Heavy-flavour production results with CMS

The latest of 8TeV and 13TeV results

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Outline

- Motivation for heavy-flavour measurements
- Experimental setup
- Overview of the latest results by CMS:
  1. $B^+$ hadron production cross sections
     CMS-PAS-BPH-15-004
     13 TeV
  2. Quarkonium production cross sections
     CMS-PAS-BPH-15-005
     13 TeV
  3. Observation of $Y(1S)$ pair production
     CMS-PAS-BPH-14-008
     8 TeV
Motivation

Heavy-flavour production is an important process to study.

In view of the Standard Model measurements:
- advancements in b/c-hadron spectroscopy
- verification of *pQCD* and *effective field theory* predictions

In view of BSM searches:
- CP-violation studies
- probing/constraining *new physics* scenarios
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

$|\eta| < 2.4$

$\sigma_{\mu\mu}: 0.6\% - 1.5\%$

Run1 data: $\sim 20.7 \text{ fb}^{-1}$

Run2 data: varies among analyses
Dedicated triggers: optimised for different analyses

CERN-CMS-DP-2016-016
Experimental setup: resonant peaks

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

CMS
Preliminary

\[ B^+ \rightarrow \mu^+ \mu^- K^+ \]

\[ J/\psi \]

\[ \psi(2S) \]

 events/7 MeV

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

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

 CMS
Preliminary

\[ Y(1S/2S/3S) \]

 CMS
Preliminary

\[ \phi \]
\[ \psi' \]
\[ B_s \]
\[ \gamma \]

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

\[ \sigma \geq 63 \text{ MeV} \]
\[ p_T > 8 \text{ GeV} \]
\[ |y^{\mu^+\mu^-}| < 1.25 \]
\[ |\eta| < 0.9 \]

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

\[ 0 \]

\[ 10 \]

\[ 10^2 \]

\[ 1 \]

\[ 10^3 \]

\[ 10^4 \]

\[ 10^5 \]

\[ 10^6 \]

\[ 10^7 \]

\[ 10^8 \]

\[ 10^9 \]

\[ 10^{10} \]

\[ \mu^+\mu^- \text{ invariant mass [GeV]} \]

\[ \omega \]

\[ \phi \]

\[ J/\psi \]

\[ \psi' \]

\[ B_s \]

\[ \gamma \]

\[ Y \]

\[ \phi \]

\[ \psi' \]

\[ B_s \]

\[ \gamma \]

\[ Y \]

\[ \text{low mass double muon} + \text{track} \]
\[ \text{double muon inclusive} \]

\[ Z \]
Using 2016 data
CERN-CMS-DP-2016-016

Experimental setup: resonant peaks

$B_d^0 \rightarrow J/\psi K_s^0$

$\Lambda_b^0 \rightarrow J/\psi \Lambda^0$

$B^+ \rightarrow \mu^+ \mu^- K^+$

$\phi(1020)$

CMS Preliminary

$B^0(J/\psi K^0_s)$

$B^0(J/\psi K_s)$

$\Lambda_b^0(J/\psi \Lambda)$

Trigger paths

- $\phi$
- $J/\psi$
- $\psi'$
- $B_s$
- $Y$
- low mass double muon + track
double muon inclusive
B$^+$ CROSS SECTION

CMS-PAS-BPH-15-004

• probing b-hadron production at higher energies wrt to Run1 measurements

• important test of QCD
B\(^+\) production: selection

Using data with 50\,ns bunch spacing: \( \mathcal{L} \approx 50.8\,\text{pb}^{-1} \)

Exclusive decay channel: \( B^+ \rightarrow J/\psi K^+ \rightarrow \mu^+ \mu^- K^+ \)

Candidate selection:

**Displaced triggered dimuon vertex**

- **L1:** \( 2 \times |\eta|^{\mu} < 1.6 \quad \text{OR} \quad \geq 1 \times |p_T^{\mu}| > 10\,\text{GeV} \)
- **HLT:** \( 2 \times |\eta|^{\mu} < 2.4 \quad \text{AND} \quad |p_T^{\mu}| > 4\,\text{GeV} \)
- \( 2.9 < m_{\mu\mu} < 3.3\,\text{GeV} \)

