Hadron yields and fluctuations at CERN SPS: system size dependence from p+p to Pb+Pb

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Based on 1711.07789 + 1811.10645

COST workshop @ Lund, February 28, 2019

Outline

What is done:

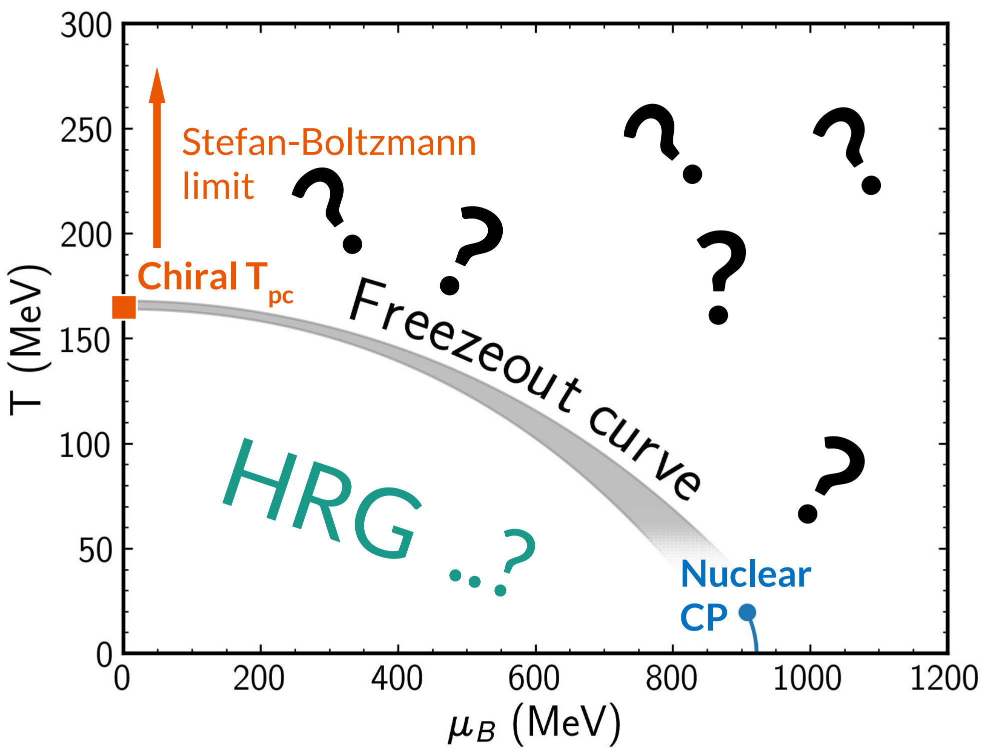
Systems: p+p, Be+Be, Ar+Sc, Pb+Pb
Energies: E_{lab}=30(31) — 150(158) GeV
Tools: HRG — Thermal-FIST, transport codes — UrQMD
Observables: K^+/π^+ ratio, $\omega[N\_]$, $\Omega[N\_, E_p]$

Contents:

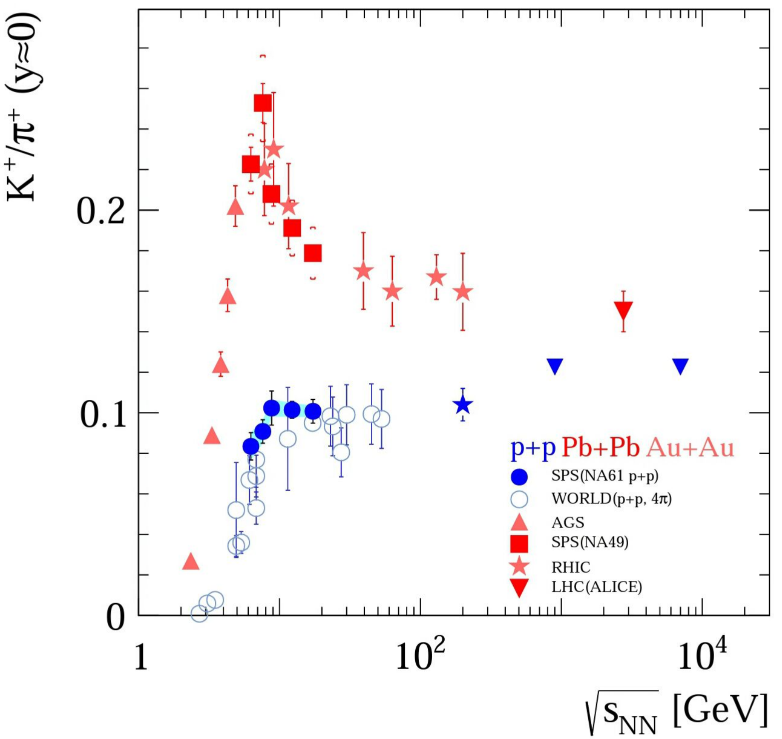
1. Why it's done;
2. CE HRG results for p+p, Be+Be, Ar+Sc, Pb+Pb;
3. Transport model for p+p, Be+Be, Ar+Sc, Pb+Pb:
   a. How b=0 collisions are related to data;
   b. Centrality effects on fluctuations;
   c. Comparison with the NA61/NA49 data;
   d. Centrality for p+p (**!**);
   e. K^+/π^+ ratio.

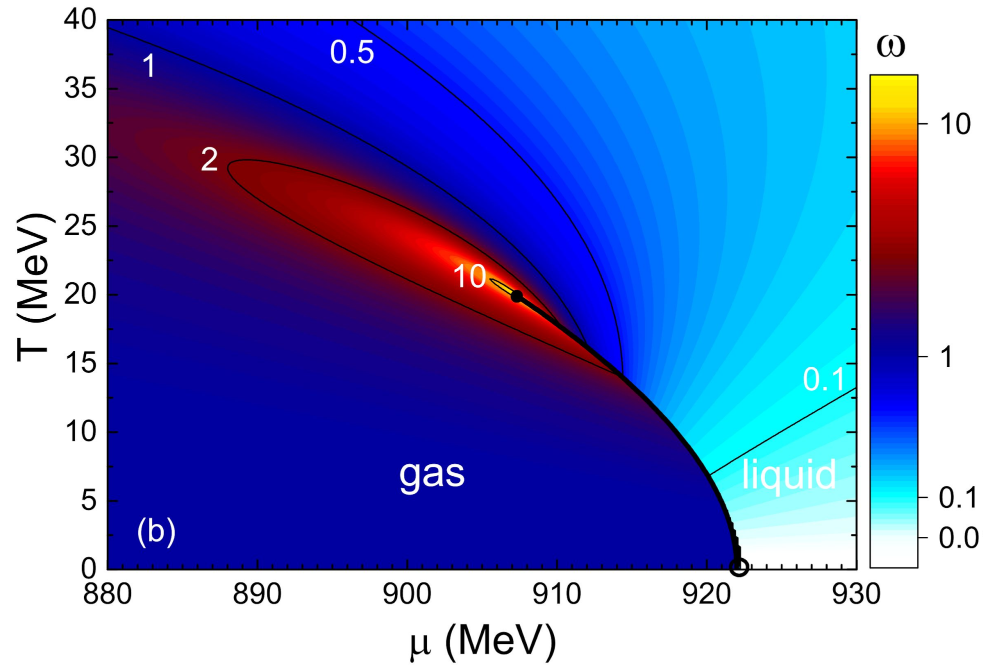
Motivation

One of the main goals of Heavy Ions physics is to study **phase structure** of QCD matter in bulk. However, yet there's still not so much known:



Observables motivation





The horn structure in **K^+/π^+** serves as experimental evidence for the onset of deconfinement and quark-gluon plasma formation [1,2]

Particle **fluctuations** reflect **critical behavior** of the system and so are useful measures to detect transitions between phases.

