



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

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

²² where the same convention for the CP coefficients as for the $B_s \rightarrow D_s K$ analysis is used:

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

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

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

²³ The coherence factor κ , the strong phase difference δ and the ratio of the suppressed
²⁴ ($b \rightarrow u$) over favored ($b \rightarrow c$) decay mode are defined as:

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

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

²⁵ In the limit of only one contributing resonance $\kappa \rightarrow 1$.

²⁶

²⁷ 2.2 Amplitude model

²⁸ The differential decay rate of a B_s meson with mass, m_{B_s} , decaying into four pseudoscalar
²⁹ particles with four-momenta $p_i = (E_i, \vec{p}_i)$ ($i = 1, 2, 3, 4$) is given by

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

³⁰ where the transition amplitude $A(\mathbf{x})$, describes the dynamics of the interaction, $d\Phi_4$
³¹ is the four-body phase space element [5], and \mathbf{x} represents a unique set of kinematic
³² conditions within the phase space of the decay. Each final state particle contributes three
³³ observables, manifesting in their three-momentum, summing up to twelve observables in
³⁴ total. Four of them are redundant due to four-momentum conservation and the overall
³⁵ orientation of the system can be integrated out. The remaining five independent degrees
³⁶ of freedom unambiguously determine the kinematics of the decay. Convenient choices
³⁷ for the kinematic observables include the invariant mass combinations of the final state
³⁸ particles

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

³⁹ or acoplanarity and helicity angles. It is however important to take into account that,
⁴⁰ while m_{12}^2, m_{23}^2 are sufficient to fully describe a three-body decay, the obvious extension
⁴¹ to four-body decays with m_{ij}^2, m_{ijk}^2 requires additional care, as these variables alone are
⁴² insufficient to describe the parity-odd moments possible in four-body kinematics.

⁴³ In practice, we do not need to choose a particular five-dimensional basis, but use the
⁴⁴ full four-vectors of the decay in our analysis. The dimensionality is handled by the phase

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

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

47 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,
 48 the four-body phase space density function is not flat in the usual kinematic variables.
 49 Therefore, an analytic expression for ϕ_4 is taken from Ref. [6].

50 The total amplitude for the $B_s \rightarrow h_1 h_2 h_3 h_4$ decay is given by the coherent sum
 51 over all intermediate state amplitudes $A_i(\mathbf{x})$, each weighted by a complex coefficient
 52 $a_i = |a_i| e^{i\phi_i}$ to be measured from data,

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

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

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

60 2.2.1 Form Factors and Resonance Lineshapes

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

86 As experimental values are usually only available for the branching fractions, Eq. (2.22)
 87 needs to be inverted to obtain values for the couplings. In practice, this is solved by
 88 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-
 89 hand side of Eq. (2.22).

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

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

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

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

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

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

112 2.2.2 Spin Densities

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

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

125 The spin projection operator $P_{(S)}^{\mu_1 \dots \mu_S \nu_1 \dots \nu_S}(p_R)$, for a resonance R , with spin $S =$
126 $\{0, 1, 2\}$, and four-momentum p_R , is given by [23]:

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

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

129 For a decay process $R \rightarrow AB$, with relative orbital angular momentum L , between
130 particle A and B , the angular momentum tensor is obtained by projecting the rank- L
131 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
132 subspace,

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

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

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

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

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

¹³⁹ where

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

¹⁴⁰ Here, a polarization vector is assigned to the decaying particle and the complex conjugate
¹⁴¹ vectors for each decay product. The spin and orbital angular momentum couplings are
¹⁴² described by the tensors $P_{(S_{AB})}(R)$ and $L_{(L_{AB})}(R)$, respectively. Firstly, the two spins S_A
¹⁴³ and S_B , are coupled to a total spin- S_{AB} state, $\Phi(\mathbf{x}|S_{AB})$, by projecting the corresponding
¹⁴⁴ polarization vectors onto the spin- S_{AB} subspace transverse to the momentum of the
¹⁴⁵ decaying particle. Afterwards, the spin and orbital angular momentum tensors are
¹⁴⁶ properly contracted with the polarization vector of the decaying particle to give a Lorentz
¹⁴⁷ scalar. This requires in some cases to include the tensor $\varepsilon_{\alpha\beta\gamma\delta} p_R^\delta$ via

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

¹⁴⁸ where $\varepsilon_{\alpha\beta\gamma\delta}$ is the Levi-Civita symbol and j refers to the arguments of X defined in
¹⁴⁹ Eqs. 2.27 and 2.28. Its antisymmetric nature ensures the correct parity transformation
¹⁵⁰ behavior of the amplitude. The spin factor for a whole decay chain, for example $R \rightarrow$
¹⁵¹ $(R_1 \rightarrow AB)(R_2 \rightarrow CD)$, is obtained by combining the two-body terms and performing a
¹⁵² sum over all unobservable, intermediary spin projections

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

¹⁵³ 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
¹⁵⁴ pseudoscalar initial/final states are involved.

¹⁵⁵ The spin factors for all decay topologies considered in this analysis are explicitly given
¹⁵⁶ in Appendix E.

157 2.3 Validation

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

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

172 The CP coefficients $C, D, \bar{D}, S, \bar{S}$ are the fit parameters in case of the phasespace-
 173 integrated pdf, while the full pdf determines $x_{\pm} = r \cos(\delta \pm (\gamma - 2\beta_s))$ and $y_{\pm} = r \sin(\delta \pm$
 174 $(\gamma - 2\beta_s))$. The fit parameters are converted to the physical observables $r, \kappa, \delta, \gamma$ using
 175 the **GammaCombo** package [29]. As shown in Tab. 2.2, 2.3 and 2.4, the fit results are
 176 in excellent agreement with the generated input values. The 1-CL contours are shown
 177 in Figs. 2.1 and 2.2. The phasespace-integrated fit is, in addition, performed with the
 178 **B2DX** fitter used for the $B_s \rightarrow D_s K$ analysis yielding identical results. Note though that
 179 some parts of the **B2DX** fitter have been taken over to our **MINT2** fitter, such that the
 180 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°

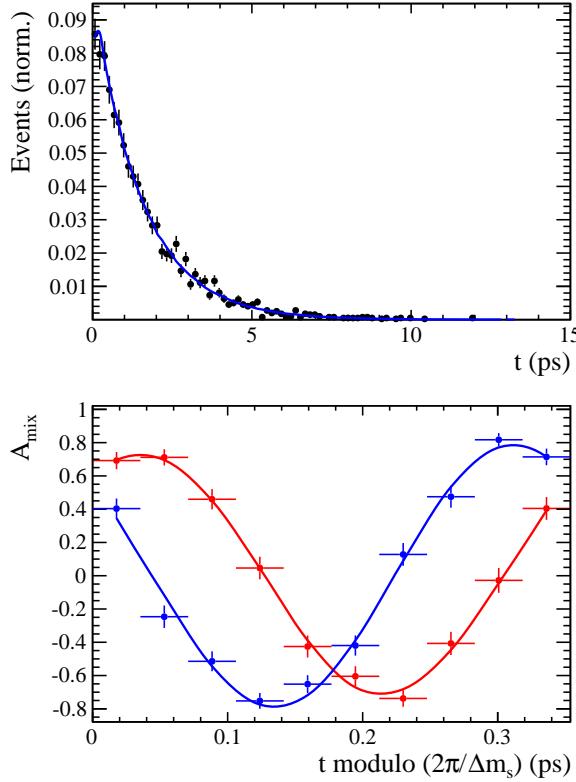


Figure 2.1: Left: Time distribution of $B_s \rightarrow D_s K\pi\pi$ events generated with EVTGEN (points with error bars) and MINT2 fit projections (solid line). Right: Time-dependent asymmetry between mixed and unmixed events over one mixing period $2\pi/\Delta m_s$ for both final state charge configurations ($D_s^\pm K^\mp\pi\pi$) in red & blue. The points are generated using EVTGEN and the MINT2 fit projections are overlaid.

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

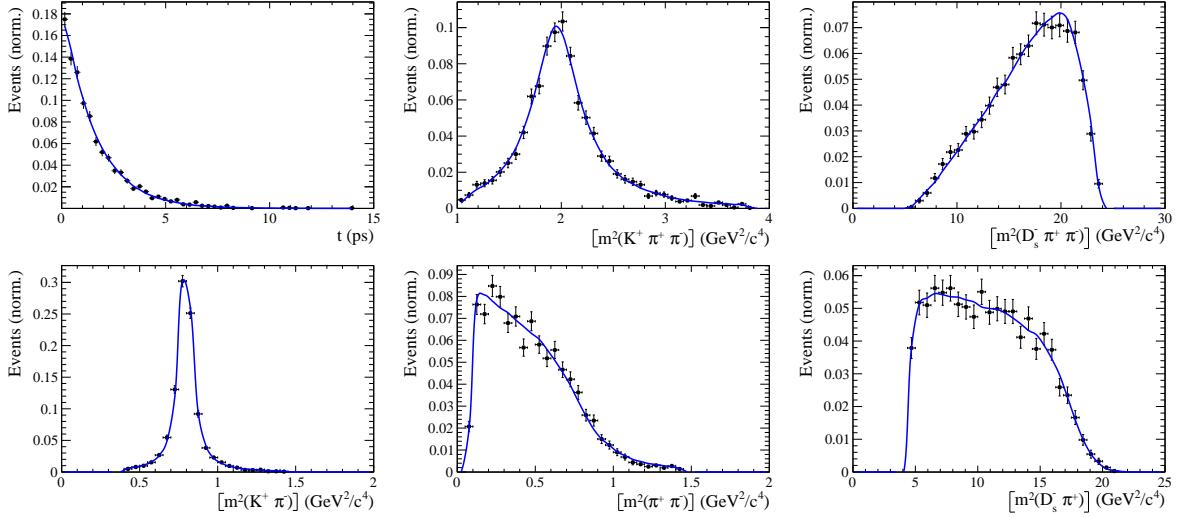


Figure 2.2: Time and invariant mass distributions of $B_s \rightarrow D_s K\pi\pi$ events generated with EVTGEN (points with error bars) and MINT2 fit projections (blue solid line).

Table 2.3: 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

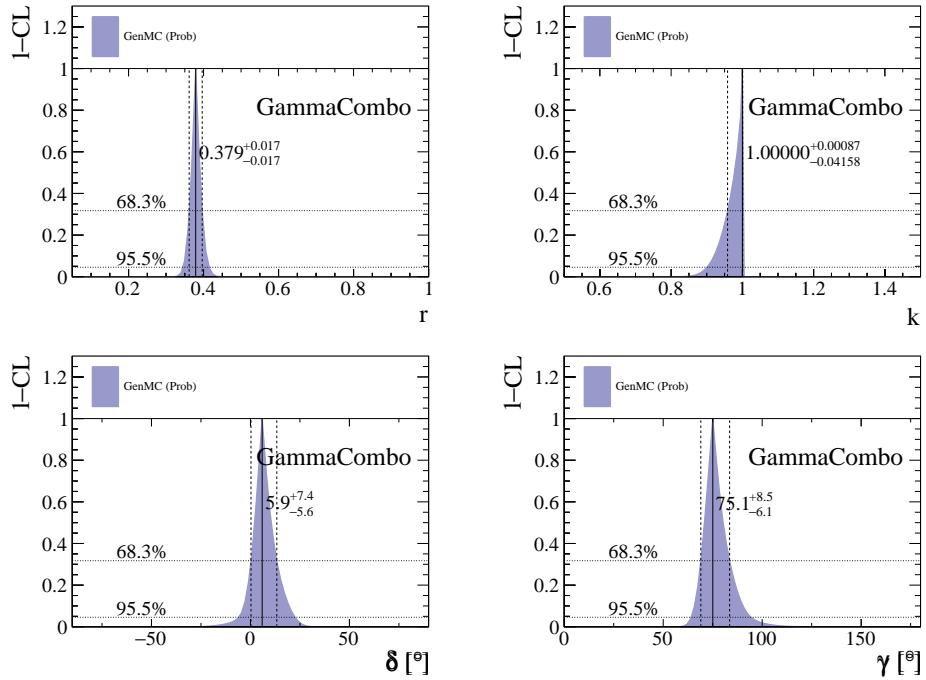


Figure 2.3: The 1-CL contours for the physical observable $r, \kappa, \delta, \gamma$ obtained with the phasespace integrated fit to the EVTGEN toy sample.

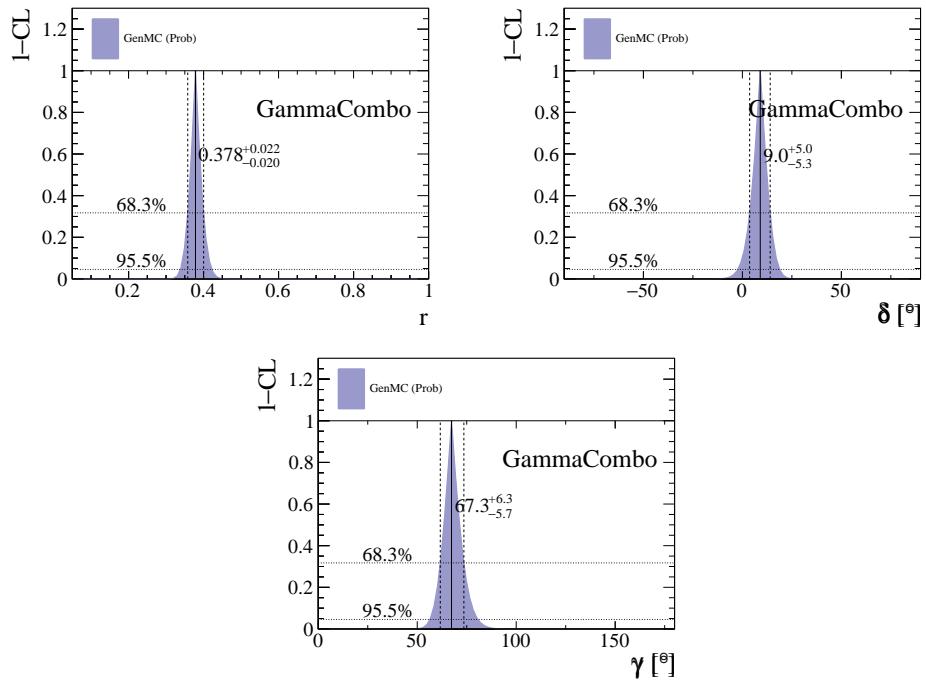


Figure 2.4: The 1-CL contours for the physical observable r, δ, γ obtained with the time-dependent amplitude fit fit to the EVTGEN toy sample.

181 3 Data samples and event selection

182 Throughout the note, we abbreviate $B_s^0 \rightarrow D_s X_s (\rightarrow K\pi\pi)$ and $B_s^0 \rightarrow D_s X_d (\rightarrow \pi\pi\pi)$,
183 identifying $X_s \rightarrow K\pi\pi$ and $X_d \rightarrow \pi\pi\pi$ as the various resonances through which the decays
184 proceed.

185 3.1 Stripping and Trigger selection

186 The dataset used for this analysis corresponds to 1 fb^{-1} of proton-proton collision
187 data collected in 2011 with a centre of mass energy $\sqrt{s} = 7\text{ TeV}$, 2 fb^{-1} collected
188 in 2012 with $\sqrt{s} = 7\text{ TeV}$ and 4 fb^{-1} collected in 2015/2016/2017 with $\sqrt{s} =$
189 13 TeV . Candidate $B_s^0 \rightarrow D_s K\pi\pi$ ($B_s^0 \rightarrow D_s \pi\pi\pi$) decays are reconstructed using the
190 `B02DKPiPiD2HHHPIDBeauty2CharmLine` (`B02DPiPiD2HHHPIDBeauty2CharmLine`) line
191 of the `BHadronCompleteEvent` stream of `Stripping21r1` (2011), `Stripping21` (2012), `Strip-`
192 `ping24r1` (2015) and `Stripping28r1p1` (2016) and `Stripping29r2` (2017). Both stripping lines
193 employ the same selection cuts, listed in Appendix A, except for the PID requirement on
194 the bachelor kaon/pion.

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

202 Due to a residual kinematic dependence on whether the event is triggered by `L0Hadron`
203 or not and on the data taking condition, the analysis is performed in four disjoint categories:
204 `[Run-I,L0-TOS]`, `[Run-I,L0-TIS]`, `[Run-II,L0-TOS]` and `[Run-II,L0-TIS]`, where for simplic-
205 ity we denote `L0Hadron-TOS` as `L0-TOS` and (`L0Global-TIS` and not `L0Hadron-TOS`) as
206 `L0-TIS`.

207 3.2 Offline selection

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

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

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

- 221 • DIRA > 0.99994

- min IP $\chi^2 < 16$ to the best PV,
- FD $\chi^2 > 100$ to the best PV,
- Vertex $\chi^2/\text{nDoF} < 8$.

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

We reconstruct the $B_s^0 \rightarrow D_s h\pi\pi$ decay through three different final states of the 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 most prominent one, while $\mathcal{BR}(D_s \rightarrow \pi\pi\pi) \approx 0.2 \cdot \mathcal{BR}(D_s \rightarrow KK\pi)$ and $\mathcal{BR}(D_s \rightarrow K\pi\pi) \approx 0.12 \cdot \mathcal{BR}(D_s \rightarrow KK\pi)$ holds for the others. For the $KK\pi$ final state we make use of the well known resonance structure; the decay proceeds either via the narrow ϕ resonance, the broader K^{*0} resonance or (predominantly) non-resonant. Within the ϕ resonance region the sample is already sufficiently clean after the stripping so that we do not impose additional criteria on the D_s daughters. For the K^{*0} and non-resonant regions consecutively tighter requirements on the particle identification and the D_s flight-distance are applied. We apply global requirements for the other final states. All cuts are summarized in Table 3.1.

3.2.1 Phase space region

Due to the comparably low masses of the final state particles with respect to the B_s mass, there is, in contrast to for example b-hadron to charmonia or charm decays, a huge phase-space available for the $B_s^0 \rightarrow D_s K\pi\pi$ decay. For the invariant mass of the $K\pi\pi$ subsystem it extends up to 3.4 GeV. It has however been observed that the decay proceeds predominantly through the low lying axial vector states $K_1(1270)$ and $K_1(1400)$, while the combinatorial background is concentrated at high $K\pi\pi$ invariant masses ($m(K\pi\pi) > 2000 \text{ MeV}$). Moreover, the strange hadron spectrum above 2 GeV is poorly understood experimentally such that a reliable extraction of the strong phase motion in that region is not possible. We consequently choose to limit the considered phase space region to $m(K\pi\pi) < 1950 \text{ MeV}$, which is right below the charm-strange threshold ($B_s^0 \rightarrow D_s^+ D_s^-$).

254 **3.2.2 Physics background vetoes**

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

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

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

261 Possible with $\pi^- \rightarrow K^-$ misidentification, vetoed by requiring $m(K^+ K_\pi^- \pi^-) \neq$
 262 $m(D^-) \pm 40$ MeV or the K^- has to fulfill more stringent PID criteria depending
 263 on the resonant region (see Table 3.1).

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

265 Possible with $\bar{p} \rightarrow K^-$ misidentification, vetoed by requiring $m(K^+ K_p^- \pi^-) \neq$
 266 $m(\Lambda_c^-) \pm 40$ MeV or the K^- has to fulfill more stringent PID criteria depending
 267 on the resonant region (see Table 3.1).

268 (c) $D^0 \rightarrow KK$:

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

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

272 (a) $D^0 \rightarrow \pi\pi$:

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

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

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

277 Possible with $\pi^- \rightarrow K^-$ misidentification, vetoed by requiring $m(K_\pi^- \pi^+ \pi^-) \neq$
 278 $m(D^-) \pm 40$ MeV or $\text{PIDK}(K^+) > 15$.

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

280 Possible with $\bar{p} \rightarrow K^-$ misidentification, vetoed by requiring $m(K_p^- \pi^+ \pi^-) \neq$
 281 $m(\Lambda_c^-) \pm 40$ MeV or $\text{PIDK}(K^-) - \text{PIDp}(K^-) > 5$.

282 (c) $D^0 \rightarrow K\pi$:

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

285 The effects of these veto cuts are illustrated in Figs. 3.1,3.2 and 3.3. To reduce cross-feed
 286 from our calibration channel into the signal channel and vice-versa we require tight PID
 287 cuts on the ambiguous bachelor kaon ($\text{PIDK}(K) > 10$)/pion ($\text{PIDK}(K) < 0$). In addition,
 288 we veto $B_s^0 \rightarrow D_s^- D_s^+$ decays which is illustrated in Fig. 3.4.

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

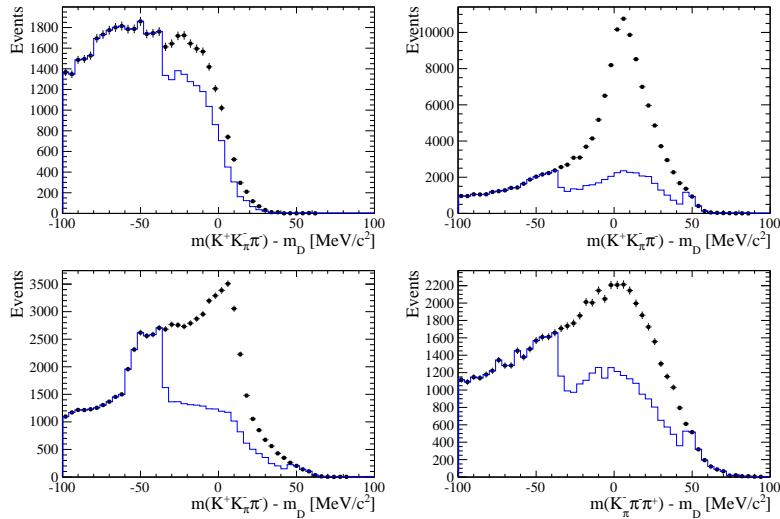


Figure 3.1: Background contributions from D^- decays where the π^- is misidentified as K^- . The D_s invariant mass is recomputed applying the pion mass hypothesis to the kaon and shown for the $D_s \rightarrow \phi\pi$, $D_s \rightarrow K^*(892)K$, $D_s \rightarrow KK\pi$ (non-resonant) and $D_s \rightarrow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

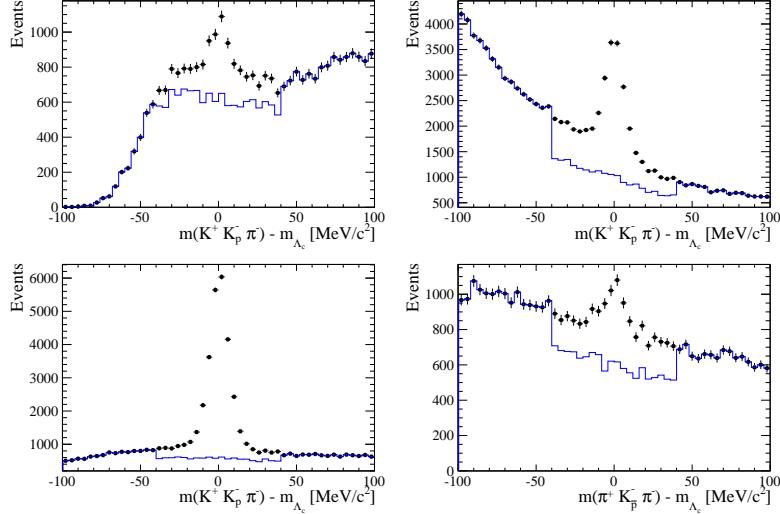


Figure 3.2: Background contributions from Λ_c decays where the \bar{p} is misidentified as K^- . The D_s invariant mass is recomputed applying the proton mass hypothesis to the kaon and shown for the $D_s \rightarrow \phi\pi$, $D_s \rightarrow K^*(892)K$, $D_s \rightarrow KK\pi$ (non-resonant) and $D_s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

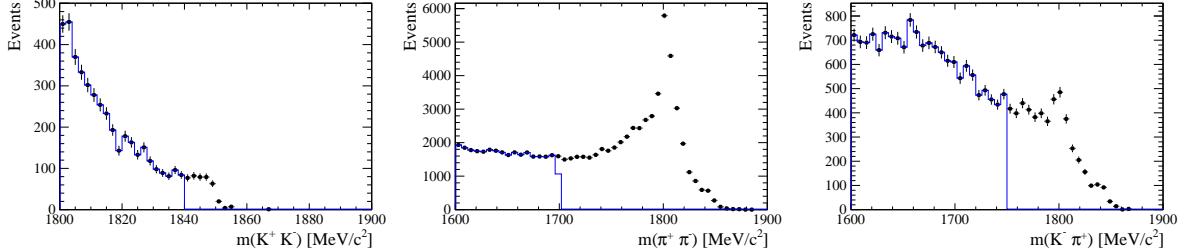


Figure 3.3: Background contributions to $D_s \rightarrow KK\pi$ (left), $D_s \rightarrow \pi\pi\pi$ (middle) and $D_s \rightarrow K\pi\pi$ (right) from $D^0 \rightarrow hh$ decays combined with a random pion.

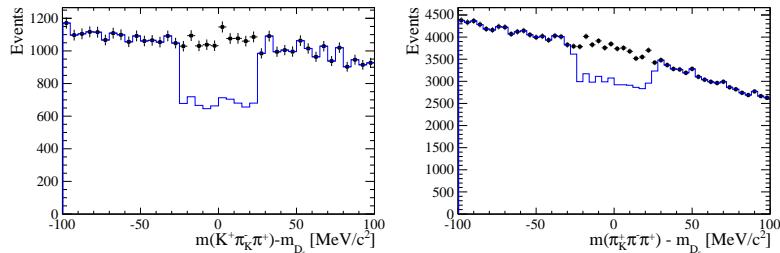


Figure 3.4: Background contributions to $B_s \rightarrow D_s K\pi\pi$ (left) and $B_s \rightarrow D_s \pi\pi\pi$ (right) from $B_s \rightarrow D_s D_s$ decays where the kaon is misidentified as pion. The $X_{s,d}$ invariant mass is recomputed applying the kaon mass hypothesis to the pion and shown without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

308 **3.2.3 Training of multivariate classifier**

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

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

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

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

339 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
340 to the training which are expected to be 100% signal efficient. Figure 3.6 shows the
341 distributions of the input variables for signal and background. As shown in Appendix B,
342 these distributions differ between data-taking period and trigger category. In particular
343 variables depending on the B_s kinematics and the event multiplicity are affected (e.g.
344 $\theta_{D_s h_i}$ or A_{pT}^{cone}). The BDTG is consequently trained separately for these categories. The
345 resulting classifier response is shown in Fig. 3.7 for each category (even and odd test
346 samples combined) and in Appendix B for each training.

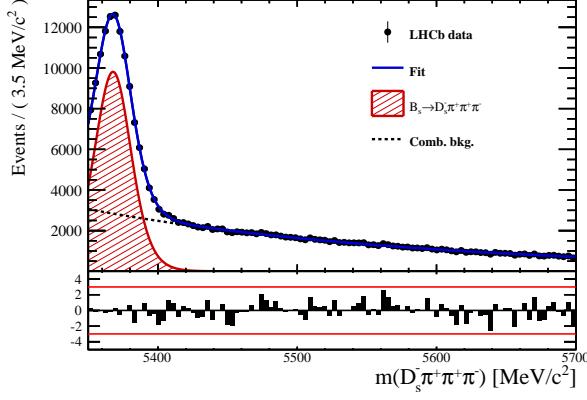


Figure 3.5: Reconstructed B_s mass for $B_s \rightarrow D_s \pi\pi\pi$ events that pass the preselection. The fitted PDF is shown in blue, the signal component in red and the background component in black.

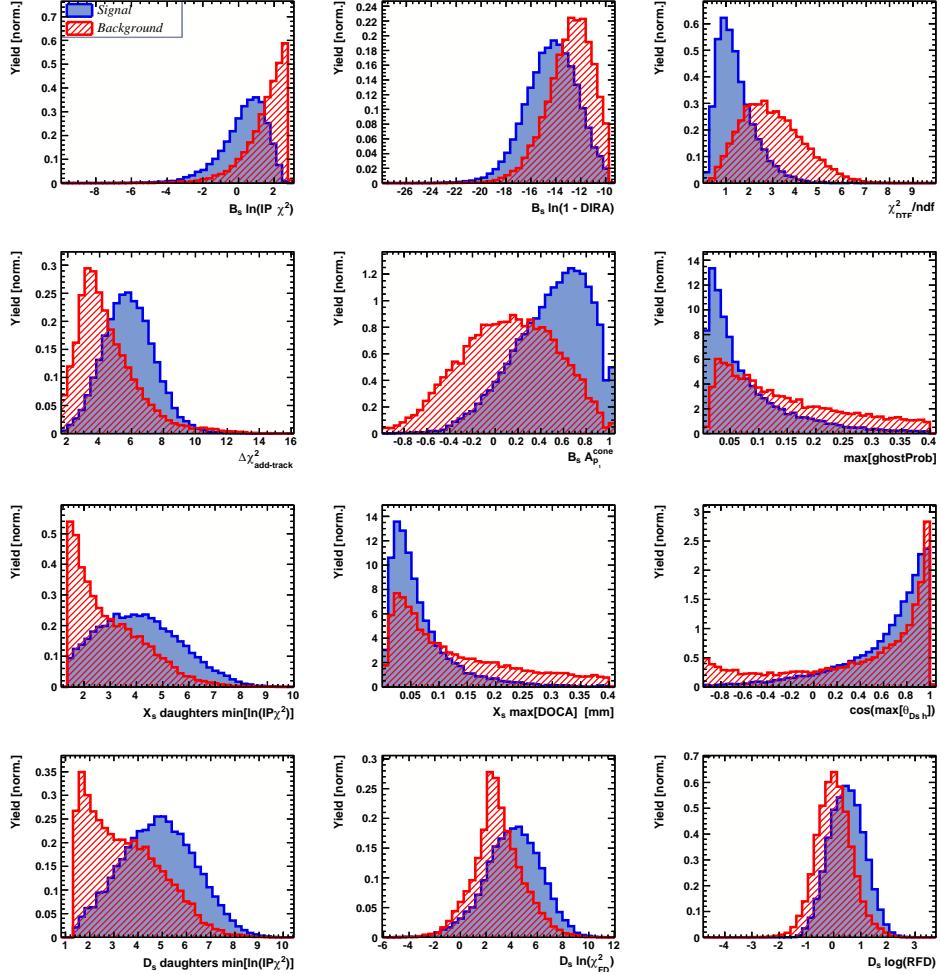


Figure 3.6: Discriminating variables used to train the BDTG for all data categories combined.

