Onset of deconfinement and search for the critical point of strongly interacting matter at CERN SPS energies

Maciej RYBCZYŃSKI
Jan Kochanowski University
Kielce, Poland

(for the NA49 and NA61/SHINE Collaborations)

Stockholm, July 17 – 24 2013

NA61/SHINE at the CERN SPS

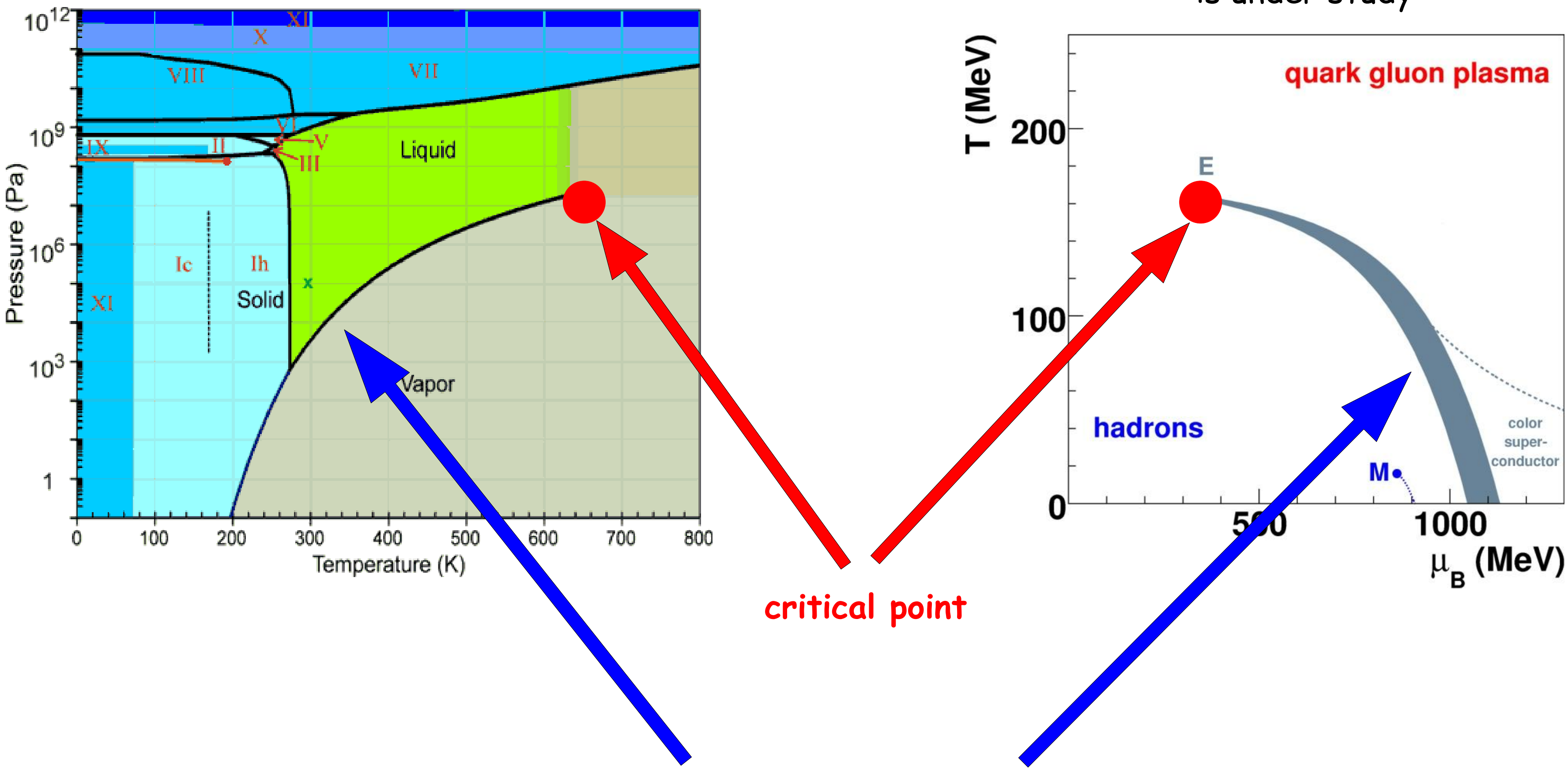
SHINE – SPS Heavy Ion and Neutrino Experiment

- Fixed target experiment in the north area of the CERN SPS
- **Succesor of NA49**
  - **Pb+Pb at 20A - 158A GeV/c**
  - **p+p, C+C, Si+Si at 158A GeV/c**
- Started in 2007
- Beams:
  - Ions (secondary: Be, primary: Ar and Xe) at 13A – *158*A GeV/c
  - Hadrons (secondary): p at 13 - 158 GeV/c, π^- at 158 and 350 GeV/c, K^- at 158 GeV/c

CONFIRMATION OF ONSET OF DECONFINEMENT

The phase diagram of water
is well established

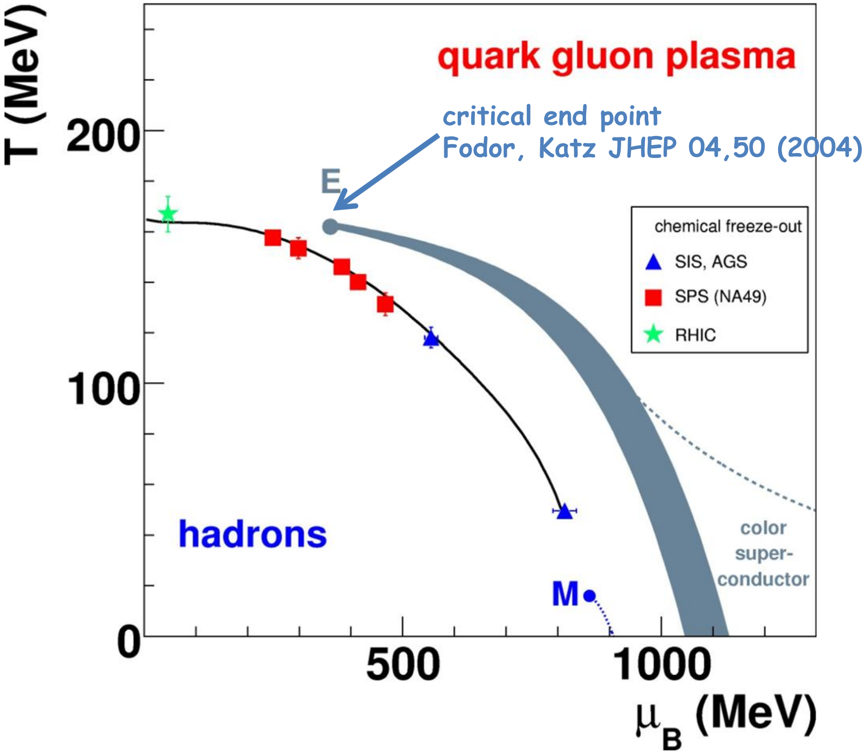
The phase diagram of
strongly interacting matter
is under study



