Search for the critical point of QCD at the CERN SPS

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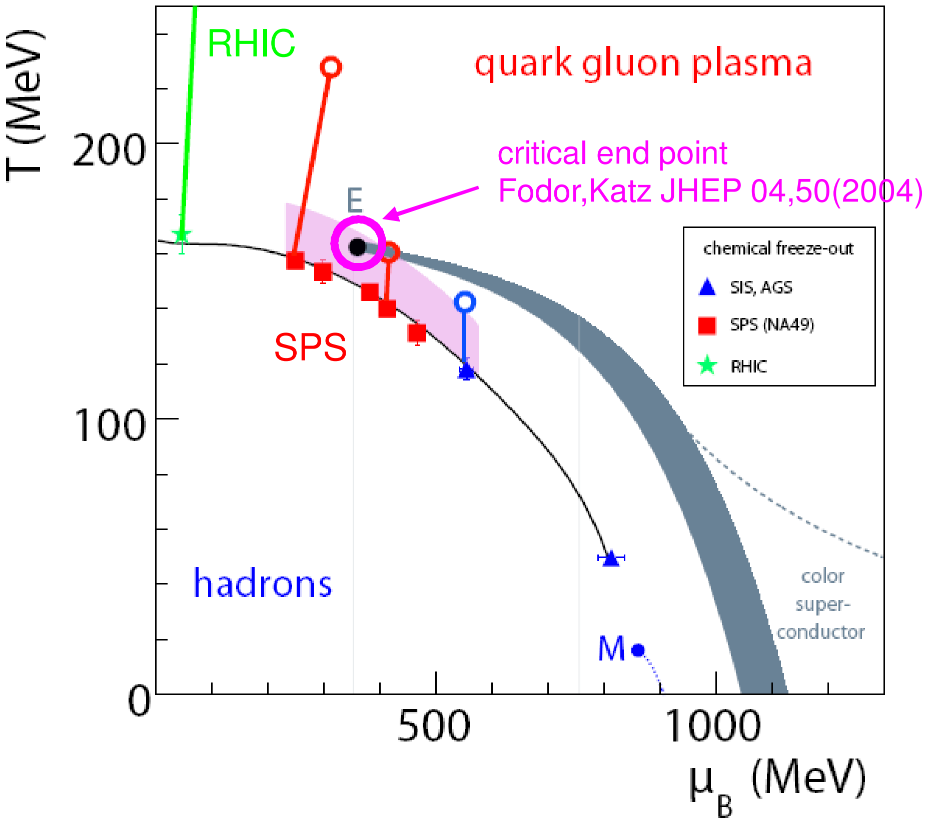
(for the NA49 and NA61 collaborations)

- Introduction – phase diagram of hadronic matter
- Onset of deconfinement in central Pb+Pb collisions at SPS energies
- Study of fluctuations and search for the critical point in NA49
- Future experimental program NA61

Phase diagram of hadronic matter



- QCD considerations suggest a first order phase boundary ending in a critical point

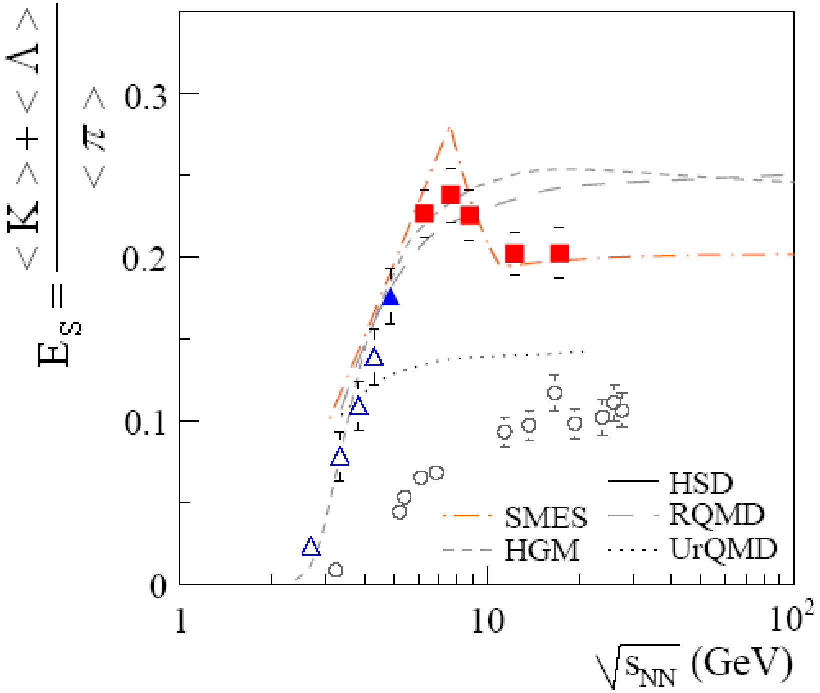
- hadrochemical freeze-out points are obtained from particle yields via statistical model fits
- T and μ_B approach the phase boundary and the estimated critical point location at the SPS

- evidence of phase transition in hadron production systematics ?
- indications of a critical point in fluctuations ?

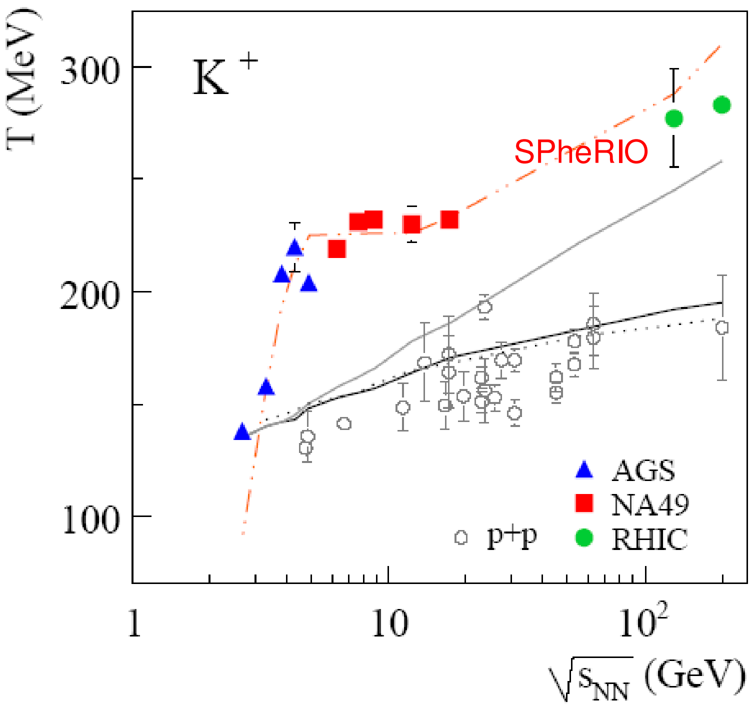
onset of deconfinement in central Pb+Pb collisions at the SPS

final NA49 results: C.Alt et al., PRC77,024903 (2008)

relative strangeness production

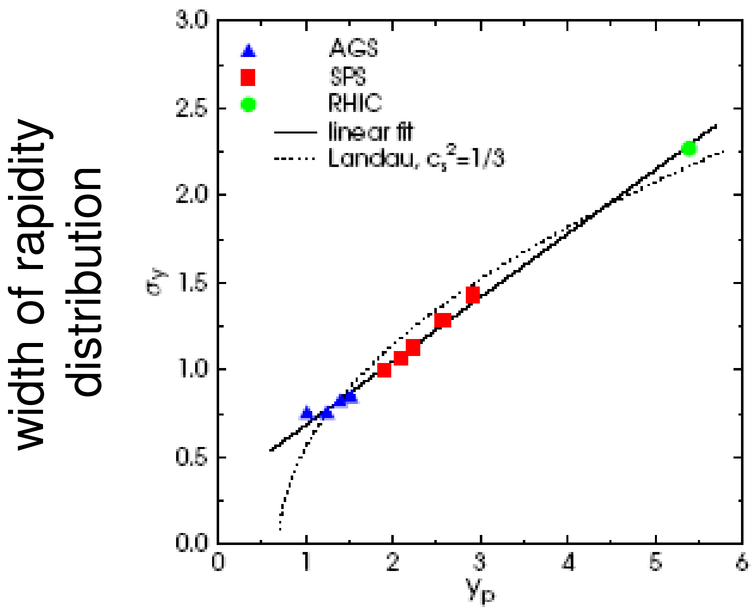


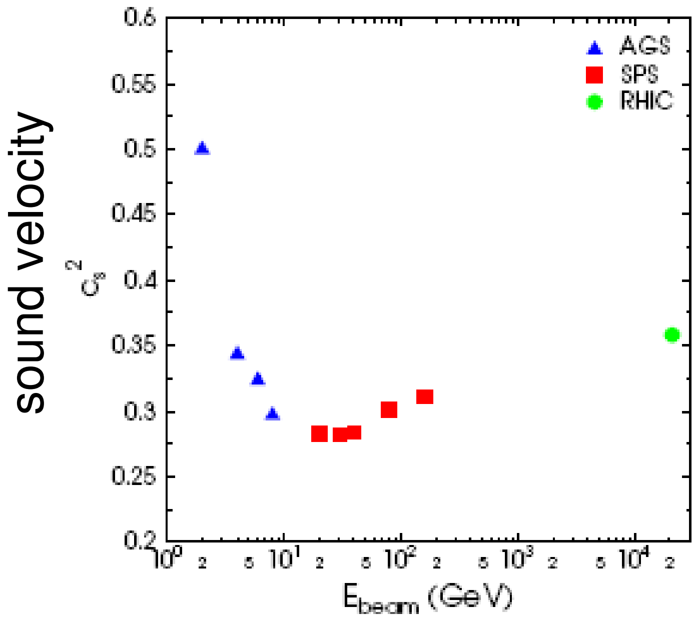
inverse m_T slope parameter



- rapid changes of hadron production properties at low SPS energy
- only models with deconfinement at the early stage describe data
- deconfinement reached in central Pb+Pb collisions above ≈ 30AGeV

estimate of sound velocity c_s





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

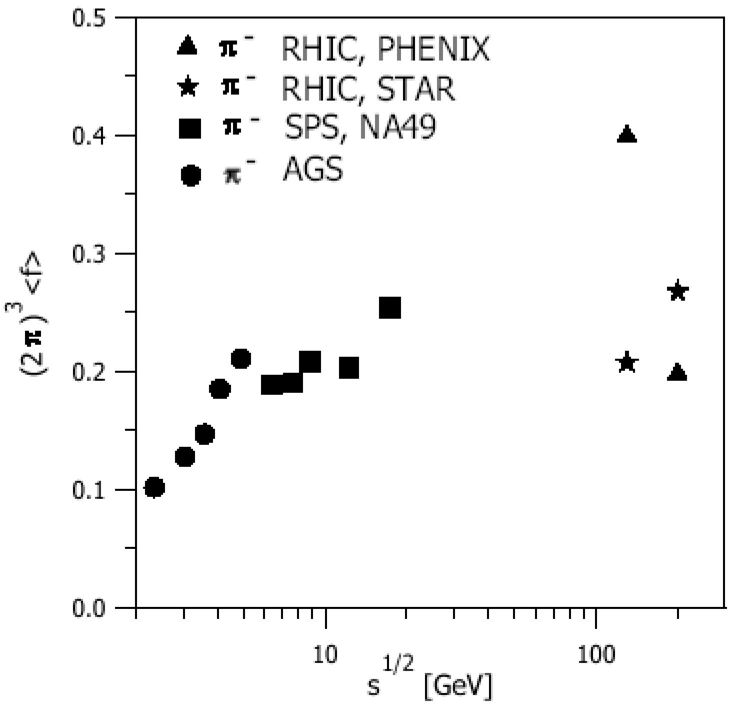
$$\sigma_y^2 = \frac{8}{3}\frac{c_s^2}{1-c_s^4}\ln(\sqrt{s_{NN}}\,/\,2m_p)$$

→ 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

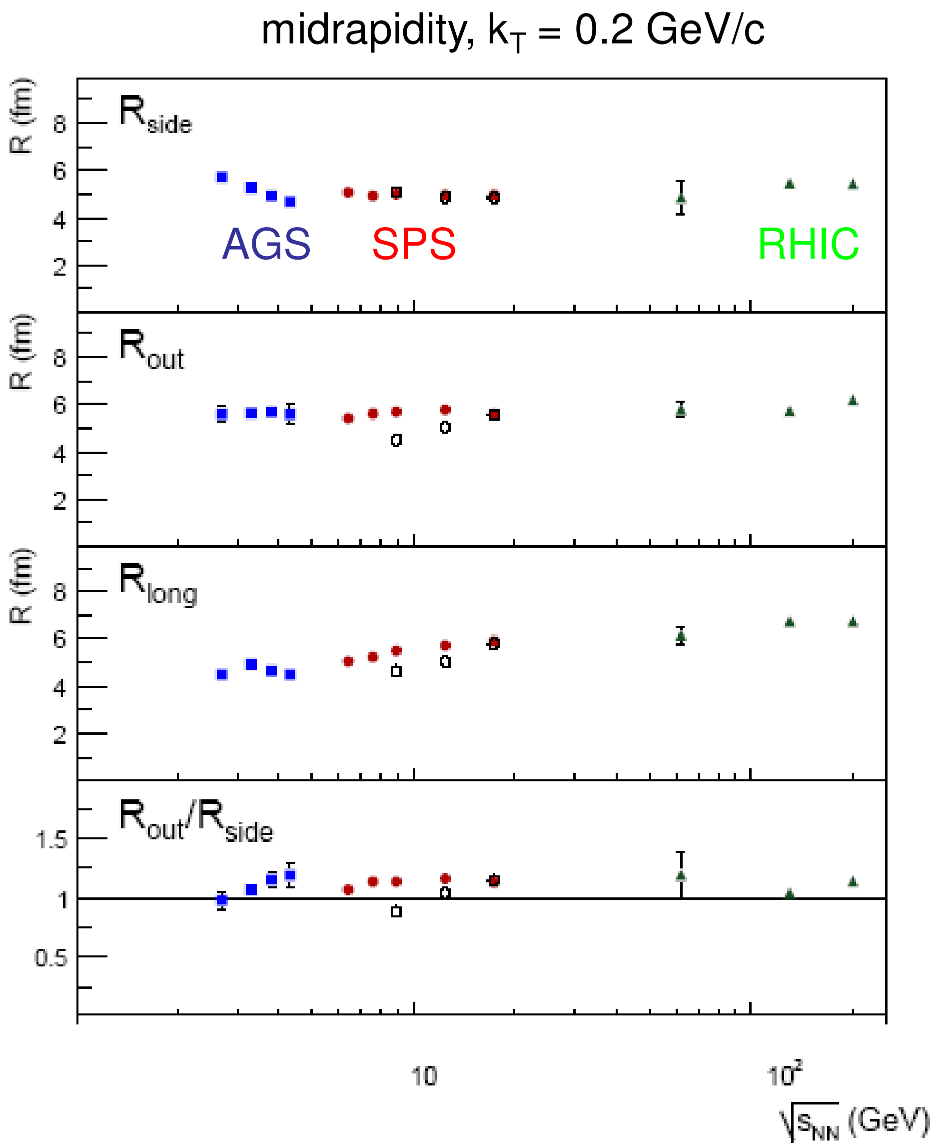
Phase space density from m_T spectra and BE correlations of π^-



