Production of charmonium states in heavy ion collisions

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Pusan National University

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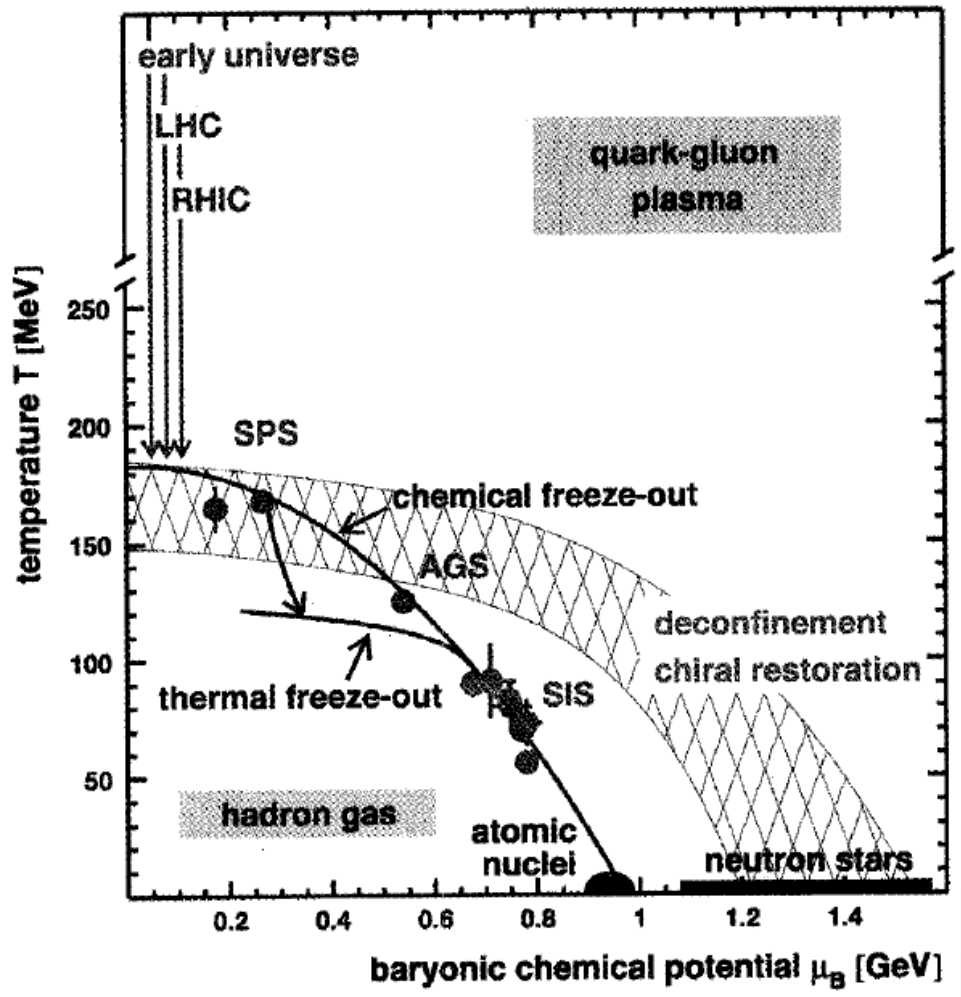
Outline

- Introduction
- Charmonium states
- Hadron production
- Charmonium states in heavy ion collisions
- Conclusion

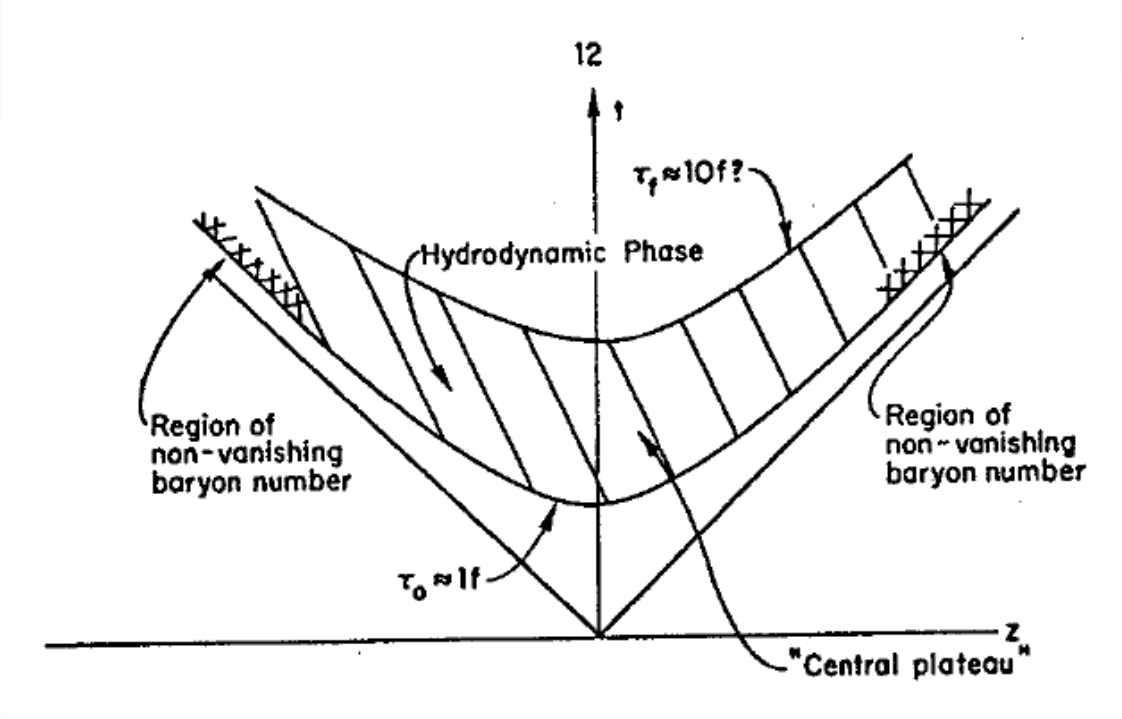
Introduction

– QCD phase diagram



P. Braun-Munzinger and J. Stachel, Nucl. Phys. A **690**, 119c (2001)

– Time evolution of quark-gluon plasma



$$\tau = \sqrt{t^2 - z^2}$$

J. D. Bjorken, Phys. Rev. D **27**, 140 (1983)

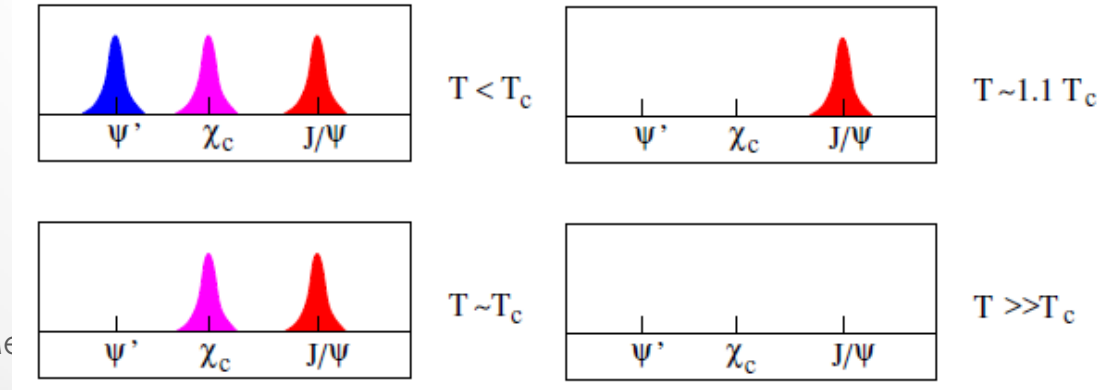
i. Collision
ii. Pre-equilibrium state and Quark-gluon plasma
iii. Hydrodynamic expansion
iv. Chemical freeze-out
v. Kinetic freeze-out