critical point

1^{st} order phase transition

CONFIRMATION OF ONSET OF DECONFINEMENT



QCD considerations suggest
a 1st order phase boundary
ending in a critical point

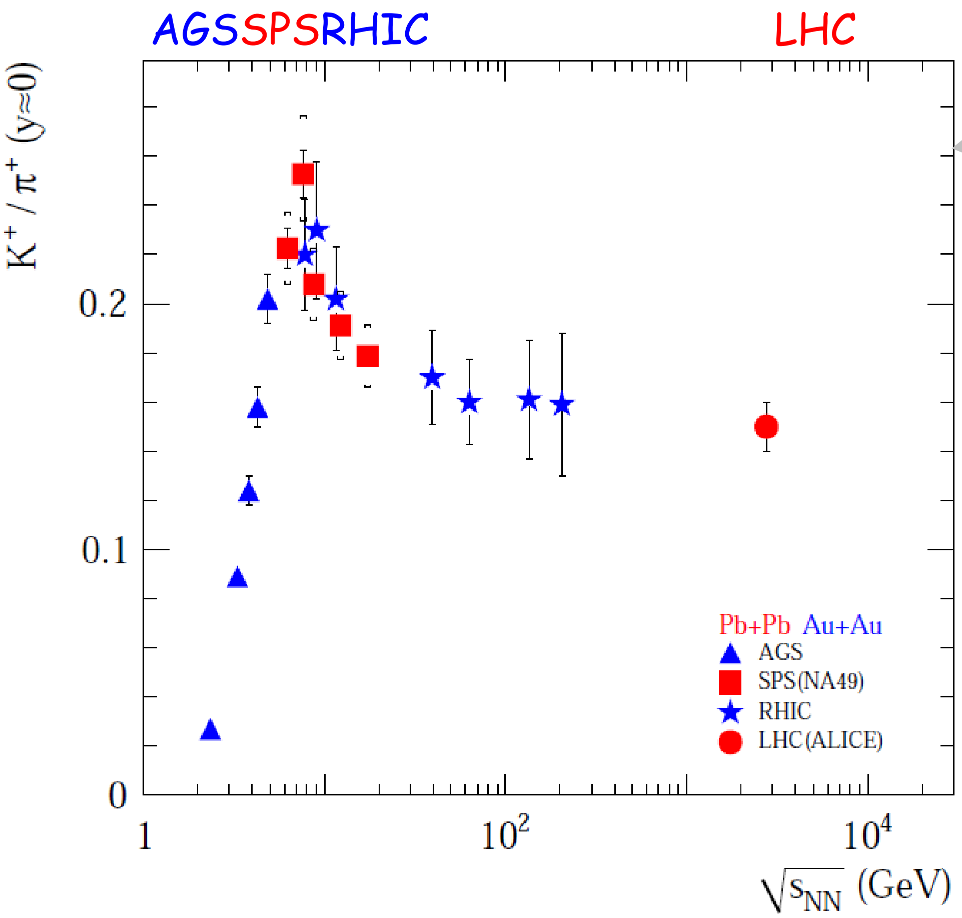
hadro-chemical freeze-out points
are obtained from statistical model fits
to measured particle yields

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

CONFIRMATION OF ONSET OF DECONFINEMENT


The horn in strangeness yield

Deconfinement

↓

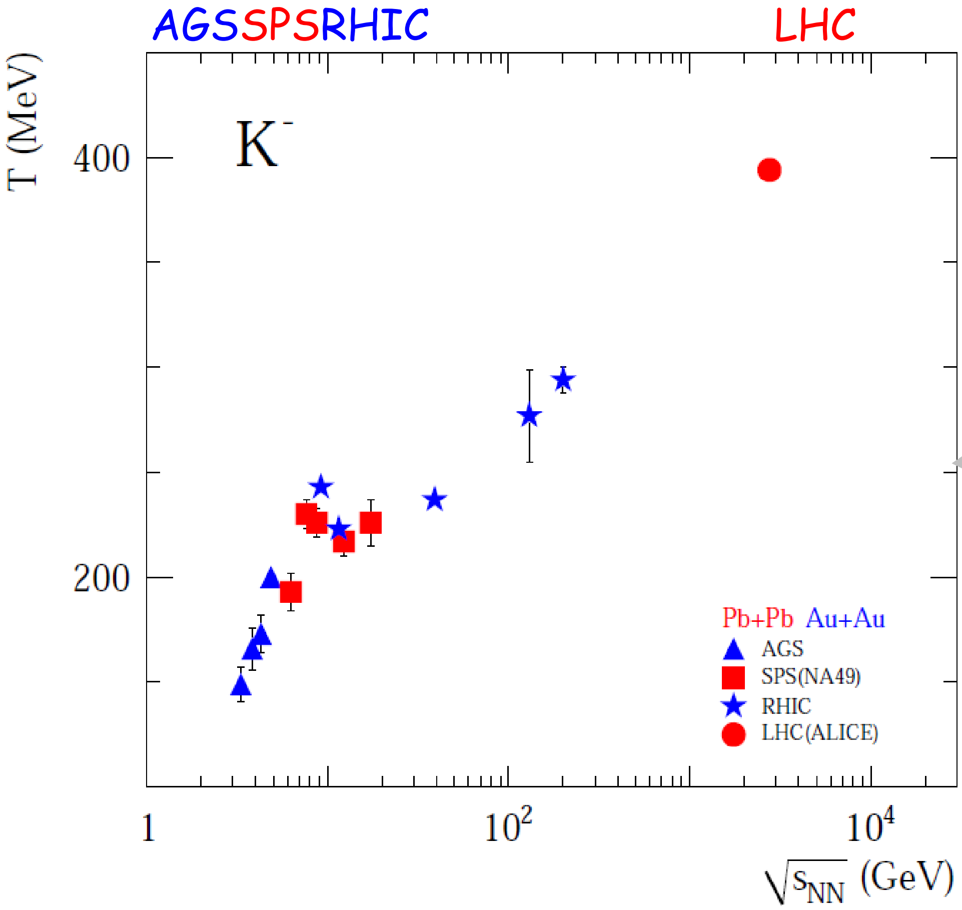
Decrease of masses of strangeness carriers and the number ratio of strange to non-strange degrees of freedom

↓

A sharp maximum in the strangeness to pion ratio

CONFIRMATION OF ONSET OF DECONFINEMENT

The step in m_T slopes



Deconfinement

↓

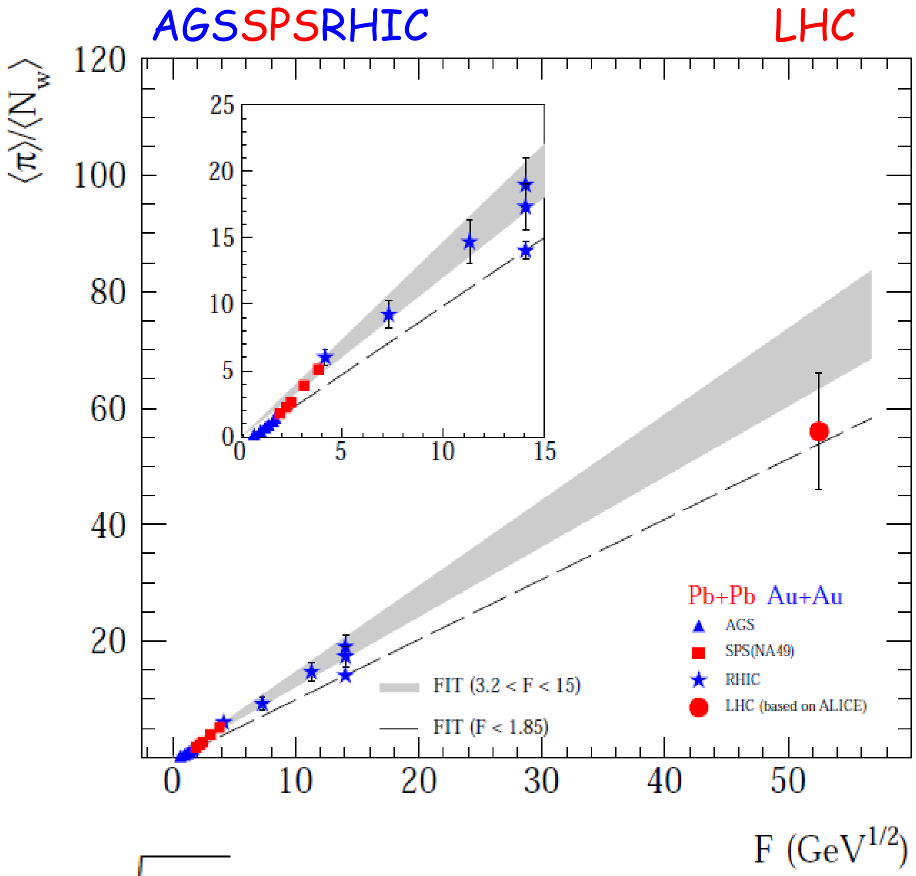
Constant temperature and pressure in the mixed phase region

↓

Weaker transverse expansion and thus weaker energy dependence of T

CONFIRMATION OF ONSET OF DECONFINEMENT

The kink in pion multiplicity



Deconfinement

↓

Increased entropy production

↓

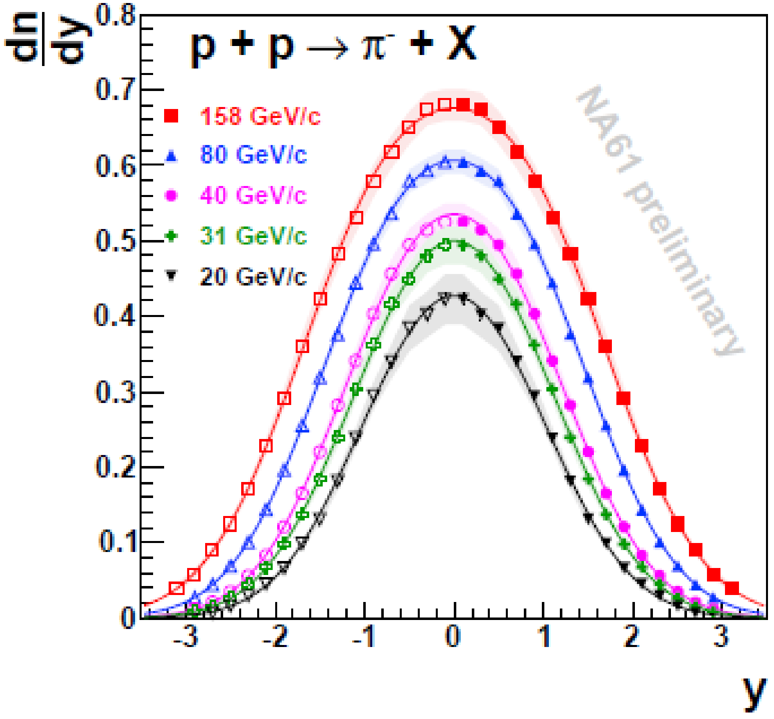
Steepening of the increase of pion production

