HYDrodynamics with JETs (HYDJET++): Latest developments and results

E. Zabrodin

in collaboration with

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

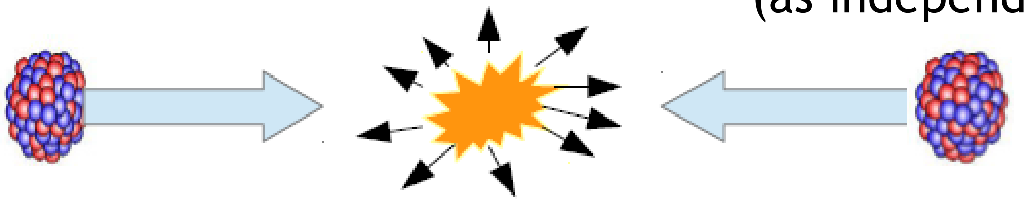
ICNFP XIII, OAC, Kolymbari, Crete, Greece, 26.08 – 04.09.2024

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 → uniform weights → effective von-Neumann rejection-acception procedure.

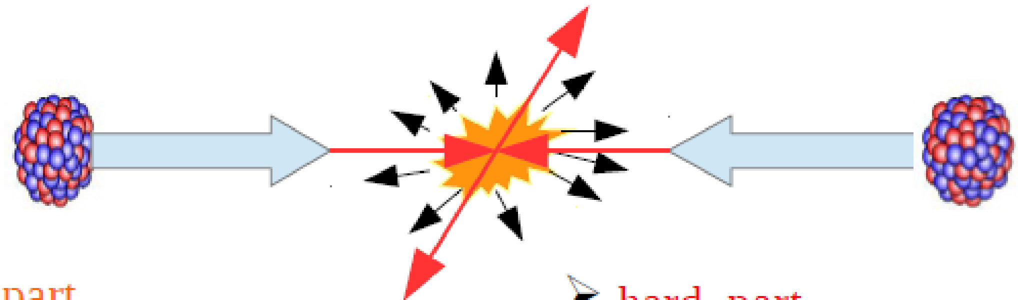
Freeze-out surface parameterizations

1. The Bjorken model with hypersurface $\tau = (t^2 - z^2)^{1/2} = const$
2. Linear transverse flow rapidity profile $\rho_u = \frac{r}{R}\rho_u^{\max}$
3. The total effective volume for particle production at

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

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://cern.ch/lokhtin/hydjet++

(latest version 2.4)

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

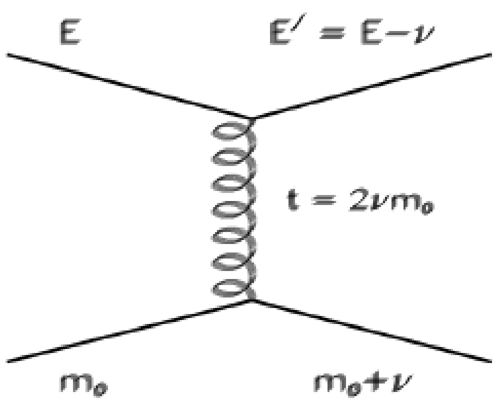
Hard component

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:

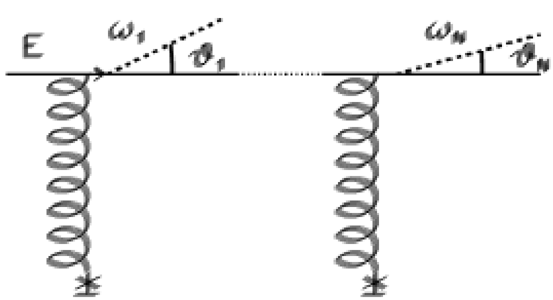
$$\Delta E(L,E) = \int_0^L dl \frac{dP(l)}{dl} \lambda(l) \frac{dE(l,E)}{dl} \qquad \frac{dP(l)}{dl} = \frac{1}{\lambda(l)} \exp(-l/\lambda(l))$$

- Collisional loss (high momentum transfer approximation)



+

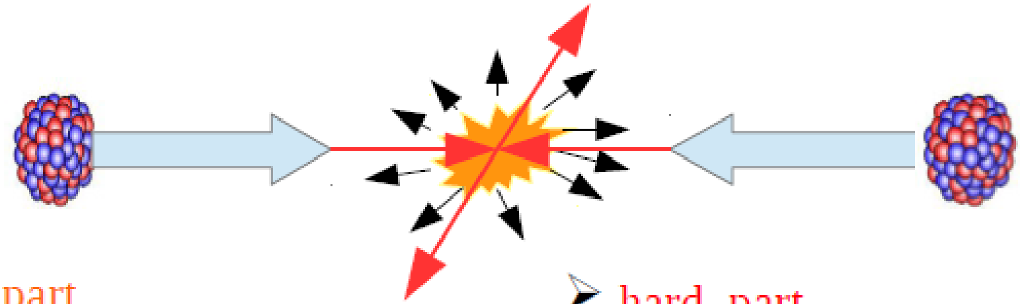
- Radiative loss (coherent gluon radiation in Baier-Dokshitzer-Mueller-Schiff formalism)



- “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)

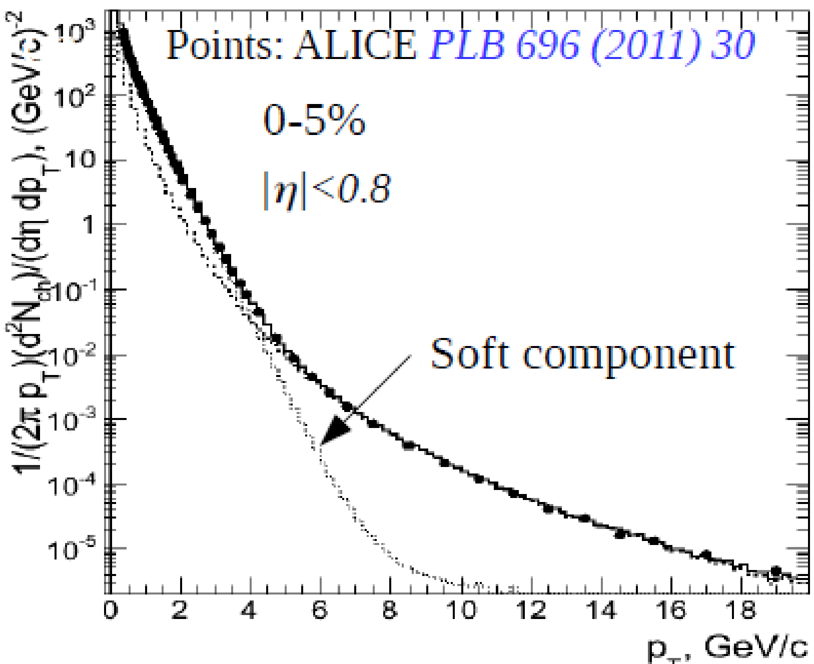
➢ hard part
(represented by hard parton scattering and later hadronization based on PYTHIA)

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)

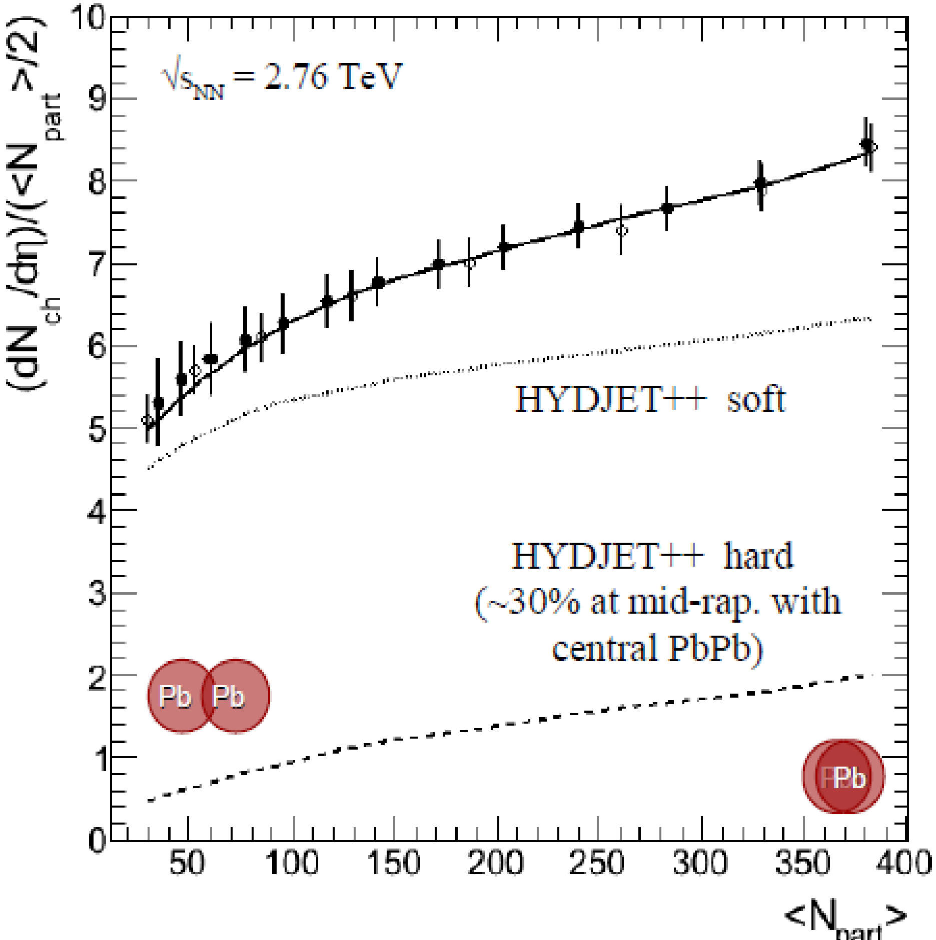
- Modification of the hard part due to interactions with the medium is simulated

