	E (A·GeV)	$\sqrt{s_{NN}}$ (GeV)
AGS BNL Au+Au	11	4.7
SPS CERN Pb+Pb	20	6.3
	30	7.6
2003	40	8.8
2002	80	12.3
1996–2000	160	17.4
RHIC BNL Au+Au	9.0×10^3	130
2001–...	2.1×10^4	200
LHC CERN	1.3×10^7	5000

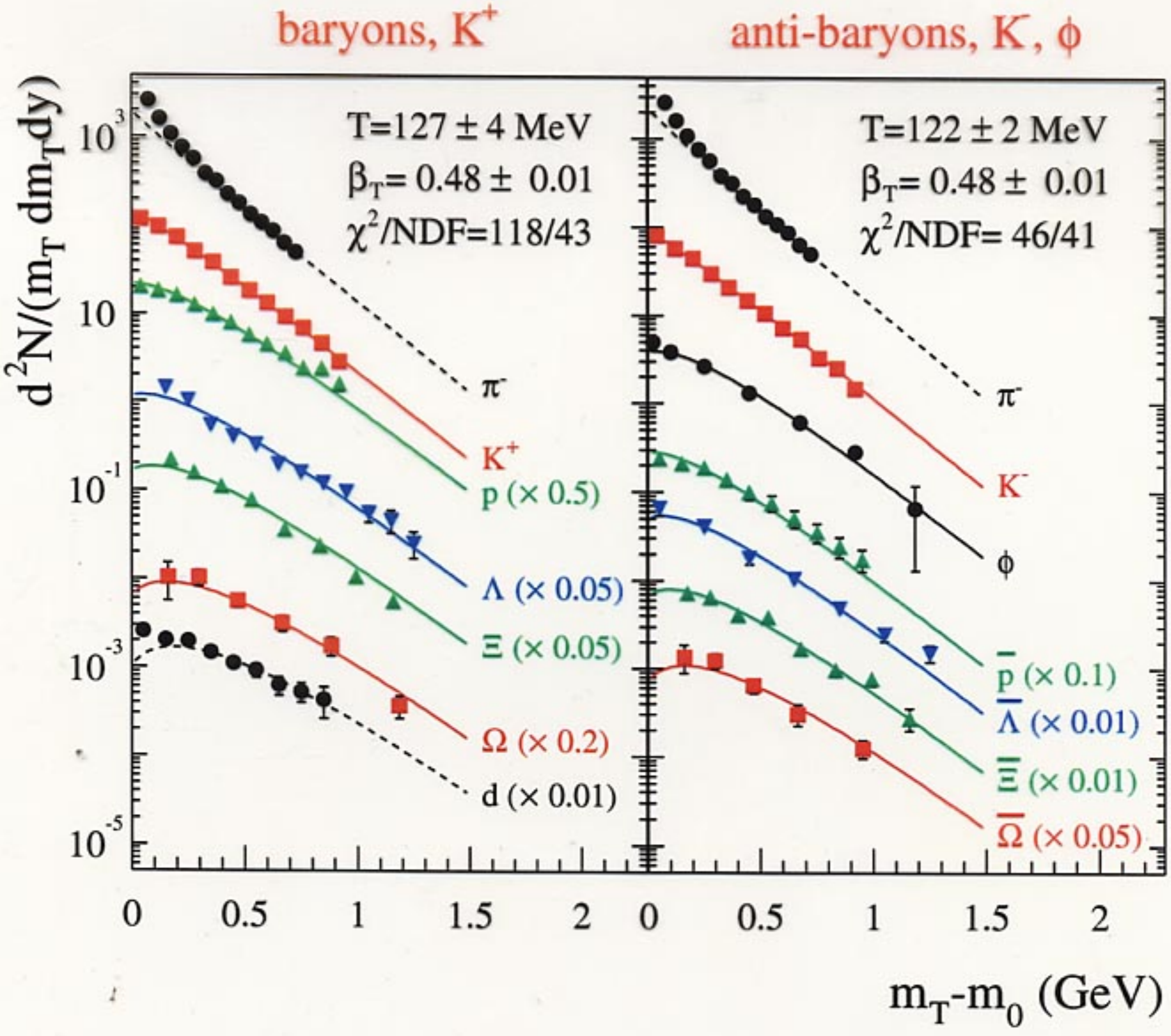
$\hbar = c = 1$ $\qquad 1\,\mathrm{fm} \simeq \dfrac{1}{200\ \mathrm{MeV}}$

$K = 1$

$m_\pi \simeq 140\ \mathrm{MeV}, \quad m_N \simeq 940\ \mathrm{MeV}$

$$\sqrt{s_{NN}} = (2 m_N^2 + 2 E m_N)^{1/2}$$

$$F \equiv (\sqrt{s} - 2 m_N)^{3/4} / s^{1/8} \simeq (\sqrt{s})^{1/2}$$

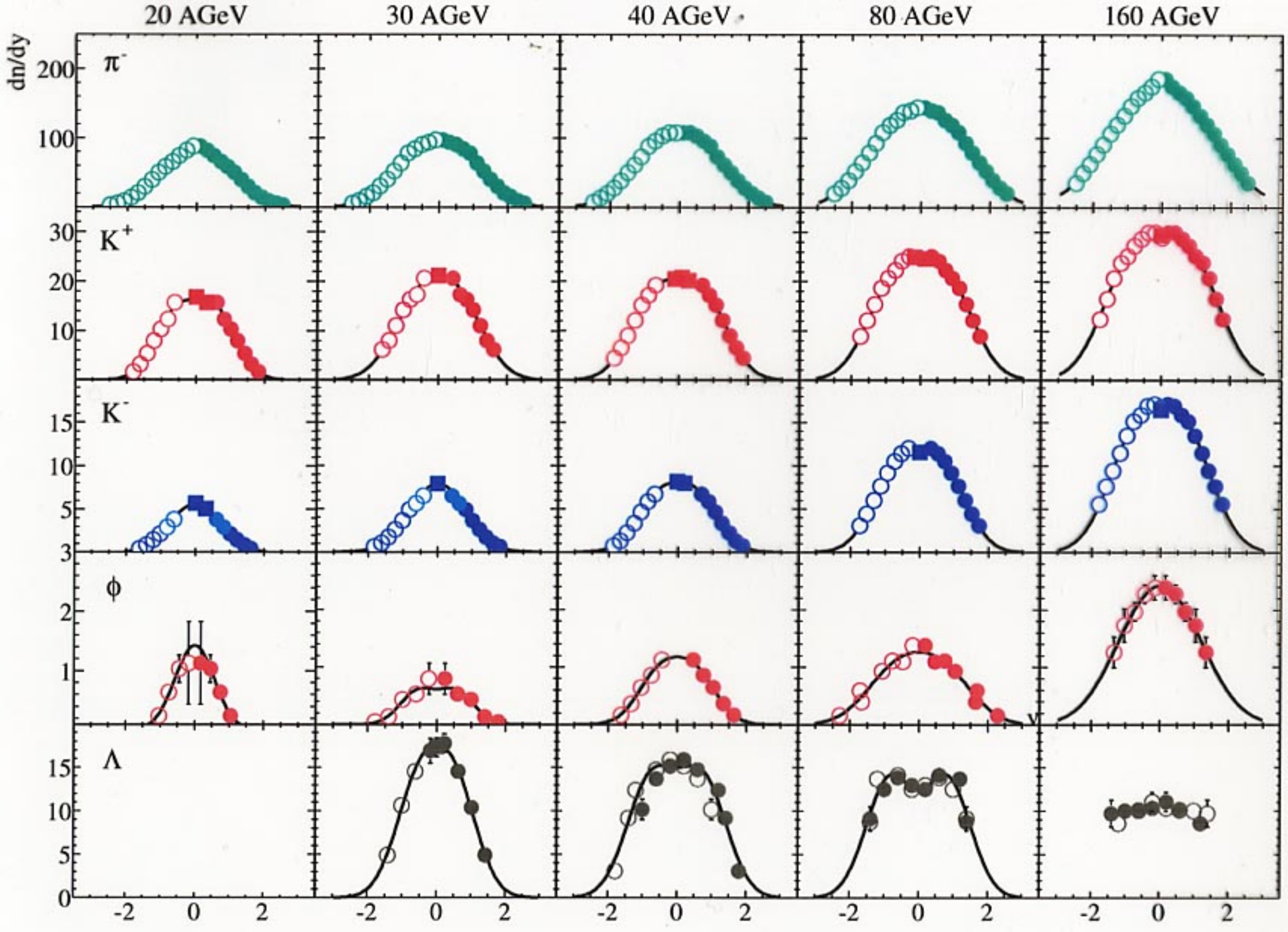


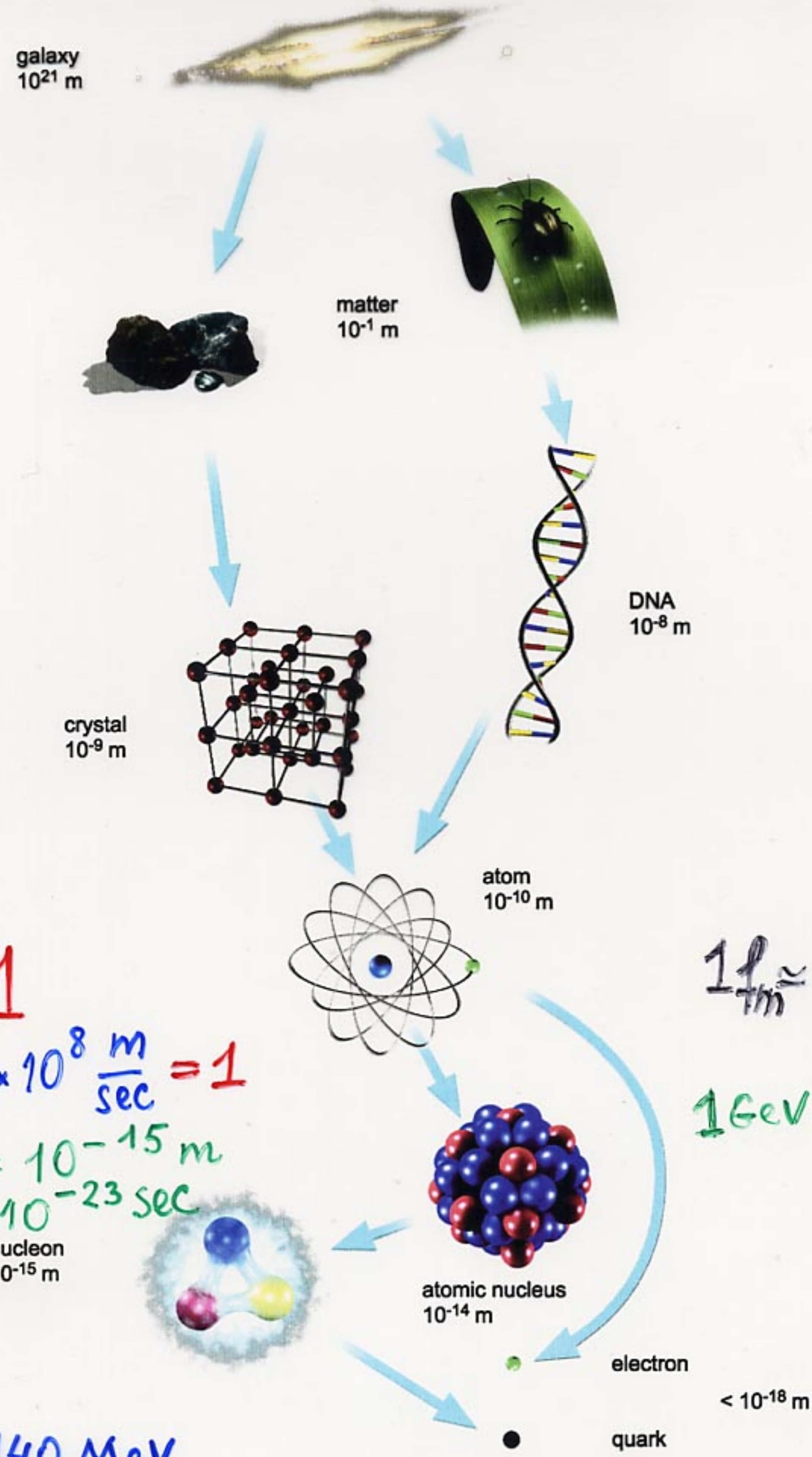
Pb+Pb , 158 A·GeV, central (~5%)