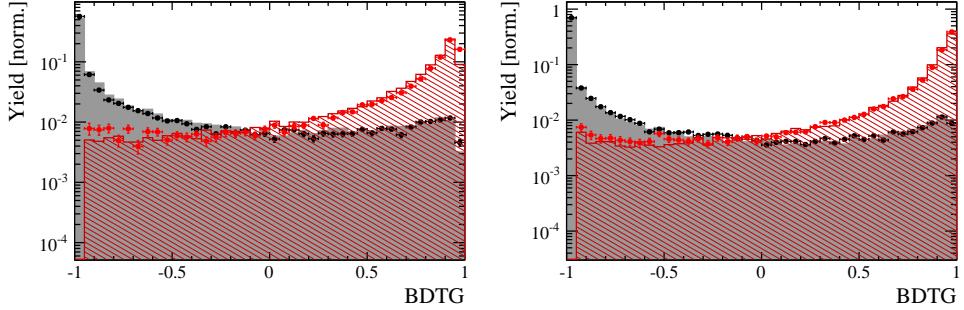


Figure 3.7: Signal (red) and background (black) distributions for the BDTG response for Run-I (left) and Run-II (right) data. Filled histograms (data points) show the BDTG response for the L0-TOS (L0-TIS) category. Even and odd test samples are combined.

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.

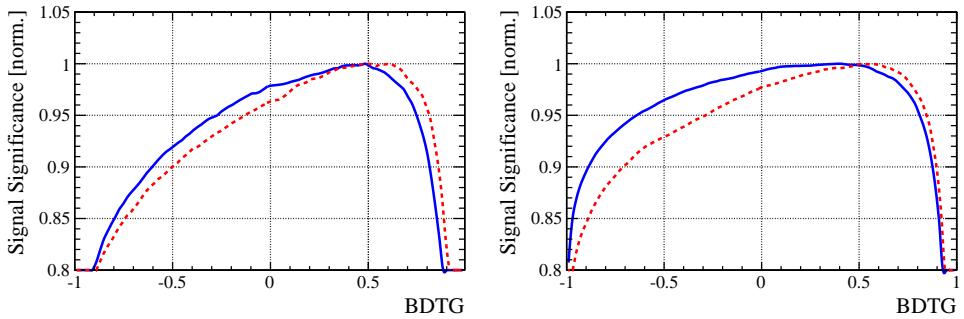


Figure 3.8: Signal significance as function of the applied cut on the BDTG response for Run-I (left) and Run-II (right) data. The scans for the L0-TOS (L0-TIS) category are shown in blue (red). The signal significance is normalized to be 1 at the optimal BDTG cut value.

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	$= 1$

358 4 Yields determination

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

364 Due to different mass resolutions, we perform the invariant mass fits simultaneously
 365 for each data-taking period and each trigger category. We further introduce four D_s final
 366 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
 367 different signal purities. The $D_s \rightarrow Kh\pi$ category combines the two D_s decay channels
 368 with the lowest statistics: $D_s \rightarrow KK\pi$ (non-resonant) and $D_s \rightarrow K\pi\pi$. This amounts to
 369 16 categories in total.

370 4.1 Signal model

371 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
 372 using a Johnson's SU function [31], which results from a variable transformation of a
 373 normal distribution to allow for asymmetric tails:

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

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

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

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

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

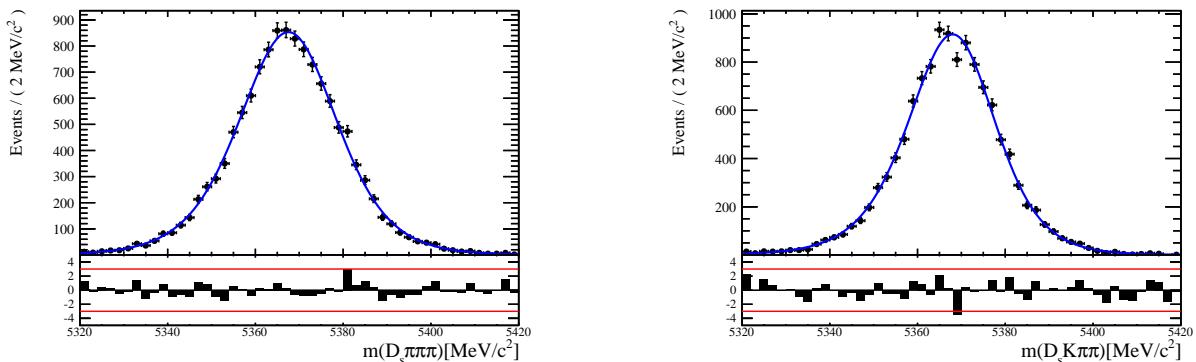


Figure 4.1: Invariant mass distributions of simulated (left) $B_s^0 \rightarrow D_s \pi\pi\pi$ and (right) $B_s^0 \rightarrow D_s K\pi\pi$ events. A fit with a Johnson's SU PDF is overlaid.

377 simulation and real data, linear scaling factors for the mean μ and width σ are determined
378 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
379 factors are determined separately for each data-taking period and each trigger category.
380

381 4.2 Background models

382 After the full selection the following residual background components have to be accounted
383 for:

384 Combinatorial background

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

389 Peaking B_d background

390 Decays of B_d mesons into the $D_s h\pi\pi$ final state are described by the B_s signal PDF
391 where the mean is shifted by the known mass difference $m_{B_s} - m_{B_d}$ [12].

393 Partially reconstructed background

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

405 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
406 shifted by $m_{B_s^0} - m_{B^0}$.

408 Misidentified background

409 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
410 pions is misidentified as a kaon, contaminate the $B_s^0 \rightarrow D_s K^+ \pi^+ \pi^-$ sample. To determine
411 the corresponding background shapes, we use simulated events passing the nominal
412 selection except for the PID cuts on the bachelor π^+ tracks. The **PIDCalib** package
413 is used to determine the p_T, η -dependent $\pi^+ \rightarrow K^+$ misidentification probability for
414 each pion. We change the particle hypothesis from pion to kaon for the pion with the
415 higher misidentification probability and recompute the invariant B_s^0 mass, $m(D_s^- \pi_K^+ \pi^+ \pi^-)$.
416 Similarly, the invariant masses $m(\pi_K^+ \pi^+ \pi^-)$ and $m(\pi_K^+ \pi^-)$ are recomputed and required
417 to be within the considered phasespace region. The background distributions are shown
418 in Fig. 4.2 (middle,right) and modeled by the sum of two Crystal Ball functions. The
419 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
420 $B_s^0 \rightarrow D_s K\pi\pi$ sample is computed by multiplying the fake rate (within the considered
421 $B_s^0 \rightarrow D_s K\pi\pi$ sample) with the total number of $B_s^0 \rightarrow D_s K\pi\pi$ events.

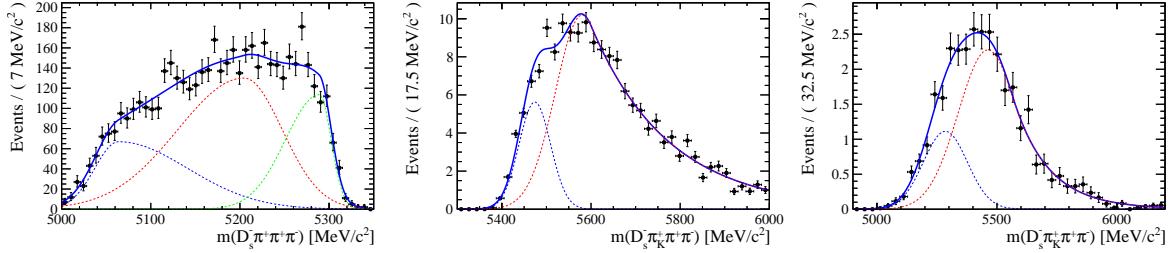


Figure 4.2: Left: Invariant mass distribution of simulated $B_s^0 \rightarrow D_s^* \pi\pi\pi$ events, where the γ/π^0 is excluded from the reconstruction. Middle: Invariant mass distribution of simulated $B_s^0 \rightarrow D_s \pi\pi\pi$ events, where one of the pions is reconstructed as a kaon taking 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.

⁴²² 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
⁴²³ determined in the mass fit to the $B_s^0 \rightarrow D_s \pi\pi\pi$ data sample which is corrected for the
⁴²⁴ $\text{PID}(\pi^+) < 0$ requirement. The $B_s^0 \rightarrow D_s^* \pi^+\pi^+\pi^-$ yield is additionally corrected for the
⁴²⁵ efficiency of the cut $m(D_s K\pi\pi) > 5200$ MeV evaluated on MC. In the fit to data, the
⁴²⁶ misidentified background yields are fixed to the predicted ones.

⁴²⁷ 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
⁴²⁸ $B_s^0 \rightarrow D_s \pi\pi\pi$ data sample to be negligible due to the low branching fractions and the
⁴²⁹ tight PID cuts on the bachelor pions.

430 4.3 Results

⁴³¹ Figure 4.3 shows the invariant mass distribution for $B_s^0 \rightarrow D_s \pi\pi\pi$ and $B_s^0 \rightarrow D_s K\pi\pi$
⁴³² candidates passing all selection criteria. The projections for all categories of the simula-
⁴³³ taneous fit are shown in Appendix C together with the results for all fitted parameters.
⁴³⁴ The integrated signal and background yields are listed in Tables 4.1 and 4.2.

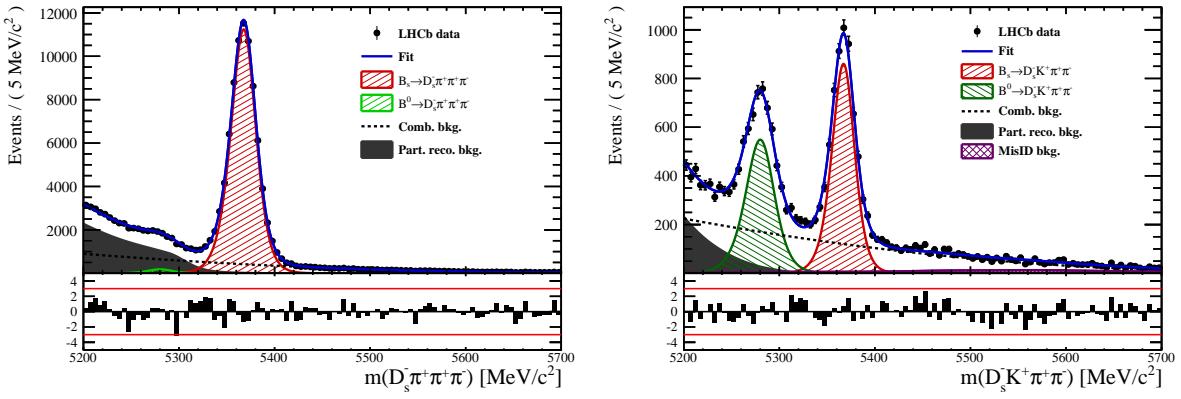


Figure 4.3: Invariant mass distribution of $B_s^0 \rightarrow D_s \pi\pi\pi$ (left) and $B_s^0 \rightarrow D_s K\pi\pi$ (right) candidates.

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	D_s final state	Signal yield
$B_s \rightarrow D_s\pi\pi\pi$	77225 ± 304	$D_s^- \rightarrow \phi^0(1020)\pi^-$	26458 ± 172
$B^0 \rightarrow D_s\pi\pi\pi$	1263 ± 454	$D_s^- \rightarrow K^{*0}(892)K^-$	23105 ± 170
Partially reconstructed bkg.	31805 ± 351	$D_s^- \rightarrow (K^-h^+\pi^-)$	15201 ± 136
Combinatorial bkg.	32821 ± 393	$D_s^- \rightarrow \pi^+\pi^-\pi^-$	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	D_s final state	Signal yield
$B_s \rightarrow D_sK\pi\pi$	5376 ± 88	$D_s^- \rightarrow \phi^0(1020)\pi^-$	1706 ± 49
$B^0 \rightarrow D_sK\pi\pi$	4384 ± 101	$D_s^- \rightarrow K^{*0}(892)K^-$	1712 ± 49
Partially reconstructed bkg.	1796 ± 96	$D_s^- \rightarrow (K^-h^+\pi^-)$	1145 ± 41
Misidentified bkg.	808 ± 0	$D_s^- \rightarrow \pi^+\pi^-\pi^-$	814 ± 36
Combinatorial bkg.	9376 ± 177		

435 5 Decay-time Resolution

436 The observed oscillation of B mesons is prone to dilution, if the detector resolution is
 437 of similar magnitude as the oscillation period. In the B_s^0 system, considering that the
 438 measured oscillation frequency of the B_s^0 [32] and the average LHCb detector resolution [33]
 439 are both $\mathcal{O}(50 \text{ fs}^{-1})$, this is the case. Therefore, it is crucial to correctly describe the
 440 decay time resolution in order to avoid a bias on the measurement of time dependent CP
 441 violation. Since the time resolution depends on the particular event, especially the decay
 442 time itself, the sensitivity on γ can be significantly improved by using an event dependent
 443 resolution model rather than an average resolution. For this purpose, we use the per-event
 444 decay time error that is estimated based on the uncertainty obtained from the global
 445 kinematic fit of the momenta and vertex positions (DTF) with additional constraints on
 446 the PV position and the D_s mass. In order to apply it correctly, it has to be calibrated.
 447 The raw decay time error distributions for $B_s^0 \rightarrow D_s\pi\pi\pi$ signal candidates are shown in
 448 Figure 5.1 for Run-I and Run-II data. Significant deviations between the two different
 449 data taking periods are observed due to the increase in center of mass energy from Run-I
 450 to Run-II, as well as (among others) new tunings in the pattern and vertex reconstruction.
 451 The decay time error calibration is consequently performed separately for both data taking
 452 periods.

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

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

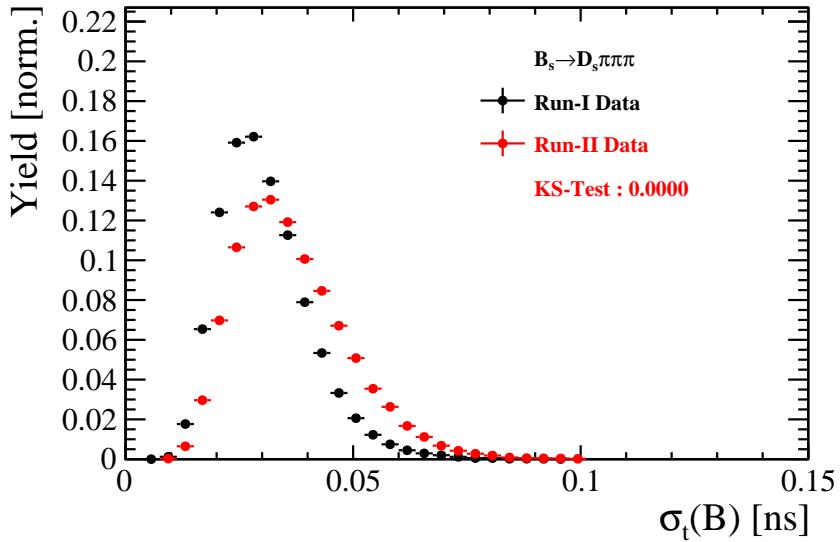


Figure 5.1: Distribution of the decay time error for $B_s^0 \rightarrow D_s\pi\pi\pi$ signal candidates for Run-I (black) and Run-II (red) data (sWeighted).

458 5.1 Calibration for Run-I data

459 For simulated $B_s^0 \rightarrow D_s K \pi\pi$ events, the spread of the differences between reconstructed
 460 decay time and true decay time, $\Delta t = t - t_{true}$, is a direct measure of the decay time
 461 resolution. The sum of two Gaussian pdfs with common mean but different widths is used
 462 to fit the distribution of the decay time difference Δt as shown in Fig. 5.2. The effective
 463 damping of the CP amplitudes due to the finite time resolution is described by the dilution
 464 \mathcal{D} . In the case of infinite precision, there would be no damping and therefore $\mathcal{D} = 1$ would
 465 hold, while for a resolution that is much larger than the B_s^0 oscillation frequency, \mathcal{D} would
 466 approach 0. For a double-Gaussian resolution model, the dilution is given by [34]

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

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

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

470 which converts the resolution into a single-Gaussian function with an effective resolution
 471 that causes the same damping effect on the magnitude of the B_s oscillation. For the Run-I
 472 $B_s^0 \rightarrow D_s K \pi\pi$ MC sample the effective average resolution is found to be $\sigma_{eff} = 39.1 \pm 0.3$ fs.

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

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

481 where the offset is fixed to 0. For comparison, the calibration function found for $B_s^0 \rightarrow D_s K$
 482 MC is also shown in Figure 5.2 [34]:

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

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

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

485 can be used for our analysis. The following calibration functions were used in the
 486 $B_s^0 \rightarrow D_s K$ analysis to estimate the systematic uncertainty on the decay-time resolution:

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

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

488 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
 489 assigned as additional systematic uncertainty.

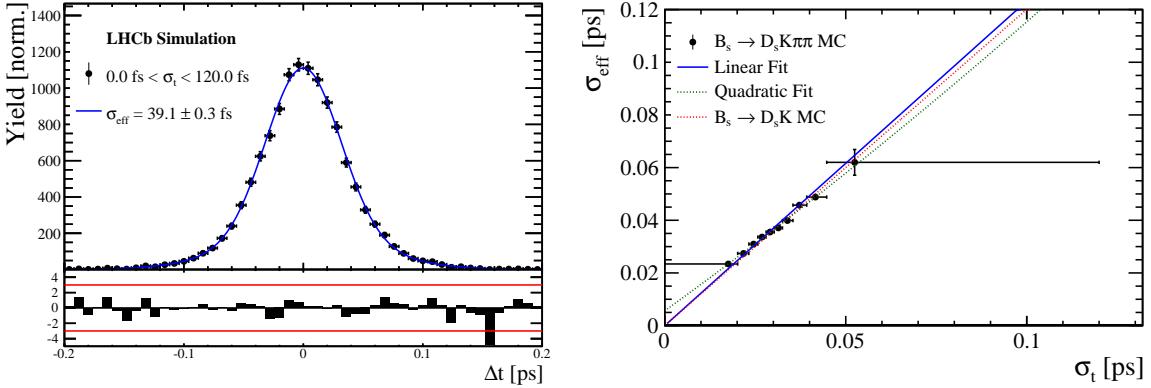


Figure 5.2: (Left) Difference of the true and measured decay time of $B_s^0 \rightarrow D_s K\pi\pi$ MC candidates. (Right) The measured resolution σ_{eff} as function of the per-event decay time error estimate σ_t for $B_s \rightarrow D_s K\pi\pi$ MC (Run-I). The fitted calibration curve is shown in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

490 5.2 Calibration for Run-II data

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

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

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

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

⁵¹⁷ is in good agreement with the one obtained for the $B_s \rightarrow J/\psi\phi$ (Run-II) analysis [35].

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

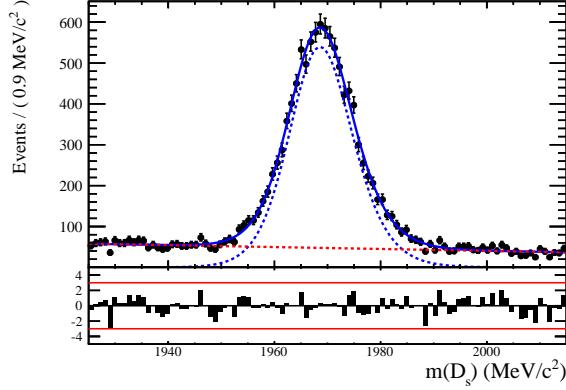


Figure 5.3: The invariant mass distribution for prompt D_s candidates.

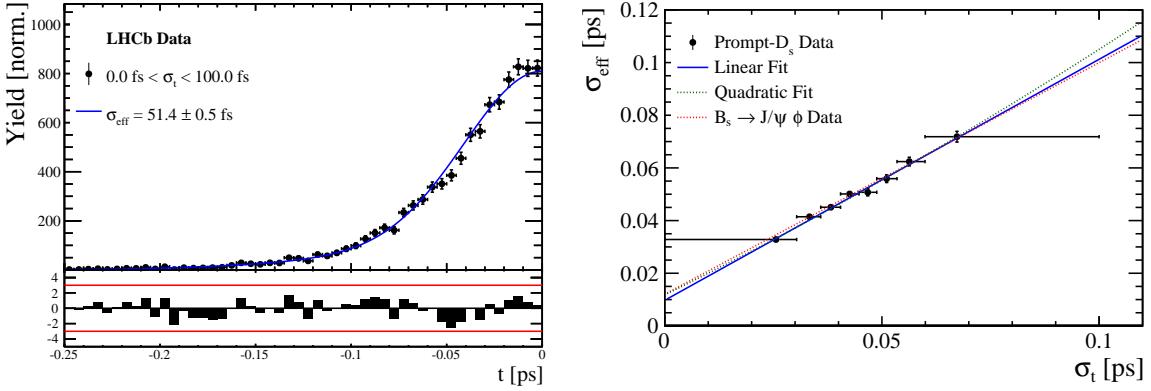


Figure 5.4: (Left) Decay-time distribution for fake B_s candidates from promptly produced D_s candidates, combined with random prompt $K\pi\pi$ bachelor tracks. (Right) The measured resolution σ_{eff} as function of the per-event decay time error estimate σ_t for fake B_s candidates (Run-II data). The 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_{vtx}^2/ndof	< 8
	χ_{DTF}^2/ndof	< 15
	t	< 0 ps
$D_s \rightarrow hhh$	χ_{vtx}^2/ndof	< 5
	DIRA	> 0.99994
	χ_{FD}^2	> 9
	p_T	> 1800 MeV
	χ_{IP}^2	< 9
	$\chi_{IP}^2(h)$	> 5
$D_s^- \rightarrow KK\pi^-$	Wrong PV veto	$nPV = 1 \parallel \min(\Delta\chi_{IP}^2) > 20$
	D^0 veto	$m(KK) < 1840$ MeV
$D_s^- \rightarrow K^*(892)K^-$	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
	$m(KK)$	$= m_\phi \pm 20$ MeV
$D_s^- \rightarrow \phi\pi^-$	PIDK(K^+)	> -10
	PIDK(K^-)	> -10
	PIDK(π^-)	< 20
	$m(KK)$	$\neq m_\phi \pm 20$ MeV
$D_s^- \rightarrow (KK\pi^-)_{NR}$	$m(K^+\pi^-)$	$= m_{K^*(892)} \pm 75$ MeV
	PIDK(K^+)	> -10
	PIDK(K^-)	> -5
	PIDK(π^-)	< 20
	$m(KK)$	$\neq m_\phi \pm 20$ MeV
$D_s \rightarrow \pi\pi\pi$	$m(K^+\pi^-)$	$\neq m_{K^*(892)} \pm 75$ MeV
	PIDK(K^+)	> 5
	PIDK(K^-)	> 5
	PIDK(π^-)	< 10
$X_s \rightarrow K\pi\pi$	PIDK(h)	< 10
	PIDp(h)	< 10
	D^0 veto	$m(\pi^+\pi^-) < 1700$ MeV
$X_s \rightarrow K\pi\pi$	$\chi_{IP}^2(h)$	< 40
	PIDK(K)	> 10
	PIDK(π)	< 5
	isMuon(h)	False
All tracks	p_T	> 500 MeV

518 **5.3 Cross-checks**

519 **5.3.1 Kinematic dependence**

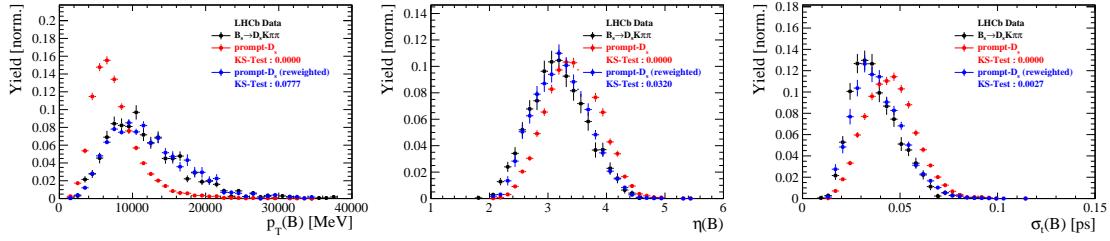


Figure 5.5

520 **5.3.2 DTF constraints**

521 6 Acceptance

522 6.1 MC corrections

523 6.1.1 Truth matching of simulated candidates

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

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

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

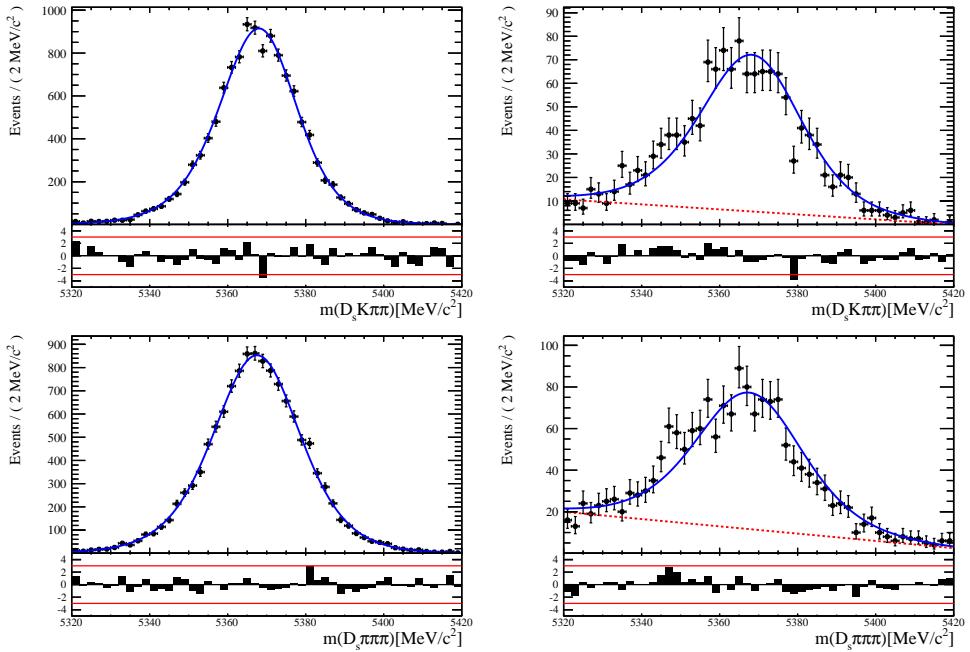


Figure 6.1: The reconstructed B_s mass distribution for simulated $B_s \rightarrow D_s K\pi\pi$ (top) and $B_s \rightarrow D_s \pi\pi\pi$ (bottom) decays classified with `BKGCAT` = 20 or 50 (left) and `BKGCAT` = 60 (right) after the full selection.

