Energy Dependence of Pb+Pb collisions at the CERN SPS

P.Seyboth, MPI für Physik, München
for the NA49 Collaboration

- Introduction
- Search for structure in the energy dependence of
  - transverse mass spectra, BE correlations, flow
  - particle yields and yield ratios
  - E-by-E fluctuations of K/π, Q
  - balance function
- medium p_T results
- Conclusion

Introduction: Pb+Pb collisions at top SPS energy

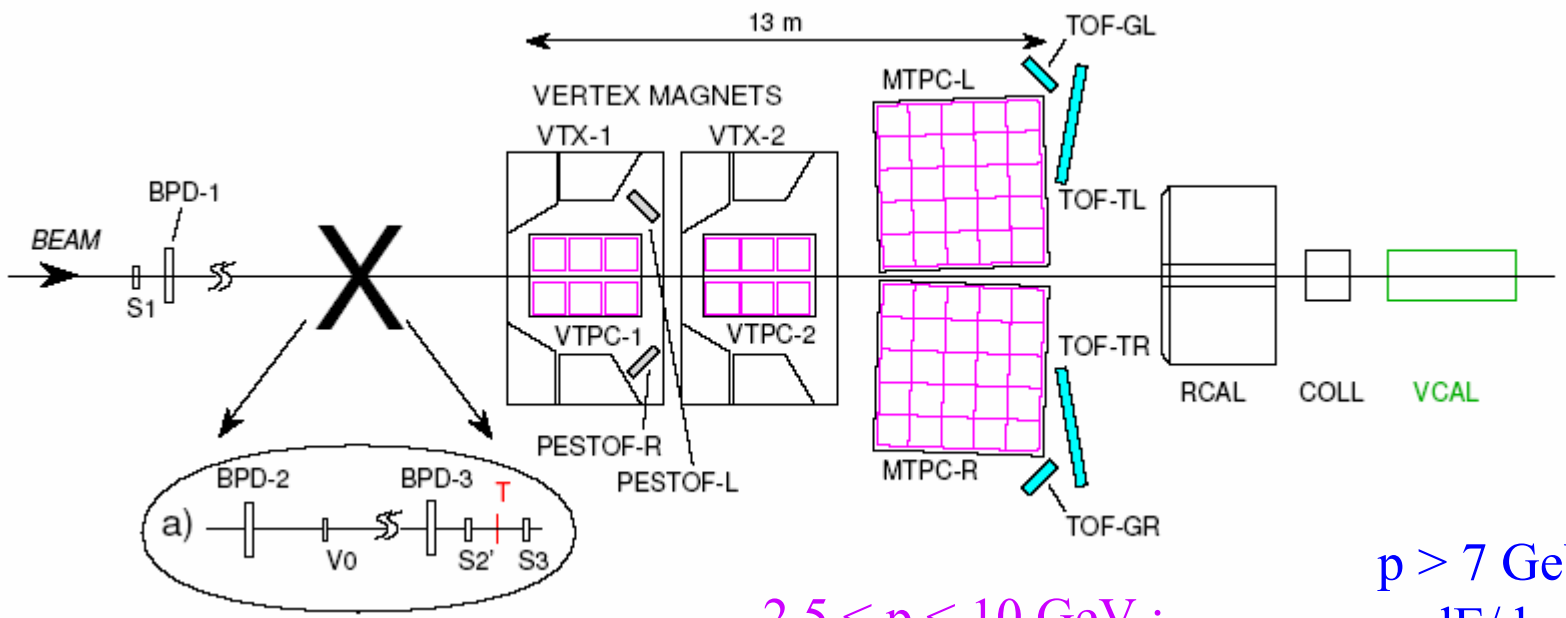
- Initial energy density exceeds the critical value predicted by lattice QCD (1 GeV / fm^3)
- Strong collective behavior
  - anisotropic and radial flow
  - transverse expansion of the matter droplet by factor 2
- Proposed signatures for deconfinement observed
  - strangeness enhancement
  - J/Ψ,Ψ' yield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

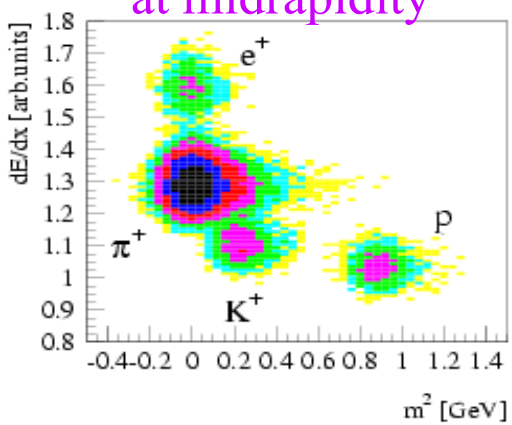
($\sqrt{s_{NN}}$ = 6.3, 7.6, 8.7, 12.3, 17.3 GeV)

The NA49 Detector

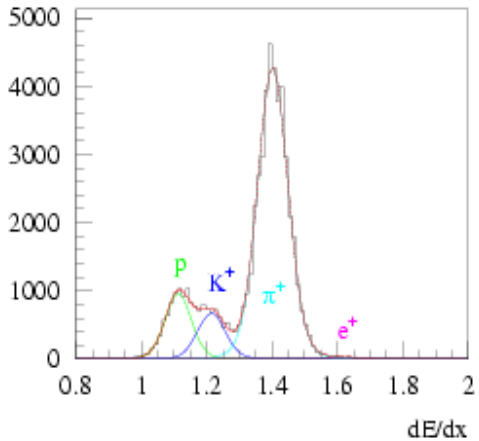


Target: 20cm liquid H_2 or Pb foil
VCAL detects projectile spectators
$\Delta p/p^2 = 7\ (0.3) \cdot 10^{-4}\ (\mathrm{GeV/c})^{-1}$
(VTPC-1, VTPC+MTPC)
dE/dx resolution 3 – 6 %
TOF resolution ~ 60 ps

2,5 < p < 10 GeV :
TOF + dE/dx
at midrapidity

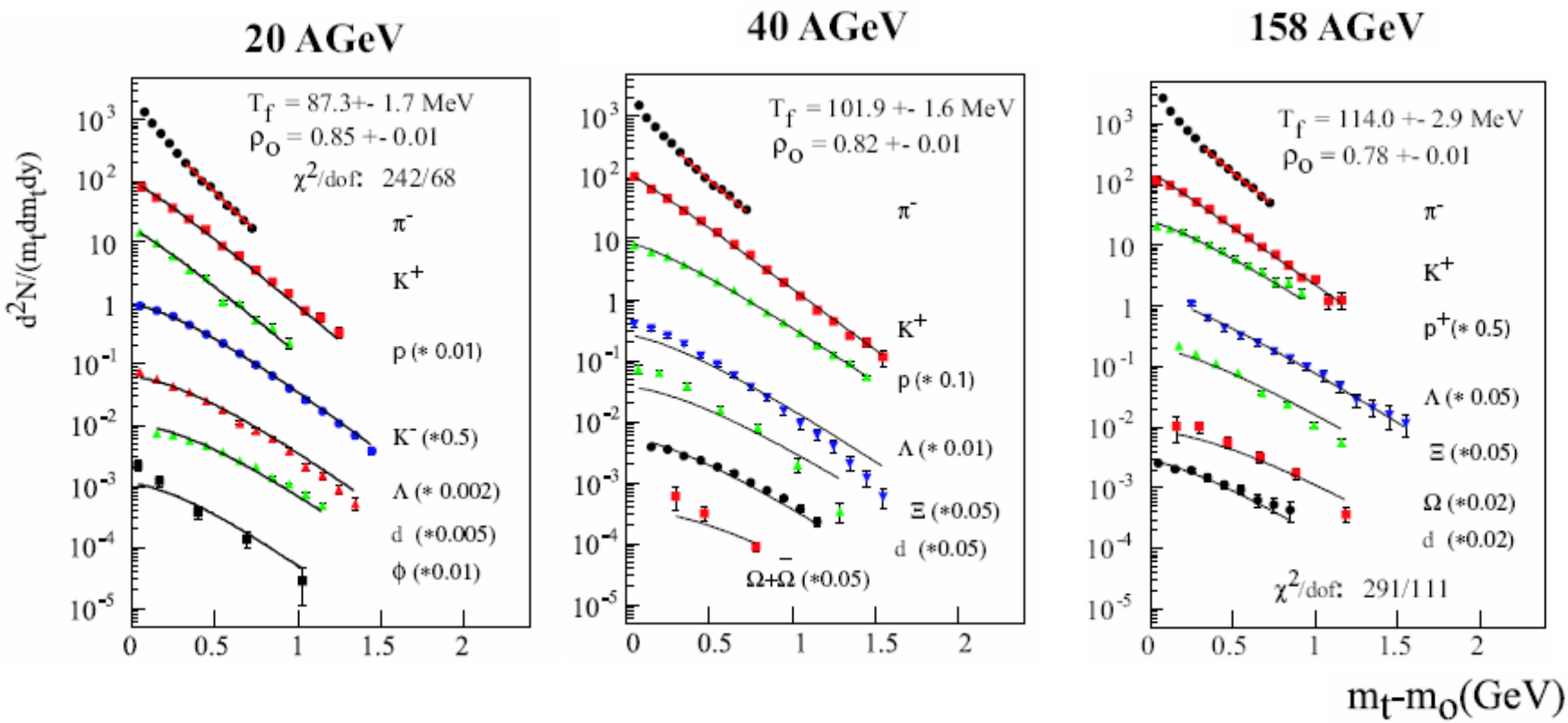


p > 7 GeV
dE/dx
forward rapidity



Transverse mass spectra at mid-rapidity

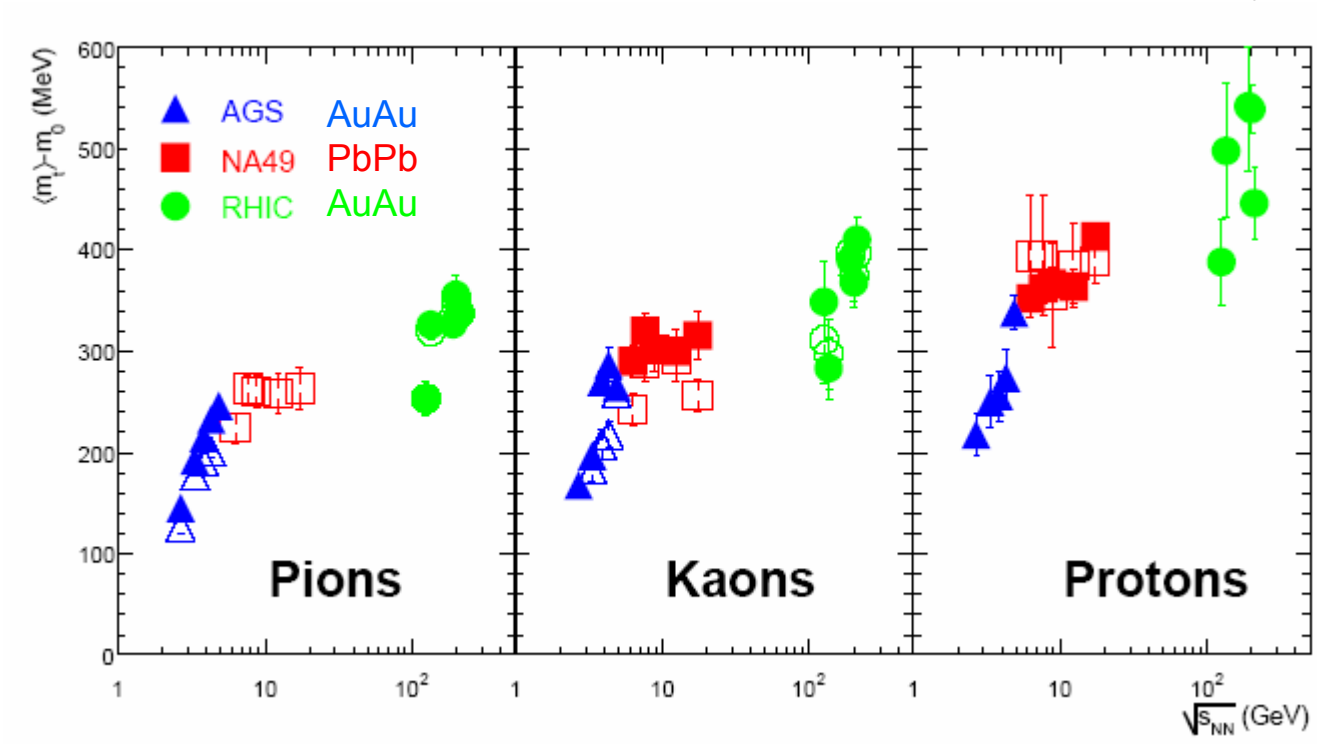
many spectra measured, “blast wave” model works at SPS



