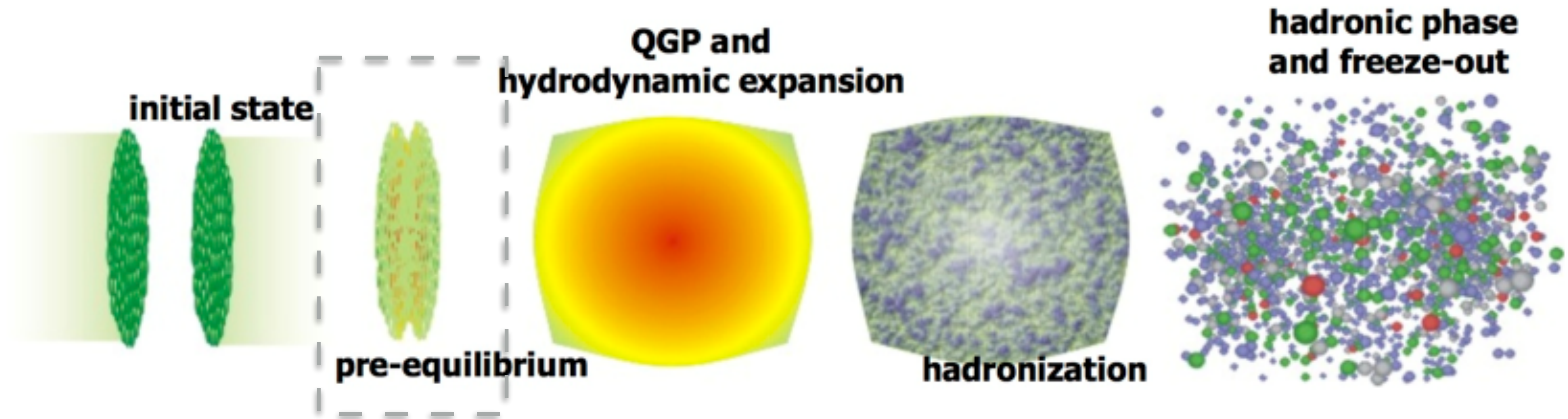
Non-equilibrium dynamics in AA collisions & origins of collective behavior in pp/pA

Sören Schlichting | University of Washington

Based on Kurkela, Mazeliauskas, Paquet, SS, Teaney NPA967 (2017) 289-292 & in preparation
Greif, Greiner, Schenke, SS, Xu arXiv:1708.02076

Challenge: Pre-equilibrium dynamics



A+A

Desirable to theoretically describe entire space-time evolution

Experimental observables show very limited sensitivity to pre-equilibrium dynamics

p+p/p+A

Early time dynamics key to understand dynamics of small systems, e.g. answer question wether or not equilibrated QGP is formed is of central importance

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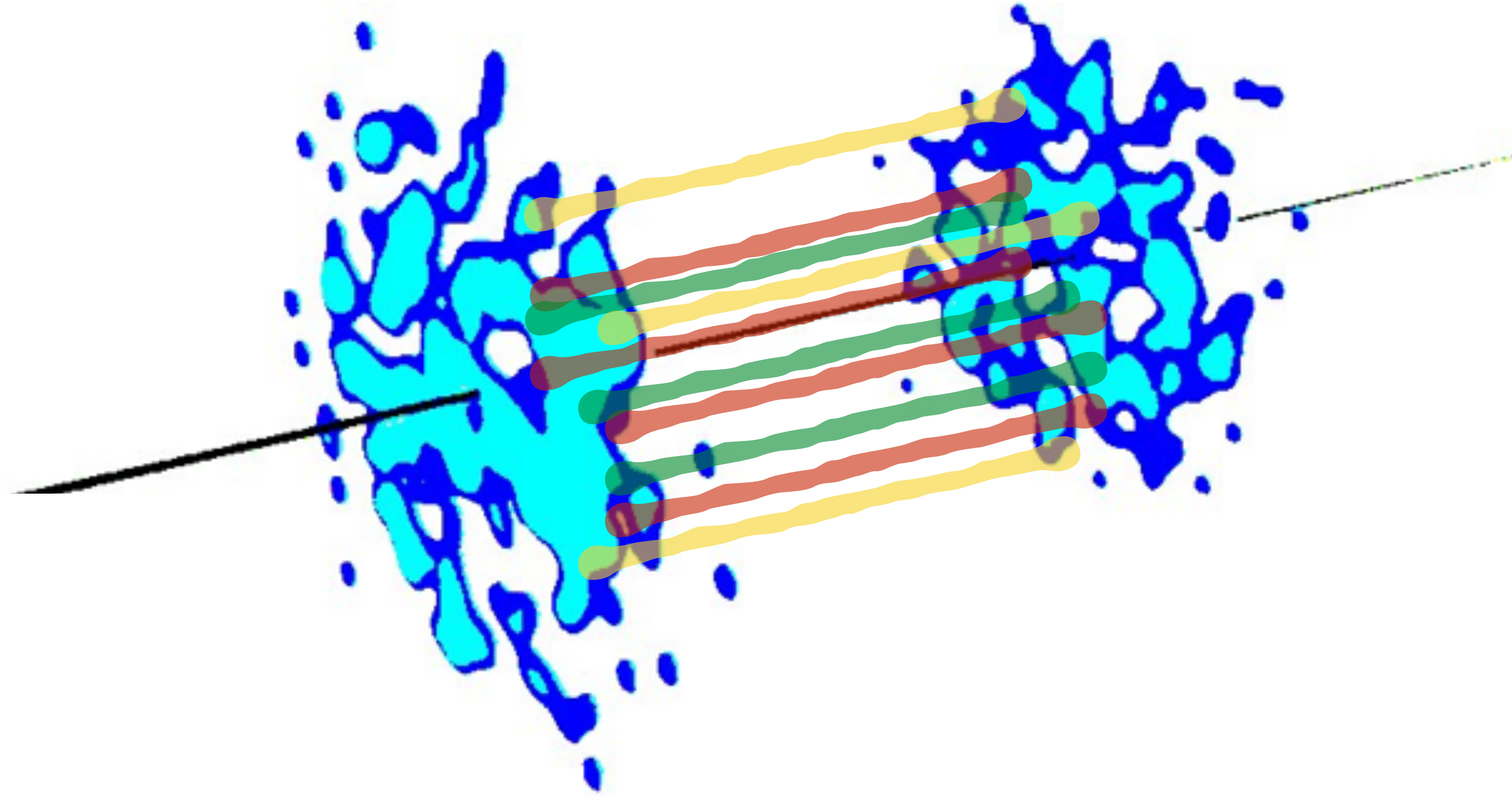
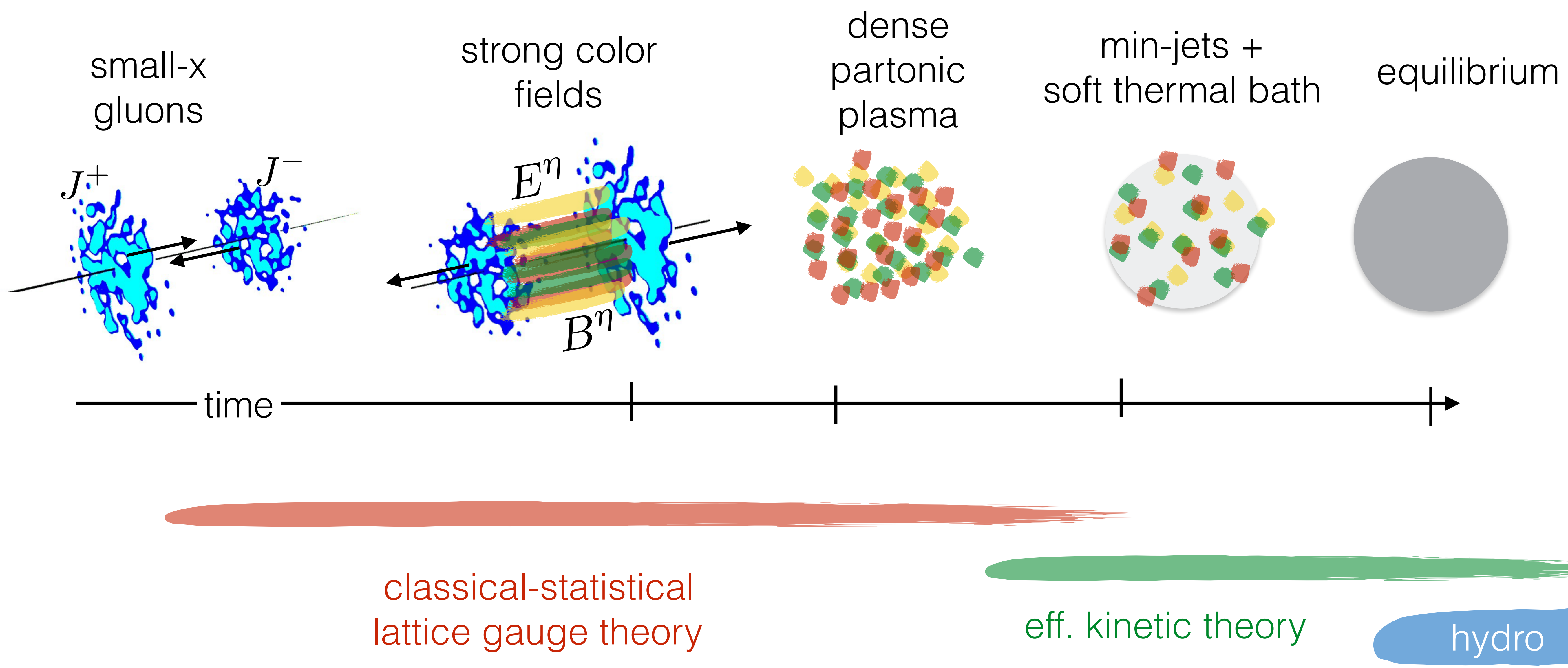


Early time dynamics &
equilibration process in A+A

Early time dynamics & equilibration process



Since different degrees of freedom dominate dynamics at different times, consistent theoretical description requires combination of weak coupling techniques

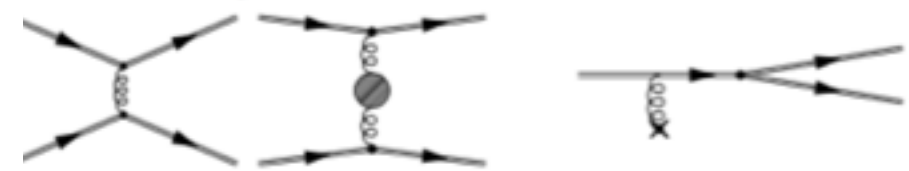
Equilibration process in HIC

Beyond very early times equilibration proceeds according to “bottom-up” scenario and can be described to LO by eff. kinetic theory

Baier, Mueller, Schiff, Son PLB502 (2001) 51-58 Kurkela, Zhu PRL 115 (2015) 182301

$$\left(\partial_\tau - \frac{p_z}{\tau}\right) f(\tau, |\mathbf{p}_\perp|, p_z) = \mathcal{C}[f]$$

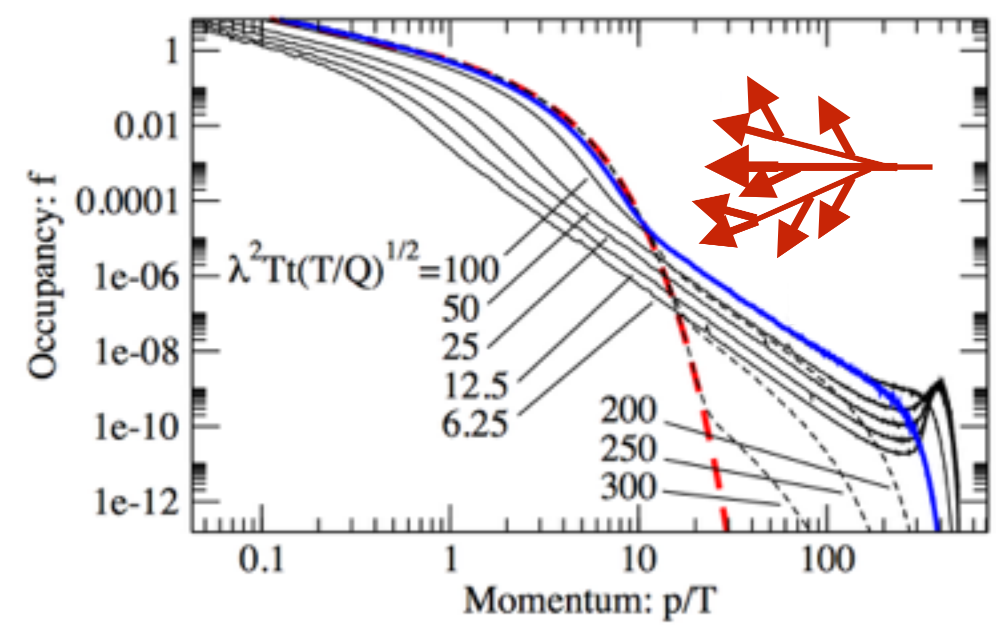
$$\mathcal{C}[f] = \underbrace{\mathcal{C}_{2\leftrightarrow 2}[f]} + \underbrace{\mathcal{C}_{1\leftrightarrow 2}[f]}$$



a) Emission of bremsstrahlung from mini-jets (~Q_s) initiates a radiative cascade

