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XVI Workshop on
Particle Correlations and Femtoscopy
& IV Resonance Workshop

WPCF 2023

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Non-equilibrium effects and spherocity in relativistic proton-nucleus collisions

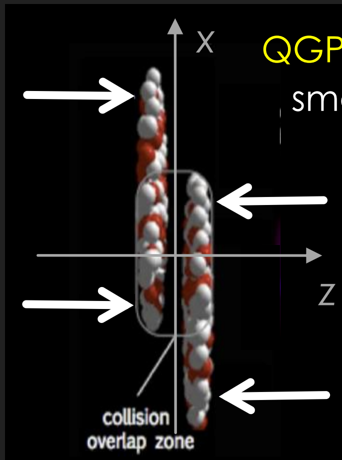
Lucia Oliva

in collaboration with
Wenkai Fan, Pierre Moreau, Steffen Bass,
Elena Bratkovskaya, Vadim Voronyuk

UNIVERSITÀ degli STUDI di CATANIA

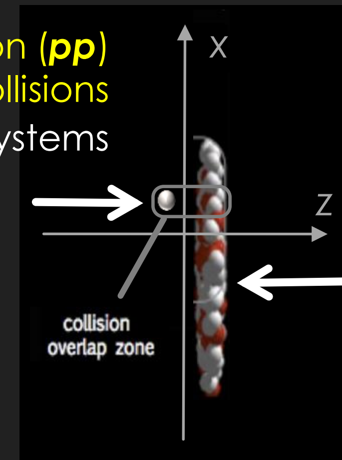
INFN CATANIA
Istituto Nazionale di Fisica Nucleare
Sezione di Catania

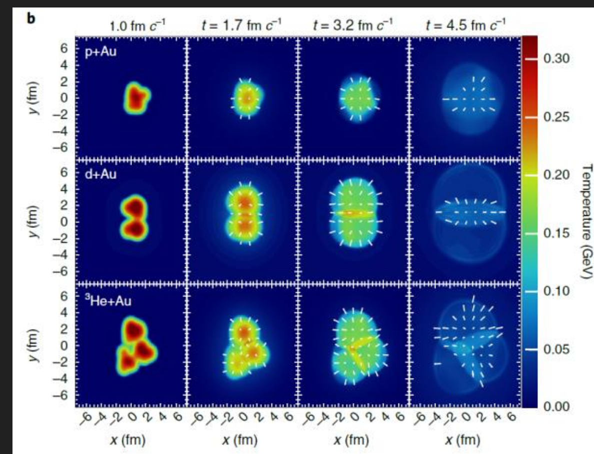
DIPARTIMENTO DI FISICA E ASTRONOMIA "ETTORE MAJORANA"

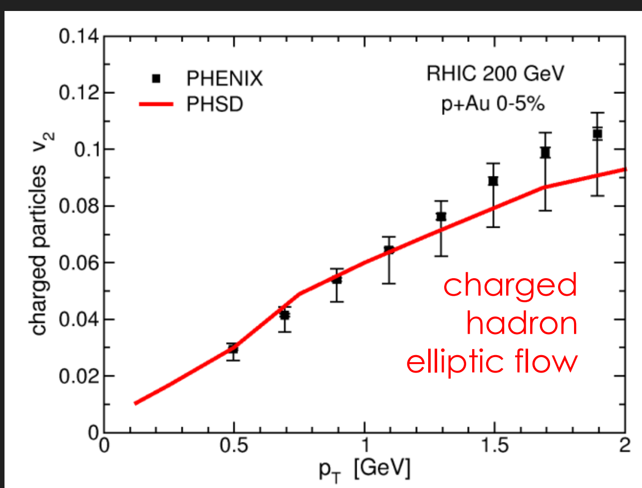


QGP initially expected only in high energy collisions of two heavy ions (***AA***)
small colliding systems regarded as control measurements

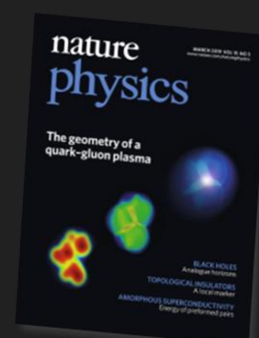
Signatures of collective flow found in proton-proton (***pp***)
and proton-nucleus (***pA***) collisions
in high-multiplicity events of small systems







LO, P. Moreau, V. Voronyuk and E. Bratkovskaya,
Phys. Rev. C 101, 014917 (2020)



PHENIX Coll.,
Nature Phys. 15, 214 (2019)

creation of short-lived QGP
droplets in small systems

Simulating large and small colliding systems

Two main approaches to describe the dynamics of hot QCD medium in relativistic nuclear collisions

HYDRODYNAMIC MODELS

macroscopic description
evolution based on conservation laws
unreasonable effectiveness of hydro

energy-momentum tensor *viscous corrections*

$$T^{\mu\nu} = e u^\mu u^\nu - \Delta^{\mu\nu}(P + \Pi) + \pi^{\mu\nu}$$

$$\partial_\mu T^{\mu\nu} = 0$$

fluid 4-velocity

TRANSPORT MODELS

microscopic description
evolution of particle distribution functions
inherent inclusion of nonequilibrium

collision integral

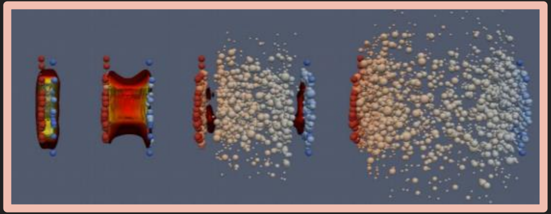
$$\left(p^\mu \partial_\mu + gQF^{\mu\nu} p_\nu \partial_\mu^p\right) f(x,p) = \mathcal{C}[f]$$

field interaction *one-particle distribution function*

Simulating large and small colliding systems

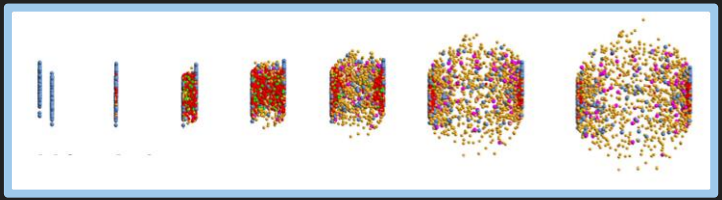
Two main approaches to describe
the dynamics of hot QCD medium
in relativistic nuclear collisions

Initial conditions +
HYDRODYNAMIC MODELS
+ hadronic afterburner (transport)
macroscopic description
evolution based on conservation laws
unreasonable effectiveness of hydro



Picture credit: MADAI Collaboration

TRANSPORT MODELS
microscopic description
evolution of particle distribution functions
inherent inclusion of nonequilibrium
suitable for the pre-equilibrium stage,
for partonic and hadronic phases



Picture credit: PHSD project

Simulating large and small colliding systems

Two main approaches to describe
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Initial conditions +
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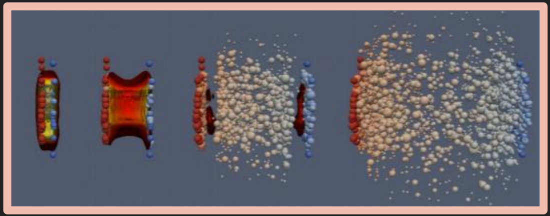

Picture credit: MADAI Collaboration

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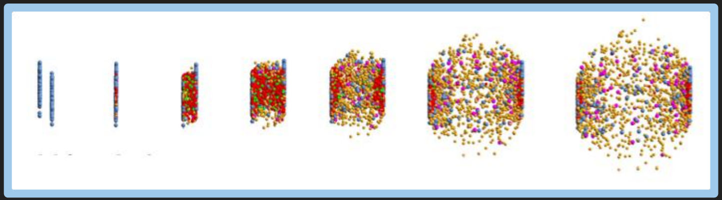
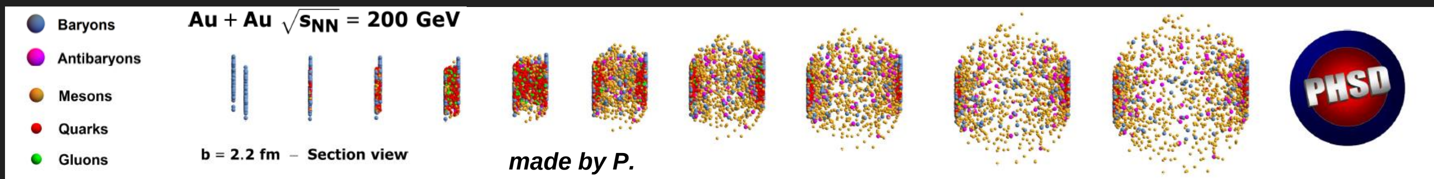


Picture credit: PHSD project

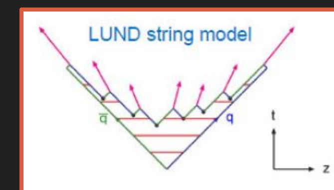
Both hybrid and transport approaches are successful in describing AA and pA
Different way of treating nonequilibrium effects

Parton-Hadron-String Dynamics – PHSD

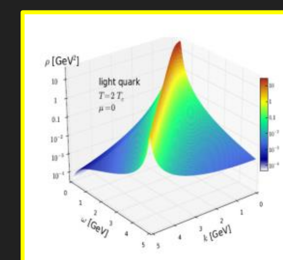
non-equilibrium off-shell transport approach
to study the phase transition from hadronic to partonic matter and the QGP properties from a microscopic origin



