Initial state effects and collectivity in p+p and p+A collisions at the LHC

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BROOKHAVEN NATIONAL LABORATORY

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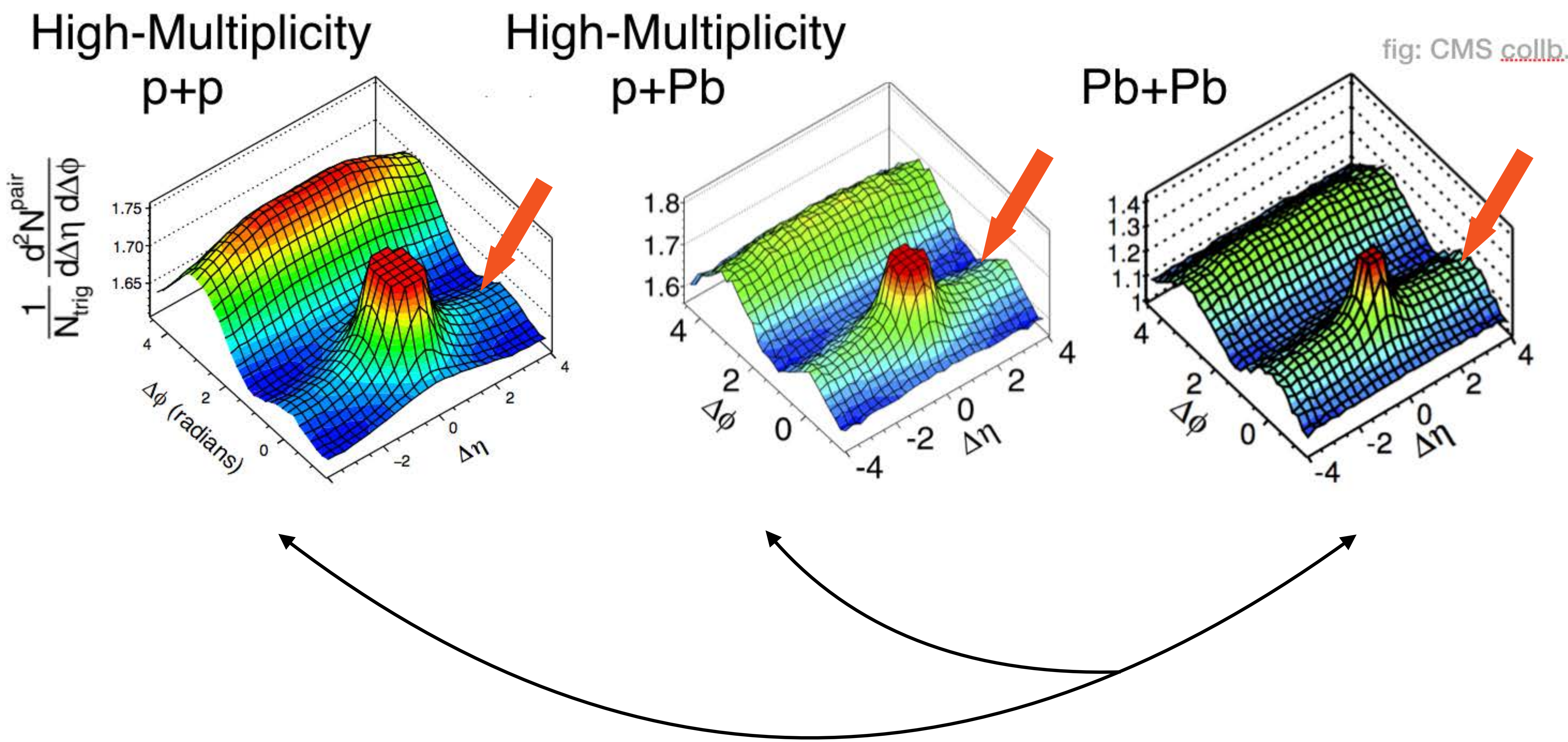
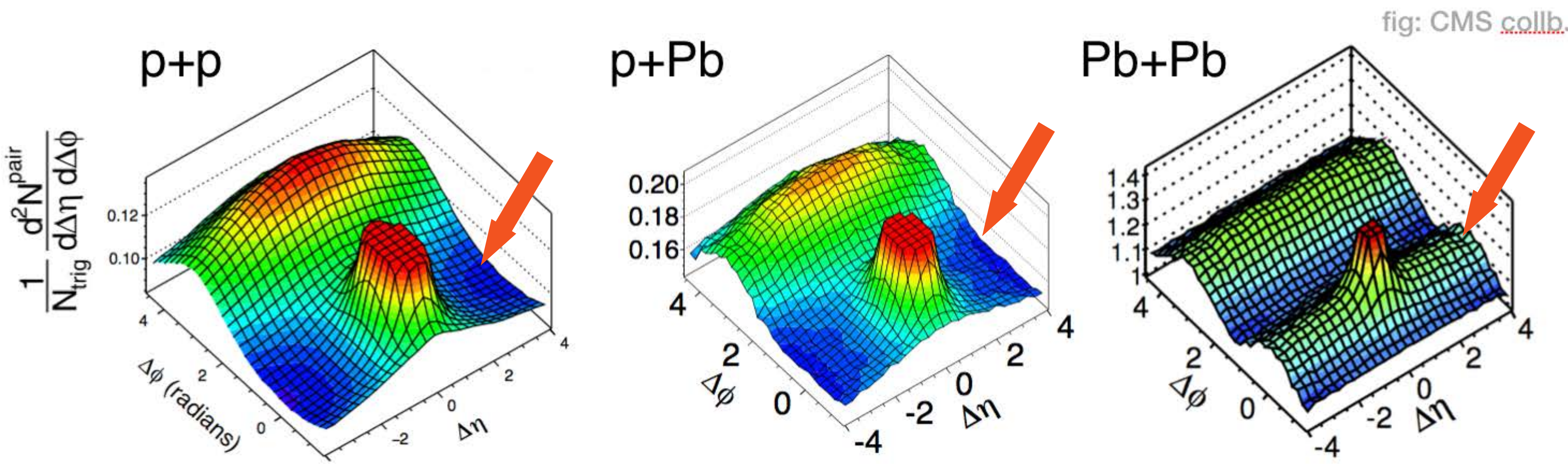
U.S. DEPARTMENT OF ENERGY | Office of Science

Ridge : remarkable effect of MPI@LHC



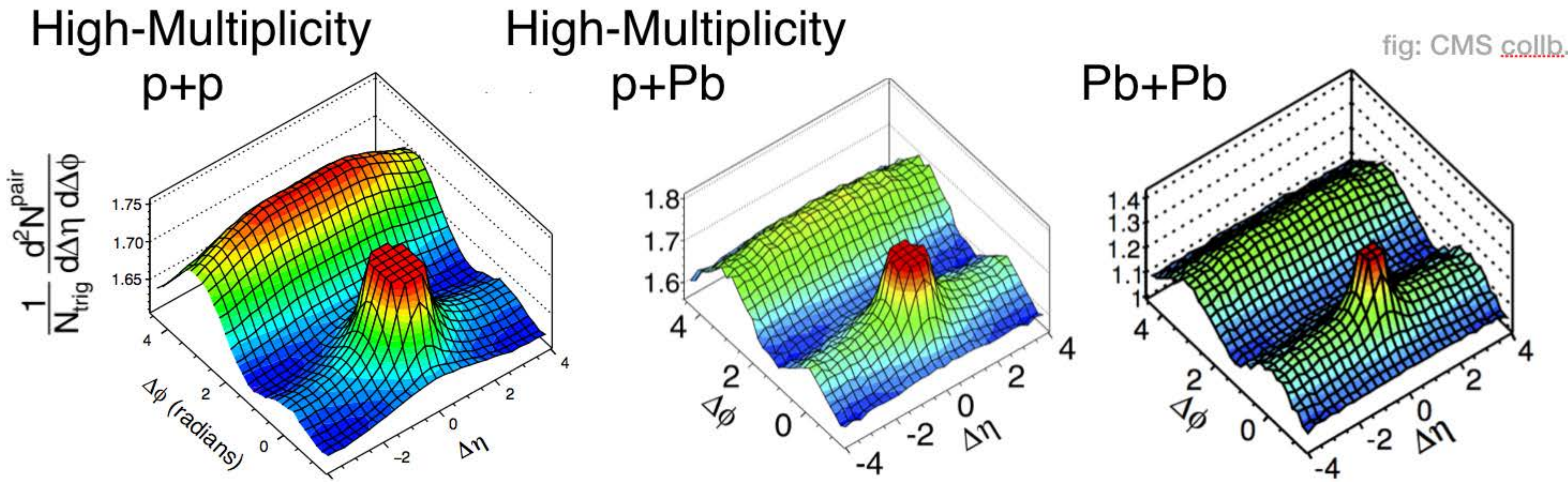
Di-hadron correlations in relative pseudorapidity (Δη) & azimuth (Δφ)
High multiplicity p+p/A → strikingly similar to A+A