Non-monotonous fluctuations ⇒ criticality

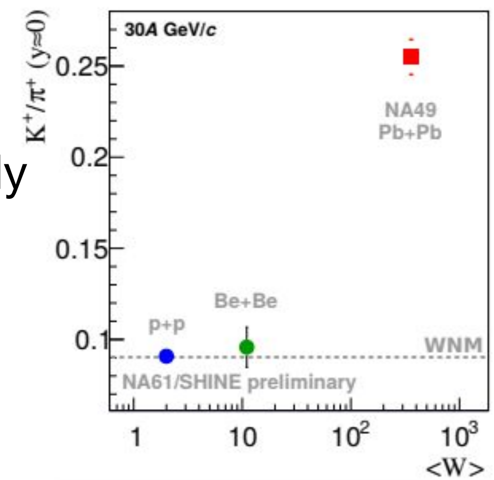
[1] N. Abgrall et al., [NA61/SHINE Collaboration]: SPSC-SR-145. CERN-SPSC-2014-031
[2] M. Gazdzicki, M.I. Gorenstein, hep-ph/9803462.
[3] V. Vovchenko, D.V. Anchishkin, M.I. Gorenstein, and R.V. Poberezhnyuk, 1506.05763

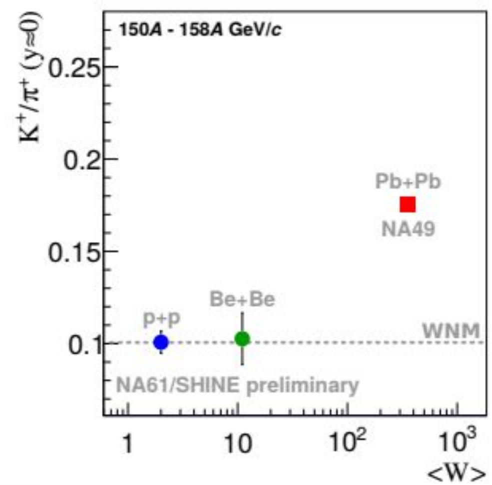
Recent NA61/SHINE data

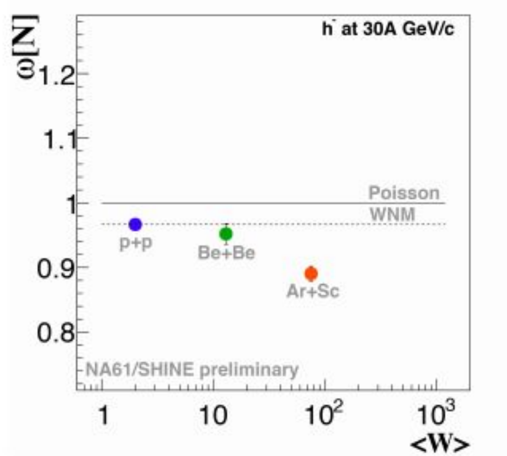
Onset of Fireball — the rapid change of hadron production properties that start when moving from Be+Be to Ar+Sc collisions discovered in recent preliminary (*checks are still in process*) NA61/SHINE results [1,2].

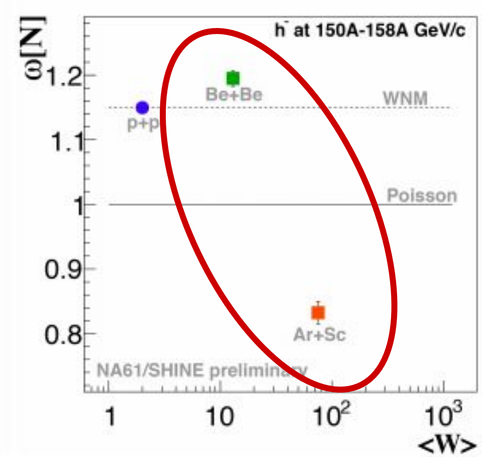
Scaled variance ω for negatively charged particles N_- :

$$\omega[N_-] = \frac{\langle N_-^2 \rangle - \langle N_- \rangle^2}{\langle N_- \rangle}$$









What does theory have to do with this data?
Are there any effects not related to QCD physics but to **imperfectiontions of the experiment**?

<W> = A+A — system size

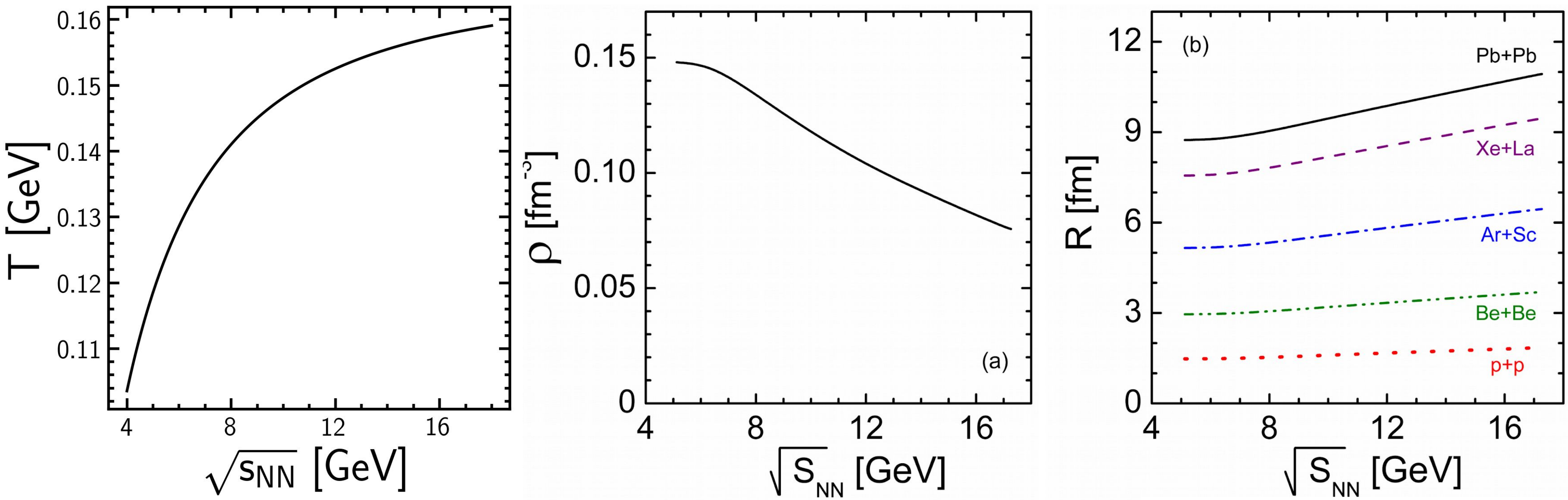
[1] A. Aduszkiewicz et al. [NA61/SHINE Collaboration], CERN-SPSC-2017-038
[2] M. Gazdzicki et al. [NA61/SHINE Collaboration], PoS CPOD2017 (2018) 012

Hadron Resonance Gas: chemical freeze-out curve

We use HRG within Thermal-FIST [1] package imposing **Canonical Ensemble** (baryon, electric, and strange charges conserved in every microstate), so:

temperature **T**, volume **V**, and strangeness suppression γ_s
are free parameters that are fixed from the data

We obtain a continuous f(A+A, $\sqrt{s_{NN}}$) freeze-out curve in CE:



Where canonical volume **V** can be found through baryonic density ρ_B (assumption)

$$R \equiv [3V/(4\pi)]^{1/3}$$

$$R = [3B/(4\pi\rho_B)]^{1/3}$$

and **T** is from [2,3]:

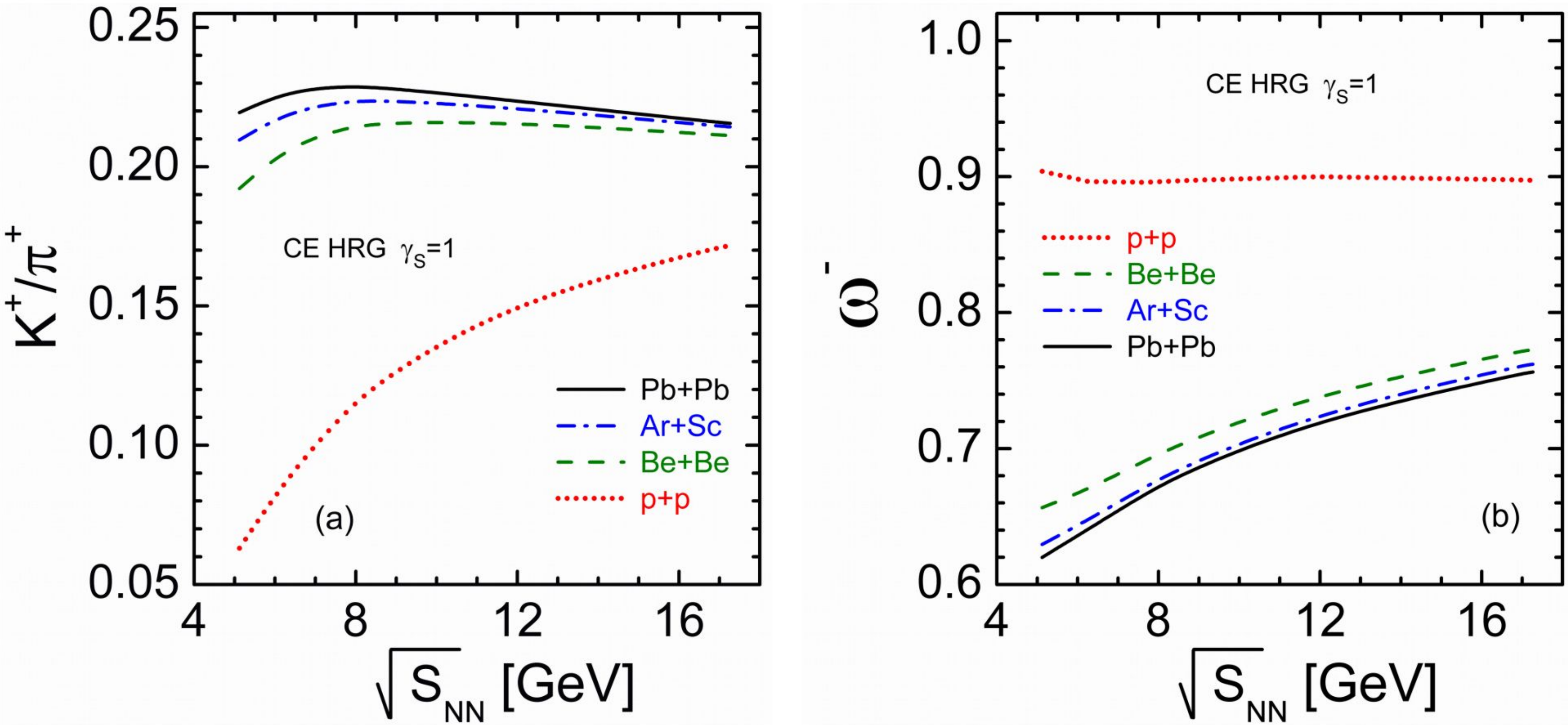
$$T(\mu_B) = a - b\,\mu_B^2 - c\,\mu_B^4$$

