Onset of Deconfinement – Experimental Evidence

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NA49 Collaboration

- Introduction
- Results from the energy scan of Pb+Pb collisions
  - Dynamical properties of the produced fireball
  - Particle composition and freeze-out
  - Indications for the onset of deconfinement:
    structure in the energy dependence near 30A GeV
  - Study of event-by-event fluctuations
- Summary and future directions

Pb+Pb collisions at top SPS energy

- Initial energy density exceeds the critical value predicted by lattice QCD (≈ 1 GeV / fm^3)
- Strong collective behavior
  - anisotropic and radial flow
  - transverse expansion of the matter droplet by factor 2
- Proposed signatures for deconfinement observed
  - strangeness enhancement
  - J/Ψ,Ψ’ yield suppression
  - di-lepton enhancement, ρ^0 modification

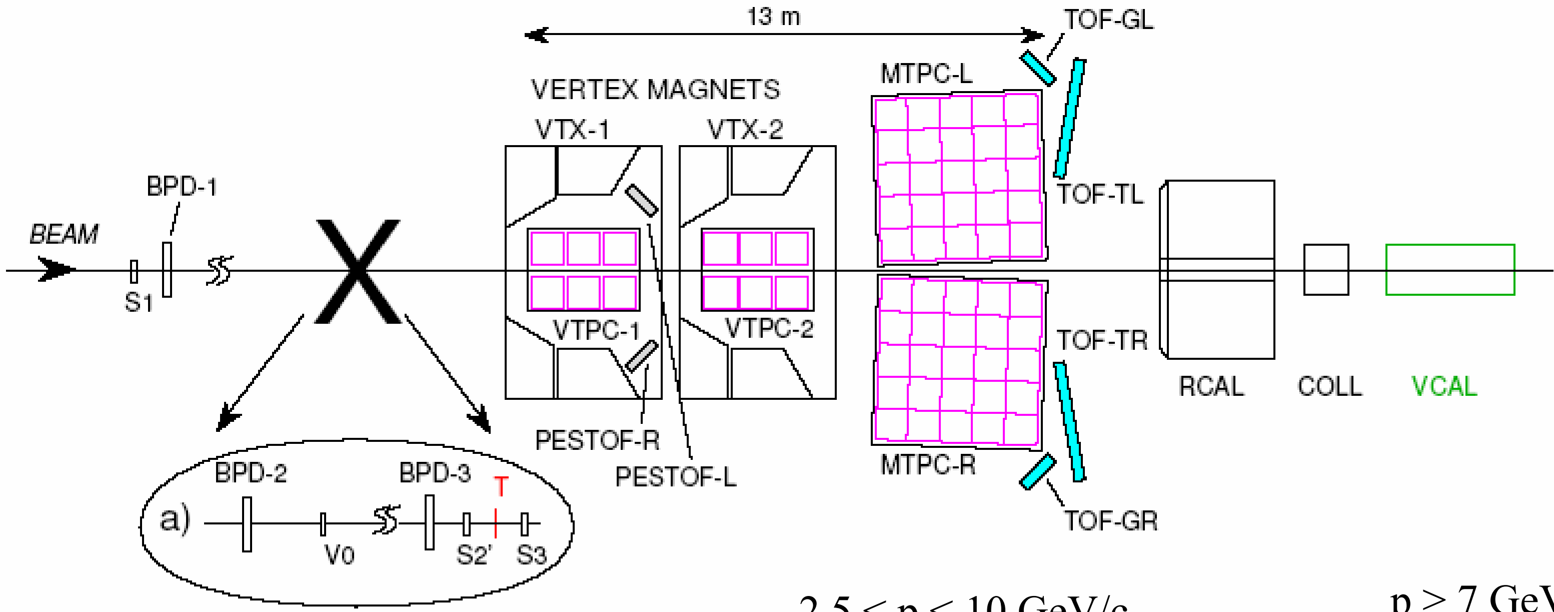
  (circumstantial evidence for a new state of matter (2000))
- Signatures not specific for deconfinement

➢ Search for a threshold by varying the energy for the largest collision system (central Pb+Pb reactions)

➢ SPS energy scan: 20, 30, 40, 80, 158 GeV/nucleon

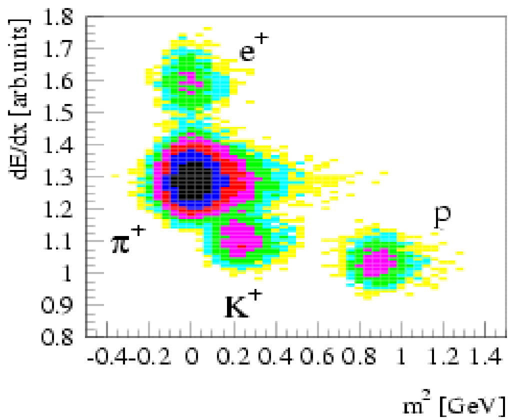
($\sqrt{s_{NN}}$ = 6.3, 7.6, 8.7, 12.3, 17.3 GeV) [completed in 2002]

The NA49 Detector

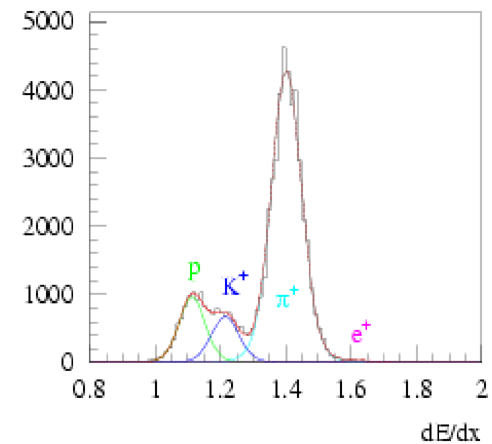


Target: Pb foil, 20 cm liquid H_2
VCAL detects projectile spectators
$\Delta p/p^2$ = 7 (0.3) • 10^{-4} $(GeV/c)^{-1}$
(VTPC-1, VTPC+MTPC)
Particle identification:
dE/dx (3 – 6 %), TOF (~ 60 ps)
decay topology (K^0_s , Λ, Ξ, Ω)
$\sqrt{s_{NN}}$ = 6.3, 7.6, 8.7, 12.3, 17.3 GeV

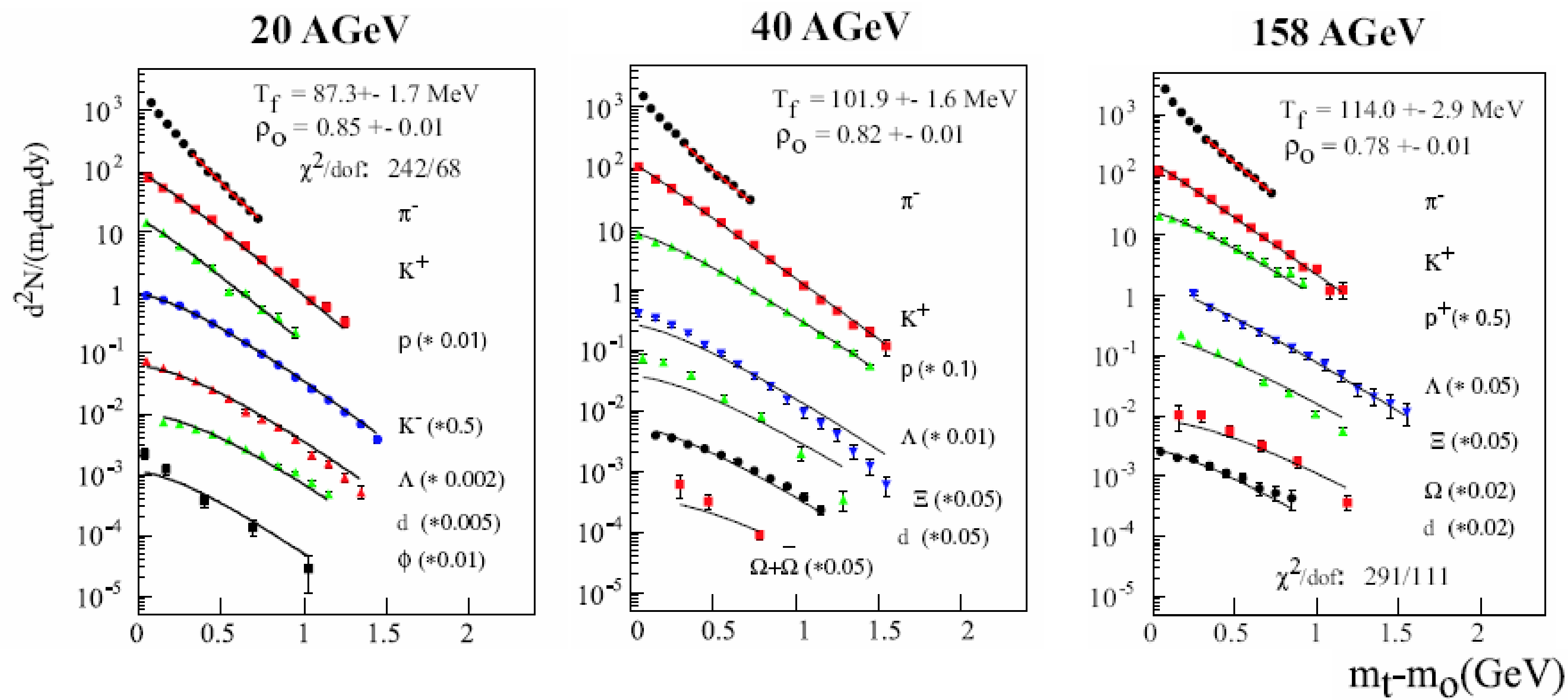
2.5 < p < 10 GeV/c
TOF + dE/dx
at midrapidity



p > 7 GeV/c
dE/dx
forward rapidity



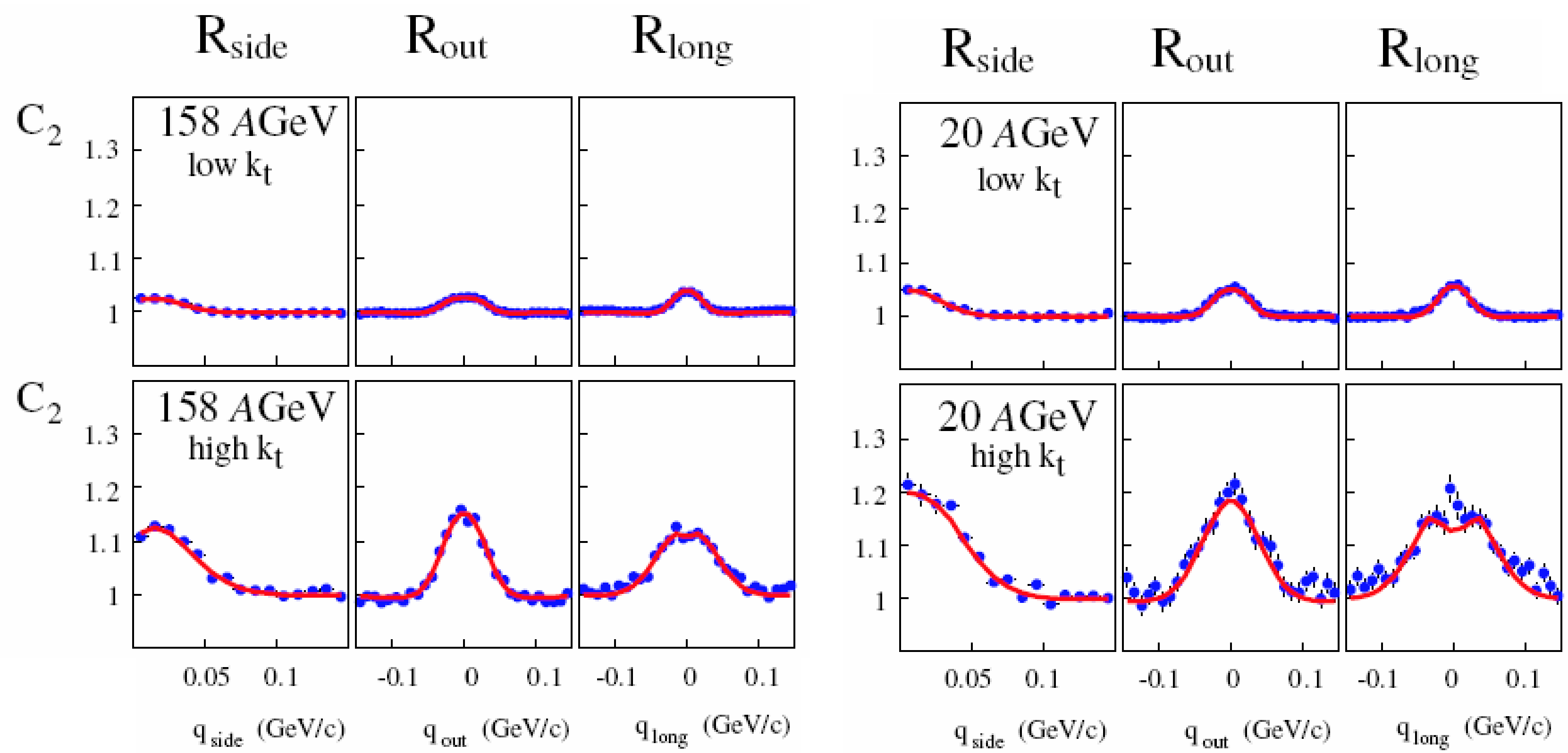
Transverse mass spectra at mid-rapidity



many spectra measured, hydrodynamics based “blast wave” model describes spectra at SPS

“kinetic” freeze out at T ≈ 90 –110 MeV, ρ_0 ≈ 0.8c at SPS

BE correlations sensitive to fireball size and flow

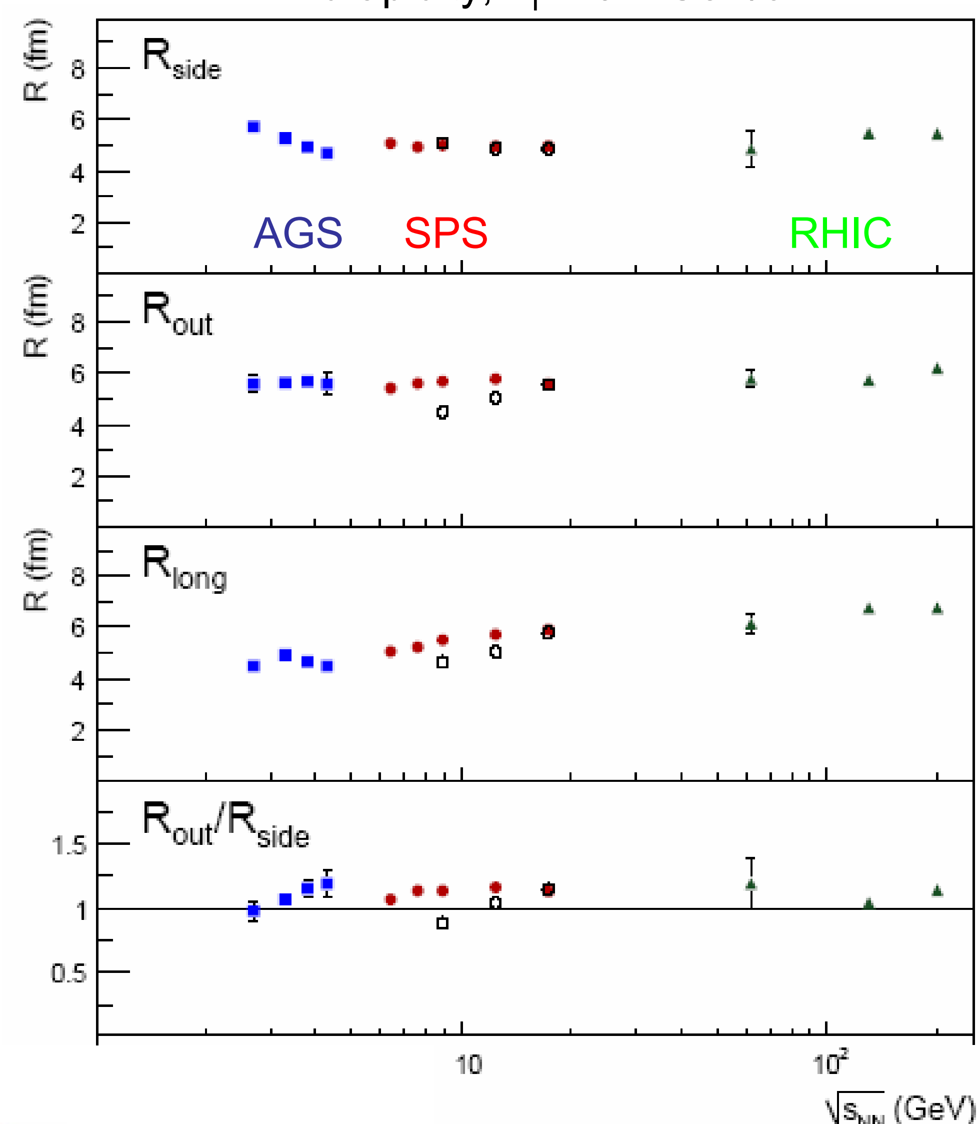


examples of $\pi^-\pi^-$ correlation functions at mid-rapidity
in the Cartesian (Bertsch, Pratt) reference frame

