Heavy-flavour decay properties with CMS

The latest of 7TeV and 8TeV results

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Outline

• Motivation for studying heavy-flavour decays

• Experimental setup

• Overview of the latest results by CMS:
  1. Observation of rare $B_s^0 \rightarrow \mu\mu$ decay
  2. Angular analysis of $B^0 \rightarrow K^{*0}\mu\mu$
  3. Measurement of $\phi_s$ and $\Delta\Gamma_s$ of $B_s^0$
  4. Measurement of the ratio $BR(B_s^0 \rightarrow J/\psi f_0) / BR(B_s^0 \rightarrow J/\psi \phi)$
Motivation

Studies of heavy-flavour decays are important for understand QCD

In view of the Standard Model measurements:

- test of $pQCD$ predictions:
  lifetime, decay rates, CP phases, asymmetries

In view of BSM searches:

- loop contributions to rare decays
Experimental setup: CMS

Compact Muon Solenoid: perfect detector for measuring muons

Muons – main experimentally measured signature in HF physics

Combination of subdetectors to identify + measure muon properties

$|\eta| < 2.4$

$\sigma_{\mu\mu}: 0.6\% - 1.5\%$
Experimental setup: triggers

Dedicated triggers: optimised for different analyses
Experimental setup: resonant peaks

**Using 2016 data**
CERN-CMS-DP-2016-016

**CMS Preliminary**

\[ E^+ E^- \] invariant mass [GeV]

\[ \sigma = 26 \text{ MeV} \]
\[ p_T > 10 \text{ GeV} \]
\[ |y| < 1.25 \]

**J/ψ**

\[ 0.9 \text{ fb}^{-1} (13 \text{ TeV}, 2016) \]

**ϕ(1020)**

\[ \sigma = 12 \text{ MeV} \]
\[ p_T > 8 \text{ GeV} \]
\[ |y| < 1.2 \]

**B_s^0 \rightarrow J/ψ K^*0**

\[ B_s^0 \rightarrow J/ψ \phi \]

**CMS Preliminary**

\[ 0.9 \text{ fb}^{-1} (13 \text{ TeV}, 2016) \]

**Trigger paths**
- φ
- J/ψ
- ψ'
- B_s
- Y
- low mass double muon + track
- double muon inclusive

**CMS Preliminary**

\[ 0.9 \text{ fb}^{-1} (13 \text{ TeV}, 2016) \]

**Events / GeV**

\[ 10^{10} \]
\[ 10^{9} \]
\[ 10^{8} \]
\[ 10^{7} \]
\[ 10^{6} \]
\[ 10^{5} \]
\[ 10^{4} \]
\[ 10^{3} \]
\[ 10^{2} \]

**Events / 7 MeV**

\[ 350 \]
\[ 300 \]
\[ 250 \]
\[ 200 \]
\[ 150 \]
\[ 100 \]
\[ 50 \]
\[ 25 \]

**Events / 5 MeV**

\[ 50000 \]
\[ 40000 \]
\[ 30000 \]
\[ 20000 \]
\[ 10000 \]

**Nazar Bartosik**

**Heavy-flavour decays at CMS**
$B_s^0 \rightarrow \mu\mu$ OBSERVATION


• combined Run1 data by CMS and LHCb
• highly suppressed in Standard Model
• perfect probe of potential new physics
$B_s^0 \rightarrow \mu\mu$: signature

LO diagram forbidden in SM
requires FCNC

only higher-order in SM
very low cross section
BR = $(3.66 \pm 0.23) \times 10^{-9}$

can be enhanced by a new BSM particle
$B_s^0 \rightarrow \mu \mu$: results


$\text{BR}(B_s^0 \rightarrow \mu \mu)$
$3.0 \times 10^{-9} \pm 30\%$

$\text{BR}(B^0 \rightarrow \mu \mu)$
$1.1 \times 10^{-9}$ at 95% CL

$\text{BR}(B_s^0 \rightarrow \mu \mu)$
$2.8 \times 10^{-9} \pm 25\%$

$\text{BR}(B^0 \rightarrow \mu \mu)$
$3.9 \times 10^{-10} \pm 40\%$

First conclusive observation of the $B_s^0 \rightarrow \mu \mu$ decay: consistent with SM

Discriminate between BSM models: \( \frac{\text{BR}(B_s^0 \rightarrow \mu\mu)}{\text{BR}(B^0 \rightarrow \mu\mu)} \)

Variation of the test statistic as a function of BR ratio

\[ R = 0.14 \pm 0.08 \pm 0.06 \]

Compatible with SM at 2.3\( \sigma \) level
$B^0 \rightarrow K^{*0} \mu\mu$  \textbf{ANGULAR ANALYSIS}


- similar to $B^0 \rightarrow \mu\mu$
  rare decay, FCNC required at LO

- promising candidate for BSM searches
B^0 \rightarrow K^{*0} \mu \mu: \text{measurement}

Measuring 3 parameters as function of q^2: \( F_L \quad A_{FB} \quad dB/dq^2 \)

characterised by 3 angular observables: \( \theta_L \quad \theta_K \quad \phi \)