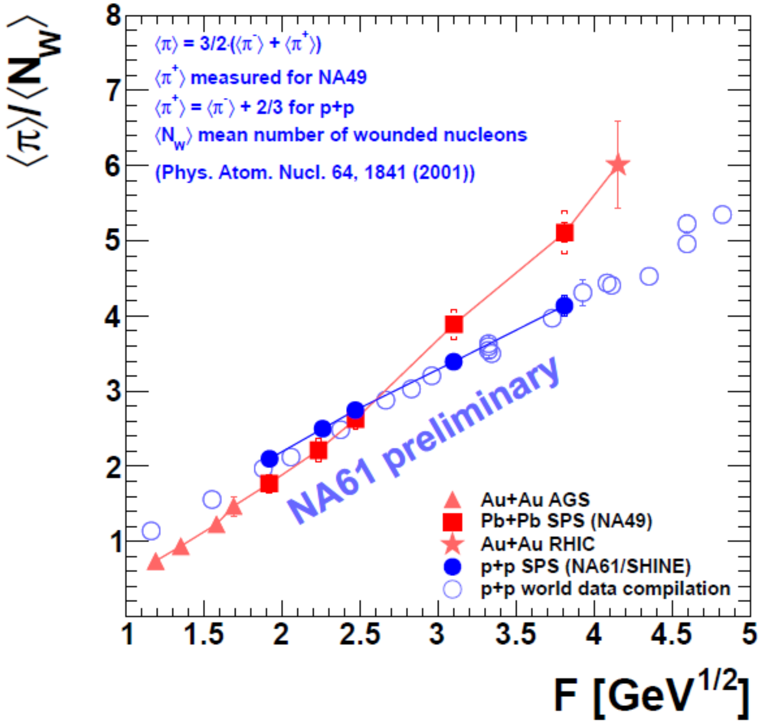
$$F = \sqrt{\sqrt{s_{NN}}}$$

$\langle\pi\rangle$ - total pion multiplicity

$\langle N_W\rangle$ - number of interacting nucleons

CONFIRMATION OF ONSET OF DECONFINEMENT





$$F \approx s_{NN}^{1/4}$$

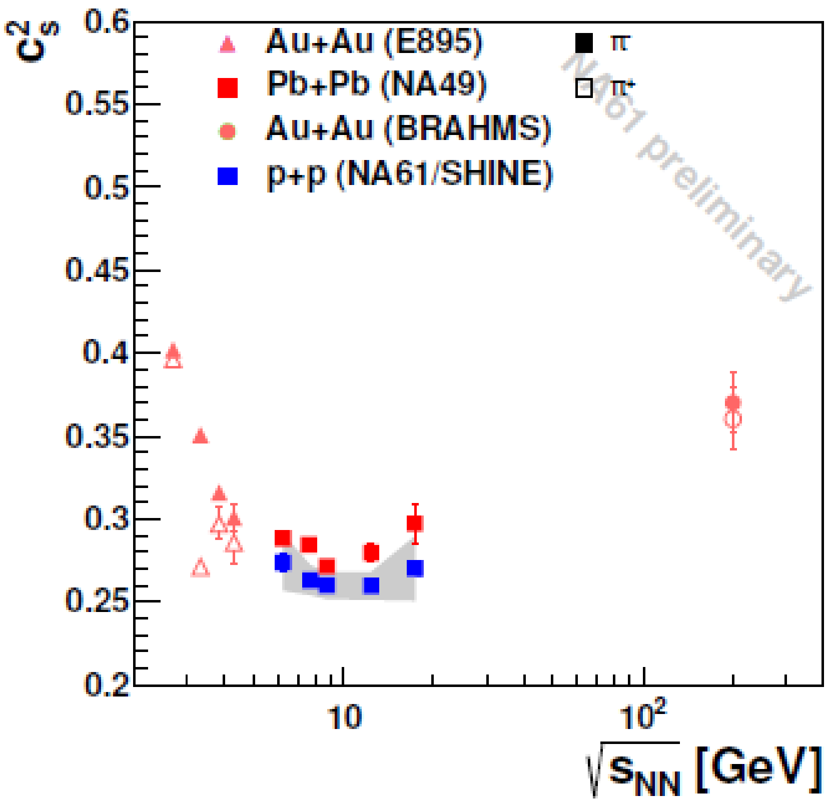
✓NA61 results agree with the previous measurements

✓π multiplicity about 200 times higher in central Pb+Pb than in p+p

✓π multiplicity at the SPS energies increases faster in central Pb+Pb than in p+p (“kink”)

✓The two dependences cross each other at about 40A GeV/c

CONFIRMATION OF ONSET OF DECONFINEMENT



$$c_S^2 = -\frac{4}{3}\frac{ln(\sqrt{s}_{NN}/2m_p)}{\sigma_y^2} + \sqrt{[\frac{4}{3}\frac{ln(\sqrt{s}_{NN}/2m_N)}{\sigma_y^2}]^2 + 1}$$

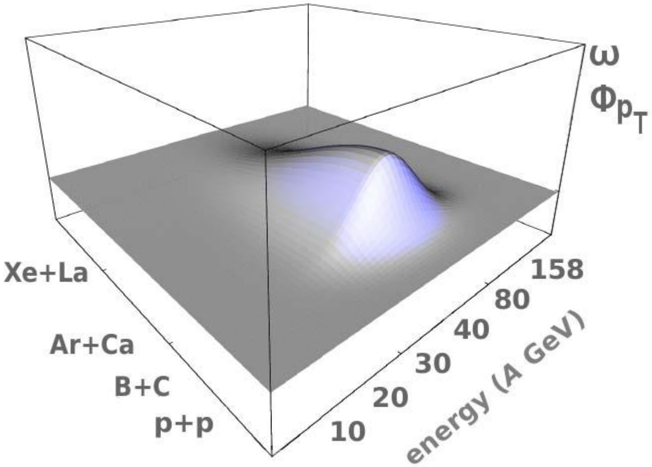
✓ c_s^2 dependence is similar in p+p and Pb+Pb

Pb+Pb: Phys. Rev. C 66, 054902 (2002), Phys. Rev. C 77, 024903 (2008)
c_s^2: E. Shuryak, Yad. Fiz. **16**, 707 (1972) [Sov. J. Nucl. Phys. **16**, 395 (1973)],
LV. Bravina et al. Phys. Rev. C 60, 024904

SEARCH FOR CRITICAL POINT

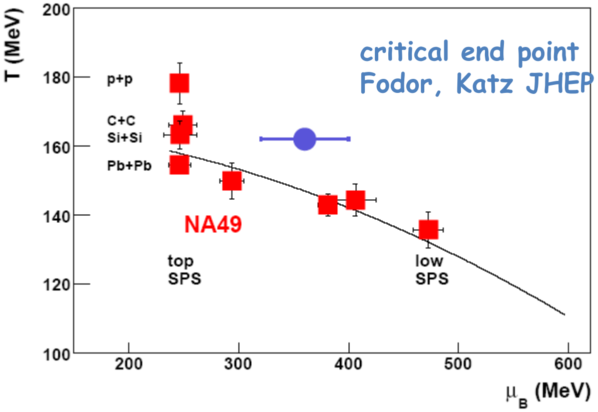
search strategy: 2-dimensional (T, μ_B) scan of phase diagram

expected "hill" of fluctuations



freeze-out points from stat. model

Becattini et al, PRC73, 044905 (2006)



