

Bundesministerium  
für Bildung  
und Forschung

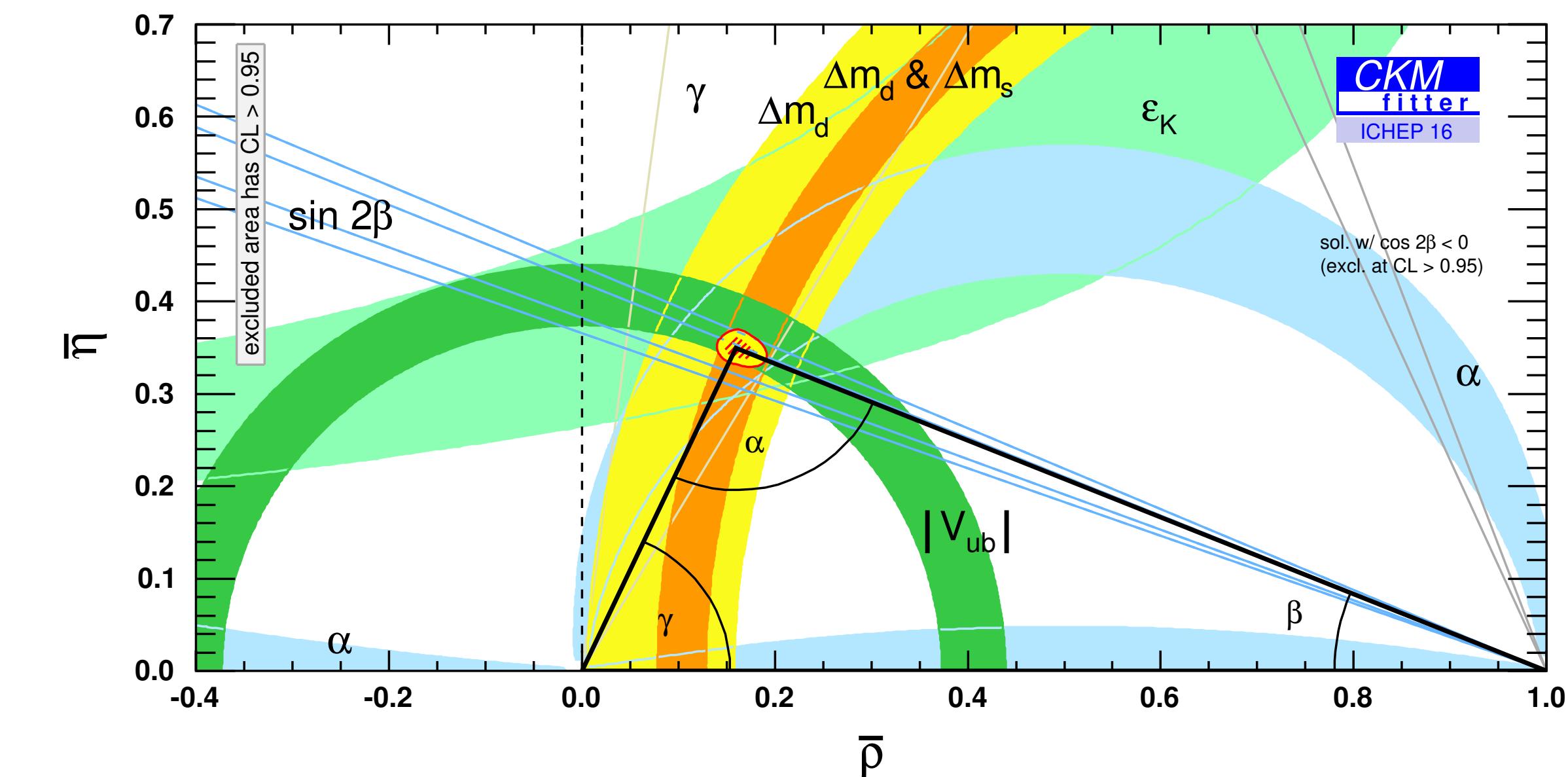
# Time-dependent $CP$ violation measurements in $B \rightarrow DX$ decays at LHCb

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on behalf of the LHCb collaboration

# Motivation

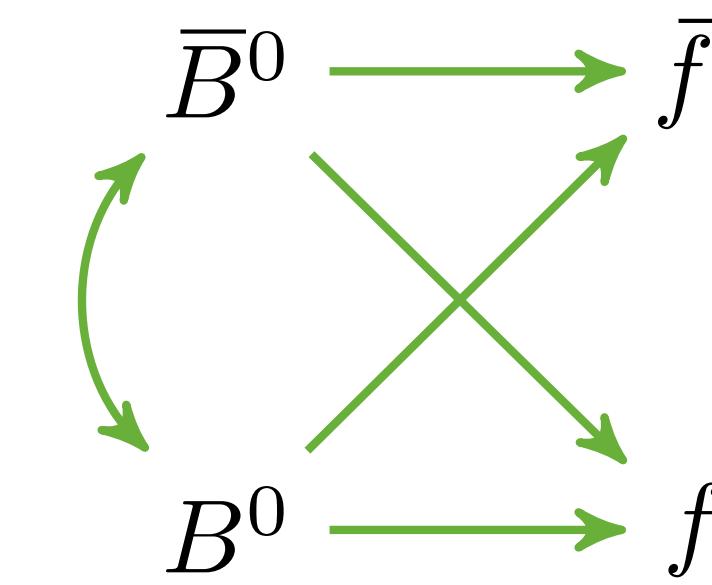
- ▶ measurement of  $CP$  violation as precision test of the SM
- ▶ transition amplitudes of weak interactions described by CKM matrix
  - 4 parameters (3 real parameters + complex phase)
  - unitary  
→ triangle in the complex plane
- ▶ discrepancy in position of the apex  
→ physics beyond SM
- ▶ weak phase  $\gamma$  is the least well measured angle
- ▶ can be tested in tree-level decays:  $\gamma = (72.1^{+5.4}_{-5.8})^\circ$  CKMfitter
  - interference of  $b \rightarrow c$  and  $b \rightarrow u$  transitions
  - time-dependent measurements in  $B^0 \rightarrow D^\mp \pi^\pm$  and  $B_s^0 \rightarrow D_s^\mp K^\pm$

$$V_{\text{CKM}} \propto \begin{pmatrix} |V_{ud}| & |V_{us}| & |V_{ub}| e^{-i\gamma} \\ -|V_{cd}| & |V_{cs}| & |V_{cb}| \\ |V_{td}| e^{-i\beta} & -|V_{ts}| e^{-i\beta_s} & |V_{tb}| \end{pmatrix}$$



# Interference $CP$ violation

- ▶ 4 possible transitions:
    - $\mathcal{A}_f : B^0 \rightarrow f$
    - $\bar{\mathcal{A}}_f : \bar{B}^0 \rightarrow f$
    - $\mathcal{A}_{\bar{f}} : B^0 \rightarrow \bar{f}$
    - $\bar{\mathcal{A}}_{\bar{f}} : \bar{B}^0 \rightarrow \bar{f}$
  - ▶ time-dependent final state

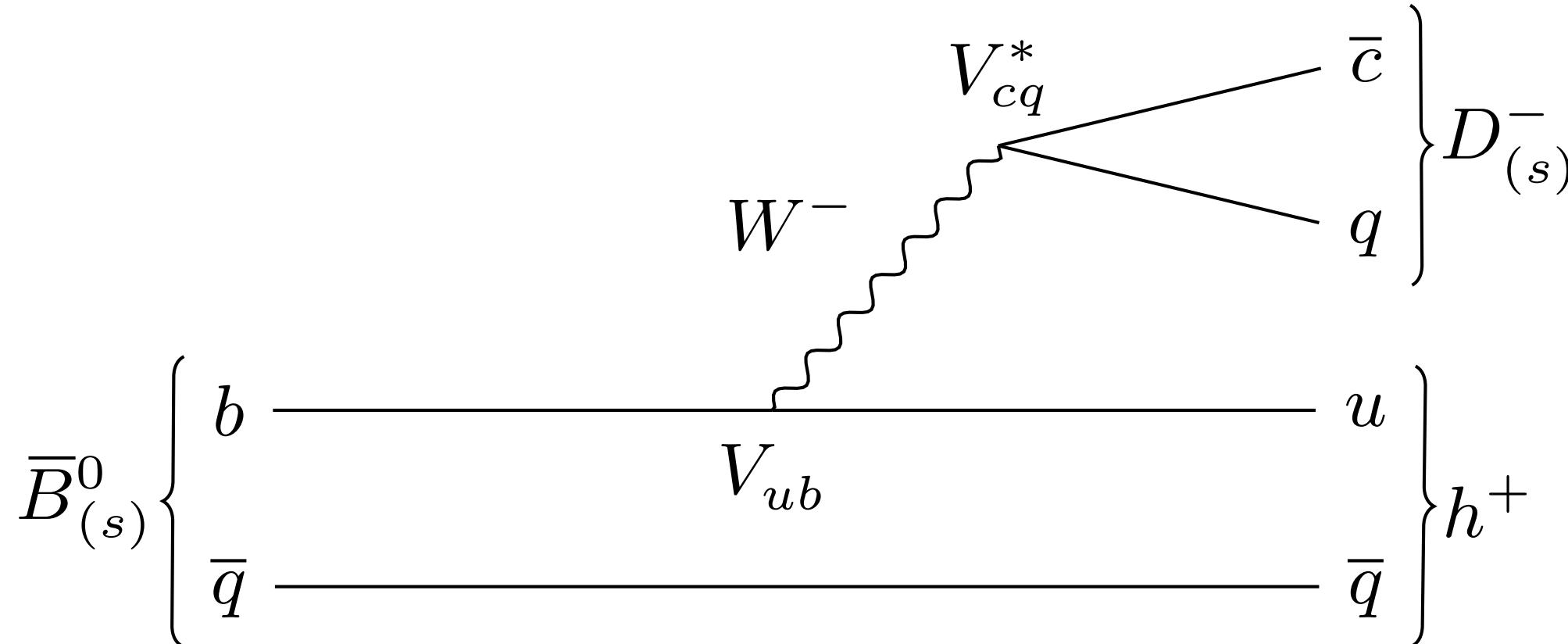
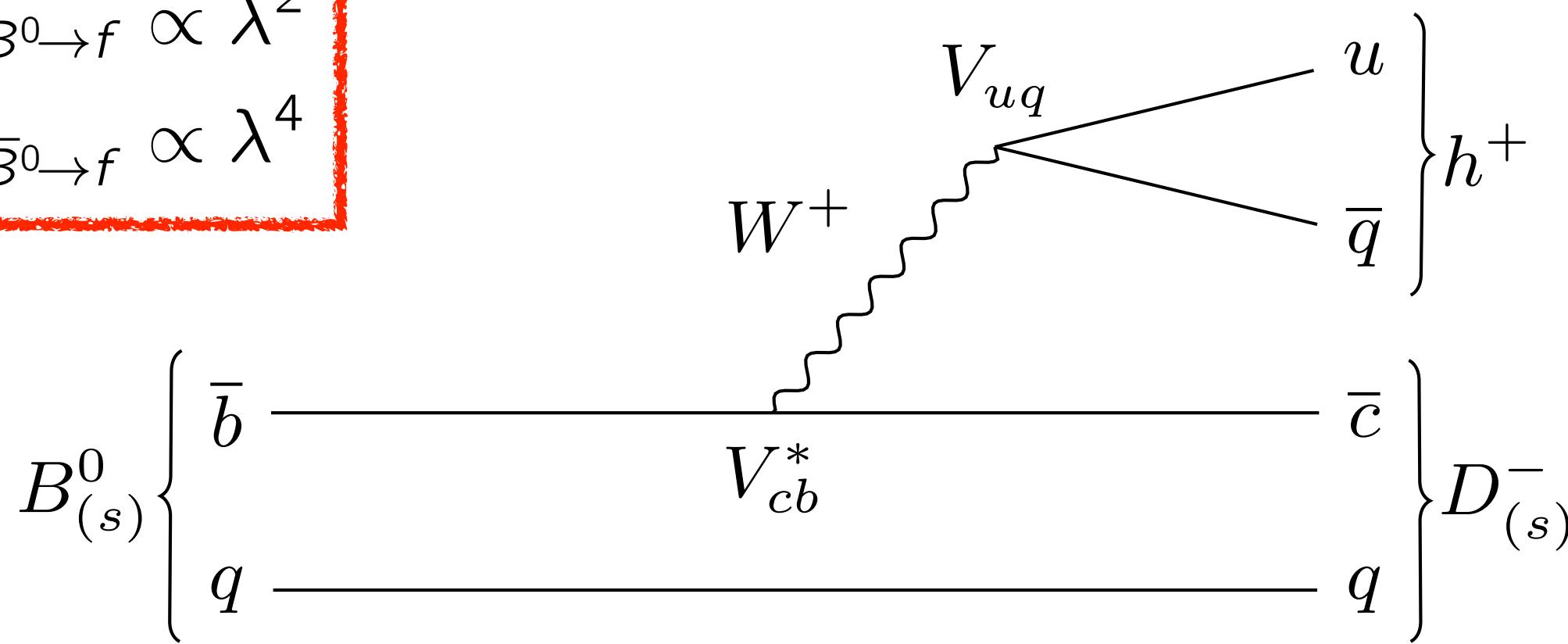


$$A_f(t) = \frac{\Gamma_{B^0 \rightarrow f}(t) - \Gamma_{\bar{B}^0 \rightarrow f}(t)}{\Gamma_{B^0 \rightarrow f}(t) + \Gamma_{\bar{B}^0 \rightarrow f}(t)}$$

$$= \frac{C_f \cos(\Delta m t) - S_f \sin(\Delta m t)}{\cosh(\Delta \Gamma / 2 t) + A_f^{\Delta \Gamma} \sinh(\Delta \Gamma / 2 t)}$$

- ▶  $B_s^0 \rightarrow D_s^\mp K^\pm$ : both interfering amplitudes are of similar size
  - ▶  $B^0 \rightarrow D^\mp \pi^\pm$ : low oscillation frequency and high statistics

$B_s^0 \rightarrow D_s^\mp K^\pm$	$B^0 \rightarrow D^\mp \pi^\pm$
$\Gamma_{B^0 \rightarrow f} \propto \lambda^3$	$\Gamma_{B^0 \rightarrow f} \propto \lambda^2$
$\Gamma_{\bar{B}^0 \rightarrow f} \propto \lambda^3$	$\Gamma_{\bar{B}^0 \rightarrow f} \propto \lambda^4$



# CP observables

$$A_f(t) = \frac{\Gamma_{B^0 \rightarrow f}(t) - \Gamma_{\bar{B}^0 \rightarrow f}(t)}{\Gamma_{B^0 \rightarrow f}(t) + \Gamma_{\bar{B}^0 \rightarrow f}(t)} = \frac{C_f \cos(\Delta m t) + S_f \sin(\Delta m t)}{\cosh(\Delta \Gamma / 2 t) + A_f^{\Delta \Gamma} \sinh(\Delta \Gamma / 2 t)}$$

$$r = \left| \frac{\bar{\mathcal{A}}_f}{\mathcal{A}_f} \right|$$

$B_s^0 \rightarrow D_s^\mp K^\pm$

$$S_{\bar{f}} = -\frac{2r_{D_s^\mp K^\pm} \sin(\delta + (\gamma - 2\beta_s))}{1 + r_{D_s^\mp K^\pm}^2}$$

$$S_f = \frac{2r_{D_s^\mp K^\pm} \sin(\delta - (\gamma - 2\beta_s))}{1 + r_{D_s^\mp K^\pm}^2}$$

$$A_f^{\Delta \Gamma} = -\frac{2r_{D_s^\mp K^\pm} \cos(\delta - (\gamma - 2\beta_s))}{1 + r_{D_s^\mp K^\pm}^2}$$

$$A_{\bar{f}}^{\Delta \Gamma} = -\frac{2r_{D_s^\mp K^\pm} \cos(\delta + (\gamma - 2\beta_s))}{1 + r_{D_s^\mp K^\pm}^2}$$

$$C_f = \frac{1 - r_{D_s^\mp K^\pm}^2}{1 + r_{D_s^\mp K^\pm}^2}$$

external input for  $\beta_s$

$B^0 \rightarrow D^\mp \pi^\pm$

$$S_f = -\frac{2r_{D^\mp \pi^\pm} \sin(\delta - (2\beta + \gamma))}{1 + r_{D^\mp \pi^\pm}^2}$$

$$S_{\bar{f}} = \frac{2r_{D^\mp \pi^\pm} \sin(\delta + (2\beta + \gamma))}{1 + r_{D^\mp \pi^\pm}^2}$$