Extracted from unbinned extended maximum likelihood fit in each bin:
\( \theta_K \quad + \quad \theta_L \quad + \quad m(K^+\pi^-\mu^+\mu^-) \rightarrow \)

1430 signal events in total
Among most precise results

Consistent with SM predictions

LCSR, lattice QCD

and with previous measurements by LHCb, BaBar, Belle, CDF
\( R_{f_0/\phi} \left( B_s^0 \right) \) BR RATIOS


\[
R_{f_0/\phi} = \frac{\mathcal{B}(B_s^0 \rightarrow J/\psi f_0) \mathcal{B}(f_0 \rightarrow \pi^+\pi^-)}{\mathcal{B}(B_s^0 \rightarrow J/\psi \phi) \mathcal{B}(\phi \rightarrow K^+K^-)}
\]

- sensitive to the lifetime of CP-odd part of \( B_s^0 \) and CP-violating phase \( \phi_s \)
- large enhancements possible by new physics
\[ R_{f_0/\phi} (B_s^0) : \text{results} \]

Calculate from yields ratio: 2 unbinned maximum likelihood fits

Large cancellation of systematic uncertainties in the ratio

\[ R_{f_0/\phi} (B_s^0) = 0.140 \pm 0.008^{\text{stat}} \pm 0.023^{\text{syst}} \]

consistent with SM prediction and previous measurements
\( \phi_s (B_s^0) \) AND \( \Delta \Gamma_s (B_s^0) \)


- CP-violating weak phase \( \phi_s \)
  - related to the CKM mixing angle \( \beta_s \)
  - very precise theoretical value

- decay-width difference \( \Delta \Gamma_s \) between light and heavy mass eigenstates

- deviation from SM possible in BSM scenarios
\[ \phi_s + \Delta \Gamma_s \left( B_s^0 \right) : \text{measurement} \]

Angular analysis of \( B_s^0 \rightarrow J/\psi \phi(1020) \): \( \psi_T \ \varphi_T \ \theta_T \)

Unbinned maximum likelihood fit to data
3 decay angles, \( m(B_s^0) \), \( \mathrm{ct} \), \( \sigma_{\mathrm{ct}} \), flavour tag

Opposite-side lepton tagging of \( B_s^0 \) flavour

70500 events used in the fit
5650 flavour tagged
**$\phi_s + \Delta \Gamma_s (B_s^0)$: results**

*Measured results in agreement with SM predictions*

\[
\phi_s = -0.075 \pm 0.097^{\text{stat}} \pm 0.031^{\text{syst}} \text{ rad}
\]

\[
\Delta \Gamma_s = 0.095 \pm 0.013^{\text{stat}} \pm 0.007^{\text{syst}} \text{ ps}^{-1}
\]

*Uncertainties dominated by available statistics*

*Significant improvement in precision expected with data from Run2*
Summary

A broad spectrum of heavy-flavour decay properties being measured by CMS

Often complementary to LHCb measurements in a different phase space

No significant deviations from SM observed so far

Substantial improvements expected in future measurements with Run2 data

- many analyses are statistically limited
- cross-sections are almost doubled at 13 TeV
- extended $p_T$ reach
Thank you for attention
Backup
**B_s^0 \rightarrow \mu\mu: details**

**CMS data:** 25 fb$^{-1}$ \hspace{1cm} **LHCb data:** 3 fb$^{-1}$

Total of $10^{12} B_s^0$ and $B^0$ produced. $B^+ \rightarrow J/\psi K^+$ for normalisation

Expected $100 \times B_s^0 \rightarrow \mu\mu$ and $10 \times B^0 \rightarrow \mu\mu$ decays

Likelihood contours for the two BRs
**B^0 \rightarrow K^{*0} \mu\mu: details**

**B^0 \rightarrow K^{*0} \mu\mu \rightarrow K^+\pi^- (K^-\pi^+) \mu\mu: hadrons**

- |m(B^0) - m(K^+\pi^-)| < 0.9 GeV
- m(K^+K^-) > 1.035 GeV (for \(\phi(1020) \rightarrow K^+K^-\) rejection)

