The J/Ψ as a probe of Quark-Gluon Plasma

Heavy Ion Meeting (HIM), *Seoul, October 9, 2004*

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Overview

- In normal vacuum, heavy quarks in a c-cbar pair feel a constant attractive force (i.e. a linearly rising potential)
- In the deconfined phase, the attractive force between c and c-bar is screened by the Quark-Gluon Plasma (QGP)
- charmonia bound states "melt", more and more with rising temperature;
- The onset of "anomalous" J/Ψ suppression in relativistic heavy ion collisions (starting from the J/Ψs from the decay of higher charmonia) signals the formation of QGP

T. Matsui and H. Satz Phys. Lett. B178, 416 (1986);
See R. Vogt, Phys. Rep. 310, 197 (1999).

Overview (cont'd)

- To say what is "anomalous", we must control the "other" sources of absorption (nuclear, hadronic);
- several calculations of dissociation cross-section have been performed:

$$h + J/\Psi \to D^{(*)} + \overline{D}^{(*)};(h = \pi,\rho,...)$$

See e.g.: T. Barnes, "Charmonium Cross Sections and the QGP", nucl-th/0306031

•I will report on our calculation:

L. Maiani, F. Piccinini, A.D. Polosa, V. Riquer,hep-ph/0402275; hep-ph/0408150

•and apply the results to the SPS, NA50 data

M.C. Abreu et al., Phys. Lett. B450, 456 (1999); M.C. Abreu et al., Phys. Lett. B477, 28 (2000). Latest analysis: http://na50.web.cern.ch/NA50/

Overview (cont'd)

- The main question:
  - DID QGP SHOW UP AT THE SPS?
- Our analysis says:
  - MOST LIKELY, YES !!
  - But we need to know better...
  - ..and study QGP more, at RHIC, LHC, ...

1. Snapshots of relativistic heavy ion collision in the c.o.m.

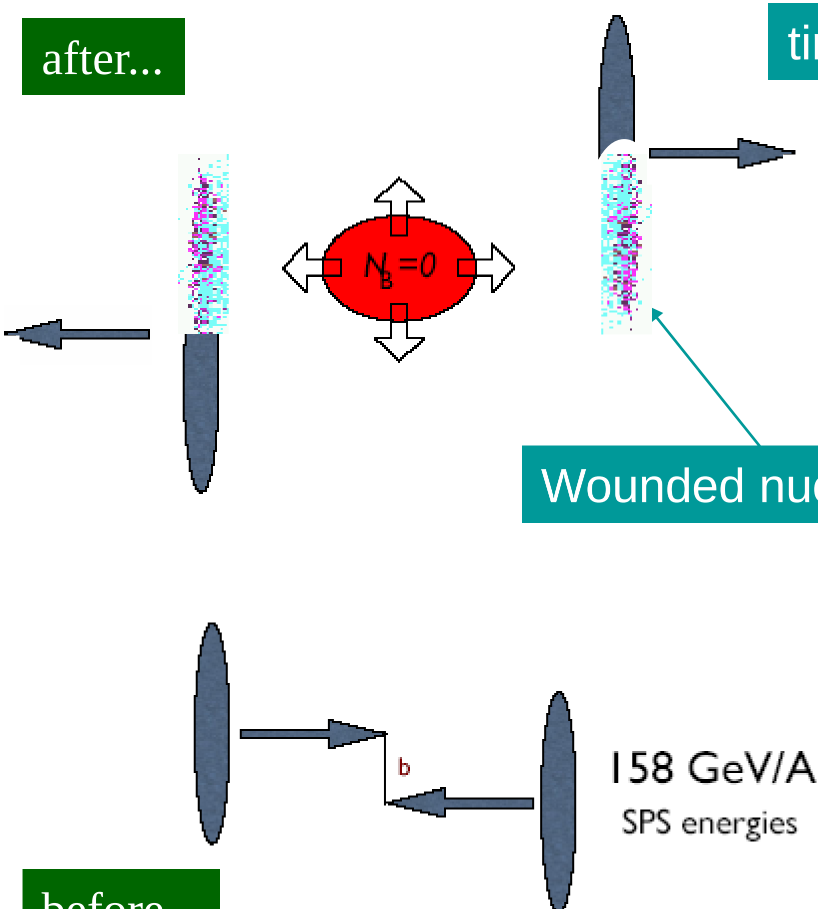
J. Bjorken, Phys. Rev. D27, 140 (1983)

U. Wiedemann, CERN Academic Training 2004

The energy of the surviving nuclear fragments seen by the Zero Degree Calorimeter in NA50 gives a measure of the impact parameter b !

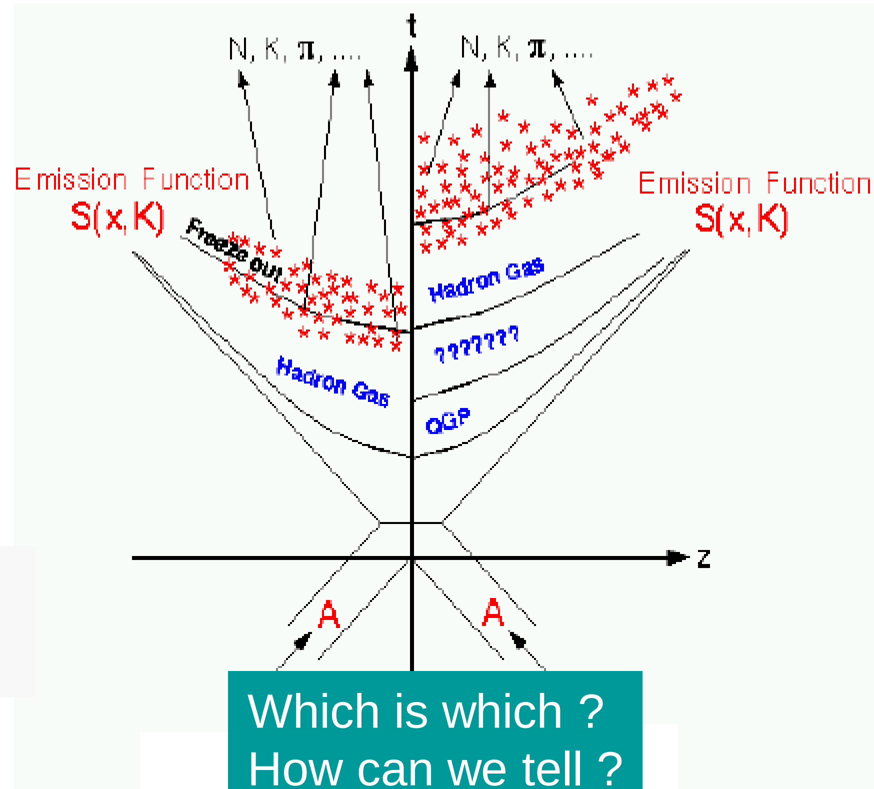
after...

time



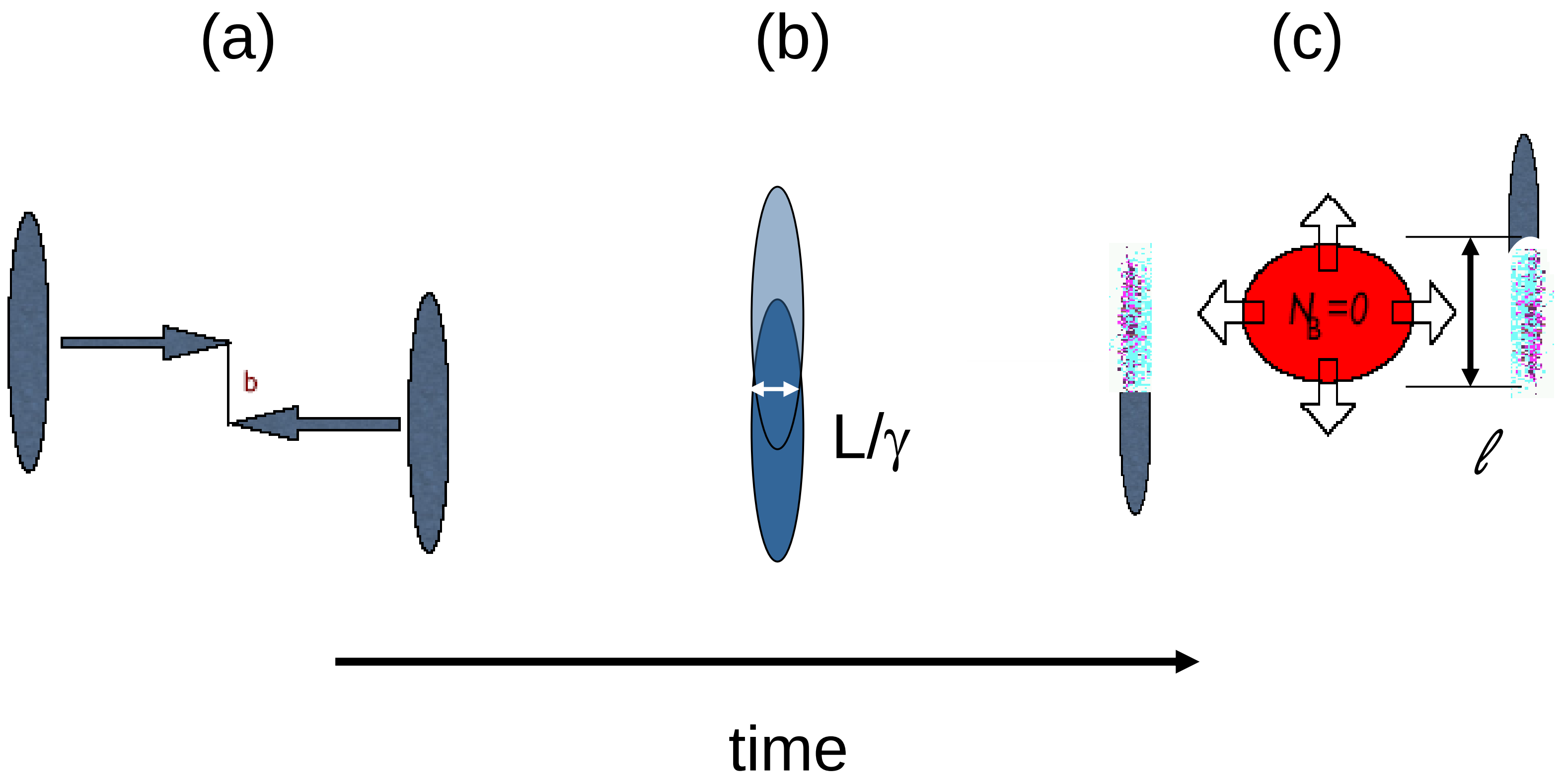
Wounded nucleons

before...



