b-flavour tagging in pp collisions

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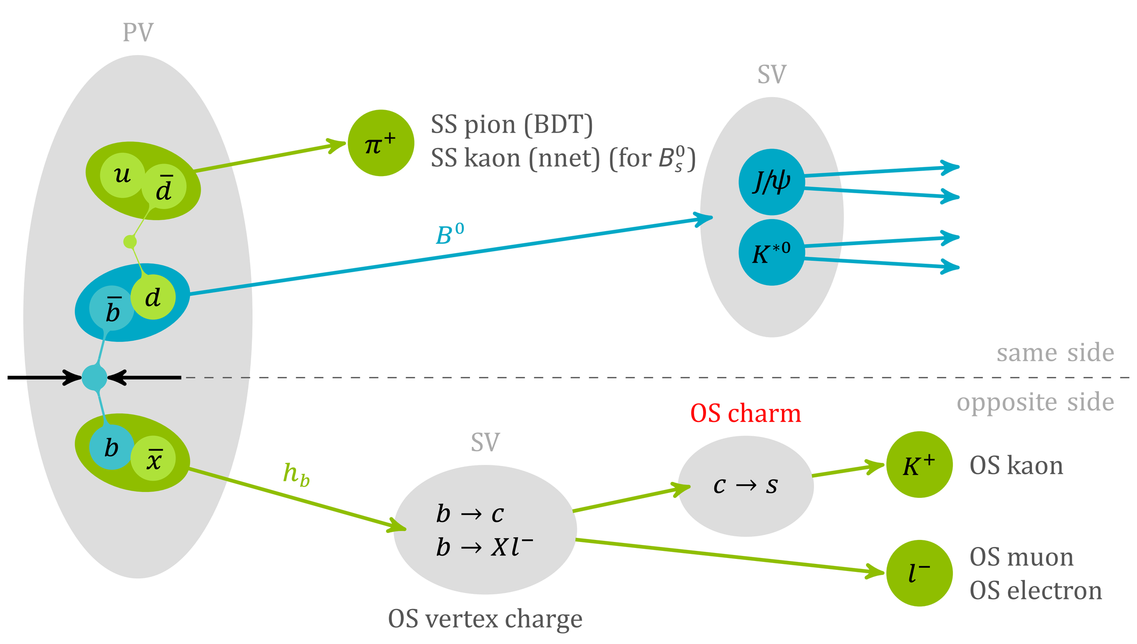
Basics

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. [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 / SS pion BDT
  - 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 / OS kaon nnet
  - D meson from the $b \rightarrow c$ decay chain $\rightarrow$ OS charm



