

Measurement of the CKM angle γ using $B_s^0 \rightarrow D_s K \pi\pi$ decays

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Abstract

We present the first measurement of the weak phase $2\beta + \gamma$ obtained from a time-dependent (amplitude) analysis of $B_s^0 \rightarrow D_s K \pi\pi$ decays using proton-proton collision data corresponding to an integrated luminosity of 5 fb^{-1} recorded by the LHCb detector.

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1 Introduction

The weak phase γ is the least well known angle of the CKM unitary triangle. A key channel to measure γ is the time-dependent analysis of $B_s^0 \rightarrow D_s K$ decays [1, 2]. To measure the weak CKM phase $\gamma \equiv \arg[-(V_{ud}V_{ub}^*)/(V_{cd}V_{cb}^*)]$, a decay with interference between $b \rightarrow c$ and $b \rightarrow u$ transitions is needed [1]. This note present the first measurement of γ using $B_s^0 \rightarrow D_s K\pi\pi$ decays, where the $K\pi\pi$ subsystem is dominated by excited kaon states such as the $K_1(1270)$ and $K_1(1400)$ resonances. To account for the non-constant strong phase across the phasespace, one can either perform a time-dependent amplitude fit or select a suitable phase-space region and introduce a coherence factor as additional hadronic parameter to the fit. This analysis is based on the first observation of the $B_s^0 \rightarrow D_s K\pi\pi$ decay by LHCb [3, 4], where the branching ratio is measured relative to $B_s^0 \rightarrow D_s \pi\pi\pi$.

2 Formalism

2.1 Decay rates and CP-observables

In the following, we choose a convention in which $\Delta\Gamma_s = \Gamma_L - \Gamma_H < 0$ and $\Delta m_s = m_H - m_L > 0$, where the indices H and L refer to the heavy and light mass eigenstates of the B_s meson. We assume $|q/p| = 1$ for the complex coefficients p and q which relate the B_s meson mass eigenstates to the flavour eigenstates.

$$A(B_s^0 \rightarrow D_s^- K^+ \pi\pi) \equiv A(x) = \sum_i a_i A_i(x) \quad (2.1)$$

$$A(B_s^0 \rightarrow D_s^+ K^- \pi\pi) \equiv \bar{A}(\bar{x}) = \sum_i \bar{a}_i \bar{A}_i(\bar{x}) \quad (2.2)$$

$$A(\bar{B}_s^0 \rightarrow D_s^- K^+ \pi\pi) = \bar{A}(x) \text{ (Assuming no direct CPV)} \quad (2.3)$$

$$A(\bar{B}_s^0 \rightarrow D_s^+ K^- \pi\pi) = A(\bar{x}) \text{ (Assuming no direct CPV)} \quad (2.4)$$

The full time-dependent amplitude pdf is given by:

$$\begin{aligned} P(x, t, q_t, q_f) \propto & [(|A(x)|^2 + |\bar{A}(x)|^2) \cosh\left(\frac{\Delta\Gamma t}{2}\right) \\ & + q_t q_f (|A(x)|^2 - |\bar{A}(x)|^2) \cos(m_s t) \\ & - 2\text{Re}(A(x)^* \bar{A}(x) e^{-iq_f(\gamma-2\beta_s)}) \sinh\left(\frac{\Delta\Gamma t}{2}\right) \\ & - 2q_t q_f \text{Im}(A(x)^* \bar{A}(x) e^{-iq_f(\gamma-2\beta_s)}) \sin(m_s t)] e^{-\Gamma t} \end{aligned} \quad (2.5)$$

where $q_t = +1, -1, 0$ for events tagged as B_s^0 , \bar{B}_s^0 or untagged events and $q_f = +1$ (-1) for $D_s^- K^+ \pi\pi$ ($D_s^+ K^- \pi\pi$) final states. Integrating over the phasespace, we get

$$\int P(x, t, q_t, q_f) dx \propto [\cosh\left(\frac{\Delta\Gamma t}{2}\right) + q_t q_f C \cos(m_s t) + \kappa D_{q_f} \sinh\left(\frac{\Delta\Gamma t}{2}\right) - q_t \kappa S_{q_f} \sin(m_s t)] e^{-\Gamma t} \quad (2.6)$$

21 where the same convention for the CP coefficients as for the $B_s \rightarrow D_s K$ analysis is used:

$$C = \frac{1 - r^2}{1 + r^2} \quad (2.7)$$

$$D_{q_f} = -\frac{2r \cos(\delta - q_f (\gamma - 2\beta_s))}{1 + r^2} \quad (2.8)$$

$$S_{q_f} = q_f \frac{2r \sin(\delta - q_f (\gamma - 2\beta_s))}{1 + r^2} \quad (2.9)$$

22 The coherence factor κ , the strong phase difference δ and the ratio of the suppressed
23 ($b \rightarrow u$) over favored ($b \rightarrow c$) decay mode are defined as:

$$\kappa e^{i\delta} \equiv \frac{\int A(x)^* \bar{A}(x) dx}{\sqrt{\int |A(x)|^2 dx} \sqrt{\int |\bar{A}(x)|^2 dx}} \quad (2.10)$$

$$r \equiv \frac{\sqrt{\int |\bar{A}(x)|^2 dx}}{\sqrt{\int |A(x)|^2 dx}}. \quad (2.11)$$

24 In the limit of only one contributing resonance $\kappa \rightarrow 1$.

25

26 2.2 Amplitude model

27 The differential decay rate of a B_s meson with mass, m_{B_s} , decaying into four pseudoscalar
28 particles with four-momenta $p_i = (E_i, \vec{p}_i)$ ($i = 1, 2, 3, 4$) is given by

$$d\Gamma = \frac{1}{2 m_{B_s}} |A(\mathbf{x})|^2 d\Phi_4, \quad (2.12)$$

29 where the transition amplitude $A(\mathbf{x})$, describes the dynamics of the interaction, $d\Phi_4$
30 is the four-body phase space element [5], and \mathbf{x} represents a unique set of kinematic
31 conditions within the phase space of the decay. Each final state particle contributes three
32 observables, manifesting in their three-momentum, summing up to twelve observables in
33 total. Four of them are redundant due to four-momentum conservation and the overall
34 orientation of the system can be integrated out. The remaining five independent degrees
35 of freedom unambiguously determine the kinematics of the decay. Convenient choices
36 for the kinematic observables include the invariant mass combinations of the final state
37 particles

$$\begin{aligned} m_{ij}^2 &= (p_i + p_j)^2, \\ m_{ijk}^2 &= (p_i + p_j + p_k)^2 \end{aligned} \quad (2.13)$$

38 or acoplanarity and helicity angles. It is however important to take into account that,
39 while m_{12}^2, m_{23}^2 are sufficient to fully describe a three-body decay, the obvious extension
40 to four-body decays with m_{ij}^2, m_{ijk}^2 requires additional care, as these variables alone are
41 insufficient to describe the parity-odd moments possible in four-body kinematics.

42 In practice, we do not need to choose a particular five-dimensional basis, but use the
43 full four-vectors of the decay in our analysis. The dimensionality is handled by the phase

44 space element which can be written in terms of any set of five independent kinematic
 45 observables, $\mathbf{x} = (x_1, \dots, x_5)$, as

$$d\Phi_4 = \phi_4(\mathbf{x}) d^5x, \quad (2.14)$$

46 where $\phi_4(\mathbf{x}) = \left| \frac{\partial \Phi_4}{\partial(x_1, \dots, x_5)} \right|$ is the phase space density. In contrast to three-body decays,
 47 the four-body phase space density function is not flat in the usual kinematic variables.
 48 Therefore, an analytic expression for ϕ_4 is taken from Ref. [6].

49 The total amplitude for the $B_s \rightarrow h_1 h_2 h_3 h_4$ decay is given by the coherent sum
 50 over all intermediate state amplitudes $A_i(\mathbf{x})$, each weighted by a complex coefficient
 51 $a_i = |a_i| e^{i\phi_i}$ to be measured from data,

$$A(\mathbf{x}) = \sum_i a_i A_i(\mathbf{x}). \quad (2.15)$$

52 To construct $A_i(\mathbf{x})$, the isobar approach is used, which assumes that the decay process
 53 can be factorized into subsequent two-body decay amplitudes [7–9]. This gives rise to
 54 two different decay topologies; quasi two-body decays $B_s \rightarrow (R_1 \rightarrow h_1 h_2) (R_2 \rightarrow h_3 h_4)$
 55 or cascade decays $B_s \rightarrow h_1 [R_1 \rightarrow h_2 (R_2 \rightarrow h_3 h_4)]$. In either case, the intermediate state
 56 amplitude is parameterized as a product of form factors B_L , included for each vertex
 57 of the decay tree, Breit-Wigner propagators T_R , included for each resonance R , and an
 58 overall angular distribution represented by a spin factor S ,

$$A_i(\mathbf{x}) = B_{L_{B_s}}(\mathbf{x}) [B_{L_{R_1}}(\mathbf{x}) T_{R_1}(\mathbf{x})] [B_{L_{R_2}}(\mathbf{x}) T_{R_2}(\mathbf{x})] S_i(\mathbf{x}). \quad (2.16)$$

59 2.2.1 Form Factors and Resonance Lineshapes

60 To account for the finite size of the decaying resonances, the Blatt-Weisskopf penetration
 61 factors, derived in Ref. [10] by assuming a square well interaction potential with radius
 62 r_{BW} , are used as form factors, B_L . They depend on the breakup momentum q , and the
 63 orbital angular momentum L , between the resonance daughters. Their explicit expressions
 64 are

$$\begin{aligned} B_0(q) &= 1, \\ B_1(q) &= 1/\sqrt{1 + (q r_{BW})^2}, \\ B_2(q) &= 1/\sqrt{9 + 3(q r_{BW})^2 + (q r_{BW})^4}. \end{aligned} \quad (2.17)$$

65 Resonance lineshapes are described as function of the energy-squared, s , by Breit-Wigner
 66 propagators

$$T(s) = \frac{1}{M^2(s) - s - i m_0 \Gamma(s)}, \quad (2.18)$$

67 featuring the energy-dependent mass $M(s)$ (defined below), and total width, $\Gamma(s)$. The
 68 latter is normalized to give the nominal width, Γ_0 , when evaluated at the nominal mass
 69 m_0 , *i.e.* $\Gamma_0 = \Gamma(s = m_0^2)$.

70 For a decay into two stable particles $R \rightarrow AB$, the energy dependence of the decay
 71 width can be described by

$$\Gamma_{R \rightarrow AB}^{(2)}(s) = \Gamma_0 \frac{m_0}{\sqrt{s}} \left(\frac{q}{q_0} \right)^{2L+1} \frac{B_L(q)^2}{B_L(q_0)^2}, \quad (2.19)$$

72 where q_0 is the value of the breakup momentum at the resonance pole [11].

73 The energy-dependent width for a three-body decay $R \rightarrow ABC$, on the other hand, is
 74 considerably more complicated and has no analytic expression in general. However, it can
 75 be obtained numerically by integrating the transition amplitude-squared over the phase
 76 space,

$$\Gamma_{R \rightarrow ABC}^{(3)}(s) = \frac{1}{2\sqrt{s}} \int |A_{R \rightarrow ABC}|^2 d\Phi_3, \quad (2.20)$$

77 and therefore requires knowledge of the resonant substructure. The three-body amplitude
 78 $A_{R \rightarrow ABC}$ can be parameterized similarly to the four-body amplitude in Eq. (2.16). In
 79 particular, it includes form factors and propagators of intermediate two-body resonances.

80 Both Eq. (2.19) and Eq. (2.20) give only the partial width for the decay into a specific
 81 channel. To obtain the total width, a sum over all possible decay channels has to be
 82 performed,

$$\Gamma(s) = \sum_i g_i \Gamma_i(s), \quad (2.21)$$

83 where the coupling strength to channel i , is given by g_i . Branching fractions \mathcal{B}_i are related
 84 to the couplings g_i via the equation [12]

$$\mathcal{B}_i = \int_{s_{min}}^{\infty} \frac{g_i m_0 \Gamma_i(s)}{|M^2(s) - s - i m_0 \sum_j g_j \Gamma_j(s)|^2} ds. \quad (2.22)$$

85 As experimental values are usually only available for the branching fractions, Eq. (2.22)
 86 needs to be inverted to obtain values for the couplings. In practice, this is solved by
 87 minimizing the quantity $\chi^2(g) = \sum_i [\mathcal{B}_i - \mathcal{I}_i(g)]^2 / \Delta \mathcal{B}_i^2$, where $\mathcal{I}_i(g)$ denotes the right-
 88 hand side of Eq. (2.22).

89 The treatment of the lineshape for various resonances considered in this analysis is
 90 described in what follows. The nominal masses and widths of the resonances are taken
 91 from the PDG [12] with the exceptions described below.

92 For the broad scalar resonance σ , the model from Bugg is used [13]. Besides $\sigma \rightarrow \pi\pi$
 93 decays, it includes contributions from the decay modes $\sigma \rightarrow KK$, $\sigma \rightarrow \eta\eta$ and $\sigma \rightarrow \pi\pi\pi\pi$
 94 as well as dispersive effects due to the channel opening of the latter. We use the Gournaris-
 95 Sakurai parametrization for the $\rho(770)^0 \rightarrow \pi\pi$ propagator which provides an analytical
 96 description of the dispersive term, $M^2(s)$ [14]. The energy-dependent width of the $f_0(980)$
 97 resonance is given by the sum of the partial widths into the $\pi\pi$ and KK channels [15],

$$\Gamma_{f_0(980)}(s) = g_{\pi\pi} \Gamma_{f_0(980) \rightarrow \pi\pi}^{(2)}(s) + g_{KK} \Gamma_{f_0(980) \rightarrow KK}^{(2)}(s), \quad (2.23)$$

98 where the coupling constants $g_{\pi\pi}$ and g_{KK} , as well as the mass and width are taken from
 99 a measurement performed by the BES Collaboration [16]. The total decay widths for
 100 both the $f_2(1270)$ and the $f_0(1370)$ meson take the channels $\pi\pi$, KK , $\eta\eta$ and $\pi\pi\pi\pi$ into
 101 account. While the two-body partial widths are described by Eq. (2.19), a model for
 102 the partial width for a decay into four pions is taken from Ref. [17]. The corresponding
 103 branching fractions are taken from the PDG [12]. The nominal mass and width of the
 104 $f_0(1370)$ resonance are taken from an LHCb measurement [18]. Equation (2.19) is used
 105 for all other resonances decaying into a two-body final state.

106 Some particles may not originate from a resonance but are in a state of relative orbital
 107 angular momentum. We denote such non-resonant states by surrounding the particle

108 system with brackets and indicate the partial wave state with an subscript; for example
109 $(\pi\pi)_S$ refers to a non-resonant di-pion S -wave. The lineshape for non-resonant states is
110 set to unity.

111 2.2.2 Spin Densities

112 The spin amplitudes are phenomenological descriptions of decay processes that are required
113 to be Lorentz invariant, compatible with angular momentum conservation and, where
114 appropriate, parity conservation. They are constructed in the covariant Zemach (Rarita-
115 Schwinger) tensor formalism [19–21]. At this point, we briefly introduce the fundamental
116 objects of the covariant tensor formalism which connect the particle’s four-momenta to
117 the spin dynamics of the reaction and give a general recipe to calculate the spin factors
118 for arbitrary decay trees. Further details can be found in Refs. [22, 23].

119 A spin- S particle with four-momentum p , and spin projection λ , is represented by the
120 polarization tensor $\epsilon_{(S)}(p, \lambda)$, which is symmetric, traceless and orthogonal to p . These
121 so-called Rarita-Schwinger conditions reduce the a priori 4^S elements of the rank- S tensor
122 to $2S + 1$ independent elements in accordance with the number of degrees of freedom of a
123 spin- S state [20, 24].

124 The spin projection operator $P_{(S)}^{\mu_1 \dots \mu_S \nu_1 \dots \nu_S}(p_R)$, for a resonance R , with spin $S =$
125 $\{0, 1, 2\}$, and four-momentum p_R , is given by [23]:

$$\begin{aligned} P_{(0)}^{\mu\nu}(p_R) &= 1 \\ P_{(1)}^{\mu\nu}(p_R) &= -g^{\mu\nu} + \frac{p_R^\mu p_R^\nu}{p_R^2} \\ P_{(2)}^{\mu\nu\alpha\beta}(p_R) &= \frac{1}{2} \left[P_{(1)}^{\mu\alpha}(p_R) P_{(1)}^{\nu\beta}(p_R) + P_{(1)}^{\mu\beta}(p_R) P_{(1)}^{\nu\alpha}(p_R) \right] - \frac{1}{3} P_{(1)}^{\mu\nu}(p_R) P_{(1)}^{\alpha\beta}(p_R), \end{aligned} \quad (2.24)$$

126 where $g^{\mu\nu}$ is the Minkowski metric. Contracted with an arbitrary tensor, the projection
127 operator selects the part of the tensor which satisfies the Rarita-Schwinger conditions.

128 For a decay process $R \rightarrow AB$, with relative orbital angular momentum L , between
129 particle A and B , the angular momentum tensor is obtained by projecting the rank- L
130 tensor $q_R^{\nu_1} q_R^{\nu_2} \dots q_R^{\nu_L}$, constructed from the relative momenta $q_R = p_A - p_B$, onto the spin- L
131 subspace,

$$L_{(L)\mu_1 \dots \mu_L}(p_R, q_R) = (-1)^L P_{(L)\mu_1 \dots \mu_L \nu_1 \dots \nu_L}(p_R) q_R^{\nu_1} \dots q_R^{\nu_L}. \quad (2.25)$$

132 Their $|\vec{q}_R|^L$ dependence accounts for the influence of the centrifugal barrier on the transition
133 amplitudes. For the sake of brevity, the following notation is introduced,

$$\begin{aligned} \varepsilon_{(S)}(R) &\equiv \varepsilon_{(S)}(p_R, \lambda_R), \\ P_{(S)}(R) &\equiv P_{(S)}(p_R), \\ L_{(L)}(R) &\equiv L_{(L)}(p_R, q_R). \end{aligned} \quad (2.26)$$

134 Following the isobar approach, a four-body decay amplitude is described as a product
135 of two-body decay amplitudes. Each sequential two-body decay $R \rightarrow A B$, with relative
136 orbital angular momentum L_{AB} , and total intrinsic spin S_{AB} , contributes a term to the
137 overall spin factor given by

$$\begin{aligned} S_{R \rightarrow AB}(\mathbf{x}|L_{AB}, S_{AB}; \lambda_R, \lambda_A, \lambda_B) &= \varepsilon_{(S_R)}(R) X(S_R, L_{AB}, S_{AB}) L_{(L_{AB})}(R) \\ &\times \Phi(\mathbf{x}|S_{AB}; \lambda_A, \lambda_B), \end{aligned} \quad (2.27)$$

¹³⁸ where

$$\Phi(\mathbf{x}|S_{AB}; \lambda_A, \lambda_B) = P_{(S_{AB})}(R) X(S_{AB}, S_A, S_B) \varepsilon_{(S_A)}^*(A) \varepsilon_{(S_B)}^*(B). \quad (2.28)$$

¹³⁹ Here, a polarization vector is assigned to the decaying particle and the complex conjugate
¹⁴⁰ vectors for each decay product. The spin and orbital angular momentum couplings are
¹⁴¹ described by the tensors $P_{(S_{AB})}(R)$ and $L_{(L_{AB})}(R)$, respectively. Firstly, the two spins S_A
¹⁴² and S_B , are coupled to a total spin- S_{AB} state, $\Phi(\mathbf{x}|S_{AB})$, by projecting the corresponding
¹⁴³ polarization vectors onto the spin- S_{AB} subspace transverse to the momentum of the
¹⁴⁴ decaying particle. Afterwards, the spin and orbital angular momentum tensors are
¹⁴⁵ properly contracted with the polarization vector of the decaying particle to give a Lorentz
¹⁴⁶ scalar. This requires in some cases to include the tensor $\varepsilon_{\alpha\beta\gamma\delta} p_R^\delta$ via

$$X(j_a, j_b, j_c) = \begin{cases} 1 & \text{if } j_a + j_b + j_c \text{ even} \\ \varepsilon_{\alpha\beta\gamma\delta} p_R^\delta & \text{if } j_a + j_b + j_c \text{ odd} \end{cases}, \quad (2.29)$$

¹⁴⁷ where $\varepsilon_{\alpha\beta\gamma\delta}$ is the Levi-Civita symbol and j refers to the arguments of X defined in
¹⁴⁸ Eqs. 2.27 and 2.28. Its antisymmetric nature ensures the correct parity transformation
¹⁴⁹ behavior of the amplitude. The spin factor for a whole decay chain, for example $R \rightarrow$
¹⁵⁰ ($R_1 \rightarrow AB$) ($R_2 \rightarrow CD$), is obtained by combining the two-body terms and performing a
¹⁵¹ sum over all unobservable, intermediary spin projections

$$\sum_{\lambda_{R_1}, \lambda_{R_2}} S_{R \rightarrow R_1 R_2}(\mathbf{x}|L_{R_1 R_2}; \lambda_{R_1}, \lambda_{R_2}) S_{R_1 \rightarrow AB}(\mathbf{x}|L_{AB}; \lambda_{R_1}) S_{R_2 \rightarrow CD}(\mathbf{x}|L_{CD}; \lambda_{R_2}), \quad (2.30)$$

¹⁵² where $\lambda_R = \lambda_A = \lambda_B = \lambda_C = \lambda_D = 0$, $S_{AB} = S_{CD} = 0$ and $S_{R_1 R_2} = L_{R_1 R_2}$, as only
¹⁵³ pseudoscalar initial/final states are involved.

¹⁵⁴ The spin factors for all decay topologies considered in this analysis are explicitly given
¹⁵⁵ in Appendix E.

156 2.3 Validation

157 The amplitude fit is performed by using the amplitude analysis tool **MINT2**. It was
 158 previously applied to analyze $D^0 \rightarrow 4\pi$ and $D^0 \rightarrow KK\pi\pi$ decays [25] which have an
 159 identical general spin structure (*i.e.* scalar to four scalar decay) then $B_s \rightarrow D_s K\pi\pi$ decays.
 160 In the course of the $D^0 \rightarrow hhhh$ analysis, the implementation of the amplitudes were
 161 extensively cross-checked against other available tool such as **qft++** [26], **AmpGen** [27] and
 162 were possible **EVTGEN** [28]. Since no additional line shapes or spin factors are needed for
 163 this analysis, we consider the amplitude calculation as fully validated.

164 This does, however, not apply to the full time-dependent amplitude pdf which is newly
 165 implemented for this analysis. To cross-check it, we use **EVTGEN** to generate toy events
 166 with time-dependent CP violation according to the **SSD_CP** event model [28]. Since this
 167 event model does not allow for multiple interfering resonances, we generate only the decay
 168 chain $B_s \rightarrow D_s (K_1(1400) \rightarrow K^*(892)\pi)$. Table 2.1 lists the generated input parameters.
 169 The toy data set is fitted with our **MINT2** implementation of the full time-dependent
 170 amplitude pdf and the phasespace-integrated pdf.

171 The CP coefficients $C, D, \bar{D}, S, \bar{S}$ are the fit parameters in case of the phasespace-
 172 integrated pdf, while the full pdf determines $x_{\pm} = r \cos(\delta \pm (\gamma - 2\beta_s))$ and $y_{\pm} = r \sin(\delta \pm$
 173 $(\gamma - 2\beta_s))$. The fit parameters are converted to the physical observables $r, \kappa, \delta, \gamma$ using
 174 the **GammaCombo** package [29]. As shown in Tab. 2.2, 2.3 and 2.4, the fit results are
 175 in excellent agreement with the generated input values. The 1-CL contours are shown
 176 in Figs. 2.1 and 2.2. The phasespace-integrated fit is, in addition, performed with the
 177 **B2DX** fitter used for the $B_s \rightarrow D_s K$ analysis yielding identical results. Note though that
 178 some parts of the **B2DX** fitter have been taken over to our **MINT2** fitter, such that the
 179 implementations are not fully independent.

Table 2.1: Input values used to generate **EVTGEN** toy events according to the **SSD_CP** event model.

| | |
|----------------|--------------------------|
| τ | 1.5 ps |
| $\Delta\Gamma$ | -0.1 ps^{-1} |
| Δm_s | 17.757 ps^{-1} |
| r | 0.37 |
| κ | 1 |
| δ | 10.0° |
| γ | 71.1° |
| β_s | 0.0° |

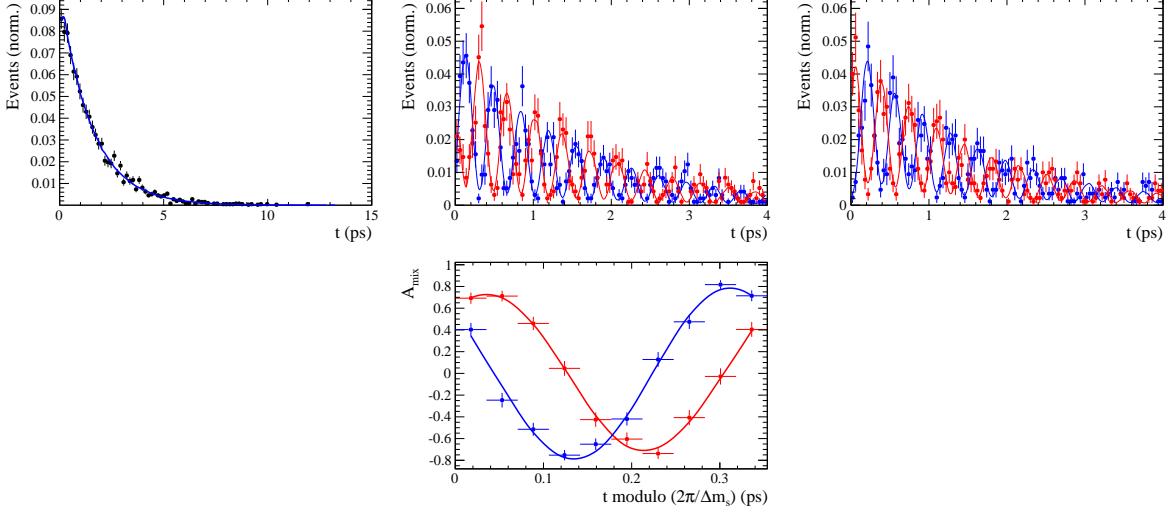


Figure 2.1: Time distribution of $B_s \rightarrow D_s K\pi\pi$ events generated with EVTGEN (points with error bars) and MINT2 fit projections (blue solid line).

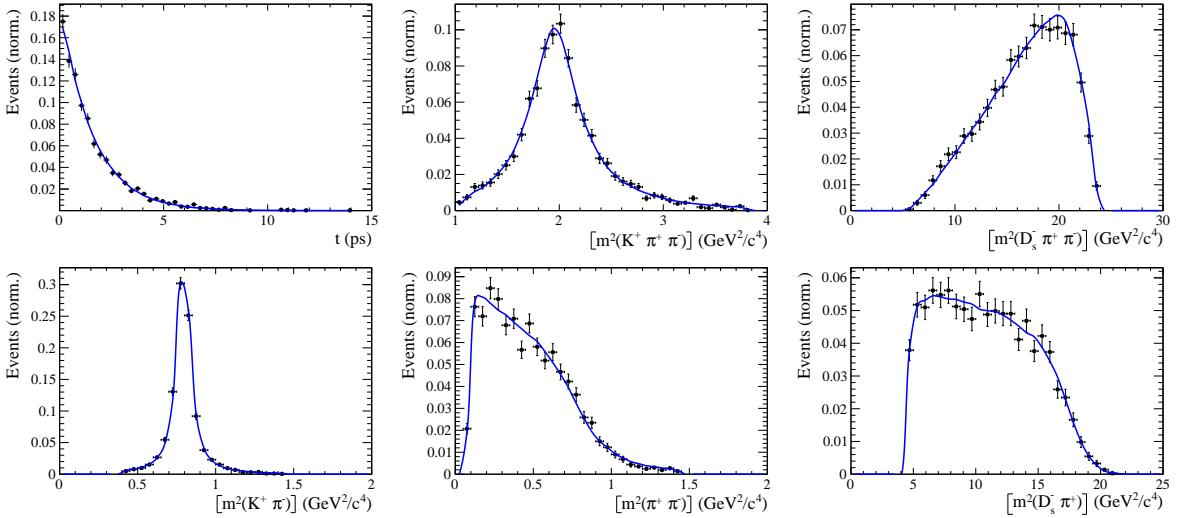


Figure 2.2: Time and invariant mass distributions of $B_s \rightarrow D_s K\pi\pi$ events generated with EVTGEN (points with error bars) and MINT2 fit projections (blue solid line).

Table 2.2: Result of the phasespace-integrated fit to EVTGEN toy events.

| | Generated | Fit result | Pull(σ) |
|-----------|-----------|--------------------|------------------|
| C | 0.759 | 0.763 ± 0.026 | 0.2 |
| D | -0.314 | -0.376 ± 0.227 | -0.3 |
| \bar{D} | -0.101 | -0.261 ± 0.246 | -0.7 |
| S | -0.570 | -0.626 ± 0.035 | 1.6 |
| \bar{S} | -0.643 | -0.669 ± 0.035 | -0.7 |

Table 2.3: Result of the time-dependent amplitude fit to EVTGEN toy events.

| | Generated | Fit result | Pull(σ) |
|-------|-----------|--------------------|------------------|
| x_- | 0.179 | 0.135 ± 0.050 | -0.9 |
| y_- | -0.324 | -0.307 ± 0.022 | 0.8 |
| x_+ | 0.057 | 0.102 ± 0.065 | 0.6 |
| y_+ | 0.366 | 0.394 ± 0.023 | 1.3 |

Table 2.4: Results for the physical observables obtained from fits to EVTGEN toy events.

| | Generated | Full PDF | Phasespace integrated |
|----------|--------------|-------------------|-----------------------|
| r | 0.370 | 0.379 ± 0.021 | 0.379 ± 0.017 |
| κ | 1.0 | 1.0 | 1.000 ± 0.059 |
| δ | 10.0° | 9.0 ± 5.1 | 5.9 ± 6.0 |
| γ | 71.1° | 67.3 ± 5.9 | 75.1 ± 6.9 |

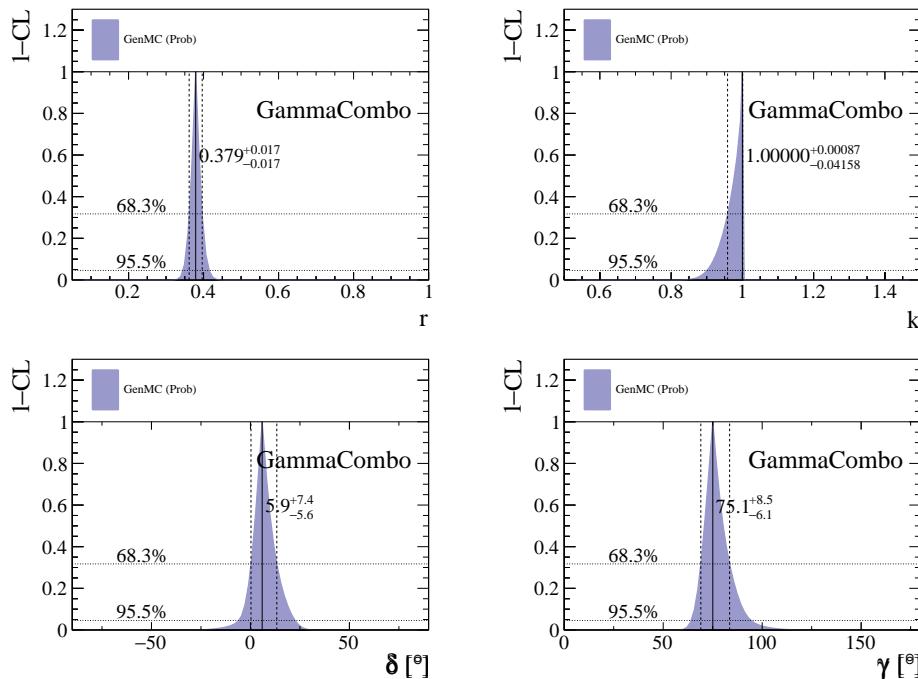


Figure 2.3: The 1-CL contours for the physical observable $r, \kappa, \delta, \gamma$ obtained with the phasespace integrated fit to the EVTGEN toy sample.

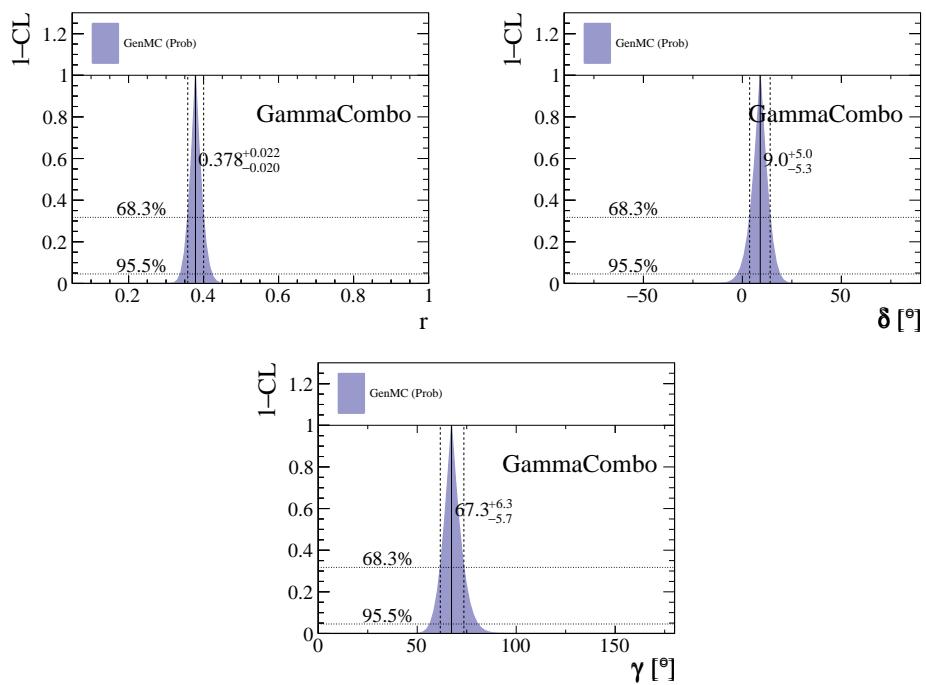


Figure 2.4: The 1-CL contours for the physical observable r, δ, γ obtained with the time-dependent amplitude fit fit to the `EVTGEN` toy sample.

180 3 Data samples and event selection

181 3.1 Stripping and Trigger selection

182 The dataset used for this analysis corresponds to 1 fb^{-1} of proton-proton collision data col-
183 lected in 2011 with a centre of mass energy $\sqrt{s} = 7 \text{ TeV}$, 2 fb^{-1} collected in 2012 with $\sqrt{s} =$
184 7 TeV and 4 fb^{-1} collected in 2015/2016/2017 with $\sqrt{s} = 13 \text{ TeV}$. Candidate $B_s^0 \rightarrow D_s K\pi\pi$
185 ($B_s^0 \rightarrow D_s \pi\pi\pi$) decays are reconstructed using the `B02DKPiPiD2HHHPIDBeauty2CharmLine`
186 (`B02DPiPiD2HHHPIDBeauty2CharmLine`) line of the `BHadronCompleteEvent` stream of
187 `Stripping21r1` (2011), `Stripping21` (2012), `Stripping24r1` (2015) and `Stripping28r1p1` (2016)
188 and `Stripping29r2` (2017). Both stripping lines employ the same selection cuts, listed in
189 Appendix A, except for the PID requirement on the bachelor kaon/pion.

190 Events that pass the stripping selection are further required to fulfill the following
191 trigger requirements: at the hardware stage, the B_s^0 candidates are required to be TOS
192 on the `L0Hadron` trigger or TIS on `L0Global`; at Hlt1, B_s^0 candidates are required to be
193 TOS on the `Hlt1TrackAllL0` (`Hlt1TrackMVA` or `Hlt1TwoTrackMVA`) trigger line for Run-I
194 (Run-II) data; at Hlt2, candidates have to be TOS on either one of the 2, 3 or 4-body
195 topological trigger lines or the inclusive ϕ trigger. More details on the used HLT lines are
196 given in Appendix A.

197 Due to a residual kinematic dependence on whether the event is triggered by
198 `L0Hadron` or not and on the data taking condition, the analysis is performed
199 in four disjoint categories: [Run-I,`L0-TOS`], [Run-I,`L0-TIS`], [Run-II,`L0-TOS`] and
200 [Run-II,`L0-TIS`], where for simplicity we denote `L0-TOS` as `L0Hadron-TOS` and `L0-TIS` as
201 (`L0Global-TIS` and not `L0Hadron-TOS`).

202 3.2 Offline selection

203 The offline selection, in particular the requirements on the D_s hadron, are guided by
204 the previous analyses of $B_s \rightarrow D_s K/\pi$, $B_d \rightarrow D^0 \pi$ as well as the branching fraction
205 measurement of $B_s^0 \rightarrow D_s K\pi\pi$ decays. Tables 3.1 and 3.2 summarize all selection
206 requirements which are described in the following.

207 Given the high number of pp interactions per bunch crossing, a large fraction of
208 events have more than one reconstructed PV. We choose the 'best' PV to be the one
209 to which the B_s candidate has the smallest χ_{IP}^2 . In instances where the association
210 of the B_s candidate to the best PV is wrong, the decay time of this candidate will be
211 incorrect. These wrongly associated candidates are rejected by requiring that the B_s
212 χ_{IP}^2 with respect to any other PV is sufficiently higher than with respect to the best PV
213 ($\Delta\chi_{IP}^2 = \chi_{IP,\text{SECONDBEST}}^2 - \chi_{IP,\text{BEST}}^2 > 20$). Events with only a single PV are not affected.

214 In order to clean up the sample and to align the Run-I to the slightly tighter Run-II
215 stripping selection, we apply the following loose cuts to the b-hadron:

- 216 • DIRA > 0.99994
- 217 • min IP $\chi^2 < 16$ to the best PV,
- 218 • FD $\chi^2 > 100$ to the best PV,
- 219 • Vertex $\chi^2/\text{nDoF} < 8$.

220 The cut on the B_s decay-time is tightened with respect to the stripping selection ($t > 0.2$ ps)
221 because, while offline we use the decay-time determined for a DTF in which the PV position,
222 the D_s and the B_s mass are constrained, in the stripping the simple decay-time returned
223 by a kinematic fit is used. The difference between these two decay-times extends up to 0.1
224 ps, thus cutting at 0.4 ps avoids any boundary effects and simplifies the time-acceptance
225 studies. We further remove outliers with poorly estimated decay times ($\delta t < 0.15$ ps).

226 We reconstruct the $B_s^0 \rightarrow D_s h\pi\pi$ decay through three different final states of the
227 D_s meson: $D_s \rightarrow KK\pi$, $D_s \rightarrow \pi\pi\pi$ and $D_s \rightarrow K\pi\pi$. Of those, $D_s \rightarrow KK\pi$ is the
228 most prominent one, while $\mathcal{BR}(D_s \rightarrow \pi\pi\pi) \approx 0.2 \cdot \mathcal{BR}(D_s \rightarrow KK\pi)$ and $\mathcal{BR}(D_s \rightarrow$
229 $K\pi\pi) \approx 0.12 \cdot \mathcal{BR}(D_s \rightarrow KK\pi)$ holds for the others. For the $KK\pi$ final state we make
230 use of the well known resonance structure; the decay proceeds either via the narrow ϕ
231 resonance, the broader K^{*0} resonance or (predominantly) non-resonant. Within the ϕ
232 resonance region the sample is already sufficiently clean after the stripping so that we do
233 not impose additional criteria on the D_s daughters. For the K^{*0} and non-resonant regions
234 consecutively tighter requirements on the particle identification and the D_s flight-distance
235 are applied. We apply global requirements for the other final states.

