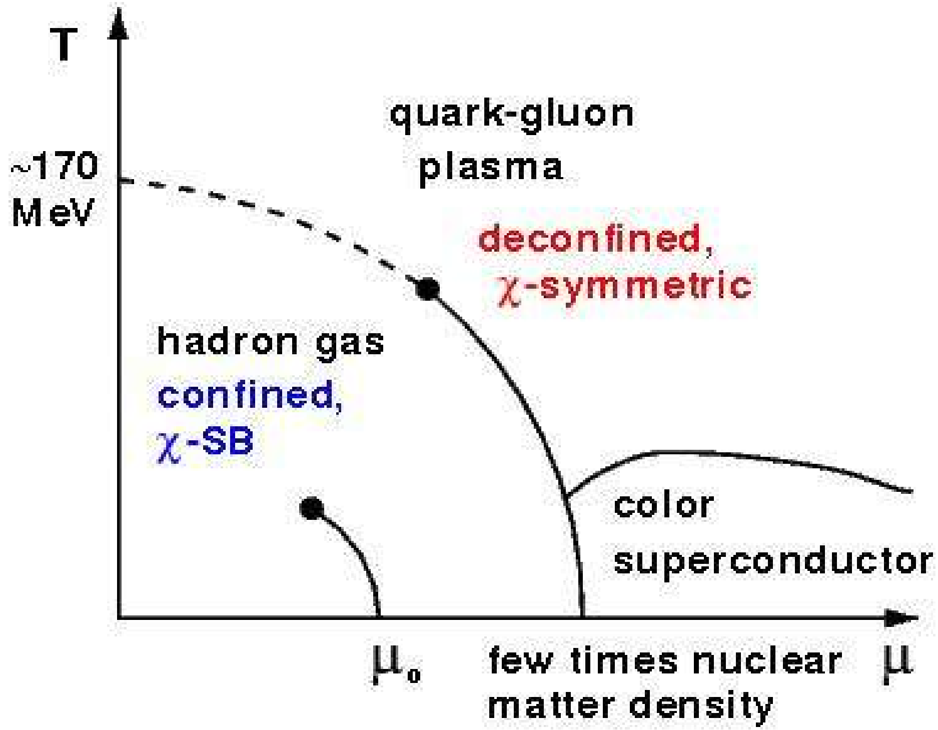
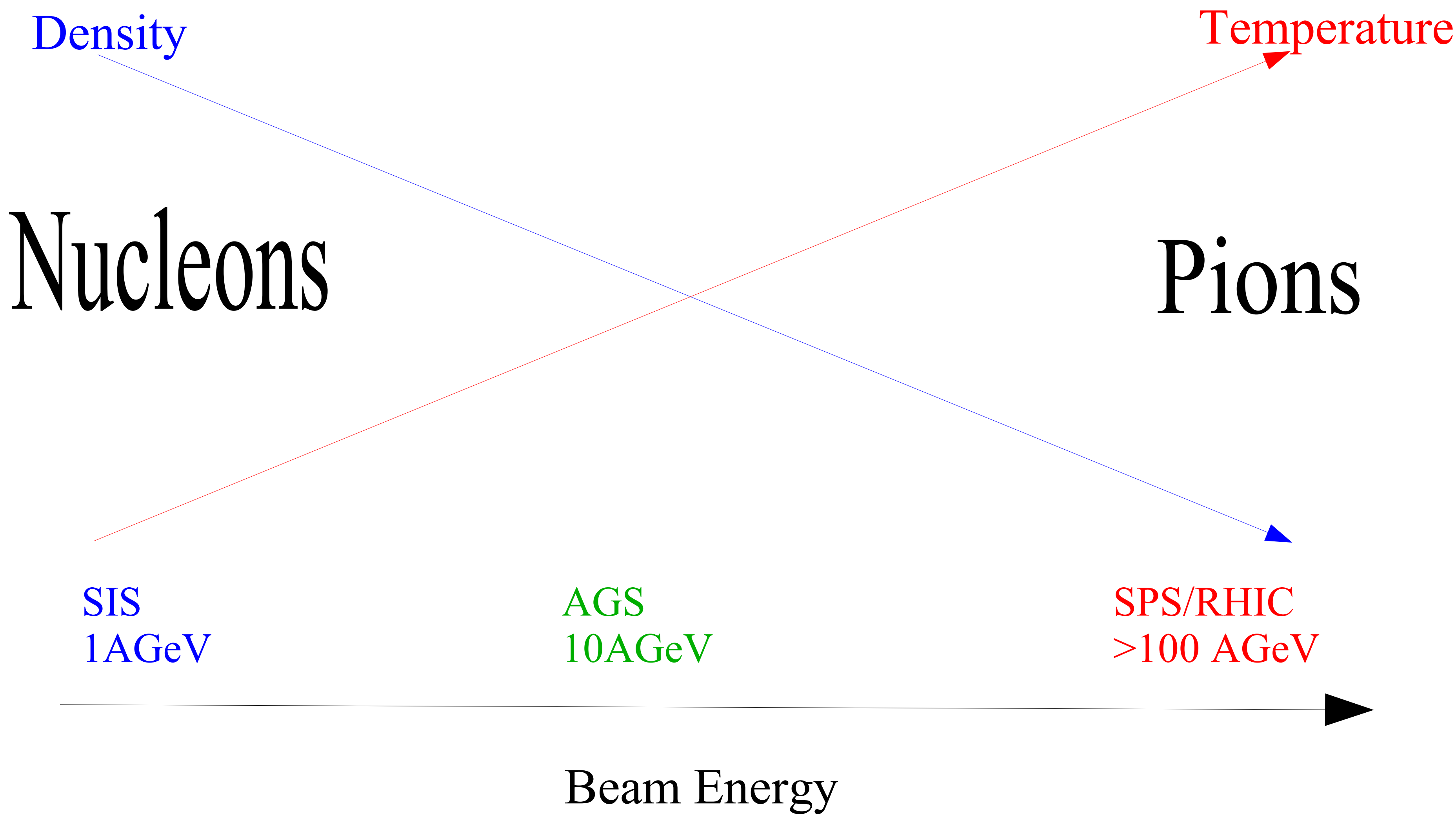
Equilibrium and Fluctuations

- Equilibrium in HI collisions ?
- Can fluctuations/correlations help?
- Strangeness (charm) as a probe of equilibrium
- Some historical remarks....
- Conclusions

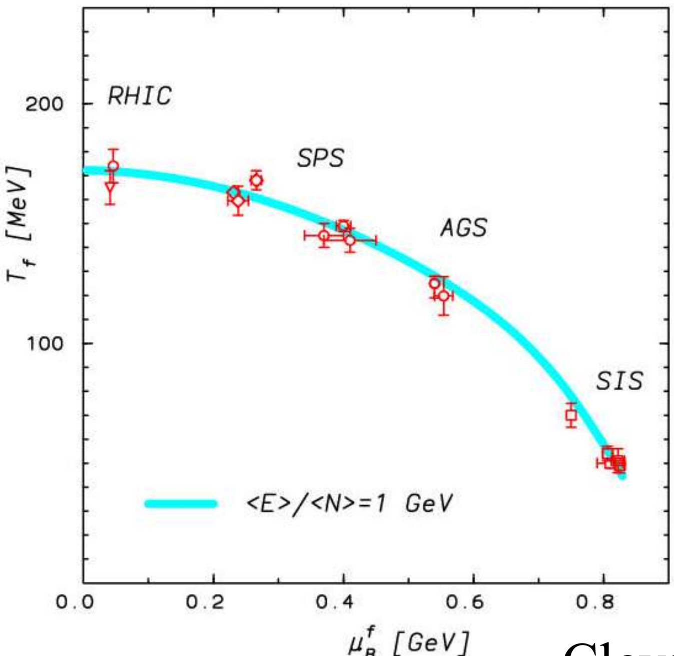
The holy quail



The different energies



Is it really all that different?



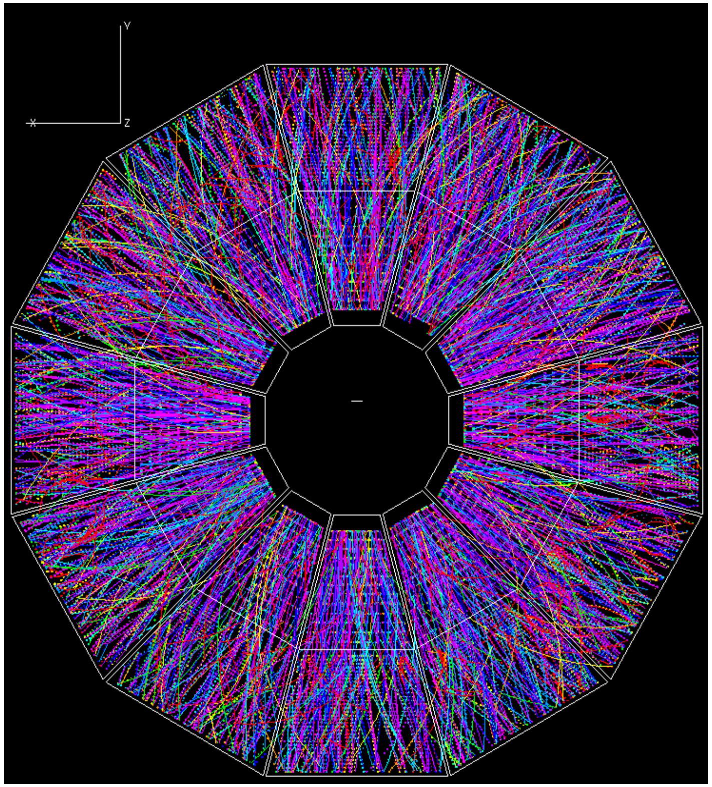
Cleymans et al.

In the statistical model, we simply have different Temperature and chemical potential

Do we have equilibrium?

Have we created Matter?

