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B_s^0 decays at Belle

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We report the measurement of the absolute branching fraction for $B_s^0 \to J/\psi\ \phi$, for $B_s^0 \to J/\psi\ K^+K^-$ and $B_s^0 \to J/\psi\ f_2'(1525)$ as well as a first observation of $B_s^0 \to J/\psi\ \eta$ and $B_s^0 \to J/\psi\ \eta'$. In addition the results for the absolute branching ratios of the decay channels $B_s^0 \to D_s^{(*)+} D_s^{(*)-}$ and a determination of the ratio $\frac{\Delta\Gamma_s}{\Gamma_s}$ are presented.
All results are based on a $121\,\mathrm{fb}^{-1}$ data sample collected with the Belle detector at the KEK-B asymmetric e^+e^- collider at the $\Upsilon(5S)$ resonance.

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1. Introduction

During its operation, the Belle detector collected over 700 fb^{-1} of data at the $\Upsilon(4S)$ resonance and 121 fb^{-1} at the $\Upsilon(5S)$ resonance. This second data sample is unique at B factories and provides the opportunity to study decays of B_S^0 mesons.
To extract the B_S^0 signal, two nearly independant kinematic variables, ΔE and M_{bc}, are used:

$$\Delta E = E_B^* - E_{beam}^* \qquad \text{and} \qquad M_{bc} = \sqrt{\left(E_{beam}^*\right)^2 - \left(p_B^*\right)^2} \tag{1.1}$$

where E_{beam}^* is the beam energy in the center of mass frame and E_B^* and p_B^* denote the energy and the momentum of the reconstructed B_S^0 meson, respectively, given in the center of mass system.
In the analyses presented below, the B_S^0 meson is fully reconstructed. However, the photon from the decay $B_S^* \to B_S^0\,\gamma$ is not included. As the energy information from this photon is lost, the signal region plotted in the M_{bc}-ΔE plane splits up into three areas, depending on the number of B_S^* mesons in the initial state. As these areas are not overlapping in M_{bc}, they can easily be separated during the analysis by choosing a certain range in M_{bc} (fig. 1(b)).

The Belle detector, located at the asymmetric e^+e^- collider KEK-B [1] in Tsukuba Japan, is a large-solid-angle magnetic spectrometer that consists of a silicon vertex detector (SVD), a 50-layer central drift chamber (CDC), an array of aerogel threshold Cherenkov counters (ACC), a barrel-like arrangement of time-of-flight scintillation counters (TOF), and an electromagnetic calorimeter comprised of CsI(Tl) crystals (ECL) located inside a super-conducting solenoid coil that provides a 1.5 T magnetic field. An iron flux-return located outside of the coil is instrumented to detect K_L^0 mesons and to identify muons (KLM). The detector is described in detail elsewhere [2].

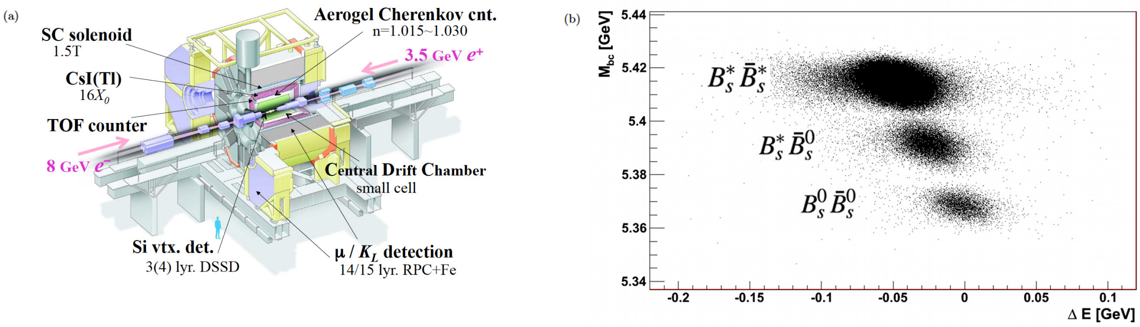

Figure 1: (a) Schematic view of the Belle detector. (b) Signal regions (from MC data) shown as a scatter plot in the $M_{bc} - \Delta E$ plane.

