Heavy Meson Production and Spectroscopy at CMS

Kai Yi
on behalf of the CMS Collaboration
June 3rd, 2014
CMS & LHC

- **LHC** Yields large amounts of data at the world’s **Highest** Energy
- It just discovered the Higgs, confirms & completes the SM
- Opportunities to perform SM measurements & search for new phenomena
Outline

• Introduction

• Observation of $B_s^0 \rightarrow \mu^+ \mu^-$

• Observation of peaking structures in $J/\psi \phi$ spectrum

• search for a new state $X_b$ decaying to $Y(1S)\pi^+\pi^-$

• $X(3872)$ production cross section

• $X_{b2}$ over $X_{b1}$ cross-section ratio

• $B_c \rightarrow J/\psi \pi^\pm \pi^\mp \pi^\mp$ & $B_c \rightarrow J/\psi \pi^\pm$ branching fractions

• Prompt double $J/\psi$ production

• Summary
CMS Detector

Key:
- Blue: Muon
- Red: Electron
- Green: Charged Hadron (e.g., Pion)
- Dashed Green: Neutral Hadron (e.g., Neutron)
- Dotted Blue: Photon

Transverse slice through CMS

- Silicon Tracker
- Electromagnetic Calorimeter
- Hadron Calorimeter
- Superconducting Solenoid

Iron return yoke interspersed with Muon chambers

Relevant sub-detectors
CMS Detector Performance

Excellent muon/silicon detectors:
- Muon system
  - High-purity muon identification
  - Good dimuon mass resolution ($\Delta m/m \sim 0.6\%$ for $J/\Psi$)
- Silicon Tracking detector
  - excellent track momentum resolution ($\Delta p_T / p_T \sim 1\%$)
  - excellent vertex reconstruction and resolution

LHC luminosity & CMS trigger:
- Collect data at increasing instantaneous luminosity
- Triggers are essential ingredients
  - Special triggers for different analysis
  - Combination of dimuon vertex, minimum di(muon) transverse momentum, and displaced dimuon vertex
Introduction

• Search for new physics by measuring deviation from standard model
  • Measuring properties of rare decays like $B_s \rightarrow \mu^+ \mu^-$, $B \rightarrow K \mu^+ \mu^-$...

• Discovery (exotic) states. Help advance our understand of hadron formation

• Test standard model, especially QCD models via precise measurements
  • Measuring heavy meson lifetime, cross section, BF, angular distributions
  • Further study less well-known mesons, like $B_c$
Observation of $B_s^0 \rightarrow \mu^+ \mu^-$

- Test SM in the loops:
  - Flavor Changing Neutral Current (FCNC)
  - No tree diagram, only higher orders

- Precise SM prediction:
  - $\beta(B_s^0 \rightarrow \mu^+ \mu^-) = (3.65 \pm 0.23) \times 10^{-9}$
  - $\beta(B_d \rightarrow \mu^+ \mu^-) = (1.06 \pm 0.09) \times 10^{-10}$

- Possible contribution from NP examples:
  - HDM BF $\propto \tan^4 \beta$ & $m(H^+)$, JHEP 05 (2006) 063; MSSM BF $\propto \tan^6 \beta$, NPB 760 (2007) 38
  - Leptoquarks JHEP 11 (2010) 073
Observation of $B_s^0 \rightarrow \mu^+\mu^-$

- The $B_s^0/B$ signals (MVA--BDT):
  - Displaced dimuon vertex
  - align momentum and flight direction
  - Isolation
- Reference--$B^+ \rightarrow J/\psi K^+$, $f_u/f_s$ from LHCb
- Combine 7&8 TeV data, Barrel & Endcap
- Two approaches:
  - Extract BF from a fit to 12 BDT bins
  - Cut BDT output (1D) as cross check

$$\beta(B_s^0 \rightarrow \mu^+\mu^-) = (3.0^{+1.0}_{-0.9}) \times 10^{-9}$$

$$\beta(B_d \rightarrow \mu^+\mu^-) < 1.1 \times 10^{-9} \text{ @95% CL}$$

Consistent with SM @current precision

Constraint BSM PS
Observation of peaks in the $J/\psi\phi$ mass spectrum in $B$ decays

- New $X/Y/Z$ states poses a challenge to conventional quark model, possibly a new door is open.