Charmonium states

– Quarkonia

1) The bound states of a heavy quark and its anti-quark
The measured stable charmonium:
the 1S scalar η_c and vector J/ψ, three 1P states χ_c (scalar, vector, and tensor), and the 2S vector state ψ'

2) The different charmonium states melt sequentially as a function of their binding strength;
the most loosely bound state disappears first, the ground state last



H. Satz, J. Phys. G. **32**, R25 (2006)

– J/ψ suppression and Debye screening

T. Matsui and H. Satz, Phys. Lett. **B178** 416 (1986)

1) At $T > T_C$ color charges are Debye screened in QGP

$$V = -\frac{4}{3}\frac{\alpha_s}{r} \rightarrow V = -\frac{4}{3}\frac{\alpha_s}{r} e^{-r/\lambda_D} \qquad \lambda_D = \frac{1}{gT\sqrt{\frac{N_C}{3} + \frac{N_f}{6}}}$$

Compared to the Bohr radius r_B , the Debye screening prevents the formation of the bound states when $r_B > \lambda_D$

2) The measure for the effect of the quark-gluon plasma on the J/ψ suppression : the nuclear modification factor

$$R_{AA} = \frac{1}{N_{Coll}} \frac{dN^{AA}_{J/\psi}/d\vec{p}_T}{dN^{pp}_{J/\psi}/d\vec{p}_T} = \frac{\sigma^{pp}_{inel}}{N_{Coll}} \frac{dN^{AA}_{J/\psi}/d\vec{p}_T}{d\sigma^{pp}_{J/\psi}/d\vec{p}_T}$$

Hadron production

– Statistical hadronization

P. Braun-Munzinger, J. Stachel, J. P. Wessels, N. Xu, Phys. Lett. **B344**, 43 (1995)
P. Braun-Munzinger, J. Stachel, J. P. Wessels, N. Xu, Phys. Lett. **B365**, 1 (1996)

1) In a chemically and thermally equilibrated system of non-interacting hadrons, the particle production yield is given by

$$N_i = V_H \frac{g_i}{2\pi^2} \int_0^\infty \frac{p^2 dp}{e^{(E_i-\mu_i)/T_H} \pm 1} \qquad E_i = \sqrt{m_i^2 + p_i^2}$$

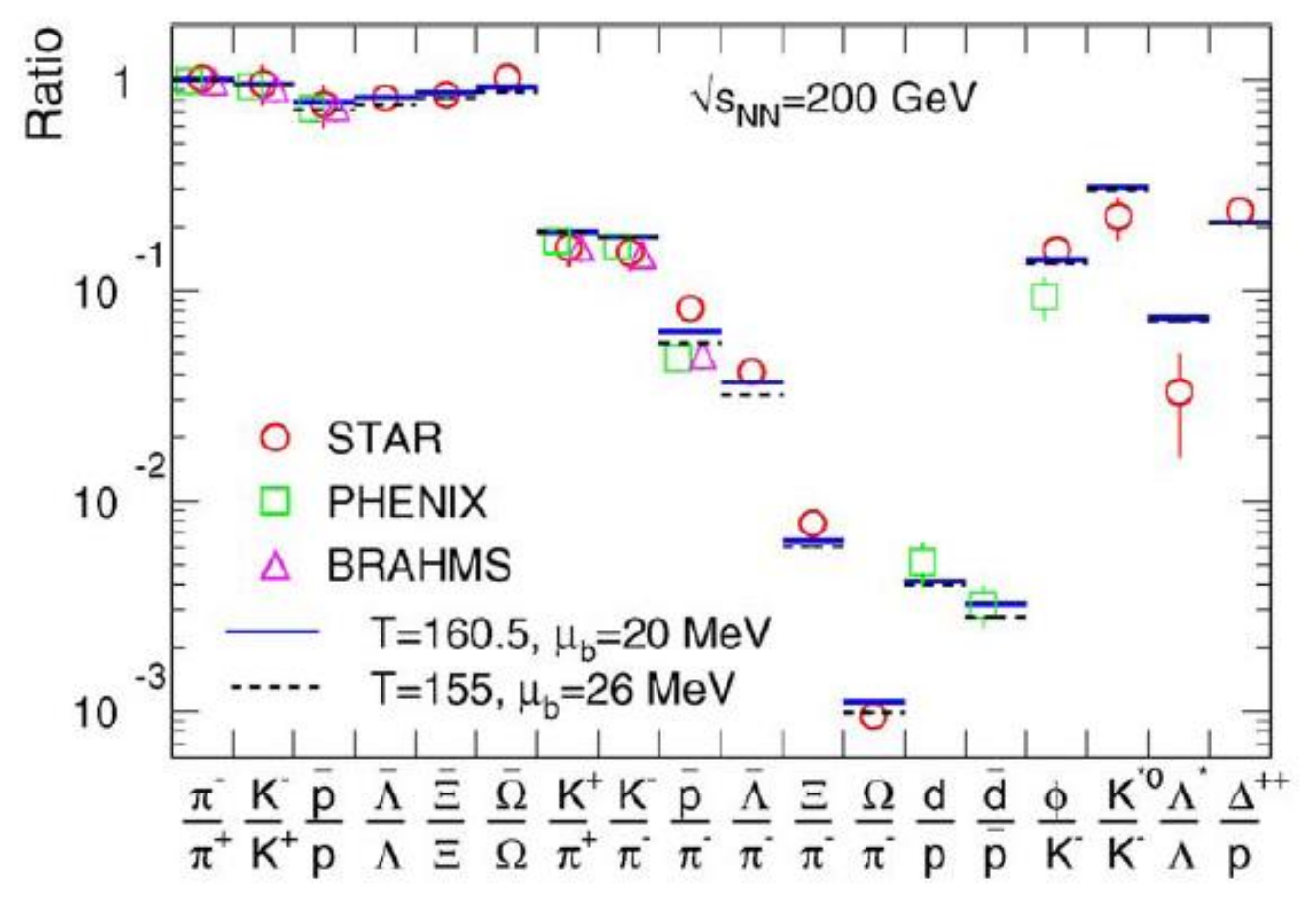
with the chemical potential

$$\mu_i = \mu_B B_i + \mu_{I_3} I_{3i} + \mu_S S_i + \mu_C C_i$$

satisfying $V\sum_i n_i B_i = N_B$, $V\sum_i n_i I_{3i} = I_3^{tot}$, $\sum_i n_i S_i = 0$, and $\sum_i n_i C_i = 0$