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

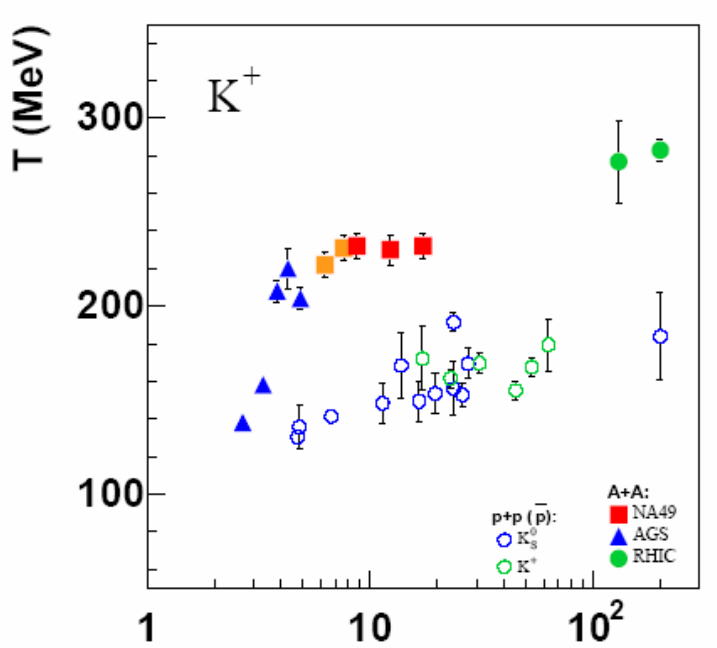
Energy dependence - average transverse mass

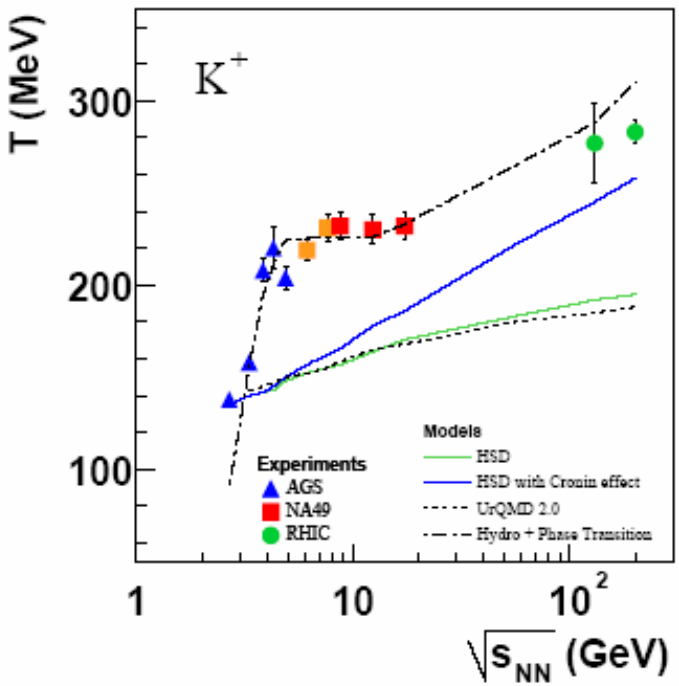
NA49 preliminary



Increase of $\langle m_T \rangle$ for abundant final state particles (π, K, p) slows sharply at the lowest SPS energy

Energy dependence – inverse slope parameters



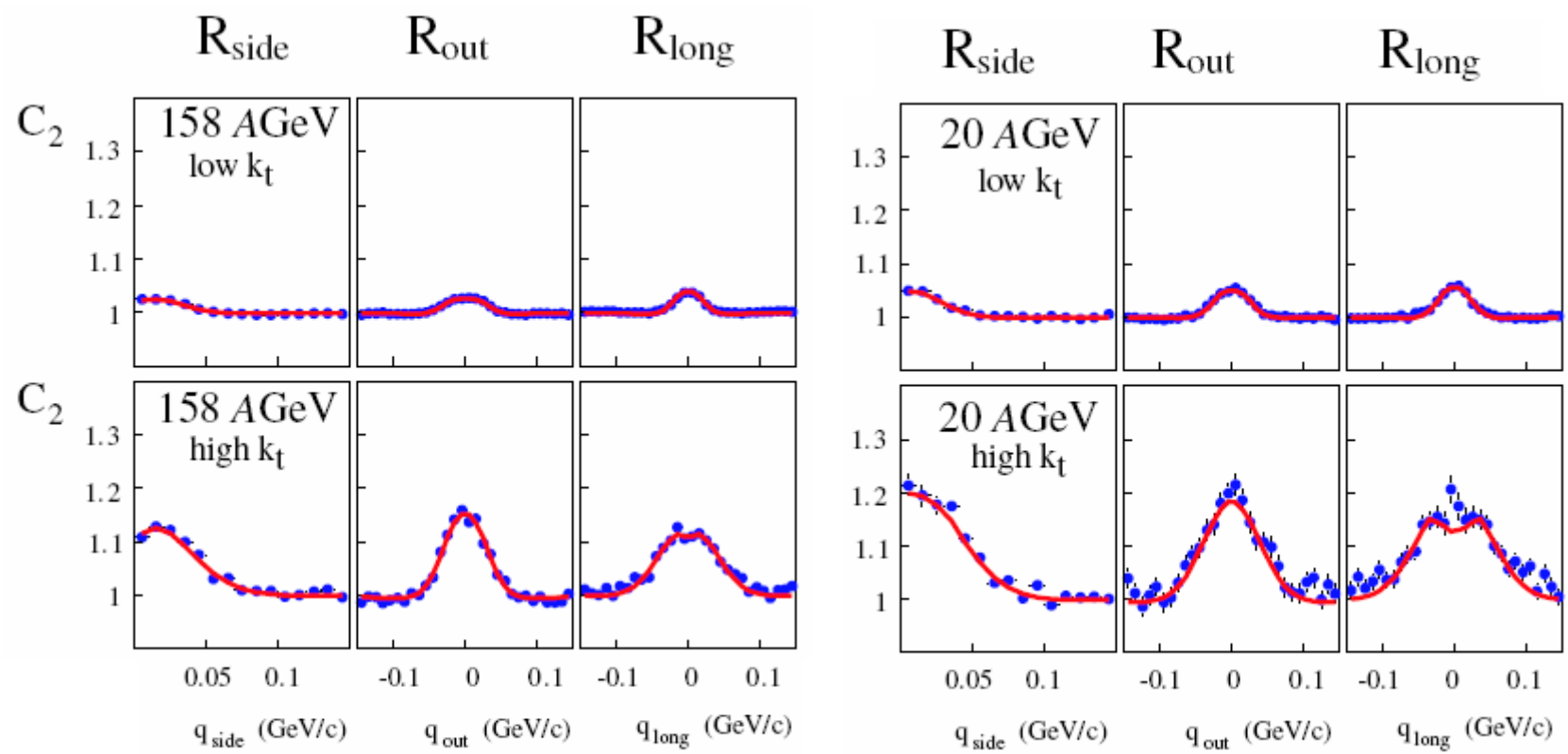


- the step-like feature is not seen for pp collisions and models without phase transition do not show it

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

(L.van Hove, PLB89(1982)253; M.Gorenstein et al.,PLB567(2003)175)
model curve SPheRIO S.Hama at al., Braz.J.Phys,34,322 (2004)

BE correlations sensitive to fireball size and flow

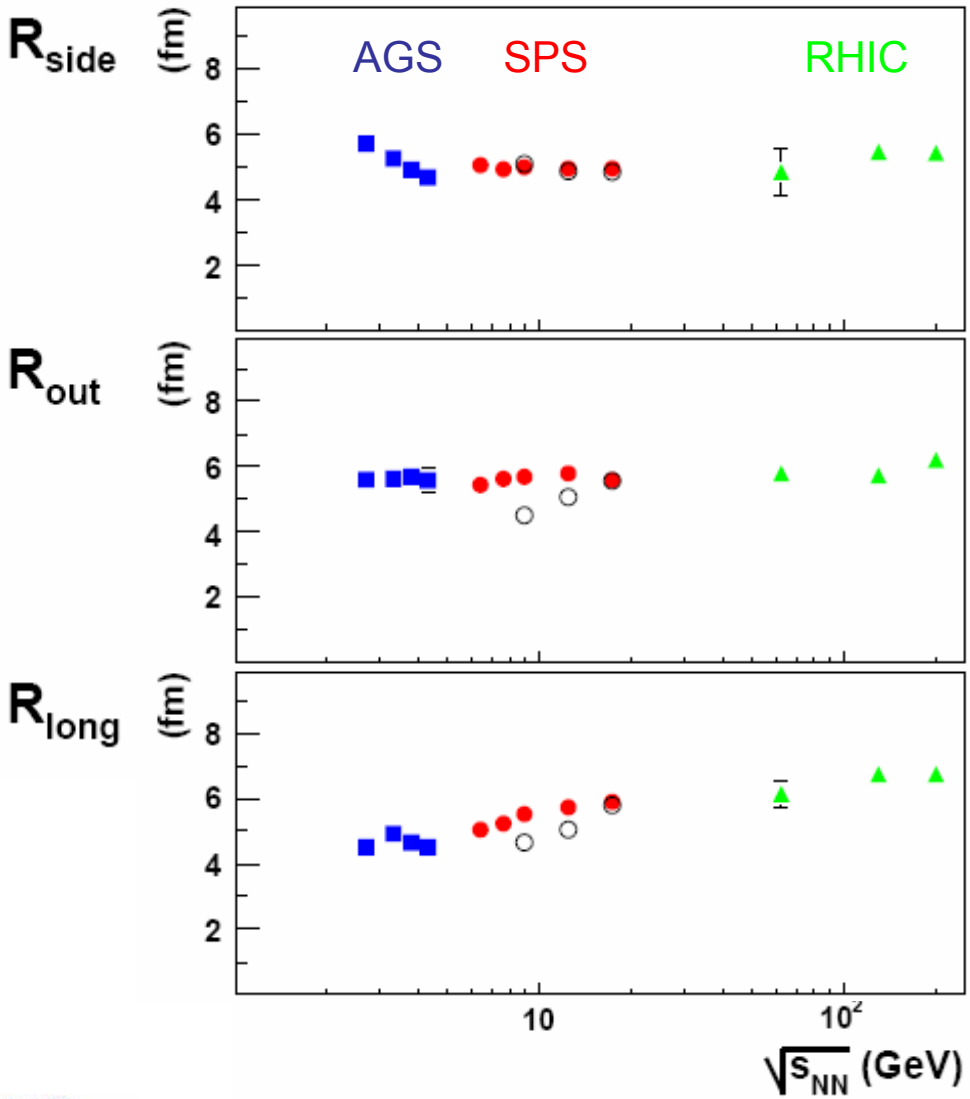


examples of $\pi^-\pi^-$ correlation functions at midrapidity in the Cartesian (Bertsch, Pratt) reference frame

