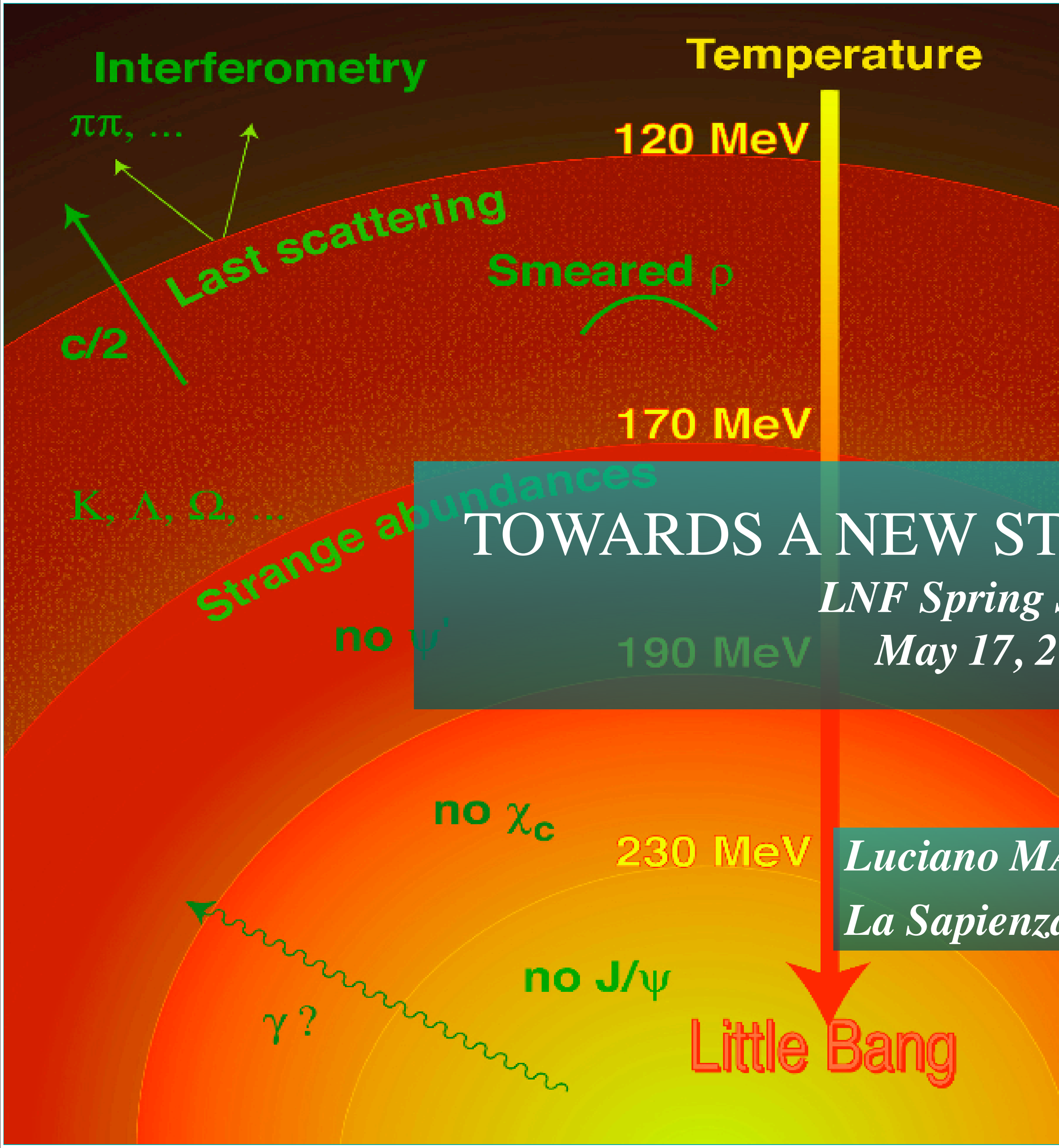


TOWARDS A NEW STATE OF MATTER

LNF Spring School

May 17, 2005

Luciano MAIANI

La Sapienza, Roma and INFN, Roma.

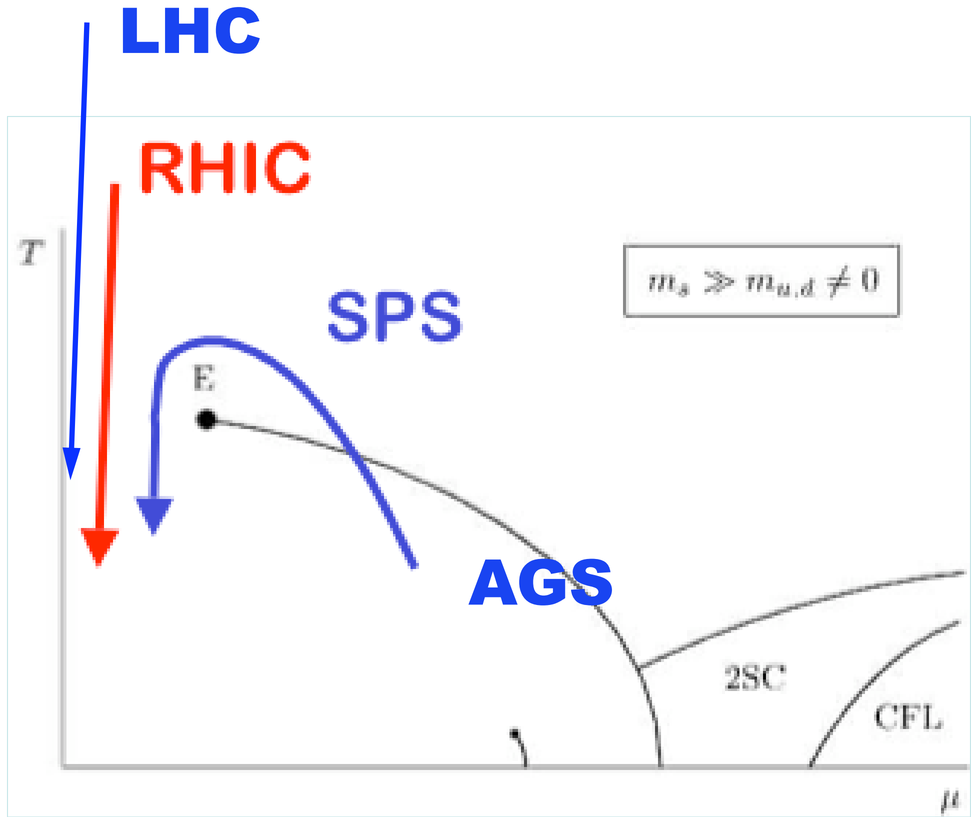
INTRODUCTION

- The Big Bang:

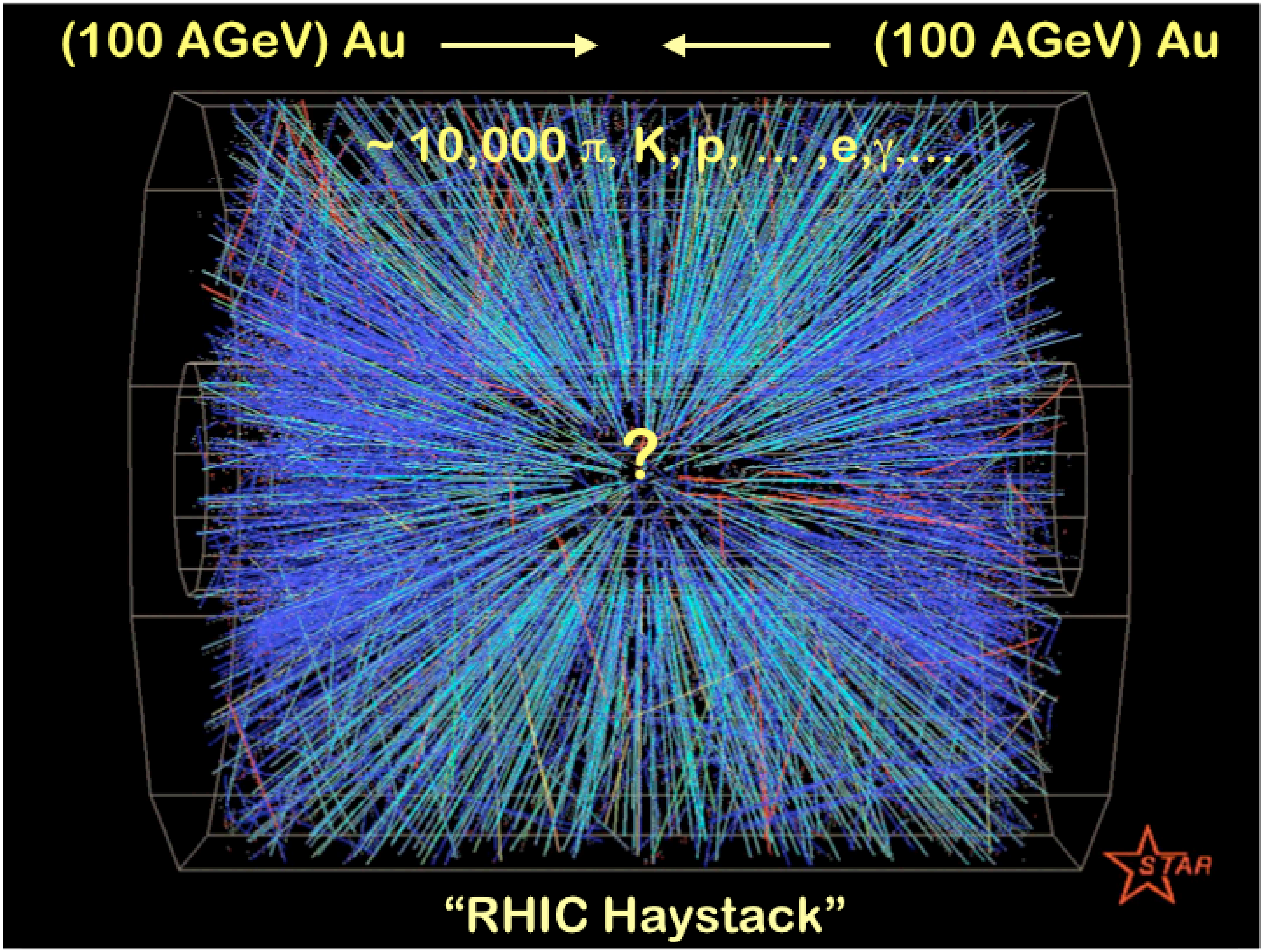
  “if we look back ...when temperature was above 10^{12} ^{0}K (100 MeV), we encounter theoretical problems of a difficulty beyond the range of modern statistical mechanics.”

  “However, the temptation to try is irresistible.”

  S. Weinberg, Gravitation and Cosmology, 1972



2SC = High baryon density
Color superconductor
$\langle ud(I=0, C=\underline{3}) \rangle \neq 0$


(100 AGeV) Au
(100 AGeV) Au
~10,000 π, K, p, … ,e,γ,…
?
STAR
"RHIC Haystack"

Where

- Alternating Gradient Synchrotron (AGS) at Brookhaven BNL
  - variety of beams, since 80's

$$\sqrt{s_{NN}}\Big|^{AGS}_{Au+Au} \simeq 2-5\ GeV$$

- CERN SPS fixed target experiments
  - variety of beams, Pb-beams since 1994

$$\sqrt{s_{NN}}\Big|^{SPS}_{Pb+Pb} < 17\ GeV$$

- Relativistic Heavy Ion Collider (RHIC) at Brookhaven BNL
  - start in 2000, so far p+p, Au+Au and d+Au

$$\sqrt{s_{NN}}\Big|^{RHIC}_{Au+Au} \leq 200\ GeV$$

- Large Hadron Collider (LHC) at CERN
  - start in 2007 with p+p, in 2008 with Pb+Pb

$$\sqrt{s_{NN}}\Big|^{LHC}_{Pb+Pb} = 5.5\ TeV$$

- total cross section $\sigma^{Pb+Pb}_{total} = 8\ barn = 10^{-24}\ cm^2$
- maximal luminosity $L^{Pb+Pb}_{max} \sim 10^{27}\ cm^{-2}\ s^{-1}$

8000 collisions per second !

