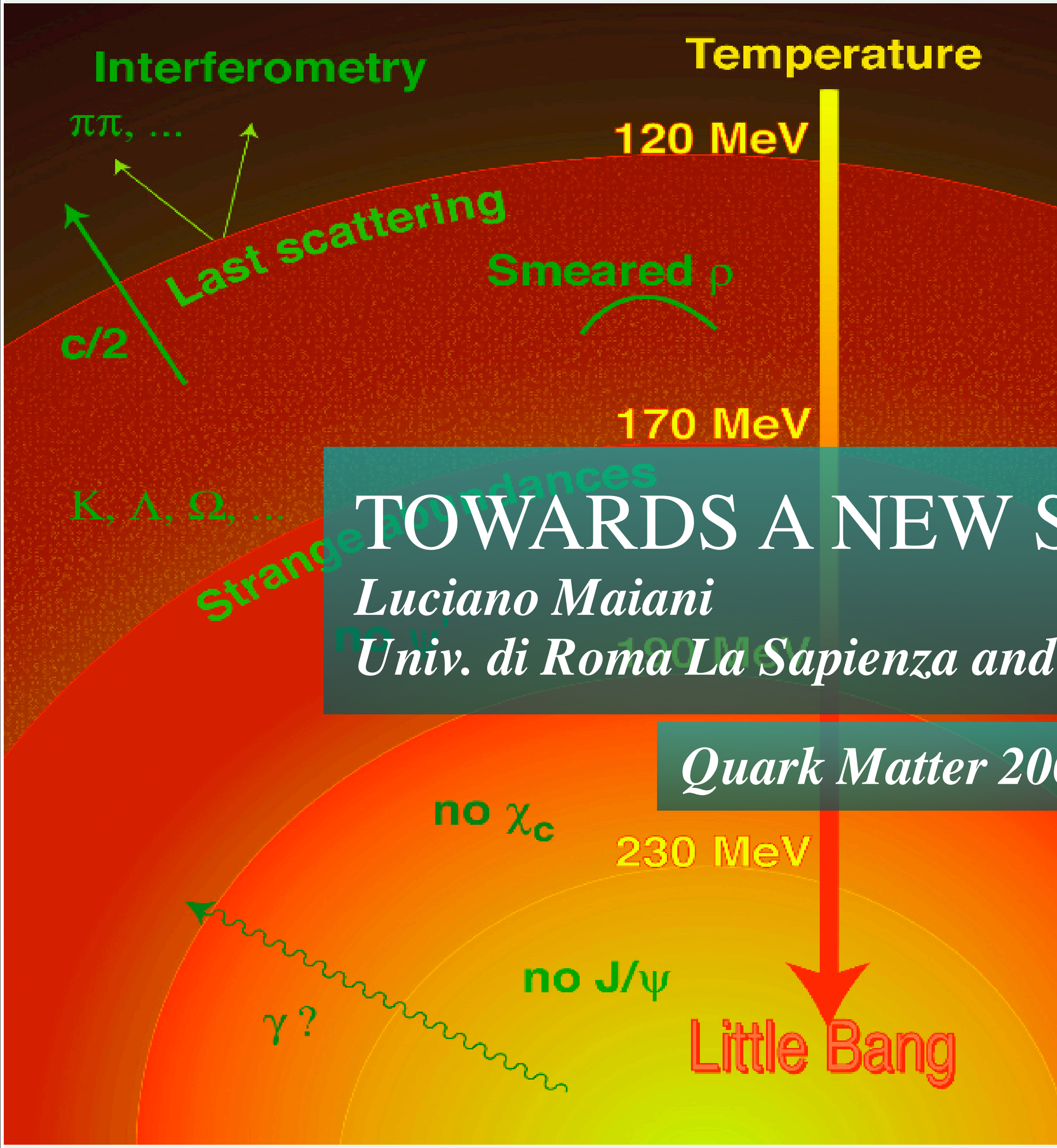
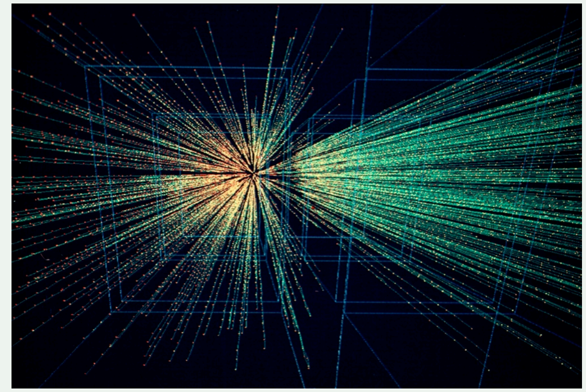


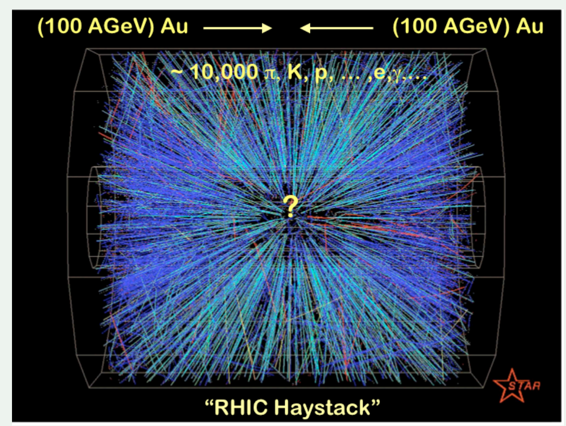


Pb-Pb @ SPS, from NA49

TOWARDS A NEW STATE OF MATTER

Luciano Maiani
Univ. di Roma La Sapienza and INFN, Roma.

Quark Matter 2005, Budapest, 4 August 2005



Au-Au @ RHIC, from STAR

INTRODUCTION

- The Big Bang:

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

"However, the temptation to try is irresistible.

…two estremely different simple models….the hope is that one or the other may come close enough to reality to lead to useful insights about the very early Universe.

S. Weinberg, Gravitation and Cosmology, 1972

- "Bootstrap" models: all hadrons are composite of one another
- "Elementary particle" model: photons, leptons, quarks (gluons… asymptotic freedom)

Both models are right, although in different energy and temperature ranges.

Composite hadrons (bootstrap, ..quarks in bags..):

- exponentially rising level spectrum, ...
- limiting temperature, T=170-180 MeV, that can be estimated from the hadron spectrum
- Just before reaching the limiting temperature, hadrons "melt" in a "deconfined state" of elementary particles.

Many questions:

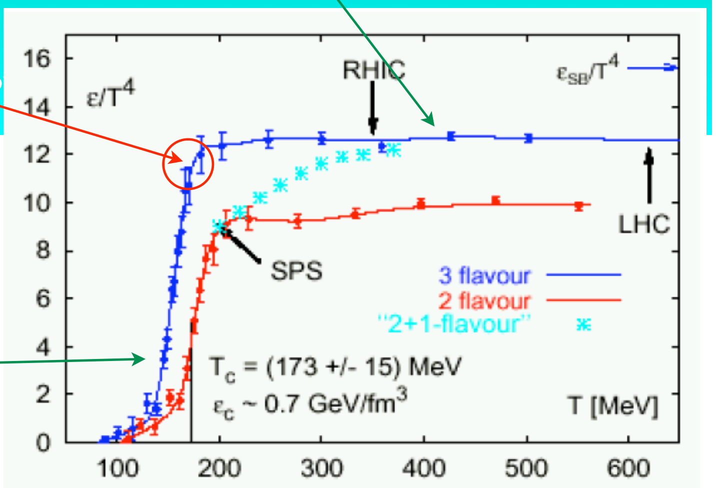
- a true phase transition ? cross-over only?
- chiral symmetry restored ??
- transition to an asymptotically free gas ??
- intermediate phase of a strongly interacting Quark Gluon P

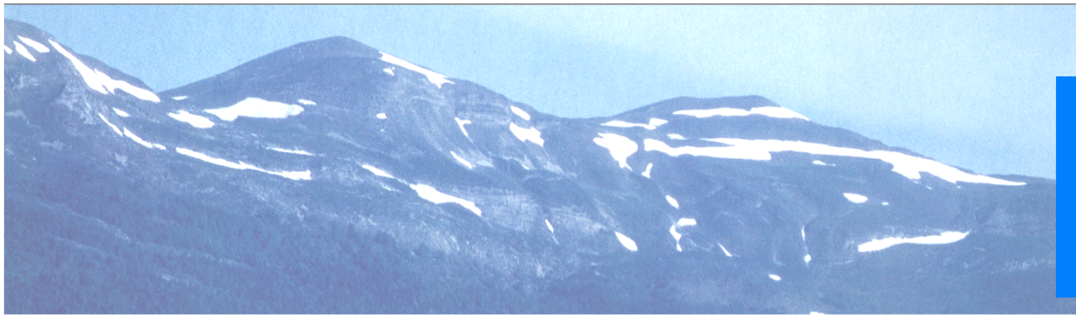
QGP ?

$\epsilon \sim 2 GeV/fm^3; T \sim 170 MeV$

Lattice QCD calculations of the energy density of hadronic matter vs. T (F. Karsch, Lattice QCD at High Temperature and Density, hep-lat/0106019).

Hadron Gas ?





- A skier (quark?) is confined inside snow patches (hadrons?)

