Quarkonium Production with CMS Experiment

Kai Yi
University of Iowa

Now given by:
Keith Ulmer
University of Colorado

on behalf of the CMS Collaboration
• The CMS detector and Muon Trigger

• $\chi_{c2}/\chi_{c1}$ Cross Section Ratio (BPH-11-010)

• $Y(ns)$ Production Cross Section (BPH-11-001) NEW

• Observation of $B_c \rightarrow J/\Psi \pi^+ \& J/\Psi \pi^+\pi^−\pi^+$ (BPH-11-003) NEW

• Conclusion
CMS Detector

- High muon reconstruction efficiency
- Good muon momentum resolution
- Good vertexing
- High purity and low rate B and quarkonium triggers from dimuons
The charmonium puzzle—"anomalous" production of charmonium at CDF (M. Mangano, Moriond QCD, 1994 and reference therein), \(\sim 50\times\) higher J/\(\Psi\) production cross section than predicted

- Color octet was the main solution to the puzzle
- Also imply feed down from higher states, including hybrid states proposal (PLB 342, 369, 1995)

Quarkonium production theoretically not well understood. Excited quarkonium states (\(\chi_{cJ}\)) account for sizeable fraction of J/\(\Psi\) production. \(\frac{\chi_{c2}}{\chi_{c1}}\) prompt ratio provides useful information for J/\(\Psi\) cross section calculation

- Study \(\chi_{cJ} \rightarrow J/\psi + \gamma\) (conversion), \(\gamma \rightarrow e^+e^-\), excellent mass resolution (\(\sim 6\) MeV)

Strategy for studying prompt \(\chi_{c2}/\chi_{c1}\) Prompt production:

- Rejecting the displaced dimuons to reduce feed-down from B decays.
- Reject \(\pi^0\) candidates to reduce background
- Photon efficiency almost cancels for cross section ratio
The Signal Extraction method

- Use un-binned likelihood fit to extract signal event yields

- Signal: double ($\chi_{c1}$, $\chi_{c2}$) or single ($\chi_{c0}$) crystal balls (parameters fixed to MC)

- $\chi_{cJ}$ states clearly resolved, given the 6 MeV mass resolution

- Background: empirical function
  
  \[ N_{\text{bkg}} = (Q - q_0)^{\alpha_1} \cdot e^{(Q-q_0) \cdot \beta_1} \]

  \[ q_0 = 3.2 \text{ GeV} \]
The results

- The $\chi_{c2}/\chi_{c1}$ cross section ratio has been measured vs $p_T$
- Up to $p_T = 25$ GeV with small uncertainties, measurement indicates slight decrease vs. $p_T$
- Large uncertainty due to unknown polarization (up to 25%)
Comparison to theory

$k_T$ factorization predicts both states in $Jz^{HX} = 0$, CMS result reported here with $Jz^{HX} = 0$ for comparison.

The naive spin counting argument gives a ratio of 5/3, which was already excluded by CDF’s measurement.

Measured ratio has been extrapolated down to zero photon $p_T$ for the comparison with the NLO NRQCD prediction.

NLO NRQCD does not predict the polarization; data show the full polarization uncertainties through the green bands.
The $J/\psi$ and $\Upsilon$ differential cross sections and polarizations still disagree with theory.

LHC (CMS, ATLAS, LHCb) provides a chance to study quarkonium production with:
- higher center-of-mass energies; larger momentum range; wide rapidity range.

- Crystal ball function for signal PDF (MC)
- Data-driven (tag & probe) efficiencies
- Previous CMS result (3 pb$^{-1}$): PRD 83:112004 (2011)

The differential cross section is calculated as:

$$\frac{d\sigma(pp \rightarrow \Upsilon(nS))}{dp_Tdy} \cdot B(\Upsilon(nS) \rightarrow \mu^+\mu^-) = \frac{N_{\text{corrected}}(p_T, y; A, \epsilon)}{\mathcal{L} \cdot \Delta p_T \cdot \Delta y}$$

Yields:
- $\Upsilon(1S) = 77931 \pm 431$
- $\Upsilon(2S) = 23847 \pm 290$
- $\Upsilon(3S) = 12308 \pm 258$
Results