$y = 0$

$$\frac{dN}{m_T\, dm_T\, dy} \sim K_1\left(\frac{m_T \operatorname{ch} y_T}{T}\right) I_0\left(\frac{p_T \operatorname{sh} y_T}{T}\right)$$

$m_T = (m^2 + p_T^2)^{1/2}$; $y_T = \operatorname{th}^{-1} v_T$, $v_T \approx 0.5$


20 AGeV
30 AGeV
40 AGeV
80 AGeV
160 AGeV
dn/dy
π^-
K^+
K^-
ϕ
Λ



$\hbar = 1$

$c = 3 \times 10^{8} \frac{m}{sec} = 1$

$1\,fm = 10^{-15}\,m$

$1\,fm/c = 10^{-23}\,sec$

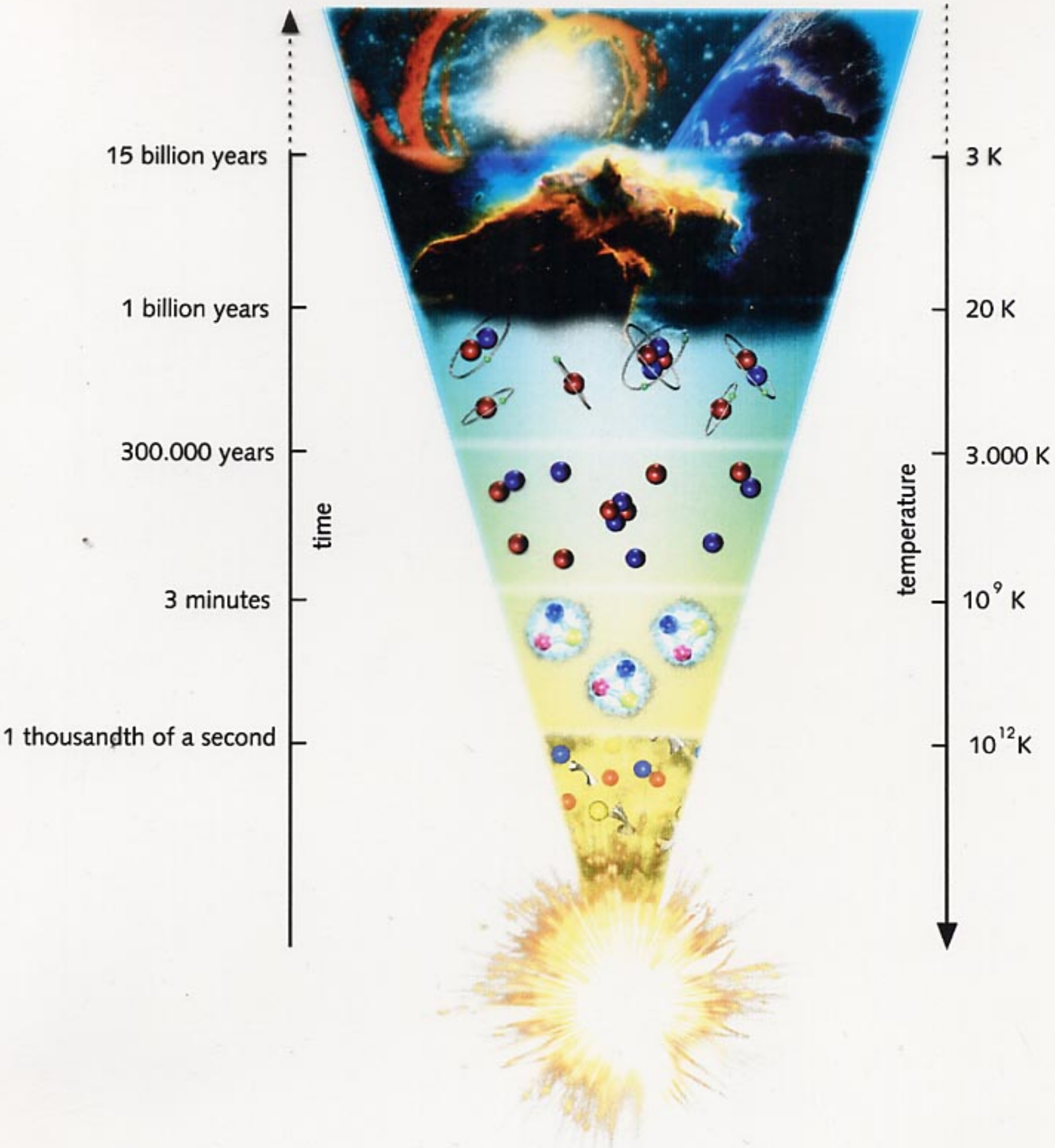
$1\,fm \simeq \frac{1}{200\,MeV}$

$1\,GeV = 1000\,MeV$

$m_\pi \simeq 140\,MeV$

$m_N \simeq 940\,MeV$

$T_c \simeq 170\,MeV$


15 billion years
1 billion years
300.000 years
3 minutes
1 thousandth of a second
time
3 K
20 K
3.000 K
10^9 K
10^{12} K
temperature

Hadrons

π^+, π^0, π^- $\qquad m_\pi \cong 140\,\mathrm{MeV}$

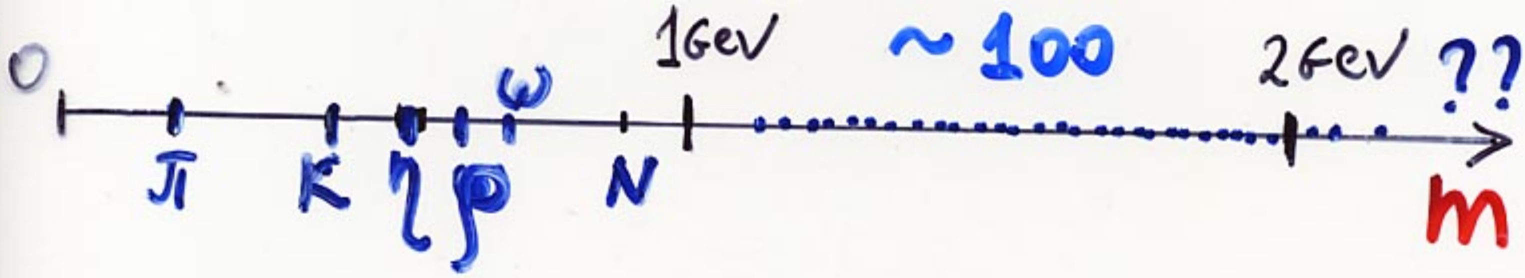
. . . .

p, n $\qquad m_N \cong 940\,\mathrm{MeV}$

. . . .

$\pi, K, \eta, \rho, \omega, \eta', f_0, a_0, \varphi, h_1, b_1, \ldots$

$N, \Delta, N^*, \Lambda, \Sigma, \Omega, \Xi, \ldots\ldots$



Mesons (Bosons) $\qquad$ **Baryons** (Fermions)

Baryons:

$Q = -1, 0, +1, \pm 2$

$B = 1, \cancel{0}, -1$

$S = 0, \pm 1, \pm 2, \pm 3$

Mesons:

$Q = 0, \pm 1$

$B = 0$

$S = 0, \pm 1$

	B	Q	S	C	B	T
u	1/3	2/3	0	0	0	0
d	1/3	-1/3	0	0	0	0
s	1/3	-1/3	-1	0	0	0
c	1/3	2/3	0	+1	0	0
b	1/3	-1/3	0	0	-1	0
t	1/3	2/3	0	0	0	+1

$(q_1, \bar{q}_2)$

$B = 0$

$Q = 0, \pm 1$

$S = 0, \pm 1$

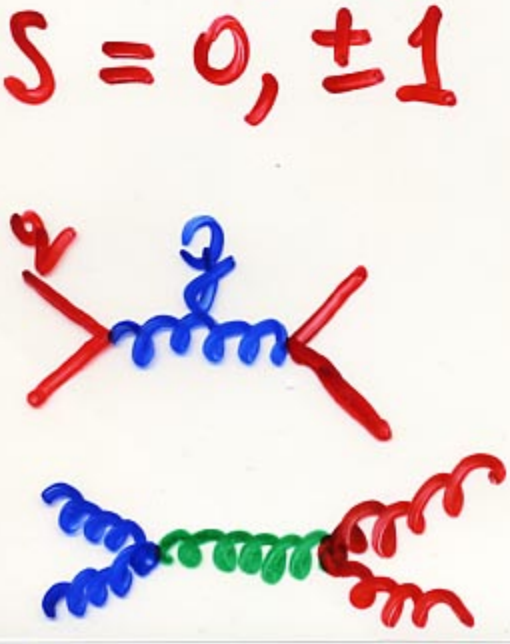
(q_1, q_2, q_3)

$(\bar{q}_1, \bar{q}_2, \bar{q}_3)$

$B = \pm 1$

$Q = 0, \pm 1, \pm 2$

$S = 0, \pm 1, \pm 2, \pm 3$



Quarks

c, b, t

	u	d	s
B	$1/3$	$1/3$	$1/3$
Q	$2/3$	$-1/3$	$-1/3$
S	0	0	-1

$q\bar{q}$ mesons

qqq baryons

$\bar{q}\bar{q}\bar{q}$ antibaryons

$\pi^+(u\bar{d})$, $\pi^-(d\bar{u})$, $K^+(u\bar{s})$, $K^-(\bar{u}s)$...

$p(uud)$, $n(udd)$, $\Delta^{++}(uuu)$, ...

$\Lambda^0(uds)$, ..., $\Xi^0(uss)$, ..., $\Omega^-(sss)$, ...