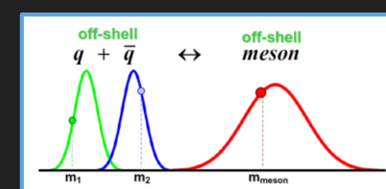
made by P. Moreau



- INITIAL NUCLEI COLLISION: nucleon-nucleon collisions lead to the formation of strings that decay to pre-hadrons
- FORMATION OF QGP: if $\varepsilon > \varepsilon_C$ pre-hadrons dissolve in massive off-shell quarks and gluons + mean-field potential



- PARTONIC STAGE: off-shell transport equations with Dynamical Quasi-Particle Model (DQPM)
- HADRONIZATION: partons with broad spectral functions hadronize to off-shell baryons and mesons



- HADRONIC PHASE: off-shell transport equations with hadron-hadron interactions

W. Cassing and E. Bratkovskaya, Phys. Rev. C 78, 034919 (2008) ; Nucl. Phys. A 831, 215 (2009)
P. Moreau, O. Soloveva, LO, T. Song et al., Phys. Rev. C 100, 014911 (2019) ; PHSD website

VISHNew (+ hadronic afterburner)

2+1D viscous hydrodynamic model

to study the QGP medium and its properties from a macroscopic point of view

$$\partial_\mu T^{\mu\nu} = 0$$

space-time evolution of the QGP via conservation equations of the energy-momentum tensor

$$T^{\mu\nu} = e\, u^\mu u^\nu - \Delta^{\mu\nu}(P + \Pi) + \pi^{\mu\nu}$$

hydro equations closed by an equation of state *P*=*P*(*e*) (lattice QCD + HRG)

time evolution of the viscous corrections via 2nd order Israel-Stewart equations

$$\begin{aligned}\tau_\Pi \dot{\Pi} + \Pi &= -\zeta\theta - \delta_{\Pi\Pi}\Pi\theta + \phi_1\Pi^2 \\ &\quad + \lambda_{\Pi\pi}\pi^{\mu\nu}\sigma_{\mu\nu} + \phi_3\pi^{\mu\nu}\pi_{\mu\nu} \\ \tau_\pi \dot{\pi}^{\langle\mu\nu\rangle} + \pi^{\mu\nu} &= 2\eta\sigma^{\mu\nu} + 2\pi_\alpha^{\langle\mu}w^{\nu\rangle\alpha} - \delta_{\pi\pi}\pi^{\mu\nu}\theta \\ &\quad + \phi_7\pi_\alpha^{\langle\mu}\pi^{\nu\rangle\alpha} - \tau_{\pi\pi}\pi_\alpha^{\langle\mu}\sigma^{\nu\rangle\alpha} \\ &\quad + \lambda_{\pi\Pi}\Pi\sigma^{\mu\nu} + \phi_6\Pi\pi^{\mu\nu}\end{aligned}$$

e: local energy density
P: local isotropic pressure
Π: bulk viscous pressure
$\pi^{\mu\nu}$: shear stress tensor

- PARTONIC STAGE: VISHNew
- HADRONIZATION: Cooper-Frye
- HADRONIC PHASE: UrQMD

H. Song and U. W. Heinz, Phys. Rev. C 77, 064901 (2008) ; Phys. Rev. C 78, 024902 (2008)
Version of the Ohio State Uni code slightly modified by Duke Uni group

Coarse-graining PHSD medium

Study the hot medium evolution with transport and hydro

➞ same initial conditions to reduce the early stage impact
➞ similar equation of state and specific shear viscosity

Y. Xu et al., Phys. Rev. C 96, 024902 (2017)
T. Song et al., Phys. Rev. C 101, 044903 (2020)
LO et al., Phys. Rev. C 106, 044910 (2022)

$$T^{\mu\nu} = e u^\mu u^\nu - \Delta^{\mu\nu}(P + \Pi) + \pi^{\mu\nu}$$

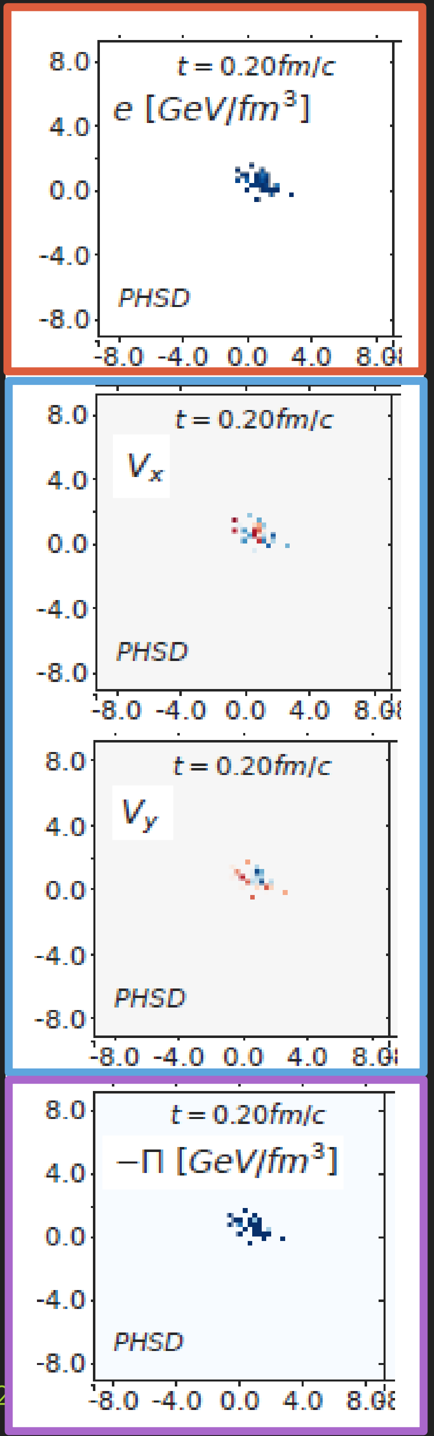
VISHNew vs **PHSD**

initialized with

$$T^{\mu\nu}(x) = \sum_i \int_0^\infty \frac{d^3p_i}{(2\pi)^3} f_i(E_i) \frac{p_i^\mu p_i^\nu}{E_i} = \frac{1}{V} \sum_i \frac{p_i^\mu p_i^\nu}{E_i}$$

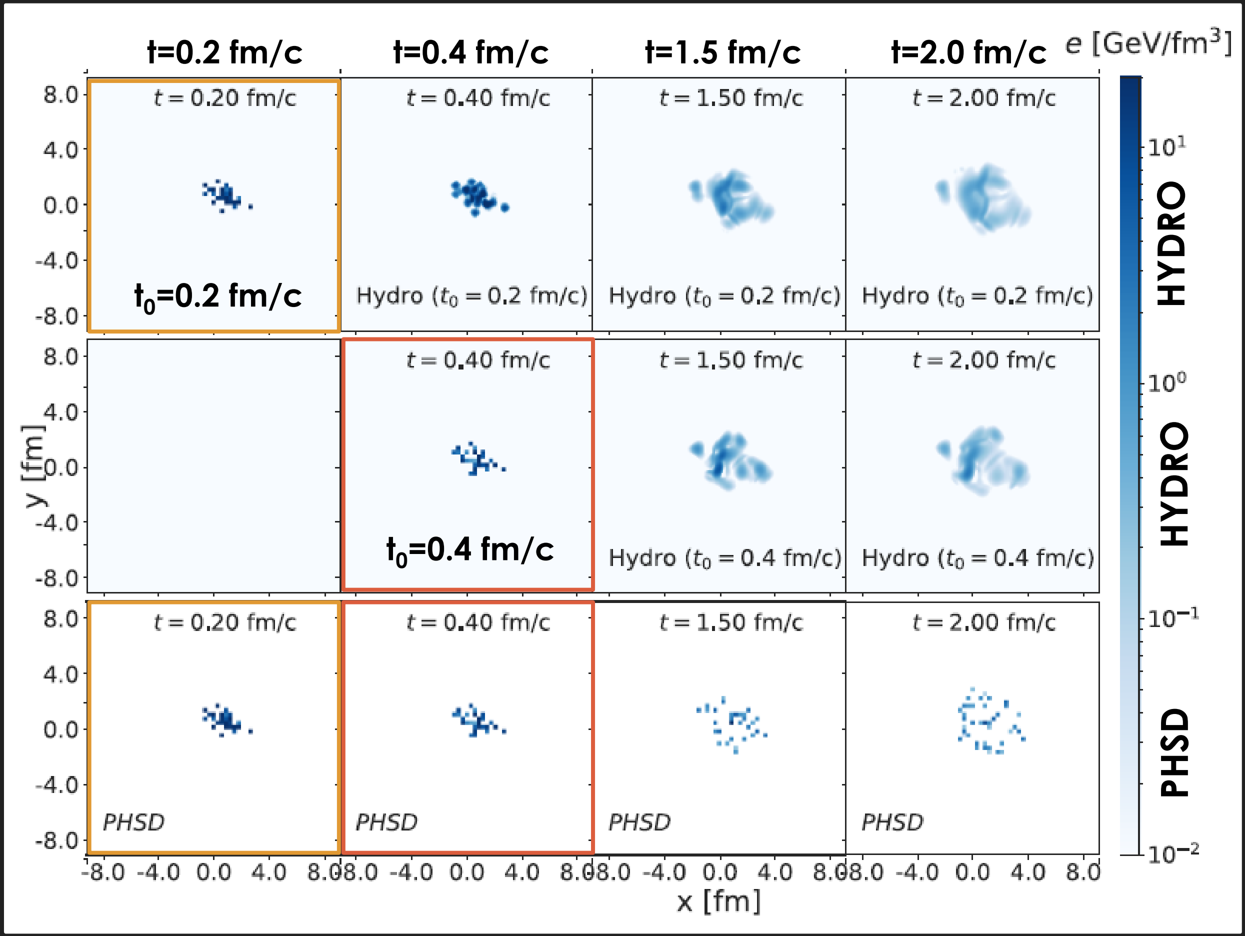
Hydro initialization time?