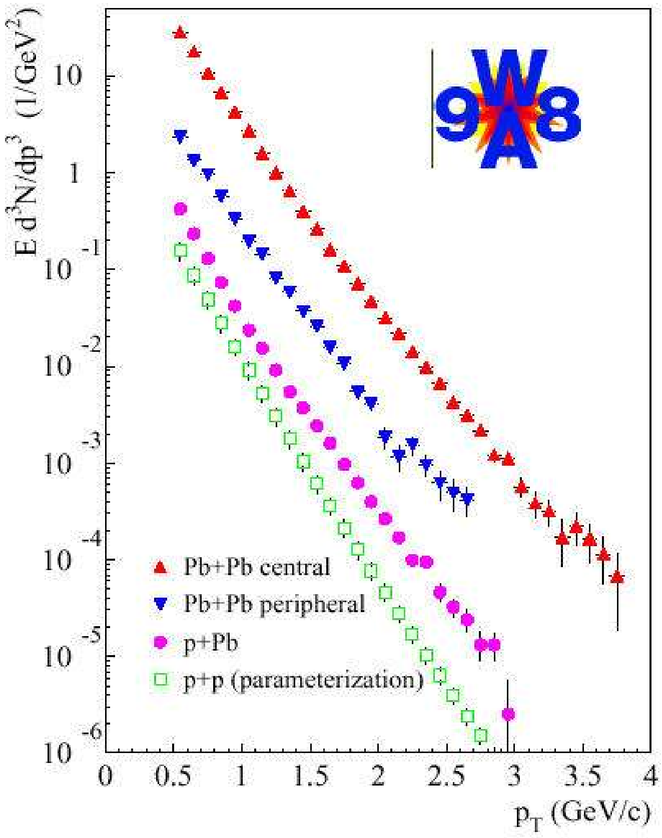
Statistical approach



Au+Au

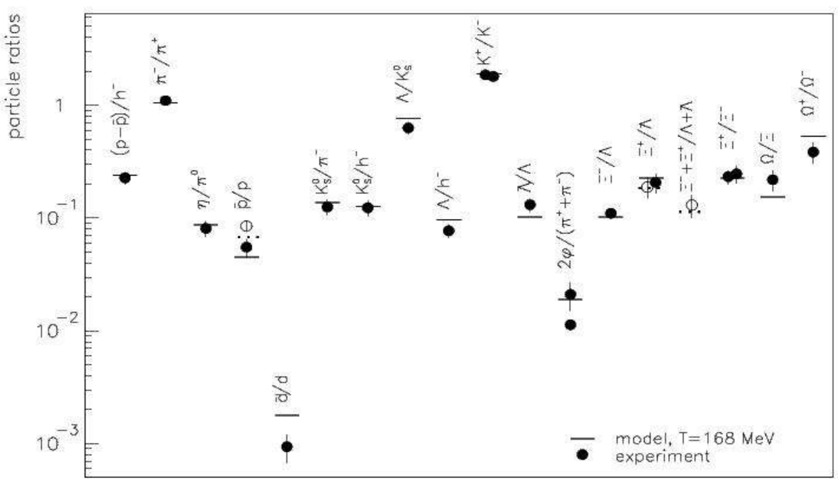
(STAR)

Particle Spectra

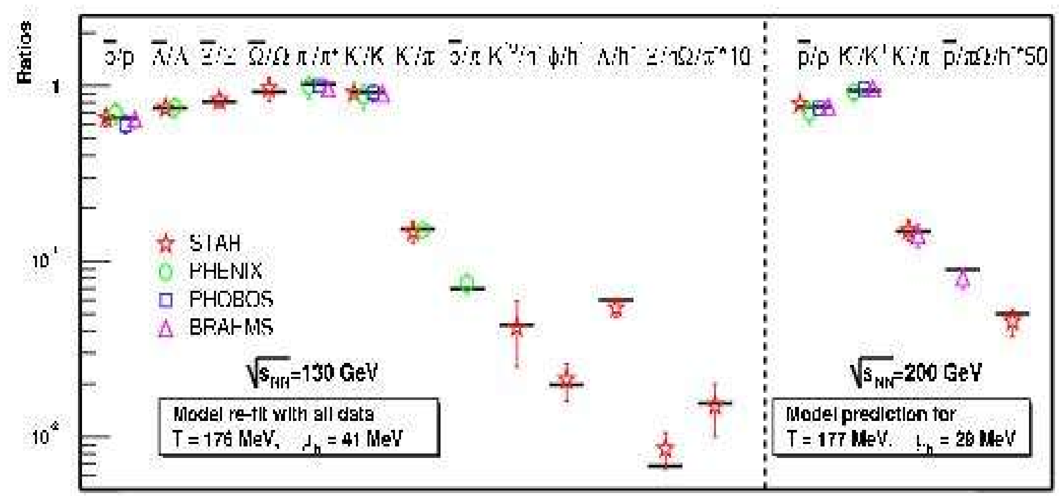


Thermal models work (reproduce even strangeness)

CERN SPS

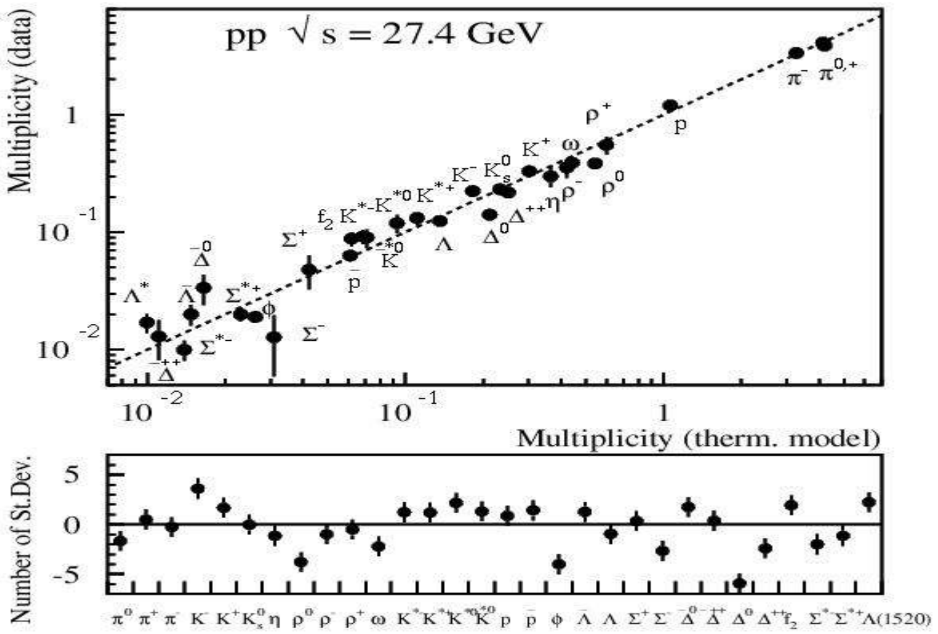


RHIC



$$\gamma_s = 1$$

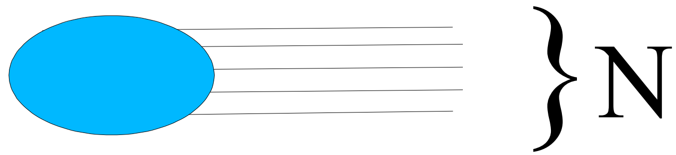
Who has ordered that??



Proton Proton

also: e^+e^-

Phase Space Dominance



$$\sigma \sim \int \left(\prod d^3 \frac{p_i}{E_i} \right) \; |M(E;\, E_1, \ldots, E_N)| \;\; \delta(E - \sum_{i=1} E_i)\, \delta^3(\vec{p} - \sum_i \vec{p}$$

Phase space dominance:

$$\sigma \sim \frac{1}{V^N} \left\langle \frac{|M|^2}{\prod_i E_i} \right\rangle \Phi\left(E;\, E_1, \ldots, E_n\right)$$

$$\Phi\left(E;\, E_1, \ldots, E_n\right) = V^N \int d^3 p_i \;\; \delta(E - \sum_{i=1} E_i)\; \delta^3(\vec{p} - \sum_i \vec{p}_i)$$

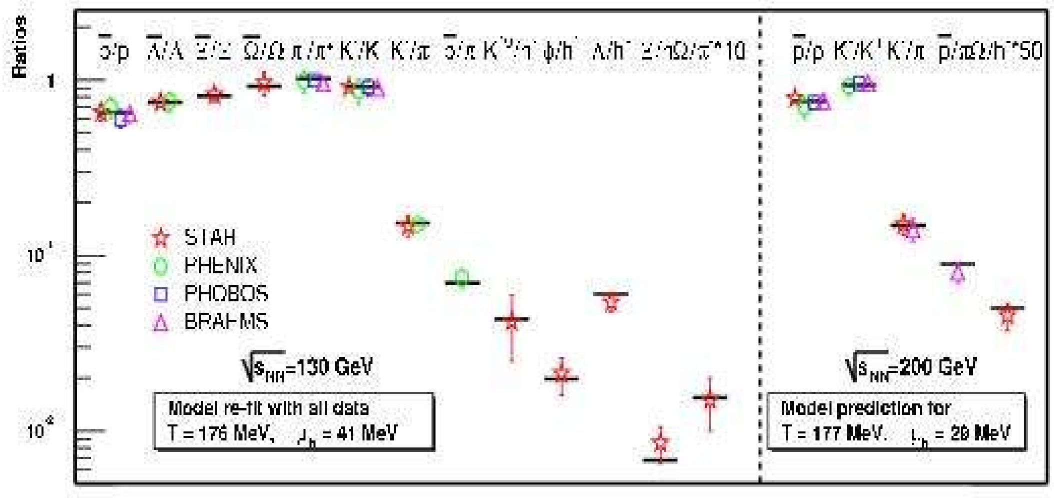
Micro canonic phase space volume

→ statistical Physics

N>> 1 → canonic or grand canonic approximation

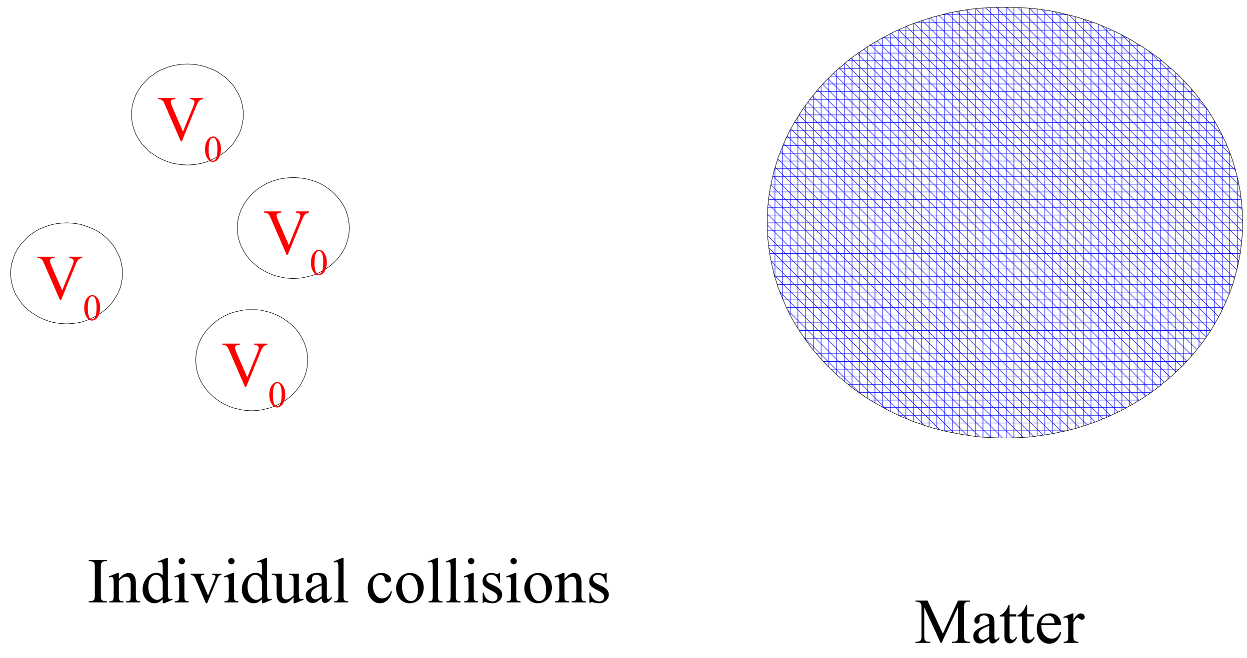
Do we have Matter?

Of Course! ?