Colour q_a $a = 1, 2, 3$

QCD Fundamental Theory of Strong Interactions

g_c $c = 1, \ldots, 8$

Asymptotic Freedom

QGP at $T \to \infty$

"ideal gas" of quarks and gluons

I. Confinement

II. Asymptotic Freedom

QCD 

Hadrons

Baryons $(q_1\, q_2\, q_3)$ $B = 1$

Mesons $(q_1\, \bar{q}_2)$ $B = 0$

$$\alpha_s(Q^2) = \frac{12\pi}{(33 - 2n_f)\ \ln \frac{Q^2}{\Lambda^2}}$$

$\Lambda \approx 200\ \mathrm{MeV}$

$q\bar{q}$ $B = 0;\ S = \pm 1, 0;\ Q = \pm 1, 0$

$$\left.\begin{matrix} qqq \\ \bar{q}\bar{q}\bar{q} \end{matrix}\right\}\ \begin{matrix} B = \pm 1;\ S = 0, \pm 1, \pm 2, \pm 3 \\ Q = 0, \pm 1, \pm 2 \end{matrix}$$

$$f_i = \frac{1}{\exp\left[\frac{(k^2+m_i^2)^{1/2}-\mu_i}{T}\right] \mp 1}$$

$$f_i \simeq e^{\mu_i/T} \exp\left[-\frac{(k^2+m_i^2)^{1/2}}{T}\right]$$

$$\rho_i = \frac{d_i}{2\pi^2}\int_0^\infty k^2\,dk\, f_i$$

$$\varepsilon_i = \frac{d_i}{2\pi^2}\int_0^\infty k^2\,dk\,\sqrt{k^2+m_i^2}\, f_i$$

$$P_i = \frac{d_i}{2\pi^2}\int_0^\infty k^2\,dk\,\frac{k^2}{3\sqrt{k^2+m_i^2}}\cdot f_i$$

$$P = \sum_i P_i\,, \qquad \rho_B = \sum_i b_i \rho_i$$

$$P(T, \mu_B)$$

$$S = \frac{\partial P}{\partial T}\,, \qquad \rho_B = \frac{\partial P}{\partial \mu_B}$$

$$\varepsilon = TS + \mu_B \rho_B - P$$

$$\varphi_m(T) = g\,\frac{m^2 T}{2\pi^2}\,K_2\left(\frac{m}{T}\right)$$

g degeneracy factor

$g = (2j+1)$

$$p(T) = T\,\varphi_m(T)$$

$$n(T) = \varphi_m(T)$$

$$\varepsilon(T) = T^2\,\frac{d\varphi_m}{dT}$$

$$\varphi_m = \frac{g}{2\pi^2}\int_0^\infty k^2\,dk\,\exp\left[-\frac{(k^2+m^2)^{1/2}}{T}\right]$$

$$\varphi_m = \frac{g}{2\pi^2}\int_0^\infty k^2\,dk\,\frac{1}{\exp\left[+\frac{(k^2+m^2)^{1/2}}{T}\right]\pm 1}$$

$m/T \longmapsto 0$

$$\varphi_0(T) = \frac{g}{2\pi^2}\int_0^\infty k^2 dk \exp\left[-\frac{k}{T}\right] \equiv$$

$$\equiv g\frac{T^3}{2\pi^2}\int_0^\infty x^2 dx\, e^{-x} = g\frac{T^3}{\pi^2}$$

$$p^{id}(T, m=0) = \frac{g}{\pi^2}T^4$$

$$\varepsilon^{id}(T, m=0) = \frac{3g}{\pi^2}T^4$$

$\varepsilon = \sigma T^4$ σ - SB const

	Boltzmann	Bose	Fermi
	e^{-x}	$\frac{1}{e^x-1}$	$\frac{1}{e^x+1}$
S-B constant	$\frac{3}{\pi^2} \cong 0.304$	$\frac{\pi^2}{30} \cong 0.329$	$\frac{7}{8}\cdot\frac{\pi^2}{30} \cong 0.288$

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

5''

$$\varphi_m(T) = \frac{1}{2\pi^2} \int_0^\infty p^2 dp \, e^{-\frac{\sqrt{p^2+m^2}}{T}}$$

$m/T \mapsto \infty$

$$\sqrt{p^2+m^2} \cong m + \frac{p^2}{2m}$$

$$\varphi_m(T) = \frac{e^{-m/T}}{2\pi^2} \int_0^\infty p^2 dp \, e^{-\frac{p^2}{2mT}} =$$

$$= \left(\frac{mT}{2\pi}\right)^{3/2} e^{-m/T}$$

$\mathcal{Z}(T,V)$ g.c. partition function

$$P(T) = T \lim_{V \mapsto \infty} \frac{\ln \mathcal{Z}(T,V)}{V}, \quad \text{pressure}$$

$$\varepsilon(T) = T \frac{dP}{dT} - P(T), \quad \text{energy density}$$

$$s(T) = \frac{dP}{dT}, \quad \text{entropy density}$$

$$\varepsilon + P = sT, \quad \text{thermod. identity}$$

$P(T)$ is a continuous function

$T = T_c$

A discontinuity of $\frac{dP}{dT}$ 1st order PT

A discontinuity of $\frac{d^2P}{dT^2}$ 2nd order PT

....

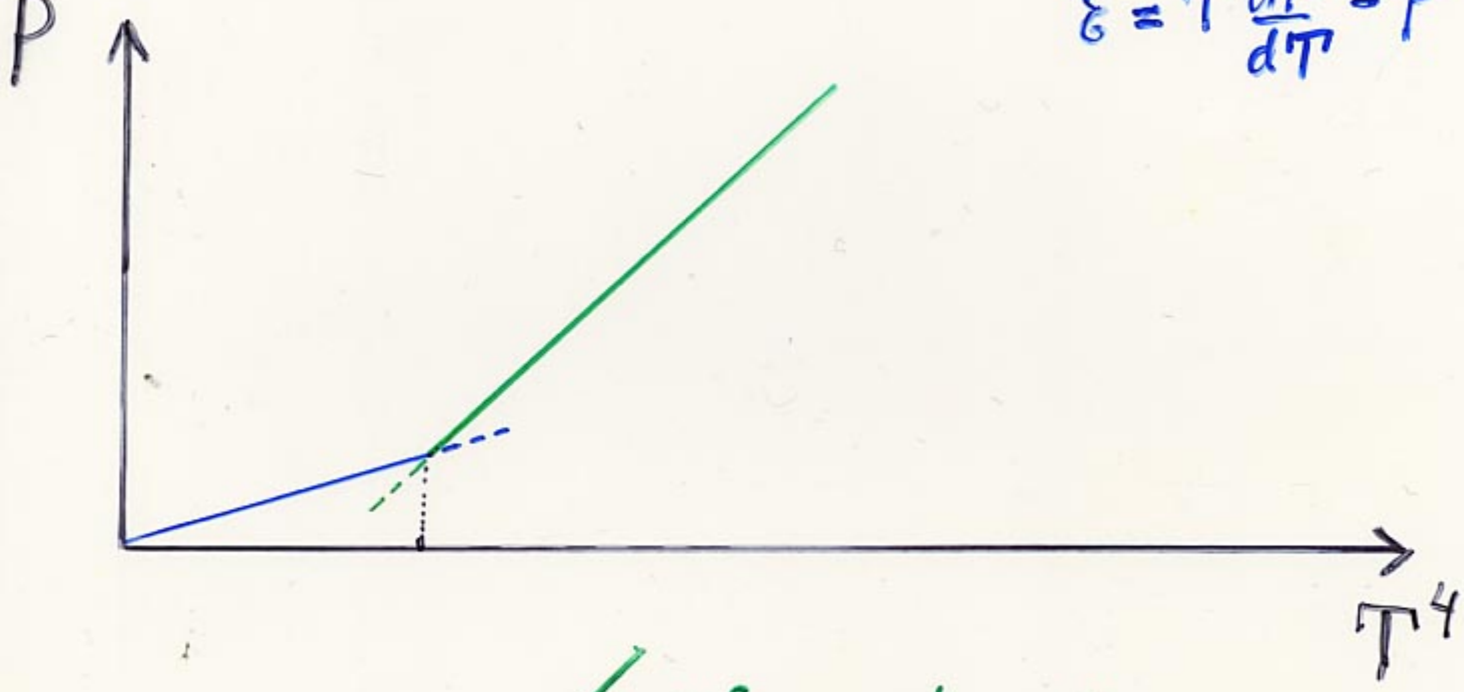
QGP $\quad p_Q = \frac{\pi^2}{90} g_Q T^4 - B$

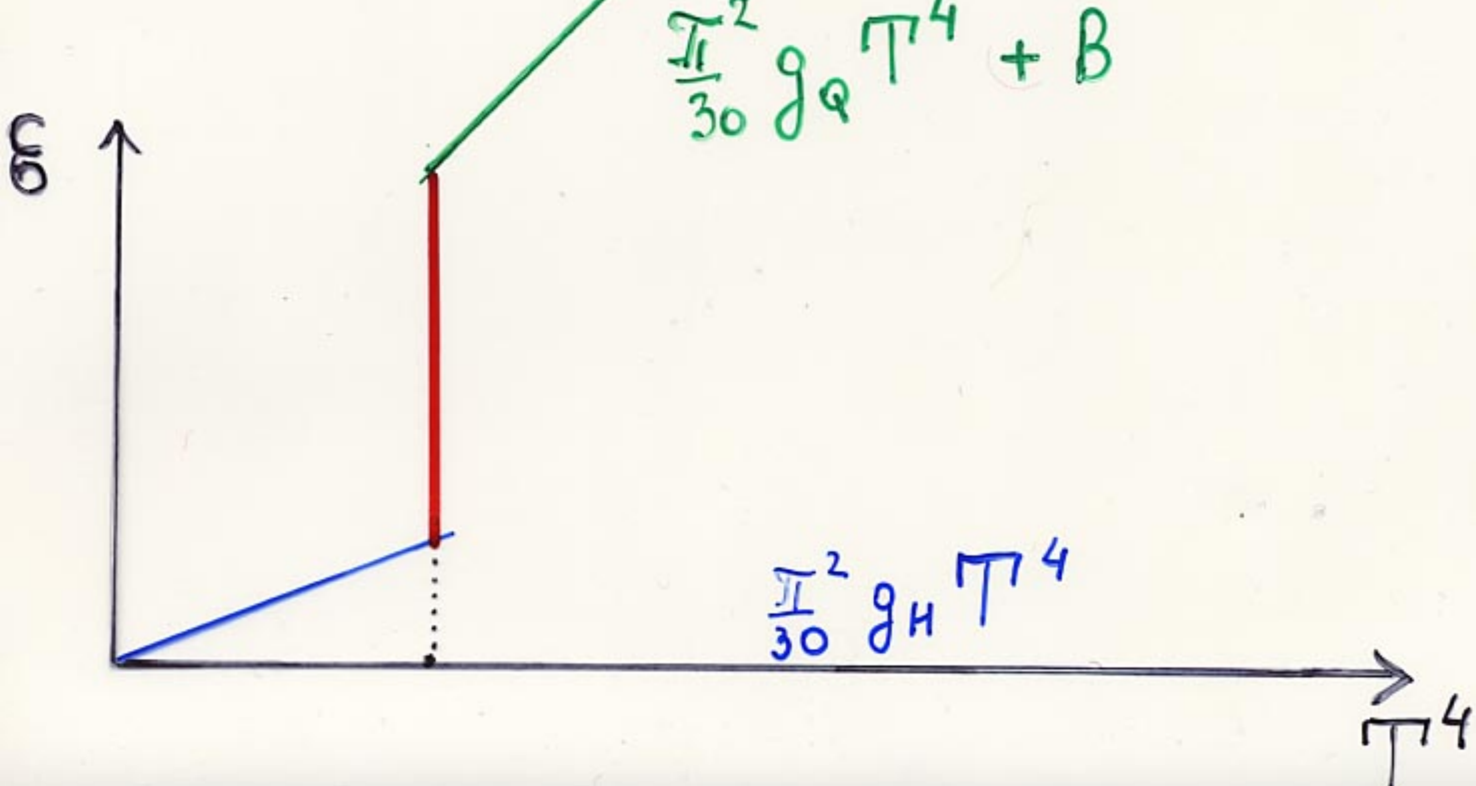
$$g_Q = 8\cdot 2 + \frac{7}{8}\cdot 2\cdot 3\cdot 3\cdot 2 = 47.5$$