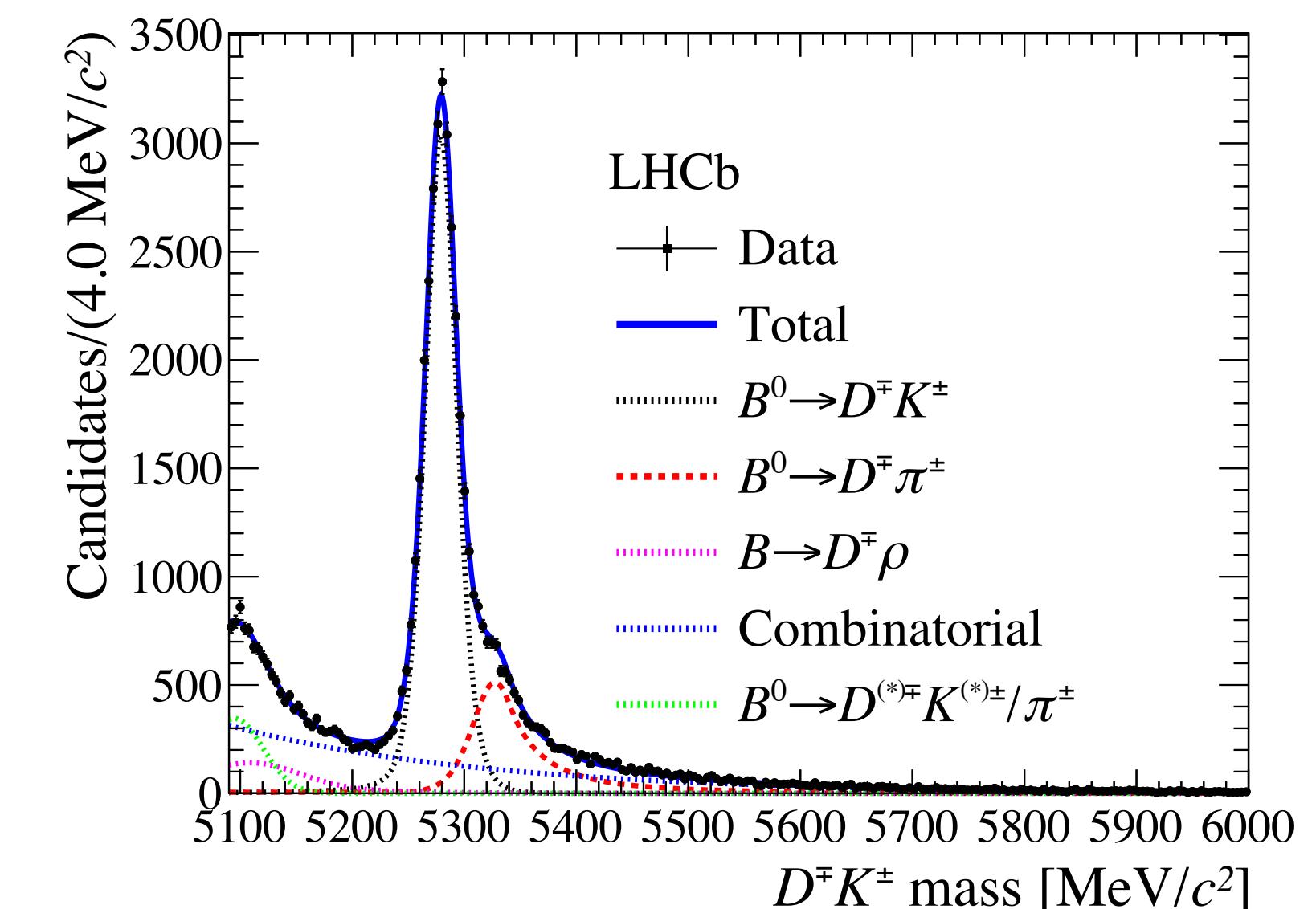
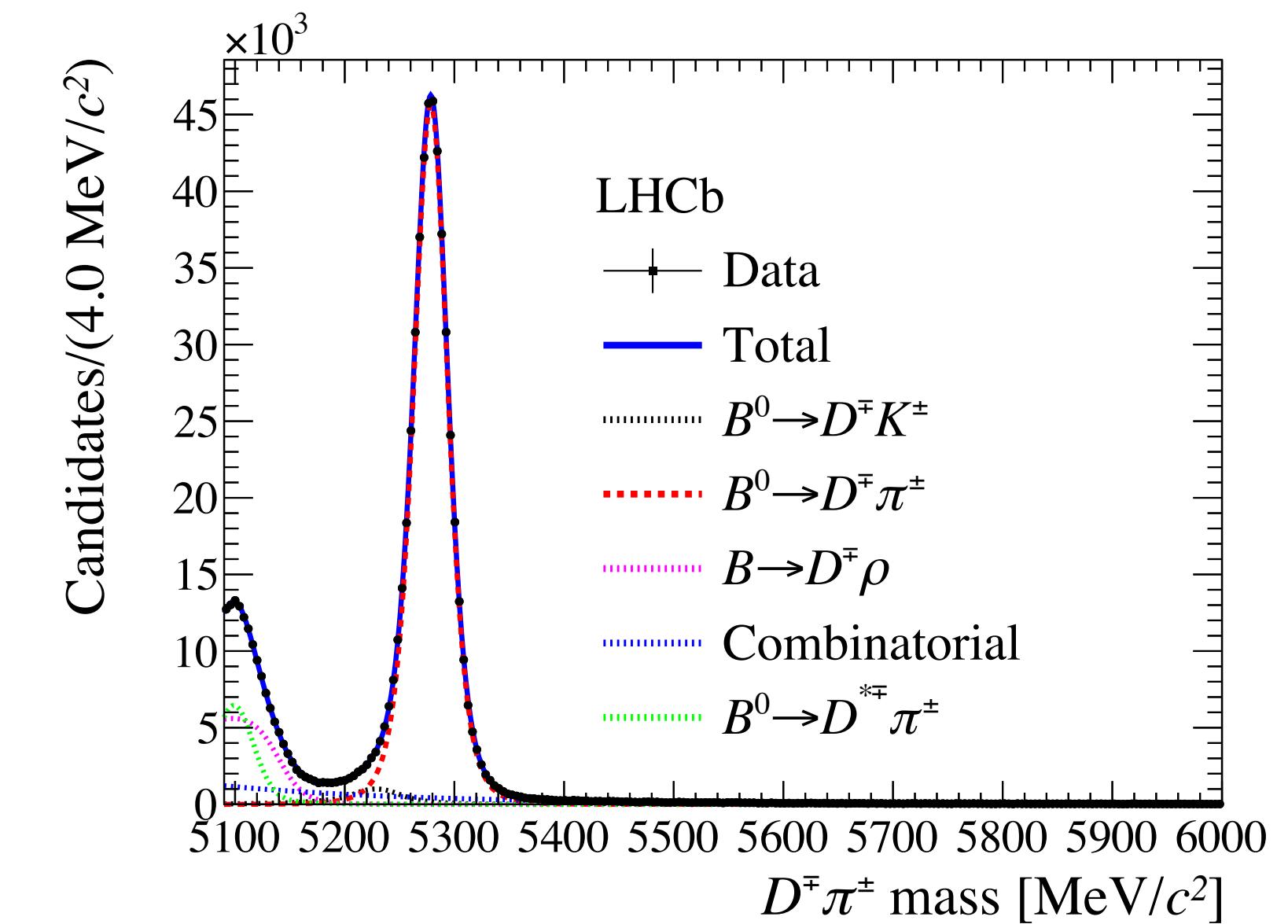
external input for  $\beta, r_{D^\mp \pi^\pm}$

- ▶ oscillation terms: sensitivity from events with known initial flavour
- ▶ hyperbolic terms: sensitivity from all events

$$B^0 \rightarrow D^\mp \pi^\pm$$

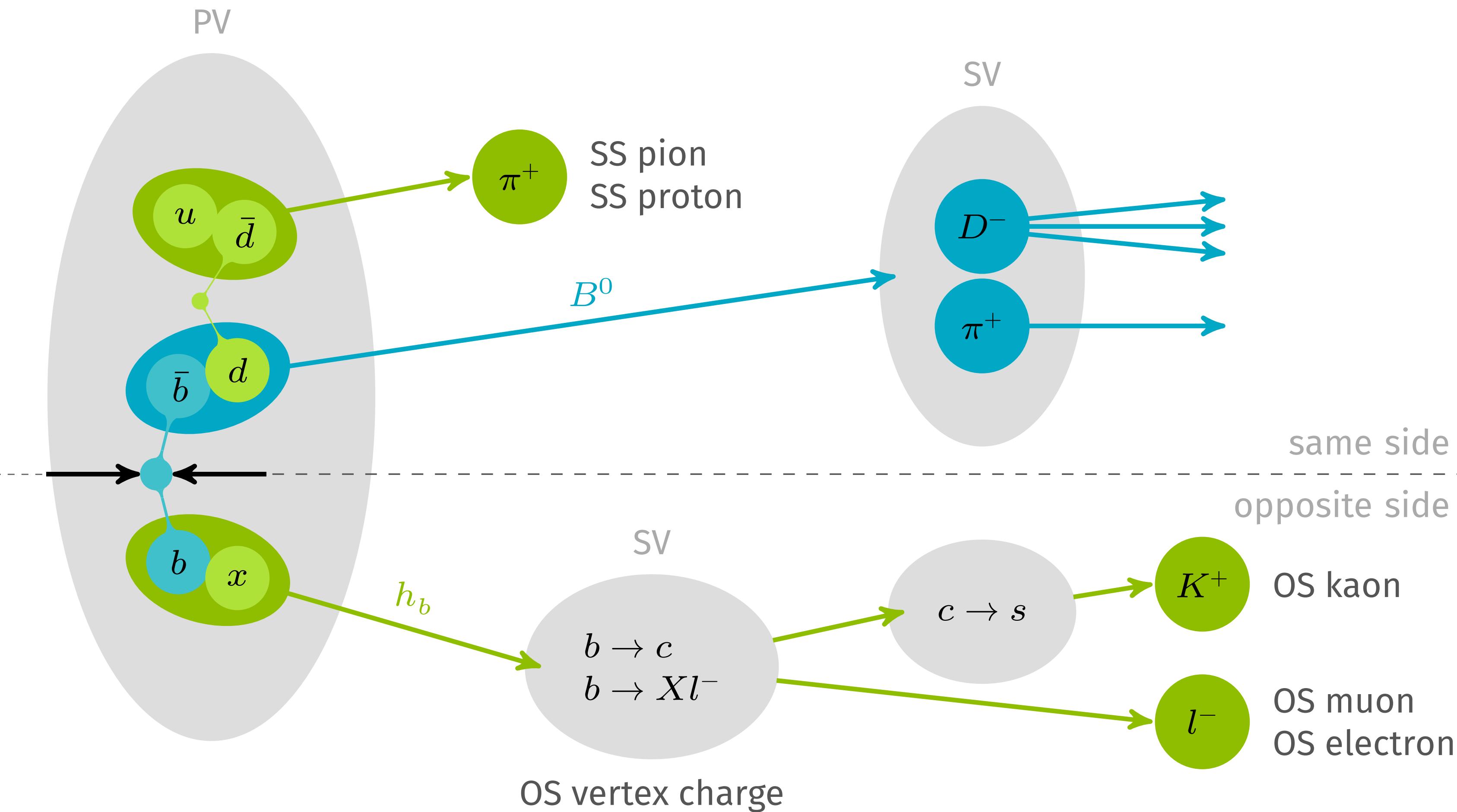
# Selection & Massfit

- ▶ sample based on  $3\text{ fb}^{-1}$  from 2011 & 2012 (7 and 8 TeV)
- ▶  $B^0 \rightarrow D^\mp \pi^\pm$  reconstructed in  $D^- \rightarrow K^+ \pi^- \pi^-$
- ▶ main offline selection of all  $(B^0, \text{PV})$  pairs
- ▶ split dataset into two disjoint subsets according to PID information (only considering tagged candidates)
  - $B^0 \rightarrow D^\mp \pi^\pm$  with  $B^0 \rightarrow D^- K^+$  cross-feed
  - $B^0 \rightarrow D^- K^+$  with a fraction of  $B^0 \rightarrow D^\mp \pi^\pm$
- ▶ samples fitted simultaneously
- ▶ reduce range for sWeight extraction: 5220 MeV/c<sup>2</sup> to 5600 MeV/c<sup>2</sup>
  - #tagged signal candidates:  $479,000 \pm 700$
  - #background candidates:  $34,400 \pm 300$



# Flavour tagging

- ▶ using both SS taggers
- ▶ retrain both taggers on  $B^0 \rightarrow J/\psi K^{*0}$
- ▶ for training reweighted to  $B^0 \rightarrow D^\mp \pi^\pm$



- ▶ using full set of available OS taggers:
  - single track taggers: OS $\mu$ , OS $e$ , OS $k$
  - OS vertex charge
  - OS charm
- ▶ overall tagging power:  $\epsilon_{\text{eff}} = (5.59 \pm 0.01)\%$
- ▶  $b\bar{b}$ -pairs are produced incoherently  
 $\rightarrow$  no effects from tag-side interference