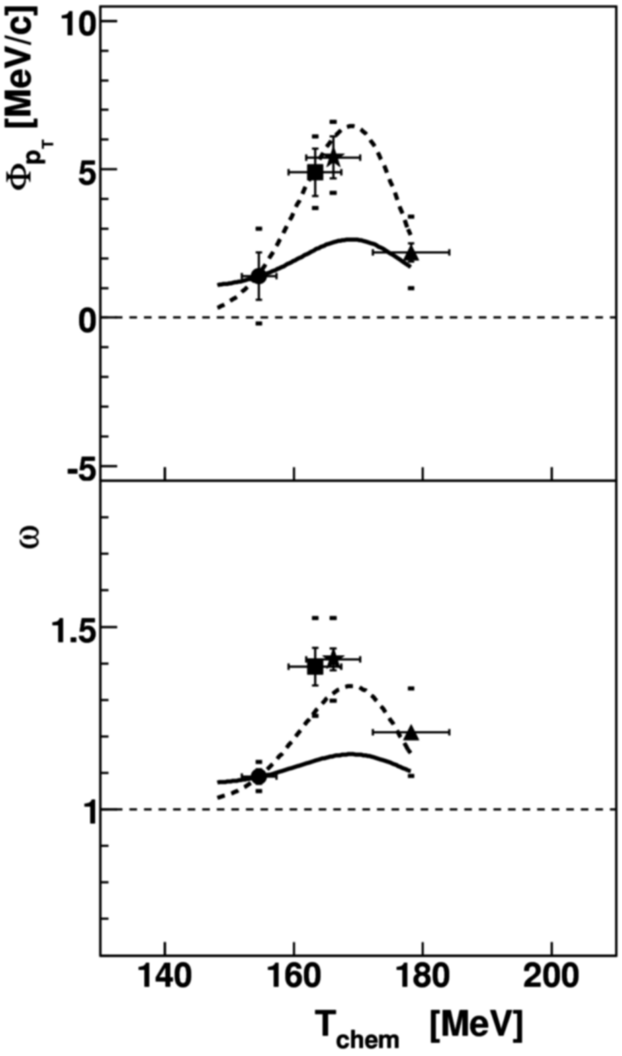
critical end point
Fodor, Katz JHEP 04,50 (2004)

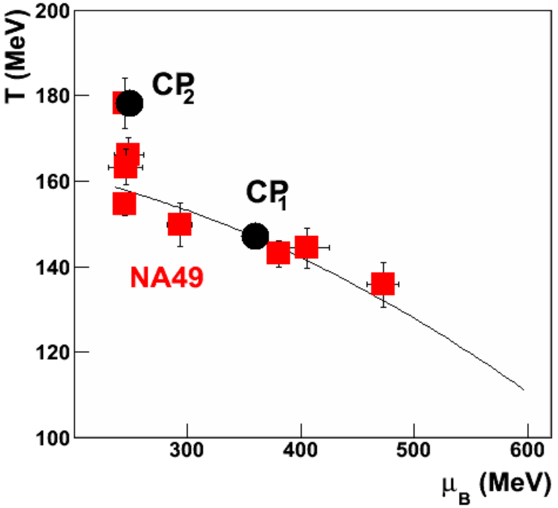
- ✓ Deconfinement necessary for observing CP effect (above 30A GeV)
- ✓ Expected size of fluctuation signals ($\sim\xi^2$) limited by short lifetime and size of collision system (correlation lengths $\xi\sim$3–6 fm for Pb+Pb)

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

SEARCH FOR CRITICAL POINT

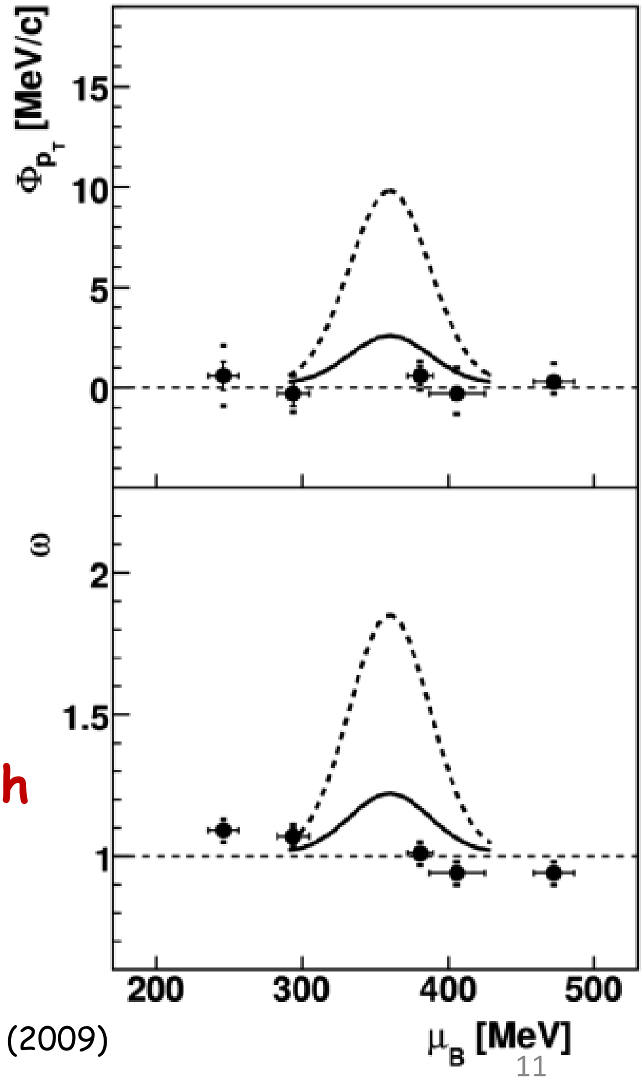
Average p_t and multiplicity fluctuations: Dependence on phase diagram coordinates





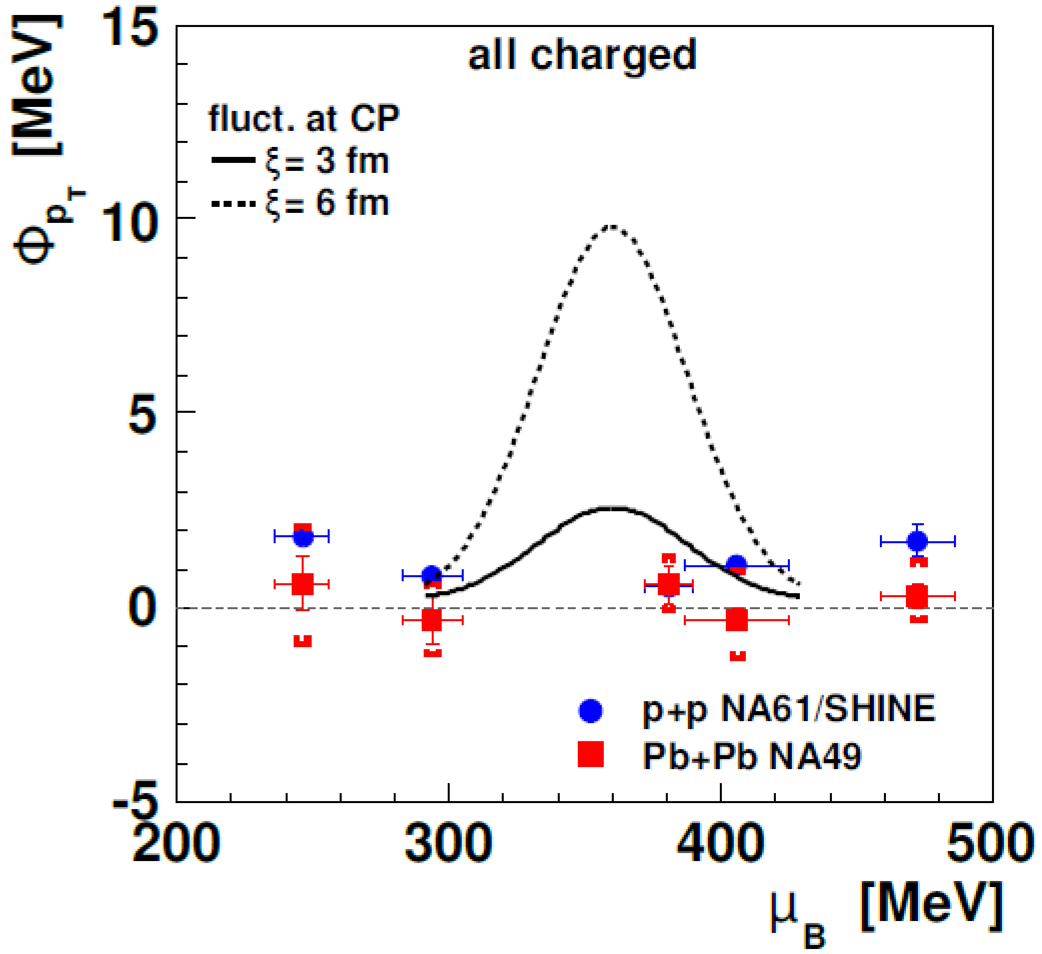
Maximum of Φ_{pT} and ω observed for C+C and Si+Si

Data are consistent with the CP_2 predictions



NA49:
see Nucl. Phys. A830, 547C-550C (2009)
for details

SEARCH FOR CRITICAL POINT



T. Czopowicz and B. Maksiak,, CPOD 2013

Collision energy dependence of Φ_{pT} for p+p and central Pb+Pb collisions does not show any anomalies expected for the critical point

SEARCH FOR CRITICAL POINT

Pion and proton intermittency analysis

Predictions of critical QCD

1. Net baryon density at midrapidity is an order parameter for the QCD critical point.
2. At the critical point the density-density correlation function in transverse momentum space of net baryons at midrapidity obeys a power-law:

$$\langle n_B(\overrightarrow{p_T})n_B(0)\rangle \sim |\overrightarrow{p_T}|^{2\phi_{2,c}}$$

3. For the *3D* Ising universality class $\phi_{2,c} = 5/6$
4. The critical power-law behaviour of the net baryon density-density correlation is transferred also to the proton density-density correlation.

