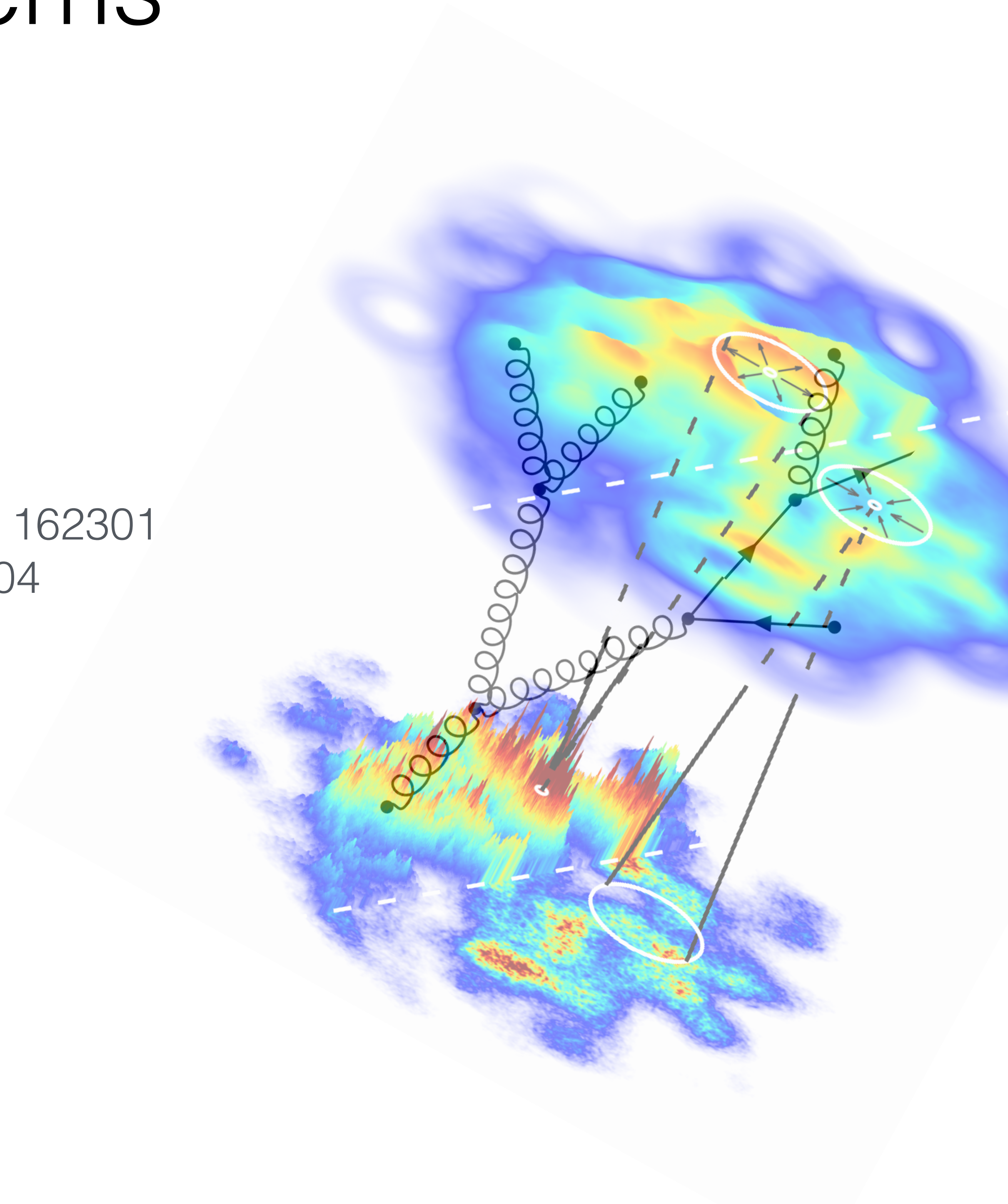
Collectivity in small systems

Sören Schlichting | Universität Bielefeld

Based on
Schenke, SS, Venugopalan PLB 747 (2015) 76-82
Schenke, SS,Tribedy, Venugopalan PRL 117 (2016) no.16, 162301
Greif, Greiner, Schenke, SS, Xu PRD96 (2017) no. 9, 091504
Greif, Greiner, Plätzer, Schenke, SS arXiv:2012.08493



CLASH Seminar
Lund University
Mar 2021

CRC-TR 211
Strong-interaction matter under extreme conditions

UNIVERSITÄT BIELEFELD

Outline

- Overview of experimental results on high-multiplicity p+p/A

  - General perspective on initial state vs. final state effects

- Color-Glass Condensate description of initial state

  - Initial state geometry & momentum correlations

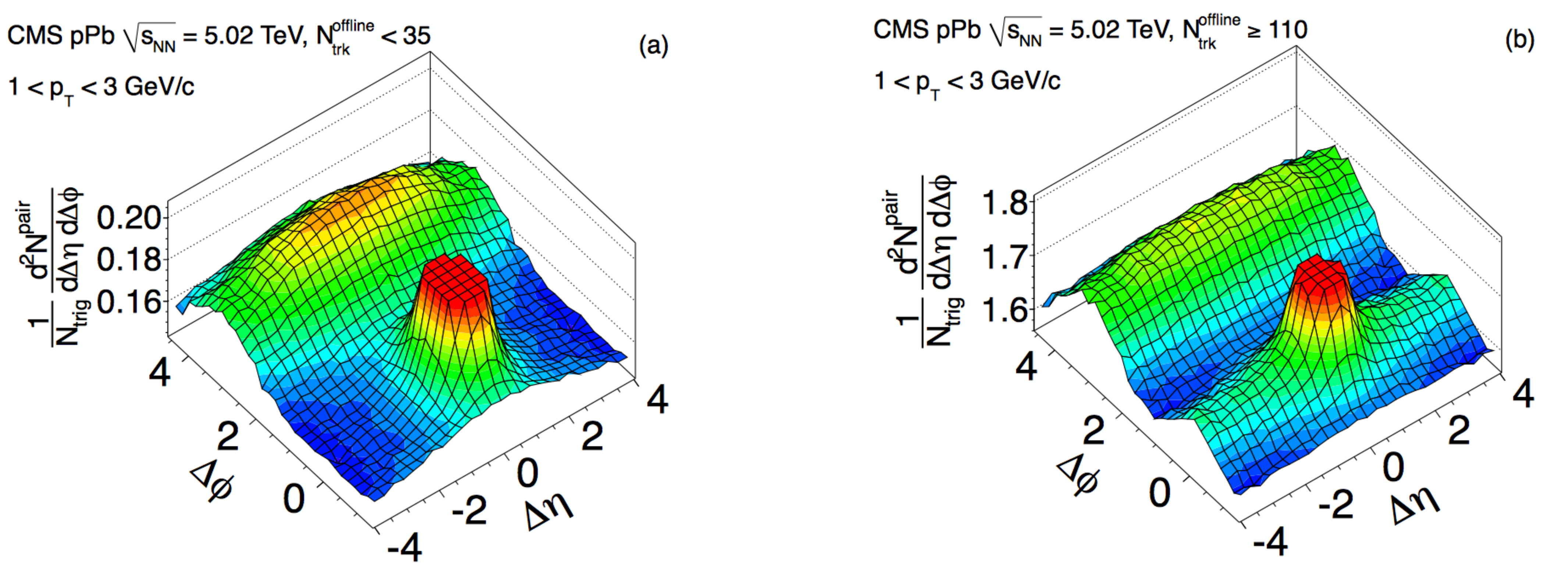
  - State of the art & challenges in phenomenological calculations

- New developments to include initial state & final state effects

- Conclusions & Perspectives

Long-range azimuthal correlations

Experimentally long-range azimuthal di-hadron correlations have been observed in high multiplicity p+p/A at LHC as well as p/d/He3+A collisions at RHIC



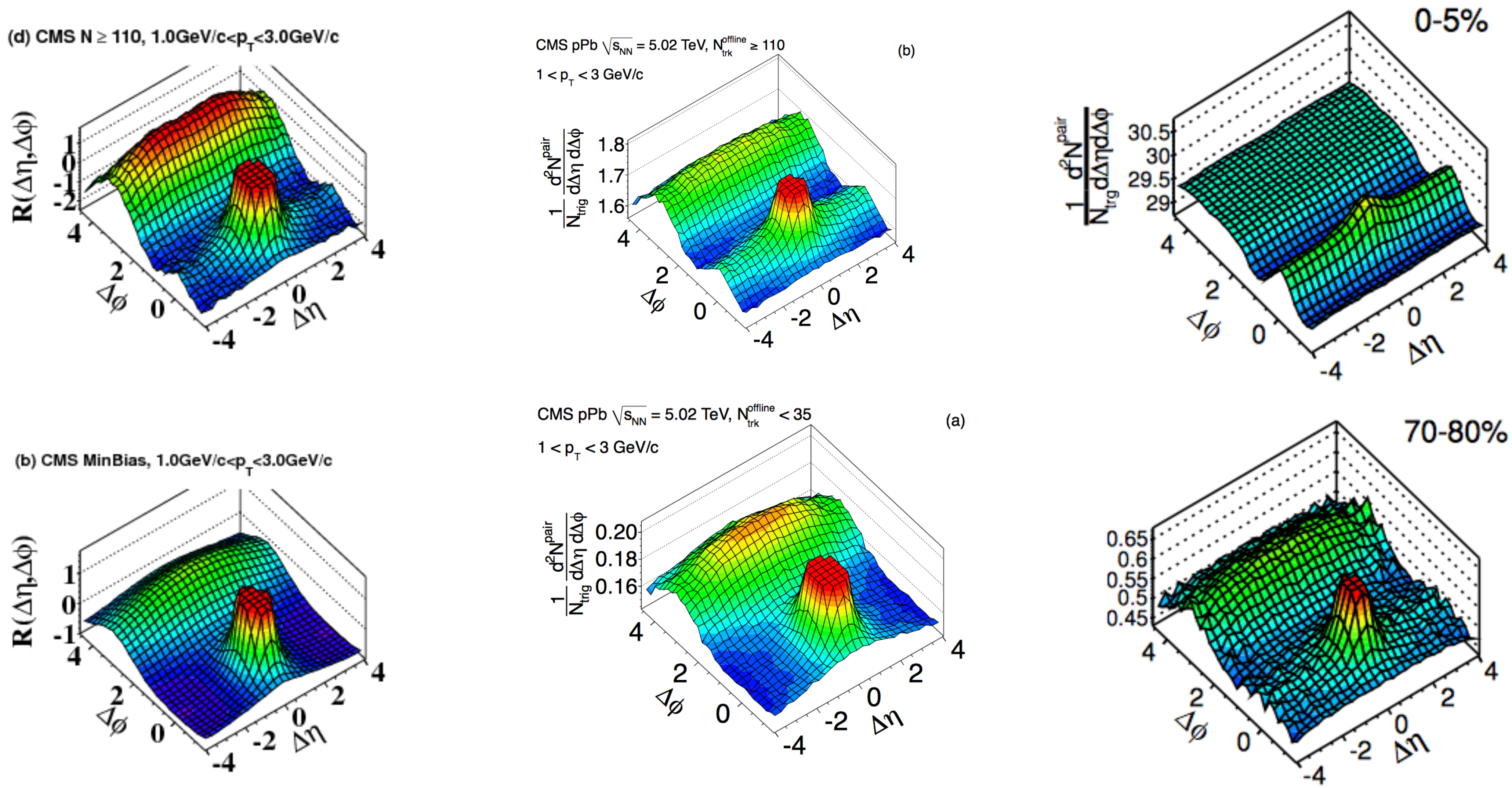
low multiplicity ——— high multiplicity →

Big surprise: No natural explanation of near-side ridge in pQCD

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

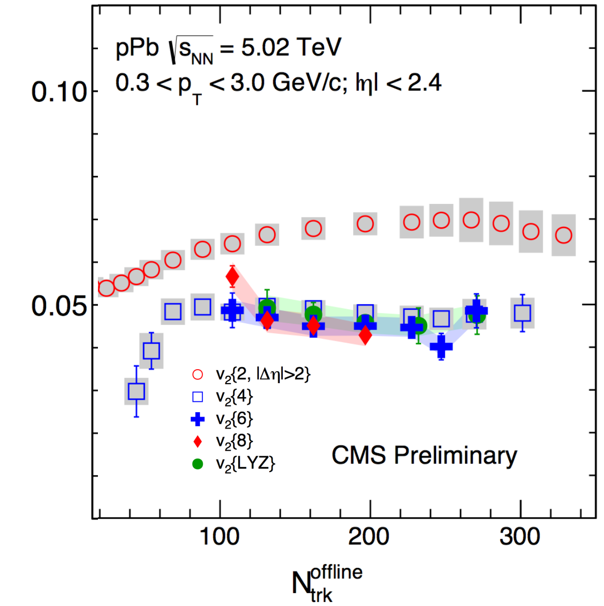
-> dependence on hadron species (mass ordering)

. . .

