Onset of Deconfinement in Pb+Pb Collisions at the Cern SPS

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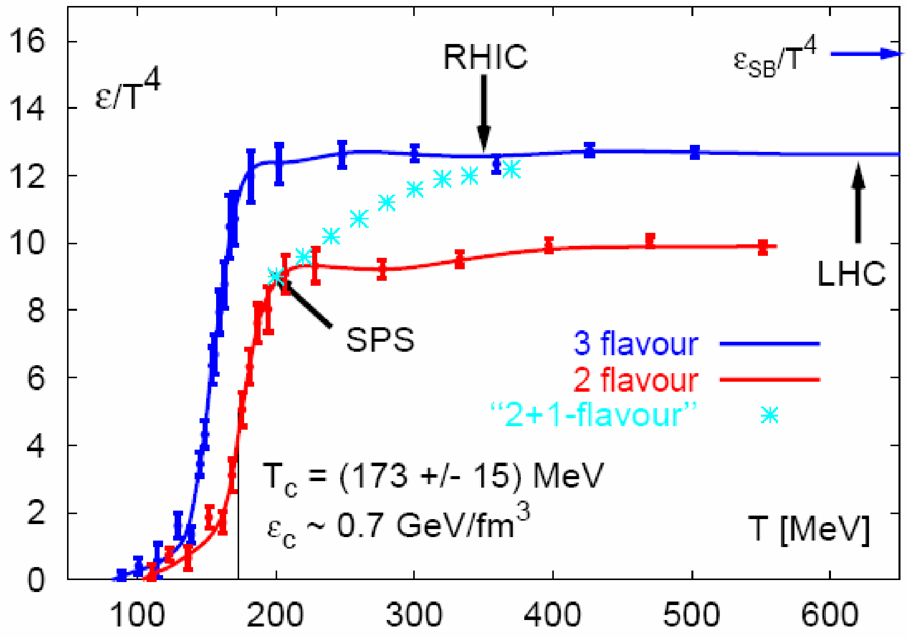
for the NA49 Collaboration

- Introduction
- Search for structures in the energy dependence of
  - transverse mass spectra, BE correlations, flow
  - particle yields and yield ratios
  - E-by-E fluctuations of $<p_T>$, K/π, Q
  - balance function
- Conclusions and future plans

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)

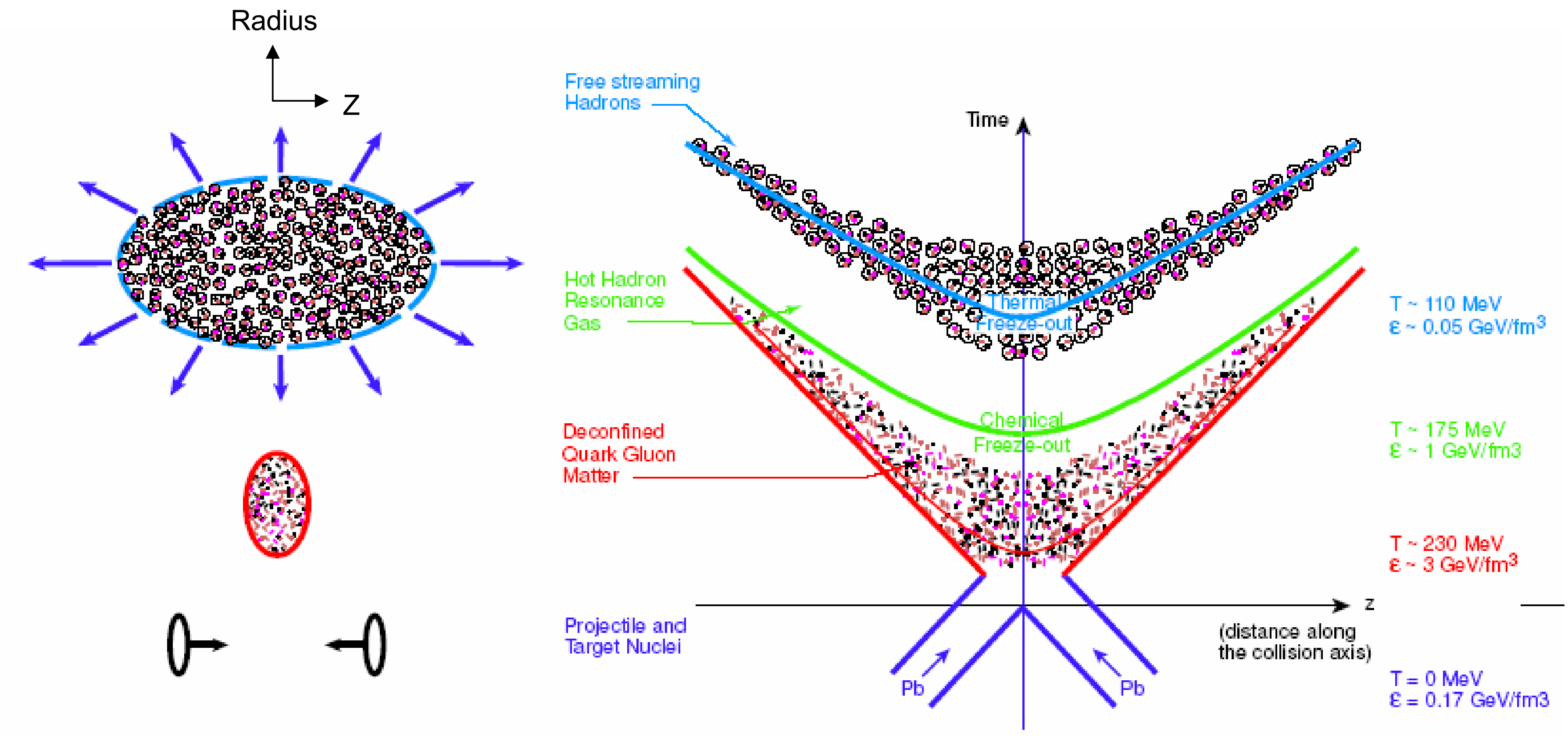


Karsch, Laermann
hep-lat/0305025

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



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)

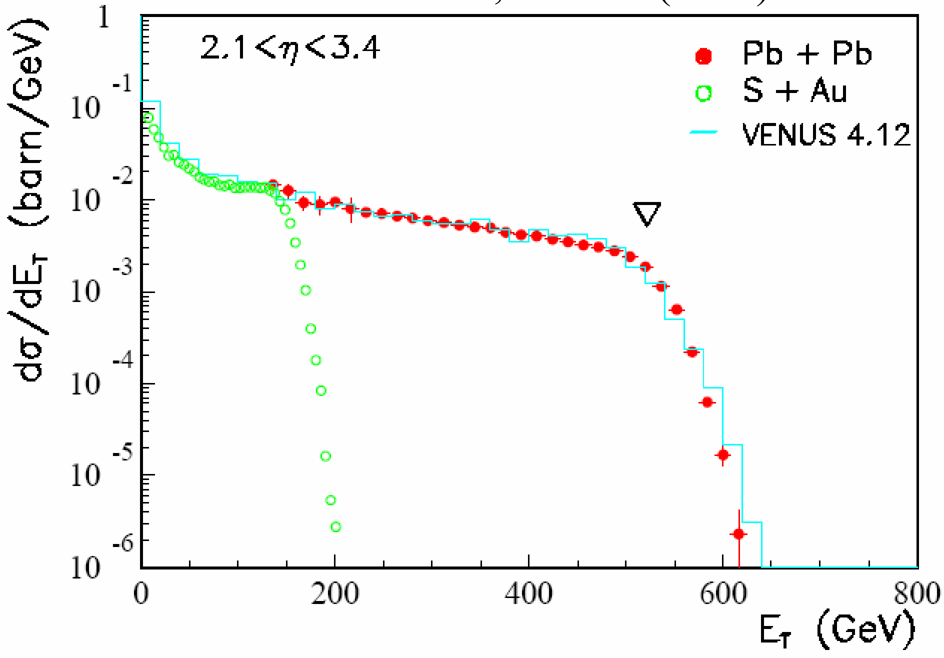
Estimate of initial energy density at 158A GeV

- from projectile energy loss and interaction volume:

$$\varepsilon = E/V \approx 0.67 \cdot \sqrt{s}_{NN} / \frac{4}{3}\pi \cdot r_0^3 \cdot \gamma^{-1} \approx 13 \text{ GeV/fm}^3$$

- from transverse energy production and Bjorken's model:

NA49, PRL 75 (1995) 3814



$$\varepsilon = (dE_T / d\eta)/(\pi \cdot R^2 \cdot \tau_o)$$

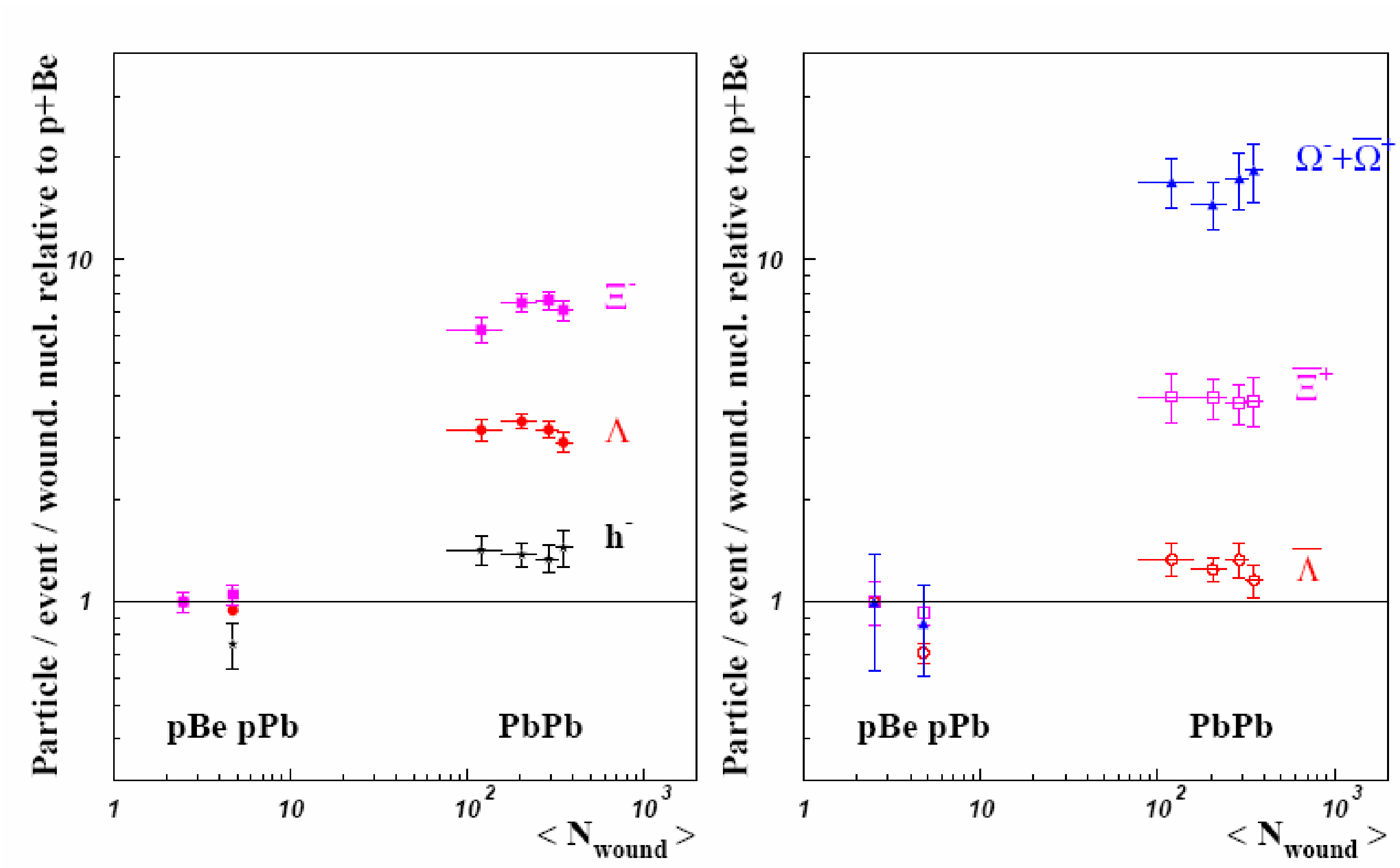
$$\approx 3.2 \text{ GeV/fm}^3$$

with $\tau_0 = 1$ fm/c

$R = 1.12 \cdot A^{1/3}$

initial energy density
$\varepsilon > \varepsilon_c \approx 1$ GeV/fm^3

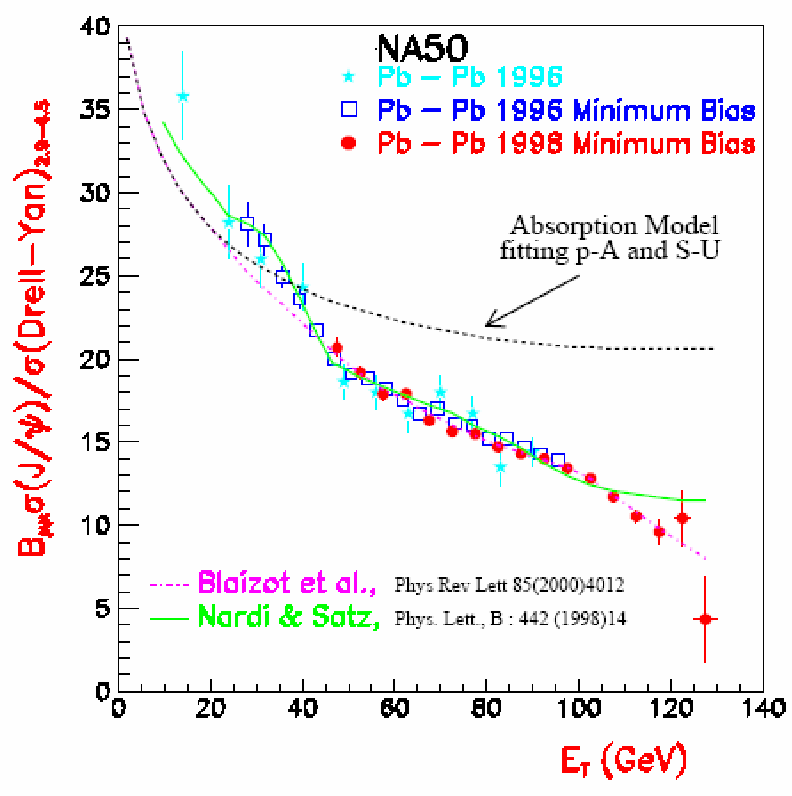
WA97: hyperon enhancement at 158A GeV

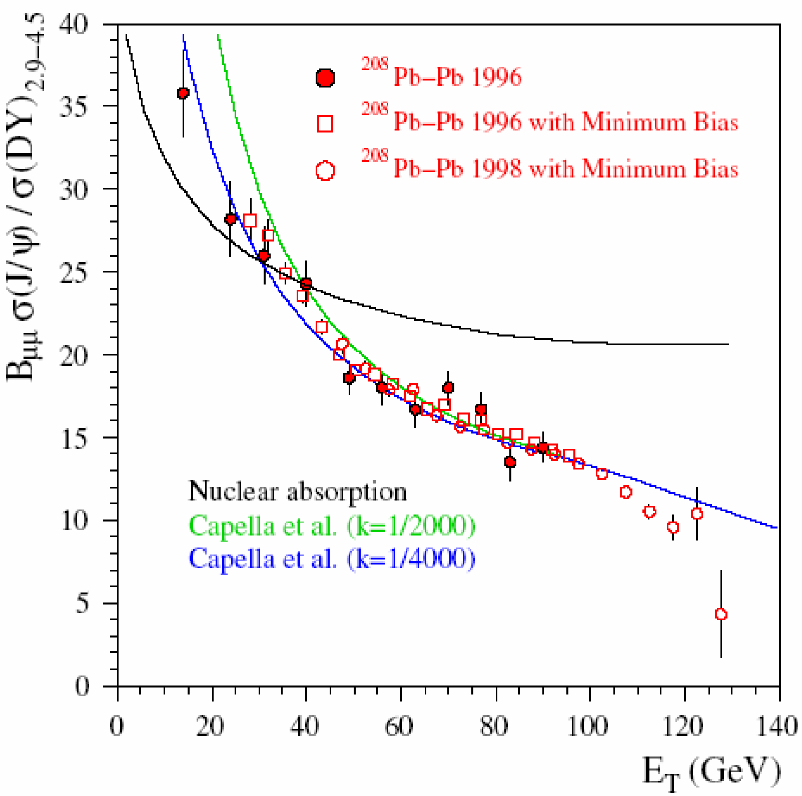


- fast equilibration of strange quarks in the QGP due to $m_S < T$

  (Koch,Müller,Rafelski 1984)
- how much enhancement due to scattering in the hadron gas phase ?

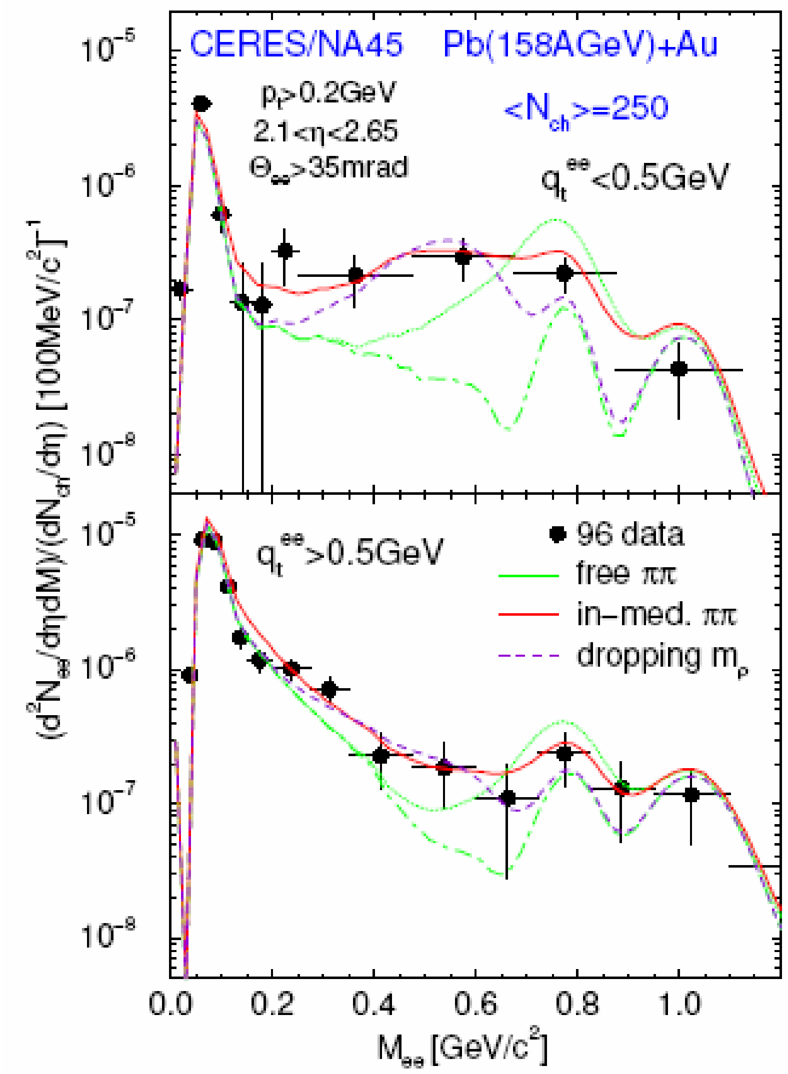
NA50: J/Ψ suppression at 158A GeV





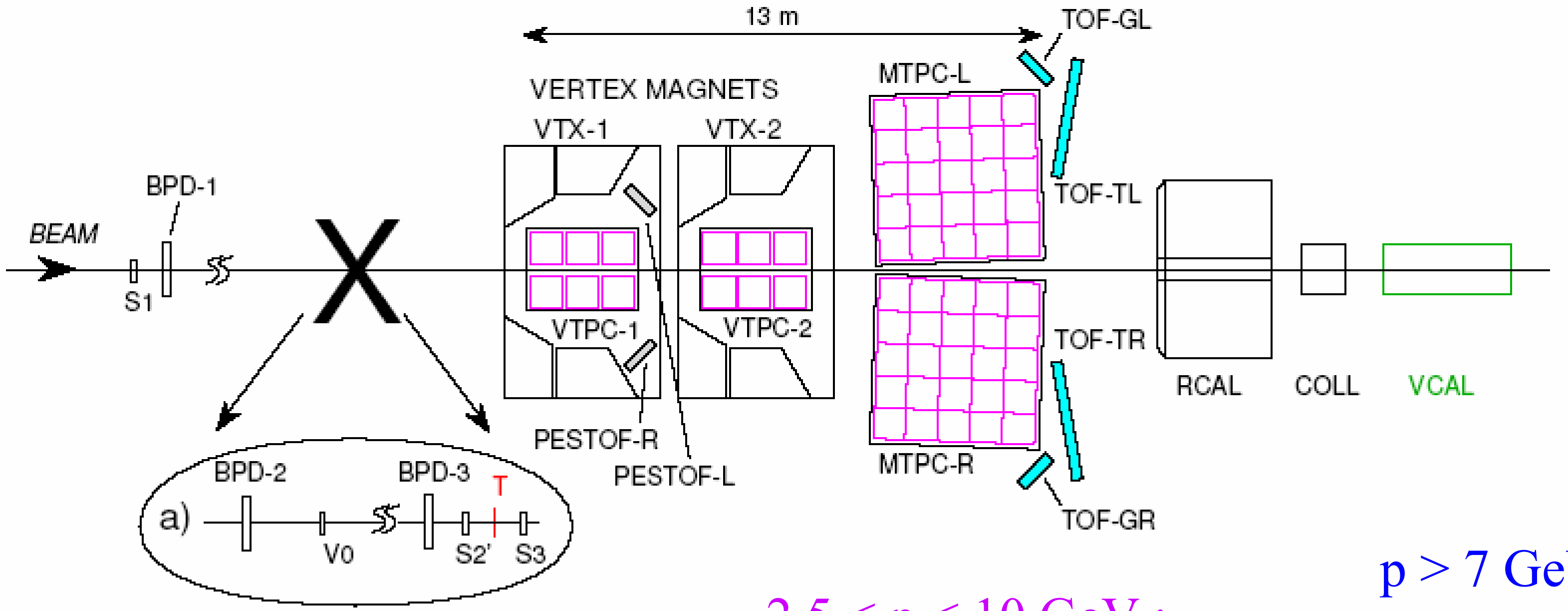
- screening of the color binding force in the QGP (Matsui, Satz 1986)
- destruction of J/Ψ by scattering on co-moving produced matter ?

