Probing the strongly interacting matter with NA61/SHINE

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- Experimental setup
- Physics program
- Single particle spectra
  - Results from p+p
  - Results from Be + Be
- E-by-E fluctuations
  - New fluctuation measures
  - Comparison to Pb + Pb data
- Summary

GOETHE UNIVERSITÄT FRANKFURT AM MAIN

The NA61/SHINE apparatus

SPS Heavy Ion and Neutrino Experiment
(3 different communities)

"successor" of NA49 with numerous upgrades

- 5 TPCs with 3 of them inside the magnetic field
- large acceptance
- high momentum resolution:

$$\sigma(p)/p^2 \approx 10^{-4}(GeV/c)^{-1}$$

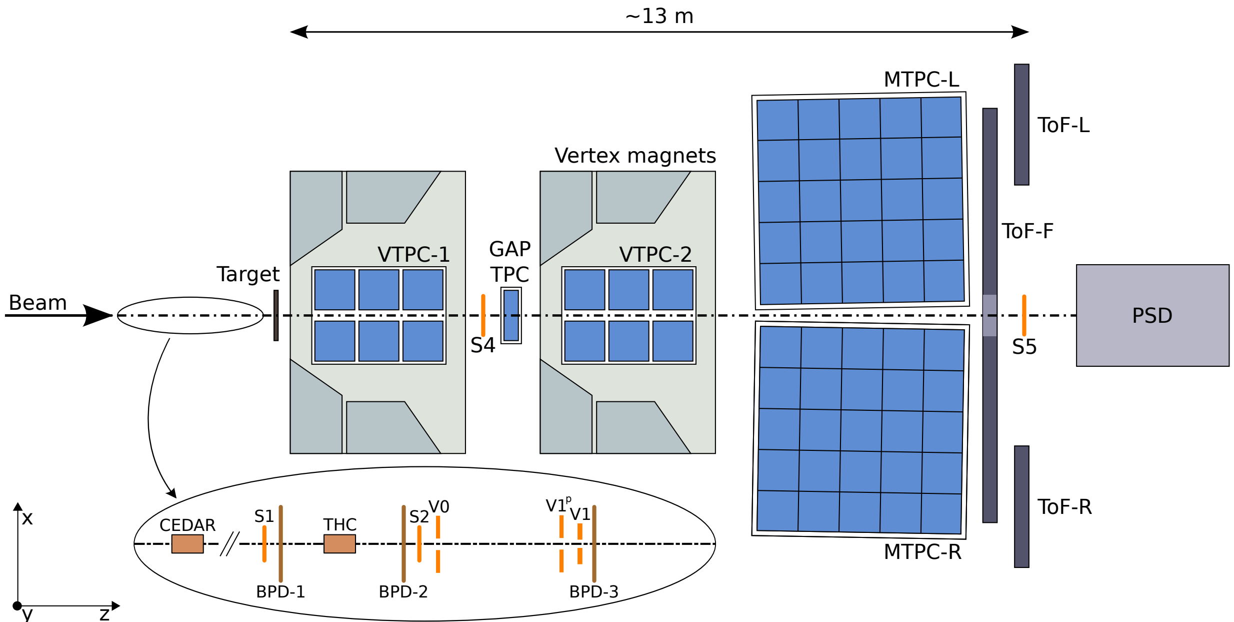
(at 9 Tm)

- precise particle identification:

$$\frac{\sigma(dE/dx)}{\langle dE/dx \rangle} \approx 4\%$$

$$\sigma(t) \approx 60\,ps$$

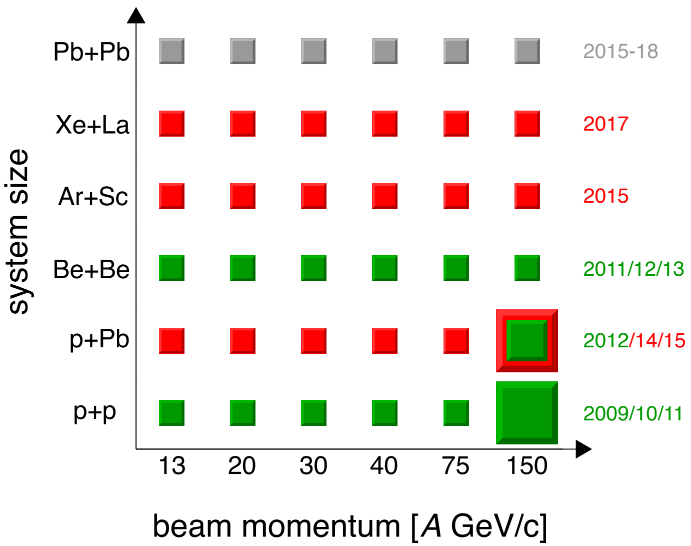
- Operates since 2007



JINST 9 (2014) P06005

in this contribution: only ion program

Heavy Ion program

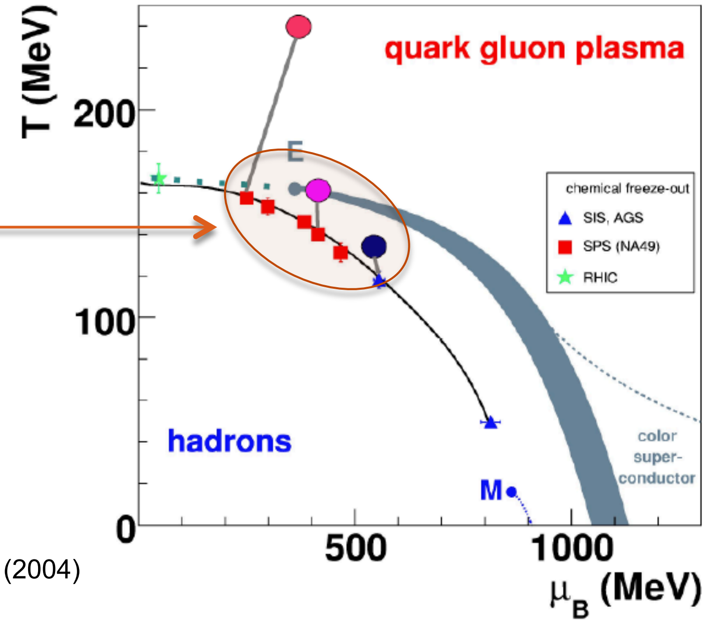


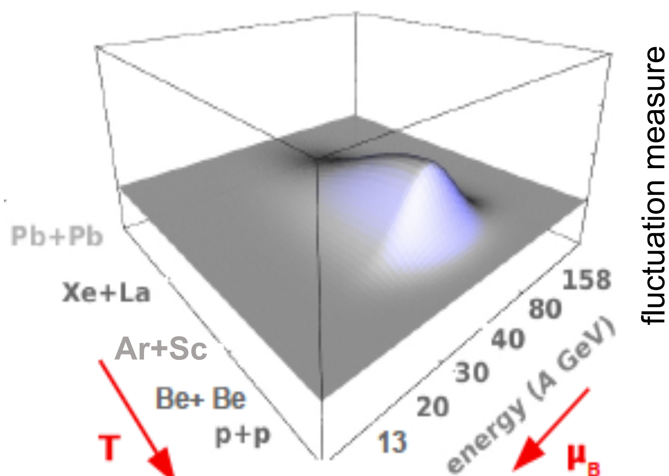
probes an interesting region on the phase diagram

for example:

T_c = 162±2MeV
μ_c = 360±40 MeV

Z. Fodor S. D. Katz, JHEP 0404, 050 (2004)





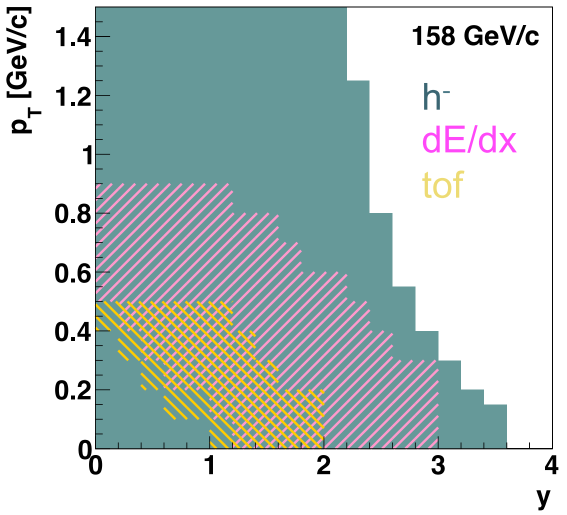
by varying the energy and/or size of the colliding system the CEP might be localized (CEP = freeze-out)