Ridge : remarkable effect of MPI@LHC



Things look very different in min-bias p+p/A collisions

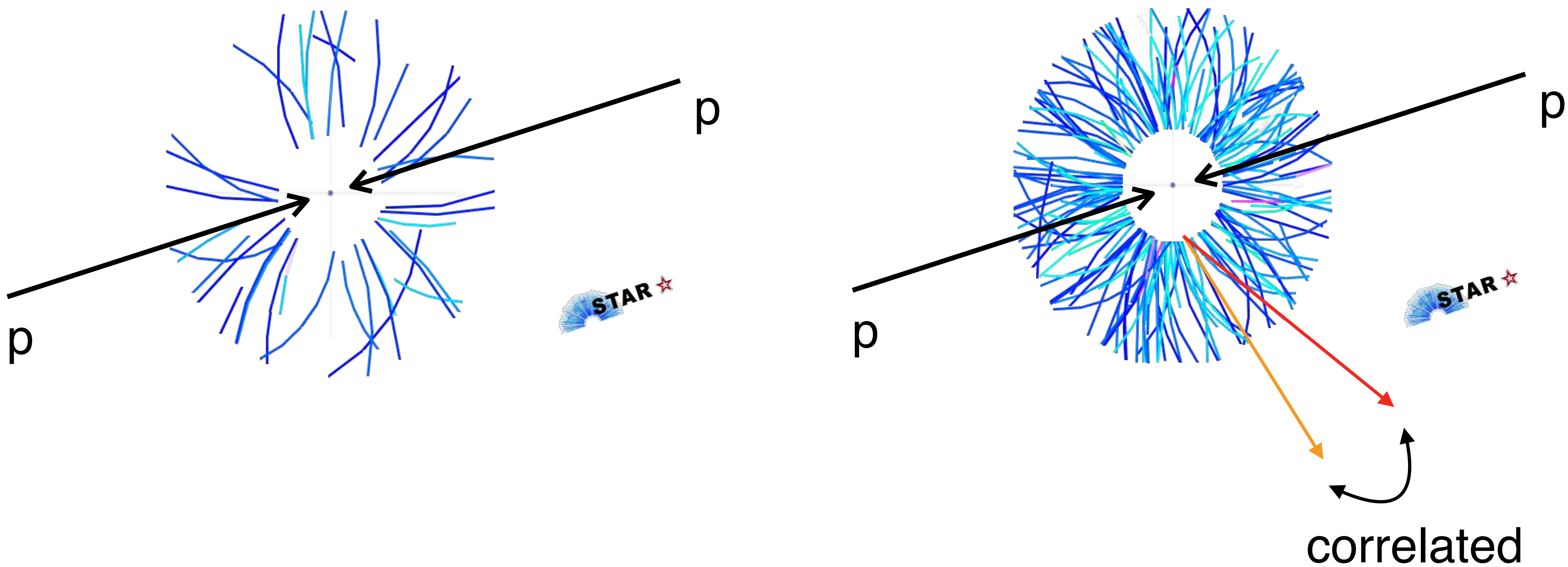
The ridge in all systems



A rare process

Not a rare process

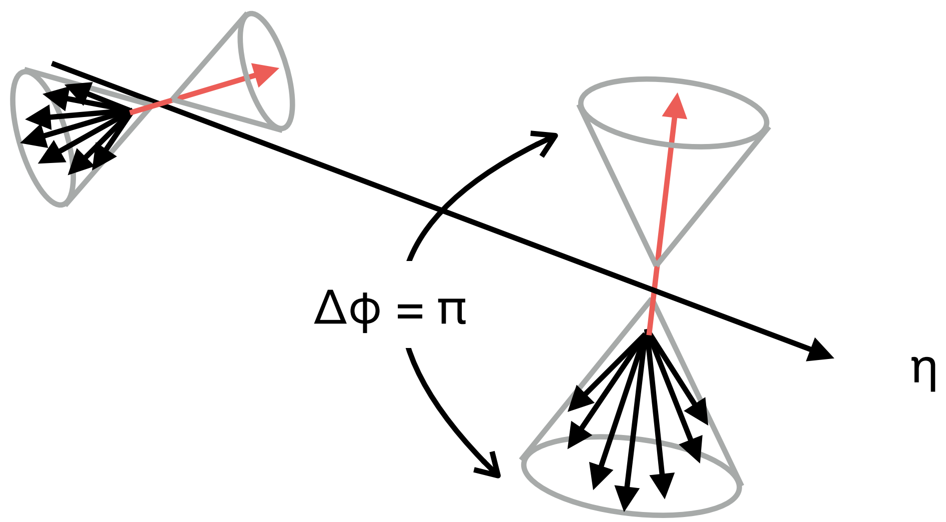
High multiplicity events & collectivity

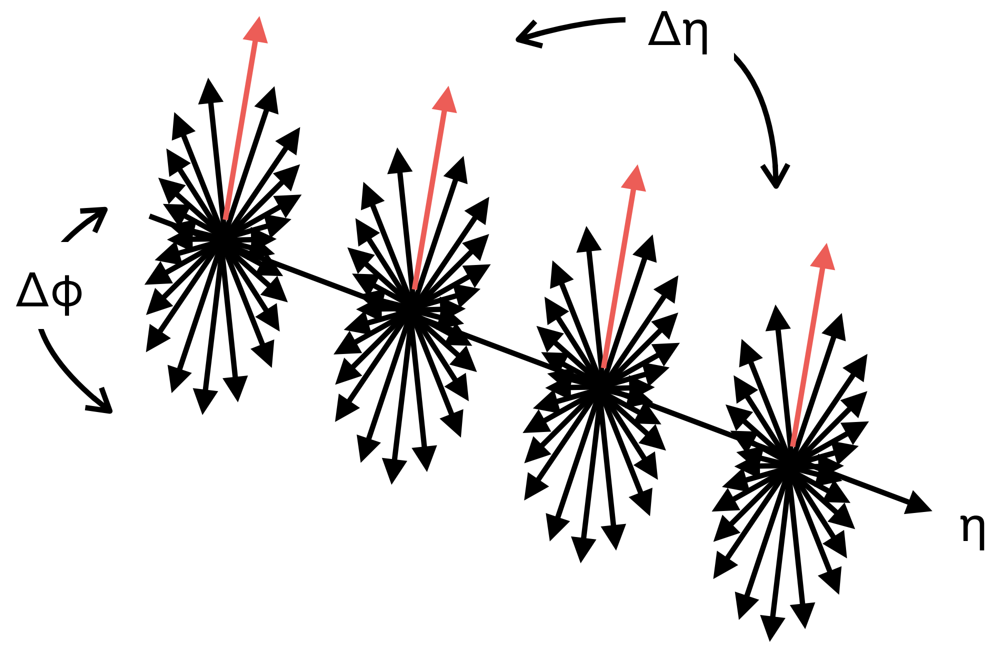


Two main puzzles :
Some times many particles come out, but why ?
The particles in high multiplicity events show collectivity.

What do I mean by collectivity ?

Strong correlations do not necessarily mean collectivity



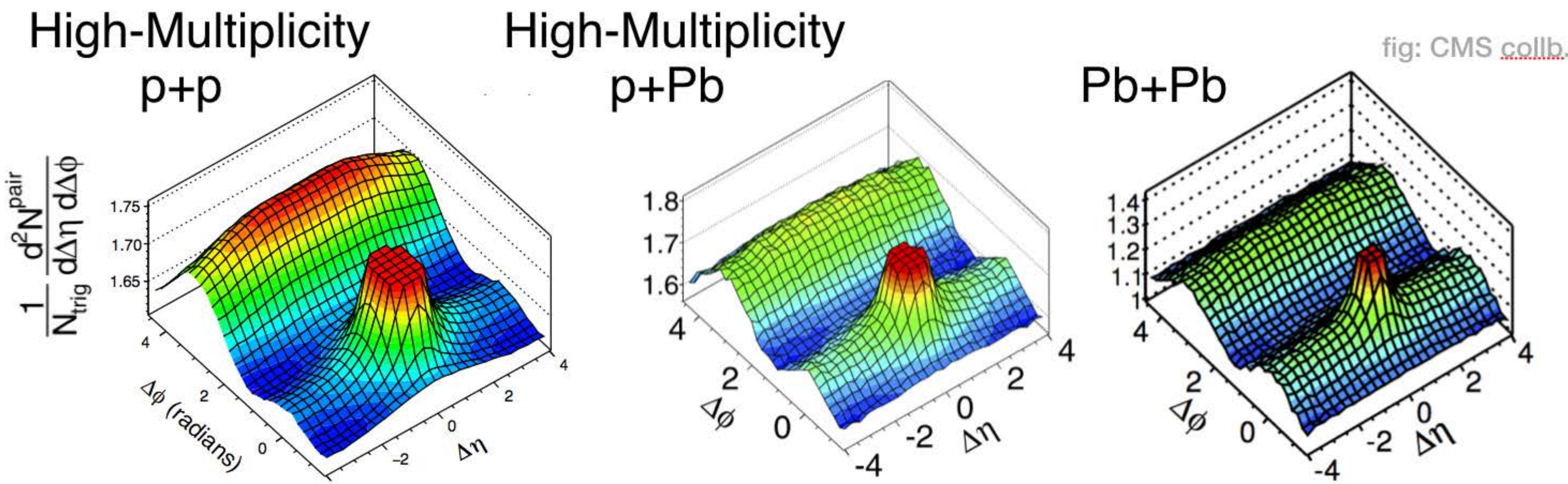


Di-jets produce strong correlations but no collectivity ~falls off 1/N (random walk)

Fluid dynamic correlations correlations in are collective

Let me give you a working definition :
Correlations among particles over a wide range of momentum space

The ridge in all systems



Approach this way (intrinsic momentum space correlations, MPIs)

Approach this way (position space correlations + fluid-dynamics)

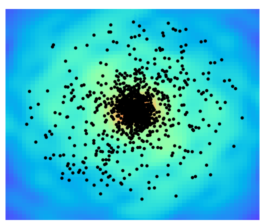
There could be different ways to approach this problem