b) Soft fragments thermalize (“bottom”) via interaction with each other

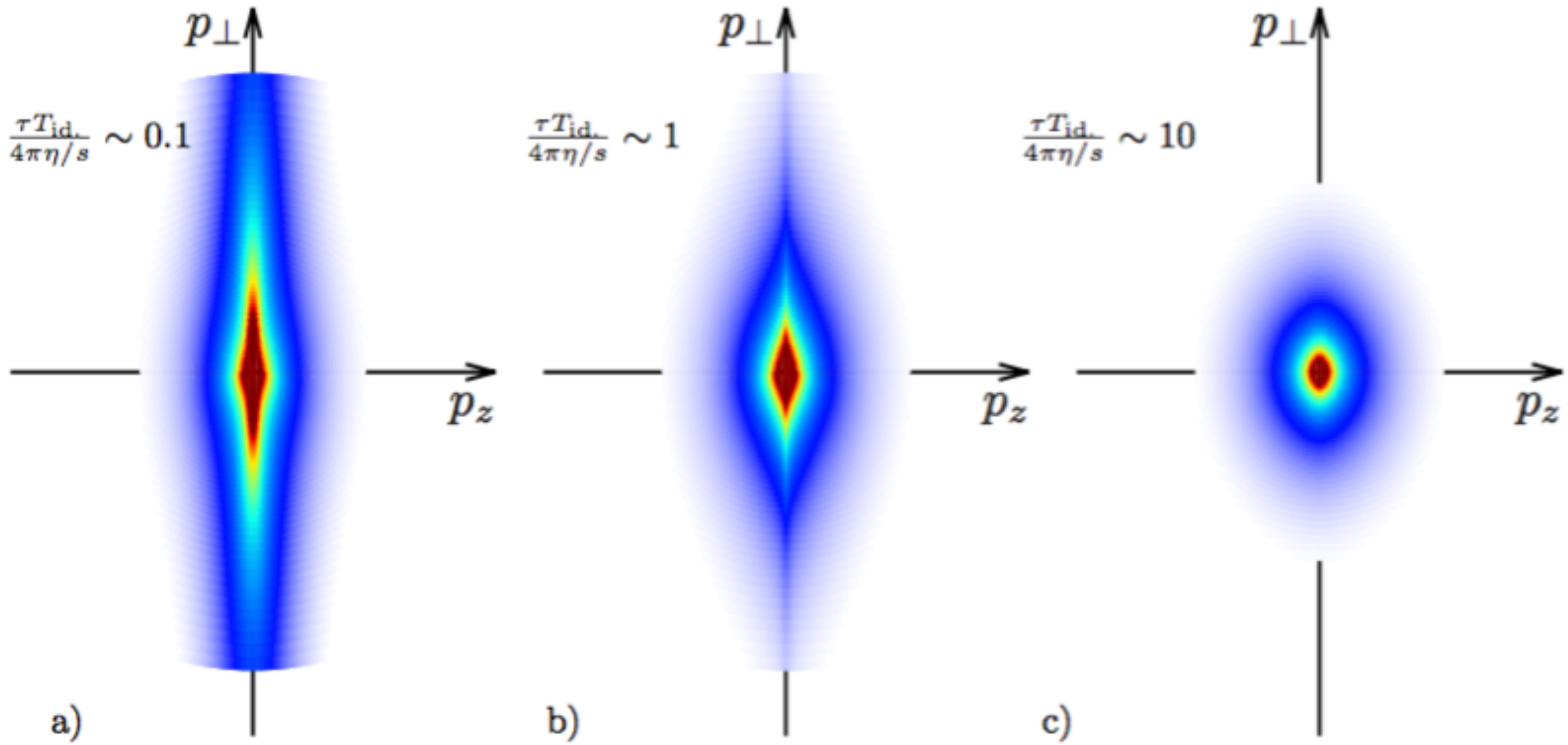
c) Quenching of mini-jets in thermal bath
-> depletes hard sector (~Q_s)
-> heats (“up”) soft bath



Kurkela, Lu PRL 113 (2014) 182301

Equilibration process in HIC

Kurkela, Mazeliauskas, Paquet, SS, Teaney NPA967 (2017) 289-292 & in preparation



Isotropization/equilibration of the plasma occurs when a mini-jet Q_s to loose all its energy

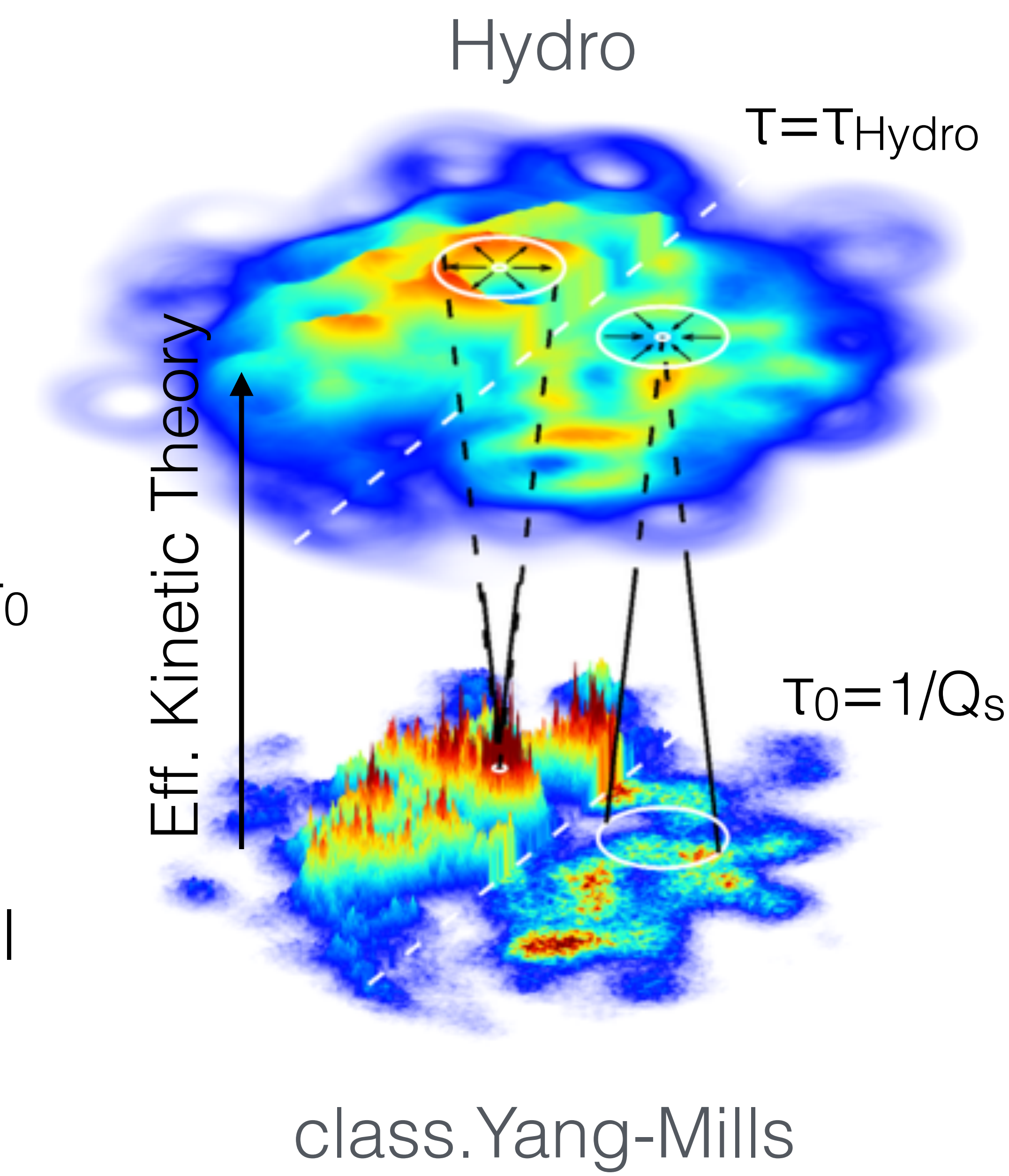
Macroscopic pre-equilibrium evolution

Extract energy-momentum tensor $T^{\mu\nu}(x)$ from classical statistical lattice simulation

Evolve $T^{\mu\nu}$ from initial time $\tau_0 \sim 1/Q_s$ to hydro initialization time τ_{Hydro} using eff. kinetic theory description

Causality restricts contributions to $T^{\mu\nu}(x)$ to be localized from causal disc $|x-x_0| < \tau_{Hydro}-\tau_0$ useful to decompose into a local average $T^{\mu\nu}_{BG}(x)$ and fluctuations $\delta T^{\mu\nu}(x)$

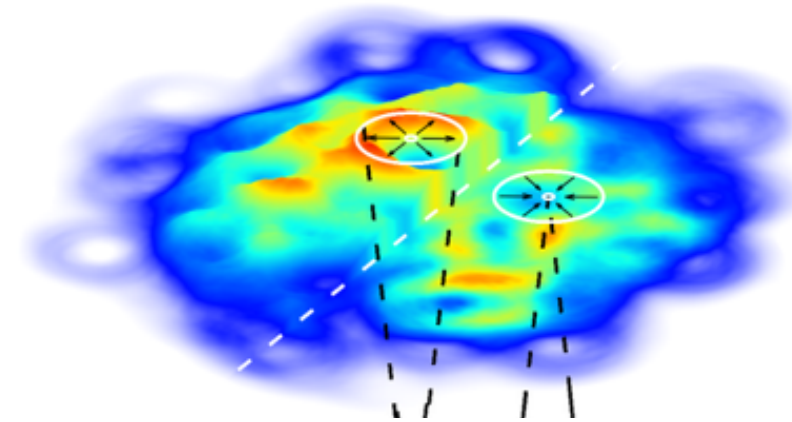
Since in practice size of causal disc is small $\tau_{Hydro}-\tau_0 << R_A$ fluctuations $\delta T^{\mu\nu}(x)$ around local average $T^{\mu\nu}_{BG}(x)$ are small and can be treated in a linearized fashion



Keegan,Kurkela, Mazeliauskas, Teaney JHEP 1608 (2016) 171
Kurkela, Mazeliauskas, Paquet, SS, Teaney (in preparation)

Macroscopic pre-equilibrium evolution

Energy-momentum tensor on the hydro surface can be reconstructed directly from initial conditions according to

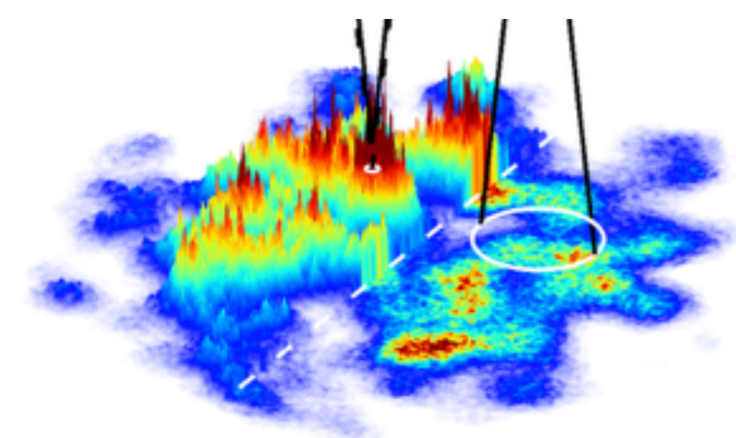


$$T^{\mu\nu}(\tau,x) = T^{\mu\nu}_{BG}\Big(Q_s(x)\tau\Big) + \int_{Disc} G^{\mu\nu}_{\alpha\beta}\Big(\tau,\tau_0,x,x_0,Q_s(x)\Big)\ \delta T^{\alpha\beta}(\tau_0,x_0)$$

non-equilibrium evolution of (local) average background

non-equilibrium Greens function of energy-momentum tensor

Effective kinetic theory simulations only need to be performed once to compute background evolution and Greens functions



Equilibration of energy momentum tensor

Extrapolations from weak-coupling limit to realistic values of α_s (~0.3) at RHIC & LHC based on scaling variables

equilibrium relaxation time $\frac{\eta/s}{\tau T} = \frac{\tau_{\text{re}}}{\tau}$, ideal temp $T_{Id}(\tau) = \frac{\langle T(\tau)\tau^{1/3}\rangle_{\tau\to\infty}}{\tau^{1/3}}$

Kurkela, Mazeliauskas, Paquet, SS, Teaney (in preparation)

