Search for the Critical Point of Strongly Interacting Matter at the CERN-SPS

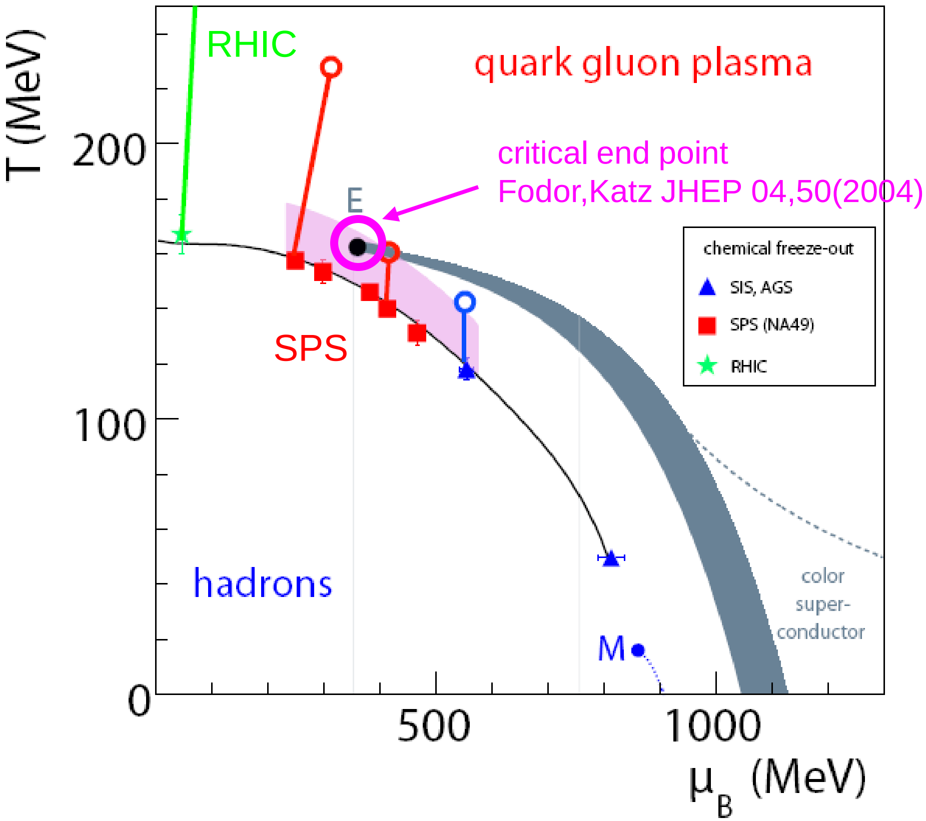
P. Seyboth
Max-Planck-Institut für Physik, München
and
Jan Kochanowski University, Kielce

Results: NA49 Future: SHINE NA61

Outline

- introduction: exploring the phase diagram of strongly interacting matter
- reminder on onset of deconfinement at SPS energies
- search for the critical point at the SPS
  - discussion of present results from NA49
  - NA61/SHINE – successor and extension of NA49
- conclusions

Exploration of phase diagram of strongly interacting matter



only central collisions are considered here

- QCD considerations suggest a 1^{st} order phase boundary ending in a critical point

- hadro-chemical freeze-out points are obtained from statistical model fits to measured particle yields
- T and μ_B approach phase boundary and estimated critical point at SPS

- evidence of onset of deconfinement from rapid changes of hadron production properties
- search for indications of the critical point as a maximum in fluctuations

evidence for the onset of deconfinement (1)

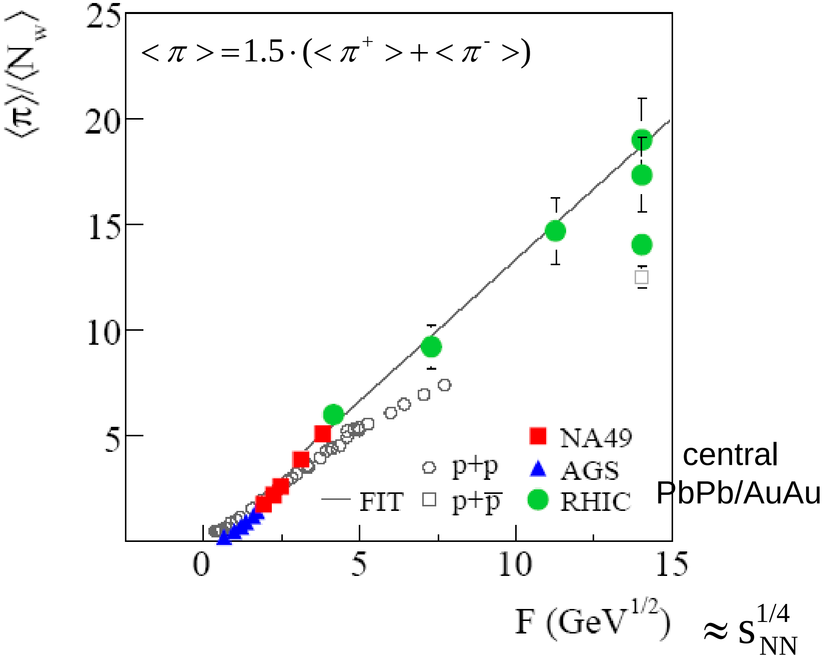
the kink

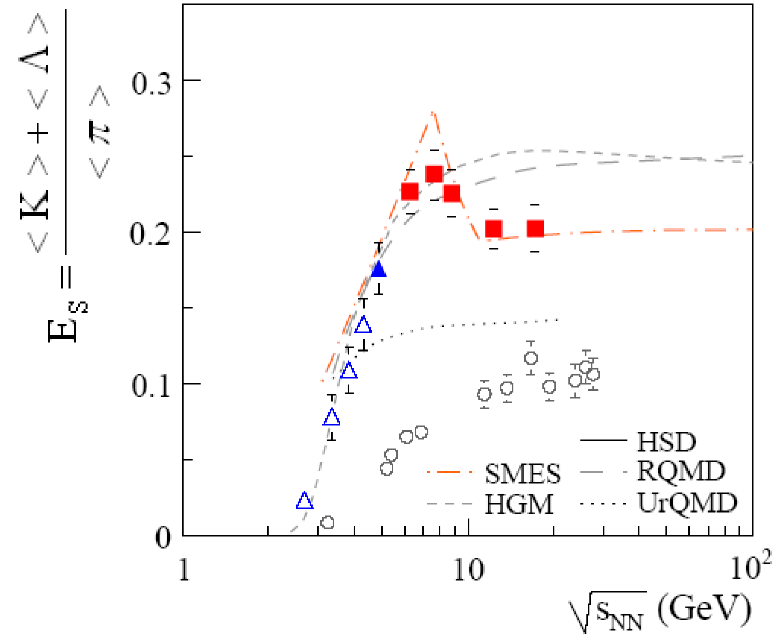
pion yield per participant

the horn

ratio of strange particle to pion yield

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





- π yield related to entropy production
- steeper increase in A+A suggests 3-fold increase of initial d.o.f

- E_s related to strangeness/entropy ratio
- plateau consistent with prediction for deconfinement

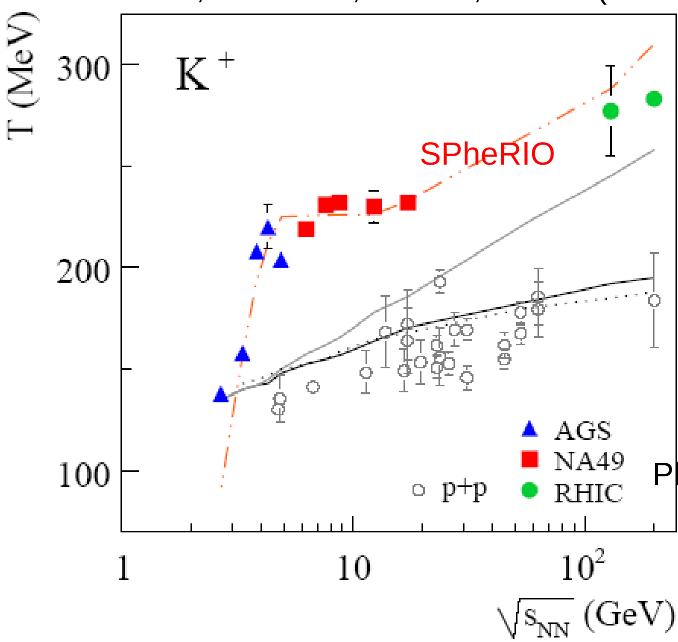
(SMES model, M.Gazdzicki and M.Gorenstein, Acta Phys. Pol.30,2705(1999))

evidence for the onset of deconfinement (2)

the step

shape of transverse mass spectra

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

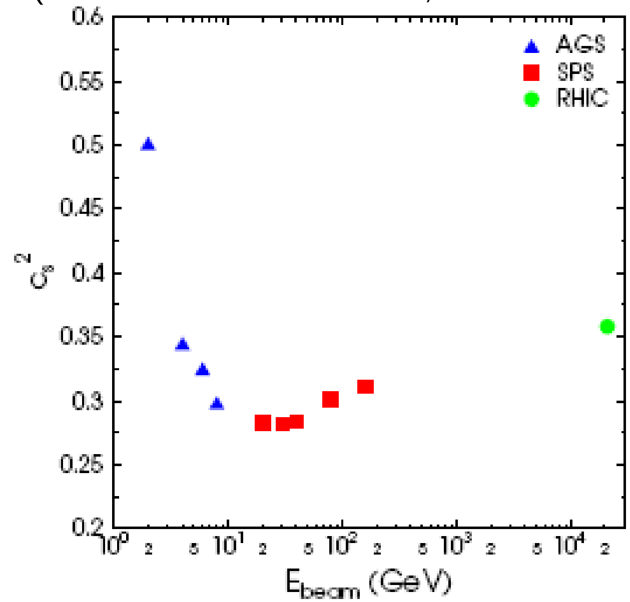


central PbPb/AuAu

the dale

estimate of sound velocity

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

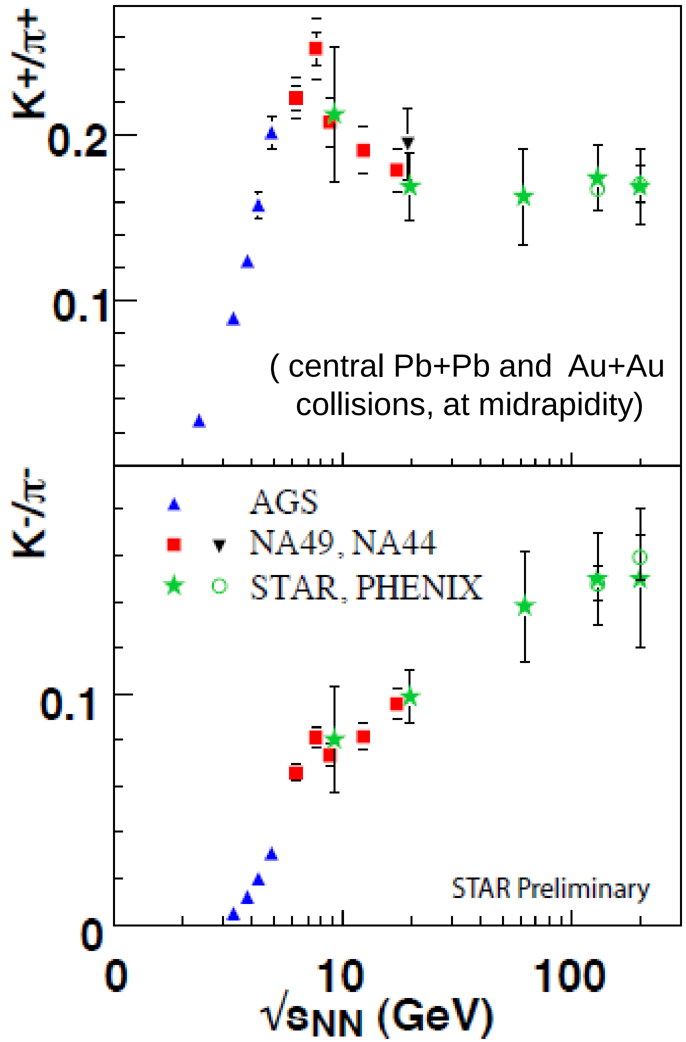


softening of transverse (step) and longitudinal (minimum of c_s) features of EoS due to mixed phase (soft point of EoS)

rapid changes of hadron production properties at low SPS energy most naturally explained by onset of deconfinement

