LHCb-ANA-20XX-YYY
September 1, 2017

Measurement of the CKM angle γ using $B_s^0 \to D_s K\pi\pi$ 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 $B_s^0 \to D_s K\pi\pi$ decays using proton-proton collision data corresponding to an integrated luminosity of xxx fb^{-1} recorded by the LHCb detector.

Contents

0 To Do List with Assignment of Tasks

1. **MC Requests (Urgent !):**
   Run-2 MC
   Phasespace MC for Dalitz Eff
   (need much higher statistics, filtered request ? on what ?)
   Ds→ 3pi MC ?
   Part. reco. bkg MC ?
   With CPV ?

2. Selection:
   Reoptimize with phasespace cuts (e.g. $m(K\pi\pi) < 2GeV$) ✓

3. Mass fits (Matthieu):
   Improve part. reco. bkg shape
   Save fitted yields in latex table

4. Use Meerkat PID resampling ✓
   (https://twiki.cern.ch/twiki/bin/view/LHCb/MeerkatPIDResampling)

5. Tagging:
   Produce new samples with tagging info (Matthieu, Philippe) ✓
   Calibration

6. Acceptance: (Matthieu)
   Compare data and MC

7. Resolution: (Matthieu)
   Compare $Bs \to DsK$ and $Bs \to DsK\pi\pi$ MC
   Get LTU $Bs \to DsK$ data sample ?

8. TD-MINT: (Philippe)
   Resolution integrals ✓
   per-event tagging
   change to MINUIT2
   add blinding

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 $B_s^0 \to D_s K$ decays [1], [2]. The $B_s^0 \to D_s K\pi\pi$ proceeds at tree level via the transitions shown in Fig. 1.1 a) and b).

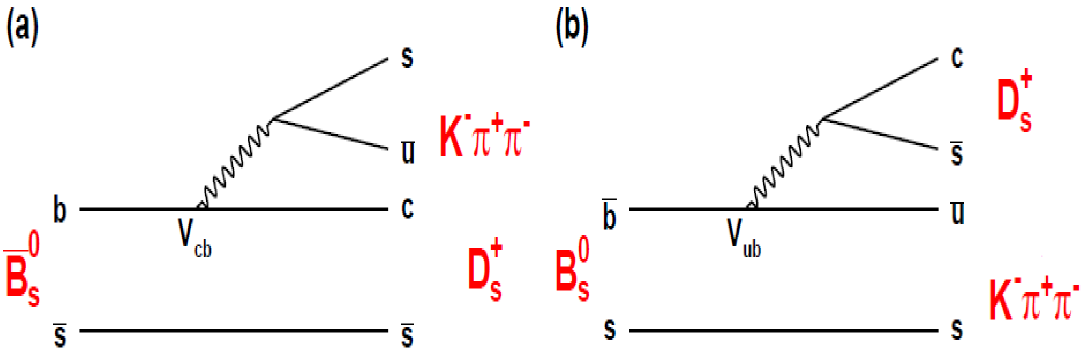


Figure 1.1: Feynman diagram of the $B_s^0 \to D_s K\pi\pi$ decay, proceeding via a) $b \to c$ transitions or b) $b \to u$ transitions.

To measure the weak CKM phase $\gamma \equiv arg[-(V_{ud}V_{ub}^*)/(V_{cd}V_{cb}^*)]$, a decay with interference between $b \to c$ and $b \to u$ transitions at tree level is needed [1]. As illustrated in Fig. 1.1, this is the case for the presented decay mode. A measurement of γ using $B_s^0 \to D_s K\pi\pi$ decays, where the $K\pi\pi$ subsystem is dominated by excited kaon states such as the $K_1(1270)$ and $K_1(1400)$ resonances, will succeed the branching ratio measurement presented in this note. It is complementary to the above mentioned analysis of $B_s^0 \to D_s K$, making use of a fully charged final state, where every track is detected in the vertex locator. To account for the non-constant strong phase across the Dalitz plot, one can either develop a time-dependent amplitude model 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 $B_s^0 \to D_s K\pi\pi$ decay presented in [3] and [4], where its branching ratio is measured relative to $B_s^0 \to D_s\pi\pi\pi$. The result obtained by the previous analysis is $0.052\ \pm 0.005\ 0.003$, where the uncertainties are statistical and systematical, respectively. The branching ratio measurement is updated, exploiting the full Run 1 data sample, corresponding to 3 fb^{-1} of integrated luminosity.

2 Sensitivity studies

2.1 PDF

First, I define the purely hadronic amplitudes for a given phasespace point x. The weak phase dependence is written latter explicitly in the pdf.

$$A(B_s^0 \to D_s^- K^+ \pi\pi) \equiv A(x) = \sum_i a_i \, A_i(x) \tag{2.1}$$

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

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

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

The full time-dependent amplitude pdf is given by:

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

where $q_t = +1$ $(-1)$for a B_s^0 $(\bar{B}_s^0)$ tag and $q_f = +1$ (-1) for $D_s^- K^+ \pi\pi$ $(D_s^+ K^- \pi\pi)$ final states.

Integrating over the phasespace, we get

$$\begin{aligned} \int P(x,t,q_t,q_f)\mathrm{d}x \propto [&\cosh\left(\frac{\Delta\Gamma\, t}{2}\right) \\ &+ q_t q_f \left(\frac{1-r^2}{1+r^2}\right) \cos\left(m_s\, t\right) \\ &- 2\left(\frac{\kappa\, r \cos(\delta - q_f(\gamma - 2\beta_s))}{1+r^2}\right) \sinh\left(\frac{\Delta\Gamma\, t}{2}\right) \\ &- 2q_t q_f \left(\frac{\kappa\, r \sin(\delta - q_f(\gamma - 2\beta_s))}{1+r^2}\right) \sin\left(m_s\, t\right)]e^{-\Gamma t} \\ = [&\cosh\left(\frac{\Delta\Gamma\, t}{2}\right) + q_t q_f\, C \cos\left(m_s\, t\right) - \kappa\, D_{q_f} \sinh\left(\frac{\Delta\Gamma\, t}{2}\right) - q_t\, \kappa\, S_{q_f} \sin\left(m_s\, t\right)]e^{-\Gamma t} \end{aligned}$$

where the C, D_{q_f}, S_{q_f} are defined exactly as for $D_s K$. The coherence factor is defined as :

$$\kappa\, e^{i\delta} \equiv \frac{\int A(x)^* \bar{A}(x) \mathrm{d}x}{\sqrt{\int |A(x)|^2 \mathrm{d}x} \sqrt{\int |\bar{A}(x)|^2 \mathrm{d}x}} \tag{2.5}$$

$$r \equiv \frac{\sqrt{\int |\bar{A}(x)|^2 \mathrm{d}x}}{\sqrt{\int |A(x)|^2 \mathrm{d}x}} \tag{2.6}$$

and appears in front of the D_{q_f}, S_{q_f} terms. This means one additional fit parameter for the lifetime fit. In the limit of only one contributing resonance $\kappa \to 1$.

2.2 Estimation of coherence factor

To estimate the coherence factor we could generate many toys with random a_i and $\bar{a}_i$ values (see https://twiki.cern.ch/twiki/pub/LHCbPhysics/Bu2DKstar/LHCb-ANA-2017-005_v1.pdf) using the set of amplitudes show in our last talk. However with so many interfering amplitudes, I would be surprised if you couldn't generate every possible value for κ. In any case, this would give us a range where to expect possible values for κ. Worst case would be $0 \leq \kappa \leq 1$.

Assumptions:

- $A(x) = \sum_i a_i\, A_i(x)$
  $\bar{A}(x) = \sum_i \bar{a}_i\, \bar{A}_i(x)$
- Use amplitudes from flavor-averaged, time-integrated fit
- Draw random a_i and $\bar{a}_i$ values
- Constraints:
  $\int (|a_i A_i(x)|^2 + |\bar{a}_i \bar{A}_i(x)|^2)\, \mathrm{d}x/N = F_i^{eff}$
  $r \approx 0.4$ (ration of CKM elements)

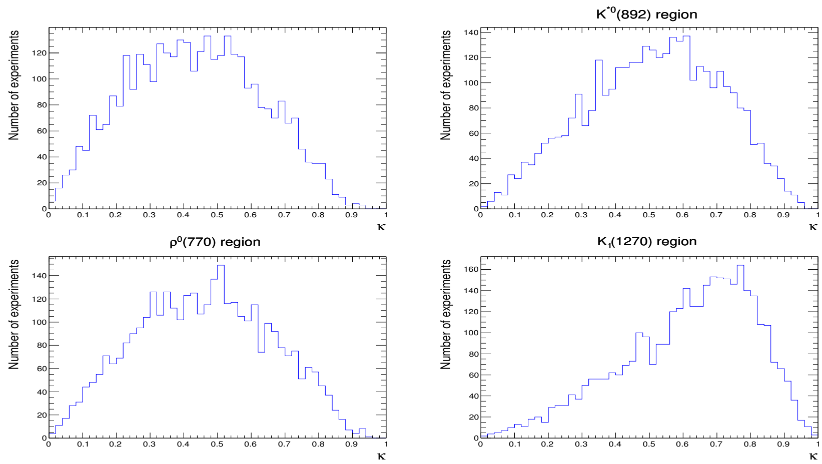


Figure 2.1

Table 2.1

Region	$<\kappa>$ (%)	Cut eff. (%)
Full	43	100
$K^*(892)$	51	43
$\rho^0(770)$	46	47
$K_1(1270)$	61	23

2.3 Results

Assumptions:

- Use amplitudes from flavor-averaged, time-integrated fit
- $r = 0.4$ (ratio of CKM elements)
- PDG values for: $\tau, \Delta m_s, \Delta\Gamma, \beta_s$
- $\epsilon(x,t) = const.$, perfect resolution
- $\epsilon_{Tag} = 0.66, <\omega>= 0.4$
- $N_{signal} = 3000$ (Run1+15/16 data)