The Qualitative picture

Initial state correlations

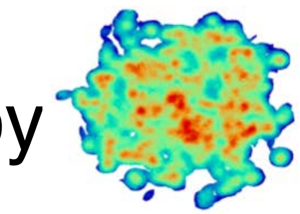
Momentum space correlations

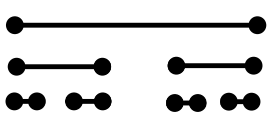
Position space correlations



(Mini-) jets,
n-parton correlations

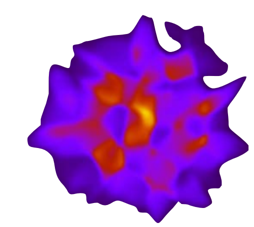
Initial spatial anisotropy

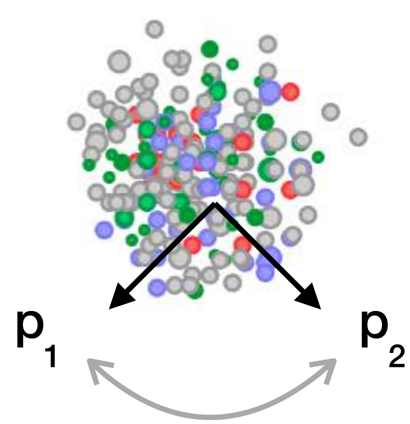




Fragmentation

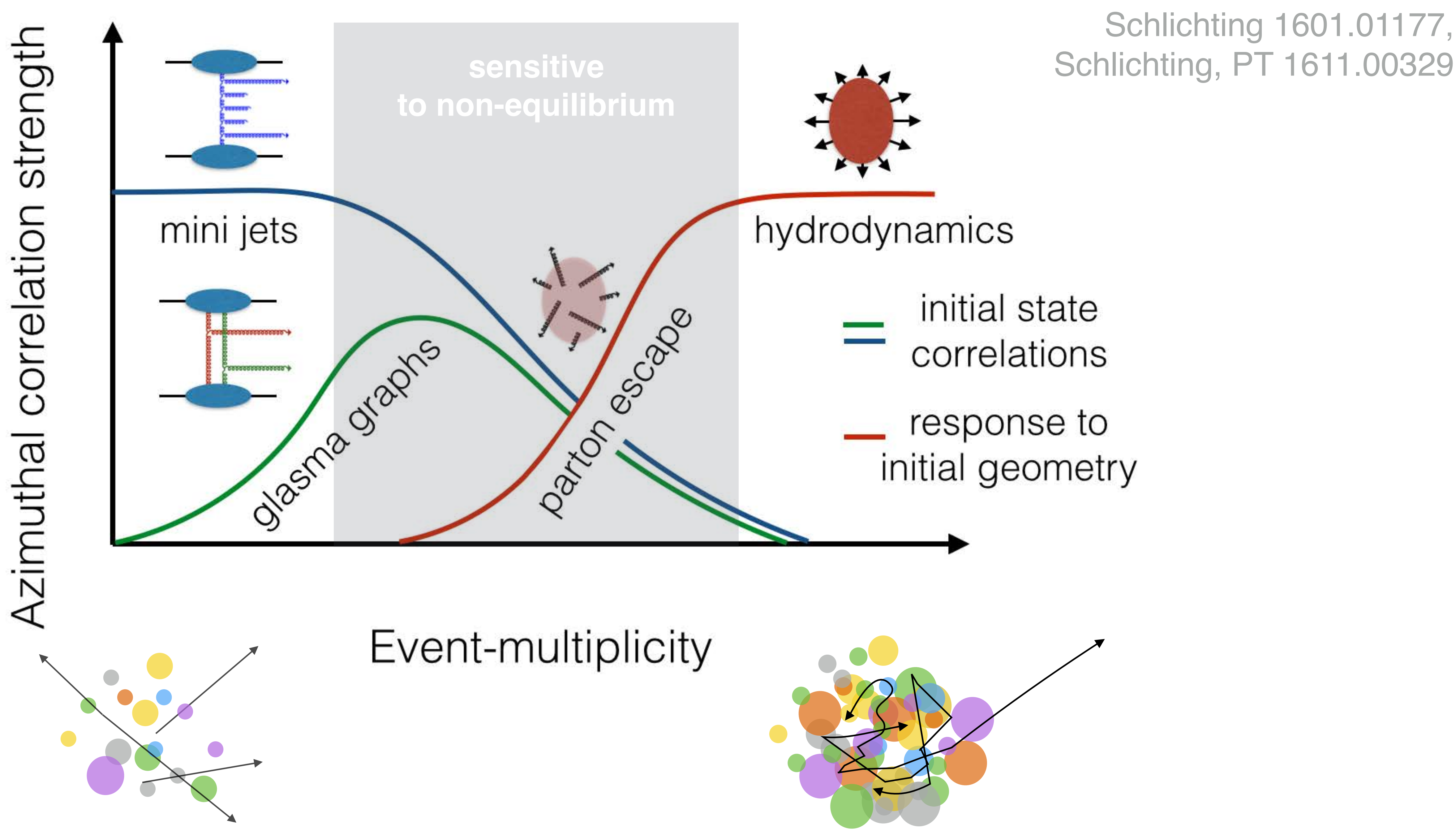
Transport,
Hydrodynamic



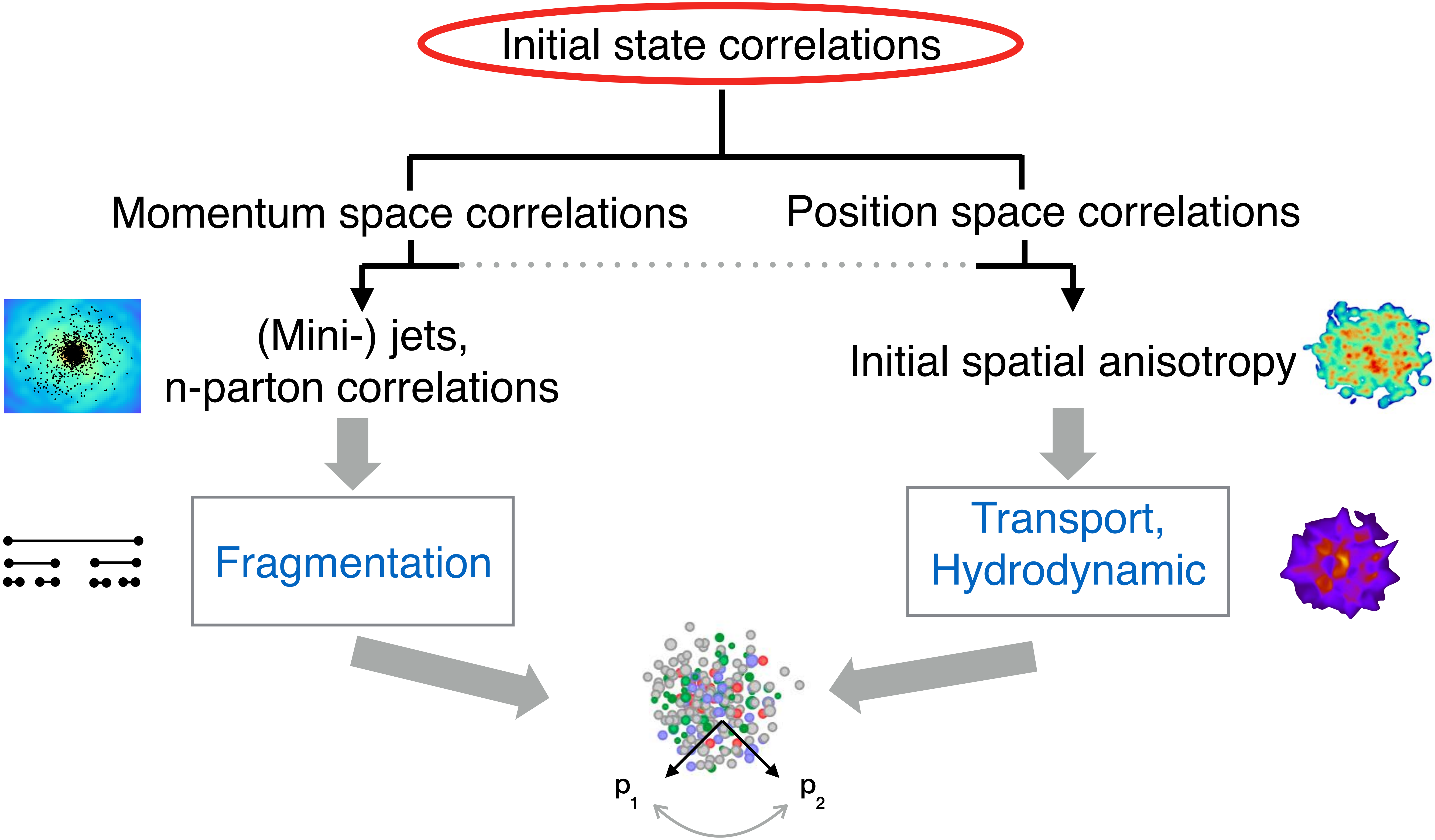


Experimentally observed correlations (both should contribute)

The Phase Diagram of Correlation



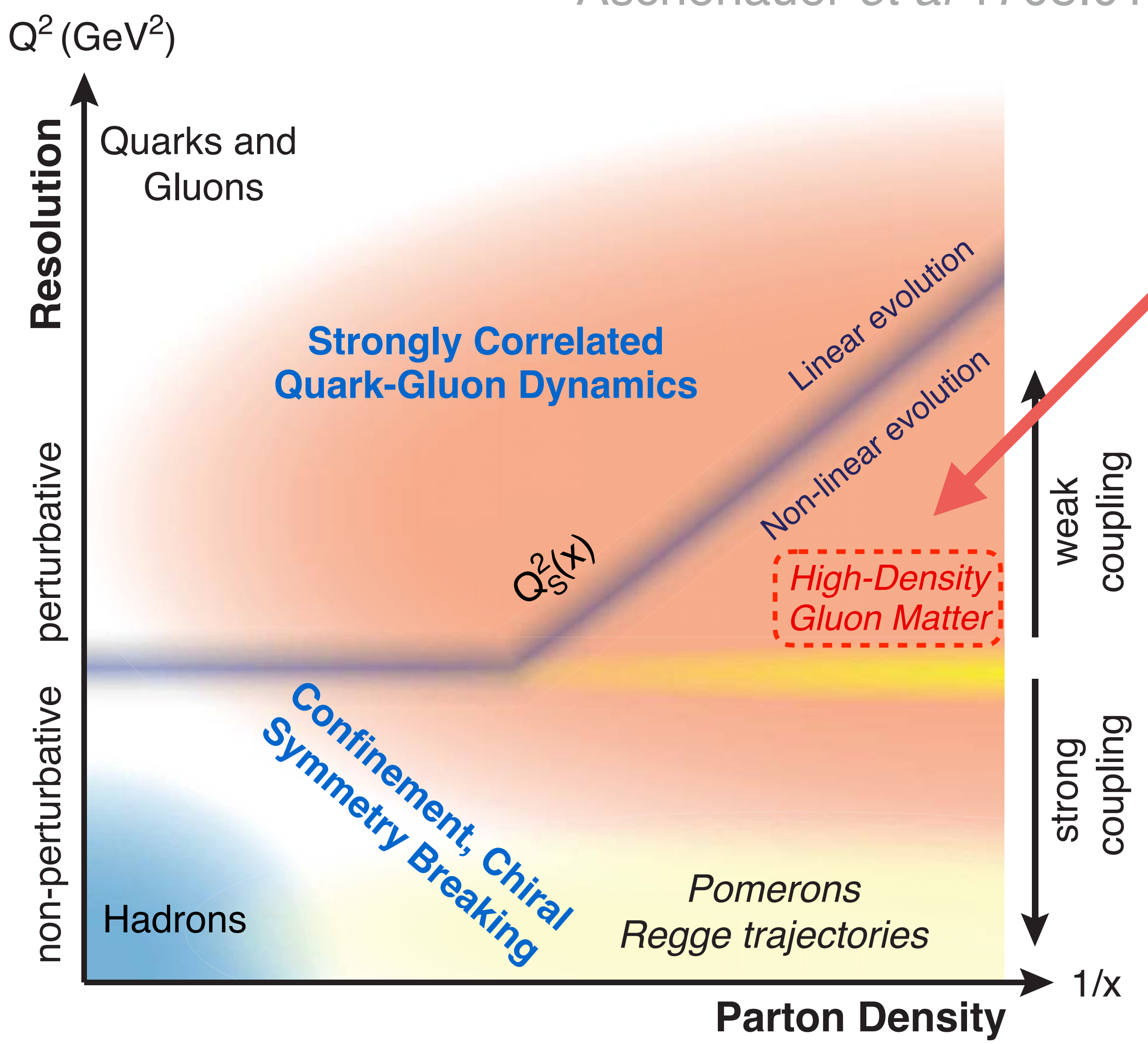
The Qualitative picture



Experimentally observed correlations (both should contribute)

The landscape of QCD : particle production

Aschenauer *et al* 1708.01527



Most of the particles are produced from this region

Non linear process leads to gluon saturation

An *ab initio* universal theory description :