What ? (@ LHC)

$$\sigma_{total}^{Pb+Pb} = 8\ barn = 10^{-24}\ cm^2 \qquad L_{max}^{Pb+Pb} \sim 10^{27}\ cm^{-2}\ s^{-1}$$

When ?	How much data ?	Data on what ?
after $15\ min \sim 10^3\ s$	$L_{integrated} = 1\ \mu b^{-1}$	• event multiplicity • low-pt hadronic spectra • particle ratios
after 1 month $\sim 10^6\ s$ (1 LHC Pb+Pb year)	$L_{integrated}^{realistic,\ reduced} = 10 - 100\ \mu b^{-1}$	• abundant high-pt processes such as jets .....
	$L_{integrated}^{optimal} = 1\ nb^{-1}$	• rare hadronic and leptonic processes ....
after 2-3 LHC years	p+Pb collisions	

T_0 = 2007/8, most likely

Relativistic Ions

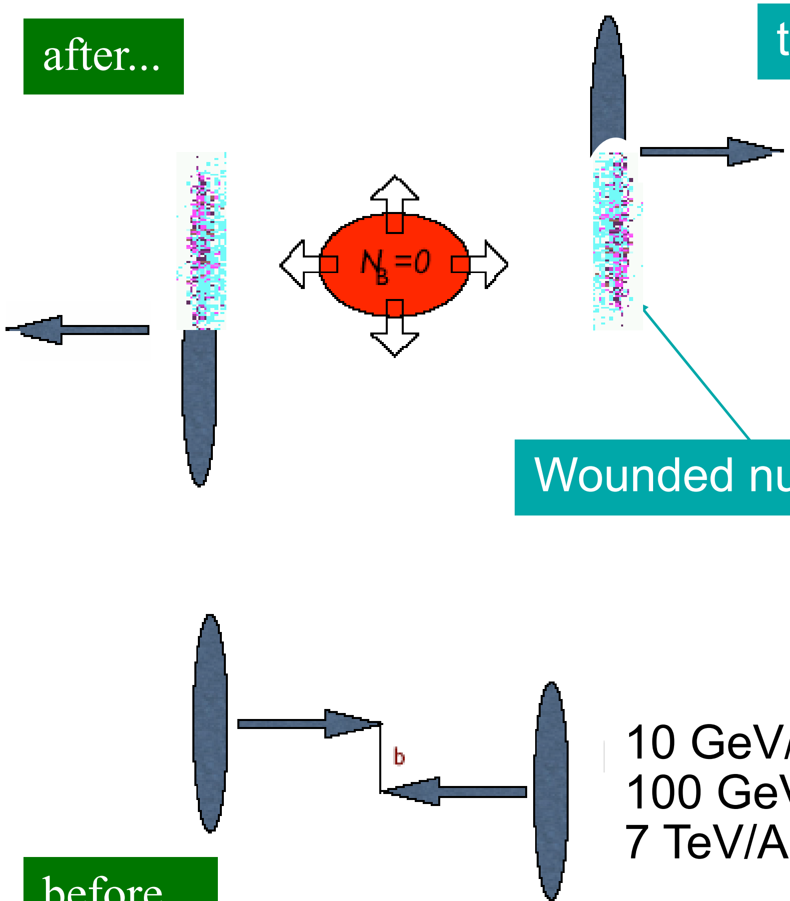
Snapshots of the collision in the c.o.m.

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

The energy of the surviving nuclear fragments seen by the Zero Degree Calorimeter (e.g. in NA50) gives a measure of the impact parameter b

time

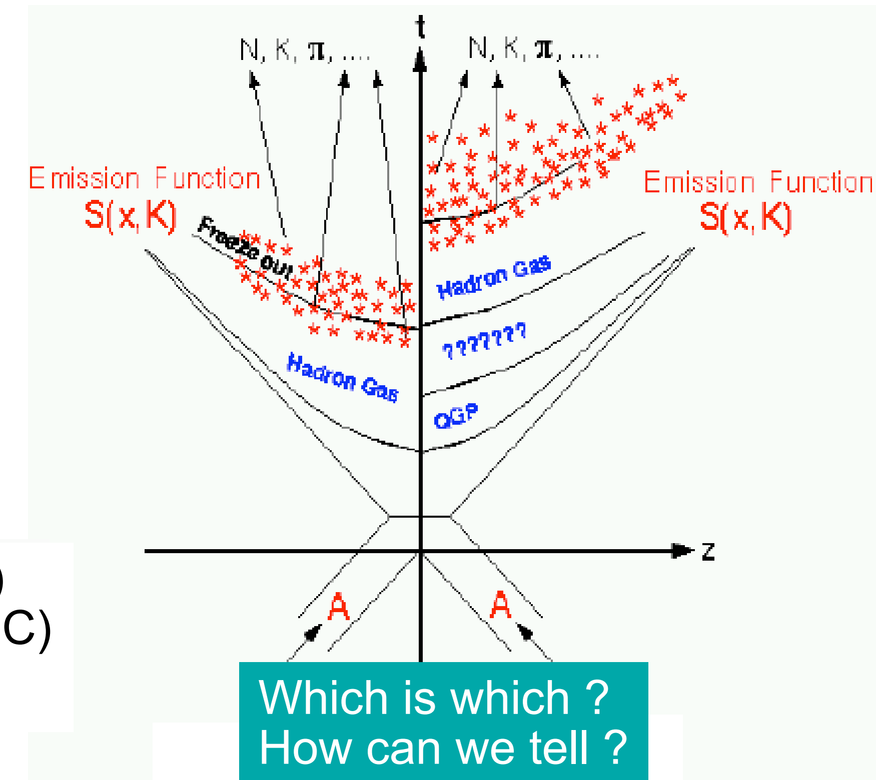
after...



Wounded nucleons

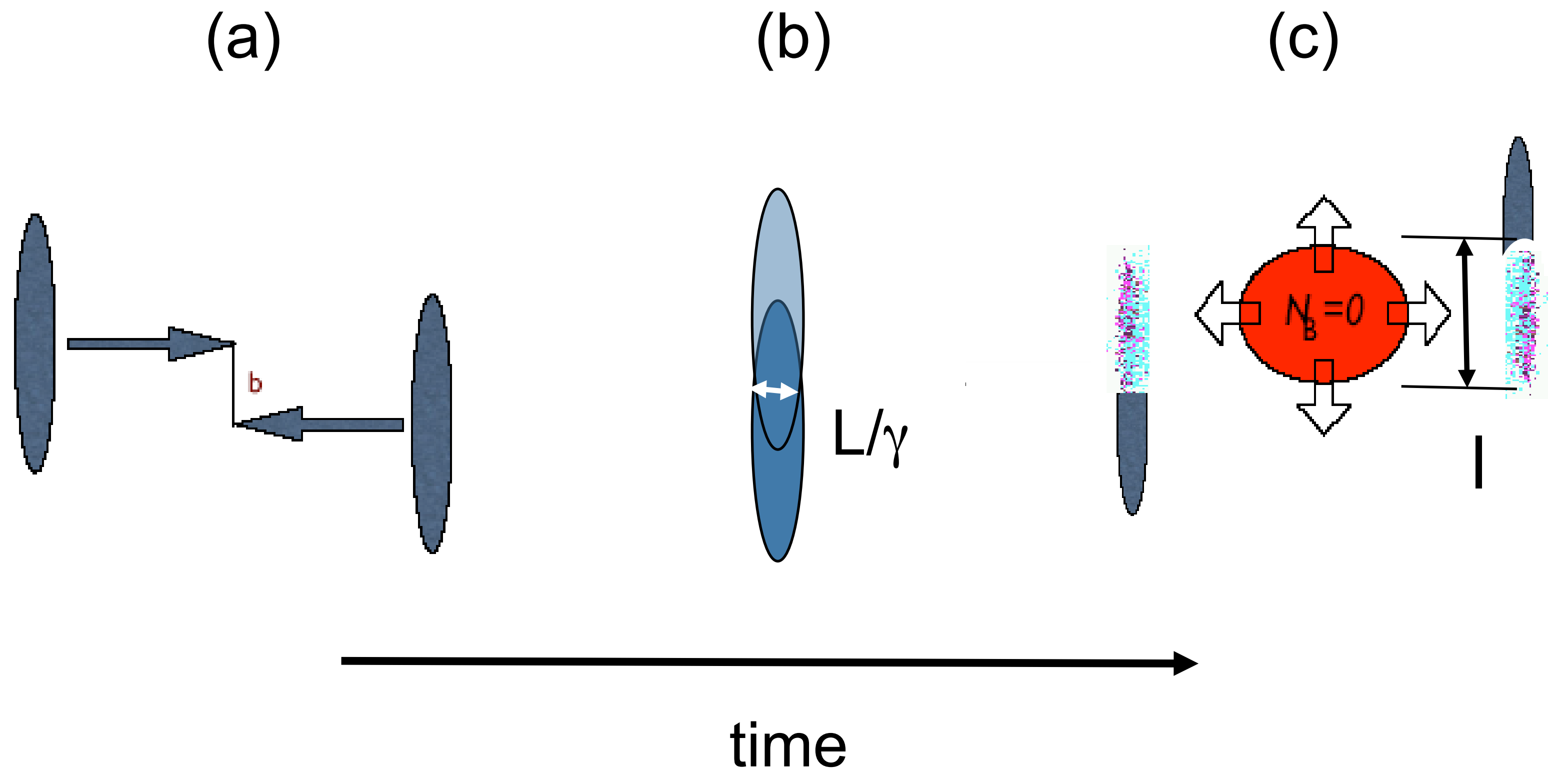
before...

10 GeV/A (SPS)
100 GeV/A (RHIC)
7 TeV/A (LHC)



Which is which ?
How can we tell ?

Geometry



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

@SPS:

For central Pb-Pb collision, one has:

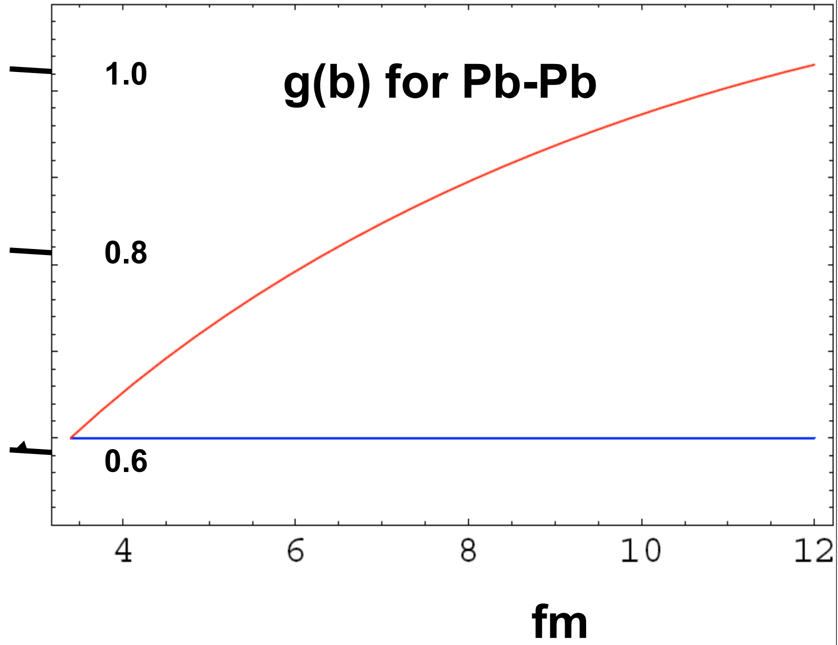
$$\frac{A(b=0)}{S(b=0)} = \frac{A}{\pi R^2} = \frac{A^{1/3}}{\pi r_0^2} = 1.5 \text{ fm}^{-2}$$

for impact parameter b:

$$\frac{A(b)}{S(b)} = g(b)\frac{A(0)}{S(0)}$$

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

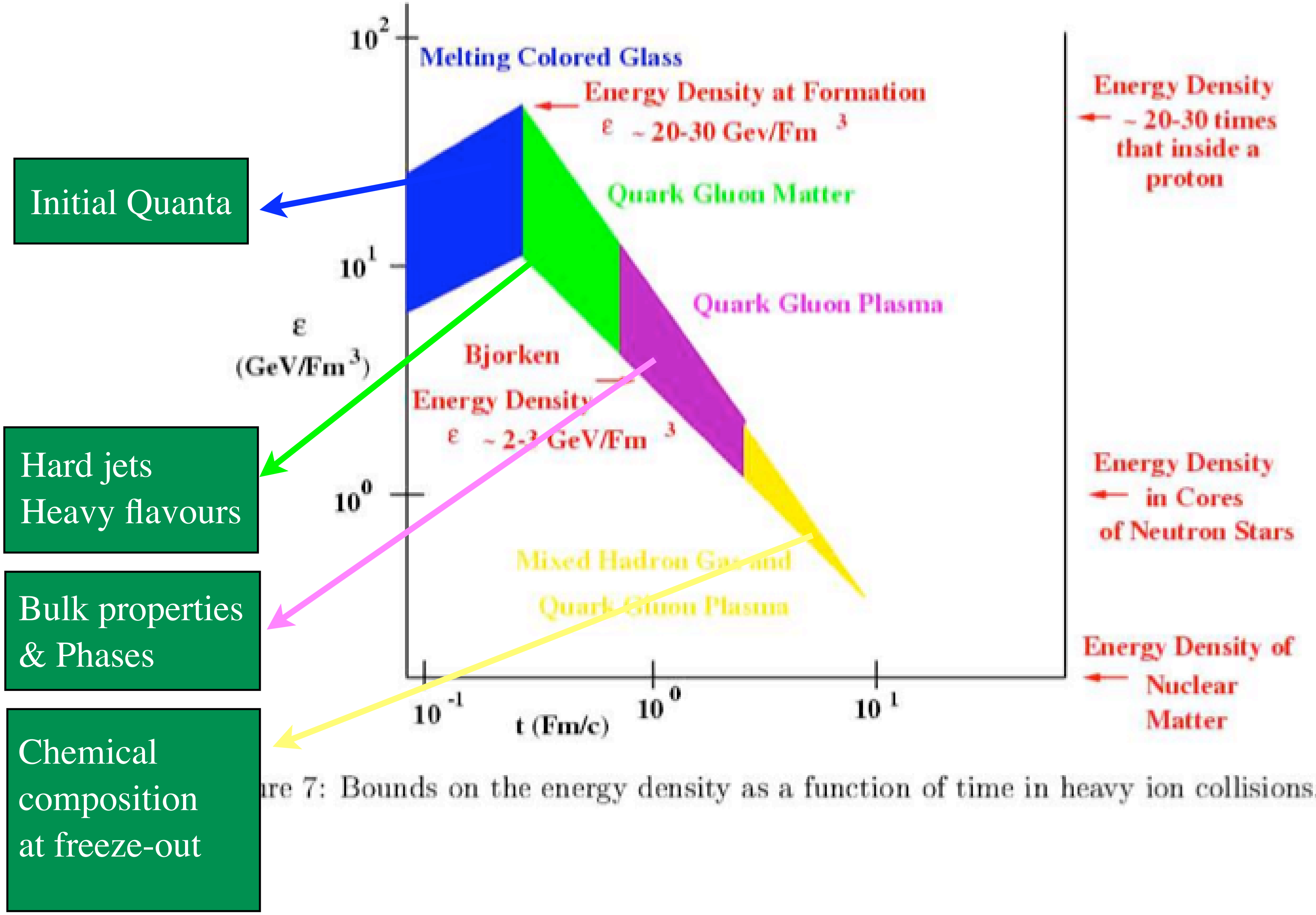
$$\varepsilon = 2.6 GeV / fm^3 \left(\frac{1 fm}{c\tau_0}\right) - (l = 12 fm)$$



Bjorken 1982

$$\varepsilon(\tau) = \frac{m_\perp dN}{\tau dy\, A_\perp} = \varepsilon(\tau_0)\frac{\tau_0}{\tau}$$

1+1D Hubble



ure 7: Bounds on the energy density as a function of time in heavy ion collisions.

@ RHIC

Four independent calibrations of Initial QGP density

$$\boxed{\varepsilon(\tau_0) \approx 100\,\varepsilon_0 = 15\ \mathrm{GeV/fm^3}}$$

1. Bjorken Backward extrapolation

$$E_T/N_\pi = 0.5\ \mathrm{GeV}, \quad dN_\pi/dy = 1000,$$
$$\tau_0 = 1/p_0 = 0.2\ \mathrm{fm}/c, \quad V = (0.2\ \mathrm{fm})\pi R^2 = 30\ \mathrm{fm^3}$$
$$\varepsilon_{Bj} = 500\ \mathrm{Gev}/30\ \mathrm{fm^3} = 100\,\varepsilon_0$$

2. Hydrodynamic initial condition needed for $v_2(p_T)$

$$\varepsilon_{Hydro} > 2\,\varepsilon_{Bj} = 500\ \mathrm{Gev}/30\ \mathrm{fm^3} = 100\,\varepsilon_0$$

KHH
TS
HN

3. Jet Tomography: $dN_g/dy = 1000$

$$\varepsilon_{Jets} \approx \varepsilon_{Bj} \approx 100\,\varepsilon_0$$

GLV
WW

4. Gluon saturation $p_T < Q_s$ predicted
   $dN_g/dy = 1000$ at $Q_{sat} = 1$ GeV at $y=0$

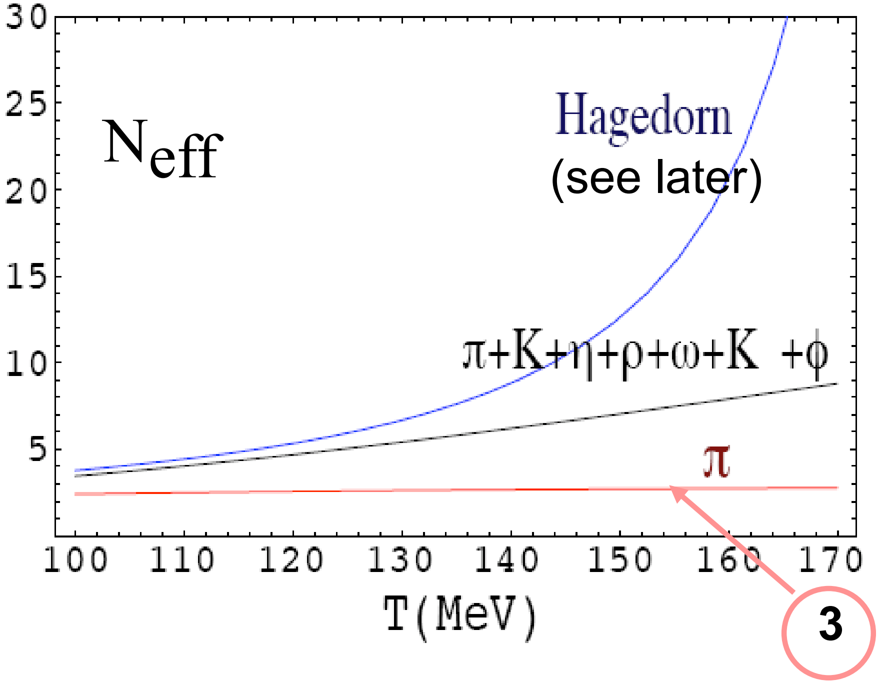
MB
McV
EKRT

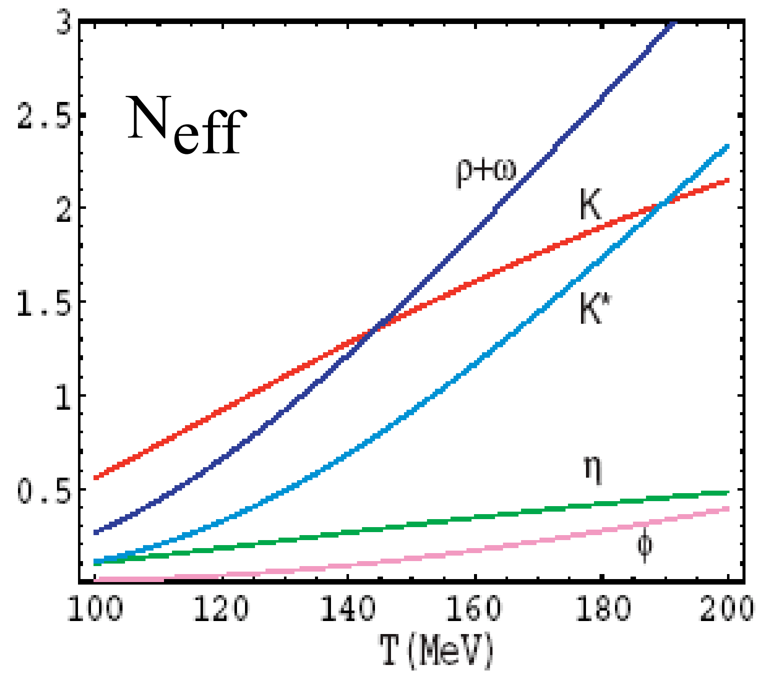
From Hadron to Hagedorn Gas

Resonance gas

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

Around T~ 150 MeV: not only pions!!
In spite of higher mass, higher resonances contribute to the energy density at temperatures around 150 MeV because of increasing multiplicities





Hagedorn's thermodynamics

J. Letessier and J. Rafelski, "Hadrons and Quark Gluon Plasma", Cambridge Monogr. Part. Phys. Nucl. Phys. Cosmol. 18 (2002).

The Exponential Hadron Mass Spectrum

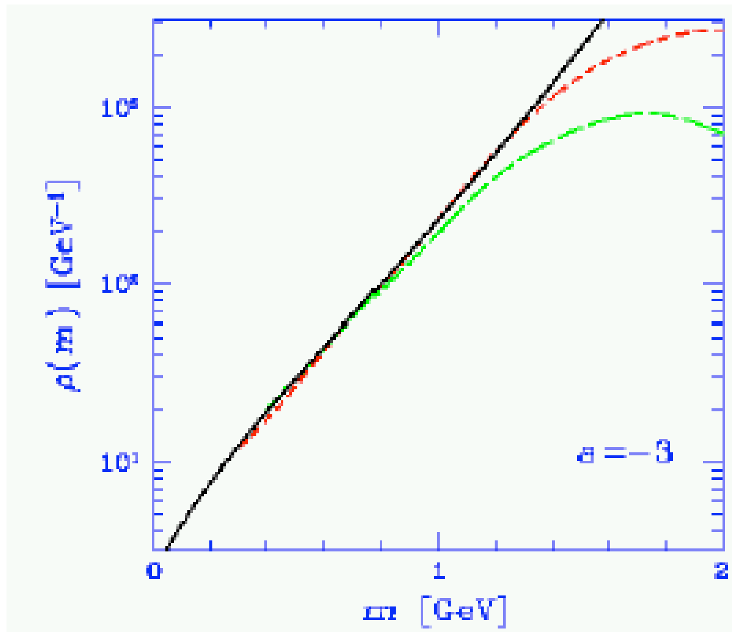
- Black line: fit to

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

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

- Green line: 1411 states of 1967

- Red line: 4627 states of 1996



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

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

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

Interpretation of the Hagedorn temperature

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

Critical behaviour is determined by the high masss part of the spectrum, m>>T. Assuming $\rho(m) \propto (m)^{-3} \exp[m(\beta-\beta_C)]$

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

$\beta_C = 1/T_H$

reg.= terms regular at β_C

$$\varepsilon \propto (\beta - \beta_c)^{-1/2}$$

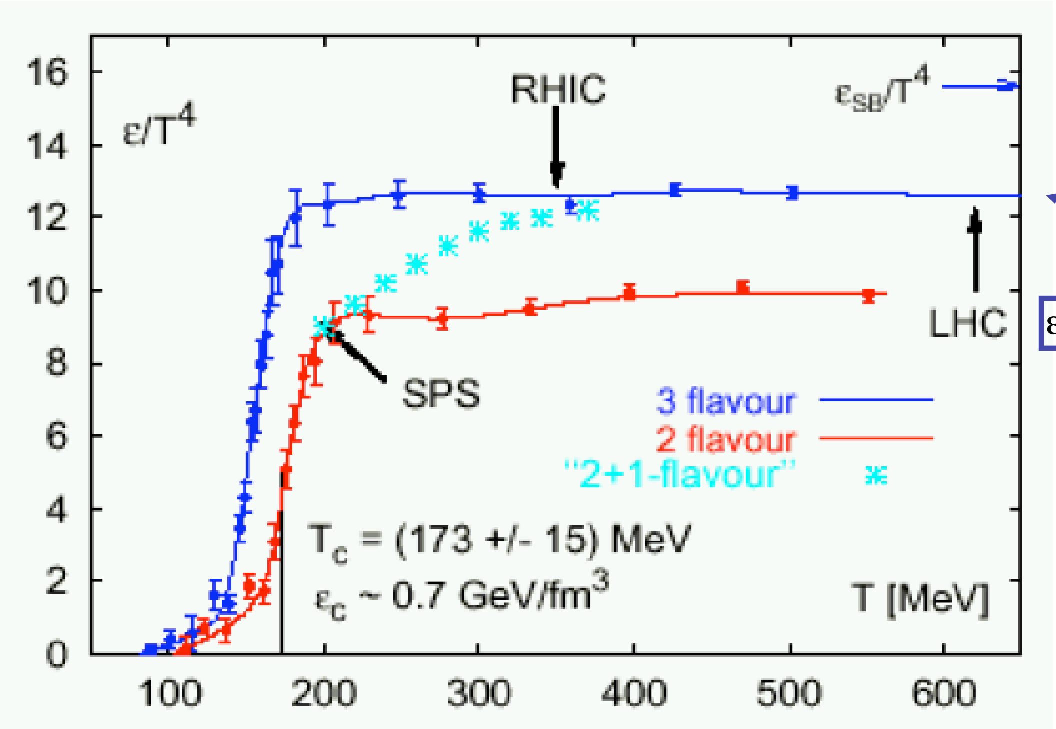
P~ reg.

$\partial P/\partial\varepsilon \propto (\beta - \beta_C)$

Rather than a limiting temperature...a second order phase transition!...to what??

