b-flavour tagging in *pp* collisions

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Basics

Introduction

Measurements of flavour oscillations and time-dependent *CP* asymmetries in neutral *B* meson systems require knowledge of the *b* quark flavour at production. This identification is performed by the Flavour Tagging (FT). [1,2]

Two independent classes of algorithms

- **same side taggers (SS)**
  use charged particles created in the fragmentation process of the *b* quark of the signal *B* meson

  - kaon for B_s^0 $\rightarrow$ SS kaon / SS kaon nnet
  - pion for B^0 $\rightarrow$ SS pion
  - proton for B^0 $\rightarrow$ SS proton

- **opposite side taggers (OS)**
  exploit the non-signal *b* quark of the initial $b\bar{b}$ pair

  - overall charge of the secondary vertex (SV)
    $\rightarrow$ OS vertex charge
  - lepton from semi-leptonic *b* hadron decays
    $\rightarrow$ OS muon / OS electron
  - kaon from the $b \rightarrow c \rightarrow s$ decay chain
    $\rightarrow$ OS kaon
  - *D* meson from the $b \rightarrow c$ decay chain
    $\rightarrow$ OS charm (New!)
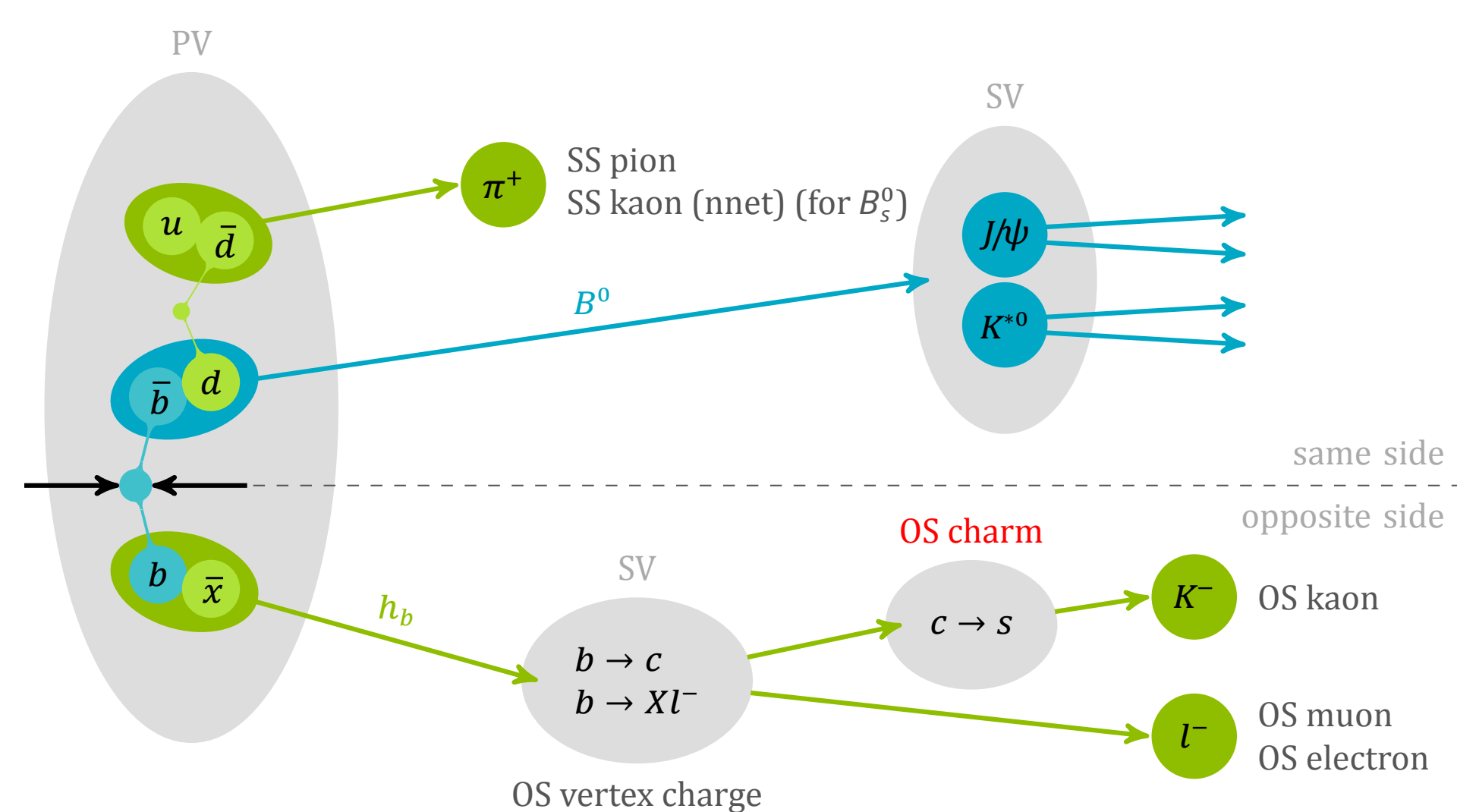
Each tagger provides a decision *d* on the initial flavour ("tag") and a probability to be wrong, η.

