Collectivity in small systems — Initial state vs. final state effects

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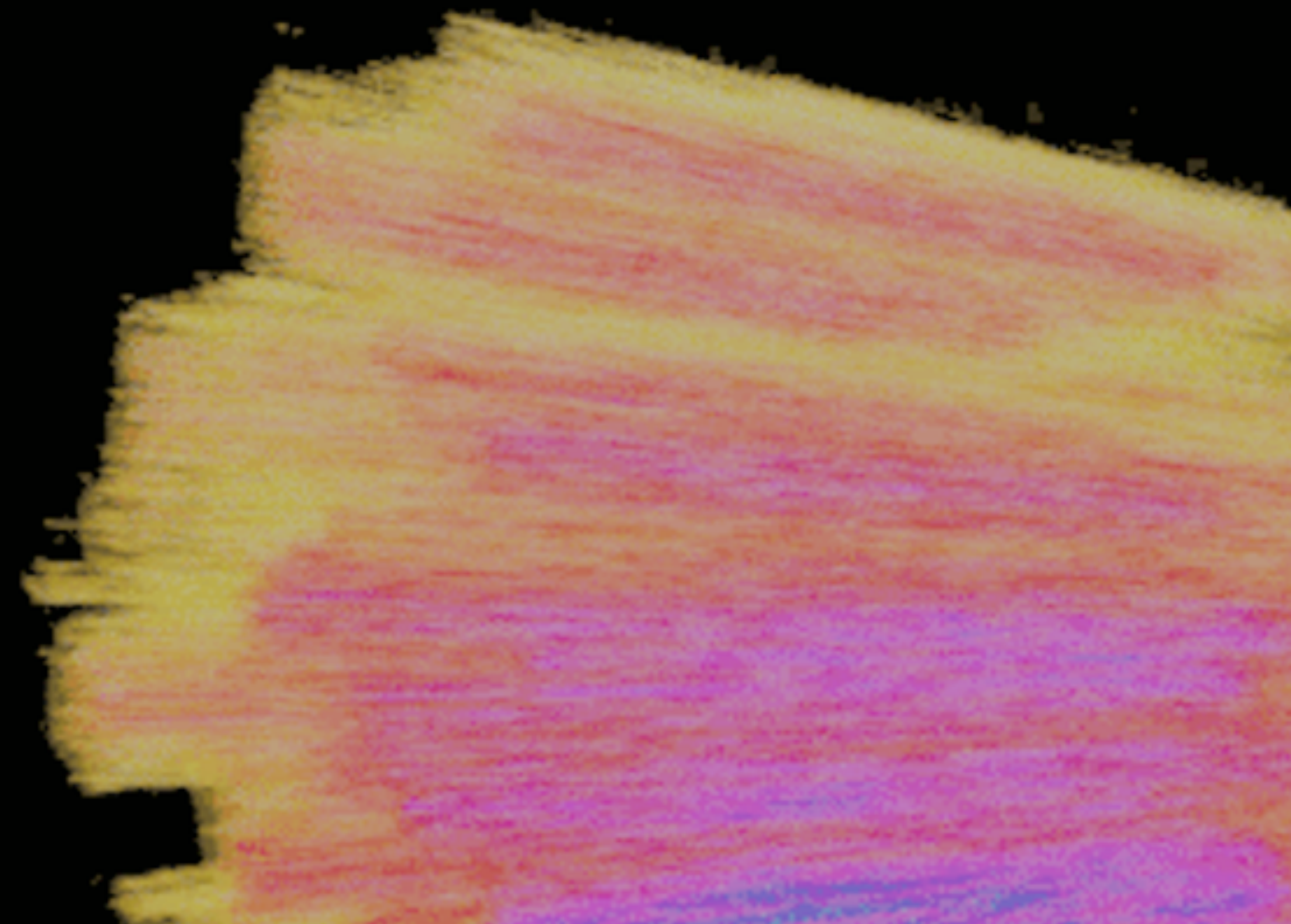

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Outline

- General perspective on initial state vs. final state effects as origin of azimuthal correlations high-multiplicity p+p/A

  - Hydrodynamic description of p+p/A

  - Initial state momentum correlations

  State of the art of phenomenological calculations

  Reviews: Dusling,Li, Schenke, Int.J.Mod.Phys. E25 (2016) no.01, 1630002
  Schlichting, Tribedy, Adv. High Energy Phys. Vol. 2016 (2016), 8460349

- New developments to quantify rel. importance of Initial state & final state effects

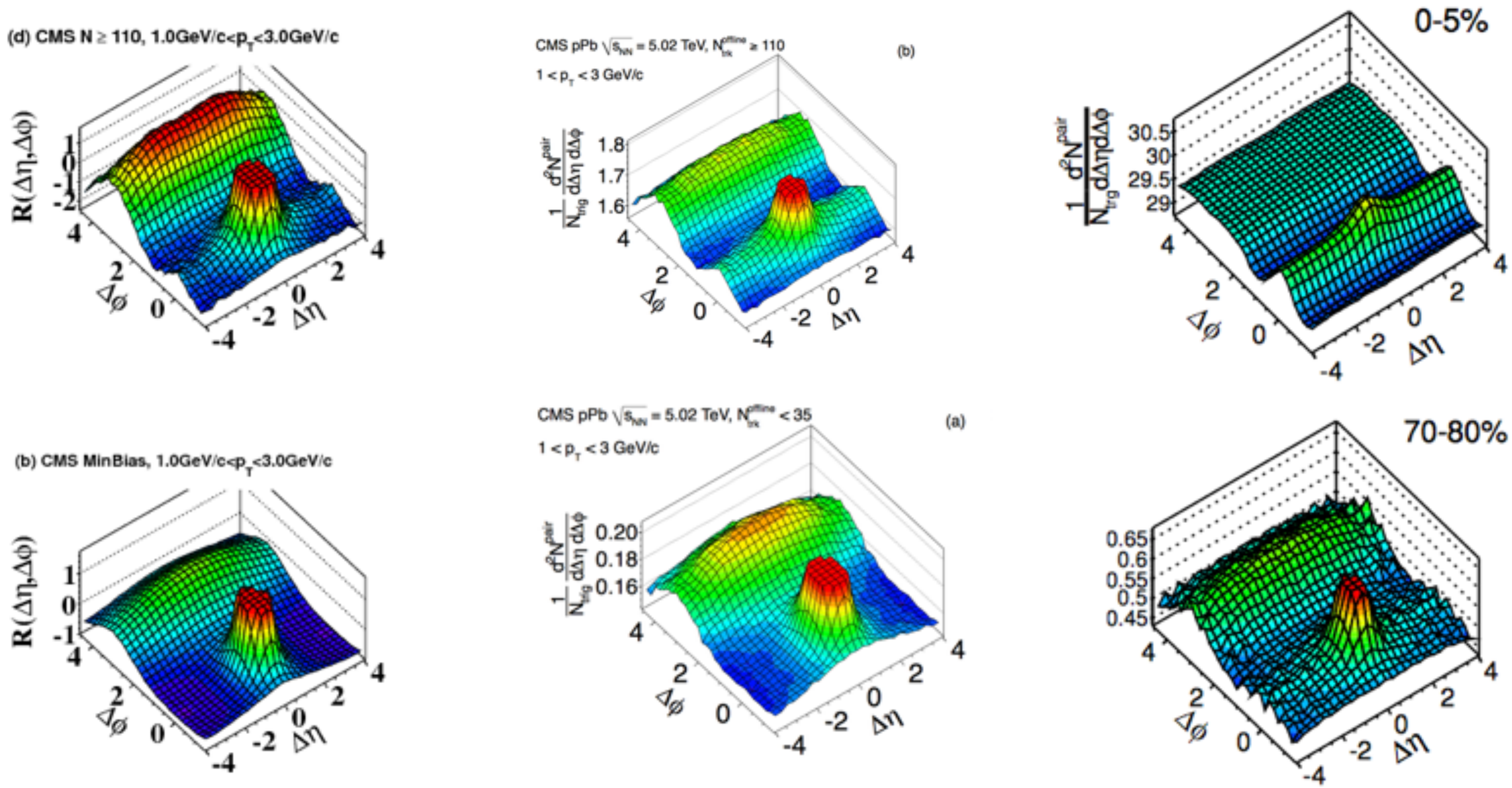
  Based on Greif, Greiner, Schenke, SS, Xu arXiv:1708.02076

- Conclusions & Perspectives

Long-range azimuthal correlations

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

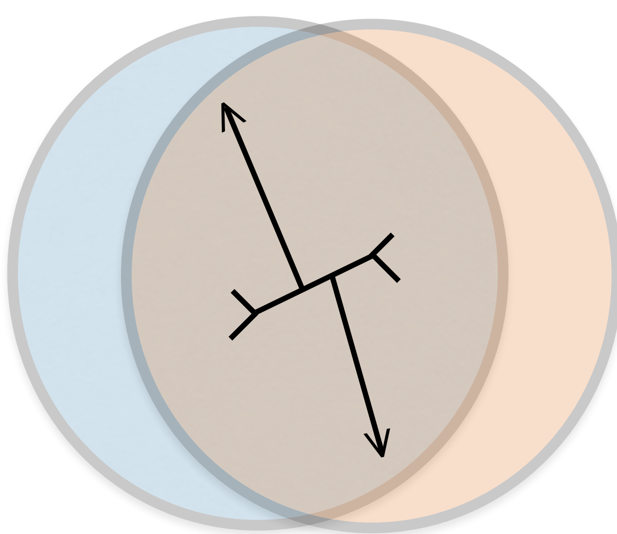
final state response to initial state geometry

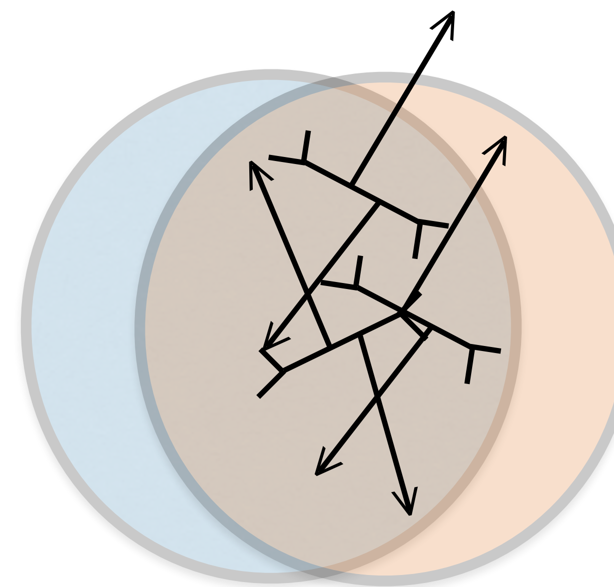
and/or

initial state momentum correlations

Nature of high-multiplicity p+p/A events

High-multiplicity events exhibit exceptionally large parton densities in the initial state

