Study of $B_s^0$ spectroscopy in the CMS experiment

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D0 collaboration, 2016: observation of a new particle X(5568) decaying into $B_s^0\pi^\pm$

**Significance 3.9$\sigma$**

- $B_s^0$ 5582±100 events

- Significance 5.1$\sigma$
  - $N_X = 133 \pm 31$
  - $M_X = 5567.8 \pm 2.9$ MeV
  - $\Gamma_X = 21.9 \pm 6.4$ MeV

- Tetraquark candidate consisting of 4 different quarks

- Fraction of $B_s^0$ mesons coming from X decays
  \[ \rho_X \equiv \frac{\sigma(p\bar{p} \to X(5568) + \text{anything}) \times \mathcal{B}(X(5568) \to B_s^0\pi^\pm)}{\sigma(p\bar{p} \to B_s^0 + \text{anything})} \]

- **D0 measured:**
  \[ \begin{align*}
  \rho_X &= 8.6\pm2.4\% & \text{for } p_T(B_s^0) > 10 \\
  \rho_X &= 9.1\pm3.1\% & \text{for } 10 < p_T(B_s^0) < 15 \\
  \rho_X &= 8.2\pm3.1\% & \text{for } 15 < p_T(B_s^0) < 30
  \end{align*} \]
LHCb does not see it! (however, in different kinematic region) \cite{PhysRevLett.117.152003(2016)}

\begin{align*}
\rho_X^{\text{LHCb}}(p_T(B_s^0) > 5 \text{ GeV}) & < 0.011 \ (0.012) \\
\rho_X^{\text{LHCb}}(p_T(B_s^0) > 10 \text{ GeV}) & < 0.021 \ (0.024) \ \text{at 90 (95) \% CL} \\
\rho_X^{\text{LHCb}}(p_T(B_s^0) > 15 \text{ GeV}) & < 0.018 \ (0.020)
\end{align*}

\textbf{D0:}
\begin{align*}
\rho_X & = 8.6\pm2.4\% \quad p_T(B_s^0) > 10 \text{ GeV} \\
\rho_X & = 8.2\pm3.1\% \quad p_T(B_s^0) > 15 \text{ GeV}
\end{align*}
Search at CMS: selection and $B_s^0$ signal

2012 data, 19.7 fb$^{-1}$

$B_s^0$ meson candidates are reconstructed via the decays $B_s^0 \rightarrow J/\psi \phi$, $\phi \rightarrow K^+K^-$, $J/\psi \rightarrow \mu^+\mu^-$

Require $B_s^0$ vertex to be significantly displaced from the PV, and its momentum to point from the PV

Fit: Double Gaussian with common mean + exponential

Additional pion is selected from tracks forming the primary vertex
B_s^0 \pi^\pm invariant mass distribution

To improve the invariant mass resolution, we use

\[ M^\Delta(B_s^0 \pi^\pm) = M(B_s^0 \pi^\pm) - M(J/\psi K^+ K^-) + m_{B_s^0}^{PDG} \]

No significant peaks, both in the signal and in sidebands B_s^0 regions
By removing the requirement on $M(K^+K^-)$ to be consistent with $\phi$ mass, we allow the $B^0 \to J/\psi K^+\pi^-$ decay to contribute to the reconstructed sample of $J/\psi K^+K^-$ candidates, into the **signal** and **right sideband** of $B_s^0$.

In this case, the $B_s^0\pi^\pm$ distribution shows peaks from the $B^{*+}\to B^0\pi^+$ decays, which have exactly the same topology and very similar kinematics.
In order to obtain numerical constraints on $X(5568)$, we fit the $\Bs\pi^\pm$ mass distribution with a sum of a smooth background function and a possible signal component (Relativistic Breit-Wigner function convolved with the resolution from MC).

The signal yield is consistent with zero.

Different cross-checks include changes of the event selection (kinematic and reconstruction quality requirements), fit function, fit region, estimation of background from $\Bs^0$ sidebands, $X$ signal sidebands, or simulation. **In every case the signal yield is consistent with zero.**
Upper limit on $\rho_X$

$\rho_X$ is a fraction of $B_s^0$ mesons produced from $X(5568)$ decays

$$\rho_X \equiv \frac{\sigma(pp \to X(5568) + ...) \times \mathcal{B}(X(5568) \to B_s^0 \pi^\pm)}{\sigma(pp \to B_s^0 + ...)} = \frac{N_{X(5568)}}{N_{B_s^0} \times \epsilon_{rel}}$$

An upper limit is $\rho_X < 1.1\%$ at 95\% C.L.

All the procedure is repeated with $p_T(B_s^0) > 15$ GeV, yielding the limit $\rho_X < 1.0\%$ @ 95\% C.L.

Comparison with the results of other collaborations:

<table>
<thead>
<tr>
<th></th>
<th>D0</th>
<th>LHCb</th>
<th>CMS</th>
<th>CDF</th>
<th>ATLAS</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p_T(B_s^0) &gt; 10$ GeV</td>
<td>8.6 ± 2.4</td>
<td>&lt; 2.4</td>
<td>&lt; 1.1</td>
<td>&lt; 6.7</td>
<td>&lt; 1.5</td>
</tr>
<tr>
<td>$p_T(B_s^0) &gt; 15$ GeV</td>
<td>8.2 ± 3.1</td>
<td>&lt; 2.0</td>
<td>&lt; 1.0</td>
<td>—</td>
<td>&lt; 1.6</td>
</tr>
</tbody>
</table>

The obtained limits are the strongest and contradict to the D0 collaboration result, thus not confirming a tetraquark candidate X(5568)
Upper limit as a function of mass and natural width of an exotic state decaying into $B^0_s\pi^\pm$

We need also pion reconstruction efficiency and the invariant mass resolution as functions of mass.