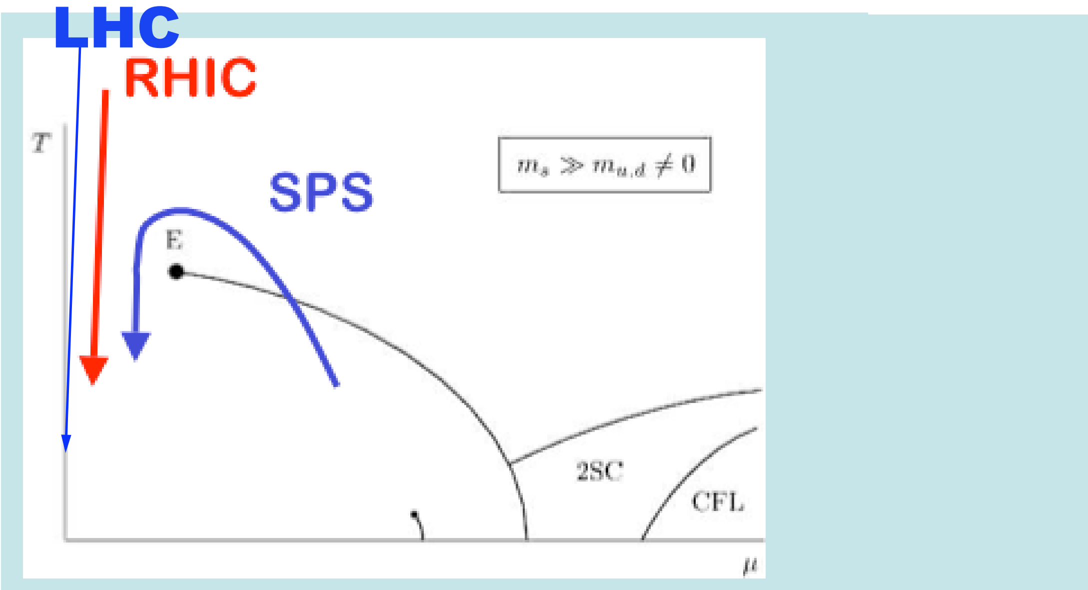
Temperature

- the skier can move further…a new phase develops

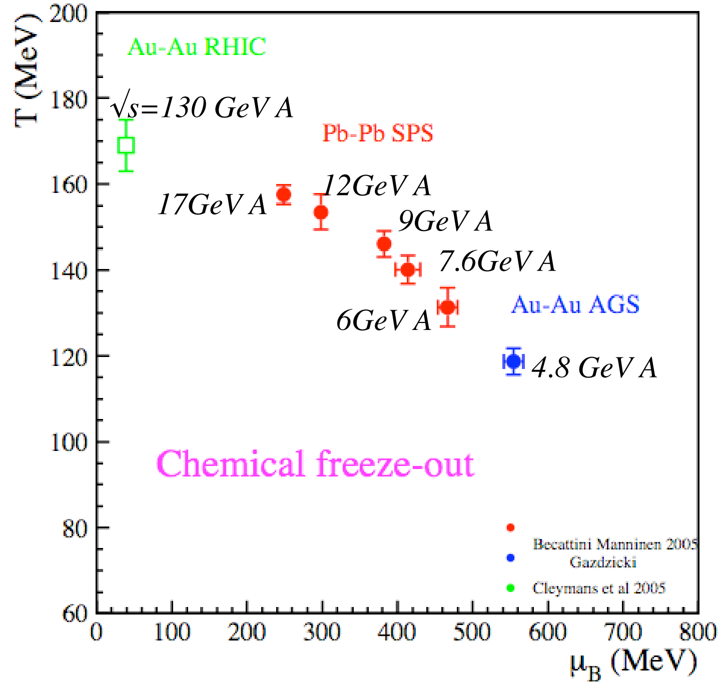
..goes up

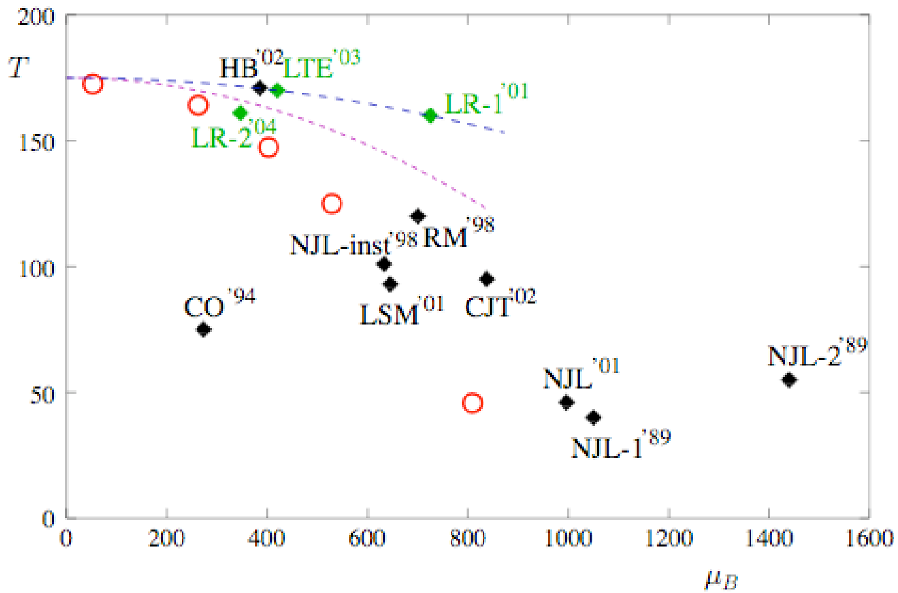
- a skier (quark?) can move freely over long distances…

..this way



Locating the QCD critical point





Theoretical methods:

- models;
- lattice:
  - Reweighting from $\mu = 0$;
  - Taylor exp. around $\mu = 0$.
  - Imaginary μ.

Fancy, facts and calculations

1. Where

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

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

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

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

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

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

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

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

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

8000 collisions per second !