# Flavour tagging calibration

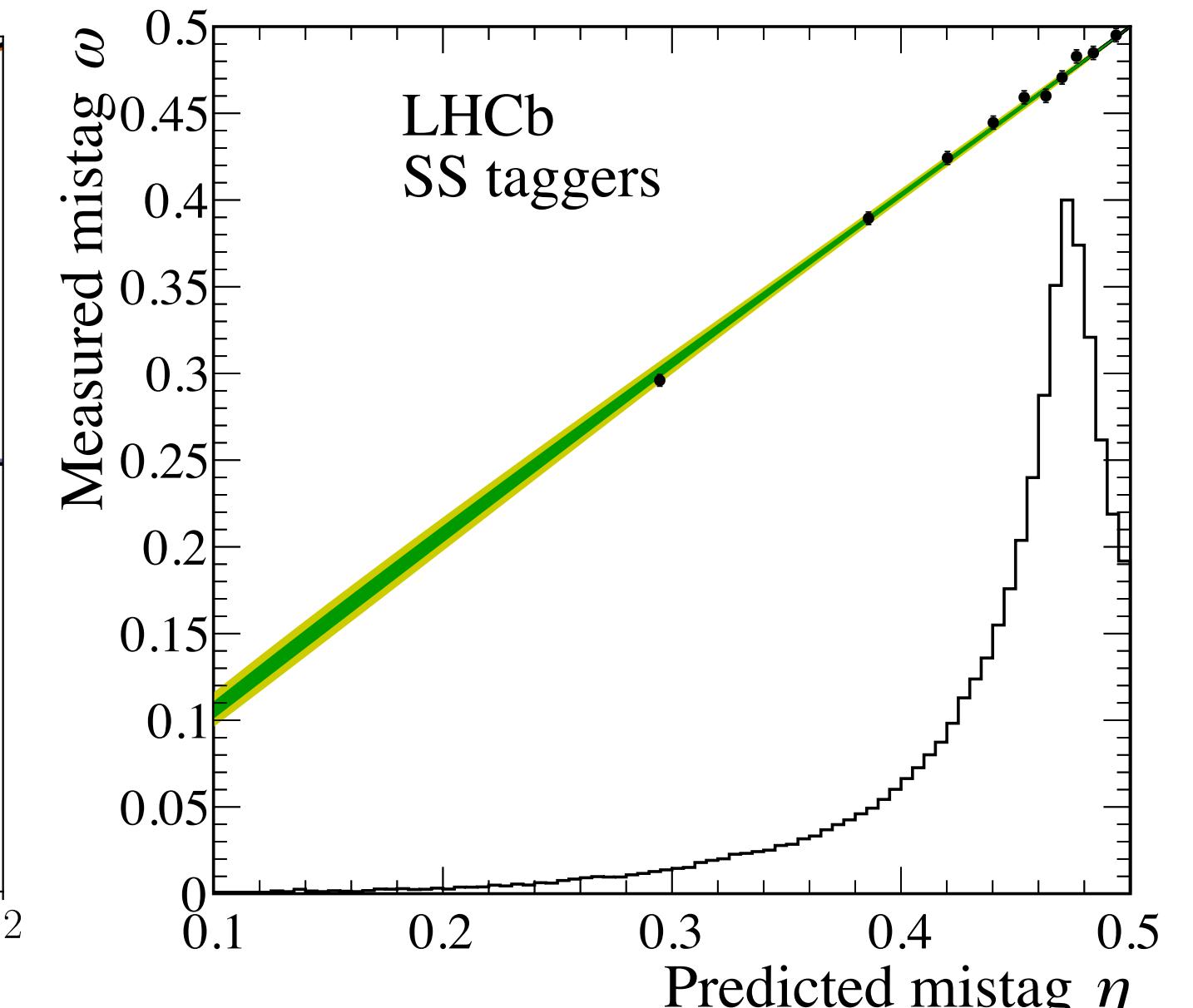
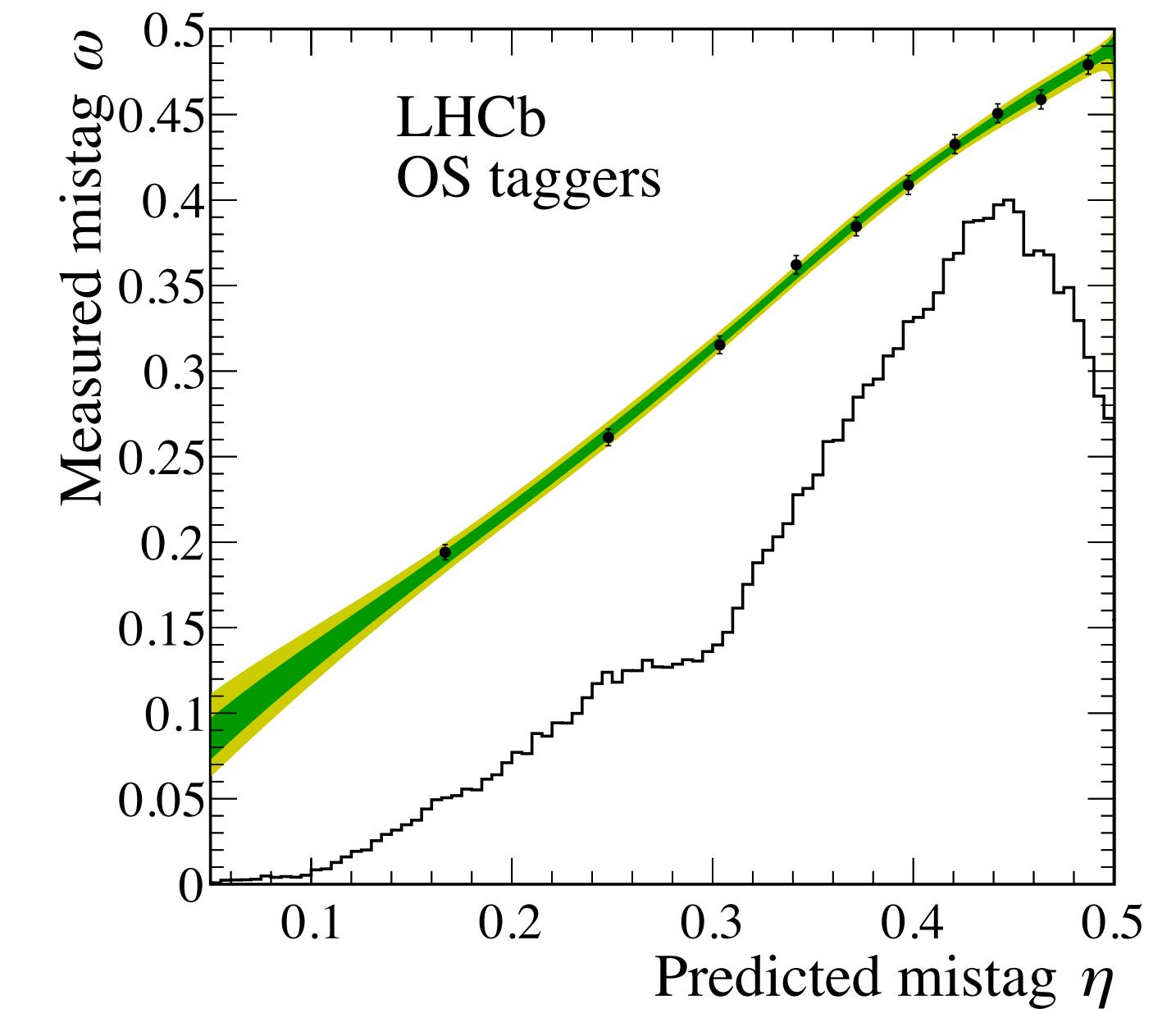
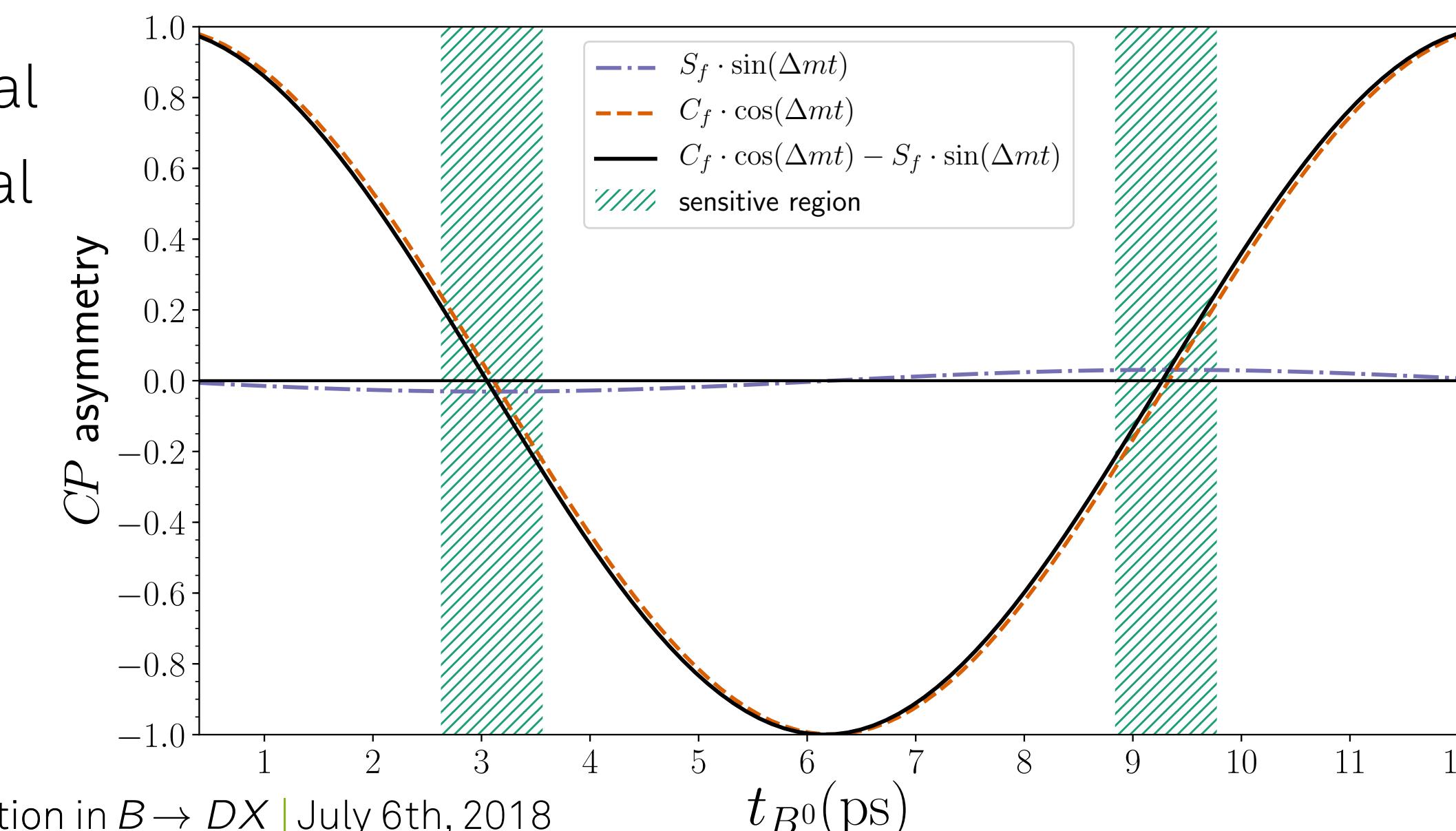
- ▶ control channel used to determine functional form of calibration  
→ possible due to fixed  $C_f$
- ▶ generalised linear models

$$\bar{\omega}(\eta) = g(h(\eta)) = g\left[g^{-1}(\eta) + \sum_{i=1}^N \left(\tilde{p}_i \frac{\Delta p_i}{2}\right) f_i(\eta)\right]$$

- link function: modified logistic function maps mistag into  $[0, 0.5]$

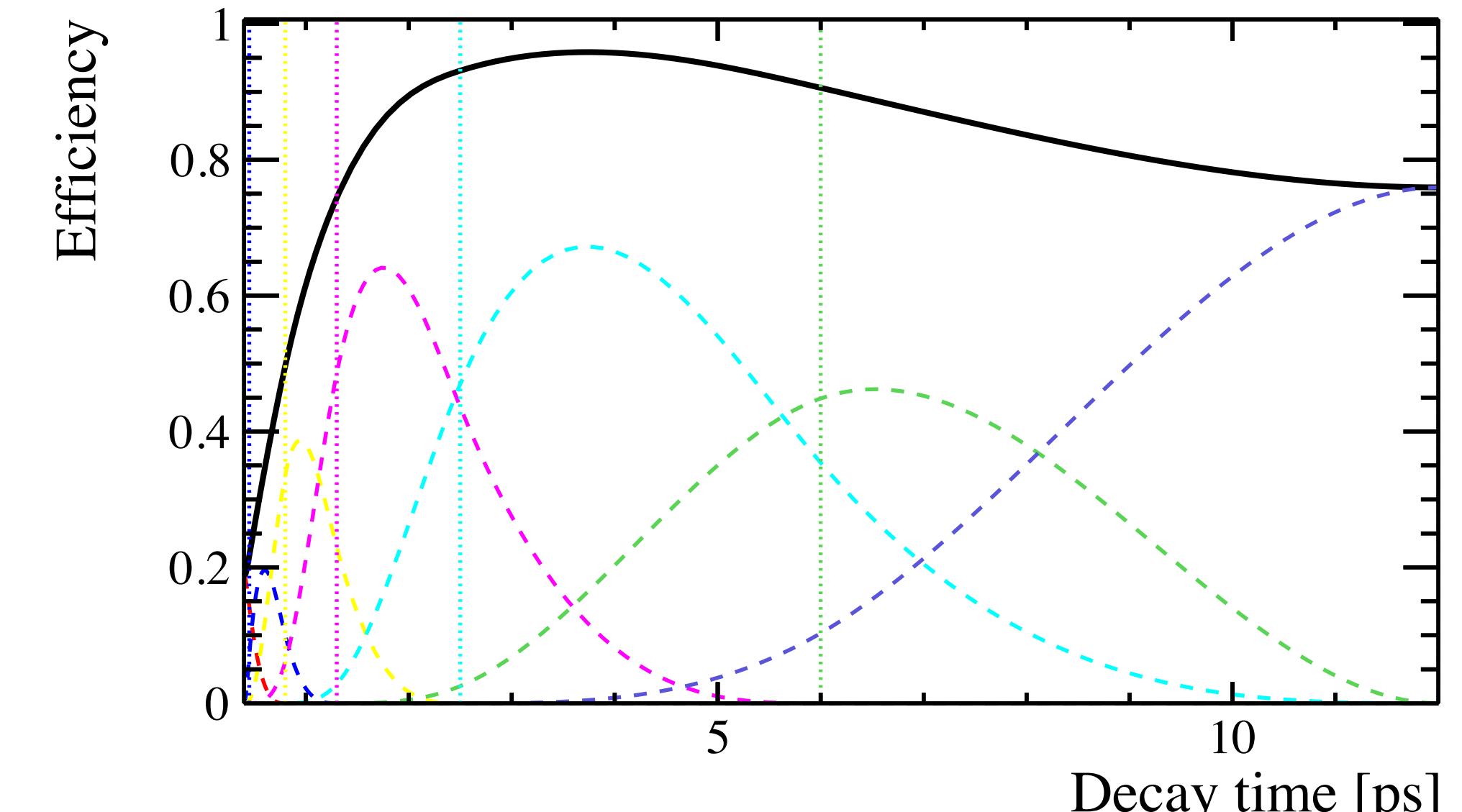
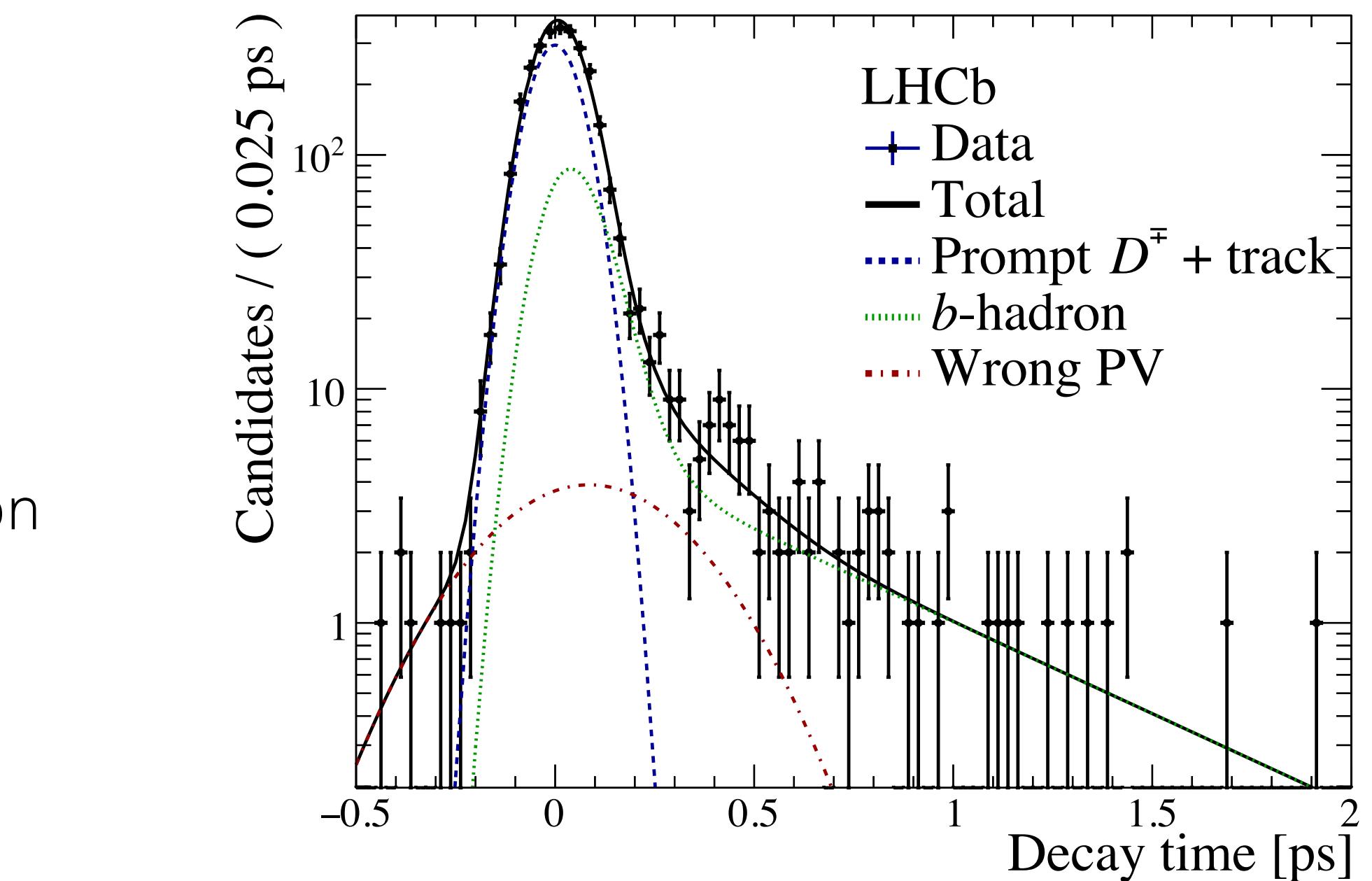
- basis function:

- OS: 5<sup>th</sup> order polynomial
- SS: 1<sup>st</sup> order polynomial



# Other ingredients

- ▶ decay-time resolution determined on *fake*  $B^0$ -candidates:  
→ genuine  $D^-$ -meson + charged track
- ▶ decay-time distribution peaking at 0 ps, width representing resolution
- ▶ width determined in bins of decay-time uncertainty
- ▶ average decay-time resolution:  $(54.9 \pm 0.4)$  fs
- ▶ decay-time dependent efficiency
- ▶ modelled with segments of cubic b-splines: 9 free parameters
- ▶ external inputs:
  - oscillation frequency:  $\Delta m_d = (0.5050 \pm 0.0023) \text{ ps}^{-1}$   
Eur. Phys. J. C (2016) 76:412
  - $B^0$  lifetime:  $\tau = (1.518 \pm 0.004) \text{ ps}$   
HFLAV

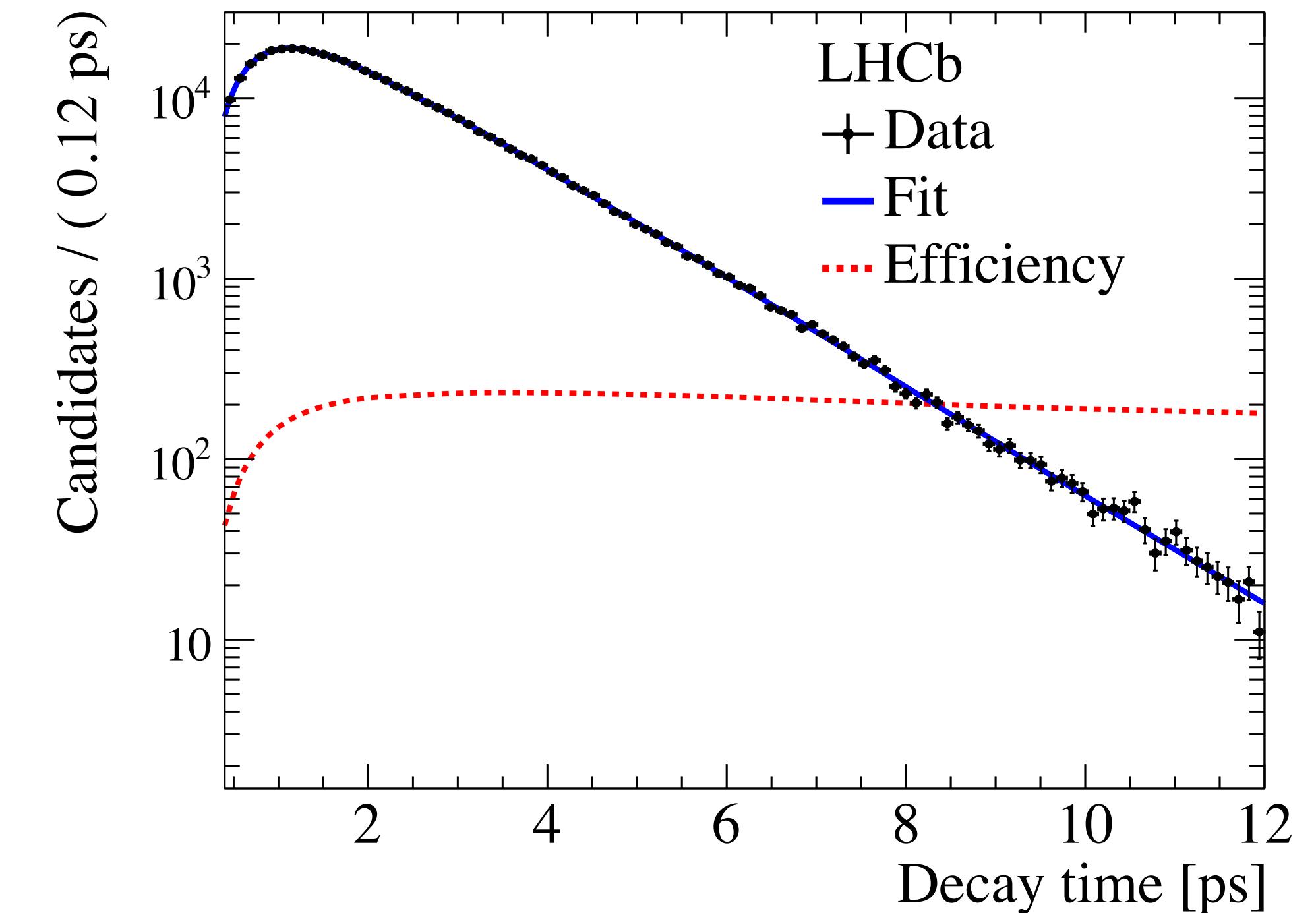


# Decay-time fit

- ▶ free parameters:
  - $CP$  parameters  $S_f$  and  $S_{\bar{f}}$
  - detection and production asymmetry:  $A_D, A_P$
  - 7 pairs of tagging calibration parameters:  $(p_i, \Delta p_i)$
  - tagging efficiencies for the OS and SS:  $\varepsilon_{tag}^{OS}, \varepsilon_{tag}^{SS}$
  - 9 parameters for the acceptance:  $v_i$
- ▶  $B^0$  decay-time and oscillation frequency Gaussian constrained
- ▶ resulting  $CP$  parameters:

$$S_f = 0.058 \pm 0.020(\text{stat}) \pm 0.011(\text{syst})$$

$$S_{\bar{f}} = 0.038 \pm 0.020(\text{stat}) \pm 0.007(\text{syst})$$



- ▶ systematic uncertainties estimated with Gaussian constraints, pseudoexperiments and variation of mass fit model

# CP asymmetries

- final state asymmetries mainly dominated by cosine function
- asymmetry between  $B^0$  and  $\bar{B}^0$  for favoured and suppressed transitions:

$$A_F = \frac{\Gamma_{B^0 \rightarrow f}(t) - \Gamma_{\bar{B}^0 \rightarrow \bar{f}}(t)}{\Gamma_{B^0 \rightarrow f}(t) + \Gamma_{\bar{B}^0 \rightarrow \bar{f}}(t)}$$

$$A_S = \frac{\Gamma_{\bar{B}^0 \rightarrow f}(t) - \Gamma_{B^0 \rightarrow \bar{f}}(t)}{\Gamma_{\bar{B}^0 \rightarrow f}(t) + \Gamma_{B^0 \rightarrow \bar{f}}(t)}$$

- significance of  $2.7\sigma$  for CP violation
- result in agreement with Belle & BaBar
- more precise than Belle & BaBar

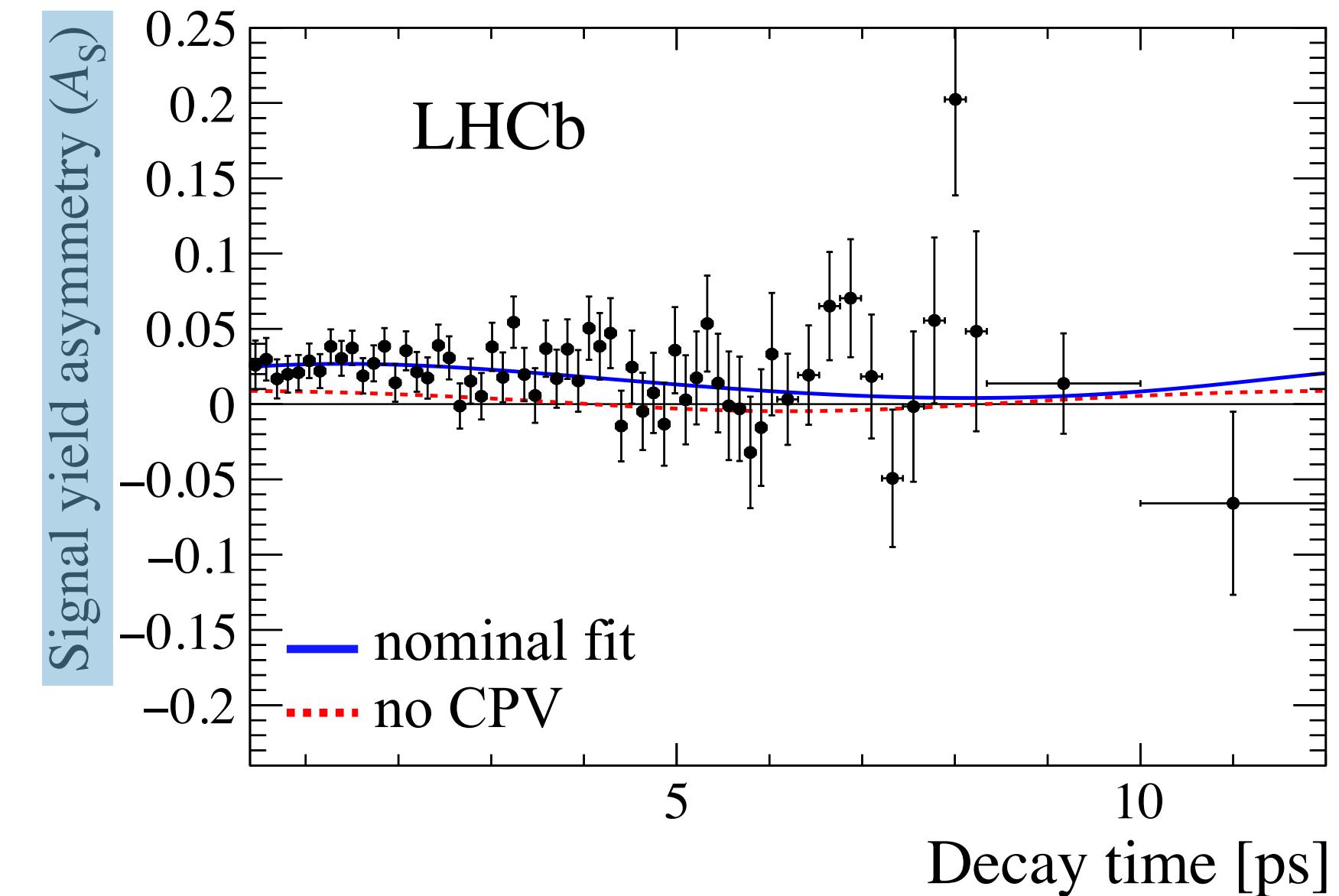
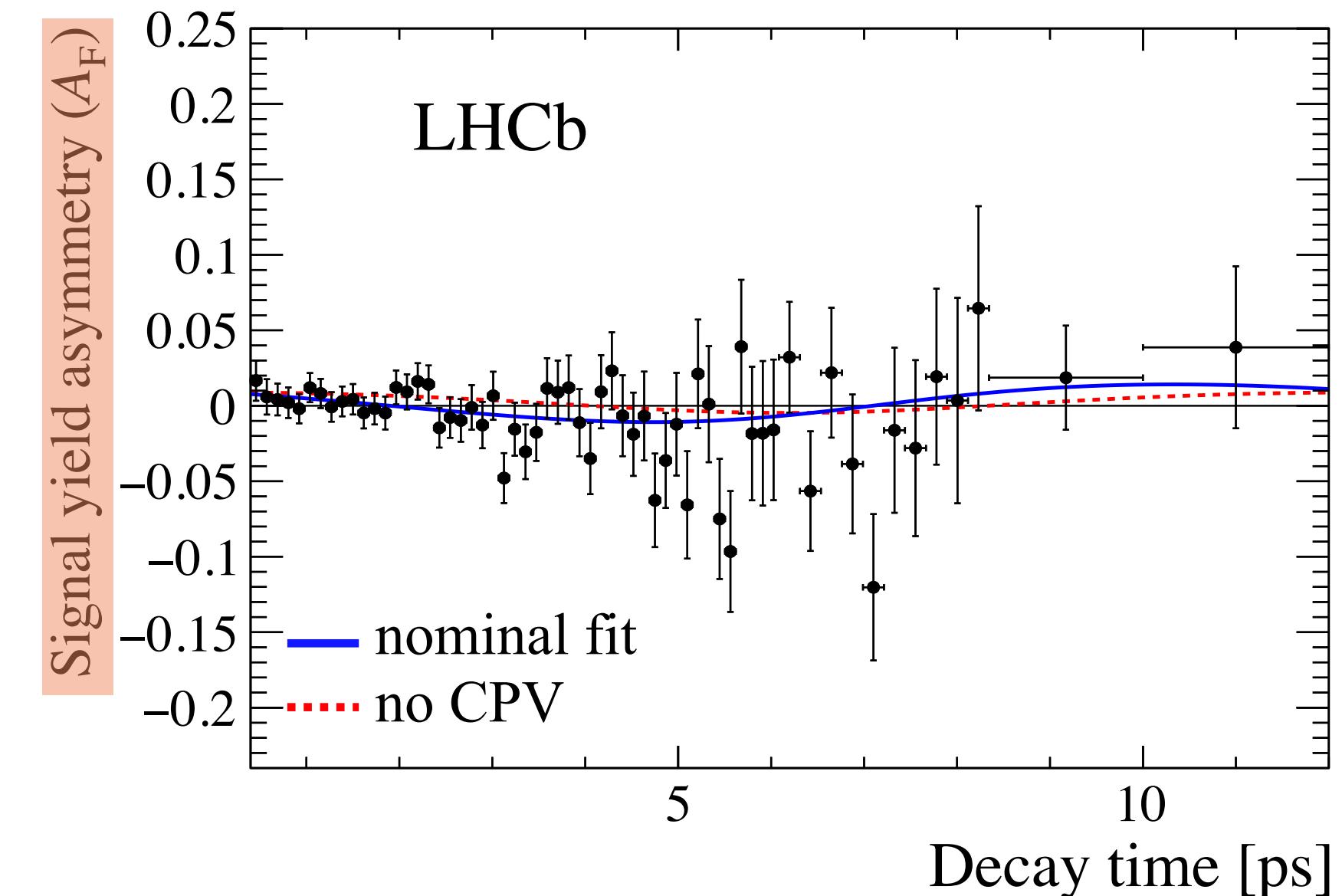
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	Belle	BaBar	LHCb
$S_f [\%]$	$6.8 \pm 3.1$	$-2.3 \pm 5.0$	$5.8 \pm 2.3$
$S_{\bar{f}} [\%]$	$3.1 \pm 3.2$	$4.3 \pm 4.8$	$3.8 \pm 2.1$