2. Precise measurement of $\mathscr{B}\left(B_S^0 \to J/\psi\,\phi\right)$ and $\mathscr{B}\left(B_S^0 \to J/\psi\,K^+K^-\right)$

The decay $B_S^0 \to J/\Psi\,\phi$ is an important mode for measuring the CP violating phase ϕ_S in $B_S\overline{B}_S$ mixing, which is of particular interest as it is expected to be sensitive to physics beyond the Standard Model [3]. While hadron collider experiments recently improved the measurement of this

parameter [4], they have to calculate the corresponding branching ratios relative to another decay channel. However, the Belle experiment can directly determine the absolute branching fractions as the final state $e^+e^- \to \Upsilon(5S) \to B_S^0\overline{B}_S^0$ is well defined at lepton collider experiments. Until now, the value of the branching fraction for $B_S^0 \to J/\Psi\,\phi$ is based on a relative measurement from the CDF experiment [5, 6, 7]. Therefore, a precise measurement of the absolute branching ratio is an important extension of the current study of the $B_S^0 \to J/\Psi\,\phi$ decay.
Furthermore, in this analysis the absolute branching fractions of the decays $B_S^0 \to J/\psi\,K^+K^-$ and $B_S^0 \to J/\psi\,f_2'(1525)$ – both have not been measured so far – are determined together with the branching ratio of $B_S^0 \to J/\psi\,\phi$. The decay $B_S^0 \to J/\psi\,f_2'(1525)$ was recently found by the LHCb [8] and D0 [9] experiments.

Candidate events are selected as follows: First, the decay $J/\psi \to \ell^+\ell^-$ is reconstructed by identifying two oppositely charged leptons (electrons or muons) with invariant mass close to the nominal J/ψ mass. A correction for energy loss through bremsstrahlung emission is applied. The J/ψ candidate is combined with two oppositely charged identified kaons. In case of the invariant kaon mass, only a lower cut of $m(K^+K^-) \geq 0.95\,\text{GeV}$ is applied, which corresponds to the lower end of the $m(K^+K^-)$ phasespace, so that the full $m(K^+K^-)$ distribution can be investigated.
Finally, to extract the B_S^0 meson signal only events with $M_{bc} > 5.4\,\text{GeV}$ are selected, which means only the dominant $B_S^*\overline{B}_S^*$ signal region is investigated as this provides the best signal to background ratio.

To determine the branching ratios a two dimensional unbinned likelihood fit in ΔE and $m(K^+K^-)$ is performed.
The probability density functions (pdfs) for the $m(K^+K^-)$ distribution are determined by investigating generic Monte Carlo (MC) data. The simulation of this data basically includes all known contributions that can be found in the PDG and additionally the decay $B_S^0 \to J/\psi\,f_2'(1525)$. In case of the ΔE distribution, the pdf parameters are adjusted by using the real data control sample from the decay $B^0 \to J/\psi\,K^*(892)$, as its final state is very similar to the final state of the investigated decays, except that one kaon is replaced by a pion.
Investigating the $m(K^+K^-)$ distribution, the peak of the ϕ meson can be clearly identified at the low energy part of the spectrum, while the peak of the $f_2'(1525)$ is located at $1.52\,\text{GeV}$. The nonresonant decay $B_S^0 \to J/\psi\,K^+K^-$ has a flat distribution up to the kinematic endpoint of the $m(K^+K^-)$ spectrum which can be modeled by an Argus function. As a consequence, the three decay modes are distinguishable via the distribution of the invariant kaon mass, rather than by performing an angular analysis.

The fit results obtained from the full $121\,\text{fb}^{-1}$ Belle data sample are presented in tab. 1 and the applied pdf model is found to be in good agreement with the data (fig. 2 and fig. 3).
With a signal yield of 158±13 (168±14) events for $B_S^0 \to J/\psi\,\phi$ in the muon (electron) channel, the corresponding branching fraction can be calculated to be

$$\mathscr{B}\left(B_S^0 \to J/\psi\,\phi\right) = \left(1.25 \pm 0.07_{\text{stat}} \pm 0.20_{\text{sys}}\right) 10^{-3} \tag{2.1}$$

This result does not include contributions from the decay channels $B_S^0 \to J/\psi\,K^+K^-$ or $B_S^0 \to$