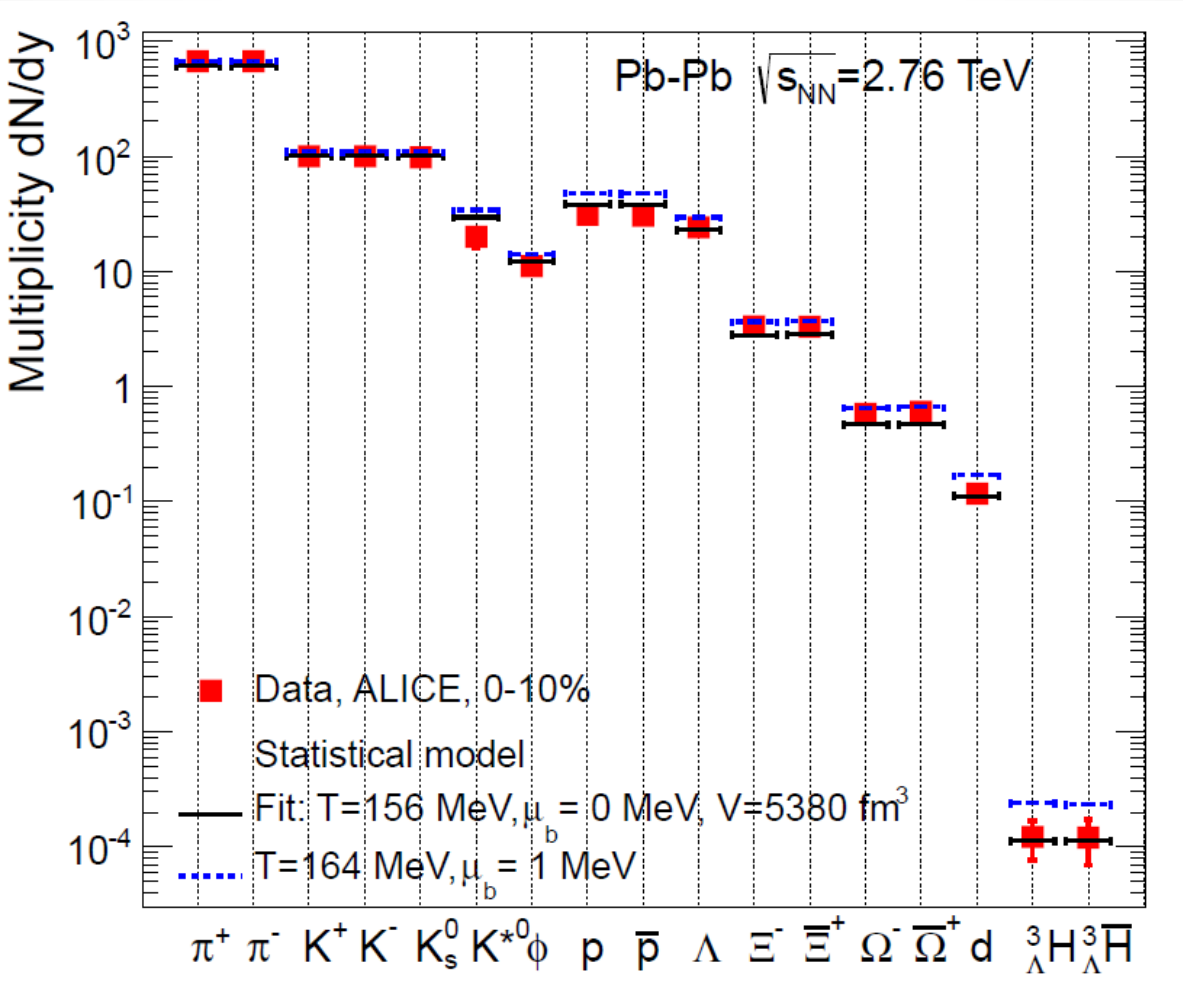
2) The hadronization temperature and the baryon chemical potential should be determined from the experimental data

3) Particle yields ratio at RHIC



A. Andronic, P. Braun-Munzinger, and J. Stachel, Nucl. Phys. A **772**, 167 (2006)

4) Particle yields ratio at LHC



J. Stachel, A. Andronic, P. Braun-Munzinger, and K. Redlich, J. Phys. Conf. Ser. **509**, 012019 (2014)

– Coalescence production of hadrons

1) Covariant coalescence

C. B. Dover, U. Heinz, E. Schnedermann, and J. Zimanyi, Phys. Rev. C **44**, 1636 (1991)

i. A covariant coalescence model for relativistically expanding fireball formed in high-energy nucleus collisions is developed and applied to predict the formation rate of hadrons like deuteron, or pentaquark

ii. Coalescence is basically a non-relativistic phenomenon

The cluster distribution factorizes for arbitrary parent rapidity distributions :

$$\frac{dN_C}{dy} = C\frac{dN_1}{dy}\frac{dN_2}{dy} \qquad N_C = CN_1N_2$$

iii. Observation of the antimatter hypernucleus

Particle type	Ratio
$^{3}_{\Lambda}\overline{\mathrm{H}}/^{3}_{\Lambda}\mathrm{H}$	0.49 ± 0.18 ± 0.07
$^{3}\overline{\mathrm{He}}/^{3}\mathrm{He}$	0.45 ± 0.02 ± 0.04
$^{3}_{\Lambda}\overline{\mathrm{H}}/^{3}\overline{\mathrm{He}}$	0.89 ± 0.28 ± 0.13
$^{3}_{\Lambda}\mathrm{H}/^{3}\mathrm{He}$	0.82 ± 0.16 ± 0.12

B. Abelev *et al*. [The STAR Collaboration], Science, **328**, 58 (2010)

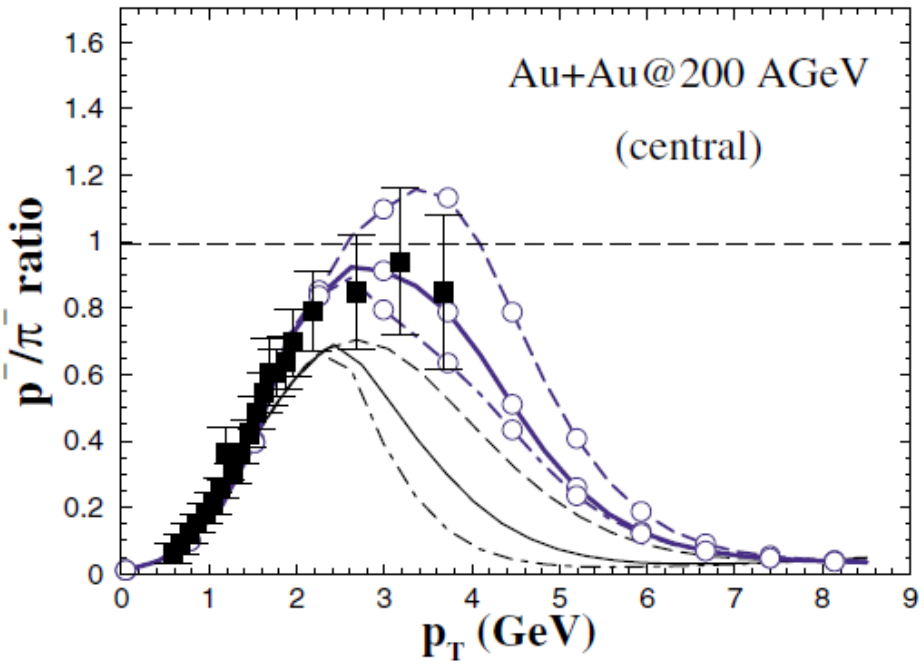
2) The puzzle in antiproton/pion ratio

V. Greco, C. M. Ko, and P. Levai, Phys. Rev. Lett. **90**, 202302 (2003)
R. J. Freis. B. Muller, C. Nonaka, and S. Bass, Phys. Rev. Lett. **90**, 202303 (2003)

A competition between two particle production mechanisms

: A fragmentation dominates at large transverse momenta and a coalescence prevails at lower transverse momento

$$p_T^{Frag} = \frac{p_T^h}{z} \quad \text{vs.} \quad p_T^{Coal} = \frac{p_T^h}{n}$$



3) Quark number scaling of the elliptic flow

Denes Molnar and Sergei A. Voloshin, Phys. Rev. Lett **91**, 092301 (2003)

