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Evidence for Statistical Production of J/ψ Mesons in Nuclear Collisions at the CERN SPS

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Abstract

The hypothesis of statistical production of J/ψ mesons at hadronization is formulated and checked against experimental data. It explains in the natural way the observed scaling behavior of the J/ψ to pion ratio at the CERN SPS energies. Using the multiplicities of J/ψ and η mesons the hadronization temperature $T_H \cong 170$ MeV is found, which agrees well with the previous estimates of the temperature parameter based on the analysis of the hadron yield systematics.

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Charmonium production in hadronic [1] and nuclear [2] collisions is usually considered to be composed of three stages: the creation of a $c\bar{c}$ pair, the formation of a bound $c\bar{c}$ state and the subsequent interaction of this $c\bar{c}$ bound state with the surrounding matter. The first process is calculated within perturbative QCD, whereas modeling of non–perturbative dynamics is needed to describe the last two stages (see, e.g. [3] and references therein). The interaction of the bound $c\bar{c}$ state with matter causes suppression of the finally observed charmonium yield relative to the initially created number of bound $c\bar{c}$ states. This initial number is assumed to be proportional to the number of Drell–Yan pairs, which then allows for the experimental study of the charmonium suppression pattern. It was proposed [4, 5] that the magnitude of the measured suppression in nuclear collisions can be used as a probe of the state of high density matter created at the early stage of the collision. The suppression of the J/ψ yield observed in p+A and O(S)+A collisions at the CERN SPS is considered to be caused by the interactions with nucleons occurring while the primordial baryons keep interpenetrating [6]. The rapid increase of the suppression (*anomalous suppression*) observed when going from peripheral to central Pb+Pb collisions [7] is often attributed to the formation of a quark–gluon plasma [8]. However alternative interpretations are still under discussion [2, 3, 9].

It was recently found [10, 11] that the mean multiplicity of J/ψ mesons increases proportionally to the mean multiplicity of pions when proton–proton (p+p), proton–nucleus (p+A) and nucleus–nucleus (A+A) collisions at CERN SPS energies are considered. We illustrate this unexpected experimental fact by reproducing in Fig. 1 the plot from Ref. [11], where the ratio $\langle J/\psi\rangle/\langle h^-\rangle$ is shown as a function of the mean number of nucleons participating in the interaction for inelastic nuclear collisions at the CERN SPS. The $\langle J/\psi\rangle$ and $\langle h^-\rangle$ denote here the mean multiplicites of J/ψ mesons and negatively charged hadrons (more than 90% are π^- mesons), respectively. We note that the analysis presented in Ref. [10] indicates that the scaling of the $\langle J/\psi\rangle/\langle h^-\rangle$ ratio is also valid for central Pb+Pb collisions at the CERN SPS.

In the standard picture of the J/ψ production based on the *hard creation* of $c\bar{c}$ pairs and the subsequent *suppression* of the bound $c\bar{c}$ states the observed scaling behavior of the J/ψ multiplicity appears to be due to an 'accidental' cancelation of several large effects. This motivates our effort to find an alternative production mechanism of J/ψ mesons which would explain the experimental data in a natural way.

In this letter we show that a scaling property of the J/ψ multiplicity

$$\frac{\langle J/\psi\rangle}{\langle h^-\rangle} \cong const(A) \tag{1}$$

can be understood assuming that a dominant fraction of J/ψ mesons is produced directly at hadronization according to the available hadronic phase space.

Since a long time [12] statistical models are used to describe hadron multiplicities in high energy collisions. Thermal hadron production models have been successfully used to fit the data on particle multiplicities in A+A collisions at the CERN SPS energies (see, e.g. [13, 14]). Due to the large number of particles a grand canonical formulation is used for the modeling of high energy heavy ion collisions [15, 14]. Recently, an impressive success of the statistical model applied to hadron multiplicities in elementary $e^+ + e^-$,

$p + p$ and $p + \bar{p}$ interactions at high energy was also reported [16]. However, in the latter case the use of a canonical formulation of the model, which assures exact conservation of the conserved charges, is necessary. The temperature parameter which characterizes the available phase space for the hadron production is found in these interactions to be 160–190 MeV [16]. It does not show any significant dependence on the type of reaction and on the collision energy. Moreover, it coincides with the chemical freeze–out temperature estimate obtained in hadron gas models for A+A collisions at the CERN SPS [13]. These facts suggest the possibility to ascribe the observed statistical properties of hadron production systematics in elementary and nuclear collisions at high energies to the statistical nature of the hadronization process [16, 14, 17].

