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Recent results with HYDJET++ model for heavy-ion collision

6th International Conference on Particle Physics and Astrophysics
29 November – 2 December 2022

Moscow, MEPhI

Outline

I. HYDJET++ event generator

II. Recent results

III. Some ongoing studies

I. HYDJET++ event generator
(HYDrodynamics + 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://lokhtin.web.cern.ch/lokhtin/hydjet++/

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

Collision event is represented as a mixture of two part:

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

The model calculations on soft and hard probes of quark-gluon plasma (including collective flow, different kinds of particle correlations, jets, D and B mesons, etc.) agree well with the experimental data.

I. HYDJET++ event generator
(HYDrodynamics + 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:

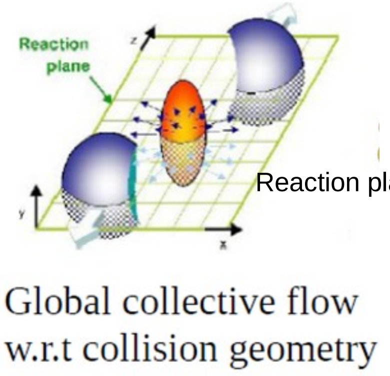
N.S.Amelin, R.Lednisky, T.A.Pocheptsov, I.P.Lokhtin, L.V.Malinina, A.M.Snigirev, Yu.A.Karpenko, Yu.M.Sinyukov, Phys. Rev. C 74 (2006) 064901, N.S.Amelin, R.Lednisky, I.P.Lokhtin, L.V.Malinina, A.M.Snigirev, Yu.A.Karpenko, Yu.M.Sinyukov, I.C.Arsene, L.Bravina, Phys. Rev. C 77 (2008) 014903

- 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.

II. RECENT RESULTS: elliptic flow at low and high p_T

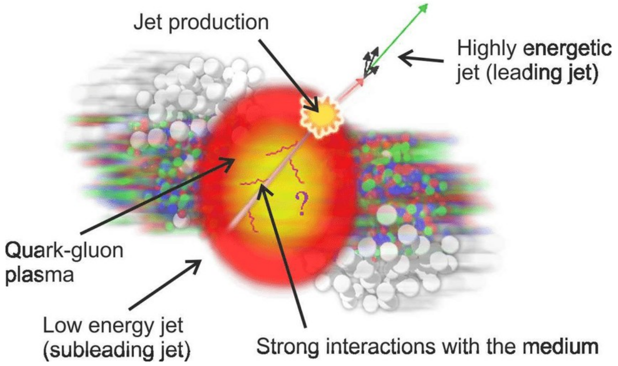
Azimuthal anisotropy of particles at low transverse momenta p_T: hydrodynamical expansion of the medium



Reaction plane is not known in experiment.

For asymmetric collisions the expansion of the medium is in accordance to initial system geometry.

Azimuthal anisotropy of particles at high transverse momenta p_T: due to jet quenching in the medium



In anisotropic medium partons suffer different energy losses according to initial system geometry → the hadron yield asymmetry is observed with respect to reaction plane.

Azimuthal asymmetry at low p_T ⟵ Correlation? ⟶ Azimuthal asymmetry at high p_T

We have tested the correlation hypothesis with the help of HYDJET++ model.

II. RECENT RESULTS: elliptic flow at low and high p_T

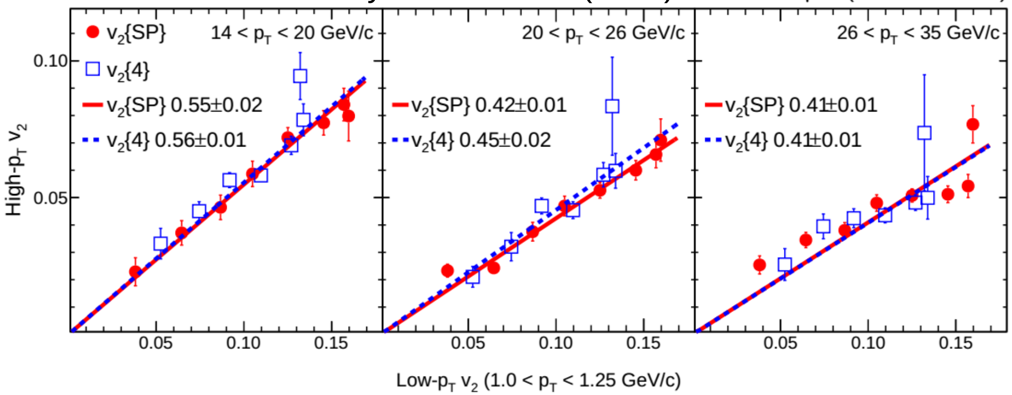
The value of anisotropic flow is characterized with Fourier coefficients:

$$E\frac{d^3N}{d^3p} = \frac{1}{\pi}\frac{d^2N}{dp_t^2 dy}\left[1 + 2\sum_{n=1}^{\infty} v_n \cos n(\phi - \Psi_n)\right]$$

