Study of the $B_s^0 \to J/\psi\phi\phi$ decay

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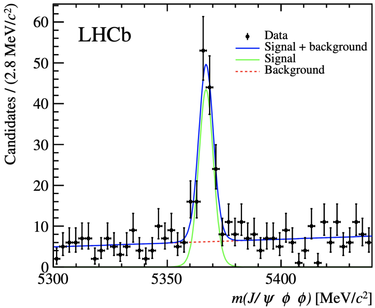
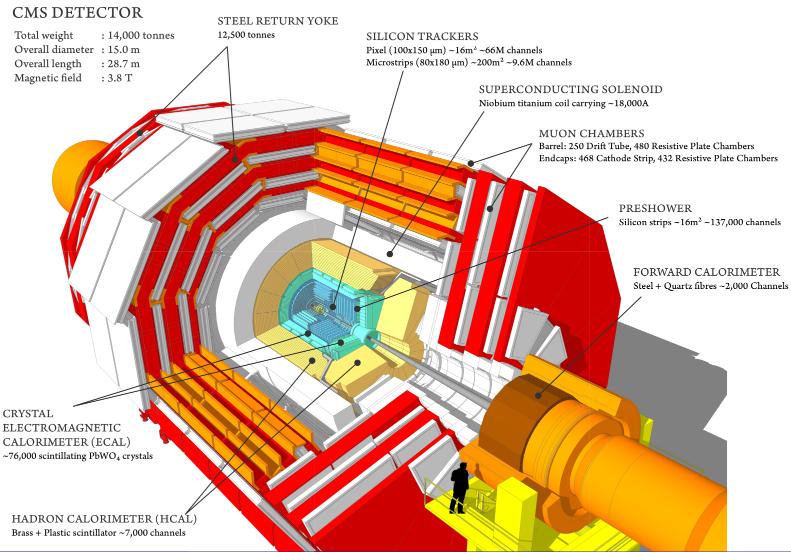
- The mass and the branching ratio are measured by the LHCb[1] collaboration. Our goal is to measure these values in the CMS experiment on more statistics.
- It is interesting to look for intermediate states in the spectra of $J\psi\phi$ and $\phi\phi$.



In the $J/\psi\phi$ spectrum the CDF collaboration discovered the state X(4140) by studying the decay of $B^+ \to J/\psi\phi K^+$ in 2009 [2], and then refined this result in 2017 [3]; the Belle and BaBar collaborations have not found a significant X(4140) signal in this channel. Experiments D0[4], CMS[5] and LHCb[6] confirmed the result of CDF.
In the $\phi\phi$ spectrum, the BES experiment has found $\eta(2225)$ state [7] in $J/\psi \to \gamma\phi\phi$ decay. In 2016, the pseudoscalar state $\eta(2100)$, scalar $f_0(2100)$ and three tensors states $f_2(2010)$, $f_2(2300)$, $f_2(2340)$ were found in the same decay $J/\psi \to \gamma\phi\phi$ [8].

CMS Experiment



Channels and data

Decay channels used:

Reference decay with J/ψ	Reference decay with $\psi(2S)$	Studied decay
$B_s^0 \to J/\psi\phi$	$B_s^0 \to \psi(2S)\phi$	$B_s^0 \to J/\psi\phi\phi$
$J/\psi \to \mu^+\mu^-$	$\psi(2S) \to J/\psi(\to \mu^+\mu^-)\pi^+\pi^-$	$J/\psi \to \mu^+\mu^-$
$\phi \to K^+K^-$	$\phi \to K^+K^-$	$\phi \to K^+K^-$

The selection is applied to the full 2016-2018 Charmonium dataset (requires the presence of a muon pair from a common detached vertex in each event):

- The entire Run2 data and MC is used for both reference decays $B_s^0 \to J/\psi\phi$ $B_s^0 \to \psi(2S)\phi$
- The entire Run2 data and MC is processed for the studied decay $B_s^0 \to J/\psi\phi\phi$
- The MC of the decay $B^0 \to J/\psi K^*$ is also processed, where K^{*0} decays into $K^+ \pi^-$. When identifying a pion as a kaon, such events will contribute to the shape of the background in the normalization channels.