NA45: low mass e^+e^- pair enhancement, ρ^0 modification



- effect of chiral restoration in the QGP
- consequence of high baryonic density ?

The NA49 Detector



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

p > 7 GeV
dE/dx
forward rapidity

Target: 20cm liquid H_2 or Pb foil

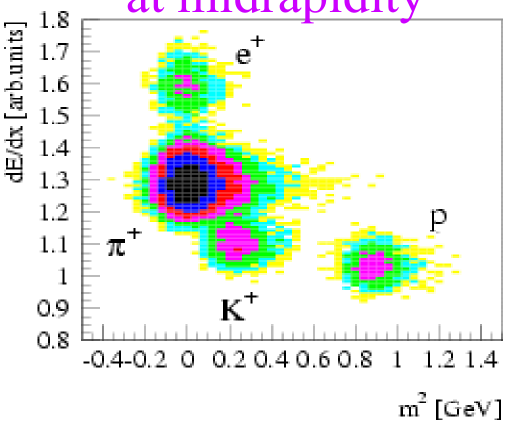
VCAL detects projectile spectators

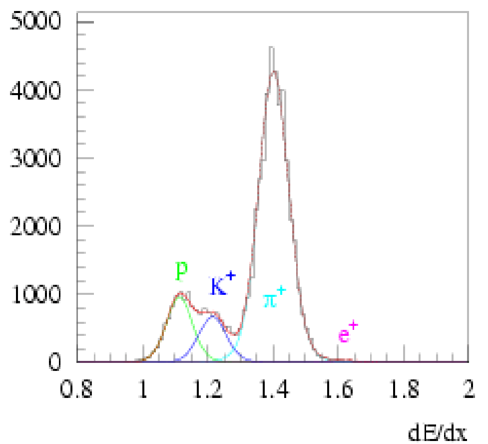
$\Delta p/p^2 = 7\ (0.3) \cdot 10^{-4}\ (GeV/c)^{-1}$

(VTPC-1, VTPC+MTPC)

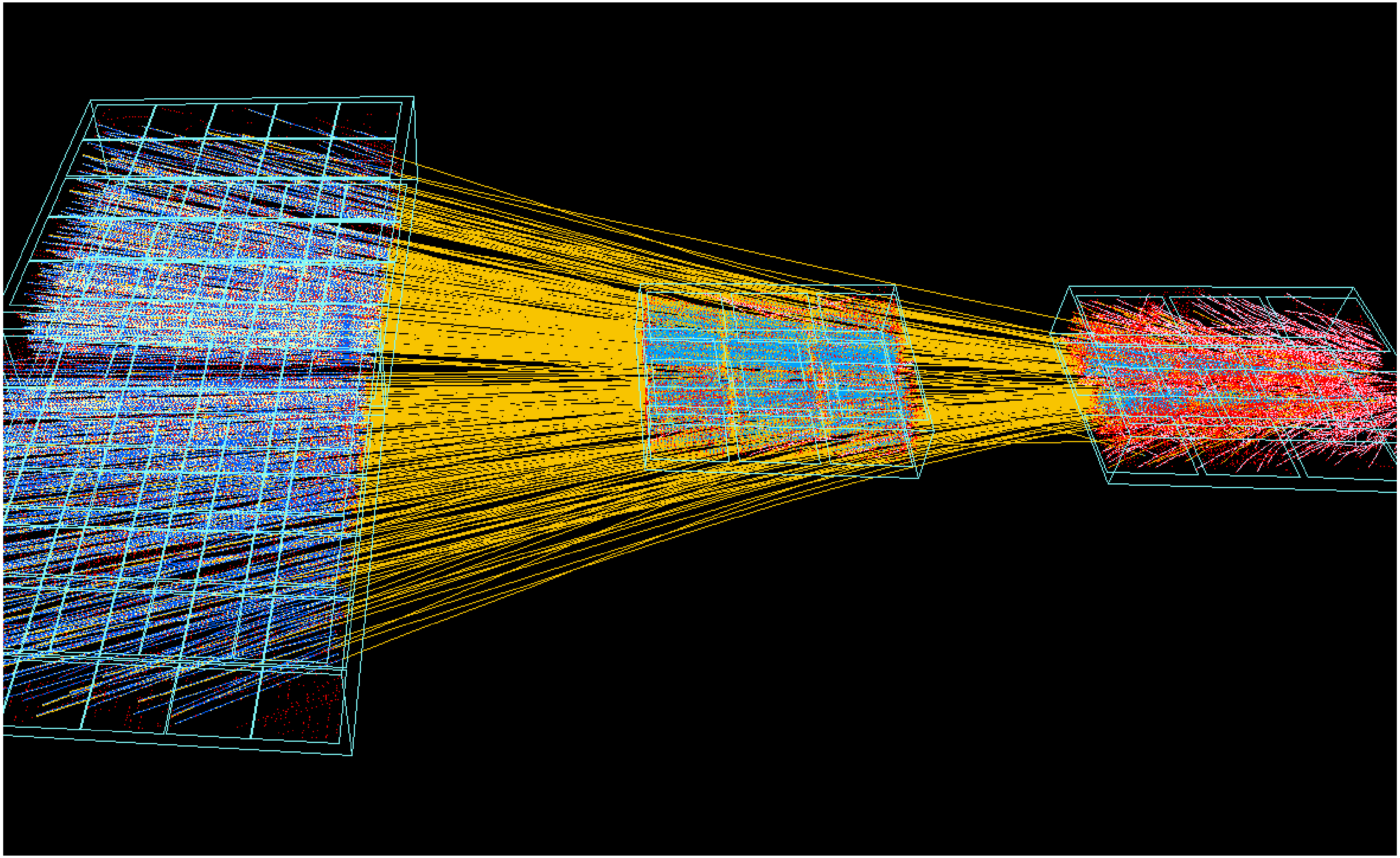
dE/dx resolution 3 – 6 %

TOF resolution ~ 60 ps



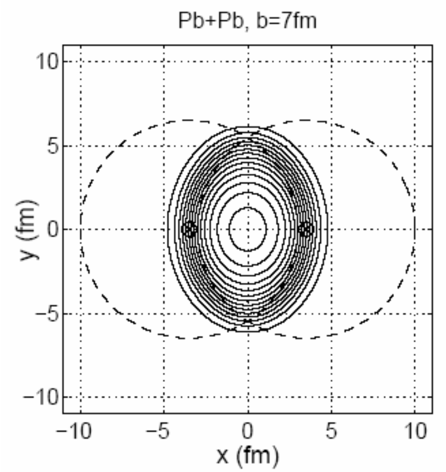


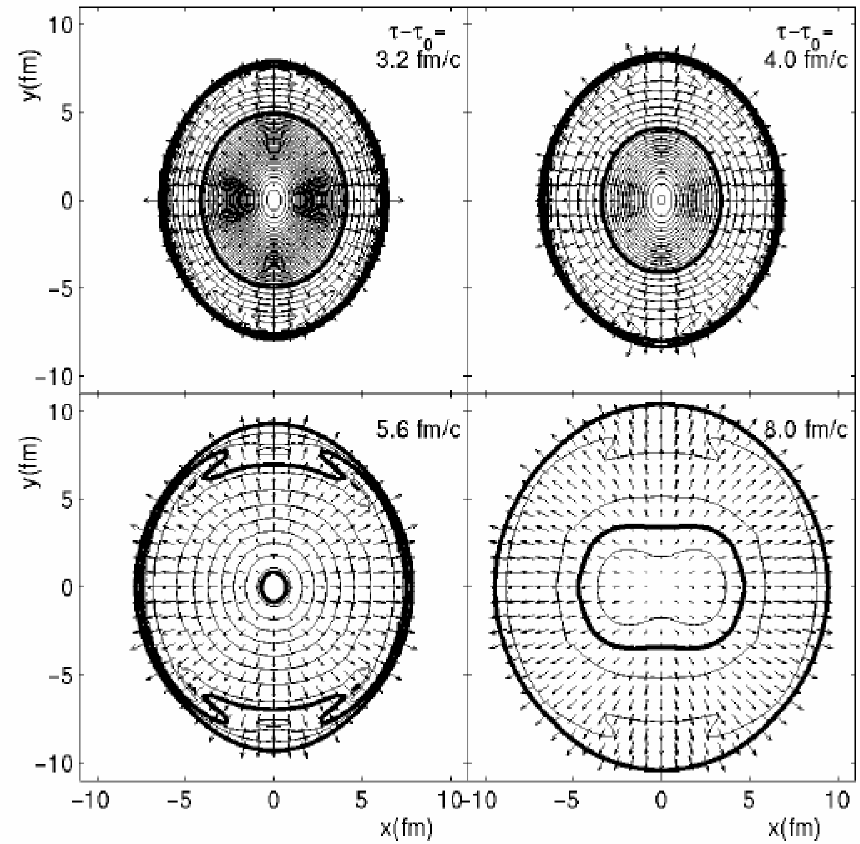
Pb+Pb collision at 158A GeV



Fireball evolution in hydrodynamics: p_T distributions, collective flow

Initial energy density → particle production, collective flow





Hydro model: Heinz, Kolb
PRC 62,054909 (2000)

Fit data with hydro motivated parameterisation : "blast wave model"

hydro model motivated parametrisation: blast wave model

Source function :

Retiere, Lisa PRC70,044907(2004)

$$S(x,K) = m_t \cosh(\eta - Y) \cdot \Omega(R, \phi_s) \exp\left(\frac{-(\tau - \tau_0)^2}{2\Delta\tau^2} \right) \cdot \frac{1}{\exp(K \cdot u / T) \pm 1}$$

T fireball temperature (uniform)

u local source velocity:
linearly increasing transverse flow, ρ_0 at surface

τ_0 freeze out time

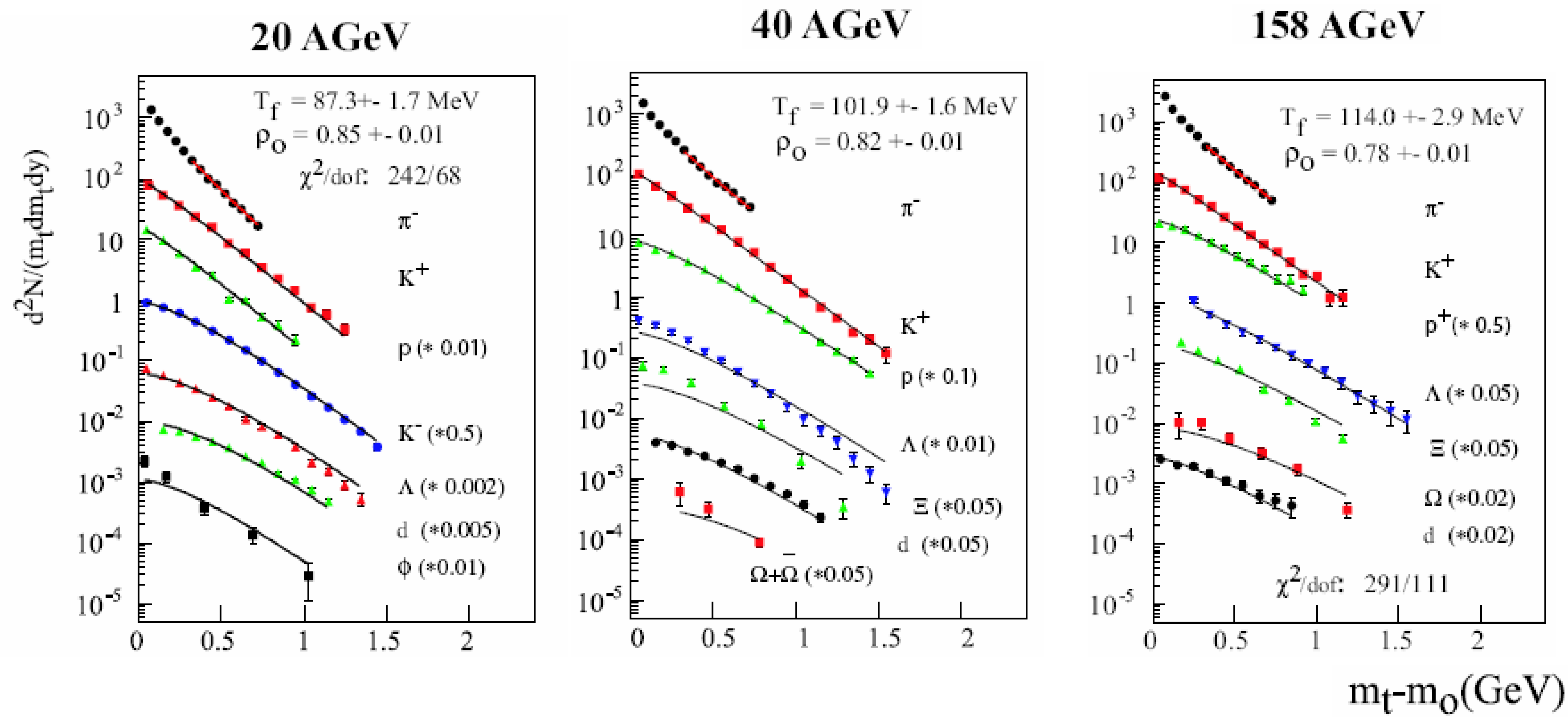
$\Delta\tau$ emission duration

$\Omega(R,\Phi_s)$ emission density:
R surface radius (box profile = constant density used)

fit parameters : $T, R, \tau_0, \Delta\tau, \rho_o$

Transverse mass spectra at mid-rapidity

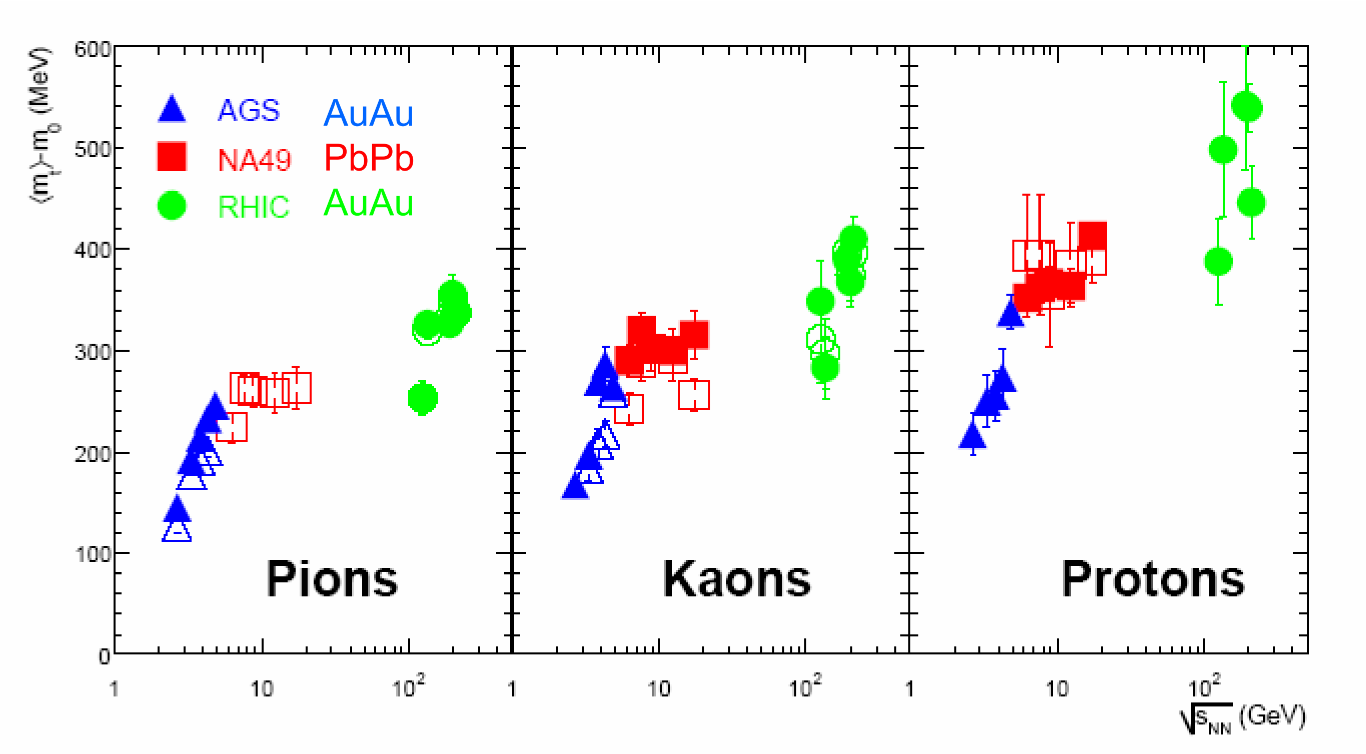
many spectra measured, "blast wave" model works at SPS



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

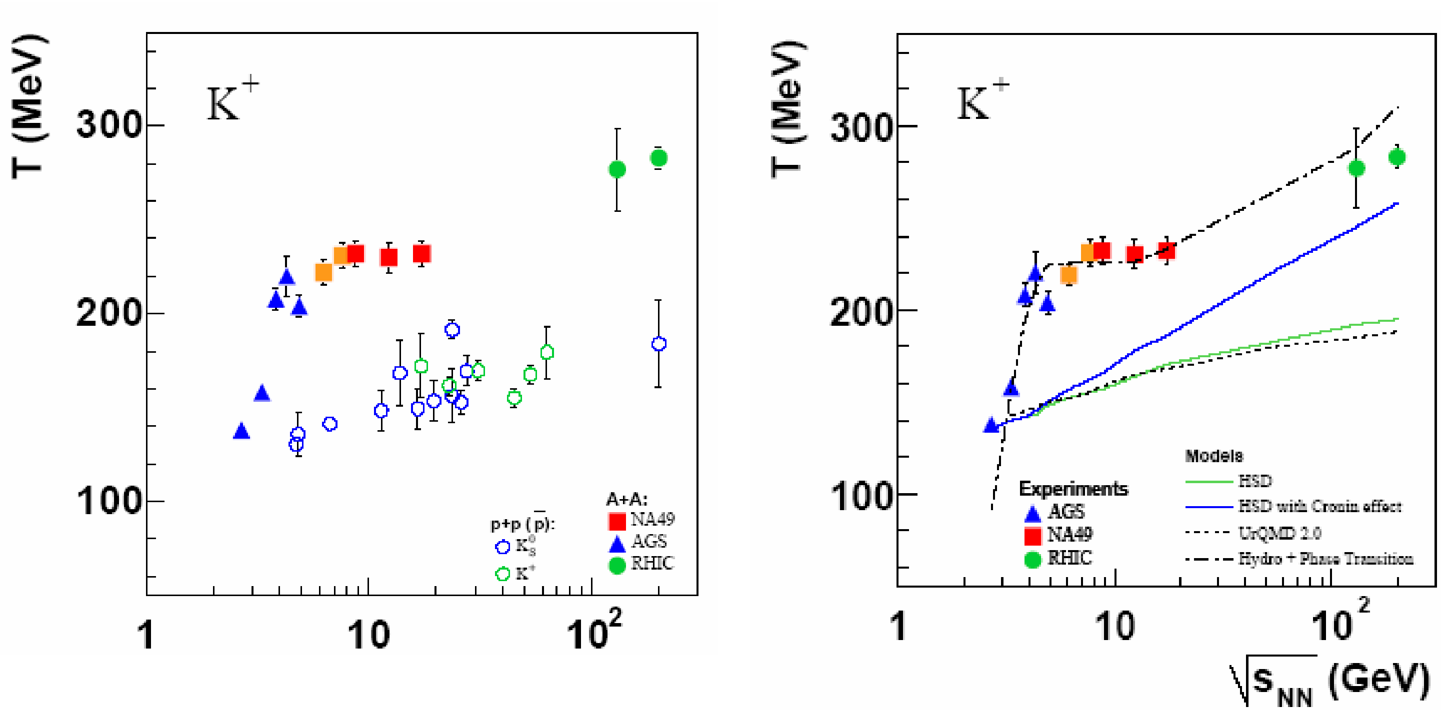
Energy dependence - average transverse mass