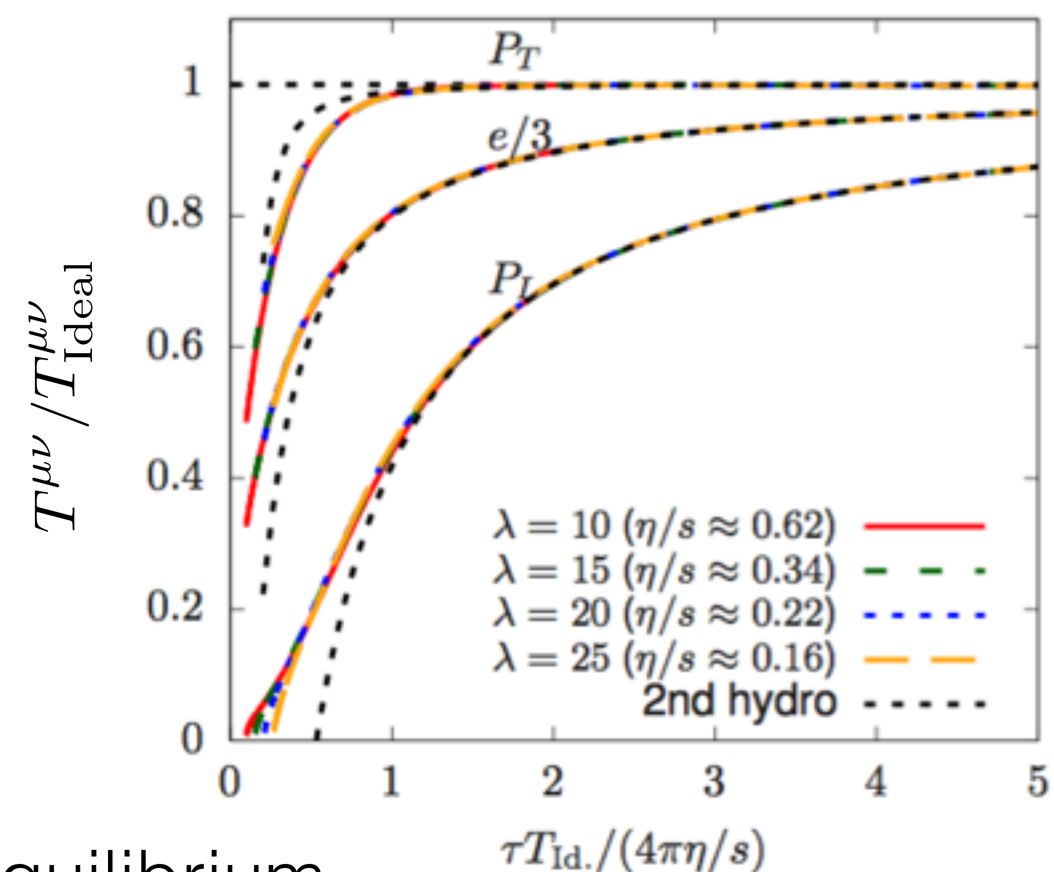
Viscous hydrodynamics applicable on reasonable time scales

$$\tau_{\text{hydro}} \approx 0.85\,\text{fm}\left(\frac{4\pi(\eta/s)}{2}\right)^{\frac{3}{2}}\left(\frac{1.6\,\text{GeV}}{\langle\tau e^{3/4}\rangle}\right)^{1/2}$$

e.g. T_{Initial} ~0.75 GeV, η/s ~2/4π, τ_{Hydro}~0.85 fm/c

Kurkela, Zhu PRL 115 (2015) 182301

Kurkela, Mazeliauskas, Paquet, SS, Teaney (in preparation)

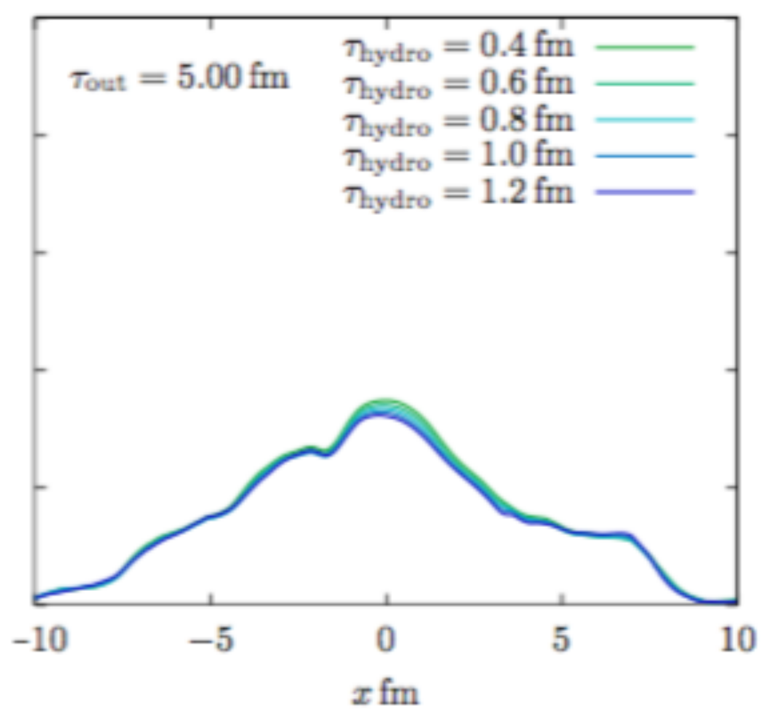


however system is still significantly out-of-equilibrium
e.g. pressure anisotropy O(1), dynamics of (mini-) jet energy loss

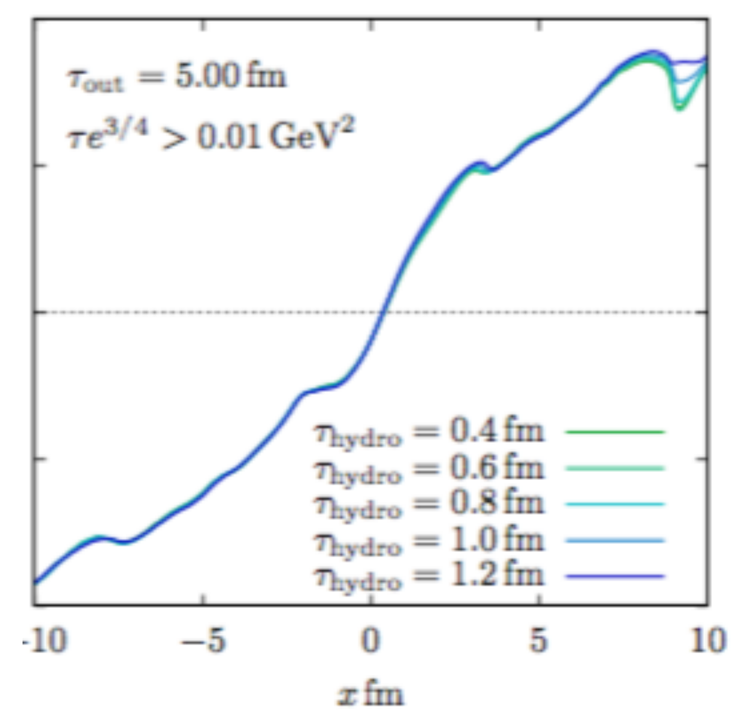
Event-by-event pre-equilibrium dynamics

Based on background evolution & response functions calculated in effective kinetic theory can now calculate pre-equilibrium dynamics macroscopically and provide event-by-event initial conditions for hydrodynamics

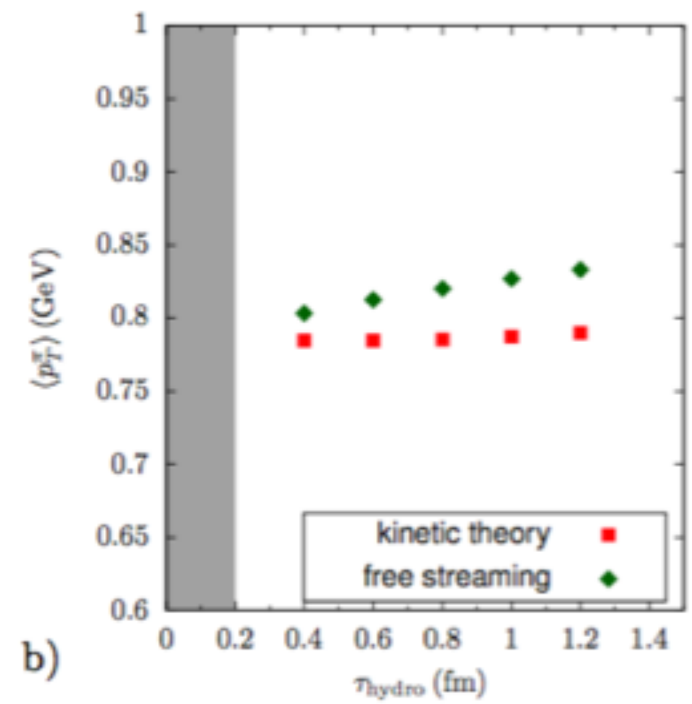
energy density



flow velocity



hadronic observables



b)

Since effective kinetic theory correctly described approach to hydrodynamics, subsequent evolution becomes insensitive of matching time τ_{Hydro}

Consistent theoretical description of entire space-time evolution of HIC

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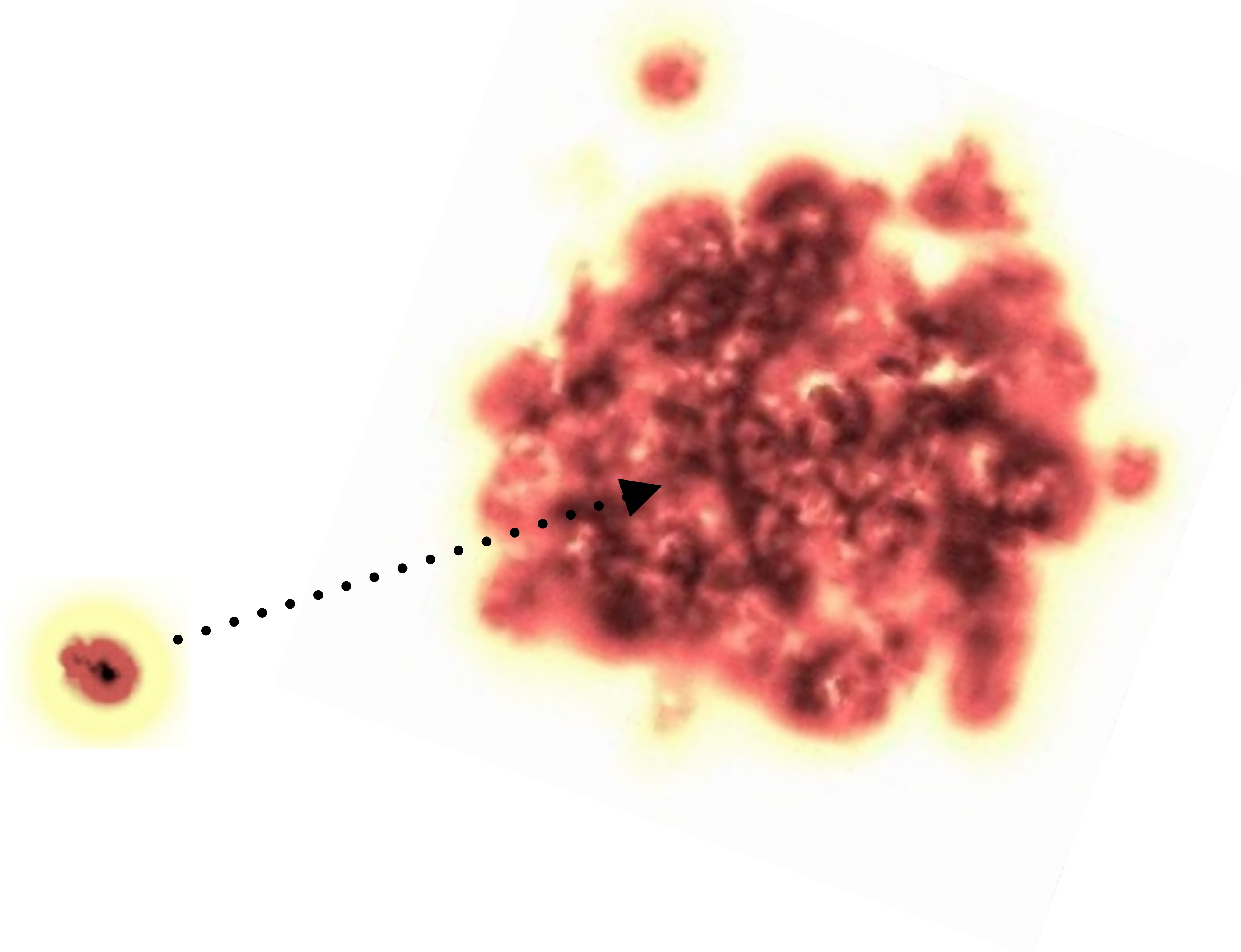