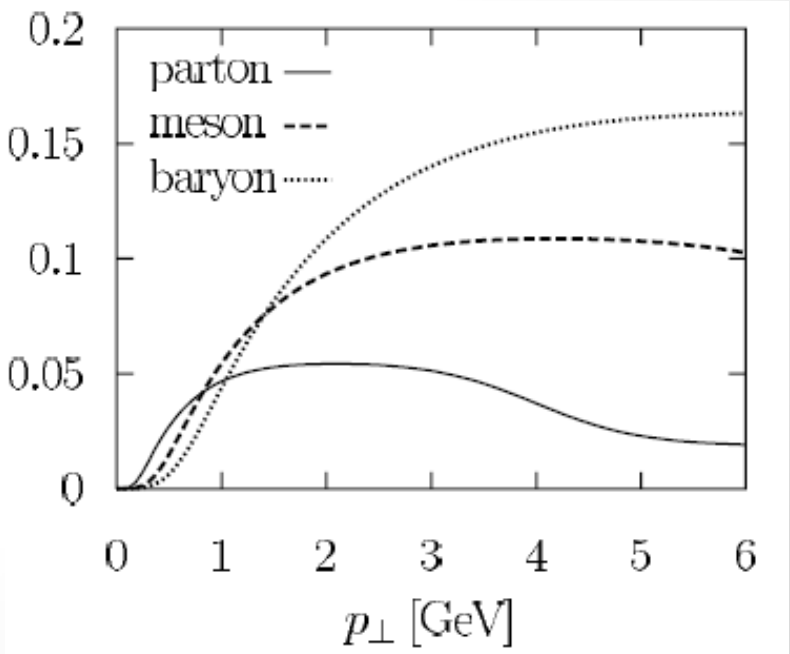
$$v_2(p_T) = \frac{\int d\varphi \cos 2\varphi \frac{d^2N}{dp_T^2}}{\int d\varphi \frac{d^2N}{dp_T^2}} \qquad \frac{dN_q}{p_T dp_T d\varphi} = \frac{1}{2\pi}\frac{dN_q}{p_T dp_T}\left[1 + 2v_{2,q}(p_T)\cos(2\varphi)\right]$$

Coalescence model predicts

$$v_{2,M}(p_T) = \frac{2v_{2,q}(p_T/2)}{1+2v_{2,q}^2(p_T/2)}$$

$$v_{2,B}(p_T) = \frac{3v_{2,q}(p_T/3)+3v_{2,q}^3(p_T/3)}{1+6v_{2,q}^2(p_T/3)}$$

$$v_{2,h}(p_T) \approx n v_{2,q}\left(\frac{1}{n}p_T\right)$$



4) Yields of hadrons

V. Greco, C. M. Ko, and P. Levai, Phys. Rev. C **68**, 034904 (2003)
R. J. Freis. B. Muller, C. Nonaka, and S. Bass, Phys. Rev. C **68**, 044902 (2003)

$$N^{Coal} = g\int\left[\prod_{i=1}^{n}\frac{1}{g_i}\frac{p_i\cdot d\sigma_i}{(2\pi)^3}\frac{d^3p_i}{E_i}\,f(x_i,p_i)\right]f^W(x_1,\cdots,x_n:p_1,\cdots,p_n)$$

with the Wigner function, the coalescence probability function

$$f^W(x_1,\cdots,x_n:p_1,\cdots,p_n)$$
$$=\int\prod_{i=1}^{n}dy_i e^{p_i y_i}\psi^*\left(x_1+\frac{y_1}{2},\cdots,x_n+\frac{y_n}{2}\right)\psi\left(x_1-\frac{y_1}{2},\cdots,x_n-\frac{y_n}{2}\right)$$

i. A Lorentz-invariant phase space integration of a space-like hypersurface constraints the number of particles in the system

$$\int p_i\cdot d\sigma_i\frac{d^3p_i}{(2\pi)^3E_i}\,f(x_i,p_i)=N_i$$

ii. The transverse momentum spectra

$$\frac{dN_M}{d^2\mathbf{p}_T} = g_M \frac{6\pi}{\tau \Delta y R_\perp^2 \Delta_p^3} \int d^2\mathbf{p}_{1T} d^2\mathbf{p}_{2T} \left.\frac{dN_q}{d^2\mathbf{p}_{1T}}\right|_{|y_1|\le \Delta y/2} \left.\frac{dN_q^-}{d^2\mathbf{p}_{2T}}\right|_{|y_2|\le \Delta y/2}$$
$$\times \delta^{(2)}(\mathbf{p}_T - \mathbf{p}_{1T} - \mathbf{p}_{2T}) \Theta\left(\Delta_p^2 - \frac{1}{4}(\mathbf{p}_{1T} - \mathbf{p}_{2T}) - \frac{1}{4}[(m_{1T} - m_{2T})^2 - (m_1 - m_2)^2]\right).$$

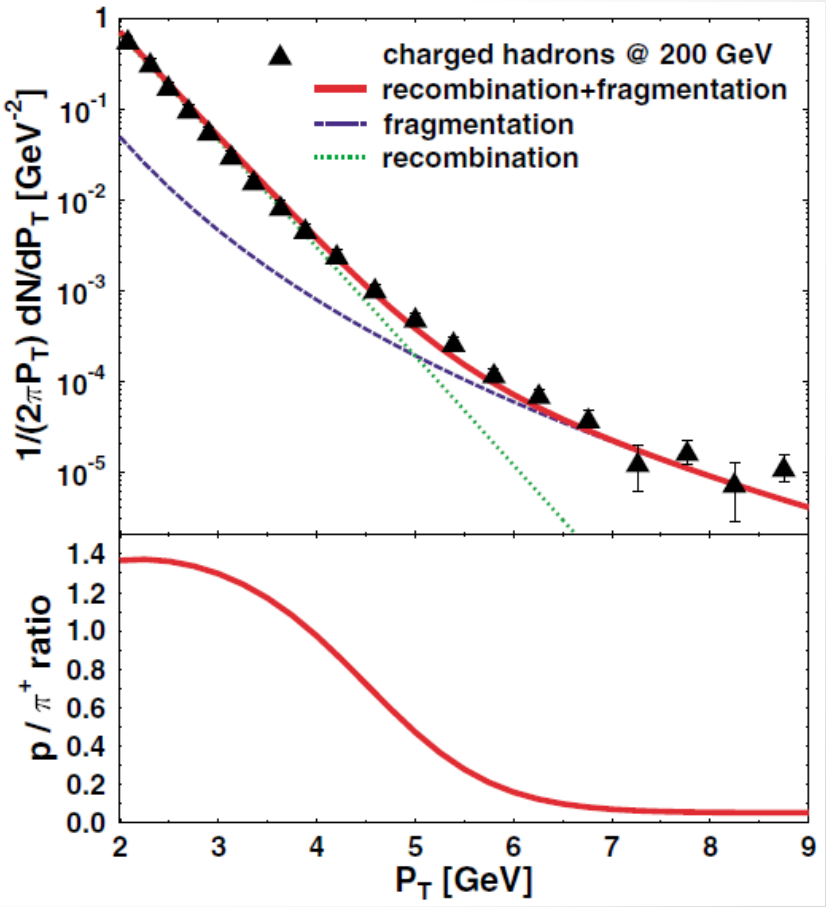
$$f_M(x_1, x_2; p_1, p_2) = \frac{9\pi}{2(\Delta_x \Delta_p)^3} \Theta(\Delta_x^2 - (x_1 - x_2)^2)$$
$$\times \Theta\left(\Delta_p^2 - \frac{1}{4}(p_1 - p_2)^2 + \frac{1}{4}(m_1 - m_2)^2\right).$$

and

$$E\frac{dN_M}{d^3P} = C_M \int_\Sigma \frac{d^3RP \cdot u(R)}{(2\pi)^3} \int \frac{d^3q}{(2\pi)^3}$$
$$\times w_a\left(R; \frac{\mathbf{P}}{2} - \mathbf{q}\right) \Phi_M^W(\mathbf{q}) w_b\left(R; \frac{\mathbf{P}}{2} + \mathbf{q}\right)$$

$$\Phi_M^W(\mathbf{q}) = \int d^3r \Phi_M^W(\mathbf{r}, \mathbf{q})$$

$$\Phi_M^W(\mathbf{r}, \mathbf{q}) = \int d^3r' e^{-i\mathbf{q}\cdot\mathbf{r}'} \varphi_M\left(\mathbf{r} + \frac{\mathbf{r}'}{2}\right) \varphi_M^*\left(\mathbf{r} - \frac{\mathbf{r}'}{2}\right)$$