Ψ_n are participant planes,
v_2 is elliptic flow,
v_3 is triangular flow and so on..

Reaction plane is not known in experiment, in the model we can directly calculate v_2

CMS Phys. Lett. B 776 (2017) 195



The points represent different collisions centrality bins:
0–5, 5–10, 10–15, 15–20, 20–30, 30–40, 40–50 и 50–60%

- v_2 at high and low p_T are correlated.
- It is suggested that the initial-state geometry is likely to be the common cause of particles anisotropy both at low and high p_T.

Cumulant method

- 2 and 4-particles correlations:

$$\langle\langle 2\rangle\rangle = \langle\langle e^{in(\varphi_1-\varphi_2)}\rangle\rangle, \qquad \langle\langle 4\rangle\rangle = \langle\langle e^{in(\varphi_1+\varphi_2-\varphi_3-\varphi_4)}\rangle\rangle$$

Double brackets here are averaging on particles and events.

$\langle\langle 2'\rangle\rangle$ and $\langle\langle 4'\rangle\rangle$ are differential correlations, where one of the particle is in a given p_T -bin.

- Cumulants of 2nd and 4th order:

$$c_n\{2\} = \langle\langle 2\rangle\rangle, \qquad c_n\{4\} = \langle\langle 4\rangle\rangle - 2\times\langle\langle 2\rangle\rangle^2$$

$$d_n\{4\} = \langle\langle 4'\rangle\rangle - 2\times\langle\langle 2'\rangle\rangle\times\langle\langle 2\rangle\rangle$$

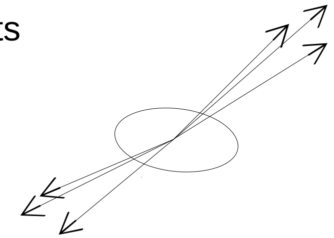
- Elliptic flow by cumulants of 4th order:

$$v_n\{4\}(p_T) = -d_n\{4\}\times(-c_n\{4\})^{-3/4}$$

II. RECENT RESULTS: elliptic flow at low and high p_T

Methods for v_2 calculations employ correlations with low-p_T particles, which suggest measurements w.r.t. the common collective geometry.

Still, back-to back jets give azimuthal anisotropy and may lead to large v_2 of non-hydro origin.



Experimentally measured v_2 at high p_T may contain two contributions:

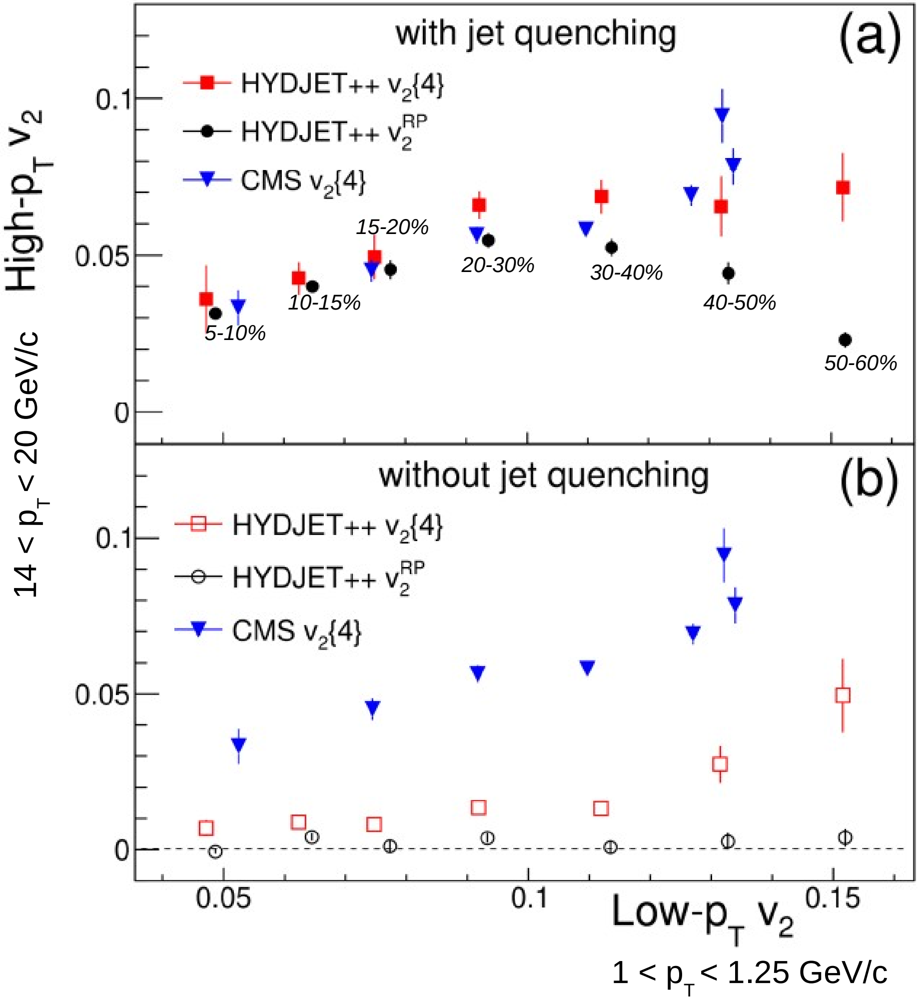
- Asymmetry with respect to back-to-back jet axis (not correlated with v_2 at low p_T)
- Asymmetry with respect to common reaction plane (correlated with v_2 at low p_T)

The elliptic flow was calculated in HYDJET++:

- Directly with respect to known in the model reaction plane angle v_2^{RP} (this anisotropy is due to jet quenching effect).
- With the cumulants of 4th order.
- With the Scalar Product method.

II. RECENT RESULTS: elliptic flow at low and high p_T

CMS data : Phys. Lett. B 776 (2017) 195



- At high p_T ($14<p_T<20$ GeV/c) anisotropy due to jet quenching increases with centrality, but for centralities > 40% begins to decrease, since energy losses decrease in more peripheral collisions.
- Anisotropy calculated with the cumulant $v_2\{4\}$ continues to grow with centrality.
- When the jet quenching is off in the model, the anisotropy $v_2^{RP} = 0$ at high p_T .
- The cumulant method $v_2\{4\}$ gives non-zero anisotropy which grows with centrality.
- This points to the presence of azimuthal correlation at high p_T. This is correlation of hadrons with respect to jet axis.
- There are more jet pairs (with random axes) in more central collisions, hence azimuthal distribution of high p_T hadrons is more isotropic.

II. RECENT RESULTS: elliptic flow at low and high p_T

Summary

- It is shown that for high p_T the cumulnat method of elliptic flow calculation $v_2\{4\}$ is sensitive both to anisotropy with respect to global reaction plane and anisotropy with respect to jet axis.
- For centralities < 40% $v_2\{4\}$ is sensitive mainly to anisotropy with respect to global reaction plane.
- For centralities >40% the contribution of anisotropy with respect to jet axis into $v_2\{4\}$ becomes significant.
- The combination of two contributions into $v_2\{4\}$ may describe the correlation between *v_2(high-p_T) and v_2(low p_T)* at all centralities.

Publications:

"Jets and elliptic flow correlations at low and high transverse momenta in ultrarelativistic A+A collisions", *Phys. Rev.* ***C*** *103, 034905 (2021)*

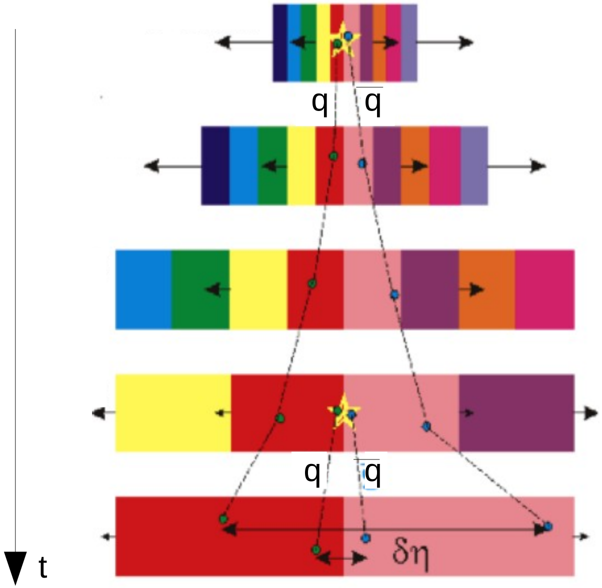
"Nature of particles azimuthal anisotropy at low and high transverse momenta in ultrarelativistic A + A collisions", *Phys. Scr. 97 064007 (2022)*