Based on the above facts we formulate a hypothesis that **a dominant fraction of the J/ψ mesons produced in hadronic and nuclear collisions at the CERN SPS energies is created at hadronization according to the available hadronic phase space.**
J/ψ mesons are neutral and unflavored, i.e. all charges conserved in the strong interaction (electric charge, baryon number, strangeness and charm) are equal to zero for this particle. Therefore, its production is not influenced by the conservation laws of quantum numbers. For suffiently high collision energies, the effect of the strict energy–momentum conservation in the statistical model formulation can be neglected. Consequently, the J/ψ production can be calculated in the grand canonical approximation and, therefore, its multiplicity is proportional to the volume, V, of the matter at hadronization. Thus, the statistical yield of J/ψ mesons at hadronization is given by

$$\begin{aligned} \langle J/\psi \rangle \quad &= \quad \frac{(2j+1)\ V}{2\pi^2} \cdot \int_0^\infty p^2 dp\ \frac{1}{\exp[(p^2+m_\psi^2)^{1/2}/T_H]\ -\ 1} \\ &\cong \quad (2j+1) \cdot V \cdot \left(\frac{m_\psi T_H}{2\pi}\right)^{3/2} \cdot \exp\left(-\ \frac{m_\psi}{T_H}\right)\ , \end{aligned} \qquad (2)$$

where $j = 1$ and $m_\psi \cong 3097$ MeV are the spin and the mass of the J/ψ meson and T_H is the hadronization temperature. The previously mentioned results of the analysis of hadron yield systematics in elementary and nuclear collisions within the statistical approach indicate that the hadronization temperature T_H is the same for different colliding systems and collision energies. This reflects the universal feature of the hadronization process.
The total entropy of the produced matter is proportional to its volume. As most of the entropy in the final state is carried by pions, the pion multiplicity is also expected to be proportional to the volume of the hadronizing matter. Thus the scaling property (1) follows directly from the hypothesis of statistical production of J/ψ mesons at hadronization and the universality of the parameter T_H.
Since elements of hadronizing matter move in the overall center of mass system the volume V in Eq. (2) characterizes in fact the sum of the proper volumes of all elements in the collision event.

The hypothesis of statistical production of J/ψ mesons at a constant hadronization temperature T_H leads to the prediction of a second scaling property of the J/ψ multiplicity, namely:

$$\frac{\langle J/\psi \rangle}{\langle h^- \rangle} \cong const(\sqrt{s}) \tag{3}$$

which should be valid for sufficiently large c.m. energies, $\sqrt{s}$. This scaling property is illustrated in Fig. 2 which shows the ratio $\langle J/\psi \rangle / \langle h^- \rangle$ as a function of $\sqrt{s}$ for proton–nucleon interactions. The experimental data on J/ψ yields are taken from a compilation given in [18]. The values of $\langle h^- \rangle$ are calculated using a parameterization of the experimental results as proposed in [19].
Onwards from the CERN SPS energies, $\sqrt{s} \cong 20$ GeV, the ratio $\langle J/\psi \rangle / \langle h^- \rangle$ is approximately constant, in line with the expected scaling behavior (3). The rapid increase of the ratio with collision energy observed below $\sqrt{s} \cong 20$ GeV should be attributed to a significantly larger energy threshold for the J/ψ production than for the pion production. In terms of the statistical approach the effect of strict energy–momentum conservation has to be taken into account by use of the microcanonical formulation of the model.