Fit to QS correlation (Gaussian) + Coulomb repulsion
$\rightarrow$ radius parameters R_i (length of homogeneity)

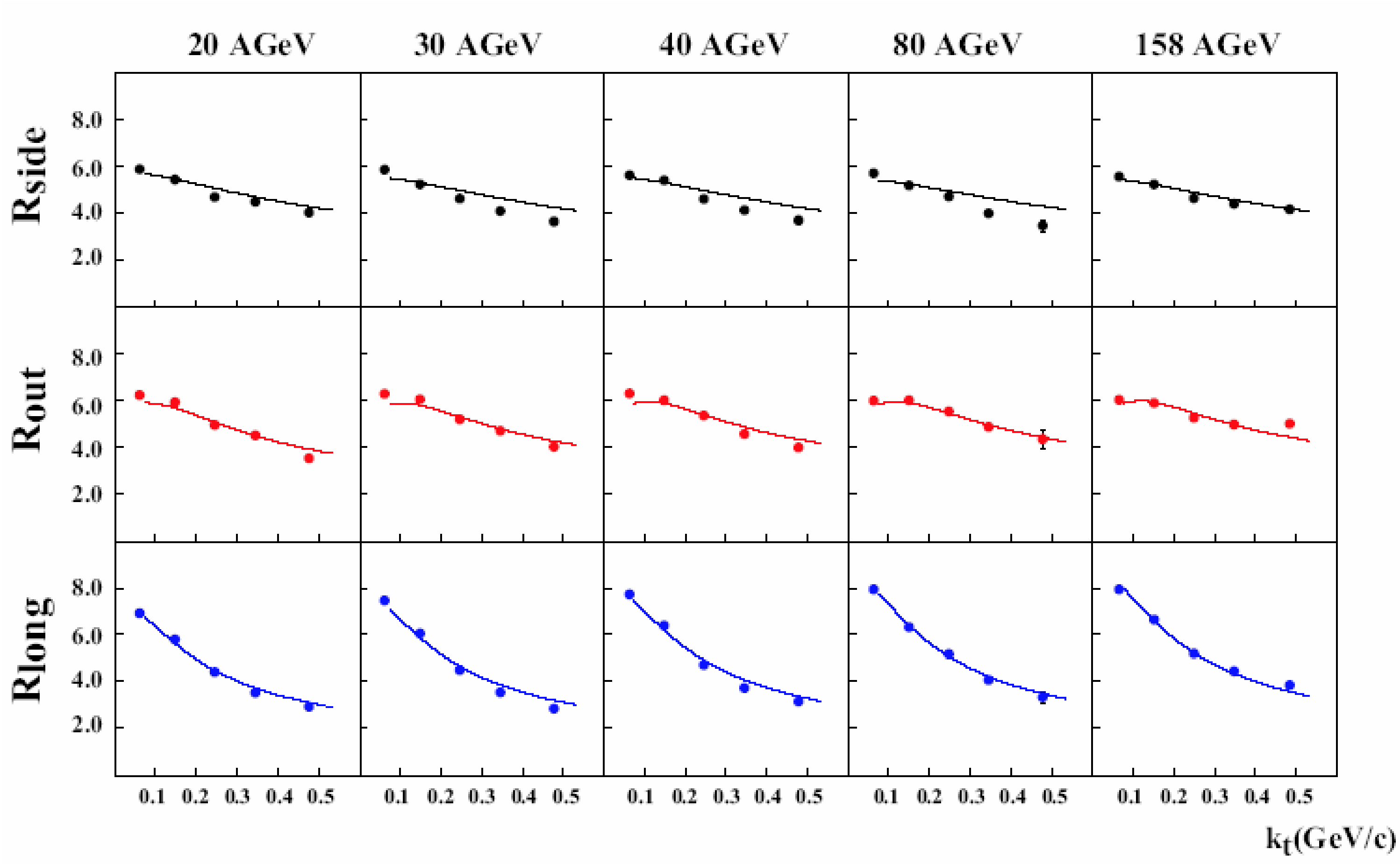
energy dependence of radius parameters

midrapidity, k_T = 0.2 GeV/c



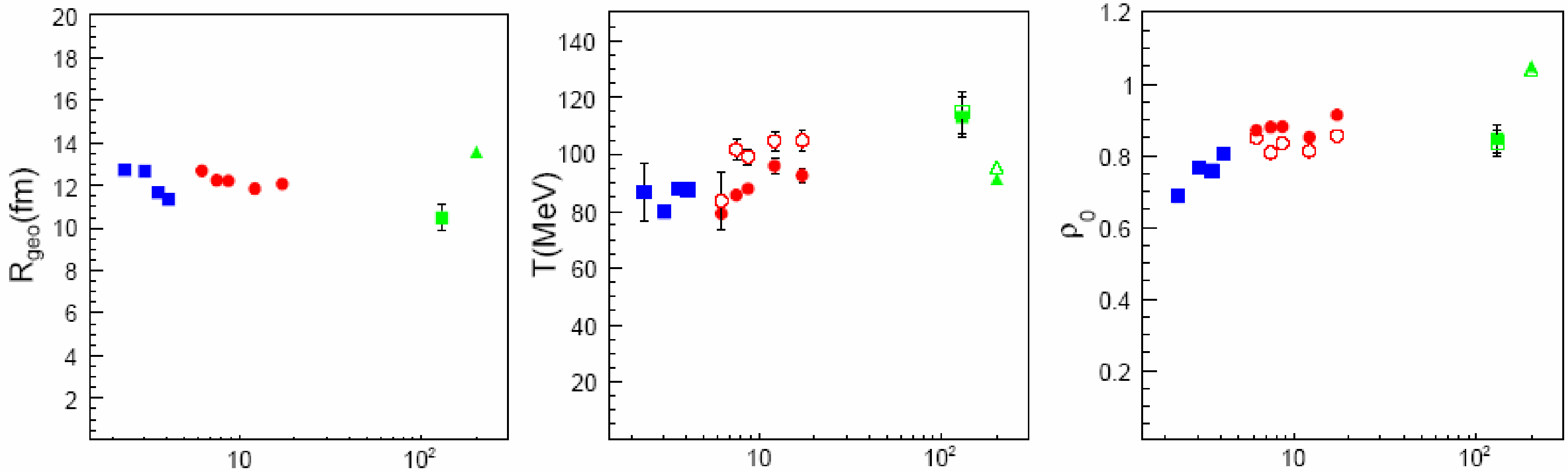
- remarkably little change of R_{side} (fireball radius) and R_{out}
- no indication of $R_{out} >> R_{side}$ i.e. long duration of π emission (1st order phase transition, soft point of EoS)
- slow rise of R_{long} (fireball lifetime)

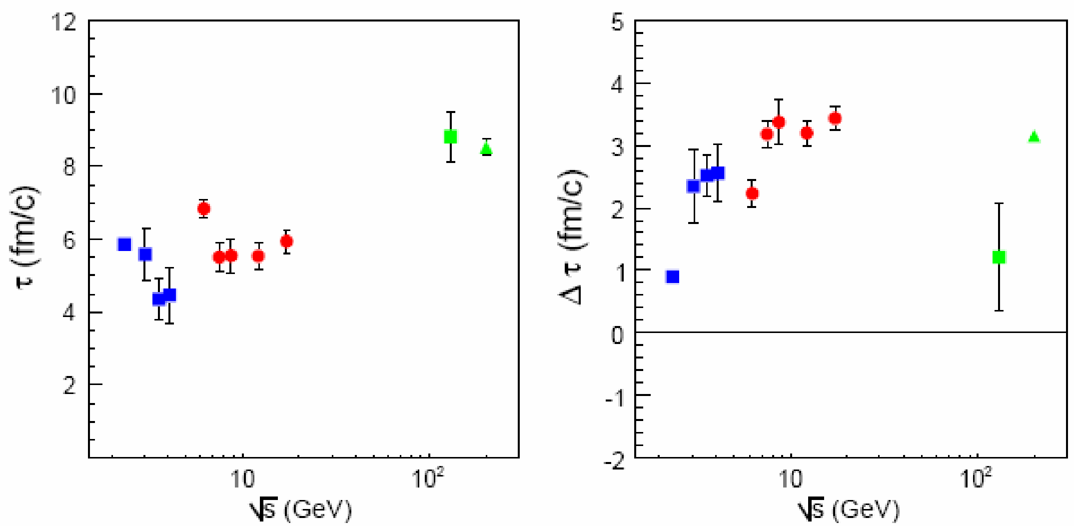
simultaneous "blast wave" fits to BE radii and π, p spectra



energy dependence of fireball parameters

blast wave parameterisation (Retiere,Lisa PRC70,044907(2004))



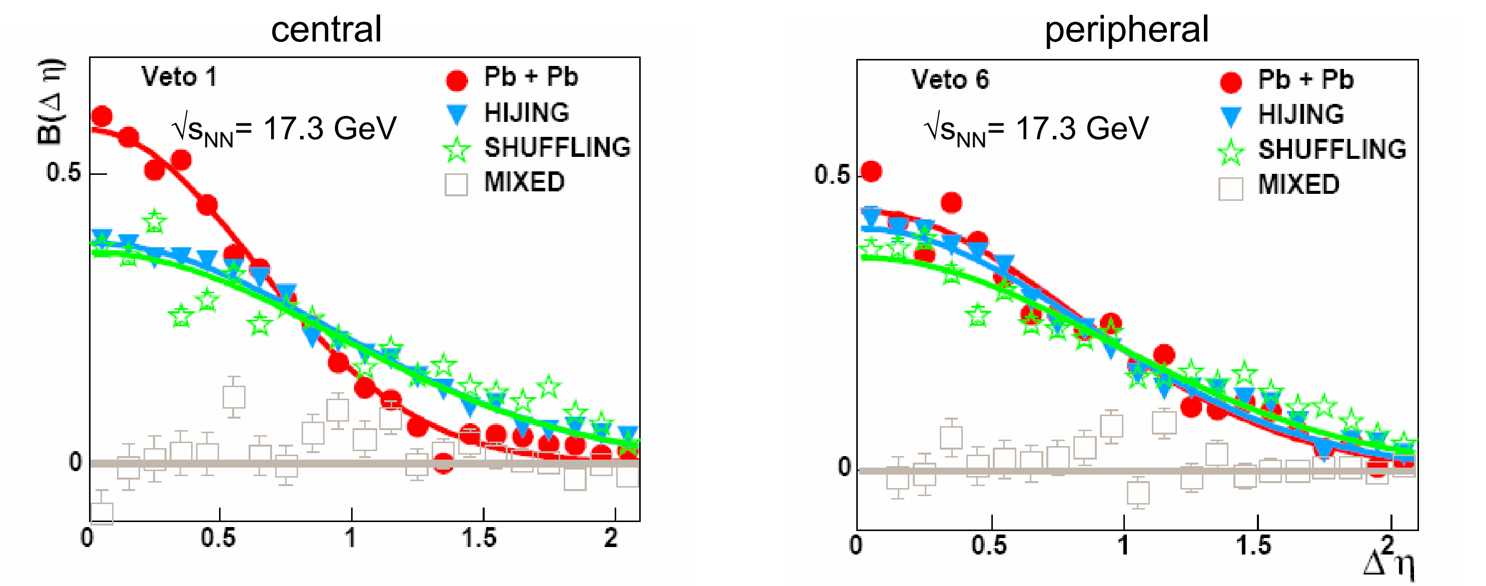


- constant radius
  $\approx 2 \cdot R_{Pb,Au}$
- slow increase of
  - freeze-out T
  - surface flow ρ_0
  - lifetime τ

Balance Function: charge correlations in pseudo-rapidity

$$B(\delta\eta) = \frac{1}{2}\left(\frac{N_{(+-)}(\delta\eta) - N_{(--)}(\delta\eta)}{N_-} + \frac{N_{(-+)}(\delta\eta) - N_{(++)}(\delta\eta)}{N_+} \right)$$

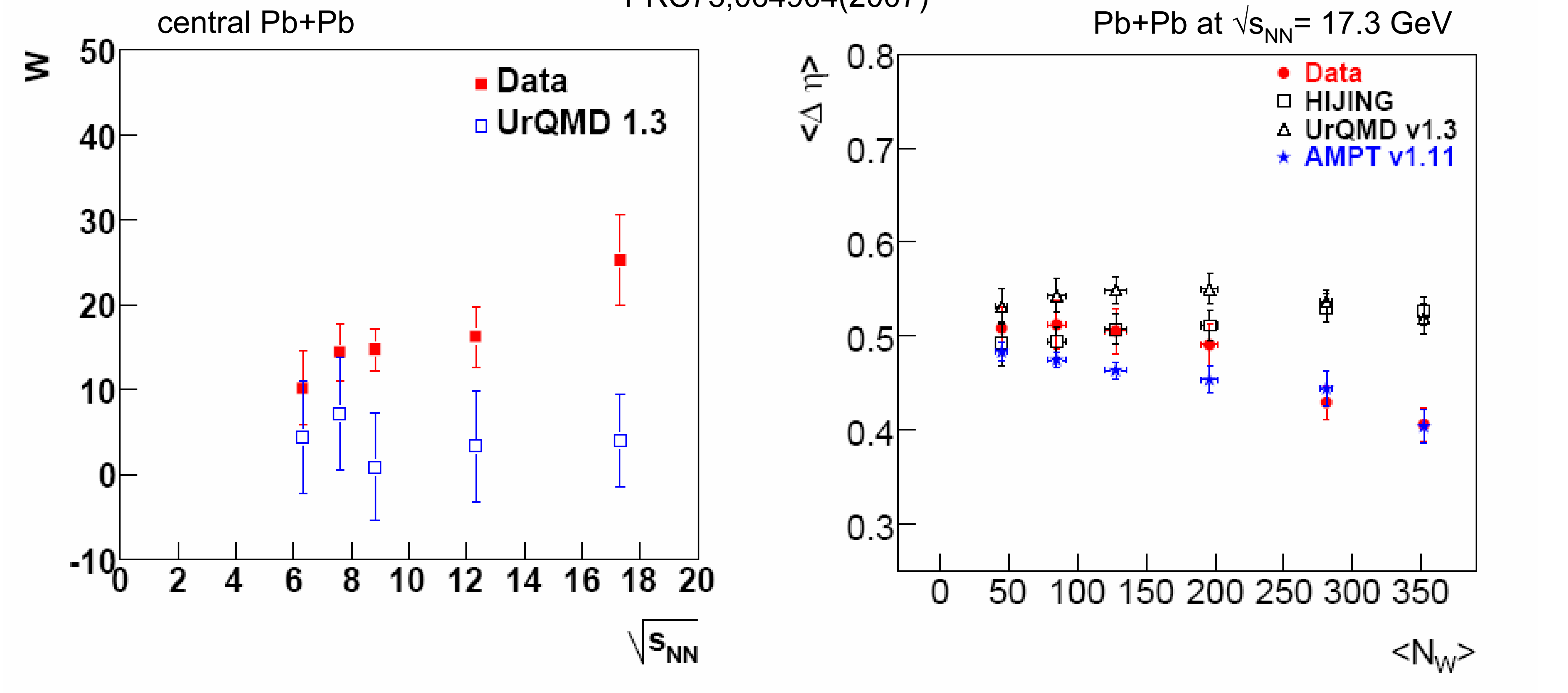
narrowing of the balance function proposed as QGP signature
(delayed hadronisation due to phase coexistence)



data compared to shuffled events: W = (<Δη>$_{shuff}$ - <Δη>$_{data}$)/ <Δη>$_{shuff}$ · 100
(scrambling of rapidities, retention of global charge conservation)

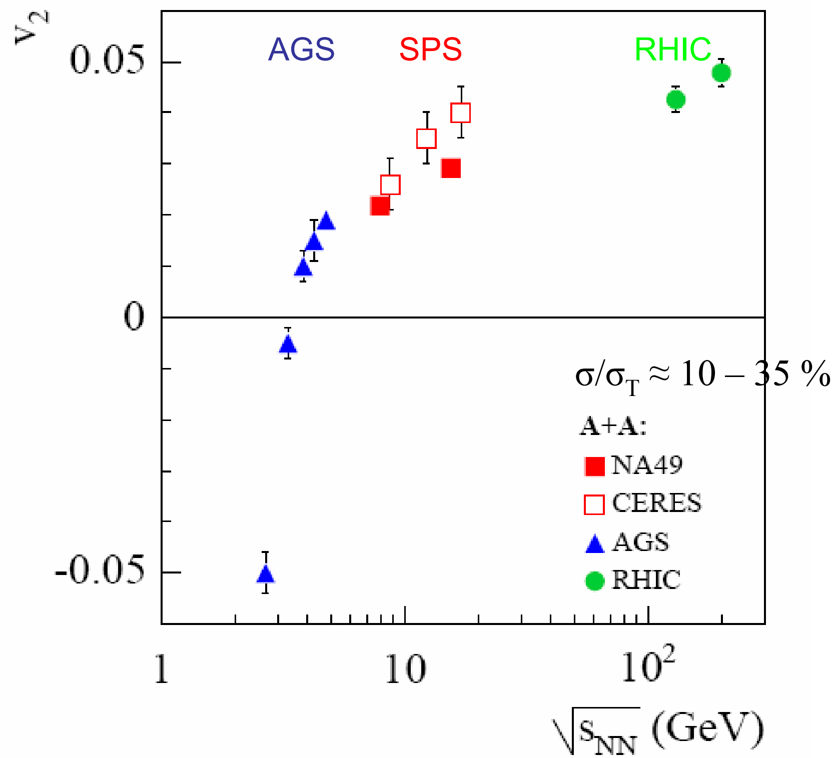
BF: model comparisons at mid-rapidity

PRC75,064904(2007)



