

Further developments of HYDJET++ (HYDrodynamicS with JETs)



E. Zabrodin

in collaboration with

**G. Ambaryan, L. Bravina, A. Chernyshov, G. Eyyubova, V. Korotkikh,
I. Lokhtin, S. Petrushanko and A. Snigirev**



ICNFP XIII, OAC, Kolymbari, Crete, Greece, 17.07 – 31.07.2025

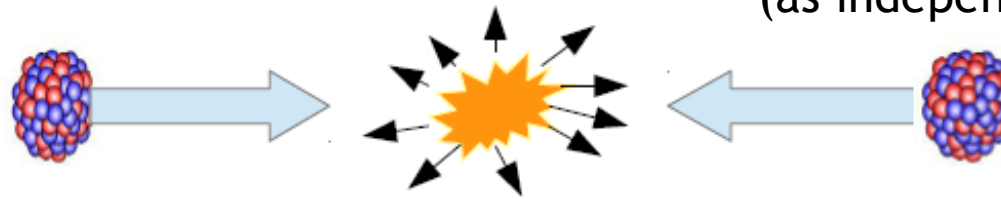


**HYDJET++ =
FASTMC + HYDJET**

HYDJET++ model for heavy ion collisions

Simplifies the pictures of heavy ion collisions as merging of 2 components:

(as independent parts)



- soft hydro-type part
(represented by hadron emission
assuming thermal equilibrium)

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

HYDJET++ (soft): main physics assumptions

A hydrodynamic expansion of the fireball is supposed to **end by a sudden system breakup** at given T and chemical potentials. Momentum distribution of produced hadrons keeps the thermal character of the equilibrium distribution.

Cooper-Frye formula:

$$p^0 \frac{d^3 N_i}{d^3 p} = \int_{\sigma(x)} d^3 \sigma_\mu(x) p^\mu f_i^{eq}(p^\nu u_\mu(x); T, \mu_i)$$

- HYDJET++ avoids straightforward 6-dimensional integration by using the special simulation procedure (like HYDJET): momentum generation in the rest frame of fluid element, then Lorentz transformation in the global frame \rightarrow uniform weights \rightarrow effective von-Neumann rejection-acceptance procedure.

Freeze-out surface parameterizations

1. The Bjorken model with hypersurface

$$\tau = (t^2 - z^2)^{1/2} = \text{const}$$

2. Linear transverse flow rapidity profile

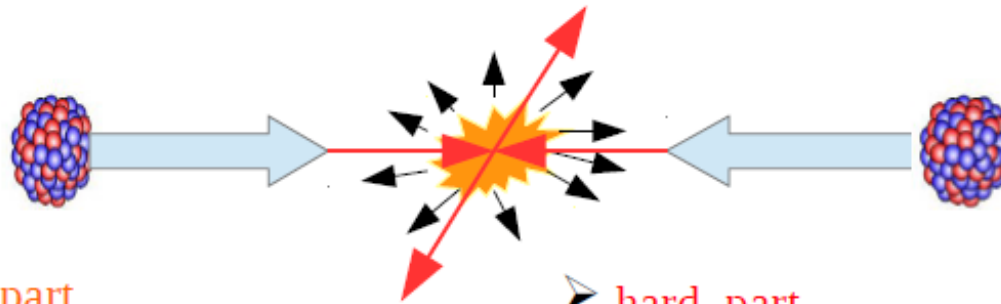
$$\rho_u = \frac{r}{R} \rho_u^{\max}$$

3. The total effective volume for particle production at

$$- V_{\text{eff}} = \int_{\sigma(x)} d^3 \sigma_\mu(x) u^\mu(x) = \tau \int_0^R \gamma_r r dr \int_0^{2\pi} d\phi \int_{\eta_{\min}}^{\eta_{\max}} d\eta = 2\pi\tau\Delta\eta \left(\frac{R}{\rho_u^{\max}} \right)^2 (\rho_u^{\max} \sinh \rho_u^{\max} - \cosh \rho_u^{\max} + 1)$$

HYDJET++ model for heavy ion collisions

Simplifies the pictures of heavy ion collisions as merging of 2 components:



➤ **soft hydro-type part**
(represented by hadron emission
assuming thermal equilibrium)

➤ **hard part**
(represented by hard parton scattering and
later hadronization)

Based on PYTHIA with quenching:
PYQUEN: I.P.Lokhtin, A.M.Snigirev,
Eur. Phys. J. 45 (2006) 211

Nuclear shadowing is accounted for:
K.Tywoniuk et al., Phys. Lett. B 657 (2007) 170

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

(latest version 2.4)

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

Hard component

Initial parton configuration

PYTHIA w/o hadronization

→ **parton rescattering & energy loss**

→ **Hadronization**

PYTHIA w hadronization

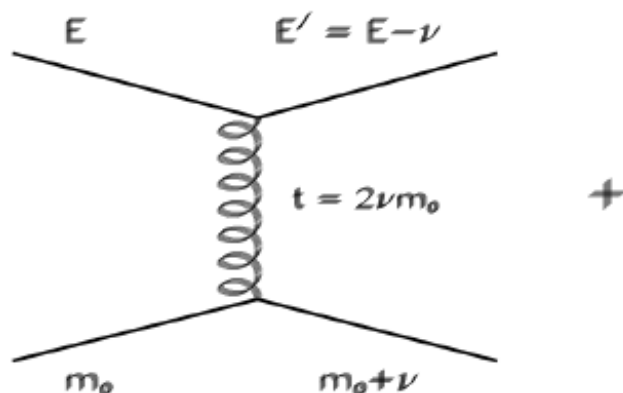
Energy loss, general kinetic integral equation with scattering probability density:

$$\Delta E(L, E) = \int_0^L dl \frac{dP(l)}{dl} \lambda(l) \frac{dE(l, E)}{dl}$$

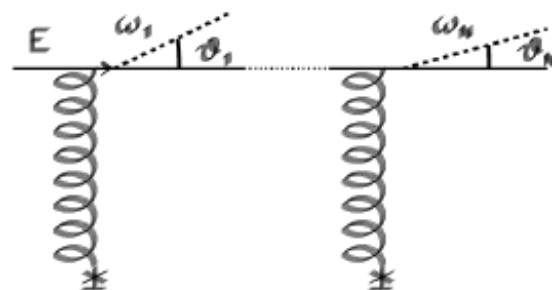
$$\frac{dP(l)}{dl} = \frac{1}{\lambda(l)} \exp(-l/\lambda(l))$$

• Collisional loss

(high momentum transfer approximation)



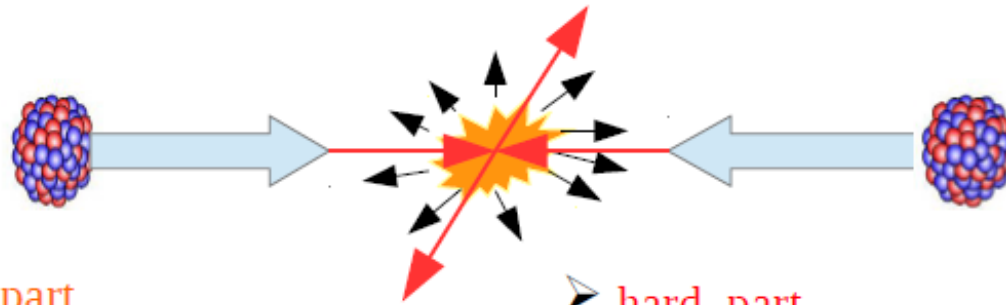
• Radiative loss (coherent gluon radiation in Baier-Dokshitzer-Mueller-Schiff formalism)



• “Dead” cone approximation for massive quarks

HYDJET++ model for heavy ion collisions

Simplifies the pictures of heavy ion collisions as merging of 2 components:

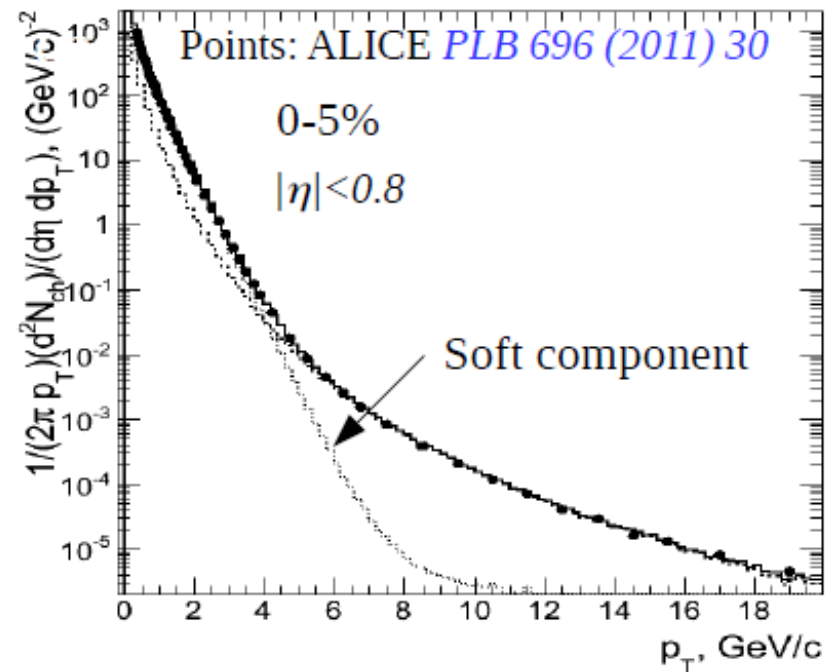


➤ **soft hydro-type part**
(represented by hadron emission assuming thermal equilibrium)

➤ **hard part**
(represented by hard parton scattering and later hadronization based on PYTHIA)

