b-flavour tagging in *pp* collisions

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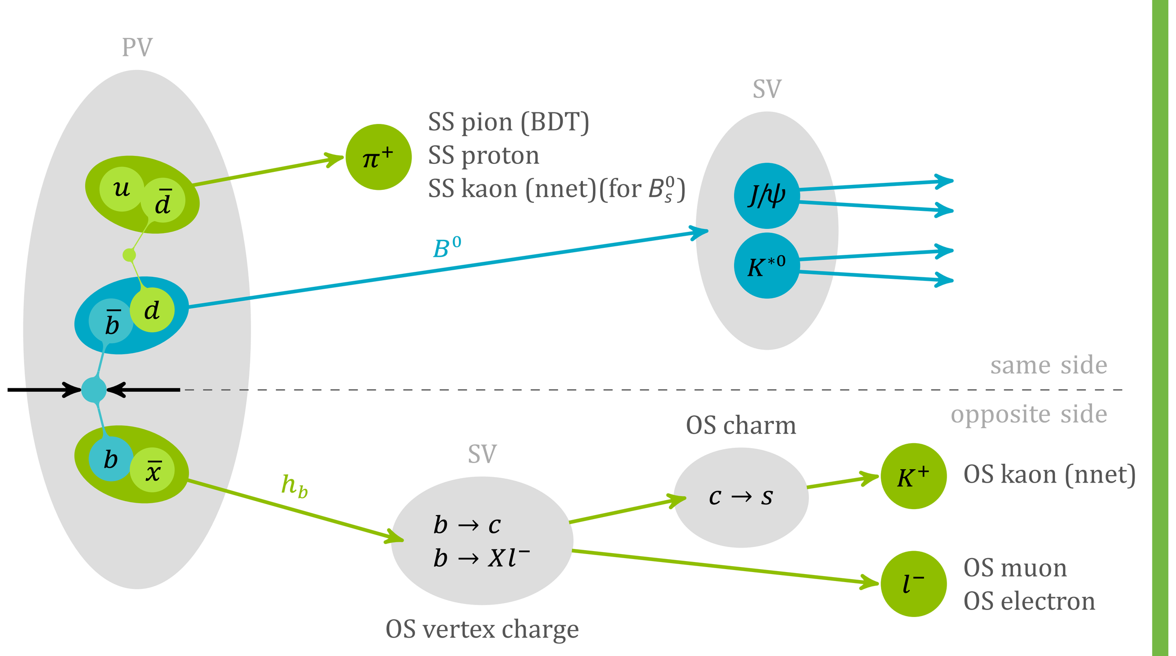
Basics

Introduction

Measurements of flavour oscillations and time-dependent *CP* asymmetries in neutral *B* meson systems require knowledge of the *b* quark production flavour. 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 → SS kaon / SS kaon nnet
  - pion for B^0 → SS pion / SS pion BDT
  - 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 / OS kaon nnet
  - *D* meson from the $b \to c$ decay chain → OS charm



Each tagger gives a decision *d* on the initial flavour ("tag") and an estimate η to be wrong.

Flavour Tagging characteristics

- **mistag probability**
  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**
  is a measure of the statistical power of the sample
  $$\varepsilon_{\text{eff}} = \varepsilon_{\text{tag}}\,(1 - 2\omega)^2$$