Lattice QCD

Finite Temperature Lattice QCD



$\boxed{\varepsilon \cong 1.6 GeV / fm^3}$

NOTE:

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

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

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

Gyulassy, Erice 2004

What is a QGP?
Theoretical limit of Hot QCD Matter

1975 QCD Predicts

QGP

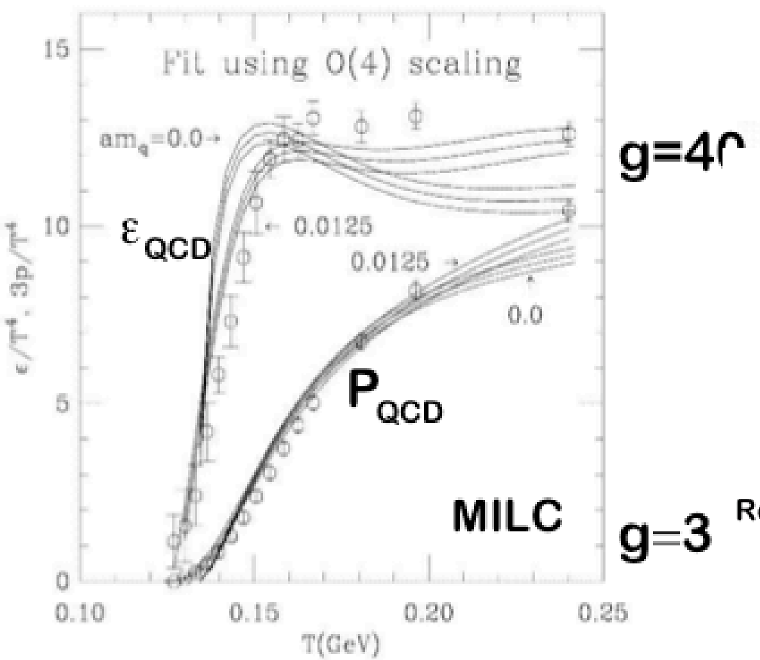
Asymptotic Freedom
Deconfinement
Chiral Symmetry

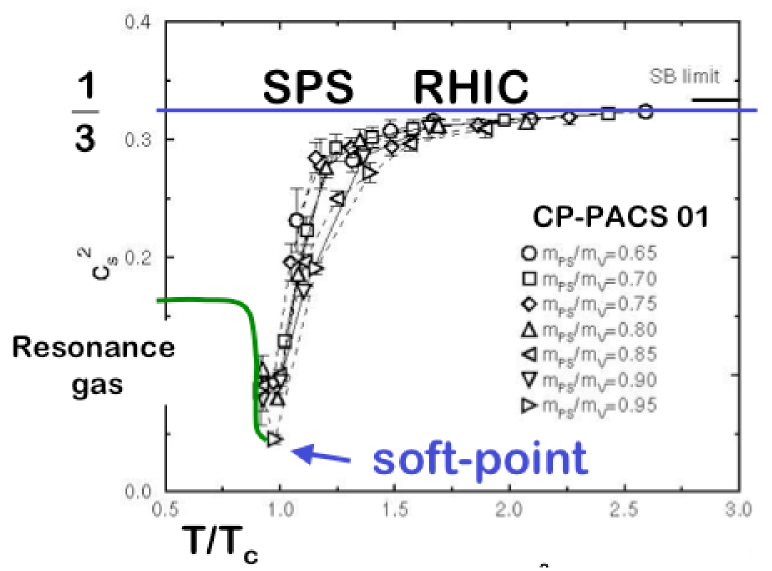
$$P_{QCD} \sim \tfrac{1}{3} K_{QCD} T^4 - B_{vac}$$

$$\varepsilon_{QCD} \sim K_{QCD} T^4 + B_{vac}$$

$$c_s^2 = dP/d\varepsilon$$

Equation of State

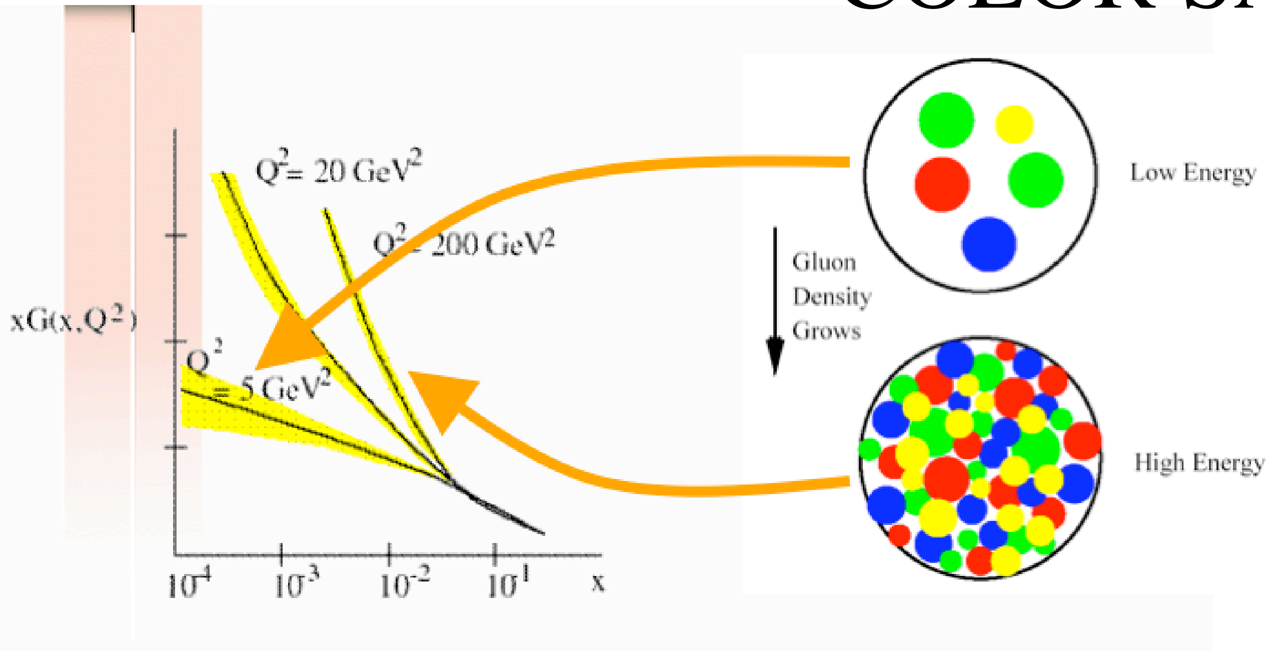




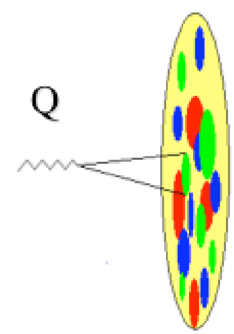
1

INITIAL QUANTA: COLOR GLASS CONDENSATE

COLOR SATURATION



McLerran, hep-ph/0311028



- Transverse area of a parton ~ $1/Q^2$
- Cross section parton-probe : $\sigma \sim \alpha_s/Q^2$
- Partons start to overlap when $S_A \sim N_A \sigma$
- The parton density saturates
- Saturation scale : $Q_s^2 \sim \alpha_s(Q_s^2) N_A/\pi R_A^2 \sim A^{1/3}$

Parton production

We assume that the number of produced particles is :

$$\left.\frac{d^2N}{d^2b\,d\eta}\right|_{|\eta|<1} = c\,\frac{N_c^2-1}{4\pi^2 N_c}\,\frac{1}{\alpha_s}\,Q_s^2$$

centrality dependence !

or

$$\left.\frac{dN}{d\eta}\right|_{|\eta|<1} = c\,N_{part}\,xG(x,Q_s^2)$$

c is the “parton liberation coefficient”;

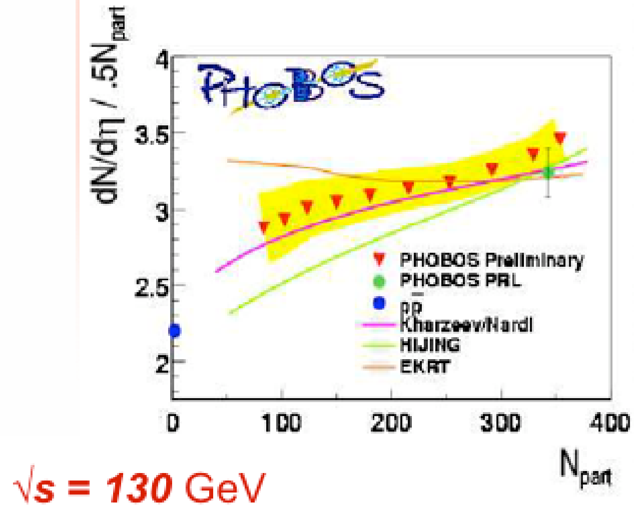
$xG(x, Q_s^2) \sim 1/\alpha_s(Q_s^2) \sim \ln(Q_s^2/\Lambda_{QCD}^2)$.

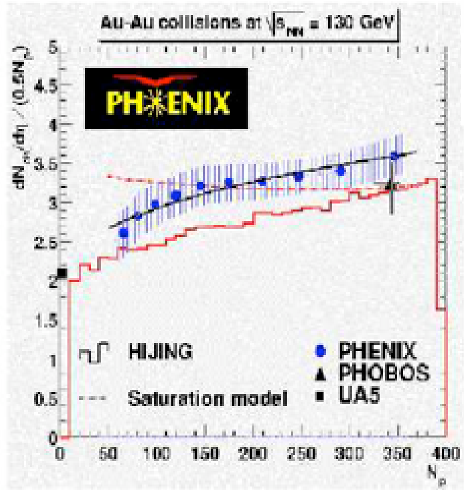
The multiplicative constant is fitted to data (PHOBOS,130 GeV, charged multiplicity, Au-Au 6% central): c = 1.23 ± 0.20

dN/dη vs Centrality at η=0

Marzia Nardi

D. Kharzeev, E. Levin,
hep-ph / 0408050
(Nucl. Phys. A)



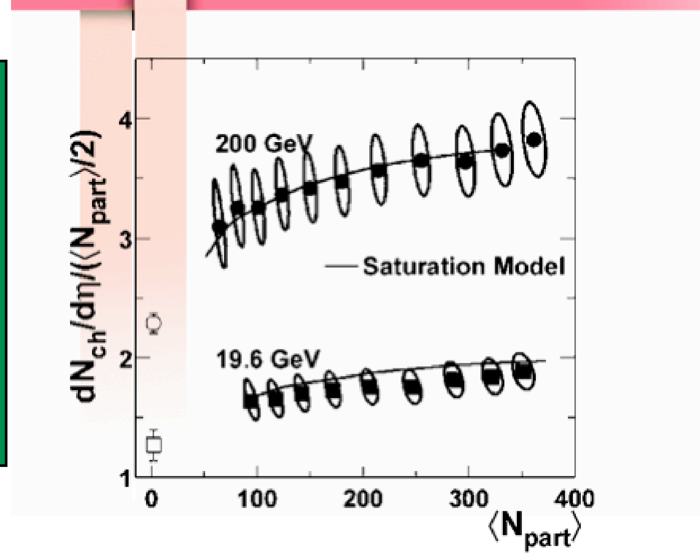


$\sqrt{s}$ = *130* GeV

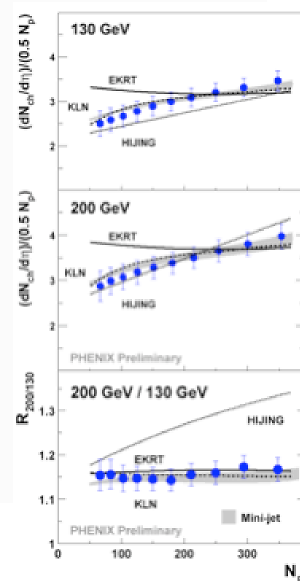
Energy and centrality dependence / RHIC

Text

How comes that final state multiplicities remember the INITIAL STATE QUANTA ?
Entropy conservation?