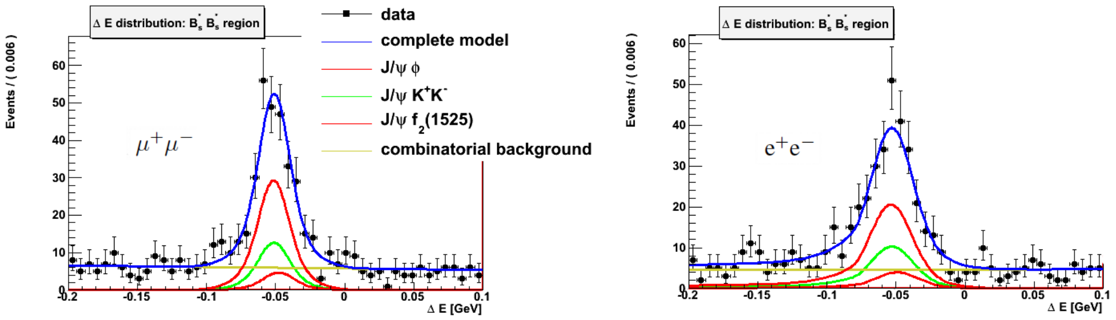

Figure 2: Fitted ΔE distribution for the $\mu^+\mu^-$ and the $\mathrm{e^+e^-}$ channel on $121\,\mathrm{fb^{-1}}$.

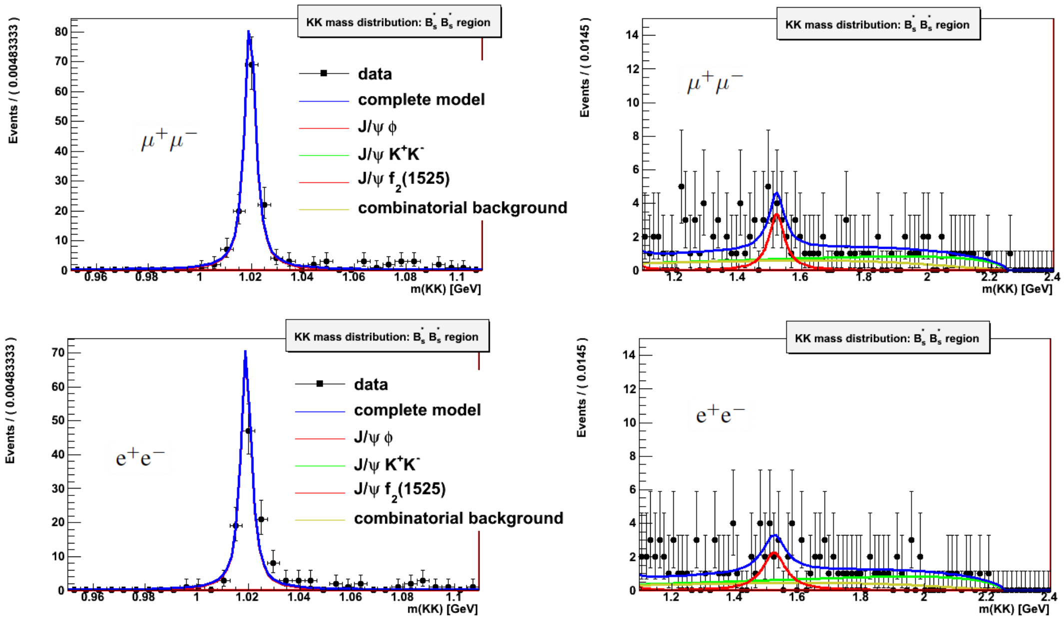

Figure 3: Fitted $\mathrm{m(K^+K^-)}$ distribution for the $\mu^+\mu^-$ and the $\mathrm{e^+e^-}$ channel on $121\,\mathrm{fb^{-1}}$. The selection $-0.07\,\mathrm{GeV} \leq \Delta\mathrm{E} \leq -0.03\,\mathrm{GeV}$ is applied.