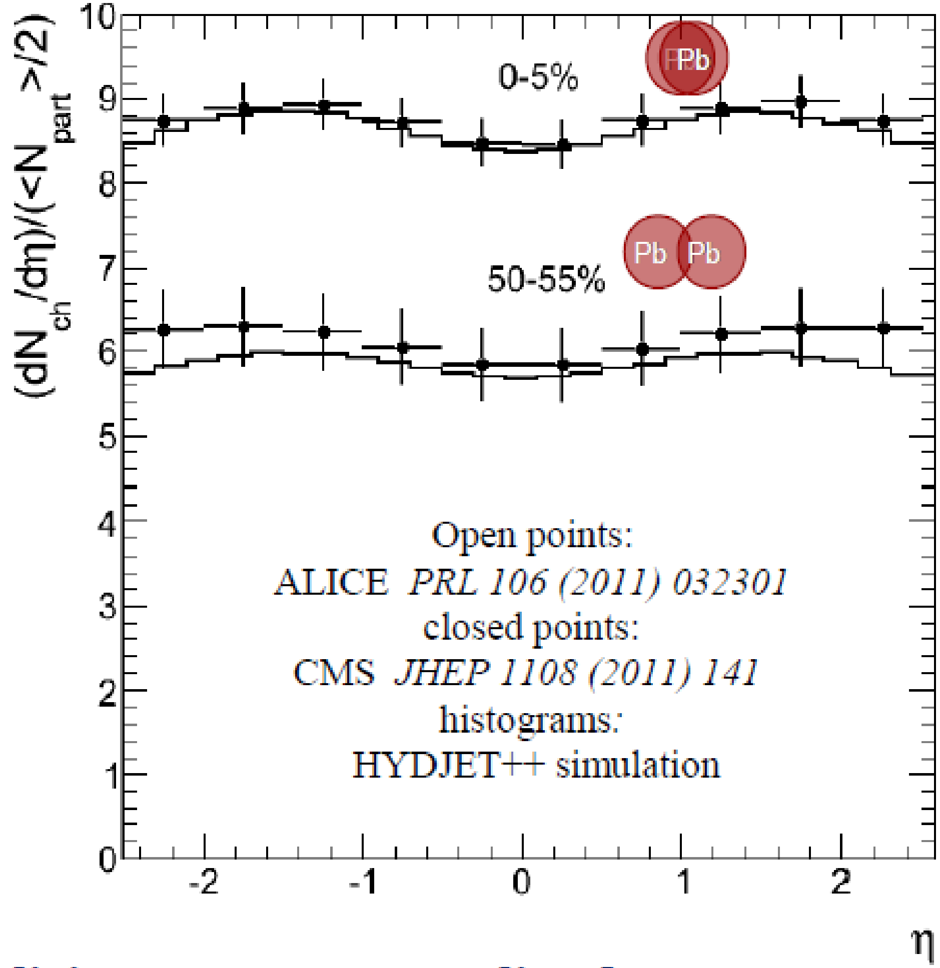
- No modification of soft part



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

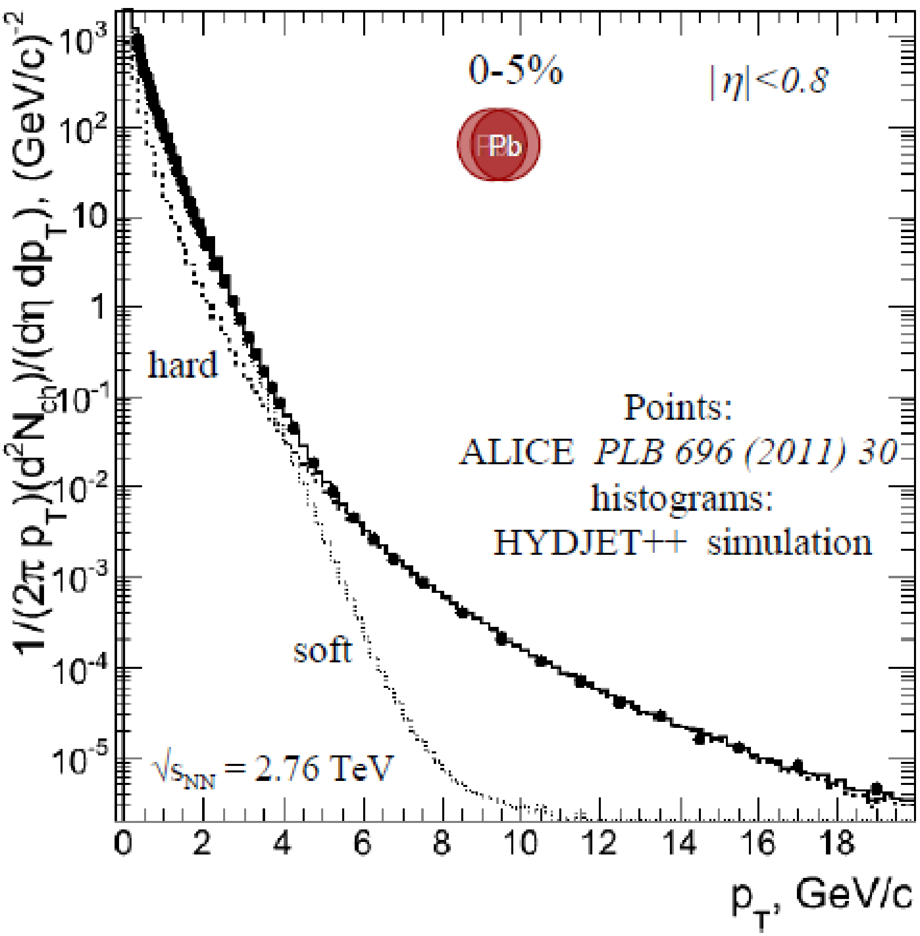


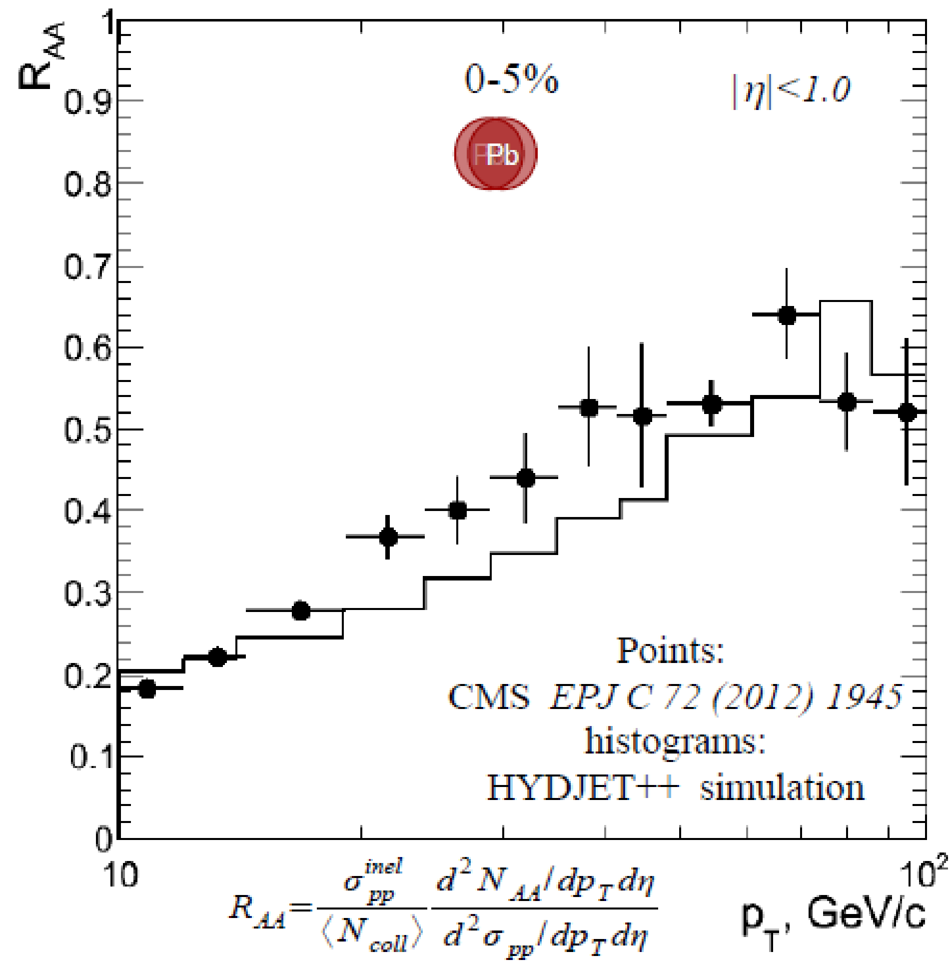


Tuned HYDJET++ reproduces multiplicity vs. event centrality down to very peripheral events, as well as approximately flat pseudorapidity distribution.

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 $p_T \sim 100$ GeV/*c*.

Comparison to STAR BES data

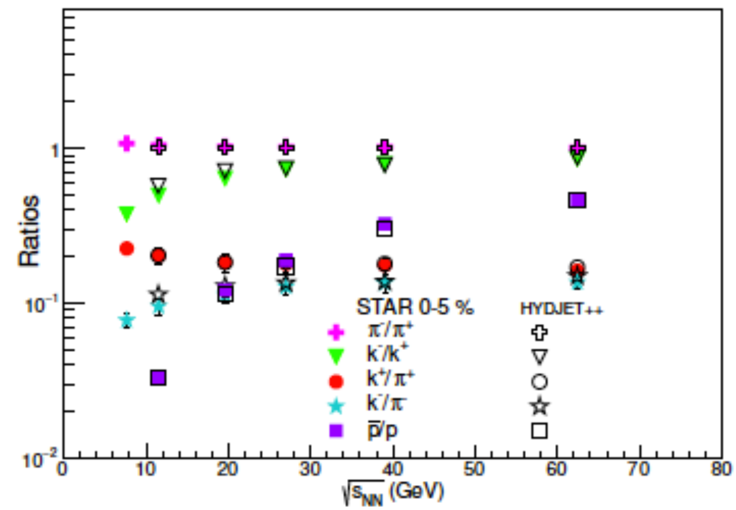


FIG. 1. Particle ratios at different beam energies.

S.R. Nayak et al., arXiv: 2405.03174 [hep-ph]

Good agreement with the data

Mass ordering of the flow (v_2, v_3)

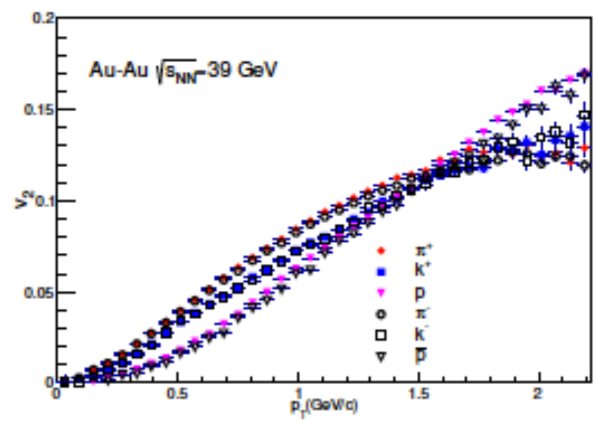


FIG. 13. v_2 of primary hadrons at $\sqrt{s_{NN}}$=39.0 GeV.

