Results on Production of B-hadrons and Onia at CMS

GRANT RILEY
REPRESENTING CMS AND THE CMS B-PHYSICS GROUP
Outline

• CMS Detector and Triggers
• Quarkonia overview
• $J/\psi$, $\Upsilon(nS)$ production
• $B$, $B_s$, $B_c$ production
• X and Y resonances
• Double Quarkonia cross section

• Summary
CMS Trigger System for Quarkonia

- CMS has collected data for 6 years at 7, 8 and 13 TeV
- Increasing instantaneous luminosity
- Triggers essential to measure specific final states in hadronic collision
  - B-Physics specific triggers
  - Double, triple and quad muon selectors
  - Vertexing and vertex displacement
  - Dimuon mass windows

L = 3.9 fb⁻¹ (\sqrt{s} = 13 TeV, 2017)
$J/\psi$, $\psi(2S)$ Cross Sections at 7 TeV

- Measure $J/\psi$ and $\psi(2S)$ xsec in bins of $p_T$, up to $p_T \sim 50$ GeV
- High precision measurement
  - Compare with model
- Test of NRQCD
  - short-distance terms governed by parton distribution functions (PDFs)
  - long-distance matrix-elements (LDMEs), fits to data
- Good agreement

- Several Questions
  - Does the scaling with energy work?
  - When do NNLO corrections become necessary
  - Higher $p_T$, do the models still agree?
$J/\psi$, $\psi(2S)$ Cross Sections at 13 TeV

- Measure $J/\psi$ and $\psi(2S)$ xsec in bins of $p_T$, up to $p_T \sim 100$ GeV
- Improves on prior reach of 50 GeV at CMS
- Do the models still work?

- Dimuon final state
- Vertex probability and $p_T$ requirements on dimuons at HLT level
- Detailed $J/\psi$ & muon acceptances and quality cuts applied after reconstruction
$J/\psi$, $\psi(2S)$ Cross Sections

- Find scaling in total cross section due to CoM energy increase
- Input to models
- Used as a baseline measurement
  - Cross section ratios
  - Multi-parton interactions

![Graph showing $J/\psi$ and $\psi(2S)$ cross sections at 7 and 13 TeV]

$2.4^{J/\psi}\text{ fb}^{-1} \mid 2.7^{\psi(2S)}\text{ fb}^{-1}$ (13 TeV)
$\Upsilon(1S)$, $\Upsilon(2S)$, $\Upsilon(3S)$ Cross Sections

- $\Upsilon$ trigger accepts 1S, 2S and 3S states
- Dimuon decay channel
- $\Upsilon(nS)$ 13 TeV compared to 7 TeV measurement
- CoM cross section scaling similar to $J/\psi$
Prompt Quarkonia

- Prompt and non-prompt contributions to $J/\psi$
- Maximum likelihood fit to measure non-prompt fraction
- Non prompt $J/\psi$ can be from B decays
- Pseudo proper decay length $l_{xy} = \frac{d_{xy}m_x}{p_T}$
- Displaced vertex measurement available to triggers
B Hadron Inclusive Cross Section at 13TeV

- Measured using $B^+ \rightarrow J/\psi K^+$
- $\sigma = 15.3 \pm 0.4(\text{stat}) \pm 2.1(\text{syst}) \pm 0.4(\text{lumi}) \mu b$
- Reasonable agreement with FONLL[1] and PYTHIA predictions


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Observation of $B_c$ Properties via Branching Ratios

- $B_c$ cross section ratio with $B$ measured at 7 TeV
- $B_c(p_T > 15 \text{ and } |y| < 1.6)$

$$\frac{\sigma(B_c^\pm) \times Br(B_c^\pm \rightarrow J/\psi\pi^\pm)}{\sigma(B^\pm) \times Br(B^\pm \rightarrow J/\psi K^\pm)} = [0.48 \pm 0.05 \text{(stat)} \pm 0.03 \text{(syst)} \pm 0.05 \text{ (}\tau_{B_c}\text{)}] \%$$

- Observation of decay to $J/\psi + 3\pi$

$$\frac{BR(B_c^\pm \rightarrow J/\psi\pi^\pm\pi^\pm\pi^\mp)}{BR(B_c^\pm \rightarrow J/\psi\pi^\pm)} = 2.55 \pm 0.80 \text{ (stat)} \pm 0.33 \text{ (syst)}^{+0.04}_{-0.01} \text{ (}\tau_{B_c}\text{)}$$

- Agrees with LHCb result [1]

Studies of Charmonium Like States

- Several states named “X” or “Y” recently found
- Many unknowns
- Some decay through $J/\psi + \text{quarkonia}$
- Add information to the puzzle
- $J/\psi$ reconstructed through $\mu^+\mu^-$ in these analyses
- $\phi$ reconstructed through $K^+K^-$

$X(3872) \rightarrow J/\psi \pi^+\pi^- : \text{Cross section ratio, non prompt fraction, compare to theory}$

$X(5568) \rightarrow B_s^0 \pi^\pm : \text{Search}$

$Y(4140) \rightarrow B^\pm \rightarrow J/\psi \phi K^\pm : \text{Mass, width}$
$X(3872) \rightarrow J/\psi \, \pi^+ \pi^-$

- Cross section ratio measured on 7TeV data
- $R = X(3872)/\psi(2S)$ cross section ratio
  - Assumed unpolarized
  - Polarization variation up to 90%

- Decays from B-hadrons found by measuring non-prompt fraction based on $l_{xy} > 100\mu m$
X(3872) → J/ψ π⁺π⁻

- Prompt cross section measured at 7 TeV
- Compared to NRQCD model [1]
- Predictions describe pT shape well, however significantly exceed measured value