Obtained 95% upper limit on $\rho_x$ as a function of mass and natural width of an exotic state decaying into $B^0_s\pi^\pm$.
P-wave $B_s^0$ states

**Orbital momentum** $L$

$\text{Total angular momentum of light subsystem } j$

$j = L \pm \frac{1}{2}$

$\text{Total angular momentum } J$

$J = j \pm \frac{1}{2}$

$L=1$

$\begin{aligned}
&j = \frac{3}{2} \\
&J = 2 \\
\end{aligned}$

$\begin{aligned}
&j = \frac{1}{2} \\
&J = 1 \\
\end{aligned}$

$\begin{aligned}
&\pm \frac{1}{2} \\
&\pm \frac{1}{2} \\
&\pm \frac{1}{2} \\
\end{aligned}$

$B_{s2}^* (5840)^0$

$B_{s1} (5830)^0$

$B_s^*$

$B_{s0}^*$

**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

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.
**Previous results on P-wave $B^0_s$ states**

Observed and studied only by CDF, D0, and LHCb, only in $B^+K^-$ channel

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<tr>
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<tbody>
<tr>
<td>$N(B_{s2}^* \to B^+K^-)$</td>
<td>$95 \pm 23$</td>
<td>$125 \pm 25$</td>
<td>$3140 \pm 100$</td>
<td>$1110 \pm 60$</td>
</tr>
<tr>
<td>$N(B_{s2}^* \to B^{**}K^-)$</td>
<td>$-$</td>
<td>$-$</td>
<td>$307 \pm 46$</td>
<td>?? $\sim 100$</td>
</tr>
<tr>
<td>$N(B_{s1} \to B^{**}K^-)$</td>
<td>$39 \pm 9$</td>
<td>$25 \pm 10$</td>
<td>$750 \pm 36$</td>
<td>$280 \pm 40$</td>
</tr>
<tr>
<td>$M(B_{s2}^*), \text{ MeV}$</td>
<td>$5839.6 \pm 0.7$</td>
<td>$5839.6 \pm 1.3$</td>
<td>$5839.99 \pm 0.21$</td>
<td>$5839.7 \pm 0.2$</td>
</tr>
<tr>
<td>$M(B_{s1}), \text{ MeV}$</td>
<td>$5829.4 \pm 0.7$</td>
<td>$-$</td>
<td>$5828.40 \pm 0.41$</td>
<td>$5828.3 \pm 0.5$</td>
</tr>
<tr>
<td>$M(B_{s2}^*) - M(B^+) - M(K^-), \text{ MeV}$</td>
<td>$66.96 \pm 0.41$</td>
<td>$66.7 \pm 1.1$</td>
<td>$67.06 \pm 0.12$</td>
<td>$66.73 \pm 0.19$</td>
</tr>
<tr>
<td>$M(B_{s1}) - M(B^{**}) - M(K^-), \text{ MeV}$</td>
<td>$10.73 \pm 0.25$</td>
<td>$11.5 \pm 1.4$</td>
<td>$10.46 \pm 0.06$</td>
<td>$10.35 \pm 0.19$</td>
</tr>
<tr>
<td>$\Gamma(B_{s2}^*), \text{ MeV}$</td>
<td>$-$</td>
<td>$-$</td>
<td>$1.56 \pm 0.49$</td>
<td>$1.4 \pm 0.4$</td>
</tr>
<tr>
<td>$\Gamma(B_{s1}), \text{ MeV}$</td>
<td>$-$</td>
<td>$-$</td>
<td>$-$</td>
<td>$0.5 \pm 0.4$</td>
</tr>
</tbody>
</table>

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

*Phys. Rev. D 90, 012013 (2014)*
Study P-wave $B^0_s$ states at CMS

- Study the $B^+K^-$ final state: measure masses, mass differences, natural width (using $B^+\rightarrow J/\psi K^+$)

- Search for the decays into $B^0K^0_s$ (using $B^0\rightarrow J/\psi K^+\pi^-$)
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 $\sim 3\%$ is used in the estimation of the systematic uncertainties

Now combine $B^+$ with a track from the same PV
B^+h^- invariant mass distributions

To describe the signal B^+K^- invariant mass distribution, we need to take into account the reflections from excited B^0 decays into B^{(*)+}\pi^- (see backup for details on the procedure)
Shapes of reflections from $B^*^0 \rightarrow B^{(*)+} \pi^-$ 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.
B⁺K⁻ invariant mass distribution

Now we fit B⁺K⁻ invariant mass distribution:

3 D-wave RBW functions convolved with resolutions

+ (x-x₀)ᵃ • Pol₆(x) for background,
  x₀ is threshold value

+ contributions from excited B⁰
  (shapes fixed to MC, yields fixed to the fit results
to the B⁺π⁻ invariant mass distribution)

<table>
<thead>
<tr>
<th>N(B_{s2}^* → BK)</th>
<th>N(B_{s2}^* → B*K)</th>
<th>N(B_{s1} → B*K)</th>
<th>Γ(B_{s2}^*), MeV</th>
<th>Γ(B_{s1}), MeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>5424 ± 269</td>
<td>455 ± 119</td>
<td>1329 ± 83</td>
<td>1.52 ± 0.34</td>
<td>0.10 ± 0.15</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>M(B_{s2}^*) − M(B) − M(K), MeV</th>
<th>M(B_{s1}) − M(B⁺) − M(K), MeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>66.926 ± 0.093</td>
<td>10.495 ± 0.089</td>
</tr>
</tbody>
</table>
The resolution parameters and the shape of $K \leftrightarrow \pi$ swapped component are fixed from simulation (see backup)

Fraction of swapped component with respect to signal = $(18.9 \pm 3.0)\%$

in the $B^0$ signal region of $\pm 2\sigma$
$B^0K^0_S$ invariant mass distribution

