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Estimate of the Υ(1S) Production Cross-Section in pp Collisions at $\sqrt{s}$ = 8 TeV

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A quark-gluon plasma (QGP), which is a deconfined partonic state at extremely high temperature and energy density, can be studied in the laboratory through heavy-ion collision experiments. One of the most striking experimental signatures posited to confirm the formation of a QGP is the suppression of the quarkonia surrounding light quarks and gluons, which arises due to the screening of color charges. The nuclear modification factor (R_{AA}), which is the ratio of the quarkonia production cross-section in pp and PbPb collisions normalized by the number of binary collisions, is an important observable used to quantify such QGP effects. However, quarkonia production can be affected by several other contributions, such as a modification of nucleon parton distribution functions (nPDFs), multiple scattering and p_T broadening, nuclear absorption, or comover break-up, known collectively as cold nuclear matter (CNM) effects. In 2015, pPb collision data acquired at the Large Hadron Collider (LHC) at $\sqrt{s_{NN}}$ = 8 TeV were used to investigate such CNM effects. In this work, we provide an estimate for the production cross-section σ_{pp} of the Υ(1S) state, from which we then extrapolate an estimate for R_{pPb} at $\sqrt{s_{NN}}$ = 8 TeV.

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I. INTRODUCTION

According to quantum chromodynamic (QCD) models, strongly interacting nuclear matter can undergo a transition to a deconfined partonic state, called a quark-gluon plasma (QGP), in extremely high temperature and large energy density environments [1,2]. One of the most striking predicted signatures of the existence of a QGP is quarkonia suppression [3,4]. Recently, the Compact Muon Solenoid (CMS) collaboration reported strong suppression of Υ (1S, 2S, 3S) states at $\sqrt{s_{NN}}$ = 2.76 TeV and 5.02 TeV in PbPb collisions [5,6], in which the most tightly bound state, Υ(1S), appeared to be less suppressed than the more loosely bound excited states, Υ (2S, 3S). This ordering can be understood theoretically using the sequential melting scenario [7,8], since bottomonium states with larger binding energies are more difficult to melt than ones with smaller binding energies in the presence of a deconfined partonic medium. However, other phenomena can affect the production of bottomonia during the initial and final collision stages, some of which could lead to quarkonia suppression depending on the binding energies involved. Therefore, measurements from a reference system, such as from proton-lead (pPb) collisions, are essential for studying such cold nuclear matter (CNM) effects.

Possible CNM candidates in the initial stage include the modification of the nucleon parton distribution functions (nPDFs) when bound within a nucleus with respect to those in a free nucleon, and multiple scattering, which leads to parton energy loss and p_T broadening [9]. Final stage candidates are nuclear absorption, *i.e.*, interactions with spectator nucleons that break up the state [10]- and comover break-up by collisions with surrounding hadrons or partons [11,12].

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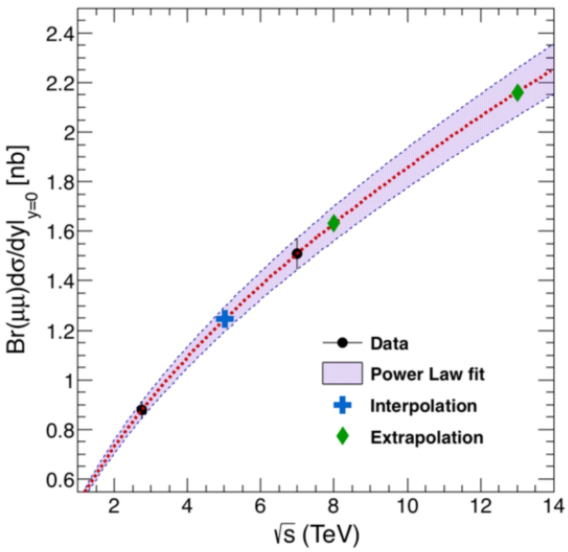

Fig. 1. (Color online) Power law fit for the Υ(1S) production cross-section at mid-rapidity. The closed black circles correspond to CMS data points, the light-blue closed crosses mark the interpolated production cross-section, and the closed green diamonds mark the extrapolated values at 8 TeV and 13 TeV. The shaded area indicates the estimated error of the power law fit.