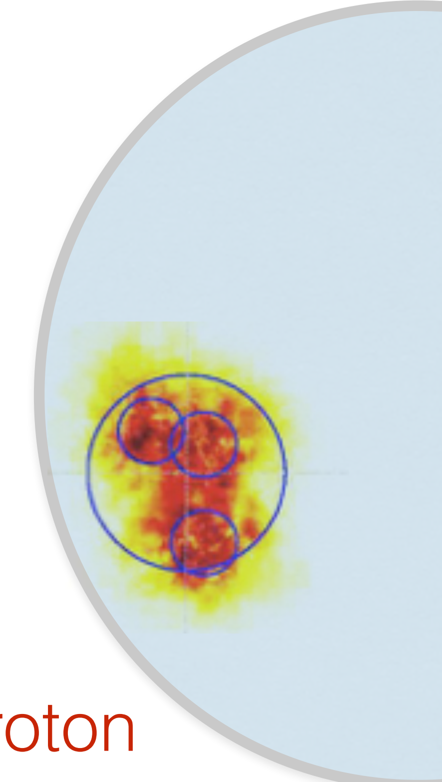




If parton densities in high-multiplicity events are sufficiently large, interaction between produced parsons can be significant

-> Creation of small droplet of QGP?
Space-time dynamics similar to A+A collision?

Hydrodynamic description of p+p/A



Generating azimuthal correlations as a response to initial state geometry requires a non-trivial event geometry

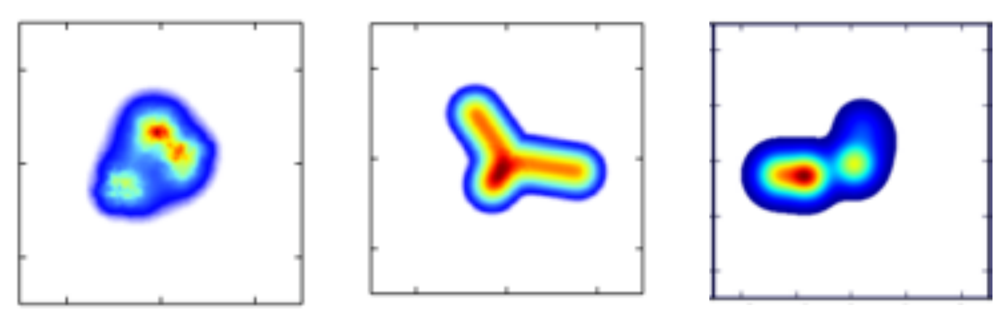
Event geometry in p+p/A collisions closely reflects impact parameter dependence of gluon distribution in proton

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



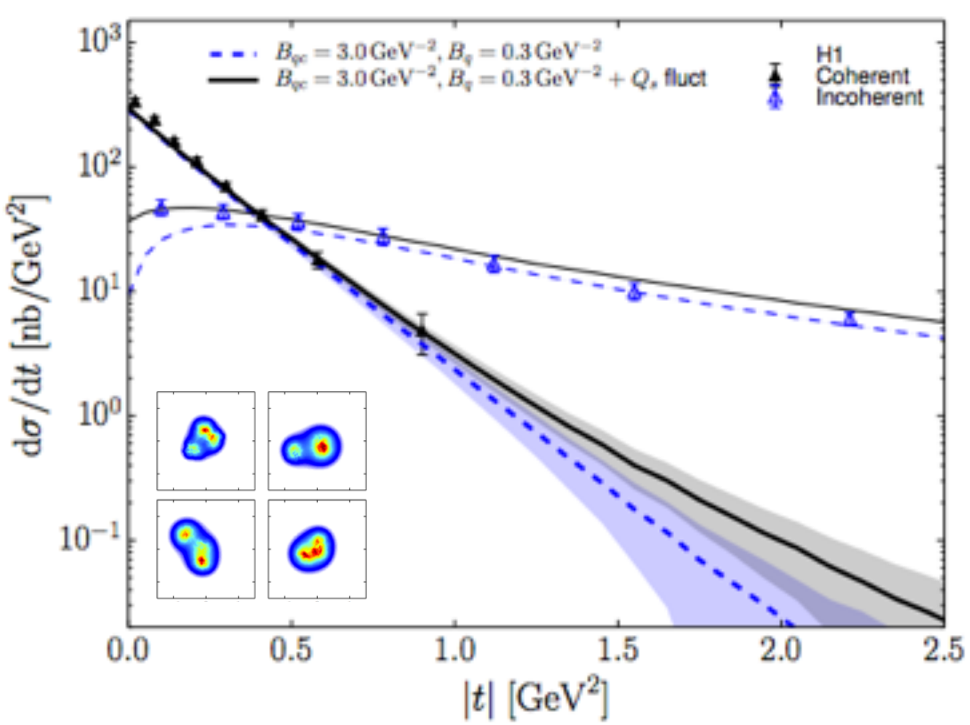
…

need to be independently constrained to be of predictive value

Hydrodynamic description of p+p/A

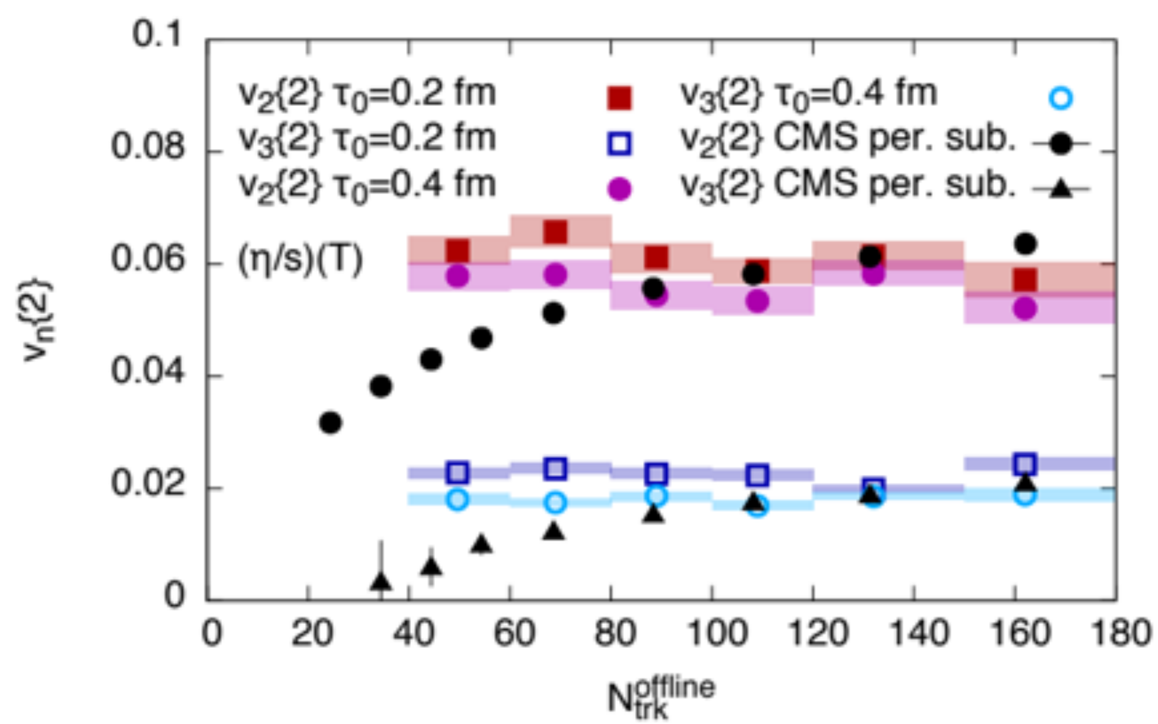
Constrain geometric fluctuations from incoh. diff. J/Ψ production as an input for event-geometry in p+Pb collisions