Fit:
- 3 D-wave RBW functions convolved with resolutions
- $(x-x_0)^a \cdot \text{Pol}_1(x)$ for bkg, $x_0$ is threshold value
- 3 contributions from $K \leftrightarrow \pi$ swap (yields fixed relative to signal: $S^*0.189$)

First observation!
- $6.3\sigma$ $B_{s2}^* \rightarrow B^0K^0_S$

First evidence!
- $3.9\sigma$

<table>
<thead>
<tr>
<th>$N(B_{s2}^* \rightarrow BK)$</th>
<th>$N(B_{s2}^* \rightarrow B^*K)$</th>
<th>$N(B_{s1} \rightarrow B^*K)$</th>
<th>$\Gamma(B_{s2}^*), \text{ MeV}$</th>
<th>$\Gamma(B_{s1}), \text{ MeV}$</th>
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<tbody>
<tr>
<td>128 ± 22</td>
<td>12 ± 11</td>
<td>34.5 ± 8.3</td>
<td>2.1 ± 1.3</td>
<td>0.4 ± 0.4</td>
</tr>
</tbody>
</table>

$\frac{M(B_{s2}^*) - M(B) - M(K), \text{ MeV}}{62.42 ± 0.48}$

$\frac{M(B_{s1}) - M(B^*) - M(K), \text{ MeV}}{5.65 ± 0.23}$

Measuring BF ratios

\[ R^0_{2\pm} = \frac{\mathcal{B}(B^*_s \rightarrow B^0 K^0_s)}{\mathcal{B}(B^*_s \rightarrow B^+ K^-)} = \frac{N(B^*_s \rightarrow B^0 K^0_s)}{N(B^*_s \rightarrow B^+ K^-)} \times \frac{\mathcal{E}(B^*_s \rightarrow B^+ K^-)}{\mathcal{E}(B^*_s \rightarrow B^0 K^0_s)} \times \frac{\mathcal{B}(B^+ \rightarrow J/\psi K^+)}{\mathcal{B}(B^0 \rightarrow J/\psi K^{*0}) \mathcal{B}(K^{*0} \rightarrow K^+ \pi^-) \mathcal{B}(K^0_s \rightarrow \pi^+ \pi^-)} \]

Ratio of the signal yields in data

Ratio of total efficiencies from MC

Known branching fractions from PDG

\[ \mathcal{B}(B^+ \rightarrow J/\psi K^+) = (1.026 \pm 0.031) \times 10^{-3}, \mathcal{B}(K^0_s \rightarrow \pi^+ \pi^-) = (0.6920 \pm 0.0005) \]

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

Formulae and efficiencies ratios for all 6 measured ratios are in backup
Sources of systematic uncertainty

Systematic uncertainties in the branching fraction ratios, mass differences and $\Gamma$, are related to:

- **Choice of the fit model**
  separate uncertainties related to the fits of $B^+\pi$, $B^+K^-$ and $B^0K_0^-$ 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 $B^0K_0^-$ final state

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

- **Fraction of K↔π 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

- **Possible detector misalignment**
  estimated using additional MC samples with distorted detector geometries

- **Finite size of the simulation samples**
  uncertainties in efficiencies = $N_{reconstructed}/N_{generated}$
**Results**

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

\[
R_{2}^{0\pm} = \frac{\mathcal{B}(B_{s2}^{*} \rightarrow B^{0}K_{S}^{0})}{\mathcal{B}(B_{s2}^{*} \rightarrow B^{+}K^{-})} = 0.432 \pm 0.077 \pm 0.075 \pm 0.021,
\]

\[
R_{1}^{0\pm} = \frac{\mathcal{B}(B_{s1} \rightarrow B^{*0}K_{S}^{0})}{\mathcal{B}(B_{s1} \rightarrow B^{*+}K^{-})} = 0.49 \pm 0.12 \pm 0.07 \pm 0.02,
\]

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

\[
R_{2*}^{0} = \frac{\mathcal{B}(B_{s2}^{*} \rightarrow B^{*0}K_{S}^{0})}{\mathcal{B}(B_{s2}^{*} \rightarrow B^{0}K_{S}^{0})} = 0.093 \pm 0.086 \pm 0.014.
\]

**Theory:** 0.42-0.46


**LHCb** 0.093±0.013±0.012

**CDF** 0.10±0.03±0.02

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

\[
R_{\sigma}^{0} = \frac{\sigma(pp \rightarrow B_{s1}X) \mathcal{B}(B_{s1} \rightarrow B^{*0}K_{S}^{0})}{\sigma(pp \rightarrow B_{s2}^{*}X) \mathcal{B}(B_{s2}^{*} \rightarrow B^{0}K_{S}^{0})} = 0.266 \pm 0.079 \pm 0.063.
\]

Results are in agreement with existing measurements of LHCb and CDF


**LHCb 2013:** [doi:10.1103/PhysRevLett.110.151803](#)

**CDF 2014:** [doi:10.1103/PhysRevD.90.012013](#)
Results

\[ \Delta M_{B_{s2}^*}^{\pm} = M(B_{s2}^*) - M_{B^+}^{PDG} - M_{K^-}^{PDG} = 66.87 \pm 0.09 \pm 0.07 \text{ MeV}, \]

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

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

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

\[ \Gamma_{B_{s2}^*} = 1.52 \pm 0.34 \pm 0.30 \text{ MeV} \]

Comparison to previous measurements

<table>
<thead>
<tr>
<th></th>
<th>(M(B_{s2}^*)-M(B^+)-M(K^-))</th>
<th>(M(B_{s1}^<em>)-M(B^{</em>+})-M(K^-))</th>
<th>(\Gamma(B_{s2}^*))</th>
</tr>
</thead>
<tbody>
<tr>
<td>LHCb</td>
<td>67.06\pm0.12</td>
<td>10.46\pm0.06</td>
<td>1.56\pm0.49</td>
</tr>
<tr>
<td>CDF</td>
<td>66.73\pm0.19</td>
<td>10.35\pm0.19</td>
<td>1.4\pm0.44</td>
</tr>
<tr>
<td>CMS</td>
<td><strong>66.87\pm0.12</strong></td>
<td><strong>10.45\pm0.11</strong></td>
<td><strong>1.52\pm0.43</strong></td>
</tr>
</tbody>
</table>