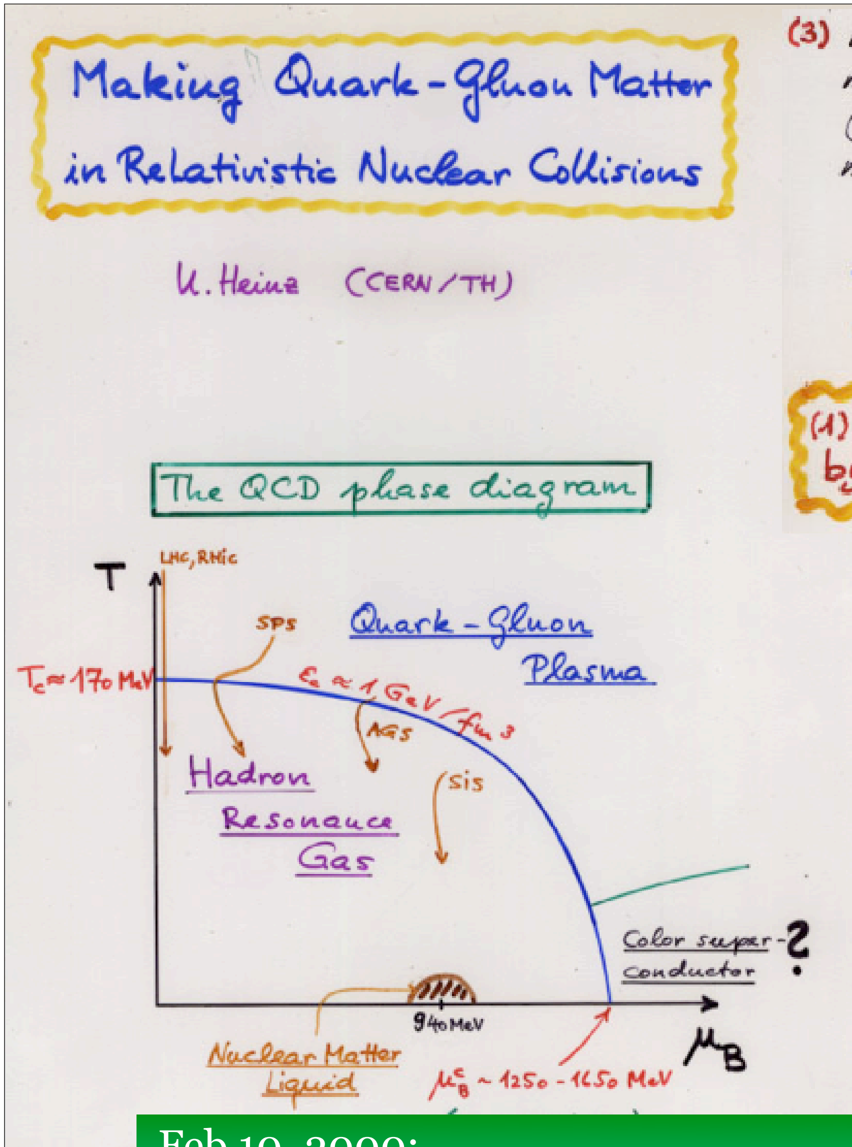
1. The SPS campaign at CERN

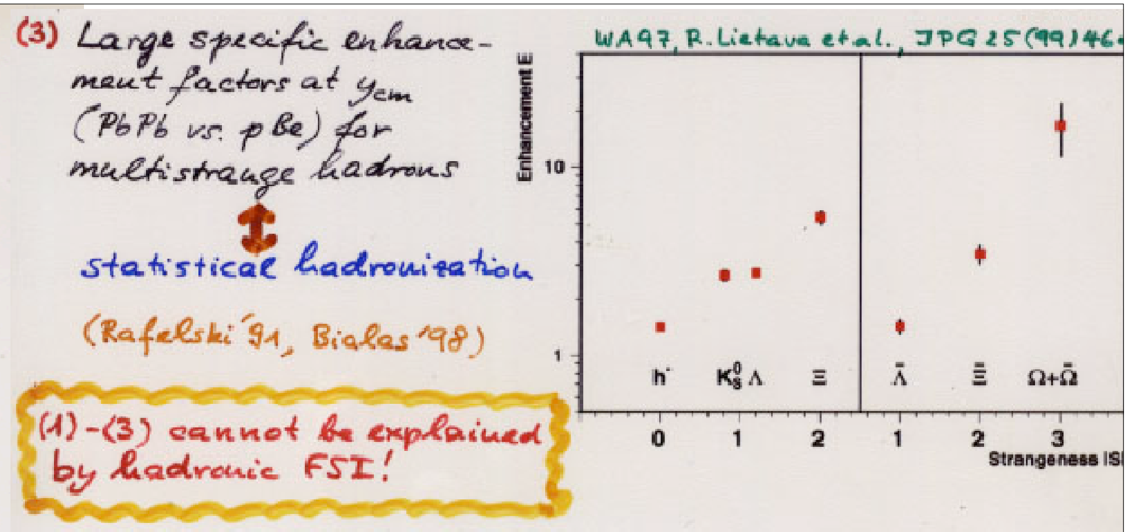
THE HEAVY ION FACILITY

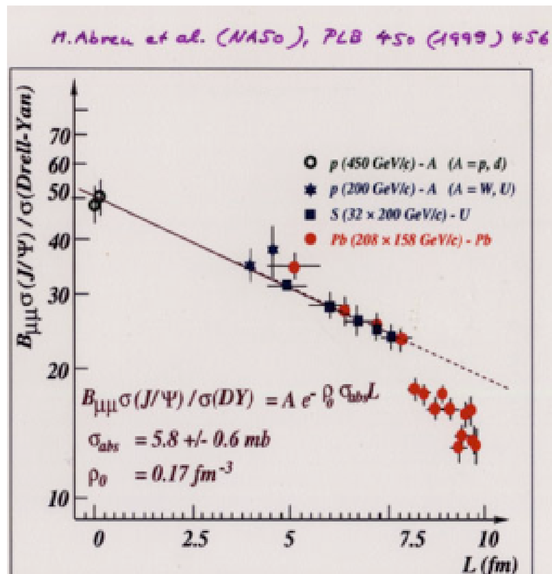
The heavy-ion facility was constructed as a collaboration between CERN and the following laboratories :

GANIL	**Caen**	**FRANCE**
INFN	**Legnaro**	**ITALY**
	Torino	**ITALY**
GSI	**Darmstadt**	**GERMANY**
Institute of Applied Physics	**Frankfurt**	**GERMANY**
Variable Energy Cyclotron (VECC)	**Calcutta**	**INDIA**
Tata Inst. of Fundamental Research (TIFR) &		
Baba Atomic Research Centre (BARC)	**Bombay**	**INDIA**
Academy of Sciences	**Prague**	**CZECH REP.**

In-cash contributions from: SWEDEN and SWITZERLAND







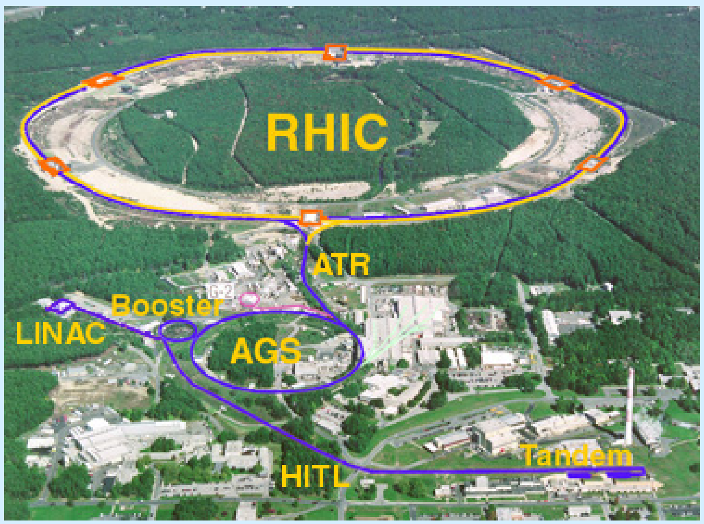
T. Matsui, H. Satz (1986)

Feb 10, 2000:

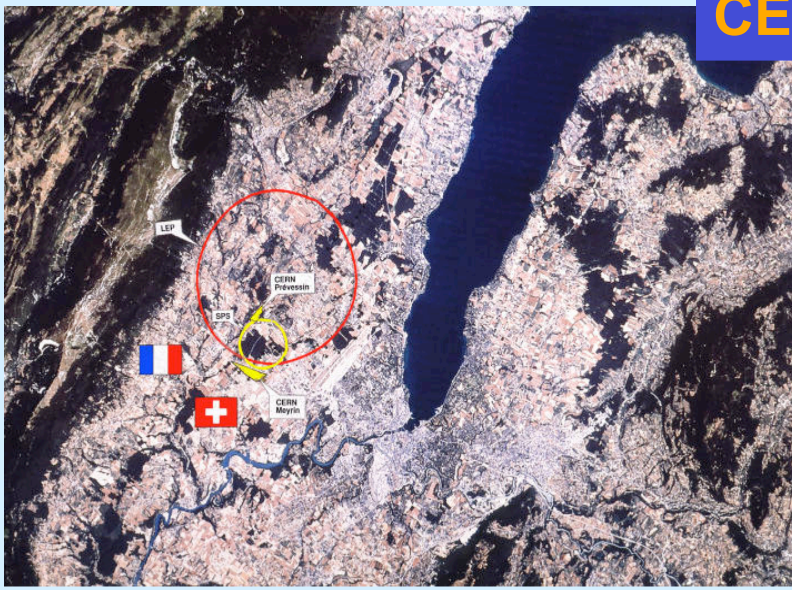
"...The data provide evidence for colour deconfinement in the early collision stage and for a collective explosion of the collision fireball in its late stages. The new state of matter exhibits many of the characteristic features of the theoretically predicted Quark-Gluon Plasma."

"...The challenge now passes to the Relativistic Heavy Ion Collider at Brookhaven and later to CERN's Large Hadron Collider."(Feb. 2000)

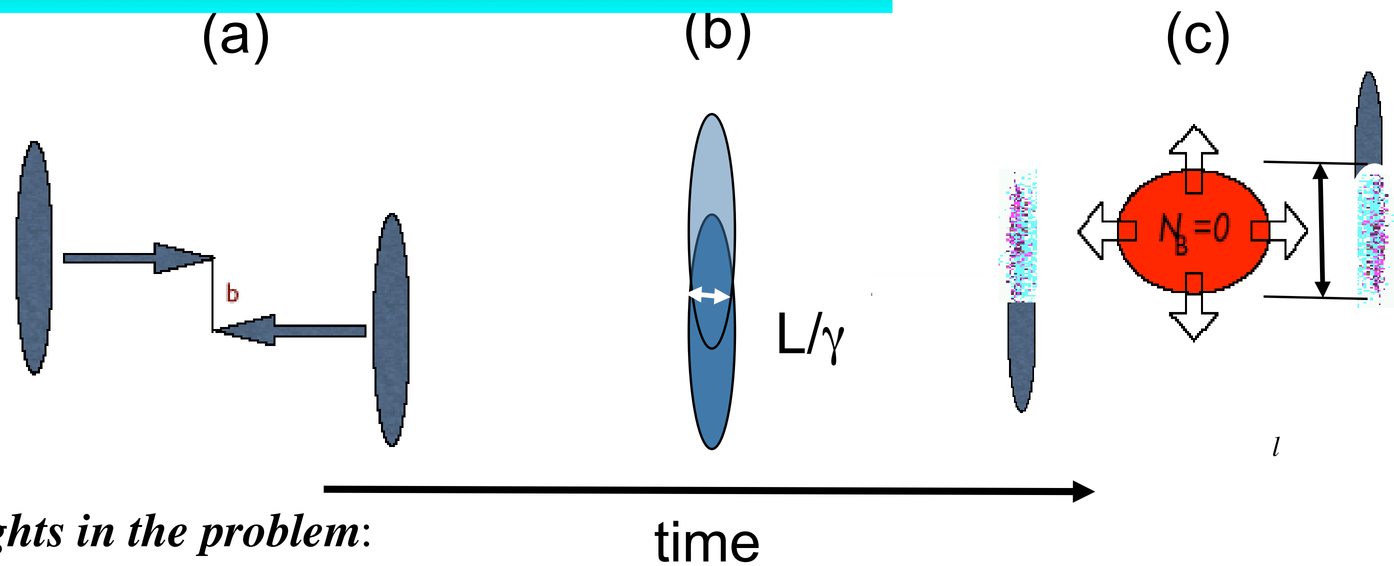
1. The Relativistic Heavy Ion Collider, Brookhaven, Summer 2000 to ...



2. The Large Hadron Collider CERN, 2007 to ...

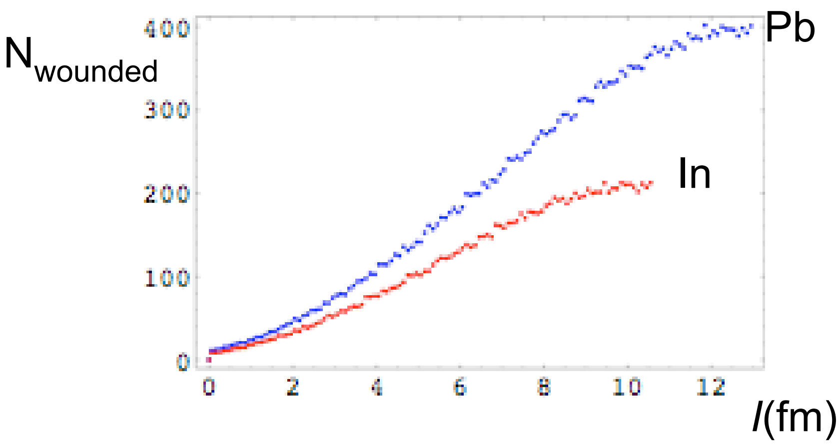


What is the critical lenght?