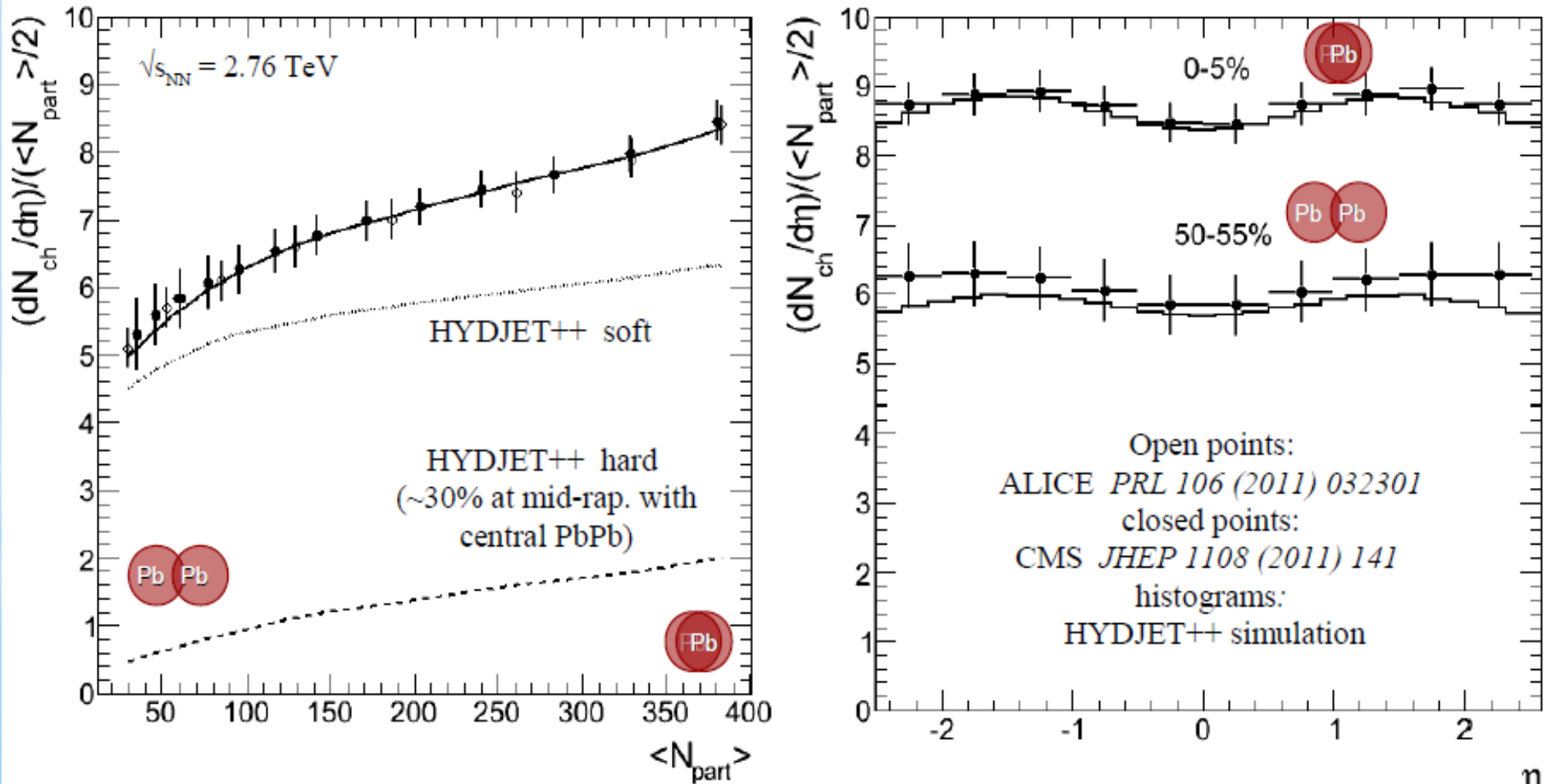
Soft and hard components:

- The contribution of the hard part to the total multiplicity is control by p_{Tmin} parameter (parton hard scattering in PYTHIA)
- Modification of the hard part due to interactions with the medium is simulated
- No modification of soft part



Charged multiplicity vs centrality and pseudorapidity in HYDJET++ at LHC

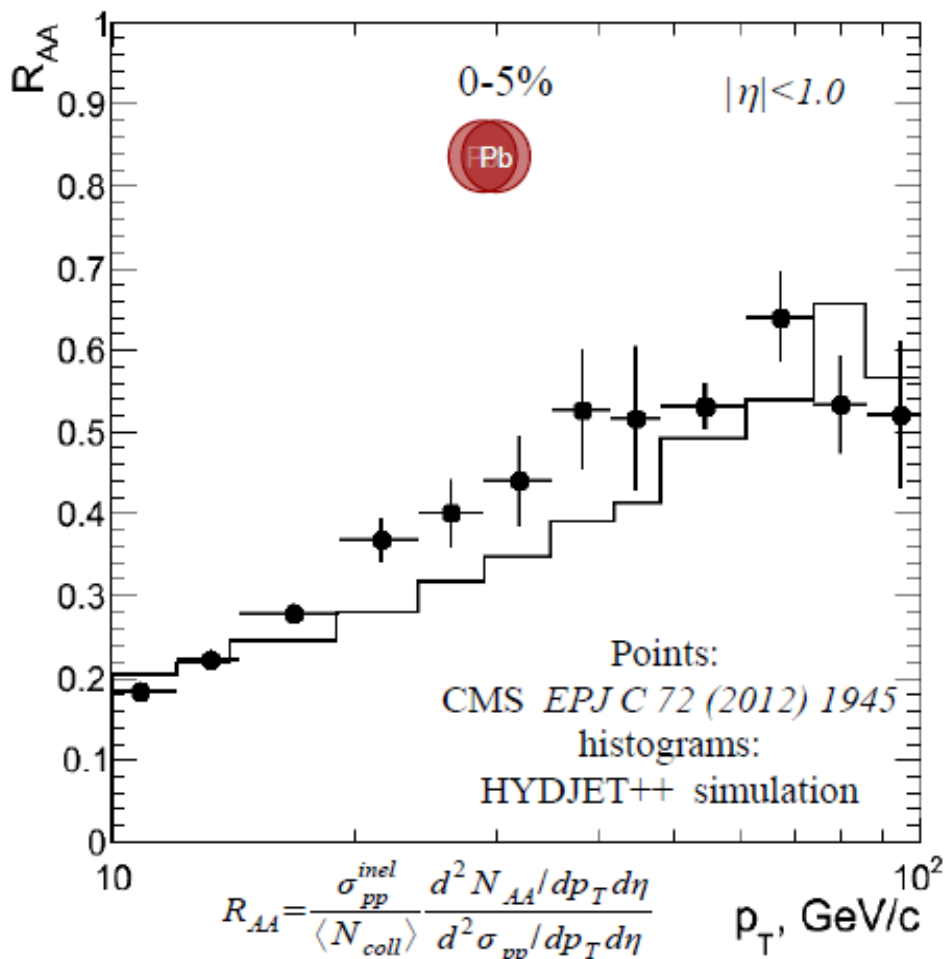
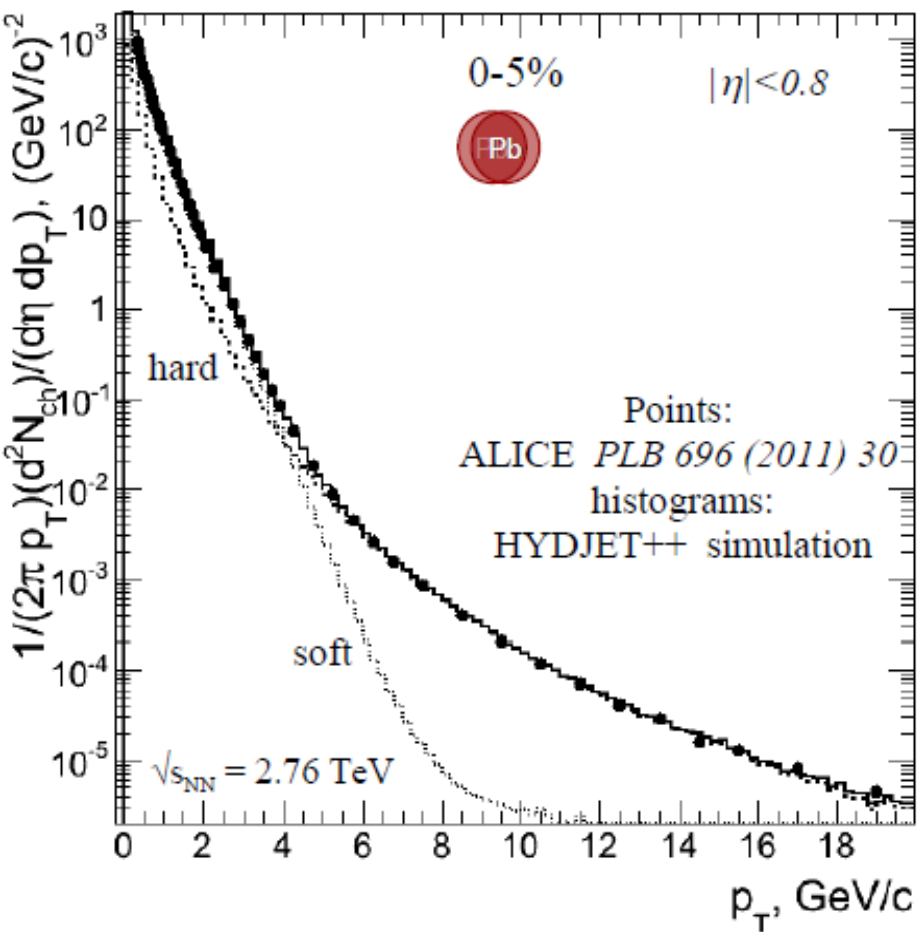
I.P. Lokhtin, A.V. Belyaev, L.V. Malinina, S.V. Petrushanko, E.P. Rogochaya, A.M. Snigirev, *Eur.Phys.J. C* (2012) 72:2045



Tuned HYDJET++ reproduces multiplicity vs. event centrality down to very peripheral events, as well as approximately flat pseudorapidity distribution.

P_T spectrum and R_{AA} factor for charged hadrons in HYDJET++ at LHC

I.P. Lokhtin, A.V. Belyaev, L.V. Malinina, S.V. Petrushanko, E.P. Rogochaya, A.M. Snigirev, *Eur.Phys.J. C* (2012) 72:2045



HYDJET++ reproduces p_T -spectrum and R_{AA} for central PbPb collisions in mid-rapidity up to $p_T \sim 100 \text{ GeV}/c$.

Comparison to STAR BES data

S.R. Nayak et al., Eur. Phys. J. Plus (2025) 140:375
(arXiv:2405.03174 [hep-ph])

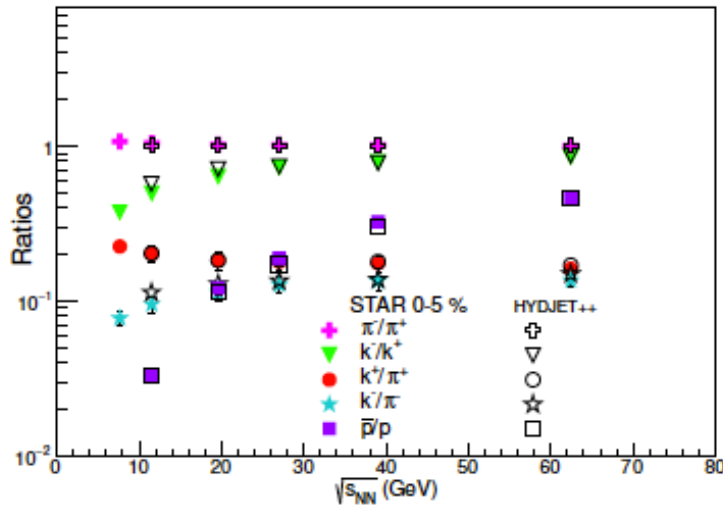


FIG. 1. Particle ratios at different beam energies.

Good agreement
with the data

Mass ordering of
the flow (v_2, v_3)

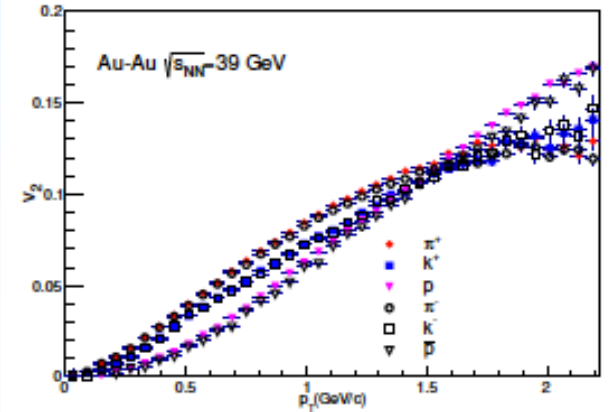


FIG. 13. v_2 of primary hadrons at $\sqrt{s_{NN}}=39.0$ GeV.