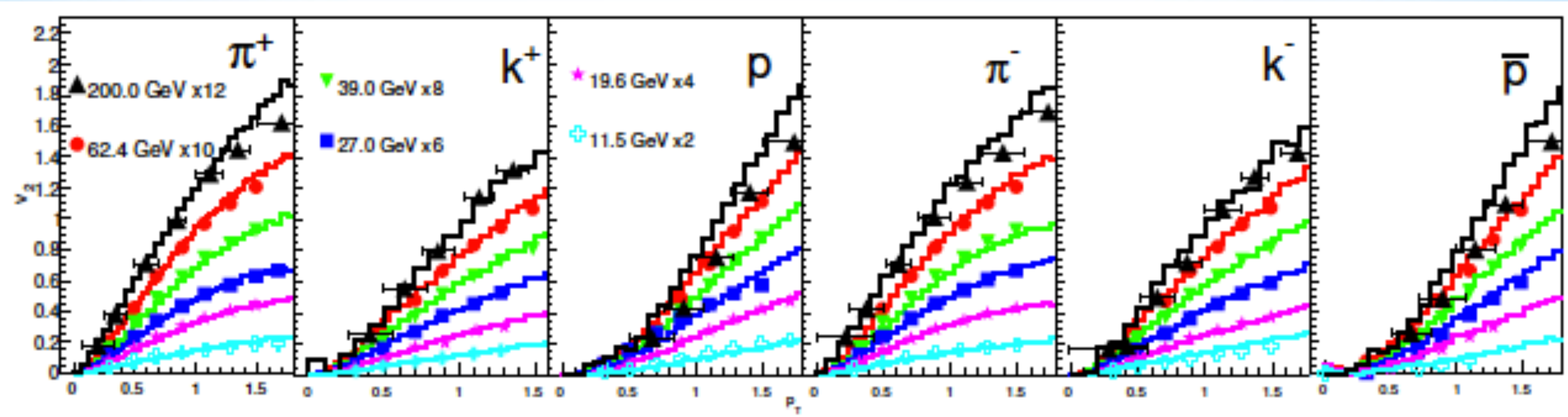
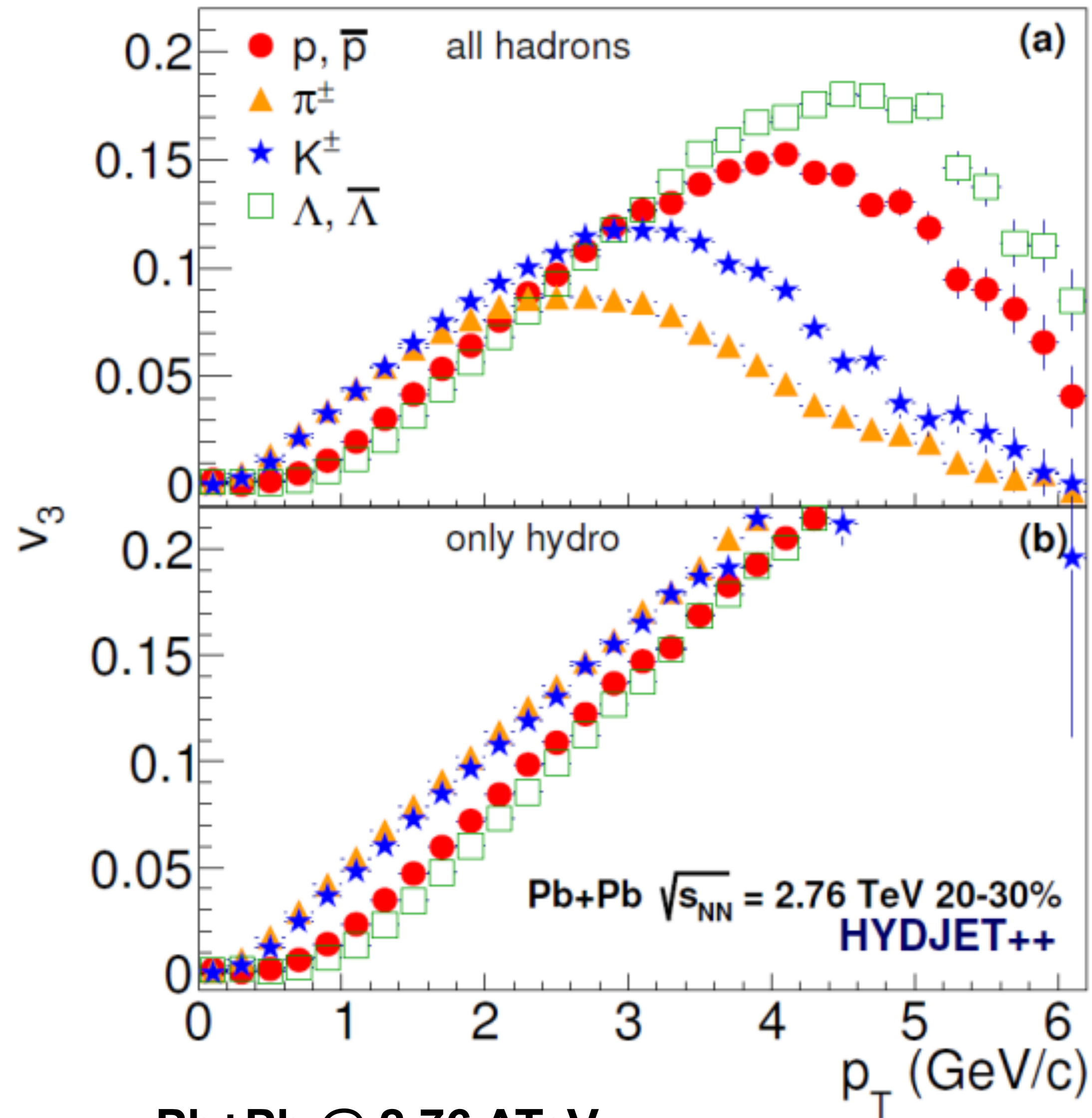


FIG. 11. v_2 at different collision energies. Markers represent experimental data. Lines of the same color show HYDJET++ results.

Interplay of hydrodynamics and jets

Triangular flow

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



Pb+Pb @ 2.76 ATeV

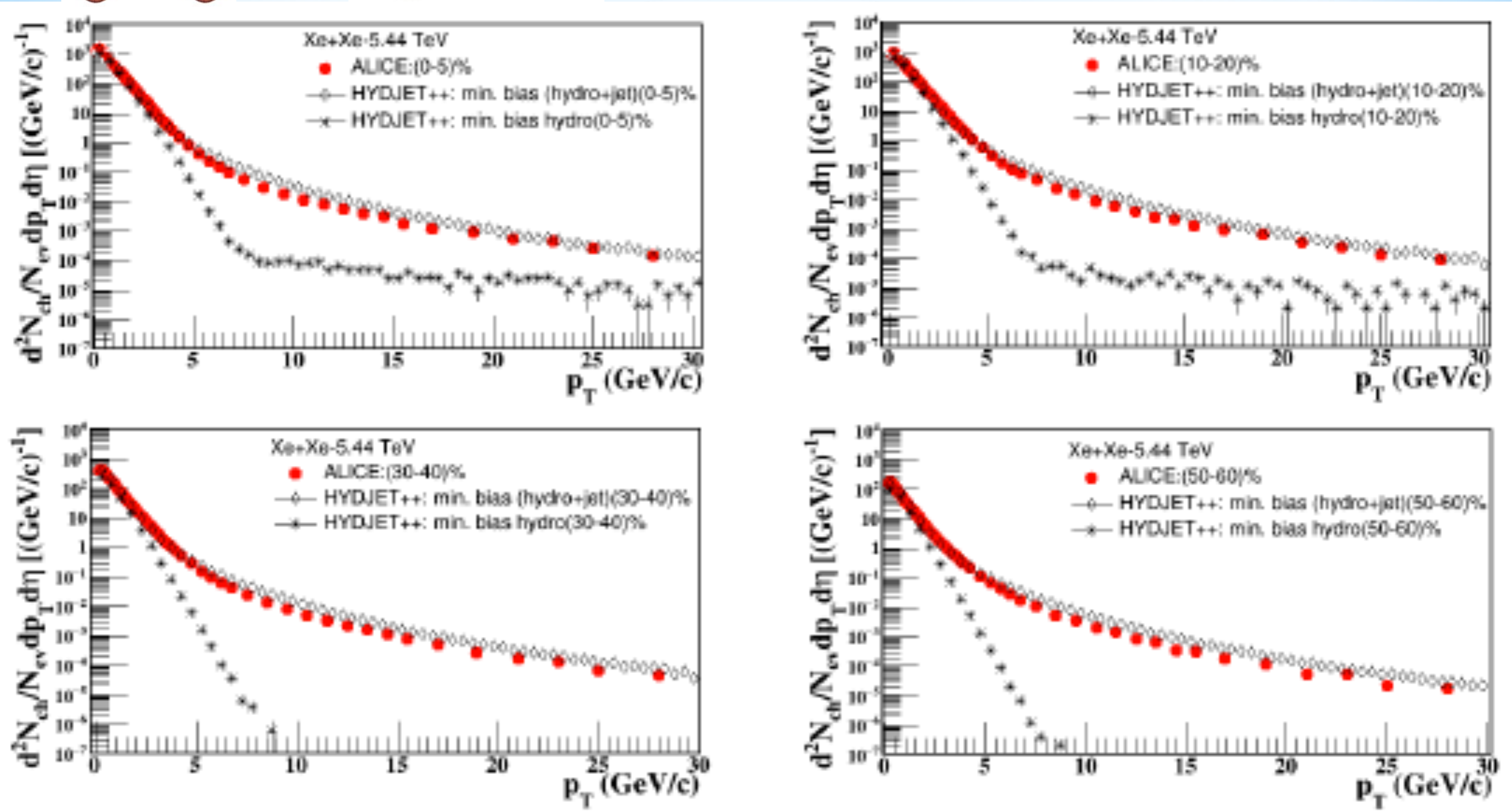
Hydrodynamics gives mass ordering of v_3

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)

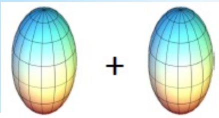
Extention to deformed systems (Xe+Xe at LHC)