Flavour Tagging characteristics

- **mistag**
  fraction of events with a wrong tagging decision
  $$\omega = \frac{N_{\text{wrong}}}{N_{\text{right}} + N_{\text{wrong}}}$$

- **tagging efficiency**
  fraction of events with a tagging decision
  $$\varepsilon_{\text{tag}} = \frac{N_{\text{right}} + N_{\text{wrong}}}{N_{\text{all}}}$$

- **effective tagging efficiency**
  represents the statistical reduction factor of a sample in a tagged analysis
  $$\varepsilon_{\text{eff}} = \varepsilon_{\text{tag}} (1 - 2\omega)^2$$
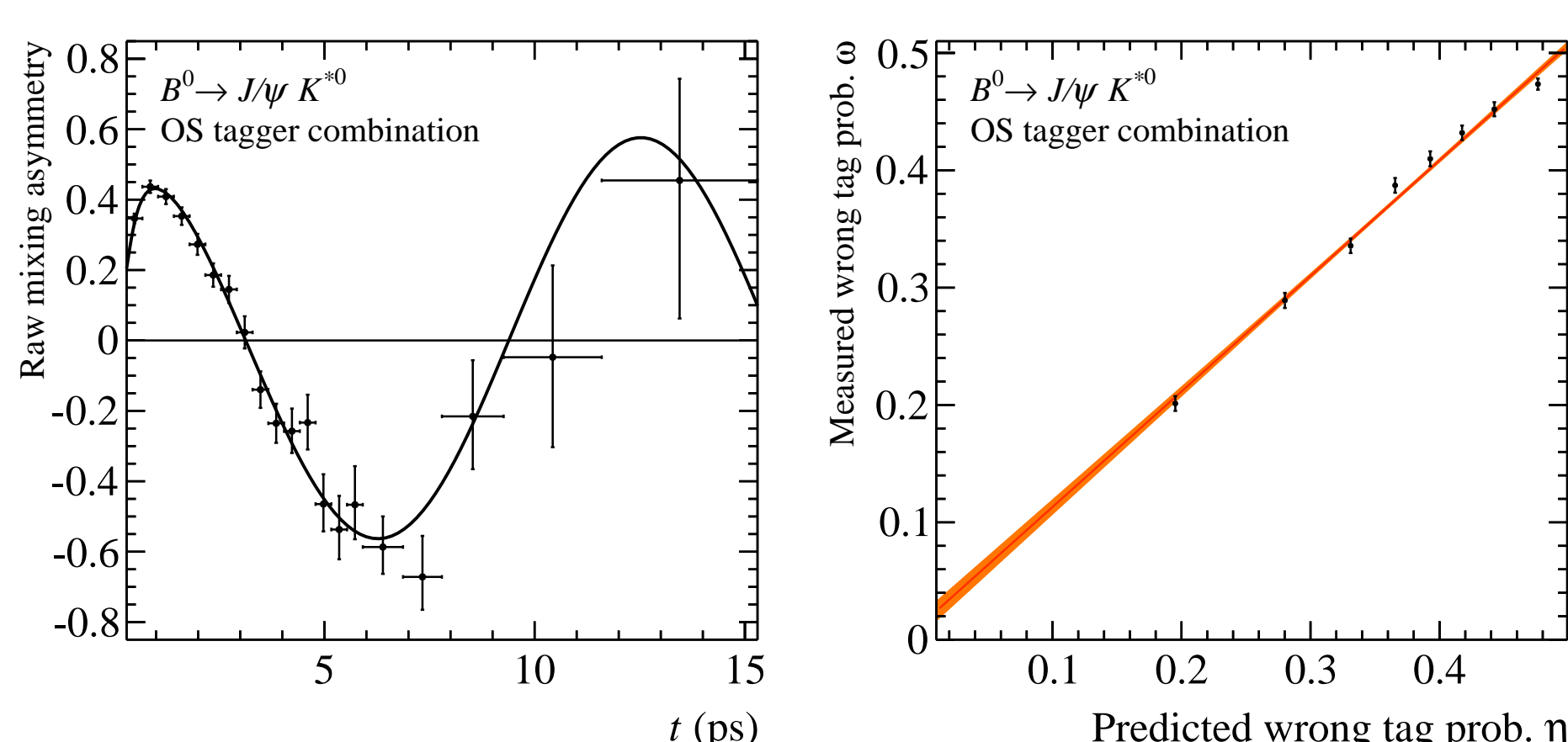
Calibration