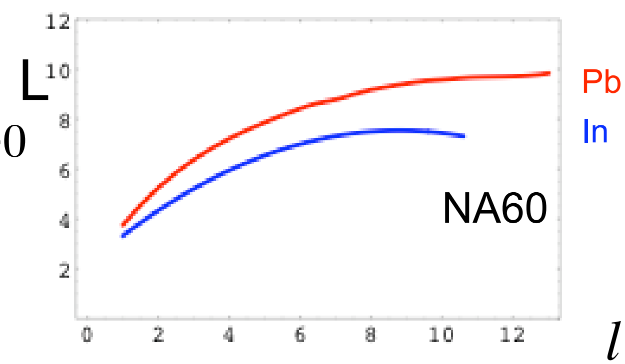


Two lenghts in the problem:

- L→ nuclear absorption; nuclear absorption coefficient $=\sigma_{abs}\,(L/\gamma)(\rho_{nucl}\gamma)$ is γ-independent.
- l = transverse size of the fireball → absorption by the (mid-rapidity) hadrons.
- l is related to the impact parameter, $l=2R-b$ and also to $N_{participants}$: $N_{part} \propto l^3$

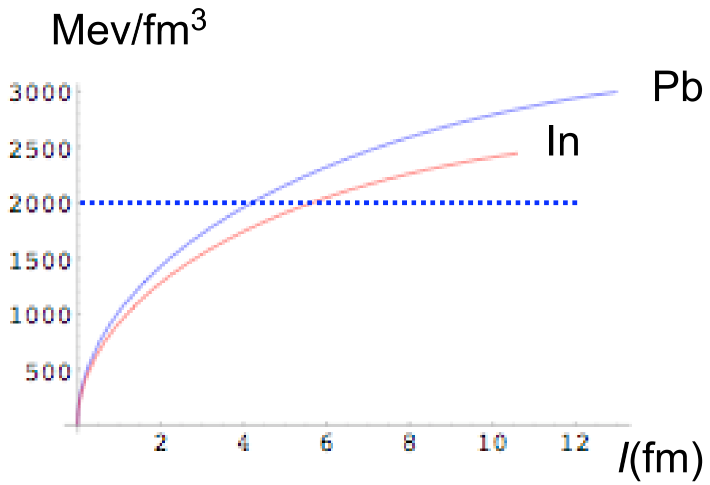


note: $\partial L/\partial l \to 0$
for $l \to 2R$



Critical lenght?

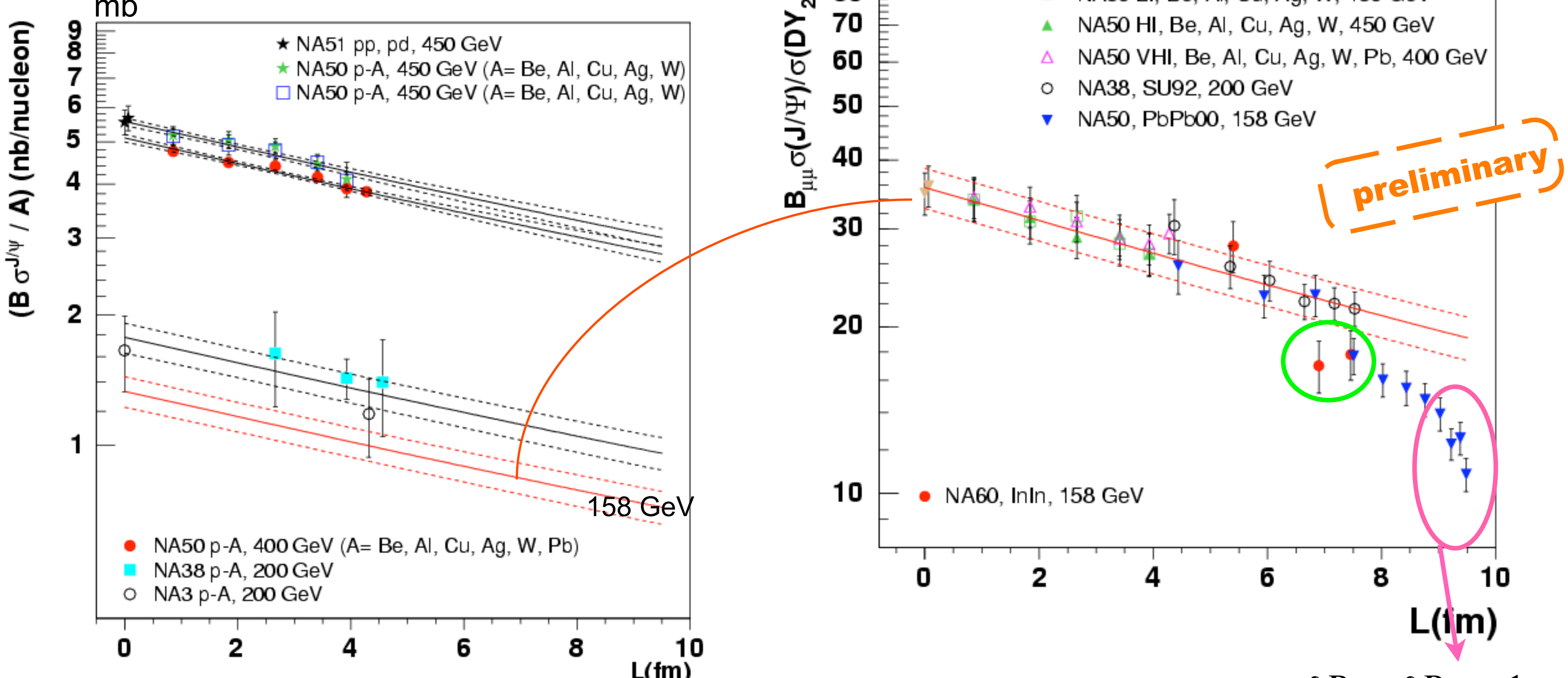
- *l* is a good candidate. At the increase of *l*, two critical quantities increase
  - the linear size of the fireball, hence its volume;
  - the average number of nucleons per unit surface, hence the energy density deposited in the fireball, according to the Bjorken formula.
- Related to the energy density, the temperature of the fireball increases: increasing centrality (i.e. *l*) we make a temperature scan which may cross the critical temperature



C. Lourenco for NA60
EPS Conference, Lisbon 2005

Comparison with previous measurements: versus L

Survival probability of the J/y :
exp(-rLs_{abs}) with s_{abs} = 4.18 ± 0.35 mb

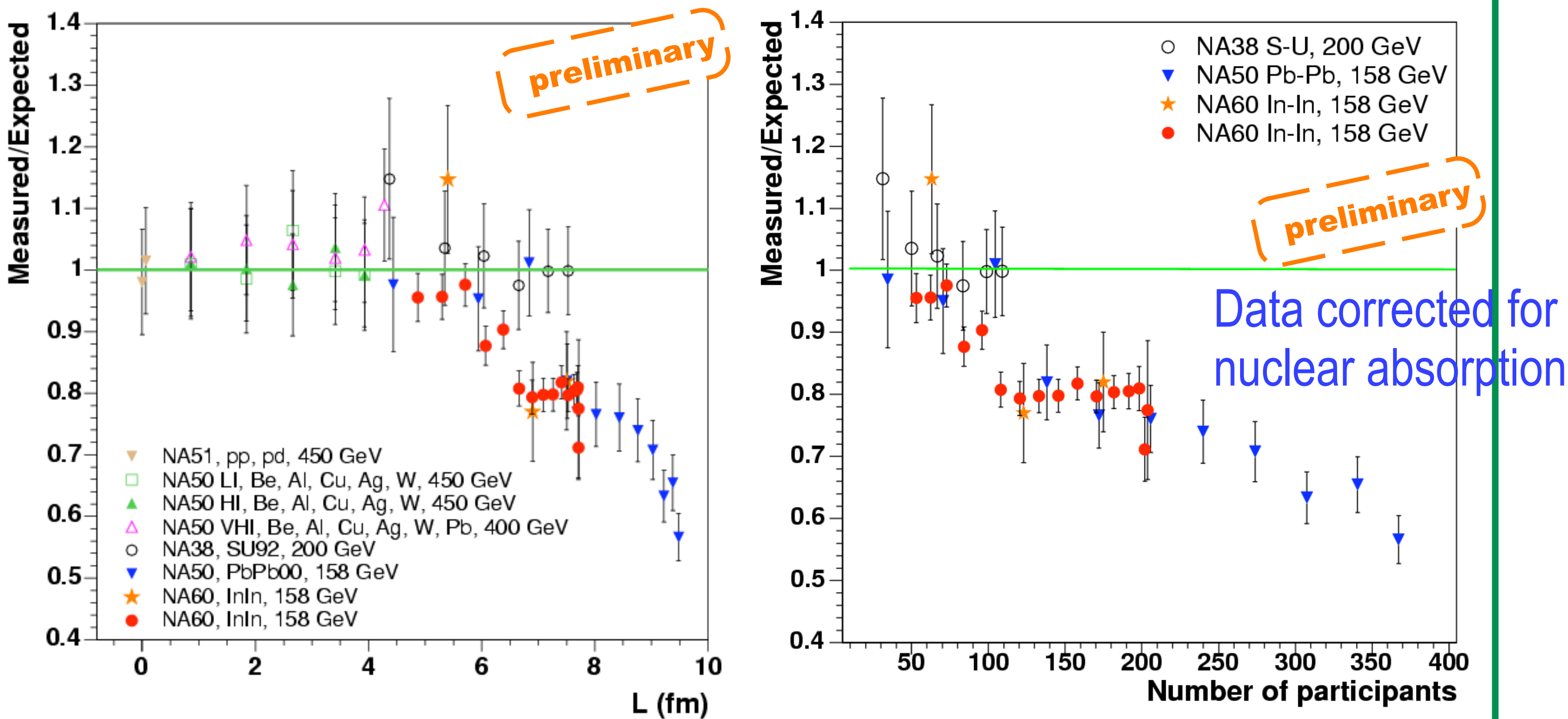


$$\frac{\partial R}{\partial L} = \frac{\partial R}{\partial l} \cdot \frac{1}{\partial L / \partial l} \rightarrow -\infty$$