$$\mu_B(\sqrt{s_{NN}}) = \frac{d}{1 + e\sqrt{s_{NN}}}$$

[1] V. Vovchenko and H. Stoecker, 1901.05249, **see also V.Vovchenko talks on Tuesday + Wednesday**
[2] J. Cleymans, H. Oeschler, K. Redlich, and S. Wheaton, hep-ph/0511094
[3] V. Vovchenko, V. V. Begun, and M. I. Gorenstein ,1512.08025

HRG: results

$$\omega[N_-] \equiv \frac{\langle N_-^2 \rangle - \langle N_- \rangle^2}{\langle N_- \rangle} \equiv \omega^-$$



- CE suppresses **strangeness** in small systems due to exact charge conservation;
- CE suppresses **fluctuations** in large systems;

HRG: comparison with the data

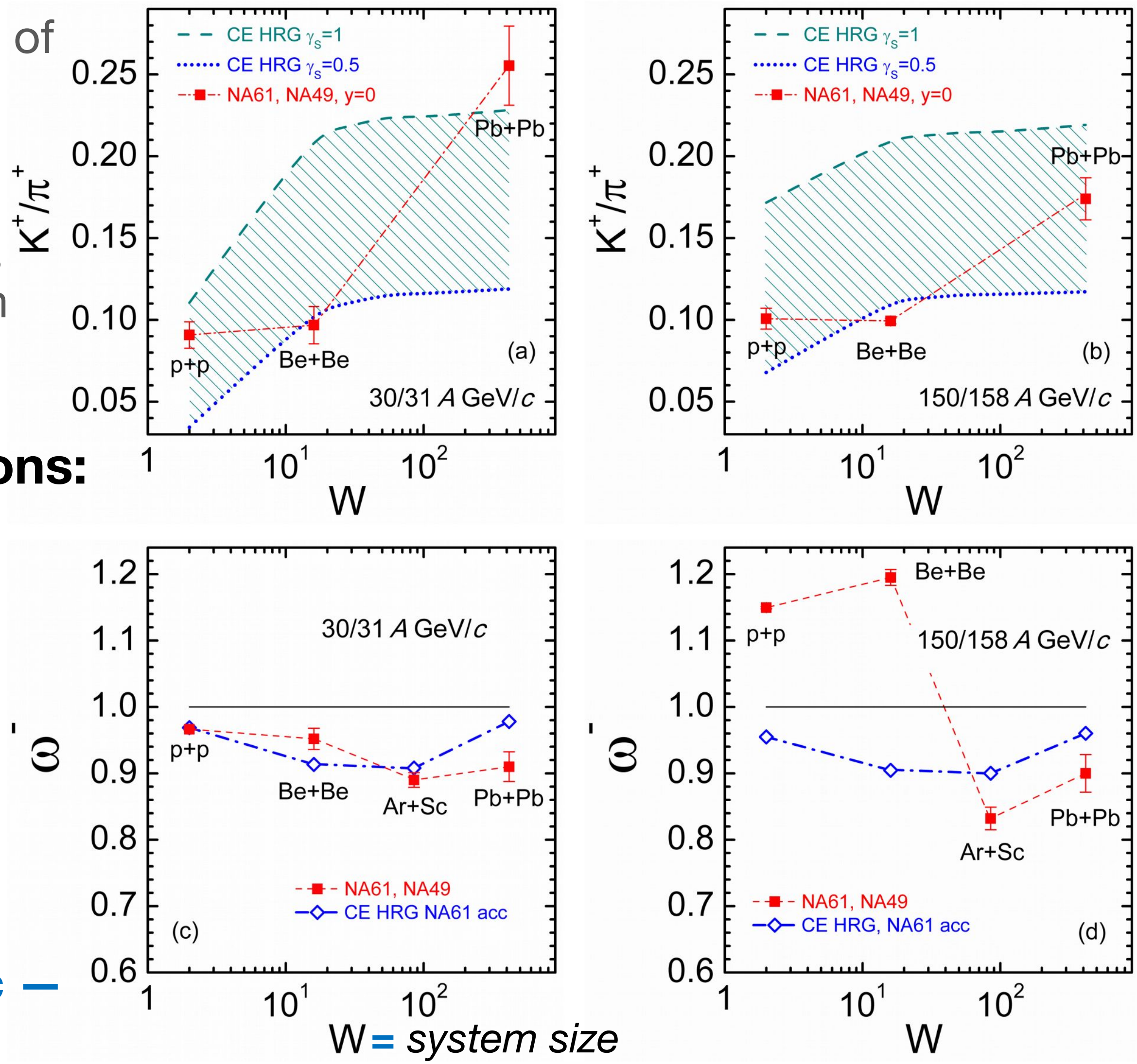
- CE suppresses multiplicities of hadrons in small systems: increase of **K^+/π^+** with **W**
- Strangeness suppression γ_s leaves a lot of room to reach the data for K^+/π^+

Finite acceptance corrections:

$$\omega^- = 1 - q + q\,\omega^-_{4\pi}$$

$$q = \langle N_- \rangle / \langle N_- \rangle_{4\pi}$$

- CE suppresses fluctuations, so $\omega < 1$
- acceptance drives $\omega \to 1$
- **not able to produce ω >1: p+p, Be+Be @ 150 *A* GeV/c — questionable**

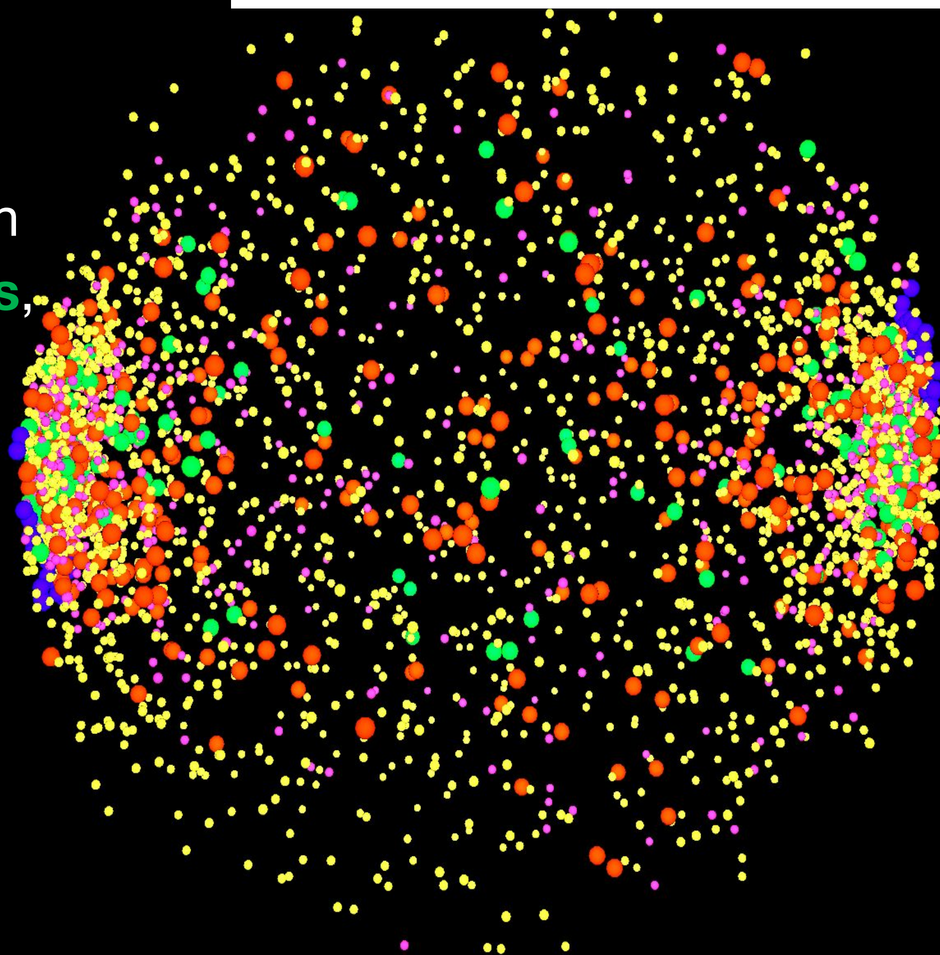


Microscopical simulations

The Ultra relativistic Quantum Molecular Dynamics (**UrQMD**) model [1,2] is a microscopic transport theory based on the covariant propagation of all hadrons on classical trajectories in combination with **stochastic binary scatterings**, **color string formation (by Pythia)** and **resonance decays**.

