B decays and other spectroscopy/resonance results from CMS

The 11th annual conference on Large Hadron Collider Physics
26.05.2023

Maksim Sergeev¹ and Sergey Polikarpov¹,² on behalf of the CMS Collaboration

¹ NRNU MEPhI, 2 LPI RAS

Work is supported by MEPhI program “Priority2030”
Observation of $B^0 \rightarrow \psi(2S)K_S^0\pi^+\pi^-$ and $B_s^0 \rightarrow \psi(2S)K_S^0$ decays
Many exotic states have been observed in the last 15 years, and the nature of most of them is still unclear:

- $Z_c(3900)^\pm$ (BELLE)
- $Z_c(4200)^\pm$ (BaBar)
- $Z_c(4430)^\pm$ (BELLE)
- $Xc(3915)$ (BELLE)
- $P(4457)^+$ (LHCb)
- $Z_{cs}(4220)^+$ (LHCb)

Decays with charmonium in the final state could be a good laboratory for CP-violation measurements.
$\psi(2S)K^0_S$ and $\psi(2S)K^0_S\pi^+\pi^-$ invariant mass distributions

Double-Gaussian function for signal
Exponential for background

Unbinned ML fits

$$N(B^0_s \rightarrow \psi(2S)K^0_S) / N(B^0 \rightarrow \psi(2S)K^0_S) = (6.8 \pm 1.4) \times 10^{-3}$$
Intermediate 2-body invariant mass distributions

Data: Plot-bkg-subtracted

Not described well by phase-space MC

Good agreement after MC reweighting

No unexpected features, only known $K^*$ and $\rho$ resonances
Results

Intermediate 3-body invariant mass distributions

Measured branching fraction ratios:

\[
R_s = \frac{\mathcal{B}(B_s^0 \rightarrow \psi(2S)K_S^0)}{\mathcal{B}(B^0 \rightarrow \psi(2S)K_L^0)} = (3.33 \pm 0.69 \text{ (stat)} \pm 0.11 \text{ (syst)} \pm 0.34 (f_s/f_d) \times 10^{-2}
\]

\[
R_{\pi^+\pi^-} = \frac{\mathcal{B}(B^0 \rightarrow \psi(2S)K_S^0\pi^+\pi^-)}{\mathcal{B}(B^0 \rightarrow \psi(2S)K_S^0)} = 0.480 \pm 0.013 \text{ (stat)} \pm 0.032 \text{ (syst)}
\]

\sim \text{ same order of magnitude as in decays with J}/\psi \text{ instead of } \psi(2S)
Observation of a new excited beauty strange baryon decaying to $\Xi_b^- \pi^+ \pi^-$

Previous results on $\Xi_b$ resonances
$J/\psi \Xi^-$ and $J/\psi \Lambda K^-$ invariant mass distributions

Double-Gaussian function for signal
Exponential for background

Unbinned ML fits

Double-Gaussian function for signal
Exponential for background
Reflection shape is fixed from MC

Selection criteria are in backup
Distributions of the invariant mass difference

The first observation of a $J^P=3/2^-$ beauty-strange baryon consistent with the theoretical predictions:

$M = 6100-6130$ MeV

$\Gamma = 1-3$ MeV

relativistic Breit–Wigner (RBW) function for signal

$M(\Xi_b(6100)^-) - M(\Xi_b^-) - 2m_{\pi^\pm} = 24.14 \pm 0.22$ (stat) $\pm 0.09$ (syst) MeV

$\Gamma(\Xi_b(6100^-)) < 1.9$ MeV @ 95% CL

confirmed by LHCb

$34 \pm 9$
Observation of the $\Lambda_{b}^{0} \rightarrow J/\psi \Xi^{-} K^{+}$ decay

CMS-PAS-BPH-22-002
b hadron decays with charmonium and a baryon allow searching for pentaquarks in \( \psi + \text{baryon} \) system in the intermediate resonance structure

\[ \Lambda_b^0 \rightarrow J/\psi p K^- \]