Methodology

- Such a power-law distribution can be observed through proton intermittency analysis in transverse momentum space.
- We have to calculate the second factorial moment of the proton transverse momentum distribution $F_2(M)$ as a function of M (M^2 = number of transverse momentum bins).
- For protons originating from a critical state (without background) we expect:

$$F_2(M) \sim M^{5/3}$$

- In real data background is always present and has to be removed.

SEARCH FOR CRITICAL POINT

Pion and proton intermittency analysis

Intermittency analysis was performed in the following systems:

- C+A with A = C, N (50000 events)
- Si+A with A = Al, Si, P (100000 events)
- Pb+Pb (1500000 events)

Event and track selection criteriae:

- Events corresponding to central collisions (centrality 0-12%)
- Particles with center of mass rapidity in the interval [–0.75, 0.75]
- Tracks corresponding to identified protons with at least 80% purity

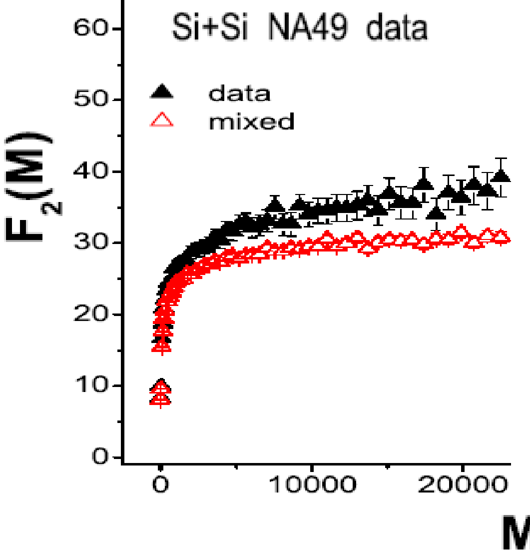
Background is removed by subtracting the moments of constructed mixed events from those of the data:

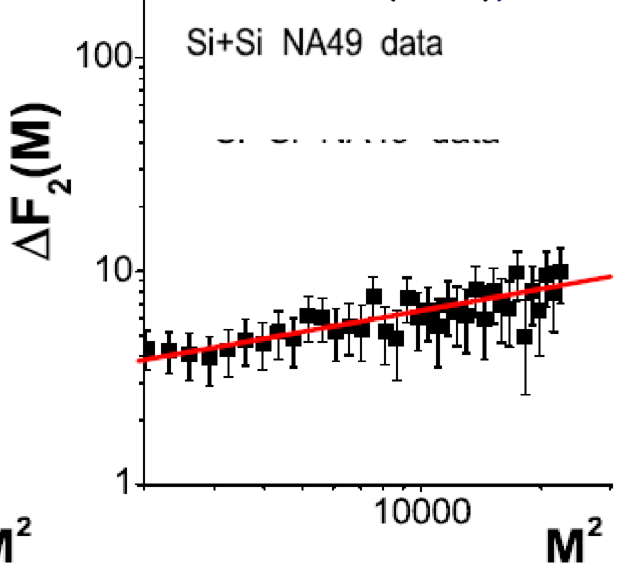
$$\Delta F_2(M) = F_2^{(data)}(M) - F_2^{(mixed)}(M)$$

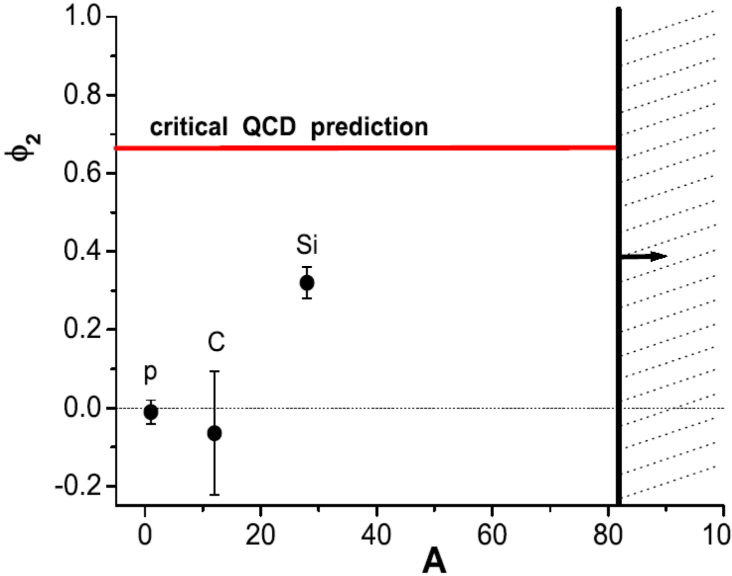
We look for a power-law behaviour $\Delta F_2(M) \sim M^{2\phi_2}$
(exactly at the critical point $\phi_2 = \phi_{2,c} = 5/6$)

SEARCH FOR CRITICAL POINT

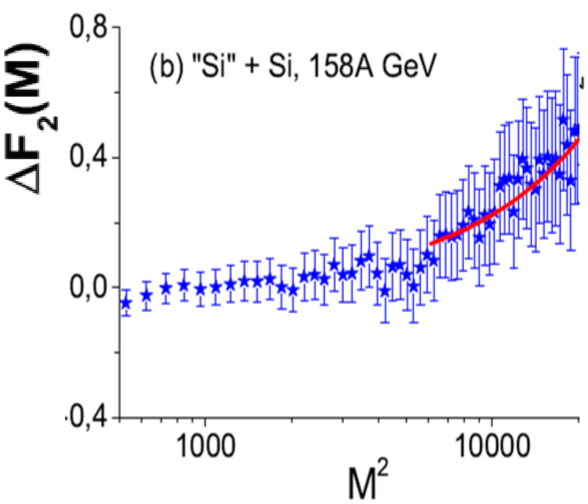
$\pi^+\pi^-$ pairs (NA49: T.Anticic et al., PRC 81, 064907(2010))

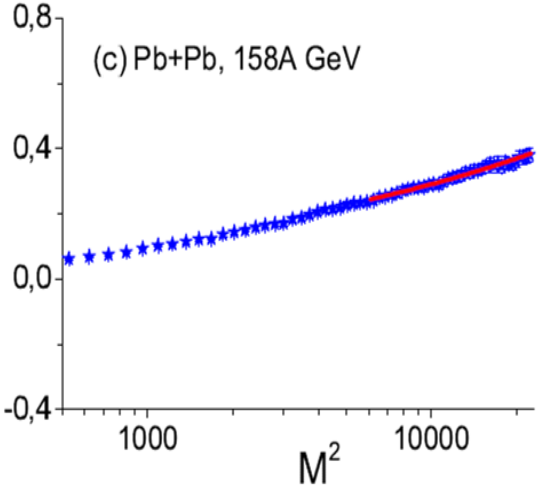


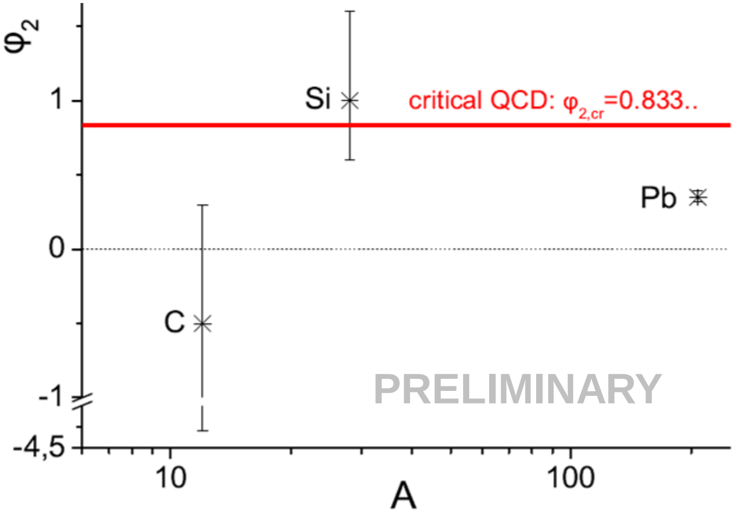




Protons (NA49: arXiv:1208.5292)







