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Non-equilibrium effects and collective dynamics in relativistic proton-nucleus collisions

UNIVERSITÀ degli STUDI di CATANIA

Lucia Oliva

Collaborators:
Wenkai Fan, Pierre Moreau, Steffen Bass, Elena Bratkovskaya, Vadim Voronyuk

INFN CATANIA
Istituto Nazionale di Fisica Nucleare
Sezione di Catania

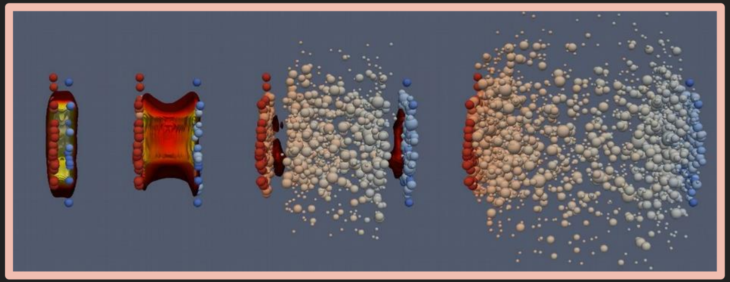
DIPARTIMENTO DI FISICA E ASTRONOMIA "ETTORE MAJORANA"

Simulating large and small colliding systems

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

HYDRODYNAMIC MODELS

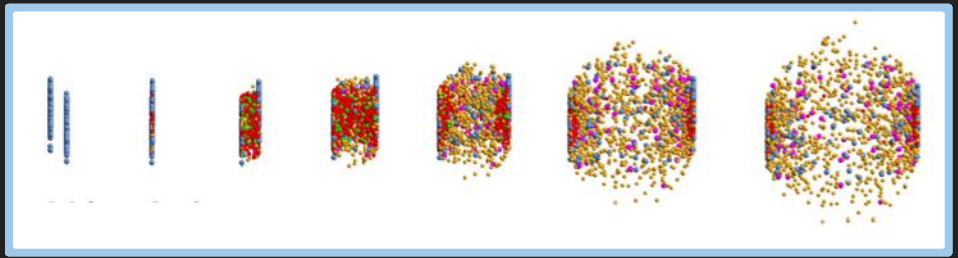
macroscopic description
evolution based on conservation laws
unreasonable effectiveness of hydrodynamics



https://webhome.phy.duke.edu/~jp401/old_music_manual

TRANSPORT MODELS

microscopic description
evolution of particle distributions functions
inherent inclusion of nonequilibrium dynamics



http://theory.gsi.de/~ebratkov/phsd-project/PHSD/index1.html

Simulating large and small colliding systems

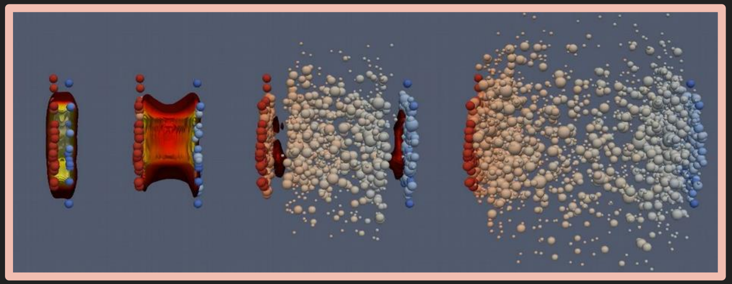
Two main approaches to describe the hot QCD medium produced in relativistic nuclear collisions

Initial conditions + **HYDRODYNAMIC MODELS** + hadronic afterburner

macroscopic description

evolution based on conservation laws

unreasonable effectiveness of hydrodynamics



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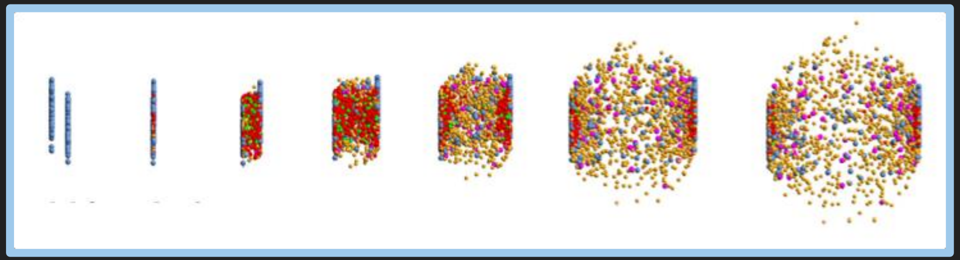
for partonic and hadronic phases



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Simulating large and small colliding systems

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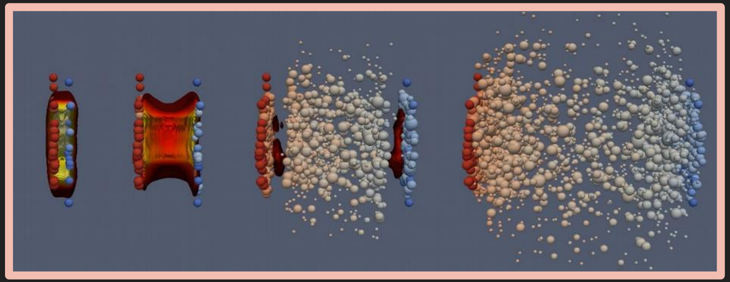

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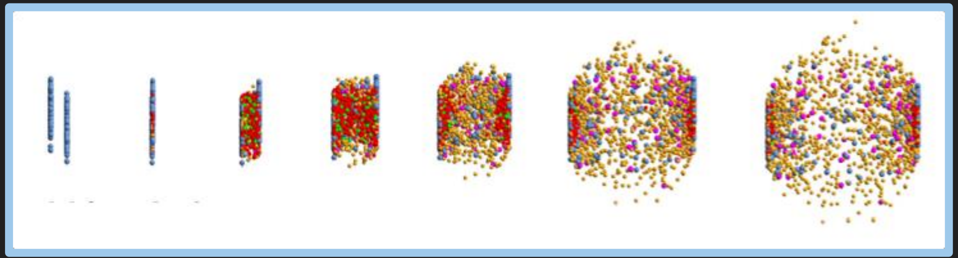

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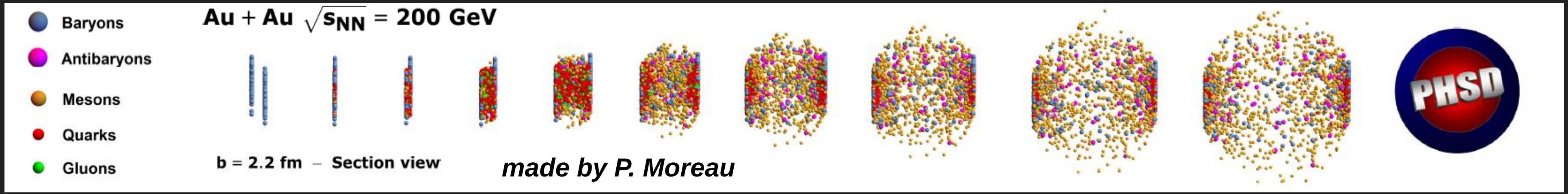
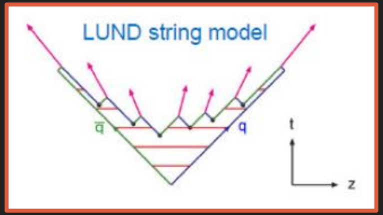
Both hybrid and transport approaches are successful in describing AA and pA collisions
Different way of treating the nonequilibrium effects in the two models
Focus on p+Pb collisions at LHC energy

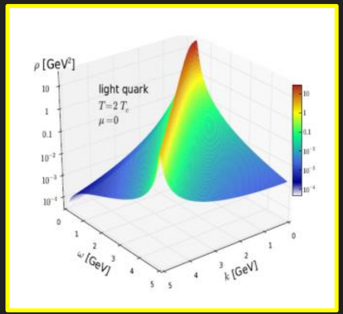
Parton-Hadron-String Dynamics – PHSD

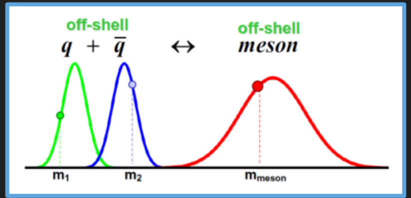
non-equilibrium off-shell transport approach
to study the phase transition from hadronic to partonic matter and the QGP properties from a microscopic origin



- INITIAL NUCLEI COLLISION: nucleon-nucleon collisions lead to the formation of strings that decay to pre-hadrons
- FORMATION OF QGP: if energy density $\varepsilon > \varepsilon_C$ pre-hadrons dissolve in massive off-shell quarks and gluons + mean-field potential
- PARTONIC STAGE: evolution based on off-shell transport equations with the Dynamical Quasi-Particle Model (DQPM) defining parton spectral functions
- HADRONIZATION: massive off-shell partons with broad spectral functions hadronize to off-shell baryons and mesons
- HADRONIC PHASE: evolution based on the 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)
Giessen/Frankfurt groups: http://theory.gsi.de/~ebratkov/phsd-project/PHSD/index1.html

VISHNew (+ hadronic afterburner)

2+1D viscous hydrodynamic model

to study the QGP medium and its properties by means of evolution laws of macroscopic quantities

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

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

$$\tau_\Pi \dot{\Pi} + \Pi = -\zeta\theta - \delta_{\Pi\Pi}\Pi\theta + \phi_1\Pi^2 + \lambda_{\Pi\pi}\pi^{\mu\nu}\sigma_{\mu\nu} + \phi_3\pi^{\mu\nu}\pi_{\mu\nu}$$

$$\tau_\pi \dot{\pi}^{\langle\mu\nu\rangle} + \pi^{\mu\nu} = 2\eta\sigma^{\mu\nu} + 2\pi_\alpha^{\langle\mu}w^{\nu\rangle\alpha} - \delta_{\pi\pi}\pi^{\mu\nu}\theta + \phi_7\pi_\alpha^{\langle\mu}\pi^{\nu\rangle\alpha} - \tau_{\pi\pi}\pi_\alpha^{\langle\mu}\sigma^{\nu\rangle\alpha} + \lambda_{\pi\Pi}\Pi\sigma^{\mu\nu} + \phi_6\Pi\pi^{\mu\nu}$$

$\boldsymbol{u^\mu}$: cell 4-velocity
$\boldsymbol{e}$: local energy density
$\boldsymbol{P}$: local isotropic pressure
$\boldsymbol{\Delta^{\mu\nu}=g^{\mu\nu}-u^\mu u^\nu}$

$\boldsymbol{\Pi}$: bulk viscous pressure
$\boldsymbol{\pi^{\mu\nu}}$: shear stress tensor
$\boldsymbol{\zeta}$: bulk viscosity
$\boldsymbol{\eta}$: shear viscosity

- PARTONIC STAGE: VISHNew
- HADRONIZATION: Cooper-Frye procedure
- 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: https://github.com/jbernhard/osu-hydro

Coarse-graining the PHSD medium

Study the nonequilibrium dynamics in the hot medium evolution of the transport and hydrodynamic approaches

- ➞ start with the same initial conditions in order to reduce the impact of the early pre-equilibrium stage
- ➞ characterize the medium with similar equation of state and shear viscosity over entropy density ratio

Y. Xu et al. (PHSD-Duke groups), Phys. Rev. C 96, 024902 (2017)
T. Song et al. (PHSD-Duke-Nantes groups), Phys. Rev. C 101, 044903 (2020)
L. Oliva et al. (PHSD-Duke groups), Phys. Rev. C 106, 044910 (2022)

PHSD vs VISHNew — initialized with

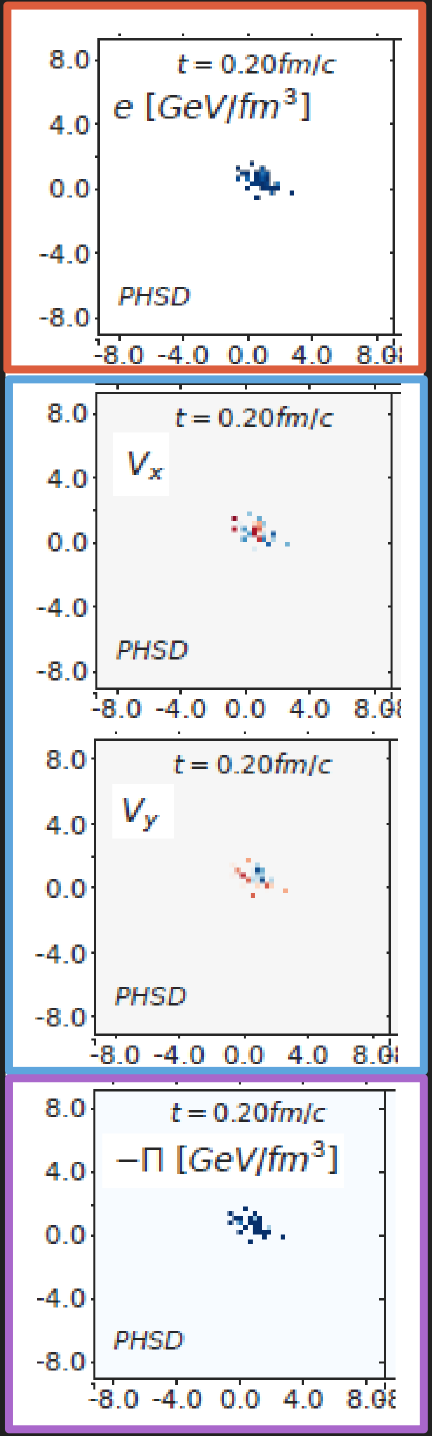
$$T^{\mu\nu} = e u^\mu u^\nu - \Delta^{\mu\nu}(P + \Pi) + \pi^{\mu\nu}$$

Coarse graining of PHSD medium in the transverse plane (cells with Δx=Δy=0.3 fm)
2D hydro ➞ initial conditions from the central longitudinal cell

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

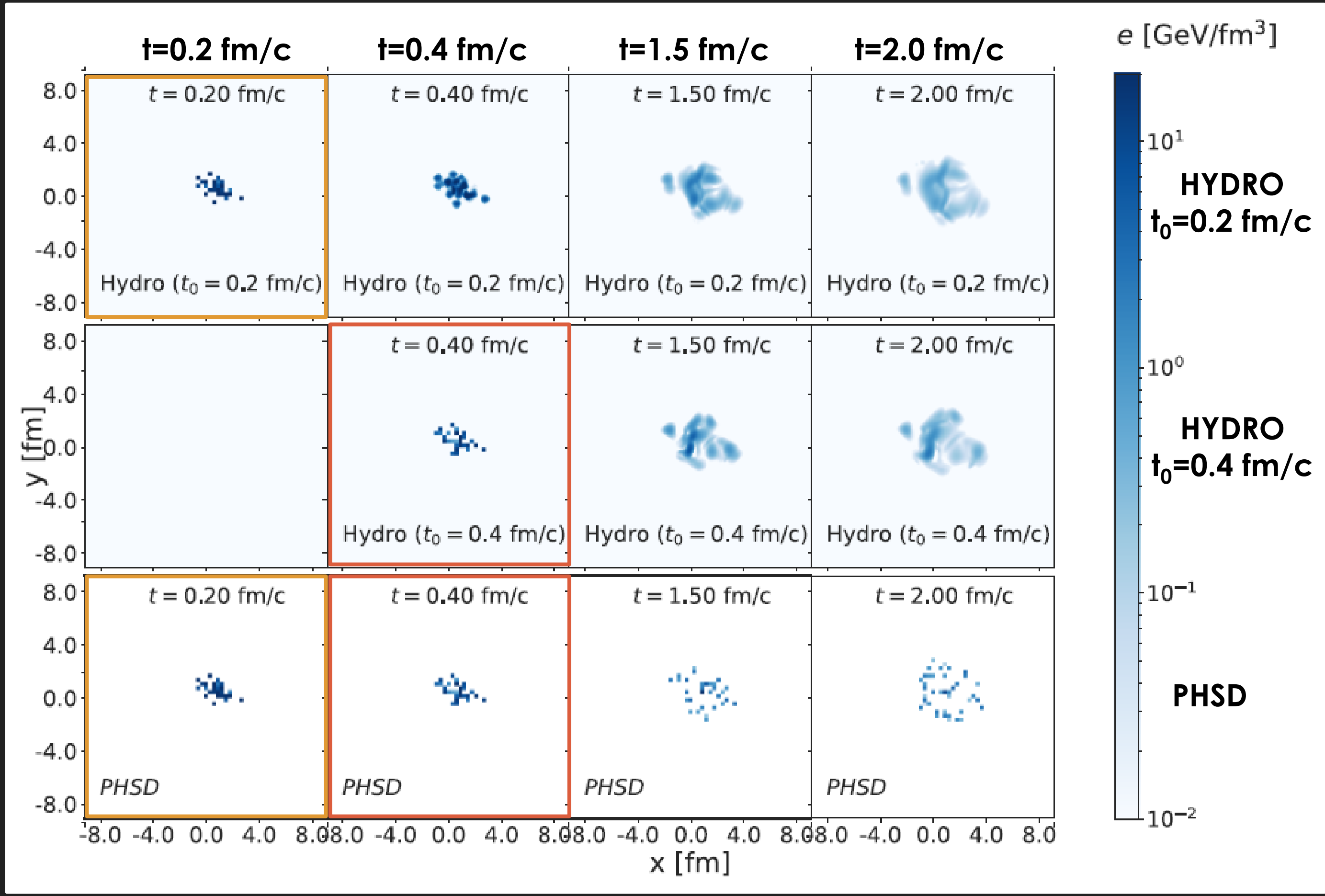
Initialization time for hydro?