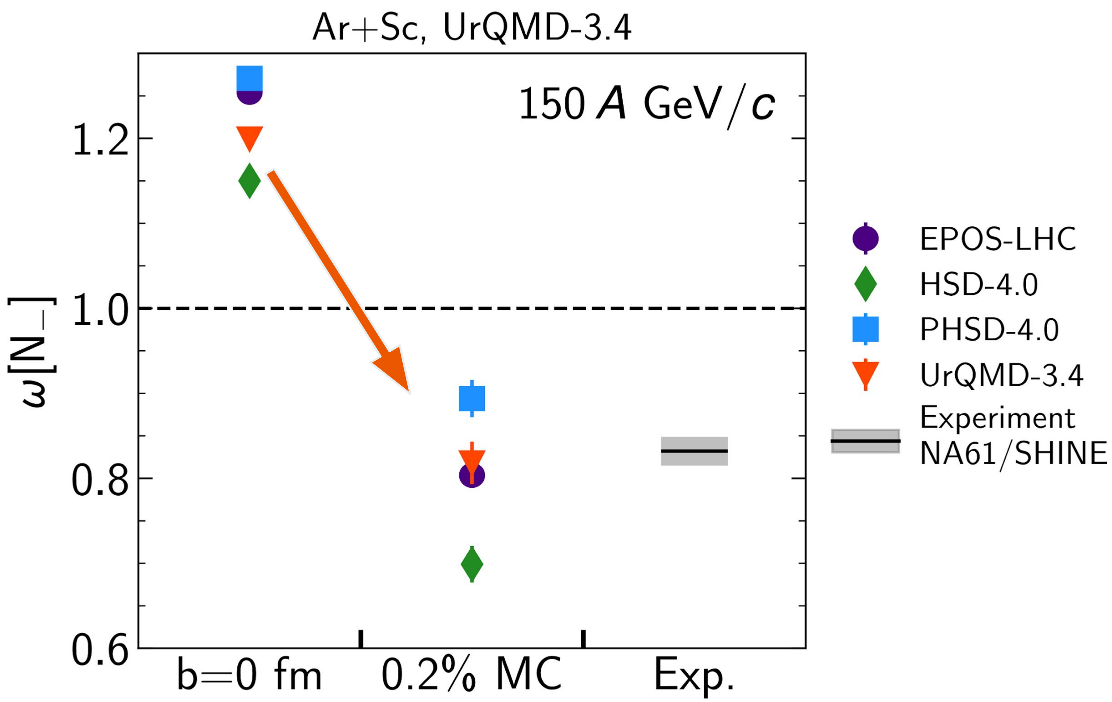
In this work: no hydro, no EoS effects, no mean fields, **only cascade + strings**.

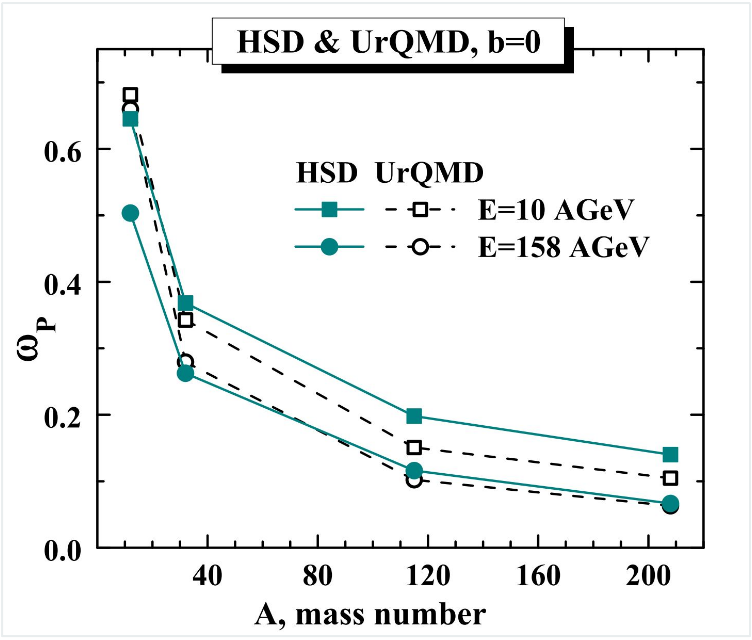
UrQMD
Frankfurt
Nantes
Duke



[1] S. A. Bass et al., nuclth/9803035
[2] M. Bleicher et al., hep-ph/9909407

Importance of centrality in intermediate systems





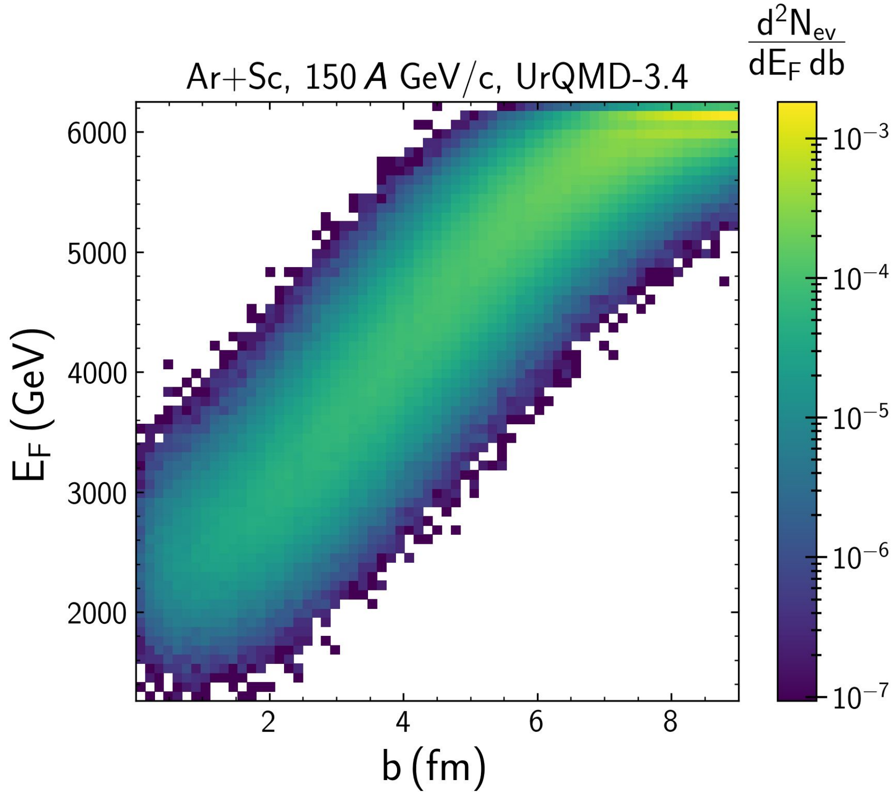
Most central events for intermediate systems cannot be approximated by b=0 fm collisions. **In b=0 fluctuations of participant number are still significant.**

Centrality selection **by multiplicity will bias** the event sample: study of **multiplicity fluctuations** in a sample of events that are preselected by multiplicity.

