b-flavour tagging in *pp* collisions

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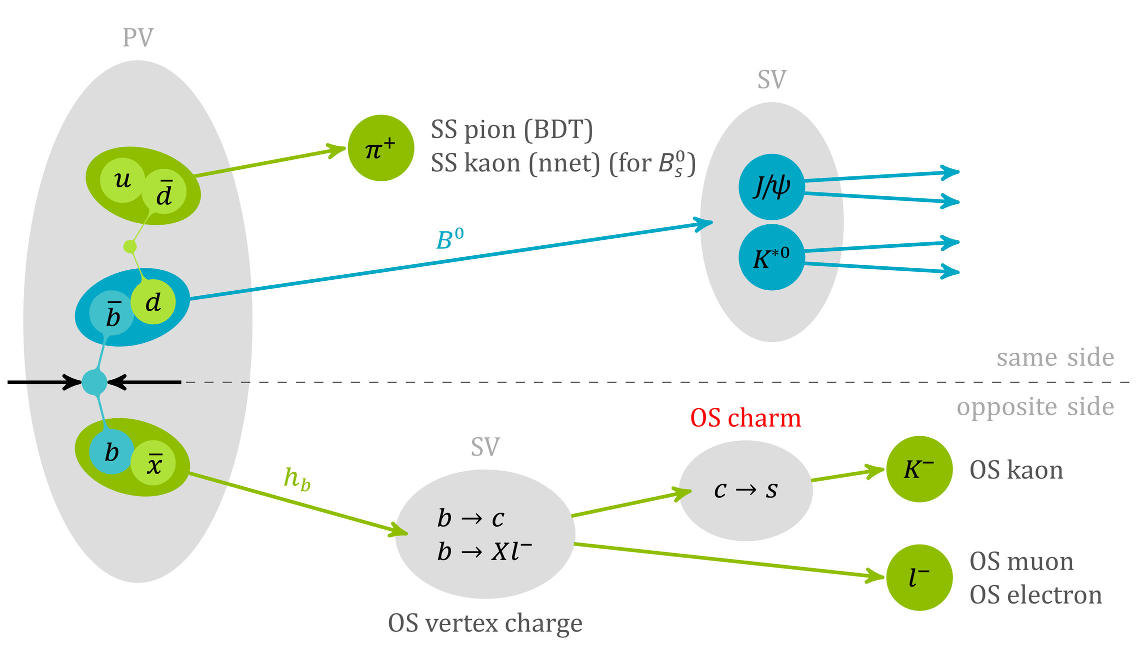
Basics

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 → SS kaon / SS kaon nnet
  - pion for B^0 → SS pion
  - proton for B^0 → 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) → OS vertex charge
  - lepton from semi-leptonic *b* hadron decays → OS muon / OS electron
  - kaon from the $b \to c \to s$ decay chain → OS kaon
  - *D* meson from the $b \to c$ decay chain → 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

$$\omega = \frac{N_{\mathrm{wrong}}}{N_{\mathrm{right}} + N_{\mathrm{wrong}}}$$

- **tagging efficiency**
  fraction of events with a tagging decision

$$\varepsilon_{\mathrm{tag}} = \frac{N_{\mathrm{right}} + N_{\mathrm{wrong}}}{N_{\mathrm{all}}}$$

- **effective tagging efficiency**
  represents the statistical reduction factor of a sample in a tagged analysis