PHOBOS

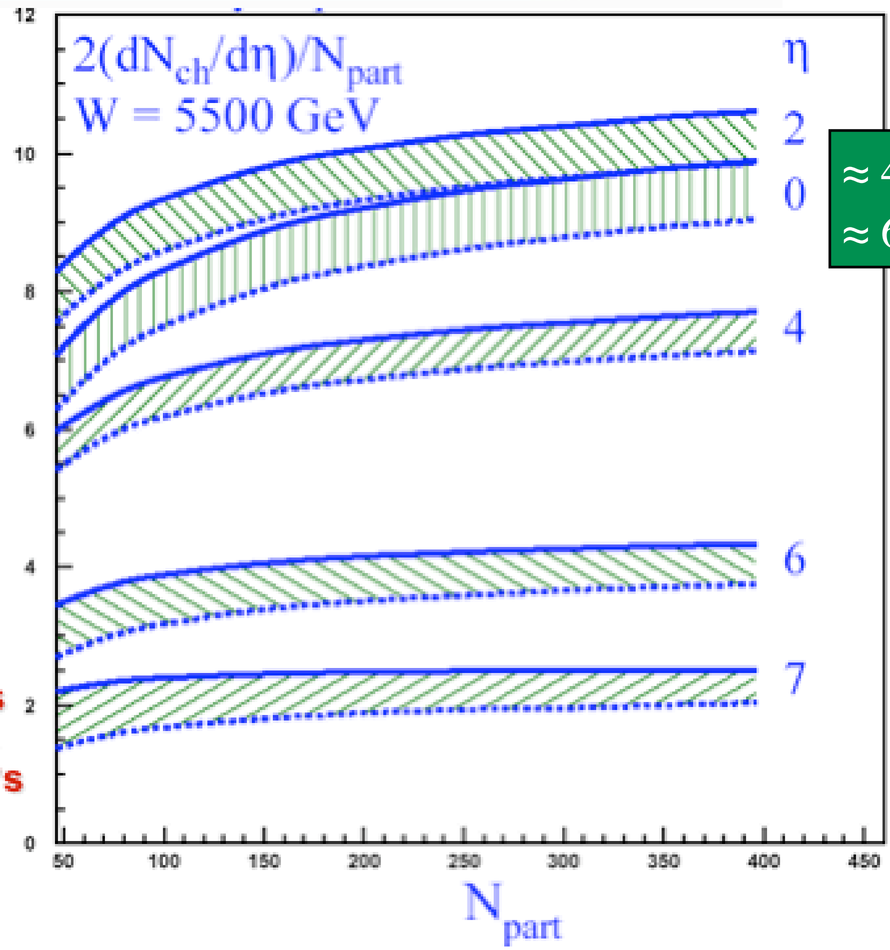


PHENIX

Marzia Nardi (Dic. 2004)

Centrality dependence / LHC

Pb-Pb collisions at LHC



≈ 4 @SPS
≈ 6 @ RHIC

Solid lines : constant α_s
dashed lines : running α_s

J/Ψ absorption at SPS

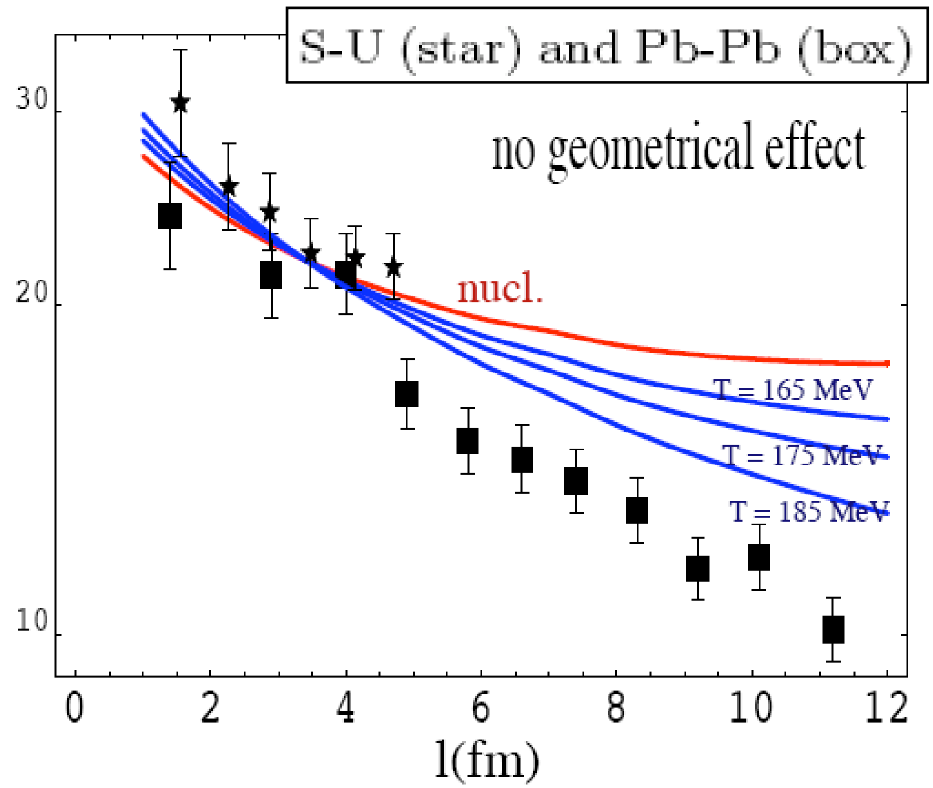
J/Ψ absorption at SPS

L.M., F. Piccinini,A. Polosa, V. Riquer
Nucl. Phys A and hep-ph/0408150

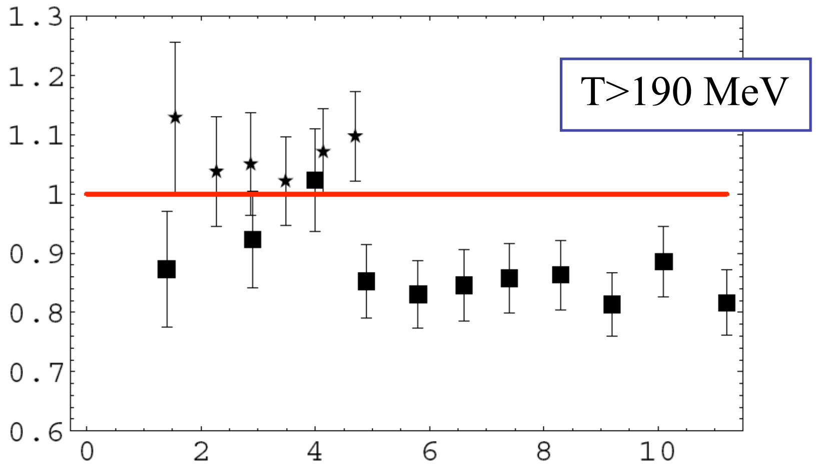
Data from NA50: M.C. Abreu et al., Phys. Lett. B450, 456 (1999); M.C. Abreu et al., Phys. Lett. B477, 28 (2000). Latest analysis: http://na50.web.cern.ch/NA50/

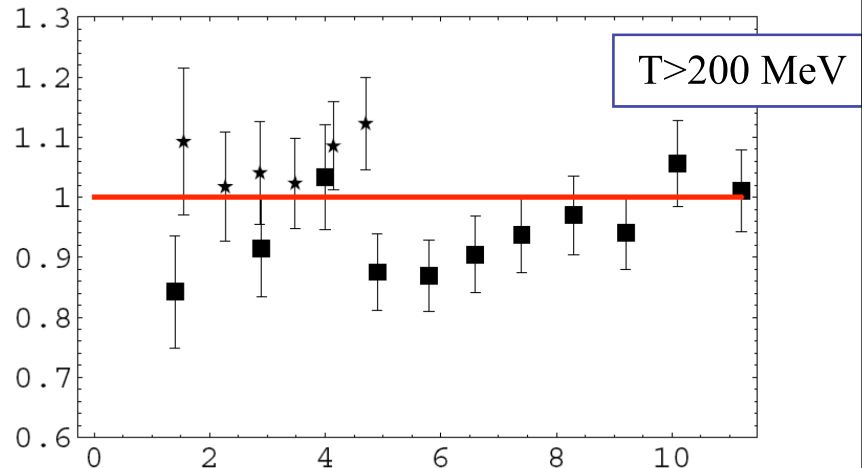
We try to fit the data for l <5 fm with a single temperature;
We find: 165 MeV< T<185 MeV
Quite consistent with hadronic temperatures;
Do not fit data for l >5fm
Is it conclusive??

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

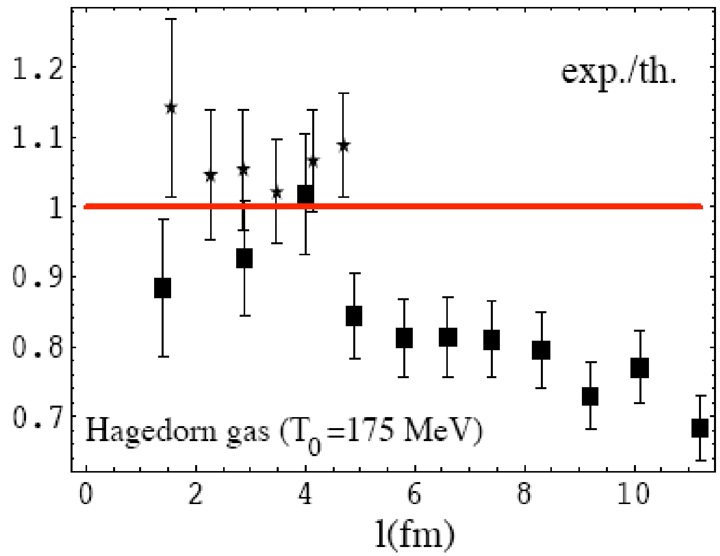


Expected (Hadron/Hagedorn gas) over Measured vs. l





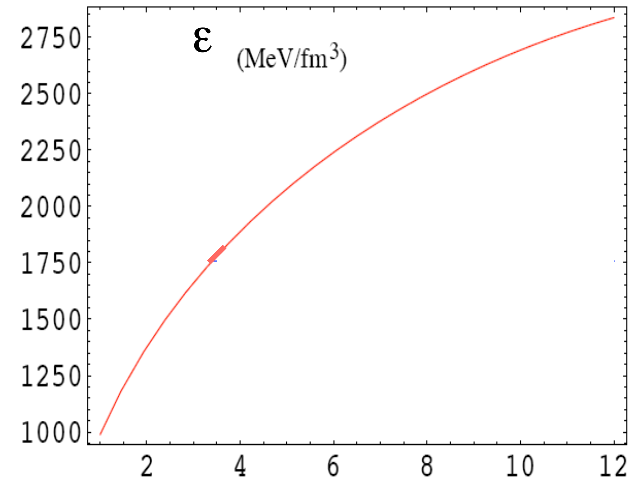
Observed /expected vs. l, T_0=175 and 185

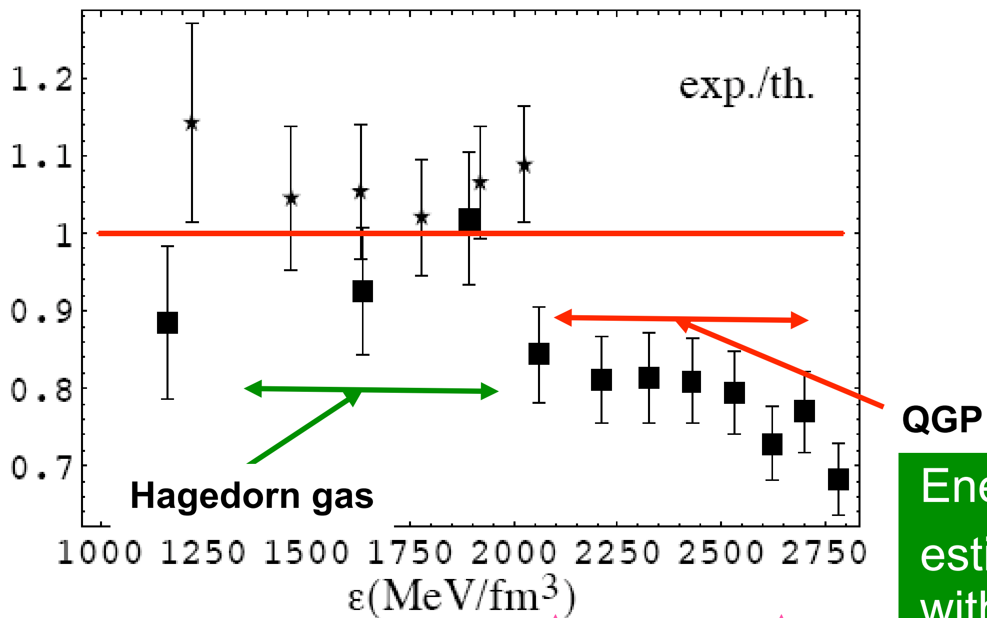


Observed /expected vs. l
T_0=175 + Hagedorn gas

Calibrating the absorption lenght with energy density

- We find: T(l=5)~168 MeV, ε(l=5)~2 GeV/fm^3
- We transform l in ε, using the geometrical factor g(b):