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



Medium evolution: hydrodynamics vs PHSD

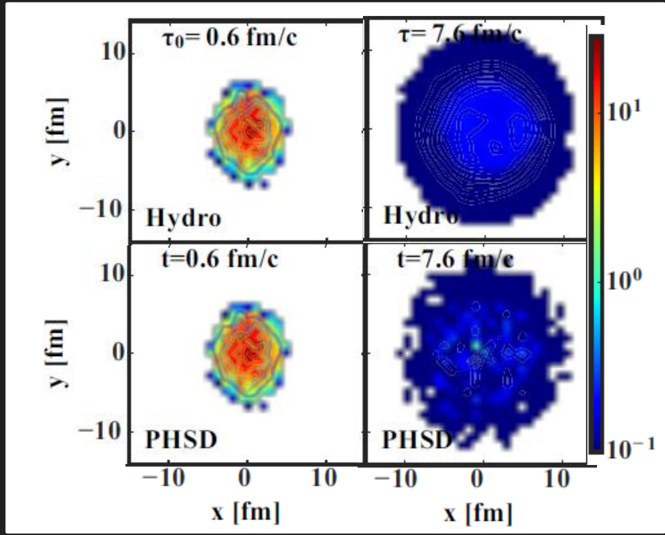
p+Pb @ LHC 5.02 TeV – b = 2 fm



- The PHSD evolution more chaotic all times
- The VISHNew code smooths the initial PHSD profile during the time evolution
- Impact of the initialization time for hydro in the final degree of smoothness

Au+Au @ RHIC 200 GeV – b = 6 fm

energy density



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

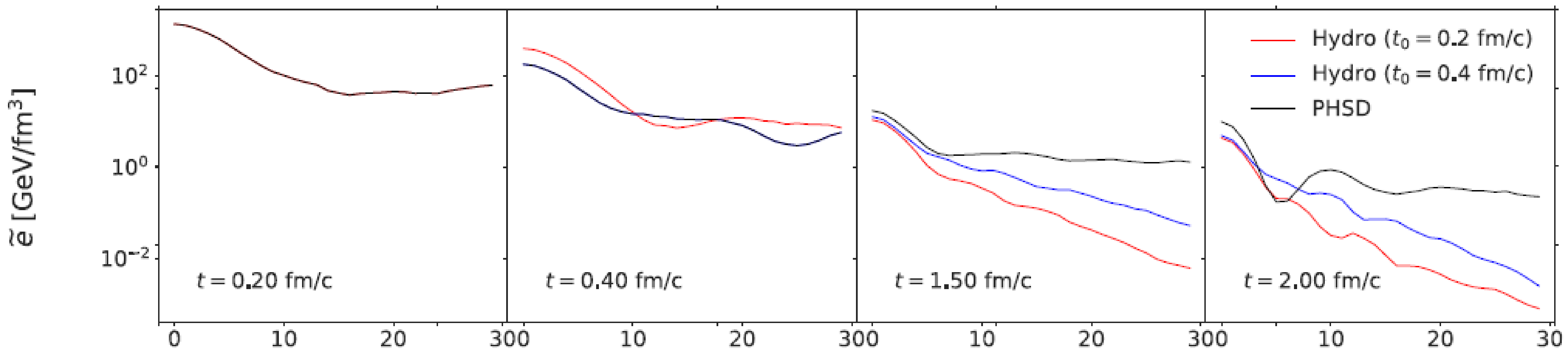
Higher degree of inhomogeneity w.r.t. to heavy-ion reactions due to the smaller space-time size of the medium produced in p+Pb collisions

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

Fourier image of energy density

The Fourier transform of the energy density profile quantifies the medium inhomogeneity

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



p+Pb @ LHC 5.02 TeV – b = 2 fm

radial distribution of the Fourier modes of the energy density

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

Shorter wavelength modes survive only in PHSD

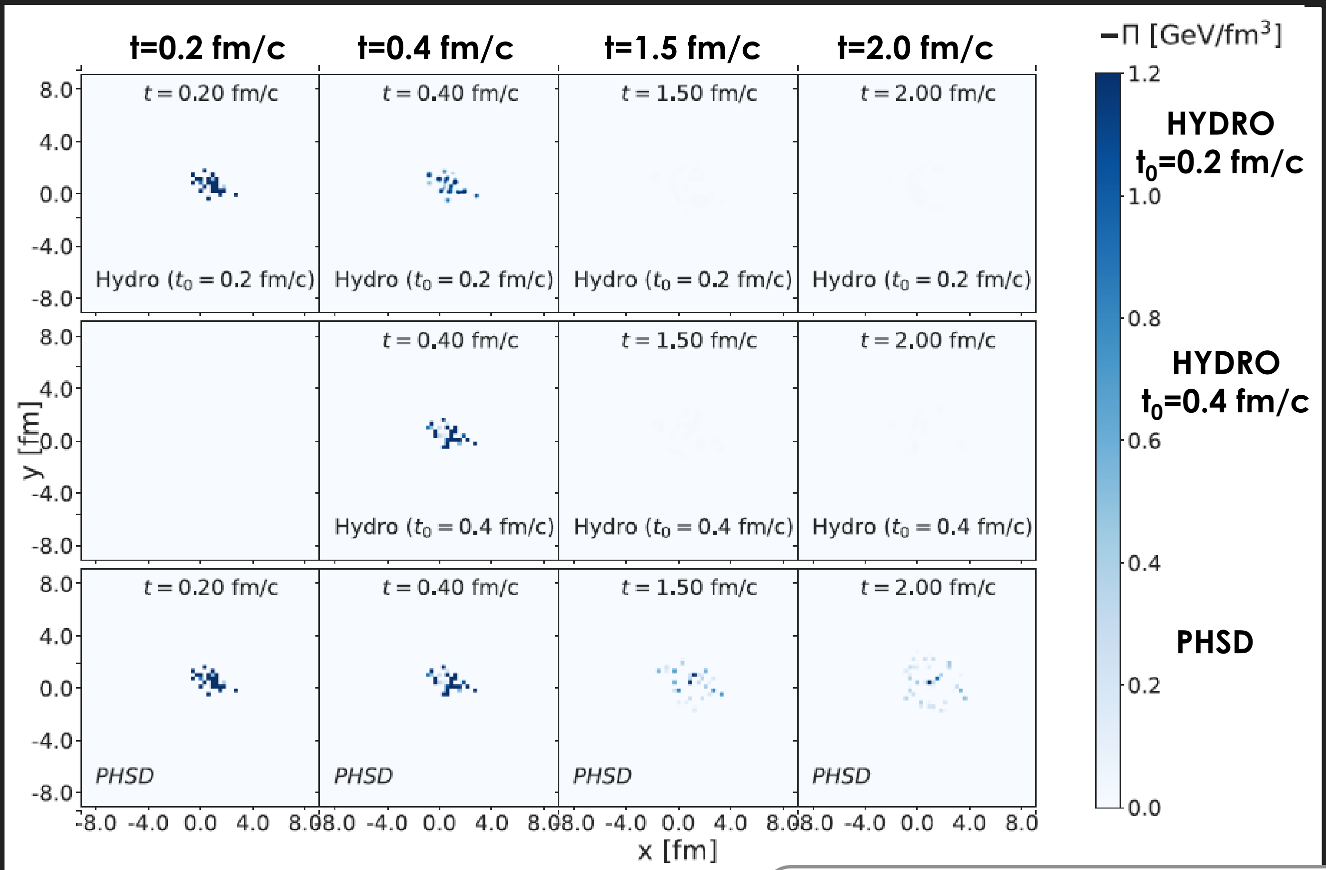
→ constant inhomogeneity of the QGP medium in the microscopic transport description

→ nonequilibrium dynamics able to preserve the medium irregularities

L. Oliva, 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

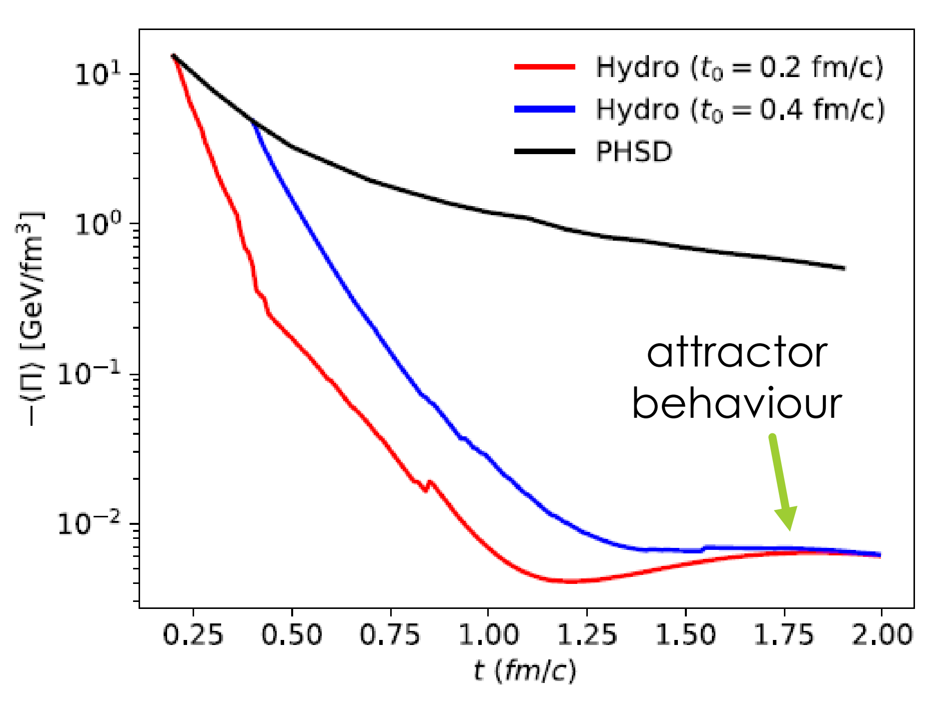


bulk viscous pressure

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

- Π drops very fast in hydro w.r.t. PHSD
- In both approaches quicker decay than in *AA*
  H. Song and U. Heinz, Phys. Rev. C 81, 024905 (2010)
- Hydro lines with different t_0 lose memory of initial conditions at ~1.8 fm/c

event-averaged Π averaged over transverse plane weighted with energy density



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

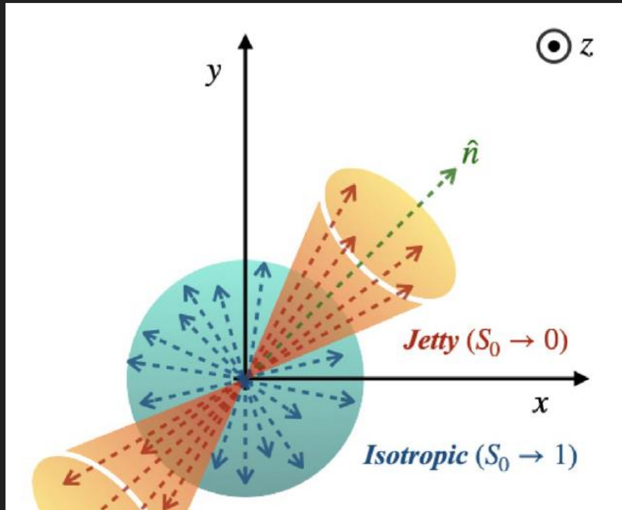
Event topology: transverse spherocity

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

difficulty to well identify QGP signals in small systems

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

➡ **event-shape engineering**



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

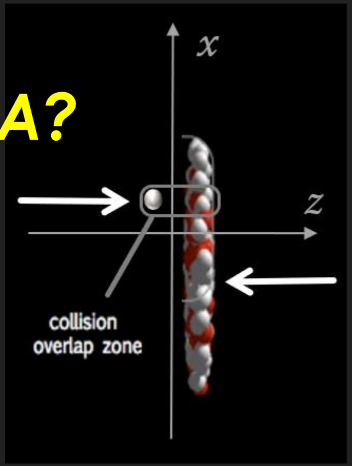
TRANSVERSE SPHEROCITY

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

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 (*pp*)
- $S_0 \to 1$: **ISOTROPIC events**
  transverse momentua isotropically distributed
  ➡ dominated by soft physics (*pp*)

pA?



pp

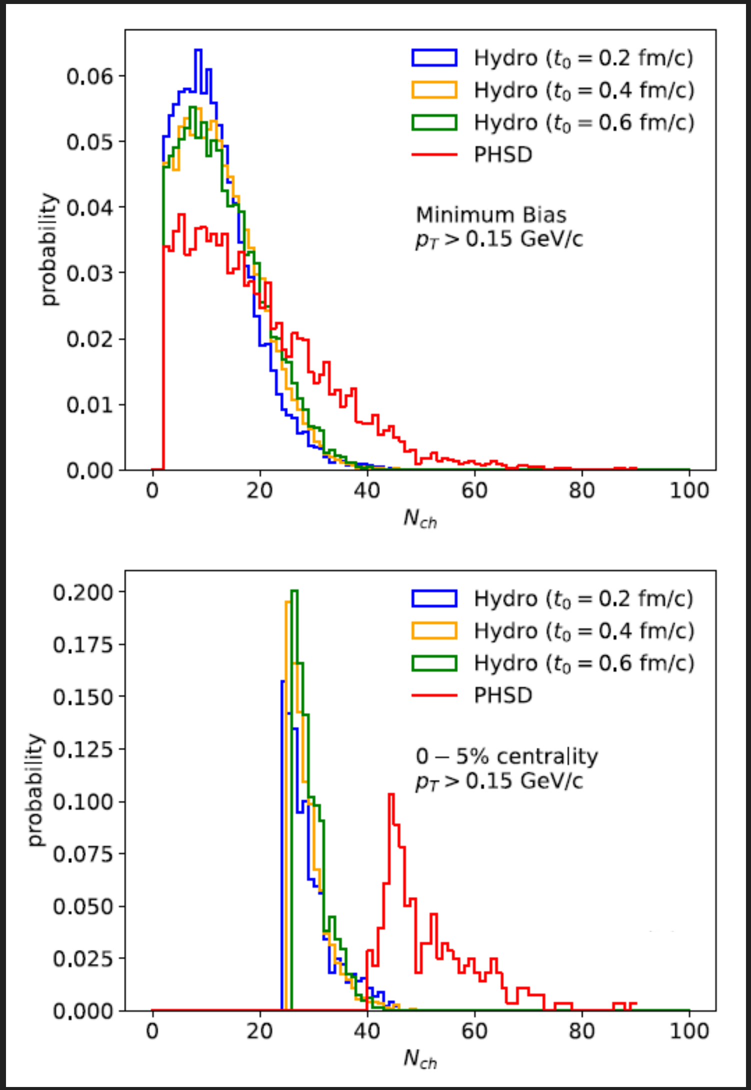
A. Khuntia et al., J. Phys. G 48, 035102 (2021)
ALICE Coll., Eur. Phys. J. C 79, 857 (2019)
A. Nassirpour, J. Phys. Conf. Ser. 1602, 012007 (2020)

