b-flavour tagging in pp collisions

Alex Birnkraut on behalf of the LHCb collaboration

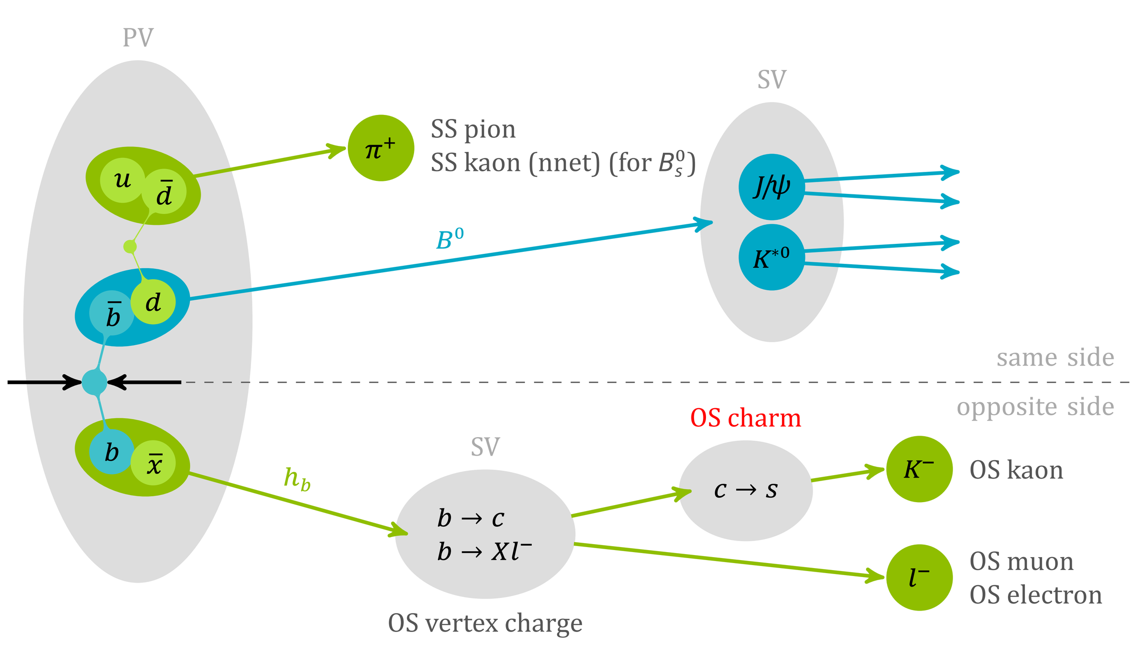
Basics

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

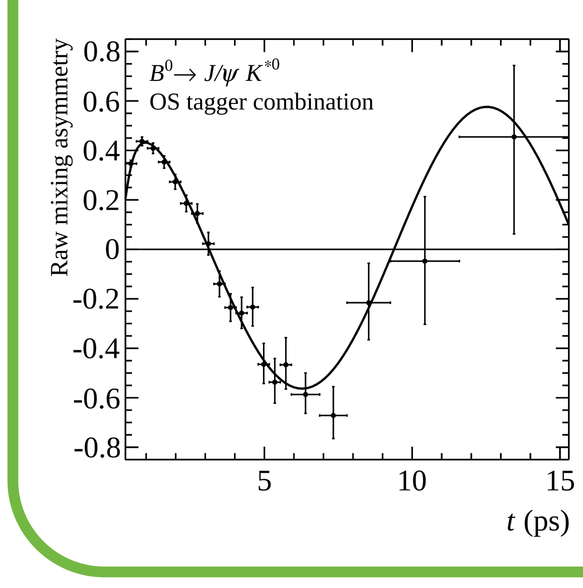
Mistag calibration

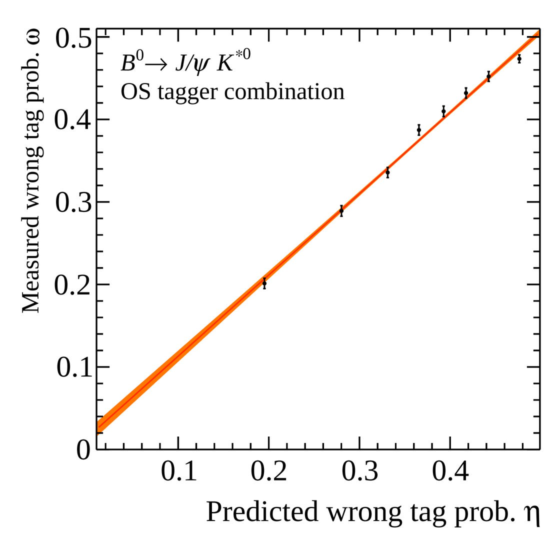
$$\omega(\eta) = p_0 + p_1 (\eta - \langle \eta \rangle)$$

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

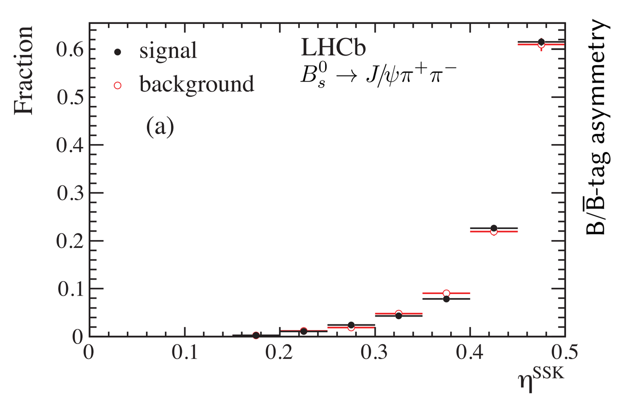
- one calibration per tagger valid for all channels
- systematic uncertainties from
  - calibration methods
