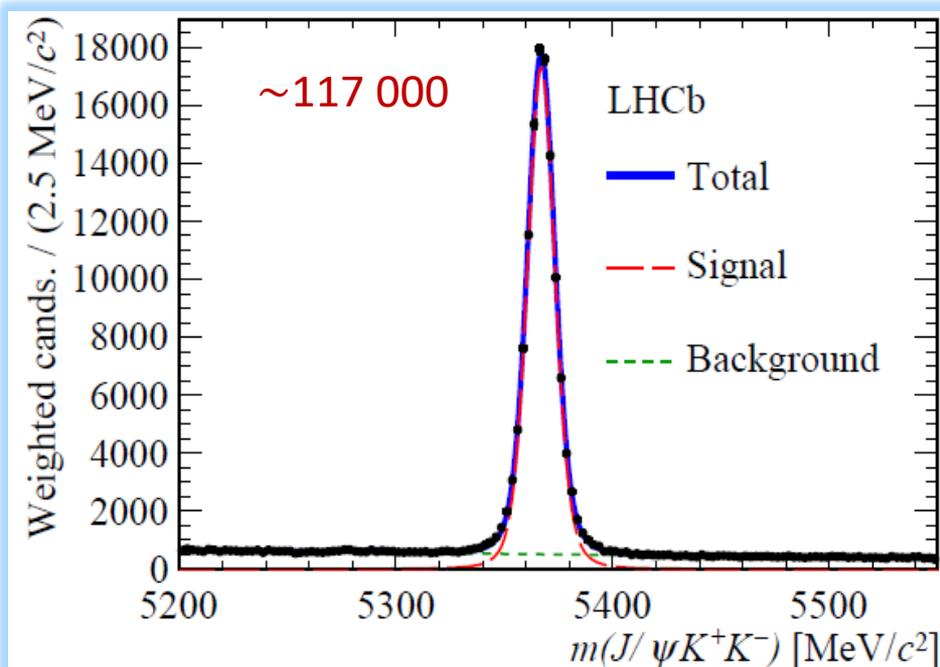
$$B_s \rightarrow J/\psi K^+ K^-$$

[LHCb-PAPER-2019-013]

$$B_s \rightarrow J/\psi \pi^+ \pi^-$$

[arXiv:1903.05530]

Selezione dei candidati: **analisi multivariata** per la reiezione del fondo combinatorio



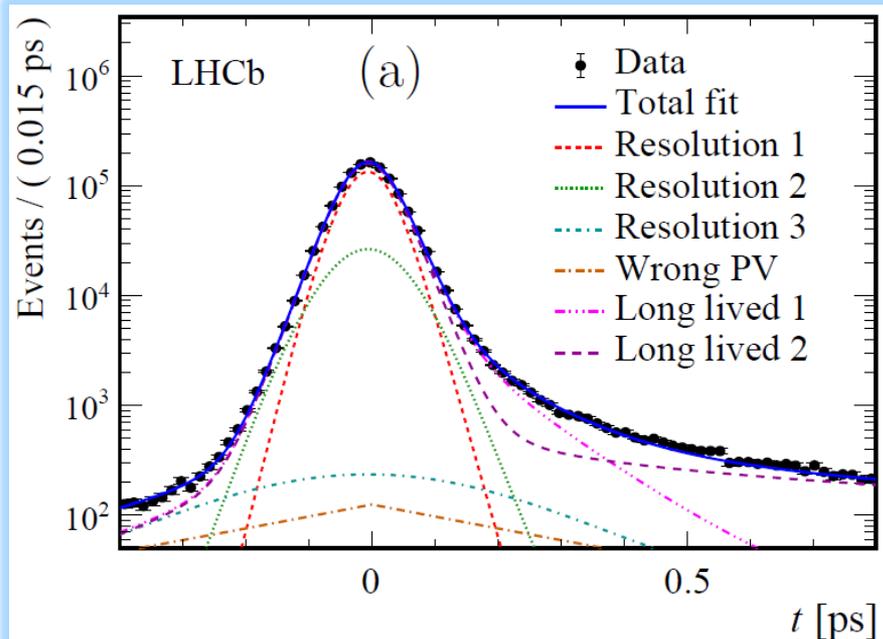
Risoluzione temporale

$$B_s \rightarrow J/\psi K^+ K^-$$

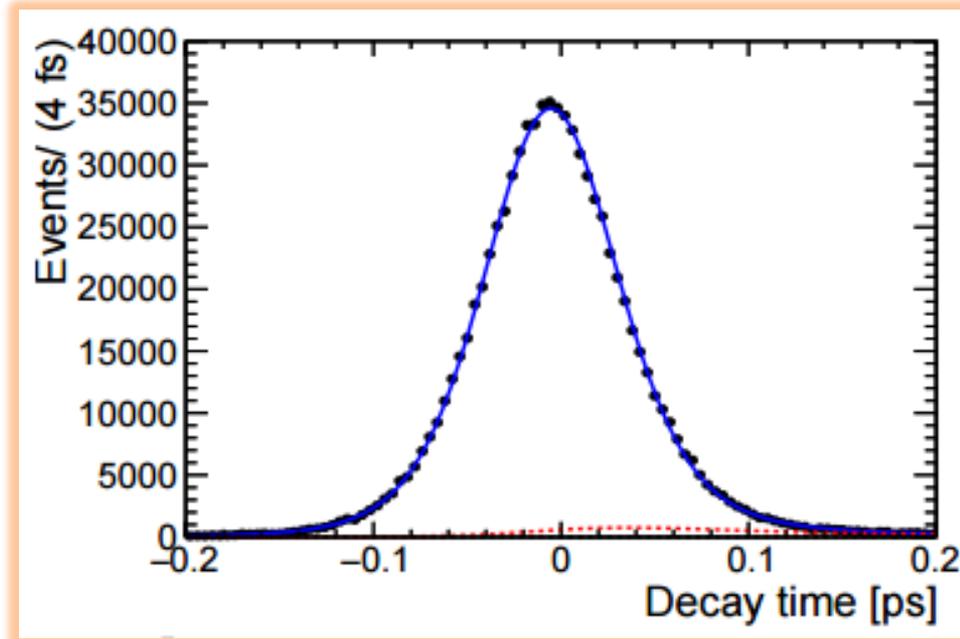
$$B_s \rightarrow J/\psi \pi^+ \pi^-$$

- Studio effettuato su un campione di $J/\psi h^- h^+$ proveniente dal VP
- Uso dell'errore sul tempo ricostruito δ_t evento per evento