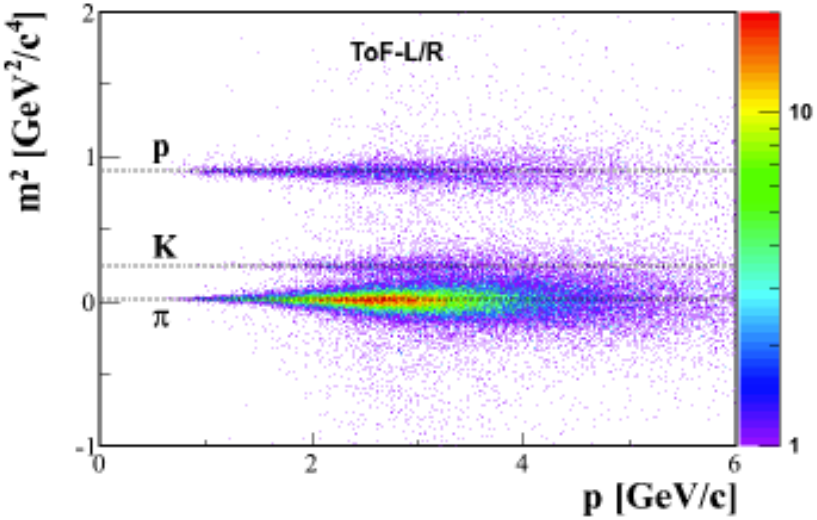
Observables:

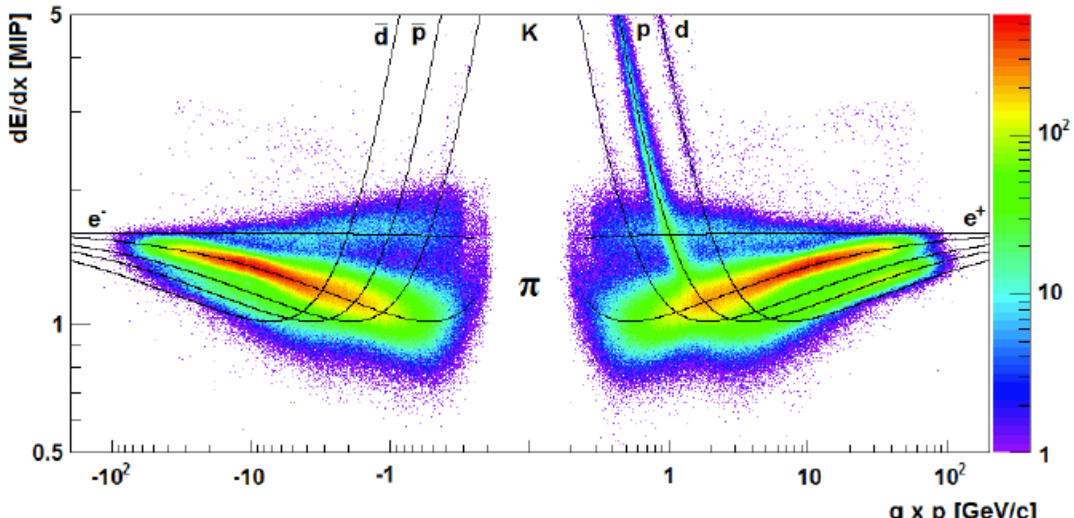
Event-by-Event fluctuations

M. Stephanov, K. Rajagopal, E. V. Shuryak, PRD 60, 114028 (1999)

Particle Identification (p+p, example)







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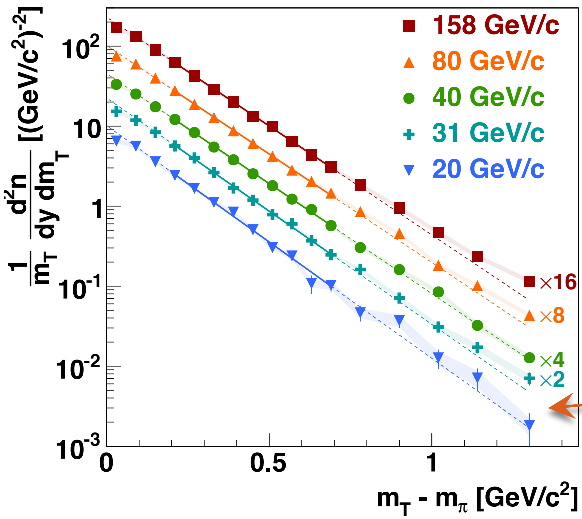
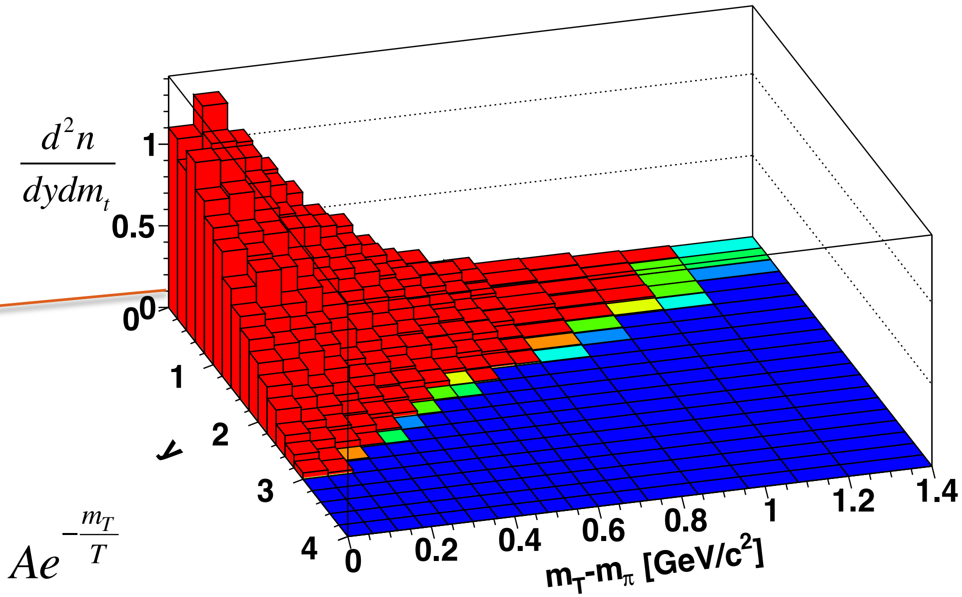
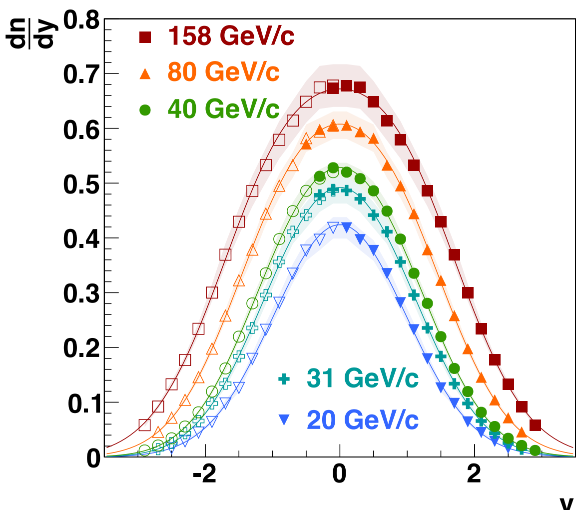
Single particle spectra (p+p, Be+Be)