236 3.2.1 Phase space region

237 Due to the comparable low masses of the final state particles with respect to the B_s
238 mass, there is, in contrast to for example b-hadron to charmonia or charm decays, a
239 huge phase-space available for the $B_s^0 \rightarrow D_s K\pi\pi$ decay. For the invariant mass of
240 the $K\pi\pi$ subsystem it extends up to 3.4 GeV. It has however been observed that the
241 decay proceeds predominantly through the low lying axial vector states $K(1270)$ and
242 $K(1400)$, while the combinatorial background is concentrated at high $K\pi\pi$ invariant
243 masses ($m(K\pi\pi) > 2000$ MeV). Moreover, the strange hadron spectrum above 2 GeV is
244 poorly understood experimentally such that an reliable extraction of the strong phase
245 motion in that region is not possible. We consequently choose the considered phase space
246 region to be $m(K\pi\pi) < 1950$ MeV, which is right below the charm-strange threshold
247 ($B_s^0 \rightarrow D_s^+ D_s^-$).

²⁴⁸ **3.2.2 Physics background vetoes**

²⁴⁹ We veto various physical backgrounds, which have either the same final state as our
²⁵⁰ signal decay, or can contribute via a single misidentification of $K \leftrightarrow \pi$, $K \leftrightarrow p$ or $\pi \leftrightarrow p$.
²⁵¹ Depending on the D_s final state different vetoes are applied in order to account for peaking
²⁵² backgrounds originating from charm meson or charmed baryon decays.

²⁵³ 1. $D_s^- \rightarrow K^+ K^- \pi^-$

²⁵⁴ (a) $D^- \rightarrow K^+ \pi^- \pi^-$:

²⁵⁵ Possible with $\pi^- \rightarrow K^-$ misidentification, vetoed by requiring $m(K^+ K_\pi^- \pi^-) \neq$
²⁵⁶ $m(D^-) \pm 40$ MeV or the K^- has to fulfill more stringent PID criteria depending
²⁵⁷ on the resonant region.

²⁵⁸ (b) $\Lambda_c^- \rightarrow K^+ \bar{p} \pi^-$:

²⁵⁹ Possible with $\bar{p} \rightarrow K^-$ misidentification, vetoed by requiring $m(K^+ K_p^- \pi^-) \neq$
²⁶⁰ $m(\Lambda_c^-) \pm 40$ MeV or the K^- has to fulfill more stringent PID criteria depending
²⁶¹ on the resonant region.

²⁶² (c) $D^0 \rightarrow KK$:

²⁶³ D^0 combined with a random π can fake a $D_s \rightarrow KK\pi$ decay, vetoed by
²⁶⁴ requiring $m(KK) < 1840$ MeV.

²⁶⁵ 2. $D_s^- \rightarrow \pi^+ \pi^- \pi^-$

²⁶⁶ (a) $D^0 \rightarrow \pi\pi$:

²⁶⁷ D^0 combined with a random π can fake a $D_s \rightarrow \pi\pi\pi$ decay, vetoed by requiring
²⁶⁸ both possible combinations to have $m(\pi\pi) < 1700$ MeV.

²⁶⁹ 3. $D_s^- \rightarrow K^- \pi^+ \pi^-$

²⁷⁰ (a) $D^- \rightarrow \pi^- \pi^+ \pi^-$:

²⁷¹ Possible with $\pi^- \rightarrow K^-$ misidentification, vetoed by requiring $m(K_\pi^- \pi^+ \pi^-) \neq$
²⁷² $m(D^-) \pm 40$ MeV or $\text{PIDK}(K^+) > 15$.

²⁷³ (b) $\Lambda_c^- \rightarrow \bar{p} \pi^+ \pi^-$:

²⁷⁴ Possible with $\bar{p} \rightarrow K^-$ misidentification, vetoed by requiring $m(K_p^- \pi^+ \pi^-) \neq$
²⁷⁵ $m(\Lambda_c^-) \pm 40$ MeV or $\text{PIDK}(K^-) - \text{PIDp}(K^-) > 5$.

²⁷⁶ (c) $D^0 \rightarrow K\pi$:

²⁷⁷ D^0 combined with a random π can fake a $D_s \rightarrow K\pi\pi$ decay, vetoed by requiring
²⁷⁸ both possible combinations to have $m(K\pi) < 1750$ MeV.

²⁷⁹ The effects of these veto cuts are illustrated in Figs. 3.1,3.2 and 3.3. To reduce cross-feed
²⁸⁰ from our calibration channel into the signal channel and vice-versa we require tight PID
²⁸¹ cuts on the ambiguous bachelor kaon/pion. In addition, we veto $B_s^0 \rightarrow D_s^- D_s^+$ decays
²⁸² which is illustrated in Fig. 3.4.

- 283 1. $X_s^+ \rightarrow K^+\pi^+\pi^-$:
- 284 (a) $B_s^0 \rightarrow D_s\pi\pi\pi$:
 285 Possible with $\pi^+ \rightarrow K^+$ misidentification, suppressed with $\text{PIDK}(K^+) > 10$.
- 286 (b) $B_s^0 \rightarrow D_s^-(D_s^+ \rightarrow K^+\pi^+\pi^-)$:
 287 Outside of considered phase-space region, see Sec. 3.2.1.
- 288 (c) $B_s^0 \rightarrow D_s^-(D_s^+ \rightarrow K^+K^-\pi^+)$:
 289 To suppress $B_s^0 \rightarrow D_s^-K^+K^-\pi^+$ background, possible with $K^- \rightarrow \pi^-$ misiden-
 290 tification, we require $\text{PIDK}(\pi^-) < 0$. In case the invariant mass of the $K^+\pi^+\pi^-$
 291 system recomputed applying the kaon mass hypothesis to the pion is close to
 292 the D_s mass ($m(K^+\pi^+\pi_K^-) = m(D_s) \pm 20$ MeV), we further tighten the cut to
 293 $\text{PIDK}(\pi^-) < -5$.
- 294 2. $X_d^+ \rightarrow \pi^+\pi^+\pi^-$:
- 295 (a) $B_s^0 \rightarrow D_sK\pi\pi$:
 296 Possible with single missID of $K^+ \rightarrow \pi^+$, suppressed with $\text{PIDK}(\pi^+) < 0$.
- 297 (b) $B_s^0 \rightarrow D_s^-(D_s^+ \rightarrow \pi^+\pi^+\pi^-)$:
 298 Outside of considered phase-space region, see Sec. 3.2.1.
- 299 (c) $B_s^0 \rightarrow D_s^-(D_s^+ \rightarrow K^+\pi^-\pi^+)$:
 300 Possible with single missID of $K^+ \rightarrow \pi^+$, vetoed by requiring $m(\pi^+\pi_K^+\pi^-) \neq$
 301 $m(D_s) \pm 20$ MeV or $\text{PIDK}(\pi^+) < -5$ for both π^+ .

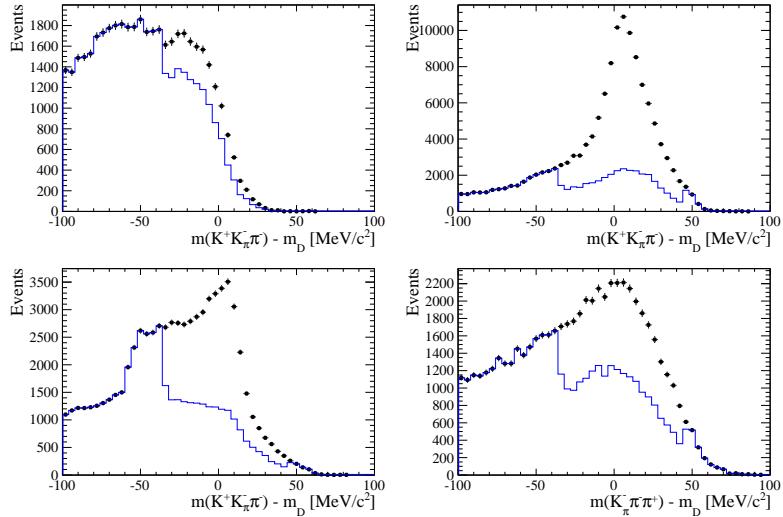


Figure 3.1: Background contributions from D^- decays where the π^- is misidentified as K^- . The D_s invariant mass is recomputed applying the pion mass hypothesis to the kaon and shown for the $D_s \rightarrow \phi\pi$, $D_s \rightarrow K^*(892)K$, $D_s \rightarrow KK\pi$ (non-resonant) and $D_s \rightarrow K\pi\pi$ final state categories from top-left to bottom-right. The distributions are shown without (black) and with (blue) the D^- -veto applied.

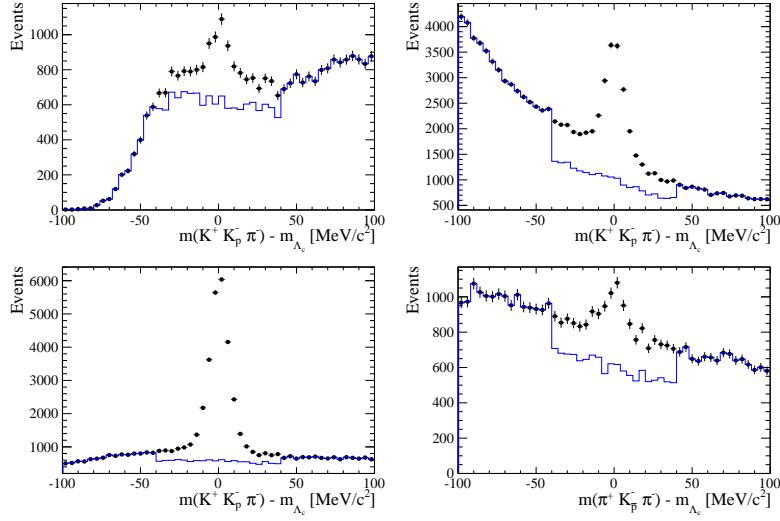


Figure 3.2: Background contributions from Λ_c decays where the \bar{p} is misidentified as K^- . The D_s invariant mass is recomputed applying the proton mass hypothesis to the kaon and shown for the $D_s \rightarrow \phi\pi$, $D_s \rightarrow K^*(892)K$, $D_s \rightarrow KK\pi$ (non-resonant) and $D_s \rightarrow K\pi\pi$ final state categories from top-left to bottom-right. The distributions are shown without (black) and with (blue) the Λ_c -veto applied.

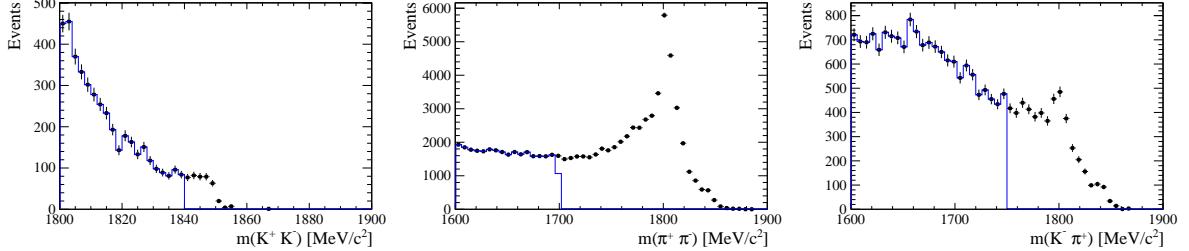


Figure 3.3: Background contributions to $D_s \rightarrow KK\pi$ (left), $D_s \rightarrow \pi\pi\pi$ (middle) and $D_s \rightarrow K\pi\pi$ (right) from $D^0 \rightarrow hh$ decays combined with a random pion.

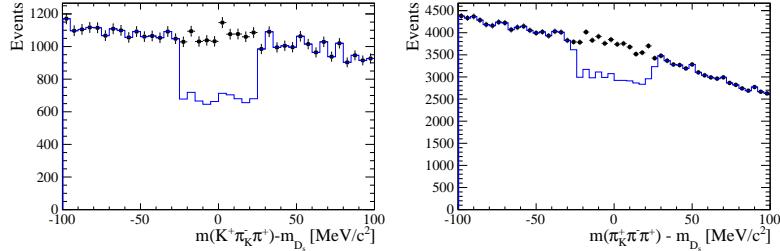


Figure 3.4: Background contributions to $B_s \rightarrow D_s K\pi\pi$ (left) and $B_s \rightarrow D_s \pi\pi\pi$ (right) from $B_s \rightarrow D_s D_s$ decays where the kaon is misidentified as pion. The $X_{s,d}$ invariant mass is recomputed applying the kaon mass hypothesis to the pion and shown without (black) and with (blue) the D_s -veto applied.

302 **3.2.3 Training of multivariate classifier**

303 The Toolkit for Multivariate Analysis (TMVA [30]) is used to train a multivariate classifier
304 (BDT with gradient boosting, BDTG) discriminating signal and combinatorial background.
305 We use $B_s \rightarrow D_s \pi\pi$ data that passes the preselection as signal proxy. The background
306 is statistically subtracted by applying `sWeights` based on the fit to the reconstructed B_s
307 mass shown in Fig. 3.5. This is a simplified version (performed in a reduced mass range)
308 of the final mass fits described in Sec. 4. The sideband data ($m(B_s) > 5500$ MeV) is used
309 as background proxy.

310 Training the classifier on a sub-sample which is supposed to be used in the final analysis
311 might cause a bias, as the classifier selects, in case of overtraining, the training events
312 more efficiently. As overtraining can not be completely avoided, we split the signal and
313 the background training samples into two disjoint subsamples according to whether the
314 event number is even or odd. We then train the classifier on the even sample and apply it
315 to the odd one, and vice-versa (cross-training).

316 The following discriminating variables are used for the BDTG training:

- 317 • logarithm of the B_s impact-parameter χ^2 , $B_s \log(\chi_{IP}^2)$
- 318 • logarithm of the cosine of the B_s direction angle, $\log(\text{DIRA})$
- 319 • fit quality of the DTF with PV constrain, χ_{DTF}^2/ndf
- 320 • logarithm of the minimal vertex quality difference for adding one extra track,
321 $\log(\Delta\chi_{add-track}^2)$
- 322 • the asymmetry between the transverse momentum of the B_s - candidate and the
323 transverse momentum of all the particles reconstructed with a cone of radius
324 $r = \sqrt{(\Delta\Phi)^2 + (\Delta\eta)^2} < 1$ rad around the B_s - candidate, $B_s A_{pT}^{\text{cone}}$
- 325 • largest ghost probability of all tracks, $\max(\text{ghostProb})$
- 326 • logarithm of the the smallest X_s daughter impact-parameter χ^2 , $X_s \log(\min(\chi_{IP}^2))$
- 327 • largest distance of closest approach of the X_s daughters, $\max(\text{DOCA})$
- 328 • cosine of the largest opening angle between the D_s and another bachelor track h_i in
329 the plane transverse to the beam, $\cos(\max \theta_{D_s h_i})$
- 330 • logarithm of the the smallest D_s daughter impact-parameter χ^2 , $D_s \log(\min(\chi_{IP}^2))$
- 331 • logarithm of the D_s flight-distance significance, $D_s \log(\chi_{FD}^2)$
- 332 • logarithm of the D_s radial flight-distance, $D_s \log(RFD)$

333 Loose cuts on the variables χ_{DTF}^2/ndf , $\Delta\chi_{add-track}^2$ and $\cos(\max \theta_{D_s h_i})$ are applied prior
334 to the training which are expected to be 100% signal efficient. Figure 3.6 shows the
335 distributions of the input variables for signal and background. As shown in Appendix B,
336 these distributions differ between data-taking period and trigger category. In particular
337 variables depending on the B_s kinematics and the event multiplicity are affected (e.g.
338 $\theta_{D_s h_i}$ or A_{pT}^{cone}). The BDTG is consequently trained separately for these categories. The
339 resulting classifier response is shown in Fig. 3.7 for each category (even and odd test
340 samples combined) and in Appendix B for each training.

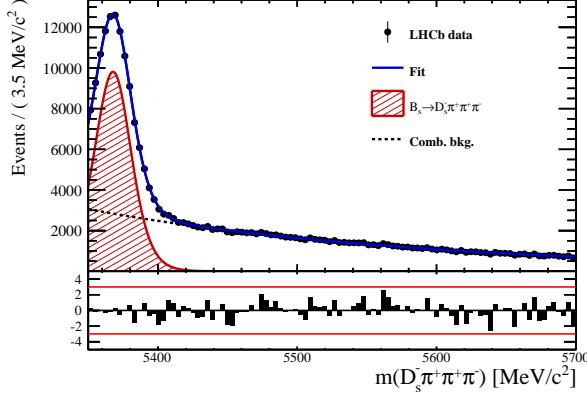


Figure 3.5: Reconstructed B_s mass for $B_s \rightarrow D_s \pi\pi\pi$ events that pass the preselection. The fitted PDF is shown in blue, the signal component in red and the background component in black.

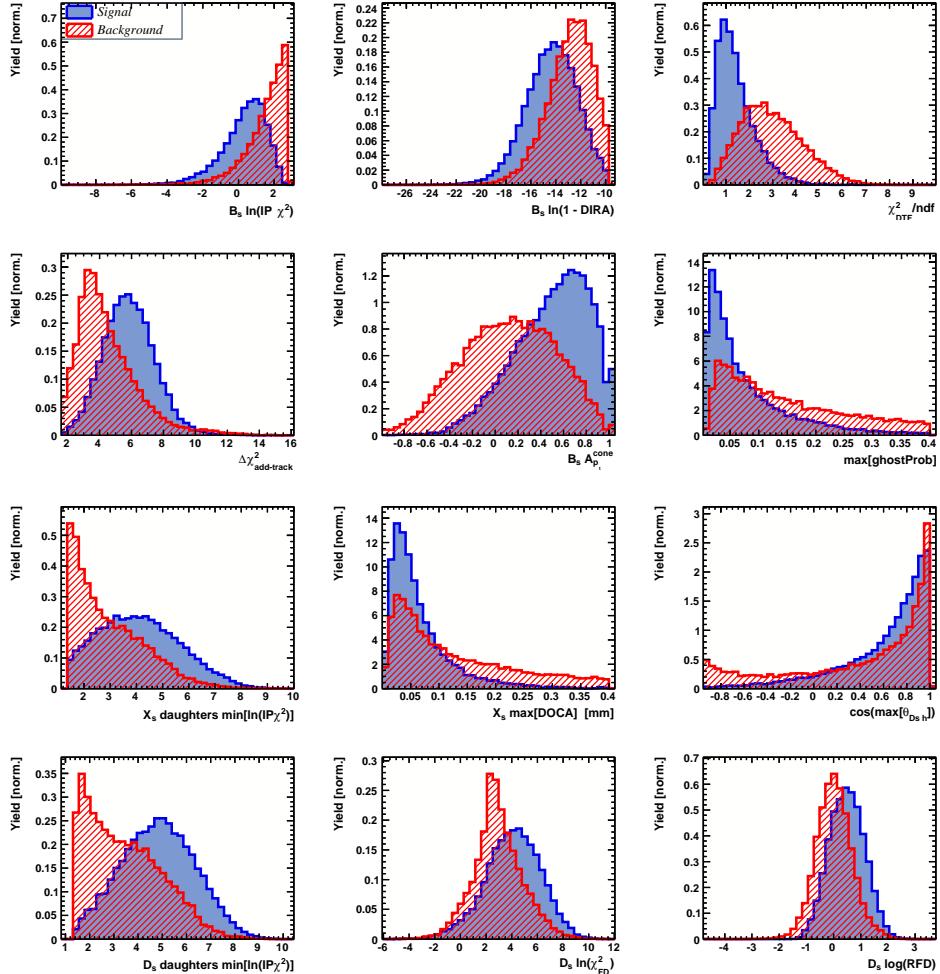


Figure 3.6: Discriminating variables used to train the BDTG for all data categories combined.

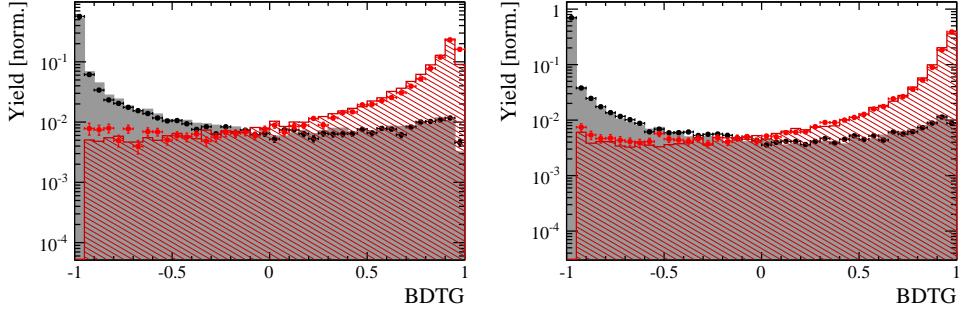


Figure 3.7: Signal (red) and background (black) distributions for the BDTG response for Run-I (left) and Run-II (right) data. Filled histograms (data points) show the BDTG response for the L0-TOS (L0-TIS) category. Even and odd test samples are combined.

3.2.4 Final selection

The cut on the BDTG output is optimized using the signal significance as figure of merit:

$$\text{FOM}(\text{BDTG}) = \frac{N_s(\text{BDTG})}{\sqrt{N_s(\text{BDTG}) + N_b(\text{BDTG})}} \quad (3.1)$$

where $N_s(\text{BDTG})$ is the $B_s \rightarrow D_s K\pi\pi$ signal yield for a given BDTG cut and $N_b(\text{BDTG})$ is the combinatorial background yield in the signal region ($m(D_s K\pi\pi) = m_{B_s} \pm 40 \text{ MeV}$). To compute the yields as function of the BDTG cut, we use the BDTG efficiencies, $\epsilon_{s,b}$, evaluated on the corresponding test samples. To fix the overall scale, it is required to know the yields at (at least) one point of the scanned range. We arbitrarily choose this fix point to be $\text{BDTG} > 0$ and perform a fit to the reconstructed B_s mass as described in Sec. 4 to obtain the yields $N_{s,b}(0)$. These yields are then efficiency corrected to calculate the yields for a given BDTG cut:

$$N_{s,b}(\text{BDTG}) = N_{s,b}(0) \cdot \frac{\epsilon_{s,b}(\text{BDTG})}{\epsilon_{s,b}(0)}. \quad (3.2)$$

Figure 3.8 shows the resulting BDTG scans for each training category.

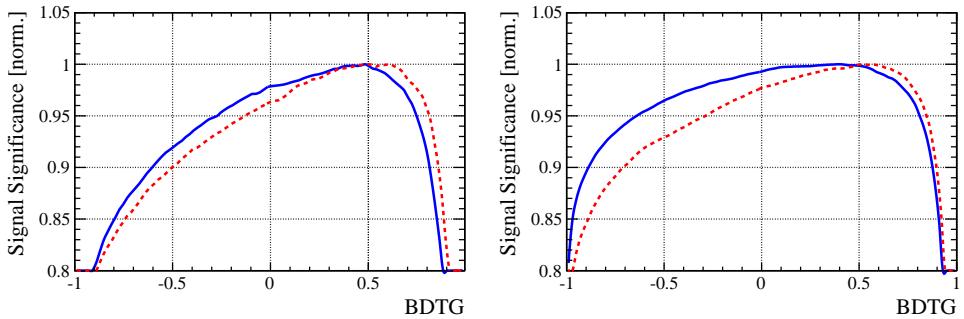


Figure 3.8: Signal significance as function of the applied cut on the BDTG response for Run-I (left) and Run-II (right) data. The scans for the L0-TOS (L0-TIS) category are shown in blue (red). The signal significance is normalized to be 1 at the optimal BDTG cut value.

Table 3.1: Offline selection requirements for $D_s \rightarrow 3h$ candidates.

| | Description | Requirement |
|------------------------------------|---|---|
| $D_s \rightarrow hh\bar{h}$ | $m(hh\bar{h})$ | $= m_{D_s} \pm 25$ MeV |
| $D_s^- \rightarrow KK\pi^-$ | D^0 veto | $m(KK) < 1840$ MeV |
| $D_s^- \rightarrow \phi\pi^-$ | $m(KK)$ PIDK(K^+) PIDK(K^-) PIDK(π^-) χ_{FD}^2 FD in z D^- veto Λ_c veto | $= m_\phi \pm 12$ MeV > -10 > -10 < 20 > 0 > -1 $m(K^+K_\pi^-\pi^-) \neq m(D^-) \pm 40$ MeV PIDK(K^-) > 5 $m(K^+K_p^-\pi^-) \neq m(\Lambda_c) \pm 40$ MeV PIDK(K^-) – PIDp(K^-) > 2 |
| $D_s^- \rightarrow K^*(892)K^-$ | $m(KK)$ $m(K^+\pi^-)$ PIDK(K^+) PIDK(K^-) PIDK(π^-) χ_{FD}^2 FD in z D^- veto Λ_c veto | $\neq m_\phi \pm 12$ MeV $= m_{K^*(892)} \pm 75$ MeV > -10 > -5 < 10 > 0 > 0 $m(K^+K_\pi^-\pi^-) \neq m(D^-) \pm 40$ MeV PIDK(K^-) > 15 $m(K^+K_p^-\pi^-) \neq m(\Lambda_c) \pm 40$ MeV PIDK(K^-) – PIDp(K^-) > 5 |
| $D_s^- \rightarrow (KK\pi^-)_{NR}$ | $m(KK)$ $m(K^+\pi^-)$ PIDK(K^+) PIDK(K^-) PIDK(π^-) χ_{FD}^2 FD in z D^- veto Λ_c veto | $\neq m_\phi \pm 12$ MeV $\neq m_{K^*(892)} \pm 75$ MeV > 5 > 5 < 10 > 4 > 0 $m(K^+K_\pi^-\pi^-) \neq m(D^-) \pm 40$ MeV PIDK(K^-) > 15 $m(K^+K_p^-\pi^-) \neq m(\Lambda_c) \pm 40$ MeV PIDK(K^-) – PIDp(K^-) > 5 |
| $D_s \rightarrow \pi\pi\pi$ | PIDK(π) PIDp(π) D^0 veto χ_{FD}^2 FD in z | < 10 < 20 $m(\pi^+\pi^-) < 1700$ MeV > 9 > 0 |
| $D_s^- \rightarrow K^-\pi^+\pi^-$ | PIDK(K) PIDK(π) PIDp(π) D^0 veto χ_{FD}^2 FD in z D^- veto Λ_c veto | > 8 < 5 < 20 $m(K^-\pi^+) < 1750$ MeV > 9 > 0 $m(K_\pi^-\pi^+\pi^-) \neq m(D^-) \pm 40$ MeV PIDK(K^-) > 15 $m(K_p^-\pi^+\pi^-) \neq m(\Lambda_c) \pm 40$ MeV PIDK(K^-) – PIDp(K^-) > 5 |

Table 3.2: Offline selection requirements for $B_s \rightarrow D_s K\pi\pi(D_s\pi\pi\pi)$ candidates.

| | Description | Requirement |
|-------------------------------------|-------------------------------|--|
| $B_s \rightarrow D_s h\pi\pi$ | $m(D_s h\pi\pi)$ | $> 5200 \text{ MeV}$ |
| | χ^2_{vtx}/ndof | < 8 |
| | DIRA | > 0.99994 |
| | χ^2_{FD} | > 100 |
| | χ^2_{IP} | < 16 |
| | χ^2_{DTF}/ndof | < 15 |
| | $\Delta\chi^2_{add-track}$ | > 2 |
| | $\cos(\max \theta_{D_s h_i})$ | > -0.9 |
| | t | $> 0.4 \text{ ps}$ |
| | δt | $< 0.15 \text{ ps}$ |
| | Phasespace region | $m(h\pi\pi) < 1.95 \text{ GeV}$ $m(h\pi) < 1.2 \text{ GeV}$ $m(\pi\pi) < 1.2 \text{ GeV}$ |
| Wrong PV veto | | $\text{nPV} = 1 \parallel \min(\Delta\chi^2_{IP}) > 20$ |
| BDTG | | $> 0.45 \text{ [Run-I,L0-TOS]}$ $> 0.50 \text{ [Run-I,L0-TIS]}$ $> 0.35 \text{ [Run-II,L0-TOS]}$ $> 0.50 \text{ [Run-II,L0-TIS]}$ |
| $X_s^+ \rightarrow K^+\pi^+\pi^-$ | PIDK(K) | > 10 |
| | PIDK(π^+) | < 10 |
| | PIDK(π^-) | < 0 |
| | D_s veto | $m(K^+\pi^+\pi_K^-) \neq m(D_s) \pm 20 \text{ MeV} \parallel \text{PIDK}(\pi^-) < -5$ |
| $X_s^+ \rightarrow \pi^+\pi^+\pi^-$ | PIDK(π^+) | < 0 |
| | PIDK(π^-) | < 10 |
| | D_s veto | $m(\pi^+\pi_K^+\pi^-) \neq m(D_s) \pm 20 \text{ MeV} \parallel \text{PIDK}(\pi^+) < -5$ |
| All tracks | hasRich | $= 1$ |

352 4 Yields determination

353 An extended unbinned maximum likelihood fit to the reconstructed B_s mass of the selected
 354 events is performed in order to determine the signal and background yields. The invariant
 355 mass $m(D_s h\pi\pi)$ is determined from a DTF constraining the mass of the D_s to the PDG
 356 value and the position of the PV. The probability density functions (PDFs) used to
 357 describe the signal and background components are described in the following.

358 Due to different mass resolutions, we perform the invariant mass fits simultaneously
 359 for each data-taking period and each trigger category. We further introduce four D_s final
 360 state categories: $D_s \rightarrow \phi\pi$, $D_s \rightarrow K^*(892)\pi$, $D_s \rightarrow \pi\pi\pi$ and $D_s \rightarrow Kh\pi$ to account for
 361 different signal purities. The $D_s \rightarrow Kh\pi$ category combines the two D_s decay channels
 362 with the lowest statistics: $D_s \rightarrow KK\pi$ (non-resonant) and $D_s \rightarrow K\pi\pi$. This amounts to
 363 16 categories in total.

364 4.1 Signal model

365 The signal B_s -mass distribution of both $B_s^0 \rightarrow D_s K\pi\pi$ and $B_s^0 \rightarrow D_s \pi\pi\pi$ is modeled
 366 using a Johnson's SU function [32], which results from a variable transformation of a
 367 normal distribution to allow for asymmetric tails:

$$\mathcal{J}(x|\mu, \sigma, \nu, \tau) = \frac{e^{-\frac{1}{2}r^2}}{2\pi \cdot c \cdot \sigma \cdot \tau \cdot \sqrt{z^2 + 1}} \quad (4.1)$$

$$r = -\nu + \frac{\operatorname{asinh}(z)}{\tau} \quad (4.2)$$

$$z = \frac{x - (\mu - c \cdot \sigma \cdot e^\tau \sinh(\nu \cdot \tau))}{c \cdot \tau} \quad (4.3)$$

$$c = \frac{e^{\tau^2} - 1}{2\sqrt{e^{\tau^2} \cdot \cosh(2\nu \cdot \tau) + 1}}. \quad (4.4)$$

368 It is conveniently expressed in terms of the central moments up to order four: The mean
 369 of the distribution μ , the standard deviation σ , the skewness ν and the kurtosis τ . The
 370 tail parameters ν and τ are fixed to the values obtained by a fit to the invariant mass
 371 distribution of simulated events shown in Fig 4.1. To account for differences between

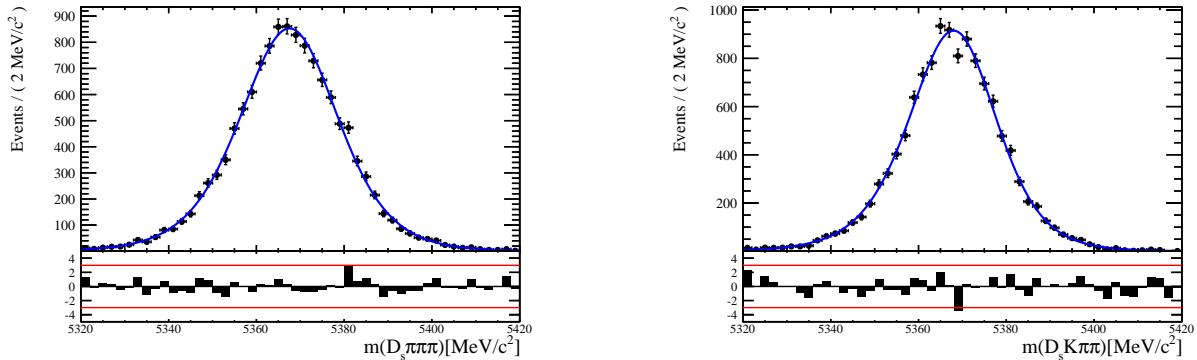


Figure 4.1: Invariant mass distributions of simulated (left) $B_s^0 \rightarrow D_s \pi\pi\pi$ and (right) $B_s^0 \rightarrow D_s K\pi\pi$ events. A fit with a Johnson's SU PDF is overlaid.

372 simulation and real data, linear scaling factors for the mean μ and width σ are determined
373 in the fit to $B_s^0 \rightarrow D_s\pi\pi\pi$ data and later fixed in the fit to $B_s^0 \rightarrow D_sK\pi\pi$ decays. The scale
374 factors are determined separately for each data-taking period and each trigger category.

375 4.2 Background models

376 After the full selection the following residual background components have to be accounted
377 for:

378 379 Combinatorial background

380 The combinatorial background is described by a second order polynomial, whose
381 parameters are determined, for each D_s final state separately, in the fit to data. For
382 systematic studies an exponential PDF is used.

383 384 Peaking B_d background

385 Decays of B_d mesons into the $D_sh\pi\pi$ final state are described by the B_s signal PDF
386 where the mean is shifted by the known mass difference $m_{B_s} - m_{B_d}$ [?].

387 388 Partially reconstructed background

389 Partially reconstructed $B_s^0 \rightarrow D_s^*\pi\pi\pi$ decays, with $D_s^* \rightarrow D_s\gamma$ or $D_s^* \rightarrow D_s\pi^0$, are expected
390 to be peaking lower than signal in the $m(D_s\pi\pi\pi)$ spectrum with large tails due to the
391 momentum carried away by the not reconstructed π^0 or γ . An empirical description for
392 the shape of this contribution is derived from a $B_s^0 \rightarrow D_s^*\pi\pi\pi$ MC sample subject to
393 the nominal $B_s^0 \rightarrow D_s\pi\pi\pi$ selection. Figure 4.2 (left) shows the respective reconstructed
394 $m(D_s\pi\pi\pi)$ distribution. A sum of three bifurcated Gaussian functions is used to describe
395 it. In the fit to data, all parameters are fixed to the ones obtained from MC except for
396 the parameter which describes the width of the right tail of the distribution to account for
397 data-simulation differences in mass resolution. The equivalent $B_s^0 \rightarrow D_s^*K\pi\pi$ component
398 contributing to the $B_s^0 \rightarrow D_sK\pi\pi$ data sample is described by the same PDF with the
399 right tail fixed to the $B_s^0 \rightarrow D_s\pi\pi\pi$ result.

400 Contributions from $B^0 \rightarrow D_s^*K\pi\pi$ decays are modeled with the $B_s^0 \rightarrow D_s^*K\pi\pi$ PDF
401 shifted by $m_{B_s^0} - m_{B^0}$.

402 403 Misidentified background

404 A small fraction of $B_s \rightarrow D_s^- \pi^+ \pi^+ \pi^-$ and $B_s^0 \rightarrow D_s^* \pi^+ \pi^+ \pi^-$ decays, where one of the
405 pions is misidentified as a kaon, contaminate the $B_s^0 \rightarrow D_s K^+ \pi^+ \pi^-$ sample. To determine
406 the corresponding background shapes, we use simulated events passing the nominal
407 selection except for the PID cuts on the bachelor π^+ tracks. The **PIDCalib** package
408 is used to determine the p_T, η -dependent $\pi^+ \rightarrow K^+$ misidentification probability for
409 each pion. We change the particle hypothesis from pion to kaon for the pion with the
410 higher misidentification probability and recompute the invariant B_s^0 mass, $m(D_s^- \pi_K^+ \pi^+ \pi^-)$.
411 Similar, the invariant masses $m(\pi_K^+ \pi^+ \pi^-)$ and $m(\pi_K^+ \pi^-)$ are recomputed and required
412 to be within the considered phasespace region. The background distributions are shown
413 in Fig. 4.2 (middle,right) and modeled by the sum of two Crystal Ball functions. The
414 expected yield of misidentified $B_s^0 \rightarrow D_s\pi\pi\pi$ ($B_s^0 \rightarrow D_s^*\pi^+\pi^+\pi^-$) candidates in the
415 $B_s^0 \rightarrow D_sK\pi\pi$ sample is computed by multiplying the fake rate (within the considered
416 B_s mass range) of 0.47% (0.61%) by the $B_s^0 \rightarrow D_s\pi\pi\pi$ ($B_s^0 \rightarrow D_s^*\pi^+\pi^+\pi^-$) yield as

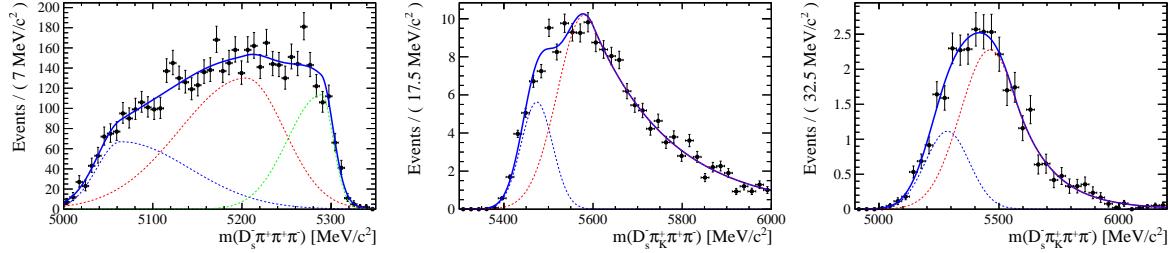


Figure 4.2: Left: Invariant mass distribution of simulated $B_s^0 \rightarrow D_s^* \pi\pi\pi$ events, where the γ/π^0 is excluded from the reconstruction. Middle: Invariant mass distribution of simulated $B_s^0 \rightarrow D_s \pi\pi\pi$ events, where one of the pions is reconstructed as a kaon taking the misidentification probability into account. Right: Invariant mass distribution for simulated $B_s^0 \rightarrow D_s^* \pi\pi\pi$ events, where the γ/π^0 from the D_s^* is excluded from reconstruction and one of the pions is reconstructed as a kaon taking the misidentification probability into account. The fitted PDF is shown in blue.

417 determined in the mass fit to the $B_s^0 \rightarrow D_s \pi\pi\pi$ data sample which is corrected for the
 418 PID($\pi^+ < 0$) requirement. The $B_s^0 \rightarrow D_s^* \pi^+ \pi^+ \pi^-$ yield is additionally corrected for the
 419 efficiency of the cut $m(D_s K\pi\pi) > 5200$ MeV evaluated on MC. In the fit to data, the
 420 misidentified background yields are fixed to the predicted ones.

421 We consider the $B_s^0 \rightarrow D_s K\pi\pi$ and $B_s^0 \rightarrow D_s^* K\pi\pi$ components contributing to the
 422 $B_s^0 \rightarrow D_s \pi\pi\pi$ data sample to be negligible due to the low branching fractions and the
 423 tight PID cuts on the bachelor pions.

424 4.3 Results

425 Figure 4.3 shows the invariant mass distribution for $B_s^0 \rightarrow D_s \pi\pi\pi$ and $B_s^0 \rightarrow D_s K\pi\pi$
 426 candidates passing all selection criteria. The projections for all categories of the simula-
 427 taneous fit are shown in Appendix C together with the results for all fitted parameters.
 428 The integrated signal and background yields are listed in Tables 4.1 and 4.2.

