Review of CMS contributions to Hadron Spectroscopy and planning forward

http://arxiv.org/abs/2204.06667

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Outline

- Introduction
- Conventional Hadron Spectroscopy Results
- Exotic Hadron Spectroscopy Results
- New Decay Modes
- Perspectives
- Prospects for future running
CMS is providing significant contributions to hadron spectroscopy, especially to the beauty and quarkonium sectors, often utilizing final states containing muon pairs. This is possible due to:

- Excellent tracking and muon identification performances
- A flexible trigger system that is essential for increasing luminosities
- Large production cross sections for heavy flavored particles

**Introduction**

Data samples

<table>
<thead>
<tr>
<th>Run-I</th>
<th>$\sqrt{s} = 7\text{TeV}$</th>
<th>2011</th>
<th>5</th>
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<tbody>
<tr>
<td>Run-II</td>
<td>$\sqrt{s} = 8\text{TeV}$</td>
<td>2012</td>
<td>20</td>
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<tr>
<td>Run-II</td>
<td>$\sqrt{s} = 13\text{TeV}$</td>
<td>2015</td>
<td>4</td>
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<td></td>
<td></td>
<td>2016</td>
<td>38</td>
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<td></td>
<td></td>
<td>2017</td>
<td>45</td>
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<td></td>
<td></td>
<td>2018</td>
<td>60</td>
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</table>
The CMS Phase-1 Detector Upgrade will be operational during Run 3, starting this summer

The CMS Phase-2 Detector Upgrade will be operational during the HL-LHC era

[Link to LHC schedule]

https://lhc-commissioning.web.cern.ch/schedule/LHC-long-term.htm
CMS Phase-II Upgrade (overview)

- A new tracker with improved $p_T$ resolution and radiation hardness, lower material budget, extended coverage
- increased muon coverage
- a new forward calorimeter with high granularity and resolution
- addition of the MIP timing detector (MTD)
- increased trigger bandwidth & latencies
- inclusion of tracking information at L1 trigger
- replacement of electronics
Conventional Hadron Spectroscopy Results
CMS observed for the first time the two radially excited states $B_c^+ (2S)$ and $B_c^{*+} (2S)$ decaying to $B_c^+ (\ast) \pi^+ \pi^-$.  
- Undetected very soft photon $B_c^{*+} (2S) \rightarrow B_c^{*+} \pi^+ \pi^-$, $B_c^{*+} \rightarrow B_c^+ \gamma$
- Mass resolution agrees with MC expectations (~6MeV)
- Local significance exceeding 6.5$\sigma$ for observing two peaks rather than one. For both single peaks, significance > 5$\sigma$.  

PRL 122 (2019) 132001
No significant dependence of the three cross section ratios on $p_T(B_c^+)$ and $|y|(B_c^+)$.

In the normalized di-pion invariant mass observed different shapes from phase space but not fully significant with the available statistics.
First observation of resolved $\chi_{bj}(3P)$ states

- $\chi_{bj}(3P)$ is particularly interesting since its properties could have been affected by the nearby $B\bar{B}^{(*)}$ thresholds.
  - Radiative decays to $Y(3S)\gamma$
  - Low energy photons detected after conversion to $e^+e^-$ pairs; $\chi_{bj}(3P)$ mass resolution of $2.18 \pm 0.32$ MeV
  - Total (2-peak) yield: $372 \pm 36$
  - 2-peak local stat. significance $>9\sigma$

The measurement supports the standard hierarchy ($J=2$ heavier than $J=1$)
This measurement fills the gap in the spin-dependent bottomonium spectrum below the open beauty threshold.

It also contributes to the understanding of non-perturbative spin-orbit interaction affecting quarkonium spectroscopy.

No CMS observation so far of the $\chi_{b0}(3P)$ radiative decay.

**TABLE II.** Mass splitting (in MeV) of $3P$-wave bottomonia in our UQM [12], Godfrey-Isgur (GI) model [16], modified GI model [17], and constituent quark model (CQM) [18]. The later three models are regarded as quenched quark models.