there are also important differences

-> in p+p/A only observed in (rare) high-multiplicity events

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



Different theoretical explanations developed in terms of

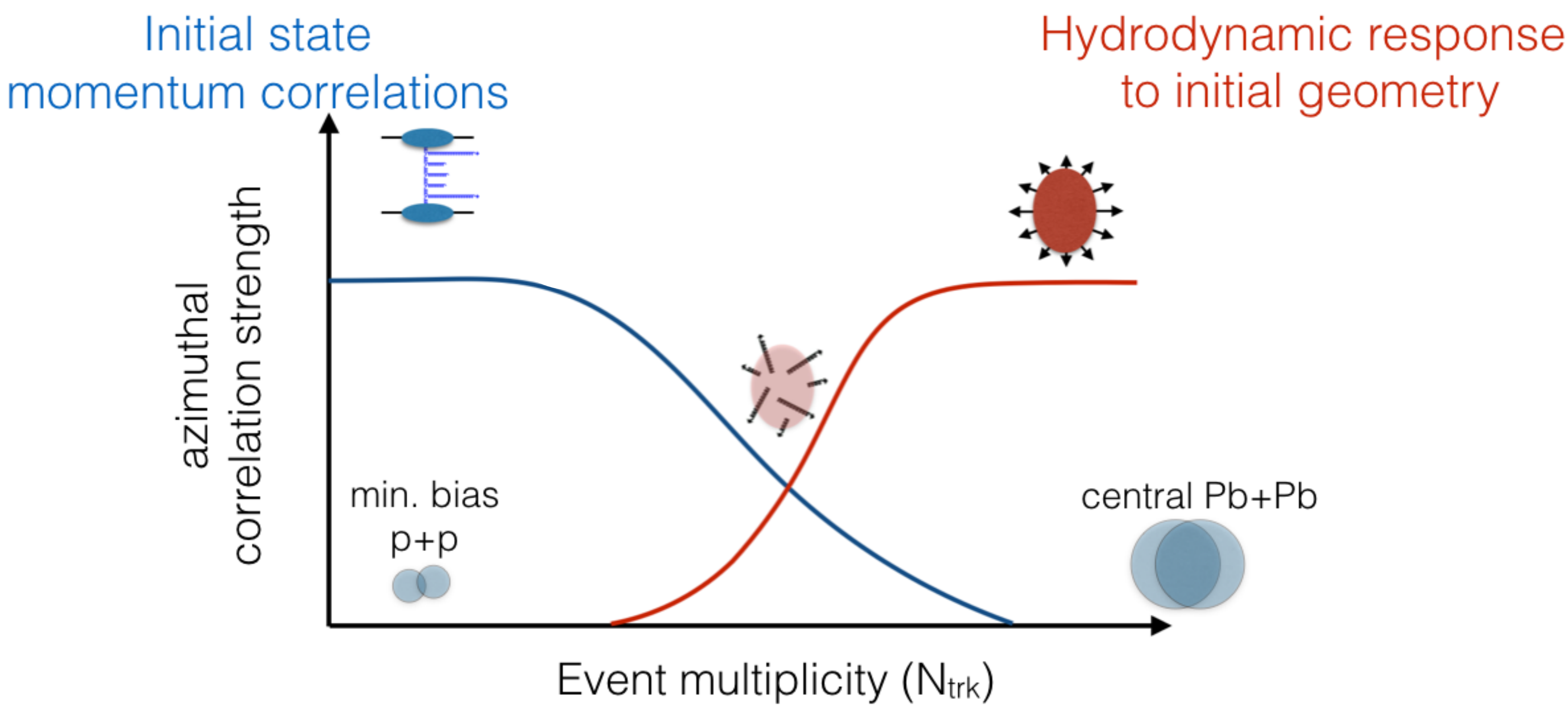
final state response to initial state geometry

and/or

initial state momentum correlations

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

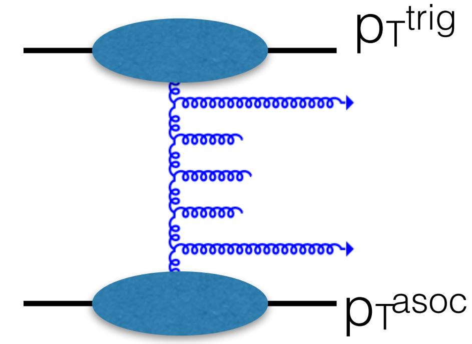


SS, Quark Matter 2015, NPA 956 (2016) 216-221; SS, Tribedy Adv. High Energy Phys. Vol. 2016 (2016), 8460349

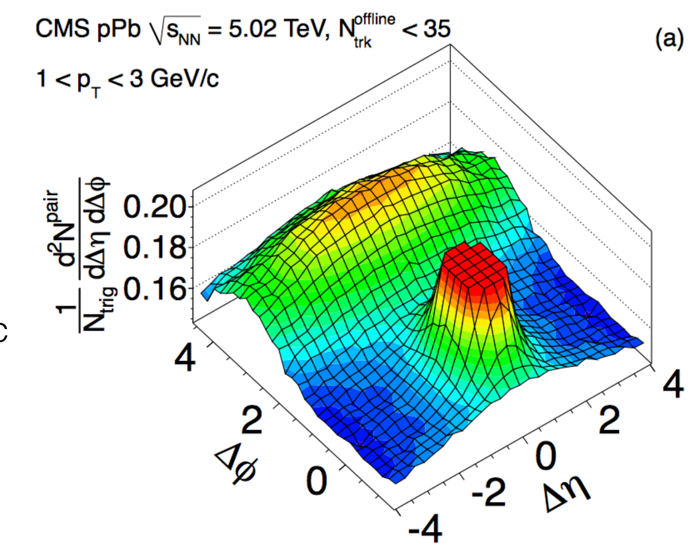
Multi-particle production & initial state correlations

Multi-particle production from a single (semi-) hard scattering, gives rise to long range (Δη) away side (Δϕ~π) correlation

Dominant process for particle production in min. bias and low multiplicity p+p/A events

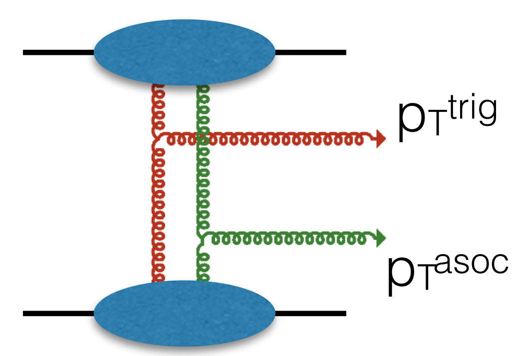


"Jet graph"



In high-multiplicity events multi parton processes become increasingly important

Correlation between produced particles directly reflect the correlations of gluons inside the wave function of projectile and the target

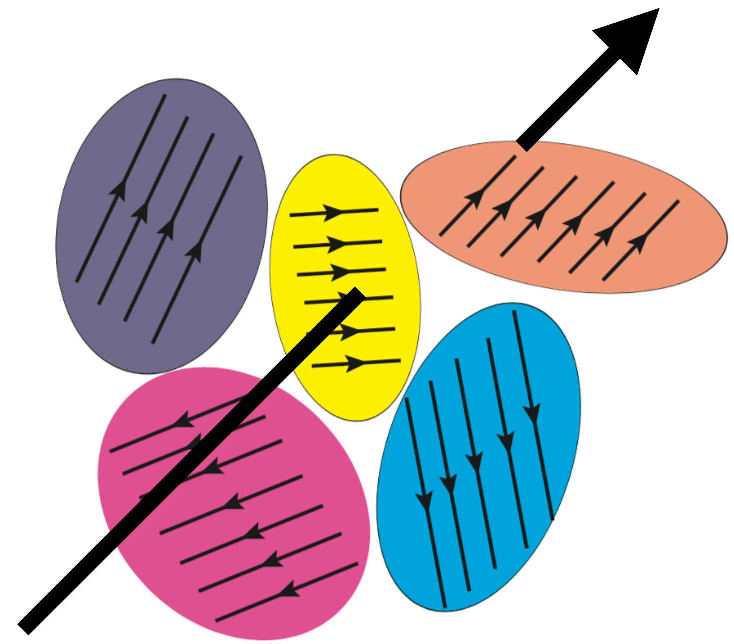


"Glasma graph"

(Gelis,Lappi Venugopalan PRD 78 (2008) 054020, PRD 79 (2009) 094017; Dumitru, Gelis, McLerran,Venugopalan NPA8 10, 91 (2008); Dumitru, Jalilian-Marian PRD 81 (2010) 094015)

Initial state correlations in high-multiplicity events

Intuitive picture at small x:



Scattering amplitude of projectile parton $V_x = \mathcal{P}\, e^{-ig\int dx^- A^+}$

Distribution of scattered partons

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

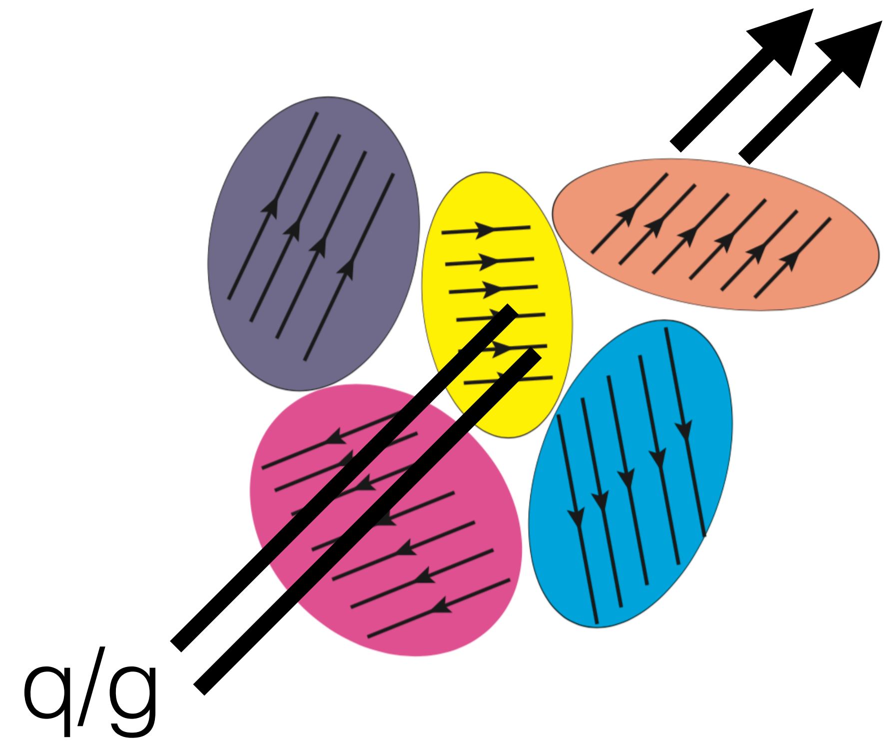
Short-distance expansion: Each parton receives a momentum kick in the direction of the light-cone electric field

$$E^i(\mathbf{b}_T) = \frac{i}{g} V(\mathbf{b}_T)\partial^i V^\dagger(\mathbf{b}_T)$$

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



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

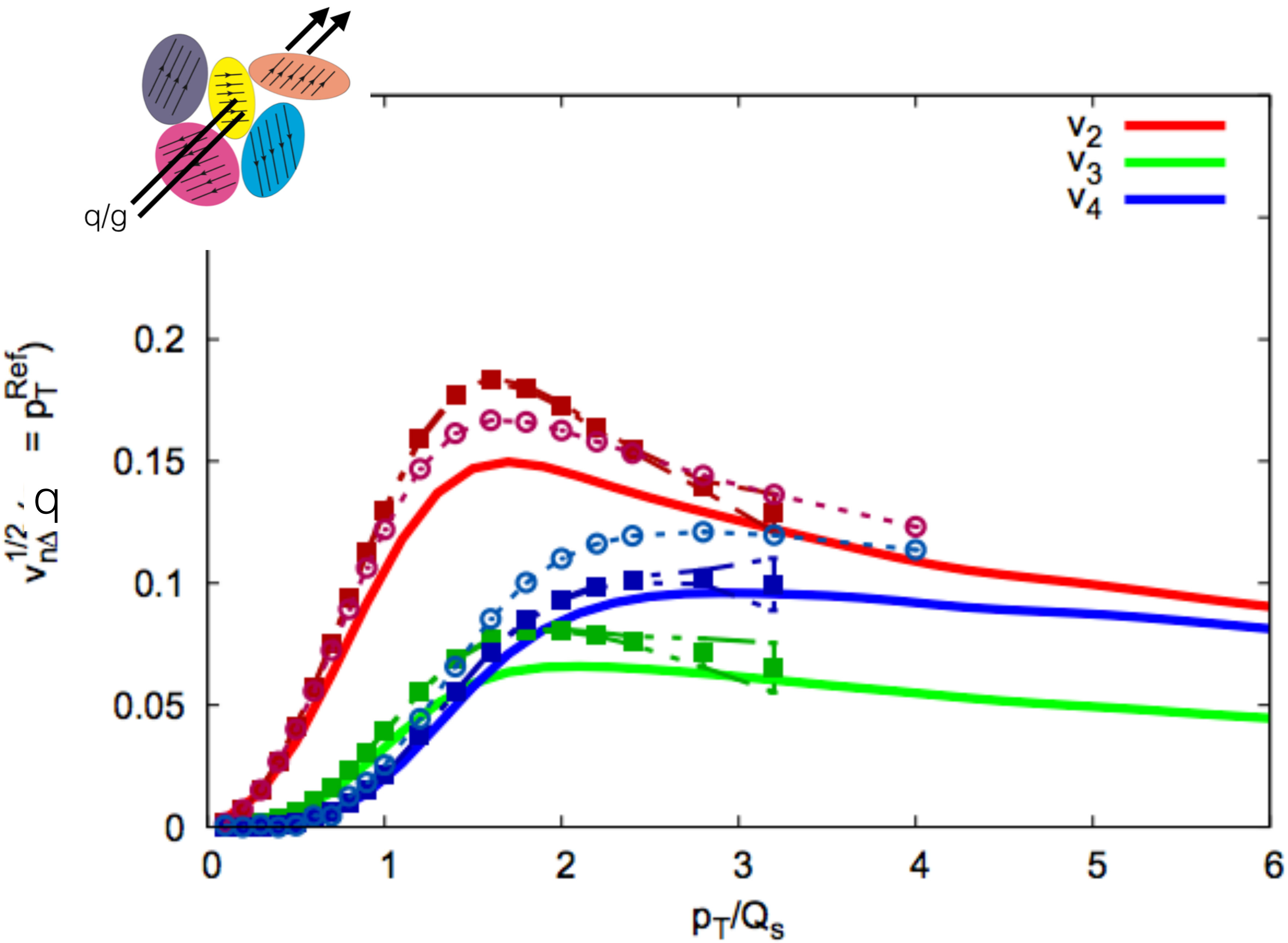
$$\left\langle \mathrm{tr}_{f/a} V(\mathbf{b}_1+\mathbf{r}_1/2) V^\dagger(\mathbf{b}_1-\mathbf{r}_1/2) \mathrm{tr}_{f/a} V(\mathbf{b}_2+\mathbf{r}_2/2) V^\dagger(\mathbf{b}_2-\mathbf{r}_2/2) \right\rangle$$