543 6.1.2 PID efficiencies

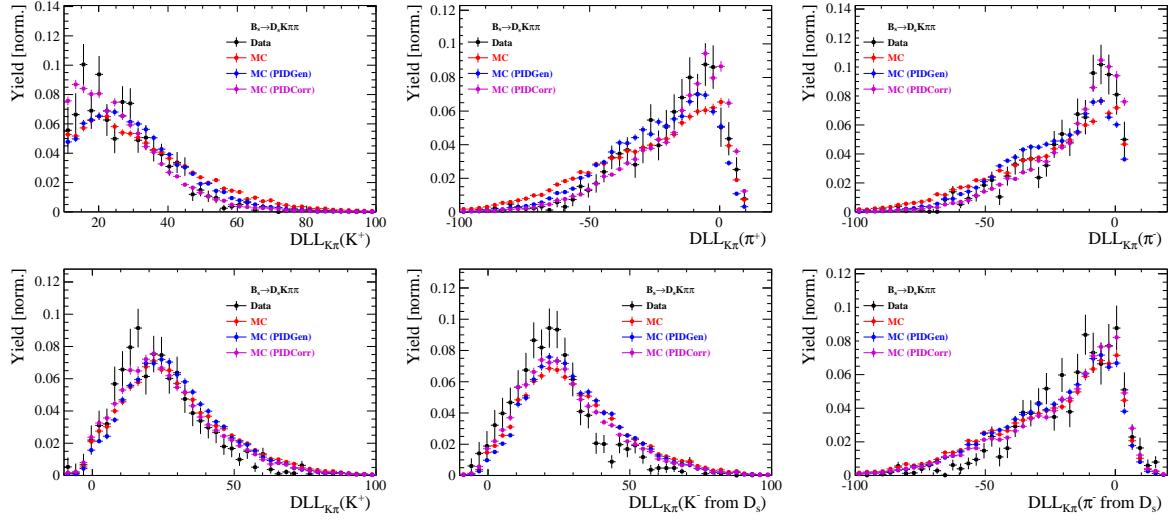


Figure 6.2

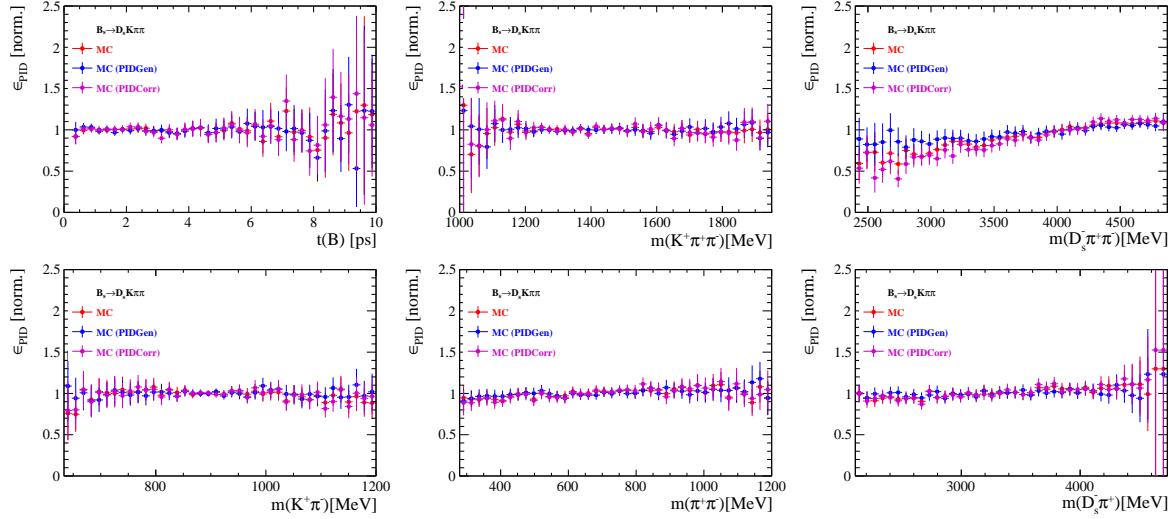


Figure 6.3

544 6.1.3 BDT efficiencies

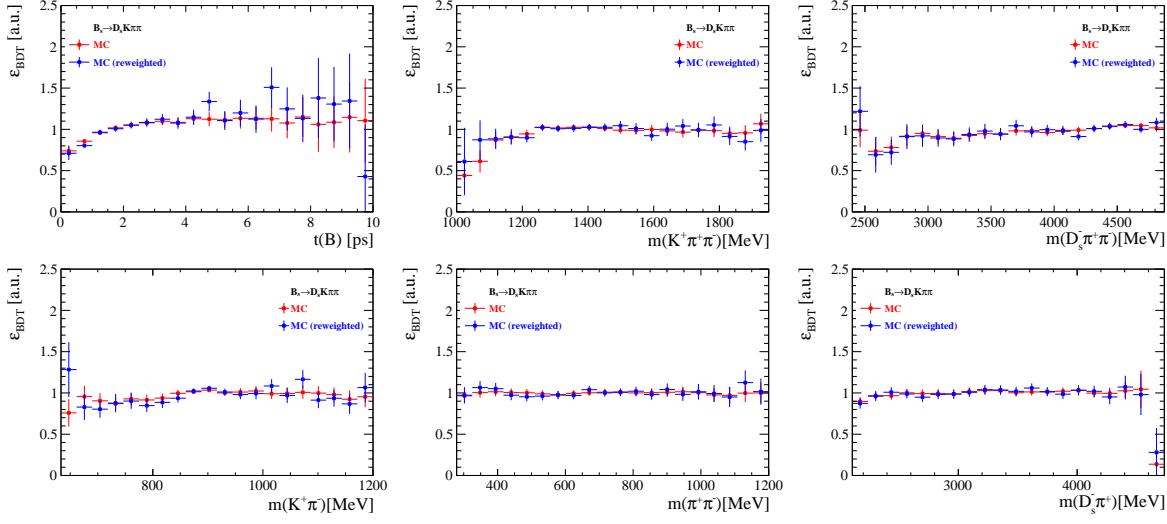


Figure 6.4

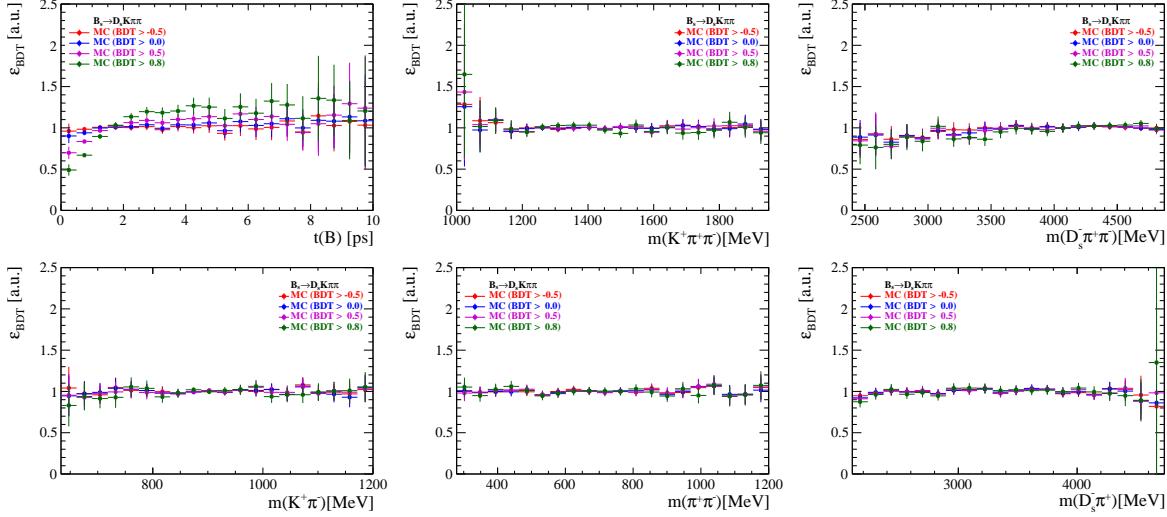


Figure 6.5

⁵⁴⁵ 6.1.4 Tracking efficiencies

546 **6.2 Decay-time acceptance**

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

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

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

560 A PDF of the form

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

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

570 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
 571 v_i , $i = [1, \dots, 8]$ are used. Since a rapid change of the decay time acceptance at low
 572 decay times due to the turn-on effect generated by the lifetime and other selection cuts is
 573 expected, more knots are placed in that regime. At higher decay times we expect linear
 574 behavior, with a possible small effect due to the VELO reconstruction. Therefore fewer
 575 knots are used. Furthermore, v_7 is fixed to 1 in order to normalize the overall acceptance
 576 function. To stabilise the last spline, v_8 is fixed by a linear extrapolation from the two
 577 previous splines:

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

578 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.

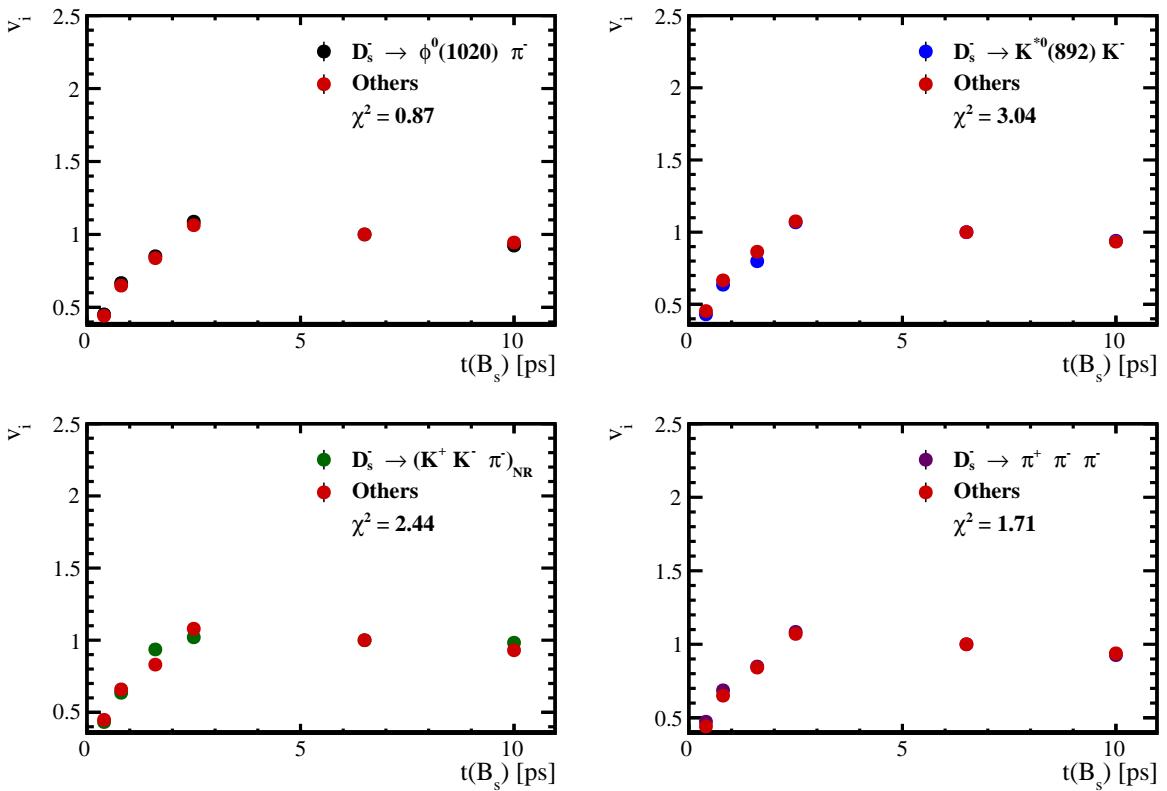


Figure 6.6: Comparison of the spline coefficients obtained from time-dependent fits to the $B_s^0 \rightarrow D_s\pi\pi\pi$ subsamples of different D_s final states. The comparison of one particular D_s state against all other states is shown.

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

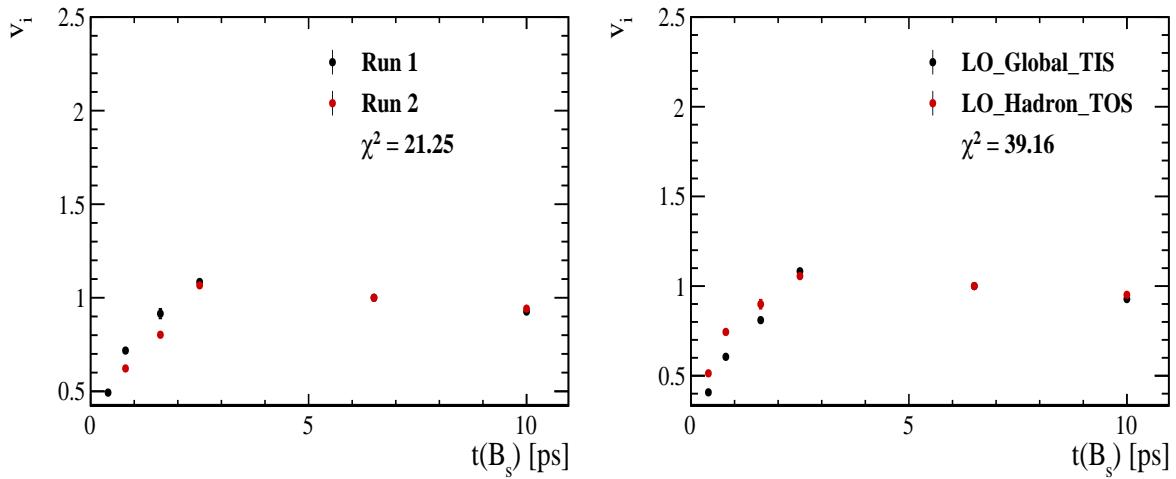


Figure 6.7: Comparison of the spline coefficients obtained from time-dependent fits to the $B_s^0 \rightarrow D_s \pi \pi \pi$ subsamples of (left) the different runs and (right) L0 trigger categories.

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

601 **6.2.2 Results**

602 The nominal fit to $B_s^0 \rightarrow D_s\pi\pi\pi$ data using this configuration is shown in Figure ??.
603 Note that the normalization of the splines in the following figures is not in scale. The fit
604 parameters obtained from the described fits to data and simulation are summarised in
605 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	0.569 ± 0.028	0.496 ± 0.015	0.966 ± 0.044
0.8	v_1	0.787 ± 0.043	0.737 ± 0.024	0.893 ± 0.049
1.6	v_2	0.899 ± 0.062	0.943 ± 0.039	0.985 ± 0.060
2.5	v_3	1.080 ± 0.030	1.093 ± 0.022	0.980 ± 0.031
6.5	v_4	1.0 (fixed)	1.0 (fixed)	1.0 (fixed)
10.0	v_5	0.930 (interpolated)	0.919 (interpolated)	1.018 (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	0.389 ± 0.020	0.506 ± 0.015	0.909 ± 0.041
0.8	v_1	0.593 ± 0.033	0.744 ± 0.024	0.897 ± 0.048
1.6	v_2	0.799 ± 0.052	0.965 ± 0.039	0.928 ± 0.052
2.5	v_3	1.112 ± 0.033	1.112 ± 0.022	0.941 ± 0.036
6.5	v_4	1.0 (fixed)	1.0 (fixed)	1.0 (fixed)
10.0	v_5	0.902 (interpolated)	0.902 (interpolated)	1.052 (interpolated)

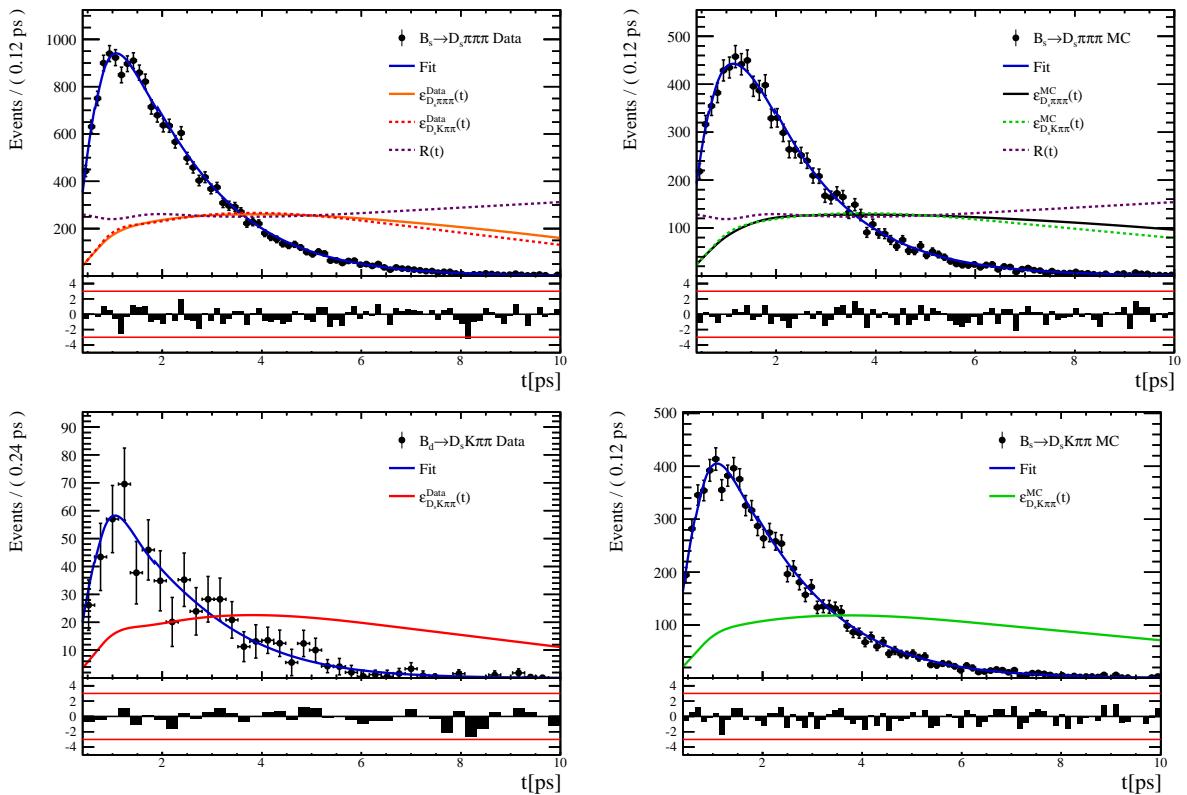


Figure 6.8

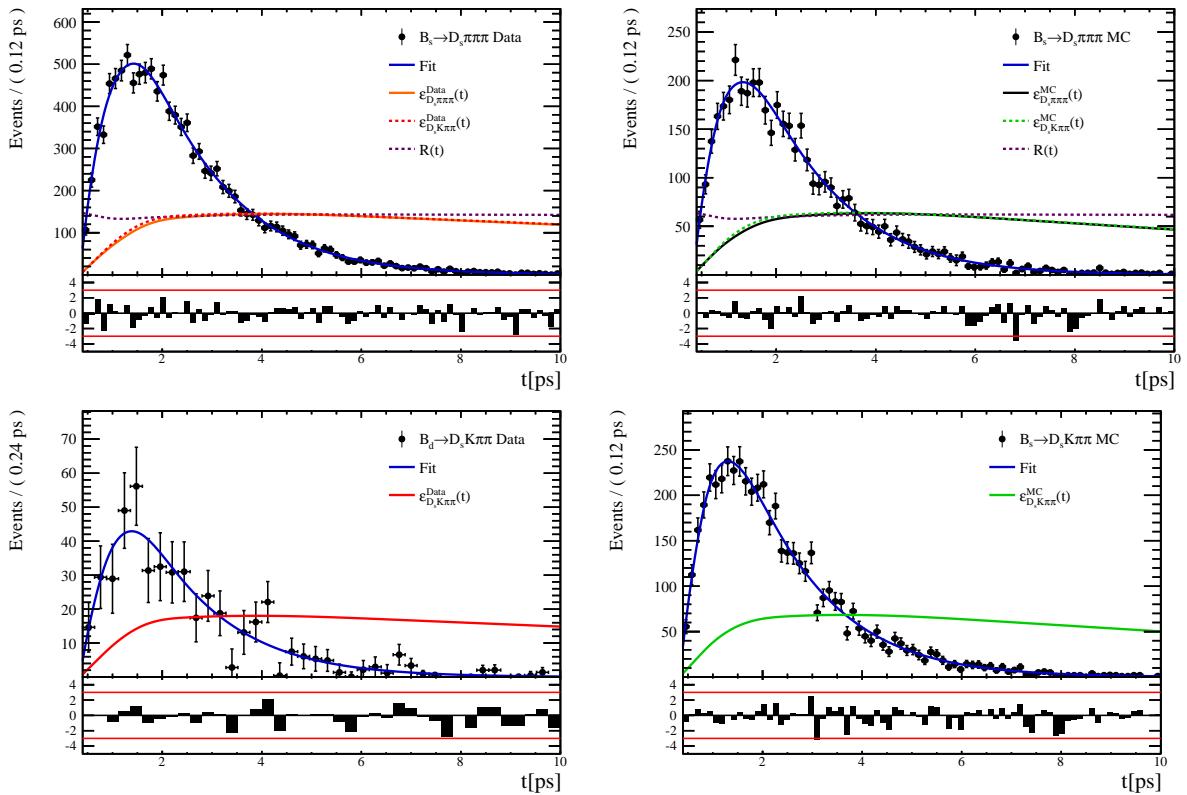


Figure 6.9:

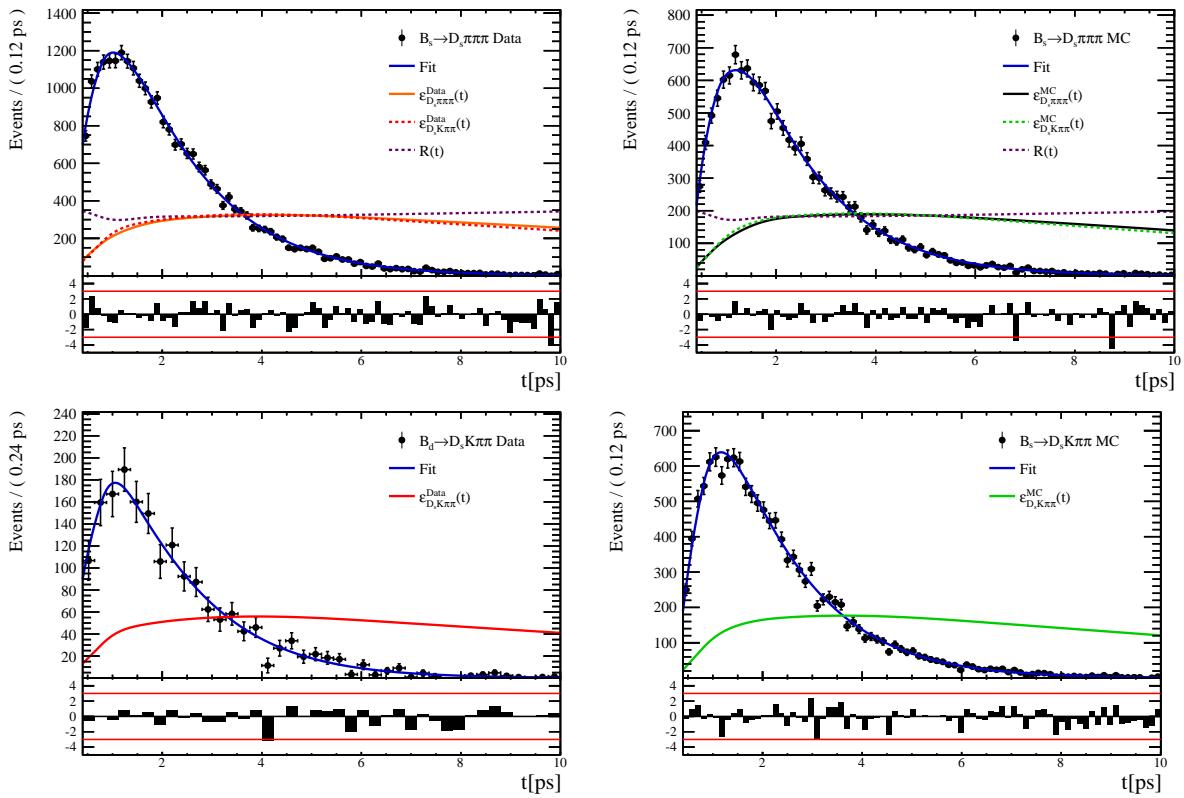


Figure 6.10

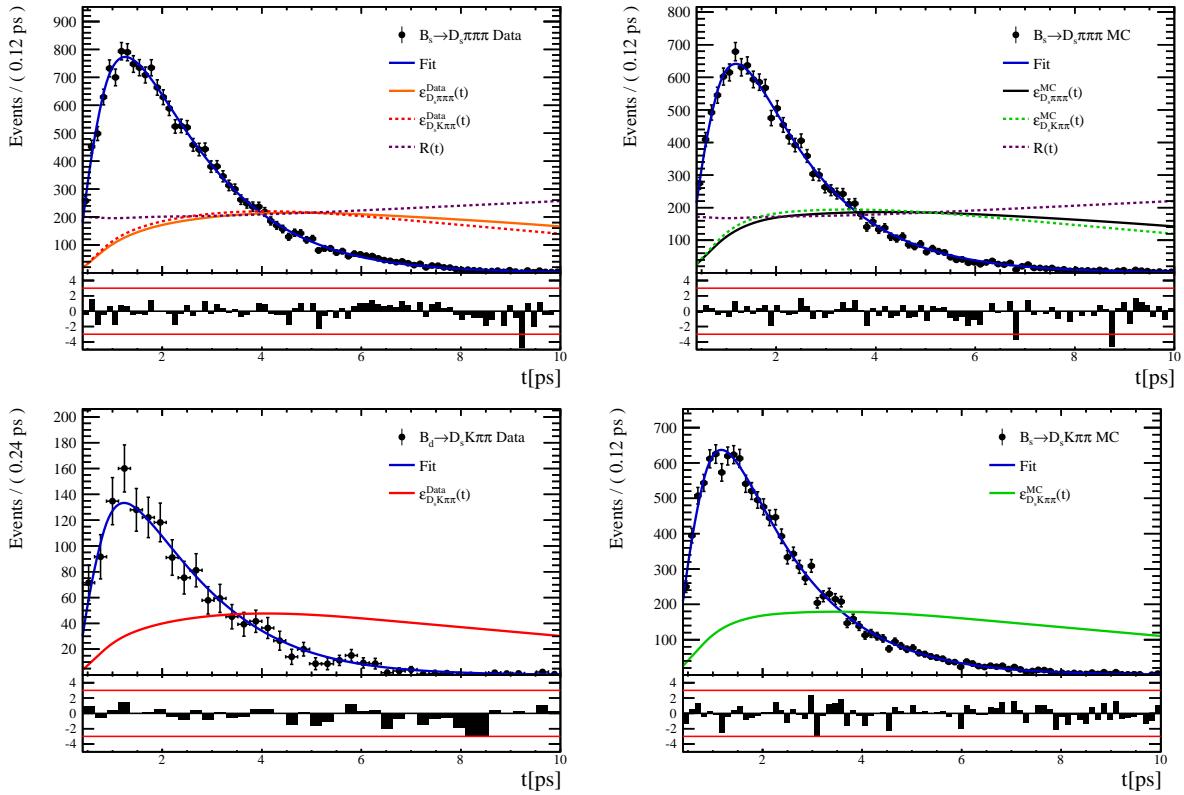


Figure 6.11:

606 **6.3 Phasespace acceptance**

607 7 Flavour Tagging

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

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

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

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

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

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

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

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

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

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

647 The tagging calibration is determined using a time-dependent fit to the full $B_s^0 \rightarrow D_s\pi\pi\pi$
 648 sample, where the mixing frequency Δm_s is fixed to the nominal PDG value [32]. The
 649 calibration procedure for the OS tagging algorithms (Sec.7.1) and the SS kaon tagger
 650 (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,
 651 which is selected following the steps described in Sec. 3. The similar selection ensures
 652 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
 653 terms of the decay kinematics, which are crucial for the flavour tagging. Section 7.3 shows
 654 the compatibility of both samples. After applying the calibration, the response of the OS
 655 and SS taggers are combined, which is shown in Sec. 7.4.

656 7.1 OS tagging calibration

657 The responses of the OS electron, muon, neural net kaon and the secondary vertex charge
 658 taggers are combined for the mistag calibration. The distributions of the predicted OS
 659 mistag for signal candidates from $B_s^0 \rightarrow D_s\pi\pi\pi$ is shown in (Run 1) Figure 7.1 and (Run
 660 2) Figure 7.2. The measured tagging power for the OS combination is $\epsilon_{eff,OS} = 4.81\%$.

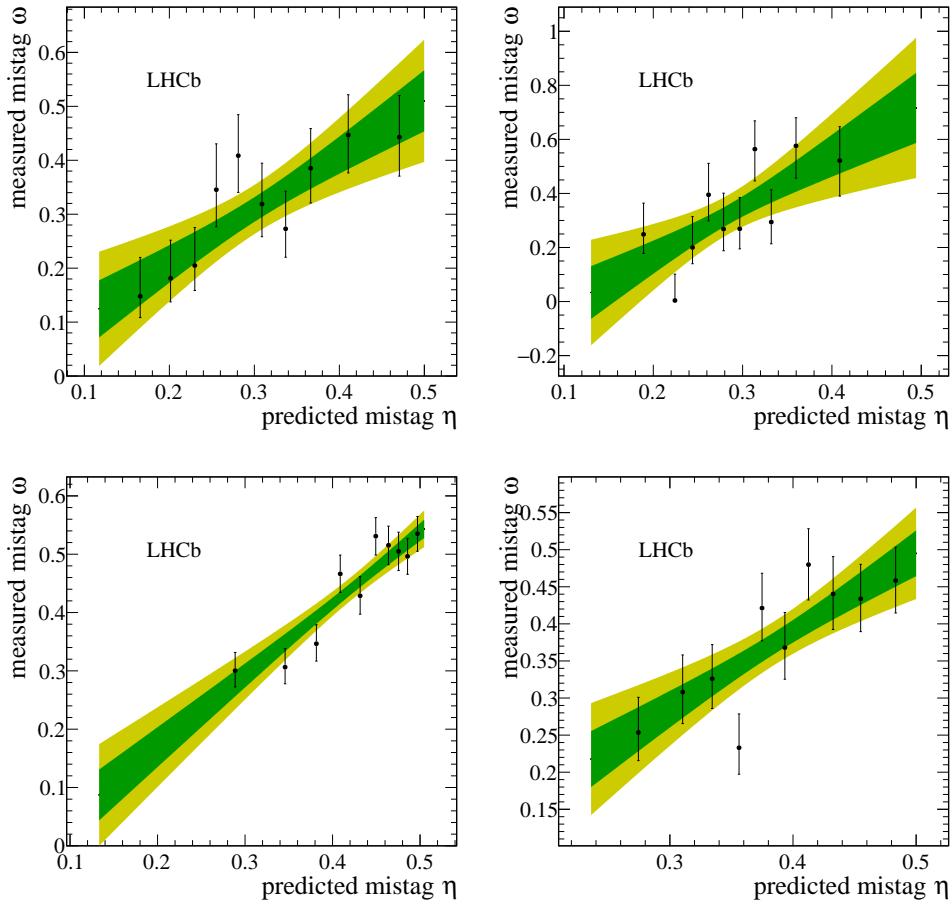


Figure 7.1: Predicted versus measured mistag probability for the (top left) OS muon, (top right) OS electron, (bottom left) OS kaon and (bottom right) OS vertex charge tagger for Run 1. A linear fit, including the 1σ and 2σ error bands is overlaid for each tagger.