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

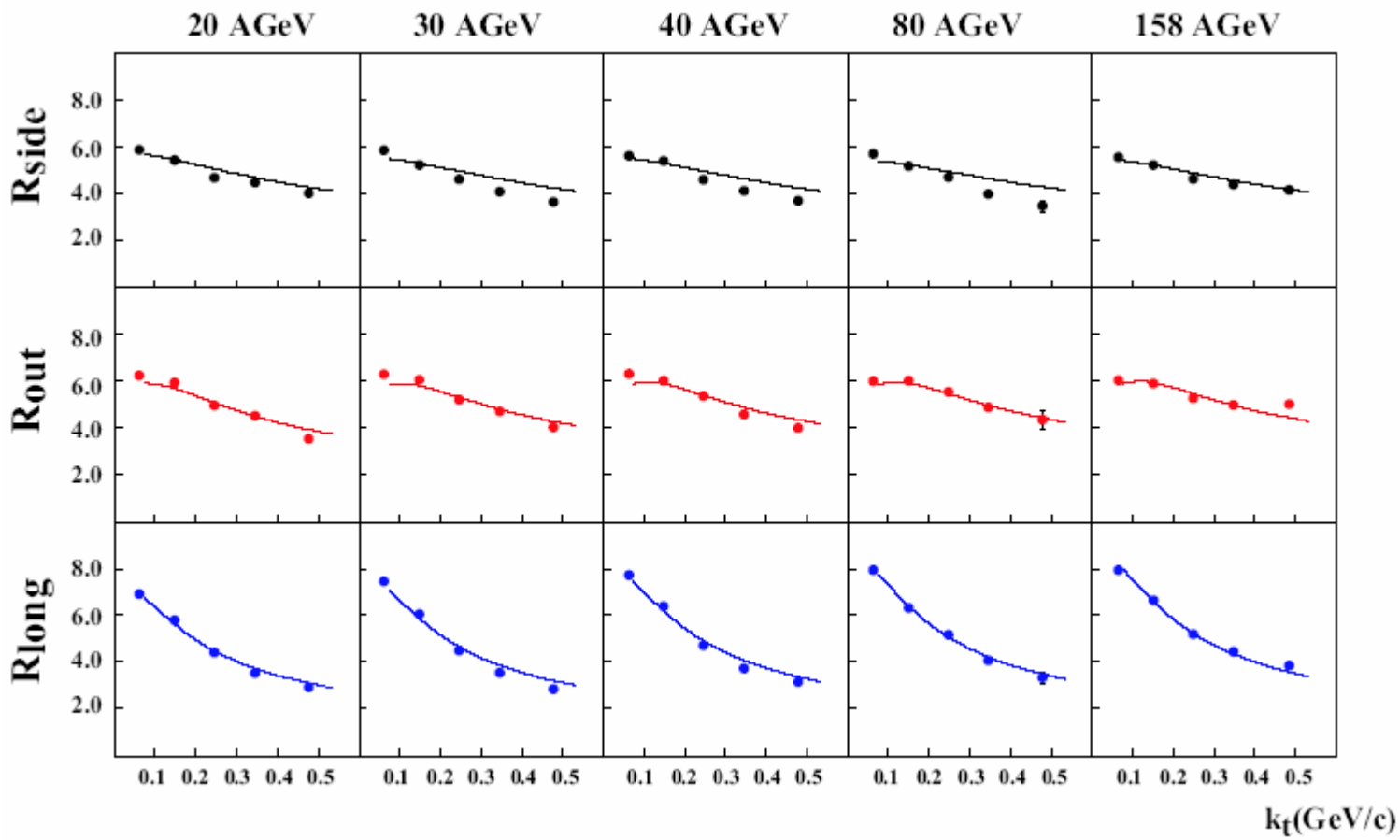
energy dependence of radius parameters

midrapidity, k_T = 0.2 GeV/c

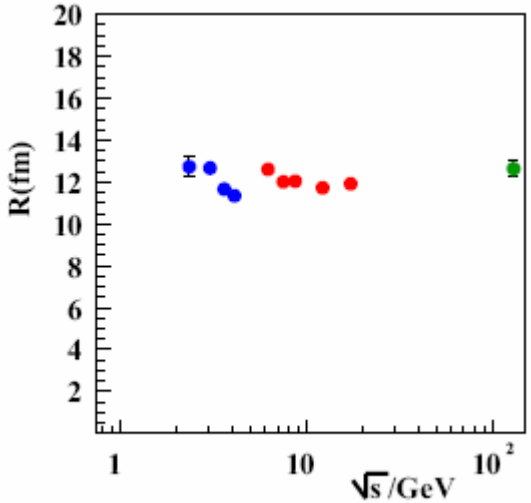


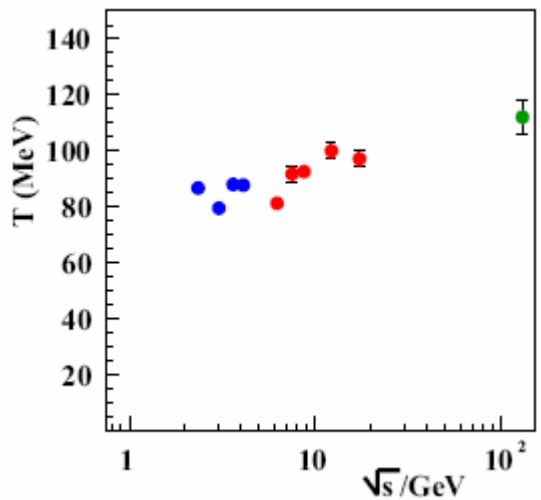
- remarkably little change of R_{side} (fireball radius) and R_{out}
- no indication of $R_{out} >> R_{side}$ i.e. long duration of π emission (soft point of EoS)
- slow rise of R_{long} (fireball lifetime)

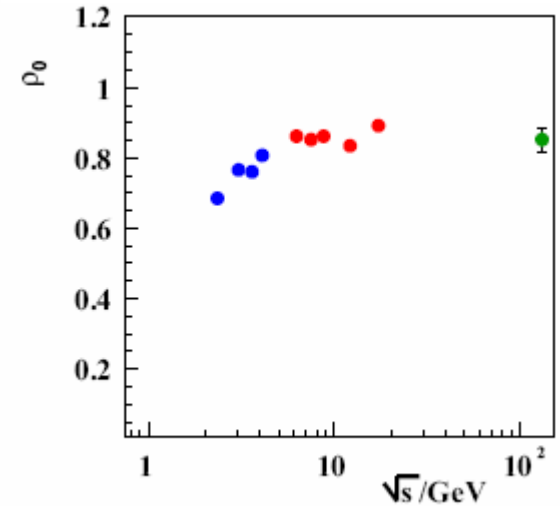
simultaneous “blast wave” fits to BE radii and π, p spectra

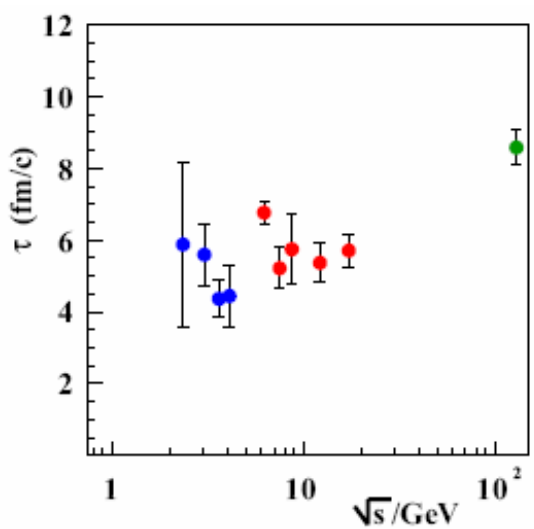


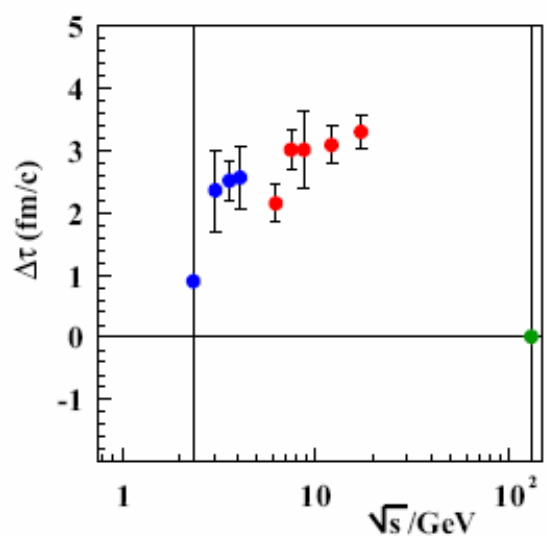
energy dependence of fireball parameters









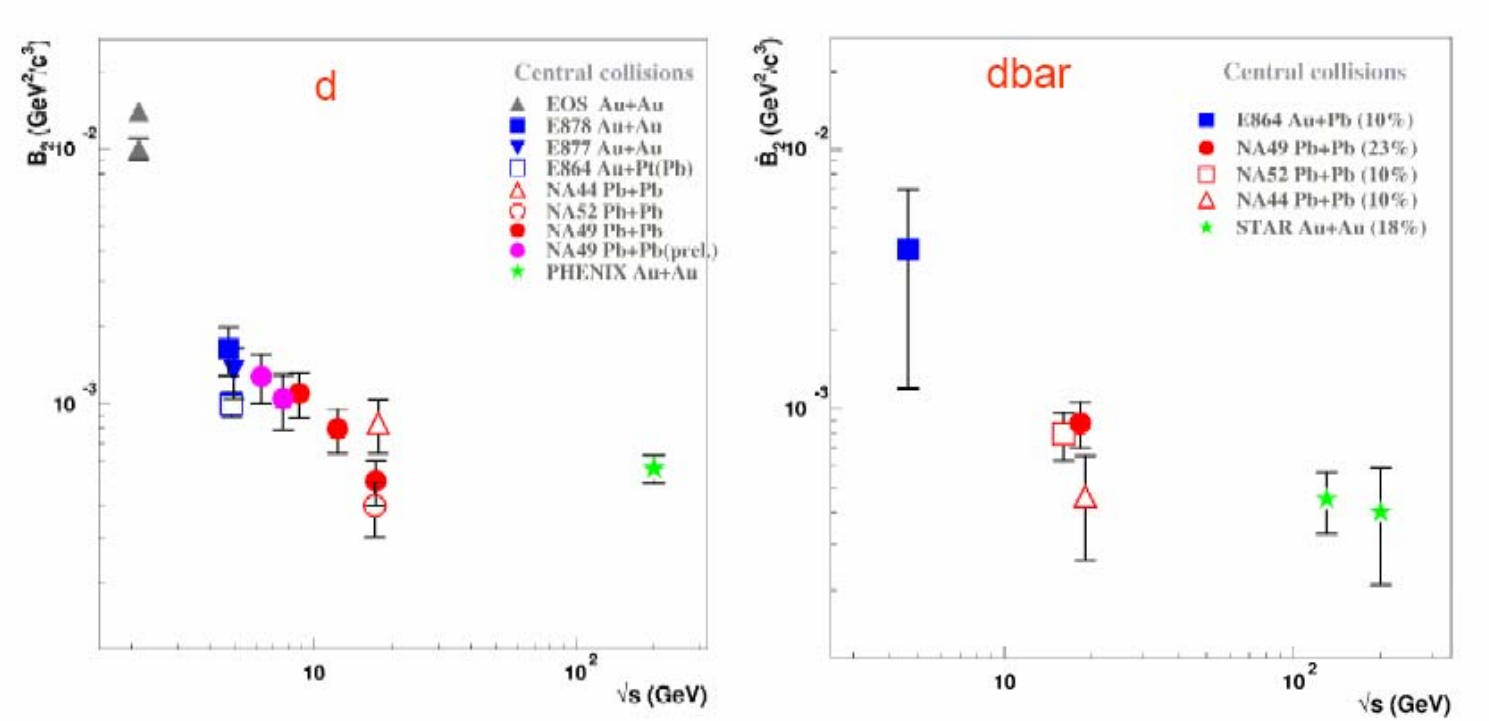


- constant radius $\approx 2 \cdot R_{Pb,Au}$
- slow increase of
  f.o. temperature T
  surface flow ρ_0
  lifetime τ

Deuteron production measures a homogeneity radius via coalescence

$$B_2 = E_d \cdot \frac{d^3N_d}{dp_d^3} / (E_p \cdot \frac{d^3N_p}{dp_p^3})^2 \qquad R_G^3 = \frac{3}{4}(\sqrt{\pi}c\hbar)^3 \, \frac{m_d}{m_p^2} \; / \; B_2$$

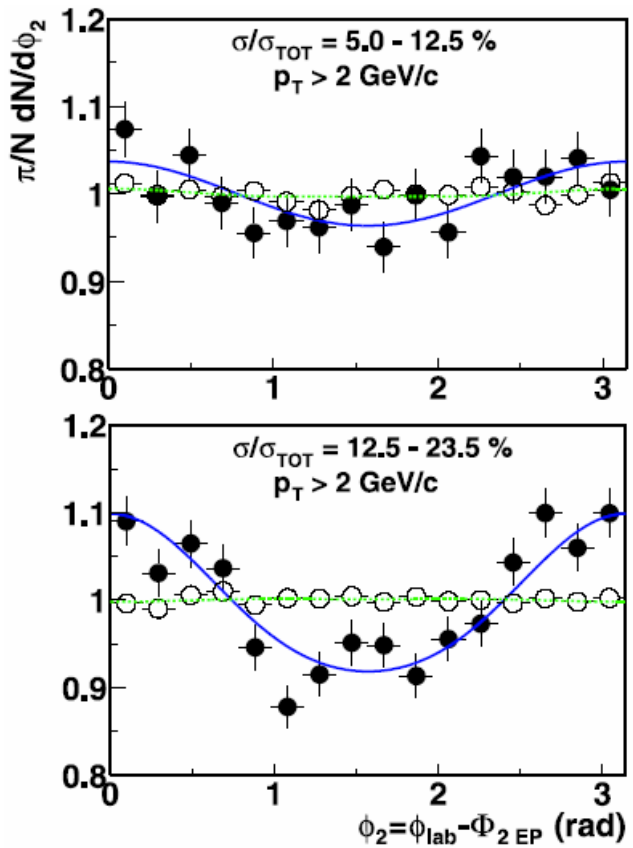
(NA49 partly preliminary)



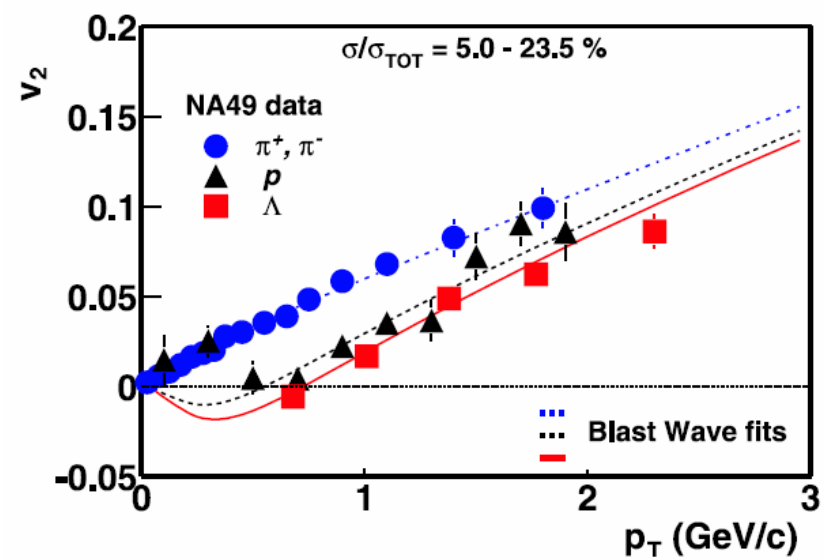
gradual decrease of coalescence factor B_2