e+p -> e+p*+J/Ψ



Mäntysaari. Schenke PRD94 (2016) no.3, 034042

p+Pb

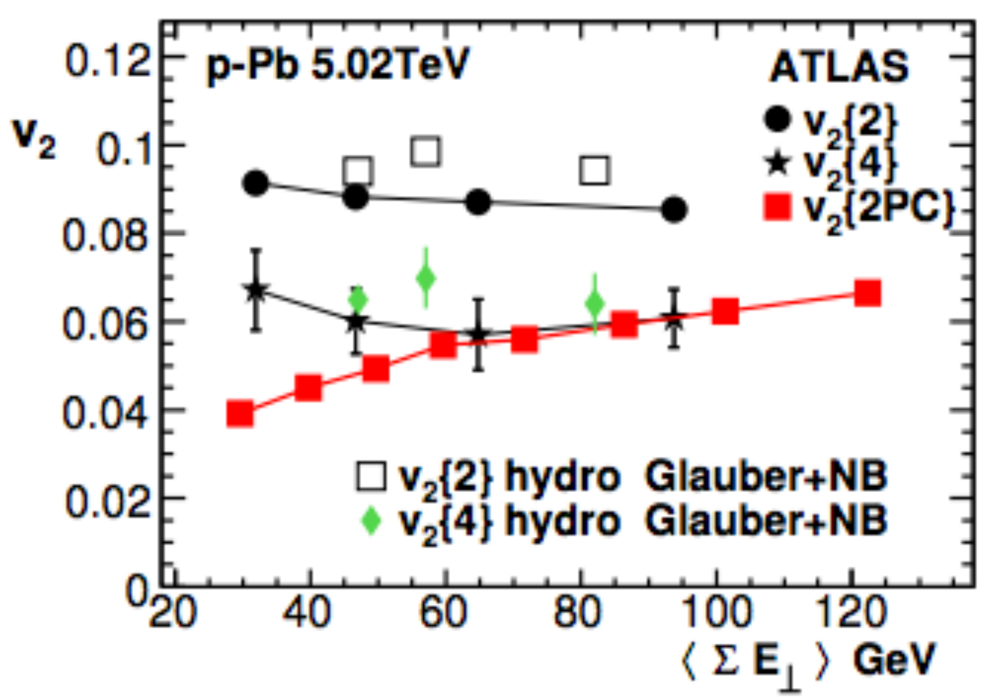


Mäntysaari. Schenke, Shen,Tribedy PLB772 (2017) 681-686

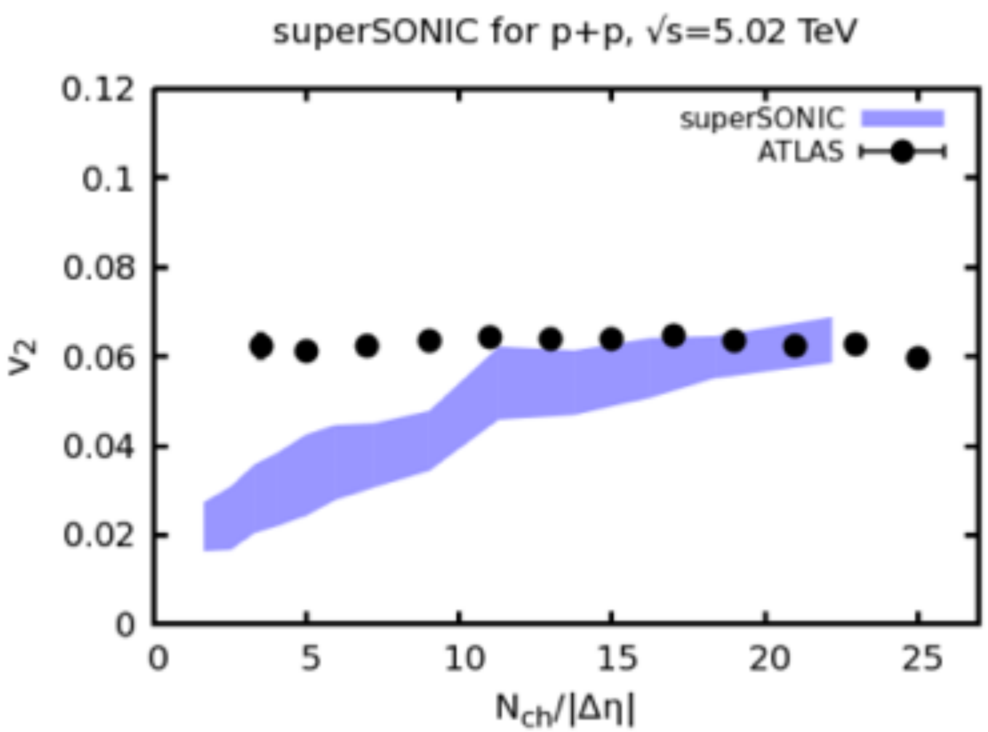
Consistent amount of geometric fluctuations of the proton needed to describe e+p and p+Pb data

Hydrodynamic description of p+p/A

Various calculations by different groups



P. Bozek, W. Broniowski, G. Torrieri, PRL 111 (2013) 172303.



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?

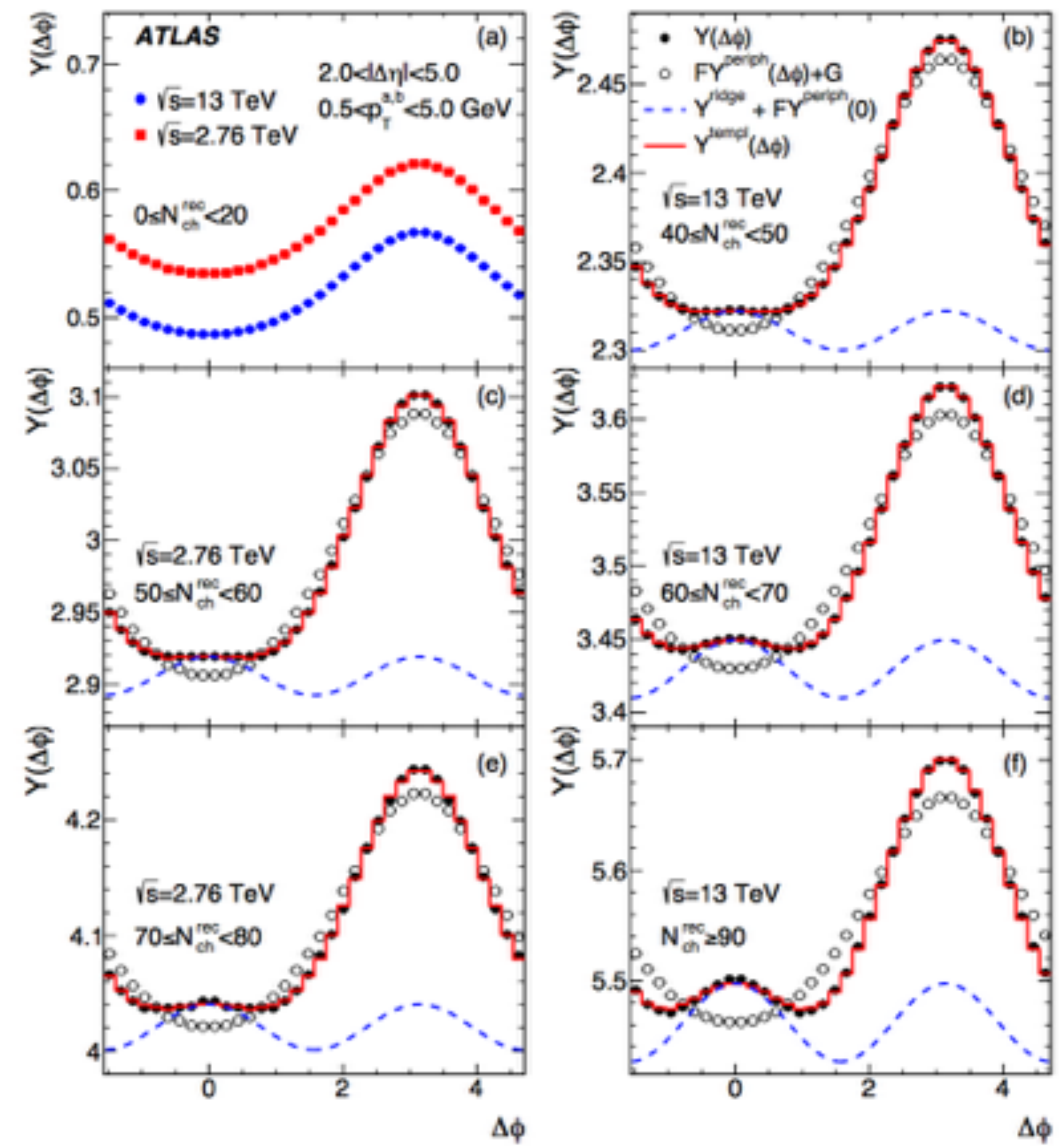
Hydrodynamic description of hadronic collisions only becomes applicable once the system is sufficiently close to local thermal equilibrium

Based on current understanding of pre-equilibrium dynamics

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

Hydrodynamic description requires significant quenching of mini jets $\sim Q_S$

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

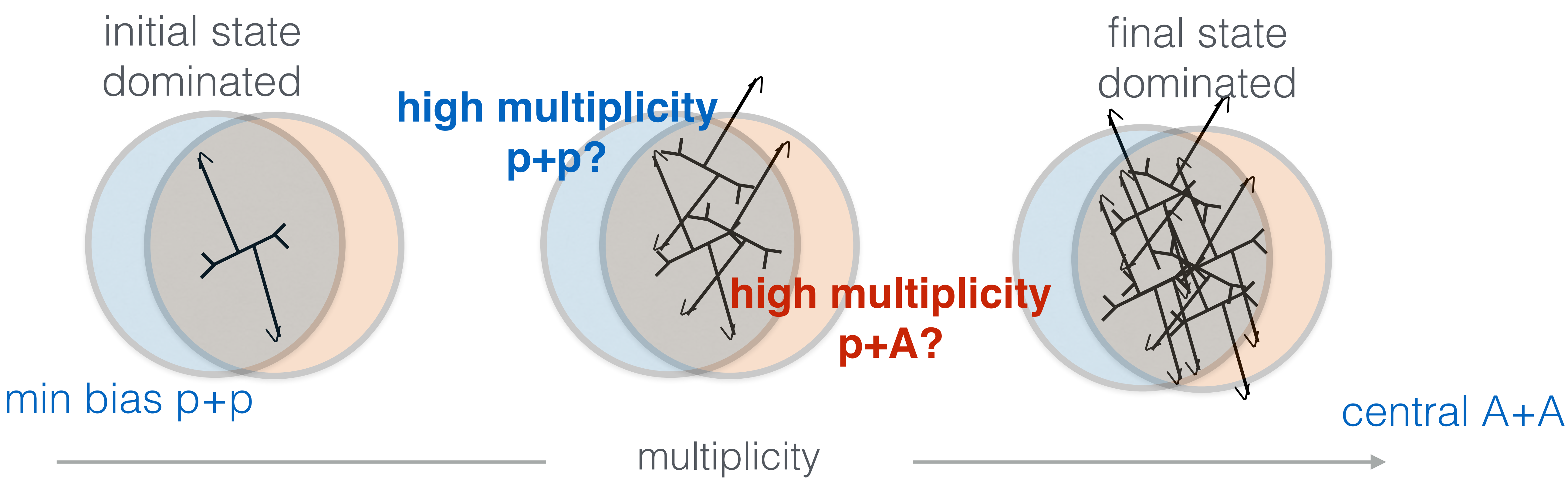


ATLAS
PRL 116 (2016) no.17, 172301

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

Collectivity in small systems w/o hydrodynamics?

