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The Transverse Momentum Distribution of J/ψ Mesons Produced in *pp* Collisions at the LHC

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Abstract: The transverse momentum distribution of J/ψ mesons produced in *pp* collisions at the center-of-mass energy 5 TeV, 7 TeV, and 13 TeV is described by the modified Hagedorn function which is based on the Tsallis function and Hagedorn function. The calculated results by the modified Hagedorn function are in accord with experimental data measured by the LHCb Collaboration at LHC. The related parameters are obtained and analyzed.

Keywords: the modified Hagedorn function; J/ψ mesons; transverse momentum distribution

1. Introduction

More and more scientific workers get involved in exploring the origin of the universe. According to modern cosmology, the quark-gluon plasma (QGP) is the initial state after the Big Bang and the original state of matter. So, exploring and studying the QGP is a way to understand the universe's evolution. In the extremely high temperature and high-density particle collision area may be production the QGP. In the experimental, accelerated the speed of the two antithetical heavy nuclei approach the speed of light and have a central collision to be formed a small 'big bang' and produced the QGP. Creating and studying the QGP has become the main goal of the high energy heavy ion collision experiment. But, the new form of nuclear matter (QGP) cannot be directly observed by the detectors. We can only analyze the final particles of relativistic heavy ion collisions to infer the properties of QGP. To date, we have got a lot of experimental data provided by the Relativistic Heavy Ion Collider (RHIC) and the Large Hadron Collider (LHC) to study. And, scientists have obtained some achievements about the QCD diagram and nuclear matter [1,2].

In the whole process of collision, the collision system is emitted particles and nuclear fragments constantly. The kinds and dynamical properties of the particles and nuclear fragments emitted at different stages are not the same. Therefore, the final products of collisions have carried on a lot of the evolution information of collision progress [3]. The transverse momentum distribution of final state particles is an important object of observation in the experimentally, it can provide more important information to study the kinetic freezing temperature, the radial velocity of particles, chemical potential, the transverse excitation degree of collision system, and so on. In this paper, we described the transverse momentum distribution of J/ψ mesons produced in *pp* collisions at different collision energy, extracted and analyzed some related parameters.

2. The model and method

In our previous work [4–8], we have revised some thermodynamic statistical distributions based on the multisource thermal model. In the work [4,5], we put forward two components of statistical models which are the two-component Elang distribution and the two-component Schwinger mechanism. We used the two revised model to analyze the transverse momentum distributions of φmesons, Ω hyperons, and negatively charged particles produced in Au-Au collisions with different centrality intervals, measured by the STAR Collaboration at 7.7 GeV, 11.5 GeV, 19.6 GeV, 27 GeV, and 39 GeV in the beam energy scan programat RHIC. And, we used the two methods to study the transverse momentum spectra of J/ψ and ϒmesons produced in *pp*, *p*-Pb, Pb-Pb collisions measured

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by LHCb and ALICE Collaboration at LHC. In the work [6], we structured a two-component statistical model which is a super position of the Tsallis statistics and the inverse power law. We used this two-component statistical model to analyze the transverse momentum distributions of J/ψ and Υmesons produced in *pp*, *p*-Pb collisions at 5 TeV, 7 TeV, 8 TeV, and 13 TeV measured by LHCb Collaboration at LHC. In the work [7], We used two models(the two-component Schwinger mechanism and the two-component statistical model which is based on the Tsallis statistics and the inverse power law) to study the Λ_c^+ , Λ_b^0 baryons, D^0 , $\overline{B}^0$ mesons and some related particles produced in *pp*, *p*-Pb collisions at 5 TeV, 7 TeV, 8 TeV,and 13 TeV. From our prophase related work, one can see that our revised models could describe the experimental data very well. And based on our revised models, we extracted some related important parameters and analyzed their trend with rapidity and collision energy. Through these studies works, we try to get some useful information about the collision mechanism, the evolution of thecollision system and the QGP.

In this work, we use the modified Hagedorn function to study the transverse momentum distribution of J/ψ mesons produced in *pp* collisions at the center-of-mass energy 5 TeV, 7 TeV, and 13 TeV. To complete this paper, we will introduce this function briefly in the following paragraphs.