A simple way to investigate these CNM effects is to compare the results from PbPb and pPb collisions to those of pp collisions, such as comparing the nuclear modification factors from different collisions, *e.g.*, comparing R_{AA} and R_{pPb}, defined by

$$R_{\mathrm{AA}} = \frac{1}{< N_{coll} >} \cdot \frac{\sigma_{PbPb}}{\sigma_{pp}}, \quad (1)$$

$$R_{\mathrm{pPb}} = \frac{1}{< N_{coll} >} \cdot \frac{\sigma_{pPb}}{\sigma_{pp}}. \quad (2)$$

Here, $< N_{coll} >$ is the average number of binary nucleon-nucleon collisions, and σ_{PbPb}, σ_{pPb}, and σ_{pp} are the production cross-sections of quarkonia in PbPb, pPb, and pp collisions, respectively. While the value of R_{AA} at 5.02 TeV has been measured by the CMS collaboration [6], no official measurement of R_{pPb} at 8 TeV has been reported to date. We note that while these results are expected to be available soon, a precise calculation of σ_{pp} for the Υ states would help researchers to understand the R_{pPb} at 8 TeV data more clearly and facilitate the identification of pure QGP contributions in the R_{PbPb} at 5.02 TeV data.

Thus, in this work, we present a fast and effective method to calculate σ_{pp} and we provide an extrapolated prediction for its magnitude at $\sqrt{s}$ = 8 TeV. According to Ref. 14, the Υ production cross section, σ_{pp}, can be described effectively by a power law function (naturally dependent on the collision energy). Since the predicted results arising from our interpolation technique are in good agreement with data measured at 5.02 TeV by the CMS collaboration, we use data acquired at 2.76 TeV and 7 TeV and the same fit function to extend our estimate of σ_{pp} to 8 TeV.

Table 1. Υ(1S) cross-section measured by CMS.

Expt	$\sqrt{s}$ (TeV)	$Br \times \sigma$ [nb]	
CMS	2.76	0.898 ± 0.033	Data
CMS	2.76	0.898 ± 0.075	Interpolation
CMS	5.02	1.331 ± 0.107	Interpolation
CMS	5.02	1.246 ± 0.050	Extrapolation
CMS	7.0	1.510 ± 0.063	Data
CMS	7.0	1.511 ± 0.064	Extrapolation
CMS	8.0	1.631 ± 0.242	Extrapolation
CMS	13.0	2.161 ± 1.060	Extrapolation

II. EXTRAPOLATION TECHNIQUE FOR THE MEASUREMENT OF THE Υ(1S) PRODUCTION CROSS-SECTION

The production of bottomonia has been studied by many experimental groups, including the CDF, D0, PHENIX, STAR, CMS, ALICE, and LHCb collaborations. In this work, we only utilized the data acquired by the CMS collaboration in order to keep our attention on the same kinematical window used in previous measurements [14]. This choice limited our analysis to that of the CMS 2.76 TeV, 5.02 TeV, and 7 TeV data to estimate the Υ(1S) production cross-section. The data sets used in our work refer to those presented in Refs. 5,6,13.

The energetic evolution of the Υ(1S) production cross-section in pp collisions at mid-rapidity is shown in Fig. 1. The cross-section at 5.02 TeV was estimated using the functional form defined in Eq. (3), with the interpolation fit indicated by the light blue crosses [14]. Also shown in the figure is the power law fitting function (red dashed line) used to extend these results to 8 TeV and 13 TeV (green diamonds). The fitting function has the form

$$f(\sqrt{s}) = A \cdot (\sqrt{s})^b, \quad (3)$$

where A and b are free parameters, and the fitted results are reported in Table 1. As shown by Fig. 1 and