NA49 preliminary



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

Energy dependence – inverse slope parameters



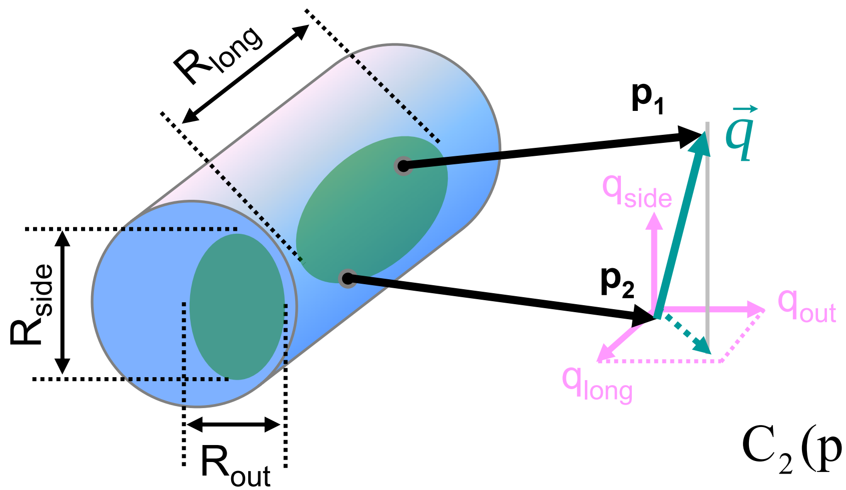
$$\frac{d\sigma}{dm_T^2\,dy} = A \cdot e^{-m_T/T}$$

- 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)

2π Bose-Einstein correlations



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

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

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

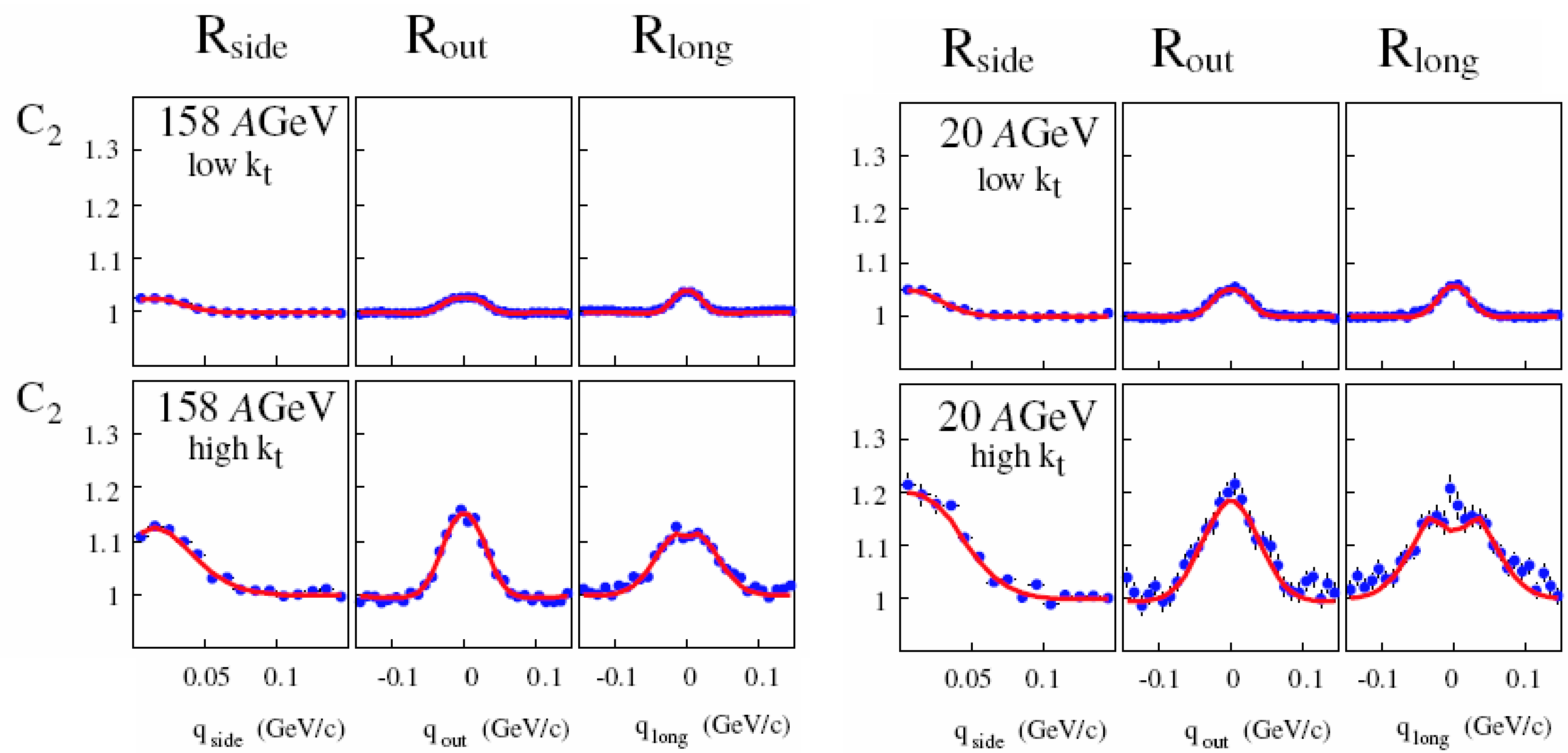
$$C_2(p_1, p_2) = \frac{P(p_1, p_2)}{P(p_1)\cdot P(p_2)} = \frac{\text{real event pairs}}{\text{mixed event pairs}}$$

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

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

- 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: $C_2(q,k)_f = p \cdot \left(W(q, r_m) \cdot C_2(q,k)_{BP} \right) + (1-p)$

BE correlations sensitive to fireball size and flow

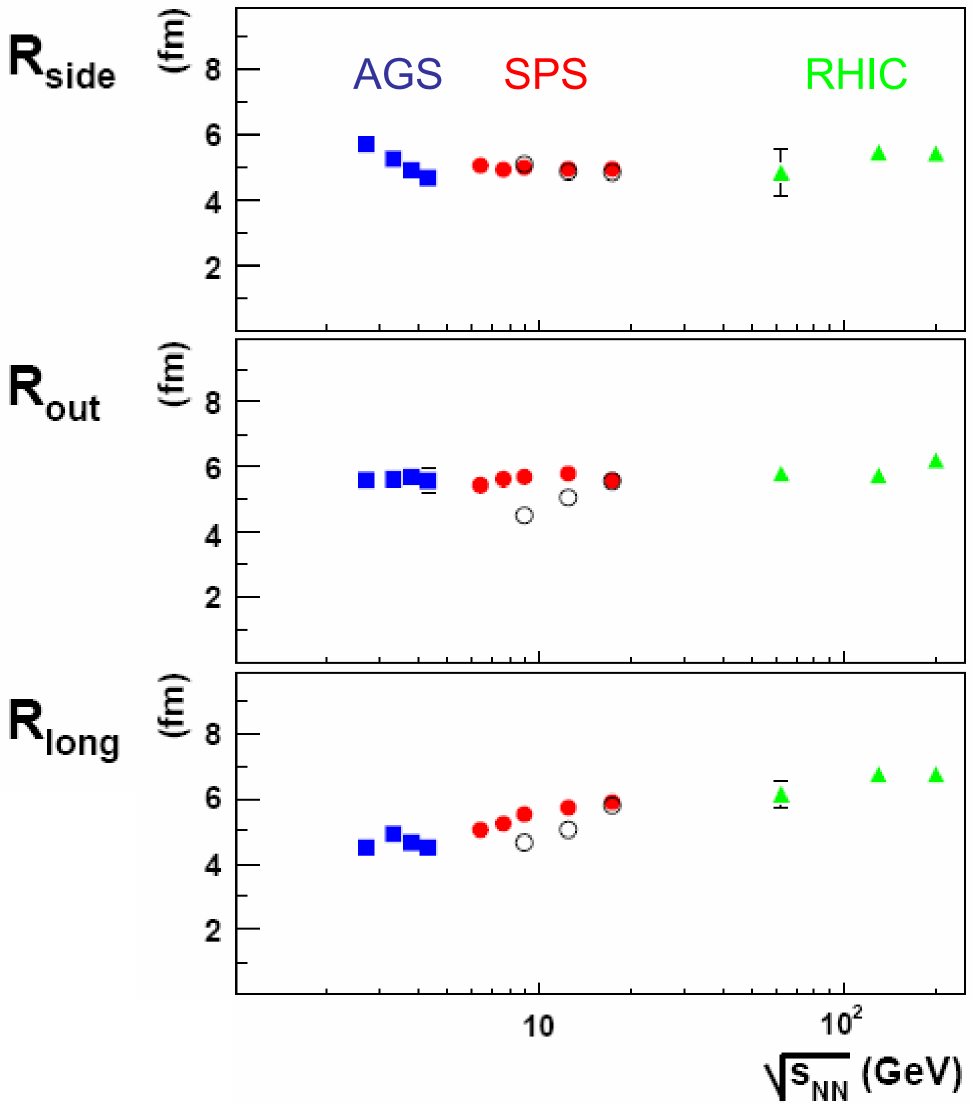


examples of $\pi^-\pi^-$ correlation functions at mid-rapidity in the Cartesian (Bertsch, Pratt) reference frame

Fit to QS correlation (Gaussian) + Coulomb repulsion

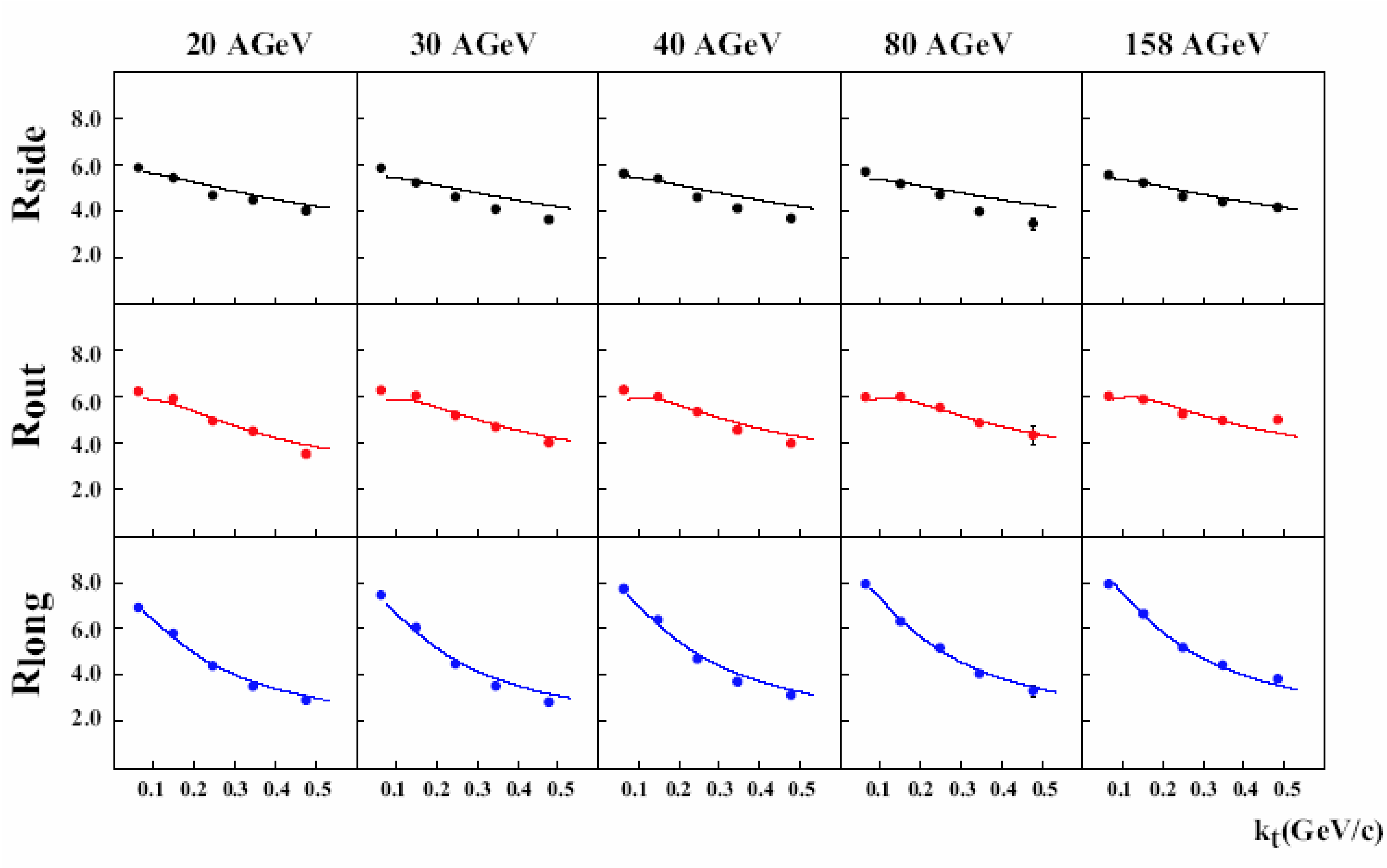
→ radius parameters R_i (length of homogeneity)

energy dependence of radius parameters

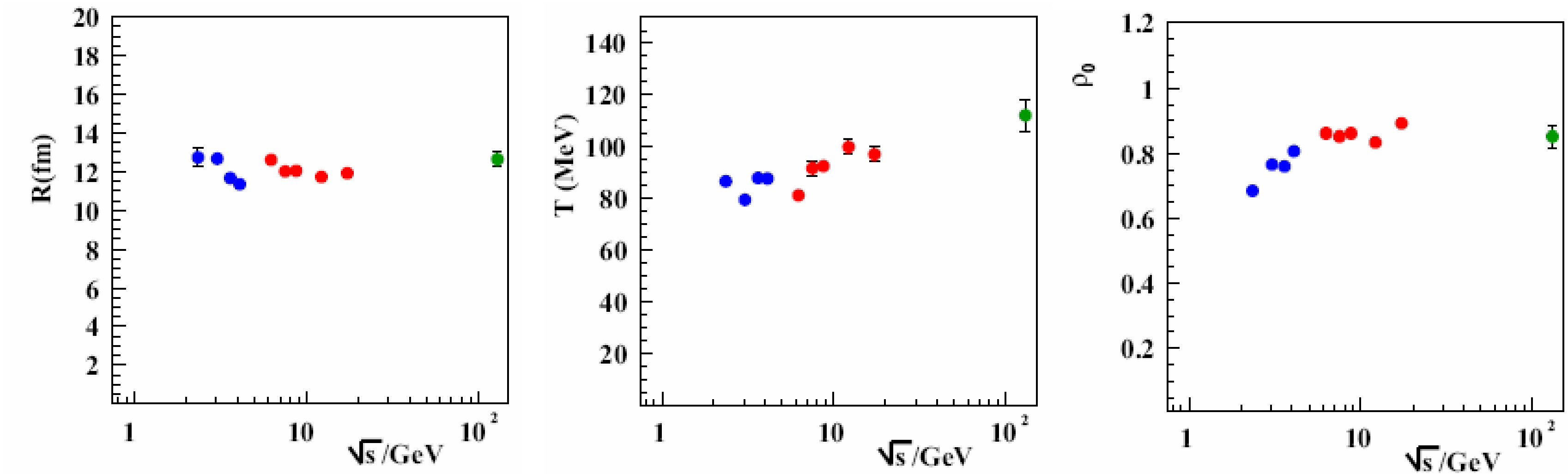


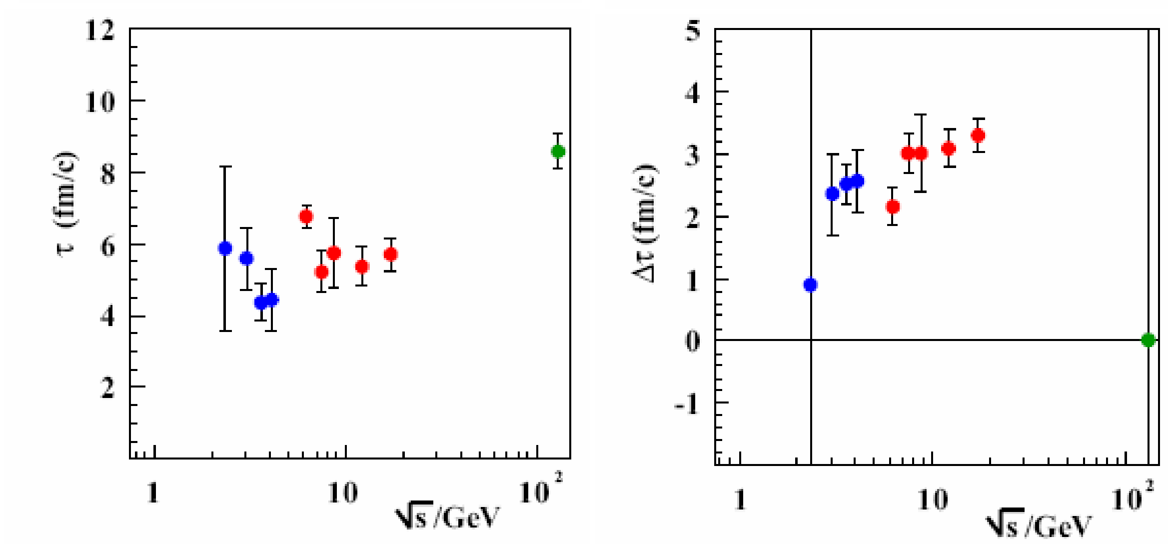
- remarkably little change of R_{side} (fireball radius) and R_{out}
- no indication of $R_{out} >> R_{side}$ i.e. long duration of π emission (1st order transition, soft point of EoS)
- slow rise of R_{long} (fireball lifetime)

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



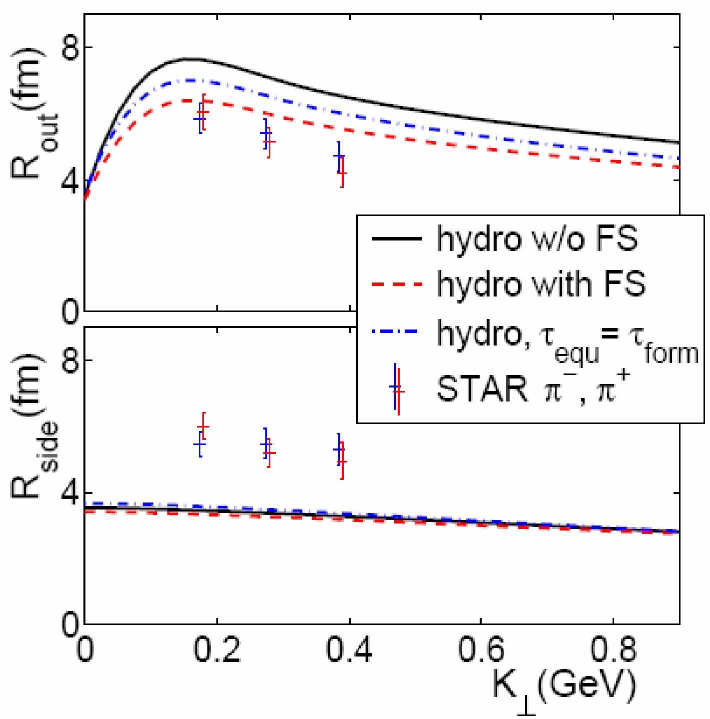
energy dependence of fireball parameters



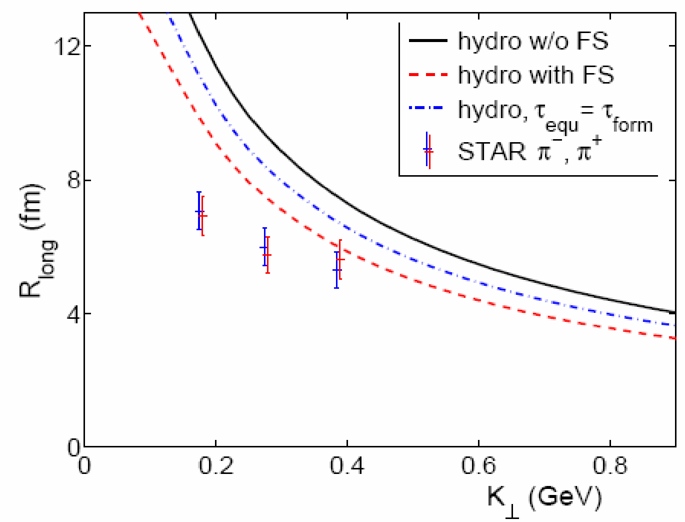


- constant radius
  $\approx 2 \cdot R_{Pb,Au}$
- slow increase of
  - freeze out T
  - surface flow ρ_0
  - lifetime τ

hydrodynamic model predictions → HBT puzzle



Heinz, Kolb: Nucl.Phys.A702,269(2002)

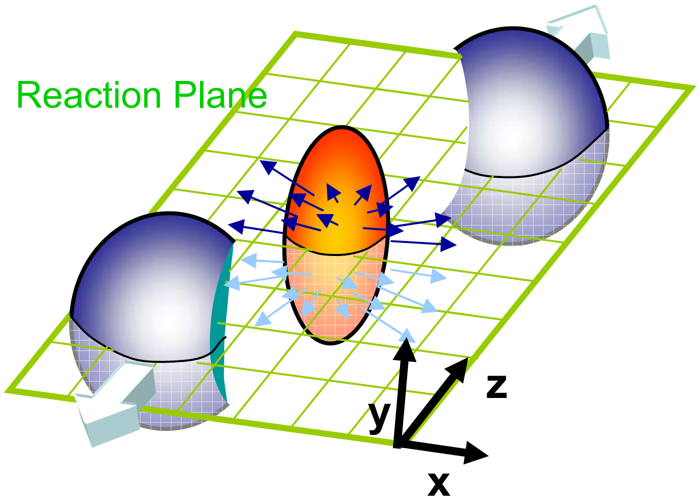


- fireball lives too long (R_{long}), emits particles for too long ($R_{out} > R_{side}$)
- problems with interpretation of BE correlations ?