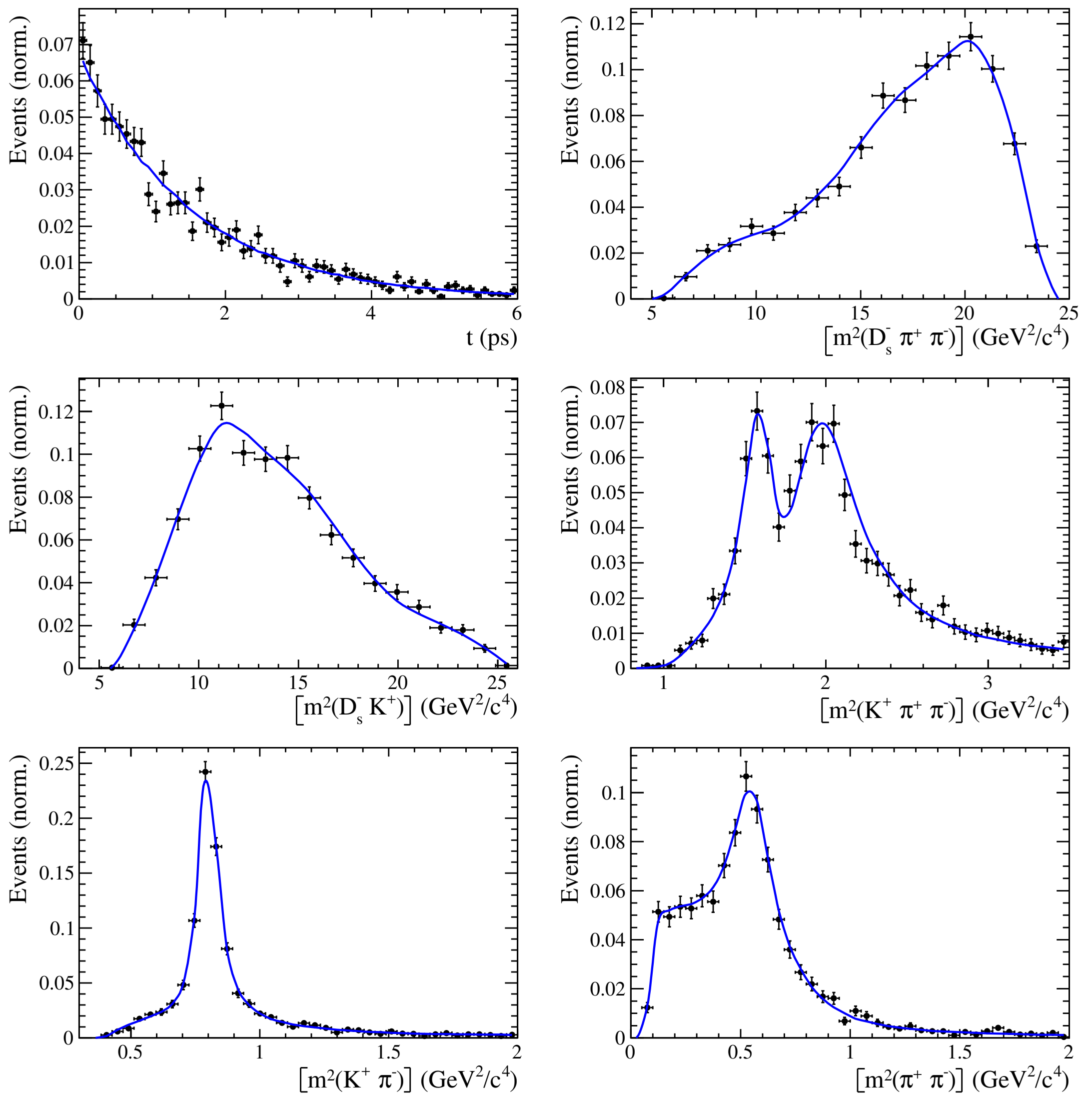
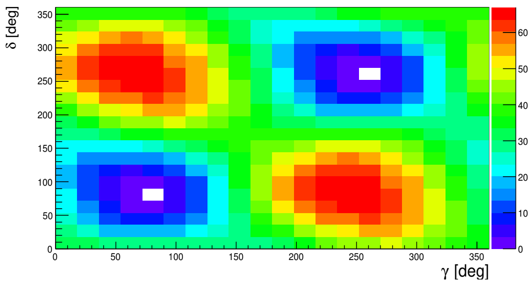


Figure 2.2: Example toy fit



Generated values:
$\gamma = 70°, \delta = 100°$
Fit result:
$\gamma = 74 \pm 15°, \delta = 84 \pm 15°$
$(\gamma = 254 \pm 15°, \delta = 264 \pm 15°)$

Figure 2.3: Likelihood scan

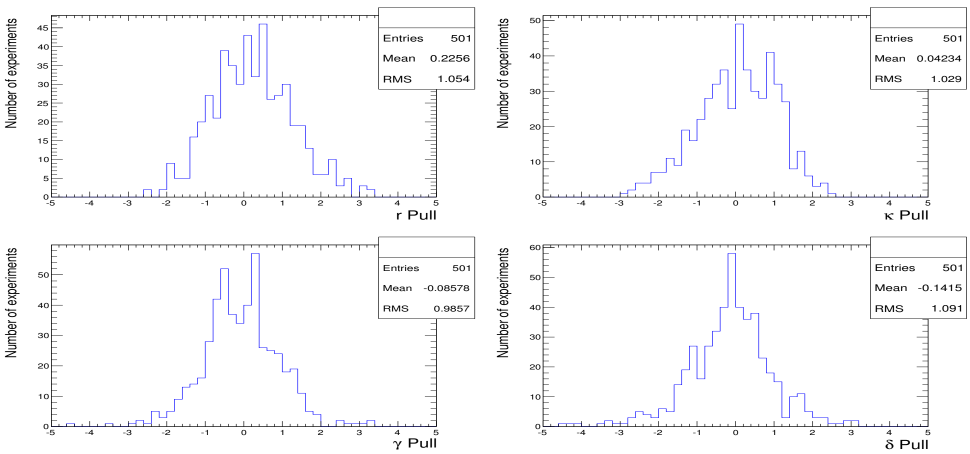


Figure 2.4: Pulls

Table 2.2

	Generated	Full PDF	Phasespace integrated
r	0.4	0.38 ± 0.06	unstable
κ	0.2	0.23 ± 0.13	0.2 (fixed)
δ	100	99 ± 22	unstable
γ	70	70 ± 17	unstable

	Generated	Full PDF	Phasespace integrated
r	0.4	0.44 ± 0.07	0.43 ± 0.11
κ	0.4	0.41 ± 0.14	0.4 (fixed)
δ	100	101 ± 19	95 ± 41
γ	70	69 ± 16	66 ± 40

	Generated	Full PDF	Phasespace integrated
r	0.4	0.41 ± 0.08	0.39 ± 0.11
κ	0.6	0.60 ± 0.13	0.6 (fixed)
δ	100	98 ± 17	92 ± 25
γ	70	68 ± 17	65 ± 28

	Generated	Full PDF	Phasespace integrated
r	0.4	0.42 ± 0.09	0.39 ± 0.09
κ	1.0	0.96 ± 0.03	1.0 (fixed)
δ	100	100 ± 17	100 ± 17
γ	70	66 ± 17	67 ± 17

3 Selection

For the presented analysis, we reconstruct the $B_s^0 \to D_s K\pi\pi$ decay through two different final states of the D_s meson, $D_s \to KK\pi$ and $D_s \to \pi\pi\pi$. Of those two final states $D_s \to KK\pi$ is the most prominent one, while $\mathcal{BR}(D_s \to \pi\pi\pi) \approx 0.2 \cdot \mathcal{BR}(D_s \to KK\pi)$ holds for the other one.
A two-fold approach is used to isolate the $B_s^0 \to D_s K\pi\pi$ candidates from data passing the stripping line. First, further one-dimensional cuts are applied to reduce the level of combinatorial background and to veto some specific physical background. This stage is specific to the respective final state in which the D_s meson is reconstructed, since different physical backgrounds, depending on the respective final state, have to be taken into account. After that, a multivariate classifier is trained which combines the information of several input variables, including their correlation, into one powerful discriminator between signal and combinatorial background. For this stage, all possible D_s final states are treated equally.

3.1 Cut-based selection

In order to minimize the contribution of combinatorial background to our samples, we apply the following cuts to the b hadron:

- DIRA > 0.99994
- min IP $\chi^2 < 20$ to any PV,
- FD $\chi^2 > 100$ to any PV,
- Vertex χ^2/nDoF < 8,
- $(Z_{D_s} - Z_{B_s^0}) > 0$, where Z_M is the z-component of the position $\vec{x}$ of the decay vertex for the B_s^0/D_s meson.

Additionally, we veto various physical backgrounds, which have either the same final state as our signal decay, or can contribute via a single misidentification of $K \to \pi$ or $K \to p$. In the following, the vetoes are ordered by the reconstructed D_s final state they apply to:

1. All:
   (a) $B_s^0 \to D_s^+ D_s^-$: $|M(K\pi\pi) - m_{D_s}| > 20$ MeV/c^2.
   (b) $B_s^0 \to D_s{}^- K^+ K^- \pi^+$: possible with single missID of $K^- \to \pi^-$, rejected by requiring π^- to fulfill $\mathrm{DLL}_{K\pi} < 5$.
2. $D_s \to KK\pi$
   (a) $B^0 \to D^+(\to K^+\pi^-\pi^+)K\pi\pi$: possible with single missID of $\pi^+ \to K^+$, vetoed by changing particle hypothesis and recompute $|M(K^+\pi^-\pi^+) - m_{Dp}| > 30$ MeV/c^2, or the K^+ has to fulfill $\mathrm{DLL}_{K\pi} > 10$.

(b) $\Lambda_b^0 \to \Lambda_c^+(\to pK^-\pi^+)K\pi\pi$: possible with single missID of $p \to K^+$, vetoed by changing particle hypothesis and recompute $M(pK^-\pi^+) - m_{\Lambda_c^+} > 30$ MeV/c^2, or the K^+ has to fulfill ($\mathrm{DLL}_{K\pi}$ - $\mathrm{DLL}_{p\pi}$) > 5.

(c) $D^0 \to KK$: D^0 combined with a random π can fake a $D_s \to KK\pi$ decay and be a background to our signal, vetoed by requiring $M(KK) < 1840\,\mathrm{MeV}/c^2$.