Reconstruction and selection

Muon selection

- $p_T(\mu^{\pm}) > 4GeV \quad p_T(\mu^+\mu^-) > 7GeV$
- $D_{xy}(\mu^+\mu^-)/\sigma_{D_{xy}(\mu^+\mu^-)} > 3$
- 3.04 GeV $< M(\mu^+\mu^-) <$ 3.15 GeV(Also J/ψ mass constraint was required)
- $\cos(\mu^+\mu^-, \mathbf{PV}) > 0.9$
- $P_{vtx}(\mu^+\mu^-) > 0.01$
- $|\eta(\mu^{\pm})| < 2.2$

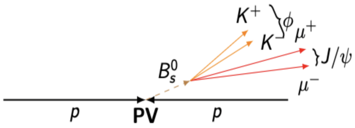
Kaon (pion) selection

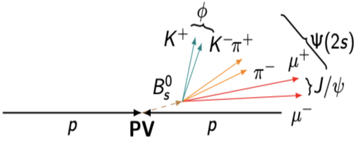
- $p_T(K^{\pm}(\pi^{\pm})) > 1GeV$
- 1.01 GeV $< M(K^+K^-) <$ 1.03 GeV

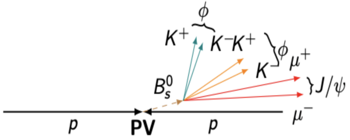
B_s^0 selection

- $p_T(B_s^0) > 10$ GeV
- $D_{xy}(B_s^0)/\sigma_{D_{xy}(B_s^0)} > 3$
- $\cos(B_s^0, \mathbf{PV}) > 0.9$
- $P_{vtx}(B_s^0) > 0.01$

- $p_T(\phi_1) > p_T(\phi_2)$ - or the selection algorithm not to choose same $\phi\phi$ pair two times

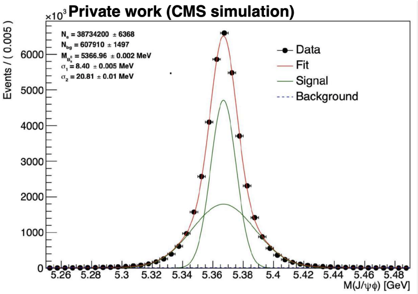




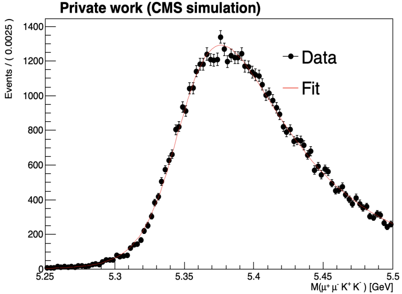


To check the reconstructed candidates for compatibility with the generated decay an additional cuts are imposed: $\Delta R^{gen} < 0.02$ for kaons and $\Delta R^{gen} < 0.004$ for muons. $\Delta R^{gen} = \sqrt{(\eta^{reco} - \eta^{gen})^2 + (\varphi^{reco} - \varphi^{gen})^2}$

$B_s^0 \to J/\psi\phi$



$B^0 \to J/\psi K^*$

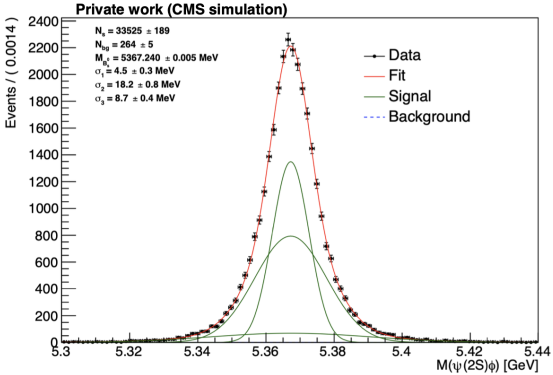


- The signal is described by double Gaussian with a common mean. The background is described by a first-order polynomial.
- Pion is assigned the Kaon mass hypothesis
- Approximation by the Johnson function