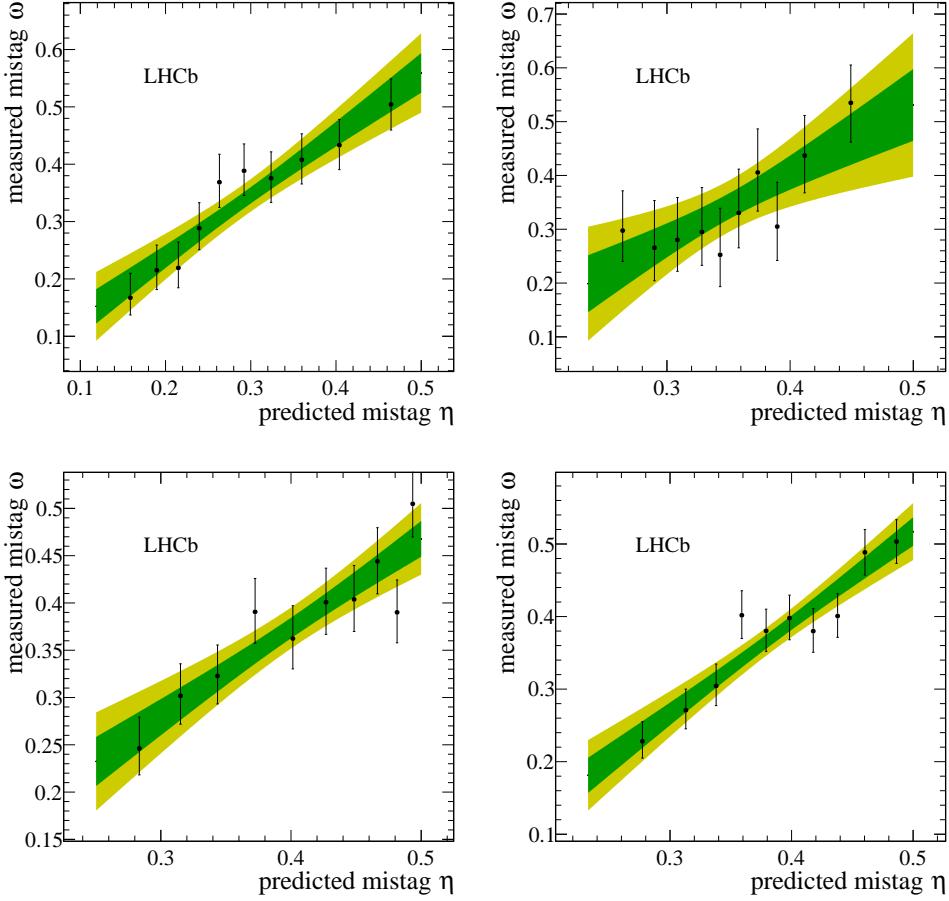


Figure 7.2: Predicted versus measured mistag probability for the (top left) OS muon, (top right) OS electron, (bottom left) OS kaon and (bottom right) OS vertex charge tagger for Run 2. A linear fit, including the 1σ and 2σ error bands is overlaid for each tagger.

661 7.2 SS tagging calibration

662 The SS neural net kaon tagger can be calibrated using the flavour-specific $B_s^0 \rightarrow D_s \pi \pi \pi$
 663 decay. Its development, performance and calibration is described in detail in [38]. Figure
 664 7.3 shows the distribution of the predicted mistag of the neural net kaon tagger. The
 665 extracted calibration parameters and tagging asymmetries are summarized in Table 7.1
 666 and the measured tagging power for this algorithm is $\epsilon_{eff,SS} = 3.22\%$.

p_0	p_1	$\langle \eta \rangle$	ϵ_{tag}	Δp_0	Δp_1	ϵ_{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 ± 0.03 (stat) ± 0.26 (cal)

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

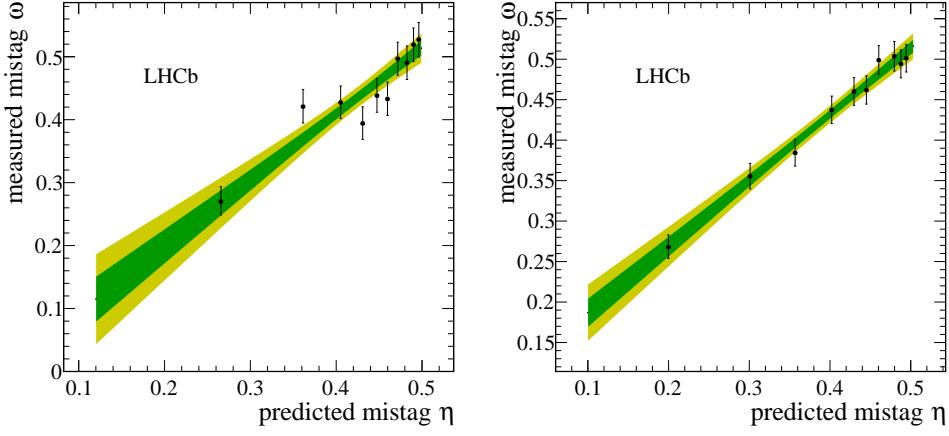


Figure 7.3: Predicted versus measured mistag probability for the SS neural net kaon tagger for (left) Run 1 and (right) Run 2. A linear fit, including the 1σ and 2σ error bands is overlaid for both distributions.

667 7.3 Tagging performance comparison between the signal and 668 normalization channel

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

675 The data distributions of the predicted mistag probability η for the OS combination and
676 the SS kaon tagger are shown Fig. 7.4.

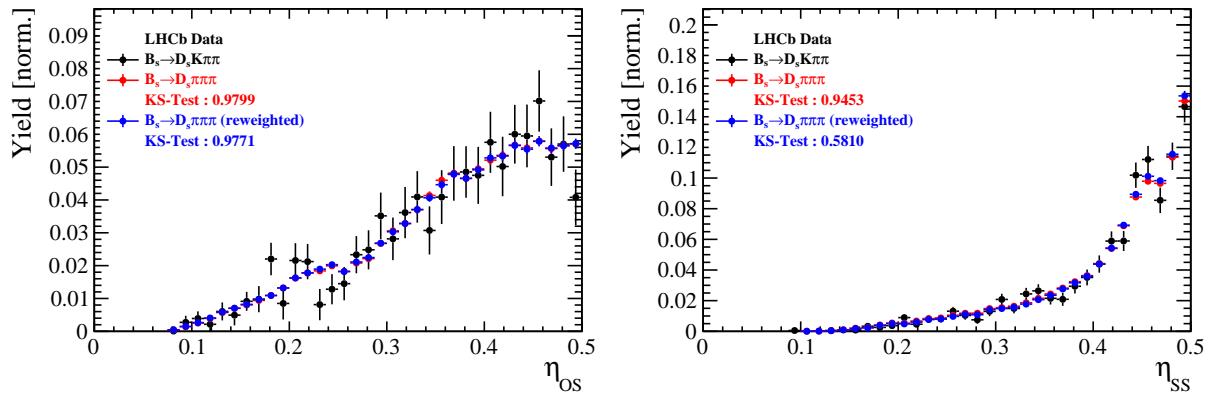


Figure 7.4: Distributions of the predicted mistag η for the OS combination (left) and the SS kaon tagger (right) for signal candidates in the $B_s^0 \rightarrow D_s K\pi\pi$ (black) and $B_s^0 \rightarrow D_s \pi\pi\pi$ (red) data samples.

677 Both, data and simulated samples, show good agreement between the signal and
678 normalization channel.

To justify the portability of the flavour tagging calibration obtained from $B_s^0 \rightarrow D_s\pi\pi\pi$ to the $B_s^0 \rightarrow D_s K\pi\pi$ channel, besides the good agreement of the distributions shown above, the dependence of the measured mistag ω on the predicted mistag η has to be compatible in both channels. This dependence is shown in Fig. 7.5 for simulated signal events of both channels, where good agreement is observed.

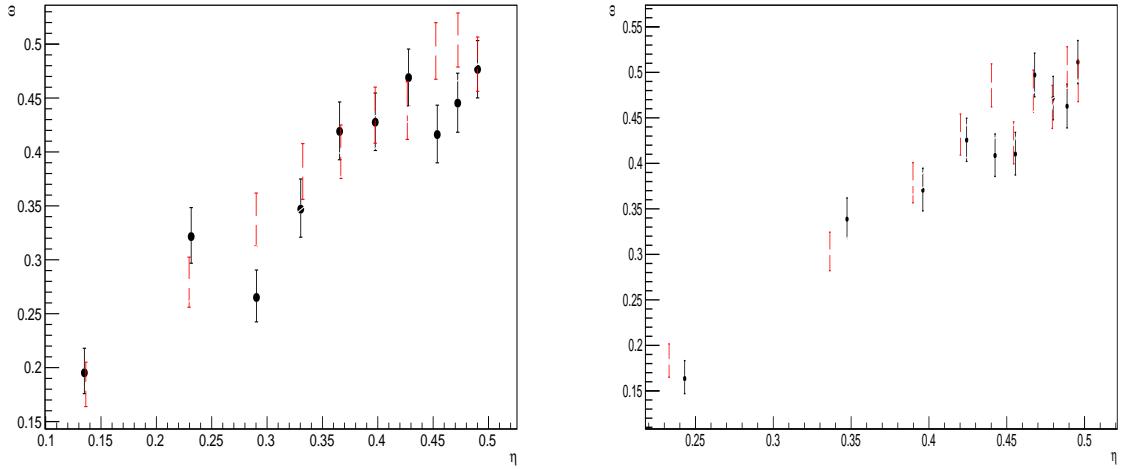


Figure 7.5: Dependence of the observed mistag ω on the predicted mistag η for the (left) OS combination and the (right) SS kaon tagger, found in the simulated $B_s^0 \rightarrow D_s K\pi\pi$ (black) and $B_s^0 \rightarrow D_s\pi\pi\pi$ (red) signal samples.

7.4 Combination of OS and SS taggers

In the time- and amplitude-dependent fit to $B_s^0 \rightarrow D_s K\pi\pi$ data, the obtained tagging responses of the OS and SS tagger will be combined after the calibration described in the previous sections is applied. Events that acquire a mistag probability greater than 0.5 after the calibration will have their tagging decision flipped. For events where only one of the two taggers fired, the combination of the tagging decision is trivial. In those events where both taggers made a decision, we use the standard combination of taggers [39] provided by the flavour tagging group. In the nominal fit, the calibrated mistags ω are combined event by event for the OS and SS tagger, thus adding one observable to the fit procedure. This ensures that the uncertainties of the OS and SS tagging calibration parameters are propagated properly to the combined tagging response for each event.

The tagging performance for the combined tagger in the categories SS tagged only, OS tagged only and SS+OS tagged, are shown in (Run 1) Tab. 7.2 and (Run 2) Tab. 7.2.

Table 7.2: 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 7.3: 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

697 8 Production and Detection Asymmetries

698 8.1 B_s Production Asymmetry

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

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

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

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

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

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

709 As for Run-II data no measurement is available yet, we determine the production asym-
710 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)	$-0.0586 \pm 0.0648 \pm 0.0150$	$0.0537 \pm 0.0447 \pm 0.0124$

711 8.2 $K^-\pi^+$ Detection Asymmetry

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

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

720 is used.

721 This asymmetry can be measured from the difference in asymmetries in the $D^+ \rightarrow$
 722 $K^-\pi^+\pi^+$ 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, η) and the π^\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.

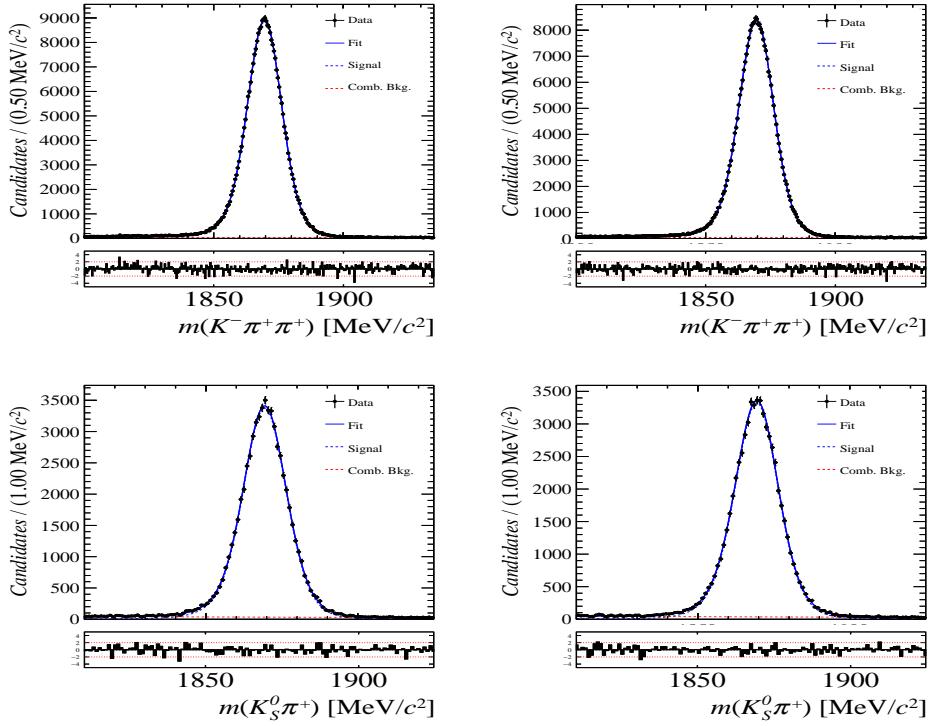


Figure 8.1: Distributions of the invariant mass of (top) $D^\pm \rightarrow K^\pm\pi^\pm\pi^\pm$ and (bottom) $D^\pm \rightarrow K_S^0\pi^\pm$ candidates for Run-I data from the calibration samples. A fit described in the text is overlaid.

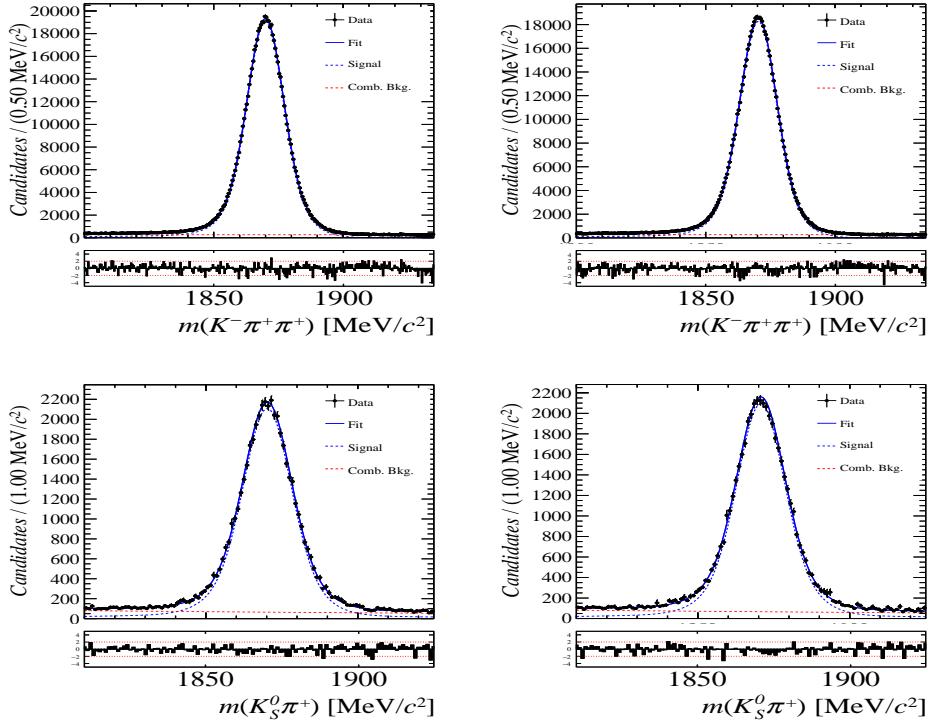


Figure 8.2: Distributions of the invariant mass of (top) $D^\pm \rightarrow K^\pm\pi^\pm\pi^\pm$ and (bottom) $D^\pm \rightarrow K_S^0\pi^\pm$ candidates for Run-II data from the calibration samples. A fit described in the text is overlaid.

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 [44] 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 all D_s final states. In the fit, the values of Γ_s and $\Delta\Gamma_s$ are fixed to
 762 the latest PDG report [12]. All tagging parameters are fixed to the central values found in
 763 the tagging calibration, described in Sec. 7. Due to the fact that the $B_s^0 \rightarrow D_s \pi\pi\pi$ decay
 764 is 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

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

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. 9.1.

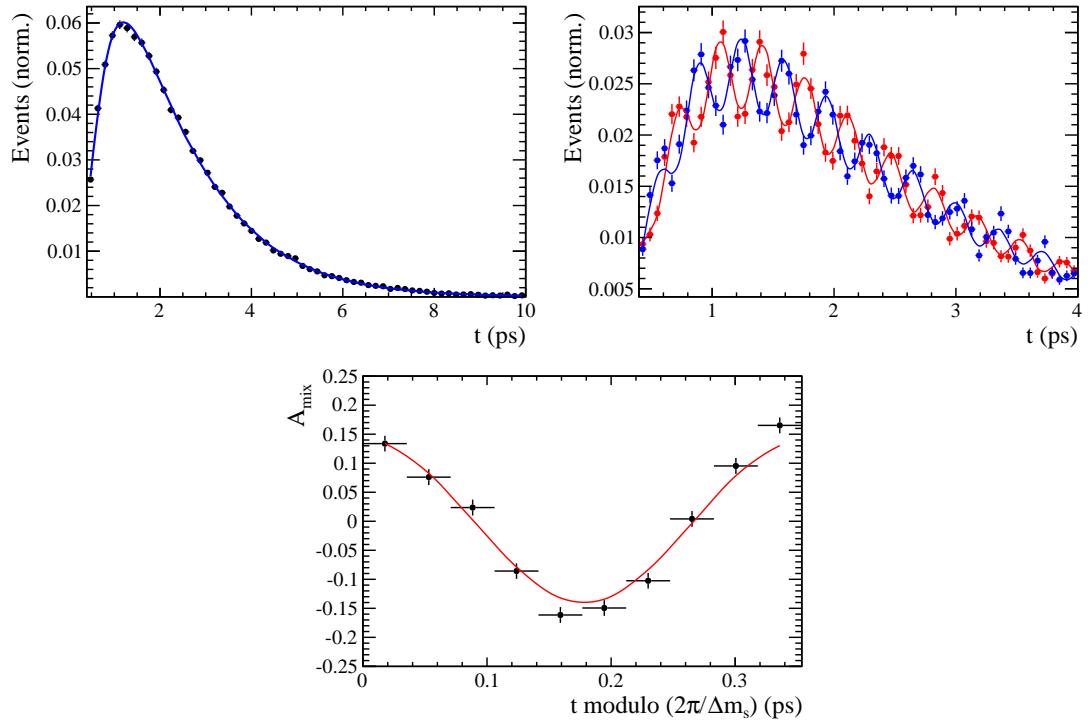


Figure 9.1: Top left: Flavour averaged decay time distribution of $B_s^0 \rightarrow D_s\pi\pi\pi$ candidates with the averaged fit overlaid. Top right: Tagged decay time distribution of mixed (red) and unmixed (blue) signal candidates with the fit described in the text overlaid. Bottom: Time-dependent asymmetry A_{mix} between mixed and unmixed B_s^0 candidates in bins of $t/(2\pi\Delta m_s)$. A fit to this distribution using a $\cos(t \cdot \Delta m_s)$ function is overlaid.

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
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
	Δm_s	$\text{xx.xx} \pm 0.0110$

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

The time-dependent fit to the sWeighted sample of $B_s^0 \rightarrow D_s K\pi\pi$ signal candidates is performed simultaneously in the four bins defined in Sec. 6.2.1, splitting the data into Run I & II and trigger category 0 (L0Hadron TOS) & 1 (L0Hadron TIS). In these four bins, the respective description of the decay-time acceptance (Sec. 6) is used as an input. As further input the decay-time resolution scaling relation, found separately for Run I & II in Sec. 5, is used in the simultaneous fit. The full fit model is given in Eq. 9.1, where $\int P(x, t, q_t, q_f)$ is:

$$\int P(x, t, q_t, q_f) dx \propto [\cosh\left(\frac{\Delta\Gamma t}{2}\right) + q_t q_f C \cos(m_s t) + \kappa D_{q_f} \sinh\left(\frac{\Delta\Gamma t}{2}\right) - q_t \kappa S_{q_f} \sin(m_s t)] e^{-\Gamma t}. \quad (9.3)$$

Note that the integration over the available phase space x gives rise to the coherence factor κ , which dilutes the sensitivity to the CP coefficients D & S and with that, also to the CKM phase γ . All input parameters from the tagging, time acceptance and resolution are fixed in the fit. The CP coefficients, as well as κ , are therefore the only parameters left floating. The data distribution and the overlaid fit is shown in Fig. 9.2.

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 \pm 0.116
D	xx.xx \pm 0.287
\bar{D}	xx.xx \pm 0.269
S	xx.xx \pm 0.162
\bar{S}	xx.xx \pm 0.163

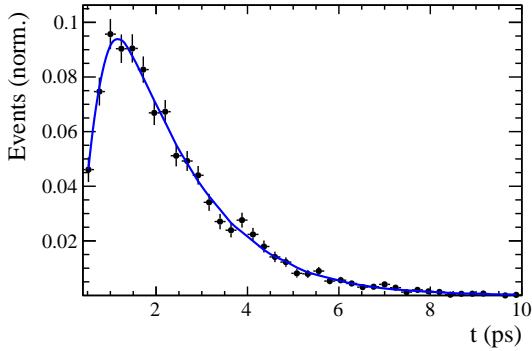


Figure 9.2: Tagged and sWeighted decay-time distribution of $B_s^0 \rightarrow D_s K\pi\pi$ signal candidates. The fit described in the text is overlaid.

9.3 sFit model validation using toy studies

The fit model and procedure is validated using pseudo experiments. 1000 toys are generated using the model described in Eq. 9.1 and 2.6. Each pseudo experiment is generated with

785 the same amount of signal events found in the Run I + 2015/2016 data samples. Figure
 786 9.3 shows the pull distributions for all CP coefficients, where every pull P of a parameter
 787 x is given as $P = \frac{x_{gen} - x_{fit}}{\Delta x}$.

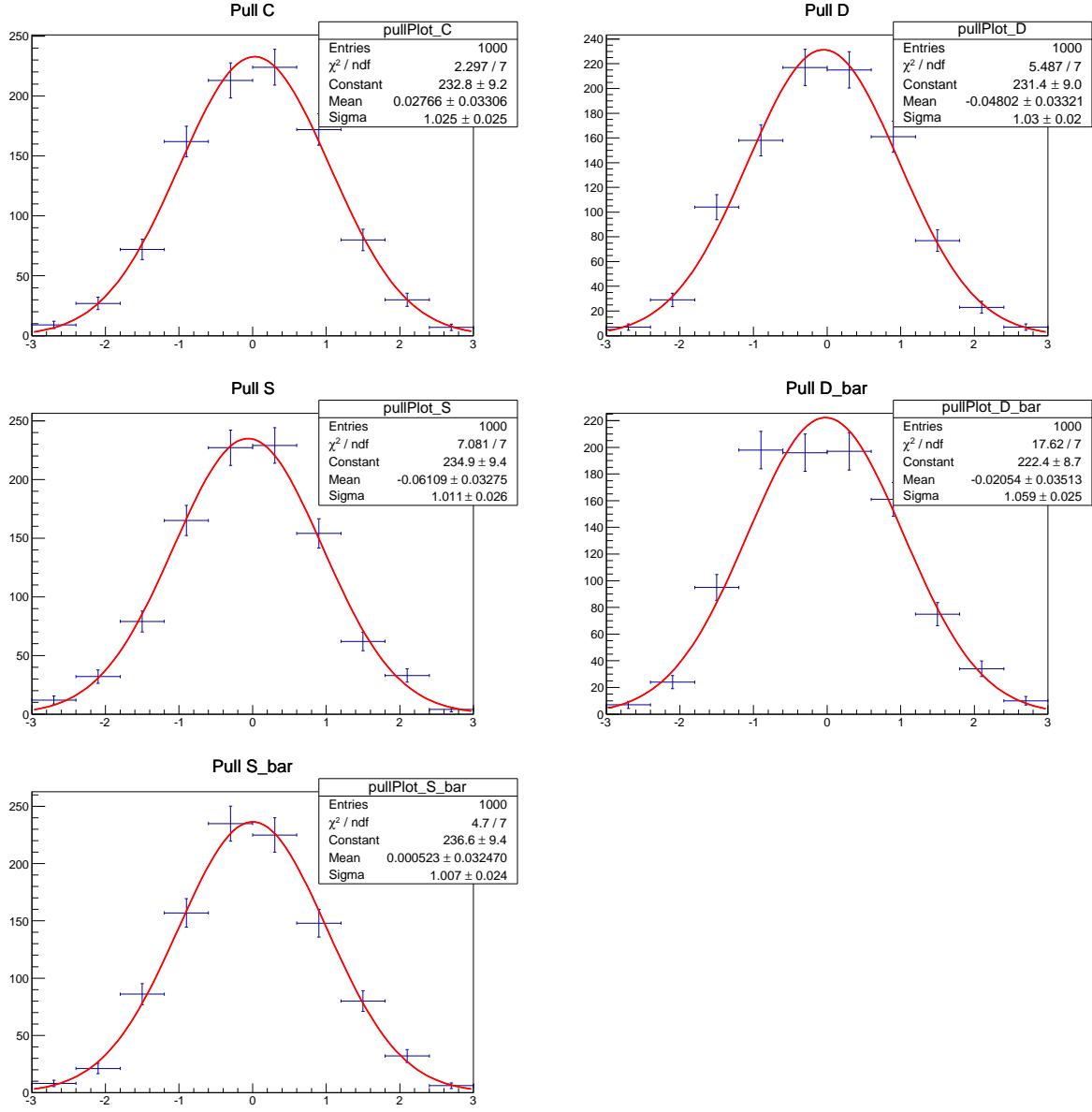


Figure 9.3: Pull distributions from toy studies for the time-dependent fit, done with 1000 pseudo experiments.

788 Table 9.3 summarizes the means μ and widths σ of these pull distributions.

Table 9.3: Pull parameters for CP coefficients from the toy studies for the time-dependent fit.

Parameter	μ of pull distribution	σ of pull distribution
C	0.0276566 ± 0.0330601	1.02492 ± 0.0251927
D	-0.0480232 ± 0.0332088	1.02998 ± 0.0237533
S	-0.0610883 ± 0.0327533	1.01134 ± 0.0256215
\bar{D}	-0.0205393 ± 0.0351271	1.05858 ± 0.0252034
\bar{S}	$0.000523013 \pm 0.0324702$	1.00746 ± 0.0244268

789 10 Time dependent amplitude fit

790 10.1 Signal Model Construction

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

797 To build the amplitude model, one could successively add amplitudes on top of one
798 another until a reasonable agreement between data and fit was achieved. However, this
799 step-wise approach is not particularly suitable for amplitude analyses as discussed in
800 Ref. [45]. Instead, we include the whole pool of amplitudes in the first instance and use
801 the Least Absolute Shrinkage and Selection Operator [45, 46] (LASSO) approach to limit
802 the model complexity. In this method, the event likelihood is extended by a penalty term

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

803 which shrinks the amplitude coefficients towards zero. The amount of shrinkage is
804 controlled by the parameter λ , to be tuned on data. Higher values for λ encourage sparse
805 models, *i.e.* models with only a few non-zero amplitude coefficients. The optimal value
806 for λ is found by minimizing the Bayesian information criteria [47] (BIC),

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

807 where N_{Sig} is the number of signal events and r is the number of amplitudes with a decay
808 fraction above a certain threshold. In this way, the optimal λ balances the fit quality
809 ($-2 \log \mathcal{L}$) against the model complexity. The LASSO penalty term is only used to select
810 the model. Afterwards, this term must be discarded in the final amplitude fit with the
811 selected model, otherwise the parameter uncertainties would be biased.

