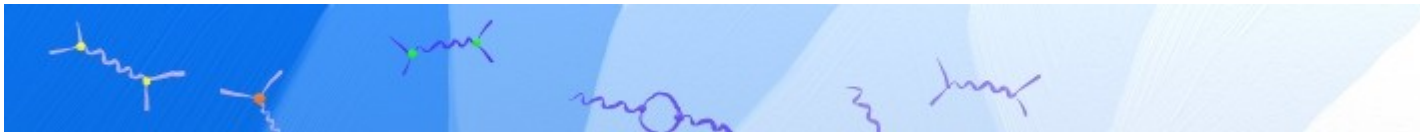




Modeling of net-charge fluctuations in relativistic heavy ion collisions

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Outline

- Net-charge fluctuations, introduction.
- Modeling of net-charge fluctuations within HYDJET++ model.
- Experimental feasibility to measure net-charge fluctuations at NICA energies.

Motivation, physic interest

- Fluctuations of conserved quantities (**B,S,Q**) in a limited phase space probe the QGP phase.

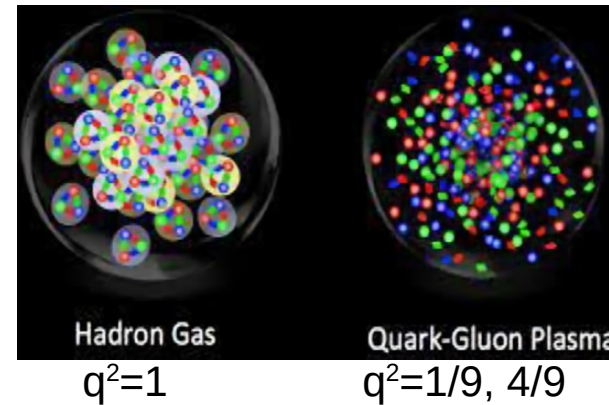
→ Differentiate partonic vs hadronic state.

$$\text{D-measure: } 4 \frac{\langle \delta Q^2 \rangle}{\langle N_{ch} \rangle}$$
$$D = \begin{cases} 4, \text{HG} \\ 3, \text{HRG} \\ 1 - 1.5, \text{QGP} \end{cases}$$

S. Jeon, V. Koch, Phys. Rev. Lett. **85**, 2076

S. Jeon, V. Koch, arXiv:hep-ph/0304012

Fluctuations of total charge $Q \sim q^2$ of sources



- Non-monotonic behavior in fluctuations as a function of beam energy are proposed as signatures of the QCD critical point.

J.Phys.G34:S437,2007; Phys. Rev. Lett. 81, 4816 (1998)

Dynamical net charge fluctuations

- Net-charge, net-proton, net-strangeness fluctuations are analysed in terms of moments of distributions (\mathbf{M} , standard deviation σ , skewness \mathbf{S} , kurtosis κ), higher moments (cumulants).
- Dynamical fluctuation variable \mathbf{v} was introduced (to get rid of statistical fluctuations) which measures deviation from Poisson behavior:

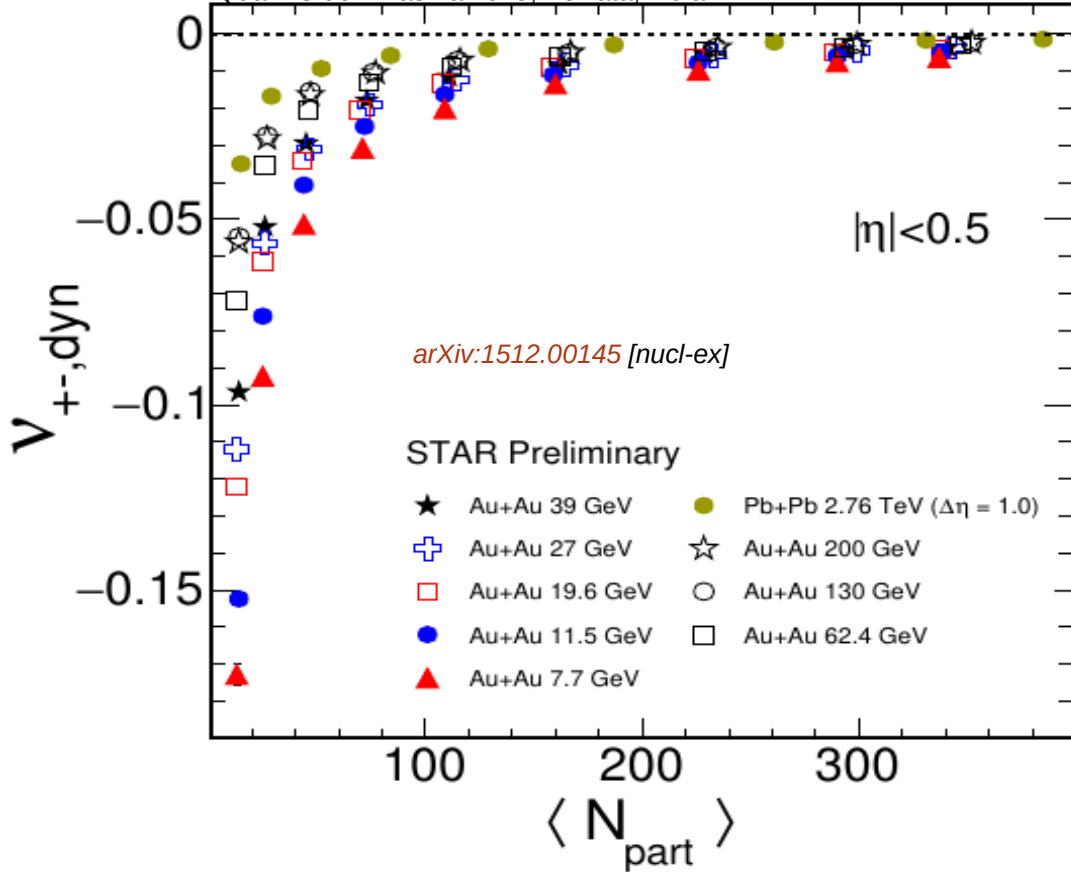
$$v_{dyn}[+, -] = \frac{\langle N_+(N_+ - 1) \rangle}{\langle N_+ \rangle^2} + \frac{\langle N_-(N_- - 1) \rangle}{\langle N_- \rangle^2} - 2 \frac{\langle N_+ N_- \rangle}{\langle N_+ \rangle \langle N_- \rangle}$$