<table>
<thead>
<tr>
<th>Systematic uncertainty</th>
<th>(R_L(10^{-3}))</th>
<th>(A_{FB}(10^{-3}))</th>
<th>(\frac{dB}{dq^2}) (%)</th>
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<tr>
<td>Simulation mismodeling</td>
<td>1–17</td>
<td>0–37</td>
<td>1.0–5.5</td>
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<td>Fit bias</td>
<td>0–34</td>
<td>2–42</td>
<td>—</td>
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<tr>
<td>MC statistical uncertainty</td>
<td>3–10</td>
<td>5–18</td>
<td>0.5–2.0</td>
</tr>
<tr>
<td>Efficiency</td>
<td>34</td>
<td>5</td>
<td>—</td>
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<td>K\pi mistagging</td>
<td>1–4</td>
<td>0–7</td>
<td>0.1–4.1</td>
</tr>
<tr>
<td>Background distribution</td>
<td>1–9</td>
<td>0–6</td>
<td>0.0–1.2</td>
</tr>
<tr>
<td>Mass distribution</td>
<td>3</td>
<td>1</td>
<td>3.2</td>
</tr>
<tr>
<td>Feed-through background</td>
<td>0–27</td>
<td>0–5</td>
<td>0.0–4.0</td>
</tr>
<tr>
<td>Angular resolution</td>
<td>6–24</td>
<td>0–5</td>
<td>0.2–2.1</td>
</tr>
<tr>
<td>Normalization to (B^0 \rightarrow K^{*0}J/\psi)</td>
<td>—</td>
<td>—</td>
<td>4.6</td>
</tr>
<tr>
<td>Total systematic uncertainty</td>
<td>36–54</td>
<td>10–68</td>
<td>6.4–8.6</td>
</tr>
</tbody>
</table>
\[ B^0 \rightarrow K^{*0} \mu\mu : m(K^+\pi^-\mu^+\mu^-) \]

7 \( q^2 \) bins

\[ q^2 = m_{\mu\mu} \]
$B^0 \rightarrow K^{*0} \mu\mu$: angles

\begin{align*}
\theta_K & : \cos(\theta_K) \\
\theta_L & : \cos(\theta_L)
\end{align*}
Selecting narrow mass windows: other resonances are negligible

| \( m(\pi^+\pi^-) - 974 \text{ MeV} \) | < 50 MeV \( f_0(980) \)
| \( m(K^+K^-) - 1020 \text{ MeV} \) | < 10 MeV \( \phi(1020) \)

Selecting 2 muons + 2 tracks

| \( m(\mu^+\mu^-) - 3097.6 \text{ MeV} \) | < 150 MeV \( J/\psi(980) \)

\( p_T(B_s^0) > 13 \text{ GeV} \)

\( ct > 100 \mu\text{m} \)

\( \cos(\alpha) > 0.994 \) \( \text{ angle between } p_T \text{ and } L_{xy} \)
Using flavour of the other B hadron in the event: opposite sign

addition $e$ or $\mu$ required in the event (assumed from OS B hadron)
neural network trained to optimise flavour-tagging efficiency
mistag probability: $30.17 \pm 0.3\%$
### $\phi_s + \Delta\Gamma_s (B_{s0})$: uncertainties

| Source of uncertainty                                      | $\phi_s$ [rad] | $\Delta\Gamma_s$ [ps$^{-1}$] | $|A_0|^2$ | $|A_S|^2$ | $|A_\perp|^2$ | $\delta_\parallel$ [rad] | $\delta_{S\perp}$ [rad] | $\delta_\perp$ [rad] | $c\tau [\mu m]$ |
|------------------------------------------------------------|----------------|-------------------------------|----------|----------|----------|--------------------------|-------------------------|------------------------|---------------------|
| *ct* efficiency                                            | 0.002          | 0.0057                        | 0.0015   | —        | 0.0023   | —                        | —                       | —                      | 1.0                 |
| Angular efficiency                                         | 0.016          | 0.0021                        | 0.0060   | 0.008    | 0.0104   | 0.674                    | 0.14                    | 0.66                   | 0.8                 |
| Kaon $p_T$ weighting                                       | 0.014          | 0.0015                        | 0.0094   | 0.020    | 0.0041   | 0.085                    | 0.11                    | 0.02                   | 1.1                 |
| *ct* resolution                                            | 0.006          | 0.0021                        | 0.0009   | —        | 0.0008   | 0.004                    | —                       | 0.02                   | 2.9                 |
| Mistag distribution modelling                              | 0.004          | 0.0003                        | 0.0006   | —        | —        | 0.008                    | 0.01                    | —                      | 0.1                 |
| Flavour tagging                                            | 0.003          | 0.0003                        | —        | —        | —        | 0.006                    | 0.02                    | —                      | —                   |
| Model bias                                                 | 0.015          | 0.0012                        | 0.0008   | —        | —        | 0.025                    | 0.03                    | —                      | 0.4                 |
| pdf modelling assumptions                                  | 0.006          | 0.0021                        | 0.0016   | 0.002    | 0.0021   | 0.010                    | 0.03                    | 0.04                   | 0.2                 |
| $|\lambda|$ as a free parameter                           | 0.015          | 0.0003                        | 0.0001   | 0.005    | 0.0001   | 0.002                    | 0.01                    | 0.03                   | —                   |
| Tracker alignment                                          | —              | —                             | —        | —        | —        | —                        | —                       | —                      | 1.5                 |
| Total systematic uncertainty                               | 0.031          | 0.0070                        | 0.0114   | 0.022    | 0.0116   | 0.680                    | 0.18                    | 0.66                   | 3.7                 |
| Statistical uncertainty                                   | 0.097          | 0.0134                        | 0.0053   | 0.008    | 0.0075   | 0.081                    | 0.17                    | 0.36                   | 2.9                 |