NA49,C.Alt et al.,PRC77,024903(2008); M.Gazdzicki et al.,arXiv:1006.1765

Verification of the NA49 results by STAR in progress

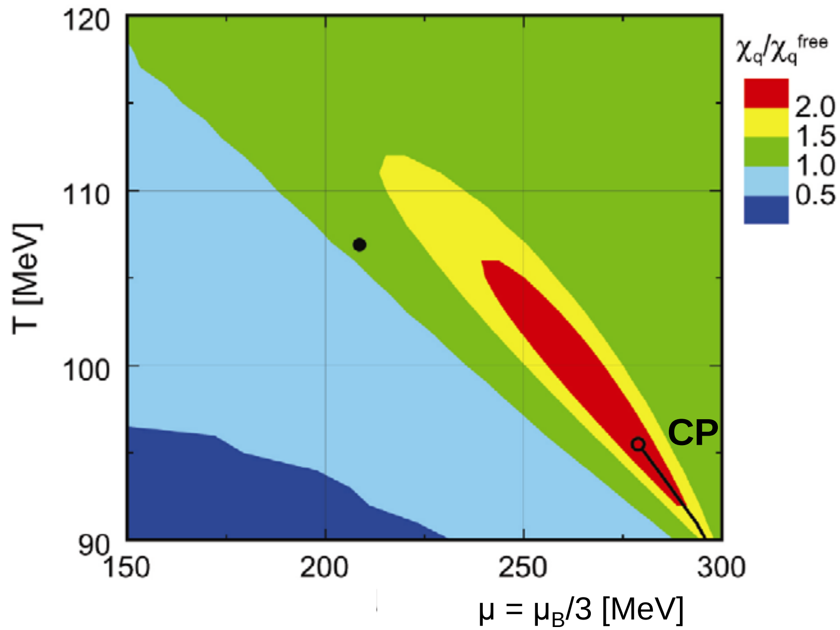


- presently available low statistics results from STAR compatible with NA49
- precise results from 2010 low energy run soon

Search for the critical point at the SPS

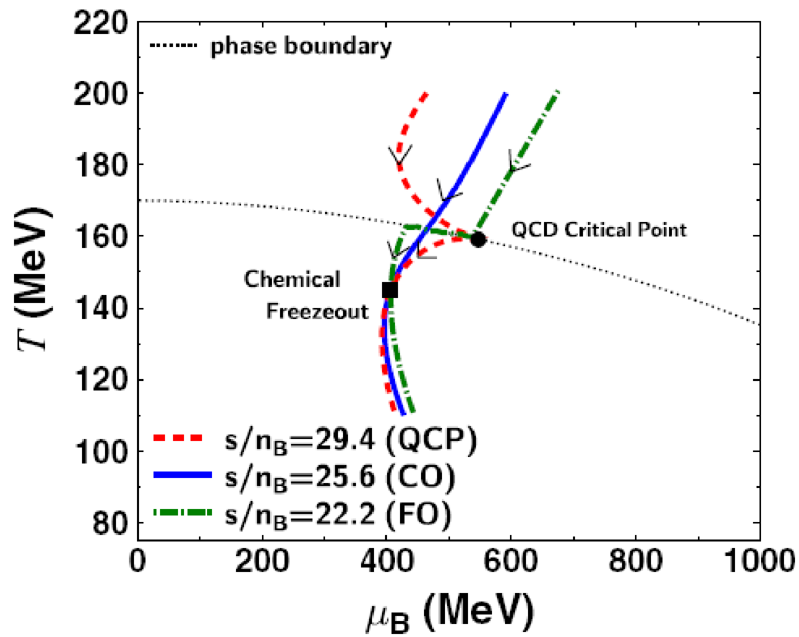
signature: enhanced fluctuations of multiplicity, p_T, …

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



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

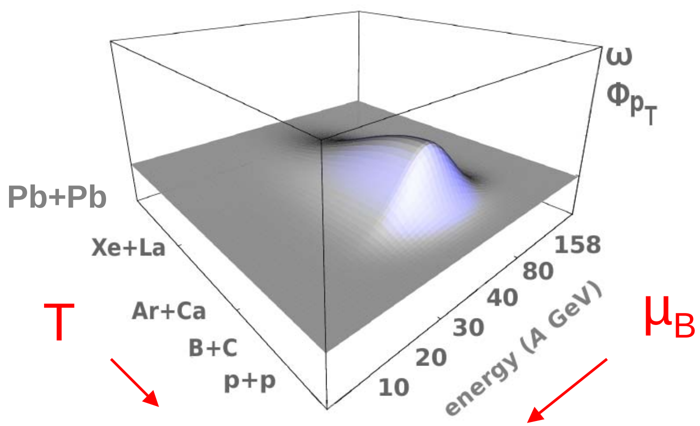
hydro predicts that evolution of the system is attracted to critical point

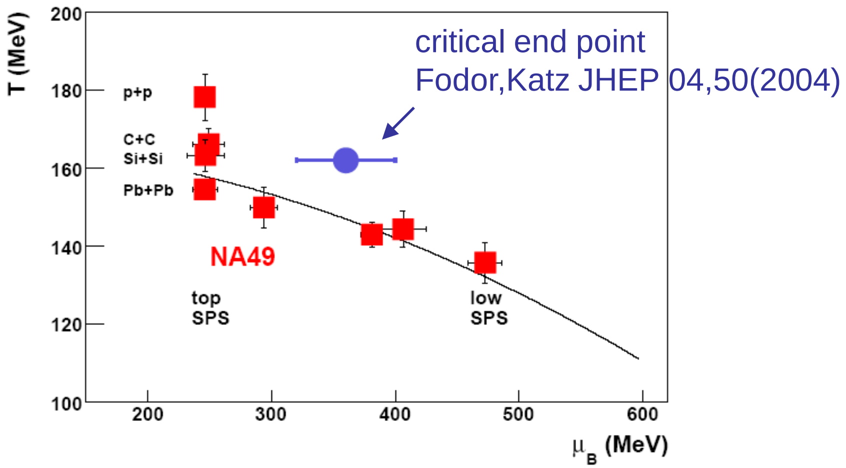


M.Asakawa et al.,
PRL 101,122302 (2008)

Search strategy of NA49 and NA61

search for “hill” in fluctuation signals
in 2d scan (T,μ_B) of phase diagram





- deconfinement necessary for observing CP effect (above 30A GeV)
- freeze-out occurs close to the critical point
- expected size of fluctuation signals ($\sim\xi^2$) limited by short lifetime and size of collision system (correlation lengths ~ 3 – 6 fm for Pb+Pb)

(M.Stephanov, K.Rajagopal,E.Shuryak, PRD60,114028(1999))

- can fluctuation signals survive later fireball evolution ??

Fluctuation measures studied by NA49

- scaled variance ω of the multiplicity distribution P(n)

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

- intensive fluctuation measure
- independent particle emission: ω = 1
- superposition model: $\omega(A+A)=\omega(N+N)+<N_{part}>\omega_{part}$
- ω sensitive to fluctuations of N_{part}

- Φ_x measure of fluctuations of observable x ($<p_T>$, $<\Phi>$, Q, …)

$$\Phi_x = \sqrt{\frac{<Z^2>}{<N>}} - \sqrt{<z^2>} \; ;$$

$$z = x - <x> \, ,$$

$$Z = \sum_{i=1}^{N} (x_i - <x>)$$

M.Gazdzicki and S.Mrowczyski, Z.Phys.C54,127(1992)

- superposition model: $\Phi_x(A+A) = \Phi_x(N+N)$
- independent particle emission: $\Phi_x = 0$
- Φ_x strongly intensive fluctuation measure independent of $<N_{part}>$ and its fluctuations

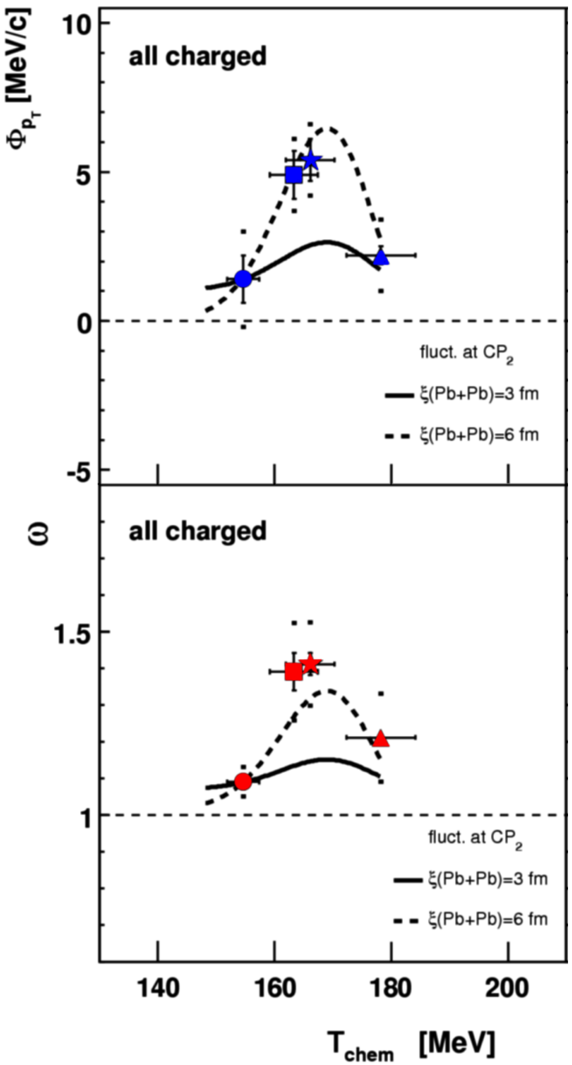
- σ_{dyn} measure of dynamical particle ratio fluctuations (K/π, p/π, K/p)

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

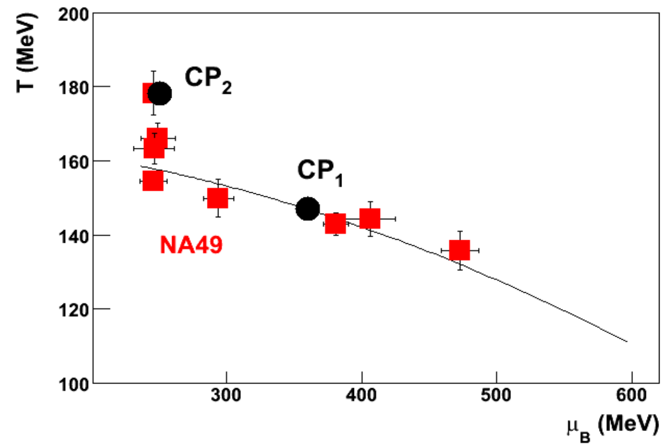
- e-by-e fit of particle multiplicities required in NA49
- mixed events used as reference
- $1/N_{part}$ dependence   Koch,Schuster PRC81,034910

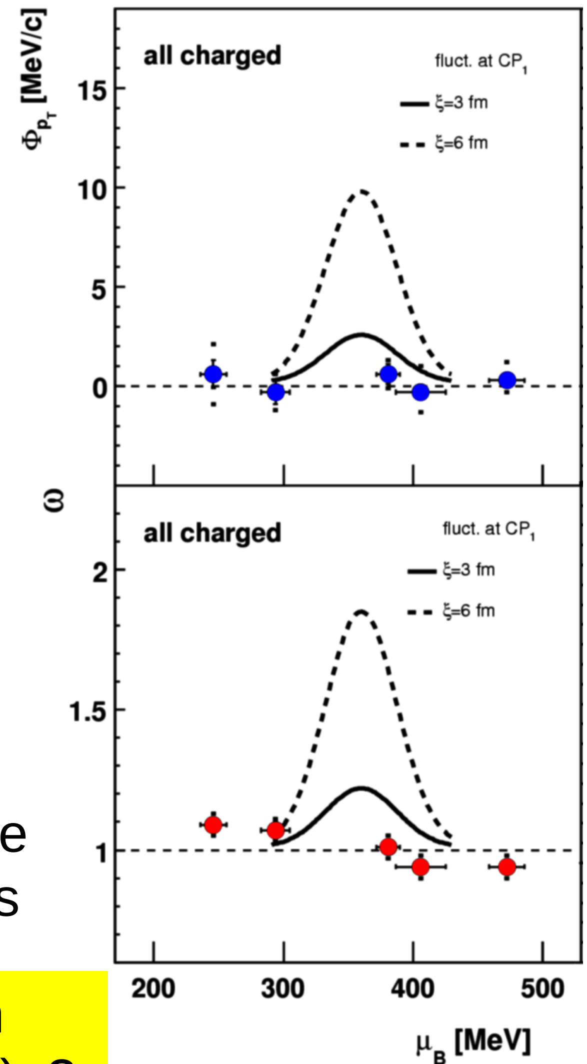
- Intermittency in low mass $\pi^+\pi^-$ pair density fluctuations in p_T space

results of critical point search from NA49



T.Anticic et al., PRC70, 034902 (2004)
C.Alt et al., PRC75, 064904 (2007)
C.Alt et al,. PRC78, 034914 (2008)
T.Anticic et al., PRC79, 044904 (2009)
B.Lungwitz, NA49 thesis (2008)





smooth energy dependence
in central Pb+Pb collisions

hint of peak at 158A GeV in
nuclear size dependence (T) ?