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

- 816 1. The fit fraction threshold for inclusion in the final model was varied within the
817 interval [0.05, 5]%. The set of selected amplitudes is stable for thresholds between
818 0.1% and 1%. Other choices result in marginally different models containing one
819 component more or less.
 - 820 2. Instead of BIC, the Akaike information criteria ($\text{AIC}(\lambda) = -2 \log \mathcal{L} + 2r$ [48]) was
821 used to optimize λ . For a given threshold, the AIC method tends to prefer lower
822 λ values. However, the set of models obtained varying the threshold within the
823 interval [0.05, 5]% is identical to the BIC method.
 - 824 3. The amplitudes selected under nominal conditions were excluded one-by-one from
825 the set of all amplitudes considered.
- 826 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

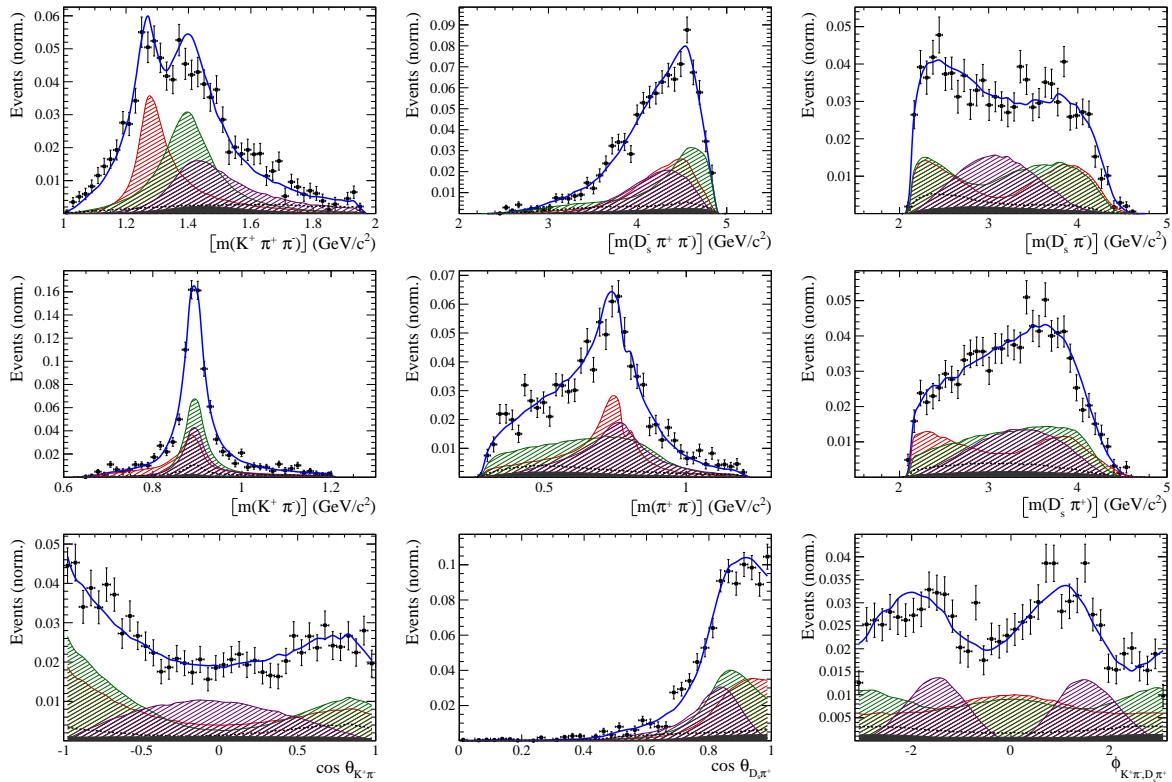


Figure 10.1

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
<i>Bugg</i> $B_s \rightarrow \text{NonResS0} (\rightarrow D_s^- K^+) \sigma (\rightarrow \pi^+ \pi^-)$	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
<i>Bugg</i> $B_s \rightarrow K(1460)^+ (\rightarrow \sigma (\rightarrow \pi^+ \pi^-) K^+) D_s^-$	8.75 \pm 1.10
$B_s \rightarrow \text{NonResS0} (\rightarrow D_s^- \pi^+) K^*(892)^0 (\rightarrow K^+ \pi^-)$	58.07 \pm 17.15
Sum	163.34 \pm 12.39

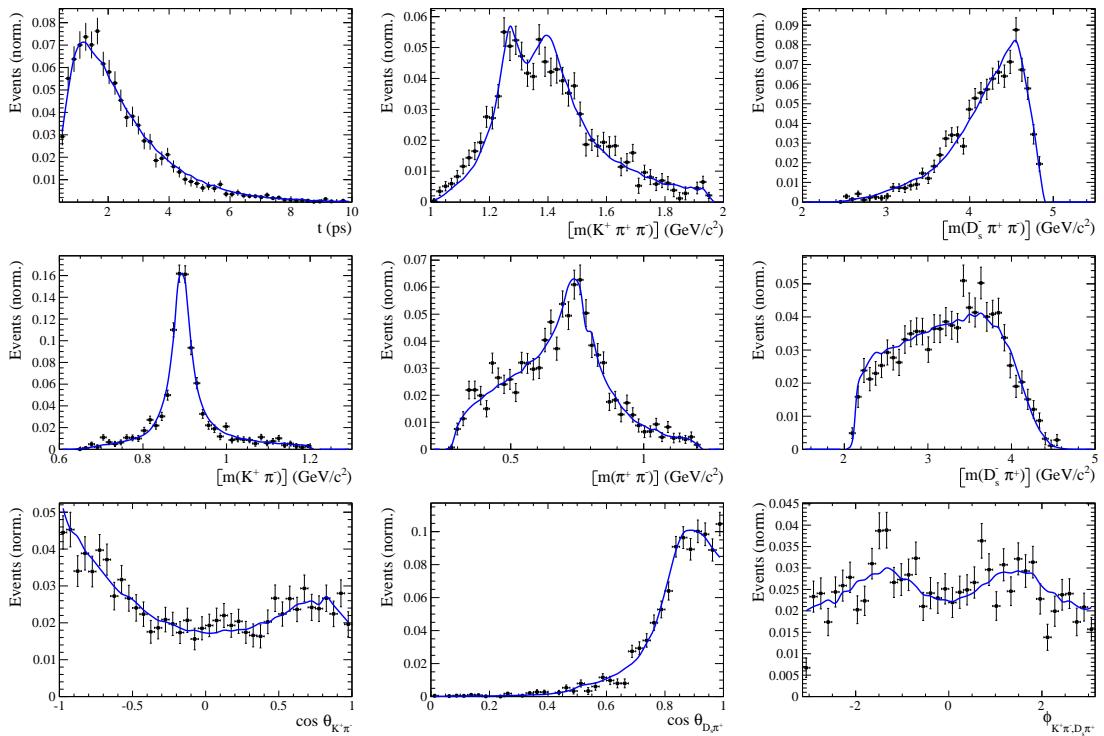


Figure 10.2

828 11 Systematic uncertainties

829 This section covers all relevant systematic uncertainties on the measured observables.
 830 In particular, the model dependent description of the invariant B_s^0 mass spectrum, the
 831 parametrization of the time acceptance using cubic splines, as well as the scaling of the
 832 time resolution and tagging calibration are potential sources of systematic errors. The
 833 largest contribution of systematic uncertainty is expected to appear in the choice of
 834 amplitudes entering the model to describe the 5 dimensional phase space, discussed in
 835 Section 10.

836 11.1 Models for B_s^0 mass distribution

837 The statistical subtraction of the residual background [44], left after the full selection,
 838 relies on the correct description of the invariant B_s^0 mass distribution. Since the choice
 839 of signal and background models is not unique, alternative descriptions which lead to
 840 slightly different yields for the signal and background components are available. The
 841 difference in yields could result in shifted values for the measured observables and are
 842 therefore treated as systematic uncertainty.

843

844 11.1.1 Signal model

845 The Johnson's SU function which is used as nominal signal model is replaced by a double
 846 Crystal Ball [49]. The crystal ball model is given by a gaussian core with an exponential
 847 tail on one side. Choosing a double Crystal Ball allows for asymmetric tails in a slightly
 848 different way compared to the Johnson's SU function. Table xXx summarizes the observed
 849 differences in signal and background yields.

850 11.1.2 Background model

851 For the description of the partially reconstructed background, a combination of the
 852 RooHILLdini and RooHORNsdini model [REF HERE] is used instead of the nominal
 853 model of three bifurcated gaussians. The HORNsdini model is used to describe the
 854 $B_s^0 \rightarrow D_s^* [\rightarrow D_s(\pi^0)] X_{s/d}$ decay, where the brackets around the π^0 indicate that it
 855 is missed in the reconstruction. The $D_s^* \rightarrow D_s\pi^0$ decay is a Vector \rightarrow Scalar-Scalar
 856 ($1^- \rightarrow 0^-0^-$) transition. Using the helicity of the D_s , one can show that this results in a
 857 double-peak structure in the reconstructed B_s^0 mass. Therefore, the HORNsdini shape
 858 consists of a gaussian-like double-peak structure:

$$859 \text{HORN}(m_{B_s^0}) = \int_a^b dm_{B_s^0} \left(m_{B_s^0} - \frac{a+b}{2} \right)^2 \mathcal{D}\mathcal{G}(m_{B_s^0} | \mu, \sigma, f_G) \left(\frac{1-\zeta}{b-a} m_{B_s^0} + \frac{b\zeta-a}{b-a} \right), \\ (11.1)$$

860 where a and b are the kinematic endpoints of the distribution and ζ is the positive,
 861 real fraction of the two peak heights. Additionally, the shape is convoluted with a gaussian
 862 to account for resolution effects.

863 The HILLdini model parametrizes the invariant mass shape of $B_s^0 \rightarrow D_s^* [\rightarrow D_s(\gamma)] X_{s/d}$
 candidates, where the γ is not reconstructed. Contrary to the previously discussed process,

864 the $Ds^* \rightarrow D_s\gamma$ is a Vector → Scalar-Vector ($1^- \rightarrow 0^-1^-$) transition. From helicity
 865 arguments, the expected shape in the mass distribution of B_s^0 candidates follows a
 866 parabolic curve without any peaking structure. To accommodate for this shape, the
 867 HILLdini model consists of a parabolic curve between the kinematic endpoints a & b:

$$HILL(m_{B_s^0}) = \begin{cases} -(m_{B_s^0} - a)(m_{B_s^0} - b), & \text{for } a < m_{B_s^0} < b \\ 0, & \text{otherwise.} \end{cases} \quad (11.2)$$

868 This shape is convoluted with the same gaussian resolution function used for the
 869 HORNSdini model. The resulting differences in yields is shown in Table xXx.

870
 871 To study systematic uncertainties originating from the description of the combinatorial
 872 background, the nominal second order polynomial is replaced by an exponential function.
 873 The changes in signal and background yields after refitting with this alternative shape are
 874 shown in Table xXx.

875

876 11.1.3 Systematic effect on observables

877 The shift of the central values of the observables in the full fit when using sWeights
 878 obtained from a combination of alternative models, as well as using only one alternative
 879 model for the signal/comb.background/part.reco.background and keeping the nominal
 880 model for the other parts, is shown in Table yYy. We conservatively choose the biggest
 881 variation as systematic uncertainty from the modelling of the invariant B_s^0 mass spectrum.

882 11.2 Decay-time acceptance

883 To investigate the systematic uncertainty related to the decay-time dependent efficiency,
 884 we vary our parametrization of the acceptance using cubic splines. This is explicitly
 885 done by choosing slightly different knot positions, varying the spline coefficients at the
 886 nominal positions within their statistical uncertainties and adding/subtracting knots
 887 in the range $0.4\text{ ps} < t < 11\text{ ps}$. Additionally, an adaptive binning scheme is used to
 888 determine the knot positions in a way that roughly equal amounts of data is covered
 889 between two knots. Strictly speaking, the variation of the spline coefficients within their
 890 uncertainty gives the statistical uncertainty of the decay-time acceptance parametrization.
 891 For the presented measurement, this is done using the Cholesky decomposition [50] of
 892 the covariance matrix of coefficients c_i , generating toy splines with randomized coefficient
 893 values $c_{i,toy}$ from this decomposition and refitting using the toy spline. Furthermore, the
 894 fit to the decay-time distribution of signal $B_s^0 \rightarrow D_s\pi\pi\pi$ candidates, used to determine
 895 the spline parametrization, is reiterated with varying fixed/constrained values for $\Delta\Gamma_s$.

896 11.2.1 Varition of knot positions

897 The nominal knot positions are changed to be:

$$k_{alt1}(t) = [0.5 \ 1 \ 1.5 \ 2 \ 3 \ 6 \ 9.5], \ k_{alt2}(t) = [0.5 \ 1 \ 1.5 \ 2 \ 3 \ 9 \ 11], \ k_{adaptive}(t) = [0.7 \ 1.2 \ 1.7 \ 2.2 \ 6.3]$$

898 11.2.2 Variation of spline coefficients

899 Due to the sizeable correlation of the spline coefficients c_i determined in Chapter 6.2, the
900 variations of the observables in the amplitude fit when changing one spline coefficient can
901 not be added up in quadrature for all coefficients. To simplify the problem, a Cholesky
902 decomposition [50] is used to generate a set of uncorrelated vectors from the covariance
903 matrix A_{cov} . It can be shown that every Hermitian positive-definite matrix, such as A_{cov} ,
904 has a unique Cholesky decomposition of the form:

$$A_{cov} = L \cdot L^T, \quad (11.3)$$

905 where L is a lower triangular matrix with real and positive diagonal entries and L^T
906 denotes the transpose of L .

907 Given the four free spline coefficients which are determined from the fit described in 6,
908 A_{cov} is a 4×4 matrix. Therefore, the lower triangular matrix L is of the form:

$$L = \begin{pmatrix} v_{11} & 0 & 0 & 0 \\ v_{12} & v_{22} & 0 & 0 \\ v_{13} & v_{23} & v_{33} & 0 \\ v_{14} & v_{24} & v_{34} & v_{44} \end{pmatrix}, \quad (11.4)$$

910 where v_{ij} are real and positive numbers. L contains four row vectors, which are by
911 construction the four decorrelated modes of the covariant matrix A_{cov} . From this modes,
912 one can form variations for each of the spline coefficients:

$$c_i = c_{nom,i} + \sum_j (r_j \cdot v_{ij}), \quad (11.5)$$

913 where $i = 1..4$, c_i is the i-th generated coefficient of the toy spline, $c_{nom,i}$ is the i-th
914 coefficient determined from the nominal decay-time dependent fit to $B_s^0 \rightarrow D_s \pi \pi \pi$, r_j are
915 normally distributed real random numbers from a distribution of unit width and v_{ij} are
916 the components of L (where i is the row index and j the column index).

917 We now generate four sets of 100 toy splines, where one of the four spline coefficients is
918 varied each time using Eq. 11.5. Thus, the time-dependent amplitude fit is repeated in
919 total 400 times with a generated toy spline and the shift of the mean value of the physics
920 observables over each of the $4 \cdot 100$ sets is quoted as uncertainty arising from $c_{i=1..4}$. The
921 uncertainties are then added in quadrature to form the overall uncertainty due to the
922 spline coefficients. Table 11.1 summarizes the results of this study.

Table 11.1: Pull parameters for CP coefficients from the toy studies for the time-dependent fit.

Parameter	μ of pull distribution	σ of pull distribution
C	$0.00271841 \pm 0.00159745$	0.0694972 ± 0.00127009
D	$-0.0115746 \pm 0.00755454$	0.331063 ± 0.00576761
S	$-0.00151265 \pm 0.000852967$	$0.0378623 \pm 0.000754181$
\bar{D}	$-0.0106657 \pm 0.00746365$	0.327998 ± 0.00581649
\bar{S}	$-0.00152321 \pm 0.000983966$	$0.0437459 \pm 0.000849528$

923 **11.3 Decay-time resolution**

924 To study systematic effects originating from the scaling of the decay-time resolution
925 σ_t , the decay-time distribution of fake B_s^0 candidates using prompt D_s is described by
926 single Gaussian function. The results of the single Gaussians in the different bins
927 of the per-event decay-time error can then be used to derive the scaling function in a
928 straightforward way. Since the distribution of the fake B_s^0 decay time does not follow a
929 perfect Gaussian distribution, two different approaches which either slightly overestimate
930 or underestimate the decay time error are used:

- 931 • A double Gaussian is fit to the decay-time distributions of fake B_s^0 candidates,
932 but only the narrow width of the core Gaussian is considered to represent the time
933 resolution in the respective bin. This method assumes that the other, broader
934 Gaussian component does not represent the decay-time resolution of the signal B_s^0
935 sample. Therefore the resolution is slightly underestimated in this case.
- 936 • A single Gaussian is fit to the decay-time distributions of fake B_s^0 candidates in a
937 wide range of $[-3\sigma_t : 1.5\sigma_t]$. Due to the tails of the distribution, which broaden the
938 width of the Gaussian function, this method slightly overestimates the decay-time
939 resolution.

940 The widths of the single Gaussians from the fits performed with the two methods in
941 bins of the per-event decay-time error is studied and a new resolution scaling function is
942 derived for both cases:

$$\sigma_{\text{eff}}^{\text{core-Gauss}}(\sigma_t) = (4.9 \pm 2.0) \text{ fs} + (0.821 \pm 0.050) \sigma_t \quad (11.6)$$

$$\sigma_{\text{eff}}^{\text{single-Gauss}}(\sigma_t) = (8.3 \pm 1.5) \text{ fs} + (0.997 \pm 0.037) \sigma_t \quad (11.7)$$

944 The scaling functions are shown in Fig. 11.1 and the systematic uncertainty to the
945 CP-observables is summarized in Table yYy.

946 **11.4 Tagging calibration**

947 **11.5 Summary of systematic uncertainties**

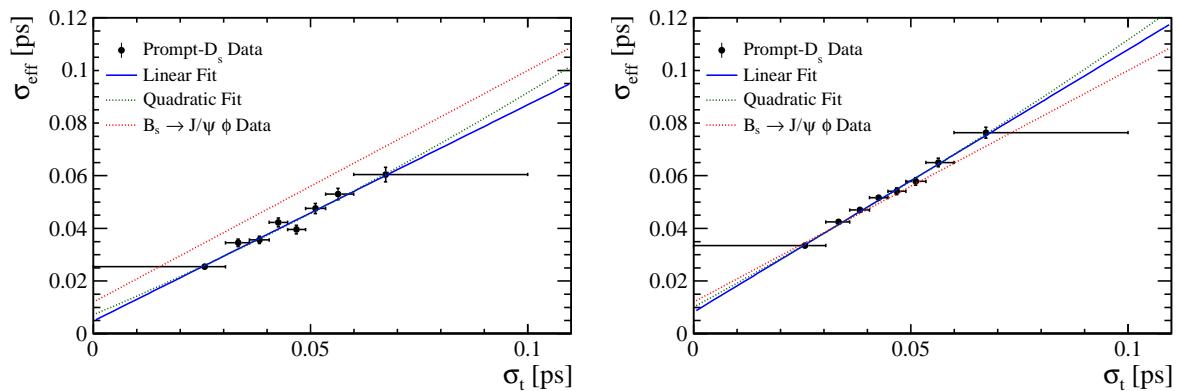


Figure 11.1: The measured resolution σ_{eff} as function of the per-event decay time error estimate σ_t for fake B_s candidates (Run-II data) when (left) only using the narrow gaussian width of the double gaussian fit model or (right) when determining the resolution using a single gaussian model. The fitted calibration curve is shown in blue for both cases.

948 A Stripping and Trigger cuts

949 The following text describes variables which are used in Table 1.1 and might be ambiguous,
 950 or which benefits are not straight forward. Where noted, different cut values are applied
 951 for Run-I and Run-II data. In Table 1.1, DOCA is the abbreviation for distance of closest
 952 approach. This variable is used to ensure that all D_s and $X_{s,d}$ daughters originate from
 953 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 MeV/ c	
Track p_T	> 100 MeV/ c	
Track IP χ^2	> 4	
Track ghost-prob.	< 0.4	
D_s mass	$m_{D_s} \pm 100$ MeV	$m_{D_s} \pm 80$ MeV
D_s Daughter p_T	$\sum_{i=1}^3 p_{t,i} > 1800$ MeV/ c	
D_s Daughter DOCA	< 0.5 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 MeV	< 3500 MeV
$X_{s,d}$ Daughter p	> 2 GeV/ c	
$X_{s,d}$ Daughter DOCA	< 0.4 mm	
$X_{s,d}$ Daughter p_T	$\sum_{i=1}^3 p_{t,i} > 1250$ 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 mm	
$X_{s,d}$ Δz	> 2.0 mm	
$X_{s,d}$ daughter PID(π)	< 10	
X_s daughter PID(K)	> -2	> 4
B_s^0 mass	[4750, 7000] MeV/ c^2	[5000, 6000] 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 ps	

954

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

960 The Hlt2 2, 3 and 4-body topological lines use a Boosted Decision Tree based on the
 961 b-hadron p_T , its flight distance χ^2 from the nearest PV and the sum of the B_s^0 and D_s
 962 vertex χ^2 divided by the sum of their number of degrees of freedom. Table 1.3 summarizes
 963 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	$> 1.7 \text{ GeV}/c$
Track p	$> 10 \text{ GeV}/c$
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	$m_\phi \pm 12 \text{ MeV}/c^2$ of PDG value
ϕp_T	$> 2.5 \text{ GeV}/c$
ϕ vertex χ^2/nDoF	< 20
ϕ IP χ^2 to any PV	> 5

B Details of multivariate classifier

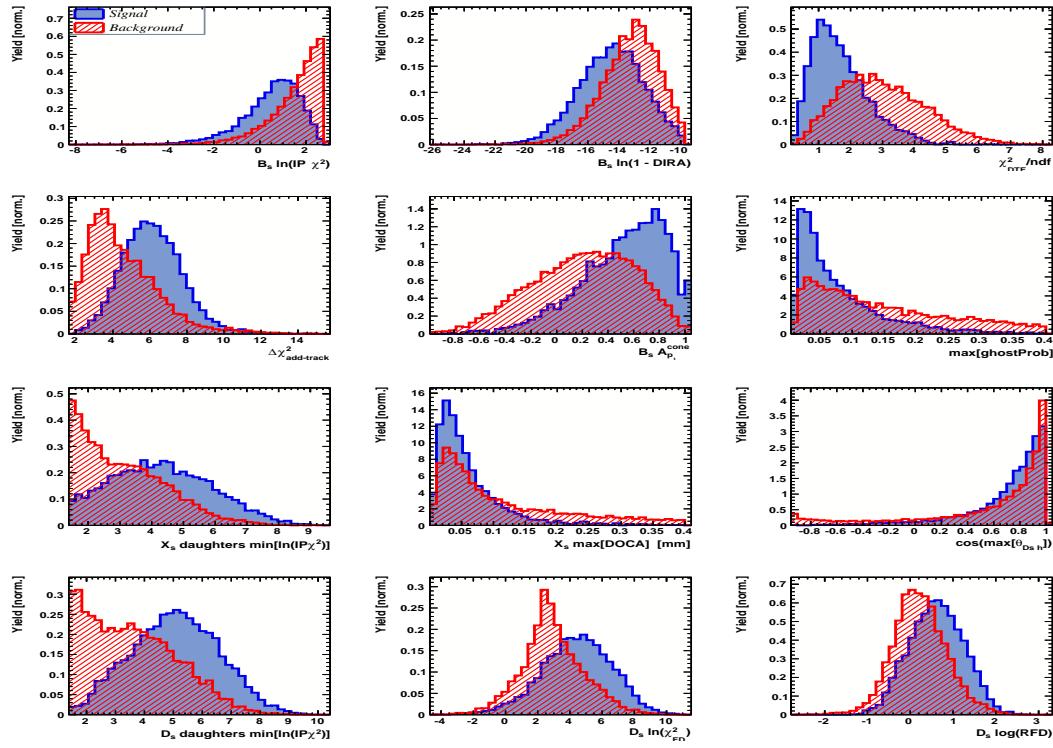


Figure A.1: Variables used to train the BDTG for category [Run-I,L0-TOS].

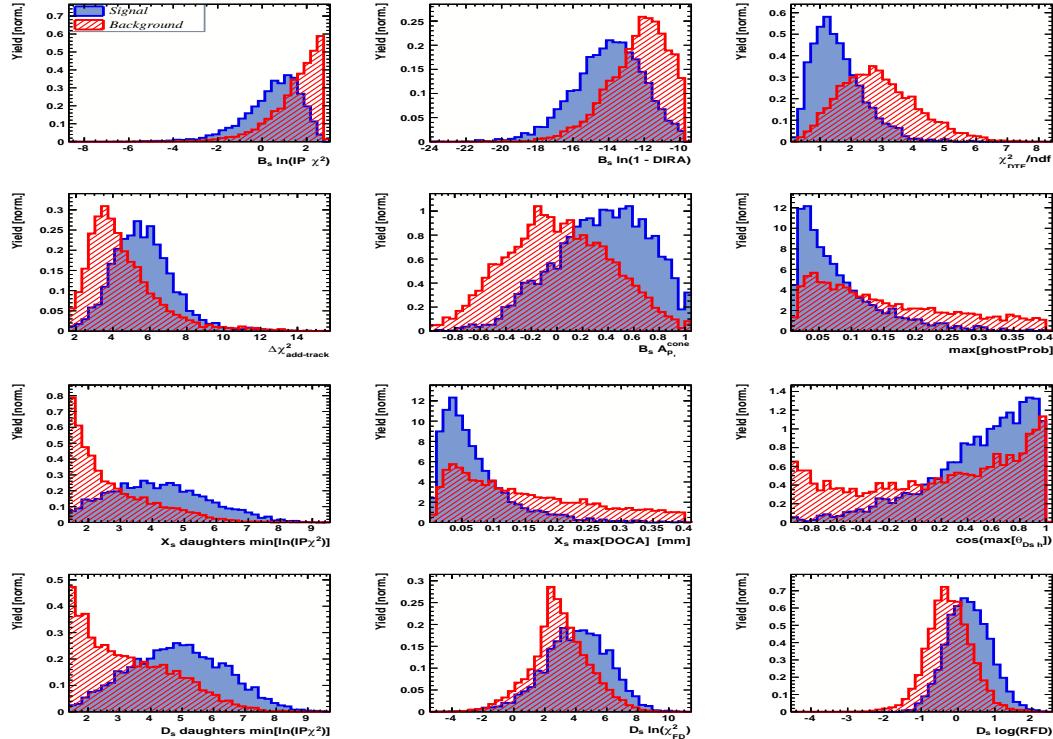


Figure A.2: Variables used to train the BDTG for category [Run-I,L0-TIS].

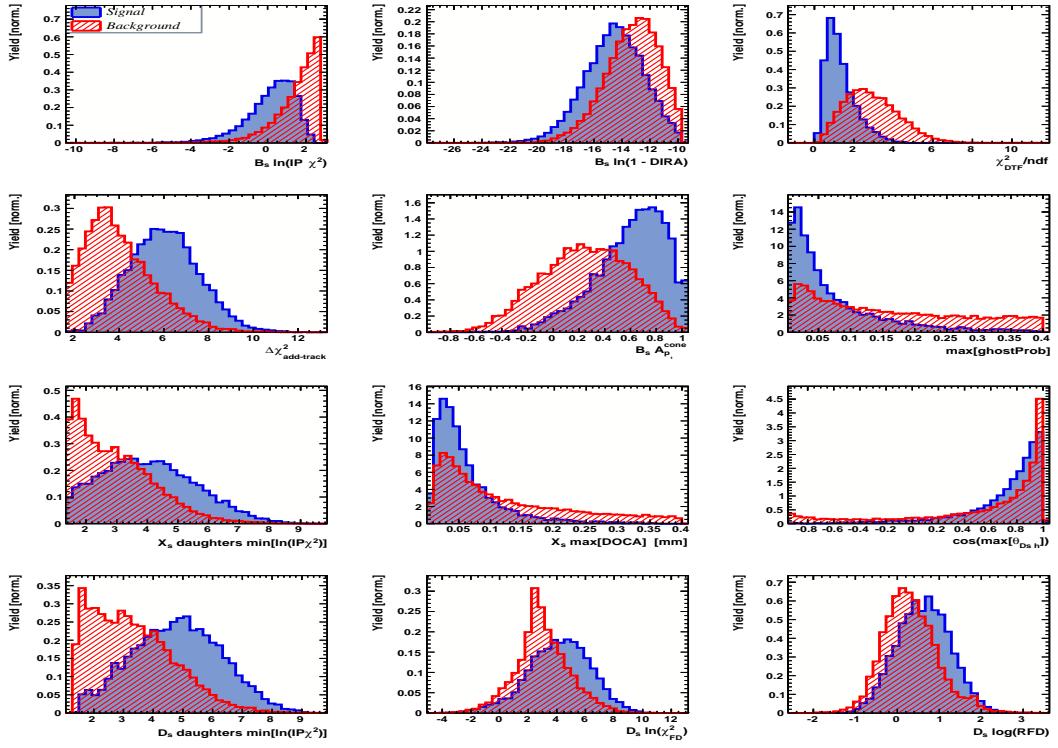


Figure A.3: Variables used to train the BDTG for category [Run-II,L0-TOS].

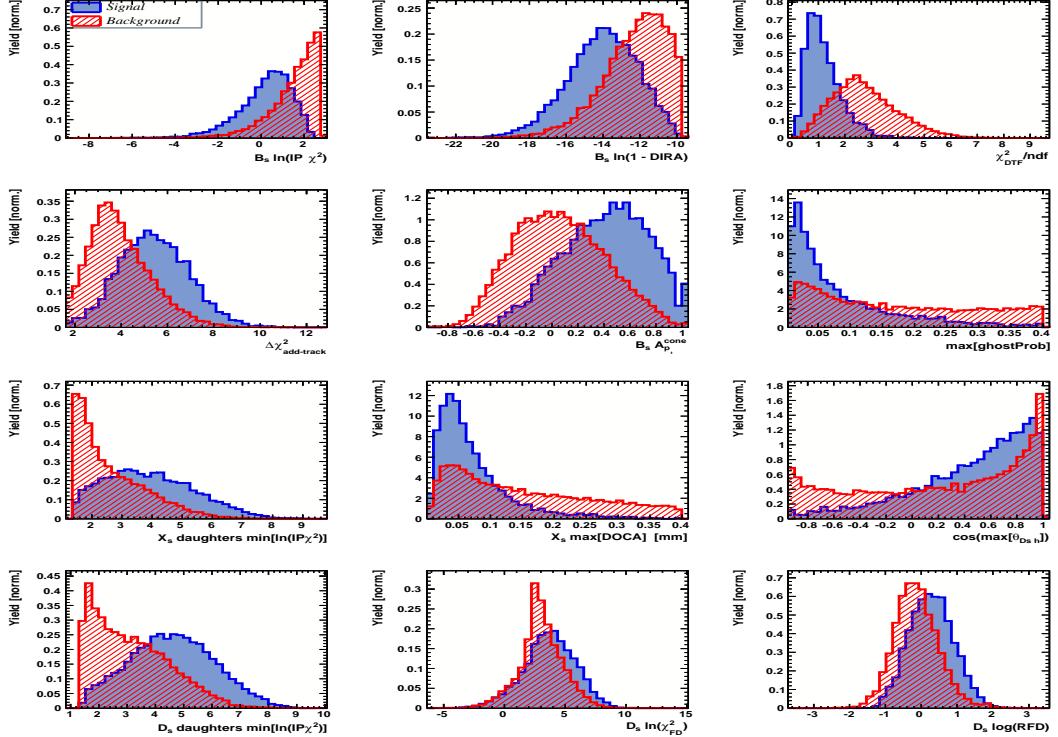


Figure A.4: Variables used to train the BDTG for category [Run-II,L0-TIS].