Modello di risoluzione: somma di tre gaussiane.



$$\sigma_{eff} \sim 45.5 \text{ fs}$$



$$\sigma_{eff} = 41.5 \text{ fs}$$

Efficienza temporale

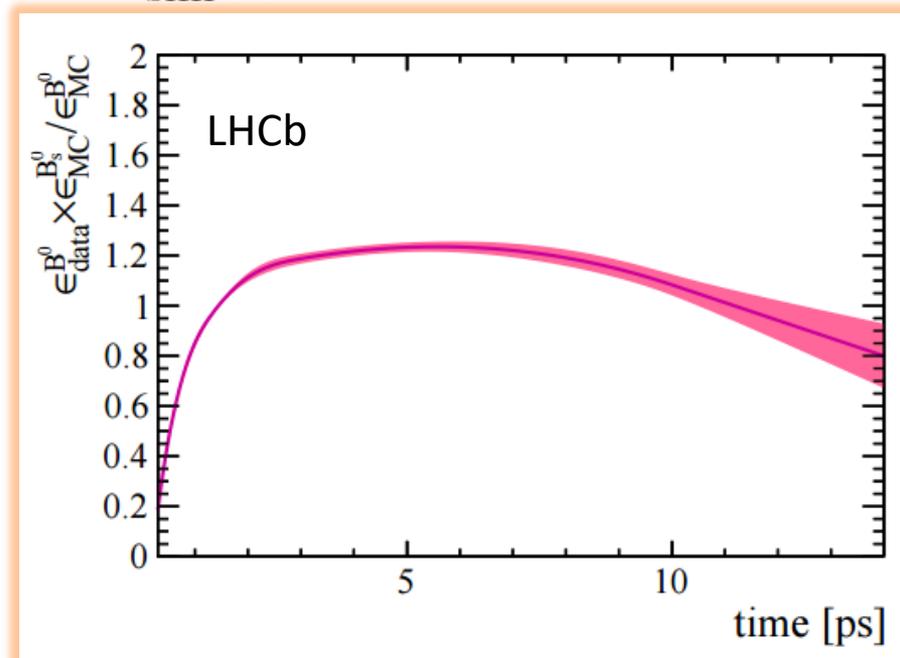
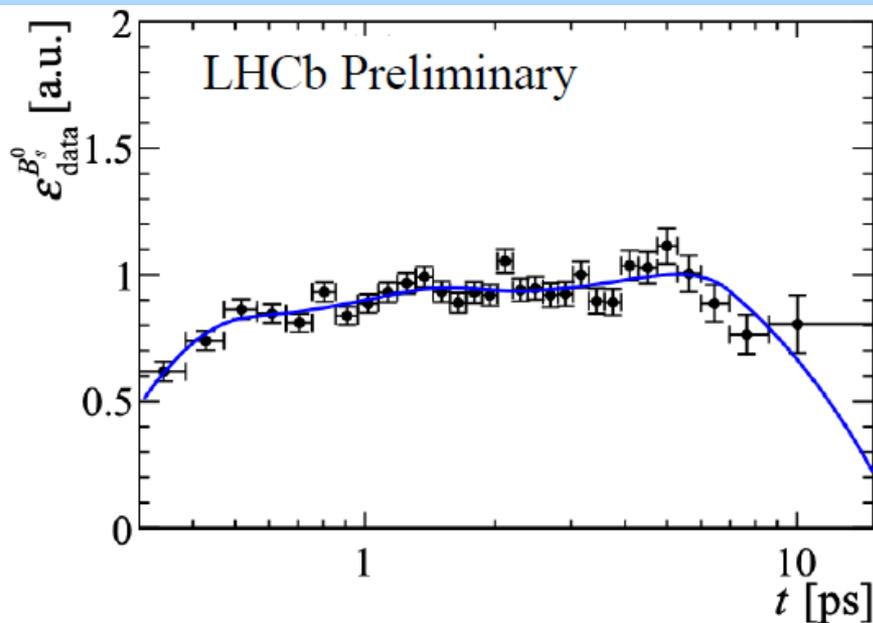
$$B_s \rightarrow J/\psi K^+ K^-$$

$$B_s \rightarrow J/\psi \pi^+ \pi^-$$

Canale di controllo: $B^0 \rightarrow J/\psi K^*(K^+ \pi^-)$ $\tau_{B^0} = 1.520 \pm 0.004$ ps [HFLAV PDG 2018].

Studio simultaneo degli andamenti in MC B_s e in MC e dati del B^0 :

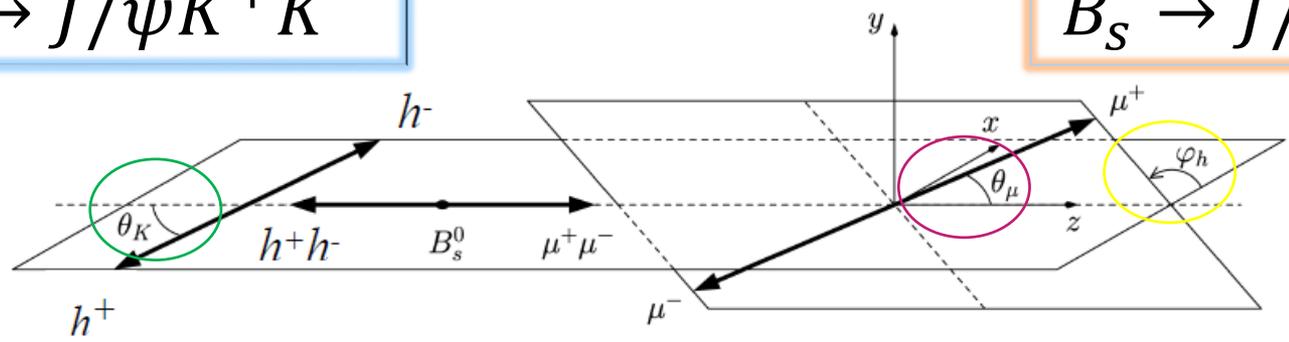
$$\epsilon_{\text{data}}^{B_s^0}(t) = \epsilon_{\text{data}}^{B^0}(t) \times \frac{\epsilon_{\text{sim}}^{B_s^0}(t)}{\epsilon_{\text{sim}}^{B^0}(t)}$$