AA

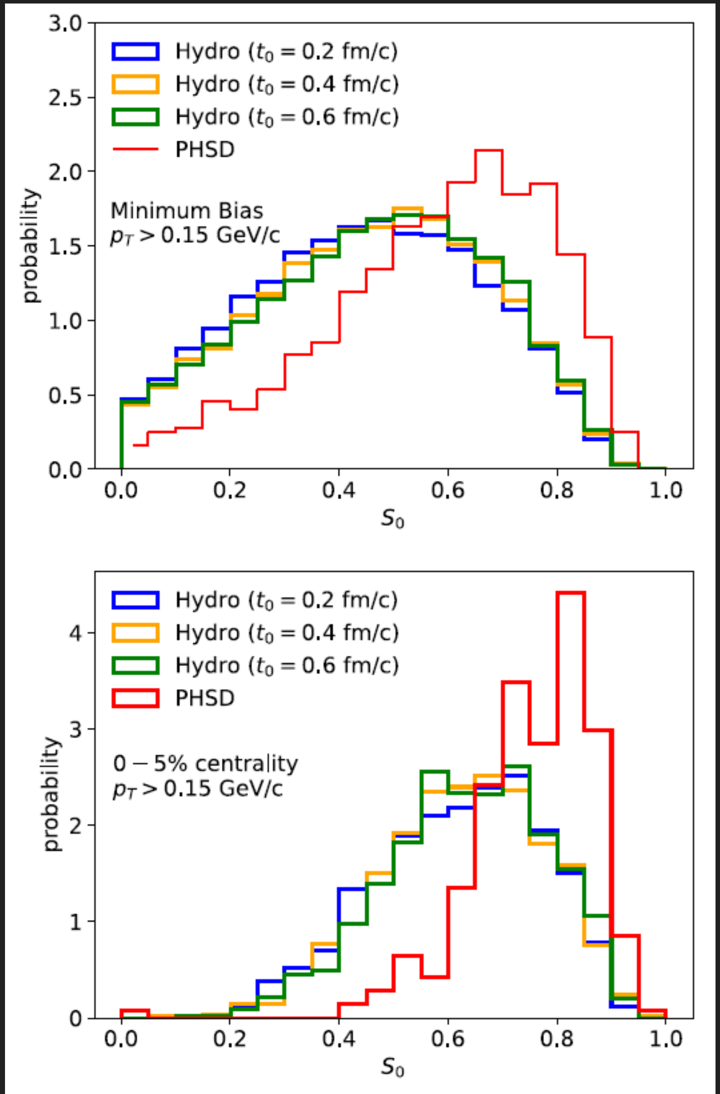
S. Prasad et al., Sci. Rep. 12, 3917 (2022)
N. Mallick et al., J. Phys. G 48, 045104 (2021)
N. Mallick et al., 2001.06849
S. Prasad et al., 2207.12133

Multi-differential event categorization

p+Pb @ LHC 5.02 TeV



charged particle distribution



transverse spherocity distribution

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

More isotropic event configurations in PHSD compared to hydro

- ➢ only partially due to different charged particle multiplicity

PHSD
vs
HYDRO

0 0.2 0.4 0.6 0.8 … t [fm/c]

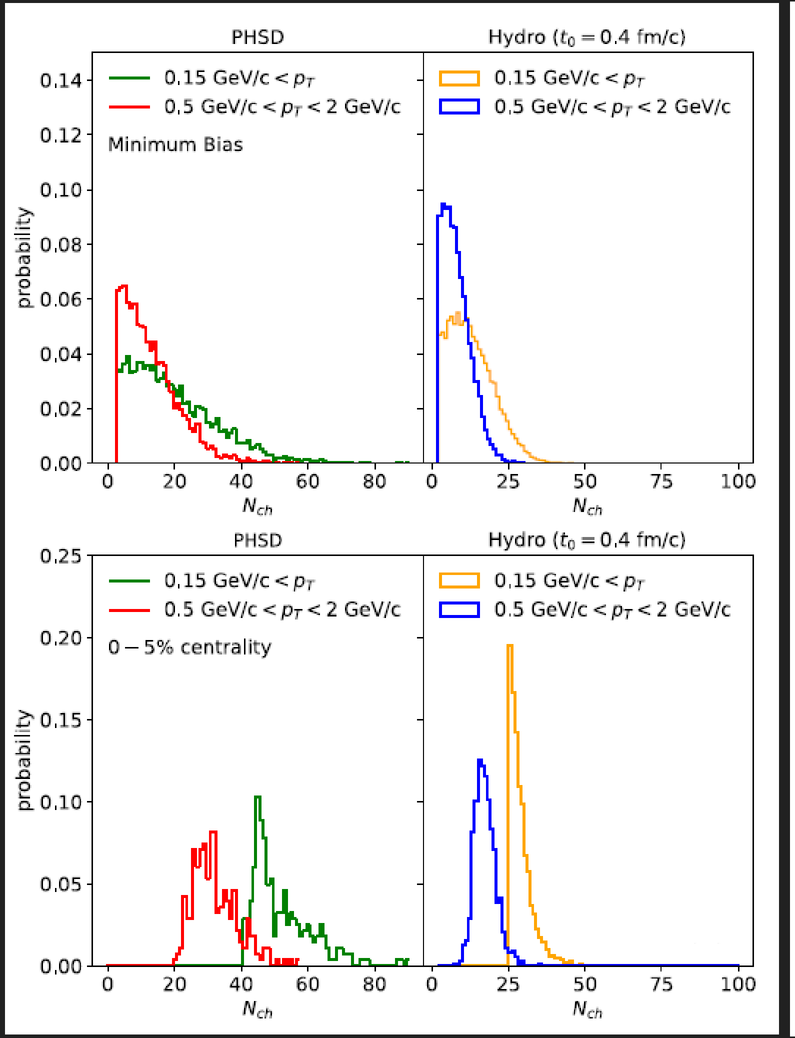
initialization time

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

Multi-differential event categorization

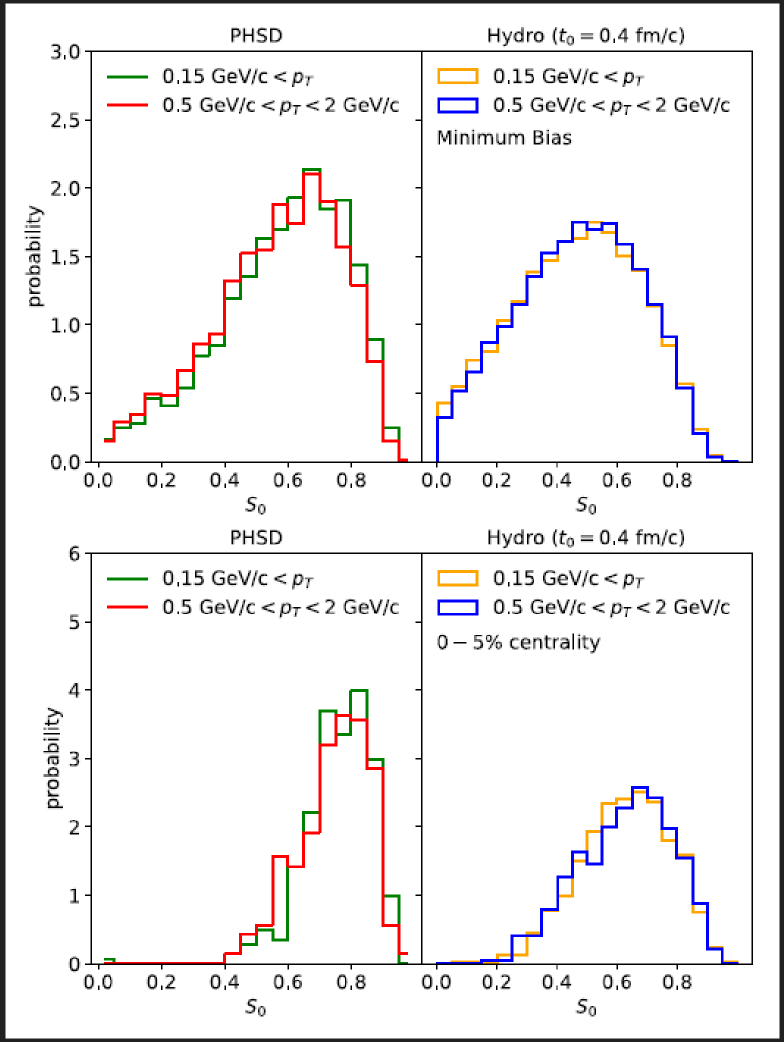
p+Pb @ LHC 5.02 TeV

PHSD HYDRO



charged particle distribution

PHSD HYDRO



transverse spherocity distribution

applying different p_T cuts
in both PHSD and hydro

- **event distribution in multiplicity CHANGES**
- **event distribution in spherocity DOES NOT CHANGE**

➢ event topology connected to the different description of the medium produced in small colliding systems

➢ multi-differential measurements important tools to study medium properties in *pA*

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

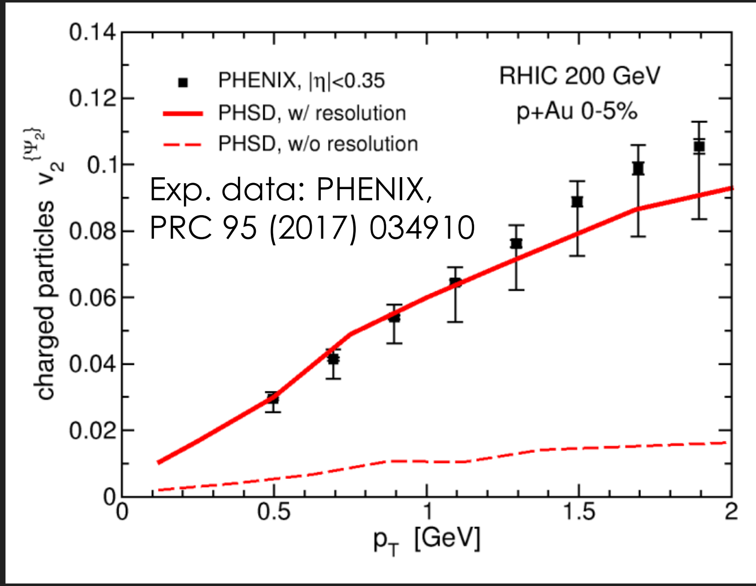
Elliptic flow in pA collisions

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

Comparable v_2 to that found in large colliding systems

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

p+Au @ RHIC 200 GeV



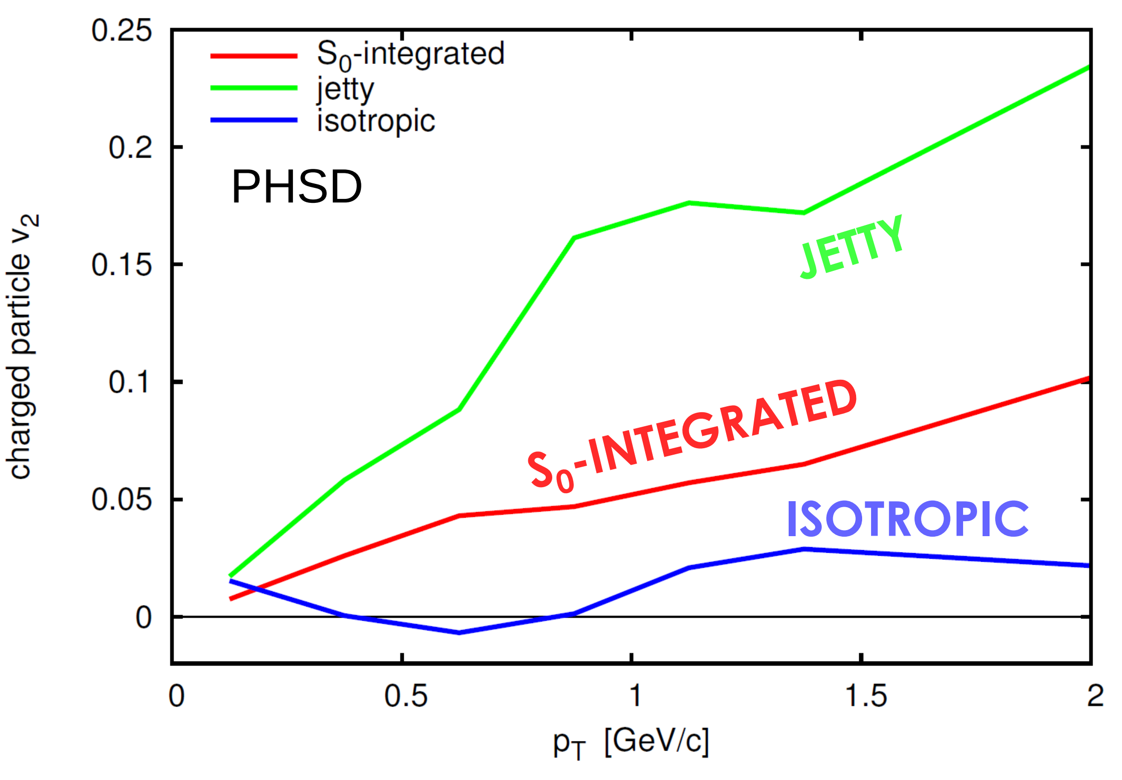
charged particle elliptic flow

Elliptic flow and trasverse spherocity in pA collisions

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

Comparable v_2 to that found in large colliding systems

p+Pb @ LHC 5.02 TeV – 10% central



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

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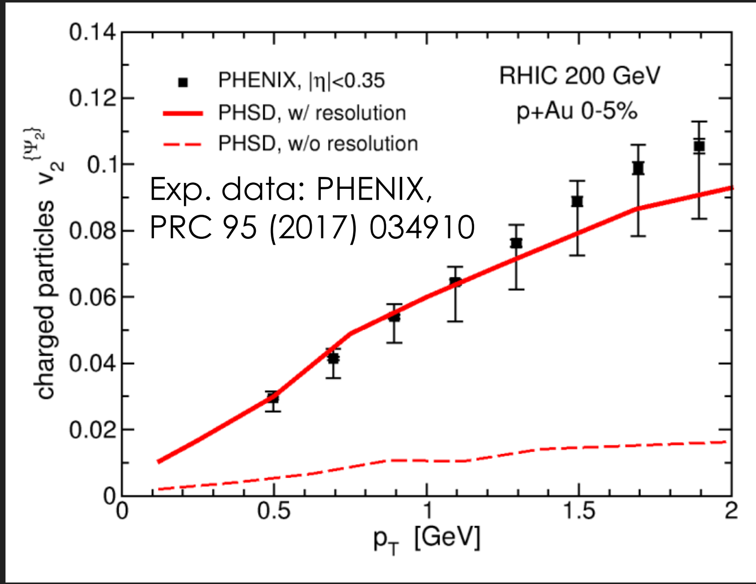


charged particle elliptic flow

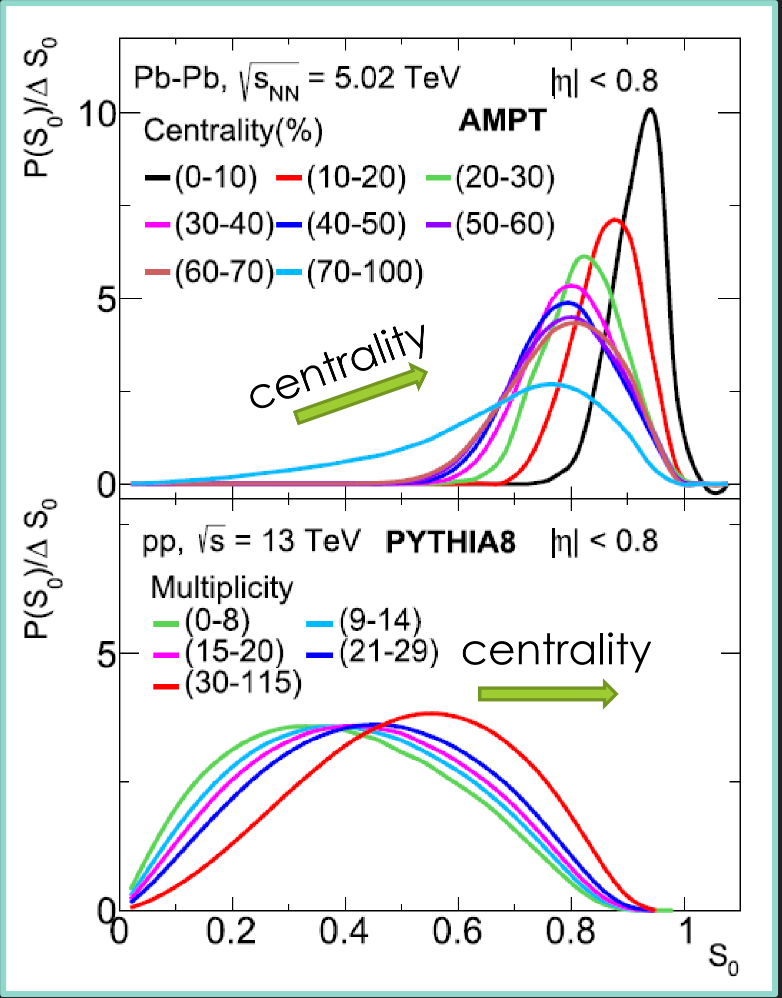
- isotropic events (high 20% S_0) → $v_2 \approx 0$
- jetty events (low 20% S_0) → predominant contribution to the v_2 of spherocity-integrated events

in agreement with AMPT results for Pb+Pb collisions
N. Mallick et al., J. Phys. G 48, 045104 (2021)