0 **0.2** **0.4** **0.6** 0.8 t [fm/c]



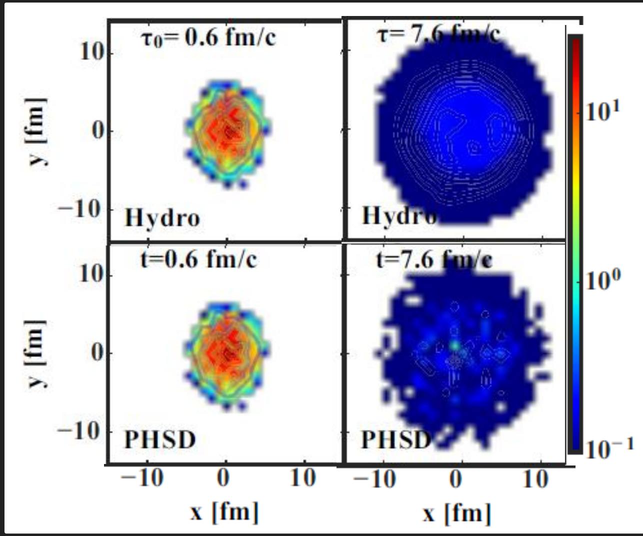
Medium evolution: hydrodynamics vs PHSD

p+Pb @ LHC 5.02 TeV – b = 2 fm



- PHSD evolution more chaotic all times
- VISHNew smooths the initial PHSD profile
- Visible impact of hydro initialization time

Au+Au @ RHIC 200 GeV b = 6 fm



Higher degree of inhomogeneity in pA than in AA

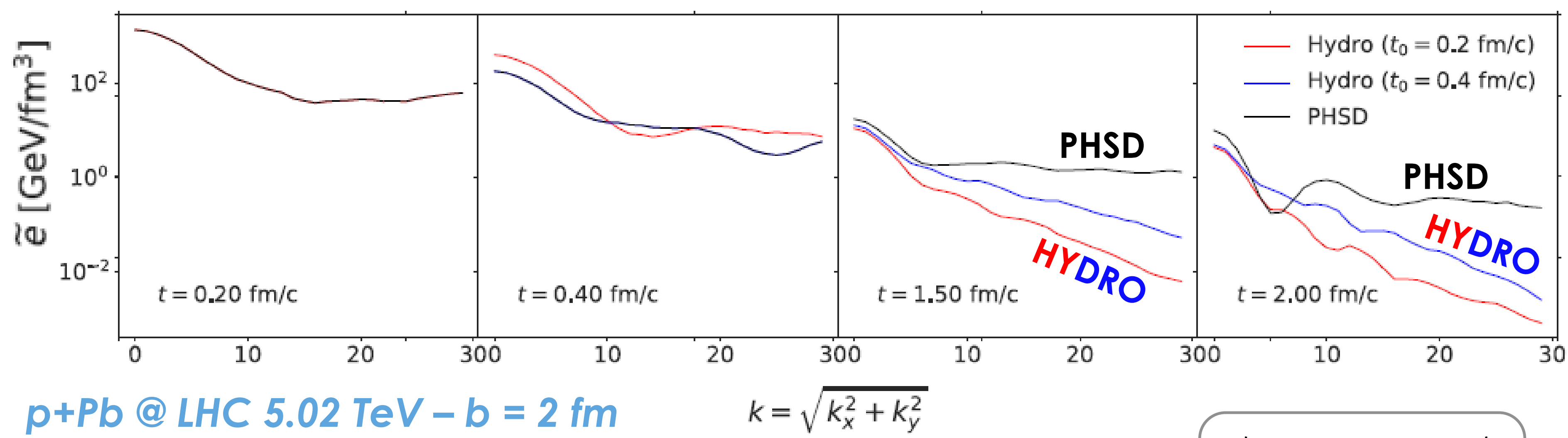
LO, W. Fan, P. Moreau, S.A. Bass and E. Bratkovskaya, Phys. Rev. C 106, 044910 (2022)

Y. Xu et al., Phys. Rev. C 96, 024902 (2017)

Quantifying medium inhomogeneity

Fourier transform of the energy density profile

$$\tilde{e}(k_x, k_y) = \frac{1}{m}\frac{1}{n}\sum_{x=0}^{m-1}\sum_{y=0}^{n-1} e(x,y)\, e^{2\pi i\left(\frac{x k_x}{L_x m} + \frac{y k_y}{L_y n}\right)}$$



$$\left\langle \tilde{e}\left(\sqrt{k_x^2 + k_y^2}\right)\right\rangle$$

radial distribution of the Fourier modes of the energy density

Shorter wavelength modes survive only in PHSD

➞ constant inhomogeneity of QGP medium in the microscopic description

➞ nonequilibrium dynamics able to preserve the medium irregularities

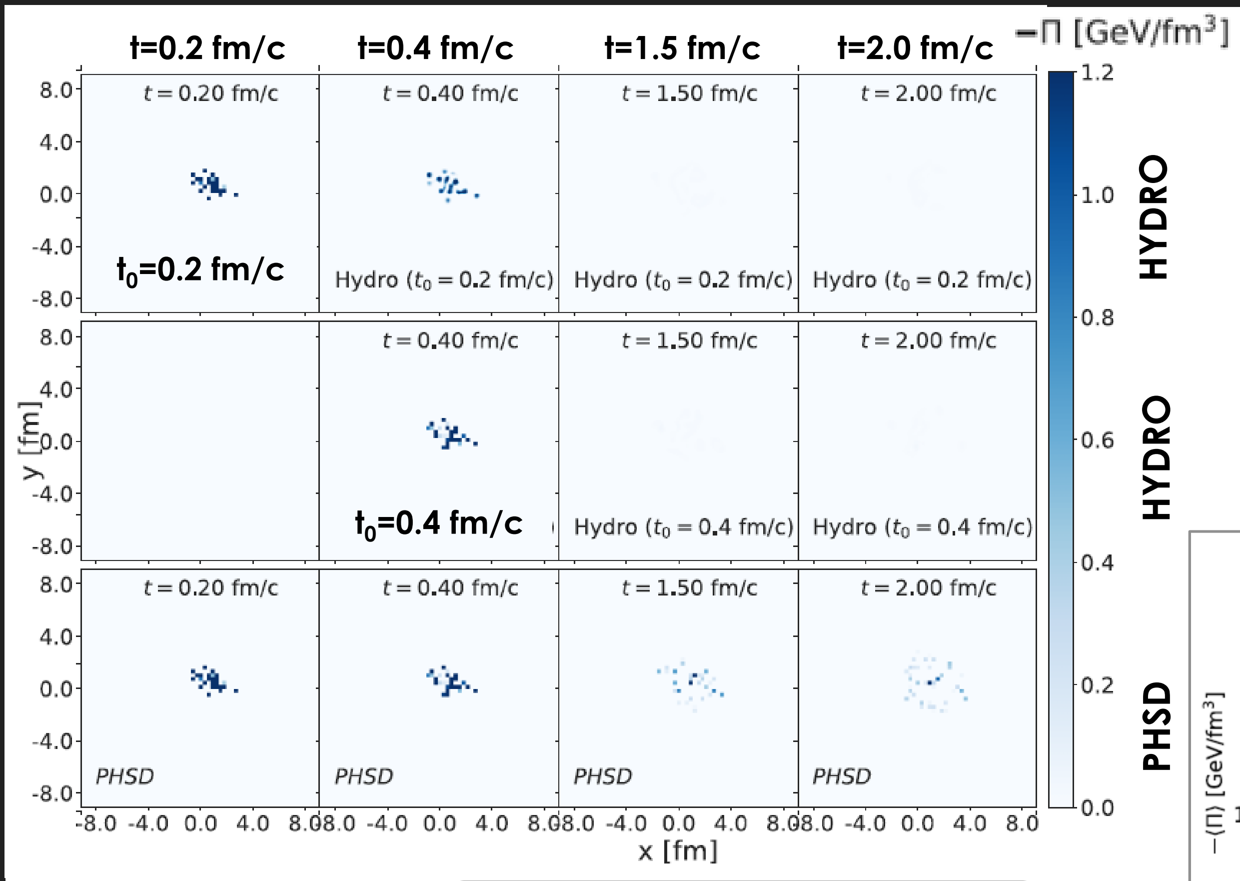
LO, W. Fan, P. Moreau, S.A. Bass and E. Bratkovskaya, Phys. Rev. C 106, 044910 (2022)