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

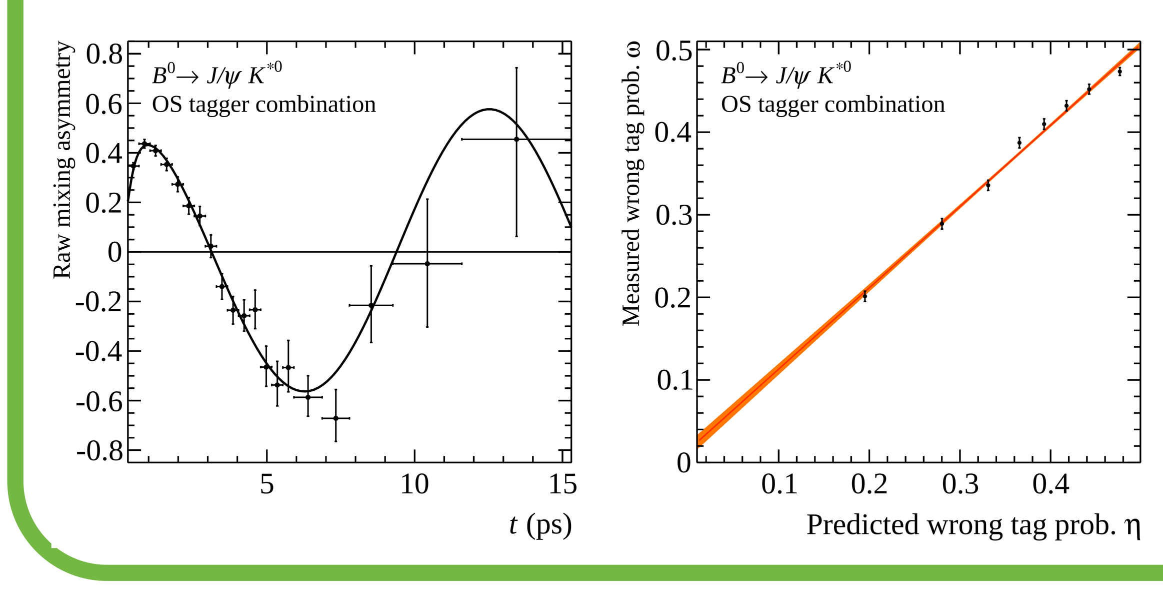
Calibration

Mistag calibration

$$\underset{\substack{\uparrow\\ \text{measured}\\ \text{ev-by-ev mistag}}}{\omega(\eta)} = p_0 + \underset{\substack{\uparrow\\ \text{estimated}\\ \text{ev-by-ev mistag}}}{p_1(\eta} - \underset{\substack{\uparrow\\ \text{mean}\\ \text{estimated mistag}}}{\langle\eta\rangle)}$$

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



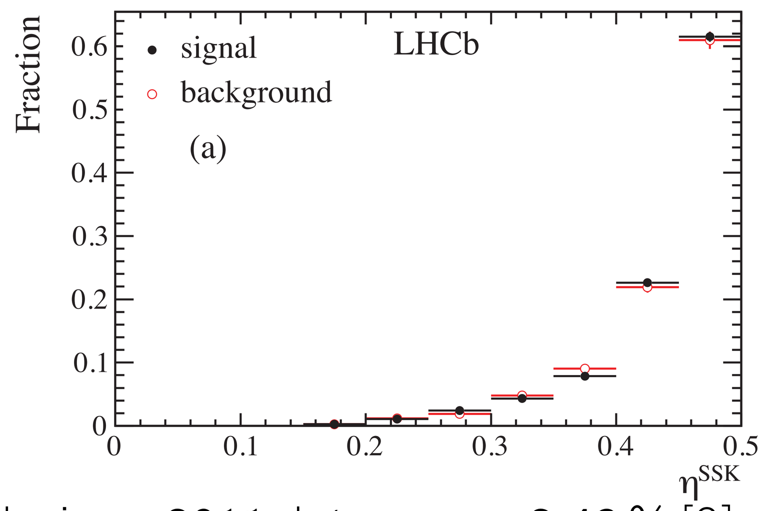
Flavour Tagging in Run I

Handling for analyses

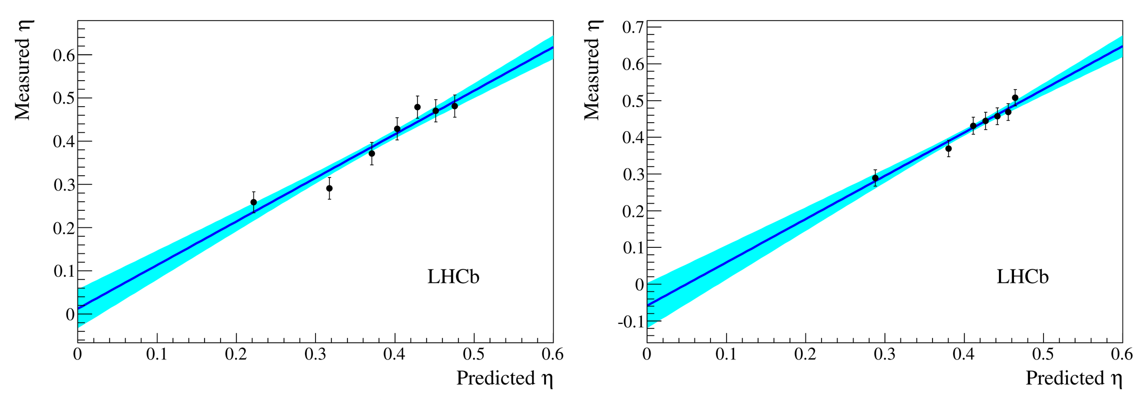
- one calibration per tagger valid for all channels
- systematic uncertainties from
  - calibration methods
  - results in different control channels
- "ad-hoc" calibration from specific control channels for analyses dominated by FT uncertainty