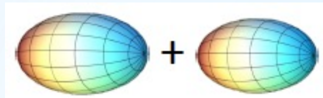
S. Pandey and B.K. Singh, Eur. Phys. J. A, 59 (2023) 6



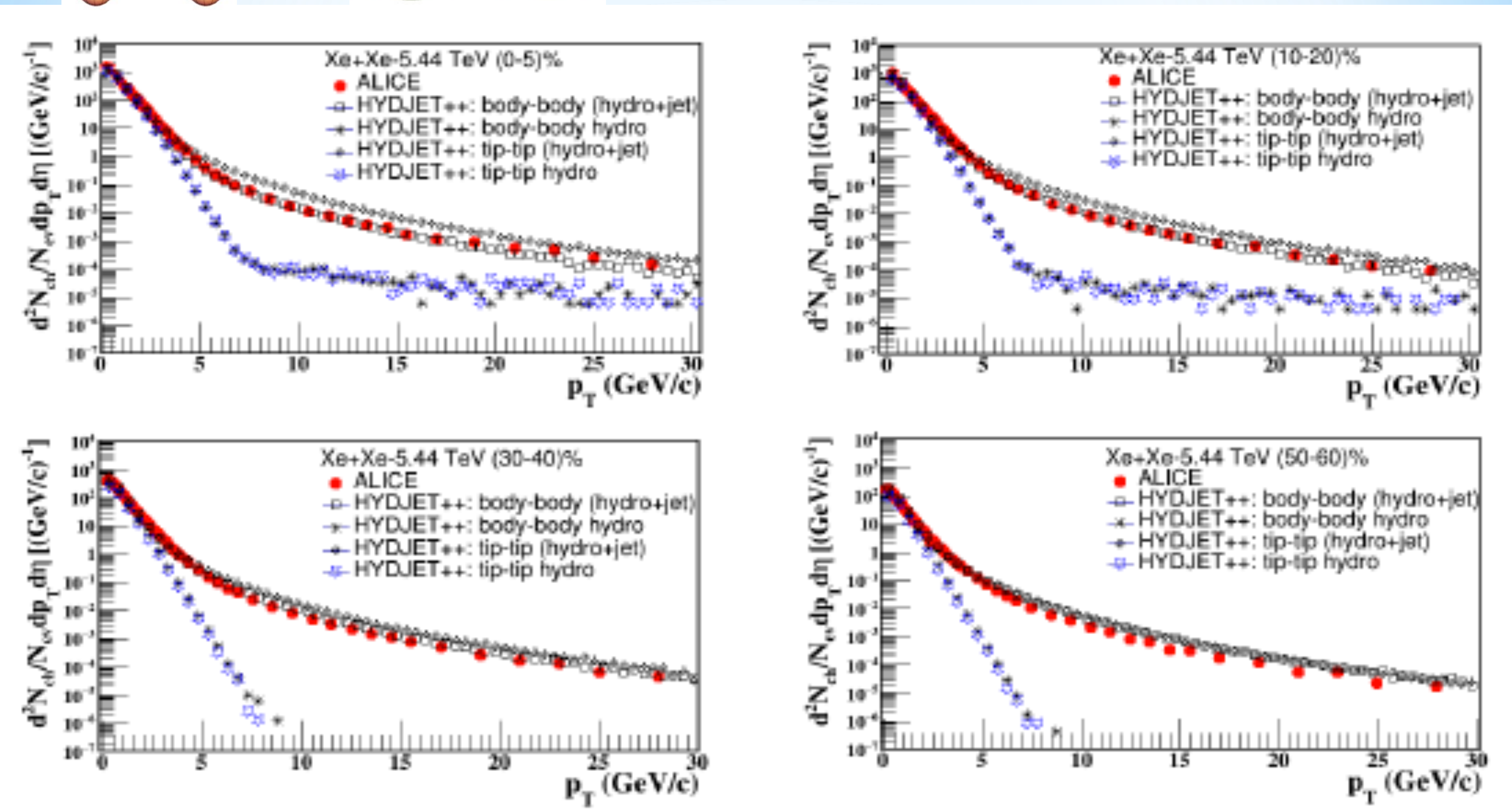
P_T spectra of all charged particles with and w/o jet part for min. bias collisions

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

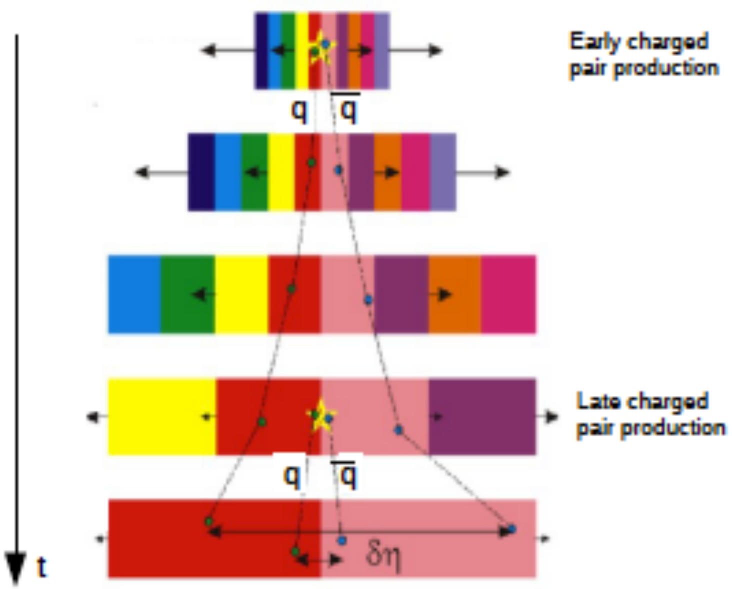
Charge balance function in Pb+Pb at LHC

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). $\Delta\eta = \eta_1 - \eta_2$; $\Delta\varphi = \varphi_1 - \varphi_2$

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

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



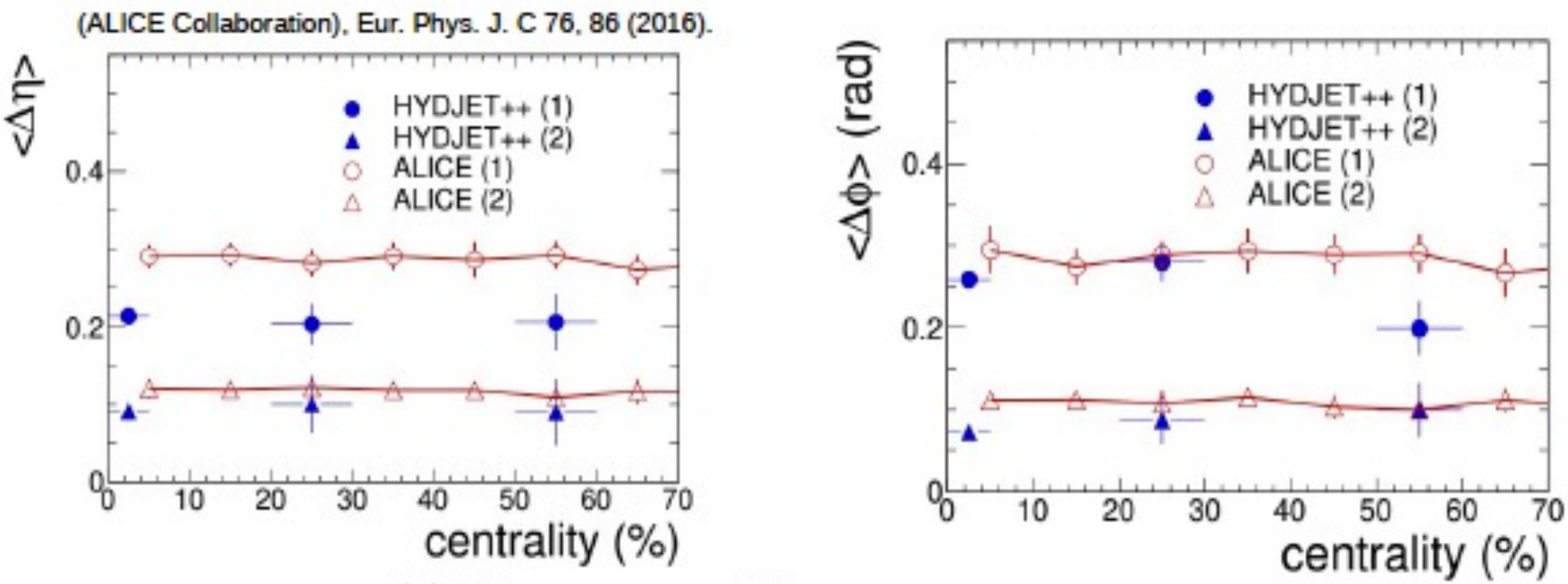
Charge Balance function probes properties and evolution of created system:

- 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) $2.0 < p_{T,\mathrm{assoc}} < 3.0 < p_{T,\mathrm{trig}} < 4.0$ GeV/c and

(2) $3.0 < p_{T,\mathrm{assoc}} < 8.0 < p_{T,\mathrm{trig}} < 15.0$ GeV/c

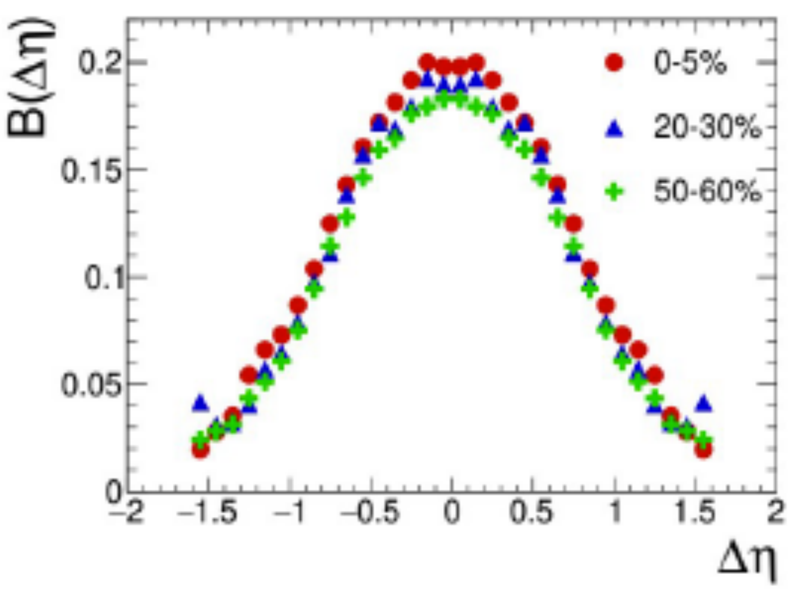
Default HYDJET++ model fairly describes the experimental data on BF width and its centrality dependence for higher p_t range (where the hard component is dominant)