✓The J/ψ is anomalously suppressed in indium-indium collisions
✓ The S-U, In-In and Pb-Pb data points *do not seem to overlap* as a function of L, the length of nuclear matter crossed by the (pre-resonant) J/ψ state

The increase of slope signals absorption in *l* *!!!*

In-In versus Pb-Pb: a second look



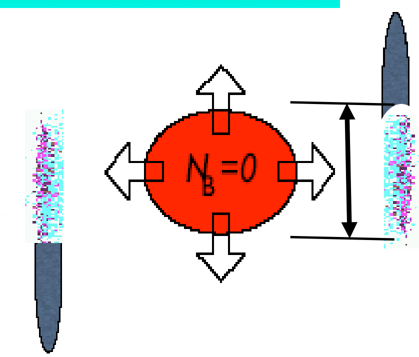
As a function of the number of participants, the J/ψ suppression pattern measured in In-In collisions by NA60 is in good agreement with the Pb-Pb pattern recently published by NA50

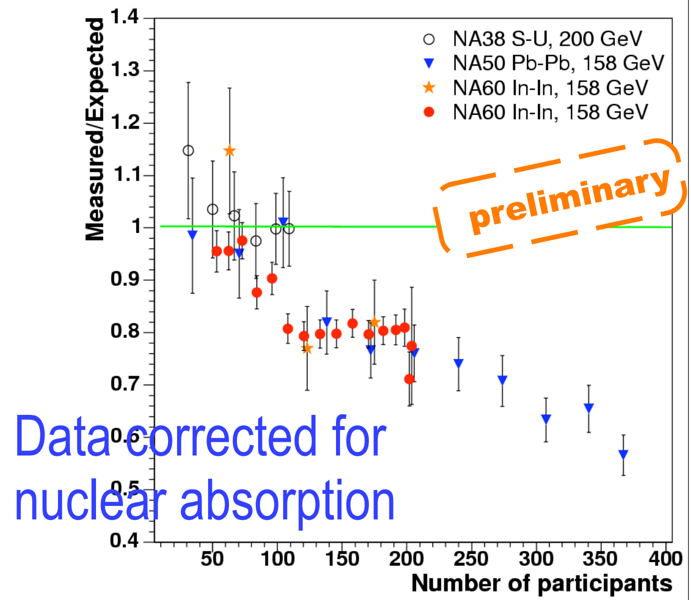
A more significant comparison requires Pb-Pb points with reduced error bars

(NA50 is working on an analysis method which does not use the DY yield as normalization)

Limitinge temperature and J/Ψ dissociation

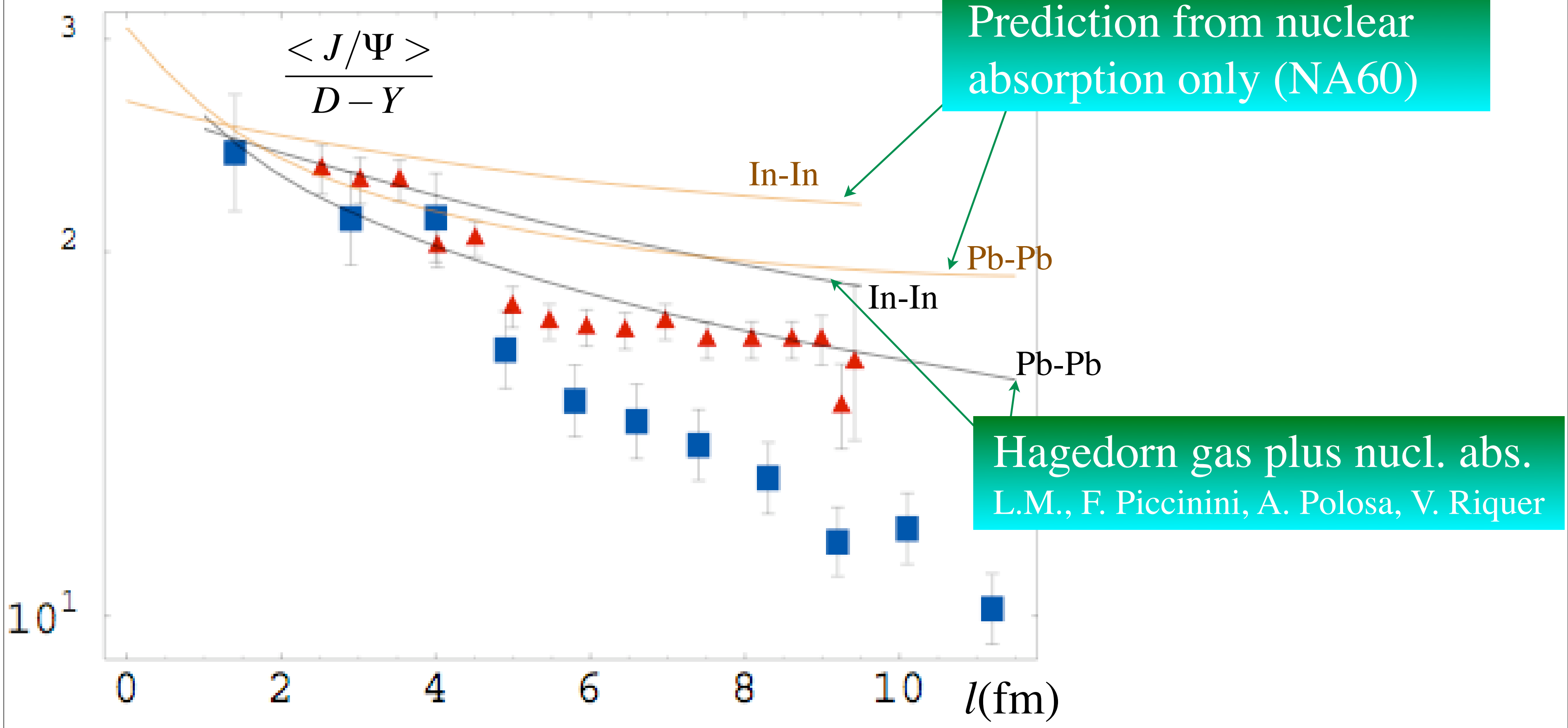
- The basic cross sections for π/ρ+ J/Ψ→open charm are large (few to 10 mb) and energy dependendent (thresholds);
- opacity increases strongly with the fireball temperature: we could account for a large absorption (but not a discontinuity) with correspondingly large T;
- A limiting temperature of 170-180 MeV is suggested by independent theoretical arguments and supported by the hadron spectrum;
- Limiting temperature implies, most likely, a limiting absorption: hadronic matter only cannot explain the observed opacity!