- no anomaly at SPS energy: effects due to local charge conservation and radial flow may dominate (Pratt, Bialas)
- microscopic model AMPT with deconfined phase reproduces BF narrowing

Anisotropic flow v_2 of pions: energy dependence



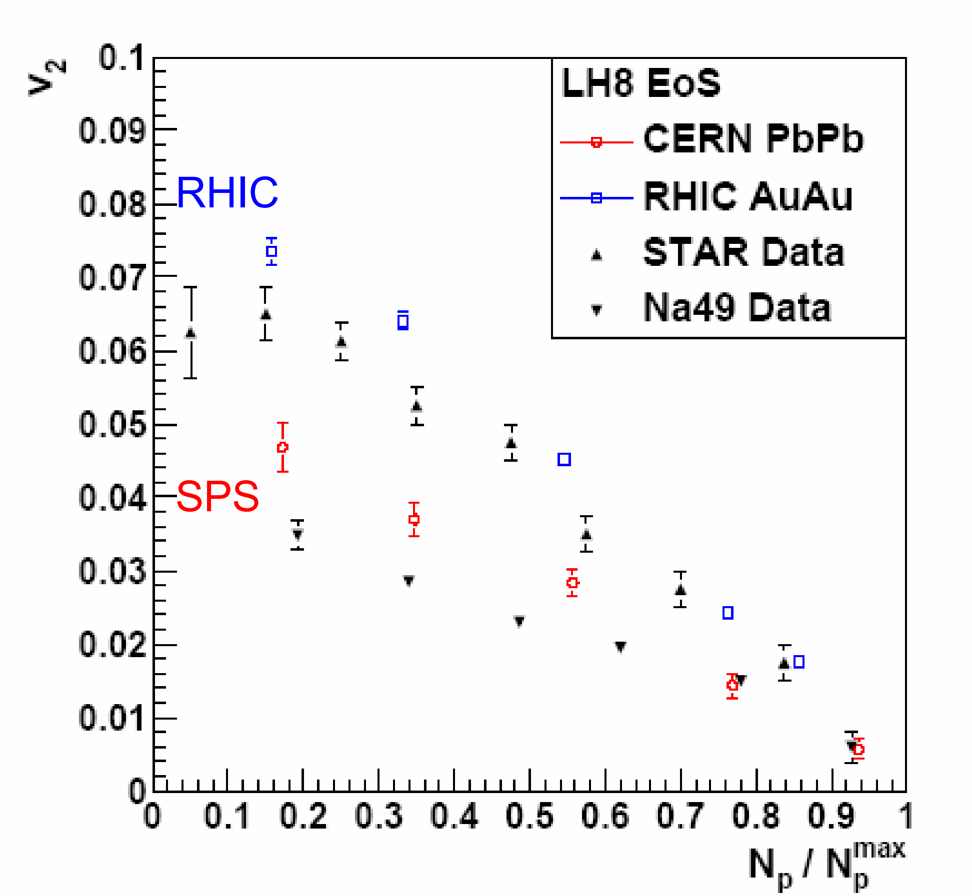
- change from out-of-plane (shadowing) to in-plane (hydro) at AGS
- rate of increase of v_2 slows between AGS and SPS
- steady rise from SPS to RHIC

(partly due to yield increase at higher p_T)

model interpretation of elliptic flow at SPS and RHIC

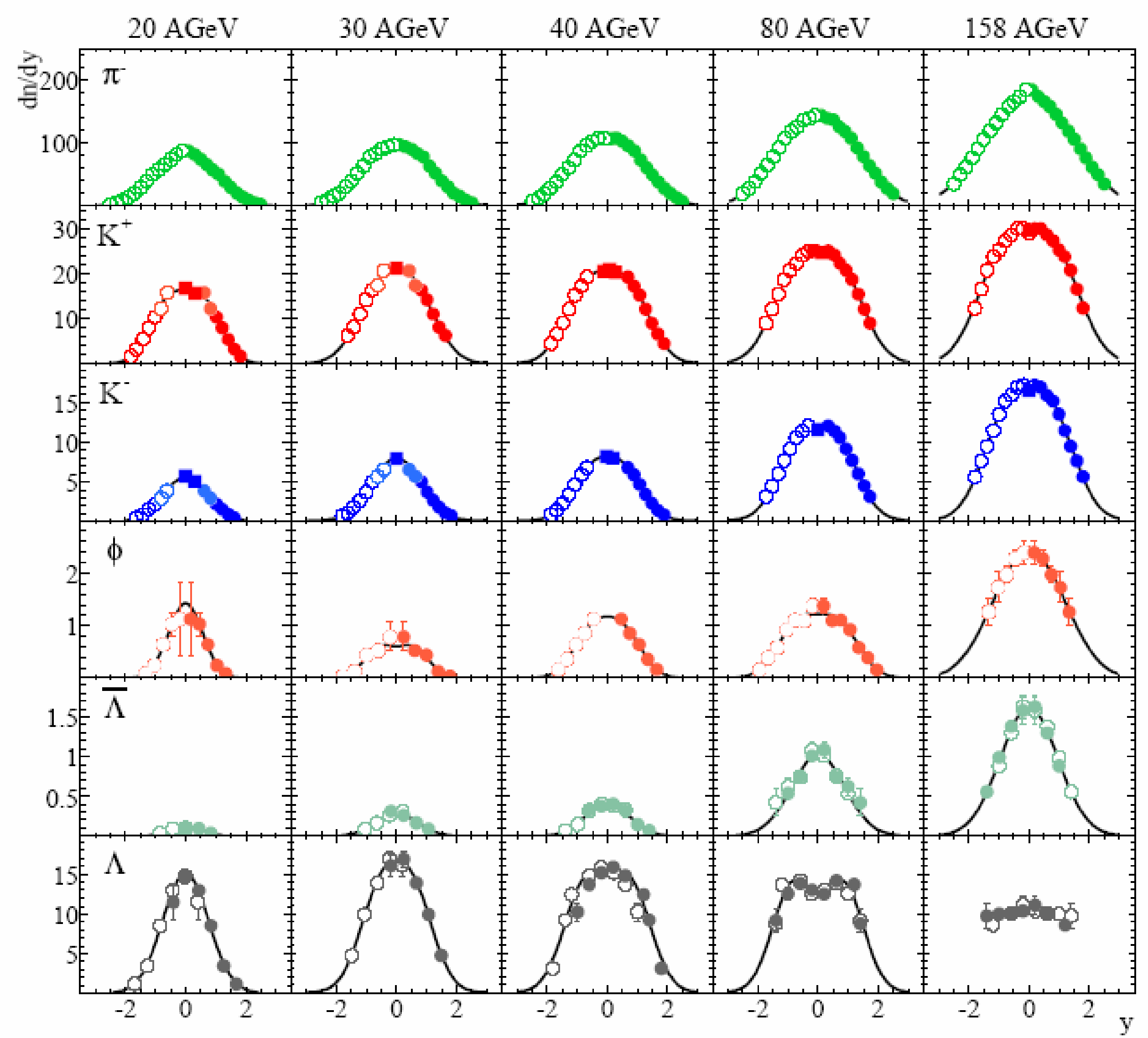
- QGP + hydrodynamic expansion
- statistical hadronisation by quark coalescence
- freeze-out via hadronic re-scattering stage (RQMD)

Teaney, Lauret, Shuryak
PRL 86 (2001) 4783



hydro model with QGP phase provides fair description of SPS and RHIC data

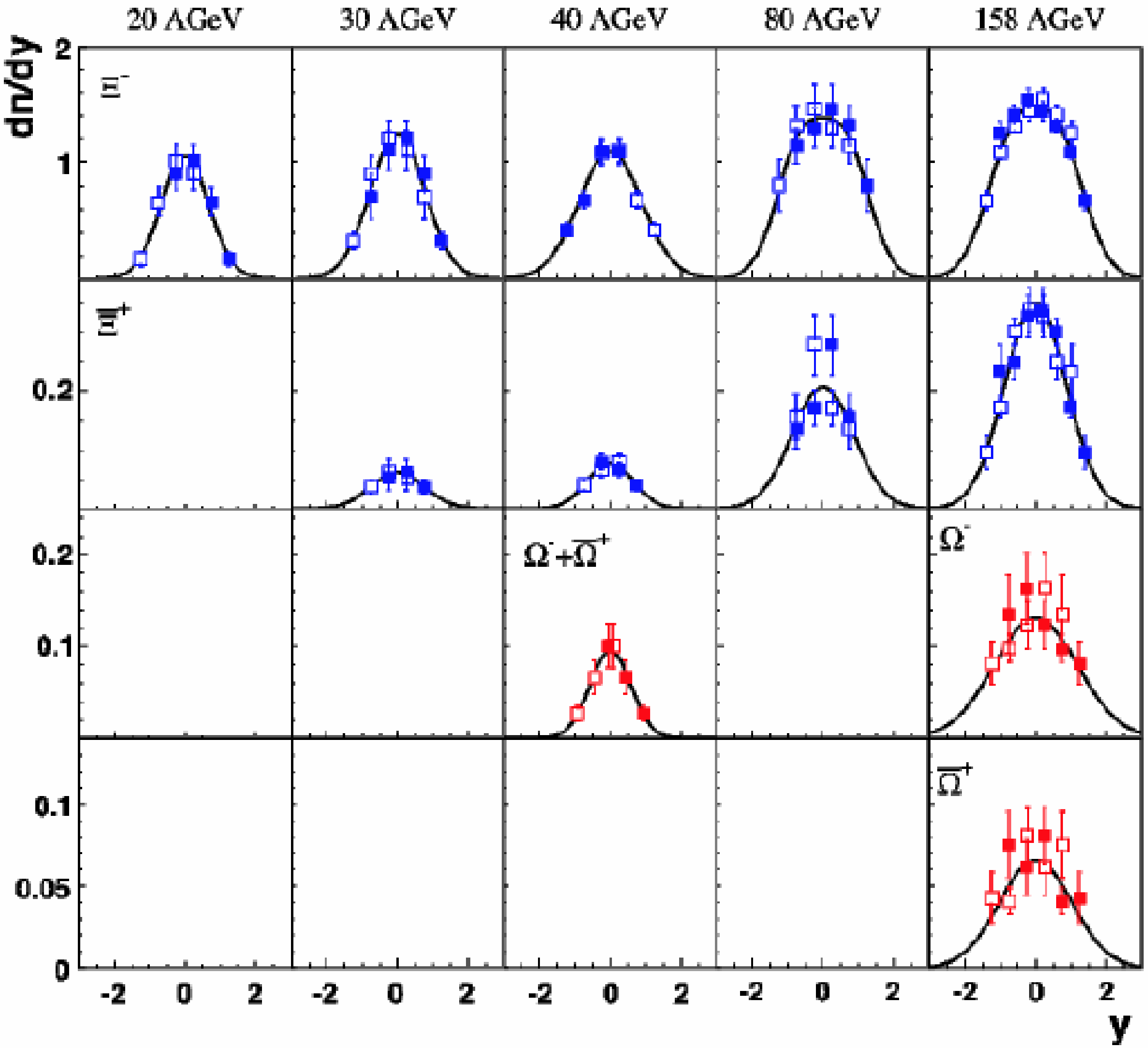
Rapidity spectra



Extraplation
→ 4π yields

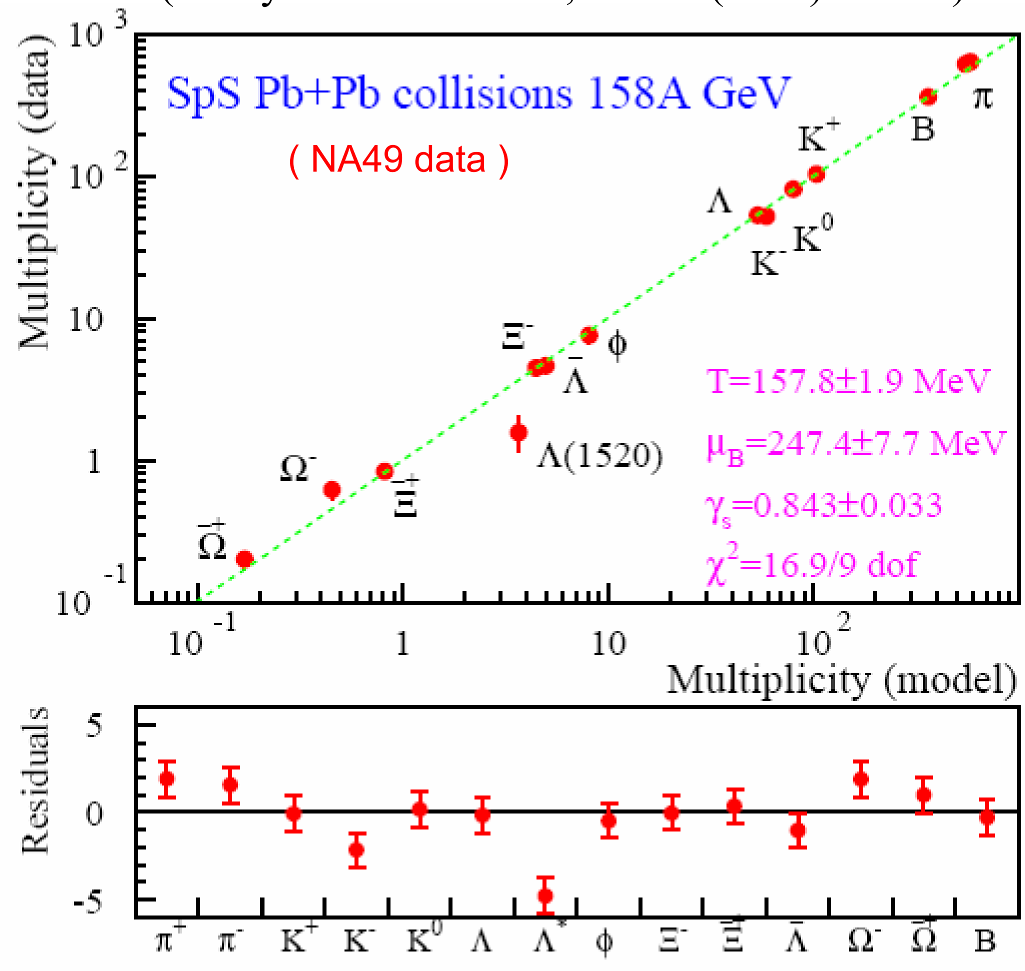
(open dots from
reflection at y_{cm}= 0)

4π yields obtained also for multi-strange hyperons Ξ, Ω



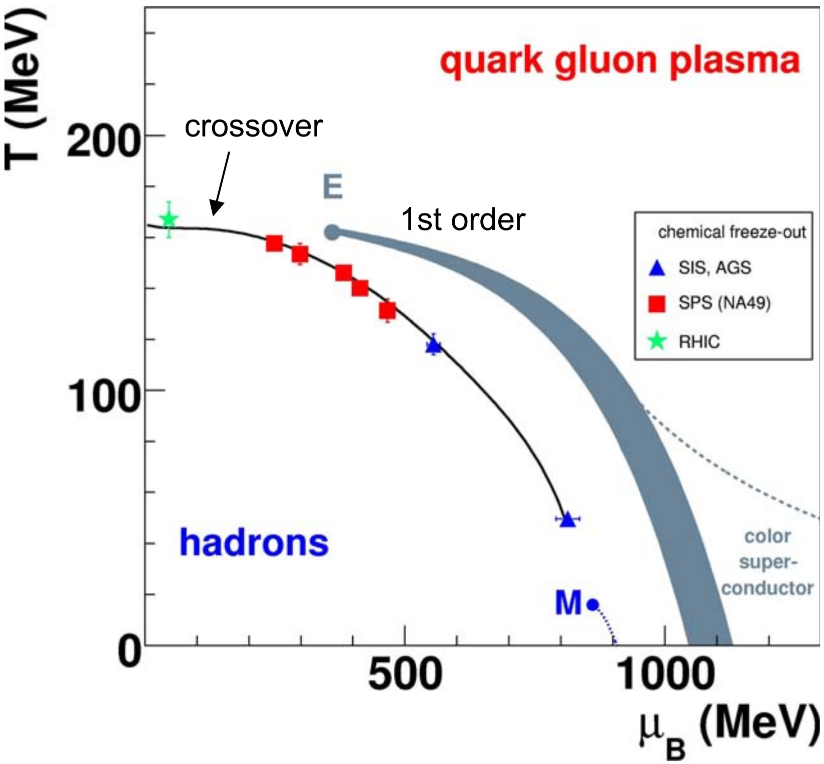
Particle yields – statistical model

(fits by F.Becattini et al, PRC69(2004)024905)