Even though final state effects will eventually dominate at very high multiplicity, wether or not this point is reached in p+p/A collisions at RHIC and LHC



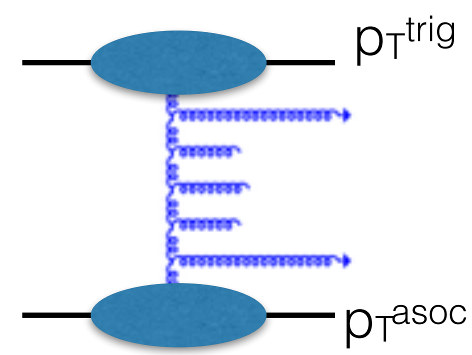
Experimentally observed correlations could also reflect modifications of initial state/early time dynamics in regime of high parton densities

Initial state correlations

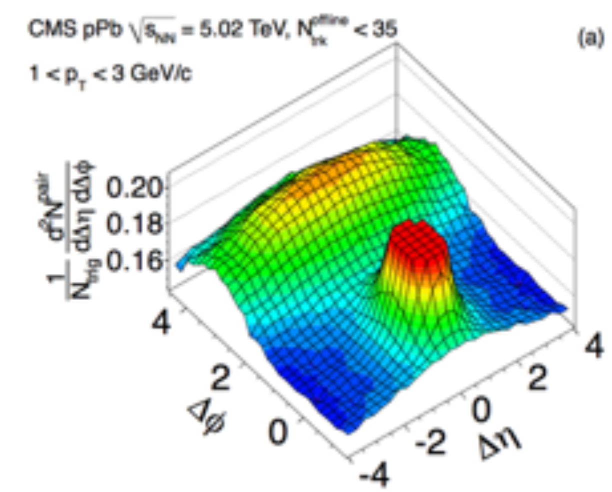
QCD multi-particle production gives rise to intrinsic momentum space correlations present in the initial state

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

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

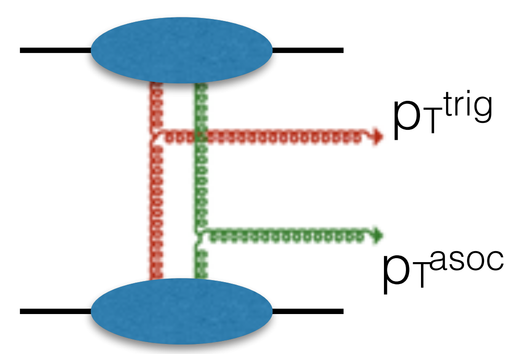


"Jet graph"

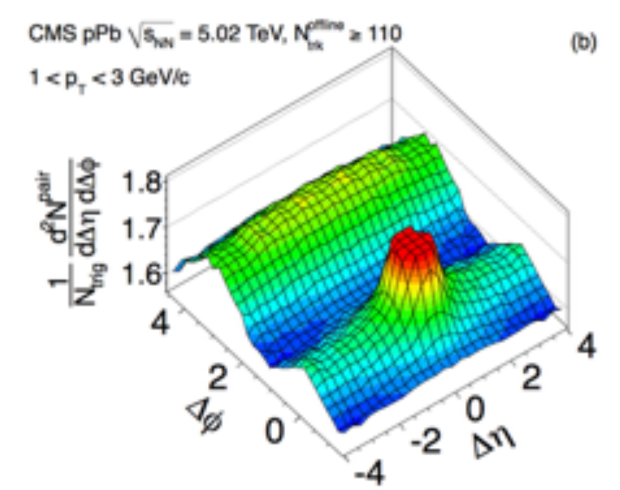


Bose-enhancement of small x gluons
gives rise to intrinsic multi-parton
correlation for $p_T \sim Q_s$ in high mult. events

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

Initial state multi-particle production

k_T factorization

Dumitru, Dusling, Gelis, Jalilian-Marian, Lappi, Venugopalan PLB 697 (2011) 21-25

Dusling, Venugopalan PRD 87 (2013) 5, 051502, PRD 87 (2013) 5, 054014, PRD 87 (2013) 9, 094034

Dusling,Tribedy, Vengopalan PRD 93 (2016) 1 014034

Hybrid formalism

Dumitru,Giannini NPA933 (2015) 212-228

Dumitru,McLerran,Skokov PLB 743 (2015) 134-137

Lappi PLB 744 (2015) 315-319

Lappi,Schenke,SS,Venugopalan JHEP 1601 (2016) 061

McLerran,Skokov NPA 947 (2016) 142-154

Dusling, Mace, Venugopaplan arXiv:1705.00745

Event-by-event classical Yang-Mills simulations

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

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

Hadronization

Fragmentation functions

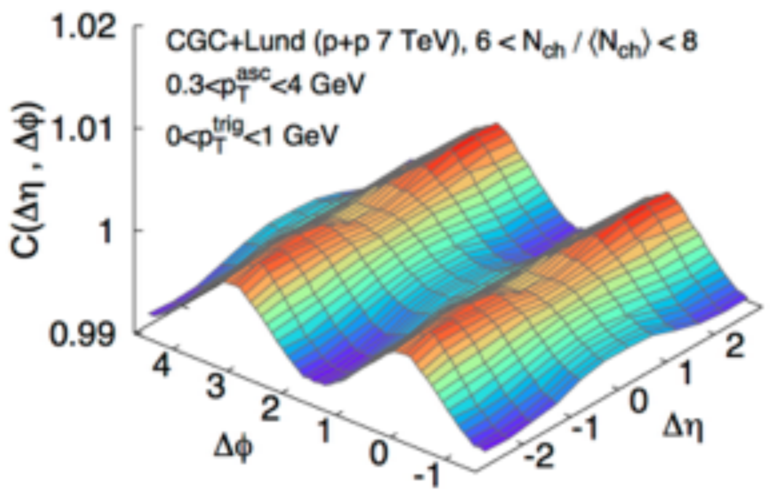
N/A

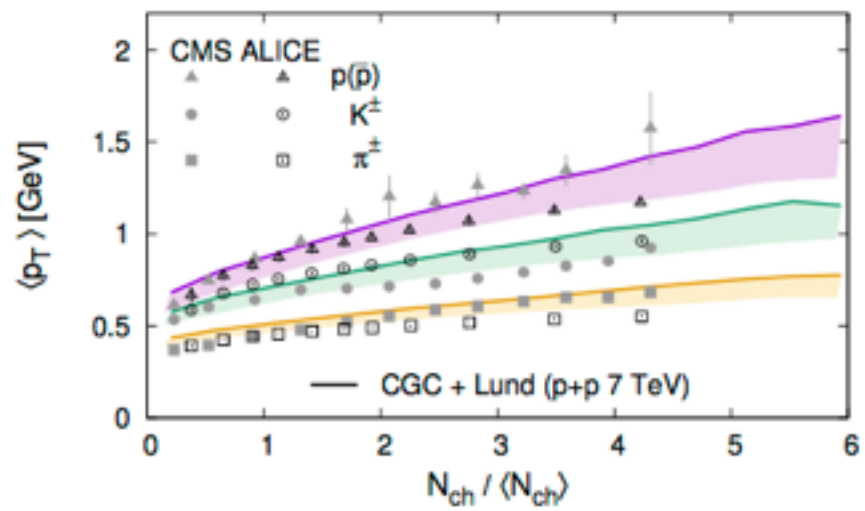
Monte-Carlo scheme (PYTHIA HSA)

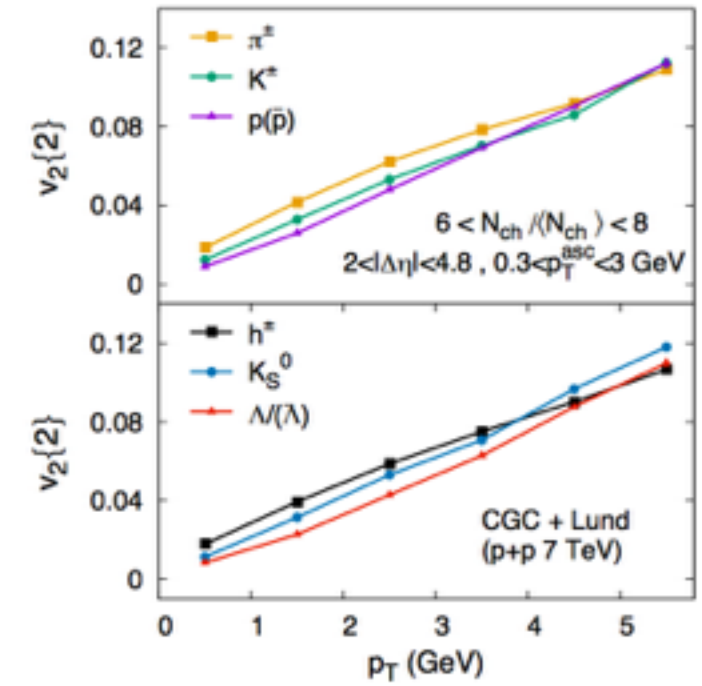
Generally the correlation is $\sim 1/N_c^2$,long range in rapidity and strongest when p_T^1, p_T^2,$\cdots\sim Q_s$,

Phenomenological calculations

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

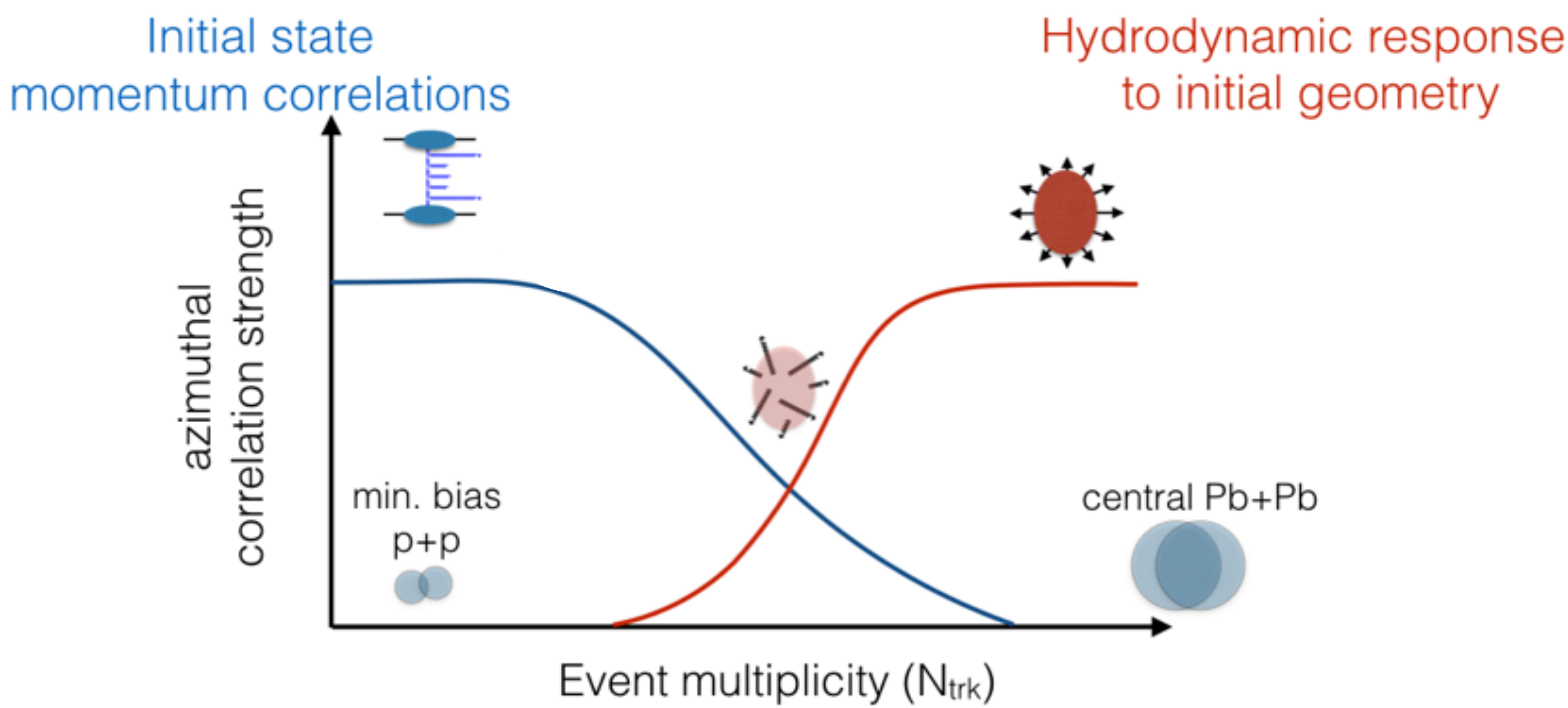
v_2/v_3 , higher-cumulants , v_2 /<p_T>mass ordering, …