  - results in different control channels
- "ad-hoc" calibration using best-suited control channels for analyses dominated by FT uncertainty

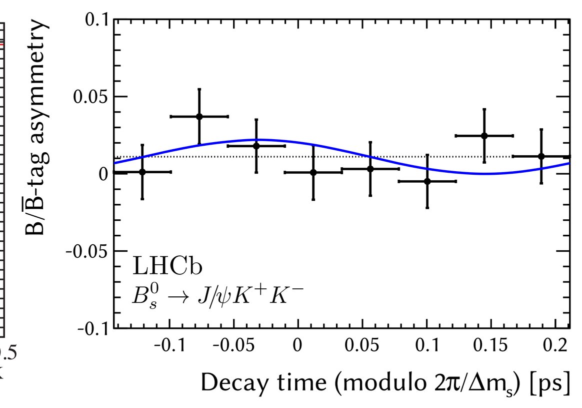
Highlights of flavour-tagged measurements

- Measurements of ϕ_s

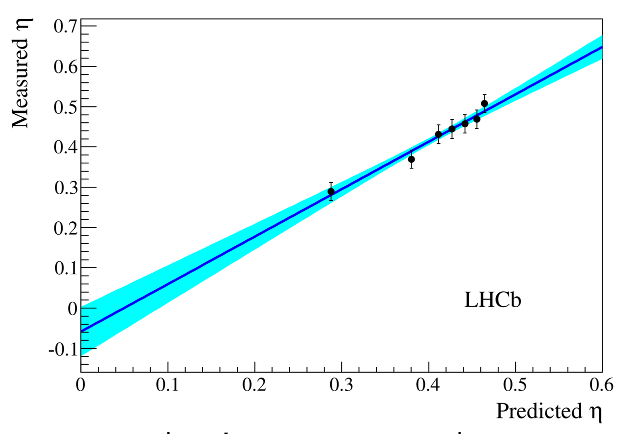
Decay mode	$\varepsilon_{\text{eff},2011}$	$\varepsilon_{\text{eff, Run I}}$
$B_s^0 \rightarrow J/\psi K^+K^-$	3.13 [3]	3.73 [4]
$\overline{B}_s^0 \rightarrow J/\psi \pi^+\pi^-$	2.43 [5]	3.89 [6]
$\overline{B}_s^0 \rightarrow D_s^+ D_s^-$	-	5.33 [7]