- $v_{dyn} < 0$ → (opposite charge) correlations dominate
- $v_{dyn} > 0$ → (same charge) fluctuations dominate
- $v_{dyn} = 0$ → independent particle production

$$\text{For } \langle N_+ \rangle \approx \langle N_- \rangle: \quad D = 4 \frac{\langle \delta Q^2 \rangle}{\langle N_{ch} \rangle} \approx \langle N_{ch} \rangle \langle v_{dyn} \rangle + 4$$

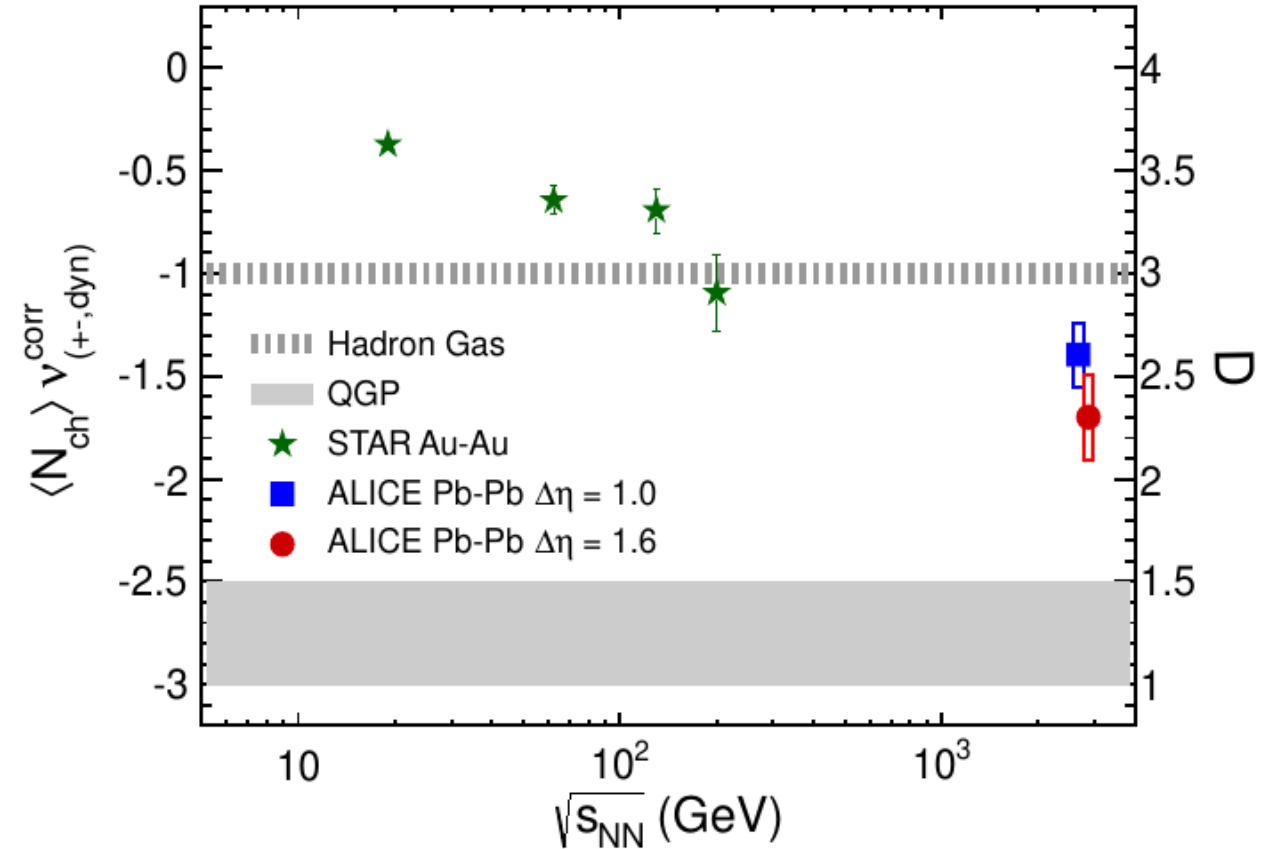
Experimental data on net-charge fluctuations

7th International Conference on Physics and Astrophysics of Quark Gluon Plasma 2015, Kolkata, India



The correction for the global charge conservation effect is needed.

Phys. Rev. Lett. 110 (2013) 152301



$$v_{\text{dyn}}^{\text{corr}} = v_{\text{dyn}} + 2/\langle N_{\text{tot}} \rangle \approx v_{\text{dyn}} + 4/\langle N_{\text{tot}} \rangle,$$

$\langle N_{\text{tot}} \rangle$ is the total multiplicity in full acceptance.