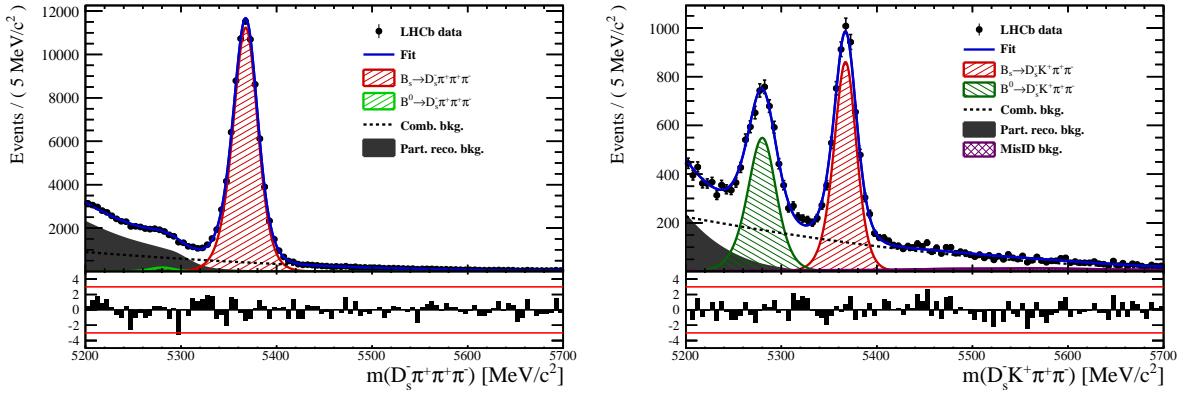


Figure 4.3: Invariant mass distribution of $B_s^0 \rightarrow D_s \pi\pi\pi$ (left) and $B_s^0 \rightarrow D_s K\pi\pi$ (right) candidates.

Table 4.1: Total signal and background yields for the $B_s \rightarrow D_s\pi\pi\pi$ sample (left) and signal yield for the different D_s final states contributing to the $B_s \rightarrow D_s\pi\pi\pi$ sample (right).

| Component | Yield | |
|---------------------------------------|-----------------|--|
| $B_s \rightarrow D_s\pi\pi\pi$ | 77225 ± 304 | |
| $B^0 \rightarrow D_s\pi\pi\pi$ | 1263 ± 454 | |
| Partially reconstructed bkg. | 31805 ± 351 | |
| Combinatorial bkg. | 32821 ± 393 | |
| D_s final state | Signal yield | |
| $D_s^- \rightarrow \phi^0(1020)\pi^-$ | 26458 ± 172 | |
| $D_s^- \rightarrow K^{*0}(892)K^-$ | 23105 ± 170 | |
| $D_s^- \rightarrow (K^-h^+\pi^-)$ | 15201 ± 136 | |
| $D_s^- \rightarrow \pi^+\pi^-\pi^-$ | 12461 ± 122 | |

Table 4.2: Total signal and background yields for the $B_s \rightarrow D_sK\pi\pi$ sample (left) and signal yield for the different D_s final states contributing to the $B_s \rightarrow D_sK\pi\pi$ sample (right).

| Component | Yield | |
|---------------------------------------|----------------|--|
| $B_s \rightarrow D_sK\pi\pi$ | 5376 ± 88 | |
| $B^0 \rightarrow D_sK\pi\pi$ | 4384 ± 101 | |
| Partially reconstructed bkg. | 1796 ± 96 | |
| Misidentified bkg. | 808 ± 0 | |
| Combinatorial bkg. | 9376 ± 177 | |
| D_s final state | Signal yield | |
| $D_s^- \rightarrow \phi^0(1020)\pi^-$ | 1706 ± 49 | |
| $D_s^- \rightarrow K^{*0}(892)K^-$ | 1712 ± 49 | |
| $D_s^- \rightarrow (K^-h^+\pi^-)$ | 1145 ± 41 | |
| $D_s^- \rightarrow \pi^+\pi^-\pi^-$ | 814 ± 36 | |

429 5 Decay-time Resolution

430 The observed oscillation of B mesons is prone to dilution, if the detector resolution is
 431 of similar magnitude as the oscillation period. In the B_s^0 system, considering that the
 432 measured oscillation frequency of the B_s^0 [33] and the average LHCb detector resolution [38]
 433 are both $\mathcal{O}(50 \text{ fs}^{-1})$, this is the case. Therefore, it is crucial to correctly describe the
 434 decay time resolution in order to avoid a bias on the measurement of time dependent CP
 435 violation. Since the time resolution depends on the particular event, especially the decay
 436 time itself, the sensitivity on γ can be significantly improved by using an event dependent
 437 resolution model rather than an average resolution. For this purpose, we use the per-event
 438 decay time error that is estimated based on the uncertainty obtained from the global
 439 kinematic fit of the momenta and vertex positions (DTF) with additional constraints on
 440 the PV position and the D_s mass. In order to apply it correctly, it has to be calibrated.
 441 The raw decay time error distributions for $B_s^0 \rightarrow D_s\pi\pi\pi$ signal candidates are shown in
 442 Figure 5.1 for Run-I and Run-II data. Significant deviations between the two different
 443 data taking periods are observed due to the increase in center of mass energy from Run-I
 444 to Run-II, as well as (among others) new tunings in the pattern and vertex reconstruction.
 445 The decay time error calibration is consequently performed separately for both data taking
 446 periods.

447 For Run-I data, we use the calibration from the closely related $B_s^0 \rightarrow D_s K$ analysis
 448 which was performed on a data sample of prompt- D_s candidates combined with a random
 449 pion track from the PV. We verify the portability to our decay channel on MC.

450 For Run-II data, a new lifetime unbiased stripping line (LTUB) has been implemented
 451 which selects prompt- D_s candidates combined with random $K\pi\pi$ tracks from the PV.

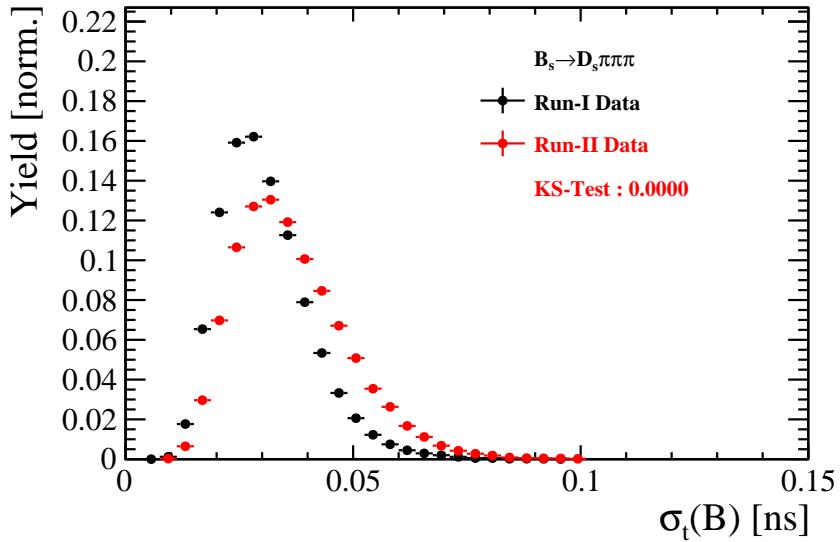


Figure 5.1: Distribution of the decay time error for $B_s^0 \rightarrow D_s\pi\pi\pi$ signal candidates for Run-I (black) and Run-II (red) data (sWeighted).

452 5.1 Calibration for Run-I data

453 For simulated $B_s^0 \rightarrow D_s K \pi\pi$ events, the spread of the differences between reconstructed
 454 decay time and true decay time, $\Delta t = t - t_{true}$, is a direct measure of the decay time
 455 resolution. The sum of two Gaussian pdfs with common mean but different widths is used
 456 to fit the distribution of the decay time difference Δt as shown in Fig. 5.2. The effective
 457 damping of the CP amplitudes due to the finite time resolution is described by the dilution
 458 \mathcal{D} . In the case of infinite precision, there would be no damping and therefore $\mathcal{D} = 1$ would
 459 hold, while for a resolution that is much larger than the B_s^0 oscillation frequency, \mathcal{D} would
 460 approach 0. For a double-Gaussian resolution model, the dilution is given by [39]

$$\mathcal{D} = f_1 e^{-\sigma_1^2 \Delta m_s^2 / 2} + (1 - f_1) e^{-\sigma_2^2 \Delta m_s^2 / 2}, \quad (5.1)$$

461 where σ_1 and σ_2 are the widths of the Gaussians, f_1 is the relative fraction of events
 462 described by the first Gaussian relative to the second and Δm_s is the oscillation frequency
 463 of B_s^0 mesons. An effective single Gaussian width is calculated from the dilution as,

$$\sigma_{eff} = \sqrt{(-2/\Delta m_s^2) \ln \mathcal{D}}, \quad (5.2)$$

464 which converts the resolution into a single-Gaussian function with an effective resolution
 465 that causes the same damping effect on the magnitude of the B_s oscillation. For the Run-I
 466 $B_s^0 \rightarrow D_s K \pi\pi$ MC sample the effective average resolution is found to be $\sigma_{eff} = 39.1 \pm 0.3$ fs.

467 To analyze the relation between the per-event decay time error δ_t and the actual
 468 resolution σ_t , the simulated $B_s^0 \rightarrow D_s K \pi\pi$ sample is divided into equal-statistics slices of
 469 δ_t . For each slice, the effective resolution is determined as described above. Details of the
 470 fit results in each slice are shown in appendix D. Figure 5.2 shows the obtained values
 471 for σ_{eff} as a function of the per-event decay time error σ_t . To account for the variable
 472 binning, the bin values are not placed at the bin center but at the weighted mean of the
 473 respective per-event-error bin. A linear function is used to parametrize the distribution.
 474 The obtained values are

$$\sigma_{eff}^{MC}(\sigma_t) = (0.0 \pm 0.0) \text{ fs} + (1.232 \pm 0.010) \sigma_t \quad (5.3)$$

475 where the offset is fixed to 0. For comparison, the calibration function found for $B_s^0 \rightarrow D_s K$
 476 MC is also shown in Figure 5.2 [39]:

$$\sigma_{eff}^{D_s K, MC}(\sigma_t) = (0.0 \pm 0.0) \text{ fs} + (1.201 \pm 0.013) \sigma_t. \quad (5.4)$$

477 Due to the good agreement between the scale factors for $B_s^0 \rightarrow D_s K$ and $B_s^0 \rightarrow D_s K \pi\pi$
 478 MC, we conclude that the resolution calibration for $B_s^0 \rightarrow D_s K$ data:

$$\sigma_{eff}^{D_s K}(\sigma_t) = (10.26 \pm 1.52) \text{ fs} + (1.280 \pm 0.042) \sigma_t \quad (5.5)$$

479 can be used for our analysis. The following calibration functions were used in the
 480 $B_s^0 \rightarrow D_s K$ analysis to estimate the systematic uncertainty on the decay-time resolution:

$$\sigma_{eff}^{D_s K}(\sigma_t) = (-0.568 \pm 1.570) \text{ fs} + (1.243 \pm 0.044) \sigma_t \quad (5.6)$$

$$\sigma_{eff}^{D_s K}(\sigma_t) = (0.0 \pm 0.0) \text{ fs} + (1.772 \pm 0.012) \sigma_t \quad (5.7)$$

482 The difference of the scale factors observed on $B_s^0 \rightarrow D_s K$ and $B_s^0 \rightarrow D_s K \pi\pi$ MC is
 483 assigned as additional systematic uncertainty.

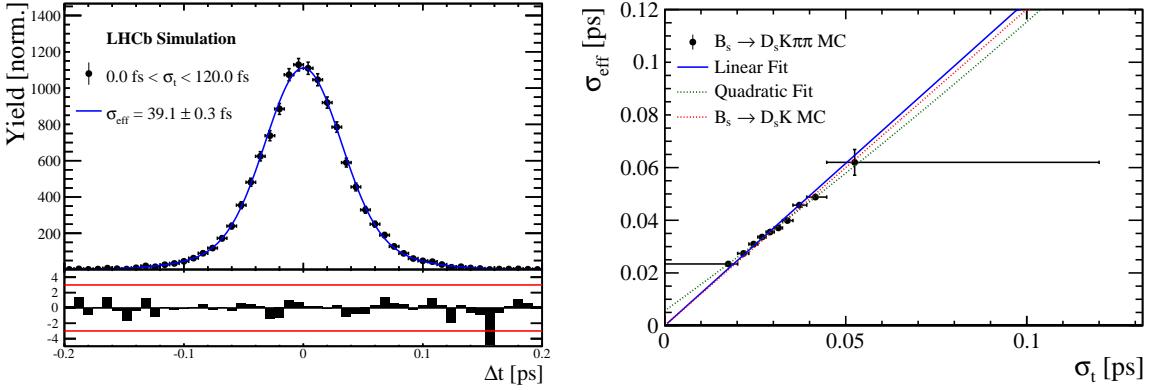


Figure 5.2: (Left) Difference of the true and measured decay time of $B_s^0 \rightarrow D_s K\pi\pi$ MC candidates. (Right) The measured resolution σ_{eff} as function of the per-event decay time error estimate σ_t for $B_s \rightarrow D_s K\pi\pi$ MC (Run-I). The fitted calibration curve is shown in blue.

484 5.2 Calibration for Run-II data

485 For the resolution calibration of Run-II data, a sample of promptly produced D_s candidates
 486 is selected using the B02DsKPiPiLTUBD2HHHBeauty2CharmLine stripping line. This
 487 lifetime-unbiased stripping line does not apply selection requirements related to lifetime
 488 or impact parameter, allowing for a study of the resolution. In order to reduce the rate
 489 of this sample it is pre-scaled in the stripping. Each D_s candidate is combined with a
 490 random kaon track and two random pion tracks which originate from the PV to obtain a
 491 sample of fake B_s candidates with a known true decay-time of $t_{true} = 0$. The difference of
 492 the measured decay time, t , of these candidates with respect to the true decay time is
 493 attributed to the decay time resolution.

494 The offline selection of the fake B_s candidates is summarized in Tab. 5.1. The selection
 495 is similar than the one for real data with the important difference that the D_s candidate
 496 is required to come from the PV by cutting on the impact parameter significance. Even
 497 after the full selection, a significant number of multiple candidates is observed. These
 498 are predominantly fake B_s candidates that share the same D_s candidate combined with
 499 different random tracks from the PV. We select one of these multiple candidates randomly
 500 which retains approximately 20% of the total candidates. The invariant mass distribution
 501 of the selected D_s candidates is shown in Fig. 5.3. To separate true D_s candidates from
 502 random combinations, the `sPlot` method is used to statistically subtract combinatorial
 503 background from the sample.

504 Figure 5.4 shows the `sWeighted` decay-time distribution for fake B_s candidates. Similar
 505 as in the previous section, the decay-time distribution is fitted with a double-Gaussian
 506 resolution model in slices of the per-event decay time error. Since some D_s candidates
 507 might actually originate from true B_s decays, the decay-time distribution of the fake B_s
 508 candidates might show a bias towards positive decay times. Therefore, we determine the
 509 decay-time resolution from the negative decay-time distribution only. Details of the fit
 510 results in each slice are shown in appendix D. The resulting calibration function:

$$\sigma_{eff}^{Data}(\sigma_t) = (9.7 \pm 1.7) \text{ fs} + (0.915 \pm 0.040) \sigma_t \quad (5.8)$$

⁵¹¹ is in good agreement with the one obtained for the $B_s \rightarrow J/\psi\phi$ (Run-II) analysis.

$$\sigma_{eff}^{J/\psi\phi}(\sigma_t) = (12.25 \pm 0.33) \text{ fs} + (0.8721 \pm 0.0080) \sigma_t \quad (5.9)$$

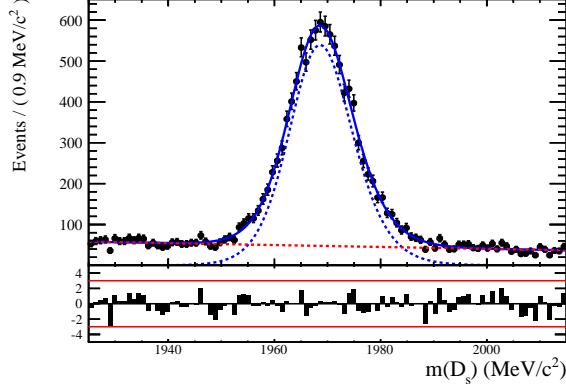


Figure 5.3: The invariant mass distribution for prompt D_s candidates.

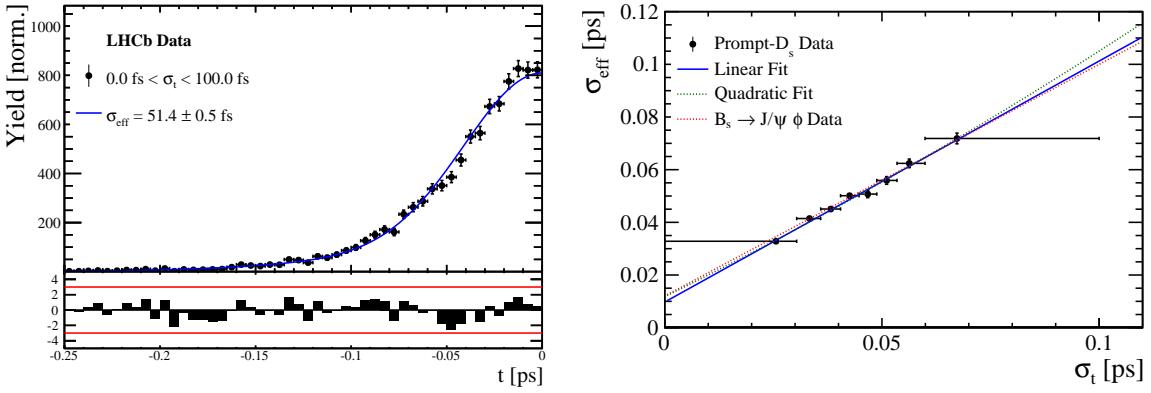


Figure 5.4: (Left) Decay-time distribution for fake B_s candidates from promptly produced D_s candidates, combined with random prompt $K\pi\pi$ bachelor tracks. (Right) The measured resolution σ_{eff} as function of the per-event decay time error estimate σ_t for fake B_s candidates (Run-II data). The fitted calibration curve is shown in blue.

Table 5.1: Offline selection requirements for fake B_s candidates from promptly produced D_s candidates combined with random prompt $K\pi\pi$ bachelor tracks.

| | Description | Requirement |
|------------------------------------|----------------------------|--|
| $B_s \rightarrow D_s K\pi\pi$ | χ^2_{vtx}/ndof | < 8 |
| | χ^2_{DTF}/ndof | < 15 |
| | t | < 0 ps |
| $D_s \rightarrow hhh$ | χ^2_{vtx}/ndof | < 5 |
| | DIRA | > 0.99994 |
| | χ^2_{FD} | > 9 |
| | p_T | > 1800 MeV |
| | χ^2_{IP} | < 9 |
| | $\chi^2_{IP}(h)$ | > 5 |
| | Wrong PV veto | $nPV = 1 \parallel \min(\Delta\chi^2_{IP}) > 20$ |
| $D_s^- \rightarrow KK\pi^-$ | D^0 veto | $m(KK) < 1840$ MeV |
| | D^- veto | $m(K^+K_\pi^-\pi^-) \neq m(D^-) \pm 30$ MeV |
| | Λ_c veto | $m(K^+K_p^-\pi^-) \neq m(\Lambda_c) \pm 30$ MeV |
| $D_s^- \rightarrow \phi\pi^-$ | $m(KK)$ | $= m_\phi \pm 20$ MeV |
| | PIDK(K^+) | > -10 |
| | PIDK(K^-) | > -10 |
| | PIDK(π^-) | < 20 |
| $D_s^- \rightarrow K^*(892)K^-$ | $m(KK)$ | $\neq m_\phi \pm 20$ MeV |
| | $m(K^+\pi^-)$ | $= m_{K^*(892)} \pm 75$ MeV |
| | PIDK(K^+) | > -10 |
| | PIDK(K^-) | > -5 |
| | PIDK(π^-) | < 20 |
| $D_s^- \rightarrow (KK\pi^-)_{NR}$ | $m(KK)$ | $\neq m_\phi \pm 20$ MeV |
| | $m(K^+\pi^-)$ | $\neq m_{K^*(892)} \pm 75$ MeV |
| | PIDK(K^+) | > 5 |
| | PIDK(K^-) | > 5 |
| | PIDK(π^-) | < 10 |
| $D_s \rightarrow \pi\pi\pi$ | PIDK(h) | < 10 |
| | PIDp(h) | < 10 |
| | D^0 veto | $m(\pi^+\pi^-) < 1700$ MeV |
| $X_s \rightarrow K\pi\pi$ | $\chi^2_{IP}(h)$ | < 40 |
| | PIDK(K) | > 10 |
| | PIDK(π) | < 5 |
| | isMuon(h) | False |
| All tracks | p_T | > 500 MeV |

512 **5.3 Cross-checks**

513 **5.3.1 Kinematic dependence**

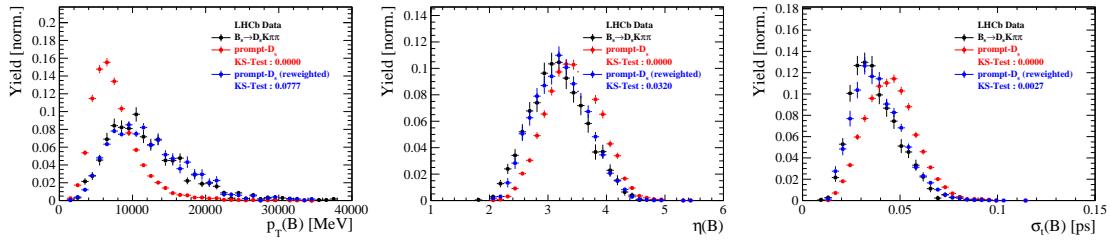


Figure 5.5

514 **5.3.2 DTF constraints**

515 6 Acceptance

516 6.1 MC corrections

517 6.1.1 Truth matching of simulated candidates

518 We use the `BackgroundCategory` tool to truth match our simulated candidates. Candidates
 519 with background category (`BKGCAT`) 20 or 50 are considered to be true signal. Background
 520 category 60 is more peculiar since it contains both badly reconstructed signal candidates
 521 and ghost background. This is due to the fact that the classification algorithms identifies
 522 all tracks for which less than 70% of the reconstructed hits are matched to generated
 523 truth-level quantities as ghosts. In particular for signal decays involving many tracks (as
 524 in our case), this arbitrary cutoff is not 100% efficient. Moreover, the efficiency is expected
 525 to depend on the kinematics which would lead to a biased acceptance determination if
 526 candidates with `BKGCAT`= 60 would be removed.

527 We therefore include `BKGCAT`= 60 and statistically subtract the ghost background by
 528 using the `sPlot` technique. The `sWeights` are calculated from a fit to the reconstructed B_s
 529 mass. The signal contribution is modeled as described in Sec. ?? and the background with
 530 a polynomial. The fit is performed simultaneously in two categories; the first includes
 531 events with `BKGCAT` = 20 or 50 and the second events with `BKGCAT` = 60. To account
 532 for the different mass resolution we use a different σ for each category, while the mean
 533 and the tail parameters are shared between them. The background component is only
 534 included for the second category.

535 A significant fraction of 8% of the true signal candidates are classified as ghosts, while
 536 only 20% of the events classified with `BKGCAT`= 60 are indeed genuine ghosts.

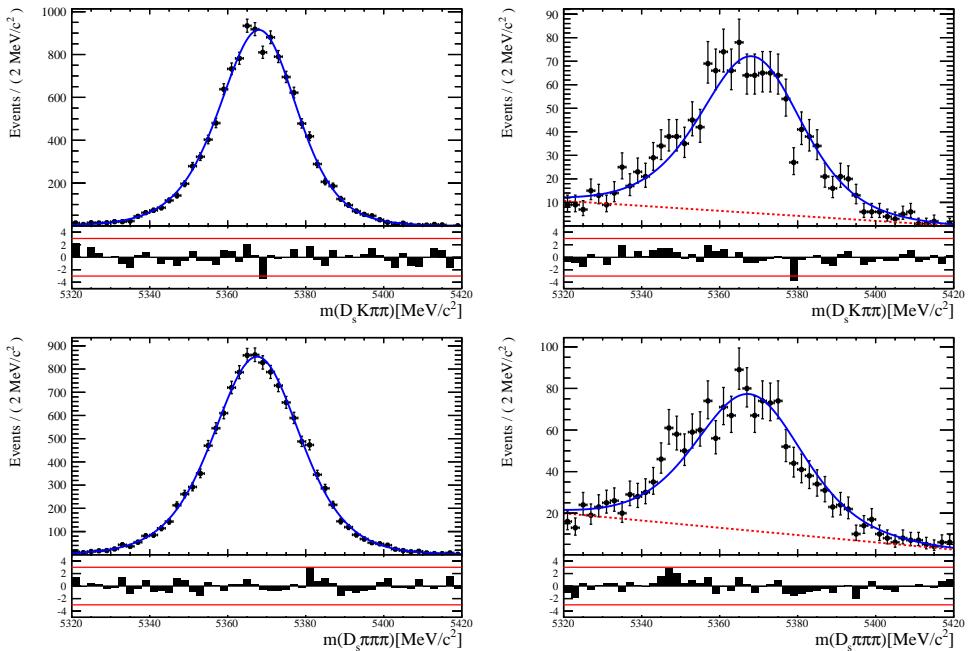


Figure 6.1: The reconstructed B_s mass distribution for simulated $B_s \rightarrow D_s K\pi\pi$ (top) and $B_s \rightarrow D_s \pi\pi\pi$ (bottom) decays classified with `BKGCAT` = 20 or 50 (left) and `BKGCAT` = 60 (right) after the full selection.

537 6.1.2 PID efficiencies

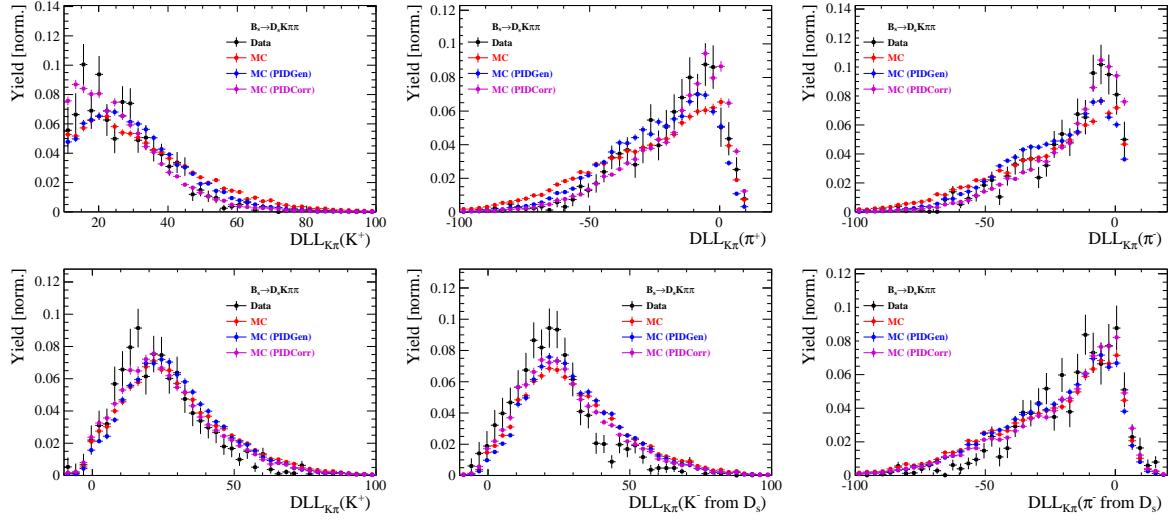


Figure 6.2

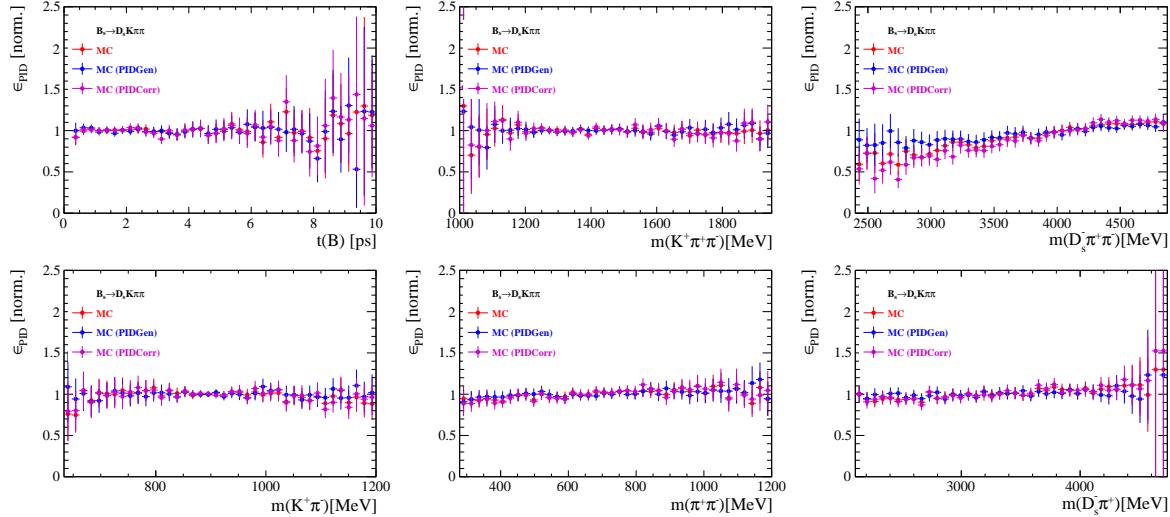


Figure 6.3

538 6.1.3 BDT efficiencies

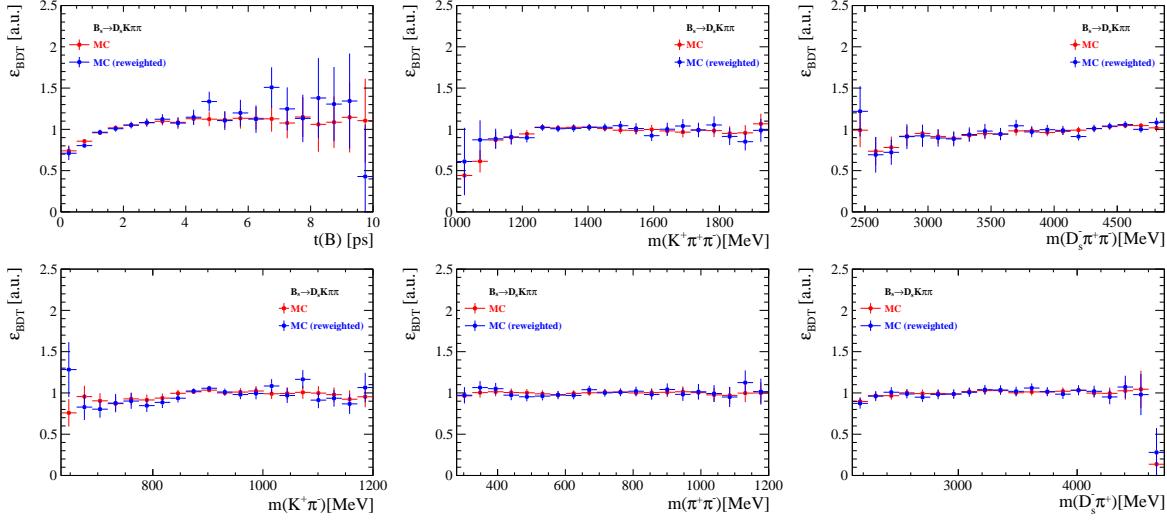


Figure 6.4

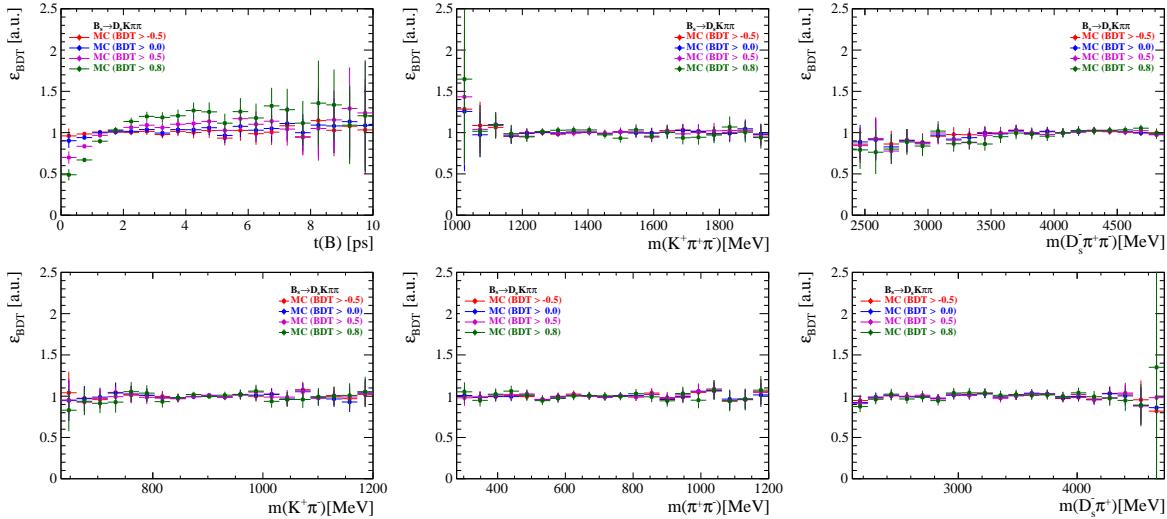


Figure 6.5

⁵³⁹ 6.1.4 Tracking efficiencies

540 **6.2 Decay-time acceptance**

541 The decay-time distribution of the B_s^0 mesons is sculpted due to the geometry of the LHCb
 542 detector and the applied selection cuts, which are described in Section 3. In particular,
 543 any requirement on the flight distance (FD), the impact parameter (IP) or the direction
 544 angle (DIRA) of the B_s^0 mesons, as well as the direct cut on the lifetime, will lead to a
 545 decay-time dependent efficiency $a(t)$. This efficiency will distort the theoretically expected,
 546 time-dependent decay rate

$$\frac{\Gamma(t)^{observed}}{dt} = \frac{\Gamma(t)^{theory}}{dt} \cdot a(t), \quad (6.1)$$

547 and has to be modelled correctly, in order to describe the observed decay rate. We
 548 use our control channel for this measurement, because for $B_s^0 \rightarrow D_s K\pi\pi$ decays the
 549 decay-time acceptance is correlated with the CP-observables which we aim to measure.
 550 Therefore, floating the CP-observables and the acceptance shape at the same time is
 551 not possible. Hence, a fit to the decay-time distribution of $B_s^0 \rightarrow D_s \pi\pi\pi$ candidates is
 552 performed and the obtained acceptance shape is corrected by the difference in shape found
 553 for the $B_s^0 \rightarrow D_s K\pi\pi$ and $B_s^0 \rightarrow D_s \pi\pi\pi$ MC.

554 A PDF of the form

$$\mathcal{P}(t', \vec{\lambda}) = \left[(e^{\Gamma_s t} \cdot \cosh(\frac{\Delta\Gamma_s t}{2}) \times \mathcal{R}(t - t')) \right] \cdot \epsilon(t', \vec{\lambda}), \quad (6.2)$$

555 is fit to the decay time distribution of $B_s^0 \rightarrow D_s \pi\pi\pi$ candidates in data. Since the
 556 fit is performed untagged, the PDF shown in Eq. 6.2 contains no terms proportional
 557 to Δm_s . The values for Γ_s and $\Delta\Gamma_s$ are fixed to the latest HFAG results [36]. The
 558 decay-time acceptance $\epsilon(t', \vec{\lambda})$ is modelled using the sum of cubic polynomials $v_i(t)$, so
 559 called Splines [37]. The polynomials are parametrised by so-called knots which determine
 560 their boundaries. Knots can be set across the fitted distribution to account for local
 561 changes in the acceptance shape. Using more knots is equivalent to using more base
 562 splines which are defined on a smaller sub-range. In total, $n + 2$ base splines $v_i(t)$ are
 563 needed to describe an acceptance shape which is parametrised using n knots.

564 For fits shown in the following, the knots have been placed at $t = [0.5, 1.0, 1.5, 2.0, 3.0, 9.5] ps$. To accommodate these 6 knot positions, 8 basic splines
 565 v_i , $i = [1, \dots, 8]$ are used. Since a rapid change of the decay time acceptance at low
 566 decay times due to the turn-on effect generated by the lifetime and other selection cuts is
 567 expected, more knots are placed in that regime. At higher decay times we expect linear
 568 behavior, with a possible small effect due to the VELO reconstruction. Therefore fewer
 569 knots are used. Furthermore, v_7 is fixed to 1 in order to normalize the overall acceptance
 570 function. To stabilise the last spline, v_8 is fixed by a linear extrapolation from the two
 571 previous splines:

$$v_N = v_{N-1} + \frac{v_{N-2} - v_{N-1}}{t_{N-2} - t_{N-1}} \cdot (t_N - t_{N-1}). \quad (6.3)$$

573 Here, $N = 8$ and t_{N-1} corresponds to the knot position associated with v_{N-1} .

6.2.1 Comparison of acceptance in subsamples

It is possible that the decay-time dependent efficiency deviates in different subsamples of our data. In particular, the acceptance could differentiate in subsamples with different final state kinematics, such as the run I & run II sample, the various D_s final states and the ways an event is triggered at the L0 stage. To investigate possible deviations, the full selected $B_s^0 \rightarrow D_s \pi\pi\pi$ sample is split into subsamples according to the categories mentioned above (run, D_s state, L0 trigger). For each subsample, the fit procedure described at the beginning of this chapter, using the pdf given by Eq. 6.2, is repeated and the obtained values for the spline coefficients v_i are compared. Figure 6.6 shows the comparison of the obtained spline coefficients for the different D_s final states.

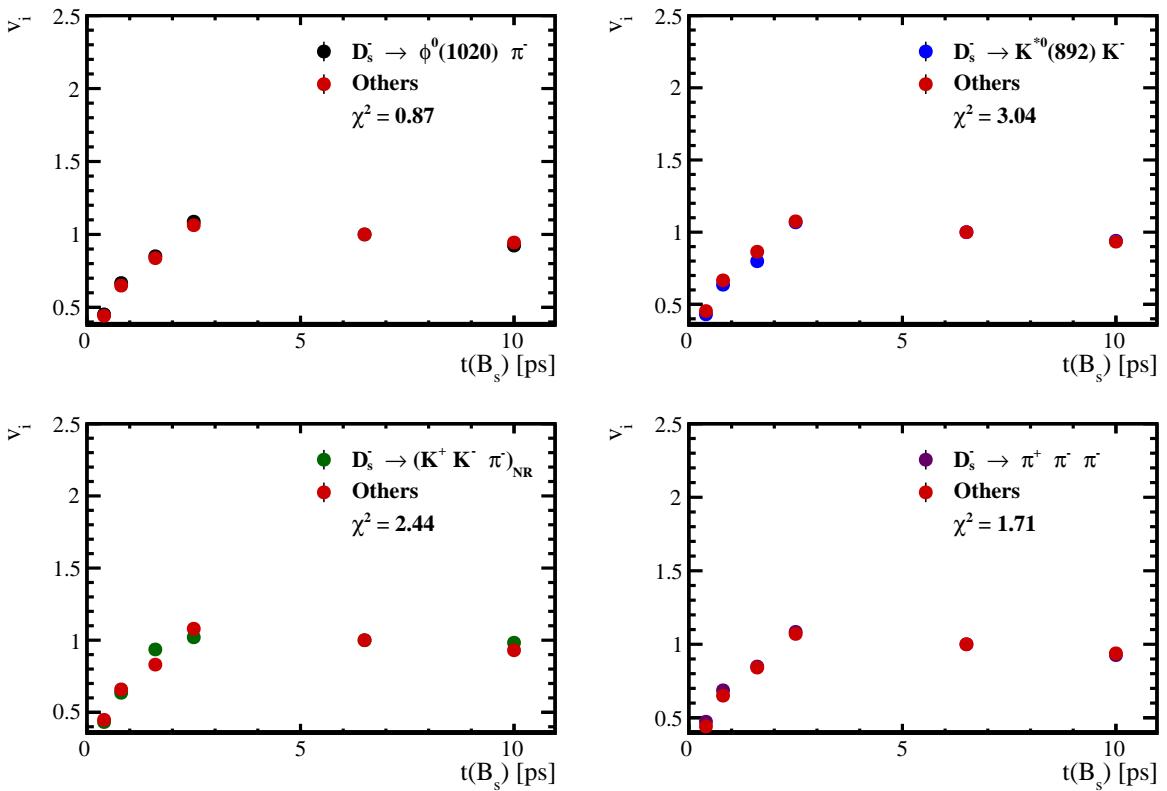


Figure 6.6: Comparison of the spline coefficients obtained from time-dependent fits to the $B_s^0 \rightarrow D_s \pi\pi\pi$ subsamples of different D_s final states. The comparison of one particular D_s state against all other states is shown.