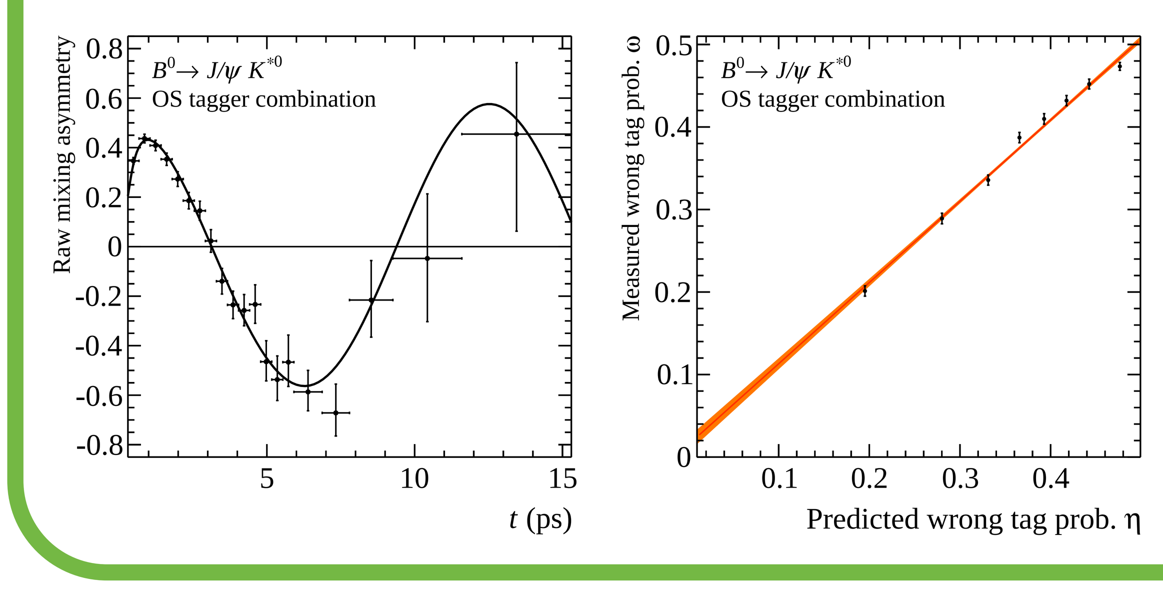
Calibration

Mistag calibration

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

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



Flavour Tagging in Run I

Strategy

- universal calibration for each tagger
- systematic uncertainties from
  - calibration methods
  - portability
- mode-specific calibration if FT becomes leading systematic uncertainty in precision analyses

Performance in analyses

Analysis	ε_{eff} on data [%] previous	latest	ratio latest/previous	references
$B_s \to J/\psi\,\pi^+\pi^-$	2.43	3.89	1.60	*Phys. Lett. B* 713 (2012) 378-386 *Phys. Lett. B* 736 (2014) 186
$B_s \to J/\psi\,K^+K^-$	3.13	3.73	1.19	*Phys. Rev.* D87 (2013) 11, 112010 *Phys. Rev. Lett.* 114 (2015) 041801
$B_s \to J/\psi\,K_s$	-	4.00		*JHEP* 1506 (2015) 131
$B_s \to \phi\phi$	3.29	5.38	1.64	*Phys. Rev. Lett.* 110 (2013) 241802 *Phys. Rev.* D90 (2014) 5, 052011
$B_s \to D_s K$	1.9	5.07	2.67	LHCb-CONF-2012-029 *JHEP* 1411 (2014) 060
$B_s \to D_s D_s$	-	5.33		*Phys. Rev. Lett.* 113 (2014) 211801
$B^0 \to J/\psi\,K_s$	2.38	3.02	1.27	*Phys. Lett. B* 721 (2013) 24-31 *Phys. Rev. Lett.* 115 (2015) 031601
$B^0 \to J/\psi\,\pi^+\pi^-$	-	3.26		*Phys. Lett. B* 742 (2015) 38-49

Performance improvements in Run I

- OS tagging improved $\mathcal{O}(15\%)$
- SS kaon tagging improved $\mathcal{O}(40\%)$

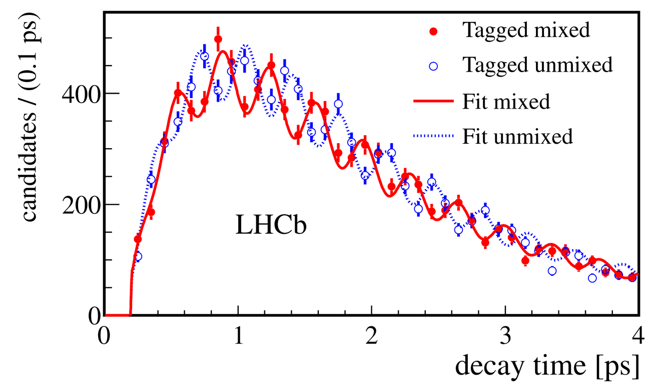
⇒ Flavour Tagging has been a success in Run I