-> 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)

Collectivity from initial state?

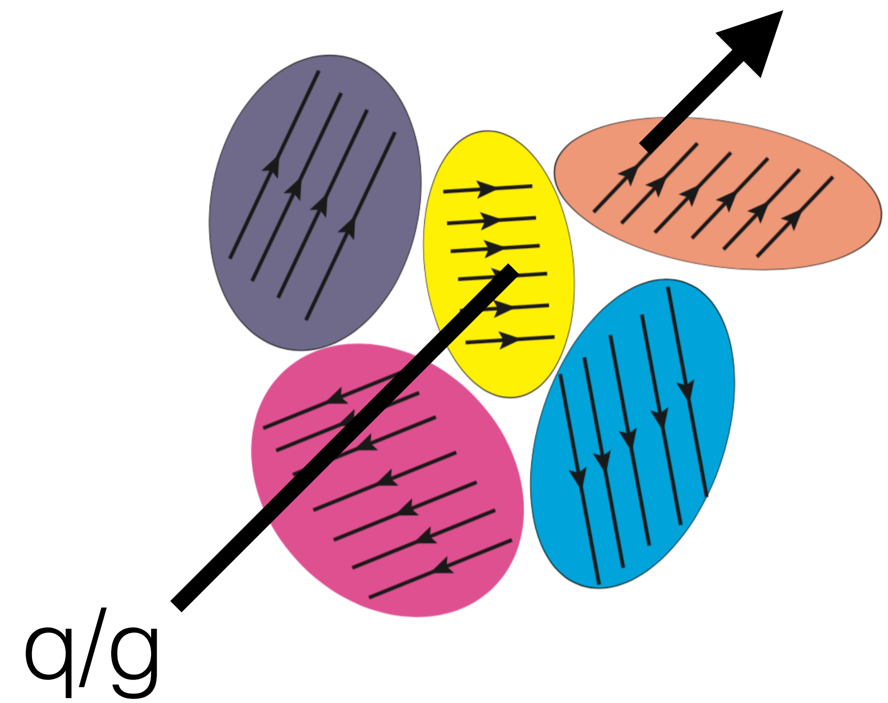


Lappi,Schenke,SS,Venugopalan
JHEP 1601 (2016) 061

Color Glass Condensate EFT

Effective field theory description of high-energy scattering in terms of light-like Wilson lines

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



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

Expansion in g (typically to LO or NLO) with gA^+ resummed to all orders rather than in perturbative expansion in g (typically to higher orders)

$$\langle \mathcal{O} \rangle = \int DV\ W_x[V]\ \mathcal{O}_{\rm cl}[V] + \mathcal{O}(g^2)$$

Hadronic structure characterized by correlation functions of V_x

Different possibilities to calculate analytically/numerically within CGC, by simulating the classical field dynamics or perturbative expansion in field strength

Phenomenological calculations in pp/A

1 Initial state multi-particle production

Perturbative CGC calculation

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

Classical Yang-Mills simulations

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

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

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

2 Hadronization

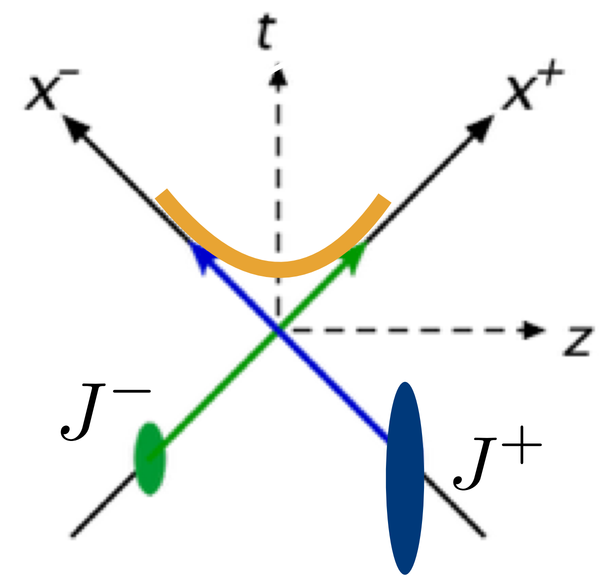
Fragmentation functions

Monte-Carlo fragmentation schemes (PYTHIA HSA, SAHARA/HERWIG)

Event-by-Event CYM

Describing projectile and target as color charges moving at the speed of light the properties of the initial state (τ=0) and early time dynamics (τ~1/Q_s) can be calculated by solving the classical Yang-Mills equations

$$[D_\mu, F^{\mu\nu}] = J^\nu$$



Initial state known analytically $$A^i(\mathbf{x}, \tau = 0) = \frac{i}{g}\left(V_1(\mathbf{x})\partial^i V_1^\dagger(\mathbf{x}) + V_2(\mathbf{x})\partial^i V_2^\dagger(\mathbf{x})\right)$$

early time dynamics can be computed based on real-time lattice techniques

Based on the knowledge of correlation functions of light-like Wilson V_1,V_2 lines one can event-by-event by simulations and calculate various observables

Event-by-event multiplicity, event shapes, multi-particle correlations, …

Basis of IP-Glasma initial state model for A+A collisions

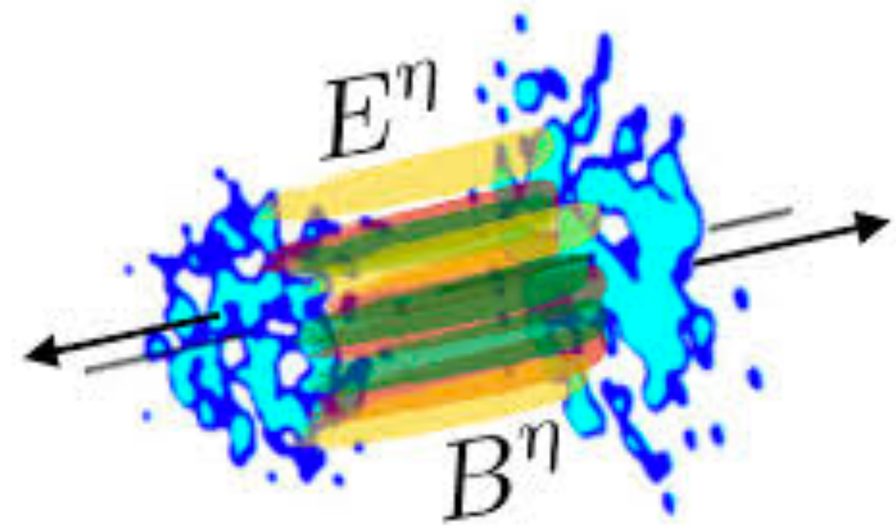
(Krasnitz, Venugopalan NPB557 (1999) 237, Lappi, McLerran NPA772 (2006) 200-212, Schenke,Tribedy,Venugopalan C86 (2012) 034908, Schenke,SS,Venugopalan PLB747 (2015) 76-82, …)

Event-by-Event CYM

Energy initially contained in coherent long. color electric and magnetic fields

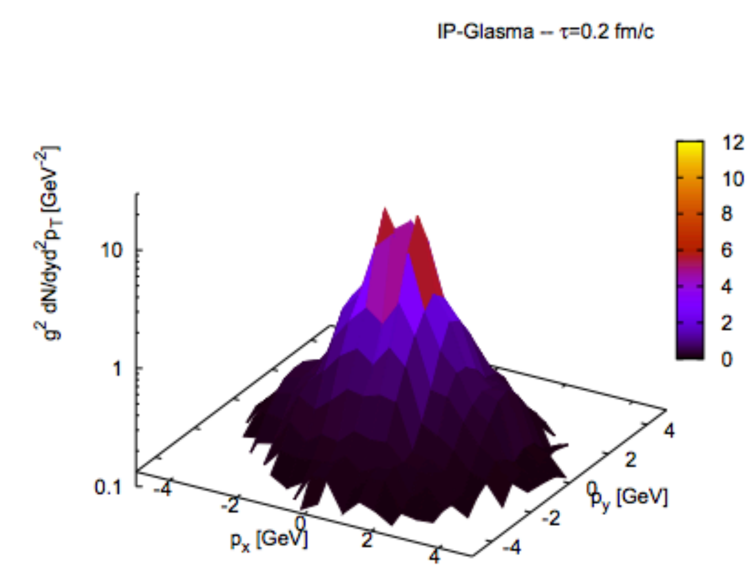
$$E^\eta(\tau,\mathbf{x}) = \frac{i}{g}\delta^{ij}\left[U_\mathbf{x}\partial_i U^\dagger_\mathbf{x}, V_\mathbf{x}\partial_j V^\dagger_\mathbf{x}\right]$$

$$B^\eta(\tau,\mathbf{x}) = \frac{i}{g}\epsilon^{ij}\left[U_\mathbf{x}\partial_i U^\dagger_\mathbf{x}, V_\mathbf{x}\partial_j V^\dagger_\mathbf{x}\right]$$



Decoherence of the fields and weak non-linearity of field equations on time scales ~1/Qs leads to interpretation of gluons produced in the collision

$$\left.\frac{dN}{d^2\mathbf{k}_\perp dy}\right|_\tau = \frac{1}{(2\pi)^2}\sum_{\lambda,a}\left|\tau g^{\mu\nu}\left(\xi^{\lambda,\mathbf{k}_\perp *}_\mu(\tau)\overleftrightarrow{\partial_\tau} A^a_\nu(\tau,\mathbf{k}_\perp)\right)\right|^2$$



Since this is a field theoretical description, it allows for simultaneous access to coordinate space and momentum space information

Phenomenological calculations

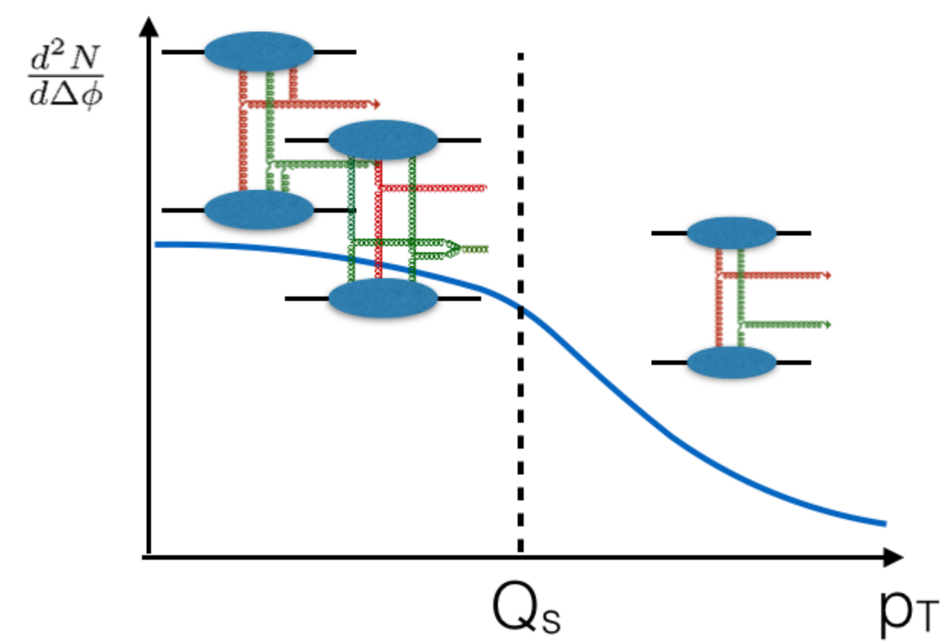
Event-by-event simulations in classical-Yang Mills theory