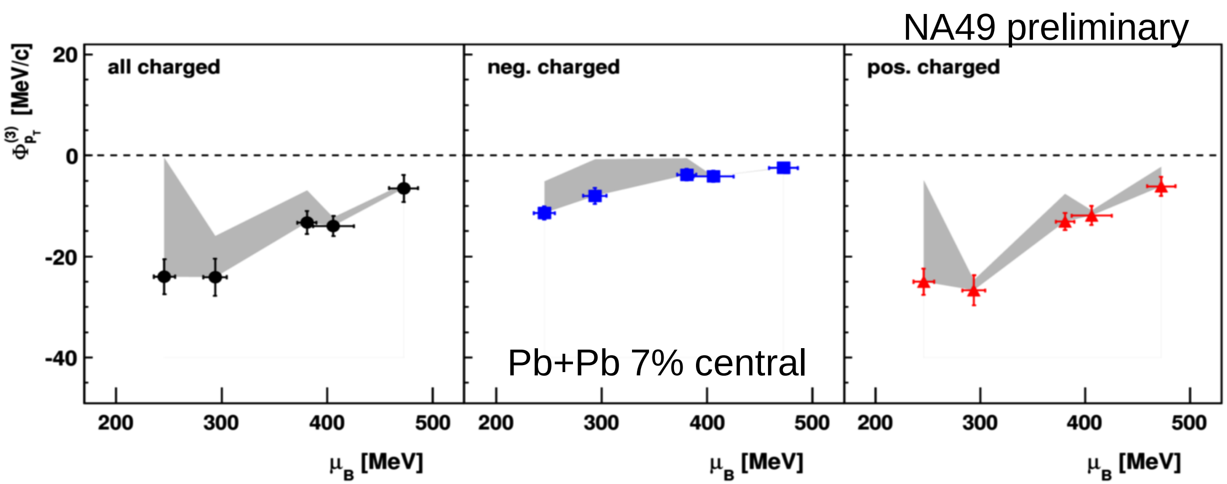
$\Phi_{p_T}^{(3)}$: 3rd moment of <p_T> fluctuations

K.Grebieszkow and M.Bogusz, NA49 preliminary

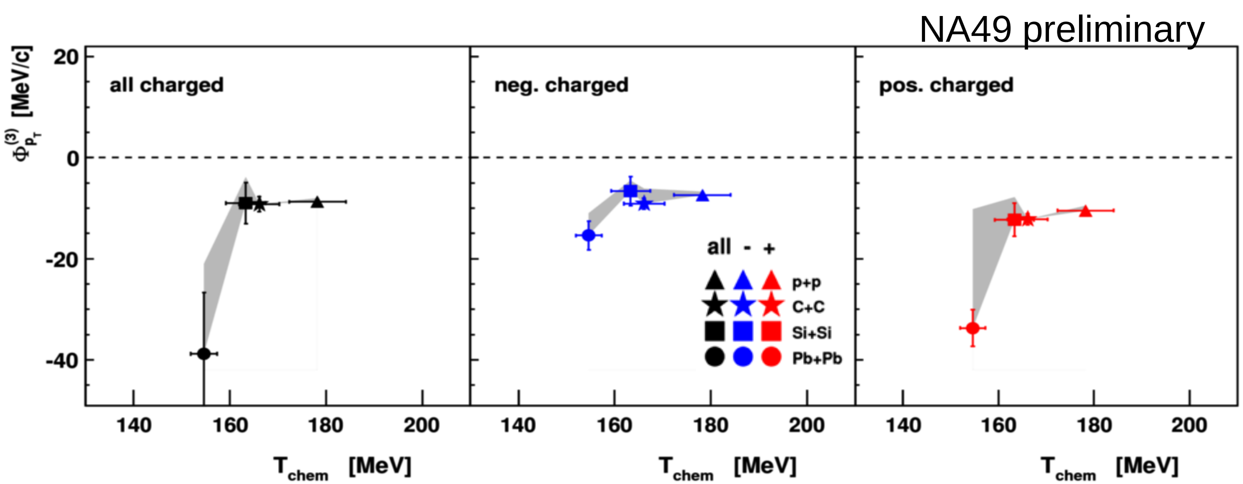
$$\Phi_{p_T}^{(n)} = \left(\frac{\langle Z_{p_T}^{2} \rangle}{\langle N \rangle}\right)^{1/n} - \left(\overline{z_{p_T}^{n}}\right)^{1/n}$$

$\Phi_{pT}^{(3)}$ has strongly intensive property like Φ_{pT}

(S.Mrowczynski,Phys.Lett.B465,8(1999))



higher moments are expected to be more sensitive to fluctuations



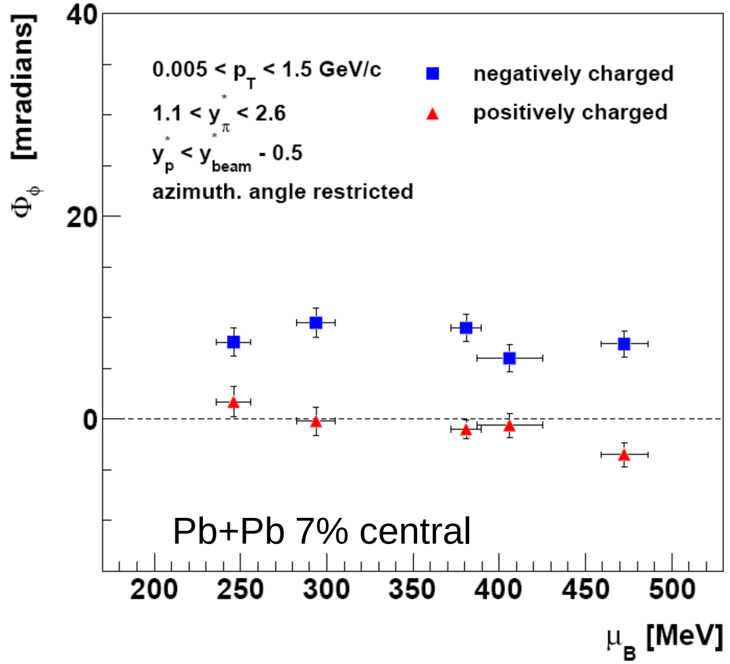
systematic errors are large

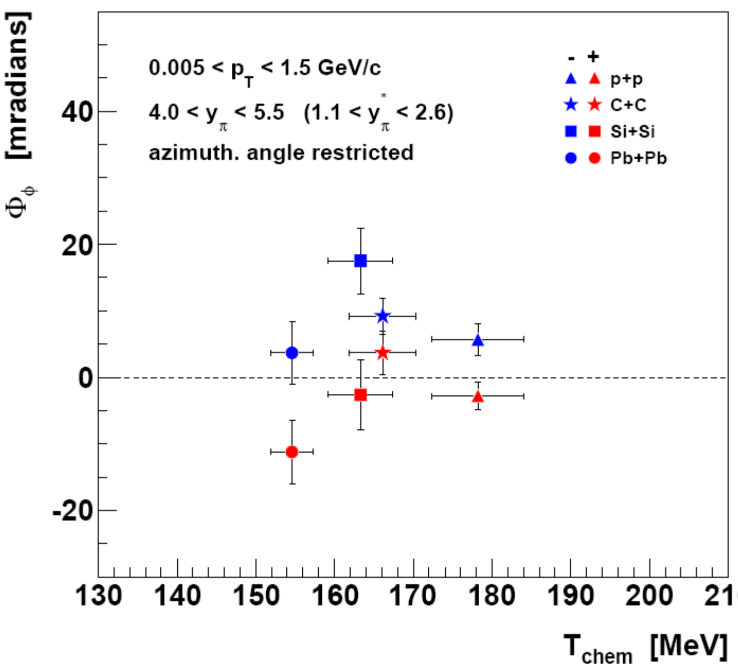
no theoretical predictions yet

Φ_ϕ : fluctuations of average azimuthal angle

K.Grebieszkow, NA49 preliminary

- plasma instabilities (S.Mrowczynski, Phys.Lett. B314,118(1993))
- flow fluctuations (S.Mrowczynski,E.Shuryak,Act.Phys.Pol.B34,4241(2003))
- onset of deconfinement, critical point





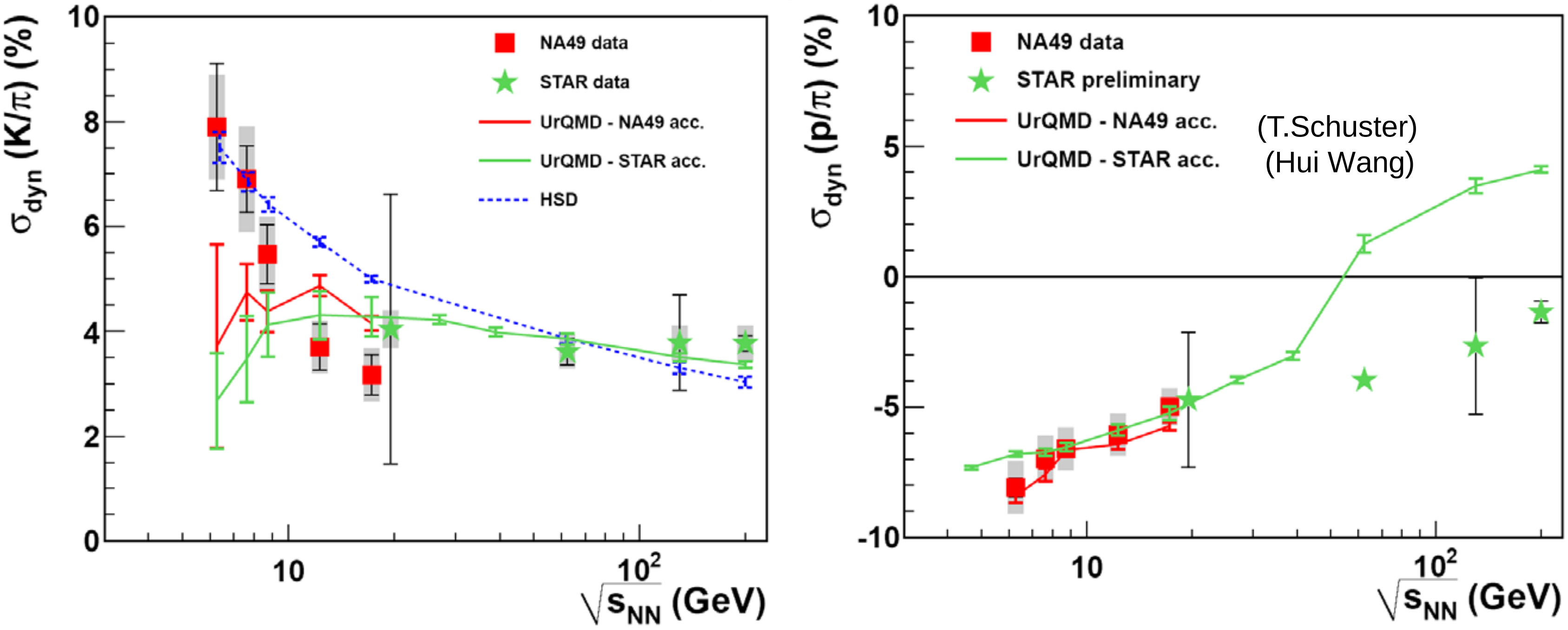
- no significant energy (μ_B) dependence in central Pb+Pb collisions
- perhaps hint of maximum in nuclear size (T) dependence

Event-by-event particle ratio fluctuations: K/π, p/π

E-by-E fit of particle ratios to dE/dx spectra in real and mixed events

$$\sigma_{dyn} = \text{sign}(\sigma^2_{data} - \sigma^2_{mix})\sqrt{|\sigma^2_{data} - \sigma^2_{mix}|} \quad ; \quad \sigma^2_{dyn} \approx |\nu_{dyn}|$$

NA49 results: PRC79,044910(2009) for 3.5 % most central Pb+Pb collisions



positive, rise towards low √s
multiplicity effect ? deconfinement ?

negative, slow rise towards high √s
effect of nucleon resonances

Koch et al.PRC81,034910 Gorenstein et al.,PLB585,237

Event-by-event particle ratio fluctuations: K/p

Koch et al.,PRL95,182301(2005)

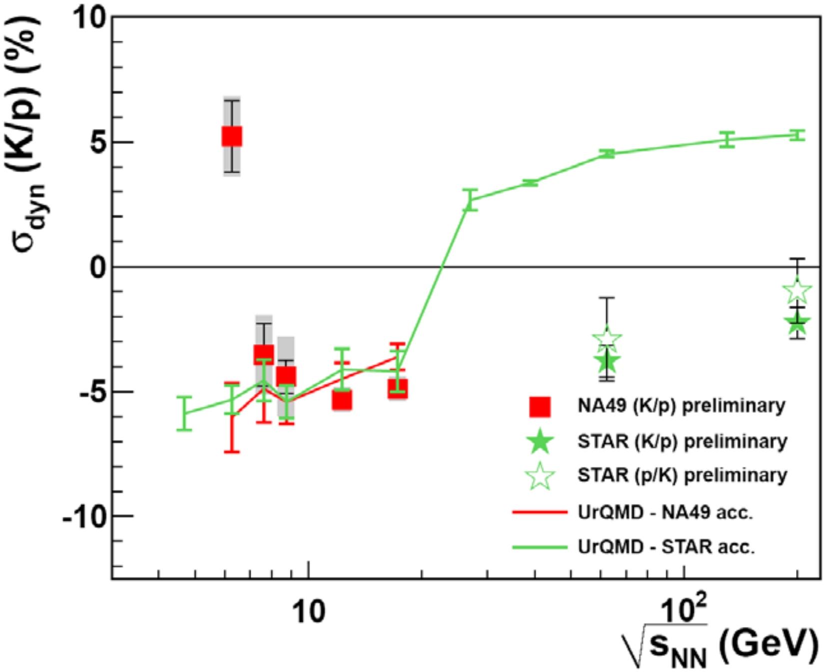
K/p fluctuations probe correlation of baryon number B and strangeness S

hadron gas: production of S unrelated to B is allowed (Kaons)

deconfined: S produced in conjunction with B (quarks)

Correlation coefficient C_{BS} can be estimated, precise relation to σ_{dyn} ?