- hadron species populated approximately according to phase space probabilities (max.entropy) (Fermi,Hagedorn)
- strangeness sector not fully saturated (Rafelski)
- statistical model successful in A+A, p+p, $e^+ + e^-$
- parameters: T, μ_B, γ_S, V

Global view - Phase diagram



(critical point E from Lattice-QCD: Fodor,Katz JHEP 04 (2004) 050)

- statistical model describes yields from SIS to RHIC energy
- T of "hadro-chemical" freeze-out increases SIS → RHIC
- μ_B decreases (increase of pion production)

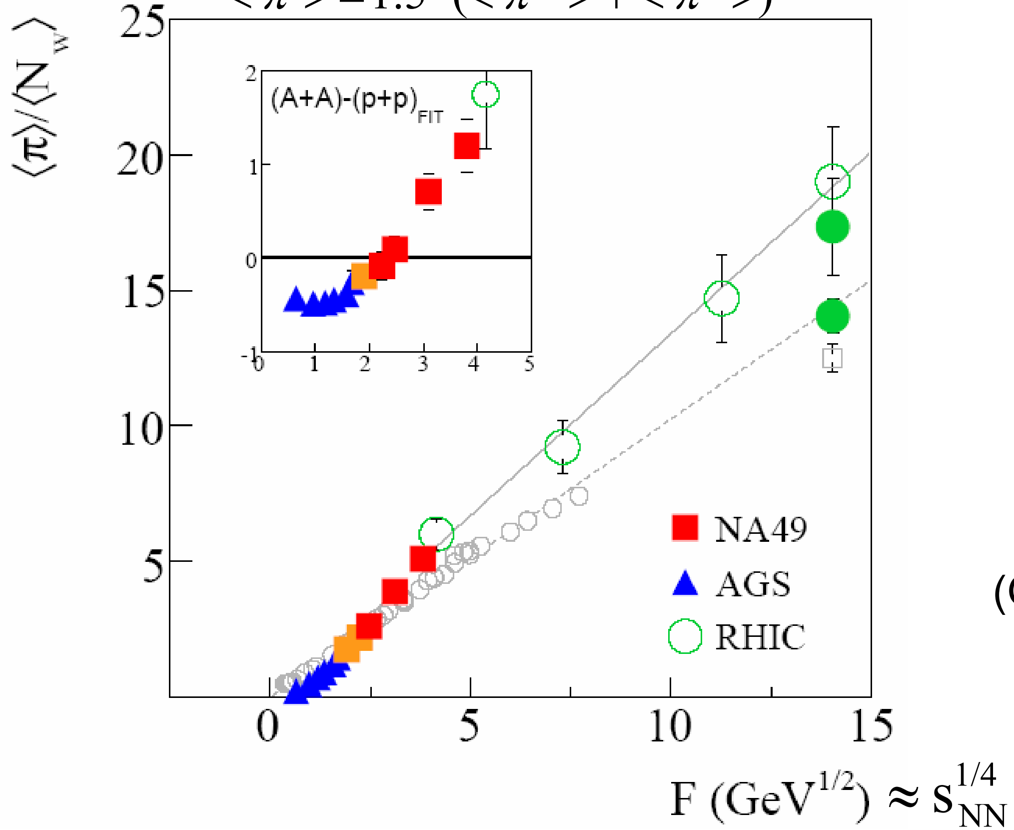
- freeze-out line E ≈ 1 GeV / particle (Cleymans and Redlich, PRL 81(1998) 5284)

hadro-chemical freeze-out parameters approach the phase boundary at SPS

Energy dependence - total pion yields

- increase of $\langle\pi\rangle/\langle N_W\rangle$ with energy gets steeper in the SPS range
- π deficit changes to enhancement compared to p+p

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



- pions are most abundant produced particle species
  → measure of produced entropy in statistical models

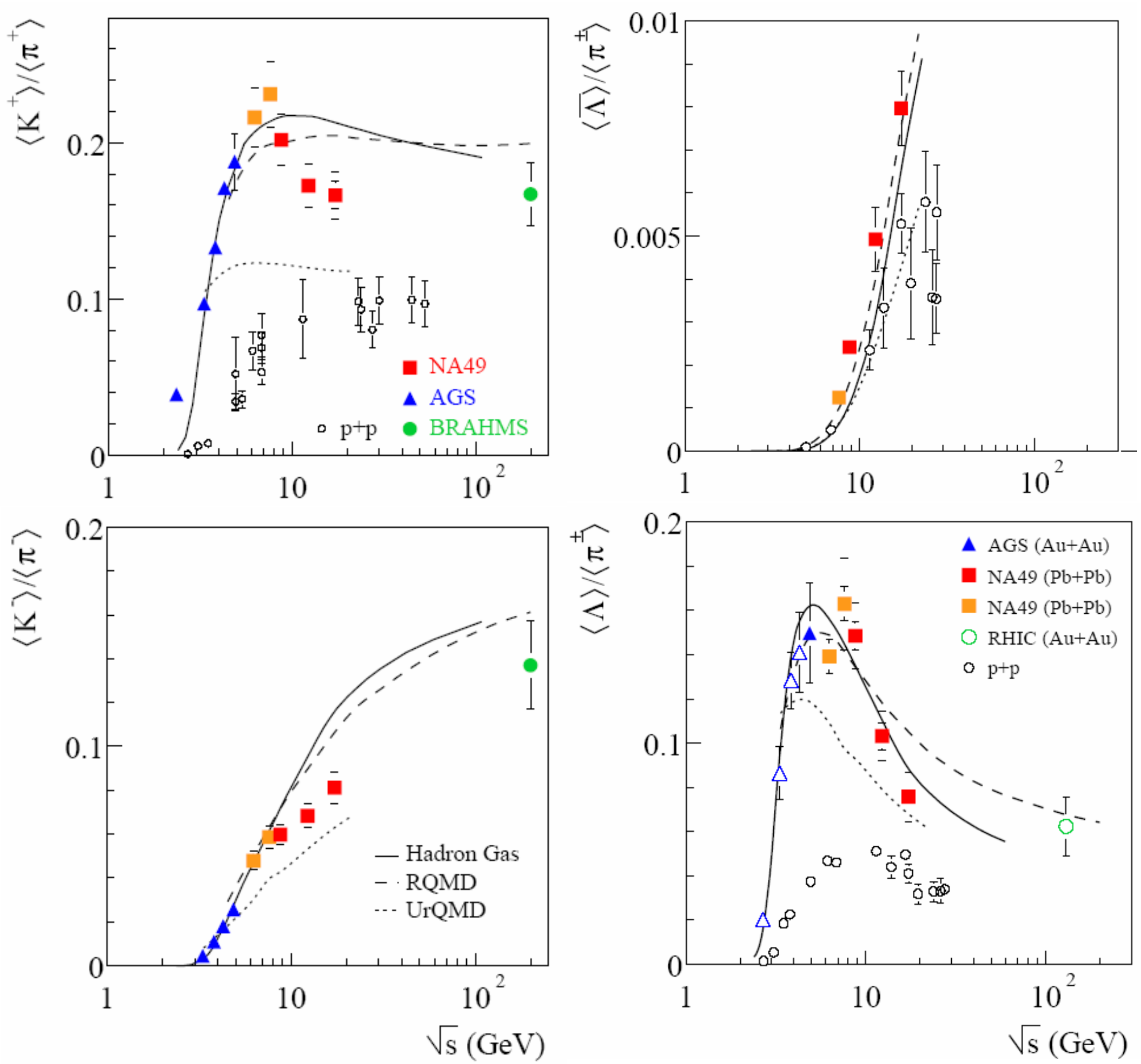
SMES: statistical model of the early stage

$$\frac{\langle\pi\rangle}{N_w} \propto \frac{S}{N_w} \propto g^{1/4} F \qquad F = \frac{(\sqrt{s}-2m_p)^{3/4}}{\sqrt{s}^{1/4}}$$

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

Increase x 3 of initial d.o.f. g between AGS and SPS ?

Energy dependence - ratio of K, Λ yields to pions



$\bar{s}$ quark carriers:

- sharp peak of K^+/π^+ ratio
- $\bar{\Lambda}$ yield small

hadronic models do not reproduce the sharp peak

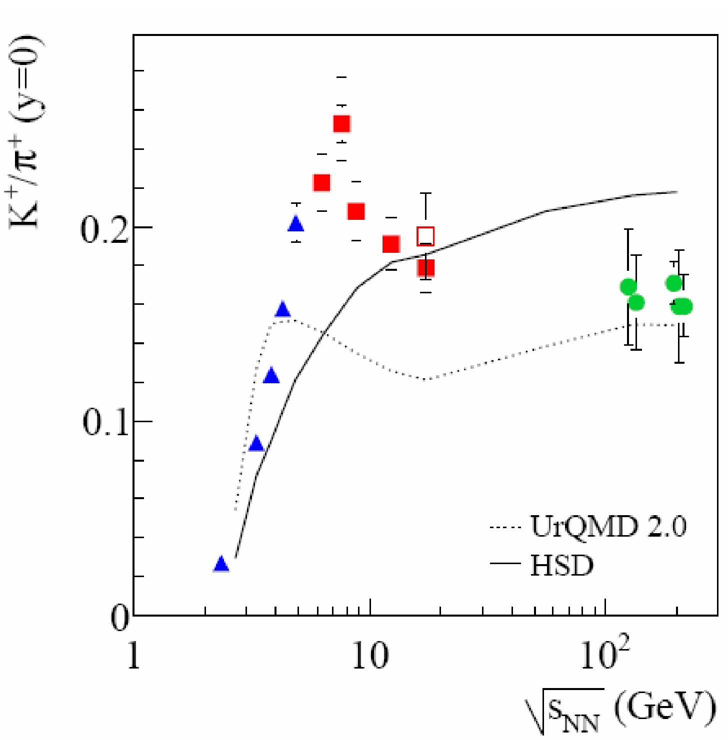
s quark carriers:

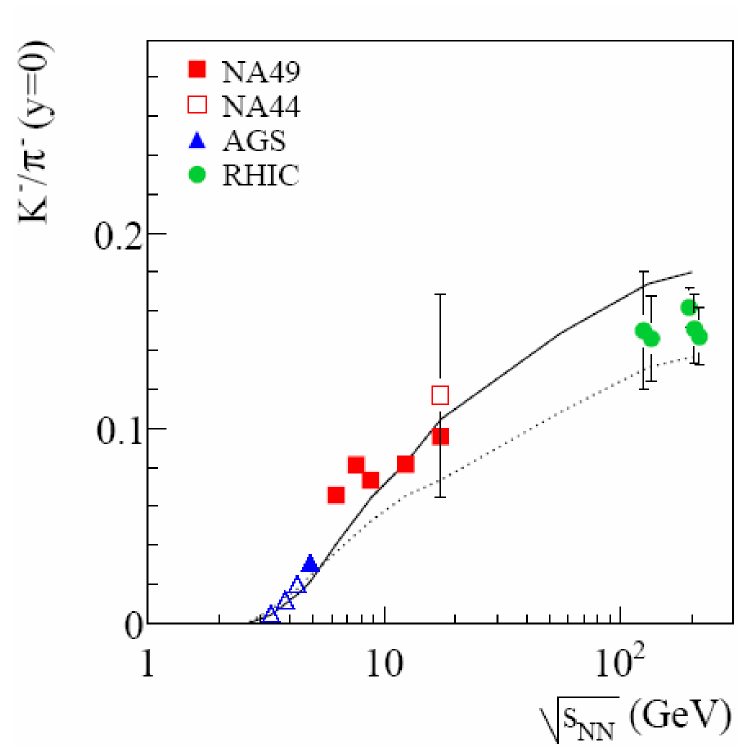
- similar peak in Λ/π ratio
- structure in K^-/π^-

$$<\pi^\pm> = \frac{1}{2}(<\pi^+> + <\pi^->)$$

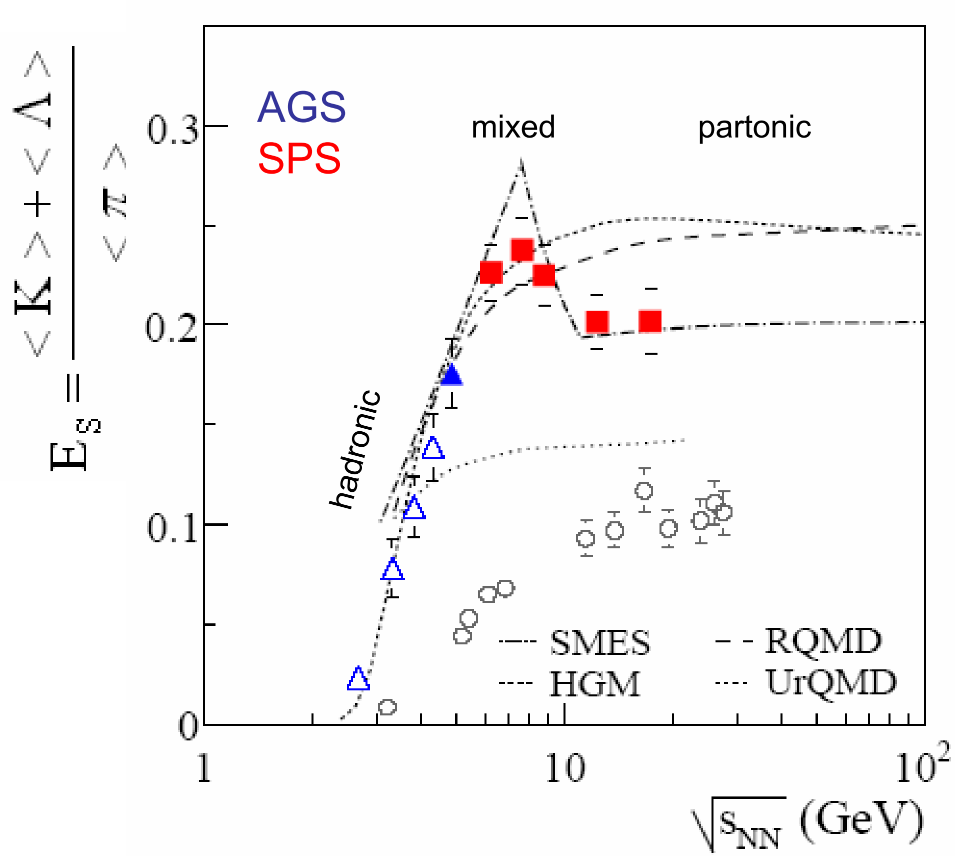
the energy dependence of the K/π ratios at mid-rapidity shows similar structure as the 4π results !

at mid-rapidity identification is from dE/dx and TOF





Energy dependence – ratio of strange hadrons to pions



strangeness to pion ratio 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 :

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

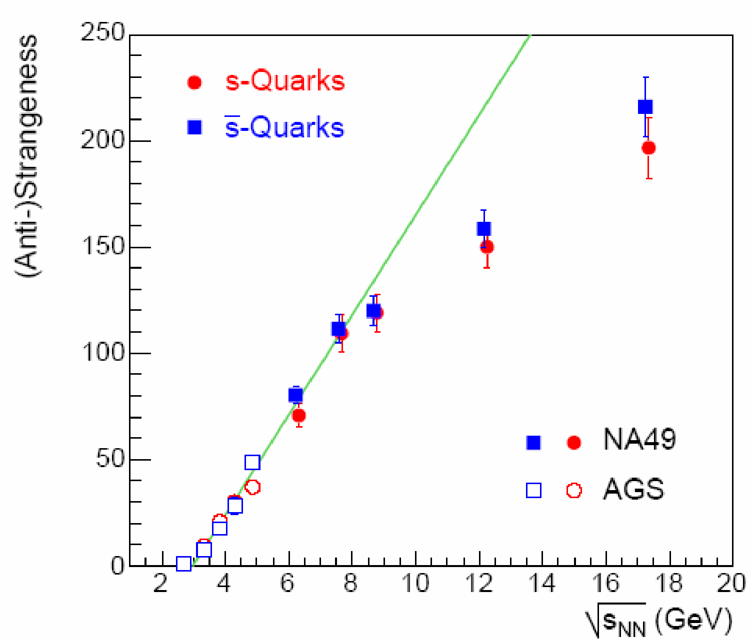
$$\approx 0.21$$

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

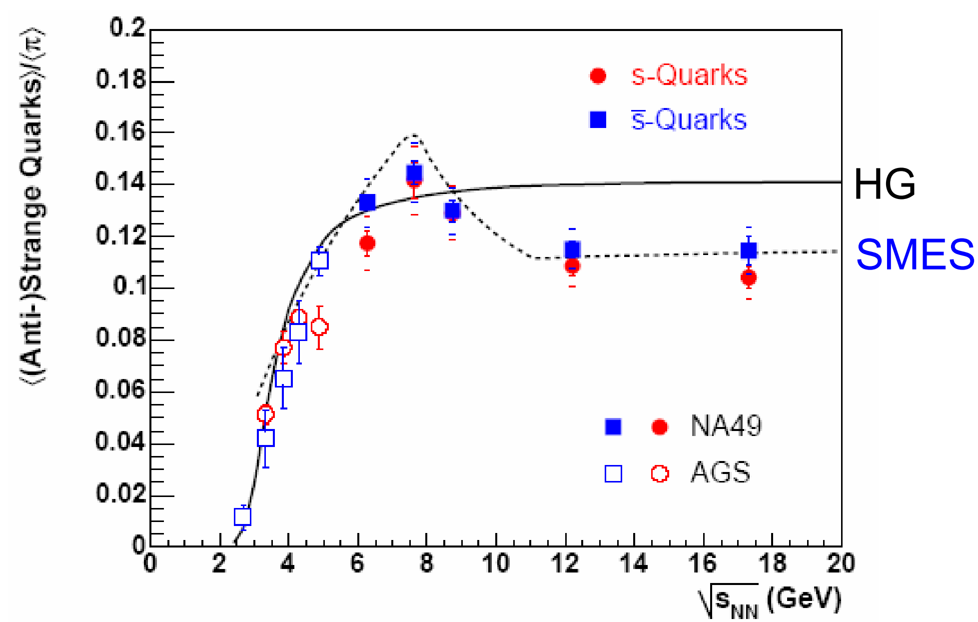
suggests onset of deconfinement at SPS

Energy dependence of total yield of s, $\bar{s}$ quarks

estimated using: isospin symmetry
unmeasured yields from statistical HG model predictions

