Measurement of CP asymmetries in $B^0_{(s)} \to \pi^+\pi^-$ and $B^0_{(s)} \to K^\pm\pi^\mp$ decays at LHCb with Run 2 data

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Motivation

CP Violation (*CPV*) searches can provide stringent tests of the Standard Model (SM)

$B \to hh'$ ($h, h' \in \{\pi, K\}$) decays particularly interesting:

- Sensitive to New Physics (NP) [4] (Penguins!)

- Theoretical predictions challenging due to non-perturbative QCD contributions
- Tensions in the global fit to these decays [3]
- *CPV* in some decays has never been measured before: $B_s^0 \to \pi^+\pi^-$

Theoreticians recommended measuring *CPV* in $B \to hh'$ decays

$B \to h^+ h'^-$ Status

- $B \to h^+ h'^-$ decays studied in Run 1 and in Run 2 (2015/16) [1] Most precise CPV measurement for $B^0 \to K^+\pi^-$, $B^0 \to \pi^+\pi^-$, $B_s^0 \to \pi^+ K^-$
- Now time to look at rarer $B_s^0 \to \pi^+\pi^-$ channel

Channel	Branching Fraction	CPV (decay) [%]	CPV (interference) [%]
$B_d^0 \to \pi^+\pi^-$	$(5.37 \pm 0.20) \cdot 10^{-6}$	-32.0 ± 3.8	-67.2 ± 3.4
$B_d^0 \to K^+\pi^-$	$(2.00 \pm 0.04) \cdot 10^{-5}$	-8.31 ± 0.34	NA
$B_s^0 \to \pi^+\pi^-$	$(7.2 \pm 1.0) \cdot 10^{-7}$	THIS WORK	THIS WORK
$B_s^0 \to \pi^+ K^-$	$(5.9 \pm 0.7) \cdot 10^{-6}$	$+22.5 \pm 1.2$	NA

THIS WORK
Analysis of entire LHCb Run 2 p-p sample (2015$\to$2018)
$\sqrt{s} = 13\,\text{TeV}$, $6\,\text{fb}^{-1}$ integrated luminosity

CPV Observables

Measurement of both time-dependent and time-integrated CPV

- Time-dependent asymmetry described by:

$$A(t) = \frac{-C\cos(\Delta m\, t) + S\sin(\Delta m\, t)}{\cosh(\frac{\Delta\Gamma}{2}\, t) + A^{\Delta\Gamma}\sinh(\frac{\Delta\Gamma}{2}\, t)}$$

(C describes CPV in the decay, S CPV in mixing-decay interference, depending on the decay $\Delta\Gamma$ and Δm are for the B^0/B^0_s)
C, S, $A^{\Delta\Gamma}$ free in the fit, check consistency with

$$C^2 + S^2 + (A^{\Delta\Gamma})^2 = 1$$

- Time-integrated (direct) asymmetry is descried by

$$A_{B\to f} = \frac{\Gamma_{\overline{B}\to\overline{f}} - \Gamma_{B\to f}}{\Gamma_{\overline{B}\to\overline{f}} + \Gamma_{B\to f}}$$

$$A_{CP}^{direct} = A_{raw} - \sum A_{exp} \qquad A_{raw} = \frac{N_{\overline{B}\to\overline{f}} - N_{B\to f}}{N_{\overline{B}\to\overline{f}} + N_{B\to f}}$$

Fit accounts for the following components:

- **Signal candidates**: $B \to h^+h'^-$ decays reconstructed in the correct $h^+h'^-$ hypothesis
- **Cross-feed background**: $B \to h^+h'^-$ decays where either h or h' is misidentified (double misidentification is neglected $\to$ unlikely)
  Problematic: they peak close to signals and bias CPV observables
- **Combinatorial background**: $h^+h'^-$ from different decays and randomly associated
  Most prominent source of background before event selection, tackled with MVA (BDT selection)
- **3-bodies background**: $B \to h^+h'^-X$ where X is not detected/reconstructed

Analysis Strategy II

Simultaneous fit to the $\pi^+\pi^-, \pi^\pm K^\mp$ final states

- signals in one spectrum become cross-feed in other spectra
  $\rightarrow$ allow for better cross-feed control
- Flavour-Specific (FS) decays help calibrate experimental effects on the fly

Observables:

- Invariant mass
- Decay time
- Flavour-tagging response
- Flavour-tagging mistag probability

Fit model: same as the one validated in the previous $B \rightarrow h^+h^-$ analysis[1]

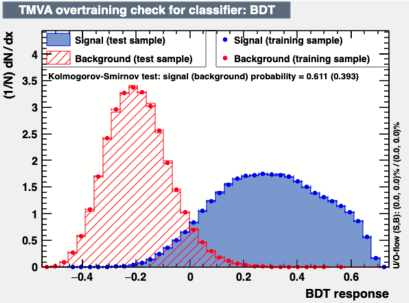
Two selections were developed:

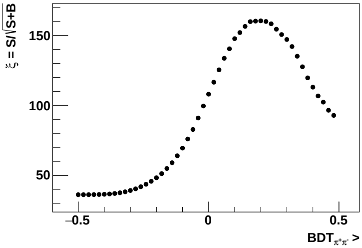
- $B^0 \rightarrow \pi^+\pi^-$
  (also get CPV observables for $B^0_{(s)} \rightarrow K^\pm\pi^\mp$)
- $B^0_s \rightarrow \pi^+\pi^-$

Selection

Event selection performed in order to tackle

- Cross-feed background: use of Particle IDentification (PID) variables, information mostly coming from the LHCb RICH
- Combinatorial background: training of 3-fold split BDT
  - optimisation of expected signal significance wrt combinatorial bkg
  - one BDT for each of the 2 selections
  - ($B_s^0 \to \pi^+\pi^-$ only)
    Big uncertainty on $\mathcal{B}(B_s^0 \to \pi^+\pi^-)$ may affect optimal BDT cut
    $\to$ toy studies were performed confirming BDT requirements