T.Schuster, NA49 preliminary



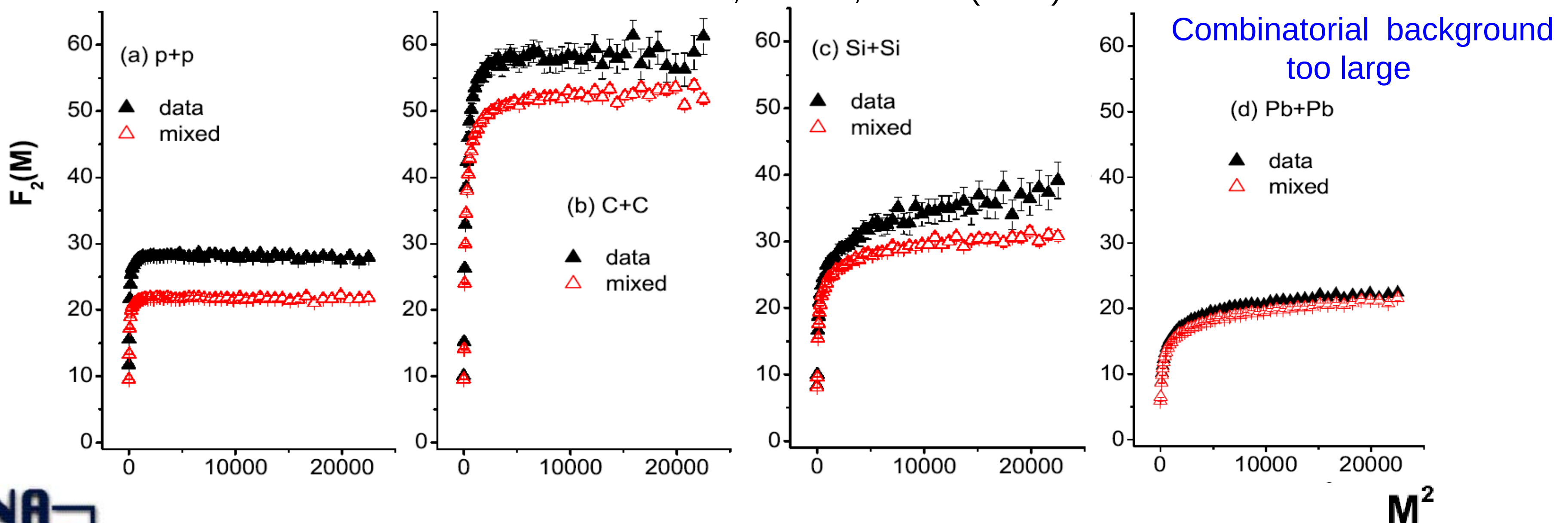
- sign change at low √s
- $1/N_k$ scaling ruled out
- related to onset of deconfinement ?

Intermittency analysis of particle density fluctuations

N.Antoniou et al., NPA693,799(2001); PRL97,032002(2006)

- at the critical point local density fluctuations with power-law singularity expected both in configuration and momentum space
  - σ field: density of σ particles, related to low-mass $\pi^+ \pi^-$ pairs
  - baryonic density: related to net baryon number (≈ protons)
- exp.observation via factorial moments in p_T space: $\Delta F_2(M) \propto M^{2\phi_2}$
  predicted intermittency index φ_2 = 2/3, 5/6
- use π+π- pairs near threshold to reduce combinatorial background
- estimate combinatorial background by mixed events and subtract

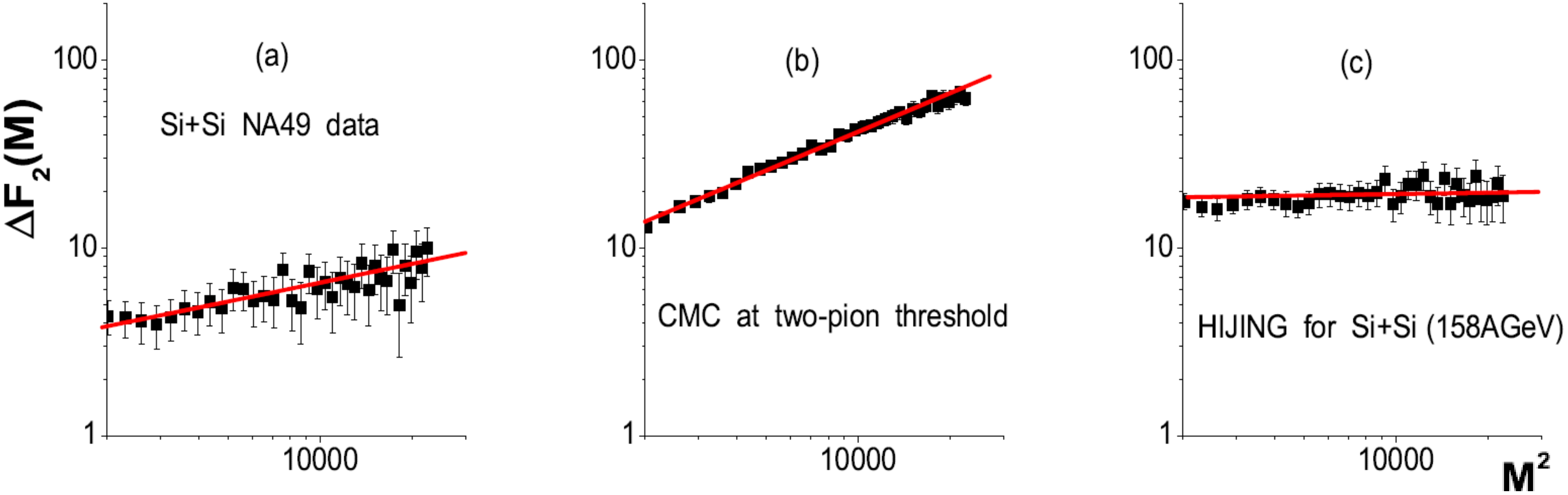
NA49 results at 158A GeV: T.Anticic et al, PRC81,064907(2010)



low mass $\pi^+\pi^-$ pair density: 2d intermittency in p_T space

NA49 results on factorial moment ΔF_2 in central Si+Si collisions

$$\Delta F_2(M) \propto M^{2\phi_2}$$

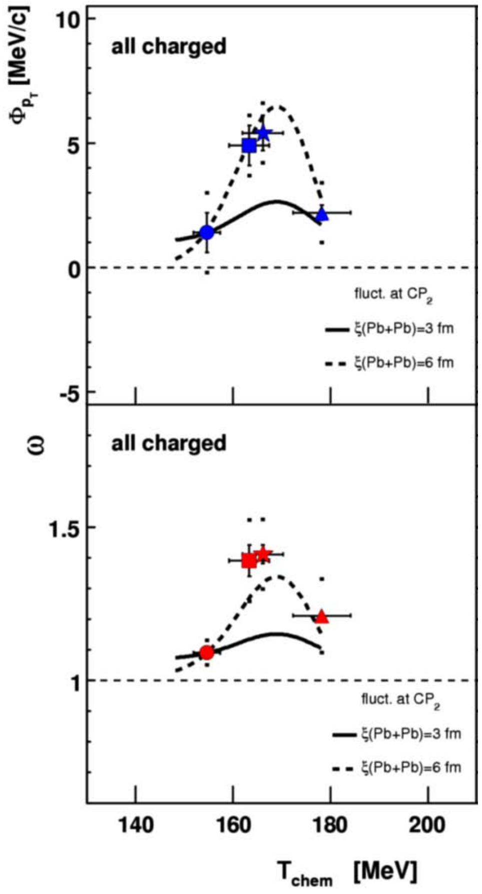


$\Phi_2 \approx$ 0.34 ± 0.04 | 0.67 ± 0.01 | 0.02 ± 0.09

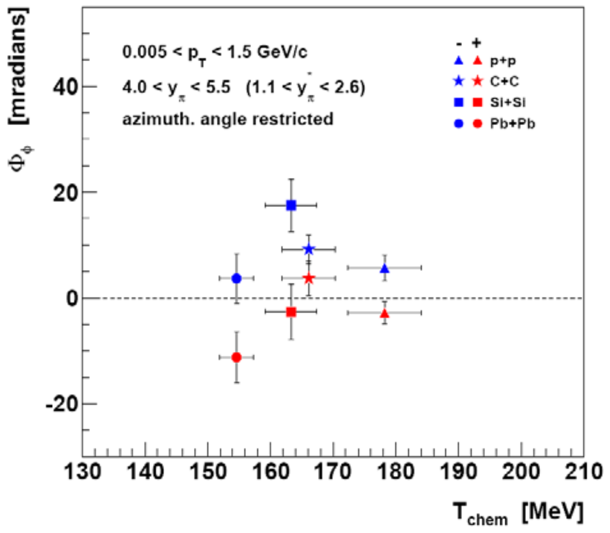
indications for an intermittency signal in Si+Si collisions at 158A GeV

proton intermittency analysis in progress

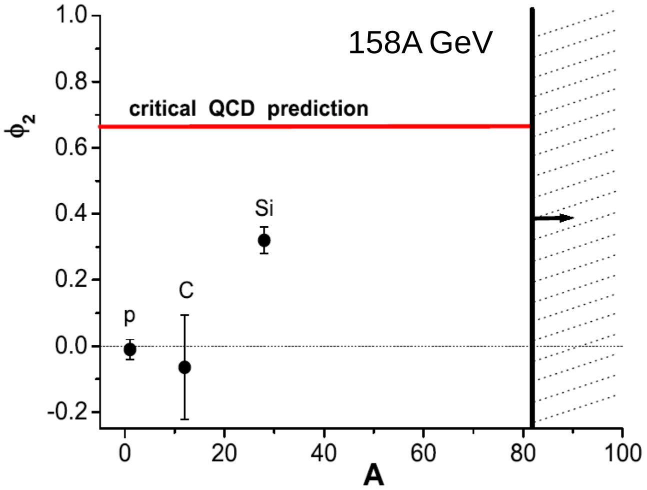
Conclusion from the critical point search in NA49



preliminary



T.Anticic et al.,PRC81,064907(2010)

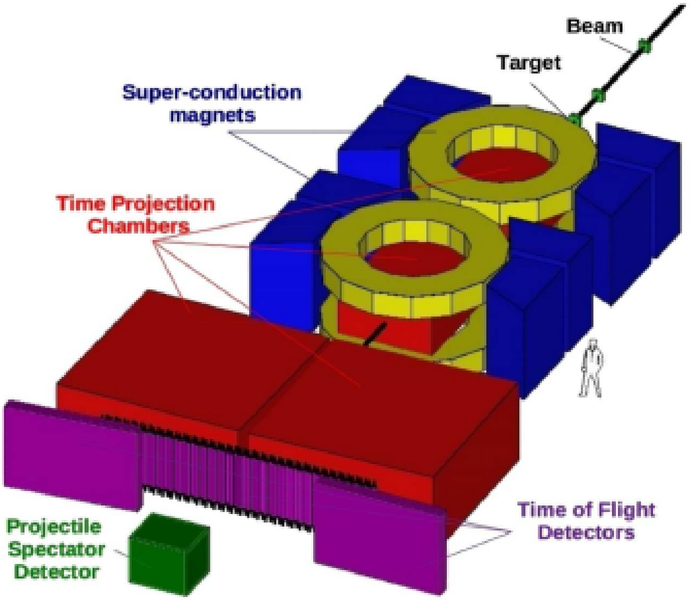


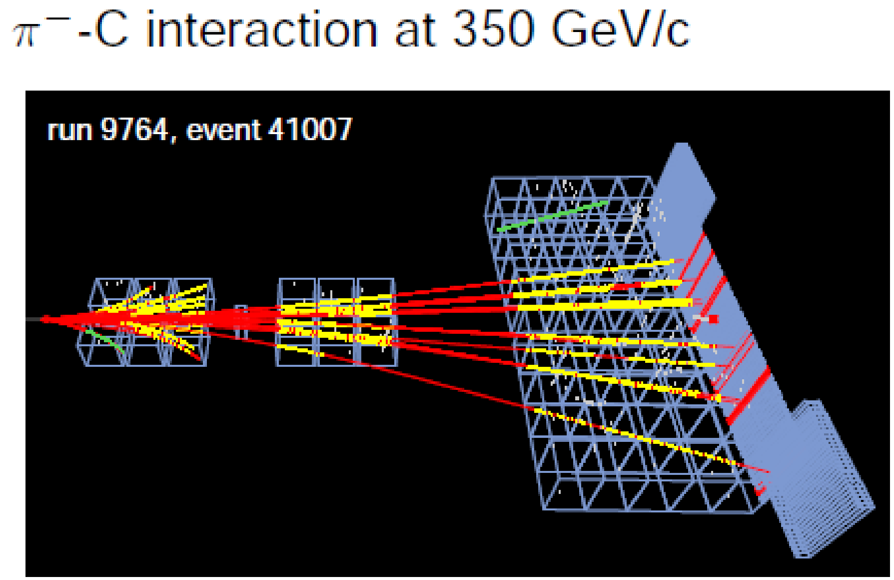
fluctuations of $<p_T>$, N_{ch}, $<\Phi>$, density of σ tend to a maximum in Si+Si collisions at 158A GeV

first hint of the hill of fluctuations ??

