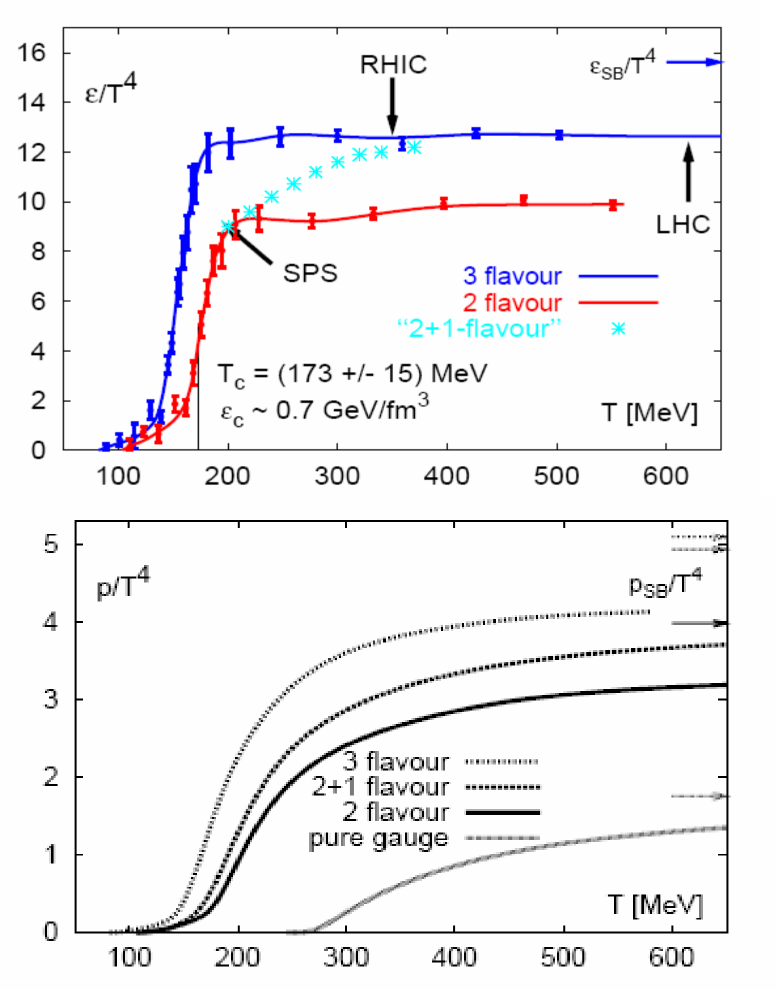
Evidence for the Onset of Deconfinement and Quest for the Critical Point by NA49 at the CERN SPS

G.Melkumov (JINR Dubna)

for NA49 collaboration

6th Int.Workshop CPOD, August 23-29 2010, JINR Dubna

QCD prediction of quark-gluon deconfinement



Pb+Pb at SPS energies:

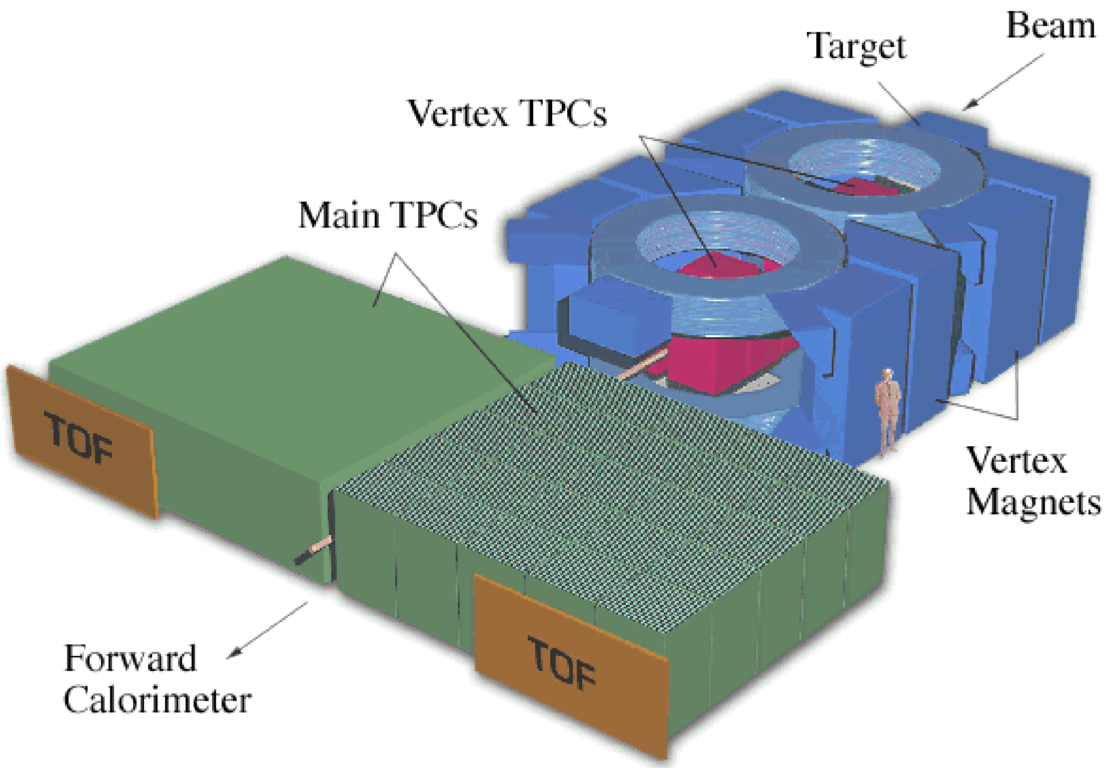
Energy density exceeds the critical value (≈ 1 GeV / fm^3)

Signatures for deconfinement
- radial & anisotropic flow
- strangeness enhancement
- J/Ψ,Ψ' yield suppression
- di-lepton enhancement & ρ^0 modification

Search for the onset of deconfinement by the energy scan at the SPS

Comprehensive study of the phase diagram of strongly interacting matter

NA49 experiment at CERN SPS



Hadron measurements in large acceptance ($y_{CM} > y > y_{beam}$)

Tracking by large-volume TPCs in SC magnet field

PID by dE/dx,TOF, decay topology, invariant mass

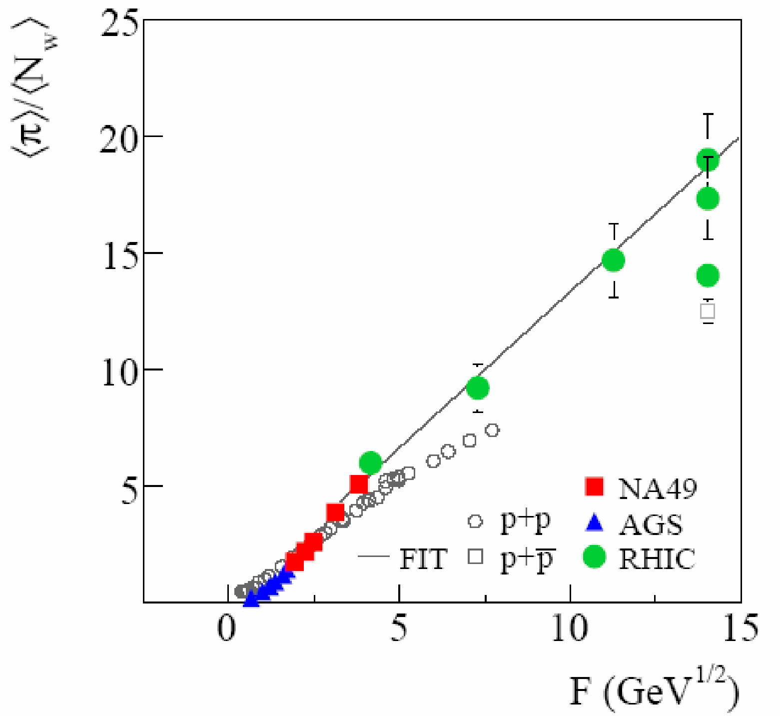
Centrality determination by Forward Calorimeter

Operating 1994-2002; p+p, C+C, Si+Si and Pb+Pb interactions at center of mass energy **6.3 – 17.3 GeV** for N+N interaction

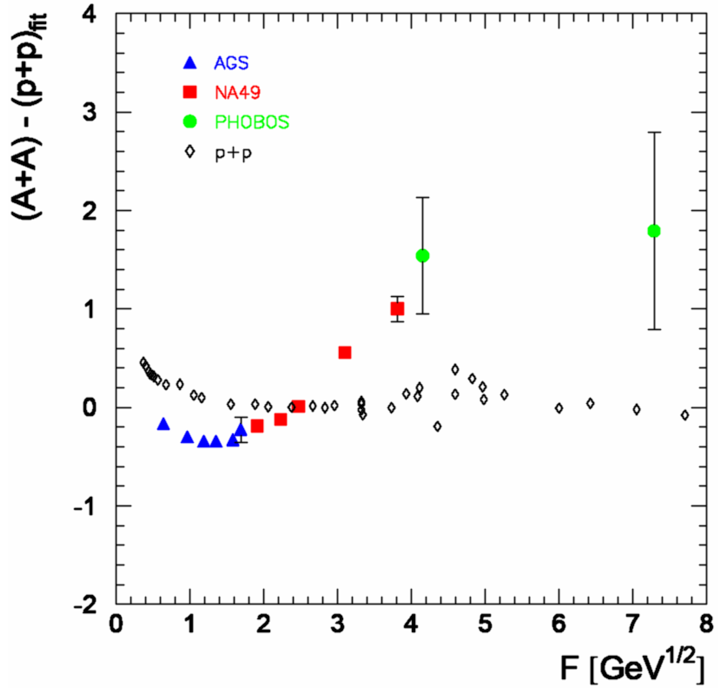
Pion energy dependence - 4π yields

Full phase space (4π)

$$<\pi>=1.5\cdot(<\pi^+>+<\pi^->)$$



Final NA49 results on the onset of deconfinemet:
C.Alt et al., PRC77,024903 (2008)



Pions measure early stage entropy. **In SMES: <** $\frac{\langle\pi\rangle}{N_w}\propto\frac{S}{N_w}\propto g^{1/4}F$ $\quad F=\frac{(\sqrt{s}-2m_p)^{3/4}}{\sqrt{s}^{1/4}}$

→ **A+A data change from "suppression" (AGS) to "enhancement" at low SPS energies**

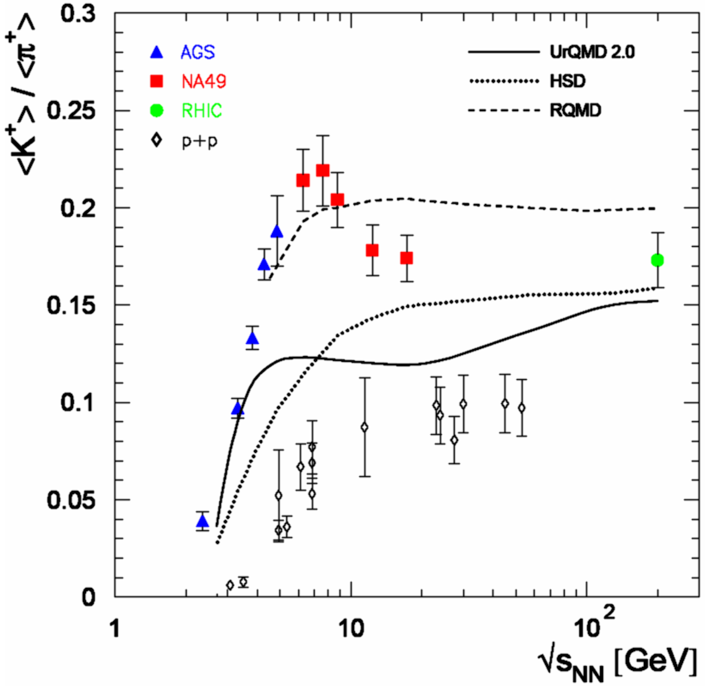
→ **Change of slope around 30A GeV**; slope in A+A increases from ≈1 (AGS) to ≈ 1.3 (top SPS+RHIC) - consistent with increase x 3 in NDF