PID Efficiencies

PID efficiencies produced thanks to high statistics/purity samples [6]

- $D^{*+} \to D^0(\to K^-\pi^+)X$ for $\pi^\pm/K^\pm$,
- $\Lambda \to p^+\pi^-$ for $p/\bar{p}$

Production of PID-efficiency maps as:

$$\varepsilon_{h\to h'}(p^i,\eta^j,n^k_{SPD}) = \frac{N^{\text{pass}}_{h\to h'}(p^i,\eta^j,n^k_{SPD})}{N^{\text{pass}}_{h\to h'}(p^i,\eta^j,n^k_{SPD}) + N^{\text{fail}}_{h\to h'}(p^i,\eta^j,n^k_{SPD})}.$$

allowing us to find kinematically-averaged PID efficiencies

$$\hat{\varepsilon}_{h^+h'^-} = \frac{1}{N}\sum_{i=1}^{N}\bar{\varepsilon}_{h^+}(p_i^+,\eta_i^+)\cdot\bar{\varepsilon}_{h'^-}(p_i^-,\eta_i^-),$$

Decay-time Effects

Time-dependent analysis $\rightarrow$ susceptible to decay-time effect

- Resolution σ_t: causes a damping of the oscillation
  Non negligible for the fast B_s^0 system oscillation
- Bias b_t: causes an effective mixing of the CPV observables

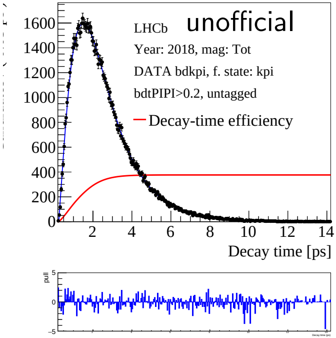
Decay-time effects measured with $J/\psi \rightarrow \mu^+\mu^-$ decays and transposed to $B \rightarrow h^+h'^-$

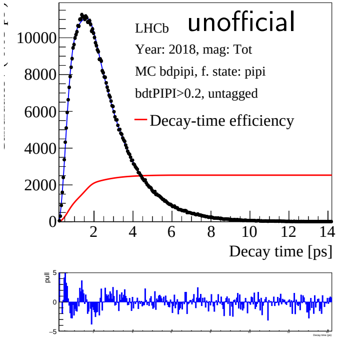
Using a single averaged value (instead of a per-event calibration) simplifies the fitting procedure without impacting too much the results (effect is less than 1% relative on CPV observables)

$$\sigma_t \simeq 41\,\text{fs}, \quad b_t \simeq -3.5\,\text{fs}$$

- Reference $B^0 \to K^+\pi^-$ (high statistics, pure exponential ($\Delta\Gamma_{B_d^0} = 0$))
- Ratio between data (for each channel) and MC reference according to

$$\varepsilon_f^{data}(t) = \varepsilon_f^{MC}(t) \cdot \frac{\varepsilon^{data}_{B_d^0 \to K\pi}(t)}{\varepsilon^{MC}_{B_d^0 \to K\pi}(t)}$$

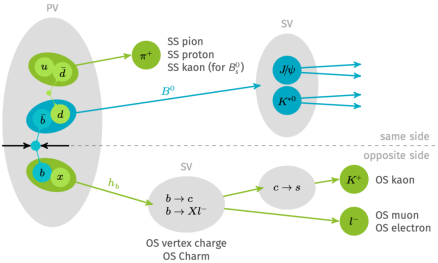




Different acceptances whether the flavour tagging responded or not

Flavour-Tagging Strategy

Tagging on a per-event basis



First calibration with $B^0 \to D^+\pi^-$ (OS and SS) and $B_s^0 \to D_s^+\pi^-$ (SS_K) (EPM [5])

OS taggers

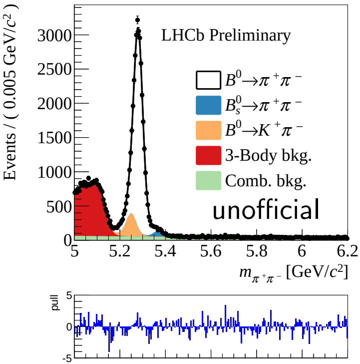
- Multiple OS taggers, assumed to be independent
- Combined tagger recalibrated on the fly during final fit with FS $B^0 \to K^+\pi^-$

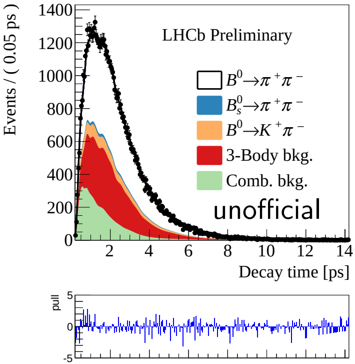
$\mathrm{SS}_{(K)}$ taggers (response is t-dependent)

- Recalibrated on the fly during final fit with FS decays
  - $\mathrm{SS}_{p/\pi}$: $B^0 \to K^+\pi^-$
  - SS_K: $B_s^0 \to \pi^+K^-$

Plan to switch to Inclusive Flavour Tagging [2] (Deepset-based ML)

$B^0 \to \pi^+\pi^-$ selection ($\pi^+\pi^-$ final state)

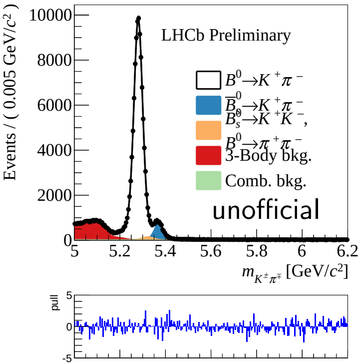


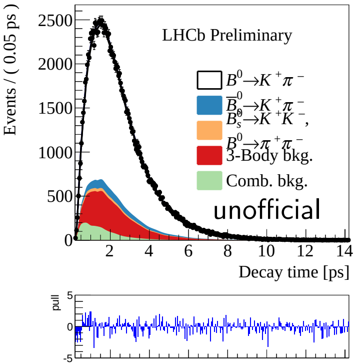


2018

$B^0 \to \pi^+\pi^-$

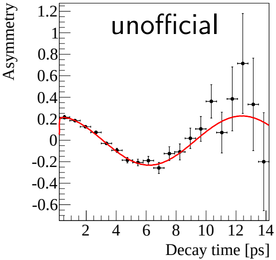
$B^0 \to \pi^+\pi^-$ selection ($K^\pm\pi^\mp$ final state)