HG $\quad p_H = \frac{\pi^2}{90} g_H T^4$

$g_H < g_Q$

$\varepsilon = T\frac{dp}{dT} - p$

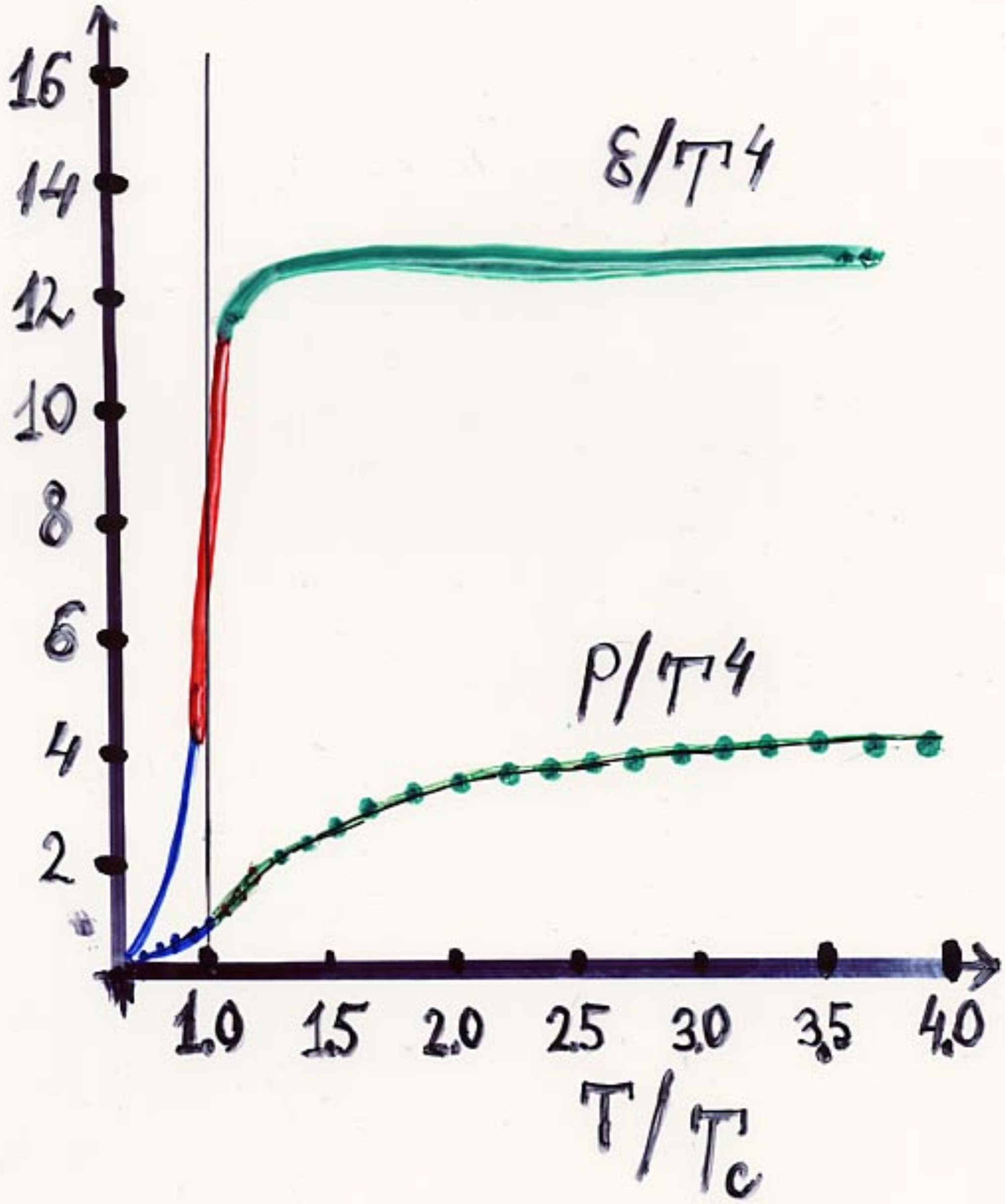




Lattice QCD

$T \gg T_c \qquad \varepsilon \simeq \sigma T^4 \, , \quad p \simeq \frac{1}{3}\varepsilon$

$$\sigma = \frac{\pi^2}{30}\Big(\underset{N_c^2-1}{8}\cdot 2 + \frac{7}{8}\cdot \underset{(2j+1)}{2}\cdot \underset{N_c}{3}\cdot \underset{n_f}{3}\cdot \underset{\bar{q}}{2}\Big)$$



$T_c \simeq 170$ MeV

"generalized" mixed phase

$$P(T,\mu) = T \lim_{V\to\infty} \frac{1}{V} \ln Z$$

$$s(T,\mu) = \frac{\partial P}{\partial T}$$

$$n(T,\mu) = \frac{\partial P}{\partial \mu}$$

$$\varepsilon(T,\mu) = T\frac{\partial P}{\partial T} + \mu\frac{\partial P}{\partial \mu} - P$$

μ_i:

$$h_{i_1} + h_{i_2} + \ldots + h_{i_k} \rightleftarrows h_{j_1} + \ldots + h_{j_n}$$

$$\begin{array}{ccccc} \downarrow & \downarrow & \downarrow & \downarrow & \downarrow \\ \mu_{i_1} & \mu_{i_2} & \mu_{i_k} & \mu_{j_1} & \mu_{j_n} \end{array}$$

$$\mu_{i_1} + \mu_{i_2} + \ldots + \mu_{i_k} = \mu_{j_1} + \ldots + \mu_{j_n}$$

$$\mu_i = b_i \mu_B + S_i \mu_S + q_i \mu_e$$

$$\varepsilon, \rho_B \longmapsto T, \mu_B$$

1). μ_S - ? $\quad \mu_B > 0 \longmapsto N_\Lambda > N_{\bar{\Lambda}}$

$\rho_S = 0 \quad \mu_S = \mu_S(T, \mu_B) > 0, \mapsto N_{K^+} > N_{K^-}$

$(\bar{s}u) \qquad (s\bar{u})$

2). μ_e - ?

$\mu_e < 0 \longmapsto N_{\pi^-} > N_{\pi^+}$

$\rho_e \approx \rho_B/2 \quad \mu_e \approx 0, \quad \rho_e \approx 0.4\rho_B$

$B \quad S \quad Q \quad C$

$\mu_B \quad \mu_S \quad \mu_e \quad \mu_c$

$$\mu_i = b_i \mu_B + S_i \mu_S + q_i \mu_e + c_i \mu_c$$

$$\mu_{\pi^+} = \mu_e$$

$$\mu_{\pi^0} = 0$$

$$\mu_{\pi^-} = -\mu_e$$

$$\mu_n = \mu_B$$

$$\mu_p = \mu_B + \mu_e$$

$$\mu_{\bar{n}} = -\mu_B$$

$$\mu_{\bar{p}} = -\mu_B - \mu_e$$

$$\mu_{K^+} = \mu_S + \mu_e$$

$$\mu_\Lambda = \mu_B - \mu_S$$

$$\boxed{\begin{matrix}\rho_B & \rho_S \\ \rho_e & \rho_c\end{matrix}}_{\,T} \longleftrightarrow \left\{ T,\ \mu_B, \mu_S, \mu_e, \mu_c \right.$$

$\rho_S = 0$

$\rho_c = 0$

A + A

T $\boxed{\begin{matrix} n & p \\ \pi^+ & \pi^0 \ \pi^- \end{matrix}}$

$\rho_B \ \rho_e$

1). $N_n = N_p$

$\rho_e = \frac{1}{2} \rho_B$

$\mu_B \qquad \mu_e = 0$

2). $N_n > N_p$

$\rho_e \approx 0.4 \rho_B$

$\mu_B, \ \mu_e < 0$

$\mu_{\pi^+} = \mu_e$

$\mu_{\pi^0} = 0$

$\mu_{\pi^-} = -\mu_e$

$N_{\pi^-} > N_{\pi^0} > N_{\pi^+}$

$$\boxed{\begin{array}{cc} N, & \bar{N} \\ K^+ & K^- \\ \Lambda & \bar{\Lambda} \end{array}}$$

$Q = \frac{1}{2} B$

$\mu_e = 0$

$\mu_B \quad \mu_S$

$\mu_N = \mu_B$

$\mu_{K^+} = \mu_S$

$\mu_\Lambda = \mu_B - \mu_S$

$$\left.\begin{array}{l} \rho_B > 0 \\ \rho_S = 0 \end{array}\right\} \longrightarrow \mu_B, \mu_S\ ?$$

$\mu_S = \mu_S(T, \mu_B)$

$\mu_B > \mu_S$

$\mu_\Lambda > \mu_{\bar{\Lambda}} \qquad N_\Lambda > N_{\bar{\Lambda}}$

$\mu_S > 0 \longleftarrow N_{K^+} > N_{K^-}$

QGP $\quad m_u, m_d, m_s \ll T$

$\mu_s = 0, \quad \frac{1}{3}\mu_B - \mu_S = 0,$

$$P_{id} = \frac{\pi^2}{90}\left(8 \cdot 2 + \frac{7}{8} \cdot 2 \cdot 3 \cdot 3 \cdot 2\right) T^4 +$$

$$+ \left(\frac{\mu_B}{3}\right)^2 T^2 + \frac{1}{2\pi^2}\left(\frac{\mu_B}{3}\right)^4$$

$$P_{QGP} = P_{id}(T, \mu_B) - B$$

MIT bag model

$$\varepsilon_{QGP} = \varepsilon_{id}(T, \mu_B) + B$$

$$f_i = \frac{1}{\exp\left[\frac{\sqrt{k^2+m_i^2}-\mu_i}{T}\right]+1}$$

$u, d \qquad \mu_{u,d} = \frac{1}{3}\mu_B$

$s \qquad \mu_s = \frac{1}{3}\mu_B - \mu_S$

$$\mu_S = 0 \quad \boxed{\mu_s = \frac{1}{3}\mu_B}$$

$$f_g = \frac{1}{\exp\left(\frac{k}{T}\right)-1}$$

"Discovery" of the QGP in Pb+Pb at 160 A GeV

2000

1. J/ψ Suppression

$$R = \frac{N_{J/\psi}}{N_{DY}}$$

T. Matsui, H. Satz
PL B 178 (1986) 416

$$\left(\frac{N_{J/\psi}}{N_{DY}}\right)_{AA} < \left(\frac{N_{J/\psi}}{N_{DY}}\right)_{pp}$$

2. Strangeness Enhancement

K/π, ..., Ω/π, Ω/N_p

$$\frac{(K/\pi)_{AA}}{(K/\pi)_{pp}} > 1, \quad \underset{\text{for } \Omega}{\gg 1}$$