MC simulation for $B_s^0 \to \psi(2S)\phi$ decay

The restriction on ΔR^{gen} is imposed similarly to the previous channel. For pions $\Delta R^{gen} < 0.02$

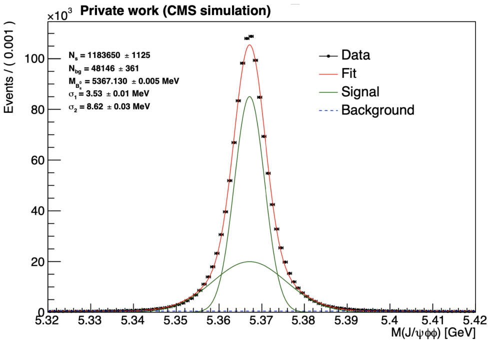
$B_s^0 \to \psi(2S)\phi$



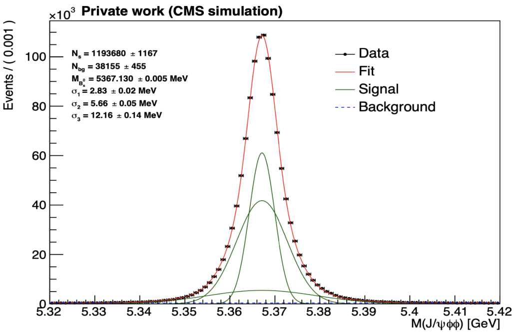
- The signal is described by a triple Gaussian function with a common mean.
- The background is described by a first-order polynomial.

Cuts on ΔR^{gen} are imposed similarly to the reference channel.

Double Gaussian fit



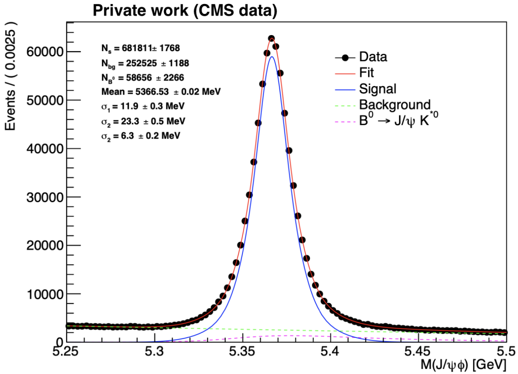
Triple Gaussian fit



As can be seen in the pictures, a double Gauss fit describes points worse than a triple Gauss fit. Moreover, for double Gauss the sigmas for the data and Monte-Carlo do not match within the error. Therefore, a triple Gauss was chosen to describe the signal.

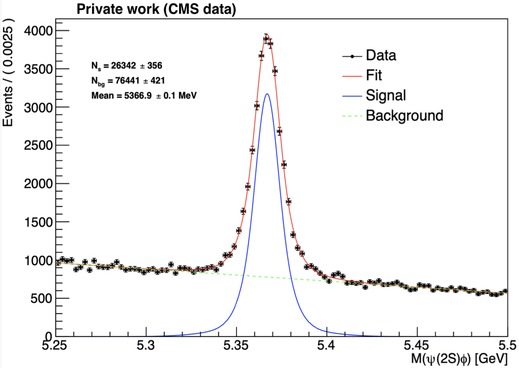
B_s^0 invariant mass in reference decays

Reference decay $B_s^0 \to J/\psi\phi$



- The signal is described by a triple Gaussian function with a common mean.
- The combinatorial background is described by a first order polynomial, and the contribution from the decay of $B^0 \to J/\psi K^{*0}$ is a Johnson function whose parameters are fixed from MC.