Investigating the obtained spline coefficients from different D_s final states, good agreement is observed between all four channels and no need to distinguish between different final states in the time-dependent amplitude fit is found. The comparison between spline coefficients for the different runs and L0 trigger categories is shown in Figure 6.7.

Significant deviations between spline coefficients obtained from the two different runs and L0 trigger categories can be observed. The deviations are most pronounced in the $(0 - 5)$ ps region, where the majority of statistics is found. Therefore, the time-dependent efficiency has to be treated separately for the runs and L0 categories. This is achieved by

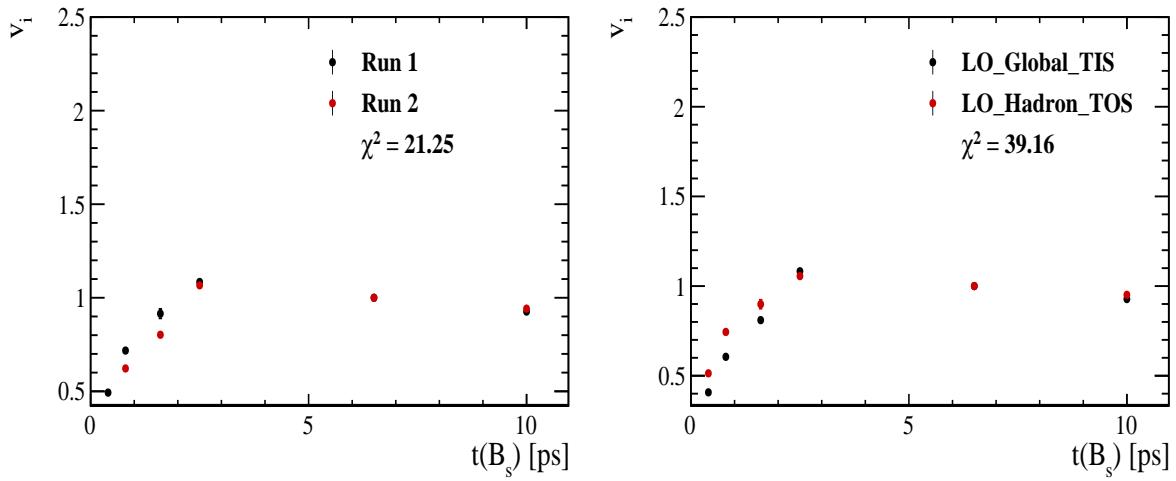


Figure 6.7: Comparison of the spline coefficients obtained from time-dependent fits to the $B_s^0 \rightarrow D_s \pi \pi \pi$ subsamples of (left) the different runs and (right) L0 trigger categories.

593 implementing a simultaneous fit, where the acceptance description is allowed to vary in
 594 the subsamples.

595 **6.2.2 Results**

596 The nominal fit to $B_s^0 \rightarrow D_s\pi\pi\pi$ data using this configuration is shown in Figure ??.
597 Note that the normalization of the splines in the following figures is not in scale. The fit
598 parameters obtained from the described fits to data and simulation are summarised in
599 Table 6.4.

Table 6.1: Time acceptance parameters for events in category [Run-I,L0-TOS].

| Knot position | Coefficient | $B_s^0 \rightarrow D_s K\pi\pi$ data | $B_s^0 \rightarrow D_s K\pi\pi$ MC | Ratio |
|---------------|-------------|--------------------------------------|------------------------------------|----------------------|
| 0.4 | v_0 | 0.561 ± 0.038 | 0.546 ± 0.022 | 0.953 ± 0.060 |
| 0.8 | v_1 | 0.826 ± 0.059 | 0.785 ± 0.034 | 0.910 ± 0.066 |
| 1.6 | v_2 | 0.843 ± 0.087 | 0.905 ± 0.056 | 1.055 ± 0.095 |
| 2.5 | v_3 | 1.154 ± 0.036 | 1.118 ± 0.028 | 0.930 ± 0.045 |
| 6.5 | v_4 | 1.0 (fixed) | 1.0 (fixed) | 1.0 (fixed) |
| 10.0 | v_5 | 0.866 (interpolated) | 0.897 (interpolated) | 1.061 (interpolated) |

Table 6.2: Time acceptance parameters for events in category [Run-I,L0-TIS].

| Knot position | Coefficient | $B_s^0 \rightarrow D_s K\pi\pi$ data | $B_s^0 \rightarrow D_s K\pi\pi$ MC | Ratio |
|---------------|-------------|--------------------------------------|------------------------------------|----------------------|
| 0.4 | v_0 | 0.368 ± 0.031 | 0.412 ± 0.020 | 0.955 ± 0.077 |
| 0.8 | v_1 | 0.583 ± 0.050 | 0.648 ± 0.033 | 0.910 ± 0.074 |
| 1.6 | v_2 | 0.939 ± 0.101 | 0.953 ± 0.061 | 0.947 ± 0.096 |
| 2.5 | v_3 | 1.052 ± 0.054 | 1.077 ± 0.035 | 1.003 ± 0.051 |
| 6.5 | v_4 | 1.0 (fixed) | 1.0 (fixed) | 1.0 (fixed) |
| 10.0 | v_5 | 0.954 (interpolated) | 0.932 (interpolated) | 0.998 (interpolated) |

Table 6.3: Time acceptance parameters for events in category [Run-II,L0-TOS].

| Knot position | Coefficient | $B_s^0 \rightarrow D_s K\pi\pi$ data | $B_s^0 \rightarrow D_s K\pi\pi$ MC | Ratio |
|---------------|-------------|--------------------------------------|------------------------------------|----------------------|
| 0.4 | v_0 | 0.486 ± 0.009 | 0.482 ± 0.009 | 1.000 ± 0.000 |
| 0.8 | v_1 | 0.691 ± 0.014 | 0.707 ± 0.015 | 1.000 ± 0.000 |
| 1.6 | v_2 | 0.851 ± 0.024 | 0.926 ± 0.026 | 1.000 ± 0.000 |
| 2.5 | v_3 | 1.061 ± 0.017 | 1.086 ± 0.018 | 1.000 ± 0.000 |
| 6.5 | v_4 | 1.0 (fixed) | 1.0 (fixed) | 1.0 (fixed) |
| 10.0 | v_5 | 0.946 (interpolated) | 0.925 (interpolated) | 1.000 (interpolated) |

Table 6.4: Time acceptance parameters for events in category [Run-II,L0-TIS].

| Knot position | Coefficient | $B_s^0 \rightarrow D_s K\pi\pi$ data | $B_s^0 \rightarrow D_s K\pi\pi$ MC | Ratio |
|---------------|-------------|--------------------------------------|------------------------------------|----------------------|
| 0.4 | v_0 | 0.300 ± 0.007 | 0.482 ± 0.010 | 1.000 ± 0.000 |
| 0.8 | v_1 | 0.476 ± 0.012 | 0.707 ± 0.016 | 1.000 ± 0.000 |
| 1.6 | v_2 | 0.725 ± 0.023 | 0.926 ± 0.026 | 1.000 ± 0.000 |
| 2.5 | v_3 | 1.064 ± 0.019 | 1.086 ± 0.018 | 1.000 ± 0.000 |
| 6.5 | v_4 | 1.0 (fixed) | 1.0 (fixed) | 1.0 (fixed) |
| 10.0 | v_5 | 0.944 (interpolated) | 0.925 (interpolated) | 1.000 (interpolated) |

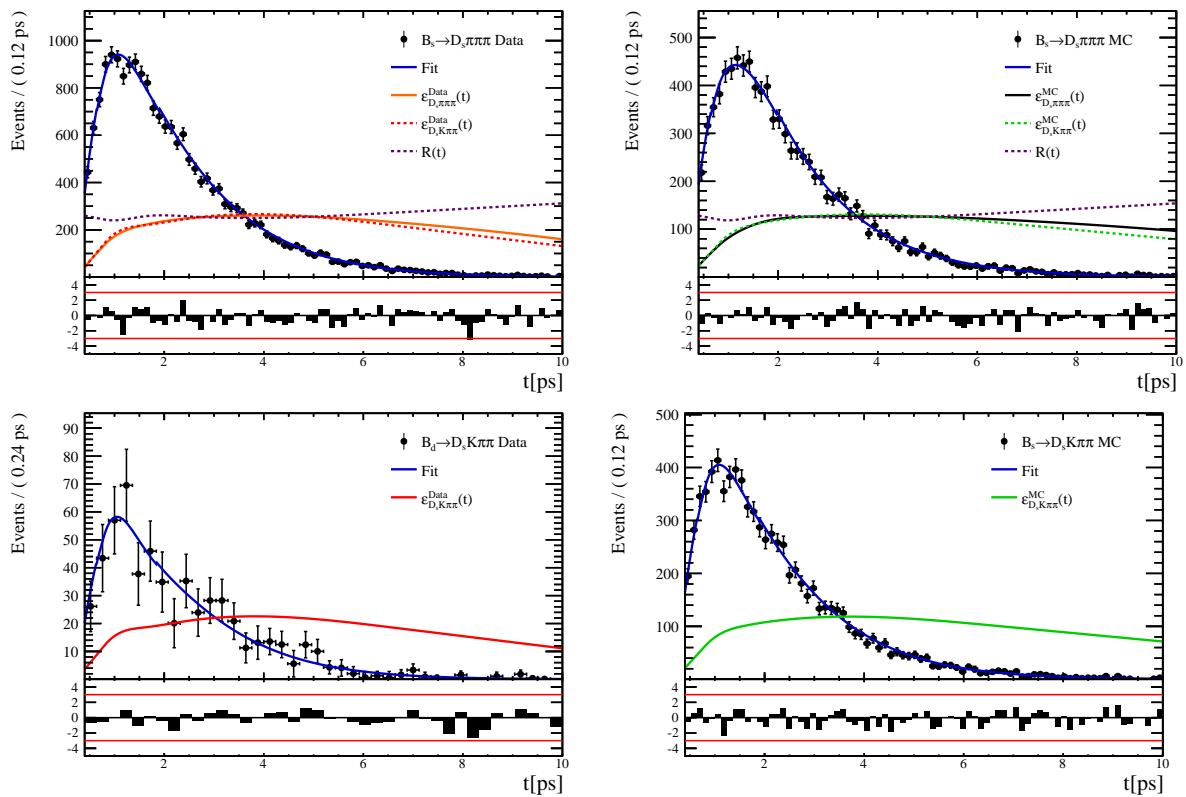


Figure 6.8

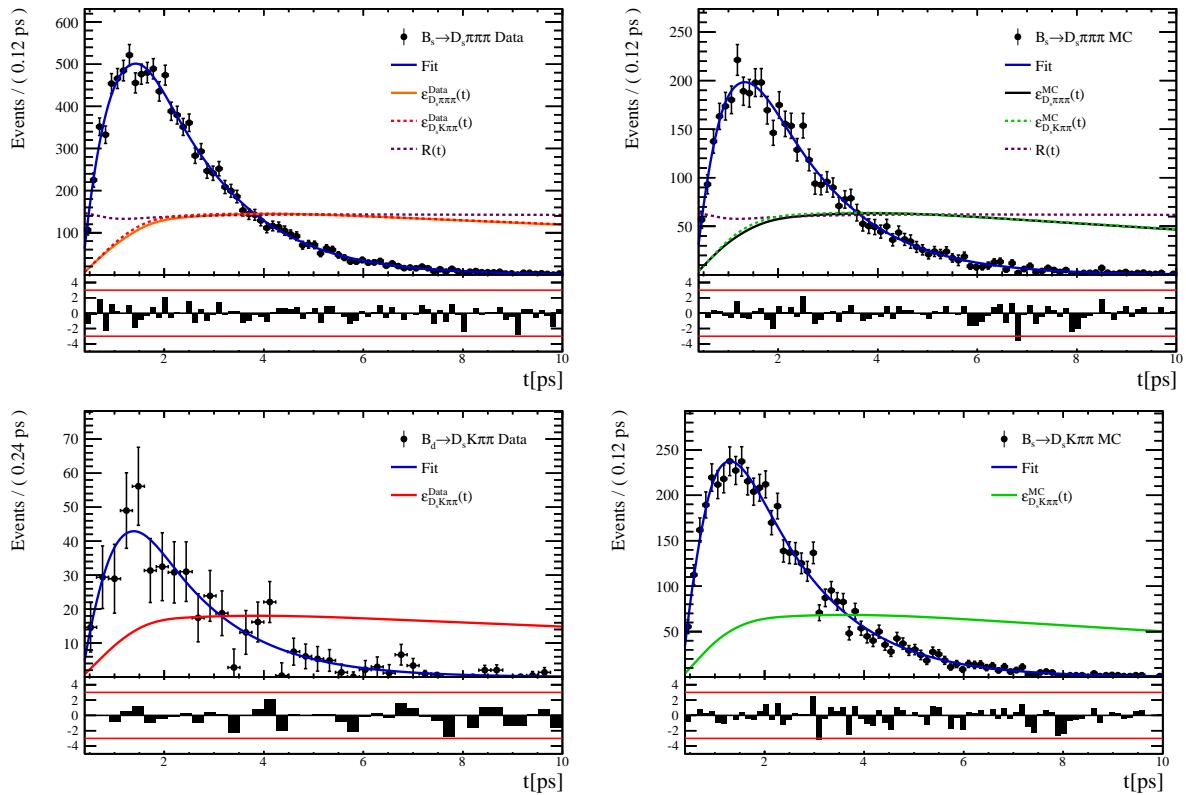


Figure 6.9

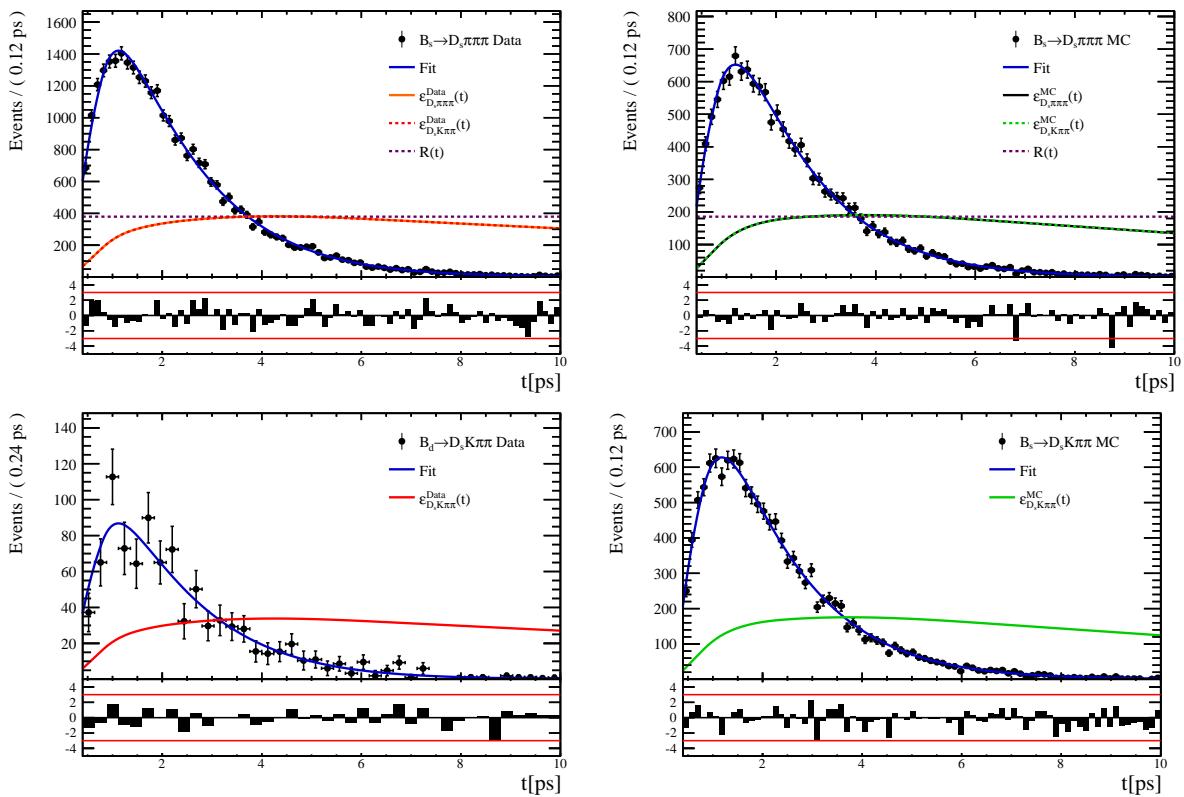


Figure 6.10

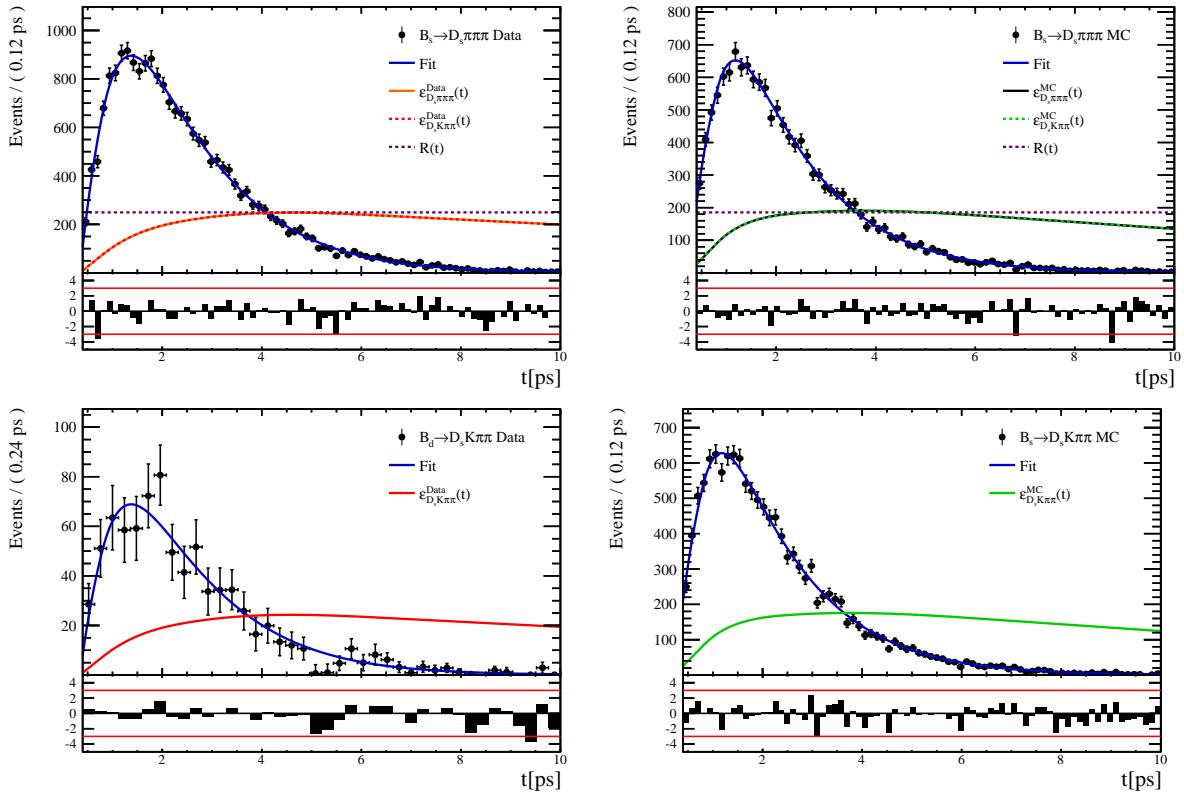


Figure 6.11

600 **6.3 Phasespace acceptance**

601 7 Flavour Tagging

602 To identify the initial flavour state of the B_s^0 meson, a number of flavour tagging algorithms
 603 are used that either determine the flavour of the non-signal b-hadron produced in the
 604 event (opposite site, OS) or use particles produced in the fragmentation of the signal
 605 candidate B_s^0/\bar{B}_s^0 (same side, SS).

606 For the same side, the algorithm searching for the charge of an additional kaon that
 607 accompanies the fragmentation of the signal candidate is used (SS-nnetKaon). For the
 608 opposite site, four different taggers are chosen: The algorithms that use the charge of an
 609 electron or a muon from semileptonic B decays (OS- e,μ), the tagger that uses the charge
 610 of a kaon from a $b \rightarrow c \rightarrow s$ decay chain (OS-nnetKaon) and the algorithm that determines
 611 the B_s^0/\bar{B}_s^0 candidate flavour from the charge of a secondary vertex, reconstructed from
 612 the OS b decay product (OS-VtxCharge). All four taggers are then combined into a single
 613 OS tagger.

614 Every single tagging algorithm is prone to misidentify the signal candidate at a certain
 615 mistag rate $\omega = (wrongtags)/(alltags)$. This might be caused by particle misidentification,
 616 flavour oscillation of the neutral opposite site B-meson or by tracks that are wrongly picked
 617 up from the underlying event. For every signal B_s^0/\bar{B}_s^0 candidate, each tagging algorithm
 618 predicts a mistag probability η , which is calculated using a combination of inputs such
 619 as the kinematics of the tagging particles. The inputs are then combined to a predicted
 620 mistag using neural networks. These are trained on simulated samples of $B_s^0 \rightarrow D_s^- \pi^+$
 621 (SS algorithm) and $B^+ \rightarrow J/\psi K^+$ (OS algorithms) decays. For the presented analysis, the
 622 measurable CP-violating coefficients are damped by the tagging dilution D , that depends
 623 on the mistag rate:

$$D = 1 - 2\omega. \quad (7.1)$$

624 This means that the statistical precision, with which these coefficients can be measured,
 625 scales as the inverse square root of the effective tagging efficiency,

$$\epsilon_{eff} = \epsilon_{tag}(1 - 2\omega)^2, \quad (7.2)$$

626 where ϵ_{tag} is the fraction of events that have a tagging decision. The flavour
 627 tagging algorithms are optimized for highest ϵ_{eff} on data, using the $B_s^0 \rightarrow D_s^- \pi^+$ and
 628 $B^+ \rightarrow J/\psi K^+$ samples.

629 Utilizing flavour-specific final states, the predicted mistag η of each tagger has to be
 630 calibrated to match the observed mistag ω on the data sample. For the calibration, a
 631 linear model of the form

$$\omega(\eta) = p_0 + p_1 \cdot (\eta - \langle \eta \rangle), \quad (7.3)$$

632 where the values of p_0 and p_1 are determined using the $B_s^0 \rightarrow D_s \pi \pi \pi$ normalization
 633 mode and $\langle \eta \rangle$ is the average estimated mistag probability $\langle \eta \rangle = \sum_{i=1}^{N_{cand}} (\eta_i)/N_{cand}$.
 634 Following this model, a perfectly calibrated tagger would lead to $\omega(\eta) = \eta$ and one would
 635 expect $p_1 = 1$ and $p_0 = \langle \eta \rangle$. Due to the different interaction cross-sections of oppositely
 636 charged particles, the tagging calibration parameters depend on the initial state flavour of
 637 the B_s^0 . Therefore, the flavour asymmetry parameters Δp_0 , Δp_1 and $\Delta \epsilon_{tag}$ are introduced.
 638 For this analysis, the calibrated mistag is treated as per-event variable, giving a larger
 639 weight to events that are less likely to have an incorrect tag. This adds one additional
 640 observable to the time- and amplitude-dependent fit.

641 The tagging calibration is determined using a time-dependent fit to the full $B_s^0 \rightarrow D_s \pi \pi \pi$

sample, where the mixing frequency Δm_s is fixed to the nominal PDG value [33]. The calibration procedure for the OS tagging algorithms (Sec.7.1) and the SS kaon tagger (Sec.7.2) is applied on the full Run I and 2015 and 2016 Run II $B_s^0 \rightarrow D_s\pi\pi\pi$ data sample, which is selected following the steps described in Sec. 3. The similar selection ensures as close as possible agreement between the $B_s^0 \rightarrow D_s\pi\pi\pi$ and $B_s^0 \rightarrow D_sK\pi\pi$ samples in terms of the decay kinematics, which are crucial for the flavour tagging. Section 7.3 shows the compatibility of both samples. After applying the calibration, the response of the OS and SS taggers are combined, which is shown in Sec. 7.4.

7.1 OS tagging calibration

The responses of the OS electron, muon, neural net kaon and the secondary vertex charge taggers are combined for the mistag calibration. Figure ?? shows the distribution of the predicted OS mistag for signal candidates from $B_s^0 \rightarrow D_s\pi\pi\pi$. The extracted calibration parameters and tagging asymmetries are summarized in Table 7.1 and the measured tagging power for the OS combination is $\epsilon_{eff,OS} = 4.81\%$.

| p_0 | p_1 | $<\eta>$ | ϵ_{tag} | Δp_o | Δp_1 | $\epsilon_{eff} [\%]$ |
|-------------------|-------------------|----------|-------------------|-------------------|-------------------|---|
| 0.025 ± 0.005 | 0.944 ± 0.048 | 0.347 | 0.517 ± 0.002 | 0.028 ± 0.005 | 0.037 ± 0.045 | $4.81 \pm 0.04 (\text{stat}) \pm 0.37 (\text{cal})$ |

Table 7.1: Calibration parameters and tagging asymmetries of the OS tagger extracted from $B_s^0 \rightarrow D_s\pi\pi\pi$ decays.

7.2 SS tagging calibration

The SS neural net kaon tagger can be calibrated using the flavour-specific $B_s^0 \rightarrow D_s\pi\pi\pi$ decay. Its development, performance and calibration is described in detail in [34]. Figure ?? shows the distribution of the predicted mistag of the neural net kaon tagger. The extracted calibration parameters and tagging asymmetries are summarized in Table 7.2 and the measured tagging power for this algorithm is $\epsilon_{eff,SS} = 3.22\%$.

| p_0 | p_1 | $<\eta>$ | ϵ_{tag} | Δp_o | Δp_1 | $\epsilon_{eff} [\%]$ |
|-------------------|-------------------|----------|-------------------|--------------------|-------------------|---|
| 0.008 ± 0.004 | 1.086 ± 0.059 | 0.381 | 0.571 ± 0.002 | -0.017 ± 0.004 | 0.135 ± 0.058 | $3.22 \pm 0.03 (\text{stat}) \pm 0.26 (\text{cal})$ |

Table 7.2: Calibration parameters and tagging asymmetries of the SS tagger extracted from $B_s^0 \rightarrow D_s\pi\pi\pi$ decays.

7.3 Tagging performance comparison between the signal and normalization channel

To justify the usage of the tagging calibration, obtained using the $B_s^0 \rightarrow D_s\pi\pi\pi$ sample, for our signal decay, the performance of the taggers in the two decay channels needs to be compatible. This is verified using both, simulated signal samples of both decays and weighted data, to compare the similarity of the mistag probabilities, tagging decisions and kinematic observables that are correlated with the tagging response, on simulation and data.

670 The distributions of the predicted mistag probability η for the OS combination and the
 671 SS kaon tagger are shown in Fig. ?? (simulation) and Fig. 7.1 (data).

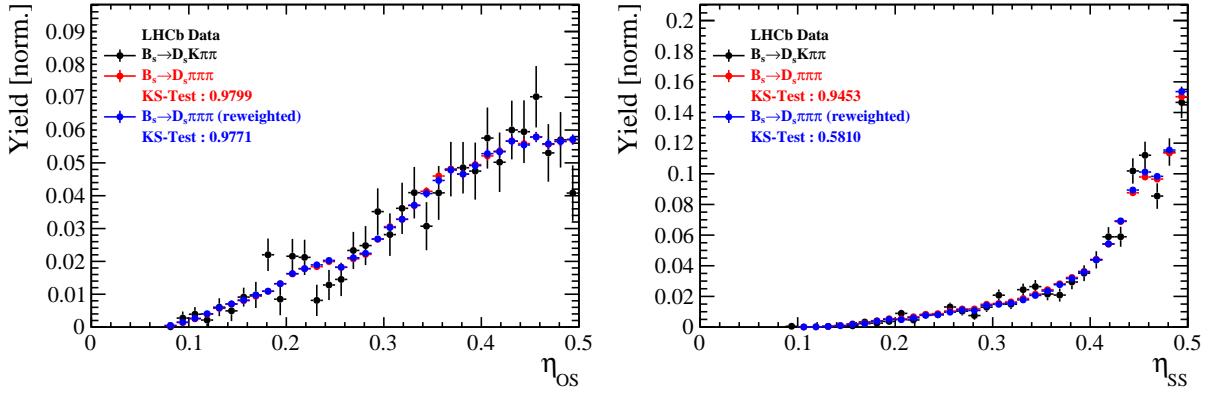


Figure 7.1: Distributions of the predicted mistag η for the OS combination (left) and the SS kaon tagger (right) for signal candidates in the $B_s^0 \rightarrow D_s K\pi\pi$ (black) and $B_s^0 \rightarrow D_s \pi\pi\pi$ (red) data samples.

672 Both, data and simulated samples, show good agreement between the signal and
 673 normalization channel. Compatibility is also seen in Fig. ??, which shows the comparison
 674 of the tagging decision distributions of the OS and SS tagger for reweighted data.

675 Fig. ?? shows the signal data distributions of the transverse B_s^0 momentum p_T , the
 676 pseudorapidity η of the signal candidate and the number of reconstructed tracks per event.
 677 Sufficient agreement is observed.

678 To justify the portability of the flavour tagging calibration obtained from $B_s^0 \rightarrow D_s \pi\pi\pi$
 679 to the $B_s^0 \rightarrow D_s K\pi\pi$ channel, besides the good agreement of the distributions shown
 680 above, the dependence of the measured mistag ω on the predicted mistag η has to be
 681 compatible in both channel. This dependence is shown in Fig. 7.2 for simulated signal
 682 events of both channels, where good agreement is observed.

683 7.4 Combination of OS and SS taggers

684 In the time- and amplitude-dependent fit to $B_s^0 \rightarrow D_s K\pi\pi$ data, the obtained tagging
 685 responses of the OS and SS tagger will be combined after the calibration described in the
 686 previous sections is applied. Events that acquire a mistag probability greater than 0.5 after
 687 the calibration will have their tagging decision flipped. For events where only one of the
 688 two taggers fired, the combination of the tagging decision is trivial. In those events where
 689 both taggers made a decision, we use the standard combination of taggers [35] provided
 690 by the flavour tagging group. In the nominal fit, the calibrated mistags ω are combined
 691 event by event for the OS and SS tagger, thus adding one variable to observable to the
 692 fit procedure. This ensures that the uncertainties of the OS and SS tagging calibration
 693 parameters are propagated properly to the combined tagging response for each event.
 694 The tagging performance for the combined tagger in the categories SS tagged only, OS
 695 tagged only and SS+OS tagged, are shown in Tab. ?? for the signal and normalization
 696 channel. The distribution of the observed mistag ω as a function of the combined mistag
 697 probability η for $B_s^0 \rightarrow D_s \pi\pi\pi$ decays is shown in Fig. 7.3.

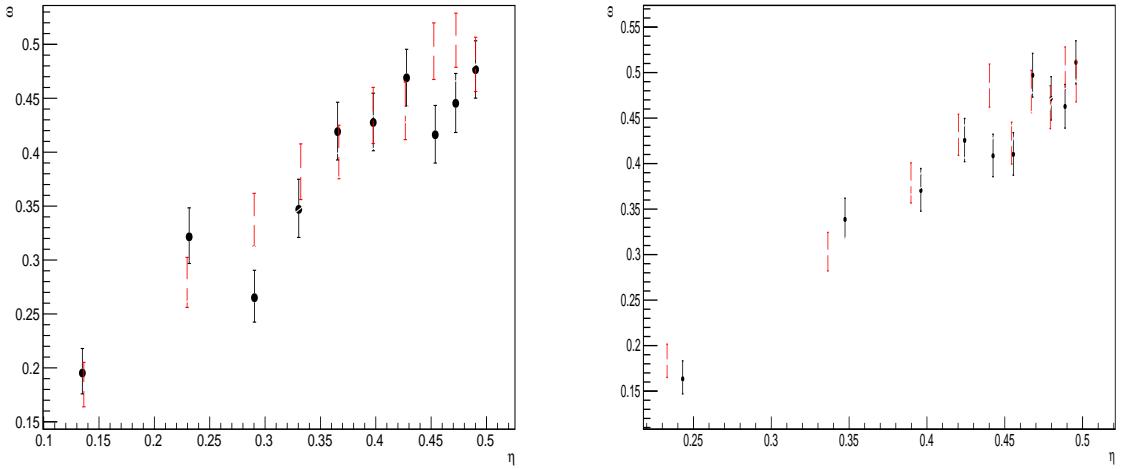


Figure 7.2: Dependence of the observed mistag ω on the predicted mistag η for the (left) OS combination and the (right) SS kaon tagger, found in the simulated $B_s^0 \rightarrow D_s K\pi\pi$ (black) and $B_s^0 \rightarrow D_s \pi\pi\pi$ (red) signal samples.

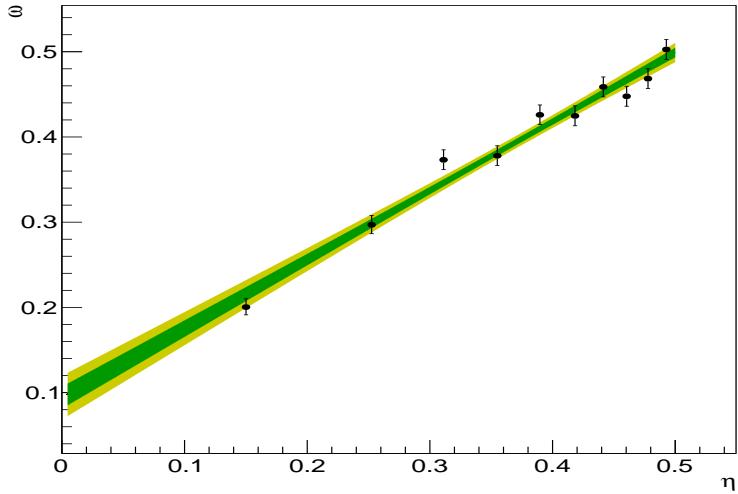


Figure 7.3: Distribution of the predicted combined mistag probability η versus the observed mistag ω for $B_s^0 \rightarrow D_s \pi\pi\pi$ signal candidates. The fit with a linear polynomial, used to determine p_0 and p_1 is overlaid.

Table 7.3: The flavour tagging performances for only OS tagged, only SS tagged and both OS and SS tagged events for Run-I data.

| $B_s \rightarrow D_s \pi\pi\pi$ | $\epsilon_{tag} [\%]$ | $\langle \omega \rangle [\%]$ | $\epsilon_{eff} [\%]$ |
|---------------------------------|-----------------------|-------------------------------|-----------------------|
| Only OS | 11.32 ± 0.09 | 37.91 ± 1.02 | 0.98 ± 0.14 |
| Only SS | 41.66 ± 0.18 | 43.78 ± 0.53 | 1.54 ± 0.23 |
| Both OS-SS | 27.17 ± 0.25 | 36.68 ± 0.81 | 2.91 ± 0.29 |
| Combined | 80.15 ± 0.32 | 40.55 ± 0.72 | 5.43 ± 0.40 |

Table 7.4: The flavour tagging performances for only OS tagged, only SS tagged and both OS and SS tagged events for Run-II data.

| $B_s \rightarrow D_s \pi\pi\pi$ | $\epsilon_{tag} [\%]$ | $\langle \omega \rangle [\%]$ | $\epsilon_{eff} [\%]$ |
|---------------------------------|-----------------------|-------------------------------|-----------------------|
| Only OS | 10.51 ± 0.07 | 35.32 ± 0.77 | 1.25 ± 0.11 |
| Only SS | 43.27 ± 0.14 | 43.29 ± 0.44 | 1.58 ± 0.17 |
| Both OS-SS | 24.77 ± 0.18 | 35.14 ± 0.61 | 3.19 ± 0.22 |
| Combined | 78.55 ± 0.24 | 39.65 ± 0.55 | 6.02 ± 0.30 |

698 8 Production and Detection Asymmetries

699 8.1 B_s Production Asymmetry

700 The production rates of b and \bar{b} hadrons in pp collisions are not expected to be identical,
 701 therefore this effect must be taken into account when computing CP asymmetries. The
 702 production asymmetry for B_s mesons is defined as:

$$A_p(B_s^0) = \frac{\sigma(\bar{B}_s^0) - \sigma(B_s^0)}{\sigma(\bar{B}_s^0) + \sigma(B_s^0)} \quad (8.1)$$

703 where σ are the corresponding production cross-section. This asymmetry was measured
 704 by LHCb in pp collisions at $\sqrt{s} = 7$ TeV and $\sqrt{s} = 8$ TeV by means of a time-dependent
 705 analysis of $B_s \rightarrow D_s^- \pi^+$ decays [40]. The results in bins of p_T and η of the B_s meson
 706 are shown in Table 8.1. To correct for the different kinematics of $B_s \rightarrow D_s^- \pi^+$ and
 707 $B_s^0 \rightarrow D_s K\pi\pi$ decays, the measured B_s production asymmetries $A_p(p_T, \eta)$ are folded with
 708 the sWeighted p_T, η distribution of our signal channel. The resulting effective production
 709 asymmetries are:

$$A_p(B_s^0)_{2011} = (-0.506 \pm 1.90)\% \quad (8.2)$$

$$A_p(B_s^0)_{2012} = (-0.164 \pm 1.30)\% \quad (8.3)$$

$$A_p(B_s^0)_{\text{Run-I}} = (-0.045 \pm 1.04)\%. \quad (8.4)$$

710 As for Run-II data no measurement is available yet, we determine the production asym-
 711 metry from $B_s \rightarrow D_s \pi\pi\pi$ data together with the tagging parameters.