NA61/SHINE – successor and extension of NA49

(**SHINE – S**PS **H**eavy **I**on and **N**eutrino **E**xperiment)

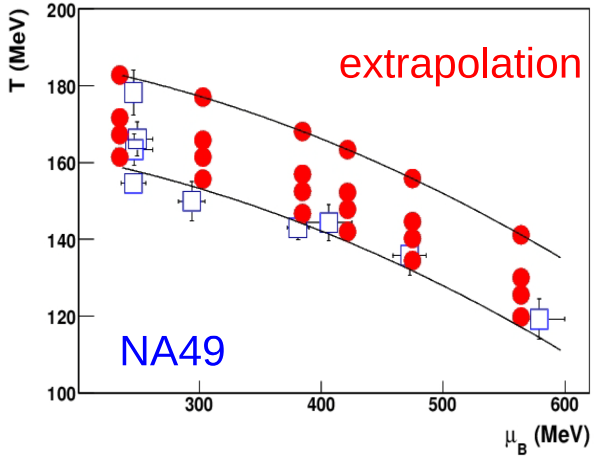


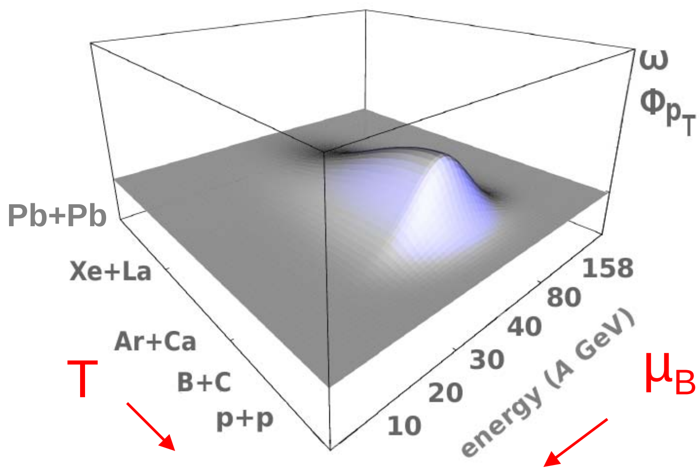


- study of the onset of deconfinement and search for the critical point
- precision particle production measurement for improving calculations of T2K neutrino beam and air shower properties (P.Auger,KASKADE)
- study of nuclear modification factor and Cronin effect using p+p and p+Pb interactions with extended range in $p_T \leq 4.5$ GeV/c

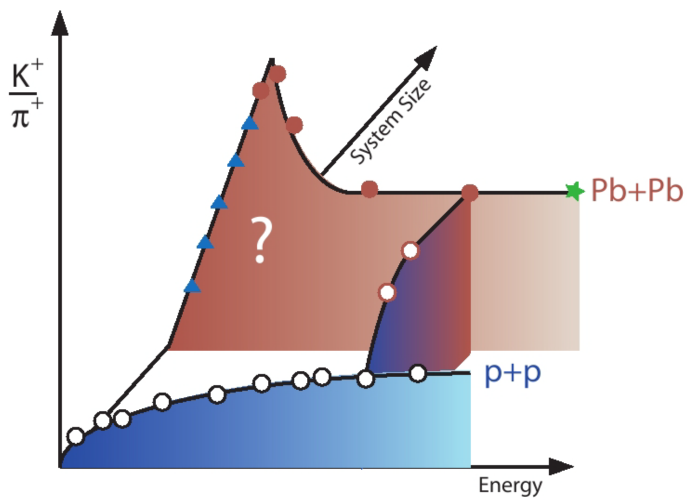
Ion physics program of NA61/SHINE: scan in energy and system size A

search for hill of fluctuations as signature of critical point

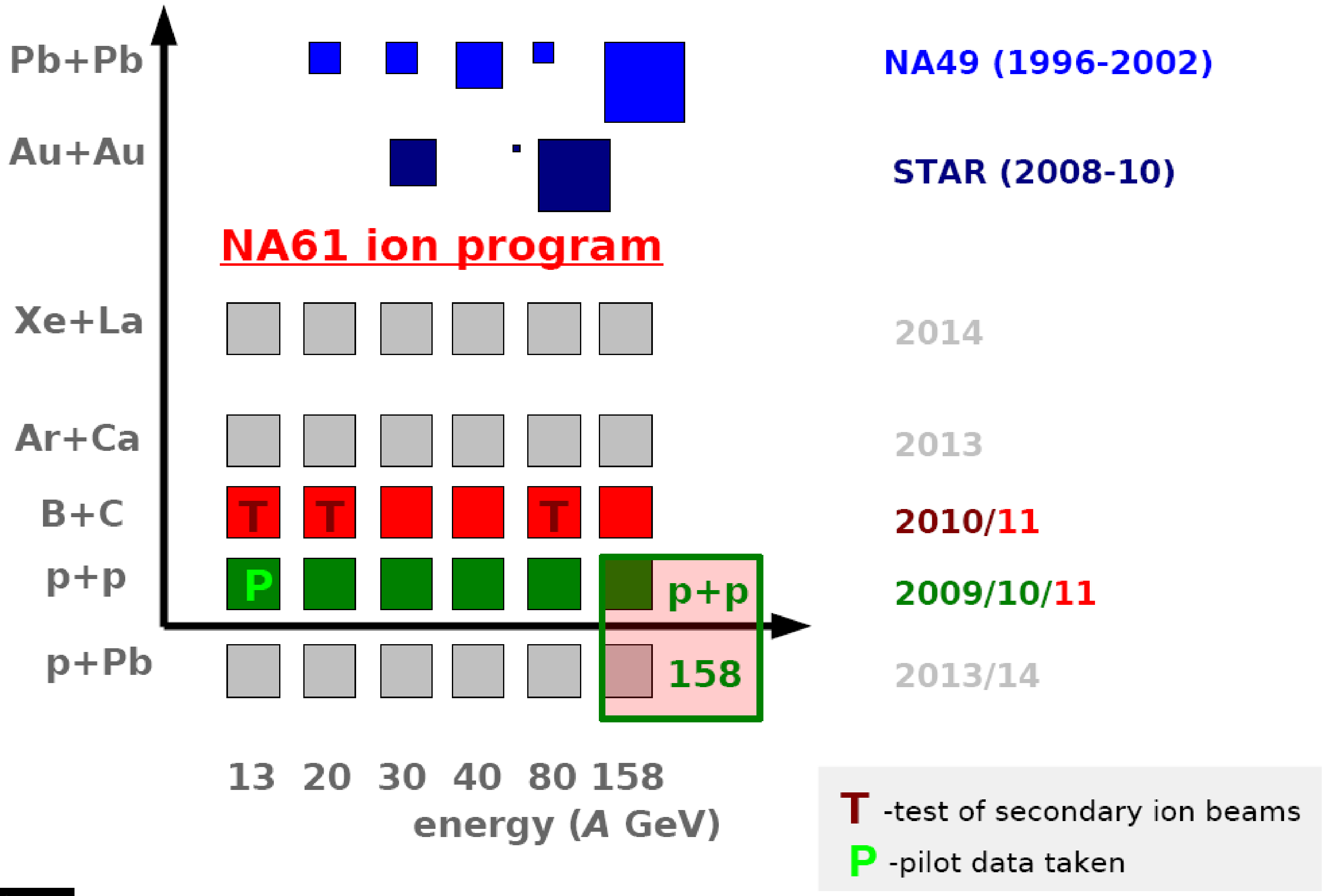




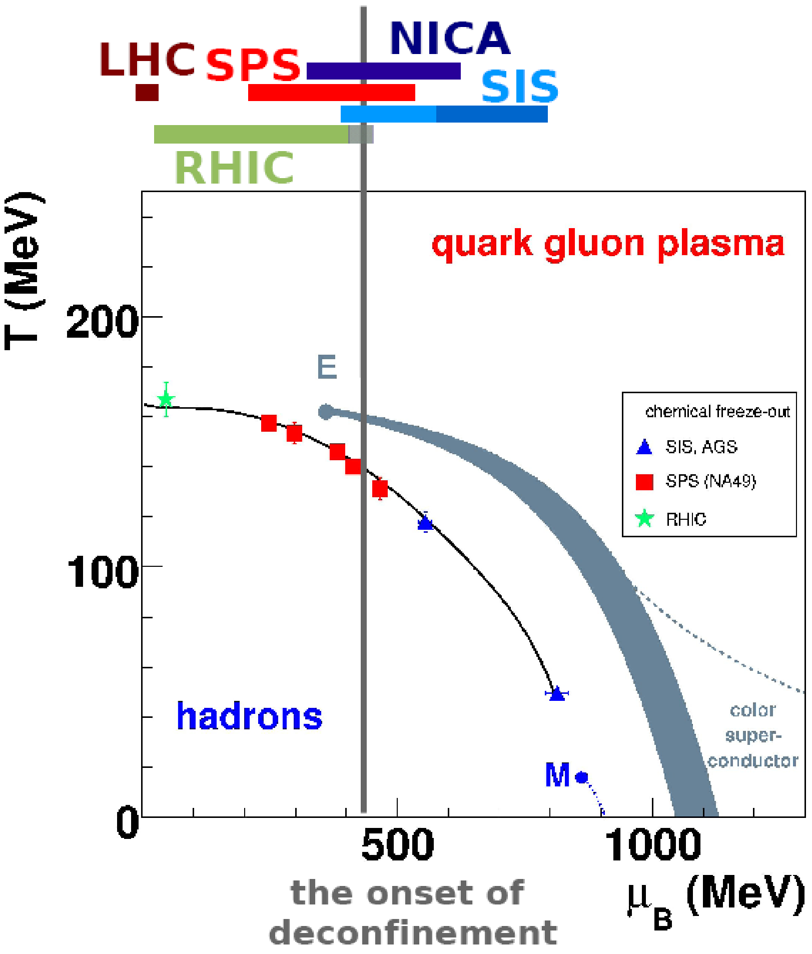
study onset of deconfinement: disappearance of horn etc.