[1] A. Motornenko, K. Grebieszkow, E. Bratkovskaya, M. I. Gorenstein, M. Bleicher, and K. Werner, 1711.07789

[2] V.P. Konchakovski, M.I. Gorenstein, E.L. Bratkovskaya and W. Greiner, 1001.3085

Centrality selection: as it's done in the experiment

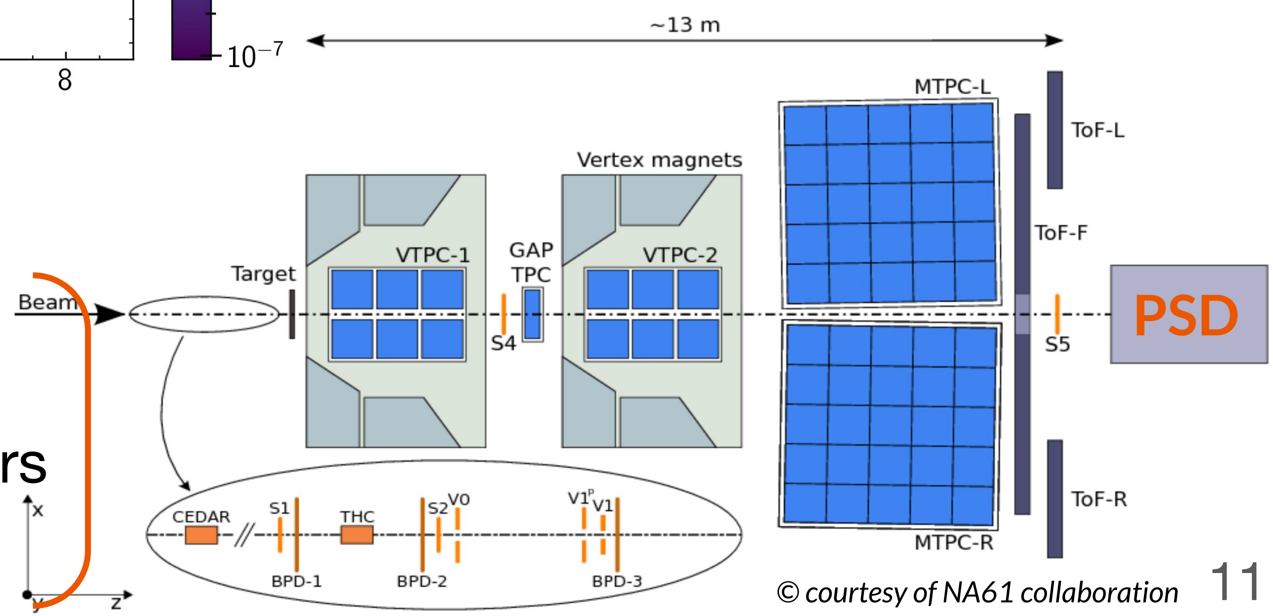


PSD (**P**rojectile **S**pectator **D**etector) is used to determine centrality on event-by-event basis.

The calorimeter measures the **energy E_F in a small angle of the forward hemisphere**. PSD is not able to identify particles, thus, not only the projectile spectators contribute to **E_F**.

Information on target spectators is absent.

+ the acceptance maps of the NA61/SHINE detectors are imposed



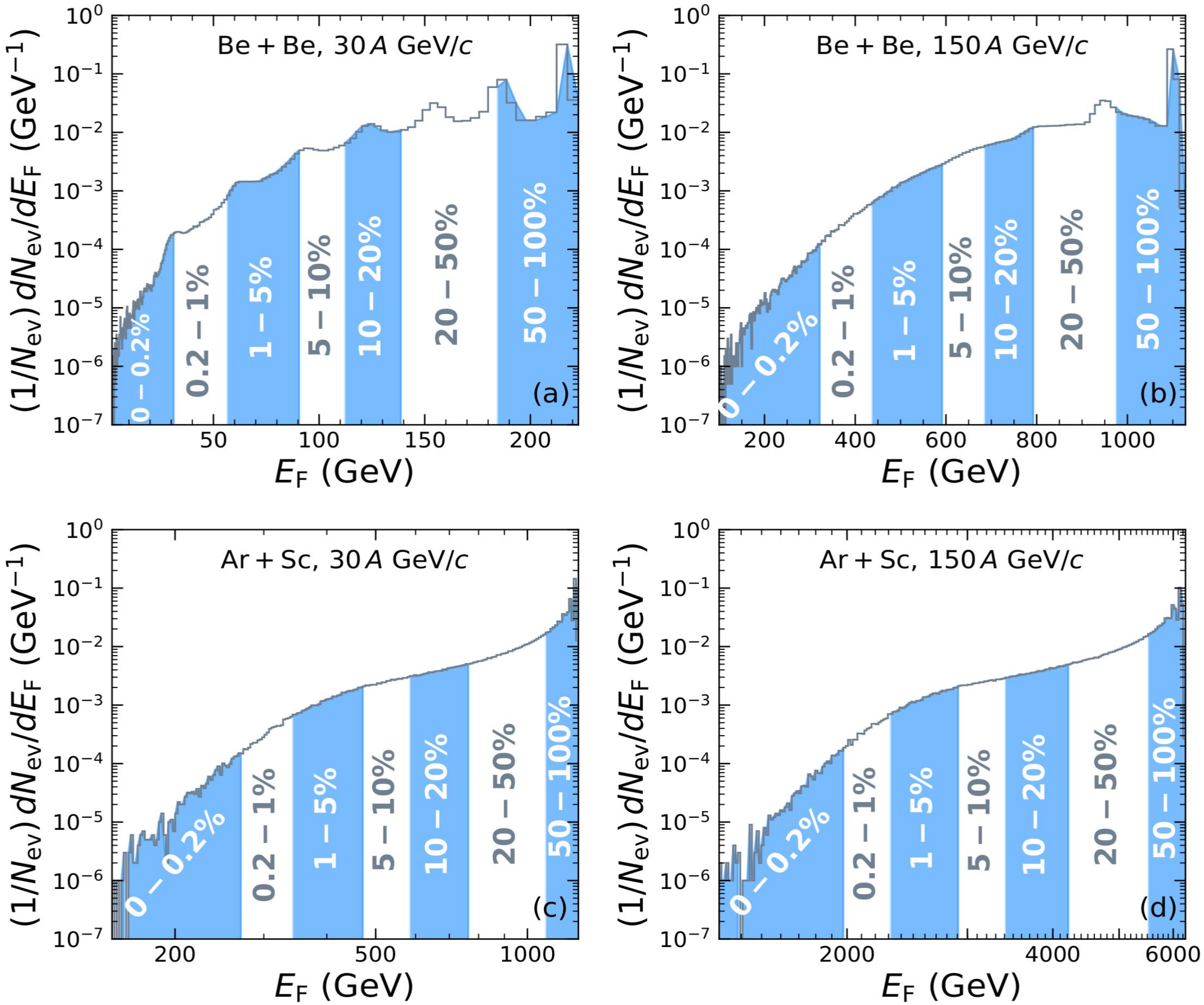
© courtesy of NA61 collaboration

Energy in PSD: unbiased centrality for fluctuations

Single peaks in spectra (for a single spectator) are smeared:

- energy of a spectator is **smeared by Fermi-motion** in nucleus (which is then boosted to the collision frame);
- PSD is a spectrometer: not able to distinguish spectator from forward particle — **all particles in forward direction are counted**

E_F is unbiased centrality measure for fluctuations analysis. Centrality by multiplicity puts bias on studied event sample — artificial reduction of fluctuations.



Color - centrality class

Omega in Be+Be and Ar+Sc

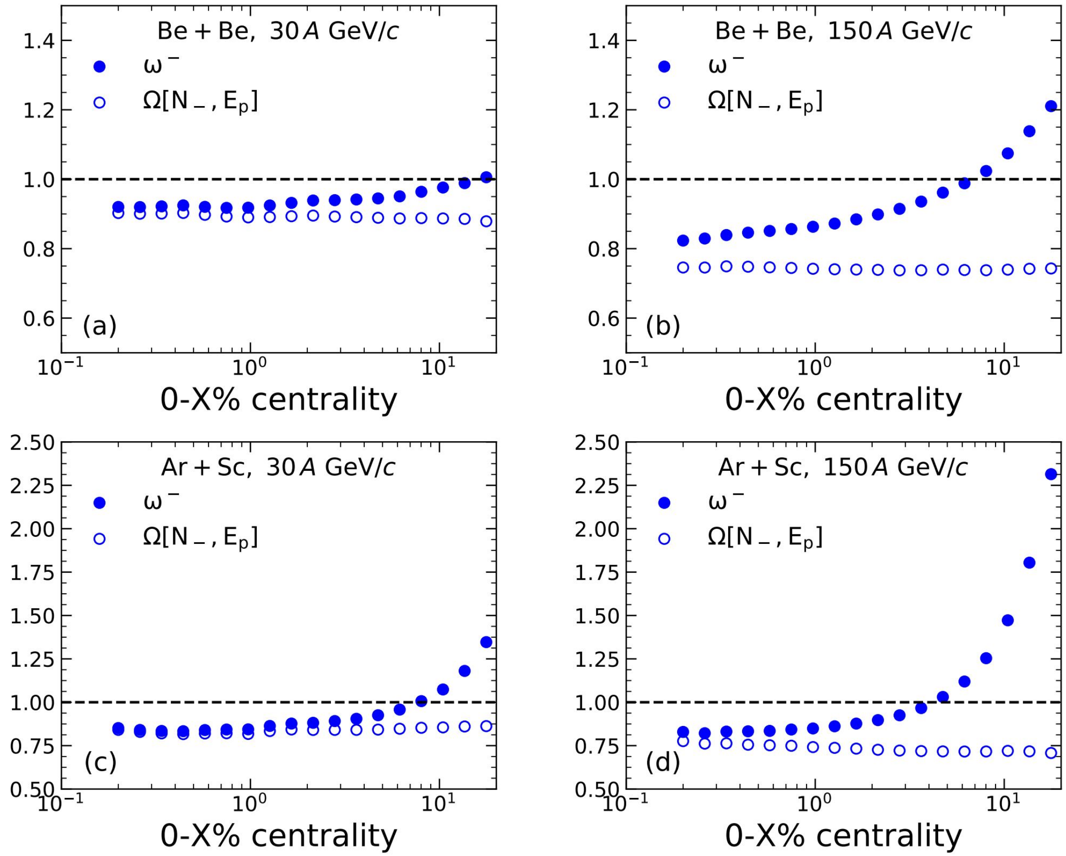
To remove effects of volume fluctuations one can construct strongly intensive scaled variance Ω[1,2]:

$$\Omega[N,E_P] = \omega[N] - (\langle N \cdot E_P\rangle - \langle N\rangle \cdot \langle E_P\rangle)/\langle E_P\rangle \quad ; \quad E_P = E_{BEAM} - E_F$$

Ω approaches scaled variance in limit of most central collision.