Table 8.1: B_s production asymmetries in kinematic bins for 2011 and 2012 data. [40]

| p_T [GeV/c] | η | $A_p(B_s^0)_{\sqrt{s}=7 \text{ TeV}}$ | $A_p(B_s^0)_{\sqrt{s}=8 \text{ TeV}}$ |
|-----------------|--------------|---------------------------------------|---------------------------------------|
| (2.00, 7.00) | (2.10, 3.00) | $0.0166 \pm 0.0632 \pm 0.0125$ | $0.0412 \pm 0.0416 \pm 0.0150$ |
| (2.00, 7.00) | (3.00, 3.30) | $0.0311 \pm 0.0773 \pm 0.0151$ | $-0.0241 \pm 0.0574 \pm 0.0079$ |
| (2.00, 7.00) | (3.30, 4.50) | $-0.0833 \pm 0.0558 \pm 0.0132$ | $0.0166 \pm 0.0391 \pm 0.0092$ |
| (7.00, 9.50) | (2.10, 3.00) | $0.0364 \pm 0.0479 \pm 0.0068$ | $0.0482 \pm 0.0320 \pm 0.0067$ |
| (7.00, 9.50) | (3.00, 3.30) | $0.0206 \pm 0.0682 \pm 0.0127$ | $0.0983 \pm 0.0470 \pm 0.0155$ |
| (7.00, 9.50) | (3.30, 4.50) | $0.0058 \pm 0.0584 \pm 0.0089$ | $-0.0430 \pm 0.0386 \pm 0.0079$ |
| (9.50, 12.00) | (2.10, 3.00) | $-0.0039 \pm 0.0456 \pm 0.0121$ | $0.0067 \pm 0.0303 \pm 0.0063$ |
| (9.50, 12.00) | (3.00, 3.30) | $0.1095 \pm 0.0723 \pm 0.0179$ | $-0.1283 \pm 0.0503 \pm 0.0171$ |
| (9.50, 12.00) | (3.30, 4.50) | $0.1539 \pm 0.0722 \pm 0.0212$ | $-0.0500 \pm 0.0460 \pm 0.0104$ |
| (12.00, 30.00) | (2.10, 3.00) | $-0.0271 \pm 0.0336 \pm 0.0061$ | $-0.0012 \pm 0.0222 \pm 0.0050$ |
| (12.00, 30.00) | (3.00, 3.30) | $-0.0542 \pm 0.0612 \pm 0.0106$ | $0.0421 \pm 0.0416 \pm 0.0162$ |
| (12.00, 30.00) | (3.30, 4.50) | $-0.0586 \pm 0.0648 \pm 0.0150$ | $0.0537 \pm 0.0447 \pm 0.0124$ |

712 8.2 $K^-\pi^+$ Detection Asymmetry

713 The presented measurement of the CKM-angle γ using $B_s^0 \rightarrow D_s K\pi\pi$ decays is sensitive
 714 to a possible charge asymmetry of the kaon. This effect can be detector induced, because
 715 kaons are known to have a nuclear cross-section which is asymmetrically dependent on
 716 the sign of their charge. It is indispensable to determine the detector induced charge
 717 asymmetry of the kaon, as fitting without taking this effect into account would introduce
 718 a ‘fake’ CP violation. Instead of determining the single track detection asymmetry of a
 719 kaon, it is found that the combined two track asymmetry of a kaon-pion pair is much
 720 easier to access [41]. Therefore the two track asymmetry is used, which is defined as

$$A^{det}(K^-\pi^+) = \frac{\epsilon^{det}(K^-\pi^+) - \epsilon^{det}(K^+\pi^-)}{\epsilon^{det}(K^-\pi^+) + \epsilon^{det}(K^+\pi^-)}. \quad (8.5)$$

721 This asymmetry can be measured from the difference in asymmetries in the $D^+ \rightarrow K^-\pi^+\pi^+$
 722 and $D^+ \rightarrow K_s^0\pi^+$ modes [42]:

$$\begin{aligned} A^{det}(K^-\pi^+) &= \frac{N(D^+ \rightarrow K^-\pi^+\pi^+) - N(D^- \rightarrow K^+\pi^-\pi^-)}{N(D^+ \rightarrow K^-\pi^+\pi^+) + N(D^- \rightarrow K^+\pi^-\pi^-)} \\ &\quad - \frac{N(D^+ \rightarrow K_s^0\pi^+) - N(D^- \rightarrow K_s^0\pi^-)}{N(D^+ \rightarrow K_s^0\pi^+) + N(D^- \rightarrow K_s^0\pi^-)} \\ &\quad - A(K^0), \end{aligned} \quad (8.6)$$

723 where possible CP violation in the $D^+ \rightarrow K_s^0\pi^+$ mode is predicted to be smaller than
 724 10^{-4} in the Standard Model [43]. The asymmetry in the neutral kaon system, $A(K^0)$, has
 725 to be taken into account as a correction.

726 We use a dedicated LHCb tool to determine $A^{det}(K^-\pi^+)$ for all data taking periods
 727 used in this analysis. A detailed description can be found in [42]. The tool provides
 728 large calibration samples of $D^\pm \rightarrow K^\pm\pi^\pm\pi^\pm$ and $D^\pm \rightarrow K_s^0\pi^\pm$ decays, which are used to
 729 determine the asymmetry following Eq. 8.6. Several weighting steps are performed to
 730 match the kinematics of the calibration samples to our signal decay sample:

731 First, weights are assigned to the K^\pm and π^\pm of the $D^\pm \rightarrow K^\pm\pi^\pm\pi^\pm$ sample, using
 732 p, η of the K^\pm and p_T, η of the π^\pm from our $B_s^0 \rightarrow D_s K\pi\pi$ signal decay. Then, weights
 733 are assigned to the $D^\pm (p_T, \eta)$ and the $\pi^\pm (p_T)$ of the $D^\pm \rightarrow K_s^0\pi^\pm$ sample to match
 734 the corresponding, weighted distributions of the $D^\pm \rightarrow K^\pm\pi^\pm\pi^\pm$ sample. In a last
 735 step, weights are assigned to match the bachelor pions ϕ distributions between the two
 736 calibration samples.

737 After the samples are weighted, fits are performed to the invariant
 738 $m(K^-\pi^+\pi^+)/m(K^+\pi^-\pi^-)$ and $m(K_s^0\pi^+)/m(K_s^0\pi^-)$ distributions to determine
 739 $A^{det}(K^-\pi^+)$. The PDFs used to describe the invariant mass distributions consist of
 740 gaussian functions for the signal component and exponentials describing the residual
 741 background.

742 The detection asymmetry is determined separately for every year and (since it is a
 743 charge asymmetry effect) magnet polarity. Serving as an example for Run-I and Run-
 744 II, the fits used to determine $N(D^+ \rightarrow K^-\pi^+\pi^+)/N(D^- \rightarrow K^+\pi^-\pi^-)$ and $N(D^+ \rightarrow$
 745 $K_s^0\pi^+)/N(D^- \rightarrow K_s^0\pi^-)$ for 2011, magnet up data and 2015, magnet up data are shown
 746 in Fig. 8.1 and 8.2 respectively. The obtained values of $A^{det}(K^-\pi^+) + A(K^0)$ for all years
 747 and polarities are shown in Table 8.2.

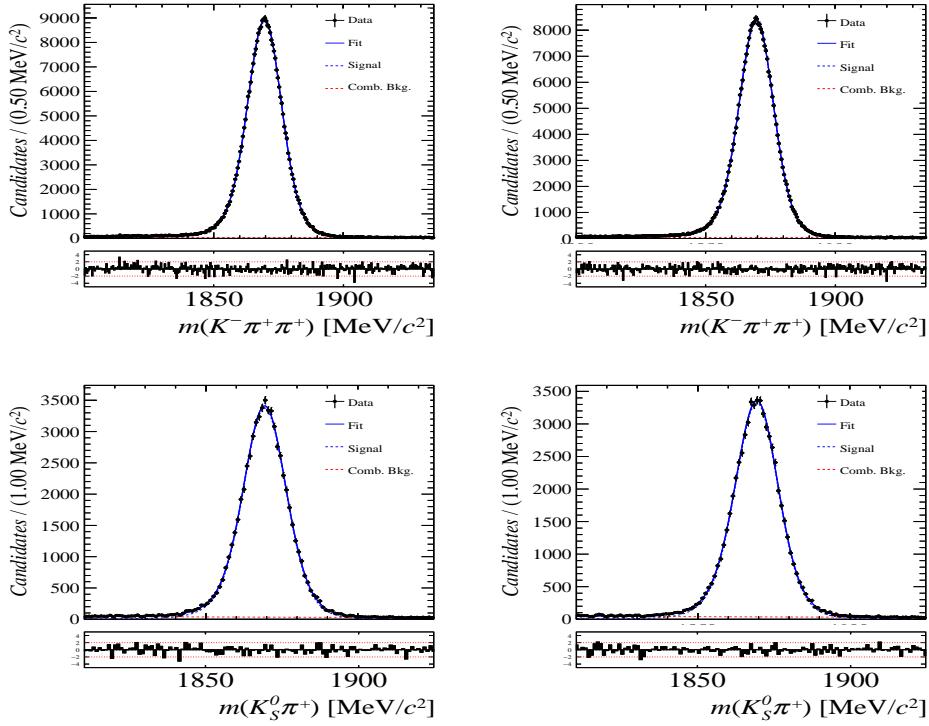


Figure 8.1: Distributions of the invariant mass of (top) $D^\pm \rightarrow K^\pm \pi^\pm \pi^\pm$ and (bottom) $D^\pm \rightarrow K_S^0 \pi^\pm$ candidates for Run-I data from the calibration samples. A fit described in the text is overlaid.

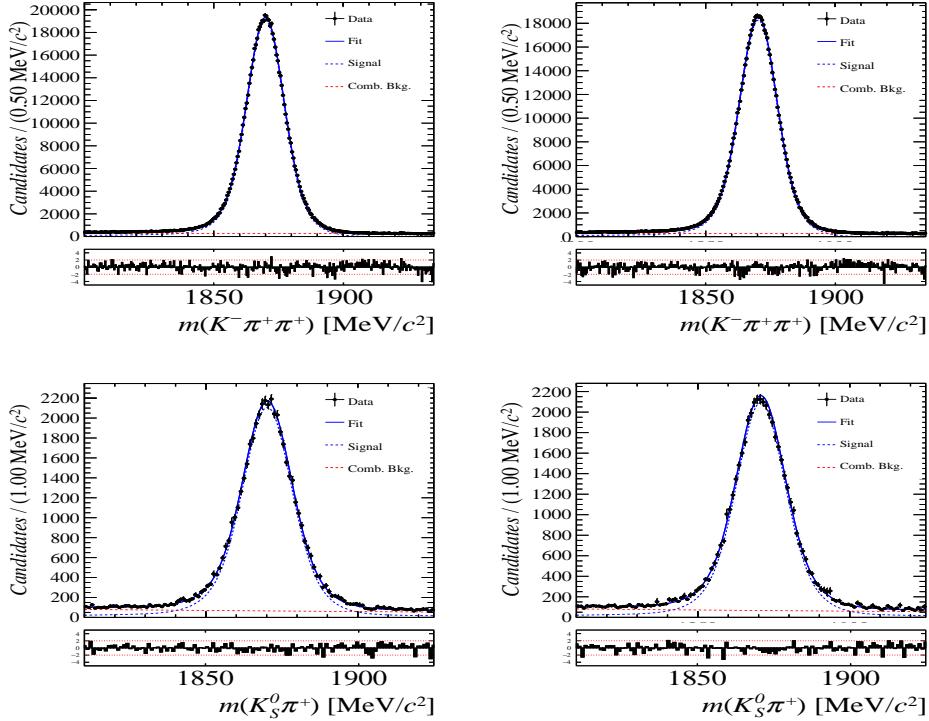


Figure 8.2: Distributions of the invariant mass of (top) $D^\pm \rightarrow K^\pm \pi^\pm \pi^\pm$ and (bottom) $D^\pm \rightarrow K_S^0 \pi^\pm$ candidates for Run-II data from the calibration samples. A fit described in the text is overlaid.

| Data sample | $A^{det}(K^-\pi^+) + A(K^0)$ [%] |
|-----------------|----------------------------------|
| Run-I | |
| 2011, mag. up | -2.01 \pm 0.32 |
| 2011, mag. down | -0.16 \pm 0.28 |
| 2011, average | -1.09 \pm 0.21 |
| 2012, mag. up | -0.90 \pm 0.20 |
| 2012, mag. down | -1.01 \pm 0.22 |
| 2012, average | -0.96 \pm 0.15 |
| Run-II | |
| 2015, mag. up | -1.36 \pm 0.36 |
| 2015, mag. down | -0.96 \pm 0.24 |
| 2015, average | -1.16 \pm 0.22 |
| 2016, mag. up | 0.50 \pm 0.88 |
| 2016, mag. down | 1.23 \pm 0.72 |
| 2016, average | 0.87 \pm 0.57 |

Table 8.2: Summary of the $K^-\pi^+$ detection asymmetry obtained from the fits to the Run-I and Run-II calibration samples.

748 9 Time dependent fit

749 This section covers the phasespace integrated, time-dependent fit to $B_s^0 \rightarrow D_s h\pi\pi$ data.
 750 We use the **sFit** technique [31] to statistically remove background from the decay time fit,
 751 leaving only the signal PDF to describe the decay time. The **sWeights** are calculated based
 752 on the fit to the reconstructed B_s mass distribution described in Sec. 4. As additional
 753 input to the fit, the tagging information (Sec. 7), as well as the decay time acceptance
 754 (Sec. 6) and resolution (Sec. 5) is used and fixed to the values obtained by the dedicated
 755 studies. Taking all inputs into account, the final time dependent fit PDF is given by

$$756 \quad \mathcal{P}\mathcal{D}\mathcal{F}(t, \vec{\lambda}) = \left(\epsilon(t) \cdot \int P(x, t, q_t, q_f) dx \right) \times \mathcal{R}(t - t'), \quad (9.1)$$

756 where $\int P(x, t, q_t, q_f) dx$ is the PDF given by Eq. 2.6, $\epsilon(t)$ is the efficiency due to the time
 757 acceptance effects and $\mathcal{R}(t - t')$ is the Gaussian time resolution function.

758 9.1 sFit to $B_s^0 \rightarrow D_s \pi\pi\pi$ data

759 The phasespace-integrated, time-dependent fit is performed to the full sWeighted sample
 760 of selected candidates from Run I and 2015+2016 Run II data, containing both possible
 761 magnet polarities and D_s final states. In the fit, the values of Γ_s and $\Delta\Gamma_s$ are fixed to the
 762 latest PDG report. All tagging parameters are fixed to the central values found in the
 763 tagging calibration, described in Sec. 7. Due to the fact that the $B_s^0 \rightarrow D_s \pi\pi\pi$ decay is
 764 flavour specific, the CP-coefficients can be fixed to $C = 1$ and $D_f = D_{\bar{f}} = S_f = S_{\bar{f}} = 0$,
 765 reducing Eq. 2.6 to

$$766 \quad \int P(x, t, q_t, q_f) dx = [\cosh\left(\frac{\Delta\Gamma t}{2}\right) + q_t q_f C \cos(m_s t)] e^{-\Gamma t}. \quad (9.2)$$

766 Note that in this case, the dependence on the coherence factor κ is dropped and the
 767 same relation as found for $B_s^0 \rightarrow D_s \pi$ decays is recovered. Therefore, the only free fit
 768 parameter left is Δm_s . The data distribution with the overlaid fit is shown in Fig.

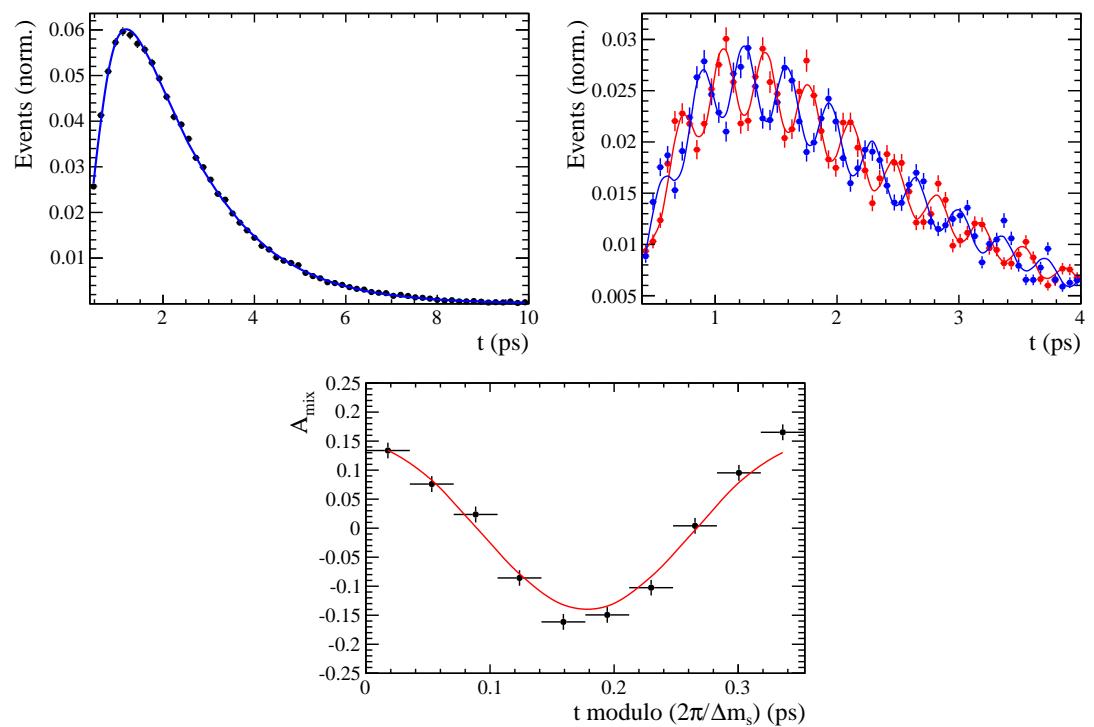


Figure 9.1

Table 9.1: Result of the phase-space integrated fit to $B_s \rightarrow D_s \pi\pi\pi$ data.

| | Fit parameter | Value |
|--------|-------------------------------------|---------------------------|
| Run-I | p_0^{OS} | 0.3896 ± 0.0101 |
| | p_1^{OS} | 0.8883 ± 0.1074 |
| | Δp_0^{OS} | 0.0161 ± 0.0104 |
| | Δp_1^{OS} | 0.0005 ± 0.1095 |
| | $\epsilon_{tag}^{\text{OS}}$ | 0.3851 ± 0.0031 |
| | $\Delta \epsilon_{tag}^{\text{OS}}$ | 0.0069 ± 0.0123 |
| | p_0^{SS} | 0.4465 ± 0.0075 |
| | p_1^{SS} | 1.0748 ± 0.1012 |
| | Δp_0^{SS} | -0.0190 ± 0.0076 |
| | Δp_1^{SS} | 0.1017 ± 0.1063 |
| | $\epsilon_{tag}^{\text{SS}}$ | 0.6882 ± 0.0029 |
| | $\Delta \epsilon_{tag}^{\text{SS}}$ | -0.0076 ± 0.0117 |
| | A_p | -0.0004 ± 0.0000 |
| | <hr/> | |
| Run-II | p_0^{OS} | 0.3669 ± 0.0074 |
| | p_1^{OS} | 0.9298 ± 0.0761 |
| | Δp_0^{OS} | 0.0118 ± 0.0085 |
| | Δp_1^{OS} | 0.0234 ± 0.0855 |
| | $\epsilon_{tag}^{\text{OS}}$ | 0.3525 ± 0.0023 |
| | $\Delta \epsilon_{tag}^{\text{OS}}$ | 0.0105 ± 0.0085 |
| | p_0^{SS} | 0.4532 ± 0.0055 |
| | p_1^{SS} | 0.9125 ± 0.0656 |
| | Δp_0^{SS} | -0.0123 ± 0.0060 |
| | Δp_1^{SS} | 0.1374 ± 0.0757 |
| | $\epsilon_{tag}^{\text{SS}}$ | 0.6804 ± 0.0023 |
| | $\Delta \epsilon_{tag}^{\text{SS}}$ | 0.0076 ± 0.0083 |
| | A_p | -0.0042 ± 0.0091 |
| | <hr/> | |
| | Δm_s | $\text{xx.xx} \pm 0.0110$ |

769 **9.2 sFit to $B_s^0 \rightarrow D_s K\pi\pi$ data**

Table 9.2: Result of the phase-space integrated fit to $B_s \rightarrow D_s K\pi\pi$ data.

| Fit parameter | Value |
|---------------|---------------|
| C | xx.xx ± 0.170 |
| D | xx.xx ± 0.390 |
| \bar{D} | xx.xx ± 0.346 |
| S | xx.xx ± 0.255 |
| \bar{S} | xx.xx ± 0.221 |

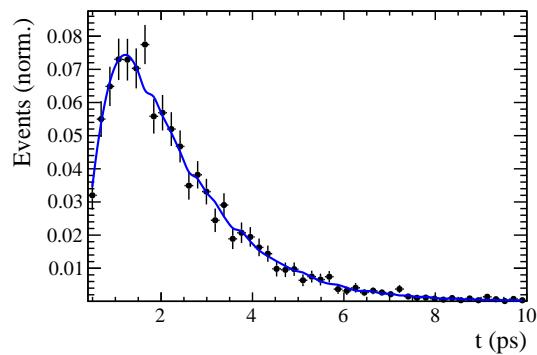


Figure 9.2

770 10 Time dependent amplitude fit

771 10.1 Signal Model Construction

772 The light meson spectrum comprises multiple resonances which are expected to contribute
773 to $B_s \rightarrow D_s K\pi\pi$ decays as intermediate states. Apart from clear contributions coming
774 from resonances such as $K_1(1270)$, $K_1(1400)$ $\rho(770)$ and $K^*(892)^0$, the remaining structure
775 is impossible to infer due to the cornucopia of broad, overlapping and interfering resonances
776 within the phase space boundary. The complete list of considered amplitudes can be
777 found in Appendix F.

778 To build the amplitude model, one could successively add amplitudes on top of one
779 another until a reasonable agreement between data and fit was achieved. However, this
780 step-wise approach is not particularly suitable for amplitude analyses as discussed in
781 Ref. [44]. Instead, we include the whole pool of amplitudes in the first instance and use
782 the Least Absolute Shrinkage and Selection Operator [44, 45] (LASSO) approach to limit
783 the model complexity. In this method, the event likelihood is extended by a penalty term

$$-2 \log \mathcal{L} \rightarrow -2 \log \mathcal{L} + \lambda \sum_i \sqrt{\int |a_i A_i(\mathbf{x})|^2 d\Phi_4}, \quad (10.1)$$

784 which shrinks the amplitude coefficients towards zero. The amount of shrinkage is
785 controlled by the parameter λ , to be tuned on data. Higher values for λ encourage sparse
786 models, *i.e.* models with only a few non-zero amplitude coefficients. The optimal value
787 for λ is found by minimizing the Bayesian information criteria [46] (BIC),

$$\text{BIC}(\lambda) = -2 \log \mathcal{L} + r \log N_{\text{Sig}}, \quad (10.2)$$

788 where N_{Sig} is the number of signal events and r is the number of amplitudes with a decay
789 fraction above a certain threshold. In this way, the optimal λ balances the fit quality
790 ($-2 \log \mathcal{L}$) against the model complexity. The LASSO penalty term is only used to select
791 the model. Afterwards, this term must be discarded in the final amplitude fit with the
792 selected model, otherwise the parameter uncertainties would be biased.

793 The set of amplitudes is selected using the optimal value of $\lambda = 28$, and is henceforth
794 called the LASSO model; Figure ??(a) shows the distribution of BIC values obtained by
795 scanning over λ where we choose the decay fraction threshold to be 0.5%. In addition, we
796 repeated the model selection procedure under multiple different conditions:

- 797 1. The fit fraction threshold for inclusion in the final model was varied within the
798 interval [0.05, 5]%. The set of selected amplitudes is stable for thresholds between
799 0.1% and 1%. Other choices result in marginally different models containing one
800 component more or less.
 - 801 2. Instead of BIC, the Akaike information criteria ($\text{AIC}(\lambda) = -2 \log \mathcal{L} + 2r$ [47]) was
802 used to optimize λ . For a given threshold, the AIC method tends to prefer lower
803 λ values. However, the set of models obtained varying the threshold within the
804 interval [0.05, 5]% is identical to the BIC method.
 - 805 3. The amplitudes selected under nominal conditions were excluded one-by-one from
806 the set of all amplitudes considered.
- 807 From that we obtained a set of alternative models shown in Appendix ??.

Table 10.1: Fit fractions for $B_s \rightarrow D_s K\pi\pi$ data.

| Decay channel | Fraction [%] |
|---|------------------|
| $B_s \rightarrow K(1)(1400)^+ (\rightarrow K^*(892)^0 (\rightarrow K^+ \pi^-) \pi^+) D_s^-$ | 34.70 ± 2.24 |
| $B_s \rightarrow K(1)(1270)^+ (\rightarrow K(0)^*(1430)^0 (\rightarrow K^+ \pi^-) \pi^+) D_s^-$ | 6.85 ± 0.94 |
| $B_s \rightarrow K(1)(1270)^+ (\rightarrow K^*(892)^0 (\rightarrow K^+ \pi^-) \pi^+) D_s^-$ | 13.08 ± 1.70 |
| $B_s \rightarrow K(1)(1270)^+ (\rightarrow \rho(770)^0 (\rightarrow \pi^+ \pi^-) K^+) D_s^-$ | 9.25 ± 0.60 |
| $B_s \rightarrow K(1460)^+ (\rightarrow K^*(892)^0 (\rightarrow K^+ \pi^-) \pi^+) D_s^-$ | 0.99 ± 0.06 |
| $BuggB_s \rightarrow K(1460)^+ (\rightarrow \sigma (\rightarrow \pi^+ \pi^-) K^+) D_s^-$ | 3.42 ± 1.49 |
| $B_s \rightarrow K^*(1410)^+ (\rightarrow K^*(892)^0 (\rightarrow K^+ \pi^-) \pi^+) D_s^-$ | 16.40 ± 1.06 |
| $B_s \rightarrow K^*(1410)^+ (\rightarrow \rho(770)^0 (\rightarrow \pi^+ \pi^-) K^+) D_s^-$ | 4.88 ± 0.68 |
| $B_s \rightarrow NonResS0 (\rightarrow D_s^- \pi^+) K^*(892)^0 (\rightarrow K^+ \pi^-)$ | 4.60 ± 1.44 |
| $BuggB_s \rightarrow NonResS0 (\rightarrow D_s^- K^+) \sigma (\rightarrow \pi^+ \pi^-)$ | 4.96 ± 0.68 |
| Sum | 99.13 ± 5.87 |

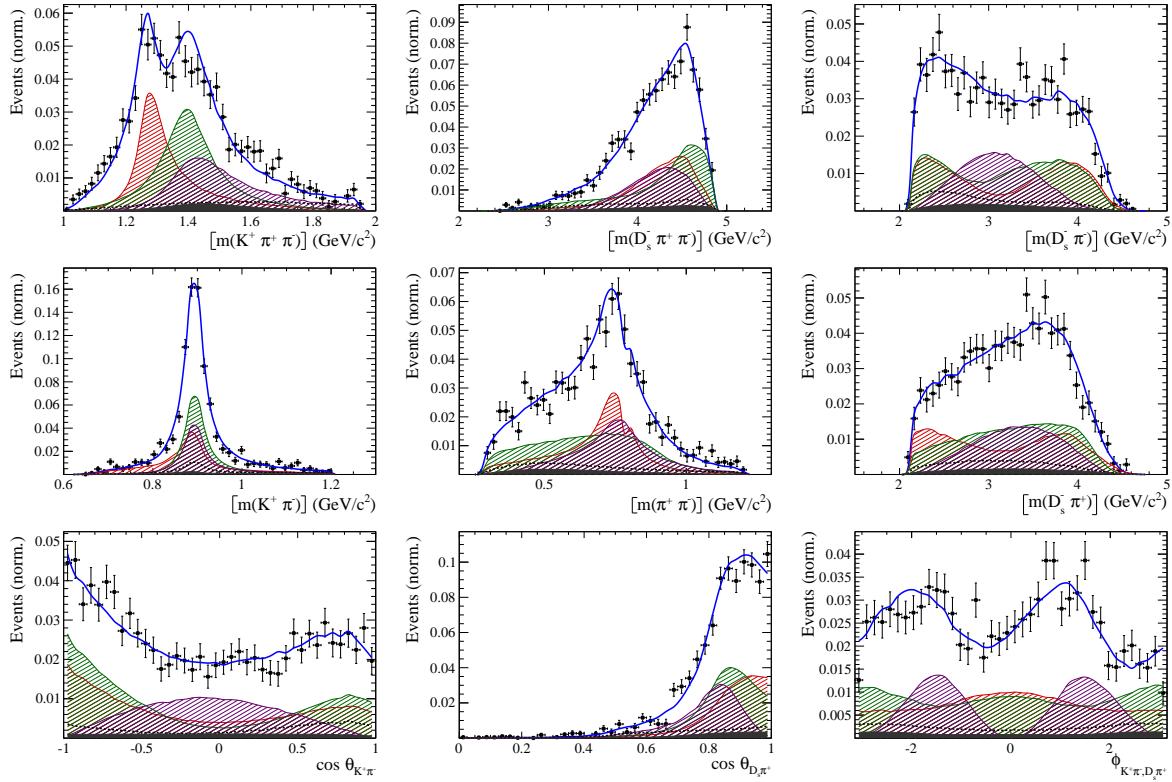


Figure 10.1

10.2 Results

Table 10.2: Result of the time-dependent amplitude fit to $B_s \rightarrow D_s K\pi\pi$ data.

| Fit parameter | Value |
|---------------|-------------------|
| x_- | xx.xx \pm 0.119 |
| y_- | xx.xx \pm 0.044 |
| x_+ | xx.xx \pm 0.060 |
| y_+ | xx.xx \pm 0.038 |

Table 10.3: Fit fractions for $B_s \rightarrow D_s K\pi\pi$ data.

| Decay channel | Fraction [%] |
|---|------------------|
| $B_s \rightarrow K(1)(1400)^+ (\rightarrow K^*(892)^0 (\rightarrow K^+ \pi^-) \pi^+) D_s^-$ | 28.77 \pm 0.20 |
| $B_s \rightarrow K(1)(1270)^+ (\rightarrow K(0)^*(1430)^0 (\rightarrow K^+ \pi^-) \pi^+) D_s^-$ | 9.32 \pm 0.06 |
| $B_s \rightarrow K(1)(1270)^+ (\rightarrow K^*(892)^0 (\rightarrow K^+ \pi^-) \pi^+) D_s^-$ | 18.13 \pm 0.12 |
| $B_s \rightarrow K(1)(1270)^+ (\rightarrow \rho(770)^0 (\rightarrow \pi^+ \pi^-) K^+) D_s^-$ | 12.80 \pm 0.09 |
| $B_s \rightarrow K^*(1410)^+ (\rightarrow K^*(892)^0 (\rightarrow K^+ \pi^-) \pi^+) D_s^-$ | 19.78 \pm 0.14 |
| $B_s \rightarrow K^*(1410)^+ (\rightarrow \rho(770)^0 (\rightarrow \pi^+ \pi^-) K^+) D_s^-$ | 5.98 \pm 0.04 |
| $BuggB_s \rightarrow NonResS0 (\rightarrow D_s^- K^+) \sigma (\rightarrow \pi^+ \pi^-)$ | 1.62 \pm 0.73 |
| Sum | 96.40 \pm 0.14 |

Table 10.4: Fit fractions for $B_s \rightarrow D_s K\pi\pi$ data.

| Decay channel | Fraction [%] |
|---|--------------------|
| $B_s \rightarrow K(1)(1400)^+ (\rightarrow K^*(892)^0 (\rightarrow K^+ \pi^-) \pi^+) D_s^-$ | 93.96 \pm 11.84 |
| $B_s \rightarrow K(1460)^+ (\rightarrow K^*(892)^0 (\rightarrow K^+ \pi^-) \pi^+) D_s^-$ | 2.55 \pm 0.32 |
| $BuggB_s \rightarrow K(1460)^+ (\rightarrow \sigma (\rightarrow \pi^+ \pi^-) K^+) D_s^-$ | 8.75 \pm 1.10 |
| $B_s \rightarrow NonResS0 (\rightarrow D_s^- \pi^+) K^*(892)^0 (\rightarrow K^+ \pi^-)$ | 58.07 \pm 17.15 |
| Sum | 163.34 \pm 12.39 |

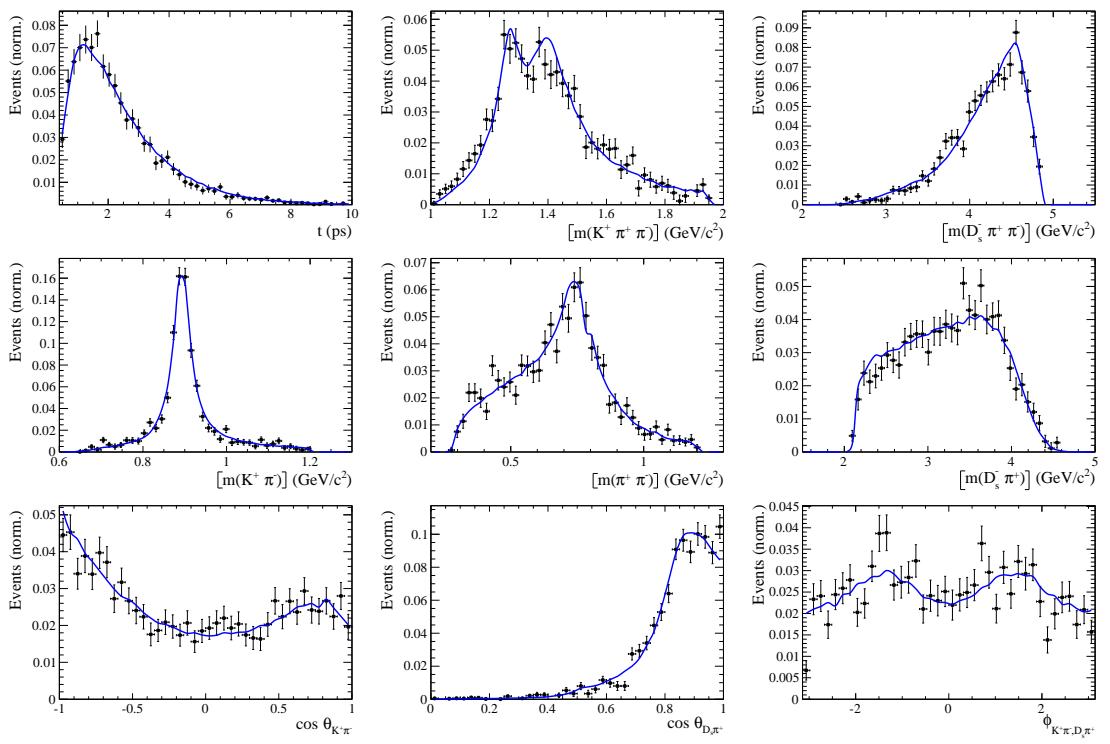


Figure 10.2

809 A Stripping and Trigger cuts

810 The following text describes variables which are used in Table 1.1 and might be ambiguous,
 811 or which benefits are not straight forward. Where noted, different cut values are applied
 812 for Run-I and Run-II data. In Table 1.1, DOCA is the abbreviation for distance of closest
 813 approach. This variable is used to ensure that all D_s and $X_{s,d}$ daughters originate from
 814 the same vertex. DIRA is the abbreviation for the cosine of the angle θ between the
 hadron's flight direction \vec{x} and it's corresponding momentum vector \vec{p} , $\cos \theta_{\vec{x}-\vec{p}}$.

Table 1.1: Summary of the stripping selections for $B_s^0 \rightarrow D_s K \pi \pi$ decays. The requirements for Run-II are only given if they have been changed.

| Variable | Stripping Cut (Run-I) | Stripping Cut (Run-II) |
|--|---|--------------------------------|
| Track χ^2/nDoF | < 3 | |
| Track p | $> 1000 \text{ MeV}/c$ | |
| Track p_T | $> 100 \text{ MeV}/c$ | |
| Track IP χ^2 | > 4 | |
| Track ghost-prob. | < 0.4 | |
| D_s mass | $m_{D_s} \pm 100 \text{ MeV}$ | $m_{D_s} \pm 80 \text{ MeV}$ |
| D_s Daughter p_T | $\sum_{i=1}^3 p_{t,i} > 1800 \text{ MeV}/c$ | |
| D_s Daughter DOCA | $< 0.5 \text{ mm}$ | |
| D_s Vertex χ^2/nDoF | < 10 | |
| D_s χ^2 -separation from PV | > 36 | |
| D_s daughter PID(π) | < 20 | |
| D_s daughter PID(K) | > -10 | |
| $X_{s,d}$ mass | $< 4000 \text{ MeV}$ | $< 3500 \text{ MeV}$ |
| $X_{s,d}$ Daughter p | $> 2 \text{ GeV}/c$ | |
| $X_{s,d}$ Daughter DOCA | $< 0.4 \text{ mm}$ | |
| $X_{s,d}$ Daughter p_T | $\sum_{i=1}^3 p_{t,i} > 1250 \text{ MeV}/c$ | |
| $X_{s,d}$ Vertex χ^2/nDoF | < 8 | |
| $X_{s,d}$ χ^2 -separation from PV | > 16 | |
| $X_{s,d}$ DIRA | > 0.98 | |
| $X_{s,d}$ $\Delta\rho$ | $> 0.1 \text{ mm}$ | |
| $X_{s,d}$ Δz | $> 2.0 \text{ mm}$ | |
| $X_{s,d}$ daughter PID(π) | < 10 | |
| X_s daughter PID(K) | > -2 | > 4 |
| B_s^0 mass | $[4750, 7000] \text{ MeV}/c^2$ | $[5000, 6000] \text{ MeV}/c^2$ |
| B_s^0 DIRA | > 0.98 | > 0.99994 |
| B_s^0 min IP χ^2 | < 25 | < 20 |
| B_s^0 Vertex χ^2/nDoF | < 10 | < 8 |
| $B_s^0 \tau_{B_s^0}$ | $> 0.2 \text{ ps}$ | |

816 Table 1.2 summarizes the trigger requirements imposed by the Hlt1 line used in this
 817 analysis for Run-I. At least one of the six decay particles must pass the listed requirements
 818 in order for the event to be stored for further analysis. For Run-II, this trigger line was
 819 updated and uses a multivariate classifier which takes the variables listed in Table 1.2 as
 820 input, rather than directly cutting on them.

821 The Hlt2 2, 3 and 4-body topological lines use a Boosted Decision Tree based on the
 822 b-hadron p_T , its flight distance χ^2 from the nearest PV and the sum of the B_s^0 and D_s
 823 vertex χ^2 divided by the sum of their number of degrees of freedom. Table 1.3 summarizes
 824 the cuts applied by the inclusive ϕ trigger, which requires that a $\phi \rightarrow KK$ candidate can
 be formed out of two tracks present in the event.

Table 1.2: Summary of the cuts applied by the Hlt1TrackAllL0 trigger for Run-I. At least one of the six decay particles must pass this requirements, in order for the event to be accepted.

| Quantity | Hlt1TrackAllL0 requirement |
|------------------------------------|----------------------------|
| Track IP [mm] | > 0.1 |
| Track IP χ^2 | > 16 |
| Track χ^2/nDoF | < 2.5 |
| Track p_T | > 1.7 GeV/c |
| Track p | > 10 GeV/c |
| Number VELO hits/track | > 9 |
| Number missed VELO hits/track | < 3 |
| Number OT+IT $\times 2$ hits/track | > 16 |

Table 1.3: Summary of the cuts applied by the Hlt2 inclusive ϕ trigger. A $\phi \rightarrow KK$ candidate, formed by two tracks in the event, must pass this requirements in order for the event to be accepted.

| Quantity | Hlt2IncPhi requirement |
|------------------------------------|---|
| ϕ mass | $m_\phi \pm 12$ MeV/ c^2 of PDG value |
| ϕp_T | > 2.5 GeV/c |
| ϕ vertex χ^2/nDoF | < 20 |
| ϕ IP χ^2 to any PV | > 5 |

B Details of multivariate classifier

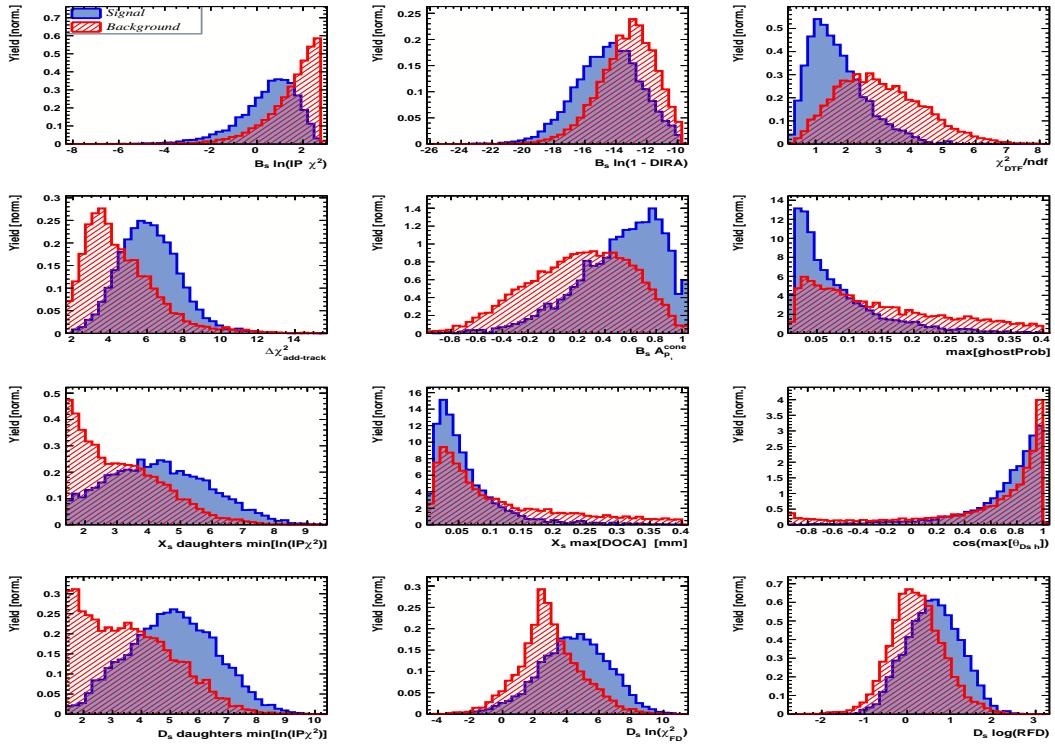


Figure A.1: Variables used to train the BDTG for category [Run-I,L0-TOS].