II. RECENT RESULTS: Charge Balance Function

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

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

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



Early charged pair production

Late charged pair production

Charge Balance function probes properties and evolution of created system:

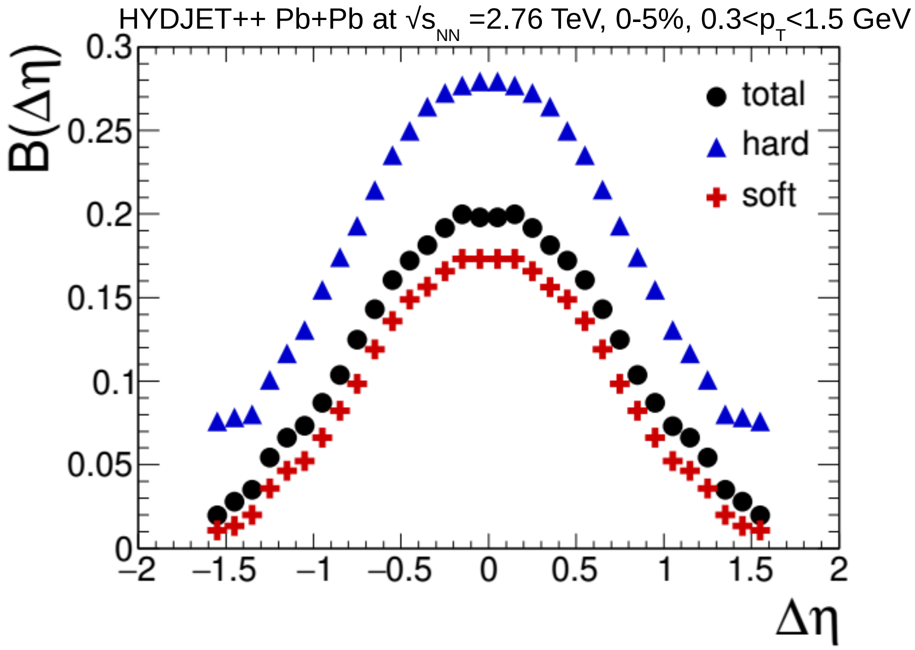
- Gives insight into charge creation mechanism
- Sensitive to collective motion (radial flow)

It is suggested, that the width of the BF is smaller in the case if particles are created at last stages of system evolution and are affected by radial flow.

II. RECENT RESULTS: Charge Balance Function

Sources of charge 2-particle correlations in HYDJET++ :

- Hard component (pQCD) accounts for charge local conservation → charge two-particle correlation in final state
- Soft component implements resonance decay → charge two-particle correlation for secondary hadrons
- Soft component: charge conservation is only fulfilled in average → no charge correlations for direct particle in a single event

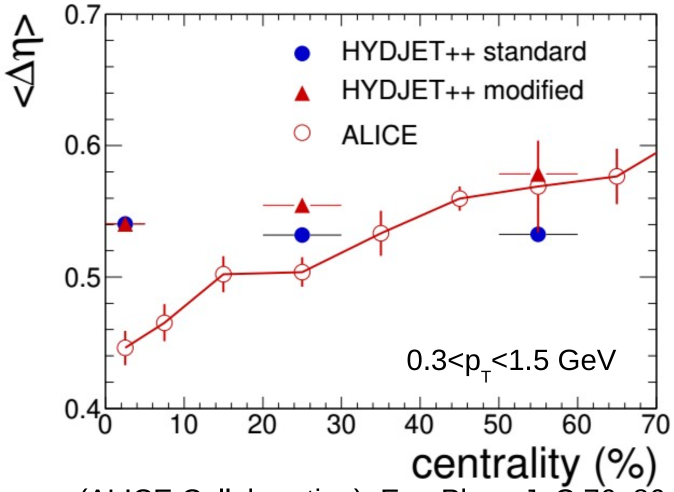


- The width of BF for hard component is larger at given p_T range.