L. Oliva, W. Fan, P. Moreau, S.A. Bass and E. Bratkovskaya, Proceeding Quark Matter 2022

Non-trivial relation between event classifiers

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



transverse spherocity distribution

More central events → more isotropic topologies

≡

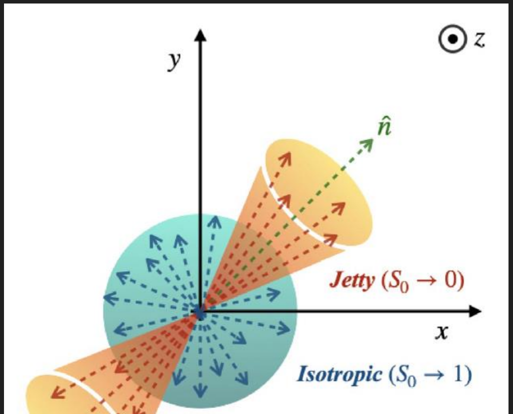
high-multiplicity collisions

in small systems where we expect a high v_2

BUT

higher v_2 for jetty topologies

in high-multiplicity events



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

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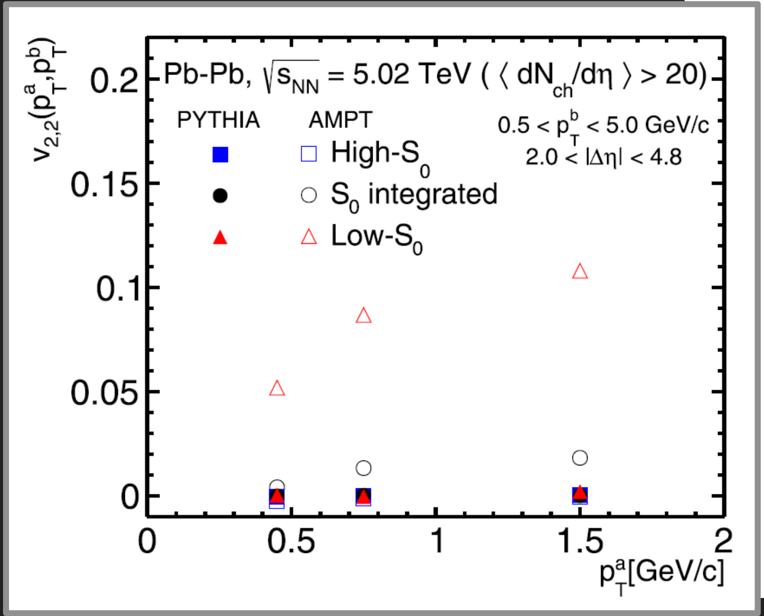
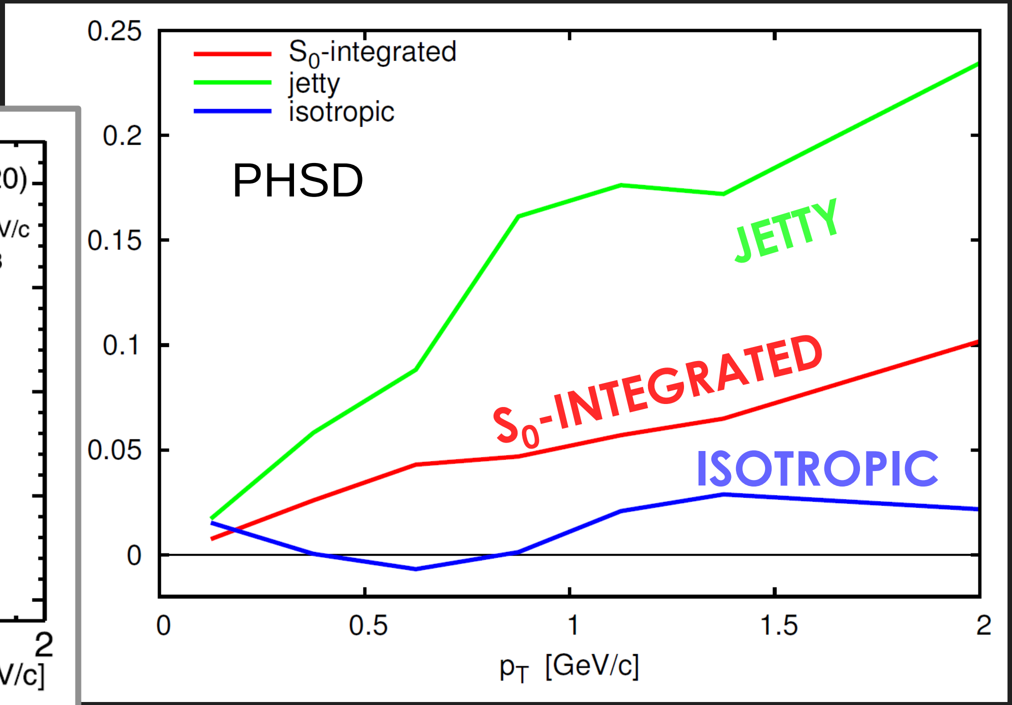


N. Mallick et al., J. Phys. G 48, 045104 (2021)



charged particle elliptic flow

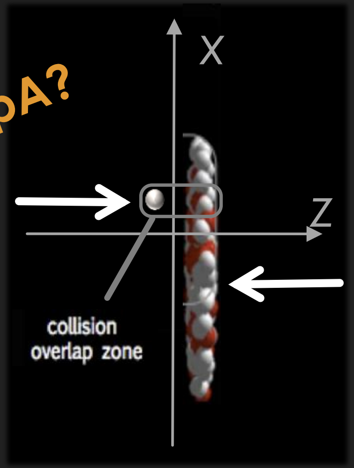
Directed flow

The directed flow v_1 is a collective sidewards particle deflection

$$v_1(y) = \langle \cos[\varphi(y)] \rangle$$

Sources of v_1 in heavy-ion collisions
- initial-state fluctuations
- orbital angular momentum
- baryon transport to midrapidity
- electromagnetic fields (EMF)

in pA?



REVIEWS

L. Oliva, Eur. Phys. J. A 56, 255 (2020)
A. Dubla, U. Gursoy and R. Snellings, Mod. Phys. Lett. A 35, 2050324 (2020)

Directed flow in pA collisions: pions

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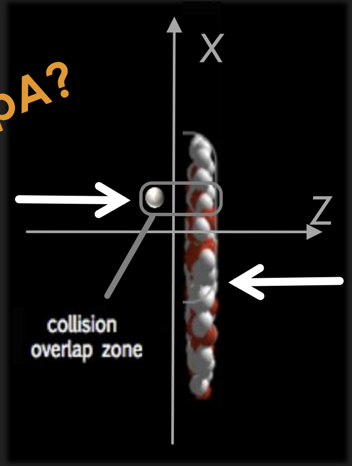
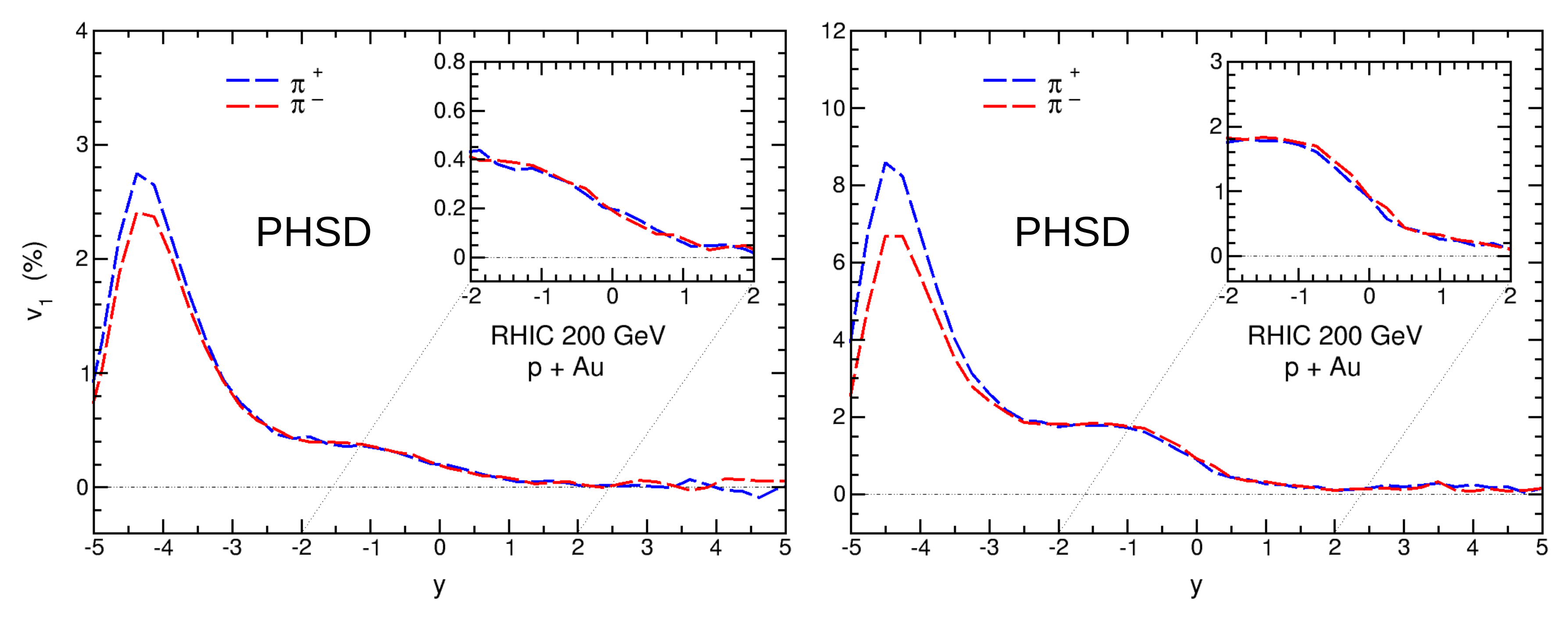


b = 2 fm *p+Au @ RHIC 200 GeV* *b = 6 fm*



rapidity dependence of the directed flow of pions

WITHOUT EMF

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

Directed flow in pA collisions: pions

The directed flow v_1 is a collective sidewards particle deflection

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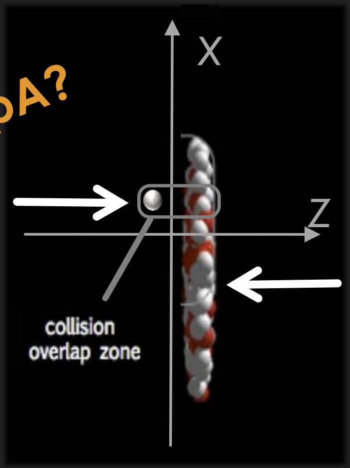

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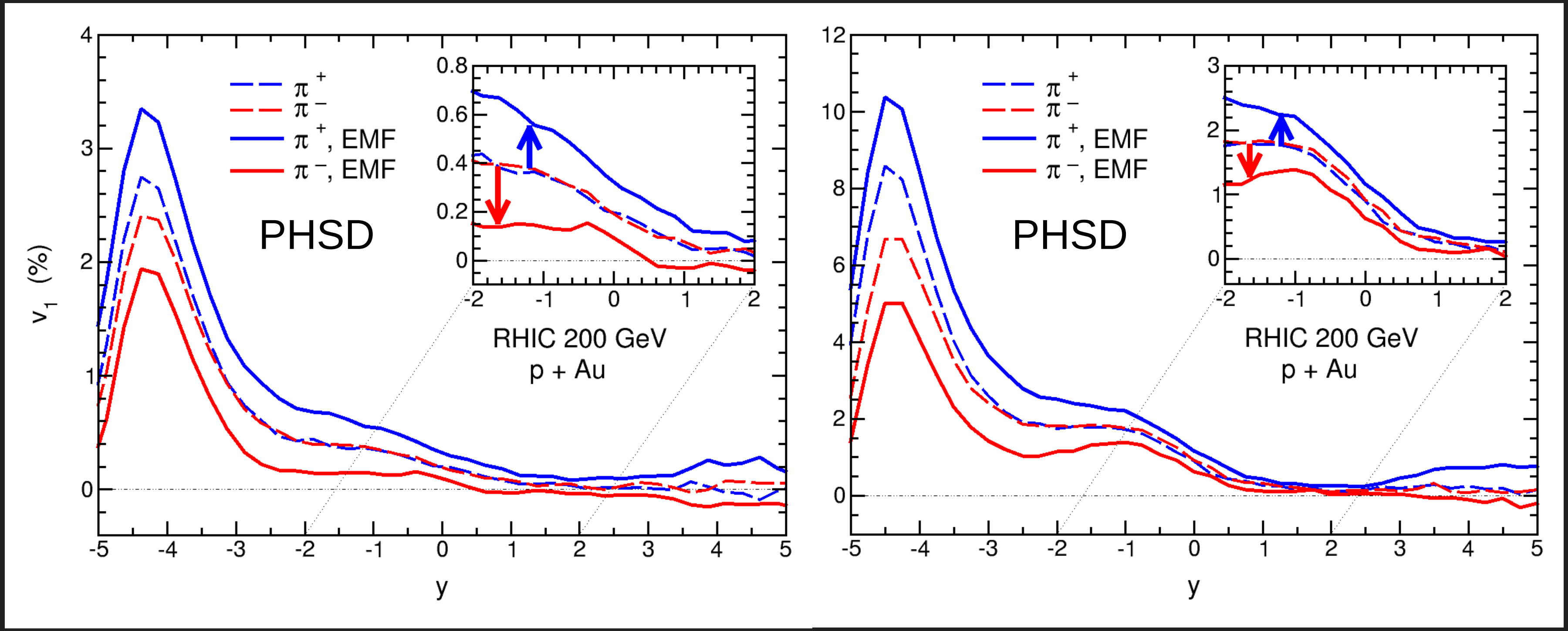


rapidity dependence of the directed flow of pions

WITH EMF

splitting of π^+ and π^- **induced by the electromagnetic field**

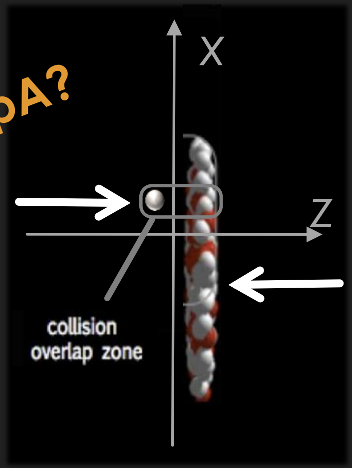
L. Oliva, P. Moreau, V. Voronyuk and E. Bratkovskaya, Phys. Rev. C 101, 014917 (2020)