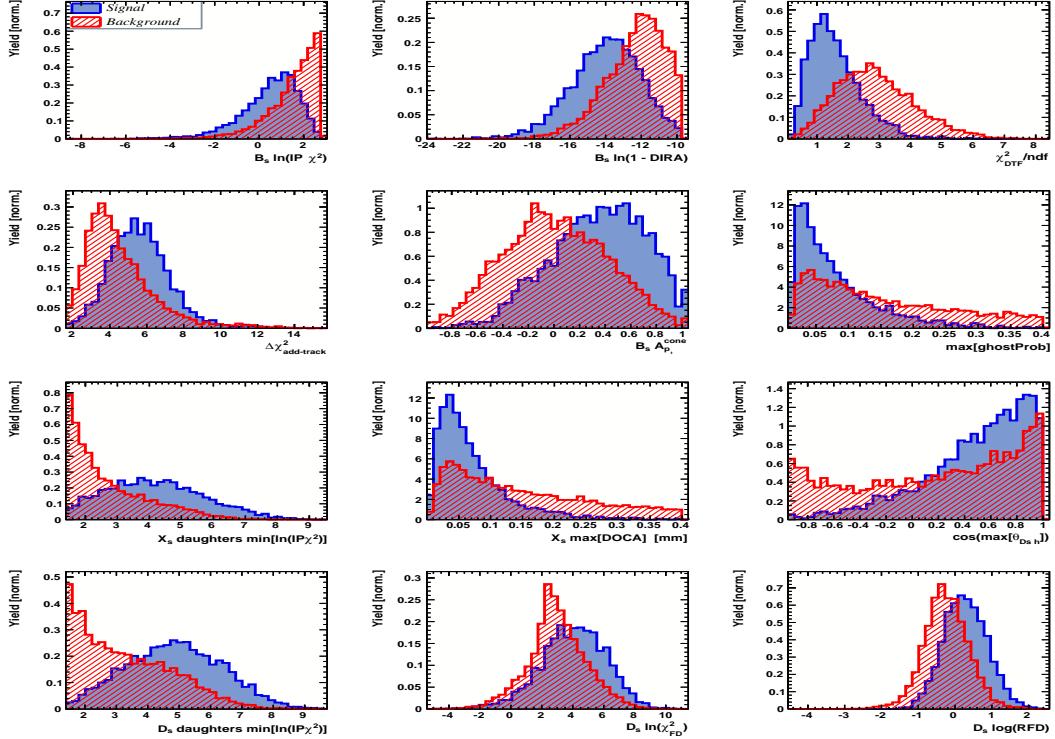


Figure A.2: Variables used to train the BDTG for category [Run-I,L0-TIS].

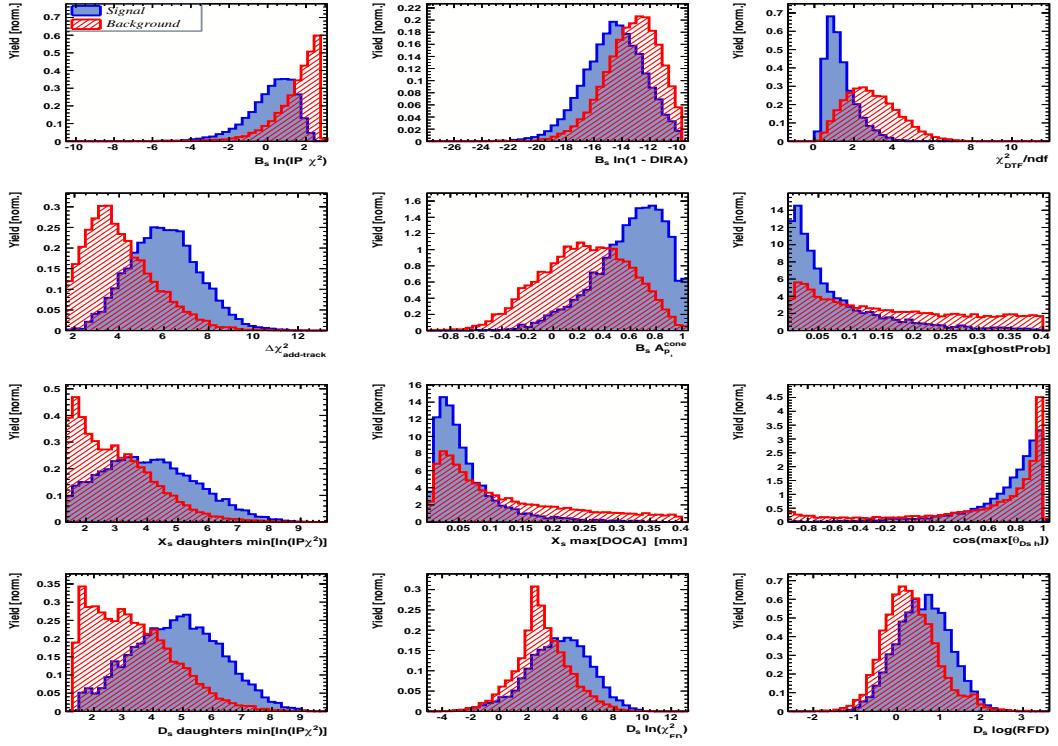


Figure A.3: Variables used to train the BDTG for category [Run-II,L0-TOS].

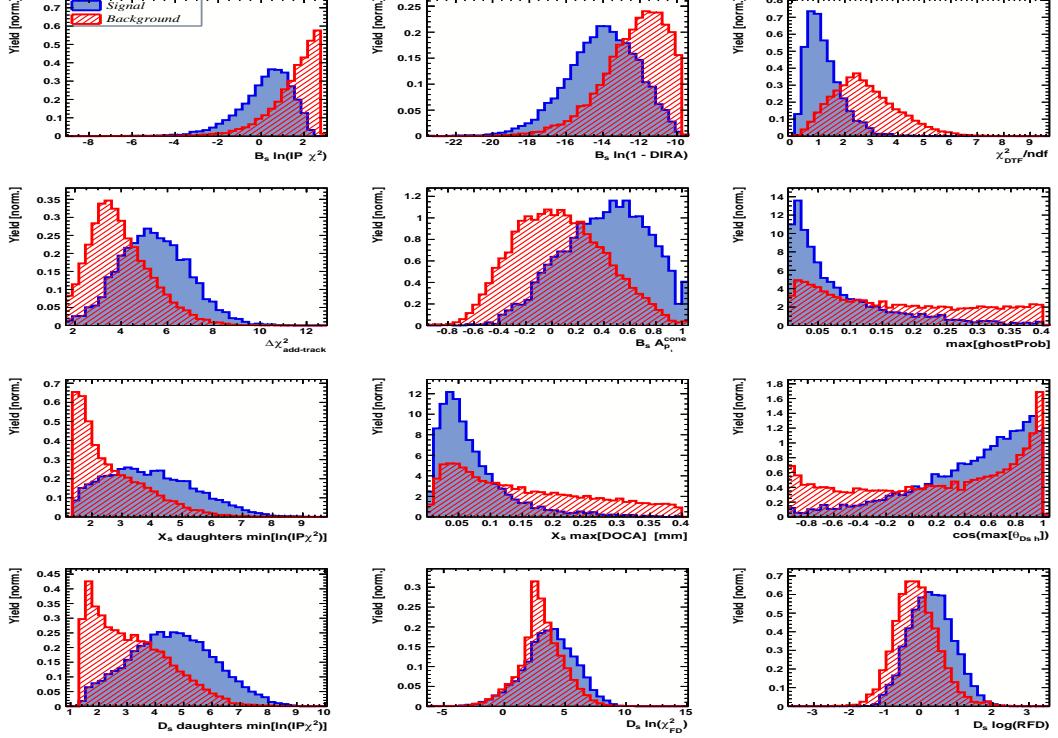


Figure A.4: Variables used to train the BDTG for category [Run-II,L0-TIS].

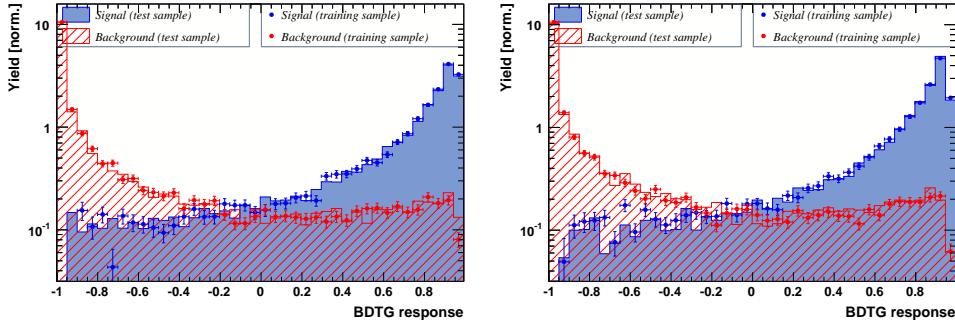


Figure A.5: Response of the classifier trained on the even and tested on the odd sample (left) and trained on the odd and tested on the even sample (right) for category [Run-I,L0-TOS].

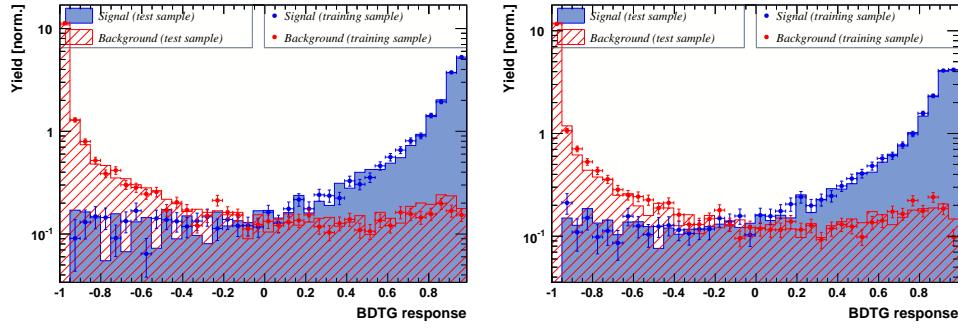


Figure A.6: Response of the classifier trained on the even and tested on the odd sample (left) and trained on the odd and tested on the even sample (right) for category [Run-I,L0-TIS].

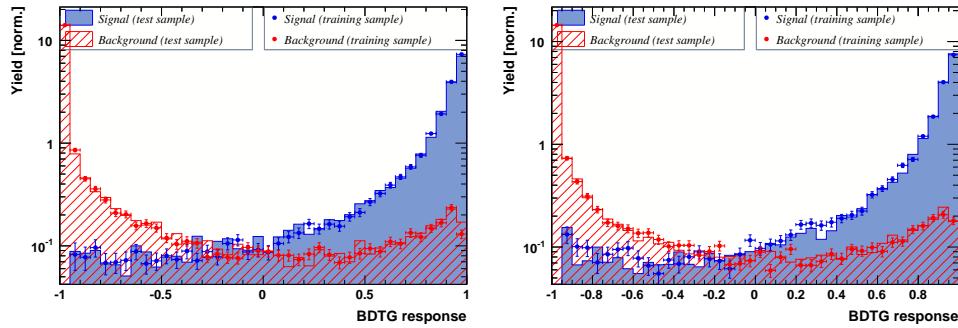


Figure A.7: Response of the classifier trained on the even and tested on the odd sample (left) and trained on the odd and tested on the even sample (right) for category [Run-II,L0-TOS].

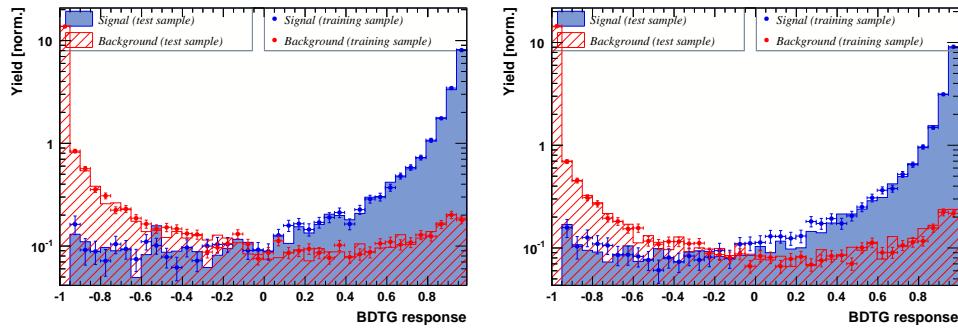


Figure A.8: Response of the classifier trained on the even and tested on the odd sample (left) and trained on the odd and tested on the even sample (right) for category [Run-II,L0-TIS].

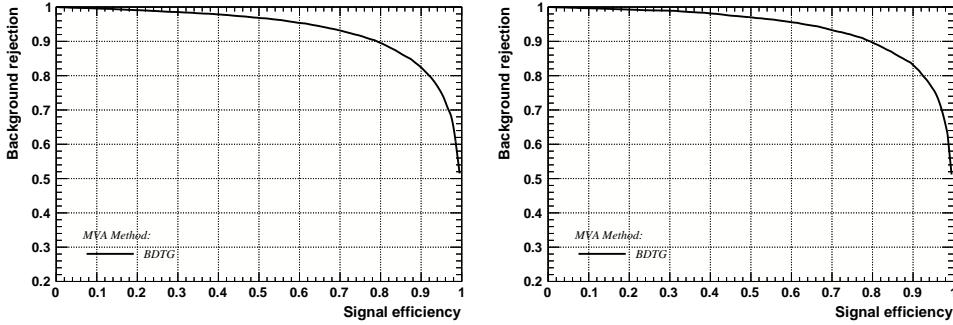


Figure A.9: Signal efficiency versus background rejection for the BDT trained on the even (left) and odd (right) sample for category [Run-I,L0-TOS].

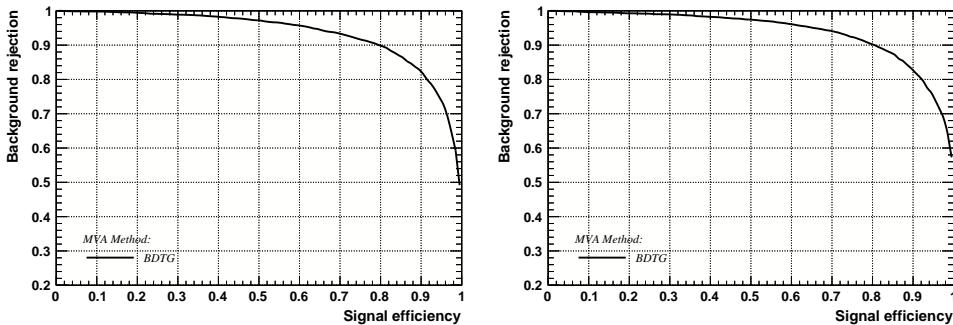


Figure A.10: Signal efficiency versus background rejection for the BDT trained on the even (left) and odd (right) sample for category [Run-I,L0-TIS].

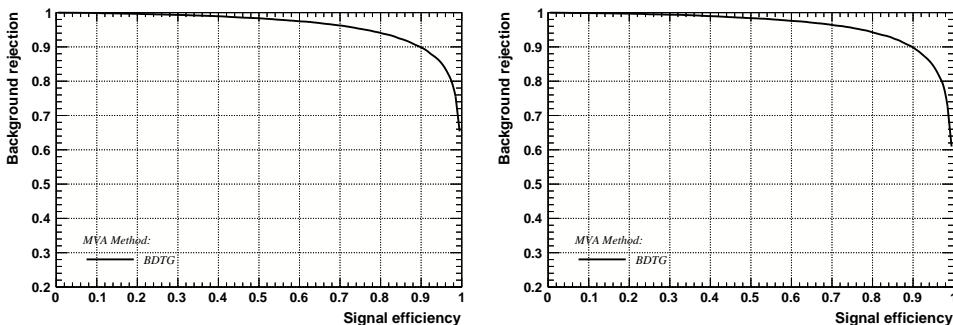


Figure A.11: Signal efficiency versus background rejection for the BDT trained on the even (left) and odd (right) sample for category [Run-II,L0-TOS].

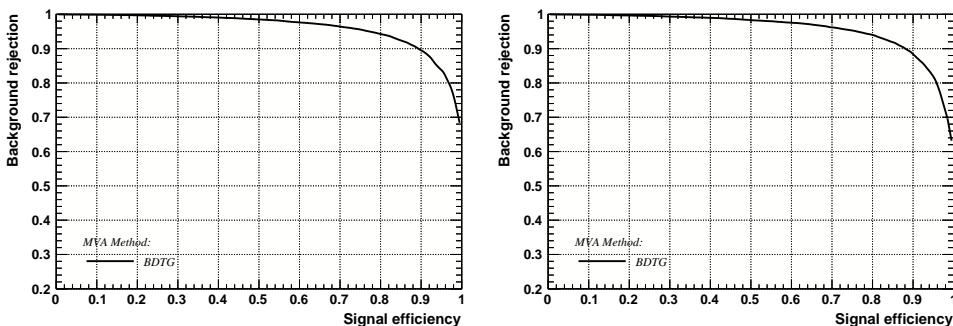


Figure A.12: Signal efficiency versus background rejection for the BDT trained on the even (left) and odd (right) sample for category [Run-II,L0-TIS].

827 C Detailed mass fits

828 In this section, all fits to the mass distribution of $B_s^0 \rightarrow D_s\pi\pi\pi$ and $B_s^0 \rightarrow D_sK\pi\pi$
 829 candidates are shown. The fits are performed simultaneously in run period (Run-I, Run-
 830 II), D_s final state ($D_s \rightarrow KK\pi$ non-resonant, $D_s \rightarrow \phi\pi$, $D_s \rightarrow K^*K$, or $D_s \rightarrow \pi\pi\pi$) and
 831 L0 trigger category.

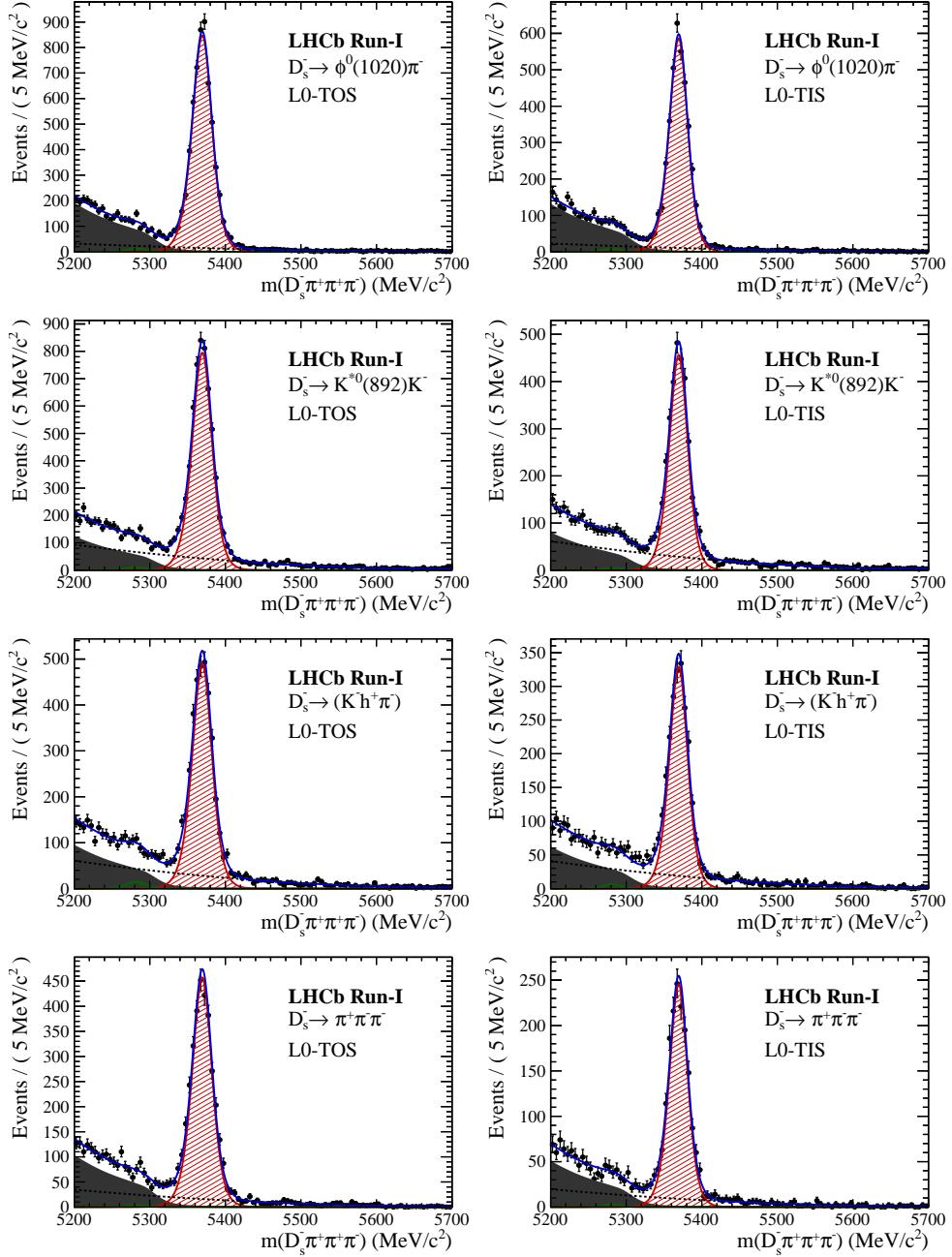


Figure B.1: Invariant mass distributions of $B_s^0 \rightarrow D_s\pi\pi\pi$ candidates for Run-I data.

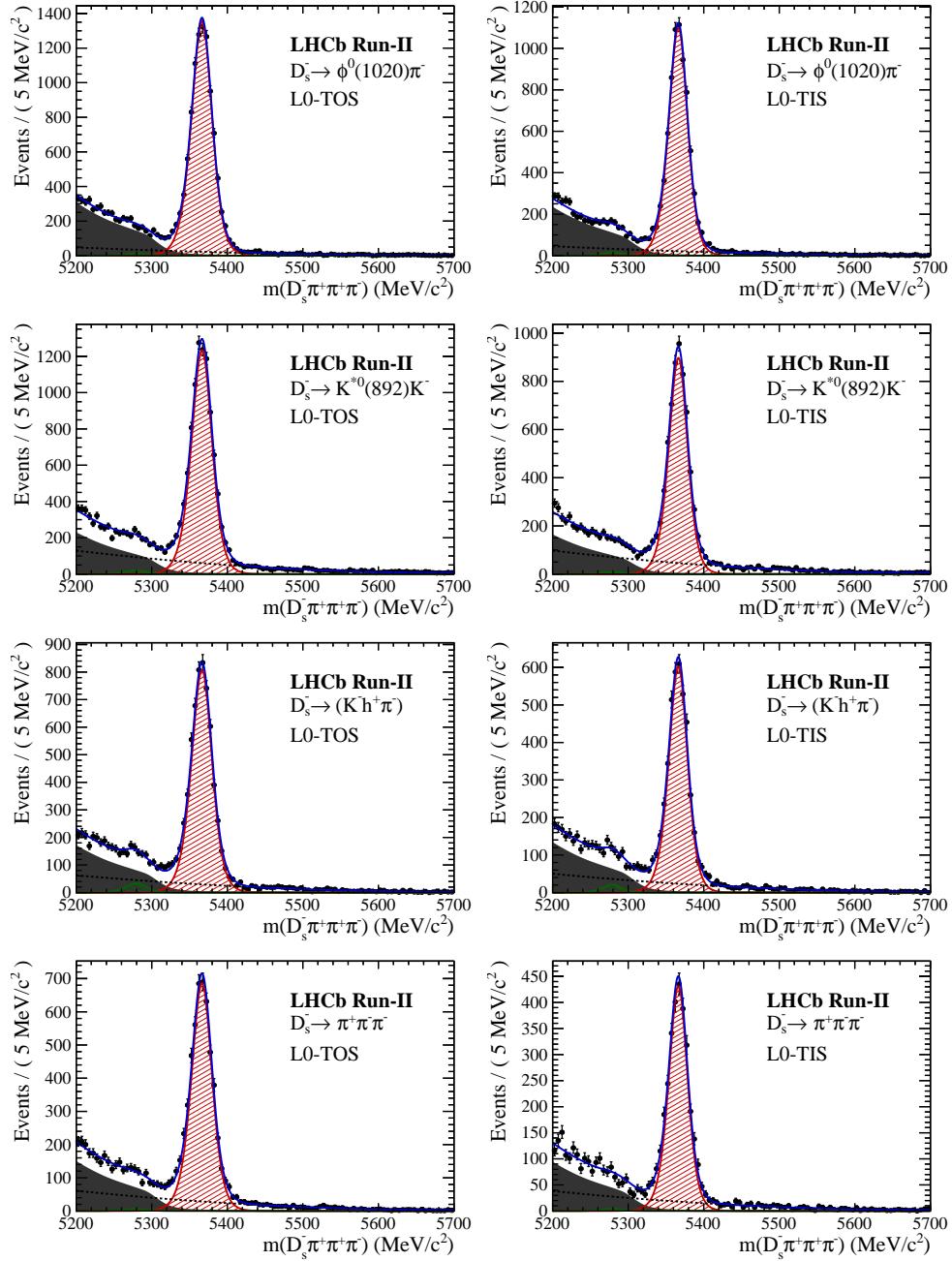


Figure B.2: Invariant mass distributions of $B_s^0 \rightarrow D_s\pi\pi\pi$ candidates for Run-II data.

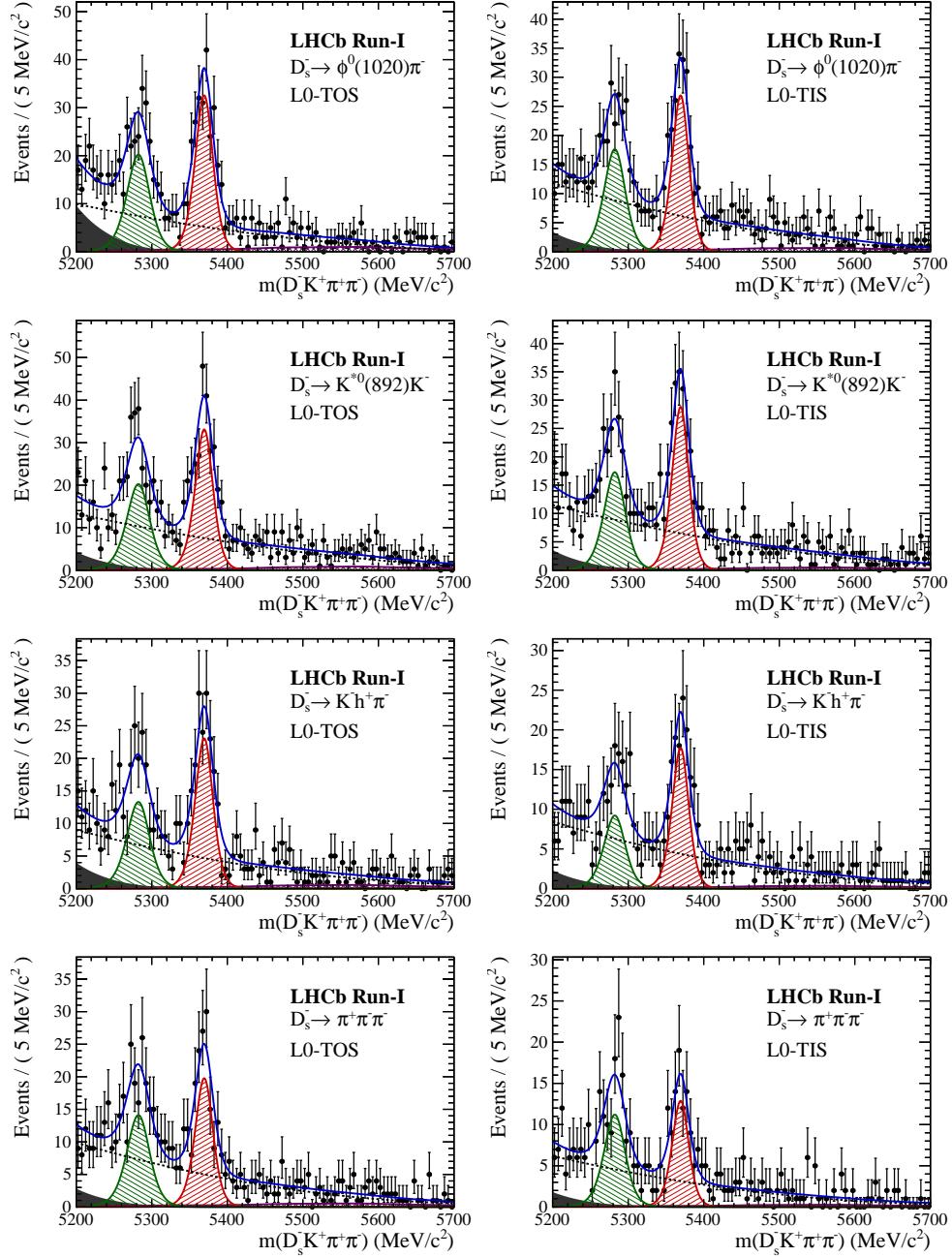


Figure B.3: Invariant mass distributions of $B_s^0 \rightarrow D_s K \pi\pi$ candidates for Run-I data.

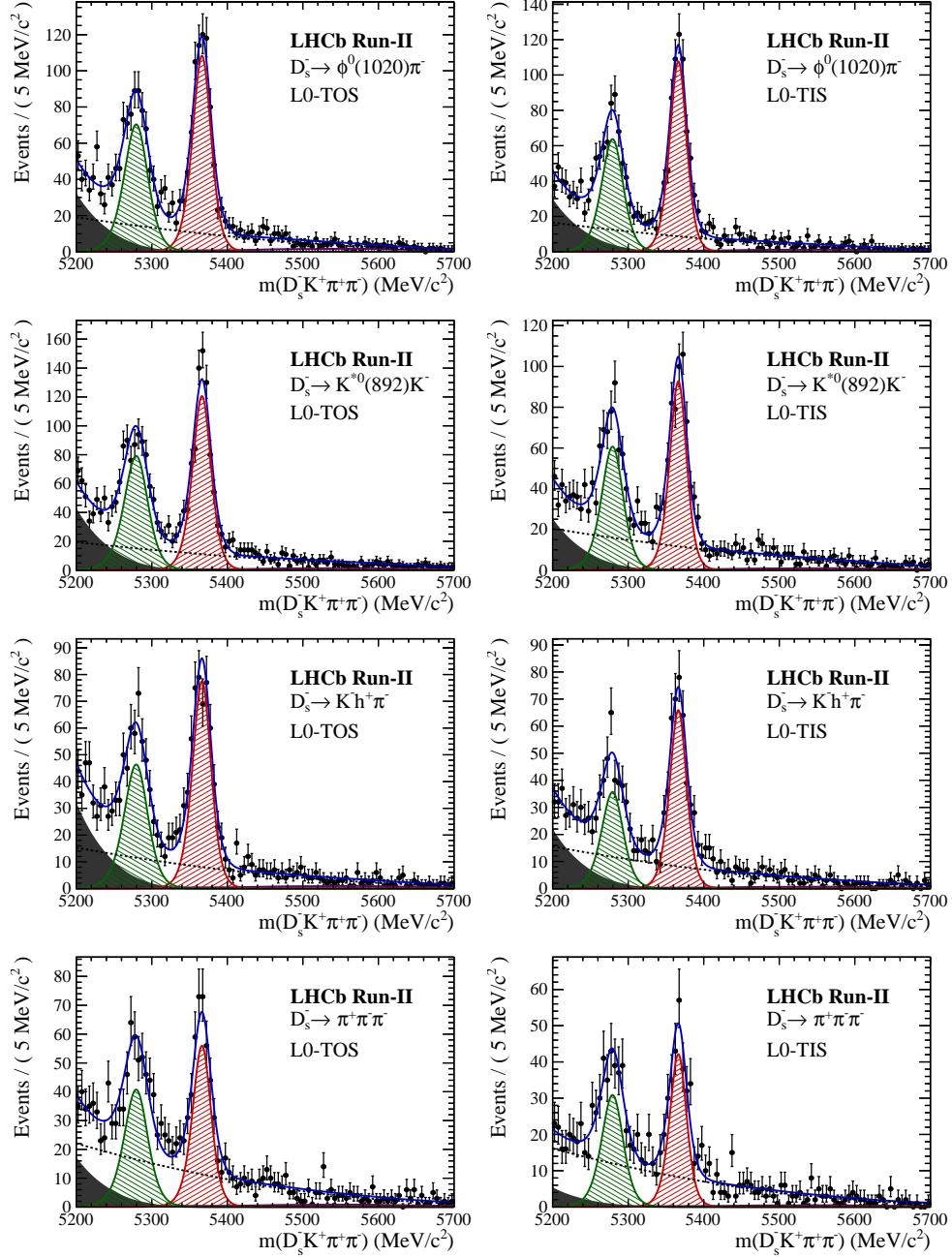


Figure B.4: Invariant mass distributions of $B_s^0 \rightarrow D_s K \pi \pi$ candidates for Run-II data.

832 D Decay-time Resolution fits

833 This section contains all fits to the distributions of the decay time difference Δt between
 834 the true and the reconstructed decay time of the truth-matched B_s^0 candidates on MC.
 835 The fits are performed in bins of the decay time error σ_t , where an adaptive binning
 836 scheme is used to ensure that approximately the same number of events are found in each
 837 bin.

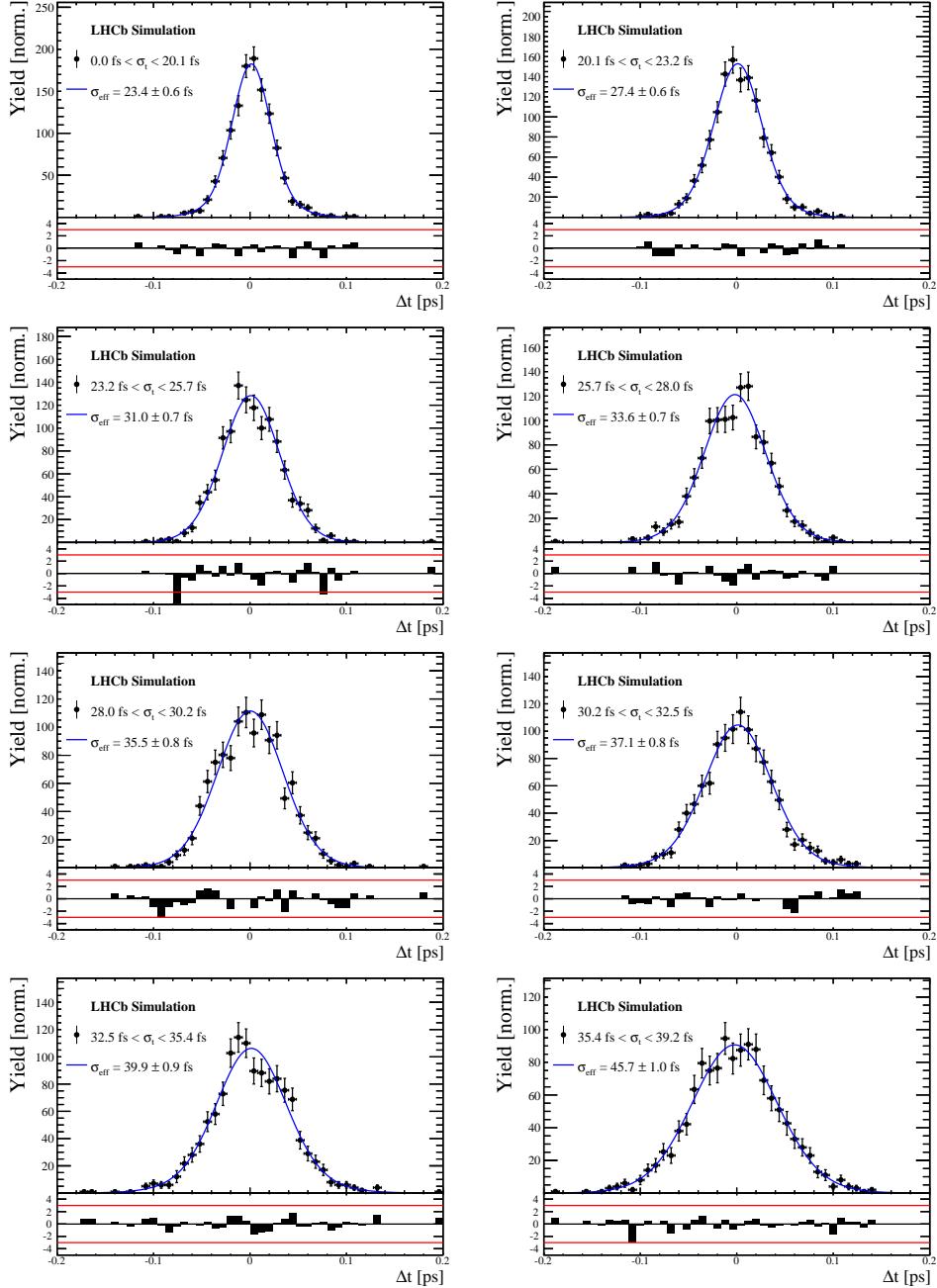


Figure C.1: Difference of the true and measured decay time of $B_s^0 \rightarrow D_s K \pi \pi$ MC candidates in bins of the per-event decay time error estimate..

| σ_t Bin [fs] | σ_1 [fs] | σ_2 [fs] | f_1 | D | σ_{eff} [fs] |
|---------------------|-----------------|-----------------|--------------|---------------------|---------------------|
| 0.0 - 20.1 | 19 ± 0.675 | 33.8 ± 1.77 | 0.75 ± 0 | 0.917 ± 0.00406 | 23.4 ± 0.599 |
| 20.1 - 23.2 | 23.4 ± 0.86 | 37.4 ± 1.95 | 0.75 ± 0 | 0.888 ± 0.00477 | 27.4 ± 0.621 |
| 23.2 - 25.7 | 28.1 ± 1.02 | 38.7 ± 2.32 | 0.75 ± 0 | 0.86 ± 0.00563 | 31 ± 0.671 |
| 25.7 - 28.0 | 30.1 ± 1.12 | 43.2 ± 2.56 | 0.75 ± 0 | 0.837 ± 0.00651 | 33.6 ± 0.734 |
| 28.0 - 30.2 | 32.4 ± 1.12 | 44.2 ± 2.59 | 0.75 ± 0 | 0.819 ± 0.00694 | 35.5 ± 0.756 |
| 30.2 - 32.5 | 32.6 ± 1.38 | 49.2 ± 3.04 | 0.75 ± 0 | 0.805 ± 0.00792 | 37.1 ± 0.841 |
| 32.5 - 35.4 | 34.4 ± 1.19 | 54.7 ± 2.85 | 0.75 ± 0 | 0.778 ± 0.0086 | 39.9 ± 0.879 |
| 35.4 - 39.2 | 41.9 ± 1.8 | 56.9 ± 4.18 | 0.75 ± 0 | 0.719 ± 0.00997 | 45.7 ± 0.962 |
| 39.2 - 44.7 | 42.2 ± 1.56 | 68.1 ± 4.01 | 0.75 ± 0 | 0.687 ± 0.0114 | 48.8 ± 1.08 |
| 44.7 - 120.0 | 55.5 ± 2.59 | 83 ± 14.7 | 0.75 ± 0 | 0.546 ± 0.0521 | 62 ± 4.89 |

Table 4.1: Measured time resolution for $B_s \rightarrow D_s K\pi\pi$ MC in bins of the per-event decay time error estimate.