LHCb, 2015: studied \( J/\psi p \) mass from \( \Lambda_b^0 \rightarrow J/\psi p K^- \)

(full 6D angular analysis with interference between resonances)

**Observed** \( P_c(4450)^+ \) and \( P_c(4380)^+ \) pentaquark candidates!

Confirmed later with a model-independent analysis (2016)

Also seen in CS \( \Lambda_b^0 \rightarrow J/\psi p \pi^- \) decay (2016)

2019: adding Run-2 data, 9x \( \Lambda_b^0 \) yield. From 1D fit of \( J/\psi p \) mass distribution, 4450 peak is now split into two + observe a new resonance, \( P_c(4312)^+ \)
Introduction

In addition to \( J/\psi p \) system, also the \( J/\psi \Lambda \) system was investigated.

LHCb 2020: \( \Xi^{-} \rightarrow J/\psi \Lambda K^{-} \)

\[ \text{Sci.Bull. 66 (2021) 1278-1287} \]

LHCb 2020: 6D full angular analysis by LHCb of \( \Xi^{-} \rightarrow J/\psi \Lambda K^{-} \) decay revealed evidence for hidden-charm strange pentaquark \( P_{cs}(4459)^0 \)

CMS-BPH-18-005, JHEP 12 (2019) 100: Based on Run-1, CMS studied the \( B^{-} \rightarrow J/\psi \Lambda p^{-} \) decay, data is consistent with no pentaquarks in \( J/\psi \Lambda \) or \( J/\psi p \)

LHCb 2022: with 6D amplitude analysis of \( B^{-} \rightarrow J/\psi \Lambda p^{-} \) decay, observe new strange pentaquark \( P_{cs}(4338)^0 \rightarrow J/\psi \Lambda \)

no significant states decaying to \( J/\psi p \)

LHCb 2022: \( B^{-} \rightarrow J/\psi \Lambda p^{-} \)

\[ P_{\psi s}^{\Lambda}(4338)^{0} \]

arXiv:2210.10346

It is interesting to note that \( J/\psi \Lambda \) pentaquarks are found to be generally narrower than \( J/\psi p \) states (7-17 vs \( \sim 10-200 \) MeV). Even narrower pentaquarks are expected for doubly-strange hidden-charm \( P_{css} \). Such states can decay into e.g. \( J/\psi \Xi^{-} \)

This motivates our search for decays having \( J/\psi \Xi^{-} \) in the decay products, i.e. \( \Lambda_{b}^{0} \rightarrow J/\psi \Xi^{-} K^{+} \)
Data and event selection

pp collisions 13 TeV, L~140 fb\(^{-1}\) (2016-2018)

Mass constraints applied on \( J/\psi \to \mu^+\mu^- \), \( \Lambda \to \pi\pi^- \) and \( \Xi^- \to \Lambda\pi^- \)
\( \Lambda_b^0 \) obtained from vertex fit of \( \mu^+\mu^-\Xi^-K^+ \)

**Normalization channel** is chosen according to the similar decay topology, to reduce the systematic uncertainties associated with the track reconstruction:
\( \Lambda_b^0 \to \psi(2S)\Lambda \), with vertex fit of \( \mu^+\mu^-\Lambda\pi^+\pi^+ \)
\( J/\psi\pi^+\pi^- \) mass close to \( M^{PDG}(\psi(2S)) \)