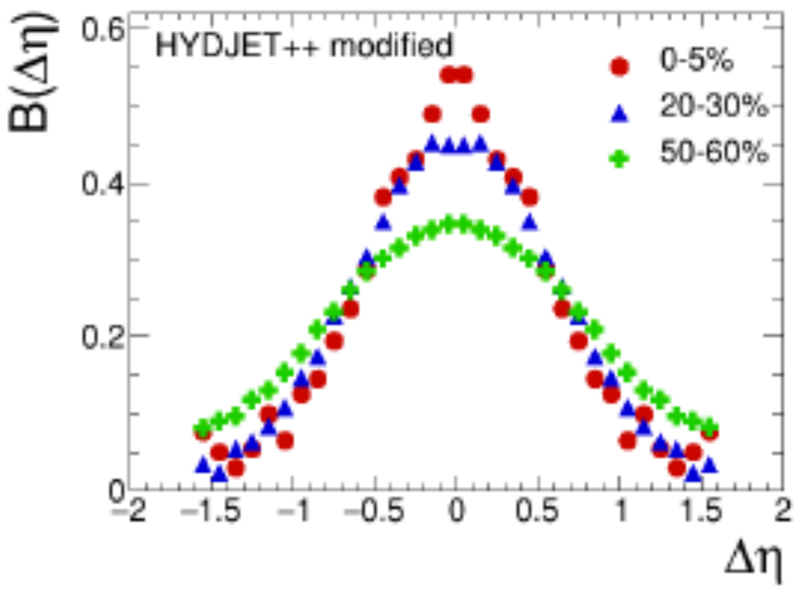
Charge balance function in Pb+Pb at LHC

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:

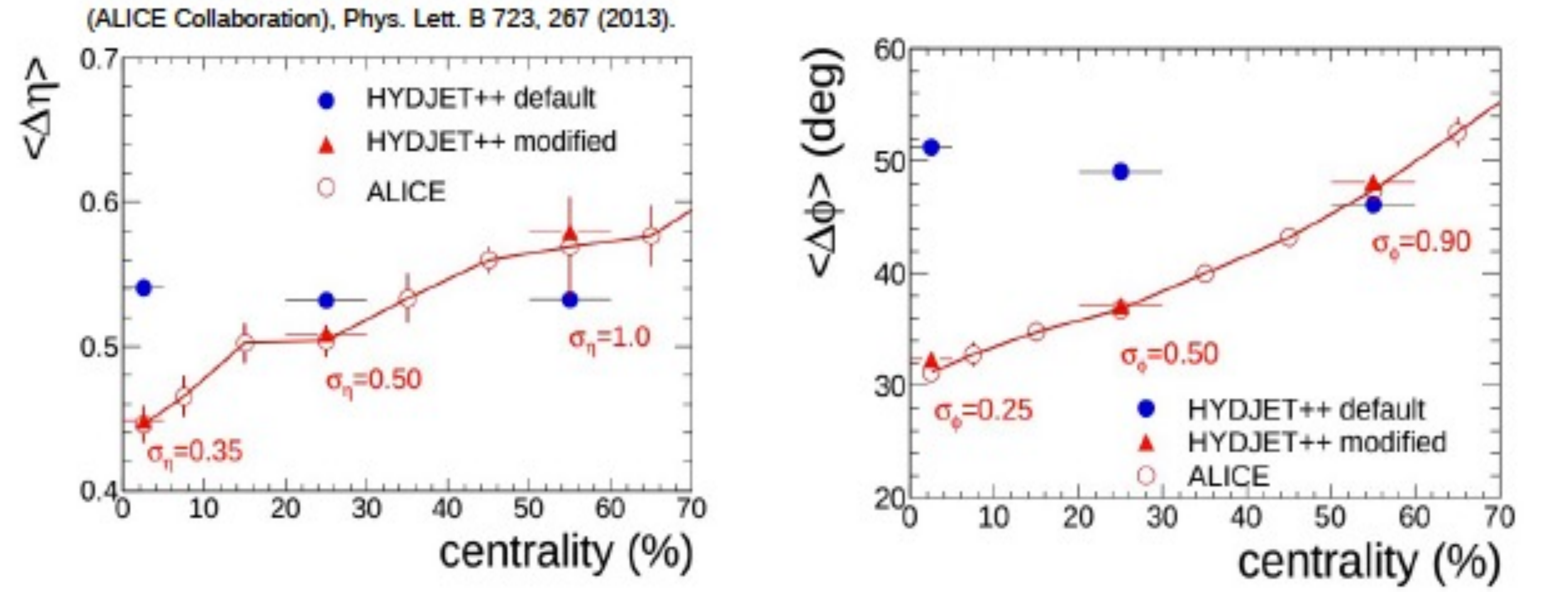
- pair production (particle-antiparticle) is introduced for charged direct hadrons in soft component
- positions of pairs (η_1, φ_1) and (η_2, φ_2) are distributed with Gaussian with certain σ_η, σ_φ





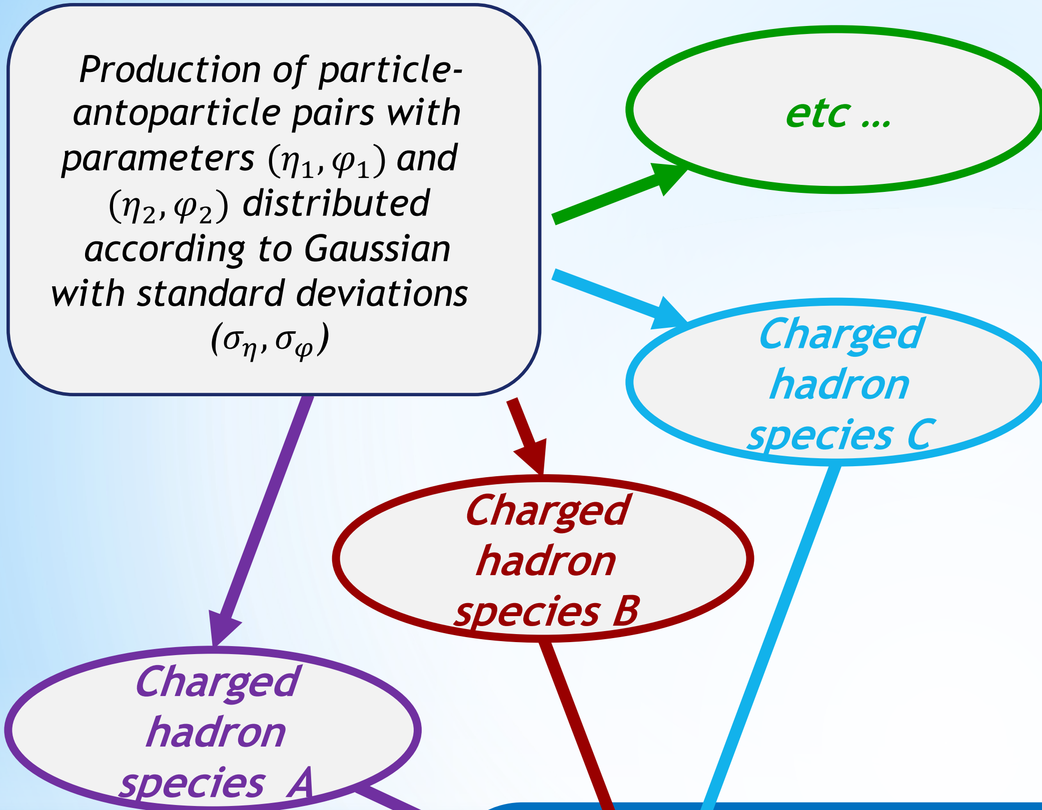
Charge balance function in Pb+Pb at LHC

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

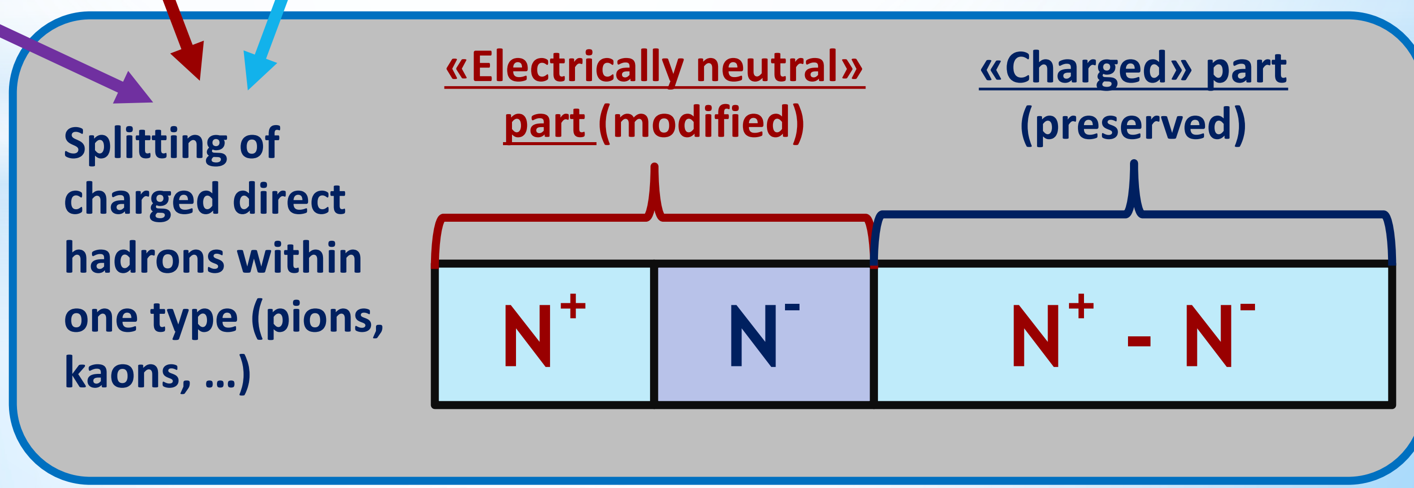


Experimental data can be reproduced with σ increasing for peripheral collisions → the charge correlations of direct hadrons become weaker, since the number of the independent particle sources, in which the charge is explicitly conserved, decreases.

