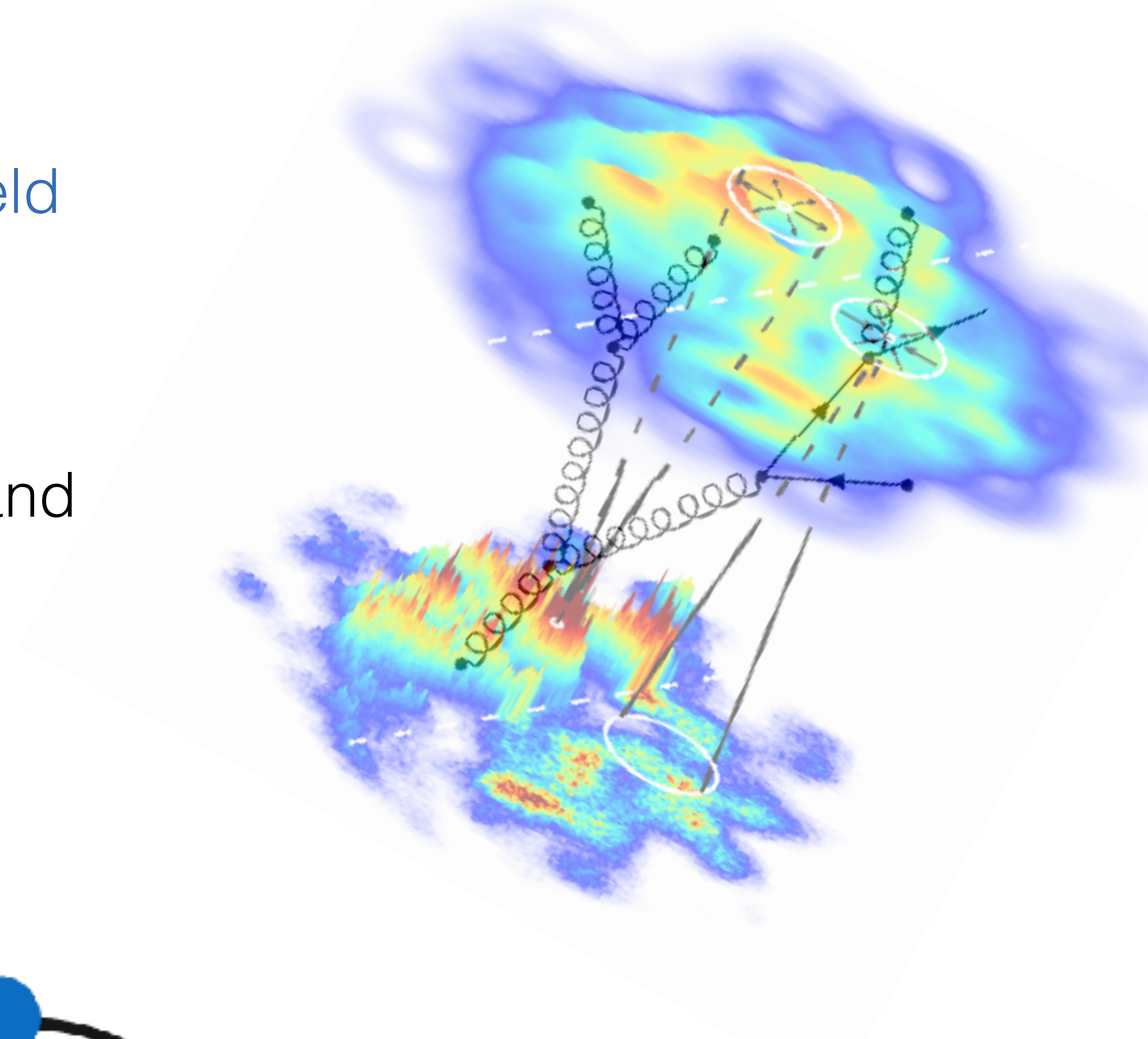
Initial state and non-equilibrium dynamics in small and large systems

Sören Schlichting | Universität Bielefeld



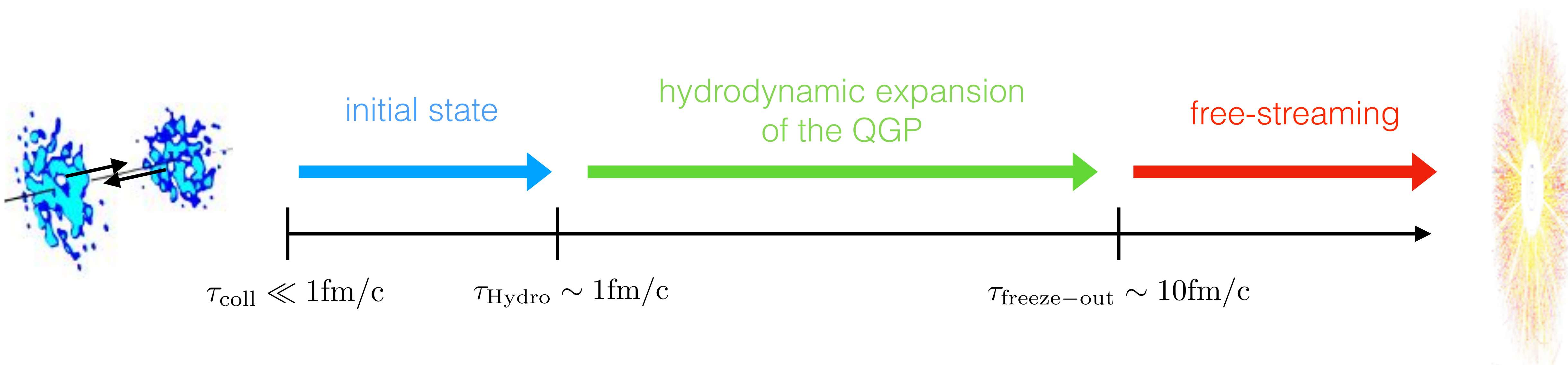
Workshop on “Opportunities of OO and pO collisions at the LHC”

CERN Feb 2021

Heavy-Ion Perspective

Dynamical description of Heavy-Ion collisions from underlying theory of QCD remains an outstanding challenge

Standard model of nucleus-nucleus (A+A) collisions based on clear separation of time scales in the reaction dynamics

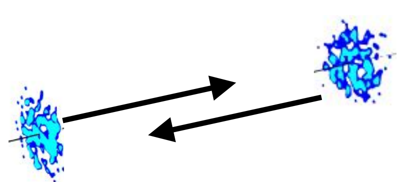


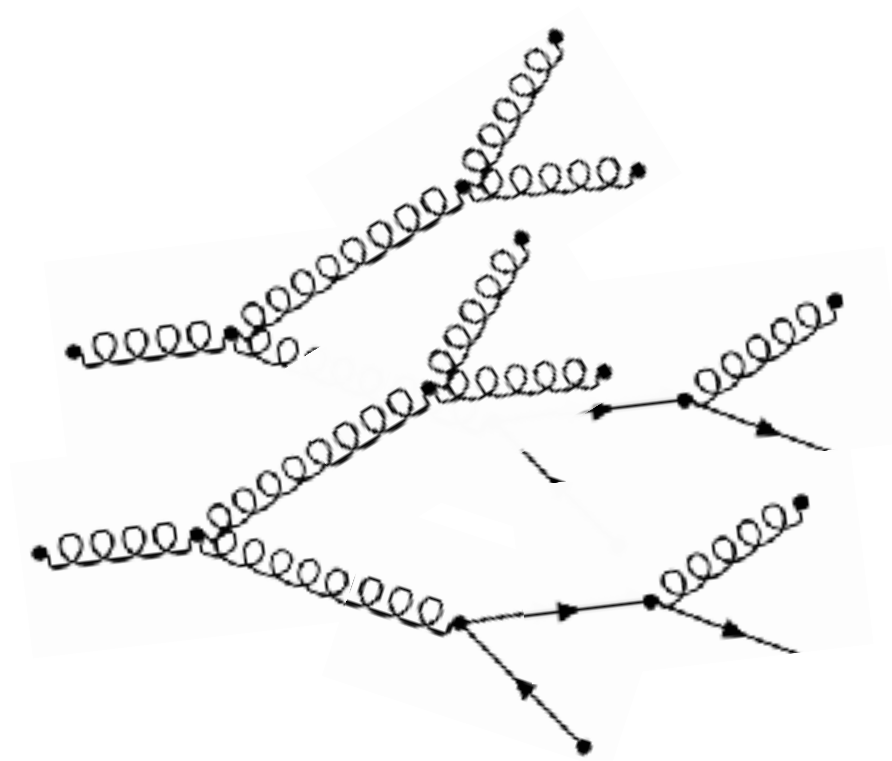
Space-time dynamics (bulk) dominated by hydrodynamics expansion