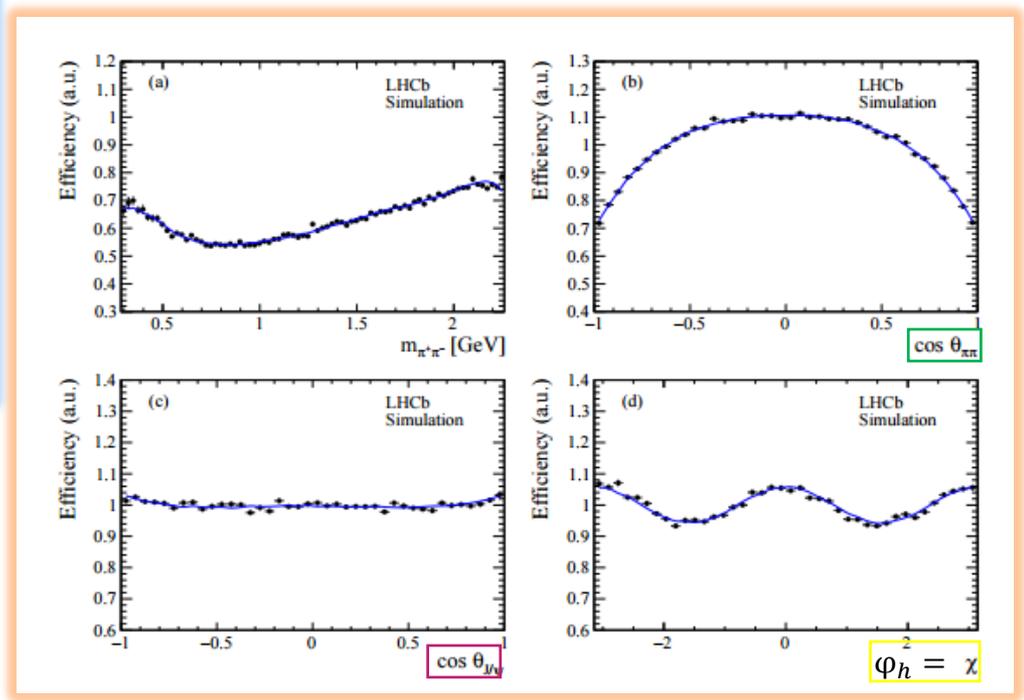
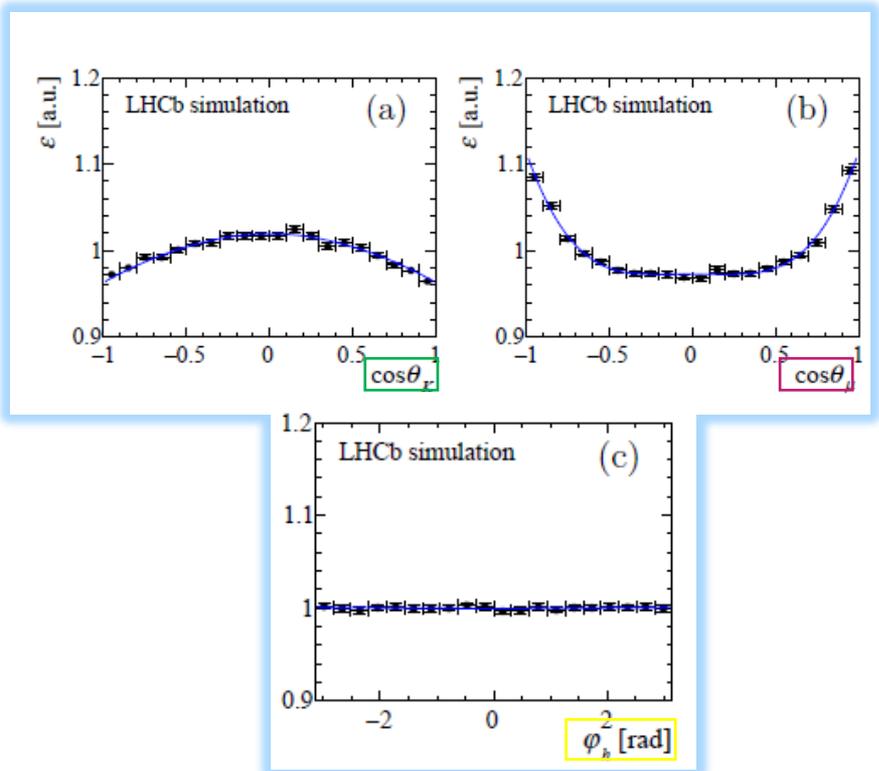
Efficienza angolare

$$B_s \rightarrow J/\psi K^+ K^-$$

$$B_s \rightarrow J/\psi \pi^+ \pi^-$$



Causata dall'accettanza geometrica del rivelatore e dalla selezione cinematica.



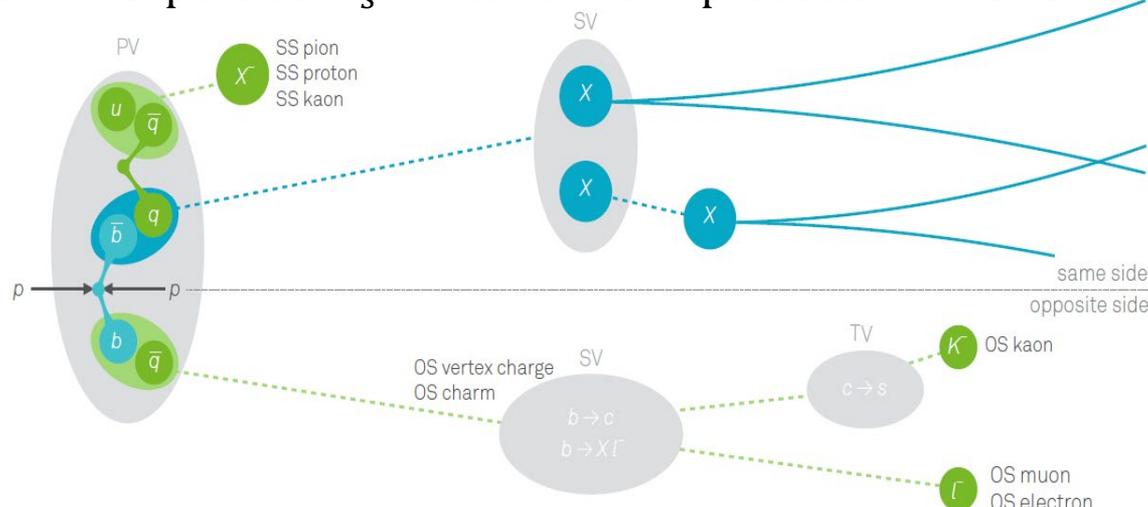
Identificazione del sapore del B

$$B_s \rightarrow J/\psi K^+ K^-$$

$$B_s \rightarrow J/\psi \pi^+ \pi^-$$

Due algoritmi di identificazione del sapore

SS: correlazione fra il sapore del B_s e la carica del K prodotto nella stessa frammentazione