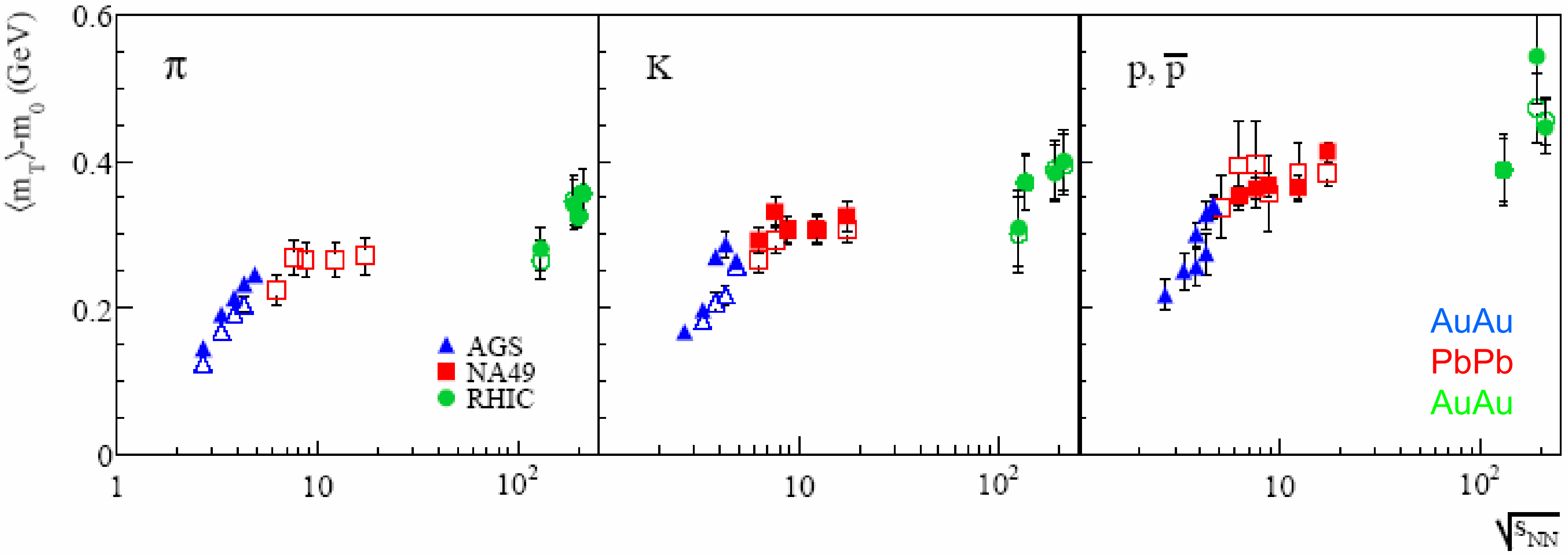


energy dependence of yields changes at 30A GeV



sharp peak, then under-saturation of strangeness content

Energy dependence - average transverse mass

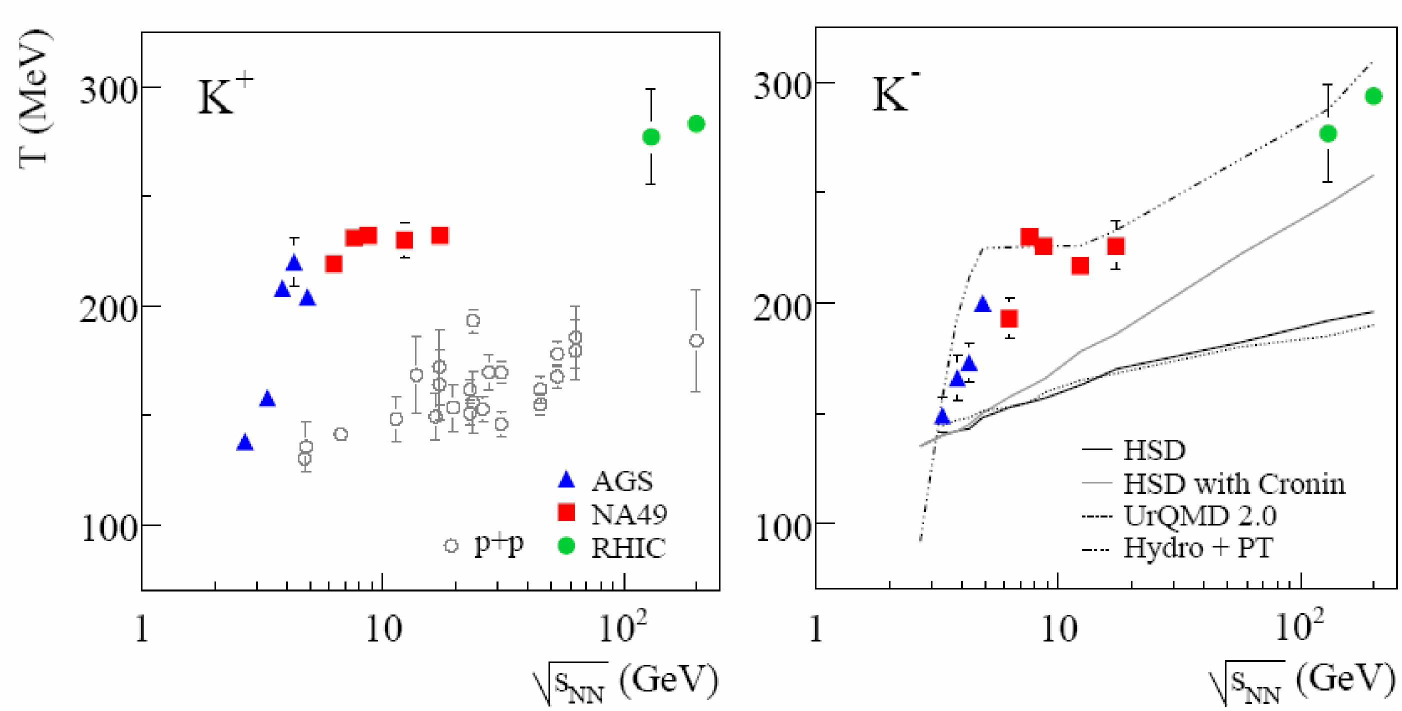


• Increase of <m_T> for abundant final state particles (π, K, p) slows sharply at the lowest SPS energy

• consistent with approximately constant pressure and temperature in a mixed phase system

(L.van Hove, PLB 89 (1982) 253; M.Gorenstein et al.,PLB 567 (2003) 175)

Energy dependence – inverse slope parameters



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

- the step-like feature observed, not seen for p+p collisions and models without phase transition

- hydrodynamic model with deconfinement phase transition starting at the SPS describes measurements

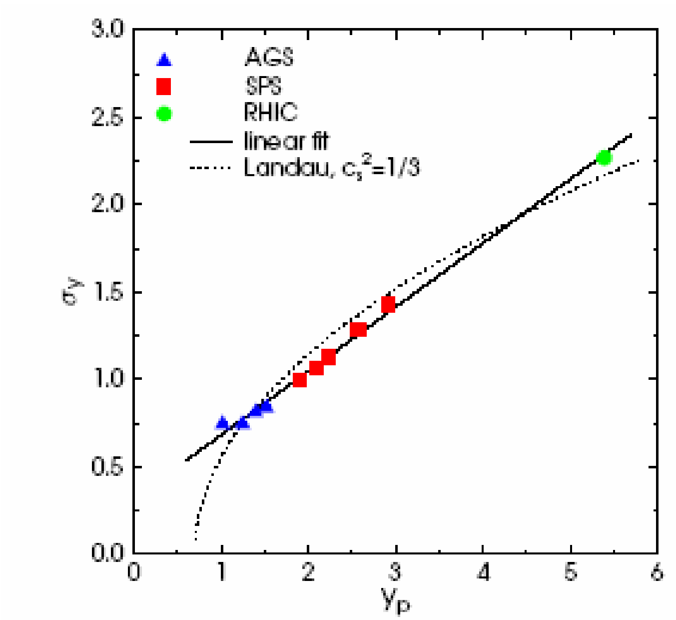
(model SPheRIO: S.Hama at al., Braz.J.Phys. 34 (2004) 322)

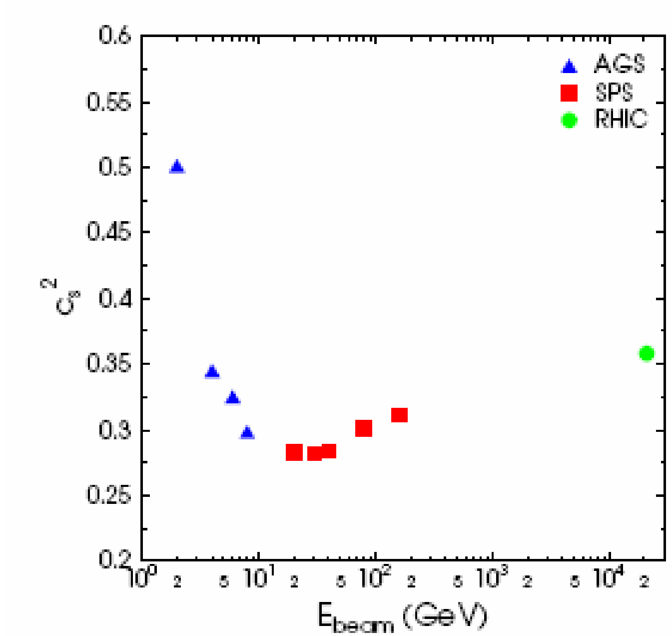
Sound velocity c_s from longitudinal momentum distributions

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

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

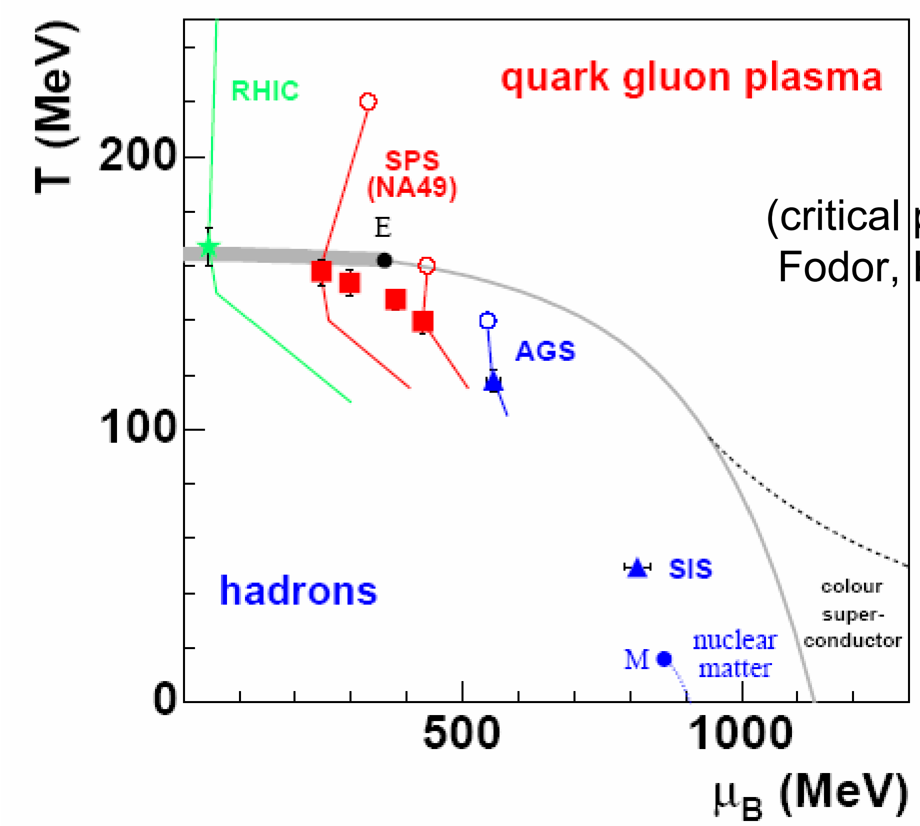
$$\sigma_y^2 = \frac{8}{3}\frac{c_s^2}{1-c_s^4}\ln(\sqrt{s_{NN}}/2m_p)$$





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

hypothetical trajectories in the phase diagram



(critical point E from Lattice-QCD: Fodor, Katz JHEP 04 (2004) 050)

significant (event-by-event) fluctuations are expected when the system hadronises close to the predicted QCD critical point E

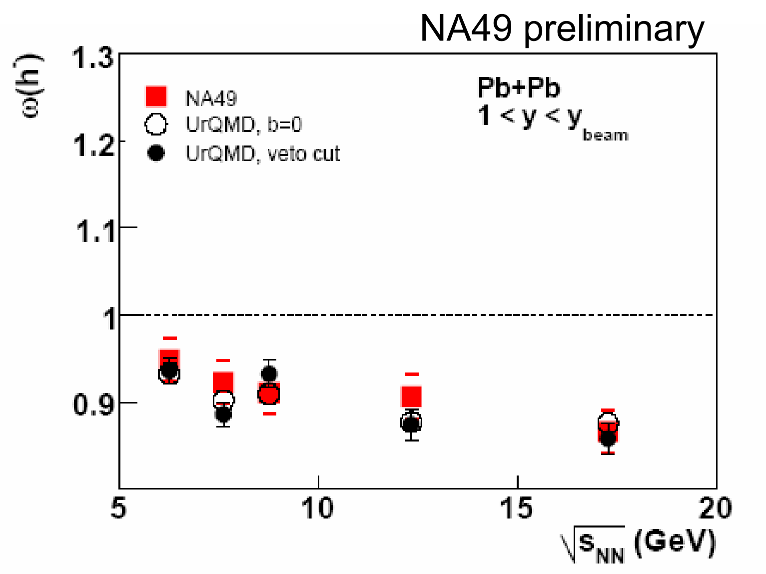
Multiplicity and $<p_T>$ fluctuations of negative hadrons vs $\sqrt{s_{NN}}$

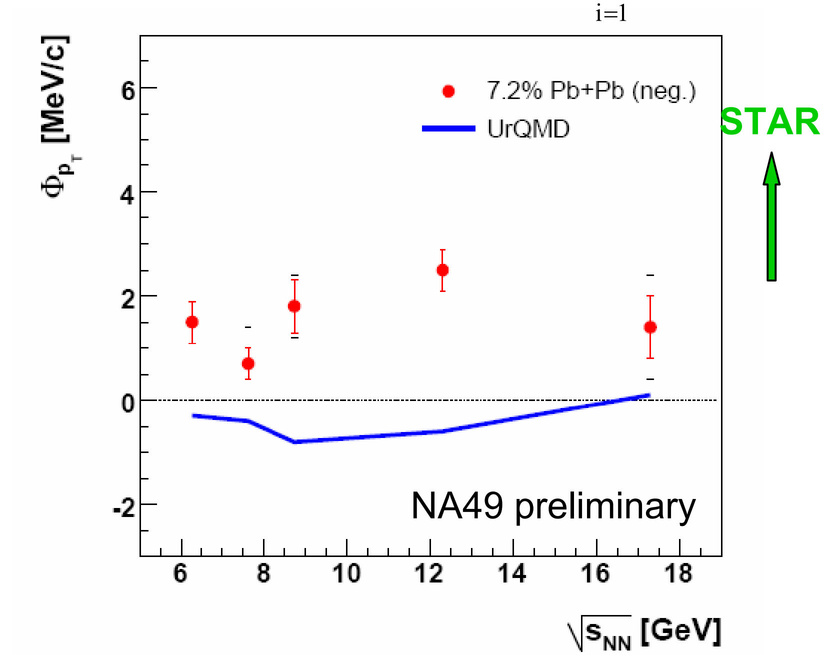
central Pb+Pb collisions $(1.1 < y_\pi < 2.6)$

