Study of P-wave B_s^0 states at the CMS experiment

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CMS-BPH-16-003, arXiv:1809.03578
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Introduction (P-wave B_s^0 states)

Orbital momentum L	*Total angular momentum of light subsystem* j $j = L \pm \frac{1}{2}$	*Total angular momentum* $J = j \pm \frac{1}{2}$	
L=1	$j = 1 + \frac{1}{2} = \frac{3}{2}$	$J = \frac{3}{2} + \frac{1}{2} = 2$	$B_{s2}^{*}(5840)^0$
		$J = \frac{3}{2} - \frac{1}{2} = 1$	$B_{s1}(5830)^0$
	$j = 1 - \frac{1}{2} = \frac{1}{2}$	$J = \frac{1}{2} + \frac{1}{2} = 1$	B_{s1}^{*}
		$J = \frac{1}{2} - \frac{1}{2} = 0$	B_{s0}^{*}

Unobserved
Predicted masses are usually below B^+K^- threshold

The decay $B_{s1} \rightarrow B^+K^-$ corresponds to (in J^P) $1^+ \rightarrow 0^-0^-$ and is forbidden *(need L=1 to conserve J, but then P is not conserved)*

The decay $B_{s1} \rightarrow B^{*+}K^-$ corresponds to (in J^P) $1^+ \rightarrow 1^-0^-$ and $\frac{3}{2}^- \rightarrow \frac{1}{2}^+ 0^-$ in j^p
In HQET j^p is also conserved $\Rightarrow$ it cannot proceed in S-wave; but can proceed in D-wave.

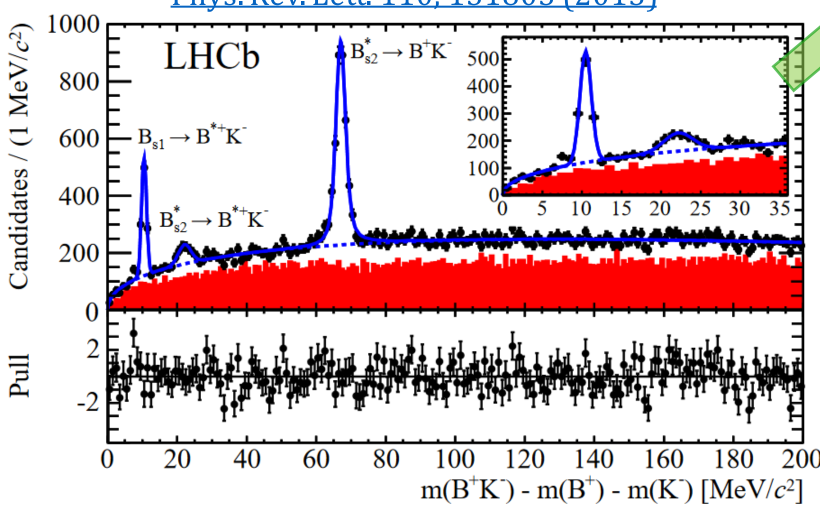
Similarly, $B_{s2}^{*} \rightarrow B^+K^-$ and $B_{s2}^{*} \rightarrow B^{*+}K^-$ decays are expected to proceed in D-wave.

Introduction (previous results)

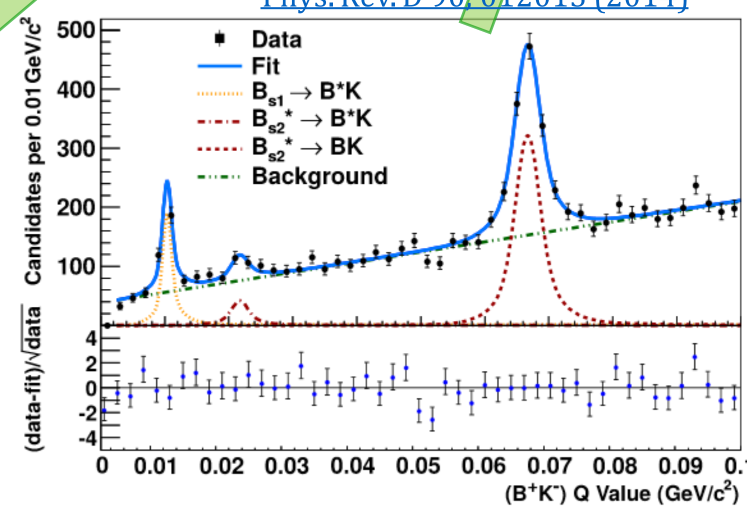
P-wave B_s^0 states were observed and studied only by CDF, D0, and LHCb in B^+K^- channel

Result	CDF 2008 [2]	D0 2008 [3]	LHCb 2013 [4]	CDF 2014 [5]
$N(B_{s2}^* \to B^+K^-)$	95 ± 23	125 ± 25	3140 ± 100	1110 ± 60
$N(B_{s2}^* \to B^{*+}K^-)$	–	–	307 ± 46	$?? \sim 100$
$N(B_{s1} \to B^{*+}K^-)$	39 ± 9	25 ± 10	750 ± 36	280 ± 40
$M(B_{s2}^*)$, MeV	5839.6 ± 0.7	5839.6 ± 1.3	5839.99 ± 0.21	5839.7 ± 0.2
$M(B_{s1})$, MeV	5829.4 ± 0.7	–	5828.40 ± 0.41	5828.3 ± 0.5
$M(B_{s2}^*) - M(B^+) - M(K^-)$, MeV	66.96 ± 0.41	66.7 ± 1.1	67.06 ± 0.12	66.73 ± 0.19
$M(B_{s1}) - M(B^{*+}) - M(K^-)$, MeV	10.73 ± 0.25	11.5 ± 1.4	10.46 ± 0.06	10.35 ± 0.19
$\Gamma(B_{s2}^*)$, MeV	–	–	1.56 ± 0.49	1.4 ± 0.4
$\Gamma(B_{s1})$, MeV	–	–	–	0.5 ± 0.4

Phys. Rev. Lett. 110, 151803 (2013)



Phys. Rev. D 90, 012013 (2014)



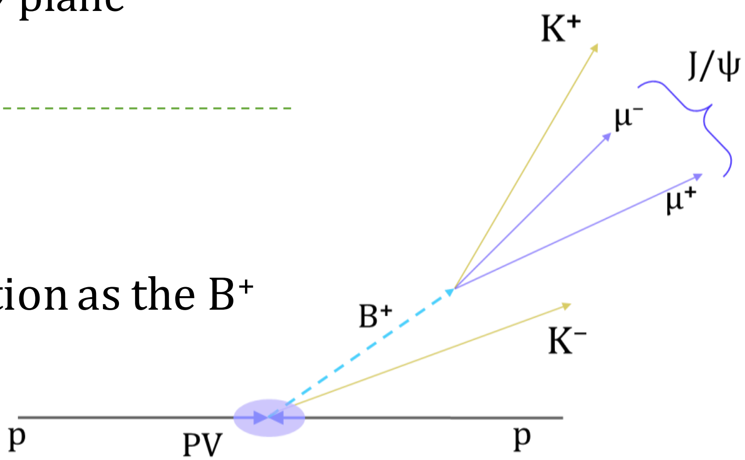
Data and event selection

2012 dataset (19.6 fb^{-1}), trigger optimized to select $B \rightarrow J/\psi$... decays, where $J/\psi \rightarrow \mu^+\mu^-$

B^+ (B^0) candidates obtained combining J/ψ with 1(2) tracks: $B^+ \rightarrow J/\psi K^+$ and $B^0 \rightarrow J/\psi K^+\pi^-$

B meson vertex required to be displaced from the PV in the transverse (*xy*) plane

B meson momentum required to point to the PV in the *xy* plane



B^+K^- channel:

Prompt K^- selected to come from the same pp interaction as the B^+

$B^0K^0_S$ channel:

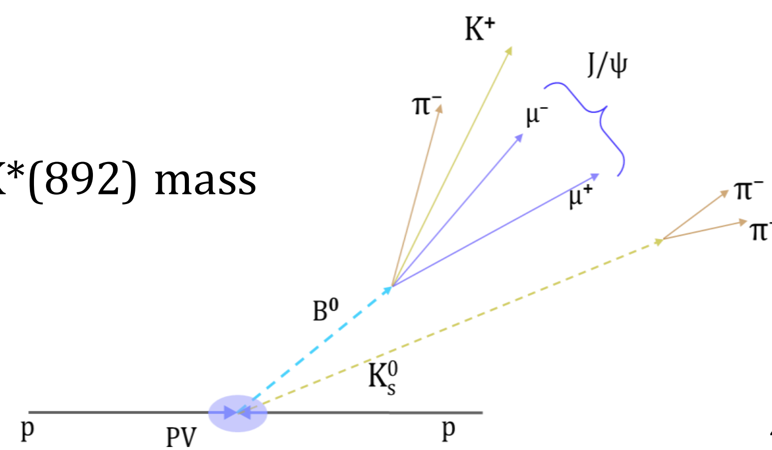
$M(K^+\pi^-)$ in ±90 MeV from K*(892) mass,

$M(K^+K^-) > 1.035$ GeV to cut out $B^0_s \rightarrow J/\psi\varphi$

K/π mass assignment: chose the candidate closer to K*(892) mass

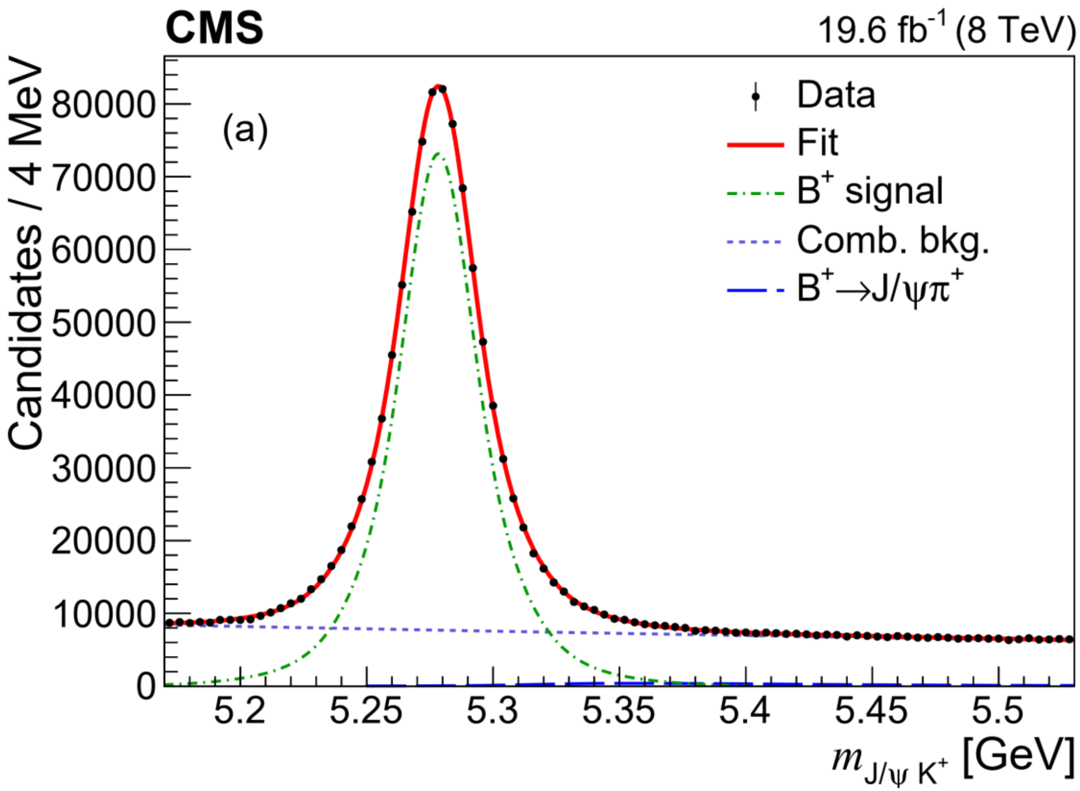
K^0_S is build from displaced 2-prong vertices