In the reference [9,10],the Hagedorn function is written as:

$$\frac{d^2N}{2\pi N_{ev}p_t dp_t dy} = C\left(1+\frac{m_t}{p_0}\right)^{-n} \quad (1)$$

In this function, *C* is the fitting constant, $m_t = \sqrt{p_t^2 + m_0^2}$ denotes the transverse mass, p_0 and *n* are the free parameters. Based on Quantum Chromodynamics, the Hagedorn function can be described the high transverse momentum part of transverse momentum distributions of hadrons very well.

It is well-known that the Tsallis function is a very useful method to study the transverse momentum of final state particles in *pp* collisions at RHIC and LHC energy range. The simplest form of the Tsallis function is:

$$\frac{d^2N}{2\pi N_{ev}p_t dp_t dy} = C_q\left(1+(q-1)\frac{m_t}{T}\right)^{-1/(q-1)} \quad (2)$$

By comparing the Hagedorn function and Tsallis function, one can see that when the parameter n can be expressed as $1/(q-1)$ and p_0 can be expressed as nT (T is effective temperature), the Hagedorn function and the Tsallis function are mathematically equivalent. So, we could revise function (1) to

$$\frac{d^2N}{2\pi N_{ev}p_t dp_t dy} = C\left(1+\frac{m_t}{nT_0}\right)^{-n} \quad (3)$$

In the references [11–14], m_t can be transform to $\langle\gamma_t\rangle(m_t - p_t\langle\beta_t\rangle)$, and $\langle\gamma_t\rangle = \frac{1}{\sqrt{1-\langle\beta_t\rangle^2}}$. In this way, function (3) can be written as

$$\frac{d^2N}{2\pi N_{ev}p_t dp_t dy} = C\left(1+\langle\gamma_t\rangle\frac{(m_t - p_t\langle\beta_t\rangle)}{nT_0}\right)^{-n} \quad (4)$$

Function (4) is the form of the modified Hagedorn function. We have used the function (4) to study the transverse momentum distribution of J/ψ mesons produced in *pp* collisions at 5 TeV, 7 TeV, 8 TeV, and 13 TeV measured by LHCb Collaboration at LHC. The following section introduced the details of our research work.

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3. Results and discussion

Figure 1 shows the transverse momentum distribution of J/ψ mesons produced in pp collisions at $\sqrt{s}$ =5 TeV. Figure 1(a) presents the results of prompt J/ψ mesons and Figure 1(b) present the results of nonprompt J/ψ mesons, respectively. The hollow symbols with the error bars represent the experimental data measured by the LHCb Collaboration in literature [15], the different rapidity ranges are denoted by different symbols in the panels. The solid curves are our results calculated by the modified Hagedorn function. The values of free parameters (n, T_0, β_t) and degree of freedom (χ^2/dof) corresponding to each curve in Figure 1 are listed in Table 1. One can see that the modified Hagedorn function could describe the experimental data measured in pp collisions at the center-of-mass energy 5 TeV by the LHCb Collaboration.The trends of parameters on the rapidity will be discussed later.

Figures 2 and 3 are similar to Figure 1. Figure 2 show the transverse momentum spectra of 2(a) prompt J/ψ, 2(b) J/ψ from b, 2(c) prompt J/ψ with fully transversely polarized, 2(d) prompt J/ψ with fully longitudinally polarized in pp collisions at $\sqrt{s}$ =7 TeV, respectively. Figures 3(a) and 3(b) show the results of prompt J/ψ and J/ψ from b mesons in pp collisions at $\sqrt{s}$ =13 TeV, respectively. The hollow symbols with the error bars represent the experimental data measured by the LHCb Collaboration in literatures [16,17]. The solid curves are our results calculated by the modified Hagedorn function. The values of free parameters (n, T_0, β_t) and degree of freedom (χ^2/dof) corresponding to each curve in Figures 2 and 3 are listed in Table 1, which will be discussed later. One can see that the results calculated by the modified Hagedorn function are fitted well with the experimental data.