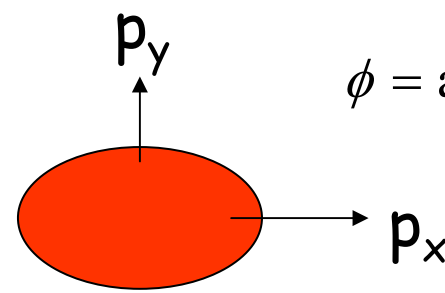
  Distortion of C_2 due to refraction of emitted pions ?

Cramer et al.: PRL 94,102302(2005); Kapusta,Li: PRC72,064902(2005); Wong: J.Phys.G30,S1053(2005)

Anisotropic flow in non-central collisions



initial spatial anisotropy



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

anisotropy in mometum space

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

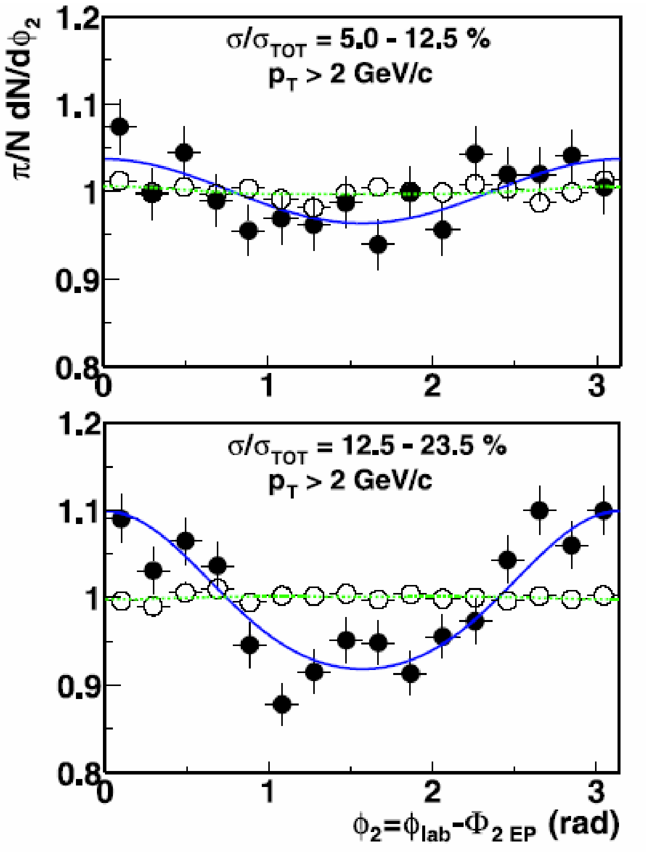
$$E\frac{dN^3}{d^3p} = \frac{1}{2\pi}\frac{d^2N}{p_t dp_t dy}\left(1 + 2v_1\cos(\phi - \Psi_R) + 2v_2\cos(2(\phi - \Psi_R) + \ldots\right)$$

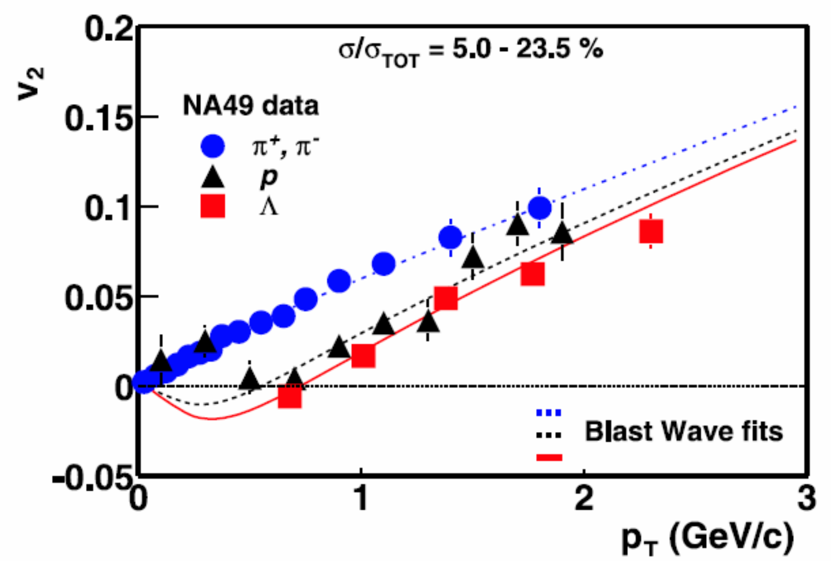
directed flow (↑ v_1) — elliptic flow (↑ v_2)

Anisotropic flow v_2

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

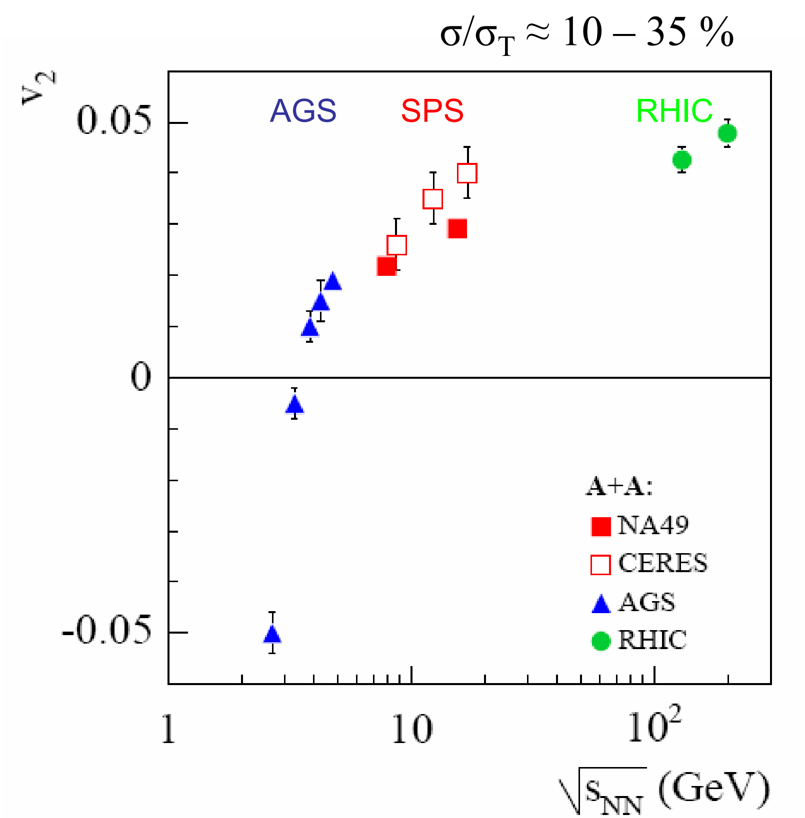
Λ elliptic flow in PbPb at 158A GeV

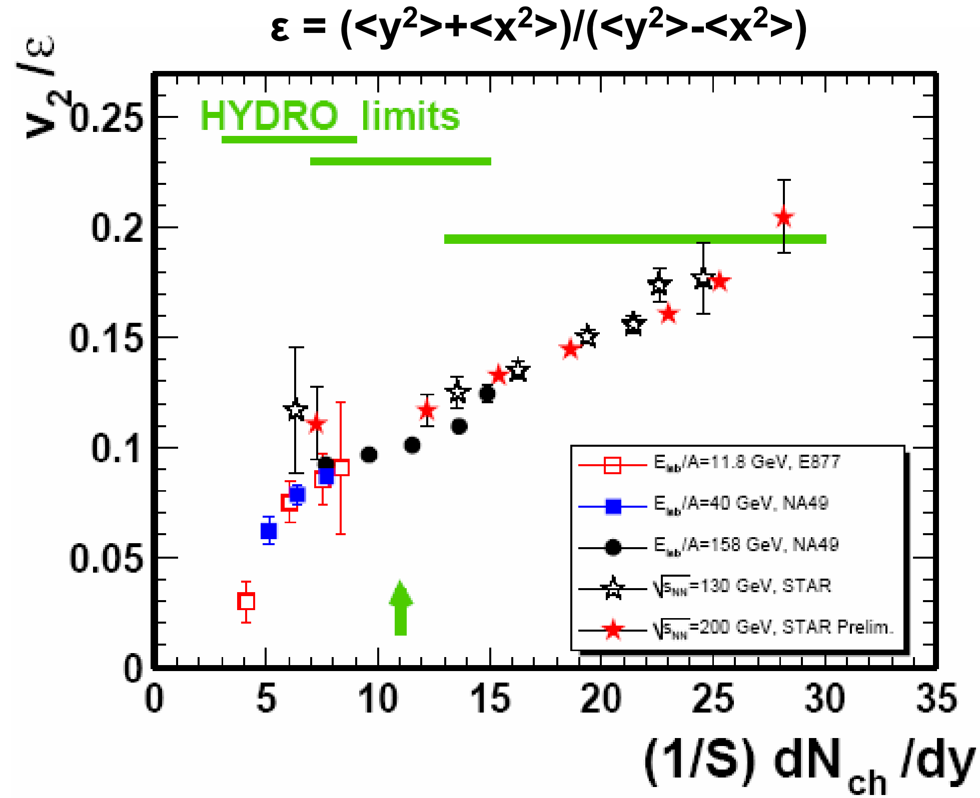




characteristic mass ordering of blast wave model also seen at SPS

Anisotropic flow v_2 of pions: energy dependence



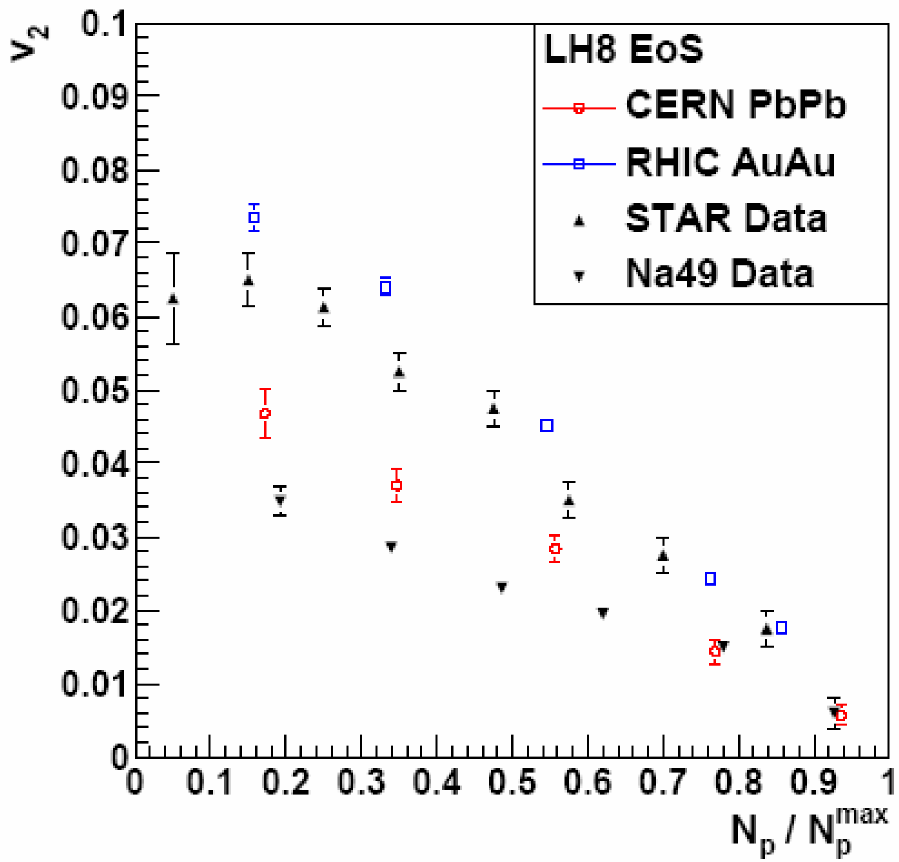


Smooth increase with collision energy towards hydrodynamic model prediction

more realistic freeze-out model

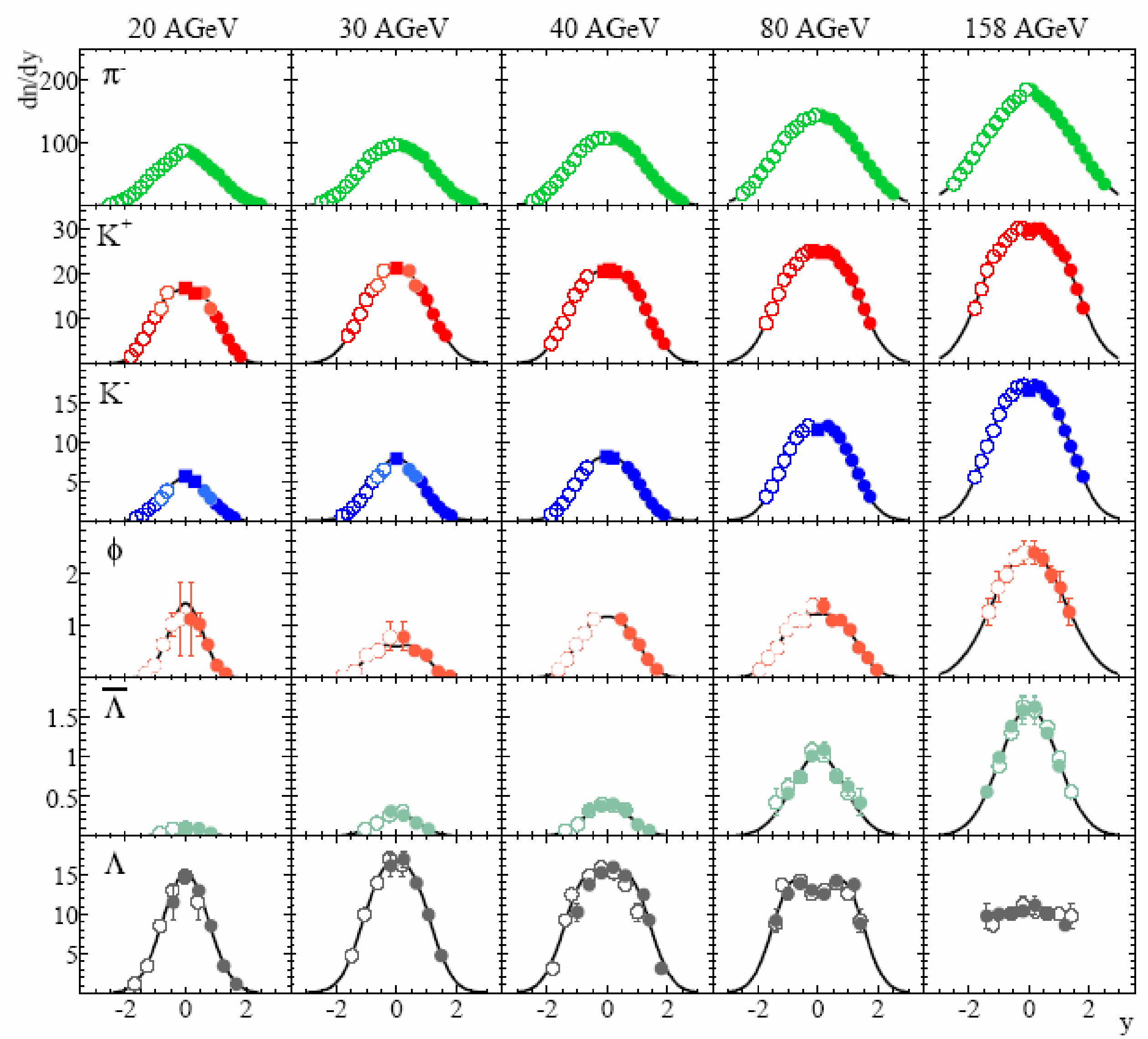
- QGP + hydro model expansion
- statistical hadronisation
- hadronic re-scattering stage (RQMD)

Teaney, Lauret, Shuryak
PRL 86 (2001) 4783



fair description
of SPS and RHIC data

Rapidity spectra

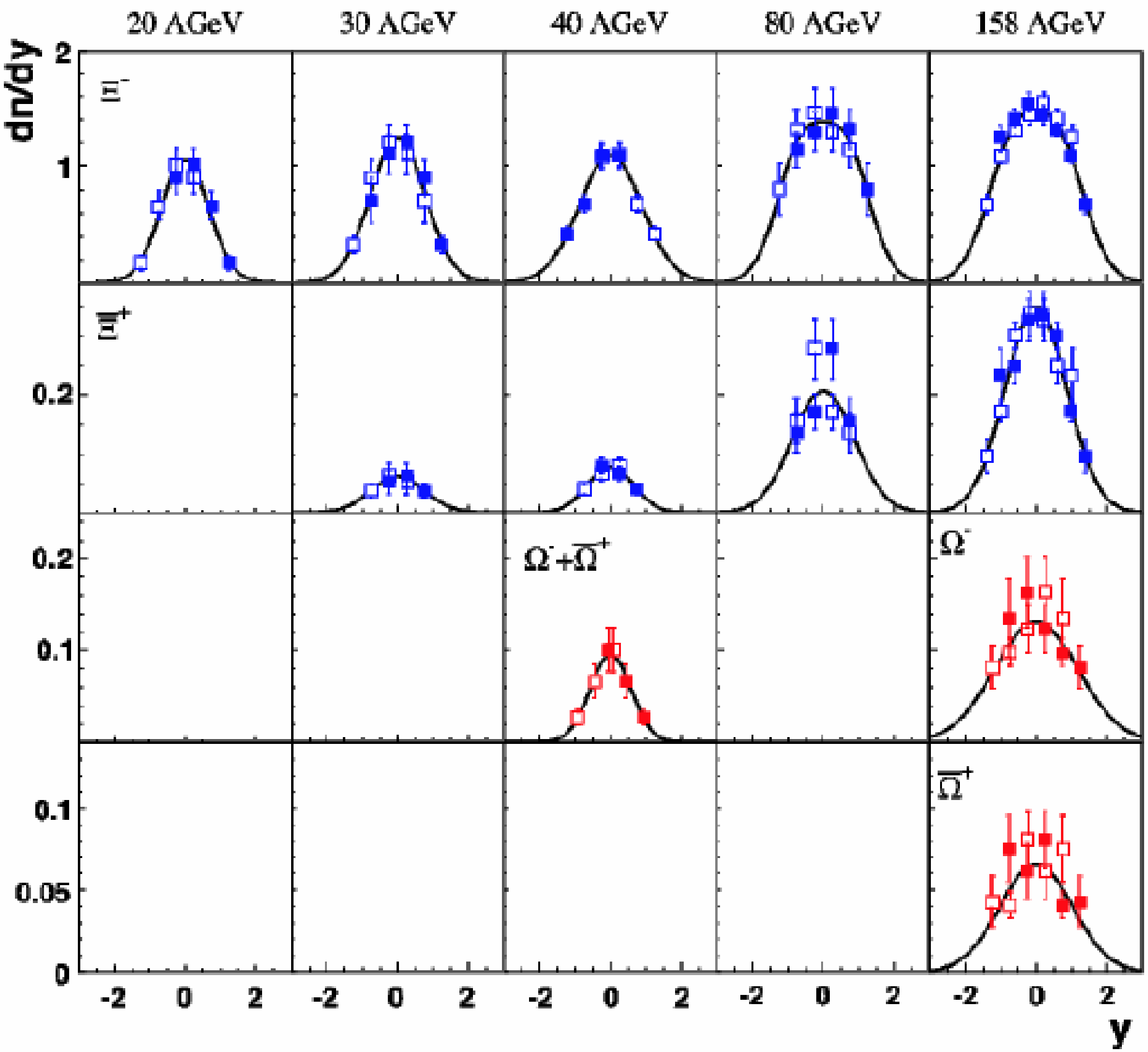


also: Ξ, Ω

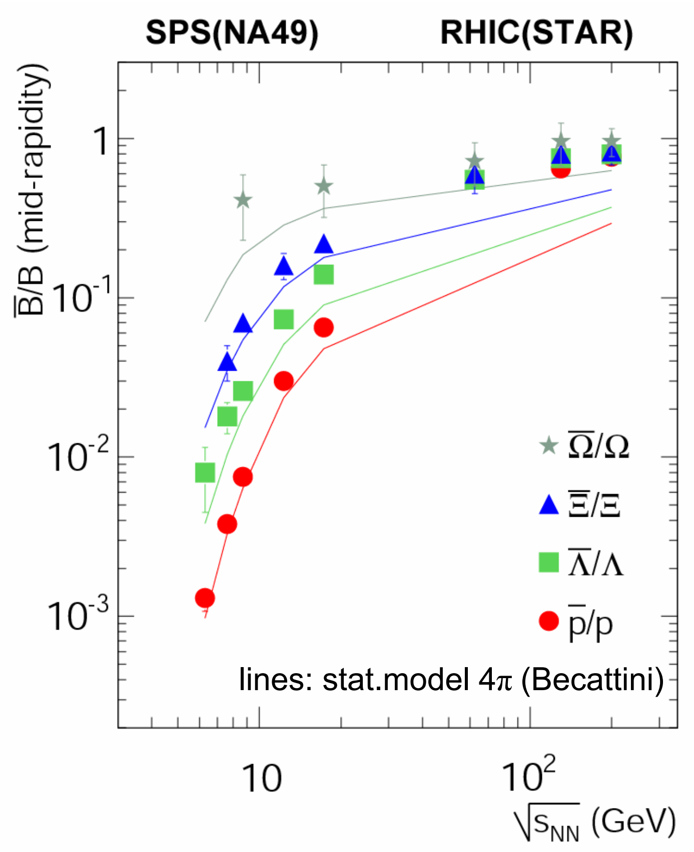
Extrapolation
→ 4π yields

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

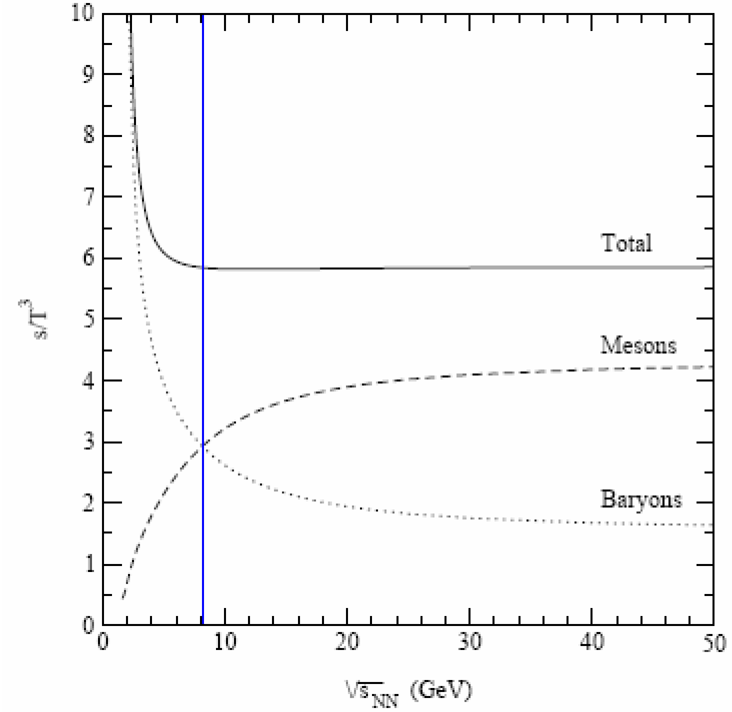
4π yields obtained also for multistrange hyperons Ξ, Ω