S.Akkelin and Y.Sinyukov, Phys.Rev. C73, 034908 (2006)

plateau of the averaged phase space density at SPS energies may be associated with the onset of deconfinement

$\pi^- \pi^-$ BE correlations: radius parameters



- remarkably little change of R_{side} (fireball radius) and R_{out}
- slow rise of R_{long} (lifetime)

- no indication of $R_{out} >> R_{side}$ i.e. long duration of π emission (1st order phase transition, soft point of EoS)

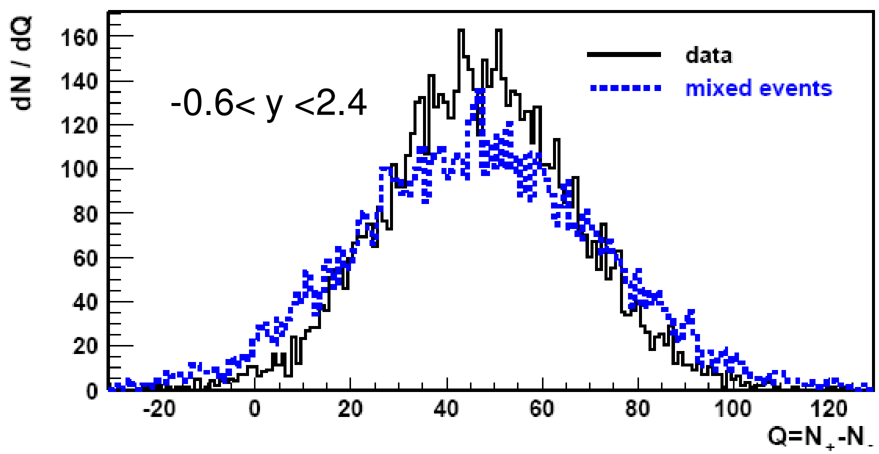
- hydro models have problems; need of more sophisticated modelling of freeze-out

Electric charge fluctuations

- Smaller in a QGP than in a hadron gas

(Jeon,Koch,Asakawa,Heinz,Müller)

Central Pb+Pb collisions 158A GeV



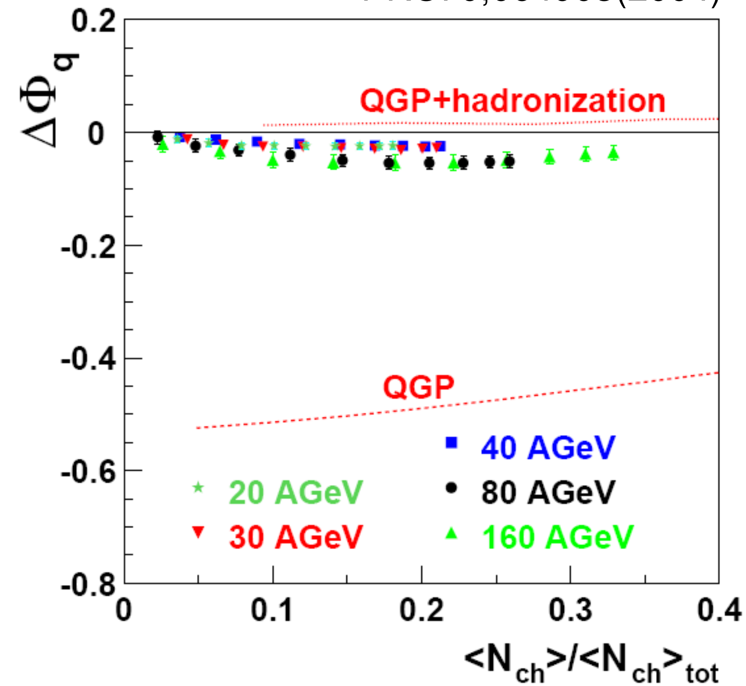
Global charge conservation

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

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

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

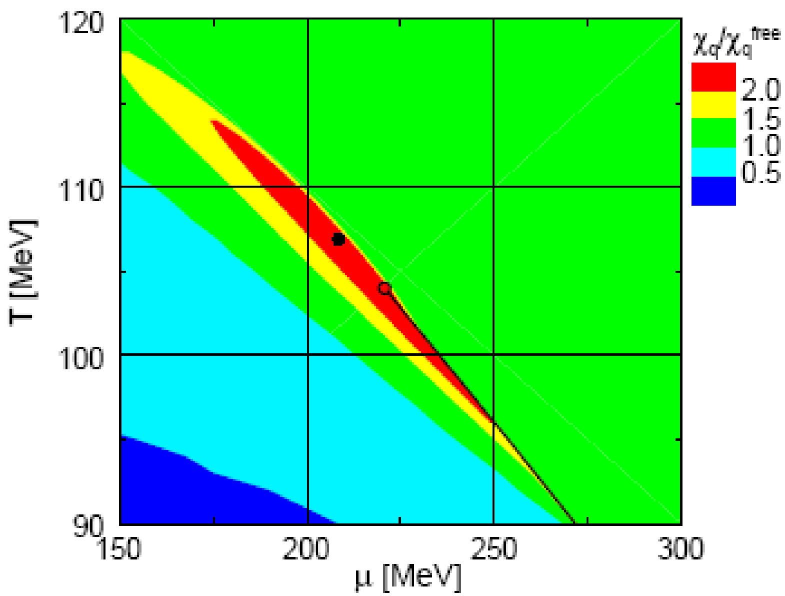
PRC70,064903(2004)



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

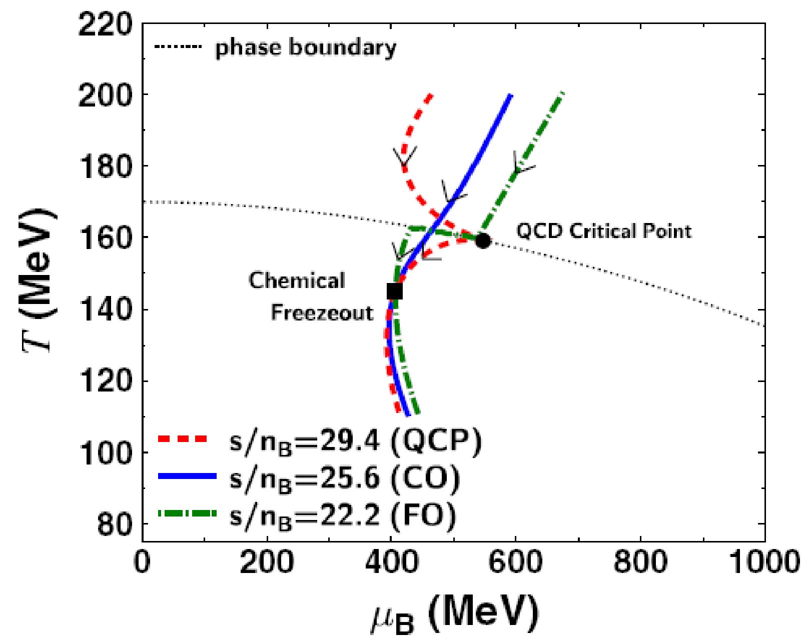
Search for the critical point in fluctuations

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



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

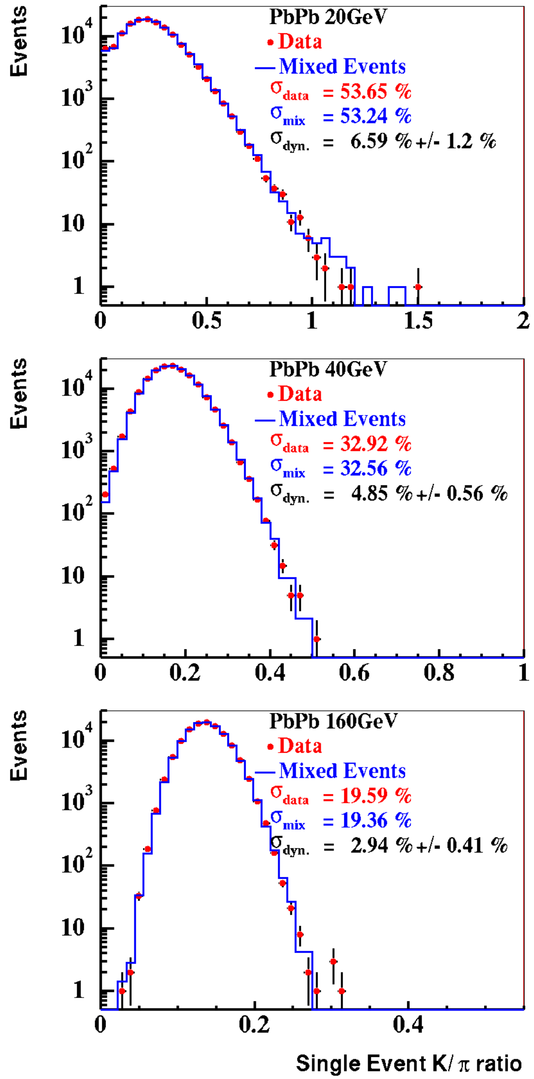
hydro predicts that evolution of the system is attracted to critical point



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

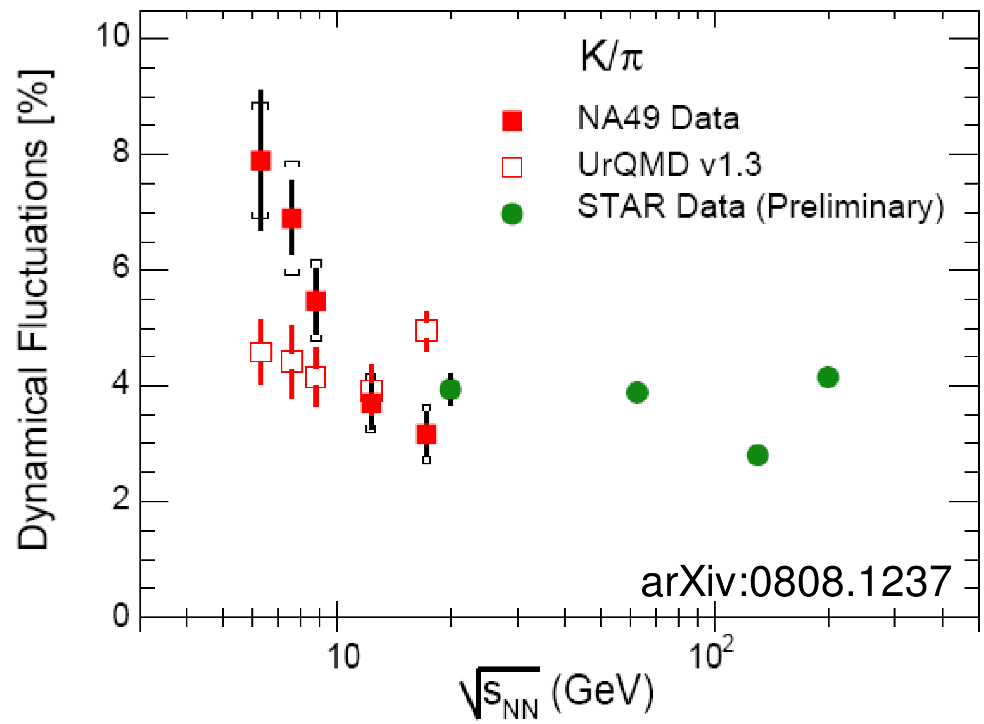
Fluctuations of the event-by-event K/π ratio