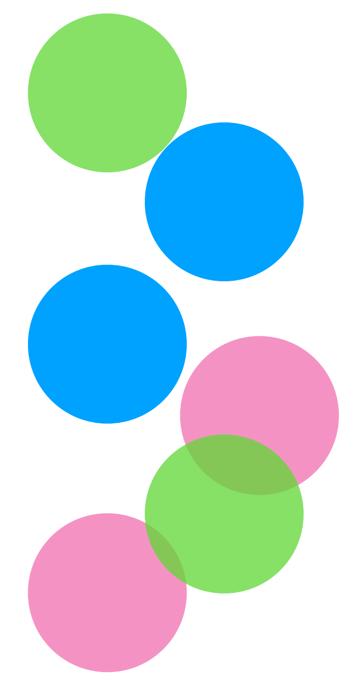
Description requires knowledge of **macroscopic properties** of initial state (energy momentum tensor $T^{\mu\nu}$, conserved currents J^{μ}) **in coordinate space** and thermodynamic/transport properties of QGP

High-Energy Perspective

Description of p+p collisions in HEP Event generators based on perturbative QCD description for hard processes (+ modelling of soft processes)





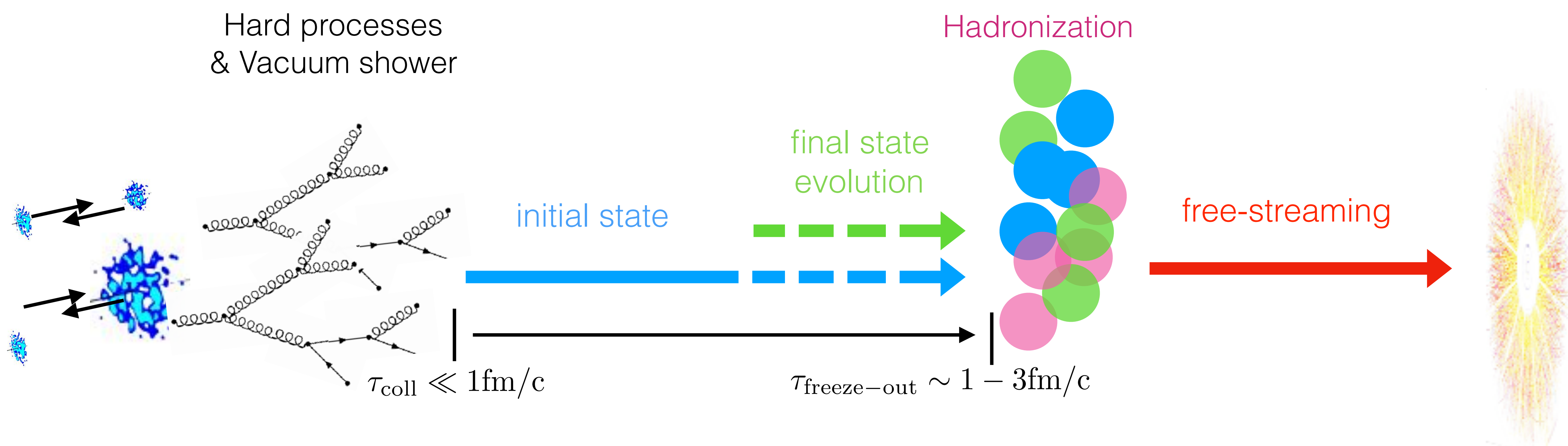


Hard processes Vacuum Shower Hadronization

Description based on **microscopic degrees of freedom in momentum space**

Small systems

Description of the onset of collective behavior in small systems at RHIC (p/d/He3+A) and LHC (p+p/A), requires a merging of the two orthogonal pictures

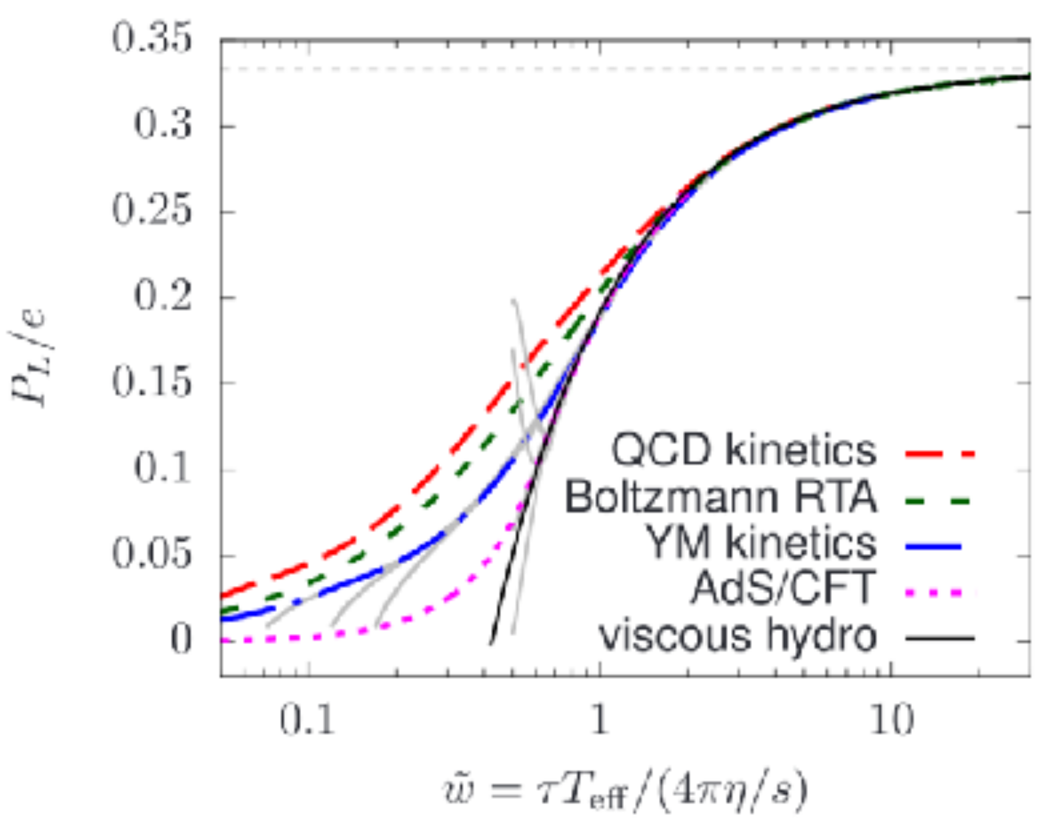


Shorter life-time of the system (~R) increases sensitivity to microscopic properties of initial state and early-time dynamics

Description may require a more detailed knowledge of **microscopic properties in momentum space and non-equilibrium dynamics** of initial state

Early time dynamics in large systems

Significant progress in understanding the onset of hydrodynamic behavior in Heavy-Ion Collisions from studies of pre-equilibrium dynamics in QCD Kinetic Theory, AdS/CFT, …



Giacalone, Mazeliauskas, SS PRL 123 (2019) 26, 262301

Viscous hydrodynamic description of QGP becomes applicable

$$\tau_{\rm hydro} \approx \tau_R^{\rm eq}(\tau) \qquad \tau_R^{\rm eq}(\tau) = \frac{4\pi\eta/s}{T_{\rm eff}(\tau)}$$

$$\tau_{\rm hydro} \approx 1.1\,{\rm fm} \left(\frac{4\pi(\eta/s)}{2}\right)^{\frac{3}{2}} \left(\frac{\langle\tau s\rangle}{4.1\,{\rm GeV}^2}\right)^{-1/2}$$

for one-dimensional Bjorken expansion (neglecting transverse expansion)

Similar conclusions for chemical equilibration of QGP at early times

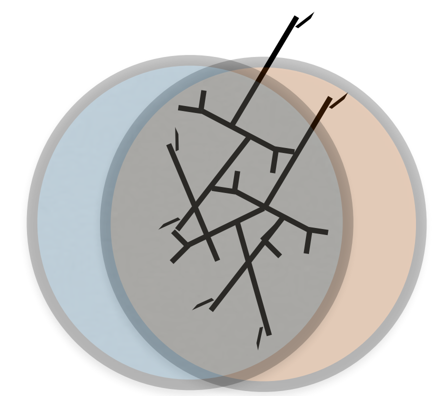
Kurkela, Mazeliauskas PRL 122 (2019) 142301; PRD 99 (2019) 5, 054018
Du, SS arXiv:2012.09079 ; arXiv:2012.09068

Hydrodynamic QGP in small systems?