Event-by-event simulations allow for a natural multiplicity selection as in experiments and an adequate treatment of impact parameter dependence and system geometry (p/d/He+A)

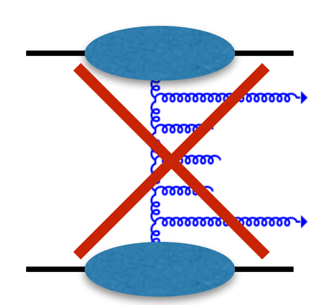
Comparison to perturbative approach:

Event-by-event simulations include multi-particle production via Glasma graphs

Simulations consistently include multiple-scattering effects (important at $p_T<Q_s$), extend beyond the range of validity of perturbative calculation



Note that classical Yang-Mills simulations do not include di-jet graphs at leading order



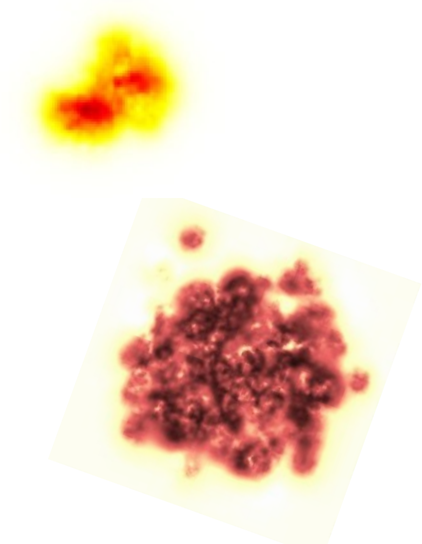
Phenomenological calculations

Event-by-event simulations in classical-Yang Mills theory

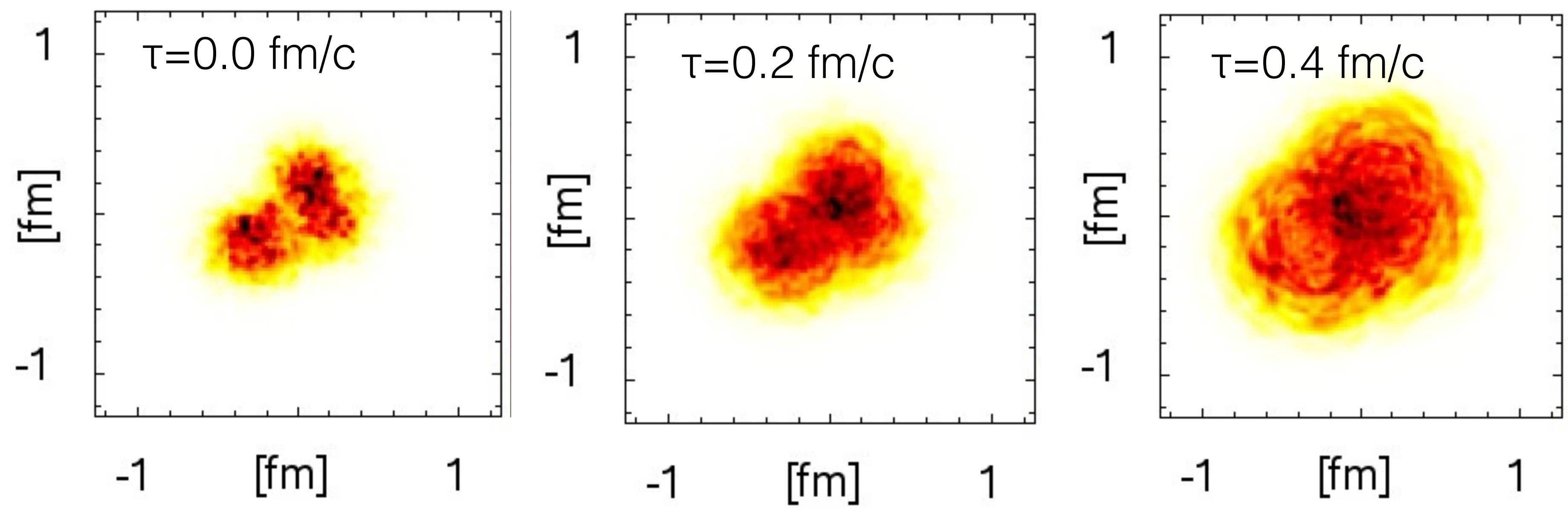
(Schenke, SS, Venugopalan PLB 747 (2015) 76-82, Schenke,SS,Tribedy,Venugopalan PRL 117 (2016) no.16, 162301, Greif, Greiner, Plätzer, Schenke, SS arXiv:2012.08493)

Geometry of the collision reflected by coordinate space profiles

proton



Pb Nucleus



Energy density profiles

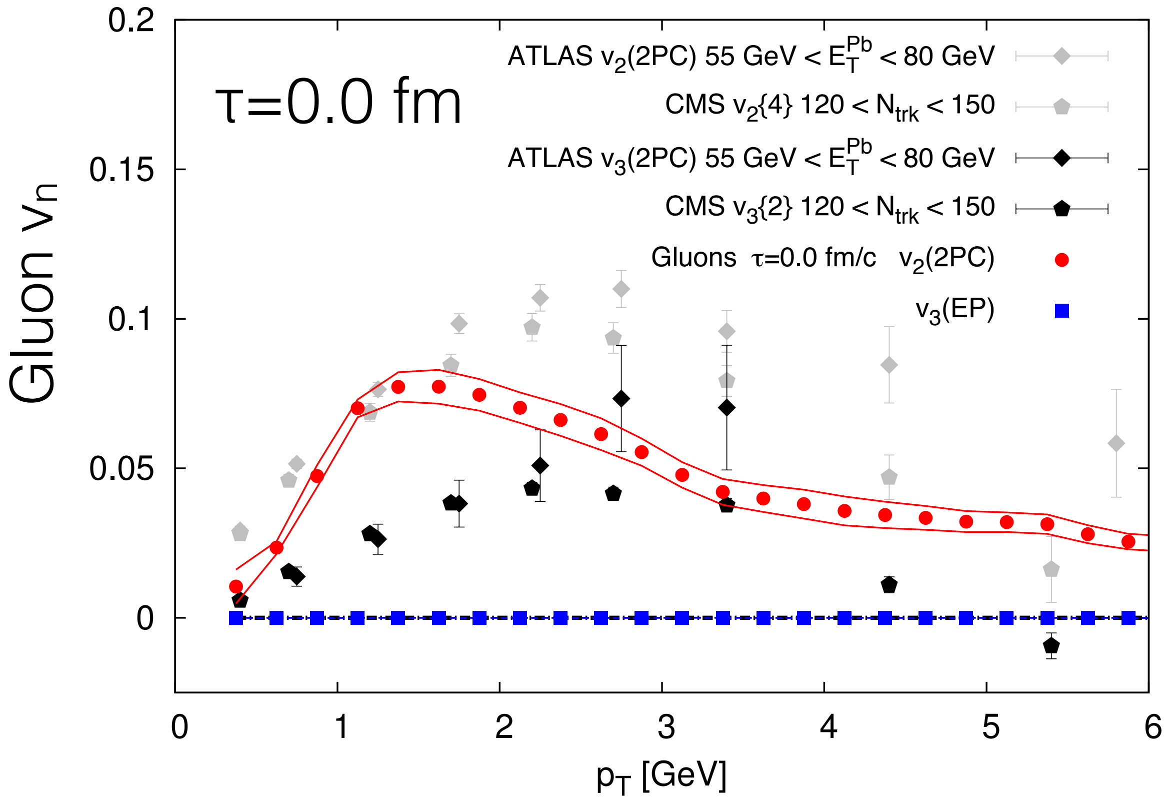
Event-by-event fluctuations of the proton geometry dominate the coordinate space profiles in p+Pb collisions

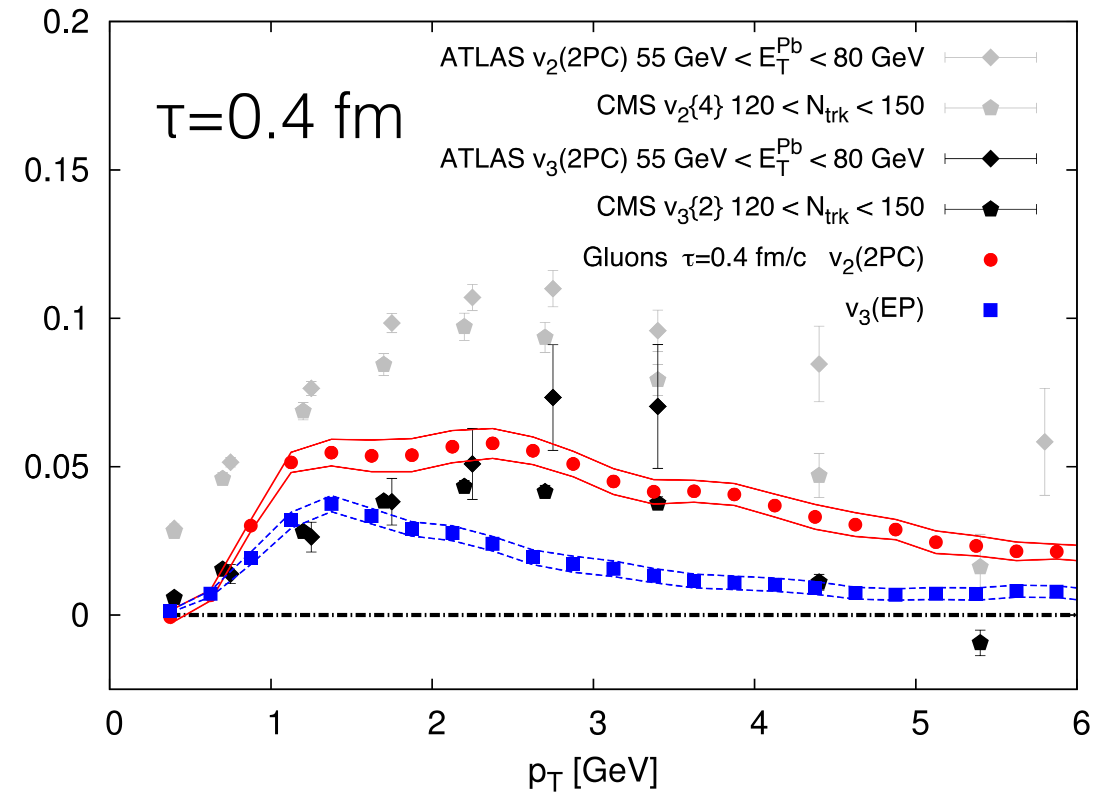
Phenomenological calculations

Event-by-event simulations in classical-Yang Mills theory

(Schenke, SS, Venugopalan PLB 747 (2015) 76-82, Schenke,SS,Tribedy,Venugopalan PRL 117 (2016) no.16, 162301)

Gluons are produced with a momentum space correlation already at $\tau=0^+$





-> Initially correlation function only features even harmonics $v_2, v_4, \ldots$

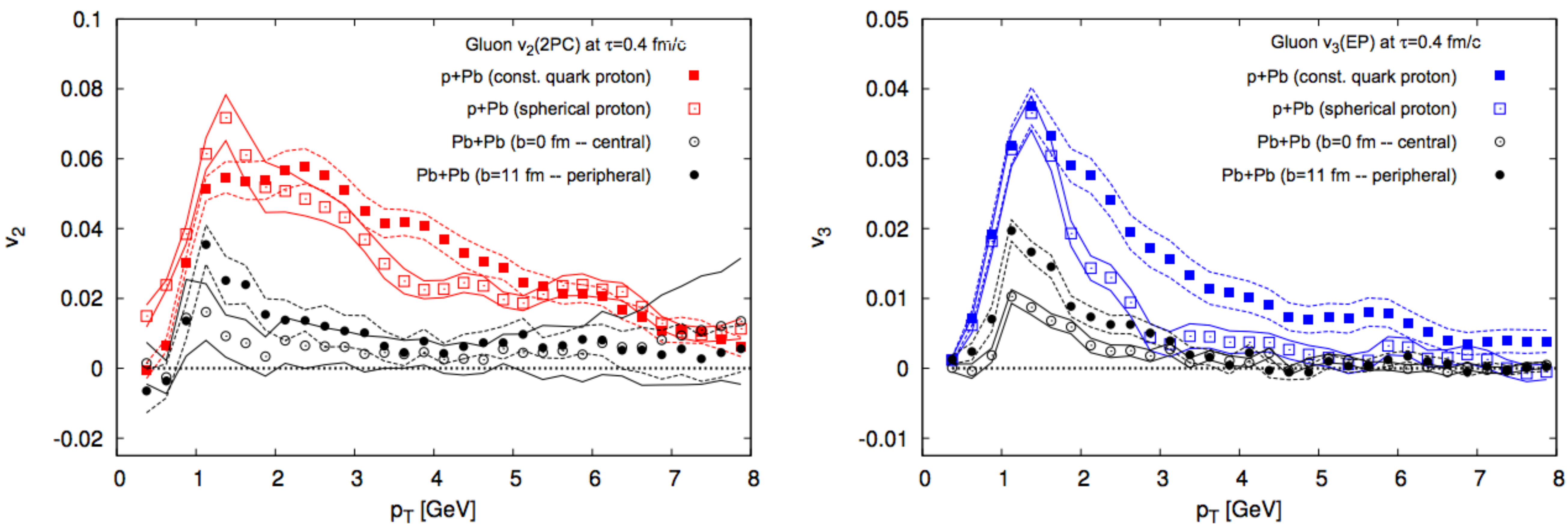
Including final state re-scattering via CYM evolution generates a positive v_3 on the time scale $\sim 1/Q_s$ of a single scattering