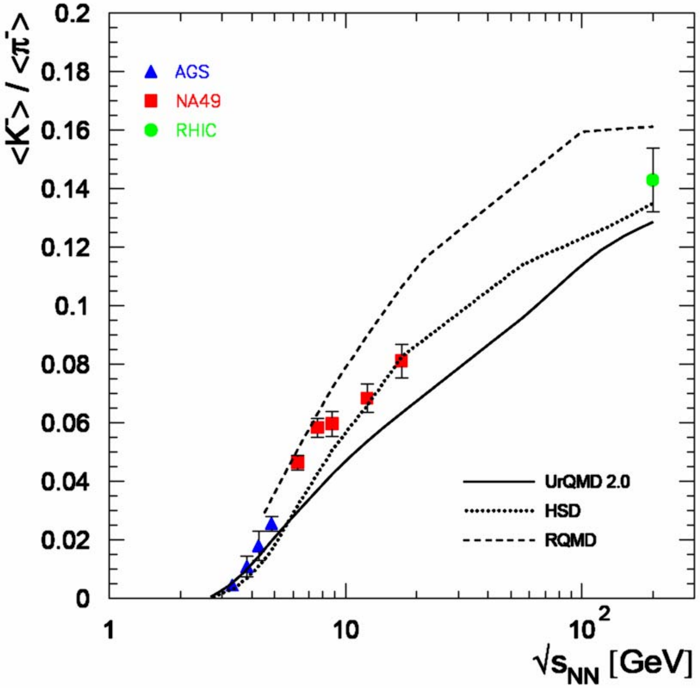
→ **No change of slope in p+p** data

M. Gazdzicki and M. Gorenstein,
Acta Phys.Pol. B30 (1999) 2705

Kaon to pion ratio

Full phase space (4π)





$s \rightarrow K^-, \Lambda$; $\bar{s} \rightarrow K^+$ $\rightarrow$ K^+ measures total strangeness

$\langle K^+ \rangle / \langle \pi^+ \rangle$ proportional to strangeness/entropy

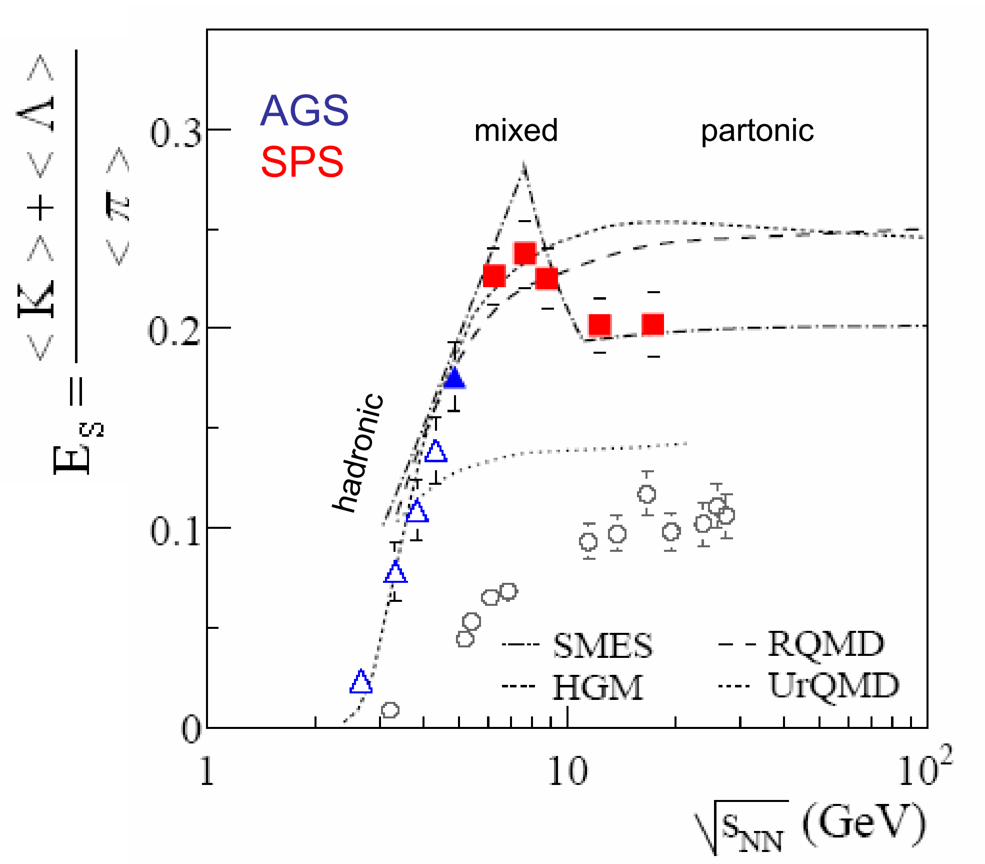
$\langle K^- \rangle / \langle \pi^- \rangle$ additionally sensitive to baryon density

Results for Pb+Pb are different from those for p+p

Sharp peak in $\langle K^+ \rangle / \langle \pi^+ \rangle$ observed at 30A GeV (even more pronounced at midrapidity)

String-hadronic models do not reproduce the data

Strangeness to entropy ratio



note: $< K > = 2 (< K^+ > + < K^- >) = 4 < K_S^0 >$

Peaks sharply at the SPS

SMES explanation:

- entropy, number of s, $\bar{s}$ quarks conserved from QGP to freeze-out
- ratio of $(s + \bar{s})$ / entropy rises rapidly with T in the hadron gas
- E_s drops to the predicted constant QGP level above the threshold of deconfinement :

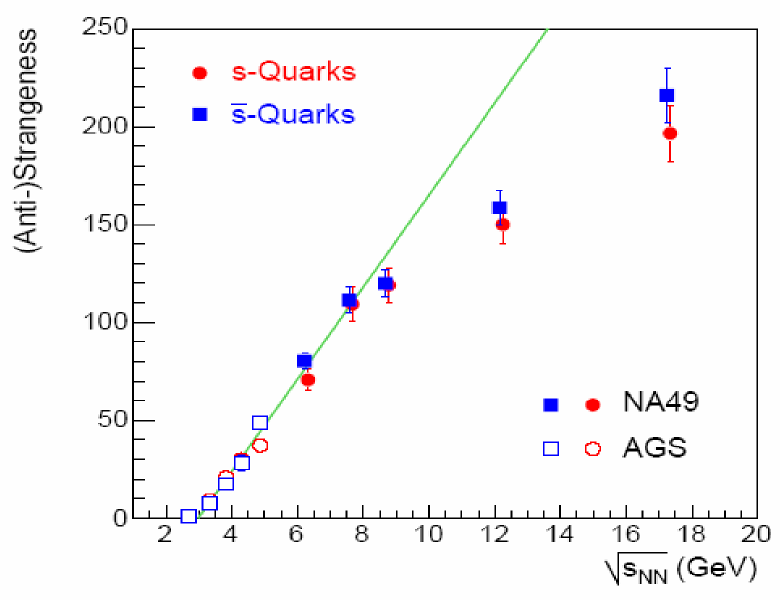
$$E_s \approx \frac{<N_S + N_{\bar{S}}>}{<\pi>} = \frac{0.74 g_s}{g_u + g_d + g_g}$$

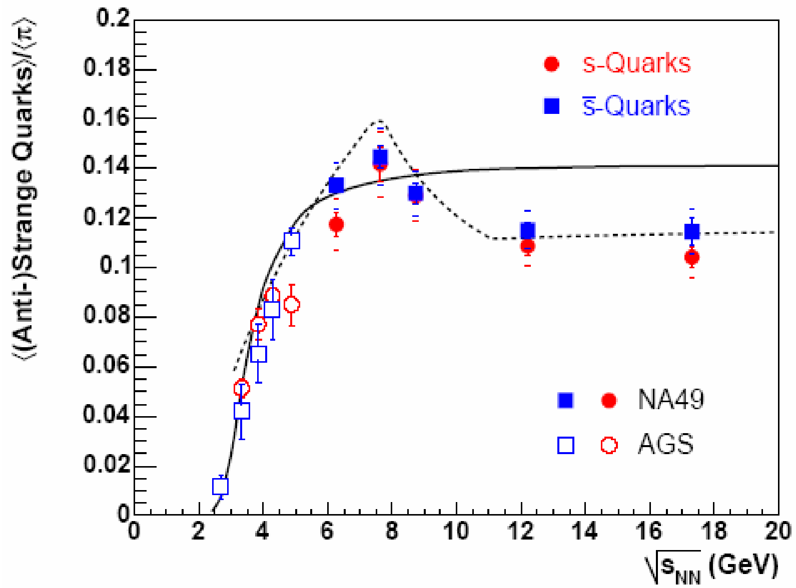
$$\approx 0.21$$

Proposed as measure of strangeness to entropy ratio (SMES)
E_s shows distinct peak at 30A GeV
Described (predicted) by model assuming phase transition (SMES)

Total s and $\bar{s}$ quark yields

Estimation: measured yields and isospin symmetry & small correction for unmeasured yields from statistical HG model predictions





HGM

SMES

s and $\bar{s}$ quark yields consistent

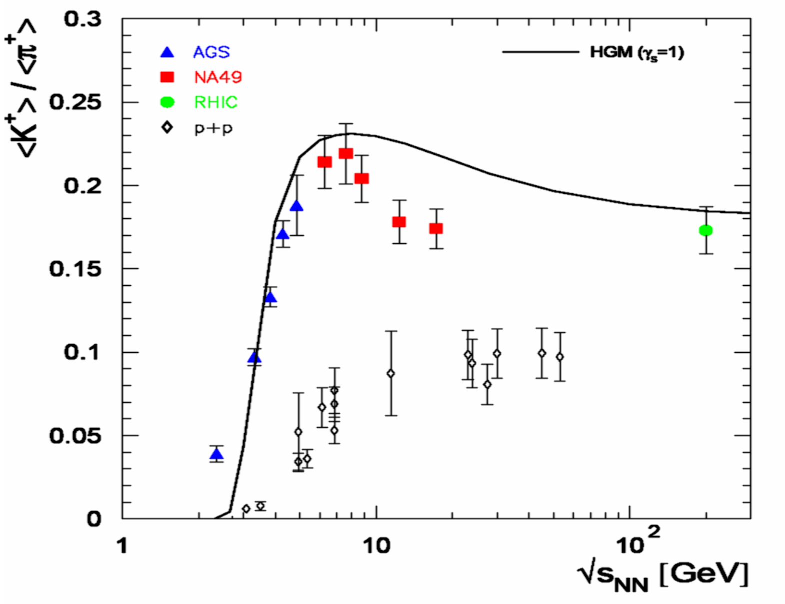
Increase of strangeness yield changes slope at 30A GeV

Relative strangeness yield peaks at 30A GeV; undersaturation of strangeness content as compared to HGM

Thermal (HG) models

- Fit to data at each energy
- Parametrisation of T, μ_B as function of energy
- Relative maximum as consequence of saturating T and decreasing μ_B
- Overestimates relative kaon yields from 30A GeV on