Conditions for formation of near equilibrium QGP controlled by the ratio of hydrodynamization time (τ_{Hydro}) and system size (R)

If τ_{Hydro} >> R insufficient time to achieve equilibrated QGP

If τ_{Hydro} << R long lived hydrodynamic QGP phase



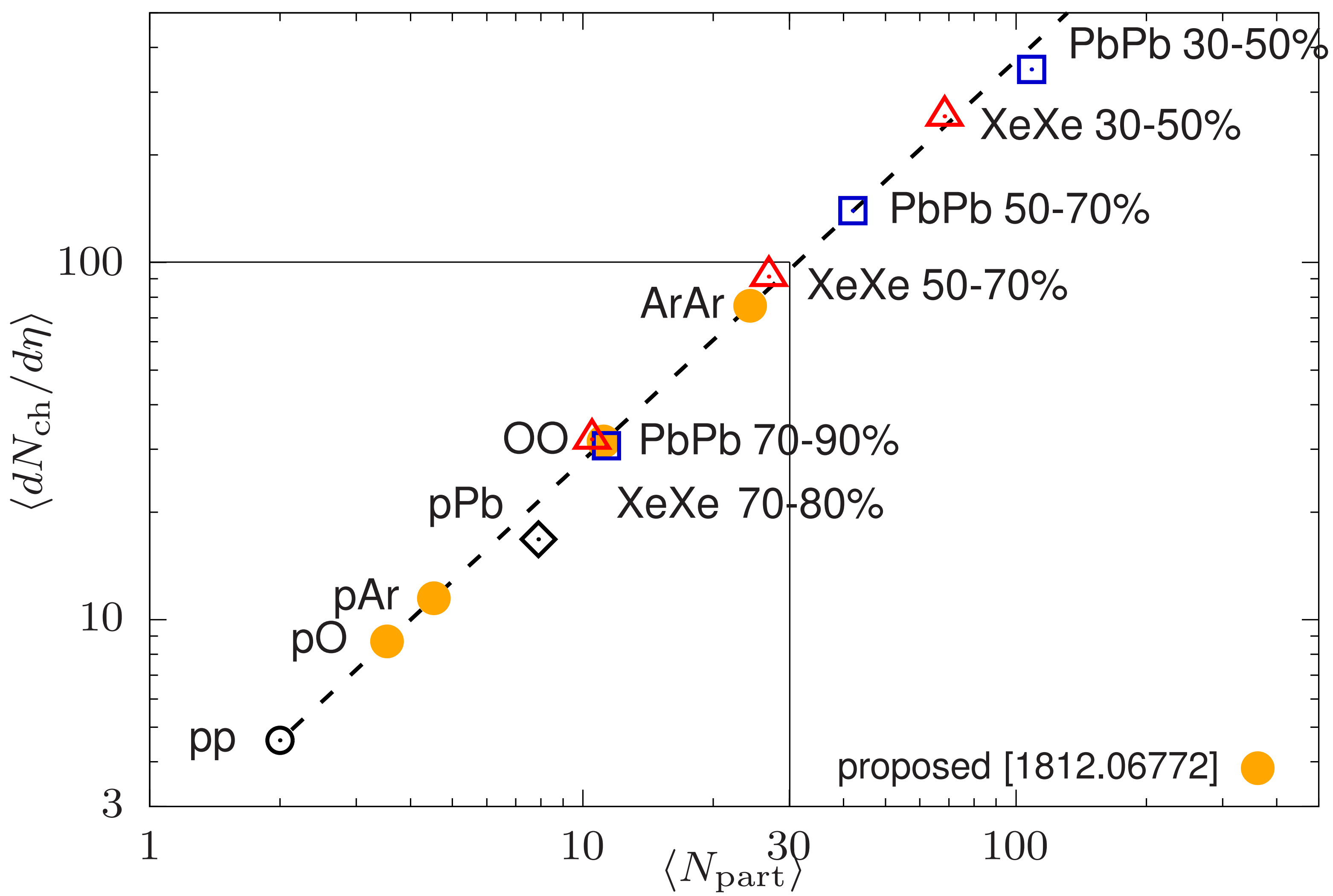
Based on estimates of the hydrodynamization time relevant multiplicity range can be estimated

$$\frac{\tau_{\mathrm{Hydro}}}{R} \simeq \left(\frac{4\pi(\eta/s)}{2}\right)^{\frac{3}{2}} \left(\frac{dN_{\mathrm{ch}}/d\eta}{63}\right)^{-\frac{1}{2}} \qquad \left.\frac{dN_{\mathrm{ch}}}{d\eta}\right|_{\mathrm{crit}} = 63 \left(\frac{\eta/s}{2/4\pi}\right)^{3} \left(\frac{\tau_{\mathrm{Hydro}}}{R}\right)^{-2}$$

where $\left.\frac{dN_{ch}}{d\eta}\right|_{min.\ bias}^{p+p\ 7TeV} \sim 6$, $\left.\frac{dN_{ch}}{d\eta}\right|_{min.\ bias}^{p+Pb\ 5.02TeV} \sim 16$, $\left.\frac{dN_{ch}}{d\eta}\right|_{0-5\%}^{Pb+Pb\ 2.76TeV} \sim 1600$

Kurkela, Mazeliauskas, Paquet, SS, Teaney PRL 122 (2019) no.12

Hydrodynamic QGP in small systems?

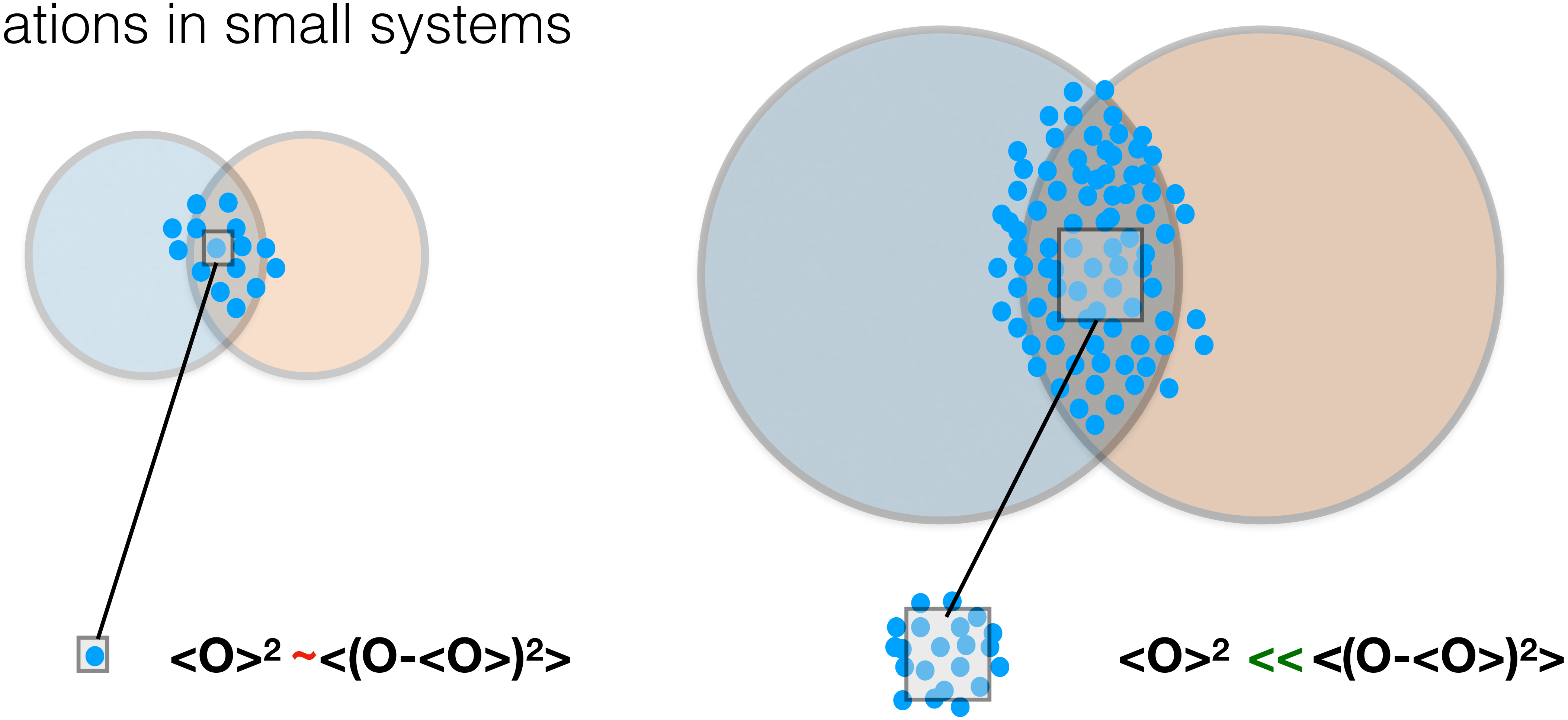


Mazeliauskas talk at Initial State 2021

Expect p+Pb and O+O fall into transition region τ_{Hydro}/R ~1 where system is expected to encounter final state interactions, but is also out-of-equilibrium for a significant part of its lifetime

Hydrodynamic QGP in small systems?