Anisotropic flow v_2

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



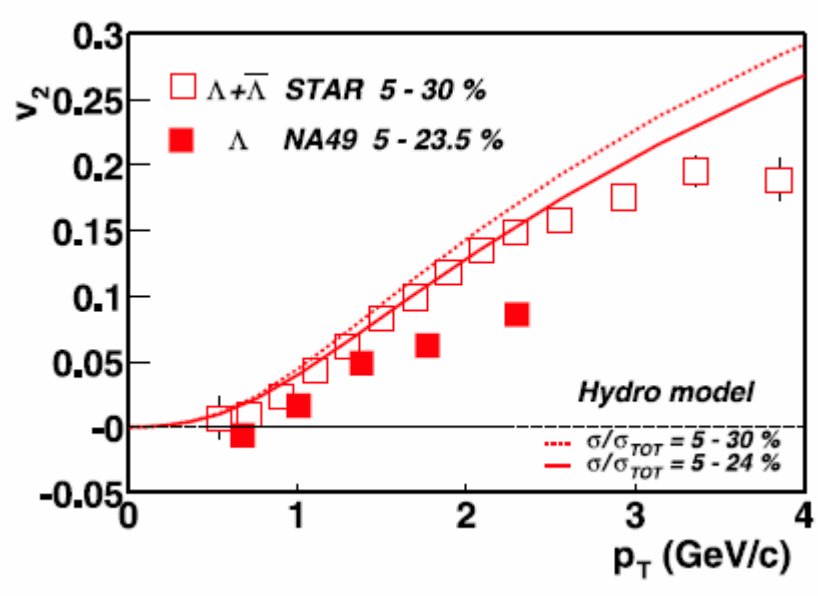
Λ elliptic flow in PbPb at 158A GeV



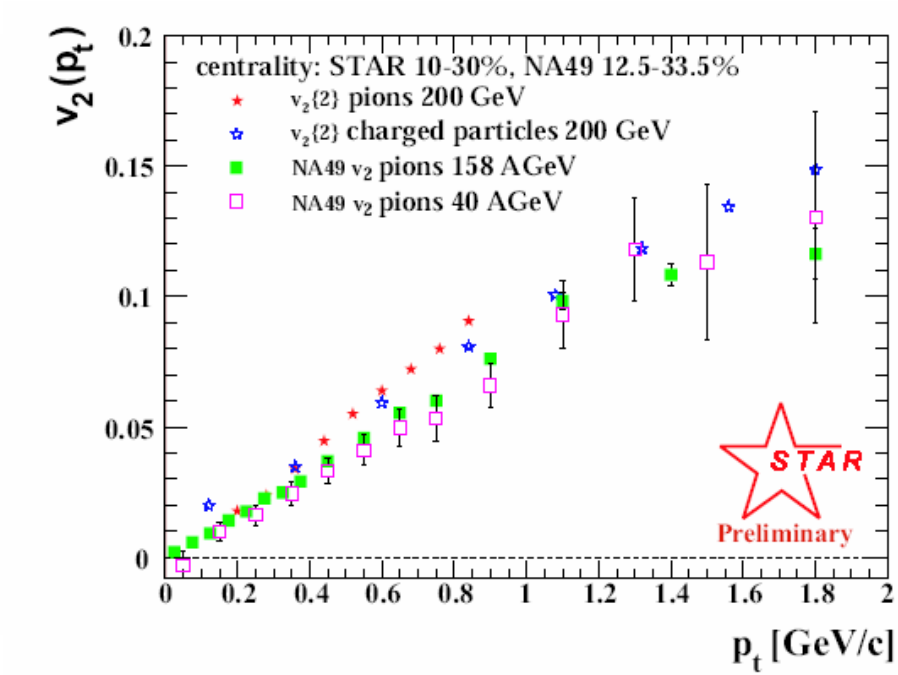
characteristic mass ordering also seen at SPS

Energy dependence of anisotropic flow $v_2(p_t)$

Λ hyperons

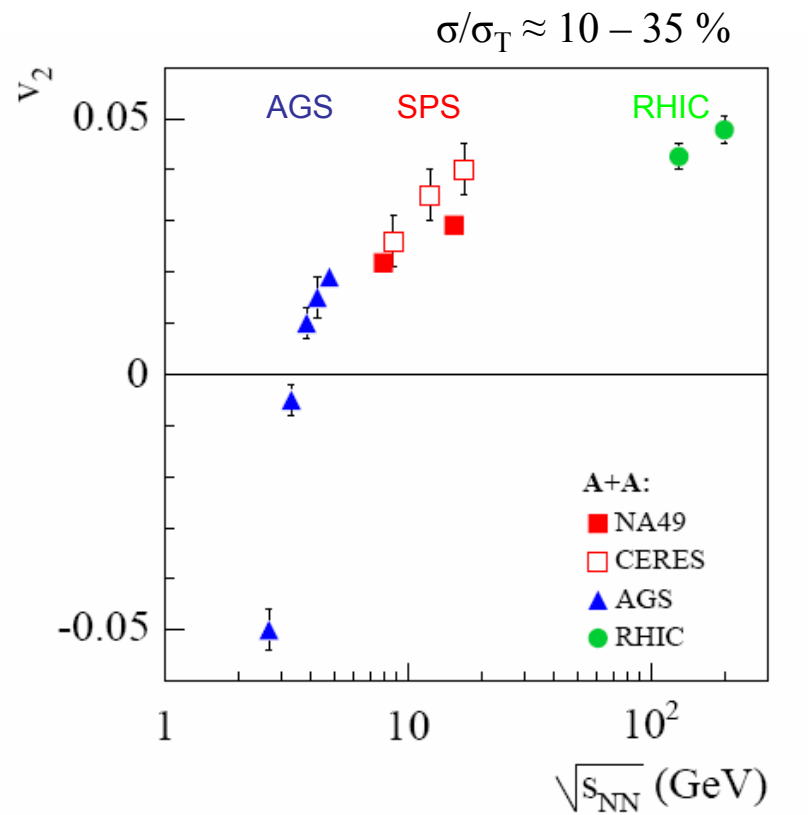


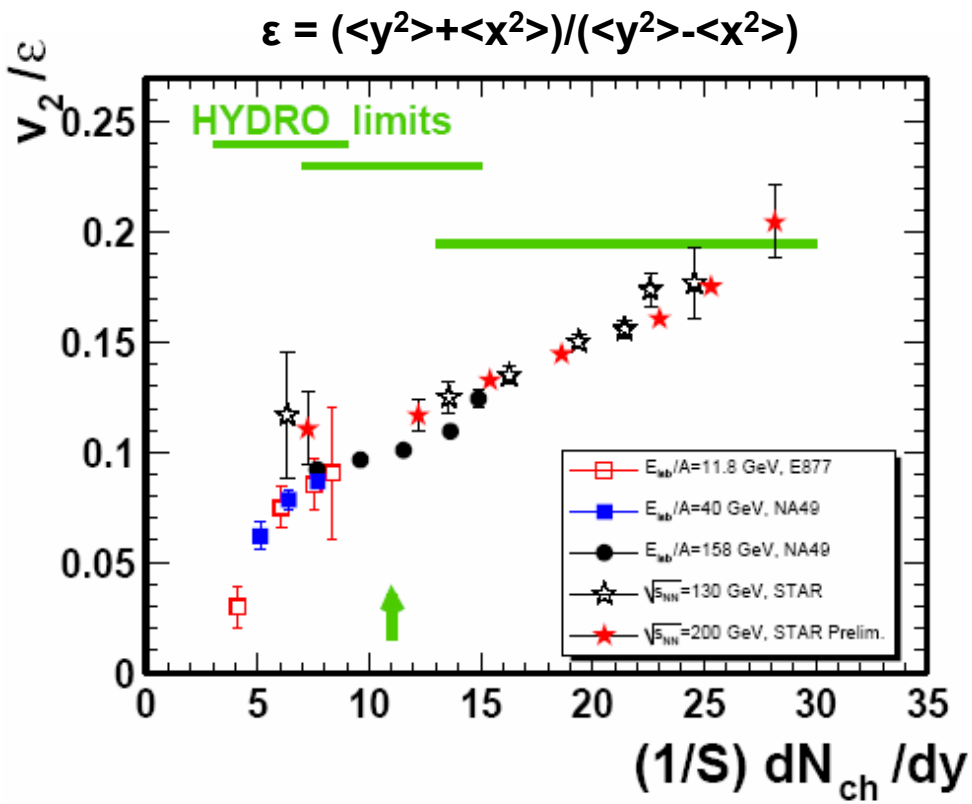
pions



elliptic flow $v_2(p_t)$ increases SPS → RHIC

Anisotropic flow v_2 of pions: energy dependence



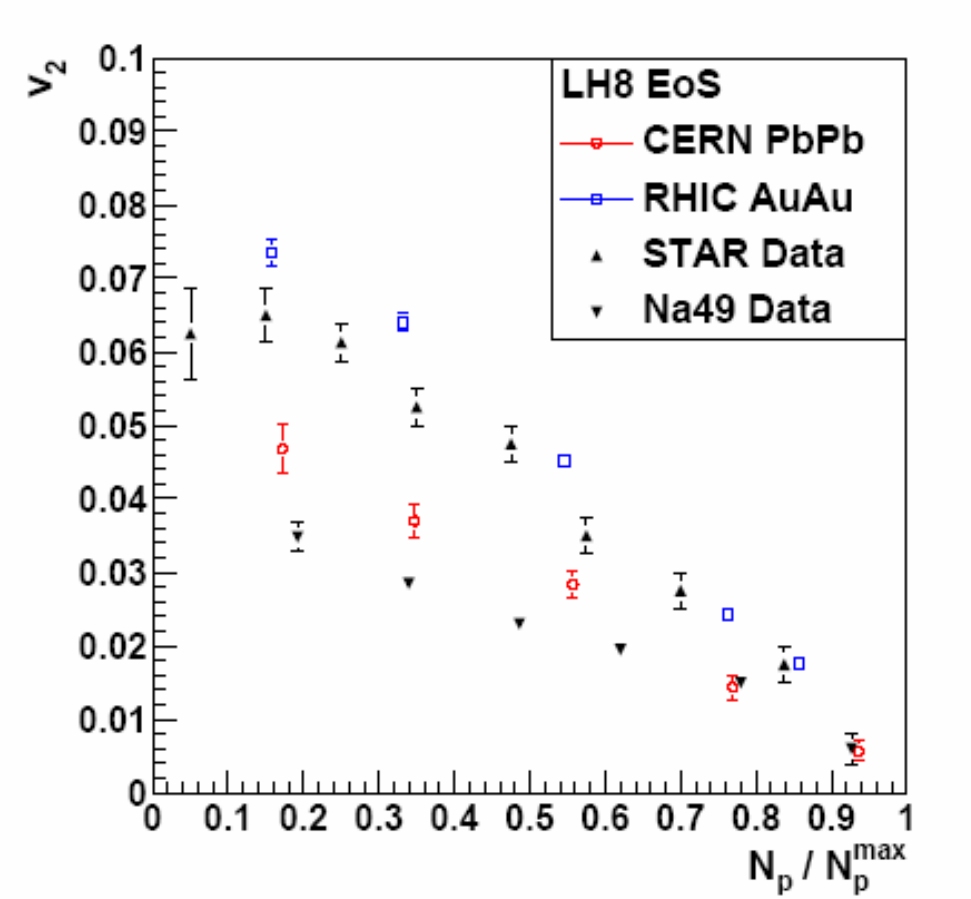


Smooth increase with collision energy towards hydrodynamic model prediction

more realistic freeze-out model

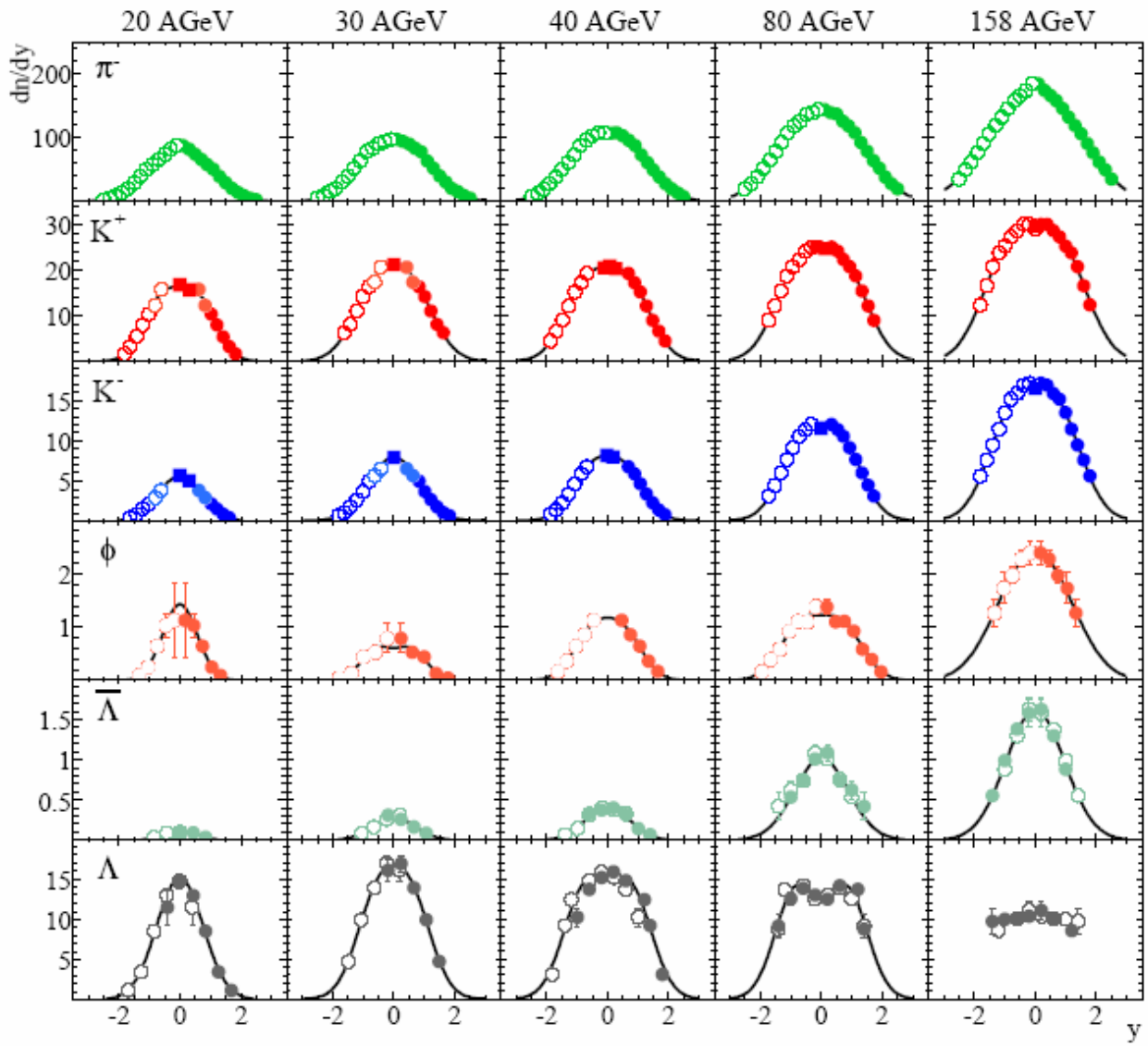
- QGP + hydro model expansion
- statistical hadronisation
- hadronic rescattering stage (RQMD)