OS: anti-correlazione fra il sapore del B_s e la carica degli stati finali dell'altro adrone b

Procedura:

- Calibrazione della probabilità di scorretta identificazione η : $\omega = p_0 + p_1(\eta - \langle \eta \rangle)$
- Definizione potere di identificazione: $\epsilon_{id} D^2$ con $D = (1 - 2\omega)$ e $\epsilon_{id} = N_B \text{ identificati} / N_B \text{ tot}$

Run1 ~ 3.73 %

Run1 ~ 3.89 %

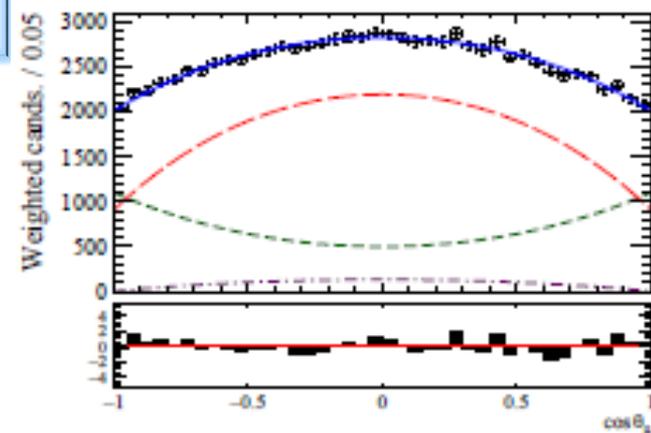
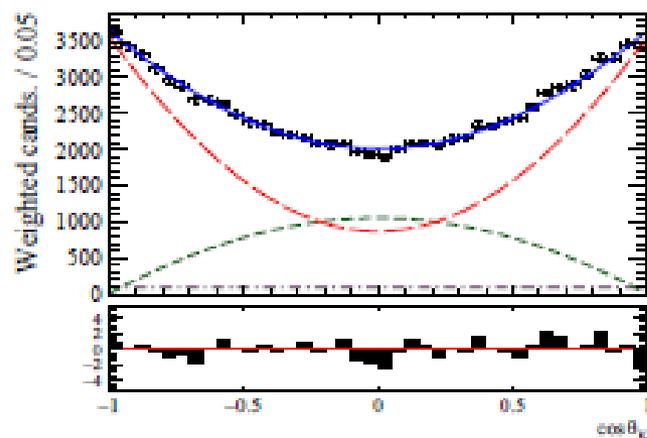
$$\text{Run2 } \epsilon_{id} D^2 = 4.73 \pm 0.34 \%$$

$$\text{Run2 } \epsilon_{id} D^2 = 5.06 \pm 0.38 \%$$

Risultati

$$B_S \rightarrow J/\psi K^+ K^-$$

CP-pari
 CP-dispari
 Componente S

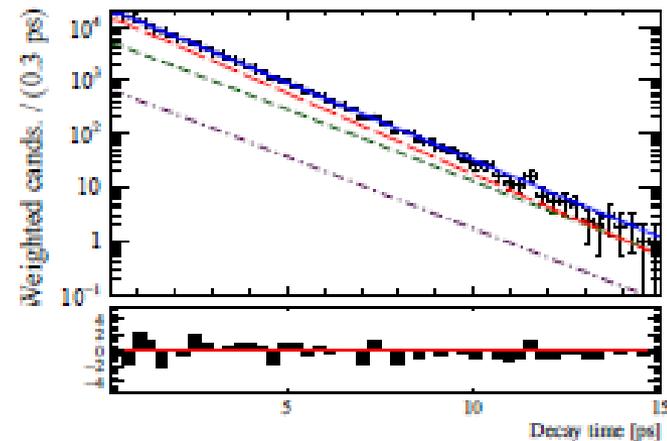
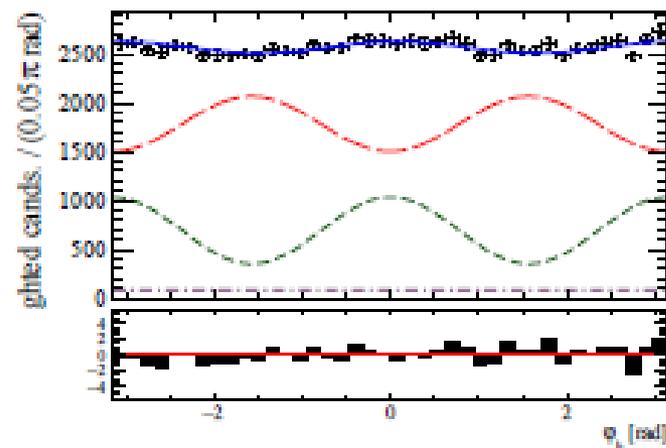