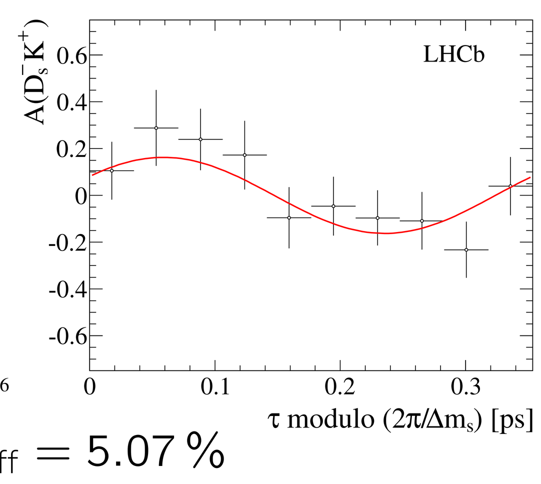
  - newest analyses profited from:
    - $\rightarrow$ including SS kaon nnet tagger
    - $\rightarrow$ re-optimisation of OS algorithms





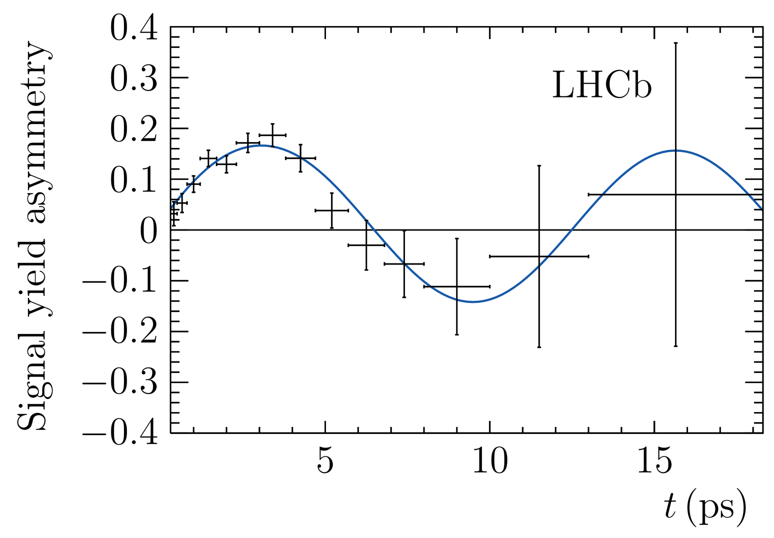
- CP violation in $B_s^0 \rightarrow D_s^\mp K^\pm$





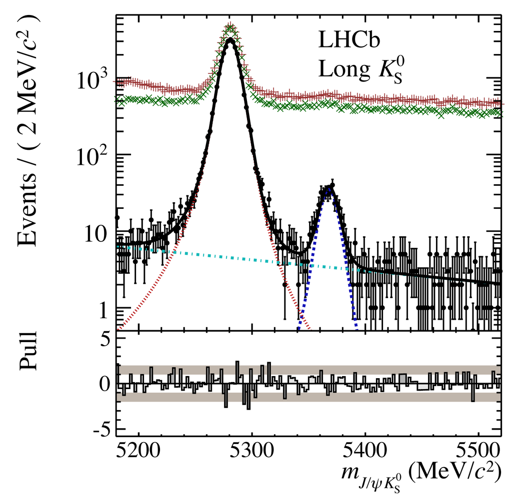
  - analysis on 2011 data: $\varepsilon_{\text{eff}} = 5.07\,\%$
  - SS kaon nnet adds more than 1.3 % to ε_{eff} [8]