<table>
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<tbody>
<tr>
<td>$\chi_{b1}(3P) - \chi_{b0}(3P)$</td>
<td>23</td>
<td>16</td>
<td>14</td>
<td>13</td>
<td>...</td>
</tr>
<tr>
<td>$\chi_{b2}(3P) - \chi_{b1}(3P)$</td>
<td>12</td>
<td>12</td>
<td>12</td>
<td>9</td>
<td>$(10.6 \pm 0.64 \pm 0.17)$</td>
</tr>
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From: M. Anwar et al., PRD99 (2019) 094005
**Confirmation of $\Lambda_b(5912)^0$ and first confirmation of $\Lambda_b(5920)^0$**

- Use $\Lambda_b^0 \to J/\psi \Lambda$ & $\Lambda_b^0 \to \psi(2S)\Lambda$ [with $\psi(2S) \to \mu\mu, J/\psi \pi\pi$] by triggering on dimuons

$$M(\Lambda_b(5912)^0) = [5912.32 \pm 0.12(stat) \pm 0.01(syst) \pm 0.17(m_{PDG}(\Lambda_b^0))]\text{MeV}$$

$$M(\Lambda_b(5920)^0) = [5920.16 \pm 0.07(stat) \pm 0.01(syst) \pm 0.17(m_{PDG}(\Lambda_b^0))]\text{MeV}$$
First confirmation of $\Lambda_b(6146)^0$ and $\Lambda_b(6152)^0$

- One-peak hypothesis vs BKG-only has significance $> 5.4 - 6.5\sigma$

$$M(\Lambda_b(6146)^0) = [6146.5 \pm 1.9\,(stat) \pm 0.8\,(syst) \pm 0.2\,(m_{PDG}(\Lambda_b^0))]\text{MeV}$$

$$M(\Lambda_b(6152)^0) = [6152.7 \pm 1.1\,(stat) \pm 0.4\,(syst) \pm 0.2\,(m_{PDG}(\Lambda_b^0))]\text{MeV}$$

Assuming a single broad resonance $X_b$ the fit with $M$ and $\Gamma$ as free parameters provides (with stat. sign. of $\sim 4\sigma$):

$$M(X_b) = [6073 \pm 5\,(stat)]\text{MeV}$$

$$\Gamma(X_b) = [55 \pm 11\,(stat)]\text{MeV}$$

Confirmed by LHCb as a further excited state: $\Lambda_b(6072)^{**0}$
Using the 2011 data, CMS observed a new \( \Xi_b \) baryon \((\Xi_b^{*0})\) via its strong decay to \( \Xi_b^+ \pi^\pm \). The \( \Xi_b \) was reconstructed via: \( \Xi_b^- \rightarrow J/\psi \Xi^- \) with significance > 5 \( \sigma \).

Recently CMS observed: \( \Xi_b^{**}(6100)^- \rightarrow \Xi_b^- \pi^+ \pi^- \), including the intermediate resonance \( \Xi_b^{*0} \rightarrow \Xi_b^- \pi^+ \) with a mass of 859±36 MeV.
The invariant mass of the final state is built by combining the fully reconstructed decays (left) with the partially reconstructed channel (right) - 30% higher mass resolution.

\[
\text{(local stat. signif. } \sim 6.2\text{-}6.7\sigma) \quad m(\Xi_b^{**-}) = [6100.3 \\
\pm 0.2\text{(stat)} \pm 0.1\text{(sys)} \\
\pm 0.6(\Xi_b^-) ] \text{ MeV}
\]

\[
\Gamma(\Xi_b^{**-}) < 1.9\text{MeV } @95\%\text{CL}
\]

The low yield does not allow a measurement of the quantum numbers. However following analogies with the established \( \Xi_c \) baryon states ...

... the new \( \Xi_b^{**}(6100)^- \) resonance is the analogue of \( \Xi_c(2815) \) and its decay sequence is consistent with the lightest orbitally excited \( \Xi_b^- \) baryon with \( J^P = 3/2^- \) [L=1 between b-quark and (ds)-diquark]
Exotic Hadron Spectroscopy Results
As soon as LHC started, CMS confirmed the $X(3872)$ state inclusively and exclusively reconstructing it in the $J/\psi \pi \pi$ final state.

- Compact multiquark?
- Loosely bound hadronic molecule?
- Mixture of charmonium and $S$-wave molecule?

NO significant dependence on $p_T$
The study of $X(3872)$ production rate in HI collisions, with reference to a standard charmonium ($\psi(2S)$), may help to separate a compact tetraquark configuration (radius $\sim 1\text{fm}$) from a large-sized configuration of a molecular state (radius $\sim 10\text{fm}$).

More statistics and improved systematics needed.

$R(\text{PbPb}) = 1.08 \pm 0.49(\text{stat.}) \pm 0.52(\text{syst.})$

$R(\text{pp}) \sim 0.1$ (both ATLAS & CMS)
Observation of new decay mode $B_s^0 \rightarrow X(3872)\phi$

- The signal of $B_s^0 \rightarrow X(3872)\phi$ is extracted with reference to the control channel $B_s^0 \rightarrow \psi(2S)\phi$ which is used as normalization for the BF measurement as many systematics cancel in the ratio.