Accounting for charge imbalance at BES RHIC, NICA

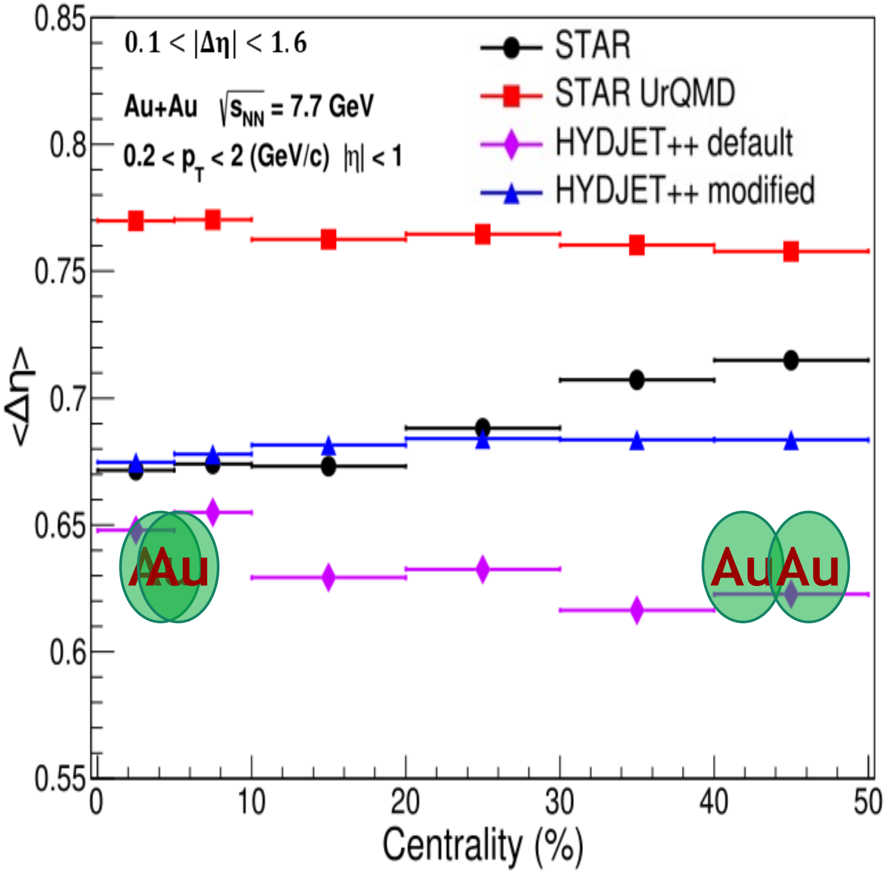


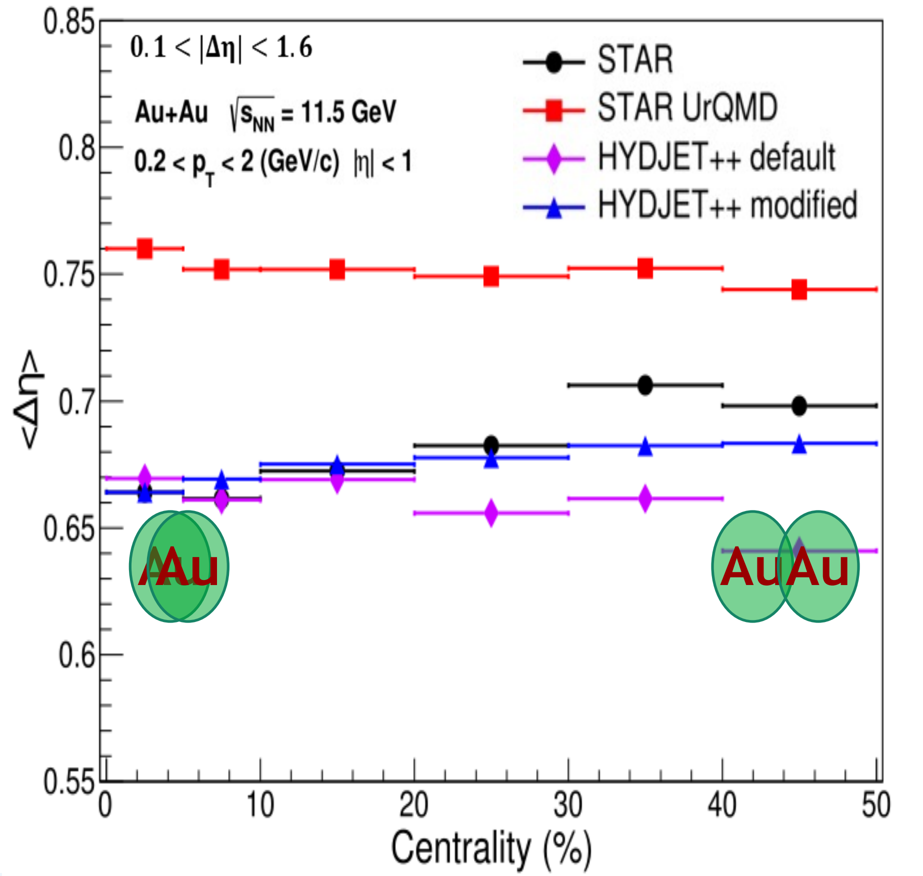
To account for the charge imbalance occurring at intermediate BES RHIC and NICA energies, the proposed modification applies only to the electrically neutral fraction of direct charged hadrons within each hadron species separately. This procedure has been implemented in the HYDJET++ model.



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 << charge fluctuations in hadron gas

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

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

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

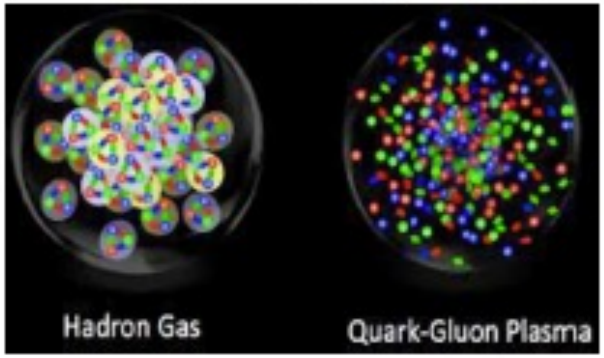
✓ $D \approx 1\text{-}1.5$ for quark-gluon plasma

For lattice QCD S. Gottlieb et al., Phys. Rev. D55, 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 $\delta Q \sim q^2$
✓ $NCF^{HG} \gg NCF^{QGP}$

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

Net-charge fluctuations in Pb+Pb at LHC

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

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

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

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

$\nu_{dyn} = 0$ –> independent particle emission

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

Strongly intensive quantity

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

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

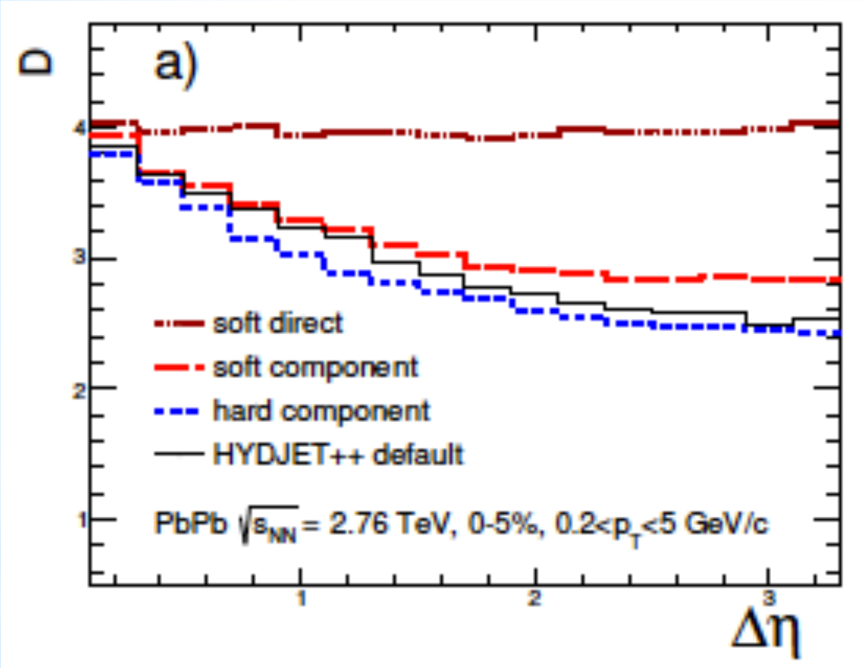
At $\langle N_+ \rangle \approx \langle N_- \rangle$: $$\Sigma[N_+, N_-] - 1 = \frac{\nu_{dyn}[+,-]}{\frac{1}{\langle N_+ \rangle} + \frac{1}{\langle N_- \rangle}}$$

