PROCEEDINGS OF SCIENCE

Quarkonium Studies at LHCb

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Heavy quarkonium and quarkonium like states are studied in proton-proton collisions at a cernter-of-mass energy of $\sqrt{s} = 7$TeV with the LHCb detector at the LHC. Based on LHCb 2010 sample of about 37 pb^{-1} collected in the year 2010, $\psi(2S)$ double differential cross section of transverse momentum ($p_{\rm T}$) and rapidity (y) is measured both in $\psi(2S) \rightarrow \mu^+\mu^-$ channel and $\psi(2S) \rightarrow J/\psi\pi^+\pi^-$ channel. With the channel of $\chi_{c1,2} \rightarrow J/\psi\gamma$, the ratio χ_{c1}/χ_{c2} is also measured as a function of J/ψ $p_{\rm T}$. With the same dataset, the measurement of $\Upsilon(1S)$ double differential cross section of $p_{\rm T}$ and y is also performed. The mass of exotic state $X(3872)$ is determined as well in the $X(3872) \rightarrow J/\psi\pi^+\pi^-$ decay. The analysis of χ_b study and $X(4140)$ search are performed including early LHCb 2011 data. The LHCb result doesn't confirm the CDF $X(4140)$ signal. The $\psi(2S)$ and $\Upsilon(1S)$ results are compared with theoretical models and they agree reasonably well.

The 2011 Europhysics Conference on High Energy Physics-HEP 2011,
July 21-27, 2011
Grenoble, Rhône-Alpes France

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PoS(EPS-HEP2011)314

1. Introduction

Since the discovery of charmonium and bottomonium states, a lot of experimental and theoretical efforts have been devoted to their production mechanism, which is still not well understood. Several models exist, e.g., the Color-Singlet (CS) and Color-Octet (CO) within the framework of Non Relativistic QCD, and the Color Evaporation Model. But none of these models can describe the previous heavy quarkonium experimental results in all aspects. At LHCb experiment (described in [1]), where proton-proton collide with a center-of-mass energy of $\sqrt{s} = 7$ TeV, abundant quarkonium states are produced at high rapidity.
In recent years, a lot of exotic states with mass between 3.9 GeV$/c^2$ and 4.7 GeV$/c^2$ have been declared, among which some of them have been established, while others need to be confirmed. For the well measured exotic states, their internal structure is still uncertain. $X(3872)$ and $X(4140)$ belong to the exotic spectroscopy. One possible nature of $X(3872)$ can be loosely bounded $D^{*0}\bar{D}^0$ state. So the precision measurement of $X(3872)$ mass compared to the $D^{*0}\bar{D}^0$ threshold is crucial. The $X(4140)$ is claimed by the the CDF Collaboration[2], however the reproduction of such particle needed at other experiment.

2. $\psi(2S)$ production cross section [3]

For the inclusive $\psi(2S)$ cross section measurement, both $\mu^+\mu^-$ and $J/\psi(1S)(\mu^+\mu^-)\pi^+\pi^-$ are used and compared. The latter mode suffers from much more combinatorial background from pions, and thus stricter selection criteria has been applied, which results in lower statistics. The inclusive integrated cross section for the two modes are found to be:

$$\sigma(\text{inclusive}\psi(2S) \to \mu^+\mu^-); 0 < p_{\rm T} \leq 12\text{GeV}/c, 2 < y \leq 4.5) = 1.88 \pm 0.02 \pm 0.31^{+0.25}_{-0.48}\mu\text{b} \quad (2.1)$$

$$\sigma(\text{inclusive}\psi(2S) \to J/\psi(1S)\pi^+\pi^-); 0 < p_{\rm T} \leq 12\text{GeV}/c, 2 < y \leq 4.5) = 0.62 \pm 0.04 \pm 0.12^{+0.07}_{-0.12}\mu\text{b} \quad (2.2)$$

where the first errors are statistical and the second errors are systematic uncertainty, which is dominated by the uncertainty the luminosity measurement (10%), while the last asymmetric errors are due to the assumption that $\psi(2S)$ is produced totally longitudinally or transversely polarized. The differential cross section of transverse momentum can be found in figure 1, where the two modes and NRQCD calculations are compared.