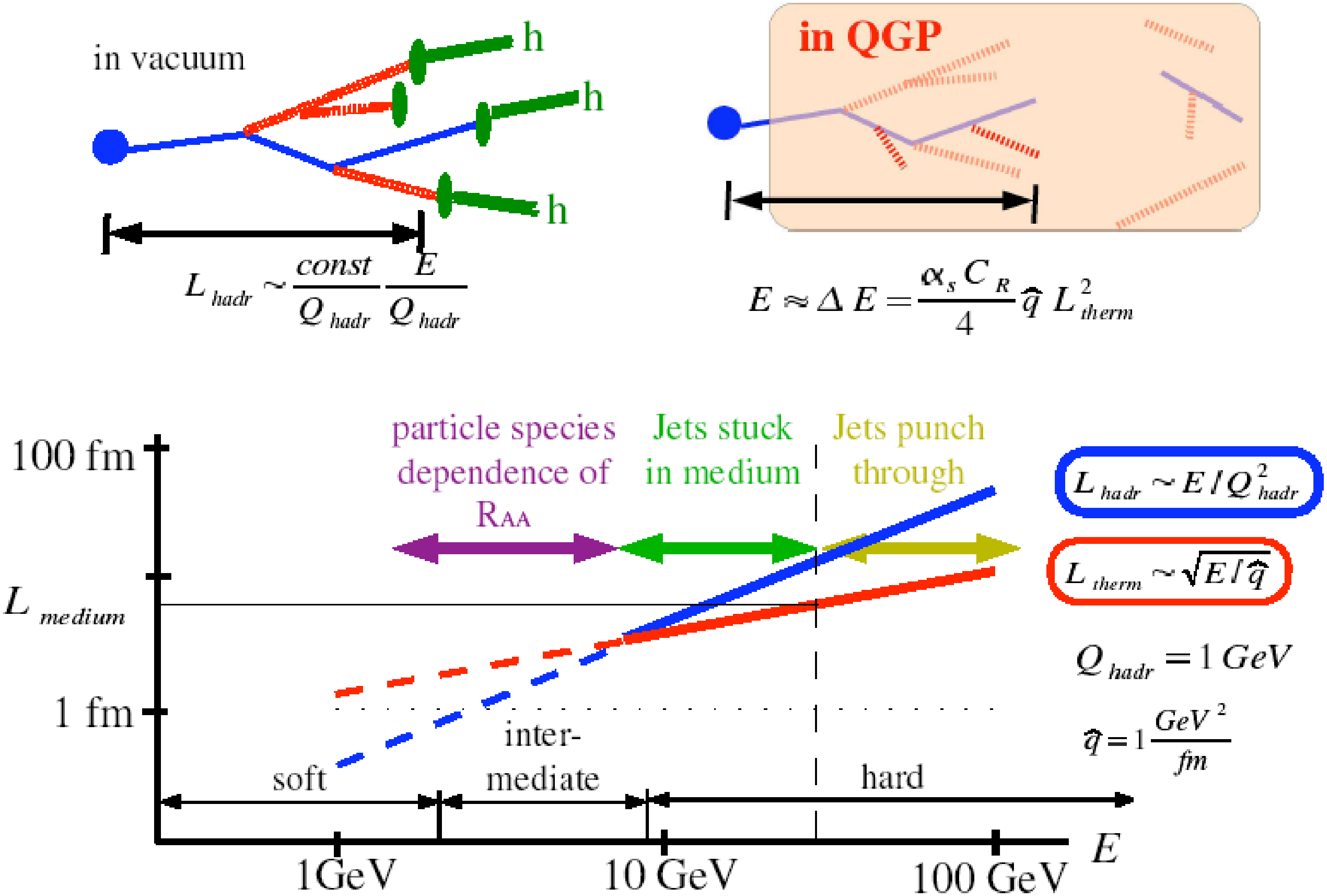


Energy density scale agrees with Bjorken estimate (2-3 GeV/fm^3, l=4-12 fm) and with melting temperatures (see Lect. 1)

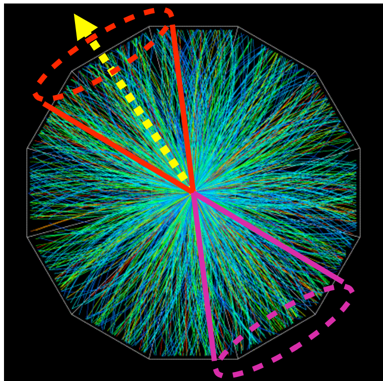
χ_c and Ψ' melt here (T=180, 190 MeV)!!

JET TOMOGRAPHY @ RHIC

Hadronization versus Thermalization of Jets



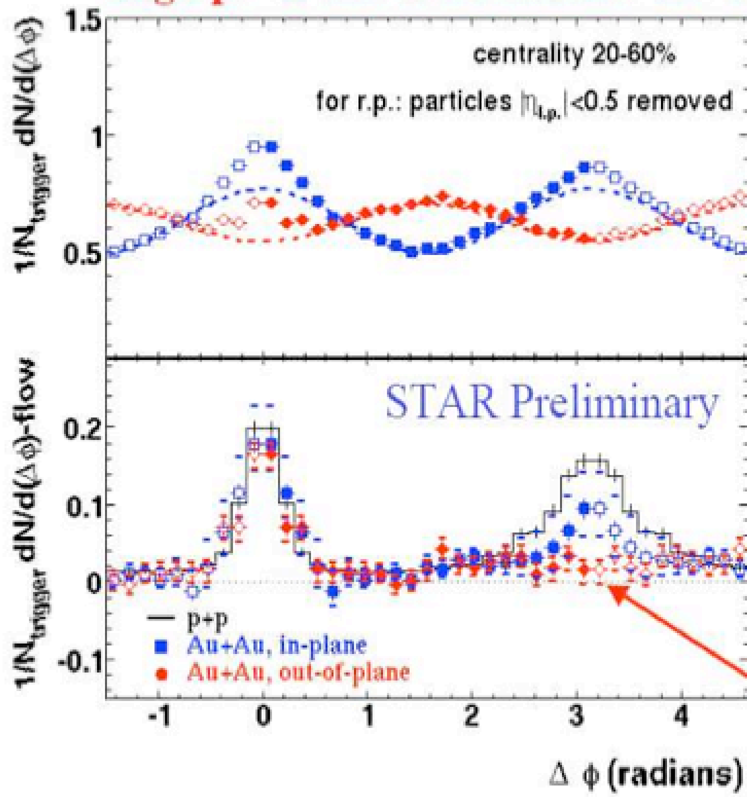
from U. Wiedemann, Quark matter 04

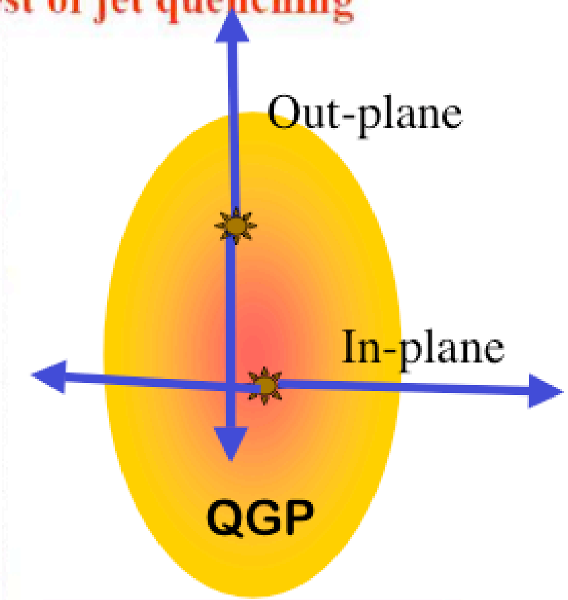


K. Filimonov: DNP 10.31.03

Di-Hadron Tomography

High pt v2 and correlation : the test of jet quenching

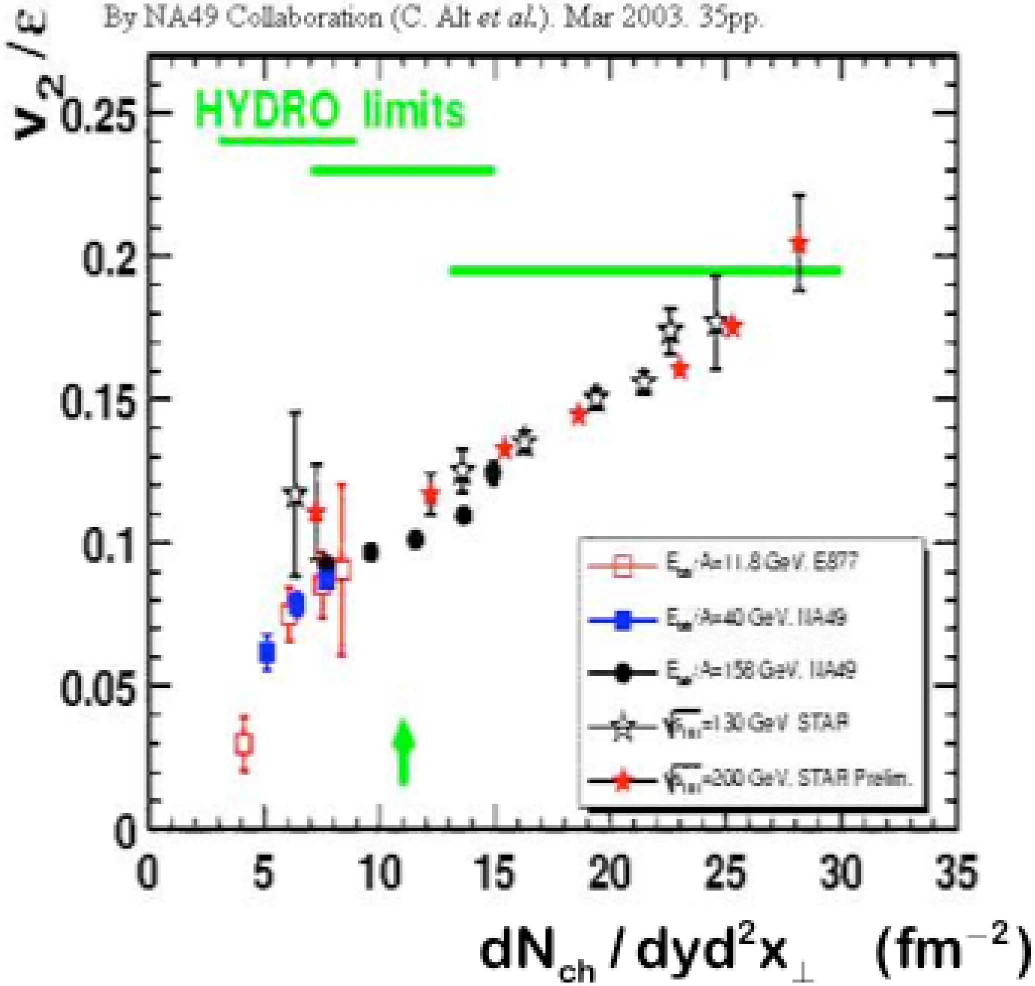




Back-to-back suppression is larger in the out-of-plane direction

A.Tang: BNL 11.18.03

2) **DIRECTED AND ELLIPTIC FLOW OF CHARGED PIONS AND PROTONS IN PB + PB COLLISIONS AT 40-A-GEV AND 158-A-GEV.**
By NA49 Collaboration (C. Alt *et al.*). Mar 2003. 35pp.



HADRON MULTIPLICITIES AT FREEZE-OUT

from F. Becattini (Milano, Dec.04)

Analisi delle molteplicita' in ioni pesanti

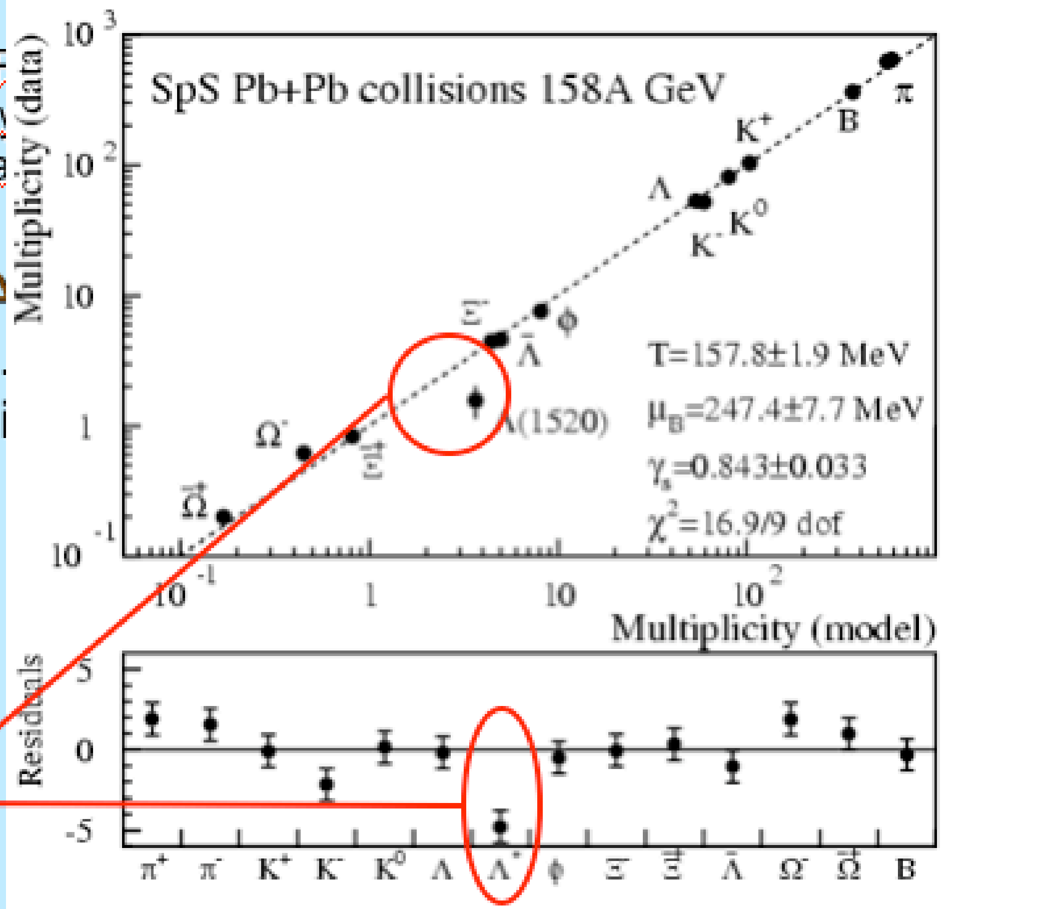
F. B., M. Gazdzicki, J. Sollfrank, Eur. P
F. B., J. Cleymans, A. Keranen,...., Phy
F. B., M. Gazdzicki, A. Keranen, J. Ma