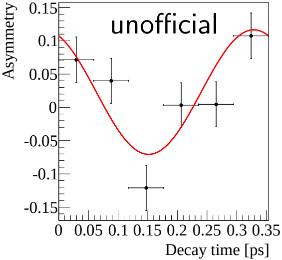


2018

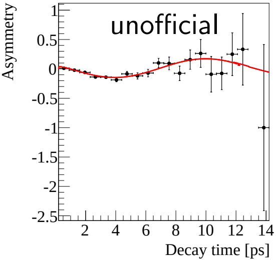
$B^0 \to \pi^+\pi^-$



$B^0 \to K^+\pi^-$



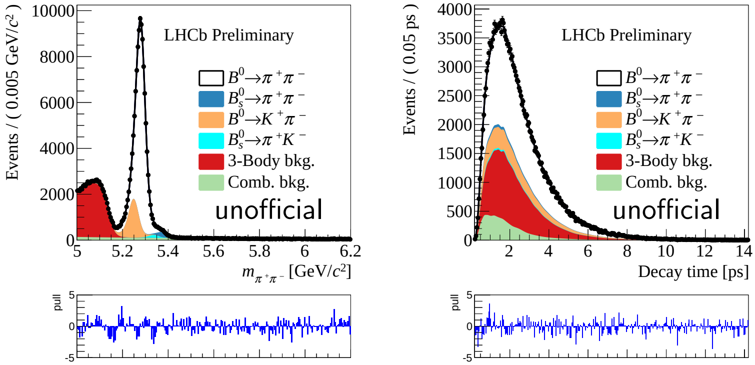
$B_s^0 \to \pi^+K^-$



$B^0 \to \pi^+\pi^-$

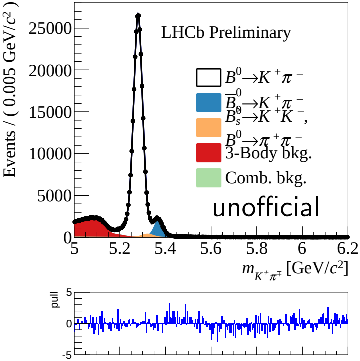
2018

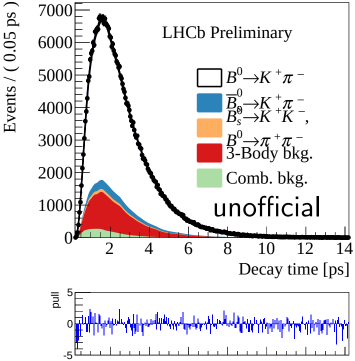
$B_s^0 \to \pi^+\pi^-$ selection ($\pi^+\pi^-$ final state)



All years

$B_s^0 \to \pi^+\pi^-$ selection ($K^\pm\pi^\mp$ final state)





All years

$B^0 \to \pi^+\pi^-$ selection

CPV observable	2015-16	2017	2018
$C(B^0 \to \pi^+\pi^-)$	-0.310 $\pm$ 0.047	-0.300 $\pm$ 0.050	-0.310 $\pm$ 0.047
$S(B^0 \to \pi^+\pi^-)$	-0.732 $\pm$ 0.043	-0.762 $\pm$ 0.047	-0.751 $\pm$ 0.044
$A_{raw}(B^0 \to K^+\pi^-)$	-0.0948 $\pm$ 0.0034	-0.0945 $\pm$ 0.0038	-0.0900 $\pm$ 0.0035
$A_{raw}(B_s^0 \to \pi^+K^-)$	0.216 $\pm$ 0.013	0.240 $\pm$ 0.014	0.224 $\pm$ 0.013

$B_s^0 \to \pi^+\pi^-$ selection

CPV observable	2015-16	2017	2018	Tot
$C(B_s^0 \to \pi^+\pi^-)$	0.32 $\pm$ 0.42	0.16 $\pm$ 0.42	-0.57 $\pm$ 0.46	-0.04 $\pm$ 0.25
$S(B_s^0 \to \pi^+\pi^-)$	-0.15 $\pm$ 0.41	0.43 $\pm$ 0.40	-0.21 $\pm$ 0.47	-0.04 $\pm$ 0.25
$-A^{\Delta\Gamma}(B_s^0 \to \pi^+\pi^-)$	-1.64 $\pm$ 0.45	-0.74 $\pm$ 0.62	-1.28 $\pm$ 0.55	-1.33 $\pm$ 0.31
$C(B^0 \to \pi^+\pi^-)$	-0.298 $\pm$ 0.057	-0.329 $\pm$ 0.062	-0.243 $\pm$ 0.052	-0.282 $\pm$ 0.032
$S(B^0 \to \pi^+\pi^-)$	-0.708 $\pm$ 0.050	-0.825 $\pm$ 0.057	-0.705 $\pm$ 0.048	-0.736 $\pm$ 0.030
$A_{raw}(B^0 \to K^+\pi^-)$	-0.0941 $\pm$ 0.0035	-0.0946 $\pm$ 0.0038	-0.0918 $\pm$ 0.0036	-0.0929 $\pm$ 0.0021
$A_{raw}(B_s^0 \to \pi^+K^-)$	0.213 $\pm$ 0.014	0.241 $\pm$ 0.014	0.223 $\pm$ 0.013	0.2243 $\pm$ 0.0080

EVERYTHING IS BLINDED

(same blinding for same observable across selections)

Raw asymmetries of the $B^0_{(s)} \to K^\pm\pi^\mp$ decays need correction for experimental asymmetries before retrieving the *CP*V observables
Account for:

- Production asymmetry: extracted from the fit
  A_{raw} from fit are already corrected by production term
- Detection asymmetry: studying $D^+ \to K^-\pi^+\pi^+$ and $D^+ \to \overline{K}^0\pi^+$

$$A^{K\pi\pi}_{\rm raw} = A^{D^+}_P + A^{K\pi}_D + A^{\pi}_D, \quad (1)$$
$$A^{K^0\pi}_{\rm raw} = A^{D^+}_P + A^{\pi}_D - A^{K^0}_D. \quad (2)$$

- PID asymmetry:
  use PID efficiency maps (integrated over $B \to h^+h'^-$ kinematics)

$$A^{K\pi}_{\rm PID}(p_K, \eta_K, \phi_K, p_\pi, \eta_\pi, \phi_\pi) = \frac{A^K_{\rm PID}(p_K, \eta_K, \phi_K) - A^\pi_{\rm PID}(p_\pi, \eta_\pi, \phi_\pi)}{1 - A^K_{\rm PID}(p_K, \eta_K, \phi_K)A^\pi_{\rm PID}(p_\pi, \eta_\pi, \phi_\pi)}, \quad (3)$$

Direct-asymmetry Corrections - Recap

Year	$A_P^{B^0}$ [%]	$A_P^{B_s^0}$ [%]
2015-16	-0.0015 $\pm$ 0.0053	-0.006 $\pm$ 0.019
2017	-0.0049 $\pm$ 0.0057	-0.001 $\pm$ 0.020
2018	-0.0051 $\pm$ 0.0053	-0.020 $\pm$ 0.018

Year	$A_D^{K\pi}$ [%]	$A_{\mathrm{PID}}^{K\pi}$ [%]
2015	-0.965 ± 0.314	-1.2 ± 0.7
2016	-1.052 ± 0.129	0.5 ± 0.3
2017	-0.936 ± 0.132	0.8 ± 0.4
2018	-0.948 ± 0.123	0.7 ± 0.3

Future Plans - Systematic Uncertainties

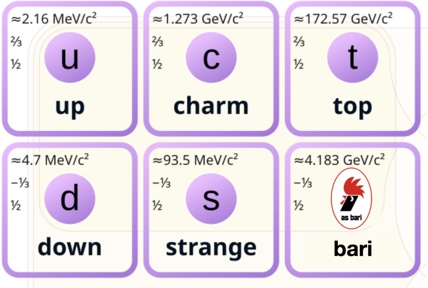
Work in progess...
Use same strategy of previous analysis
Plan to consider:

- PID efficiencies
- External physical inputs
- Decay-time resolution average value
- Flavour-tagging parametrisation
- Decay-time acceptances (acceptance shape, the ability of the MC to reproduce the acceptance ratio and reference channel statistics)
- Fit model

Strategy: generate 100 toys with either

- alternative models
- bootstrapping fit-input values

Thanks for your attention!



📷: JJ Harrison,
Eudyptula minor, the smallest penguin on Earth

[1] Roel Aaij et al.
Observation of CP violation in two-body $B^0_{(s)}$-meson decays to charged pions and kaons.
JHEP, 03:075, 2021.

[2] Roel Aaij et al.
Inclusive B-meson flavour-tagging algorithm at LHCb.
8 2025.

[3] Bhubanjyoti Bhattacharya, Marianne Bouchard, Luke Hudy, Alexandre Jean, David London, and Christopher MacKenzie.
Anomalies in hadronic B decays: An update.
Phys. Rev. D, 112(5):056014, 2025.

[4] Lorenzo Calibbi, Andreas Crivellin, Fiona Kirk, Claudio Andrea Manzari, and Leonardo Vernazza.
Z' models with less-minimal flavour violation.
Phys. Rev. D, 101(9):095003, 2020.

[5] (LHCb) Flavour Tagging Working Group.
EspressoPerformanceMonitor documentation.
https://gitlab.cern.ch/lhcb-ft/EspressoPerformanceMonitor.

[6] Olli Lupton, Lucio Anderlini, Barbara Sciascia, and Vladimir Gligorov.
Calibration samples for particle identification at LHCb in Run 2.
Technical report, CERN, Geneva, 2016.

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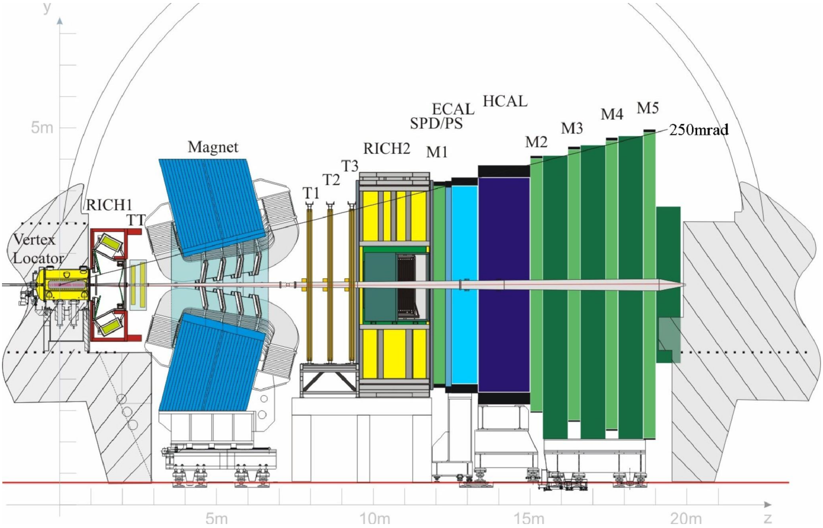
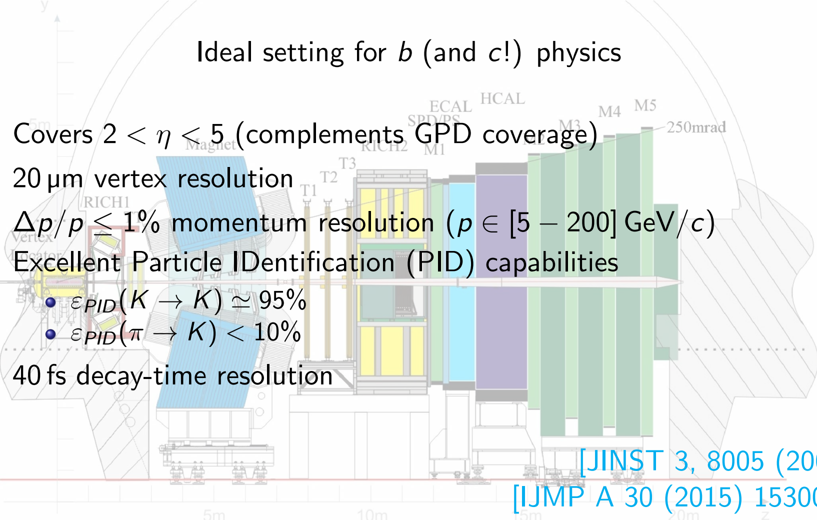

