

Charm and Charmonium in A+A Collisions at CERN SPS

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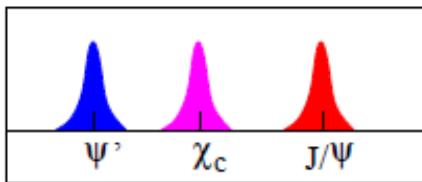
1. J/psi suppression in nucleus-nucleus collisions.
2. Statistical model for J/pi production.
3. Statistical coalescence model.
4. Estimates for open charm production at the SPS.
5. Transverse momentum spectra.
6. Open charm enhancement as a signal of deconfinement.

I. J/Psi suppression

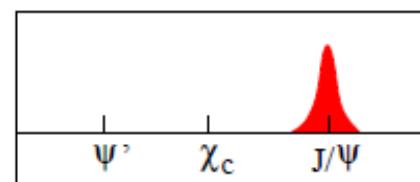
Matsui and Satz, Phys. Lett. B (1986)
2621 citation

Announcement in 2000:

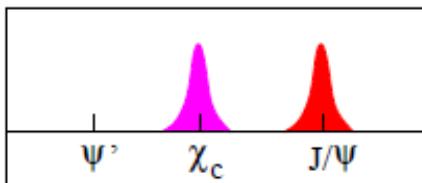
J/Psi suppression by the QGP – the main signature of the QGP discovered in Pb+Pb collisions at the CERN SPS.



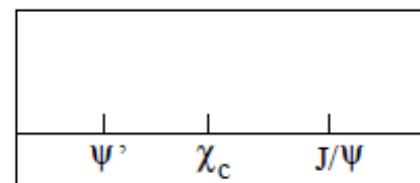
$$T < T_c$$



$$T_\chi < T < T_\Psi$$

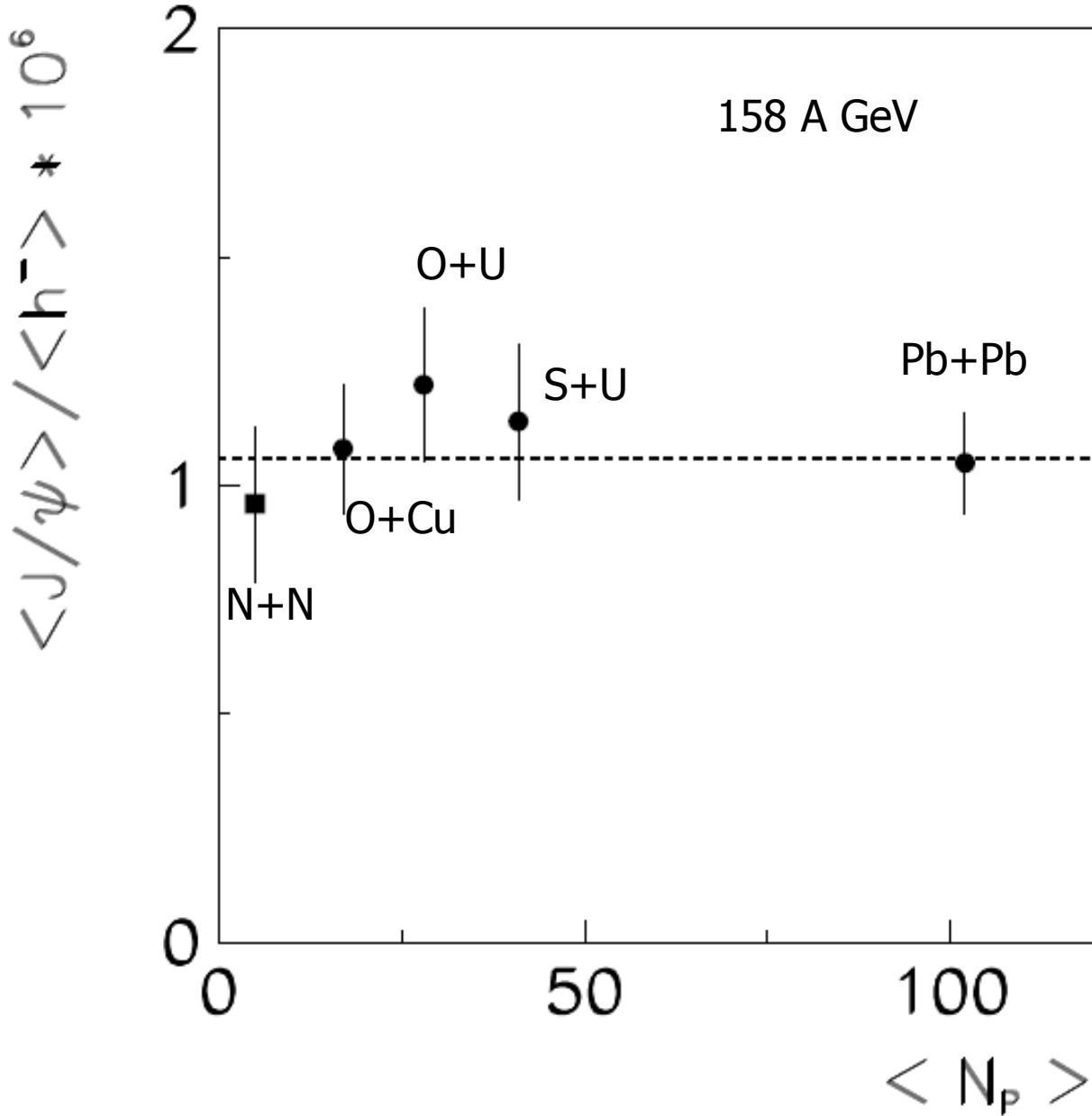


$$T_{\Psi'} < T < T_\chi$$



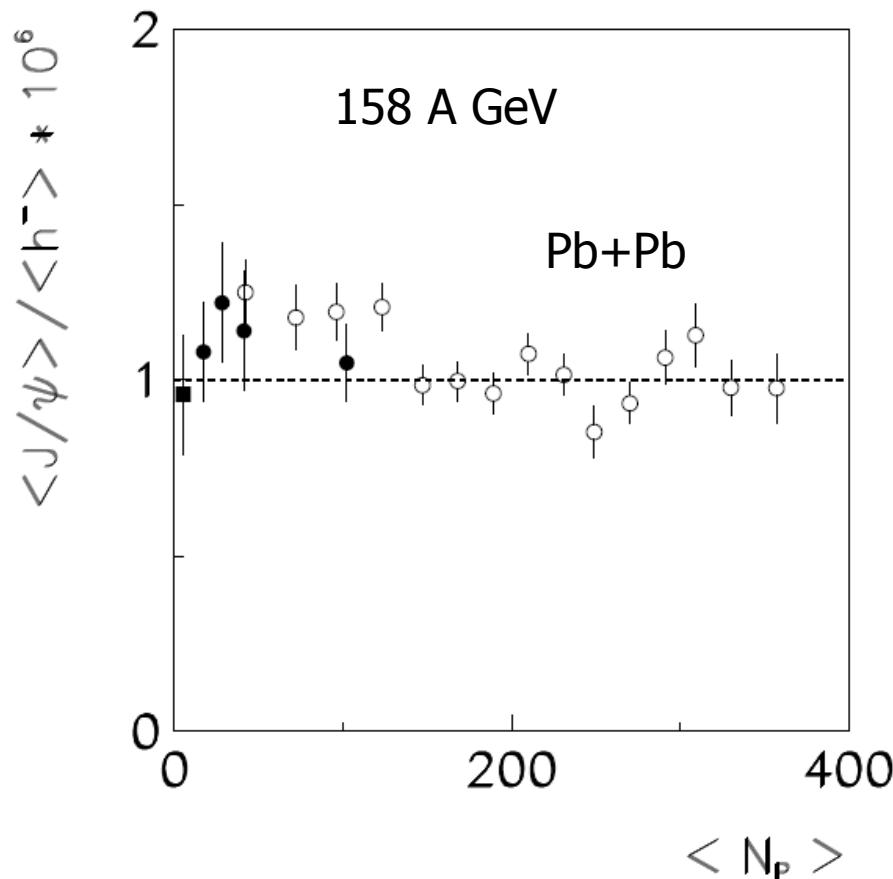
$$T > T_\Psi$$

II. Statistical Production



Statistical production: $\langle J/\psi \rangle \propto \langle h^- \rangle \propto V \propto N_p$

$$\frac{\langle J/\psi \rangle}{\langle h^- \rangle} \cong \text{const}$$



Hard parton production: $\langle J/\psi \rangle \propto N_p^{4/3}$ and further suppression