$$\varepsilon_{\mathrm{eff}} = \varepsilon_{\mathrm{tag}}\,(1 - 2\omega)^2$$

Calibration

Mistag calibration

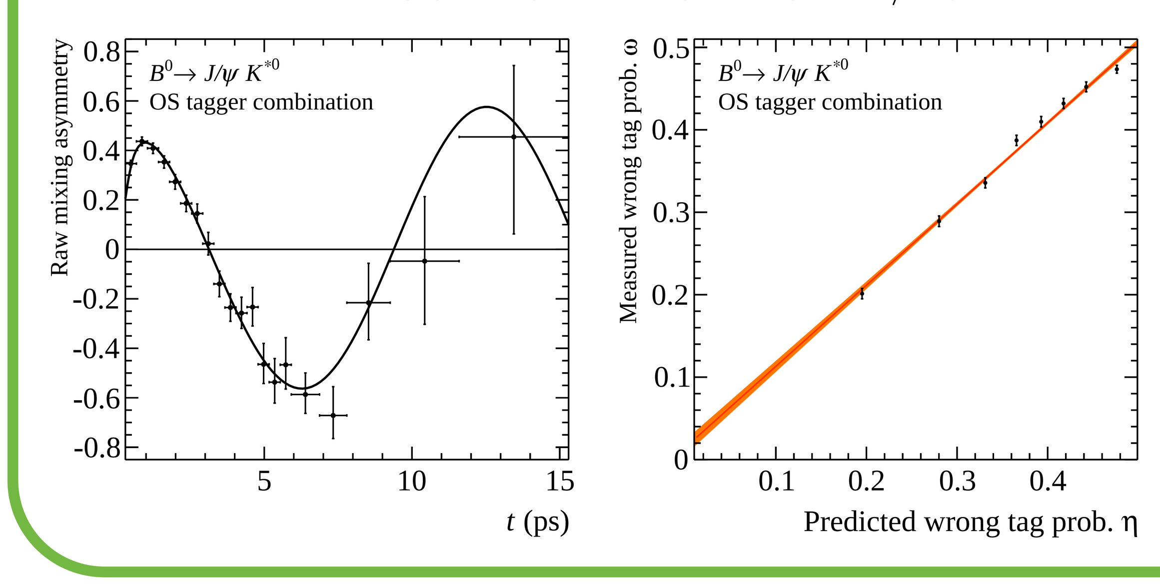
$$\omega(\eta) = p_0 + p_1\,(\eta - \langle\eta\rangle)$$

calibrated ev-by-ev mistag — estimated ev-by-ev mistag — mean estimated mistag

Several flavour-specific decay channels are used

- $B^+ \to J/\psi\, K^+$, $B^+ \to D^0\pi^+$
  charged channels: extract ω by comparing tag decision with charge of the final state
- $B^0 \to J/\psi\, K^{*0}$, $B^0 \to D^{*-}\mu^+\nu_\mu$, $B_s^0 \to D_s^-\pi^+$, ...
  neutral channels: full time-dependent analysis to extract ω from the mixing asymmetry