**\( J/\psi \) candidate:** \( \mu\mu \) pair with \( |p_T| > 10\,\text{GeV} \)

**\( K^+ \) candidate:** track with \( |p_T| > 1\,\text{GeV} \)
B$^+$ production: cross-section

Differential measurement: as function of $Q$ ($Q = p_T$ or $|y|$ of B$^+$)

\[
\frac{d\sigma(pp \rightarrow B^+ X)}{dQ} = \frac{N_{\text{sig}}}{2A\epsilon \cdot B\mathcal{L} \cdot \Delta Q}
\]

signal yield in bin $\Delta Q$

result for a single charge

acceptance $\times$ efficiency

$A$: from B$^+$ MC simulations

$\epsilon$: data-driven from inclusive $J/\psi \rightarrow \mu\mu$

$\text{BR}(B^+ \rightarrow J/\psi K^+) \times \text{BR}(J/\psi \rightarrow \mu\mu)$

$13$ TeV

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Heavy-flavour production at CMS
Signal yields: extracted from invariant mass of $B^+$ candidates

Extended unbinned likelihood fit in each bin of the measurement

- **signal component**
  - double gaussian
- **combinatorial bkg.**
  - exponential function
- **misreconstructed bkg.**
  - error function
Comparison of Data, MC and FONLL calculations at 7 TeV and 13 TeV

Theory predictions in reasonable agreement with the measurement

Improved precision of FONLL predictions at 13 TeV
QUARKONIUM CROSS SECTION

CMS-PAS-BPH-15-005

• testing the factorisation hypothesis of NRQCD

• extending the $p_T$ reach of the previous measurement using Run1 data
Quarkonium production: selection

Using data with 25 ns bunch spacing: \( \mathcal{L} \approx 2.7 \, \text{fb}^{-1} \)

5 S-wave charmonium states: \( J/\psi \), \( \psi(2S) \), \( Y(1/2/3S) \)

Candidate selection:

High-\( p_T \) \( \mu\mu \) pair in central rapidity
- L1: \( 2 \times |\eta|^{\mu} < 1.6 \)
- HLT: \( |p_T|^{\mu\mu} > 10 \, \text{GeV} \) \( [J/\psi] \)
  \( |p_T|^{\mu\mu} > 8 \, \text{GeV} \) \( [\psi(2S), Y(nS)] \)
- specific \( m_{\mu\mu} \) windows for each state

Only \( \mu\mu \) flying away from each other
\( \Delta \varphi < 0 \)
\( \Delta \varphi = \varphi(\mu^+) - \varphi(\mu^-) \)

-3.8 T

B field
Quarkonium production: cross section

Double-differential measurement: as function of $p_T$ and $|y|$

Signal yield in a 2D bin

Maximum likelihood fit to $m_{\mu\mu}$ spectra

$$B(Q \rightarrow \mu^+ \mu^-) \times \frac{d^2\sigma^Q}{dp_T dy} = \frac{N^Q(p_T, |y|)}{\mathcal{L} \cdot \Delta p_T \Delta y} \cdot \left( \frac{1}{\epsilon(p_T, |y|)A(p_T, |y|)} \right)$$

| $J/\psi$ | Bin width |
| $\psi(2S)$ | Average inverse acceptance $\times$ efficiency |
| $Y(1S)$ | $A$: from MC simulations |
| $Y(2S)$ | $\epsilon$: data-driven using Tag&Probe |
| $Y(3S)$ | $\epsilon_{\mu\mu} = \epsilon_{\mu 1} \cdot \epsilon_{\mu 2} \cdot \rho \quad \leftarrow$ for high-$p_T \mu\mu$ correlations |
Quarkonium production: signal yields

Signal yields: extracted from invariant mass of meson candidates

Extended unbinned likelihood fit in each bin of the measurement

- **background**
- exponential function

**Signal yields:**

- **$J/\psi$**
  - $20 < p_T < 21$ GeV
  - $|y| < 0.3$
  - $\chi^2/\text{ndf} = 0.98$