$$\phi_S = -0.080 \pm 0.041 \pm 0.006 \text{ rad}$$

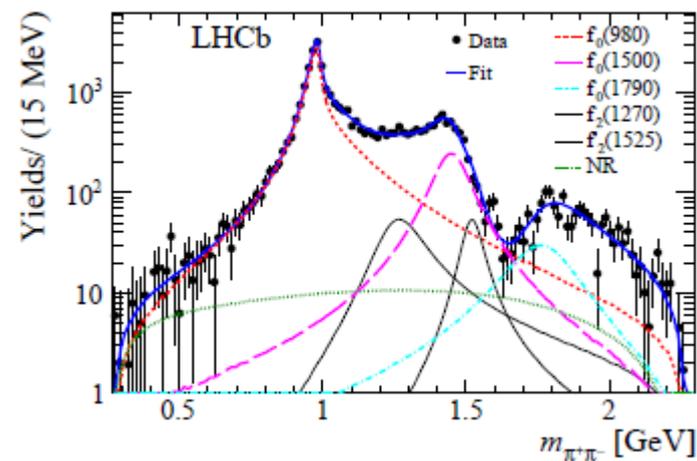
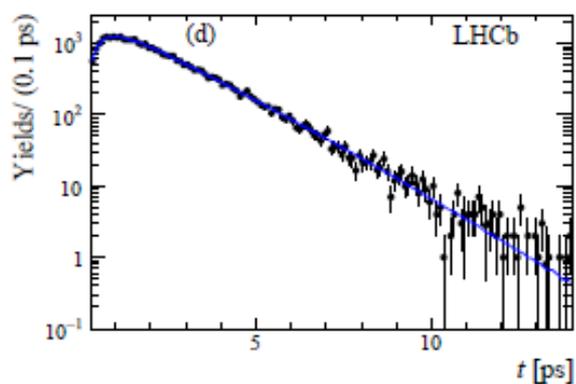
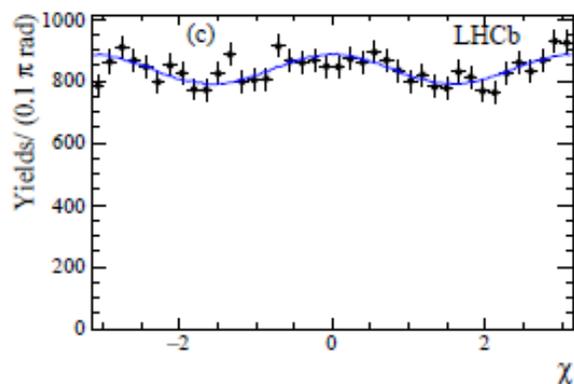
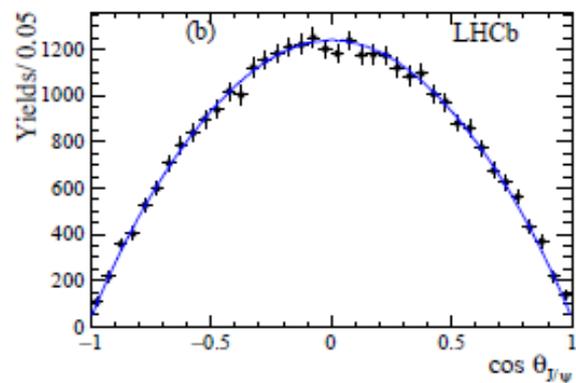
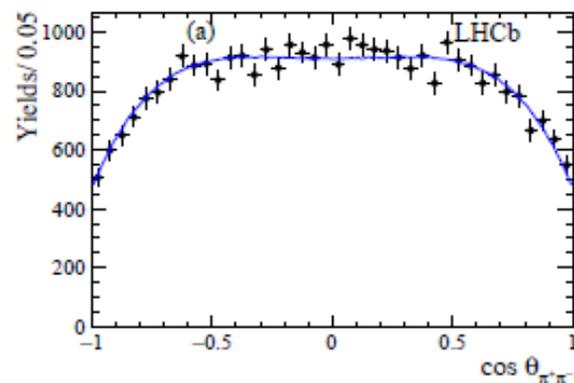
$$|\lambda| = 1.006 \pm 0.016 \pm 0.006$$

$$\Gamma_S - \Gamma_d = -0.0041 \pm 0.0024 \pm 0.0015 \text{ ps}^{-1}$$

$$\Delta\Gamma_S = 0.0772 \pm 0.0077 \pm 0.0026 \text{ ps}^{-1}$$



$$B_S \rightarrow J/\psi \pi^+ \pi^-$$

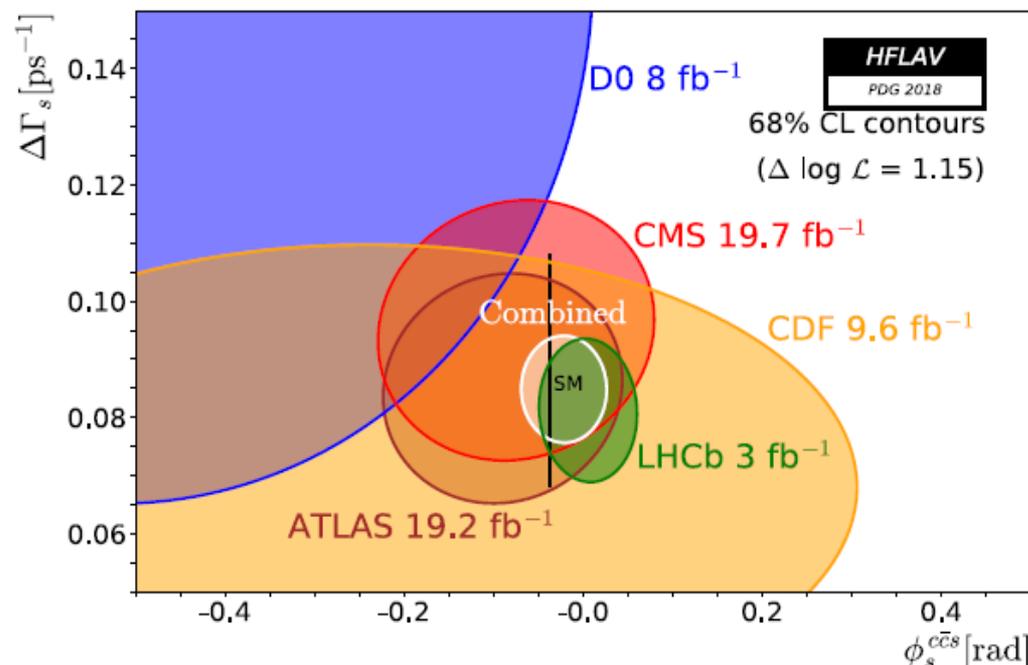


$$\phi_S = -0.057 \pm 0.060 \pm 0.011 \text{ rad}$$

$$|\lambda| = 1.01_{-0.06}^{+0.08} \pm 0.03$$

$$\Gamma_H - \Gamma_d = -0.050 \pm 0.004 \pm 0.004 \text{ ps}^{-1}$$

Risultati con tutti i canali studiati a LHCb



Stato dell'arte pre Moriond 2019 [PDG 2018]:

$$\phi_s = -0.021 \pm 0.031 \text{ rad}$$

$$\Delta\Gamma_s = 0.088 \pm 0.006 \text{ ps}^{-1}$$

$$\phi_s = -0.040 \pm 0.025 \text{ rad}$$

$$|\lambda| = 0.991 \pm 0.010$$

$$\Gamma_s = 0.6563 \pm 0.0021 \text{ ps}^{-1}$$

$$\Delta\Gamma_s = 0.0812 \pm 0.0048 \text{ ps}^{-1}$$

ϕ_s è in accordo:

- entro 0.1σ con il MS

$$\phi_s^{MS} = -0.03686_{-0.00068}^{+0.00096} \text{ rad}$$

- entro 1.6σ con $\phi_s = 0$

$|\lambda|$ è in accordo:

- entro 0.9σ con $|\lambda| = 1$

Γ_s/Γ_d è in accordo:

- entro 1.4σ con HQE
- $$\frac{\Gamma_s}{\Gamma_d} = 1.0006 \pm 0.0025$$

Risultati con tutti i canali studiati a LHCb

$$\begin{aligned}\phi_s &= -0.040 \pm 0.025 \text{ rad} \\ |\lambda| &= 0.991 \pm 0.010 \\ \Gamma_s &= 0.6563 \pm 0.0021 \text{ ps}^{-1} \\ \Delta\Gamma_s &= 0.0812 \pm 0.0048 \text{ ps}^{-1}\end{aligned}$$

ϕ_s è in accordo:

- entro 0.1σ con il *MS*

$$\phi_s^{MS} = -0.03686^{+0.00096}_{-0.00068} \text{ rad}$$

- entro 1.6σ con $\phi_s = 0$

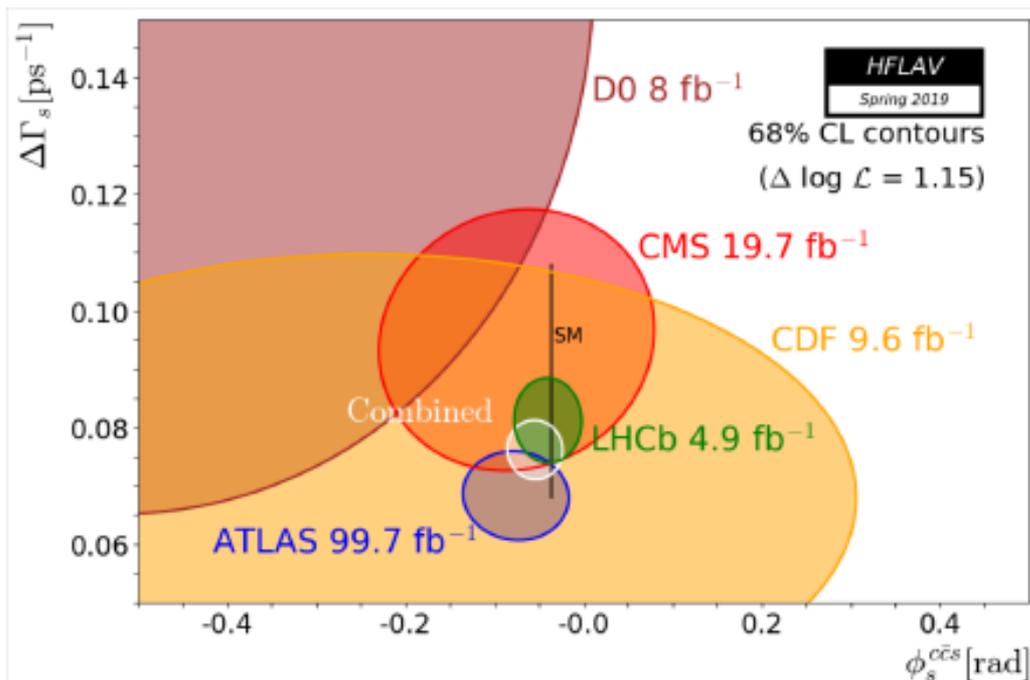
$|\lambda|$ è in accordo:

- entro 0.9σ con $|\lambda| = 1$

Γ_s/Γ_d è in accordo:

- entro 1.4σ con *HQE*

$$\frac{\Gamma_s}{\Gamma_d} = 1.0006 \pm 0.0025$$



Stato dell'arte attuale [HFLAV 2019]:

$$\begin{aligned}\phi_s &= -0.054 \pm 0.021 \text{ rad} \\ \Delta\Gamma_s &= 0.076 \pm 0.003 \text{ ps}^{-1}\end{aligned}$$