Viscous corrections

p+Pb @ LHC 5.02 TeV – b = 2 fm

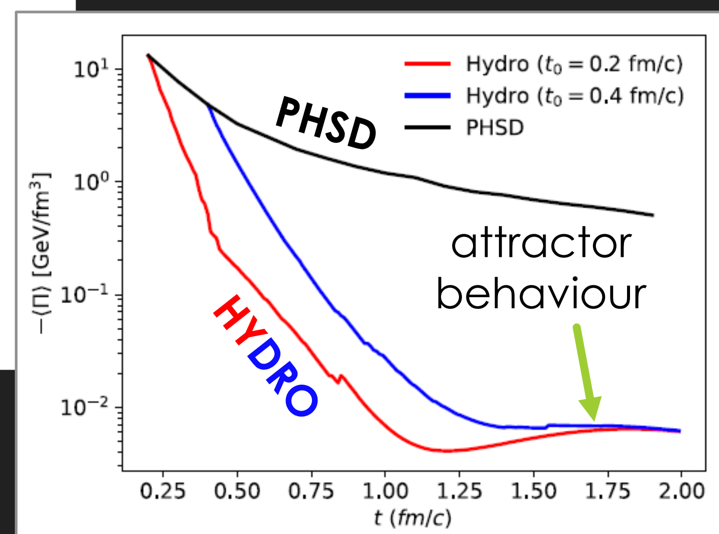
quicker decay than in *AA*

H. Song and U. W. Heinz, Phys. Rev. C 81, 024905 (2010)



- Π drops much faster in hydro than in PHSD
- Hydro lines lose memory of initial conditions at ~1.8 fm/c

averaged Π



bulk viscous pressure

$$\Pi = -\frac{1}{3}\Delta_{\mu\nu}T^{\mu\nu} - P$$

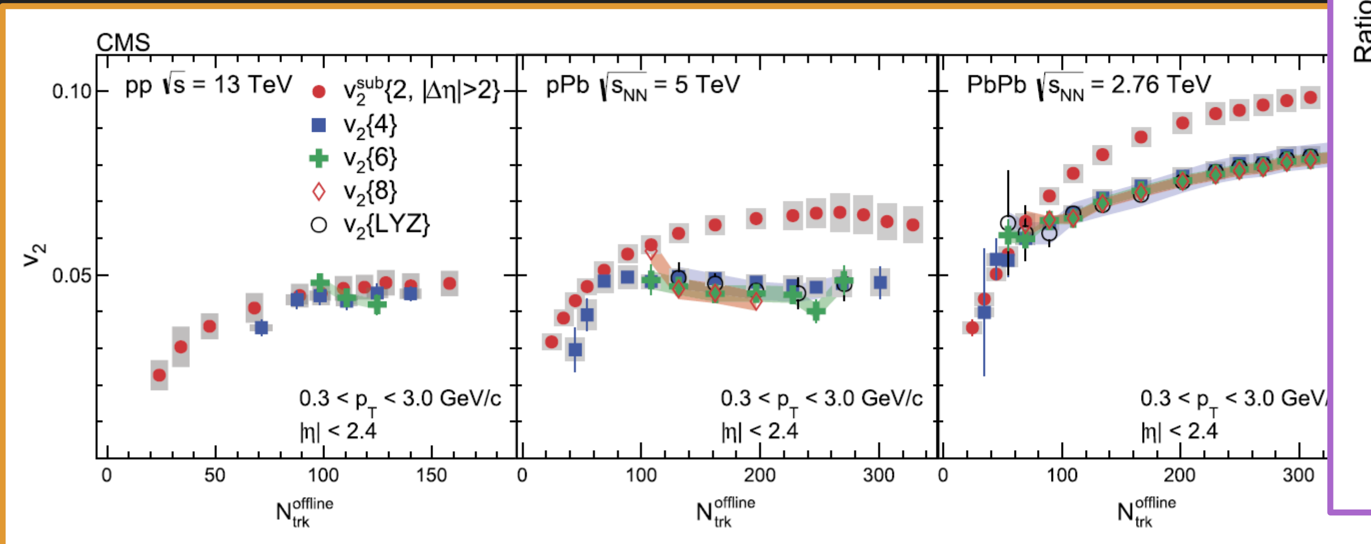
LO, W. Fan, P. Moreau, S.A. Bass and E. Bratkovskaya, Phys. Rev. C 106, 044910 (2022)

QGP signals in small systems

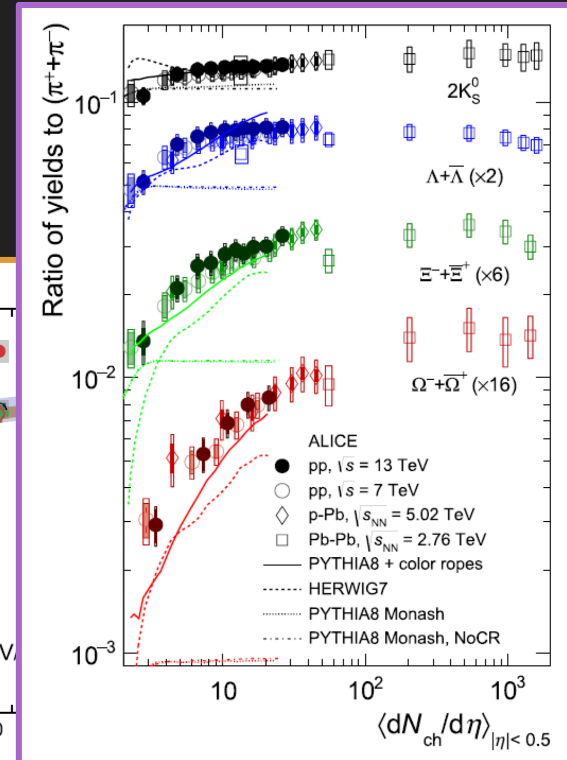
strangeness enhancement

Experimental evidence of collective-like behaviour in high-multiplicity *pp* and *pA* collisions

elliptic flow



CMS Collaboration, Phys. Lett. B 765, 193 (2017)



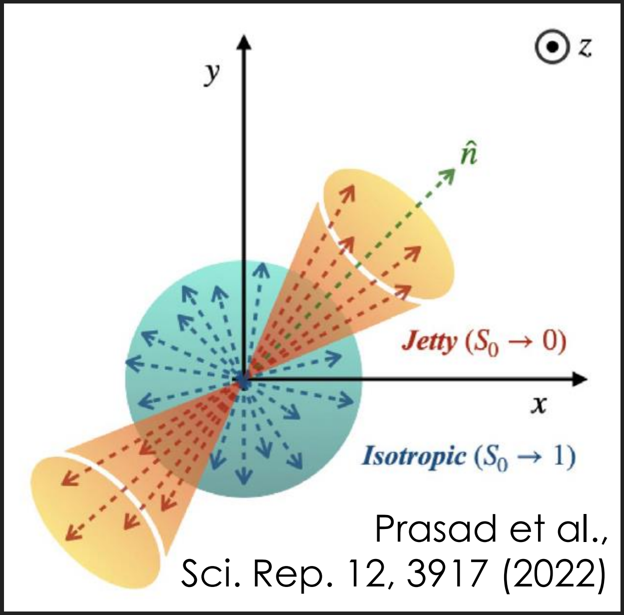
ALICE Collaboration, Eur. Phys. J. C 80, 693 (2020)

difficulty to well identify QGP signals in small systems

→ attempts to study observables through novel **multi-differential methods**

→ **event-shape engineering**

Event topology: transverse spherocity



$$S_0 \equiv \frac{\pi^2}{4} \min_{\hat{\mathbf{n}}_\mathbf{s}} \left(\frac{\sum_i |\mathbf{p}_{\mathbf{Ti}} \times \hat{\mathbf{n}}_\mathbf{s}|}{\sum_i p_{Ti}} \right)^2$$

TRANSVERSE SPHEROCITY

event-shape observable

A. Banfi, G. Salam and G. Zanderighi, JHEP 06, 038 (2010)

- $S_0 \to 0$: **JETTY events**
  all transverse momenta (anti)parallel or sum dominated by a single track
  ➞ dominated by hard physics in *pp*
- $S_0 \to 1$: **ISOTROPIC events**
  transverse momentua isotropically distributed
  ➞ dominated by soft physics in *pp*

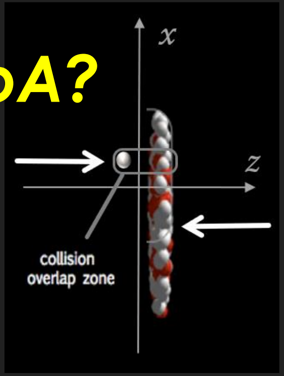
A. Khuntia et al., J. Phys. G 48, 035102 (2021)
A. Ortiz et al., Nucl. Phys. A 941, 78 (2015)
ALICE Coll., Eur. Phys. J. C 79, 857 (2019)
A. Nassirpour, J. Phys. Conf. Ser. 1602, 012007 (2020)

pp

S. Prasad et al., Sci. Rep. 12, 3917 (2022)
N. Mallick et al., J. Phys. G 48, 045104 (2021)
S. Prasad et al., Phys. Rev. D 107, 074011 (2023)