Directed flow in pA collisions: kaons

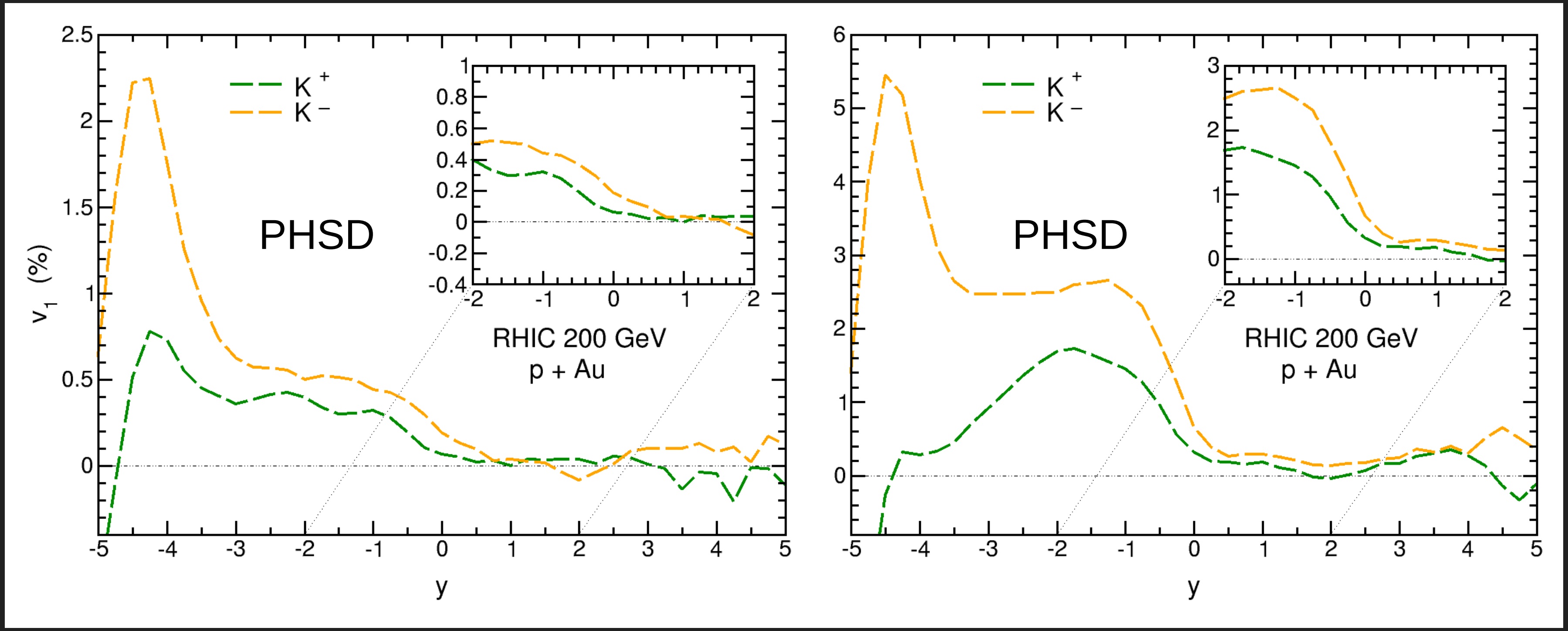
The directed flow v_1 is a collective sidewards particle deflection

$$v_1(y) = \langle \cos[\varphi(y)] \rangle$$

Sources of v_1 in heavy-ion collisions
- initial-state fluctuations
- orbital angular momentum
- baryon transport to midrapidity
- electromagnetic fields (EMF)



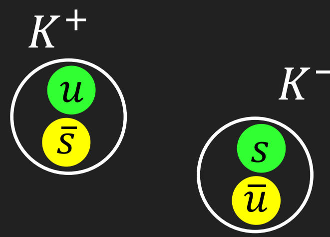
b = 2 fm *p+Au @ RHIC 200 GeV* *b = 6 fm*



rapidity dependence of the directed flow of kaons

WITHOUT EMF

splitting of K^+ and K^- **induced by baryon transport to midrapidity**



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

Directed flow in pA collisions: kaons

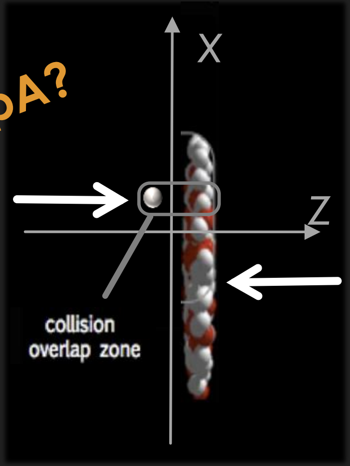
The directed flow v_1 is a collective sidewards particle deflection

$$v_1(y) = \langle \cos[\varphi(y)] \rangle$$

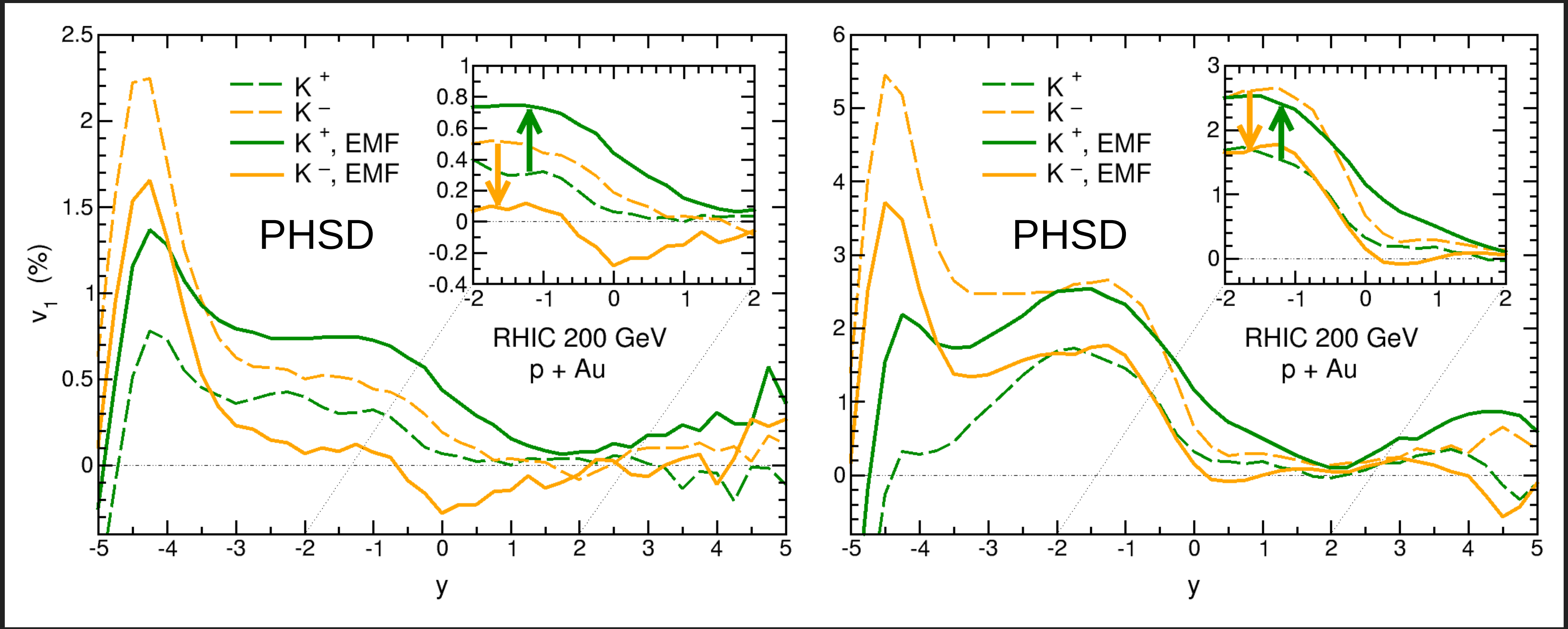
Sources of v_1 in heavy-ion collisions

- initial-state fluctuations
- orbital angular momentum
- baryon transport to midrapidity
- electromagnetic fields (EMF)

in pA?



b = 2 fm *p+Au @ RHIC 200 GeV* *b = 6 fm*



rapidity dependence of the directed flow of kaons

WITH EMF

splitting of K^+ and K^- **induced by the electromagnetic fields dominates**

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

Directed flow in pA collisions: high multiplicity events

The directed flow v_1 is a collective sidewards particle deflection

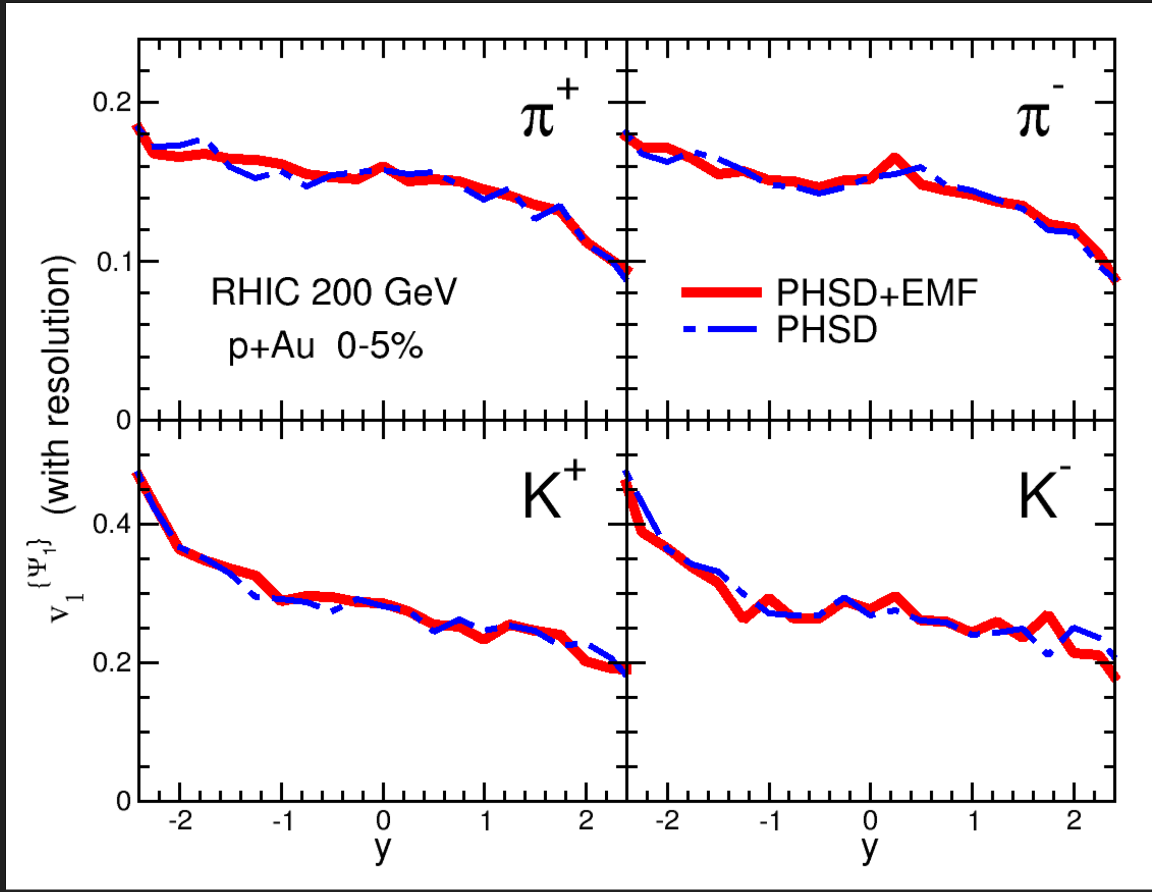
$$v_1(y) = \frac{\langle \cos[\varphi(y) - \Psi_1] \rangle}{Res(\Psi_1)}$$

event-plane angle

event-plane angle resolution

rapidity dependence of the directed flow of pions and kaons

p+Au @ RHIC 200 GeV – 0-5% central



5% central collisions

no visible changes with and without EMF

How to EXPERIMENTALLY observe the SPLITTING IN THE DIRECTED FLOW of positively and negatively ch. particles IN PROTON-NUCLEUS COLLISIONS?

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

Conclusions

Study of **nonequilibrium effects** and **transverse spherocity** in *p+Pb* collisions at LHC energy by comparing the microscopic **transport** approach **PHSD** and the 2+1D viscous **hydro** model **VISHNew**

- hydrodynamics dissolves more efficiently than PHSD the initial hot spots; in PHSD the nonequilibrium dynamics preserves the medium irregularities during the whole evolution
- The initially very large bulk viscous pressure Π experiences a power-law decay in PHSD remaining nonzero during the QGP lifetime; in hydro it approaches quickly zero
- In *pA* collisions both *e* and Π keep also in hydro a high degree of inhomogeneity due to the smaller space-time size of the produced medium compared to heavy-ion reactions

- Transverse spherocity is an event-shape observable that separates jetty and isotropic topologies
- The PHSD dynamics favors more isotropic event configurations compared to hydro

Study of **collective flow coefficients** with **PHSD**

- ❑ Preliminary 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 $v_2 \simeq 0$.
- ❑ The splitting in the directed flow v_1 of positively and negatively charged hadrons is connected to the baryon transport to midrapidity and electromagnetic fields. How to observe it in *pA* collisions?