In order to see clearly the relationship of free parameters (n, T_0, β_t) and rapidity(y) for J/ψ mesons produced in pp collisions at 5 TeV, 7 TeV and13 TeV, we plot the parameter values listed in Table 1 in Figure 4. In this Figure, the solid symbols are parameters and the solid lines are our fitted results by the least square method. One can see that one parameter (n) is increased with the rapidity increase, and the other two parameters (T_0 and β_t) are decreased with the rapidity increase. In addition, we find the trend of β_t has an abnormal phenomenon for J/ψ mesons produced in pp collisions at $\sqrt{s}$ = 7TeV.

In this paper, we described the transverse momentum distribution of J/ψ mesons produced in pp collisionsat the center-of-mass energy 5 TeV, 7 TeV， and 13 TeV by the modified Hagedorn function. From our calculated curves and the experimental data are present in Figures 1–3 and the degree of freedom (χ^2/dof) listed in Table 1, we found that the modified Hagedorn function is good way to study the transverse momentum distribution of J/ψ mesons produced in pp collisions at LHC energy regions. Based on the work of describing the transverse momentum distribution of J/ψ mesons, we extracted the three free parameters (n, T_0, β_t). As mentioned in literature [10], for point quark–quark scattering n ≈ 4, and the n parameter gets bigger when multiple scattering centers are involved [10,18–20]. Our research result show the parameter n is increased with the rapidity increase and not obviously different with the collision energy increased at LHC. This result suggests that with the rapidity increased, the more multiple scattering centers are involved. β_t is the average transverse (radial) flow velocity, and T_0 is an estimate for kinetic freeze-out temperature. The two parameters (T_0 and β_t) are decreased with the rapidity increase. This result means that the collision system may be have faster expansion and higher excitation degree in low rapidity region.

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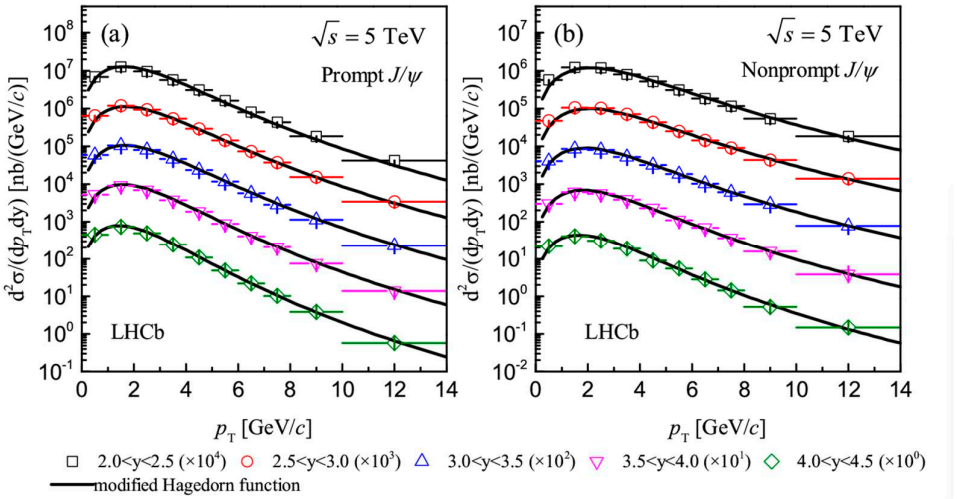

Figure 1. Transverse momentum distribution of(a) prompt J/ψ (b) nopromptJ/ψmesonsproduced in pp collisions at $\sqrt{s}$ =5 TeV.The hollowsymbolswith the error bars represent the experimental data of the LHCb Collaboration in literature [15], the curves are our results calculated by the modified Hagedorn function.