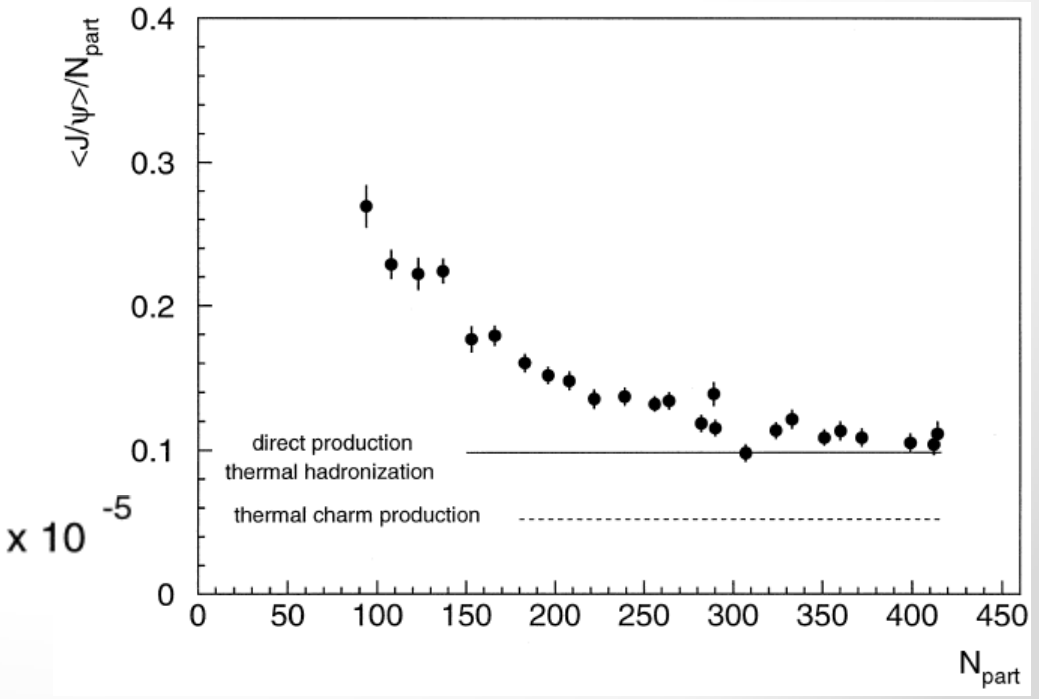
Charmonium states in heavy ion collisions

– Statistical hadronization of J/ψ mesons

P. Braun-Munzinger and J. Stachel, Phys. Lett. **B490**, 196 (2000)

1) All $c\bar{c}$ pairs are produced in direct, hard collisions. Charmed hadron production proceeds through a state of chemical equilibrium near or at the phase boundary

i. The yield of directly produced charm is slightly larger than that produced if charm is in full chemical equilibrium



– Charmonium production in heavy ion collis

1) Charmonium production ratios versus statistical predictions

Ratio	$\psi'/(J/\psi)$	$\chi_{c1}/(J/\psi)$	$\chi_{c2}/(J/\psi)$
Experimental	0.23	1.06	1.50
Statistical	0.045	0.113	0.148

H. Satz, J. Phys. G. **32**, R25 (2006)

2) The production yield ratio between the J/ψ and the ψ'

T	160	170	180
$dN_{J/\psi}/dy$	0.0111	0.0106	0.0103
$N_{\psi'}/N_{J/\psi}$	0.031	0.037	0.045

A. Andronic, P. Braun-Munzinger, K. Redlich, and J. Stachel, Phys. Lett. B **571,** 36 (2003)

3) Statistical Hadronization of charmed mesons

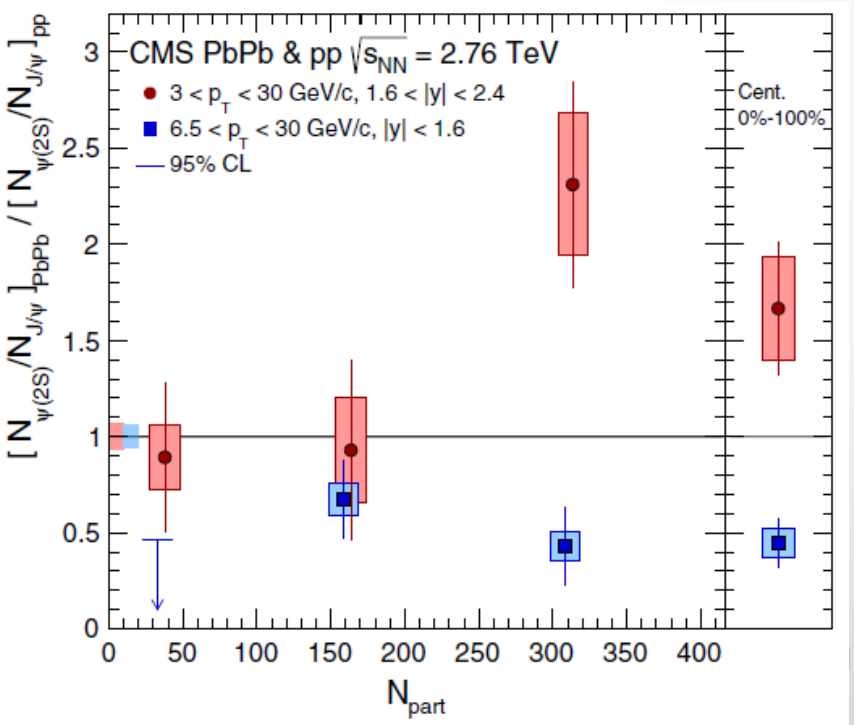
$$N_i = V_H \frac{g_i}{2\pi^2} \int_0^\infty \frac{p^2 dp}{\gamma_i^{-1} e^{E_i/T_H} \pm 1} \qquad \gamma_c = 6.40$$

S. Cho et al, (EXHIC Collaboration), Phys. Rev. Lett. **106**, 212001

$$\frac{N_{\psi(2S)}}{N_{J/\psi(2S)} + 0.603 N_{\psi(2S)} + 0.348 N_{\chi_{c1}} + 0.198 N_{\chi_{c2}}} = 0.040$$

4) The production yield ratio between the J/ψ and the ψ'

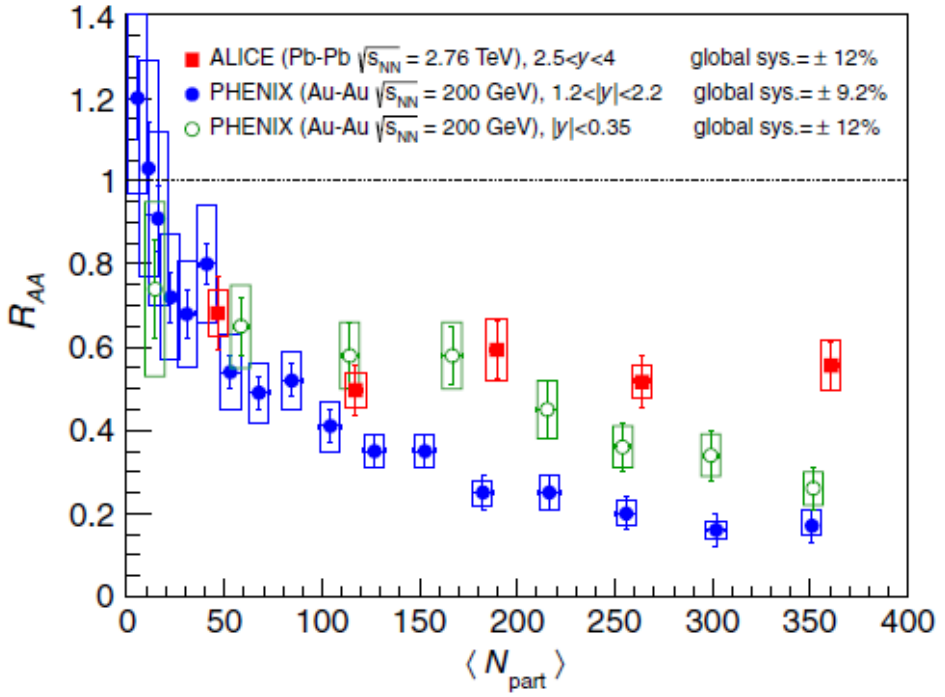
V. Khachatryan et al,
Phys. Rev. Lett. **113,** 262301 (2014)