J. Rafelski, B. Müller
PRL 48 (1982) 1066
56 (1986) 2334E
.....

HG

NO strange Hadrons

QGP

NO $s, \bar{s}$ quarks

T= 150 MeV

$t_{eq} \simeq 100$ fm/c

$t_{eq} \simeq 10$ fm/c

$$\frac{\left(\frac{K^+}{\pi^+}\right)_{AA}}{\left(\frac{K^+}{\pi^+}\right)_{pp}}$$

should strongly increase if the QGP is formed

! strangeness enhancement

* Real A+A gives different initial condit. (RQMD, UrQMD)

** multiple hadron collisions

* $\left(\frac{\text{strangenes}}{\text{entropy}}\right)^{eq}_{HG} > \left(\frac{\text{strangeness}}{\text{entropy}}\right)^{eq}_{QGP}$

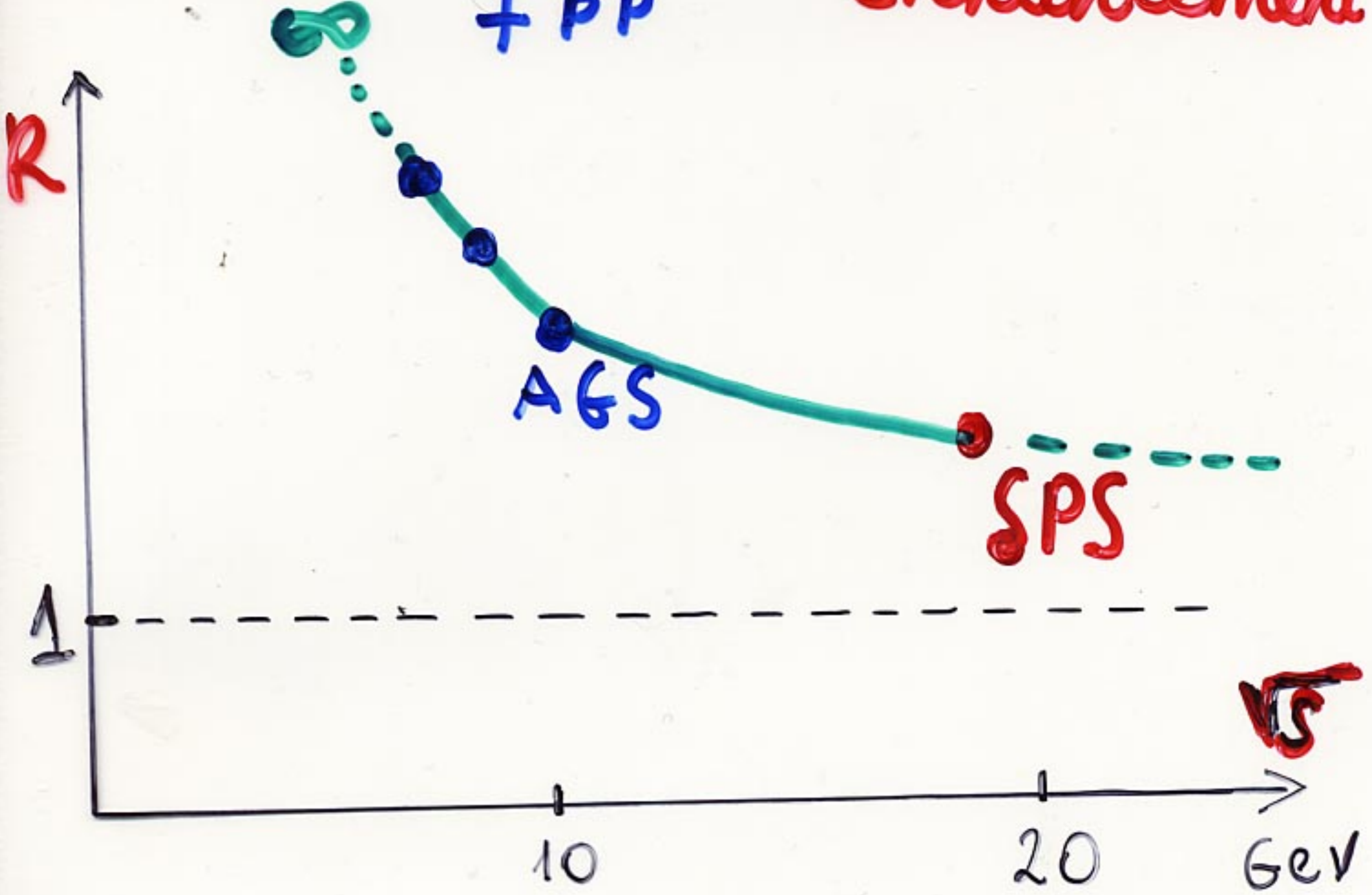
$N_s + N_{\bar{s}}$ – ?

$$f = \frac{N_s + N_{\bar{s}}}{\langle \pi \rangle}, \quad \frac{N_s + N_{\bar{s}}}{N_p}, \quad \frac{K^+}{\pi^+}, \ldots$$

$\ldots, \Omega/\pi$

$f_{AA}(\sqrt{s})$ strong increase if QGP is formed

$$R(\sqrt{s}) = \frac{f_{AA}}{f_{pp}}$$ strangeness enhancement



(1974) J/ψ $j = 1$ $m_{J/\psi} \simeq 3.1$ GeV

J/ψ →

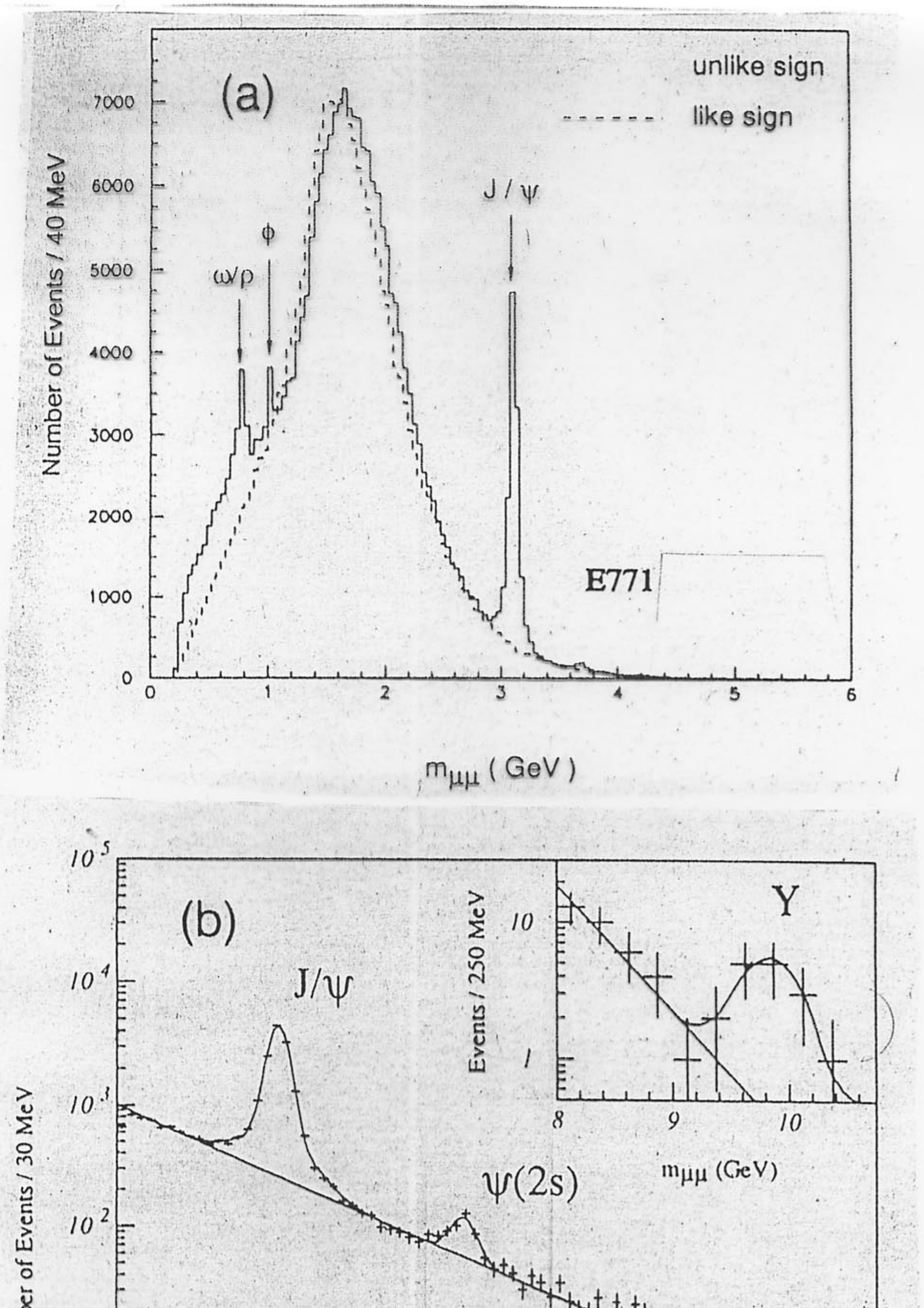
- { c quark, $m_c \simeq 1.3$ GeV
- { $(c\bar{q})$ $(\bar{c}q)$ $q = u, d, s$
  D - mesons open charm
- { $(c\bar{c})$ $\eta_c, \chi_c, \ldots, \psi', \ldots$ charmonia
- { (cqq) $q = u, d, s$
  charmed baryons
- { (ccq) - ? (ccc) - ??
- { b quark, $m_b \simeq 4.2$ GeV
  B - mesons, $\Upsilon, \chi_b, \ldots \Upsilon', \ldots$
  Bottom baryons
  . . .

Matsui, Satz (1986)

J/ψ suppression in QGP

$J/\psi \to \mu^+ \mu^-$ 6% $\psi' \to \mu^+ \mu^-$ 1%

$\rho, \omega, \phi \to \mu^+ \mu^-$ $10^{-4} \div 10^{-5}$


(a)
unlike sign
like sign
Number of Events / 40 MeV
ω/ρ
ϕ
J / ψ
E771
$m_{\mu\mu}$ (GeV)
(b)
J/ψ
ψ(2s)
Υ
Events / 250 MeV
$m_{\mu\mu}$ (GeV)
Number of Events / 30 MeV
E771
$m_{\mu\mu}$ (GeV)