K^0_S momentum required to point to PV in the *xy* plane



more details: see backup

B^+ invariant mass distribution



Modelled with triple Gaussian function with common mean for signal, exponential for bkg
additional small contribution to account for Cabibbo suppressed $B^+ \rightarrow J/\psi\pi^+$ decay

The B^+ invariant mass resolution is consistent between data and MC
Effective resolution* is about 24 MeV

$$* \; \sigma_{eff} = \sqrt{f_1\sigma_1^2 + f_2\sigma_2^2 + (1 - f_1 - f_2)\sigma_3^2}$$

A small difference of ~3% is used in the estimation of the systematic uncertainties

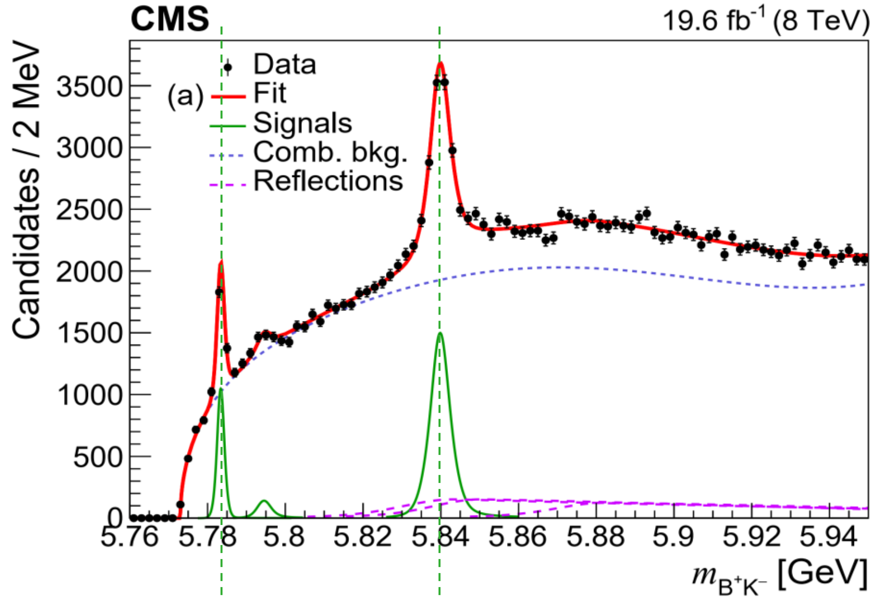
Now combine B^+ with a track from the same PV

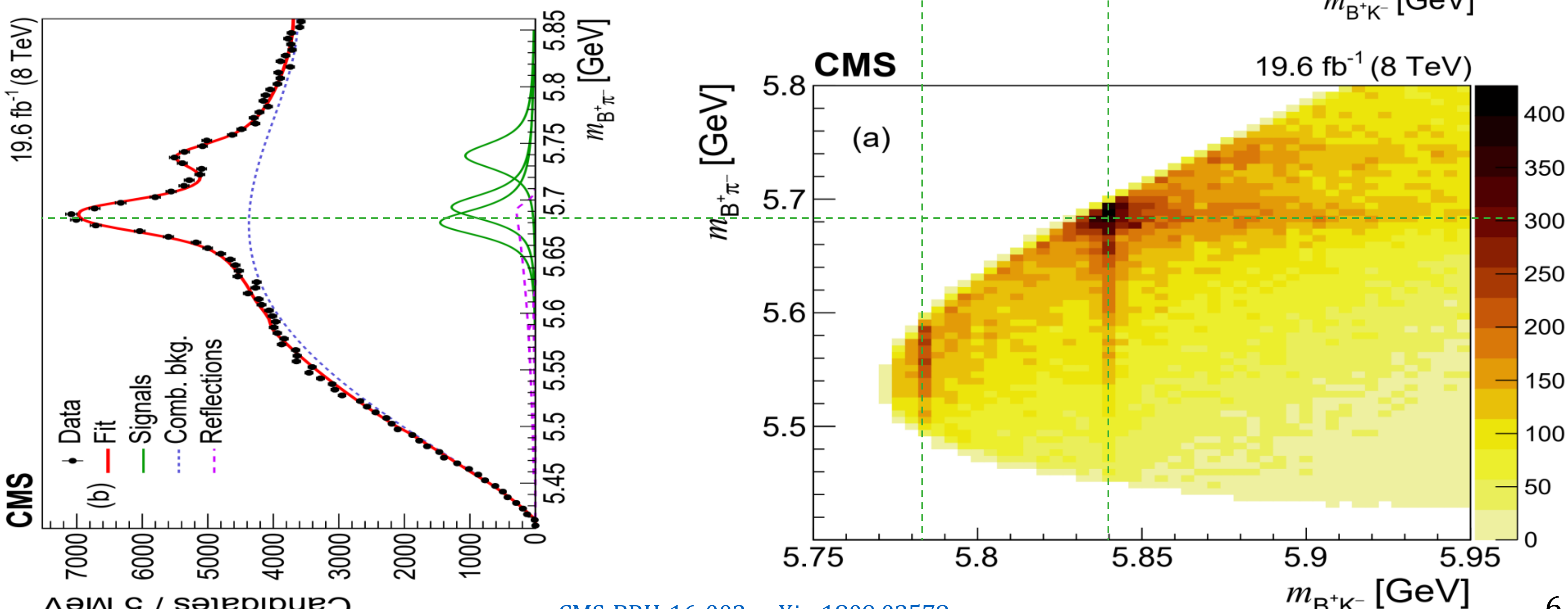
CMS-BPH-16-003, arXiv:1809.03578

B^+h^- invariant mass distributions

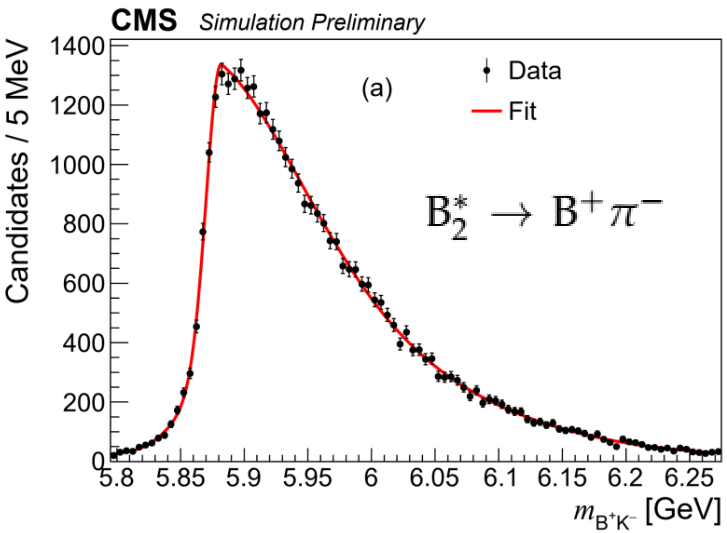
To describe the signal B^+K^- invariant mass distribution, we obtain the yields of reflections from excited B^0 decays using data (fit to $B^+\pi^-$ invariant mass distribution) and their shapes using MC

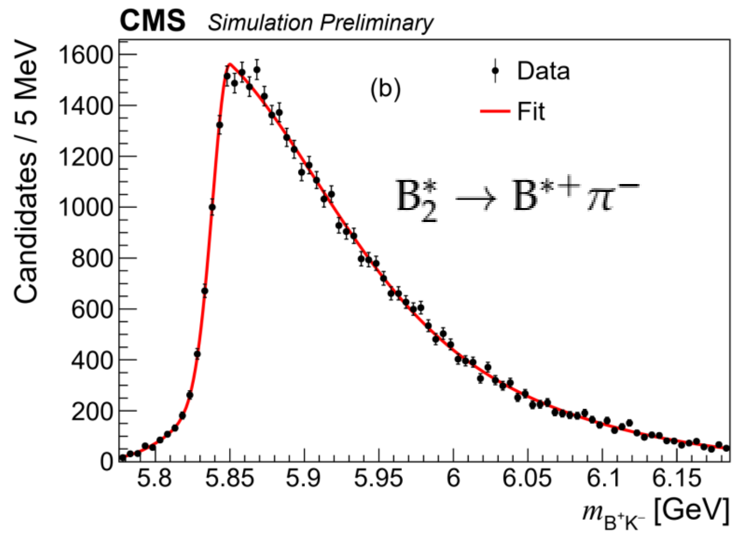
(see slide in backup for details)

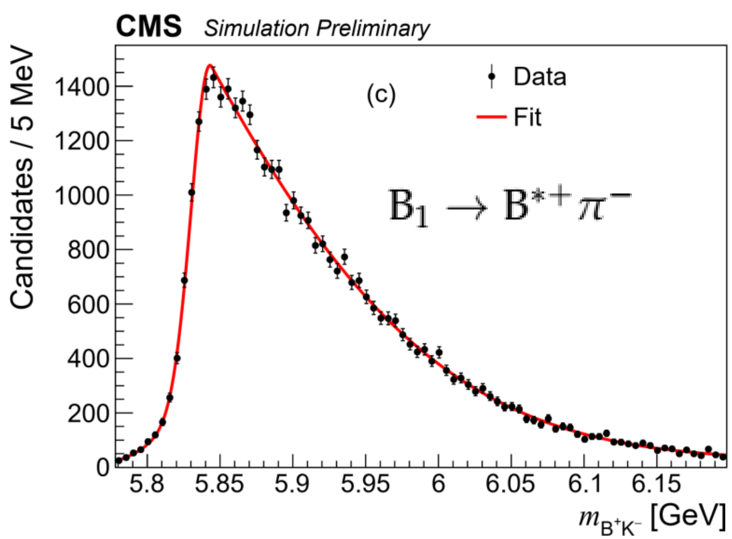




Shape of reflections from $B^{*0} \to B^{(*)+}\pi^-$ decays in B^+K^- invariant mass distribution







The shapes obtained using simulated events are approximated with a product of one-sided double-Gaussian function and sum of two Gaussian functions