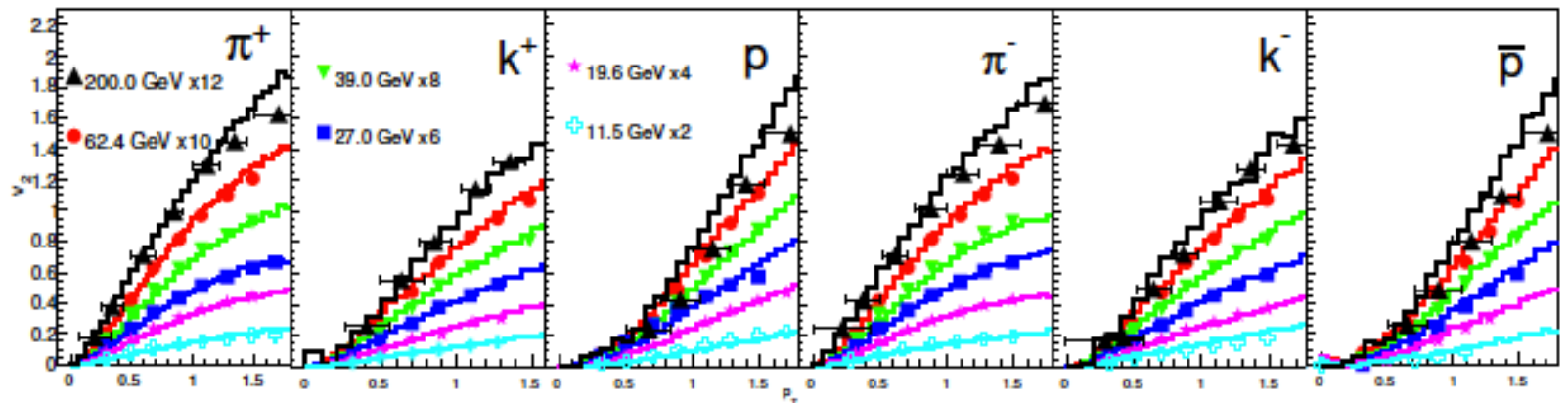
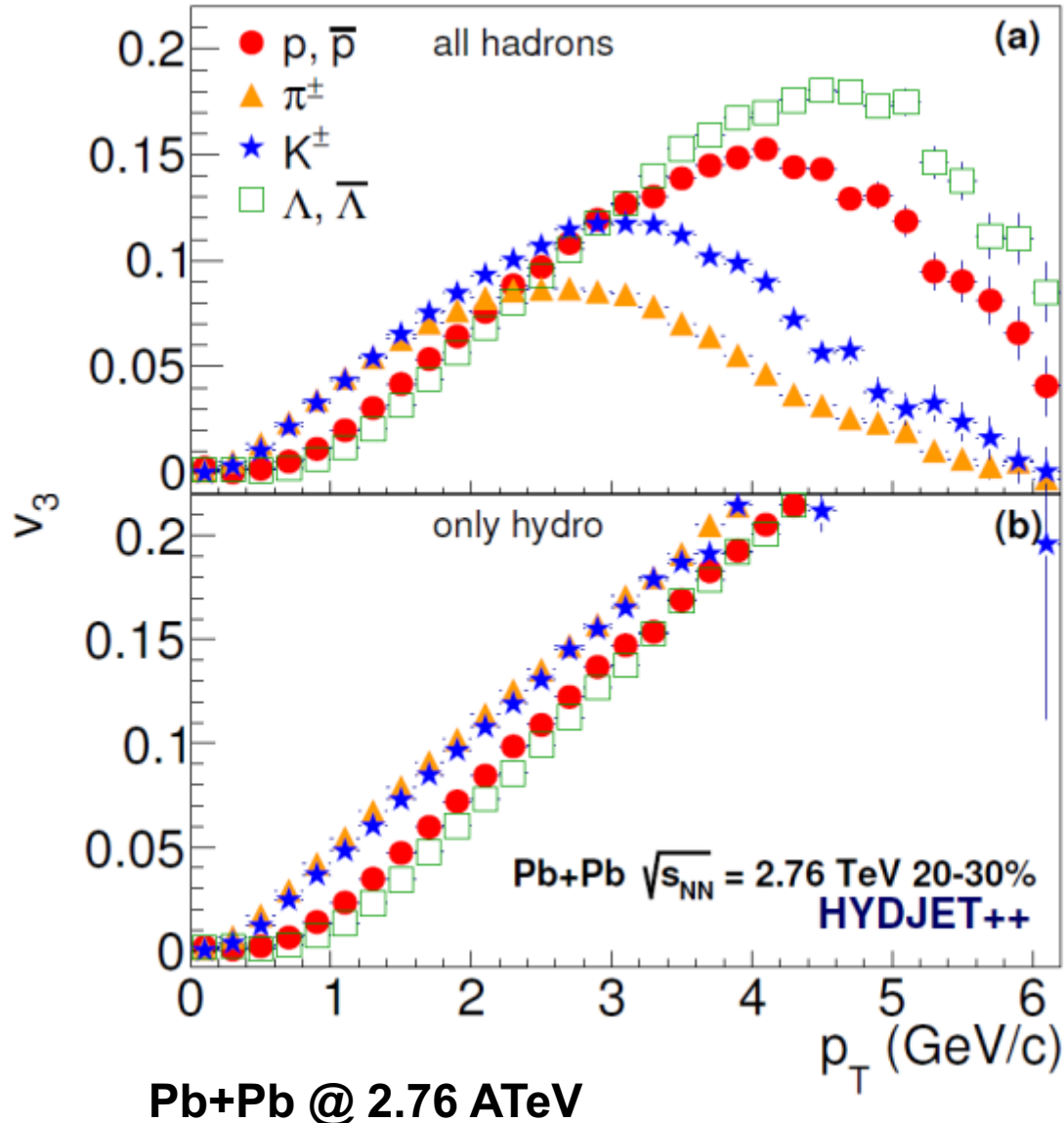


FIG. 11. v_2 at different collision energies. Markers represent experimental data. Lines of the same color show HYDJET++ results.

Interplay of hydrodynamics and jets

Triangular flow

J. Crkovska et al., PRC 95 (2017) 014910



Hydrodynamics gives
mass ordering of v_3

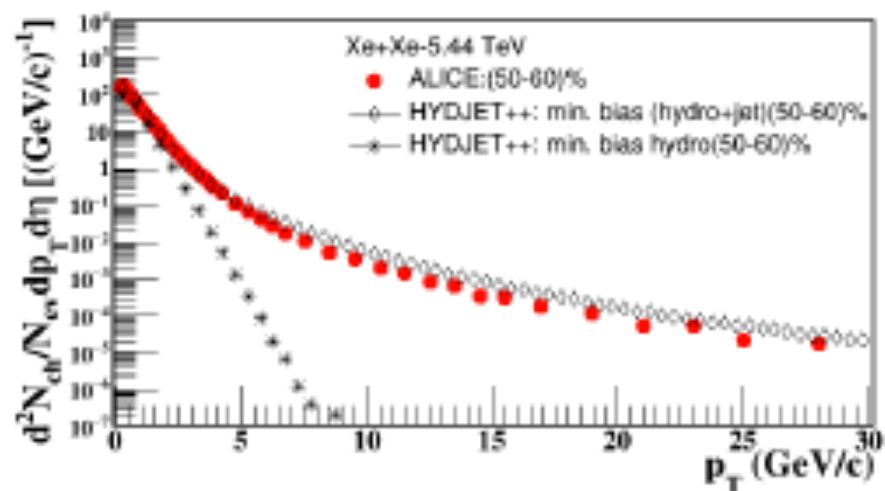
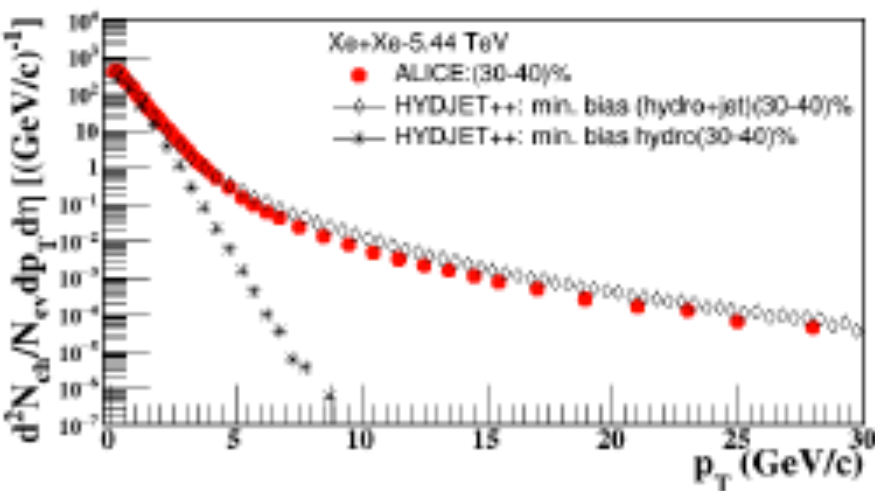
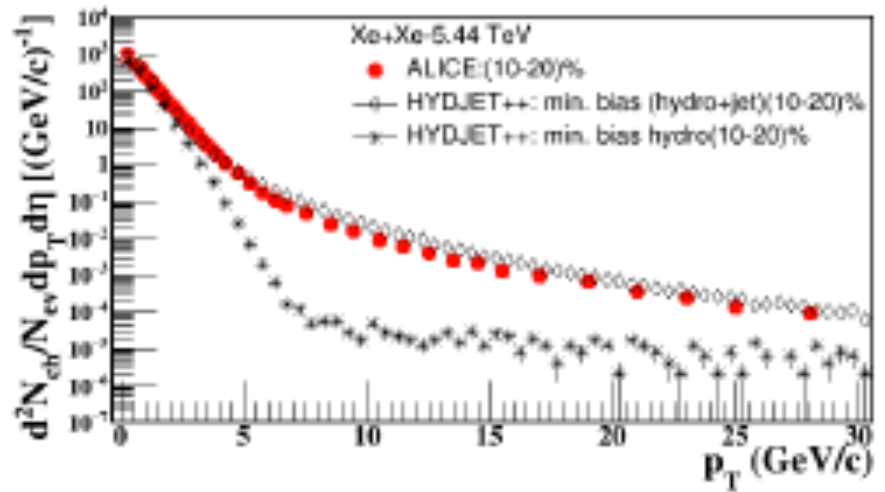
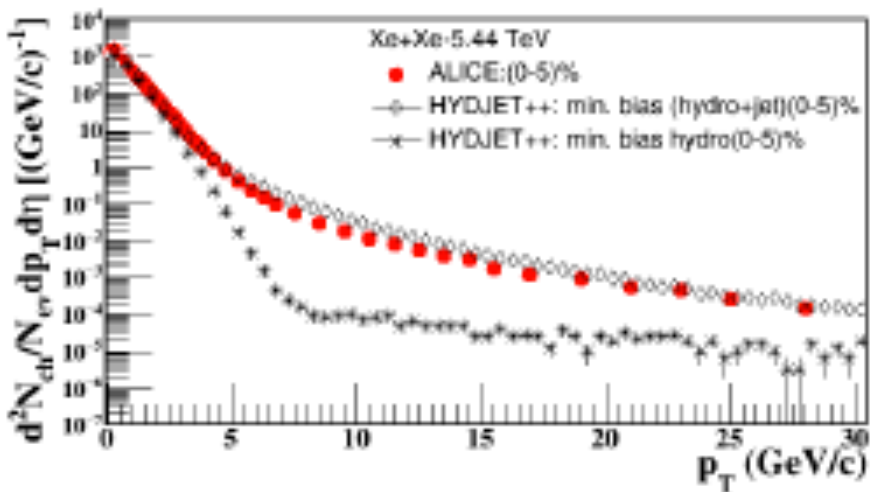
The model possesses
crossing of baryon
and meson branches