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PRD 73 (2006) 092003

PRD 73 (2006) 111101



$$B_s^0 \rightarrow D_s^\mp K^\pm$$

# Sample preparation

- ▶ sample based on  $3 \text{ fb}^{-1}$  from 2011 & 2012 (7 and 8 TeV)
- ▶ multidimensional fit to different  $D_s^-$  final states ( $KK\pi, K\pi\pi, \pi\pi\pi$ )
- ▶ all single track taggers (OS $\mu$ , OS $e$ , OS $k$ ) + OS vertex charge + SS kaon
- ▶ calibration performed on  $B_s^0 \rightarrow D_s^- \pi^+$ 
  - performance:  $\epsilon_{\text{eff}} = (5.80 \pm 0.25) \%$
- ▶ per-event decay time resolution determined on *fake*  $B^0$ -candidates
- ▶ decay time acceptance taken from  $B_s^0 \rightarrow D_s^- \pi^+$  and weighted by ratio from simulation
- ▶ external inputs:

$$\Gamma_s = (0.6643 \pm 0.0020) \text{ ps}^{-1}$$

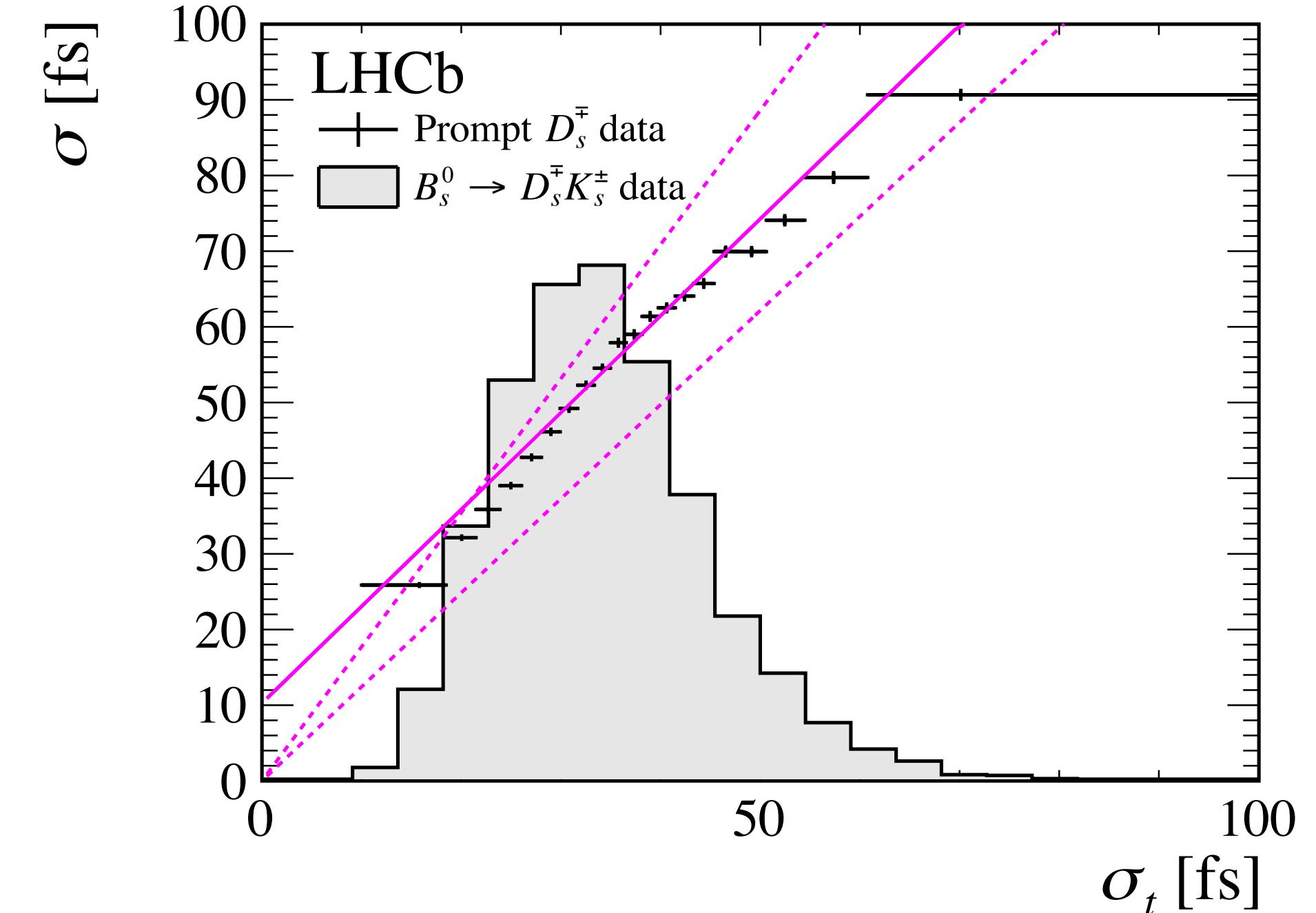
$$\Delta m_s = (17.757 \pm 0.021) \text{ ps}^{-1}$$

New J. Phys. 15 (2013) 053021

$$\Delta\Gamma_s = (0.083 \pm 0.006) \text{ ps}^{-1}$$

$$A_{\text{det}} = (1 \pm 1) \%$$

JHEP 07 (2014) 041



$$\rho(\Gamma_s, \Delta\Gamma_s) = -0.239$$

$$A_{\text{prod}} = (1.1 \pm 2.7) \%$$

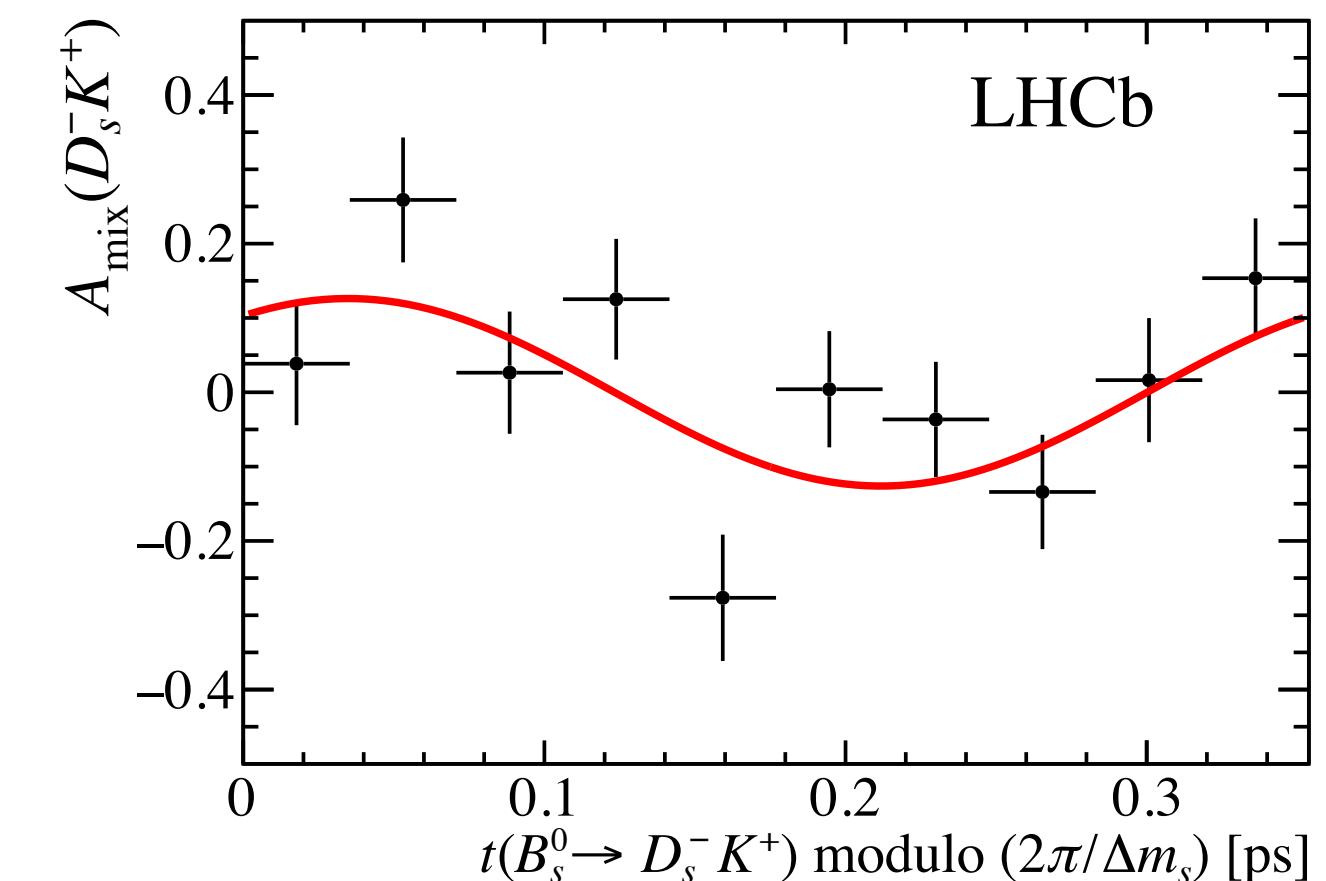
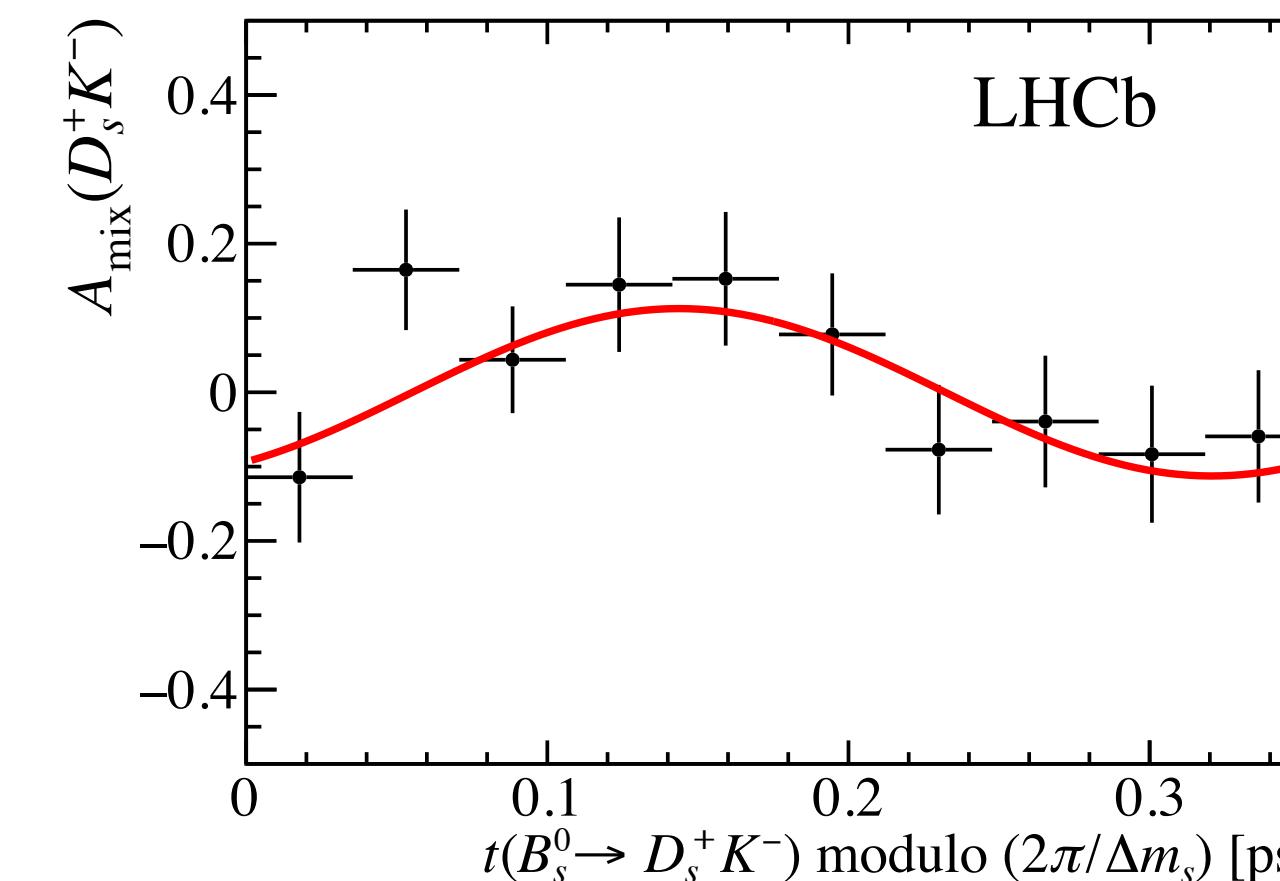
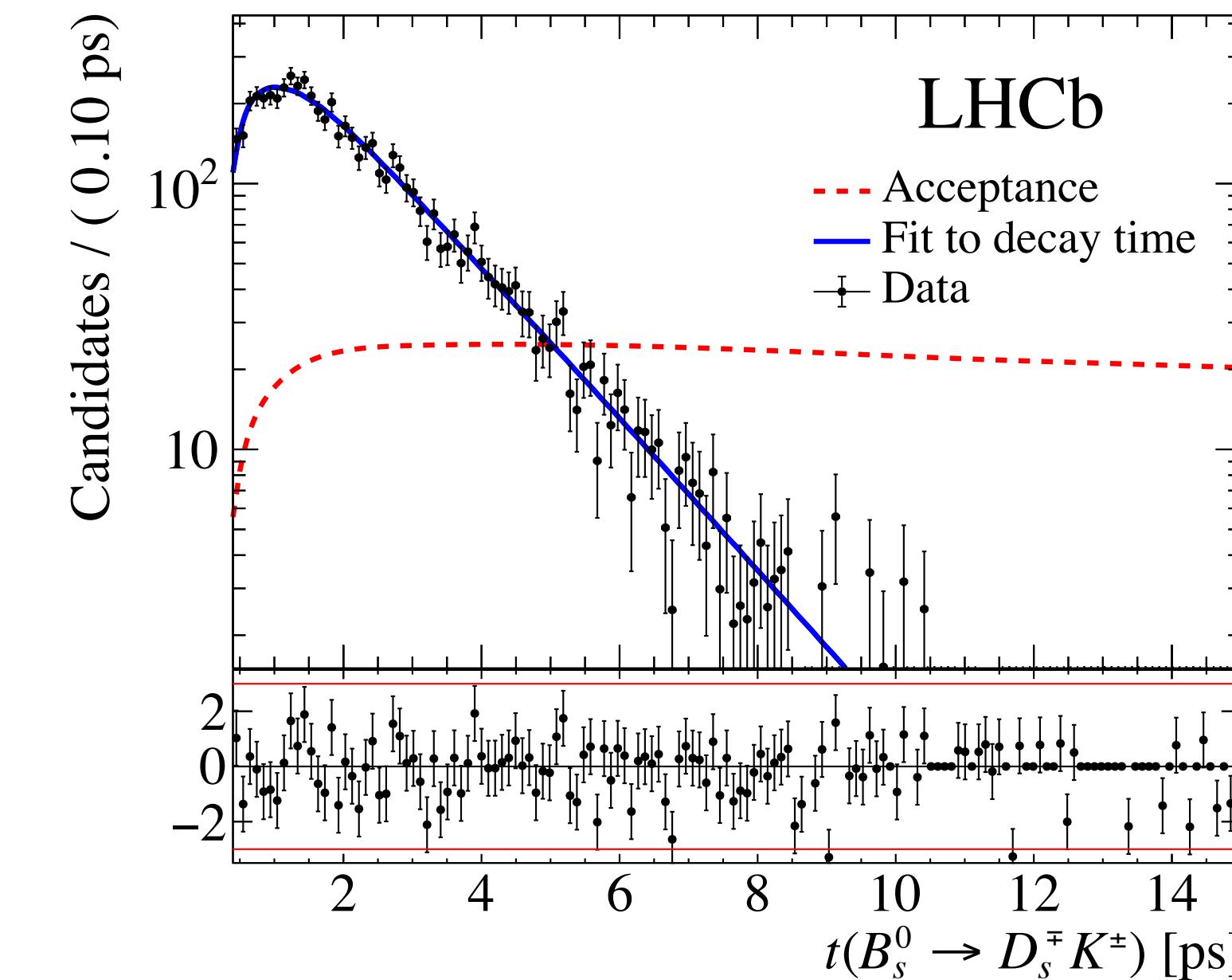
Phys. Lett. B739 (2014) 218

# Decay time fit & asymmetries

- ▶ external inputs fixed to central values
- ▶ tagging calibration parameters floating within Gaussian constraints
- ▶ obtained  $CP$  parameters:

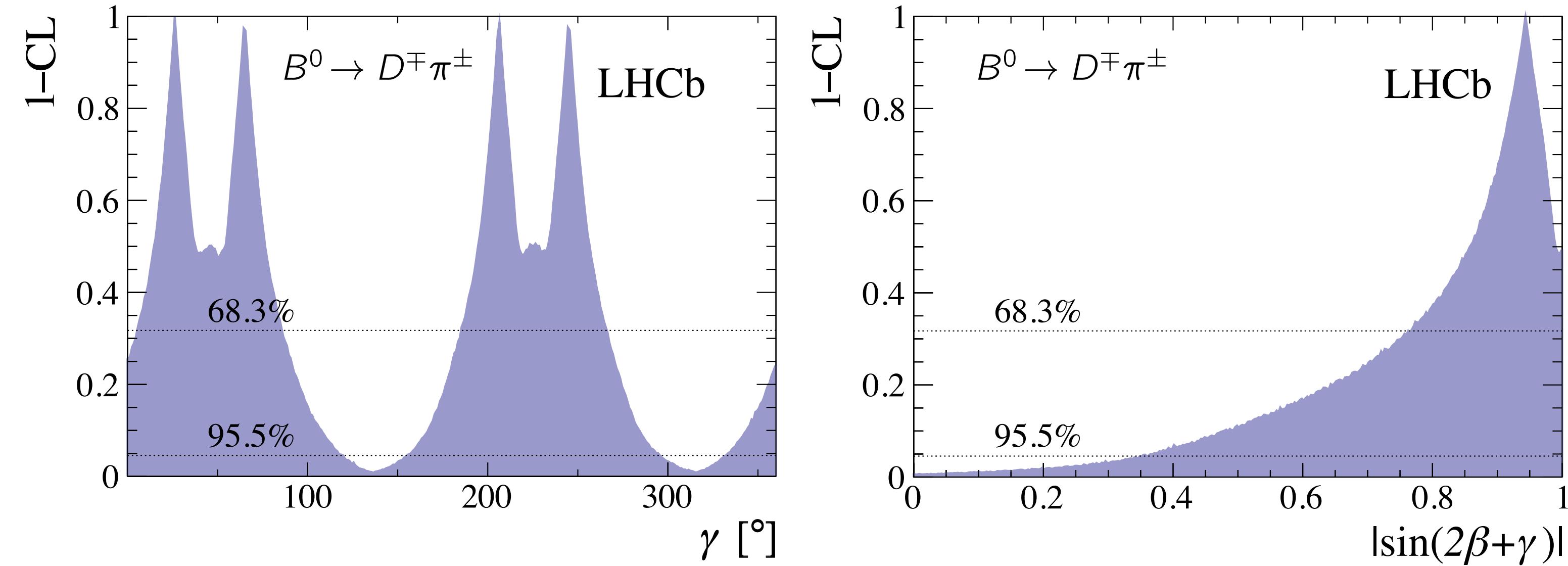
Parameter	Value
$C_f$	$0.730 \pm 0.142 \pm 0.045$
$A_f^{\Delta\Gamma}$	$0.387 \pm 0.277 \pm 0.153$
$A_{\bar{f}}^{\Delta\Gamma}$	$0.308 \pm 0.275 \pm 0.152$
$S_f$	$-0.519 \pm 0.202 \pm 0.070$
$S_{\bar{f}}$	$-0.489 \pm 0.196 \pm 0.068$

- ▶ systematic uncertainties estimated using pseudoexperiments and simulation
- ▶  $CP$  asymmetries folded into one mixing period  
 → evidence of oscillation

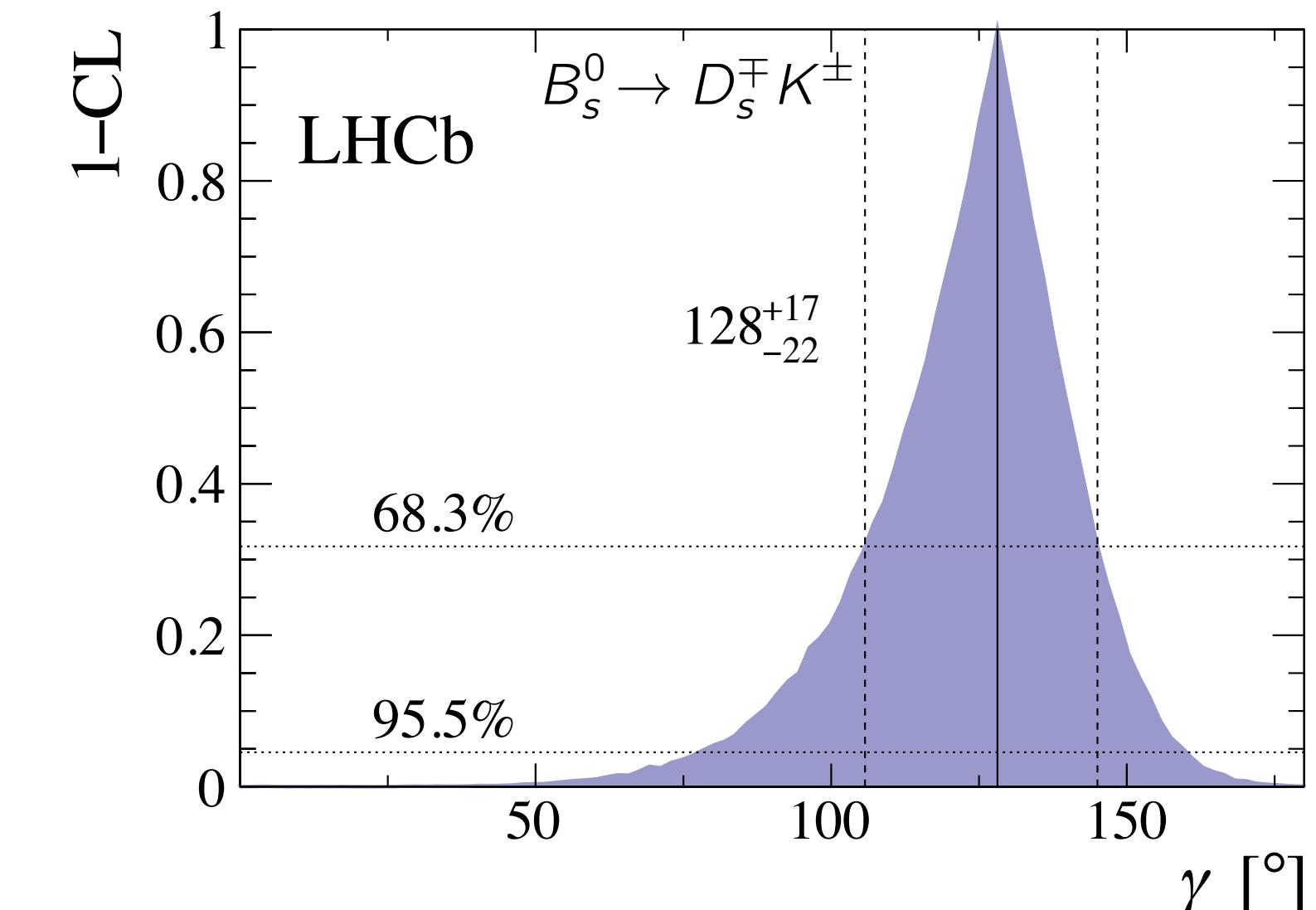


# Determining the angle $\gamma$

- ▶ frequentist approach
- ▶  $B^0 \rightarrow D^\mp \pi^\pm$  using external input for  $r$  (and  $\beta$ )
- ▶ confidence intervals at 68% CL:
  - $\gamma \in [5, 86]^\circ \cup [185, 266]^\circ$
  - $\delta_{D^\mp \pi^\pm} \in [-41, 41]^\circ \cup [140, 220]^\circ$
  - $|\sin(2\beta + \gamma)| \in [0.77, 1.0]$

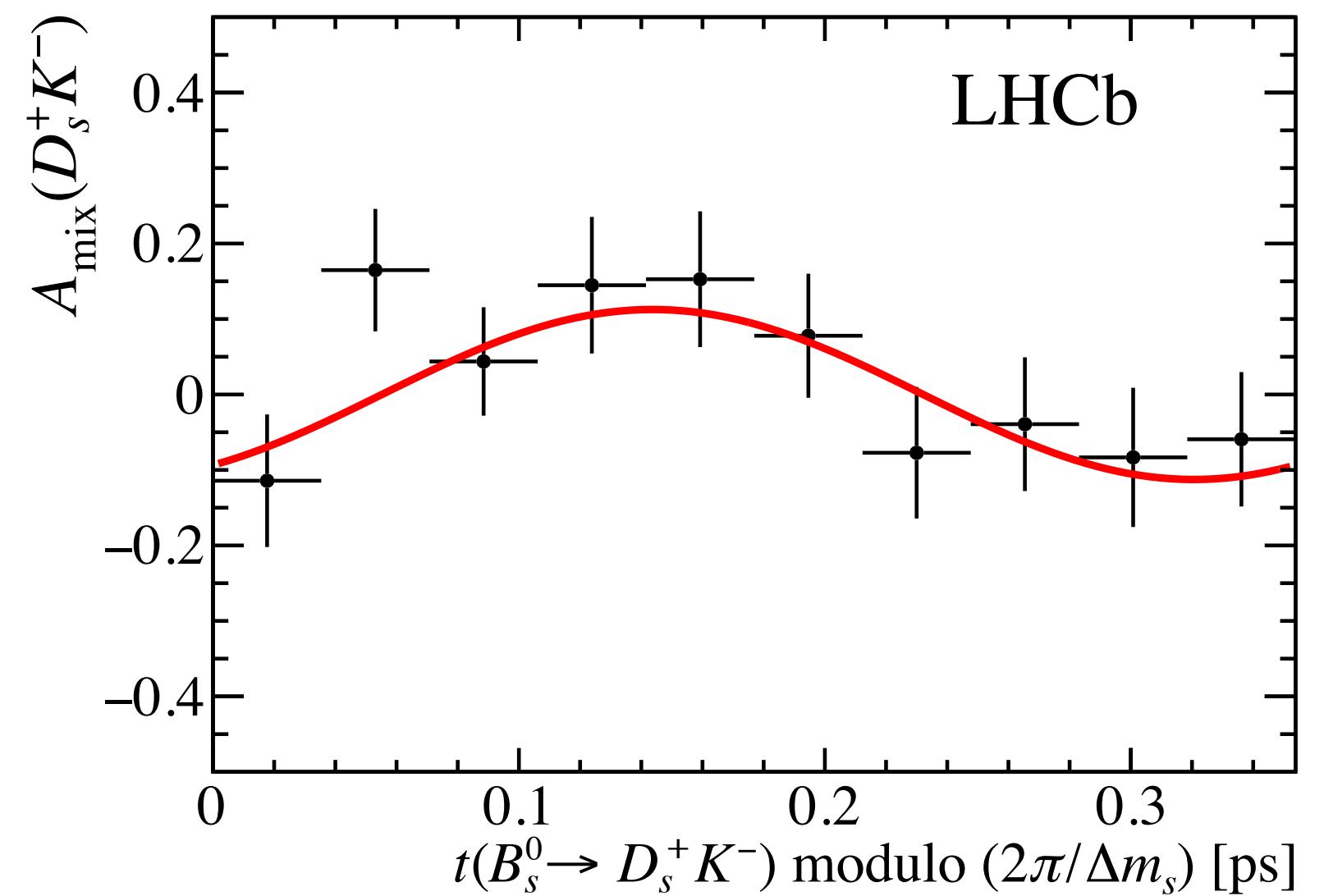
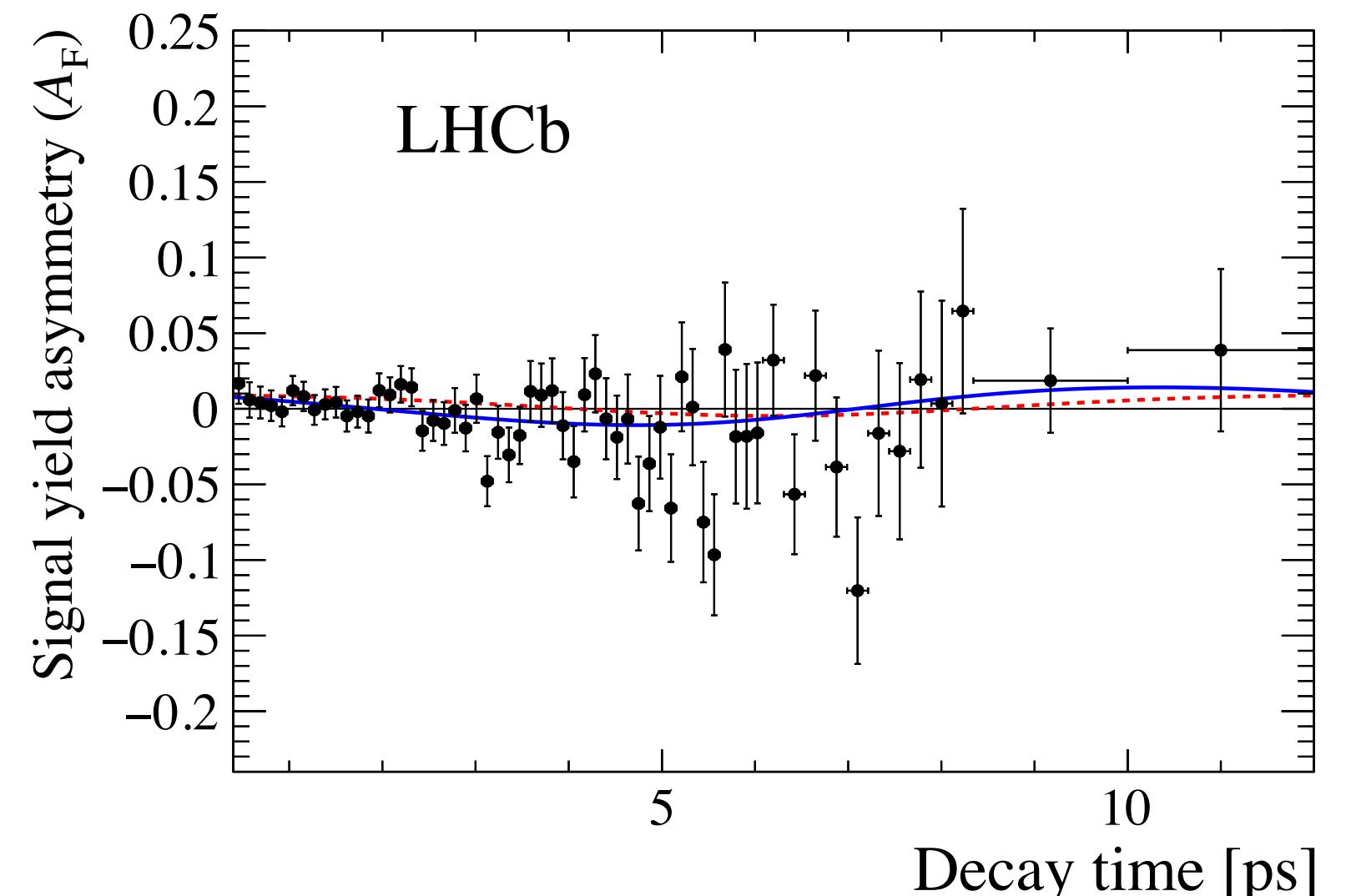


- ▶ For  $B_s^0 \rightarrow D_s^\mp K^\pm$  only external input for  $\beta_s$  needed
  - $\gamma = (128^{+17}_{-22})^\circ$
  - $\delta_{D_s^\mp K^\pm} = (358^{+13}_{-14})^\circ$
  - $r_{D_s^\mp K^\pm} = 0.37^{+0.10}_{-0.09}$