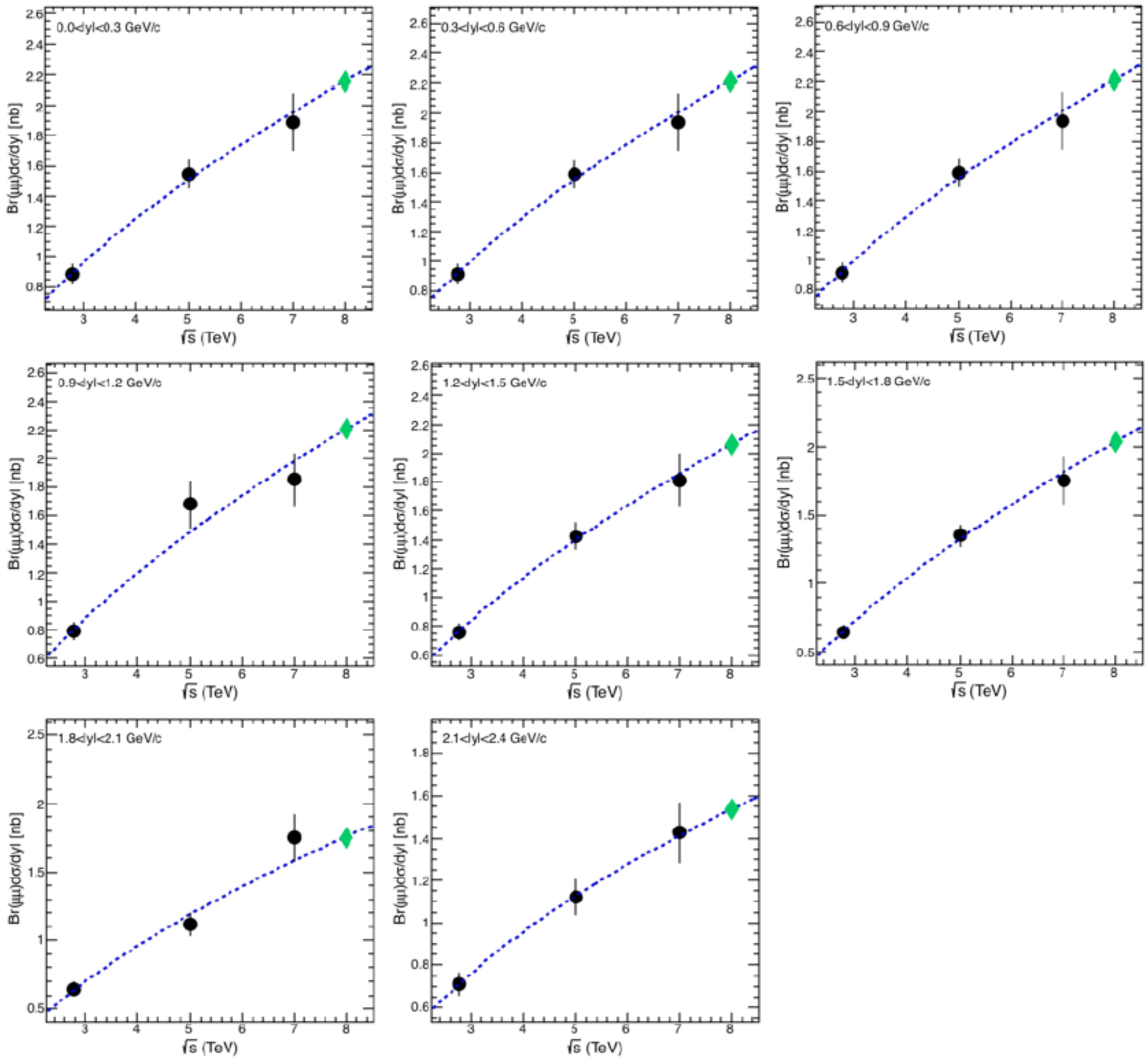

Fig. 2. (Color online) Υ(1S) production cross-section as a function of rapidity. Rapidity bins: 0.0∼0.3, 0.3∼0.6, 0.6∼0.9, 0.9∼1.2, 1.2∼1.5, 1.5∼1.8, 1.8∼2.1, and 2.1∼2.4. The closed black circles correspond to CMS measurements at 2.76 TeV and 7 TeV, while the closed green diamonds mark the extrapolated results for 8 TeV.

Table 1, the interpolated Υ(1S) production cross-section matches the CMS data measured at $\sqrt{s}$ = 2.76 TeV well, and lies well within the given uncertainty. The interpolation technique predicts that the Υ(1S) production cross-section at $\sqrt{s}$ = 5.02 TeV is 1.331 ± 0.107 (nb) at the mid-rapidity point, while the extrapolated fit yields 1.631 ± 0.242 and 2.161 ± 1.060 (nb) for 8 TeV and 13 TeV, respectively. The power law fit depicted in Fig. 1 is given by $f(\sqrt{s}) = (0.490 \pm 0.044) \cdot (\sqrt{s})^{1.158\pm0.121}$.