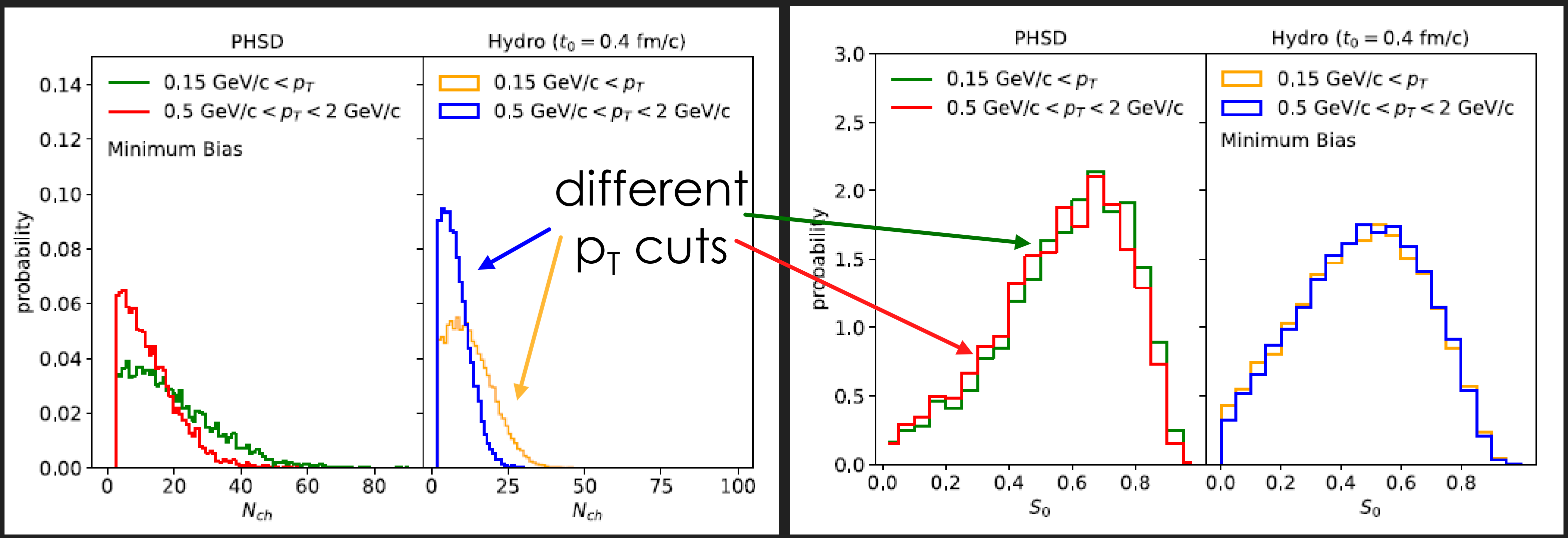
AA

pA?



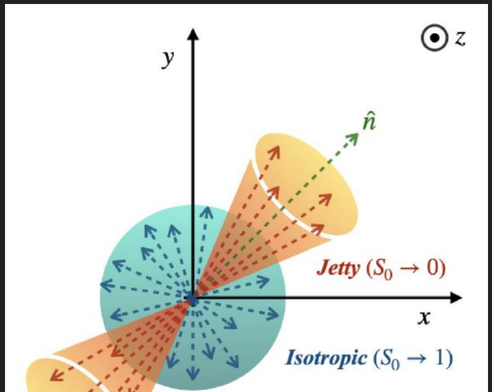
Multi-differential event categorization

PHSD HYDRO PHSD HYDRO



charged particle distribution *transverse spherocity distribution*

p+Pb @ LHC 5.02 TeV



Prasad et al., Sci. Rep. 12, 3917 (2022)

More isotropic event configurations in PHSD compared to hydro

- event topology connected to the different description of the medium in transport and hydro approaches
- multi-differential measurements promising tools to study medium properties in *pA*

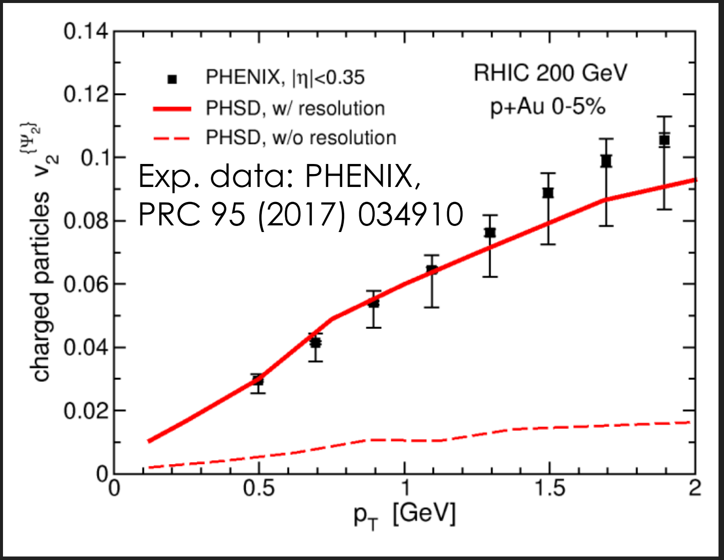
Elliptic flow in *pA*

$$v_2(p_T) = \frac{\langle \cos[2(\varphi(p_T) - \Psi_2)] \rangle}{Res(\Psi_2)}$$

In high-multiplicity *pA* events v_2 comparable to that found in *AA*

LO, P. Moreau, V. Voronyuk and E. Bratkovskaya, Phys. Rev. C 101, 014917 (2020)

p+Au @ RHIC 200 GeV



charged particle elliptic flow

Elliptic flow and trasverse spherocity in *pA*

$$v_2(p_T) = \frac{\langle \cos[2(\varphi(p_T) - \Psi_2)] \rangle}{Res(\Psi_2)}$$

LO, P. Moreau, V. Voronyuk and E. Bratkovskaya, Phys. Rev. C 101, 014917 (2020)

In high-multiplicity *pA* events v_2 comparable to that found in *AA*

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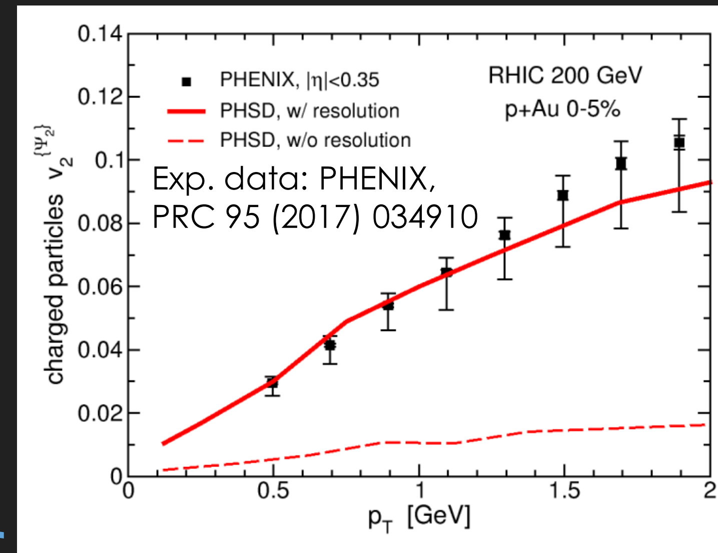
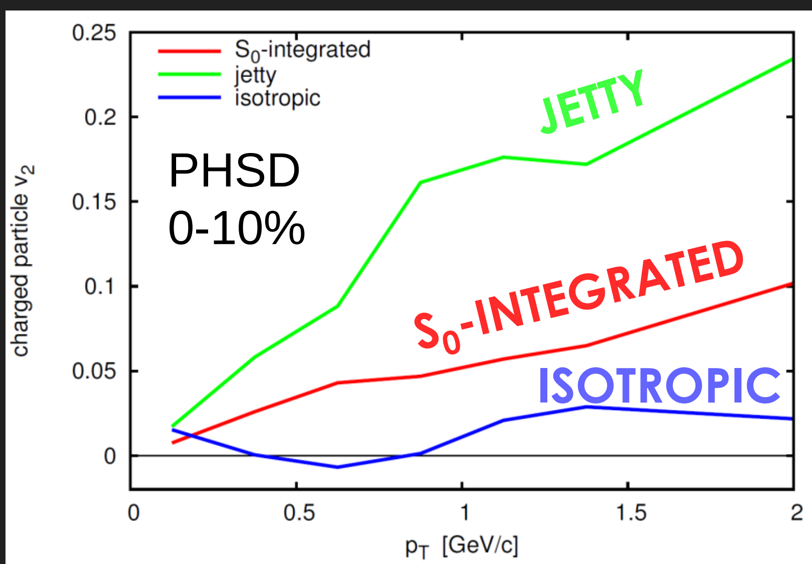


p+Pb @ LHC 5.02 TeV



charged particle elliptic flow

- ❑ isotropic events (high 20% S_0) ➞ $v_2 \approx 0$
- ❑ jetty events (low 20% S_0) ➞ predominant contribution to the v_2 of spherocity-integrated events

in agreement with AMPT results for Pb+Pb

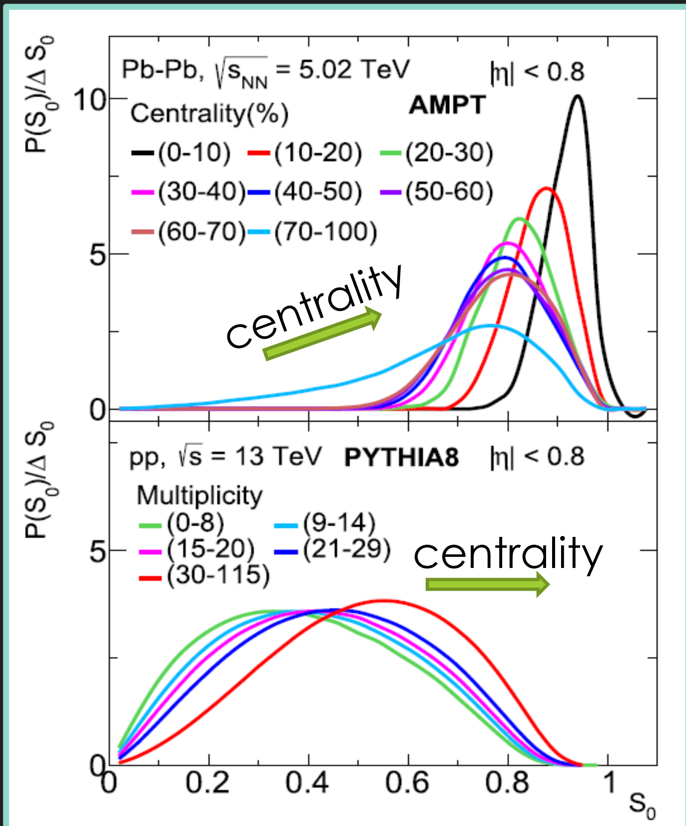
N. Mallick et al., J. Phys. G 48, 045104 (2021)