baryonic density decreases rapidly at SPS energies



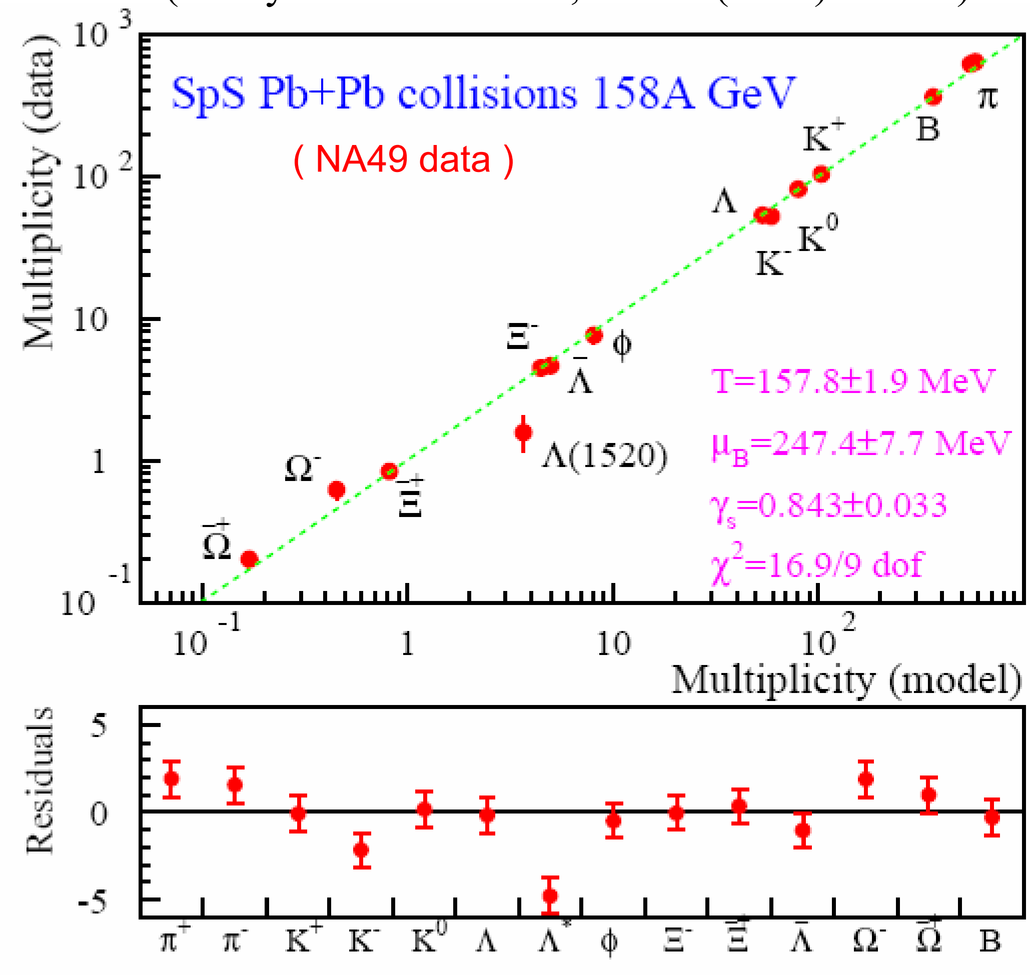
Statistical Model :
Cleymans et al.,PLB615,50(2005)



transition from baryon to meson dominated final state at SPS

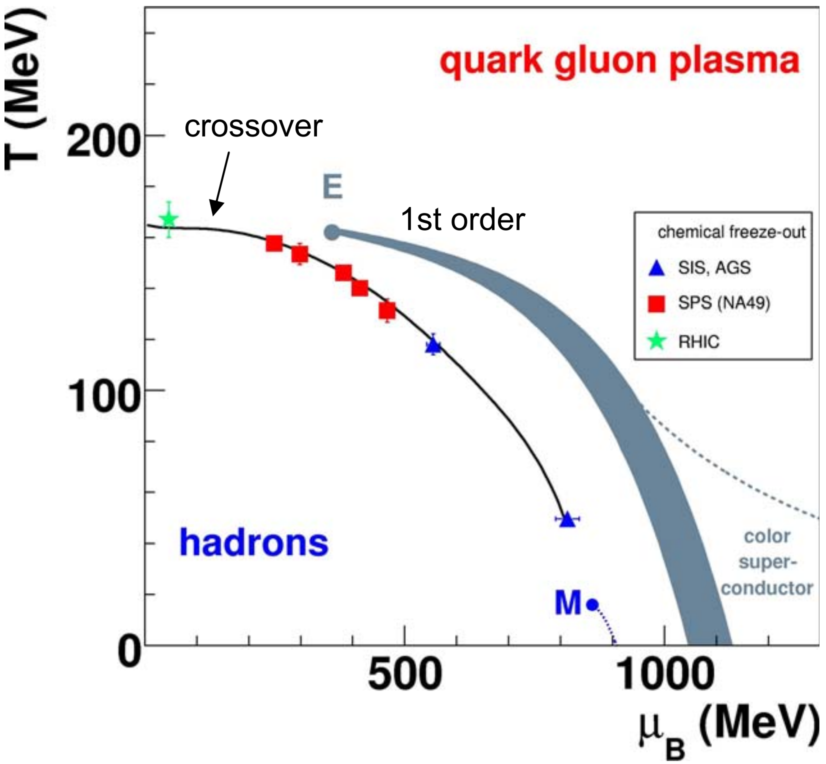
Particle yields – statistical model

(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
- increase 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)

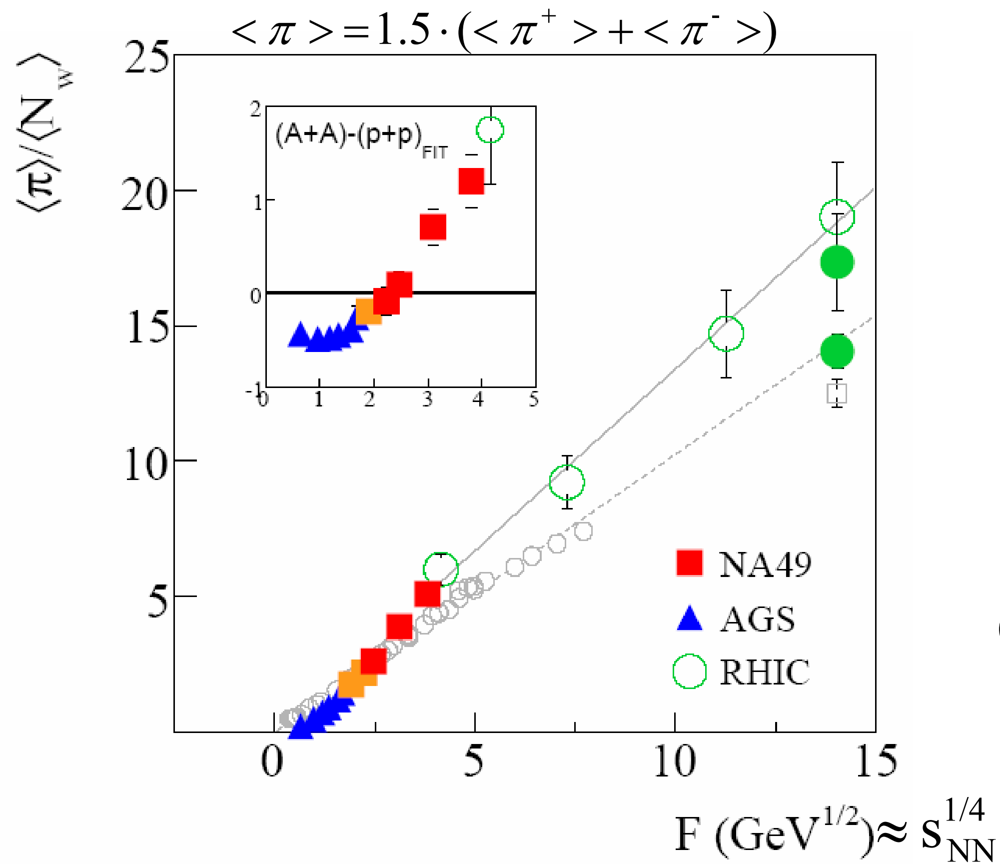
- statistical model describes yields from SIS to RHIC energy
- T of "hadrochemical" freeze out increases SIS → RHIC
- μ_B decreases (increase of pion production)
- freeze out line E ≈ 1 GeV / particle

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

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

Energy dependence - 4π yields

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



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

SMES: statistical model of the early stage

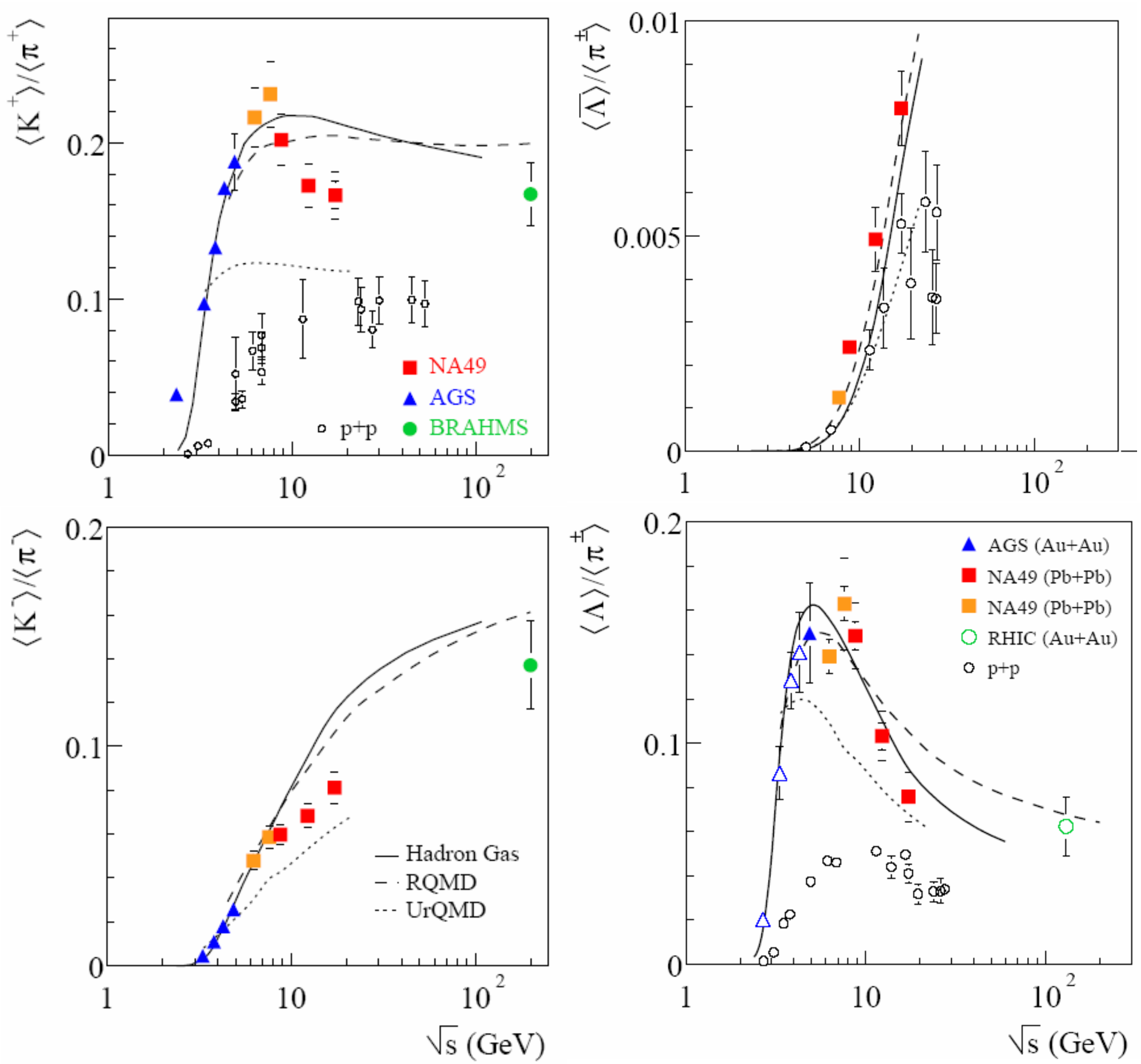
$$\frac{\langle \pi \rangle}{N_w} \propto \frac{S}{N_w} \propto g^{1/4} F$$

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

(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

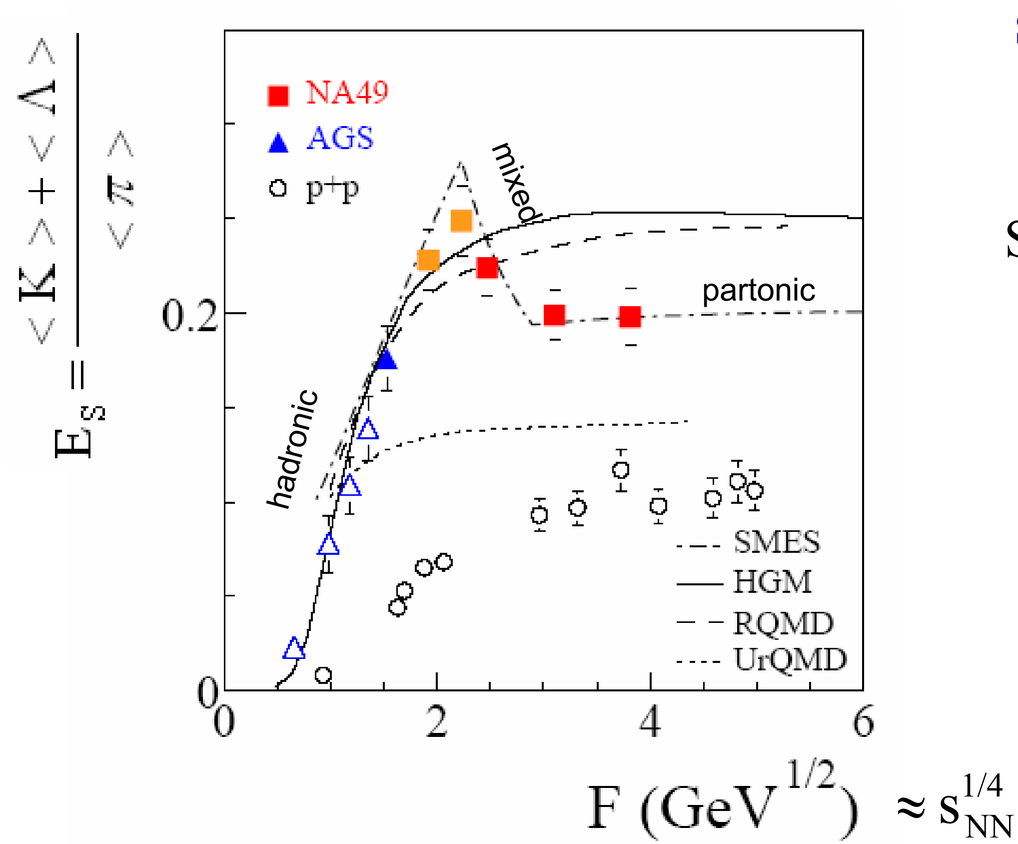
hadronic models do not reproduce the sharp peak

s quark carriers:

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

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

Energy dependence – 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

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

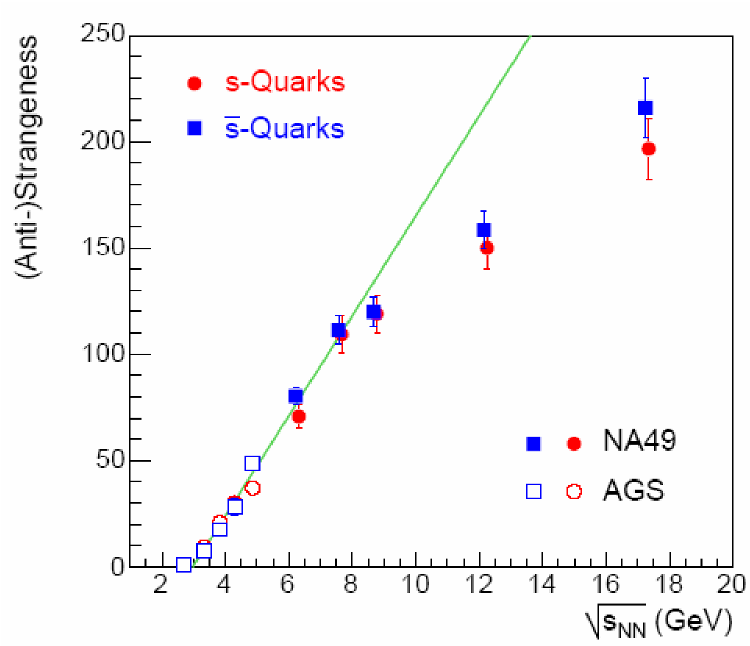
$$\approx 0.21$$

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

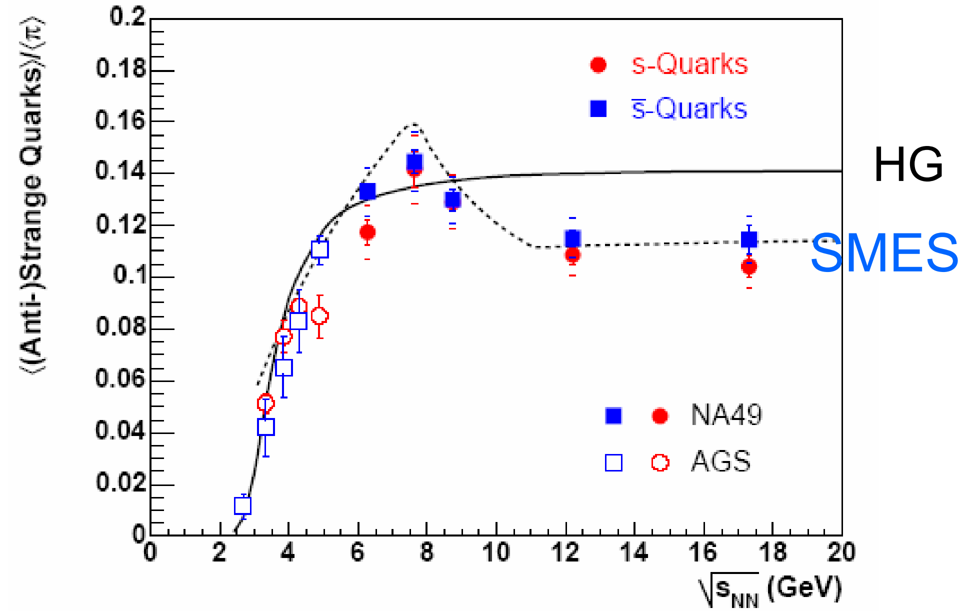
suggests onset of deconfinement at SPS

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



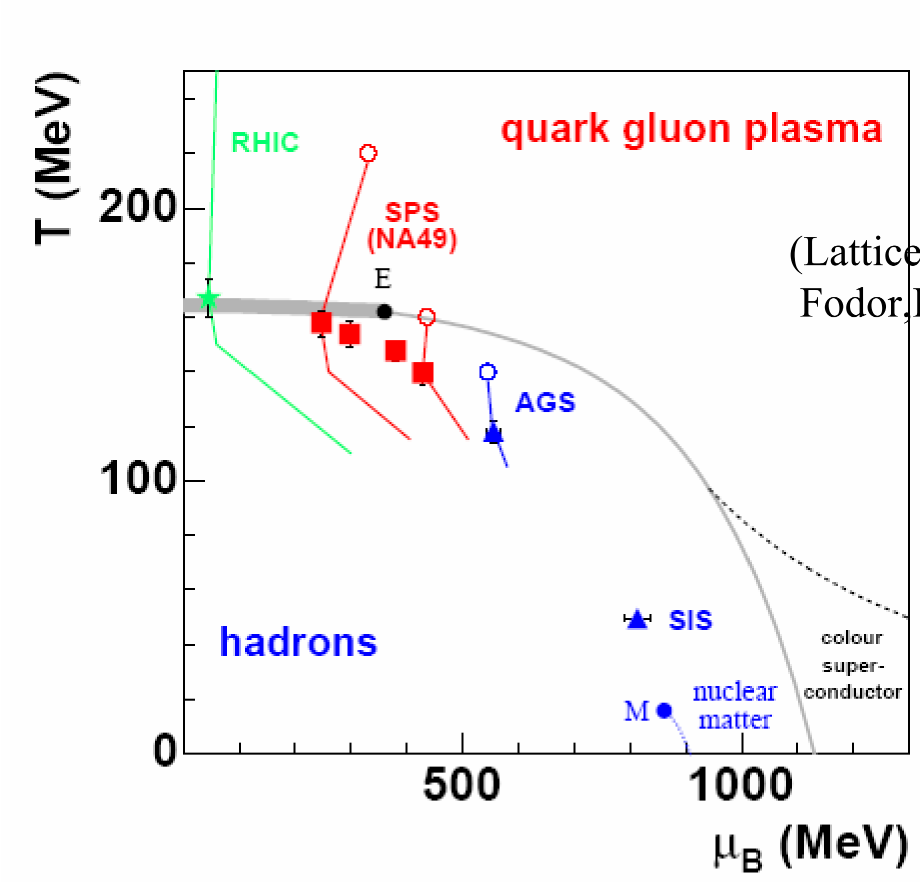
s - quark carriers:	$\bar{s}$ - quark carriers:
K^-, K^0 [1)]	K^+, $\bar{K}^0$ [1)]
$\Lambda+\Sigma^0$, $\Sigma^\pm$ [2)]	$\bar{\Lambda}+\bar{\Sigma}^0$, $\bar{\Sigma}^\pm$ [2)]
Ξ^-, Ξ^0, Ω^- [3)]	$\bar{\Xi}^+$, $\bar{\Xi}^0$, $\bar{\Omega}^+$ [3)]