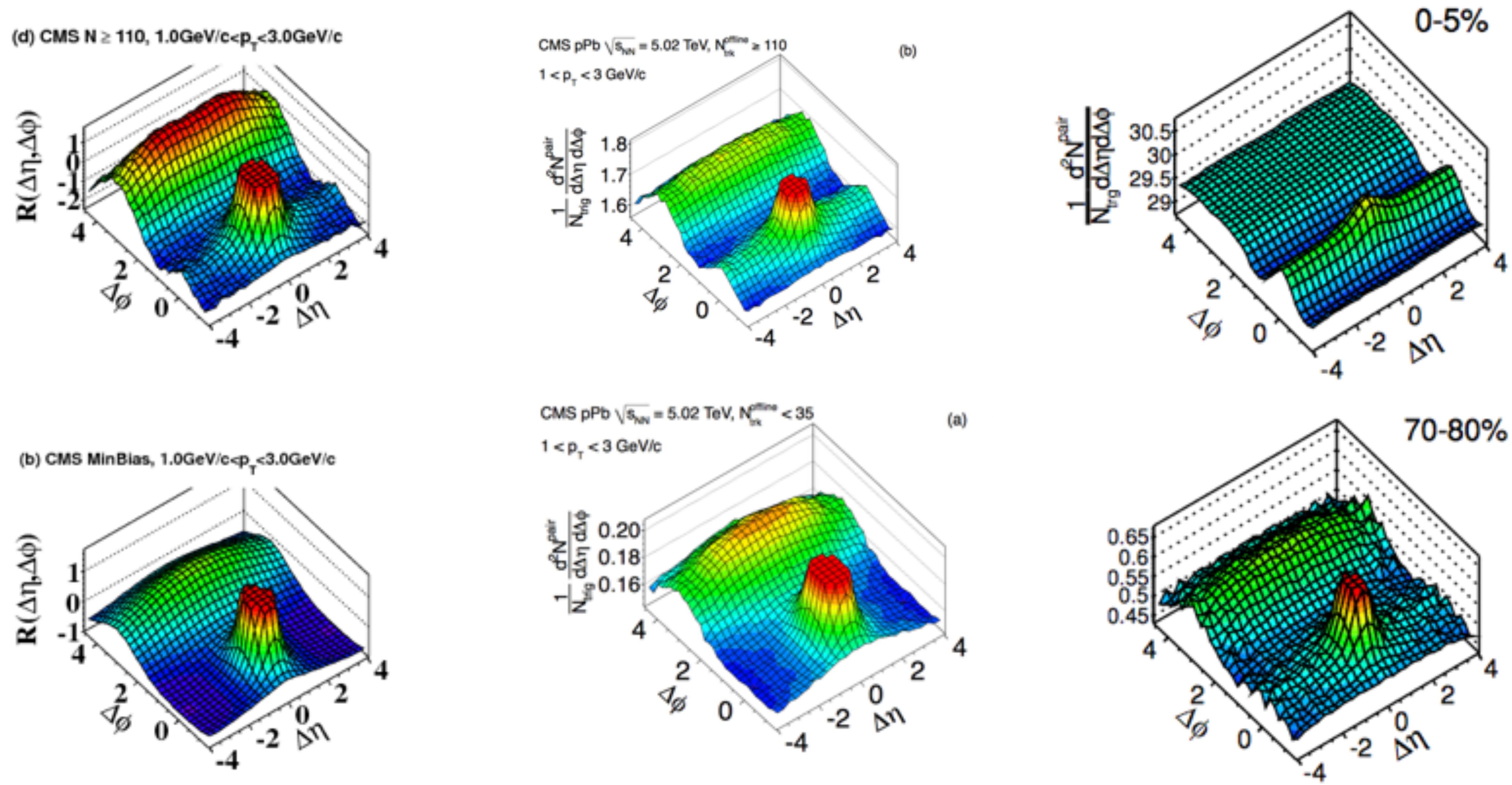
Collectivity in small systems (p+p,p/d/He3+A)

Collectivity in small systems

high multiplicity

low multiplicity

p+p	p+Pb	Pb+Pb
7 TeV	5.02 TeV	2.76 TeV



Surprising similarities as conventionally p+p/A provide background measurements for A+A

Collectivity in small systems

Even though many features of near-side ride in p+p/A are similar to observations in A+A collisions,

-> correlations between many (n>2) particles

-> dependence on hadron species (mass ordering)

…

there are also important differences

-> unambiguous observations in p+p/A only in high-multiplicity events

-> so far no observation of jet-quenching in p+p/A

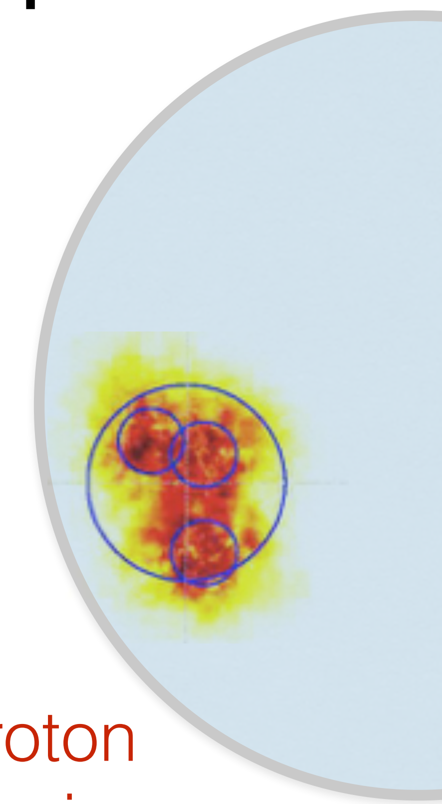
Different theoretical explanations developed in terms of

final state response to initial state geometry

and/or

initial state momentum correlations

Hydrodynamic description of p+p/A



Generation of transverse flow & azimuthal correlations as a response to initial state geometry

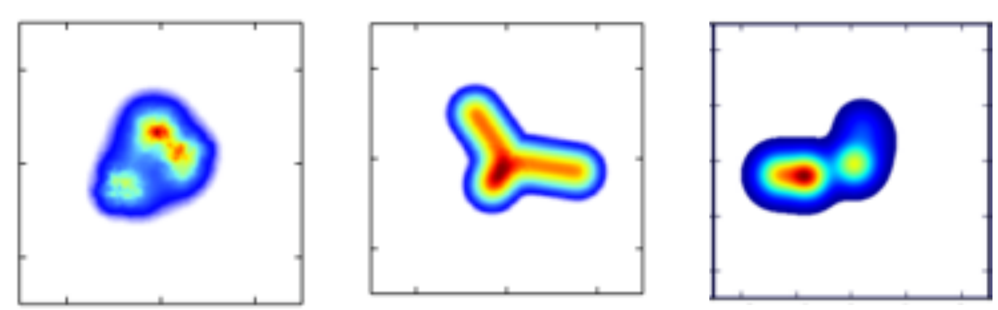
Event geometry in p+p/A collisions closely reflects impact parameter dependence of gluon distribution in proton

Schenke, Venugopalan PRL 113 (2014) 102301
SS, Schenke PLB 739 (2014) 313-319
Mäntysaari, Schenke, Shen, Tribedy arXiv:1705.03177

-> event-by-event fluctuation of the proton necessary to generate sizable anisotropies

Various models of fluctuating proton sub-structure emerging

Mäntysaari, Schenke PRD 94 (2016) no.3, 034042
Bozek, Broniowski, Rybczynski PRC 94 (2016) no.1, 014902
Habich, Miller, Romatschke, Xiang EPJ. C76 (2016) no.7, 408
Welsh, Singer, Heinz PRC 94 (2016) no.2, 024919



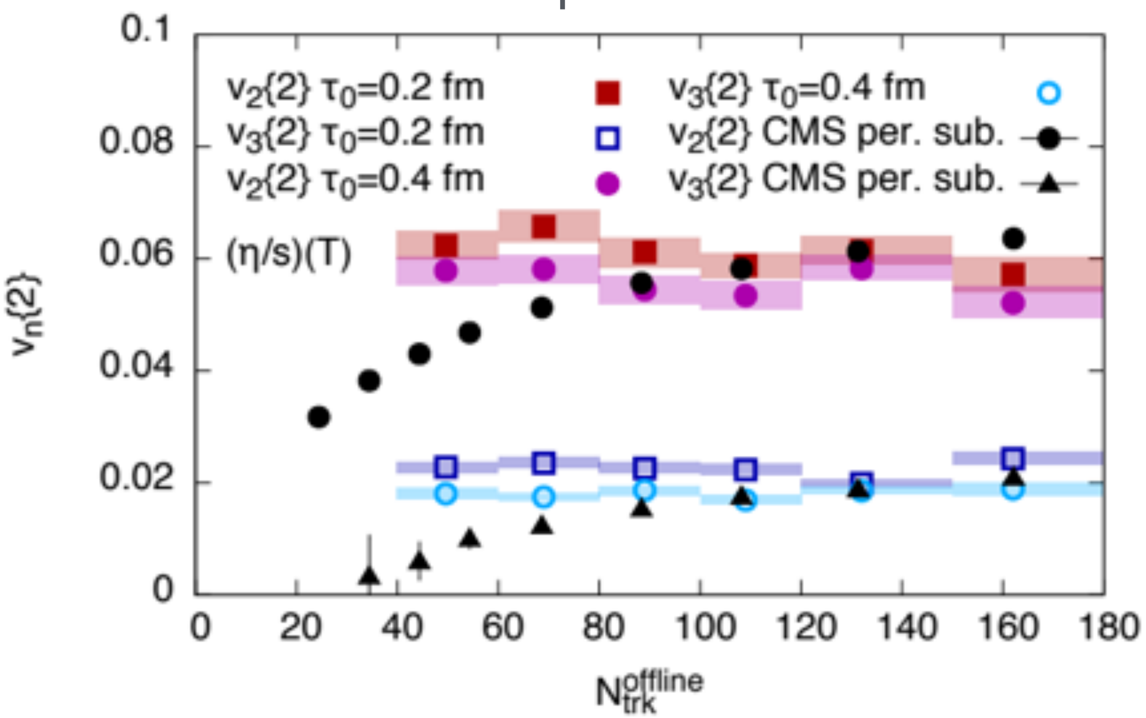
…

need to be independently constrained e.g. by diffractive DIS

Hydrodynamic description of p+p/A

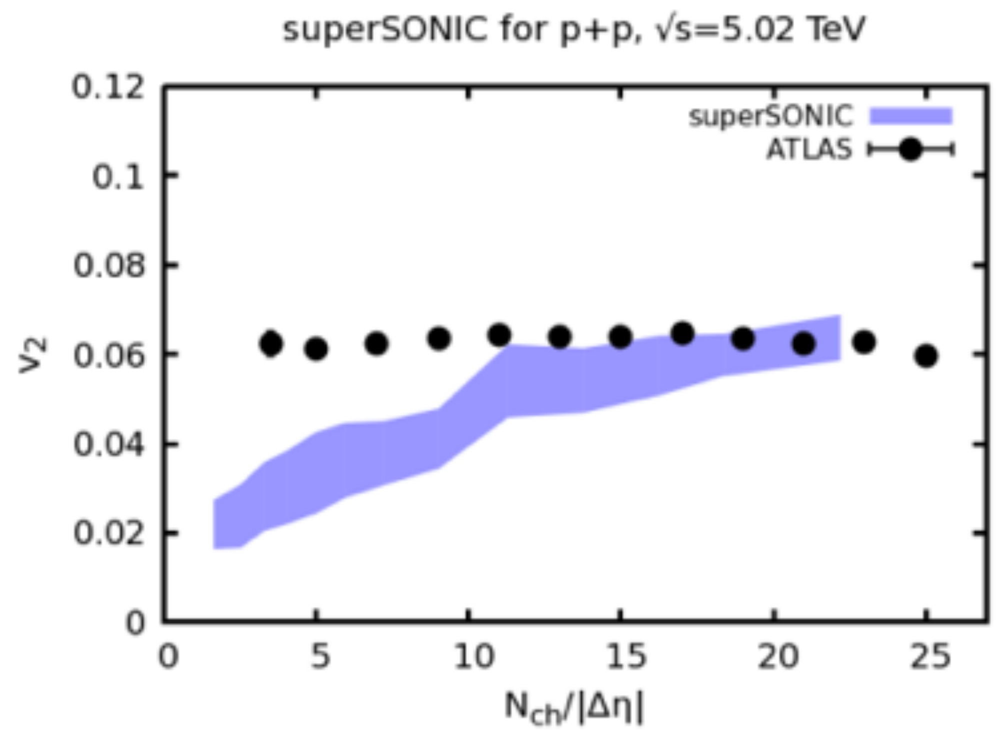
Various phenomenological calculations by different groups

p+Pb



Mäntysaari. Schenke, Shen,Tribedy PLB772 (2017) 681-686

p+p



Weller, Romatschke 1701.07145

. . .

Generally provide successful phenomenological description of azimuthal correlations in high-multiplicity p+p/A

Caveats: viscous corrections? pre-equilibrium?, …

Validity of hydrodynamics in p+p/A?