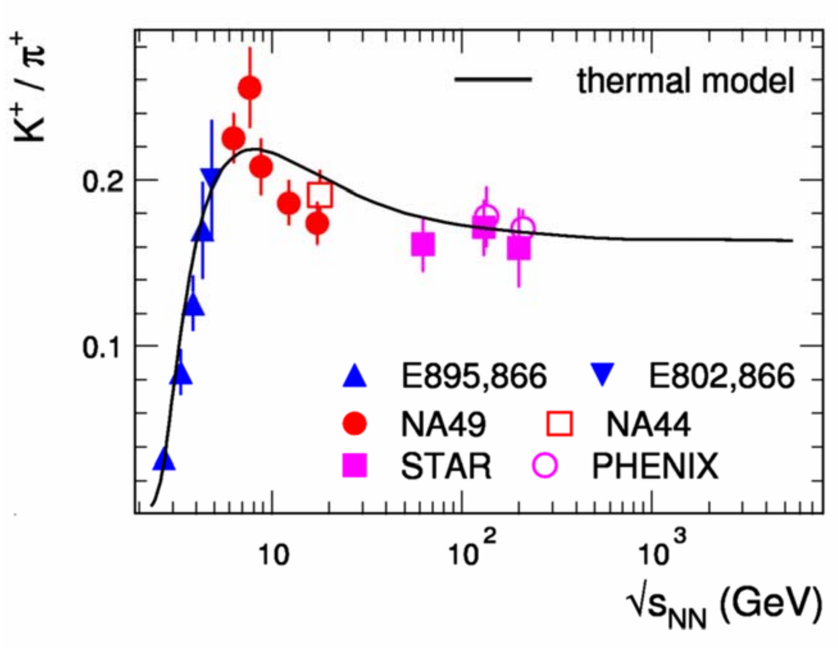
A. Andronic, P. Braun-Munzinger and J. Stachel, Nucl. Phys. A 772 (2006) 167



HG model (extended version)

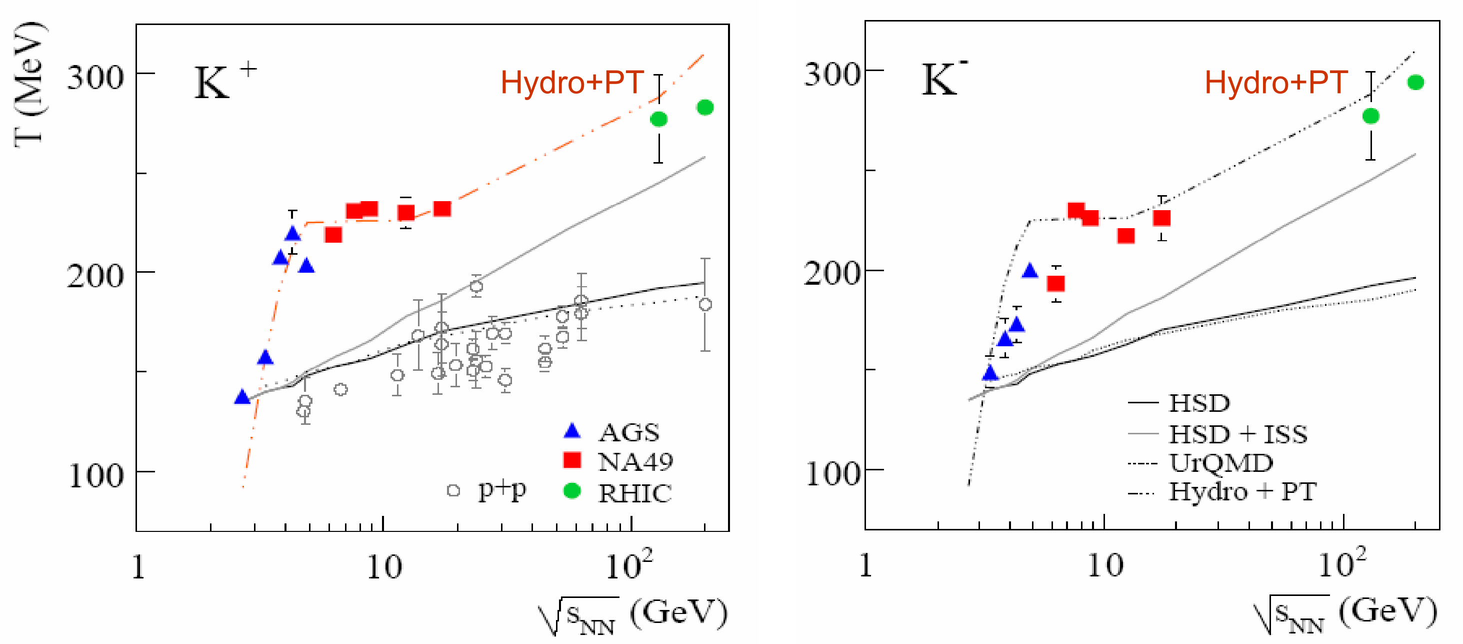
- Inclusion of higher-mass resonances (up to 3 GeV) improves description of K/π data: Feed-down predominantly into pions → increased pion yield
- Limiting temperature reached somewhere at SPS

A. Andronic, P. Braun-Munzinger and J. Stachel, arXiv:0812.1186 [nucl-th]



Kaon inverse slope parameter

$$\frac{d\sigma}{dm_T^2\,dy} = A \cdot e^{-m_T/T}$$



- The step-like feature observed at SPS energies, not seen for p+p collisions and in models without phase transition

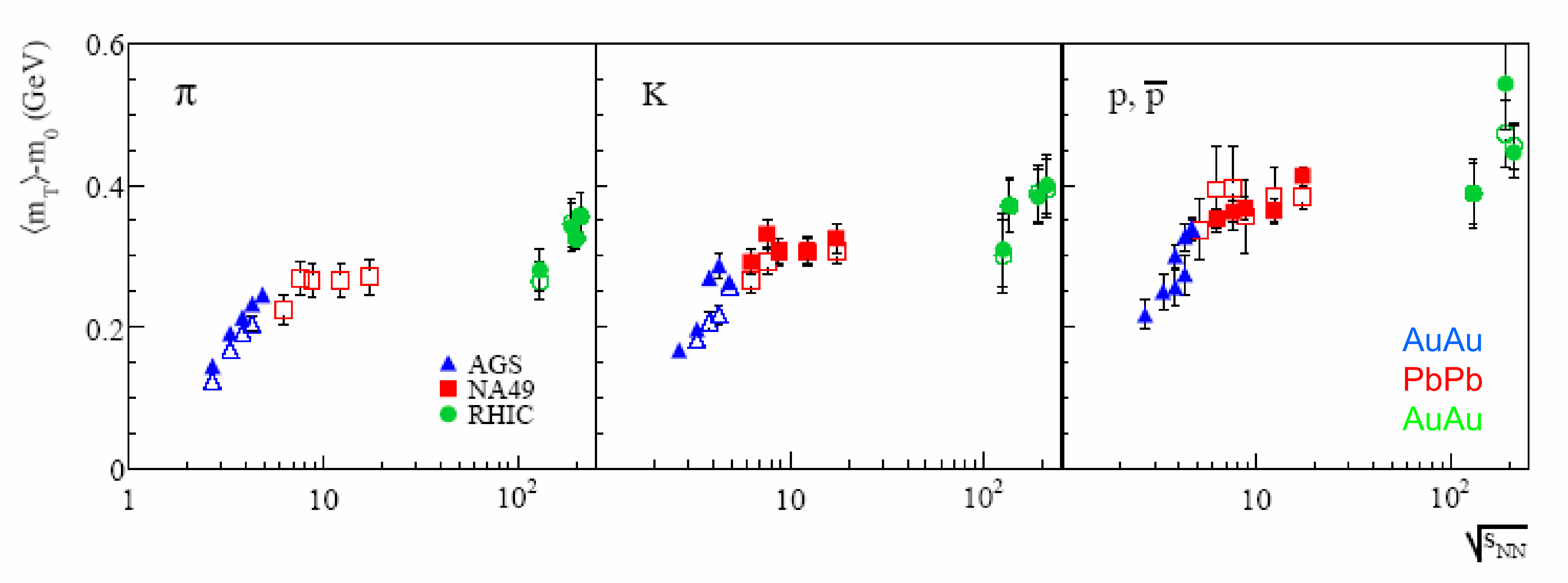
- Consistent with approximately constant temperature and pressure in mixed phase (latent heat)(softest point of EoS)

M. Gorenstein et al., Phys. Lett. B 567 (2003) 175

- Hydrodynamical model with deconfinement phase transition starting at lower SPS energies describes data

S. Hama et al., Braz. J. Phys. 34 (2004) 322

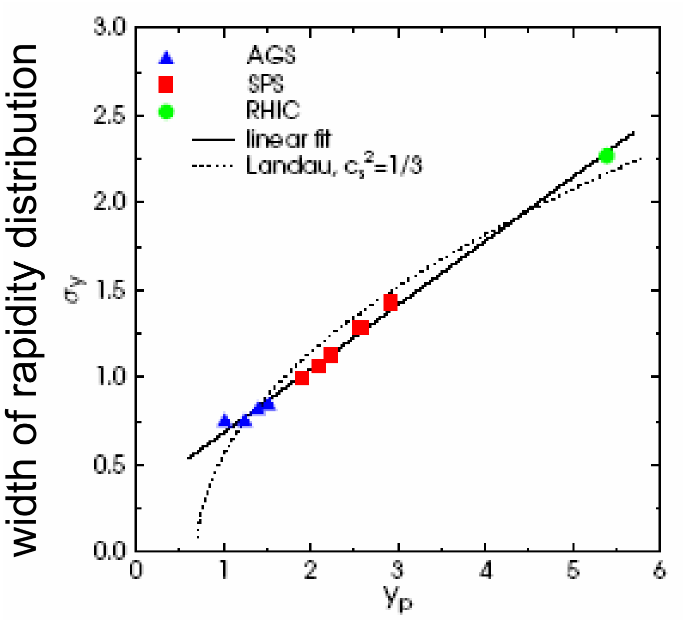
Mean transverse mass

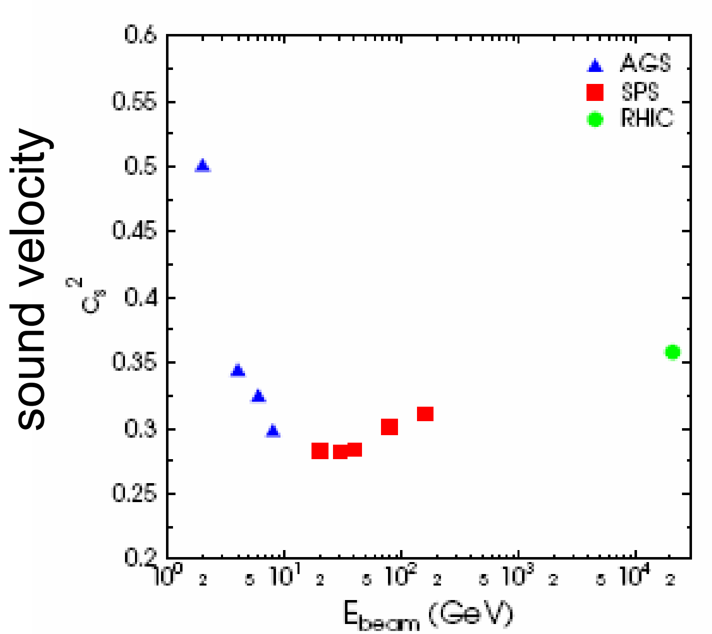


• Step like behaviour of <m_T> observed for π, K, p

• Increase of <m_T> for abundant final state particles (π, K, p) slows sharply at the lowest SPS energy