3. $D_s \to \pi\pi\pi$

   (a) $D^0 \to \pi\pi$: combined with a random π can fake a $D_s \to \pi\pi\pi$ decay and be a background to our signal, vetoed by requiring both possible combinations to have $M(\pi\pi) < 1700\,\mathrm{MeV}/c^2$.

The most prominent final state used in this analysis is $B_s^0 \to D_s(\to KK\pi)K\pi\pi$, where the D_s decay can either proceed via the narrow ϕ resonance, the broader K^{*0} resonance, or non resonant. Depending on the decay process being resonant or not, we apply additional PID requirements on this final state:

- resonant case:
  - $D_s^+ \to \phi\pi^+$, with $|M(K^+K^-) - m_\phi| < 20$ MeV/c^2 : no additional requirements, since ϕ is narrow and almost pure K^+K^-.
  - $D_s^+ \to \overline{K}^{*0}K^+$, with $|M(K^-\pi^+) - m_{K^{*0}}| < 75$ MeV/c^2 : $\mathrm{DLL}_{K\pi} > 0$ for kaons, since this resonance is more than ten times broader than ϕ.
- non resonant case: $\mathrm{DLL}_{K\pi} > 5$ for kaons, since the non resonant category has significant charmless contributions.

For the $D_s \to \pi\pi\pi$ final state, we apply global PID requirements:

- $\mathrm{DLL}_{K\pi} < 10$ for all pions.
- $\mathrm{DLL}_{p\pi} < 10$ for all pions.

3.2 Multivariate stage

We use TMVA [5] to train a multivariate discriminator, which is used to further improve the signal to background ratio. The 17 variables used for the training are:

- max(ghostProb) over all tracks
- cone(p_T) asymmetry of every track, which is defined to be the difference between the p_T of the π/K and the sum of all other p_T in a cone of radius $r = \sqrt{(\Delta\Phi)^2 + (\Delta\eta)^2}$ < 1 rad around the signal π/K track.
- min($\mathrm{IP}\chi^2$) over the X_s daughters
- max(DOCA) over all pairs of X_s daughters
- min($\mathrm{IP}\chi^2$) over the D_s daughters

- D_s and B_s^0 DIRA
- D_s FD significance
- $\max(\cos(D_s h_i))$, where $\cos(D_s h_i)$ is the cosine of the angle between the D_s and another track i in the plane transverse to the beam
- B_s^0 IPχ^2, FDχ^2 and Vertex χ^2

Various classifiers were investigated in order to select the best performing discriminator. Consequently, a boosted decision tree with gradient boost (BDTG) is chosen as nominal classifier. We use truth-matched MC as signal input. Simulated signal candidates are required to pass the same trigger, stripping and preselection requirements, that were used to select the data samples. For the background we use events from the high mass sideband ($m_{B_s^0 candidate} > 5600$ MeV$/c^2$) of our data samples. As shown in Fig. 3.1, this mass region is sufficiently far away from signal structures and is expected to be dominantly composed of combinatorial background.

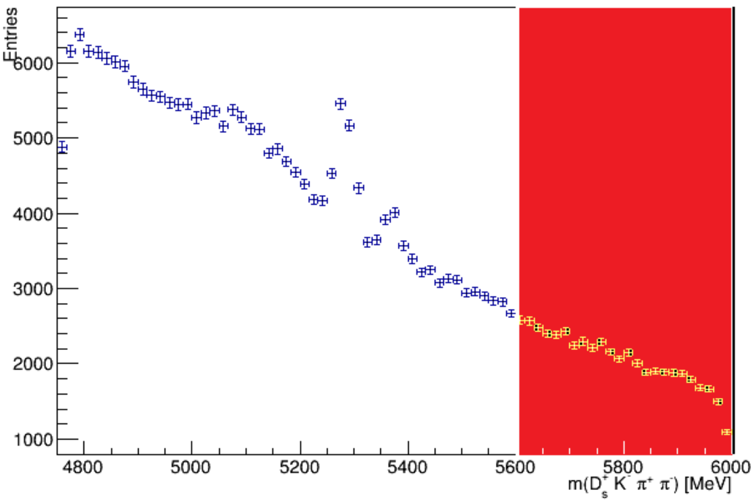


Figure 3.1: Invariant mass distribution of preselected $B_s^0 \to D_s K\pi\pi$ candidates. The red coloured region with $m_{B_s^0 candidate} > 5600$ MeV$/c^2$ is used as background input for the boosted decision tree.

The distributions of the input variables for signal and background are shown in Fig. 3.2.

The relative importance of the input variables for the BDTG training is summarized in Table 3.1.

The BDTG output distribution for test and training samples is shown in Fig 3.3. No sign of overtraining is observed.

We determine the optimal cut value by maximizing the figure of merit $S/\sqrt{S+B}$ where S is the signal yield and B the background yield in the signal region, defined to be within ± 50 MeV$/c^2$ of the nominal B_s^0 mass. To avoid a bias in the determination of the branching fraction, we determine S and B using our normalization channel. All trigger,

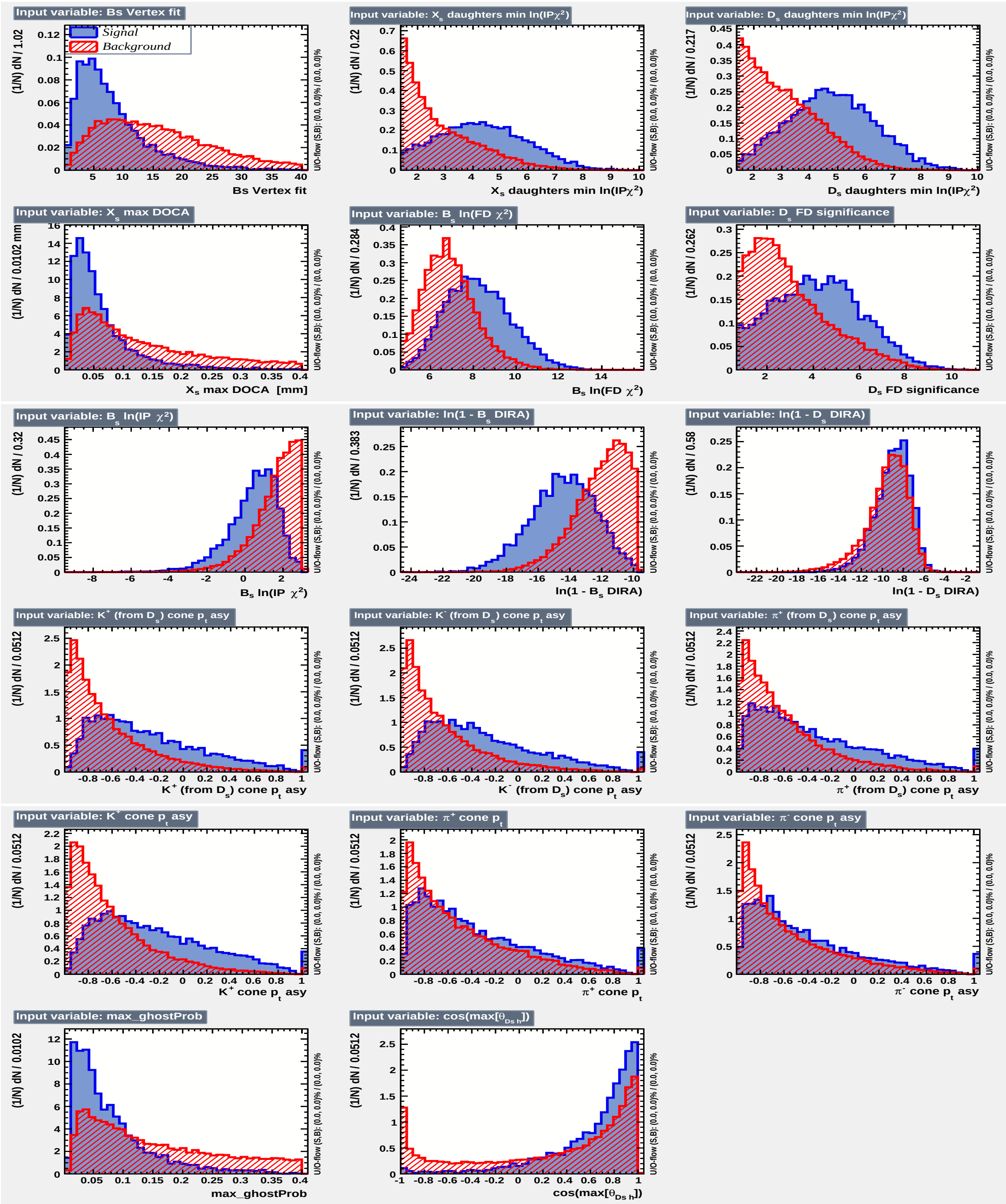


Figure 3.2: Distributions of the input variables used in the BDTG training. The background is shown as red hatched, while the signal is depicted solid blue.

stripping and additional selection criteria described in this and the previous chapter are applied to the $B_s^0 \to D_s\pi\pi\pi$ data samples. After that, we perform a simplified version of the fit to the invariant mass distribution of $B_s^0 \to D_s\pi\pi\pi$ candidates described in Sec. **??**. Here, a Gaussian function to model the signal and an exponential function to model combinatorial background is used. From this fit we estimate the number of signal events in our normalization channel. Multiplying that number with the PDG branching fraction

Variable	relative importance [%]
pi_minus_ptasy_1.00	7.32
log_Ds_FDCHI2_ORIVX	7.23
K_plus_ptasy_1.00	7.17
log_Ds_DIRA	6.96
Bs_ENDVERTEX_CHI2	6.82
max_ghostProb	6.76
pi_plus_ptasy_1.00	6.57
log_DsDaughters_min_IPCHI2	6.21
log_Bs_DIRA	6.15
K_plus_fromDs_ptasy_1.00	6.10
log_XsDaughters_min_IPCHI2	5.87
K_minus_fromDs_ptasy_1.00	5.62
cos(Ds h)	5.58
log_Bs_IPCHI2_OWNPV	5.08
log_Bs_FDCHI2_OWNPV	4.04
Xs_max_DOCA	3.98
pi_minus_fromDs_ptasy_1.00	2.59

Table 3.1: Summary of the relative importance of each variable in the training of the BDTG.