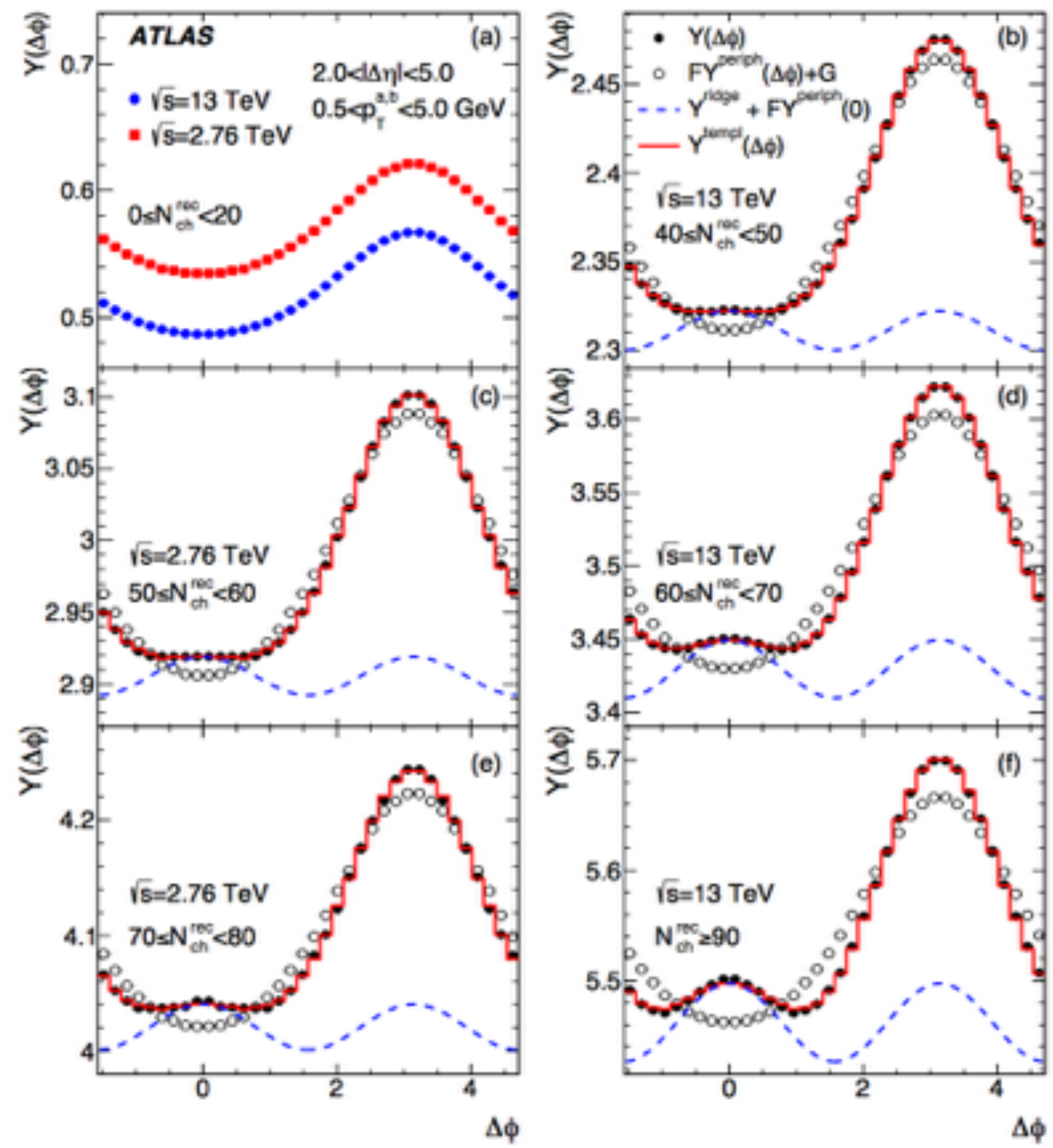
Hydrodynamic description of hadronic collisions only becomes applicable once the system is sufficiently close to local thermal equilibrium

Based on understanding of pre-eq dynamics

Initial state of hadronic collisions described by collection of mini-jets with typical momenta Q_S~ 2 GeV

Hydrodynamic description requires significant quenching of mini jets ~Q_S

Experimental results in high-multiplicity p+p reveal little to no change of the away side (mini-) jet peak



ATLAS
PRL 116 (2016) no.17, 172301

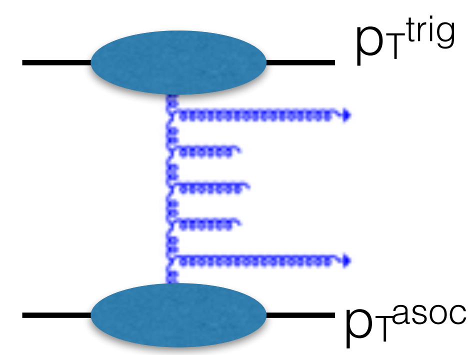
Challenge: Strongly interacting QGP vs. no evidence of (mini-) jet-quenching?

Initial state correlations

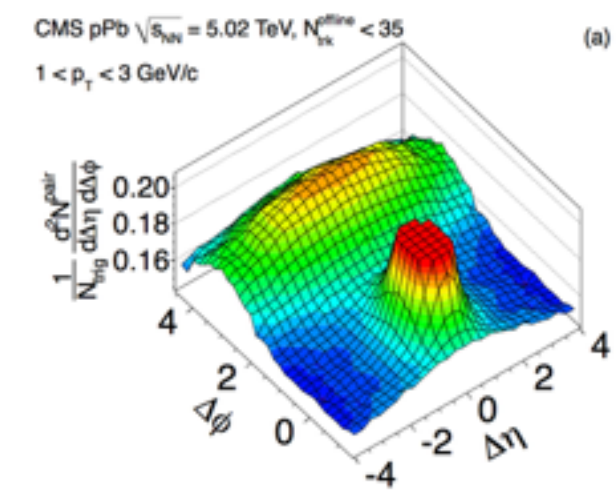
QCD multi-particle production gives rise to intrinsic momentum space correlations present in the initial state

Di-jet like correlations dominate at high p_T and low mult.

long range ($\Delta\eta$) back-to-back ($\Delta\phi \sim \pi$)

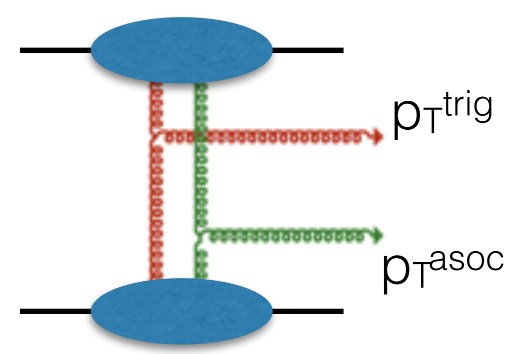


"Jet graph"

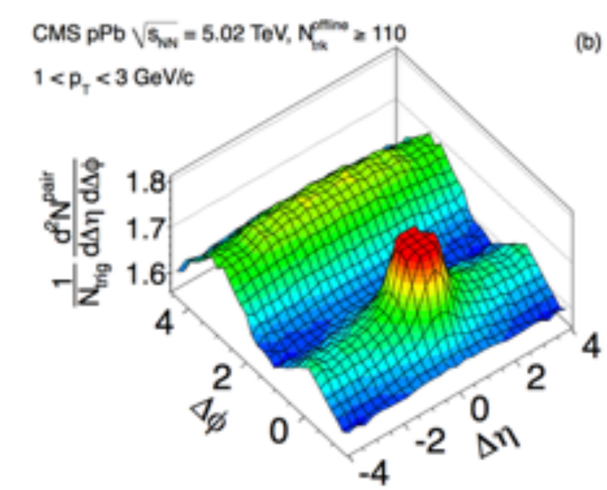


Bose-enhancement of small x gluons gives rise to intrinsic multi-parton correlation for $p_T \sim Q_s$ in high mult. events

long range ($\Delta\eta$) symmetric ($\Delta\phi \sim 0, \pi/2$)



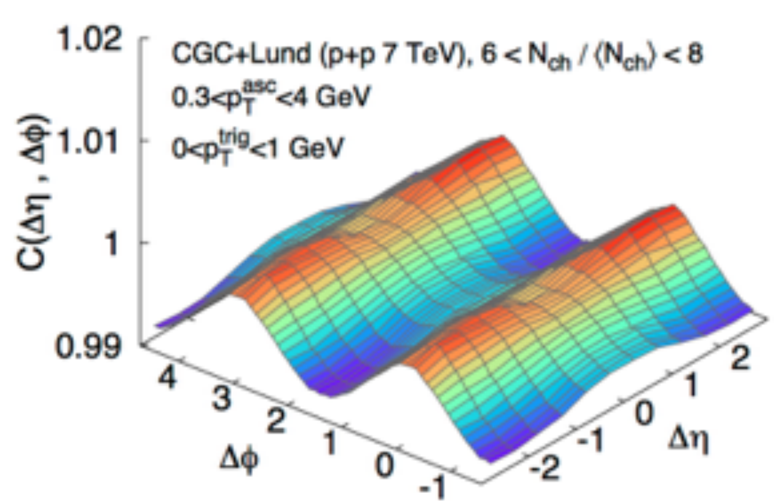
"Glasma graph"

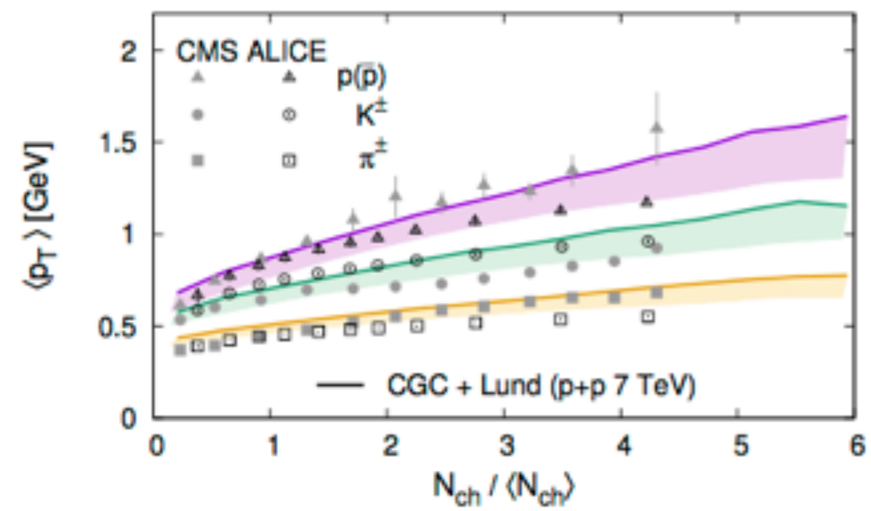


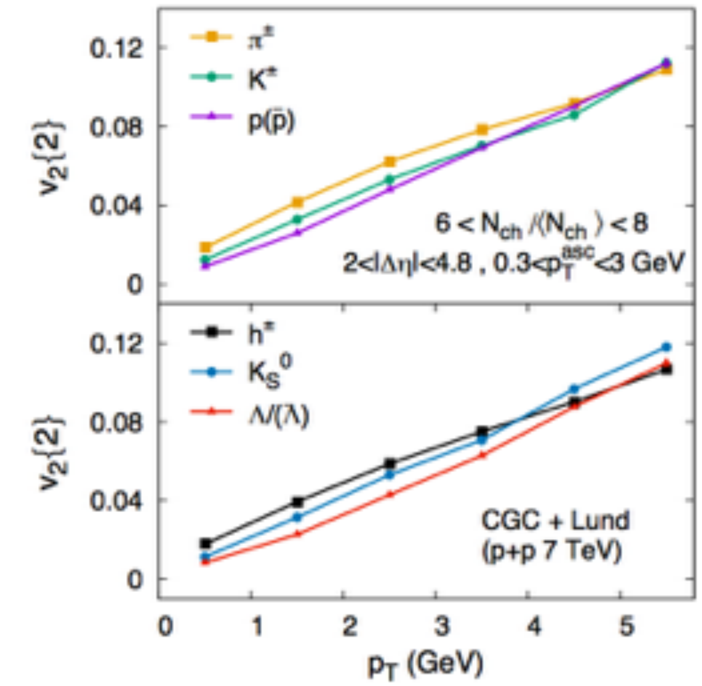
Several calculations point to the fact that initial state effects can be sizable in small systems (p+p, p+A, a+A)

Phenomenological calculations

Example: Event-by-event simulations in classical-Yang Mills theory + MC Lund string fragmentation







(Schenke,SS,Tribedy, Venugopalan PRL 117 (2016) no.16, 162301)

Various phenomenologically important aspects have been addressed in different calculations

v_2/v_3 , higher-cumulants , v_2 /<p_T>mass ordering, …

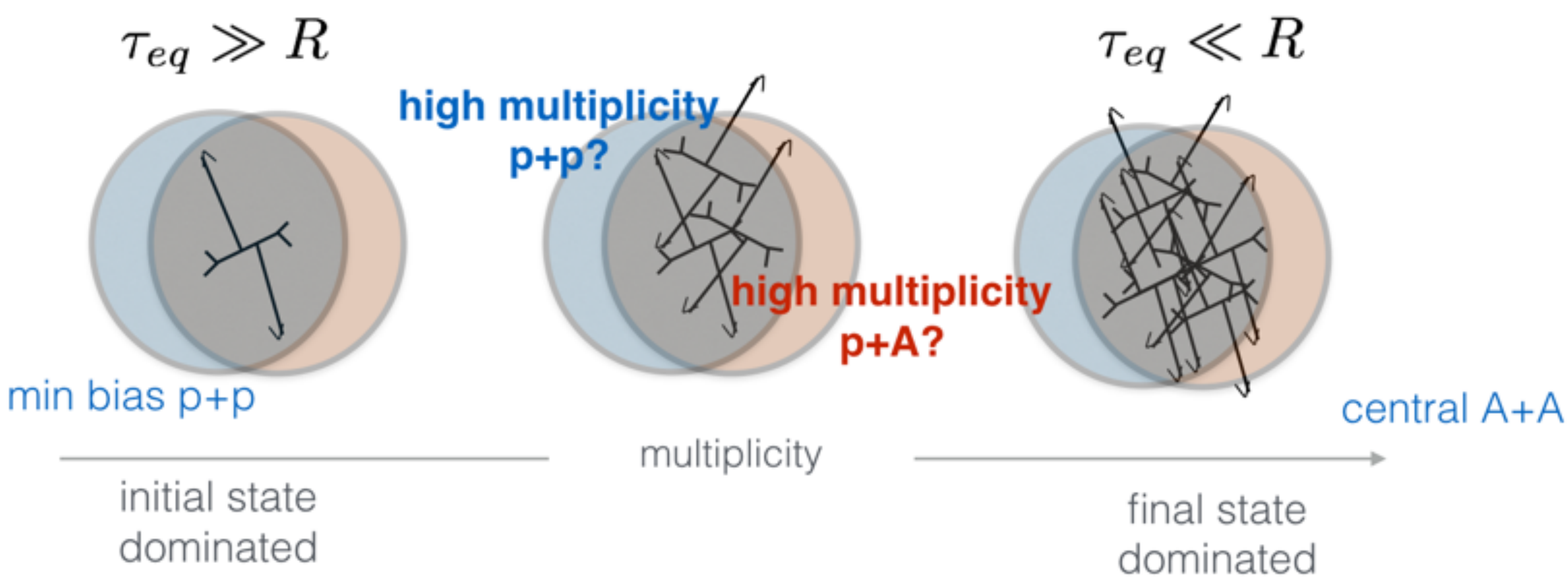
showing that characteristic features of the data can be reproduced.