More signal : Estimate of sound velocity





Landau hydrodynamical model (E.Shuryak,Yad.Fiz.16, 395(1972))

$$\sigma_y^2 = \frac{8}{3}\frac{c_s^2}{1-c_s^4}\ln(\sqrt{s_{NN}}/2m_p)$$

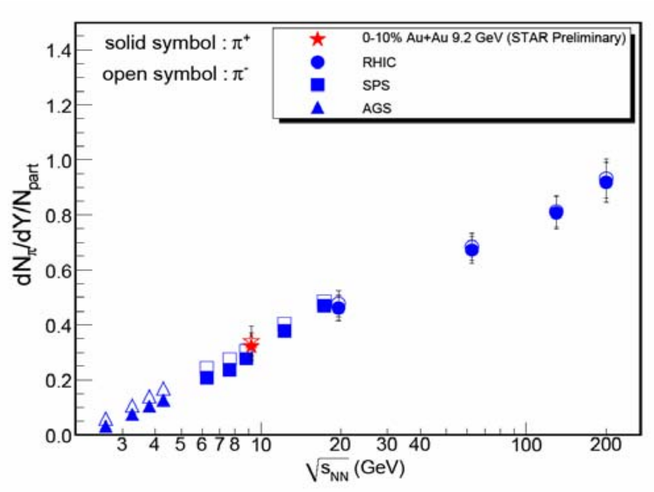
→ sound velocity can be derived from measurements

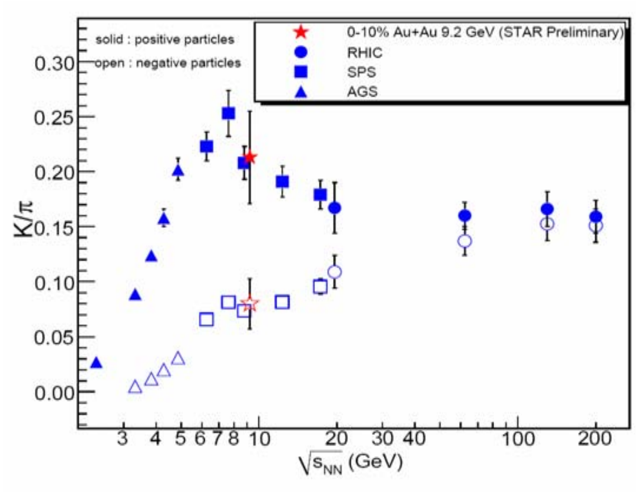
H.Petersen and M.Bleicher, nucl-th/0611001

Minimum of sound velocity c_s (softest point of EoS) around 30A GeV

STAR confirmation of NA49 results

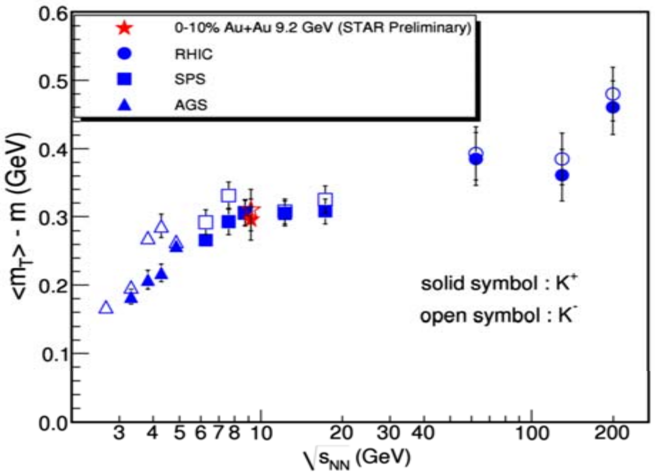
NA49 pion and kaon yields confirmed (at mid-rapidity) by low-energy STAR results ($\sqrt{s_{NN}}$ = 9.2 and 19.6 GeV)

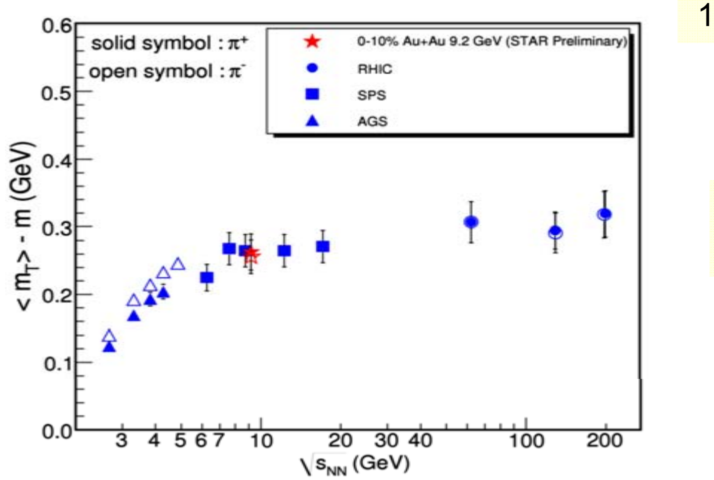




L.Kumar et al. (STAR), J.Phys. G36: 064066 (2009)

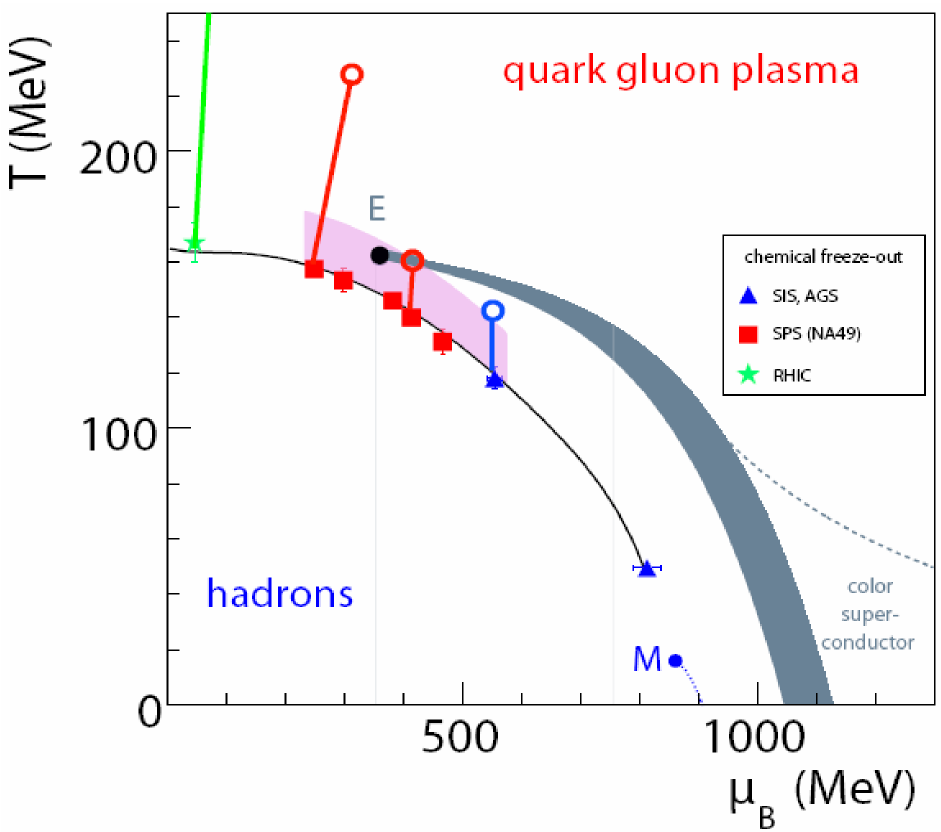
G.Wang et al.(STAR), Nucl. Phys. A 830 (2009) 19c-26c





D.Cebra et al., arXiv: 0903.4702 [nucl-ex]

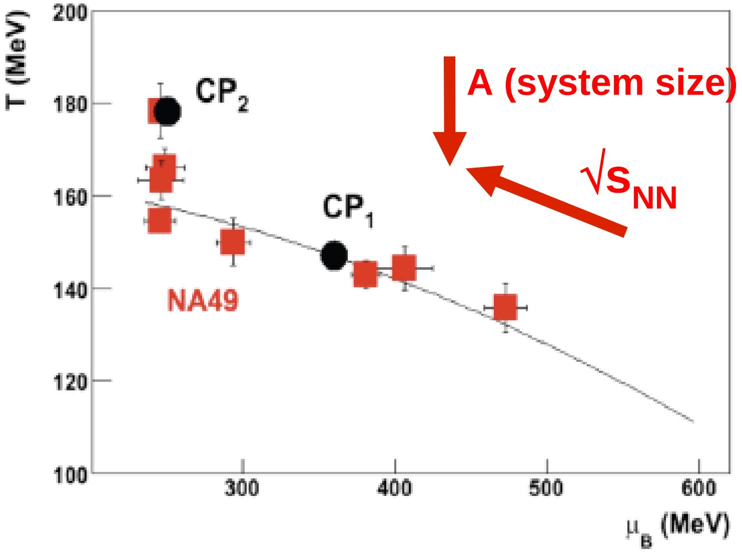
Phase diagram of hadronic matter



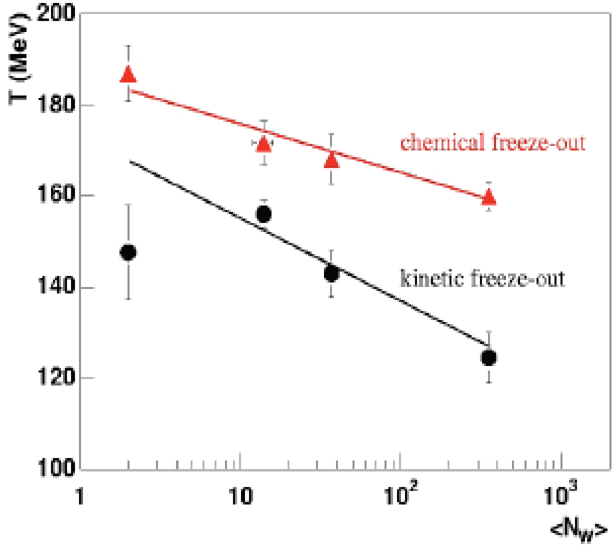
- QCD considerations suggest a first order phase boundary ending in a critical point
- Hadrochemical freeze-out points are obtained from particle yields via statistical model fits
- Freeze-out temperature T and baryon chemical potential μ_B approach the phase boundary and the estimated critical point location at the SPS

For strongly interacting matter maximum of CP signal expected when freeze-out happens near CP

Search for the critical point



p+p C+C Si+Si Pb+Pb at 158*A* GeV



F.Becattini et al., Phys. Rev. C 73, 044905 **(2006)**
I.Kraus et al., Phys.Rev.C76, 064903 (2007)

- Small systems freeze out at higher temperatures:
  - Chemical and kinetic freeze-out temperatures decrease with increasing system size
- A 2-D scan (T,μ_B) is possible by varying (A,$\sqrt{s}$)

Event-by-event multiplicity & transverse momentum fluctuations

Φ_{pT} - measures transverse momentum fluctuations on event-by-event basis

$$\Phi_{p_T} = \sqrt{\frac{<Z^2>}{<N>}} - \sqrt{<z^2>}$$

$$z = p_T - <p_T> \qquad Z = \sum_{i=1}^{N}(p_T^i - <p_T>)$$

ω- measures multiplicity fluctuations on event-by-event basis

$$\omega = \frac{Var(n)}{<n>} = \frac{<n^2> - <n>^2}{<n>}$$

If A+A is a **superposition** of independent N+N

Φ_{pT} (A+A) = Φ_{pT} (N+N)

Φ_{pT} is independent of N_{part} fluctuations

ω (A+A) = ω (N+N) + < n > ω_{part}

< n > - mean multiplicity of hadrons from a single N+N

ω_{part} - fluctuations in N_{part}

ω is strongly dependent on N_{part} fluctuations

For a system of **independently emitted particles** (no inter-particle correlations)