MOLTI A

J. Cleymans, H. Satz, P.

J. Rafelski, W. Broni

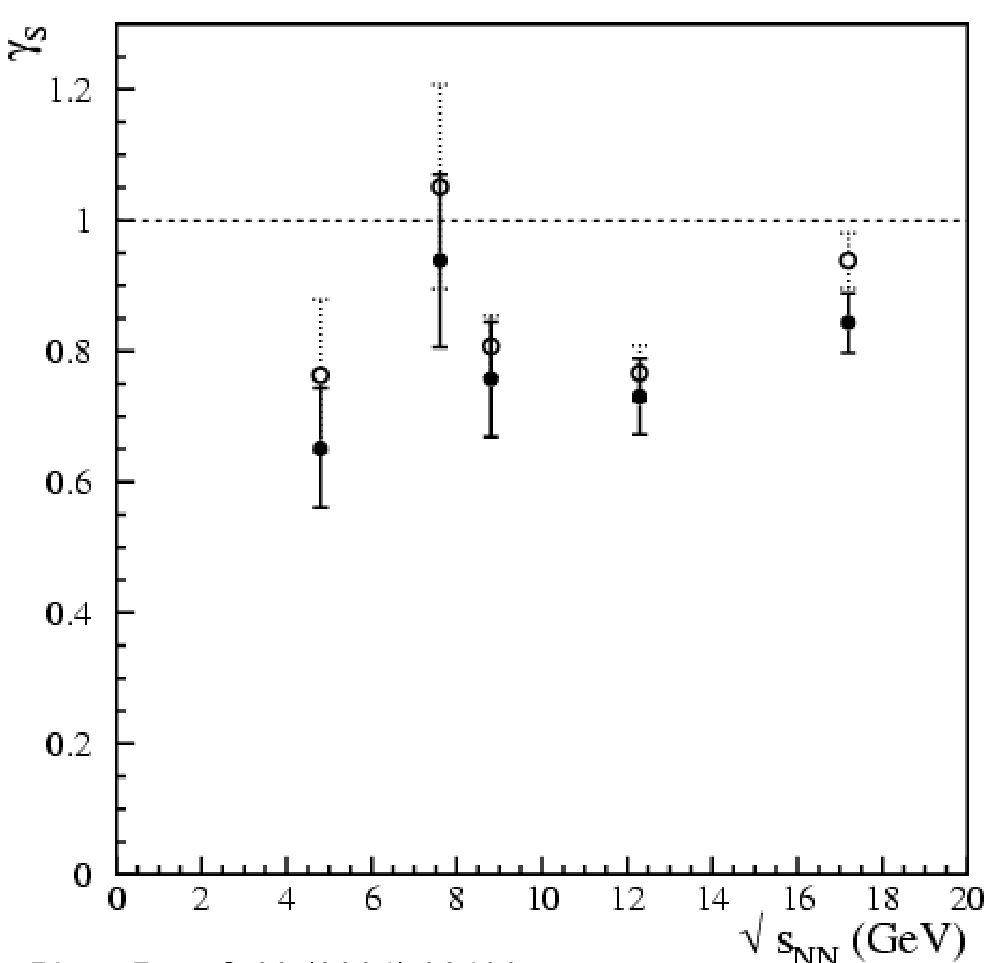
Fit to full phase space multiplicities by NA49 with T, μ_B, V, γ_S



Phys. Rev. C 69 (2004) 024905

Indication of rescattering?
$\Lambda(1520) \rightarrow pK^-$ Γ =15.6 MeV

Strangeness suppression



Phys. Rev. C 69 (2004) 024905

$\gamma_S \approx 1$ at RHIC

using midrapidity ratios

W. Florkowski et al.,
Acta Phys. Pol. 33, 761

About γ_S at SPS

- There are few strange quarks in initial state,
- normal hadron reactions do not “have time to equilibrate strangeness, at SPS
- hence the need of a “fudge factor” γ_S.
- in deconfined phase, strange quarks equilibrate because of small current mass, and strange hadrons form from recombination: hence $\gamma_S = 1$
- strangeness enhancement at SPS: is there a correlation of γ_S with centrality, i.e. with J/Ψ absorption?

NA 49 Collaboration

System-Size Dependence of Strangeness Production in Nucleus-Nucleus Collisions at $\sqrt{s_{NN}} = 17.3$ GeV

3arna,[4] J. Bartke,[6] L. Betev,[10,9] H. Białkowska,[19] A. Billmeier,[9] C
R. Bramm,[9] R. Brun,[10] P. Bunčić,[9,10] V. Cerny,[3] P. Christakoglou,
[8] A. Dimitrov,[18] P. Dinkelaker,[9] V. Eckardt,[14] G. Farantatos,[2] D. Fli
l,[4] M. Gaździcki,[9] G. Georgopoulos,[2] E. Gładysz,[6] K. Grebieszko
. Kliemant,[9] S. Kniege,[9] V. I. Kolesnikov,[8] T. Kollegger,[9] E. Korna
s,[3] M. van Leeuwen,[1] P. Lévai,[4] L. Litov,[18] B. Lungwitz,[9] M. Ma
v,[18] B. W. Mayes,[11] G. L. Melkumov,[8] C. Meurer,[9] A. Mischke,[7]
illa,[4] A. D. Panagiotou,[2] D. Panayotov,[18] A. Petridis,[2] M. Pikna,[3]
ordt,[9] A. Richard,[9] C. Roland,[5] G. Roland,[5] M. Rybczyński,[12] A.
[4] P. Seyboth,[14] F. Siklér,[4] B. Sitar,[3] E. Skrzypczak,[20] G. Stefanek
. Sziklai,[4] T. A. Trainor,[17] V. Trubnikov,[20] D. Varga,[4] M. Vassiliou,
A. Wetzler,[9] Z. Włodarczyk,[12] I. K. Yoo,[16] J. Zaranek,[9] and J. Zir

(NA49 Collaboration)

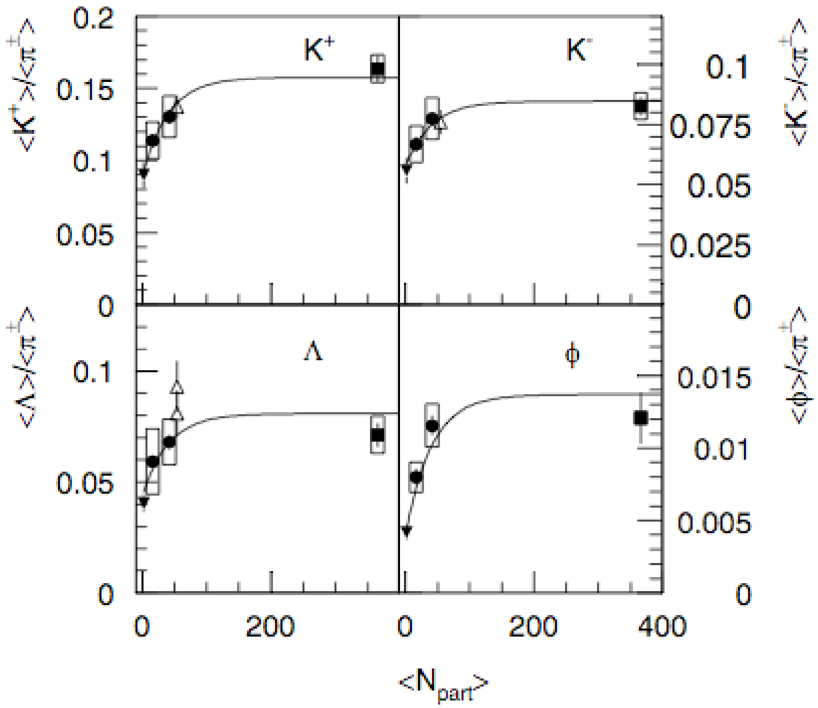


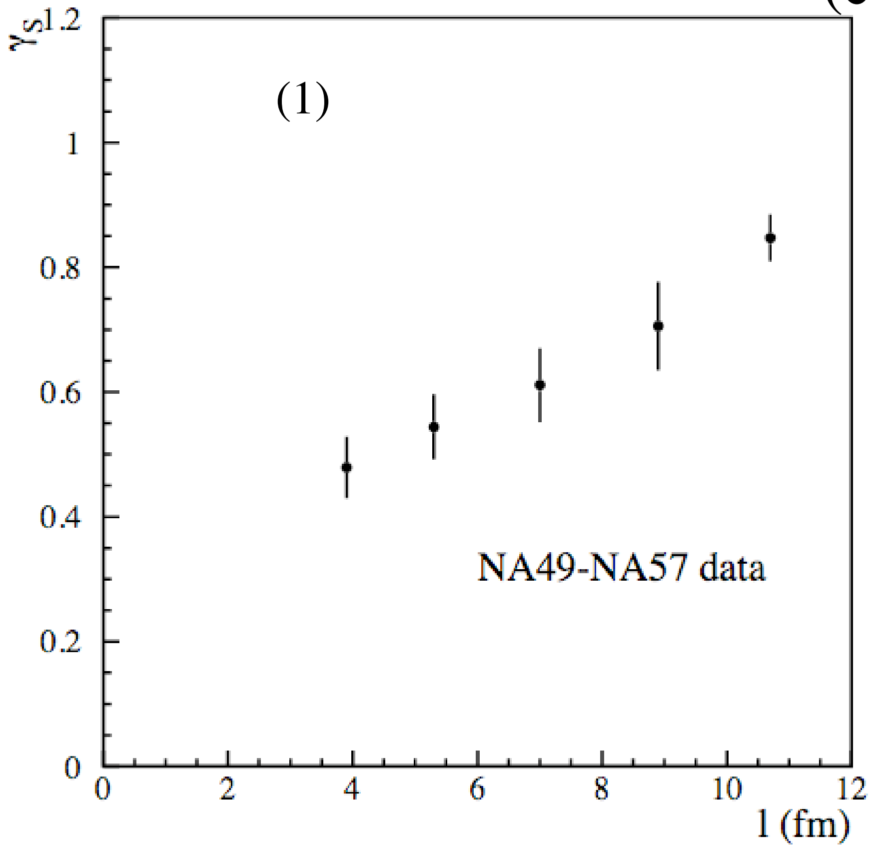
FIG. 3. Experimental ratios of $\langle K^+\rangle$, $\langle K^-\rangle$, $\langle\phi\rangle$, and $\langle\Lambda\rangle$ to $\langle\pi^\pm\rangle$ plotted as a function of system-size (▼ $p+p$; ● C + C and Si + Si; △ S + S; ■ Pb + Pb). Statistical errors are shown as error bars, systematic errors if available as rectangular boxes. The curves are shown to guide the eye and represent a functional form $a - b\cdot\exp(-\langle N_{\rm part}\rangle/40)$. At $\langle N_{\rm part}\rangle = 60$ they rise to about 80% of the difference of the ratios between $N_{\rm part} = 2$ and 400.

Preliminary
Not to be quoted !!