Consistent with existing measurements of LHCb and CDF


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: $0.31 \pm 0.06$ 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
No X(5568) signal is found
upper limit is set on the fraction of $B_s^0$ mesons produced from X(5568) decays:

$$\rho_X < 1.1 \% \text{ at } 95\% \text{ C.L}$$

This is the most stringent limit to date, and it contradicts to the D0 result
Upper limit is also set as a function of mass and width of exotic state

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

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

Measure 4 BF ratios

$$\frac{\mathcal{B}(B_{s2}^* \rightarrow B^0 K_S^0)}{\mathcal{B}(B_{s2}^* \rightarrow B^{+} K^-)}, \frac{\mathcal{B}(B_{s1} \rightarrow B^{*0} K_S^0)}{\mathcal{B}(B_{s1} \rightarrow B^{*+} K^-)}, \frac{\mathcal{B}(B_{s2}^* \rightarrow B^{*+} K^-)}{\mathcal{B}(B_{s2}^* \rightarrow B^{+} K^-)}, \frac{\mathcal{B}(B_{s2}^* \rightarrow B^{*0} K_S^0)}{\mathcal{B}(B_{s2}^* \rightarrow B^{0} K_S^0)}$$

Measure 2 BF x σ ratios

$$\frac{\sigma(pp \rightarrow B_{s1} \ldots) \times \mathcal{B}(B_{s1} \rightarrow B^{*+} K^-)}{\sigma(pp \rightarrow B_{s2}^* \ldots) \times \mathcal{B}(B_{s2}^* \rightarrow B^{+} K^-)}, \frac{\sigma(pp \rightarrow B_{s1} \ldots) \times \mathcal{B}(B_{s1} \rightarrow B^{*0} K_S^0)}{\sigma(pp \rightarrow B_{s2}^* \ldots) \times \mathcal{B}(B_{s2}^* \rightarrow B^{0} K_S^0)}$$

Measure 6 mass differences, 2 masses and the natural width

- $M(B_{s2}^*) - M(B^0) - M(K^-)$
- $M(B_{s1}) - M(B^{*+}) - M(K^-)$
- $M(B_{s2}^*) - M(B^0) - M(K_S^0)$ (new)
- $M(B_{s1}) - M(B^{*0}) - M(K_S^0)$ (new)
- $M(B_{s2}^*)$
- $\Gamma(B_{s2}^*)$
- $M(B^0) - M(B^+)$
- $M(B^{*0}) - M(B^{*+})$ (new)
- $\Gamma(B^*)$
Thank you !
Overview

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

"Reflections":

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

From K\(\leftrightarrow\pi\) swap in B\(^0\)K\(_S^0\) channel, yields fixed relative to the signal yields

We also measure masses, mass differences and \(\Gamma(B_{s2}^\ast)\) in these decays

<table>
<thead>
<tr>
<th>Final state</th>
<th>(N(B_{s2}^\ast \rightarrow BK))</th>
<th>(N(B_{s2}^\ast \rightarrow B^\ast K))</th>
<th>(N(B_{s1} \rightarrow B^\ast K))</th>
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<td>B(^{+})K(^-)</td>
<td>5424 ± 269</td>
<td>455 ± 119</td>
<td>1329 ± 83</td>
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<td>B(^0)K(_S^0)</td>
<td>128 ± 22</td>
<td>12 ± 11</td>
<td>34.5 ± 8.3</td>
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CMS-BPH-16-003, arXiv:1809.03578
\[ R^0_2 = \frac{\mathcal{B}(B^*_s \rightarrow B^0 K^0_s)}{\mathcal{B}(B^*_s \rightarrow B^- K^-)} = 0.432 \pm 0.077 \text{ (stat)} \pm 0.075 \text{ (syst)} \pm 0.021 \text{ (PDG)} \]
\[ R^0_1 = \frac{\mathcal{B}(B_{s1} \rightarrow B^{*0} K^0_s)}{\mathcal{B}(B_{s1} \rightarrow B^{*+} K^-)} = 0.492 \pm 0.122 \text{ (stat)} \pm 0.068 \text{ (syst)} \pm 0.024 \text{ (PDG)} \]
\[ R^{\pm}_{2*} = \frac{\mathcal{B}(B^*_s \rightarrow B^{*+} K^-)}{\mathcal{B}(B^*_s \rightarrow B^+ K^-)} = 0.081 \pm 0.021 \text{ (stat)} \pm 0.015 \text{ (syst)}, \]
\[ R^0_{2*} = \frac{\mathcal{B}(B^*_s \rightarrow B^{*0} K^0_s)}{\mathcal{B}(B^*_s \rightarrow B^0 K^0_s)} = 0.093 \pm 0.086 \text{ (stat)} \pm 0.014 \text{ (syst)}, \]
\[ R^\pm_0 = \frac{\sigma(pp \rightarrow B_{s1} \ldots) \times \mathcal{B}(B_{s1} \rightarrow B^{*+} K^-)}{\sigma(pp \rightarrow B^{*+} \ldots) \times \mathcal{B}(B^*_s \rightarrow B^+ K^-)} = 0.233 \pm 0.019 \text{ (stat)} \pm 0.018 \text{ (syst)} \]
\[ R^0_0 = \frac{\sigma(pp \rightarrow B_{s1} \ldots) \times \mathcal{B}(B_{s1} \rightarrow B^{*0} K^0_s)}{\sigma(pp \rightarrow B^{*+} \ldots) \times \mathcal{B}(B^*_s \rightarrow B^0 K^0_s)} = 0.266 \pm 0.079 \text{ (stat)} \pm 0.063 \text{ (syst)} \]