- **$\psi(2S)$**
  - $22.5 < p_T < 25$ GeV
  - $|y| < 0.3$
  - $\chi^2/\text{ndf} = 0.79$

**Graphs:**

- Crystal-Ball + Gaussian fit
- 2.4 fb$^{-1}$ (13 TeV)
- 2.7 fb$^{-1}$ (13 TeV)

**Y(1/2/3S)**

- CMS Preliminary
- $22 < p_T < 24$ GeV
- $|y| < 0.6$
- $\chi^2/\text{ndf} = 1.0$

CMS Preliminary

- Total fit
- Background
Quarkonium production: results

Shapes consistent across rapidity regions
Quarkonium production: results

Radial excitations relative to ground states

2.4 $\psi$ fb$^{-1}$, 2.7 $\psi(2S)$ fb$^{-1}$ (13 TeV)

$\psi(2S) / J/\psi$

$|y| < 1.2$

$\psi(2S) / \psi$

CMS Preliminary

$\psi(2S)$ / $J/\psi$

$|y| < 1.2$

$\psi$ fb$^{-1}$ (13 TeV)

$Y(2S) / Y(1S)$

$|y| < 1.2$

$Y(3S) / Y(1S)$

CMS Preliminary

$Y(1S)$

$Y(2S) / Y(1S)$

$Y(3S) / Y(1S)$

$|y| < 1.2$
Quarkonium production: results

Charmonium non-prompt fraction: 13 TeV vs 7 TeV

$p_T$ reach significantly extended with the 13 TeV measurement
Charmonium production: results

Comparison of the measurements at 7 TeV and 13 TeV

Same $p_T$ dependence in Run1 and Run2

Increase of cross-section consistent with expectations from the PDF evolution
Y(1S) PAIR OBSERVATION

CMS-PAS-BPH-14-008

• never observed before (evidence by DØ)
• first step in searches for tetra-quarks
• important test of QCD predictions
Y(1S)-pair observation: selection

Using data from Run1: \( \mathcal{L} \approx 20.7 \text{ fb}^{-1} \)

Searching for: \( 2 \times Y(1S) \rightarrow \mu\mu \)

Candidate selection:

\( \geq 4 \) muons

- HLT: \( \geq 1 \) pair with \( 8.5 < m_{\mu\mu} < 11 \text{ GeV} \)
- total 0 electric charge
- oppositely charged \( \rightarrow \) kinematic fit

Y(1S) candidate:

\(|y| < 2.0 \quad p_T < 50 \text{ GeV}\)
Two discriminating variables: higher $m_{\mu\mu}$, lower $m_{\mu\mu}$

2D unbinned likelihood fit over the integrated $|y|$ region

- **signal**: $2 \times$ Crystal-Ball
- **combinatorial bkg.**: 1st order Chebyshev Polynomial

![Graphs showing 2D unbinned likelihood fit](image)

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Heavy-flavour production at CMS
Y(1S)-pair observation: results

Inclusive cross-section measured: $|y| < 2.0 \quad p_T < 50$ GeV

Signal yield: $38 \pm 7$ events

Total cross section: $68.8 \pm 12.7 \text{stat} \pm 7.4 \text{syst} \pm 2.8 \text{BR} \text{ pb}$

assuming isotropic $Y(1S) \rightarrow \mu\mu$ decays

Expected to change by up to $+36\%$ (longitudinal) or $-38\%$ (transverse) in case of extreme polarisation scenarios
Summary

Differential $B^+$ cross section measured at 13 TeV
- extended $p_T$ reach up to 100 GeV
- reasonable agreement with FONLL and Pythia8 predictions

Double-differential quarkonia cross sections at 13 TeV
- consistent with 7 TeV results
- awaiting comparison to theoretical predictions

First observation of double $Y(1S)$ production at 8 TeV
- inclusive cross section measured (statistics limited)
- first step in search for tetra-quarks

Presented measurements constitute an important input for improving our understanding of QCD
Thank you for attention