Mistag calibration

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

- p_0, p_1: calibrated ev-by-ev mistag
- η: estimated ev-by-ev mistag
- $\langle\eta\rangle$: mean estimated mistag

Several flavour-specific decay channels are used

- $B^+ \rightarrow J/\psi\,K^+$, $B^+ \rightarrow D^0\pi^+$
  charged channels: extract ω by comparing tag decision with charge of the final state

- $B^0 \rightarrow J/\psi\,K^{*0}$, $B^0 \rightarrow D^{*-}\mu^+\nu_\mu$, $B_s^0 \rightarrow D_s^-\pi^+$, …
  neutral channels: full time-dependent analysis to extract ω from the mixing asymmetry
  $$\mathcal{A}_{\text{mix}}(t) \propto (1 - 2\omega)\cos(\Delta m_{d/s}t)$$

## Flavour Tagging in Run I

Usage in analyses

- one calibration per tagger valid for all channels
- systematic uncertainties from
  - calibration methods
  - results in different control channels
- "ad-hoc" calibration using best-suited control channels for analyses dominated by FT uncertainty

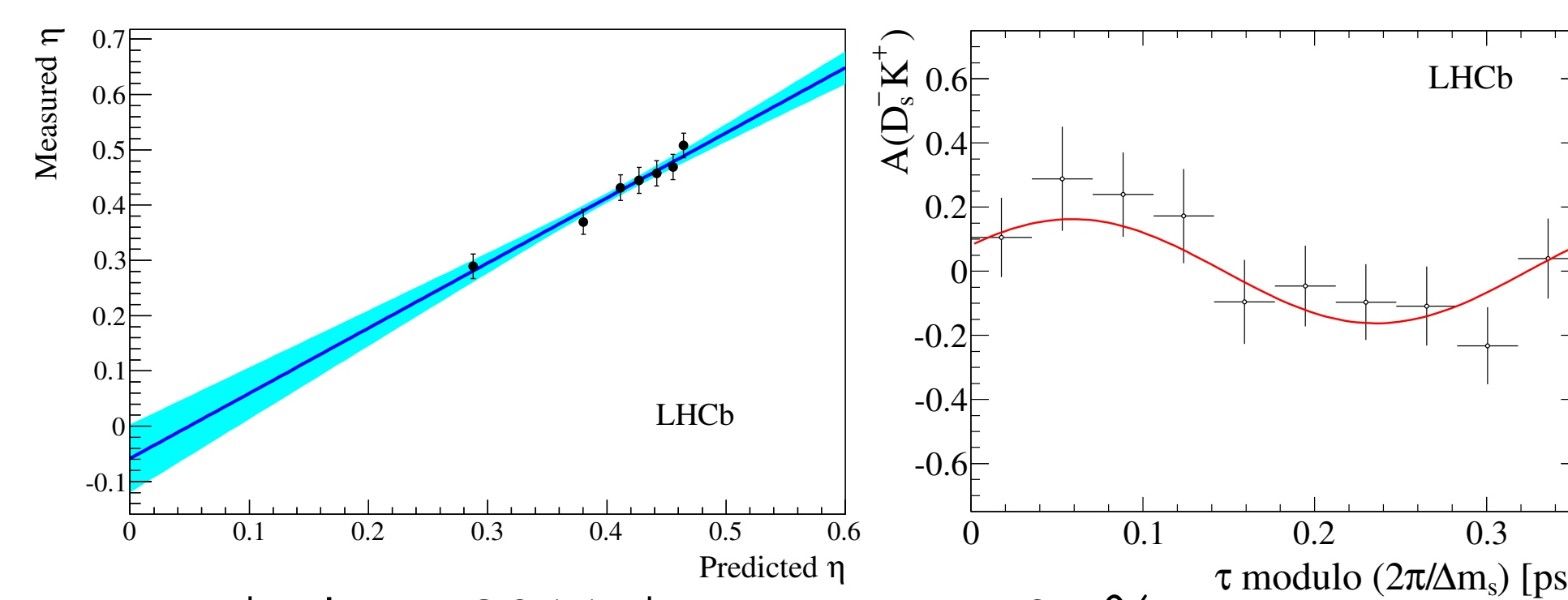### Highlights of flavour-tagged measurements