The reason for the
mass ordering break
at 2 GeV/c is traced to
hard processes (jets)

Extention to deformed systems (Xe+Xe at LHC)



S. Pandey and B.K. Singh, Eur. Phys. J. A, 59 (2023) 6

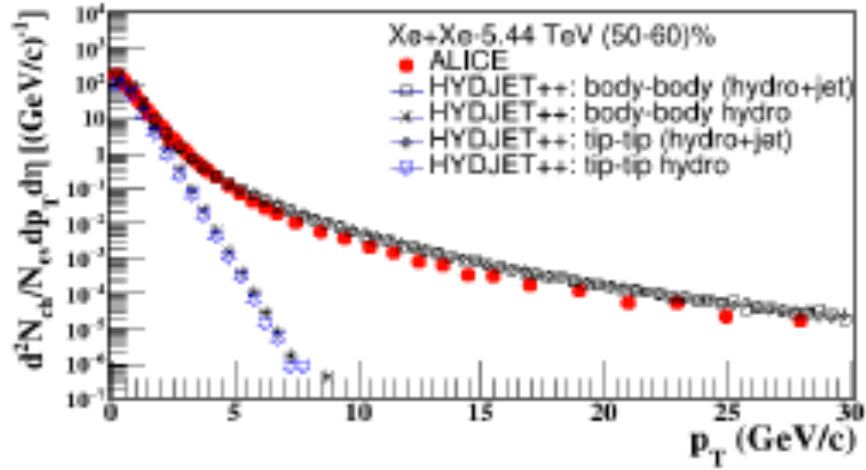
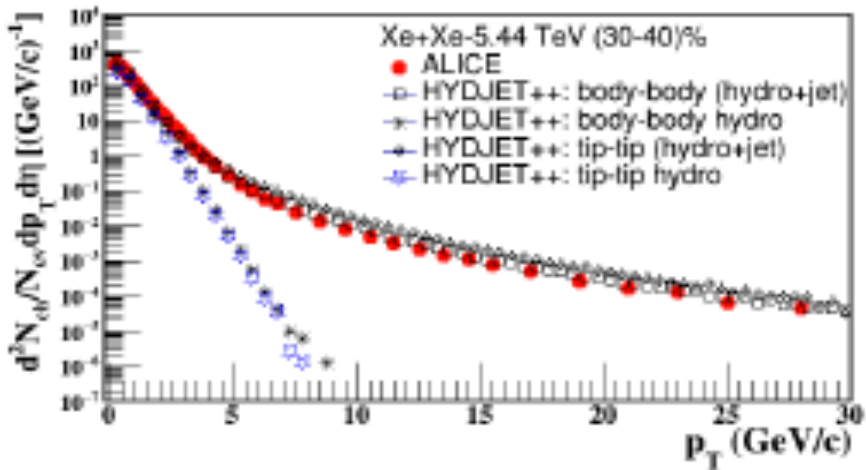
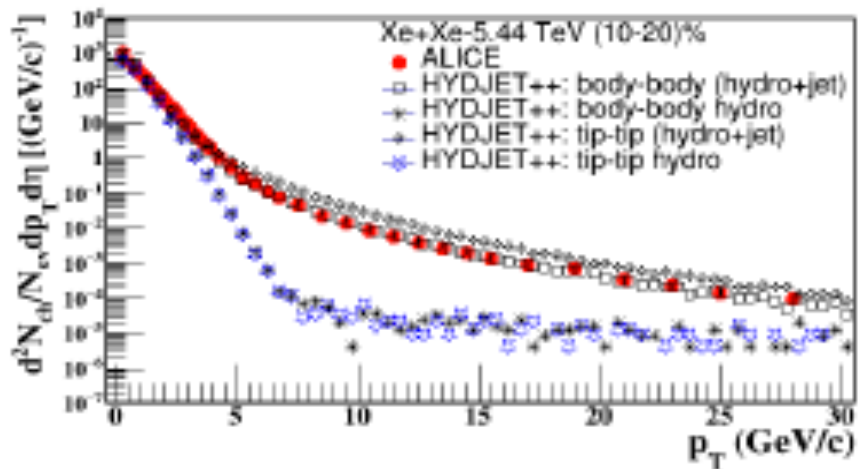
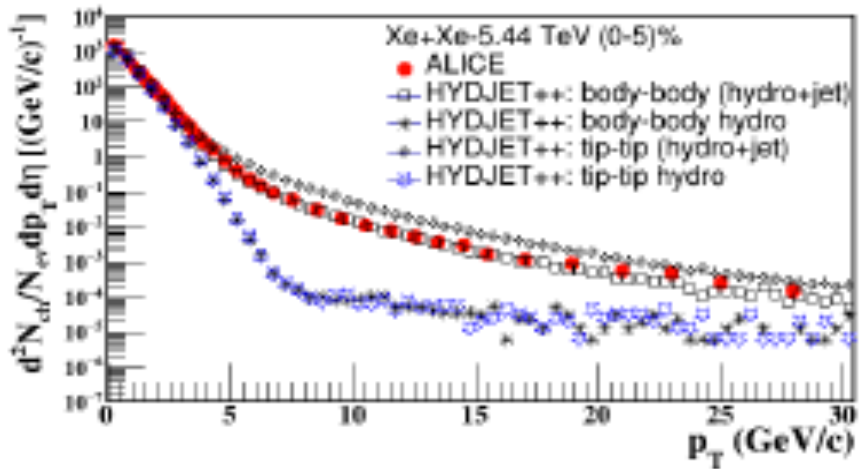


P_T spectra of all charged particles with and w/o jet part for min. bias collisions

Extention to deformed systems (Xe+Xe at LHC)



S. Pandey and B.K. Singh, Eur. Phys. J. A, 59 (2023) 6



p_T spectra of all h^{ch} with and w/o jet part for body-body and tip-tip collisions

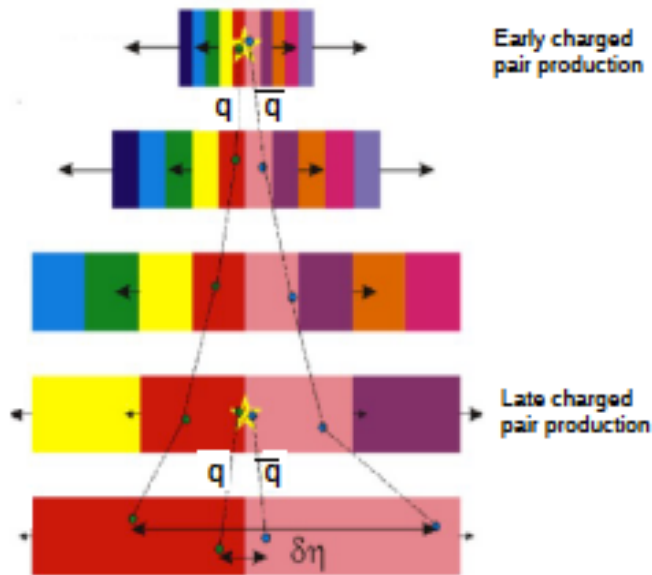
Charge balance function in Pb+Pb at LHC

A. Chernyshov et al., Chin. Phys. C 47 (2023) 084107

Two-particle correlations of charged particles, with (η_1, φ_1) and (η_2, φ_2) , $\Delta\eta = \eta_1 - \eta_2$; $\Delta\varphi = \varphi_1 - \varphi_2$

$$B(\Delta\eta) = \frac{1}{2} \left[\frac{\langle N_{+-}(\Delta\eta) \rangle - \langle N_{++}(\Delta\eta) \rangle}{\langle N_+ \rangle} + \frac{\langle N_{-+}(\Delta\eta) \rangle - \langle N_{--}(\Delta\eta) \rangle}{\langle N_- \rangle} \right]$$

$\langle N_{\pm\mp}(\Delta\eta) \rangle$ is the average number of opposite-charge pairs, separated with $\Delta\eta$. The correlations are corrected for background (pairs from mixed events).



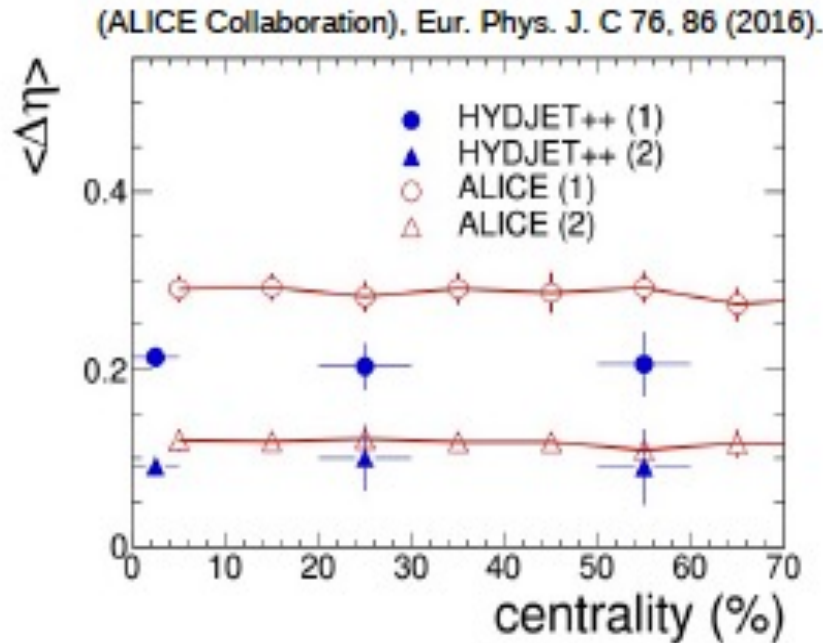
Charge Balance function probes properties and evolution of created system:

- Gives insight into charge creation mechanism
- Sensitive to collective motion (radial flow)

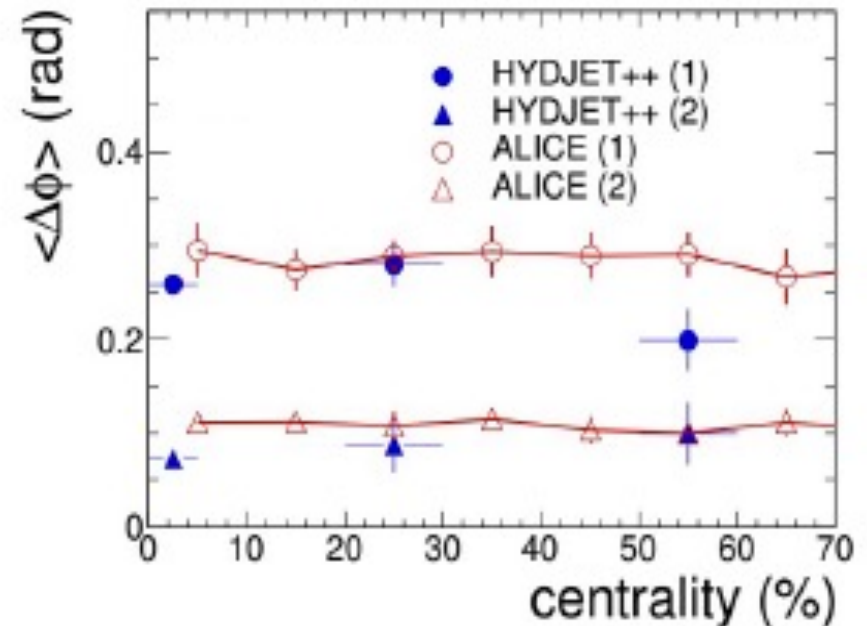
It is suggested, that the width of the BF is smaller in the case if particles creation at the late stage of system evolution and is affected by radial flow.