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

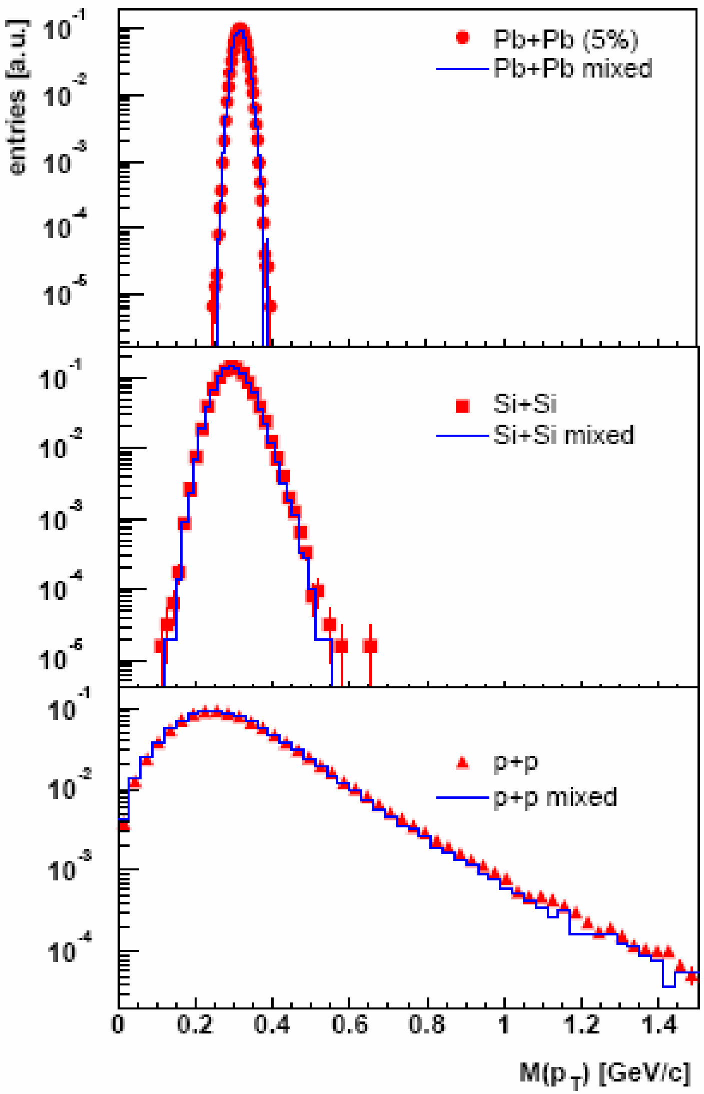
hypothetical trajectories in the phase diagram



(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

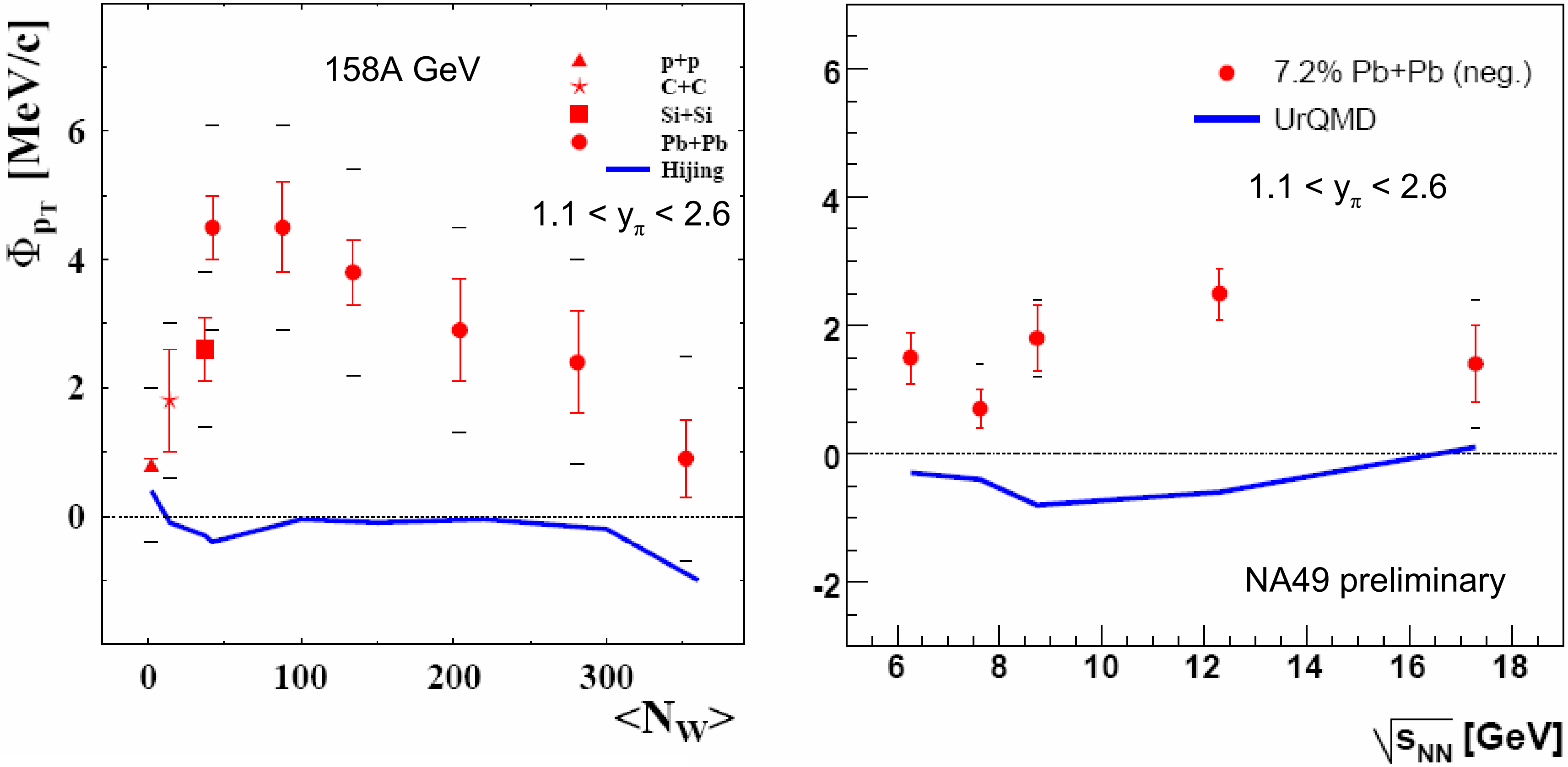
Event-by-event fluctuations of <p_T> (negative hadrons)



- distributions of <p_T> similar for real and mixed events
- non-statistical (dynamical) fluctuations are small

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

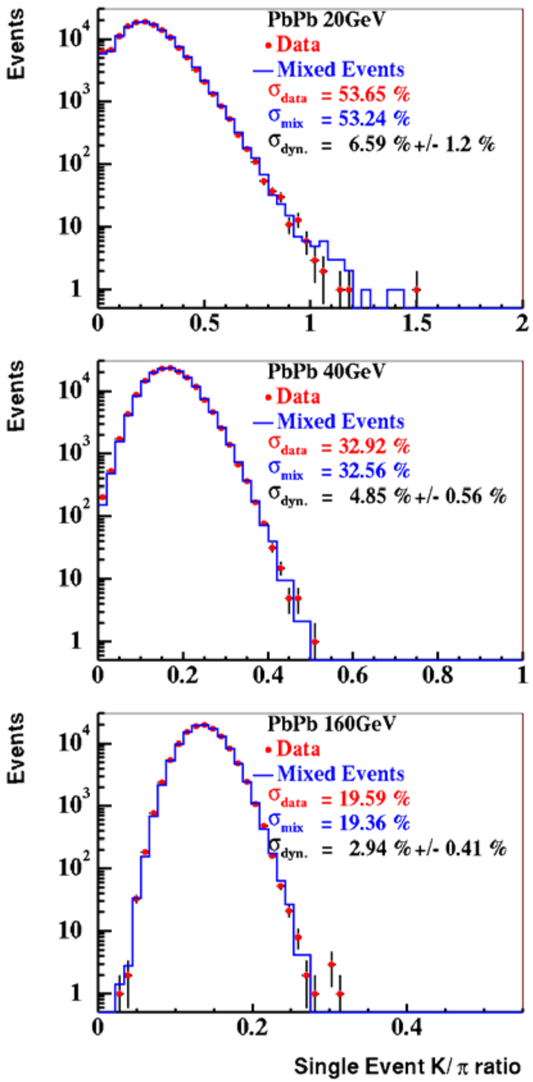
measure: $\Phi p_T = \sqrt{\frac{<Z^2>}{<N>}} - \sqrt{<z^2>}$ $\quad z = p_T - <p_T>$ $\quad Z = \sum_{i=1}^{N}(p_T^i - <p_T>)$



increase for peripheral collisions, no increase at lower energy

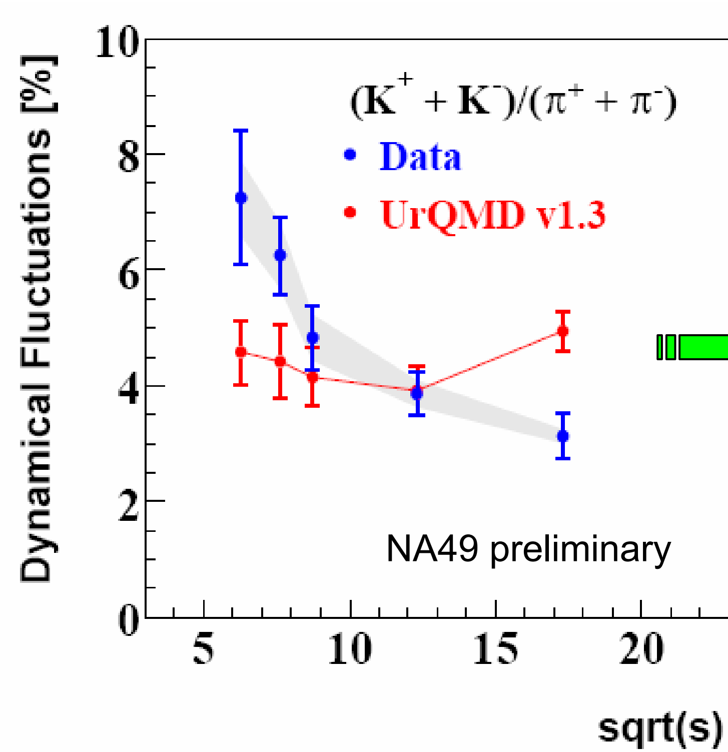
The Event-by-Event K/π ratio

Beam Energy



maximum likelihood fit for each event

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



STAR

Increased fluctuation signal at lower beam energies

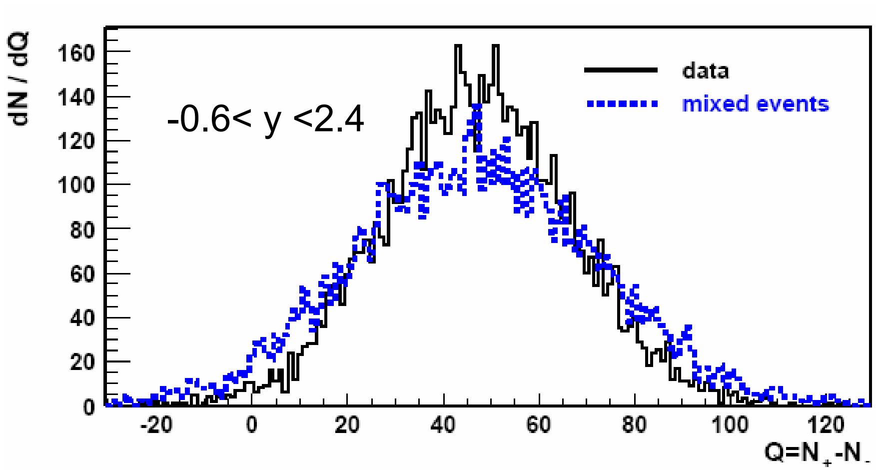
Electric charge fluctuations

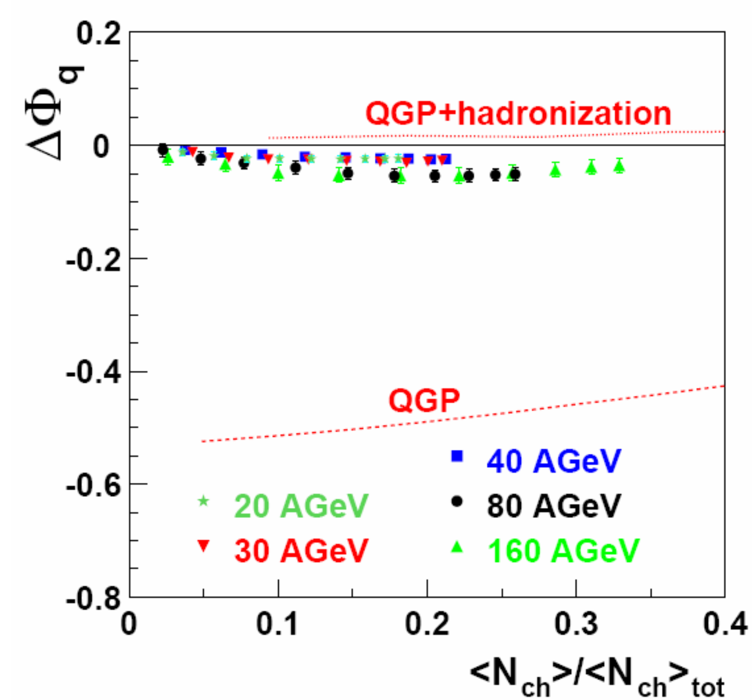
- Smaller in a QGP than in a hadron gas

(Jeon,Koch,Asakawa,Heinz,Müller)

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

Central Pb+Pb collisions 158A GeV





Global charge conservation

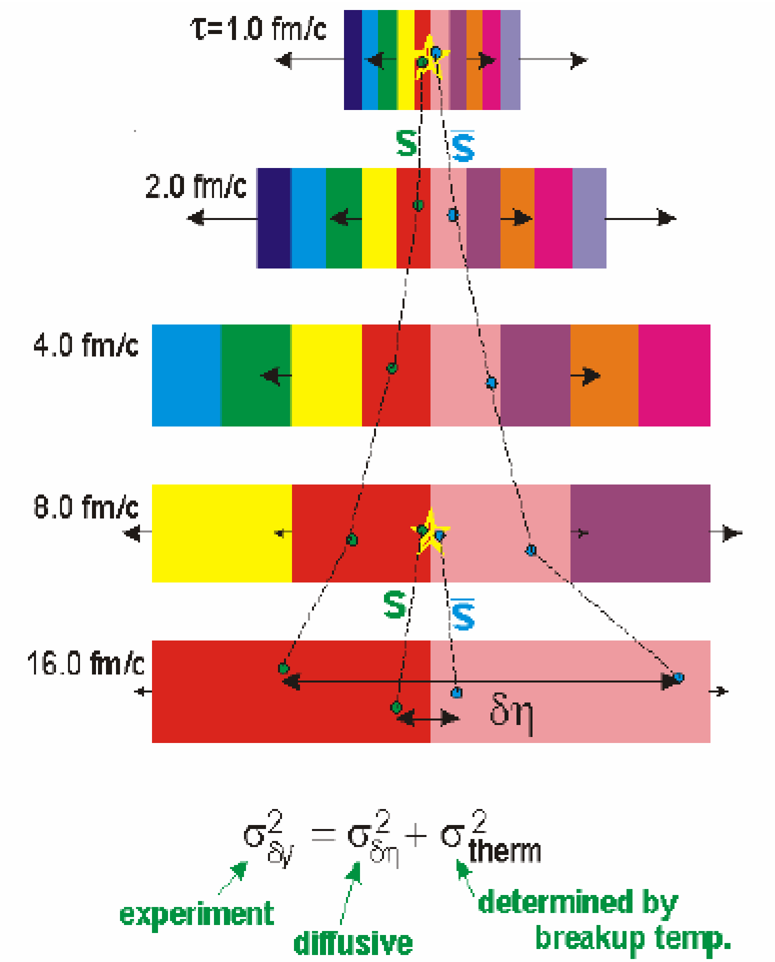
$$\Phi_q = \sqrt{\frac{<Z^2>}{<N>}} - \sqrt{\overline{z^2}}$$

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

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

Balance Function

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

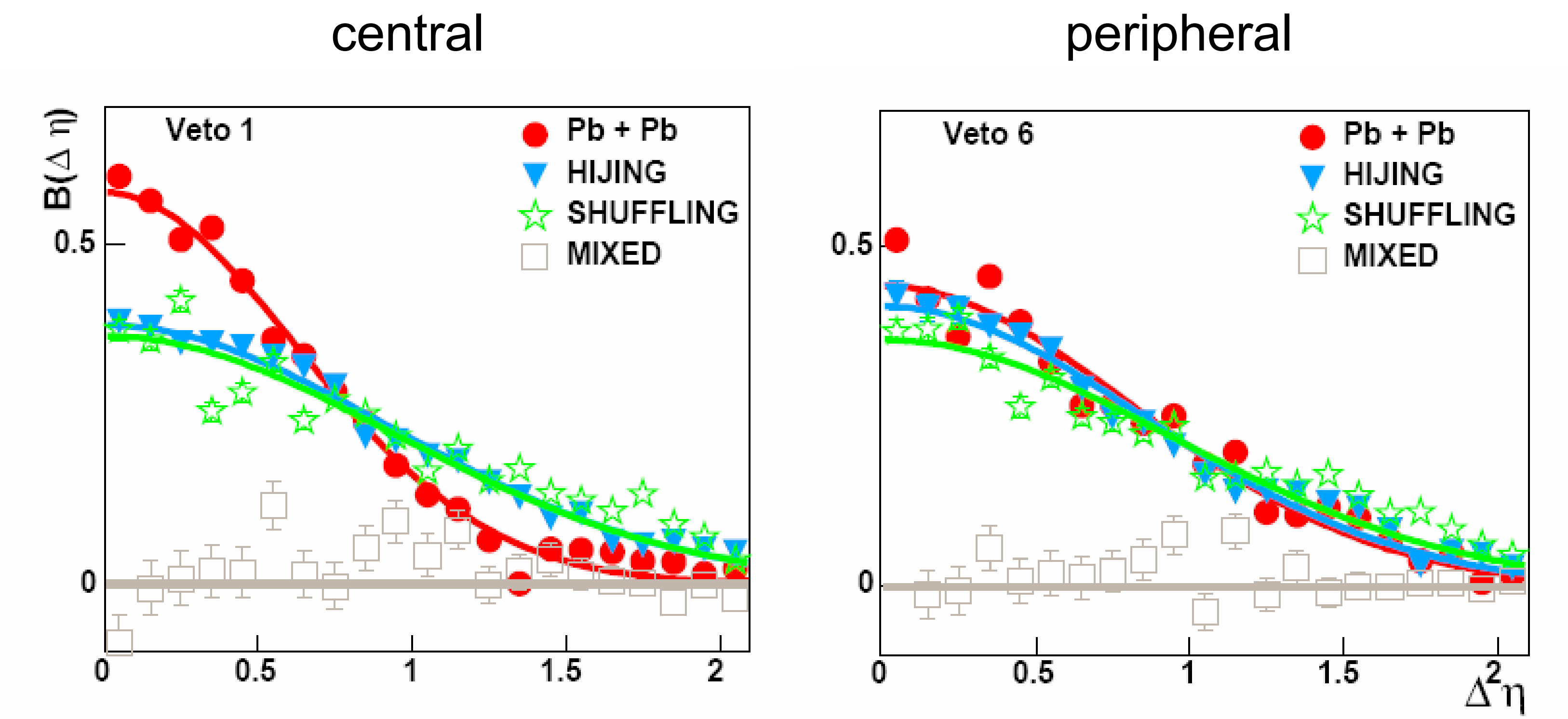


- oppositely charged particles created at the same point in space – time
- particles get separated in rapidity by thermal motion (rescattering) and developing collective flow
- early produced pairs are separated more in rapidity than late produced pairs
- separation δη quantified by the balance function:

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

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

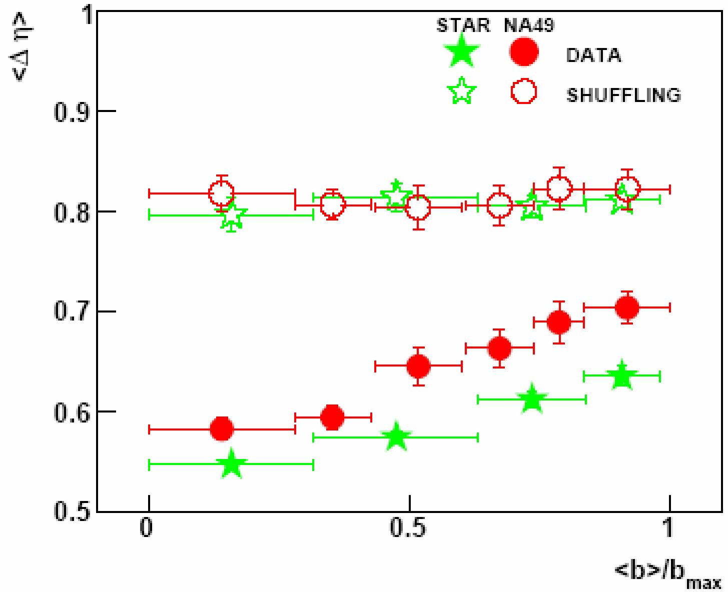
measurements of the balance function (charged particles)



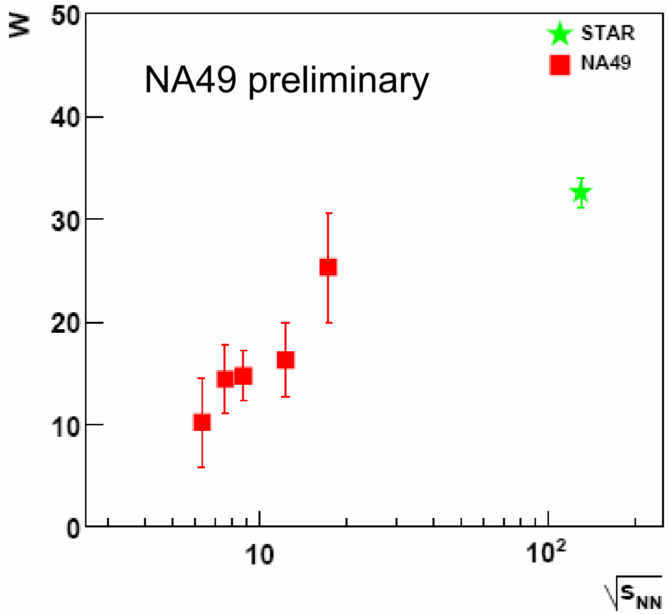
data compared to shuffled events (scrambling of rapidities, retention of global charge conservation effect)

energy dependence of the charge balance function width

narrowing proposed as QGP signature



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

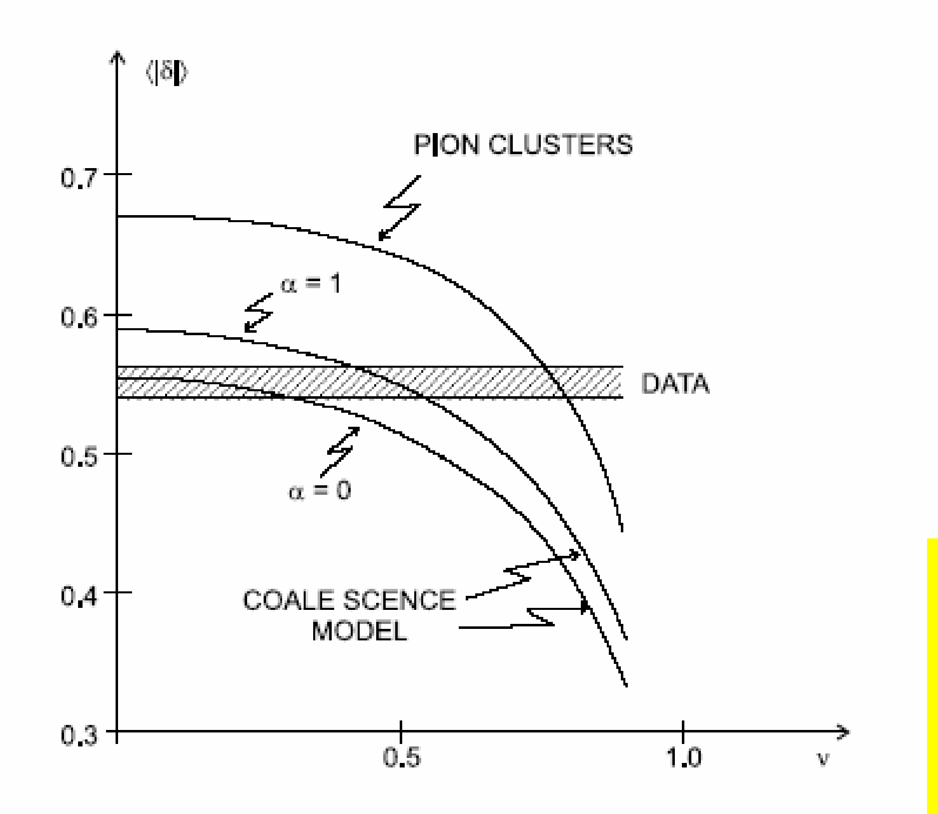


narrowing of width <Δη> seen at RHIC and SPS

narrowing relative to global charge conservation reference gets stronger with energy

effect probably due to local charge conservation and radial flow

Predictions of the balance function width <|δ|> in the quark coalescence model (A.Bialas, PLB 579, 31 (2004))



- radial flow reduces the width of the balance function in a pion cluster production model
- uncorrelated neutral clusters of pions (successful in pp reactions) require excessive radial flow v
- quark coalescence model reproduces measured width in central collisions with reasonable radial flow velocity v ≈ 0.4

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 the CERN SPS
- Structure in the energy dependence of m_T spectra and of pion and strangeness production indicate
  onset of deconfinement at low SPS energy
- In correlation and fluctuations no convincing signal yet of sharp phase transition or critical point; search continues

Future Plans

Further experimental studies preferentially with an improved detector should be done to explore:

- properties of the onset of deconfinement
- possible existence of the critical point of QCD

Future programs under discussion:

- study of light and heavy ion collisions with an upgraded NA49 detector at the SPS (letter of intent CERN-SPSC-2006-001)
- feasibility study and intent of low-energy running at RHIC

Additional collaborators are welcome

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]

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Extra slides for discussion

NA49 energy scan program of central Pb+Pb collisions

search for structure in the energy dependence of observables which may be linked to the onset of deconfinement

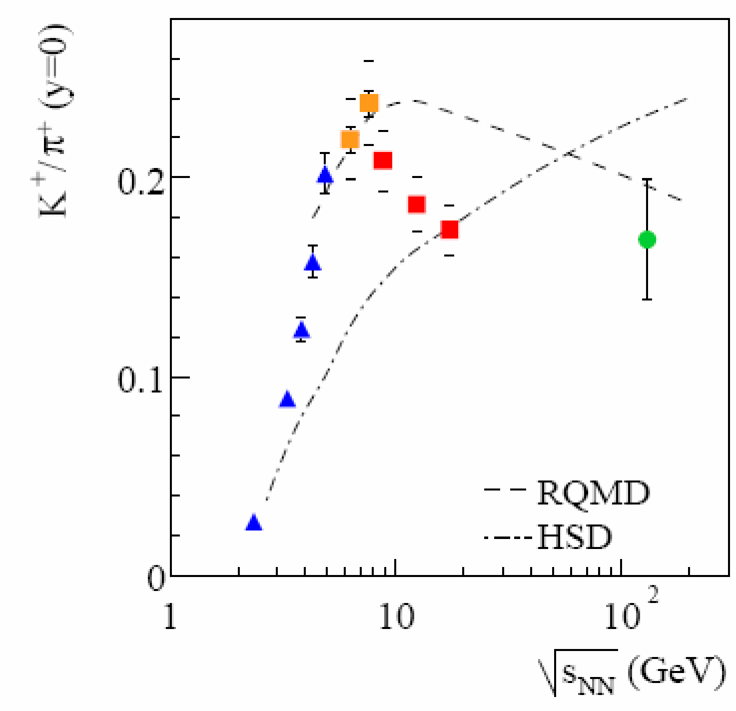
Beam Energy	Centrality	Event Statistics	Taken in
158A GeV	10 %	800 k	1996
158A GeV	20 %	3,000 k	2000
80A GeV	7 %	300 k	2000
40A GeV	7 %	700 k	1999
30A GeV	7 %	400 k	2002
20A GeV	7 %	300 k	2002

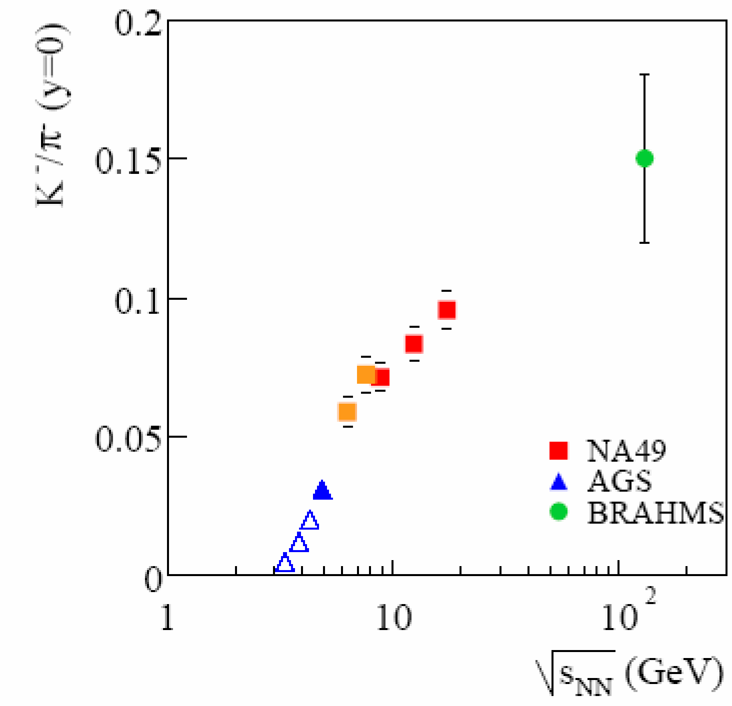
PRC 66(2003) 054902

preliminary (2002 runs: 30A GeV, 20A GeV)

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

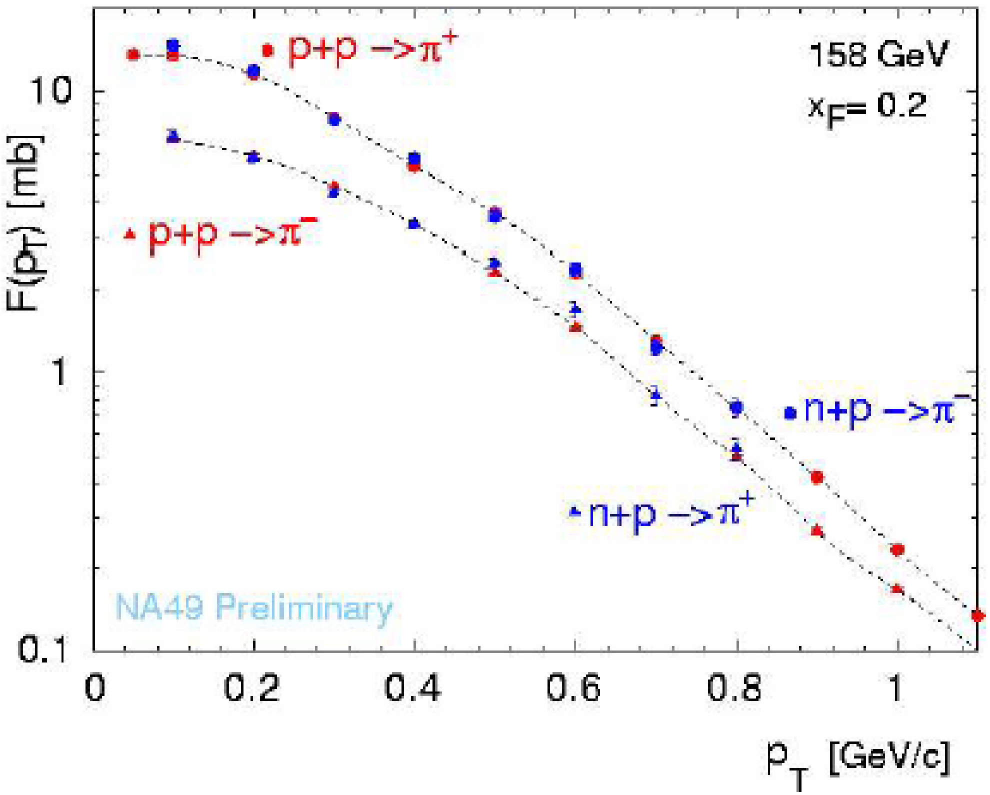
at midrapidity identification is from dE/dx and TOF





Aside: isospin effects

See, e.g. A. Rybicki, QM04



π^+ production in p+p
=
π^- production in n+p

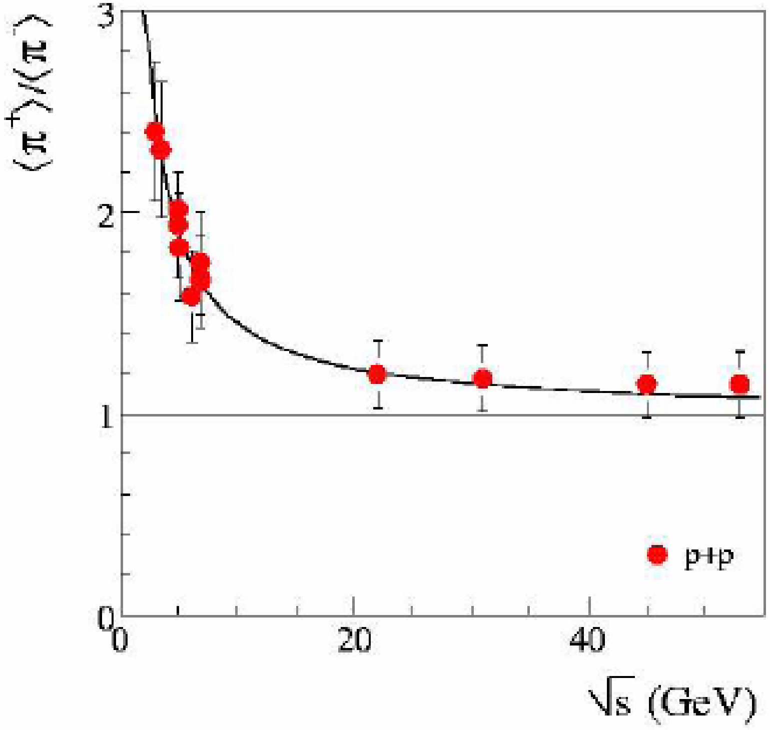
No such effect seen for K^+ and K^-

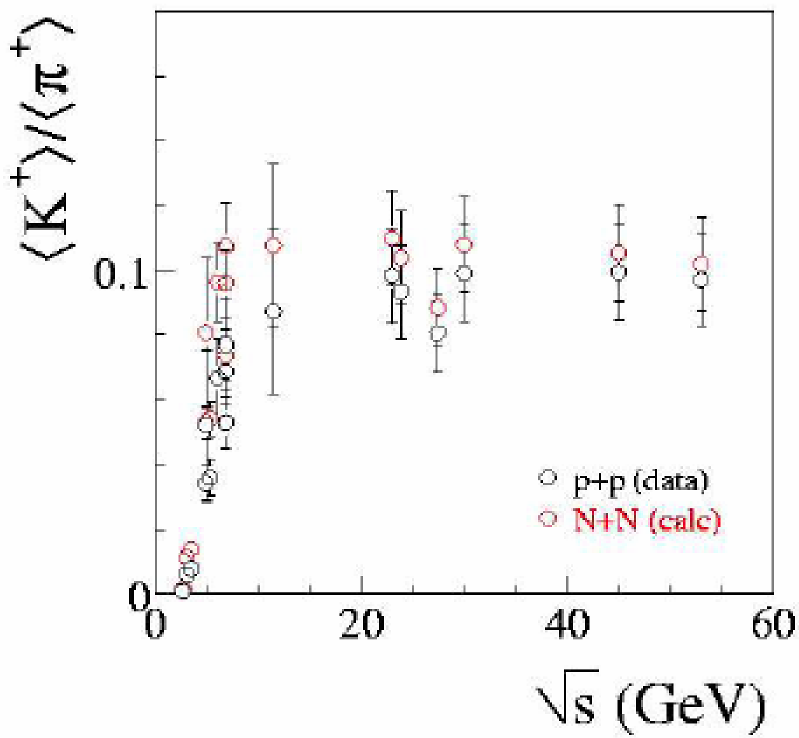
Potentially important effect when comparing K^+/π^+ in p+p and Pb+Pb (60% n, 40% p)

Estimate isospin effect on the K/π ratio

K^+/π^+ in nucleon+nucleon (N+N) collisions calculated as:

$$\left.\frac{K^{+'}}{\pi^{+'}}\right|_{N+N} = 0.4\left.\frac{K^{+'}}{\pi^{+'}}\right|_{p+p} + 0.6\left.\frac{K^{+'}}{\pi^{+'}}\right|_{n+p} = \left.\frac{K^{+'}}{\pi^{+'}}\right|_{p+p}\left(0.4 + 0.6\left.\frac{\pi^{+'}}{\pi^{-'}}\right|_{p+p}\right)$$





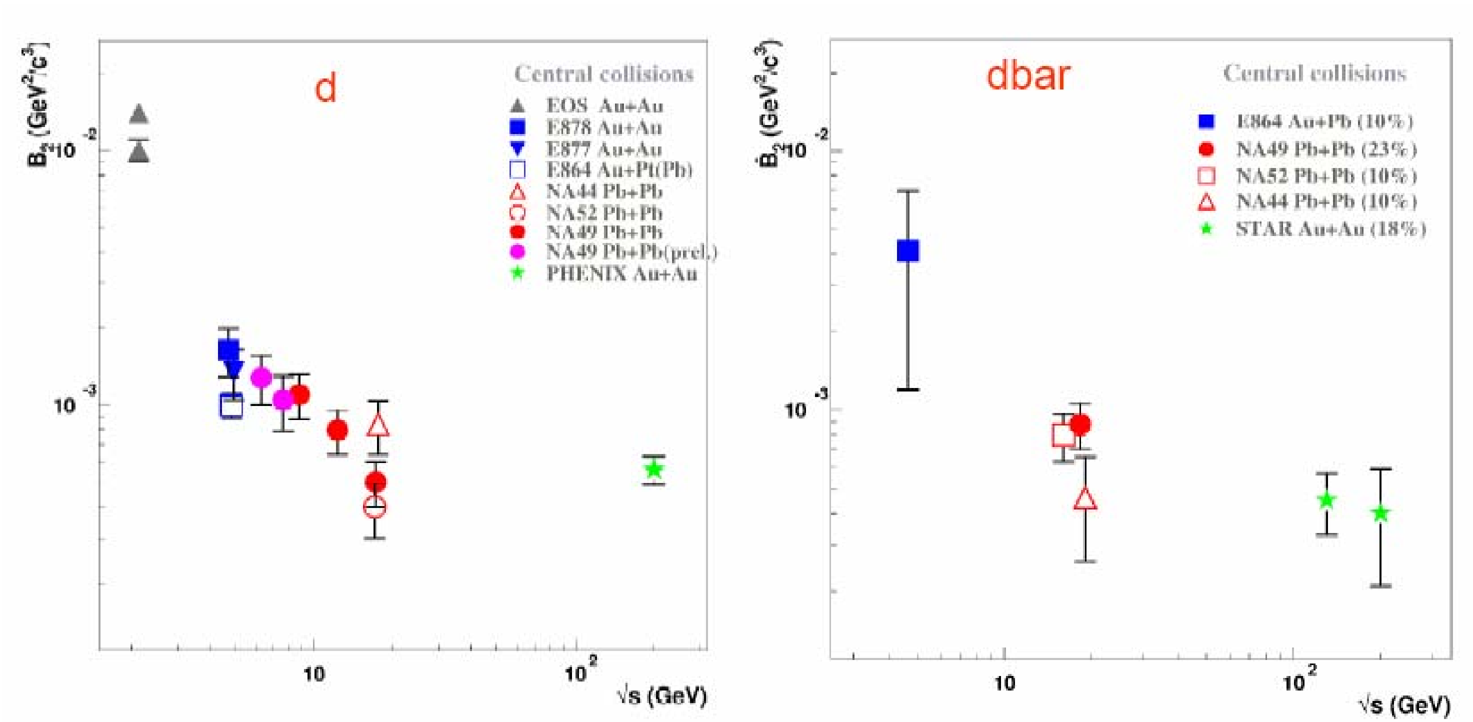
π^+/π^- sharply decreases from threshold