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

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

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



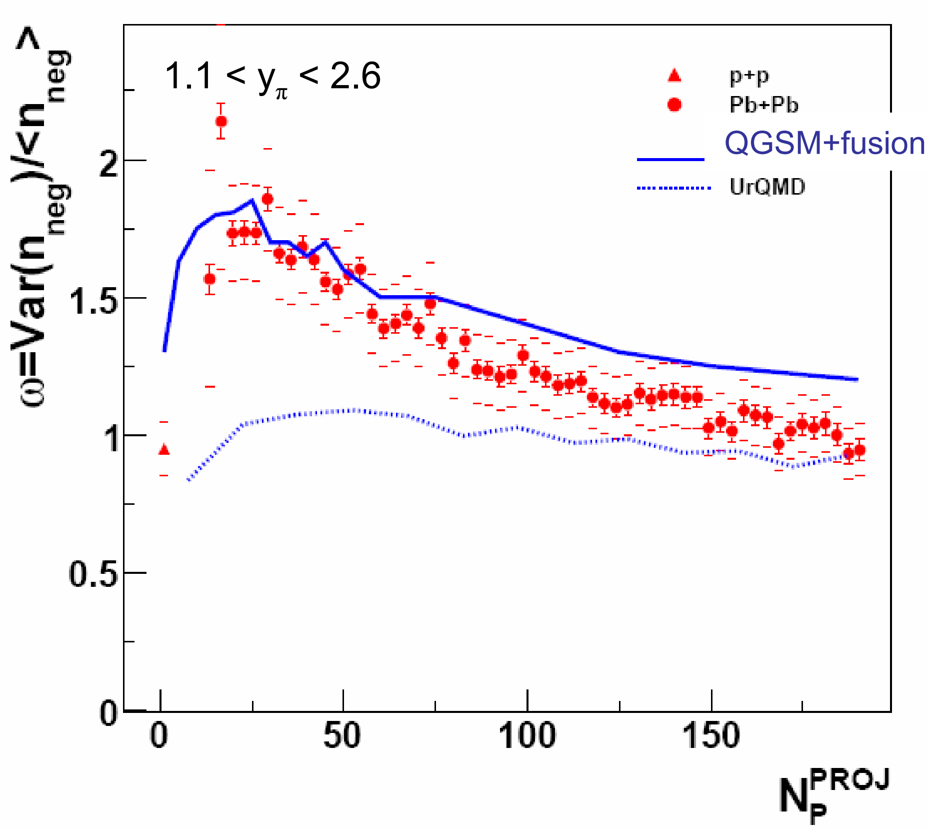


- no indication of maximum at SPS for central Pb+Pb collisions
- predictions for critical point ($\Delta\omega \approx 0.1$, $\Delta\Phi_{Pt} \approx 10$ MeV/c) excluded

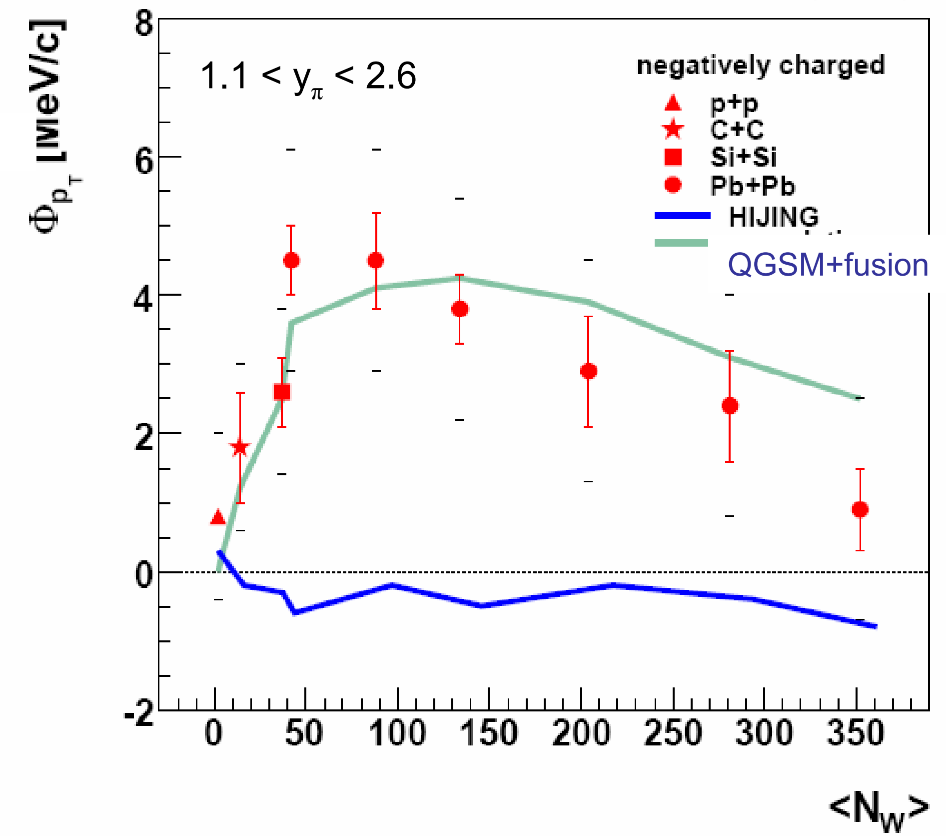
(M. Stephanov et al., PRD60,114028 (1999))

Multiplicity and $\langle p_T \rangle$ fluctuations of negative hadrons: centrality dependence in Pb+Pb collisions at 158A GeV

PRC75,064904(2007)



PRC70,034902(2004)

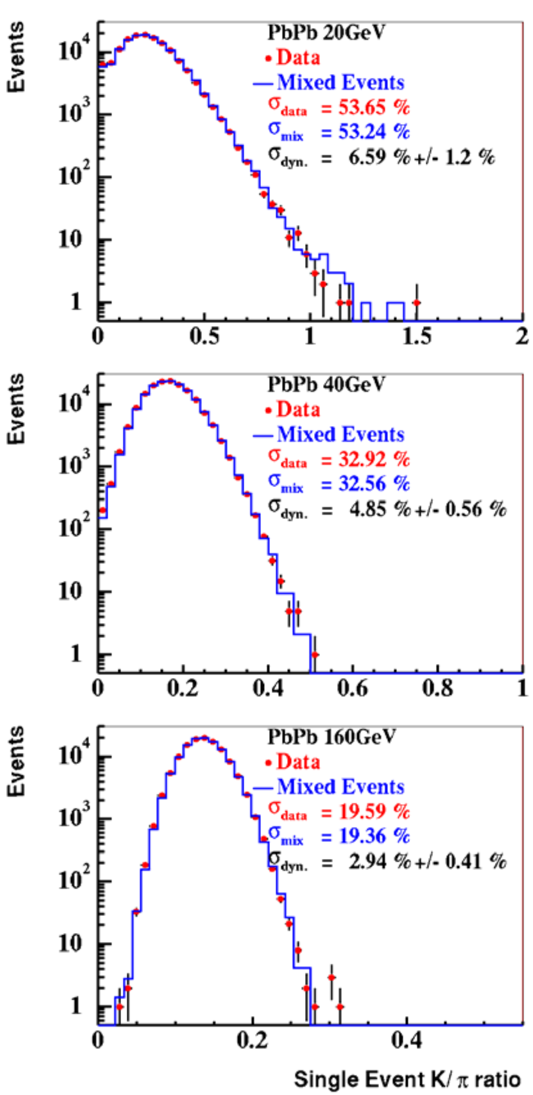


decrease towards central collisions; effect of string fusion ?

(E.Ferreiro et al, PRC 69, 034901 (2004))

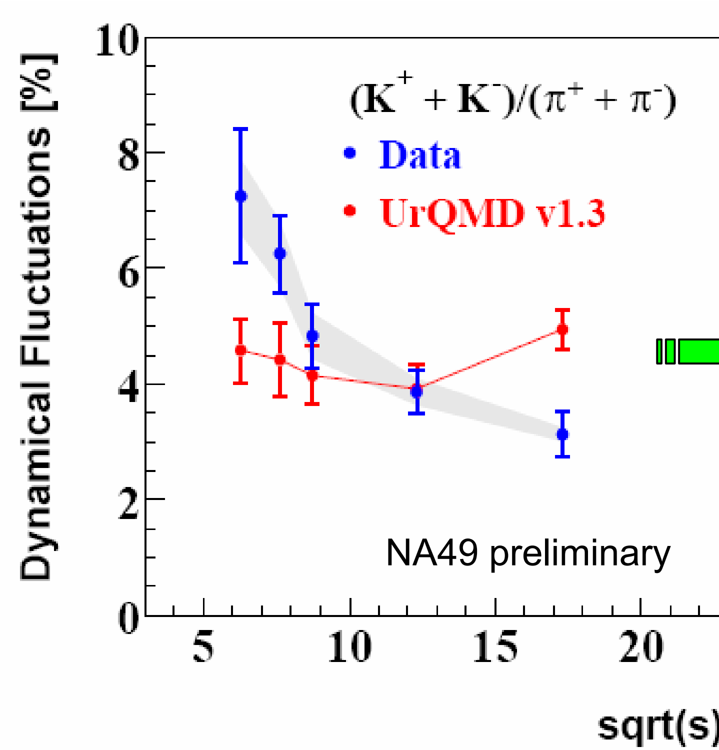
The Event-by-Event K/π ratio

Beam Energy



maximum likelihood fit for each event

$$\sigma^2_{dyn} = \sigma^2_{data} - \sigma^2_{mixed}$$



STAR

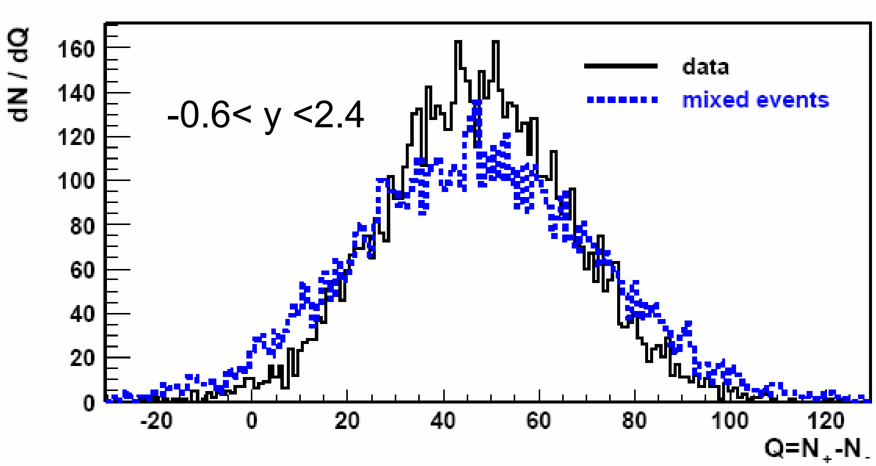
Fluctuations increase at lower energy
effect of onset of deconfinement ?

M.Gorenstein et al.,PLB585(2004)237

Electric charge fluctuations

- Smaller in a QGP than in a hadron gas
  (Jeon,Koch,Asakawa,Heinz,Müller)

Central Pb+Pb collisions 158A GeV



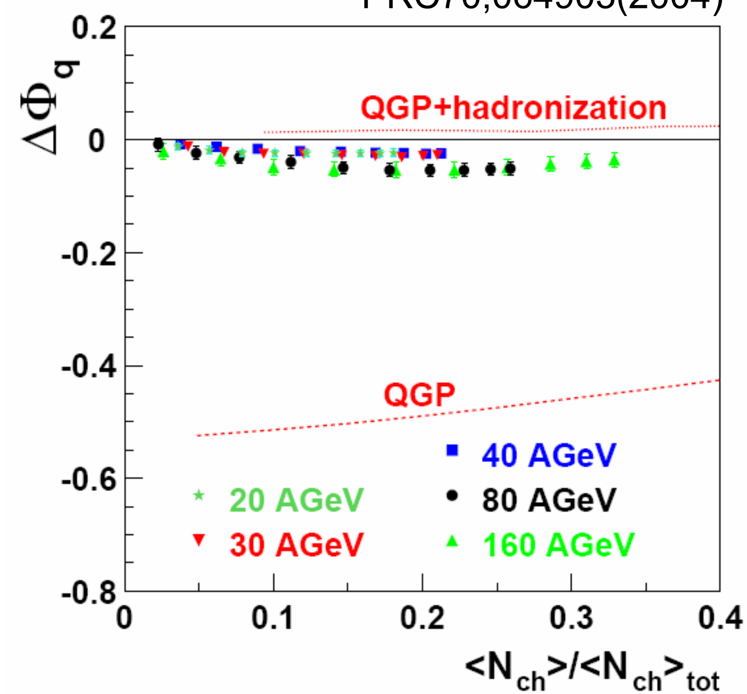
Global charge conservation

$$\Phi_q = \sqrt{\frac{< Z^2 >}{< N >}} - \sqrt{\overline{z^2}}$$

$$z = q - \overline{q} \qquad Z = \sum_{i=1}^{N} (q_i - \overline{q})$$

$$\Delta\Phi_q = \Phi_q - \Phi_{q,gcc}$$

PRC70,064903(2004)



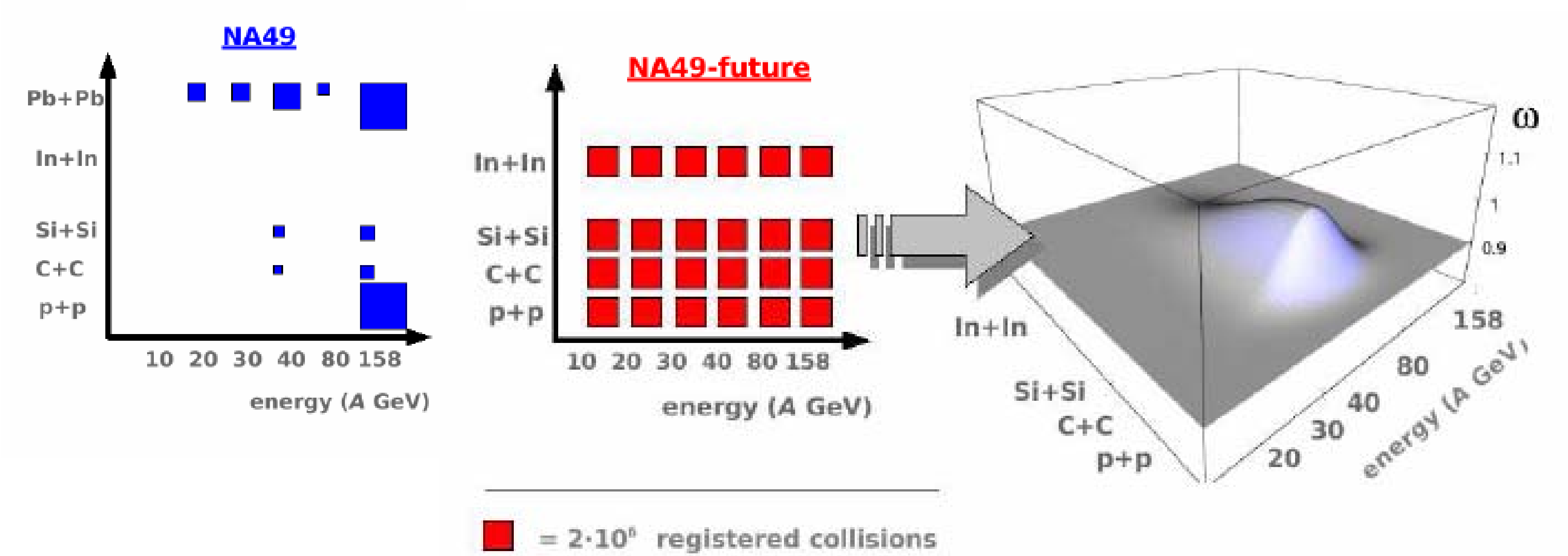
QGP signature probably erased by hadronisation (Bialas) or the effect of resonance decays (Zaranek)

Summary of main results

- strong collective behavior in Pb+Pb (Au+Au) reactions:
  growing radial and anisotropic flow AGS → SPS → RHIC
- initial energy density reaches range of deconfinement
  at the CERN SPS
- Freeze-out of hadron composition at SPS occurs close to the
  QCD phase boundary and the critical point
- energy scan reveals structure around 30A GeV:
  not reproduced by hadronic models
  consistent with onset of deconfinement at low SPS energy
- correlations and fluctuations show no convincing signal yet
  of sharp phase transition or critical point

Future Plans

- Search for the QCD critical point in fluctuations
- Study details of the onset of deconfinement
  → scan SPS energies with smaller size nuclei



- NA61 (upgraded NA49 detector) will start data taking with protons this year and with S ions in 2009
- also planned: low energy Au+Au run at RHIC (2010), NICA at DUBNA (2013) and CBM program at FAIR (2015)