\[ \Delta M^\pm_{B^*_s} = M(B^*_s) - M(B^+) - M(K^-) = 66.870 \pm 0.093 \text{ (stat)} \pm 0.073 \text{ (syst) MeV}, \]
\[ \Delta M^0_{B^*_s} = M(B^*_s) - M(B^0) - M(K^0_s) = 62.37 \pm 0.48 \text{ (stat) \pm 0.07 (syst) MeV}, \]
\[ \Delta M^{\pm}_{B_{s1}} = M(B_{s1}) - M(B^{*+}) - M(K^-) = 10.452 \pm 0.089 \text{ (stat)} \pm 0.063 \text{ (syst) MeV}, \]
\[ \Delta M^0_{B_{s1}} = M(B_{s1}) - M(B^{*0}) - M(K^0_s) = 5.61 \pm 0.23 \text{ (stat) \pm 0.06 (syst) MeV}, \]

\[ M(B^*_s) = 5839.86 \pm 0.09 \pm 0.07 \pm 0.15 \text{ MeV} \]
\[ M(B_{s1}) = 5828.78 \pm 0.09 \pm 0.06 \pm 0.28 \text{ MeV} \]

\[ m_{B^0} - m_{B^+} = 0.57 \pm 0.49 \text{ (stat) \pm 0.10 \text{ (syst) \pm 0.02 (PDG) MeV}} \]
\[ m_{B^{*0}} - m_{B^{*+}} = 0.91 \pm 0.24 \text{ (stat) \pm 0.09 \text{ (syst) \pm 0.02 (PDG) MeV}} \]

\[ \Gamma(B^*_s) = 1.52 \pm 0.34 \text{ (stat) \pm 0.30 \text{ (syst) MeV}} \]
BACKUP
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 \(J/\psi\) 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 \(B^+\)

\(B^0K_S^0\) channel:
\(M(K^+\pi^-)\) in ±90 MeV from \(K^*(892)\) mass,
\(M(K^+K^-) > 1.035\) GeV to cut out \(B_S^0 \rightarrow J/\psi\phi\)
K/\(\pi\) mass assignment: chose the candidate closer to \(K^*(892)\) mass

\(K_S^0\) is build from displaced 2-prong vertices
\(K_S^0\) momentum required to point to PV in the \(xy\) plane

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

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

$+ (x-x_0)^a \cdot Pol_m(x)$ for background, $x_0$ is threshold value, $Pol_m(x)$ is polynomial of degree $m$

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

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 $B_2^*\rightarrow B^+\pi^-$, $B_2^*\rightarrow B^{*-}\pi^-$, and $B_1^*\rightarrow B^+\pi^-$ decays, respectively
Data and event selection

2012 dataset (19.6 fb\(^{-1}\)), trigger optimized to select \(B \rightarrow J/\psi\ldots\) 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

\[
\begin{align*}
P_{\text{vtx}}(B) & > 1\% \\
\text{PV is chosen as the one with best pointing angle} \\
L_{xy}/\sigma_{L_{xy}}(B) & > 5.0 \\
\cos \alpha_{xy} & > 0.99 \text{ (B momentum points to PV in xy plane)} \\
\text{B mass in } \sim \pm 2 \sigma_{\text{eff}} \text{ from PDG}
\end{align*}
\]

**\(B^+K^-\) channel:** \(K^-\) is chosen from PV track collection

**\(B^0K^0_S\) channel:**
\[M(K^+\pi^-) \text{ in } \pm 90\text{ MeV from } K^*(892) \text{ mass,}
\]
\[M(K^+,K^-) > 1.035\text{ GeV to cut out } B^0_s \rightarrow J/\psi \phi
\]
\(K/\pi\) mass assignment: chose the candidate closer to \(K^*(892)\) mass

\(K^0_S\) is build from displaced 2-prong vertices
\[\cos \alpha_{xy} > 0.999 \text{ (} K^0_S \text{ momentum points to PV in xy plane)}
\]
B^+K^- signal extraction logic

- Fit to B^*[0] → B^+π^- MC samples to obtain signal resolutions
- Fit to B^*[0] → B^+π^- MC samples (if reconstructed as B^+π^-)
- Fit to B_{s1,2}^*[0] → B^+K^- MC samples to obtain reflection shapes
- Fit to B_{s1,2}^*[0] → B^+K^- MC samples (if reconstructed as B^+K^-)
- Fit to B^+K^- distribution in data, with signal resolutions fixed to MC
  • reflections from B^*[0] shapes and yields fixed
  • Signal resolutions fixed to MC
- Yields of B^*[0] → B^+π^- contributions
- Fit to B^+π^- invariant mass distribution in data, with signal resolutions from MC and fixed shapes of reflections from B_{s1,2}^*[0] → B^+K^-
- Signal yields, mass differences, Γ
The shapes of reflections from $B_{s1,2}^0$ decays in $B^+\pi^-$ invariant mass

Product of a Gaussian function and 1-sided Gaussian function

$$F(x; ...) = G_L(x; m_L, \sigma_L) \ast \exp \left( -\frac{(x - m_c)^2}{2\sigma^2} \right) \ast \left( (1 - f) G_R(x; m_R, \sigma_R1) + f G_R(x; m_R, \sigma_R2) \right)$$

where

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

and

$$G_R(x; m, \sigma) = \begin{cases} 
1 & \text{if } x \leq m \\
\exp\left(-\frac{1}{2} \left(\frac{x-m}{\sigma}\right)^2\right) & \text{if } x \geq m
\end{cases}$$