Charge balance function in Pb+Pb at LHC

A. Chernyshov et al., Chin. Phys. C 47 (2023) 084107



- (1) $2.0 < p_{T,assoc} < 3.0 < p_{T,trig} < 4.0$ GeV/c and
(2) $3.0 < p_{T,assoc} < 8.0 < p_{T,trig} < 15.0$ GeV/c



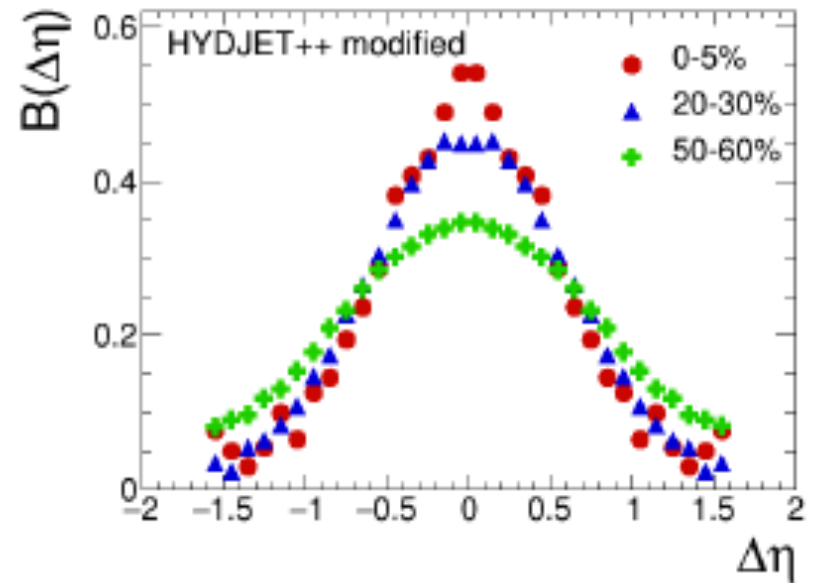
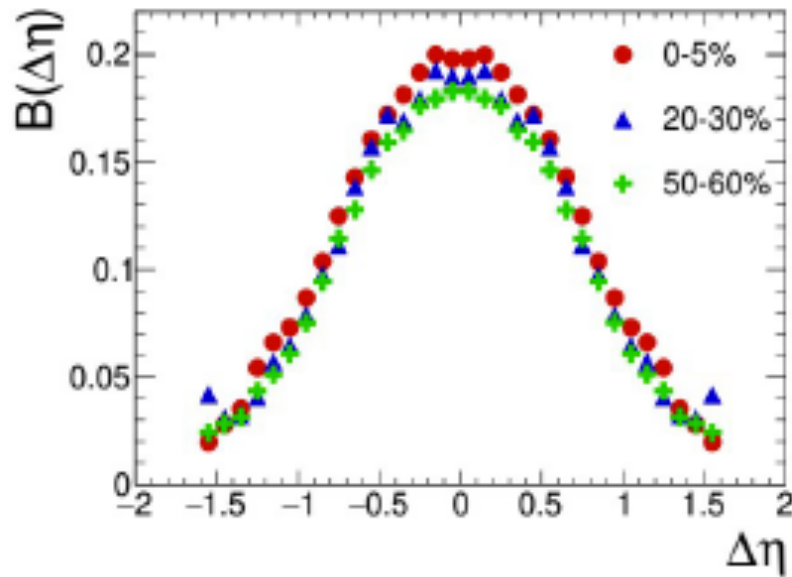
Default HYDJET++ model fairly describes the experimental data on BF width and its centrality dependence for higher p_t range (where the hard component is dominant)

Charge balance function in Pb+Pb at LHC

A. Chernyshov et al., Chin. Phys. C 47 (2023) 084107

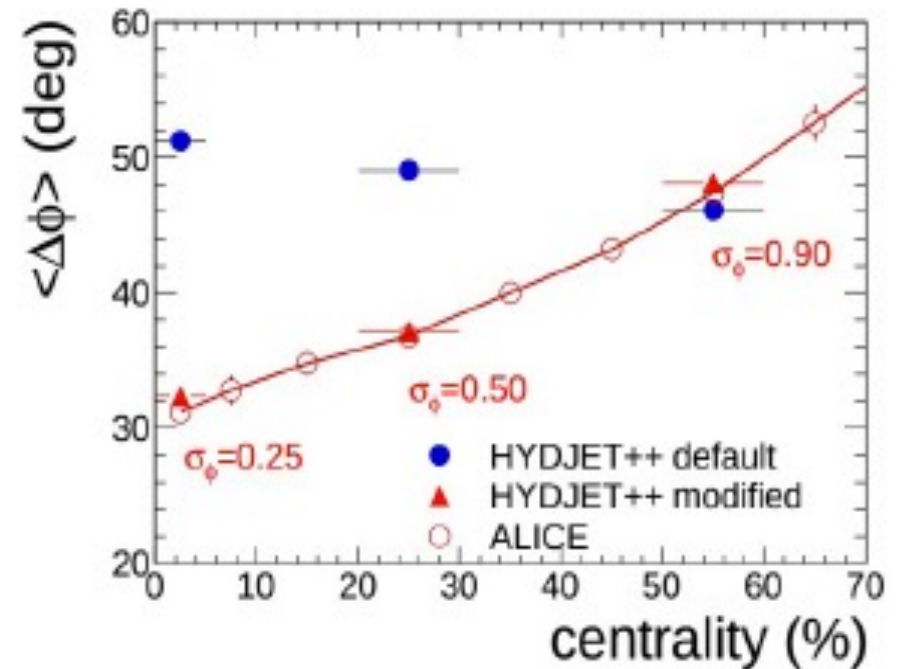
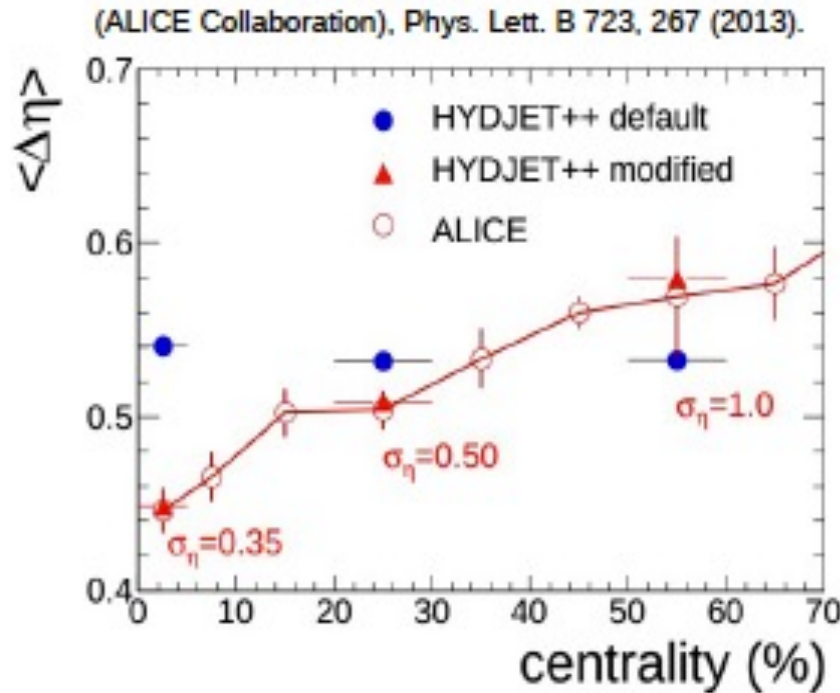
The approach to take into account the event-by-event charge conservation in HYDJET++ model has been developed:

- pair production (particle-antiparticle) is introduced for charged direct hadrons in soft component
- positions of pairs (η_1, φ_1) and (η_2, φ_2) are distributed with Gaussian with certain $\sigma_\eta, \sigma_\varphi$



Charge balance function in Pb+Pb at LHC

A. Chernyshov et al., Chin. Phys. C 47 (2023) 084107



Experimental data can be reproduced with σ increasing for peripheral collisions \rightarrow the charge correlations of direct hadrons become weaker, since the number of the independent particle sources, in which the charge is explicitly conserved, decreases.

Accounting for charge imbalance at BES RHIC, NICA

Production of particle-antiparticle pairs with parameters (η_1, φ_1) and (η_2, φ_2) distributed according to Gaussian with standard deviations $(\sigma_\eta, \sigma_\varphi)$

etc ...

Charged hadron species C

Charged hadron species B

Charged hadron species A

To account for the charge imbalance occurring at intermediate BES RHIC and NICA energies, the proposed modification applies only to the electrically neutral fraction of direct charged hadrons within each hadron species separately. This procedure has been implemented in the HYDJET++ model.

Splitting of charged direct hadrons within one type (pions, kaons, ...)