Thank you for your attention

lucia.oliva@dfa.unict.it

Coarse-graining the PHSD medium

Study the nonequilibrium dynamics in the hot medium evolution of the transport and hydrodynamic approaches

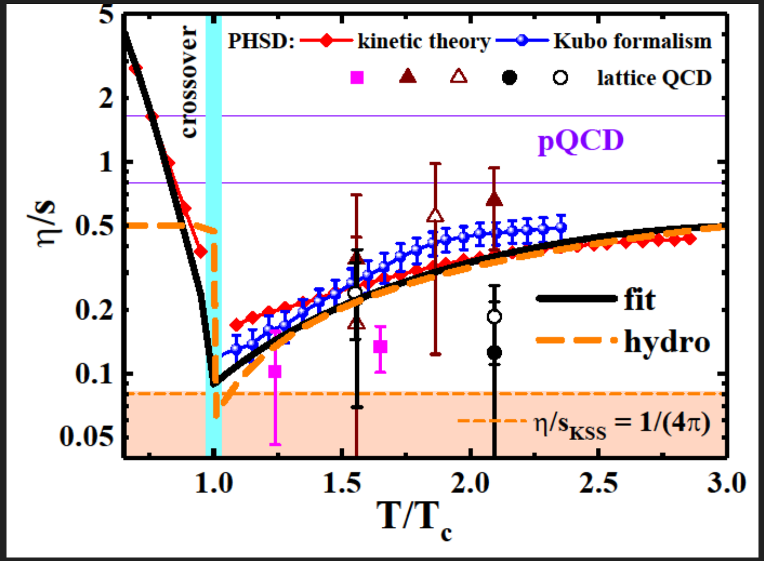
→ start with the same initial conditions in order to reduce the impact of the early pre-equilibrium stage

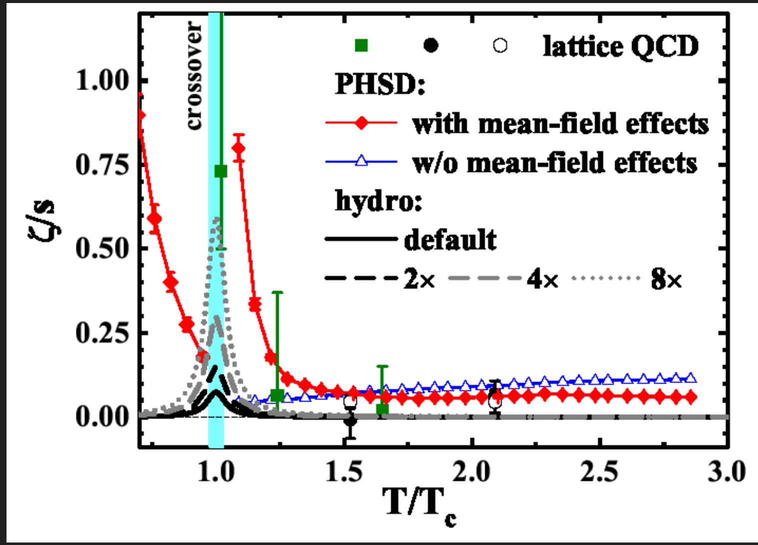
→ characterize the medium with similar equation of state and shear viscosity over entropy density ratio

Y. Xu et al. (PHSD-Duke groups), Phys. Rev. C 96, 024902 (2017)
T. Song et al. (PHSD-Duke-Nantes groups), Phys. Rev. C 101, 044903 (2020)
L. Oliva et al. (PHSD-Duke groups), 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

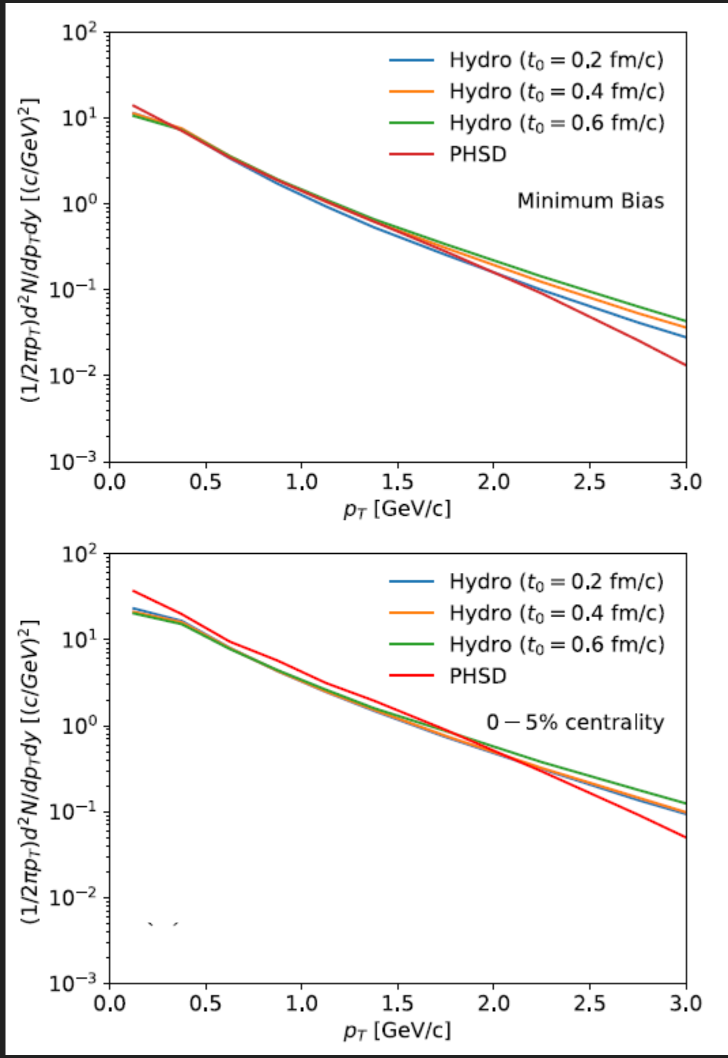
η/s(T) : the hydro code uses a parametrization obtained from PHSD

ζ/s(T) : much smaller in the hydro code than in PHSD simulations

Y. Xu, P. Moreau, T. Song, M. Nahrgang, S.A. Bass and E. Bratkovskaya, Phys. Rev. C 96, 024902 (2017)

Multiplicity: PHSD vs hydrodynamics

p+Pb @ LHC 5.02 TeV

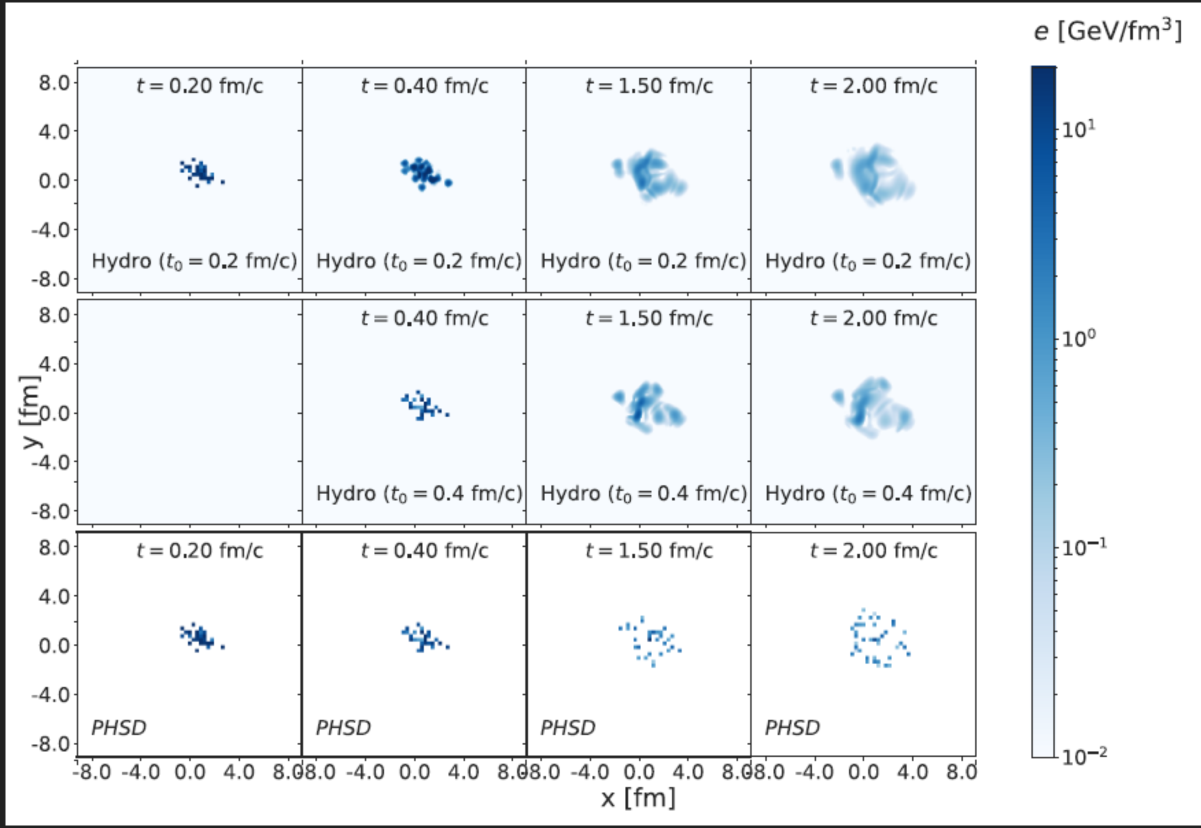


charged particle p_T-spectrum

transverse momentum spectra of charged particles at midrapidity

- ✓ PHSD and hydro agree fairly well for $0.5 < p_T < 2$ GeV/c
- ✓ mild dependence of hydro results on the initialization time: connection of more pronounced hot spots to harder spectra

B. Schenke, P. Tribedy and R. Venugolapan, Phys. Rev. Lett. 108, 252301 (2012)

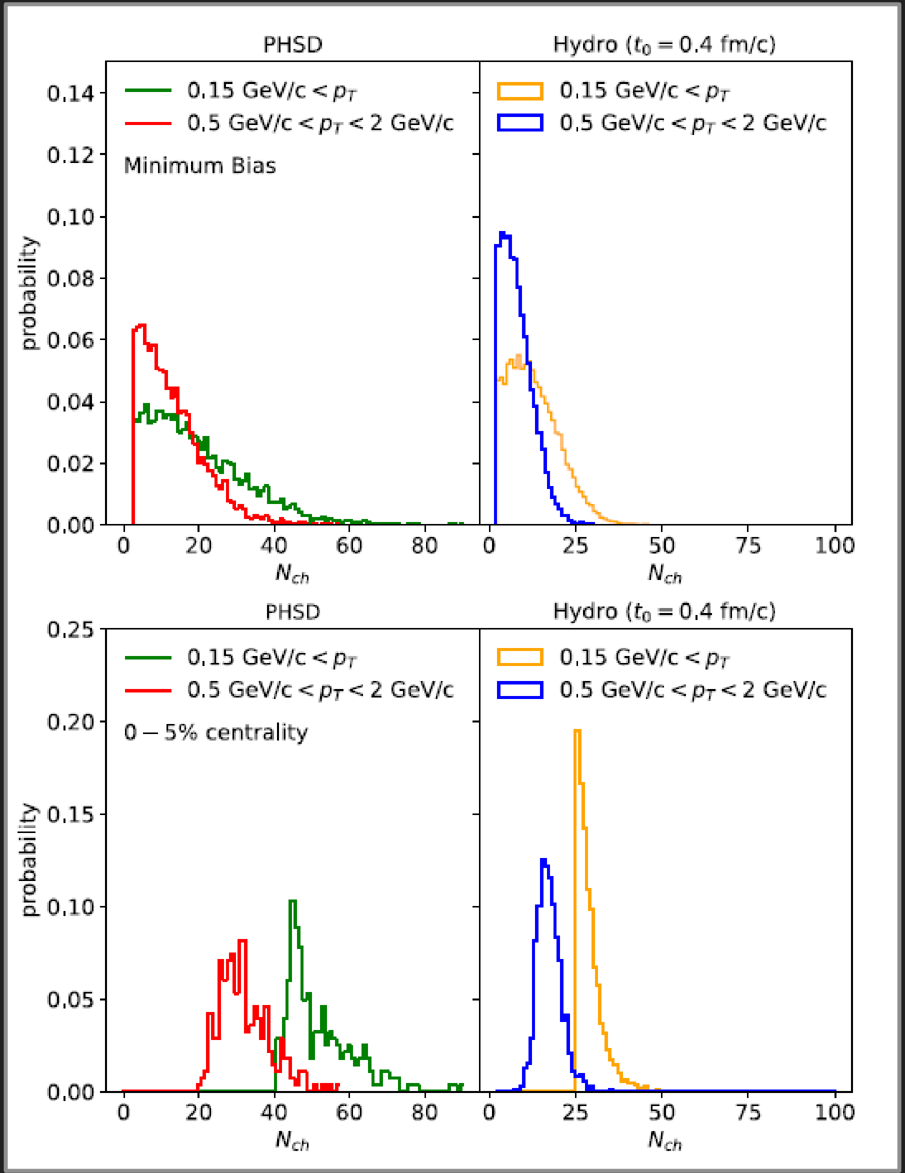


L. Oliva, W. Fan, P. Moreau, S.A. Bass and E. Bratkovskaya, Phys. Rev. C 106, 044910 (2022)

energy density

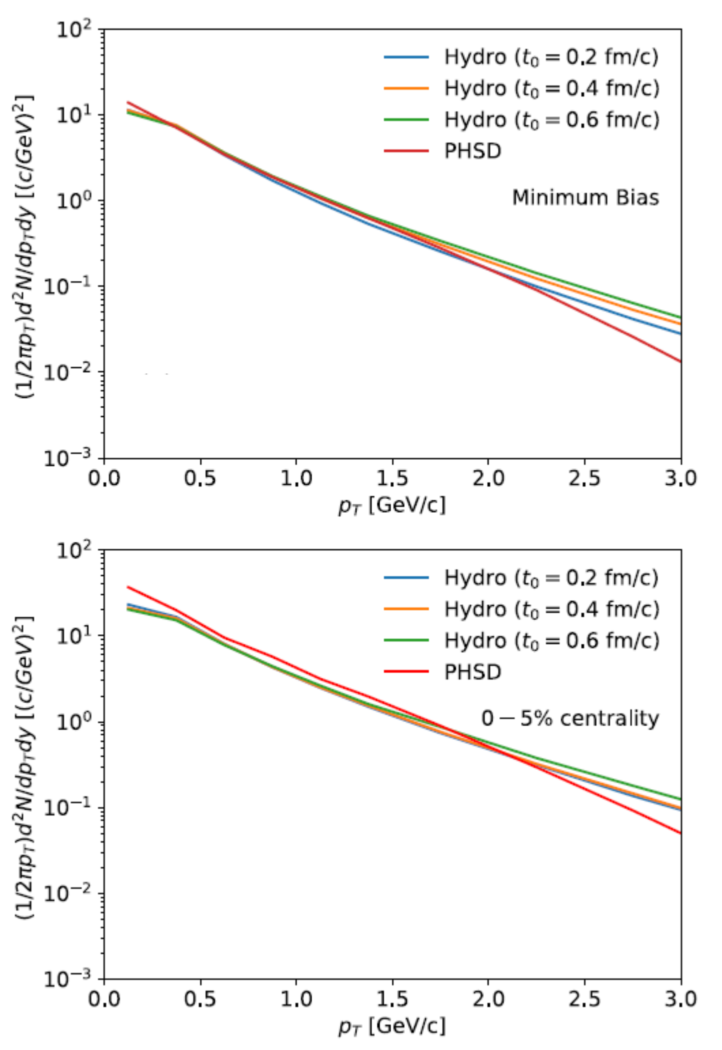
Multiplicity: PHSD vs hydrodynamics

p+Pb @ LHC 5.02 TeV



charged particle distribution

in both PHSD and hydro **event distribution in multiplicity CHANGES applying different p_T cuts**