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

Qualitative picture of dynamics

Generally speaking to understand the dynamics over the full range of multiplicities from low multiplicity p+p to central A+A collisions we eventually expect to see a transition from initial state to final state dominance

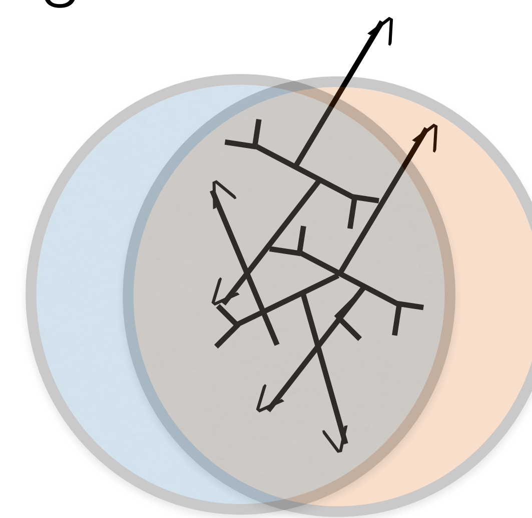


SS, Quark Matter 2015, NPA 956 (2016) 216-221; SS, Tribedy Adv. High Energy Phys. Vol. 2016 (2016), 8460349

Initial state vs. final state effects

Based on recent progress in understanding of pre-equilibrium dynamics at weak coupling, one can attempt to estimate the transition region

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



Criterion: mini-jet equilibration time < system size

Kurkela, Zhu PRL 115 (2015) no.18, 182301

$$Q_s\tau_{eq} \simeq 10(\eta/s)^{4/3}(g^2N_c)^{1/3} \simeq 6 \quad (\eta/s = 5/4\pi \mid \lambda = 10)$$

$$\frac{dN}{dy} \simeq \frac{1}{4}\, Q_s^2 \pi R_p^2 \qquad\qquad \frac{\tau_{eq}}{R_p} \simeq \sqrt{\frac{50}{dN/dy}}$$

Ball-park estimate for transition from initial state to final state regime indicates that a lot of the interesting dynamics observed in high-multiplicity p+p/A collisions could well be in the transition region

Development of new theoretical approaches crucial to describe the relevant physics across wide kinematic range probed in RHIC/LHC experiments

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 ($\tau<0.2$ fm) in classical Yang-Mills theory, based on IP-Glasma framework

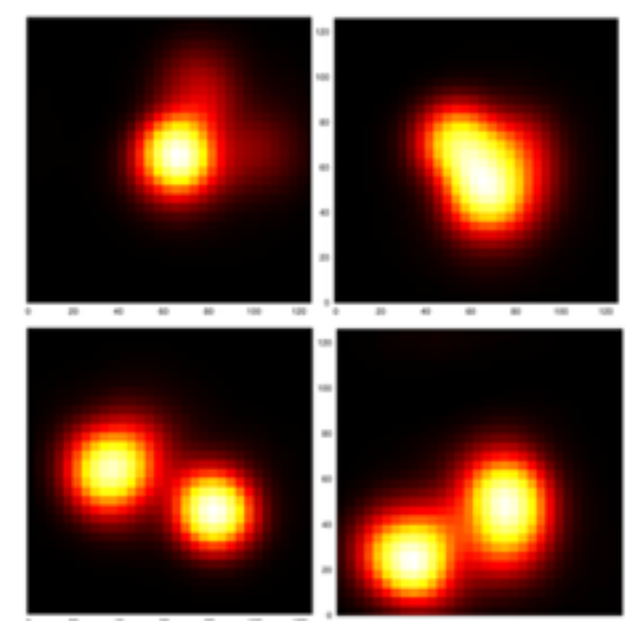
   hadronic structure input constrained by DIS

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

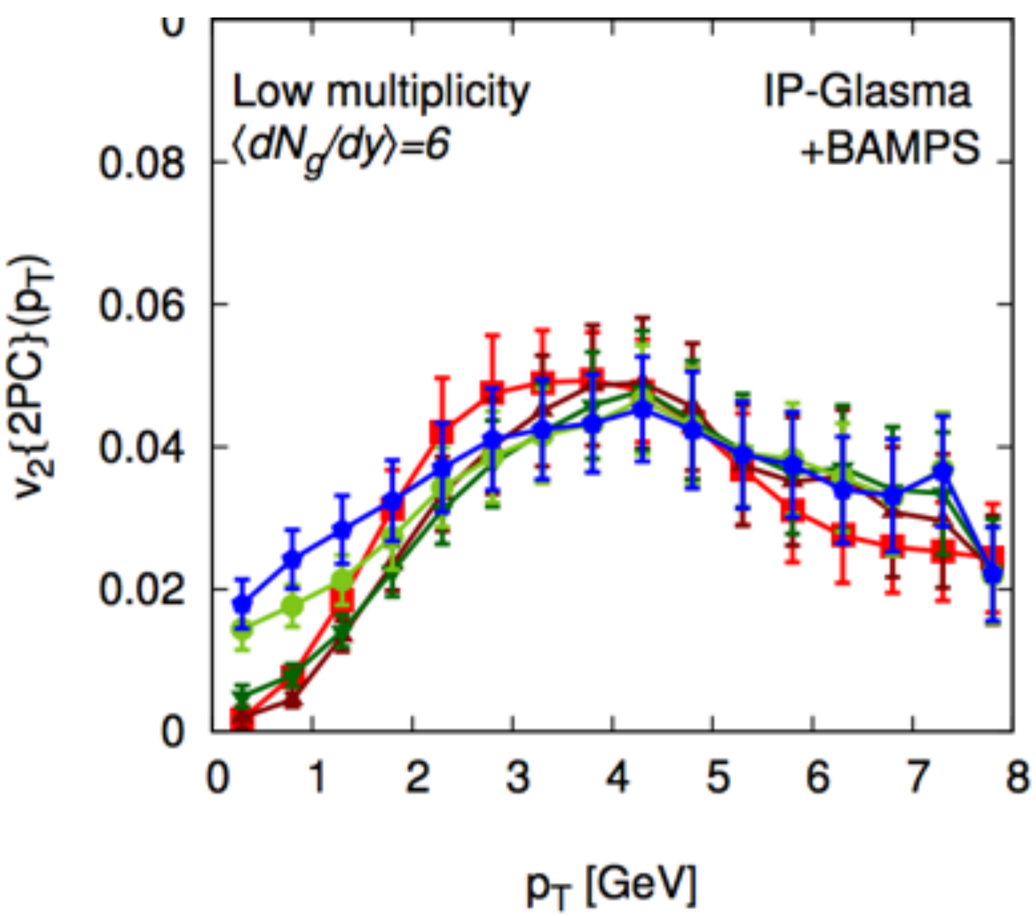


-> Extract time evolution of partonic v_2 to assess the relative importance of initial state & final state effects in small systems

High multiplicity vs. low multiplicity

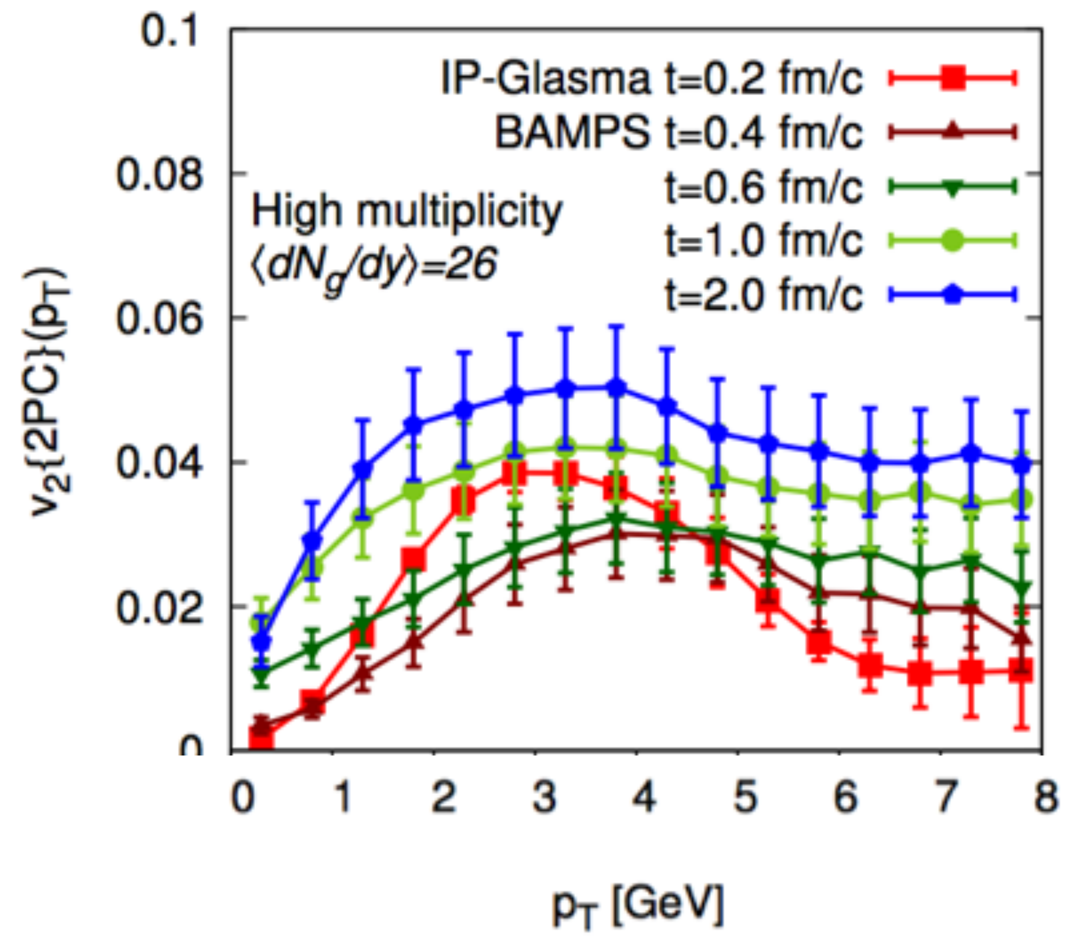
(Greif, Greiner, Schenke, SS, Xu arXiv:1708.02076)