Which is which ?
How can we tell ?

Geometry (cont'd)



L→ nuclear absorption;

ℓ=2R-b → absorption by the fireball;

Bjorken's estimate of the energy density of the fireball

Nucleon number/unit area (increases with centrality)

$$\epsilon = \frac{A(b)}{S(b)}\left(\frac{dE}{dy}\right)\frac{1}{ct} \qquad \frac{dE}{dy} = \frac{dN_{ch}}{dy}\left(1+\frac{N_{\rm neutr}}{N_{ch}}\right)\langle E\rangle \simeq 3\times 1.5\times 400 \text{ MeV} = 1.8 \text{ GeV}$$

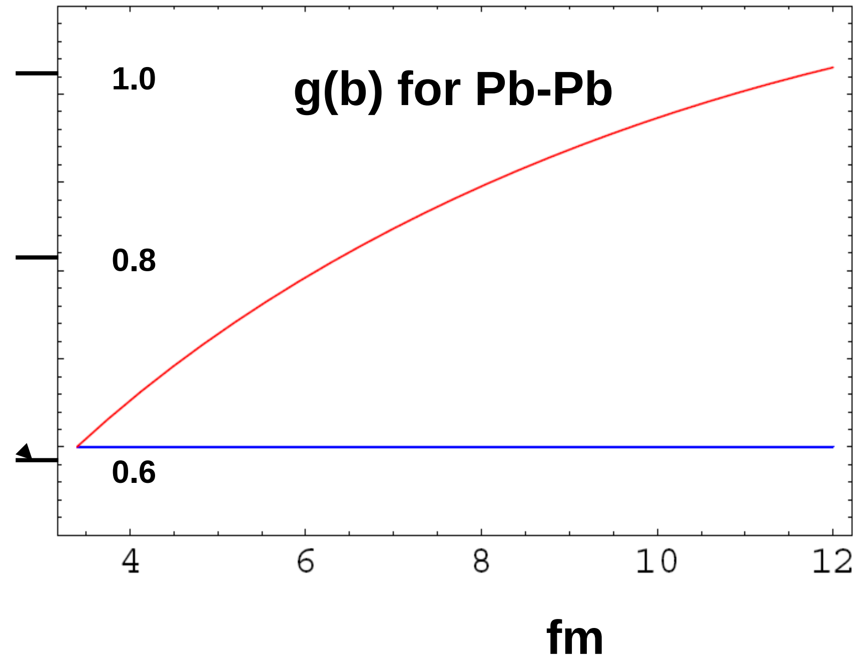
Longitudinal dimension

For central Pb-Pb collision:

$$\frac{A(b=0)}{S(b=0)} = \frac{A}{\pi R^2} = \frac{A^{1/3}}{\pi r_0^2} = 1.5 \text{ fm}^{-2}$$

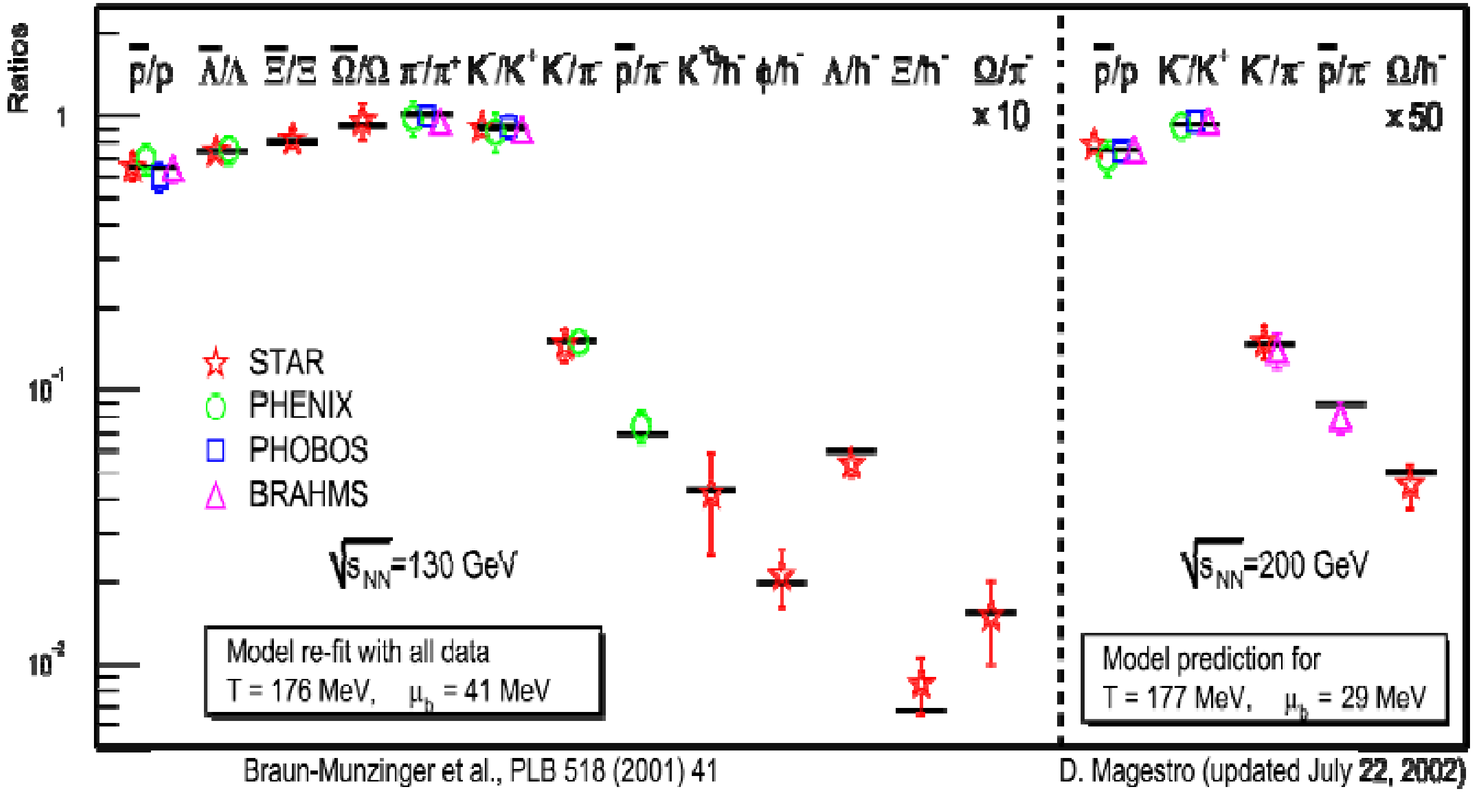
$$\varepsilon = 1.8 GeV/fm^3 \left(\frac{1 fm}{c\tau_0}\right) - (l = 4 fm)$$

$$\varepsilon = 2.6 GeV/fm^3 \left(\frac{1 fm}{c\tau_0}\right) - (l = 12 fm)$$



Does the fireball thermalize? (cont'd)

- Hadrons at freeze-out are thermal, T=170-180 MeV

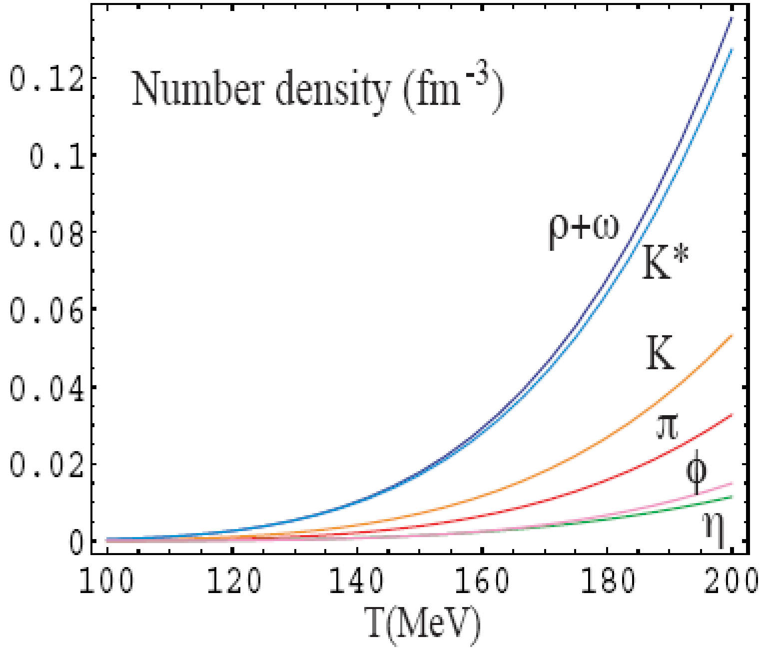


2. Hadron resonance gas

Low energy,
Low centrality

$$\rho(T) = \frac{N}{2\pi^2}\int_{E_{\rm th.}}^{\infty} dE \frac{pE}{e^{E/kT}-1}.$$

N is the total multiplicity (spin times charge, $N = 3, 9$ for pion and for ρ, respectively) and $p = \sqrt{E^2 - m^2}$.