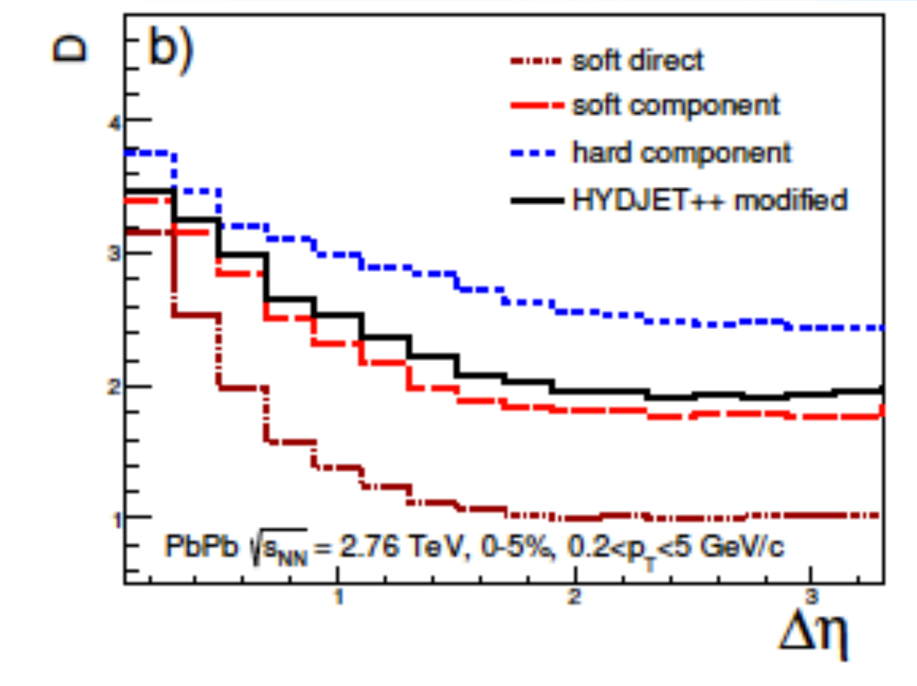
Net-charge fluctuations in Pb+Pb at LHC

G. Ambaryan et al., arXiv: 2408.09550 [nucl-th]

HYDJET++ default

HYDJET++ modified





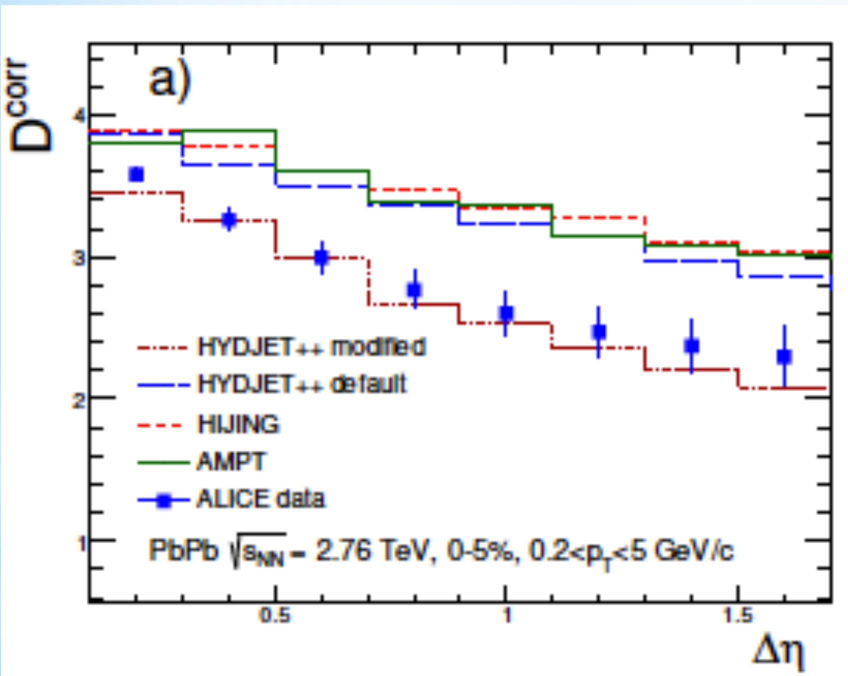
(a) in case of ansence of the charge correlations between directly produced hadrons decays of resonances lead to decrease of D , whereas

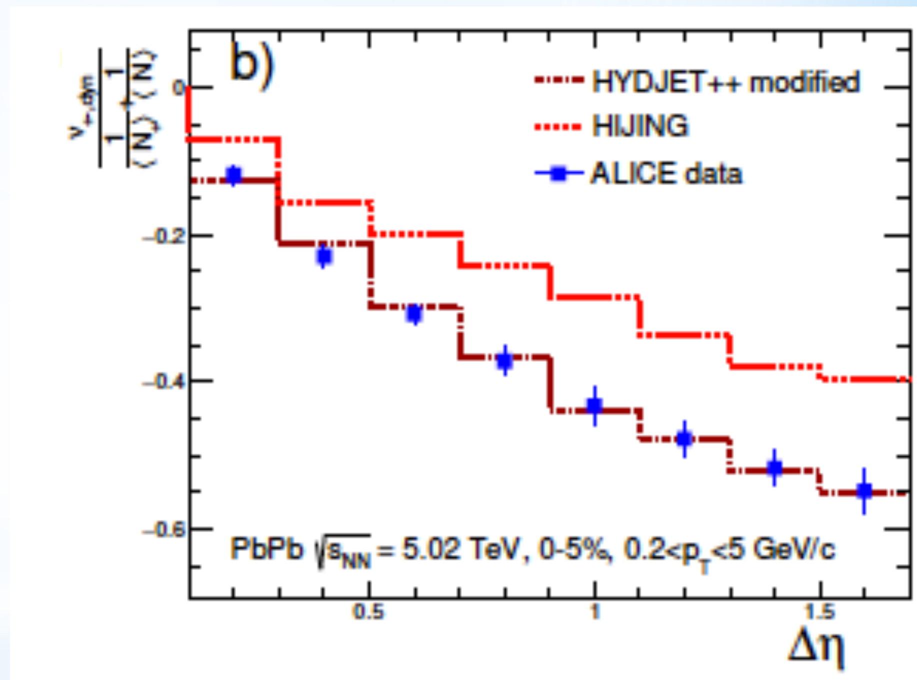
(b) in case of initially strong correlations between the directly produced hadrons with unlike charges it leads to increase of D

Net-charge fluctuations in Pb+Pb at LHC

G. Ambaryan et al., arXiv: 2408.09550 [nucl-th]

HYDJET++ (default, modified) and other models vs data (√s = 2.76 ; 5.02 TeV)





Correction for global charge conservation:

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

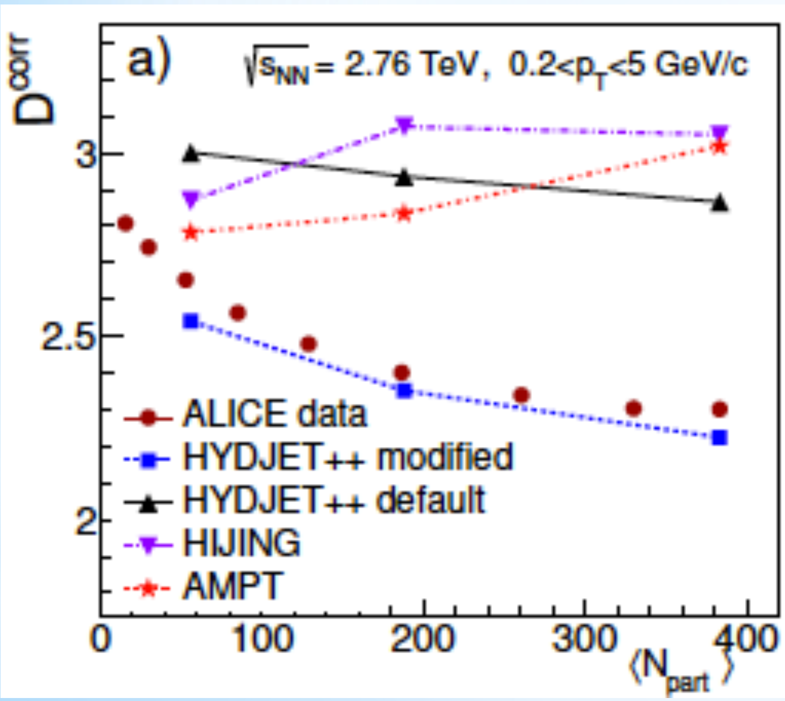
$$C_\mu = \langle N_+\rangle^2/\langle N_-\rangle^2 \text{ and } C_\eta = 1 - \langle N_{ch}\rangle/\langle N_{tot}\rangle$$

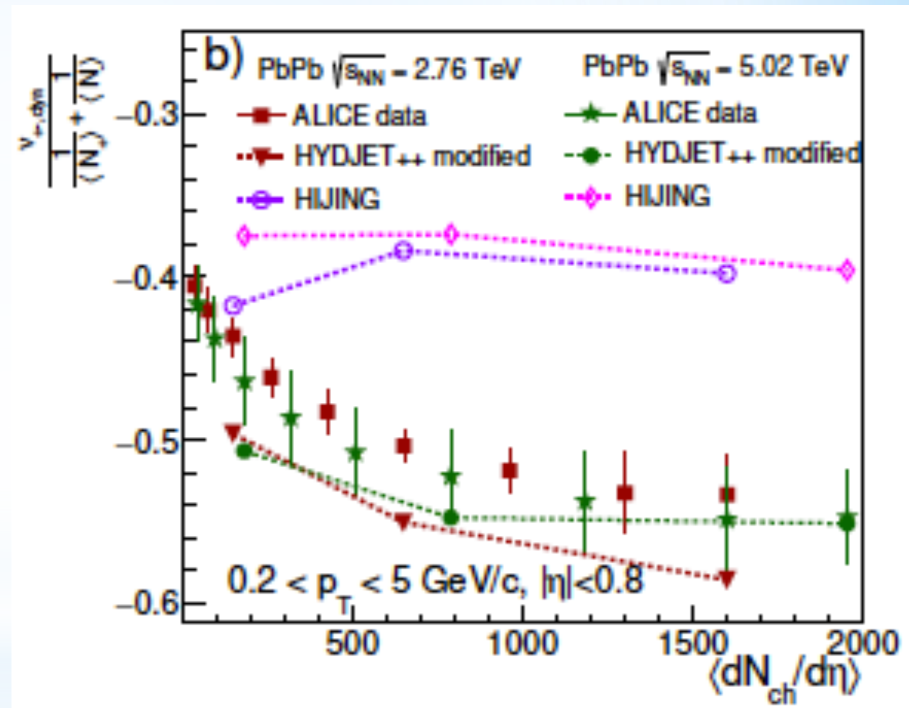
Pseudorapidity dependence of both D and $\Sigma - 1$ is fairly reproduced