CMS Simulation Preliminary

Data
Fit

Candidates / 3 MeV

$5.45$  $5.5$  $5.55$  $5.6$  $5.65$  $5.7$

$5.48$  $5.5$  $5.55$  $5.6$  $5.65$  $5.7$

$5.5$  $5.52$  $5.54$  $5.56$  $5.58$  $5.6$

$5.45$  $5.5$  $5.55$  $5.6$  $5.65$  $5.7$

$5.48$  $5.5$  $5.55$  $5.6$  $5.65$  $5.7$

$5.5$  $5.52$  $5.54$  $5.56$  $5.58$  $5.6$

$5.45$  $5.5$  $5.55$  $5.6$  $5.65$  $5.7$

$5.48$  $5.5$  $5.55$  $5.6$  $5.65$  $5.7$

$5.5$  $5.52$  $5.54$  $5.56$  $5.58$  $5.6$
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

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

where $G(x; \sigma_{01}, \sigma_{02}, \phi, m_0) = \begin{cases} 
(1 - \phi) \exp\left(-\frac{(x-m_0)^2}{2\sigma_{01}^2}\right) + \phi \exp\left(-\frac{(x-m_0)^2}{2\sigma_{02}^2}\right) & \text{if } x < m_0 \\
1 & \text{if } x > m_0
\end{cases}$
B⁰ invariant mass distribution (MC)

B⁰ is reconstructed in the decay to J/ψK⁺π⁻, where kaon and pion can be misidentified (swapped) in the reconstruction. The selection requirements are

\[ M(K^+\pi^-) \text{ in } \pm 90 \text{ MeV from } K^*(892) \text{ mass,} \]
\[ M(K^+,K^-) > 1.035 \text{ GeV to cut out } B_s^0 \rightarrow J/\psi \phi, \text{ as in P5’ analysis} \]

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:

![Graphs showing the B⁰ invariant mass distribution with fitted curves for Triple Gaussian and Bifurcated Gaussian.](attachment:image.png)
The resolution parameters and the shape of $K\leftrightarrow\pi$ swapped component are fixed from simulation (see backup).

The $B^0$ signal region [5245, 5313] MeV includes $\sim220000$ signal candidates and $\sim41000$ $K\leftrightarrow\pi$ swap candidates $\Rightarrow$ “fraction of swapped component w.r.t. signal” = $(18.9\pm0.3)\%$

Vary the signal resolution by $+\text{ and } -3\%$ (see $B^+\text{ fit}$) $\Rightarrow$ variation of this fraction is $(18.9\pm3.0)\%$ (uncertainty will be considered as systematics source)
### Systematic uncertainties in the branching fraction ratios

\[
R_{2}^{0\pm} = \frac{\mathcal{B}(B_{s2}^{*} \rightarrow B^{0}K_{S}^{0})}{\mathcal{B}(B_{s2}^{*} \rightarrow B^{+}K^{-})}
\]

\[
R_{1}^{0\pm} = \frac{\mathcal{B}(B_{s1} \rightarrow B^{*0}K_{S}^{0})}{\mathcal{B}(B_{s1} \rightarrow B^{*+}K^{-})}
\]

<table>
<thead>
<tr>
<th>Source</th>
<th>(R_{2}^{0\pm})</th>
<th>(R_{1}^{0\pm})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Track reconstruction efficiency</td>
<td>7.8</td>
<td>7.8</td>
</tr>
<tr>
<td>(m_{B^{+}\pi^{-}}) distribution model</td>
<td>2.5</td>
<td>2.0</td>
</tr>
<tr>
<td>(m_{B^{+}K^{-}}) distribution model</td>
<td>2.4</td>
<td>4.6</td>
</tr>
<tr>
<td>(m_{B^{0}K_{S}^{0}}) distribution model</td>
<td>14</td>
<td>8.1</td>
</tr>
<tr>
<td>Mass resolution</td>
<td>0.7</td>
<td>2.2</td>
</tr>
<tr>
<td>Fraction of KPS</td>
<td>2.6</td>
<td>2.6</td>
</tr>
<tr>
<td>Non-K*0 contribution</td>
<td>5.0</td>
<td>5.0</td>
</tr>
<tr>
<td>Finite size of simulated samples</td>
<td>1.2</td>
<td>1.2</td>
</tr>
<tr>
<td>Total</td>
<td>18</td>
<td>14</td>
</tr>
</tbody>
</table>

### Systematic uncertainty in %

\[
R_{2*}^{\pm} = \frac{\mathcal{B}(B_{s2}^{*} \rightarrow B^{*+}K^{-})}{\mathcal{B}(B_{s2}^{*} \rightarrow B^{+}K^{-})}
\]

\[
R_{2*}^{0} = \frac{\mathcal{B}(B_{s2}^{*} \rightarrow B^{*0}K_{S}^{0})}{\mathcal{B}(B_{s2}^{*} \rightarrow B^{0}K_{S}^{0})}
\]

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

\[
R_{\sigma}^{0} = \frac{\sigma(pp \rightarrow B_{s1} \ldots) \times \mathcal{B}(B_{s1} \rightarrow B^{*0}K_{S}^{0})}{\sigma(pp \rightarrow B_{s2}^{*} \ldots) \times \mathcal{B}(B_{s2}^{*} \rightarrow B^{0}K_{S}^{0})}
\]