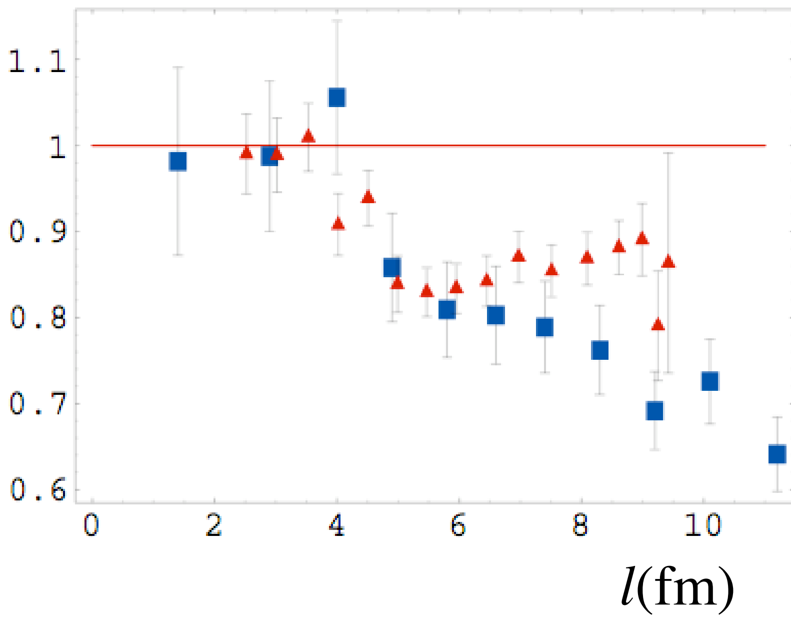


Including the new Indium NA60 data

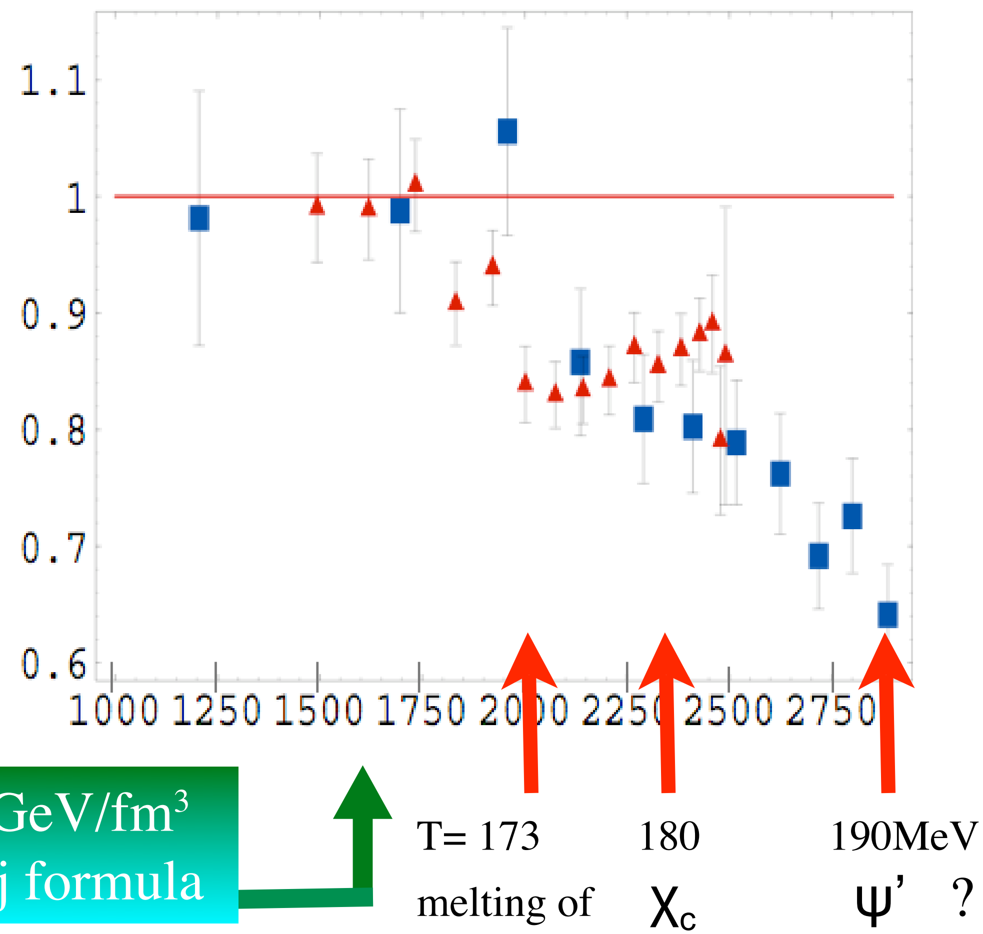
DATA:
- Pb-Pb, NA50(http://na50.web. cern .ch/NA50/
- In-In, NA60 (EPS05, Lisbon)



Observed/Expected vs. *l* ***shows clear discontinuity***



Observed/Expected vs. Energy density

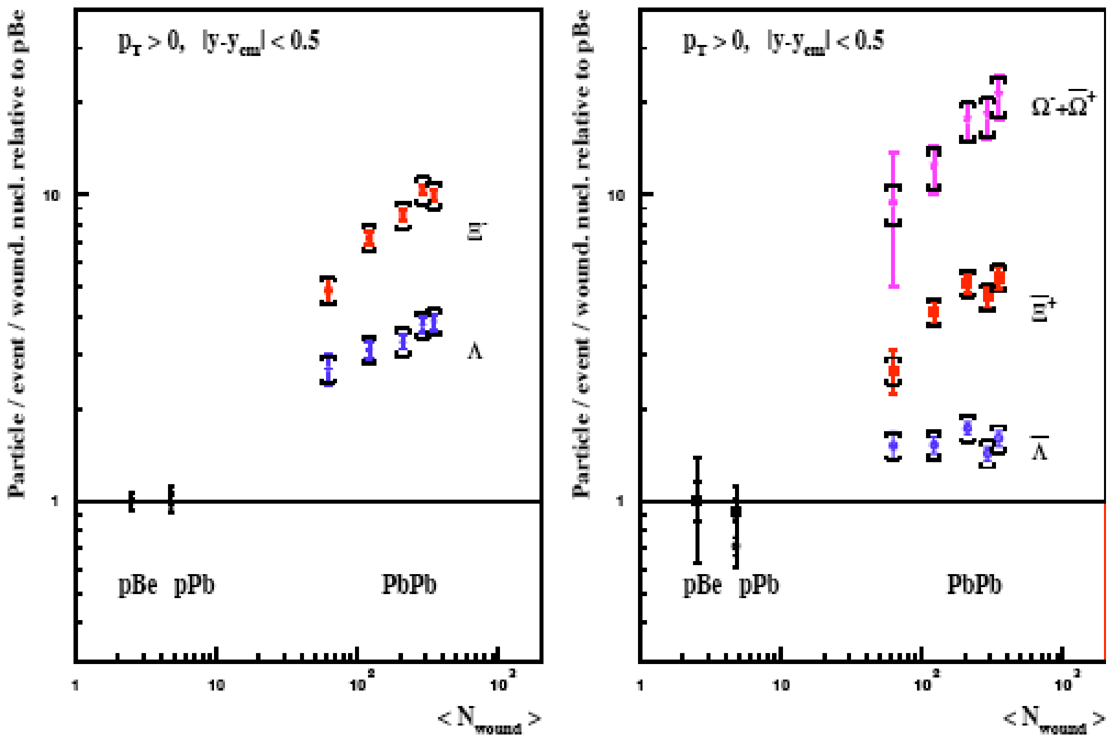


- Assume that *l*=4 corresponds to ≈ 2 GeV/fm^3
- Scale the energy density using the Bj formula

The Strangeness Enhancement @ SPS

NA57 Enhancement

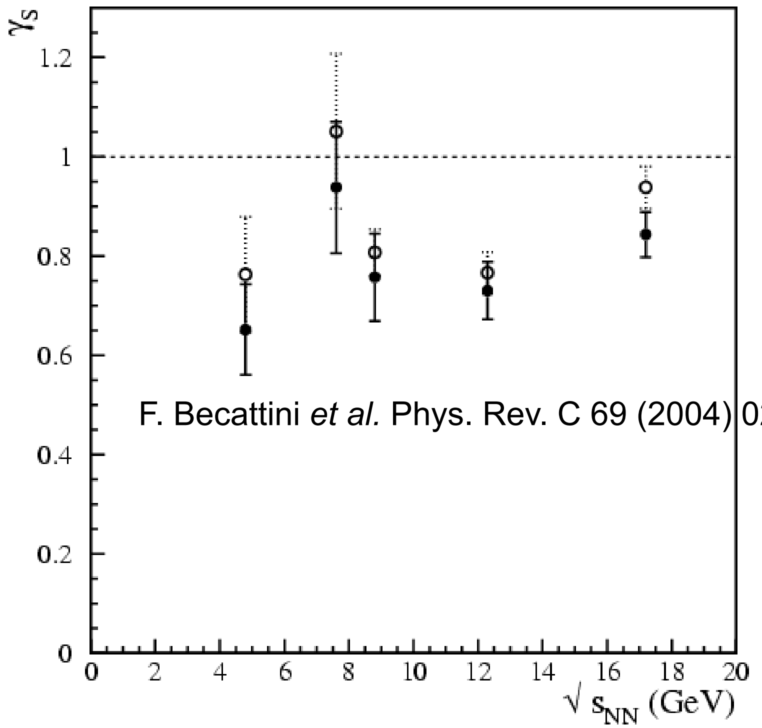
158 A·GeV Pb+Pb NA57



Michael C. Mitrovski NA57 - NA49 Workshop - CERN - 17.08.2004 6/12

Statistical abundances at chemical freeze-out

- Described by statistical distribution: $\rho_s(T) = \gamma_s^{n_S}\, e^{\frac{\vec{\mu}\cdot\vec{q}-E}{T}}$
-
- observed enhancement described by rising values of γ_s



F. Becattini *et al.* Phys. Rev. C 69 (2004) 024905

$\gamma_s \approx 1$ at RHIC
using midrapidity ratios

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

But....
what is it γ_s ?

About γ_S at SPS

L. Maiani: Concluding Remarks
ALICE-ITALIA, Catania, 12 Jan. 2005

- There are few strange quarks in the initial state, A+A;
- 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 strange quark mass, strange hadrons form from quark recombination: hence $\gamma_S \rightarrow 1$
- strangeness enhancement at SPS: is there a correlation of γ_S with centrality, i.e. with J/Ψ absorption?

PRL **94,** 052301 (2005) PHYSICAL REVIEW LETTERS week ending 11 FEBRUARY 2005

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

NA49 Collaboration

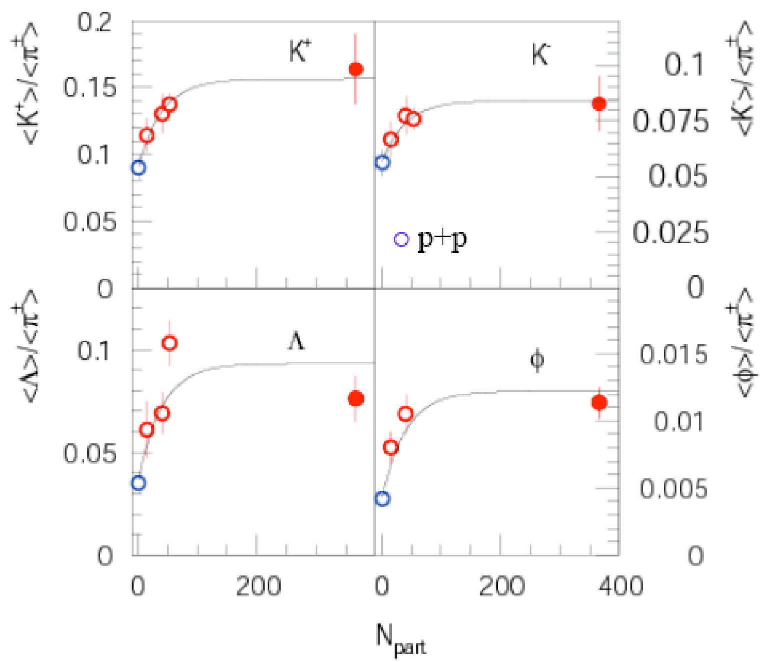
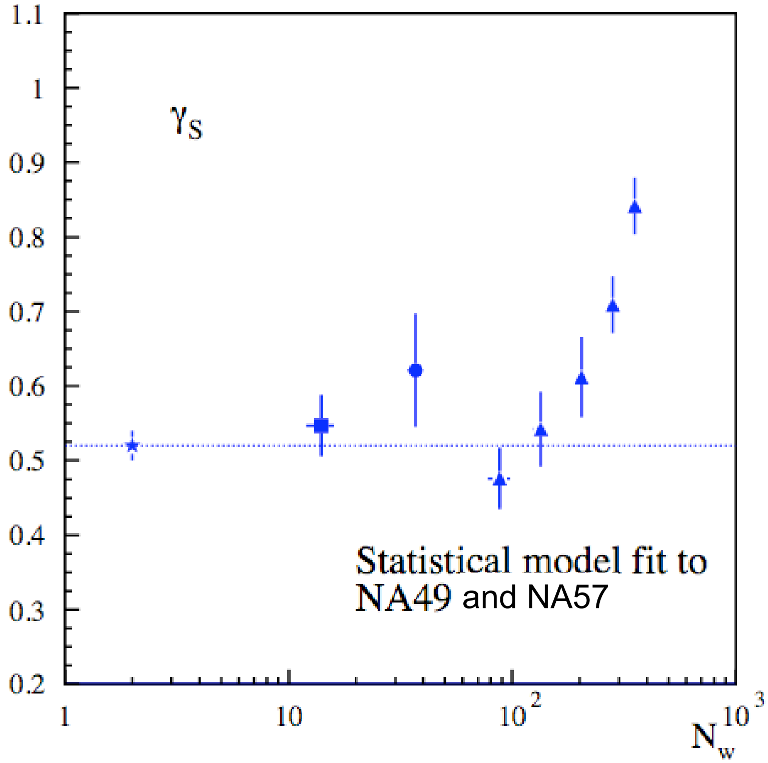