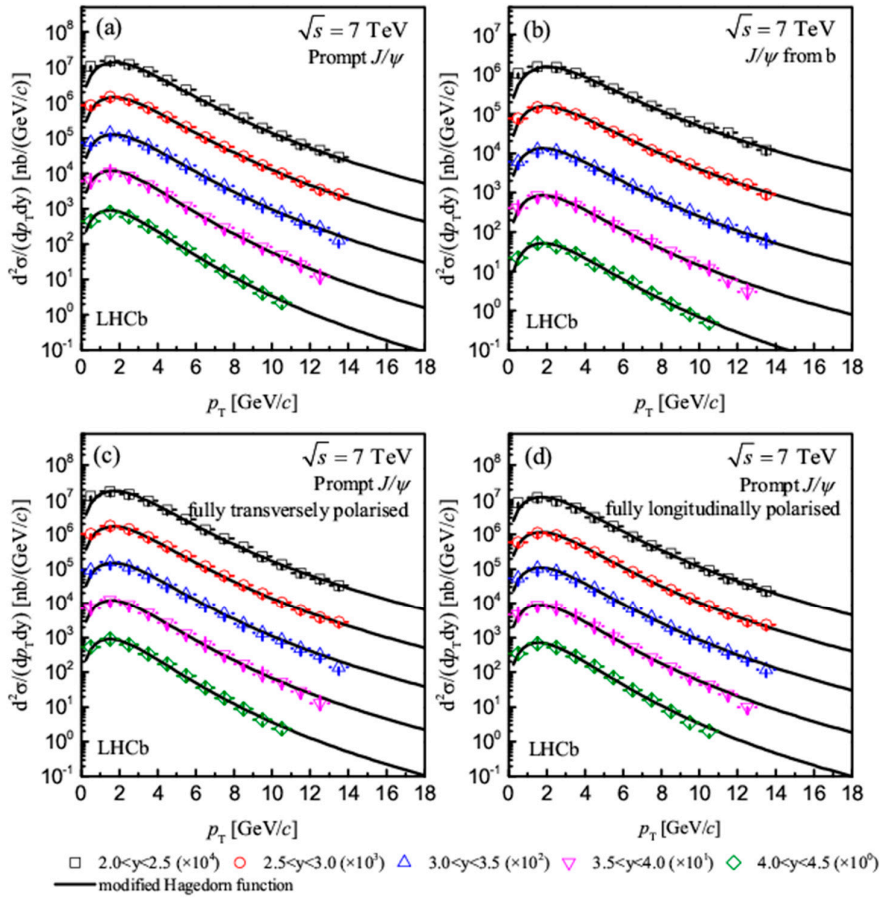

Figure 2. The same as Figure 1, but showing the results of(a) prompt J/ψ (b) J/ψ from b (c) prompt J/ψ (assuming fully transversely polarised) (d)prompt J/ψ (assuming fully longitudinally polarised)

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mesons produced in *pp* collisions at $\sqrt{s}=7$TeV. The experimental data are pouted from the literature [16].