Second caveat applies due to increased importance of fluctuations in small systems



Description in terms of thermodynamics/expectation values becomes increasingly questionable in small systems

Not aware of any quantitative insights, but relevance definitely needs to be explored further

Dynamics of small systems

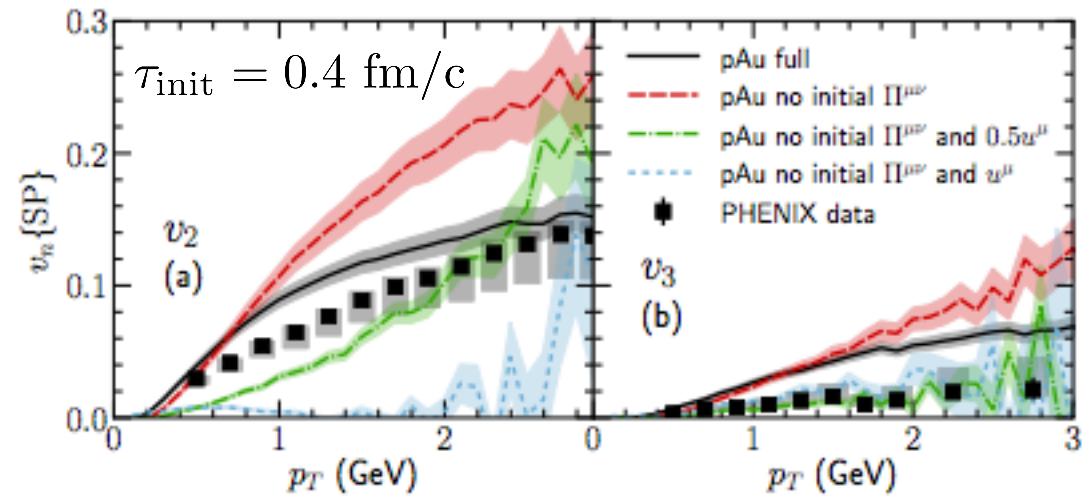
Hydro models

Best developed models in HICs

Non-hydrodynamic modes (included in every hydro code) can play an important role

Pre-flow and initial viscous corrections become important

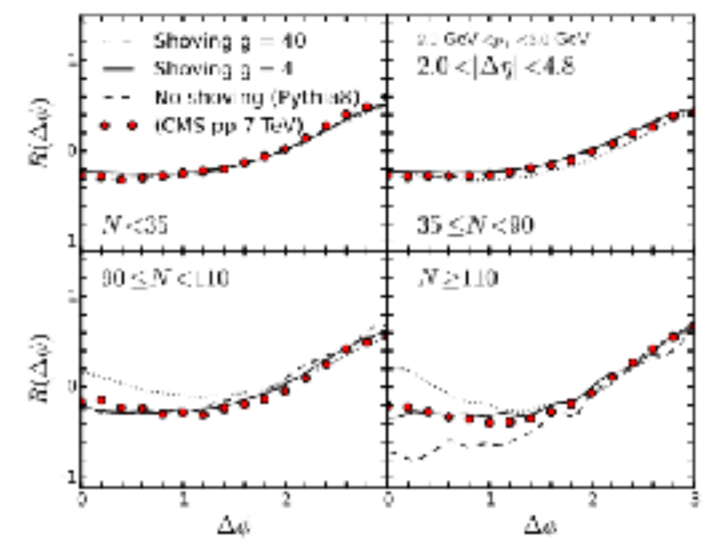
B. Schenke, C. Shen, and P. Tribedy talk presented at Rice Workshop



HEP Event Generators (PYTHIA,…)

New ideas to include coordinate space information & final state effects

c.f. talk by C.Bierlich



Bierlich, Gustafsson, Lönnblad *PLB* 779 (2018) 58-63

Kinetic transport

New developments in transport models & (semi-) analytic transport studies provide insight beyond the two extremes

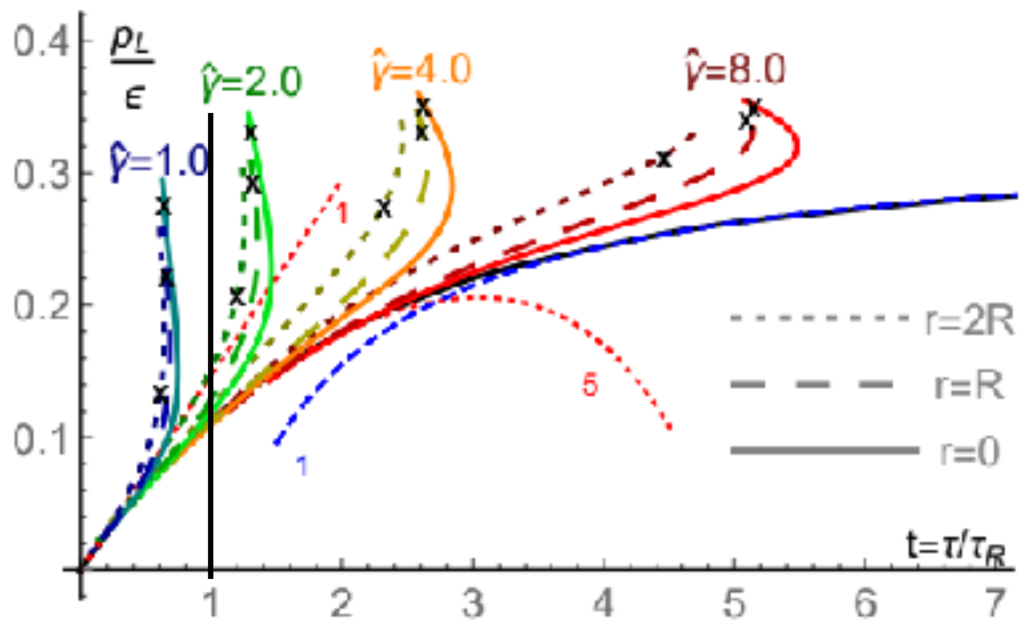
Kurkela,Wiedemann,Wu; Borghini, Roch, Kersting; Greif,Greiner,Schenke,SS,Xu; ….

(Non-equilibrium) dynamics of small systems

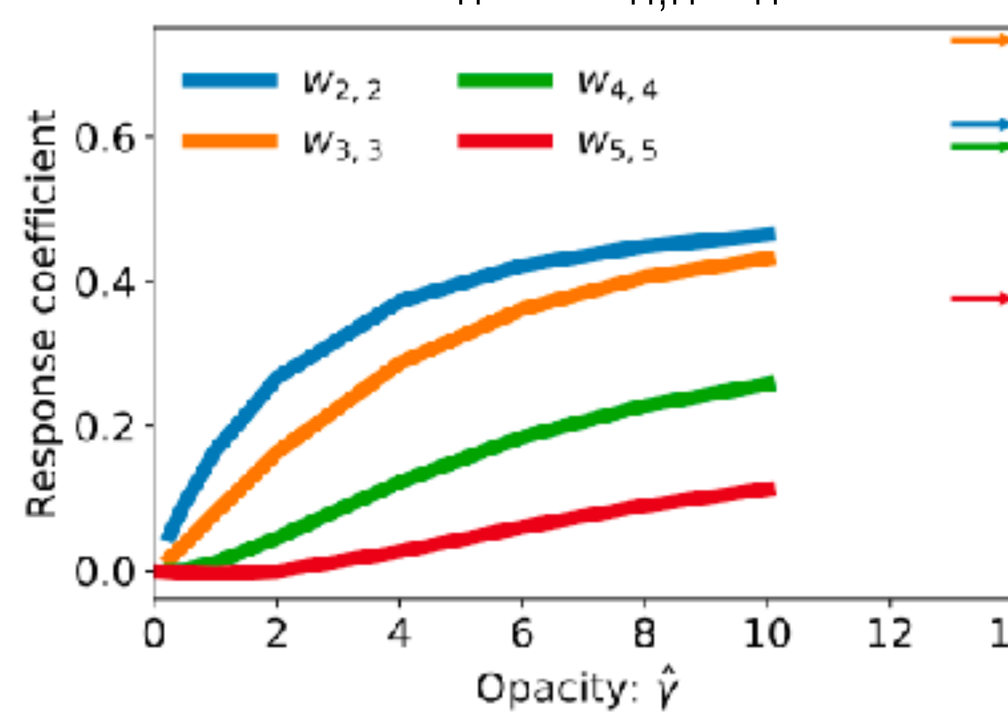
Even though models are not (yet?) QCD, they interpolate between limiting behaviors of free-streaming (HEP) and hydrodynamic transport (Heavy-Ions)

Conformal transport model (Boltzmann RTA)—
System size/Multiplicity dependence
only on single opacity parameter

$$\hat{\gamma} = \frac{1}{5} R^{3/4} \left(\frac{\frac{1}{\pi R^2} \frac{dE_T^0}{d\eta}}{\frac{\pi^2}{30} \nu_{\text{eff}}} \right)^{1/4} \left(\frac{\eta}{s} \right)^{-1} \overset{p+Pb}{\sim} O(1)$$



$V_n \sim W_{n,n}\, \varepsilon_n$



Kurkela,Wiedemann,Wu EPJC 79 (2019) 11, 965 Kurkela,vdSchee,Wiedemann,Wu PRL 124 (2020) 10, 102301; Kurkela Taghavi, Wiedemann, Wu PLB 811 (2020) 135901