Status and plans for ion collisions at SPS energies



QCD critical point searches – future experimental landscape



partly complementary programs

CERN SPS 2011
BNL RHIC 2010
DUBNA NICA 2016 ?
GSI SIS-CBM 2017 ?

strong points of NA61:

- tight constraint on spectators
- high event rate at all SPS energies
- flexibility to change A and energy
- overlap with AGS energy
- coverage of full forward hemisphere

strong points of BNL/STAR:

- full azimuthal acceptance
- acceptance unchanged with energy
- excellent TOF identification
- low track density

Conclusions

- evidence for onset of deconfinement at SPS energies – check in progress by STAR low energy scan at RHIC

- critical point predicted to be accessible at SPS energies

- 2D scan of fluctuations in μ_B,T phase diagram started by NA49 and is continuing in NA61/SHINE

- hints of a maximum of fluctuations for Si+Si at 158A GeV → strong motivation for NA61/SHINE program

- looking forward to STAR results from RHIC low energy scan wish success to future programs at NICA and CBM/FAIR

Backup Slides

Landscape of heavy ion experimental programs

Facility	SPS	RHIC	NICA	SIS-100 (SIS-300)	LHC
Laboratory	CERN Geneva	BNL Brookhaven	JINR Dubna	FAIR GSI Darmstadt	CERN Geneva
Exper.	NA61/SHINE	STAR PHENIX	MPD	HADES, CBM	ALICE ATLAS CMS
Start	2009(11)	2010	2016	2017 (2019)	2009
cms energy [GeV/(N+N)]	5.1 – 17.3	7.7 (6.3?) – 39	4 – 11	2.3 – ~5 (~5 – 8.5)	5500 14000 (p+p)
Physics	CP & OD	CP & OD	OD & HDM	HDM (OD & CP)	PDM

Estimates of effects due to the critical point

correlation length ξ at the critical point not divergent but limited by finite size and lifetime of the fireball

parameterization: $\xi = \min(c_1 A^{1/3} ,\ c_2 A^{1/9})$ (M.Stephanov, private comm.)

size lifetime

suggesting $\xi(\text{Pb+Pb}) = 3 \rightarrow 6$ fm

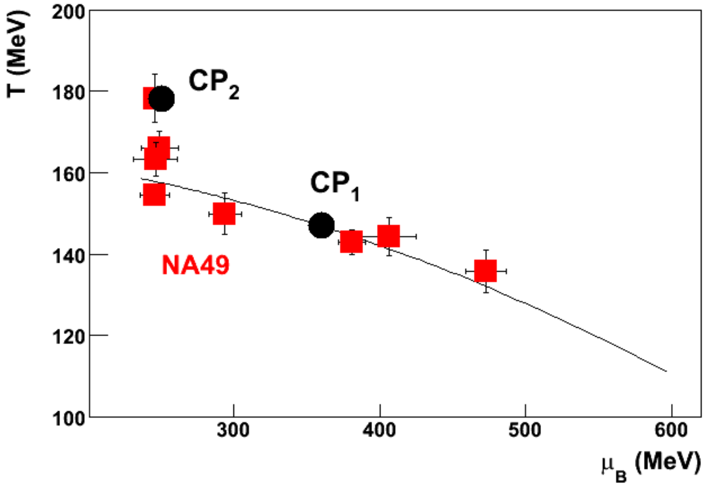
$\xi(\text{p+p}) = 1 \rightarrow 2$ fm

range of correlation effect estimated from QCD calculations:

$\sigma(\mu_B) = 30$ MeV, $\sigma(T) = 10$ MeV

(Hatta,Ikeda,PRD67,014028(2003)

freeze-out points from
Becattini et al, PRC73, 044905 (2006)

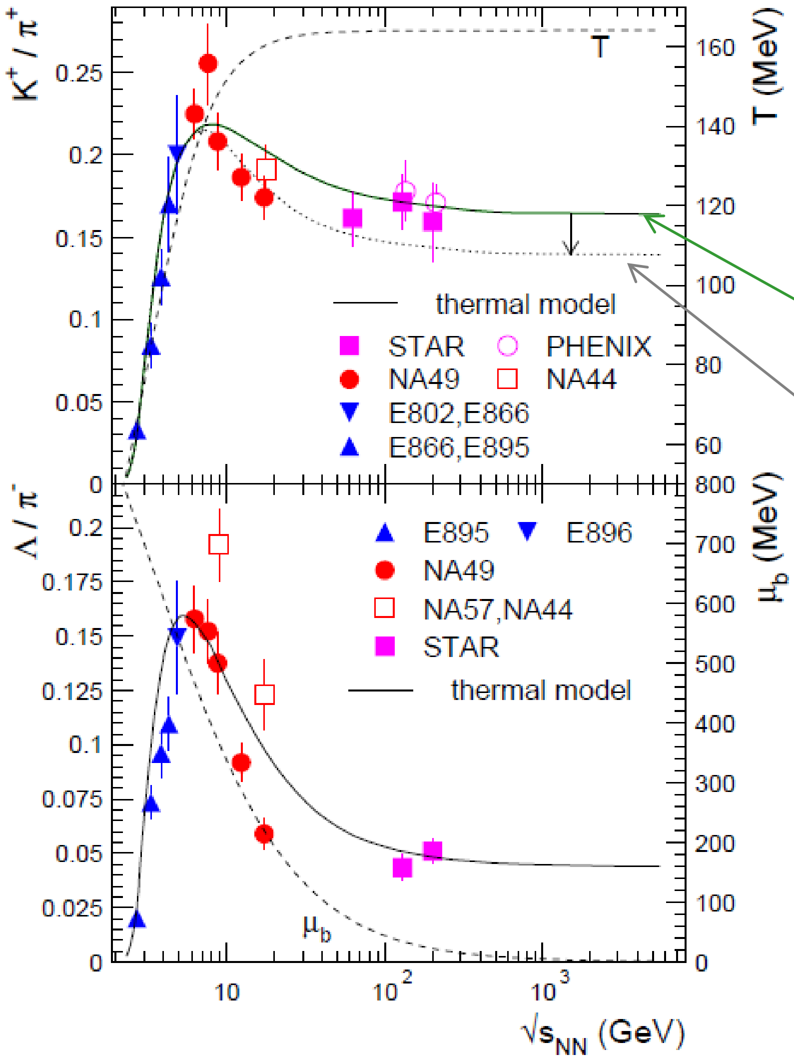


considered examples:

- μ_B= 360 MeV (lattice QCD,Fodor-Katz)
  T = 147 MeV (chem. freeze-out line)
- μ_B= 250 MeV (data 158A GeV)
  T = 178 MeV (fit of p+p data)

Statistical hadron gas model with additional assumptions

ratios at midraidity



recent extension of statistical hadron gas model

Andronic, Braun-Munzinger, Stachel, PLB 673,142 (2009)

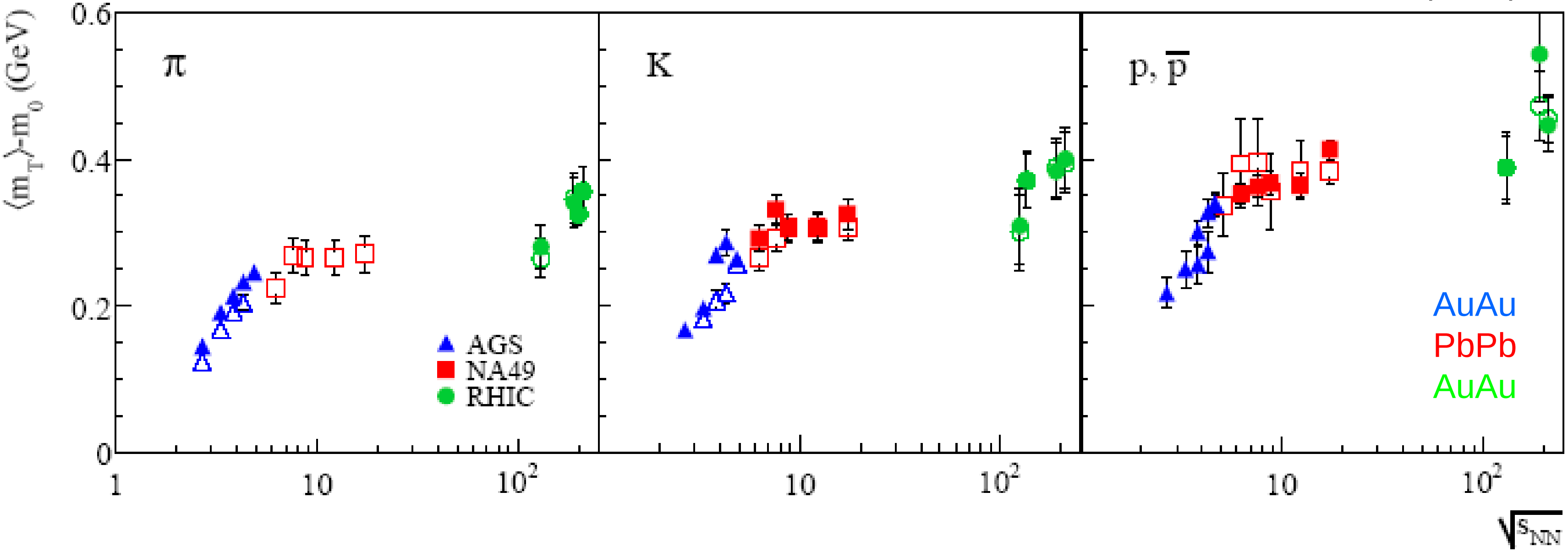
full PDG high mass spectrum

Further extension with exponential mass spectrum

"Our results imply that hadronic observables near and above the 'horn' structure … provide a link to the QCD phase transition"

Plateau of average transverse mass

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

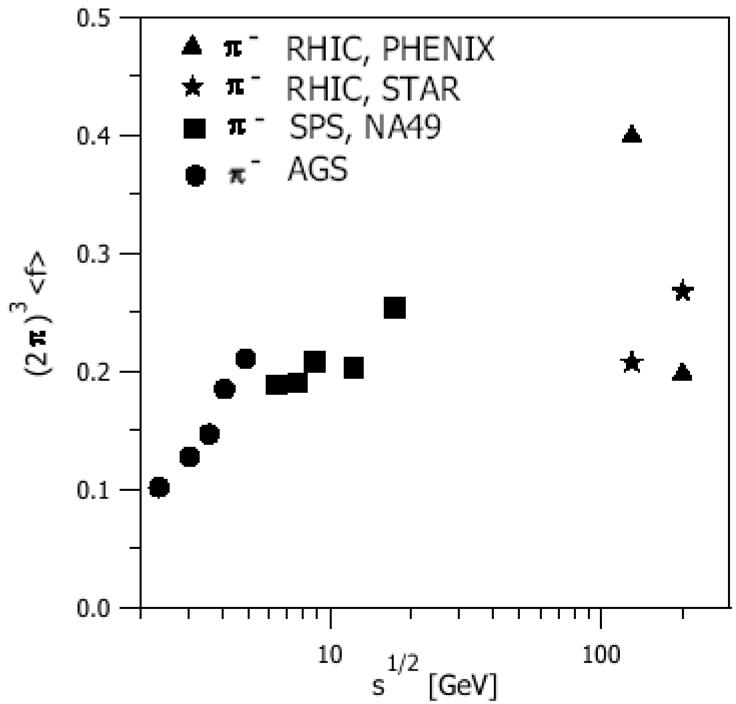


- Increase of $<m_T>$ for abundant final state particles (π, K, p) slows sharply at the lowest SPS energy

- 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)

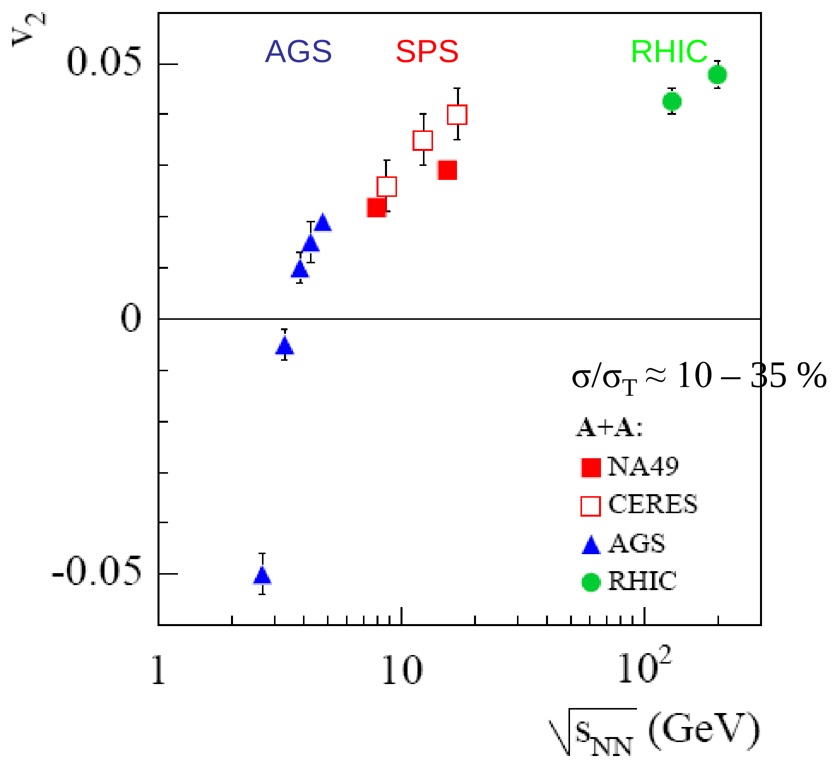
Phase space density from m_T spectra and BE correlations of π^-