Phenomenological calculations

Event-by-event simulations in classical-Yang Mills theory

(Schenke, SS, Venugopalan PLB 747 (2015) 76-82, Schenke,SS,Tribedy,Venugopalan PRL 117 (2016) no.16, 162301)

Gluons are produced with a momentum space correlation already at $\tau=0^{+}$



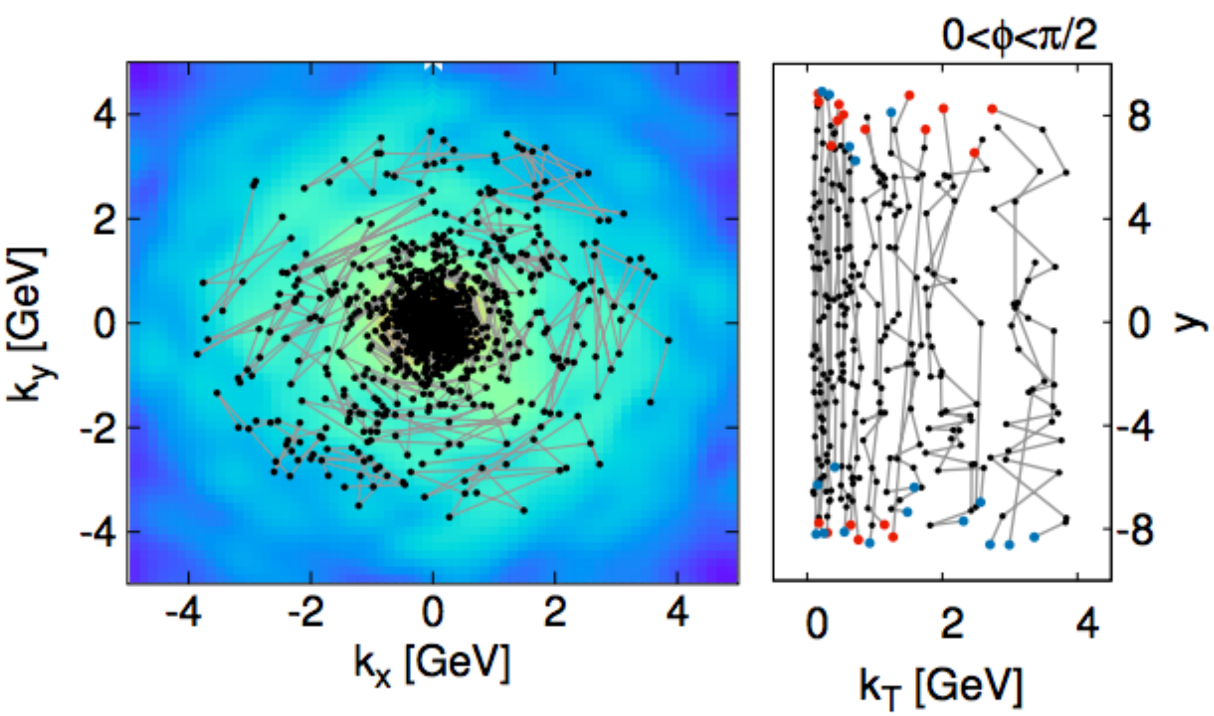
Significantly larger effects in small (p+Pb) vs large (Pb+Pb) systems

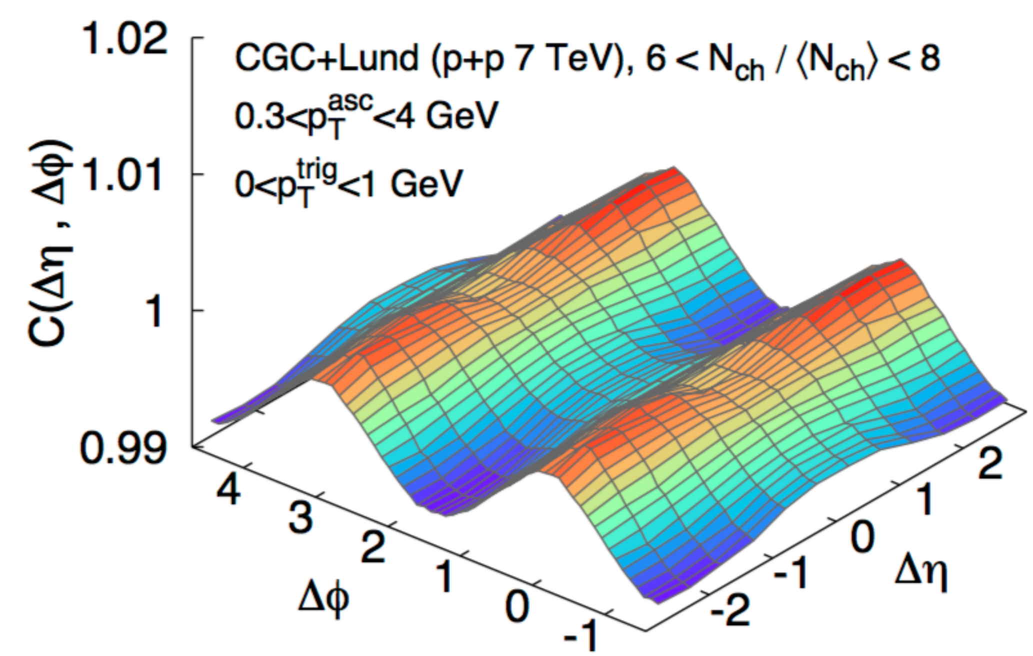
Phenomenological calculations

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

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

Extract event-by-event gluon spectra from classical Yang-Mills simulation and sample individual gluons to perform fragmentation in PYTHIA





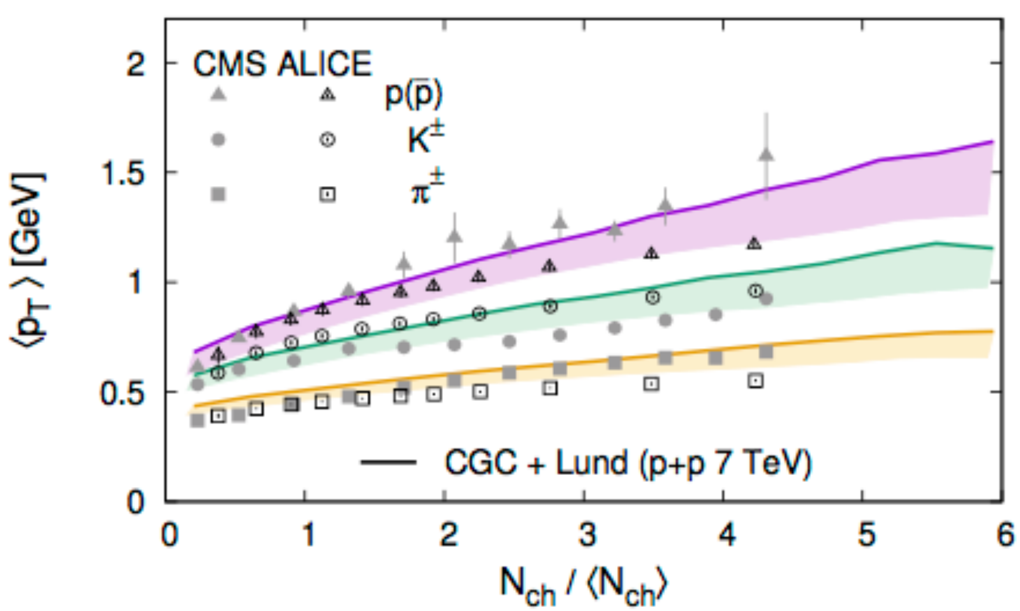
-> Direct comparison of hadronic observables with experiment

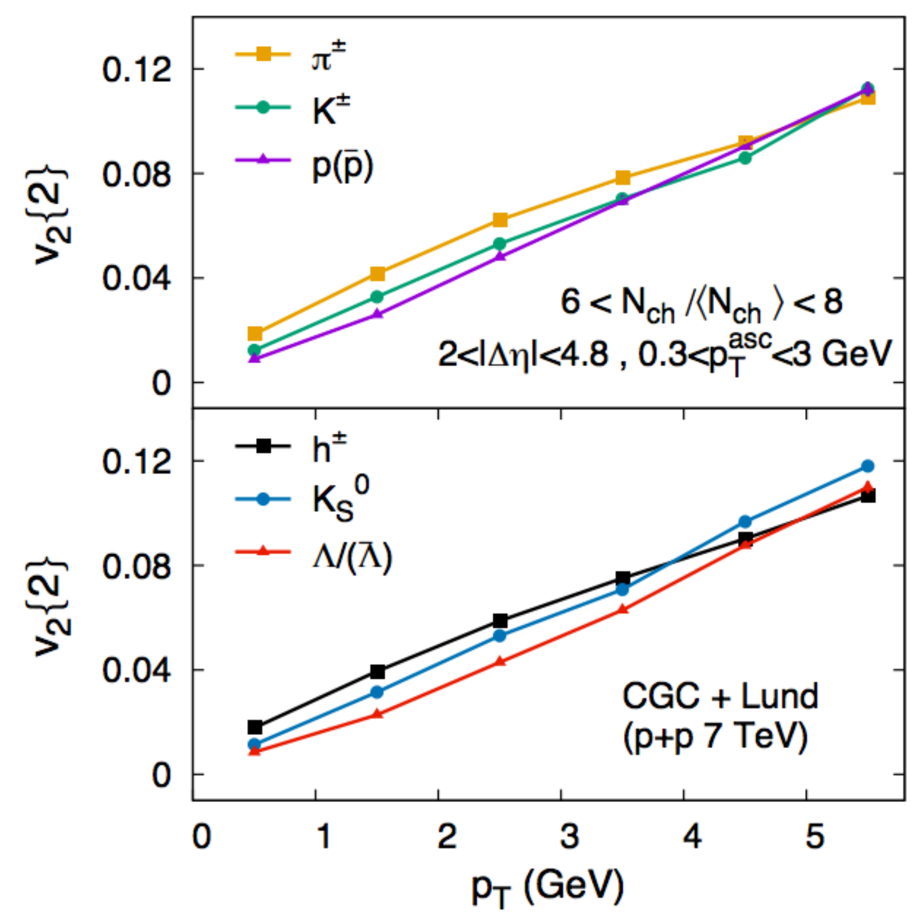
Phenomenological calculations

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

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

Initial state correlations at the gluon level combined with string fragmentation naturally reproduces characteristic features of hadronic observables





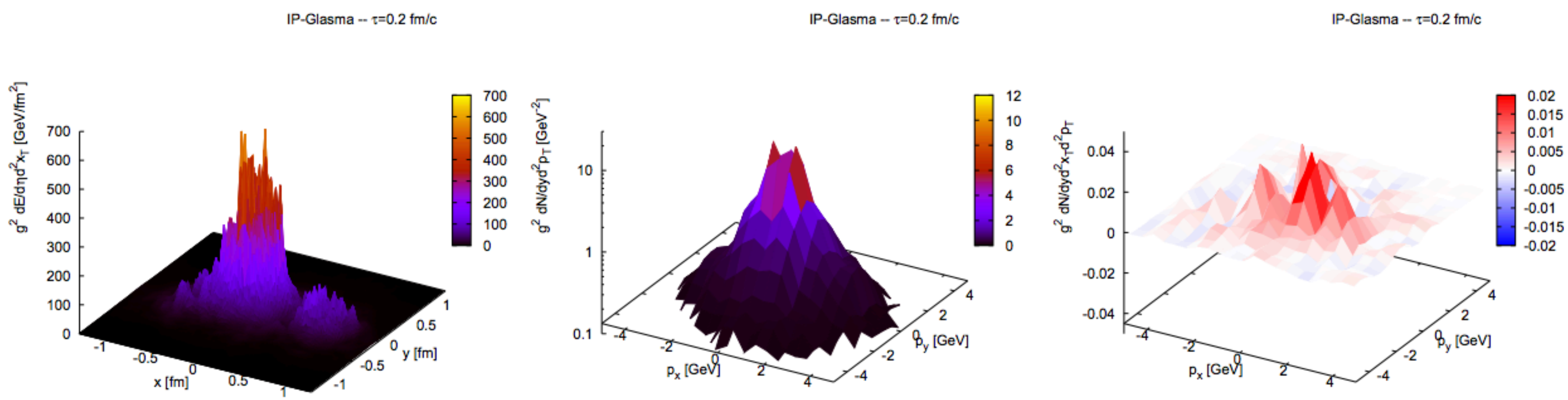
Initial state gluons have non-zero v_2 and increasing $<p_T>$ as a function of multiplicity