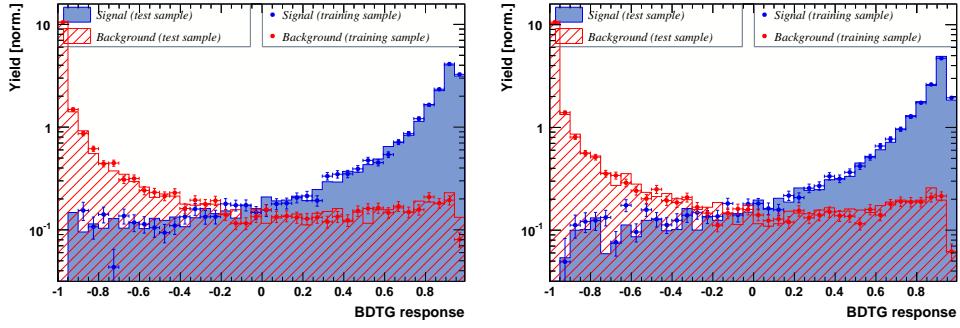


Figure A.5: Response of the classifier trained on the even and tested on the odd sample (left) and trained on the odd and tested on the even sample (right) for category [Run-I,L0-TOS].

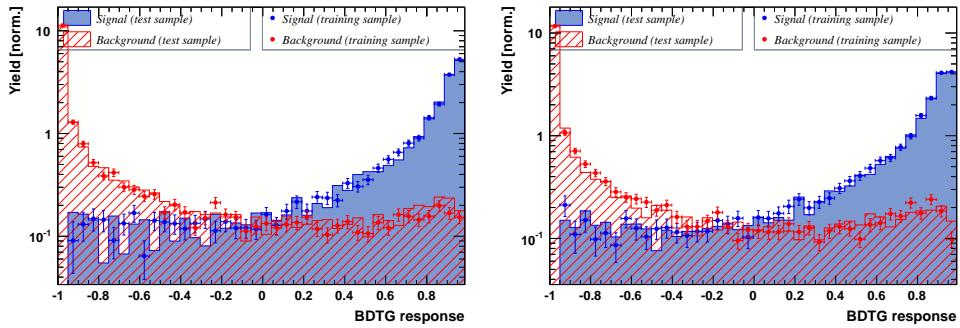


Figure A.6: Response of the classifier trained on the even and tested on the odd sample (left) and trained on the odd and tested on the even sample (right) for category [Run-I,L0-TIS].

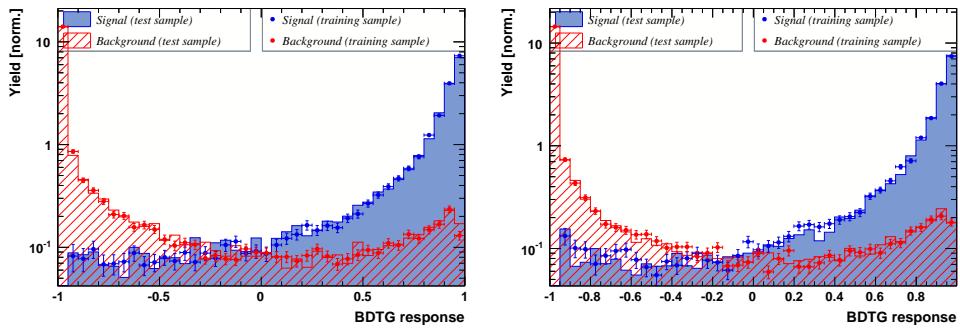


Figure A.7: Response of the classifier trained on the even and tested on the odd sample (left) and trained on the odd and tested on the even sample (right) for category [Run-II,L0-TOS].

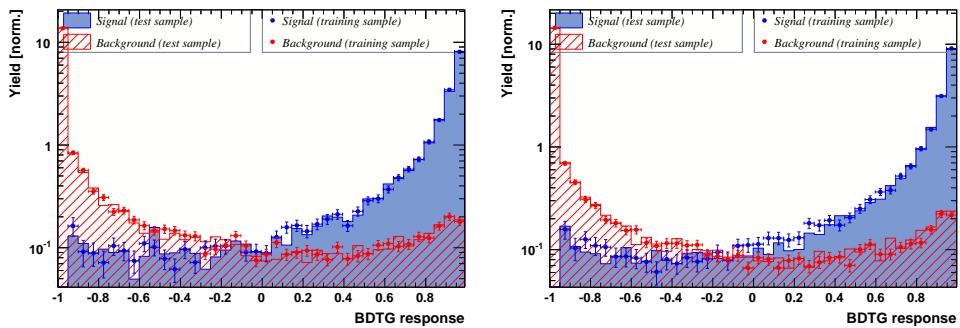


Figure A.8: Response of the classifier trained on the even and tested on the odd sample (left) and trained on the odd and tested on the even sample (right) for category [Run-II,L0-TIS].

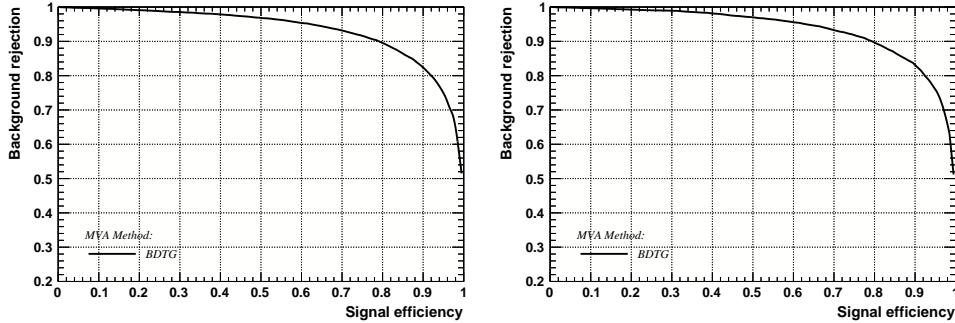


Figure A.9: Signal efficiency versus background rejection for the BDT trained on the even (left) and odd (right) sample for category [Run-I,L0-TOS].

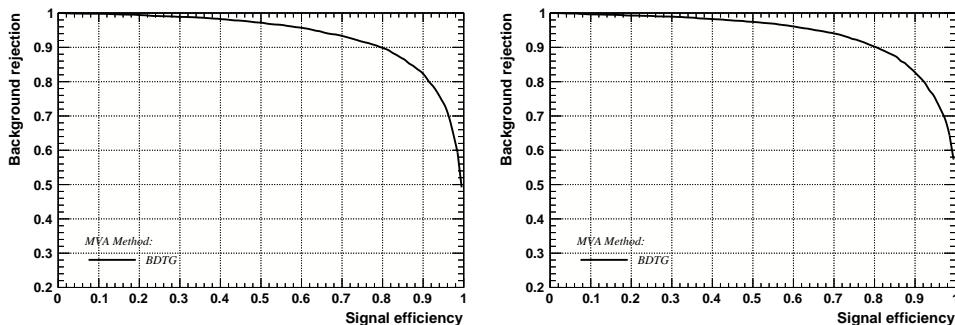


Figure A.10: Signal efficiency versus background rejection for the BDT trained on the even (left) and odd (right) sample for category [Run-I,L0-TIS].

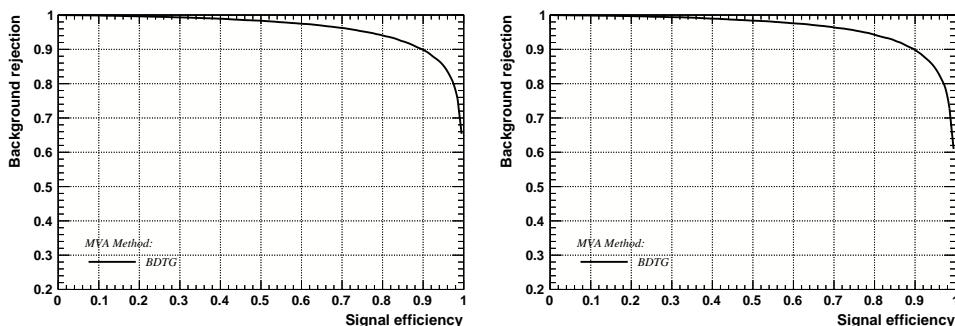


Figure A.11: Signal efficiency versus background rejection for the BDT trained on the even (left) and odd (right) sample for category [Run-II,L0-TOS].

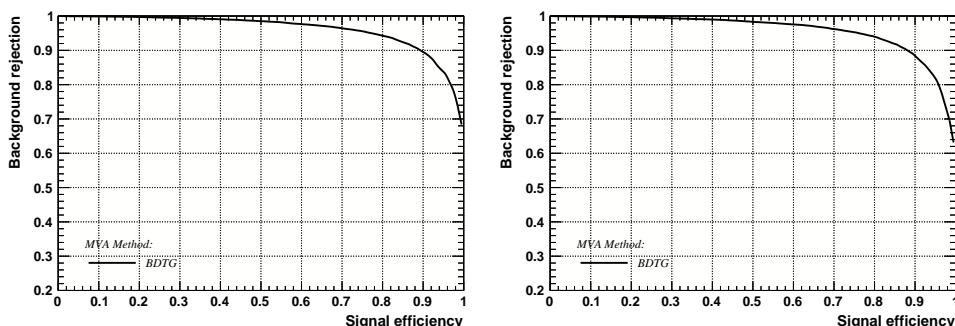


Figure A.12: Signal efficiency versus background rejection for the BDT trained on the even (left) and odd (right) sample for category[Run-II,L0-TIS].

966 C Detailed mass fits

967 In this section, all fits to the mass distribution of $B_s^0 \rightarrow D_s\pi\pi\pi$ and $B_s^0 \rightarrow D_sK\pi\pi$
968 candidates are shown. The fits are performed simultaneously in run period (Run-I, Run-
969 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
970 L0 trigger category.

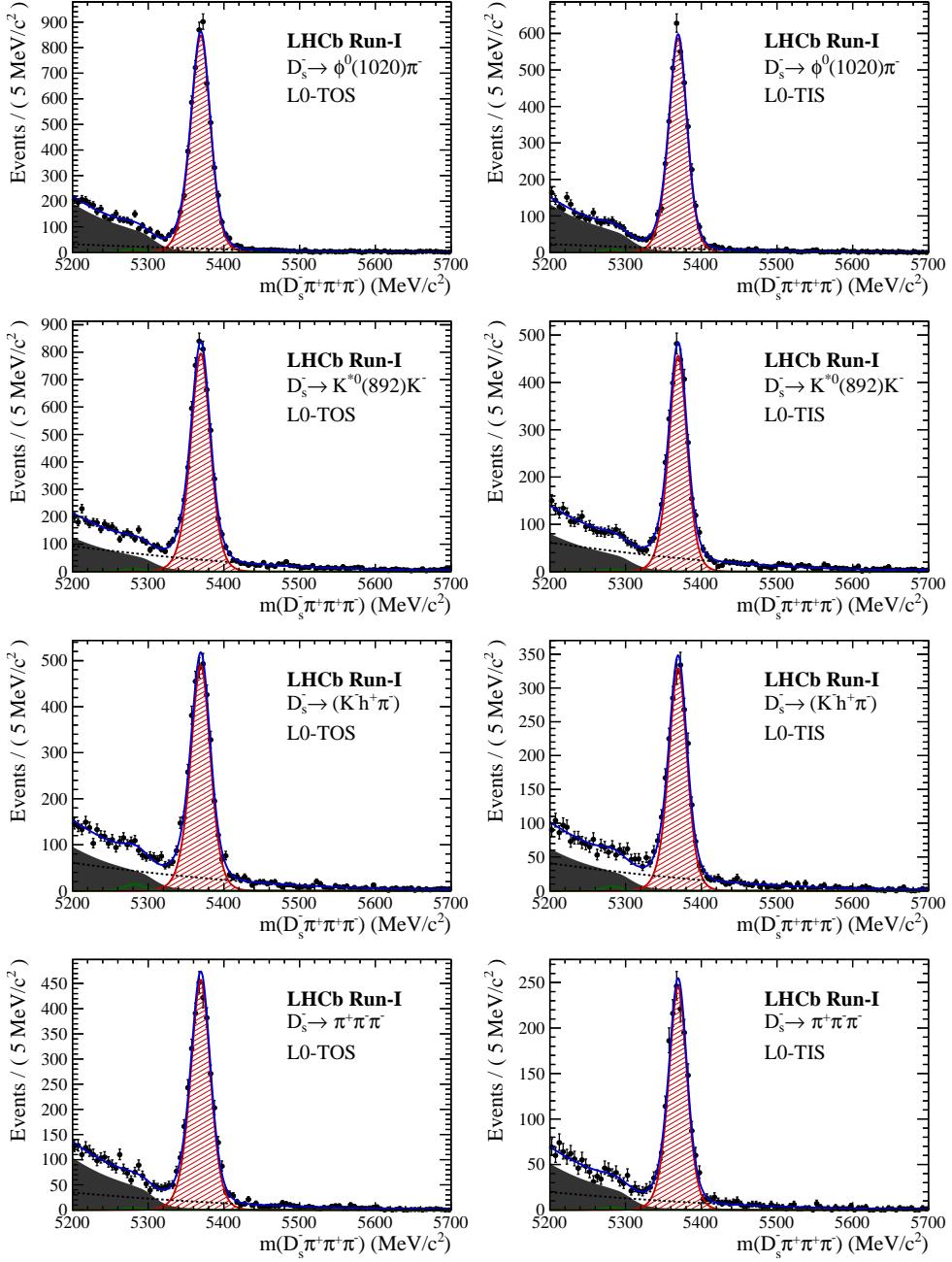


Figure B.1: Invariant mass distributions of $B_s^0 \rightarrow D_s\pi\pi\pi$ candidates for Run-I data.

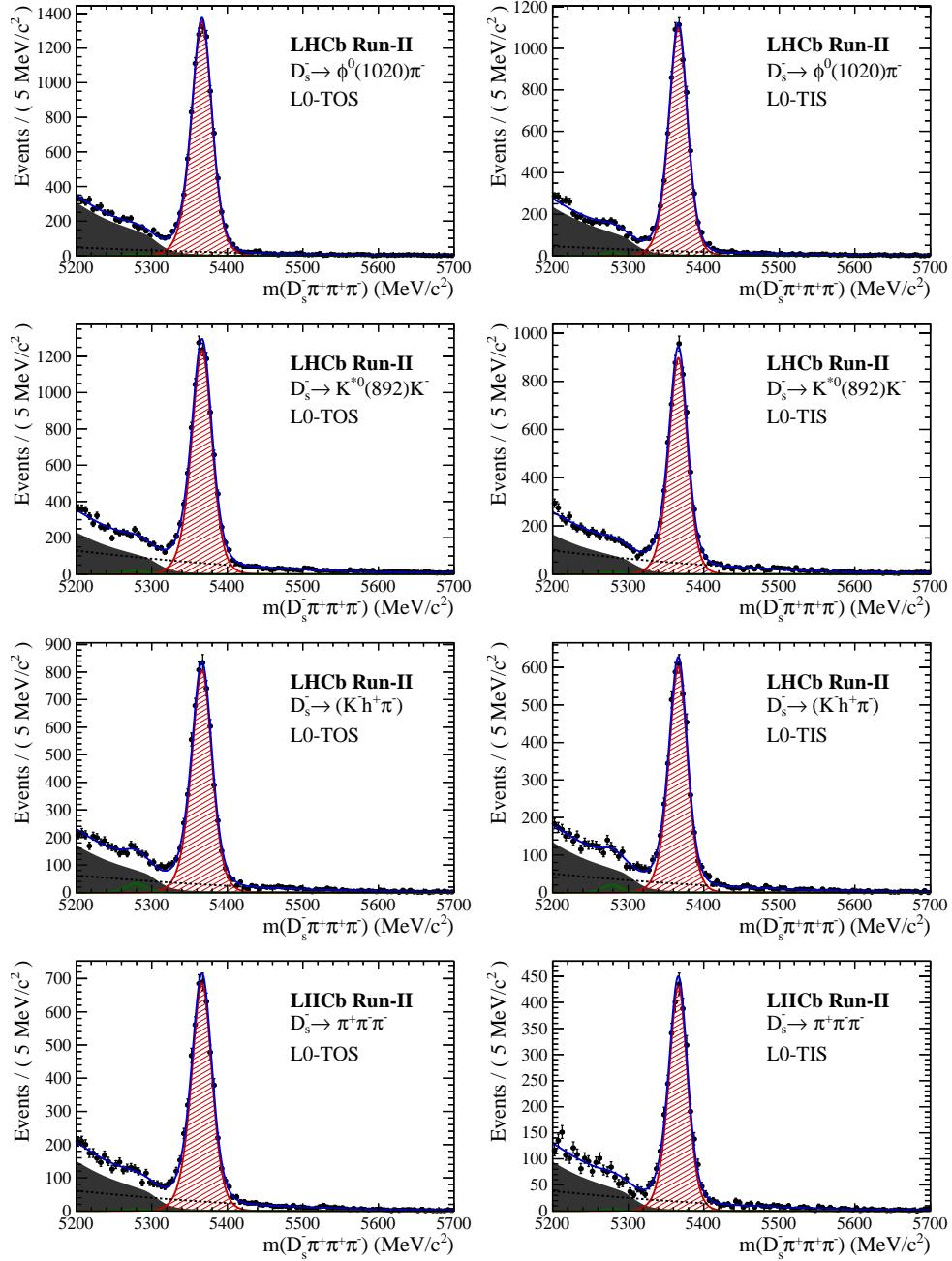


Figure B.2: Invariant mass distributions of $B_s^0 \rightarrow D_s \pi^+ \pi^- \pi^+$ candidates for Run-II data.

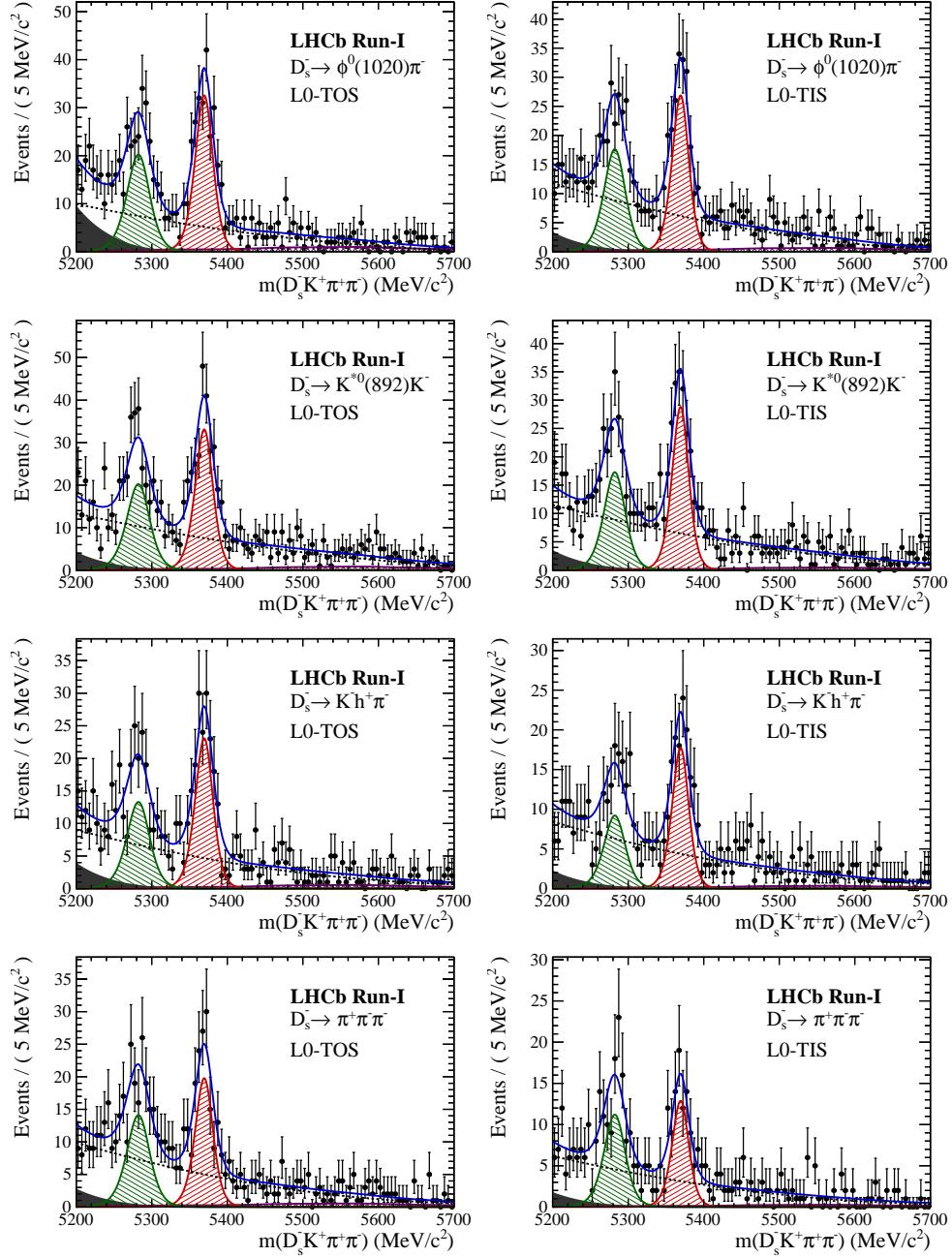


Figure B.3: Invariant mass distributions of $B_s^0 \rightarrow D_s K \pi \pi$ candidates for Run-I data.

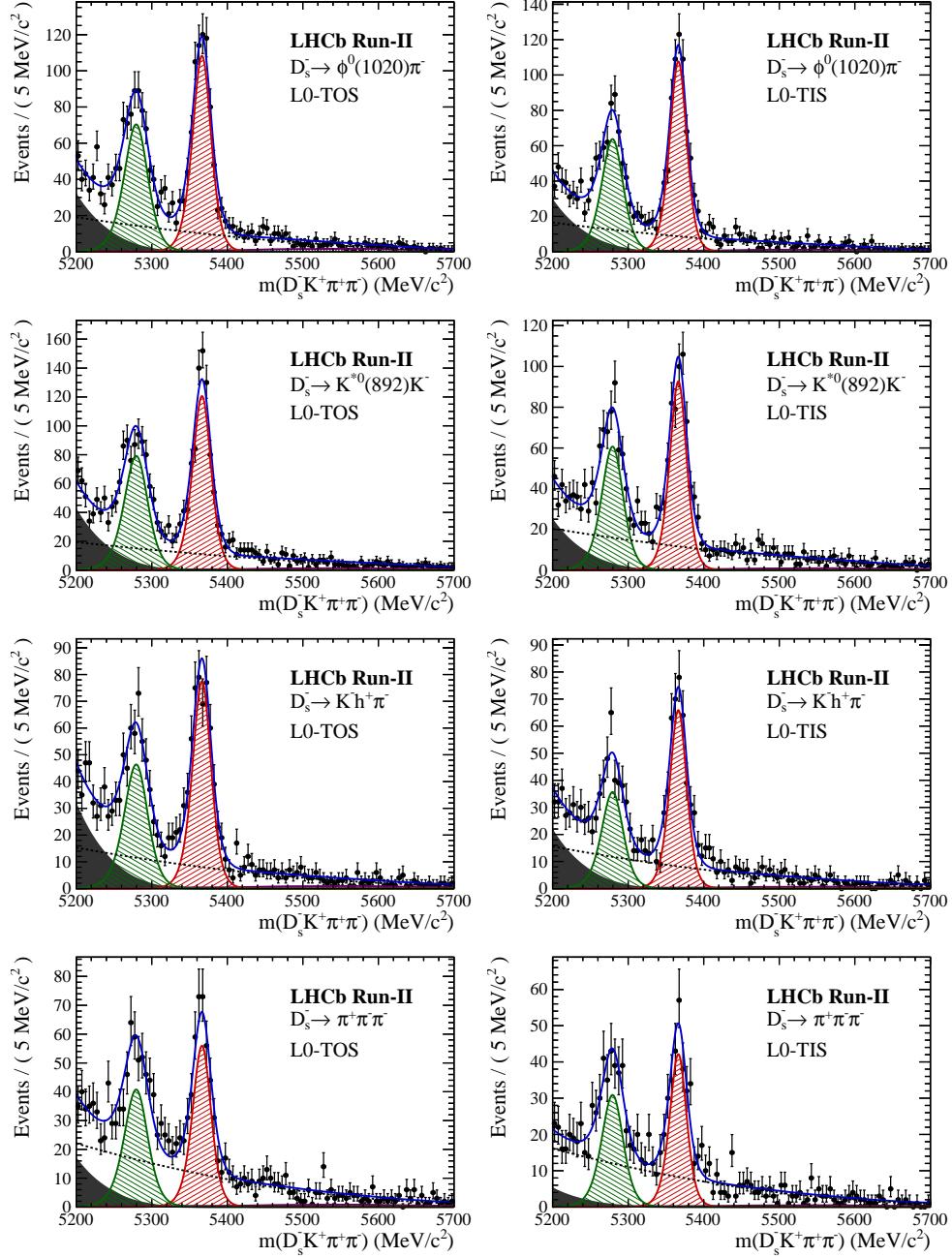


Figure B.4: Invariant mass distributions of $B_s^0 \rightarrow D_s K \pi\pi$ candidates for Run-II data.

971 D Decay-time Resolution fits

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

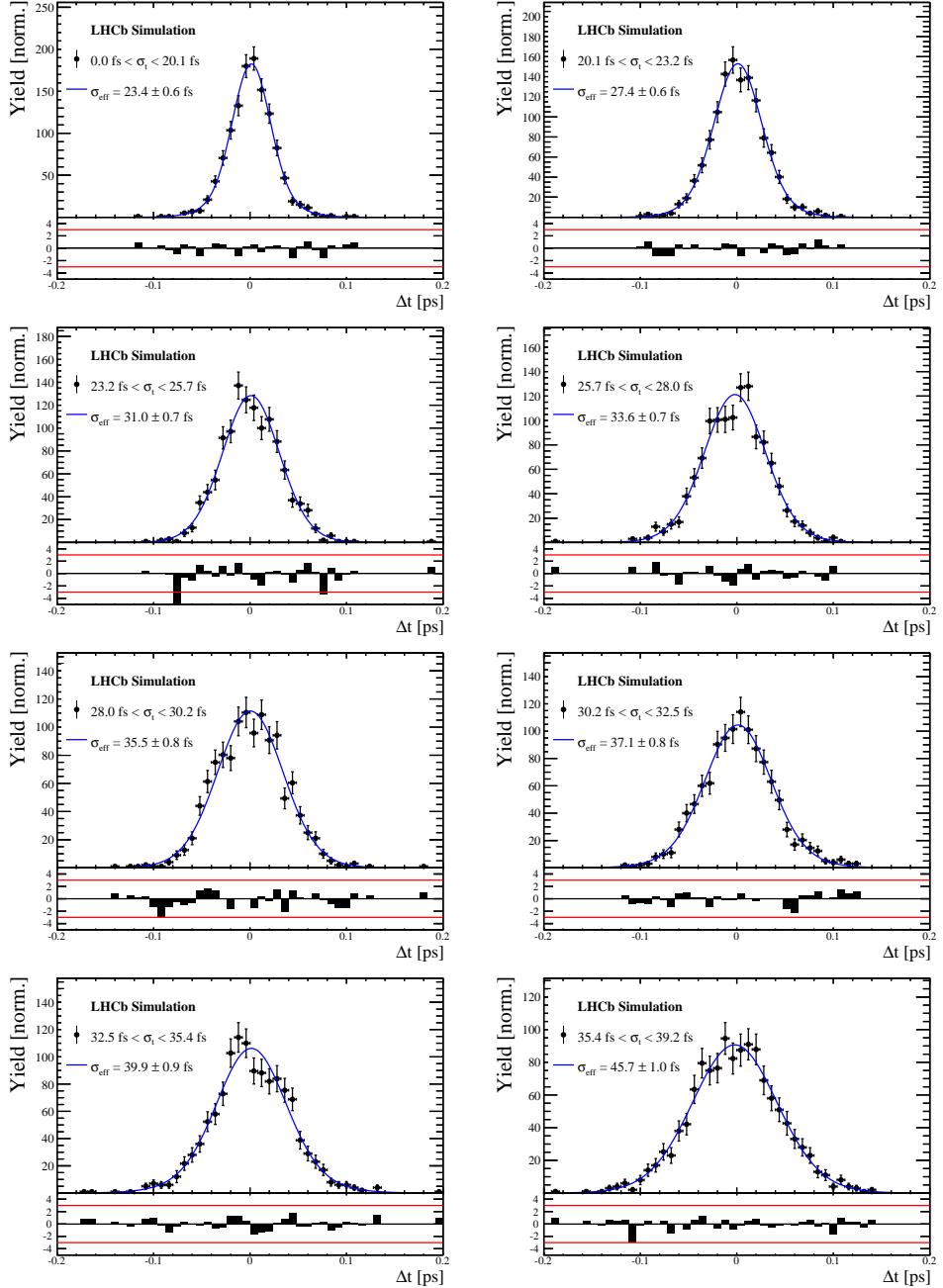


Figure C.1: Difference of the true and measured decay time of $B_s^0 \rightarrow D_s K \pi \pi$ MC candidates in bins of the per-event decay time error estimate..

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.