Beam Energy ↓



maximum likelihood fit for each event

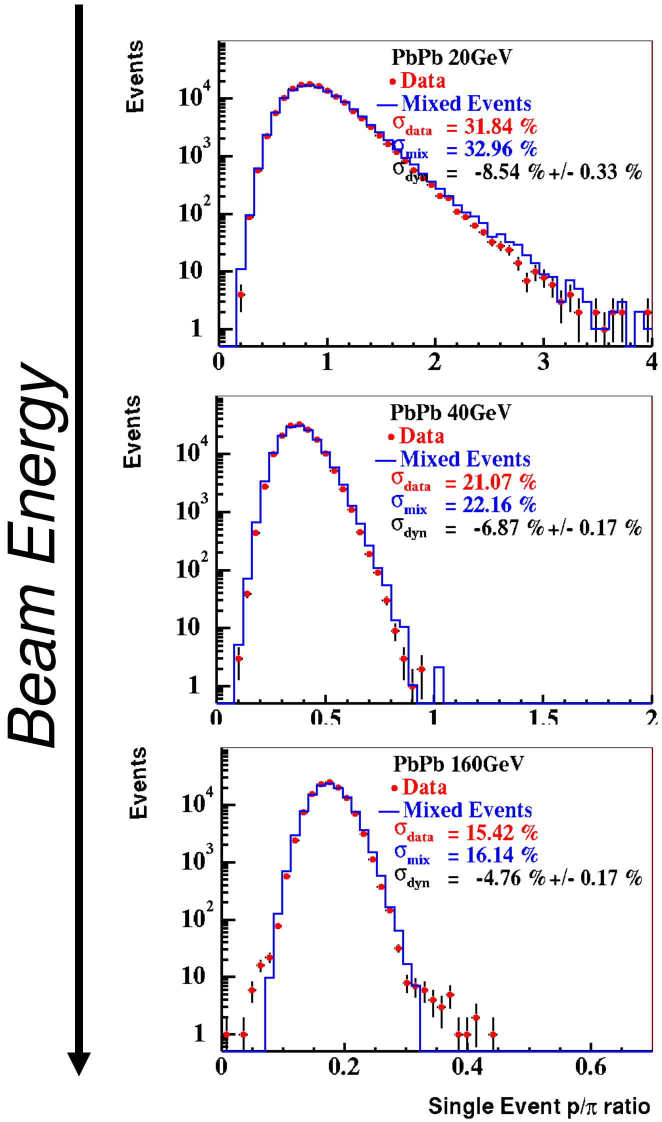
$$\sigma^2_{dyn} = \sigma^2_{data} - \sigma^2_{mixed}$$

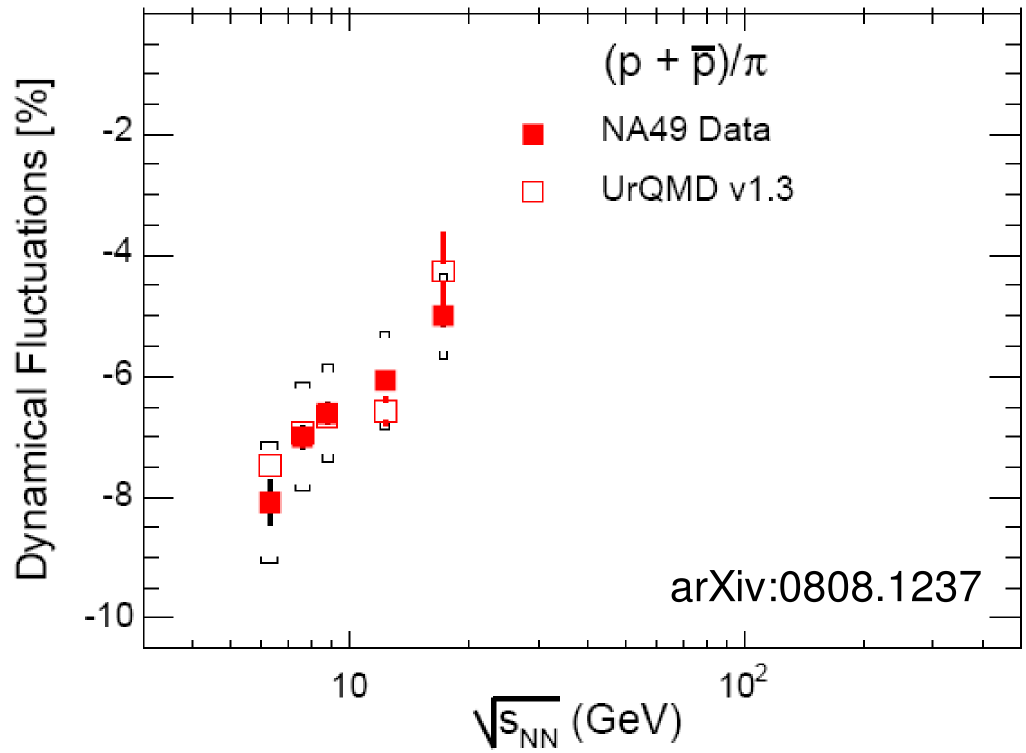


Fluctuations increase at lower energy
effect of onset of deconfinement ?

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

Fluctuations of 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 ?

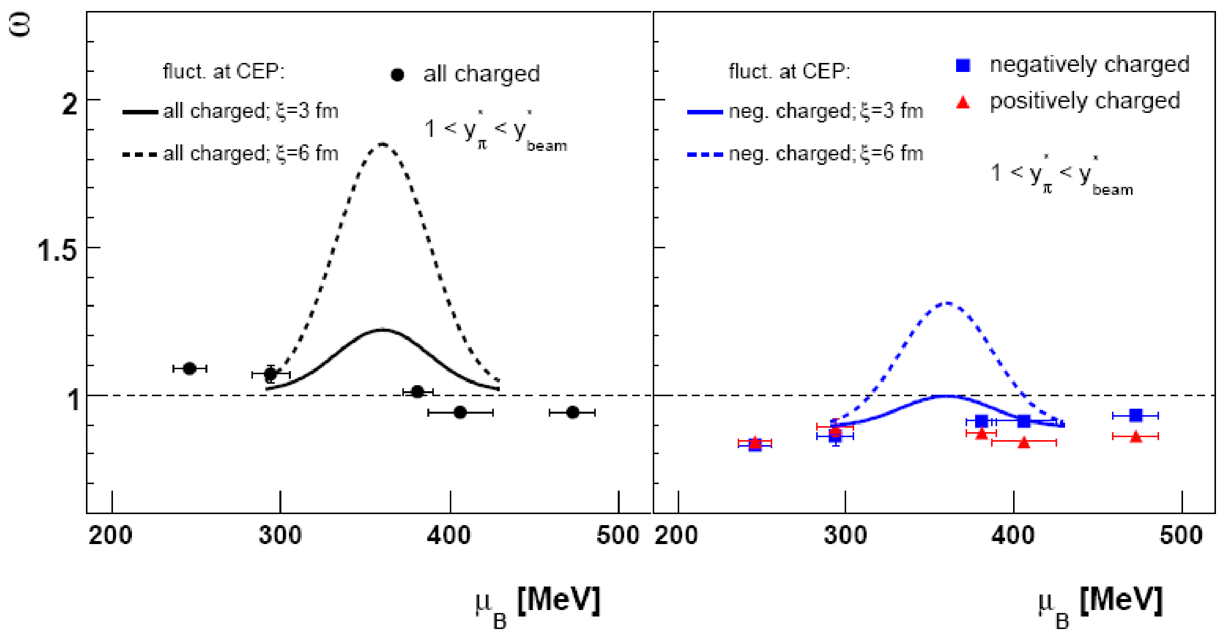
Event-by-event fluctuations of multiplicity

large fluctuations are expected if hadronisation occurs close to the QCD critical point

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

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

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



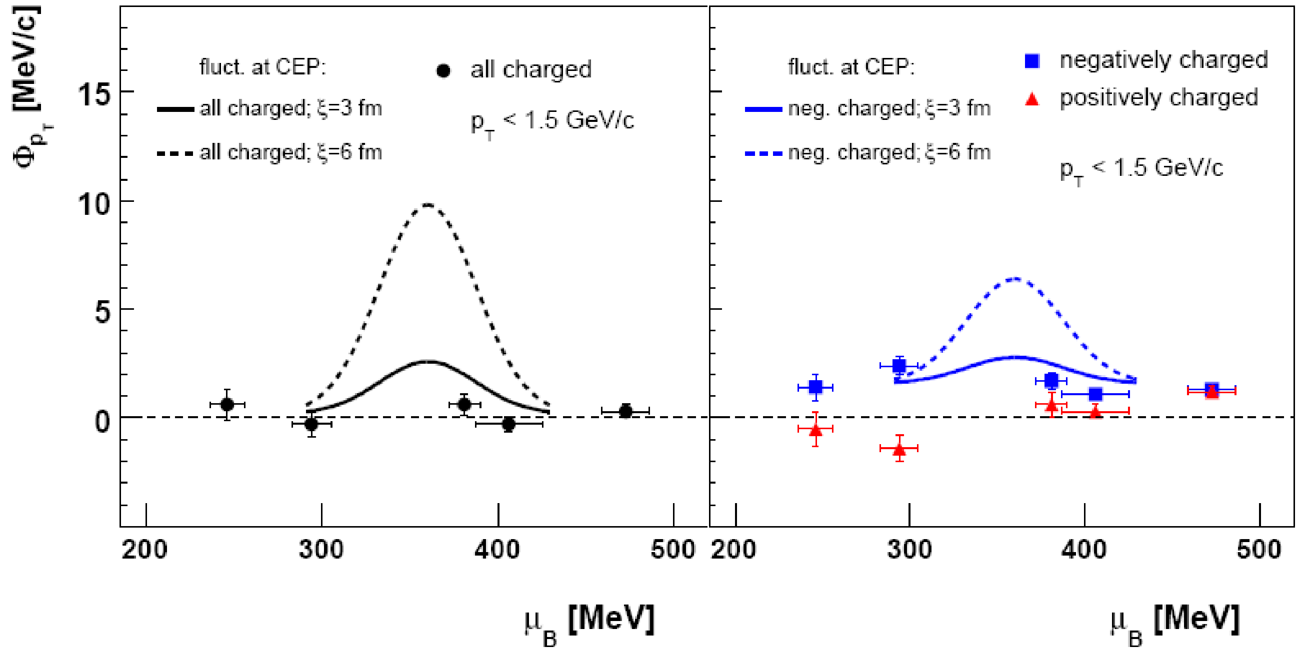
no peak for ω in central Pb+Pb collisions at the SPS

Event-by-event fluctuations of $<p_T>$

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

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

NA49 C.Alt et al., arXiv:0810.5510

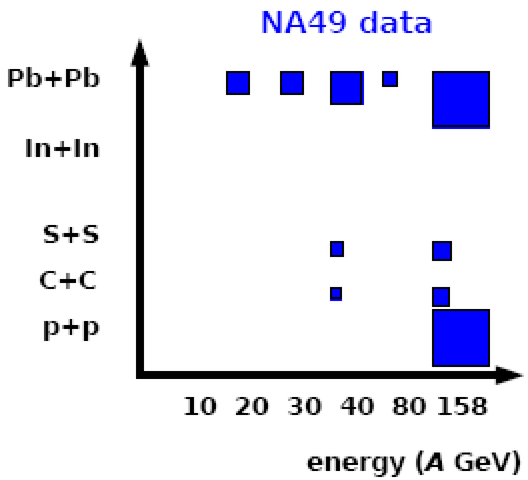


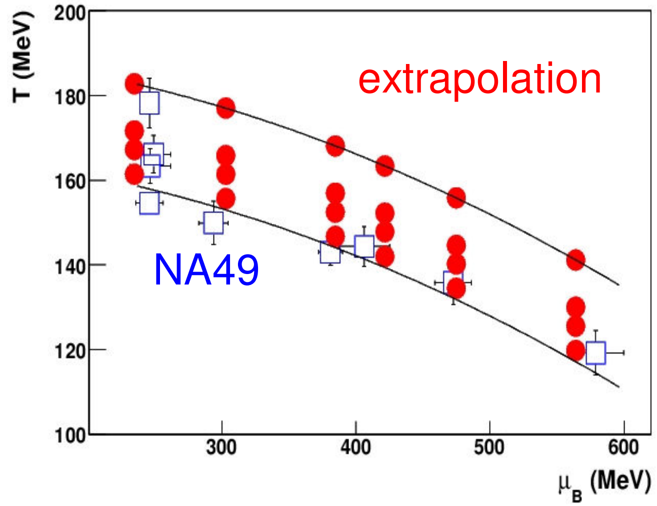
CP estimates based on: M.Stephanov, K.Rajagopal,E.Shuryak, PRD60,114028(1999)
Y.Hatta and T.Ikeda, PRD67,014028(2003)

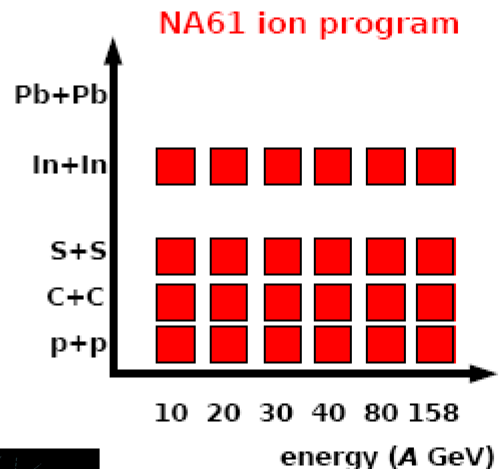
no indications of critical point in central Pb+Pb collisions at the SPS