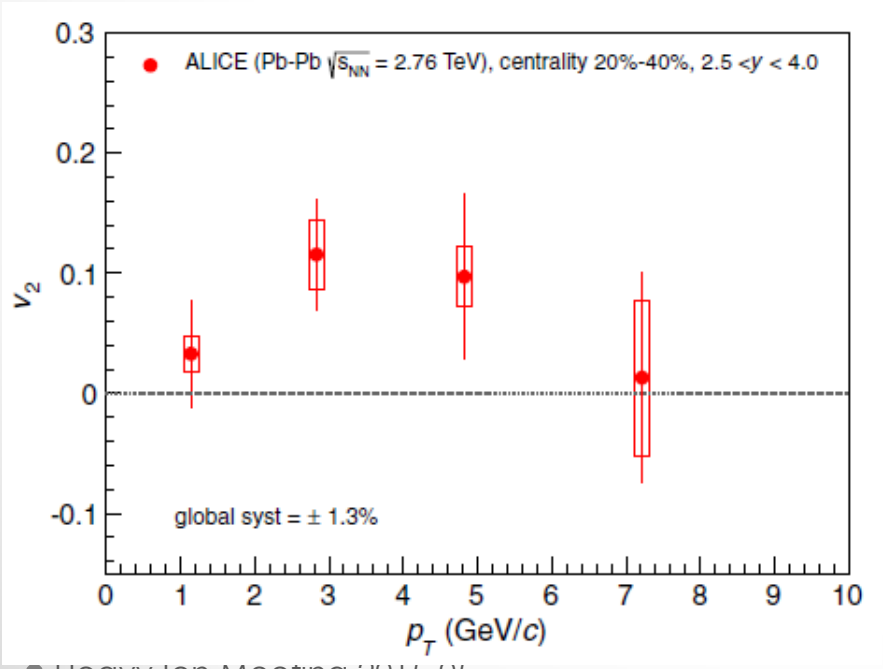


– Regeneration of J/ψ mesons

1) The nuclear modification factor of J/ψ mesons

B. Abelev et al, (ALICE Collaboration), Phys. Rev. Lett. **109**, 072301





2) Elliptic flow of the J/ψ

E. Abbas et al, Phys. Rev. Lett. **111**, 162301 (2013)

– Charmonium production by recombinatio

1) Coalescence production of charmonia - PYTHIA

$$\frac{d^2N_M}{d\mathbf{p}_{\mathrm{T}}^2} = g_M \int \prod_{i=1}^{2} \frac{p_i \cdot d\sigma_i \, d^3\mathbf{p}_i}{(2\pi)^3 E_i} f_q(x_1, p_1) f_{\bar{q}}(x_2, p_2) \times f_M(x_1, p_1; x_2, p_2) \delta^{(2)}(\mathbf{p}_{\mathrm{T}} - \mathbf{p}_{1\mathrm{T}} - \mathbf{p}_{2\mathrm{T}})$$

Number of charmonia produced from charm-quark coalescence at mid-rapidity in central collisions of Au + Au at $\sqrt{s} = 200$ GeV

	$N_{J/\psi}$	$N_{\chi c}$	$N_{\psi'}$
PYTHIA	0.8×10^{-3}	0.5×10^{-4}	0.2×10^{-4}

V. Greco, C. M. Ko, and R. Rapp, Phys. Lett. B **595**, 202 (2004)

2) The transverse momentum distribution of the charmonium yield

$$N_\psi = g_\psi \int p_c \cdot d\sigma_c p_{\bar{c}} \cdot d\sigma_{\bar{c}} \frac{d^3\vec{p}_c}{(2\pi)^3 E_c} \frac{d^3\vec{p}_{\bar{c}}}{(2\pi)^3 E_{\bar{c}}} f_c(r_c, p_c) f_{\bar{c}}(r_{\bar{c}}, p_{\bar{c}}) W_\psi(r_c, r_{\bar{c}}; p_c, p_{\bar{c}}),$$

$$\frac{dN_\psi}{d^2\vec{p}_T} = \frac{g_\psi}{V} \int d^3\vec{r} d^2\vec{p}_{cT} d^2\vec{p}_{\bar{c}T} \delta^{(2)}(\vec{p}_T - \vec{p}_{cT} - \vec{p}_{\bar{c}T}) \frac{dN_c}{d^2\vec{p}_{cT}} \frac{dN_{\bar{c}}}{d^2\vec{p}_{\bar{c}T}} W_\psi(\vec{r}, \vec{k})$$

V. Greco, C. M. Ko, and P. Levai, Phys. Rev. C **68**, 034904 (2003)

2) Gaussian Wigner functions for different charmonium states

$$W_s(\vec{r},\vec{k}) = 8e^{-\frac{r^2}{\sigma^2}-k^2\sigma^2}$$

$$W_p(\vec{r},\vec{k}) = \left(\frac{16}{3}\frac{r^2}{\sigma^2} - 8 + \frac{16}{3}\sigma^2k^2\right)e^{-\frac{r^2}{\sigma^2}-k^2\sigma^2}$$

$$W_{\psi_{10}}(\vec{r},\vec{k}) = \frac{16}{3}\Big(\frac{r^4}{\sigma^4} - 2\frac{r^2}{\sigma^2} + \frac{3}{2} - 2\sigma^2k^2 + \sigma^4k^4 - 2r^2k^2 + 4(\vec{r}\cdot\vec{k})^2\Big)e^{-\frac{r^2}{\sigma^2}-k^2\sigma^2}.$$

3) Coulomb Wigner functions

S. Cho, arXiv: 1408.4756

$$W_\psi(\vec{r},\vec{k}) = \int d^3\vec{q}\,\psi^*(\vec{r}+\vec{q}/2)e^{i\vec{k}\cdot\vec{q}}\psi(\vec{r}-\vec{q}/2)$$

$$= \int \frac{d^3\vec{q}}{(2\pi)^3}\tilde{\psi}^*(\vec{k}+\vec{q}/2)e^{-i\vec{r}\cdot\vec{q}}\tilde{\psi}(\vec{k}-\vec{q}/2),$$

$$W_{\psi_{1S}}(\vec{r},\vec{k}) = \frac{16}{a_0^5}\int_0^1 duu(1-u)e^{-2i(1-2u)\vec{k}\cdot\vec{r}}e^{-2rC(u)}\left(\frac{3}{C(u)^5} + \frac{6}{C(u)^4}r + \frac{4}{C(u)^3}r^2\right),$$