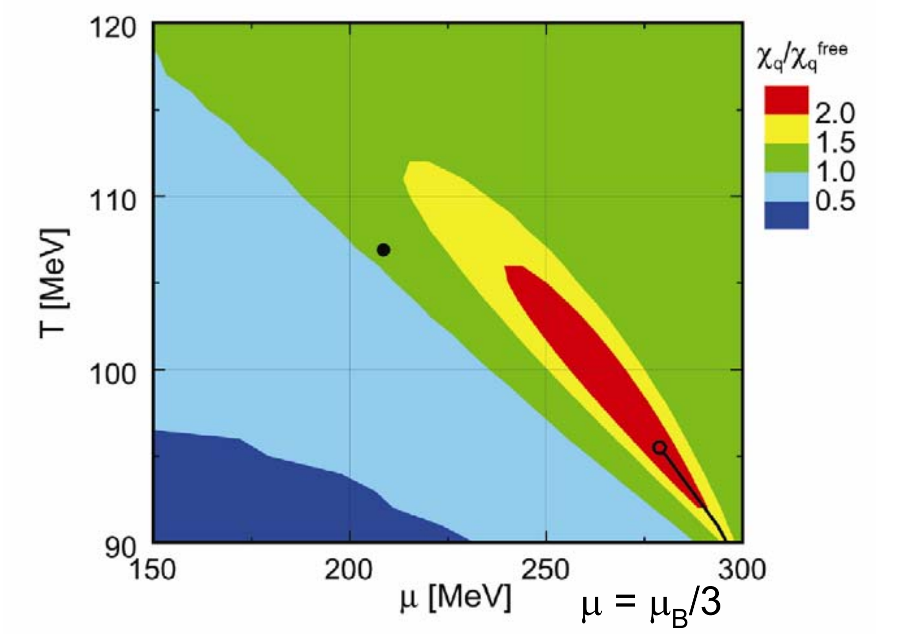
$\Phi_{pT} = 0$

For **Poissonian multiplicity distribution**

$\omega = 1$

Effects (singularities) at critical point

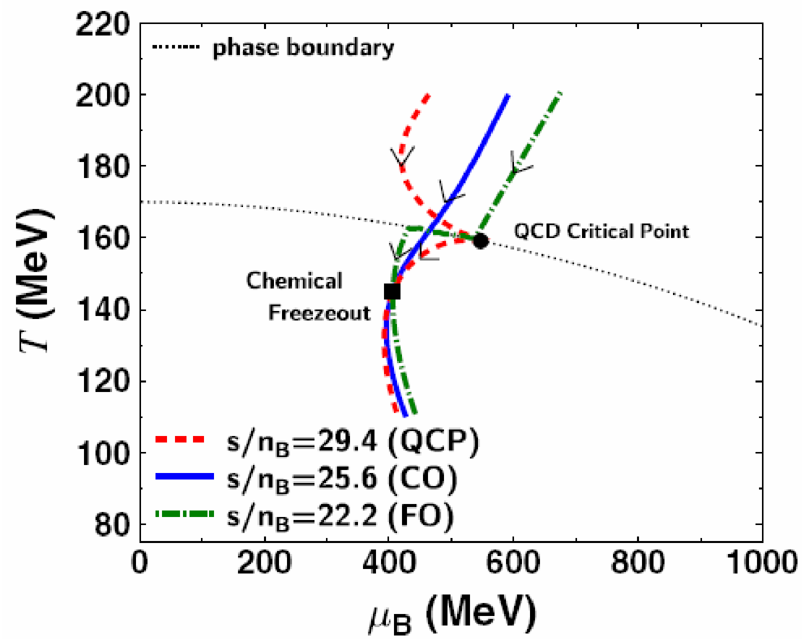
effects of critical point are expected over a range of T, μ_B



Y.Hatta and T.Ikeda, PRD67,014028 (2003)

We do not need to hit precisely the critical point because
a large region can be affected

hydro predicts that evolution of the system is attracted to critical point



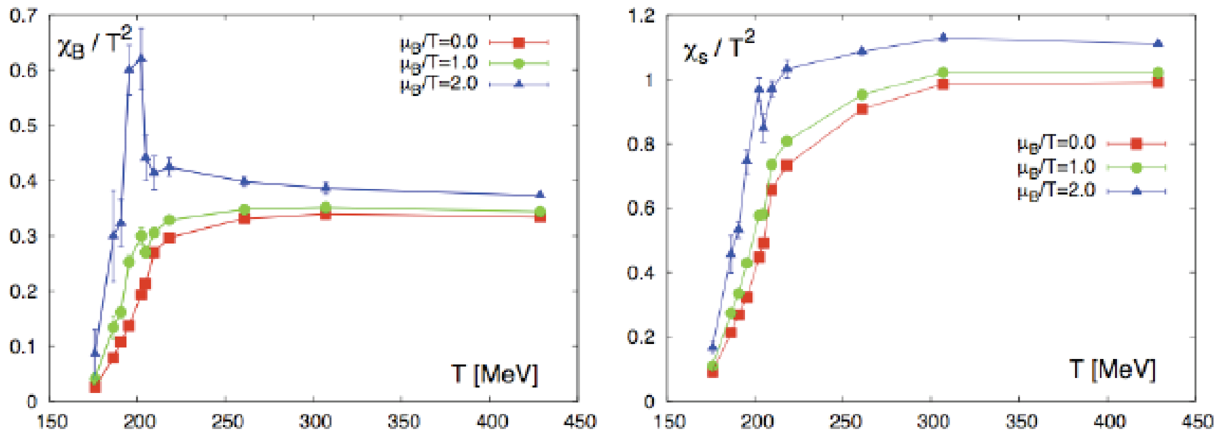
M.Asakawa et al.,PRL 101,122302(2008)

For a given chemical freeze-out point three isentropic trajectories (n_B/s = const.) are shown

The presence of the critical point can deform the trajectories describing the evolution of the expanding fireball in the (T,μ_B) phase diagram

Quark number susceptibilities

- Lattice calculations show change in quark number susceptibilities

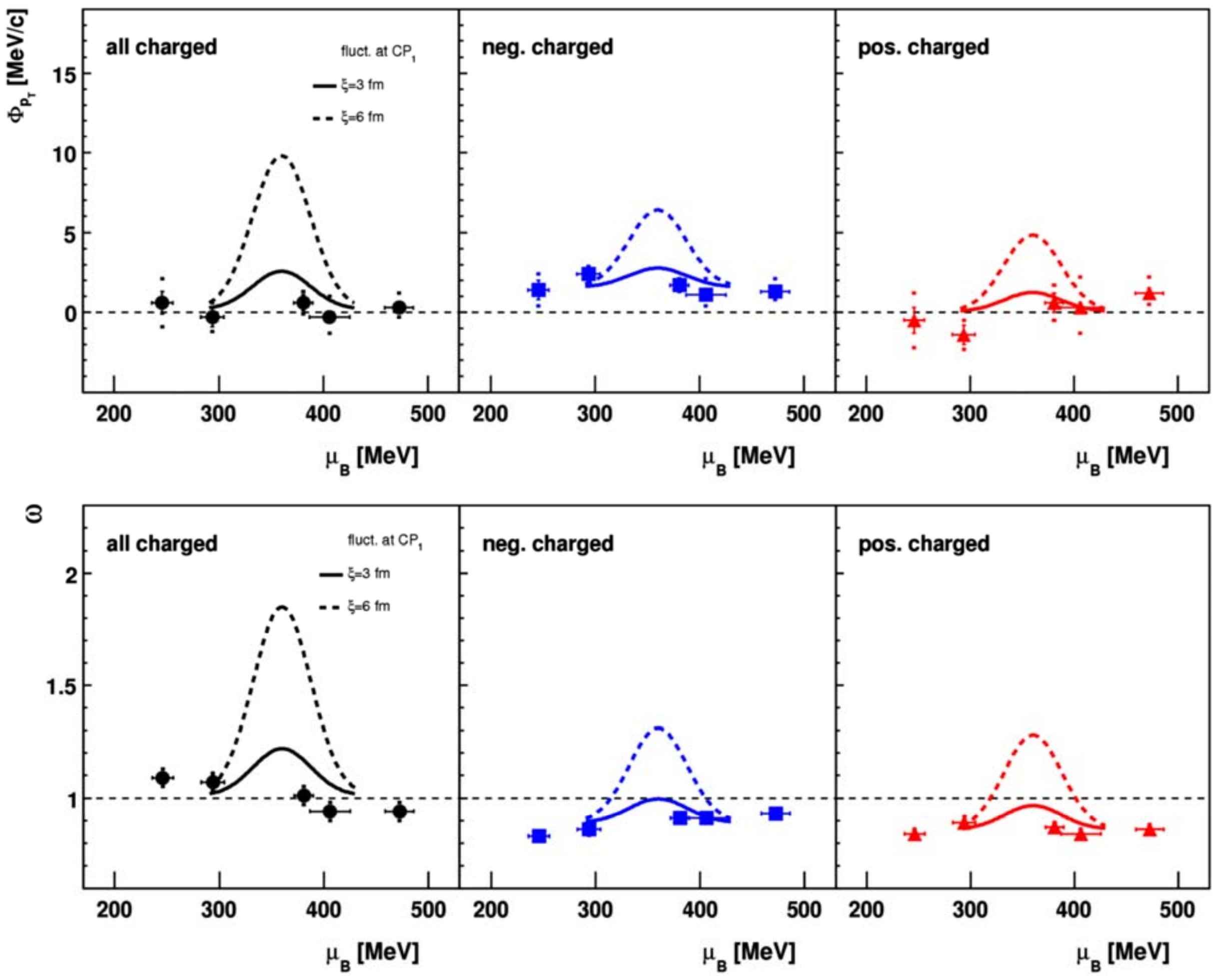


F. Karsch, PoS (CPOD07) 026 and PoS (Lattice 2007) 015

- Direct connection to number fluctuations $\chi \sim \langle N^2 \rangle$
- Step seen for light and strange quarks
- Smooth transition at $\mu_B = 0$
- Light quark number susceptibility diverges at the critical point

Event-by-event <p_T> & multiplicity fluctuations

Energy dependence for central Pb+Pb collisions



NA49 C.Alt et al., PRC78,034914 (2008)

NA49 T.Anticic et al., PRC79,044904 (2009)

CP_1 location:
$\mu_B(CP_1)$ = 360 MeV
$T(CP_1) \approx$ 147 (chemical freeze-out temperature for Pb+Pb at μ_B = 360 MeV)

CP estimates based on:

M. Stephanov, K.Rajagopal,E.Shuryak, PRD60,114028(1999) Y.Hatta and T.Ikeda, PRD67,014028(2003)

base-lines for CP_1 predictions (curves) are mean Φ_{pT} and ω values for 5 energies

No significant energy dependence at SPS energies

Data show no evidence for critical point fluctuations

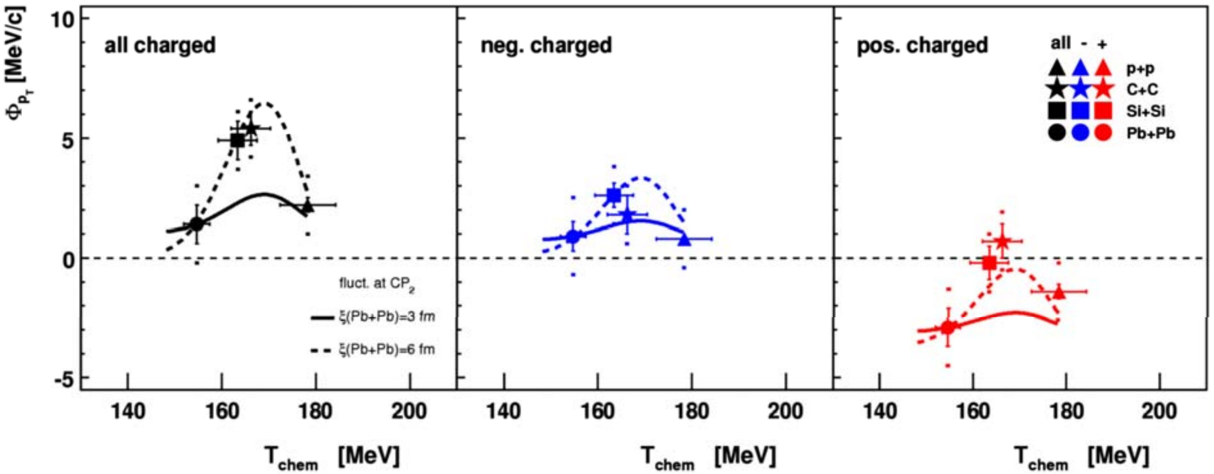
System size dependence of fluctuatios

Pt data: PRC70,034902 (2004)