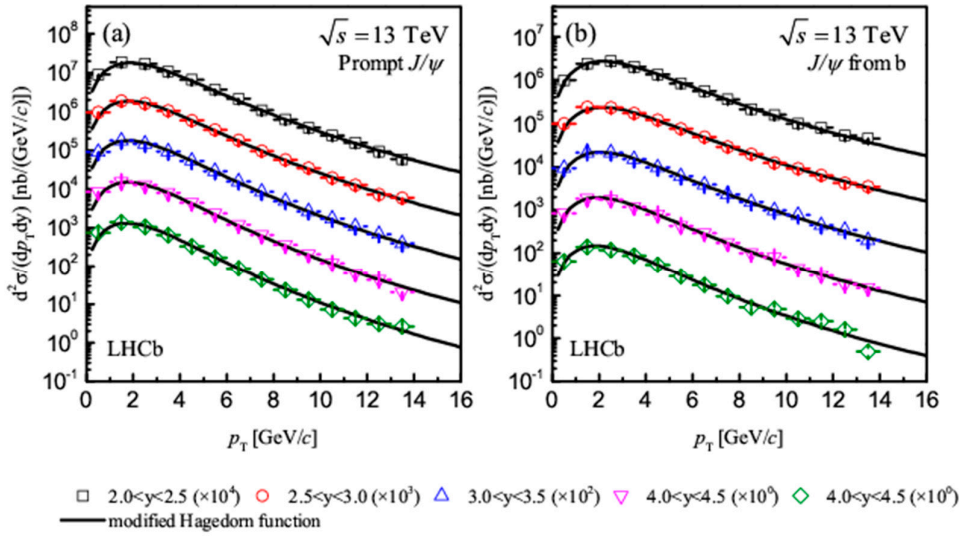

Figure 3. The same as Figure 1, but showing the results of(a) prompt J/ψ (b) J/ψ from b mesons produced in *pp* collisions at $\sqrt{s}=13$ TeV. The experimental data are pouted from the literature [17].

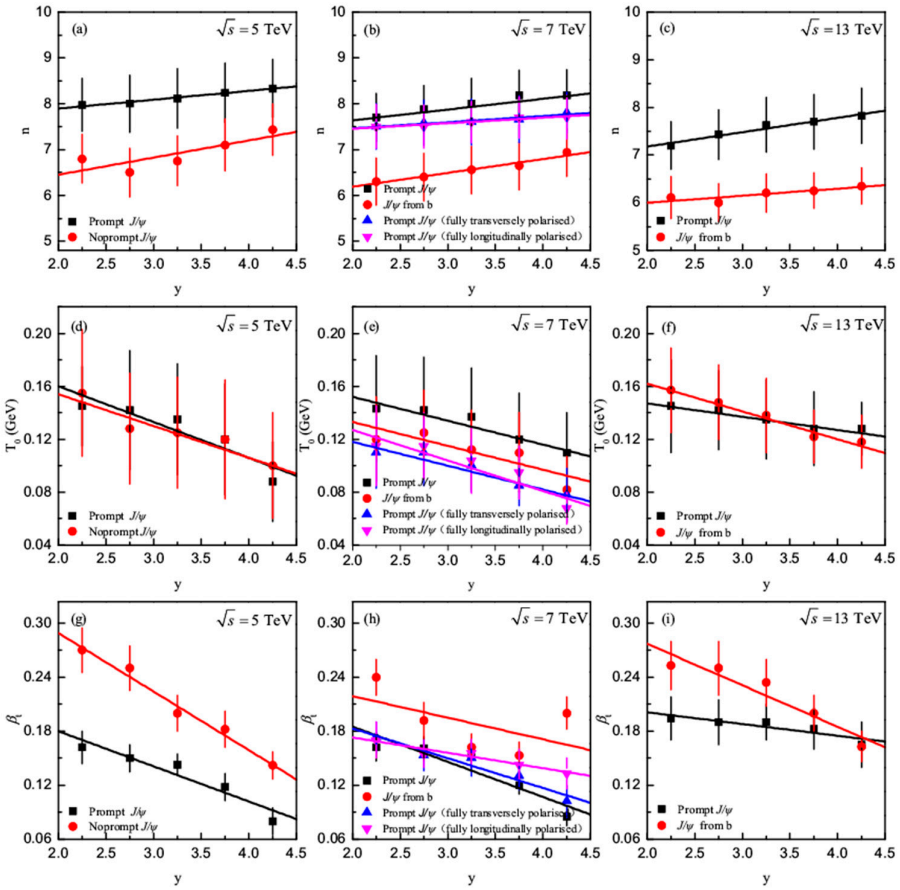

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Figure 4. The relationship of free parameters (n, T_0, β_t) and rapidity(y) for J/ψmesons produced in *pp* collisions at 5 TeV, 7 TeV, and13TeV. The solid symbols are quoted in Table 2, and the lines are our fitted results by the least square method.

Table 1. Values of parameters and χ^2/dof corresponding to the curves in Figures 1–3.