π⁻ spectra, p+p



corrected double differential multiplicity





$$\frac{1}{m_T}\frac{d^2n}{dydm_T} = Ae^{-\frac{m_T}{T}}$$

$$\frac{dn}{dy} = \frac{\langle \pi^- \rangle(\sigma_0, y_0)}{2\sigma_0\sqrt{2\pi}}\left[e^{-\frac{(y-y_0)^2}{2\sigma_0^2}} + e^{-\frac{(y+y_0^2)}{2\sigma_0^2}}\right]$$

$$\sigma^2 = y_0^2 + \sigma_0^2$$

NA61: EPJ C74 (2014) 2794

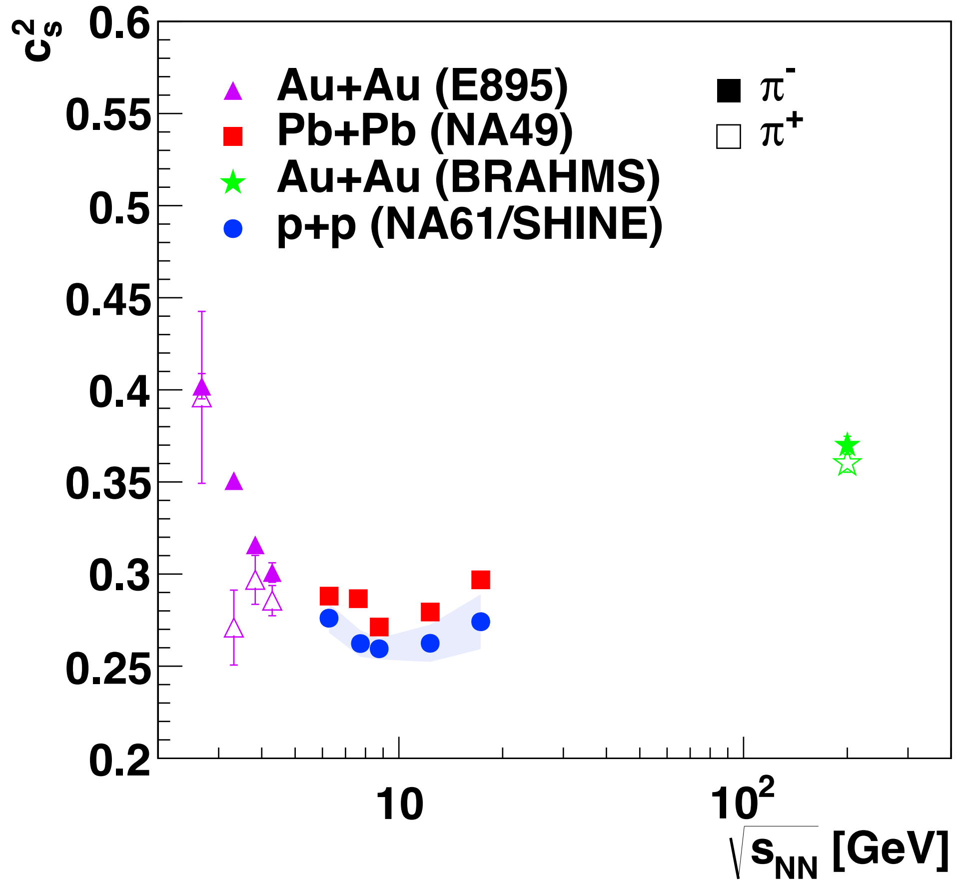
Softening of EOS in p+p?

Fermi-Landau initial conditions
Ideal Hydrodynamical expansion

$$p(\varepsilon) = c_s^2 \varepsilon$$

$$\frac{dn}{dy} = \frac{K s_{NN}^{1/4}}{\sqrt{2\pi\sigma_y^2}} e^{-\frac{y^2}{2\sigma_y^2}}$$

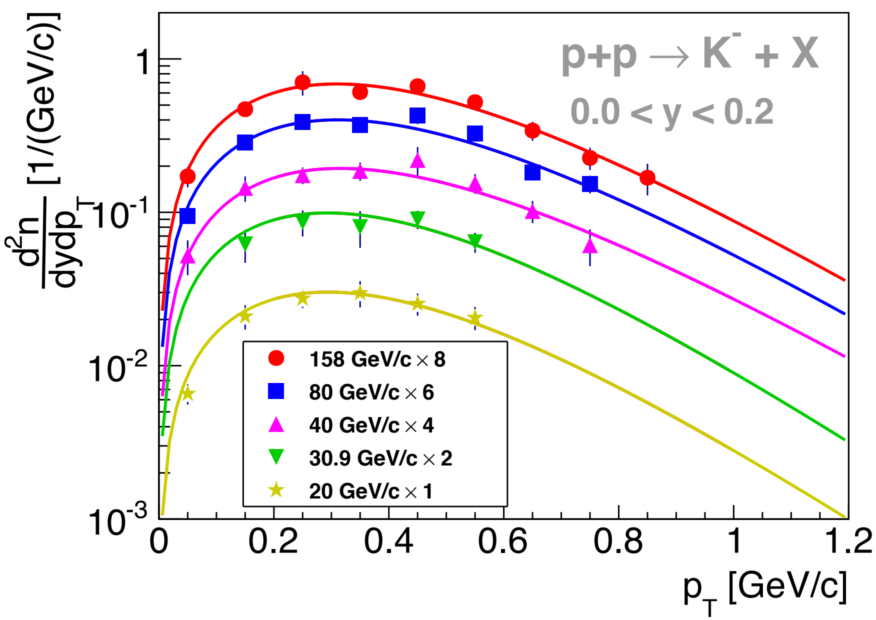
$$\sigma_y^2 = \frac{8}{3}\frac{c_s^2}{1-c_s^4}\ln\left(\frac{\sqrt{s}}{2m_N}\right)$$

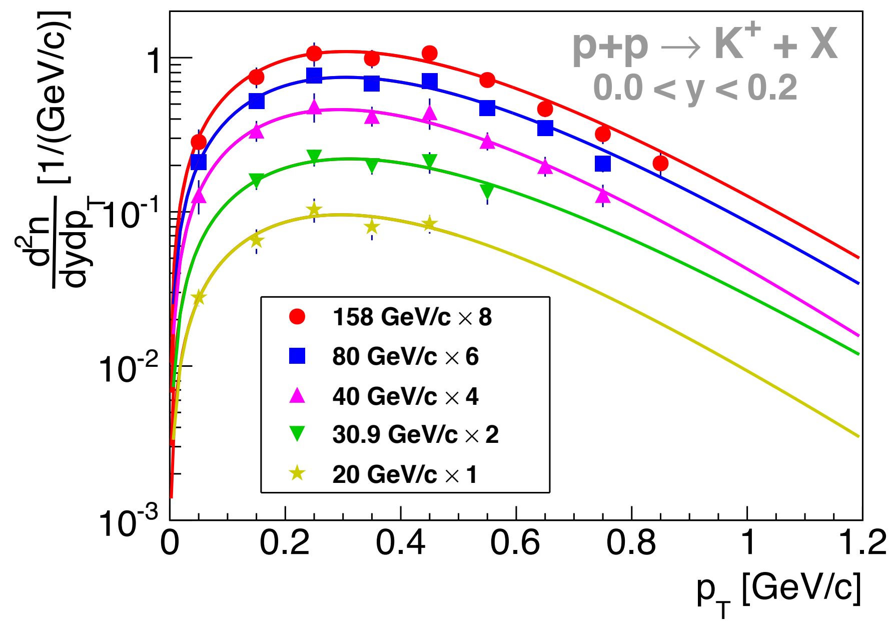


L. D. Landau, Izv. Akad. Nauk, 17, 51 (1953)
E. V. Shuryak, Yad. Fiz., 16, 395 (1972)
M. Bleicher, arXiv:hep-ph/0509314v1
NA61: EPJ C74 (2014) 2794

Kaon spectra, p+p

dE/dx + TOF analysis at mid - rapidity





Similar T_{eff} for both charges

$$\langle N_{K^+=u\bar{s}} \rangle > \langle N_{K^-=\bar{u}s} \rangle$$

$$\frac{d^2N}{dp_T dy} = C \frac{p_T}{T_{eff}\left(m_K + T_{eff}\right)} e^{-\frac{m_T^K - m_K}{T_{eff}}}$$