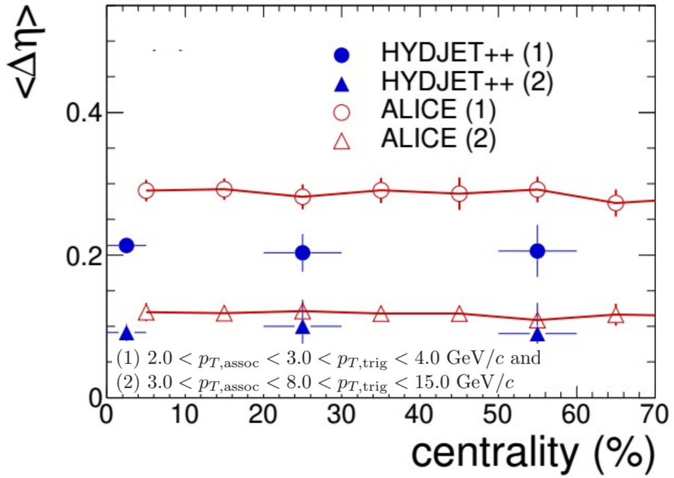
Note: The contribution of soft and hard component changes with centrality in the model (the effective volume of fireball in soft component decreases for peripheral collisions).

II. RECENT RESULTS: Charge Balance Function

(ALICE Collaboration), Phys. Lett. B 723, 267 (2013).



(ALICE Collaboration), Eur. Phys. J. C 76, 86 (2016).



Balance function width: $\langle \Delta\eta \rangle = \sum_{i=1}^{k} [B(\Delta\eta_i) \cdot \Delta\eta_i] / \sum_{i=1}^{k} B(\Delta\eta_i)$

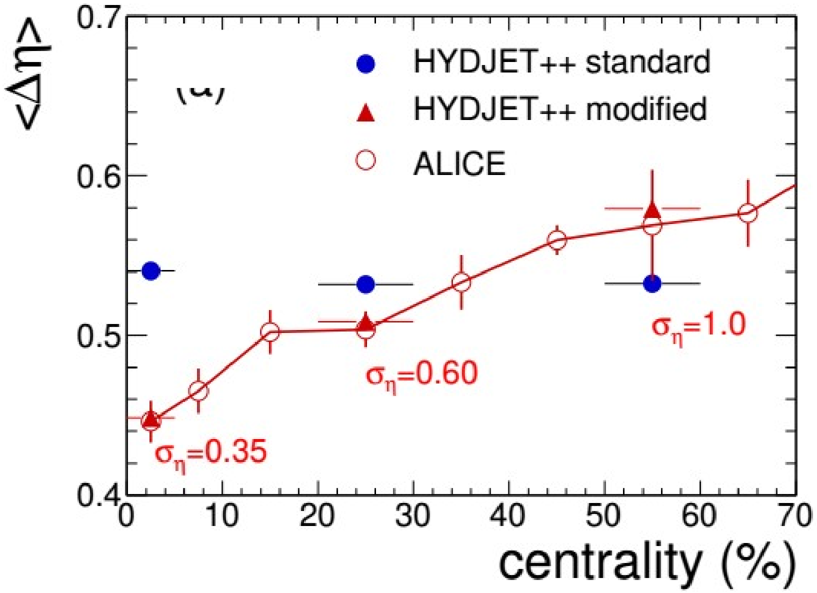
- Default HYDJET++ model doesn't describe the experimental centrality dependence. The width of BF due to final state charge correlations (resonance decay) and parton fragmentation in hard processes is not enough to reproduce data for central collisions.

- One may consider the additional increasing of hard part for peripheral collisions to reproduce experimental trend.

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

II. RECENT RESULTS: Charge Balance Function

(ALICE Collaboration), Phys. Lett. B 723, 267 (2013).



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 charge direct hadrons in soft component of the model
- positions of pairs (η_1, φ_1) and (η_2, φ_2) are distributed with Gaussian with certain σ_η, σ_φ

- 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.

II. RECENT RESULTS: Charge Balance Function Summary

- It was shown, that final state charge correlations (resonance decay) and charge correlations due to hard parton production are not enough to reproduce experimental width of the BF at LHC and to describe its centrality dependence.