CMS-PAS-BPH-16-003

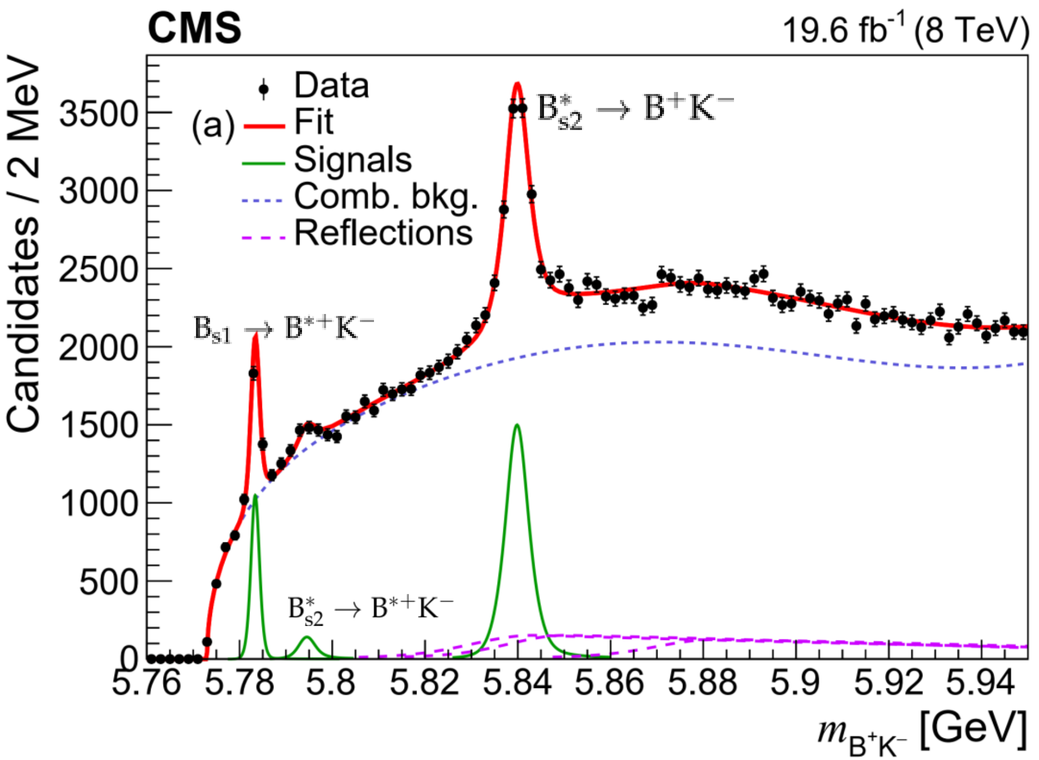
B^+K^- invariant mass distribution

Now we fit B^+K^- invariant mass distribution:

3 D-wave RBW functions convolved with resolutions

+ $(x-x_0)^a \bullet Pol_6(x)$ for background,
x_0 is threshold value

+ contributions from excited B^0
(shapes fixed to MC, yields fixed to the fit results to the $B^+\pi^-$ invariant mass distribution)



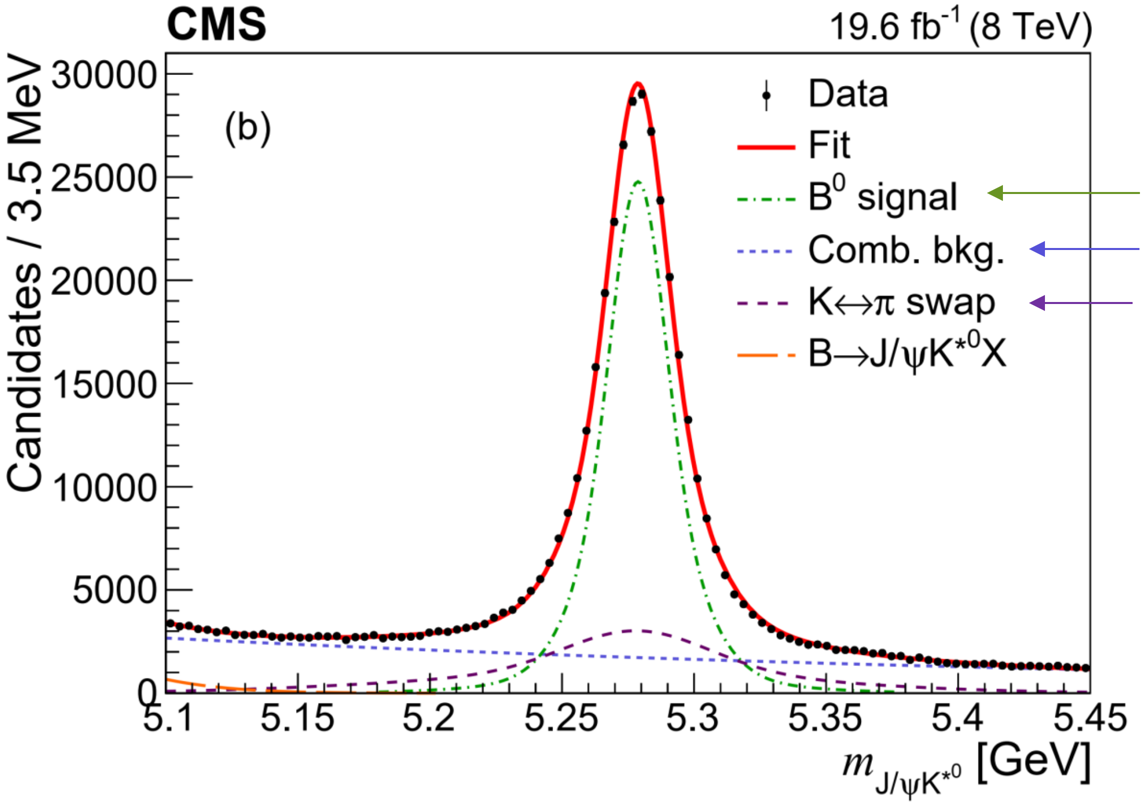
$N(B^*_{s2} \to BK)$	$N(B^*_{s2} \to B^*K)$	$N(B_{s1} \to B^*K)$	$\Gamma(B^*_{s2})$, MeV	$\Gamma(B_{s1})$, MeV
5424 ± 269	455 ± 119	1329 ± 83	1.52 ± 0.34	0.10 ± 0.15

$M(B^*_{s2}) - M(B) - M(K)$, MeV	$M(B_{s1}) - M(B^*) - M(K)$, MeV
66.926 ± 0.093	10.495 ± 0.089

CMS-BPH-16-003, arXiv:1809.03578

$B^0 K_S^0$ final state

$B^0 \to J/\psi K^+\pi^-$ invariant mass distribution



Triple Gaussian with common mean

Exponential

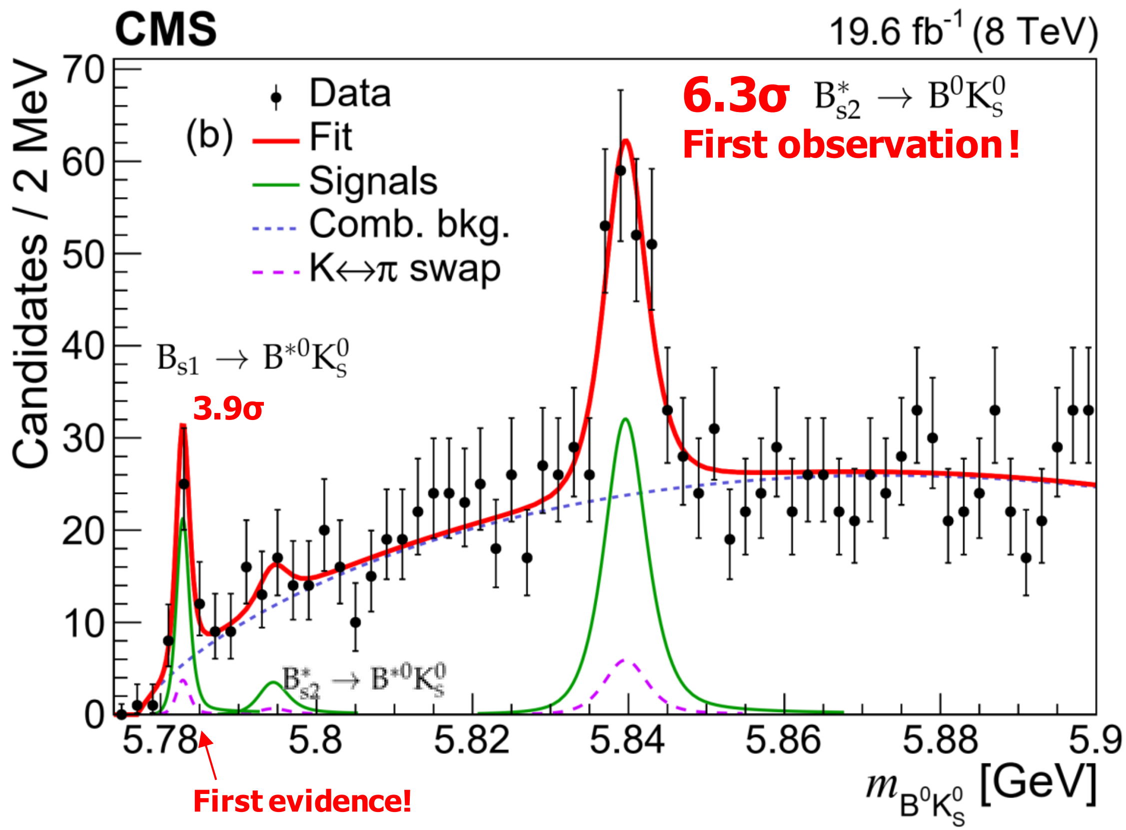
Double Gaussian (2nd is asymmetric)

The resolution parameters and the shape of K↔π swapped component are fixed from simulation (see backup)

Fraction of swapped component with respect to signal = (18.9±3.0)%
in the B^0 signal region of ±2σ

$B^0K^0_S$ invariant mass distribution

Fit:
- 3 D-wave RBW functions convolved with resolutions
- $(x\text{-}x_0)^a \bullet Pol_1(x)$ for bkg, x_0 is threshold value
- 3 contributions from K↔π swap (yields fixed relative to signal: S*0.189)



$N(B^*_{s2} \to BK)$	$N(B^*_{s2} \to B^*K)$	$N(B_{s1} \to B^*K)$	$\Gamma(B^*_{s2})$, MeV	$\Gamma(B_{s1})$, MeV
128 ± 22	12 ± 11	34.5 ± 8.3	2.1 ± 1.3	0.4 ± 0.4

$M(B^*_{s2}) - M(B) - M(K)$, MeV	$M(B_{s1}) - M(B^*) - M(K)$, MeV
62.42 ± 0.48	5.65 ± 0.23

CMS-BPH-16-003, arXiv:1809.03578

Measuring BF ratios

Ratio of the signal yields in data

Ratio of total efficiencies from MC ~ 16

$$R_2^{0\pm} = \frac{\mathcal{B}(\mathrm{B}^*_{s2} \to \mathrm{B}^0\mathrm{K}^0_S)}{\mathcal{B}(\mathrm{B}^*_{s2} \to \mathrm{B}^+\mathrm{K}^-)} = \frac{N(\mathrm{B}^*_{s2} \to \mathrm{B}^0\mathrm{K}^0_S)}{N(\mathrm{B}^*_{s2} \to \mathrm{B}^+\mathrm{K}^-)} \times \frac{\epsilon(\mathrm{B}^*_{s2} \to \mathrm{B}^+\mathrm{K}^-)}{\epsilon(\mathrm{B}^*_{s2} \to \mathrm{B}^0\mathrm{K}^0_S)} \times \frac{\mathcal{B}(\mathrm{B}^+ \to \mathrm{J}/\psi\mathrm{K}^+)}{\mathcal{B}(\mathrm{B}^0 \to \mathrm{J}/\psi\mathrm{K}^{*0})\mathcal{B}(\mathrm{K}^{*0} \to \mathrm{K}^+\pi^-)\mathcal{B}(\mathrm{K}^0_S \to \pi^+\pi^-)}$$