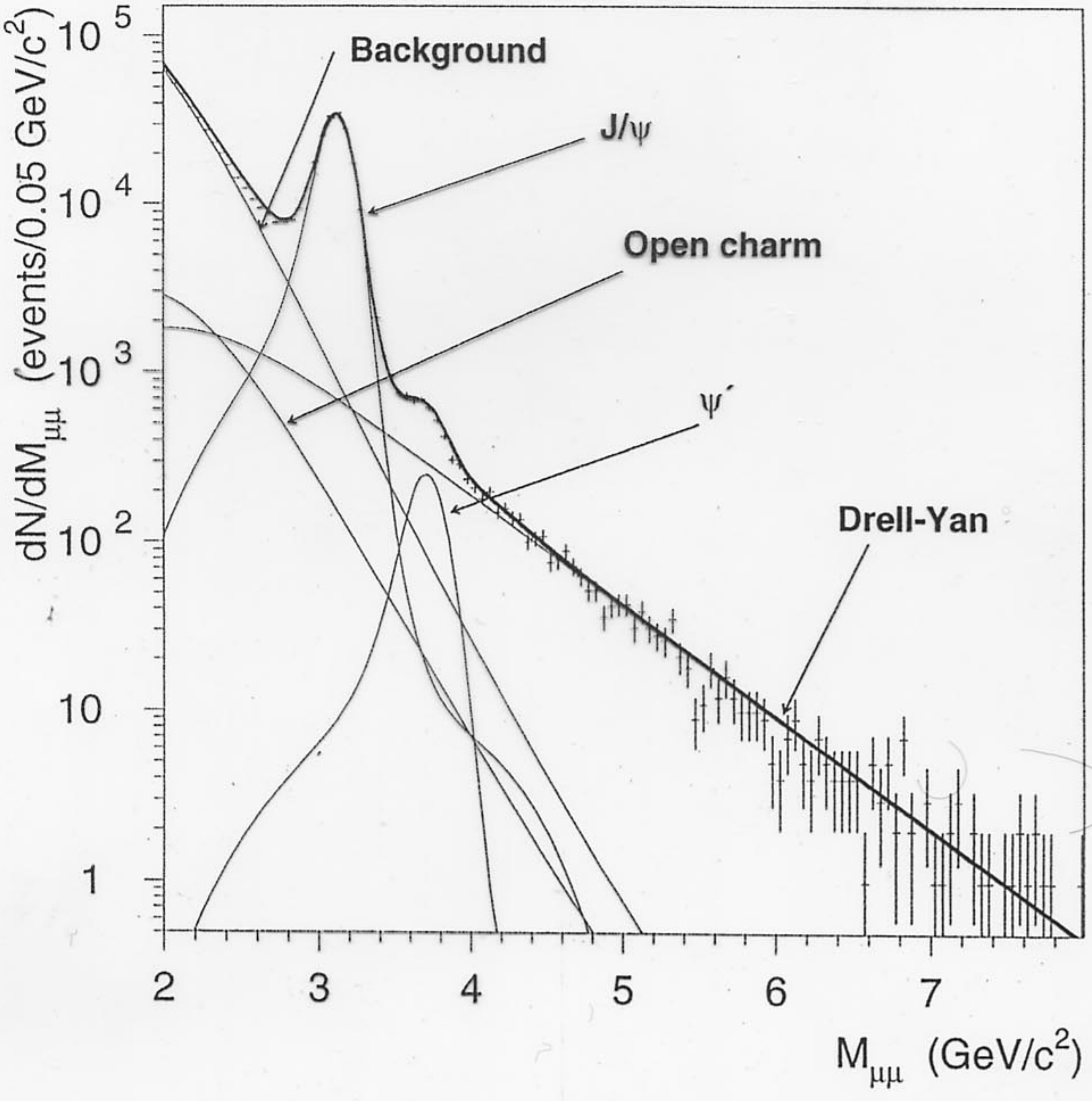
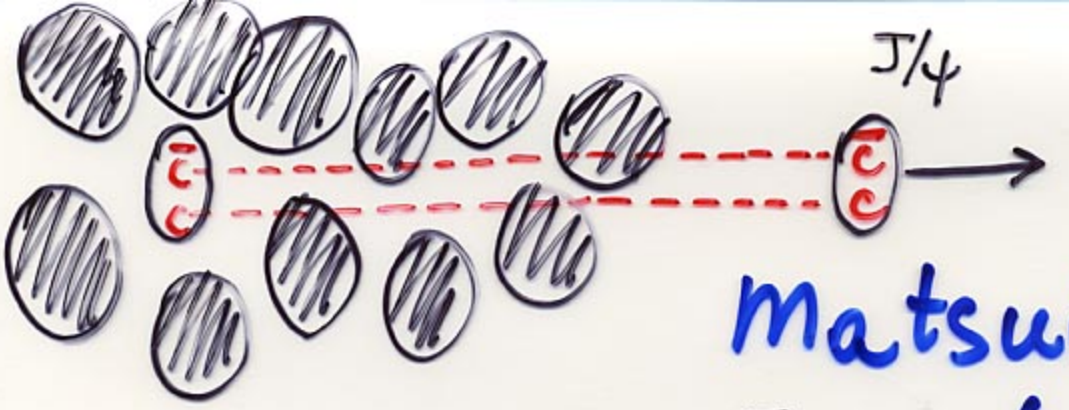
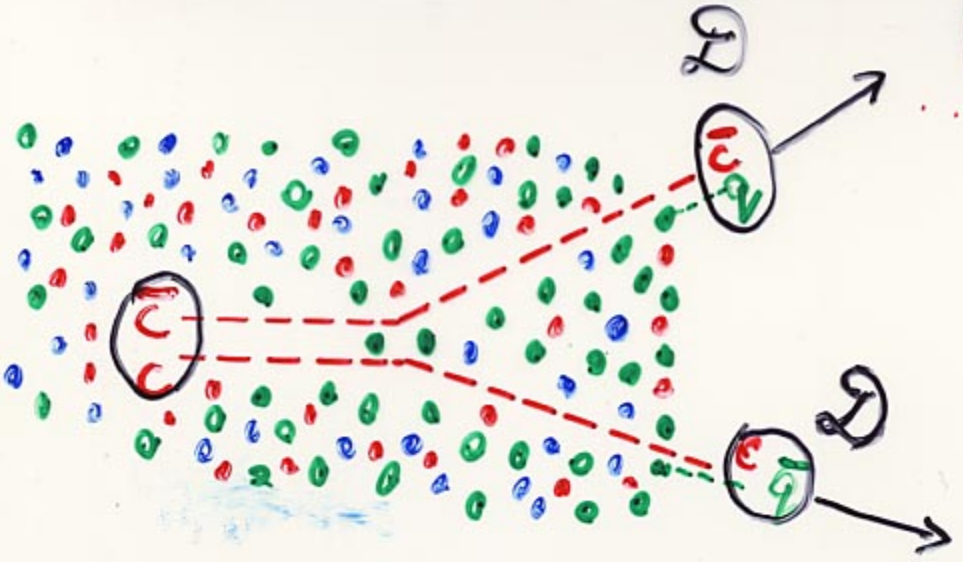


Figure 1: Opposite-sign muon pair invariant mass spectrum for Pb-Pb collisions a 158 GeV/c incident momentum. Data collected in 1996.



Hadron Gas

Matsui, Satz (1986)



QGP

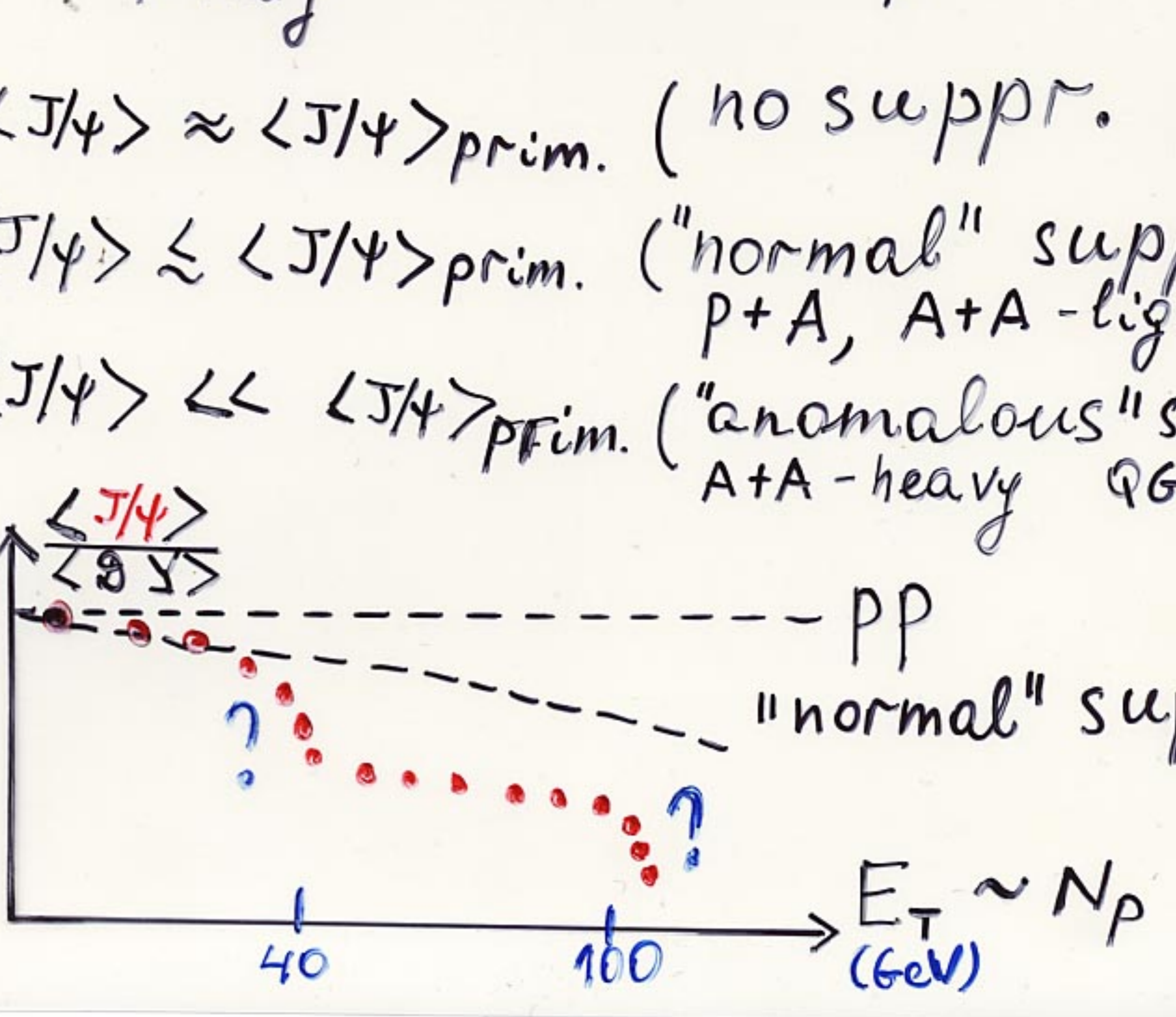
$J/\psi \to \mu^+ \mu^-$ 6%

$\langle J/\psi \rangle_{primary} \sim \langle DY \rangle \sim N_p^{4/3}$

$\langle J/\psi \rangle \approx \langle J/\psi \rangle_{prim.}$ (no suppr. p+p)

$\langle J/\psi \rangle \lesssim \langle J/\psi \rangle_{prim.}$ ("normal" suppr.) p+A, A+A - light

$\langle J/\psi \rangle \ll \langle J/\psi \rangle_{prim.}$ ("anomalous" suppr. A+A - heavy QGP !?)