Highlights of successful FT uses

- CP violation in $\overline{B}_s^0 \rightarrow J/\psi\,\pi^+\pi^-$

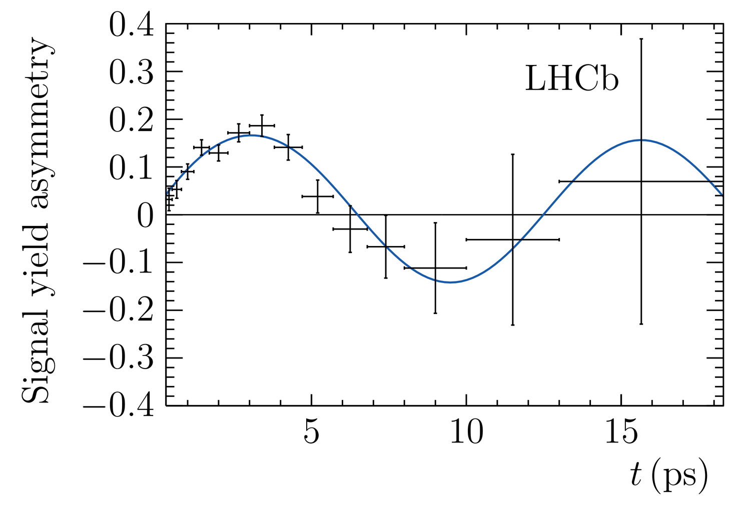


  - analysis on 2011 data: $\varepsilon_{\text{eff}} = 2.43\,\%$ [3]
  - full Run I analysis: $\varepsilon_{\text{eff}} = 3.89\,\%$ [4]
  - newest analysis profited from
    - $\rightarrow$ including SS kaon nnet tagger
    - $\rightarrow$ re-optimisation of OS algorithms
- CP violation in $B_s^0 \rightarrow D_s^{\mp}K^{\pm}$

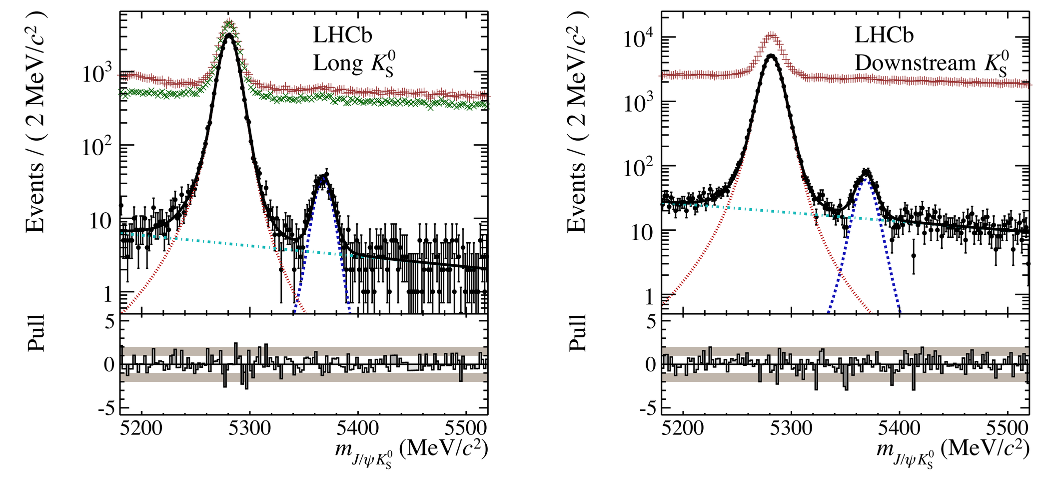


  - SS kaon nnet (right) adds more than 1.3 % to ε_{eff} (OS calibration left) [5]