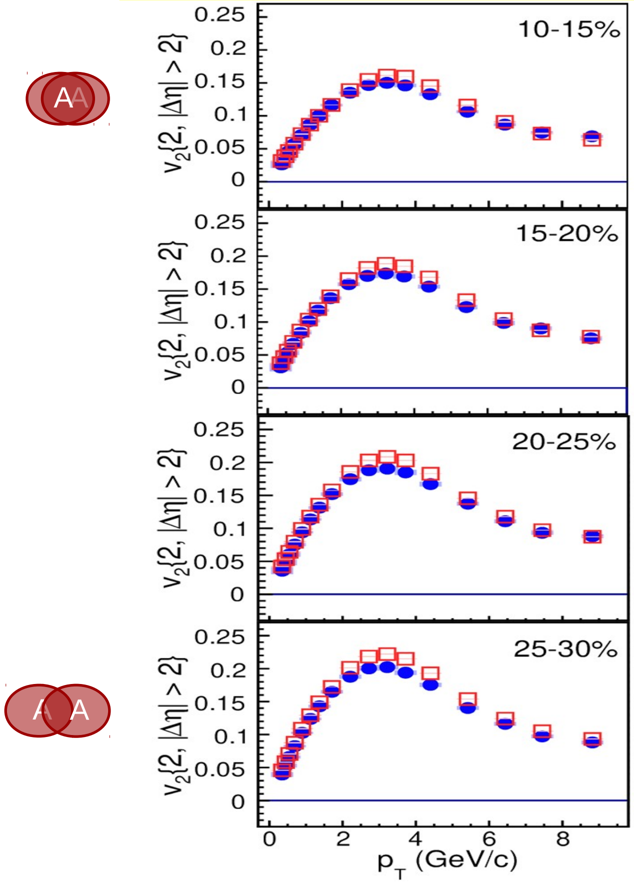
- The modification of the statistical production mechanism of soft part of the HYDJET++ was implemented for direct hadrons. The approach accounts for the event-by-event charge conservation (at freeze-out stage). It allows to reproduce the experimentally observed centrality dependence of BF in PbPb collisions at LHC energies. **This procedure has been implemented for the first time in Monte Carlo event generators of a such kind.**

- Experimentally observed narrowing of BF for higher p_T is reproduced by HYDJET++ and is defined by hard processes and hadronisation.

The publication is under way:
https://arxiv.org/abs/2211.05874

III. ONGOING STUDIES: A-dependence of elliptic and triangular flow

CMS experiment
Phys. Rev, C 100 (2019) 044902

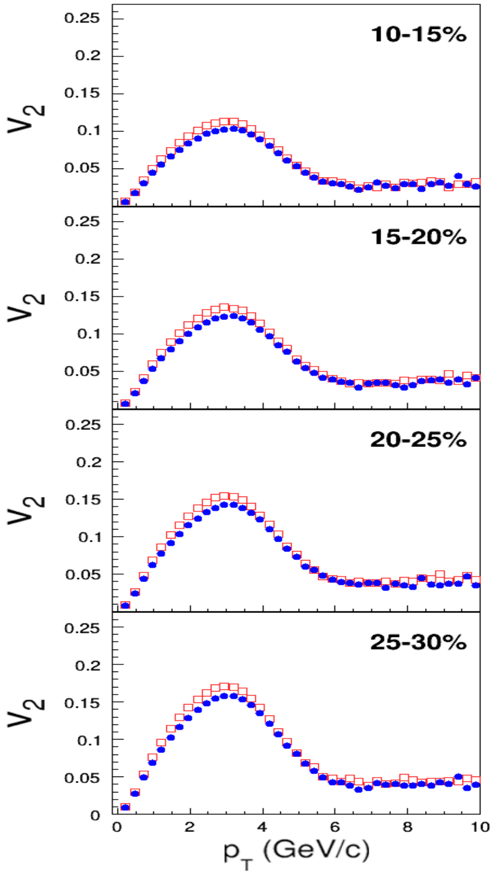


HYDJET++ can reproduce elliptic flow of Xe+Xe vs Pb+Pb collisions at similar energy in the semi-central region.

More detailed tuning of the HYDJET++ model for elliptic flow of Xe+Xe collisions is in progress.