- Di-pion invariant mass spectrum compared to simulation
- Resonant $\rho^0 \rightarrow \pi\pi$ intermediate state (red)
- Non-resonant (blue)
- Intermediate $\rho^0$ better agrees with data

Search for $X(5568) \rightarrow B_s^0 \pi^\pm$

- Evidence for 5588 MeV $X$ state from D0 [1]
- CMS searches at 8TeV using 19.7 $fb^{-1}$
- $B_s^0 pT > 10$ GeV

No significant resonance found

Data (points) compared to sideband $B_s^0$ (blue)

Upper limit set on $\rho_X$ the production rate times branching fraction $B$

$$\rho_X \equiv \frac{\sigma(pp\rightarrow X+\text{anything} \times B(X\rightarrow B_s^0 \pi^\pm))}{\sigma(pp\rightarrow B_s^0 + \text{anything})} < 3.9\% \text{ at 95\% CL}$$

Search for $Y(4140)$ in the $B^\pm \to J/\psi \phi K^\pm$ Decay

- Observation ($>5\sigma$) in 7TeV data $5.2 fb^{-1}$
- $M_{Y(4140)} = 4148.0 \pm 2.4\,(\text{stat}) \pm 6.3\,(\text{syst})\,\text{MeV}$
- $\Gamma_{Y(4140)} = 28^{+15}_{-11}\,(\text{stat}) \pm 19\,(\text{syst})\,\text{MeV}$
- Additional mass peak not established
- Possible reflection
- $M_{\text{peak}2} = 4313.8 \pm 5.3\,(\text{stat}) \pm 7.3\,(\text{syst})\,\text{MeV}$
- $\Gamma_{\text{peak}2} = 38^{+30}_{-15}\,(\text{stat}) \pm 16\,(\text{syst})\,\text{MeV}$
- $\Delta m = m(\mu^+\mu^-K^+K^-) - m(\mu^+\mu^-)$
- Seen by CDF\[1], and LHCb[2]
- Not seen by Belle[3], BaBar[4]

Prompt Double Quarkonia Production

- Double quarkonia production phase space @ CMS nicely complements LHCb
- 4 muon final state accesses many decay channels
- Muon reconstruction in CMS
  - Good resolution ($\frac{\Delta m}{m} \sim 0.6\%$) for $J/\psi$
  - High purity Muon ID
- Silicon tracking
  - $p_T$ resolution $\sim 1\%$, 3.8 T magnetic field
  - Good vertex reconstruction
- Potential grounds for discovery
  - $\eta_b$ (highly suppressed by current predictions)
  - Pseudo-scalar Higgs (NMSSM)
  - Tetraquark bound state
- Non-trivial contribution from double parton-scattering (DPS)
  - Cannot be modeled by current NRQCD predictions
- Non-trivial contributions from Next-to-Leading Order (NLO) SPS as well
  - Models released recently begin to approach NLO and NNLO

$\mu^+ \mu^- \mu^+ \mu^-$

\[
\begin{cases} 
J/\psi \\
\psi(2S) \\
\Upsilon(nS)
\end{cases}
\]
Prompt Double $J/\psi$ Production

- Use 3-muon trigger
- 2 dimuon candidates compatible with $J/\psi$
- Dimuon and 4-muon vertex probability requirements
- Assuming unpolarized $J/\psi$

$J/\psi$ acceptance critical
- CMS gives access to high $p_T$ regime
- Complementary to LHCb
- New model produced based on this measurement
• 2d scatter plot of selected $\Upsilon \Upsilon \rightarrow 4\mu$ events
• Observation of $\Upsilon$ pair production $>5\sigma$
Prompt Double $\Upsilon$ Observation

- Yield extracted with 2D maximum likelihood fit
- Signal is modeled by 2 Crystal-ball functions
- Background is 1st order polynomial

$$\sigma(pp \to \Upsilon\Upsilon) = 68.8 \pm 12.7\,(\text{stat}) \pm 7.4\,(\text{syst}) \pm 2.8\,(\text{BR})\,\text{pb}$$

- 38 ± 7 signal events for $\Upsilon(1S)\Upsilon(1S)$
- Small hint of $\Upsilon(1S)\Upsilon(2S)$
- Not enough statistics to extract DPS/SPS fraction

$\sigma(p p \rightarrow \Upsilon \Upsilon) = 68.8 \pm 12.7\,(\text{stat}) \pm 7.4\,(\text{syst}) \pm 2.8\,(\text{BR})\,\text{pb}$
Effective Cross Section of DPS

- $\sigma_{eff}$ represents the effective size of partonic interaction in the proton, should be independent of $\sqrt{s}$
- Jet measurements so far show higher values than quarkonia
- DPS contribution from quarkonia is predicted for CMS based on 7TeV cross section measurements
- CMS can provide several more points in runs with higher statistics

$$\sigma_{eff} = \frac{1}{2} \frac{\sigma_{\text{single } J}}{\sigma_{d\psi}}$$

Estimate [1]:
- 13 % SPS LO
- 60 % SPS NLO
- 27 % DPS

CMS is contributing in many different quarkonia measurements

Stay tuned for exciting results in the future!
Backup
Quarkonia spectrum: Bottom
Prompt double $J/\psi$ non-resonant production

- Non-resonant prompt model at 7TeV consists of DPS and LO SPS
- Non-prompt is B model, combinatorial background
- Prompt & non-prompt shapes derived from MC
- Combinatorial shapes from sideband analysis
- Good understanding of non-prompt production is critical to search for resonances
- SPS+DPS does not well describe cross section measurement
  ➔ new models were developed to include NNLO SPS