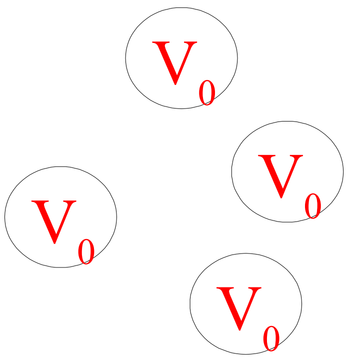
Ratios
STAR
PHENIX
PHOBOS
BRAHMS
Model re-fit with all data
Model prediction for

Matter or not?



Strangeness (Charm) might help

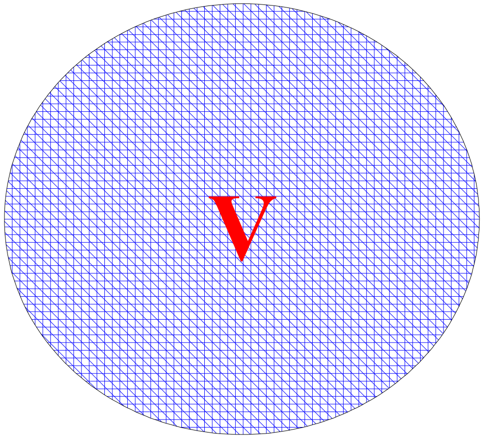
Individual collisions



Strangeness conservation important

$N_s \sim V_0^2$

Matter

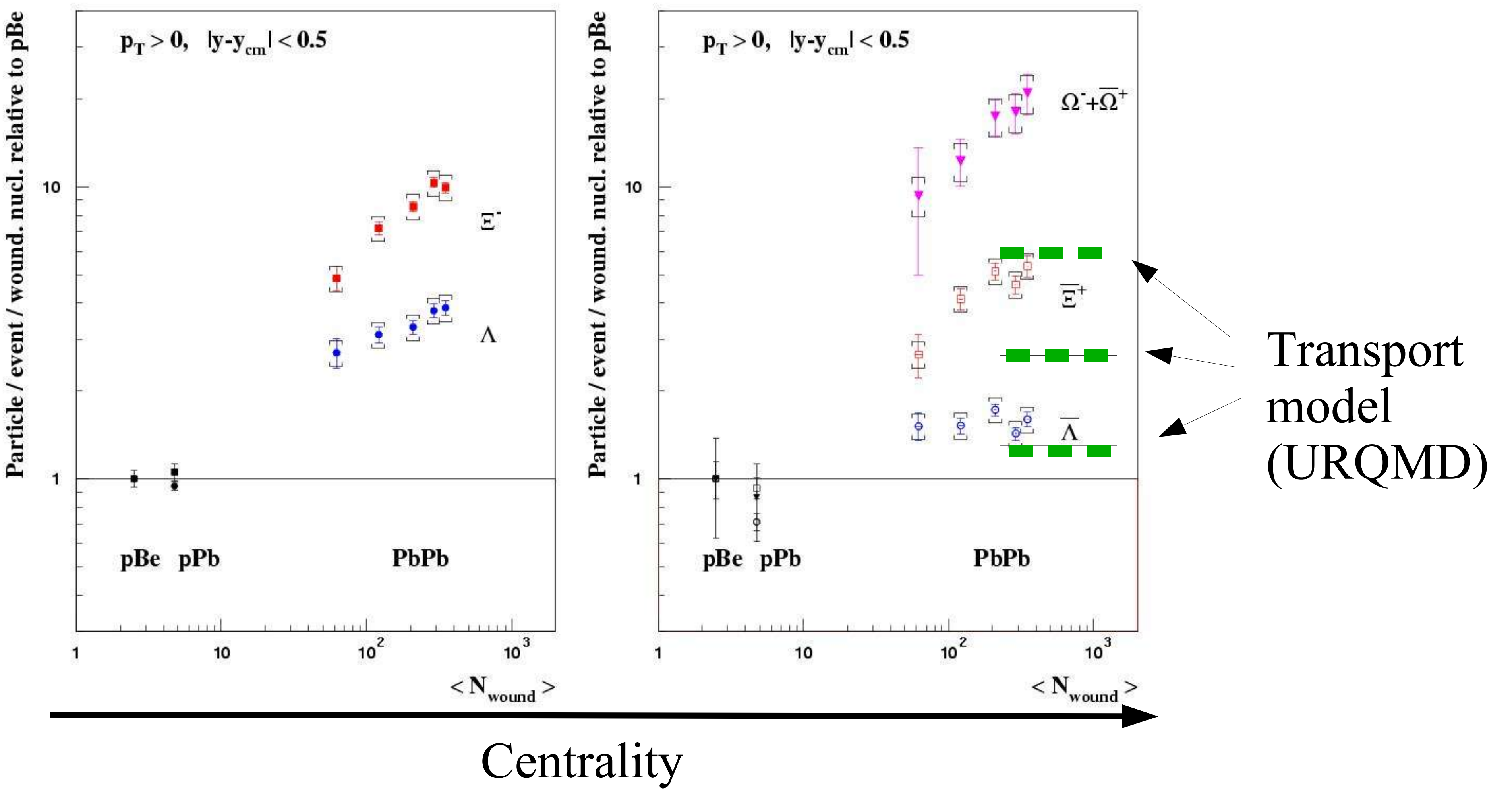


Strangeness conservation irrelevant

$N_s \sim V$

Strangeness enhancement/suppression?

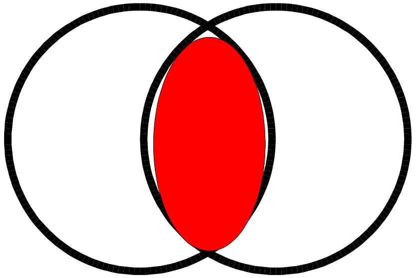
NA57



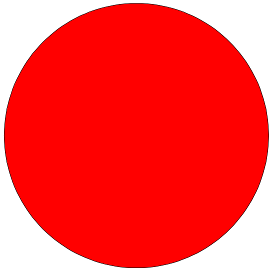
One simple explanation

Canonical “suppression” (Redlich et al)

Explicit Strangeness conservation relevant for small systems

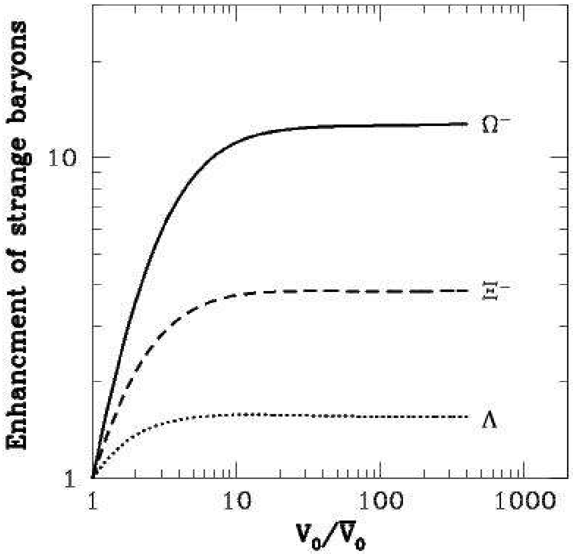


peripheral

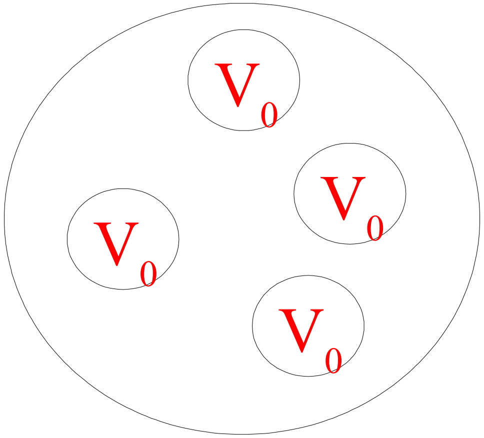


central

Redlich et al.



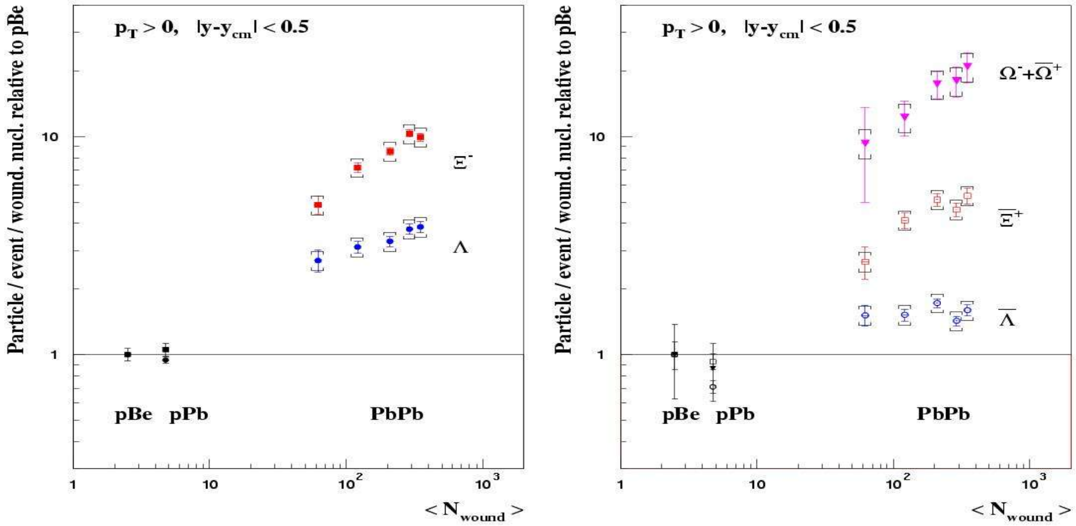
Strangeness equilibrium at SPS ?