② $$\langle J/\psi \rangle = \frac{(2j+1)}{2\pi^2} V \int_0^\infty \frac{k^2 dk}{\exp\left[\frac{(k^2+m_\psi^2)^{1/2}}{T}\right]-1}$$

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

$j = 1, \quad m_\psi = 3097$ MeV

$$\frac{\langle J/\psi \rangle}{\langle h^- \rangle} \cong \mathrm{const}(A, \sqrt{s})$$

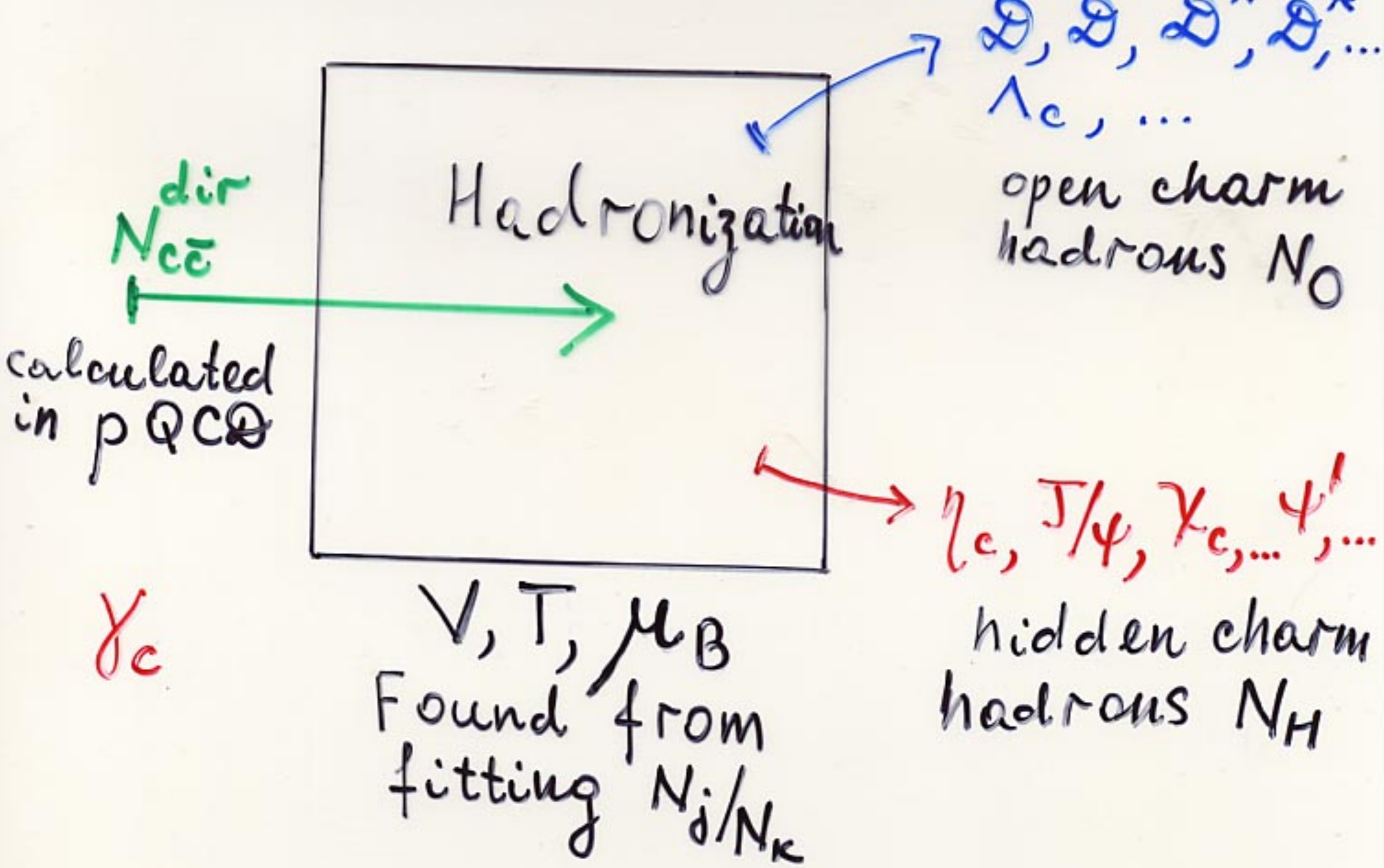
M. Gaździcki, M. Gorenstein

Phys. Rev. Lett. 83 (1999) 4009

$T \approx 176$ MeV

$$\frac{\langle J/\psi \rangle}{\langle h \rangle}$$

Braun-Munzinger, Stachel (2000)



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

$N_O(V, T, \mu_B)$ g.c.e.

1). N_O c.e. 2). $P(N_{c\bar{c}}^{dir})$ – Poisson distr.

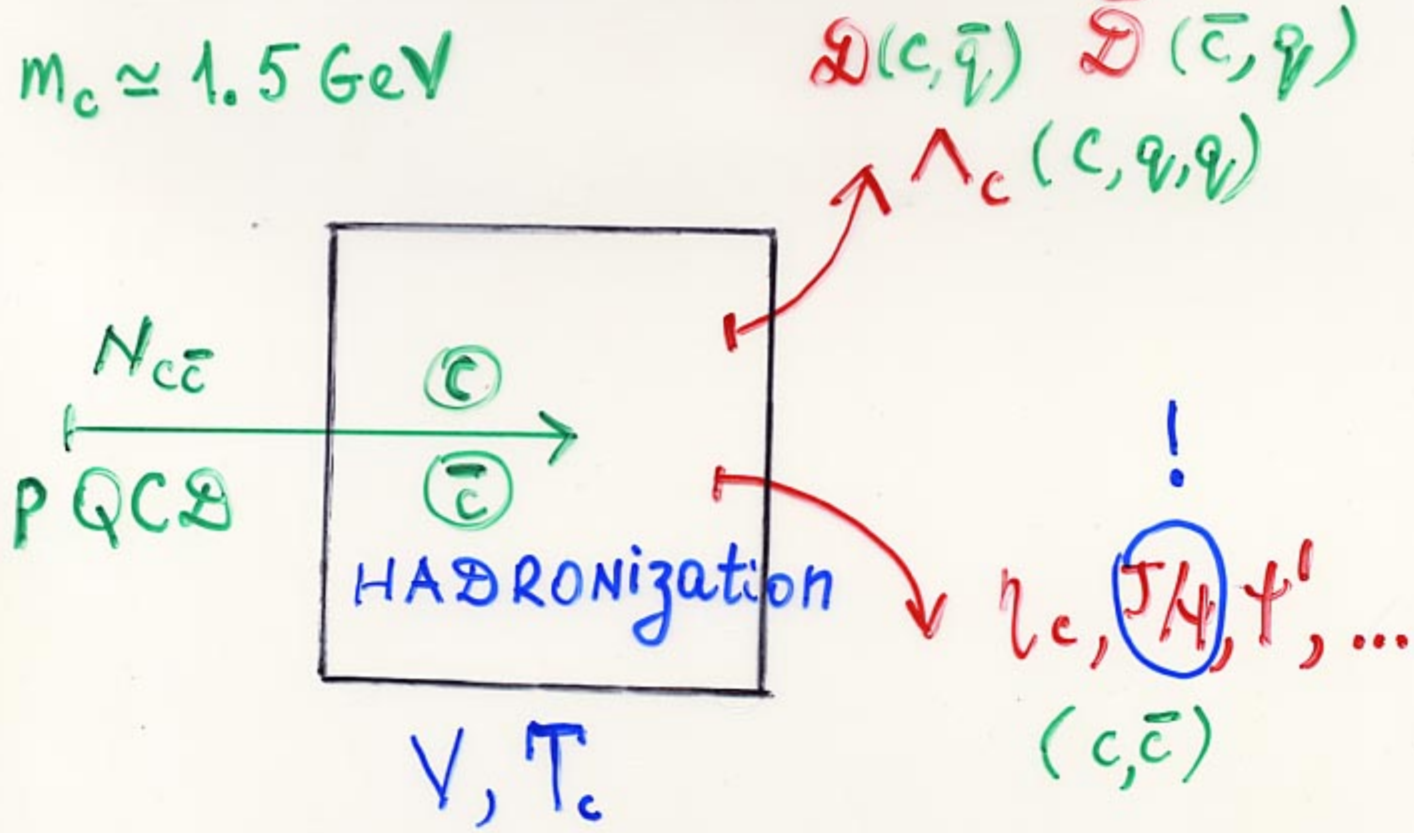
$$\langle J/\psi \rangle \cong \overline{N}_{c\bar{c}} \left(1 + \overline{N}_{c\bar{c}}\right) \frac{N_{J/\psi}^{tot}}{N_O^2}$$

M.G., Kostyuk, Stöcker, Greiner (2001)

Phys. Lett. B (2001, 2002)

A + A

$m_c \simeq 1.5$ GeV



Pb+Pb 160 A·GeV

$$\langle N_{c\bar{c}} \rangle < 1$$

Exact Charm Conservation

! ~~g.c.e.~~

M. Gorenstein et al

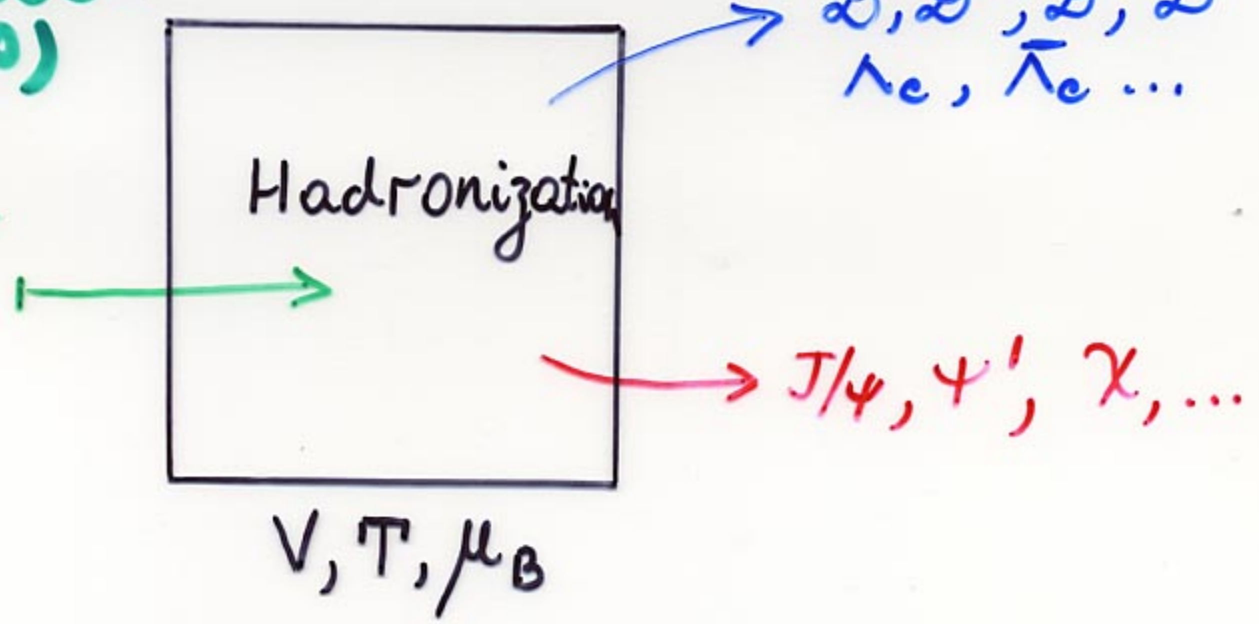
Phys. Rev. Lett. 83 (1999) 4009

Phys. Lett B509 (2001) 277

B523 (2001) 60, B524 (2002) 265

Braun-Munzinger
Stachel
(2000)

$$I \downarrow N_{c\bar{c}}^{dir} \downarrow \gamma_c$$



$$N_j = d_j V e^{\mu_j/T} \left(\frac{m_j T}{2\pi}\right)^{3/2} \exp\left(-\frac{m_j}{T}\right)$$

$$\mu_j = b_j \mu_B + s_j \mu_S + c_j \mu_c$$

$$\mu_S = \mu_S(T, \mu_B) \qquad \mu_c = \mu_c(T, \mu_B)$$

$$N_H^{c.e.} = N_H \qquad N_H = \sum_{i \in \text{hidden}} N_i$$

$$N_O^{c.e.} = N_O \frac{I_1(N_O)}{I_0(N_O)} \qquad N_O = \sum_{j \in \text{open}} N_j$$

$$\frac{I_1(N_O)}{I_0(N_O)} \begin{array}{l} \nearrow 1, \quad N_O \gg 1 \\ \searrow \frac{N_O}{2}, \quad N_O \ll 1 \end{array}$$

$$\frac{\langle \psi' \rangle_{th}}{\langle J/\psi \rangle_{th}} = \left(\frac{m_{\psi'}}{m_{J/\psi}}\right)^{3/2} \exp\left[-\frac{(m_{\psi'} - m_{J/\psi})}{T}\right]$$

$$\frac{\langle \psi' \rangle_{th}}{\langle J/\psi \rangle_{th}} = \begin{cases} \nearrow 0.04 & (T = 170\ \mathrm{MeV}) \\ \searrow 0.05 & (T = 180\ \mathrm{MeV}) \end{cases}$$

$$\frac{\langle \psi' \rangle}{\langle J/\psi \rangle} = 0.04 \div 0.05$$

Pb + Pb (158 AGeV)

