Ψ and Υ Production in Proton-Proton Collisions at E=13 TeV

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Abstract
This article is an extension of our recent studies of Ψ and Υ production cross sections in proton-proton collisions at the LHC with E=√s=8.0 TeV to E=13 TeV
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1 Differential Rapidity Cross Sections for $\frac{d\sigma_{pp \rightarrow \psi(\lambda=0)} }{dy}$
Production Via p-p Collisions at E= 13 TeV

The present work is an extension of our previous study of Ψ and Υ production via p-p Collisions at √s =E= 8.0 TeV[1] to 13 TeV. We use the theory described in detail in Ref[2] based on the octet model[3, 4, 5] for p-p production of heavy quark states.

The differential rapidity cross section for the $J/\Psi, \Psi(2S)$ meson production for the helicity $\lambda = 0$ is given by [2].

$$\frac{d\sigma_{pp \rightarrow \psi(\lambda=0)} }{dy} = A_\Phi \frac{1}{x(y)} f_\psi(x(y), 2m) f_\delta(a/x(y), 2m) d\frac{dx}{dy},$$

where $y$=rapidity, $a = 4m^2/s$, $s = E^2$, $A_\Phi = \frac{5\pi^3 a^2}{288 m^4}$, $< O_8^\phi(1S_0) >$, with $\alpha_s=.118$, $< O_8^\phi(1S_0) >=.0087 GeV^3$, and $f_\delta$ is the gluonic distribution function. In the present work $E = \sqrt{s} = 13.0$ TeV and for $J/\Psi, \Psi(2S)$ production $m \simeq 1.5$ GeV.

The rapidity variable, $y$, used for differential cross sections, is

$$y(x) = \frac{1}{2} ln\left(\frac{E + p_z}{E - p_z}\right),$$

$$E = \sqrt{s} = \sqrt{m^2 + p_z^2},$$

$$p_z = \frac{\sqrt{s}}{2} (x - \frac{a}{x}).$$
The functions of rapidity $x(y), \frac{dx}{dy}$ are

$$x(y) = 0.5 \left[ \frac{m}{E} (\exp y - \exp (-y)) + \sqrt{\left( \frac{m}{E} (\exp y - \exp (-y)) \right)^2 + 4a} \right]$$

$$\frac{dx(y)}{dy} = \frac{m}{2E} (\exp y + \exp (-y)) \left[ 1 + \frac{\frac{m}{E} (\exp y - \exp (-y))}{\sqrt{\left( \frac{m}{E} (\exp y - \exp (-y)) \right)^2 + 4a}} \right].$$

The gluonic distribution $f_g(x(y), 2m)$ for the range of $x$ needed for $E = 13.0\ \text{TeV}$ is \[2\]

$$f_g(x(y)) = 275.14 - 6167.6 \times x + 36871.3 \times x^2.$$ \[4\]

Using the method of QCD sum rules it was shown\[6\] that the $\Psi(2S)$ is a 50%-50% mixture (with approximately a 10% uncertainty) of standard quarkonium and hybrid quarkonium states. This solved the problem of the branching ratios of hadronic decays of the $\Psi(2S)$ to the $J/\Psi$. Thus the $\Psi(2S)$ state is

$$|\Psi(2S) > = -0.7|c\bar{c}(2S) > + \sqrt{1 - 0.5}|c\bar{g}(2S) > ,$$

while the $J/\Psi$ state is essentially a standard $c\bar{c}$ state

$$|J/\Psi(1S) > = |c\bar{c}(1S) > ,$$

with $c$ a charm quark. Also in Ref\[6\] it was shown that the $\Upsilon(3S)$ state is approximately 50%-50% mixture of a standard and hybrid bottomonium state,

$$|\Upsilon(3S) > = -0.7|b\bar{b}(3S) > + \sqrt{1 - 0.5}|b\bar{g}(3S) > ,$$

with $b$ a bottom quark, which we refer to as a mixed heavy quark hybrid state, while the $\Upsilon(1S)$ and $\Upsilon(2S)$ are standard $b\bar{b}$ states. This solved the problem of $\sigma$ decays of $\Upsilon$ states\[6\].

For $J/\Psi(1S)$ production $A_\Phi = A_{\Psi(1S)} \simeq 1.85 \times 10^{-7} \text{ nb}$. For $\Psi(2S)$ production with the standard model $A_{\Psi(2S)} \simeq 0.039 A_{\Psi(1S)}$, while with the mixed hybrid theory $A_{\Psi(2S)} \simeq 0.122 A_{\Psi(1S)}$.

With the parameters given above for $J/\Psi(1S)$ and $\Psi(2S)$ production, from Eq(1), $\frac{d\sigma_{pp\rightarrow\Psi(1S)}}{dy}$ and $\frac{d\sigma_{pp\rightarrow\Psi(2S)}}{dy}$, are shown in Figure 1. Note that $\frac{d\sigma_{pp\rightarrow\Psi(2S-\text{standard})}}{dy}$ is much smaller than $\frac{d\sigma_{pp\rightarrow\Psi(2S-\text{hybrid})}}{dy}$, which is important for studies of the possible production of the Quark Gluon Plasma (QGP) in Relativistic High Energy Collisions (RHIC). See, e.g., Ref\[7\].