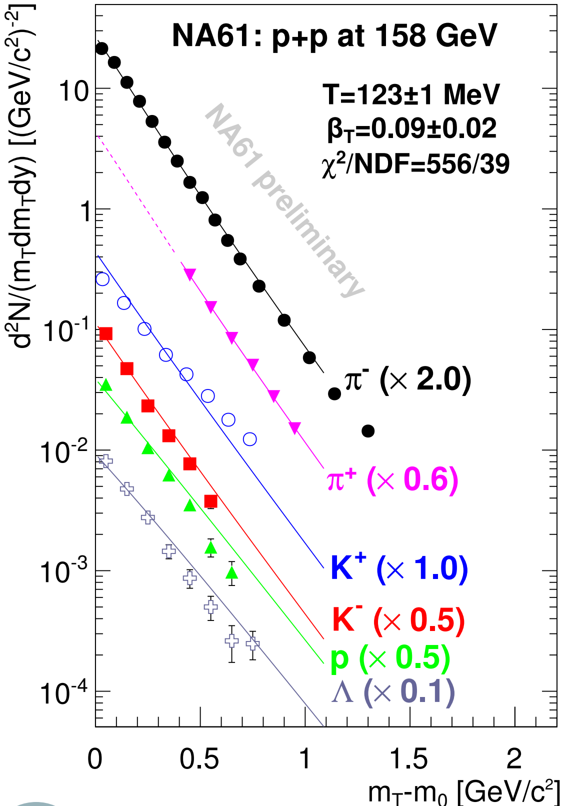
$C \rightarrow \frac{dN}{dy}$

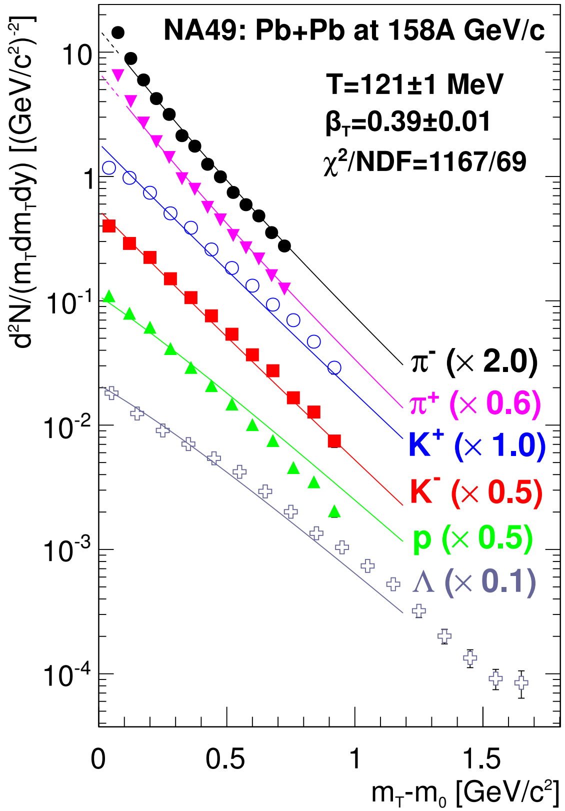
Blast Wave Model

$$\frac{d^2 N_i}{m_T dm_T dy} = A_i m_T K_1\left(\frac{m_T \cosh\rho}{T}\right) I_0\left(\frac{p_T \sinh\rho}{T}\right)$$

PRC 48, 2462 (1993)

$$\rho = a\tanh\beta_T$$



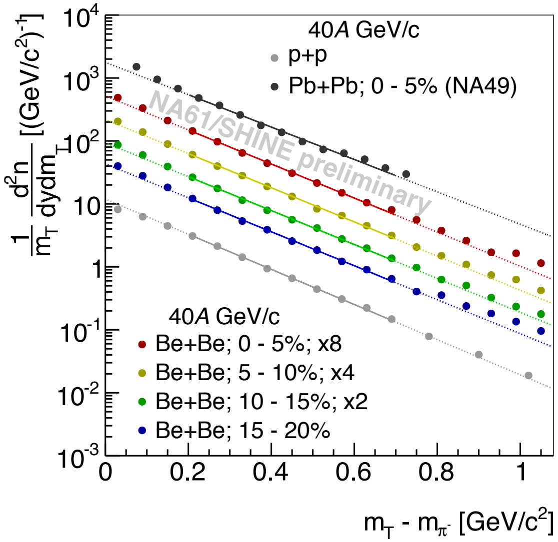


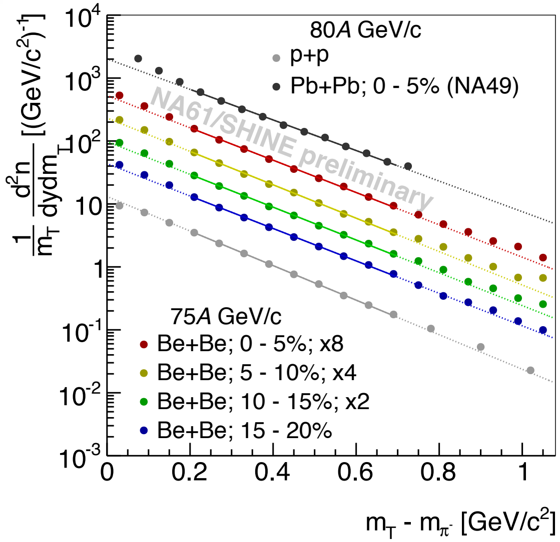
mid-rapidity spectra

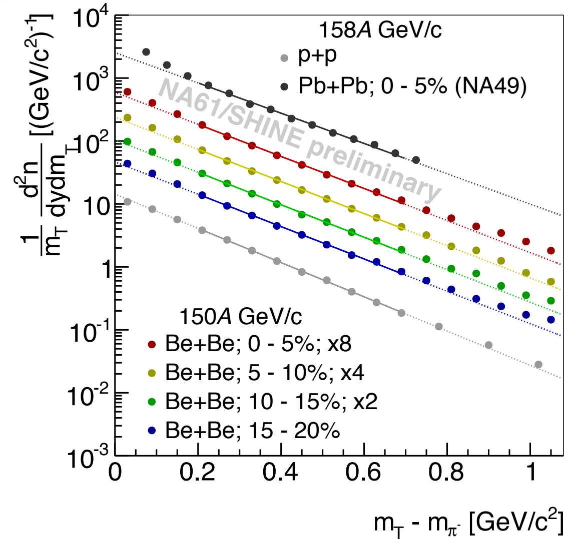
- p+p:
  exponential (almost)
- Pb+Pb:
  exponential dependence
  is modified by the transverse
  flow.

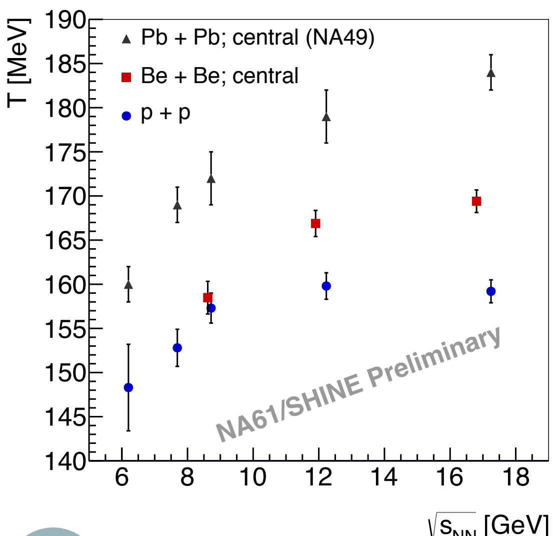
NA49: PRC77 (2008) 024903
PRC66 (2002) 054902

π⁻ spectra, Be+Be









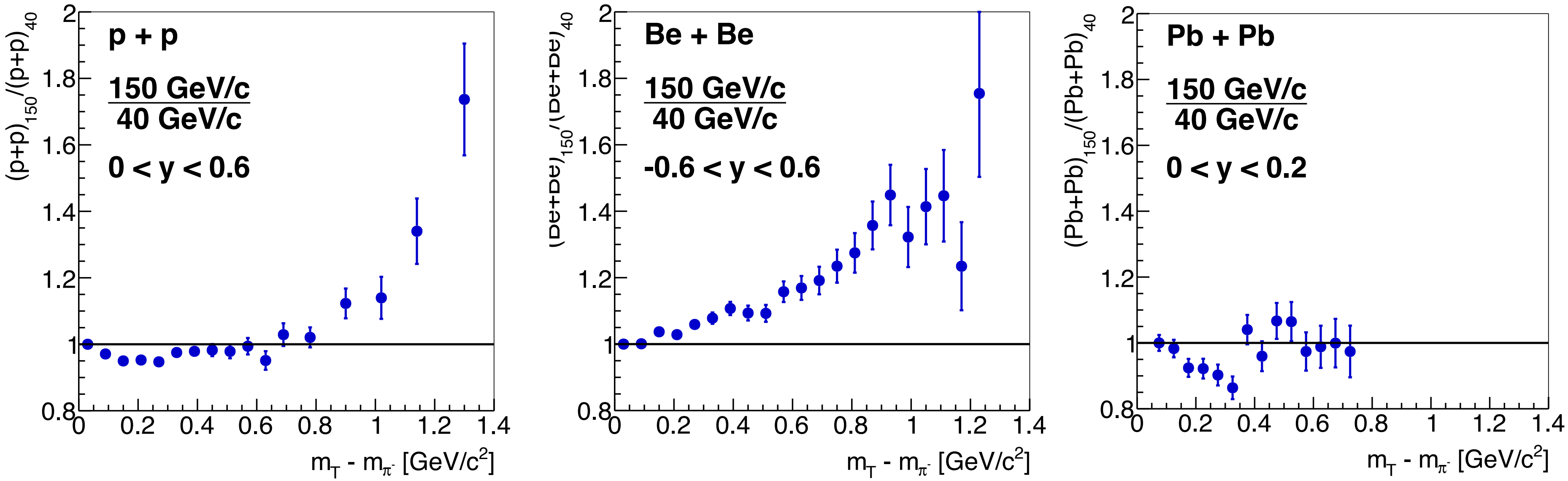
Similar slopes for p+p and Be+Be at 40A GeV/c