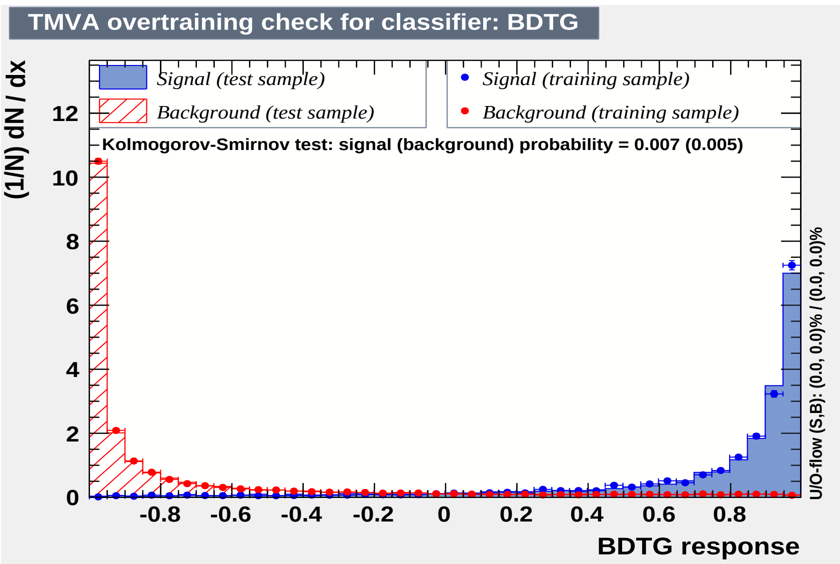


Figure 3.3: BDTG output classifier distribution for (blue) signal and (red) background. The response of an independent test sample (dots) is overlaid.

of $\frac{\mathcal{B}(B_s^0 \to D_s K\pi\pi)}{\mathcal{B}(B_s^0 \to D_s \pi\pi\pi)}$ and the ratio of efficiencies discussed in Sec. ?? allows us to estimate the expected number of $B_s^0 \to D_s K\pi\pi$ signal decays. The number of background events can then be computed as

$$N_{bkg} = N_{all} - N_{sig}|_{m_{B_s^0} \pm 50\,\mathrm{MeV}/c^2}. \tag{3.1}$$

186 The efficiency curves as a function of the cut value are shown in Fig. 3.4. The optimal
187 cut value is found to be BDTG > 0.7012. At this working point the signal efficiency is
188 estimated to be 72.47 %, while the background rejection in the signal region is 97.38 %.

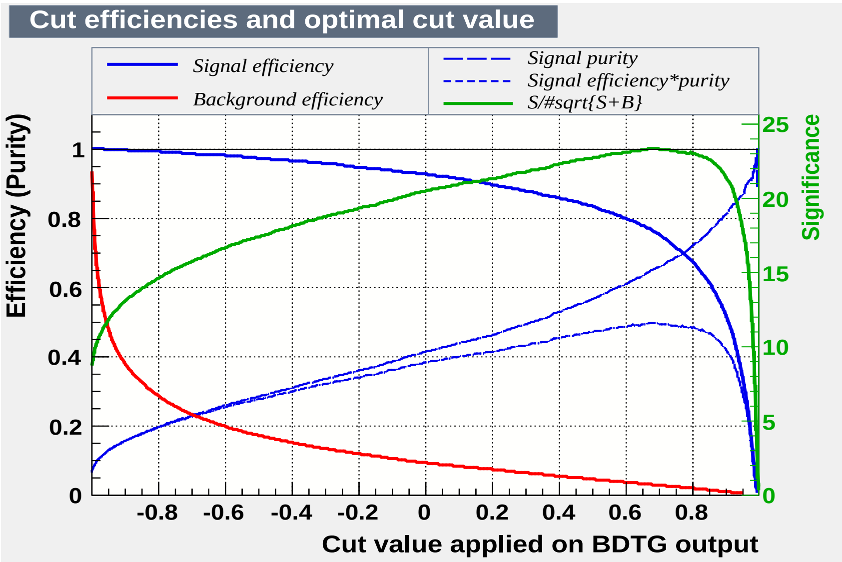


Figure 3.4: Efficiency and purity curves for (blue) signal, (red) background and the (green) FoM curve, as a function of the chosen cut value.

4 Fits to invariant mass distributions of signal and normalization channel

In order to properly model the invariant mass distribution of $B_s^0 \to D_s K\pi\pi$ and $B_s^0 \to D_s\pi\pi\pi$ candidates, the expected signal shape, as well as the expected shape for the combinatorial and physical background has to be known. This model can then be used to fit the distributions and obtain signal sWeights [6], which are employed to suppress the residual background that is still left in the sample, for the time-dependent amplitude fit.

4.1 Signal models for $\mathrm{m}(D_s\pi\pi\pi)$ and $m(D_s K\pi\pi)$

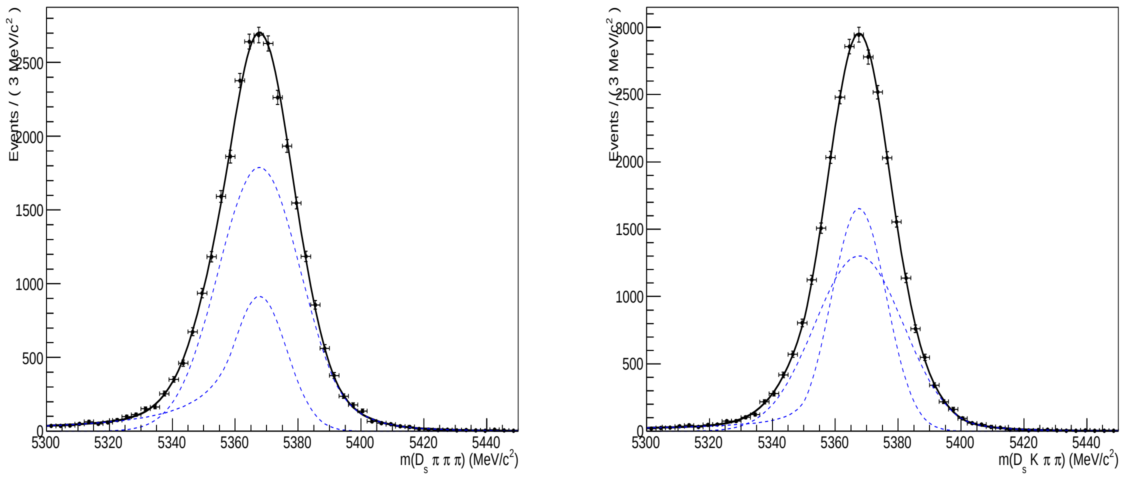


Figure 4.1: Invariant mass distributions of simulated (left) $B_s^0 \to D_s\pi\pi\pi$ and (right) $B_s^0 \to D_s K\pi\pi$ events. A fit of the sum of two Crystal Ball functions to each distribution is overlaid. The dotted lines represent the individual Crystal Ball functions.

The mass distribution of $B_s^0 \to D_s K\pi\pi$ signals is modeled using two Crystal Ball functions, which share the same mean μ, but are allowed to have different widths σ_1 and σ_2. Another double Crystal Ball function is used to account for the contribution of the $B^0 \to D_s K\pi\pi$ decay, which is also present in the $m(D_s K\pi\pi)$ spectrum. The core width, as well as the tail parameters and the ratio of the two individual Crsystal Ball functions are fixed to values obtained by a fit to the invariant mass distribution of simulated events shown in Fig 4.1. The second width σ_2 and the shared mean μ are floated in the fit to account for possible differences between the simulation and real data.
The same approach is used to describe the invariant mass distribution of $B_s^0 \to D_s\pi\pi\pi$ candidates. A double Crystal Ball function is used to model the signal, the parameters are determined by a fit to the invariant mass of simulated $B_s^0 \to D_s\pi\pi\pi$ decays, shown in Fig 4.1. The second width and the shared mean are floated to account for differences between data and MC.

4.2 Background models for $\mathrm{m}(D_s\pi\pi\pi)$

Different background sources arise in the invariant mass spectrum of candidates in the normalization mode.
The following backgrounds have to be accounted for:

- Combinatorial background: This contribution arises from either a real D_s, which is paired with random tracks to form the B_s^0 candidates, or via real X_d's, which are combined with three tracks that fake a D_s candidate to form a fake B_s^0.
- Partially reconstructed $B_s^0 \to D_s{}^*\pi\pi\pi$ decays, with $D_s{}^* \to D_s\gamma$ or $D_s{}^* \to D_s\pi^0$, where the γ/π^0 is not reconstructed in the decay chain.

In both cases of combinatorial background, the distribution in the invariant mass of B_s^0 candidates is expected to be smooth and decrease with higher masses. Therefore, one exponential function is used to model these contributions.
The shape of the $B_s^0 \to D_s{}^*\pi\pi\pi$ contribution is expected to be peaking in the $m(D_s\pi\pi\pi)$ spectrum, with large tails due to the missing momentum, which is carried away by the π^0 or γ. The pion or photon from $D_s{}^* \to D_s(\gamma/\pi^0)$ is excluded from the reconstruction. We model the shape of this contribution using the sum of three bifurcated Gaussian functions. The shape parameters, as well as the yield of this contribution, are directly determined on data from a fit to the $m(D_s\pi\pi\pi)$ invariant mass distribution.

4.3 Background models for $m(D_sK\pi\pi)$

For the signal channel, the following background sources have to be considered:

- Combinatorial background: same contributions as discussed in Sec. 4.2.
- Partially reconstructed $B_s^0 \to D_s{}^*K\pi\pi$ decays, with $D_s{}^* \to D_s\gamma$ or $D_s{}^* \to D_s\pi^0$, where the γ/π^0 is not reconstructed in the decay chain.
- Partially reconstructed $B^0 \to D_s{}^*K\pi\pi$ decays, with $D_s{}^* \to D_s\gamma$ or $D_s{}^* \to D_s\pi^0$, where the γ/π^0 is not reconstructed in the decay chain.
- Misidentified $B_s^0 \to D_s\pi\pi\pi$ decays, where one of the pions is wrongly identified as a kaon $\pi \to K$.
- Misidentified, partially reconstructed $B_s^0 \to D_s{}^*\pi\pi\pi$ decays, where one of the pions is wrongly identified as a kaon $\pi \to K$ and the γ/π^0 from $D_s{}^* \to D_s\gamma/\pi^0$ is not reconstructed.