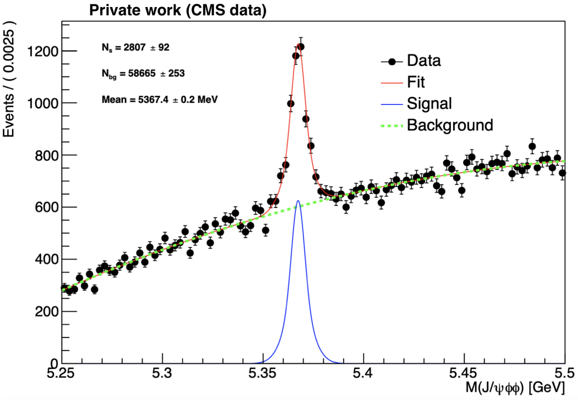
Reference decay $B_s^0 \to \psi(2S)\phi$



- The signal is described by a triple Gaussian function with a common mean.
- Background is described with first order polynomial function

B_s^0 invariant mass in studied decay

Studied decay



- The signal is described by a triple Gaussian function with a common mean. The parameters are fixed from the MC simulation.
- The background is described using a second order polynomial.

Total efficiency and branching ratio

channel	ε^{gen}, %	$\varepsilon^{rec\&sel}$, %	ε, %
$B_s^0 \to J/\psi\phi\phi$	2.834 ± 0.027	10.428 ± 0.011	0.295 ± 0.003
$B_s^0 \to J/\psi\phi$	3.415 ± 0.029	14.206 ± 0.002	0.485 ± 0.004
$B_s^0 \to \psi(2S)\phi$	2.659 ± 0.0266	3.501 ± 0.019	0.093 ± 0.001

Branching ratios can be calculated using the following formulas:

$$\frac{\mathcal{B}(B_s^0 \to J/\psi\phi\phi)}{\mathcal{B}(B_s^0 \to J/\psi\phi)} = \frac{N(B_s^0 \to J/\psi\phi\phi) \cdot \epsilon(B_s^0 \to J/\psi\phi)}{\epsilon(B_s^0 \to J/\psi\phi\phi) \cdot N(B_s^0 \to J/\psi\phi) \cdot \mathcal{B}(\phi \to K^+K^-)}$$

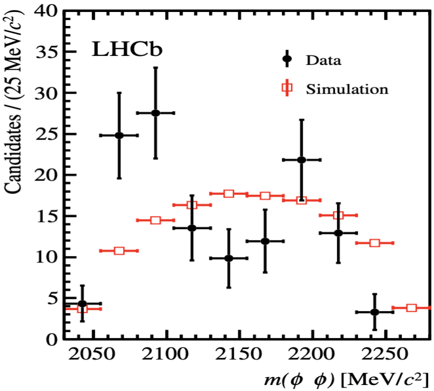
$$\frac{\mathcal{B}(B_s^0 \to J/\psi\phi\phi)}{\mathcal{B}(B_s^0 \to \psi(2S)\phi)} = \frac{N(B_s^0 \to J/\psi\phi\phi) \cdot \epsilon(B_s^0 \to \psi(2S)\phi) \cdot \mathcal{B}(\psi(2S) \to J/\psi\pi^+\pi^-)}{\varepsilon(B_s^0 \to J/\psi\phi\phi) \cdot N(B_s^0 \to \psi(2S)\phi) \cdot \mathcal{B}(\phi \to K^+K^-)}$$

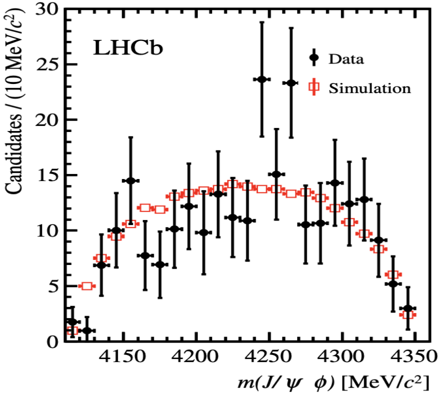
Systematic uncertainties

Source	Relative uncertainty , %
Background model in $J/\psi\phi$ distribution	0.5
Background model in $J/\psi\phi\phi$ distribution	0.4
Signal model in $J/\psi\phi$ distribution	3.8
Signal model in $J/\psi\phi\phi$ distribution	3.2
Uncertainty in the efficiency ratio	1.3
Two additional charged tracks reconstruction	3.2
non-res. events in $J/\psi\phi$ distribution	3.2
non-res. events in $J/\psi\phi\phi$ distribution	3.4
Total systematic uncertainty	7.7