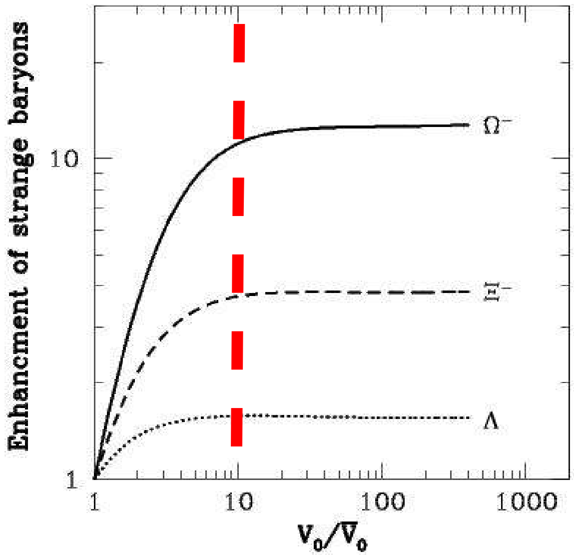


Canonical “suppression”
i.e. for small system strangeness conservation becomes relevant

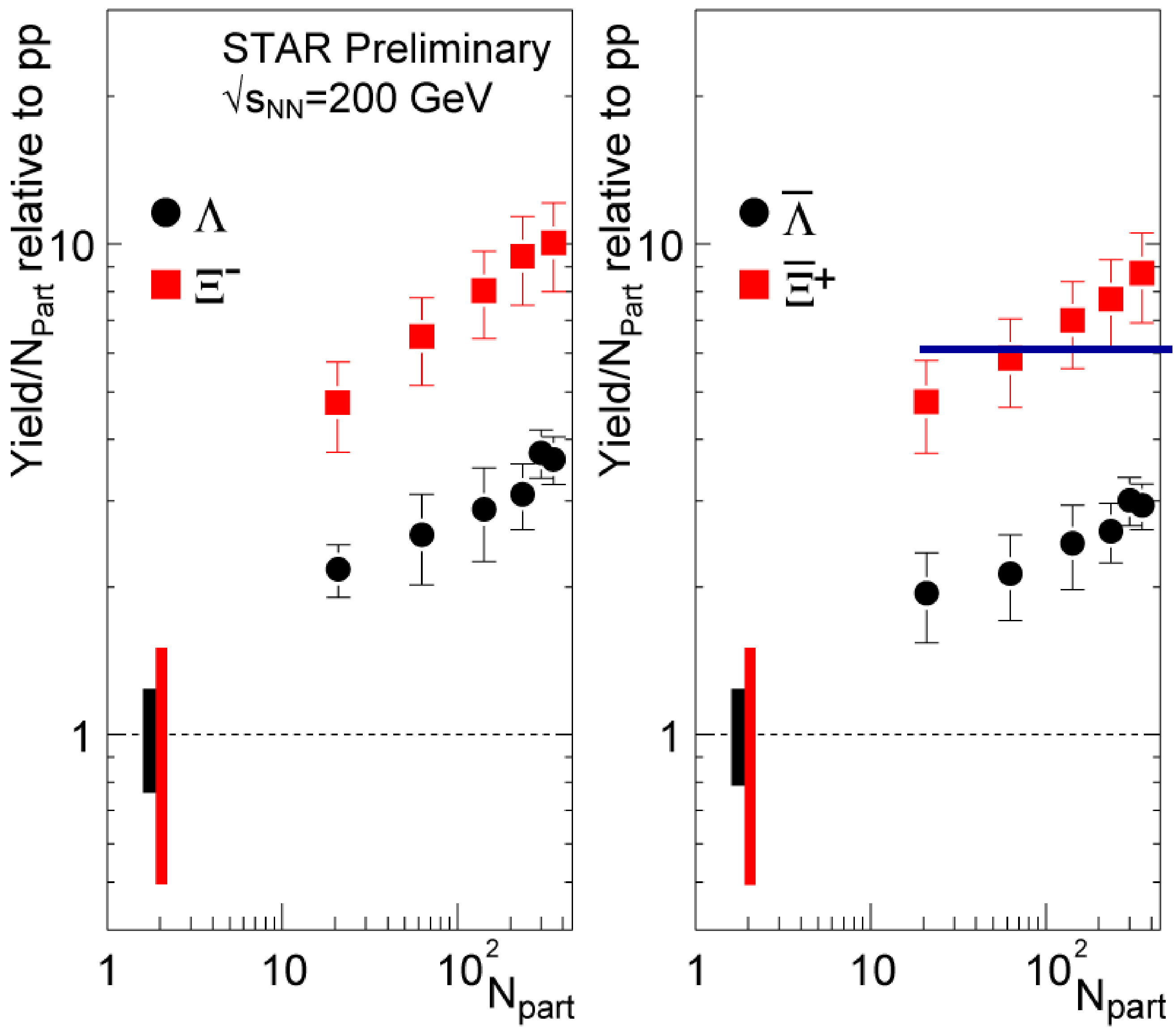
Redlich et al.

NA57





And at RHIC? Same story!

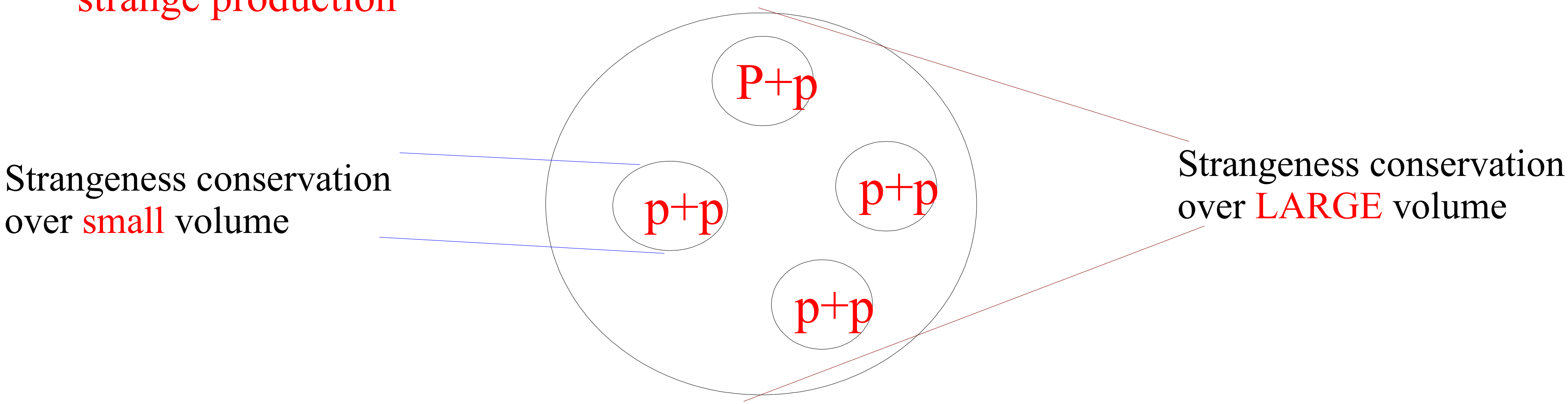


Do we have Matter?

$$\Phi_{A+A} \gg \Phi_{p+p}$$

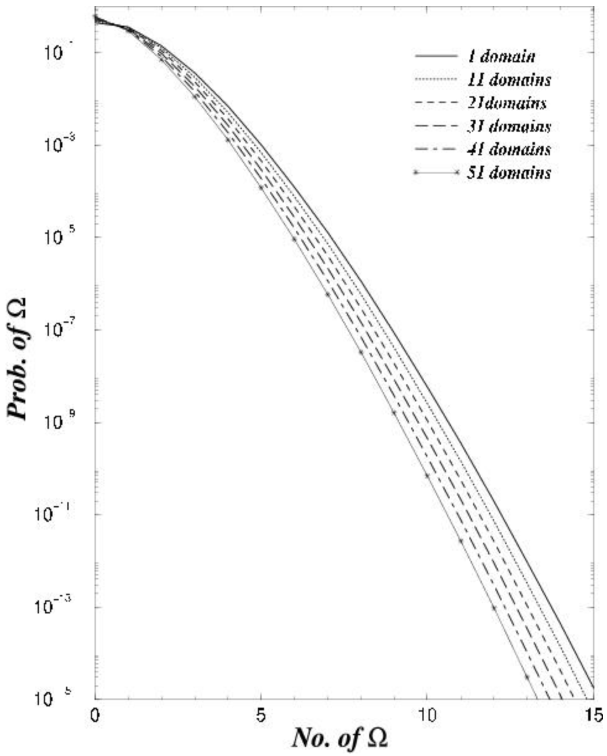
Look at observables which are strongly phase space **suppressed** in p+p

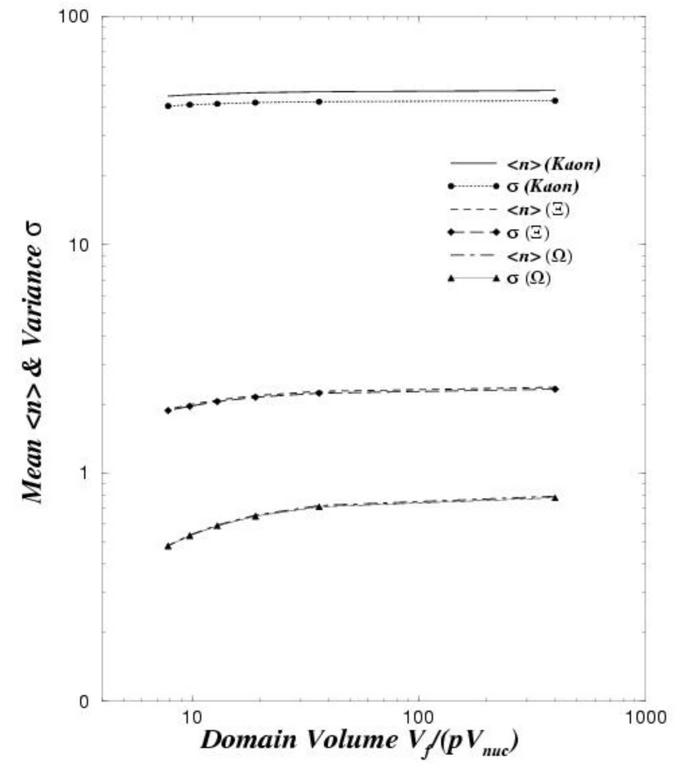
Example: Omega production, Open charm should be even more sensitive. Also multi strange production



Strangeness equilibrium at RHIC ?

(A. Majumder)

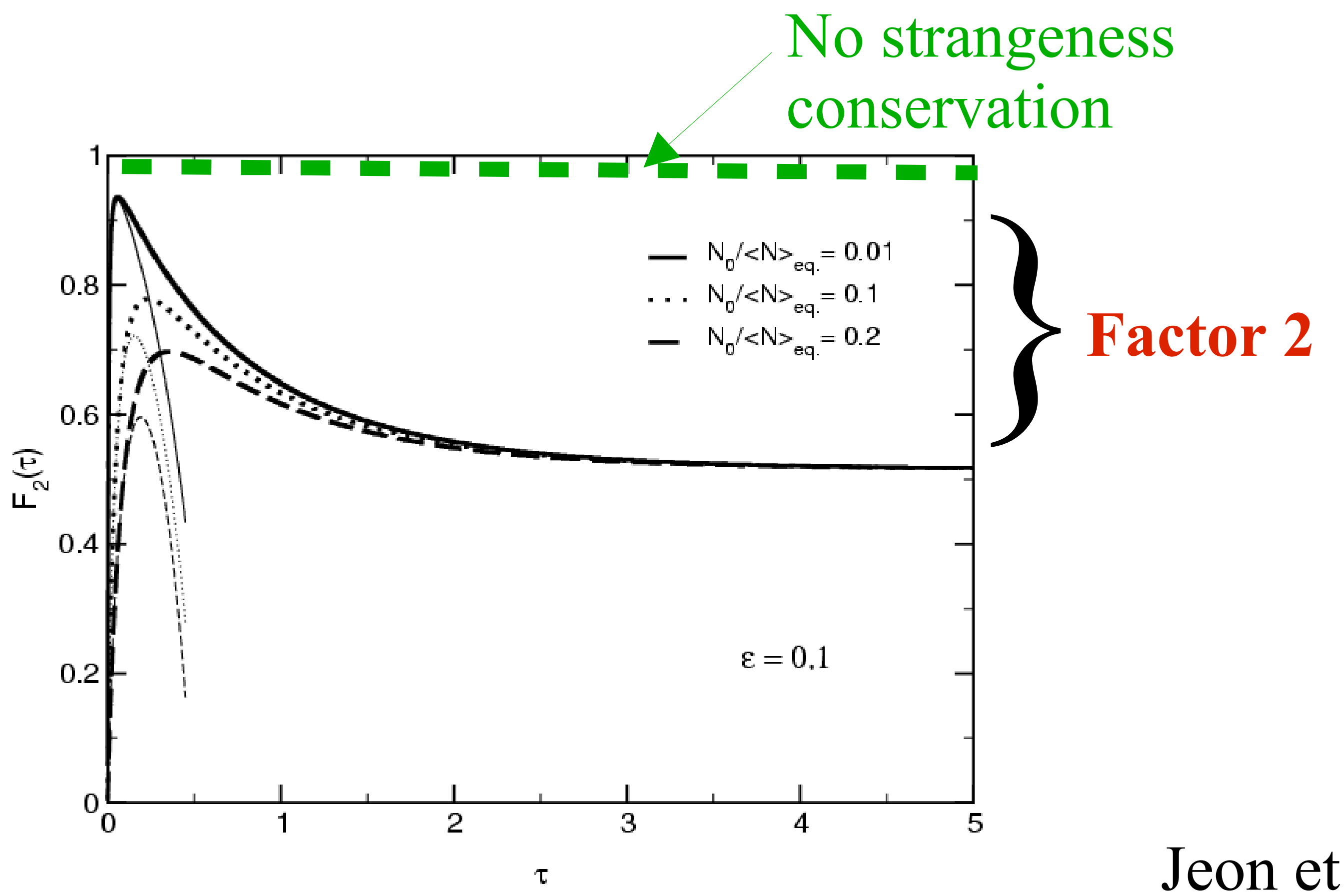




Need to measure 5 OMEGAS per event!!!!