The NA49 Collaboration

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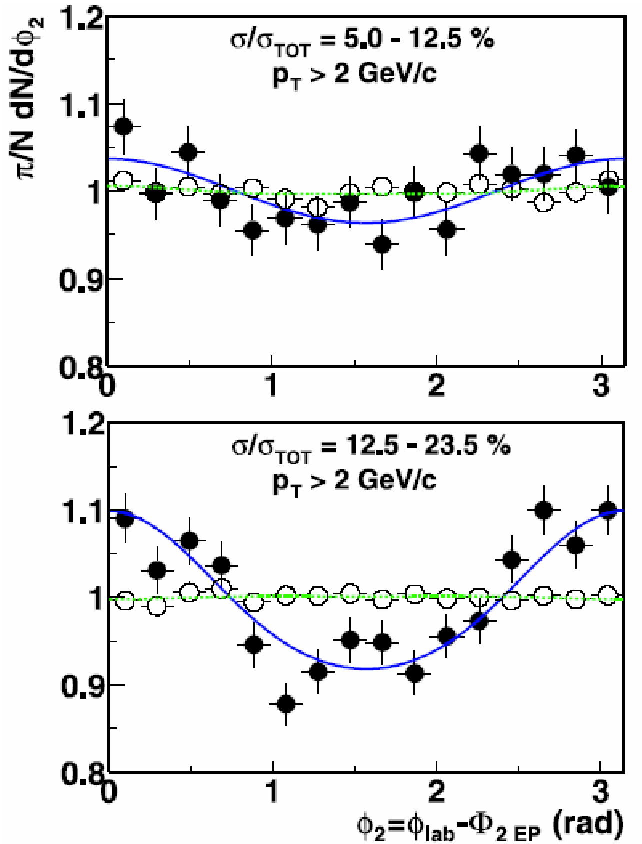
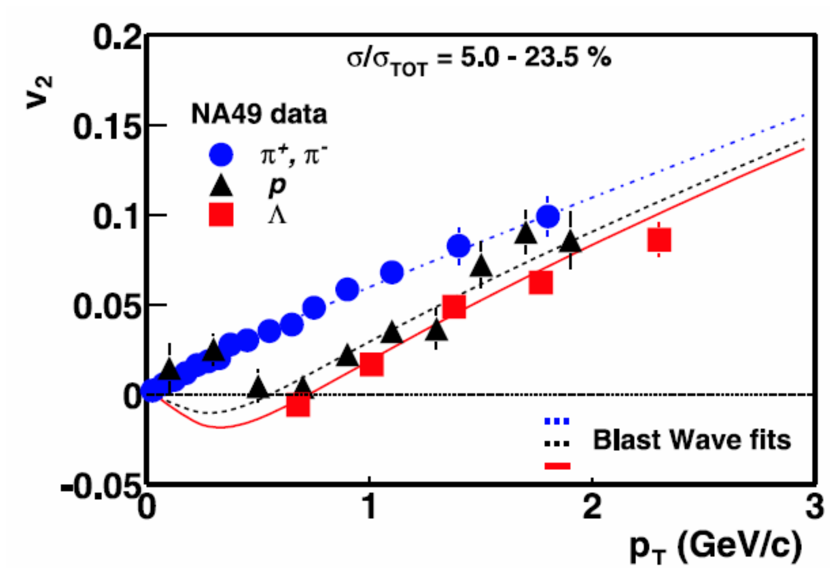
Backup Slides

Anisotropic flow v_2

Initial anisotropy ε in non-central collisions transformed into momentum anisotropy v_2 by pressure at early reaction stage

Λ elliptic flow in PbPb at 158A GeV

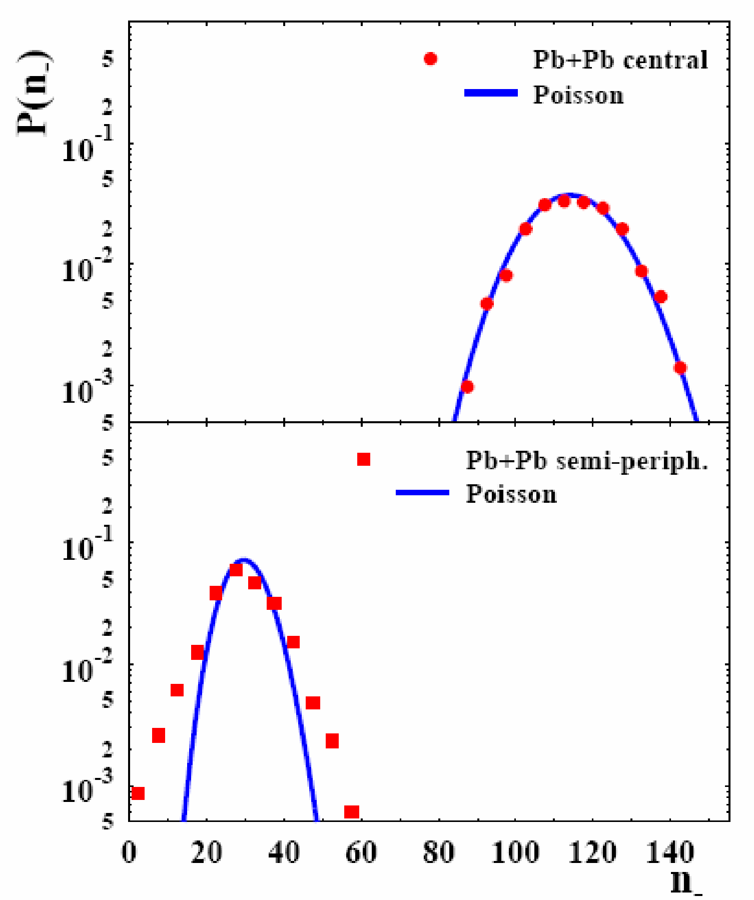




characteristic mass ordering due to radial collective flow already seen at SPS

Event-by-event fluctuations of negative hadron multiplicity

Pb+Pb at 158AGeV, $1.1 < y_\pi < 2.6$



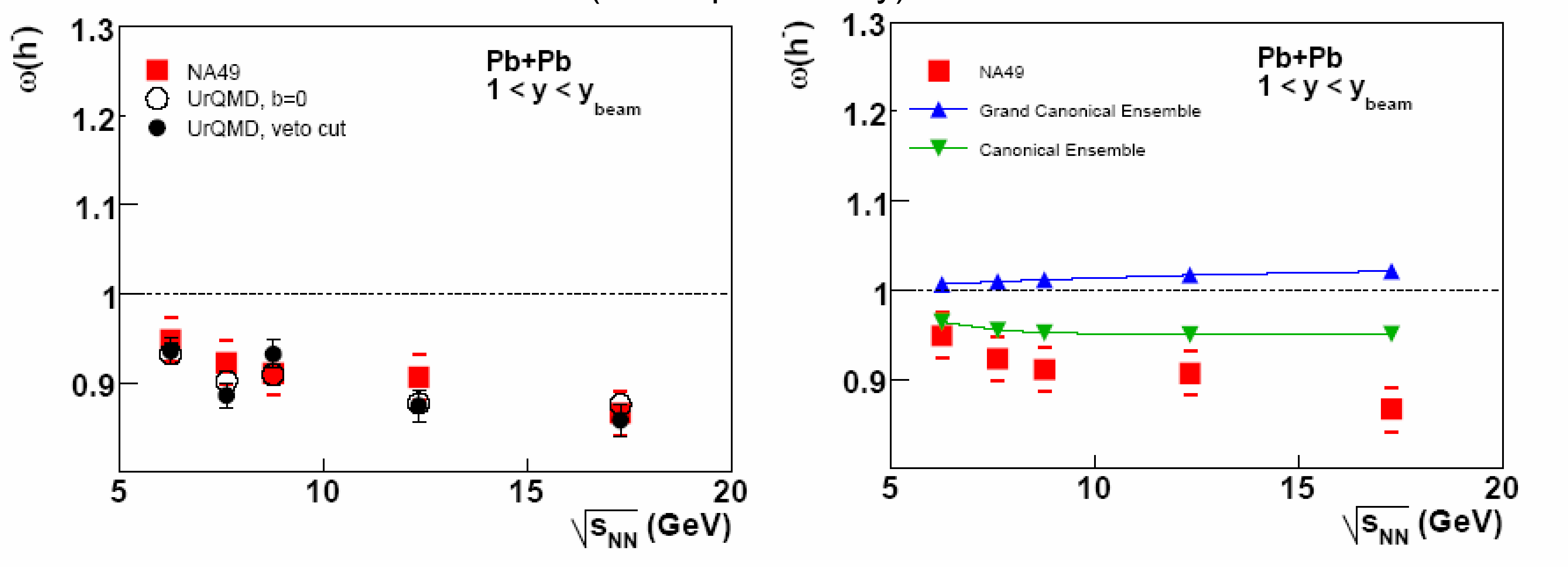
- fluctuations measured at forward rapidity ($1.1 < y_\pi < 2.6$) where azimuthal acceptance is best
- number of projectile participants fixed by projectile spectator energy cut; no restriction on target participants
- central collisions: fluctuations nearly Poissonian (independent emission)
- peripheral collisions: fluctuations exceed Poissonian

measure: $\omega = Var(n\_)/<n\_>$

Event-by-event fluctuations of negative hadron multiplicity

energy dependence (forward rapidity)

(Na49 preliminary)

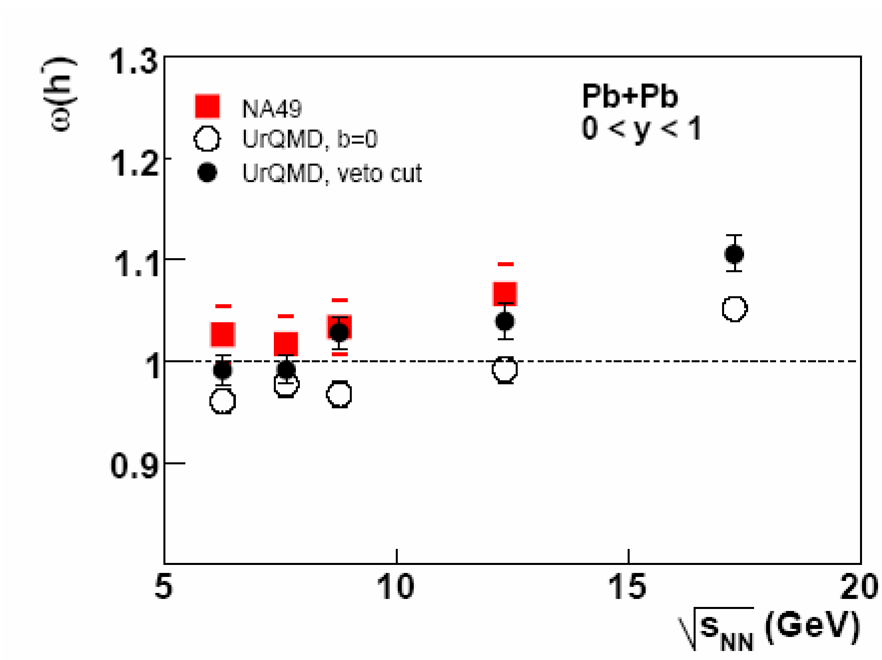


- fluctuations in central Pb+Pb collisions small, no anomalies
- results close to UrQMD and statistical model predictions

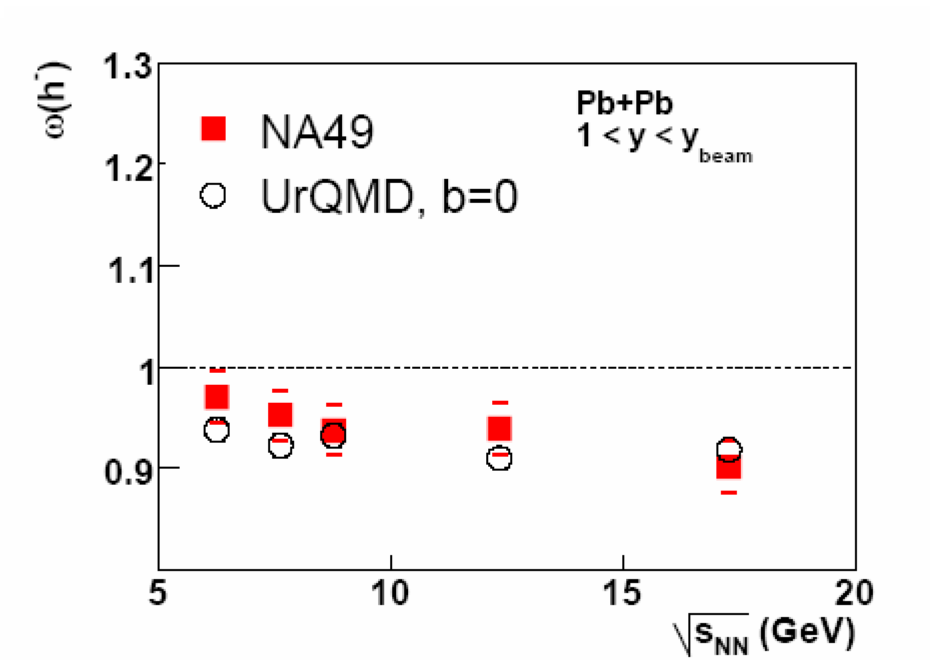
Event-by-event fluctuations of negative hadron multiplicity

similar observations

near midrapidity

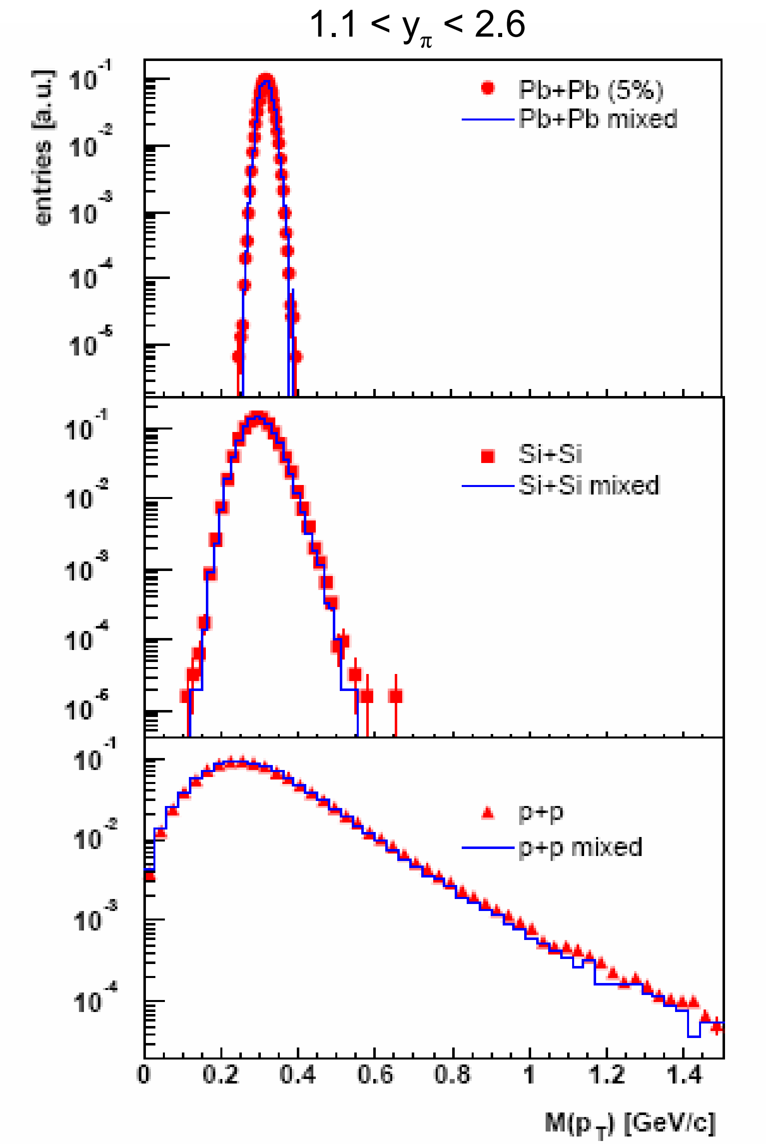


for $p_T <$ 500 MeV/c



(Na49 preliminary)

Event-by-event fluctuations of <p_T> (negative hadrons)



- distributions of <p_T> similar for real and mixed events
- no evidence for distinct event classes
- non-statistical (dynamical) fluctuations are small, < few %