- Signal yield determined from a simultaneous 2D fit of the distributions:
  $m(J/\psi \pi^+\pi^-)$, $m(K^+K^-)$

$$N(B_s^0 \rightarrow X(3872)\phi) = 299 \pm 39$$

significance $> 6\sigma$
Observation of new decay mode $B_S^0 \rightarrow X(3872)\phi$

- Branching fraction consistent with that of the $B^0 \rightarrow X(3872)K^{(*)0}$

$$B(B_S^0 \rightarrow X(3872)\phi)B(X(3872) \rightarrow J/\psi\pi^+\pi^-) = (4.14 \pm 0.54\text{(stat)} \pm 0.32\text{(syst)} \pm 0.46(B)) \times 10^{-6}$$

$$B(B^0 \rightarrow X(3872)K^0)B(X(3872) \rightarrow J/\psi\pi^+\pi^-) = (4.3 \pm 1.3) \times 10^{-6}$$

- Significant difference in BF ratio ($B_S^0$ to $B^+$ compared to the $\psi(2S)$ modes):

$$\frac{B(B_S^0 \rightarrow X(3872)\phi)}{B(B^+ \rightarrow X(3872)K^+)} = 0.482 \pm 0.063\text{(stat)} \pm 0.037\text{(syst)} \pm 0.070(B)$$

$$\frac{B(B_S^0 \rightarrow \psi(2S)\phi)}{B(B^+ \rightarrow \psi(2S)K^+)} = 0.87 \pm 0.10$$

- This suggests a difference in the production dynamics of the exotic $X(3872)$ state in $B^0$ and $B_S^0$ decays compared to $B^+$ with respect to the standard $\psi(2S)$. 
Looked for the $X_b \rightarrow Y(1S)\,^+$ decay, analogous to $X(3872) \rightarrow J/\psi\,^+$

The Molecular Model suggests to search close to the $B\bar{B}^{(*)}$ threshold of 10.562 GeV

\[ R = \frac{(pp \rightarrow X_b)}{(pp \rightarrow Y(2S))} \cdot \frac{BF(X_b \rightarrow Y(1S)\,^+)}{BF(Y(2S) \rightarrow Y(1S)\,^+)} \]

95% CL upper limit set on the ratio $R$:

- observed UL range: 0.9% to 5.4%

Similar result from ATLAS
Recent theoretical predictions of tetraquarks consisting of two beauty quarks and two antiquarks and having mass of about $2 \times M(Y(1S))$ or $2 \times M(\eta_b)$, that is in the 18-19 GeV range.

No significant narrow excess of candidates observed above the background expectation in the $Y(1S)\mu^+\mu^-$ final state.

Upper limits on the product of the production cross section of a resonance & the BF to the final state of 4 muons via an intermediate $Y(1S)$ are set @95% CL.
- New $b$ hadron decay modes studied
Observation of the \(B^0 \rightarrow \psi(2S)K_S^0\pi^+\pi^-\) and \(B_s^0 \rightarrow \psi(2S)K_S^0\) decays.

\[
\frac{B(Bs^0 \rightarrow \psi(2S)K_S^0)}{B(B^0 \rightarrow \psi(2S)K_S^0)} = (3.33 \pm 0.69 \text{ (stat)} \pm 0.11 \text{ (syst)} \pm 0.34 \text{ (fs / fd)}) \times 10^{-2}
\]

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

Observation of the \(\Lambda_b^0 \rightarrow J/\psi \Lambda \phi\) decay. (13 TeV, 60 fb\(^{-1}\))

\[
\frac{B(\Lambda_b^0 \rightarrow J/\psi \Lambda \phi)}{B(\Lambda_b^0 \rightarrow \psi(2S)\Lambda)} = (8.26 \pm 0.90 \text{ (stat)} \pm 0.68 \text{ (syst)} \pm 0.11 \text{(B)}) \times 10^{-2}
\]
Observation of the decay mode $B^*_s(5840)^0 \rightarrow B^0 K^0$ and measurement of its BF relative to $B^*_s(5840)^0 \rightarrow B^+ K^-$. 

$$R^0_{2} = \frac{\mathcal{B}(B^*_s \rightarrow B^0 K^0)}{\mathcal{B}(B^*_s \rightarrow B^+ K^-)} = 0.432 \pm 0.077 \pm 0.075 \pm 0.021$$

$$\Gamma_{B^*_s} = 1.52 \pm 0.34 \pm 0.30 \text{ MeV}$$

Observation of the decay mode $B^+ \rightarrow \psi(2S)\phi(1020)K^+$. 

$$\mathcal{B}(B^+ \rightarrow \psi(2S)\phi K^+) = (4.0 \pm 0.4 \text{ (stat)} \pm 0.6 \text{ (syst)} \pm 0.2 \text{ (B)}) \times 10^{-6}$$
 Perspectives and Prospects
Particular strengths of the CMS detector and reconstruction algorithms for this type of physics are:

- The **large muon acceptance**, especially useful for the extraction of **bottomonium** signals and in general for all **double quarkonia**.