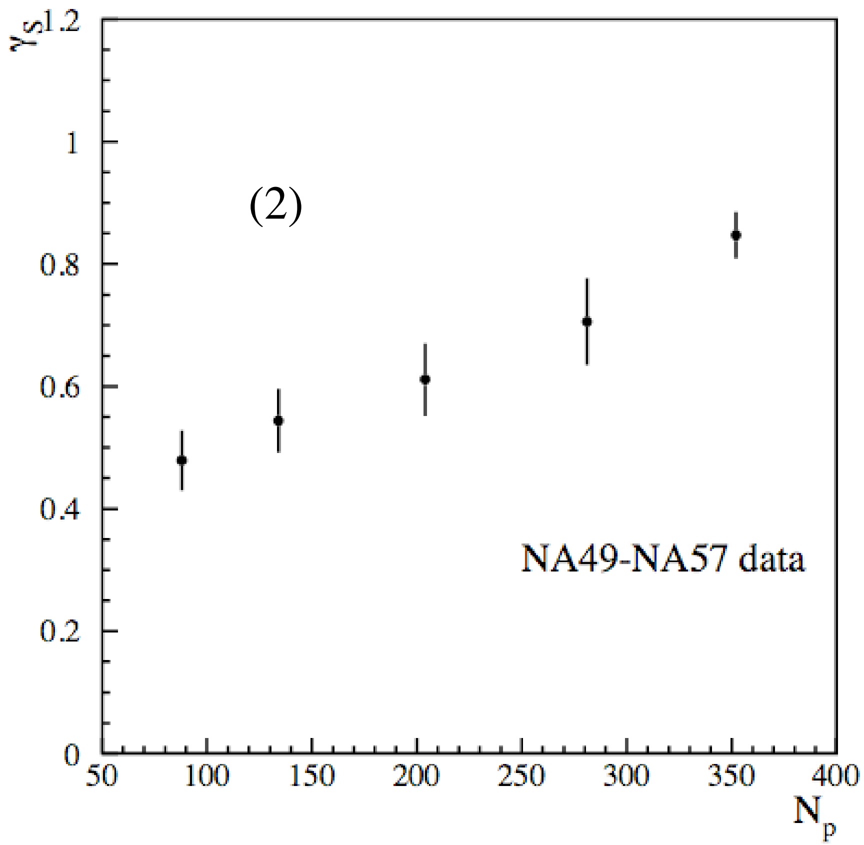
γ_S vs :

1) centrality (fm)
2) participating nucleons

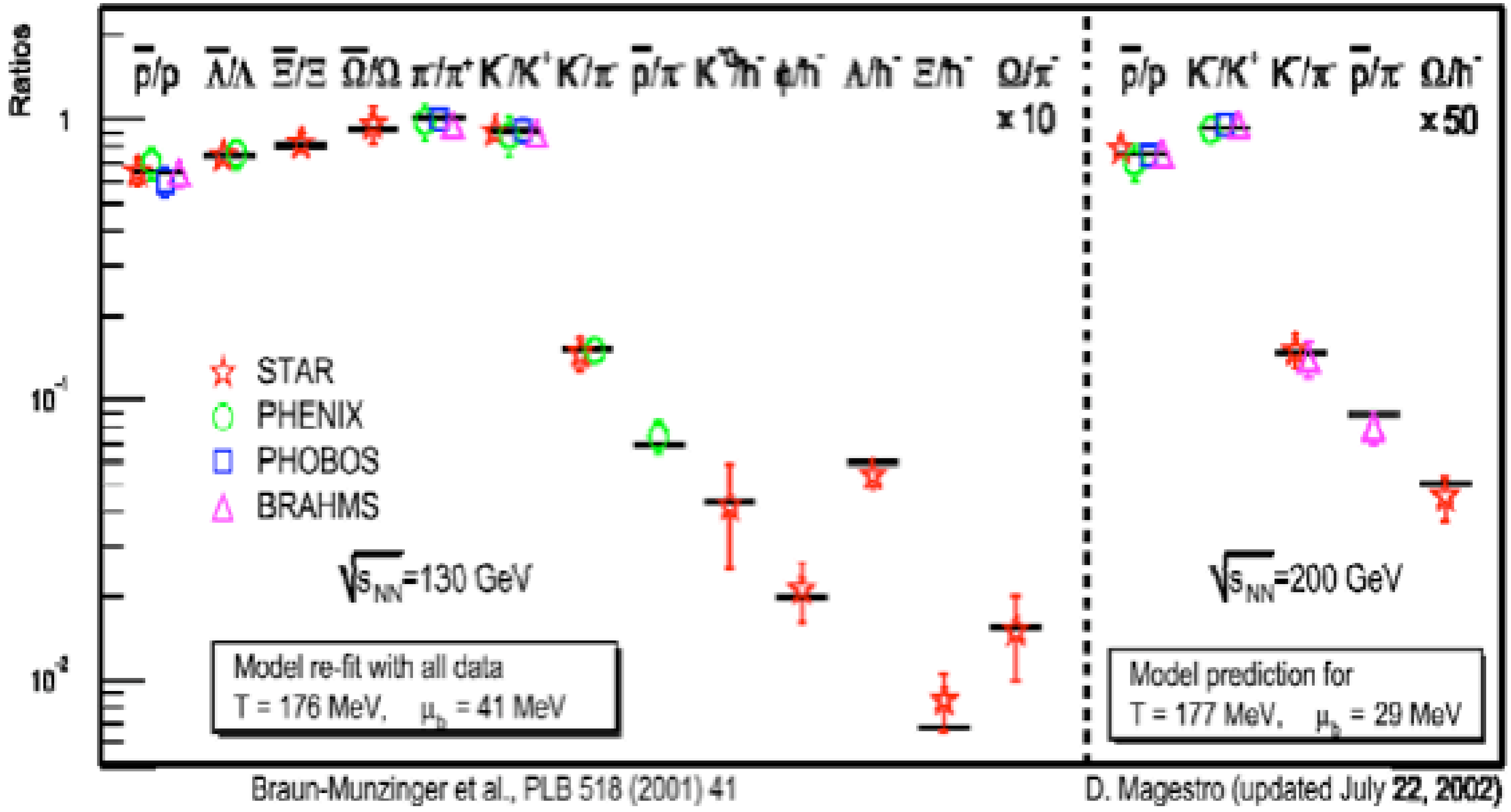
(c



Analysis by F. Becattini



Hadrons at RHIC: $\gamma_S = 1$



CONCLUSIONS

@ SPS

- All indications are that deconfinement is seen @SPS
- strangeness enhancement and J/Ψ suppression should be correlated (γ_S. vs centrality?)
- SPS may offer the unique possibility to bring us precisely at the onset of deconfinement....we may have to come back!

@ RHIC

- new phenomena, new probes:
  - jet tomography
  - collective motion
  - b-quarkonia could be a useful probe
- initial quanta: Color Glass Condensate?
- a very dense, fluid phase is seen: is it QGP?
- what is it a strongly interacting QGP?

Useful probes @ LHC (considerations of a new comer)

-
- initial state quanta:
  - hard jets
  - hard, heavy quarks (what about top?)
  - Z, W
- bulk properties of QGP:
  - jet tomography
  - collective motion, hydrodynamical flow..
  - quarkonia not so useful: too many b’s around

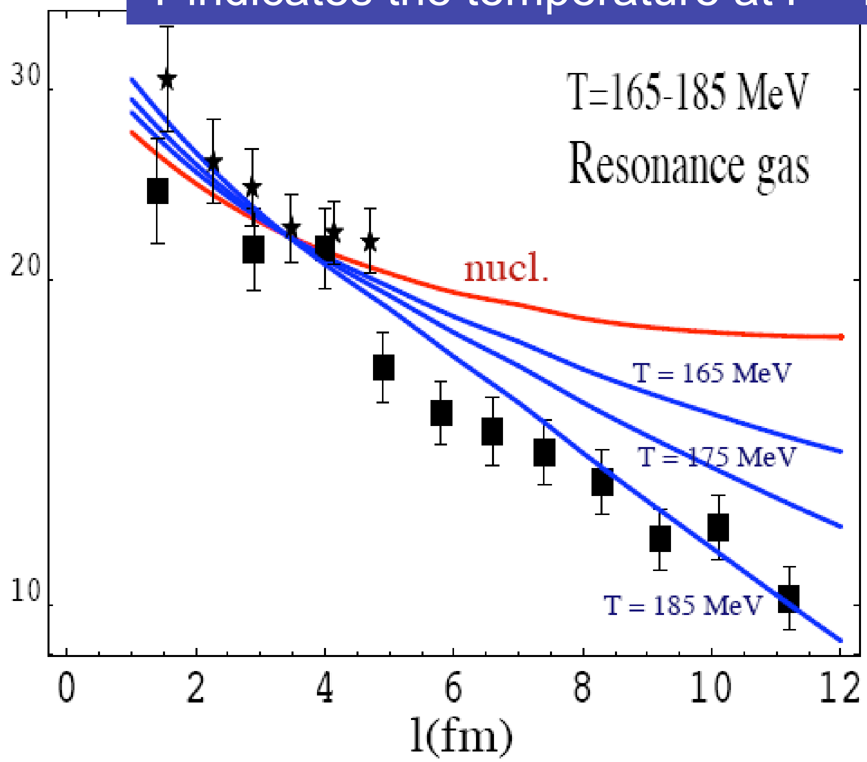
big surprises are possible!

APPENDIX

Extrapolating to higher centrality

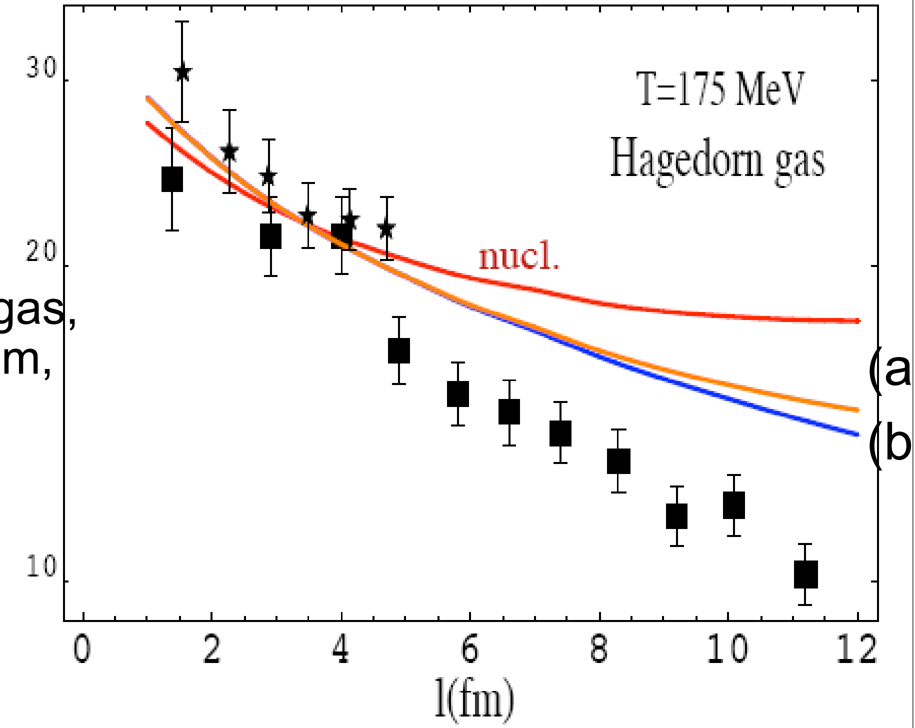
- We use the energy density-temperature relation of Ps+Vect meson gas;
- Marginal fit (but not too bad)
- However, T(l ~ 12 fm) =185-205 MeV;
- Are these T realistic for a hadron gas ?

T indicates the temperature at l ~ 4fm;



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



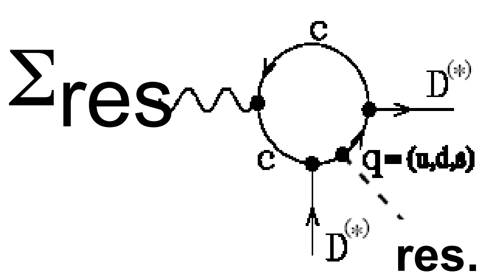
The sharp rise of degrees of freedom near the Hagedorn temperature makes so that T does not rise at all (b), the dissociation curve cannot become harder, prediction falls short from explaining the drop observed by NA50.

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.

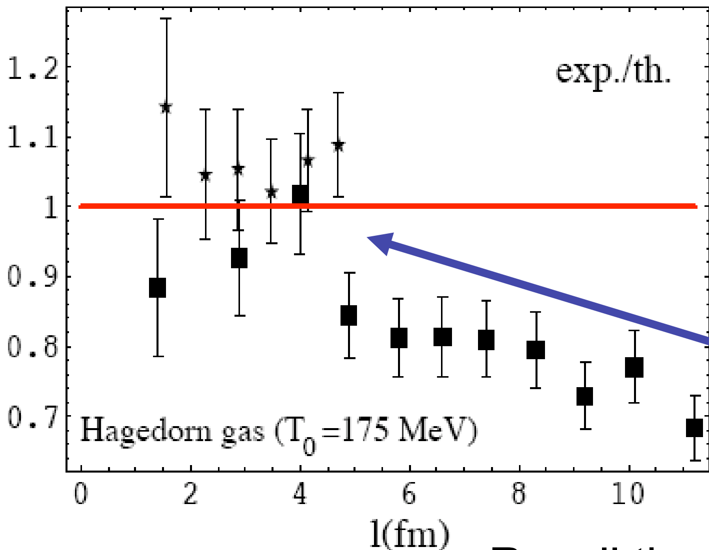


= Open the q-qbar lines of π

$$q + J/\Psi \rightarrow D + \overline{D} + q'$$

Dissociation by QGP??

Bold speculations...



Observed /expected vs. l
T_0=175 + Hagedorn gas

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