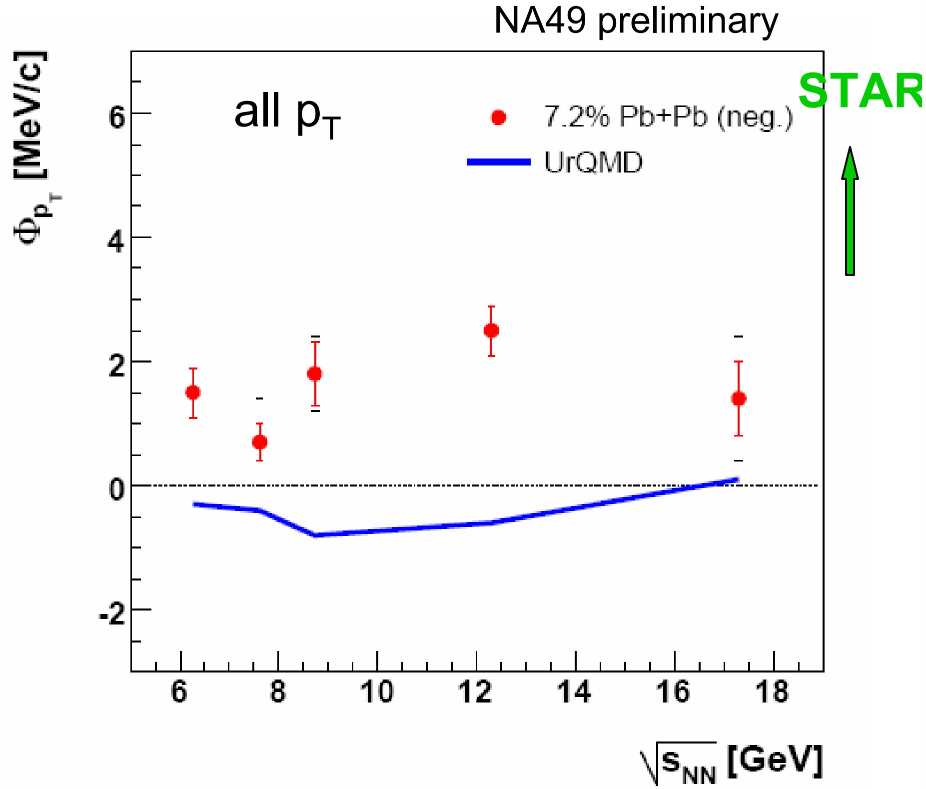
measure: Φ_{pT}

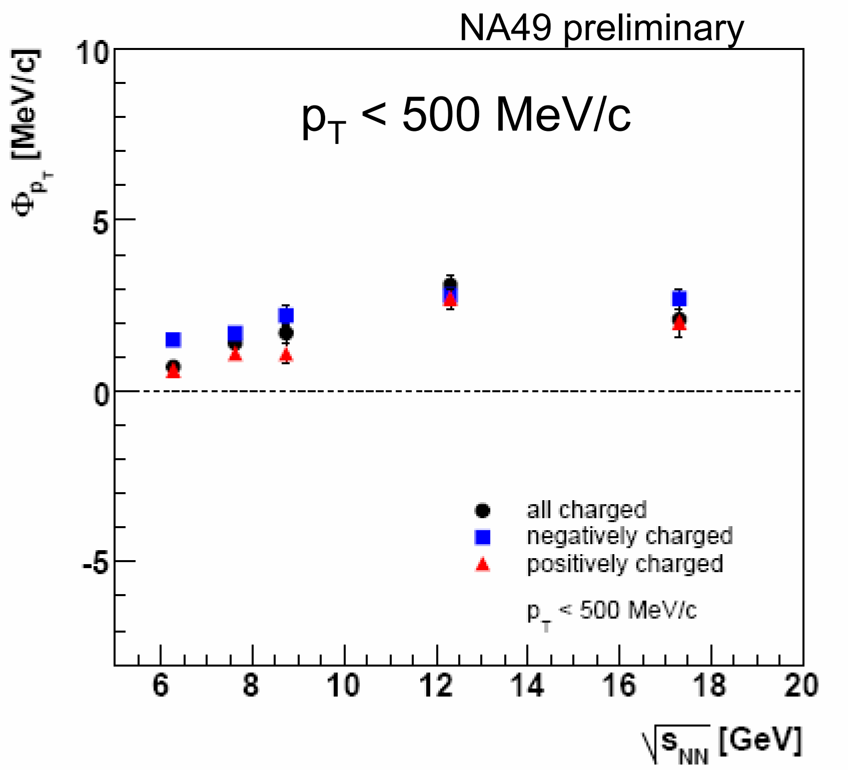
$$\Phi p_T = \sqrt{\frac{< Z^2 >}{< N >}} - \sqrt{<z^2>}$$

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

Event-by-event fluctuations of $<p_T>$ (negative hadrons)

energy dependence $(1.1 < y_\pi < 2.6)$



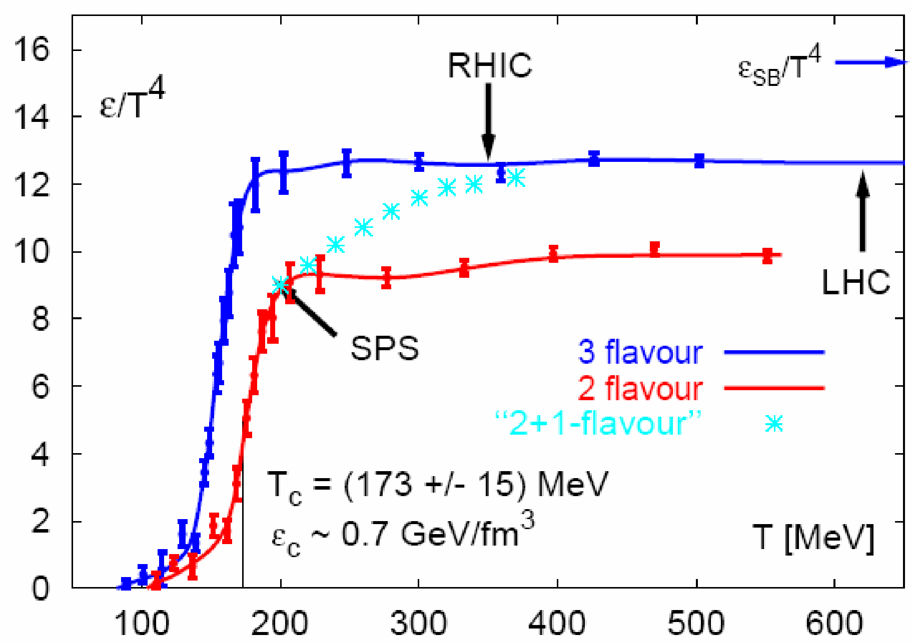


- no significant change with energy at SPS for central Pb+Pb collisions
- no indication of critical point (maximum of ≈ 8 MeV/c predicted)

(M. Stephanov)

QCD predicts quark, gluon deconfinement in high temperature and/or density hadron matter

- hadrons overlap at densities > 0.5 fm^{-3} → deconfinement (Collins,Perry 1974)
- quantitative predictions from Lattice QCD (non-perturbative)

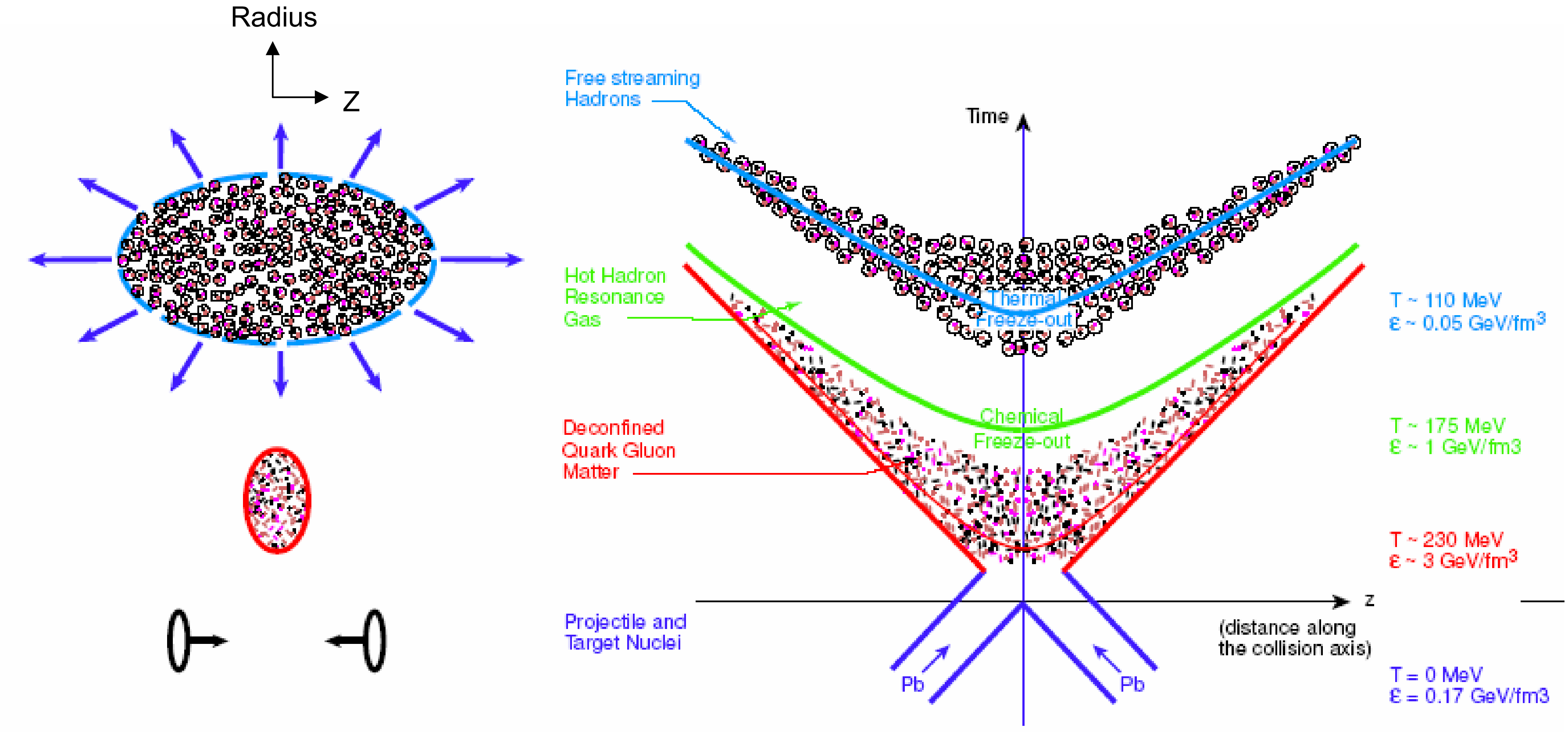


Karsch, Laermann hep-lat/0305025

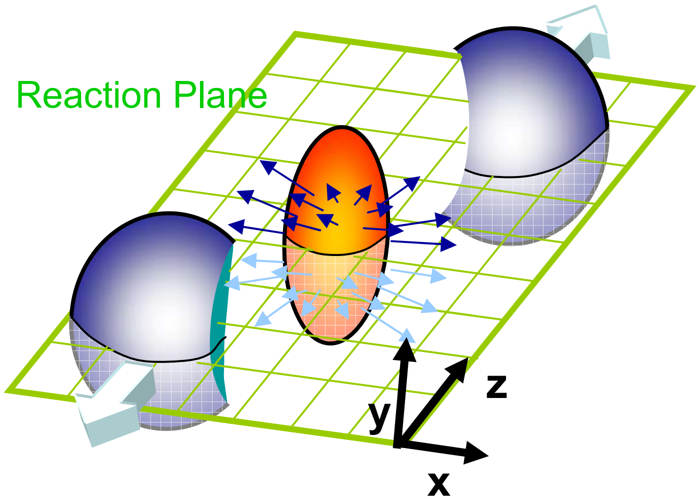
for $\mu_q = 0$

Such conditions can be reached for a few fm/c in a large nucleus volume in relativistic heavy ion collisions

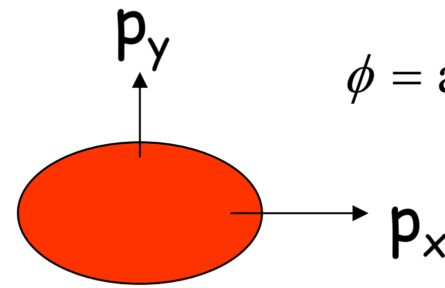
Schematic of a relativistic heavy-ion collision



Anisotropic flow in non-central collisions



initial spatial anisotropy



$$\phi = \text{atan}\,\frac{p_y}{p_x}$$

anisotropy in mometum space

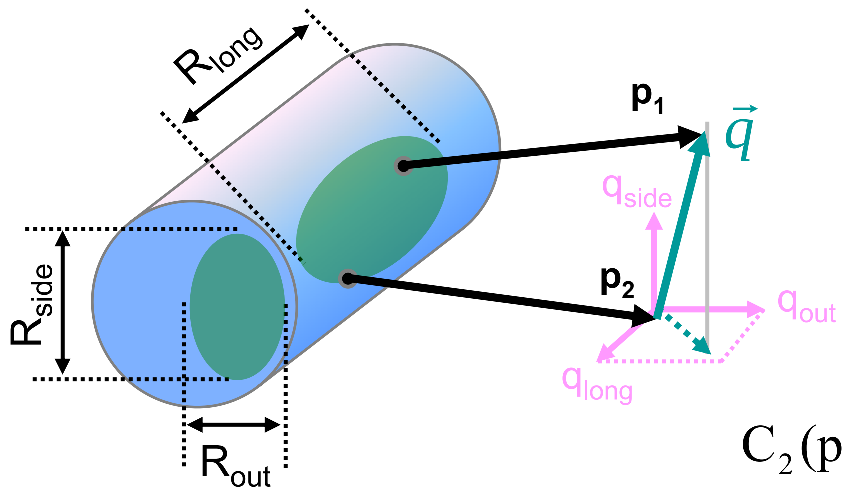
- sensitive to pressure gradients in the early stage of fireball evolution
- self quenching spatial anisotropy, radial flow continues to increase

$$E\frac{dN^3}{d^3p} = \frac{1}{2\pi}\frac{d^2N}{p_t dp_t dy}\left(1 + 2v_1\cos(\phi - \Psi_R) + 2v_2\cos(2(\phi - \Psi_R) + \ldots\right)$$

directed flow

elliptic flow

2π Bose-Einstein correlations



U.Wiedemann, U.Heinz, review Phys.Rept. 319, 145 (1999)

$$\vec{q} = \vec{p}_2 - \vec{p}_1$$

$$\vec{k} = \frac{1}{2}(\vec{p}_2 + \vec{p}_1)$$

$$C_2(p_1, p_2) = \frac{P(p_1, p_2)}{P(p_1) \cdot P(p_2)} = \frac{\text{real event pairs}}{\text{mixed event pairs}}$$

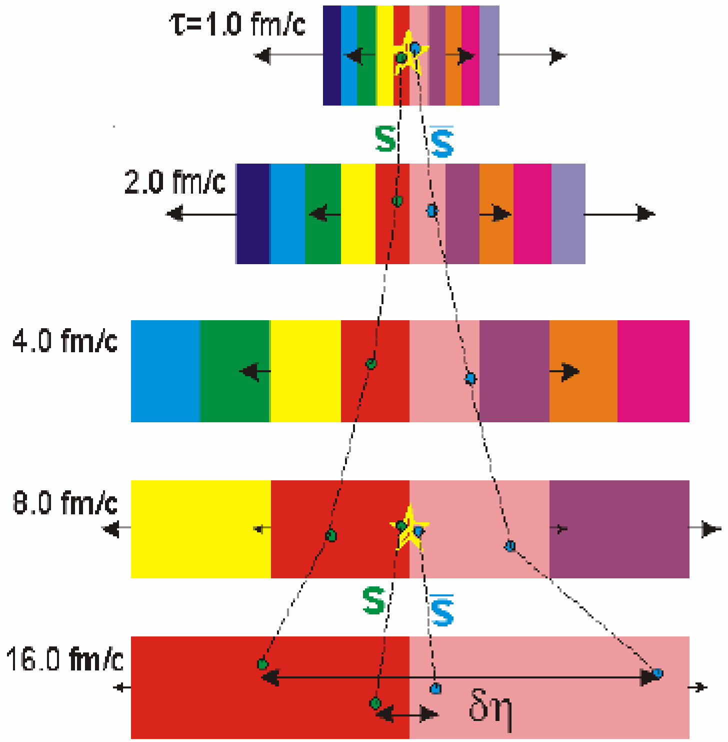
- quantum statistics requires symmetry of the wave function of identical bosons
- space, time separation of emission points → momentum space correlations
- Gaussian (Pratt, Bertsch) parameterization:

$$C_2(q, p_1, p_2)_{BP} = 1 + \lambda \cdot \exp\left(-q_{side}^2 R_{side}^2 - q_{out}^2 R_{out}^2 - q_{long}^2 R_{long}^2 - 2 q_{out} q_{long} R_{outlong}^2 \right)$$

- R_i are lengths of homogeneity, regions over which q can be small
  → sensitivity to fireball size, flow, temperature
- Coulomb repulsion must be taken into account (Sinyukov et al., PLB 432(1998)248)
- fit function: $C_2(q,k)_f = p \cdot \left(W(q, r_m) \cdot C_2(q,k)_{BP} \right) + (1 - p)$

Balance Function

Bass,Danielewicz,Pratt: PRL 85,2689(2000)



$$\sigma^2_{\delta y} = \sigma^2_{\delta\eta} + \sigma^2_{therm}$$

experiment
diffusive
determined by breakup temp.

- oppositely charged particles created at the same point in space – time
- particles get separated in rapidity by thermal motion (re-scattering) and developing collective flow
- early produced pairs are separated more in rapidity than late produced pairs
- separation δη quantified by the balance function:

$$B(\delta\eta) = \frac{1}{2}\left(\frac{N_{(+-)}(\delta\eta) - N_{(--)}(\delta\eta)}{N_-} + \frac{N_{(-+)}(\delta\eta) - N_{(++)}(\delta\eta)}{N_+}\right)$$

delayed hadronisation =
narrowing of balance function
predicted as signature of
first order phase transition

Pb+Pb collision at 158A GeV