III. RESULTS AND DISCUSSION

Our extrapolation of the Υ(1S) production cross-section was performed with respect to two kinematic variables-the absolute rapidity and the transverse momentum-and was obtained using the same technique described above.

1. Rapidity distribution

The fit to the Υ(1S) production cross-section was performed in 8 absolute rapidity bins: 0.0∼0.3, 0.3∼0.6, 0.6∼0.9, 0.9∼1.2, 1.2∼1.5, 1.5∼1.8, 1.8∼2.1, and 2.1∼2.4, and with integrated transverse momentum. Fig. 2 shows the power law fit results for the 8 absolute rapidity bins. The closed black circles represent data points measured by CMS at $\sqrt{s}$ = 2.76 TeV, 5.02 TeV, and 7 TeV in *pp* collisions [5,6,13], while the extrapolated results are represented by the green closed diamonds. On

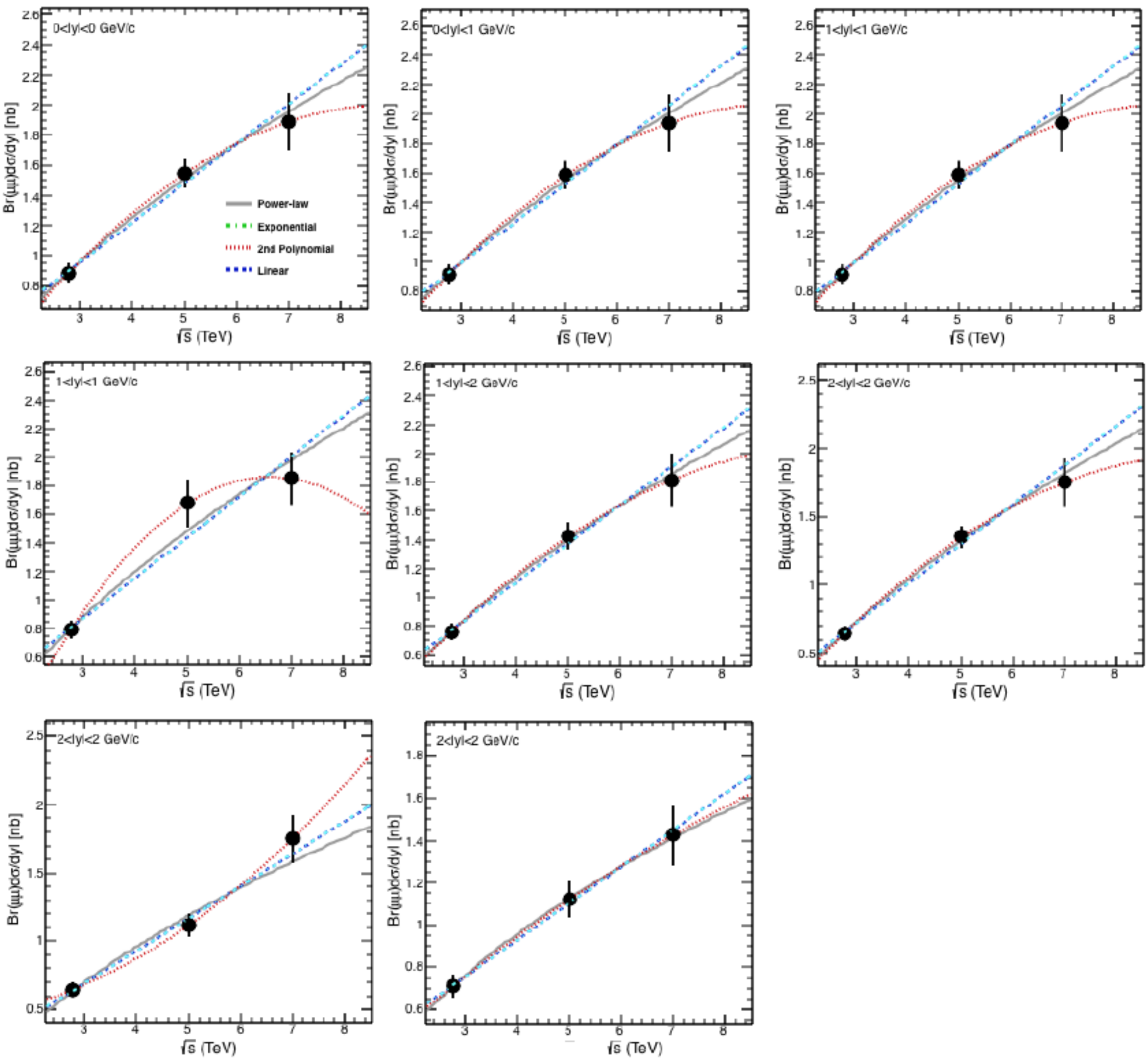

Fig. 3. (Color online) Systematic study of the 8 absolute rapidity regions using three different kinds of fitting functions. The gray line marks our default power-law fit, while the green, red, and blue dashed lines correspond to exponential, 2nd-order polynomial, and linear fitting functions, respectively.

the other hand, Fig. 3 shows the results of a systematic study of the indicated absolute rapidity regions using three different kinds of fitting functions. The gray line marks the power-law fit, which was used as our default fit, while the green, red, and blue dashed lines correspond to exponential, 2nd-order polynomial, and linear fitting functions, respectively. It is clear that the 2nd-order polynomial fit provides a measure of the systematic uncertainty, and that the maximum uncertainty does not exceed 22%.