Effect of radial flow for Pb+Pb at all energies

Onset of collective effects in Be+Be above 40A GeV

Onset of collective effects

Normalized ratio of m_T spectra at different energies



Enhancement above 1 GeV	Enhancement in whole range	no m_t dependence
phase space effect	radial flow at 150A GeV/c	similar radial flow at both energies

A. Rustamov, Int. Conf. FAIR in Europe, 2014, Worms, Germany

Chemical (particle number) E-by-E Fluctuations

A novel approach, the Identity Method

- The problem: Event by event particle identification
- The strategy:
  - for each measurement x_i and particle j in an event one defines

$$w_j(x_i) = \frac{\rho_j(x_i)}{\sum_j \rho_j(x_i)}$$

  - for each event one constructs:

$$W_j = \sum_i w_j(x_i)$$

- finally one calculates moments of W distribution

$$\begin{pmatrix} \langle W_p^2 \rangle - b_p \\ \langle W_k^2 \rangle - b_k \\ \langle W_p W_k \rangle - b_{pk} \end{pmatrix} = A \begin{pmatrix} \langle N_p^2 \rangle \\ \langle N_k^2 \rangle \\ \langle N_p N_k \rangle \end{pmatrix}$$

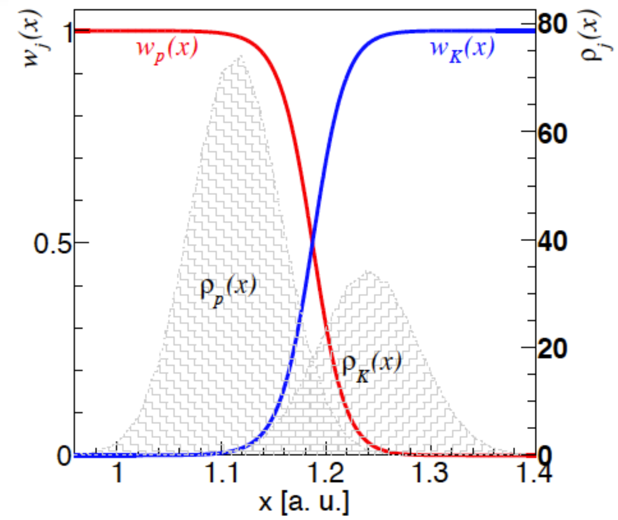
fully defined by a specific combinations of $\rho_j(x)$

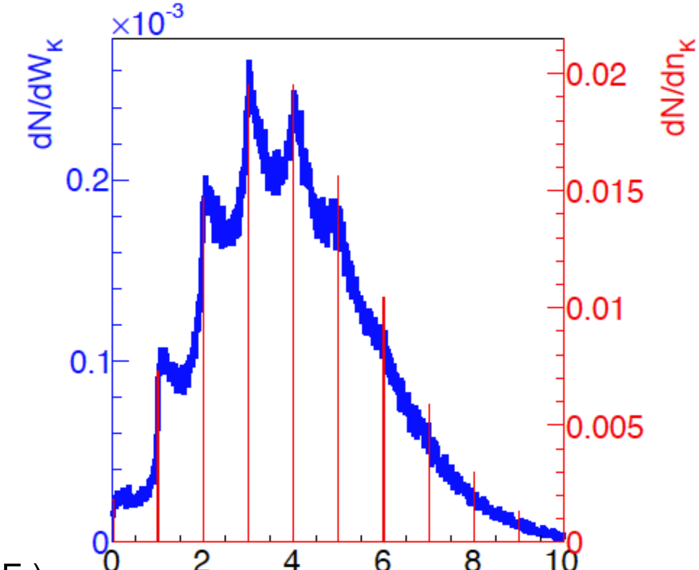
M. Gazdzicki et al., PRC 83, 054907 (2011)

M. I. Gorenstein, PRC 84, 024902 (2011), second moments

A. Rustamov, M. I. Gorenstein, PRC 86, 044906 (2012), (third and higher moments)

Implementation: TIdentity module (being used in NA49, NA61SHINE, ALICE)





Fluctuation measures

$$\omega_N = \frac{\langle N^2 \rangle - \langle N \rangle^2}{\langle N \rangle}$$

$$\Sigma[A,B] = \frac{\langle B \rangle \omega_A + \langle A \rangle \omega_B - 2\left(\langle AB \rangle - \langle A \rangle \langle B \rangle\right)}{\langle A+B \rangle}$$

$$\Phi[A,B] = \frac{\sqrt{\langle A \rangle \langle B \rangle}}{\langle A+B \rangle}\left[\sqrt{\Sigma[A,B]} - 1\right]$$

Wounded Nucleon Model: $\langle \mathrm{N} \rangle \propto \mathrm{N_w}$

GCE: $\langle \mathrm{N} \rangle \propto V$

ω_N depends on volume (N_w) fluctuations

$\Sigma[A,B]$, $\Phi[A,B]$ – depend neither on volume (N_w) nor on its fluctuations

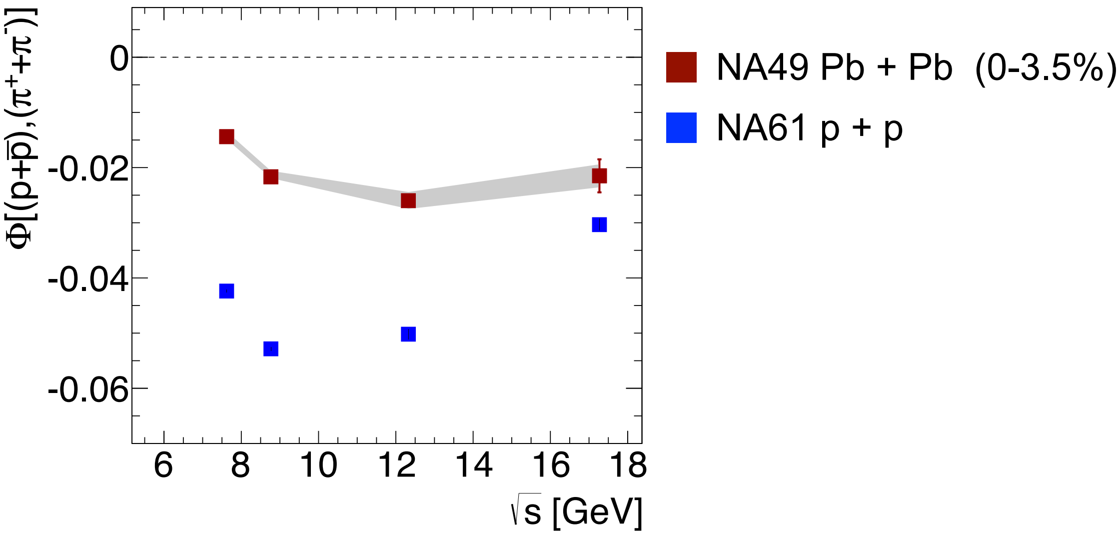
fluctuation measures are acceptance dependent