$$\mathcal{A}_{\mathrm{mix}}(t) \propto (1 - 2\omega)\cos(\Delta m_{d/s}\, t)$$



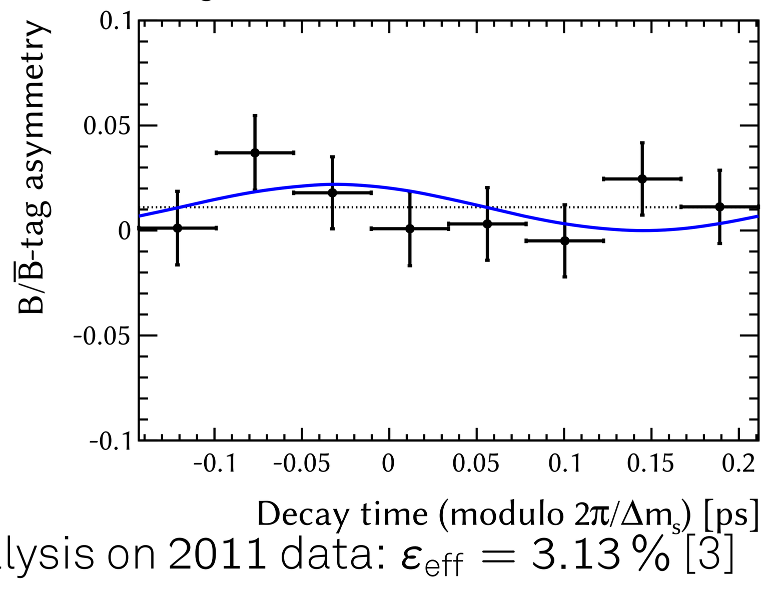
Flavour Tagging in Run I

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

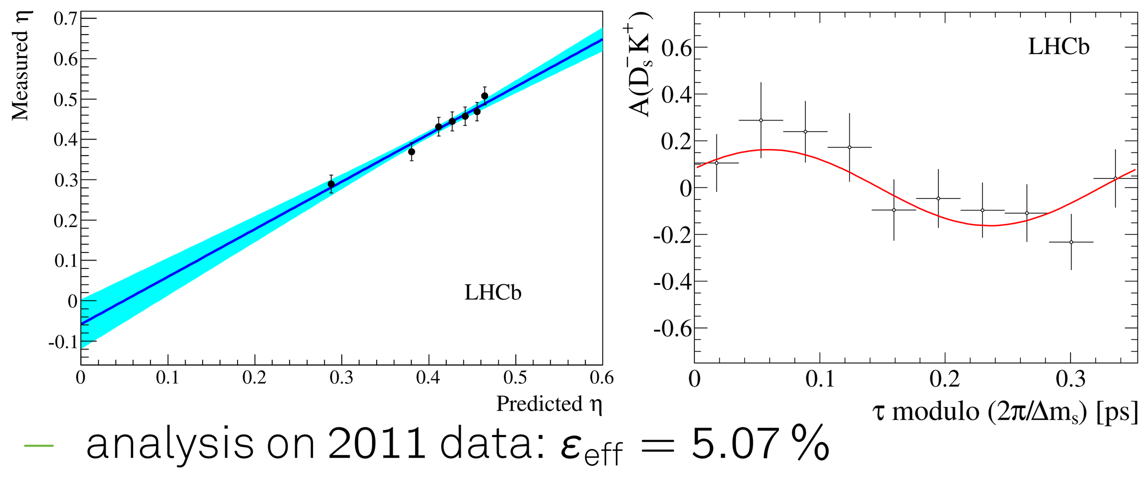
Highlights of flavour-tagged measurements

- *CP* violation in $B_s^0 \to J/\psi\, K^+K^-$



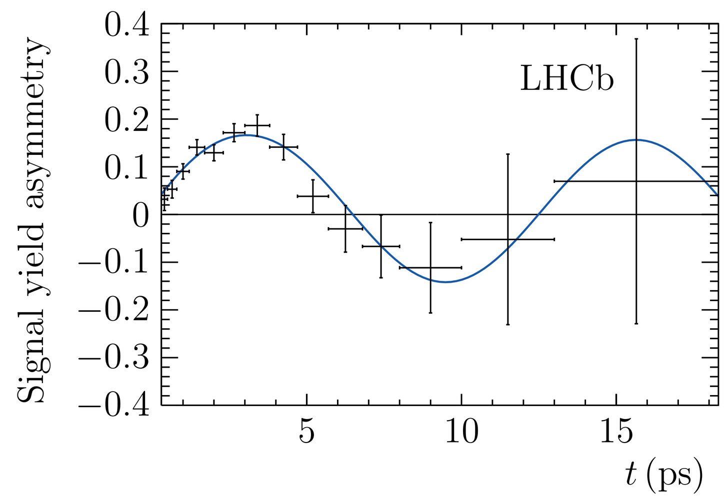
  - analysis on 2011 data: $\varepsilon_{\mathrm{eff}} = 3.13\,\%$ [3]
  - full Run I analysis: $\varepsilon_{\mathrm{eff}} = 3.73\,\%$ [4]
  - newest analysis profited from
    → including SS kaon nnet tagger
    → re-optimisation of OS algorithms