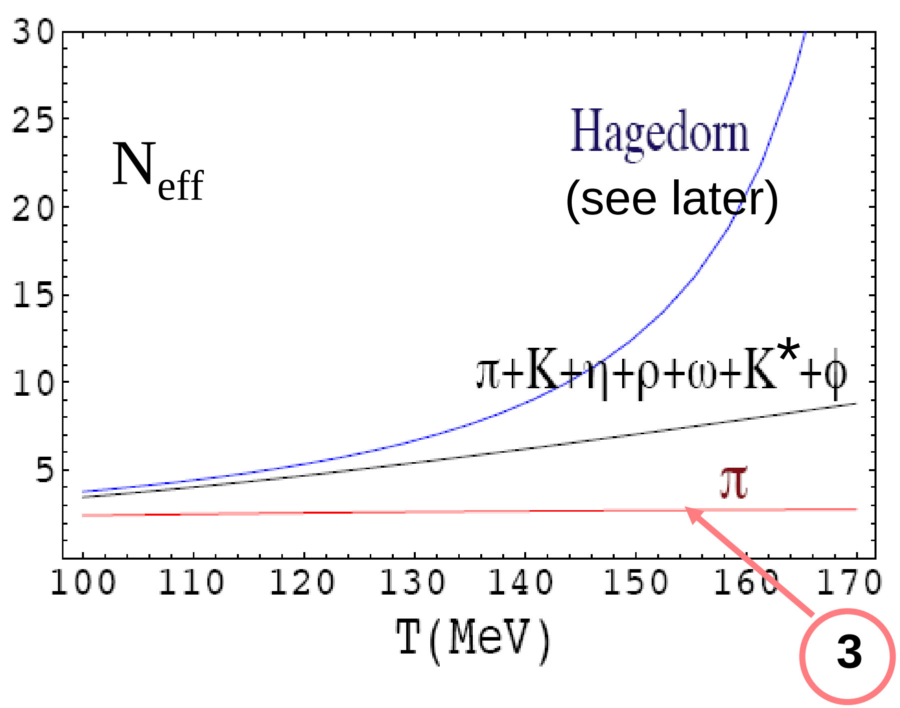
Threshold for
M+J/Psi -> D $^{(*)}$ D$^{(*)}$

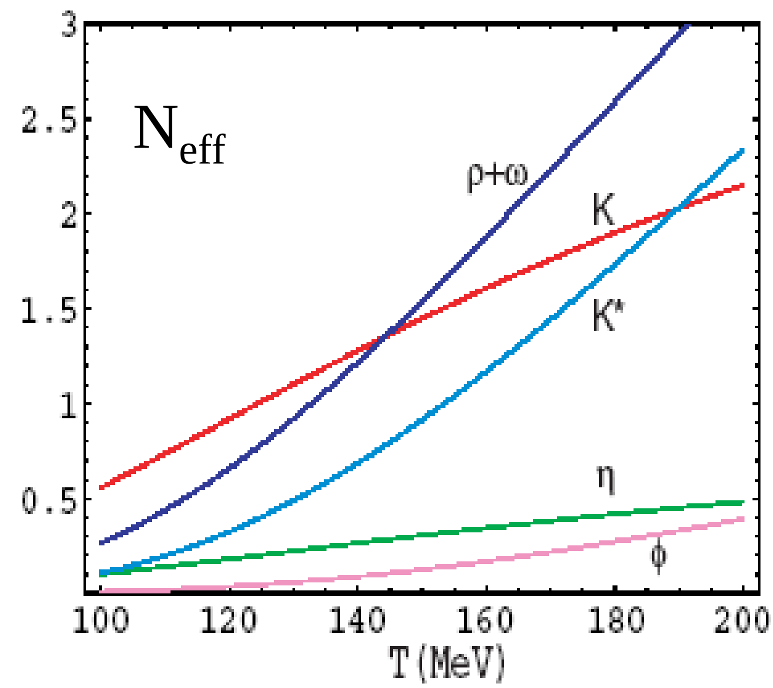
Resonance gas (cont'd)

$$\epsilon(T) = \frac{N}{2\pi^2}\int_m^\infty dE \frac{pE^2}{e^{E/kT}-1} \qquad N_{eff} = \frac{\varepsilon(T)}{\varepsilon_0(T)} \qquad \epsilon_0 = T^4\pi^2/30$$

Not only pions !!

In spite of higher mass, higher resonances contribute to the energy density at temperatures around 150 MeV because of increasing multiplicities





3. Hagedorn's thermodynamics

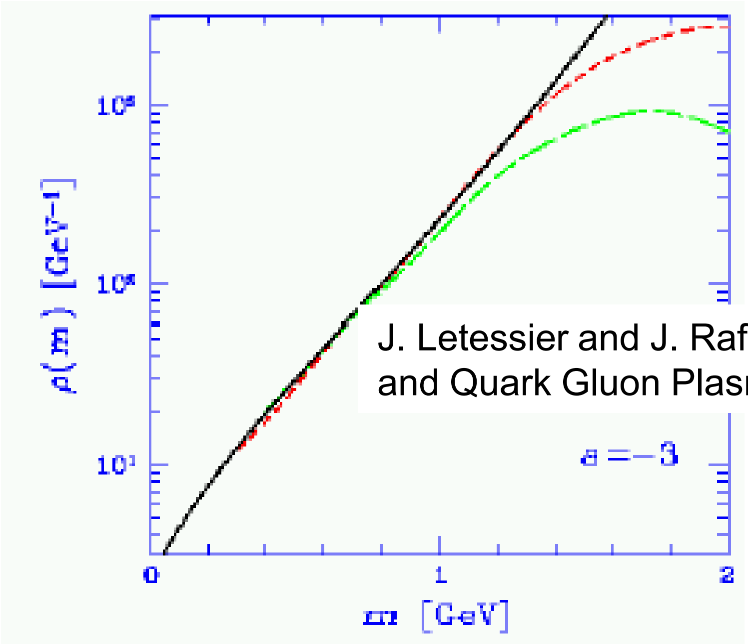
The Exponential Hadron Mass Spectrum

- Black line: fit to

$$\rho(m)=c\left(m_a^2+m^2\right)^{-3/2}\exp\left[\frac{m}{T_H}\right]$$

$$m_a=0.66\ GeV\ ,\quad T_H=158\ MeV$$

- Green line:
  1411 states of 1967
- Red line:
  4627 states of 1996



J. Letessier and J. Rafelski, "Hadrons and Quark Gluon Plasma", (2002).

- Experimental lines include Gaussian smoothing, $\sigma_{\overline{m}}=\Gamma_{\overline{m}}/2\sim 200\ MeV$

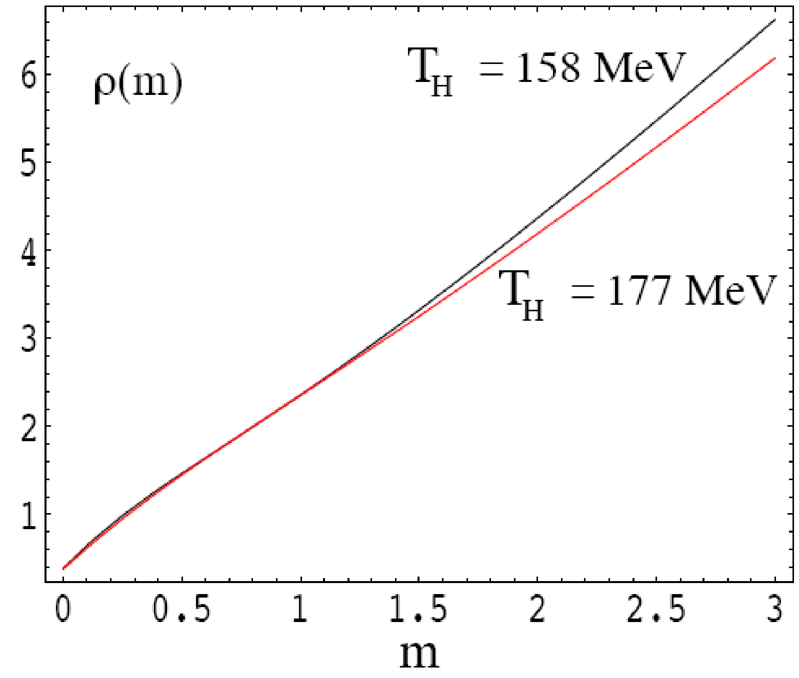
$$\rho(m)=\sum_i\delta(m-m_i)\rightarrow\sum_{\overline{m}=m_\pi,m_\rho,\ldots}\frac{g_{\overline{m}}}{\sqrt{2\pi}\,\sigma_{\overline{m}}}\exp\left[\frac{-(m-\overline{m})^2}{2\sigma_{\overline{m}}^2}\right]$$

NOTE: $\rho_{tot}=\rho(m)+3\delta(m-m_\pi)$

Varying the Hagedorn Temperature

T_H must be consistent with observed temperatures at freeze-out!!

C= 0.7, mo= 0.66 GeV, T=158 MeV, or
C= 1.66, mo= 0.88 GeV, T=173 MeV
give very similar results for m<1.5 GeV



$$\rho(m) = \frac{C}{(m^2 + m_0^2)^{3/2}} \exp\left(\frac{m}{T_H}\right)$$

From the hadron spectrum, T can be stretched up to ≈180 MeV

Interpretation of the Hagedorn temperature

N. Cabibbo and G. Parisi, Phys. Lett. 59B, 67 (1975) (and Erice ’75).

Use non-relativistic, Boltzmann approx.: critical behaviour is determined by the high masss part of the spectrum, m>>T

$$\ln Z_H = \frac{V}{(2\pi\beta)^{3/2}} \int \frac{C}{(m^2+m_0^2)^{3/2}} (m)^{3/2} e^{-m(\beta-\beta_c)} dm$$