y
5m
Magnet
RICH1
TT
Vertex
Locator
T1
T2
T3
RICH2
M1
SPD/PS
ECAL
HCAL
M2
M3
M4
M5
250mrad
5m
10m
15m
20m
z

LHCb Run 1-2 Detector

Ideal setting for b (and c!) physics

- Covers $2 < \eta < 5$ (complements GPD coverage)
- $20\,\mu\mathrm{m}$ vertex resolution
- $\Delta p/p \lesssim 1\%$ momentum resolution ($p \in [5-200]\,\mathrm{GeV}/c$)
- Excellent Particle IDentification (PID) capabilities
  - $\varepsilon_{PID}(K \to K) \simeq 95\%$
  - $\varepsilon_{PID}(\pi \to K) < 10\%$
- $40\,\mathrm{fs}$ decay-time resolution



[JINST 3, 8005 (2008)]
[IJMP A 30 (2015) 1530022]

Data Sample

- Data comes from Run 2 (2015-16-17-18) p-p collisions at $\sqrt{s}$=13 TeV
- Integrated luminosity: 6 fb^{-1}

Trigger requirements

- L0: `L0Hadron_TOS OR L0Global_TIS`
- HLT1: `Hlt1TrackMVADecision_TOS`
- HLT2: `Hlt2B2HHDecision_TOS`

Stripping: `StrippingB2HHBDTLine`
(same as HLT2, see Table $\rightarrow$)
(Stripping (stream): 2015:`24r1` (FTag), 2016:`28r1` (FTag), 2017:`29r2p2` (BHadronCompleteEvent), 2018:34 (BHadronCompleteEvent))

Stripping/HLT2 requirements

Variable	Requirement
Track p_T	$>$ 1 GeV/c
Track χ^2_{IP}	$>$ 16
Track χ^2	$<$ 3
$m_{\pi^+\pi^-}$	$\in$ 4.5-6.2 GeV/c^2
$p_T^+ + p_T^-$	$>$ 4.5 GeV/c
χ^2_{DOCA}	$<$ 9
$p_T(B)$	$>$ 1.2 GeV/c
DIRA(B)	$>$ 0.99
$\chi^2_{\mathrm{IP}}(B)$	$<$ 9
$\chi^2_{\mathrm{FD}}(B)$	$>$ 100

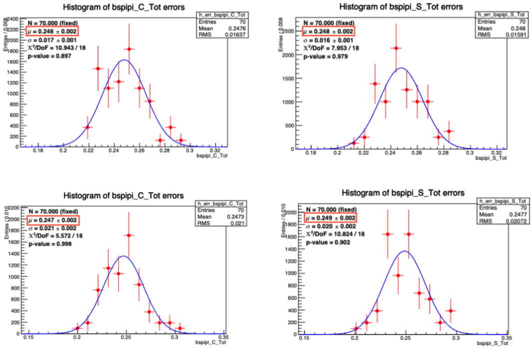
$B_s^0 \to \pi^+\pi^-$ Toys

Verify the cut choice is optimal

Fit data at different BDT cuts around optimal selection cut (0.78, 0.8, 0.83, 0.86, 0.89) with *CP*V in $B_s^0 \to \pi^+\pi^-$ fixed to 0

From fitted values generate 70 toys and see distribution of fitted *CP*V observables for $B_s^0 \to \pi^+\pi^-$

$\to$ no improvements observed in the other cuts



- Prompt $J/\psi \to \mu^+\mu^-$ as calibration sample
- From `PromptJPsi2MuMuControlLine` (see backup)
- Low bkg, removed with sPlot technique
- Use measured decay time of prompt J/ψ to estimate decay-time resolution (σ_t) as a function of decay-time error (δ_t)

$$\sigma_t(\delta_t) = p_0 + p_1(\delta_t - 0.04)\,\text{ps}$$

- Calibration parameters from 2D unbinned maximum likelihood to decay time (t) vs decay-time error (δ_t)

Decay-Time Resolution Calibration (II)

- Differences between calibration and signal channels are corrected using MC on a per-event basis

$$\sigma_t(\delta t_i) = \sigma^{\text{data}}_{t,J/\psi\to\mu^+\mu^-}(\delta t_i) \cdot \frac{\sigma^{\text{MC}}_{t,B^0_s\to K^+K^-}(\delta t_i)}{\sigma^{\text{MC}}_{t,J/\psi\to\mu^+\mu^-}(\delta t_i)}$$

- Use average decay-time resolution for all events (introduces a small[1] systematic)
width $\tilde{\sigma}_t = 40.7 \pm 0.2\,\text{fs}$; bias $\tilde{\delta}_t = -3.1\,\text{fs}$
calculated accounting for dilution (D) of B^0_s oscillation

$$D_i = \exp\left(\frac{-\Delta {m_s}^2 \sigma_t^2(\delta t_i)}{2}\right) \to \langle D\rangle = \frac{\sum_i^N D_i}{N} \to \tilde{\sigma}_t = \frac{\sqrt{-2\ln\langle D\rangle}}{\Delta m_s}$$

where the sum is done on a pure $B^0_s \to K^+K^-$ data sample

[1] 1% in value in $B^0_s \to K^+K^-$ CPV search

Signal Model

$$p_{sig}(\vec{x}) = p_{sig}(m) \cdot p_{sig_{\psi}}(t, \vec{\xi}_{tag}, \vec{\eta}_{tag}). \tag{4}$$