➡ **if Ω approaches ω — collisions are violent enough.**

At 1% centrality class all systems converge to a reasonable agreement between Ω and ω.



[1] M. Gazdzicki and S. Mrowczynski, Z. Phys. C 54, 127 (1992)
[2] M. I. Gorenstein and M. Gazdzicki, Phys. Rev. C 84, 014904 (2011)

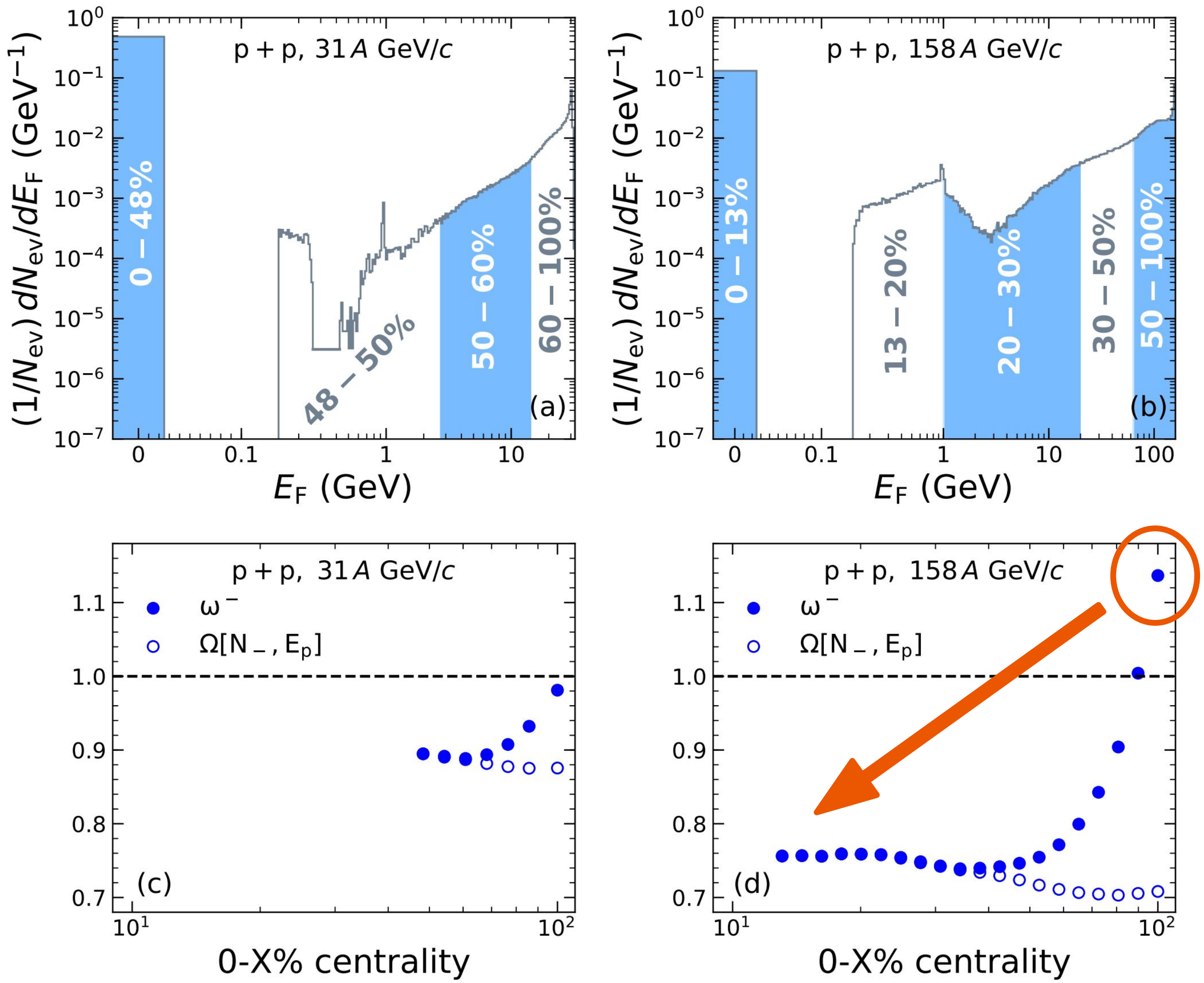
Centrality for p+p

Impact parameter b is an ill defined quantity for p+p, but one may consider most “violent” p+p collisions defined by **small E_{fwd}**:

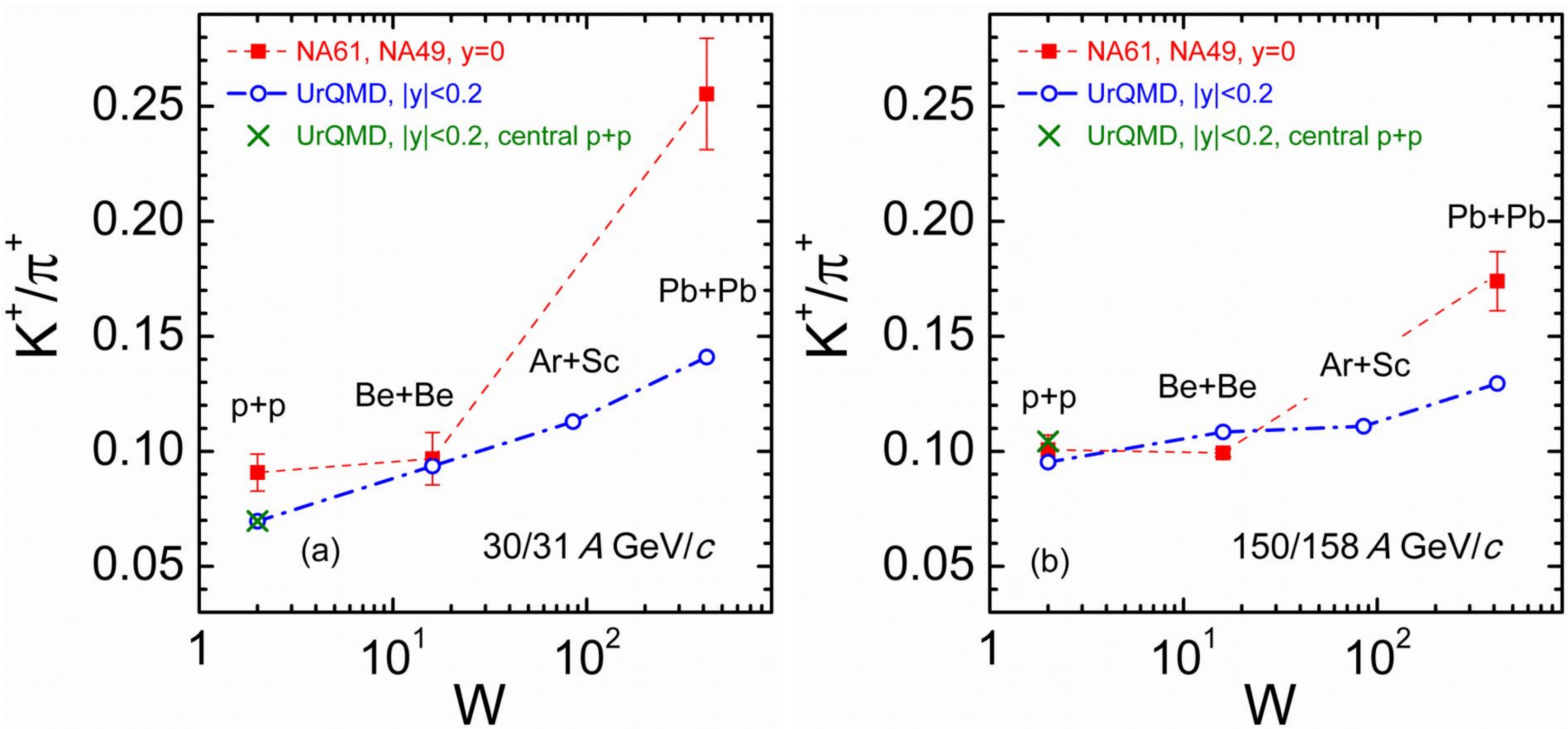
Peaks correspond to emission of single pion and nucleon respectively.