Color Glass Condensate

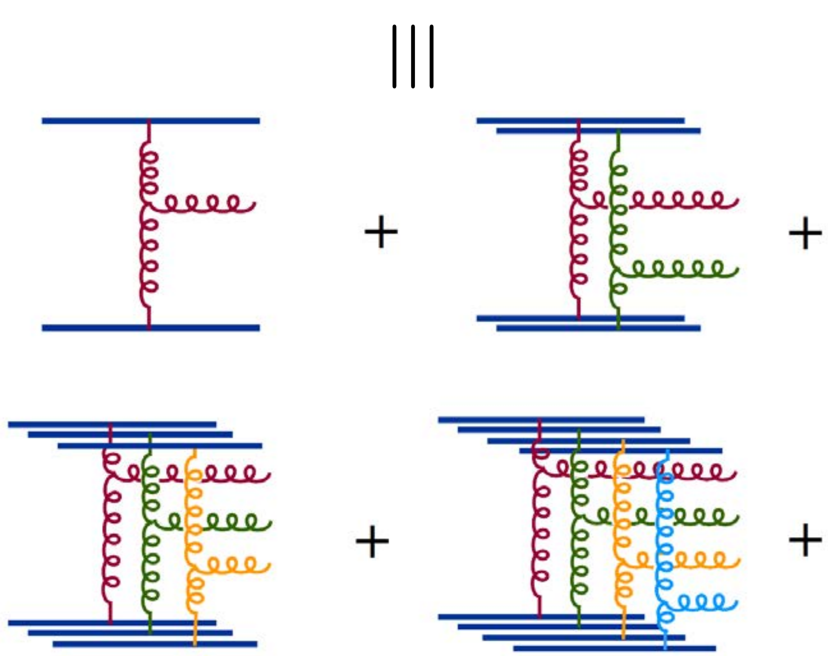
The IP-Glasma model of CGC

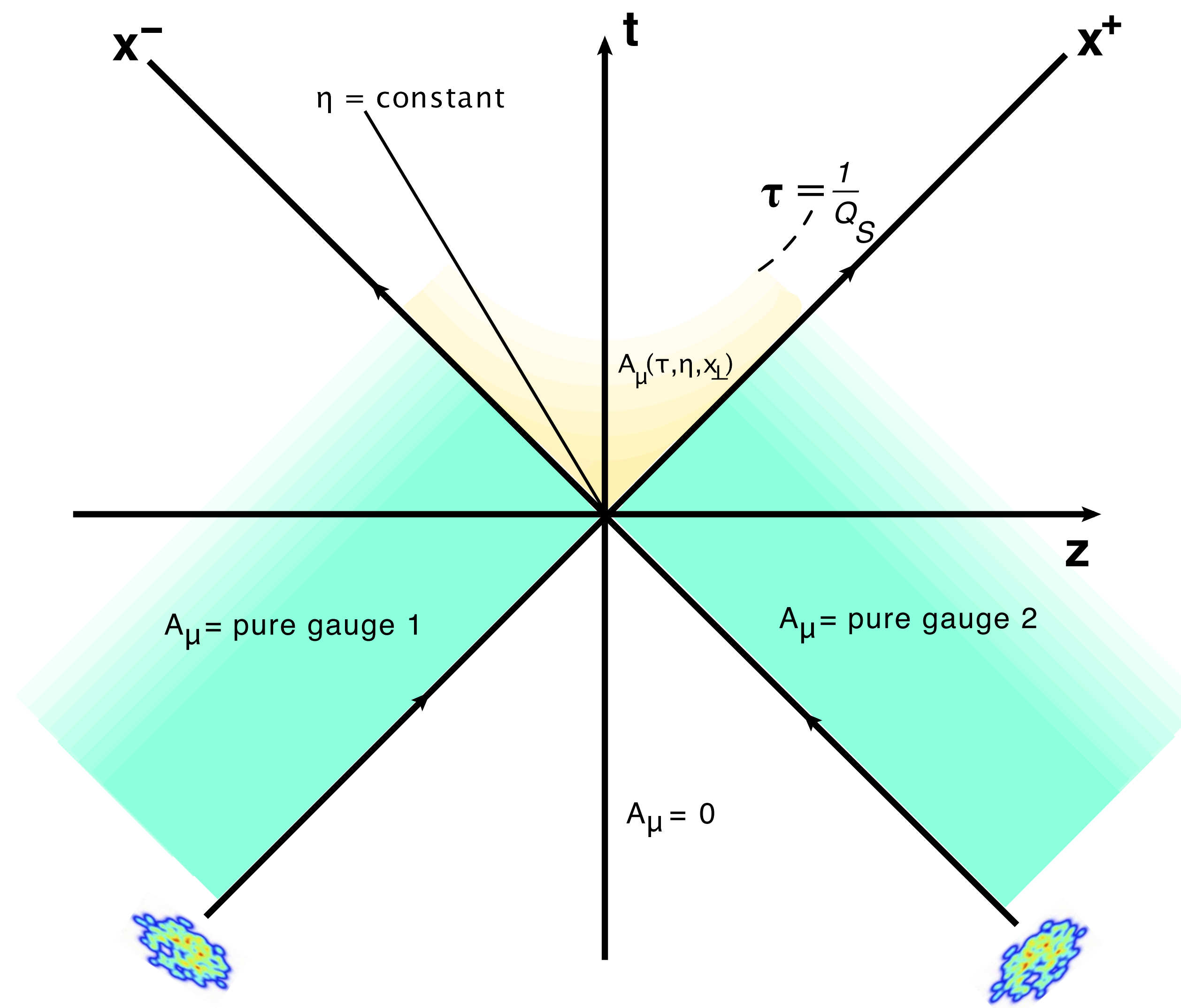
- Compute fields due to fluctuating color charge density inside colliding hadrons/nuclei by solving

$$[D_\mu, F_{\mu\nu}] = J_\nu$$

- Compute & evolve the color fields after collisions

$$A^i = A^i_{(A)} + A^i_{(B)} \qquad A^\eta = \frac{ig}{2}\left[A^i_{(A)}, A^i_{(B)}\right]$$





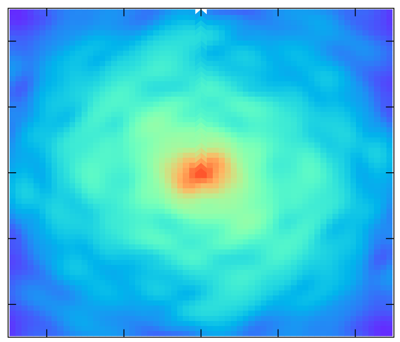
Multiparton interactions (MPIs) are naturally included in this approach

Schenke, PT, Venugopalan Phys. Rev. Lett. 108 (2012) 252301

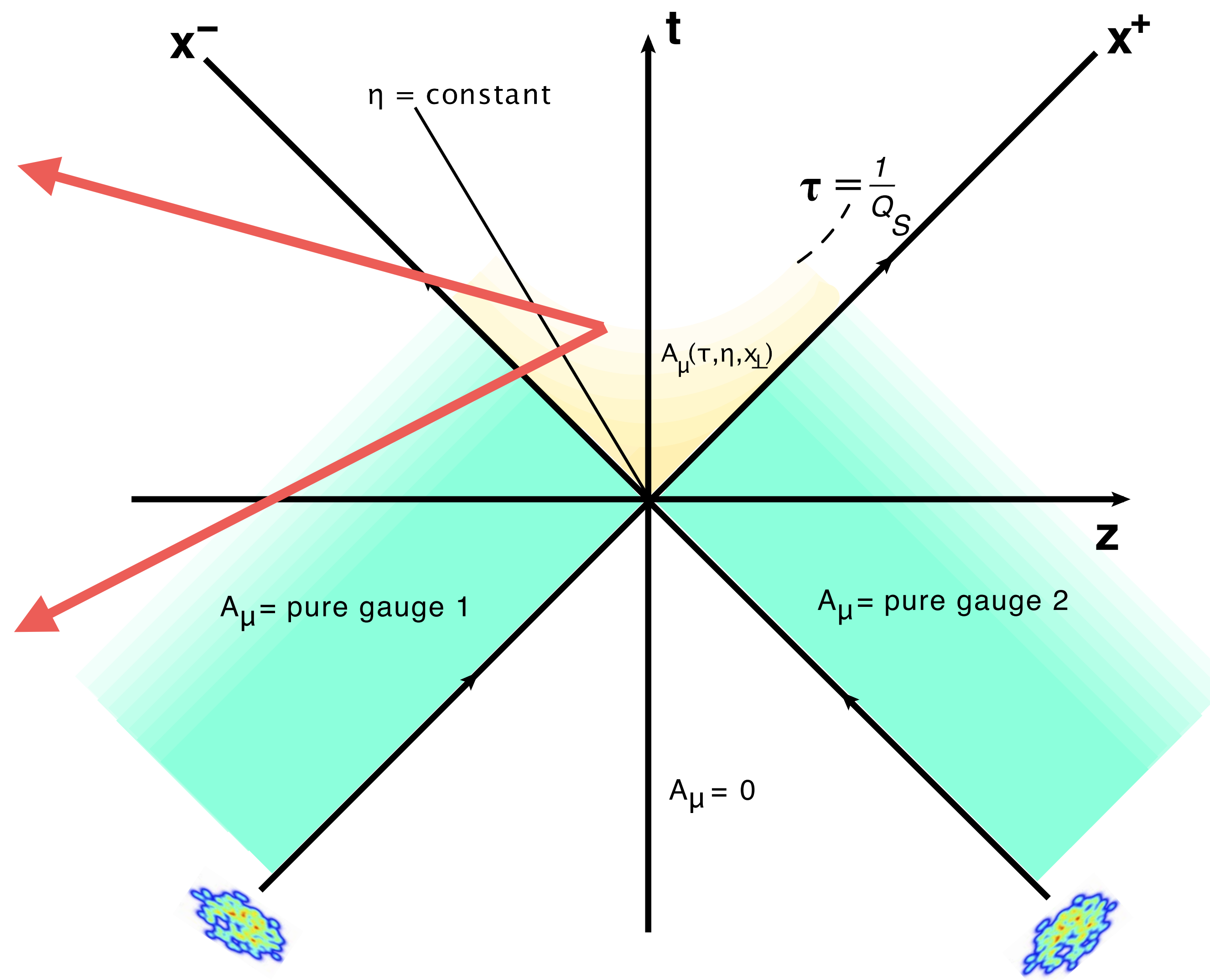
Initial state correlations : IP-Glasma model

Momentum space information

$$\frac{dN}{d\mathbf{k}_T dy}$$

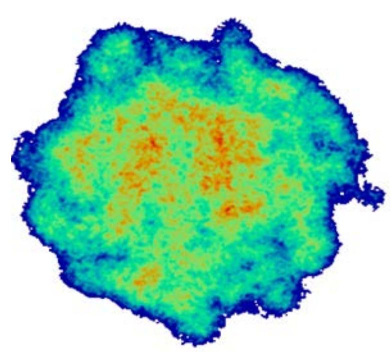


Input for PYTHIA, p+p collisions



Position space information

$$T_{\mu,\nu}(\tau, x_{\perp}, \eta)$$



Input for hydro, transport, p+A , A+A collisions

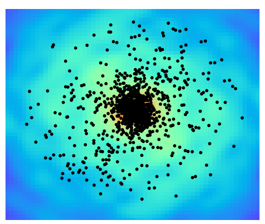
Schenke, PT, Venugopalan Phys. Rev. Lett. 108 (2012) 252301

The Qualitative picture

IP-Glasma (CGC Initial state correlations)

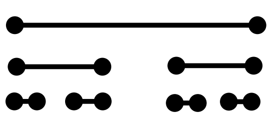
Momentum space correlations

Position space correlations



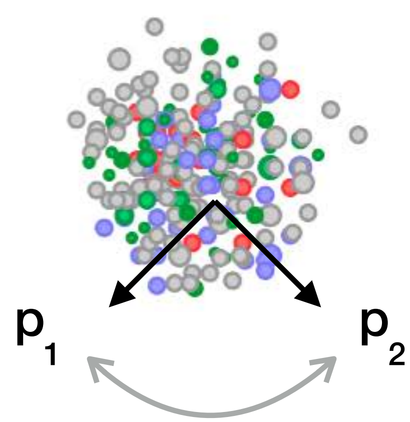
(Mini-) jets,
n-parton correlations

Initial spatial anisotropy



Fragmentation

Transport,
Hydrodynamic

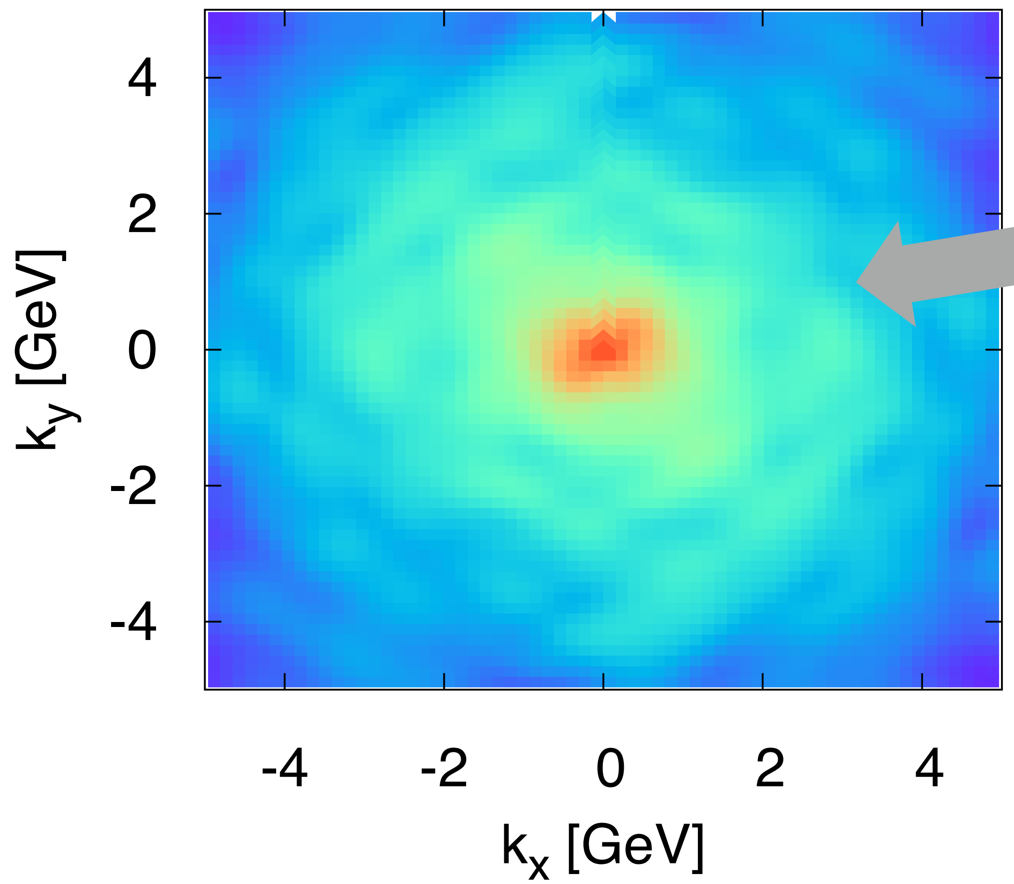


Experimentally observed correlations (both should contribute)