- *CP* violation in $B_s^0 \to D_s^{\mp}K^{\pm}$



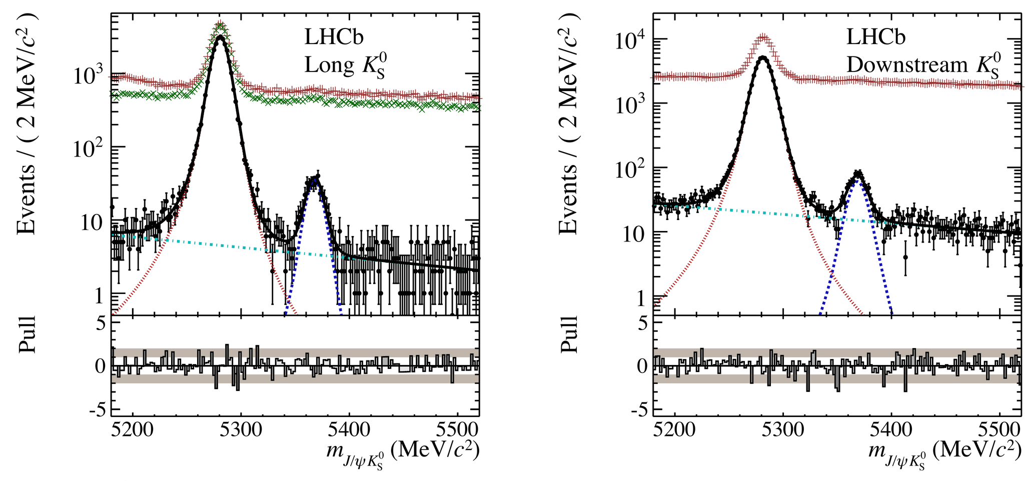
  - analysis on 2011 data: $\varepsilon_{\mathrm{eff}} = 5.07\,\%$
  - SS kaon nnet adds more than $1.3\,\%$ to $\varepsilon_{\mathrm{eff}}$ [5]

- *CP* violation in $B^0 \to J/\psi\, K_S^0$ ($\sin 2\beta$)
  - analysis on 2011 data: $\varepsilon_{\mathrm{eff}} = 2.38\,\%$ [6]
  - full Run I analysis: $\varepsilon_{\mathrm{eff}} = 3.02\,\%$ [7]
    → SS pion tagger adds more than $0.376\,\%$ to $\varepsilon_{\mathrm{eff}}$



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

- *CP* violation in $B_s^0 \to J/\psi\, K_S^0$
  - not possible to exclude B^0 events in selection



  - B_s^0 events: $\varepsilon_{\mathrm{eff}} = 4.00\,\%$ [8]
  - B^0 events: $\varepsilon_{\mathrm{eff}} = 2.62\,\%$ [8]
    → small contribution of SS kaon for B^0 due to:
      - same-side protons misidentified as kaons
      - kaons from same-side K^* (892)
    ⇒ 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 $\varepsilon_{\mathrm{tag}}$	Relative $\varepsilon_{\mathrm{eff}}$
$D^0 \to K^-\pi^+$	10.0 %	24.0 %
$D^0 \to K^-\pi^+\pi^+\pi^-$	5.9 %	8.4 %
$D^+ \to K^-\pi^+\pi^+$	10.3 %	2.6 %
$D^0, D^+ \to K^-\pi^+X$	69.7 %	61.5 %
$D^0, D^+ \to K^-e^+X$	0.5 %	0.2 %
$D^0, D^+ \to K^-\mu^+X$	3.4 %	0.3 %
$\Lambda_c^+ \to p^+K^-\pi^+$	0.2 %	2.4 %