3. $\Upsilon(1S)$ cross section [4]

The $\Upsilon(1S)$ double differential cross section is measured in mode of $\Upsilon(1S) \to \mu^+\mu^-$. The integrated cross section at LHCb is:

$$\sigma(pp \to \Upsilon(1S)X; 0 < p_{\rm T} < 15\text{GeV}/c, 2 < y < 3.5) = 108.3 \pm 0.7^{+30.9}_{-25.8}\text{nb} \quad (3.1)$$

The first error is statistical and the second is systematic uncertainty, which includes the luminosity uncertainty and unknown $\Upsilon(1S)$ polarization. The differential cross section as a function of transverse momentum can be found in figure 2, in which the NRQCD prediction are compared.

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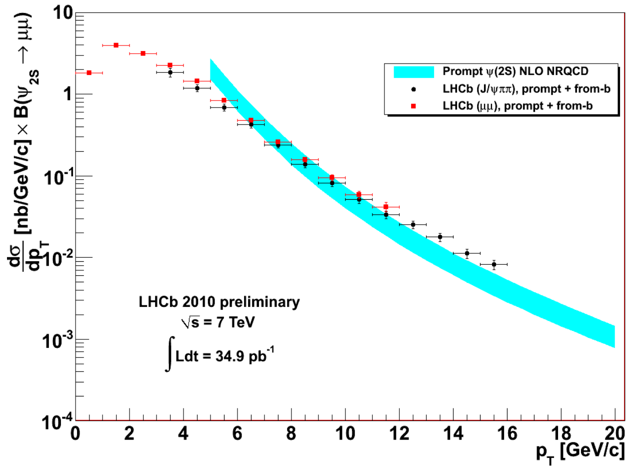

Figure 1: Comparison of the LHCb results for the differential production cross section of $\psi(2S)$ with the predictions for prompt production by the NLO NRQCD model. LHCb data also includes $\psi(2S)$ from decay of b hadrons, which contributes 10% at low p_{T} and the fraction increases as a function of p_{T} to about 40%.

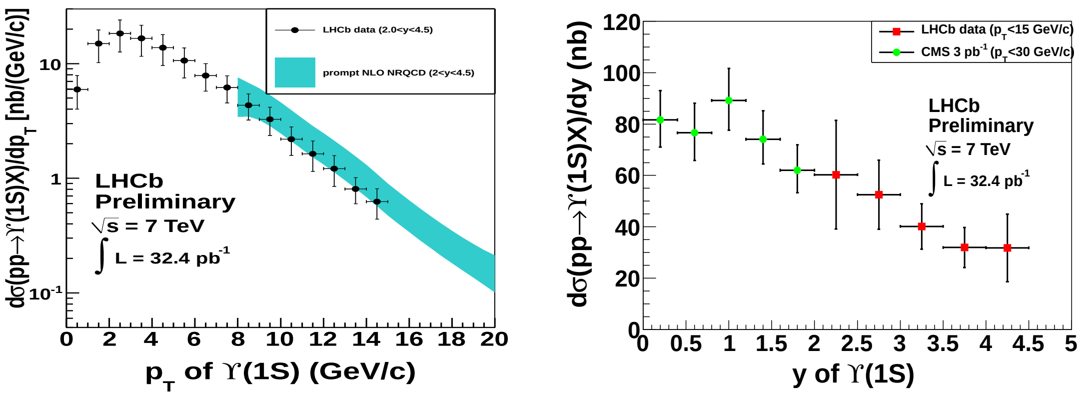

Figure 2: Left plot shows the differential $\Upsilon(1S)$ production cross section as a function of p_{T}, compared with the LO NRQCD. The plot on the right shows the cross section as a function of rapidity integrated over transverse momentum. In the same plot CMS results are also plotted.