- Total cross section:
  \[ \sigma(pp \rightarrow Y(1S) X) \cdot B(Y(2S) \rightarrow \mu^+\mu^-) = (8.55 \pm 0.05^{+0.88}_{-0.78} \pm 0.34) \, nb \]
  \[ \sigma(pp \rightarrow Y(2S) X) \cdot B(Y(2S) \rightarrow \mu^+\mu^-) = (2.21 \pm 0.03^{+0.24}_{-0.21} \pm 0.09) \, nb \]
  \[ \sigma(pp \rightarrow Y(3S) X) \cdot B(Y(3S) \rightarrow \mu^+\mu^-) = (1.11 \pm 0.02^{+0.13}_{-0.12} \pm 0.04) \, nb \]

- Cross-Section Ratios.
- Unknown polarization affects acceptance: up to 24% effects
• Fiducial cross section not affected by acceptance & unknown polarization uncertainty

• Systematic uncertainty sources:
  • muon ID & trigger (4-10%).
  • Two muon efficiency correlation (4-10%)
  • Fit method, FSR.
Comparison to Theory and LHCb

NRQCD gives best $p_T$ shape match to data

CMS and LHCb results complimentary in coverage and show good agreement in overlap
Observation of $B_c$ via $J/\Psi \pi^+$ and $J/\Psi \pi^+\pi^-\pi^+$

- The “last” meson observed through its semileptonic decay at CDF
- The least understood meson due to
  - Low production rate
  - Short lifetime (naïve expectation—1/3 of B hadron)
- Properties not well measured—mass, lifetime
- A unique place to study heavy quark dynamics due to two different heavy quarks

- Reconstructed channels: $J/\Psi \pi^+$, $J/\Psi \pi^+\pi^-\pi^+$
- Displaced $J/\Psi$ trigger, constrain $J/\Psi$ mass to its nominal mass
Observation of $B_c \rightarrow J/\Psi \pi^+$ and $J/\Psi \pi^+ \pi^- \pi^+$

New!

$J/\Psi \pi^+$

Mass ($B_c$) = $6.272 \pm 0.003$ (stat) GeV
$N_{B_c} = 330 \pm 36$ (stat)
$\sigma(B_c) = 26 \pm 4$ MeV

$J/\Psi \pi^+ \pi^- \pi^+$

Mass ($B_c$) = $6.265 \pm 0.004$ (stat) GeV
$N_{B_c} = 108 \pm 19$ (stat)
$\sigma(B_c) = 21 \pm 4$ MeV
Conclusions

• CMS is producing high quality results on heavy flavor physics.
• Presented results:
  • Measurement of the $\chi_{c2}/\chi_{c1}$ production cross-section ratio up to unprecedented $J/\psi$ $p_T$'s with quite small uncertainties
  • $\Upsilon$(ns) cross section measurement extended to $p_T < 50$ GeV
  • Observation of $B_c \rightarrow J/\Psi\pi^+$ and $J/\Psi\pi^+\pi^-\pi^+$

• More results to come from 2011 data. Analysis of 2012 data in progress. See other relevant CMS results at ICHEP 2012:
  • Valentin Knunz: Measurement of $Y$(1S), $Y$(2S) and $Y$(3S) polarizations with the CMS experiment, 7 July, 14:30, TR6 – QCD, Jet, Parton Distribution
  • Keith Ulmer: Heavy Flavor Results from CMS, 6 July, 15:00, TR9+TR5+TR7

• https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsBPH
CMS vs. LHCb and CDF

$\chi_{c2}/\chi_{c1}$ cross-section ratio vs. $p_T$ measured by CMS, LHCb and CDF, for different $y$ windows and collision energies.

CMS data extends to higher $p_T$ and has smaller uncertainties than previous measurements.
Muon efficiencies

- Use data-driven measurements of the muon efficiency ("tag-and-probe" method) on dedicated trigger streams
  - In events with a $J/\psi$ candidate, ask for one well-identified muon ("tag")
  - The other muon ("probe") can pass or not pass the selection $S$ under investigation
  - The fitted $N_{\text{pass-S}}/N_{\text{all}}$ yield gives an unbiased estimate of the efficiency $\varepsilon_S$

- Limitation of the method: assumes efficiency factorization, does not take into account correlations due e.g. to trigger requirements
  (Small) MC corrections required
Converted Photon

CMS Preliminary

pp, $\sqrt{s} = 7\,\text{TeV}$

L = 4.62 fb$^{-1}$

- pixel barrel layers
- silicon pixel layers
- silicon strip layers

CMS Simulation

$\rho_{\text{conv}} \times \varepsilon_{\text{rec}}$

$p_T(y) [\text{GeV/c}]$