Exploring change in response requires sufficient control over geometry

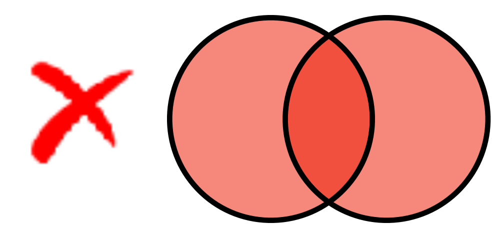
Geometry of small & large systems

Spatial distribution of partons in protons/nuclei responsible for collision geometry in the transverse plane

Pb+Pb/O+O: Spatial distribution of nucleons inside nucleus provide dominant source of eccentricity

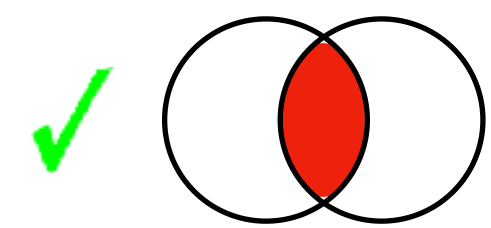
Energy deposition in the transverse overlap area for each N-N collision

IP-Glasma, EKRT $\quad \epsilon(\mathbf{x}_\perp) \propto T_A(\mathbf{x}_\perp) T_B(\mathbf{x}_\perp)$



Schenke, Tribedy, Venugopalan PRC86 (2012) 034908
Niemi,Eskola,Paatalainen, PRC 93 (2016) no.2, 024907

TrENtO (p=0) $\quad s(\mathbf{x}_\perp) \propto T_A^{1/2}(\mathbf{x}_\perp) T_B^{1/2}(\mathbf{x}_\perp)$



Moreland, Bernhard, Bass PRC 92 (2015) no.1, 011901

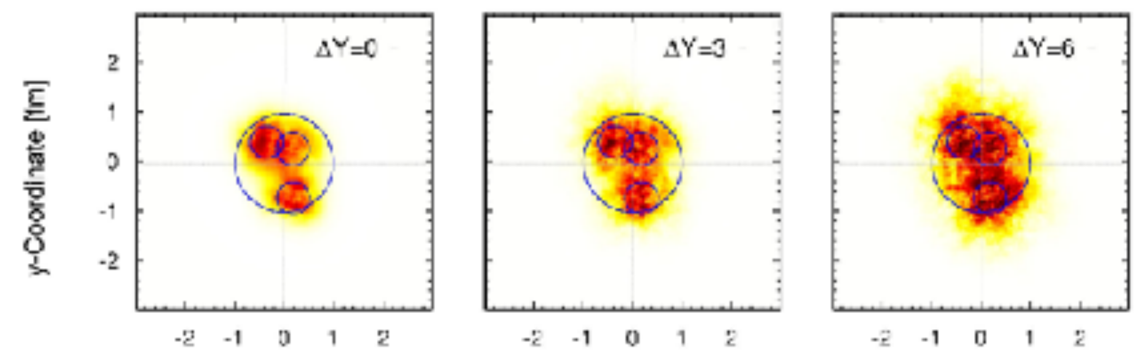
Successful description of experimental data over range of energies and systems

Geometry of small systems

p+Pb/O: Spatial distribution of partons in protons dominates eccentricities

Sub-nucleonic fluctuations play a crucial role for geometry in small systems

Schenke, Venugopalan PRL 113 (2014) 102301
Mäntyisaari, Schenke, Chen, Tribedy, PLB 772 (2017) 681-686
Welsh, Singer, Heinz PRC 94 (2016) 2, 024919



Schenke,SS PLB 739 (2014) 313-319

Despite constraints from DIS experiments, still large modelling uncertainties

Challenge to disentangle effects in final state observables $v_2 \sim w_{2,2}\, \boldsymbol{\varepsilon}_2$
as different initial states and evolution models can lead to same prediction

O+O: Significantly more controlled geometry allows to separate effects of eccentricity and response

p+O/p+Pb/p+Au: Similar geometry but different opacity

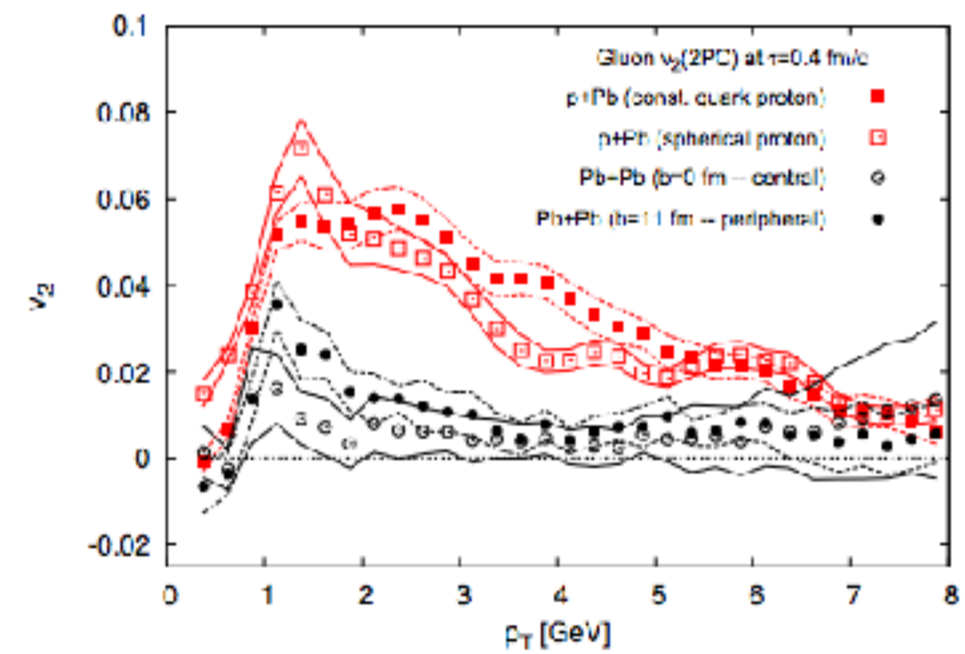
Initial state momentum correlation

Beyond the initial state geometry, which can induce momentum correlations due to final state interactions, there are also intrinsic initial state momentum correlations

di-jets, initial state momentum ansiotropies, …

General features at the parton level

- ~5% for p+Pb collisions
- suppressed as ~$1/N_{ch}$ for large systems
- uncorrelated with event geometry
- expected to be reasonably long range in η



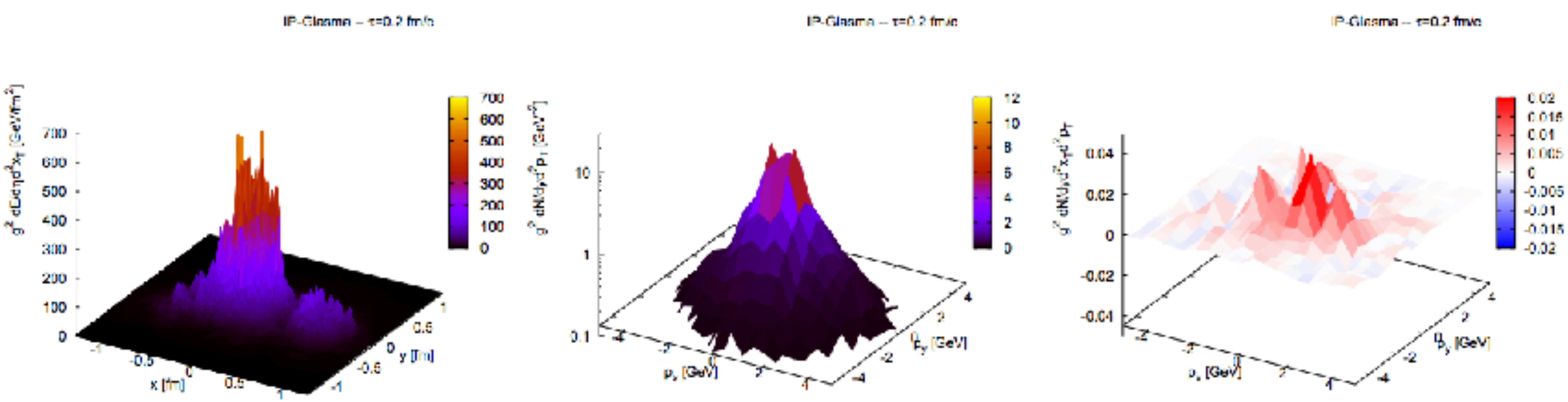
Schenke, SS, Venugopalan PLB 747 (2015) 76-82

Even though such correlations exist at early times, to what extent they survive depends on the significance of final state interaction

(Non-equilibrium) dynamics of small systems

Color-Glass Condensate initial state models (IP-Glasma) include information on collision geometry and initial momentum anistropy