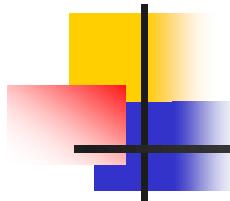
$$\langle J/\psi \rangle = \frac{2j+1}{2\pi^2} V \int_0^\infty p^2 dp \exp\left[-\frac{\sqrt{m^2 + p^2}}{T}\right]$$

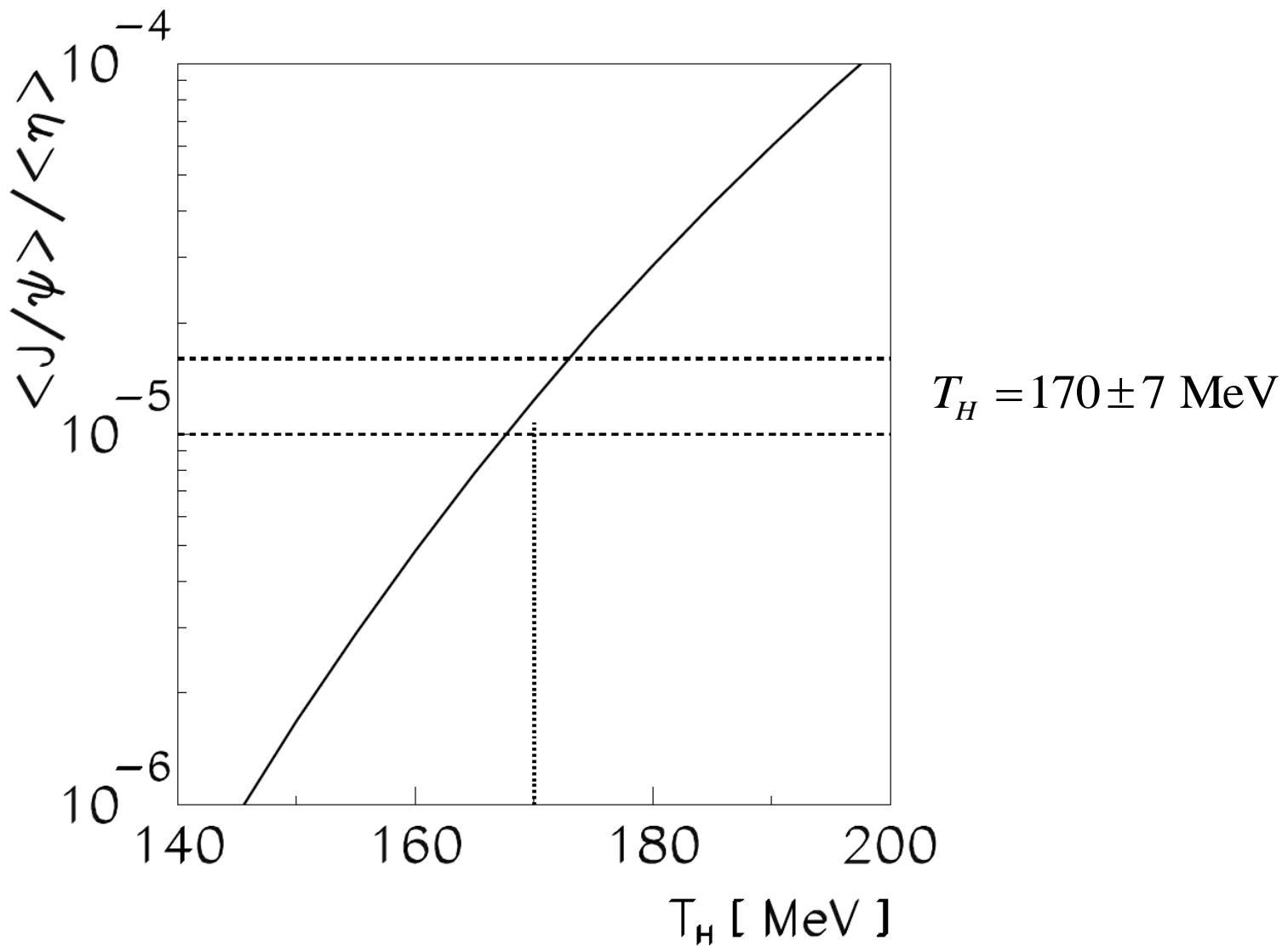
$$\cong (2j+1) V \left(\frac{mT}{2\pi}\right)^{3/2} \exp\left(-\frac{m}{T}\right)$$

$$j=1, m \cong 3.1 \text{ GeV}$$

Statistical production: $\langle J/\psi \rangle \propto \langle h^- \rangle \propto V \propto N_p$

$$\frac{\langle J/\psi \rangle}{\langle h^- \rangle} \cong \text{const}$$


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



III. Statistical Coalescence Model

$$N_{c\bar{c}}^{\text{dir}} = \frac{1}{2} \gamma_c N_O + \gamma_c^2 N_H$$

Braun-Munzinger and Stachel, Phys Lett. B (2000)

$N_{c\bar{c}}^{\text{dir}}$ is assumed to be fixed by hard parton collisions (not measured)

N_O is thermal multiplicity of open charm hadrons

γ_c additional parameter because of incomplete charm equilibration
(similar to γ_s for strangeness)

N_H is hidden charm multiplicity

$$N_{O(H)} = \sum_{j \subset O(H)} N_j = \sum_{j \subset O(H)} d_j V \left(\frac{m_j T}{2\pi} \right)^{3/2} \exp \left(- \frac{m_j}{T} \right)$$

1). $N_{c\bar{c}}^{\text{dir}} = 0.17$ in central Pb+Pb collisions ($N_P = 400$) was assumed

2). $Vn_B(T, \mu_B) = N_P$,

3). γ_c ,

4). $\langle J/\psi \rangle = \gamma_c^2 N_{J/\psi}$

Statistical Coalescence Model with Exact Charm Conservation

MIG, Kostyuk, Stoecker, Greiner, Phys. Lett. B (2000)

$$N_{c\bar{c}}^{\text{dir}} = \frac{1}{2} \gamma_c N_o \frac{I_1(\gamma_c N_o)}{I_0(\gamma_c N_o)} + \gamma_c^2 N_H$$