4. χ_{c1}, χ_{c2} ratio [5]

The χ_c mesons are identified through the decays $\chi_c \to J/\psi(1S)\gamma$. Both kinds of photons used for the analysis, gammas converted to di-electrons which result in two clusters in Electro-Magnetic (EM) calorimeter and gammas reconstructed from single EM clusters. With good energy resolution, the LHCb experiment can resolve the two χ_c states. The ratio is measured as a function of $J/\psi(1S)$ transverse momentum in figure 3, in which the NRQCD calculation is compared with the result.
The χ_b states are also constructed at LHCb with LHCb 2011 data, and we intend to measure the cross section in the future.

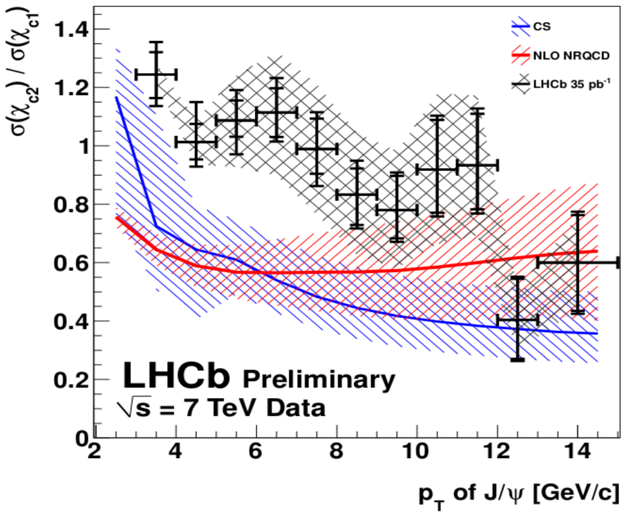

Figure 3: Measured χ_{c1}/χ_{c2} ratio as a function of $J/\psi(1S)$ transverse momentum compared to NRQCD prediction.

5. $X(3872)$ mass and cross section measurement [6]

$X(3872)$ is studied with $X(3872) \to J/\psi(1S)\pi^+\pi^-$ decay and $\psi(2S) \to J/\psi(1S)\pi^+\pi^-$ is used as control channel. The reconstructed mass is scaled by a constant factor, and this is calibrated by $\psi(2S) \to J/\psi(1S)\pi^+\pi^-$. With 35pb^{-1} LHCb 2010 data, we have about 600 events. The measured $X(3872)$ mass is $3871.96 \pm 0.46(\text{stat}) \pm 0.1(\text{syst})\text{MeV}/c^2$.
For $X(3872)$ production measurement, the detection efficiency is calculated as function of transverse momentum and rapidity. The kinematic region is restricted to be $2.5 < y < 4.5$ and $5 < p_{\text{T}} < 20\text{GeV}/c$ because of the efficiency. And then a event by event correction is performed to calculate the yield. Because the branch fraction of $X(3872) \to J/\psi(1S)\pi^+\pi^-$ is known, the joint production cross section is given as:

$$\sigma_{x(3872)} \times \mathscr{B}(X(3872) \to J/\psi(1S)\pi^+\pi^-) = 4.74 \pm 1.10(\text{stat}) \pm 1.01(\text{syst})\text{nb} \qquad (5.1)$$

6. $X(4140)$ search [7]