C. Pruneau, S. Gavin, S. Voloshin, Phys. Rev. C 66, 044904 (2002).

HYDJET++ event generator

(HYDroynamics + JETs)

I.Lokhtin, A.Snigirev, Eur. Phys. J. C 46 2011 (2006)

I.Lokhtin, L.Malinina, S.Petrushanko, A.Snigirev, I.Arsene, K.Tywoniuk, Comp.Phys.Comm. 180 779 (2009)

<http://lav01.sinp.msu.ru/~igor/hydjet++>

HYDJET++ is designed to simulate symmetric A+A collisions at high energy (RHIC, LHC), and is extended to intermediate energy (NICA, FAIR).

Collision event is represented as a mixture of two parts:

- hadron production at thermalised stage based on hydrodynamical ideas
- hard parton-parton interactions (pQCD calculations), parton energy loss simulation with further hadronisation.

HYDJET++ event generator

(HYDroynamics + JETs)

Hard “jet” component:

PYTHIA w/o hadronization



PYQUEN (PYthia QUENched)

<http://lokhtin.web.cern.ch/lokhtin/pyquen/>

I.P.Lokhtin, A.M.Snigirev, Eur. Phys. J. 45 (2006) 211

Parton rescattering & energy loss
(collisional, radiative) + emitted gluons



Parton hadronization and final particle formation
PYTHIA6.4 with hadronization

Soft hydro-type component:
is based on the adapted **FAST MC** model:

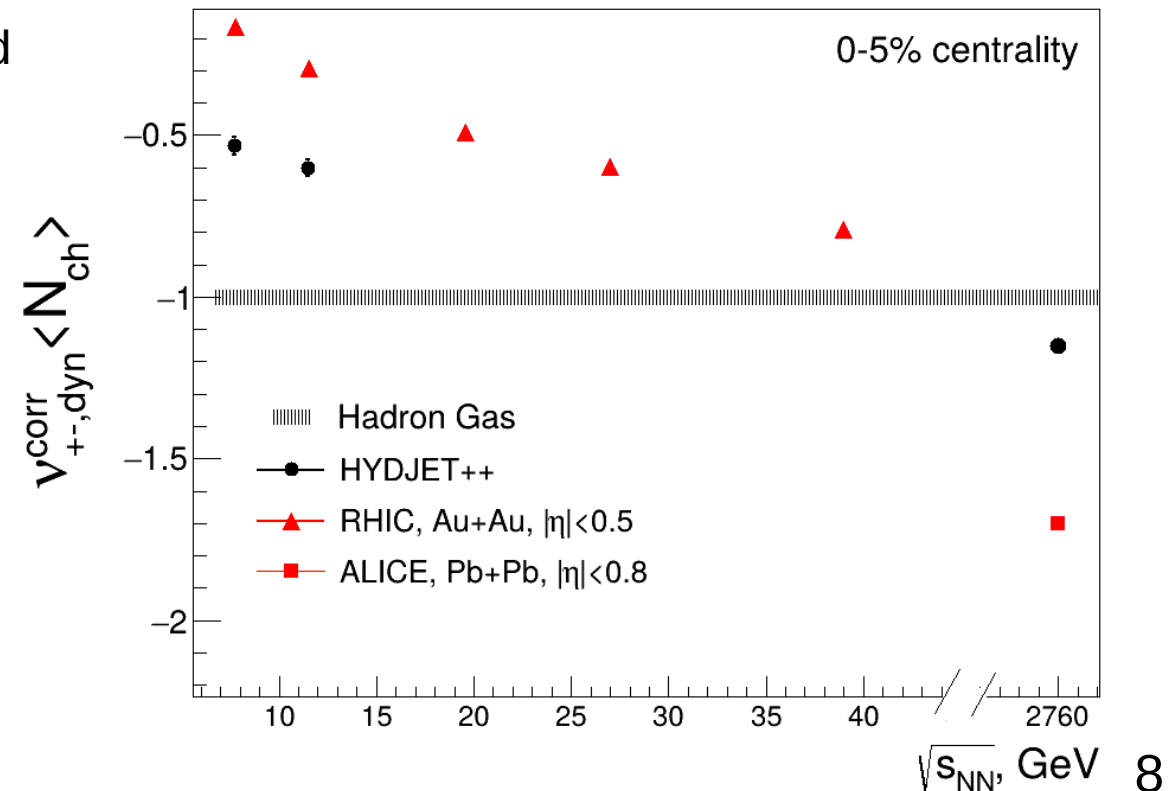
N.S.Amelin, R.Lednisky, T.A.Pocheptsov, I.P.Lokhtin, L.V.Malinina, A.M.Snigirev, Yu.A.Karpenko, Yu.M.Sinyukov, Phys. Rev. C 74 (2006) 064901, N.S.Amelin, R.Lednisky, I.P.Lokhtin, L.V.Malinina, A.M.Snigirev, Yu.A.Karpenko, Yu.M.Sinyukov, I.C.Arsene, L.Bravina, Phys. Rev. C 77 (2008) 014903

- multiplicities are determined assuming **thermal equilibrium**;
- hadrons are produced on the hypersurface represented by a **parameterization** of relativistic hydrodynamics with given **freeze-out conditions**;
- decays of **hadronic resonances** are taken into account (360 particles from SHARE data table) with “home-made” decayer;
- Set of parameters is tuned in order to describe experimental data
- Written within ROOT framework (C++)

Contributions of two components are regulated by a parameter: minimal p_T of hard parton-parton scattering.