## 2 Differential Rapidity Cross Sections for $\Upsilon(1S), \Upsilon(2S), \Upsilon(3S)$ Production Via p-p Collisions at $E = 13$ TeV

The differential rapidity cross sections for $\Upsilon$ production are given by Eq(1) with $m \simeq 5\ \text{GeV}$. $A_{\Upsilon(1S)} \simeq 5.0 \times 10^{-9}$, $A_{\Upsilon(2S)} \simeq 0.039 x A_{\Upsilon(1S)}$, $A_{\Upsilon(3S)} \simeq 0.0064 x A_{\Upsilon(1S)}$ for the standard model, and $A_{\Upsilon(3S)} \simeq 0.012 x A_{\Upsilon(1S)}$ for the mixed hybrid theory. $\frac{d\sigma_{pp\rightarrow\Upsilon(nS)}}{dy}$ are shown in Figure 2. Note that $\frac{d\sigma_{pp\rightarrow\Upsilon(nS-\text{standard})}}{dy}$ is much smaller than $\frac{d\sigma_{pp\rightarrow\Upsilon(nS-\text{hybrid})}}{dy}$, which also is used for studies of the possible production of the QGP via (RHIC).
The differential rapidity cross sections for $J/\Psi(1S)$ and $\Psi(2S)$ production for the standard model and the mixed hybrid theory are shown in Figure 1.

Figure 1: $d\sigma/dy$ for p-p collisions at $\sqrt{s} = 13.0$ TeV producing $J/\Psi(1S)$; and $\Psi(2S)$ for the standard model (dashed curve) and the mixed hybrid theory.
Figure 2: dσ/dy for p-p collisions at $\sqrt{s} = 13.0$ TeV producing $\Upsilon(1S)$, $\Upsilon(2S)$, and $\Upsilon(3S)$ for the standard model (dashed curve) and the mixed hybrid theory.
3 Ratio of $\Psi(2S)$ to $J/\Psi(1S)$ and $\Upsilon(2S), \Upsilon(3S)$ to $\Upsilon(1S)$ cross sections

Since there is uncertainty in the magnitude of the cross sections, shown in Figures 1 and 2, an essential test of our mixed heavy hybrid theory for heavy quark production are the ratios of cross section for the production of heavy quark states.

As discussed in earlier publications[8, 1, 2] the estimated $\Psi(2S)$ to $J/\Psi(1S)$ ratios for the standard model and the mixed hybrid theory for p-p production are

$$\sigma(\Psi(2S))/\sigma(J/\Psi(1S))|_{\text{standard}} \simeq 0.27$$
$$\sigma(\Psi(2S))/\sigma(J/\Psi(1S))|_{\text{hybrid}} \simeq 0.67 \pm 0.07 .$$

(8)

The ratio for the mixed hybrid theory shown in Eq(8) is consistent with the PHENIX experimental result for $E=200$ GeV[9], while the ratio for the standard model is not consistent with experiment. This ratio should be approximately independent of energy[2]. Presumably, this will be tested by the production of $J/\Psi(1S)$ and $\Psi(2S)$ states via 13 TeV p-p collisions in the near future [10, 11].

The estimated $\Upsilon(2S), \Upsilon(3S)$ to $\Upsilon(1S)$ ratios, as discussed in Refs[8, 2] are

$$\Upsilon(2S)/\Upsilon(1S)|_{\text{standard}} \simeq \Upsilon(2S)/\Upsilon(1S)|_{\text{hybrid}} \simeq 0.27$$
$$\Upsilon(3S)/\Upsilon(1S)|_{\text{standard}} \simeq .04$$
$$\Upsilon(3S)/\Upsilon(1S)|_{\text{hybrid}} \simeq 0.14 - 0.22 .$$

(9)

These ratios have been determined in recent LHCb experiments at 8 TeV[12] and 2.76 TeV [13]. These LHCb measurements show that for the $\Upsilon(2S)/\Upsilon(1S)$ ratio the standard model, which is the same in the mixed hybrid theory, is correct, while the experimental $\Upsilon(3S)/\Upsilon(1S)$ ratio is consistent with the mixed hybrid theory whereas the standard model prediction is much too small.

4 Conclusions

Our results for the rapidity dependence of $d\sigma/dy$, shown in the figures, and the ratio of cross sections should be useful for experimentalists studying heavy quark production in p-p collisions at 13 TeV at the LHC. It is also a further test of the validity of the mixed heavy quark hybrid theory, for which at lower energy p-p collisions the ratios of $\sigma(\Psi(2S))/\sigma(J/\Psi(1S))$ and $\sigma(\Upsilon(3S))/\sigma(\Upsilon(1S))$ have been shown to be in agreement, within errors, with the mixed hybrid theory, but not the standard quark-antiquark model . This is very important since we are using the mixed hybrid heavy quark theory to test the creation of the Quark Gluon Plasma via Relativistic Heavy Ion Collision experiments.

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