Net-charge fluctuations in Pb+Pb at LHC

G. Ambaryan et al., arXiv: 2408.09550 [nucl-th]

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



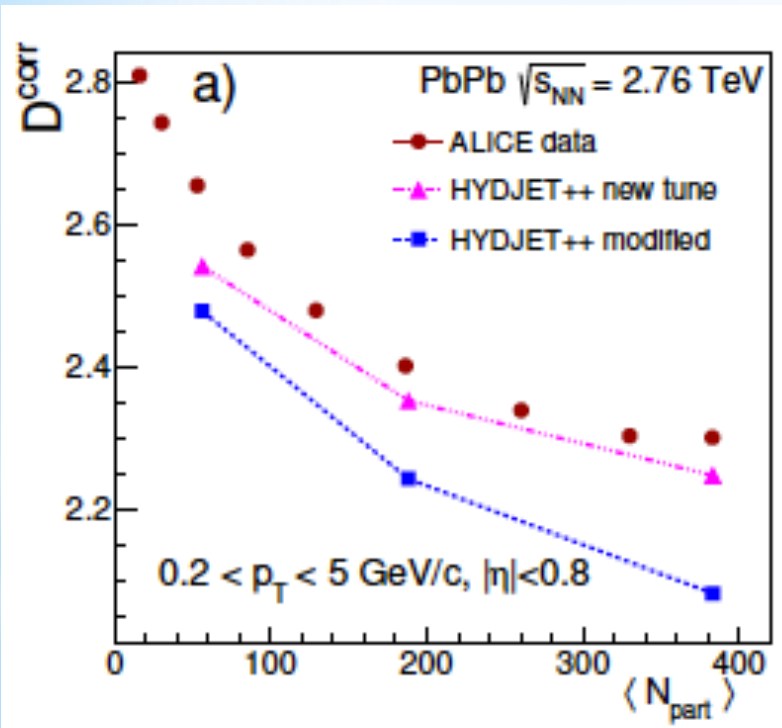


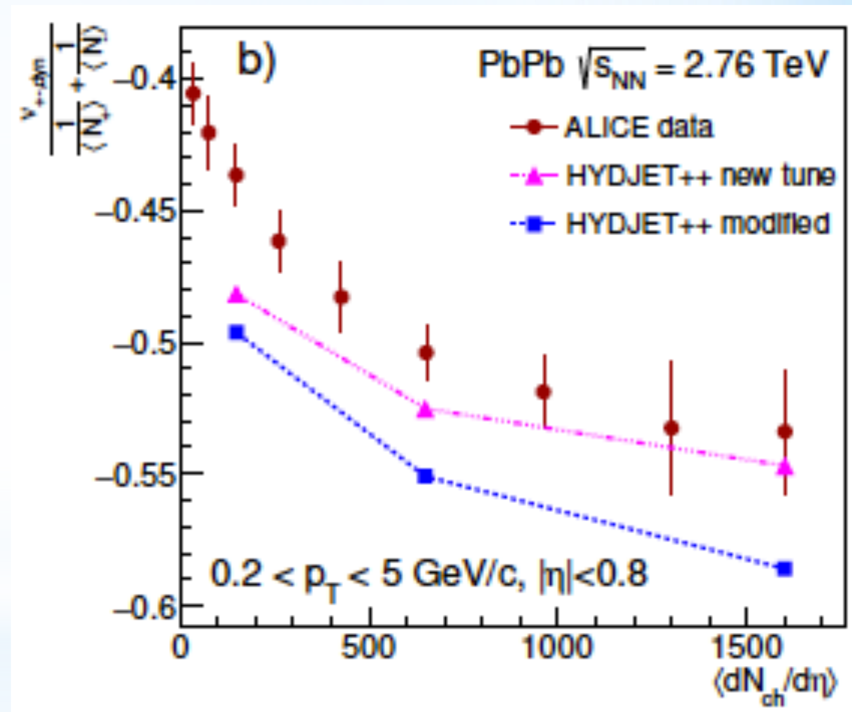
Centrality dependence of D and especially of $\Sigma - 1$ is reproduced rather qualitatively => for better quantitative description we need further tuning of σ_η

Net-charge fluctuations in Pb+Pb at LHC

G. Ambaryan et al., arXiv: 2408.09550 [nucl-th]

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





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

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.

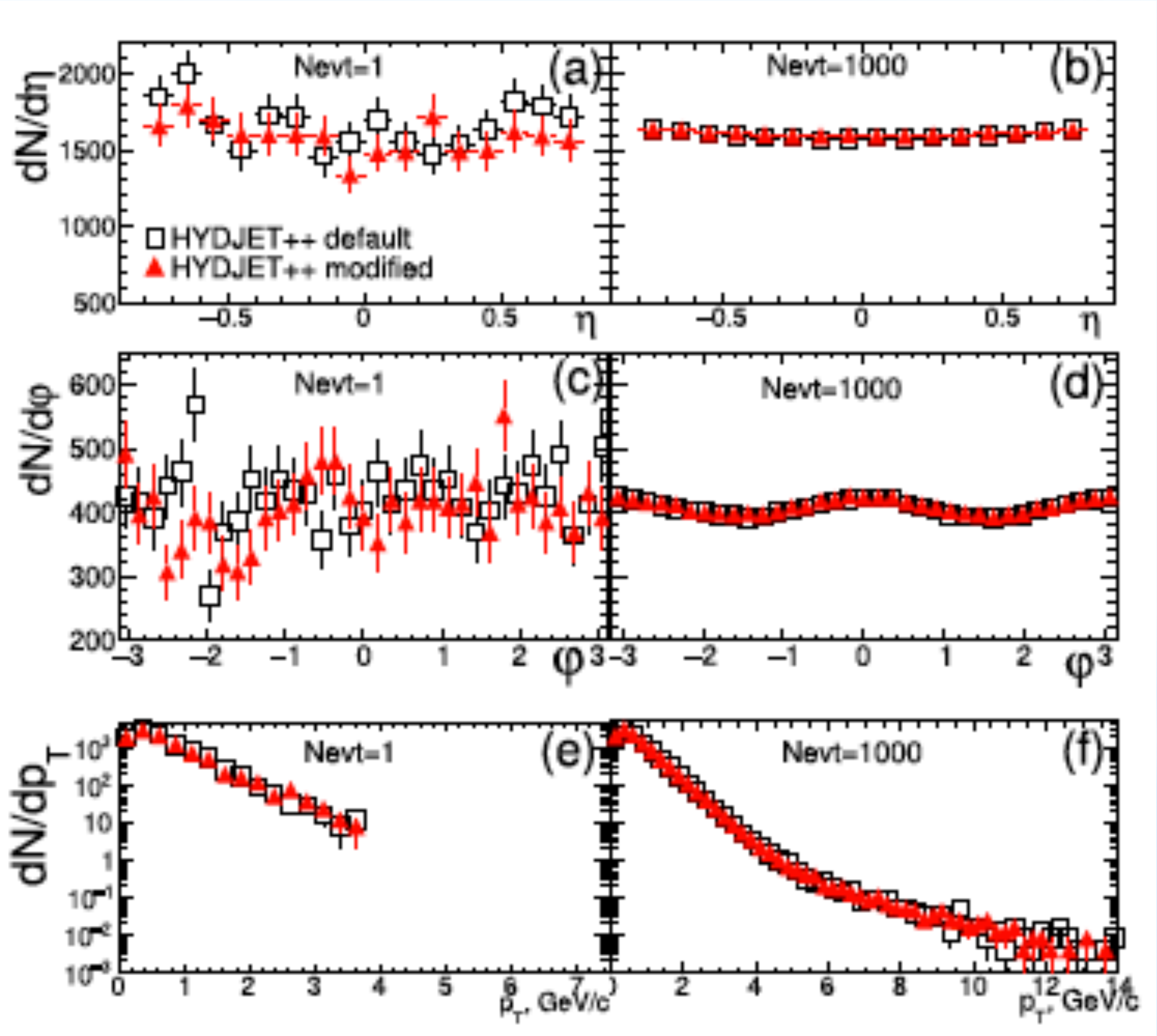
Within this approach:

- ***Centrality dependence of the widths of charge balance functions in Pb+Pb collisions at LHC 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***

THANK YOU FOR YOUR ATTENTION !

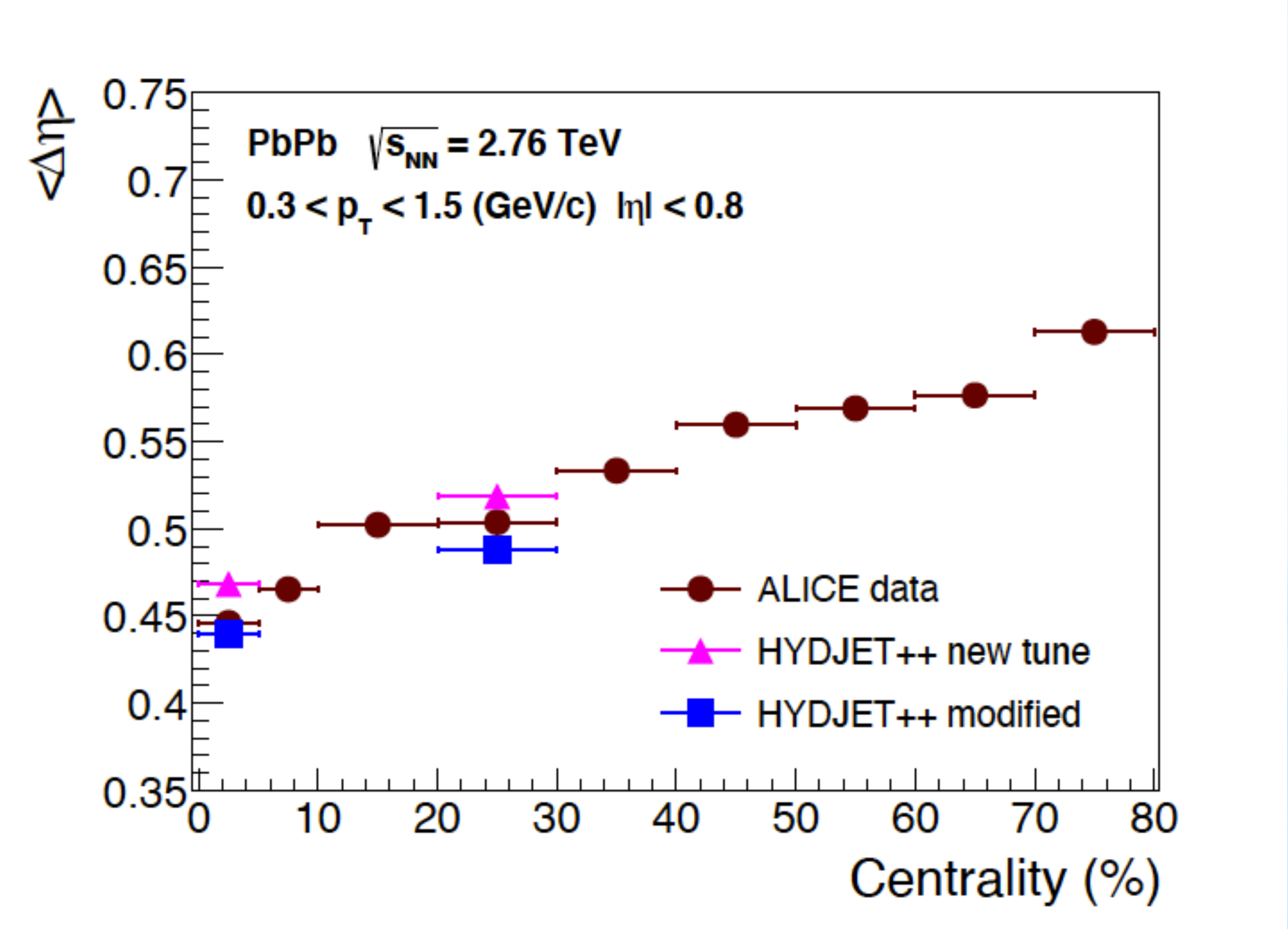
Back-up Slides

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



No difference for N_{evt} > 100

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



The difference is within 7% limit