Net-charge fluctuations with HYDJET++

- The model calculations of soft and hard probes of quark-gluon plasma (e.g. collective flow, different kinds of particle correlations, jets, D and B mesons, etc.) agree well with the experimental data.
- HYDJET++ model doesn't describe the experimental centrality dependence width of the Balance Function. Neither it can describe experimental data on net-charge fluctuations.
- Charge correlations at low p_T are mainly defined by the soft part:
 - charge independent thermal production of direct hadrons,
 - Resonance decays.
- The net-charged fluctuations (v_{dyn} , D-measure)
 - are underestimated at RHIC BES energies.
 - are overestimated at LHC energies.



HYDJET++ model modification

- Correlated charge pair (+-) production at freeze-out surface was introduced for direct hadrons (one may think about it as correlated charge production at parton level as well).
- At LHC energies the exact $N_+=N_-$ for direct hadrons is fulfilled.
- At lower energies the pair (+-) production is implemented for **the part** of direct hadrons, to account for the charge imbalance of the system at RHIC/NICA energies. (see A. Chernyshov's talk)
- The strength of the correlation in angles (η , ϕ) is regulated by the parameter σ of the model, which can be tuned to describe the data.

The values of correlation length parameters for Balance Function description

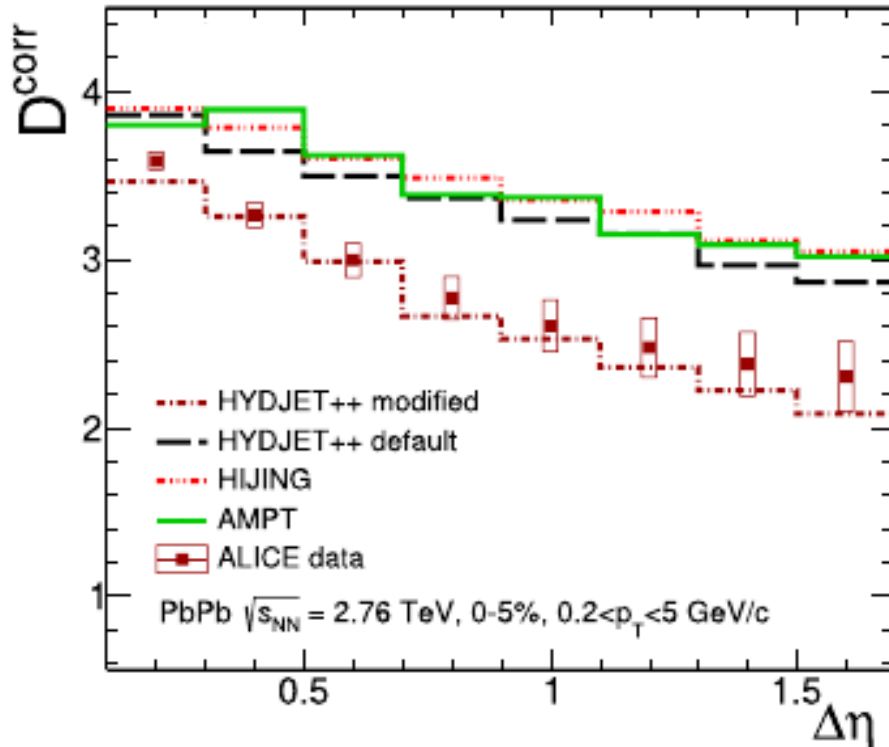
Centrality, %	σ_η		2.76 TeV, 5.02 TeV
	7.7 GeV	11.5 GeV	
0-5	1.25	1.00	0.5
5-10	1.35	1.08	
10-20	1.47	1.17	
20-30	1.62	1.30	0.7
30-40	1.80	1.44	
40-50	2.00	1.60	
50-60			1.1

- The resulting charge correlations are defined by correlation length of direct hadrons production and resonance decay.
- The correlation length decreases with collision energy and with centrality.

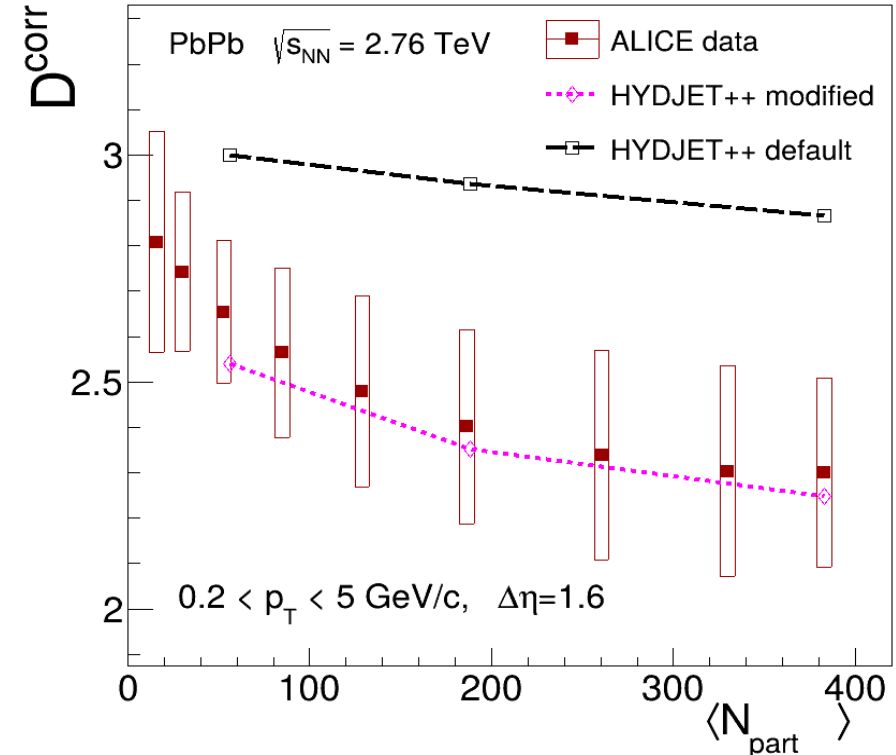
Net-charge fluctuations with HYDJET++, LHC energies

- Data and modified HYDJET++ are corrected for the global charge conservation.
- The default HYDJET++ doesn't require correction, since it employs grand canonical ensemble (the charge is conserved on average over events).