CGC meets Lund fragmentation of PYTHIA

IP-Glasma gluon dist→ Sampling gluons → Strings → Hadronization

$$\frac{dN}{d\mathbf{k}_T dy}$$



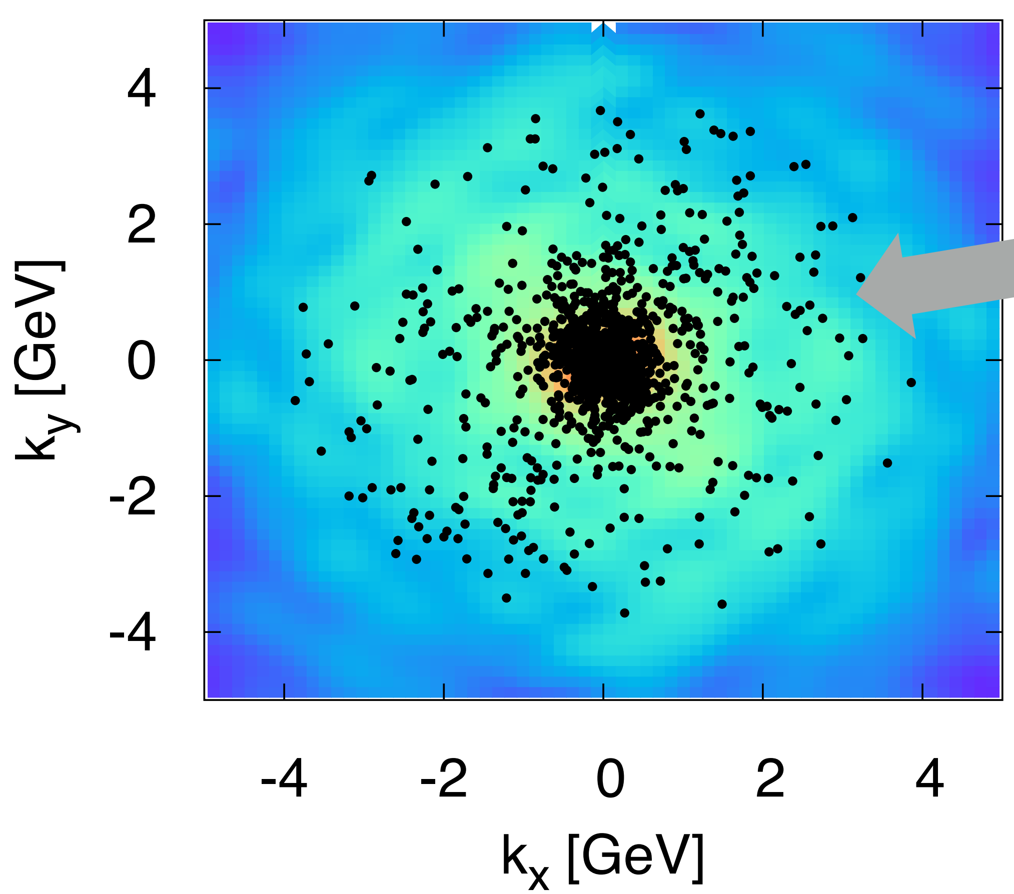
Momentum space anisotropy is already built in

Schenke, PT, Venugopalan Phys. Rev. Lett. 108 (2012) 252301

CGC meets Lund fragmentation of PYTHIA

IP-Glasma gluon dist→ Sampling gluons → Strings → Hadronization

$$\frac{dN}{d\mathbf{k}_T dy}$$



Sampled gluons carry momentum space anisotropy

Schenke, PT, Venugopalan Phys. Rev. Lett. 108 (2012) 252301

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IP-Glasma gluon dist → Sampling gluons → Strings → Hadronization

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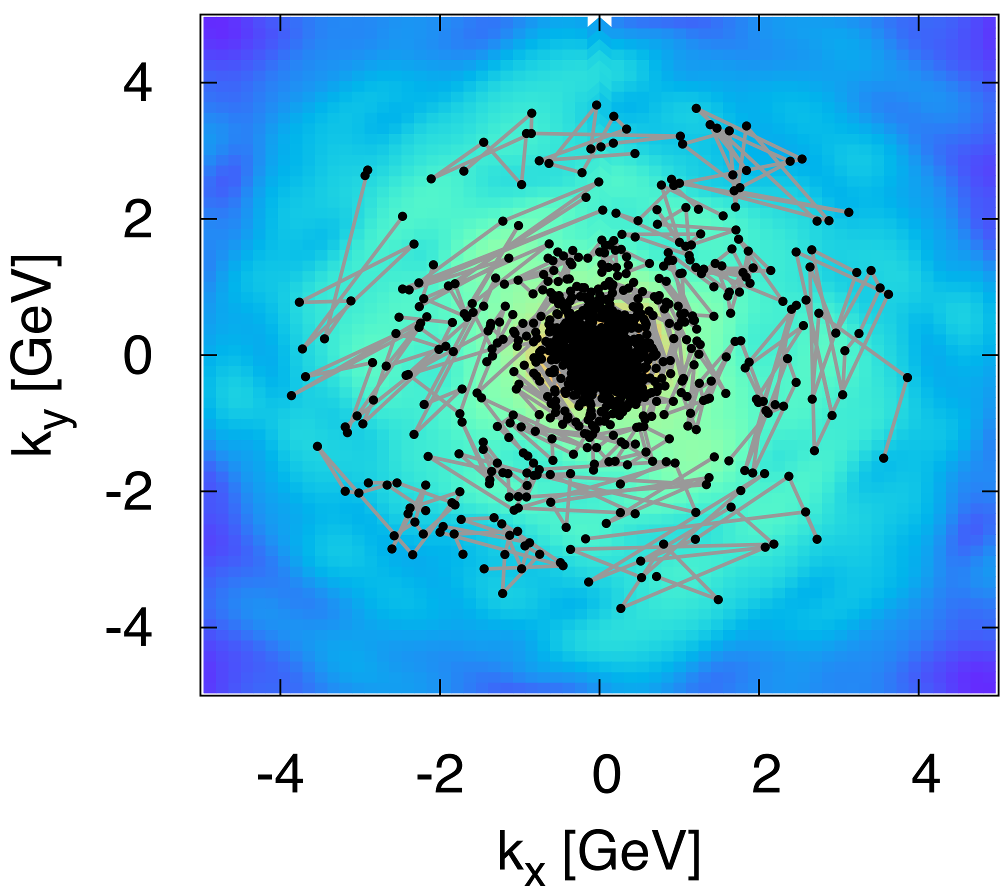
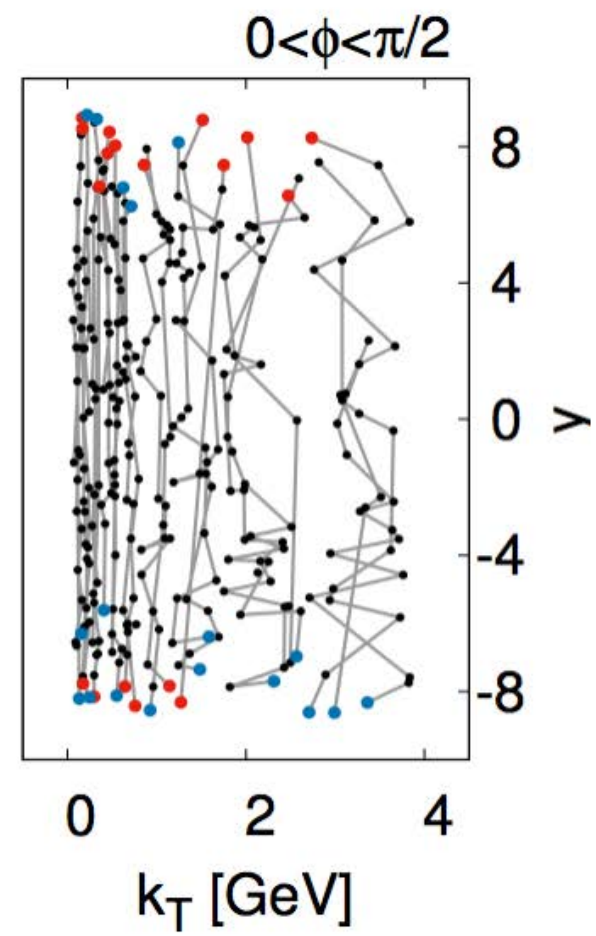


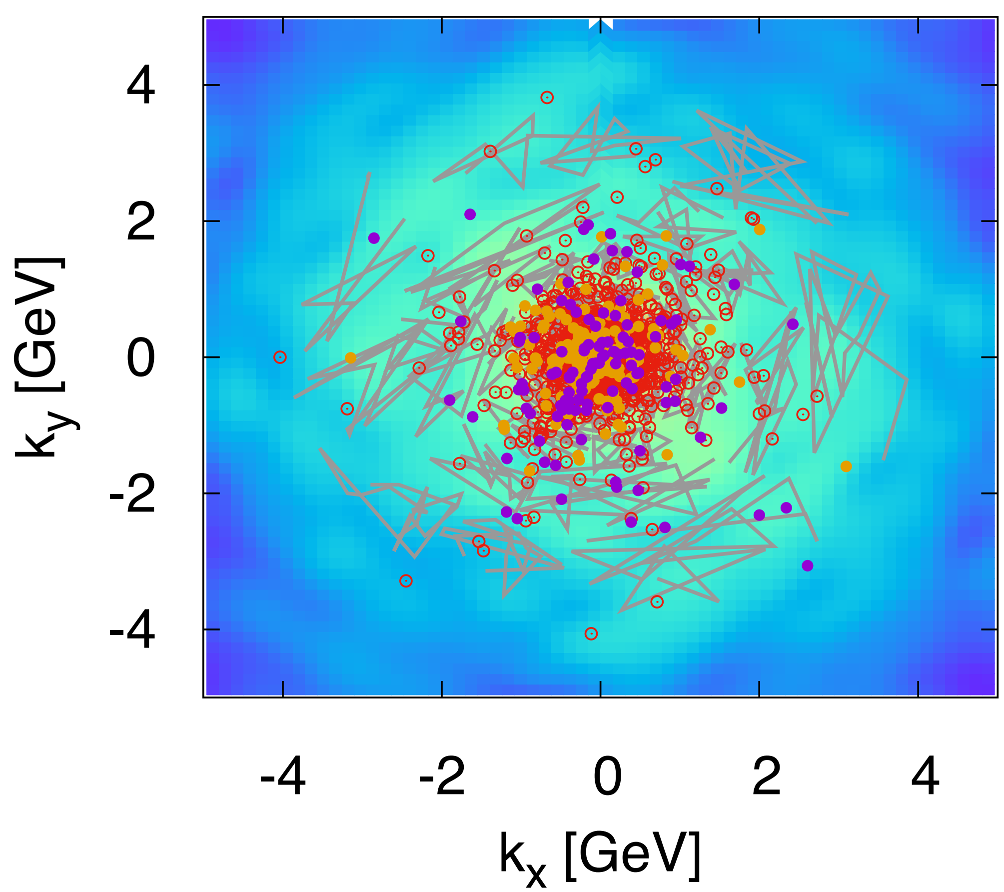


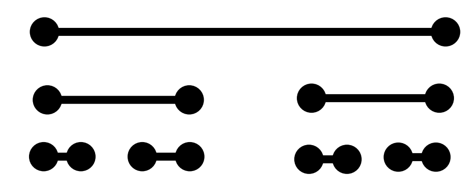
No color-reconnection effect unlike standard PYTHIA