The extrapolated values of the Υ(1S) production cross-section are plotted in Fig. 4 as a function of the absolute rapidity and for the indicated collision energies. The red dashed line in the figure corresponds to the predicted value of the Υ(1S) production cross-section at $\sqrt{s}$ = 8 TeV obtained from our extrapolated results, while the shaded red area outlines the estimated uncertainties based on the maximum variation of the fitted results using the three different kinds of fitting function noted above. The power law fitting parameters used to generate the extrapolated results are listed in Table 2. As shown in Fig. 4, the interpolated results are in good agreement with the experimental data, confirming that the fit parameters in Table 2 are reliable [14], and consequently, that the extrapolated results are also reasonable. The resulting extrapolated Υ(1S) production cross-sections in each rapidity bin are listed in Table 3.

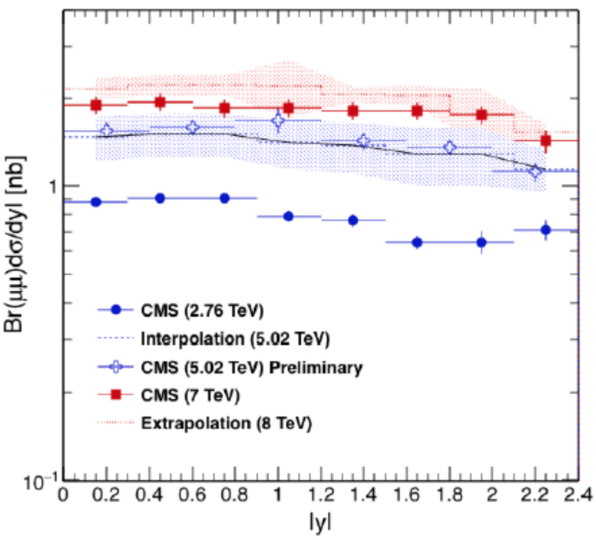

Fig. 4. (Color online) Υ(1S) production cross-sections as a function of rapidity. The closed blue circles and closed red squares correspond to CMS 2.76 TeV and 7 TeV data points, respectively, while the open blue crosses correspond to preliminary CMS results at 5.02 TeV. The blue dashed lines mark interpolated results, while the blue shaded areas indicate their corresponding uncertainties [14]. The red dashed line shows the extrapolated results, with the red shaded areas marking the associated estimated uncertainties.

Table 2. Power law fit parameters for the extrapolations shown in Fig. 2 [14].

Rapidity Bins	Parameter A	Parameter b
0.0∼0.3	0.384 ± 0.077	1.638 ± 0.275
0.3∼0.6	0.399 ± 0.080	1.625 ± 0.275
0.6∼0.9	0.399 ± 0.080	1.625 ± 0.275
0.9∼1.2	0.311 ± 0.062	1.831 ± 0.275
1.2∼1.5	0.296 ± 0.059	1.863 ± 0.275
1.5∼1.8	0.216 ± 0.043	2.148 ± 0.275
1.8∼2.1	0.216 ± 0.043	2.148 ± 0.275
2.1∼2.4	0.332 ± 0.066	1.497 ± 0.275

Table 3. Extrapolated Υ(1S) production cross-sections in marked absolute rapidity bins.