$\mathrm{J}/\psi\,\mathrm{f}_2'(1525)$ and is in agreement with the current PDG value as well as with the old and the current results from the CDF experiment [5, 6, 7].
Summarizing all contributions to the systematic error that are presented in tab. 2, the total systematic error concerning $\mathscr{B}\left(\mathrm{B_S^0} \to \mathrm{J}/\psi\,\phi\right)$ is determined to be 16%. The dominant contribution to the systematic error is the uncertainty in $\mathrm{f_S}$, the ratio of $\mathrm{B_S^*\overline{B}_S^*}$ events within all produced $\mathrm{b\overline{b}}$ pairs, which is therefore limiting the accuracy of the analysis at the present time.
The fit result for the nonresonant component $\mathrm{B_S^0} \to \mathrm{J}/\psi\,\mathrm{K^+K^-}$ is 89±13 (110±16) events in the muon (electron) channel, which leads to

$$\mathscr{B}\left(\mathrm{B_S^0} \to \mathrm{J}/\psi\,\mathrm{K^+K^-}\right) = \left(0.36 \pm 0.04_{\mathrm{stat}} \pm 0.08_{\mathrm{sys}}\right) 10^{-3} \tag{2.2}$$

channel	$J/\psi\,\phi$	$J/\psi\,K^+K^-$	$J/\psi\,f_2'(1525)$	combinatorial background
$\mu^+\mu^-$	158±13	89±13	25.3±8.5	304±20
e^+e^-	168±14	110±16	32.6±10.5	239±20

Table 1: Signal yields for the $\mu^+\mu^-$ and the e^+e^- channel on 121 fb^{-1}.

Parameter	Error	%
Luminosity	0.847 fb^{-1}	0.7
$\sigma_{b\bar{b}}^{\Upsilon(5S)}$ [10]	0.014 nb	4.6
f_S [11]	0.029	15.0
$\mathscr{B}(J/\psi \to \mu^+\mu^-)$ [5]	0.0006	1.0
$\mathscr{B}(J/\psi \to e^+e^-)$ [5]	0.0006	1.0
$\mathscr{B}(\phi \to K^+K^-)$ [5]	0.005	1.0
$\mathscr{B}(f'_2(1525) \to K^+K^-)$ [5]	0.011	2.5
$\varepsilon_{\text{MC statistic}}$ $(\mu^+\mu^-)$	0.001	0.2
$\varepsilon_{\text{MC statistic}}$ (e^+e^-)	0.001	0.3
$\varepsilon_{\text{Polarisation}}$ $(\mu^+\mu^-)$	0.005	1.5
$\varepsilon_{\text{Polarisation}}$ (e^+e^-)	0.004	1.3
tracking		1.4
lepton and kaon ID		2.0
PDF shape $B_S^0 \to J/\psi_{\mu^+\mu^-}\,\phi$	3.7 events	2.3
PDF shape $B_S^0 \to J/\psi_{e^+e^-}\,\phi$	4.6 events	2.7
PDF shape $B_S^0 \to J/\psi_{\mu^+\mu^-}\,K^+K^-$	10.5 events	11.8
PDF shape $B_S^0 \to J/\psi_{e^+e^-}\,K^+K^-$	22.6 events	20.5
PDF shape $B_S^0 \to J/\psi_{\mu^+\mu^-}\,f'_2(1525)$	1.9 events	7.7
PDF shape $B_S^0 \to J/\psi_{e^+e^-}\,f'_2(1525)$	3.3 events	10.2

Table 2: Contributions to the systematic error in the absolute branching fractions.

The estimated significance of this measurement is 5.3 σ, including the systematic uncertainty. This value does not contain events from $B_S^0 \to J/\psi\,\phi$. However, the contribution from the decay $B_S^0 \to J/\psi\,f_2'(1525)$ is not separated from this result. The dominant sources of the systematic error are the uncertainty in f_S and the pdf shape.

The fit results for the decay $B_S^0 \to J/\psi\,f'_2(1525)$ are 25.3 ± 8.5 (32.6 ± 10.5) events in the muon (electron) channel. The corresponding branching fractions can be calculated to be

$$\mathscr{B}\left(B_S^0 \to J/\psi\,f_2'(1525)\right) = \left(0.24 \pm 0.06_{\text{stat}} \pm 0.04_{\text{sys}}\right) 10^{-3} \tag{2.3}$$

which has a statistical significance of 4.0σ, taking into account the systematic uncertainties.