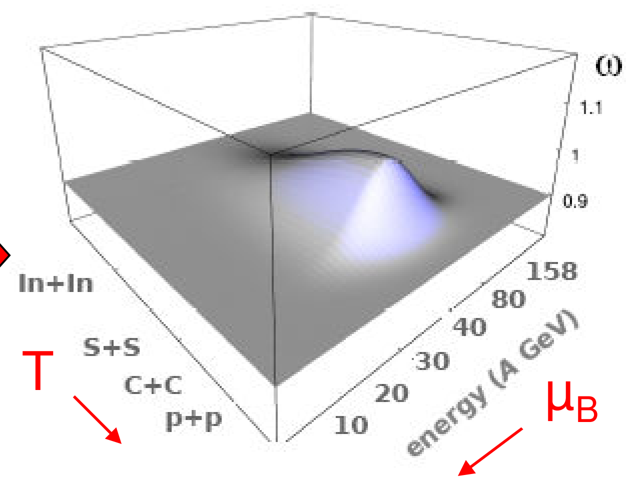
Continuation of search for the critical point by NA61

strategy: scan in energy and system size A



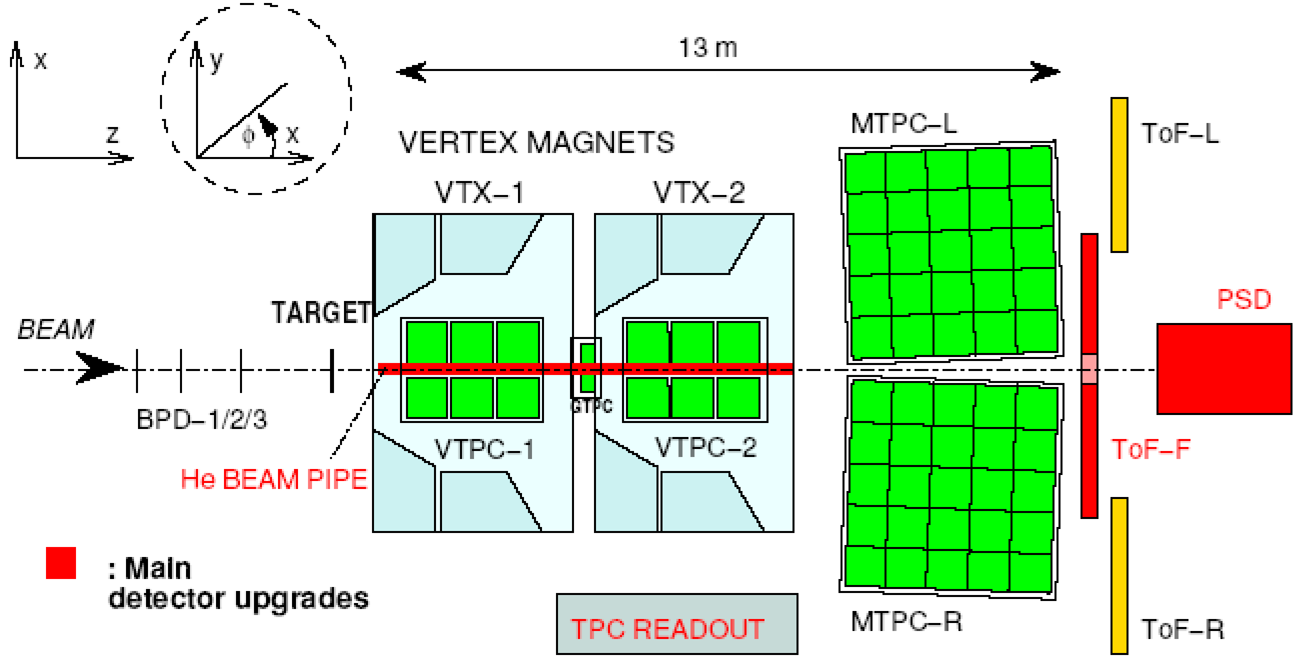






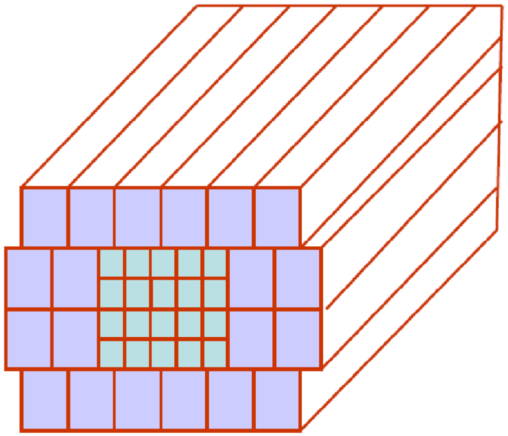
CP → hill in fluctuations

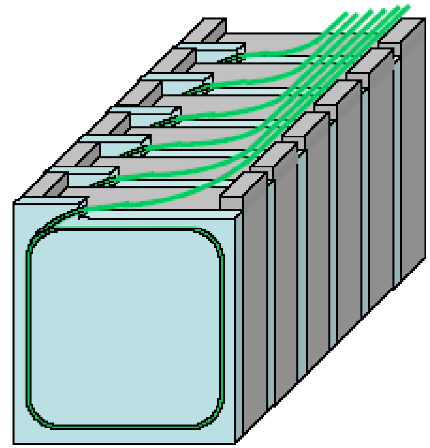
NA61 will use the upgraded NA49 detector



- new TPC readout and DAQ completed
  → data taking rate increase x 10 (80 Hz)
- new zero degree calorimeter PSD, single nucleon resolution
- He-filled beam pipe through VTPCs to reduce δ-ray background

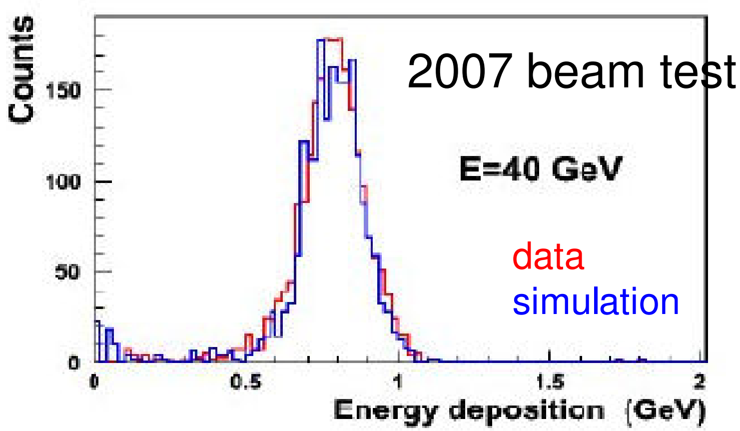
Projectile Spectator Detector under construction



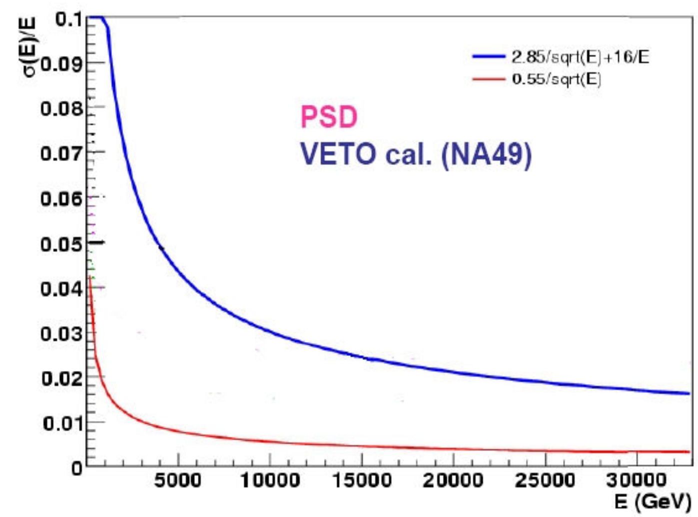


- 60 lead/scintillator sandwiches
- 10 longitudinal sections
- 6 WLS-fiber/MAPD
- 10 MAPDs/module
- 10 Amplifiers with gain~40

-- 40 modules (20 small +20 large ones)
-- can be used for reaction plane meas



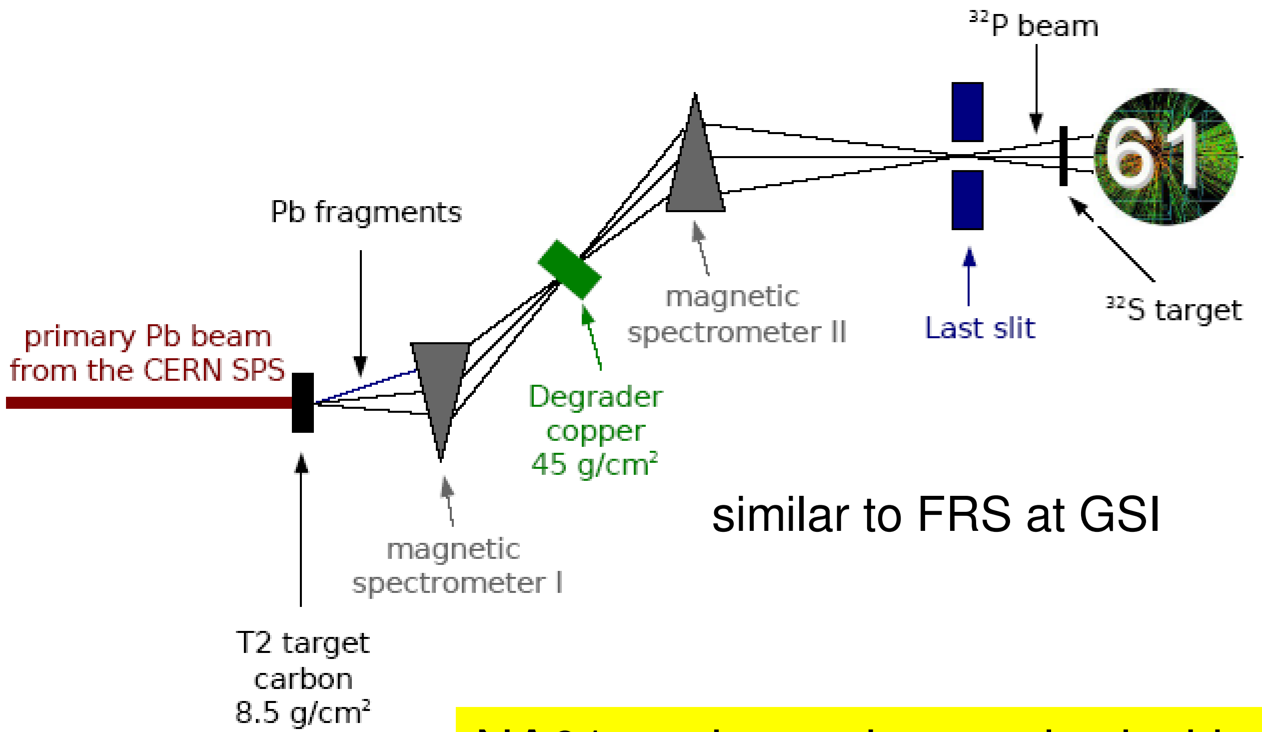
expected energy resolution

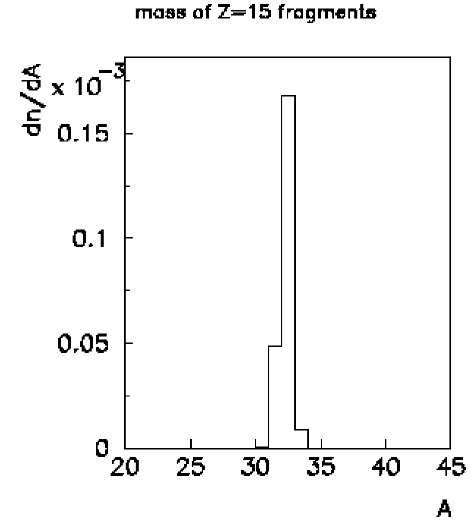


SHINE NA61

planned schedule of NA61 for ion beams

- NA61 ion program accepted by SPSC in 2007,
  run with A ~ 32 recommended
- required compatibility with Pb ions in I-LHC motivates
  use of fragmentation beam
- start with ^{32}P ions anticipated in 2011



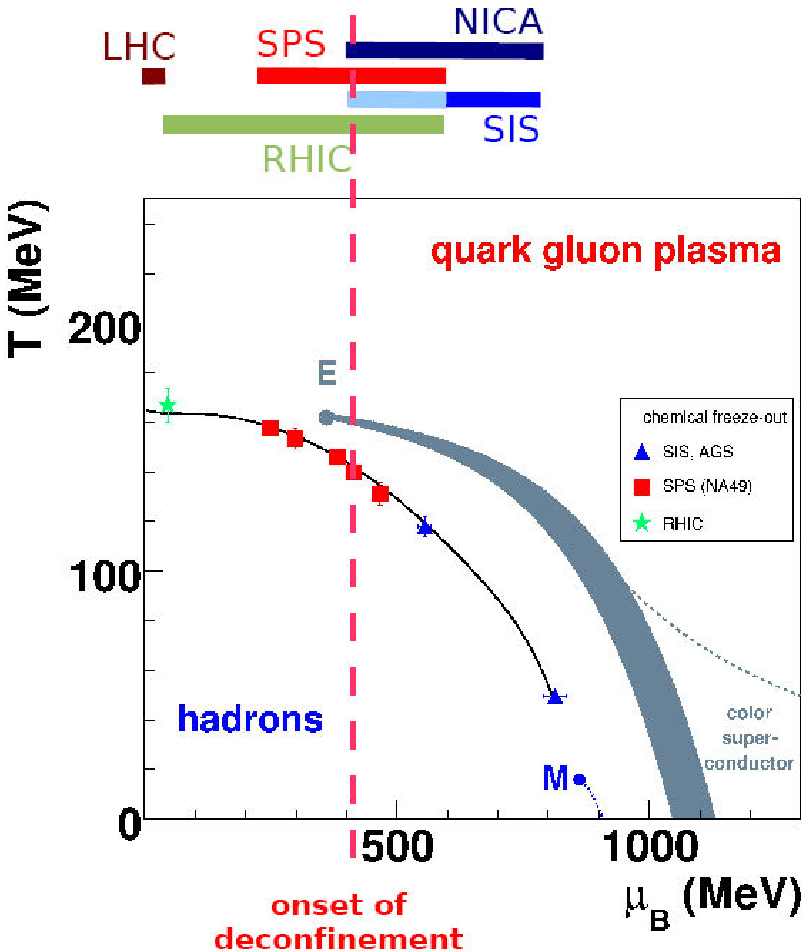


similar to FRS at GSI

result after charge selection by trigger

NA61 goals can be reached with fragmentation beam

QCD critical point searches – experimental landscape



partly complementary programs
planned at CERN SPS 2011
BNL RHIC 2010
DUBNA NICA 2013
GSI SIS-CBM 2016

strong points of NA61:

- covers region of onset of deconfinement
- large acceptance → 4π yields
- tight constraint on spectators
- high event rate at all SPS energies
- flexibility to change A and energy

Conclusions

- the existence of the critical point of hadron matter is an important prediction of QCD that must be tested
- predictions locate the critical point in the phase diagram region accessible with ion-ion reactions at SPS energies
- no indications have yet been found in Pb+Pb collisions
- NA61 will perform a systematic search in A and energy starting in 2011
- complementary search programs are planned at RHIC, NICA and CBM

The NA49 Collaboration

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The NA61 Collaboration

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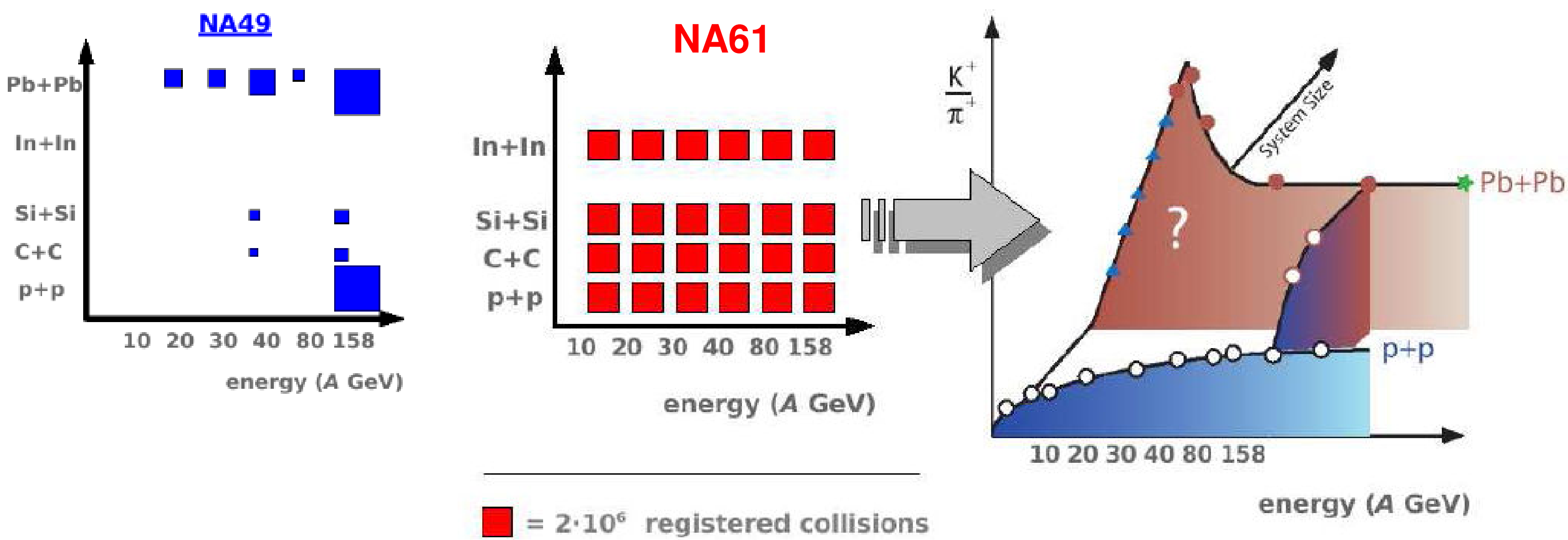
Backup slides

Future plans (NA61)

- scan energies of SPS with smaller size nuclei
- NA61 (using the upgraded NA49 detector) was approved by CERN; begin of ion program with A = 32 nuclei in 2011 ?

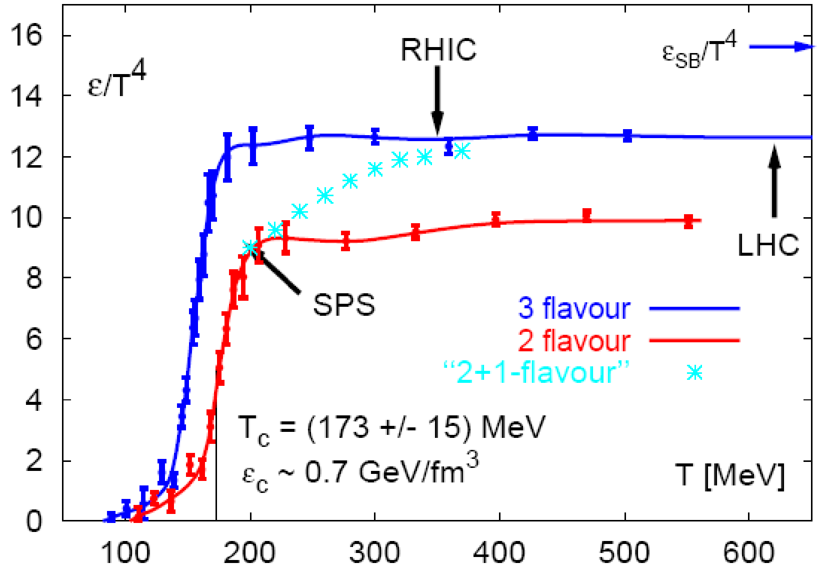
(1) study of details of the onset of deconfinement

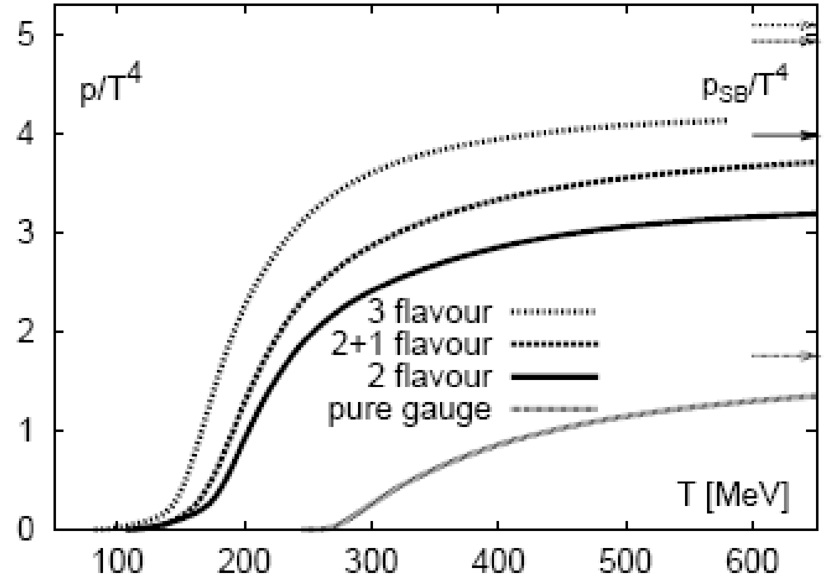


QCD predicts quark, gluon deconfinement in high temperature and/or density hadron matter

- 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 already at the SPS

Pb+Pb collisions at top SPS energy

- initial energy density exceeds the critical value predicted by lattice QCD (≈ 1 GeV / fm^3)
- signatures for deconfinement observed at SPS in 2000
  - strong radial and anisotropic flow of produced matter
  - strangeness enhancement
  - J/Ψ,Ψ' yield suppression
  - di-lepton enhancement, ρ^0 modification
- unfortunately signatures not specific for deconfinement

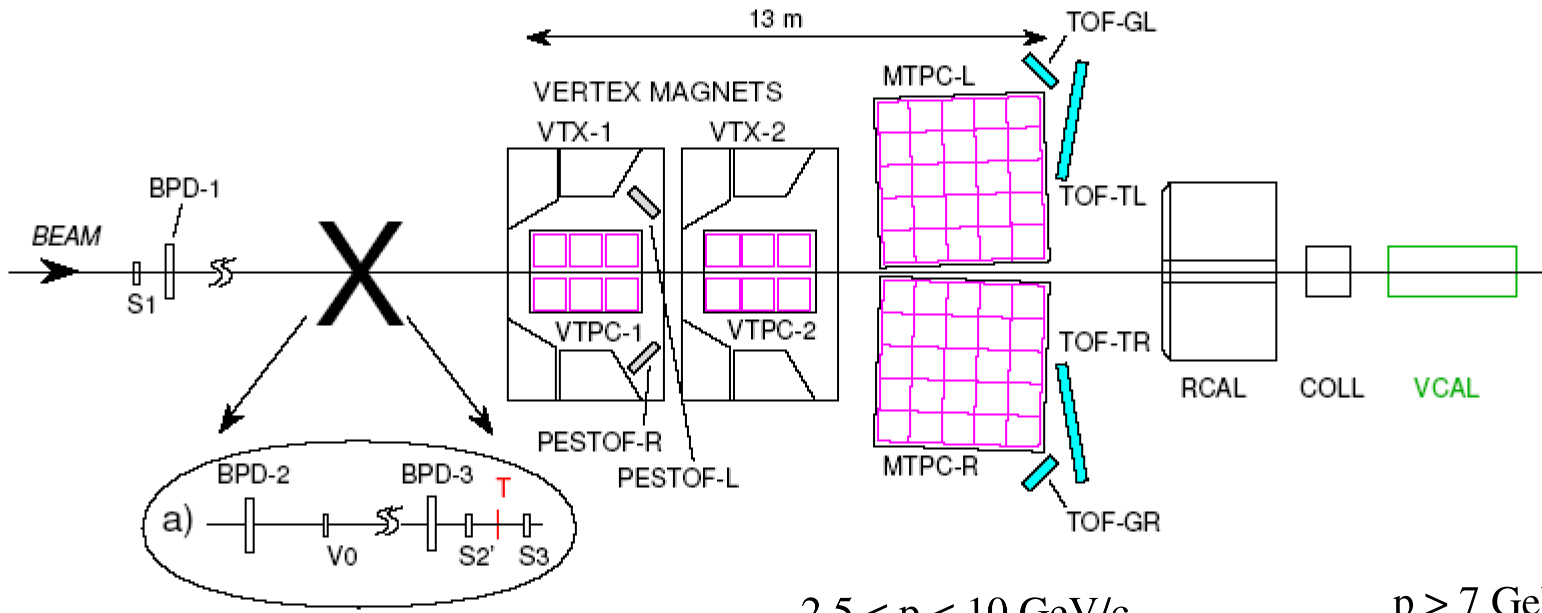
➢ NA49 search for a threshold by varying the energy for the largest collision system (central Pb+Pb reactions)

➢ 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} $(\mathrm{GeV}/c)^{-1}$

(VTPC-1, VTPC+MTPC)

Particle identification:

dE/dx (3 – 6 %), TOF (~ 60 ps)

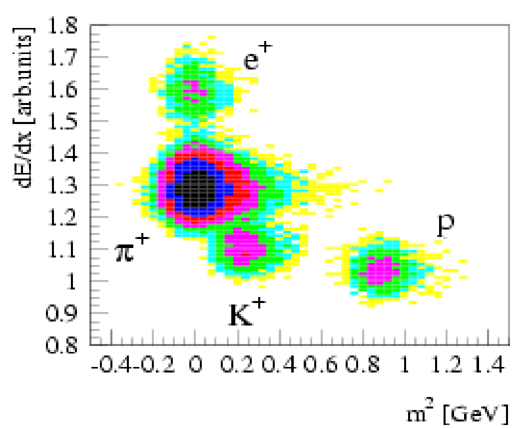
decay topology (K^0_s , Λ, Ξ, Ω)