«Electrically neutral» part (modified)

«Charged» part (preserved)

N^+

N^-

$N^+ - N^-$

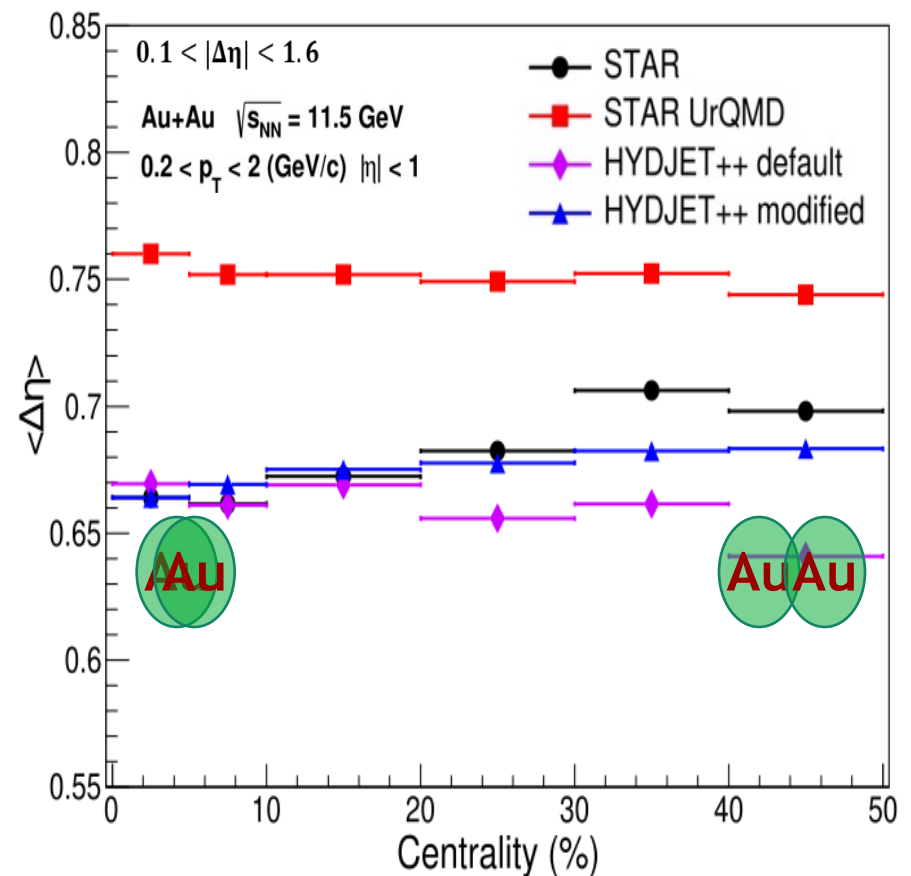
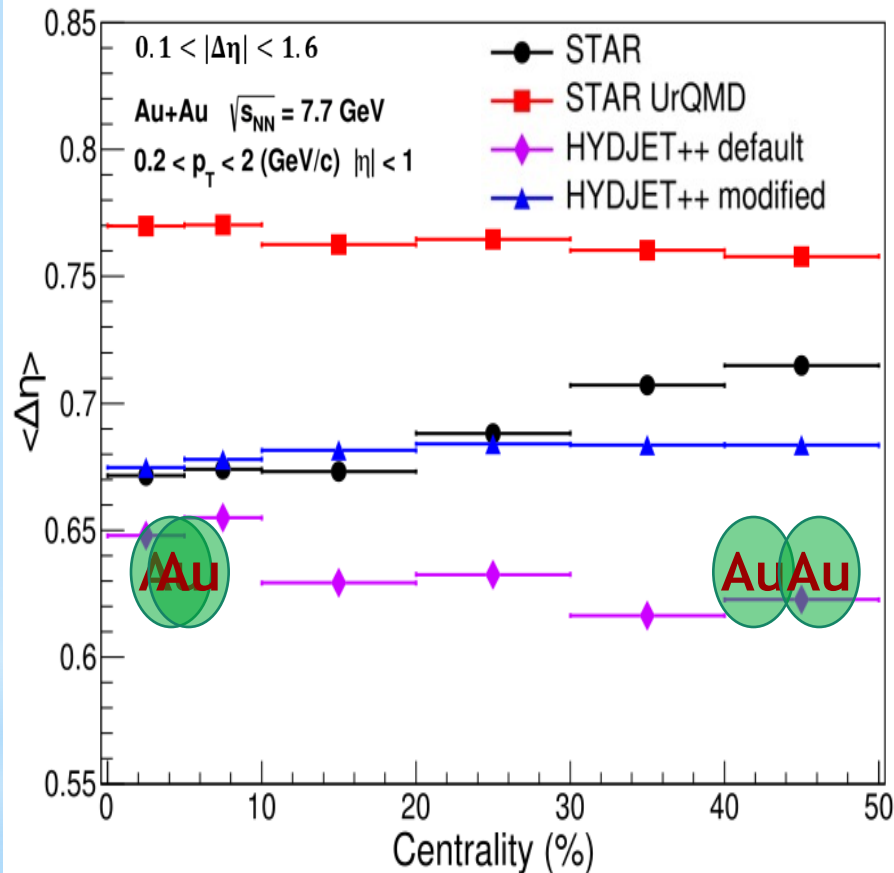
Tuning HYDJET++ parameters with the STAR data for Au+Au at 7.7 and 11.5 GeV

		π^+/π^-	K^+/K^-	p/\bar{p}
7.7 GeV	RHIC STAR	0.93 ± 0.12	2.70 ± 0.31	141 ± 24
	HYDJET++	0.89	2.70	130
	$\mu_{I,S,B}$ (MeV)	6	100	429
11.5 GeV	RHIC STAR	0.95 ± 0.14	2.03 ± 0.28	29.3 ± 5.3
	HYDJET++	0.93	1.99	28.2
	$\mu_{I,S,B}$ (MeV)	7	72	313

Ratios of oppositely charged hadrons in central Au+Au collisions at BES RHIC energies measured by STAR (upper rows) and calculated with HYDJET++ (middle rows). Bottom rows present the chemical potentials of isospin, baryon charge and strangeness, respectively.

Charge balance function in Au+Au at 7.7 and 11.5 GeV

E.Z. et al., ZETP 166 (2024) 340



UrQMD and the standard version of HYDJET++ do not reproduce the experimental dependences of the CBF rapidity widths on centrality. The modified HYDJET++ allows to significantly improve the description of the data up to 30% of centrality (with some underestimation of the data for more peripheral collisions).

Net-charge fluctuations in Pb+Pb at LHC

- NCF are considered as a possible signal of QGP:
charge fluctuations in QGP \ll charge fluctuations in hadron gas

$$D = 4 \frac{\langle \delta Q^2 \rangle}{\langle N_{\text{ch}} \rangle}$$

- ✓ $D \approx 4$ for hadron gas
- ✓ $D \approx 3$ after decays of resonances

S. Jeon and V. Koch, *Phys. Rev. Lett.* **85**, 2076 (2000)

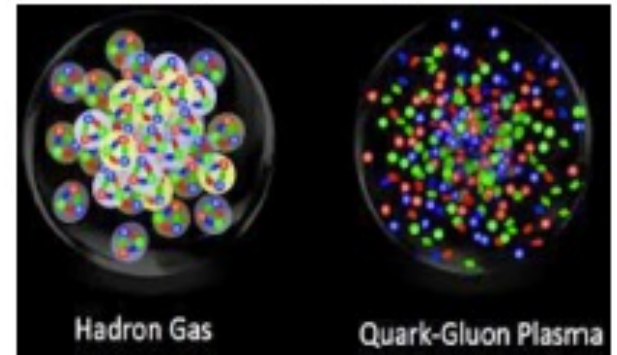
- ✓ $D \approx 1-1.5$ for quark-gluon plasma

For lattice QCD S. Gottlieb et al., *Phys. Rev. D* **55**, 6852 (1997).

- ✓ For the quark coalescence, however, $D \approx 3.3$

A. Bialas, *Phys. Lett. B* **532**, 249 (2002)

Net-charge $Q = N_+ - N_-$



$$q^2 = 1$$

$$q^2 = \frac{1}{9}, \frac{4}{9}$$

- ✓ Fluctuations $\delta Q \sim q^2$
- ✓ $\text{NCF}^{\text{HG}} \gg \text{NCF}^{\text{QGP}}$

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

Net-charge fluctuations in Pb+Pb at LHC

$$\nu_{+-} = \left\langle \left(\frac{N_+}{\langle N_+ \rangle} - \frac{N_-}{\langle N_- \rangle} \right)^2 \right\rangle \quad \nu_{+-,stat} = \frac{1}{\langle N_+ \rangle} + \frac{1}{\langle N_- \rangle}$$

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

$$D = 4 \frac{\langle \delta Q^2 \rangle}{\langle N_{ch} \rangle} = \langle N_{ch} \rangle \nu_{+-,dyn} + 4$$

$\nu_{dyn} > 0 \rightarrow$ correlations ++, -- dominate

$\nu_{dyn} < 0 \rightarrow$ correlations +- dominate

$\nu_{dyn} = 0 \rightarrow$ independent particle emission

Strongly intensive quantity

$$\Sigma[N_+, N_-] = \frac{1}{\langle N_+ \rangle + \langle N_- \rangle} [\langle N_+ \rangle \omega_- + \langle N_- \rangle \omega_+ - 2Cov(N_+, N_-)] , \quad \omega_+ = \frac{\langle N_+^2 \rangle - \langle N_+ \rangle^2}{\langle N_+ \rangle} .$$

M. I. Gorenstein and M. Gazdzicki, PRC 84, 014904

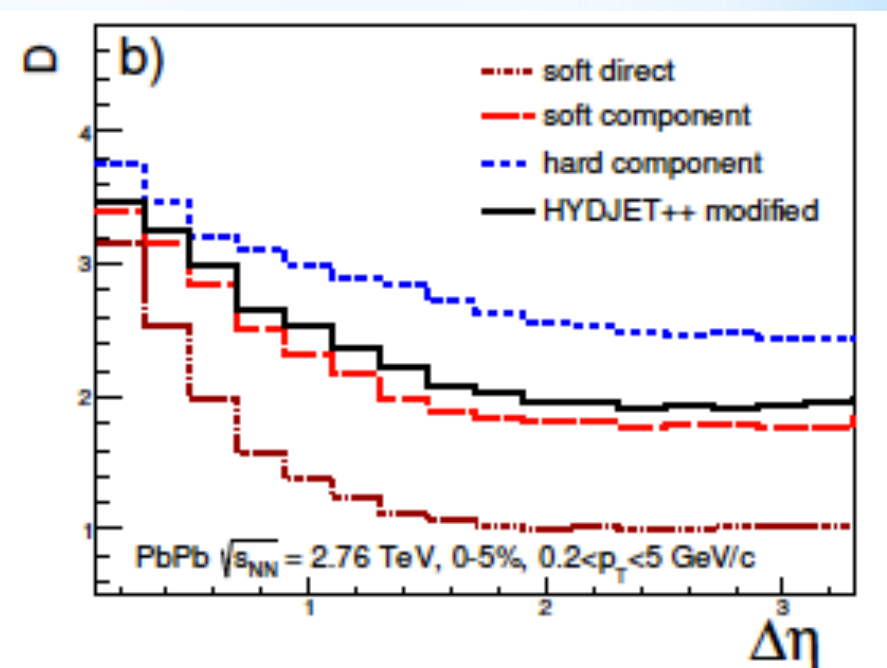
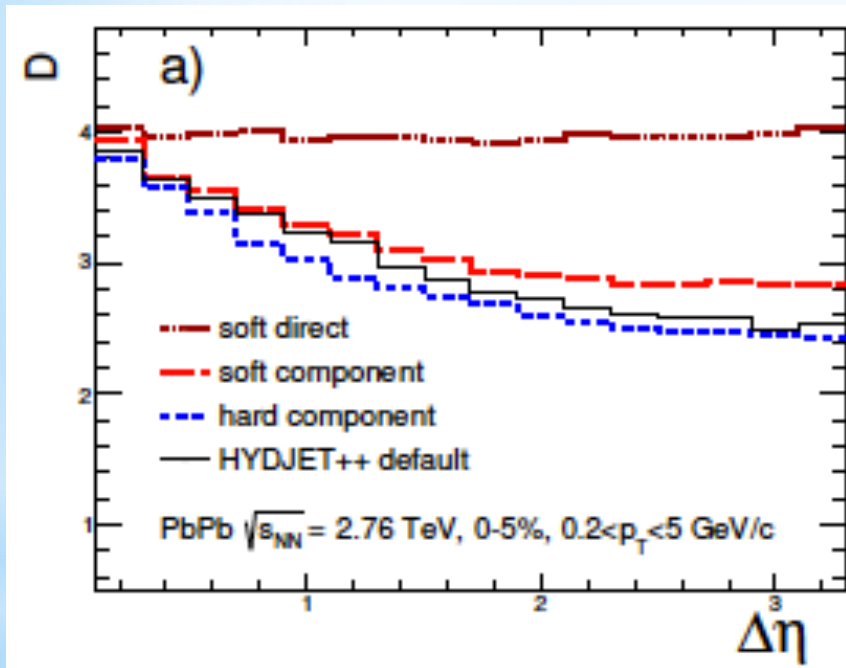
$$\text{At } \langle N_+ \rangle \approx \langle N_- \rangle \quad : \quad \Sigma[N_+, N_-] - 1 = \frac{\nu_{dyn}[+, -]}{\frac{1}{\langle N_+ \rangle} + \frac{1}{\langle N_- \rangle}}$$