Known branching fractions from PDG

$\mathcal{B}(\mathrm{B}^+ \to \mathrm{J}/\psi\mathrm{K}^+) = (1.026 \pm 0.031) \times 10^{-3}$, $\mathcal{B}(\mathrm{K}^0_S \to \pi^+\pi^-) = (0.6920 \pm 0.0005)$

$\mathcal{B}(\mathrm{B}^0 \to \mathrm{J}/\psi\mathrm{K}^{*0}) = (1.28 \pm 0.05) \times 10^{-3}$, $\mathcal{B}(\mathrm{K}^{*0} \to \mathrm{K}^+\pi^-) = (0.99754 \pm 0.00021)$

Formulae and efficiencies ratios for all 6 measured ratios are in backup

CMS-BPH-16-003, arXiv:1809.03578

Sources of systematic uncertainty

Systematic uncertainties on the branching fraction ratios are related to:

- **Choice of the fit model**
  separate uncertainties related to the fits of $B^+\pi^-$, B^+K^- and $B^0K^0_S$ invariant mass distributions; largest deviation of the results under changes of the fit model is used as systematic uncertainty

- **Track reconstruction efficiency (3.9% per extra track)**
  7.8% since 2 more tracks to reconstruct in $B^0K^0_S$ final state

- Mass resolution
  largest change of the resulting ratios under simultaneous variations of resolution by ±3%

- Fraction of $K\leftrightarrow\pi$ swapped component
  largest change of the resulting ratios under variations of this fraction by ±3%

- Uncertainty on m_{B*}-m_B
  largest change of the resulting ratios under variations of m_{B*}-m_B by ± PDG uncertainty

- Non-K^* contribution in $B^0\rightarrow J/\psi K^+\pi^-$ decay
  estimated by fitting background-subtracted $K^+\pi^-$ invariant mass distribution

- Finite size of the simulation samples
  uncertainties from the previous slide

Next slide shows these uncertainties and the total systematic uncertainties for the 6 measured ratios

Results

Uncertainties here are, respectively, statistical, systematic, related to PDG uncertainties

new
$$R_2^{0\pm} = \frac{\mathcal{B}(B_{s2}^* \to B^0 K_S^0)}{\mathcal{B}(B_{s2}^* \to B^+ K^-)} = 0.432 \pm 0.077 \pm 0.075 \pm 0.021,$$

Theory: 0.43 arXiv:1202.1224, arXiv:1607.02812

new
$$R_1^{0\pm} = \frac{\mathcal{B}(B_{s1} \to B^{*0} K_S^0)}{\mathcal{B}(B_{s1} \to B^{*+} K^-)} = 0.49 \pm 0.12 \pm 0.07 \pm 0.02,$$

2.5σ

Theory: 0.23 arXiv:1202.1224,

$$R_{2*}^{\pm} = \frac{\mathcal{B}(B_{s2}^* \to B^{*+} K^-)}{\mathcal{B}(B_{s2}^* \to B^+ K^-)} = 0.081 \pm 0.021 \pm 0.015,$$

LHCb 0.093±0.013±0.012
CDF 0.10±0.03±0.02

new
$$R_{2*}^{0} = \frac{\mathcal{B}(B_{s2}^* \to B^{*0} K_S^0)}{\mathcal{B}(B_{s2}^* \to B^0 K_S^0)} = 0.093 \pm 0.086 \pm 0.014.$$

LHCb 0.232±0.014±0.013

$$R_{\sigma}^{\pm} = \frac{\sigma(pp \to B_{s1}X)\,\mathcal{B}(B_{s1} \to B^{*+} K^-)}{\sigma(pp \to B_{s2}^*X)\,\mathcal{B}(B_{s2}^* \to B^+ K^-)} = 0.233 \pm 0.019 \pm 0.018,$$

new
$$R_{\sigma}^{0} = \frac{\sigma(pp \to B_{s1}X)\,\mathcal{B}(B_{s1} \to B^{*0} K_S^0)}{\sigma(pp \to B_{s2}^*X)\,\mathcal{B}(B_{s2}^* \to B^0 K_S^0)} = 0.266 \pm 0.079 \pm 0.063.$$

Results are in agreement with existing measurements of LHCb and CDF

CMS 2018: CMS-BPH-16-003, arXiv:1809.03578
LHCb 2013: doi:10.1103/PhysRevLett.110.151803
CDF 2014: doi:10.1103/PhysRevD.90.012013

Results

$$\Delta M^{\pm}_{B^*_{s2}} = M(B^*_{s2}) - M^{PDG}_{B^+} - M^{PDG}_{K^-} = 66.87 \pm 0.09 \pm 0.07\,\text{MeV},$$

new

$$\Delta M^{0}_{B^*_{s2}} = M(B^*_{s2}) - M^{PDG}_{B^0} - M^{PDG}_{K^0_S} = 62.37 \pm 0.48 \pm 0.07\,\text{MeV},$$

$$\Delta M^{\pm}_{B_{s1}} = M(B_{s1}) - M^{PDG}_{B^{*+}} - M^{PDG}_{K^-} = 10.45 \pm 0.09 \pm 0.06\,\text{MeV},$$

new

$$\Delta M^{0}_{B_{s1}} = M(B_{s1}) - M^{PDG}_{B^{*0}} - M^{PDG}_{K^0_S} = 5.61 \pm 0.23 \pm 0.06\,\text{MeV}.$$

$$\Gamma_{B^*_{s2}} = 1.52 \pm 0.34 \pm 0.30\,\text{MeV}$$

Comparison to previous measurements

	$M(B^*_{s2})-M(B^+)-M(K^-)$	$M(B_{s1})-M(B^{*+})-M(K^-)$	$\Gamma(B^*_{s2})$
LHCb	67.06±0.12	10.46±0.06	1.56±0.49
CDF	67.73±0.19	10.35±0.19	1.4±0.44
CMS	**66.87±0.12**	**10.45±0.11**	**1.52±0.43**

2^{nd} and 3^{rd} column are consistent with existing measurements of LHCb and CDF

Measurement of $M(B^*_{s2})-M(B^+)-M(K^-)$ agrees with LHCb, not with CDF

CMS 2018: CMS-BPH-16-003, arXiv:1809.03578
LHCb 2013: doi:10.1103/PhysRevLett.110.151803
CDF 2014: doi:10.1103/PhysRevD.90.012013

Results

We also measure the mass differences between neutral and charged $B^{(*)}$ mesons:

$$M_{B^0} - M_{B^+} = 0.57 \pm 0.49 \pm 0.10 \pm 0.02\,\text{MeV}$$

$$M_{B^{*0}} - M_{B^{*+}} = 0.91 \pm 0.24 \pm 0.09 \pm 0.02\,\text{MeV}$$

The first mass difference is known with much better precision: (0.31 ± 0.06) MeV [PDG] while there are no measurements for the second one.

We present a new method to measure these mass differences!
It may become very precise with more data

Summary

First observation (6.3σ) of the $B_{s2}^{*} \to B^0 K_S^0$ decay

First evidence (3.9σ) for the $B_{s1} \to B^{*0} K_S^0$ decay

Measure 4 BF ratios $\frac{\mathcal{B}(B_{s2}^{*} \to B^0 K_S^0)}{\mathcal{B}(B_{s2}^{*} \to B^+ K^-)}, \frac{\mathcal{B}(B_{s1} \to B^{*0} K_S^0)}{\mathcal{B}(B_{s1} \to B^{*+} K^-)}, \frac{\mathcal{B}(B_{s2}^{*} \to B^{*+} K^-)}{\mathcal{B}(B_{s2}^{*} \to B^+ K^-)}, \frac{\mathcal{B}(B_{s2}^{*} \to B^{*0} K_S^0)}{\mathcal{B}(B_{s2}^{*} \to B^0 K_S^0)}$

Measure 2 BF x σ ratios $\frac{\sigma(pp \to B_{s1} \dots) \times \mathcal{B}(B_{s1} \to B^{*+} K^-)}{\sigma(pp \to B_{s2}^{*} \dots) \times \mathcal{B}(B_{s2}^{*} \to B^+ K^-)}, \frac{\sigma(pp \to B_{s1} \dots) \times \mathcal{B}(B_{s1} \to B^{*0} K_S^0)}{\sigma(pp \to B_{s2}^{*} \dots) \times \mathcal{B}(B_{s2}^{*} \to B^0 K_S^0)}$

Measure 6 mass differences and the B_{s2}^{*} natural width

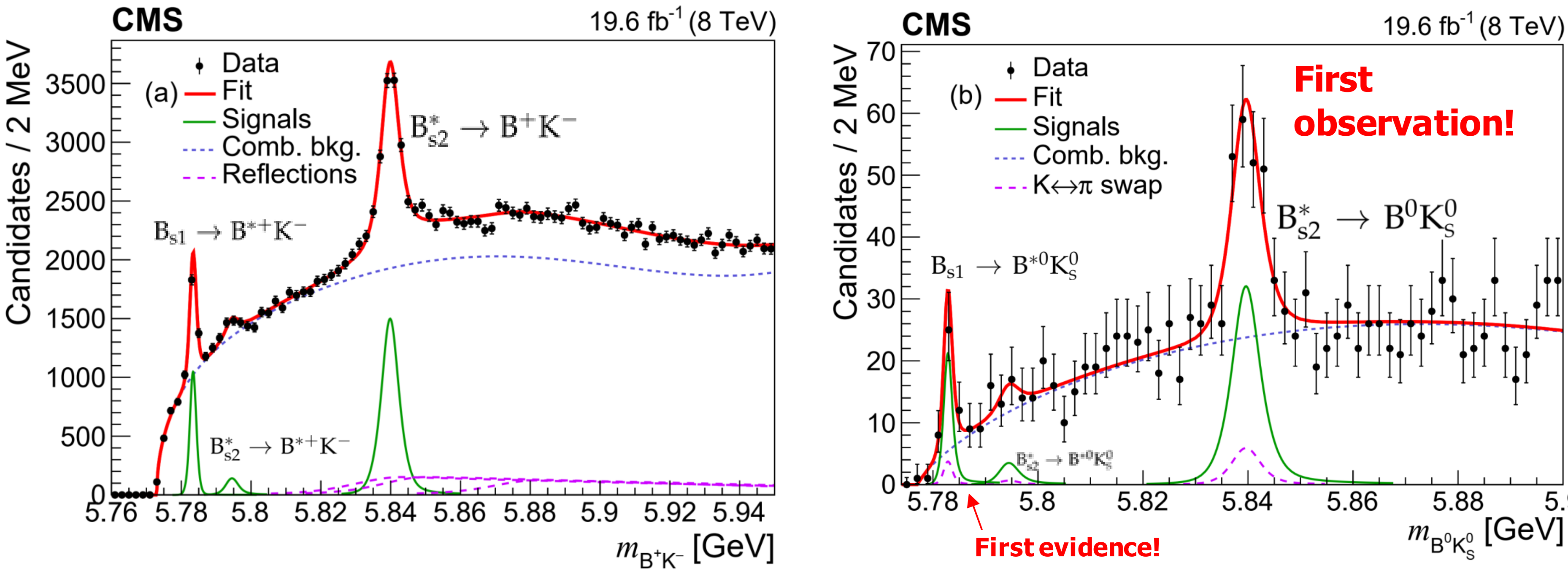
- $M(B_{s2}^{*}) - M(B^+) - M(K^-)$
- $M(B_{s1}) - M(B^{*+}) - M(K^-)$
- $M(B_{s2}^{*}) - M(B^0) - M(K_S^0)$ ***(first measurement)***
- $M(B_{s1}) - M(B^{*0}) - M(K_S^0)$ ***(first measurement)***
- $M(B^{*+}) - M(B^+)$
- $M(B^{*0}) - M(B^0)$ ***(first measurement)***
- $\Gamma(B_{s2}^{*})$

We also report the mass measurements $M(B_{s2}^{*})$ and $M(B_{s1})$ *(in backup)*

The results are in agreement with previous measurements, if they exist

Thank you !