$$C(u) = (1/a_0^2 + 4u(1-u)k^2)^{1/2}$$

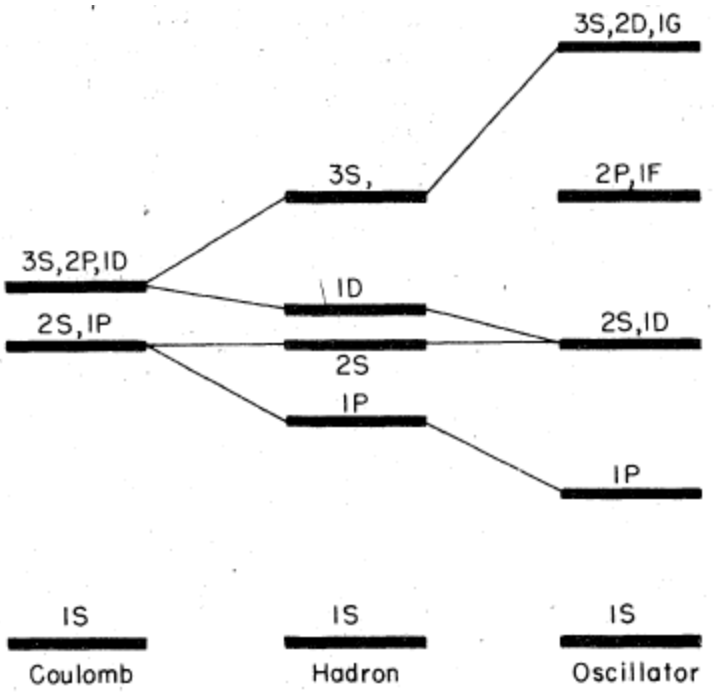
$$W_{\psi_{2S}}(\vec{r},\vec{k}) = \frac{1}{32a_0^9}\int_0^1 duu^2(1-u)^2e^{-2i(1-2u)\vec{k}\cdot\vec{r}}\left(\frac{105}{D(u)^9} + \frac{210}{D(u)^8}r + \frac{180}{D(u)^7}r^2 + \frac{80}{D(u)^6}r^3 + \frac{16}{D(u)^5}r^4\right)e^{-2rD(u)}$$

$$-\frac{1}{4a_0^7}\int_0^1 duu(1-u)e^{-2i(1-2u)\vec{k}\cdot\vec{r}}\left(\frac{15}{D(u)^7} + \frac{30}{D(u)^6}r + \frac{24}{D(u)^5}r^2 + \frac{8}{D(u)^4}r^3\right)e^{-2rD(u)}$$

$$+\frac{2}{a_0^5}\int_0^1 duu(1-u)e^{-2i(1-2u)\vec{k}\cdot\vec{r}}\left(\frac{3}{D(u)^5} + \frac{6}{D(u)^4}r + \frac{4}{D(u)^3}r^2\right)e^{-2rD(u)},$$

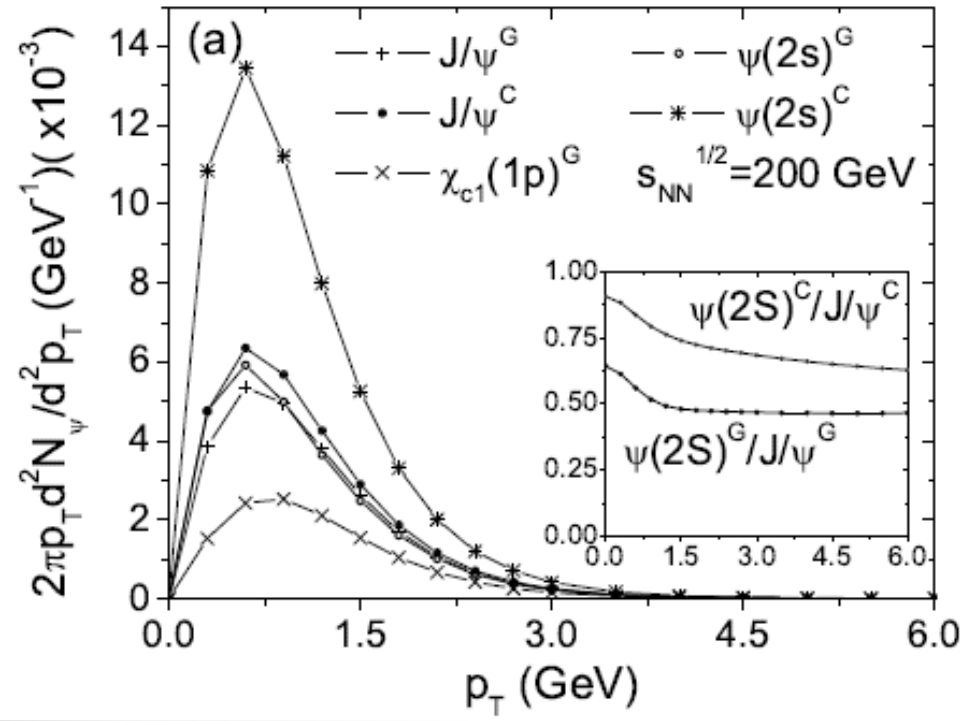
$$D(u) = (1/(2a_0)^2 + 4u(1-u)k^2)^{1/2}$$

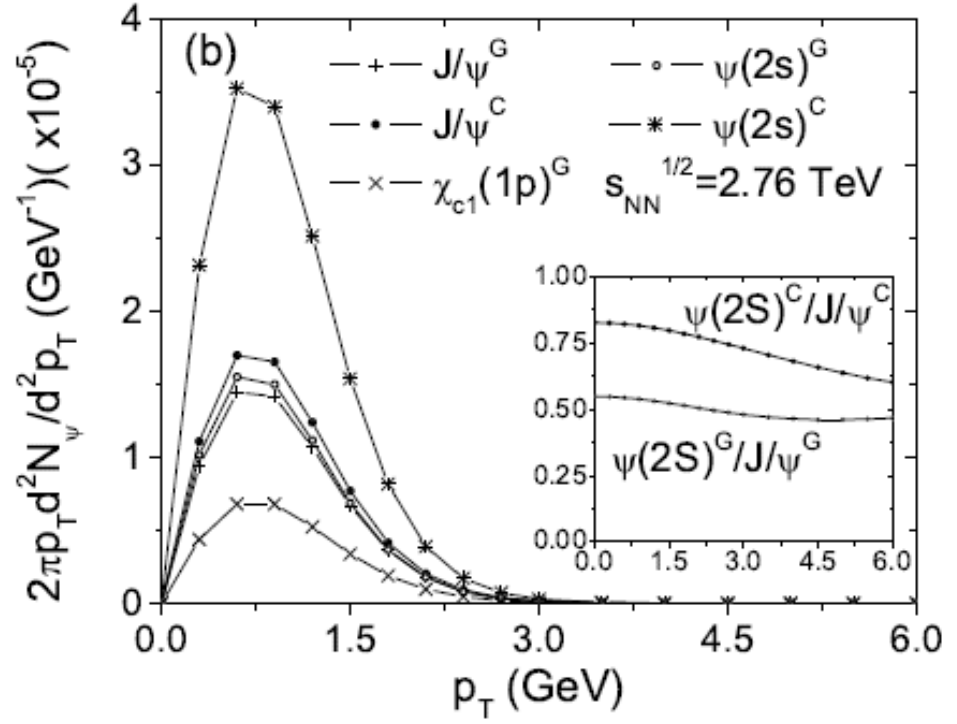
4) Charmonium wave functions



E. Eichten, K. Gottfried, T. Kinoshita, K. D. Lane, T-M, Yan, Phys. Rev. D **17**, 3090 (1978)

5) Transverse momentum distributions





6) Integration of the Wigner function over the spatial coordinates

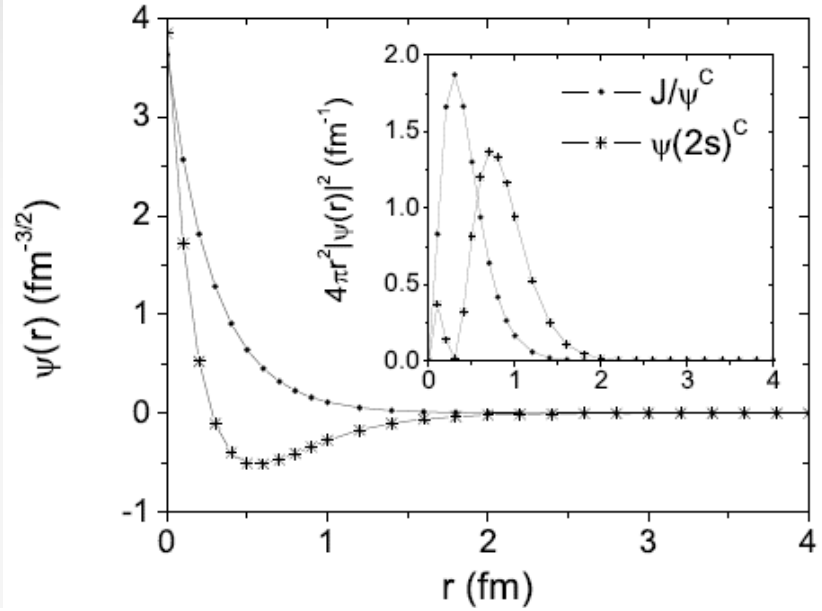
$$\int d^3\vec{r} W_\psi(\vec{r},\vec{k})$$