Challenge: Even though sizable correlations are expected to be present in the initial state, so far these calculations do not take into account possible modifications due to final state effects

Origins of collectivity in pp/pA

Which mechanism dominates depends on opacity of the medium

Expect to see a transition from initial state to final state dominance from low multiplicity p+p to central A+A collisions



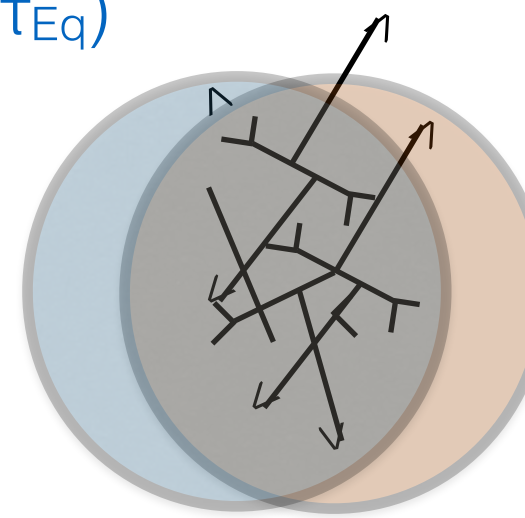
Based on weak coupling picture of pre-equilibrium dynamics one can estimate the where the transition takes place

D.Teaney Initial Stages 2016 | SS, Tribedy Adv. High Energy Phys. Vol. 2016 (2016), 8460349

QGP in small system?

Criterion for QGP formation: equilibration time (τ_{Eq}) < system size (τ_{Eq})

$$\tau_{Eq} \simeq (4\pi\eta/s)^{3/2} \left(\frac{\frac{4}{3}\frac{\pi^2}{30}\nu_{eff}}{\langle s\tau \rangle_\infty} \right)^{1/2} \qquad \langle s\tau \rangle_\infty \simeq \frac{S}{N} \frac{1}{\pi R^2} \frac{dN}{dy}$$



$$\frac{\tau_{eq}}{R} \simeq \left(\frac{4\pi\eta/s}{2} \right)^{3/2} \left(\frac{dN/dy}{25} \right)^{-1/2} \left(\frac{S/N}{7} \right)^{-1/2} \left(\frac{\nu_{eff}}{16} \right)^{1/2}$$

R_p

Ball-park estimate for transition from initial state to final state regime indicates that high-multiplicity p+p/A collisions appear to be in the transition region

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

So far most of theoretical studies have focus on limits τ_{Eq} << R or τ_{Eq} >> R

Development of new theoretical approaches crucial to describe physics across wide kinematic range probed in RHIC/LHC experiments where τ_{Eq} ~ R and one is sensitive to non-equilibrium dynamics

Non-equilibrium description of initial state & final state effects

Event-by-event classical-Yang Mills + parton cascade

1. Simulate particle production and early time dynamics (τ<0.2 fm) in classical Yang-Mills theory, based on IP-Glasma framework

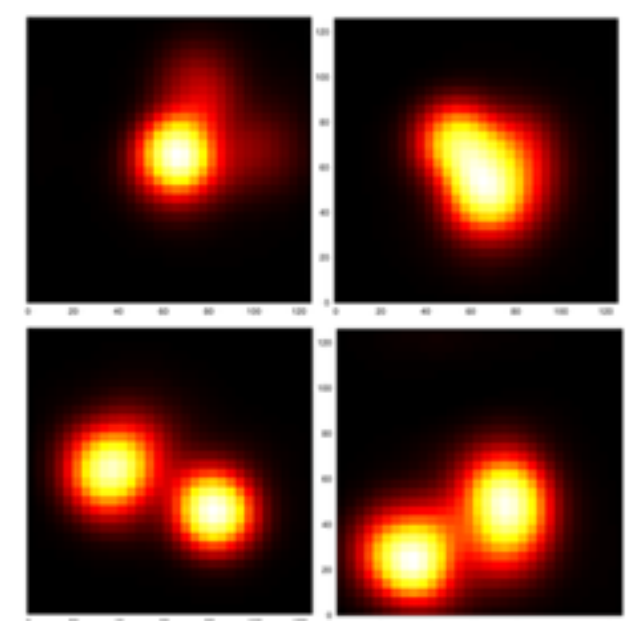
   hadronic structure input constrained by DIS

2. Extract phase-space distribution dN/d^2xd^2p of gluons from classical Yang-Mills simulations, which contains full information on

   - initial state momentum correlations
   - non-trivial event geometry

3. Simulate final state dynamics in parton cascade (BAMPS) including pQCD 2<->2 and 2<->3 processes

Event geometry

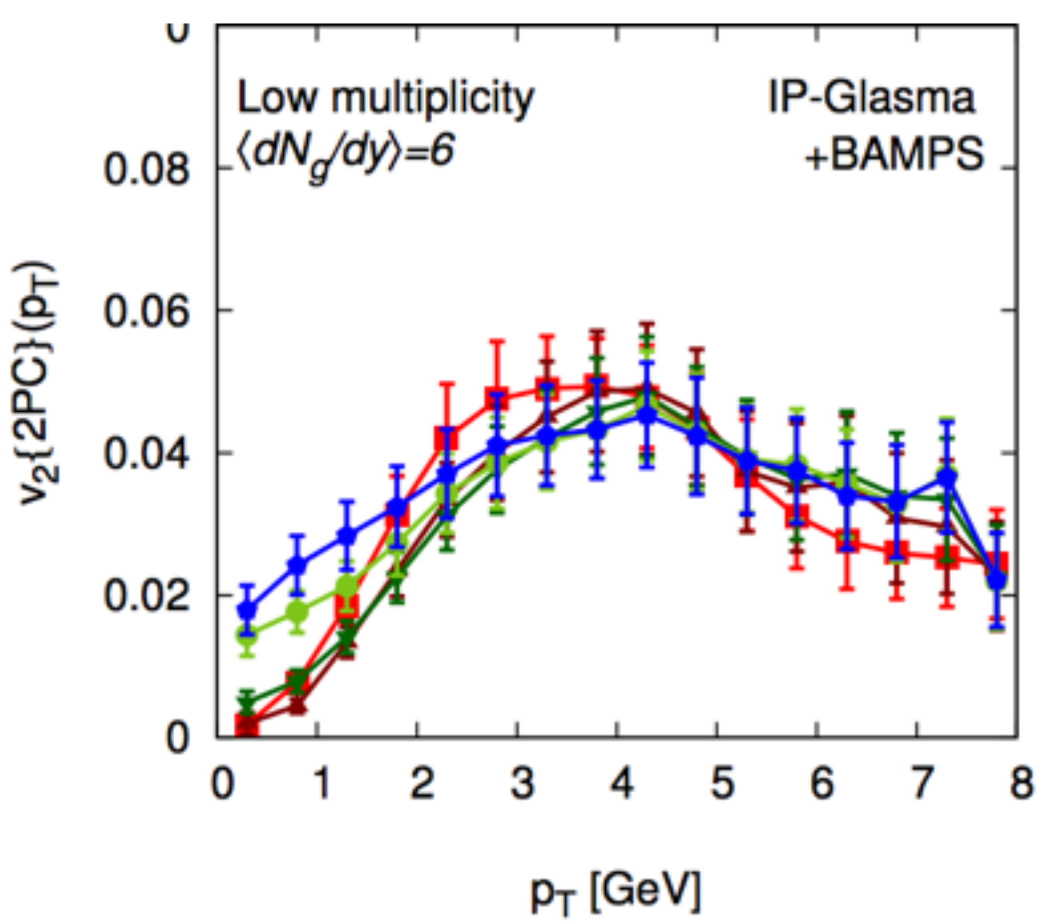


-> Extract time evolution of partonic v_2 to assess the relative importance of initial state & final state effects in small systems

High multiplicity vs. low multiplicity

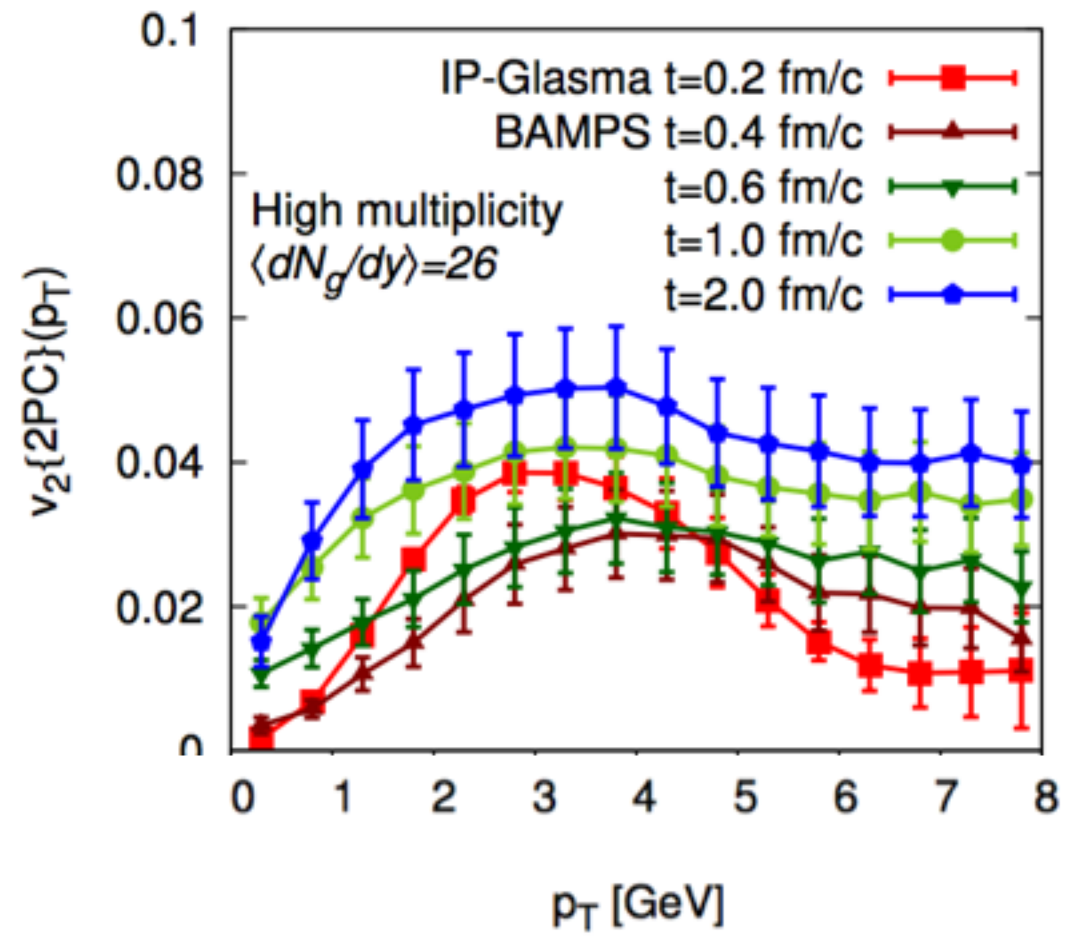
(Greif, Greiner, Schenke, SS, Xu arXiv:1708.02076)

low mult. p+Pb



Very little modification of initial state correlations

high mult. p+Pb



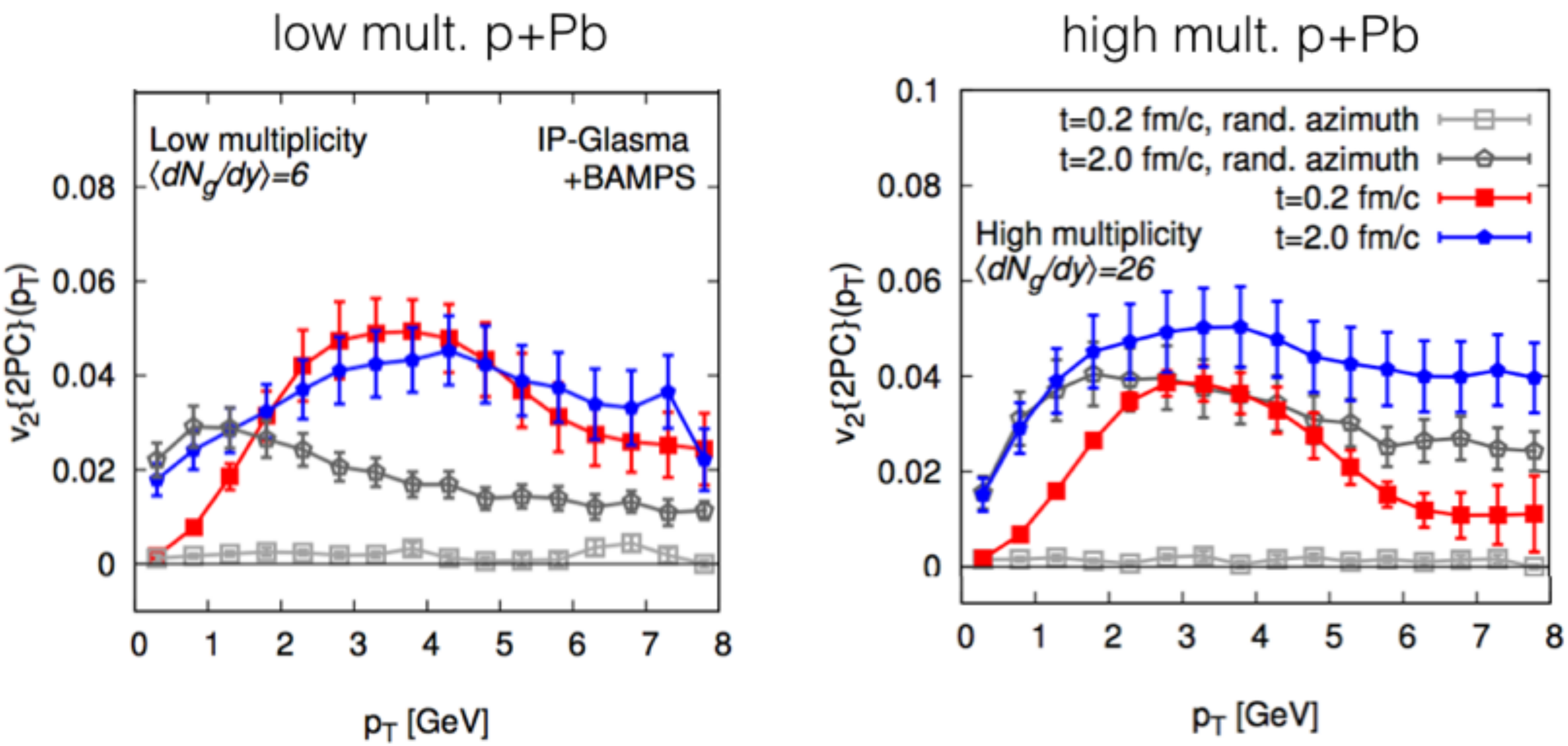
Strong modification of initial state correlations