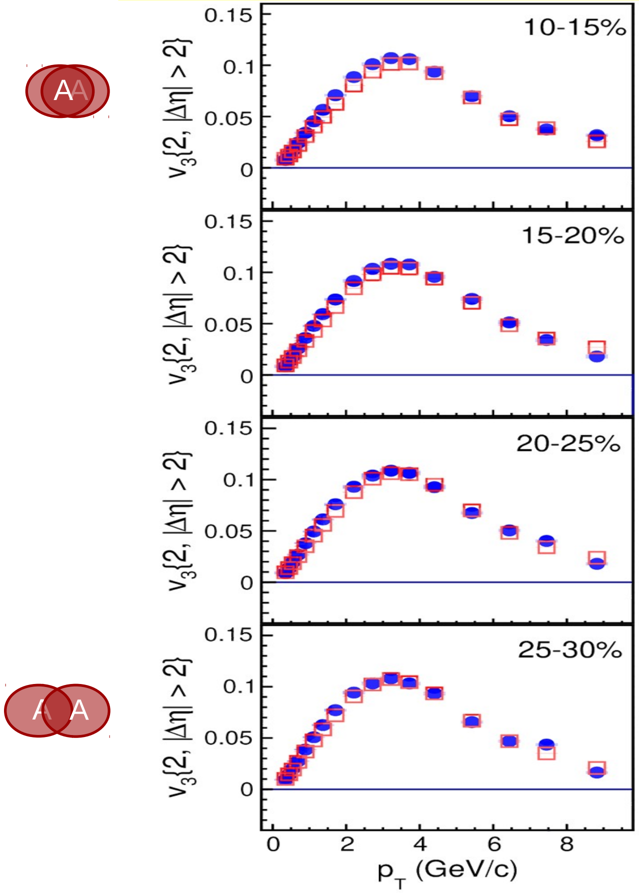
XeXe $\sqrt{s_{NN}} = 5.44$ TeV
PbPb $\sqrt{s_{NN}} = 5.02$ TeV

HYDJET++ 2.4



III. ONGOING STUDIES: A-dependence of elliptic and triangular flow

CMS experiment
Phys. Rev, C 100 (2019) 044902

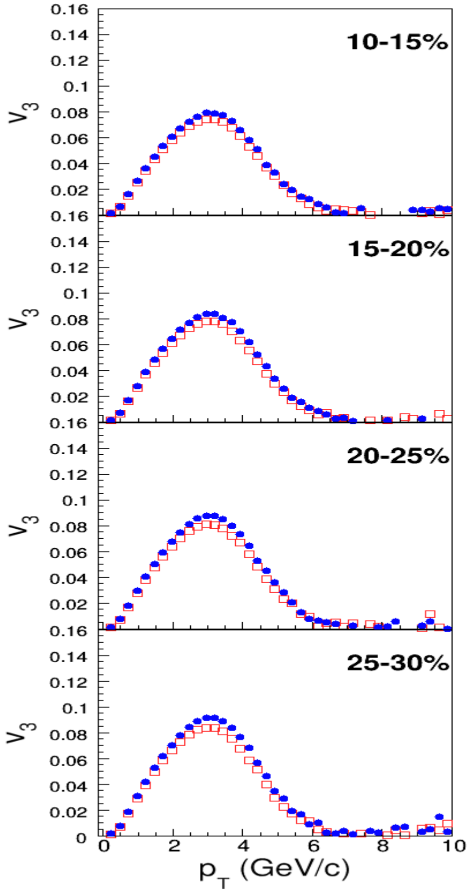


HYDJET++ can reproduce triangular flow of Xe+Xe vs Pb+Pb collisions at similar energy in the semi-central region.

More detailed tuning of the HYDJET++ model for elliptic flow of Xe+Xe collisions is in progress.

XeXe $\sqrt{s_{NN}} = 5.44$ TeV
PbPb $\sqrt{s_{NN}} = 5.02$ TeV

HYDJET++ 2.4



III. A-dependence of elliptic and triangular flow : Summary

- HYDJET++ can reproduce elliptic and triangular flow of Xe+Xe vs Pb+Pb collisions at similar energy in the semi-central region. More detailed tuning of the HYDJET++ model for azimuthal anisotropy of Xe+Xe collisions is in progress.

The end

HYDJET++ recent results on elliptic flow correlation between v_2 at low and high p_T and charge balance function were presented, along with some ongoing studies of collective flow A-dependence.

Thank you!