Highlight analyses using flavour tagging

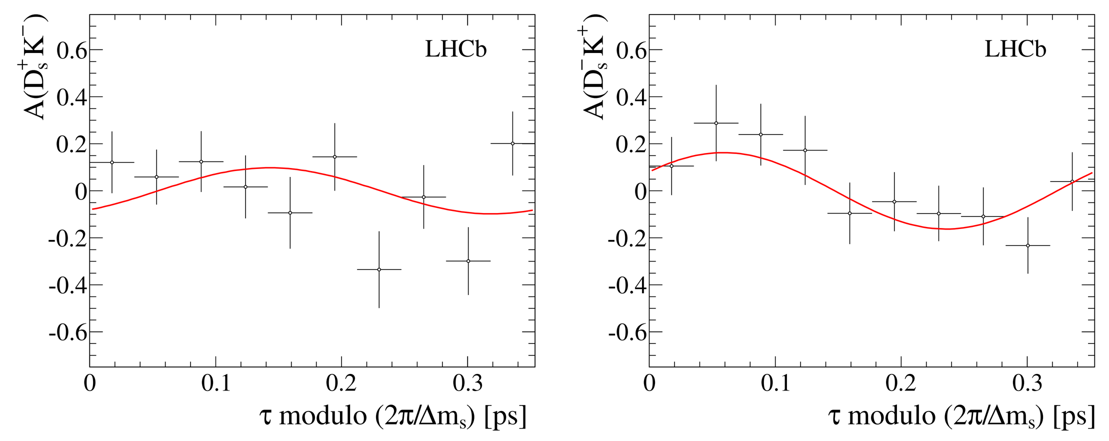
Measurement of Δm_s

Determination of the $B_s^0 - \bar{B}_s^0$ oscillation frequency with $B_s^0 \to D_s^-\pi^+$ [3].

$e^{-\Gamma t}(\ldots + d\cos(\Delta m t))$



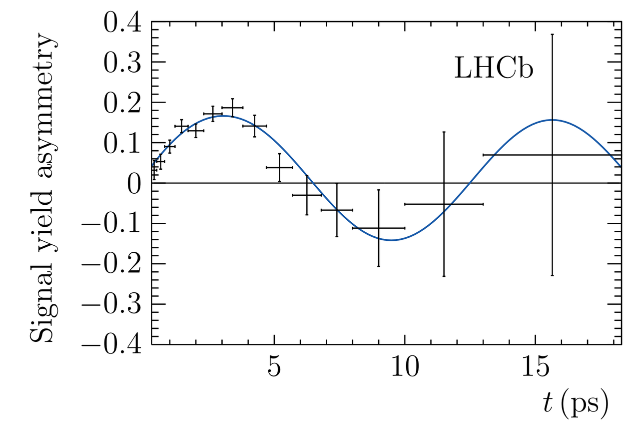
CP analysis of $B_s^0 \to D_s^{\mp}K^{\pm}$ decays



→ SS kaon nnet adds more than 1.3 % to ε_{eff} [4]

Measurement of $\sin 2\beta$

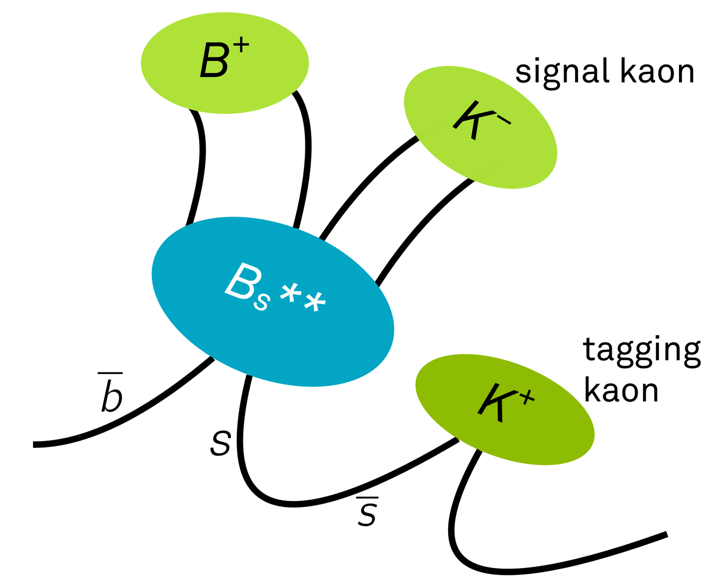
→ precision analysis
→ mode-specific calibration with $B^+ \to J/\psi K^+$ and $B^0 \to J/\psi K^{*0}$ [5]