- **Measurements of ϕ_s**

Decay mode	$\varepsilon_{\text{eff},2011}$	$\varepsilon_{\text{eff, Run I}}$
$B_s^0 \rightarrow J/\psi\,K^+K^-$	3.13 [3]	3.73 [4]
$B_s^0 \rightarrow J/\psi\,\pi^+\pi^-$	2.43 [5]	3.89 [6]
$\bar{B}_s^0 \rightarrow D_s^+D_s^-$	-	5.33 [7]

  - newest analyses profited from:
    $\rightarrow$ including SS kaon nnet tagger
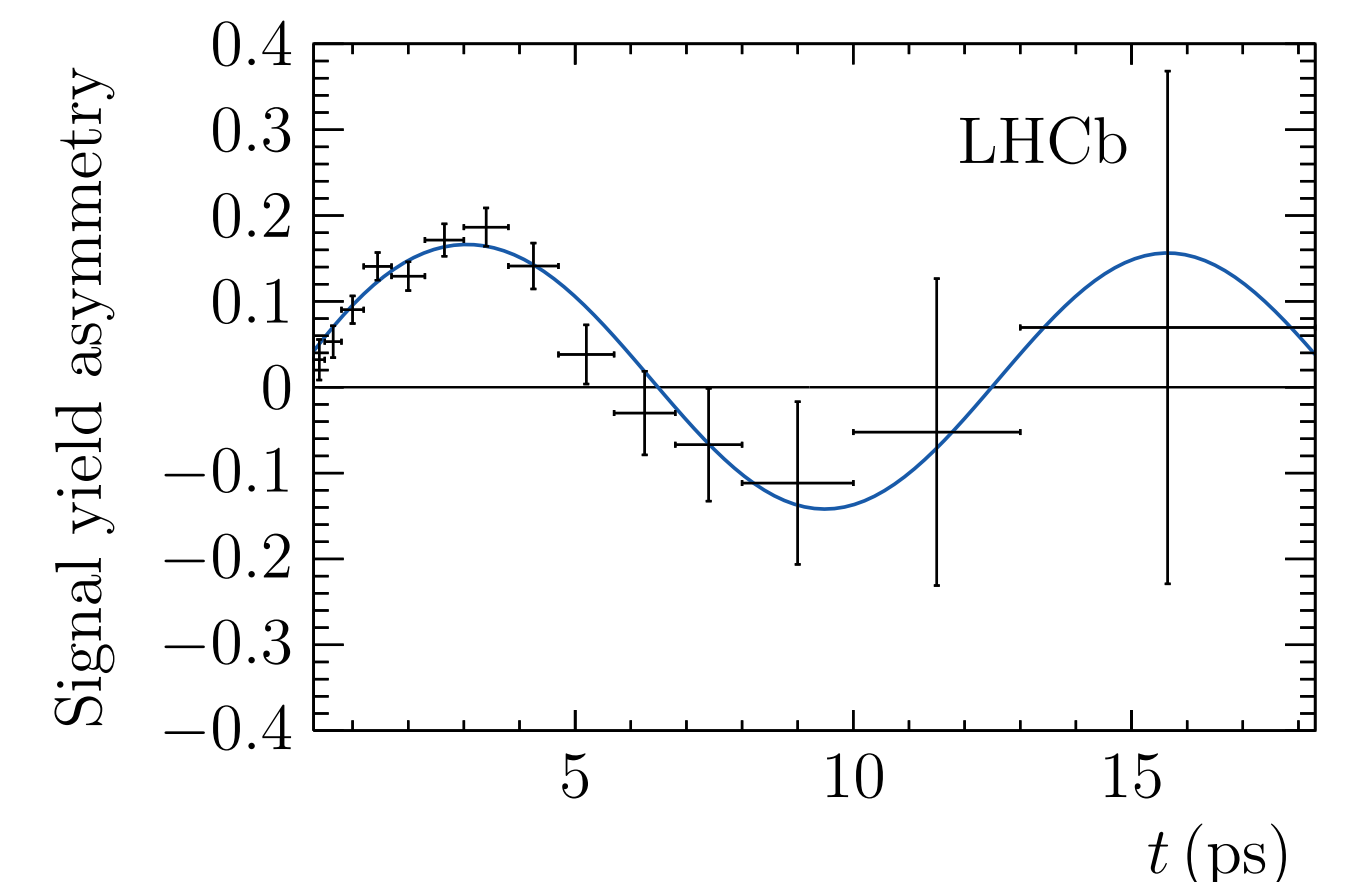 $\rightarrow$ re-optimisation of OS algorithms
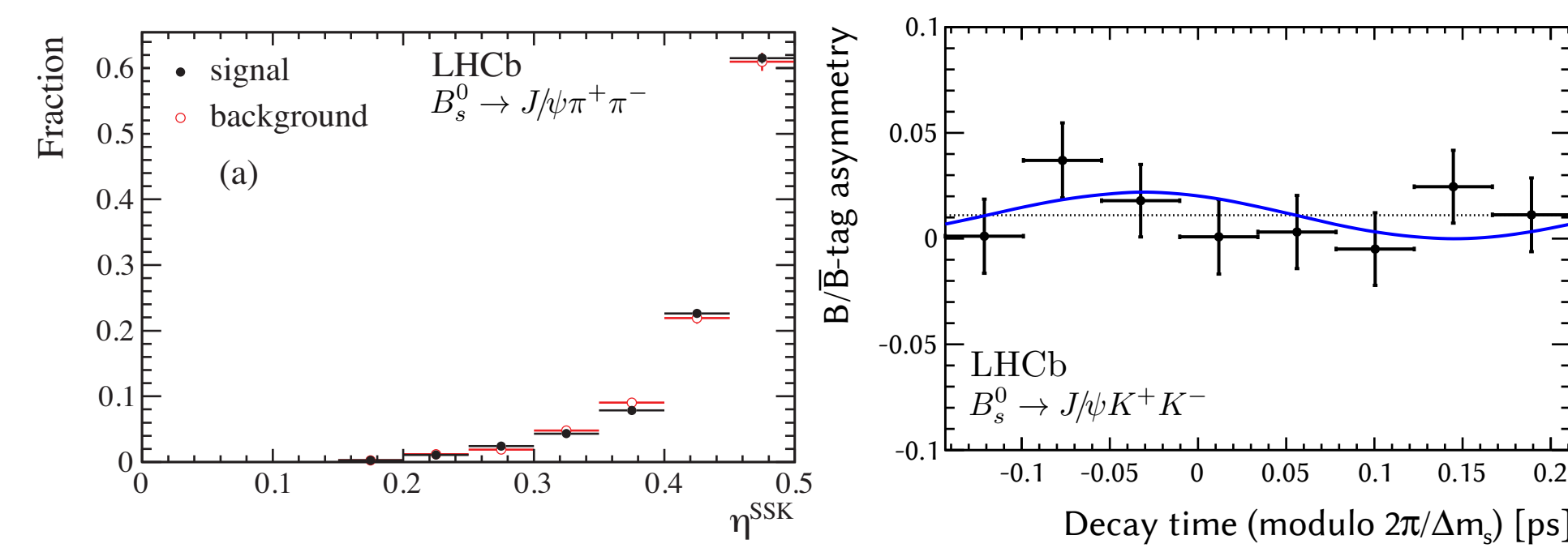
- **CP violation in $B_s^0 \rightarrow D_s^\mp K^\pm$**