low mult. p+Pb



Very little modification of initial state correlations

high mult. p+Pb



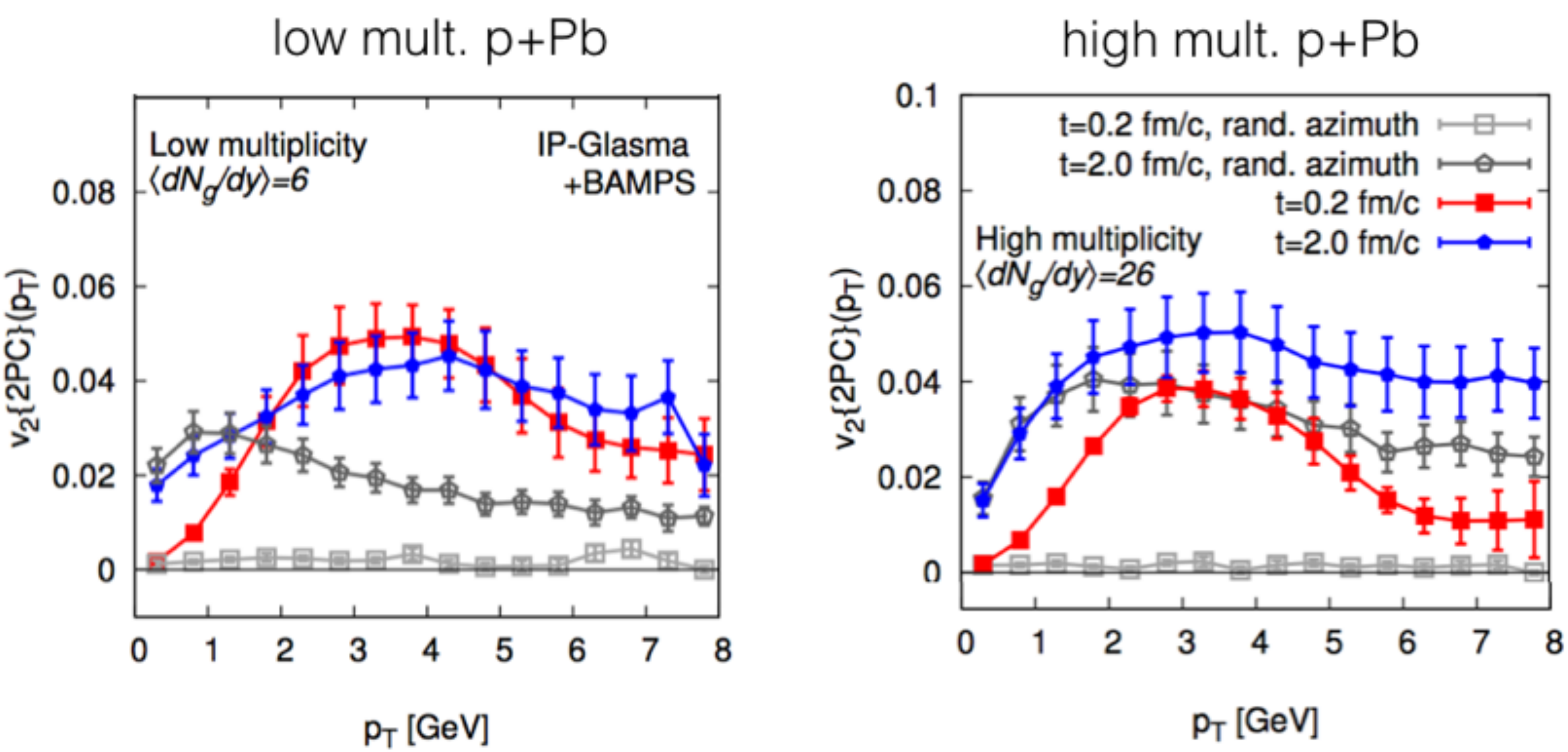
Strong modification of initial state correlations

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



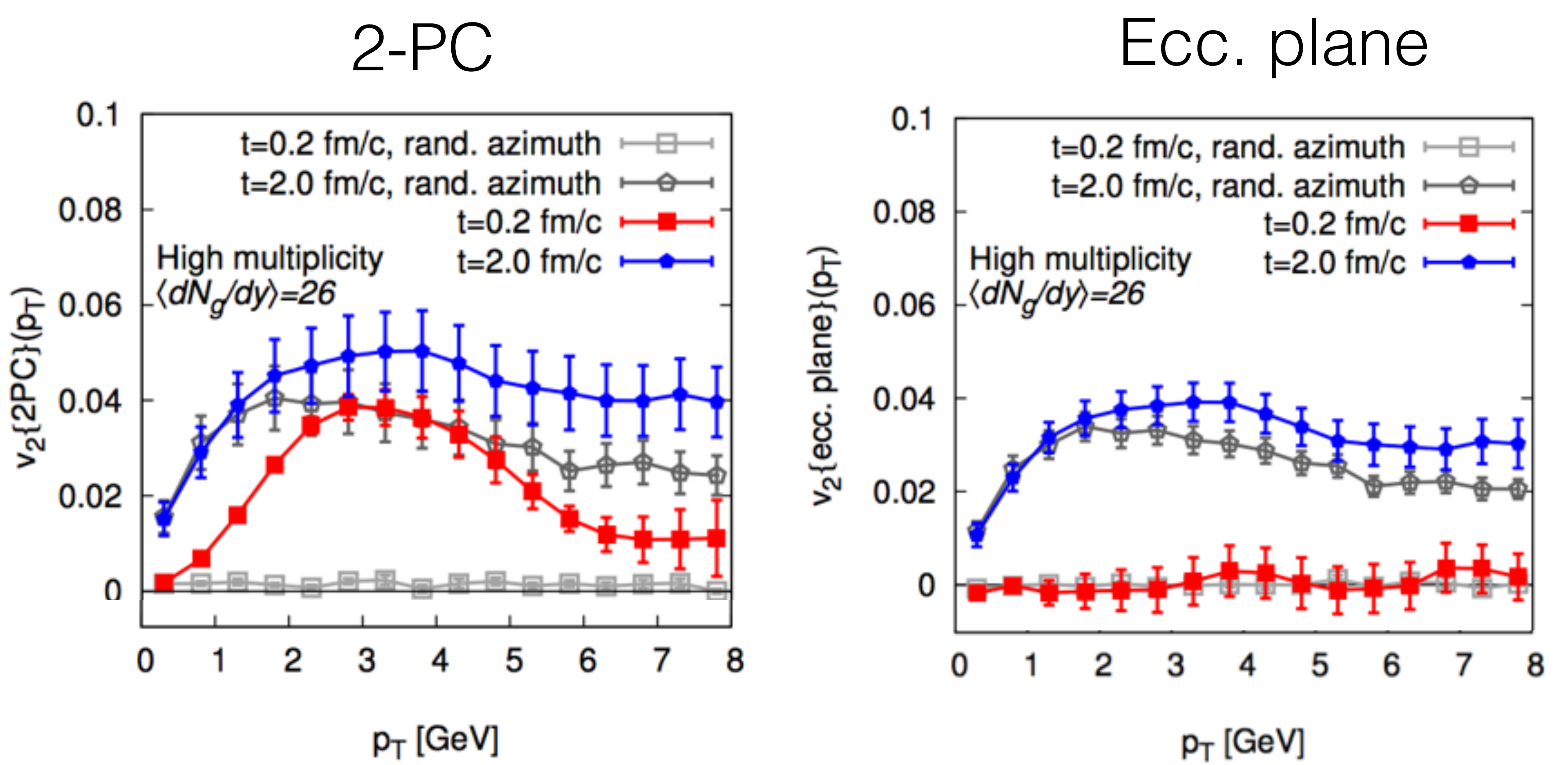
low p_T (<2 GeV): dominance of final state effects