The combinatorial background is expected to be non-peaking in the spectrum of the invariant mass of $B_s^0 \to D_sK\pi\pi$ candidates. An exponential function is used to model this contribution.
The shape of the partially reconstructed background without misID is taken from our normalization channel, where it can be directly fitted by the sum of three bifurcated Gaussian functions as described above. In the signal mass fit, all shape parameters for the $B_s^0 \to D_s{}^*K\pi\pi$ background are fixed to the input values from our normalization fit.

For the contribution of the $B^0 \to D_s{}^*K\pi\pi$ background, the same shape is used but the means μ_i of the bifurcated gaussians are shifted down by $m_{B_s^0} - m_{B^0}$ [?]. The yields of both contributions are directly determined in the nominal fit.
To determine the shape of misidentified $B_s^0 \to D_s\pi\pi\pi$ candidates in the $m(D_sK\pi\pi)$ spectrum, we take a truth-matched signal MC sample of our normalization channel. We then use the PIDCalib package to determine the $\pi \to K$ fake rate. For every candidate in our MC sample, a (momentum) p and (pseudorapidity) η-dependent event weight is computed and assigned. We flip the particle hypothesis from pion to kaon for the π with the biggest miss-ID weight for each event and recompute the invariant B_s^0 mass. This distribution is then modeled using two Crystal Ball functions. The distribution and the fit are shown in Fig. 4.2(left).

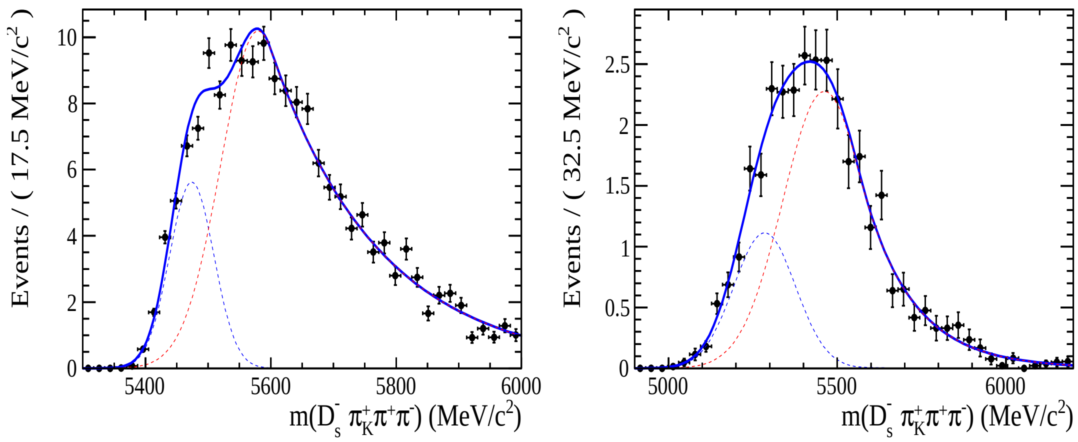


Figure 4.2: Invariant mass distribution of (left) simulated $B_s^0 \to D_s\pi\pi\pi$ events, where one of the π's is reconstructed as a K and the misID probability for each event is taken into account. The corresponding distribution for simulated $B_s^0 \to D_s{}^*\pi\pi\pi$ events, where the γ/π^0 from the $D_s{}^*$ is excluded from reconstruction, is shown on the right. The solid, black curve on each plot corresponds to the fit consisting of two Crystal Ball functions.

The expected yield of misidentified $B_s^0 \to D_s\pi\pi\pi$ candidates in the $m(D_sK\pi\pi)$ spectrum is computed by multiplying the fake probability of $\propto 3.2\%$, which is derived from PIDCalib, by the yield of $B_s^0 \to D_s\pi\pi\pi$ signal candidates, determined in the nominal mass fit of our normalization channel.
In the same way as mentioned above, we can determine the rate of misidentified, partially reconstructed $B_s^0 \to D_s{}^*\pi\pi\pi$ decays in our sample of $B_s^0 \to D_sK\pi\pi$ decays using PIDCalib and a MC sample of $B_s^0 \to D_s{}^*\pi\pi\pi$ events. The invariant mass distribution we obtain when we exclude the γ/π^0, flip the the particle hypothesis $\pi \to K$ and apply the event weights given by the fake rate, is shown in Fig. 4.2 (right). The fit of two Crystal Ball functions to this distribution is overlaid. The yield of this contribution is determined from the yield of $B_s^0 \to D_s{}^*\pi\pi\pi$ candidates in the nominal mass fit of our normalization channel, multiplied by the misID probability of $\propto 3.6\%$.

4.4 Fit to $B_s^0 \to D_s\pi\pi\pi$ candidates

An unbinned maximum likelihood fit is performed simultaneously to the invariant mass distribution of $B_s^0 \to D_s\pi\pi\pi$ candidates. As discussed in Sec. 4.1, the fit is given as the sum of the double Gaussian signal model, the sum of three bifurcated Gaussian functions to model the partially reconstructed $B_s^0 \to {D_s}^* \pi\pi\pi$ background and an Exponential function to account for combinatorial background. The invariant mass distribution and the fit is shown in Fig. 4.3. All simultaneously performed fits to the $m(D_s\pi\pi\pi)$ distribution, ordered by the respective D_s final state, can be found in the Appendix A.1. The obtained yields are summarized in Table 4.1.

4.5 Fit to $B_s^0 \to D_s K\pi\pi$ candidates

The shape of the invariant mass distribution of$B_s^0 \to D_s K\pi\pi$ candidates is described by the sum of two double Gaussian functions for the B^0 and B_s^0 signal, two sums of three bifurcated Gaussians for the $B_s^0/B^0 \to {D_s}^* K\pi\pi$ partially reconstructed background contributions and two sums of double Crystal Ball functions for the single misID $B_s^0 \to D_s\pi\pi\pi$ and the partially reconstructed, misidentified $B_s^0 \to {D_s}^*\pi\pi\pi$ decays. A simultaneous unbinned maximum likelihood fit is performed and the result is shown in Fig. 4.3. All simultaneously performed fits to the $m(D_s K\pi\pi)$ distribution, ordered by the respective D_s final state, can be found in the Appendix A.1. The obtained yields are summarized in Table 4.1.

4.6 Extraction of signal weights

The sPlot technique [6] is used to extract signal weights from the fits to the invariant mass distributions of our signal and normalizaton channel. This statistical tool assignes a weight to every event, according to it's position in the respective mass distribution, given the fitted signal and background models. The weights can then be used to suppress the background components in every other observable distribution of interest. Figure 4.4 shows the distribution of weights across the invariant mass spectra of $B_s^0 \to D_s\pi\pi\pi$ and $B_s^0 \to D_s K\pi\pi$ candidates.

invariant mass spectrum/fit component	yield 2011	yield 2012	yield 2015	yield 2016
$m(D_s K\pi\pi)$				
$B_s^0 \to D_s K\pi\pi$	351 ± 26	858 ± 40		
$B^0 \to D_s K\pi\pi$	821 ± 41	1721 ± 67		
$B_s^0 \to {D_s}^* K\pi\pi$	629 ± 68	1333 ± 129		
$B^0 \to {D_s}^* K\pi\pi$	1252 ± 188	2653 ± 400		
$B_s^0 \to D_s\pi\pi\pi$	257 (fixed)	582 (fixed		)
$B_s^0 \to {D_s}^*\pi\pi\pi$	359 (fixed)	845 (fixed)		
combinatorial	2999 ± 154	6689 ± 240		
$m(D_s\pi\pi\pi)$				
$B_s^0 \to D_s\pi\pi\pi$	7671 ± 96	17379 ± 148		
$B_s^0 \to {D_s}^*\pi\pi\pi$	9984 ± 193	23479 ± 357		
combinatorial	10341 ± 204	21737 ± 373		

Table 4.1: Summary of yields from the fits to Run1 and Run2 data.

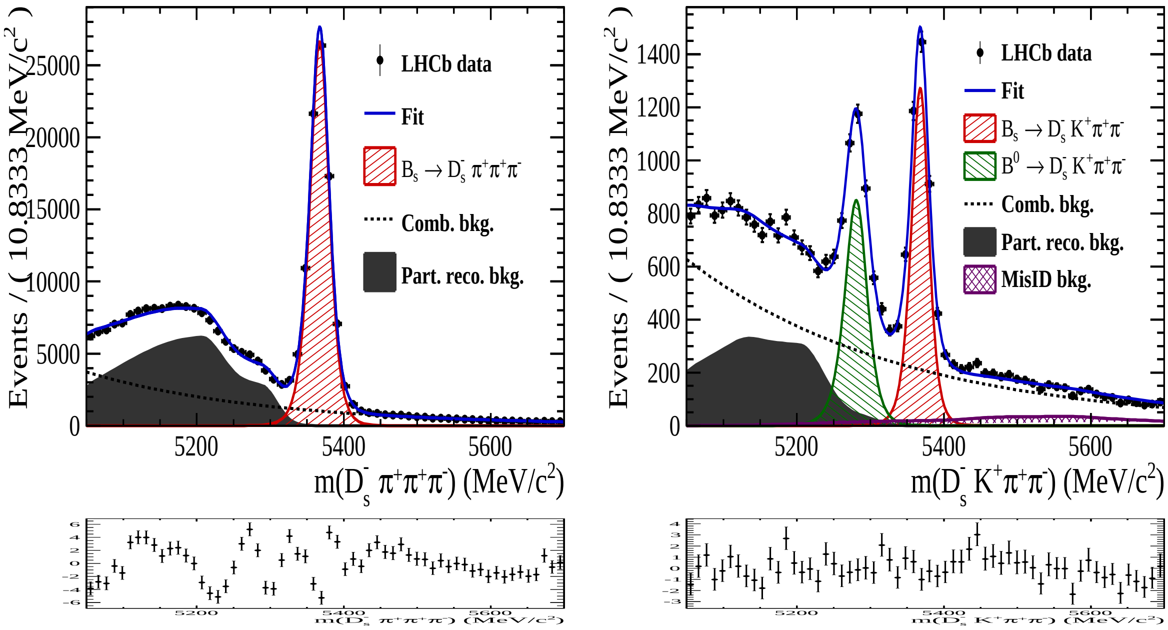


Figure 4.3: Invariant mass distribution of (left) $B_s^0 \to D_s\pi\pi\pi$ and (right) $B_s^0 \to D_sK\pi\pi$ candidates for Run1 and Run2 data. The respective fit described in the text is overlaid.