  - analysis on 2011 data: $\varepsilon_{\text{eff}} = 5.07\,\%$
  - SS kaon nnet adds more than 1.3 % to ε_{eff} [8]

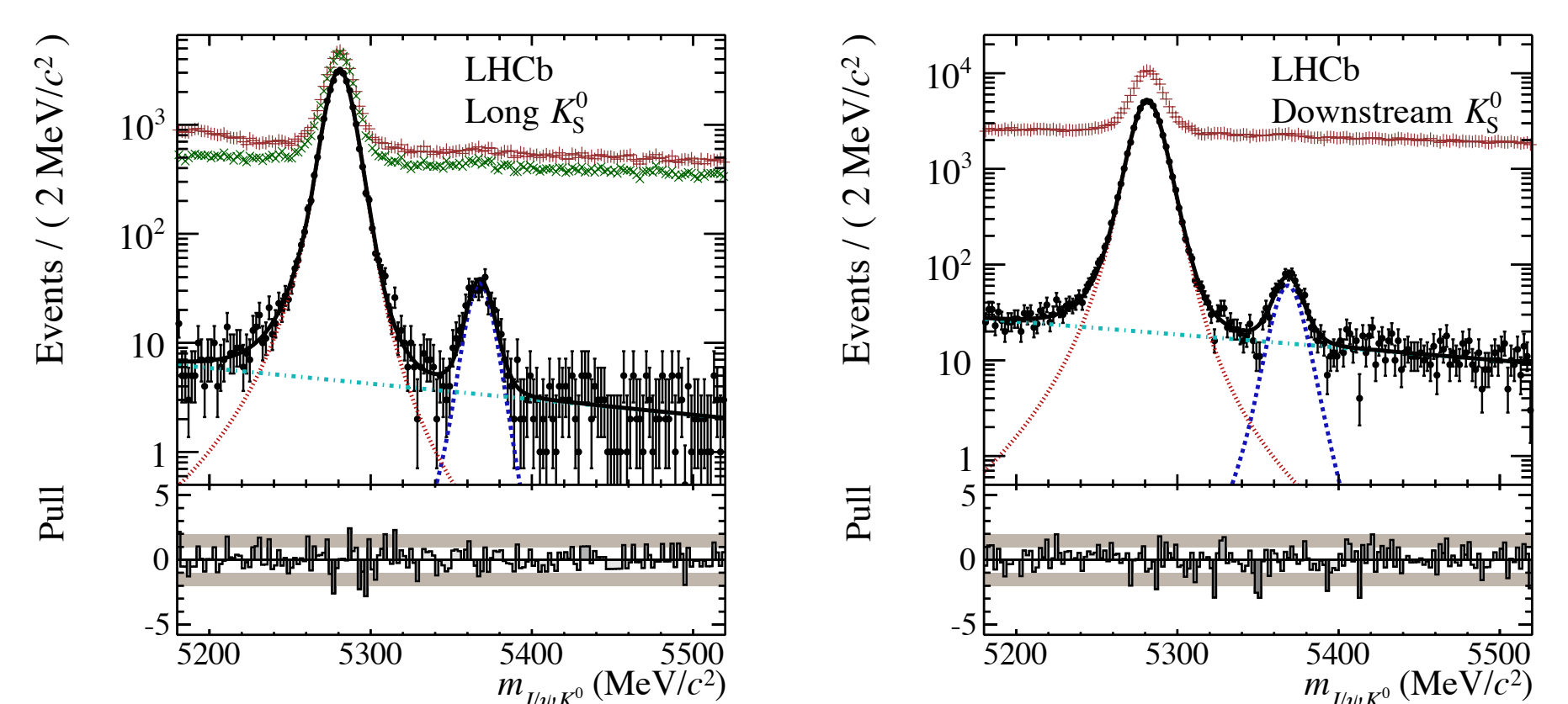- **CP violation in $B^0 \rightarrow J/\psi\,K_S^0$ (sin 2β)**