Extract full single particle phase space information from correlation functions of gluon fields



Notion of localized quasi particles becomes increasingly problematic as de Broglie wave-length becomes comparable to system size

Greif, Greiner, Schenke, SS, Xu PRD96 (2017) no. 9, 091504; Greif, Greiner, Plätzer, Schenke, SS arXiv:2012.08493

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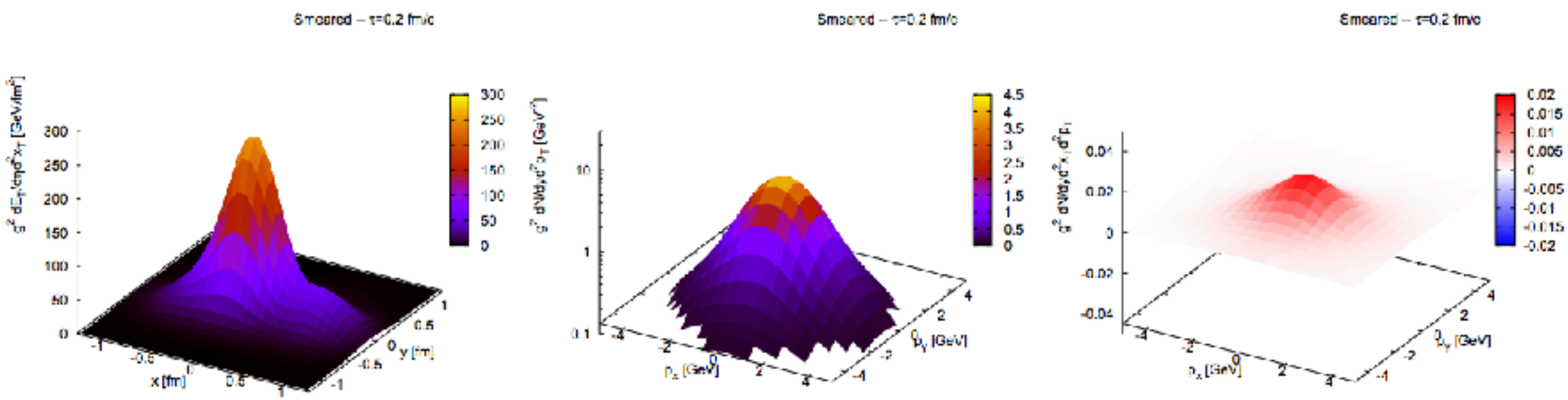
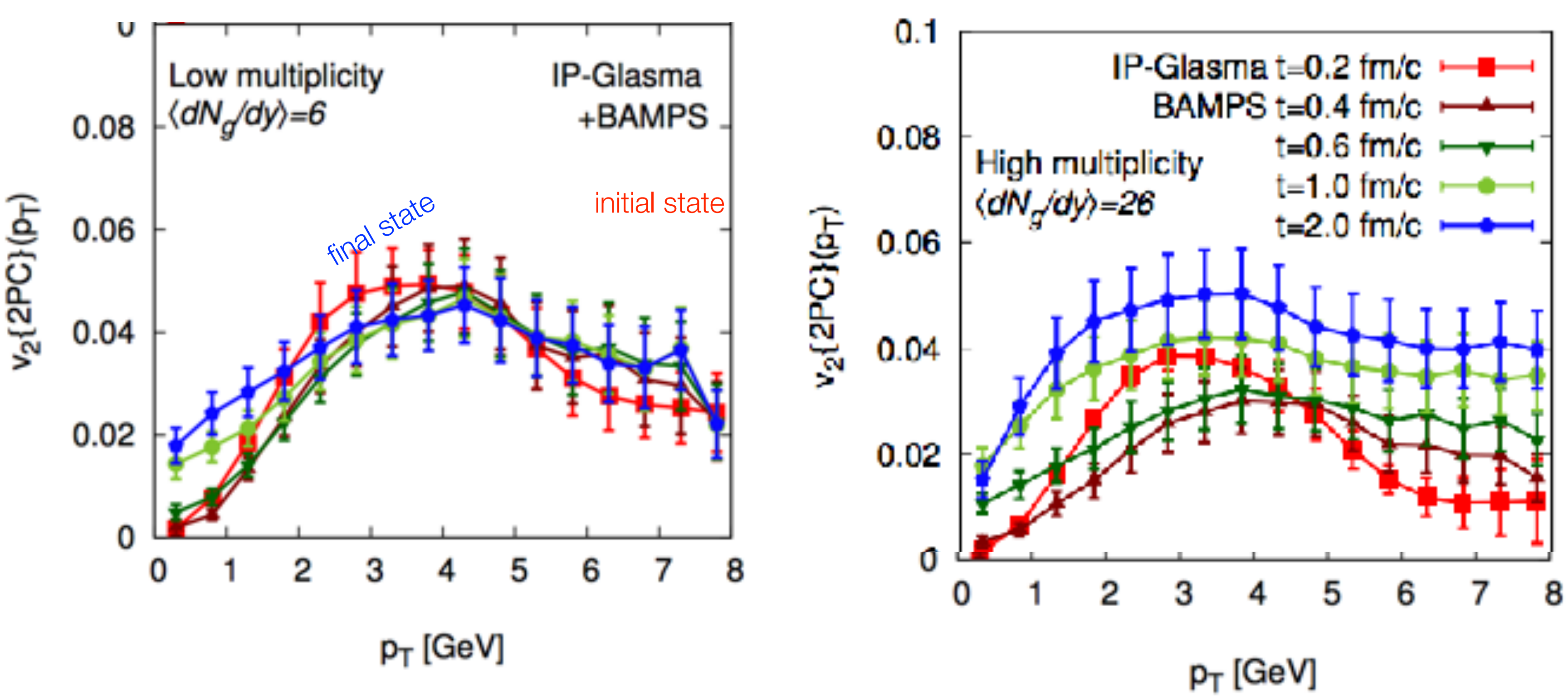


Smearing of the phase-space distribution with minimal uncertainy (~hbar) removes positivity violations, but also decreases eccentricity and momentum space anisotropy

Greif, Greiner, Schenke, SS, Xu PRD96 (2017) no. 9, 091504; Greif, Greiner, Plätzer, Schenke, SS arXiv:2012.08493

(Non-equilibrium) dynamics of small systems

Based on Color-Glass Condensate initial state model (IP-Glasma)
+ pQCD transport (BAMPS) in the final state



Simultaneous development of geometric response & destruction of initial state correlations; still rather small v_2 but challenging to compare to hadronic observables measured in experiment

Greif, Greiner, Schenke, SS, Xu PRD96 (2017) no. 9, 091504

(Non-equilibrium) dynamics of small systems

Hydrodynamic simulations including initial state momentum anisotropy encoded in dissipative components of energy-momentum tensor + final state effects (IP-Glasma+MUSIC+URQMD)