- The ability to use effectively **photon conversions** for the precise measurement of radiative spectroscopic transitions \((E_\gamma > 400\text{MeV})\) when resolution is important. For rare processes calorimeter photons can be exploited as well.

- The **good efficiency for the low momentum tracks**, both prompt and displaced from the Primary Vertex. Displaced tracks are crucial for the reconstruction of the \(K_S^0 \to \pi^+\pi^-\), \(\Lambda^0 \to p\pi^-\) and \(\Xi^- \to \Lambda^0\pi^-\) decays.

For example, the \(\pi^-\) from the \(\Xi^- \to \Lambda^0\pi^-\) decays are **very soft** and **displaced**!
The B-physics parking campaign has recorded $\sim 10^{10}$ unbiased decays of beauty hadron during the 2018 Run, exploiting the flexibility of CMS data taking model (as luminosity drops in the fill the L1 rate is kept $\sim$constant & the HLT rate increased towards the end of each fill). **Trigger/tag-side requires a muon coming from a displaced vertex.** Completed reconstruction of these 12B events at the end of 2019 [http://cds.cern.ch/record/2704495] and we have on tape:

- **B-parked data set opens several prospects for spectroscopy studies;** its potentiality is still being studied.
- The possibility to continue B-parking efforts in Run-3 is currently under consideration.
- Further spectroscopy in charm sector can be carried out utilizing semileptonic decays; charmed hadrons can be produced:
  - either at tag side ($b \rightarrow c \mu \nu$)
  - and at probe side (when $c \rightarrow s \mu \nu$ at tag side)
“Standard” triggers will record large amounts of well-reconstructed b-hadrons in charmonium decay modes, as well as charmonium and bottomonium states.

- Smart compromise between available trigger rate and kinematic threshold under investigation for Run-3 and beyond
- High Level Trigger (HLT) budget rate limit will require clever selection and prioritization to target all signal topologies of interest

The bottomonia and charmonia High Level Triggers are confirmed in the 2022 trigger menu essentially unchanged inspite of the instantaneous luminosity and pileup increase.
Tracking at HLT has changed/evolved from Run 2 to Run 3.

- For Run 3 the goal is to maintain efficiencies & fake rate levels while reducing the timing & controlling the rate budget.
- 2018: 3 main global tracking iterations covering from $p_T > 0.4\text{GeV}$ AND an efficiency recovery iteration at $p_T > 1.2\text{GeV}$
- 2022: One single global iteration covering from $p_T > 0.3\text{GeV}$ by means of tracks seeded by the Patatrack Pixel Tracks that are obtained exploiting heterogeneous HLT farm (CPU+GPU) [*].

Specifically for the B-Physics purposes, the GPU pixel tracks are selected in the region around a dimuon candidate. The new displaced charmonium + tracks HLT paths are useful also for spectroscopy studies. Examples:

- $B_c^0(2S)$ & $B_c^*(2S)$
- $B_{s2}^*$ and excited $B_s^0$ mesons

The data to be collected in Run 3 and Run 4 will help achieve very interesting new results and updated results integrating and/or complementing LHCb results.

- In Phase-2, the availability of tracking information at Level-1 trigger will be crucial in retaining the full physics potential when pile up conditions increase to $<\text{PU}>\sim 200$.
- The new MIP Timing Layer (MTD) will allow in Phase-2:
  - Some hadronic PID capabilities for the softer tracks
  - An upgrade of the 3D vertex to a 4D vertex, allowing precision timing for charged hadrons and converted photons and an effective pile up mitigation
- CMS has proven to be one of the leading experiments in the hadron spectroscopy. The full potentiality of Run 2 is still being explored.

- A lot more to come in Run 3 and the HL-LHC era.
Backup
Expected PID performance

- Expected performance in identifying charged pions, kaons and protons as a function of transverse momentum and rapidity in the barrel and endcap regions of the CMS Phase 2 detector (assuming 30-40 ps time resolution).