Equilibrium at SIS-energies

$$F_2 = \frac{\langle N(N-1)\rangle}{\langle N\rangle^2}$$

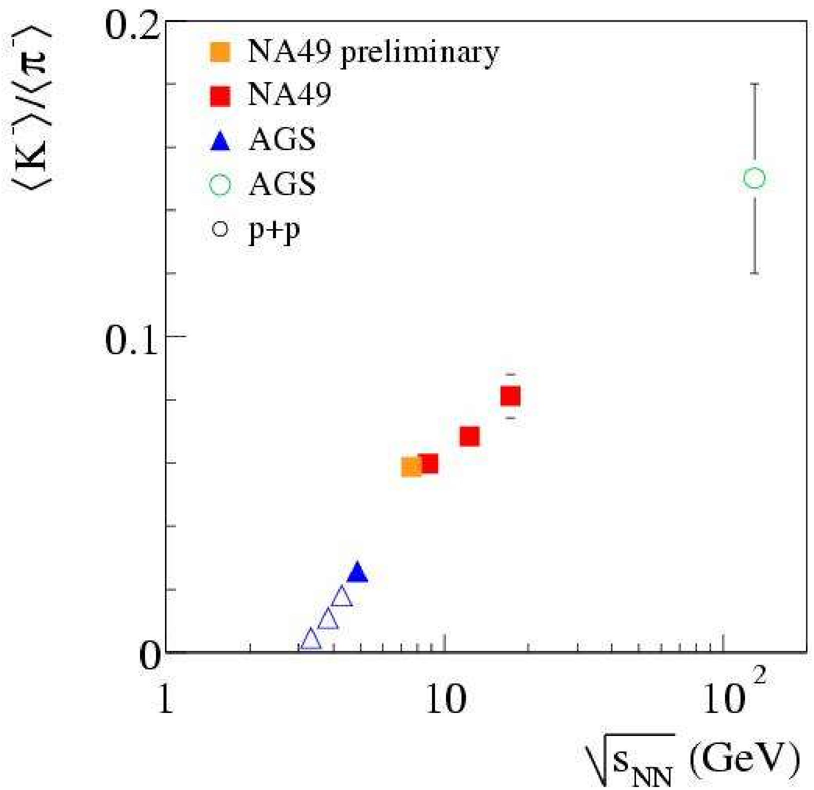


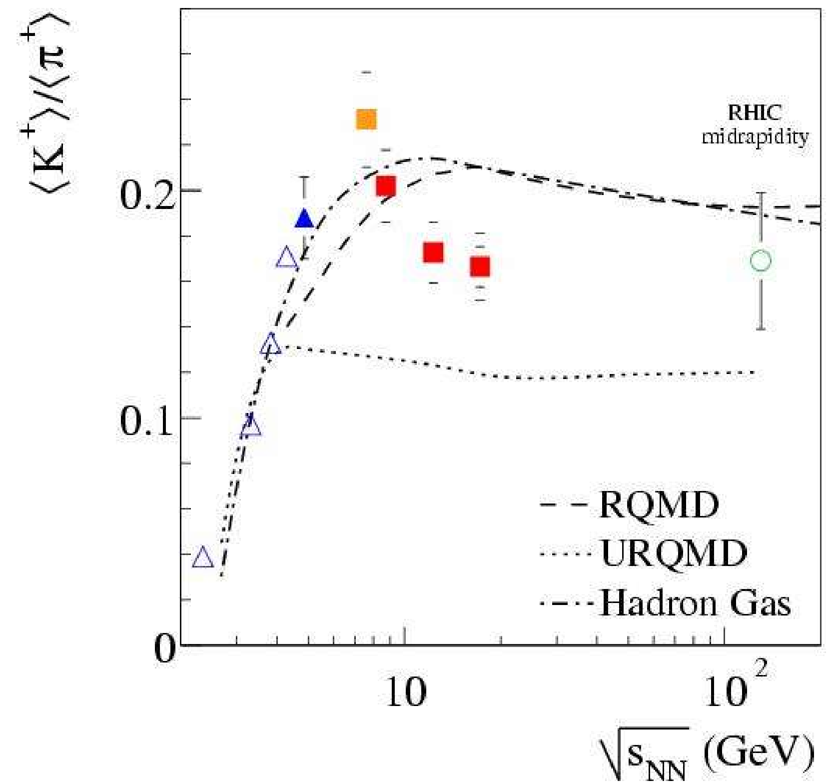
Jeon et al, NPA 2001

Even more strange stuff

NA49 has measured the
excitation function for
kaon production form (20) 30 -158 AGEV

Energy Dependence : Total K/π Ratios

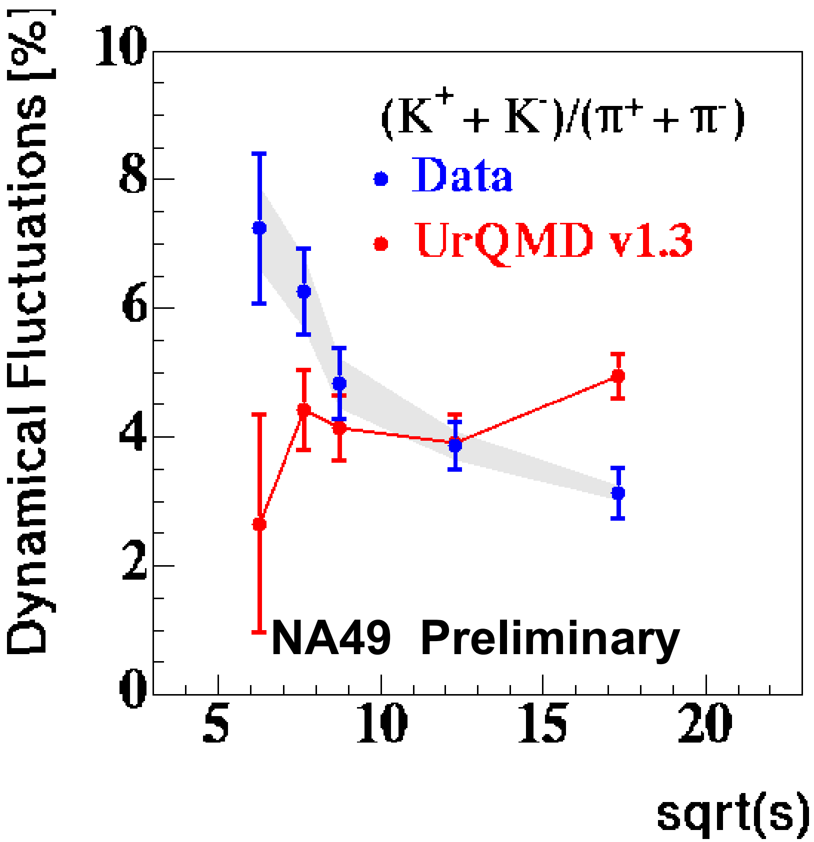


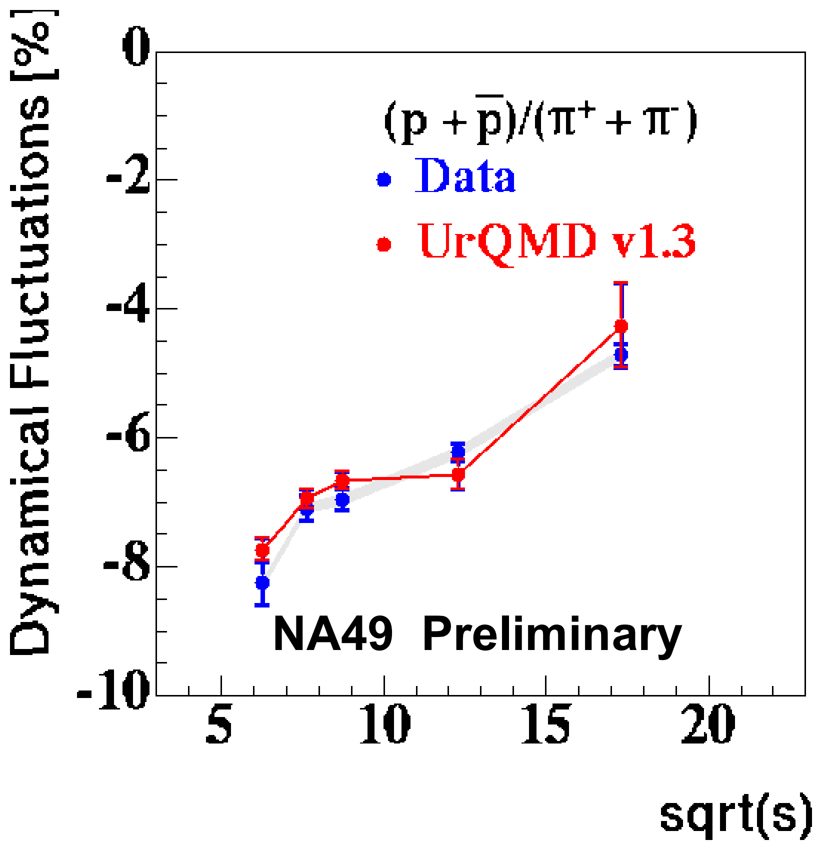


Sharp maximum for K^+/π^+ !

Indication for kink structure also for K^-/π^- ?