Teaney, Lauret, Shuryak
PRL 86 (2001) 4783



fair description
of SPS and RHIC data

Rapidity spectra

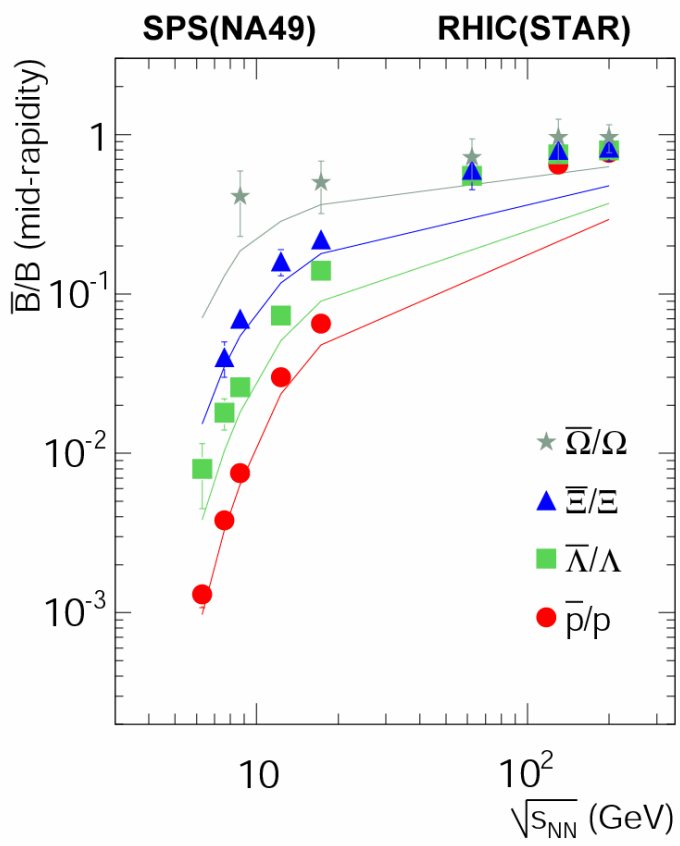


also: Ξ, Ω

Extrapolation
→ 4π yields

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

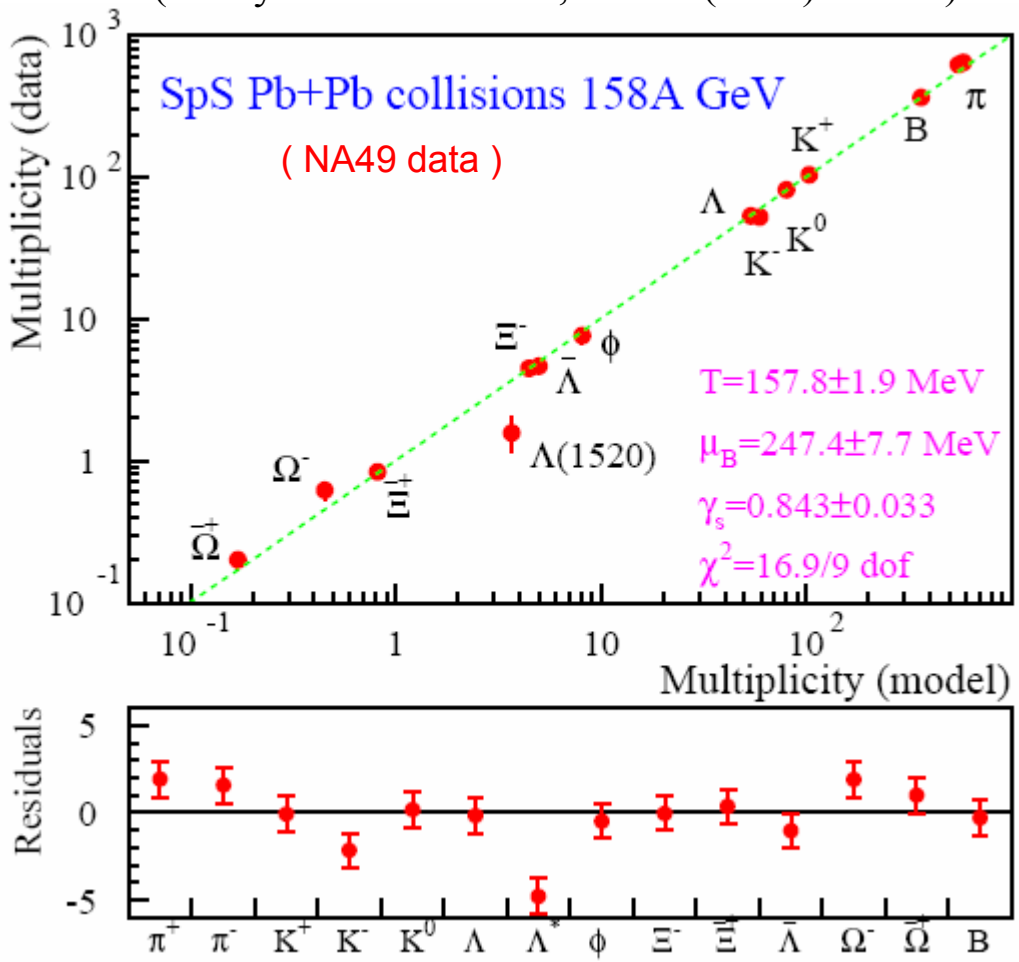
baryonic density decreases rapidly at SPS energies



transition from baryon to meson dominated final state at SPS

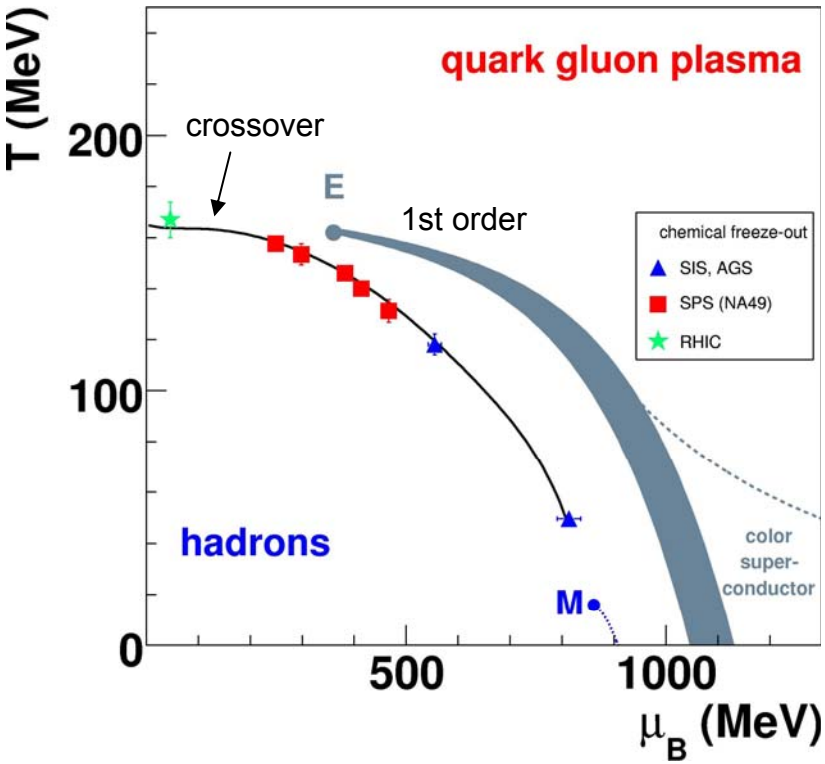
Particle yields – statistical model

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



- hadron species populated according to phase space probabilities (max.entropy) (Fermi,Hagedorn)
- strangeness sector not fully saturated (Rafelski)
- statistical model successful, T, μ_B, γ_S, V
- incease of $\gamma_S = 0.5 \rightarrow 0.8$ from p+p to A+A shows: relaxation of canonical suppression not enough !

Global view - Phase diagram



(Lattice-QCD phase boundary: Fodor,Katz JHEP04(2004)050)

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

- freeze out line E ≈ 1 GeV / particle

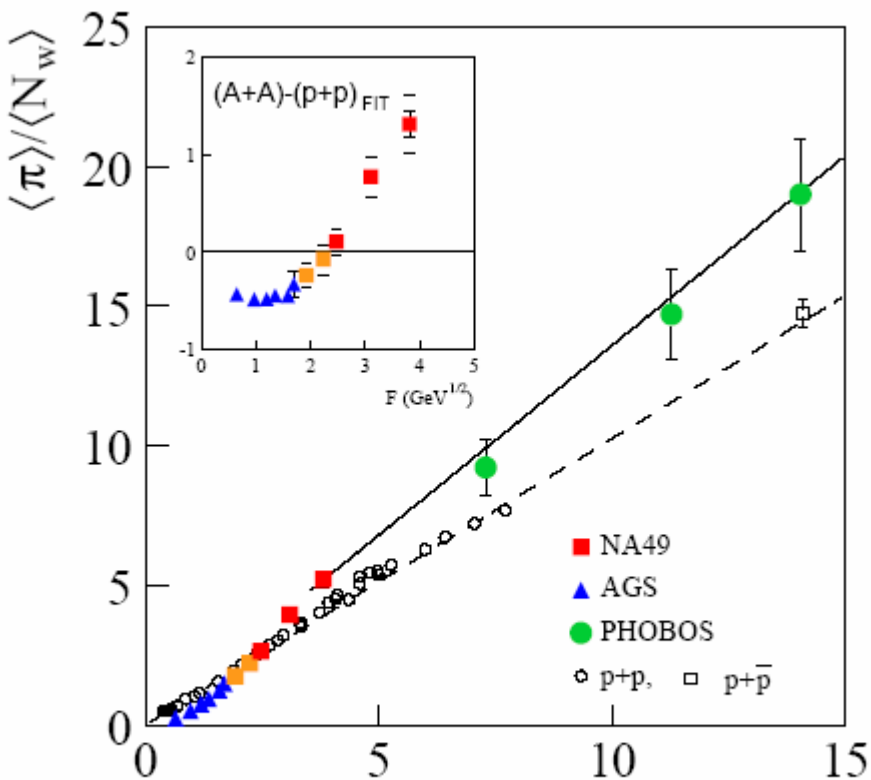
(Cleymans and Redlich, PRL 81(1998) 5284)