There’s a non-vanishing probability for $\mathbf{E_F=0}$ (no particles are emitted in the PSD). **We define those events as “most central”**

For “most central” p+p one obtains $\omega_- < 1$.

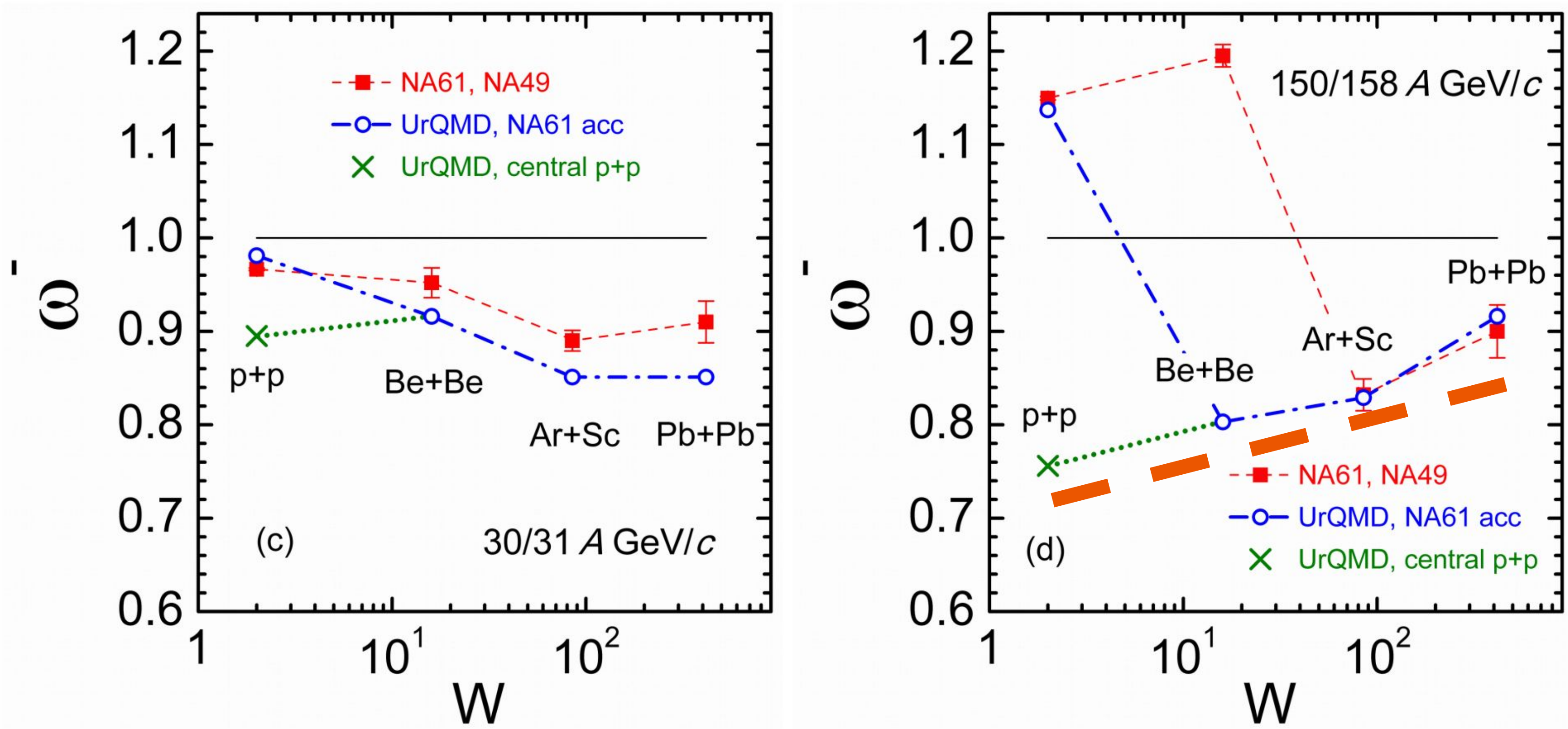


K^+/π^+ from UrQMD



- UrQMD underestimates strange production for large systems — known issue;
- Small systems are Ok;
- Centrality in p+p doesn’t affect ratio.

Fluctuations in UrQMD



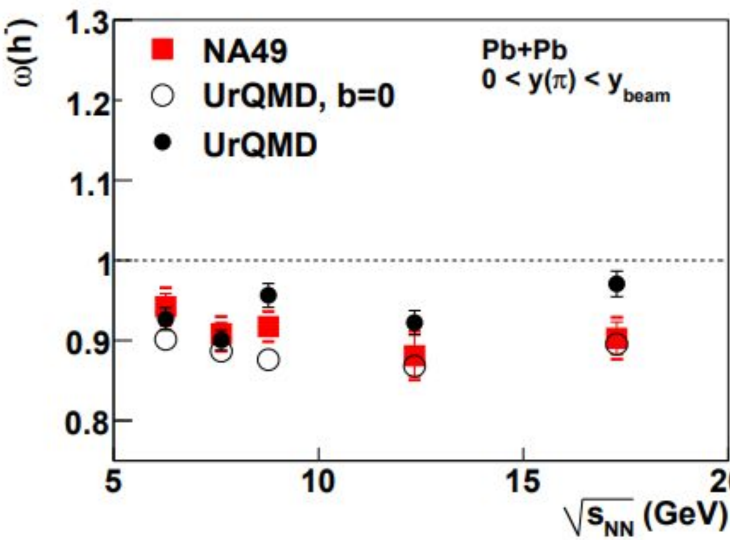
- Centrality in p+p reduces fluctuations, so $\omega < 1$;
- UrQMD describes the data except Be+Be @ 150 GeV — there are still exp. checks of this datapoint;
- Comparison of inelastic p+p with most central A+A — apples with oranges;
- Centrality in p+p provides a monotonous increase of ω @ 150 GeV/c.

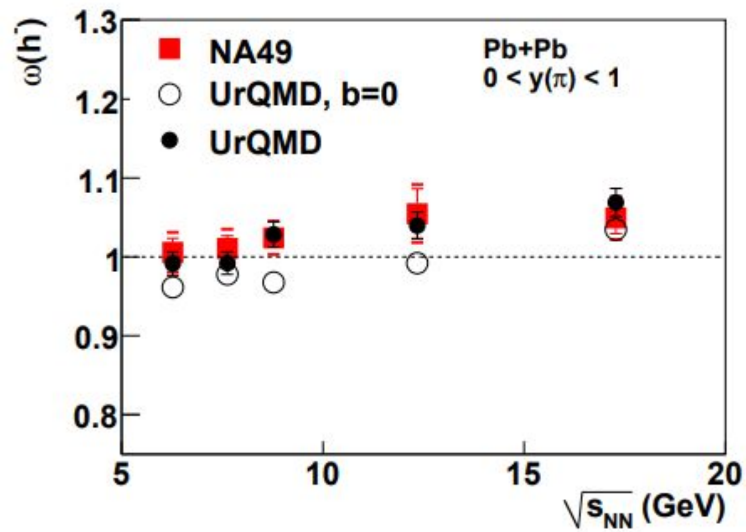
Summary

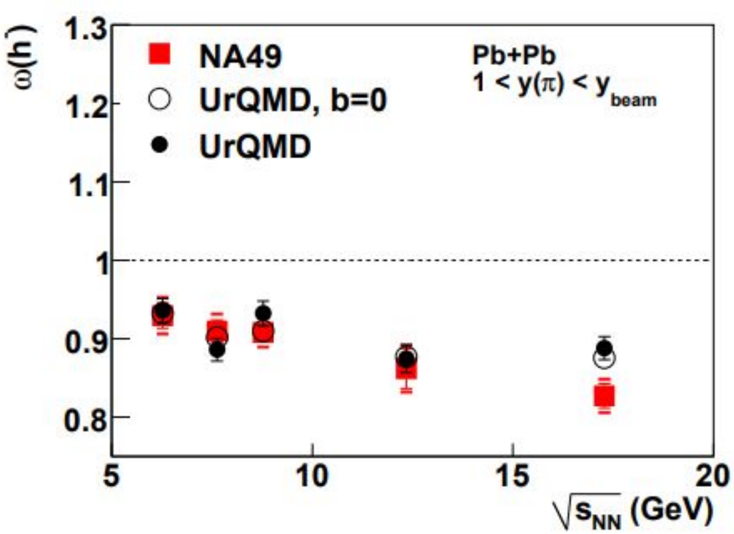
- **Canonical effects** are important in **small systems**;
- The CE HRG gives qualitative **agreement for K^+/π^+**, but cannot provide fluctuations $\omega > 1$ for small systems;
- UrQMD describes scaled variance ω, but:
  - Intermediate size systems require centrality to be done exactly as in the experiment;
- **Centrality may be introduced for p+p collisions** — this may be a reason of discrepancy between the data and CE HRG;
    - **centrality → measure of how violent collision is**
- Experimental procedures (centrality, acceptance) **hide underlying physics** — so comparison of the data and theory is not transparent;
- Description of K^+/π^+ in large systems is still a problem in UrQMD

Thanks for your attention!