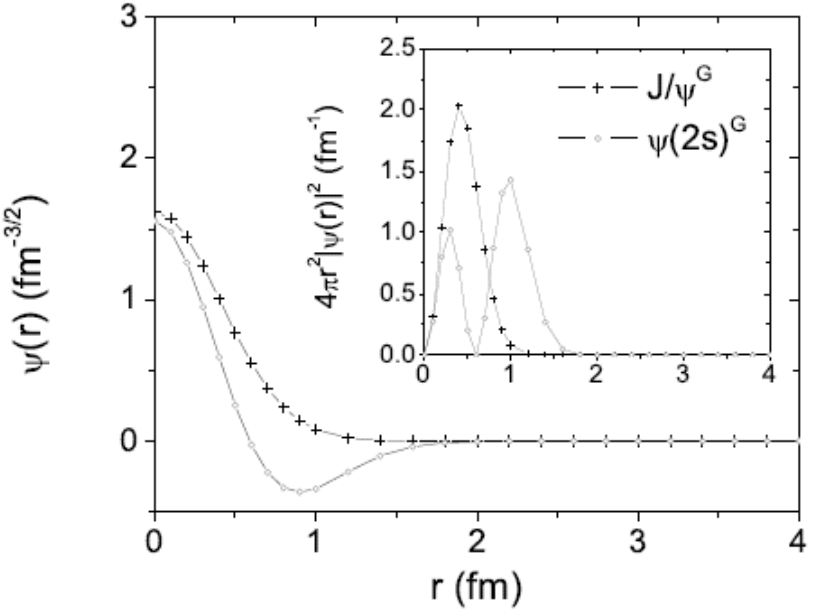
$$= \begin{cases} (2\sqrt{\pi}\sigma)^3 e^{-k^2\sigma^2} & \psi_s^G; J/\psi \\ \frac{2}{3}(2\sqrt{\pi}\sigma)^3 e^{-k^2\sigma^2}\sigma^2k^2 & \psi_p^G; \chi_c \\ \frac{2}{3}(2\sqrt{\pi}\sigma)^3 e^{-k^2\sigma^2}\left(\sigma^2k^2-\frac{3}{2}\right)^2 & \psi_{10}^G; \psi(2S) \\ 64\pi\frac{a_0^3}{(a_0^2k^2+1)^4} & \psi_{1S}^C; J/\psi \\ 8\pi a_0^3\frac{(a_0^2k^2-1/4)^2}{(a_0^2k^2+1/4)^6} & \psi_{2S}^C; \psi(2S) \end{cases}$$

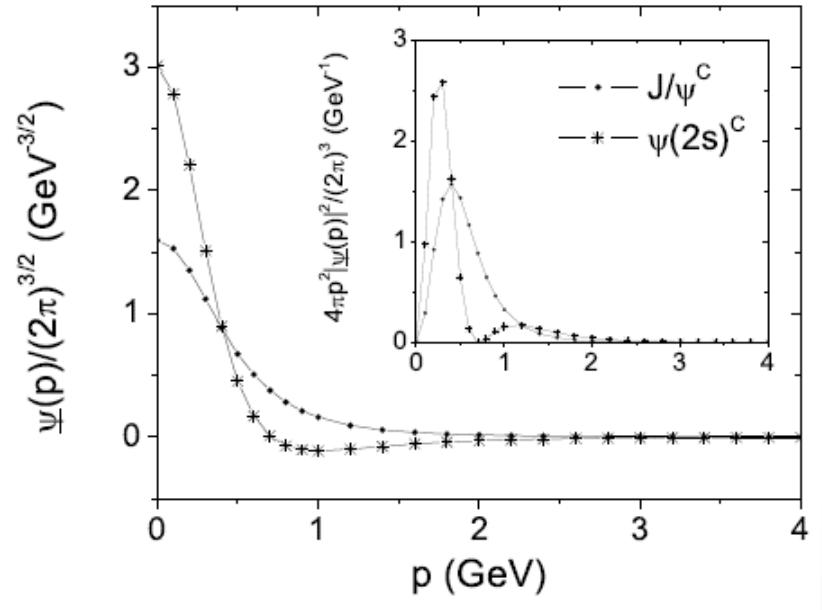
$$\int d^3\vec{r} W(\vec{r},\vec{p}) = \left|\varphi(\vec{p})\right|^2$$

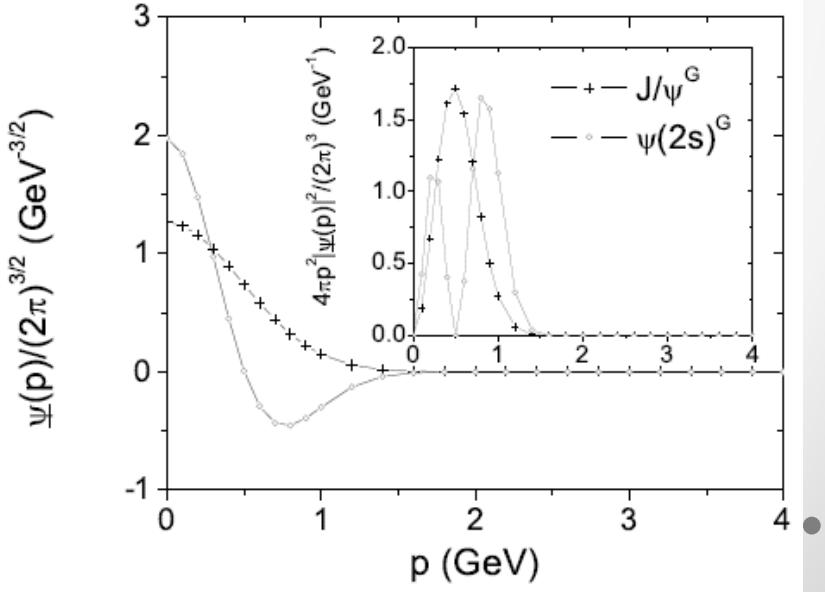
M. Hillery, R. F. O'Connel, M. O. Scully and E. P. Wigner, Phys. Rept. **106**, 121 (1984)

7) Wave function distributions









Conclusion

– Production of charmonium states in heavy ion collisions

1) Light quark hadron yields are well explained by the statistical hadronization model
2) Many aspects of the heavy ion collision experimental results have been explained by the coalescence model
3) The production of heavy quarks hadrons, or charmonium can also be understood by the coalescence model
4) The enhanced transverse momentum distribution of ψ(2S) mesons compared to that of J/ψ mesons, originated from intrinsic wave function distributions of ψ(2S) and J/ψ mesons, provides a plausible explanation for the measurement of the nuclear modification factor ratio between the ψ(2S) and J/ψ meson.