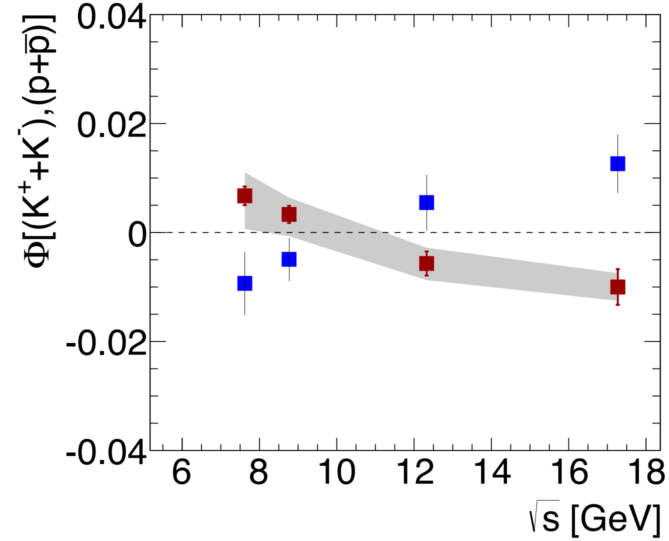
A. Bzdak, V. Koch, Phys. Rev. C86 (2012) 044904
NA49: Phys. Rev. C89 (2014) 054902

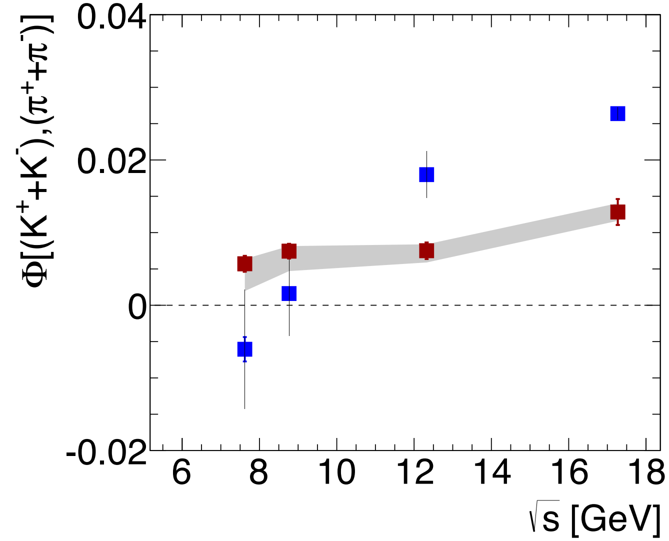
↓

compare the results in a common acceptance

Φ, both charges (common acceptance)







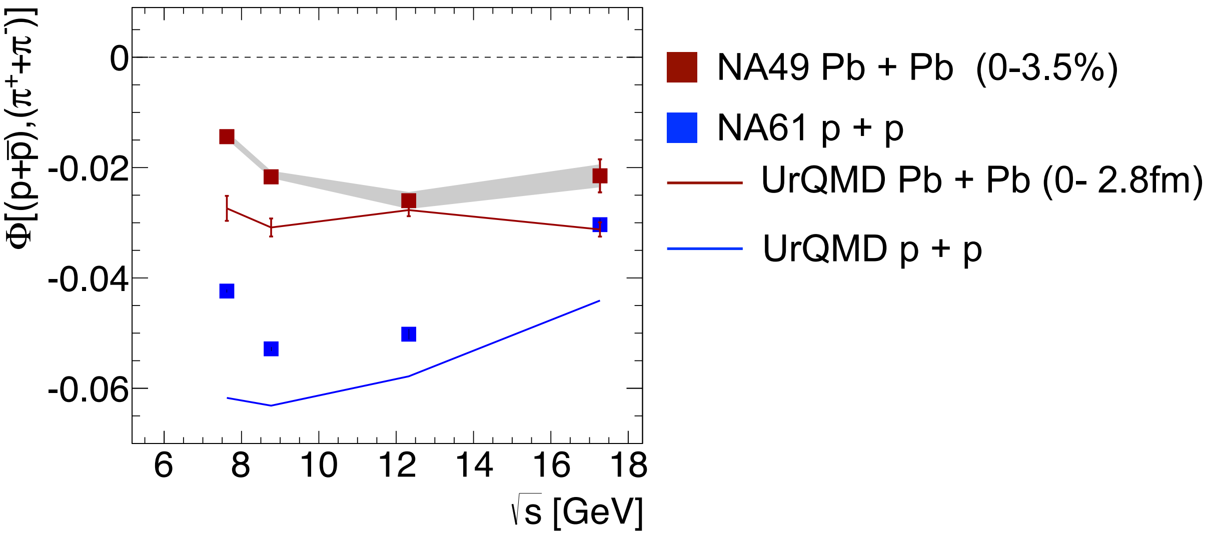
[p,π] – smaller values compared to Pb+Pb

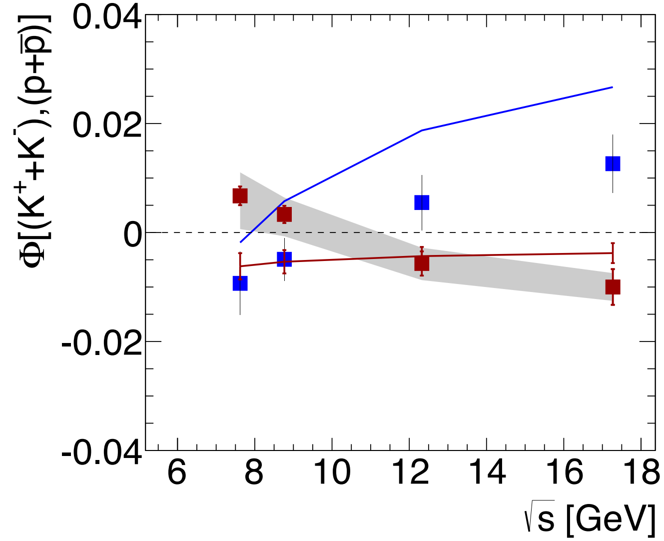
[K,p] – sign change above 40A GeV/c (p+p, Pb+Pb)

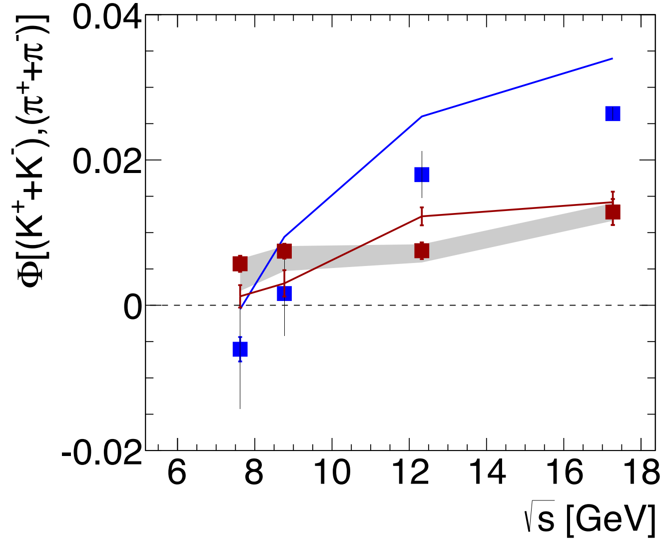
[K,π] – sign change in case of p+p

A. Rustamov, POS (2013) 005
M. Mackowiak-Pawlowska, POS (2013) 048

Φ, both charges (common acceptance)







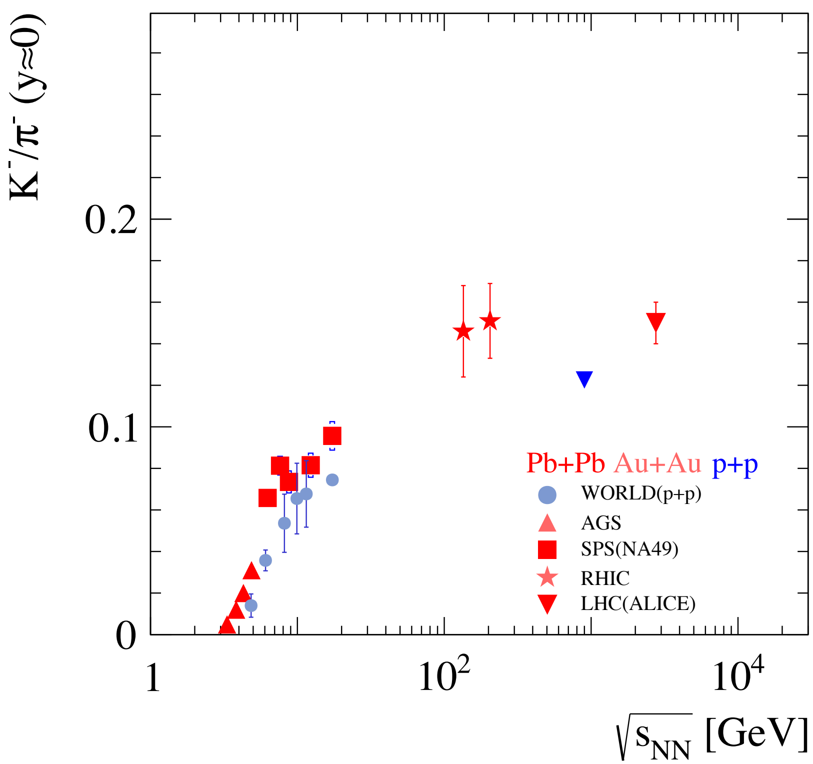
[p,π] and [K,π]: UrQMD follows the measured trend