Fluctuations (NA49, QM2004)

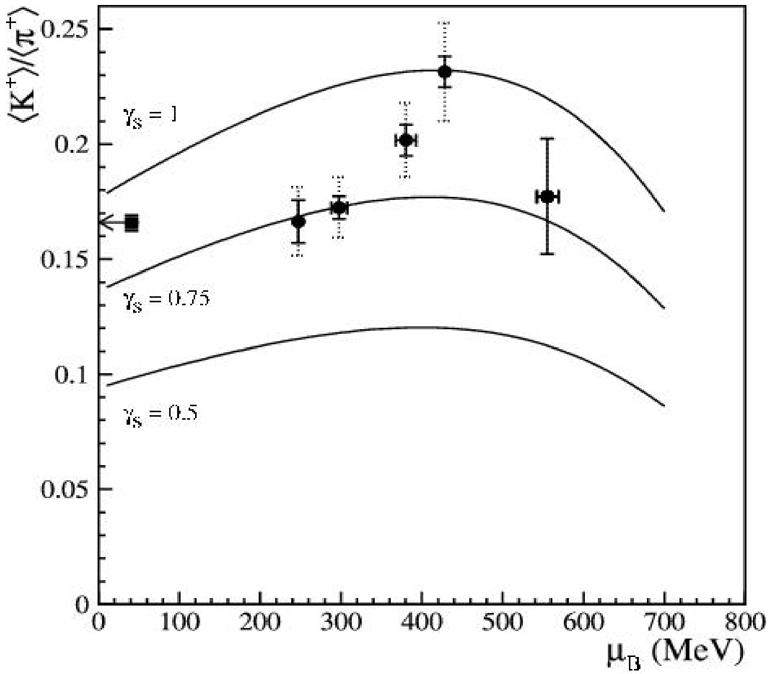




- K/π fluctuations increase towards lower beam energy
  - Significant enhancement over hadronic cascade model
- p/π fluctuations are negative
  - indicates a strong contribution from resonance decays

Thermal model

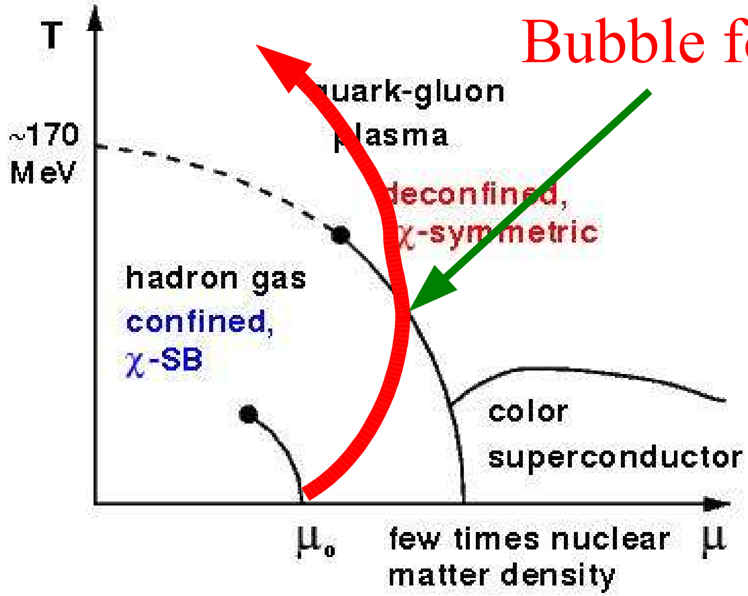
(Becattini et al)



Thermal model cannot describe data!
Here jump in γ_s is needed

- Isospin effect? (A. Rybicki)
  - Does not explain magnitude of K/π
- Long thermalization time?
  - Fluctuations should be Poisson!

What else?



Bubble formation: Spinodial instability (J. Randrup)
or standard a la Landau

Consequence: strangeness enhancement (A. Majumder)

Enhancement through bubbles

S_1 S_2 S_3 S_4 S_5

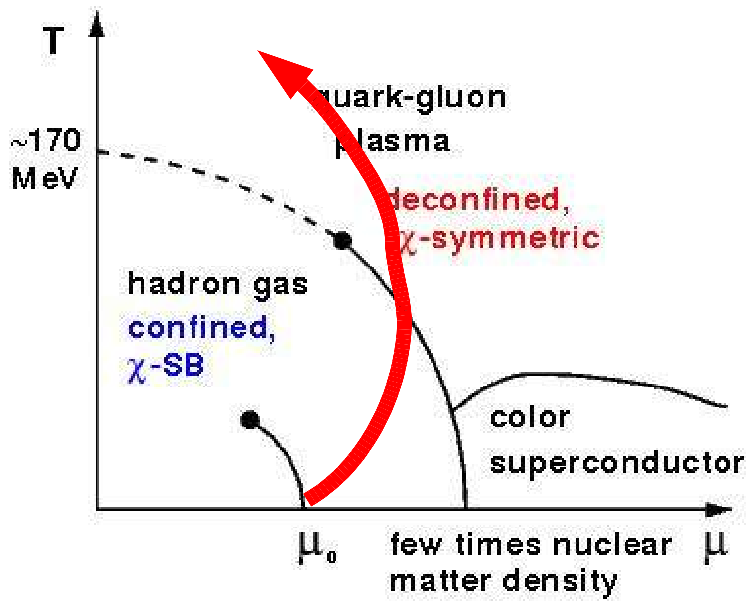
$$\sum S_i = 0 \qquad \sum |S_i| > 0$$

Strangeness conservation in each box: $\sum |S_i| > 0$ Even at T=0

A simple model

- Distribute S_i for a QGP
- Hadronize each box while conserving strangeness
- Since <|S|> large in QGP, strangeness enhancement in HG

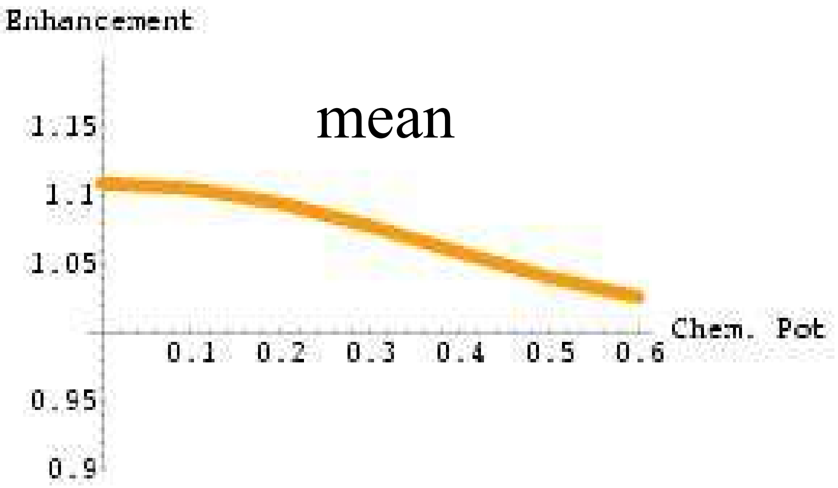
Some (preliminary) numbers

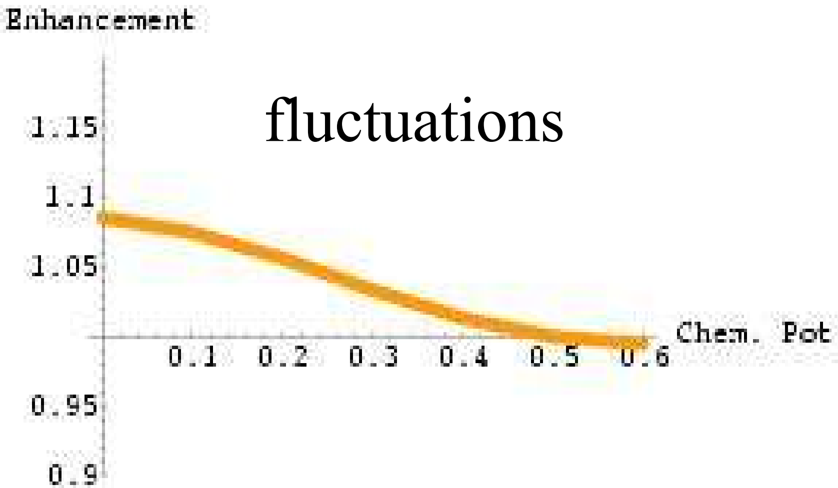


V_{QGP}=20 fm^3

V_{hadron}=60 fm^3

T = 170 MeV

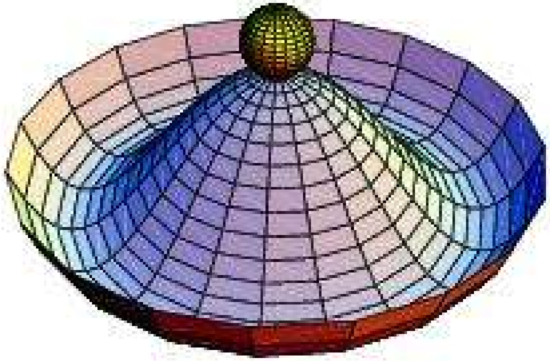




Once upon a time....

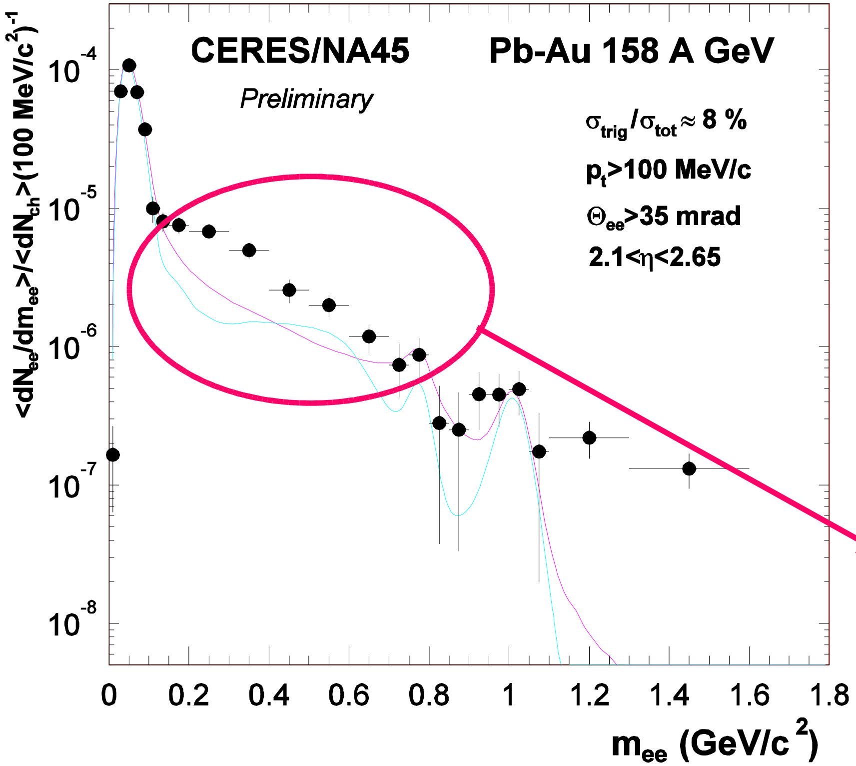
there was something called ....