hadrochemical freeze out parameters approach the phase boundary at SPS

Energy dependence - π yields

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

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



$F\ (\mathrm{GeV}^{1/2}) \approx s_{NN}^{1/4}$

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

SMES: statistical model of the early stage

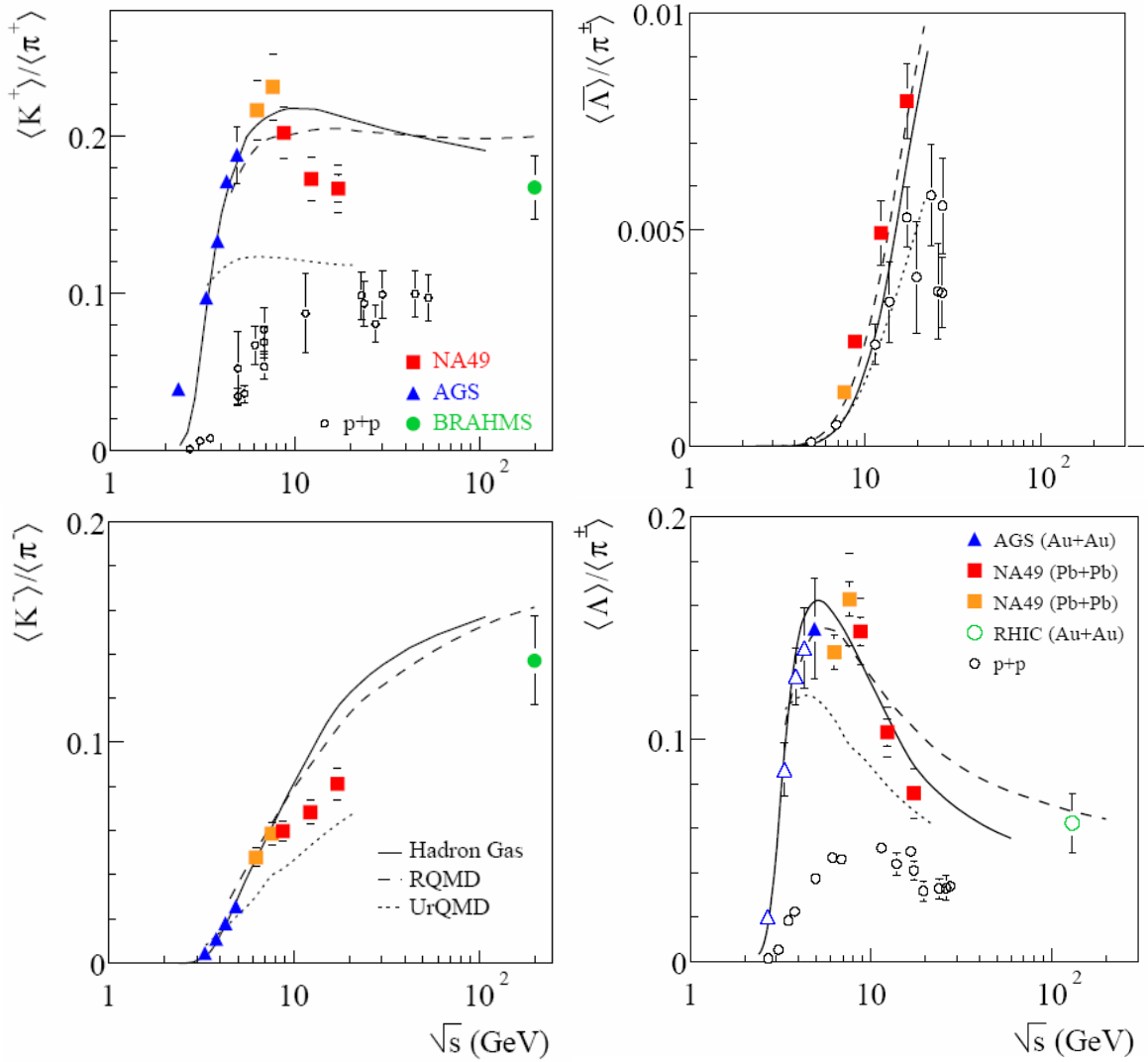
$$\frac{\langle \pi \rangle}{N_w} \propto \frac{S}{N_w} \propto g^{1/4} F$$

$$F = \frac{(\sqrt{s} - 2m_p)^{3/4}}{\sqrt{s}^{1/4}}$$

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

Increase 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 (yet ?) reproduce the sharp peak

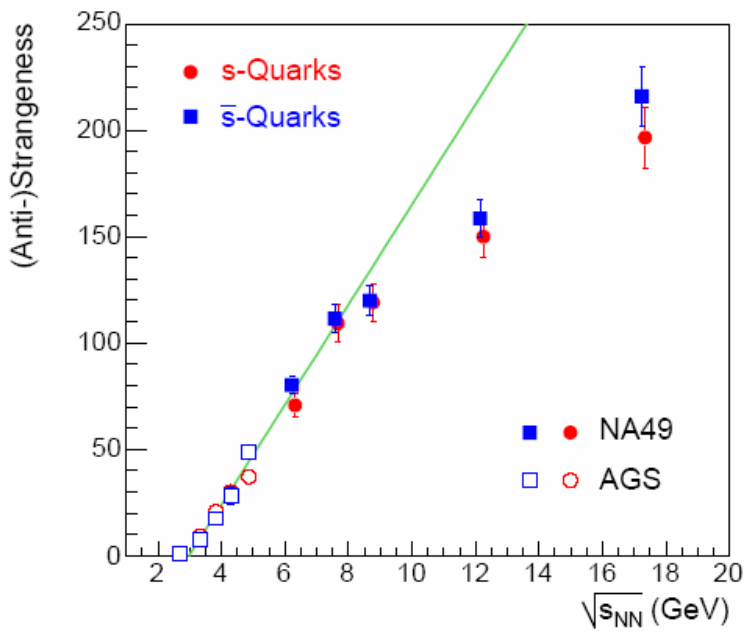
s quark carriers:

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

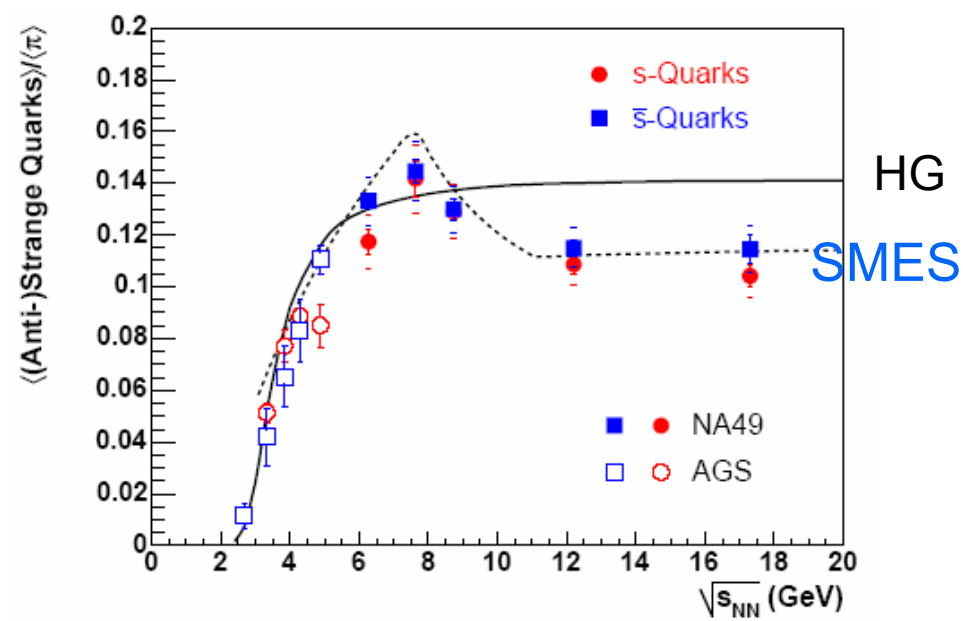
$$<\pi^{\pm}> = \frac{1}{2}(<\pi^{+}> + <\pi^{-}>)$$

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

energy dependence of yields changes at 30A GeV



sharp peak, then under-saturation of strangeness content



s - quark carriers: K^-, K^0 [1]; $\Lambda+\Sigma^0$, $\Sigma^\pm$ [2]; Ξ^-, Ξ^0, Ω^- [3]

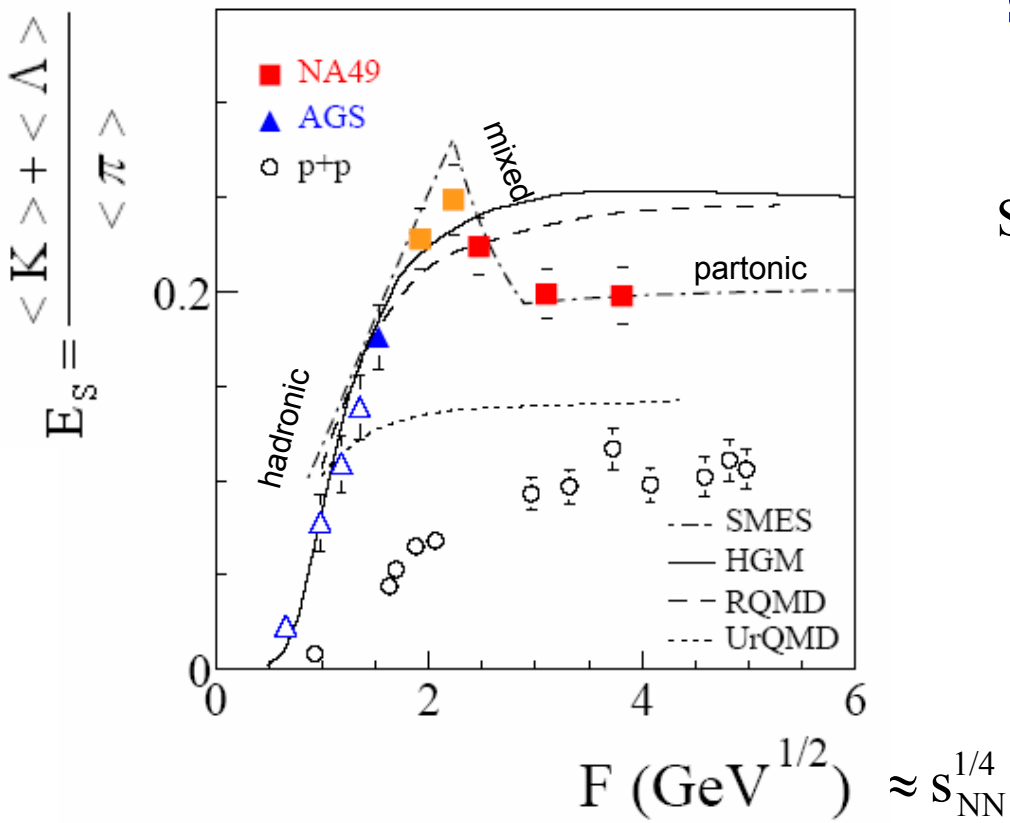
$\bar{s}$ - quark carriers: K^+, $\bar{K}^0$ [1]; $\bar{\Lambda}+\bar{\Sigma}^0$, $\bar{\Sigma}^\pm$ [2]; $\bar{\Xi}^+$, $\bar{\Xi}^0$, $\bar{\Omega}^+$ [3]

[1] $\langle K^0\rangle \approx \langle K^+\rangle$, $\langle \bar{K}^0\rangle \approx \langle K^-\rangle$ due to isospin symm.

[2] empirical factor $\langle \Sigma^\pm\rangle \approx 0.6 \langle \Lambda\rangle$

[3] from hadron gas model if not measured

Energy dependence – ratio of strange hadrons to pions



strangeness to pion ratio peaks sharply at the SPS

SMES explanation:

- entropy, number of s,sbar quarks conserved from QGP to freezeout
- ratio of strange/nonstrange d.o.f. rises rapidly with T in hadron gas
- E_s drops to predicted constant level above the deconfinement threshold

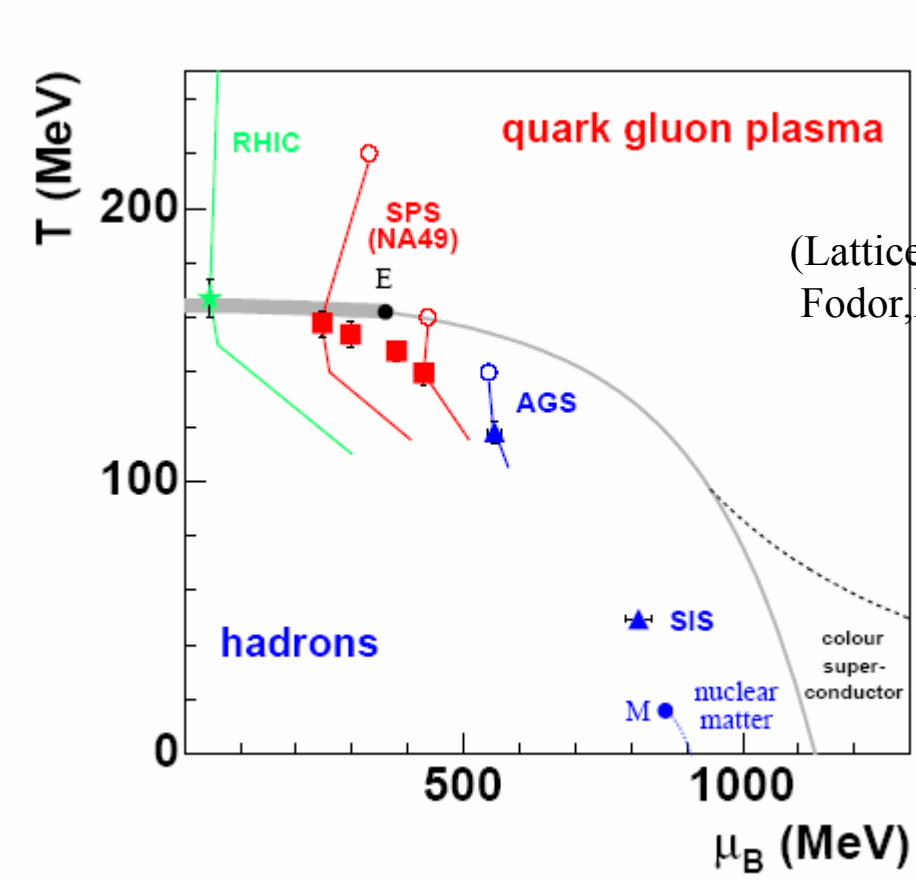
$$E_S \approx \frac{<N_S + N_{\bar{S}}>}{<\pi>} = \frac{0.74\, g_s}{g_u + g_d + g_g}$$

$$\approx 0.21$$

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

suggests onset of deconfinement at SPS

hypothetical trajectories in the phase diagram

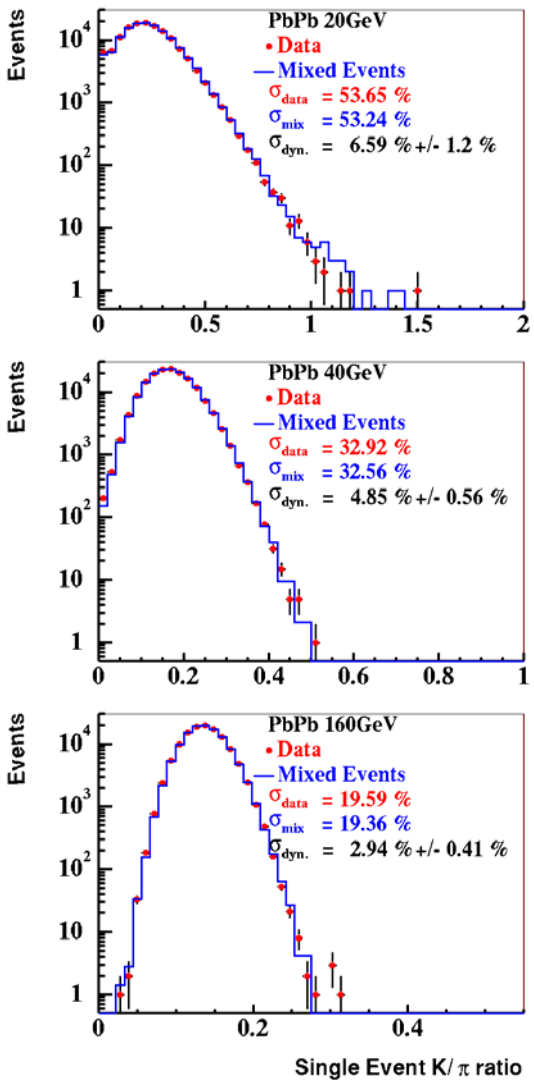


(Lattice-QCD phase boundary:
Fodor,Katz JHEP04(2004)050)