CGC meets Lund fragmentation of PYTHIA

IP-Glasma gluon dist→ Sampling gluons → Strings → Hadronization

$$\frac{dN}{d\mathbf{k}_T dy}$$





$$f(z, m_T) = \frac{1}{z}(1-z)^a \exp\left(-\frac{b\, m_T{}^2}{z}\right)$$

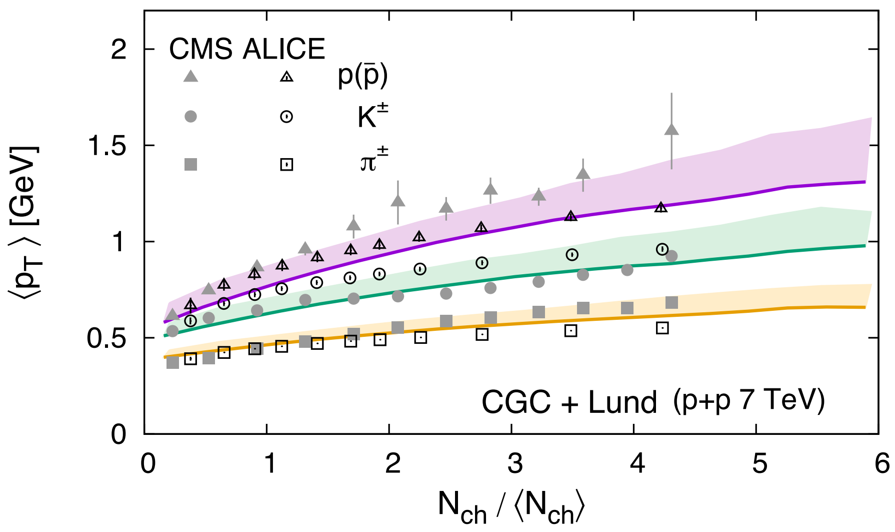
Lund String Fragmentation

A new Monte-Carlo event generator : CGC+Lund (CGC+PYTHIA)

Results from CGC + PYTHIA (Lund)

Schenke, PT, Venugopalan Phys. Rev. Lett. 108 (2012) 252301

Mass ordering of p_T

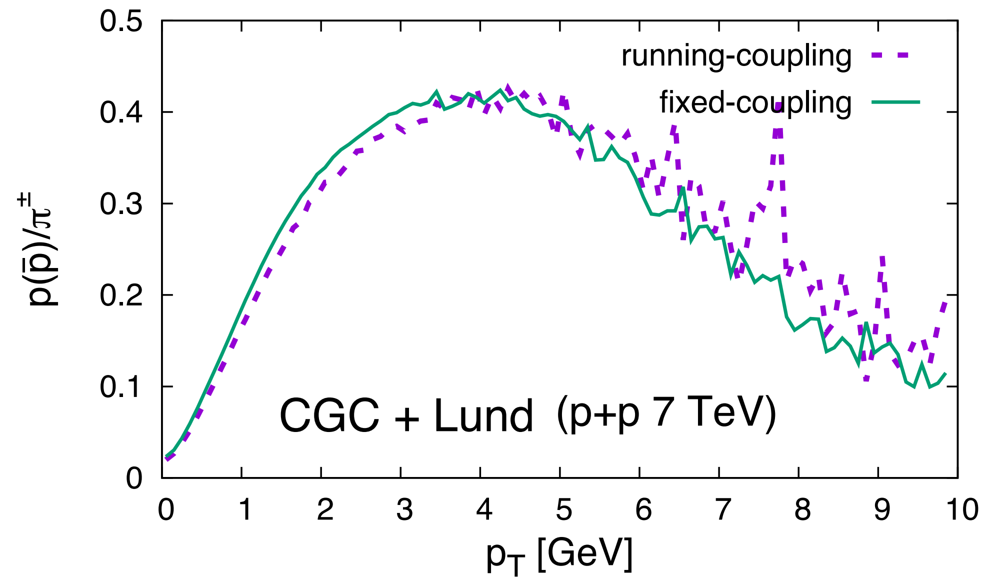


$$N_g \propto Q_S^2 S_\perp$$

$$\langle p_T \rangle_g \propto \langle Q_S \rangle$$

$$\langle p_T \rangle_g \propto \sqrt{N_g / S_\perp}$$

proton to pion ratio



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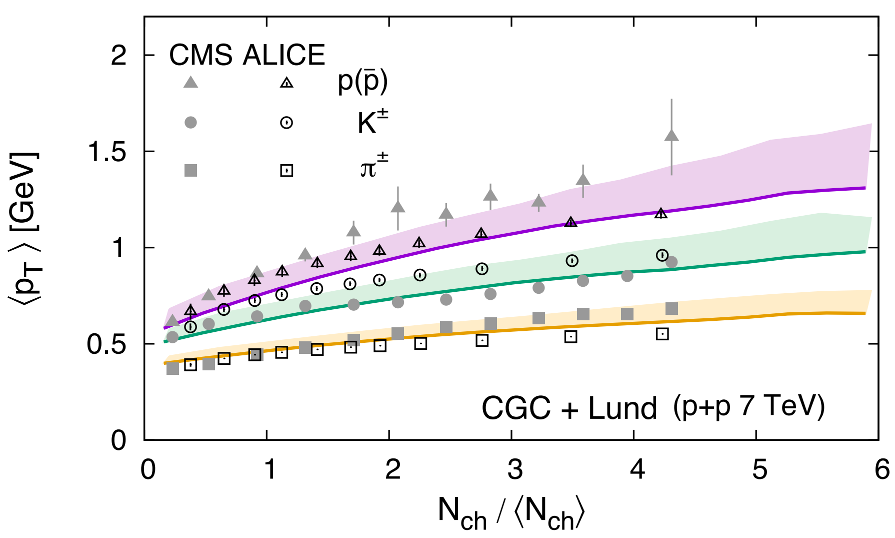

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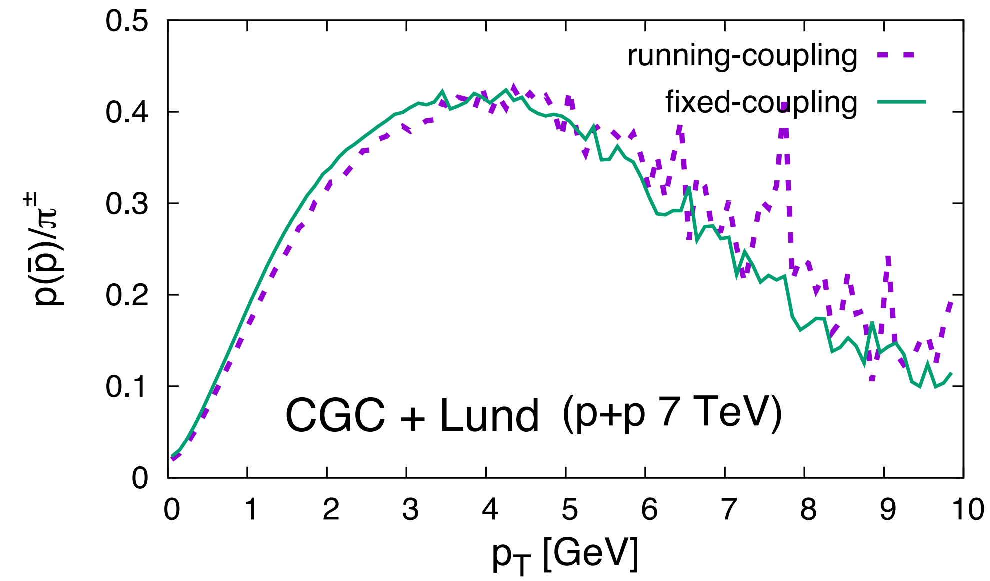
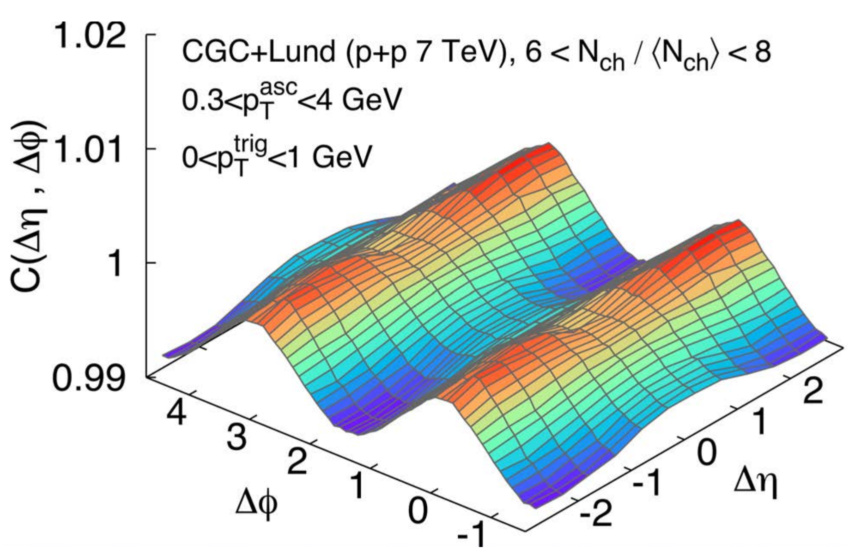
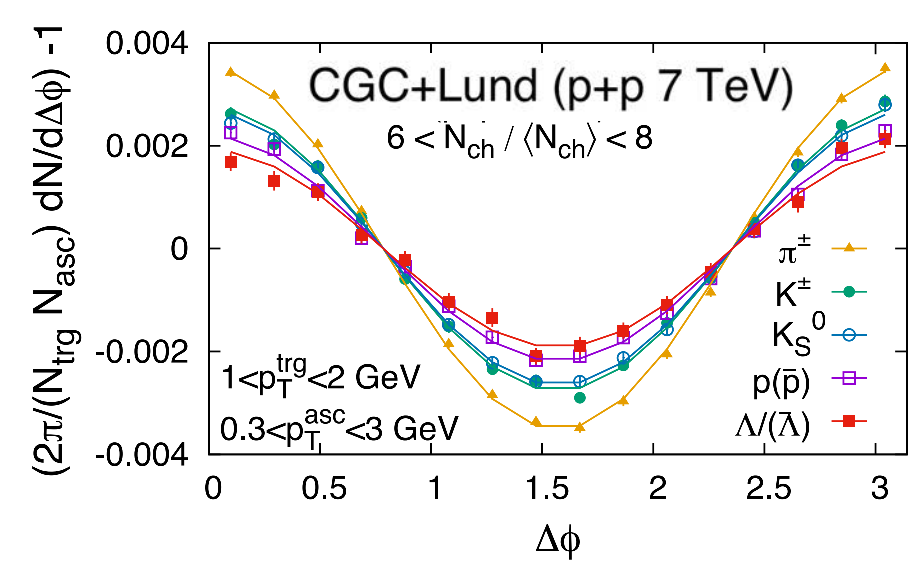


Ridge and its mass ordering





The Qualitative picture

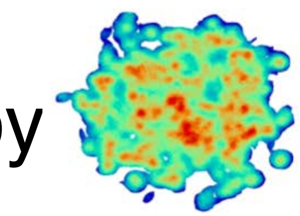
IP-Glasma (CGC Initial state correlations)