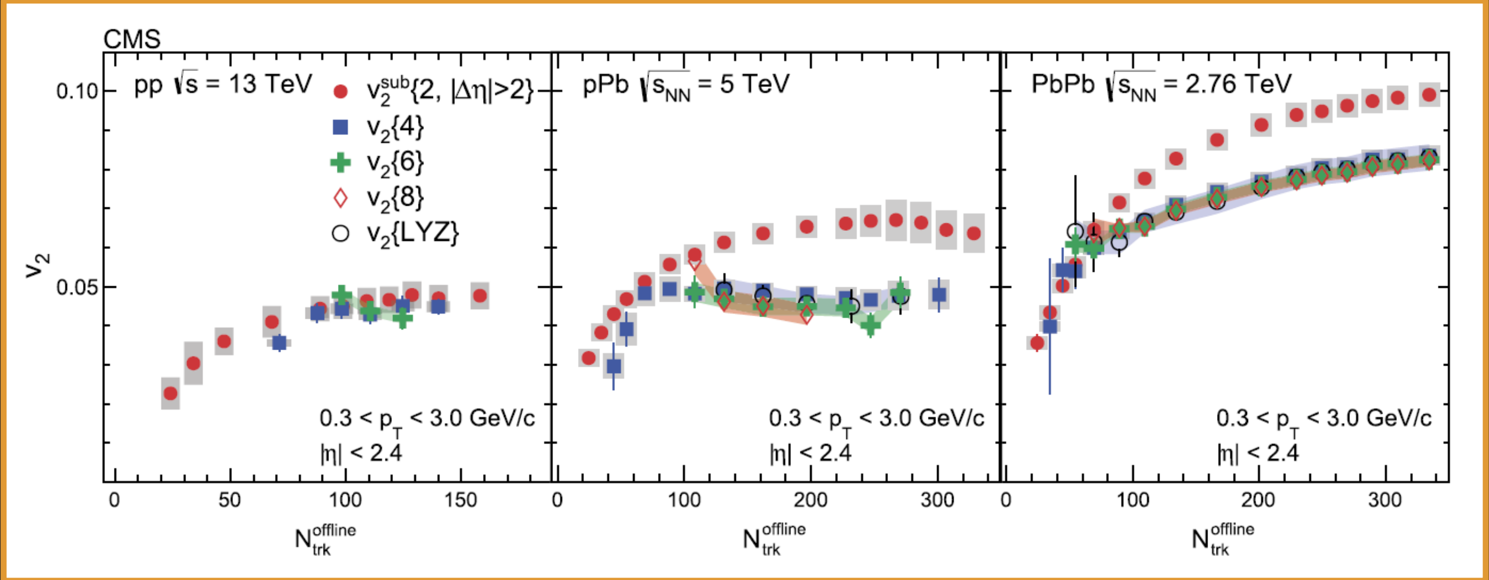


charged particle p_T-spectrum

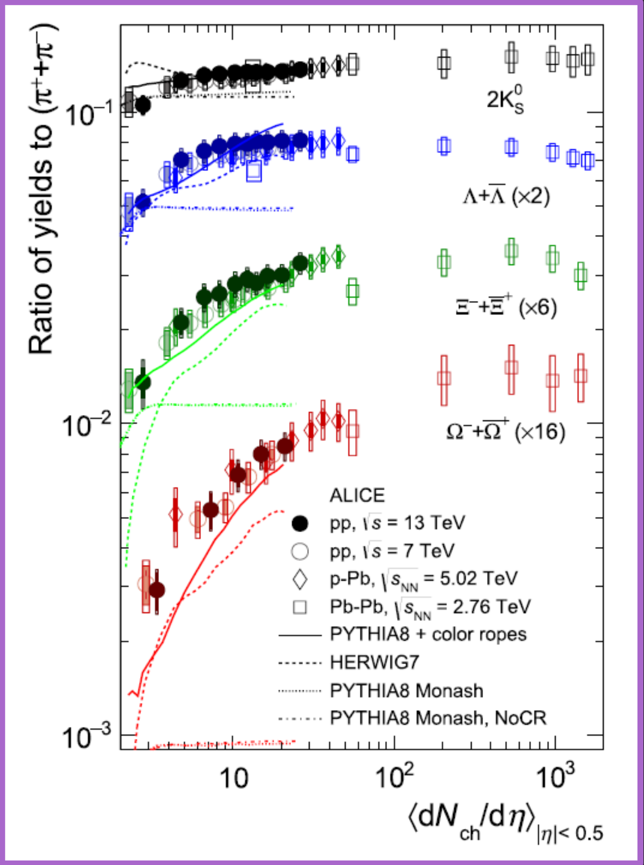
L. Oliva, W. Fan, P. Moreau, S.A. Bass and E. Bratkovskaya, Phys. Rev. C 106, 044910 (2022)

QGP signals in small systems

Experimental evidence of collective-like behaviour
in high-multiplicity *pp* and *pA* collisions
long-range correlations, elliptic flow, strangeness enhancement



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



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

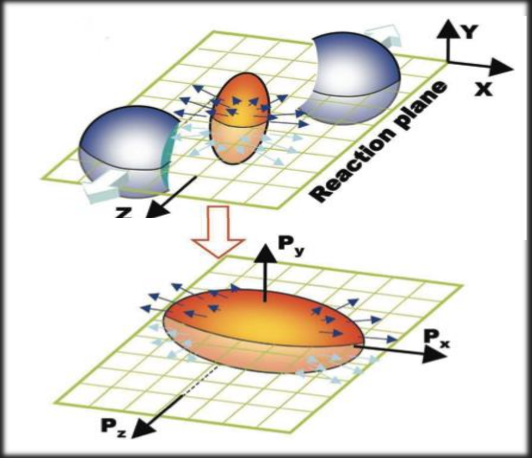
Theoretically explainable with the formation of QGP

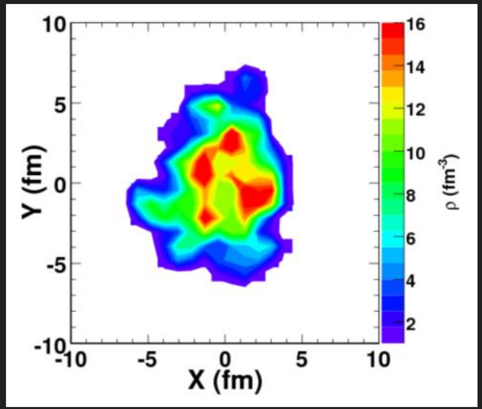
J. Nagle and W. Zajc, Ann. Rev. Nucl. Part. Sci. 68, 211 (2018)

difficulty to well identify QGP signals in small systems
➞ attempts to study observables through novel **multi-differential methods**
➞ **event-shape engineering**

Anisotropic radial flow v_n

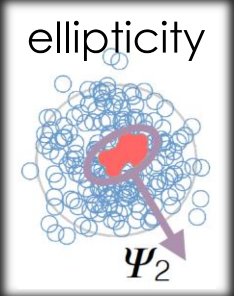
Quark-Gluon Plasma: hydrodynamical behavior with very low specific viscosity η/s and formation of collective flows

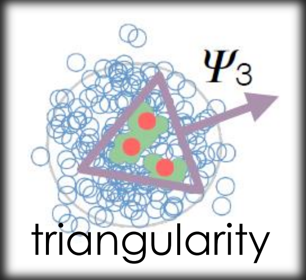




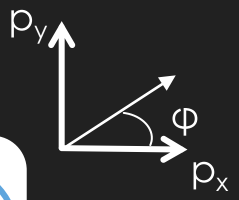
S. Plumari *et al.*,
Phys. Rev. C 92 (2015) 054902

heavy-ion collisions:
not a simple **almond shape** but a **"lumpy" profile** due to fluctuations of nucleon position in the overlap region





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



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

flow coefficients

event-plane angle

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

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

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

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

event-plane angle resolution
(three-subevent method)

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

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

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

INITIAL-STATE FLUCTUATIONS AND FINITE EVENT MULTIPLICITY

Generalized Transport Equations (GTE)

After the first order gradient expansion of the Wigner transformed Kadanoff-Baym equations and separation into the real and imaginary parts one obtain GTE which describes the dynamics of broad strongly interacting quantum states

drift term — Vlasov term — backflow term — collision term = ‚gain‘ - ‚loss‘ term

$$\diamond\{P^2 - M_0^2 - Re\Sigma^{ret}_{XP}\}\{S^<_{XP}\} - \diamond\{\Sigma^<_{XP}\}\{ReS^{ret}_{XP}\} = \frac{i}{2}\left[\Sigma^>_{XP}S^<_{XP} - \Sigma^<_{XP}S^>_{XP}\right]$$

$$\diamond\{F_1\}\{F_2\} := \frac{1}{2}\left(\frac{\partial F_1}{\partial X_\mu}\frac{\partial F_2}{\partial P^\mu} - \frac{\partial F_1}{\partial P_\mu}\frac{\partial F_2}{\partial X^\mu}\right)$$

off-shell behavior

GTE govern the propagation of the Green functions

$i\,S^<_{XP} = A_{XP}\,N_{XP}$

N_{XP} → number of particles

A_{XP} → particle spectral function

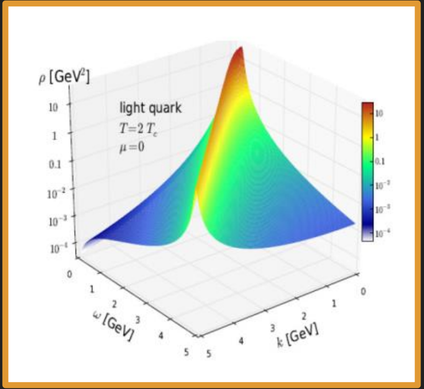
Dressed propagators (S_q, Δ_g)

$$S = (P^2 - \Sigma^2)^{-1}$$

with complex self-energies (Σ_q, Π_g):

$$\Sigma = m^2 - i2\gamma\omega$$

- the real part describes a dynamically generated mass (m_q, m_g)
- the imaginary part describes the interaction width (γ_q, γ_g)



Cassing and Juchem, NPA 665 (2000) 377; 672 (2000) 417; 677 (2000) 445

EMF in tranport approaches

In a kinetic framework the transport equations should be coupled to the Maxwell equations for describing the EMF produced in HICs and their effect on final observables

$$\left\{\frac{\partial}{\partial t}+\left(\frac{\mathbf{p}}{p_0}+\nabla_{\mathbf{p}}U\right)\nabla_{\mathbf{r}}+(-\nabla_{\mathbf{r}}U+e\mathbf{E}+e\mathbf{v}\times\mathbf{B})\nabla_{\mathbf{p}}\right\}f=\mathcal{C}[f]$$

TRANSPORT EQUATIONS

Lorentz force

$$\nabla\cdot\mathbf{B}=0 \qquad \nabla\times\mathbf{E}=-\frac{\partial\mathbf{B}}{\partial t} \qquad \nabla\cdot\mathbf{E}=4\pi\rho \qquad \nabla\times\mathbf{B}=\frac{\partial\mathbf{E}}{\partial t}+\frac{4\pi}{c}\mathbf{j}$$

MAXWELL EQUATIONS

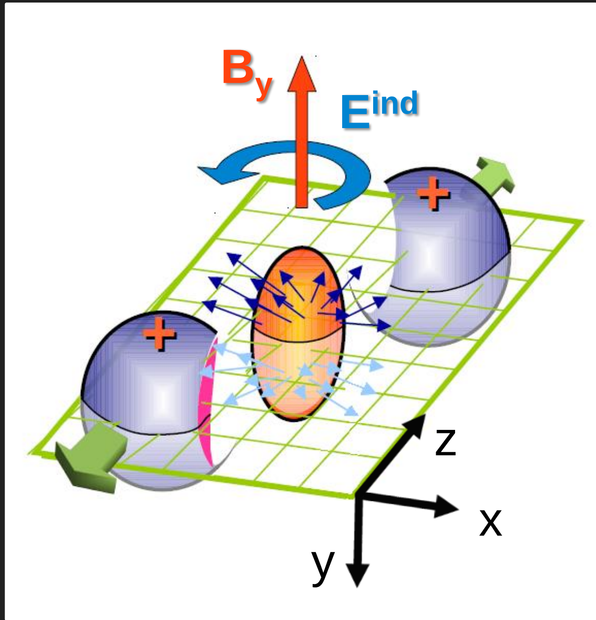
charge distribution

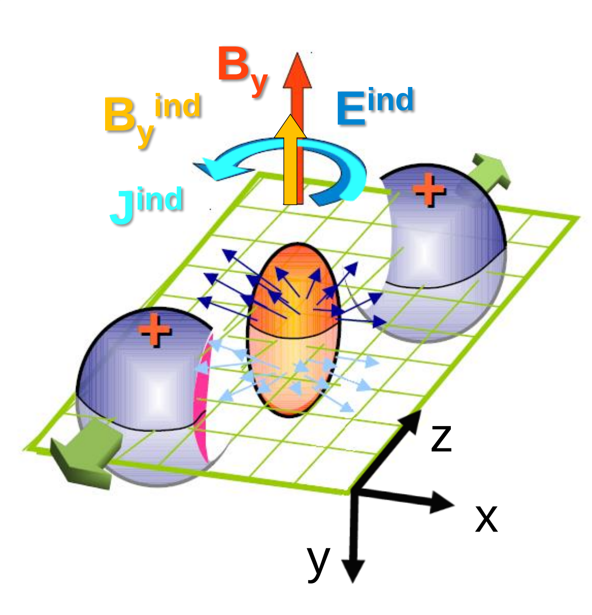
electric current

For a complete description

- nontrivial electromagnetic response of the QGP (electromagnetic conductivity, chiral conductivity, …)
- consistent solution of evolution equations for the many-particle system and the EMF

Electromagnetic fields in HICs





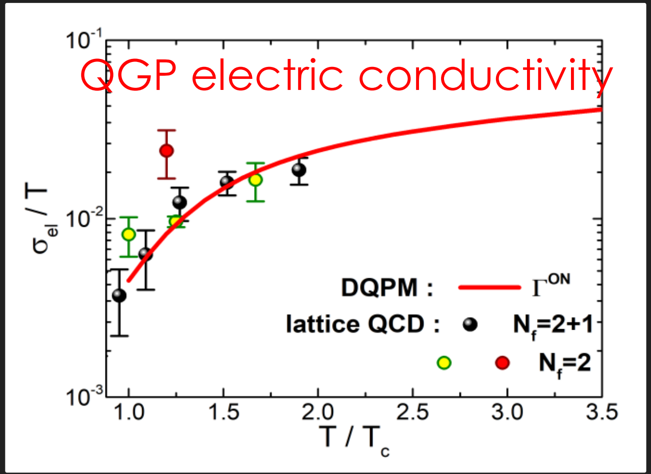
Huge **magnetic field** in the overlapping area of the collision

- in ultrarelatvistic HICs **$eB \approx$ 5-50 m_π^2 ~ 10^{18}-10^{19} G**
- dominated by the y component
- mainly produced by spectators protons
- intense electric field generated by Faraday induction

Theoretical calculations indicates that QGP is a good electric conductor

Ohm's law

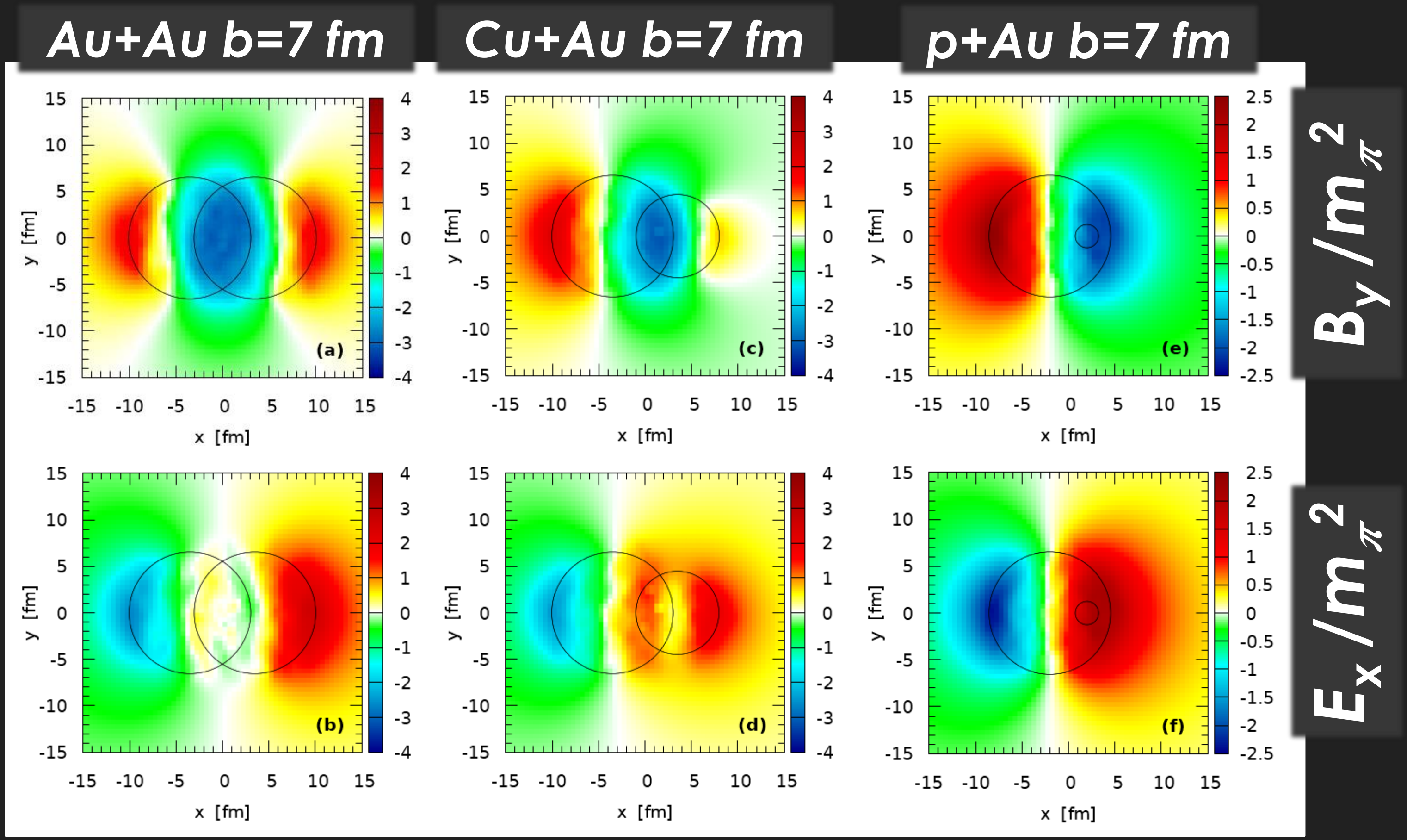
$$J = \sigma_{el} E$$



Soloveva, Moreau and Bratkovskaya, Phys. Rev. C 101, 045203 (2020)