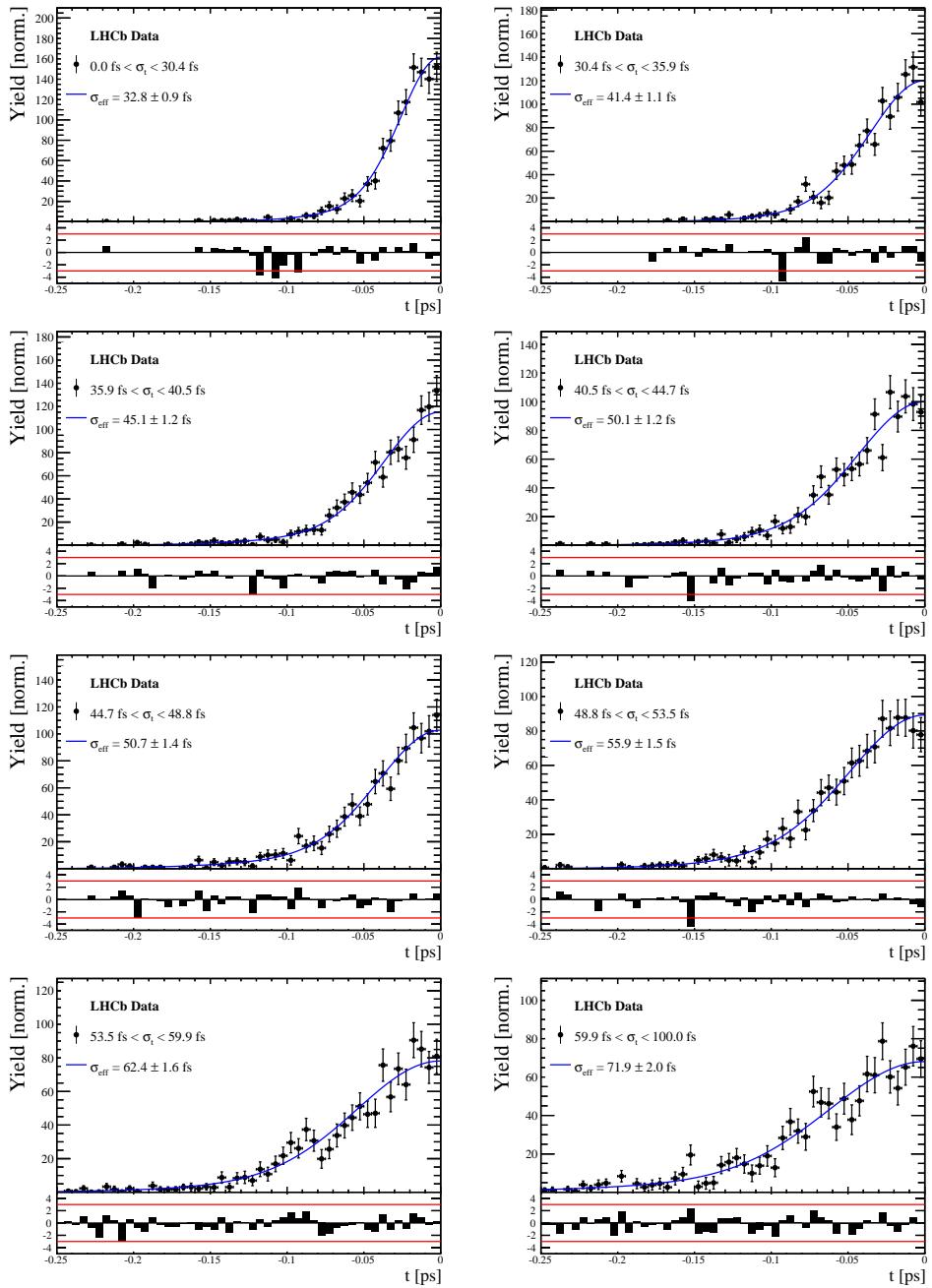


Figure C.2: Decay-time distribution for fake B_s candidates from promptly produced D_s candidates, combined with random prompt $K\pi\pi$ bachelor tracks, for bins in the per-event decay time error estimate.

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.

977 E Spin Amplitudes

978 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	$B[D] \rightarrow (T_1 T_2)$, $T_1 \rightarrow (P_1 P_2)$, $T_2 \rightarrow (P_3 P_4)$	$L_{(2)\alpha\beta}(B) L_{(2)}^{\alpha\gamma}(T_1) L_{(2)\gamma}^\beta(T_2)$

979 F Considered Decay Chains

980 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
$B_s \rightarrow D_s^- [K_1(1270)^+ [S, D] \rightarrow \pi^+ K^*(892)^0]$
$B_s \rightarrow D_s^- [K_1(1270)^+ \rightarrow \pi^+ K^*(1430)^0]$
$B_s \rightarrow D_s^- [K_1(1270)^+ [S, D] \rightarrow K^+ \rho(770)^0]$
$B_s \rightarrow D_s^- [K_1(1270)^+ [S, D] \rightarrow K^+ \omega(782)]$
$B_s \rightarrow D_s^- [K_1(1400)^+ [S, D] \rightarrow \pi^+ K^*(892)^0]$
$B_s \rightarrow D_s^- [K_1(1400)^+ [S, D] \rightarrow K^+ \rho(770)^0]$
$B_s \rightarrow D_s^- [K(1460)^+ \rightarrow \pi^+ \kappa]$
$B_s \rightarrow D_s^- [K(1460)^+ \rightarrow K^+ \sigma]$
$B_s \rightarrow D_s^- [K(1460)^+ \rightarrow \pi^+ K^*(892)^0]$
$B_s \rightarrow D_s^- [K(1460)^+ \rightarrow K^+ \rho(770)^0]$
$B_s \rightarrow D_s^- [K^*(1410)^+ \rightarrow \pi^+ K^*(892)^0]$
$B_s \rightarrow D_s^- [K^*(1410)^+ \rightarrow K^+ \rho(770)^0]$
$B_s \rightarrow D_s^- [K_2^*(1430)^+ \rightarrow \pi^+ K^*(892)^0]$
$B_s \rightarrow D_s^- [K_2^*(1430)^+ \rightarrow K^+ \rho(770)^0]$
$B_s \rightarrow D_s^- [K^*(1680)^+ \rightarrow \pi^+ K^*(892)^0]$
$B_s \rightarrow D_s^- [K^*(1680)^+ \rightarrow K^+ \rho(770)^0]$
$B_s \rightarrow D_s^- [K_2(1770)^+ \rightarrow \pi^+ K^*(892)^0]$
$B_s \rightarrow D_s^- [K_2(1770)^+ \rightarrow K^+ \rho(770)^0]$
$B_s \rightarrow \sigma^0(D_s^- K^+_S)$
$B_s [S, P, D] \rightarrow \sigma^0(D_s^- K^+_V)$
$B_s \rightarrow \rho(770)^0 (D_s^- K^+_S)$
$B_s [S, P, D] \rightarrow \rho(770)^0 (D_s^- K^+_V)$
$B_s \rightarrow K^*(892)^0 (D_s^- \pi^+_S)$
$B_s [S, P, D] \rightarrow K^*(892)^0 (D_s^- \pi^+_V)$
$B_s \rightarrow (D_s^- K^+_S) (\pi^+ \pi^-)_S$

981 G MC corrections

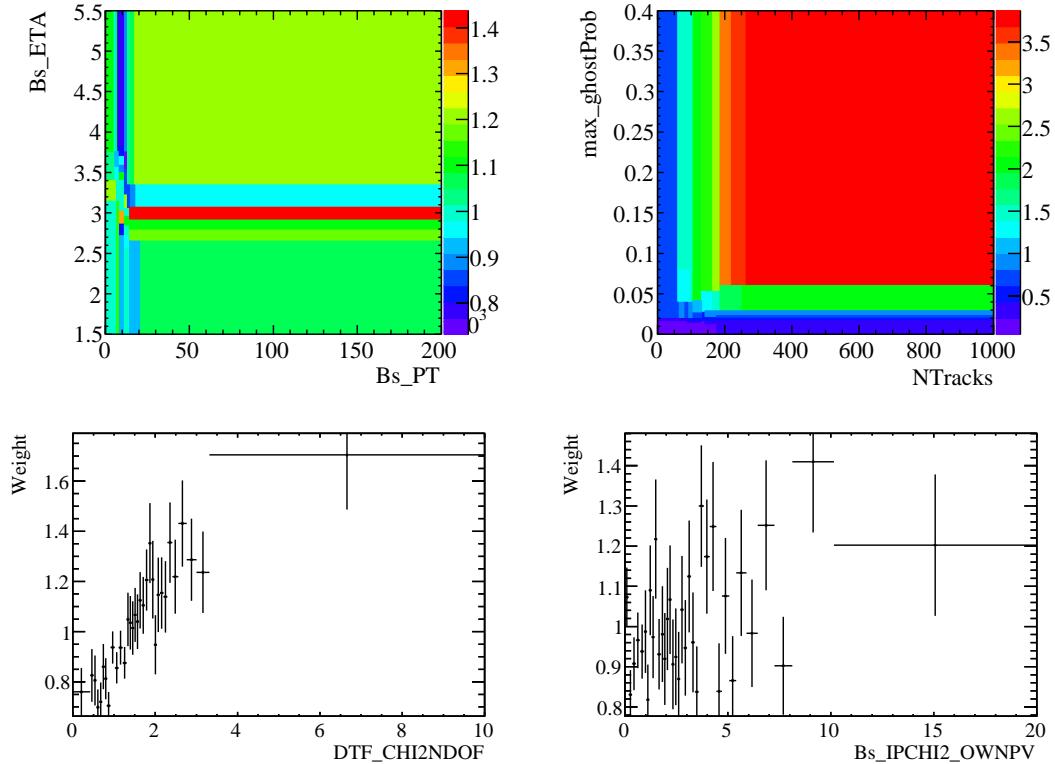


Figure C.1: Weights applied to correct for Data/MC differences.

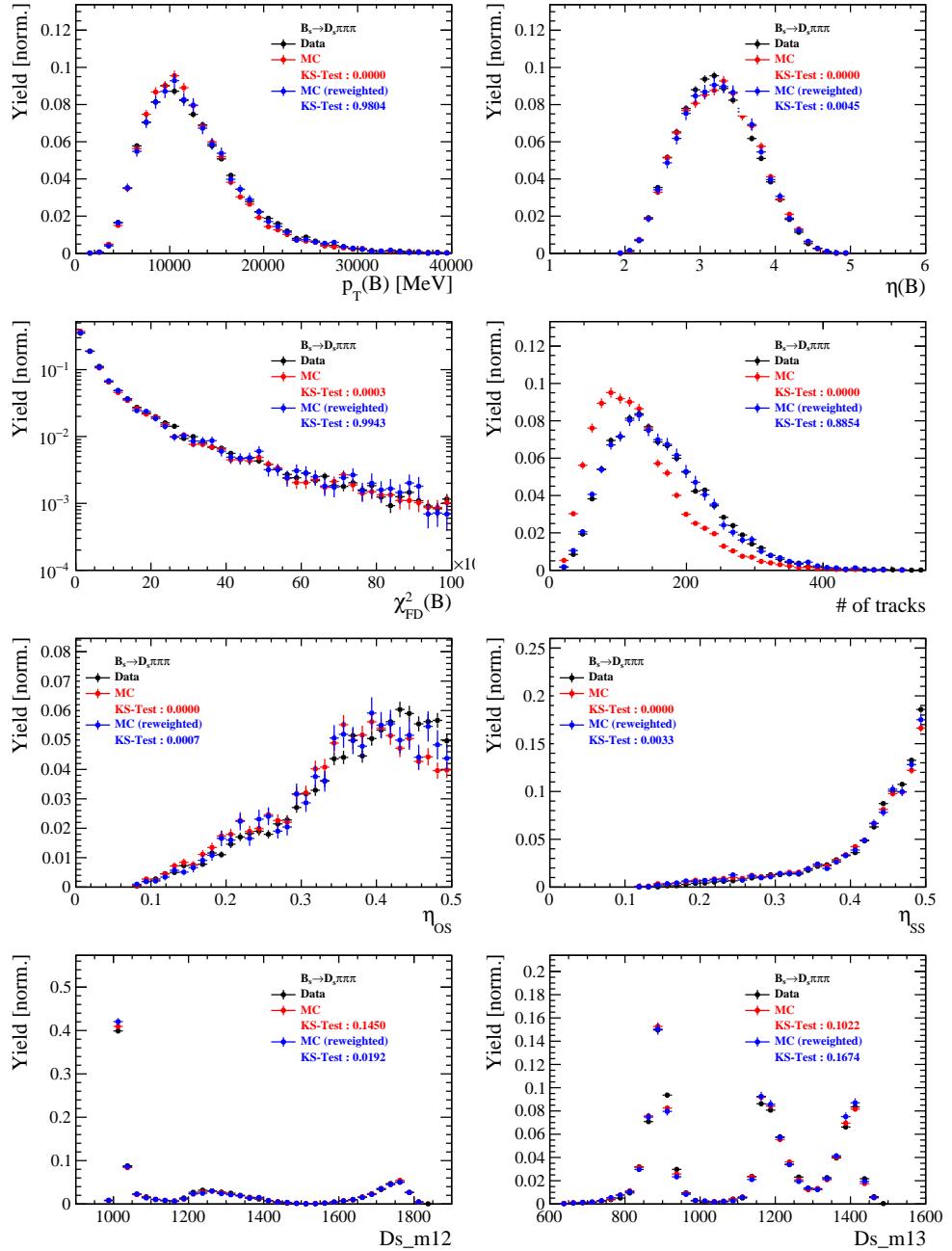


Figure C.2: Comparison of selected variables for $B_s \rightarrow D_s\pi\pi\pi$ decays.

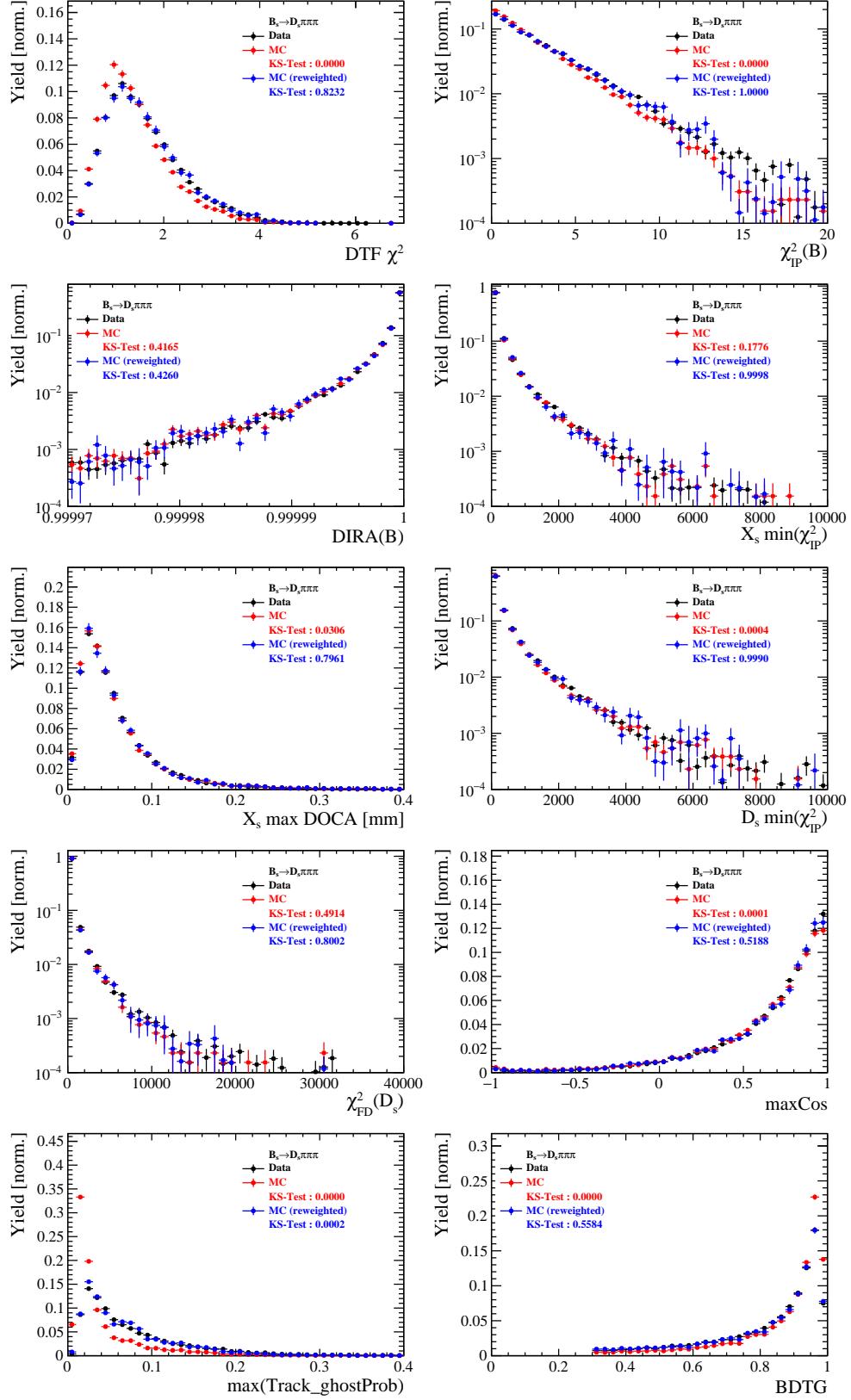


Figure C.3: Comparison of BDTG input variables and classifier response for $B_s \rightarrow D_s\pi\pi\pi$ decays.

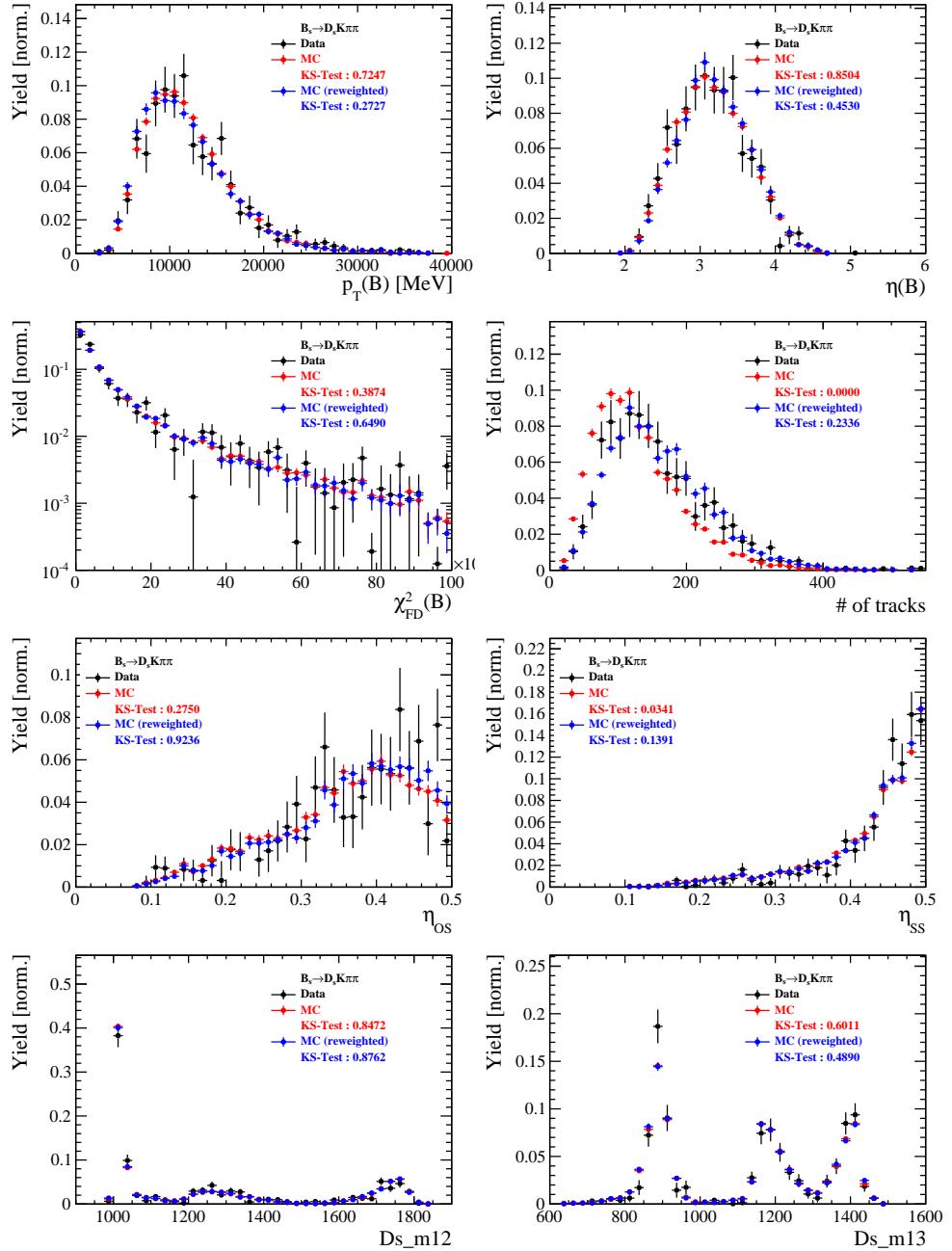


Figure C.4: Comparison of selected variables for $B_s \rightarrow D_s K\pi\pi$ decays.

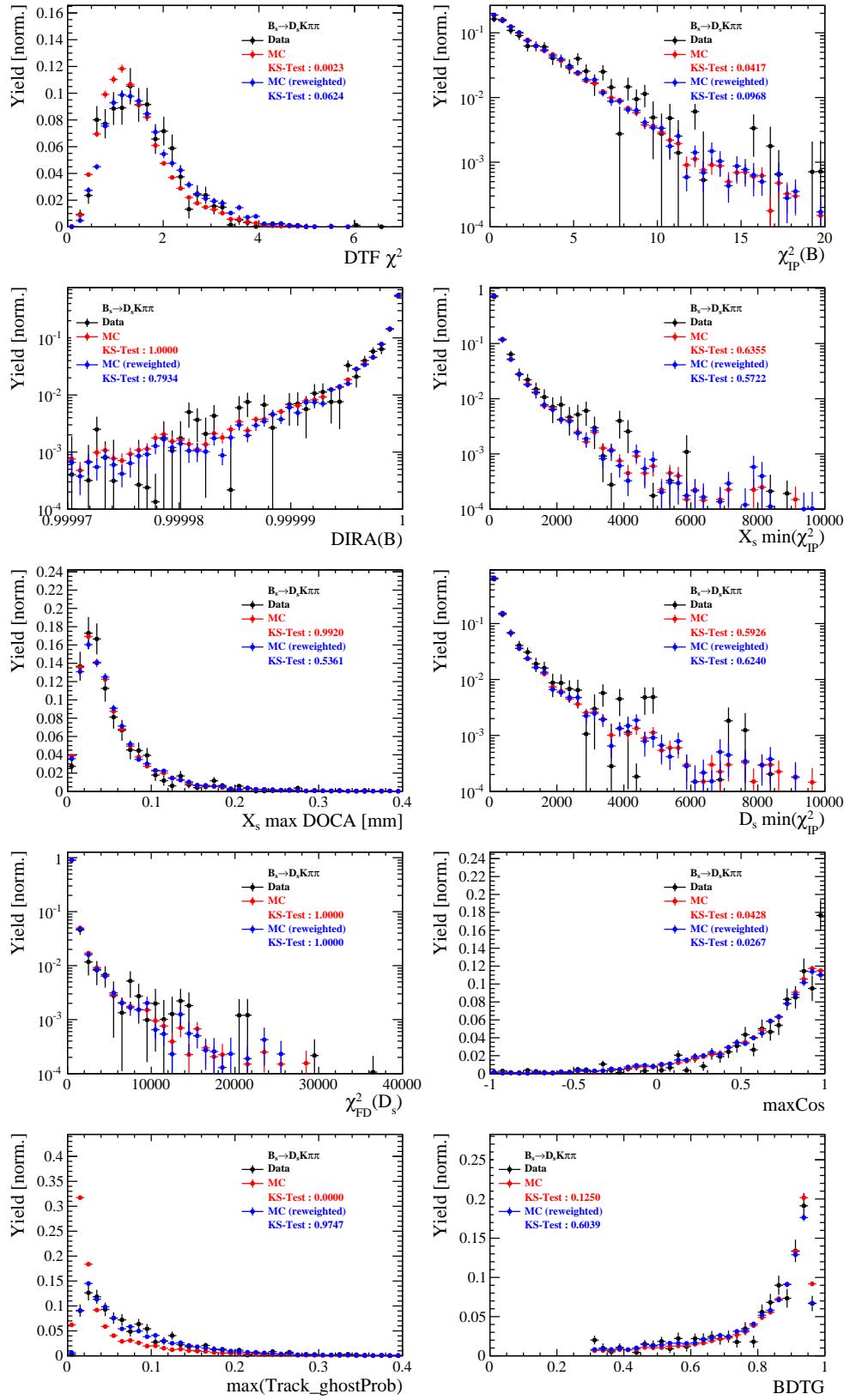


Figure C.5: Comparison of BDTG input variables and classifier response for $B_s \rightarrow D_s K\pi\pi$ decays.

982 H Data distributions

983 H.1 Comparison of signal and calibration channel

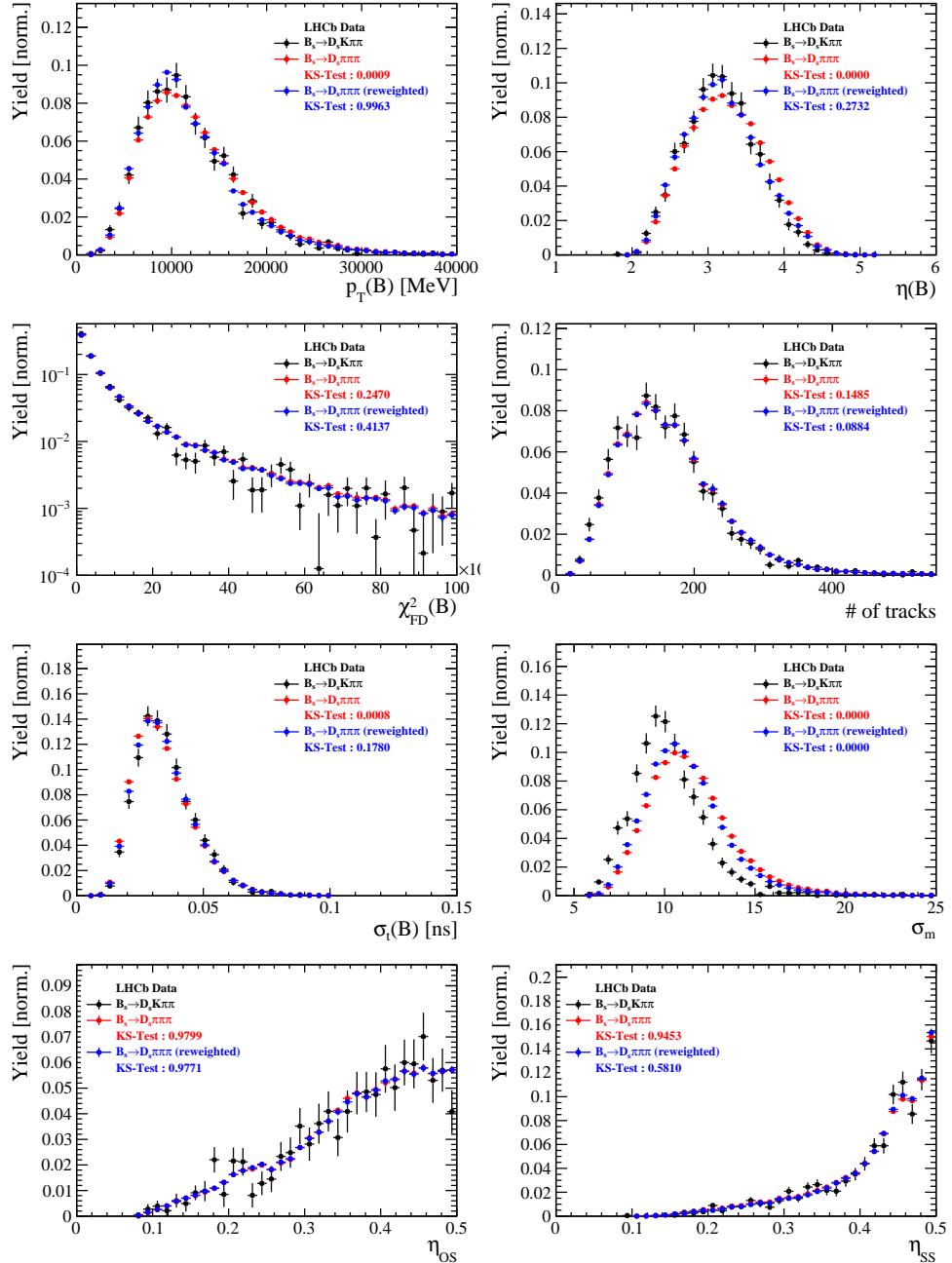


Figure C.1: Comparison of selected variables.