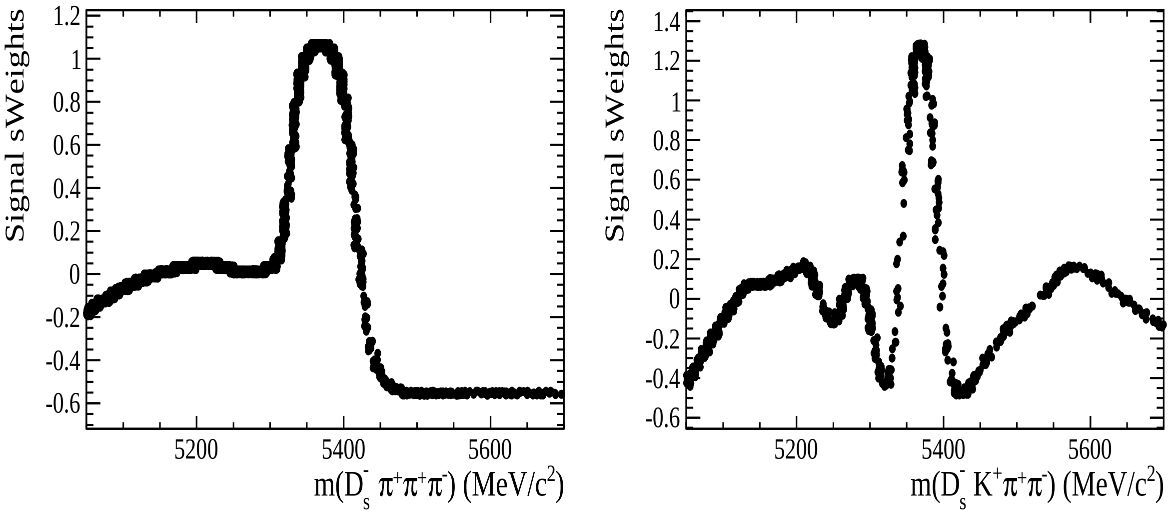


Figure 4.4: Distribution of sWeights across the invariant mass of (left) $B_s^0 \to D_s\pi\pi\pi$ and (right) $B_s^0 \to D_sK\pi\pi$ candidates for Run1 and Run2 data.

5 Decay-time Acceptance

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

$$\frac{\Gamma(t)^{observed}}{dt} = \frac{\Gamma(t)^{theory}}{dt} \cdot a(t), \tag{5.1}$$

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

A PDF of the form

$$\mathcal{P}(t^{'}, \vec{\lambda}) = \left[(e^{\Gamma_s t} \cdot cosh(\frac{\Delta\Gamma_s t}{2}) \times \mathcal{R}(t - t^{'})\right] \cdot \epsilon(t^{'}, \vec{\lambda}), \tag{5.2}$$

is fit to the decay time distribution of $B_s^0 \to D_s\pi\pi\pi$ candidates in data. Since the fit is performed untagged, the PDF shown in Eq. 5.2 contains no terms proportional to Δm_s. The values for Γ_s and $\Delta\Gamma_s$ are fixed to the latest HFAG results [7]. The decay-time acceptance $\epsilon(t^{'}, \vec{\lambda})$ is modelled using the sum of cubic polynomials $v_i(t)$, so called Splines [8]. The polynomials are parametrised by so-called knots which determine their boundaries. Knots can be set across the fitted distribution to account for local changes in the acceptance shape. Using more knots is equivalent to using more base splines which are defined on a smaller sub-range. In total, $n+2$ base splines $v_i(t)$ are needed to describe an acceptance shape which is parametrised using n knots.

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 accomodate these 6 knot positions, 8 basic splines v_i, $i = [1, ..., 8]$ are used. Since a rapid change of the decay time acceptance at low decay times due to the turn-on effect generated by the lifetime and other selection cuts is expected, more knots are placed in that regime. At higher decay times we expect linear behaviour, with a possible small effect due to the VELO reconstruction. Therefore fewer knots are used. Furthermore, v_7 is fixed to 1 in order to normalize the overall acceptance function. To stabilise the last spline, v_8 is fixed by a linear extrapolation from the two previous splines:

$$v_N = v_{N-1} + \frac{v_{N-2} - v_{N-1}}{t_{N-2} - t_{N-1}} \cdot (t_N - t_{N-1}). \tag{5.3}$$

Here, $N = 8$ and t_{N-1} corresponds to the knot position associated with v_{N-1}. The nominal fit to $B_s^0 \to D_s\pi\pi\pi$ data using this configuration is shown in Figure 5.1. Note that the normalization of the splines in the following figures is not in scale.

The fits to $B_s^0 \to D_s\pi\pi\pi$ and $B_s^0 \to D_s K\pi\pi$ simulation are shown in Figure 5.2.

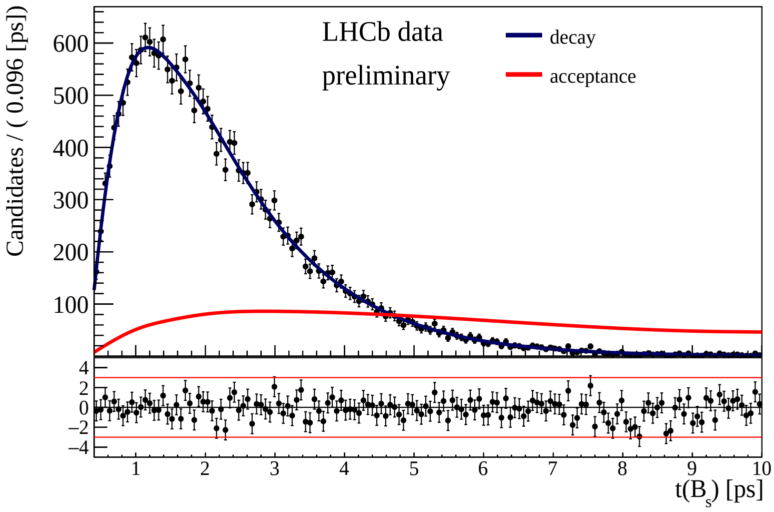


Figure 5.1: Decay-time distribution of $B_s^0 \to D_s\pi\pi\pi$ candidates for the Run 1 data sample. The fit described in the text is overlaid. The red line shows the spline function describing the acceptance and the blue line depicts the total fit function.

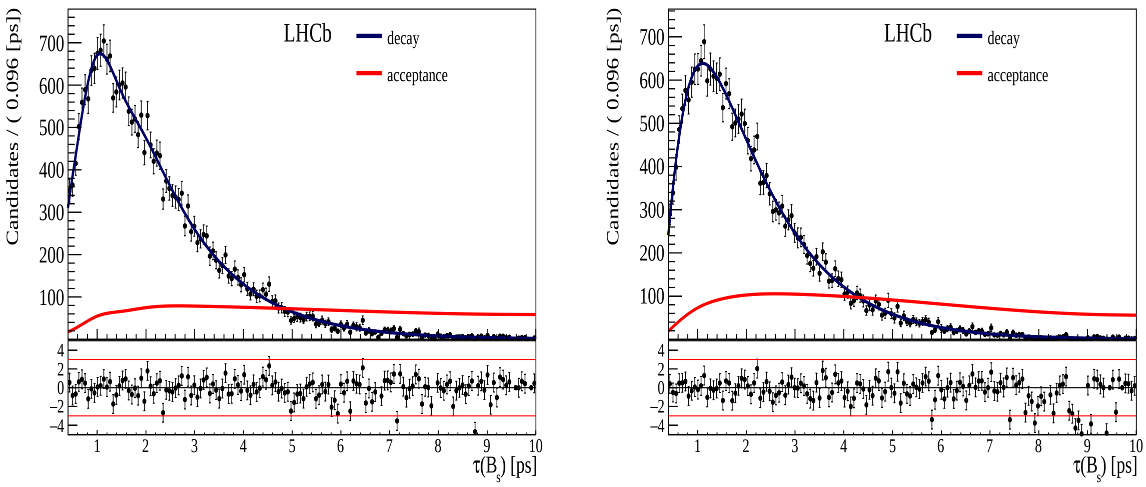


Figure 5.2: Decay-time distribution of (left) $B_s^0 \to D_s\pi\pi\pi$ and (right) $B_s^0 \to D_sK\pi\pi$ candidates in MC using truth information. The fit described in the text is overlaid. The red line shows the spline function describing the acceptance and the blue line depicts the total fit function.

The fit parameters obtained from the described fits to data and simulation are summarised in Table 5.1.

Parameter	Fit to $B_s^0 \to D_s\pi\pi\pi$ data	Fit to $B_s^0 \to D_s\pi\pi\pi$ MC	Fit to $B_s^0 \to D_sK\pi\pi$ MC
v_1			
v_2			
v_3			
v_4			
v_5			
v_6			
v_7	fixed	fixed	fixed

Table 5.1: Summary of the obtained parameters from the acceptance fits described above.