Rapidity Bins	Extrapolated Cross Section (nb)
0.0∼0.3	2.155 ± 0.181
0.3∼0.6	2.211 ± 0.179
0.6∼0.9	2.211 ± 0.179
0.9∼1.2	2.204 ± 0.484
1.2∼1.5	2.061 ± 0.121
1.5∼1.8	2.037 ± 0.165
1.8∼2.1	1.757 ± 0.386
2.1∼2.4	1.536 ± 0.087

2. Transverse momentum distribution

We also considered an estimate for the Υ(1S) production cross-section by carrying out our extrapolation technique for 6 p_T bins: 0.0∼2.0, 2.0∼4.0, 4.0∼6.0, 6.0∼9.0, 9.0∼12.0, and 12.0∼30.0 (GeV/c) within a rapidity range of $|y| < 2.4$. The power law fits for each of the 6 p_T bins are presented in Fig. 5. As before, the closed black circles correspond to data points measured by the CMS collaboration at $\sqrt{s}$ = 2.76 TeV, 5.02 TeV, and 7 TeV in pp collisions [5,6,13], while the closed green diamonds mark our extrapolated results. As we did for the rapidity, we also conducted a systematic study of the analyzed transverse momentum regions using three different fitting functions. Fig. 6 shows the results of this analysis, where the gray lines mark the default power-law fit, while the green, red, and blue dashed lines correspond to the exponential, 2nd-order polynomial, and linear functions, respectively. As before, the 2nd-order polynomial provides an estimate of the systematic uncertainty, but we see that the maximum uncertainty does not exceed 21.8%.

The extrapolated Υ(1S) production cross-sections are plotted in Fig. 7 as a function of the transverse momentum for the indicated collision energies. The blue dashed line corresponds to the extrapolated estimate of the Υ(1S) production cross-section at $\sqrt{s}$ = 8 TeV, while the shaded red area marks the uncertainty region, as was noted in the previous section. The power law fit parameters used for this extrapolation are listed in Table 4. As Fig. 7 shows, the interpolated results are in good agreement with the experimental data, and confirm that the indicated fitting parameters for the transverse momentum distribution (Table 4) are reliable [14], as per our earlier rapidity discussion. The extrapolated Υ(1S) production cross-sections for each transverse momentum bin are listed in Table 5.

IV. CONCLUSION

The Υ(1S) production cross-section in pp collisions at $\sqrt{s}$ = 8 TeV was studied using an extrapolation technique, which is a very fast and effective way to estimate its value using existing CMS 2.76 TeV, 5.02 TeV and 7