Momentum space correlations

Position space correlations

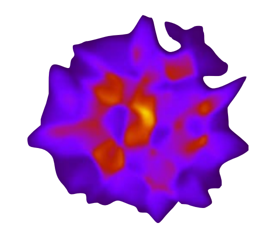
(Mini-) jets,
n-parton correlations

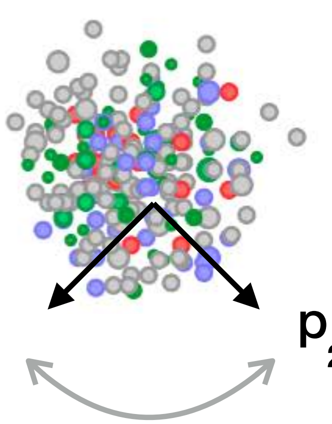
Initial spatial anisotropy



Fragmentation

Transport,
Hydrodynamics



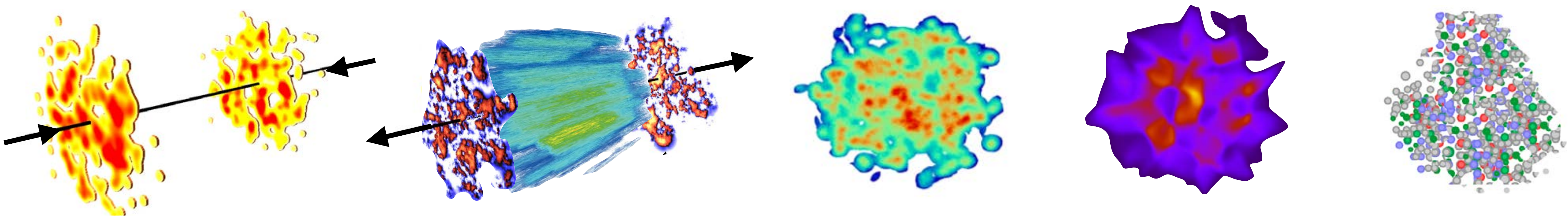


Experimentally observed correlations (both should contribute)

A fluid dynamic simulation (p+A, A+A)

Heavy ion collisions have been studied extensively

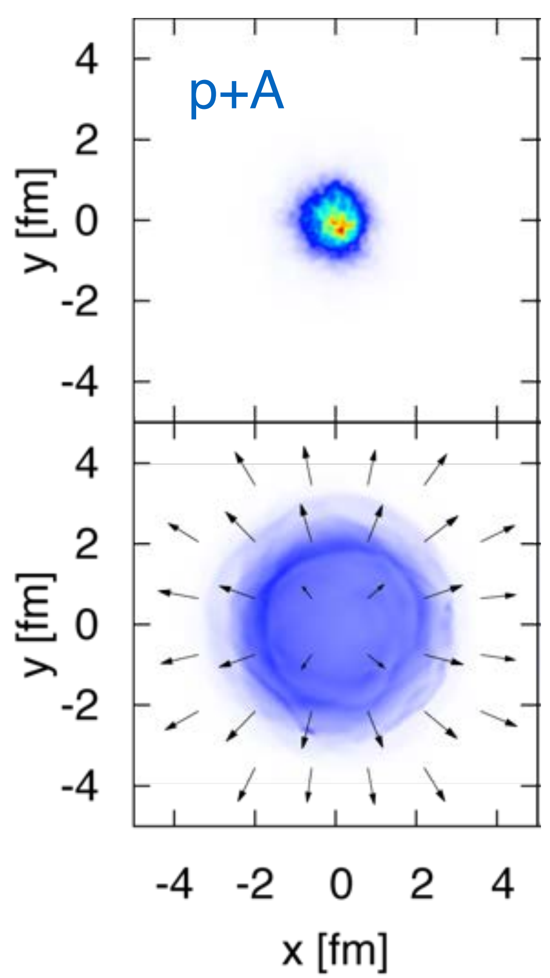
CGC | Glasma | Pre-equilibrium evolution | Hydrodynamic evolution | Hadronization

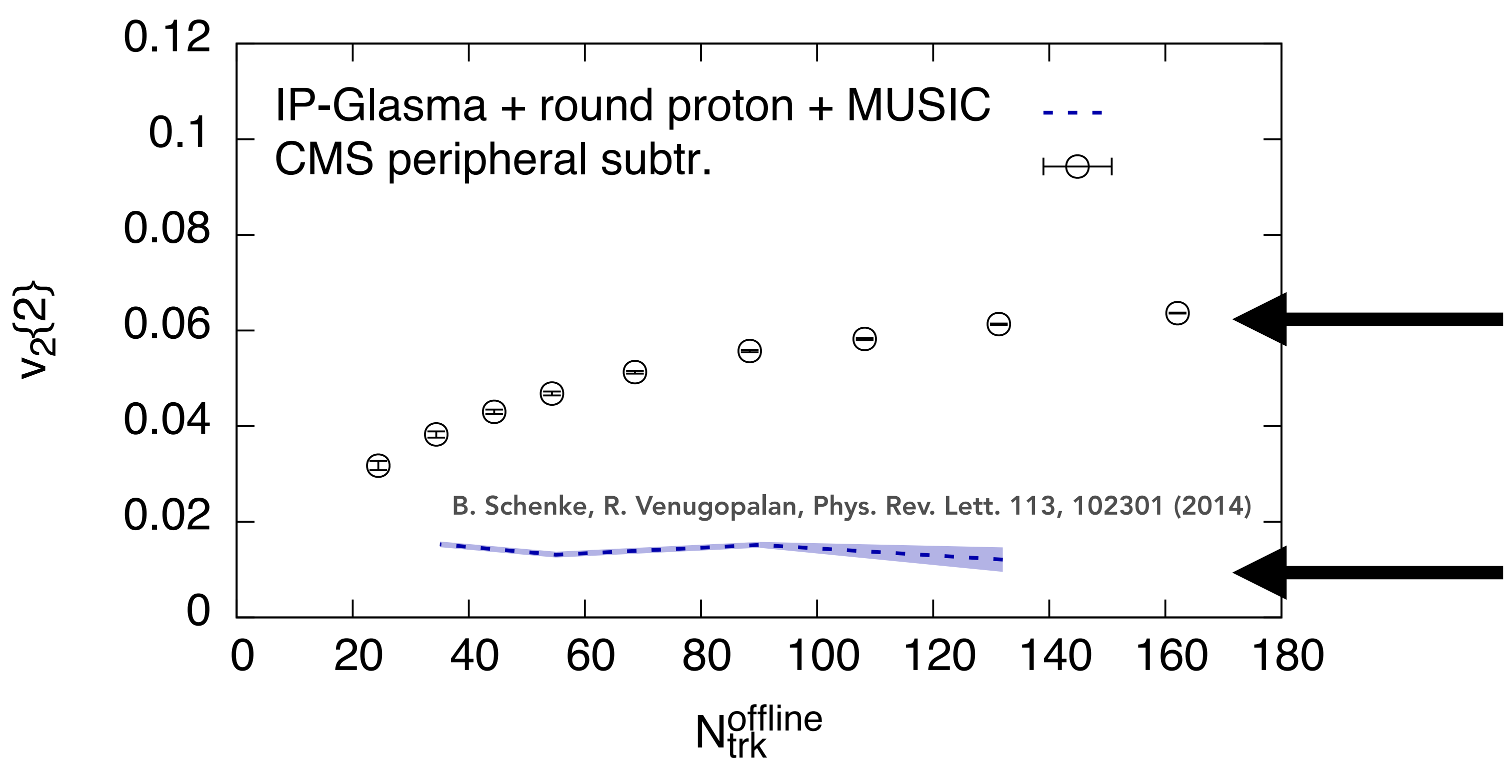


Observation of long-range ridge-like azimuthal correlations is a signature of fluid-dynamic response to boost-invariant initial spatial anisotropy

Results from CGC + Hydrodynamics (p+Pb)

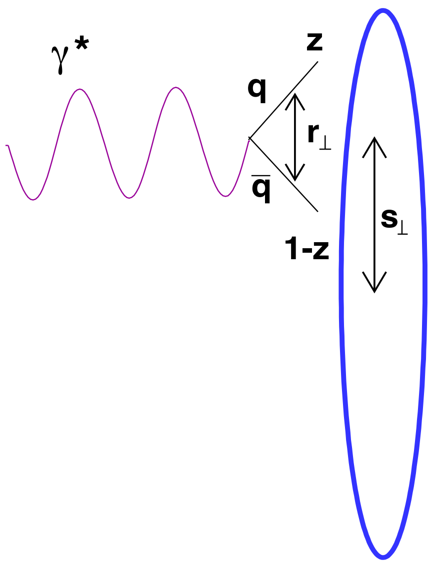
In CGC (IP-Glasma) the initial spatial anisotropy for p+Pb collisions is determined by the shape of proton





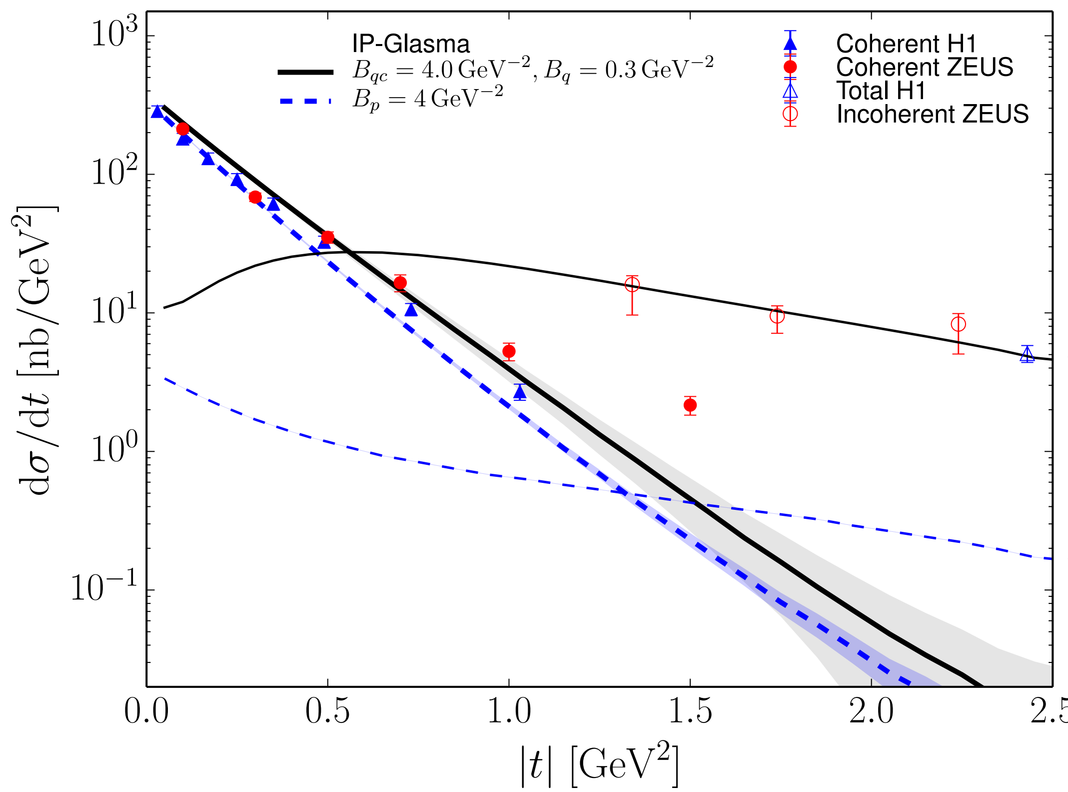
HERA DIS e+p data → round proton → not eccentric enough, can't generate azimuthal anisotropy like data

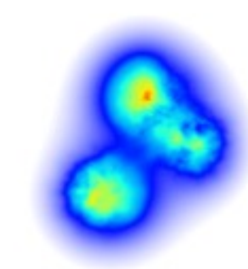
New inputs from DIS data: snapshot of proton



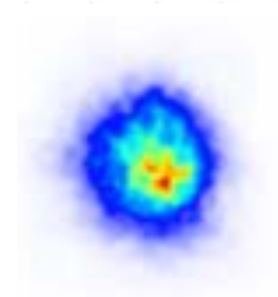
Probing the spatial structure of the hadrons