$\beta_c = 1/T_H$

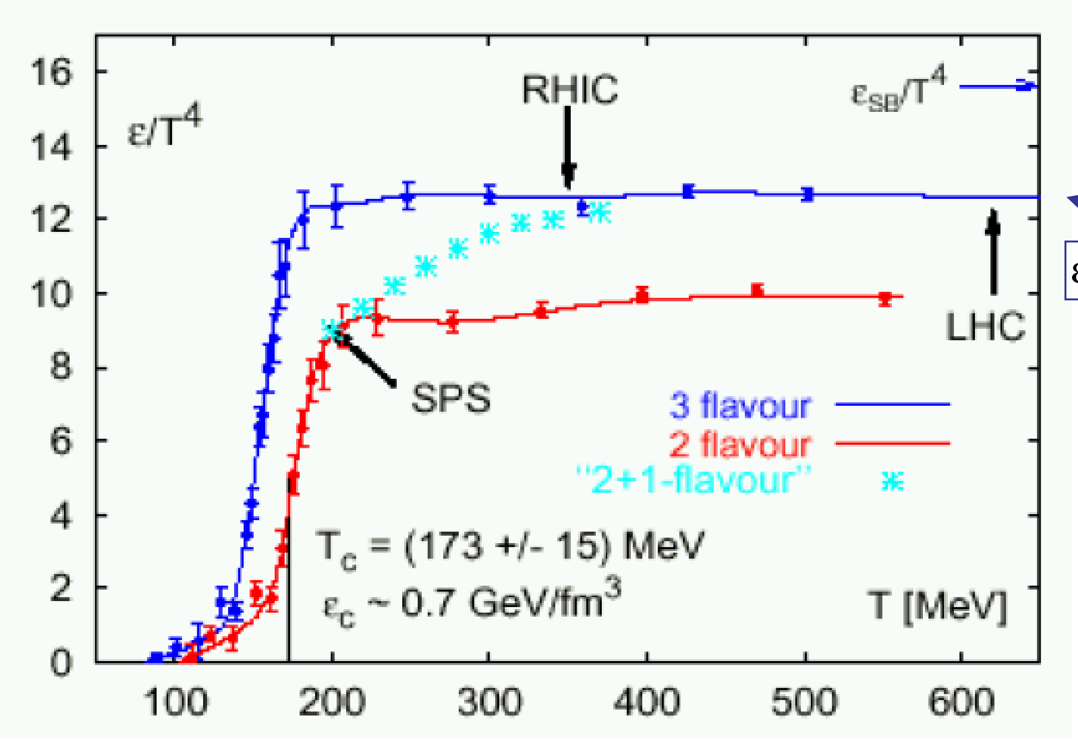
$E_0 >> m_0$

reg.= terms regular at β_c

One finds: $$\frac{\ln Z_H}{V} = A(\beta-\beta_c)^{1/2} + reg.$$ $$\varepsilon \propto (\beta-\beta_c)^{-1/2}$$

Rather than a limiting temperature...a second order phase transition!

4. Finite Temperature Lattice QCD



$\varepsilon \cong 1.6 GeV / fm^3$

NOTE:

$$\varepsilon_{Stefan-Boltzmann} = N_{eff} \frac{\pi^2}{30} T^4 \approx \frac{N_{eff}}{3} T^4$$

$$N_{eff,QGP}(n_f) \cong 8 \cdot 2 + (\frac{7}{8})(4 \cdot 3) n_f$$

$$\frac{N_{eff,QGP}(3)}{3} \cong 16$$

5. Debye screening of charmonia

$$\phi(\vec{k}) = \frac{4\pi Q}{\vec{k}^2 + \chi^2}$$

(In a plasma)

$$\chi^2 = 4\pi e^2 \sum_a Z_a \left(\frac{\partial n_a}{\partial \mu_a}\right)_{T,V}$$

The quarkonium potential:

$$V(r) = \sigma r - \frac{\alpha_c}{r}$$

is screened by the plasma (Matsui-Satz)

$$V(r) = \frac{\sigma}{\chi(T)}(1 - e^{-\chi(T)r}) - \frac{\alpha_c}{r} e^{-\chi(T)r}$$

Dominates at large r

For large enough T the screening can prevent the formation of J/ψ

Perturbative estimates of the screening

$$\frac{\mu(T)}{T_c} = \sqrt{1 + \frac{n_f}{6}}\, g\left(\frac{T}{T_c}\right)\frac{T}{T_c},$$

where the temperature-dependent runnin

$$g^2\left(\frac{T}{T_c}\right) = \frac{48\pi^2}{(33 - 2n_f)\ln F^2},$$

	J/ψ	ψ'	$\chi_c(1P)$
M (GeV)	3.07	3.698	3.5
r (fm)	0.453	0.875	0.696
τ_F (fm)	0.89	1.5	2.0
M_D (GeV)	2.915	3.177	3.198
μ_D (GeV)	0.699	0.357	0.342

The values of T_D (MeV) from perturbative estimates assuming the high-temperature limit

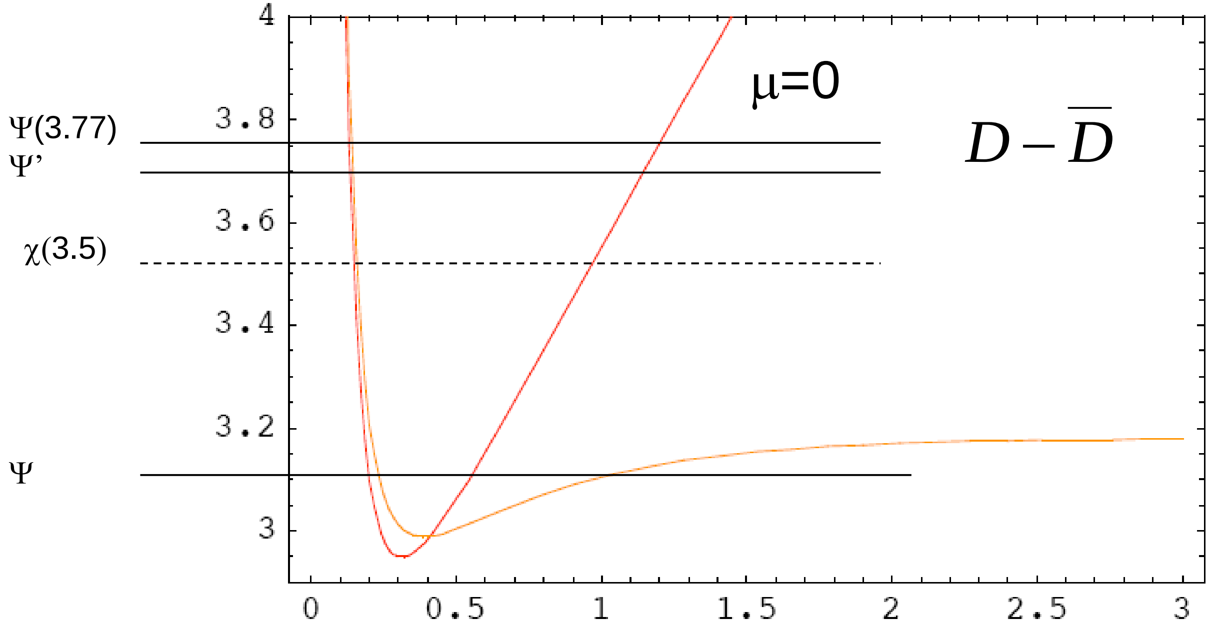
	$n_f = 2$	$n_f = 3$
J/ψ	451	406
ψ'	211	189
χ_c	185	178

T_D

$$V_{eff} = 2m_C + \frac{1}{m_C r^2} + V(r)$$

$$V(r) = \frac{\sigma}{\mu}(1 - e^{-\mu r}) - \frac{\alpha_c}{r} e^{-\mu r}$$

$2m_c$=2.64 GeV
σ = 0.192GeV^2
α_c=0.471



μ= 357 MeV
(T=178 MeV)

Ψ(1S), M= 3097 MeV
Ψ(2S), M= 3686 MeV

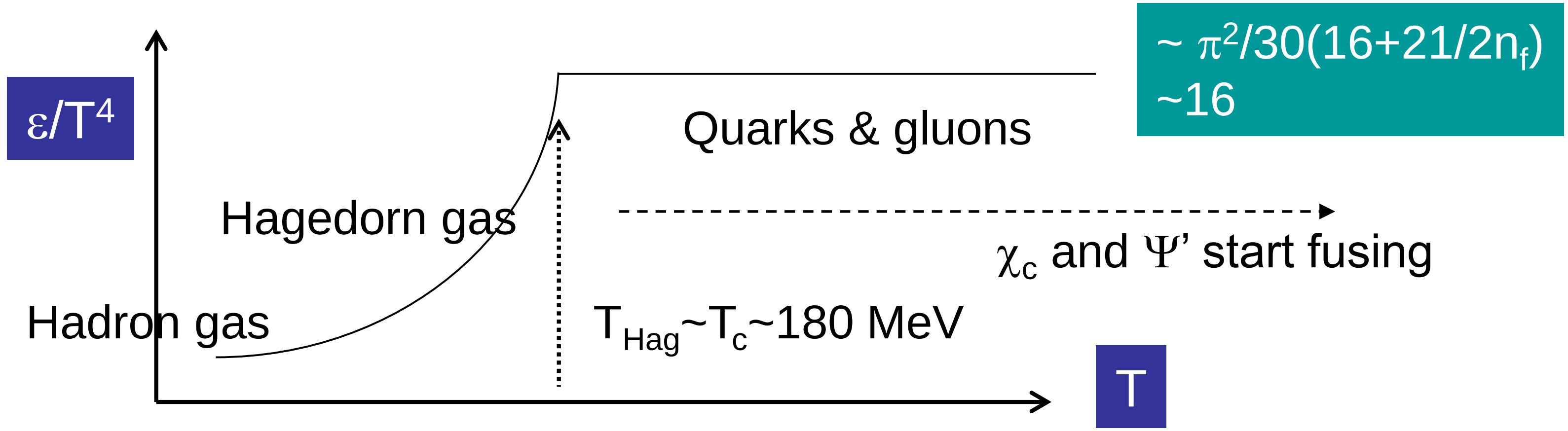
Above threshold:

Ψ(3.77), M= 3770.0 $\pm$ 2.4 MeV
Y(4.04), M= 4040 $\pm$ 10 MeV

χ_{c0}(1P), M= 3415 MeV
χ_{c1}(1P), M= 3510 MeV
χ_{c2}(1P), M= 3556 MeV

Summing up

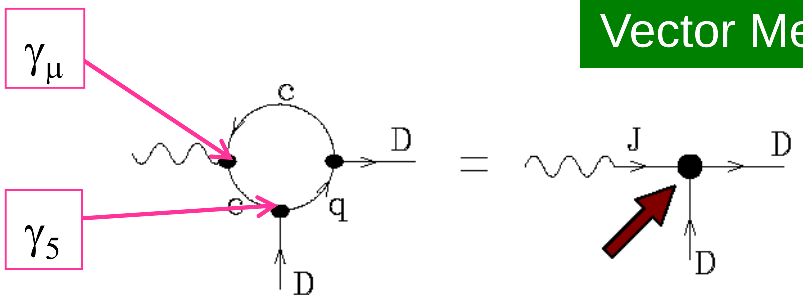
- The fireball produced in collisions with low energy density is ~ a pion gas at some T;
- Increasing ε, e.g. by increasing c.o.m. energy and/or centrality, T increases and higher resonances are produced;
- Increasing temperature becomes difficult because more and more energy goes in exciting resonances rather then increasing kinetic energy, i.e. T: $dT/d\varepsilon \sim (\beta-\beta_c)^{3/2}$, as we approach the limiting Hagedorn temperature;
- When hadron bags are in contact, bags fuse and quarks and gluon are liberated
- A cartoon representing this:



6. Cross secctions in the Constituent Quark Model

A. Deandrea, N. Di Bartolomeo, R. Gatto, G. Nardulli, A.D. Polosa
Phys.Rev.D58:034004,1998, hep-ph/9802308

Effective Ps meson-quark couplings (Georgi-Manohar);
Vector Meson Dominance;



$$j_\mu^{e.m.} = \frac{M_J^2}{f_J}\Psi_\mu$$

f_J from $J \to \mu^+\mu^-$

same for ρ, ω, ϕ

loop-diagram= $\frac{M_J^2}{f_J}\frac{g_{JDD}}{p^2 - M_J^2}$

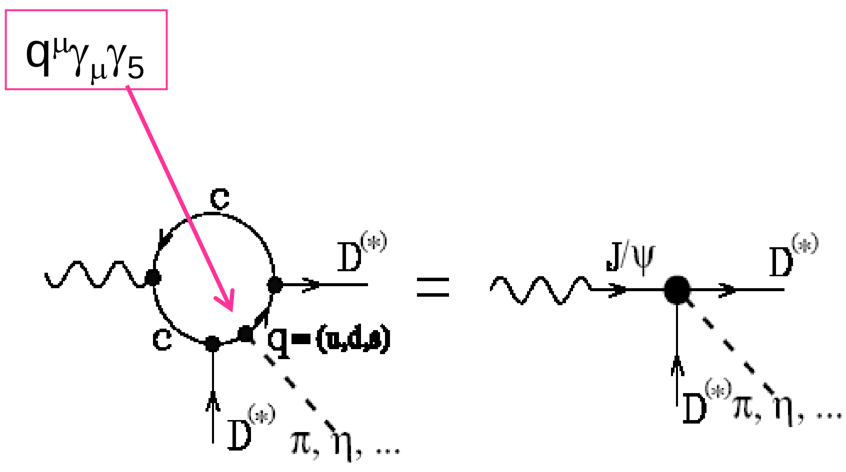


FIG. 1: Basic diagrammatic equation to compute g_3 and g_4 couplings.

loop-diagram= $f_\pi \frac{M_J^2}{f_J}\frac{g_{JDD\pi}}{p^2 - M_J^2}$

SU3 (for Ps) and nonet symmetry (for V)

A CONSTITUENT QUARK MESON MODEL FOR HEAVY MESON PROCESSES.

A. Deandrea, N. Di Bartolomeo, R. Gatto, G. Nardulli, A.D. Polosa

Phys.Rev.D58:034004,1998, **hep-ph/9802308**

The model has been tested in several B and D decays

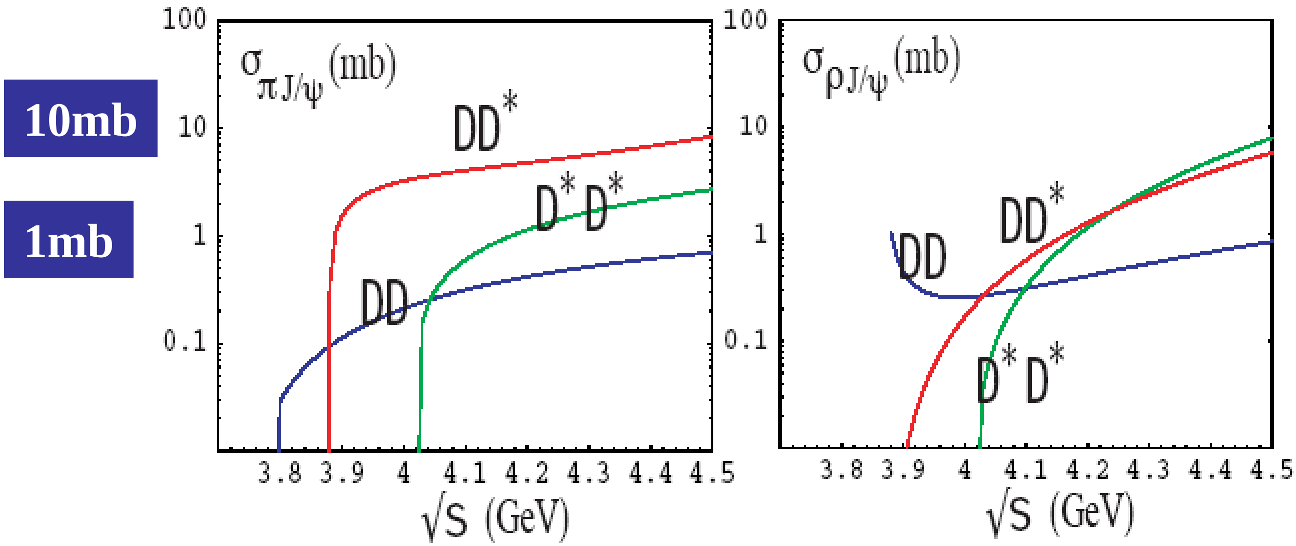
$$\Delta_H = M_H - M_Q$$

Decay mode	$\Delta_H = 0.3$	$\Delta_H = 0.4$	$\Delta_H = 0.5$	Exp.
$B \to D\ell\nu$	3.0	2.7	2.2	1.9 ± 0.5 [14]
$B \to D^*\ell\nu$	7.6	6.9	5.9	4.68 ± 0.25 [14]
$B \to D_0\ell\nu$	0.03	0.005	0.003	–
$B \to D_1^{*\prime}\ell\nu$	0.03	0.008	0.0045	–
$B \to D_1^*\ell\nu$	0.27	0.18	0.13	0.74 ± 0.16 [30]
$B \to D_2^*\ell\nu$	0.43	0.34	0.30	< 0.65

TABLE VI. Branching ratios (%) for semileptonic B decays. Theoretical predictions for three values of Δ_H and experimental results (for B^0 decays). Units of Δ_H in GeV.

Decay mode	$\Delta_H = 0.4$ GeV	$\Delta_H = 0.5$ GeV	Exp.
$D^{*0} \to D^0\pi^0$	65.5	70.1	61.9 ± 2.9
$D^{*0} \to D^0\gamma$	34.5	29.9	38.1 ± 2.9
$D^{*+} \to D^0\pi^+$	71.6	71.7	68.3 ± 1.4
$D^{*+} \to D^+\pi^0$	28.0	28.1	30.6 ± 2.5
$D^{*+} \to D^+\gamma$	0.4	0.24	$1.1^{+2.1}_{-0.7}$

Theoretical and experimental D^* branching ratios (%). Theoretical values are computed with $\Delta_H = 0.4,\ 0.5$



The cross sections for the processes $(\pi^+, \rho^+) + J/\psi \to D^{(*)}\bar{D}^{(*)}$ versus energy.

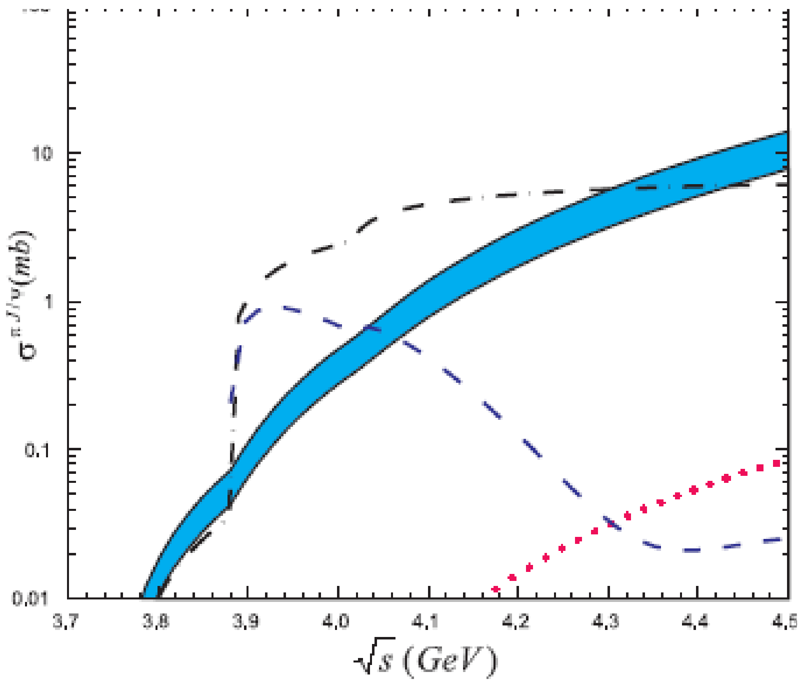
Comparison with other approaches

T.Barnes, nucl-th/0306031 Charmonium Cross Sections and the QGP

Fig. 1: Cross sections calculated with various approaches: QCD sum rules (band), short-distance QCD (dotted line), meson-exchange models (dot-dashed lines), non-relativistic constituent quark model (dashed line) [13].

10mb

1mb



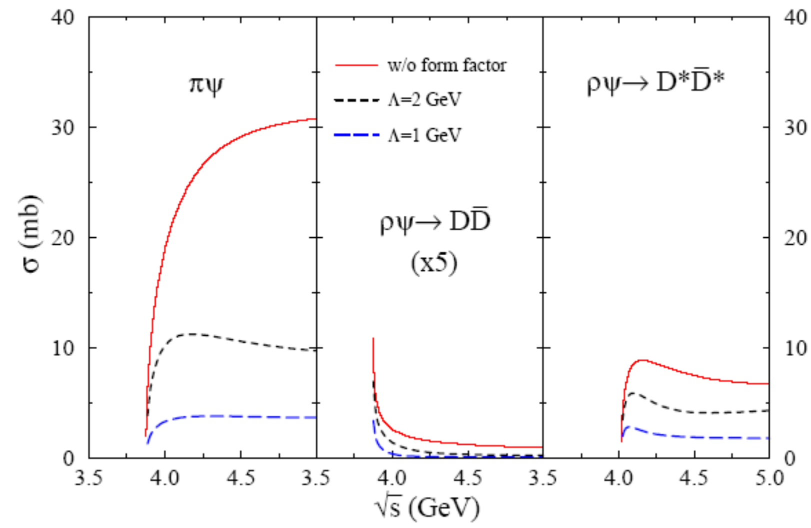


FIG. 6: A strong suppression of dissociation cross sections is found on incorporating hadronic form factors in meson exchange models. This example is Fig.4 of Lin and Ko [29].