[K,p] – UrQMD does not show a sign change

A. Rustamov, POS (2013) 005
M. Mackowiak-Pawlowska, POS (2013) 048

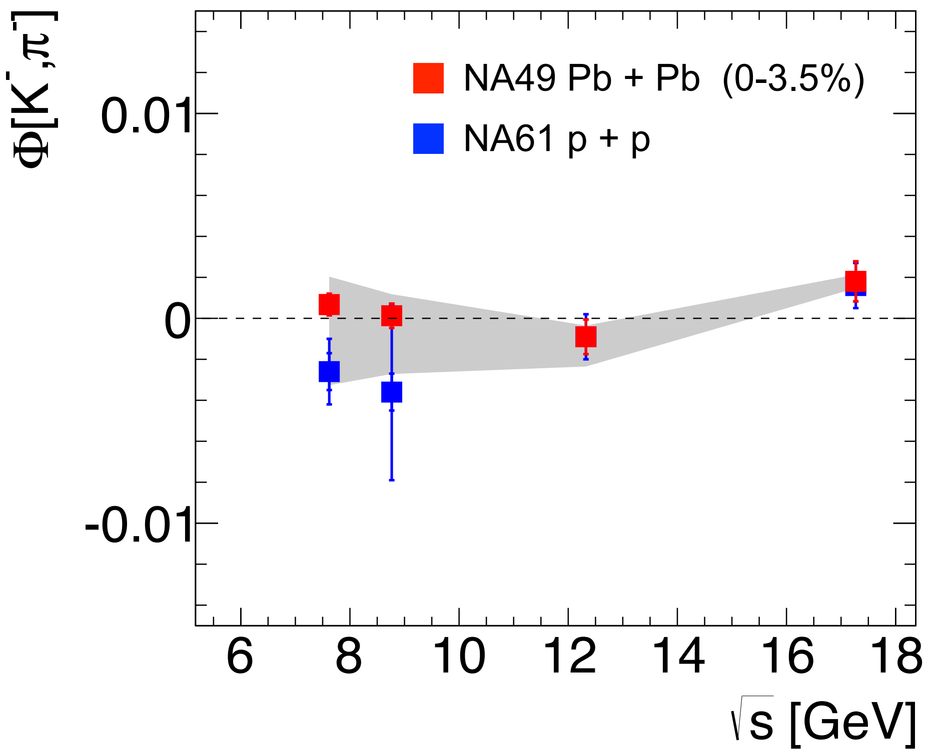
Negative charges

first moments



- smooth excitation functions
- no significant differences between p + p and A + A

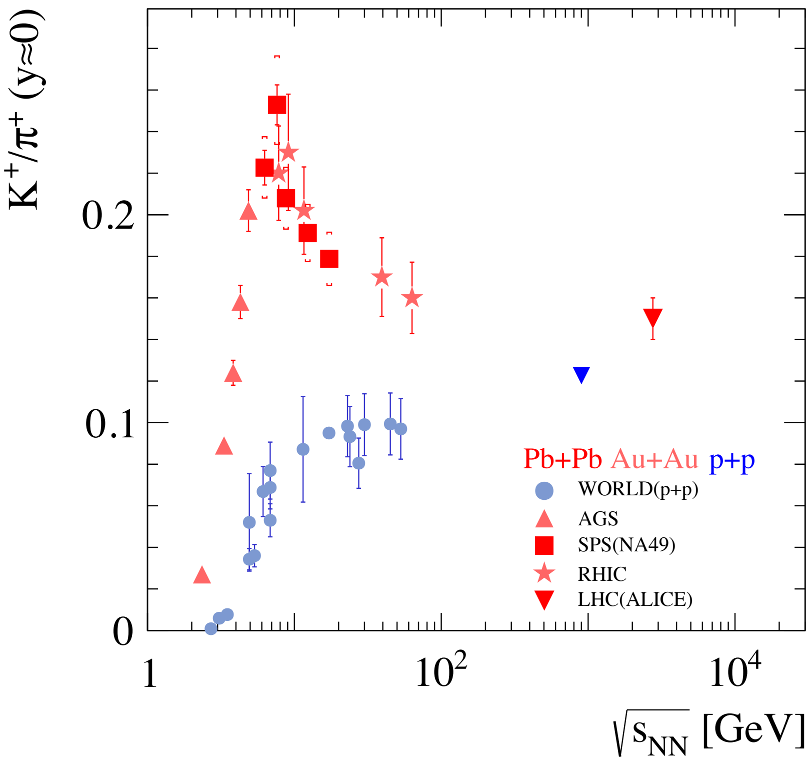
second moments



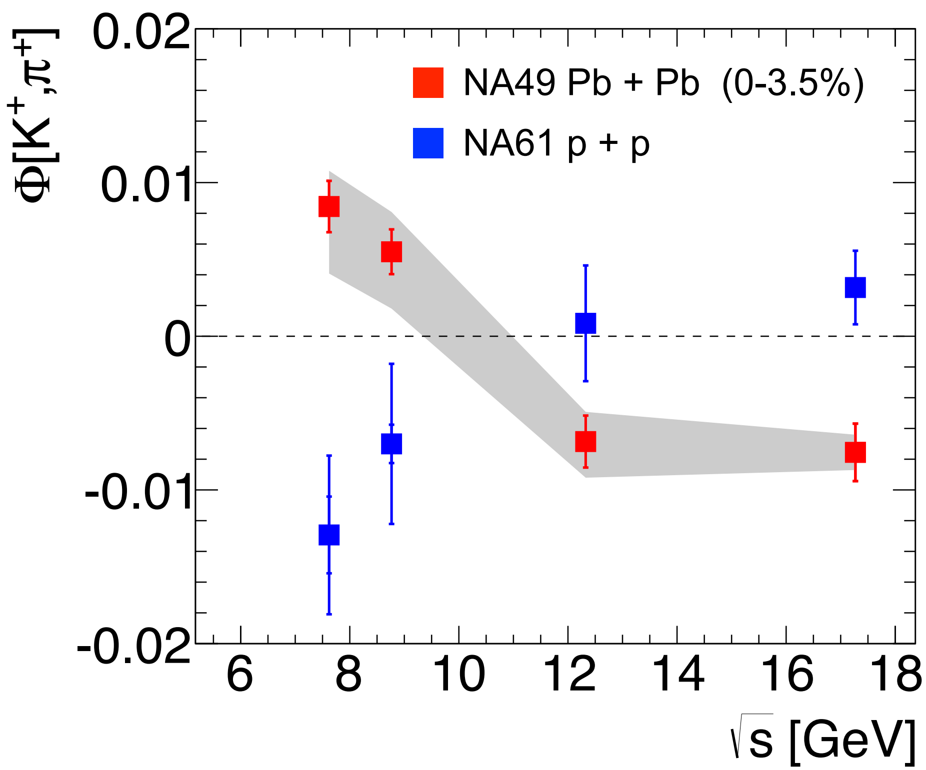
- no significant differences between p + p and Pb + Pb

Positive charges

first moments



second moments



- structures in A + A excitation function
- smooth dependence in p+p?
- significant differences between p + p and A + A

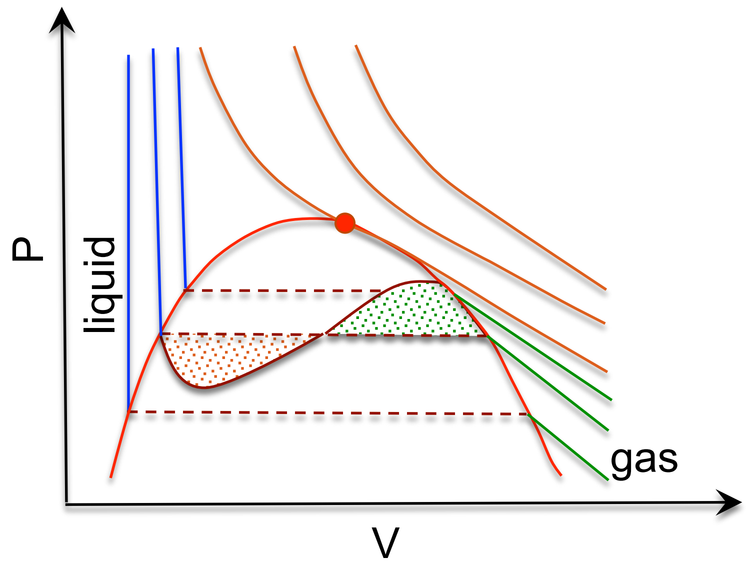
- structures in excitations functions both in Pb + Pb and p+p.