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

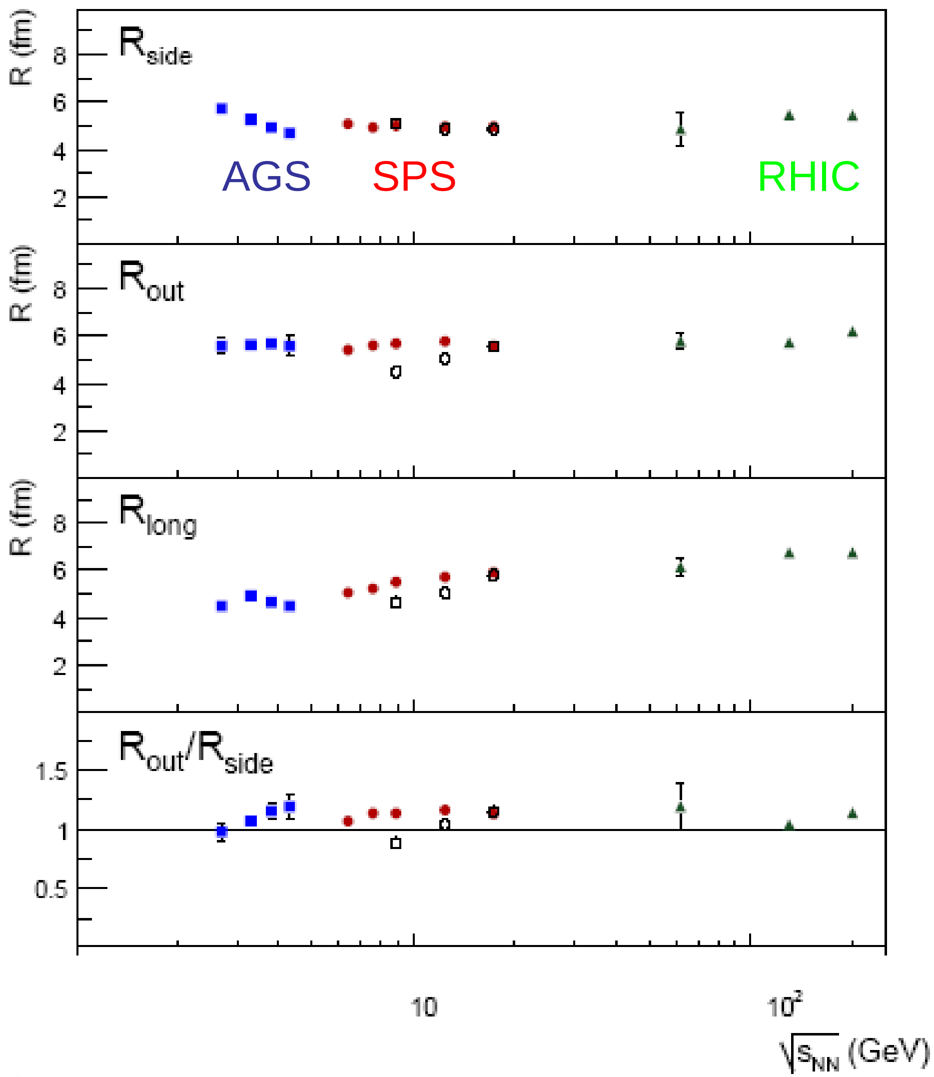
Anisotropic flow v_2 of pions: energy dependence



- change from out-of-plane (shadowing) to in-plane (hydro) at AGS
- rate of increase of v_2 slows between AGS and SPS
- increase above AGS partly due to increase of yield at higher p_T
- steady rise from SPS to RHIC, no structure at onset of deconfinement

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

midrapidity, k_T = 0.2 GeV/c



- 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)

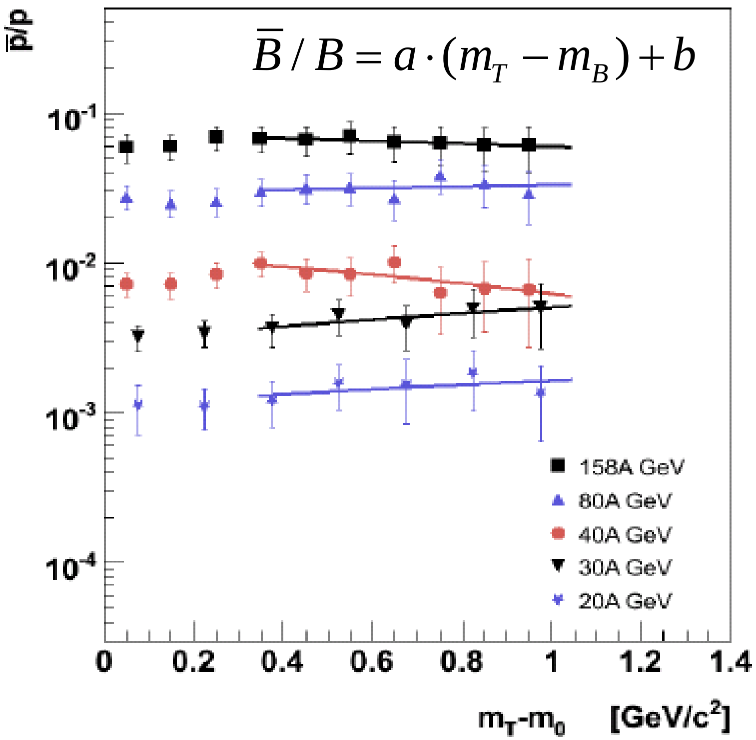
- hydro models have problems; need of more sophisticated modelling of freeze-out

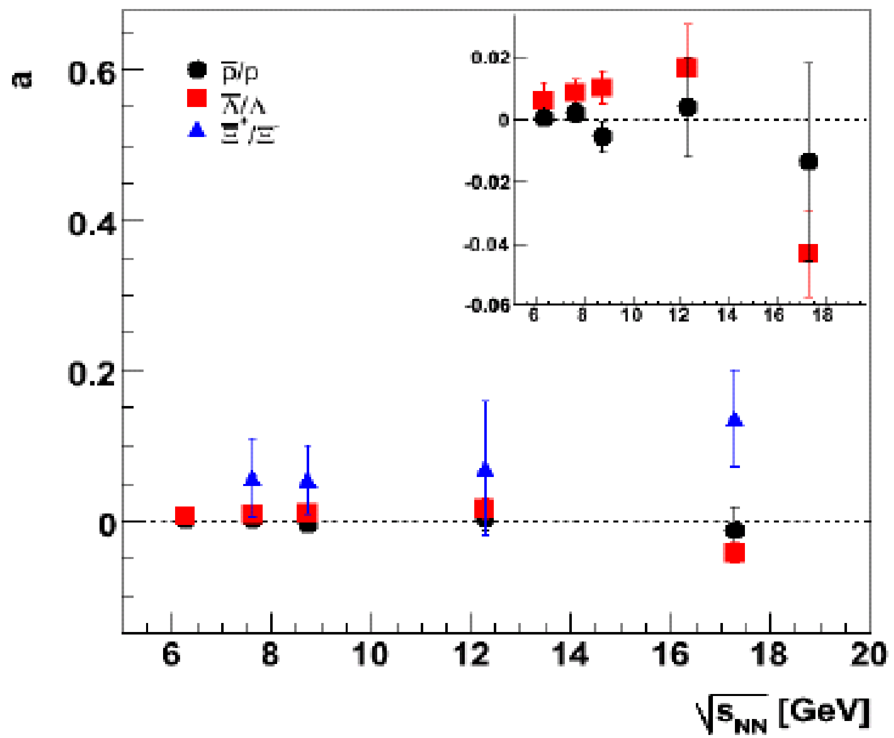
effect of critical point on m_T spectra of baryons/antibaryons

evolution trajectory of fireball close to critical point →

- anti-p/p ratio predicted to decrease with m_T (in contrast to effect of annihilation of pbar)

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



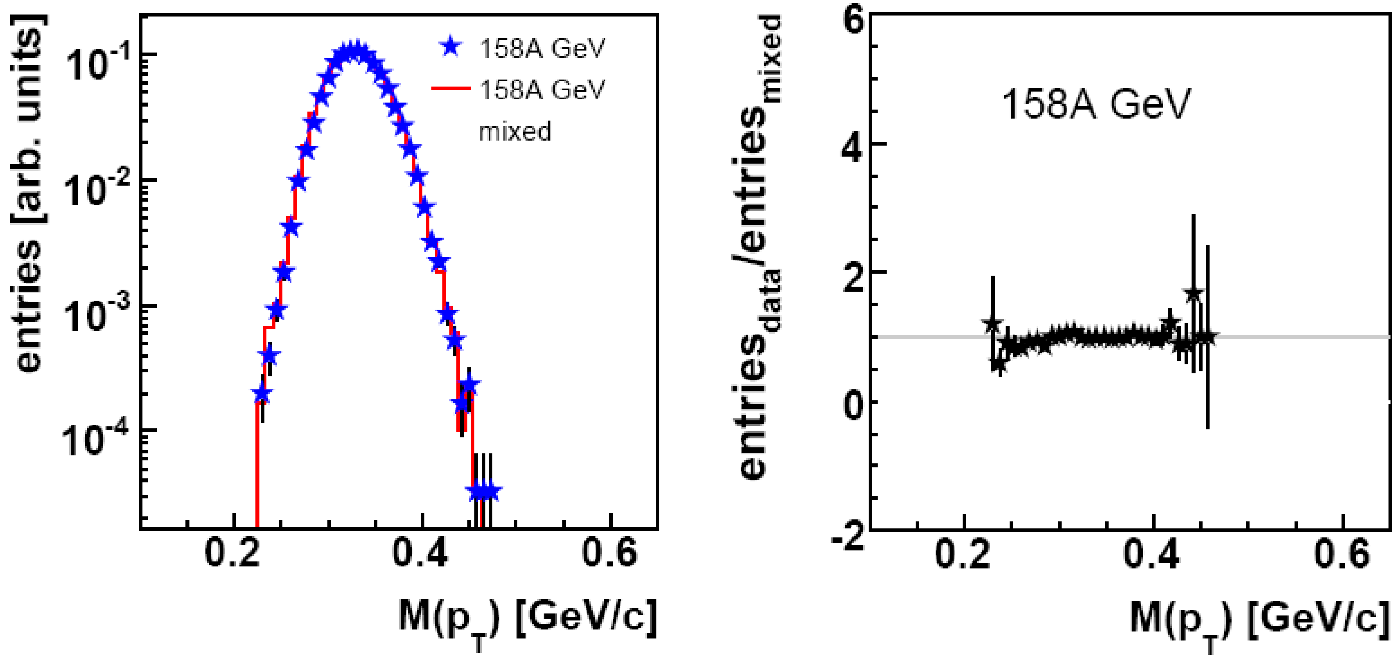


fitted slope parameter a close to zero for anti-p/p,anti- Λ/Λ,anti-Ξ/Ξ

Conjectured effect not seen for central Pb+Pb collisions at SPS energies

fluctuations of average transverse momentum $\langle p_T \rangle$

5 % most central Pb+Pb collisions at 158A GeV:



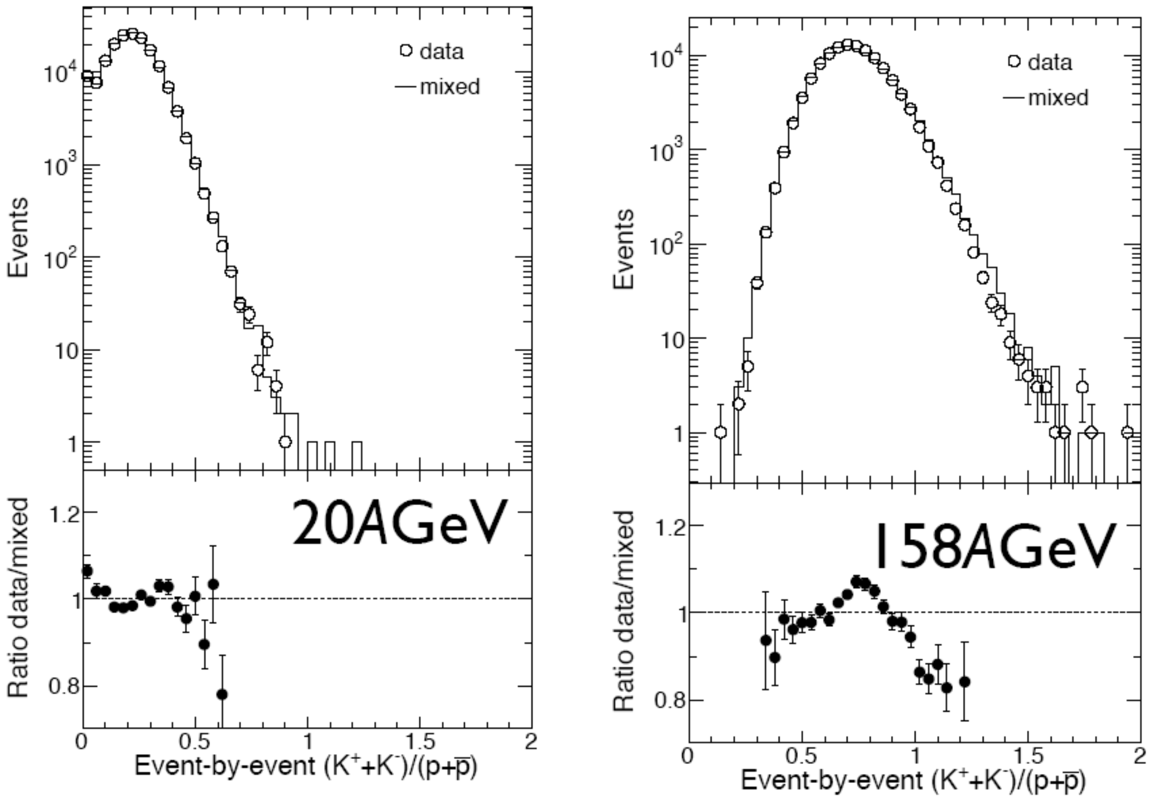
$$\Phi_{p_T} = \sqrt{\frac{\langle Z^2 \rangle}{\langle N \rangle}} - \sqrt{\langle z^2 \rangle}$$