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

2.5 < p < 10 GeV/c

TOF + dE/dx

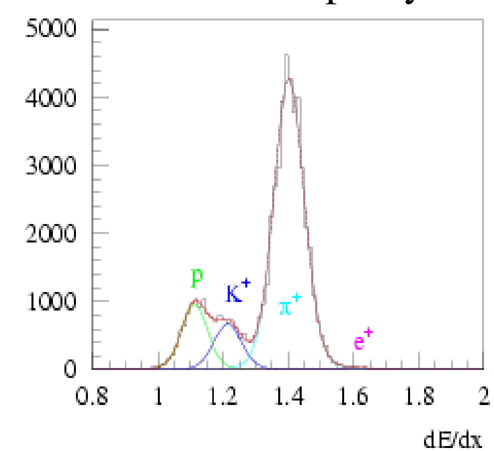
at midrapidity



p > 7 GeV/c

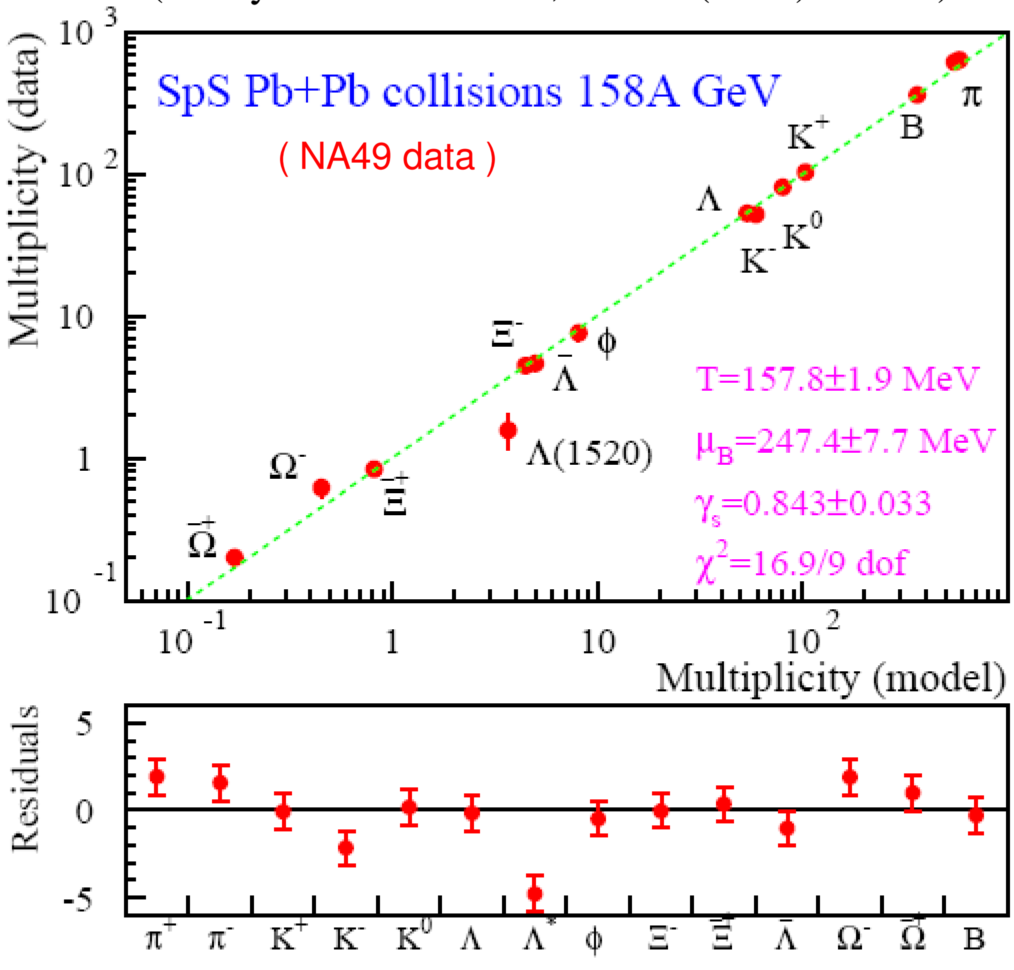
dE/dx

forward rapidity



Particle yields – statistical model

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



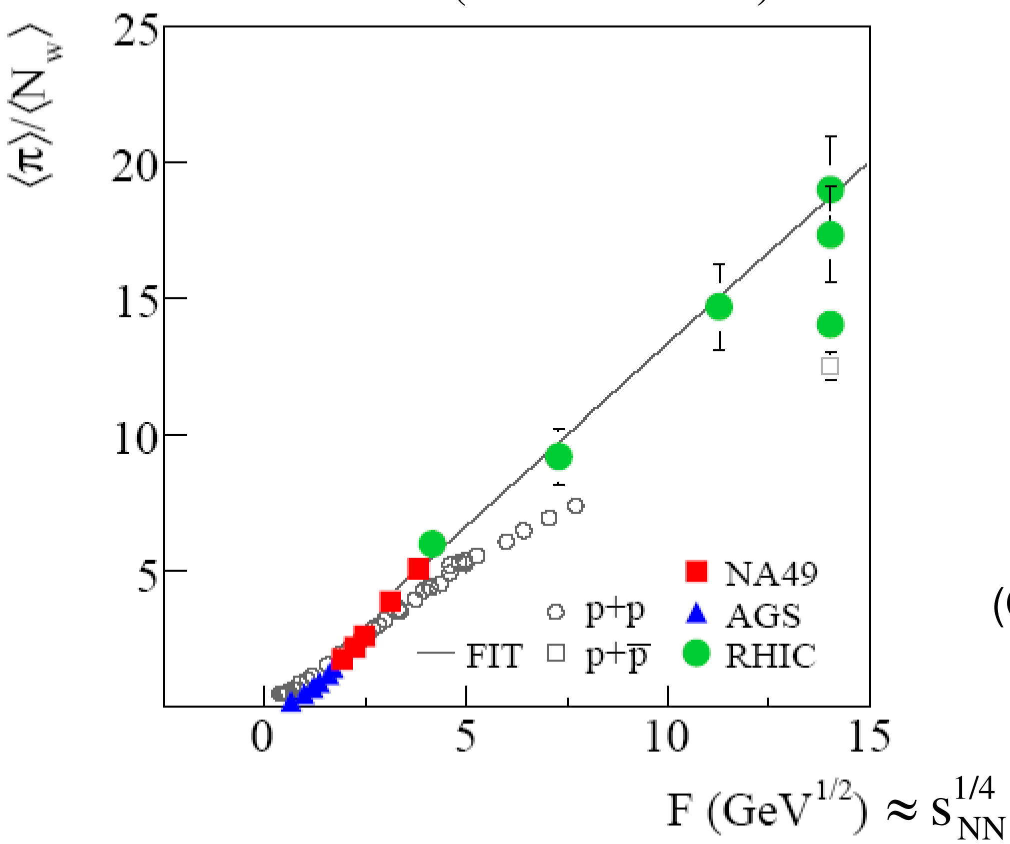
- hadron species populated approximately according to phase space probabilities (max.entropy) (Fermi,Hagedorn)
- strangeness sector not fully saturated (Rafelski)
- statistical model successful in A+A, p+p, $e^+ + e^-$
- parameters: T, μ_B, γ_S, V

Total pion yields

(C.Alt et al.,PRC77,024903(2008))

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

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



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

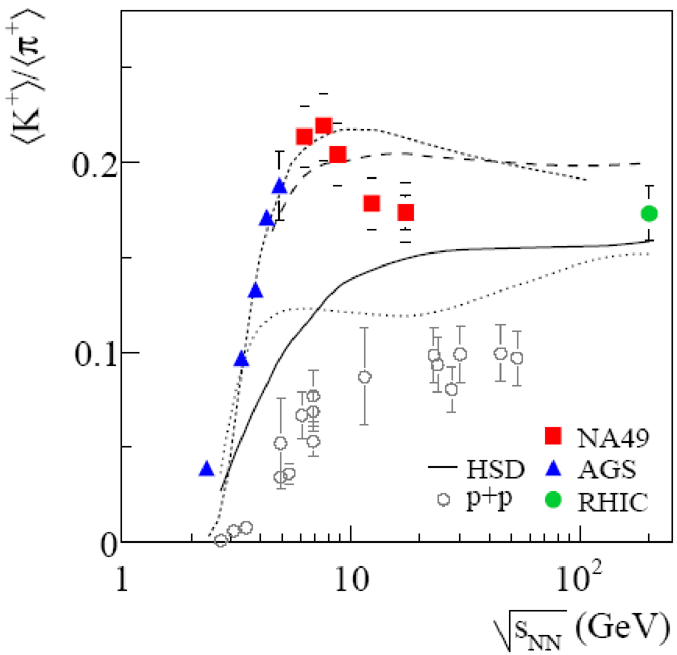
SMES: statistical model of the early stage

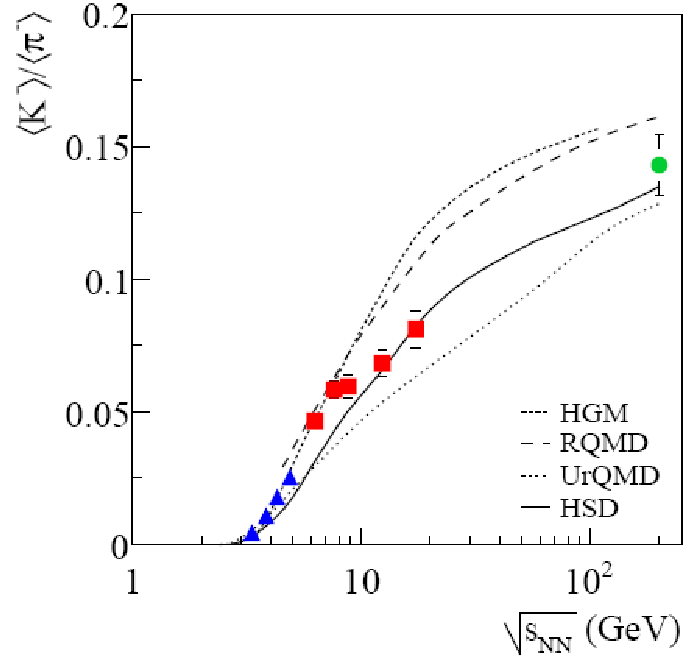
$$\frac{\langle \pi \rangle}{N_w} \propto \frac{S}{N_w} \propto g^{1/4} F \qquad F = \frac{(\sqrt{s} - 2m_p)^{3/4}}{\sqrt{s}^{1/4}}$$

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

consistent with x3 increase of initial d.o.f., g, at SPS

Ratio of kaon to pion yields





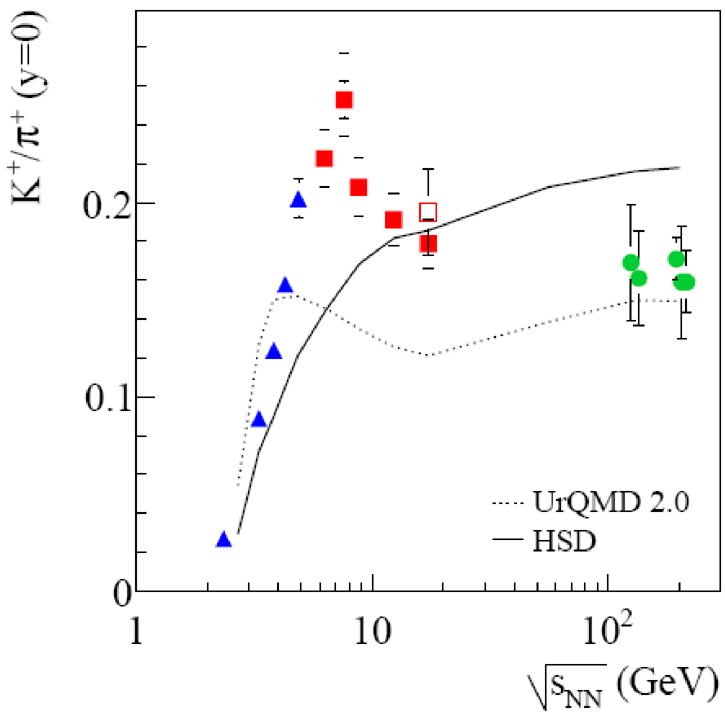
at SPS energies produced $\bar{s}$ quarks are mostly contained in kaons (equally in K^+ and K^0), s quarks are shared between K^-, $\bar{K}^0$ and hyperons

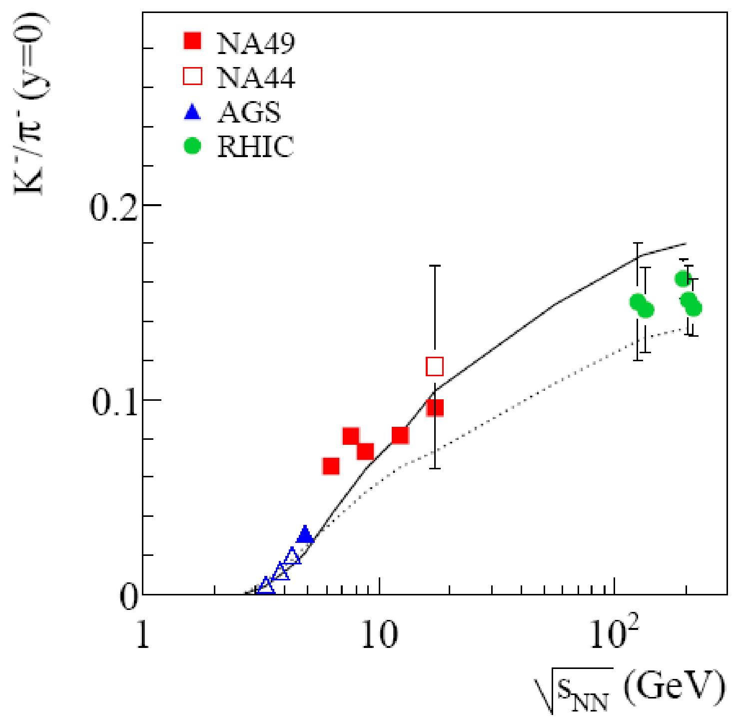
→ $\langle K^+ \rangle$ a measure of total strangeness yield

sharp peak observed in relative strangeness production $\langle K^+ \rangle / \langle \pi^+ \rangle$ at SPS not reproduced by hadronic models

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

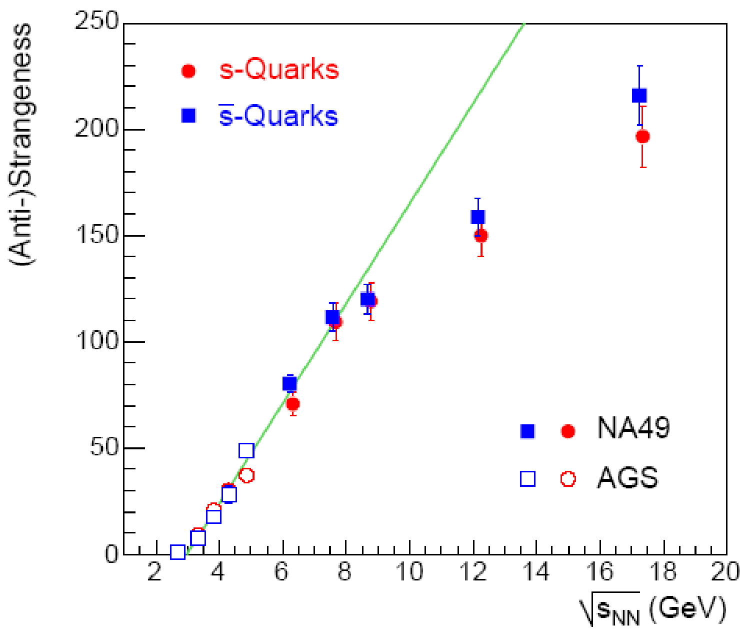
at mid-rapidity identification is from dE/dx and TOF