Summary

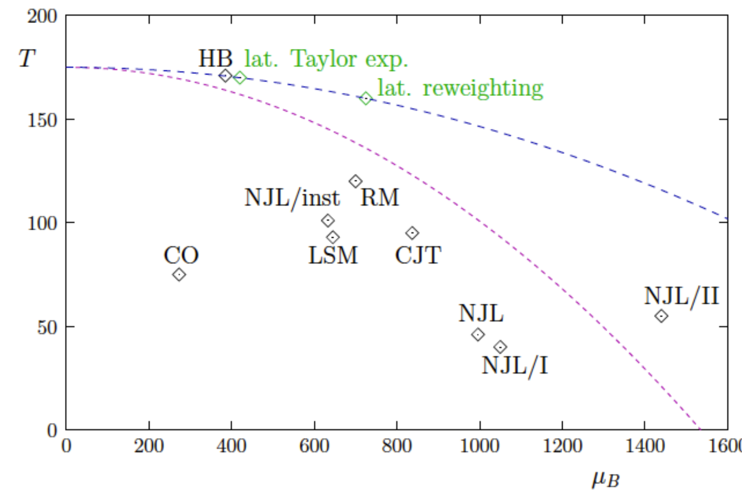
- Particle spectra
  - High precision double – differential pion spectra were measured in p+p and Be+Be collisions at 5 different energies
  - Onset of collectivity is observed in Be+Be reactions above 40A GeV/c projectile momenta

- E-by-E fluctuations
  - A new unfolding method has been employed for extracting second moments of identified particle multiplicity distributions
  - Obtained results in p+p reactions are compared to those from Pb+Pb of NA49 and UrQMD transport model
  - Like in case of the first moments, the deviations between p+p and Pb+Pb data are observed only for positive K, π pairs.

Landscape of critical points



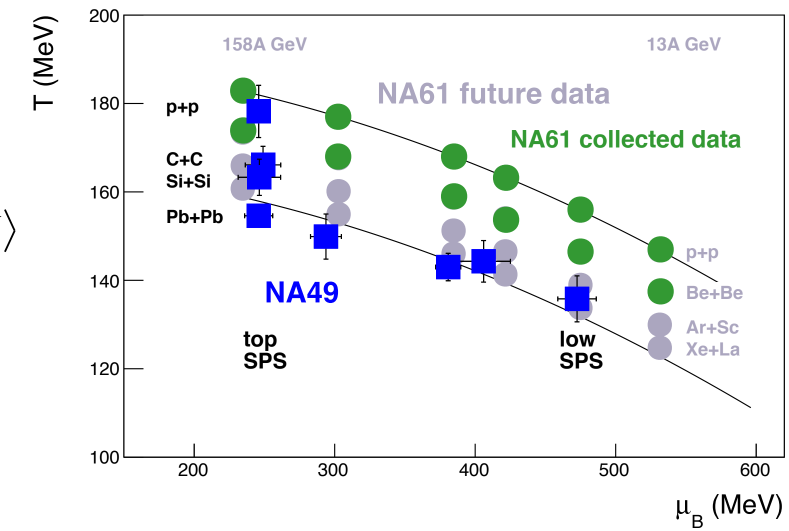
courtesy of M. Stephanov: arXiv:hep-ph/0402115v1



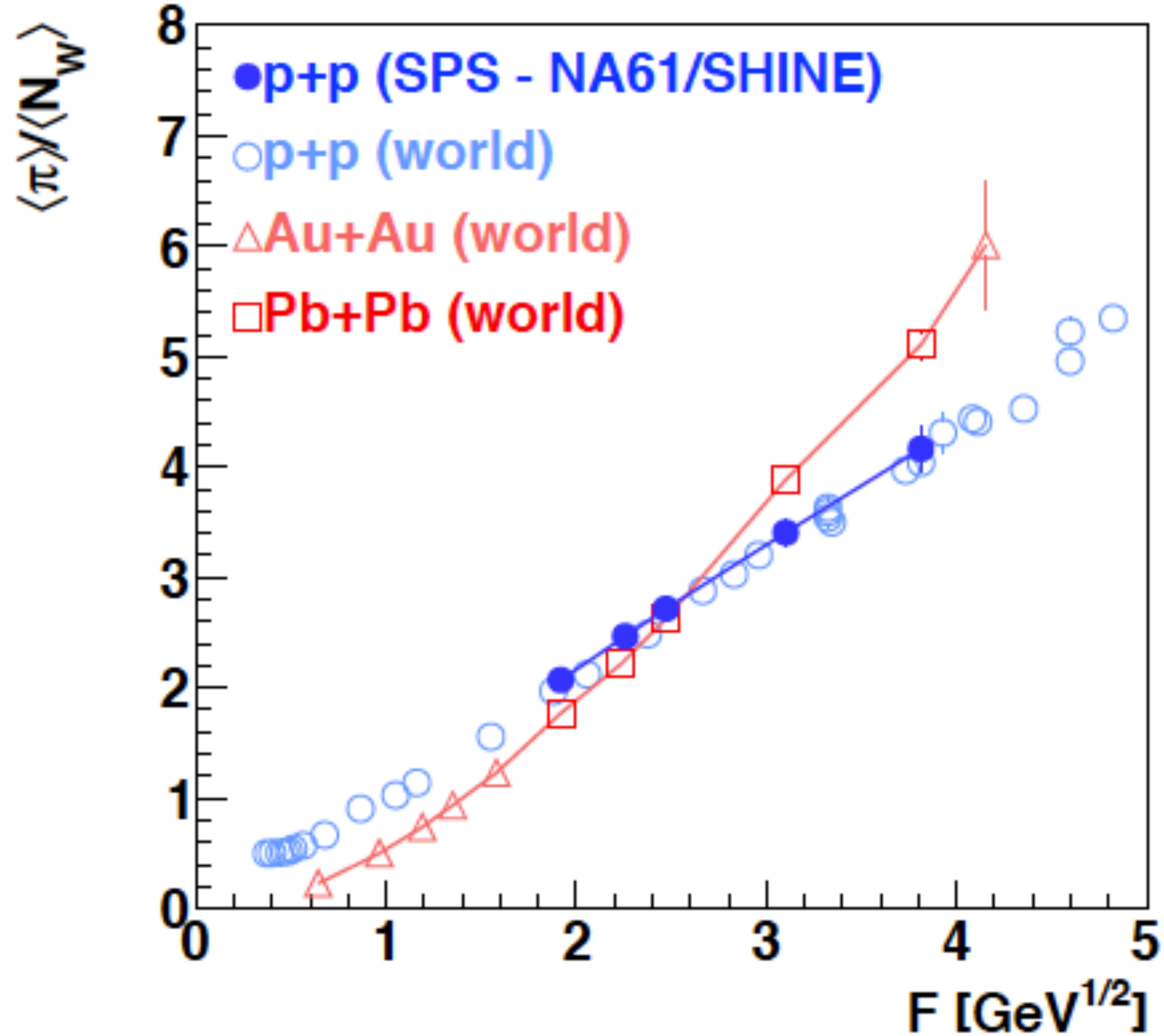
Multiplicity fluctuations in GCE

$$\langle N^2\rangle - \langle N\rangle^2 = \langle N\rangle T k_T / v \xrightarrow{PV=NT} \langle N^2\rangle - \langle N\rangle^2 = \langle N\rangle$$

$$k_T = \frac{1}{v(-\partial P/\partial v)}, \qquad v = \frac{V}{N}$$



Einstein, Annalen der Physik, 33, 1910



A. Rustamov, Int. Conf. FAIR in Europe, 2014, Worms, Germany