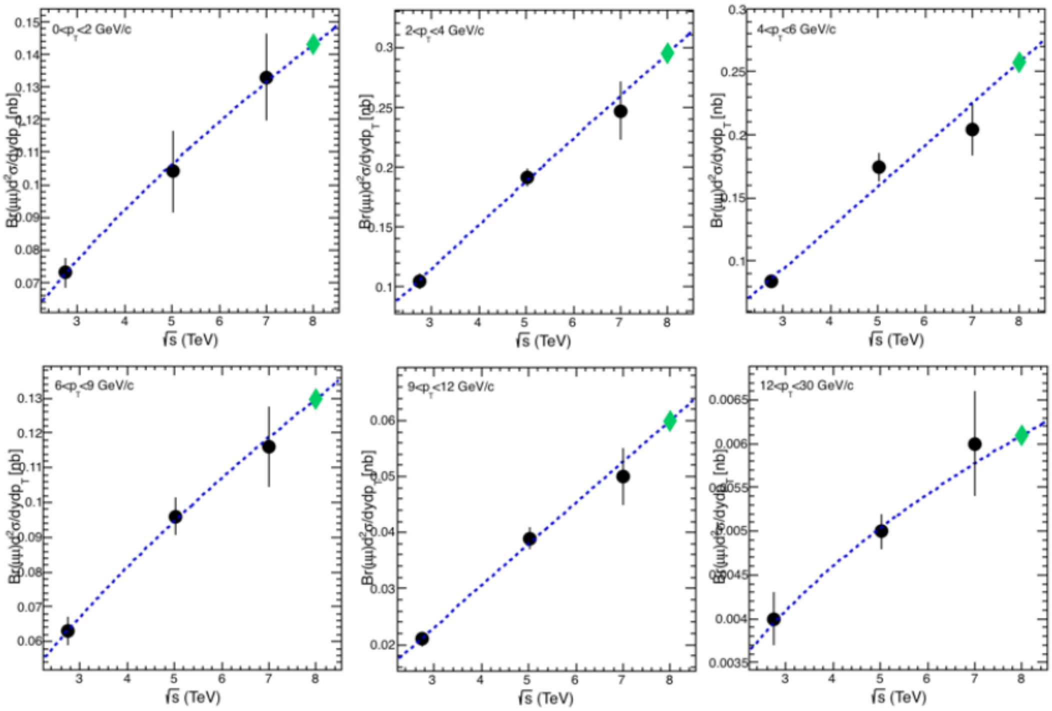

Fig. 5. (Color online) Υ(1S) production cross-sections as a function of the transverse momentum within a rapidity range $|y| < 2.4$. Transverse momentum bins: 0.0∼2.0, 2.0∼4.0, 4.0∼6.0, 6.0∼8.0, 8.0∼12.0, and 12.0∼30.0 (GeV/c). The closed black circles correspond to CMS measurements at 2.76 TeV and 7 TeV, while the closed green diamonds indicated the extrapolated results for 8 TeV.

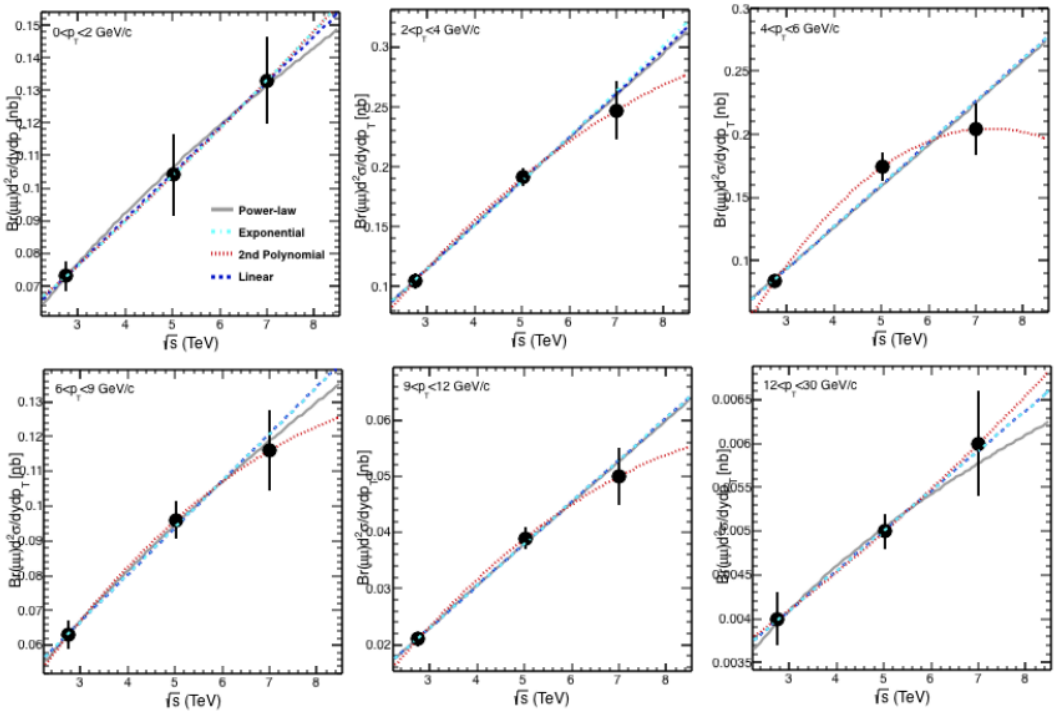

Fig. 6. (Color online) Systematic study of the 6 transverse momentum regions using three different kinds of fitting functions. The gray line marks our default power-law fit, while the green, red, and blue dashed lines correspond to exponential, 2nd-order polynomial, and linear fitting functions, respectively.