The η -window dependence of D for different models.



The centrality D dependence at a certain η -window.

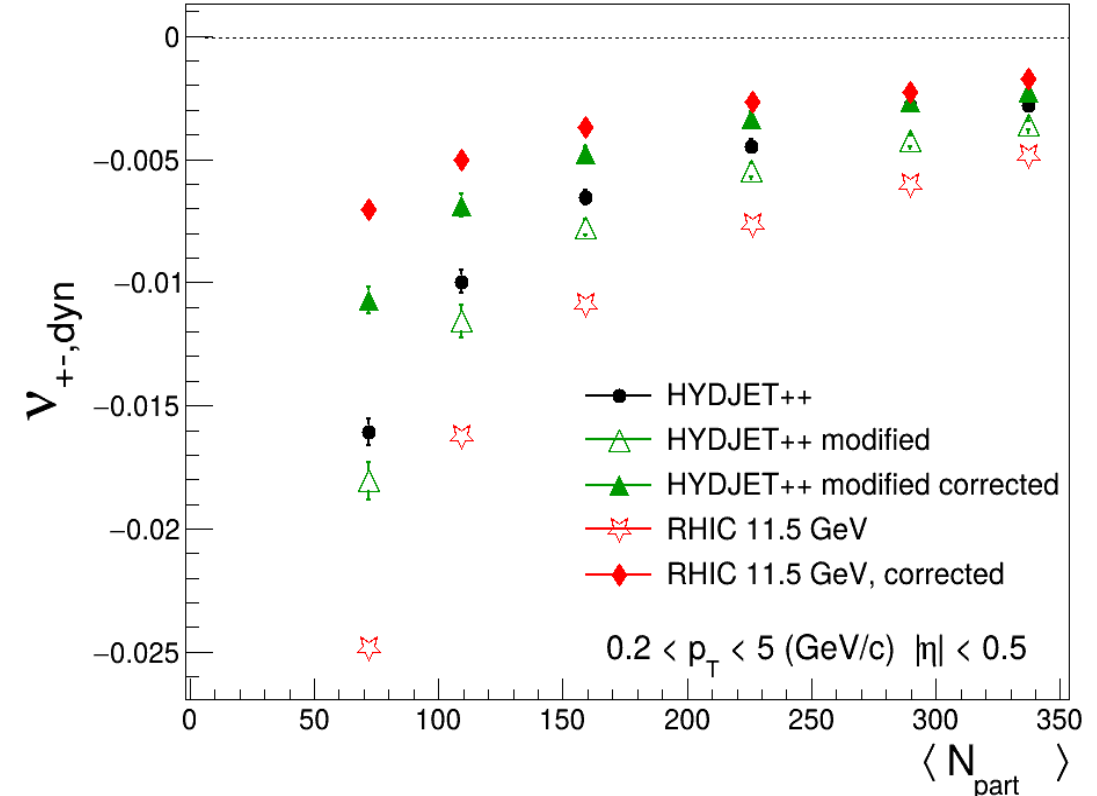
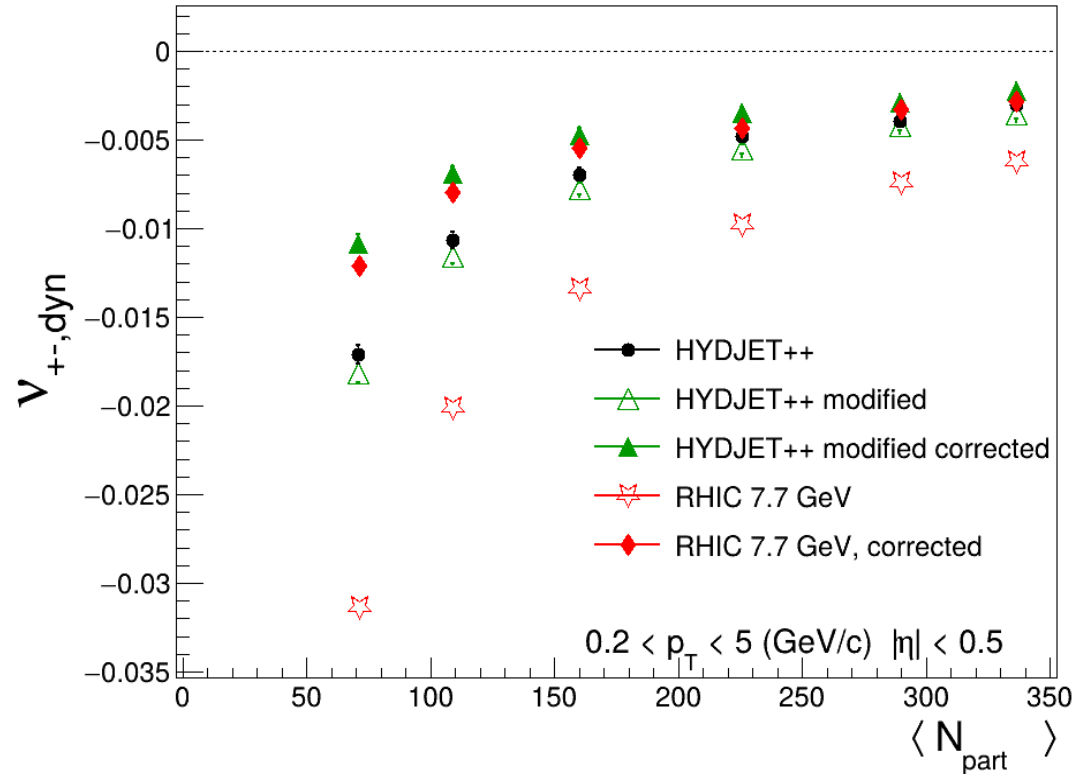