Figure	Type	*n*	T_0(GeV)	β_t	χ^2/dof	$\langle p_T \rangle$(GeV/c)	$\sqrt{\langle p_T^2 \rangle/2}$(GeV/$c$)
	2.0<y<2.5	7.975±0.580	0.145±0.030	0.162±0.018	1.875	2.647±0.051	2.238±0.088
	2.5<y<3.0	8.000±0.620	0.142±0.045	0.150±0.015	0.751	2.600±0.042	2.199±0.067
Figure 1(a)	3.0<y<3.5	8.120±0.650	0.135±0.042	0.143±0.012	0.694	2.526±0.023	2.134±0.033
	3.5<y<4.0	8.243±0.650	0.120±0.042	0.118±0.015	0.402	2.397±0.014	2.024±0.028
	4.0<y<4.5	8.335±0.635	0.088±0.030	0.080±0.015	0.357	2.191±0.032	1.849±0.034
Figure 1(b)	2.0<y<2.5	6.800±0.530	0.155±0.048	0.270±0.025	1.467	3.350±0.038	2.840±0.027
	2.5<y<3.0	6.500±0.530	0.128±0.042	0.250±0.025	1.672	3.298±0.033	2.809±0.078
	3.0<y<3.5	6.752±0.543	0.125±0.042	0.200±0.020	0.379	3.036±0.027	2.592±0.026
	3.5<y<4.0	7.102±0.570	0.120±0.045	0.182±0.020	0.333	2.852±0.029	2.428±0.027
	4.0<y<4.5	7.433±0.565	0.100±0.040	0.142±0.015	0.883	2.584±0.032	2.196±0.031
Figure 2(a)	2.0<y<2.5	7.703±0.522	0.143±0.040	0.162±0.015	1.256	2.706±0.093	2.294±0.104
	2.5<y<3.0	7.880±0.520	0.142±0.040	0.161±0.013	0.352	2.657±0.064	2.248±0.100
	3.0<y<3.5	8.000±0.550	0.137±0.037	0.152±0.013	0.460	2.590±0.033	2.189±0.053
	3.5<y<4.0	8.182±0.550	0.120±0.035	0.120±0.010	0.312	2.414±0.013	2.040±0.012
	4.0<y<4.5	8.184±0.556	0.110±0.030	0.085±0.010	0.173	2.300±0.024	1.947±0.013
Figure 2(b)	2.0<y<2.5	6.303±0.517	0.120±0.032	0.240±0.020	1.490	3.316±0.075	2.833±0.109
	2.5<y<3.0	6.400±0.520	0.125±0.032	0.192±0.020	0.277	3.143±0.062	2.696±0.082
	3.0<y<3.5	6.555±0.520	0.112±0.030	0.162±0.015	0.153	2.951±0.037	2.534±0.021
	3.5<y<4.0	6.648±0.520	0.110±0.030	0.153±0.015	0.483	2.886±0.035	2.477±0.019
	4.0<y<4.5	6.935±0.525	0.082±0.025	0.200±0.018	0.147	2.827±0.021	2.403±0.014
Figure 2(c)	2.0<y<2.5	7.505±0.500	0.110±0.027	0.173±0.017	0.823	2.679±0.035	2.270±0.013
	2.5<y<3.0	7.583±0.500	0.110±0.025	0.153±0.017	0.440	2.604±0.028	2.208±0.028
	3.0<y<3.5	7.602±0.503	0.100±0.020	0.150±0.020	0.690	2.559±0.020	2.169±0.012
	3.5<y<4.0	7.660±0.510	0.085±0.015	0.130±0.015	0.578	2.445±0.022	2.072±0.012
	4.0<y<4.5	7.801±0.450	0.078±0.020	0.102±0.018	0.227	2.322±0.018	1.967±0.010
Figure 2(d)	2.0<y<2.5	7.503±0.477	0.115±0.030	0.170±0.020	0.706	2.688±0.025	2.279±0.036
	2.5<y<3.0	7.505±0.470	0.115±0.025	0.155±0.015	0.158	2.646±0.023	2.246±0.029
	3.0<y<3.5	7.600±0.450	0.104±0.025	0.156±0.015	0.254	2.588±0.018	2.193±0.011
	3.5<y<4.0	7.702±0.450	0.095±0.020	0.143±0.017	0.945	2.500±0.015	2.116±0.013
	4.0<y<4.5	7.706±0.474	0.068±0.012	0.133±0.017	0.283	2.386±0.019	2.018±0.014
Figure 3(a)	2.0<y<2.5	7.202±0.500	0.145±0.035	0.194±0.024	0.950	2.940±0.037	2.500±0.059
	2.5<y<3.0	7.430±0.520	0.142±0.030	0.190±0.025	0.849	2.853±0.022	2.421±0.049
	3.0<y<3.5	7.632±0.578	0.135±0.030	0.190±0.020	0.799	2.777±0.012	2.349±0.018
	3.5<y<4.0	7.701±0.580	0.128±0.028	0.183±0.023	1.703	2.716±0.005	2.296±0.084
	4.0<y<4.5	7.820±0.580	0.128±0.020	0.165±0.025	1.578	2.637±0.003	2.230±0.031
Figure 3(b)	2.0<y<2.5	6.107±0.443	0.157±0.032	0.253±0.027	0.439	3.574±0.084	3.055±0.037
	2.5<y<3.0	6.000±0.400	0.148±0.028	0.250±0.030	0.540	3.581±0.055	3.065±0.088
	3.0<y<3.5	6.203±0.403	0.138±0.028	0.234±0.026	0.608	3.402±0.021	2.912±0.033
	3.5<y<4.0	6.252±0.372	0.122±0.020	0.200±0.020	0.529	3.217±0.026	2.762±0.091
	4.0<y<4.5	6.350±0.380	0.118±0.020	0.163±0.017	1.909	3.053±0.022	2.629±0.036