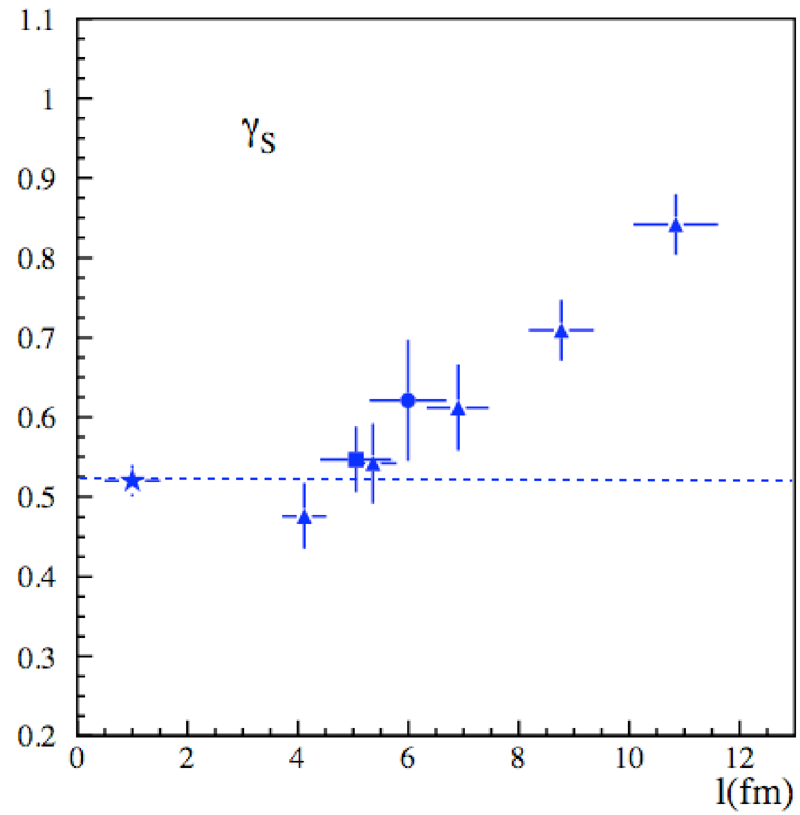
FIG. 3. Experimental ratios of $\langle K^+\rangle$, $\langle K^-\rangle$, $\langle\phi\rangle$, and $\langle\Lambda\rangle$ to $\langle\pi^\pm\rangle$ plotted as a function of system-size (▼ $p + p$; ● C + C and Si + Si; △ S + S; ■ Pb + Pb). Statistical errors are shown as error bars, systematic errors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

γ_s versus centrality

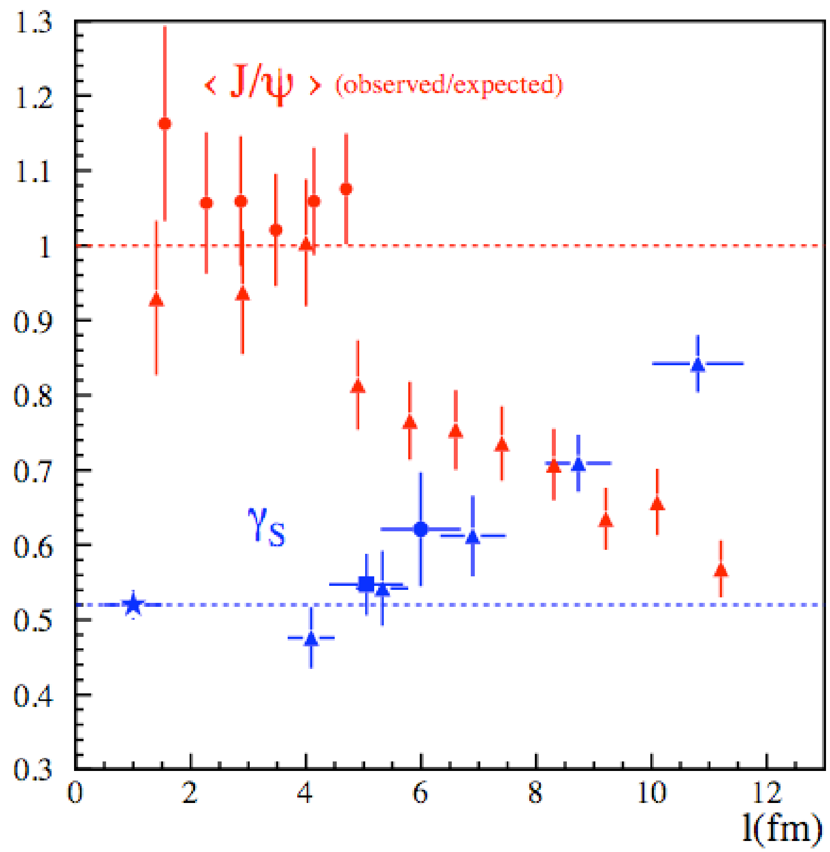
F. Becattini, L. Maiani, F. Piccinini,
A. Polosa, V. Riquer, *in preparation*



- ▲ Pb-Pb, NA49/57
- ● Si-Si, NA49
- ■ C-C, NA49
- ☆ P-P



J/Ψ suppression and Strangeness Enhancement are correlated !



F. Becattini, L. Maiani, F. Piccinini, A. Polosa, V. Riquer, *in preparation*

J/Ψ:
- ▲ Pb-Pb, NA50
- ● S-U, NA50

γ_S:
- ▲ Pb-Pb, NA??
- ● Si-Si, NA
- ■ C-C, NA
- ☆ P-P

A strong indication for the formation of a new phase
The SPS is just at the onset of deconfinement !!

2. A glimpse at RHIC results

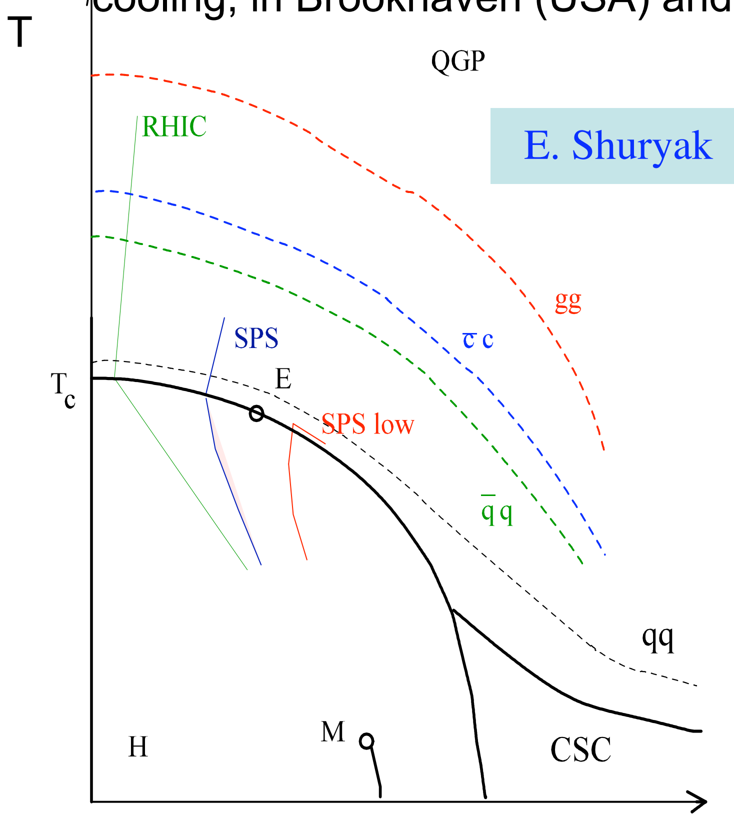
Main findings at RHIC

- Partciles are produced from matter which seems to be well equilibrated (by the time it is back in hadronic phase), N1/N2 =exp(-(M_1-M_2)/T)
- Very robust collective flows were found, indicating very strongly coupled Quark-Gluon Plasma (sQGP)
- Strong quenching of large pt jets: they do not fly away freely but are mostly (up to 90%)

absorbed by the matter. The deposited energy seem To go into hydrodynamical motion (conical flow)