Charged currents are induced in the QGP by the Faraday electric field that in turn generates a magnetic field pointing towards the initial one

EMF from large to small systems



initial transvese profiles at RHIC 200 GeV

intense electric fields directed from the heavy nuclei to light one in the overlap region of asymmetric colliding systems due to the different number of protons in the two nuclei

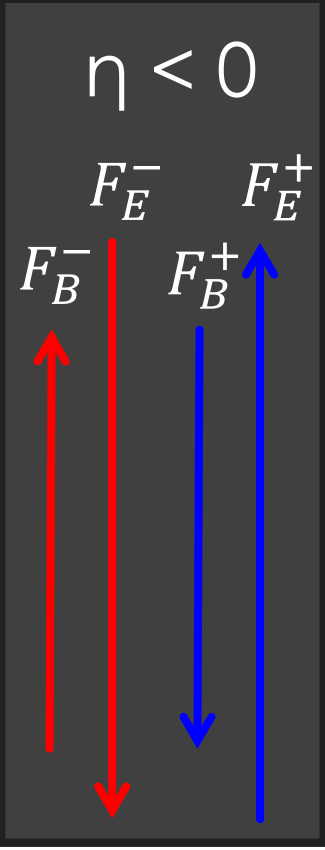
Voronyuk, Toneev, Voloshin and Cassing, Phys. Rev. C 90, 064903 (2014)
Oliva, Moreau, Voronyuk and Bratkovskaya, Phys. Rev. C 101, 014917 (2020)

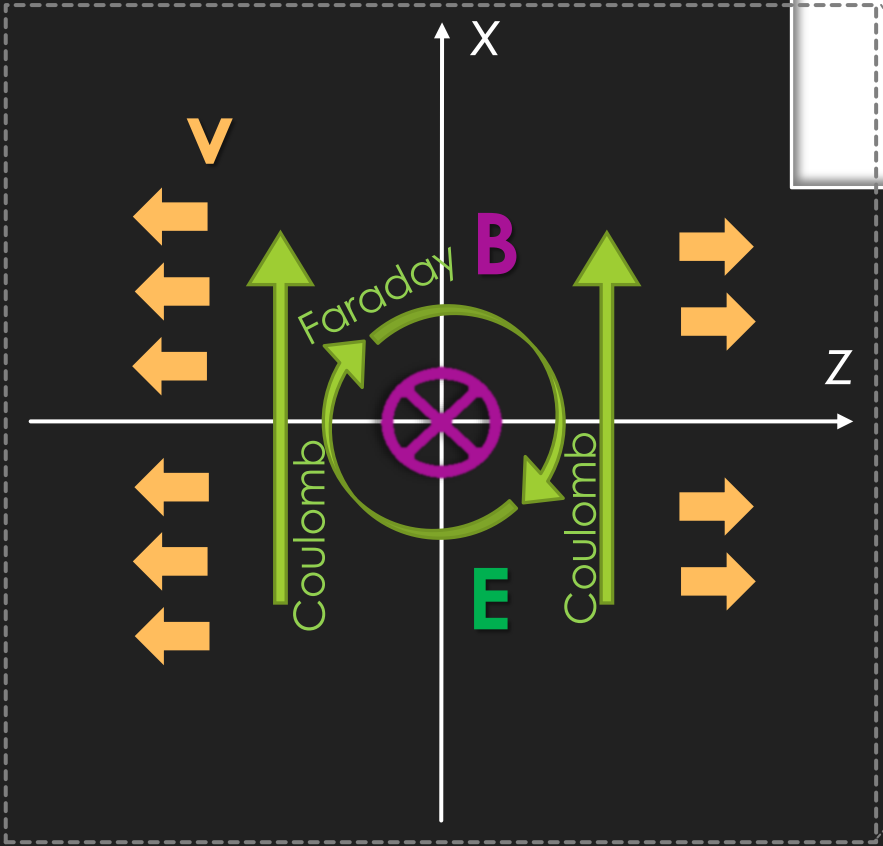
Directed flow and electromagnetic fields

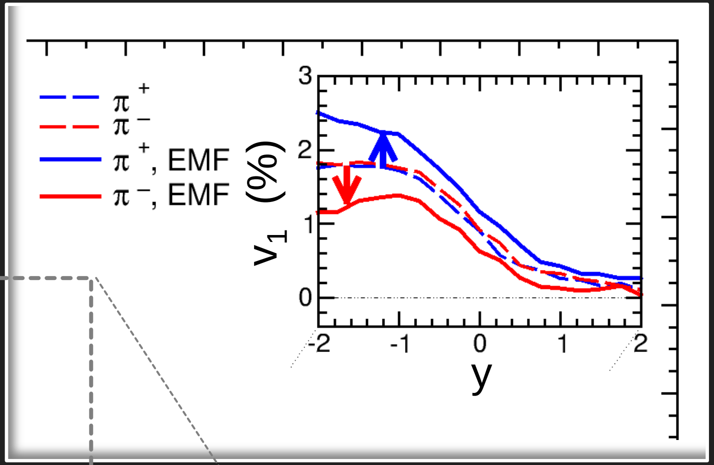
rapidity dependence of the DIRECTED FLOW

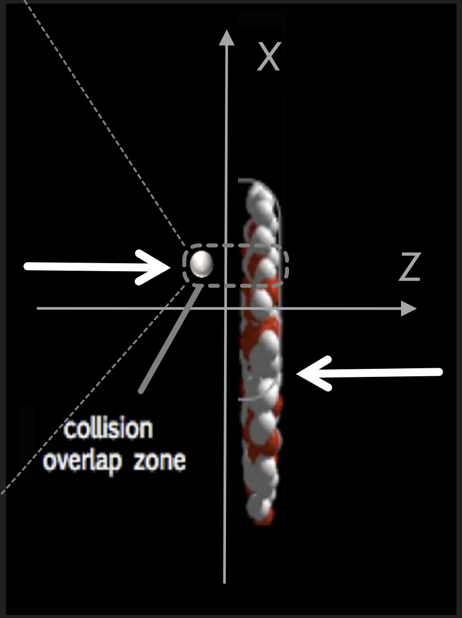
collective sidewards deflection of particles

$$v_1 = \langle \cos\varphi \rangle = \langle p_x / p_T \rangle$$









$$\boldsymbol{F}_{\boldsymbol{Lorentz}} = q(\boldsymbol{E} + \boldsymbol{v} \times \boldsymbol{B})$$

Directed flow and baryon transport to midrapidity

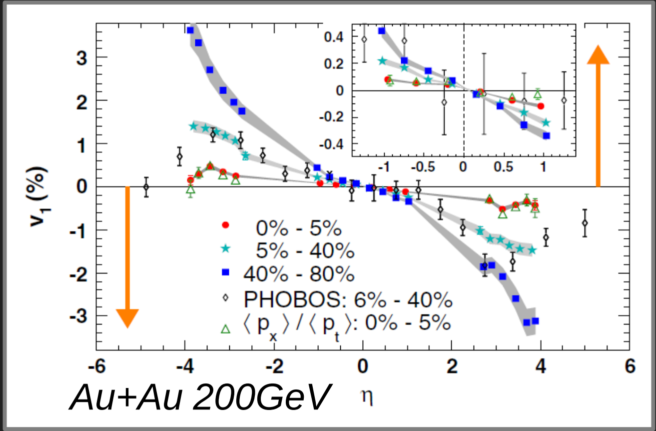
The directed flow v_1 is a collective sidewards particle deflection

$$v_1(y) = \langle \cos[\varphi(y)] \rangle$$

different v_1 in simulations without EMF

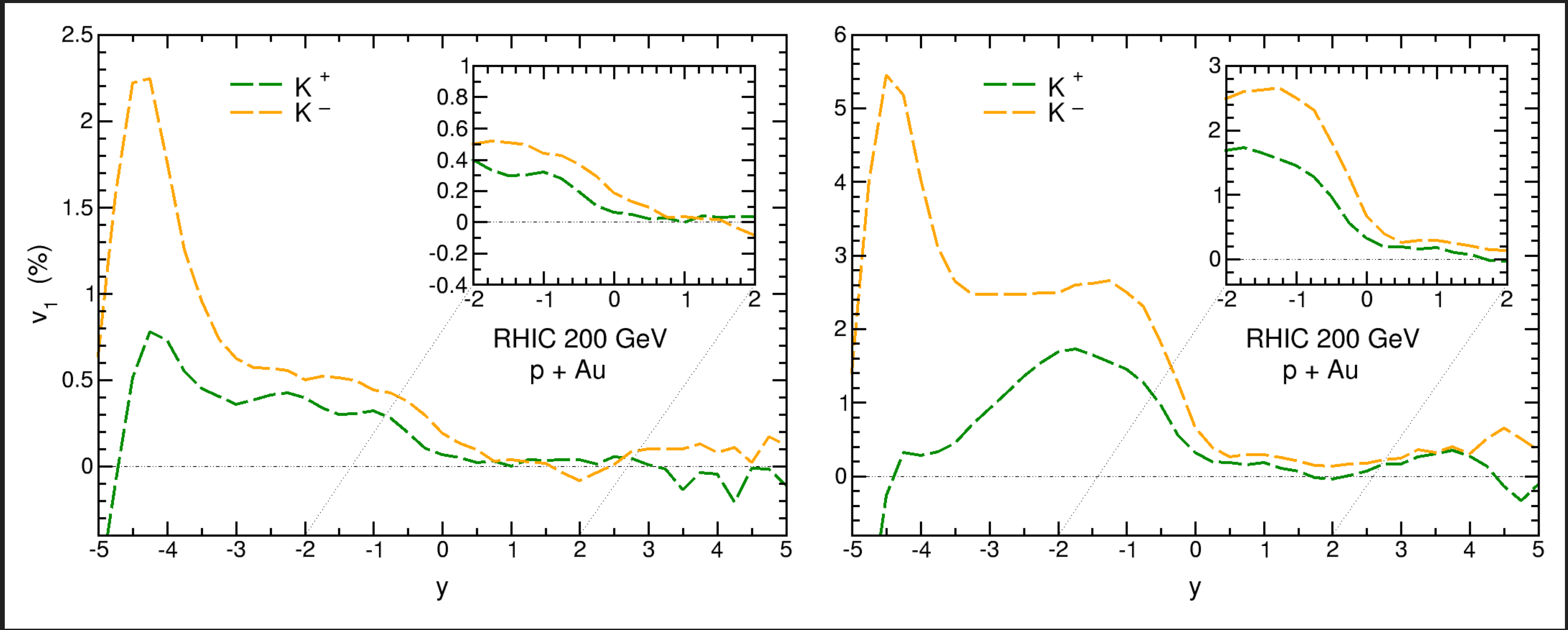
more contributions to K^+ $(\bar{s}u)$ w.r.t. K^- $(s\bar{u})$ from quarks of the initial colliding nuclei

STAR Coll., PRL 120 (2018) 062301



STAR Coll., PRL 101 (2008) 252301

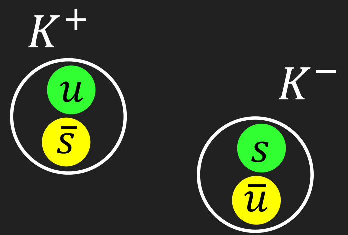
b = 2 fm *p+Au @ RHIC 200 GeV* *b = 6 fm*



rapidity dependence of the directed flow of kaons

WITHOUT EMF

splitting of K+ and K−
induced by baryon transport to midrapidity



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

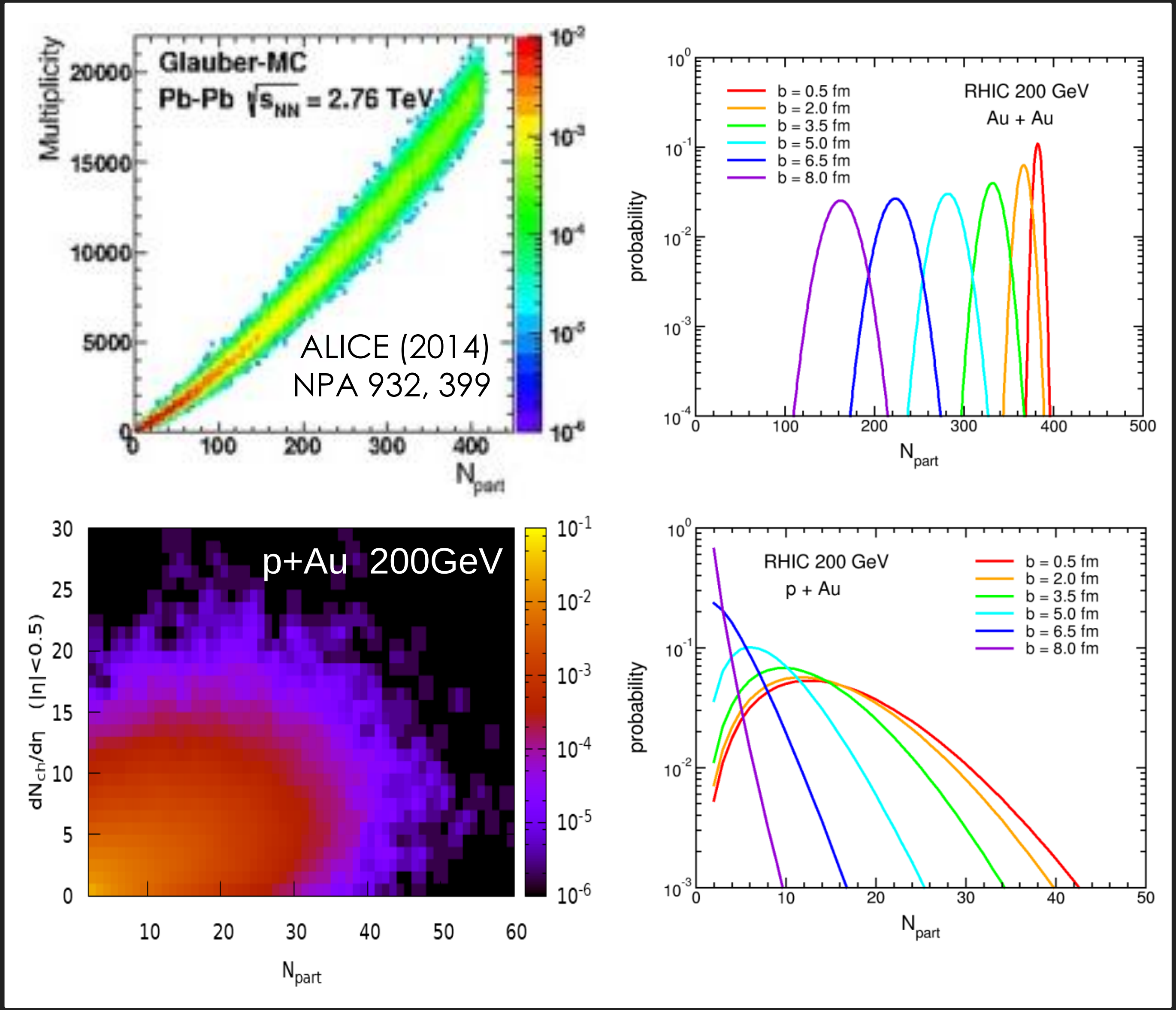
Centrality determination : A+A vs p+A

A+A

centrality characterizes the amount of overlap in the interaction area

p+A

multiplicity fluctuation mixes events from different impact parameters



LO, Moreau, Voronyuk and Bratkovskaya, PRC 101 (2020) 014917