"DCC"



Mass spectrum and models

Run 2000 Pb-Au 158 AGeV/c:



S. Yurevitch, PhD in prep.

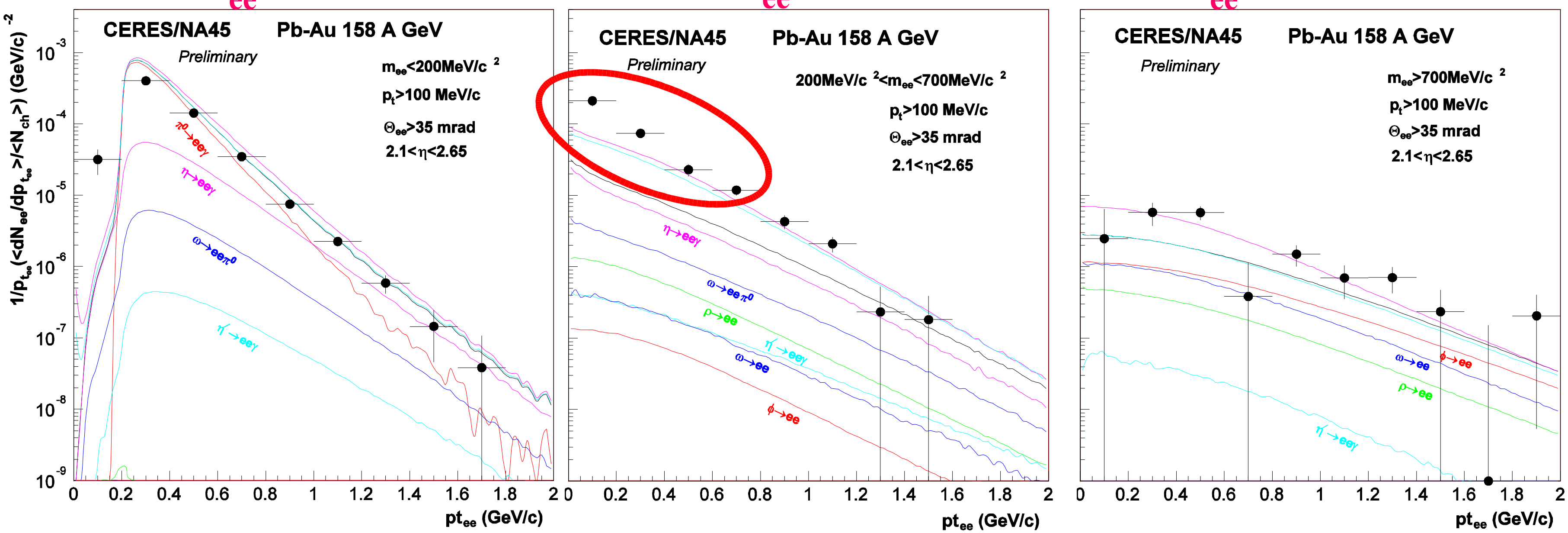
modified ρ-spectral function

Brown-Rho scaling

Low-mass enhancement over models?

Transverse momentum spectra

$m_{ee}<0.2\ GeV/c^2$ | $0.2<m_{ee}<0.7\ GeV/c^2$ | $m_{ee}>0.7\ GeV/c^2$



modified ρ-spectral function

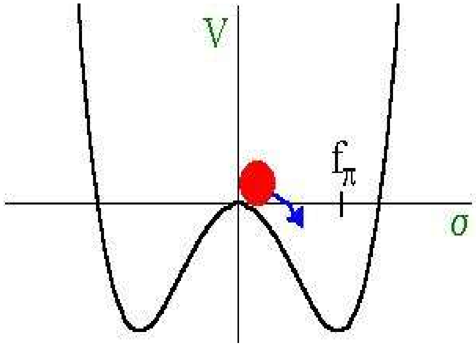
Brown-Rho scaling

S. Yurevitch, PhD in preparation

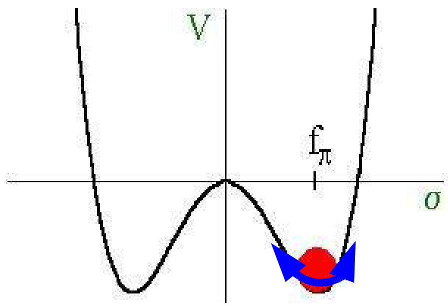
- **Enhancement located at low p_t**

- **Larger enhancement due to improved low p_t acceptance**

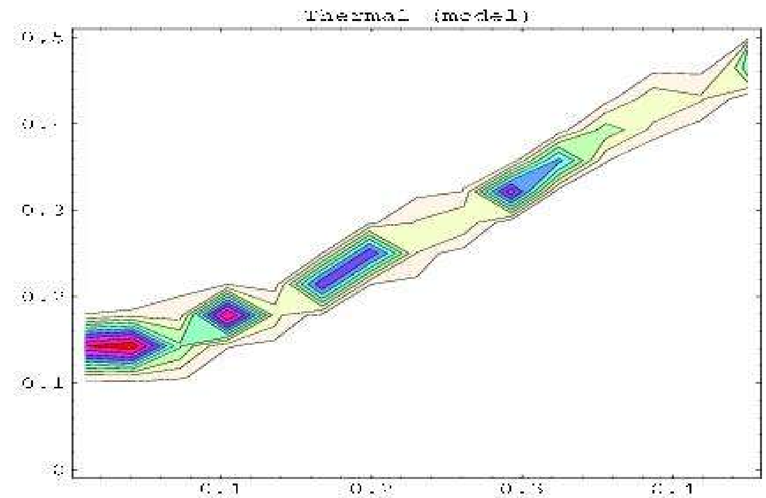
“DCC” dispersion relation



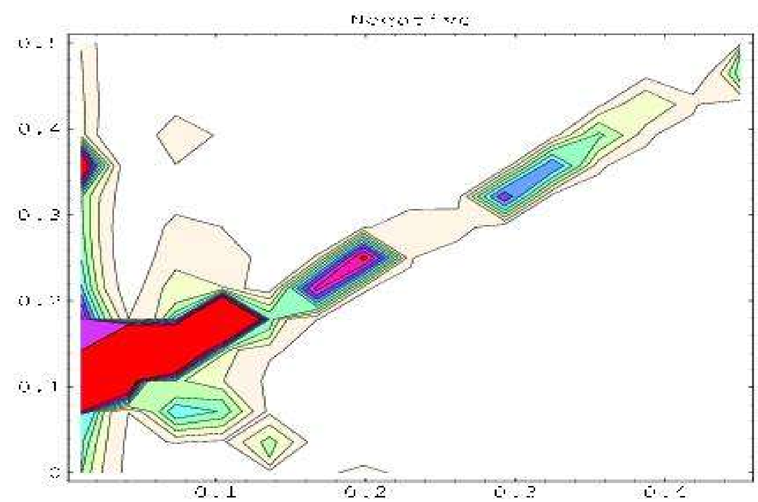
“Quench”



“Parametric resonance”



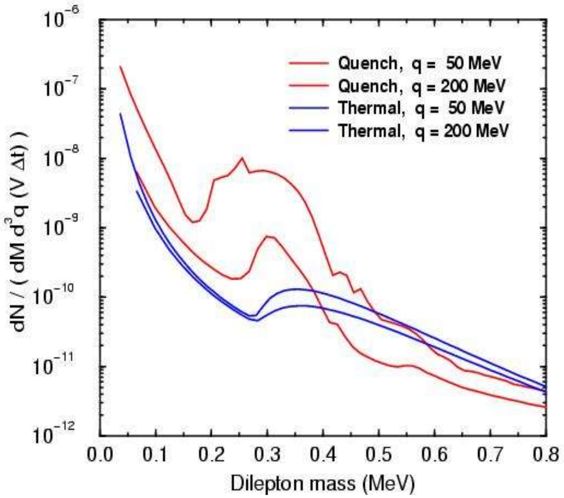
Thermal

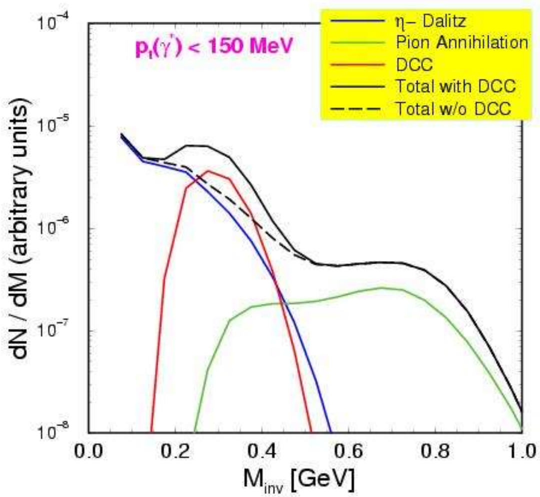


DCC

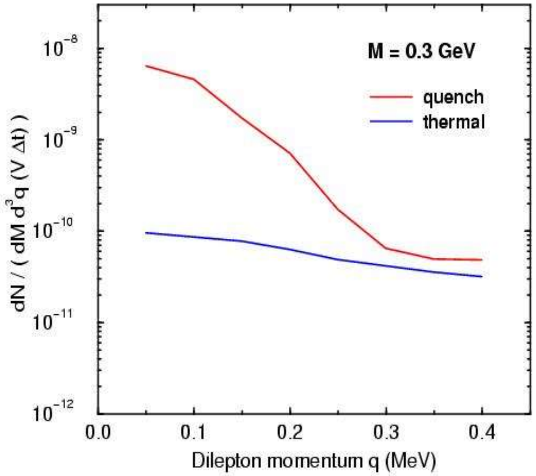
DCC dileptons

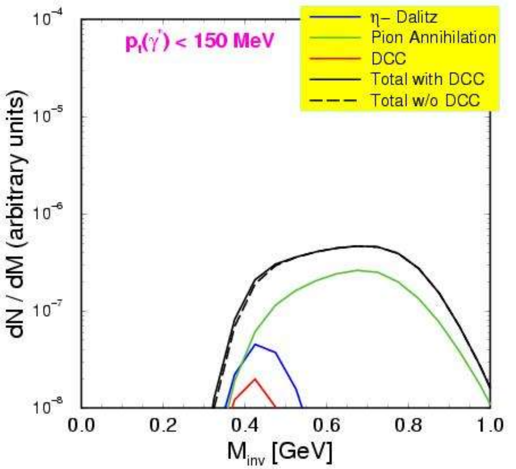
Y. Kluger et al, PRC57(1998) 280; NPA638 (1998) 447