6 Decay-time Resoution

The observed oscillation of B mesons is prone to dilution, if the detector resolution is of similar magnitude as the oscillation period. In the B_s^0 system, considering that the measured oscillation frequency of the B_s^0 [9] and the average LHCb detector resolution [10] are both $\mathcal{O}(50\,\mathrm{fs}^{-1})$, this is the case. Therefore, it is crucial to correctly describe the decay time resolution in order to avoid a bias on the measurement of time dependent CP parameters.
In the presented analysis, we assume a gaussian resolution function with different widths for each event. This gives rise to a per-event decay time error σ_t, which is computed separately for every event along with the proper time t, by the decay time fitter. Furthermore, the per-event decay time error σ_t is usualy underestimated by the decay time fitter, making it necessary to derive a scaling function, which matches the per-event error to the actually measured decay time resolution. In the following, we investigate the Run1 and Run2 MC samples to find the proper decay time resolution in bins of the per-event decay time erros and derive a scaling function from that.

6.1 Formalism

Describtion here ...

6.2 Results

Summary of results and MC/Data correction from D_sK here ...

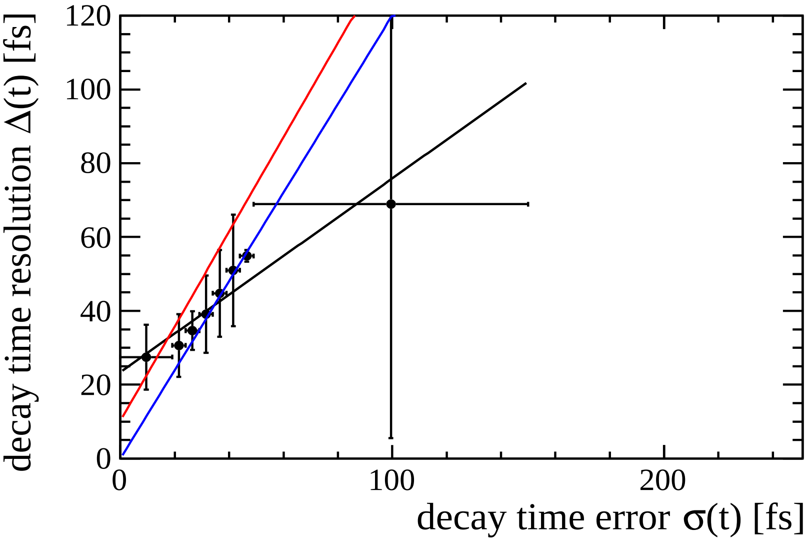


Figure 6.1: Decay-time resolution of $B_s^0 \to D_s K\pi\pi$ candidates from MC. The fit described in the text is overlaid.

σ_t Bin [fs]	σ_1 [fs]	σ_2 [fs]	f_1	D	σ_{eff} [fs]
0to19	22.57 ± 0.96	45.57 ± 4.061	0.827 ± 0.057	0.89 ± 0.067	27.46 ± 8.82
19to24	24.64 ± 1.03	46.65 ± 3.109	0.768 ± 0.061	0.86 ± 0.070	30.64 ± 8.48
24to29	30.96 ± 0.90	58.76 ± 5.684	0.884 ± 0.045	0.83 ± 0.05	34.66 ± 5.28
29to34	35.28 ± 1.54	57 ± 6.698	0.839 ± 0.098	0.79 ± 0.10	39.09 ± 10.47
34to39	37.05 ± 2.36	61.98 ± 5.769	0.707 ± 0.12	0.73 ± 0.12	44.76 ± 11.78
39to44	68.38 ± 8.33	42.15 ± 3.583	0.331 ± 0.18	0.66 ± 0.16	50.98 ± 15.11
44to49	199.9 ± 100.1	53.72 ± 1.419	0.020 ± 0.014	0.62 ± 0.02	54.89 ± 1.60
49to150	68.75 ± 165.3	68.92 ± 4.603	0.001 ± 0.97	0.47 ± 0.65	68.92 ± 63.42

Table 6.1: Summary of the obtained parameters from the resolution fits described above.

A Appendix

A.1 Detailed mass fits

In this section, all fits to the mass distribution of $B_s^0 \to D_s\pi\pi\pi$ and $B_s^0 \to D_sK\pi\pi$ candidates are shown. The fits are performed simultaneously for every year of datataking (2011, 2012, 2015 and 2016) and the D_s decay ($D_s \to KK\pi$ non-resonant, $D_s \to \phi\pi$, $D_s \to K^*K$, or $D_s \to \pi\pi\pi$) through which the final state is reached.

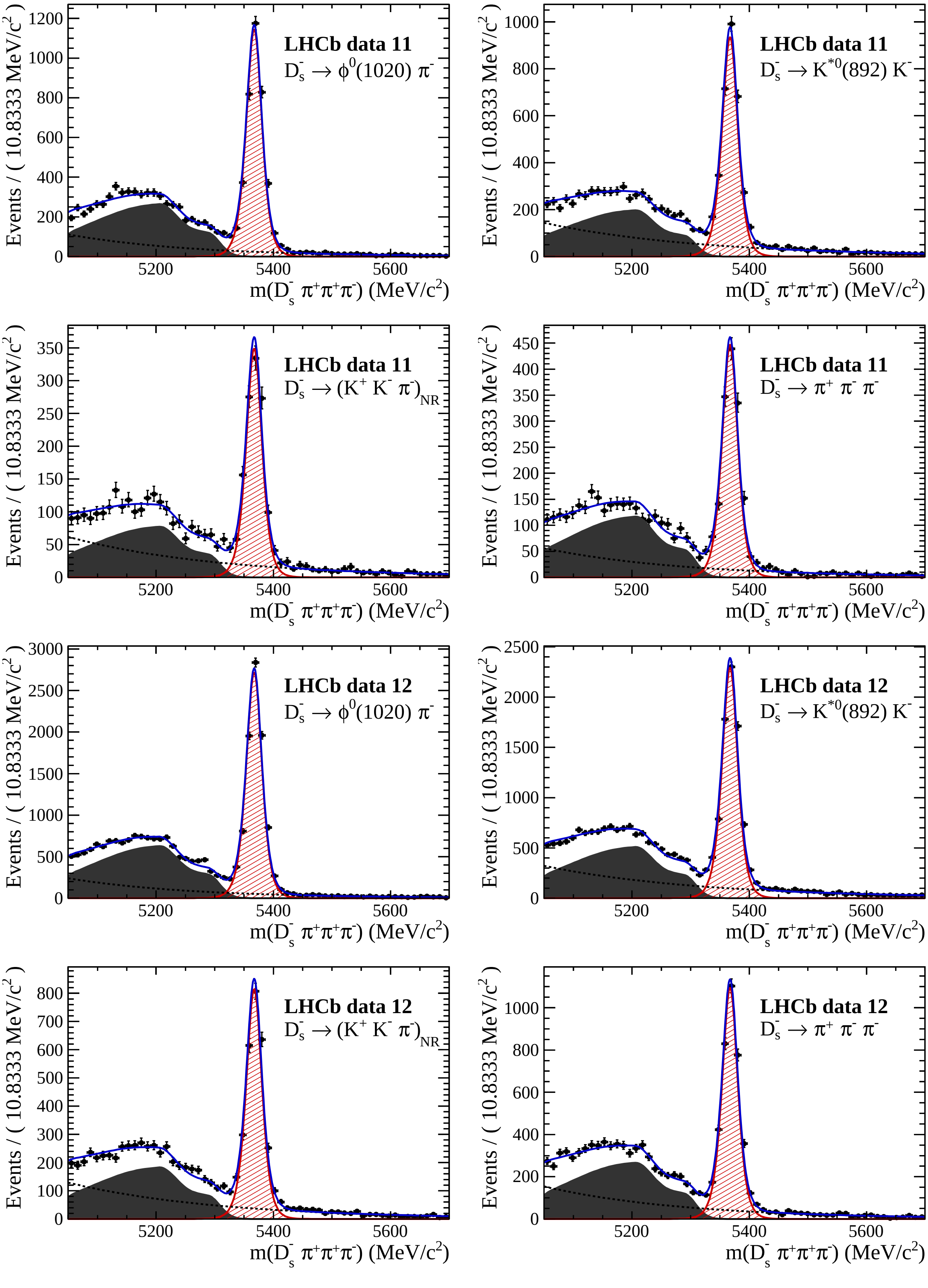


Figure 1.1: Invariant mass distributions of $B_s^0 \to D_s\pi\pi\pi$ candidates, ordered by D_s final state, for Run1 data. The fit described in 4.4 is overlaid.