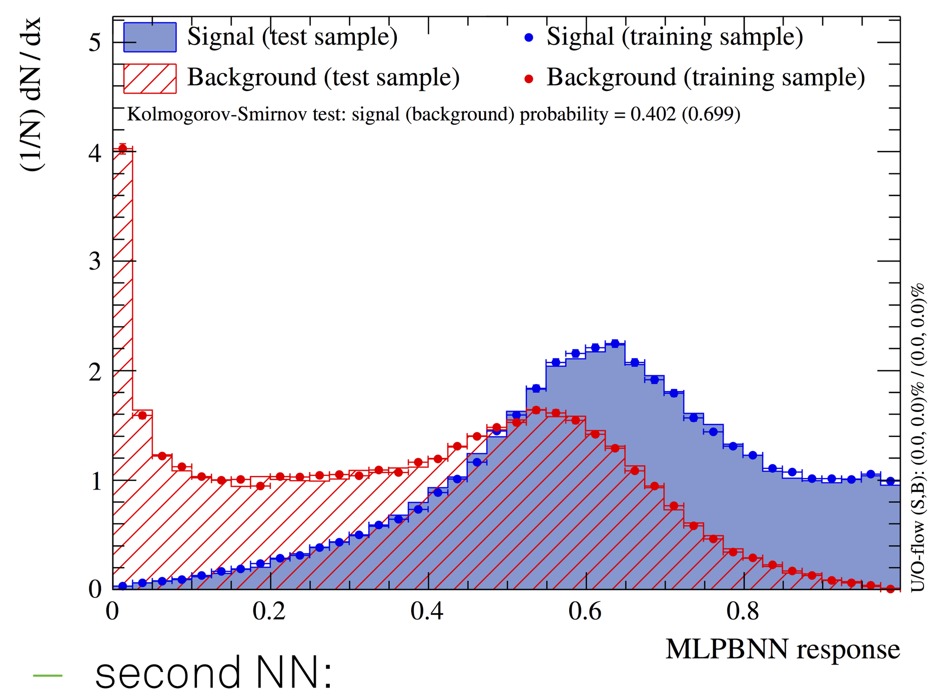
- one boosted decision tree (BDT) for each mode [9]
- clean measure of *B* meson flavour (low mistag)
- stand-alone tagging power of $\epsilon_{\mathrm{eff}} = 0.30\,\%$ to $0.40\,\%$

SS pion calibration

- calibration performed with $B^0 \to J/\psi\, K^{*0}$
- full evaluation of systematic uncertainties
- used for the first time in the measurements of
  - $\sin(2\beta)$ with $B^0 \to J/\psi\, K_S^0$
    ⇒ precision comparable to *B*-factories
    ⇒ $\varepsilon_{\mathrm{eff}}^{\mathrm{SS}\pi} = 0.38\,\%$
  - $\sin(2\beta_{\mathrm{eff}})$ with $B^0 \to J/\psi\, \pi^+\pi^-$
    ⇒ $\varepsilon_{\mathrm{eff}}^{\mathrm{SS}\pi} = 0.54\,\%$

SS kaon tagging using neural nets (NN)

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



  - second NN:
    - assigns final tag and mistag based on multiple candidates[10]
- SS kaon nnet tagger is a great success, compared to the previous cut-based SS kaon it gives
  - $B_s^0 \to D_s^-\pi^+$: 50 % relative improvement in $\varepsilon_{\mathrm{eff}}$
  - $B_s^0 \to J/\psi\,\phi$: 41 % relative improvement in $\varepsilon_{\mathrm{eff}}$

References

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[2] LHCb Collaboration, R. Aaij et. al., *Optimization and calibration of the same-side kaon tagging algorithm using hadronic B_s^0 decays in 2011 data,* LHCb-CONF-2012-033

[3] LHCb Collaboration, R. Aaij et. al., *Measurement of CP violation and the B_s^0 meson decay width difference with $B_s^0 \to J/\psi\, K^+K^-$ and $\bar{B}_s^0 \to J/\psi\,\pi^+\pi^-$ decays,* Phys.Rev. D87 (2013) 112010

[4] LHCb Collaboration, R. Aaij et. al., *Precision measurement of CP violation in $B_s^0 \to J/\psi\, K^+K^-$ decays,* Phys.Rev.Lett. 114 (2015) 4 041801

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

[6] LHCb Collaboration, R. Aaij et. al., *Measurement of the time-dependent CP asymmetry in $B^0 \to J/\psi\, K_S^0$ decays,* Phys.Lett. B721 (2013) 24-31

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[9] LHCb Collaboration, R. Aaij et. al., *B flavor tagging using reconstructed charm decays at the LHCb experiment,* LHCb-PAPER-2015.027

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