Schenke, Mantysaari 1603.04349





eccentric proton

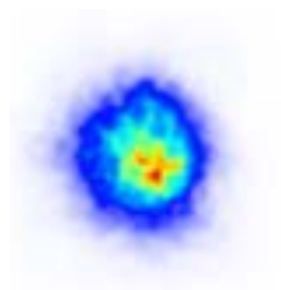


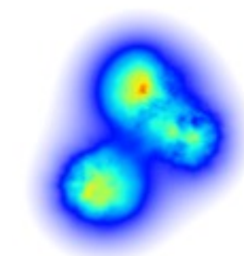
round proton

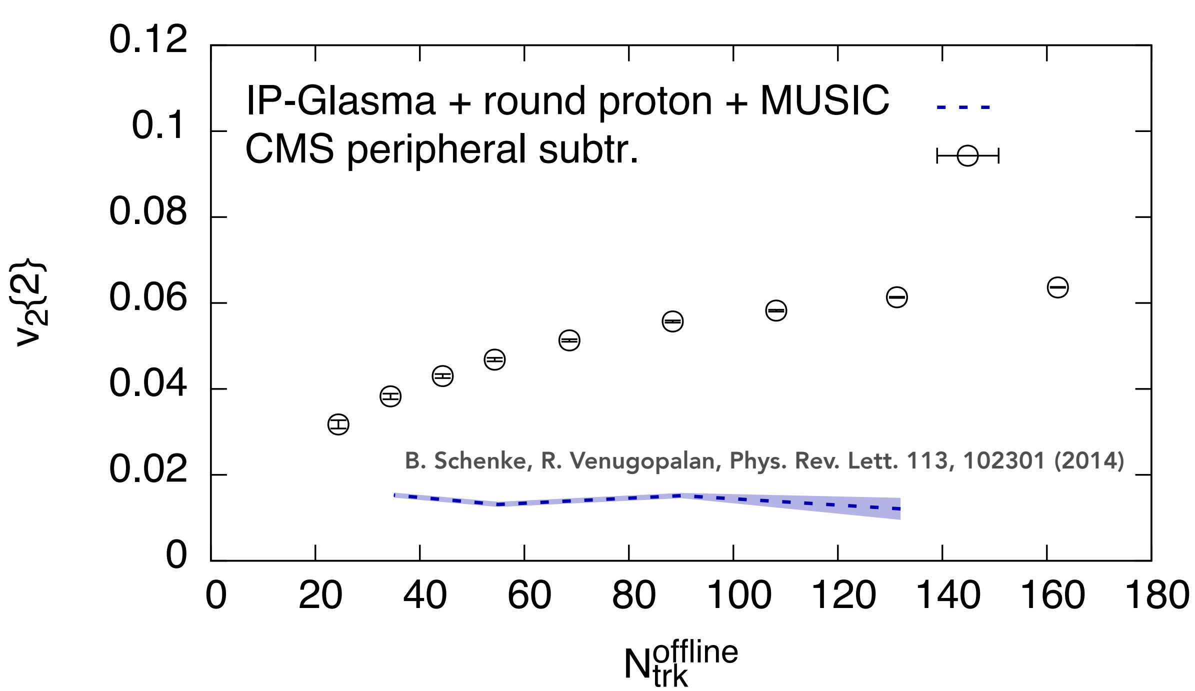
Quark structure (hotspots) → essential to describe Incoherent DIS data

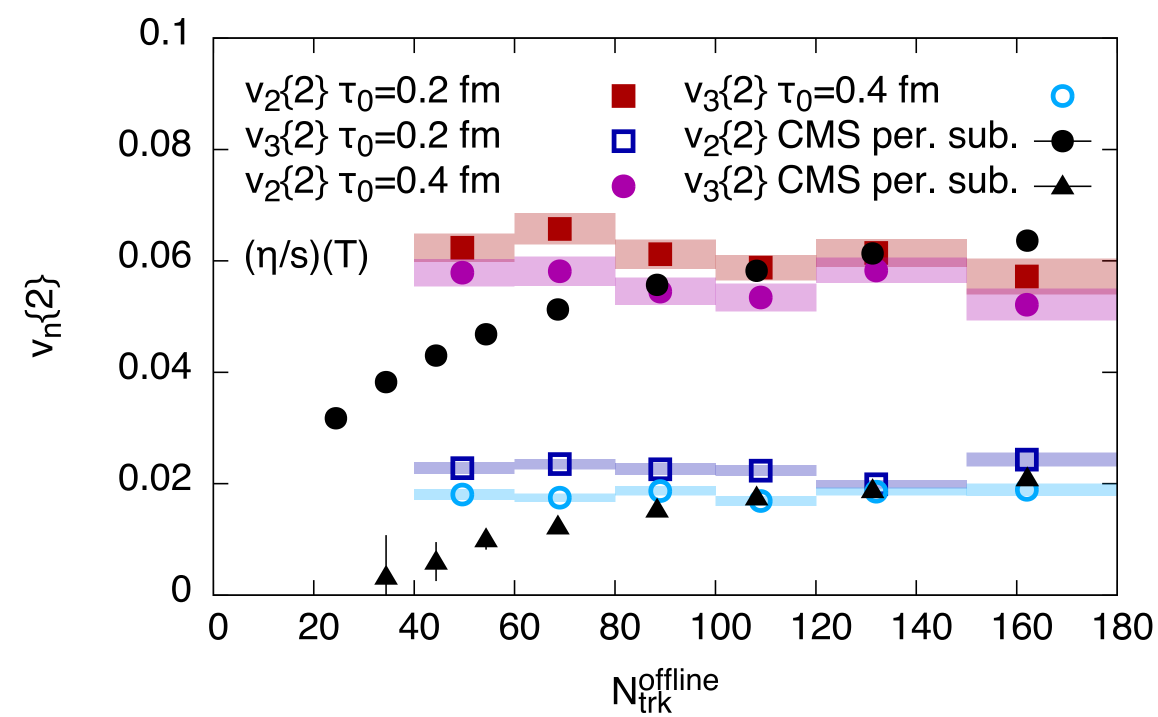
Results from CGC + Hydrodynamics + transport

Mantysaari, Schenke, Shen, PT 1705.03177









With eccentric proton (hot spot) much better agreement is achieved

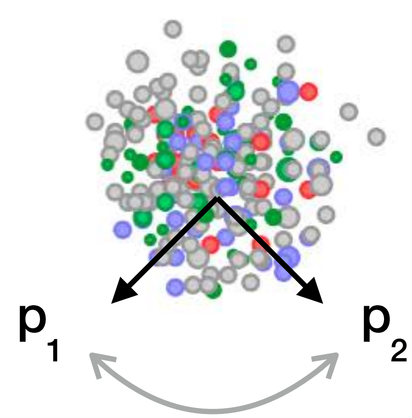
Combined approach

IP-Glasma (CGC Initial state correlations)

Momentum space correlations

Position space correlations

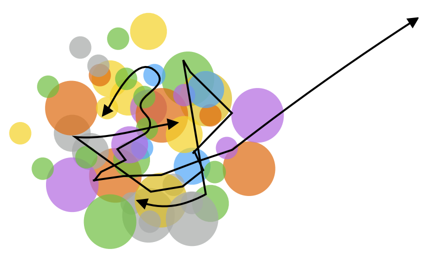
Partonic Transport (parton cascade)

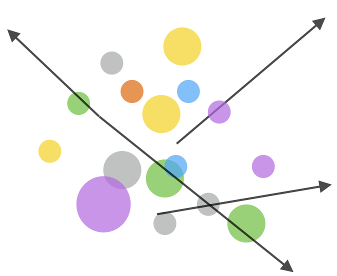


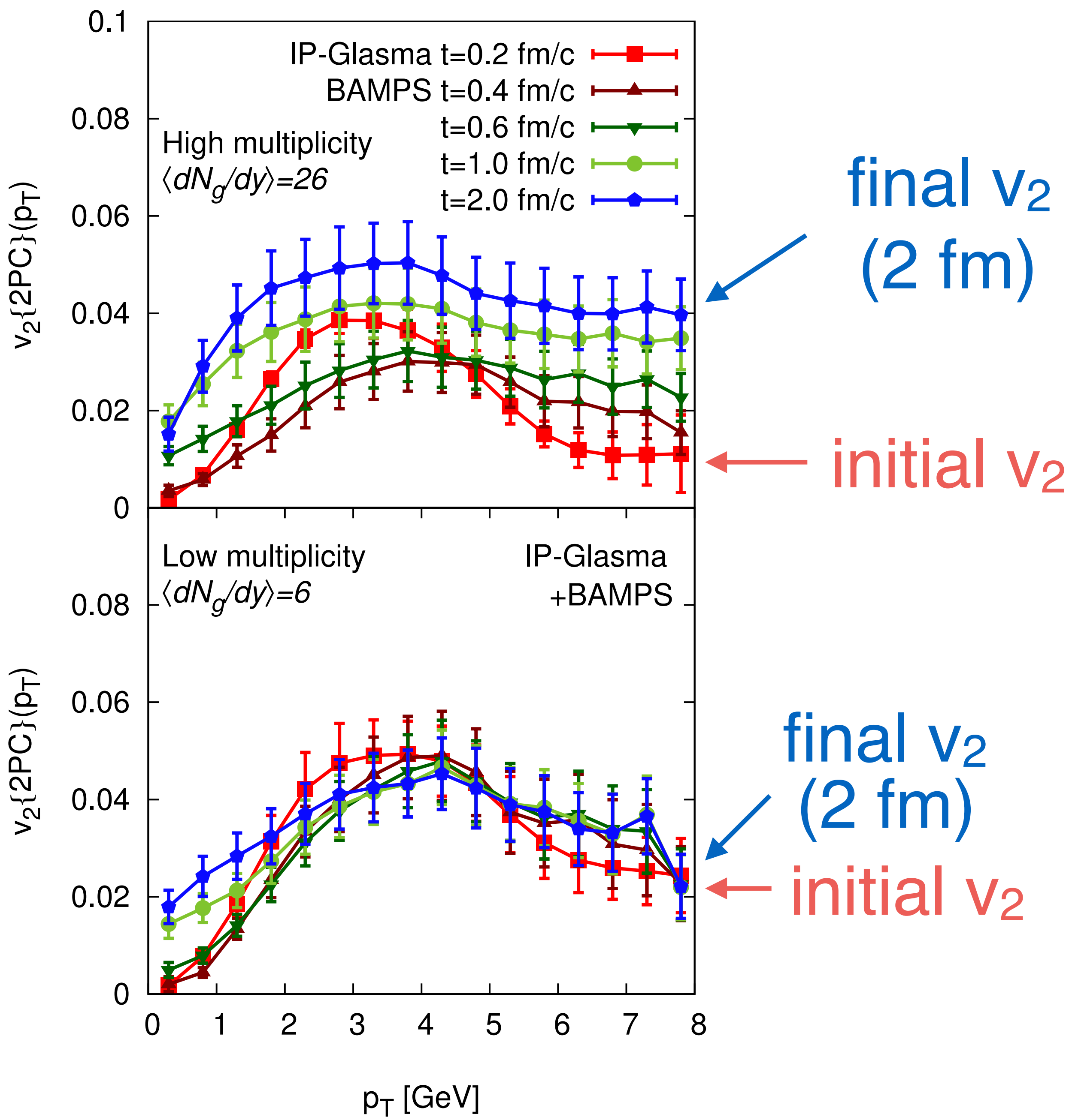
Combined approach

IP-Glasma (CGC)+**B**oltzmann **A**pproach to **M**ultiparton **S**catterings (BAMPS)

Greif, Greiner, Schenke, Schlichting, Xu 1708.02076







Initial state dominate :
low mult & high p_T

Final state dominate :
high mult & low p_T

Summary

Observation in high multiplicity events in small collision systems show remarkable similarity with heavy ion collision & evidence of collectivity

- Many aspects of such collective behavior can be explained by purely initial state effects due to momentum space correlations

- In sufficiently high multiplicity events, initial state effects momentum space correlations will eventually dilute to show sensitivity to spatial & geometric correlations

The framework of CGC provides an *ab initio* approach to describe both initial state momentum and position space correlations. When combined with Lund (PYTHIA), Hydrodynamics or partonic transport, one can explain global data in p+p, p+A & A+A, in principle have a combined description of all systems into a single framework.