LO, W. Fan, P. Moreau, S.A. Bass and E. Bratkovskaya, Acta Phys. Polon. Supp. 16, 68 (2023)

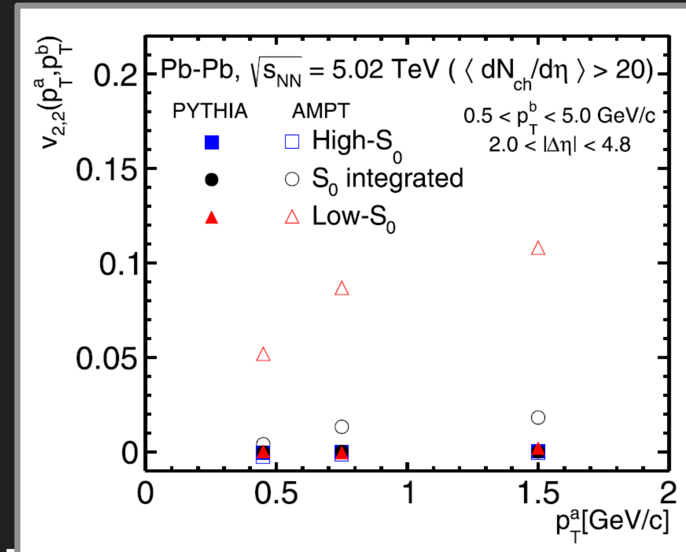
Non-trivial relation between event classifiers

N. Mallick et al., J. Phys. G 48, 045104 (2021)

In *AA*, *pA*, *pp*
more central events ≡ high-multiplicity collisions in *pA*
↓
more isotropic topologies

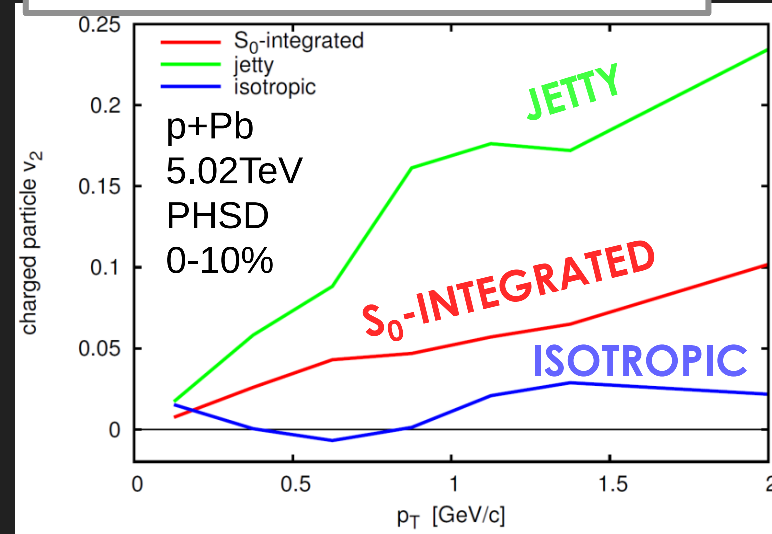


S. Prasad et al., Sci. Rep. 12, 3917 (2022)



In *AA* and *pA* higher v_2 for jetty topologies

In *pA* higher v_2 for high-multiplicity events



LO et al., Acta Phys. Polon. Supp. 16, 68 (2023)

lucia.oliva@dfa.unict.it

Conclusions

Study of **nonequilibrium effects** and **transverse spherocity**
in *p+Pb* collisions at LHC energy by comparing
the PHSD **transport** approach and the VISHNew **hydro** model

- hydro dissolves efficiently initial hot spots in energy density *e*; PHSD preserves medium irregularities
- The bulk viscous pressure *Π* quickly vanishes in hydro; in PHSD it remains nonzero during the QGP lifetime
- In *pA* collisions *e* and Π keep in both approaches a high degree of inhomogeneity than in *AA*
- Transverse spherocity is an event-shape observable that separates jetty and isotropic topologies
- PHSD favors more isotropic event configurations compared to hydro
- Analysis on the elliptic flow v_2 by applying multiplicity + spherocity event selection: in high-multiplicity class, jetty events contribute predominantly to v_2 while isotropic events have $v_2 \simeq 0$

Thank you for your attention

Coarse-graining the PHSD medium

Study the hot medium evolution with transport and hydro

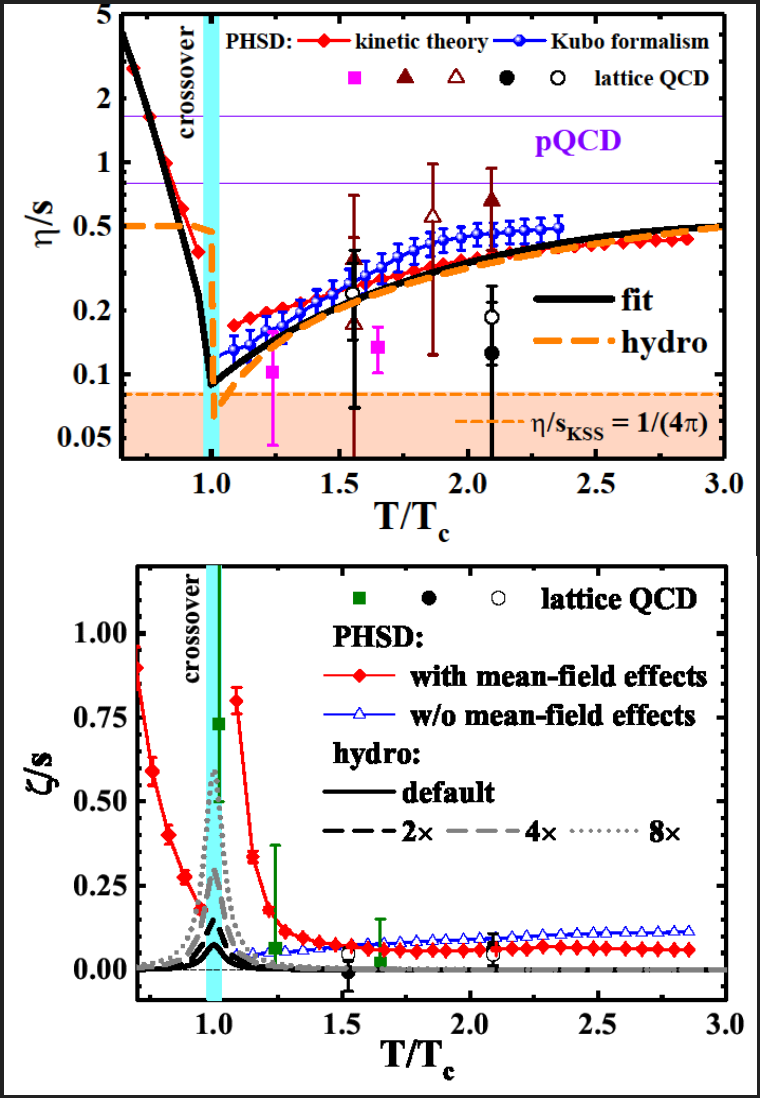
➞ same initial conditions to reduce the early stage impact

➞ similar equation of state and specific shear viscosity

Y. Xu et al., Phys. Rev. C 96, 024902 (2017)
T. Song et al., Phys. Rev. C 101, 044903 (2020)
LO et al., Phys. Rev. C 106, 044910 (2022)

0 **0.2** **0.4** **0.6** 0.8 t [fm/c] ➞ Initialization time for hydro?