  - analysis on 2011 data: $\varepsilon_{\text{eff}} = 2.38\,\%$ [9]
  - full Run I analysis: $\varepsilon_{\text{eff}} = 3.02\,\%$ [10]
    $\rightarrow$ SS pion tagger adds more than 0.376 % to ε_{eff}

  - precision analysis $\rightarrow$ "ad-hoc" FT calibration
    $\rightarrow$ OS algorithms calibrated with $B^+ \rightarrow J/\psi\,K^+$
    $\rightarrow$ SS pion calibrated with $B^0 \rightarrow J/\psi\,K^{*0}$

- **CP violation in $B_s^0 \rightarrow J/\psi\,K_S^0$**

  - not possible to exclude B^0 events in selection

  - B_s^0 events: $\varepsilon_{\text{eff}} = 4.00\,\%$ [11]
  - B^0 events: $\varepsilon_{\text{eff}} = 2.62\,\%$ [11]
    $\rightarrow$ small contribution of SS kaon for B^0 due to:
    - same-side protons misidentified as kaons
    - kaons from same-side K^* (892)
    $\rightarrow$ kaons have opposite charge for B^0: tagging decision has to be inverted

Developments

OS charm tagger (preliminary)

- reconstruct $D^0/D^\pm/D^*$ decays related to OS *b* decay

Decay mode	Relative ε_{tag}	Relative ε_{eff}
$D^0 \rightarrow K^-\pi^+$	10.0 %	24.0 %
$D^0 \rightarrow K^-\pi^+\pi^+\pi^-$	5.9 %	8.4 %
$D^+ \rightarrow K^-\pi^+\pi^+$	10.3 %	2.6 %
$D^0, D^+ \rightarrow K^-\pi^+X$	69.7 %	61.5 %
$D^0, D^+ \rightarrow K^-e^+X$	0.5 %	0.2 %
$D^0, D^+ \rightarrow K^-\mu^+X$	3.4 %	0.3 %
$\Lambda_c^+ \rightarrow p^+K^-\pi^+$	0.2 %	2.4 %