The branching ration for $B_S^0 \to J/\psi\,f'_2(1525)$, relative to the branching fraction for $B_S^0 \to J/\psi\,\phi$, is determined to

$$\frac{\mathscr{B}\left(B_S^0 \to J/\psi\,f'_2(1525)\right)}{\mathscr{B}\left(B_S^0 \to J/\psi\,\phi\right)} = 19.3 \pm 4.6_{\text{stat}} \pm 3.1_{\text{sys}}\,\% \tag{2.4}$$

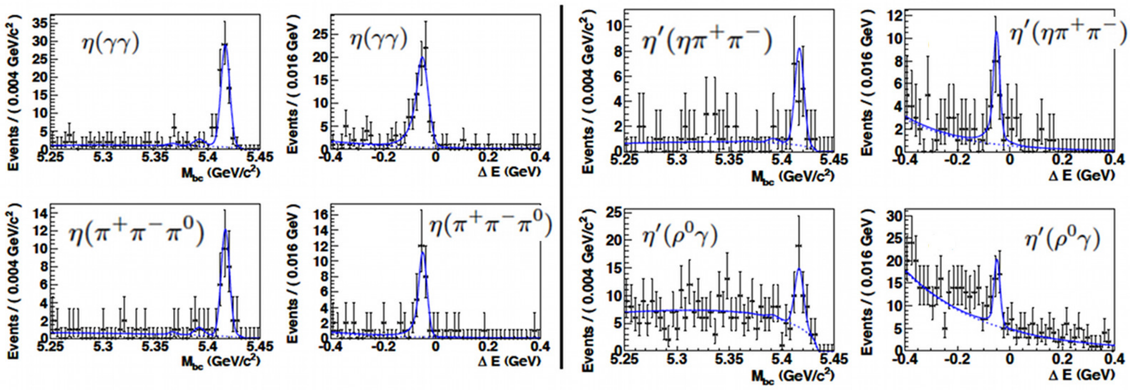

Figure 4: Fitted $\mathrm{M_{bc}}$ and $\Delta\mathrm{E}$ distributions for $\mathrm{B_s^0} \to \mathrm{J}/\psi\,\eta$ (left) and $\mathrm{B_s^0} \to \mathrm{J}/\psi\,\eta'$ (right). The solid lines present the projection of the fit results, while the dotted curves illustrate the background component.

which is in very good agreement with the reported results from LHCb with $26.4 \pm 2.7 \pm 2.4\,\%$ [8] and from D0 with $22 \pm 5 \pm 4\,\%$ [9].

3. First observation of $\mathrm{B_s^0} \to \mathrm{J}/\psi\,\eta$ and $\mathrm{B_s^0} \to \mathrm{J}/\psi\,\eta'$

The measurement of the decays $\mathrm{B_s^0} \to \mathrm{J}/\psi\,\eta$ and $\mathrm{B_s^0} \to \mathrm{J}/\psi\,\eta'$ provides the possibility to investigate new CP-even eigenstates. Furthermore, the SU(3) flavor symmetry predicts the ratio of these two branching fractions to be close to one and therefore, a measurement of these decay channels would allow to test the SU(3) symmetry as well as the $\eta - \eta'$ mixing (for more detail, see *e.g.* [12, 13, 14, 15]).
However, these decays have not been observed so far. The L3 experiment published an upper limit of $\mathscr{B}\left(\mathrm{B_s^0} \to \mathrm{J}/\psi\,\eta\right) < 3.8 \cdot 10^{-3}$ at a 90% confidence level [16].

To determine the branching fractions of $\mathrm{B_s^0} \to \mathrm{J}/\psi\,\eta$ and $\mathrm{B_s^0} \to \mathrm{J}/\psi\,\eta'$ the $\mathrm{B_s^0}$ meson is fully reconstructed in five different final states. While the J/ψ meson is identified via two oppositely charged leptons, the η meson is reconstructed from a $\gamma\gamma$ or $\pi^+\pi^-\pi^0$ state and the η' meson is expected to decay into a $\rho^0\gamma$ or a $\eta\pi^+\pi^-$ final state. For more detailed information on the reconstruction and the fitting method in this analysis see [17].
The fit is performed as a two dimensional unbinned, extended maximum likelihood fit in $\Delta\mathrm{E}$ and $\mathrm{M_{bc}}$, simultaneously for all five final states. The fit results are presented in fig. 4 where the applied pdf model shows a good agreement with the data in all subchannels. With 141 ± 14 (86 ± 14) events found for $\mathrm{B_s^0} \to \mathrm{J}/\psi\,\eta$ ($\mathrm{B_s^0} \to \mathrm{J}/\psi\,\eta'$), the corresponding branching fractions are calculated to