Table 4. Power law fit parameters for the extrapolations shown in Fig. 5 [14].

p_T Bins (GeV/c)	Parameter A	Parameter b
0.0∼2.0	0.038 ± 0.007	1.289 ± 0.254
2.0∼4.0	0.041 ± 0.007	1.838 ± 0.254
4.0∼6.0	0.032 ± 0.006	1.907 ± 0.254
6.0∼8.0	0.032 ± 0.006	1.312 ± 0.255
8.0∼12.0	0.008 ± 0.001	1.864 ± 0.253
12.0∼30.0	0.003 ± 0.001	0.871 ± 0.269

Table 5. Extrapolated Υ(1S) production cross-sections in marked transverse momentum bins.

p_T Bins (GeV/c)	Extrapolated Cross Section (nb)
0.0∼2.0	0.143 ± 0.005
2.0∼4.0	0.275 ± 0.027
4.0∼6.0	0.258 ± 0.056
6.0∼8.0	0.130 ± 0.007
8.0∼12.0	0.060 ± 0.006
12.0∼30.0	0.006 ± 0.001

TeV datasets. These cross-section estimates are essential for measurements of the nuclear modification factor, (R_{pPb}) obtained from pPb collision data analysis at $\sqrt{s}$ = 8 TeV, which is used to examine CNM effects from the results of reference 5.02 TeV PbPb collisions. Our extrapolation technique yields a value of 1.631 ± 0.242 (nb) measured at the mid-rapidity point for $\sqrt{s}$ = 8 TeV, which we expect will be confirmed by subsequent data analysis.

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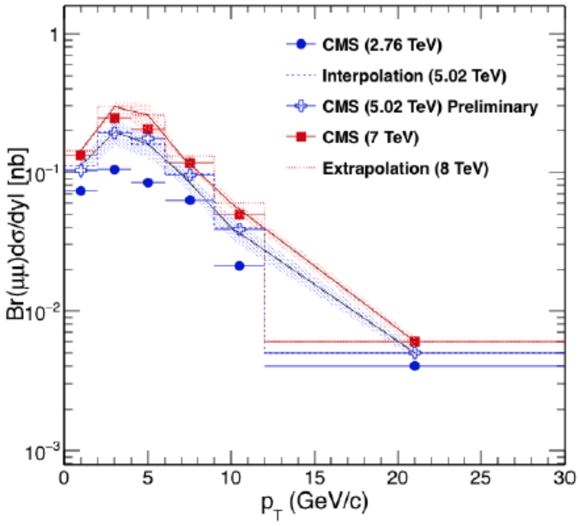
REFERENCES

[1] F. Karsch and E. Laermann, *Quark-Gluon Plasma III*, R. C. Hwa and X.-N. Wang eds. (World Scientific Publishing Co. Pte. Ltd., 2004).
[2] E. V. Shuryak, Sov. Phys. JETP **47**, 212 (1978).
[3] T. Matsui and H. Satz, Phys. Lett. B **178**, 416 (1986).



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[4] Á. Mocsy and P. Petreczky, Phys. Rev. Lett. **99**, 211602 (2007).
[5] V. Khachatryan, A. M. Sirunyan, A. Tumasyan, W. Adam and E. Asilar *et al.* [CMS Collaboration], Eur. Phys. J. C **77**, 252 (2017).
[6] CMS Collaboration, CMS PAS-HIN-16-023, 2016.
[7] R. L. Thews, M. Schroedter and J. Rafelski, Phys. Rev. C **63**, 211602 (2001).
[8] A. Andronic, P. Braun-Munzinger, K. Redlich and J. Stachel, Nucl. Phys. A **789**, 334 (2007).
[9] R. Vogt, Phys. Rev. C **81**, 044903 (2010).
[10] C. Gerschel and J. Hüfner, Phys. Rev. B **207**, 253 (1988).
[11] M. Laine, O. Philipsen, P. Romatschke and M. Tassler, J. High Energy Phys. **03**, 054 (2007).
[12] R. Sharma and I. Vitev, Phys. Rev. C **87**, 044905 (2013).
[13] CMS Collaboration, Phys. Lett. B **727**, 101 (2013).
[14] S. Cho and D. H. Moon, J. Korean Phys. Soc. **71**, 134 (2017).