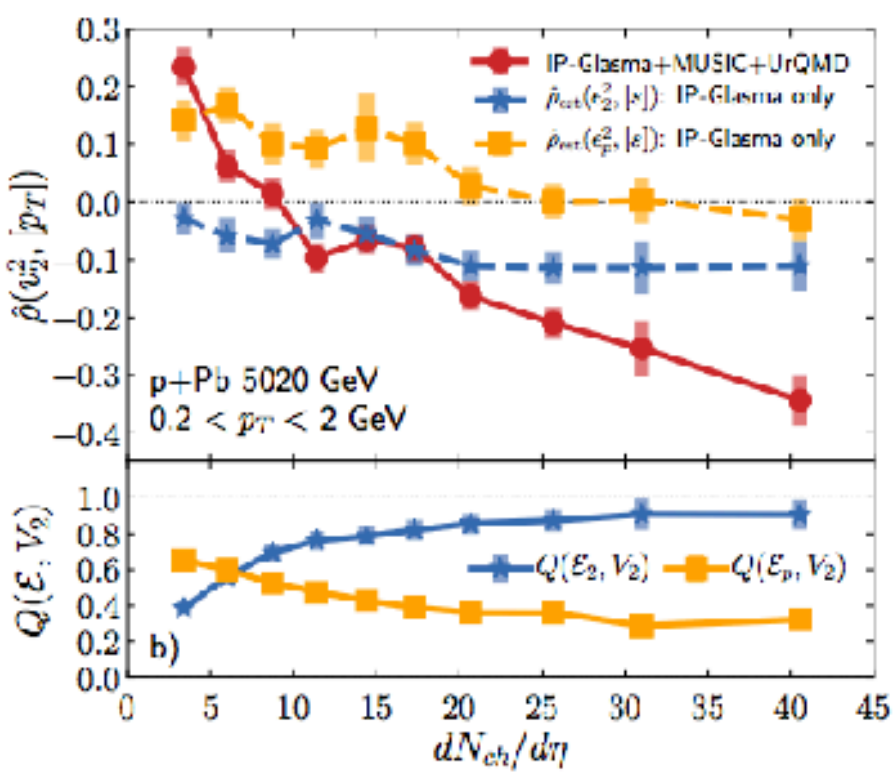
Correlations between v_2

initial eccentricity

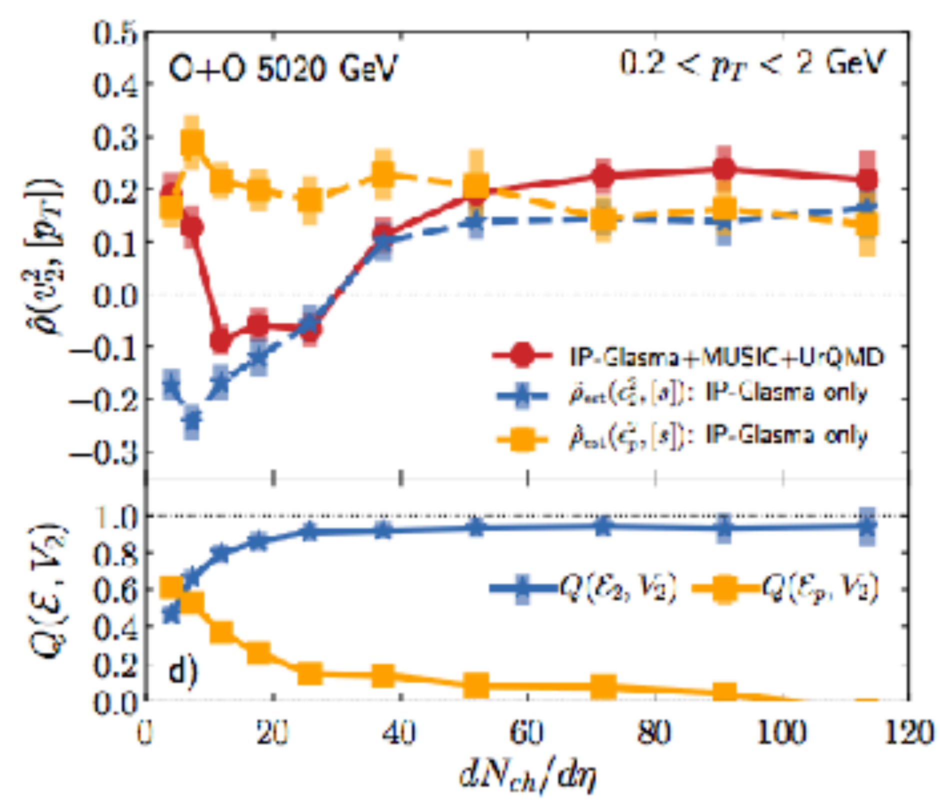
$$\mathcal{E}_2 = \varepsilon_2 e^{i2\psi_2} = \frac{\langle x^2 - y^2\rangle + i\langle 2xy\rangle}{\langle x^2 + y^2\rangle},$$

initial momentum anisotropy

$$\mathcal{E}_p = \varepsilon_p e^{i2\phi_2^p} = \frac{\langle T^{xx} - T^{yy}\rangle + i\langle 2T^{xy}\rangle}{\langle T^{xx} + T^{yy}\rangle},$$



Giacalone, Schenke, Shen, PRL 125 (2020) 19, 192301

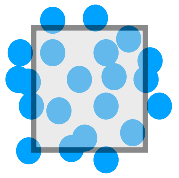


Sensitivity of p_T,v_2 correlation to change in dominant mechanism

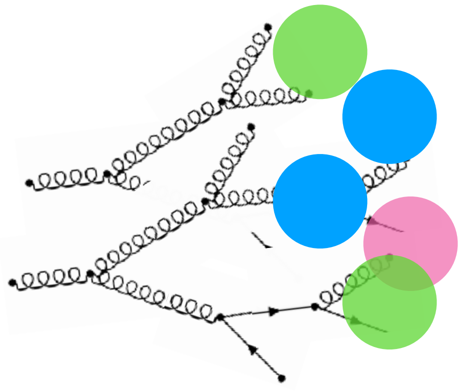
Hadronization of small systems

Different hadronization mechanisms implemented in Heavy-Ion and High-Energy Physics

Heavy-Ions: Coordinate space picture based on proximity to local thermal equilibrium



HEP: Momentum space picture based on underlying hard process & color structure of event

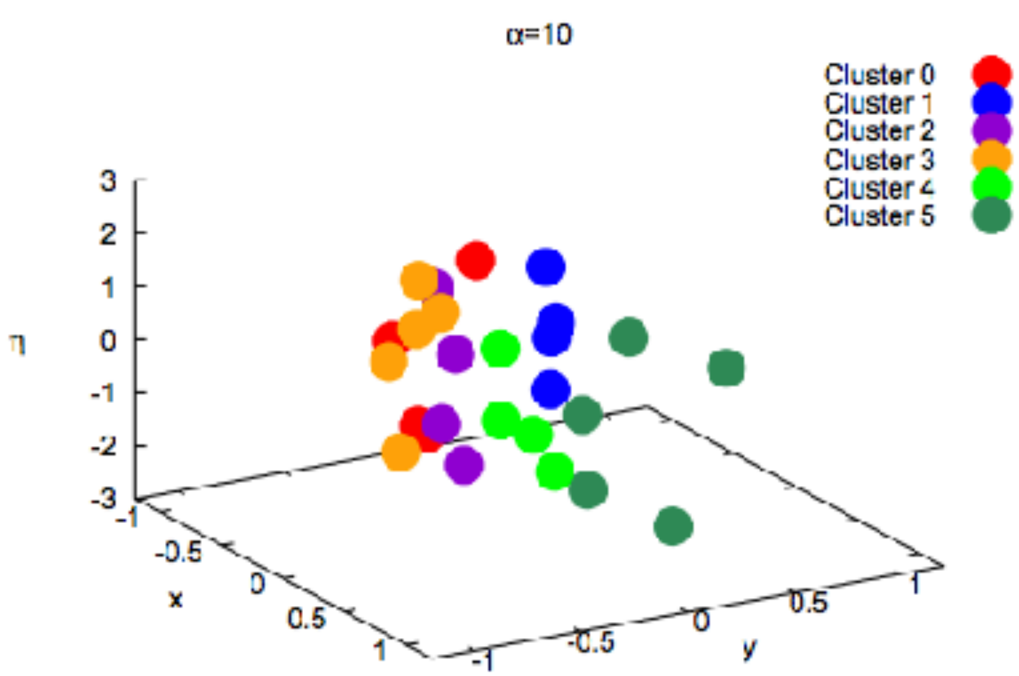


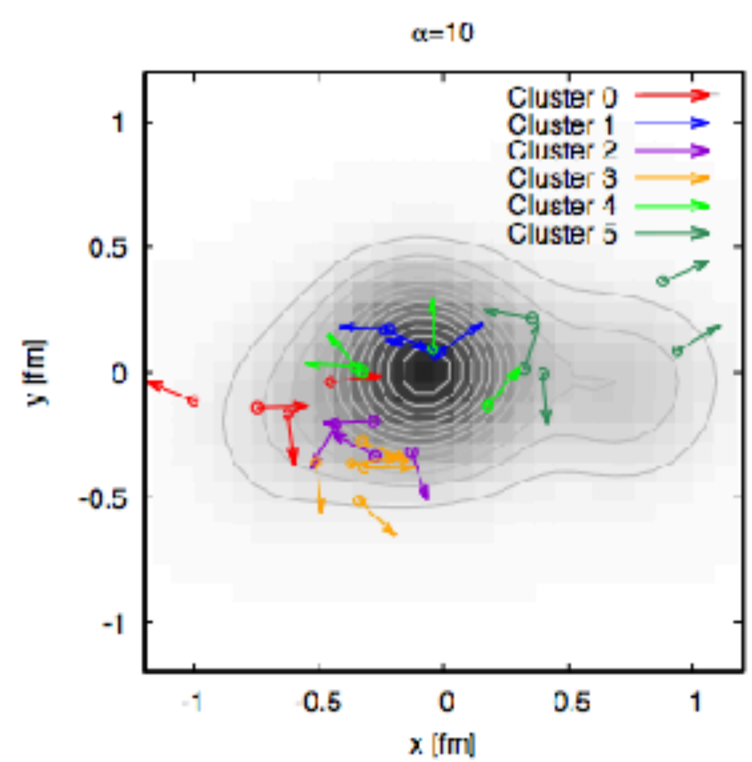
Since hadronic observables are used to describe flow, it is important effects of hadronization on observables as well as validity & connections between the two orthogonal pictures

Hadronization of small systems

Developed space-time clustering (SAHARA) based on DCA of final state partons as a first attempt to connect the two pictures and study hadronization effects