Overview



Final state	$N(B^*_{s2} \to BK)$	$N(B^*_{s2} \to B^*K)$	$N(B_{s1} \to B^*K)$
B^+K^-	5424 ± 269	455 ± 119	1329 ± 83
$B^0K^0_S$	128 ± 22	12 ± 11	34.5 ± 8.3

B^+ is reconstructed in $J/\psi K^+$ channel

B^0 is reconstructed in $J/\psi K^+\pi^-$ channel

“Reflections”:

From $B^{**} \to B^{(*)+}\pi^-$ in B^+K^- channel, yields fixed from the fit to $B^+\pi^-$ invariant mass;

From K↔π swap in $B^0K^0_S$ channel, yields fixed relative to the signal yields

We also measure masses, mass differences and $\Gamma(B^*_{s2})$ in these decays

CMS-BPH-16-003, arXiv:1809.03578

CMS-BPH-16-003, arXiv:1809.03578

Summary of all reported measurements

$$R_2^{0\pm} = \frac{\mathcal{B}(B_{s2}^* \to B^0 K_S^0)}{\mathcal{B}(B_{s2}^* \to B^+ K^-)} = 0.432 \pm 0.077\,(\text{stat}) \pm 0.075\,(\text{syst}) \pm 0.021\,(\text{PDG})$$

$$R_1^{0\pm} = \frac{\mathcal{B}(B_{s1} \to B^{*0} K_S^0)}{\mathcal{B}(B_{s1} \to B^{*+} K^-)} = 0.492 \pm 0.122\,(\text{stat}) \pm 0.068\,(\text{syst}) \pm 0.024\,(\text{PDG})$$

$$R_{2*}^{\pm} = \frac{\mathcal{B}(B_{s2}^* \to B^{*+} K^-)}{\mathcal{B}(B_{s2}^* \to B^+ K^-)} = 0.081 \pm 0.021\,(\text{stat}) \pm 0.015\,(\text{syst}),$$

$$R_{2*}^{0} = \frac{\mathcal{B}(B_{s2}^* \to B^{*0} K_S^0)}{\mathcal{B}(B_{s2}^* \to B^0 K_S^0)} = 0.093 \pm 0.086\,(\text{stat}) \pm 0.014\,(\text{syst}),$$

$$R_{\sigma}^{\pm} = \frac{\sigma(pp \to B_{s1}\ldots) \times \mathcal{B}(B_{s1} \to B^{*+} K^-)}{\sigma(pp \to B_{s2}^*\ldots) \times \mathcal{B}(B_{s2}^* \to B^+ K^-)} = 0.233 \pm 0.019\,(\text{stat}) \pm 0.018\,(\text{syst})$$

$$R_{\sigma}^{0} = \frac{\sigma(pp \to B_{s1}\ldots) \times \mathcal{B}(B_{s1} \to B^{*0} K_S^0)}{\sigma(pp \to B_{s2}^*\ldots) \times \mathcal{B}(B_{s2}^* \to B^0 K_S^0)} = 0.266 \pm 0.079\,(\text{stat}) \pm 0.063\,(\text{syst})$$

$$\Delta M_{B_{s2}^*}^{\pm} = M(B_{s2}^*) - M(B^+) - M(K^-) = 66.870 \pm 0.093\,(\text{stat}) \pm 0.073\,(\text{syst})\,\text{MeV},$$

$$\Delta M_{B_{s2}^*}^{0} = M(B_{s2}^*) - M(B^0) - M(K_S^0) = 62.37 \pm 0.48\,(\text{stat}) \pm 0.07\,(\text{syst})\,\text{MeV},$$

$$\Delta M_{B_{s1}}^{\pm} = M(B_{s1}) - M(B^{*+}) - M(K^-) = 10.452 \pm 0.089\,(\text{stat}) \pm 0.063\,(\text{syst})\,\text{MeV},$$

$$\Delta M_{B_{s1}}^{0} = M(B_{s1}) - M(B^{*0}) - M(K_S^0) = 5.61 \pm 0.23\,(\text{stat}) \pm 0.06\,(\text{syst})\,\text{MeV},$$

$$M(B_{s2}^*) = 5839.86 \pm 0.09 \pm 0.07 \pm 0.15\,\text{MeV}$$

$$M(B_{s1}) = 5828.78 \pm 0.09 \pm 0.06 \pm 0.28\,\text{MeV}$$

$$m_{B^0} - m_{B^+} = 0.57 \pm 0.49\,(\text{stat}) \pm 0.10\,(\text{syst}) \pm 0.02\,(\text{PDG})\,\text{MeV}$$

$$m_{B^{*0}} - m_{B^{*+}} = 0.91 \pm 0.24\,(\text{stat}) \pm 0.09\,(\text{syst}) \pm 0.02\,(\text{PDG})\,\text{MeV}$$

$$\Gamma(B_{s2}^*) = 1.52 \pm 0.34\,(\text{stat}) \pm 0.30\,(\text{syst})\,\text{MeV}$$

Highlighted in yellow are the first measurements

BACKUP

$B^+\pi^-$ invariant mass distribution

To obtain yields of these reflections, we fit $B^+\pi^-$ invariant mass distribution:

3 D-wave RBW functions convolved with resolutions *(from MC)*

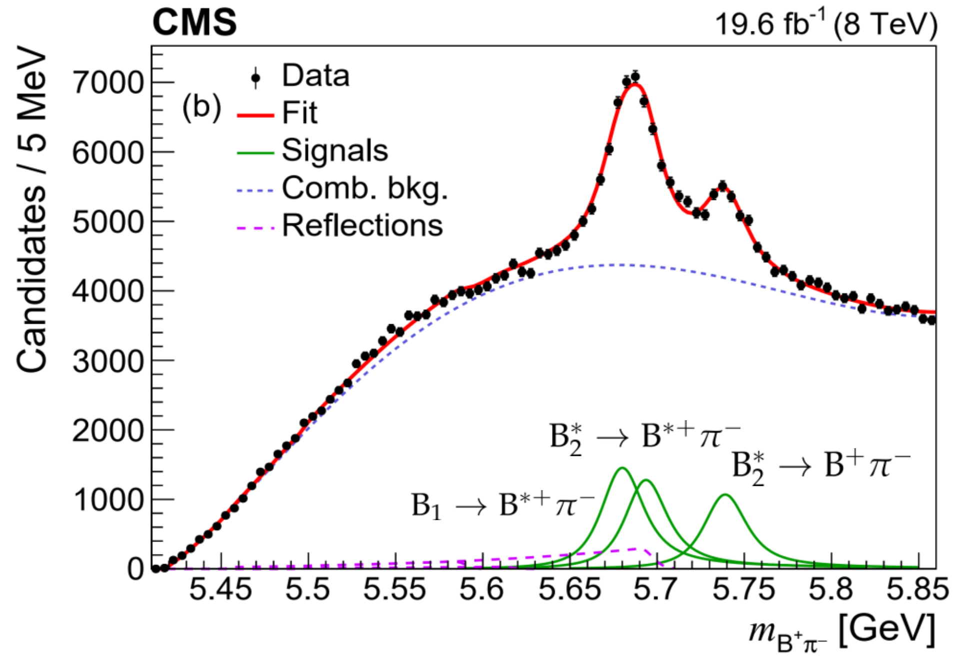
+ $(x-x_0)^a \bullet Pol_m(x)$ for background,

x_0 is threshold value, $Pol_m(x)$ is polynomial of degree m

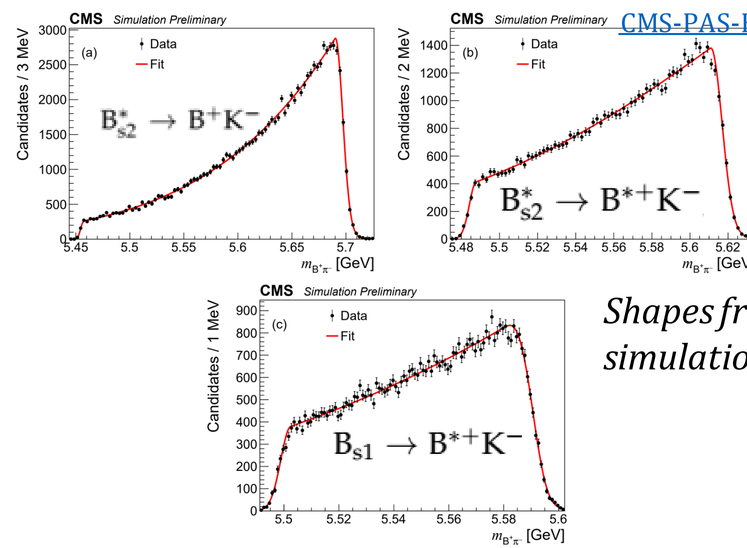
+ (small) contributions from $B_{s1,2}^{(*)}$

In the baseline fit, masses and natural widths of excited B^0 states are fixed to PDG

The fit returns yields of about 8500, 10500 and 12000 events for the $B_2^* \to B^+\pi^-$, $B_2^* \to B^{*+}\pi^-$, and $B_1^* \to B^+\pi^-$ decays, respectively



CMS-PAS-BPH-16-003



Shapes from simulation

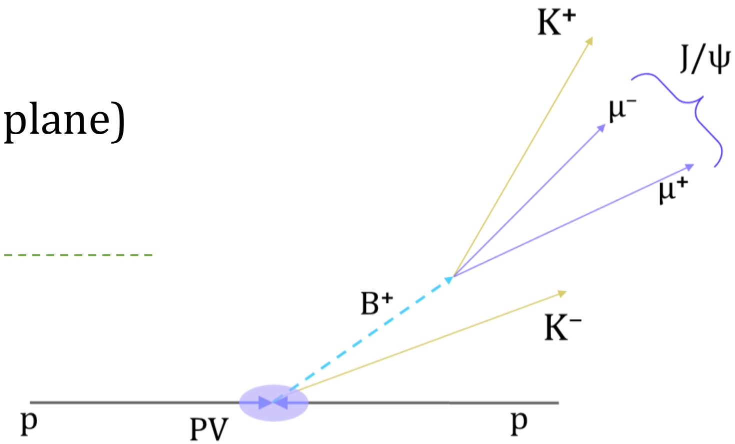
CMS-BPH-16-003, arXiv:1809.03578

Data and event selection

Common selection for B^+ and B^0

- 2012 dataset (19.6 fb^{-1}), trigger optimized to select $B \to J/\psi$ … decays
- Muons matched to trigger; $p_T(\mu^\pm) > 3.5$ GeV/c, $|\eta(\mu^\pm)| < 2.2$
- Standard CMS "high purity" tracks, $p_T > 1$ GeV