Factor $\frac{I_1(\gamma_c N_o)}{I_0(\gamma_c N_o)}$ is due to the exact charm conservation

$$\langle J/\psi \rangle = \gamma_c^2 N_{J/\psi}^{\text{tot}} = \gamma_c^2 [N_{J/\psi} + Br(\psi') N_{\psi'} + Br(\chi_1) N_{\chi_1} + Br(\chi_2) N_{\chi_2}]$$

$$Br(\psi') \cong 0.54, \quad Br(\chi_1) \cong 0.27, \quad Br(\chi_2) \cong 0.14$$

$$\langle J/\psi \rangle \Big|_{\text{exp}} = \gamma_c^2 N_{J/\psi}^{\text{tot}} \Big|_{\text{therm}} \rightarrow \gamma_c^2 \rightarrow N_{c\bar{c}}^{\text{dir}}$$

$N_{c\bar{c}}^{\text{dir}} = 3 \cdot 10^{-4}$ was the estimate for NN collisions at $\sqrt{s} = 17.3 \text{ GeV}$

Assuming a linear dependence on N_P one finds $N_{c\bar{c}}^{\text{dir}} = 0.06$

for most central Pb+Pb collisions with $N_P = 400$

But for hard parton collisions with $N_P^{4/3}$ one obtains $N_{c\bar{c}}^{\text{dir}} = 0.35$

Pb+Pb at $\sqrt{s_{NN}} = 17.3 \text{ GeV}$

A: $T = 168 \text{ MeV}, \mu_B = 266 \text{ MeV}$

Table 1

N_p	$\langle J/\psi \rangle \cdot 10^4$	$N_{J/\psi}^{tot} \cdot 10^4$	N_O	γ_c	$N_{c\bar{c}}^{dir}$	
	NA50 data	Eq.(7)	Set A	Eq.(6)	Thermal	Poisson
	Compil. [3]	Set A			Eq.(5)	Eq.(9)
100	2.2 ± 0.2	0.56	0.26	2.0	0.066	0.064
200	3.9 ± 0.2	1.1	0.52	1.9	0.21	0.20
300	6.4 ± 0.6	1.7	0.79	2.0	0.46	0.41
360	6.9 ± 0.7	2.0	0.94	1.9	0.57	0.51

1) $N_{c\bar{c}}^{dir} \cong 0.6$

for central Pb+Pb

B: $T = 175 \text{ MeV}, \mu_B = 240 \text{ MeV},$

Table 2

N_p	$\langle J/\psi \rangle \cdot 10^4$	$N_{J/\psi}^{tot} \cdot 10^4$	N_O	γ_c	$N_{c\bar{c}}^{dir}$	
	NA50 data	Eq.(7)	Set B	Eq.(6)	Thermal	Poisson
	Compil. [3]	Set B			Eq.(5)	Eq.(9)
100	2.2 ± 0.2	1.1	0.39	1.4	0.072	0.070
200	3.9 ± 0.2	2.2	0.77	1.3	0.23	0.22
300	6.4 ± 0.6	3.3	1.17	1.4	0.50	0.45
360	6.9 ± 0.7	4.0	1.40	1.3	0.62	0.55

2) $N_{c\bar{c}}^{dir} \sim N_P^\alpha,$

$\alpha = 1.6 - 1.7$

IV. Open Charm Estimates

Perturbative QCD:

$$\sigma(pp \rightarrow c\bar{c}) = \sigma_o \left(1 - \frac{M_0}{\sqrt{s}}\right)^a \left(\frac{\sqrt{s}}{M_0}\right)^b$$

$$N_{c\bar{c}}^{\text{pQCD}} = C \sigma(pp \rightarrow c\bar{c}) N_p^{4/3}$$

$$C \approx 11 \text{ barn}^{-1}$$

HG:

$$N_{c\bar{c}}^{\text{HG}} = \frac{1}{2} N_o \frac{I_1(N_o)}{I_0(N_o)} + N_H$$

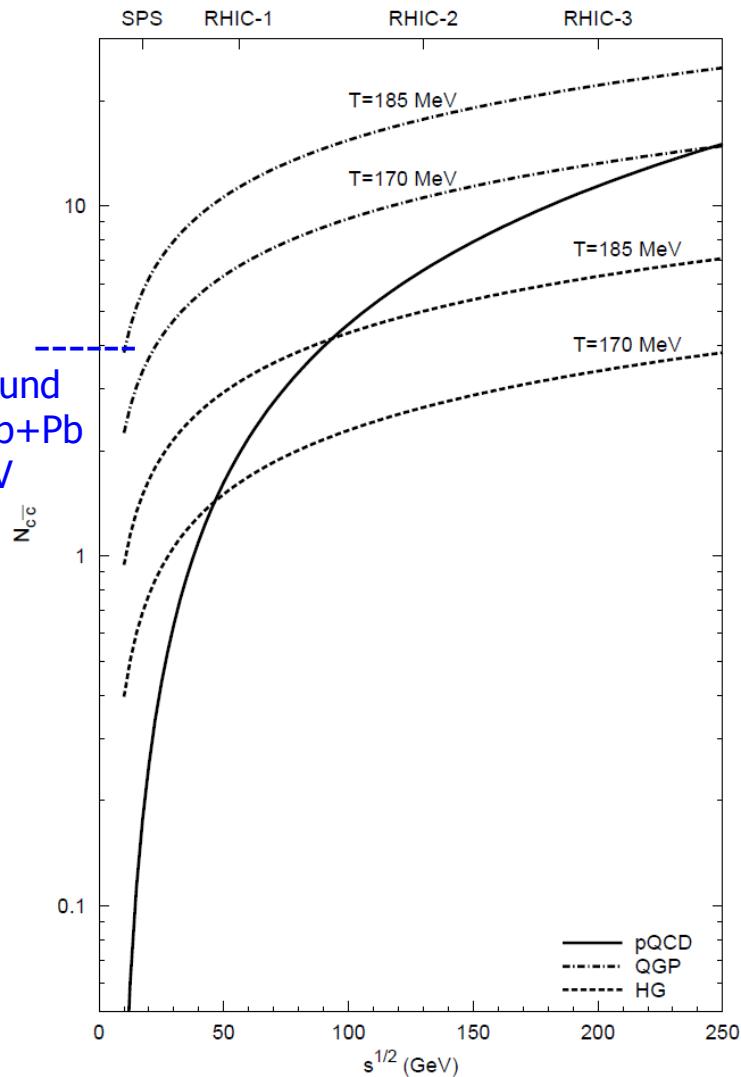
$$V_{\text{HG}} n_B^{\text{HG}}(T, \mu_B) = N_p$$

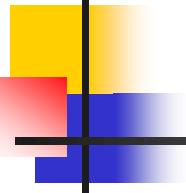
QGP:

$$N_{c\bar{c}}^{\text{QGP}} = \frac{1}{2} (N_c + N_{\bar{c}}) \frac{I_1(N_c + N_{\bar{c}})}{I_0(N_c + N_{\bar{c}})}$$