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

- superposition: $\Phi(AA) = \Phi(NN)$
- uncorrelated particle emission: $\Phi = 0$
- insensitive to fluctuations of impact parameter (volume)

strongly intensive observable

Event-by-event particle ratio fluctuations (example K/p)



NA49 preliminary

3.5 % most central
Pb+Pb collisions:

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

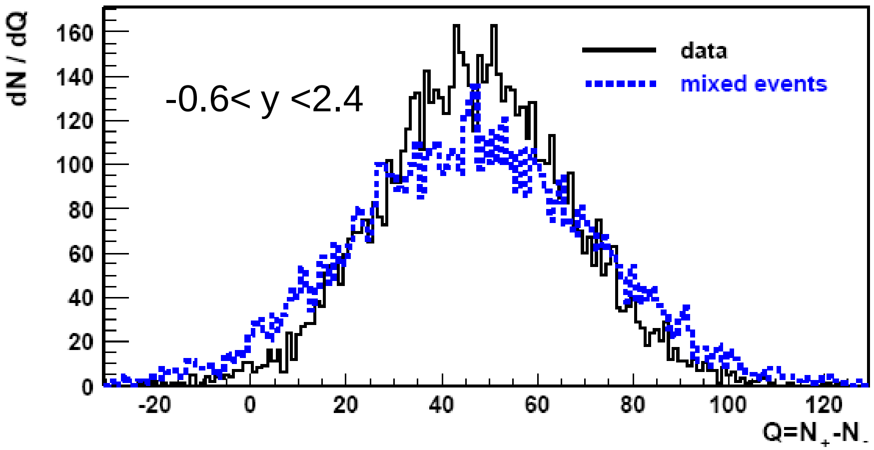
- e-by-e fit of particle multiplicities required in NA49
- mixed events (no correlations) used as reference

$1/N_{part}$ dependence

Electric charge fluctuations

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

Central Pb+Pb collisions 158A GeV



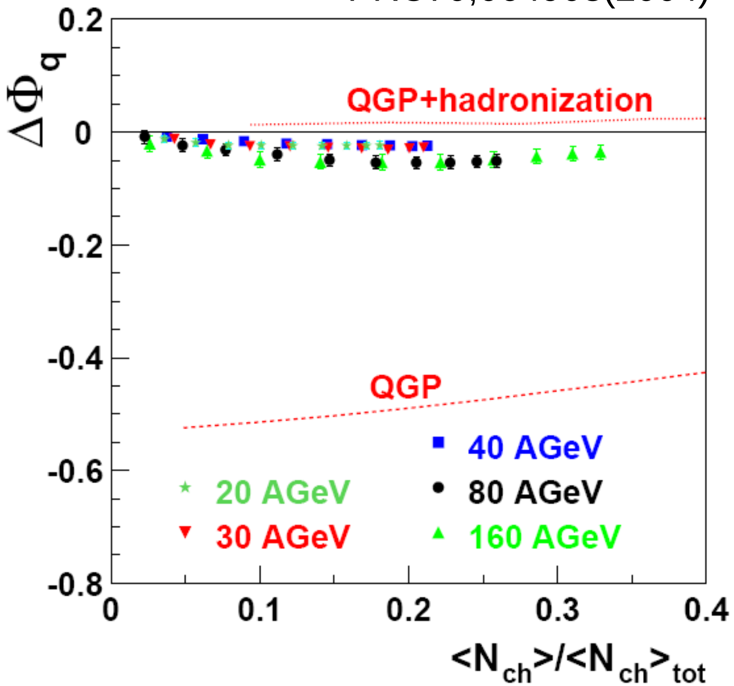
Global charge conservation

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

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

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

PRC70,064903(2004)



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

New measure Ψ of particle ratio fluctuations

M.Gazdzicki, K.Grebieszkow, M.Mackowiak, S.Mrowczynski (more detail in talk at CPOD2010)

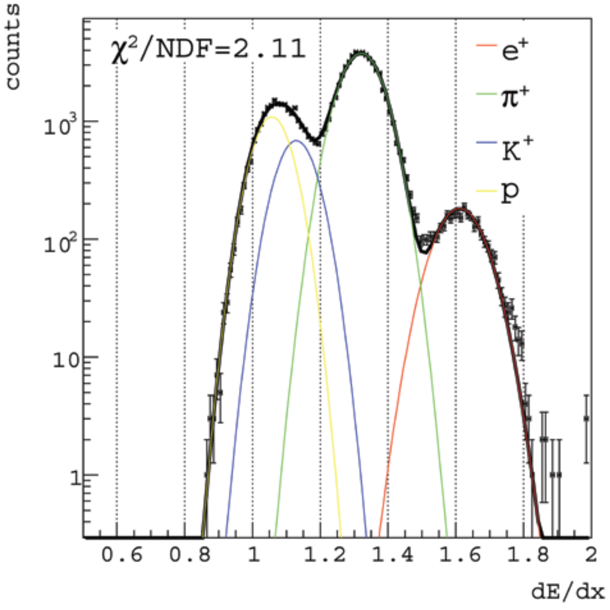
Ψ generalizes the Φ_x measure to the situation of imperfect identification,
retains advantages of Φ_x: strongly intensive measure, no $1/N_{part}$ dilution
not required: e-by-e fits of particle ratios
mixed event reference: $\Psi_{mix} = 0$

Identity method:

- obtain inclusive probability distribution ρ_h of particle type h from fit to inclusive dE/dx distribution

$$\int \rho_h(dE/dx)\,d(dE/dx) = \langle N_h \rangle$$
$$\int \rho(dE/dx)\,d(dE/dx) = \langle N \rangle$$

- $w_{h,i} = \rho_h(dE/dx_i) / \rho(dE/dx_i)$ probablity for particle i having identity h



$$\Psi_{w_h} = \frac{\langle Z^2 \rangle}{\langle N \rangle} - \overline{z^2}$$

$$z = w_{h,i} - \overline{w_h}$$ single-particle variable

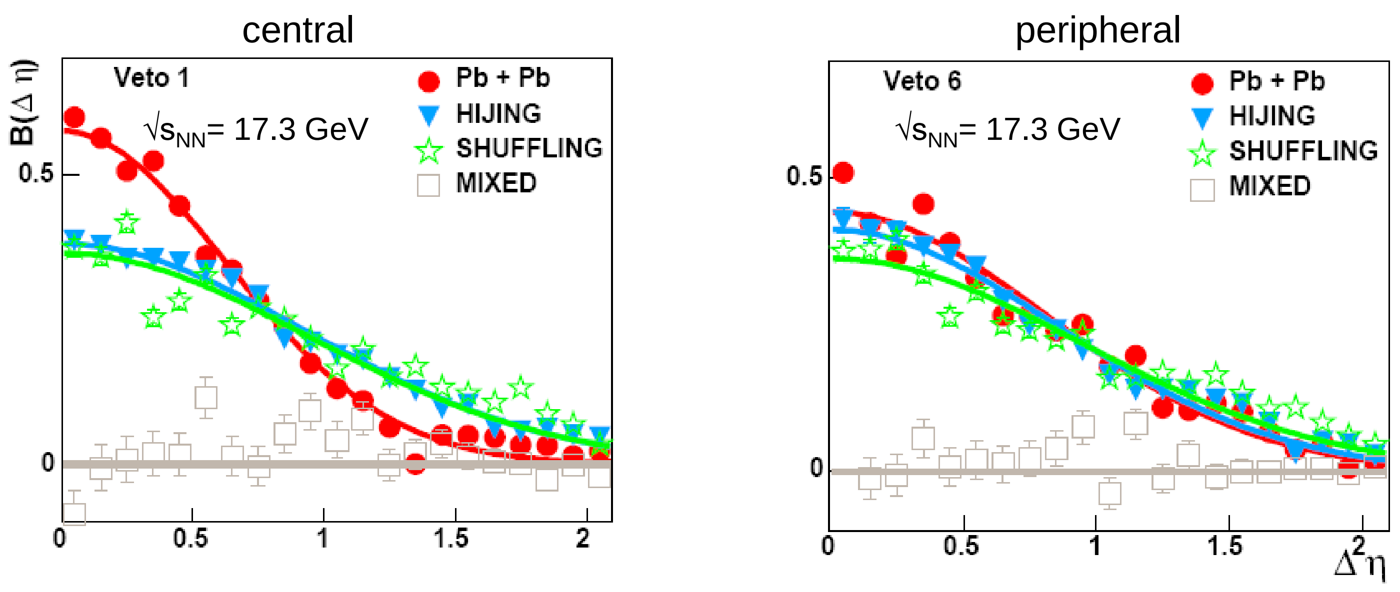
$$Z = \sum_{i=1}^{n} (w_{h,i} - \overline{w_h})$$ event variable

- effect of limited resolution can be corrected in a model independent way

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)

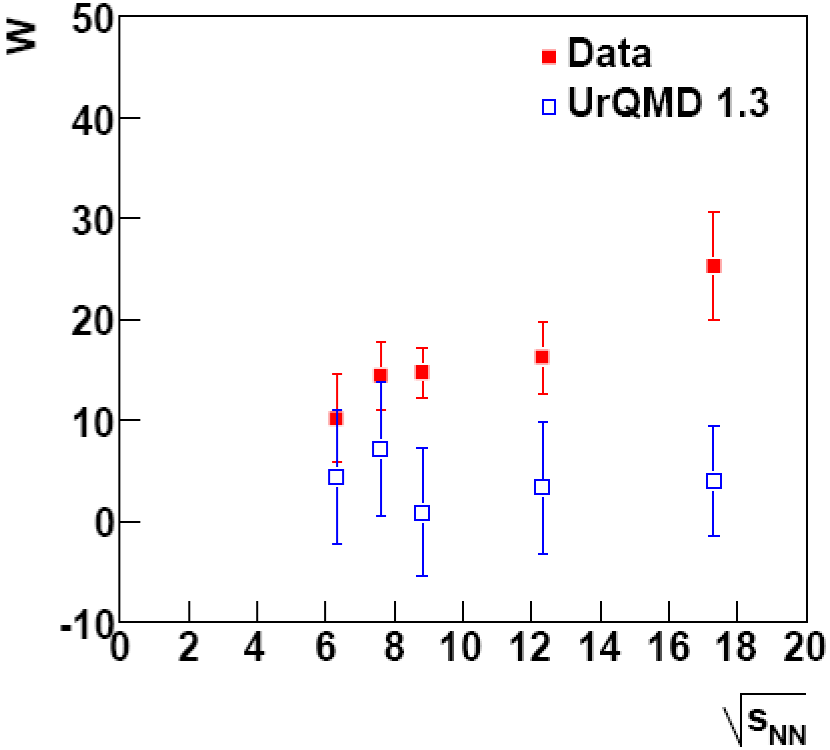


data compared to shuffled events: $W = (\langle\Delta\eta\rangle_{shuff} - \langle\Delta\eta\rangle_{data}) / \langle\Delta\eta\rangle_{shuff} \cdot 100$
(scrambling of rapidities, retention of global charge conservation)

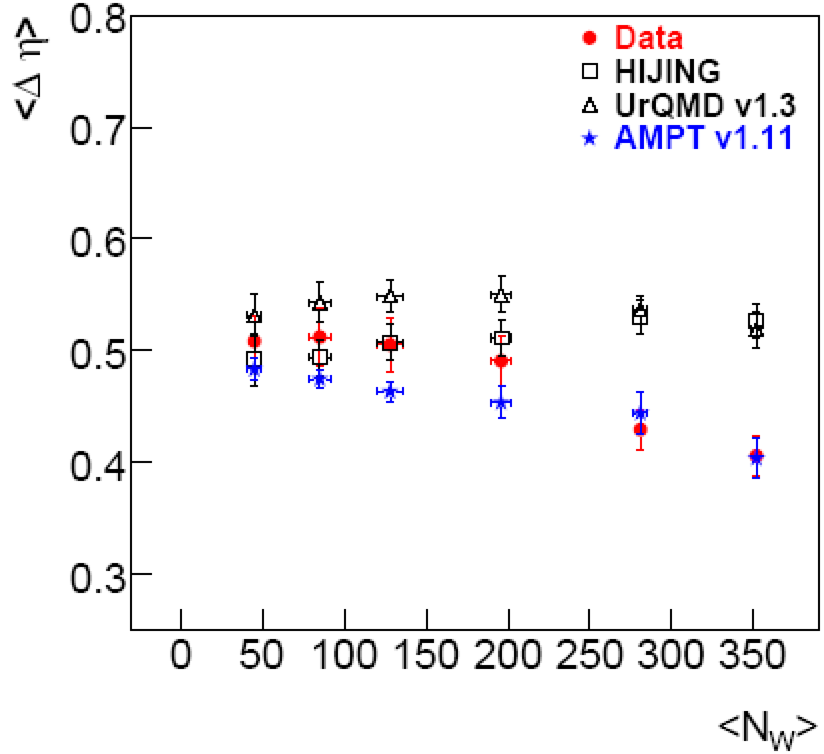
BF: model comparisons at mid-rapidity

PRC75,064904(2007)

central Pb+Pb



Pb+Pb at $\sqrt{s_{NN}}$= 17.3 GeV



- 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