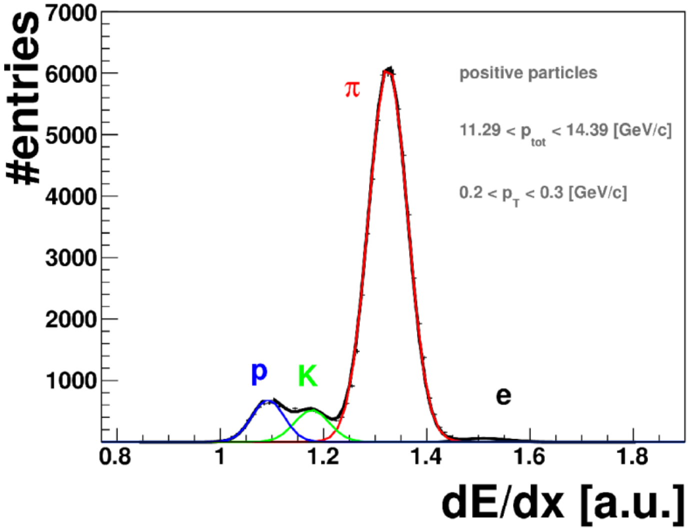
Critical point close to freeze-out points of Si+Si and Pb+Pb system at 158A GeV ?

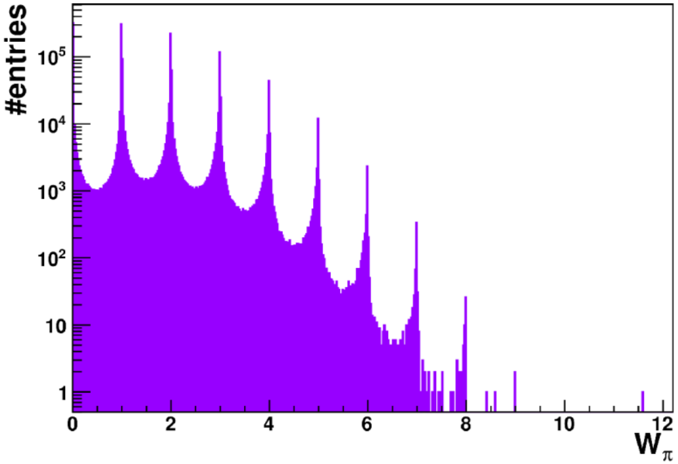
FLUCTUATIONS OF IDENTIFIED PARTICLES

dE/dx information doesn't allow to identify each particle uniquely as the dE/dx distributions overlap

The **identity method* allows to** obtain second and third moments (pure and mixed) of identified particle multiplicity distributions corrected for misidentification effect

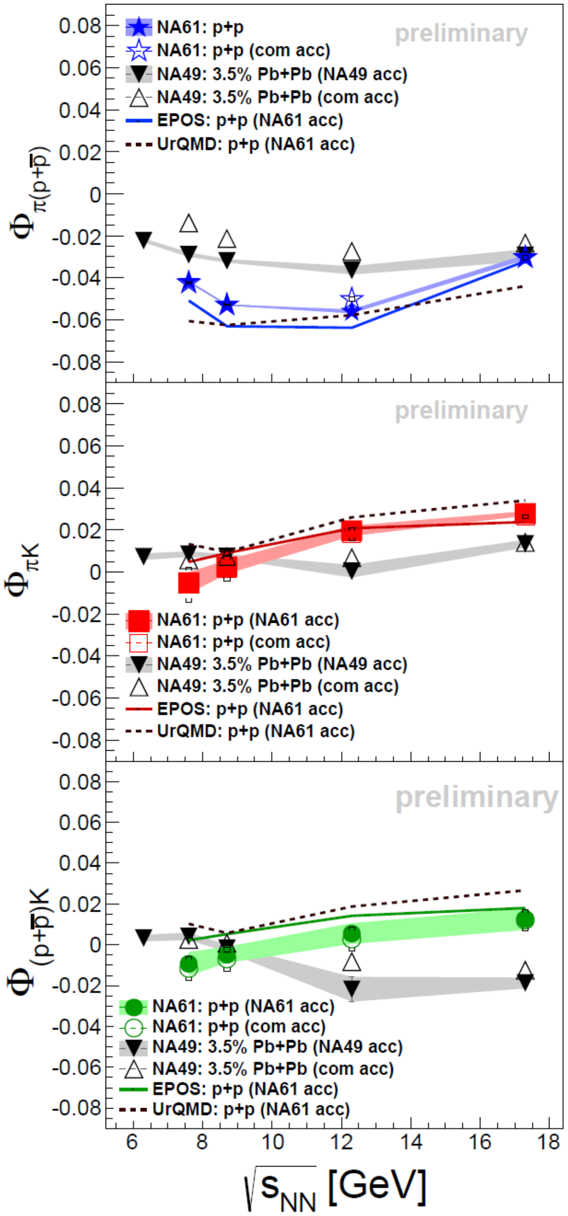
First fluctuation measurements of p+p – unique opportunity to compare Pb+Pb and p+p results at the SPS energies





*Phys. Rev. C83, 054907 (2011), Phys. Rev C84, 024902 (2011)
arXiv:nucl-th/1204.6632

Φ MEASURE OF THE FLUCTUATIONS BETWEEN DIFFERENT PARTICLES



$$\Phi_{ij} = \frac{\sqrt{\langle N_i\rangle\langle N_j\rangle}}{\langle N_i + N_j\rangle}\cdot\left(\sqrt{\Sigma_{ij}} - 1\right)$$

where $\Sigma_{ij} = [\langle N_i\rangle\omega_j + \langle N_j\rangle\omega_i - 2(\langle N_iN_j\rangle - \langle N_i\rangle\langle N_j\rangle)]/\langle N_i + N_j\rangle$

Φ=0 for independent particle production

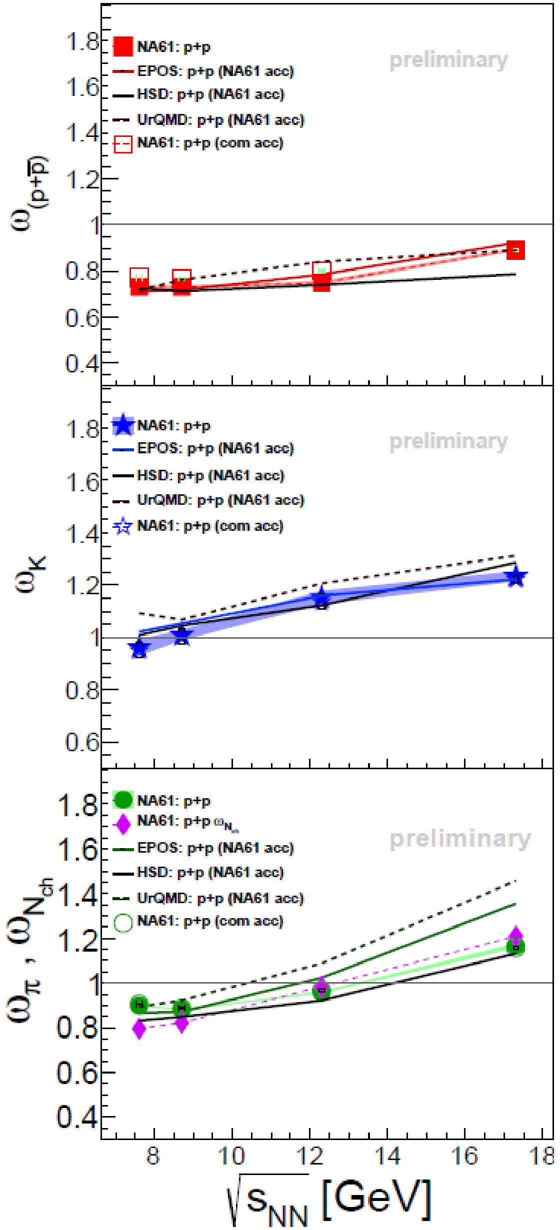
Fluctuations of πp affected by conservation laws and resonance decays (PRC70, 064903).