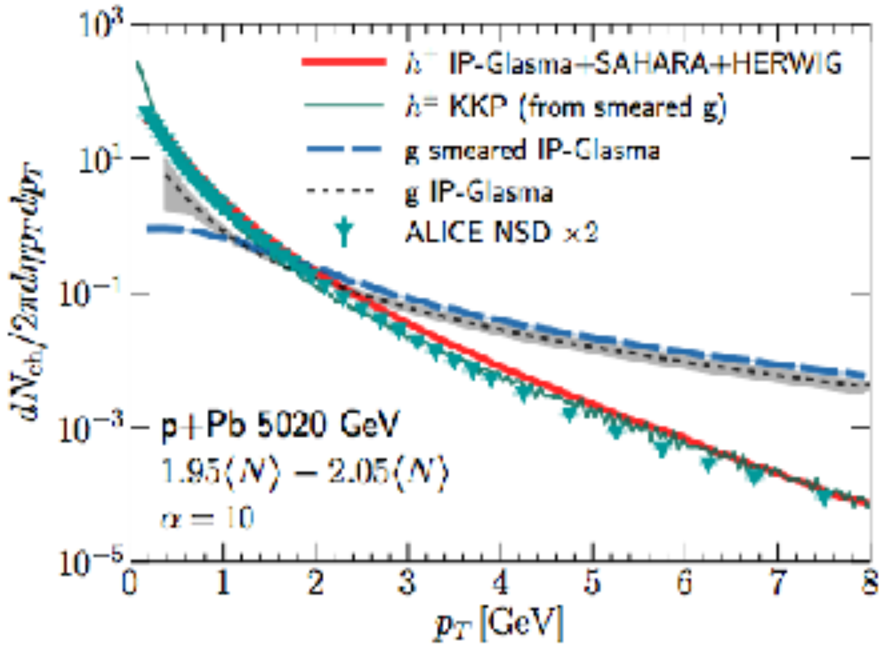
Soft gluon production in IP-Glasma -> Space time clustering in SAHARA -> Hadronization in Herwig





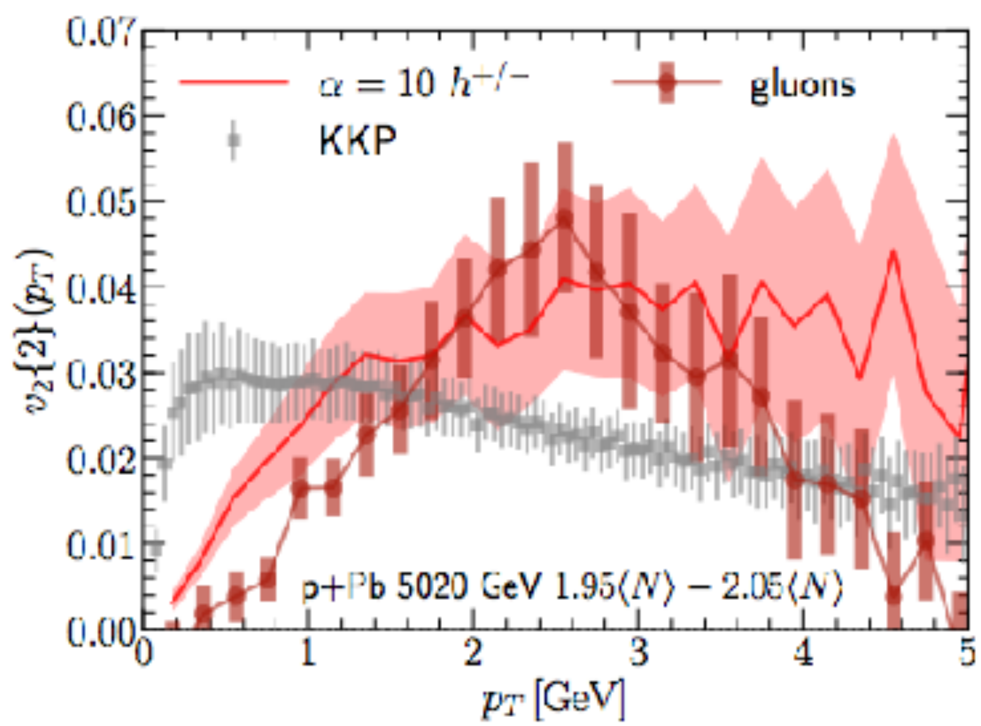
Greif, Greiner, Plätzer, Schenke, SS arXiv:2012.08493

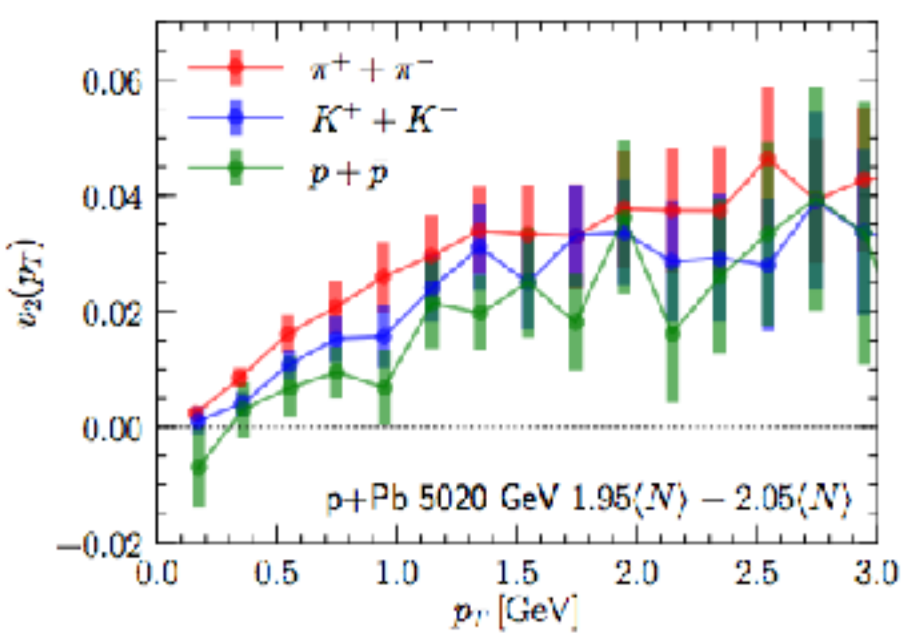
Hadronization of small systems



Small sensitivity of inclusive particle spectra

Significant sensitivity of flow observables on hadronization; Similar v2 for partons/hadrons





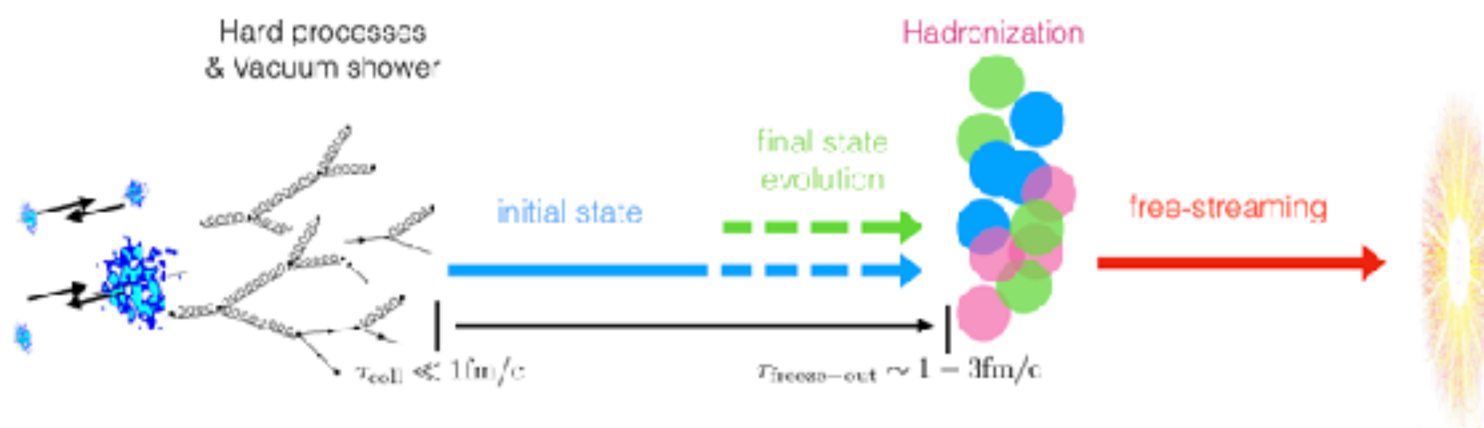
Splitting of v_2 of identified particles natural not indicative of final state effects

Greif, Greiner, Plätzer, Schenke, SS arXiv:2012.08493

Conclusions & Outlook

Large systems: Based on microscopic insights and tight constraints from experimental data global macroscopic properties of initial state and early time dynamics are under reasonable control

Small systems: Challenge to connect Heavy-Ion and HEP pictures of hadronic collisions requires new theoretical developments regarding



nucleon structure, non-equilibrium dynamics, hadronization

Controlled geometry of O+O allows to study dynamics in a regime where non-equilibrium effects are expected to be important

Similar geometries in p+O/p+Pb/p+Au as well as O+O at different energies allow to assess opacity dependence