The statistical J/ψ multiplicity (2) depends on two parameters, T_H and V. In general the calculation of the hadron yields in the statistical model should take into account the conservation of charges and resonance feeddown contributions. However, a simple way to estimate of the crucial temperature parameter in Eq. (2) from the experimental data is possible, provided that we find a second hadron which has the properties of the J/ψ meson i.e. it is neutral, unflavored and stable with respect to strong decays. The best candidate is the η meson. The multiplicity of η mesons seems to obey also the scaling properties (1) and (3). We note, however, that the data on η production are scarce. The independence of the $\langle \eta \rangle / \langle \pi^0 \rangle$ ratio on the collision energy was observed quite a long time ago [20]. Recent data on η production in central Pb+Pb collisions at the CERN SPS [21] suggest that the $\langle \eta \rangle / \langle \pi^0 \rangle$ ratio is also independent of the size of the colliding objects. In order to illustrate this scaling Fig. 3 shows the $\langle \eta \rangle / \langle \pi^0 \rangle$ ratio as a function of the number of interacting nucleons for inelastic p+p [22] and S+S [23] interactions and for central Pb+Pb [21] collisions at the CERN SPS energies (158–400 A GeV).
From the ratios, $\langle J/\psi \rangle / \langle h^- \rangle$ and $\langle \eta \rangle / \langle \pi^0 \rangle$, presented in Fig. 1 and Fig. 3 we estimate a mean ratio $\langle J/\psi \rangle / \langle \eta \rangle = (1.3 \pm 0.3) \cdot 10^{-5}$. Here we use the experimental ratio $\langle \pi^0 \rangle / \langle h^- \rangle \cong 1$ in N+N interactions [24]. Under the hypothesis of the statistical production of J/ψ and η mesons at hadronization the measured ratio can be compared to the ratio calculated using Eq. (2):

$$\frac{\langle J/\psi \rangle}{\langle \eta \rangle} \cong 3 \cdot \left(\frac{m_\psi}{m_\eta} \right)^{3/2} \cdot \exp\left(\frac{m_\eta - m_\psi}{T_H} \right) , \tag{4}$$

where $m_\eta \cong 547$ MeV is the mass of the η meson. This leads to an estimate of the hadronization temperature, $T_H = 170 \pm 2$ MeV. Assuming a maximum 50% uncertainty on the $\langle J/\psi \rangle / \langle \eta \rangle$ ratio due to the contribution from resonance decays[4] we obtain an estimate of an additional systematic error on T_H of about 7 MeV. A graphical solution of

[4] An estimate of the fraction of the η yield from decays of heavy hadrons in p+p interactions is about 50% [16], which is close to the measured fraction of J/ψ yield originating from decays (30–50%) [25, 2].

Eq. (4) is shown in Fig. 4 which illustrates the high sensitivity of the estimate of the T_H parameter by using the $\langle J/\psi \rangle / \langle \eta \rangle$ ratio. This is due to the large difference between mass of the J/ψ and the η mesons.

In summary, we show that the J/ψ production in hadronic and nuclear collisions can be understood assuming that a dominant fraction of J/ψ mesons is produced at hadronization according to the available hadronic phase space. The estimate of the hadronization temperature based on J/ψ multiplicity, $T_H \approx 170$ MeV, agrees well with the values of the temperature parameter obtained from the analysis of the hadron yield systematics in $e^+ + e^-$, $p + p$, $p + \bar{p}$ interactions and nucleus–nucleus collisions.

If the new interpretation of the J/ψ data presented in this letter is correct, it may have several important implications:

1. J/ψ yields are not sensitive to the state of high density matter created at the early stage of A+A collisions because their production takes place at hadronization.

2. The creation of the J/ψ mesons is due to the straight thermal production at hadronization and not due to the coalescence of $c\bar{c}$ quarks produced before hadronization. Therefore the yield of J/ψ mesons is independent of the production of open charm, which is carried mainly by the D mesons in the final state. The D meson multiplicity is determined by the number of $c\bar{c}$ quark pairs created in the early *parton stage* before the hadronization.

3. Due to the large mass of J/ψ mesons the data on their production are very sensitive to the value of the hadronization temperature and therefore allow for a precise study of the hadronization process.