Significant difference between low and high-multiplicity events, due to larger number of large angle scatterings

Initial state vs. final state effects

(Greif, Greiner, Schenke, SS, Xu arXiv:1708.02076)

Isolate different effects by manually removing initial state momentum correlations



low p_T (<2 GeV): dominance of final state effects

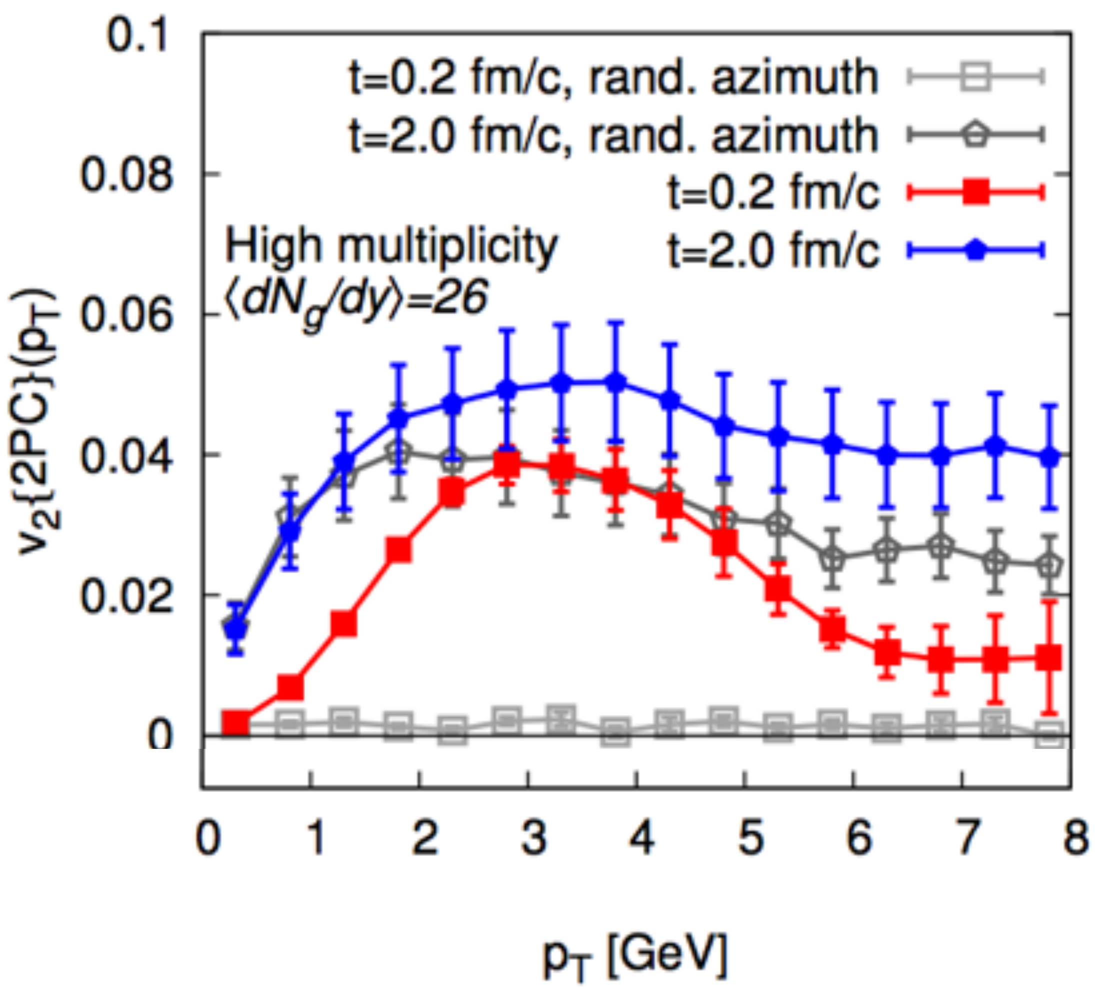
high p_T (>2 GeV): competition of initial & final state

Initial state vs. final state effects

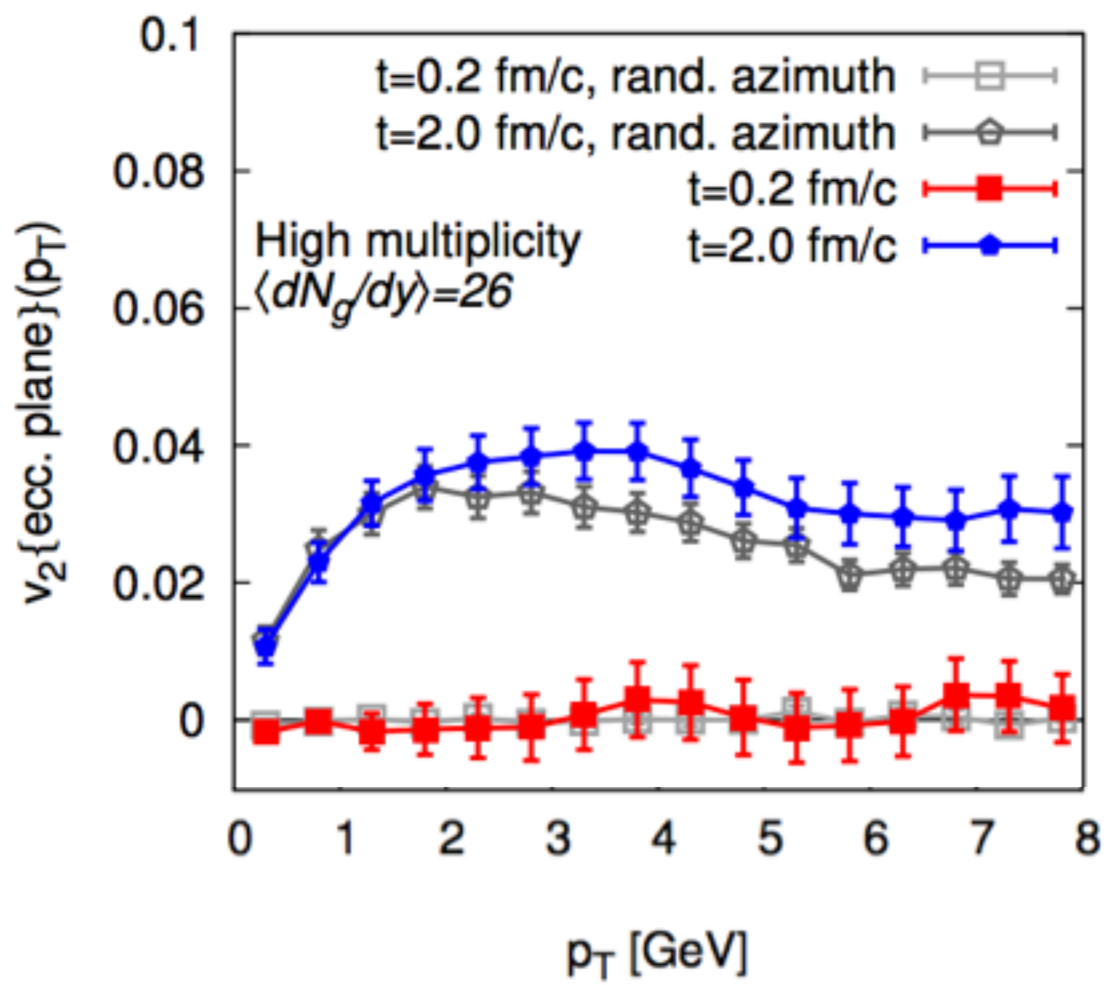
(Greif, Greiner, Schenke, SS, Xu arXiv:1708.02076)

Compare $v_2\{2\}$ with correlation w.r.t to geometric eccentricity plane

2-PC



Ecc. plane



Even though average number of scatterings per particle is quite small (N_{Scat} = 5.6 ±1.1) with only large angle scatterings ($N_{large\ angle}$ = 1 ± 0.18), low momentum v_2 in high multiplicity events is of geometric origin

Initial state vs. final state effects

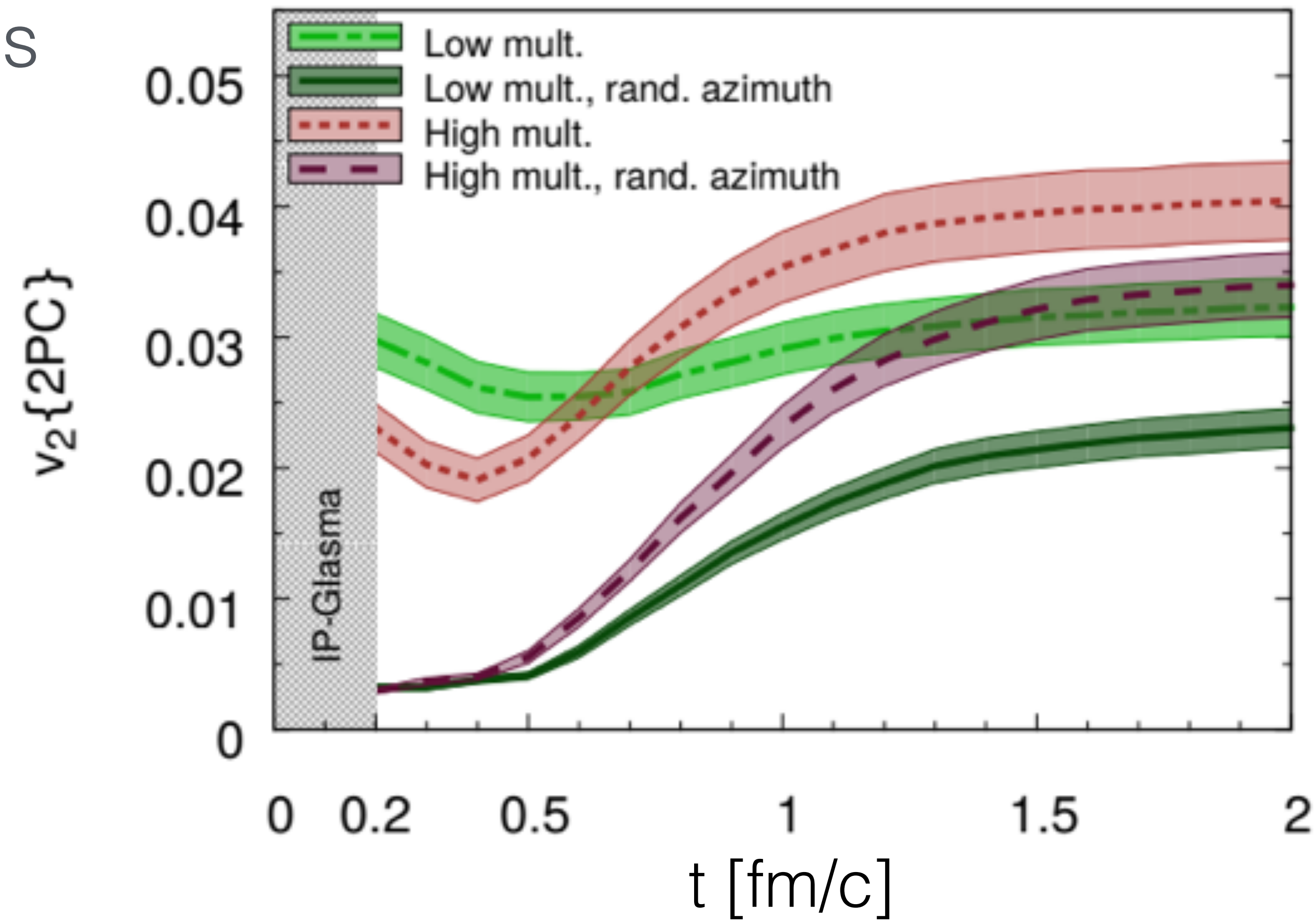
(Greif, Greiner, Schenke, SS, Xu arXiv:1708.02076)