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



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

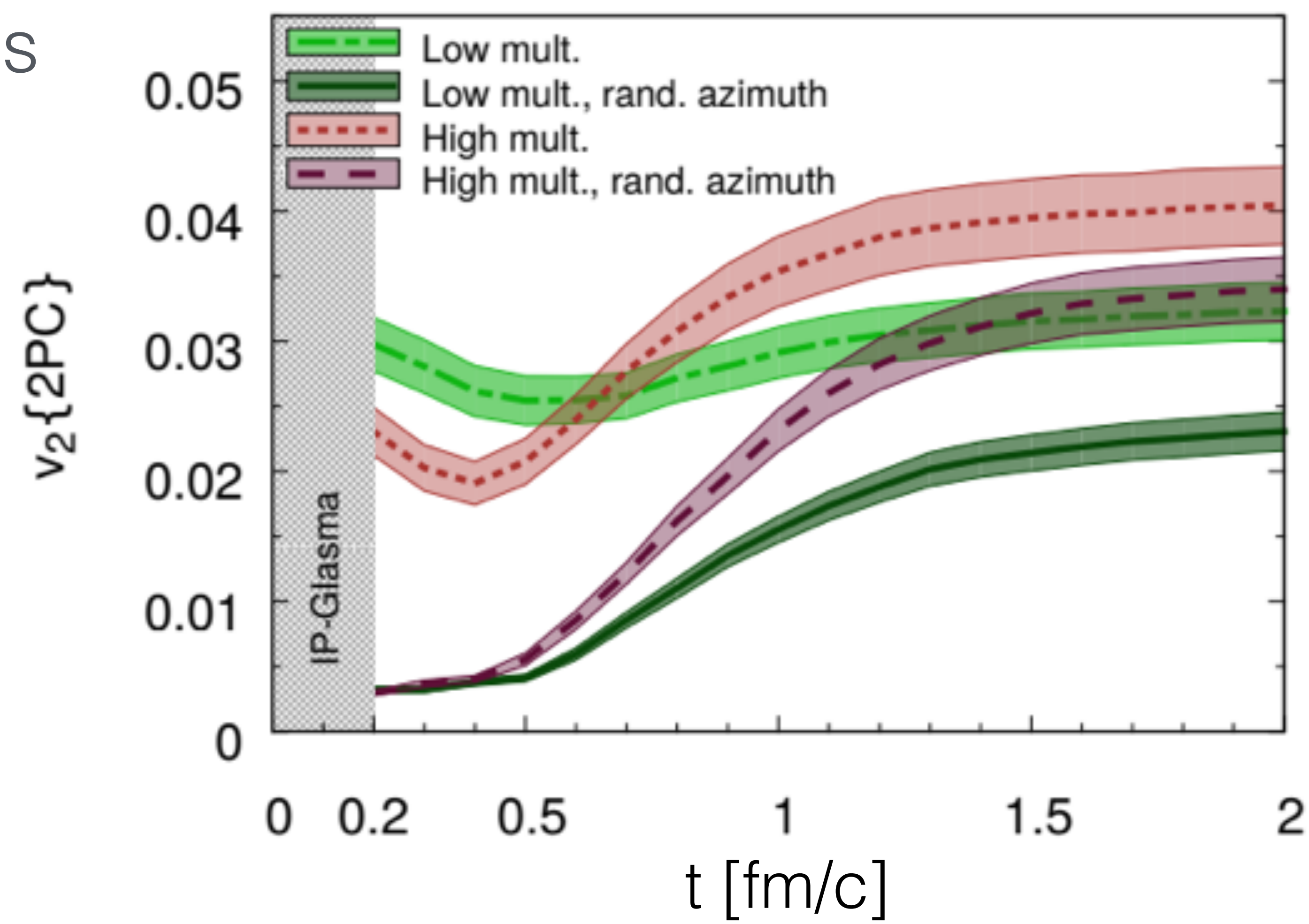
(Greif, Greiner, Schenke, SS, Xu arXiv:1708.02076)

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



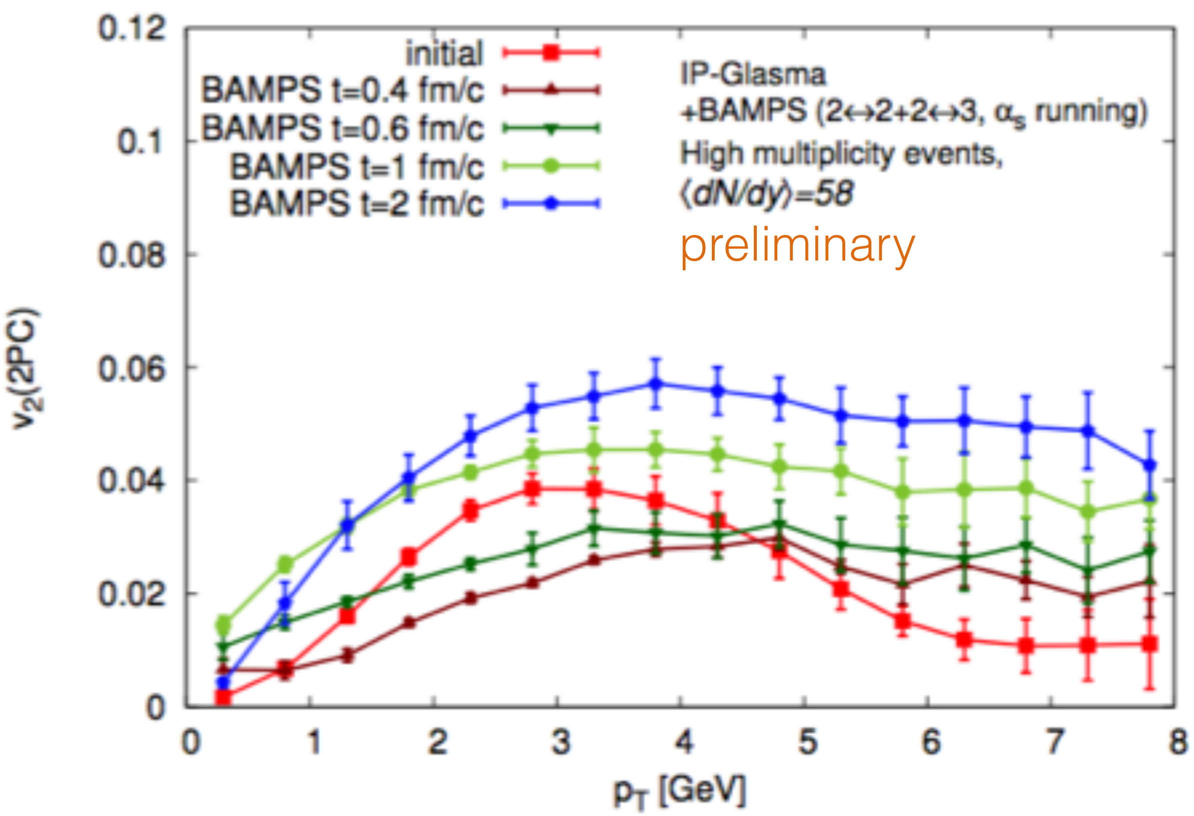
Even though geometric response ultimately dominates at low p_T, there are still sizable effects of initial state correlations even on the p_T integrated v_2 (~25 % for high.mult. and ~50% for low mult.)

Sensitivity to pre-equilibrium dynamics

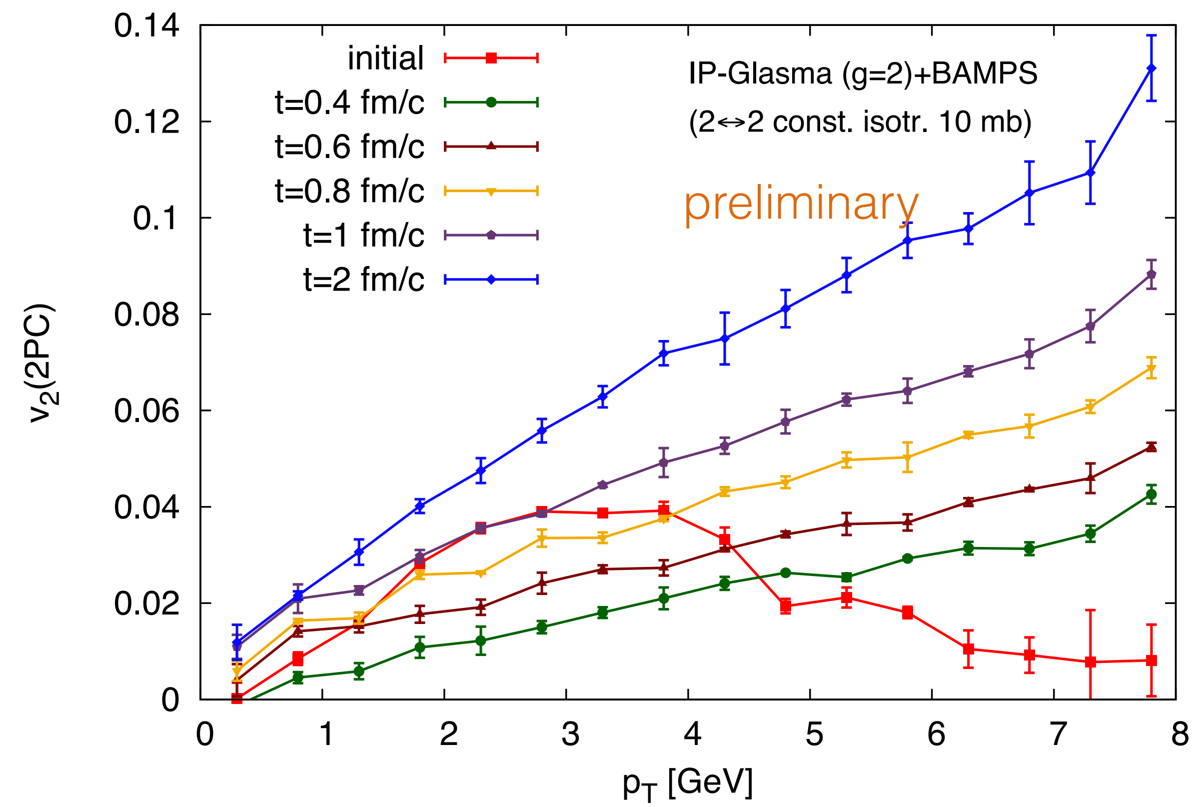
(Greif, Greiner, Schenke, SS, Xu work in progress)

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)

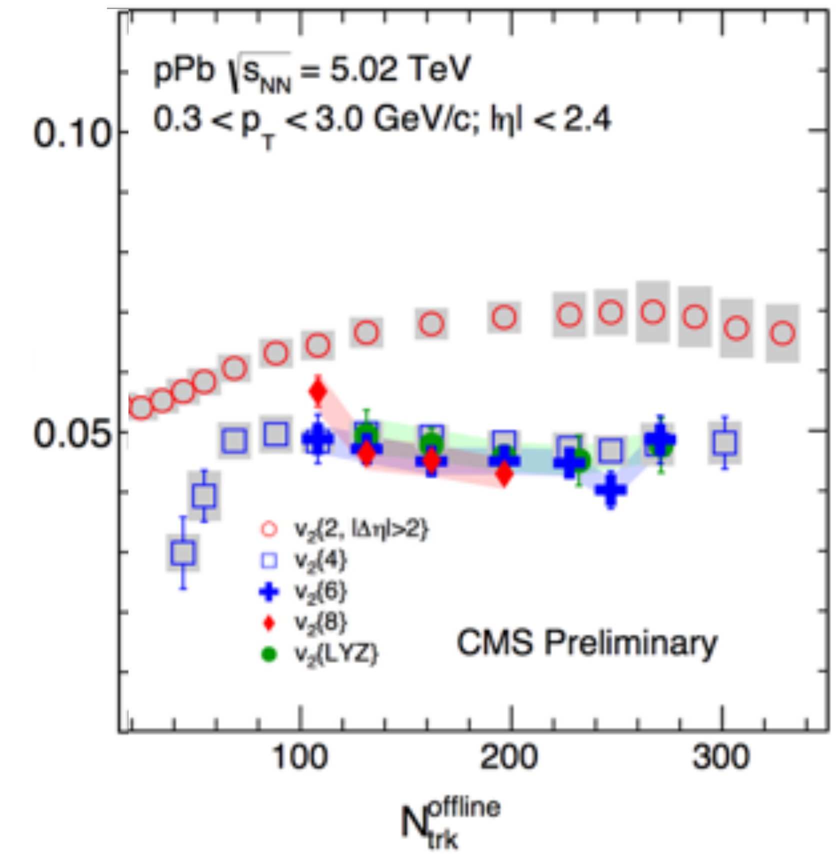
Prove of principle that azimuthal correlations in small systems can provide sensitivity to pre-equilibrium dynamics

Collective behavior?