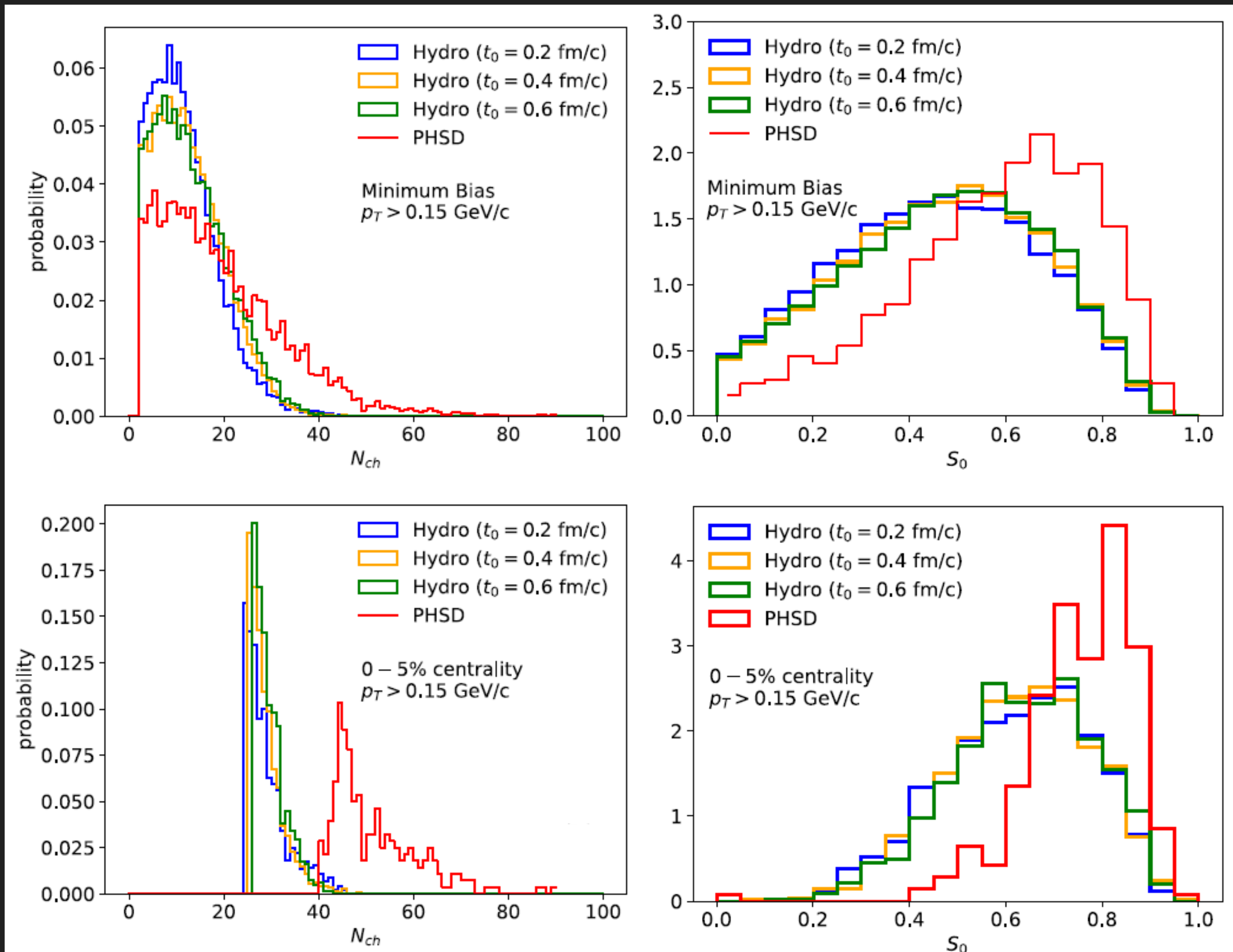
Specific viscosities in the two models
η/s(T) : the hydro code uses a parametrization obtained from PHSD
ζ/s(T) : much smaller in the hydro code than in PHSD



LO, W. Fan, P. Moreau, S.A. Bass and E. Bratkovskaya, Phys. Rev. C 106, 044910 (2022)

Multi-differential event categorization

p+Pb @ LHC 5.02 TeV



charged particles
$|\eta| < 0.5$
$p_T > 0.15$ GeV/c
$N_{trk} \geq 3$ for S_0

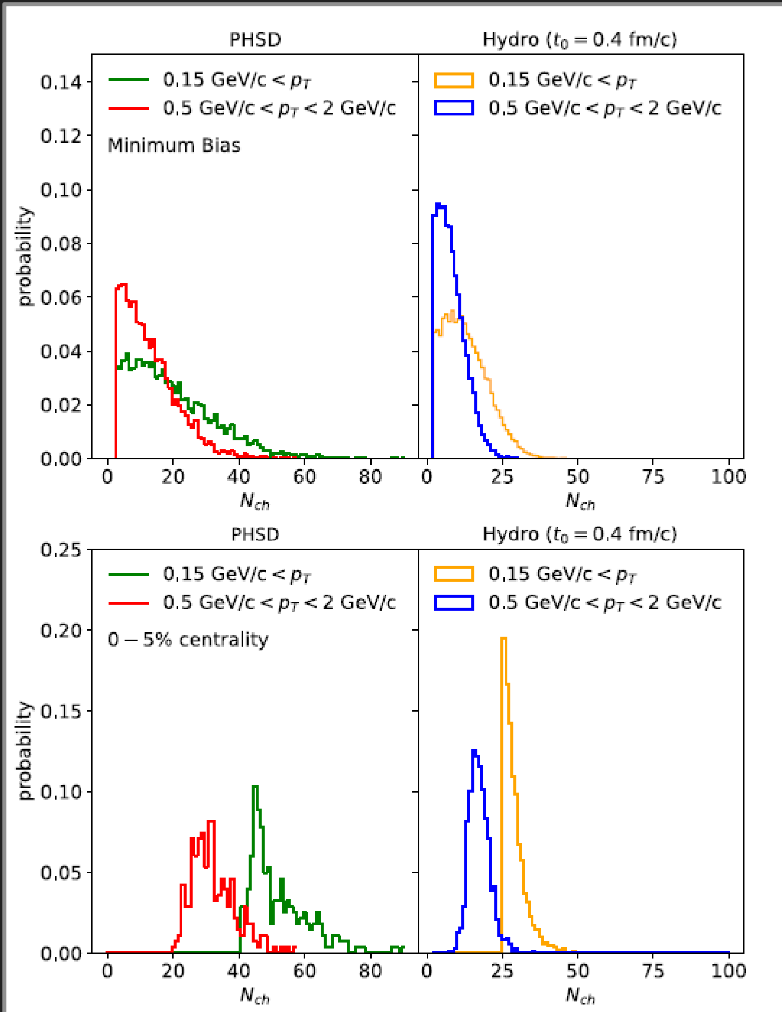
More isotropic configurations in PHSD than in hydro

charged particle distr. ***transverse spherocity distr.***

LO, W. Fan, P. Moreau, S.A. Bass and E. Bratkovskaya, Phys. Rev. C 106, 044910 (2022)