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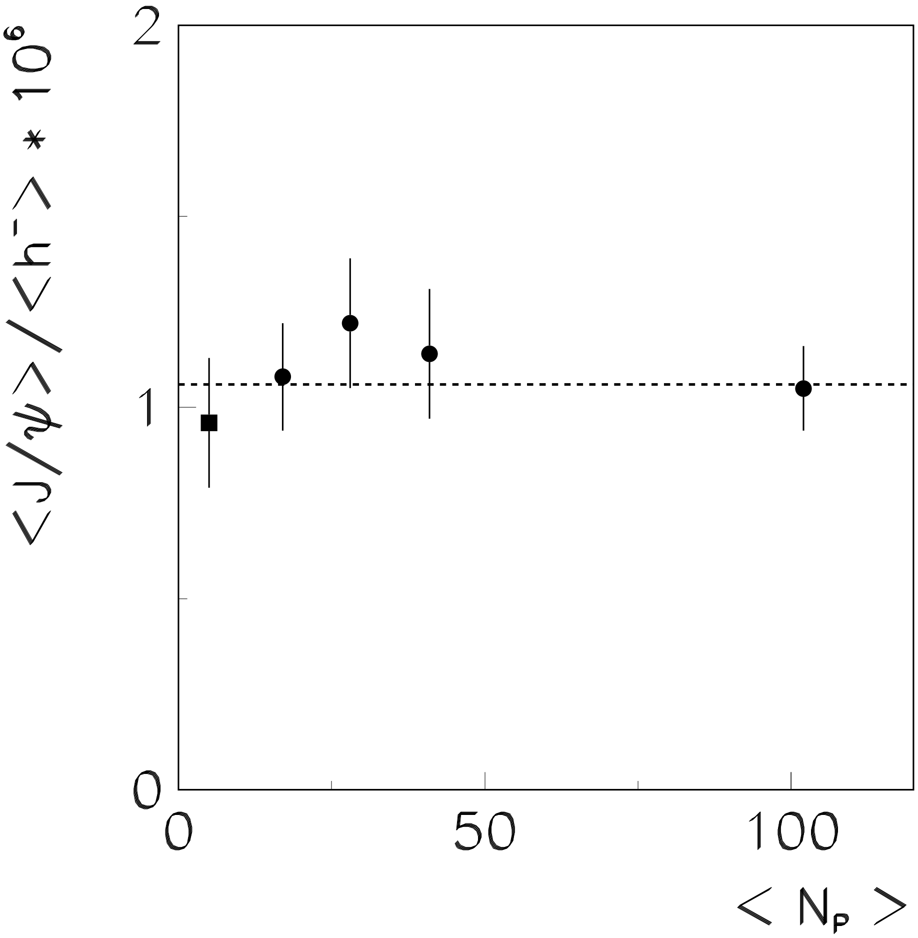

Figure 1: The ratio of the mean multiplicities of J/ψ mesons and negatively charged hadrons for inelastic nucleon–nucleon (square) and inelastic O+Cu, O+U, S+U and Pb+Pb (circles) interactions at 158 A·GeV plotted as a function of the mean number of participant nucleons. For clarity the N+N point is shifted from $\langle N_P \rangle = 2$ to $\langle N_P \rangle = 5$. The dashed line indicates the mean value of the ratio.