String fragmentation naturally leads to mass ordering properties of p_T and v_2

Phenomenological calculations

Event-by-event simulations in classical-Yang Mills theory
+ space-time local Cluster Hadronization (HERWIG)

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



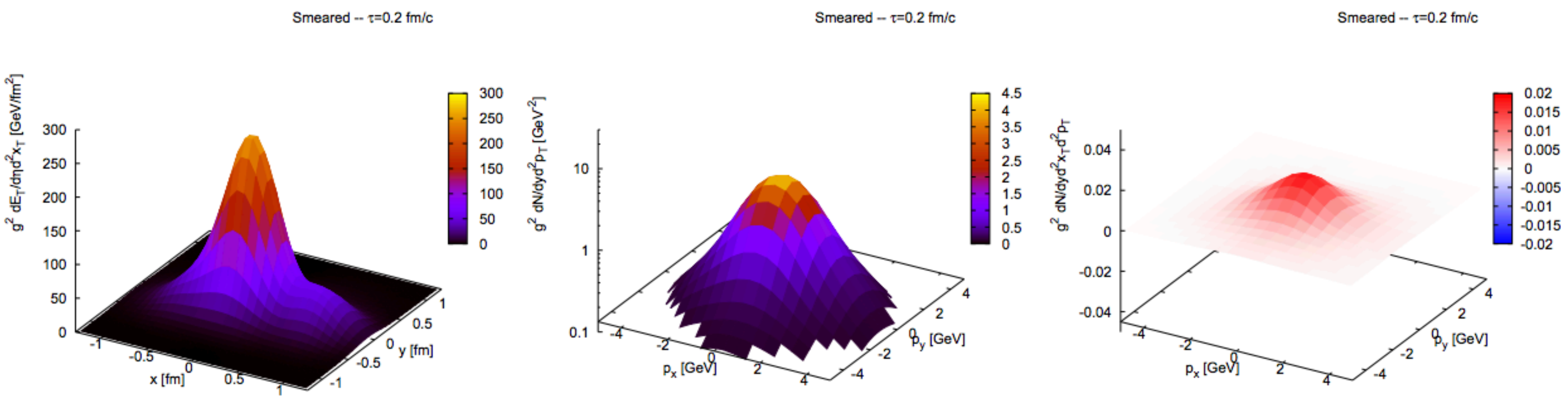
Notion of localized quasi particles becomes increasingly problematic as de Broglie wave-length becomes comparable to system size

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

Phenomenological calculations

Event-by-event simulations in classical-Yang Mills theory
+ space-time local Cluster Hadronization (HERWIG)

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



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

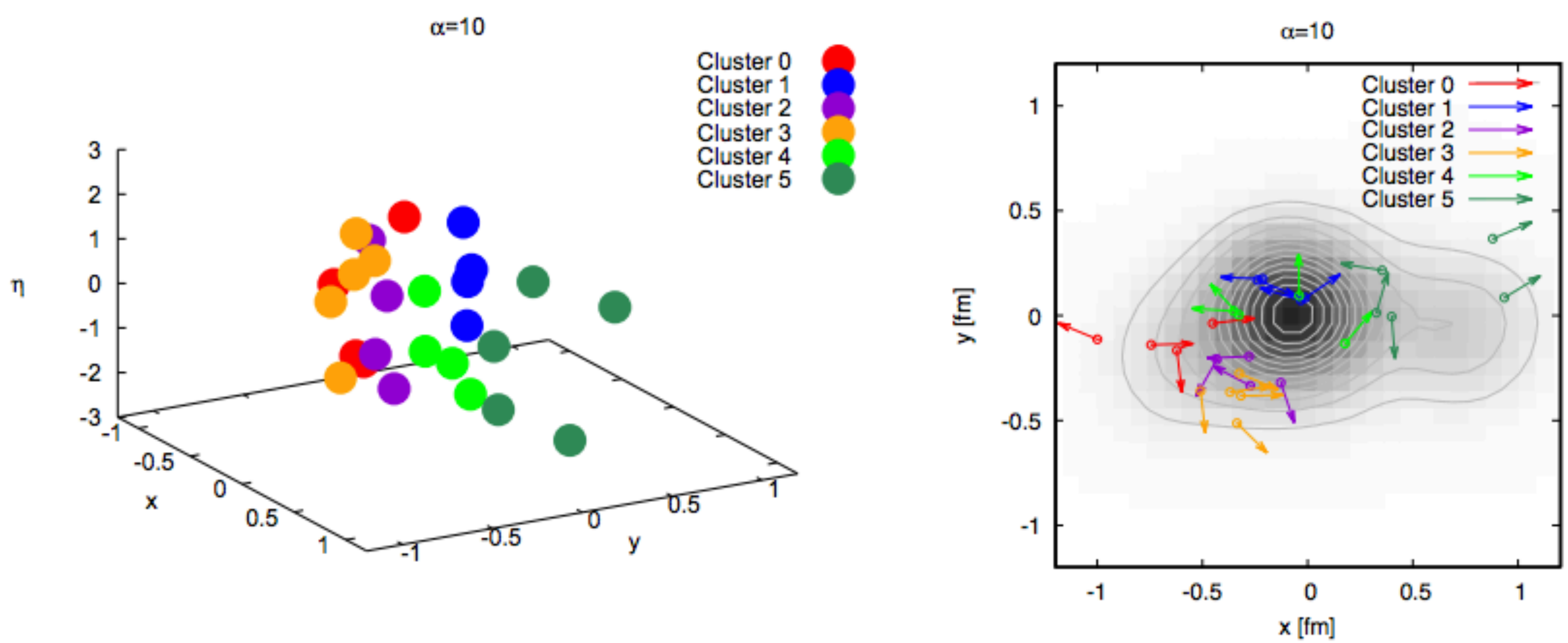
Greif, Greiner, Schenke, SS, Xu PRD96 (2017) no. 9, 091504; Greif, Greiner, Plätzer, Schenke, SS arXiv:2012.08493

Phenomenological calculations

Event-by-event simulations in classical-Yang Mills theory
+ space-time local Cluster Hadronization (HERWIG)

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

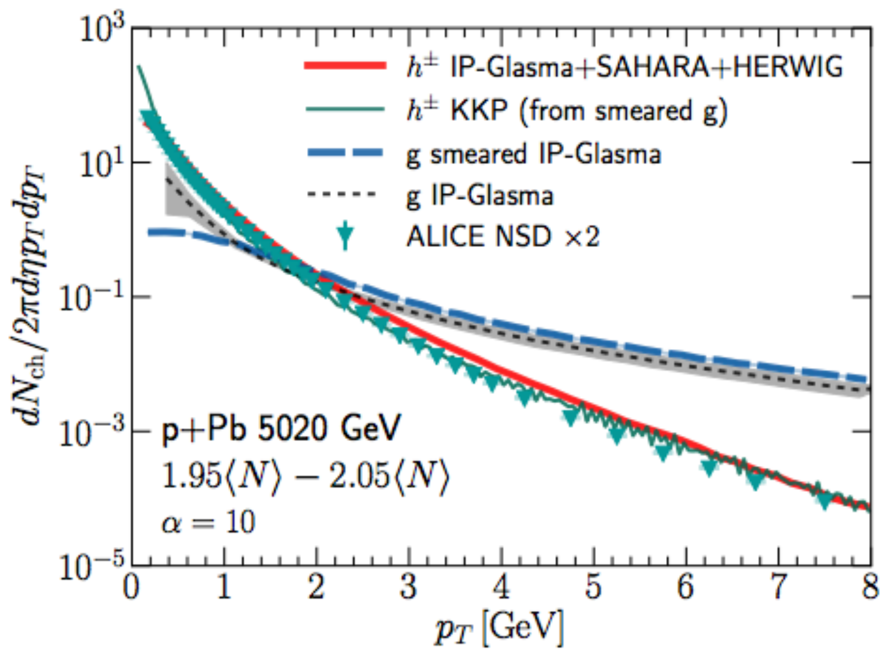
Soft gluon production in IP-Glasma -> Space time clustering in SAHARA -> Hadronization in Herwig



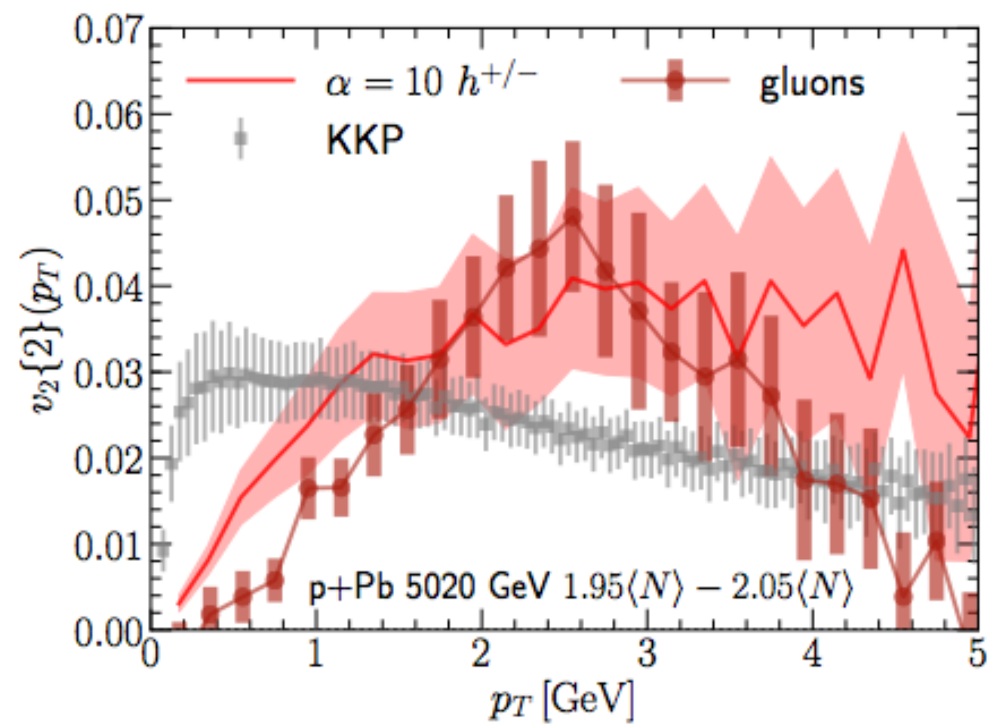
Greif, Greiner, Plätzer, Schenke, SS arXiv:2012.08493

Phenomenological calculations

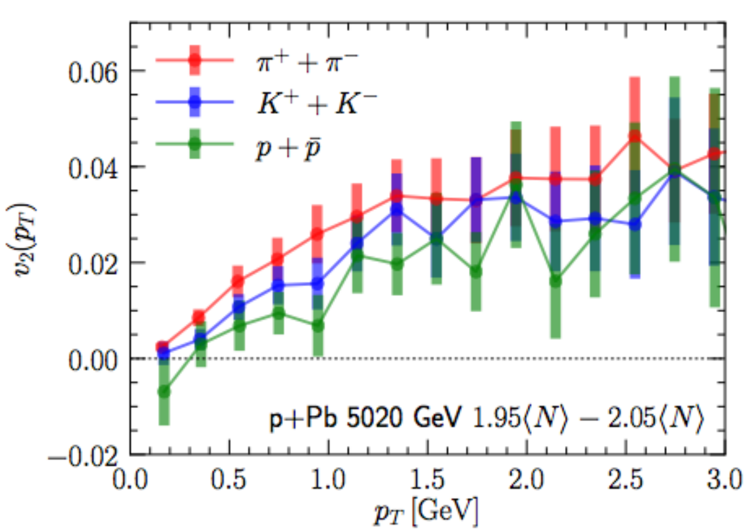
Event-by-event simulations in classical-Yang Mills theory
+ space-time local Cluster Hadronization (HERWIG)



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



Small sensitivity of inclusive particle spectra



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

Initial state effects

Several different calculations point to the fact that initial state effects can be sizable in small systems