Developments

SS kaon calibration with excited B_s^0 states

- SS kaon taggers calibrated with $B_s^0 \to D_s^-\pi^+$ only
  - limited statistics
  - time-dependent analysis required
- new idea: calibrate with B_s^{**0} decays
  - narrow states
  - reconstruct in $B_s^{**0} \to B^+K^-$ decays
  - calibrate by counting, as in other charged modes



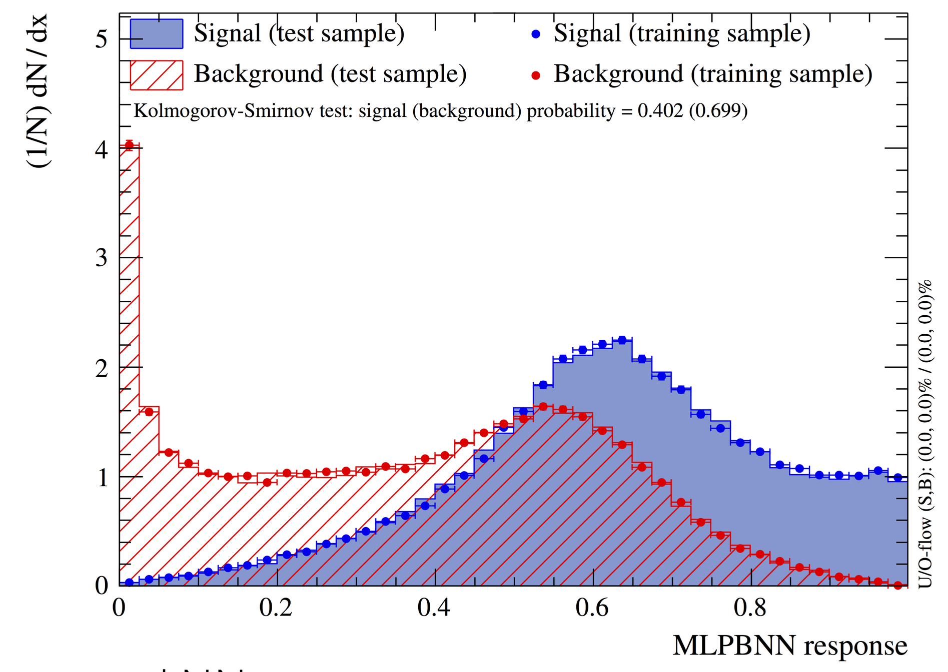
- true independent crosscheck for $B_s^0 \to D_s^-\pi^+$
- results in agreement with $B_s^0 \to D_s^-\pi^+$ channel

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
    ⇒ $\varepsilon_{\text{eff}}^{\text{SS}\pi} = 0.38\,\%$
  - $\sin(2\beta_{\text{eff}})$ with $B^0 \to J/\psi\pi^+\pi^-$
    ⇒ $\varepsilon_{\text{eff}}^{\text{SS}\pi} = 0.54\,\%$

OS and 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. OS *b* hadron tracks ⇒ signal for OS kaon nnet
    3. underlying event tracks



  - second NN:
    - receives up to 3 candidates
    - assigns final tag and mistag
- 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 ε_{eff}
  - $B_s^0 \to J/\psi\,\phi$: 41 % relative improvement in ε_{eff}

OS charm tagger

- reconstruct $D^0/D^{\pm}/D^*$ decays related to OS *b* decay
- one boosted decision tree (BDT) for each mode
- clean measure of *B* meson flavour (low mistag)
- adds about 0.37 % to ϵ_{eff}

SS pion BDT and SS proton

- promising new taggers based on BDT's
- development ongoing

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., *Precision measurement of the $B_s^0 - \bar{B}_s^0$ oscillation frequency with the decay $B_s^0 \to D_s^-\pi^+$,* New J.Phys. 15 (2013) 053021

[4] 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

[5] LHCb Collaboration, R. Aaij et. al., *Measurement of CP violation in $B^0 \to J/\psi K_S$ decays,* LHCb-PAPER-2015-004