Diapositive di supporto

Sistematiche $B_S \rightarrow J/\psi KK$

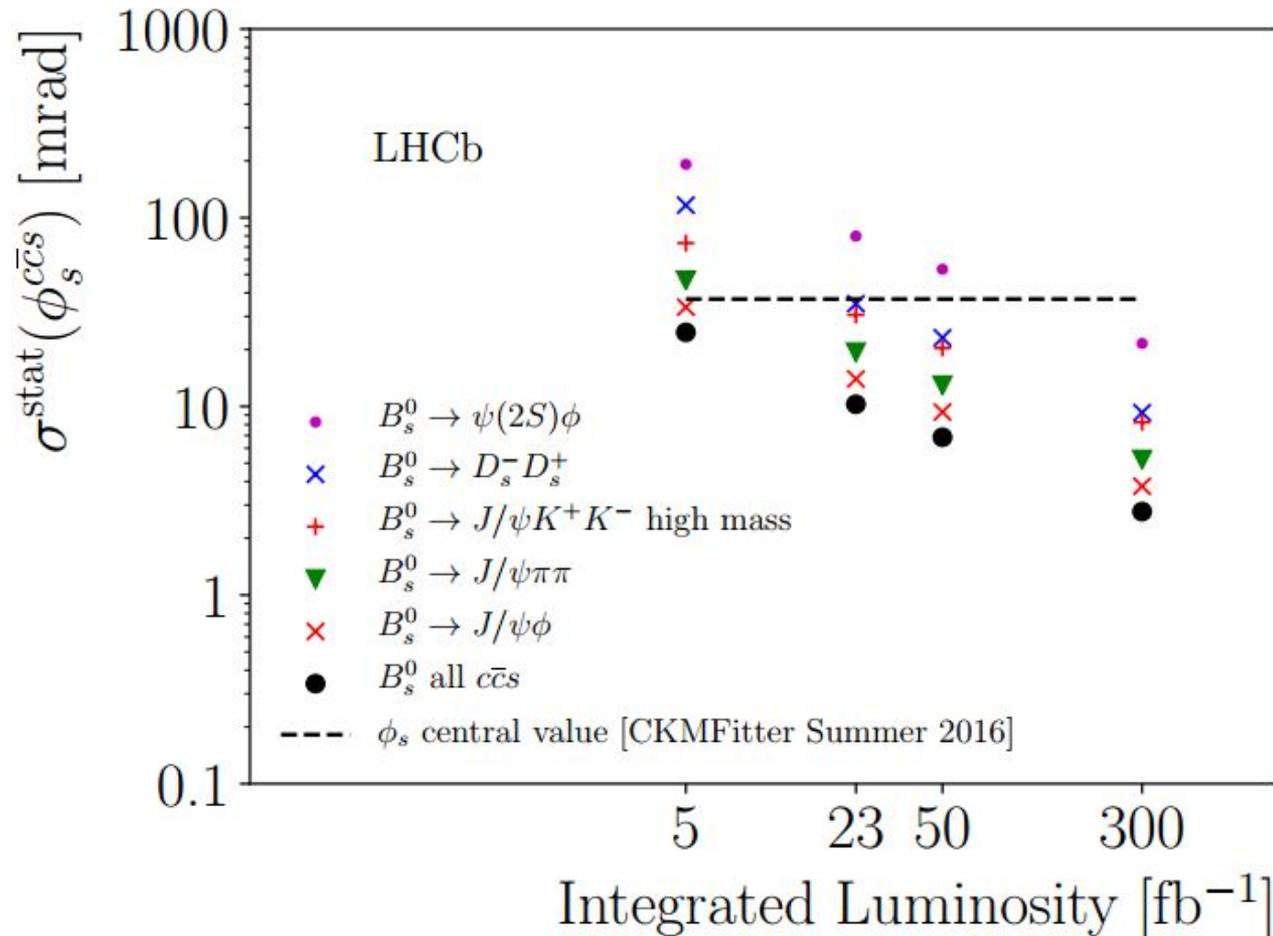
Source	$ A_0 ^2$	$ A_{\perp} ^2$	ϕ_s [rad]	$ \lambda $	$\delta_{\perp} - \delta_0$ [rad]	$\delta_{\parallel} - \delta_0$ [rad]	$\Gamma_s - \Gamma_d$ [ps $^{-1}$]	$\Delta\Gamma_s$ [ps $^{-1}$]	Δm_s [ps $^{-1}$]
Mass width parametrisation	0.0006	0.0005	-	-	0.05	0.009	-	0.0002	0.001
Mass factorisation	0.0002	0.0004	0.004	0.0037	0.01	0.004	0.0007	0.0022	0.016
Multiple candidates	0.0006	0.0001	0.0011	0.0011	0.01	0.002	0.0003	0.0001	0.001
Fit bias	0.0001	0.0006	0.001	-	0.02	0.033	-	0.0003	0.001
C_{SP} factors	-	0.0001	0.001	0.0010	0.01	0.005	-	0.0001	0.002
Quadratic OS tagging	-	-	-	-	-	-	-	-	-
Time res.: statistical	-	-	-	-	-	-	-	-	-
Time res.: prompt	-	-	-	-	-	0.001	-	-	0.001
Time res.: mean offset	-	-	0.0032	0.0010	0.08	0.001	0.0002	0.0003	0.005
Time res.: Wrong PV	-	-	-	-	-	0.001	-	-	0.001
Ang. acc.: statistical	0.0003	0.0004	0.0011	0.0018	-	0.004	-	-	0.001
Ang. acc.: correction	0.0020	0.0011	0.0022	0.0043	0.01	0.008	0.0001	0.0002	0.001
Ang. acc.: low-quality tracks	0.0002	0.0001	0.0005	0.0014	-	0.002	0.0002	0.0001	-
Ang. acc.: t & σ_t dependence	0.0008	0.0012	0.0012	0.0007	0.03	0.006	0.0002	0.0010	0.003
Dec.-time eff.: statistical	0.0002	0.0003	-	-	-	-	0.0012	0.0008	-
Dec.-time eff.: $\Delta\Gamma_s = 0$ sim.	0.0001	0.0002	-	-	-	-	0.0003	0.0005	-
Dec.-time eff.: knot pos.	-	-	-	-	-	-	-	-	-
Dec.-time eff.: p.d.f. weighting	-	-	-	-	-	-	0.0001	0.0001	-
Dec.-time eff.: kin. weighting	-	-	-	-	-	-	0.0002	-	-
Length scale	-	-	-	-	-	-	-	-	0.004
Quadratic sum of syst.	0.0024	0.0019	0.0061	0.0064	0.10	0.037	0.0015	0.0026	0.018

Sistematiche $B_s \rightarrow J/\psi\pi\pi$

Source	$\Gamma_H - \Gamma_{B^0}$ [fs ⁻¹]	$ \lambda $ [$\times 10^{-3}$]	ϕ_s [mrad]
t acceptance	2.0	0.0	0.3
τ_{B^0}	0.2	0.5	0.0
Efficiency ($m_{\pi\pi}, \Omega$)	0.2	0.1	0.0
t resolution width	0.0	4.3	4.0
t resolution mean	0.3	1.2	0.3
Background	3.0	2.7	0.6
Flavour tagging	0.0	2.2	2.3
Δm_s	0.3	4.6	2.5
Γ_L	0.3	0.4	0.4
B_c^+	0.5	-	-
Resonance parameters	0.6	1.9	0.8
Resonance modelling	0.5	28.9	9.0
Production asymmetry	0.3	0.6	3.4
Total	3.8	29.9	11.0

Prospetti per il futuro: $\phi_s^{c\bar{c}s}$

[LHCb PUB 2018-009]



$$\phi_s^{MS} = -0.03686_{-0.00068}^{+0.00096} \text{ rad} \quad \text{A } 300 \text{ fb}^{-1} \quad \sigma_{\phi_s} \sim 4 \text{ mrad in } B_s \rightarrow J/\psi \phi(KK)$$