- one boosted decision tree (BDT) for each mode [12]
- clean measure of *B* meson flavour (low mistag)
- stand-alone tagging power of $\varepsilon_{\text{eff}} = 0.30\,\%$ to $0.40\,\%$
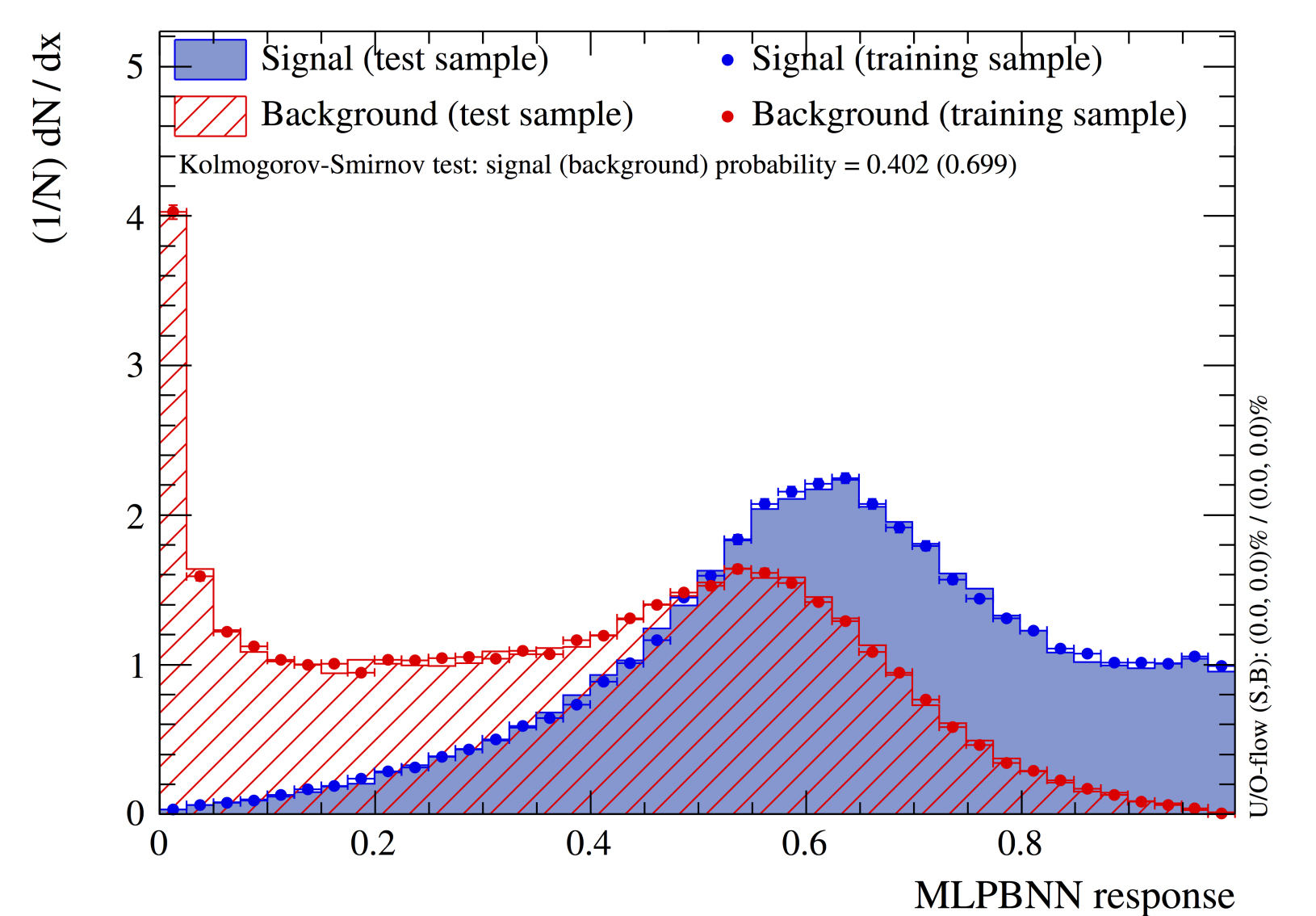
SS pion calibration

- calibration performed with $B^0 \rightarrow J/\psi\,K^{*0}$
- full evaluation of systematic uncertainties
- used for the first time in the measurements of

  - $\sin(2\beta)$ with $B^0 \rightarrow J/\psi\,K_S^0$
    $\Rightarrow \varepsilon_{\text{eff}}^{\text{SS}\pi} = 0.38\,\%$

  - $\sin(2\beta_{\text{eff}})$ with $B^0 \rightarrow J/\psi\,\pi^+\pi^-$
    $\Rightarrow \varepsilon_{\text{eff}}^{\text{SS}\pi} = 0.54\,\%$

SS kaon tagging using neural nets (NN)

- basic idea: use two NN
  - first NN distinguishes between:
    1. fragmentation tracks
       $\Rightarrow$ signal for SS kaon nnet
    2. underlying event tracks

  - second NN:
    $\circ$ assigns final tag and mistag based on multiple candidates [13]

- SS kaon nnet tagger is a great success, compared to the previous cut-based SS kaon it gives
  - $B_s^0 \rightarrow D_s^-\pi^+$: 50 % relative improvement in ε_{eff}
  - $B_s^0 \rightarrow J/\psi\,\phi$: 41 % relative improvement in ε_{eff}

References

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[8] LHCb Collaboration, R. Aaij et. al., *Measurement of CP asymmetry in $B_s^0 \rightarrow D_s^\mp K^\pm$ decays*, JHEP 1411 (2014) 060

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