Invariant mass: 2 gaussians + johnson tail

Decay time: depends on the final state (CP vs FS)

$$\begin{aligned} p_{sig_{\mathrm{FS}}}(t, \Omega^{sig}, \overline{\Omega}^{sig})) \propto \quad & (1-\psi\mathcal{A}_{CP})(1-\psi\mathcal{A}_{\mathrm{f}})\cdot \\ & \cdot \Big[\quad \big[(1-\mathcal{A}_P)\Omega^{sig} + (1+\mathcal{A}_P)\overline{\Omega}^{sig}\big] H_+(t) + \\ & + \psi\big[(1-\mathcal{A}_P)\Omega^{sig} - (1+\mathcal{A}_P)\overline{\Omega}^{sig}\big] H_-(t)\Big], \end{aligned} \tag{5}$$

$$\begin{aligned} p_{sig_{\mathrm{CP}}}(t, \Omega^{sig}, \overline{\Omega}^{sig})) \propto \quad & \Big[\big[(1-\mathcal{A}_P)\Omega^{sig} + (1+\mathcal{A}_P)\overline{\Omega}^{sig}\big] I_+(t) + \\ & + \quad \big[(1-\mathcal{A}_P)\Omega^{sig} - (1+\mathcal{A}_P)\overline{\Omega}^{sig}\big] I_-(t)\Big], \end{aligned} \tag{6}$$

$$H_+(t)=\left\{\left[\exp(-\Gamma\, t')\cosh\left(\frac{\Delta\Gamma}{2}\, t'\right)\right]\otimes R(t-t')\right\}\cdot\varepsilon(t), \tag{7}$$

$$H_-(t)=\left\{\left[\exp(-\Gamma\, t')\cos\left(\Delta m\, t'\right)\right]\quad\otimes R(t-t')\right\}\cdot\varepsilon(t), \tag{8}$$

$$I_+(t) = \left\{\left[\exp(-\Gamma\, t')\cdot\left[\cosh\left(\frac{\Delta\Gamma}{2}\, t'\right)+\right.\right.\right. \tag{9}$$

$$\left.\left.\left.+A_f^{\Delta\Gamma}\sinh\left(\frac{\Delta\Gamma}{2}\, t'\right)\right]\right]\otimes R(t-t')\right\}\cdot\varepsilon(t), \tag{10}$$

$$I_-(t) = \left\{\left[\exp(-\Gamma\, t')\cdot\left[C_f\cos(\Delta m\, t')+\right.\right.\right. \tag{11}$$

$$\left.\left.\left.-S_f\sin(\Delta m\, t')\right]\right]\otimes R(t-t')\right\}\cdot\varepsilon(t), \tag{12}$$

Signal Tagging

$$\Omega^{sig}(t, \vec{\xi}_{tag}, \vec{\eta}_{tag}) = \Omega^{sig}_{\mathrm{OS}}(\xi_{\mathrm{OS}}, \eta_{\mathrm{OS}}) \cdot \Omega^{sig}_{\mathrm{SS}_{(K)}}(t, \xi_{\mathrm{SS}_{(K)}}, \eta_{\mathrm{SS}_{(K)}}), \tag{13}$$

$$\overline{\Omega}^{sig}(t, \vec{\xi}_{tag}, \vec{\eta}_{tag}) = \overline{\Omega}^{sig}_{\mathrm{OS}}(\xi_{\mathrm{OS}}, \eta_{\mathrm{OS}}) \cdot \overline{\Omega}^{sig}_{\mathrm{SS}_{(K)}}(t, \xi_{\mathrm{SS}_{(K)}}, \eta_{\mathrm{SS}_{(K)}}). \tag{14}$$

$$\begin{aligned}\Omega^{sig}_T(\xi_T, \eta_T) = &\left[\delta_{\xi_T,+1}\left[1 - \omega^{sig}_T(\eta_T)\right] + \delta_{\xi_T,-1}\omega^{sig}_T(\eta_T)\right]\varepsilon^{sig}_T h^{sig}_T(\eta_T) + \\ &+ \delta_{\xi_T,0} k^{sig}_T U(\eta_T),\end{aligned} \tag{15}$$

$$\begin{aligned}\overline{\Omega}^{sig}_T(\xi_T, \eta_T) = &\left[\delta_{\xi_T,-1}\left[1 - \bar{\omega}^{sig}_T(\eta_T)\right] + \delta_{\xi_T,+1}\bar{\omega}^{sig}_T(\eta_T)\right]\bar{\varepsilon}^{sig}_T h^{sig}_T(\eta_T) + \\ &+ \delta_{\xi_T,0} \bar{k}^{sig}_T U(\eta_T),\end{aligned} \tag{16}$$

Cross-feed Model

Invariant mass: KDE on simulated samples surviving selection
Decay time: same as signal + accounting for the FS↔CP final-state swap

$$p_{\mathrm{CP}\to\mathrm{FS}}(t,\Omega^{sig},\overline{\Omega}^{sig}) \propto \Big[\left[(1-\mathcal{A}_P)\Omega^{sig}+(1+\mathcal{A}_P)\overline{\Omega}^{sig}\right]I_+(t)+ \\ + \left[(1-\mathcal{A}_P)\Omega^{sig}-(1+\mathcal{A}_P)\overline{\Omega}^{sig}\right]I_-(t)\Big], \quad (17)$$

$$p_{\mathrm{FS}\to\mathrm{CP}}(t,\Omega^{sig},\overline{\Omega}^{sig}) \propto (1+\mathcal{A}_{CP}\mathcal{A}_{\mathrm{f}})\left[(1-\mathcal{A}_P)\Omega^{sig}+(1+\mathcal{A}_P)\overline{\Omega}^{sig}\right]H_+(t)+ \\ -(\mathcal{A}_{CP}+\mathcal{A}_{\mathrm{f}})\left[(1-\mathcal{A}_P)\Omega^{sig}-(1+\mathcal{A}_P)\overline{\Omega}^{sig}\right]H_-(t). \quad (18)$$