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

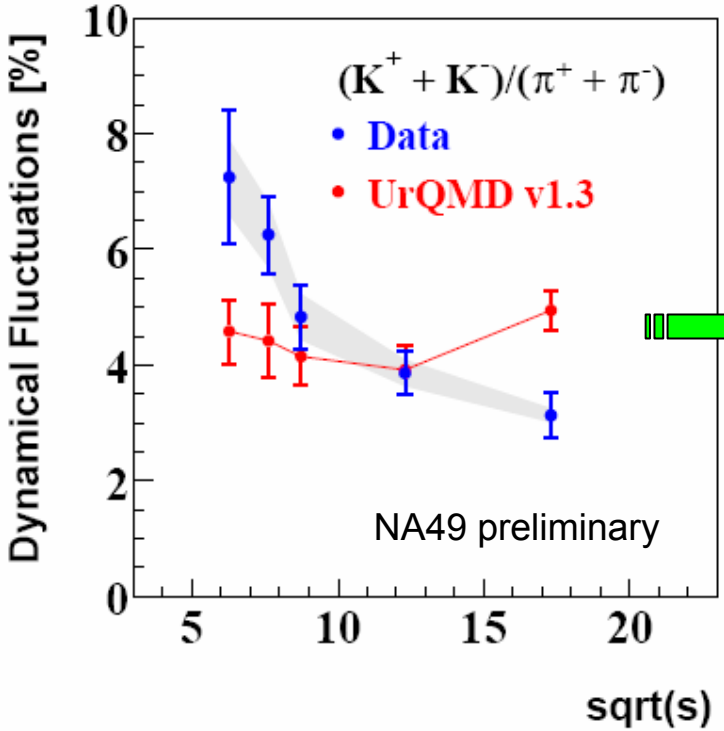
The Event-by-Event K/π ratio

Beam Energy



max.likelihood fit for each event

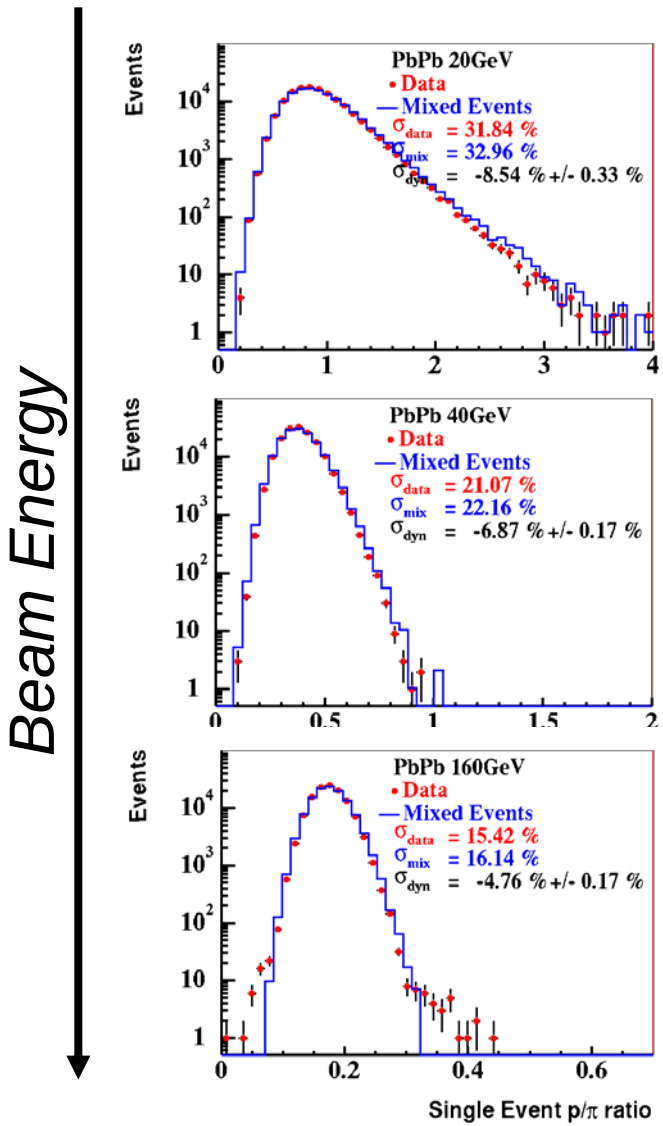
$$\sigma^2_{dyn} = \sigma^2_{data} - \sigma^2_{mixed}$$

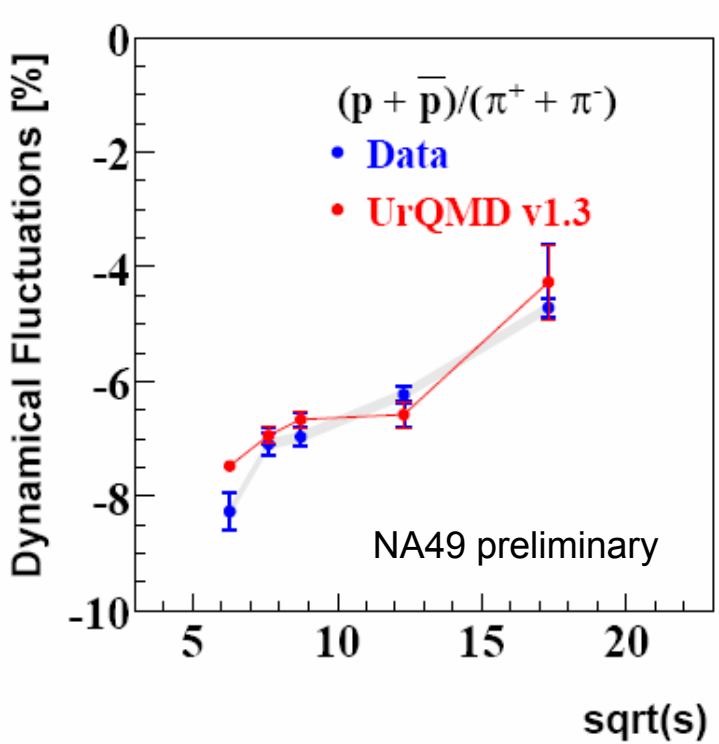


STAR

Increased fluctuation signal at lower beam energies

The Event-by-Event $(p + \bar{p})/\pi$ ratio



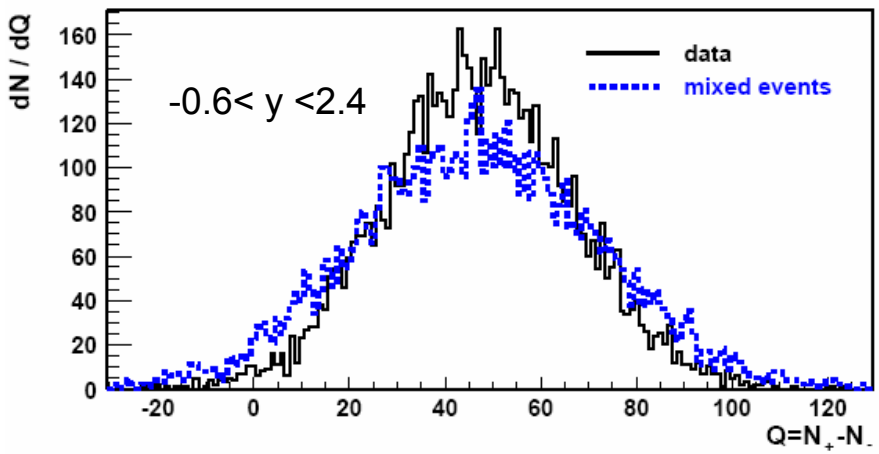


The distribution of the E-by-E p/π ratio is narrower for data than mixed events. Effect of baryon resonance decay ?

Electric charge fluctuations

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

Central Pb+Pb collisions 158A GeV

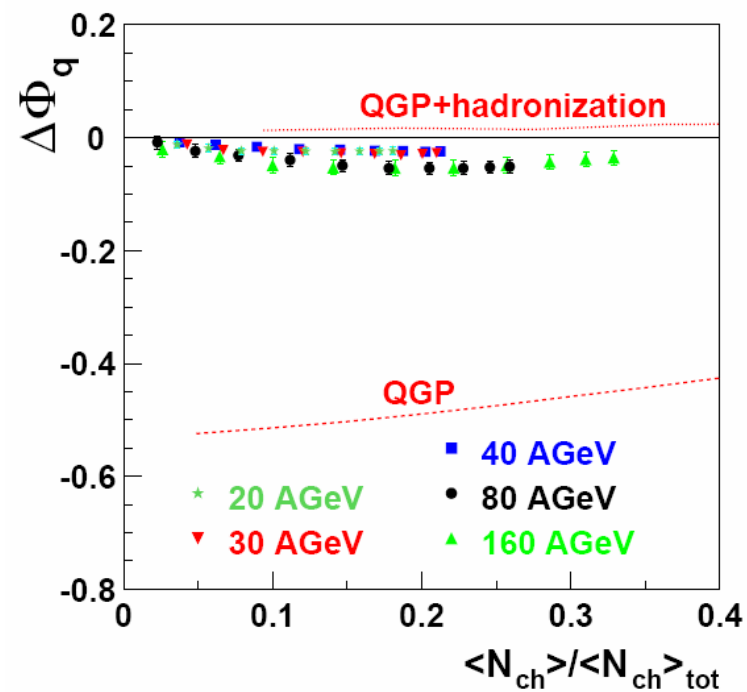


Global charge conservation

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

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

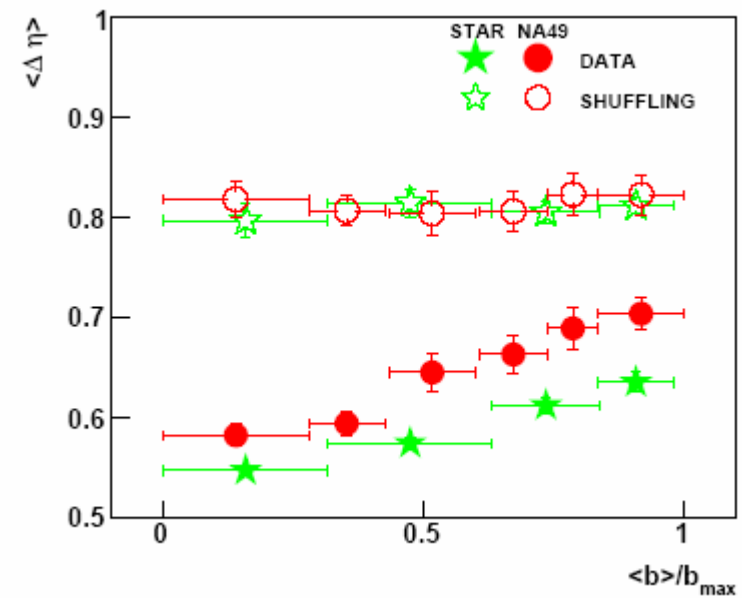
$$\Delta\Phi_q = \Phi_q - \Phi_{q,gcc}$$