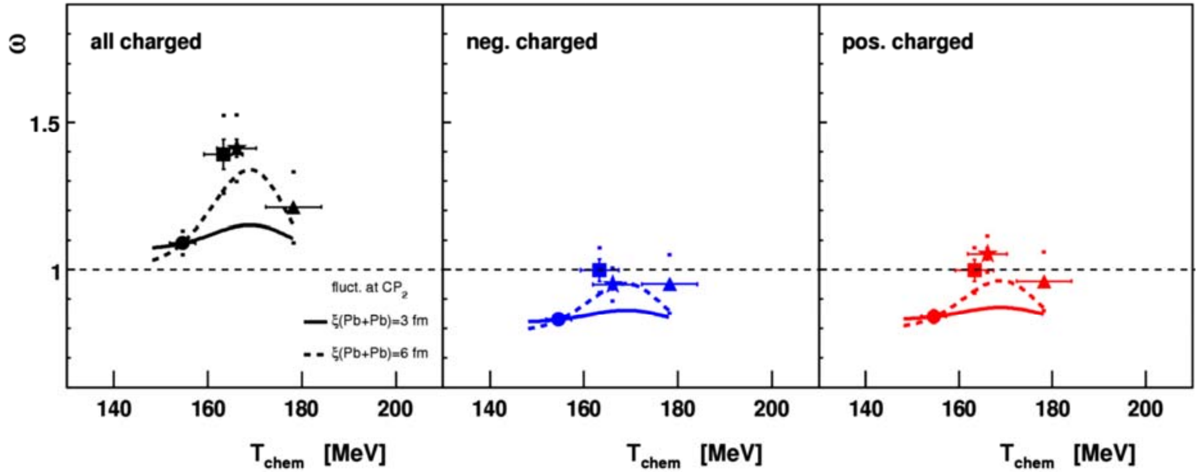
ω data: pp - PRC75,064904 (2007)

Pb+Pb - PRC78,034914 (2008)

CC,SiSi - B.Lungwitz (PhD)



CP$_2$ location:
μ_B(CP$_2$) ≅ 250 MeV = μ_B (A+A at 158A GeV)
T (CP$_2$) = 178 MeV = T_{chem} (p+p)



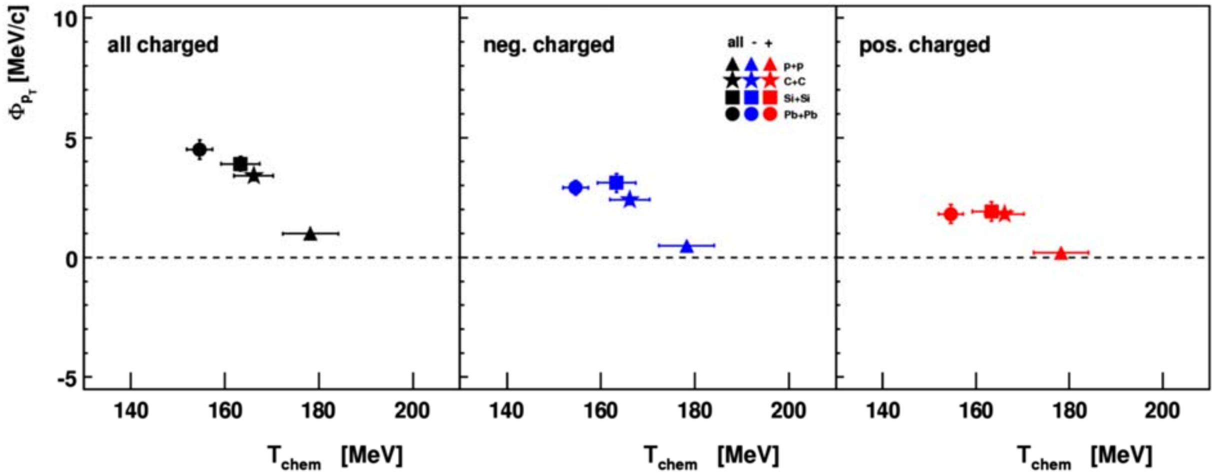
CP$_2$ predictions (curves) normalized to reproduce Φ_{pT} and ω value for central Pb+Pb collisions

Data are consistent with the CP$_2$ predictions

Maximum of Φ_{pT} and ω observed for C+C and Si+Si

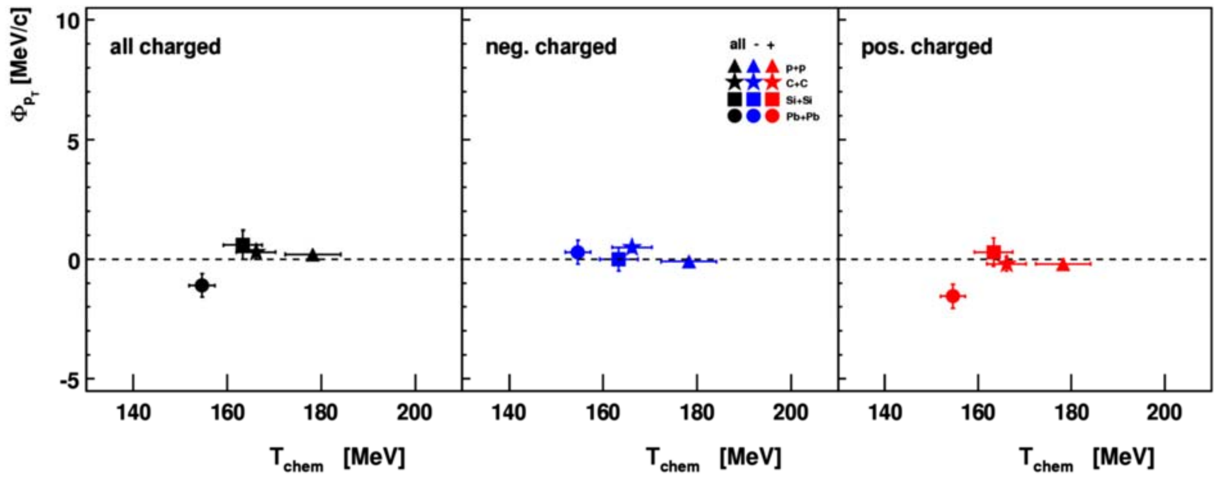
Event-by-event fluctuations at low p_T

Expectations: fluctuations due to the critical point originate mainly from low p_T pions
Stephanov, Rajagopal, Shuryak, PR**D60**, 114028 (1999)



low p_T region
p_T < 0.5 GeV/c
signal observed

NA49 preliminary



high p_T region
p_T > 0.5 GeV/c
fluctuations consistent with zero

Correlations observed predominantly at low p_T
No more maximum of Φ_{pT} due to large correlations in Pb+Pb; their origin is currently analyzed (short range correlations considered)

Higher moments of <p_T> fluctuation

Higher moments of Φ measure (K.Grebieszkow, M.Bogusz)

Higher moments have been advertised as a probe for the phase transition and critical point effects

St. Mrówczyki Phys. Lett. **B465**, 8 (1999)

M.A.Stepanov, Phys.Rev.Lett. 102, 032301 (2009)

Advantage: the amplitude of critical point peak is proportional to higher powers of the correlation length. Examples for second and fourth moments:

$$\langle N^2\rangle \propto \xi^2, \quad \langle N^4\rangle \propto \xi^7$$

Definition:

Single particle variable $z_{p_T} = p_T - \bar{p}_T$ $\bar{p}_T$ - inclusive avarage

Event variable $Z_{P_T} = \sum_{i=1}^{N}(p_T - \bar{p}_T)$ (summation runs over particles in a given event)

$$\Phi_{p_T} \equiv \Phi^{(2)}_{p_T} = \sqrt{\frac{\langle Z^2_{p_T}\rangle}{\langle N\rangle}} - \sqrt{\overline{z^2_{p_T}}}$$

$\langle \dots \rangle$ - averaging over events

Higher moments: $$\Phi^{(n)}_{p_T} = \left(\frac{\langle Z^2_{p_T}\rangle}{\langle N\rangle}\right)^{1/n} - \left(\overline{z^n_{p_T}}\right)^{1/n}$$

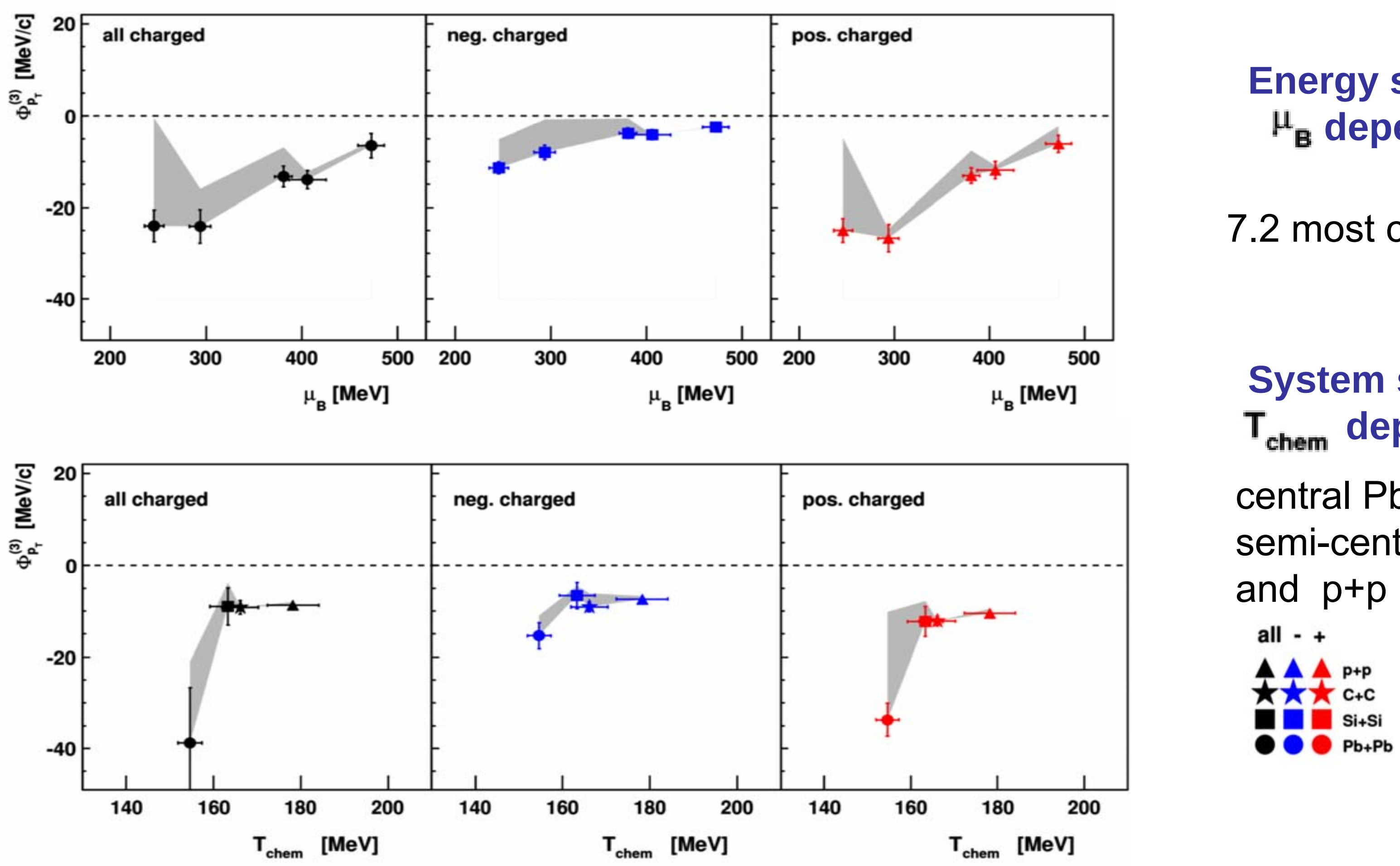
So far we were using second moment: $\Phi^{(2)}_{pT}$

1. In a superposition model $\Phi^{(2)}_{pT}$ (A+A) = $\Phi^{(2)}_{pT}$ (N+N)
2. For independently emitted particles $\Phi^{(2)}_{pT} = 0$

According to S. Mrówczyński Phys. Lett. B465, 8 (1999) only the 3rd moment preserves the above (1. and 2.) properties of the 2nd moment (higher moments *not*). In particular only $\Phi^{(2)}_{pT}$ and $\Phi^{(3)}_{pT}$ are *intensive* as thermodynamic quantities.