G. O. Ambaryan, A. S. Chernyshov, G. Kh. Eyyubova, V. L. Korotkikh, I. P. Lokhtin, S. V. Petrushanko, A. M. Snigirev, E. E. Zabrodin, *Chinese Phys. C* **49** 014109 (2025)

- The modification of the model with σ_η tuned for BF data allows to describe net-charge fluctuations as well.

Net-charge fluctuations with HYDJET++, NICA energies

- Correction for the data is estimated as : $v_{\text{dyn}}^{\text{corr}} = v_{\text{dyn}} + 2/\langle N_{+tot} \rangle$
- Correction for the modified HYDJET++ model: $v_{\text{dyn}}^{\text{corr}} = v_{\text{dyn}} + C * 2/\langle N_{+tot} \rangle$, where $C = \langle N_{-} \rangle / \langle N_{tot} \rangle$
- $\langle N_{+tot} \rangle$ is estimated from the model (both for data and model).



- The correction procedure introduces theoretical uncertainty to the model results at these energies (due to features of modification algorithm).
- With the parameters tuned for the BF description at $\sqrt{s_{NN}} = 7.7, 11.5$ GeV and the proper correction procedure the net-charge fluctuation data can be described satisfactorily.

Conclusions on the model study within HYDJET++

- In the default HYDJET++ model the net-charged fluctuations (v_{dyn} , D-measure) are
 - underestimated at low energies ($\sqrt{s_{\text{NN}}} = 7.7, 11.5 \text{ GeV}$)
 - overestimated at LHC energies ($\sqrt{s_{\text{NN}}} = 2.76, 5.02 \text{ TeV}$)
- The modification of the model allows to reproduce the data on Balance Function provided that the correlation length of the thermal hadron production at freeze-out stage is
 - smaller than the resonance decay correlation length at LHC
 - larger than the resonance decay correlation length at NICA
- The same correlation length parameters can be used for net-charge fluctuation description in a broad collision energy range, though uncertainty is introduced due to the correction procedure for the global charge conservation effect.

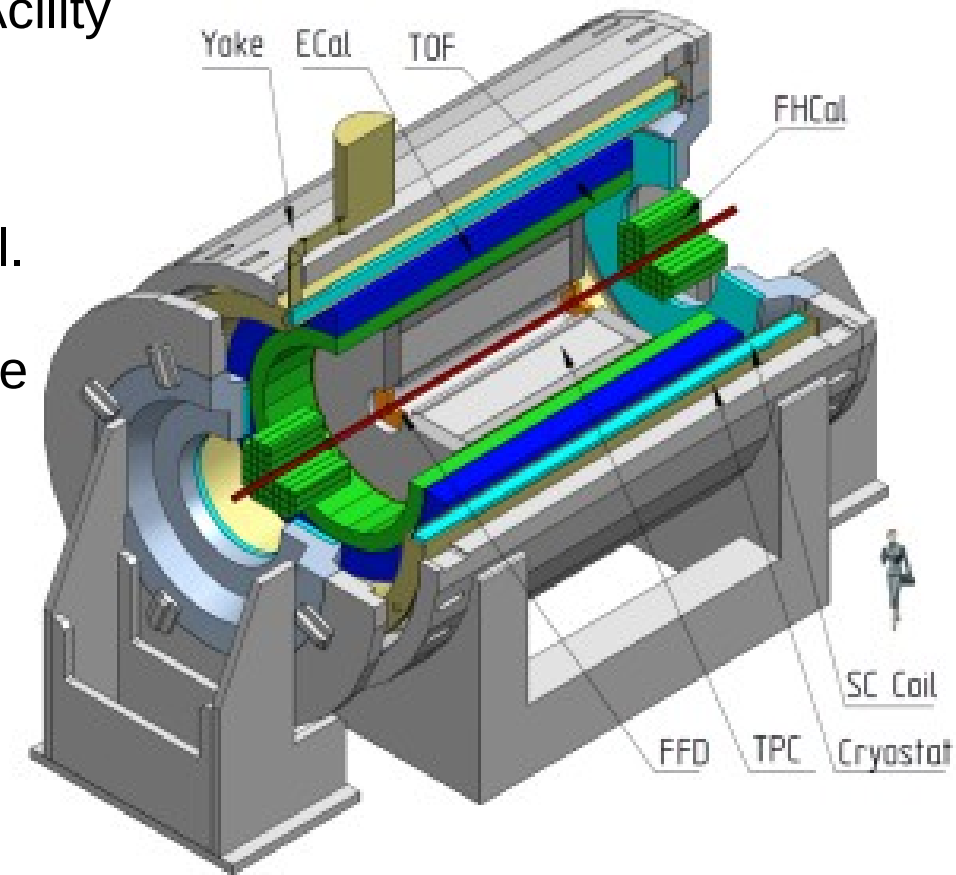
Experimental feasibility to measure net-charge fluctuations at MPD, NICA

The Multi-Purpose Detector (MPD) is one of the two dedicated heavy-ion collision experiments of the Nuclotron-based Ion Collider fAcility (NICA).