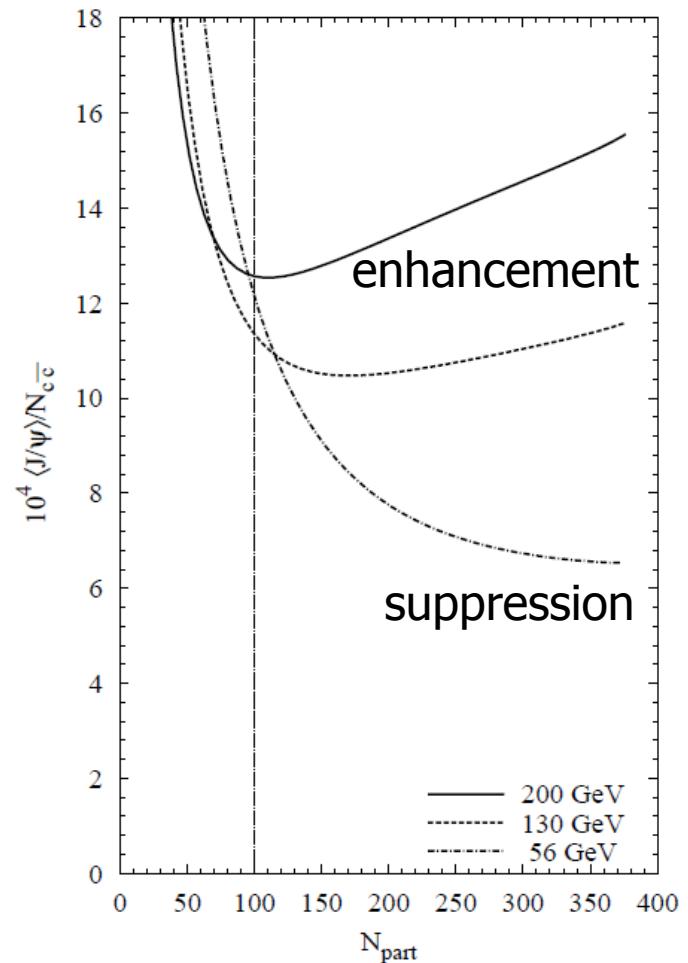
$$V_{\text{QGP}} s_{\text{QGP}}(T) = V_{\text{HG}} s_{\text{HG}}(T)$$

NA49
upper bound
central Pb+Pb
158 AGeV



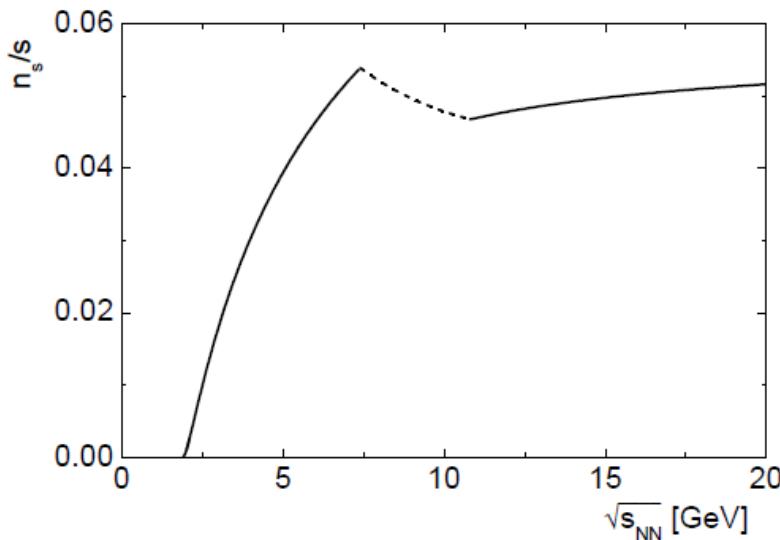


$$R = \frac{< J/\psi >}{N_{c\bar{c}}} \sim \begin{cases} (< N_\pi >)^{-1} \sim (\sqrt{s_{NN}})^{-1/2} N_p^{-1}, & N_{c\bar{c}} \ll 1 \\ \frac{N_{c\bar{c}}}{< N_\pi >} \sim N_p^{1/3}, & N_{c\bar{c}} \gg 1 \end{cases}$$



Statistical model of the early stage

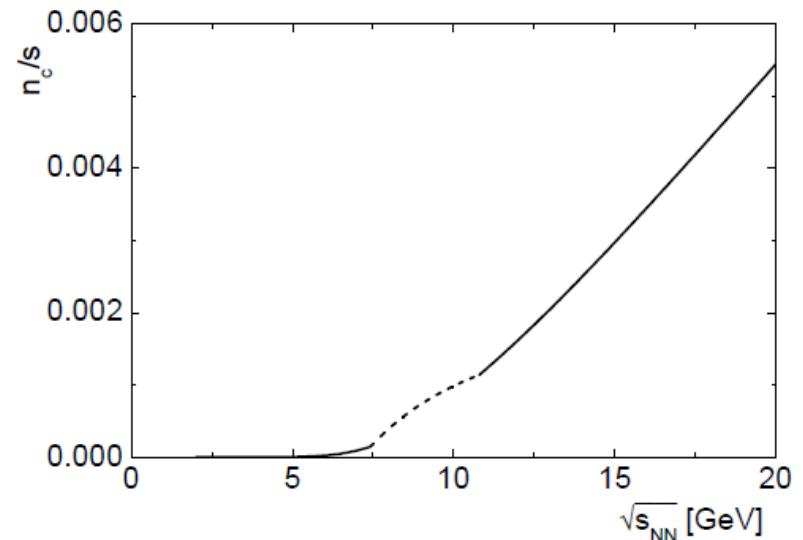
Strangeness/Entropy



$$g_w^s = 14, \quad g_Q^s = 12$$

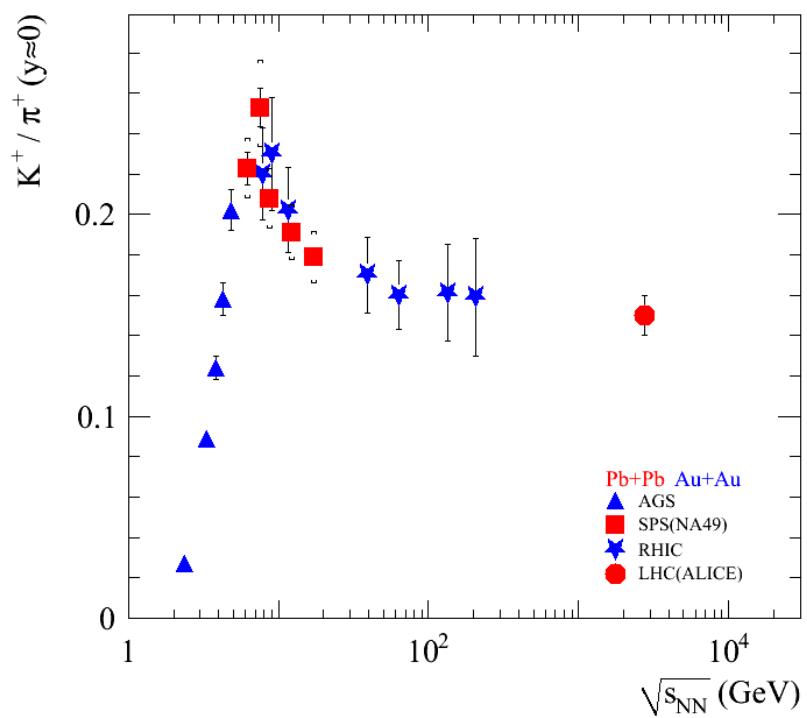
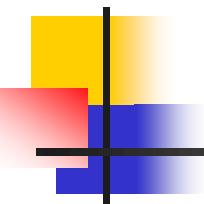
$$m_w^s = 500 \text{ MeV}, \quad m_Q^s = 200 \text{ MeV}$$