Various phenomenologically important aspects have been addressed in different calculations

v_2/v_3 ,collectivity, mass ordering, …

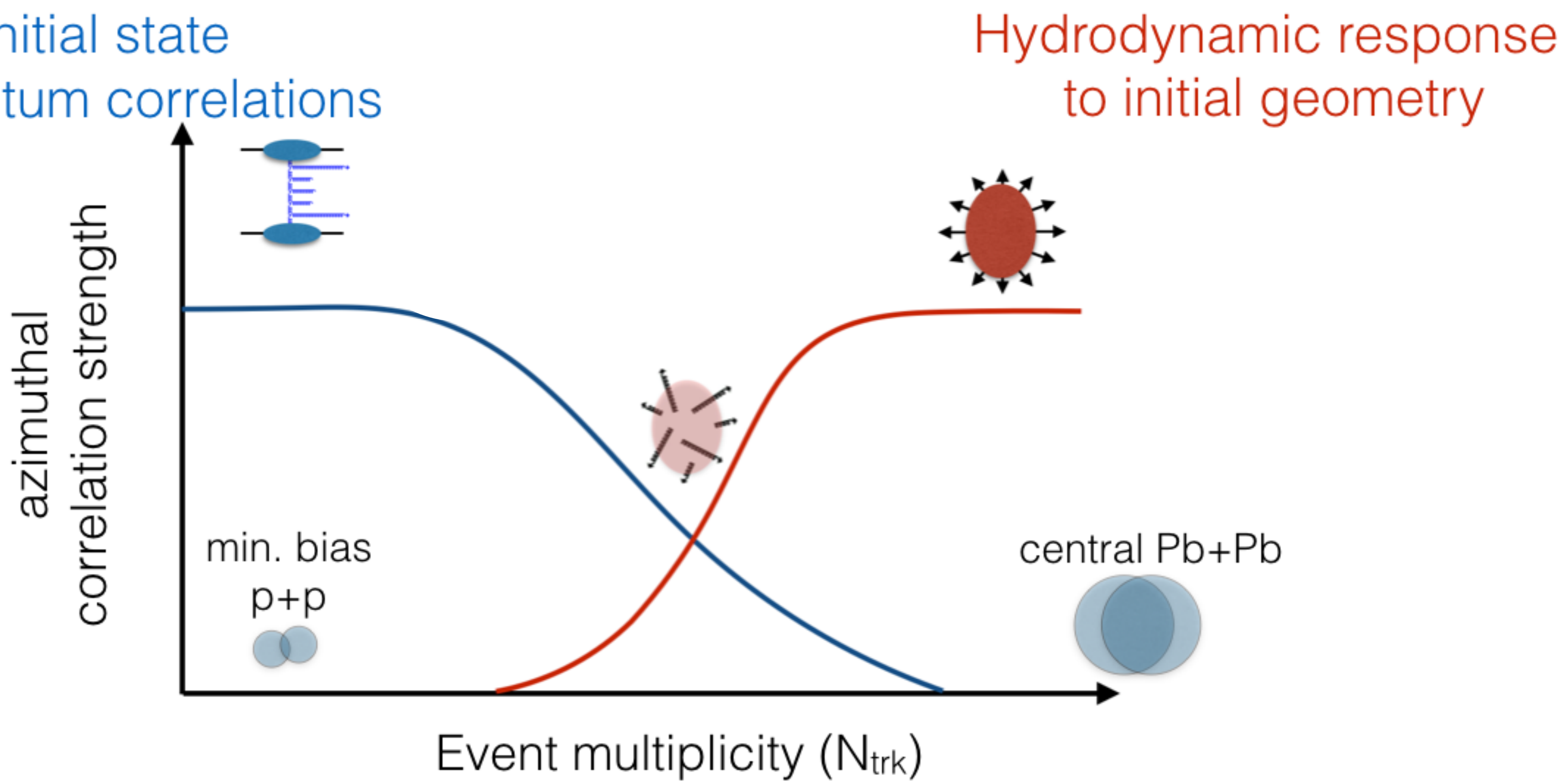
Unfortunately, so far no single calculation including all relevant effects (di-jets, multiple scattering, collectivity, hadronization) at the same time

Caveat:

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

Initial state vs. final state effects

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

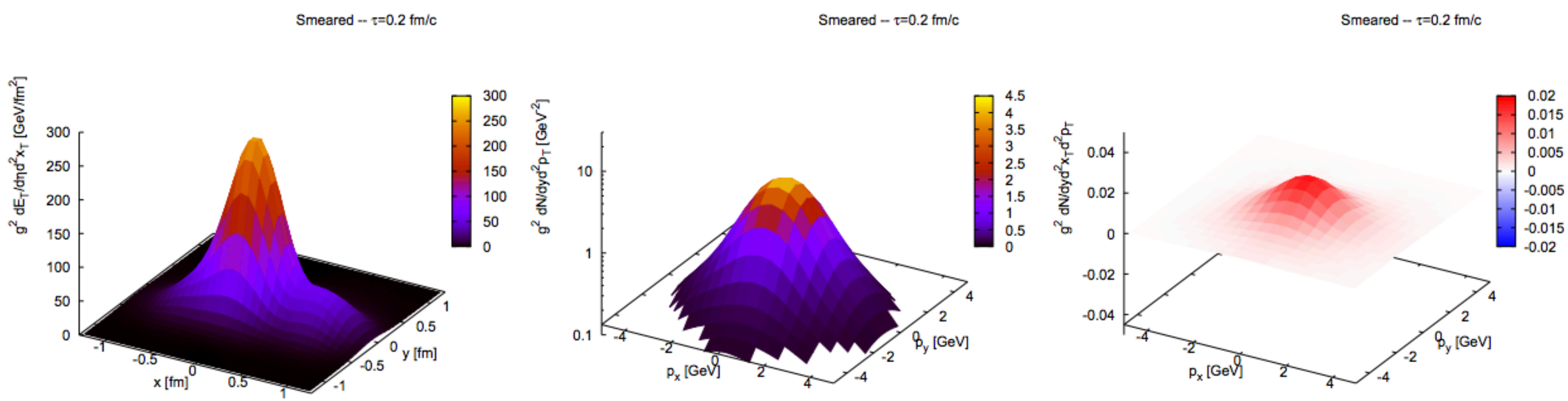
Initial state vs. final state effects

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

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

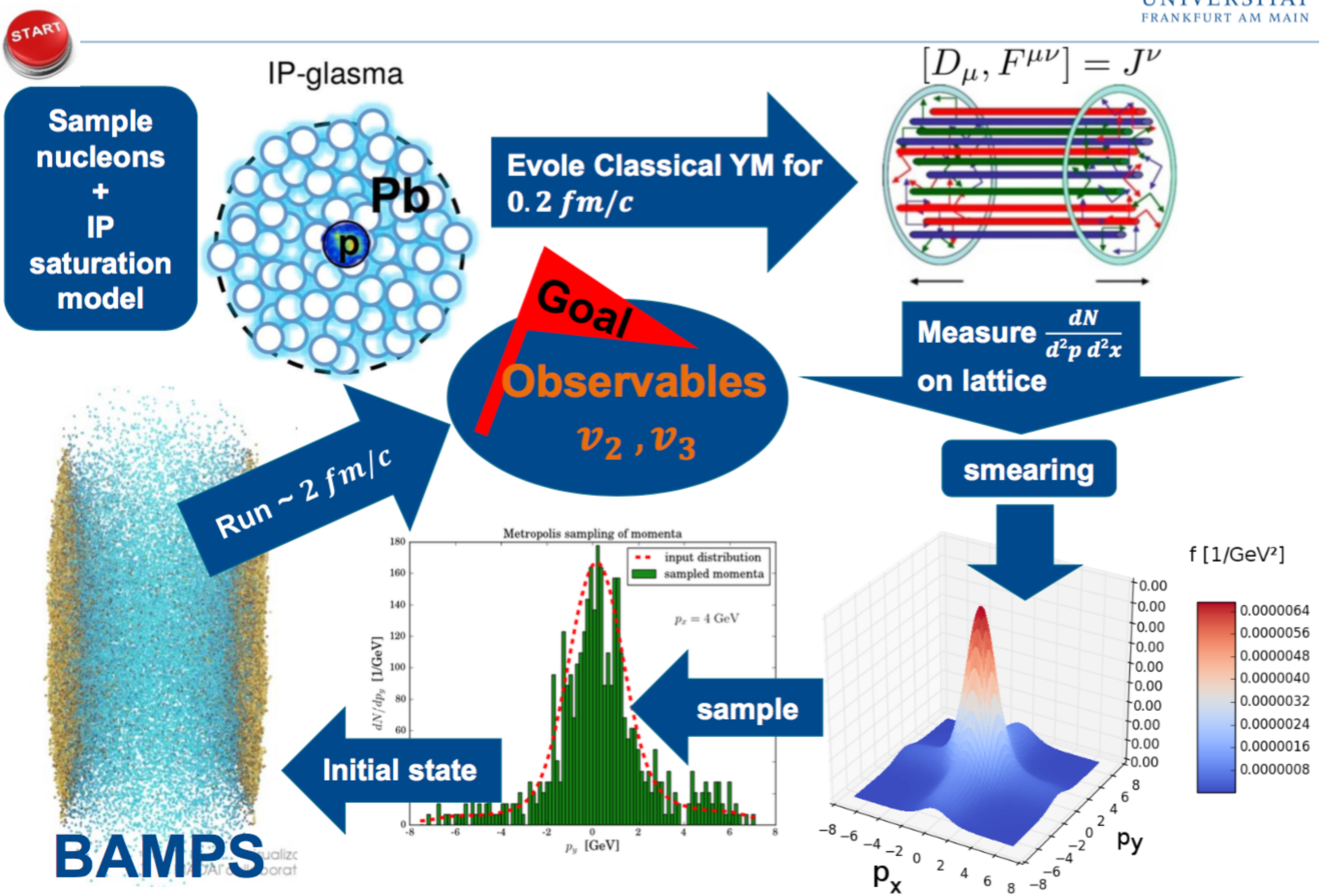
Phenomenological assessment of relative importance of initial state & final state effects by matching initial state to parton cascade