Higher moments of $<p_T>$ fluctuation

NA49 preliminary



$\Phi_{pT}^{(3)}$ - 3rd moment

Energy scan - μ_B dependence

7.2 most centralPb+Pb

System size scan - T_{chem} dependence

central Pb+Pb
semi-central C+C,Si+Si
and p+p

TTR corrections for energy scan (5% acceptance)
TTR corrections for system size dependence (20% acceptance)
Systematic error of 7% due to corrections for two track resolution (TTR)

Fluctuations of azimuthal particle distribution

NA49 preliminary

Analysis using Φ_ϕ measure (K.Grebieszkow, T.Cetner)

Motivation

search for plasma instabilities

Mrówczyński, Phys.Lett.**B314**:118-121,1993

critical point, onset of deconfinement

flow fluctuations

Mrówczyński, Shuryak, Acta Phys.Polon.**B34**:4241-4256,2003

Miller, Snellings, nucl-ex/0312008

$$z_\phi \equiv \phi - \overline{\phi}$$

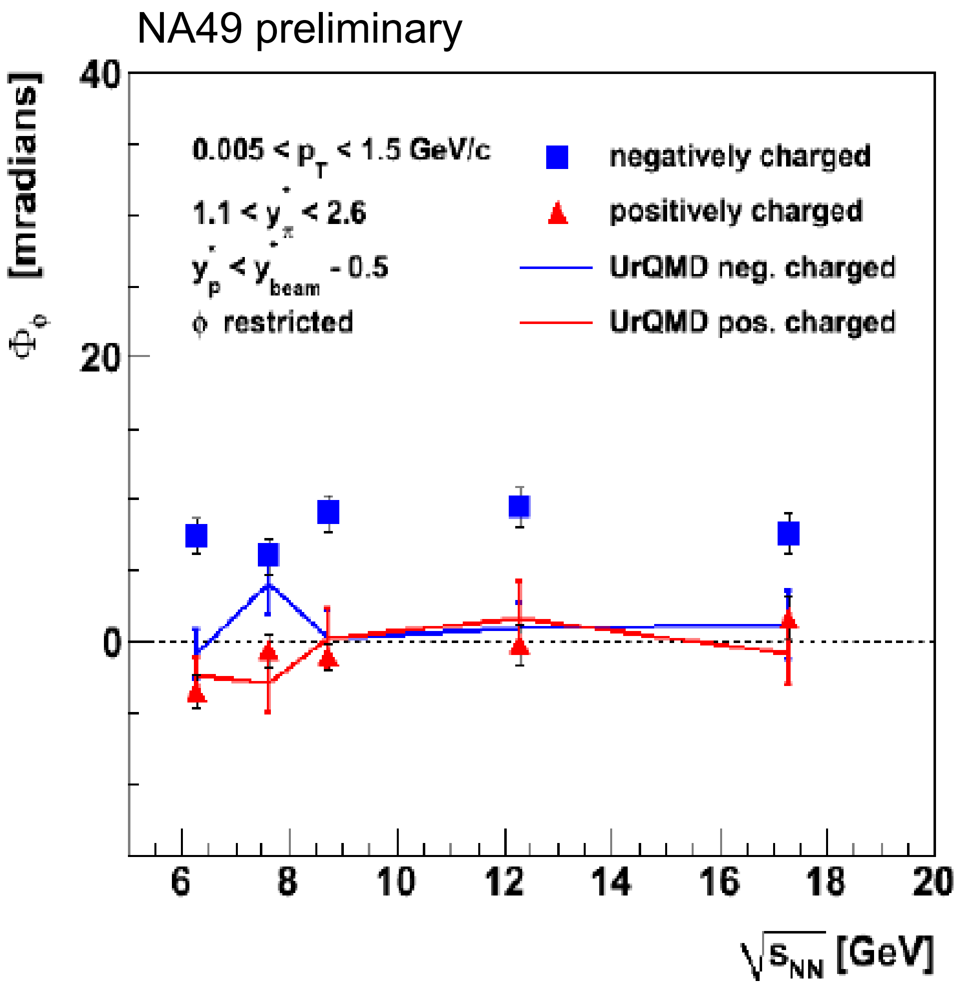
$$\mathbf{Z}_\phi \equiv \sum_{i=1}^{N} (\phi_i - \overline{\phi})$$

$$\Phi_\phi \equiv \sqrt{\frac{\langle \mathbf{Z}_\phi^2 \rangle}{\langle N \rangle}} - \sqrt{\overline{z_\phi^2}}$$

Energy dependence

Energy dependence of Φ_ϕ for 7.2% most central Pb+Pb collisions.

Comparison with UrQMD 1.3



Remarks:

$\Phi_\phi(neg) > 0$

$\Phi_\phi(pos) \approx 0$

Φ_ϕ weakly depends on energy

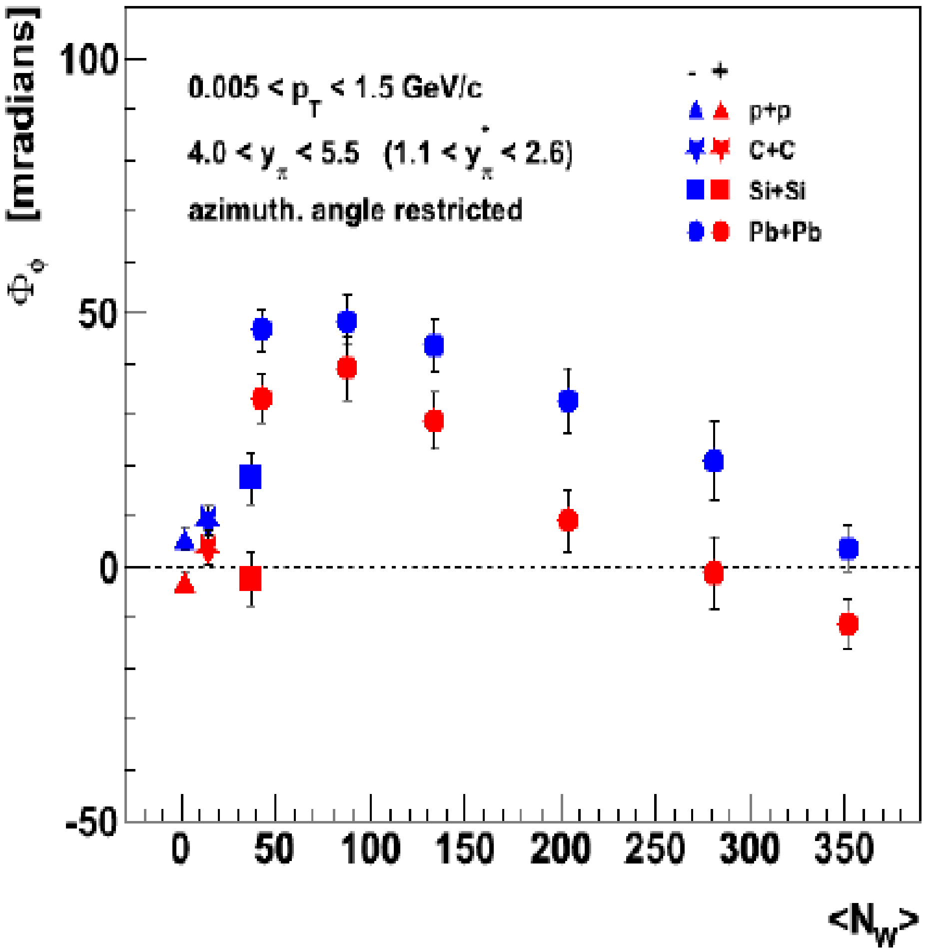
neg: different than UrQMD

System size dependence

System size dependence of Φ_ϕ as a function of number of wounded nucleons N_W.

p+p, C+C, Si+Si and 6 centrality bins of Pb+Pb collisions at 158A GeV.

NA49 preliminary



Remarks:

$\Phi_\phi > 0$

significant maximum for peripheral Pb+Pb

qualitatively similar effect was observed for multiplicity N and transverse momentum p_T fluctuation analysis J.Phys.**G30**:S701-S708,2004

Effect still not understood

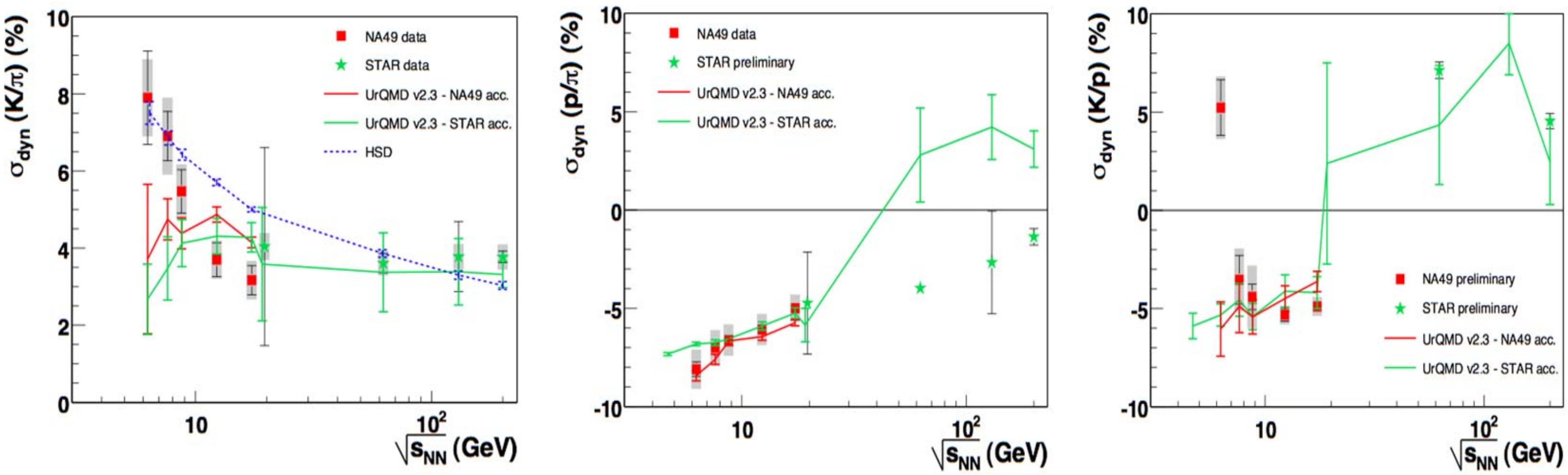
Event-by-event hadron ratio fluctuations