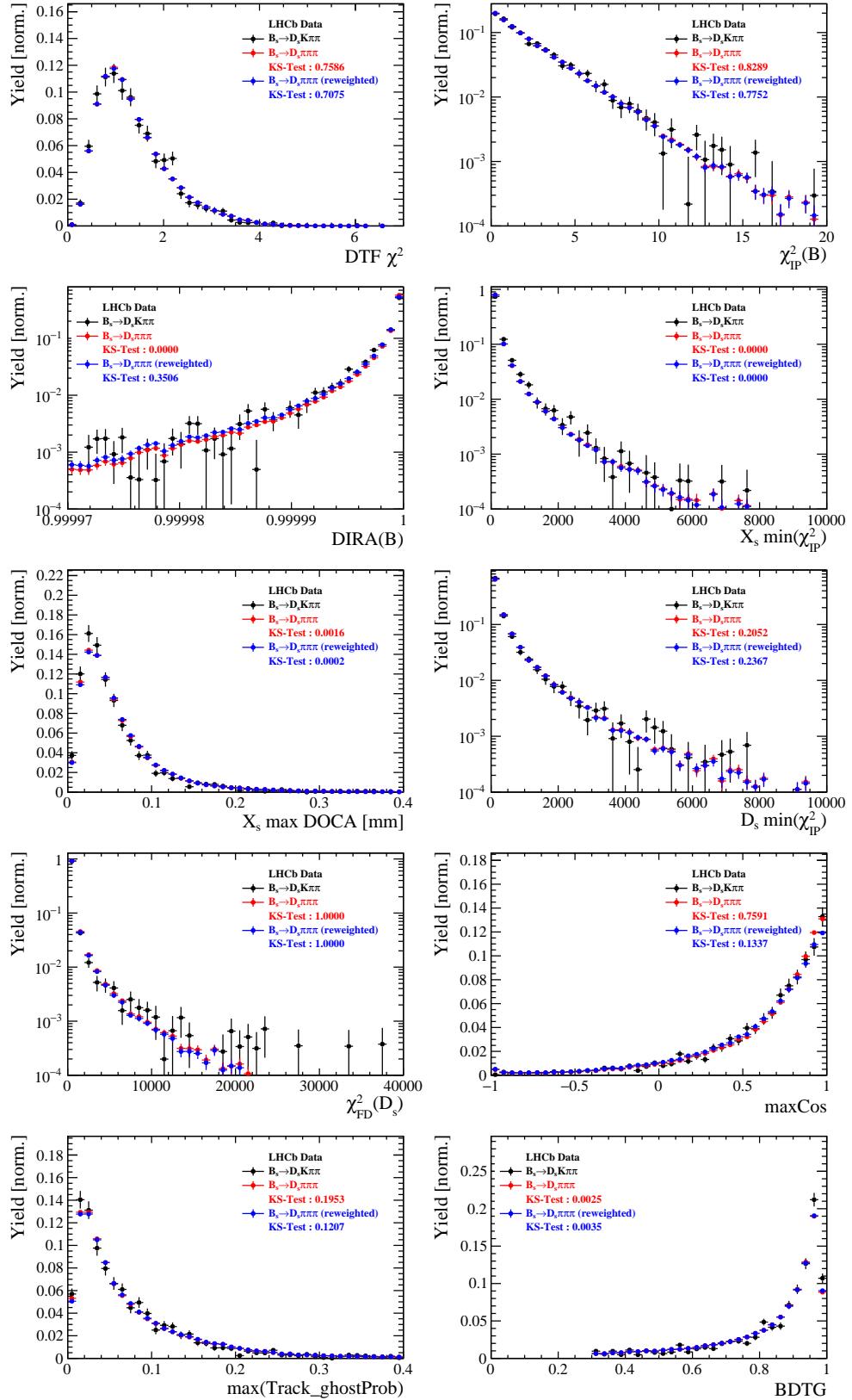


Figure C.2: Comparison of BDTG input variables and classifier response.

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

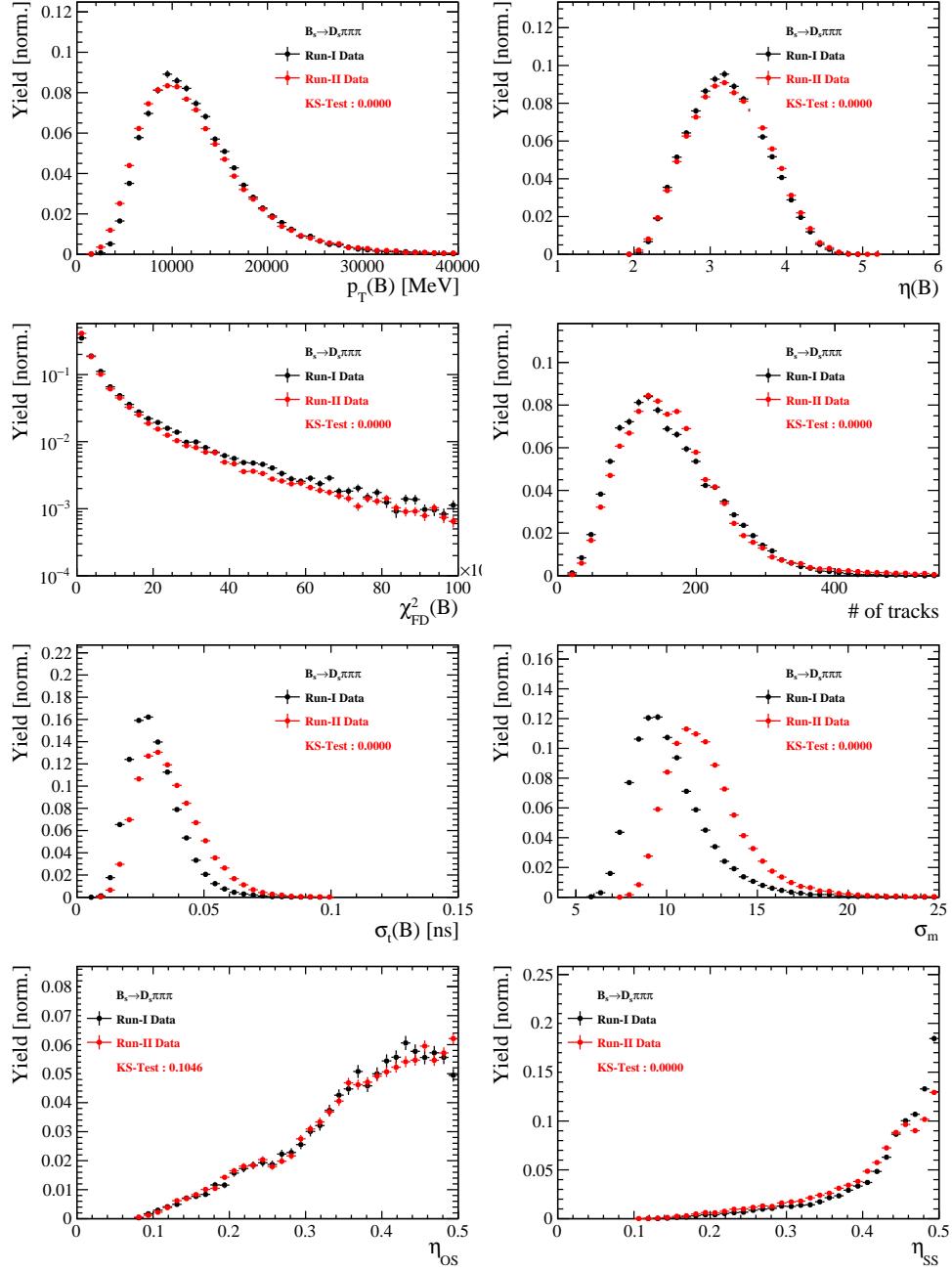


Figure C.3: Comparison of selected variables.

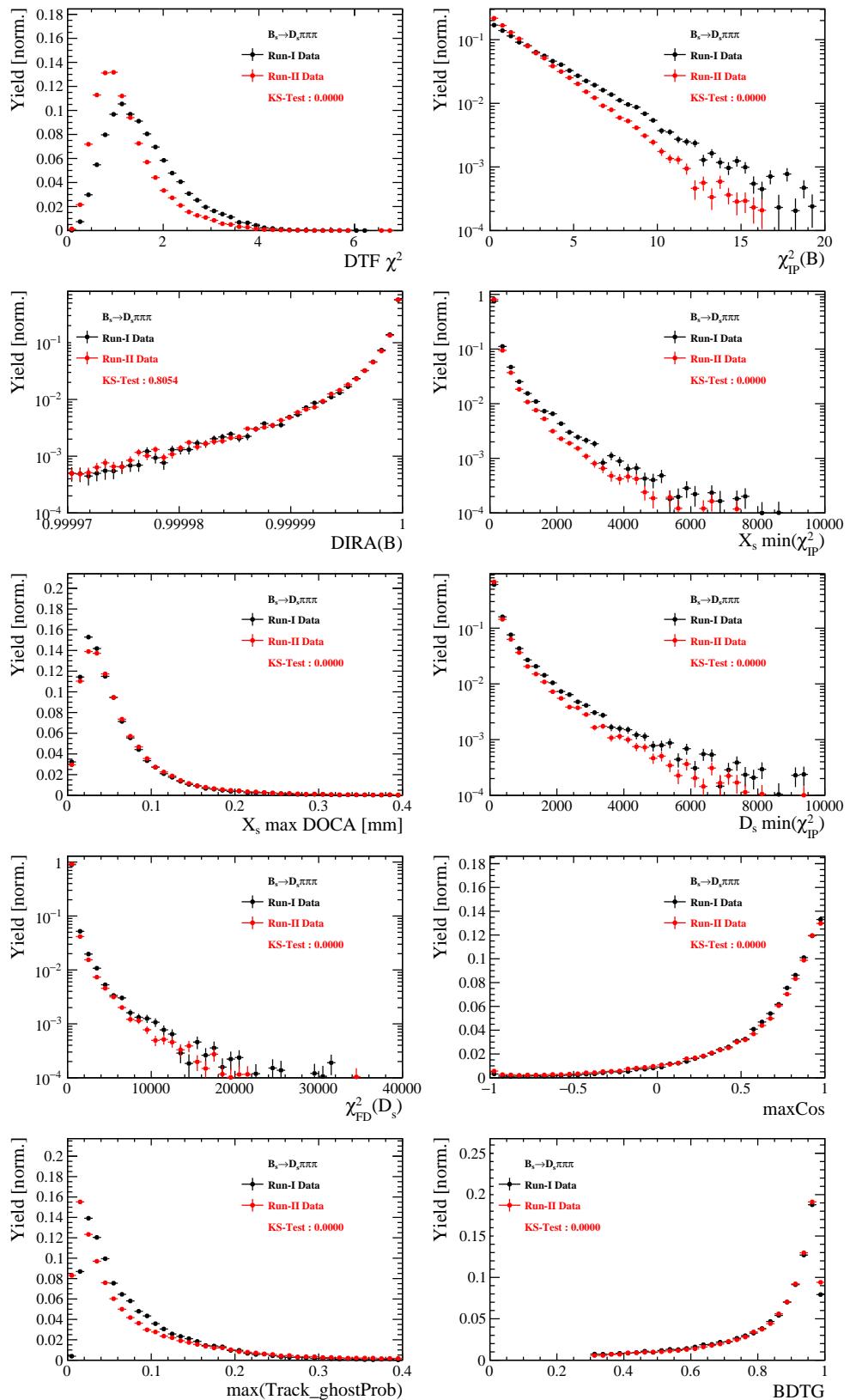


Figure C.4: Comparison of BDTG input variables and classifier response.

985 H.3 Comparison of D_s final states

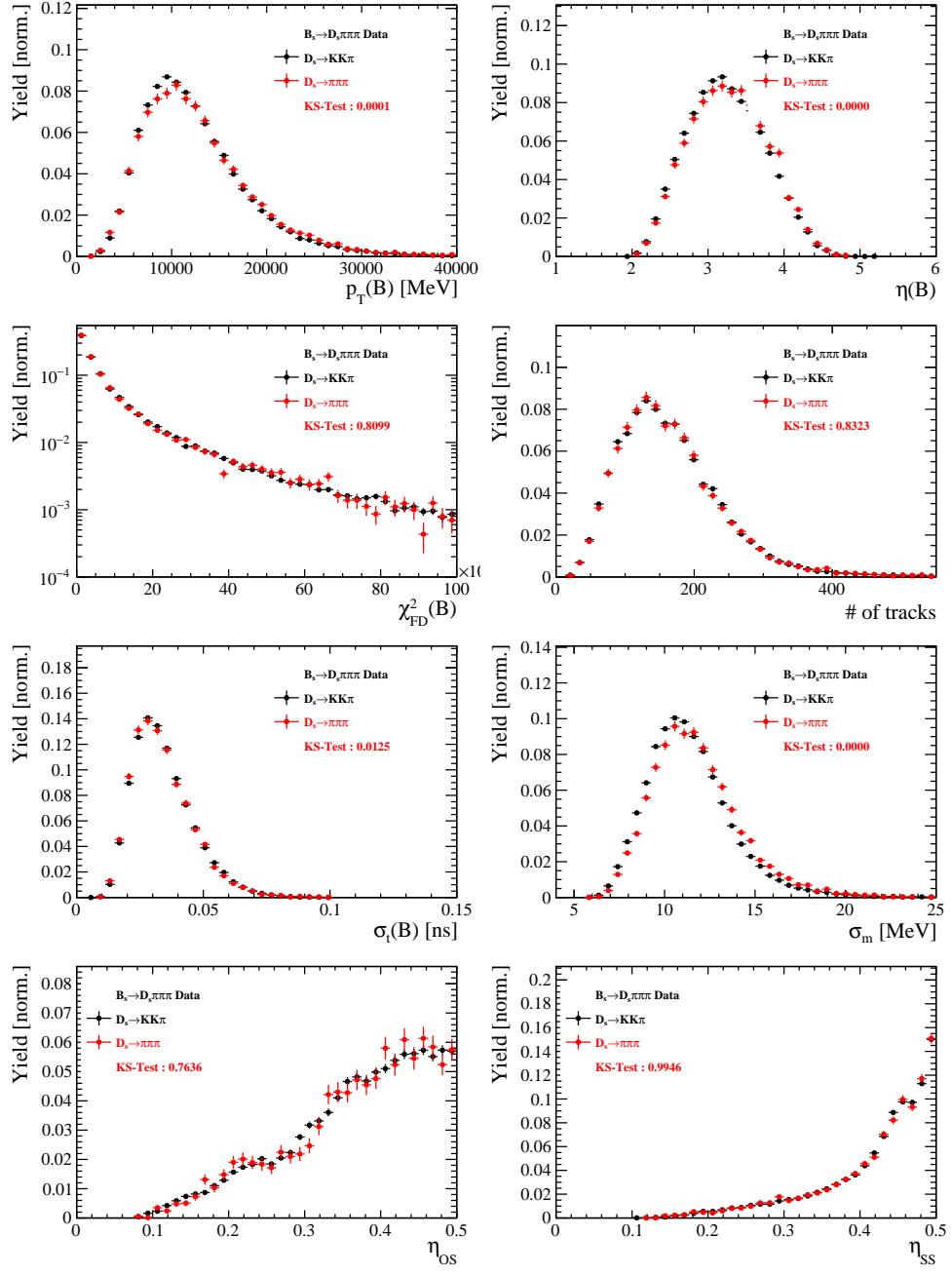


Figure C.5: Comparison of selected variables.

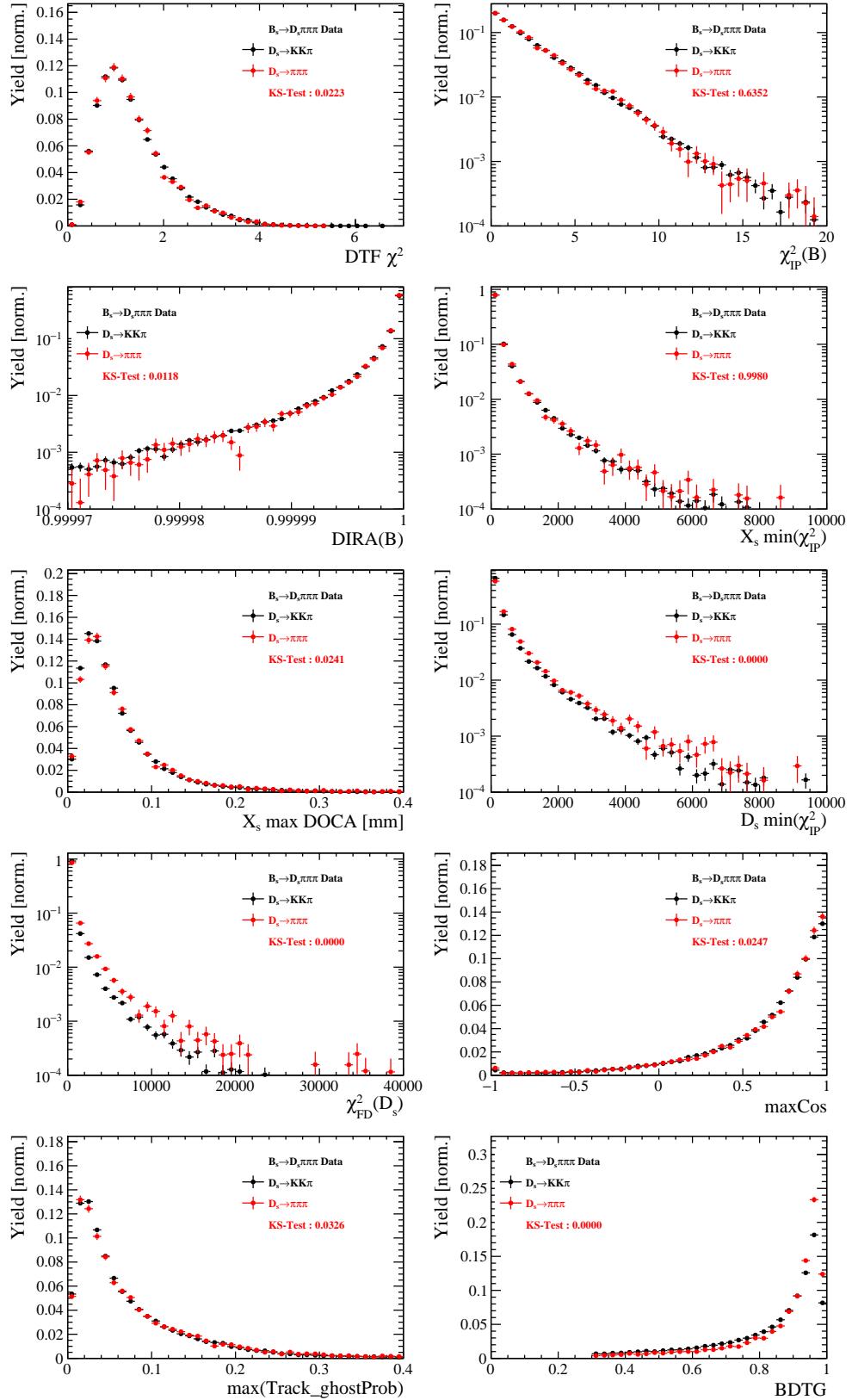


Figure C.6: Comparison of BDTG input variables and classifier response.

986 H.4 Comparison of trigger categories

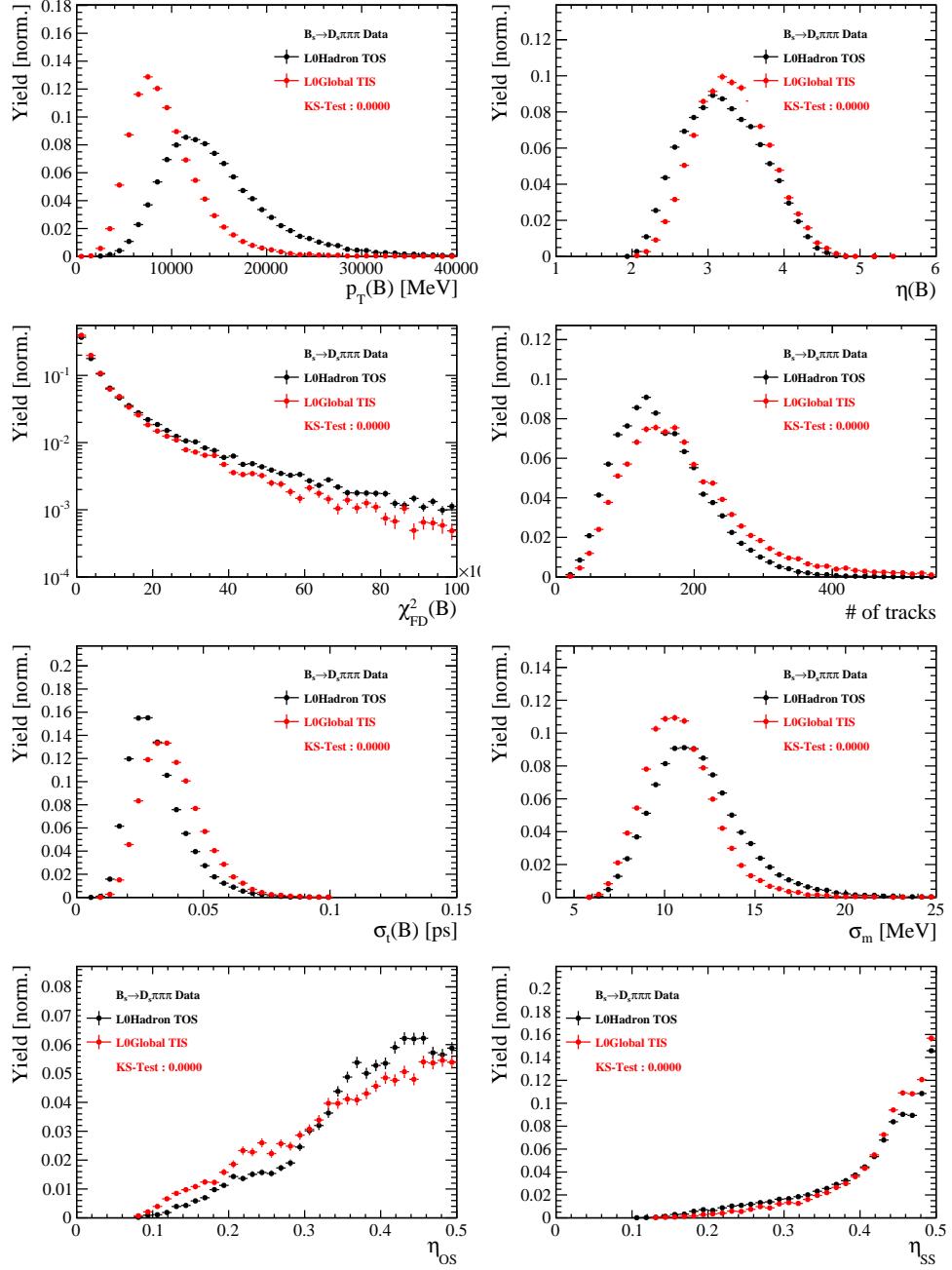


Figure C.7: Comparison of selected variables.

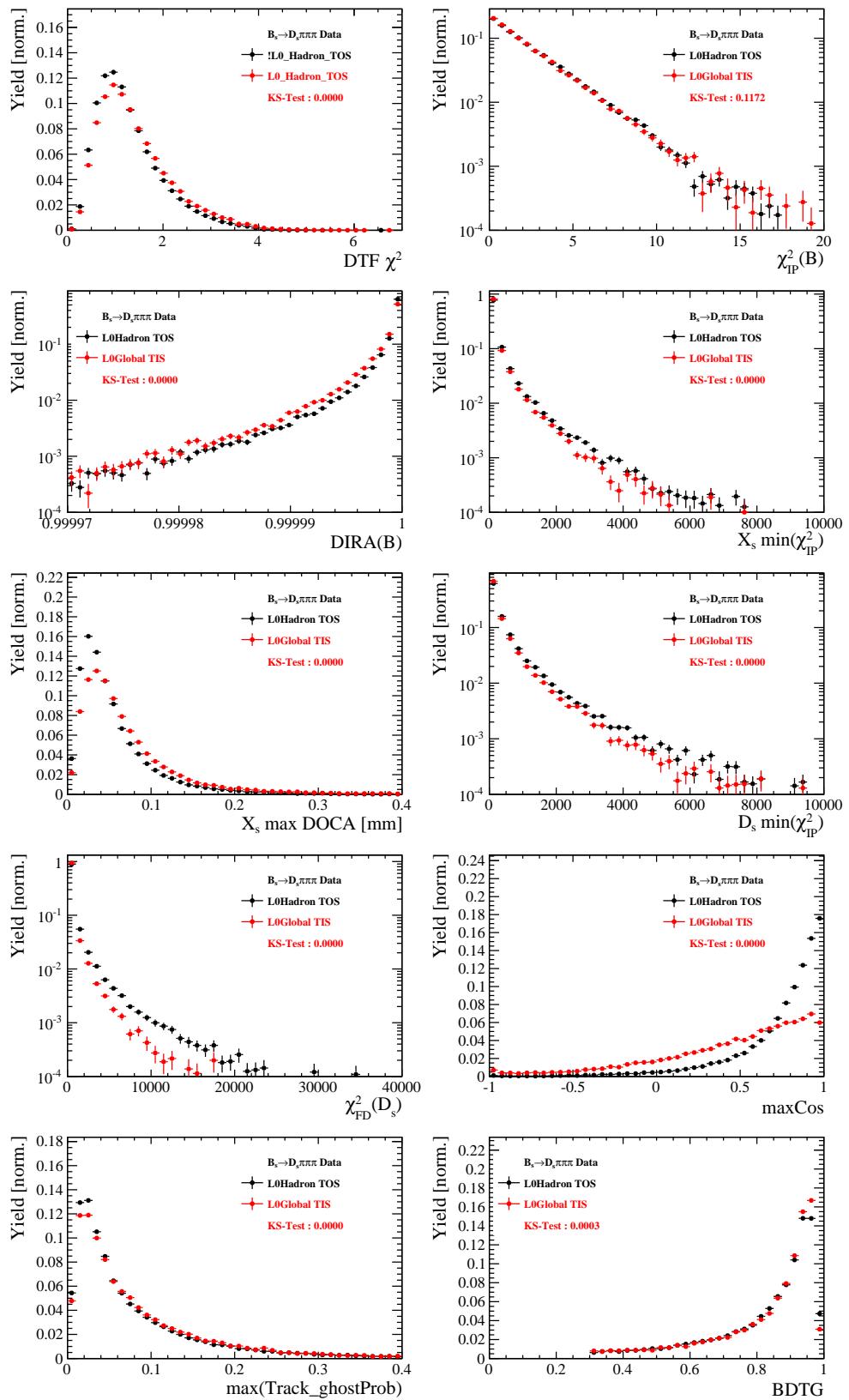


Figure C.8: Comparison of BDTG input variables and classifier response.

987 H.5 Comparison of B_s and B_d decays

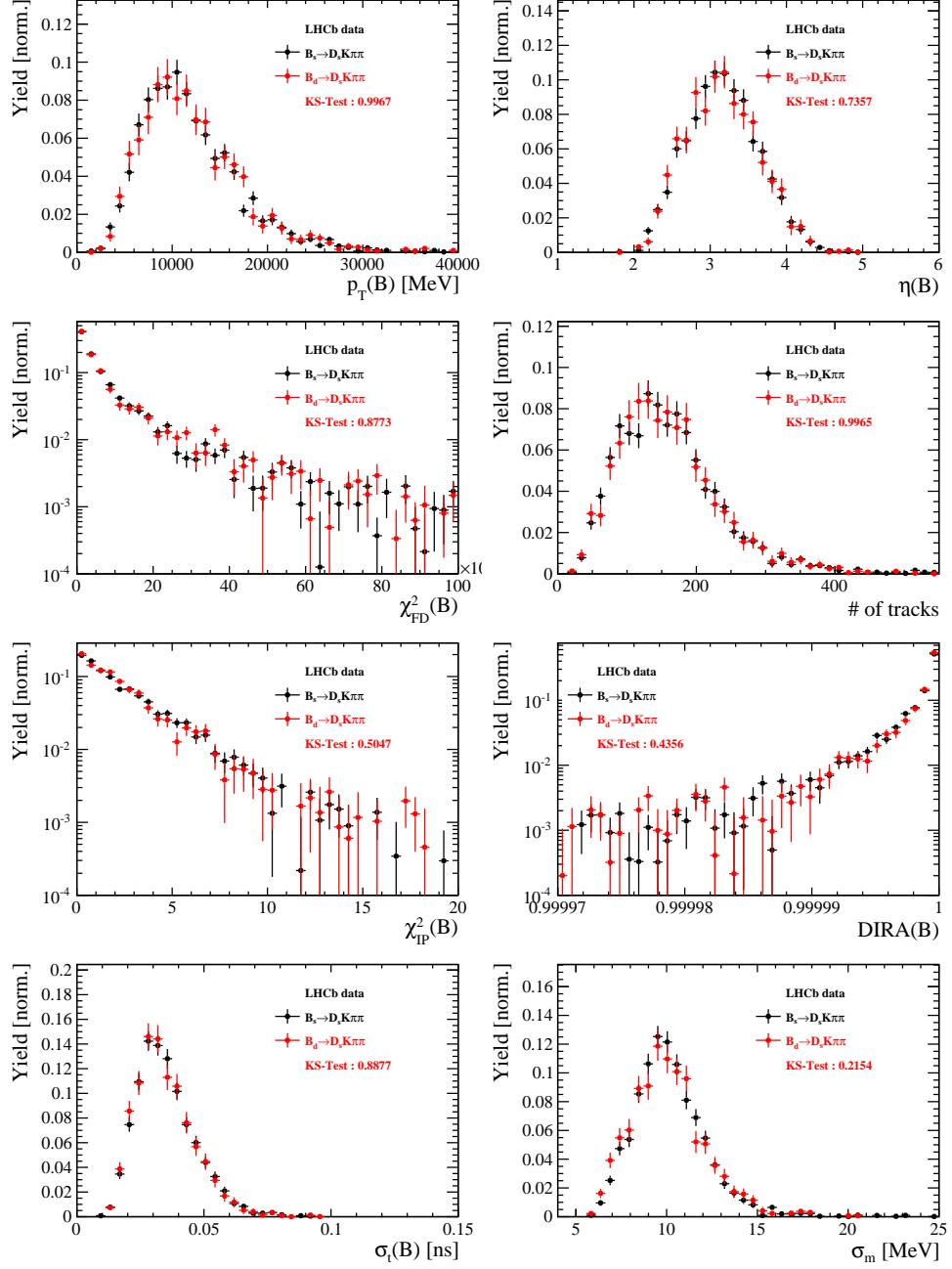


Figure C.9: Comparison of selected variables.

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