1 to few mb cross-sections
but for perturbative QCD

7. J/Ψ Absorption

Nuclear interactions

The mean free path is defined by:

$$\lambda^{-1} \approx \rho\sigma$$

ρ_{nucl}=$0.17\ fm^{-3}$

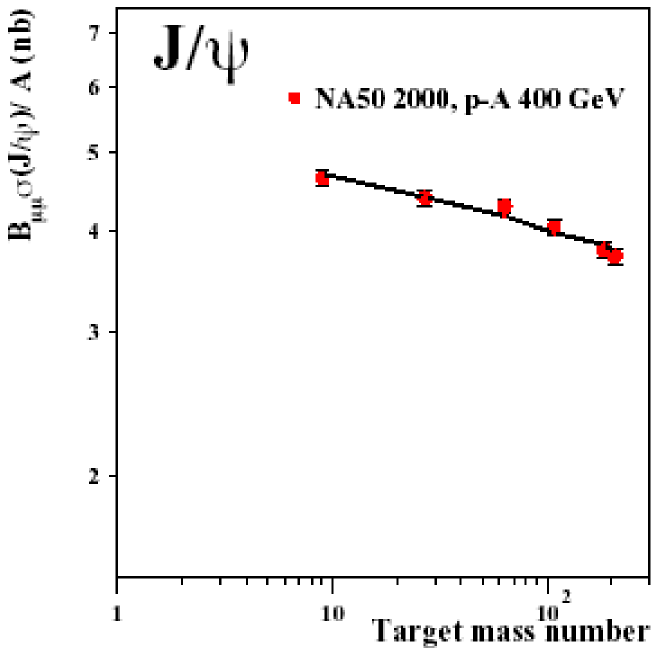
σ_{nucl}=$4.3 \pm 0.6\ mb$ Measured by NA50 in pA collisions

Then we can define the attenuation function:

$$A(x) = N exp\left[-\frac{x}{\lambda_{nucl}}\right]$$

where x=L=f(b) as given by the Glauber theory.

See papers by the NA50 collab.



A very important calibration!!

Attenuation factors

$$A_{\text{comoving}} \propto \exp\left[-\Sigma_i \langle \rho_i \sigma_i \rangle \frac{3}{8} l\right]$$

Assumes spherical fireball.
For a flat disk: 3/8(~0.38) $\rightarrow$4/3π~0.42

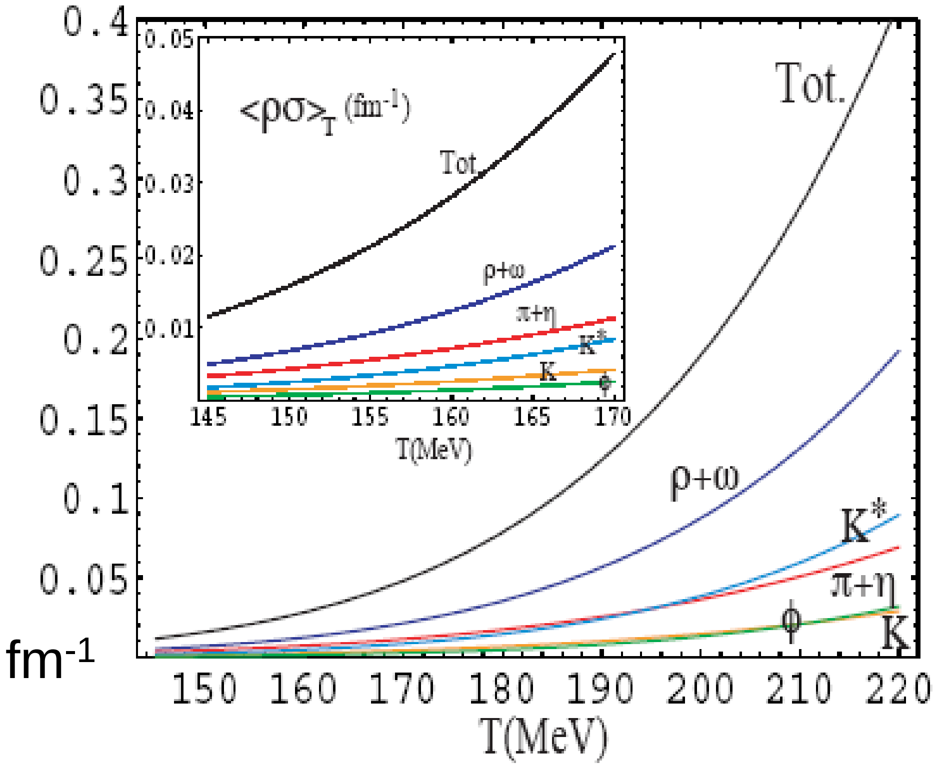
$$A_{nuclear} \propto exp(-\rho_{nucl.} \cdot \sigma_{nucl.} \cdot L)$$

NA50 gives L(b);
We can express all dimensions as functions of ℓ=2R-b

$$A = N \times \exp[-\rho_{\text{nucl.}} \sigma_{\text{nucl.}} L(l)] \times \exp\left[-\Sigma_i \langle \rho_i \sigma_i \rangle \frac{3}{8} l\right]$$

Thermal averages in the hadron gas

$$\lambda^{-1} = \langle \rho \cdot \sigma_{x+J/\psi \to D^{(*)}D^{(*)}} \rangle_T = \frac{N}{2\pi^2} \int_{E_{\rm th.}}^{\infty} dE \, \frac{pE\sigma(E)}{e^{E/kT} - 1}$$



'IG. 6: The inverse absorption lengths as a function of temperature.

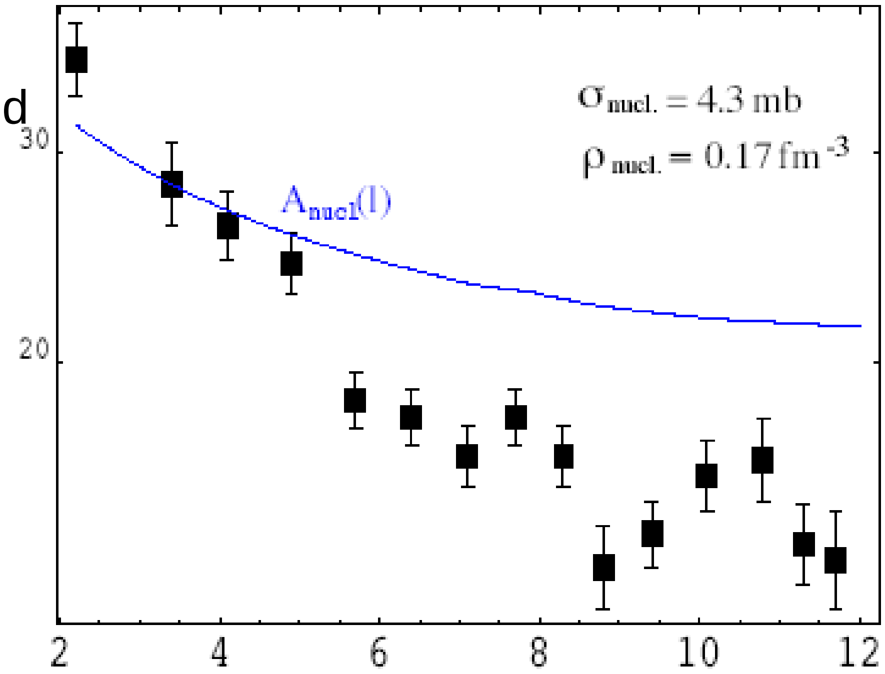
- Absorption lenght by fireball is quite comparable to $\lambda^{-1}_{nuclear} \sim 0.07 fm^{-1}$
- Absorption increases quite strongly with temperature: it can provide a good thermometer!!

Vector mesons are very important.
What about other resonances (e.g. A_1)?
No advantage from threshold or multiplicity, unfavoured by mass.

8. Results

Nuclear attenuation function

J/Ψ yield



L (fm)

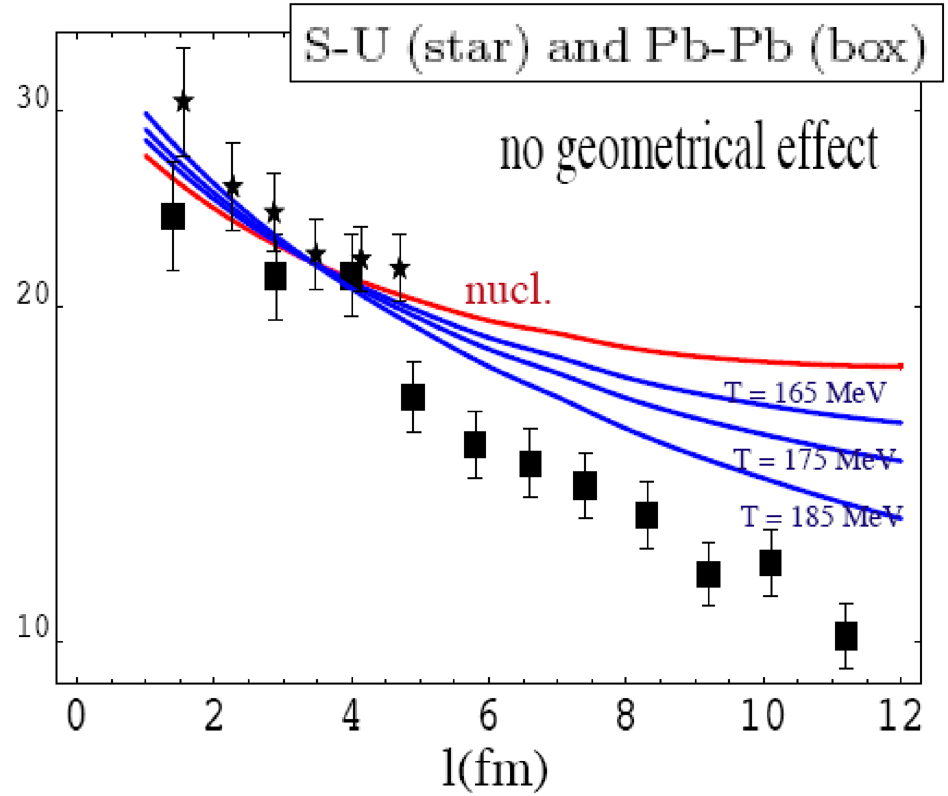
Pb-Pb data from NA50, (published data)

Insufficient to reproduce the observed attenuation.