Change of particle (e.g. strangeness) production properties **close to the phase transition:**

- Two **distinct event classes** (with/without QGP) or
- The **mixed phase** (coexistence of hadronic and partonic matter for 1st order phase transition) may be reflected in **larger event-by-event fluctuations**

$$\sigma_{dyn} = \mathrm{sign}\left(\sigma^2_{data} - \sigma^2_{mix}\right)\sqrt{\left|\sigma^2_{data} - \sigma^2_{mix}\right|}$$

STAR: arXiv: 0901.1795 [nucl-ex]
NA49: arXiv: 0808.1237 [nucl-ex]; PoS CPOD (2009) 029



p/π – reproduced by hadronic models (SPS), understood in terms of resonance decay

Interesting effects: **K/π – steep rise towards low SPS energies; distinctive description by hadronic string models**
K/p – opposite sign plateau at SPS and RHIC; jump at lowest SPS energy

Summary

Onset of deconfinement indicated in inclusive observables in central Pb+Pb colisions at lower SPS energies of about 30A GeV:
Results are not reproduced by hadron-string models (RQMD, UrQMD, HSD).
Described (predicted) by model assuming phase transition (SMES)
Other possible observable for the onset of deconfinement: sound velocity

E-by-E azimuthal fluctuations (Φ_{ϕ} measure):
Weak energy dependence.for cental Pb+Pb collisions
System size dependence is qualitatively similar to the multiplicity and transverse momentum fluctuation results in NA49 i.e. the significant rise of the measured fluctuation towards a smaller colliding systems

Energy dependence of E-by-E hadron ratio fluctuations:
Interesting effects at lower SPS energies, but their relation to the onset of deconfinement is not clear

Summary (cont.)

No indications of the critical point in the energy dependence of multiplicity and mean transverse momentum fluctuations **in central Pb+Pb collisions**

System size dependence of the critical point at 158A GeV shows:

- a **maximum of mean p_T and multiplicity fluctuations** in the complete p_T range $\rightarrow$ consistent with the predictions
- an **increase** (from p+p up to Pb+Pb) **of mean p_T fluctuations in the low p_T region**; high p_T particles show no fluctuation signal (effects of short range correlations on Φ_{pT} and ω ?)

Higher moment of Pt fluctuations (Φ measure):

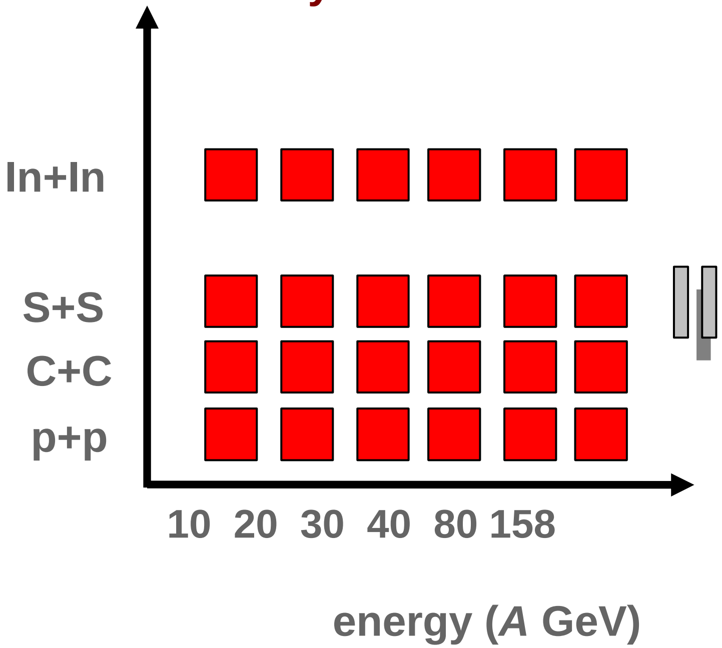
analysis of the 3rd moment of Pt fluctuations for the energy and system size dependence is in progress

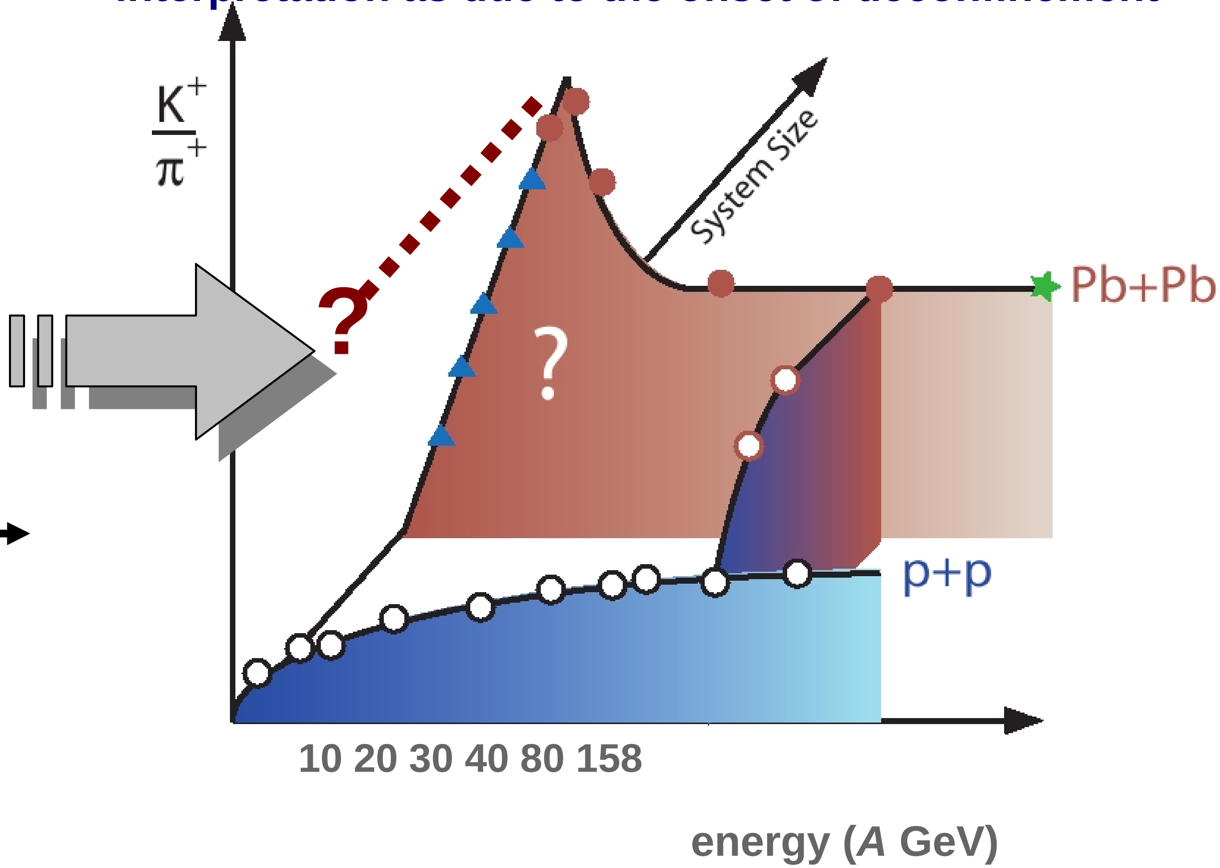
A detailed energy and system-size scan is necessary to investigate the properties of the onset of deconfinement and to establish the existence of the critical point → **NA61/SHINE**

NA61 → Study of the onset of deconfinement

Establish the system size dependence of the anomalies observed in Pb+Pb collisions-further test interpretation as due to the onset of deconfinement

New data to be registered by NA61



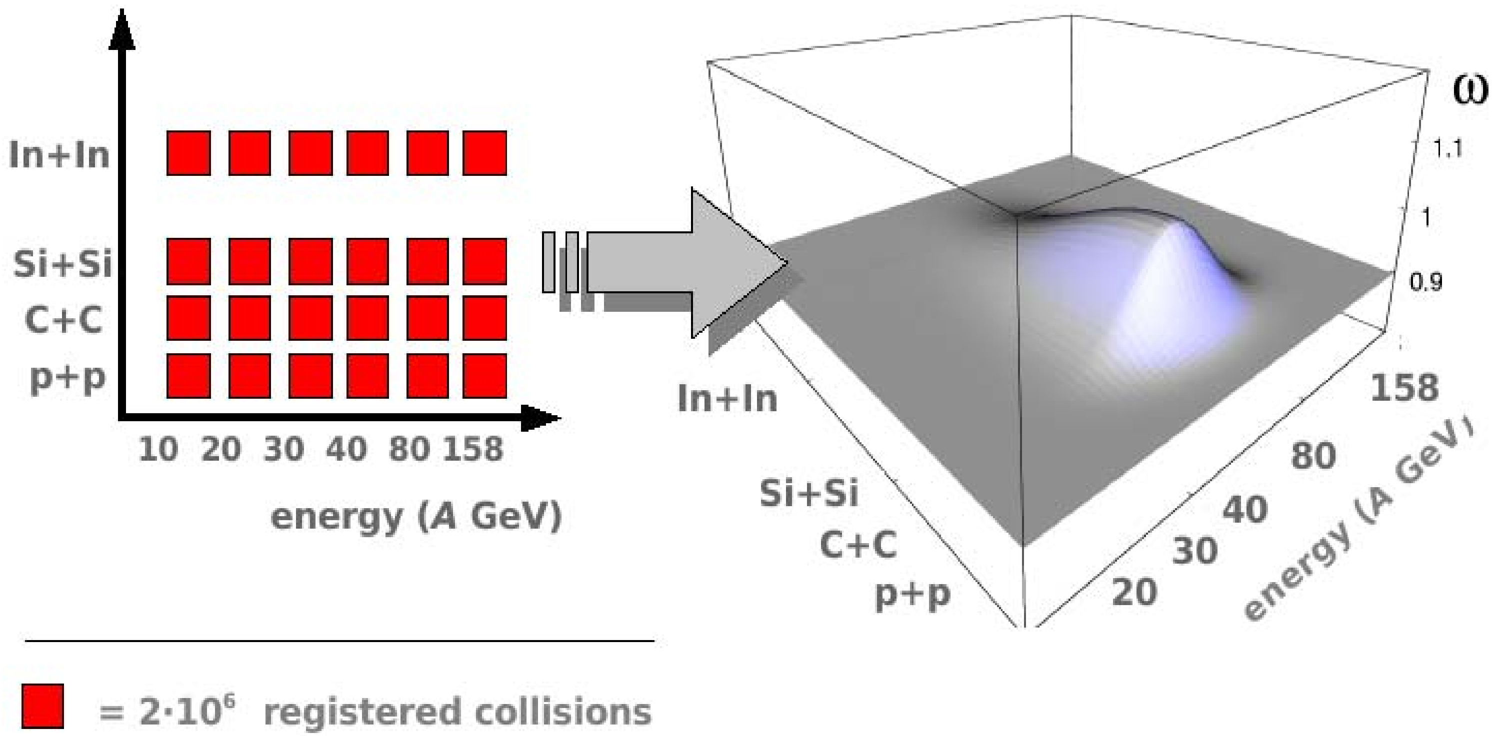


It is expected that the "horn" like structure should be the same for S+S and Pb+Pb collisions and then rapidly disappear for smaller systems

NA61 → Search for the QCD critical point

New data to be registered by NA61

Critical point of strongly interacting matter by an observation of a hill of fluctuations in two dimensional plane (energy)-(system size)



The critical point should lead to an increase of multiplicity and transverse momentum fluctuations