Charm/Entropy



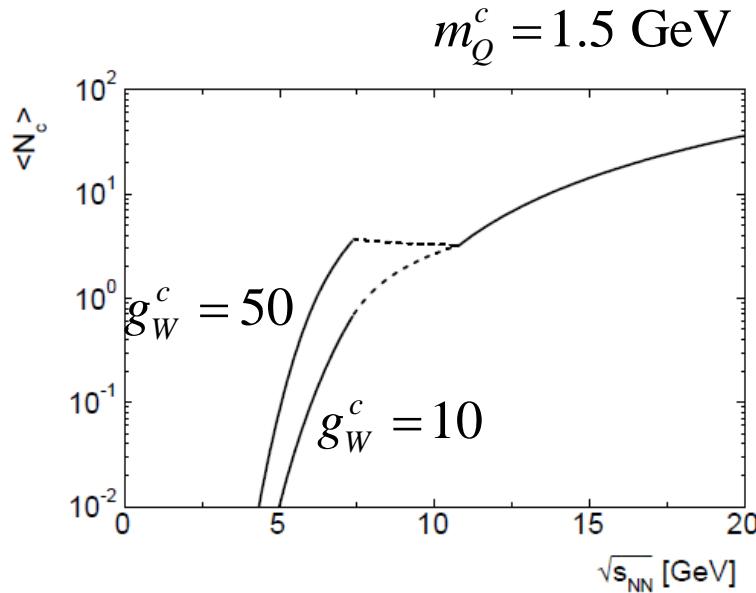
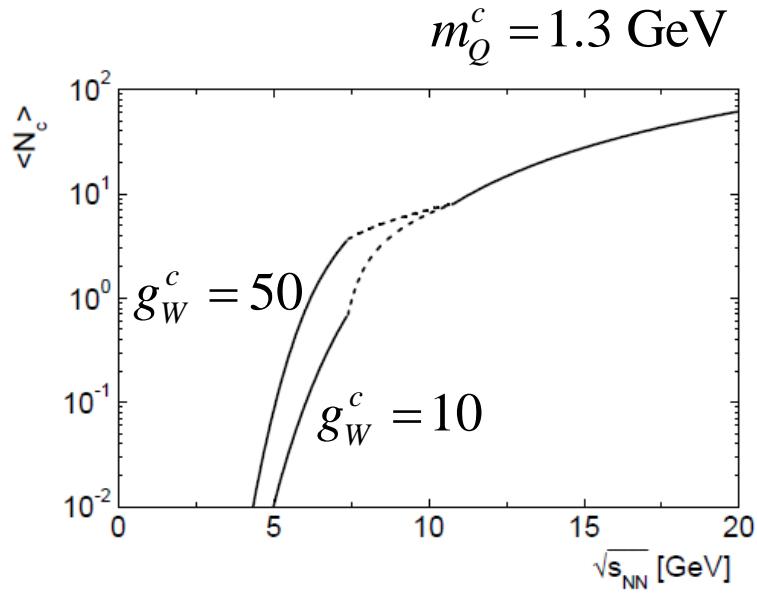
$$g_w^c = 10, \quad g_Q^c = 12$$

$$m_w^c = 1800 \text{ MeV}, \quad m_Q^c = 1300 \text{ MeV}$$

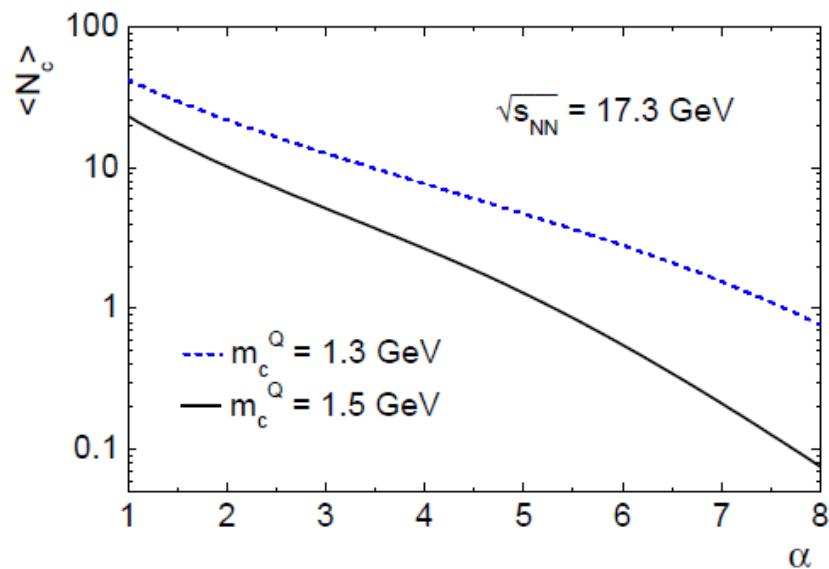
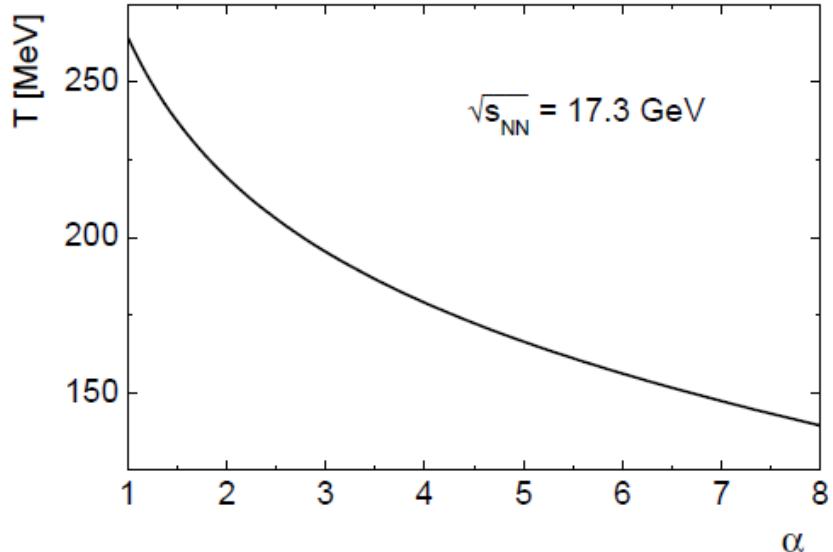


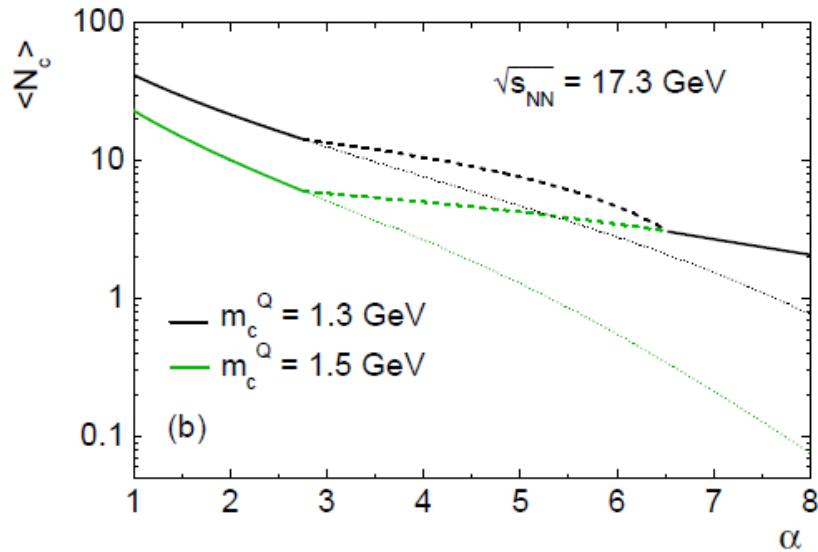
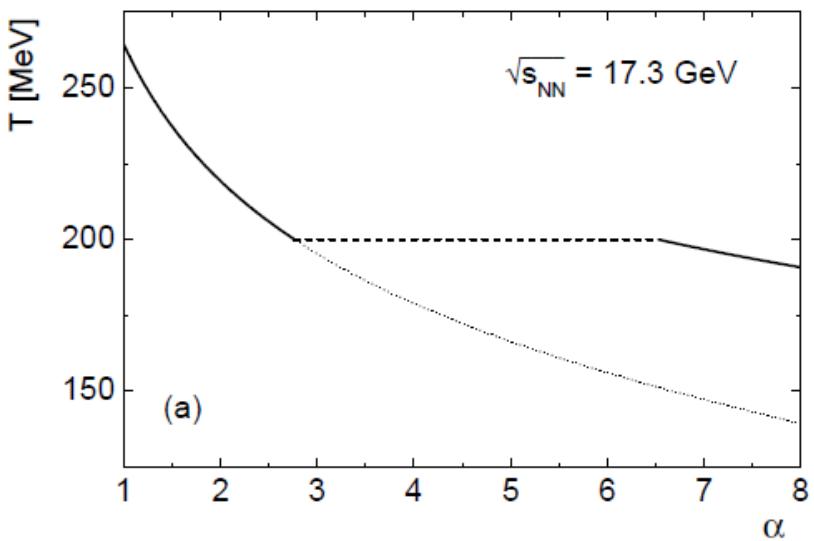
D^\pm / π^\pm