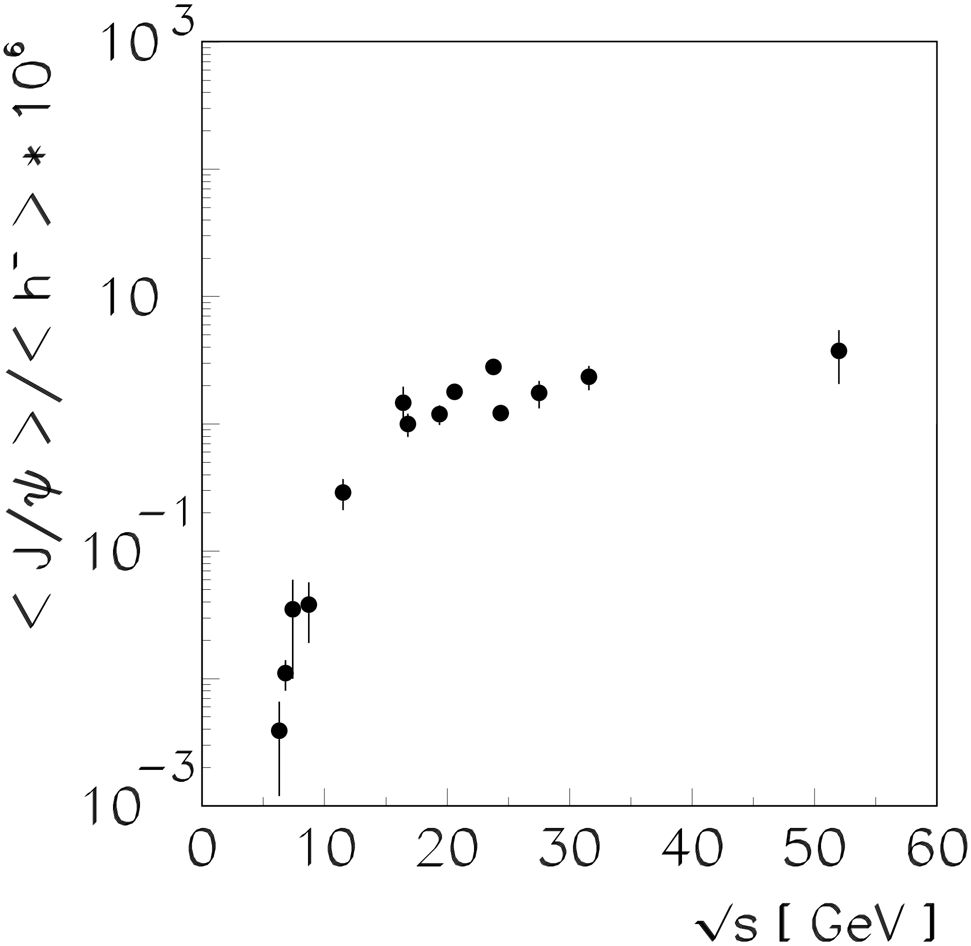

Figure 2: The ratio of the mean multiplicities of J/ψ mesons and negatively charged hadrons for inelastic proton–nucleon interactions as a function of the collision energy in the center of mass system.