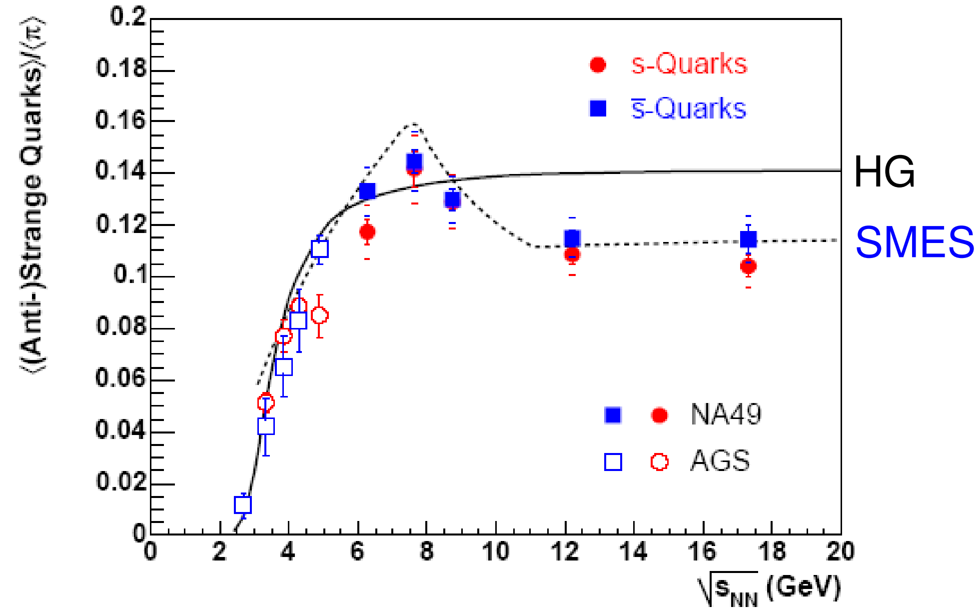




Total yield of s, $\bar{s}$ quarks

estimated using: measured yields and isospin symmetry
+ correction for unmeasured yields from statistical HG model predictions

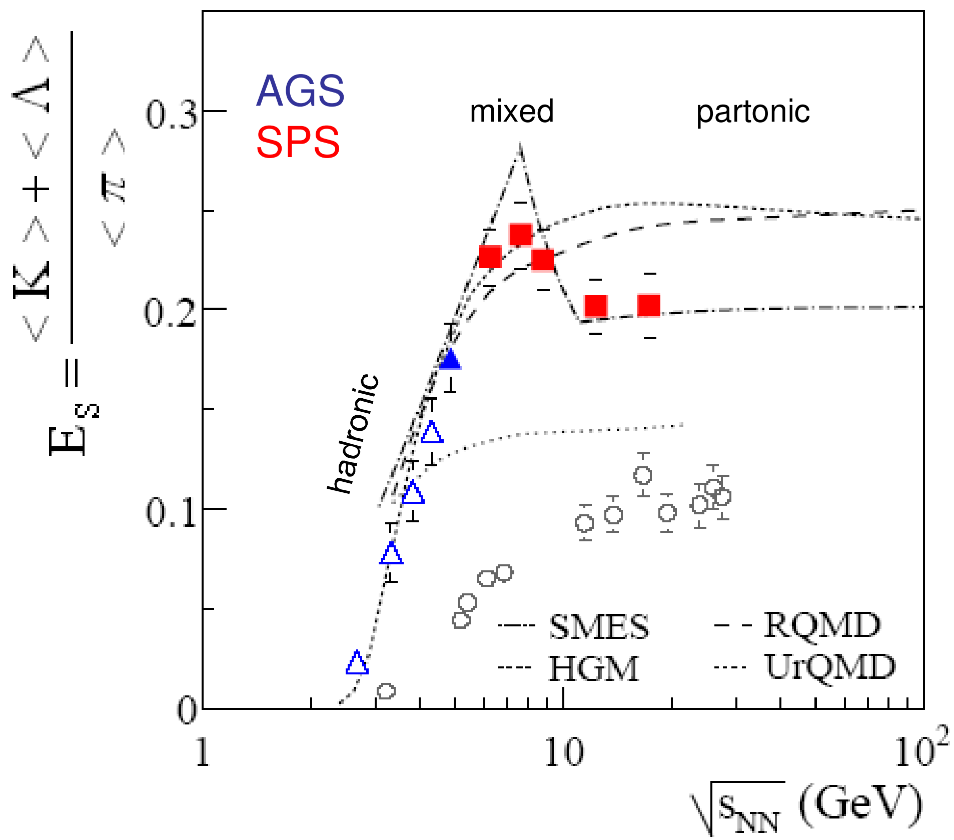




increase of yields with energy
changes slope at 30A GeV

sharp peak, then under-saturation
of strangeness content

Ratio of strange hadron to pion yields



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

strangeness to pion ratio peaks sharply at the SPS

SMES explanation:

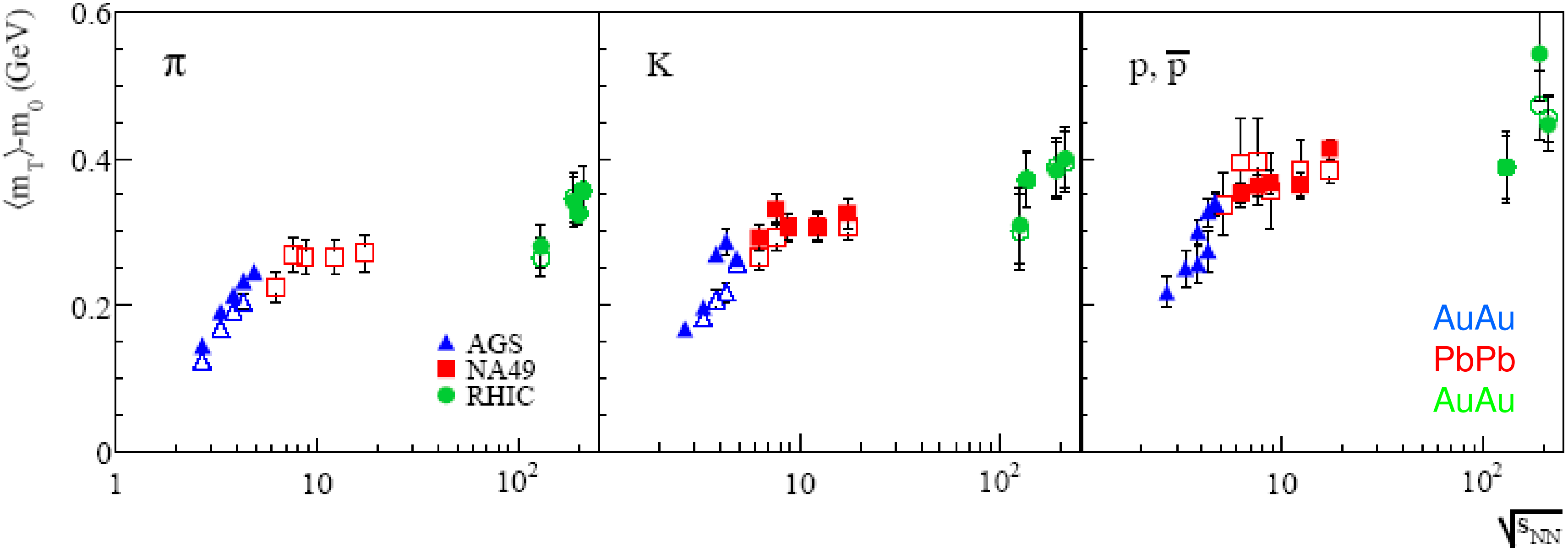
- entropy, number of s, $\bar{s}$ quarks conserved from QGP to freeze-out
- ratio of $(s + \bar{s})$ / entropy rises rapidly with T in the hadron gas
- E_s drops to the predicted constant QGP level above the threshold of deconfinement :

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

$$\approx 0.21$$

suggests onset of deconfinement at SPS

Average transverse mass

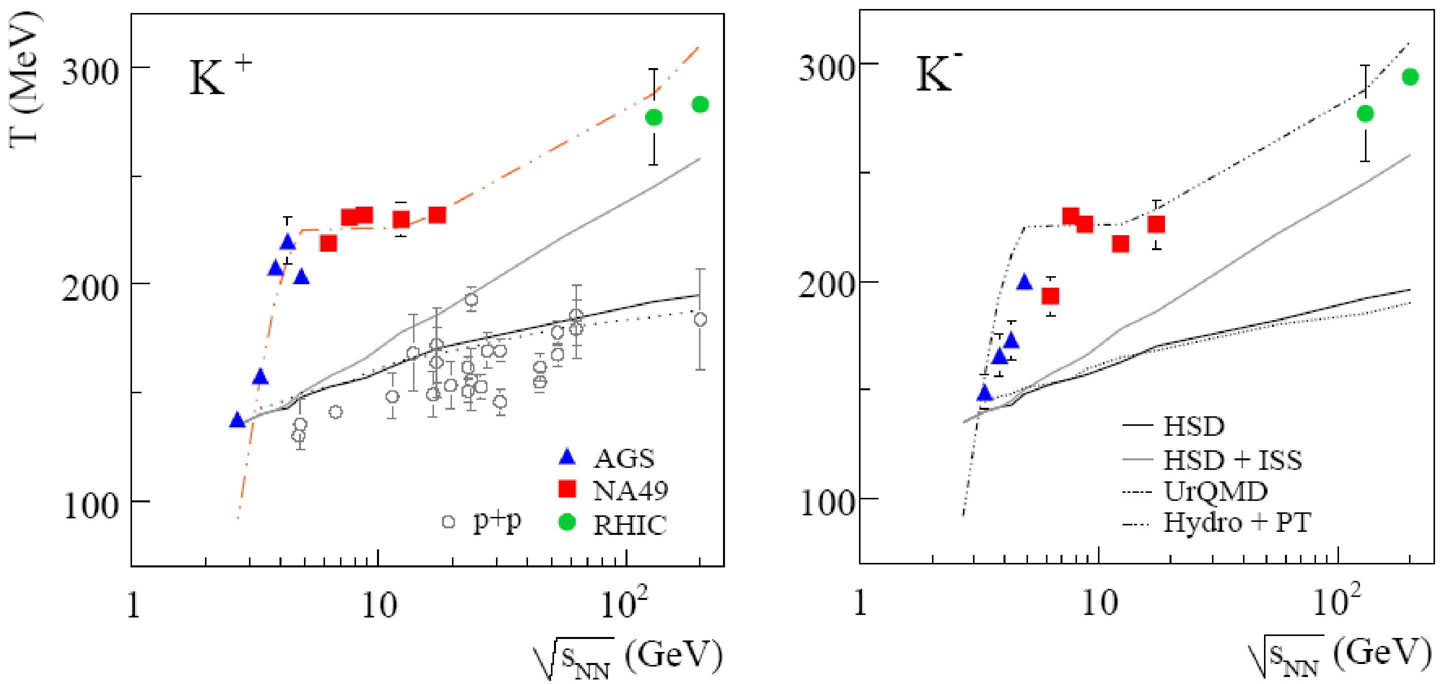


- Increase of <m$_T$> for abundant final state particles (π, K, p) slows sharply at the lowest SPS energy

- 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)

Inverse slope parameters



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

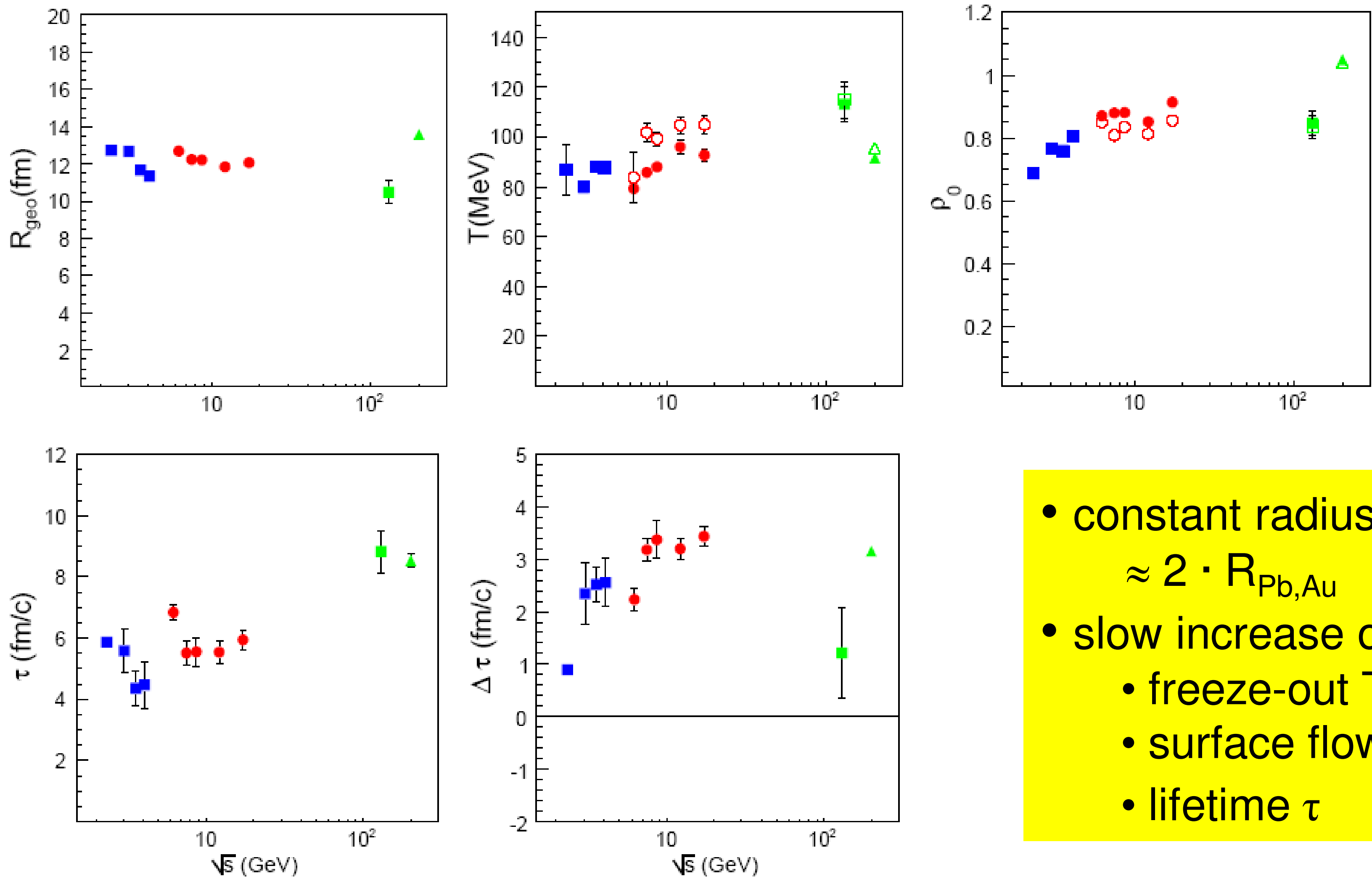
- the step-like feature observed, not seen for p+p collisions and models without phase transition