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

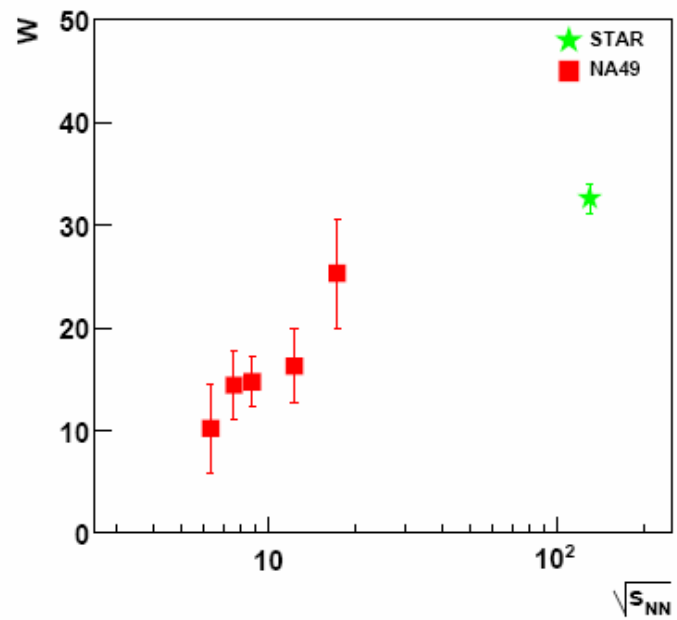
energy dependence of the charge balance function width

narrowing proposed as QGP signature



narrowing of width <Δη> seen at RHIC and SPS

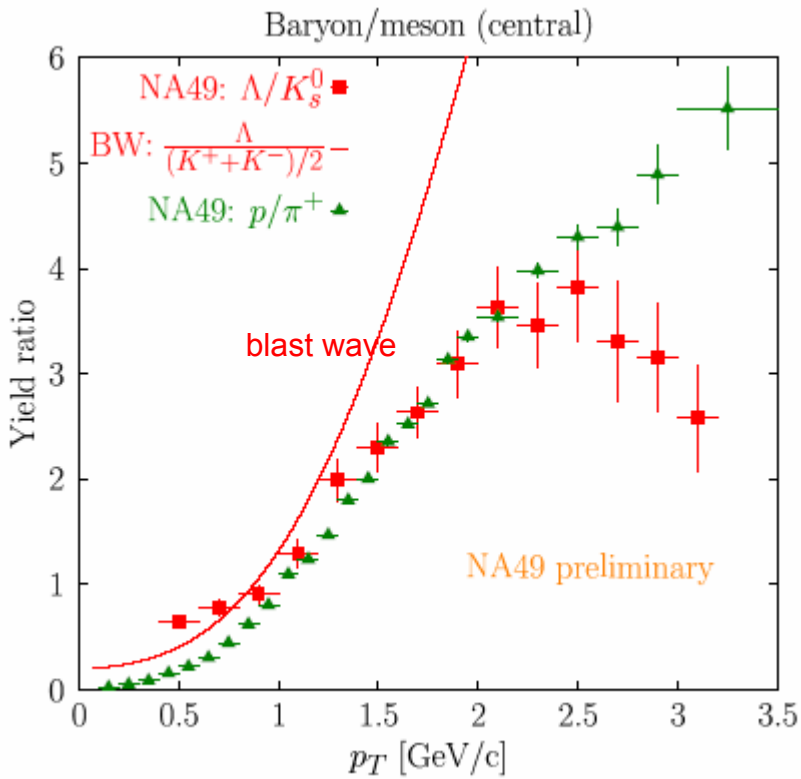
$W = (\langle\Delta\eta\rangle_{shuff} - \langle\Delta\eta\rangle_{data}) / \langle\Delta\eta\rangle_{shuff}$

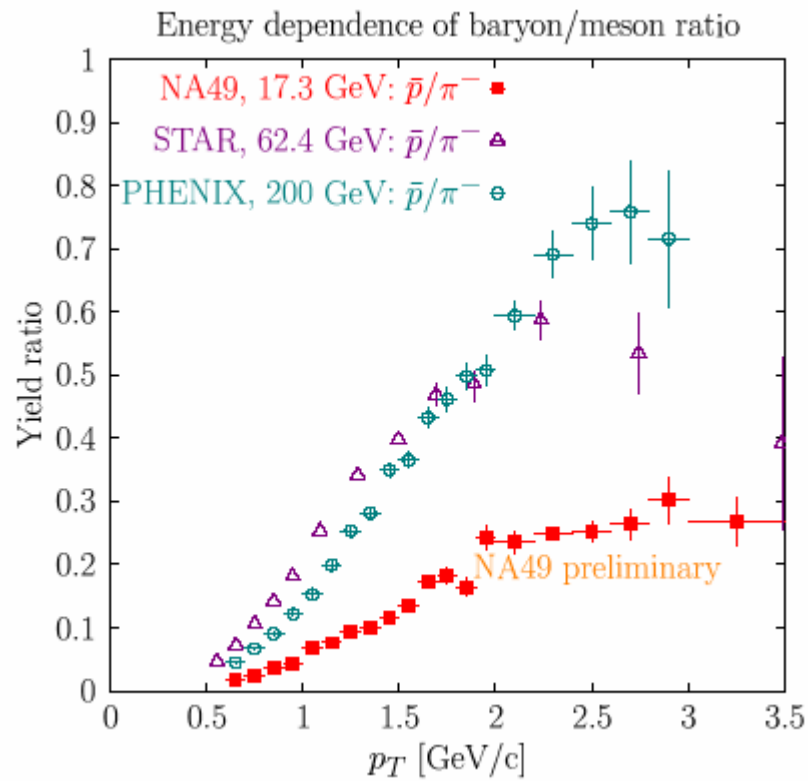


narrowing relative to global charge conservation reference gets stronger with energy

effect probably due to local charge conservation and radial flow

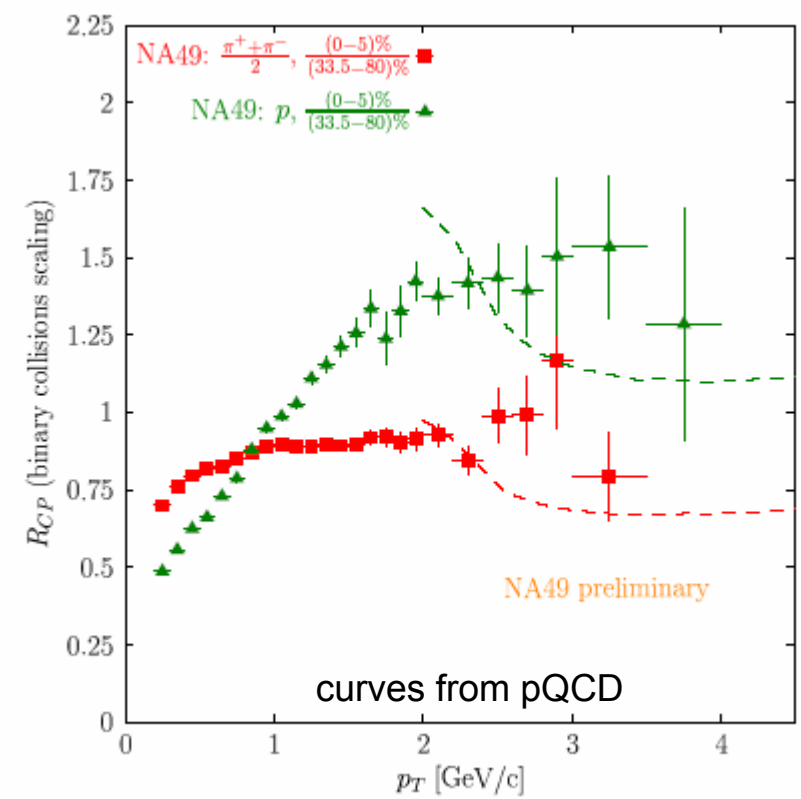
baryon/meson yield ratio at medium p_t

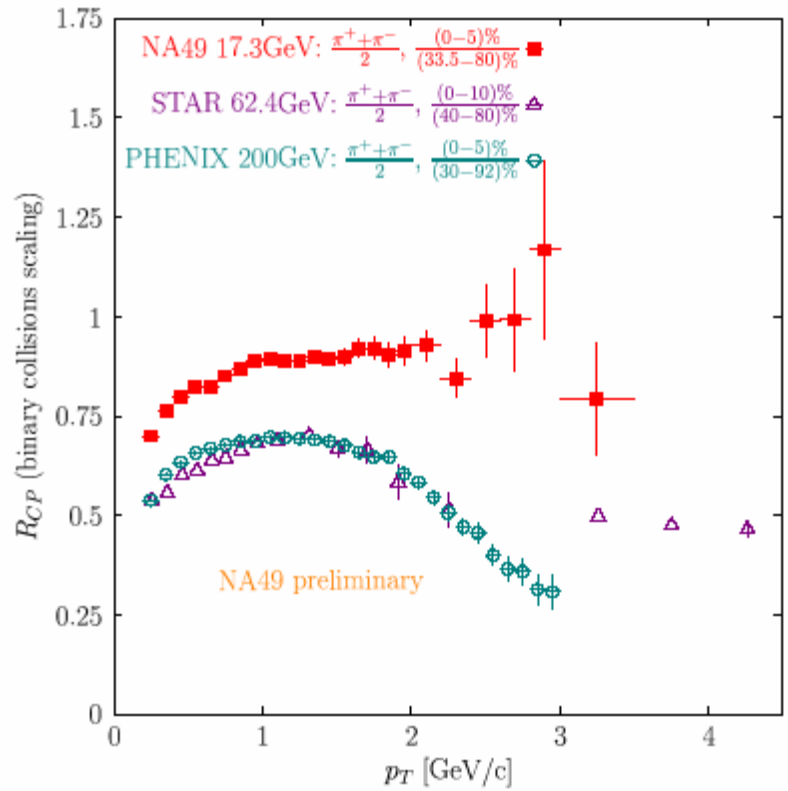




initial rise (radial flow) and saturation also observed at SPS

R_{CP} at SPS and RHIC





- Cronin effect stronger at SPS, indication of saturation
- NA49 not sensitive to suppression, p_T range insufficient

Conclusions

- Strong collective behavior in Pb+Pb (Au+Au) reactions:
  increasing radial and anisotropic flow AGS → SPS → RHIC
- Initial energy density reaches range of deconfinement at SPS
- Structure in the energy dependence of m_T spectra and
  of pion and strangeness production indicate
  onset of deconfinement at low SPS energy
- No convincing signals of a phase transition or critical point
  in correlations and fluctuations yet, search continues
- Further experimental studies preferentially with an improved
  detector should be done to explore the possible existence
  of the critical point of QCD

The NA49 collaboration

C. Alt[9], T. Anticic[21], B. Baatar[8],D. Barna[4], J. Bartke[6], L. Betev[10], H. Białkowska[19], C. Blume[9], B. Boimska[19], M. Botje[1], J. Bracinik[3], R. Bramm[9], P. Bunčić[10], V. Cerny[3], P. Christakoglou[2], O. Chvala[14], J.G. Cramer[16], P. Csató[4], P. Dinkelaker[9], V. Eckardt[13], D. Flierl[9], Z. Fodor[4], P. Foka[7], V. Friese[7], J. Gál[4], M. Gaździcki[9,11], V. Genchev[18], G. Georgopoulos[2], E. Gładysz[6], K. Grebieszkow[20], S. Hegyi[4], C. Höhne[7], K. Kadija[21], A. Karev[13], M. Kliemant[9], S. Kniege[9], V.I. Kolesnikov[8], E. Kornas[6], R. Korus[11], M. Kowalski[6], I. Kraus[7], M. Kreps[3], M. van Leeuwen[1], P. Lévai[4], L. Litov[17], B. Lungwitz[9], M. Makariev[17], A.I. Malakhov[8], M. Mateev[17], G.L. Melkumov[8], M. Mitrovski[9], J. Molnár[4], St. Mrówczyński[11], V. Nicolic[21], G. Pálla[4], A.D. Panagiotou[2], D. Panayotov[17], A. Petridis[2], M. Pikna[3], D. Prindle[16], F. Pühlhofer[12], R. Renfordt[9], C. Roland[5], G. Roland[5], M. Rybczyński[11], A. Rybicki[6,10], A. Sandoval[7], N. Schmitz[13], T. Schuster[9], P. Seyboth[13], F. Siklér[4], B. Sitar[3], E. Skrzypczak[20], G. Stefanek[11], R. Stock[9], H. Ströbele[9], T. Susa[21], I. Szentpétery[4], J. Sziklai[4], P. Szymanski[10,19], V. Trubnikov[19], D. Varga[4,10], M. Vassiliou[2], G.I. Veres[4,5], G. Vesztergombi[4], D. Vranić[7], A. Wetzler[9], Z. Włodarczyk[11] I.K. Yoo[15], J. Zimányi[4]

[1]NIKHEF, Amsterdam, Netherlands. [2]Department of Physics, University of Athens, Athens, Greece. [3]Comenius University, Bratislava, Slovakia. [4]KFKI Research Institute for Particle and Nuclear Physics, Budapest, Hungary. [5]MIT, Cambridge, USA. [6]Institute of Nuclear Physics, Cracow, Poland. [7]Gesellschaft für Schwerionenforschung (GSI), Darmstadt, Germany. [8]Joint Institute for Nuclear Research, Dubna, Russia. [9]Fachbereich Physik der Universität, Frankfurt, Germany. [10]CERN, Geneva, Switzerland. [11]Institute of Physics Świetokrzyska Academy, Kielce, Poland. [12]Fachbereich Physik der Universität, Marburg, Germany. [13]Max-Planck-Institut für Physik, Munich, Germany. [14]Institute of Particle and Nuclear Physics, Charles University, Prague, Czech Republic. [15]Department of Physics, Pusan National University, Pusan, Republic of Korea. [16]Nuclear Physics Laboratory, University of Washington, Seattle, WA, USA. [17]Atomic Physics Department, Sofia University St. Kliment Ohridski, Sofia, Bulgaria. [18]Institute for Nuclear Research and Nuclear Energy, Sofia, Bulgaria. [19]Institute for Nuclear Studies, Warsaw, Poland. [20]Institute for Experimental Physics, University of Warsaw, Warsaw, Poland. [21]Rudjer Boskovic Institute, Zagreb, Croatia.