- $P_{vtx}(B)$ > 1%
- PV is chosen as the one with best pointing angle
- L_{xy}/σ_{Lxy} (B) > 5.0
- $\cos\alpha_{xy}$ >0.99 (B momentum points to PV in xy plane)
- B mass in $\sim\pm2\sigma_{eff}$ from PDG



B^+K^- channel: K^- is chosen from PV track collection

$B^0K^0_S$ channel:

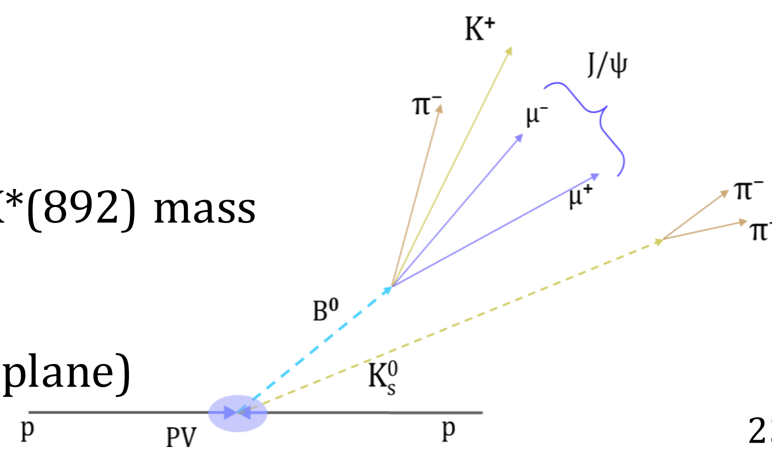
$M(K^+\pi^-)$ in ±90 MeV from K*(892) mass,

$M(K^+,K^-) > 1.035$ GeV to cut out $B^0_S \to J/\psi\varphi$

K/π mass assignment: chose the candidate closer to K*(892) mass

K^0_S is build from displaced 2-prong vertices

$\cos\alpha_{xy}$ >0.999 (K^0_S momentum points to PV in xy plane)



B^+K^- signal extraction logic

Fit to $B^{*0} \to B^+\pi^-$ MC samples to obtain signal resolutions

Fit to $B^{(*)}_{s1,2} \to B^+K^-$ MC samples to obtain reflection shapes (if reconstructed as $B^+\pi^-$)

Fit to $B^+\pi^-$ invariant mass distribution in data, with signal resolutions from MC and fixed shapes of reflections from $B^{(*)}_{s1,2} \to B^+K^-$

Yields of $B^{*0} \to B^+\pi^-$ contributions

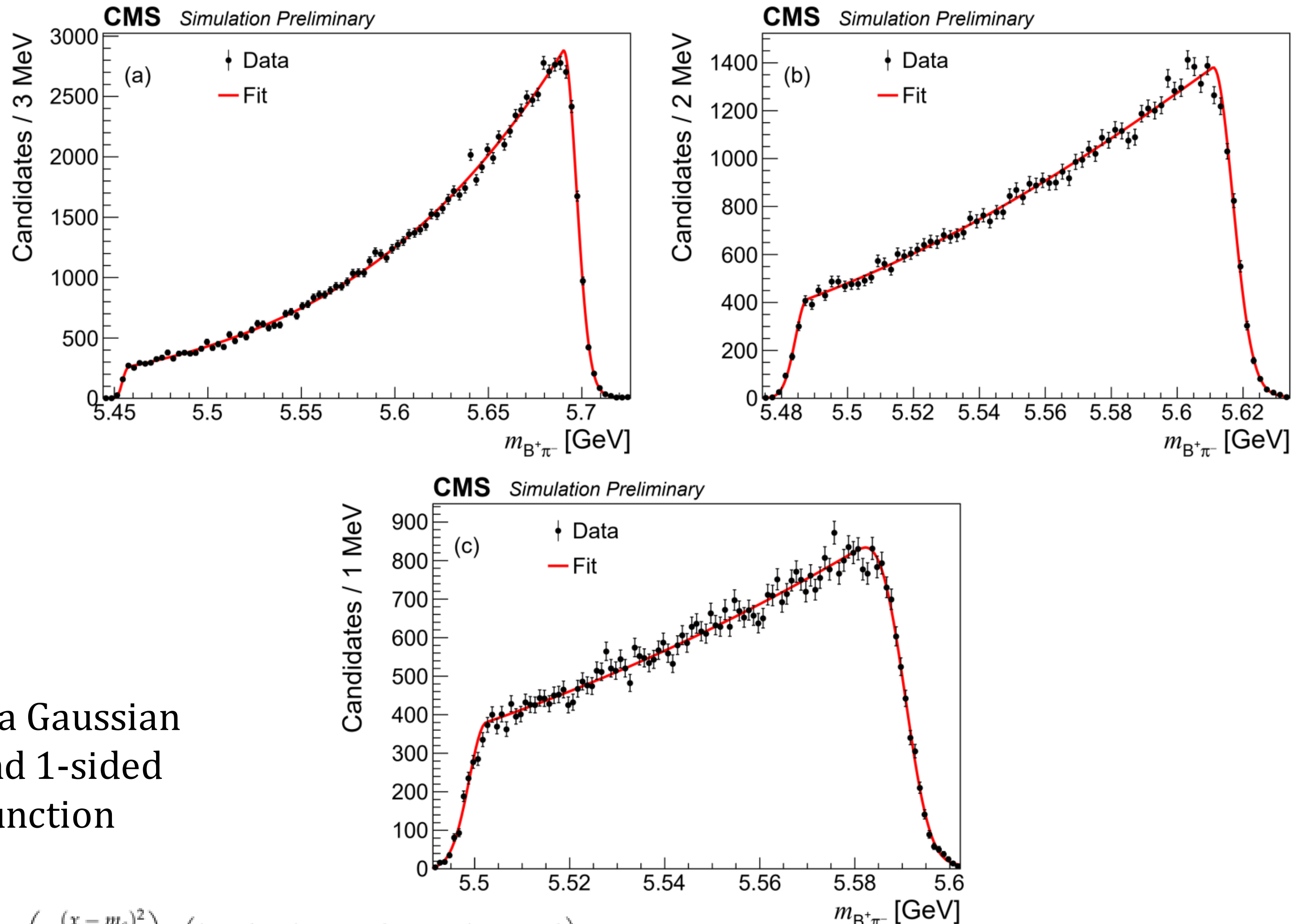
Fit to $B^{*0} \to B^+\pi^-$ MC samples to obtain reflection shapes (if reconstructed as B^+K^-)

Fit to $B^{(*)}_{s1,2} \to B^+K^-$ MC samples to obtain signal resolutions

Fit to B^+K^- distribution in data, with
- reflections from B^{*0} shapes and yields fixed
- Signal resolutions fixed to MC

Signal yields, mass differences, Γ

The shapes of reflections from $B^0_{s1,2}$ decays in $B^+\pi^-$ invariant mass



Product of a Gaussian function and 1-sided Gaussian function

$$F(x;\ ...) = G_L(x; m_L, \sigma_L) * exp\left(-\frac{(x-m_c)^2}{2\sigma_c^2}\right) * \left((1-f)\, G_R(x; m_R, \sigma_{R1})\ + f\, G_R(x; m_R, \sigma_{R2})\right)$$

$$\text{where } G_L(x; m, \sigma) = \begin{cases} exp(-\frac{1}{2}\left(\frac{x-m}{\sigma}\right)^{\lambda_L}) & \text{if } x \leqslant m \\ 1 & \text{if } x \geqslant m \end{cases}$$

$$\text{and } \quad G_R(x; m, \sigma) = \begin{cases} 1 & \text{if } x \leqslant m \\ exp(-\frac{1}{2}\left(\frac{x-m}{\sigma}\right)^{\lambda_R}) & \text{if } x \geqslant m \end{cases}$$

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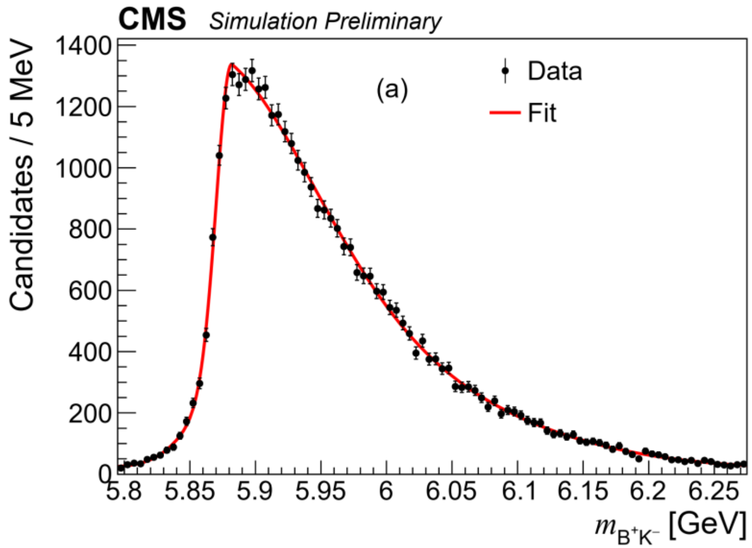
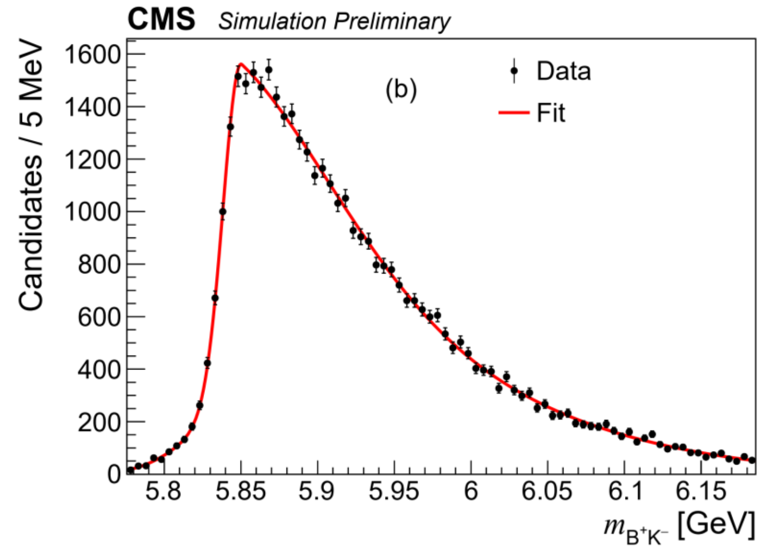
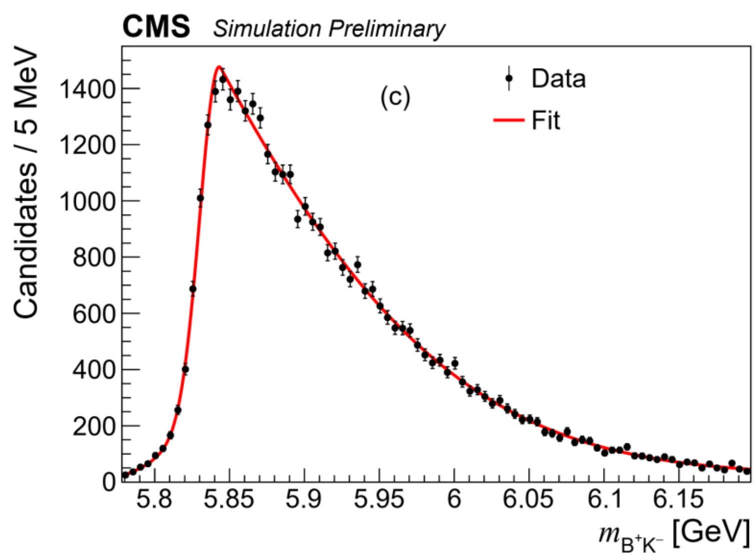
The shapes of reflections from B^{0*} decays in B^+K^- invariant mass