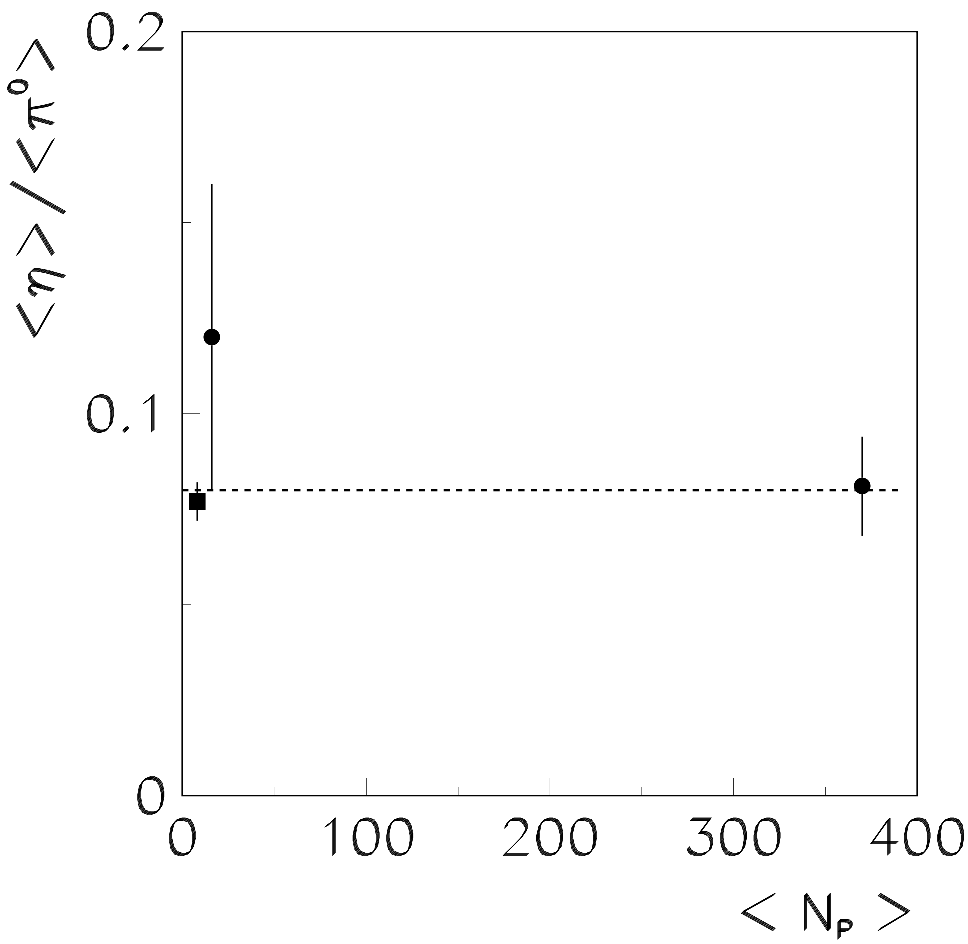

Figure 3: The ratio of the mean multiplicities of η mesons and π^0 mesons for inelastic p+p and S+S interactions and central Pb+Pb collisions at the CERN SPS energies as a function of the number of interacting nucleons. The result for Pb+Pb collisions was obtained in the rapidity interval 2.3–2.9.

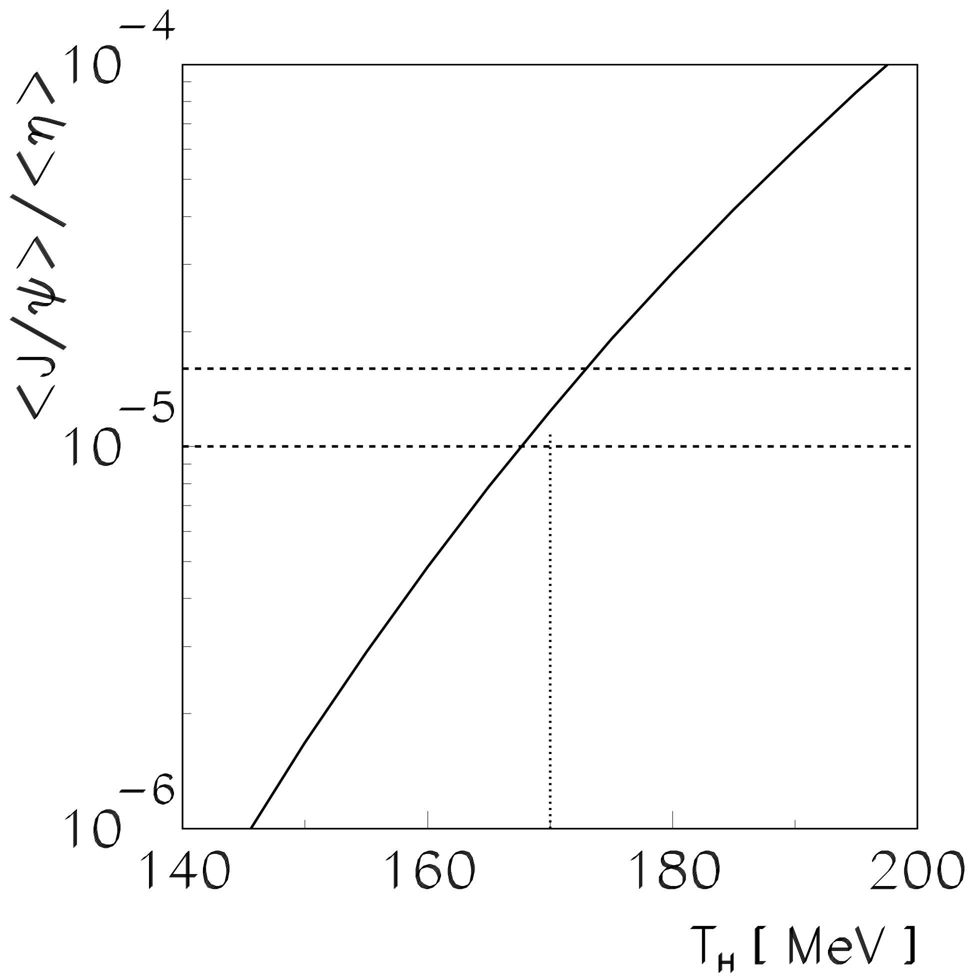

Figure 4: The $\langle J/\psi\rangle/\langle\eta\rangle$ ratio calculated under hypothesis of the statistical production of J/ψ and η mesons at hadronization (solid line) as a function of the hadronization temperature. Band shown by dashed lines is drawn at $\pm\sigma$ around the mean experimental value of the $\langle J/\psi\rangle/\langle\eta\rangle$ ratio. The dotted line indicates $T_H = 170$ MeV.