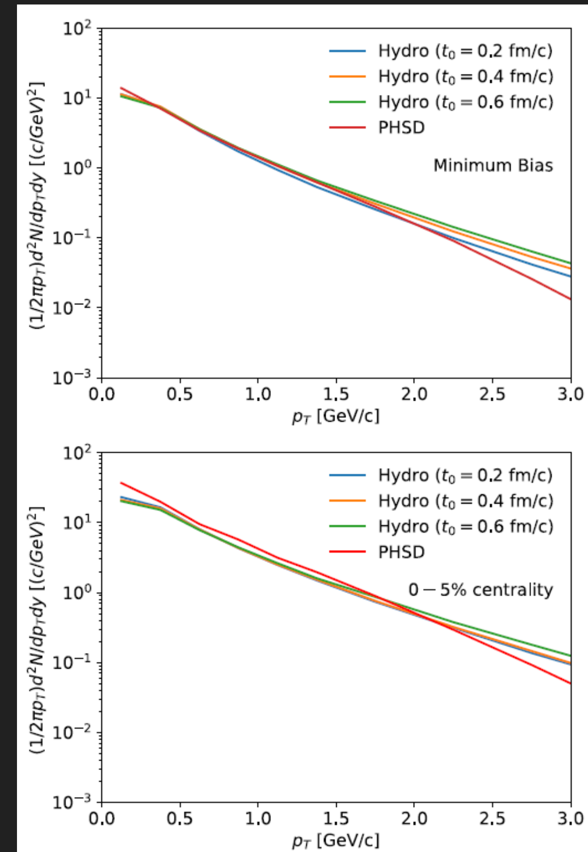
Multiplicity: PHSD vs hydrodynamics

charged particle distribution



event distribution in multiplicity CHANGES applying different p_T cuts

p+Pb @ LHC 5.02 TeV



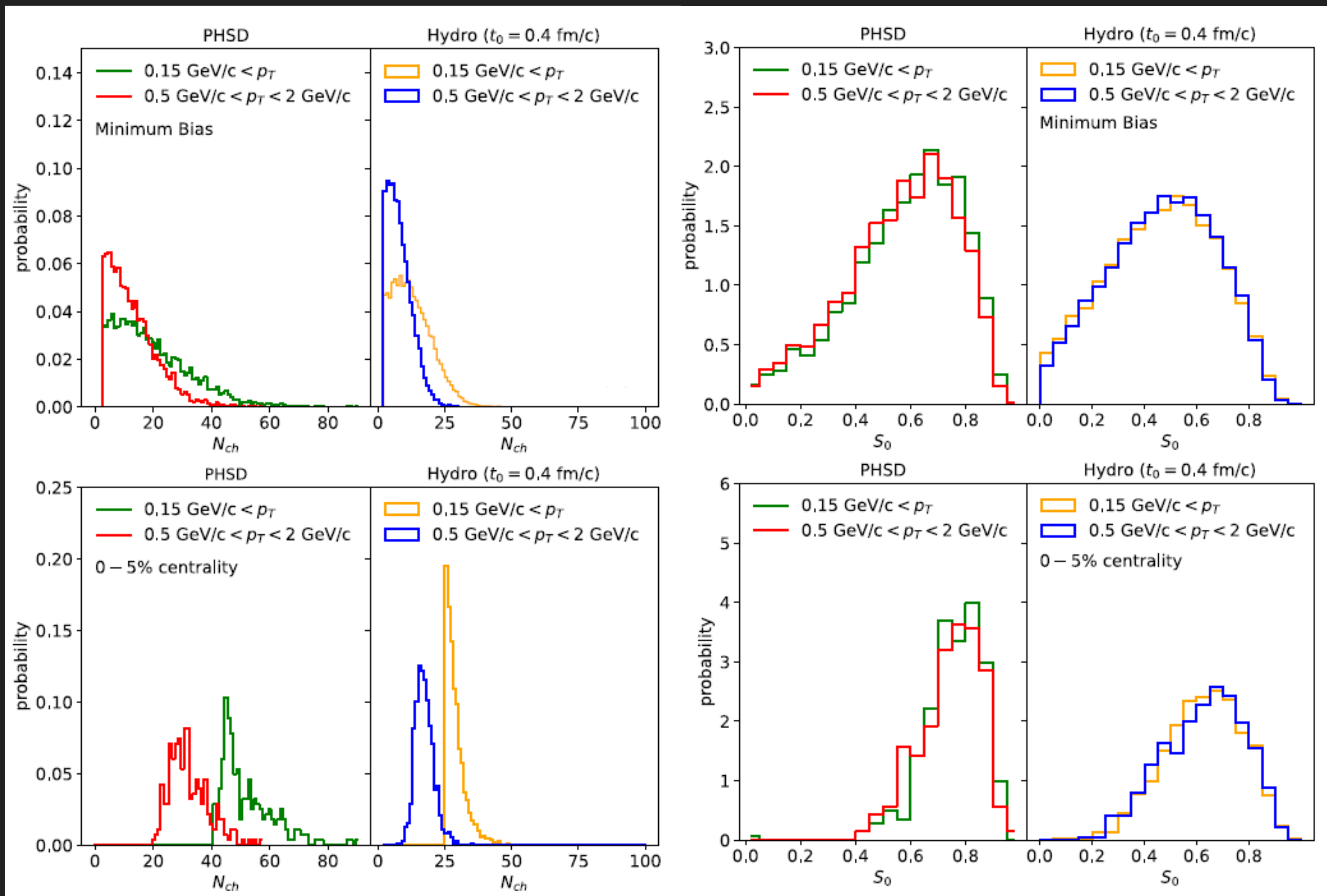
charged particle p_T-spectrum

LO, W. Fan, P. Moreau, S.A. Bass and E. Bratkovskaya, Phys. Rev. C 106, 044910 (2022)

Multi-differential event categorization

p+Pb @ LHC 5.02 TeV

PHSD **HYDRO** **PHSD** **HYDRO**



charged particle distr. ***transverse spherocity distr.***

applying p_T cuts

- N_{ch}-distr. CHANGES
- S_0-distr. DOES NOT CHANGE

event topology connected to the different medium description

importance of multi-differential measurements in *pA*

LO, W. Fan, P. Moreau, S.A. Bass and E. Bratkovskaya, Phys. Rev. C 106, 044910 (2022)

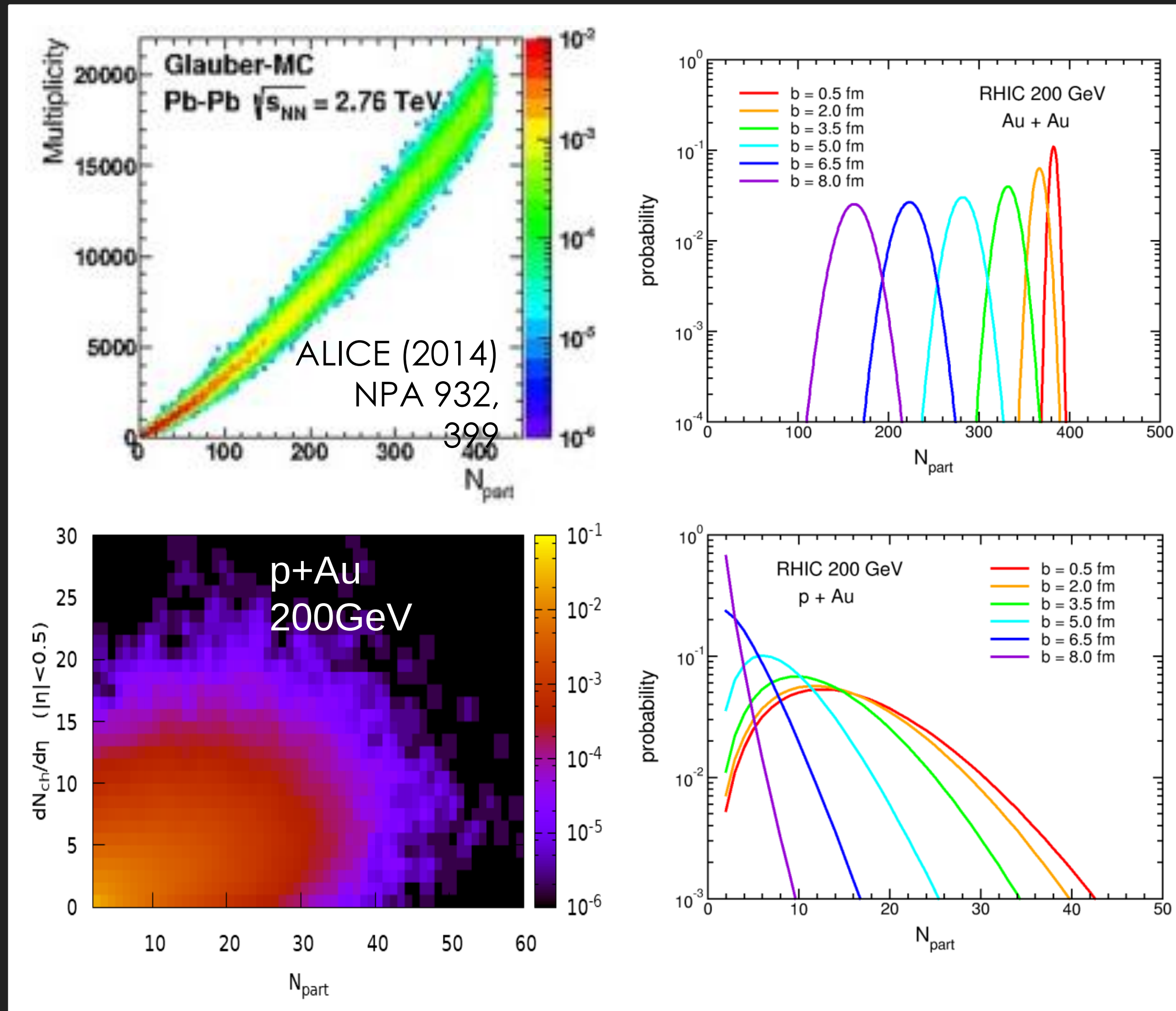
Centrality determination : A+A vs p+A

A+A

centrality characterizes the amount of overlap in the interaction area

p+A

multiplicity fluctuation mixes events from different impact parameters

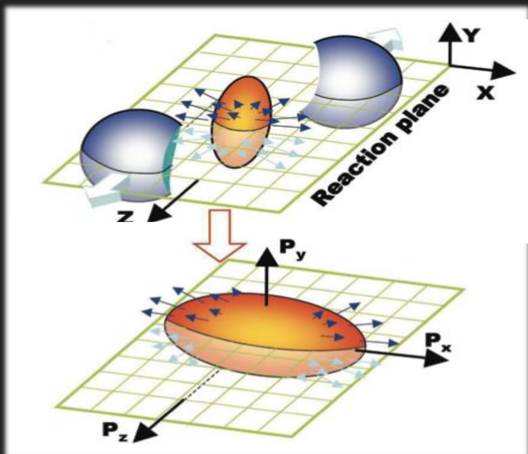


LO, P. Moreau, V. Voronyuk and E. Bratkovskaya, Phys. Rev. C 101, 014917 (2020)

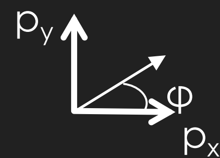
Anisotropic radial flow v_n

azimuthal particle distributions
w.r.t. the reaction plane

QGP: hydrodynamic behavior with very low η/s and formation of collective flows



$$\frac{dN}{d\varphi} \propto 1 + \sum_n 2 v_n(p_T) \cos[n(\varphi - \Psi_n)]$$



flow coefficients

event-plane angle

$$v_n = \frac{\langle \cos[n(\varphi - \Psi_n)] \rangle}{Res(\Psi_n)}$$

event-plane
angle resolution

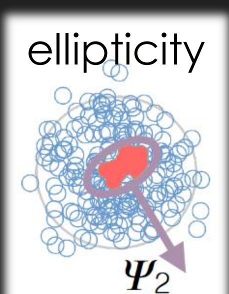
important especially for
small system, e.g. p+A

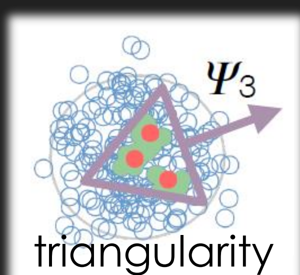
$$\Psi_n = \frac{1}{n}\,\mathrm{atan2}(Q_n^y, Q_n^x)$$

$$Q_n^x = \sum_i \cos[n\varphi_i]$$

$$Q_n^y = \sum_i \sin[n\varphi_i]$$

heavy-ion collisions:
not a simple **almond shape**
but a **"lumpy" profile**





finite number of particles produces limited resolution in Ψ_n determination
⇨ v_n must be corrected up to what they would be relative to real reaction plane

A. Poskanzer and S. Voloshin, Phys. Rev. C 58, 1671 (1998)