?



$$V = \frac{4\pi r_0^3 A_P / 3}{\sqrt{s_{NN}} / 2m_N} \rightarrow \alpha V$$



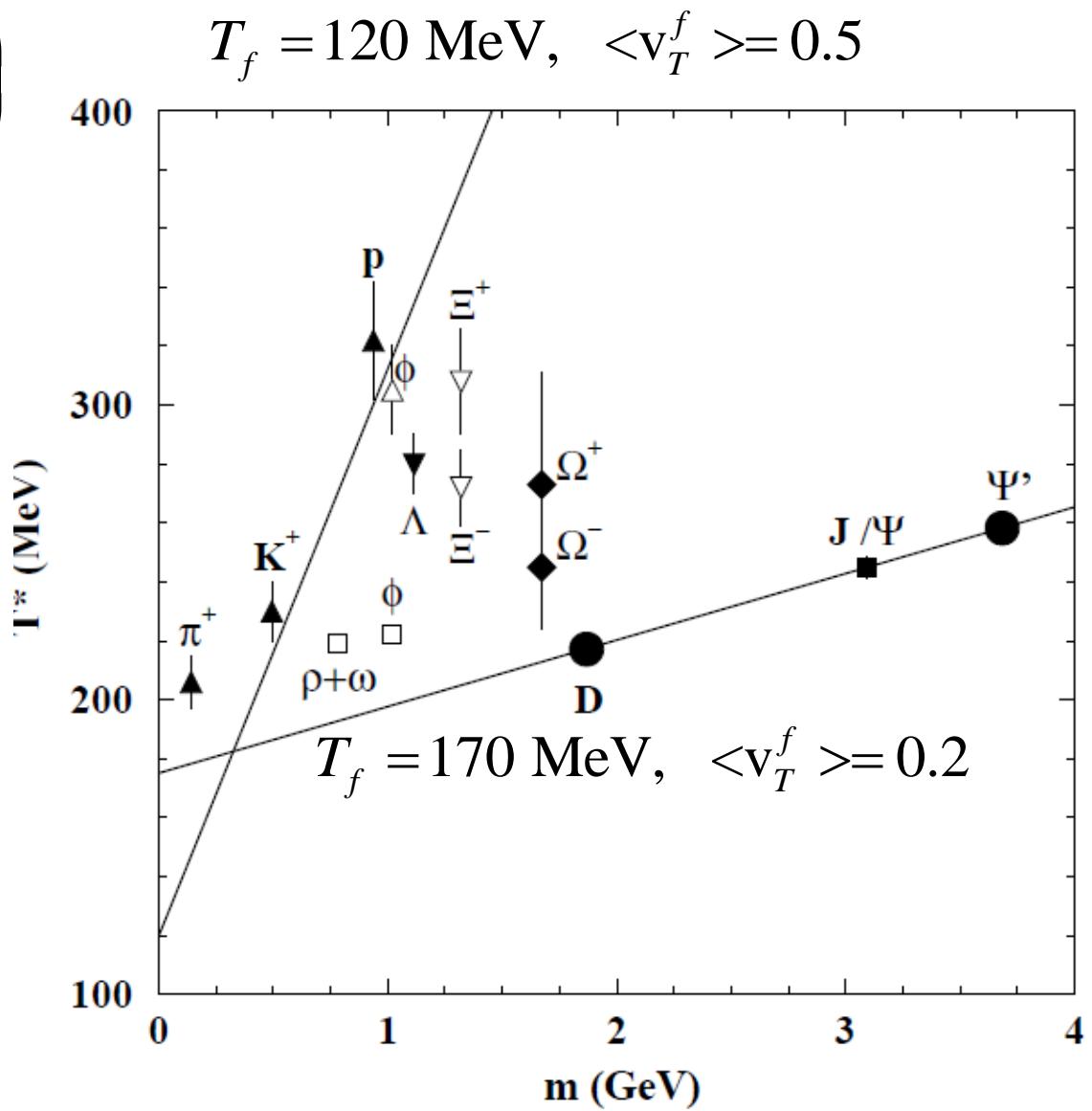


V. Transverse Momentum Spectra

$$\frac{1}{m_T} \frac{dN}{dm_T} = C \exp\left(-\frac{m_T}{T^*}\right)$$

$$T^* = T_f + \frac{2}{\pi} m \langle v_T^f \rangle^2$$

Bugaev, MIG, Gazdzicki,
Phys. Lett. B (2001)





$$\frac{1}{m_T} \frac{dN}{dm_T} \sim m_T \int_0^R r dr K_1\left(\frac{m_T \cosh y_T}{T}\right)$$