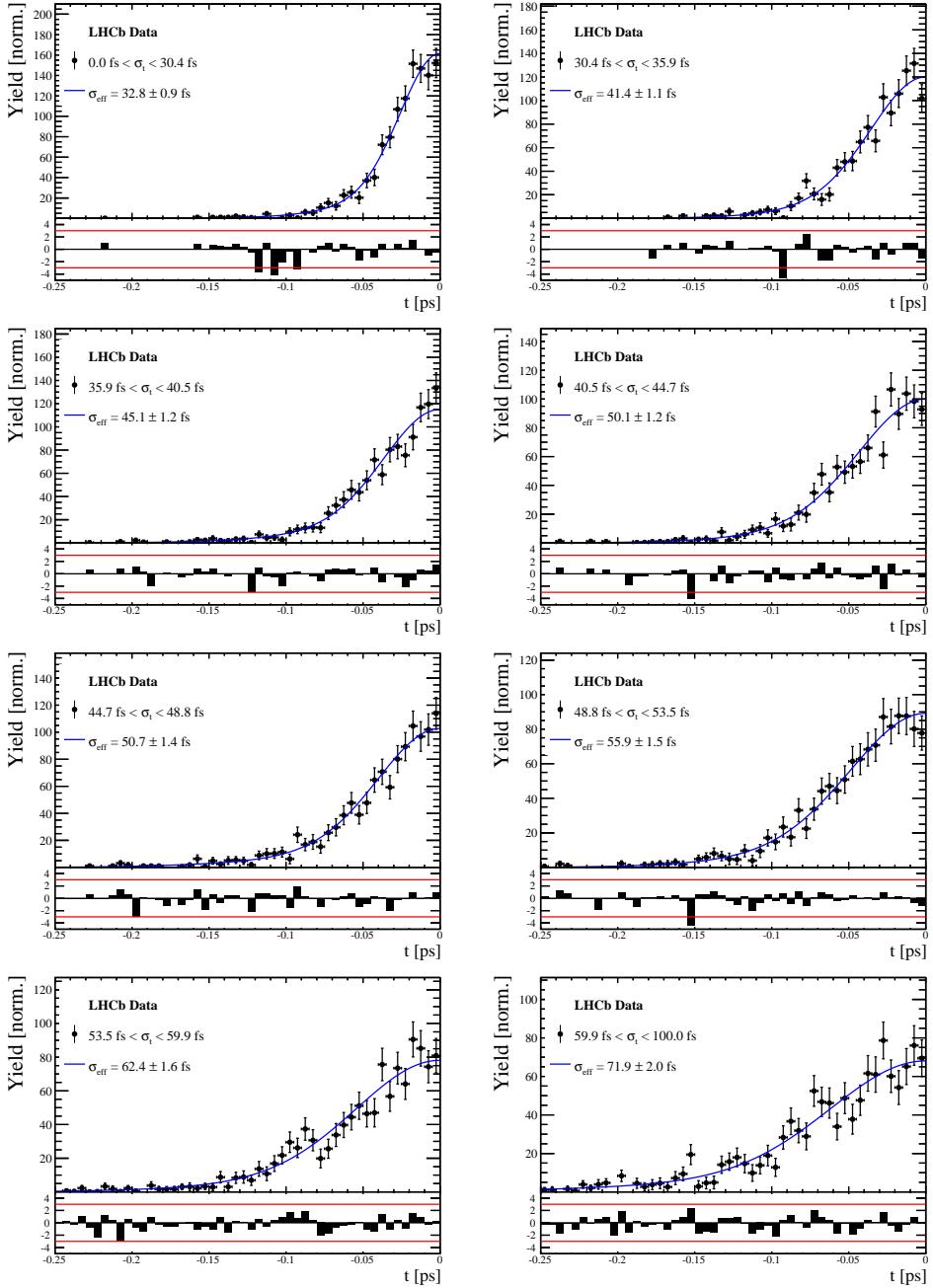


Figure C.2: Decay-time distribution for fake B_s candidates from promptly produced D_s candidates, combined with random prompt $K\pi\pi$ bachelor tracks, for bins in the per-event decay time error estimate.

| σ_t Bin [fs] | σ_1 [fs] | σ_2 [fs] | f_1 | D | σ_{eff} [fs] |
|---------------------|-----------------|-----------------|--------------|---------------------|---------------------|
| 0.0 - 30.4 | 25.4 ± 1.03 | 50.7 ± 2.77 | 0.75 ± 0 | 0.844 ± 0.00822 | 32.8 ± 0.942 |
| 30.4 - 35.9 | 34.5 ± 1.46 | 60.2 ± 3.48 | 0.75 ± 0 | 0.763 ± 0.0108 | 41.4 ± 1.08 |
| 35.9 - 40.5 | 35.6 ± 1.35 | 71.3 ± 3.84 | 0.75 ± 0 | 0.726 ± 0.0121 | 45.1 ± 1.18 |
| 40.5 - 44.7 | 42.3 ± 1.65 | 73.3 ± 4.21 | 0.75 ± 0 | 0.673 ± 0.0132 | 50.1 ± 1.24 |
| 44.7 - 48.8 | 39.6 ± 1.64 | 84.8 ± 5.07 | 0.75 ± 0 | 0.666 ± 0.0145 | 50.7 ± 1.36 |
| 48.8 - 53.5 | 47.6 ± 1.94 | 82.4 ± 5.48 | 0.75 ± 0 | 0.611 ± 0.0157 | 55.9 ± 1.46 |
| 53.5 - 59.9 | 53 ± 2.15 | 95.3 ± 6.84 | 0.75 ± 0 | 0.541 ± 0.0174 | 62.4 ± 1.63 |
| 59.9 - 100.0 | 60.5 ± 2.8 | 125 ± 14 | 0.75 ± 0 | 0.443 ± 0.0204 | 71.9 ± 2.03 |

Table 4.2: Measured time resolution for prompt- D_s data in bins of the per-event decay time error estimate.

838 E Spin Amplitudes

839 The spin factors used for $B \rightarrow P_1 P_2 P_3 P_4$ decays are given in Table 5.1.

Table 5.1: Spin factors for all topologies considered in this analysis. In the decay chains, S , P , V , A , T and PT stand for scalar, pseudoscalar, vector, axial vector, tensor and pseudotensor, respectively. If no angular momentum is specified, the lowest angular momentum state compatible with angular momentum conservation and, where appropriate, parity conservation, is used.

| Number | Decay chain | Spin amplitude |
|--------|--|--|
| 1 | $B \rightarrow (P P_1)$, $P \rightarrow (S P_2)$, $S \rightarrow (P_3 P_4)$ | 1 |
| 2 | $B \rightarrow (P P_1)$, $P \rightarrow (V P_2)$, $V \rightarrow (P_3 P_4)$ | $L_{(1)\alpha}(P) L_{(1)}^\alpha(V)$ |
| 3 | $B \rightarrow (A P_1)$, $A \rightarrow (V P_2)$, $V \rightarrow (P_3 P_4)$ | $L_{(1)\alpha}(B) P_{(1)}^{\alpha\beta}(A) L_{(1)\beta}(V)$ |
| 4 | $B \rightarrow (A P_1)$, $A[D] \rightarrow (P_2 V)$, $V \rightarrow (P_3 P_4)$ | $L_{(1)\alpha}(B) L_{(2)}^{\alpha\beta}(A) L_{(1)\beta}(V)$ |
| 5 | $B \rightarrow (A P_1)$, $A \rightarrow (S P_2)$, $S \rightarrow (P_3 P_4)$ | $L_{(1)\alpha}(B) L_{(1)}^\alpha(A)$ |
| 6 | $B \rightarrow (A P_1)$, $A \rightarrow (T P_2)$, $T \rightarrow (P_3 P_4)$ | $L_{(1)\alpha}(B) L_{(1)\beta}(A) L_{(2)}^{\alpha\beta}(T)$ |
| 7 | $B \rightarrow (V_1 P_1)$, $V_1 \rightarrow (V_2 P_2)$, $V_2 \rightarrow (P_3 P_4)$ | $L_{(1)\mu}(B) P_{(1)}^{\mu\alpha}(V_1) \epsilon_{\alpha\beta\gamma\delta} L_{(1)}^\beta(V_1) p_{V_1}^\gamma L_{(1)}^\delta(V_2)$ |
| 8 | $B \rightarrow (PT P_1)$, $PT \rightarrow (V P_2)$, $V \rightarrow (P_3 P_4)$ | $L_{(2)\alpha\beta}(B) P_{(2)}^{\alpha\beta\gamma\delta}(PT) L_{(1)\gamma}(PT) L_{(1)\delta}(V)$ |
| 9 | $B \rightarrow (PT P_1)$, $PT \rightarrow (S P_2)$, $S \rightarrow (P_3 P_4)$ | $L_{(2)\alpha\beta}(B) L_{(2)}(PT)^{\alpha\beta}$ |
| 10 | $B \rightarrow (PT P_1)$, $PT \rightarrow (T P_2)$, $T \rightarrow (P_3 P_4)$ | $L_{(2)\alpha\beta}(B) P_{(2)}^{\alpha\beta\gamma\delta}(PT) L_{(2)\gamma\delta}(T)$ |
| 11 | $B \rightarrow (T P_1)$, $T \rightarrow (V P_2)$, $V \rightarrow (P_3 P_4)$ | $L_{(2)\mu\nu}(B) P_{(2)}^{\mu\nu\rho\alpha}(T) \epsilon_{\alpha\beta\gamma\delta} L_{(2)\rho}^\beta(T) p_T^\gamma P_{(1)}^{\delta\sigma}(T) L_{(1)\sigma}(V)$ |
| 12 | $B \rightarrow (T_1 P_1)$, $T_1 \rightarrow (T_2 P_2)$, $T_2 \rightarrow (P_3 P_4)$ | $L_{(2)\mu\nu}(B) P_{(2)}^{\mu\nu\rho\alpha}(T_1) \epsilon_{\alpha\beta\gamma\delta} L_{(1)}^\beta(T_1) p_{T_1}^\gamma L_{(2)\rho}^\delta(T_2)$ |
| 13 | $B \rightarrow (S_1 S_2)$, $S_1 \rightarrow (P_1 P_2)$, $S_2 \rightarrow (P_3 P_4)$ | 1 |
| 14 | $B \rightarrow (V S)$, $V \rightarrow (P_1 P_2)$, $S \rightarrow (P_3 P_4)$ | $L_{(1)\alpha}(B) L_{(1)}^\alpha(V)$ |
| 15 | $B \rightarrow (V_1 V_2)$, $V_1 \rightarrow (P_1 P_2)$, $V_2 \rightarrow (P_3 P_4)$ | $L_{(1)\alpha}(V_1) L_{(1)}^\alpha(V_2)$ |
| 16 | $B[P] \rightarrow (V_1 V_2)$, $V_1 \rightarrow (P_1 P_2)$, $V_2 \rightarrow (P_3 P_4)$ | $\epsilon_{\alpha\beta\gamma\delta} L_{(1)}^\alpha(B) L_{(1)}^\beta(V_1) L_{(1)}^\gamma(V_2) p_B^\delta$ |
| 17 | $B[D] \rightarrow (V_1 V_2)$, $V_1 \rightarrow (P_1 P_2)$, $V_2 \rightarrow (P_3 P_4)$ | $L_{(2)\alpha\beta}(B) L_{(1)}^\alpha(V_1) L_{(1)}^\beta(V_2)$ |
| 18 | $B \rightarrow (T S)$, $T \rightarrow (P_1 P_2)$, $S \rightarrow (P_3 P_4)$ | $L_{(2)\alpha\beta}(B) L_{(2)}^{\alpha\beta}(T)$ |
| 19 | $B \rightarrow (V T)$, $T \rightarrow (P_1 P_2)$, $V \rightarrow (P_3 P_4)$ | $L_{(1)\alpha}(B) L_{(2)}^{\alpha\beta}(T) L_{(1)\beta}(V)$ |
| 20 | $B[D] \rightarrow (TV)$, $T \rightarrow (P_1 P_2)$, $V \rightarrow (P_3 P_4)$ | $\epsilon_{\alpha\beta\delta\gamma} L_2^{\alpha\mu}(B) L_{2\mu}^\beta L_{(1)}^\gamma(V) p_B^\delta$ |
| 21 | $B \rightarrow (T_1 T_2)$, $T_1 \rightarrow (P_1 P_2)$, $T_2 \rightarrow (P_3 P_4)$ | $L_{(2)\alpha\beta}(T_1) L_{(2)}^{\alpha\beta}(T_2)$ |
| 22 | $B[P] \rightarrow (T_1 T_2)$, $T_1 \rightarrow (P_1 P_2)$, $T_2 \rightarrow (P_3 P_4)$ | $\epsilon_{\alpha\beta\gamma\delta} L_{(1)}^\alpha(B) L_{(2)}^{\beta\mu}(T_1) L_{(2)\mu}^\gamma(T_2) p_B^\delta$ |
| 23 | $B[D] \rightarrow (T_1 T_2)$, $T_1 \rightarrow (P_1 P_2)$, $T_2 \rightarrow (P_3 P_4)$ | $L_{(2)\alpha\beta}(B) L_{(2)}^{\alpha\gamma}(T_1) L_{(2)\gamma}^\beta(T_2)$ |

F Considered Decay Chains

840 The various decay channels considered in the model building are listed in Table 6.1.

Table 6.1: Decays considered in the LASSO model building.

| Decay channel |
|---|
| $B_s \rightarrow D_s^- [K_1(1270)^+ [S, D] \rightarrow \pi^+ K^*(892)^0]$ |
| $B_s \rightarrow D_s^- [K_1(1270)^+ \rightarrow \pi^+ K^*(1430)^0]$ |
| $B_s \rightarrow D_s^- [K_1(1270)^+ [S, D] \rightarrow K^+ \rho(770)^0]$ |
| $B_s \rightarrow D_s^- [K_1(1270)^+ [S, D] \rightarrow K^+ \omega(782)]$ |
| $B_s \rightarrow D_s^- [K_1(1400)^+ [S, D] \rightarrow \pi^+ K^*(892)^0]$ |
| $B_s \rightarrow D_s^- [K_1(1400)^+ [S, D] \rightarrow K^+ \rho(770)^0]$ |
| $B_s \rightarrow D_s^- [K(1460)^+ \rightarrow \pi^+ \kappa]$ |
| $B_s \rightarrow D_s^- [K(1460)^+ \rightarrow K^+ \sigma]$ |
| $B_s \rightarrow D_s^- [K(1460)^+ \rightarrow \pi^+ K^*(892)^0]$ |
| $B_s \rightarrow D_s^- [K(1460)^+ \rightarrow K^+ \rho(770)^0]$ |
| $B_s \rightarrow D_s^- [K^*(1410)^+ \rightarrow \pi^+ K^*(892)^0]$ |
| $B_s \rightarrow D_s^- [K^*(1410)^+ \rightarrow K^+ \rho(770)^0]$ |
| $B_s \rightarrow D_s^- [K_2^*(1430)^+ \rightarrow \pi^+ K^*(892)^0]$ |
| $B_s \rightarrow D_s^- [K_2^*(1430)^+ \rightarrow K^+ \rho(770)^0]$ |
| $B_s \rightarrow D_s^- [K^*(1680)^+ \rightarrow \pi^+ K^*(892)^0]$ |
| $B_s \rightarrow D_s^- [K^*(1680)^+ \rightarrow K^+ \rho(770)^0]$ |
| $B_s \rightarrow D_s^- [K_2(1770)^+ \rightarrow \pi^+ K^*(892)^0]$ |
| $B_s \rightarrow D_s^- [K_2(1770)^+ \rightarrow K^+ \rho(770)^0]$ |
| $B_s \rightarrow \sigma^0(D_s^- K^+)_S$ |
| $B_s [S, P, D] \rightarrow \sigma^0(D_s^- K^+)_V$ |
| $B_s \rightarrow \rho(770)^0 (D_s^- K^+)_S$ |
| $B_s [S, P, D] \rightarrow \rho(770)^0 (D_s^- K^+)_V$ |
| $B_s \rightarrow K^*(892)^0 (D_s^- \pi^+)_S$ |
| $B_s [S, P, D] \rightarrow K^*(892)^0 (D_s^- \pi^+)_V$ |
| $B_s \rightarrow (D_s^- K^+)_S (\pi^+ \pi^-)_S$ |

842 G MC corrections

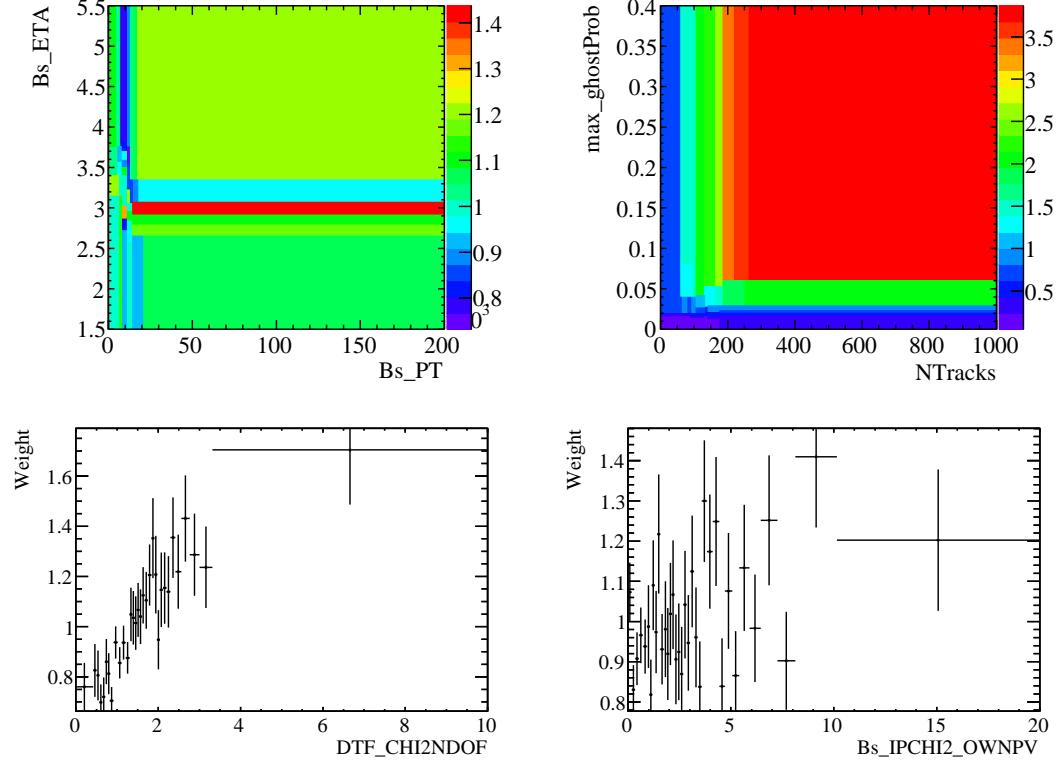


Figure C.1: Weights applied to correct for Data/MC differences.

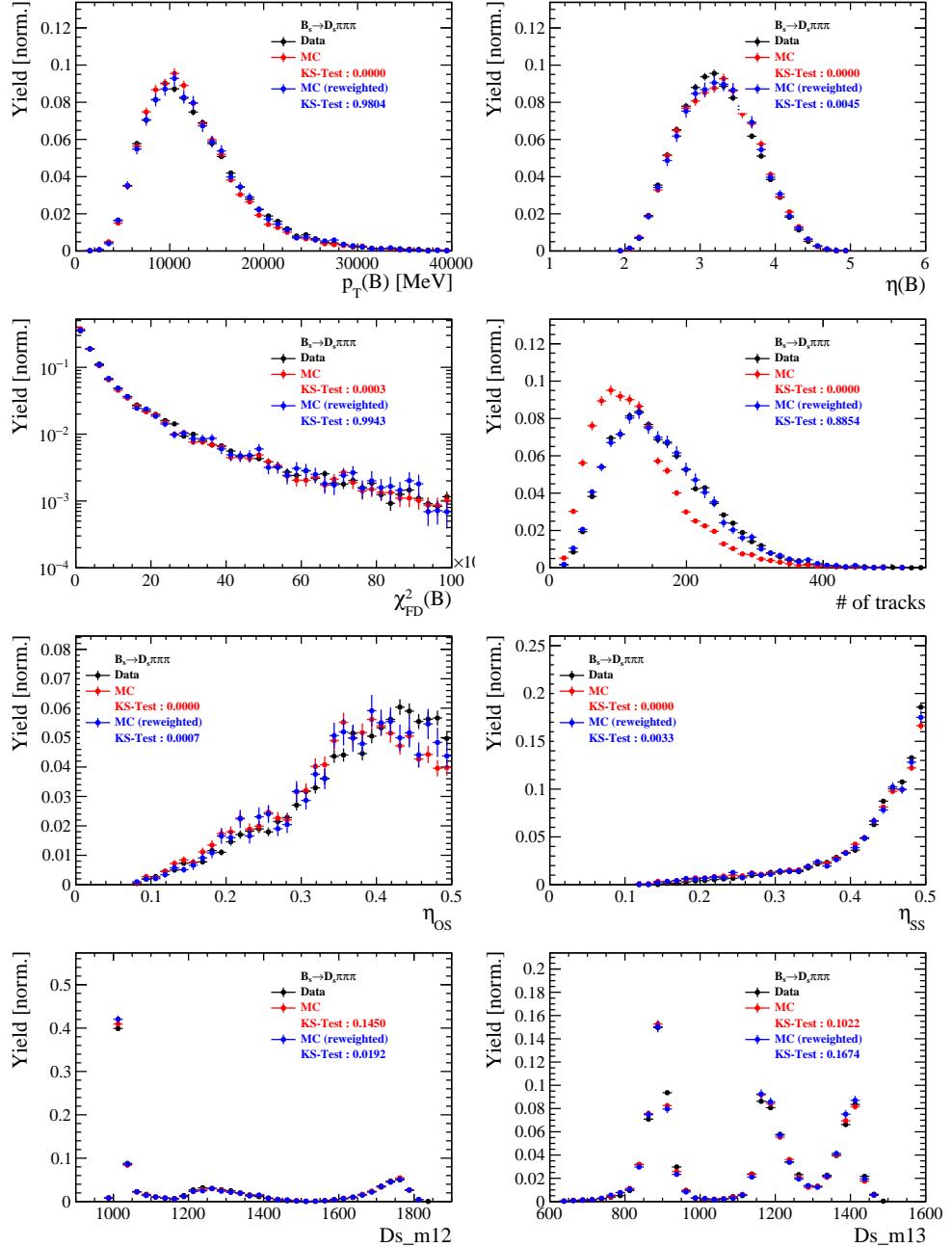


Figure C.2: Comparison of selected variables for $B_s \rightarrow D_s \pi\pi\pi$ decays.

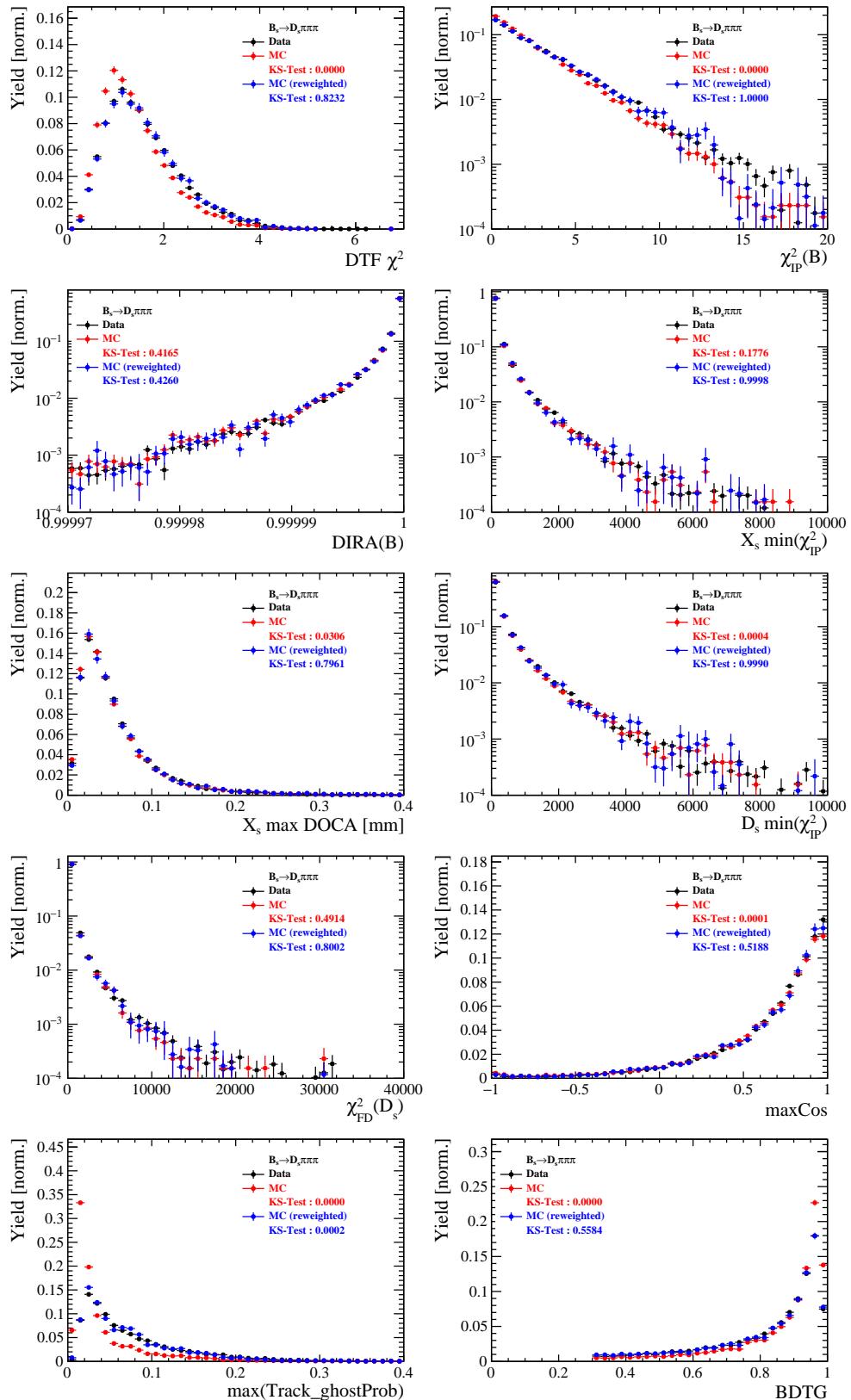


Figure C.3: Comparison of BDTG input variables and classifier response for $B_s \rightarrow D_s \pi\pi\pi$ decays.

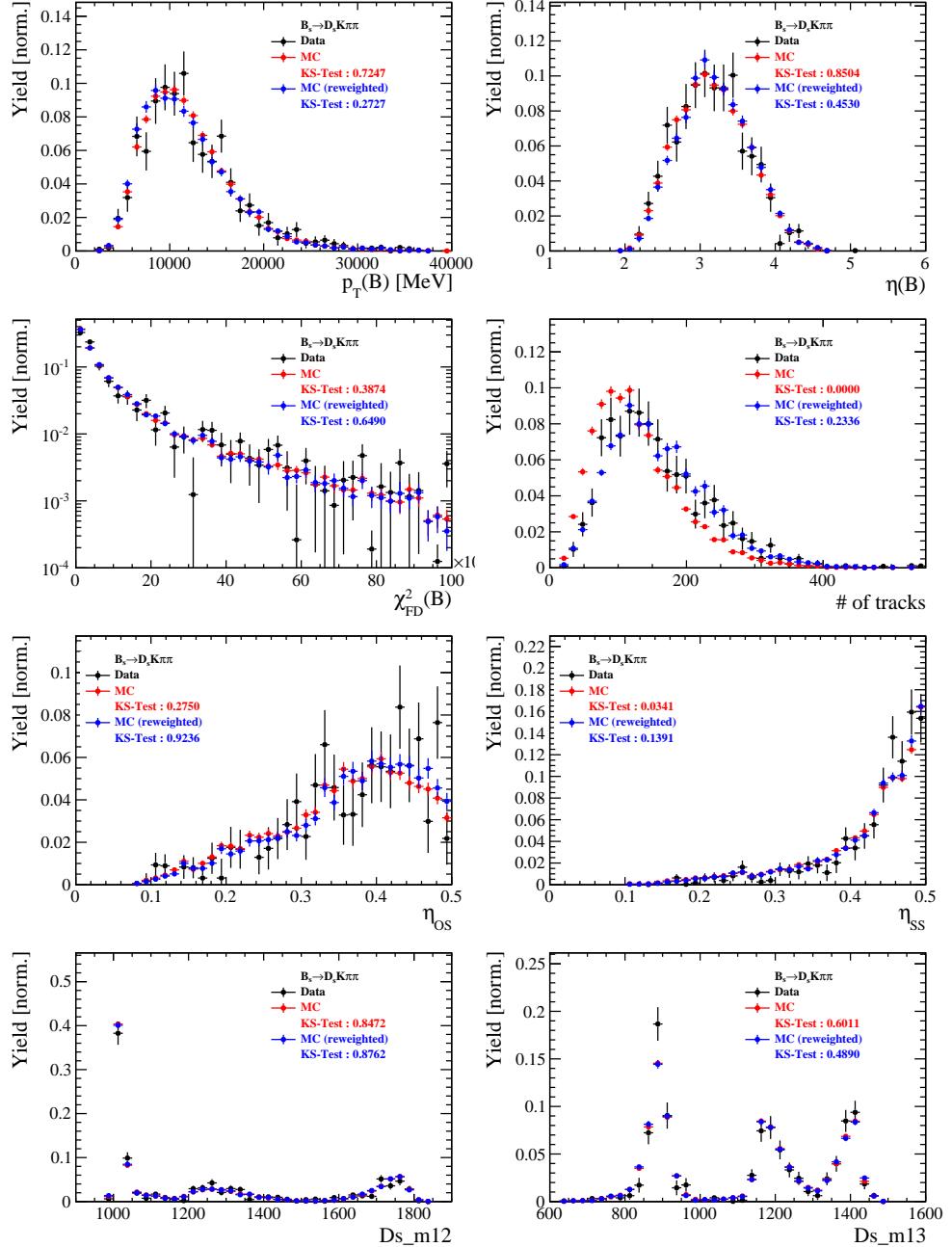


Figure C.4: Comparison of selected variables for $B_s \rightarrow D_s K\pi\pi$ decays.

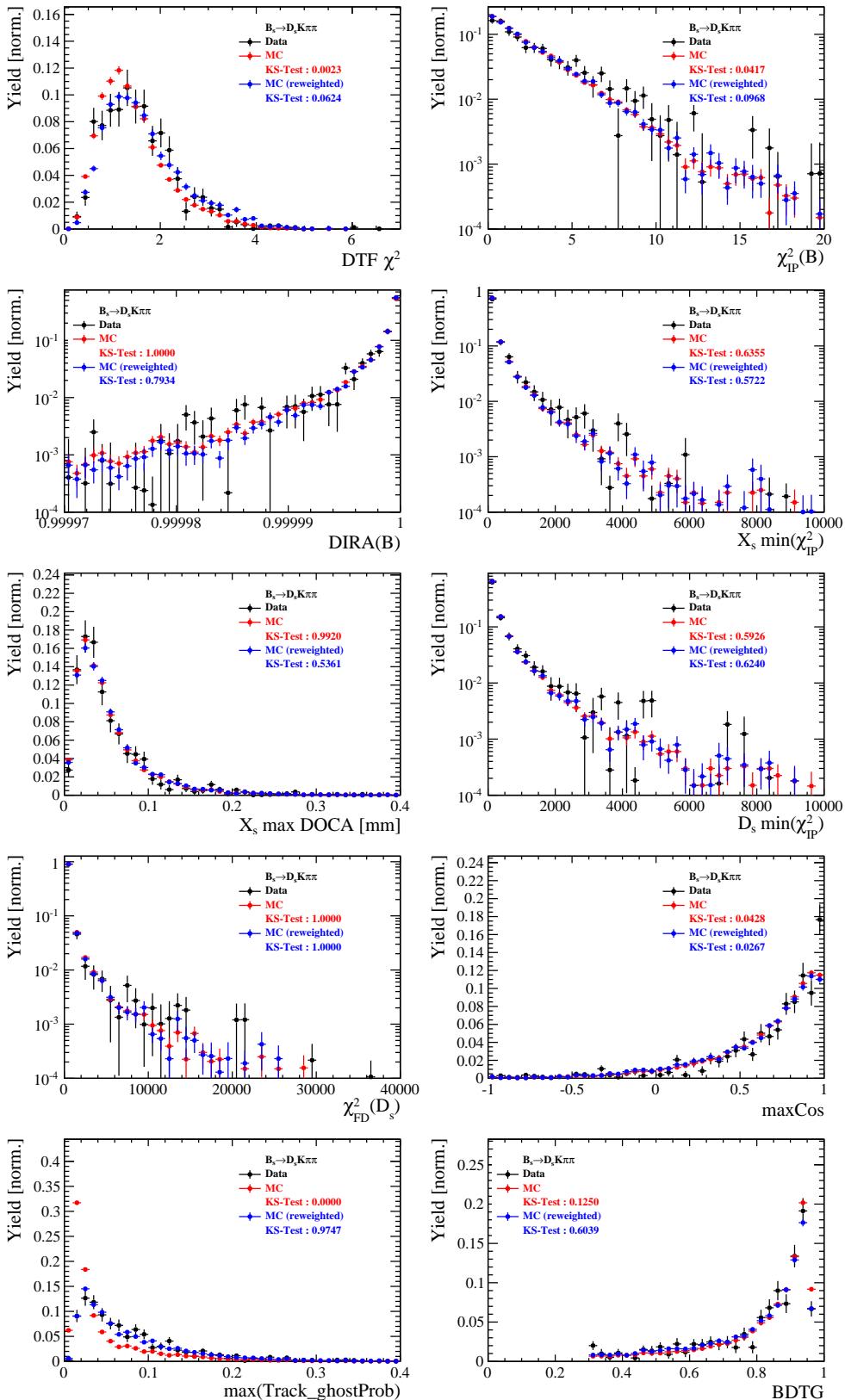


Figure C.5: Comparison of BDTG input variables and classifier response for $B_s \rightarrow D_s K\pi\pi$ decays.

843 H Data distributions

844 H.1 Comparison of signal and calibration channel

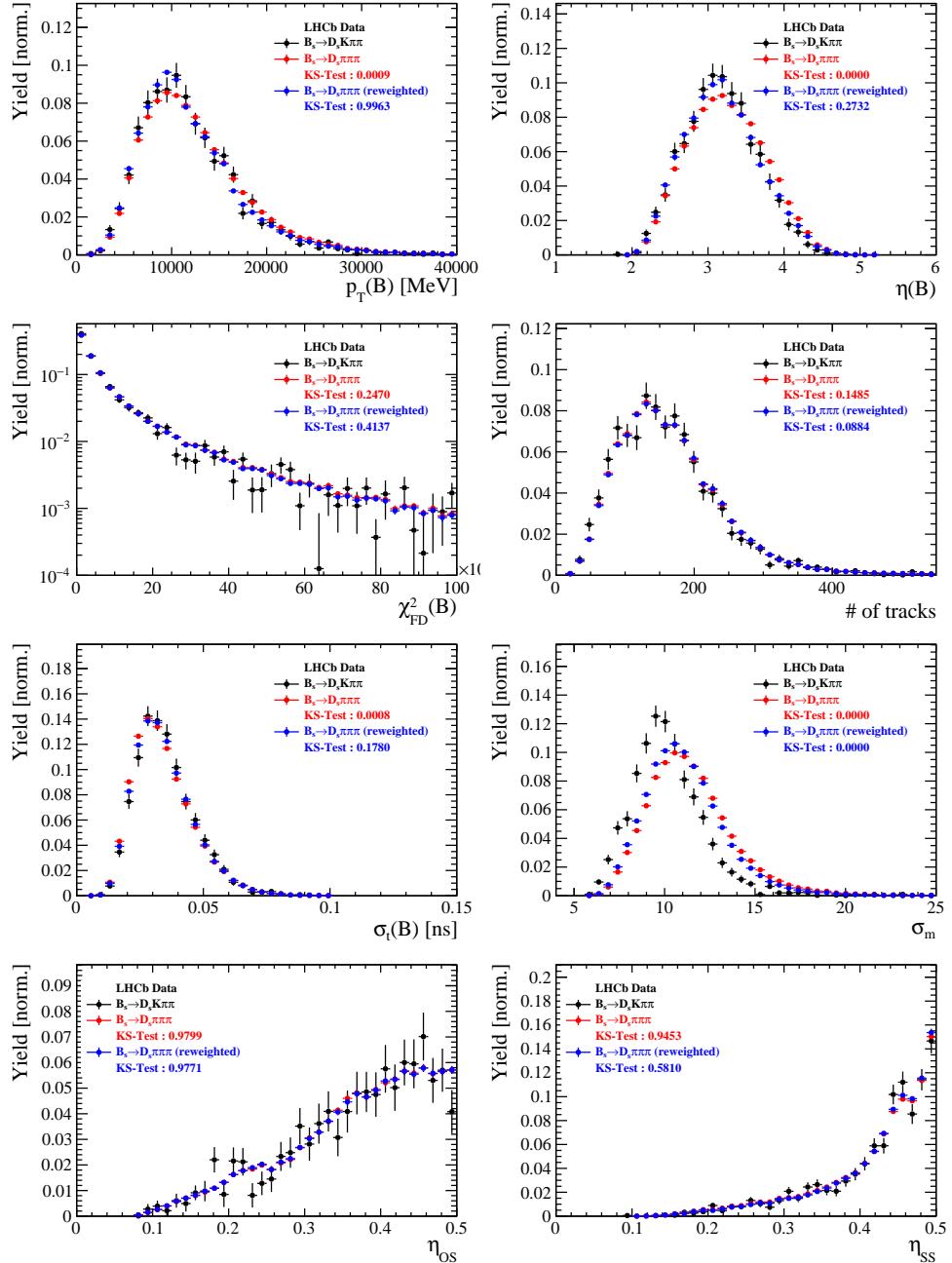


Figure C.1: Comparison of selected variables.