- CDF reported evidence for a structure $Y(4140)$ with mass $4143.4^{+2.9}_{-3.0}\pm 1.2_{\text{syst}}$ MeV and width $15.3^{+10.4}_{-6.1}\pm 2.5_{\text{syst}}$ MeV.
  - if confirmed, candidate for an exotic meson.
  - LHCb did not confirm the existence of $Y(4140)$ and put an upper limit on its production.

- An independent check at CMS.
Observation of peaks in the $\text{J}/\psi\phi$ mass spectrum in $B$ decays

$B^+ \rightarrow \text{J}/\psi\phi K^+$

$2011$ dataset, $5.2 \text{ fb}^{-1}$

$2480 \pm 160$ $B^+$ events

Largest $B^+ \rightarrow \text{J}/\psi\phi K^+$ sample to date.

Negligible non-$\phi$ components.

arXiv 1309.6920 [hep-ex], accepted by PLB
Observation of peaks in the $J/\psi\phi$ mass spectrum in $B$ decays

Investigating the $\Delta m = m(\mu^+\mu^-K^+K^-) - m(\mu^+\mu^-)$

- exclude $\Delta m > 1.568$ GeV region to avoid bkg from $B_s \rightarrow \psi(2S)\phi \rightarrow J/\psi\pi^+\pi^-\phi$ decays

$\Delta m$ spectrum obtained by:
- dividing the dataset in 20MeV $\Delta m$ bins
- extracting the number of $B$ signal in each $\Delta m$ bin by fitting the $J/\psi\phi K$ spectrum

<table>
<thead>
<tr>
<th>Yield</th>
<th>Mass (MeV)</th>
<th>$\Gamma$ (MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>310 ± 70</td>
<td>4148.0 ± 2.4(stat) ± 6.3(syst)</td>
<td>28$^{+15}_{-11}$(stat) ± 19(syst)</td>
</tr>
<tr>
<td>418 ± 170</td>
<td>4313.8 ± 5.3(stat) ± 7.3(syst)</td>
<td>38$^{+30}_{-15}$(stat) ± 16(syst)</td>
</tr>
</tbody>
</table>

CMS confirmed $Y(4140)$ with a significance $>5$ standard deviations, and saw evidence for a second structure in the same mass spectrum

Later D0 also confirmed $Y(4140)$ with a significance of $3\sigma$
Cross Check with clean $B^+ \rightarrow J/\psi \phi K$ Sample

Additional requirements:

- kaon $p_T > 1.5$ GeV
- $B^+$ vertex CL > 10%
- $B^+$ vertex detachment: >7X from beamspot
- $m(K^+K^-)$ within 7 MeV of $\phi$ mass

Solid structures appear in clean B sample.

40% of default B signal, 10X less non-B background
Further Investigation in the whole $\Delta m$ region

The $\Delta m$ spectrum after subtracting $B^0_s$ contribution but including non-B evens, within $1.5\sigma$ ($\sigma = 9.3\text{MeV}$) of the $B$ mass.

The extension of the $\Delta m$ spectrum, after subtracting non-B background, to the full phase space.

The events in previous cutoff region are consistent with phase space.