$$\times I_0\left(\frac{p_T \sinh y_T}{T}\right)$$

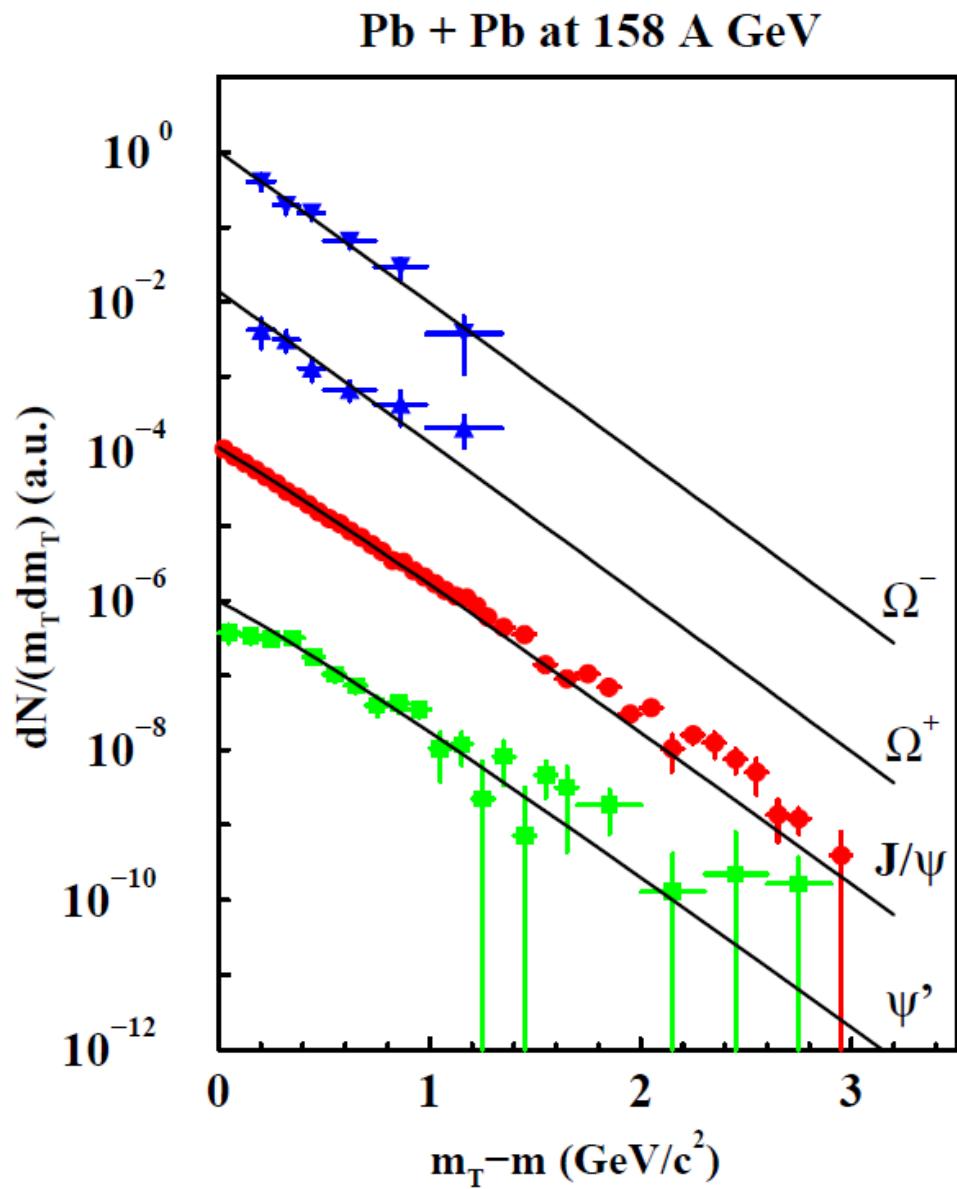
$$v_T = \tanh^{-1} \nu_T$$

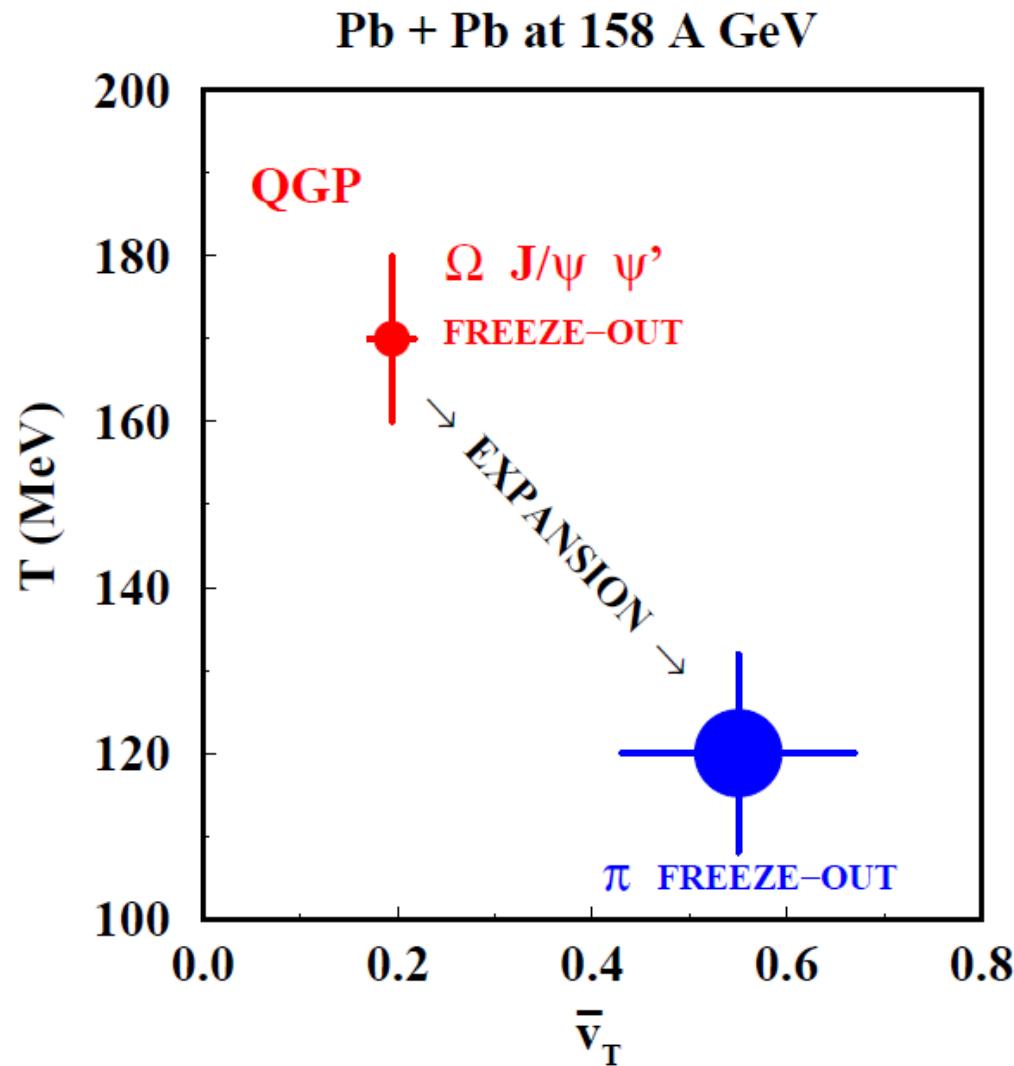
$$\frac{1}{m_T} \frac{dN}{dm_T} \sim$$

$$\times \sqrt{m_T} \exp\left[-\frac{m_T(1+\bar{\nu}_T^2)}{T}\right] I_0\left(\frac{p_T \bar{\nu}_T}{T}\right)$$

$$T = 170 \text{ MeV} \quad \bar{\nu}_T = 0.2$$

Bugaev, MIG, Gazdzicki,
Phys. Rev. Lett. B (2002)





VI. Open Charm Enhancement as a Signal of Deconfinement

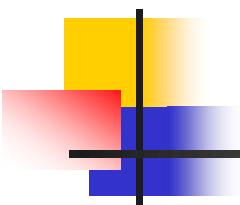
$$N_{c\bar{c}}^{AA} = N_{\text{coll}} N_{c\bar{c}}^{NN}, \quad N_{\text{coll}} \sim N_p^{4/3}$$

$N_{c\bar{c}}^{AA} = 0.15 \div 0.3$ In central Pb+Pb collisions at 158 A GeV

Statistical Coalescence Model:

$$\langle J/\psi \rangle \rightarrow N_{c\bar{c}}^{AA} = 0.5 \div 0.6,$$

$$N_{c\bar{c}}^{AA} \sim N_p^\alpha, \quad \alpha \cong 1.7$$



$$gg \rightarrow c\bar{c}, \quad q\bar{q} \rightarrow c\bar{c}$$

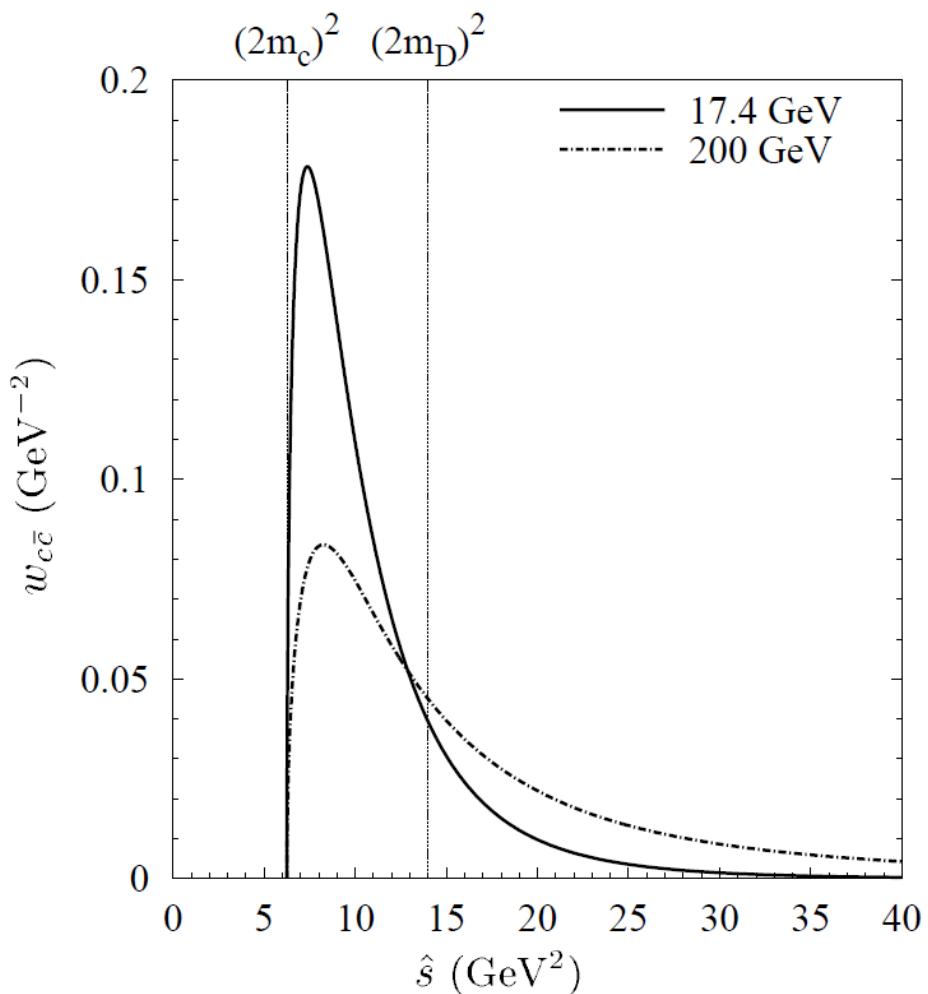
$$\hat{s} = s x_1 x_2$$

$$\sigma_{NN \rightarrow c\bar{c}+X}(s)$$

$$= \sum_{(1,2)} \int_0^1 f(x_1) dx_1 \int_0^1 f(x_2) dx_1$$

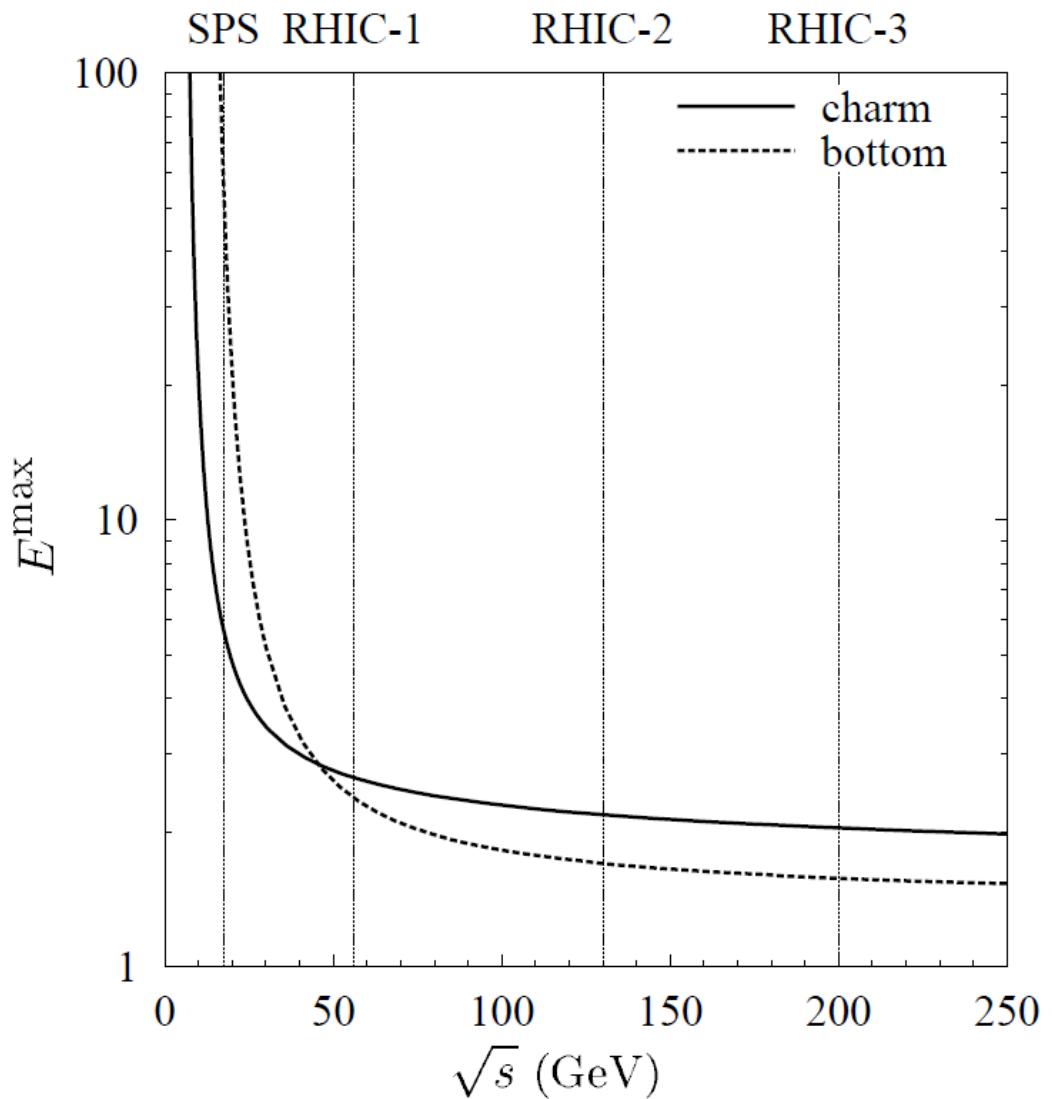
$$\times \sigma_{NN \rightarrow c\bar{c}+X}(\hat{s})$$

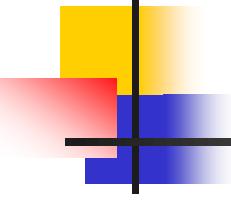
$$w_{c\bar{c}}(\hat{s}; s) = \frac{d\sigma_{NN \rightarrow c\bar{c}+X}/d\hat{s}}{\sigma_{NN \rightarrow c\bar{c}+X}(s)}$$



$$\sigma_{NN \rightarrow c\bar{c} + X}^*(s) = \int_{(2M_D)^2}^{\sqrt{s-2m_N^2}} d\hat{s} \, d\sigma_{NN \rightarrow c\bar{c} + X} / d\hat{s}$$

$$E^{\max} = \frac{\sigma_{NN \rightarrow c\bar{c} + X}^*(s)}{\sigma_{NN \rightarrow c\bar{c} + X}(s)}$$





Summary

1. Model estimates for open charm yields in Pb+Pb collisions at the SPS energy region vary by almost two order of magnitude.
2. J/psi multiplicity can be strongly connected with open charm yield.
3. Collision energy and centrality dependence of the open charm yield can be very sensitive to the creation of the deconfined matter just at the SPS energy.