Backup: Centrality selection for Pb+Pb





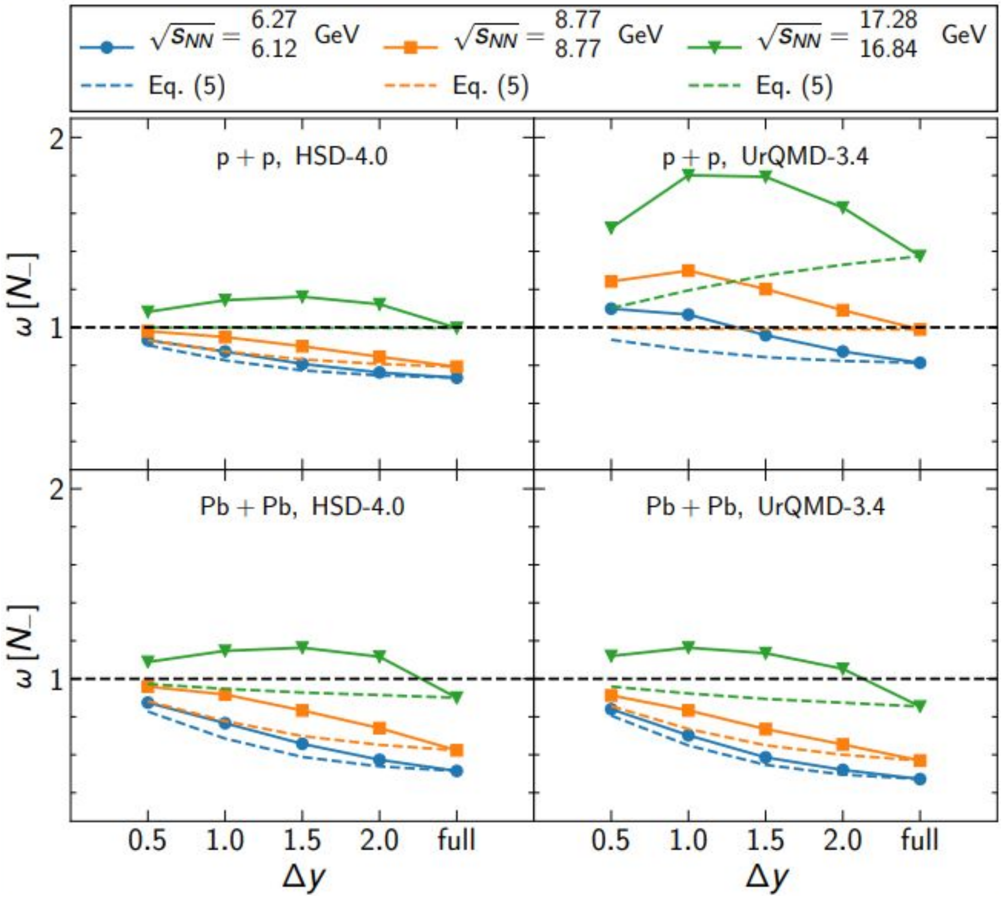


● — 1% most central by VETO calorimeter

b=0 fm is a good approximation for Pb+Pb collisions

Figs taken from:
NA49 Collaboration: B. Lungwitz, et al, 10.1103/PhysRevC.78.034914, arXiv:0712.3216

Backup: Acceptance effects



ω $[N_{ch}]$ in p+p (top) and Pb+Pb (bottom) collisions calculated in different rapidity regions within HSD (left) and UrQMD (right) models.

Scaled variance ω if acceptance (rapidity cut Δy) is applied:

$$\omega_{acc}[X] = 1 - q + q\omega[X]\,,$$

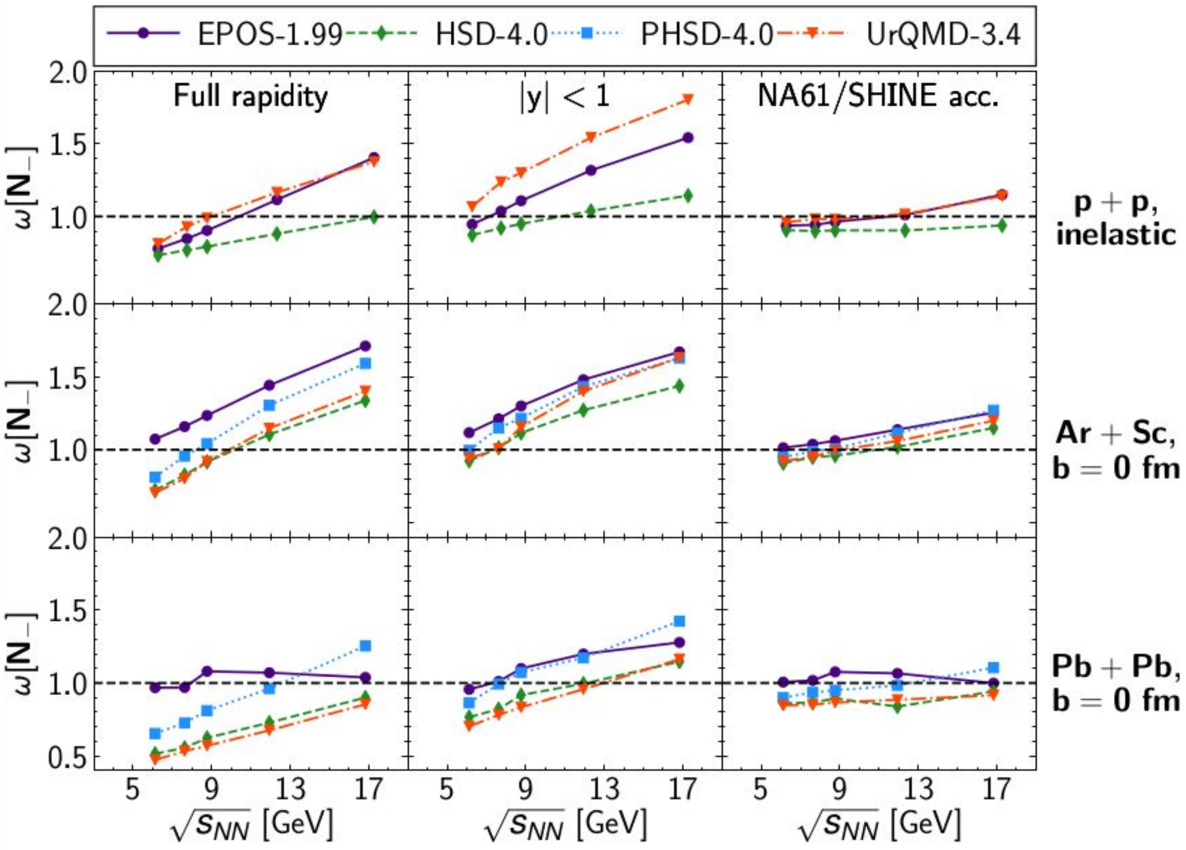
$$0 < q = \frac{\langle X_{acc}\rangle}{\langle X\rangle} < 1$$

assumes binomial statistics for particle to be accepted. Too naive.

ω grows as function of Δy because conservation laws become suppressed, but then ω → 1 as Δy → 0 to fulfill Poisson statistics.

A. Motornenko, K. Grebieszkow, E. Bratkovskaya, M. I. Gorenstein, M. Bleicher, and K. Werner, 1711.07789

Backup: b=0 collisions — to examine models



$$\omega[N_-] = \frac{\langle N_-^2 \rangle - \langle N_- \rangle^2}{\langle N_- \rangle}$$

- No non-monotonous behavior;
- Violation of KNO scaling in EPOS Pb+Pb ($\omega \not\propto \langle N \rangle$)
- significant suppression of ω by NA61/SHINE acceptance.

b=0 events doesn't show any non-monotonous behavior so no critical phenomena in the models

A. Motornenko, K. Grebieszkow, E. Bratkovskaya, M. I. Gorenstein, M Bleicher, and K. Werner, 1711.07789