\( \Lambda_b^0 \) vertex should be away from PV in transverse plane
PV selected by smallest angle between \( \Lambda_b^0 \) momentum and the line joining PV and \( \Lambda_b^0 \) decay vertex
\( \Lambda_b^0 \) baryon momentum should be aligned with that line
Calculation of branching fraction ratio

\[ \mathcal{R} \equiv \frac{\mathcal{B}(\Lambda^0_b \to \psi(2S)\Lambda)}{\mathcal{B}(\Lambda^0_b \to J/\psi K^+)} \equiv \]

\[ \frac{N(\Lambda^0_b \to J/\psi \Xi^- K^+)}{N(\Lambda^0_b \to \psi(2S)\Lambda)} \times \frac{\epsilon_{\psi(2S)\Lambda}}{\epsilon_{J/\psi \Xi^- K^+}} \times \frac{\mathcal{B}(\psi(2S) \to J/\psi \pi^+ \pi^-)}{\mathcal{B}(\Xi^- \to \Lambda \pi^-)} \]

Ratio of the signal yields in data

Ratio of total efficiencies from MC = 5.06±0.29

Known branching fractions from PDG

\[ \mathcal{B}(\psi(2S) \to J/\psi \pi \pi) = (34.68 \pm 0.30)\% \]

\[ \mathcal{B}(\Xi^- \to \Lambda \pi) = (99.887 \pm 0.035)\% \]
Invariant mass distributions

Student-T function for signal
Exponential for background

Unbinned ML fits

First observation!

$m(\Lambda_b^0) = 5619.3 \pm 0.3$ MeV consistent with PDG

$m(\Lambda_b^0) = 5625.9 \pm 3.2$ MeV

$\sigma = 8.9 \pm 0.4$ MeV consistent with MC

$\sigma = 10.4 \pm 3.2$ MeV
Data: sPlot-bkg-subtracted
No narrow peaks in J/ψΞ⁻ (also with narrower bins)
Good data-MC agreement
(not unexpected with 46 signal events)
## Systematic uncertainties

<table>
<thead>
<tr>
<th>Source</th>
<th>Uncertainty (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Signal model</td>
<td>3.9</td>
</tr>
<tr>
<td>Background model</td>
<td>6.7</td>
</tr>
<tr>
<td>Non-$\psi$ (2S) contribution</td>
<td>2.5</td>
</tr>
<tr>
<td>Finite size of MC</td>
<td>5.6</td>
</tr>
<tr>
<td>Tracking efficiency</td>
<td>2.3</td>
</tr>
<tr>
<td>Alternative selection criteria</td>
<td>33.5</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>35.0</strong></td>
</tr>
</tbody>
</table>

- Vary the fit model, deviation in $R = \text{syst. uncertainty}$
- In $\Lambda_b^0 \rightarrow \Lambda J/\psi \pi^+ \pi^+$ sample, evaluated vis sPlot
- Different $p_T$ spectra between signal and norm. channels
- Conservative estimate, based on variation of cuts near trigger/reconstruction thresholds. Accounts for correlation between the sample and its subsample
First observation of $\Lambda_b^0 \rightarrow J/\psi \Xi^- K^+$

- **The first decay to have $J/\psi \Xi^-$ system in decay products**
- No significant narrow peaks in $J/\psi \Xi^-$ mass distribution
  - With 46 signal events, our sensitivity is very limited
- Measured branching fraction ratio:

$$
\mathcal{R} \equiv \frac{B(\Lambda_b^0 \rightarrow J/\psi \Xi^- K^+)}{B(\Lambda_b^0 \rightarrow \psi(2S) \Lambda)} = (2.54 \pm 0.78 \text{ (stat)} \pm 0.89 \text{ (syst)} \pm 0.02(B)) \%$

~ same order of magnitude as $\Lambda_b^0 \rightarrow J/\psi \Lambda \phi$ decay that has similar Feynman diagram:
Summary

- CMS is an active experiment in flavor spectroscopy
- We observe for the first time:
  - \( B_s^0 \rightarrow \psi(2S)K_s^0 \) decay
  - \( B^0 \rightarrow \psi(2S)K_s^0\pi^+\pi^- \) decay
  - \( \Xi_b(6100)^- \) beauty-strange baryon
  - \( \Lambda_b^0 \rightarrow J/\psi\Xi^-K^+ \) decay [NEW RESULT]