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



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

New Model: Initial + Final state interactions



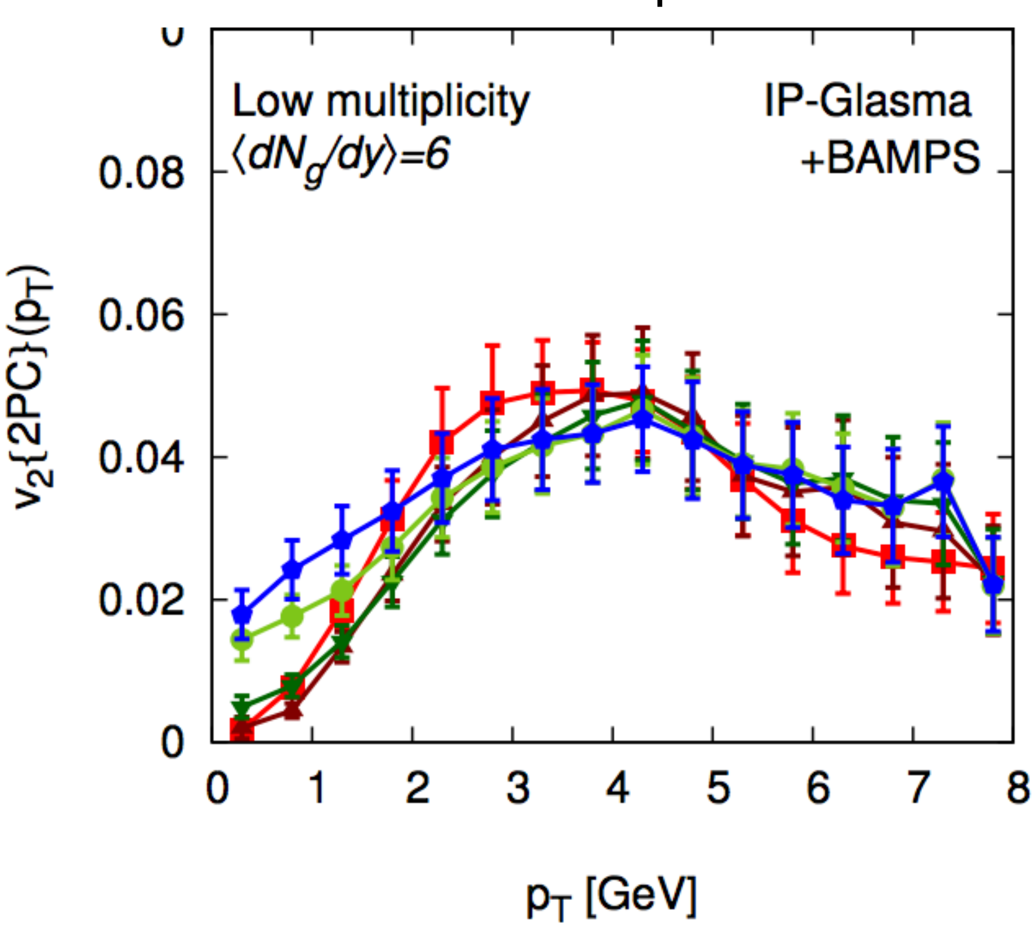
slide by M.Greif

High multiplicity vs. low multiplicity

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

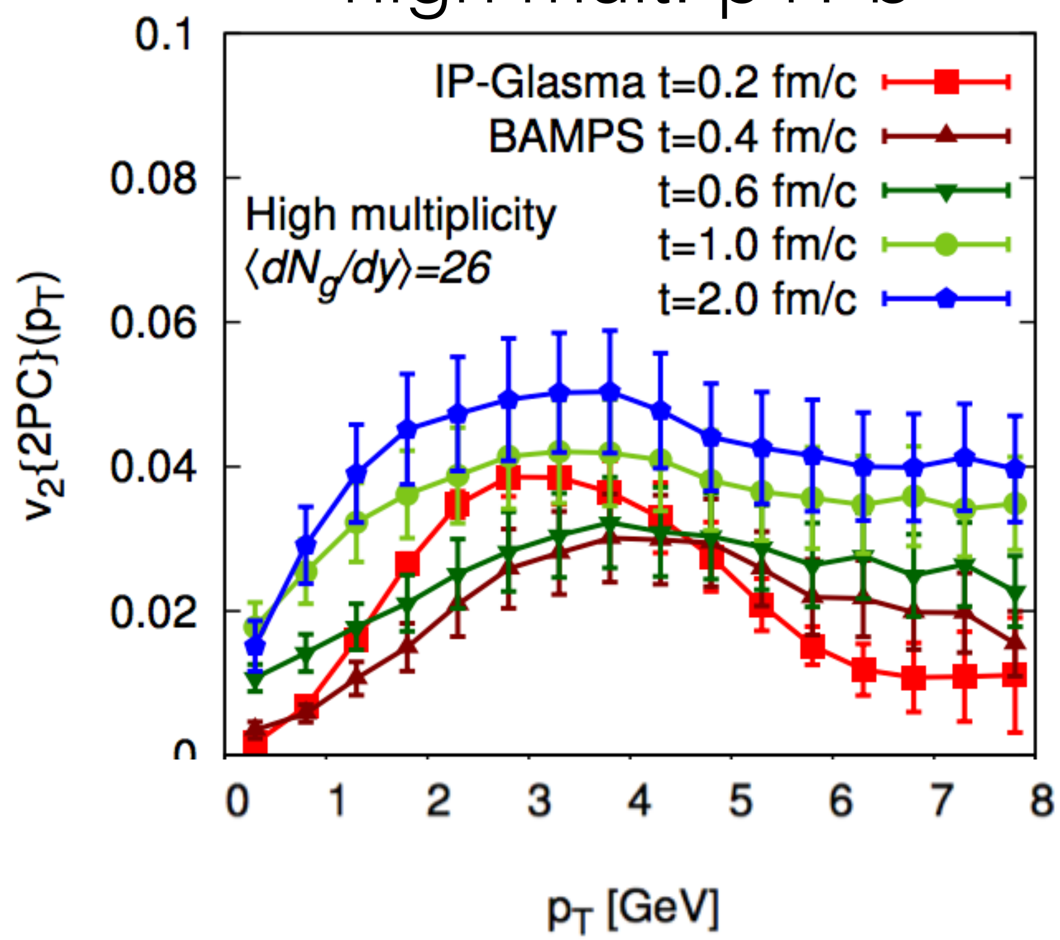
Greif, Greiner, Schenke, SS, Xu PRD96 (2017) no. 9, 091504

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

N_{Scat} = 4.5 ±1.1 $N_{large\ angle}$ = 0.53 ± 0.14

N_{Scat} = 5.6 ±1.1 $N_{large\ angle}$ = 1 ± 0.18

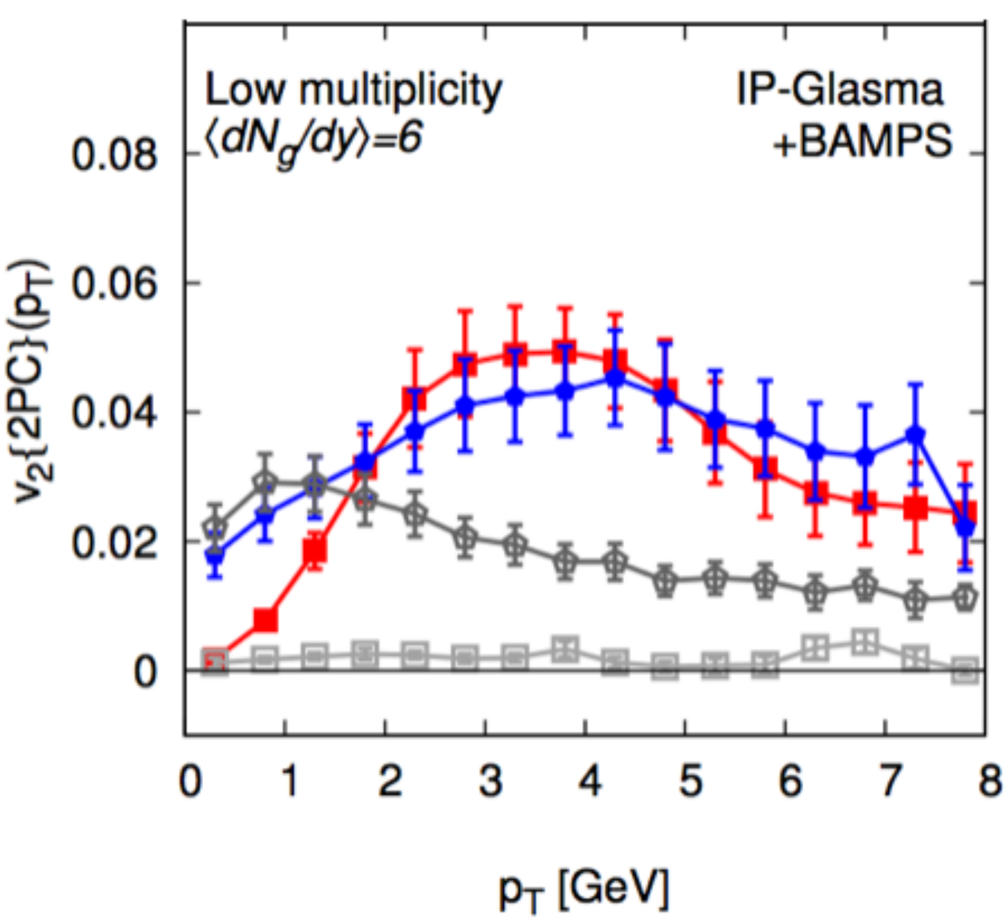
Initial state vs. final state effects

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

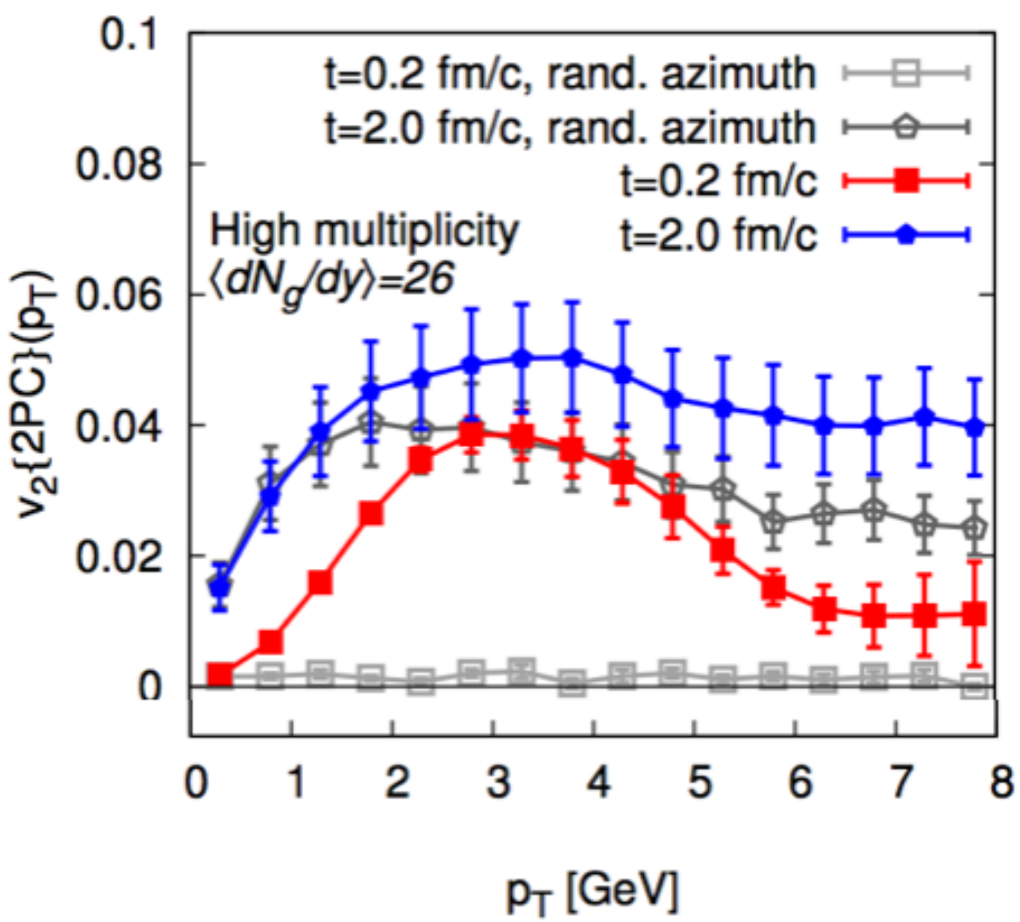
Greif, Greiner, Schenke, SS, Xu PRD96 (2017) no. 9, 091504

Isolate different effects by manually removing initial state momentum correlations

low mult. p+Pb



high mult. p+Pb



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

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

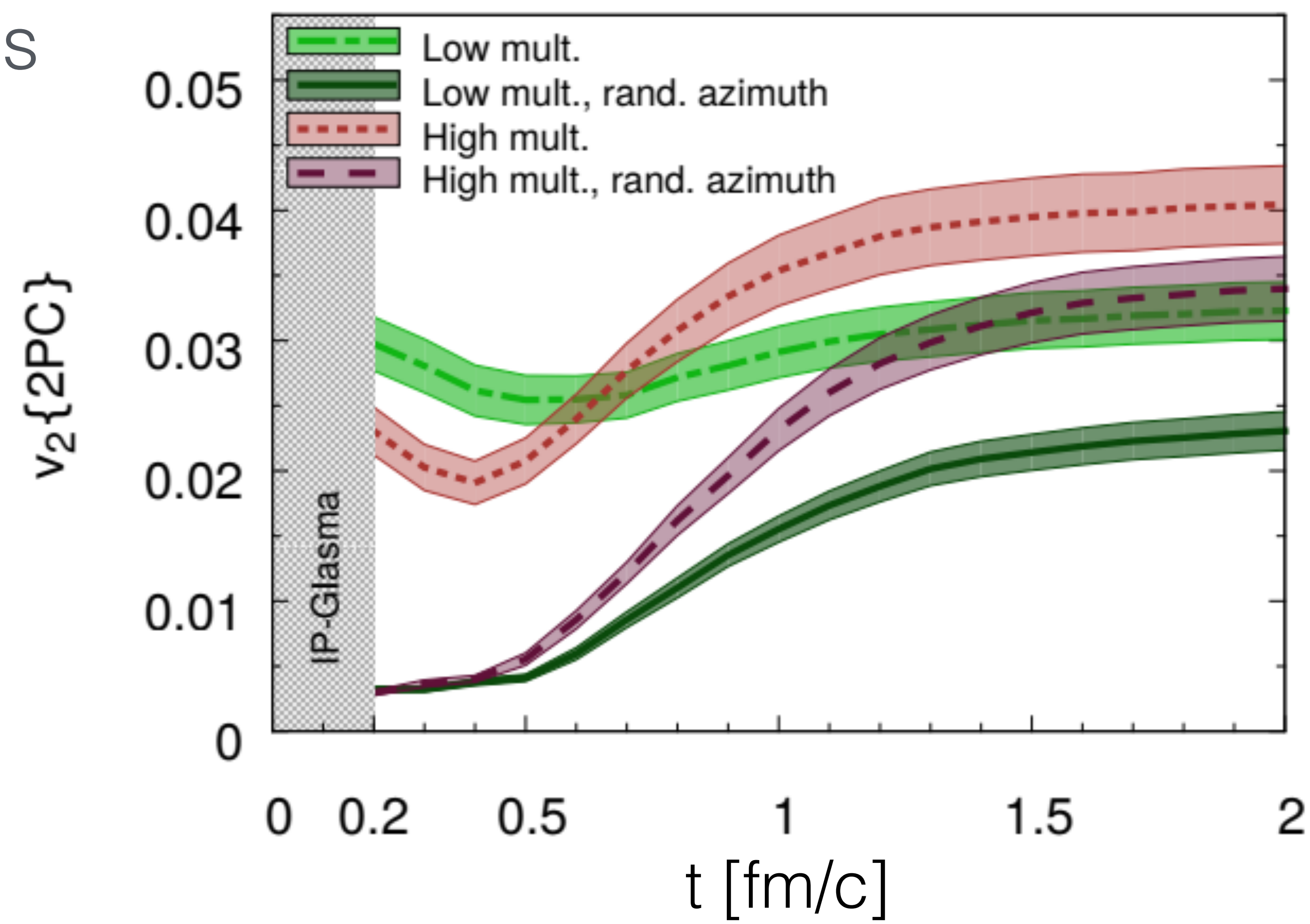
Greif, Greiner, Schenke, SS, Xu PRD96 (2017) no. 9, 091504

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.)

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 from pp to AA

Consistent theoretical description across a large range of multiplicities and transverse momenta requires development of new models including both initial state and final state effects

-> Connections with unresolved problems in A+A (equilibration, intermediate p_T physics,…)

New models including both initial state and final state effects provide first hints at relative importance of initial vs. finals state as a function of multiplicity

Still lots of work still to be done in connecting soft/hard particle production