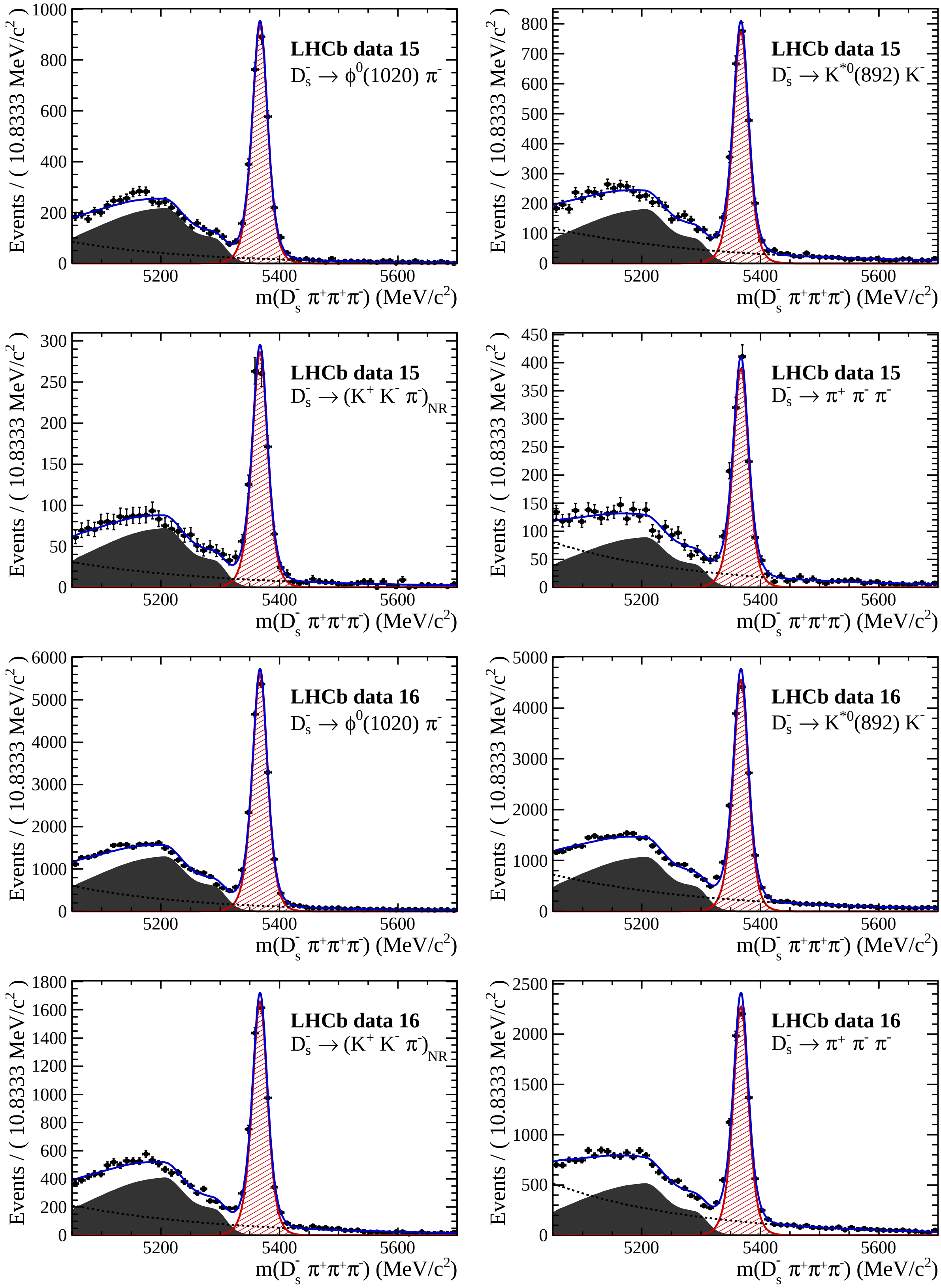


Figure 1.2: Invariant mass distributions of $B_s^0 \to D_s\pi\pi\pi$ candidates, ordered by D_s final state, for Run2 data. The fit described in 4.4 is overlaid.

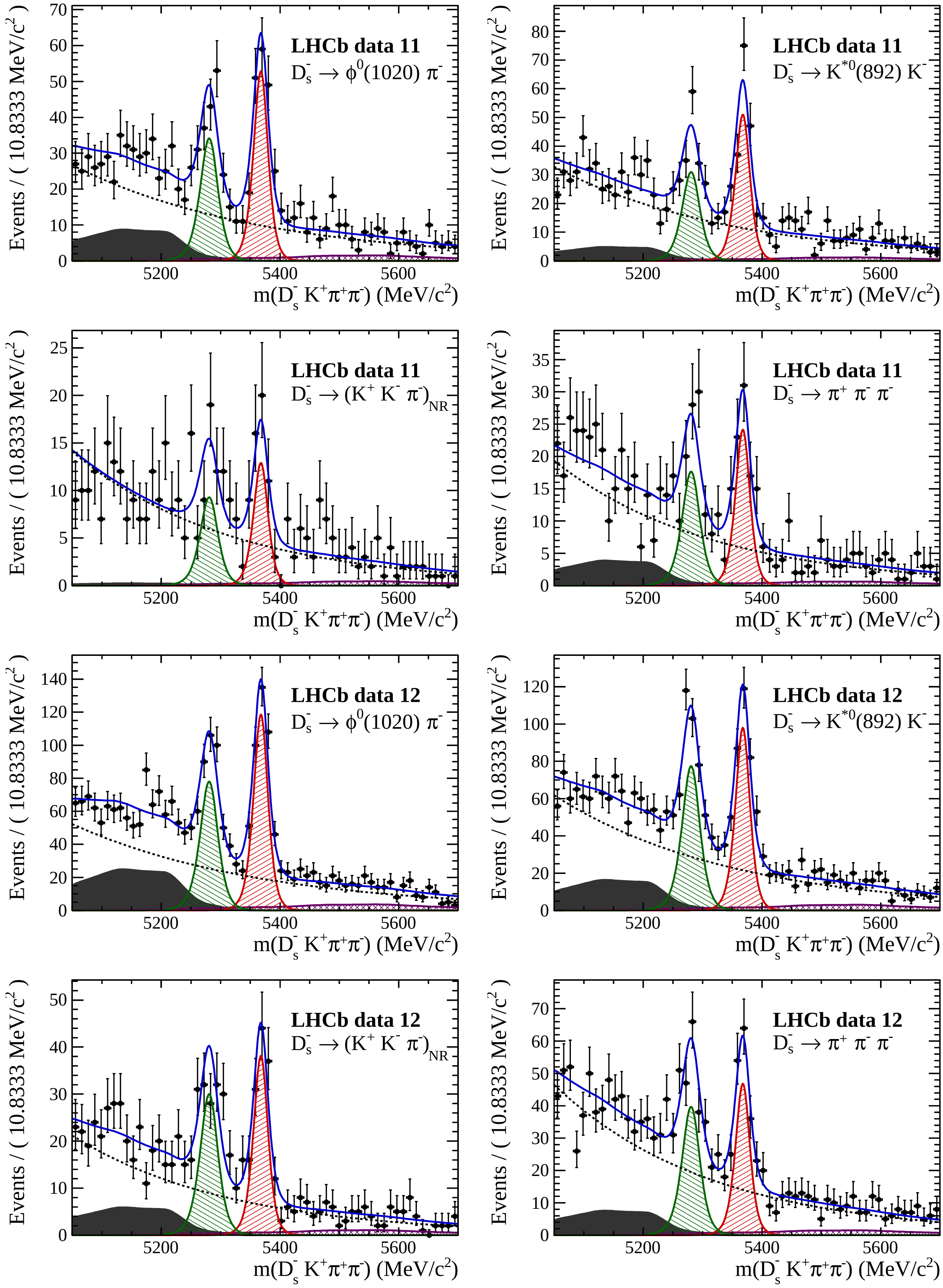


Figure 1.3: Invariant mass distributions of $B_s^0 \to D_s K\pi\pi$ candidates, ordered by D_s final state, for Run1 data. The fit described in 4.5 is overlaid.

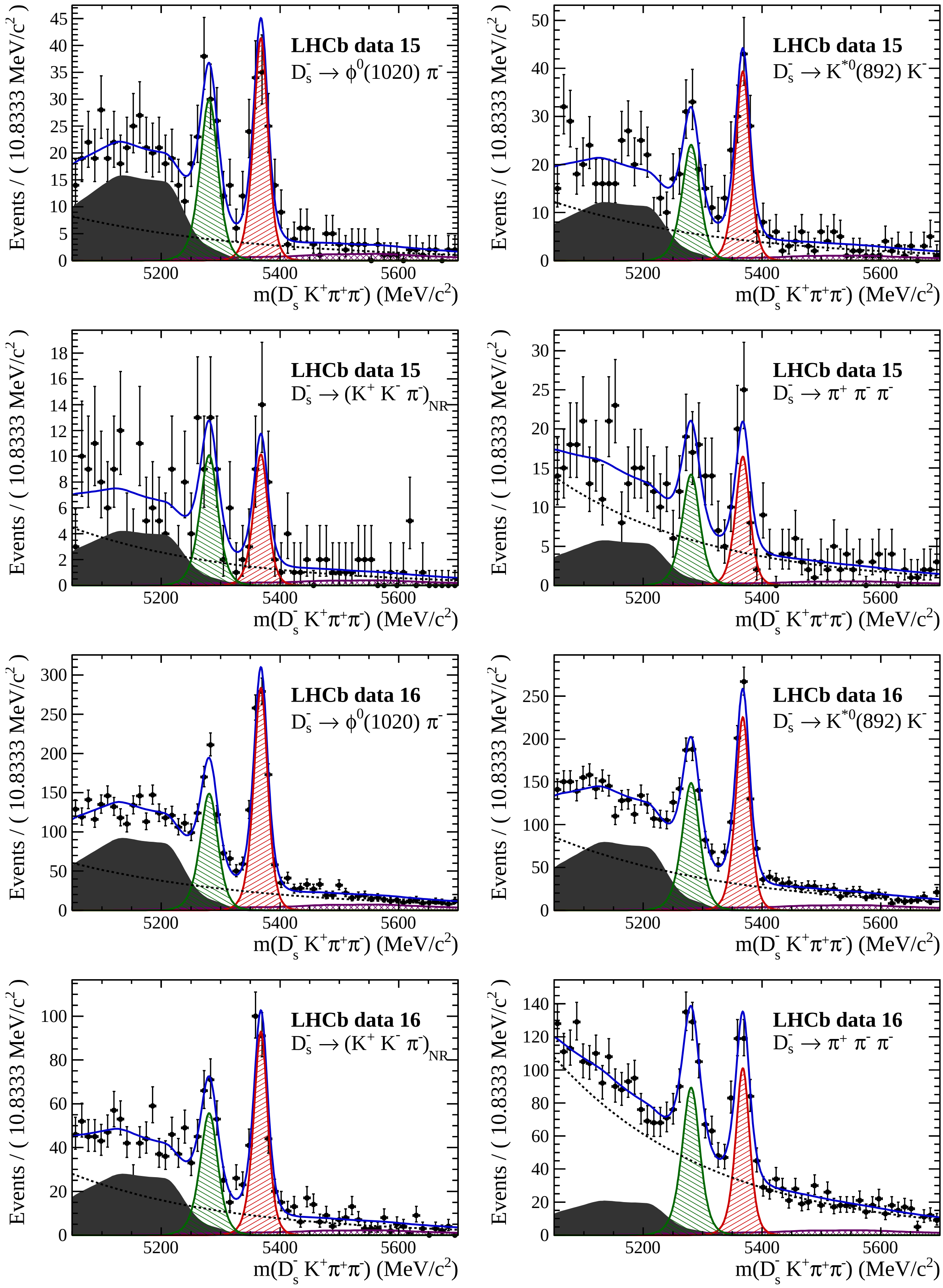


Figure 1.4: Invariant mass distributions of $B_s^0 \to D_s K\pi\pi$ candidates, ordered by D_s final state, for Ru2 data. The fit described in 4.5 is overlaid.

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