Thank you for attention!
BACKUP
Selection criteria for $B^0$ and $B^0_S$

pp collisions 13 TeV, $L \sim 104$ fb$^{-1}$ (2017-2018)

**Trigger:**

$\psi(2S) \rightarrow \mu^+\mu^-$, $p_T(\mu^+\mu^-) > 18$ GeV

$p_T(\mu^+) > 3$ GeV, $P_{vtx}(\mu\mu) > 1\%$

$K^0_S \rightarrow \pi^+\pi^-$

$P_{vtx}(\pi^+\pi^-) > 1\%$

$m(\pi^+\pi^-) \pm 20$ MeV around PDG value

Distance significance $D_{xy}/\sigma > 5$

Angle between $p$ and $D$: $\cos(\alpha) > 0.99$

$p_T(K^0_S) > 1$ GeV

$B^0 \rightarrow \psi(2S)K^0_S$

$P_{vtx}(\mu^+\mu^-K^0_S) > 5\%$

Distance significance $D_{xy}/\sigma > 5$

Angle between $p$ and $D$: $\cos(\beta) > 0.99$

$B^0 \rightarrow \psi(2S)K^0_S \pi^+\pi^-$

$p_T(\pi^\pm) > 0.9$ GeV

$P_{vtx}(\mu^+\mu^-K^0_S\pi^+\pi^-) > 5\%$

Distance significance $D_{xy}/\sigma > 5$

Angle between $p$ and $D$: $\cos(\beta) > 0.99$
Calculation of branching fraction ratio

$R_s \equiv \frac{\mathcal{B}(B_s^0 \rightarrow \psi(2S)K_S^0)}{\mathcal{B}(B^0 \rightarrow \psi(2S)K_S^0)} = \frac{f_d}{f_s}\frac{\epsilon(B^0 \rightarrow \psi(2S)K_S^0)}{\epsilon(B_s^0 \rightarrow \psi(2S)K_S^0)} \frac{N(B_s^0 \rightarrow \psi(2S)K_S^0)}{N(B^0 \rightarrow \psi(2S)K_S^0)}$

Fragmentation fraction ratio

Ratio of total efficiencies from MC

Ratio of the signal yields in data

$R_{\pi^+\pi^-} \equiv \frac{\mathcal{B}(B^0 \rightarrow \psi(2S)K_S^0\pi^+\pi^-)}{\mathcal{B}(B^0 \rightarrow \psi(2S)K_S^0)} = \frac{\epsilon(B^0 \rightarrow \psi(2S)K_S^0\pi^+\pi^-)}{\epsilon(B^0 \rightarrow \psi(2S)K_S^0)} \frac{N(B^0 \rightarrow \psi(2S)K_S^0\pi^+\pi^-)}{N(B^0 \rightarrow \psi(2S)K_S^0)}$
## Systematic uncertainties

<table>
<thead>
<tr>
<th>Source</th>
<th>$R_s$</th>
<th>$R_{\pi^+\pi^-}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Background model</td>
<td>2.5</td>
<td>0.8</td>
</tr>
<tr>
<td>Signal model</td>
<td>1.5</td>
<td>0.8</td>
</tr>
<tr>
<td>Shape of $B_s^0 \to \psi(2S)K_S^0K^{\mp}\pi^{\pm}$ contribution</td>
<td>—</td>
<td>0.5</td>
</tr>
<tr>
<td>Finite size of simulation samples</td>
<td>1.3</td>
<td>1.1</td>
</tr>
<tr>
<td>Intermediate resonances</td>
<td>—</td>
<td>5.0</td>
</tr>
<tr>
<td>Tracking efficiency</td>
<td>—</td>
<td>4.2</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>3.2</td>
<td>6.7</td>
</tr>
</tbody>
</table>
Selection criteria for $\Xi_b(6100)^-$

pp collisions 13 TeV, L~140 fb$^{-1}$ (2016-2018)