$$\mathscr{B}\left(\mathrm{B_s} \to \mathrm{J}/\psi\,\eta\right) = \left(5.10 \pm 0.50_{\mathrm{stat}} \pm 0.25_{\mathrm{sys}}\ {}^{+1.14}_{-0.79}(\mathrm{N}_{\mathrm{B_s^{(*)}}\overline{\mathrm{B}}_\mathrm{s}^{(*)}})\right) \cdot 10^{-4} \tag{3.1}$$

$$\mathscr{B}\left(\mathrm{B_s} \to \mathrm{J}/\psi\,\eta'\right) = \left(3.71 \pm 0.61_{\mathrm{stat}} \pm 0.18_{\mathrm{sys}}\ {}^{+0.83}_{-0.57}(\mathrm{N}_{\mathrm{B_s^{(*)}}\overline{\mathrm{B}}_\mathrm{s}^{(*)}})\right) \cdot 10^{-4} \tag{3.2}$$

The dominant systematic error is the uncertainty in $\mathrm{f_S}$, which is quoted separately as third error in equations 3.1 and 3.2.

channel	signal yield	$\mathscr{B}$ [%]	significance
$D_s^+ D_s^-$	$33.1^{+6.0}_{-5.4}$ events	$0.58^{+0.11}_{-0.09}\,{}_{stat} \pm 0.13_{sys}$	$11.5\,\sigma$
$D_s^{*\pm} D_s^{\mp}$	$44.5^{+5.8}_{-5.5}$ events	$1.8 \pm 0.2_{stat} \pm 0.4_{sys}$	$10.1\,\sigma$
$D_s^{*+} D_s^{*-}$	$24.4^{+4.1}_{-3.8}$ events	$2.0 \pm 0.3_{stat} \pm 0.5_{sys}$	$7.8\,\sigma$

Table 3: Results for $B_s^0 \to D_s^{(*)+} D_s^{(*)-}$ on $121\,\text{fb}^{-1}$.

The ratio of these two branching fractions is determined to be

$$\frac{\mathscr{B}(B_s \to J/\psi\,\eta')}{\mathscr{B}(B_s \to J/\psi\,\eta)} = 0.73 \pm 0.14_{stat} \pm 0.02_{sys} \tag{3.3}$$

While the result for $B_s^0 \to J/\psi\,\eta$ is in agreement with the upper limit obtained from the L3 experiment, the determined ratio shows a deviation at a $2.1\,\sigma$ level with respect to the prediction.

4. Observation of $B_s^0 \to D_s^{(*)+} D_s^{(*)-}$ and determination of $\Delta\Gamma_s$

While previous measurements of the decay width difference $\Delta\Gamma_s$ are based on the decay mode $B_s^0 \to J/\psi\,\phi$ [18, 19, 20], the decay channels $B_s^0 \to D_s^{(*)+} D_s^{(*)-}$ can provide another possibility to investigate CP violation in the $B_s^0 \overline{B}_s^0$ system. Assuming that these decays have CP-even final states and saturate the decay width difference $\Delta\Gamma_s^{CP}$ [21], the ratio $\Delta\Gamma_s/\Gamma_s$ is simply depending on the branching fraction including all CP-even decay modes and the CP violating phace ϕ_s [22]

$$\frac{\Delta\Gamma_s}{\Gamma_s} = \frac{1/\cos\phi_s - \sqrt{(1/\cos\phi_s)^2 - 4\mathscr{B}(1-\mathscr{B})}}{1-\mathscr{B}} \tag{4.1}$$

In this analysis the B_s^0 meson is reconstructed in the three final states $B_s^0 \to D_s^+ D_s^-$, $B_s^0 \to D_s^{*\pm} D_s^{\mp}$ and $B_s^0 \to D_s^{*+} D_s^{*-}$ with $D_s^{\pm} \to \phi\pi^{\pm}$, $K_s^0 K^{\pm}$, $\overline{K}^{*0} K^{\pm}$, $\phi\rho^{\pm}$, $K_s^0 K^{*\pm}$, $\overline{K}^{*0} K^{*\pm}$. Afterwards a two dimensional unbinned, extended maximum-likelihood fit is performed in ΔE and M_{bc}. The results are presented in fig. 5 and tab. 3. For more detailed information on the reconstruction and fit method see [23].
The total signal yield is determined to be $102.0^{+9.3}_{-8.6}$ events which corresponds to an absolute branching fraction of