Small increase of πK fluctuations with increasing energy.

Φ≈0 indicates weak if any correlations in particle production.

UrQMD and EPOS closely reproduce data

SCALED VARIANCE OF MULTIPLICITY DISTRIBUTION



$$\omega = \frac{\langle N^2\rangle - \langle N\rangle^2}{\langle N\rangle} = \frac{\mathrm{Var}(N)}{\langle N\rangle}$$

ω=1 for Poisson distribution

Fluctuations can not be corrected for the limited acceptance (results are presented in NA61 acceptance*)

ω_{p+p} is below 1 for all SPS energies possibly due to baryon number conservation (B = 2).

ω_K is above 1 for all SPS energies possibly due to strangeness conservation (S = 0).

ω_π increases with increasing energy reflecting increase of ω_{Nch} measured in full phase-space acceptance.

HSD and EPOS reproduce measured scaled variances.

*https://edms.cern.ch/document/1237791/1

SUMMARY

Onset of deconfinement:
discovery confirmed, systematic studies in progress:

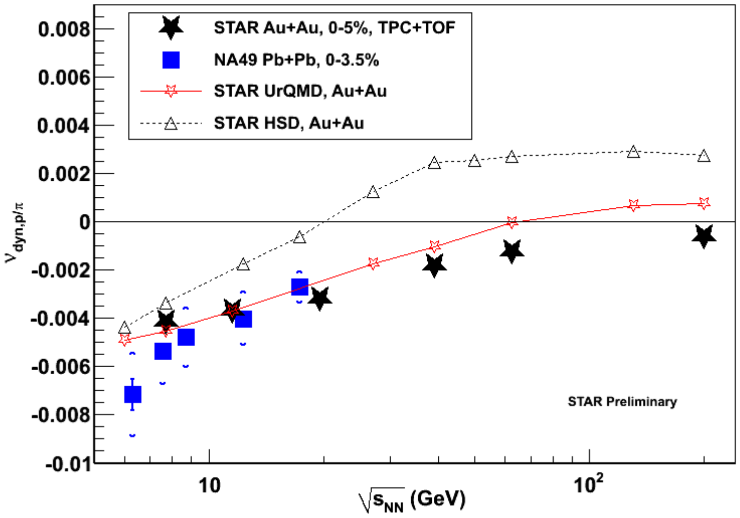
- results from RHIC agree with the relevant NA49 data,
- first LHC data confirm the interpretation,
- NA61/SHINE studies system size dependence of the observed signals.

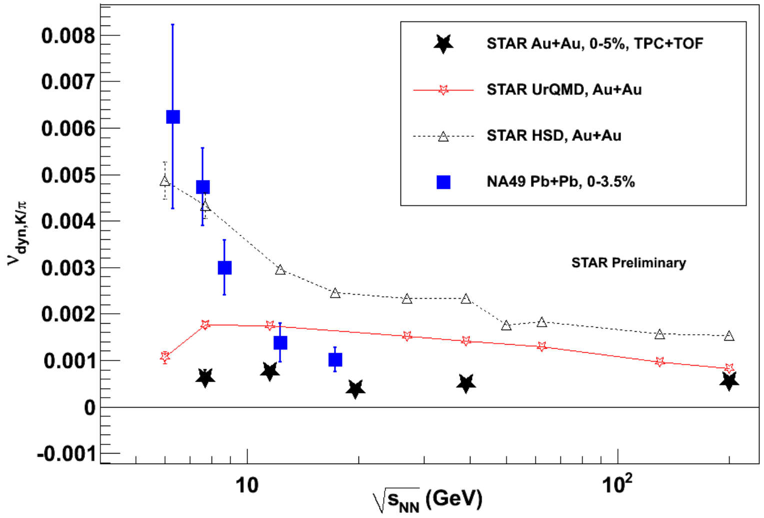
Search for the critical point:

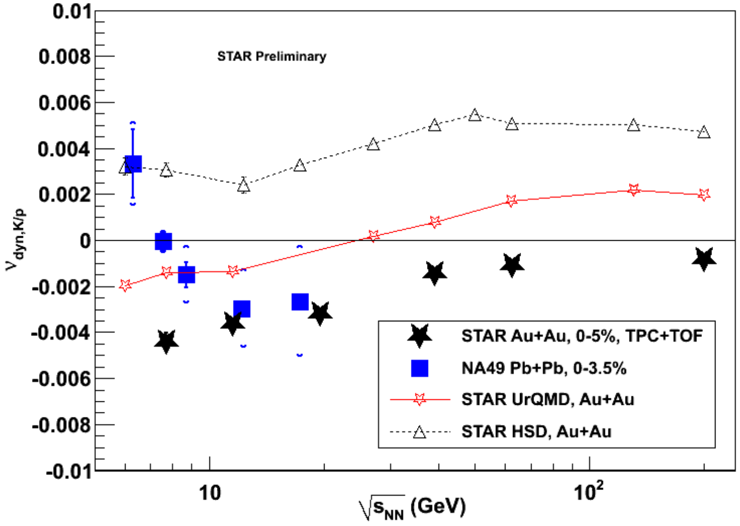
- NA49 hints of a maximum of fluctuations in Si+Si at 158A GeV
- NA61/SHINE performs systematic search via system size energy scan,
- conservation laws seem to play important role in p+p,
- EPOS model reproduces chemical fluctuations in p+p collisions.

ADDITIONAL SLIDES

NA49 vs. STAR







[K,p] and [K,π] results from NA49 and STAR are significantly different at low energies.

NA49 results use identification via the identity method

What is the reason for this difference?
✓bias in the used methods
✓acceptance effects