Time Projection Chamber (TPC) is enclosed by the TOF barrel. The TPC is the main tracker, and in conjunction with the TOF they will provide precise momentum measurements and particle identification.

THE MPDROOT

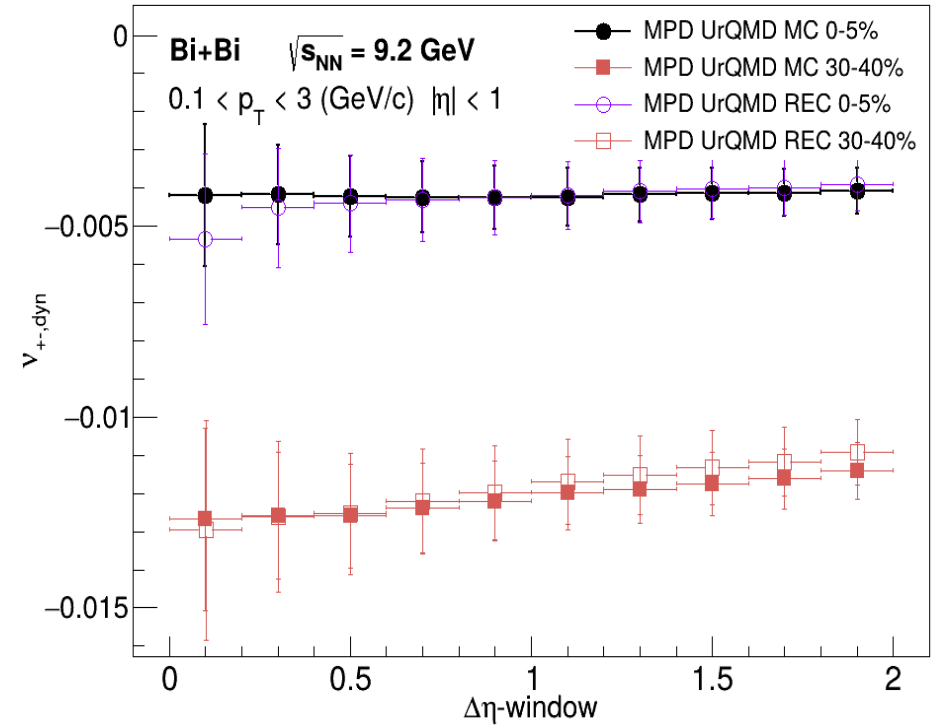
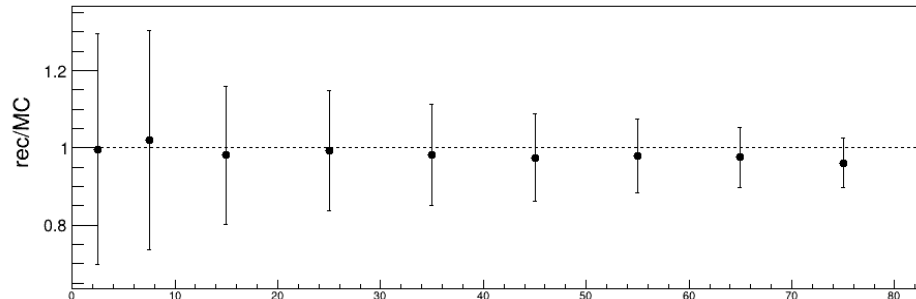
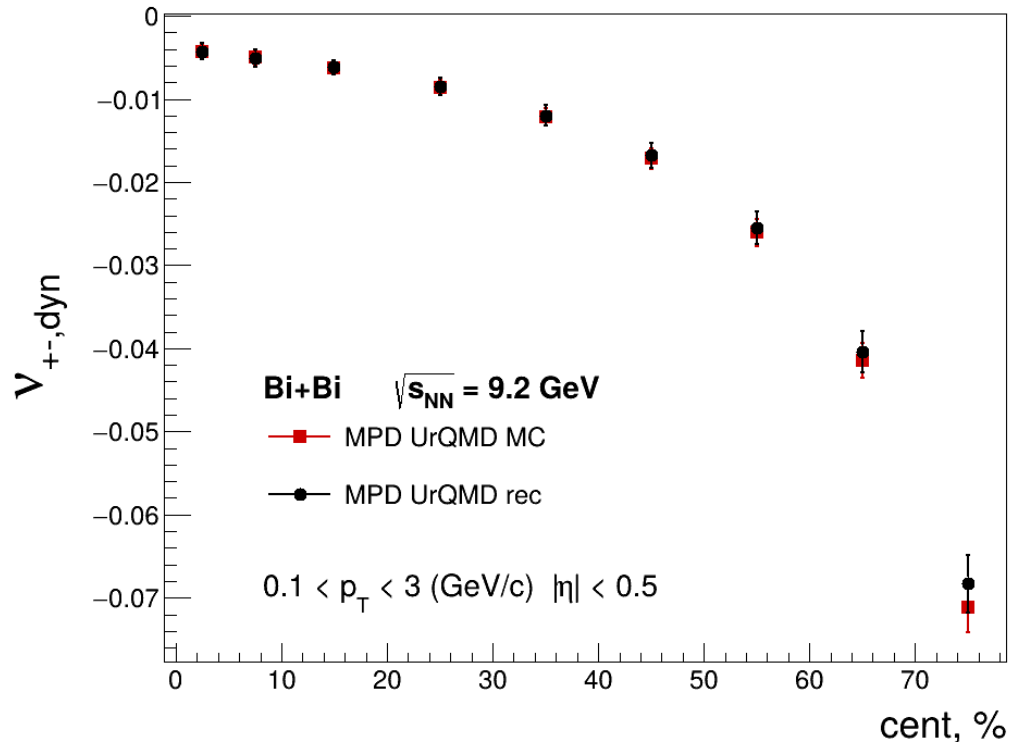
Mpdroot is the off-line software framework for simulation, reconstruction and physics analyses of the simulated or experimental data for MPD experiment.