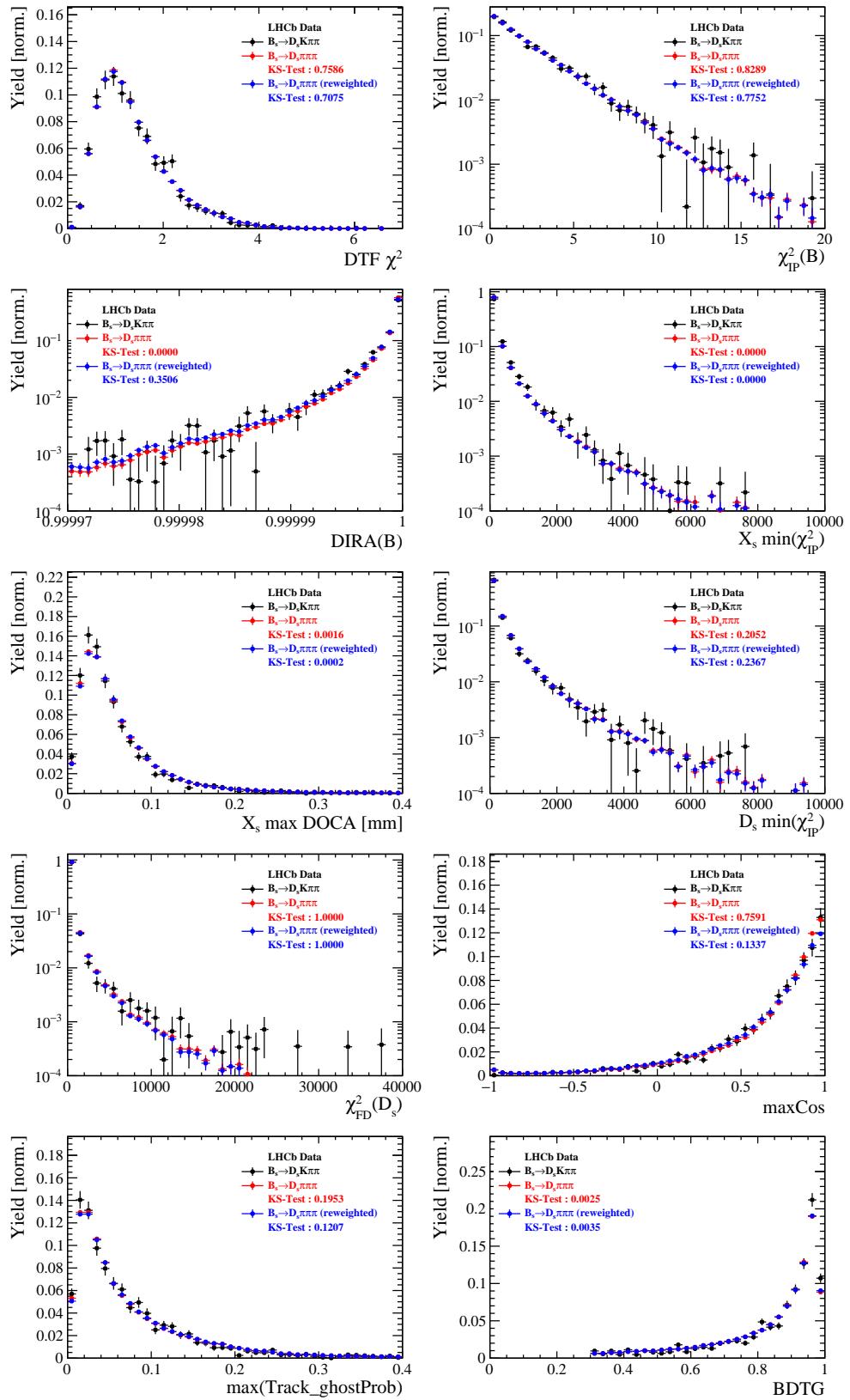


Figure C.2: Comparison of BDTG input variables and classifier response.

845 H.2 Comparison of Run-I and Run-II data

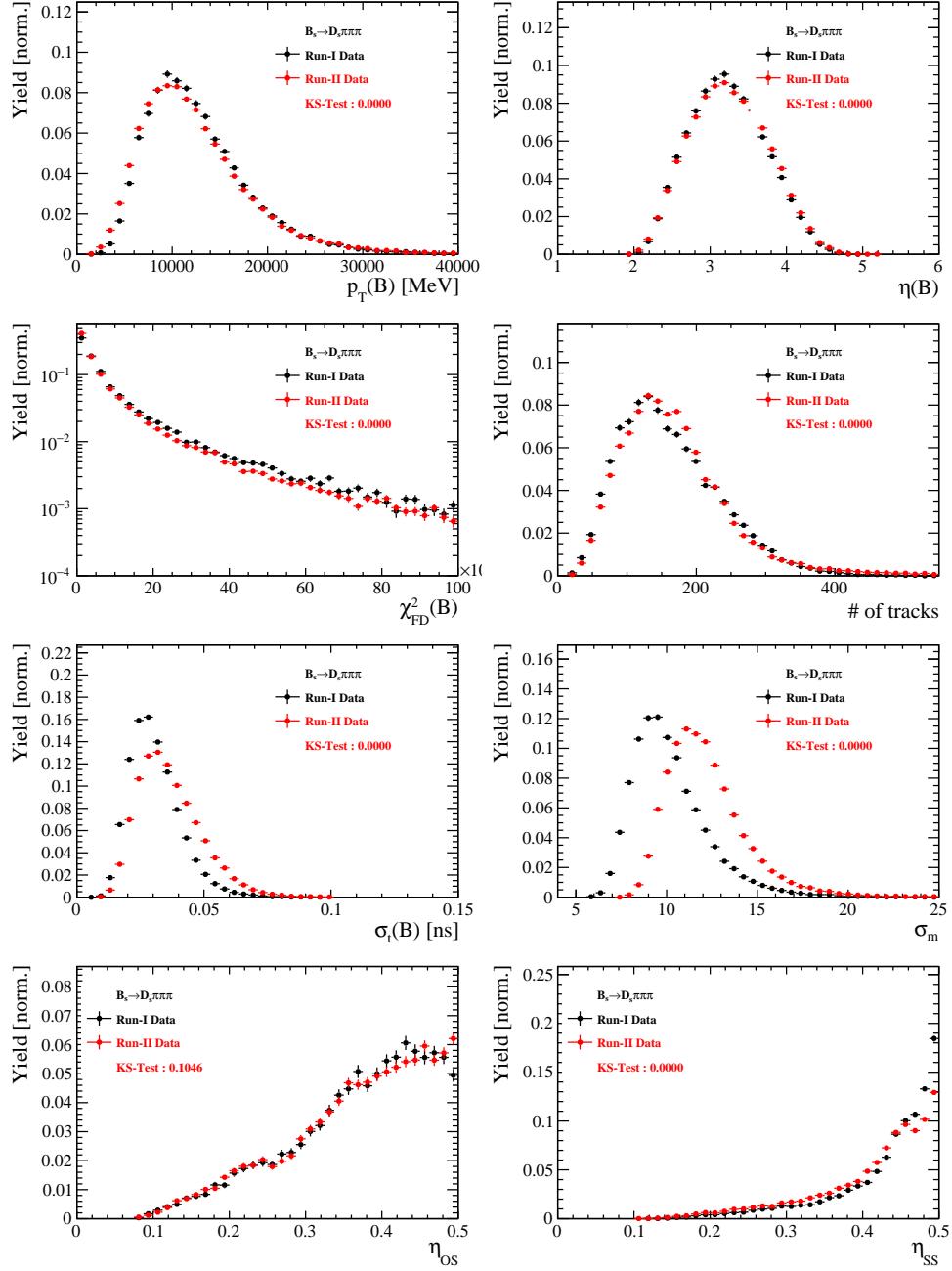


Figure C.3: Comparison of selected variables.

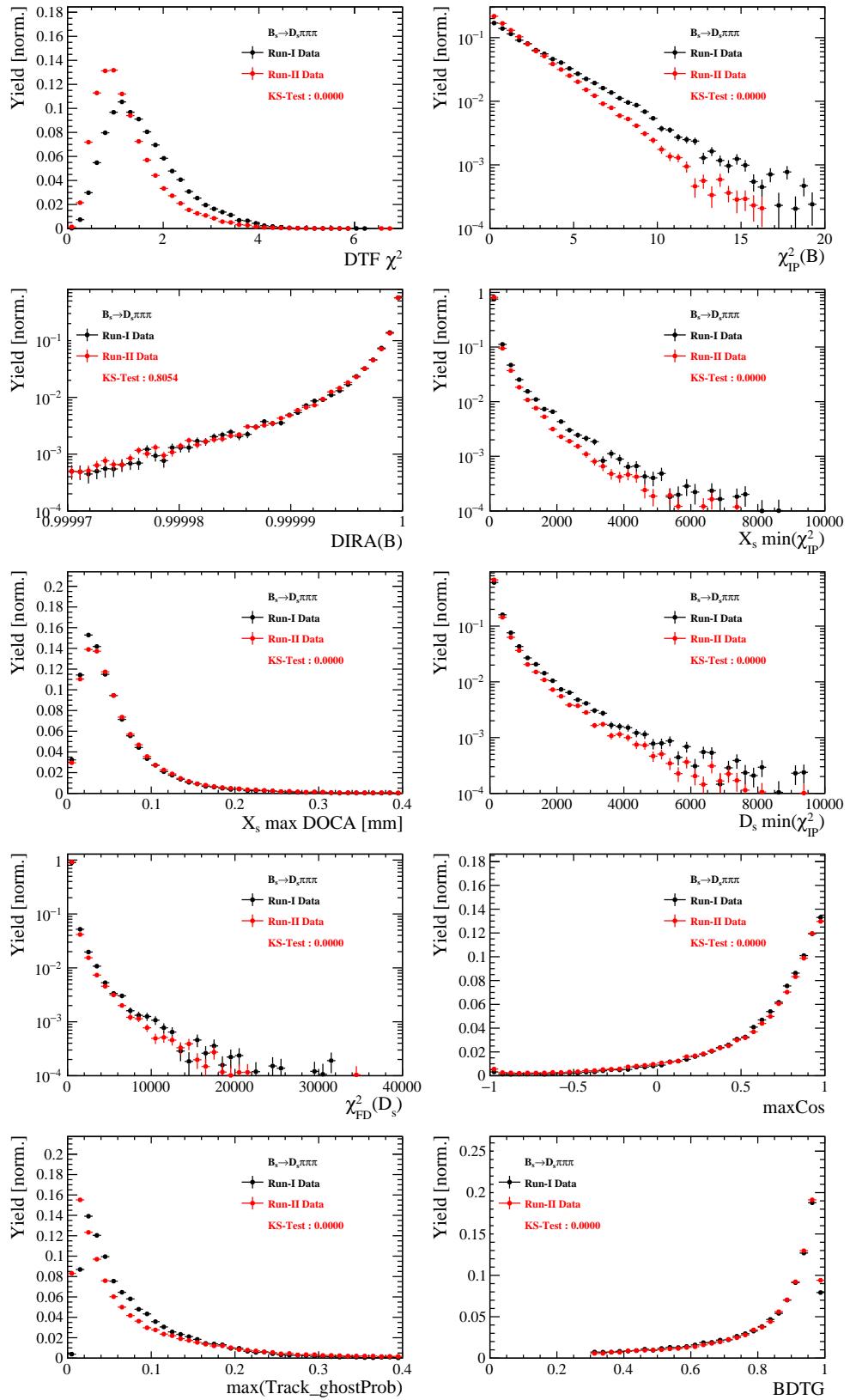


Figure C.4: Comparison of BDTG input variables and classifier response.

846 H.3 Comparison of D_s final states

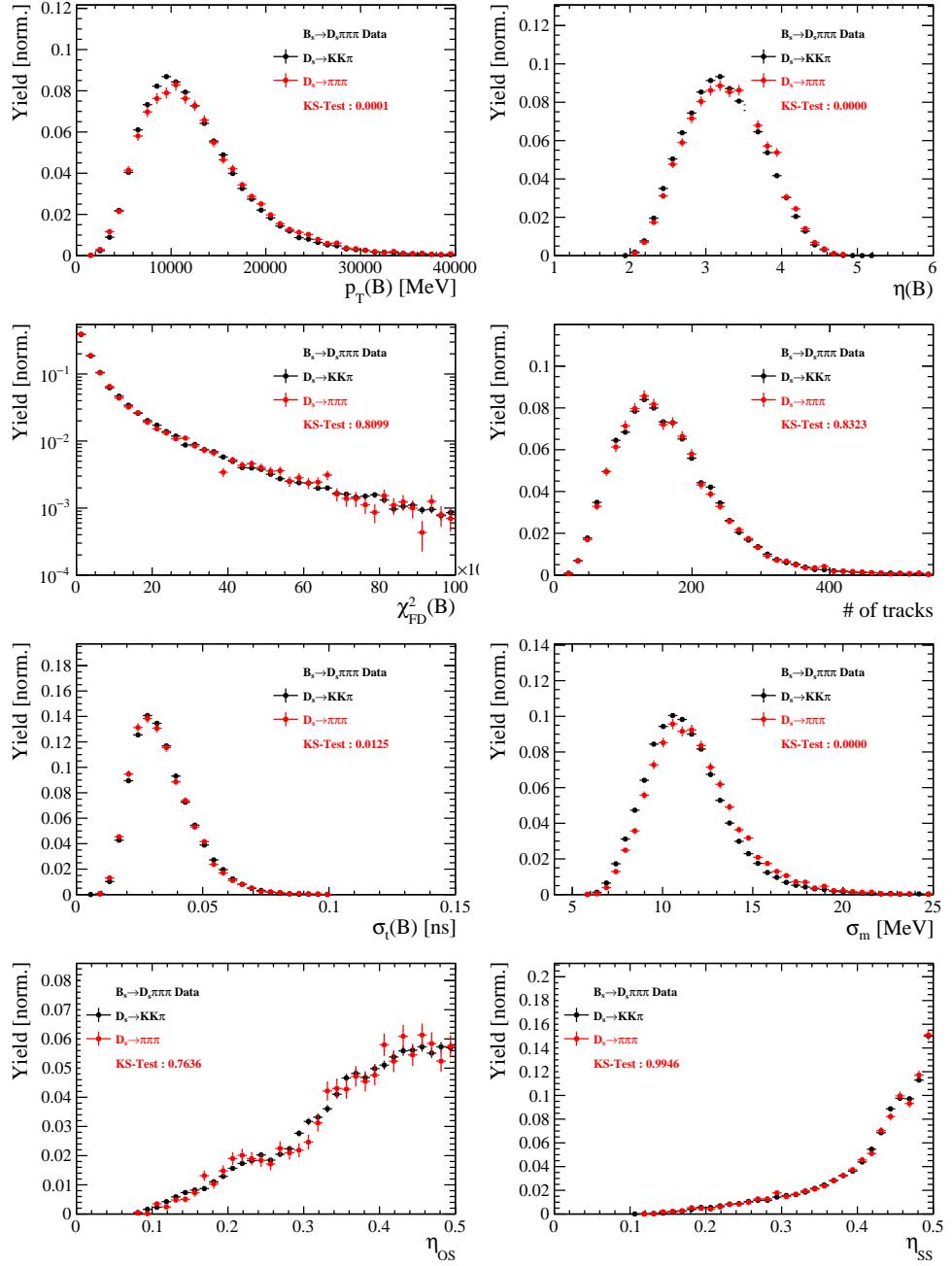


Figure C.5: Comparison of selected variables.

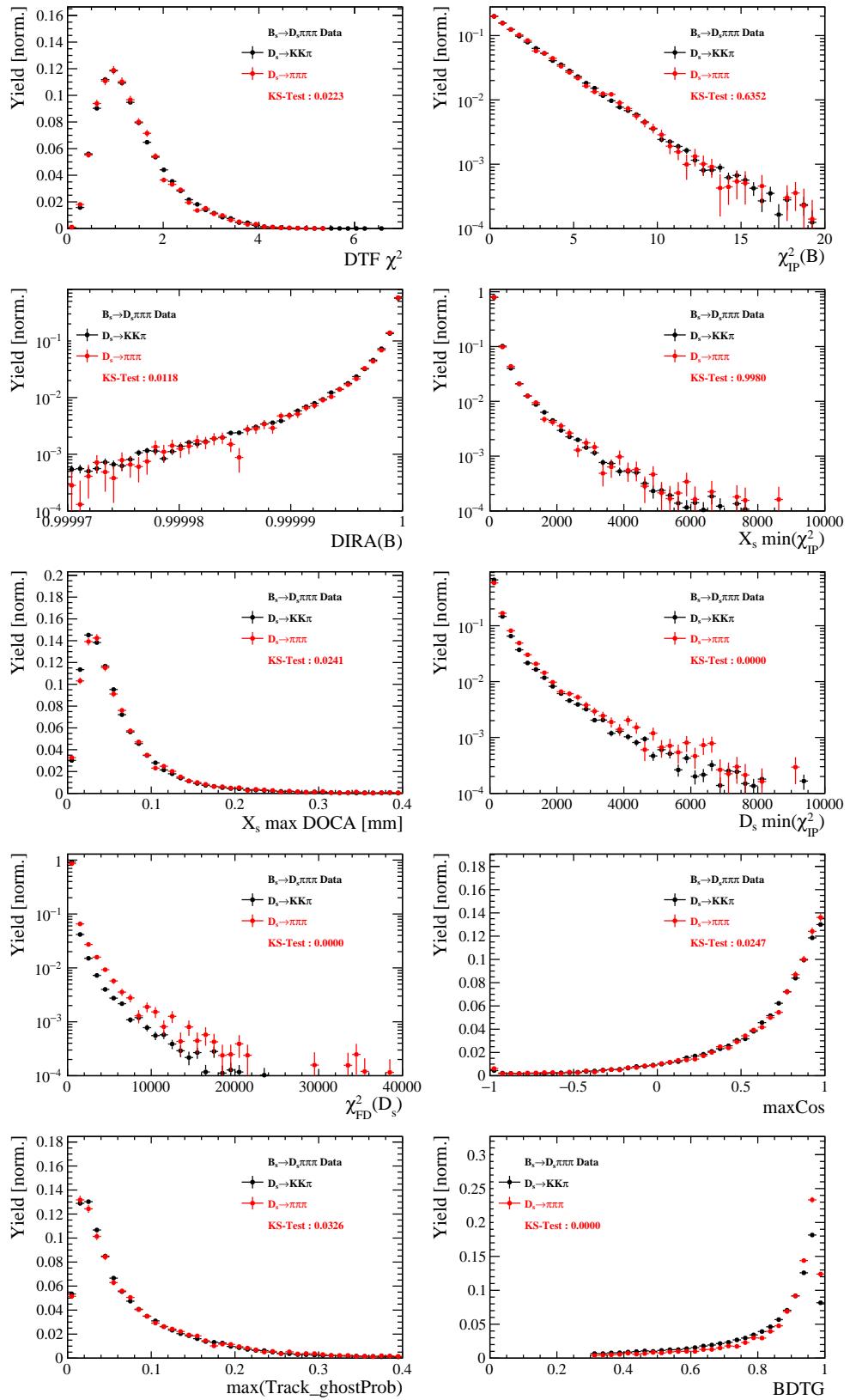


Figure C.6: Comparison of BDTG input variables and classifier response.

847 H.4 Comparison of trigger categories

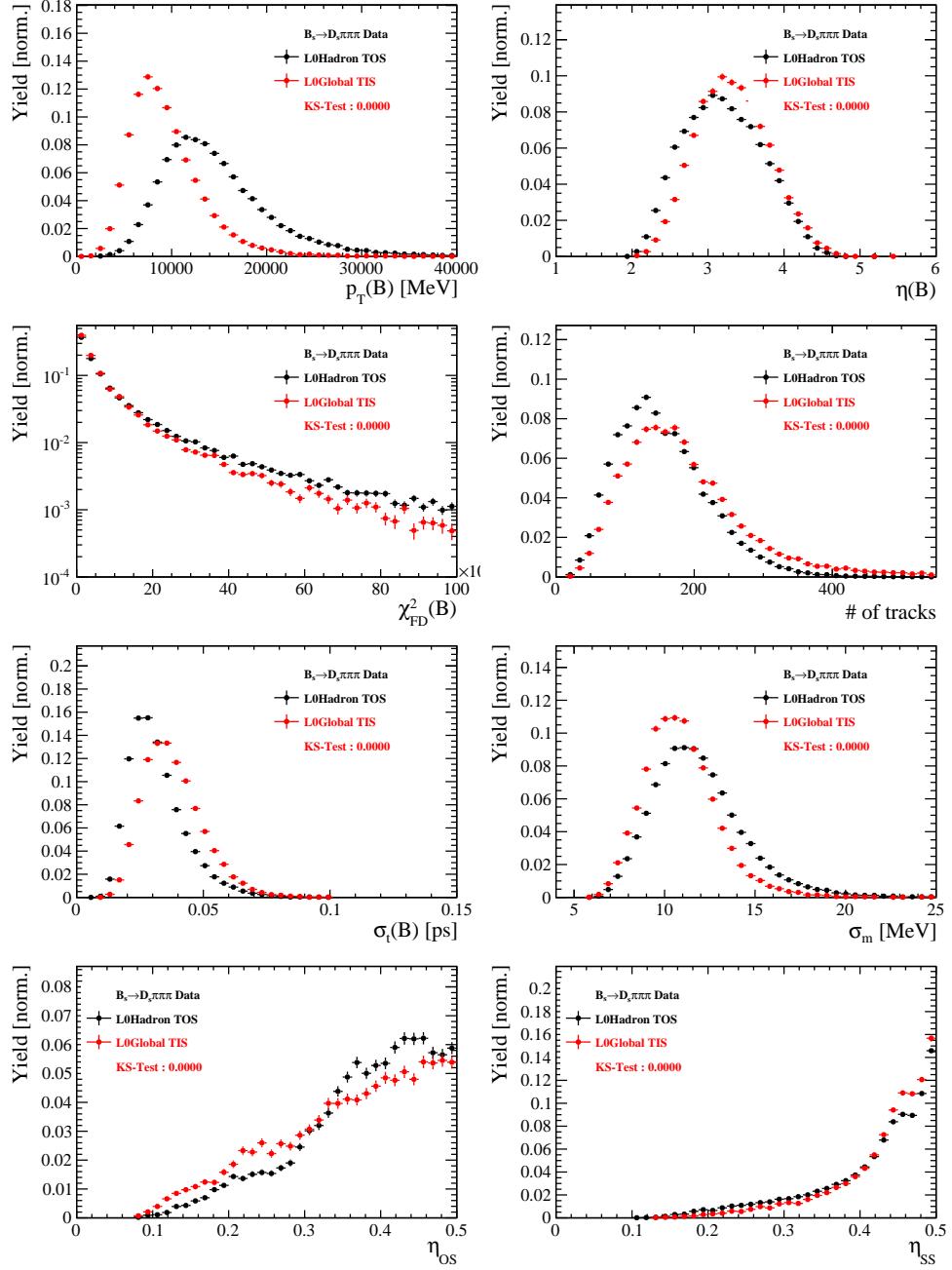


Figure C.7: Comparison of selected variables.

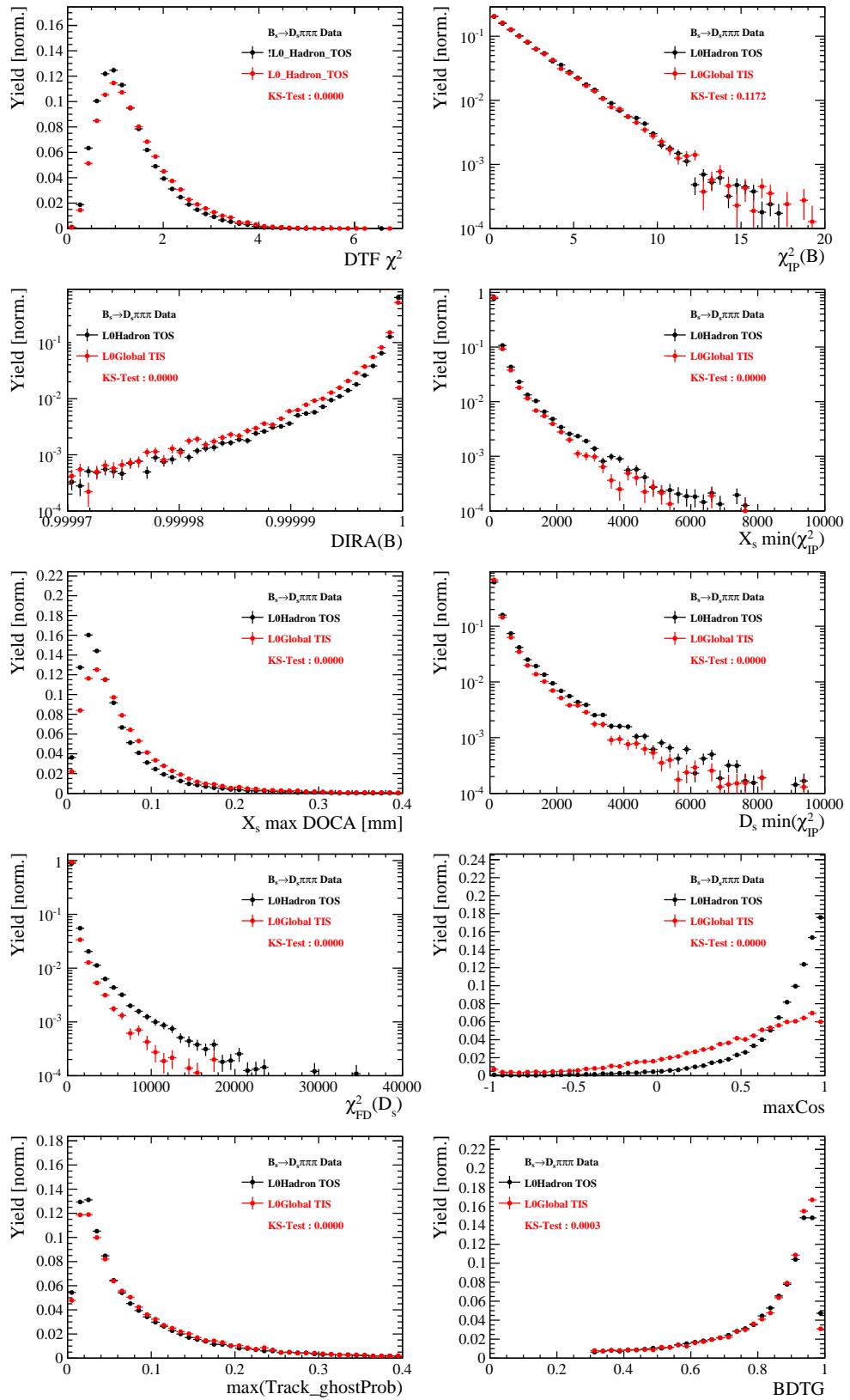


Figure C.8: Comparison of BDTG input variables and classifier response.

848 H.5 Comparison of B_s and B_d decays

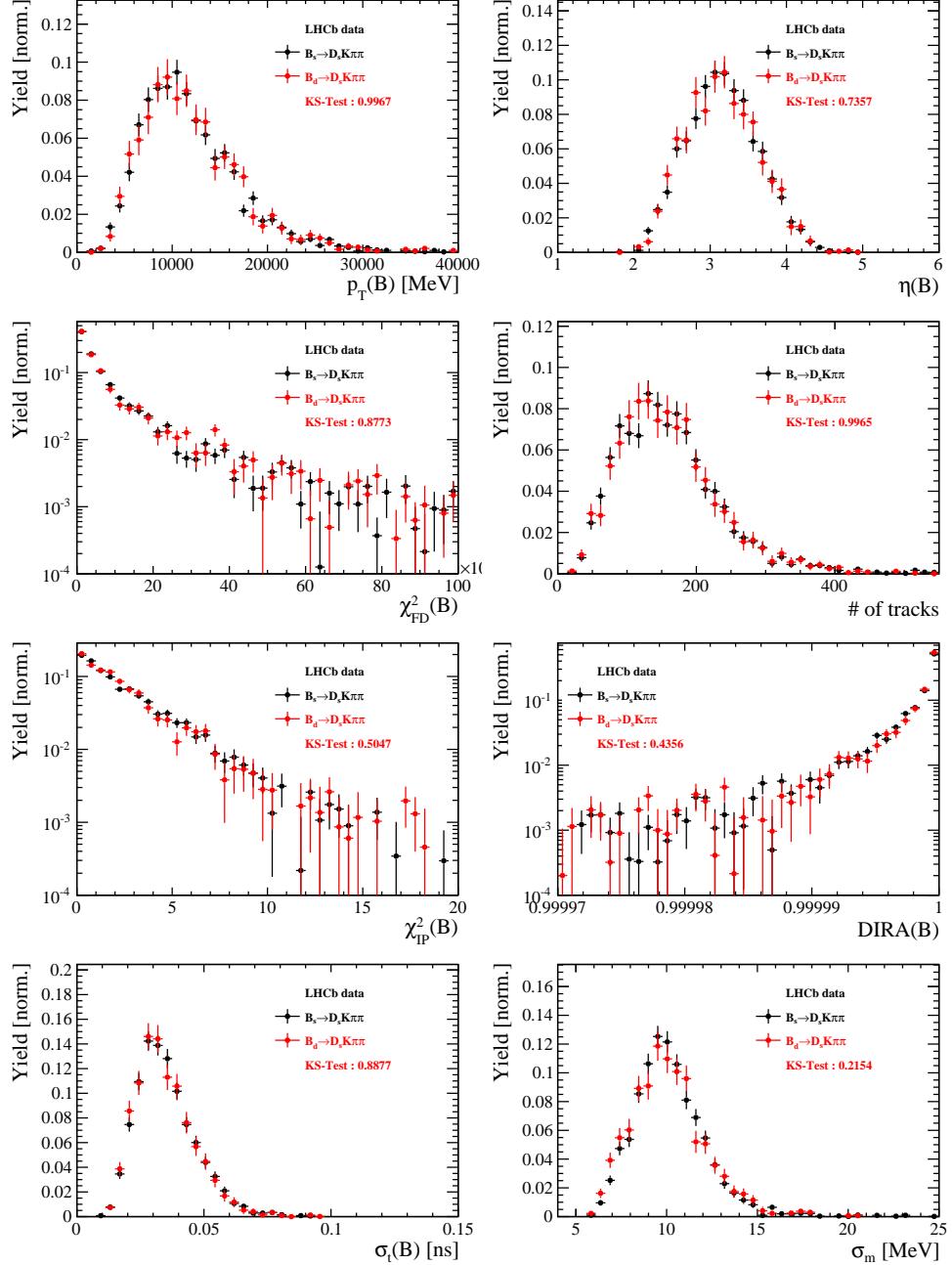


Figure C.9: Comparison of selected variables.

849 References

- 850 [1] R. Fleischer, *New strategies to obtain insights into CP violation through $B(s) \rightarrow D(s) \rightarrow K \pi$, $D(s)^* \rightarrow K \pi$, ... and $B(d) \rightarrow D \pi$, $D^* \pi$, ... decays*, Nucl.
851 Phys. **B671** (2003) 459, arXiv:hep-ph/0304027.
- 853 [2] K. De Bruyn *et al.*, *Exploring $B_s \rightarrow D_s^{(*)\pm} K^\mp$ Decays in the Presence of a Sizable*
854 *Width Difference $\Delta\Gamma_s$* , Nucl. Phys. **B868** (2013) 351, arXiv:1208.6463.
- 855 [3] S. Blusk, *First observations and measurements of the branching fractions for the*
856 *decays $\bar{B}_s^0 \rightarrow D_s^+ K^- \pi^+ \pi^-$ and $\bar{B}^0 \rightarrow D_s^+ K^- \pi^+ \pi^-$* .
- 857 [4] LHCb, S. Blusk, *Measurement of the CP observables in $\bar{B}_s^0 \rightarrow D_s^+ K^-$ and first obser-*
858 *vation of $\bar{B}_{(s)}^0 \rightarrow D_s^+ K^- \pi^+ \pi^-$ and $\bar{B}_s^0 \rightarrow D_{s1}(2536)^+ \pi^-$* , 2012. arXiv:1212.4180.
- 859 [5] M. E. Peskin and D. V. Schroeder, *An Introduction To Quantum Field Theory* (*Frontiers in Physics*), Westview Press, 1995.
- 861 [6] E. Byckling and K. Kajantie, *Particle Kinematics*, John Wiley & Sons, 1973.
- 862 [7] S. Mandelstam, J. E. Paton, R. F. Peierls, and A. Q. Sarker, *Isobar approximation*
863 *of production processes*, Annals of Physics **18** (1962), no. 2 198 .
- 864 [8] D. J. Herndon, P. Söding, and R. J. Cashmore, *Generalized isobar model formalism*,
865 Phys. Rev. D **11** (1975) 3165.
- 866 [9] J. J. Brehm, *Unitarity and the isobar model: Two-body discontinuities*, Annals of
867 Physics **108** (1977), no. 2 454 .
- 868 [10] F. von Hippel and C. Quigg, *Centrifugal-barrier effects in resonance partial decay*
869 *widths, shapes, and production amplitudes*, Phys. Rev. D **5** (1972) 624.
- 870 [11] J. D. Jackson, *Remarks on the phenomenological analysis of resonances*, Il Nuovo
871 Cimento Series 10 **34** (1964), no. 6 1644.
- 872 [12] Particle Data Group, C. Patrignani *et al.*, *Review of Particle Physics*, Chin. Phys.
873 **C40** (2016), no. 10 100001.
- 874 [13] D. V. Bugg, *The mass of the σ pole*, Journal of Physics G Nuclear Physics **34** (2007)
875 151, arXiv:hep-ph/0608081.
- 876 [14] G. J. Gounaris and J. J. Sakurai, *Finite-width corrections to the vector-meson-*
877 *dominance prediction for $\rho \rightarrow e^+ e^-$* , Phys. Rev. Lett. **21** (1968) 244.
- 878 [15] S. M. Flatté, *Coupled-channel analysis of the $\pi\eta$ and KK systems near KK threshold*,
879 Physics Letters B **63** (1976), no. 2 224 .
- 880 [16] BES Collaboration, M. Ablikim *et al.*, *Resonances in $J/\psi \rightarrow \phi\pi^+\pi^-$ and ϕK^+K^-* ,
881 Phys. Lett. **B607** (2005) 243, arXiv:hep-ex/0411001.
- 882 [17] D. V. Bugg, *A study in depth of $f_0(1370)$* , Eur. Phys. J. **C52** (2007) 55,
883 arXiv:0706.1341.

- [884] [18] LHCb Collaboration, R. Aaij *et al.*, *Analysis of the resonant components in $B_s \rightarrow J/\psi \pi^+ \pi^-$* , Phys. Rev. **D86** (2012) 052006, [arXiv:1204.5643](#).
- [885]
- [886] [19] C. Zemach, *Use of angular momentum tensors*, Phys. Rev. **140** (1965) B97.
- [887] [20] W. Rarita and J. Schwinger, *On a theory of particles with half integral spin*, Phys. Rev. **60** (1941) 61.
- [888]
- [889] [21] S. U. Chung, *General formulation of covariant helicity-coupling amplitudes*, Phys. Rev. D **57** (1998) 431.
- [890]
- [891] [22] B. S. Zou and D. V. Bugg, *Covariant tensor formalism for partial wave analyses of ψ decay to mesons*, Eur. Phys. J. **A16** (2003) 537, [arXiv:hep-ph/0211457](#).
- [892]
- [893] [23] V. Filippini, A. Fontana, and A. Rotondi, *Covariant spin tensors in meson spectroscopy*, Phys. Rev. **D51** (1995) 2247.
- [894]
- [895] [24] J.-J. Zhu, *Explicit expressions of spin wave functions*, [arXiv:hep-ph/9906250](#).
- [896] [25] P. d'Argent *et al.*, *Amplitude Analyses of $D^0 \rightarrow \pi^+ \pi^- \pi^+ \pi^-$ and $D^0 \rightarrow K^+ K^- \pi^+ \pi^-$ Decays*, JHEP **05** (2017) 143, [arXiv:1703.08505](#).
- [897]
- [898] [26] M. Williams, *Numerical Object Oriented Quantum Field Theory Calculations*, Comput. Phys. Commun. **180** (2009) 1847, [arXiv:0805.2956](#).
- [899]
- [900] [27] LHCb, R. Aaij *et al.*, *Studies of the resonance structure in $D^0 \rightarrow K^\mp \pi^\pm \pi^\pm \pi^\mp$ decays*, Submitted to: Eur. Phys. J. C (2017) [arXiv:1712.08609](#).
- [901]
- [902] [28] D. J. Lange, *The EvtGen particle decay simulation package*, Nucl. Instrum. Meth. **A462** (2001) 152.
- [903]
- [904] [29] *Gammacombo package*, 2014.
- [905] [30] A. Hoecker *et al.*, *TMVA: Toolkit for Multivariate Data Analysis*, PoS **ACAT** (2007) 040, [arXiv:physics/0703039](#).
- [906]
- [907] [31] M. Pivk and F. R. Le Diberder, *sPlot: A statistical tool to unfold data distributions*, Nucl. Instrum. Meth. **A555** (2005) 356, [arXiv:physics/0402083](#).
- [908]
- [909] [32] N. L. Johnson, *Systems of frequency curves generated by methods of translation*, Biometrika **36** (1949), no. 1/2 149.
- [910]
- [911] [33] Particle Data Group, K. A. Olive *et al.*, *Review of Particle Physics*, Chin. Phys. **C38** (2014) 090001.
- [912]
- [913] [34] LHCb, R. Aaij *et al.*, *A new algorithm for identifying the flavour of B_s^0 mesons at LHCb*, JINST **11** (2016), no. 05 P05010, [arXiv:1602.07252](#).
- [914]
- [915] [35] LHCb collaboration, R. Aaij *et al.*, *Opposite-side flavour tagging of B mesons at the LHCb experiment*, Eur. Phys. J. **C72** (2012) 2022, [arXiv:1202.4979](#).
- [916]

- [36] Heavy Flavor Averaging Group, Y. Amhis *et al.*, *Averages of b-hadron, c-hadron, and τ -lepton properties as of summer 2014*, arXiv:1412.7515, updated results and plots available at <http://www.slac.stanford.edu/xorg/hfag/>.
- [37] T. M. Karbach, G. Raven, and M. Schiller, *Decay time integrals in neutral meson mixing and their efficient evaluation*, arXiv:1407.0748.
- [38] LHCb collaboration, R. Aaij *et al.*, *LHCb detector performance*, Int. J. Mod. Phys. **A30** (2015) 1530022, arXiv:1412.6352.
- [39] LHCb, R. Aaij *et al.*, *Measurement of CP asymmetry in $B_s^0 \rightarrow D_s^\mp K^\pm$ decays*, Submitted to: JHEP (2017) arXiv:1712.07428.
- [40] LHCb, R. Aaij *et al.*, *Measurement of B^0 , B_s^0 , B^+ and Λ_b^0 production asymmetries in 7 and 8 TeV proton-proton collisions*, Phys. Lett. **B774** (2017) 139, arXiv:1703.08464.
- [41] H. Gordon, R. W. Lambert, J. van Tilburg, and M. Vesterinen, *A Measurement of the $K\pi$ Detection Asymmetry*, Tech. Rep. LHCb-INT-2012-027. CERN-LHCb-INT-2012-027, CERN, Geneva, Feb, 2013.
- [42] A. Davis *et al.*, *Measurement of the instrumental asymmetry for $K^- \pi^+$ -pairs at LHCb in Run 2*, Tech. Rep. LHCb-PUB-2018-004. CERN-LHCb-PUB-2018-004, CERN, Geneva, Mar, 2018.
- [43] I. I. Y. Bigi and H. Yamamoto, *Interference between Cabibbo allowed and doubly forbidden transitions in $D \rightarrow K(S)$, $K(L) + \pi$'s decays*, Phys. Lett. **B349** (1995) 363, arXiv:hep-ph/9502238.
- [44] B. Guegan, J. Hardin, J. Stevens, and M. Williams, *Model selection for amplitude analysis*, JINST **10** (2015), no. 09 P09002, arXiv:1505.05133.
- [45] R. Tibshirani, *Regression shrinkage and selection via the Lasso*, Journal of the Royal Statistical Society, Series B **58** (1994) 267.
- [46] G. Schwarz, *Estimating the dimension of a model*, Ann. Statist. **6** (1978) 461.
- [47] H. Akaike, *A new look at the statistical model identification*, IEEE Transactions on Automatic Control **19** (1974) 716.