3-body Background Model

Invariant mass: ARGUS (endpoints depend on the spectrum) convoluted with double-gaussian resolution
Decay time: derived with KDE, accounting for tagging response

$$p_{3b}(t|\xi_{\mathrm{SS}}) = \delta_{|\xi_{\mathrm{SS}}|,1}\, T_1(t) + \delta_{|\xi_{\mathrm{SS}}|,0}\, T_0(t), \tag{19}$$

Tagging:

$$\Omega^{3b}(\vec{\xi}_{tag}, \vec{\eta}_{tag}) = \Omega^{3b}_{\mathrm{OS}}(\xi_{\mathrm{OS}}, \eta_{\mathrm{OS}}) \cdot \Omega^{3b}_{\mathrm{SS}_{(K)}}(\xi_{\mathrm{SS}_{(K)}}, \eta_{\mathrm{SS}_{(K)}}), \tag{20}$$

$$\Omega^{3b}_T(\xi_T, \eta_T) = \delta_{\xi_T,1}\varepsilon^{3b}_T h^{3b}_T(\eta_T) + \delta_{\xi_T,-1}\bar{\varepsilon}^{3b}_T h^{3b}_T(\eta_T) + \delta_{\xi_T,0}(1 - \varepsilon^{3b}_T - \bar{\varepsilon}^{3b}_T)U(\eta_T). \tag{21}$$

Combinatorial Background

Invariant mass:

$$p(m|t) \propto e^{-\alpha(t)\, m}, \tag{22}$$

$$\alpha(t) = p_0\left[1 + \tanh\left[p_1(t - p_2)\right]\right], \tag{23}$$

(different α depending on the FT response)
Decay time: KDE on high invariant-mass sideband accounting for different tagging responses

$$p_{comb}(t|\vec{\xi}_{tag}) = \sum_{j=0,1}\sum_{k=0,1} \delta_{|\xi_{\rm OS}|,j}\delta_{|\xi_{{\rm SS}_{(K)}}|,k}\, T_{jk}(t), \tag{24}$$

$B^0 \to \pi^+\pi^-$ Selection Results

Yield	2015-16	2017	2018
$N(B^0 \to \pi^+\pi^-)$	$\pm$	$\pm$	$\pm$
$N(B^0 \to K^+\pi^-)$	$\pm$	$\pm$	$\pm$
$N(B_s^0 \to \pi^+\pi^-)$	$\pm$	$\pm$	$\pm$
$N(B_s^0 \to \pi^+K^-)$	$\pm$	$\pm$	$\pm$
$N(\text{3-body}_{\pi^+\pi^-})$	$\pm$	$\pm$	$\pm$
$N(\text{3-body}_{K^\pm\pi^\mp,1})$	$\pm$	$\pm$	$\pm$
$N(\text{3-body}_{K^\pm\pi^\mp,2})$	$\pm$	$\pm$	$\pm$
$N(\text{comb}_{\pi^+\pi^-})$	$\pm$	$\pm$	$\pm$
$N(\text{comb}_{K^\pm\pi^\mp})$	$\pm$	$\pm$	$\pm$

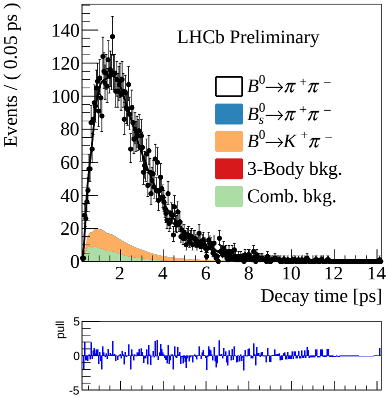
CPV observable	2015-16	2017	2018
$C(B^0 \to \pi^+\pi^-)$	-0.310 $\pm$ 0.047	-0.300 $\pm$ 0.050	-0.310 $\pm$ 0.047
$S(B^0 \to \pi^+\pi^-)$	-0.732 $\pm$ 0.043	-0.762 $\pm$ 0.047	-0.751 $\pm$ 0.044

$B_s^0 \to \pi^+\pi^-$ Selection Results

Yield	2015-16	2017	2018	Tot
$N(B^0 \to \pi^+\pi^-)$	$\pm$	$\pm$	$\pm$	$\pm$
$N(B^0 \to K^+\pi^-)$	$\pm$	$\pm$	$\pm$	$\pm$
$N(B_s^0 \to \pi^+\pi^-)$	$\pm$	$\pm$	$\pm$	$\pm$
$N(B_s^0 \to \pi^+K^-)$	$\pm$	$\pm$	$\pm$	$\pm$
$N(\text{3-body}_{\pi^+\pi^-})$	$\pm$	$\pm$	$\pm$	$\pm$
$N(\text{3-body}_{K^\pm\pi^\mp,1})$	$\pm$	$\pm$	$\pm$	$\pm$
$N(\text{3-body}_{K^\pm\pi^\mp,2})$	$\pm$	$\pm$	$\pm$	$\pm$
$N(\text{comb}_{\pi^+\pi^-})$	$\pm$	$\pm$	$\pm$	$\pm$
$N(\text{comb}_{K^\pm\pi^\mp})$	$\pm$	$\pm$	$\pm$	$\pm$