<table>
<thead>
<tr>
<th>Source</th>
<th>(R_{2*}^{\pm})</th>
<th>(R_{2*}^{0})</th>
<th>(R_{\sigma}^{\pm})</th>
<th>(R_{\sigma}^{0})</th>
</tr>
</thead>
<tbody>
<tr>
<td>(m_{B^{+}\pi^{-}}) distribution model</td>
<td>2.9</td>
<td>—</td>
<td>2.7</td>
<td>—</td>
</tr>
<tr>
<td>(m_{B^{+}K^{-}}) distribution model</td>
<td>17</td>
<td>—</td>
<td>7.1</td>
<td>—</td>
</tr>
<tr>
<td>(m_{B^{0}K_{S}^{0}}) distribution model</td>
<td>—</td>
<td>13</td>
<td>—</td>
<td>24</td>
</tr>
<tr>
<td>Mass resolution</td>
<td>1.2</td>
<td>3.0</td>
<td>1.5</td>
<td>1.1</td>
</tr>
<tr>
<td>Uncertainties in (M_{B^{*}}^{PDG} - M_{B}^{PDG})</td>
<td>7.7</td>
<td>4.8</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Finite size of simulated samples</td>
<td>1.1</td>
<td>1.3</td>
<td>1.1</td>
<td>1.3</td>
</tr>
<tr>
<td>Total</td>
<td>19</td>
<td>15</td>
<td>7.8</td>
<td>24</td>
</tr>
</tbody>
</table>

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Systematic uncertainties

Four mass differences obtained from the fits

\[
\Delta M_{B_{s2}^\pm} = M(B_{s2}^\pm) - M_{B^\pm}^{PDG} - M_{K^-}^{PDG}, \quad \Delta M_{B_{s1}^\pm} = M(B_{s1}^\pm) - M_{B^{*+}}^{PDG} - M_{K^-}^{PDG}
\]

\[
\Delta M_{B_{s2}^0} = M(B_{s2}^0) - M_{B^0}^{PDG} - M_{K_S^0}^{PDG}, \quad \Delta M_{B_{s1}^0} = M(B_{s1}^0) - M_{B^{*0}}^{PDG} - M_{K_S^0}^{PDG}
\]

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

\[
M_{B^0} - M_{B^+} = \Delta M_{B_{s2}^\pm} - \Delta M_{B_{s2}^*} + M_{K^-}^{PDG} - M_{K_S^0}^{PDG}
\]

\[
M_{B^{*0}} - M_{B^{*+}} = \Delta M_{B_{s1}^\pm} - \Delta M_{B_{s1}^*} + M_{K^-}^{PDG} - M_{K_S^0}^{PDG}
\]

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.

<table>
<thead>
<tr>
<th>Source</th>
<th>(\Delta M_{B_{s2}^\pm} )</th>
<th>(\Delta M_{B_{s1}^\pm} )</th>
<th>(\Delta M_{B_{s2}^*} )</th>
<th>(\Delta M_{B_{s1}^*} )</th>
<th>(M_{B^0} - M_{B^+} )</th>
<th>(M_{B^{<em>0}} - M_{B^{</em>+}} )</th>
<th>(\Gamma_{B_{s2}^*} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>(m_{B^+\pi^-}) distribution model</td>
<td>0.024</td>
<td>0.008</td>
<td>—</td>
<td>—</td>
<td>0.024</td>
<td>0.008</td>
<td>0.11</td>
</tr>
<tr>
<td>(m_{B^+K^-}) distribution model</td>
<td>0.011</td>
<td>0.043</td>
<td>—</td>
<td>—</td>
<td>0.011</td>
<td>0.043</td>
<td>0.11</td>
</tr>
<tr>
<td>(m_{B^0K_S^0}) distribution model</td>
<td>—</td>
<td>—</td>
<td>0.039</td>
<td>0.038</td>
<td>0.039</td>
<td>0.038</td>
<td>—</td>
</tr>
<tr>
<td>Uncertainties in (M_{B^{*+}}^{PDG} - M_{B}^{PDG})</td>
<td>0.012</td>
<td>0.003</td>
<td>0.003</td>
<td>0.0001</td>
<td>0.012</td>
<td>0.003</td>
<td>0.03</td>
</tr>
<tr>
<td>Shift from reconstruction</td>
<td>0.056</td>
<td>0.044</td>
<td>0.050</td>
<td>0.042</td>
<td>0.075</td>
<td>0.061</td>
<td>—</td>
</tr>
<tr>
<td>Detector misalignment</td>
<td>0.036</td>
<td>0.005</td>
<td>0.031</td>
<td>0.006</td>
<td>0.038</td>
<td>0.008</td>
<td>0.15</td>
</tr>
<tr>
<td>Mass resolution</td>
<td>0.007</td>
<td>0.005</td>
<td>0.005</td>
<td>0.005</td>
<td>0.009</td>
<td>0.007</td>
<td>0.20</td>
</tr>
<tr>
<td>Total</td>
<td>0.073</td>
<td>0.063</td>
<td>0.071</td>
<td>0.057</td>
<td>0.098</td>
<td>0.085</td>
<td>0.30</td>
</tr>
</tbody>
</table>
**B^0K^0 signal significance**

Estimated using likelihood ratio of fits with and without signal component

\[ P = \text{TMath.Prob}(\log L_S - \log L_0, 1) \]

\[ \text{Signif} = \sqrt{2} \cdot \text{Tmath.ErfcInverse}(P) \]

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 \( \Gamma \) uncertainties from PDG are as well Gaussian-constrained.