The map: the QCD Phase Diagram

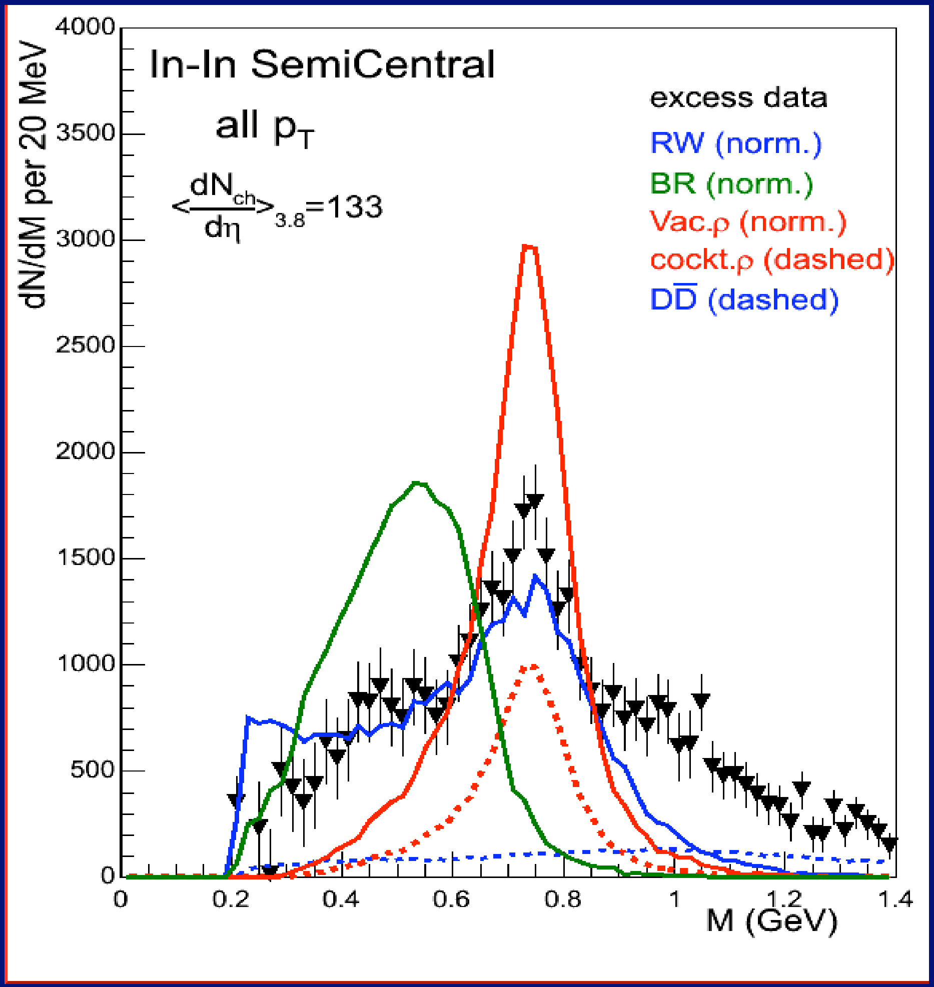
The lines marked RHIC and SPS show the paths matter makes while cooling, in Brookhaven (USA) and CERN (Switzerland)



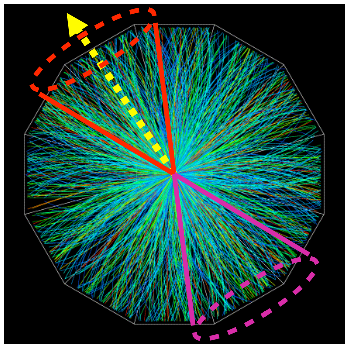
Chemical potential
mu

- a strongly interacting quark-gluon liquid !
- coexisting with the most bound hadrons (ρ, ω, ϕ, J/Psi)
- may there be color non singlet as well (Shuryak)???
- SPS can still be useful !

Comparison of data to RW, BR and Vacuum ρ



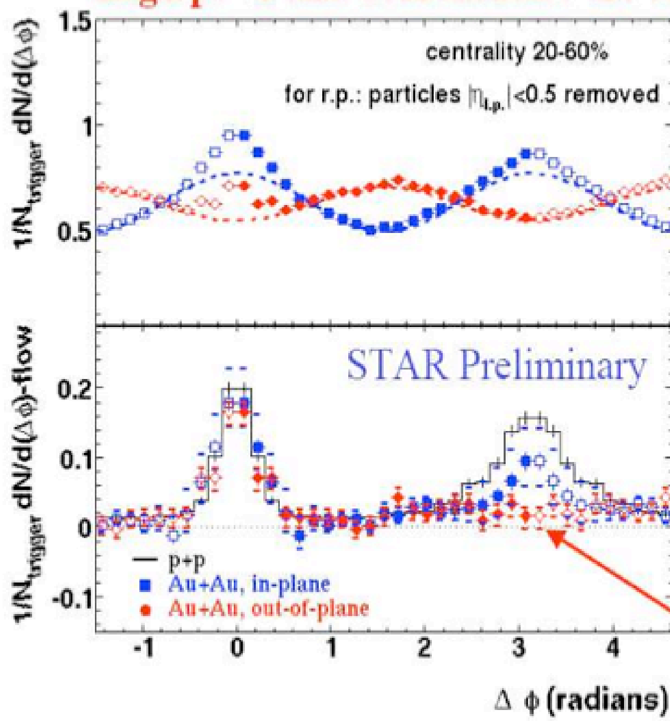
Data and model predictions as shown (propagated through NA60) roughly represent the respective spectral functions, averaged over space-time and momenta.

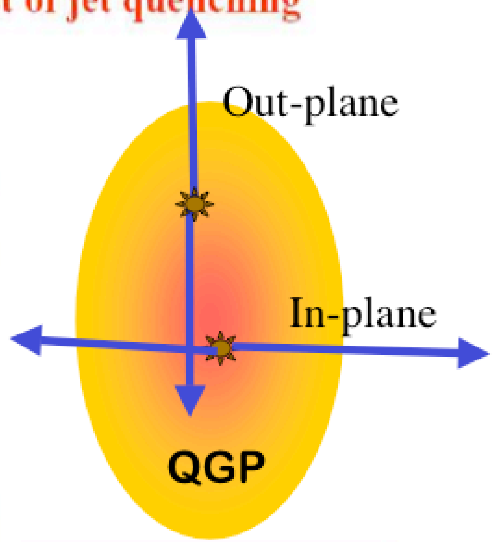


K. Filimonov: DNP 10.31.03

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

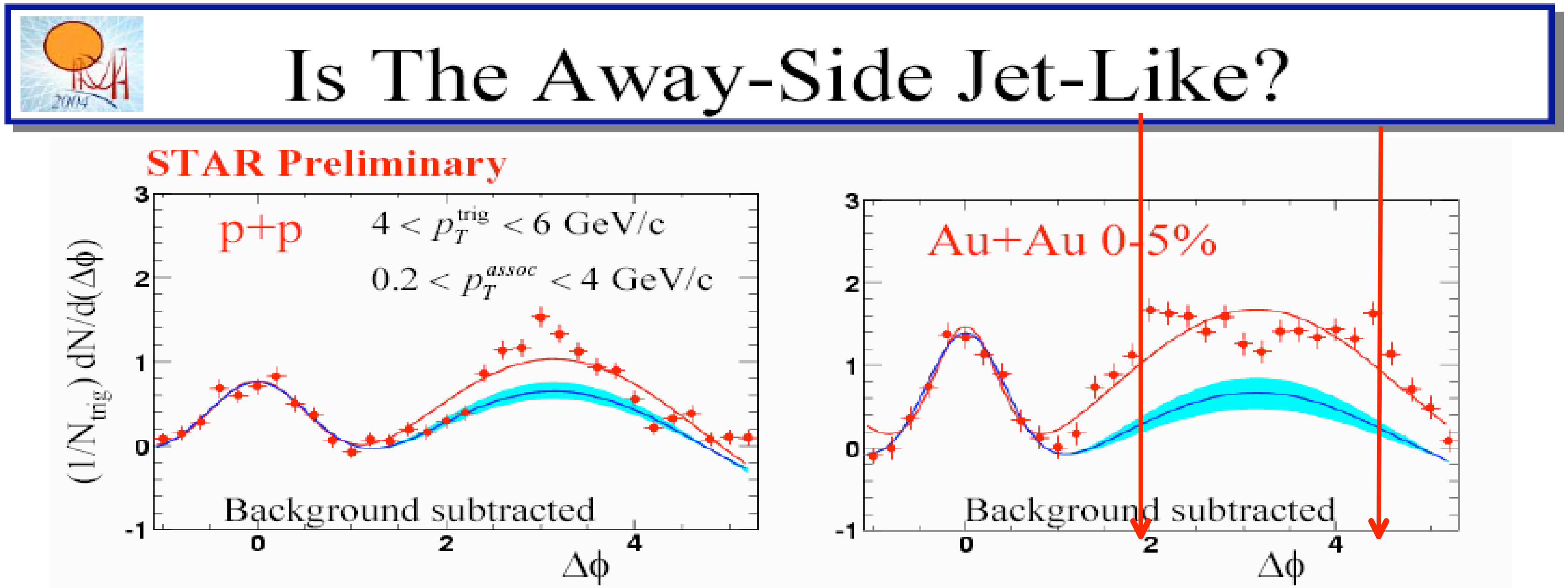
A.Tang: BNL 11.18.03

13

Is such a sonic boom already observed?

Mean Cs=.33 time average over 3 stages=>

flow of matter normal to the Mach cone seems to be observed! See data from STAR,



Away-side looks jet-like in p+p, not central Au+Au!

3. Conclusions

@ SPS

- All indications are that deconfinement is seen @SPS
- strangeness enhancement and J/Ψ suppression are correlated (γ_S. vs centrality) !!
- SPS offers the unique possibility to study precisely the onset of deconfinement....
- to be considered in long term planning of the SPS!

@ RHIC

- Deconfined phase is showing unexpected properties
- 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: strongly interacting Quarks and Gluons?
- Which excitations populate the QG Liquid?

Useful probes @ LHC

- initial state quanta:
  - hard jets
  - hard, heavy quarks (what about top?)
  - Higgs
- bulk properties of QGP:
  - jet tomography
  - collective motion, hydrodynamical flow..
  - quarkonia will form from recombination: enhancement!

big surprises are possible!