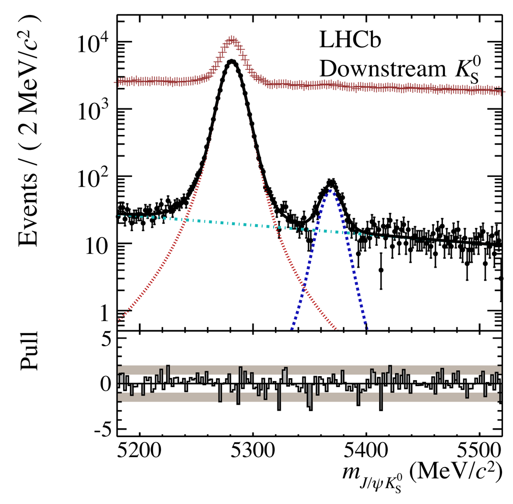
- CP violation in $B^0 \rightarrow J/\psi K_S^0$ (sin 2β)
  - analysis on 2011 data: $\varepsilon_{\text{eff}} = 2.38\,\%$ [9]
  - full Run I analysis: $\varepsilon_{\text{eff}} = 3.02\,\%$ [10]
    - $\rightarrow$ SS pion tagger adds more than 0.376 % to ε_{eff}



  - 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 tagging power of SS kaon for B^0:
      - 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 %

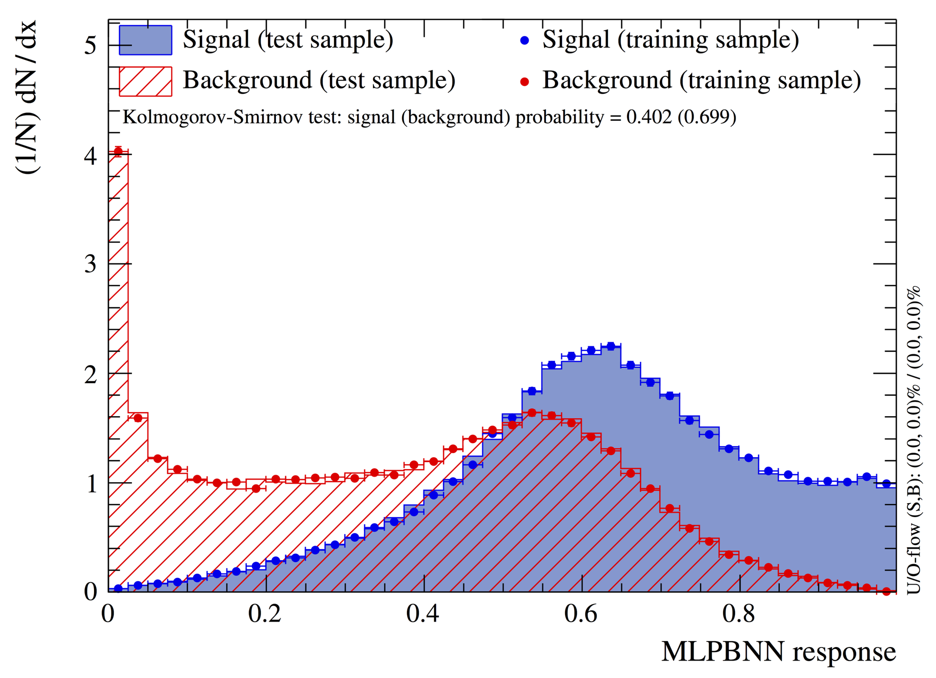
- one boosted decision tree (BDT) for each mode [12]
- clean measure of B meson flavour (low mistag)
- stand-alone tagging power of $\varepsilon_{\text{eff}} = 0.30\,\%$ to $0.40\,\%$

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:
    - 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

[1] LHCb Collaboration, R. Aaij et. al., *Opposite-side flavour tagging of B mesons at the LHCb experiment, Eur.Phys.J.* C72 (2012) 2022

[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 $B_s^0 \rightarrow J/\psi K^+K^-$ and $\overline{B}_s^0 \rightarrow J/\psi \pi^+\pi^-$ decays,* Phys.Rev. D87 (2013) 11, 112010

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

[5] 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

[6] 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) 186-195

[7] LHCb Collaboration, R. Aaij et. al., *Measurement of the CP-violating phase ϕ_s in $\overline{B}_s^0 \rightarrow D_s^+ D_s^-$ decays,* Phys.Rev.Lett. 113 (2014) 21, 211801

[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

[9] 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

[10] 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) 3, 031601

[11] LHCb Collaboration, R. Aaij et. al., *Measurement of the time-dependent CP asymmetries in $B_s^0 \rightarrow J/\psi K_S^0$,* JHEP 1506 (2015) 131

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

[13] 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