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

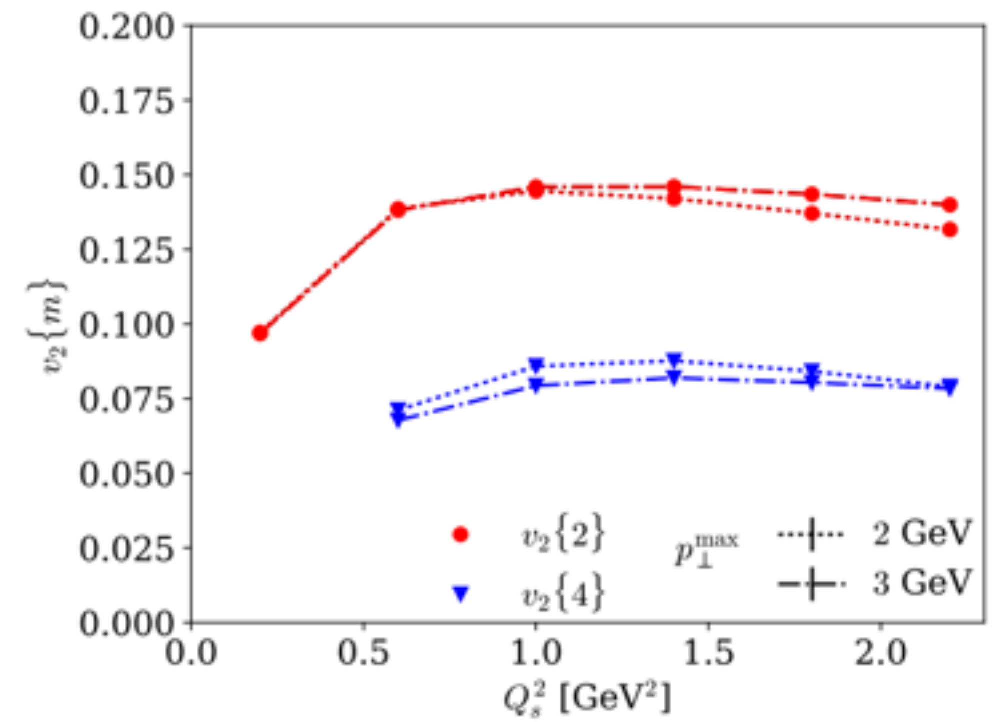
Clearly geometric correlations with the event geometry carry over to all (low p_T) particles

-> 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

Conclusions & Perspectives

Observation of long. range azimuthal correlations in small systems are challenging us to develop a unified picture of the space-time evolution of hadronic collisions

-> Exciting connections with unresolved problems in A+A (equilibration, intermediate p_T physics)

Showed first calculation including both initial state and final state effects, based on weak-coupling description (class. YM + pQCD transport)

-> 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

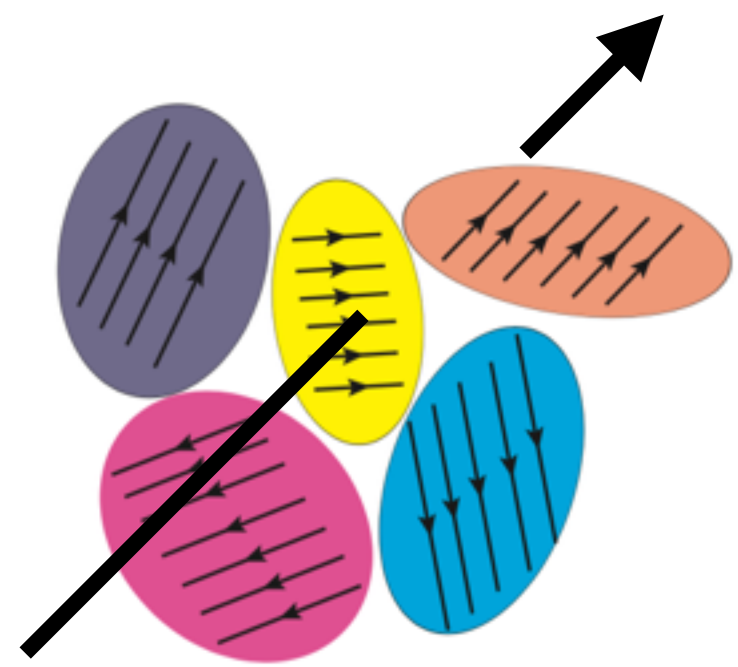
Still lots of work to be done concerning in particular interplay soft physics <-> high-p_T/jets

Backup

Initial state correlations in high-multiplicity events

Intuitive picture at small x:

Bose enhancement of small x gluons in wave function allows treatment as a classical color field



Scattering amplitude of projectile parton

$$V_x = \mathcal{P}\, e^{-ig\int dx^- A^+}$$

Distribution of scattered partons

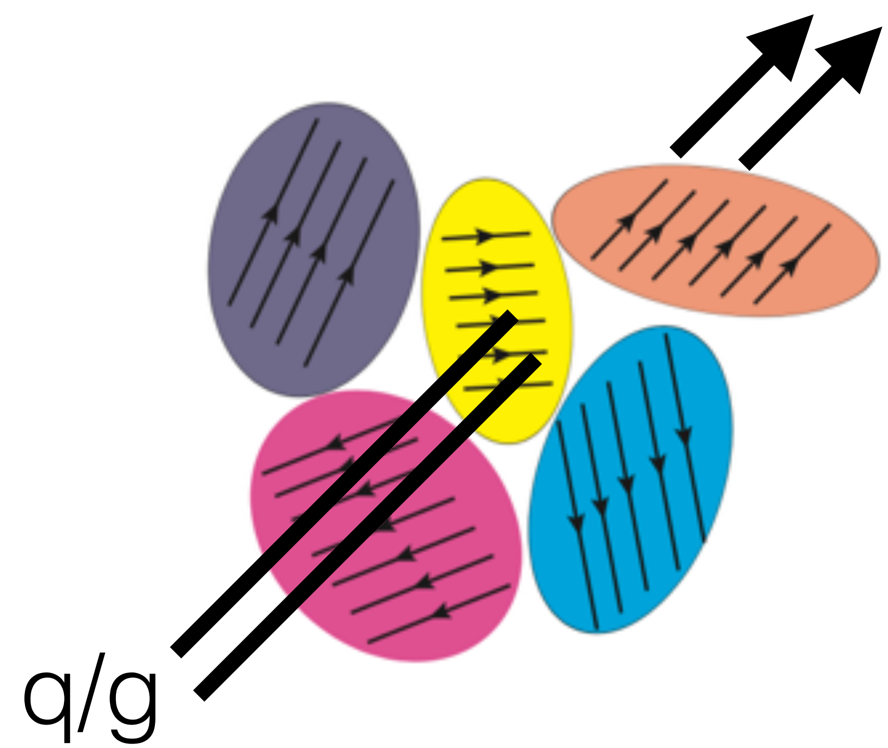
$$\frac{dN_{q/g}}{d^2\mathbf{k}_T} = \int_{\mathbf{p}_T,\mathbf{b}_T,\mathbf{r}_T} W_{q/g}(\mathbf{p}_T,\mathbf{b}_T)\, e^{-i(\mathbf{k}_T-\mathbf{p}_T)\mathbf{r}_T} \quad \mathrm{tr}_{f/a} V(\mathbf{b}_T+\mathbf{r}_T/2)V^\dagger(\mathbf{b}_T-\mathbf{r}_T/2)$$

Short-distance expansion: Each parton receives a momentum kick in the direction of the light-cone electric field $E^i(\mathbf{b}_T) = \frac{i}{g}V(\mathbf{b}_T)\partial^i V^\dagger(\mathbf{b}_T)$

Initial state correlations in high-multiplicity events

Intuitive picture at small x:

Each parton scattering off the same domain receives a kick in the direction of the chromo-electric field which leads to a correlation in azimuthal angle



$$\left\langle \frac{dN_{q/g}}{d^2\mathbf{k}_1 d^2\mathbf{k}_2} \right\rangle = \int_{\mathbf{p}_1,\mathbf{b}_1,\mathbf{r}_1}^{\mathbf{p}_2,\mathbf{b}_2,\mathbf{r}_2} W_{q/g}(\mathbf{p}_1,\mathbf{b}_1)\, e^{-i(\mathbf{k}_1-\mathbf{p}_1)\mathbf{r}_1}\, W_{q/g}(\mathbf{p}_2,\mathbf{b}_2)\, e^{-i(\mathbf{k}_2-\mathbf{p}_2)\mathbf{r}_2}$$

$$\left\langle \mathrm{tr}_{f/a} V(\mathbf{b}_1+\mathbf{r}_1/2) V^\dagger(\mathbf{b}_1-\mathbf{r}_1/2) \mathrm{tr}_{f/a} V(\mathbf{b}_2+\mathbf{r}_2/2) V^\dagger(\mathbf{b}_2-\mathbf{r}_2/2) \right\rangle$$

-> Near-side ($\Delta\phi \sim 0$) azimuthal correlation $\sim 1/(N_c^2\, Q_s^2\, S_T)$

Since the decoration of color fields inside nucleus is slow ($\Delta\eta_{corr} \sim 1/\alpha_s$) correlations are naturally long range in rapidity

(Kovner,Lublinsky PRD 83 (2011) 034017; Dumitru, Giannini NPA 933 (2014) 212-228; Dumitru, Skokov PRD 91 (2015) 7, 074006; Lappi, Schenke, SS, Venugopalan 1509.03499)