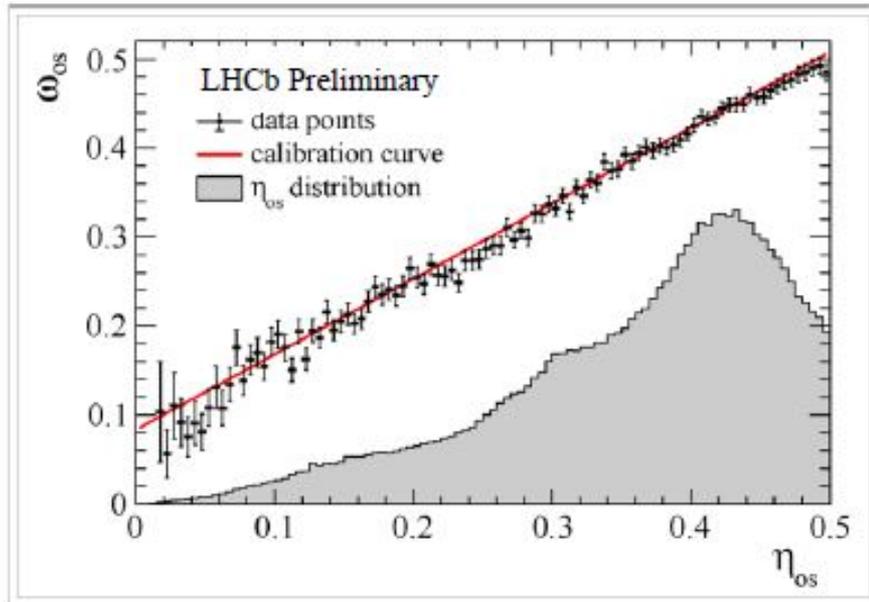
Modelli ampiezza $m(\pi\pi)$

Component	Fit fractions (%)	Transversity fractions (%)		
		0		⊥
Solution I				
$f_0(980)$	60.09 ± 1.48	100	—	—
$f_0(1500)$	8.88 ± 0.87	100	—	—
$f_0(1790)$	1.72 ± 0.29	100	—	—
$f_2(1270)$	3.24 ± 0.48	13 ± 3	37 ± 9	50 ± 10
$f'_2(1525)$	1.23 ± 0.86	40 ± 13	31 ± 14	29 ± 25
NR	2.64 ± 0.73	100	—	—
Solution II				
$f_0(980)$	93.05 ± 1.12	100	—	—
$f_0(1500)$	6.47 ± 0.41	100	—	—
$f_0(1710)$	0.74 ± 0.11	100	—	—
$f_2(1270)$	3.22 ± 0.44	17 ± 4	30 ± 8	53 ± 10
$f'_2(1525)$	1.44 ± 0.36	35 ± 8	31 ± 12	34 ± 17
NR	8.13 ± 0.79	100	—	—

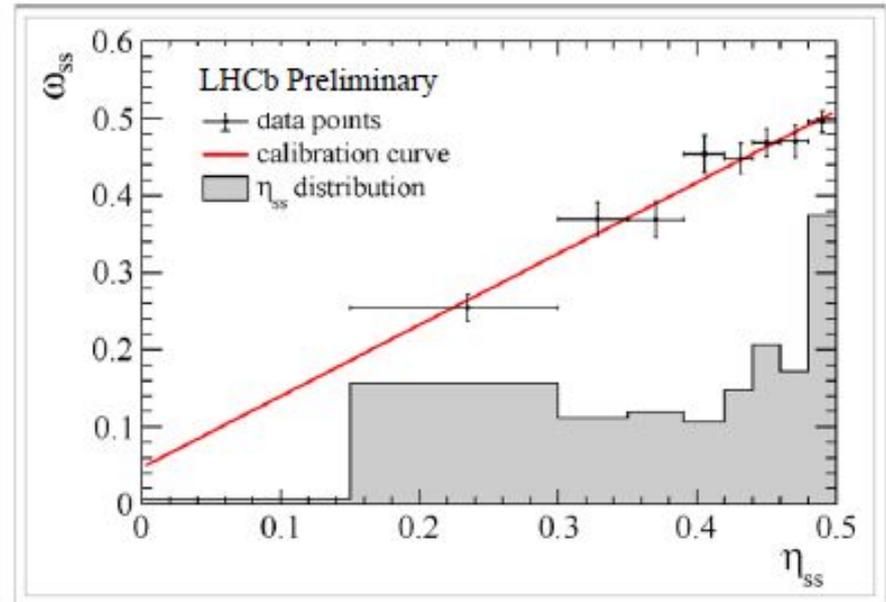
Calibrazione degli algoritmi di identificazione del sapore dei B

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

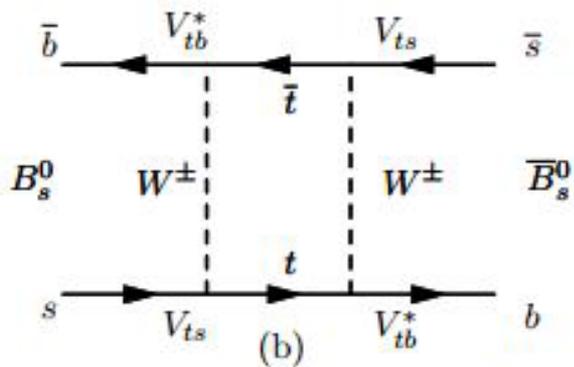
OS calibrato con $B^+ \rightarrow J/\psi K^+$



SS calibrato con $B_S^0 \rightarrow D_S^- \pi^+$



Mescolamento mesoni B



$$i \frac{d}{dt} \begin{pmatrix} |B(t)\rangle \\ |\bar{B}(t)\rangle \end{pmatrix} = \mathcal{H} \begin{pmatrix} |B(t)\rangle \\ |\bar{B}(t)\rangle \end{pmatrix}, \text{ dove}$$

$$\mathcal{H} = \left(M - \frac{i}{2} \Gamma \right) = \left(\begin{pmatrix} M_{11} & M_{12} \\ M_{12}^* & M_{22} \end{pmatrix} - \frac{i}{2} \begin{pmatrix} \Gamma_{11} & \Gamma_{12} \\ \Gamma_{12}^* & \Gamma_{22} \end{pmatrix} \right)$$

Fenomeno mescolamento:

$$|B_L\rangle \propto p |B\rangle + q |\bar{B}\rangle$$

$$|B_H\rangle \propto p |B\rangle - q |\bar{B}\rangle$$

$$|B_{H/L}(t)\rangle = e^{-iM_{H/L}t} e^{-\Gamma_{H/L}t/2} |B_{H/L}\rangle$$

$$|B(t)\rangle = g_+(t) |B\rangle + \frac{q}{p} g_-(t) |\bar{B}\rangle$$

$$|\bar{B}(t)\rangle = \frac{p}{q} g_-(t) |B\rangle + g_+(t) |\bar{B}\rangle$$

$$\Gamma_q = \frac{\Gamma_L + \Gamma_H}{2} \equiv \frac{1}{\tau},$$

$$g_+(t) = e^{-im_q t} e^{-\Gamma_q t/2} \left[\cosh \frac{\Delta\Gamma_q t}{4} \cos \frac{\Delta m_q t}{2} - i \sinh \frac{\Delta\Gamma_q t}{4} \sin \frac{\Delta m_q t}{2} \right]$$

$$g_-(t) = e^{-im_q t} e^{-\Gamma_q t/2} \left[-\sinh \frac{\Delta\Gamma_q t}{4} \cos \frac{\Delta m_q t}{2} + i \cosh \frac{\Delta\Gamma_q t}{4} \sin \frac{\Delta m_q t}{2} \right]$$