Product of a double-Gaussian function and double 1-sided Gaussian function



$$F(x;\ \sigma_{01}, \sigma_{02}, m_0, \sigma_1, m_1, \sigma_2, m_2, f, \phi) = G(x; \dots) * \left(exp(-\frac{(x-m_1)^2}{2\sigma_1^2}) + f * exp(-\frac{(x-m_2)^2}{2\sigma_2^2}) \right)$$

$$\text{where } G(x;\ \sigma_{01}, \sigma_{02}, \phi, m_0) = \begin{cases} (1-\phi)\, exp(-\frac{(x-m_0)^2}{2\sigma_{01}^2}) + \phi\, exp(-\frac{(x-m_0)^2}{2\sigma_{02}^2}) & \text{if } x < m_0 \\ 1 & \text{if } x > m_0 \end{cases}$$

CMS-PAS-BPH-16-003

B^0 invariant mass distribution (MC)

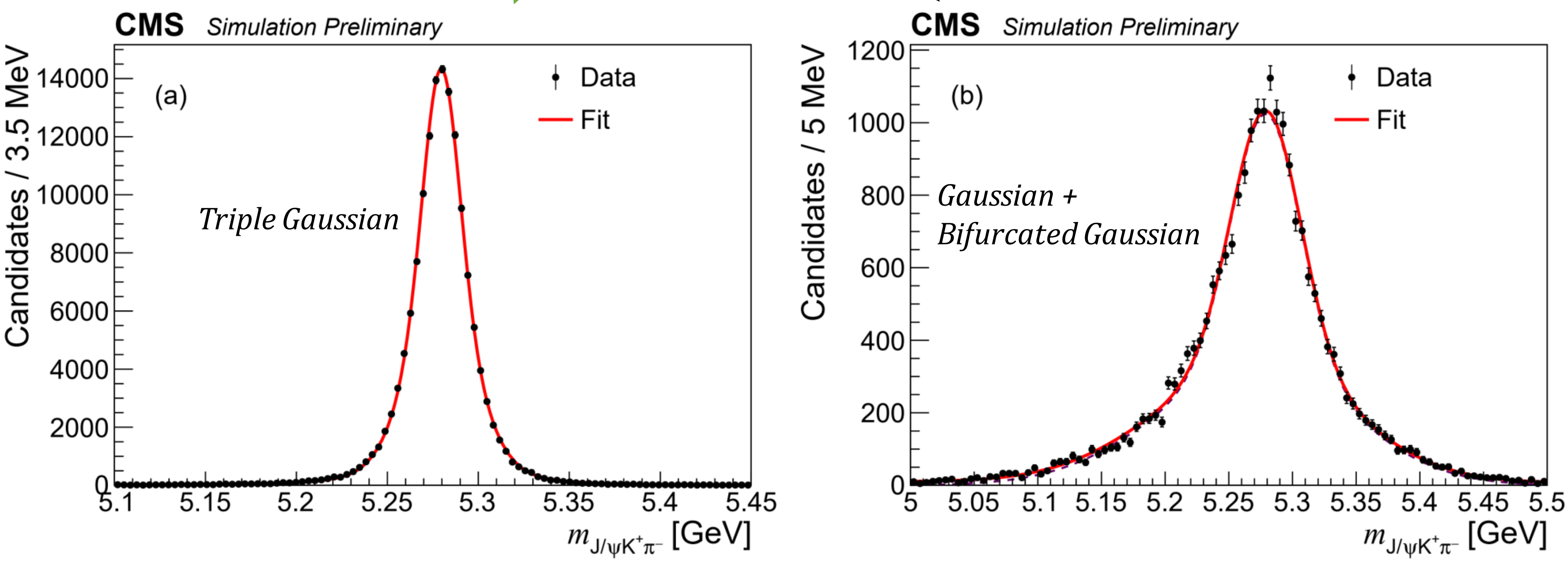
B^0 is reconstructed in the decay to $J/\psi K^+\pi^-$, where kaon and pion can be misidentified (swapped) in the reconstruction. The selection requirements are

$M(K^+\pi^-)$ in ±90 MeV from K(892) mass,*

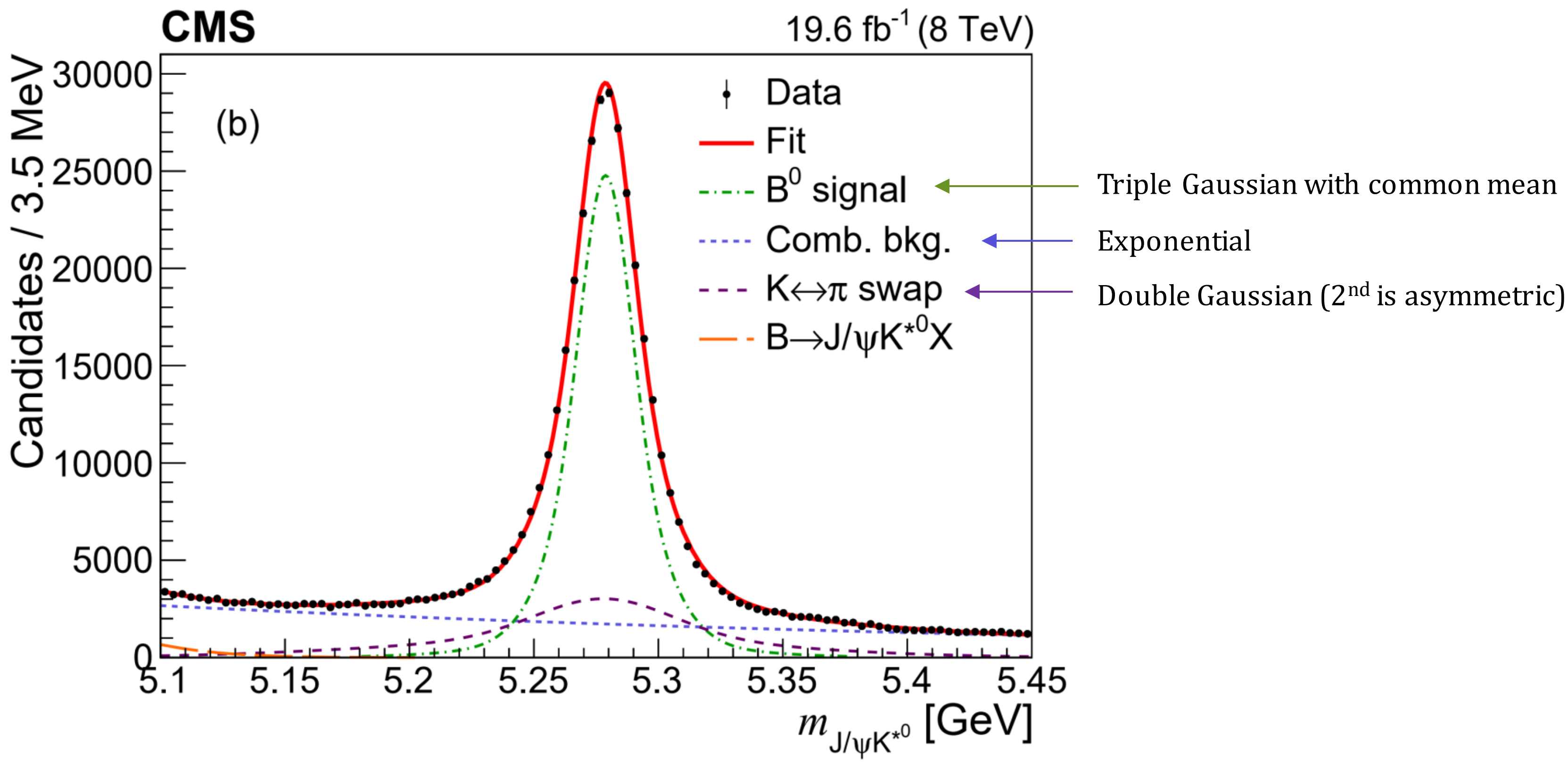
$M(K^+,K^-) > 1.035$ GeV to cut out $B_s^0 \to J/\psi\varphi$, as in P5' analysis

K/π mass assignment: as in P5', chose the candidate closer to K(892) mass*

We use MC to obtain the signal resolution and shape of K↔π swapped component:



B^0 invariant mass distribution



The resolution parameters and the shape of K↔π swapped component are fixed from simulation (see backup)

The B^0 signal region [5245, 5313] MeV includes ~220000 signal candidates and ~41000 K↔π swap candidates ⇒ "fraction of swapped component w.r.t. signal" = (18.9±0.3)%

Vary the signal resolution by + and – 3% (see B^+ fit) ⇒ variation of this fraction is (18.9±3.0)% (uncertainty will be considered as systematics source)

CMS-PAS-BPH-16-003

Systematic uncertainties in the branching fraction ratios

$$R_2^{0\pm} = \frac{\mathcal{B}(B_{s2}^* \to B^0 K_S^0)}{\mathcal{B}(B_{s2}^* \to B^+ K^-)}$$

$$R_1^{0\pm} = \frac{\mathcal{B}(B_{s1} \to B^{*0} K_S^0)}{\mathcal{B}(B_{s1} \to B^{*+} K^-)}$$

Systematic uncertainty in %

Source	$R_2^{0\pm}$	$R_1^{0\pm}$
Track reconstruction efficiency	7.8	7.8
$m_{B^+\pi^-}$ distribution model	2.5	2.0
$m_{B^+K^-}$ distribution model	2.4	4.6
$m_{B^0K_S^0}$ distribution model	14	8.1
Mass resolution	0.7	2.2
Fraction of KPS	2.6	2.6
Non-K^{*0} contribution	5.0	5.0
Finite size of simulated samples	1.2	1.2
Total	18	14

$$R_{2*}^{\pm} = \frac{\mathcal{B}(B_{s2}^* \to B^{*+} K^-)}{\mathcal{B}(B_{s2}^* \to B^+ K^-)} \quad R_{2*}^{0} = \frac{\mathcal{B}(B_{s2}^* \to B^{*0} K_S^0)}{\mathcal{B}(B_{s2}^* \to B^0 K_S^0)}$$

$$R_{\sigma}^{\pm} = \frac{\sigma(pp \to B_{s1} \ldots) \times \mathcal{B}(B_{s1} \to B^{*+} K^-)}{\sigma(pp \to B_{s2}^* \ldots) \times \mathcal{B}(B_{s2}^* \to B^+ K^-)}$$

$$R_{\sigma}^{0} = \frac{\sigma(pp \to B_{s1} \ldots) \times \mathcal{B}(B_{s1} \to B^{*0} K_S^0)}{\sigma(pp \to B_{s2}^* \ldots) \times \mathcal{B}(B_{s2}^* \to B^0 K_S^0)}$$