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Table 2. Values of intercepts, slopes, and χ^2/dof corresponding to the lines in Figures 4 and 5.

Figure	Type	Intercept	Slope	χ^2/dof
Figure 4(a)	prompt J/ψ	7.509±0.057	0.193±0.017	0.003
	nopromptJ/ψ	5.703±0.429	0.374±0.129	0.193
Figure 4(b)	prompt J/ψ	7.168±0.101	0.253±0.030	0.010
	J/ψ from b	5.585±0.111	0.302±0.033	0.014
	prompt J/ψ(fully transversely polarized)	7.195±0.067	0.134±0.020	0.006
	prompt J/ψ(fully longitudinally polarized)	7.211±0.064	0.121±0.019	0.006
Figure 4(c)	prompt J/ψ	6.577±0.108	0.301±0.033	0.012
	J/ψ from b	5.703±0.141	0.148±0.042	0.035
Figure 4(d)	prompt J/ψ	0.214±0.019	-0.027±0.006	0.095
	nopromptJ/ψ	0.202±0.014	-0.024±0.004	0.029
Figure 4(e)	prompt J/ψ	0.188±0.010	-0.018±0.003	0.021
	J/ψ from b	0.169±0.018	-0.018±0.005	0.116
	prompt J/ψ(fully transversely polarized)	0.154±0.008	-0.018±0.002	0.041
	prompt J/ψ(fully longitudinally polarized)	0.173±0.015	-0.023±0.005	0.252
Figure 4(f)	prompt J/ψ	0.167±0.004	-0.010±0.001	0.008
	J/ψ from b	0.204±0.005	-0.021±0.002	0.020
Figure 4(g)	prompt J/ψ	0.258±0.021	-0.039±0.006	0.684
	nopromptJ/ψ	0.419±0.015	-0.065±0.005	0.145
Figure 4(h)	prompt J/ψ	0.263±0.026	-0.039±0.008	1.336
	J/ψ from b	0.267±0.061	-0.024±0.018	3.890
	prompt J/ψ(fully transversely polarized)	0.249±0.014	-0.033±0.004	0.172
	prompt J/ψ(fully longitudinally polarized)	0.207±0.007	-0.017±0.002	0.072
Figure 4(i)	prompt J/ψ	0.227±0.011	-0.013±0.003	0.071
	J/ψ from b	0.369±0.025	-0.046±0.007	0.339
Figure 5(a)	prompt J/ψ	3.197±0.106	-0.223±0.032	5.515
	nopromptJ/ψ	4.310±0.122	-0.396±0.037	3.867
Figure 5(b)	prompt J/ψ	3.219±0.079	-0.211±0.024	1.735
	J/ψ from b	3.827±0.106	-0.247±0.032	3.345
	prompt J/ψ(fully transversely polarized)	3.089±0.052	-0.157±0.016	1.976
	prompt J/ψ(fully longitudinally polarized)	3.049±0.049	-0.150±0.015	1.941
Figure 5(c)	prompt J/ψ	3.268±0.014	-0.149±0.004	0.639
	J/ψ from b	4.279±0.121	-0.281±0.036	2.582
Figure 5(d)	prompt J/ψ	2.708±0.090	-0.191±0.027	1.809
	nopromptJ/ψ	3.658±0.115	-0.334±0.035	3.347
Figure 5(e)	prompt J/ψ	2.730±0.063	-0.180±0.019	1.212
	J/ψ from b	3.290±0.072	-0.216±0.022	3.840
	prompt J/ψ(fully transversely polarized)	2.619±0.045	-0.148±0.013	4.597
	prompt J/ψ(fully longitudinally polarized)	2.594±0.043	-0.130±0.013	2.625
Figure 5(f)	prompt J/ψ	2.791±0.015	-0.133±0.005	0.121
	J/ψ from b	3.635±0.101	-0.231±0.030	1.463