No indication of maximum in isospin-corrected p+p results

Deuteron production measures a homogeneity radius via coalescence

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

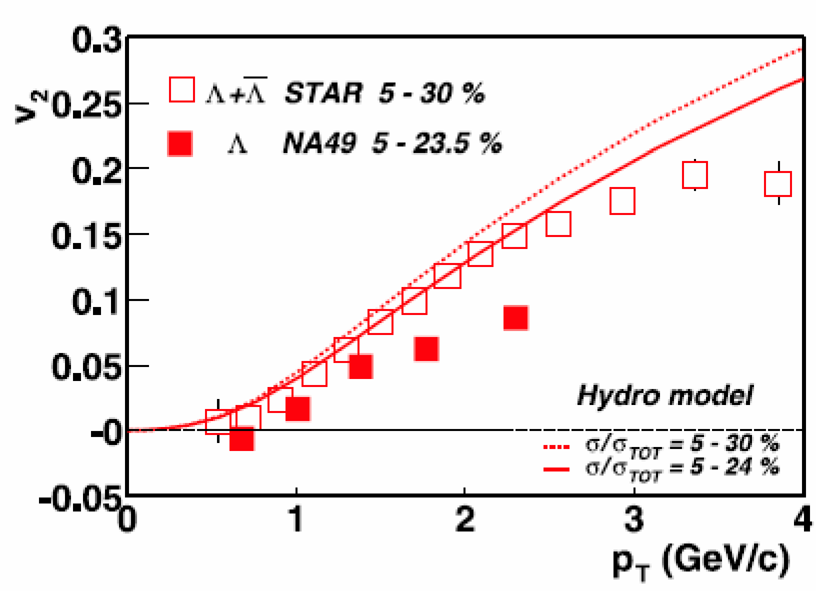
(NA49 partly preliminary)

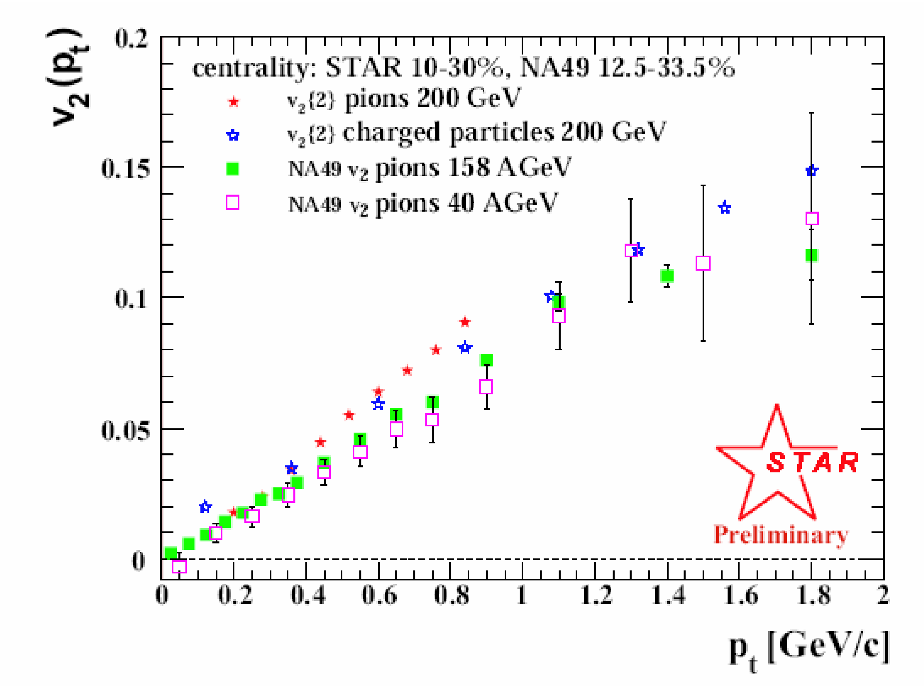


gradual decrease of coalescence factor B_2

Energy dependence of anisotropic flow $v_2(p_t)$

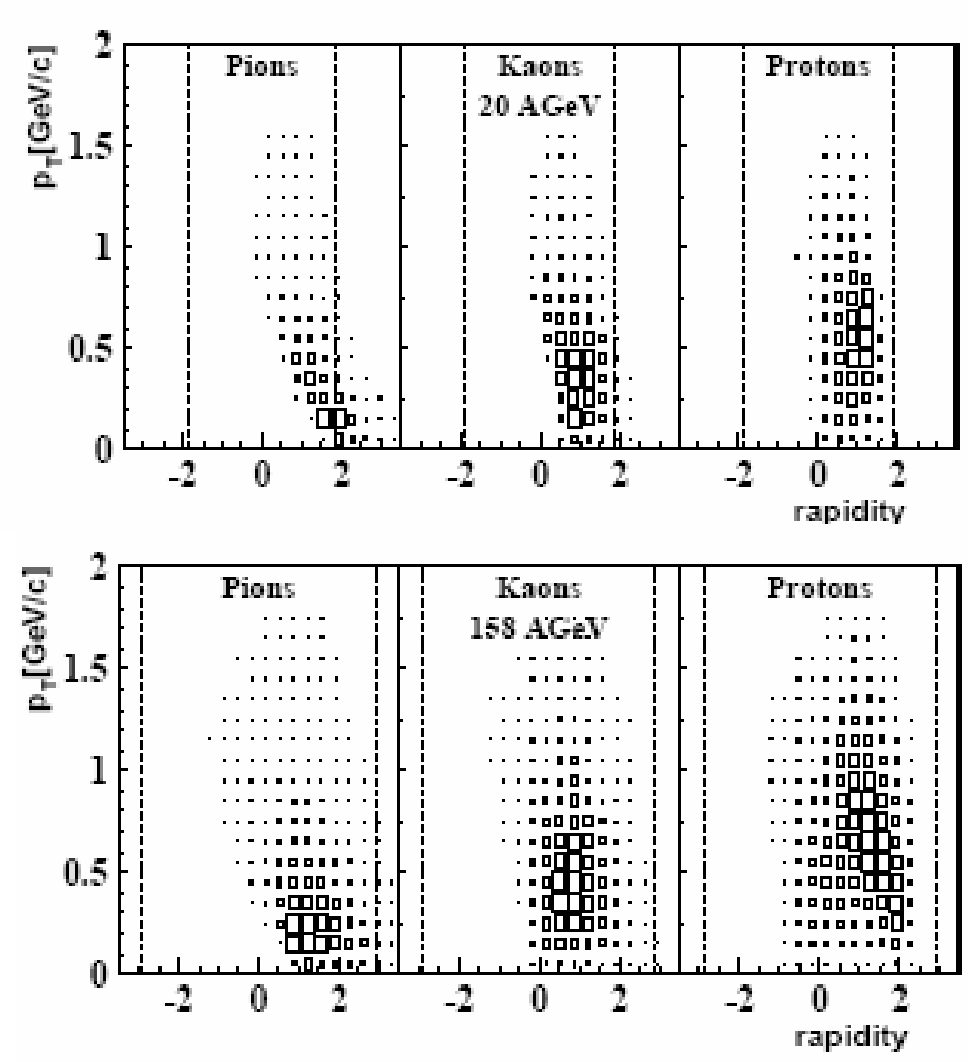
Λ hyperons   pions





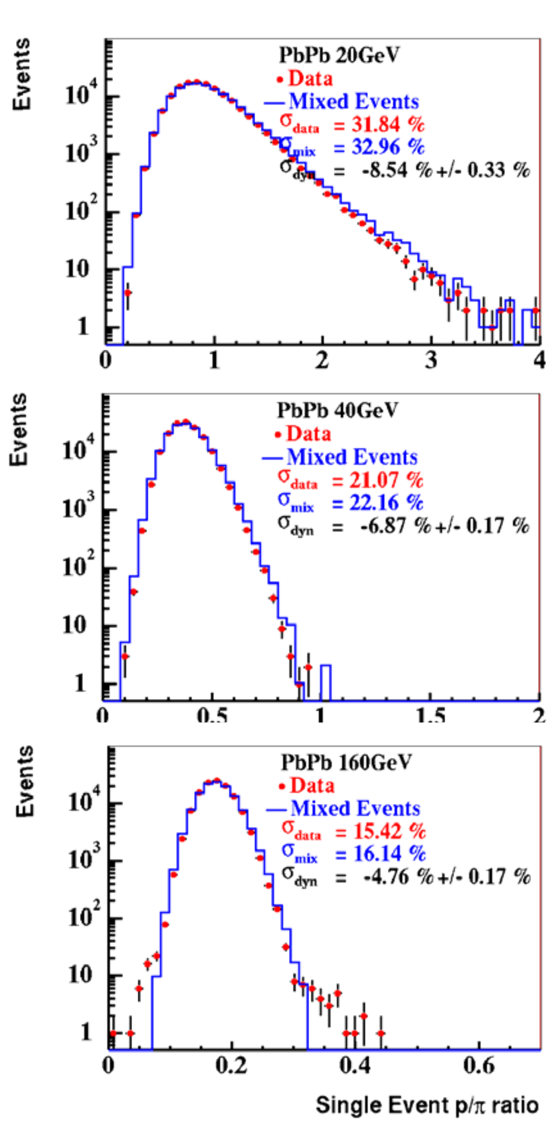
elliptic flow $v_2(p_t)$ increases SPS → RHIC

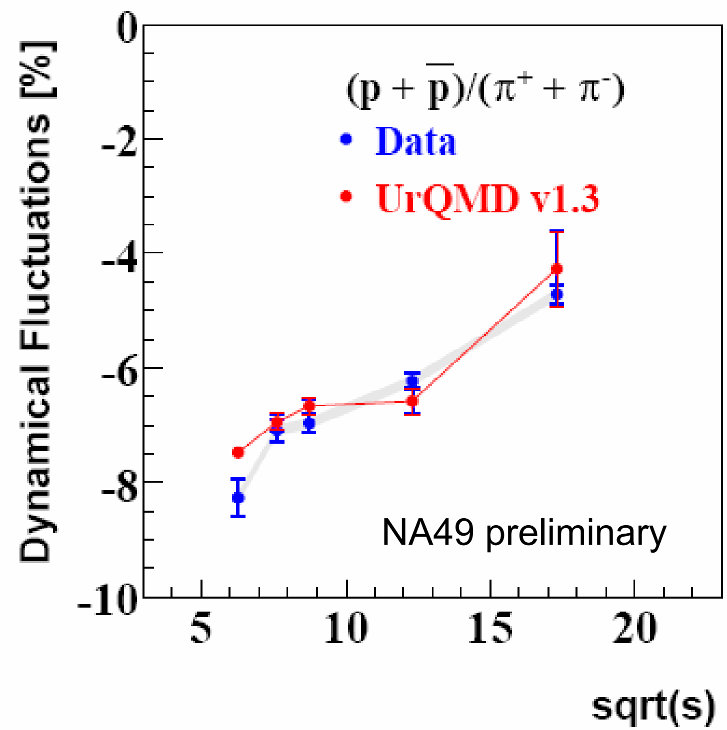
acceptance for K/π and (p+pbar)/π fluctuation studies



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

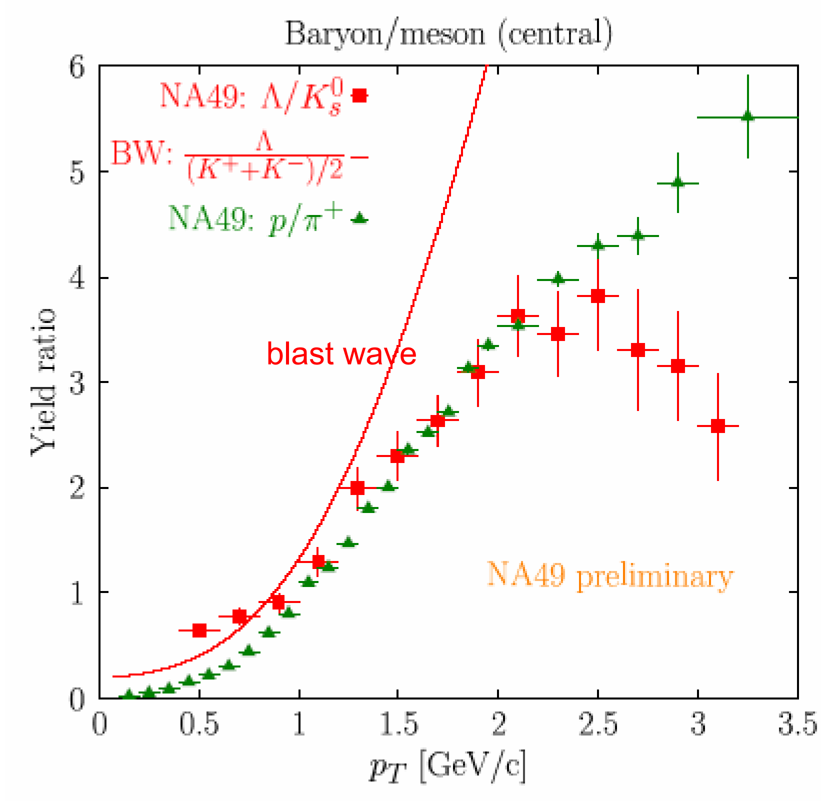
Beam Energy

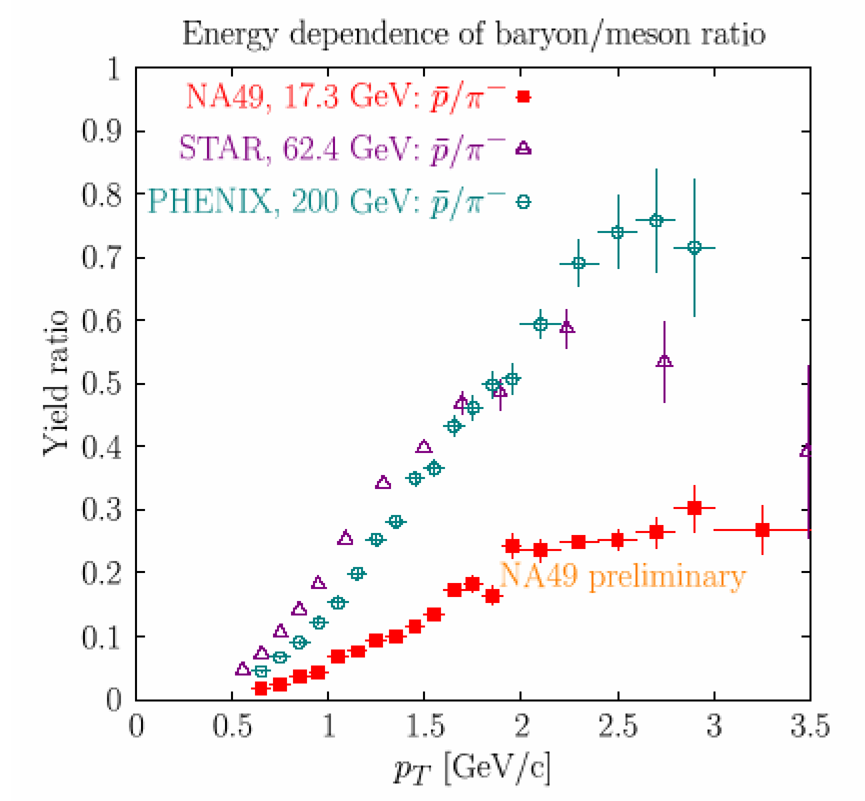




The distribution of the E-by-E p/π ratio is narrower for data than mixed events.
Effect of baryon resonance decay ?

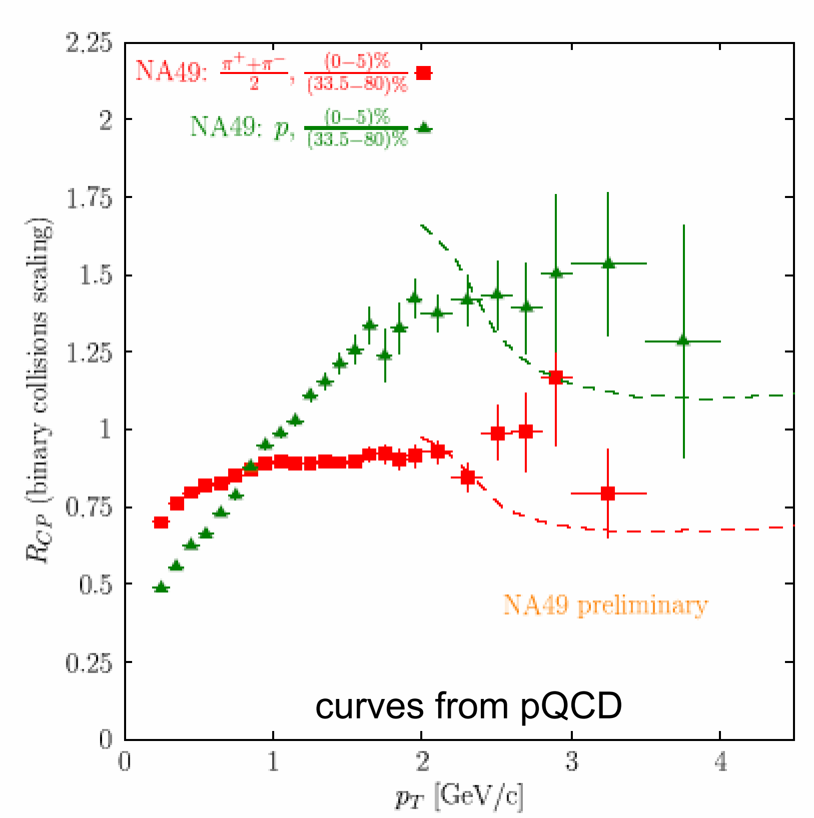
baryon/meson yield ratio at medium p_t

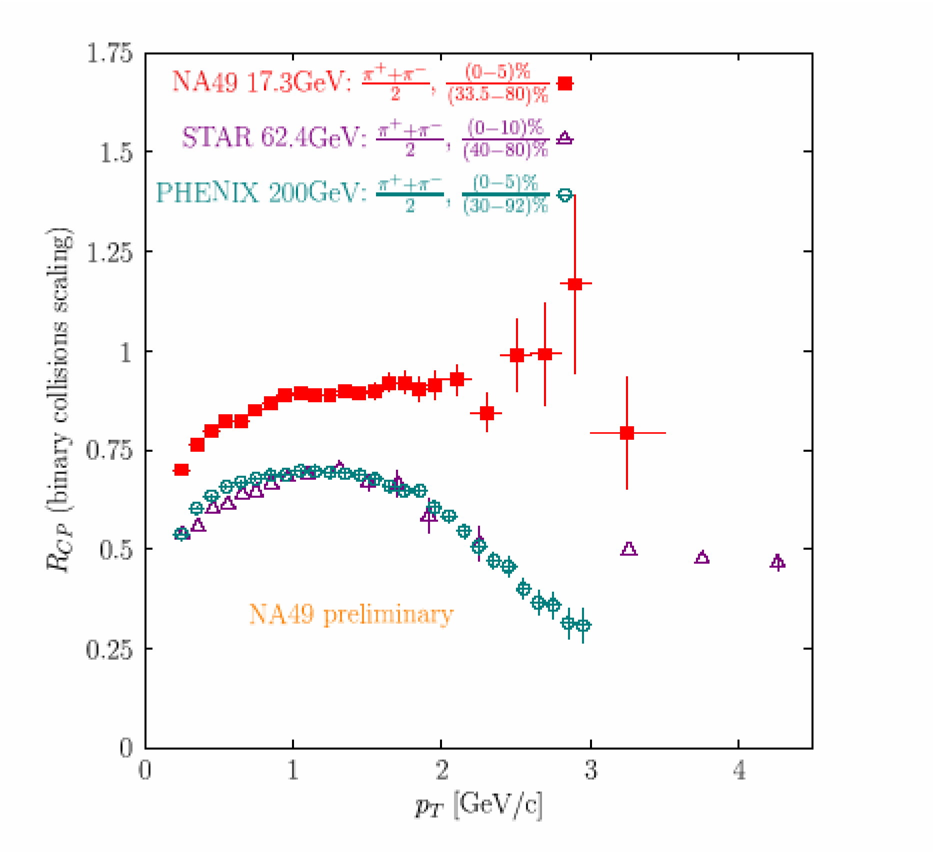




initial rise (radial flow) and saturation also observed at SPS

R_{CP} at SPS and RHIC





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