The absence of strong activity in the high-$\Delta m$ region reinforces our conclusion that the near-threshold narrow structure is not due to a reflection of other resonances. Demands an explanation
Search for new bottomonium state decaying to $Y(1S)\pi^+\pi^-$

- Exotic resonance $X(3872)$ discovered in the final state $J/\psi\pi^+\pi^-$

- A bottomonium counterpart $X_b$ may exist and decays into $Y(1S)\pi^+\pi^-$
  - Mass close to the BB or BB* threshold, 10.562 and 10.604 GeV
  - Similar to $X(3872)$, narrow width and sizable branching ratio into $Y(1S)\pi^+\pi^-$
  - Look for a peak in the $Y(1S)(\mu^+\mu^-)\pi^+\pi^-$ invariant mass spectrum

- Measure $R = \frac{\sigma_{X_b} \times BR(X_b \to Y(1S)\pi^+\pi^-)}{\sigma_{Y(2S)} \times BR(Y(2S) \to Y(1S)\pi^+\pi^-)}$ as a function of $X_b$ mass—[10,11] GeV

- kinematic region: $p_T(Y(1S)\pi^+\pi^-) > 13.5$ GeV and $|y(Y(1S)\pi^+\pi^-)| < 2.0$
**X_b candidate reconstruction**

- X_b candidates reconstructed by associating the Y(1S) to 2 pion tracks
  
  - optimized to maximize expected signal significance near Y(2S) mass

  - Expected significance > 5σ if X_b BR * cross-section > 6.56% of the corresponding Y(2S) → Y(1S)π⁺π⁻ value (analogous to X(3872) → J/ψπ⁺π⁻)

  \[ JHEP 04 (2013) 154 \]

- Separate “barrel” and “endcaps” events to exploit better mass resolution and lower background in the barrel region

- **No structure** apart from Y(2S) and Y(3S)

2012 dataset ~20 fb⁻¹
X_b search: mass scan

- Explore 10.06-10.31 and 10.40-10.99 GeV mass regions

- Shift X_b expected mass in 10 MeV intervals and evaluate signal significance

  - X_b signal modeled with a Gaussian function
    - Fix signal width to value from the simulation (3.8 to 16.4 MeV)

  - background parametrized with a 3rd order polynomial

- for each mass point, evaluate

\[
R = \frac{\frac{N_{obs}^{X_b}}{N_{obs}^{Y(2S)}} \epsilon_{X_b}}{\epsilon_{Y(2S)}}
\]

observed yields of X_b and Y(2S) candidates
overall efficiencies estimated from simulation

Assumptions:
- same production mechanism for Y(2S) and X_b
- both produced unpolarized
- same dipion mass distribution for X_b and Y(2S)
$X_b$ Limit

- Local p-values calculated using asymptotic approach and combining results of fits to the barrel and endcap regions

- Systematic uncertainties implemented as nuisance parameters

No significant excess is observed
95% CL upper limit on the cross-sections*branching fractions ratio: 0.9 - 5.4 %
X(3872) cross section

- The X(3872) was discovered in 2003 by Belle
  - Later it was confirmed by CDF, D0, Babar
  - Its nature is uncertain ➔ exotic candidate
- Previous analyses (before CMS measurement) prefer JPC=1++ or 2-+
  - CMS measurement assumed 1++
  - Later LHCb measured its JPC as 1++,  PRL 110, 222001 (2013)
- It is produced both promptly and from B decays at LHC
  - CMS measures both prompt and non-prompt cross section
X(3872) cross section

- \( R = \frac{\text{X(3872)}}{\psi(2S)} \) cross section ratio
  - X(3872) and \( \psi(2S) \) are assumed unpolarized
  - Variation up to 90\% due to polarization

- Non-prompt fraction (B decays)
  - Separated based on \( L_{xy} \)
    \[
    L_{xy}^{X(3872)} = \frac{L_{xy}^{X(3872)}}{p_T} \cdot m_{X(3872)}
    \]
  - Non-prompt events (\( l_{xy} > 100 \mu m \))
  - Contribution from prompt <0.1\%
  - Cross-checked by 2D fit to the mass and \( l_{xy} \)
X(3872) cross section

- Prompt cross section compared to NRQCD
  JHEP02 (2012) 011 Phys Rev D81 114018

- Compared to simulations with and w/o intermediate $\rho^0$ in the $J/\psi \pi^+\pi^-$ decay

NRQCD predictions significantly exceed the measured value, while $p_T$ dependence is reasonably well described.

The intermediate $\rho^0$ decay gives better agreement with data.
Measurements of cross sections and feed-down fractions of P-wave quarkonia are crucial to understand quarkonium production.