# Conclusion

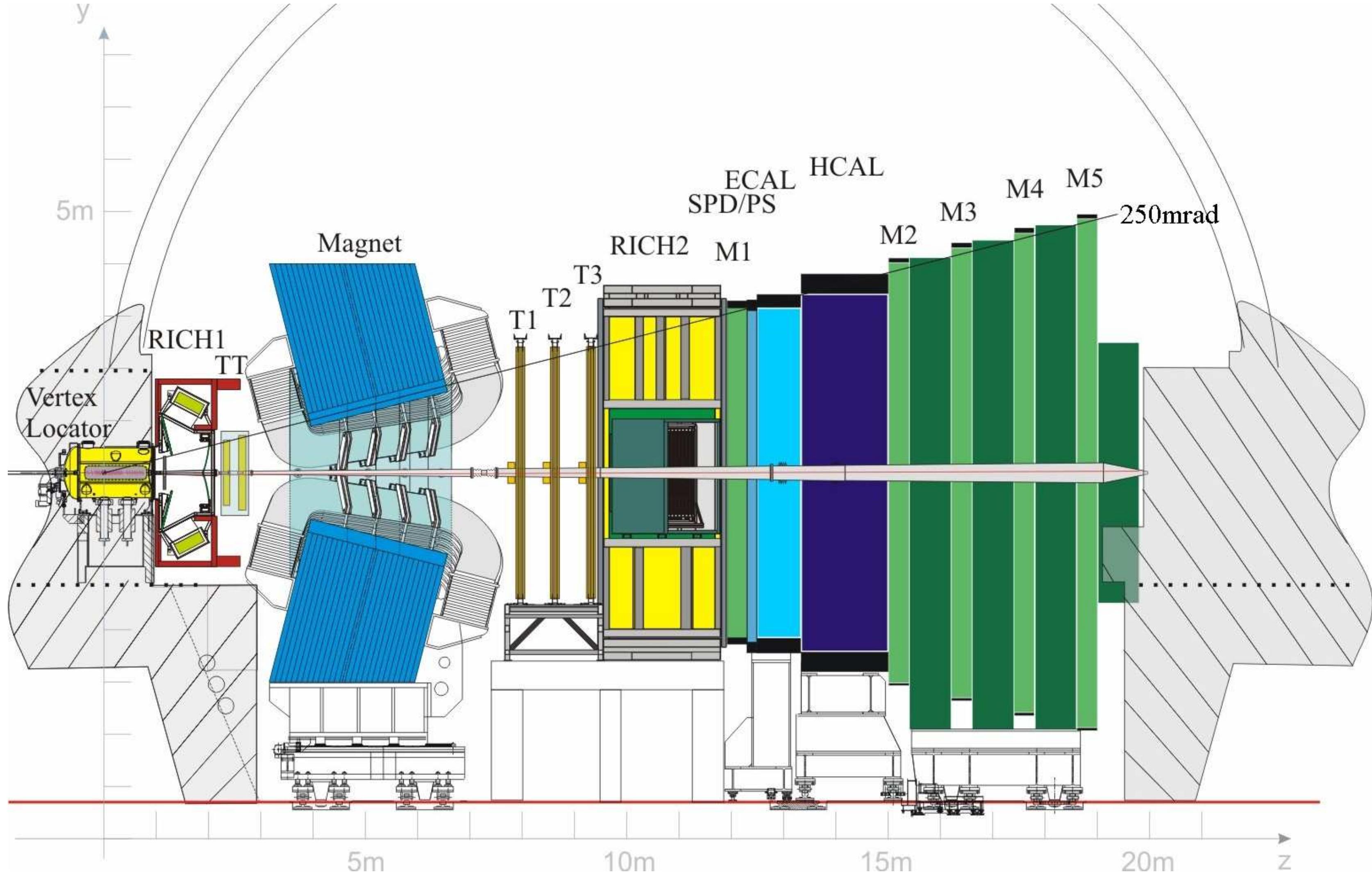
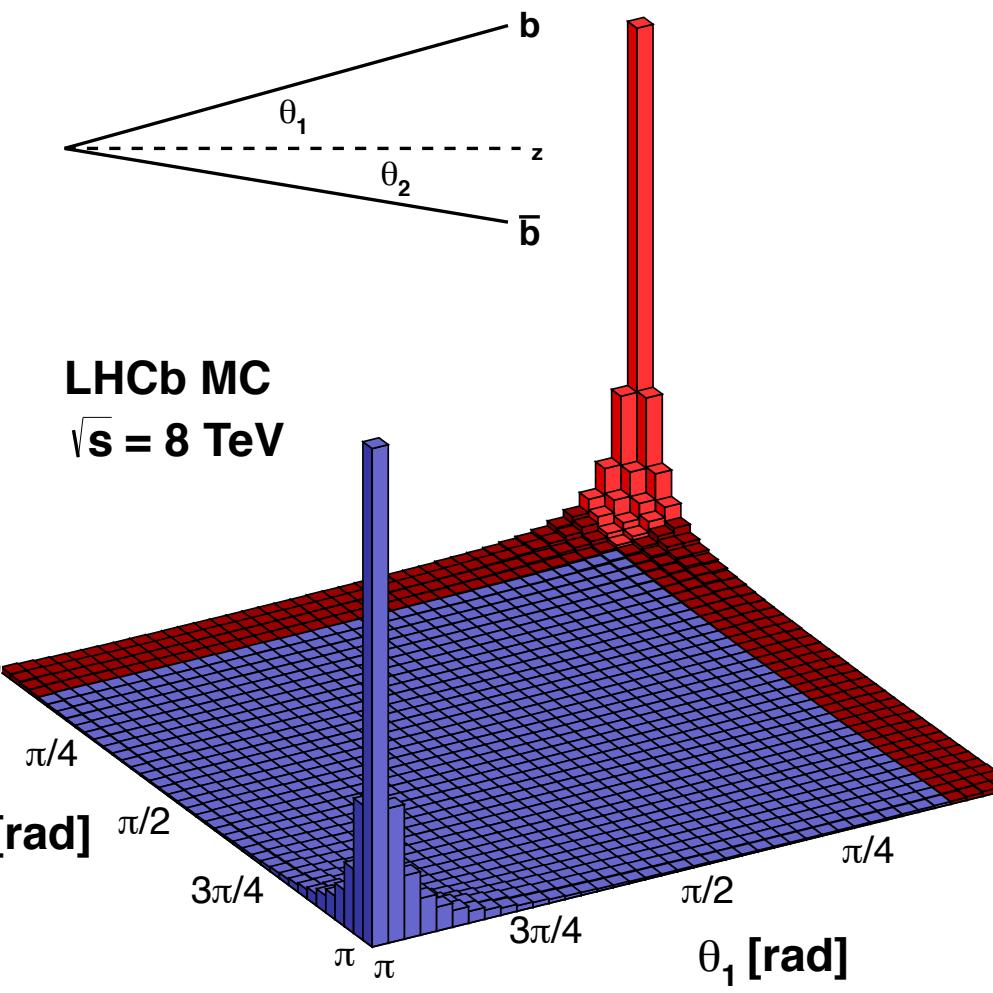
- ▶ presented time-dependent results on  $\gamma$  from  $B^0 \rightarrow D^\mp \pi^\pm$  and  $B_s^0 \rightarrow D_s^\mp K^\pm$
- ▶  $B^0 \rightarrow D^\mp \pi^\pm$ :
  - $\gamma \in [5, 86]^\circ \cup [185, 266]^\circ$  @ 68 % CL
  - agrees quite well with world average
- ▶  $B_s^0 \rightarrow D_s^\mp K^\pm$ :
  - $\gamma = (128^{+17}_{-22})^\circ$
  - shows some tension with world average
    - uncertainties still quite large for both results
- ▶ measurements statistically limited
  - Run II data will improve sensitivity
- ▶ LHCb collaboration provides its own  $\gamma$  combination
  - See Mark Whitehead's talk!



# BACKUP

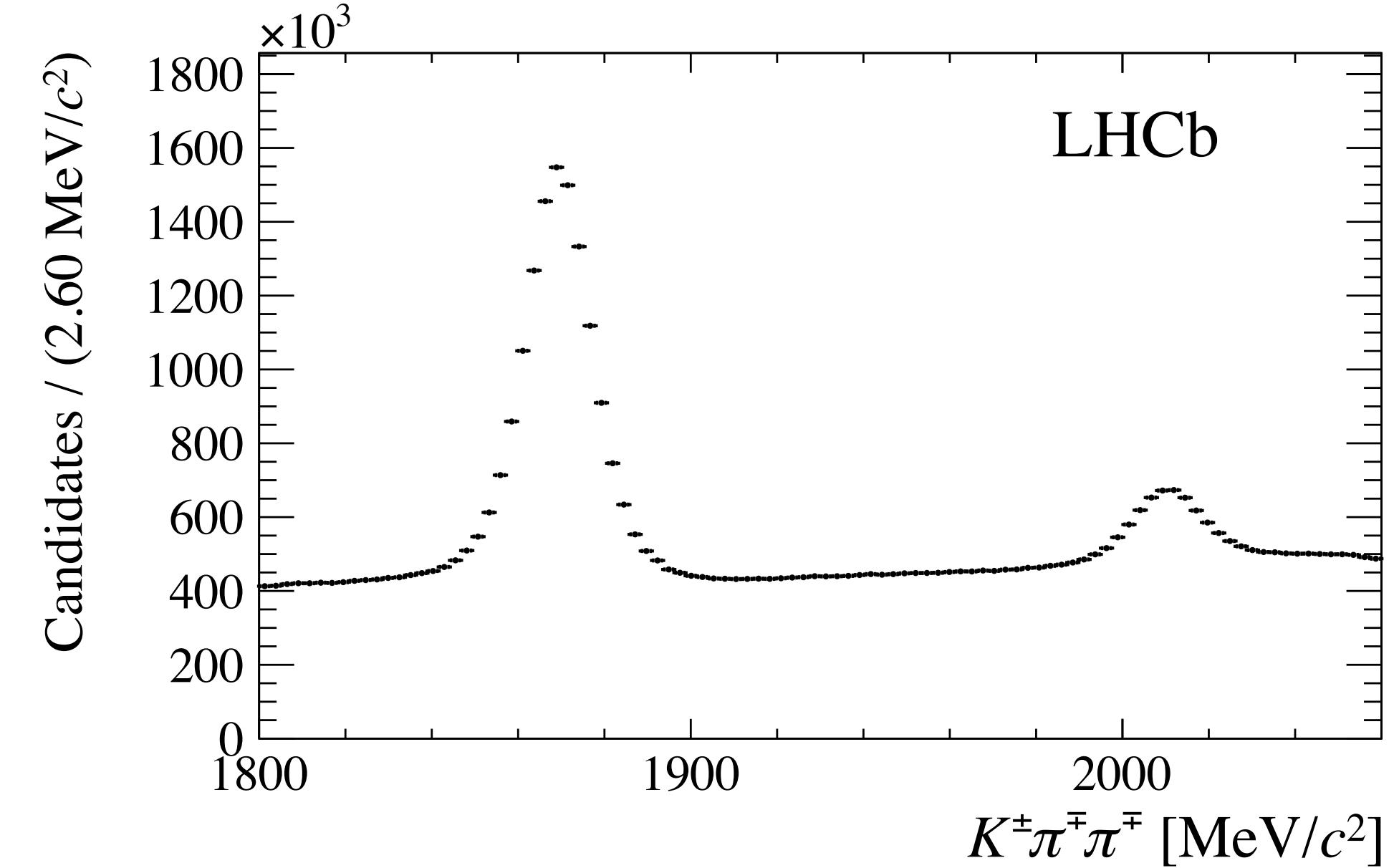
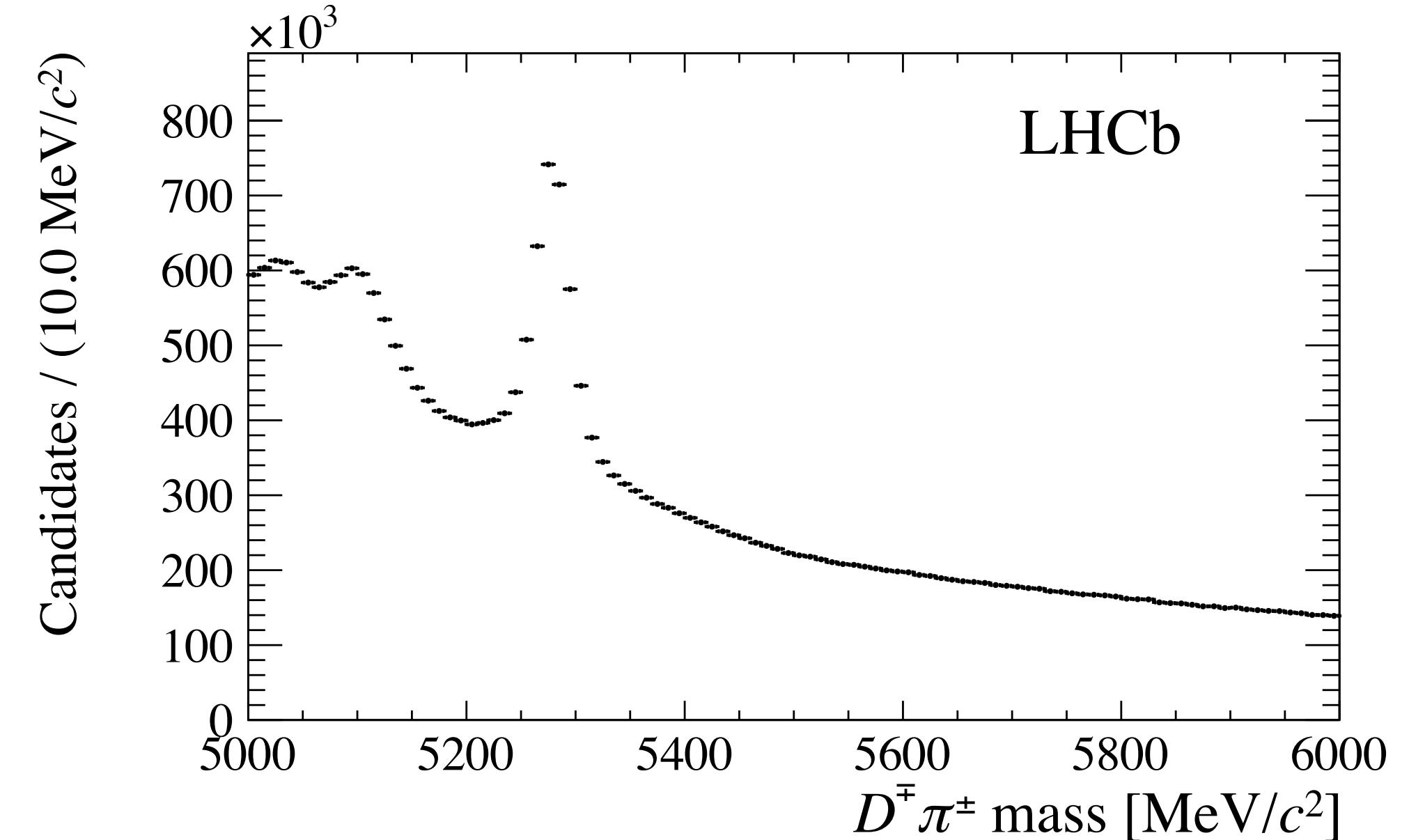
# The LHCb detector

- ▶ incoherent production of  $b\bar{b}$ -pairs
- ▶ precise  $\pi/K$  identification
  - $\epsilon(K \rightarrow K) \sim 95\%$
  - misID( $\pi \rightarrow K$ )  $\sim 5\%$



# Selection & Datasample

- ▶ sample based on  $3 \text{ fb}^{-1}$  from 2011 & 2012 (7 and 8 TeV)
- ▶  $B^0 \rightarrow D^\mp \pi^\pm$  reconstructed in  $D^- \rightarrow K^+ \pi^- \pi^-$
- ▶ loose preselection
- ▶ main offline selection of all  $(B^0, \text{PV})$  pairs:
  - vetoing physical backgrounds
  - reduction of combinatorial background with a BDT
- ▶ FoM: statistical uncertainty of  $CP$  violation parameters
  - apply selection
  - perform massfit to extract yields
  - generate toy sample
  - perform decay time fit to extract uncertainties
- ▶ overall signal efficiency:  $70.7 \pm 0.1\%$
- ▶ combinatoric background rejection:  $99.911 \pm 0.002\%$