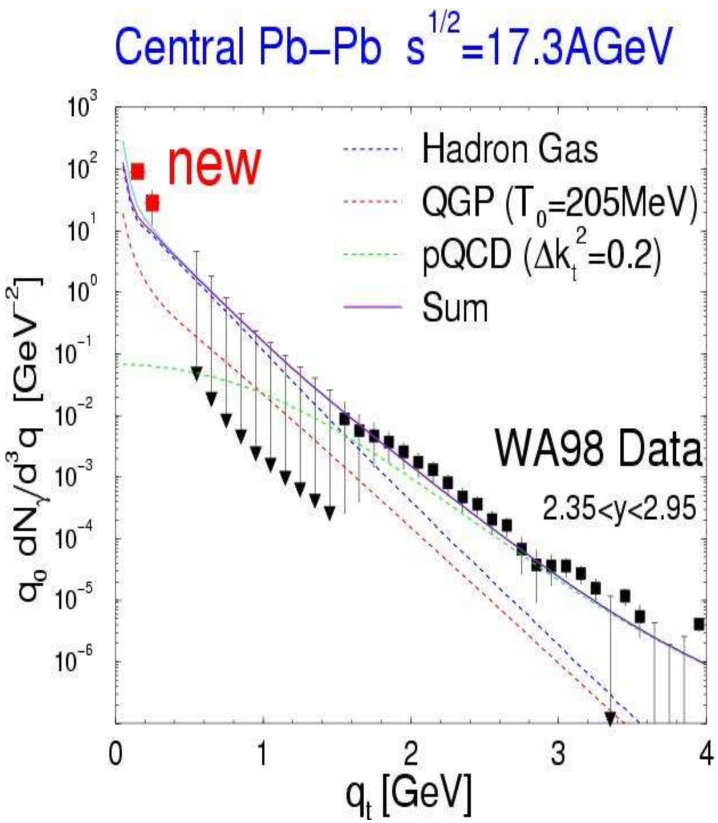
Softer cut
p_t>60 MeV





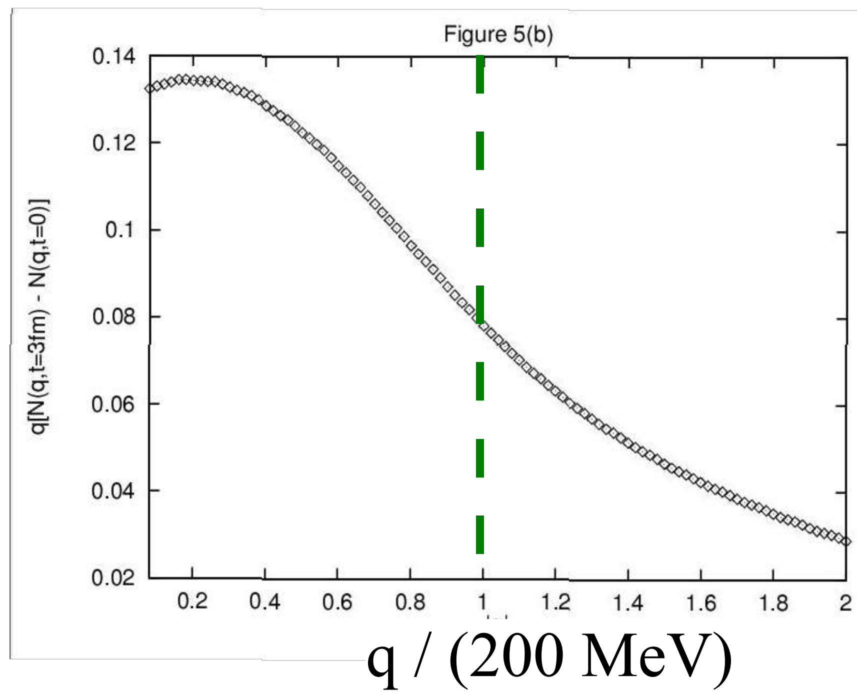
Original cuts
p_t>200 MeV

And Photons!



WA98, Phys. Rev. Lett. 93 (022301), 2004
K. Reygers, Hard Probes 2004

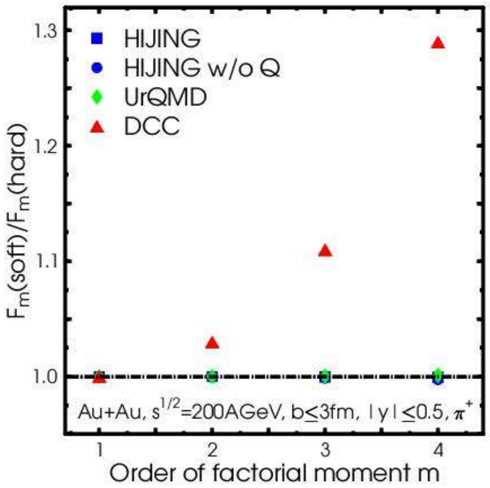
Boyanovsky et al, Phys.Rev.D56:5233-5250,1997



Predict enhancement of low momentum photons

What next?

- Need to look carefully at soft pions
  - Neutral pion fraction $n_0/(n_+ + n_- + n_o)$ not so good.
  - Possibly factorial moments (J. Randrup et al PRC62(2000)041901)
  - Back to back π^+-π^- correlations (J. Randrup et al PRC65(2002) 05906)
  - ....



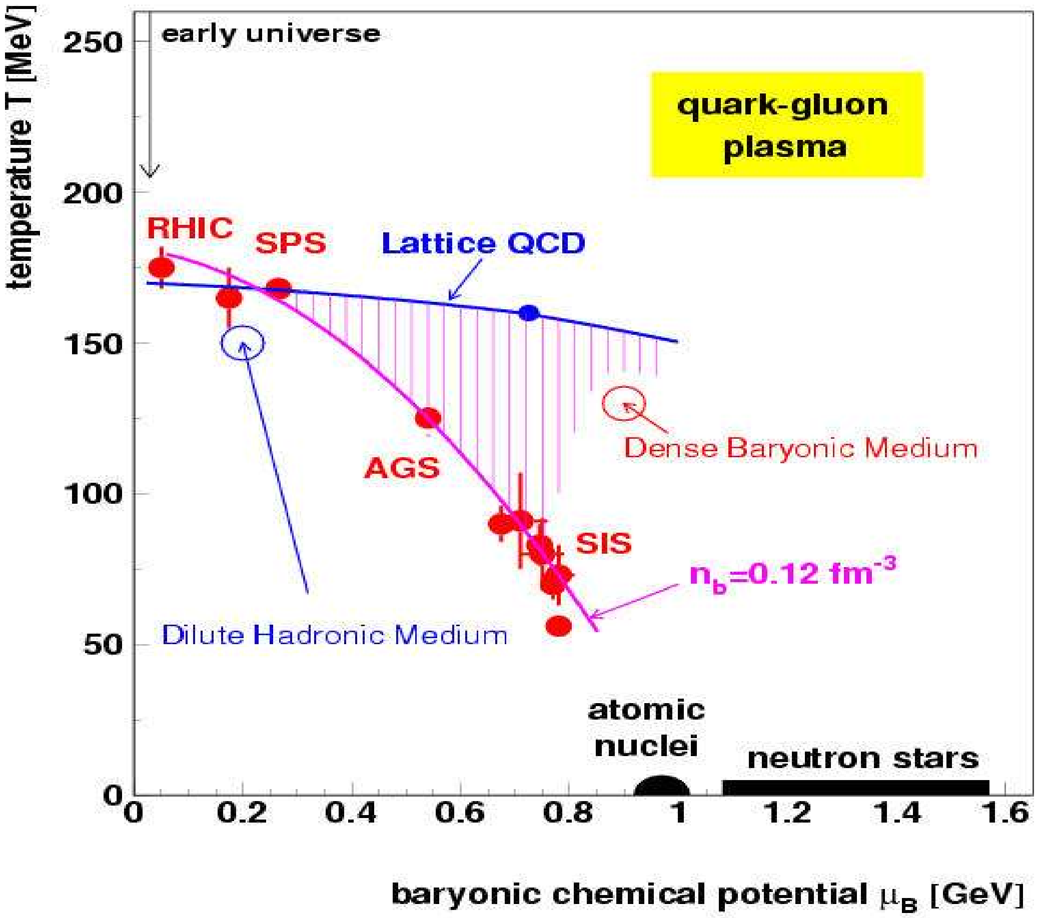
Summary

- Equilibrium vs Phase Space in Heavy Ion collisions not really settled
  - Difficult to address Charm @ RHIC will certainly help
  - Strangeness useful at lower energies

- Rather interesting structure in excitation function of K/π
  - Bubble formation “not inconsistent” with the structures in mean and fluctuations

- Interesting enhancement in low mass Dileptons (CERES) ($m \approx 2\ m_\pi$, $p_t < 200$ MeV)
  - Consistent with prediction from “DCC” like pion modes
- Interesting enhancement in low momentum Photons (WA98)
  - Consistent with prediction from “DCC” like pion modes

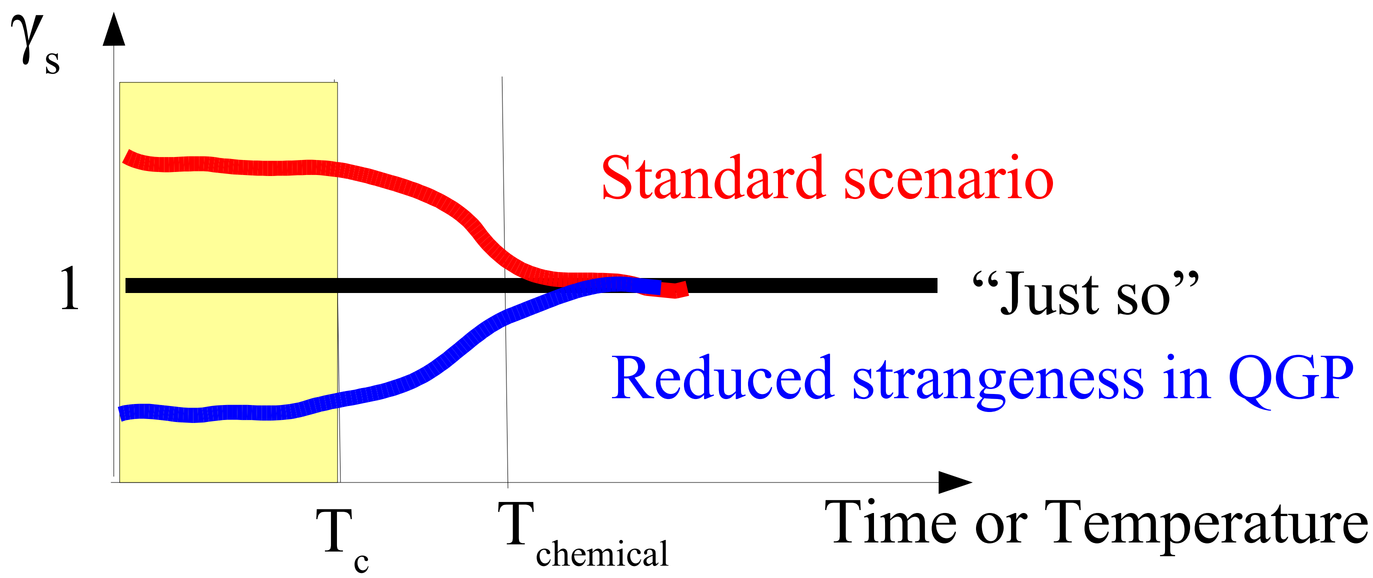
Outlook


early universe
quark-gluon plasma
RHIC
SPS
Lattice QCD
AGS
SIS
Dense Baryonic Medium
n_b=0.12 fm^{-3}
Dilute Hadronic Medium
atomic nuclei
neutron stars
temperature T [MeV]
baryonic chemical potential μ_B [GeV]
0
50
100
150
200
250
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6

Heavy Ion 101 Quiz

"FACTS":

- We have seen the Quark Gluons Plasma
- $T_{chemical} = T_c$
- $\gamma_s = 1$



Strangeness and the QGP

- More strange quanta in a Quark Gluon Plasma (QGP) than in a hadron gas (HG)
- Equilibration time shorter in QGP than in hadron gas
  - gluon fussion
  - lower threshold

Strangeness enhancement as signal for QGP

Some definitions

- "strangeness" = strange + anti-strange
- "strangness suppression factor" γ_s

$$N_K = \gamma_s \int d^3 p \, \exp(-\beta(E_k + \mu_s)$$
$$N_\Lambda = \gamma_s \int d^3 p \, \exp(-\beta(E_\Lambda - \mu_s - \mu$$

$\gamma_s > 1$ Strangeness enhancement