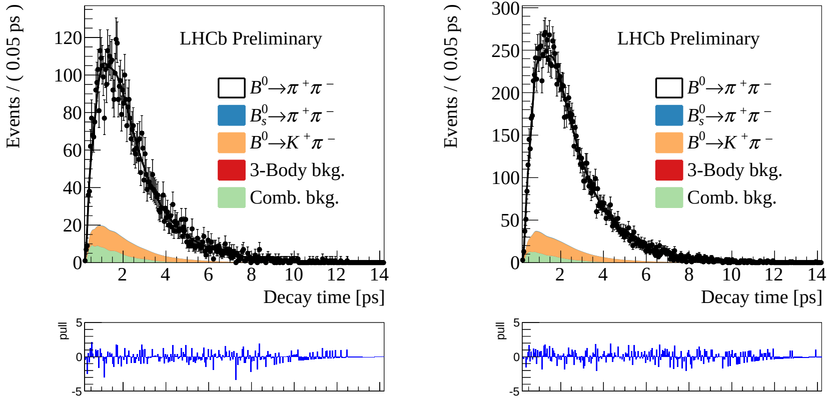
CPV observable	2015-16	2017	2018	Tot
$C(B_s^0 \to \pi^+\pi^-)$	0.32 ± 0.42	0.16 ± 0.42	-0.57 ± 0.46	-0.04 ± 0.25
$S(B_s^0 \to \pi^+\pi^-)$	-0.15 ± 0.41	0.43 ± 0.40	-0.21 ± 0.47	-0.04 ± 0.25
$-A^{\Delta\Gamma}(B_s^0 \to \pi^+\pi^-)$	-1.64 ± 0.45	-0.74 ± 0.62	-1.28 ± 0.55	-1.33 ± 0.31
$C(B^0 \to \pi^+\pi^-)$	-0.298 ± 0.057	-0.329 ± 0.062	-0.243 ± 0.052	-0.282 ± 0.032

$B^0 \to \pi^+\pi^-$ - Mass 5.23→5.32 GeV/c^2



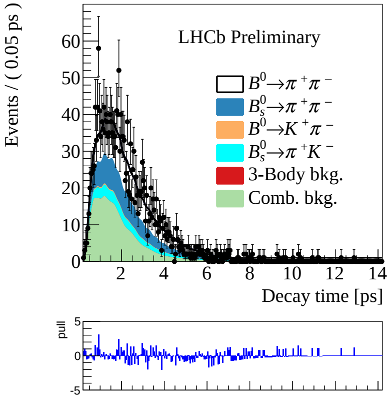
$\pi^+\pi^-$ final state, B tagged, OS (left) SS (right), 2018

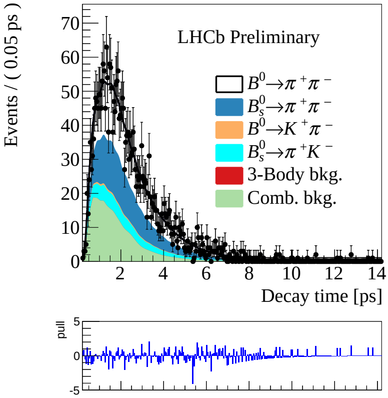
$B^0 \to \pi^+\pi^-$ - Mass 5.23→5.32 GeV/c^2



$\pi^+\pi^-$ final state, $\overline{B}$ tagged, OS (left) SS (right), 2018

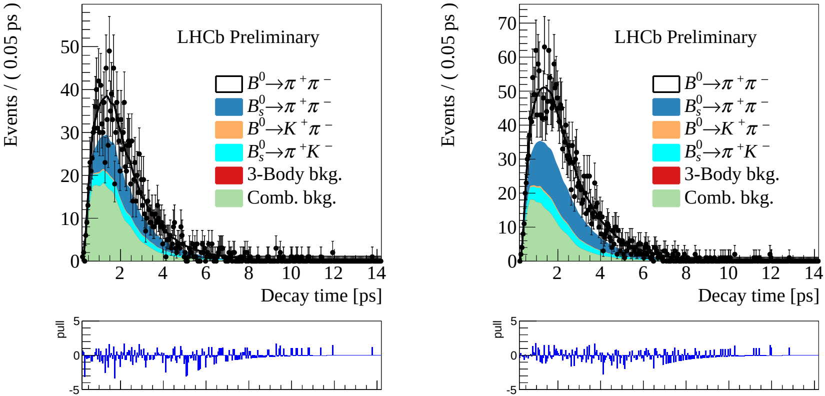
$B_s^0 \to \pi^+\pi^-$ - Mass 5.33→5.45 GeV/c^2





$\pi^+\pi^-$ final state, B tagged, OS (left) SS (right), All years

$B_s^0 \to \pi^+\pi^-$ - Mass 5.33→5.45 GeV/c^2



$\pi^+\pi^-$ final state, $\overline{B}$ tagged, OS (left) SS (right), All years

Old Analysis Systematics

Source	$C_{\pi\pi}$	$S_{\pi\pi}$	$A_{CP}^{B^0}$	$A_{CP}^{B_s^0}$
Time acceptance				
Model	0.0048	0.0027	0.0005	0.0005
Calibration channel	0.0028	0.0013	0.0003	0.0057
Transport between modes	0.0038	0.0019	0.0010	0.0001
Time resolution				
Width	0.0015	0.0026	0.0001	0.0001
Bias	0.0003	0.0003	0.0000	0.0000
Average	0.0004	0.0007	0.0000	0.0000
Input parameters	0.0029	0.0018	0.0001	0.0001
B_s^0 from B_c^+	–	–	–	–
Flavour tagging				
SSK calibration	–	–	–	–
Calibration model	0.0012	0.0013	0.0000	0.0000
$H_b \to h^+h'^-$ mass model	0.0065	0.0078	0.0004	0.0074
Cross-feed model	0.0075	0.0044	0.0001	0.0001
Comb. bkg. model	0.0057	0.0030	0.0001	0.0015
Part. reco. model	0.0043	0.0063	0.0005	0.0036
PID in fit model	0.0020	0.0031	0.0002	0.0016
PID asymmetry	–	–	0.0028	0.0028
Det. asymmetry	–	–	0.0012	0.0012
Total	0.0145	0.0128	0.0033	0.0108