Similarly, systematic uncertainties are obtained for the other two branching ratios (see Backup).

sPlot (LHCb result)

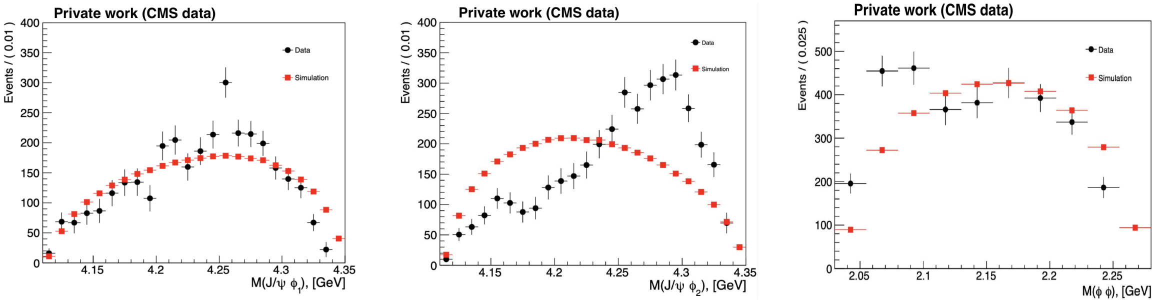




"The disagreement between data and simulation can be due to either intermediate resonances or the simplified description of the decay." [1]

sPlot for intermediate mass frames

Using the invariant mass $J/\psi\phi\phi$ as a "separating" variable in the sPlot [9] method, it is possible to separate the component corresponding to the signal of B_s^0 in the spectra $J/\psi\phi$ and $\phi\phi$.



Conclusions

- The data and MC of the entire Run 2 has been processed for $B_s^0 \to J/\psi\phi\phi$ and reference decays.
- Signals of the studied decay and two normalization decays are received. The total efficiencies and systematic uncertainties are evaluated.
- The sPlot technique is applied to intermediate invariant masses. The distributions significantly differ from phase space.

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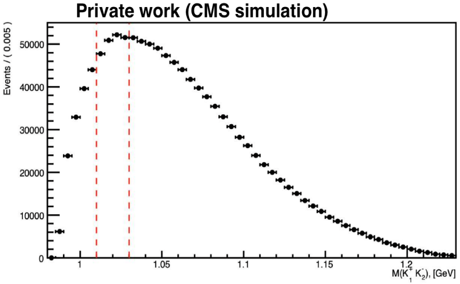
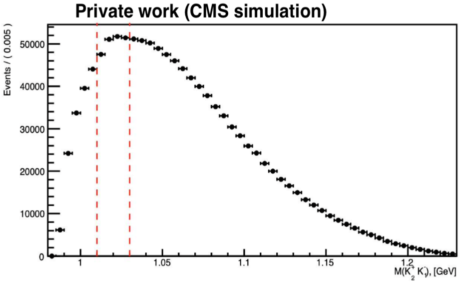
Nuclear Instruments and Methods in Physics Research – . 555. – №. 1-2. – . 356-369.

Backup slides

Double candidates

The distributions of invariant masses for the "wrong-coupled" kaons from the MC data are shown in the figure. The red lines represent the imposed cuts.





If $B_s^0 \to J/\psi(K_1^+K_1^-)(K_2^+K_2^-)$ passes all selection cuts then candidate $B_s^0 \to J/\psi(K_1^+K_2^-)(K_2^+K_1^-)$ also passes all cuts in 1.5% of events, resulting in a duplicate candidate. Therefore, in order to eliminate double counting, an event is selected in which the delta-mass $\sqrt{(M(K_i^+K_j^-) - M_{PDG}(\phi))^2 + (M(K_k^+K_m^-) - M_{PDG}(\phi))^2}$ is less.