Experimental feasibility to measure net-charge fluctuations at MPD

BiBi at $\sqrt{s_{NN}} = 9.2$ GeV simulated with UrQMD model in MPDROOT software was utilized.

The results are shown at MPD Cross-PWG meeting June17, 2025: <https://indico.jinr.ru/event/5473/>



- v observable is robust against random efficiency losses.
- Holds only if efficiency is independent on multiplicity
[C. Pruneau, S. Gavin, S. Voloshin, Phys. Rev. C 66, 044904 \(2002\).](#)
- Good MC-rec agreement.

backup

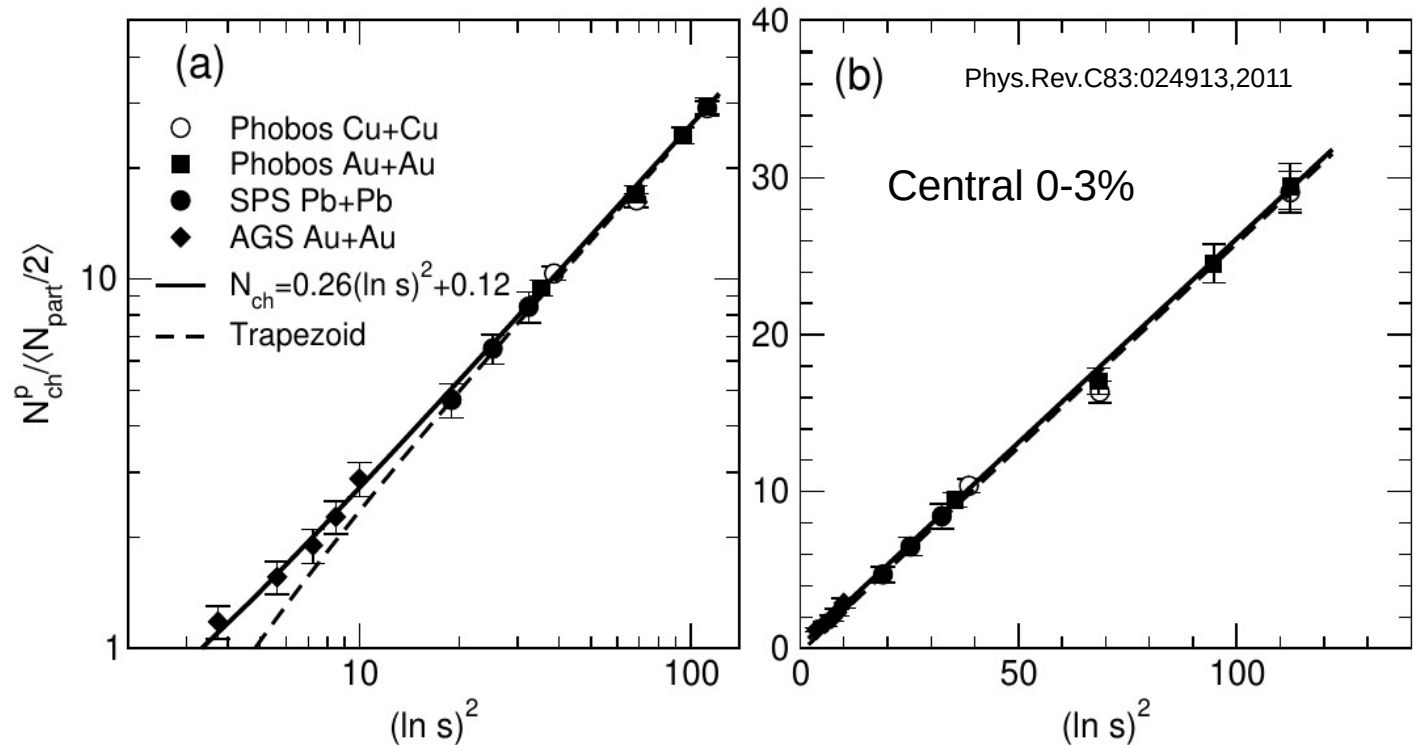
➤ At lower energies the correction for the global charge conservation is essential.

$$v^{\text{corr}} = v + \frac{2}{\langle N_{+tot} \rangle}$$

Estimation of $\langle N_{\text{total}} \rangle$ from model

HYDJET++	7.7 Gev	11.5 Gev	N+, 11.5
0-5	940	1091	633
5-10	718.7	904.4	528.5
10-20	595.8	687.5	401
20-30	407.6	468.4	276
30-40	267.3	305.7	178
40-50	167	190.2	112

$\langle N_{\text{total}} \rangle$ from data



Eq.(15)	7.7 GeV	11.5 GeV
0-5%	749	1066

$$\frac{N_{ch}^{tpz}}{\langle N_{part}/2 \rangle} = 0.26(\ln s_{NN})^2 + 0.12, \quad (15)$$