Results for the hadron gas

Data from NA50: M.C. Abreu et al., Phys. Lett. B450, 456 (1999); M.C. Abreu et al., Phys. Lett. B477, 28 (2000). Latest analysis: http://na50.web.cern.ch/NA50/

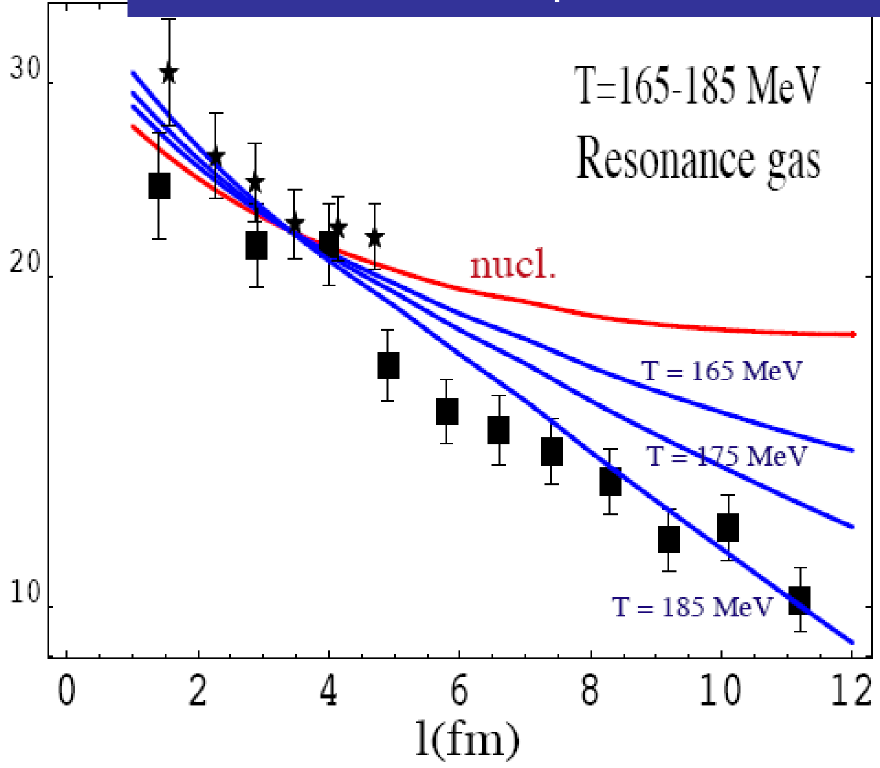
We try to fit the data for ℓ<5 fm with a single temperature;
We find: 165 MeV< T<185 MeV
Quite consistent with hadronic temperatures;
Do not fit data for ℓ>5fm
Is it conclusive??



Not yet:
If we go to higher centrality, the energy density increases (nucleon # per unit area increases)
T increases→absorption increases

Extrapolating to higher centrality

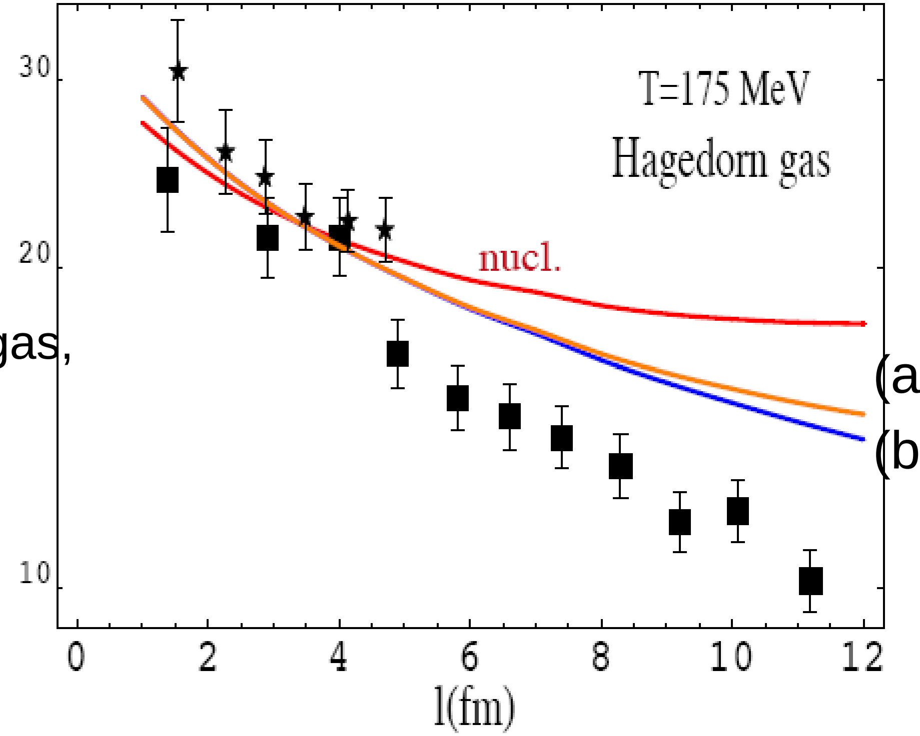
T indicates the temperature at ℓ ~ 4fm;



- We use the energy density-temperature relation of Ps+Vect meson gas;
- Marginal fit (but not too bad)
- However, T(ℓ ~ 12 fm) =185-205 MeV;
- Are these T realistic for a hadron gas ?

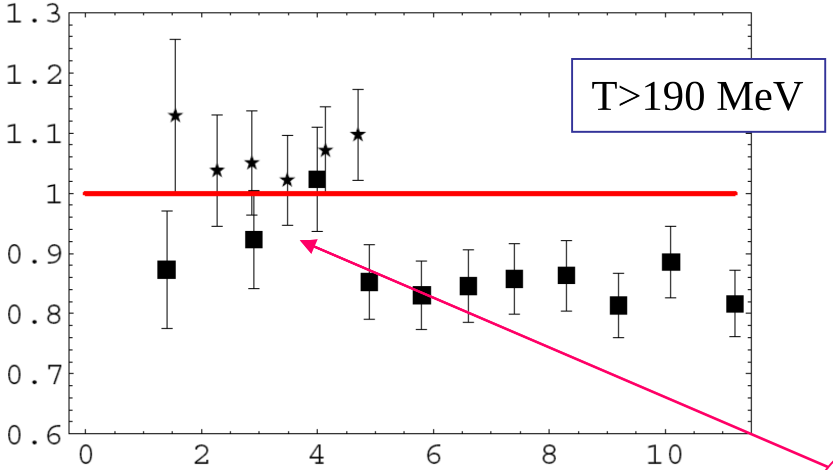
Absorption by a Hagedorn gas

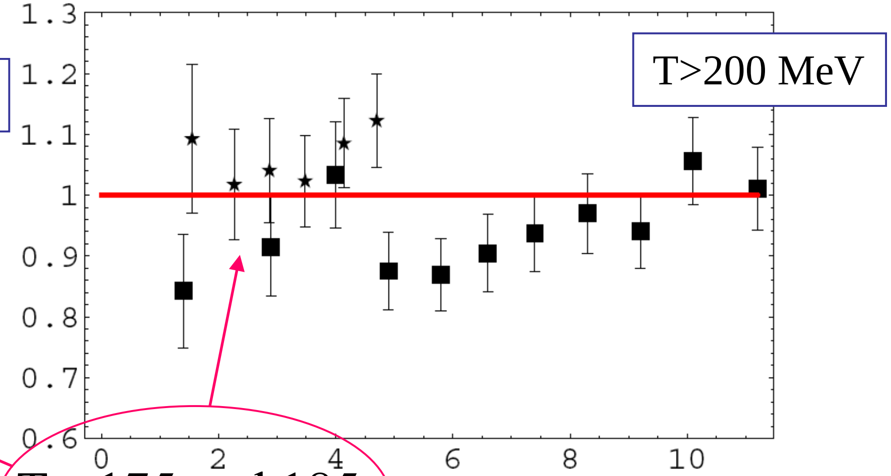
Assume:
Only pseudoscalar and vector mesons are relevant to dissociate the *J/ψ*.
Extrapolate to increasing centrality with the energy-temperature relation of the Hagedorn gas, $T_{Hagedorn}$=177 MeV (consistent with spectrum, freeze-out, lattice)
Initial temperature *T* = 175 MeV



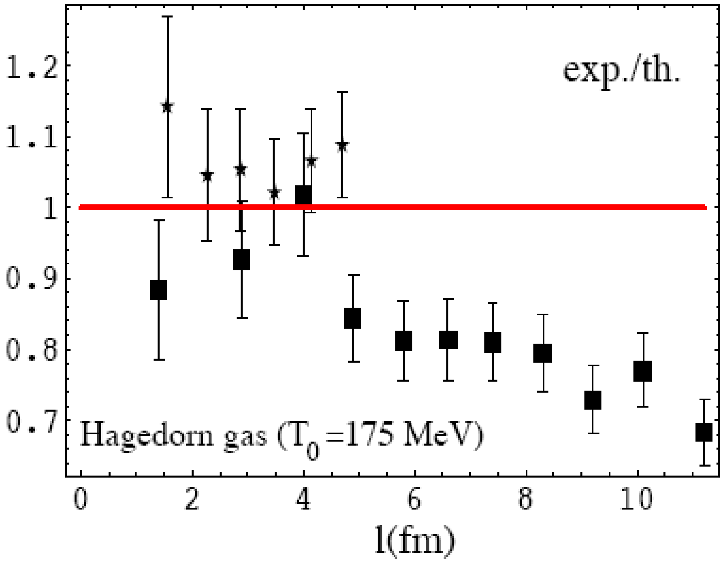
The sharp rise of degrees of freedom near the Hagedorn temperature makes so that T does not rise at all (b), the dissociation curve cannot become harder, prediction falls short from explaining the drop observed by NA50.