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

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

energy dependence of fireball parameters

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

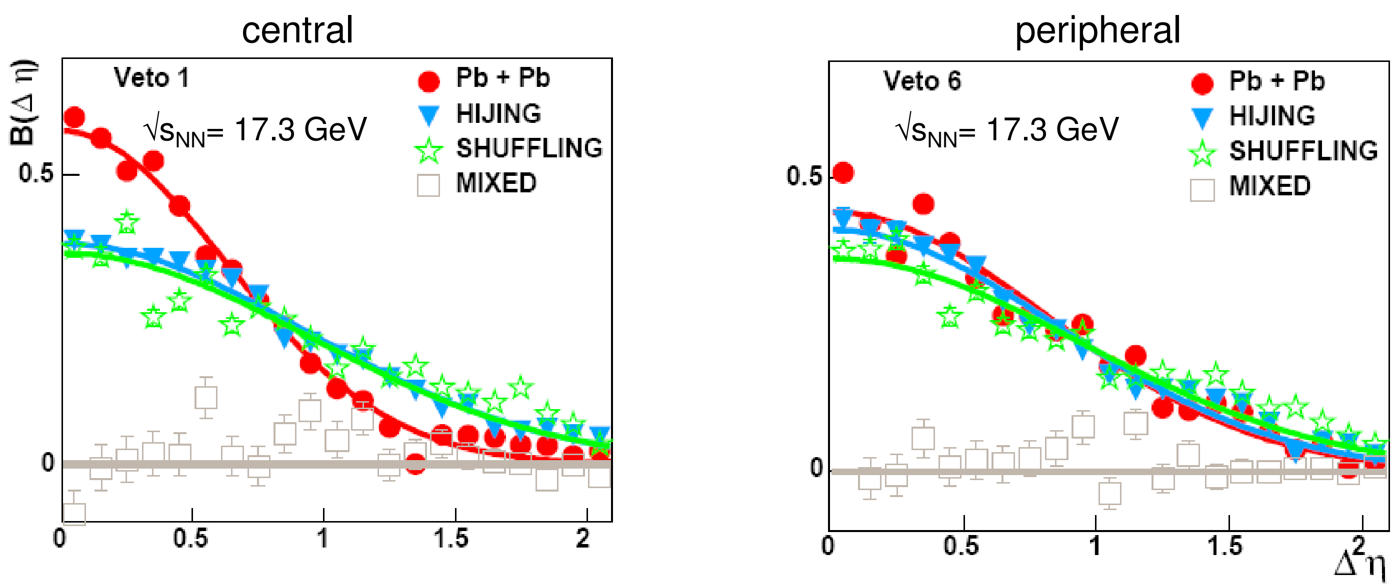


- constant radius
  $\approx 2 \cdot R_{Pb,Au}$
- slow increase of
  - freeze-out T
  - surface flow ρ_0
  - lifetime τ

Balance Function: charge correlations in pseudo-rapidity

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

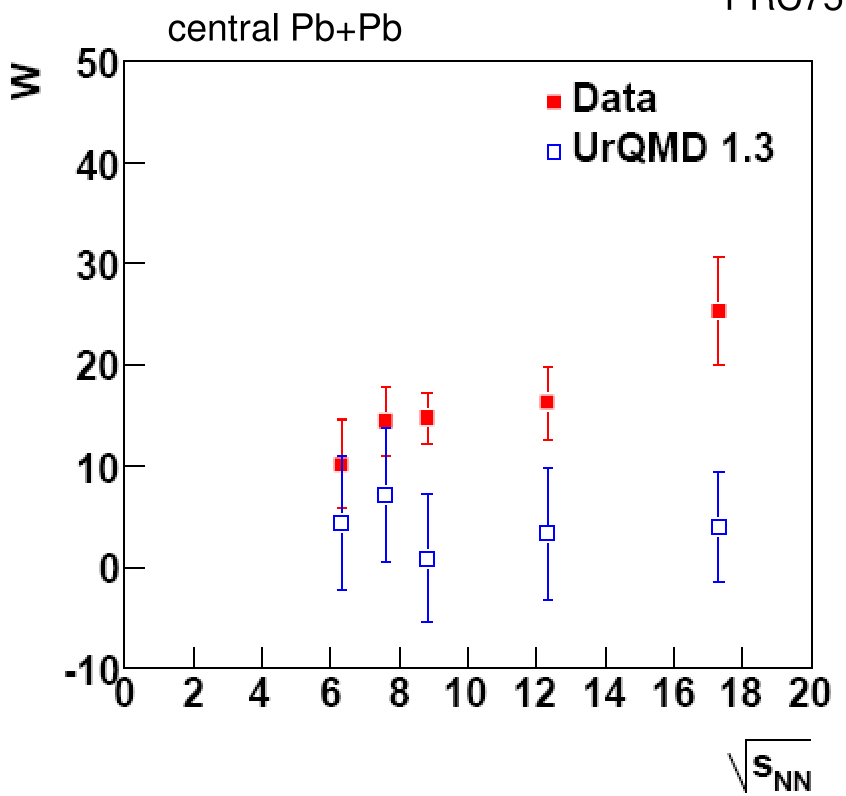
narrowing of the balance function proposed as QGP signature
(delayed hadronisation due to phase coexistence)

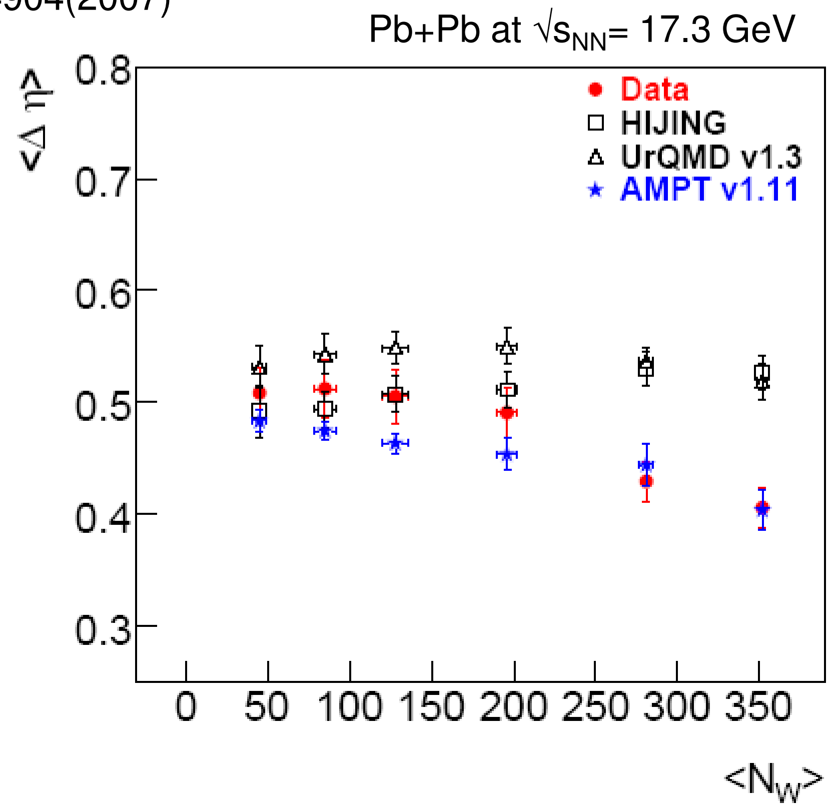


data compared to shuffled events: $W = (\langle\Delta\eta\rangle_{shuff} - \langle\Delta\eta\rangle_{data}) / \langle\Delta\eta\rangle_{shuff} \cdot 100$
(scrambling of rapidities, retention of global charge conservation)

BF: model comparisons at mid-rapidity

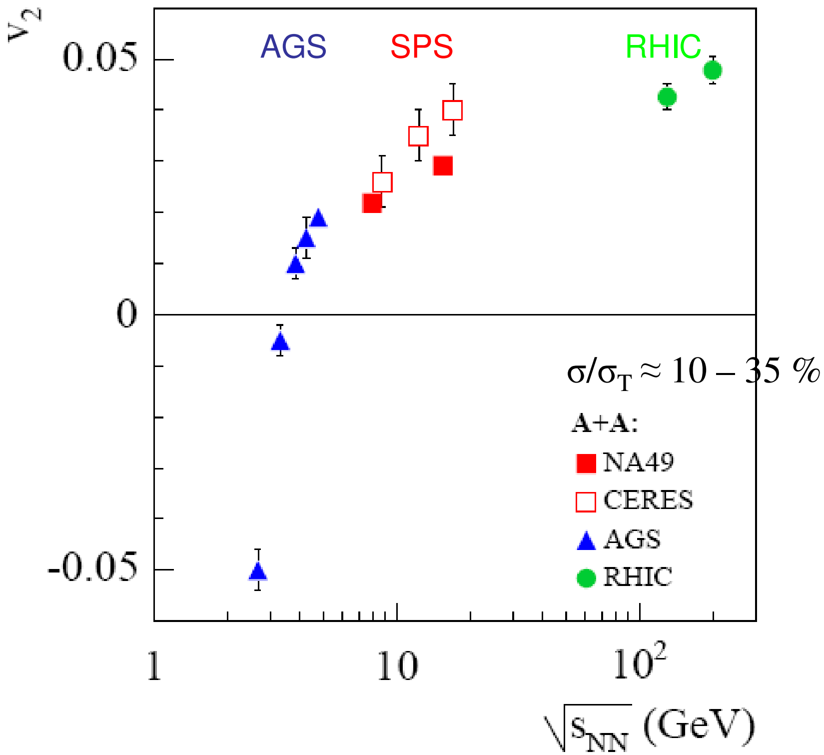
PRC75,064904(2007)





- 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



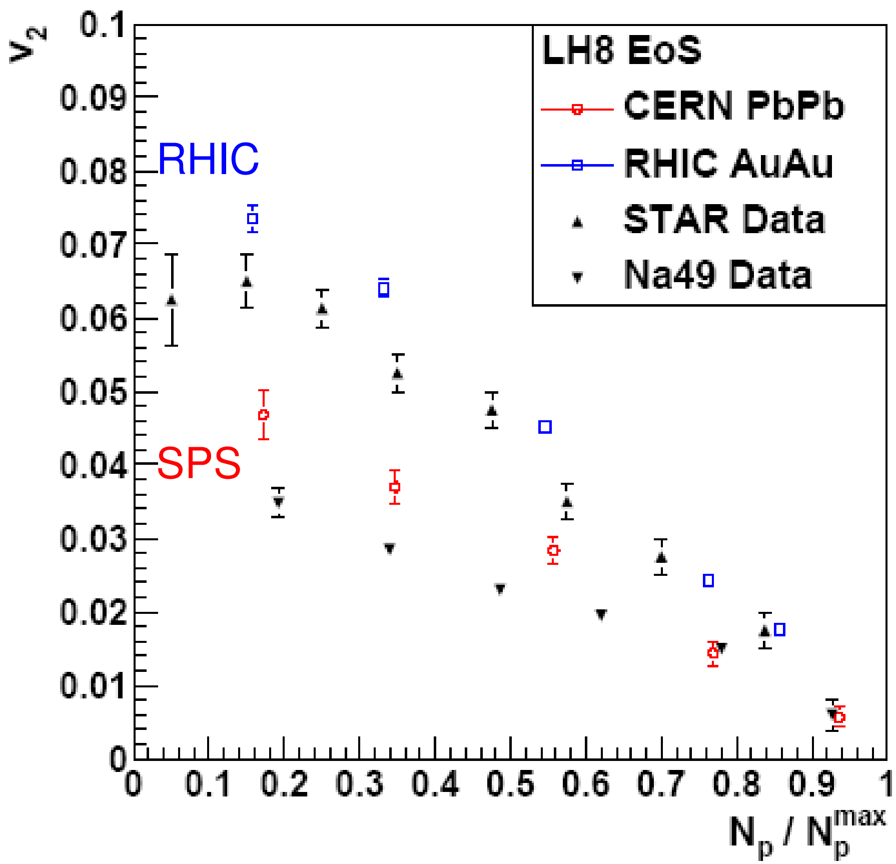
- change from out-of-plane (shadowing) to in-plane (hydro) at AGS
- rate of increase of v_2 slows between AGS and SPS
- steady rise from SPS to RHIC

  (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