Source	Relative uncertainty, %
Background model in $J/\psi\phi$ distribution	0.5
Background model in $\psi(2S)\phi$ distribution	1.0
Signal model $J/\psi\phi$ distribution	3.8
Signal model in $\psi(2S)\phi$ distribution	3.3
Uncertainty in the efficiency ration	1.4
Two additional tracks reconstruction	3.2
non-res. events in $J/\psi\phi$ distribution	3.2
non-res. events in $\psi(2S)\phi$ distribution	6.6
Total systematic uncertainty	9.6

Source	Relative uncertainty, %
Background model in $\psi(2S)\phi$ distribution	1.0
Background model in $J/\psi\phi\phi$ distribution	0.4
Signal model in $\psi(2S)\phi$ distribution	3.3
Signal model in $J/\psi\phi\phi$ distribution	3.2
Uncertainty in the efficiency ration	1.5
non-res. events in $\psi(2S)\phi$ distribution	6.6
non-res. events in $J/\psi\phi\phi$ distribution	3.4
Total systematic uncertainty	8.9

Total efficiency is defined as the product of the efficiency of the generator filters and the reconstruction efficiency:

$$\varepsilon = \varepsilon^{gen} \cdot \varepsilon^{rec\&sel}$$

Reconstruction efficiency could be found as the ratio of the number of reconstructed events to the number of events in the ordered MC dataset:

$$\varepsilon^{rec\&sel} = \frac{N_{rec\&sel}}{N_{DAS}}$$

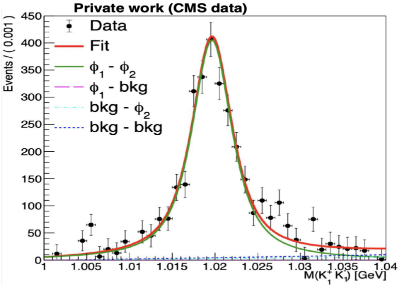
- **Filters ($J/\psi\phi$ $J/\psi\phi\phi$):** $|\eta(\mu^{\pm})| < 2.5$; $p_T(\mu^{\pm}) > 3$ GeV; $|\eta(K^{\pm})| < 2.5$; $p_T(K^{\pm}) > 0.5$ GeV.
- **Filters ($\psi(2S)\phi$) :** $|\eta(\mu^{\pm})| < 2.5$; $p_T(\mu^{\pm}) > 2.5$ GeV; $|\eta(\pi^{\pm})| < 3.0$; $p_T(\pi^{\pm}) > 0.4$ GeV; $p_T(\phi) > 0.8$ GeV; $p_T(J/\psi) > 5$ GeV; $p_T(\psi(2S)) > 5$ GeV.

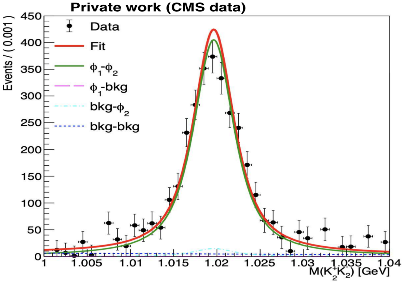
To calculate the generator efficiency, an additional Monte-Carlo data was generated, where filters are removed (N_{in}). After applying filters to this data, the number of events that passed the filters was obtained (N_{out}).

$$\varepsilon^{gen} = \frac{N_{out}}{N_{in}}$$

In order to take into account the contribution of non-resonant events, the sPlot method was used.

A 2D fit was performed. The background is described by a polynomial of the first degree, and the signal is a convolution of double Gauss and Breit-Wigner. The number of background events in the signal region (1.01 GeV, 1.03 GeV) was taken as a systematic uncertainty N=95.





Similar procedure was done for normalization decays. ($J/\psi\phi$ decay: 1D fit for K^+K^- mass sPlot N $= 21782$; $\psi(2S)\phi$ decay: 2D fit for K^+K^- mass and $J/\psi\pi^+\pi^-$ mass sPlot N $= 1816$)

Backup slides

sPlot for min and max M($J/\psi\phi$)