$$\mathscr{B} = \left(4.3 \pm 0.4_{stat} \pm 0.5_{sys} \pm 0.9\,[\mathscr{B}]_{sys}\right)\,\% \tag{4.2}$$

where the last systematic error is due to uncertainties in external parameters as f_s and the $D_s^{\pm}$ branching fractions, which form the most important contributions to the total systematic error.
Assuming that the CP violation is negligible ($\phi_s = 0$) the ration $\Delta\Gamma_s/\Gamma_s$ is calculated with the above branching fraction to be

$$\frac{\Delta\Gamma_s}{\Gamma_s} = 0.090 \pm 0.009 \pm 0.022 \tag{4.3}$$

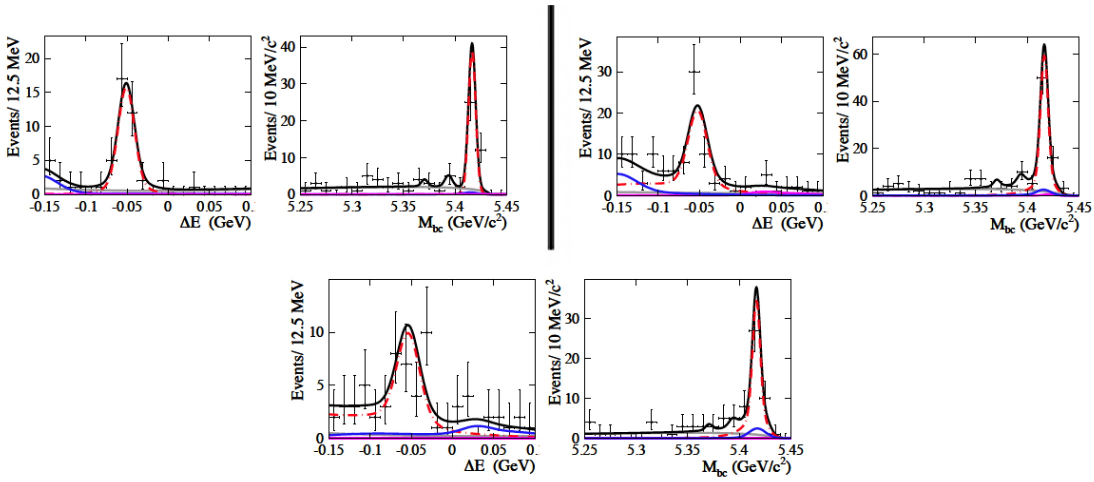

Figure 5: Fitted ΔE and M_{bc} distributions for $B_S^0 \to D_S^+ D_S^-$ (upper left plot), $B_S^0 \to D_S^{*\pm} D_S^{\mp}$ (upper right plot) and $B_S^0 \to D_S^{*+} D_S^{*-}$ (lower plot). The solid black line presents the complete pdf model, the red line shows the signal from correct reconstructed wrong combined events, the purple line indicates the cross-feed and the grey line illustrates the background.

which is consistent with theory predictions and comparable with results from hadron collider experiments.

5. Summary

We performed a precise measurement of the absolute branching fraction for $B_S^0 \to J/\psi\,\phi$, for $B_S^0 \to J/\psi\, f_2'(1525)$ and the inclusive branching ratio for $B_S^0 \to J/\psi\, K^+K^-$. The results concerning the branching fractions of $B_S^0 \to J/\psi\,\phi$ and $B_S^0 \to J/\psi\, f_2'(1525)$ are in good agreement with previous measurements from other experiments.
Furthermore, we presented the first observation of $B_S^0 \to J/\psi\,\eta$ and $B_S^0 \to J/\psi\,\eta'$. While the result for the branching fraction of $B_S^0 \to J/\psi\,\eta$ is in agreement with the upper limit of a former measurement, the ratio of the two branching fractions shows a deviation of $2.1\,\sigma$ level with regard to the prediction.
In addition we presented a precise measurement of the absolute branching ratios for $B_S^0 \to D_S^{(*)+} D_S^{(*)-}$ and a determination of $\frac{\Delta\Gamma_S}{\Gamma_S}$ which is comparable with results from hadron collider experiments and consistent with theory predictions.

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