**Muon and $J/\psi$ selection**
- $p_T(\mu^\pm) > 3$ GeV/c
- $|\eta(\mu^\pm)| < 2.4$
- $J/\psi_{vtxprob} > 0.01$
- $|m_{\mu^+\mu^-} - m_{J/\psi}^{PDG}| < 100$ MeV

**$\Lambda$ selection**
- $|m_\Lambda - m_\Lambda^{PDG}| < 10$ MeV
- $\Lambda_{vtxprob} > 0.01$
- $p_T(\Lambda) > 1$ GeV/c
- $\cos(\Sigma, \Lambda) > 0$

**$\Xi_b^0$ selection**
- Intermediate decay of $\Xi_b^{++} \rightarrow \Xi_b^0 \pi^-$:
- $8m_{\Sigma^0} - 8m_{\Xi_b^0}^{PDG} < 5$ MeV

**$\Xi$ selection**
- $p_T(\pi_{\Xi}) > 0.25$ GeV/c
- $\Xi_{vtxprob} > 0.01$
- $|m_{\Lambda\pi} - m_{\Xi}^{PDG}| < 9.5$ MeV
- $d_{xy}(\pi_{\Xi}) > 0.9 \sigma_{xy}(\pi_{\Xi})$
- $\cos(\Xi, \Xi) > 0.999$

**$\Xi_b$ selection**
- $|m_{J/\psi \Xi} - m_{\Xi_b}^{fit}| < 54$ MeV
- $(\Xi_b)_{vtxprob} > 0.01$
- $(\Xi_b)_{detach}$ $\text{significance} > 3$
- $p_T(\Xi_b) > 10$ GeV/c
- $\cos(PV, \Xi_b) > 0.99$

*PV is selected as the one with smallest 3D pointing angle, as in BPH-15-002, BPH-16-003, BPH-17-005, BPH-18-005, BPH-19-002, BPH-19-003.*

Charge-conjugate states are implied
Optimization of selection criteria

**Punzi formula** is used for optimization, as it does not rely on $S$ normalization

$$ f = \frac{S}{(\frac{463}{13} + 4\sqrt{B} + 5\sqrt{25} + 8\sqrt{B} + 4B)} $$

$S$ is number of signal events from MC (double-Gaussian function with common mean)

$B$ is expected number of background events in the signal region

Extracted from data with $m_{PDG} (\Lambda_b^0) \pm 2\sigma_{eff}$ region excluded from the (bkg-only, exponential) fit.

Wrong-sign events are added to the sample to improve statistics.

CS and WS distributions are found to be consistent.

The bkg integral in the signal region is taken as $B$
## Systematic uncertainties

<table>
<thead>
<tr>
<th>Source</th>
<th>Uncertainty (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Signal model</td>
<td>3.9</td>
</tr>
<tr>
<td>Background model</td>
<td>6.7</td>
</tr>
<tr>
<td>Non-ψ(2S) contribution</td>
<td>2.5</td>
</tr>
<tr>
<td>Finite size of MC</td>
<td>5.6</td>
</tr>
<tr>
<td>Tracking efficiency</td>
<td>2.3</td>
</tr>
<tr>
<td>Alternative selection criteria</td>
<td>33.5</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>35.0</strong></td>
</tr>
</tbody>
</table>

1) Uncertainty of efficiency ratio due to limited MC statistics

2) Signal model choice:
   - Student-T is baseline, alternatives are
     - Double-gaussian
     - Johnson PDF

3) Tracking efficiency

4) Background model choice:
   - Exp is baseline, alternatives are
     - 2nd degree polynomial
     - Modified threshold pdf \((x-x_0)^a \cdot \exp\)
     - Modified threshold pdf \((x-x_0)^3 \cdot \text{Pol}_1\)

5) Potential non-ψ(2S) contribution

6) Alternative selection criteria:
   - it accounts the correlation of the statistical uncertainties