Figures from: T. Tarnowsky, proceedings of Quark Matter 2011

NA49 vs. STAR

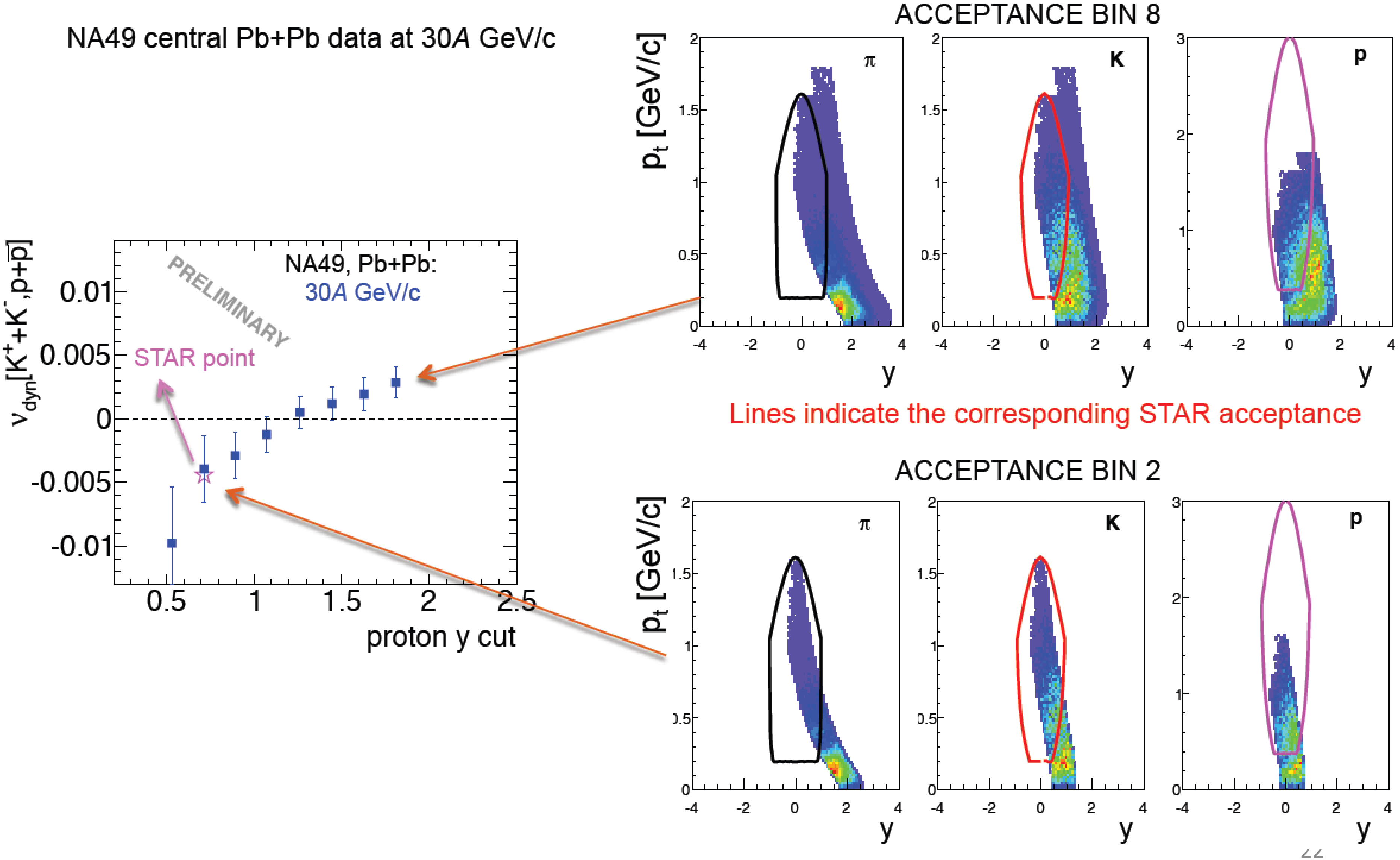
Dependence on acceptance

NA49 central Pb+Pb data at 30*A* GeV/c

ACCEPTANCE BIN 8

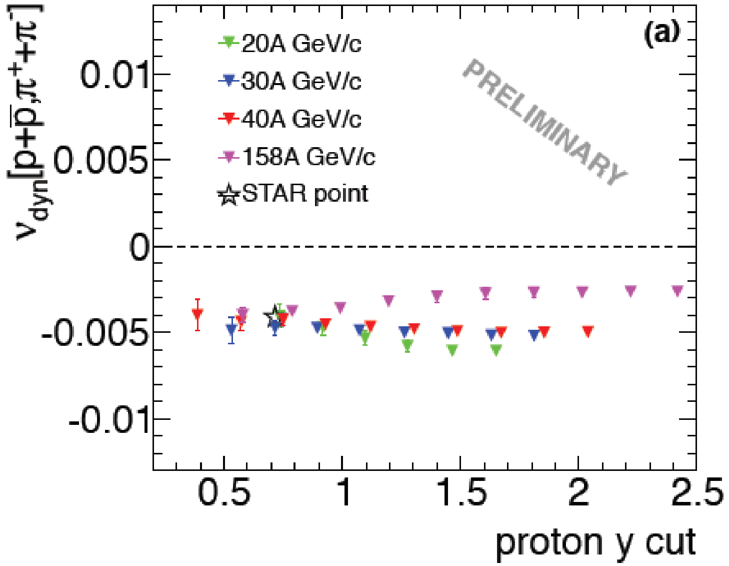
Lines indicate the corresponding STAR acceptance

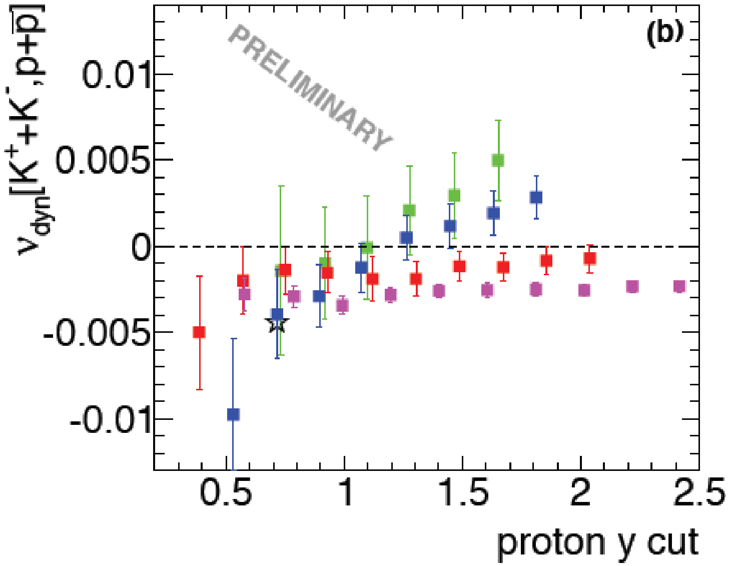
ACCEPTANCE BIN 2

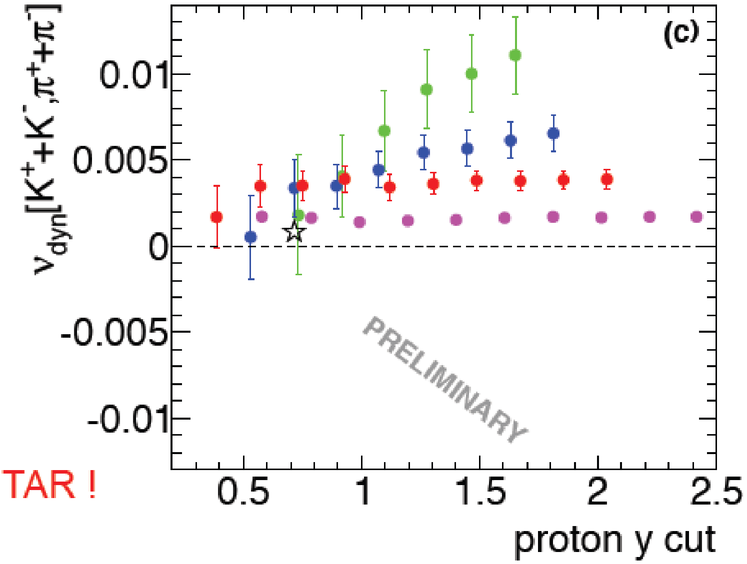


NA49 vs. STAR

Dependence on acceptance







[p,π]: no strong acceptance dependence

[K,π]: at 20*A* and 30*A* GeV/c there is a strong acceptance dependence

[K,p]: at 20*A* and 30*A* GeV/c there is a strong acceptance dependence

acceptance coverage appears to explain the difference with STAR !

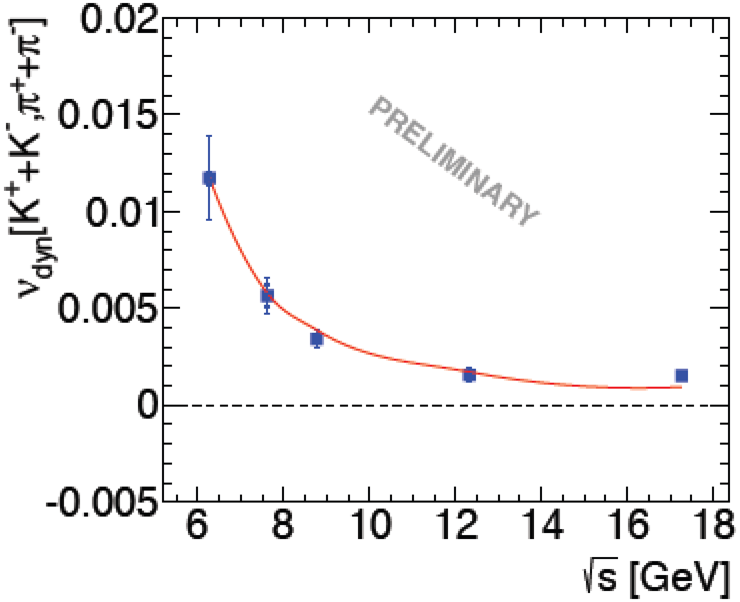
NA49 vs. STAR

$v_{dyn}[A,B]$ reexamined

$$v_{dyn}[A,B]=\frac{\langle A^2\rangle}{\langle A\rangle^2}+\frac{\langle B^2\rangle}{\langle B\rangle^2}-2\frac{\langle AB\rangle}{\langle A\rangle\langle B\rangle}-\left(\frac{1}{\langle A\rangle}+\frac{1}{\langle B\rangle}\right)$$

Poisson scaling:

$$v_{dyn}\left(\sqrt{s}\right)=v_{dyn}(6.3\,\mathrm{GeV})\frac{\left[\frac{1}{\langle\pi\rangle}+\frac{1}{\langle K\rangle}\right]_{\sqrt{s}}}{\left[\frac{1}{\langle\pi\rangle}+\frac{1}{\langle K\rangle}\right]_{6.3\,\mathrm{GeV}}}$$



After little algebra:

$$\boxed{\frac{v_{dyn}[A,B]}{\frac{1}{\langle A\rangle}+\frac{1}{\langle B\rangle}}=\Sigma^{AB}-1}$$

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

V. Koch, T. Schuster, PRC 81, 034910 (2010)   M. I. Gorenstein, M. Gazdzicki et al., PRC 84, 014904 (2011)

Poisson scaled $v_{dyn}[A,B]$ is nothing else but the shifted $\sum^{AB}$