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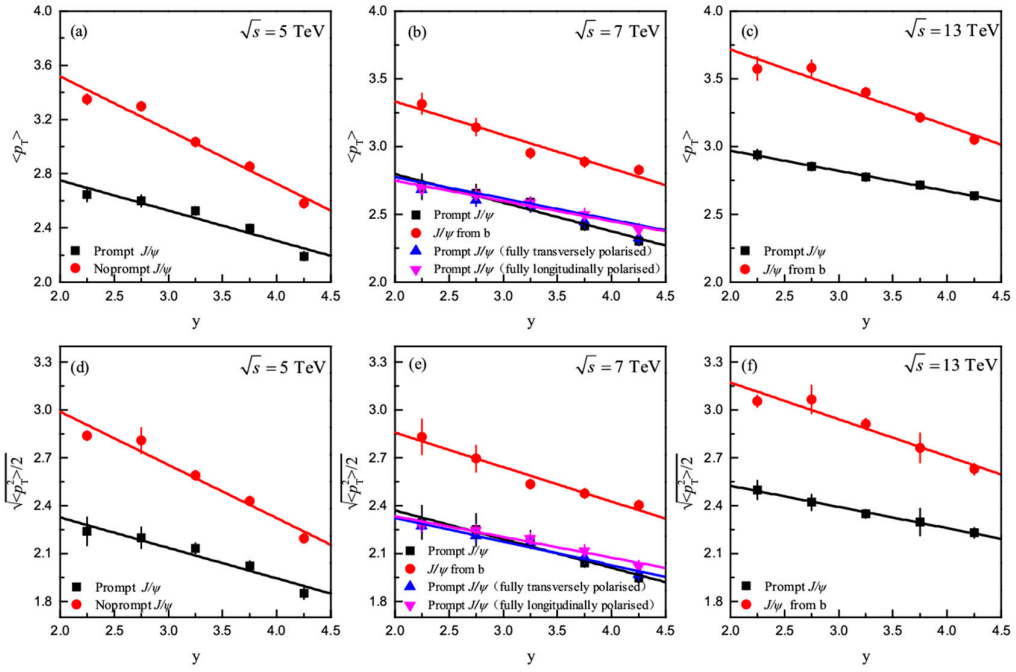

Figure 5. The same as Figure 4, but showing the relationship between physical quantity ((a)-(c) $\langle p_T \rangle$,(d)-(f) $\sqrt{\frac{\langle p_T^2 \rangle}{2}}$)and $y$forJ/ψmesons produced in pp collisions at 5 TeV, 7 TeV, and13 TeV.

Data Availability Statement: All data are quoted from the mentioned references. As a phenomenological work, this paper does not report new data.

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Conflicts of Interest: The authors declare that there are no conflicts of interest regarding the publication of this paper.

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