$N_{part} = 100 \div 400$

$$R(N_p, \sqrt{s}) = \frac{\langle J/\psi \rangle}{N_{c\bar{c}}^{dir}}$$

$$N_{c\bar{c}}^{dir} = \frac{1}{2} \gamma_c N_0 \frac{I_1(\gamma_c N_0)}{I_0(\gamma_c N_0)} + \underbrace{\cancel{\gamma_c^2 N_H}}_{\sim 0}$$

$$\langle J/\psi \rangle = \gamma_c^2 N_{J/\psi}^{tot}$$

$$N_{J/\psi}^{tot} \sim N_0 \sim V \sim \langle \pi \rangle \sim N_p \sqrt{s}^{1/2}$$

$$N_{c\bar{c}}^{dir} \sim N_p^{4/3} \sqrt{s}^{\beta} , \qquad \beta \simeq 1.13$$

M.G., A. Kostyuk, et. al.

hep-ph/0104071 (Phys. Lett. B 2001)

hep-ph/0012292 (J. Phys. G 2001)

I. $N_{c\bar{c}}^{dir} \ll 1$

$$N_{c\bar{c}}^{dir} \simeq \frac{1}{4} \gamma_c^2 N_0^2$$

$$R(N_p, \sqrt{s}) \simeq \frac{N_{J/\psi}^{tot}}{N_0^2/4} \sim \frac{1}{V} \sim N_p^{-1} \sqrt{s}^{-1/2}$$

J/ψ suppression

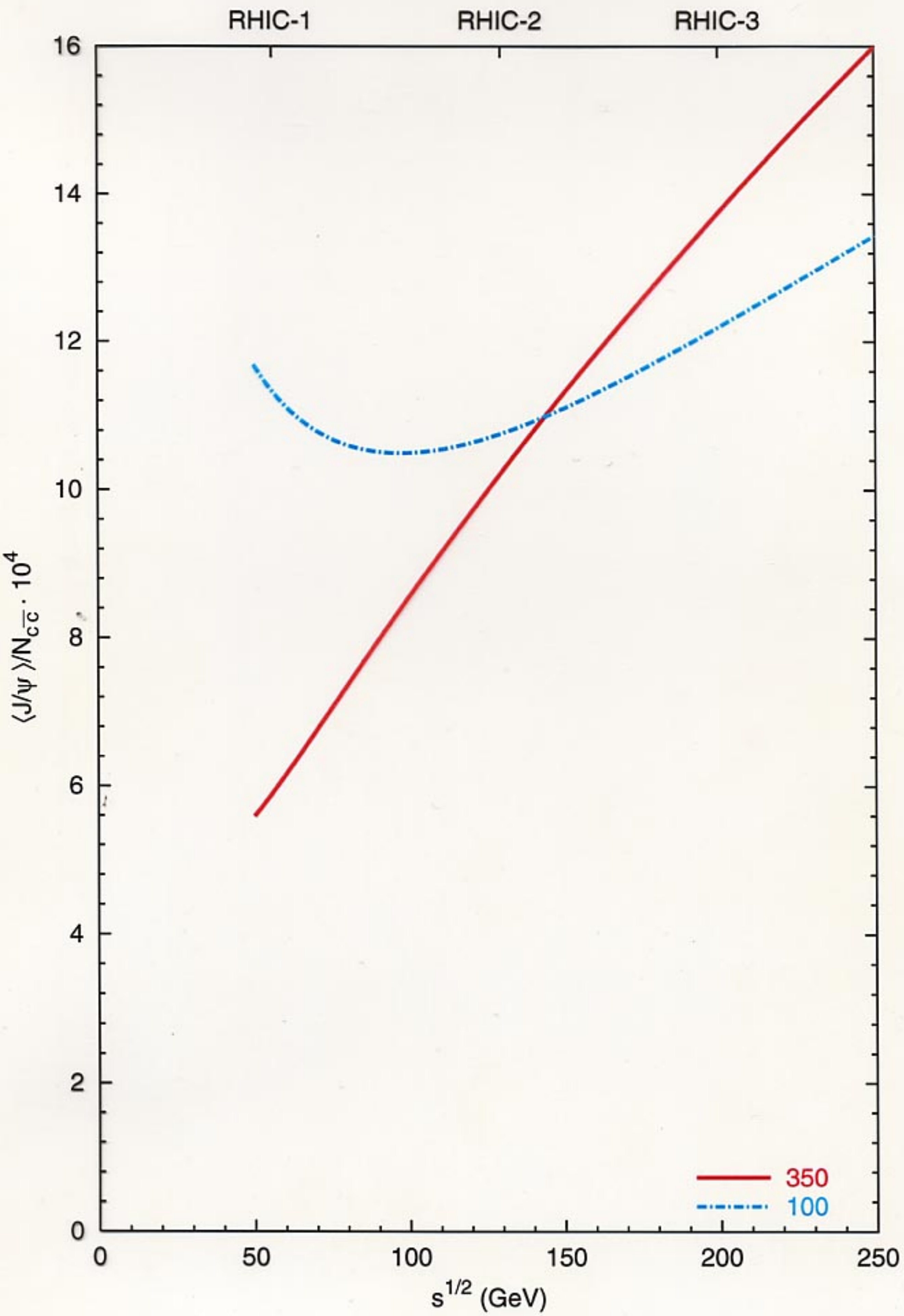
II. $N_{c\bar{c}}^{dir} \gg 1$

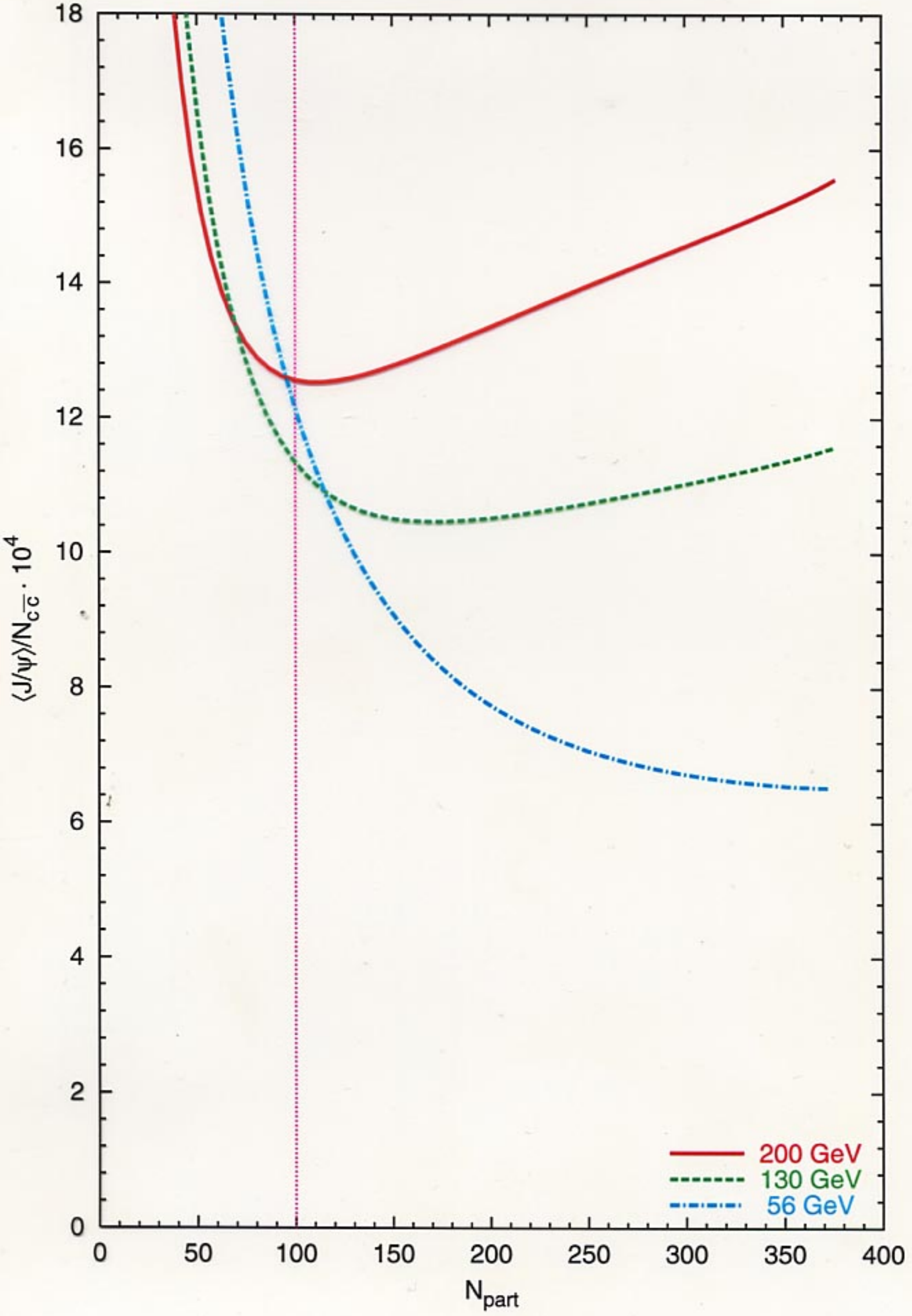
$$N_{c\bar{c}}^{dir} \simeq \frac{1}{2} \gamma_c N_0$$

$$R(N_p, \sqrt{s}) \simeq \frac{\gamma_c N_{J/\psi}^{tot}}{N_0/2} \sim \frac{N_{c\bar{c}}^{dir}}{V}$$

$$\sim N_p^{1/3} (\sqrt{s})^{\beta - 1/2}$$

J/ψ enhancement


RHIC-1
RHIC-2
RHIC-3
16
14
12
10
8
6
4
2
0
⟨J/ψ⟩/N_{c c̄} · 10^4
350
100
0
50
100
150
200
250
s^{1/2} (GeV)



18
16
14
12
10
8
6
4
2
0
$\langle J/\psi \rangle / N_{c\bar{c}} \cdot 10^4$
0
50
100
150
200
250
300
350
400
N_{part}
200 GeV
130 GeV
56 GeV