Net-charge fluctuations in Pb+Pb at LHC

G. Ambaryan et al., Chin. Phys. C 49 (2025) 014109

HYDJET++ default

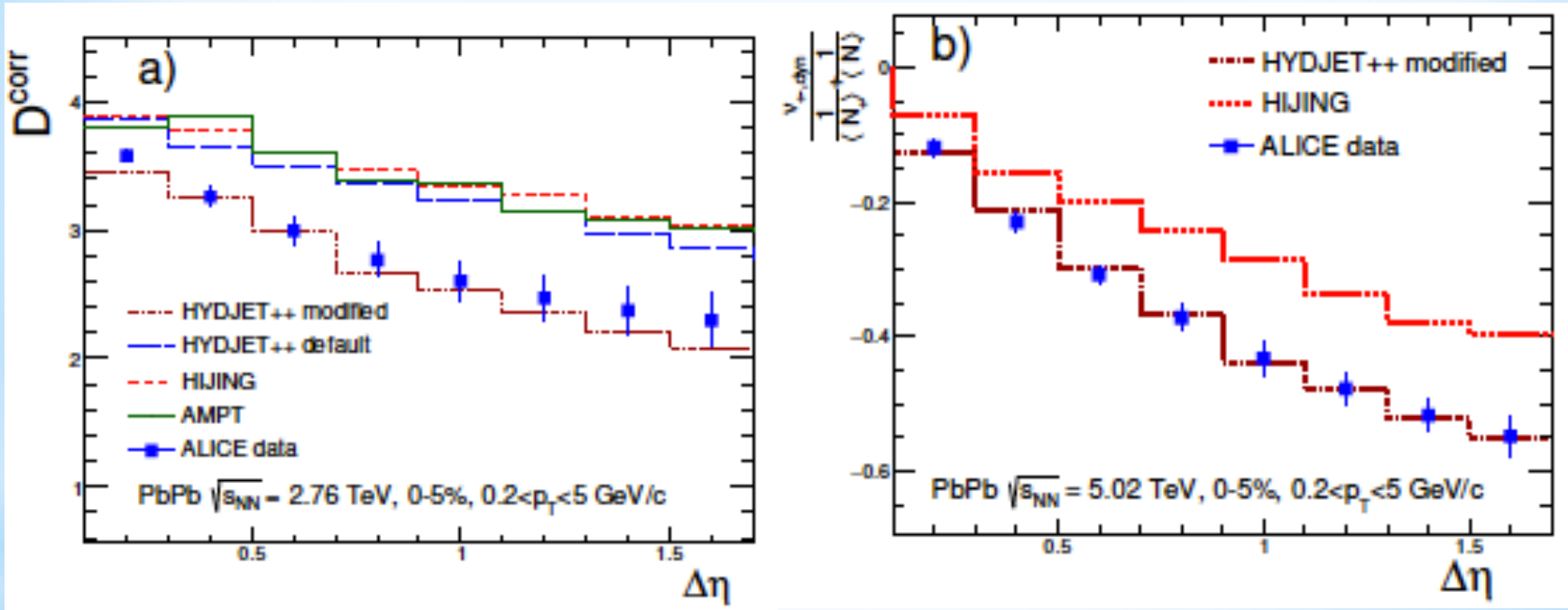
HYDJET++ modified



- (a) in case of absence of the charge correlations between directly produced hadrons decays of resonances lead to decrease of D , whereas
- (b) in case of initially strong correlations between the directly produced hadrons with unlike charges it leads to increase of D

Net-charge fluctuations in Pb+Pb at LHC

HYDJET++ (default ; modified) and other models vs data ($\sqrt{s} = 2.76 ; 5.02$ TeV)



Correction for global charge conservation:

$$D^{\text{corr}} = (\nu_{+-,\text{dyn}} \langle N_{ch} \rangle + 4) / (C_{\mu} C_{\eta})$$

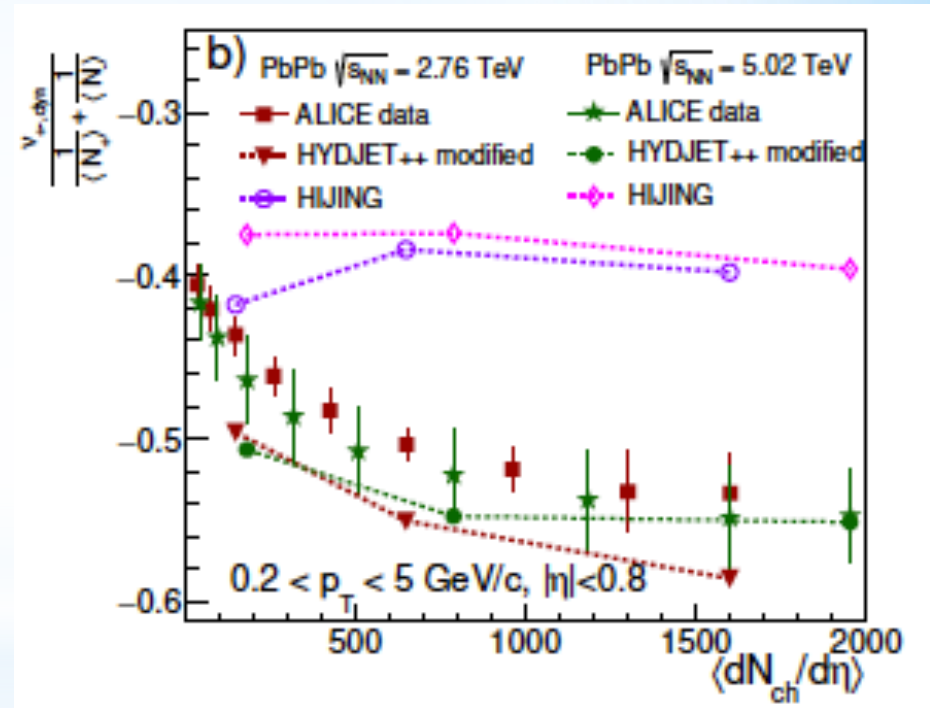
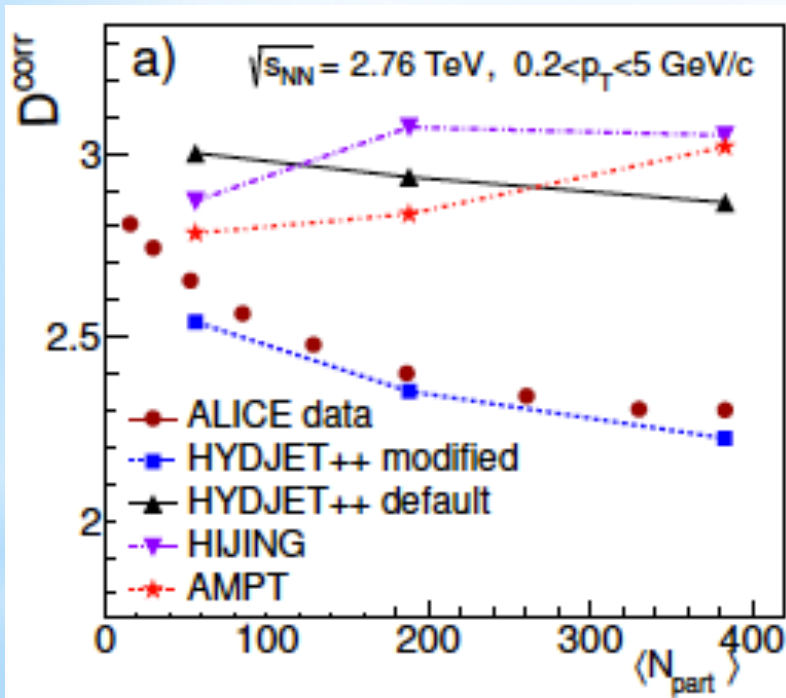
$$C_{\mu} = \langle N_{+} \rangle^2 / \langle N_{-} \rangle^2 \text{ and } C_{\eta} = 1 - \langle N_{ch} \rangle / \langle N_{tot} \rangle$$

Pseudorapidity dependence of both D and $\Sigma - 1$ is fairly reproduced

Net-charge fluctuations in Pb+Pb at LHC

G. Ambaryan et al., Chin. Phys. C 49 (2025) 014109

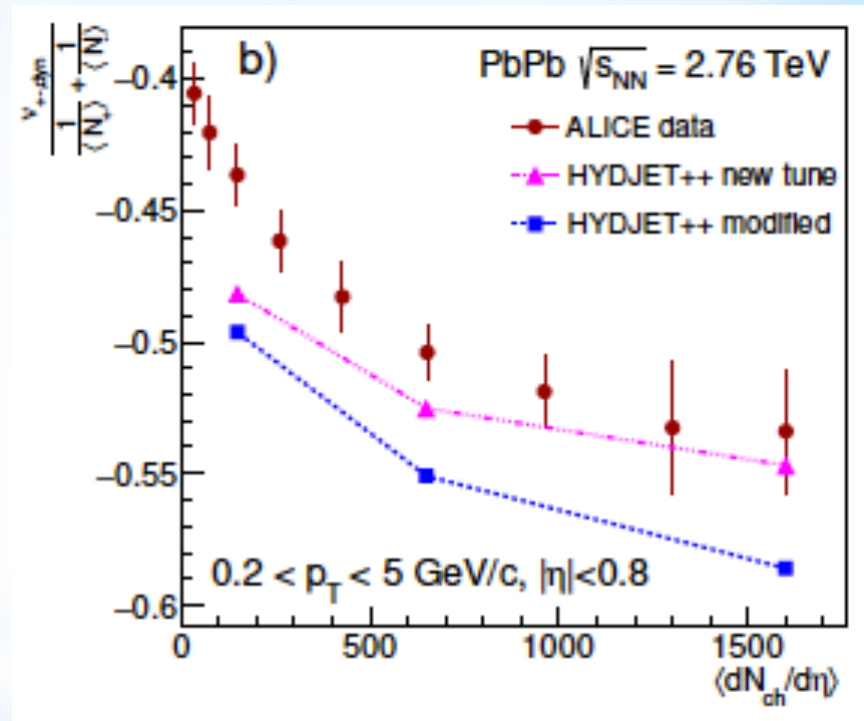
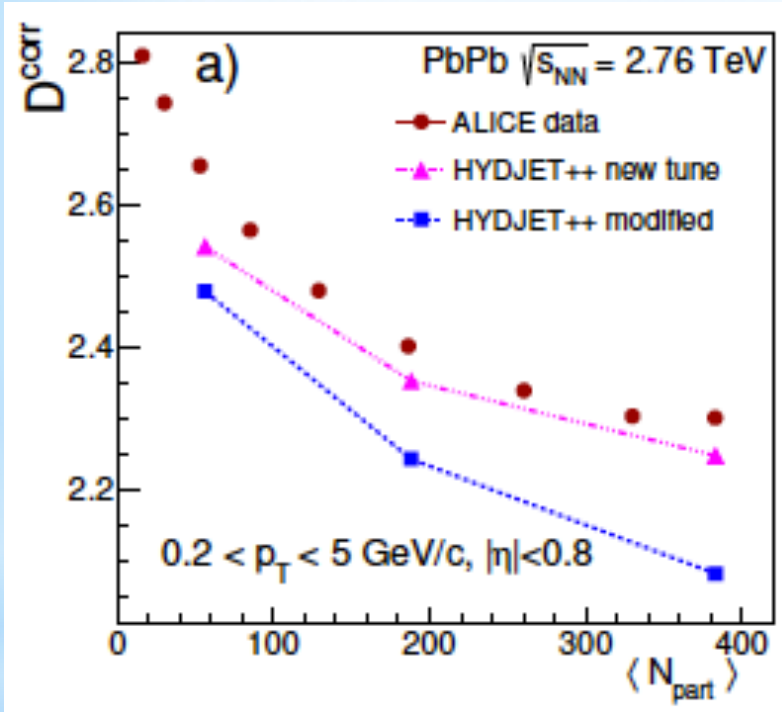
HYDJET++ (default, modified) and other models vs data ($\sqrt{s} = 2.76 ; 5.02$ TeV)