Overall view





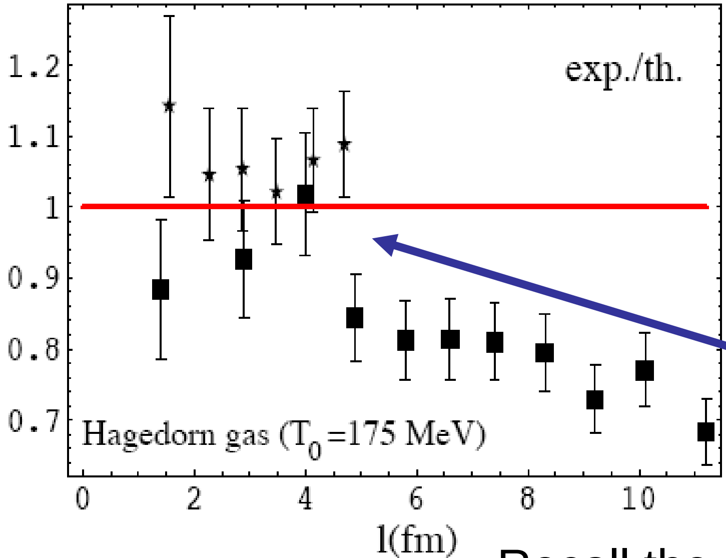
Observed /expected vs. ℓ, T_0=175 and 185



Observed /expected vs. ℓ

T_0=175 + Hagedorn gas

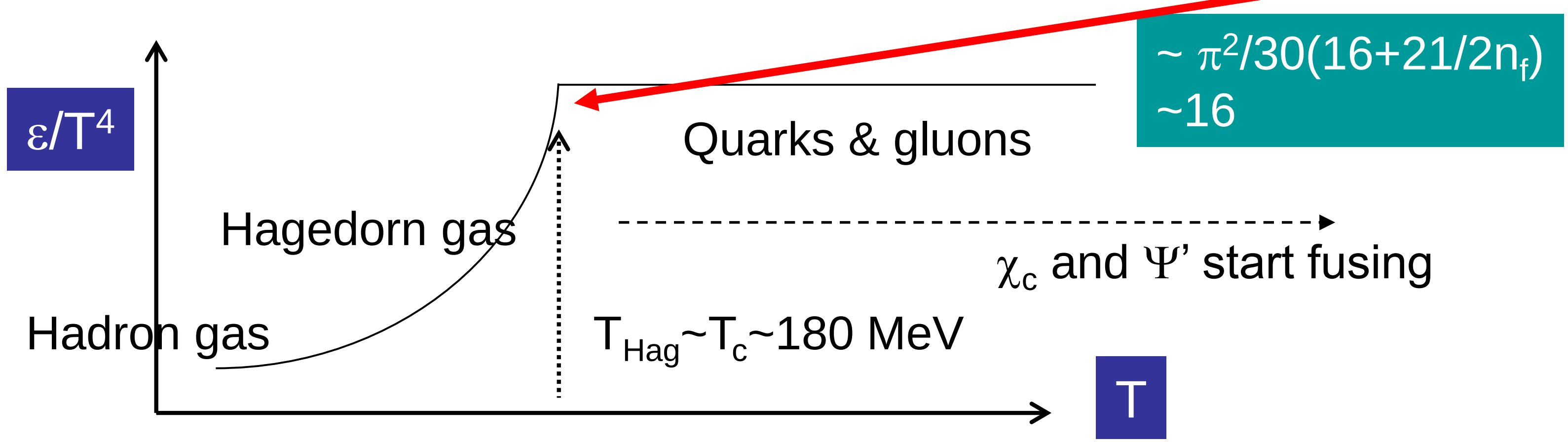
Bold speculations...



Observed /expected vs. ℓ

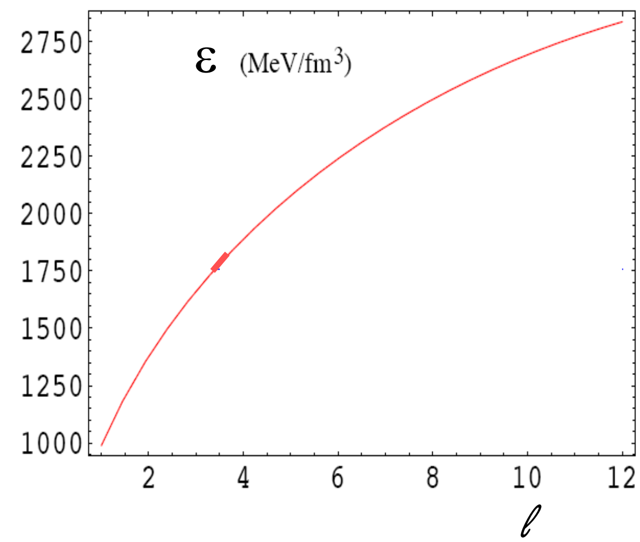
T_0=175 + Hagedorn gas

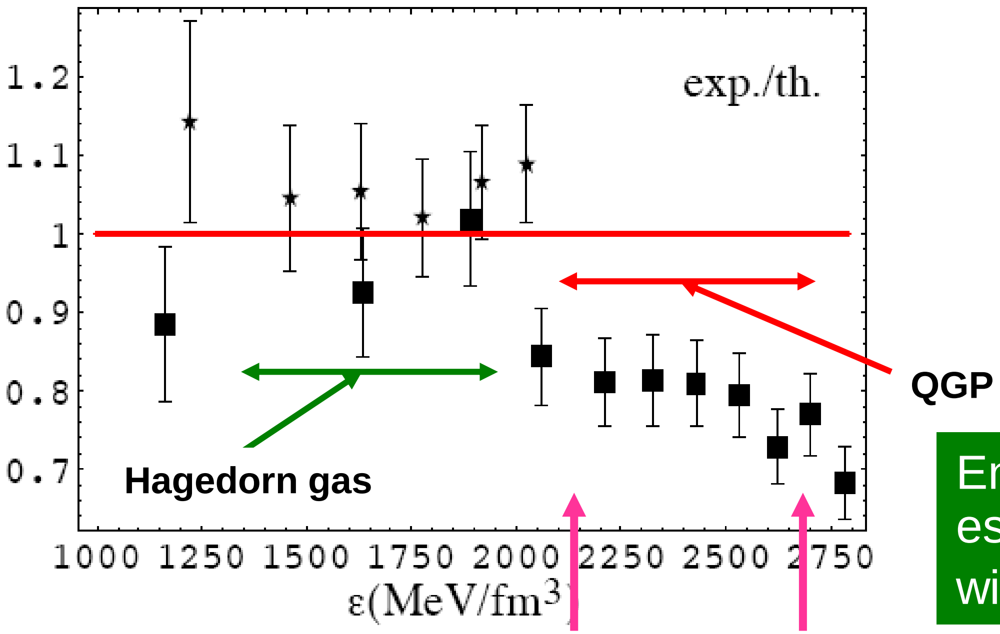
Recall the overall picture and assume that ℓ=5fm is here:



- Require :

  $N_{eff(Hag)}(\ell=5) \sim 16$ (like QGP)
- We find: $T(\ell=5) \sim 168$ MeV, $\varepsilon(\ell=5) \sim 2$ GeV/fm^3
- We transform ℓ in ε, using the geometrical factor g(b):





Energy density scale agrees with Bjorken estimate (2-3 GeV/fm^3, ℓ=4-12 fm) and with melting temperatures (see Lect. 1)

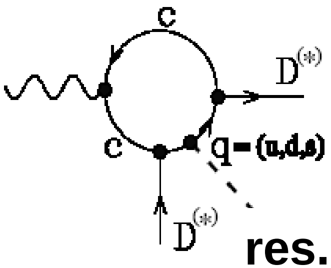
χ_c and Ψ' melt here (T=180, 190 MeV)!!

Some comment

The curve shown represents the limiting absorption from a hadron gas, anything harder is due to the dissociation of the *J/ψ* in the quark-gluon plasma phase.

Some word of caution:
Dissociation by higher resonances has been neglected.
The decreasing couplings of the higher resonances may eventually resum up to a significant effect, which would change the picture.

However, in all cases where this happens, like e.g. in deep inelastic lepton-hadron scattering, the final result reproduces the result of free quarks and gluons.
In our case, this would mean going over the Hagedorn temperature into the quark and gluon gas, which is precisely what the fig. seems to tell us.

Σ_{res} 

= Open the q-qbar lines of π ⟶ $$q + J/\Psi \to D + \overline{D} + q'$$

Dissociation by QGP??

J/Ψ as a probe of QGP: conclusions

- When the idea was proposed, it was believed that J/Ψ would suffer very little absorption from nuclear matter and from the “comoving particles” (σ<1 mb) hence very little background to the QGP signal;
- Nuclear absorption measured from p-A cross sections (but uncertainties still remain!) ~ 4-5 mb, attenuation lenght ~ 0.07 fm, signal:noise ~ 1;
- Absorption by comoving particles: many calculations, results mostly in the few mb range;
- We have made a complete analysis of Ps and V meson cross-sections, in a reliable model (QCM) tested in other processes, and applied the results to a hadron gas made of Ps and V mesons;
- Effects of comovers (i) non negligible and (ii) strongly T dependent;
- If we allow T in excess of 200 MeV we can fit NA50 results in this hadron gas, no QGP, only marginally;
- If there is a limiting temperature to the hadronic phase around 170 MeV, comovers cannot explain the drop in J/Ψ production seen at large centralities by NA50;
- The picture that QGP sets in at centrality ~ 5 fm is consistent with known T and energy density ranges;
- The drop in J/Y would be due first to χ_c and, later, to Ψ’ melting;

J/Ψ as a probe of QGP: conclusions

- SPS has most likely seen the QGP;
- RHIC data on J/Ψ would be extremely useful, to check the signal aginst other signatures
- The analysis can be extended to Y: LHC data eagerly wanted !

The study of charmonia in QGP is not concluded with the demonstration that QGP exists

Level spectrum vs. T could give a lot of interesting infos on the dynamics of quark and gluons and probe deeply the new phase of matter