Systematic uncertainty in %

Source	$R_{2*}^{\pm}$	R_{2*}^{0}	$R_{\sigma}^{\pm}$	R_{σ}^{0}
$m_{B^+\pi^-}$ distribution model	2.9	—	2.7	—
$m_{B^+K^-}$ distribution model	17	—	7.1	—
$m_{B^0K_S^0}$ distribution model	—	13	—	24
Mass resolution	1.2	3.0	1.5	1.1
Uncertainties in $M_{B^*}^{PDG} - M_{B}^{PDG}$	7.7	4.8	—	—
Finite size of simulated samples	1.1	1.3	1.1	1.3
Total	19	15	7.8	24

Systematic uncertainties

Four mass differences obtained from the fits

$$\Delta M^{\pm}_{B^*_{s2}} = M(B^*_{s2}) - M^{PDG}_{B^+} - M^{PDG}_{K^-}, \qquad \Delta M^{\pm}_{B_{s1}} = M(B_{s1}) - M^{PDG}_{B^{*+}} - M^{PDG}_{K^-}$$

$$\Delta M^{0}_{B^*_{s2}} = M(B^*_{s2}) - M^{PDG}_{B^0} - M^{PDG}_{K^0_S}, \qquad \Delta M^{0}_{B_{s1}} = M(B_{s1}) - M^{PDG}_{B^{*0}} - M^{PDG}_{K^0_S}$$

allow to measure the mass differences between neutral and charged $B^{(*)}$ mesons:

$$M_{B^0} - M_{B^+} = \Delta M^{\pm}_{B^*_{s2}} - \Delta M^{0}_{B^*_{s2}} + M^{PDG}_{K^-} - M^{PDG}_{K^0_S}$$

$$M_{B^{*0}} - M_{B^{*+}} = \Delta M^{\pm}_{B_{s1}} - \Delta M^{0}_{B_{s1}} + M^{PDG}_{K^-} - M^{PDG}_{K^0_S}$$

Additional systematic uncertainties are related to

> Shift from reconstruction: values obtained from the reconstructed MC differ a bit from those in the generation configuration. Our measurements are corrected by these shifts, and value of each shift is used as systematic uncertainty.

> Detector misalignment: 18 additional MC samples for each measurement are produced with differently distorted detector geometry, and maximum deviation from the case of no misalignment is taken as systematic uncertainty.

Source	$\Delta M^{\pm}_{B^*_{s2}}$	$\Delta M^{\pm}_{B_{s1}}$	$\Delta M^{0}_{B^*_{s2}}$	$\Delta M^{0}_{B_{s1}}$	$M_{B^0} - M_{B^+}$	$M_{B^{*0}} - M_{B^{*+}}$	$\Gamma_{B^*_{s2}}$
$m_{B^+\pi^-}$ distribution model	0.024	0.008	—	—	0.024	0.008	0.11
$m_{B^+K^-}$ distribution model	0.011	0.043	—	—	0.011	0.043	0.11
$m_{B^0K^0_S}$ distribution model	—	—	0.039	0.038	0.039	0.038	—
Uncertainties in $M^{PDG}_{B^*} - M^{PDG}_{B}$	0.012	0.003	0.003	0.0001	0.012	0.003	0.03
Shift from reconstruction	0.056	0.044	0.050	0.042	0.075	0.061	—
Detector misalignment	0.036	0.005	0.031	0.006	0.038	0.008	0.15
Mass resolution	0.007	0.005	0.005	0.005	0.009	0.007	0.20
Total	0.073	0.063	0.071	0.057	0.098	0.085	0.30

CMS-BPH-16-003, arXiv:1809.03578

$B^0K^0_S$ signal significance

Estimated using likelihood ratio of fits with and without signal component

P = TMath.Prob(Log L_S – Log L_0, 1)
Signif = $\sqrt{2}$ · Tmath.ErfcInverse(P)

where
L_0 corresponds to fit with signal
L_S corresponds to fit without signal

For these fits, systematic uncertainties of resolution and fraction of swapped component are included as Gaussian constraints in likelihood; Mass and Γ uncertainties from PDG are as well Gaussian-constrained

Obtained significance is:

6.3σ for the $B^*_{s2} \to B^0 K^0_S$ decay

3.9σ for the $B_{s1} \to B^{*0} K^0_S$ decay

They vary in [6.3, 7.0]σ and [3.6, 3.9]σ with variations of fit range and bkg model

Measured BF ratios

CMS-BPH-16-003, arXiv:1809.03578

$$R_2^{0\pm} = \frac{\mathcal{B}(\mathrm{B}_{s2}^* \to \mathrm{B}^0\mathrm{K}_S^0)}{\mathcal{B}(\mathrm{B}_{s2}^* \to \mathrm{B}^+\mathrm{K}^-)} = \frac{N(\mathrm{B}_{s2}^* \to \mathrm{B}^0\mathrm{K}_S^0)}{N(\mathrm{B}_{s2}^* \to \mathrm{B}^+\mathrm{K}^-)} \times \frac{\epsilon(\mathrm{B}_{s2}^* \to \mathrm{B}^+\mathrm{K}^-)}{\epsilon(\mathrm{B}_{s2}^* \to \mathrm{B}^0\mathrm{K}_S^0)} \times \frac{\mathcal{B}(\mathrm{B}^+ \to \mathrm{J}/\psi\mathrm{K}^+)}{\mathcal{B}(\mathrm{B}^0 \to \mathrm{J}/\psi\mathrm{K}^{*0})\mathcal{B}(\mathrm{K}^{*0} \to \mathrm{K}^+\pi^-)\mathcal{B}(\mathrm{K}_S^0 \to \pi^+\pi^-)}$$

$$R_1^{0\pm} = \frac{\mathcal{B}(\mathrm{B}_{s1} \to \mathrm{B}^{*0}\mathrm{K}_S^0)}{\mathcal{B}(\mathrm{B}_{s1} \to \mathrm{B}^{*+}\mathrm{K}^-)} = \frac{N(\mathrm{B}_{s1} \to \mathrm{B}^{*0}\mathrm{K}_S^0)}{N(\mathrm{B}_{s1} \to \mathrm{B}^{*+}\mathrm{K}^-)} \times \frac{\epsilon(\mathrm{B}_{s1} \to \mathrm{B}^{*+}\mathrm{K}^-)}{\epsilon(\mathrm{B}_{s1} \to \mathrm{B}^{*0}\mathrm{K}_S^0)} \times \frac{\mathcal{B}(\mathrm{B}^+ \to \mathrm{J}/\psi\mathrm{K}^+)}{\mathcal{B}(\mathrm{B}^0 \to \mathrm{J}/\psi\mathrm{K}^{*0})\mathcal{B}(\mathrm{K}^{*0} \to \mathrm{K}^+\pi^-)\mathcal{B}(\mathrm{K}_S^0 \to \pi^+\pi^-)},$$

$$R_{2*}^{\pm} = \frac{\mathcal{B}(\mathrm{B}_{s2}^* \to \mathrm{B}^{*+}\mathrm{K}^-)}{\mathcal{B}(\mathrm{B}_{s2}^* \to \mathrm{B}^+\mathrm{K}^-)} = \frac{N(\mathrm{B}_{s2}^* \to \mathrm{B}^{*+}\mathrm{K}^-)}{N(\mathrm{B}_{s2}^* \to \mathrm{B}^+\mathrm{K}^-)} \times \frac{\epsilon(\mathrm{B}_{s2}^* \to \mathrm{B}^+\mathrm{K}^-)}{\epsilon(\mathrm{B}_{s2}^* \to \mathrm{B}^{*+}\mathrm{K}^-)},$$

$$R_{2*}^{0} = \frac{\mathcal{B}(\mathrm{B}_{s2}^* \to \mathrm{B}^{*0}\mathrm{K}_S^0)}{\mathcal{B}(\mathrm{B}_{s2}^* \to \mathrm{B}^0\mathrm{K}_S^0)} = \frac{N(\mathrm{B}_{s2}^* \to \mathrm{B}^{*0}\mathrm{K}_S^0)}{N(\mathrm{B}_{s2}^* \to \mathrm{B}^0\mathrm{K}_S^0)} \times \frac{\epsilon(\mathrm{B}_{s2}^* \to \mathrm{B}^0\mathrm{K}_S^0)}{\epsilon(\mathrm{B}_{s2}^* \to \mathrm{B}^{*0}\mathrm{K}_S^0)},$$

$$R_{\sigma}^{\pm} = \frac{\sigma(\mathrm{pp} \to \mathrm{B}_{s1}\ldots) \times \mathcal{B}(\mathrm{B}_{s1} \to \mathrm{B}^{*+}\mathrm{K}^-)}{\sigma(\mathrm{pp} \to \mathrm{B}_{s2}^*\ldots) \times \mathcal{B}(\mathrm{B}_{s2}^* \to \mathrm{B}^+\mathrm{K}^-)} = \frac{N(\mathrm{B}_{s1} \to \mathrm{B}^{*+}\mathrm{K}^-)}{N(\mathrm{B}_{s2}^* \to \mathrm{B}^+\mathrm{K}^-)} \times \frac{\epsilon(\mathrm{B}_{s2}^* \to \mathrm{B}^+\mathrm{K}^-)}{\epsilon(\mathrm{B}_{s1} \to \mathrm{B}^{*+}\mathrm{K}^-)},$$

$$R_{\sigma}^{0} = \frac{\sigma(\mathrm{pp} \to \mathrm{B}_{s1}\ldots) \times \mathcal{B}(\mathrm{B}_{s1} \to \mathrm{B}^{*0}\mathrm{K}_S^0)}{\sigma(\mathrm{pp} \to \mathrm{B}_{s2}^*\ldots) \times \mathcal{B}(\mathrm{B}_{s2}^* \to \mathrm{B}^0\mathrm{K}_S^0)} = \frac{N(\mathrm{B}_{s1} \to \mathrm{B}^{*0}\mathrm{K}_S^0)}{N(\mathrm{B}_{s2}^* \to \mathrm{B}^0\mathrm{K}_S^0)} \times \frac{\epsilon(\mathrm{B}_{s2}^* \to \mathrm{B}^0\mathrm{K}_S^0)}{\epsilon(\mathrm{B}_{s1} \to \mathrm{B}^{*0}\mathrm{K}_S^0)},$$

Relative efficiencies

$$\frac{\epsilon(B_{s2}^{*} \to B^{+}K^{-})}{\epsilon(B_{s2}^{*} \to B^{0}K_{S}^{0})} = 15.77 \pm 0.18, \quad \frac{\epsilon(B_{s1} \to B^{*+}K^{-})}{\epsilon(B_{s1} \to B^{*0}K_{S}^{0})} = 16.33 \pm 0.20,$$

$$\frac{\epsilon(B_{s2}^{*} \to B^{+}K^{-})}{\epsilon(B_{s2}^{*} \to B^{*+}K^{-})} = 0.961 \pm 0.010, \quad \frac{\epsilon(B_{s2}^{*} \to B^{0}K_{S}^{0})}{\epsilon(B_{s2}^{*} \to B^{*0}K_{S}^{0})} = 0.970 \pm 0.012,$$

$$\frac{\epsilon(B_{s2}^{*} \to B^{+}K^{-})}{\epsilon(B_{s1} \to B^{*+}K^{-})} = 0.953 \pm 0.010, \quad \frac{\epsilon(B_{s2}^{*} \to B^{0}K_{S}^{0})}{\epsilon(B_{s1} \to B^{*0}K_{S}^{0})} = 0.987 \pm 0.012,$$

Their uncertainties are used as systematic uncertainties