Centrality dependence of D and especially of $\Sigma - 1$ is reproduced rather qualitatively \Rightarrow for better quantitative description we need further tuning of σ_η

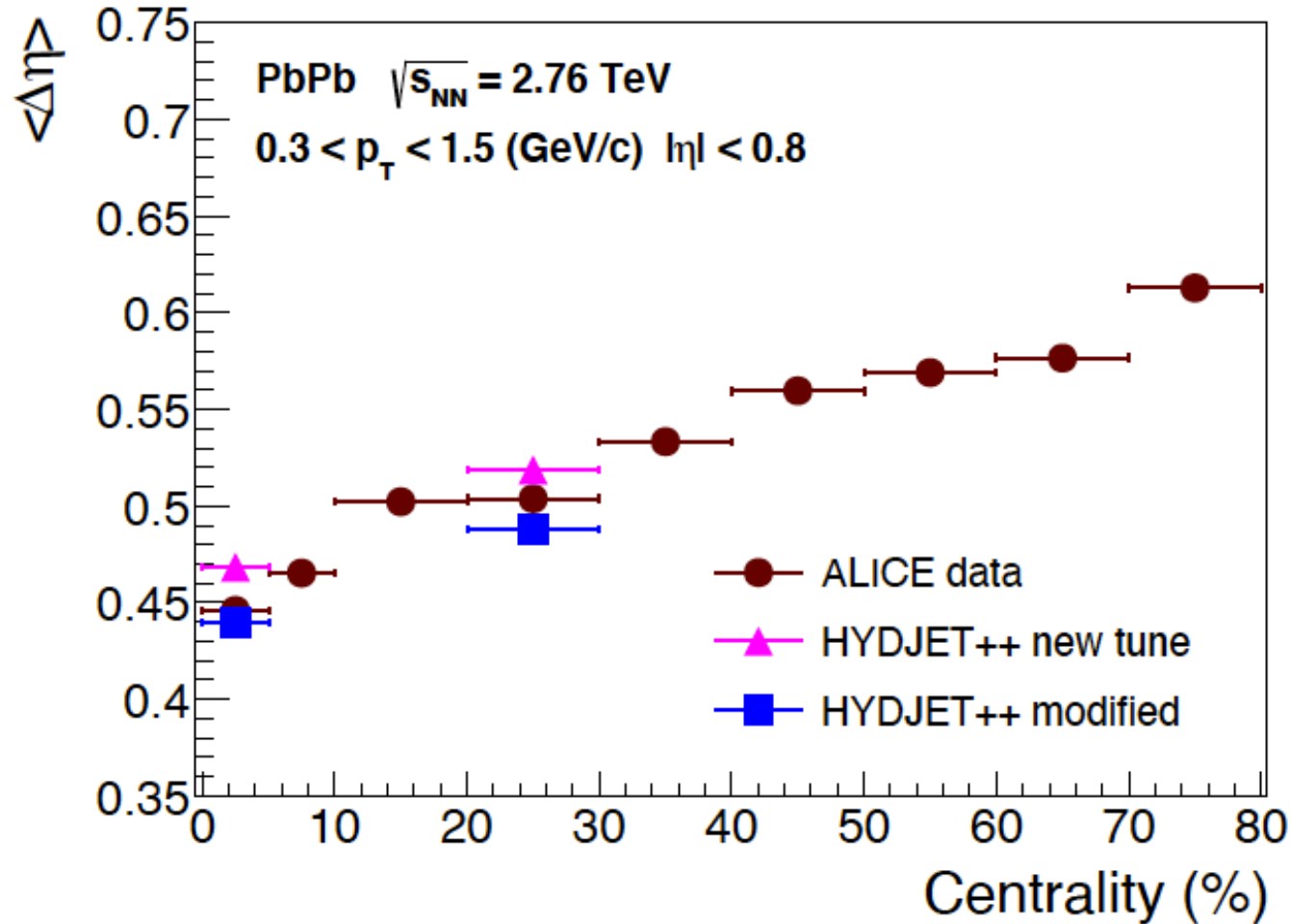
Net-charge fluctuations in Pb+Pb at LHC

HYDJET++ (modified and with new tune) vs data



Centrality dependence of both parameters, D and $\Sigma - 1$ is reproduced quite well

Charge balance function in Pb+Pb at LHC with new tune for σ_η



The difference is within 7% limit

CONCLUSIONS

HYDJET++ was essentially modified by means of the explicit inclusion of charge conservation in a statistical approach (canonical ensemble). This procedure has been implemented for the first time in Monte Carlo event generators of such a kind.

Within this approach:

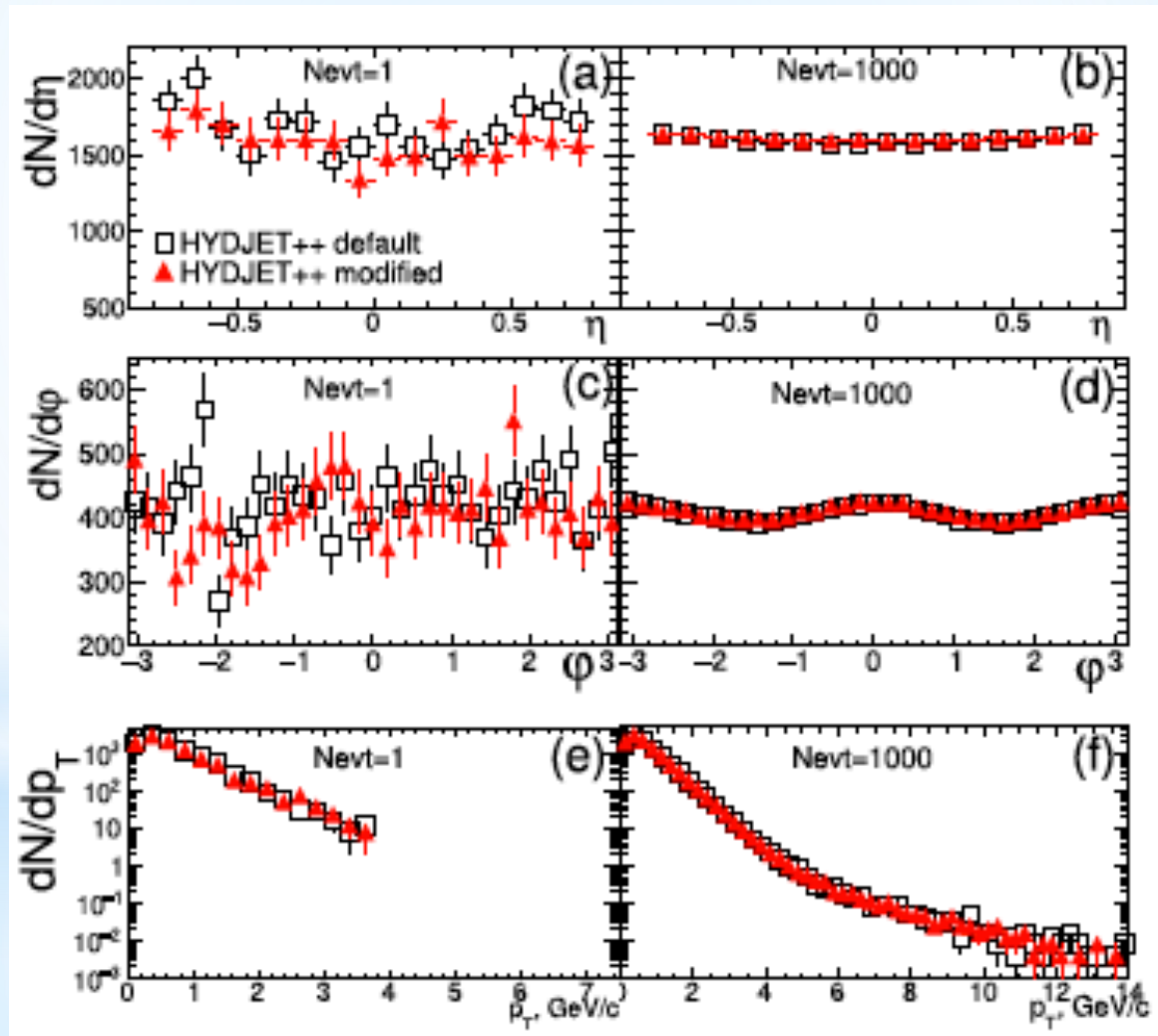
- *Centrality dependence of the widths of charge balance functions in A+A collisions at LHC and BES RHIC energies is reproduced*
- *With increasing transverse momentum the transition to a single source of charge correlations, i.e., jets, takes place*
- *Centrality and $\Delta\eta$ dependences of the fluctuations of the net electric charge of hadrons in these collisions are well described*
- *Decays of resonances in the case of initially strong correlations between the directly produced hadrons with unlike charges leads to increase of the parameters D & Σ*
- *But in the case of absence of these correlations (infinite correlation length) decays of resonances lead to decrease of D & Σ*

An aerial photograph showing the wake of a boat moving through clear, turquoise water. The wake consists of a central line of white, frothy water that branches out into smaller, swirling patterns on either side. The overall scene is bright and dynamic, with the white foam contrasting sharply against the vibrant blue-green water.

**THANK YOU FOR
YOUR ATTENTION !**

Back-up Slides

Charge balance function in Pb+Pb at LHC modified vs default HYDJET++



No difference for $N_{\text{evt}} > 100$