Relative production cross-section ratios of P-waves are by themselves interesting tests of (NR)QCD.

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsBPH13005
X_b reconstruction in CMS

- CMS already performed the measurement of X_c cross section ratio

- Same with X_b using 2012 data (~20 fb^{-1})

- Reconstruct via the radiative decay
  - X_{c1,2} \rightarrow J/\psi \gamma
  - X_{b1,2}(nP) \rightarrow \Upsilon(nS) \gamma

- Small cross section and mass difference between X_{b1} and X_{b2} (19.4 MeV)

- Use photon conversions in the silicon tracker
The $X_{b1,2}$ signals

Divide $X_{b1,2}$ in four bins of $Y(1S)$ transverse momentum in the range 7-40 GeV

Considered phase space:
$|y^\gamma| < 1.5$
$|\eta^\gamma| < 1.0$

Shape of the signal peaks based on simulation studies

Mass resolution ~5 MeV
$X_{b2}/X_{b1}$ cross section ratio

\[ R = \frac{\sigma(pp \to \chi_{b2} + X)}{\sigma(pp \to \chi_{b1} + X)} = \frac{N_{\chi_{b2}}}{N_{\chi_{b1}}} \cdot \frac{\frac{\epsilon_1}{\epsilon_2}}{\frac{B(\chi_{b1}(1P) \to Y(1S) + \gamma)}{B(\chi_{b2}(1P) \to Y(1S) + \gamma)}} \]

- Yields of $X_{b1,2}$ signal candidates
- $\epsilon_{12}$ acceptance and efficiency
- Ratio of BR from PDG

No significantly dependent on $Y(1S)$ transverse momentum

Theoretical prediction: ratio increase at low $p_T$.

Based on CMS $X_c$ result

PRD 86 (2012) 074027

Uncertainties:
- Error bars → statistical
- Colored bands → total
Measurement of \( B_c \) Branching Fractions

- A unique heavy-quark dynamics from two different heavy flavors (bc)
  - Both quarks compete in the decay
- Experimental knowledge rather poor (only produced at hadron colliders)
  - Only few decay channels have been observed so far
  - No cross section measurement is available

- Here we show the CMS measurements of

\[
\frac{BR(B_c^\pm \rightarrow J/\psi\pi^\pm\pi^\pm\pi^\mp)}{BR(B_c^\pm \rightarrow J/\psi\pi^\pm)} = \frac{N(B_c^\pm \rightarrow J/\psi\pi^\pm)}{N(B^\pm \rightarrow J/\psi K^\pm)} \times \epsilon_{B_c^\pm} = \frac{Y_{B_c}}{Y_B}
\]

\[
\frac{\sigma(B_c^\pm) \times BR(B_c^\pm \rightarrow J/\psi\pi^\pm)}{\sigma(B^\pm) \times BR(B^\pm \rightarrow J/\psi K^\pm)} = \frac{N(B_c^\pm \rightarrow J/\psi\pi^\pm\pi^\pm\pi^\mp)}{N(B_c^\pm \rightarrow J/\psi\pi^\pm)} \times \epsilon_{B_c^\pm \rightarrow J/\psi\pi^\pm\pi^\pm\pi^\mp} = \frac{Y_{3\pi}}{Y_{B_c}}
\]

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsBPH13005
Event selection

- Selection criteria optimized to maximize $S/\sqrt{S+B}$
- Consider the kinematic phase space $p_T(B_c) > 15$ GeV and $|y(B_c)| < 1.6$
  - $p_T(B^+) > 15$ GeV and $|y(B^+)| < 1.6$ for the $B^+ \to J/\psi K^+$ normalization channel

$B_c \to J/\psi \pi^\pm \pi^\mp \pi^\pm$

$B_c \to J/\psi \pi^\pm$

$B^\pm \to J/\psi K^\pm$

$92 \pm 27$ events

$176 \pm 19$ events

$90398 \pm 357$ events

2011 dataset
~ 5 fb$^{-1}$
Efficiency evaluation

Different strategy for different mesons and different channels:

- $B_c \rightarrow J/\psi \pi^\pm$ and $B^\pm \rightarrow J/\psi K^\pm$ signals
  - efficiency parametrized as a function of the $B$ meson $p_T$

- $B_c \rightarrow J/\psi \pi^\pm \pi^\pm \pi^{\mp}$ channel
  - Many sub-structures involved--treat as 5-body in entire PS
  - Description independent of the decay mode
  - Efficiency parametrized as
    \[
    \epsilon = \left| p_0 + p_1 \cdot x + p_2 \cdot y + p_3 \cdot z + p_4 \cdot w + p_5 \cdot r + p_6 \cdot t + p_7 \cdot s \right|
    \]
  - Determine 7D free parameters using a ML fit on generated events
  - Use $B_c \rightarrow J/\psi 3\pi$ non resonant MC, where all PS configurations are covered

7 independent mass-combinations

- $m^2(\mu^+\pi^+)_\text{low}$
- $m^2(\pi^+\pi^-)_\text{high}$
- $m^2(\mu^+\pi^-)$
- $m^2(\pi^+\pi^+)$
- $m^2(\mu^-\pi^+)_\text{low}$
- $m^2(\mu^-\pi^+)_\text{high}$
- $m^2(\mu^-\pi^-)$
B_{c} Branching Fraction results

The two ratios are measured to be

\[
\frac{\text{Br}(B_{c}^{\pm} \to J/\psi\pi^{\pm}\pi^{\pm}\pi^{\mp})}{\text{Br}(B_{c}^{\pm} \to J/\psi\pi^{\pm})} = 2.43 \pm 0.76 \text{ (stat)}^{+0.46}_{-0.44} \text{ (syst)}
\]

in good agreement with LHCb measurement

\[
\frac{BR(B_{c}^{\pm} \to J/\psi\pi^{\pm}\pi^{\pm}\pi^{\mp})}{BR(B_{c}^{\pm} \to J/\psi\pi^{\pm})} = 2.41 \pm 0.30 \pm 0.33 \quad \text{Phys. Rev. Lett. 108 (2012) 251802}
\]

\[
\frac{\sigma(B_{c}^{\pm}) \times \text{Br}(B_{c}^{\pm} \to J/\psi\pi^{\pm})}{\sigma(B^{\pm}) \times \text{Br}(B^{\pm} \to J/\psi K^{\pm})} = (0.48 \pm 0.05 \text{ (stat)} \pm 0.04 \text{ (syst)} ^{+0.05}_{-0.03} \text{ (t}_{B_{c}} \text{))} \times 10^{-2}
\]

complementary to the LHCb result, which covers p_{T}(B_{c}(B^{+})) > 4 \text{ GeV} \text{ and } 2.5<\eta<4.5

\[
R_{c/u} = (0.68 \pm 0.10 \text{ (stat)} \pm 0.03 \text{ (syst)} \pm 0.05 \text{ (lifetime)})\%
\]

Separate prompt J/ψ (μ⁺μ⁻) pairs based on significance of two J/ψ distance

First time @high-\(p_T\) region, no solid model. Complementary to LHCb (\(p_T\) and rapidity)

SPS (single parton scattering) vs DPS (double parton scattering)?

Evidence of excess at |Dy| > 2.6 indicative of DPS?

\[ \sigma_{\text{tot}} = 1.49 \pm 0.07(\text{stat}) \pm 0.13(\text{syst}) \text{ nb} \]
Summary

• Thanks to the excellent LHC and CMS performances

• Made important measurements of B-hadrons and quarkonium

• Demonstrated CMS can/will play important role in new physics searches and exotic states studies

Stay tuned!

All CMS B-Physics results are available at https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsBPH
Backup
The $\Delta m$ spectrums for datasetA (left, dimuon $p_T>7$ GeV), datasetB(right, dimuon $p_T>7$ GeV and each muon $p_T>4$ GeV) with corresponding relative efficiency curves