Evolution of azimuthal correlations

t~0 - 0.2 fm:
Dominated by initial state

t~0.2 - 0.5 fm:
Scatterings partially destroy initial state correlation.

t~0.5 - 1.0 fm:
New correlations build up in response to geometry



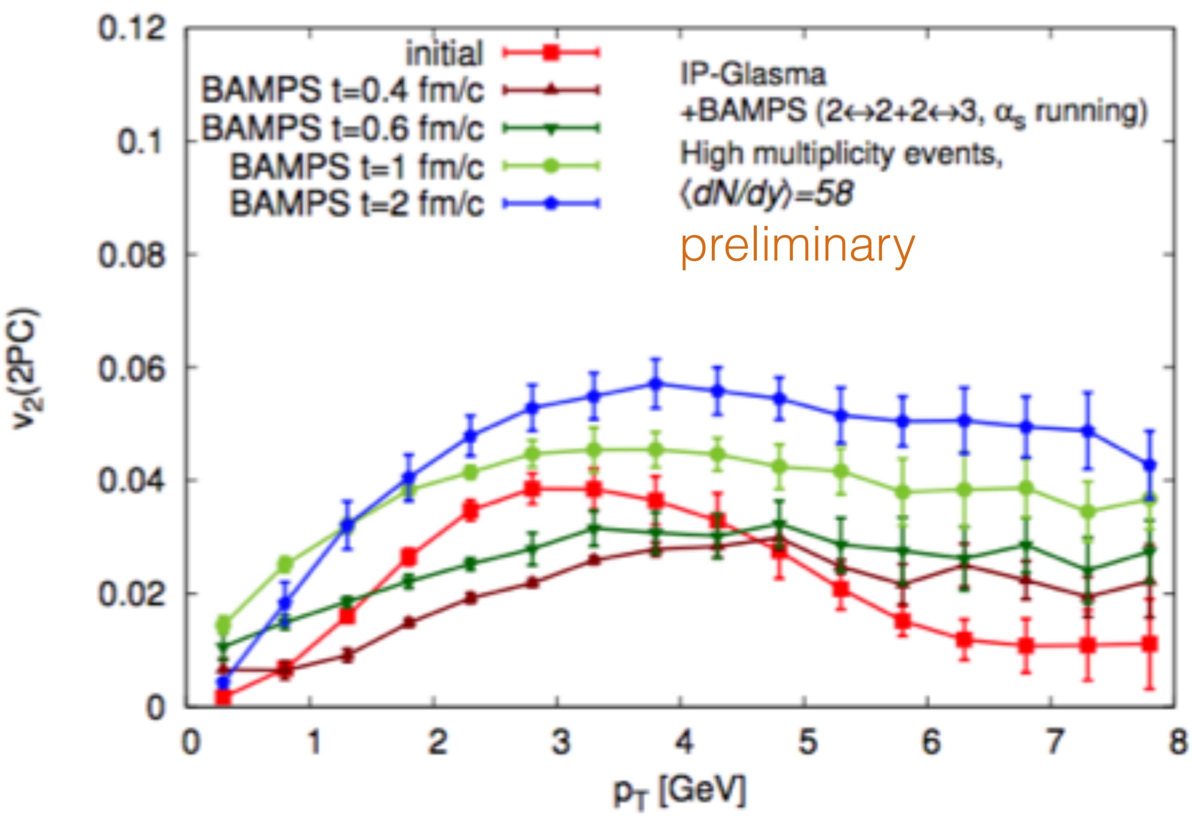
Even though geometric response ultimately dominates at low p_T, there are still sizable effects of initial state correlations even on the p_T integrated v_2 (~25 % for high.mult. and ~50% for low mult.)

Sensitivity to pre-equilibrium dynamics

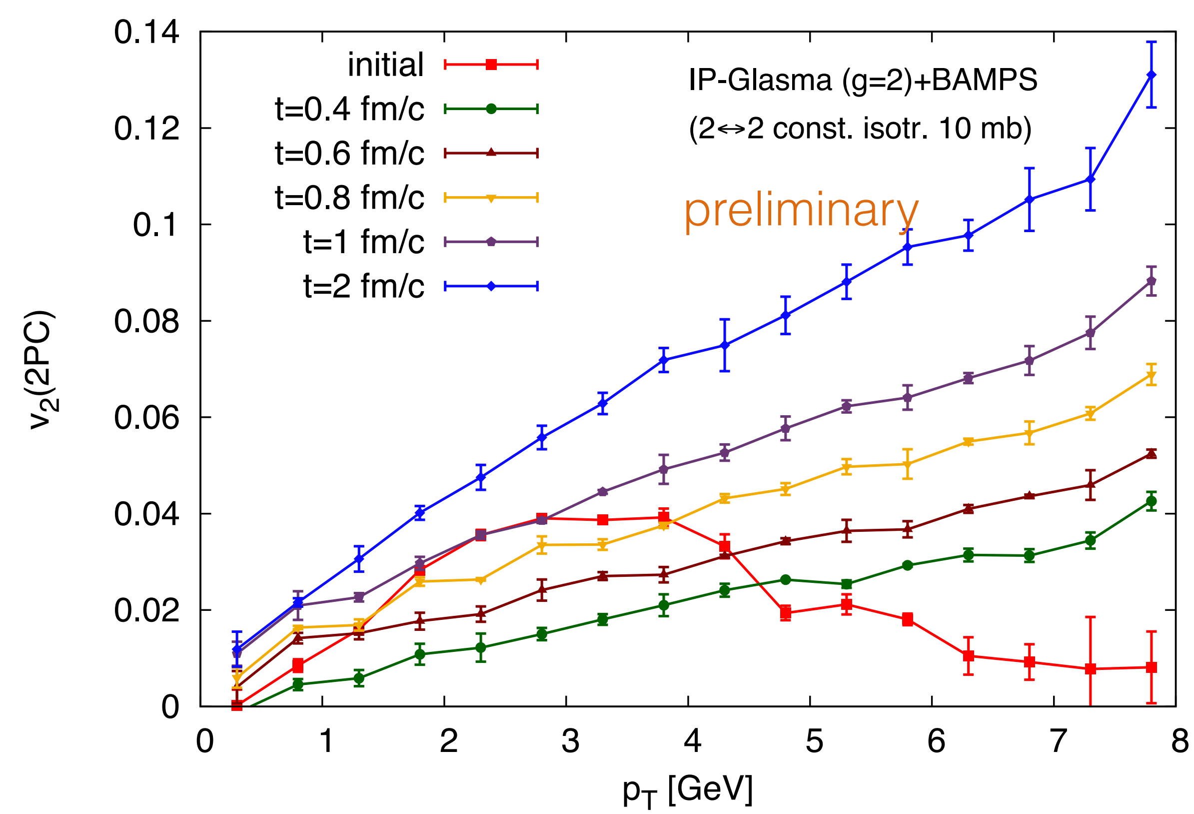
(Greif, Greiner, Schenke, SS, Xu work in progress)

Quantitative features of evolution is quite sensitive to pre-equilibrium dynamics — initial state correlations never washed out completely

pQCD



const. isotropic cross-section



Clear discrepancy between 2<->2 and 2<->3 pQCD processes and naive toy model with const. isotropic cross-section (at lest at high p_T)

Prove of principle that azimuthal correlations in small systems can provide sensitivity to pre-equilibrium dynamics

Conclusions & Perspectives

Early time pre-equilibrium dynamics is key to develop a unified picture of the space-time evolution of hadronic collisions from pp to AA

Completely dynamical description possible within weak coupling approach

A+A: Event-by-event initial conditions for hydrodynamic simulations

p+p/A: Constraints of formation of thermalized QGP

Non-equilibrium simulations of small systems

-> Clear demonstration that both initial state & final state effects are important with relative strength dependent on multiplicity & transverse momentum

Change of paradigm: Consistent theoretical description across experimental range of multiplicities and transverse momenta requires both initial state and final state effects

Still lots of work to be done concerning in particular interplay soft physics <-> high-p_T/jets

INT program - "Origins of Correlations in High Energy Collisions"

Organizers: A. Dumitru, C. Loizides, B. Schenke, S. Schlichting

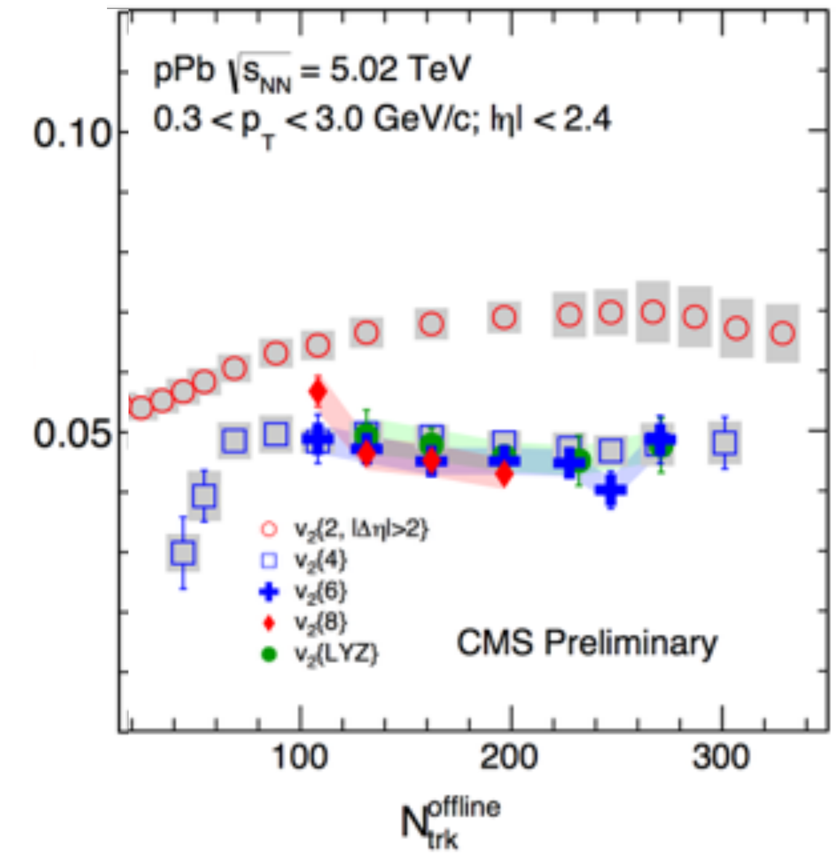
Subject to funding constraints of INT

Dates (tentative): April 29 - May 24, 2019

Backup

Collective behavior?

Higher order cumulants (m>2) provide clear evidence that (some of) correlations are between many particles

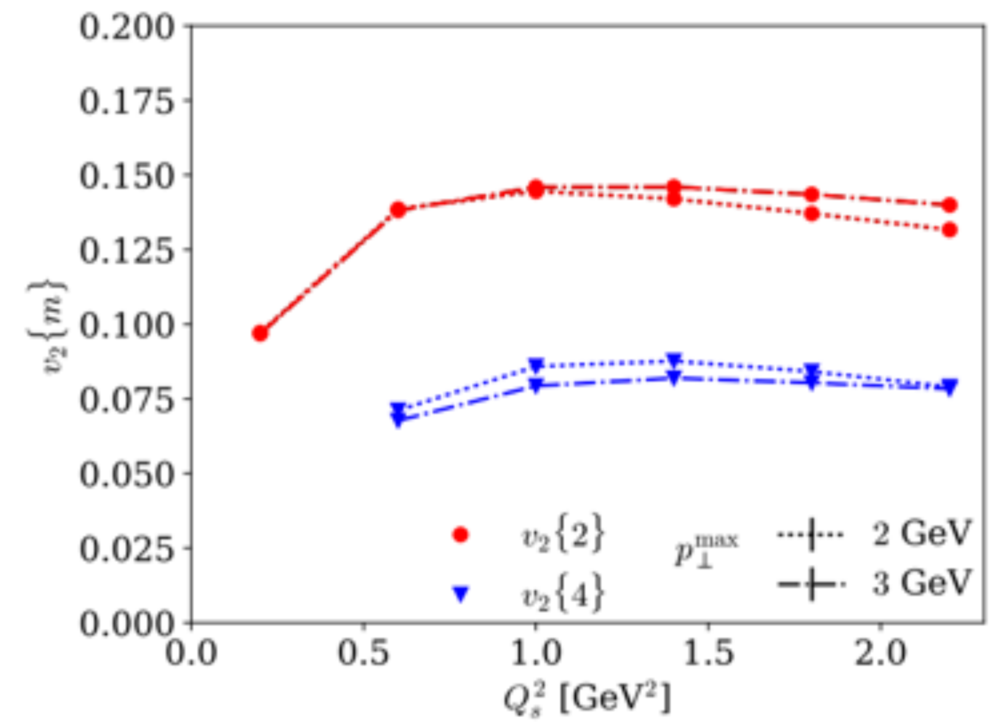


Clearly geometric correlations with the event geometry carry over to all (low p_T) particles

-> naturally expect sizable $v_n\{m\}$ (m>2) in microscopic non-equilibrium framework

Genuine multi particle correlations also present in initial state

Dusling, Mace, Venugopalan arXiv:1705.00745



Dusling, Mace, Venugopalan arXiv:1705.00745

Should expect contributions from both; important to clarify dominant effects within combined framework