In the search of CDF $X(4140)$, LHCb uses the same channel $X(4140) \to J/\psi(1S)\phi$ in the decay of $B^+ \to X(4140)K^+$ with a integrated luminosity of about 400pb^{-1}. The signature is described by the mass difference of $M(J/\psi(1S)\phi) - M(\phi)$. To model the mass distribution, the signal is described by Breit-Wigner function convoluted with resolution, and the Breit-Wigner mass and width is fixed to CDF results. Two kinds of shapes are used to describe the combinatorial backgrounds, the 3-body phase space and the quadratic polynomial (see figure 4). For the 3-body phase space, the signal yield is 7 ± 5 while for quadratic polynomial we have 0 ± 3 events. The results are compared to $39 \pm 9 \pm 5$ extracted from the CDF $B^+ \to X(4140)K^+$ branch fraction. With the yields, at $90\%\, C.L.$ LHCb have:

$$\frac{\mathscr{B}(B^+ \to X(4140)K^+), X(4140) \to J/\psi(1S)\phi}{\mathscr{B}(B^+ \to J/\psi(1S)\phi K^+)} < 0.07(3 - \text{body phase space}) \qquad (6.1)$$

or < 0.04 for quadratic polynomial background model.

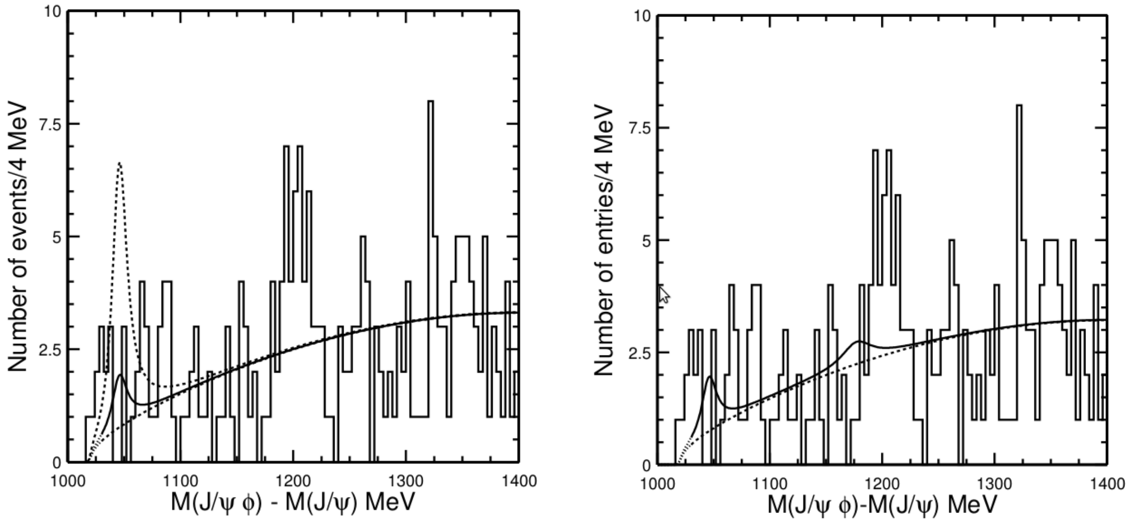

Figure 4: The yield extraction of $X(4140)$, for the left plot 3-body phase space is used to describe the background, while the plot on the right uses 2-nd order polynomial to model it.

7. Conclusion

The production cross sections of $\Upsilon(1S)$ and $\psi(2S)$ and the ratio of χ_{c1}/χ_{c2} have been measured in different transverse momentum bins (and rapidity bins). The results are compared to NRQCD predictions. LHCb has measured the mass and production cross section of $X(3872)$. With about 400pb^{-1} data, LHCb doesn't confirm the CDF $X(4140)$ exotic state.

References

[1] The LHCb Collaboration, JINST **3** (2008) S08005.

[2] The CDF Collaboration, arXiv:1101.6058.

[3] The LHCb Collaboration, LHCb-CONF-2011-026.

[4] The LHCb Collaboration, LHCb-CONF-2011-016.

[5] The LHCb Collaboration, LHCb-CONF-2011-020.

[6] The LHCb Collaboration, LHCb-CONF-2011-021.

[7] The LHCb Collaboration, LHCb-ANA-2011-054.