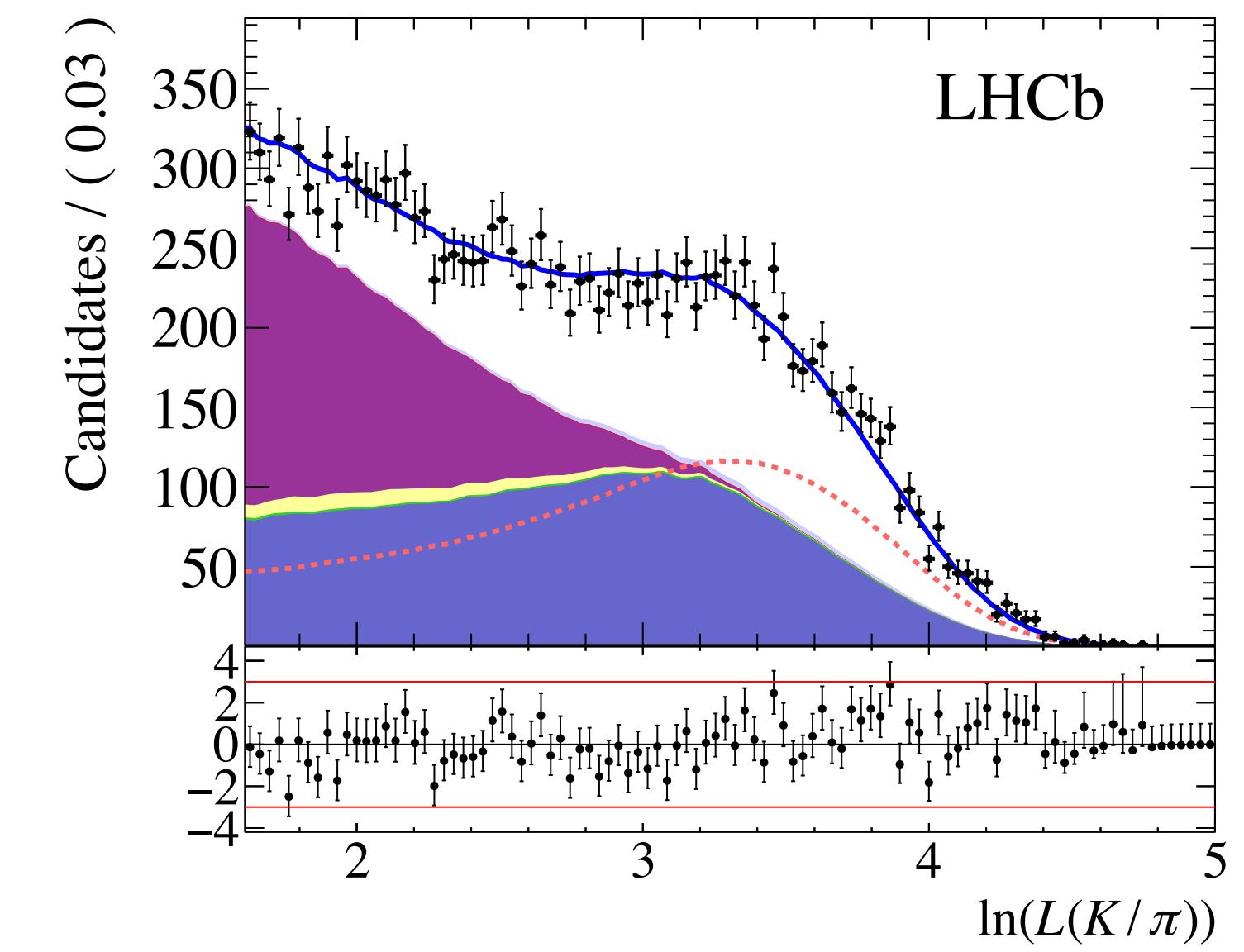
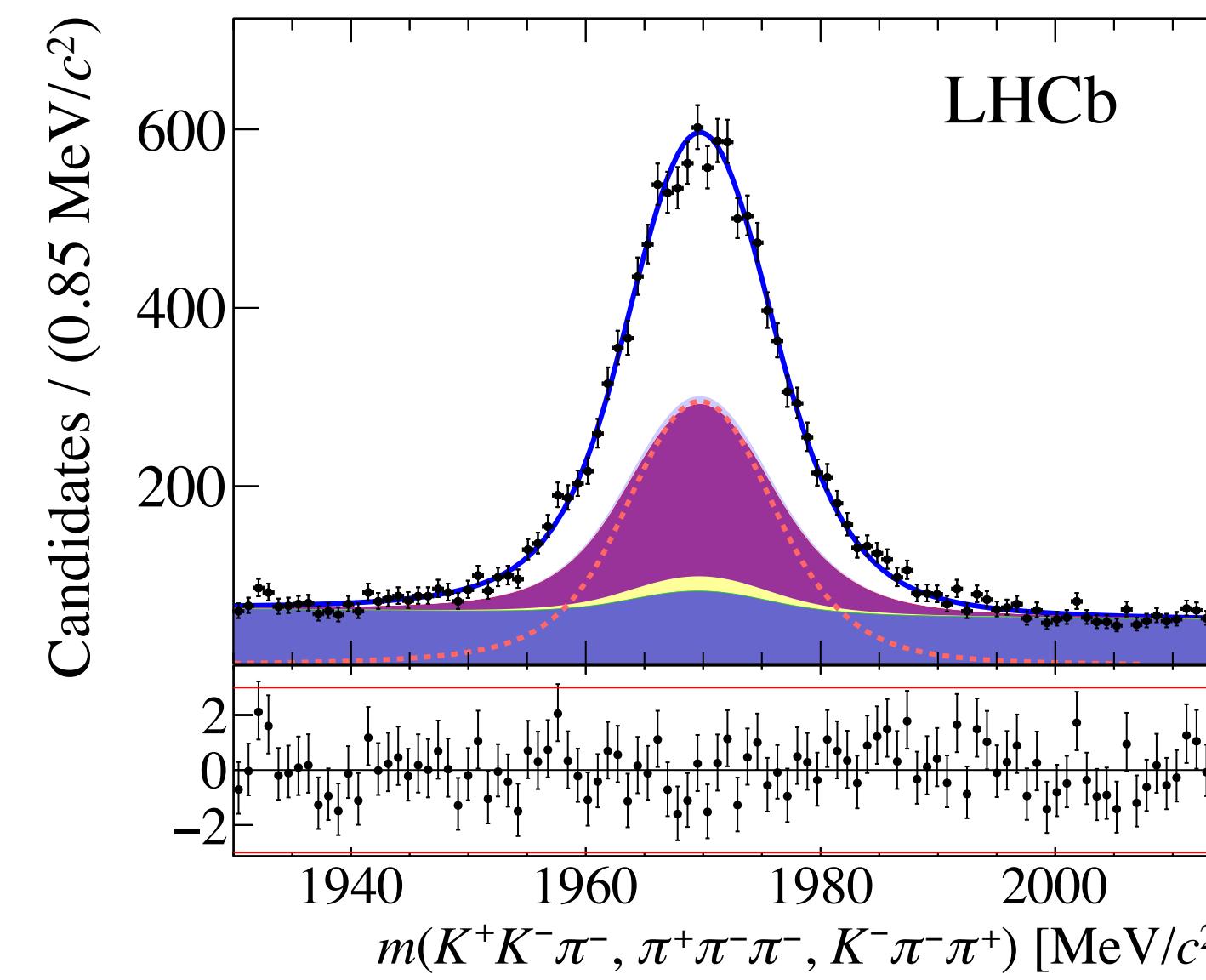
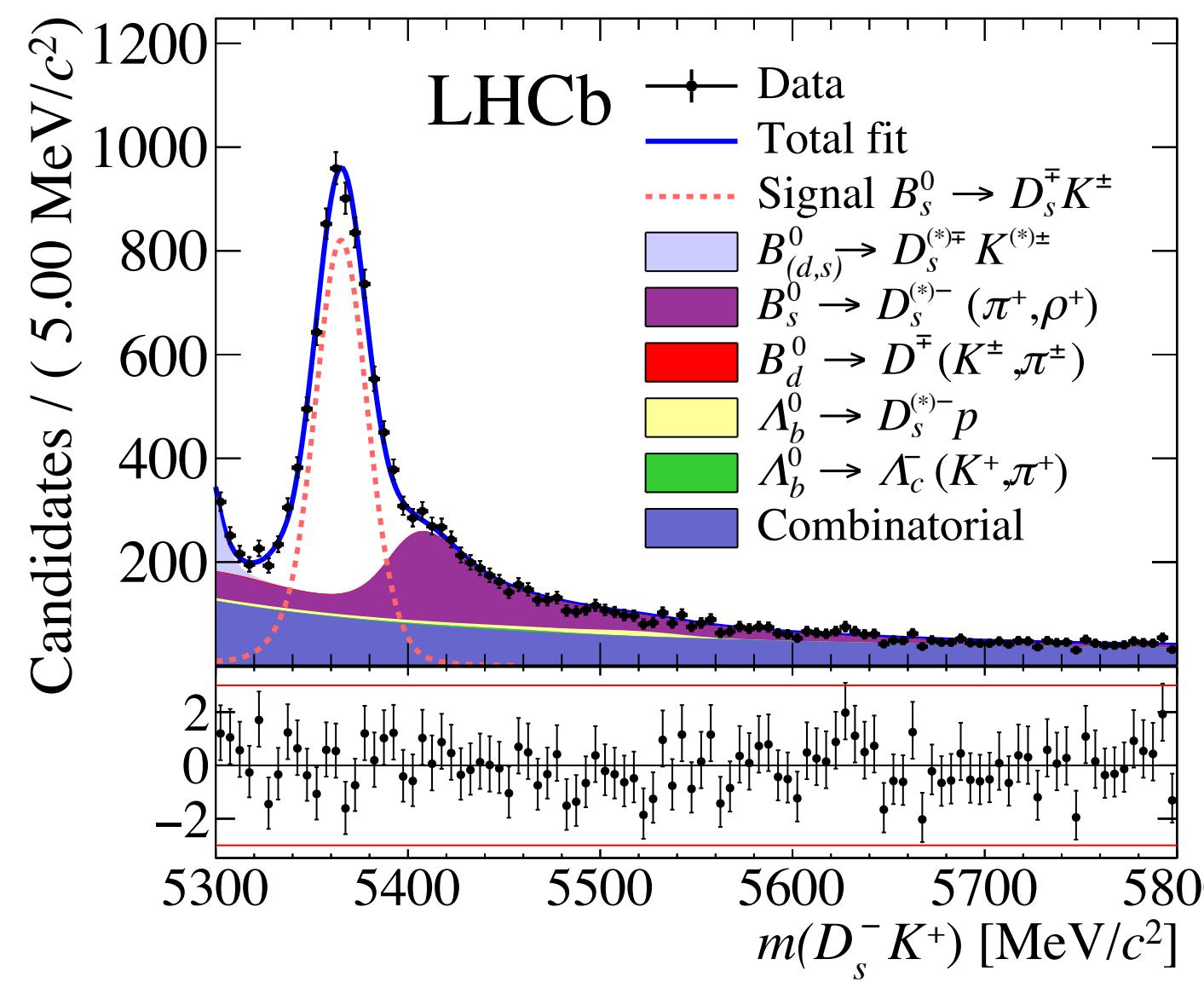
# Systematic uncertainties $B^0 \rightarrow D^\mp \pi^\pm$

- ▶ considered 10 sources of systematic uncertainties
  - uncertainties estimated by Gaussian constraints:  
 $\Delta m_d, \tau, \text{PID efficiencies}$
  - uncertainties estimated with toys:
    - tagging calibration models
    - tagging efficiency asymmetries
    - decay-time resolution & acceptance model
    - assumptions on  $\Delta\Gamma$  and  $C_f/C_{\bar{f}}$
  - varied background subtraction
  - fit biases: entire analysis validated on MC showing biases up to given values
- ▶ largest uncertainty from external input for oscillation frequency
- ▶ measurement statistically limited

Source	$S_f$	$S_{\bar{f}}$
uncertainty of $\Delta m$	0.0073	0.0061
fit biases	0.0068	0.0018
background subtraction	0.0042	0.0023
flavour-tagging models	0.0011	0.0015
flavour-tagging efficiency asymmetries	0.0012	0.0015
decay-time resolution	0.0012	0.0008
PID efficiencies	0.0008	0.0008
acceptance model	0.0007	0.0007
assumption on $\Delta\Gamma$	0.0007	0.0007
assumption on $C_f$ and $C_{\bar{f}}$	0.0006	0.0006
total	0.0111	0.0073
statistical uncertainties	0.0198	0.0199

# Selection & Massfit $B_s^0 \rightarrow D_s^\mp K^\pm$

- ▶ sample based on  $3\text{ fb}^{-1}$  from 2011 & 2012 (7 and 8 TeV)
- ▶ physical backgrounds suppressed using combination of PID information and kinematic vetoes
- ▶ combinatoric background suppressed with a BDT
- ▶ multidimensional fit to different  $D_s^-$  final states ( $KK\pi, K\pi\pi, \pi\pi\pi$ )



- ▶ #signal candidates:  $5955 \pm 90$

# Tagging performance $B_s^0 \rightarrow D_s^\mp K^\pm$

- ▶ effective tagging efficiency on  $B_s^0 \rightarrow D_s^\mp K^\pm$ :
- ▶ control channel  $B_s^0 \rightarrow D_s^- \pi^+$ :

$B_s^0 \rightarrow D_s^- \pi^+$	$\varepsilon_{\text{tag}} [\%]$	$\varepsilon_{\text{eff}} [\%]$
OS only	$12.94 \pm 0.11$	$1.41 \pm 0.11$
SS only	$39.70 \pm 0.16$	$1.29 \pm 0.13$
Both OS and SS	$24.21 \pm 0.14$	$3.10 \pm 0.18$
Total	$76.85 \pm 0.24$	$5.80 \pm 0.25$

- ▶ calibration parameters obtained on  $B_s^0 \rightarrow D_s^- \pi^+$ :

	$\langle \eta \rangle$	$p_0$	$p_1$	$\varepsilon_{\text{tag}} [\%]$
OS	0.370	$0.3740 \pm 0.0061 \pm 0.0004$	$1.094 \pm 0.063 \pm 0.012$	$37.15 \pm 0.17$
SS	0.437	$0.4414 \pm 0.0047 \pm 0.0002$	$1.084 \pm 0.068 \pm 0.006$	$63.90 \pm 0.17$
	-	$\Delta p_0$	$\Delta p_1$	$\Delta \varepsilon_{\text{tag}} [\%]$
OS	-	$0.0138 \pm 0.0060 \pm 0.0001$	$0.126 \pm 0.062 \pm 0.002$	$-1.14 \pm 0.72$
SS	-	$-0.0180 \pm 0.0047 \pm 0.0002$	$0.134 \pm 0.067 \pm 0.002$	$0.82 \pm 0.72$

# Systematic uncertainties $B_s^0 \rightarrow D_s^\mp K^\pm$

- ▶ estimated using large sets of pseudoexperiments
  - generated with central values from decay time fit
  - fitted with same procedure as on data - varying fit model by systematic effect

Source	$C_f$	$A_f^{\Delta\Gamma}$	$A_{\bar{f}}^{\Delta\Gamma}$	$S_f$	$S_{\bar{f}}$
Detection asymmetry	0.02	0.28	0.29	0.02	0.02
$\Delta m_s$	0.11	0.02	0.02	0.20	0.20
Tagging and scale factor	0.18	0.02	0.02	0.16	0.18
Tagging asymmetry	0.02	0.00	0.00	0.02	0.02
Correlation among observables	0.20	0.38	0.38	0.20	0.18
Closure test	0.13	0.19	0.19	0.12	0.12
Acceptance, simulation ratio	0.01	0.10	0.10	0.01	0.01
Acceptance data fit, $\Gamma_s, \Delta\Gamma_s$	0.01	0.18	0.17	0.00	0.00
Total	0.32	0.55	0.55	0.35	0.35