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



  - precision analysis $\rightarrow$ "ad-hoc" 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 $B_s^0 \rightarrow J/\psi\,K_S^0$
  - B_s^0 events: $\varepsilon_{\text{eff}} = 4.00\,\%$ [8]
  - B^0 events: $\varepsilon_{\text{eff}} = 2.62\,\%$ [8]
    - $\rightarrow$ also small contribution of SS kaon for B^0
    - $\rightarrow$ origins of this effect:
      - 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

- 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 %

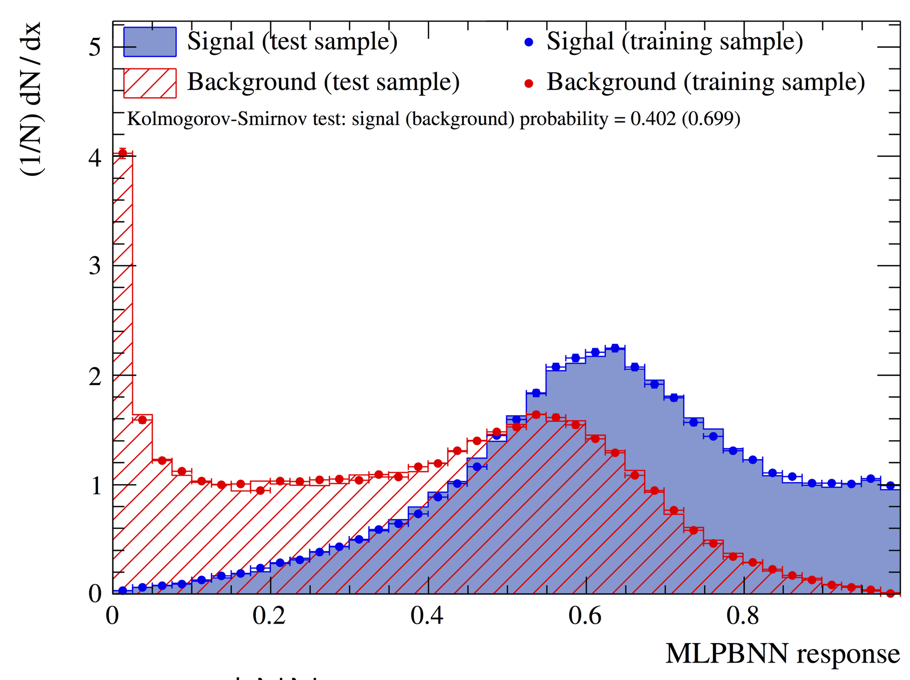
- one boosted decision tree (BDT) for each mode [9]
- clean measure of B meson flavour (low mistag)
- stand-alone tagging power of $\epsilon_{\text{eff}} = 0.30\,\%$ to $0.40\,\%$

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(2β) with $B^0 \rightarrow J/\psi\,K_S^0$
    - $\Rightarrow$ precision comparable to B-factories
    - $\Rightarrow$ $\varepsilon_{\text{eff}}^{\text{SS}\pi} = 0.38\,\%$
  - 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:
    - receives up to 3 candidates
    - assigns final tag and mistag [10]
- 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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[3] LHCb Collaboration, R. Aaij et. al., *Measurement of the CP-violating phase ϕ_s in $\overline{B}_s^0 \rightarrow J/\psi\,\pi^+\pi^-$ decays,* Phys.Lett. B713 (2012) 378-386

[4] LHCb Collaboration, R. Aaij et. al., *Measurement of the CP-violating phase ϕ_s in $\overline{B}_s^0 \rightarrow J/\psi\,\pi^+\pi^-$ decays,* Phys.Lett. B736 (2014) 186

[5] 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

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

[7] LHCb Collaboration, R. Aaij et. al., *Measurement of CP violation in $B^0 \rightarrow J/\psi\,K_S^0$ decays,* Phys.Rev.Lett. 115 (2015) 031601

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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

[10] G. A. Krocker, *Development and calibration of a same side kaon tagging algorithm and measurement of the $B_s^0 - \overline{B}_s^0$ oscillation frequency Δm_s at the LHCb experiment,* PhD thesis, Heidelberg U., Sep, 2013, CERN-THESIS-2013-213