**Obtained significance** is:

- **6.3\( \sigma \)** for the \( B^*_{s2} \rightarrow B^0K^0 \) decay
- **3.9\( \sigma \)** for the \( B^*_{s1} \rightarrow B^{*0}K^0 \) decay

They vary in [6.3, 7.0]\( \sigma \) and [3.6, 3.9]\( \sigma \) with variations of fit range and bkg model.
Measured BF ratios

\[ R_{2}^{0\pm} = \frac{\mathcal{B}(B_{s2}^{*} \to B^{0}K_{S}^{0})}{\mathcal{B}(B_{s2}^{*} \to B^{+}K^{-})} = \frac{N(B_{s2}^{*} \to B^{0}K_{S}^{0})}{N(B_{s2}^{*} \to B^{+}K^{-})} \times \frac{\epsilon(B_{s2}^{*} \to B^{+}K^{-})}{\epsilon(B_{s2}^{*} \to B^{0}K_{S}^{0})} \times \frac{\mathcal{B}(B^{+} \to J/\psi K^{+})}{\mathcal{B}(B^{0} \to J/\psi K^{*0})\mathcal{B}(K^{*0} \to K^{+}\pi^{-})\mathcal{B}(K_{S}^{0} \to \pi^{+}\pi^{-})} \]

\[ R_{1}^{0\pm} = \frac{\mathcal{B}(B_{s1} \to B^{*0}K_{S}^{0})}{\mathcal{B}(B_{s1} \to B^{*+}K^{-})} = \frac{N(B_{s1} \to B^{*0}K_{S}^{0})}{N(B_{s1} \to B^{*+}K^{-})} \times \frac{\epsilon(B_{s1} \to B^{*+}K^{-})}{\epsilon(B_{s1} \to B^{*0}K_{S}^{0})} \times \frac{\mathcal{B}(B^{+} \to J/\psi K^{+})}{\mathcal{B}(B^{0} \to J/\psi K^{*0})\mathcal{B}(K^{*0} \to K^{+}\pi^{-})\mathcal{B}(K_{S}^{0} \to \pi^{+}\pi^{-})} \]

\[ R_{2}^{*} = \frac{\mathcal{B}(B_{s2}^{*} \to B^{*+}K^{-})}{\mathcal{B}(B_{s2}^{*} \to B^{+}K^{-})} = \frac{N(B_{s2}^{*} \to B^{*+}K^{-})}{N(B_{s2}^{*} \to B^{+}K^{-})} \times \frac{\epsilon(B_{s2}^{*} \to B^{+}K^{-})}{\epsilon(B_{s2}^{*} \to B^{*+}K^{-})} \]

\[ R_{2}^{0\pm} = \frac{\mathcal{B}(B_{s2}^{*} \to B^{*0}K_{S}^{0})}{\mathcal{B}(B_{s2}^{*} \to B^{*+}K^{-})} = \frac{N(B_{s2}^{*} \to B^{*0}K_{S}^{0})}{N(B_{s2}^{*} \to B^{*+}K^{-})} \times \frac{\epsilon(B_{s2}^{*} \to B^{*0}K_{S}^{0})}{\epsilon(B_{s2}^{*} \to B^{*+}K^{-})} \]

\[ R_{\sigma}^{0} = \frac{\sigma(pp \to B_{s1} \ldots)}{\sigma(pp \to B_{s2} \ldots)} \times \mathcal{B}(B_{s1} \to B^{*+}K^{-}) = \frac{N(B_{s1} \to B^{*+}K^{-})}{N(B_{s2}^{*} \to B^{+}K^{-})} \times \frac{\epsilon(B_{s2}^{*} \to B^{*+}K^{-})}{\epsilon(B_{s1} \to B^{*+}K^{-})} \]

\[ R_{\sigma}^{0} = \frac{\sigma(pp \to B_{s1} \ldots)}{\sigma(pp \to B_{s2} \ldots)} \times \mathcal{B}(B_{s1} \to B^{*0}K_{S}^{0}) = \frac{N(B_{s1} \to B^{*0}K_{S}^{0})}{N(B_{s2}^{*} \to B^{*0}K_{S}^{0})} \times \frac{\epsilon(B_{s2}^{*} \to B^{*0}K_{S}^{0})}{\epsilon(B_{s1} \to B^{*0}K_{S}^{0})} \]
Relative efficiencies

\[
\frac{\epsilon(B_{s2}^* \rightarrow B^+K^-)}{\epsilon(B_{s2} \rightarrow B^0K_S^0)} = 15.77 \pm 0.18, \quad \frac{\epsilon(B_{s1} \rightarrow B^{*-}K^-)}{\epsilon(B_{s1} \rightarrow B^{*0}K_S^0)} = 16.33 \pm 0.20,
\]

\[
\frac{\epsilon(B_{s2}^* \rightarrow B^+K^-)}{\epsilon(B_{s2} \rightarrow B^*+K^-)} = 0.961 \pm 0.010, \quad \frac{\epsilon(B_{s2}^* \rightarrow B^0K_S^0)}{\epsilon(B_{s2} \rightarrow B^*0K_S^0)} = 0.970 \pm 0.012,
\]

\[
\frac{\epsilon(B_{s2}^* \rightarrow B^+K^-)}{\epsilon(B_{s1} \rightarrow B^*+K^-)} = 0.953 \pm 0.010, \quad \frac{\epsilon(B_{s2}^* \rightarrow B^0K_S^0)}{\epsilon(B_{s1} \rightarrow B^{*0}K_S^0)} = 0.987 \pm 0.012,
\]

Their uncertainties are used as systematic uncertainties.
CMS experiment

CMS DETECTOR
Total weight: 14,000 tonnes
Overall diameter: 15.0 m
Overall length: 28.7 m
Magnetic field: 3.8 T

STEEL RETURN YOKE
12,500 tonnes

SILICON TRACKERS
Pixel (100x150 μm) ~16 m² ~66M channels
Microstrips (80x180 μm) ~200 m² ~9.6M channels

SUPERCONDUCTING SOLENOID
Niobium titanium coil carrying ~18,000A

MUON CHAMBERS
Barrel: 250 Drift Tube, 480 Resistive Plate Chambers
Endcaps: 540 Cathode Strip, 576 Resistive Plate Chambers

PRESHOWER
Silicon strips ~16 m² ~137,000 channels

FORWARD CALORIMETER
Steel + Quartz fibres ~2,000 Channels

CRYSTAL ELECTROMAGNETIC CALORIMETER (ECAL)
~76,000 scintillating PbWO₄ crystals

HADRON CALORIMETER (HCAL)
Brass + Plastic scintillator ~7,000 channels