Thermalization/Isotropization in heavy-ion collisions

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Based on work in collaboration with
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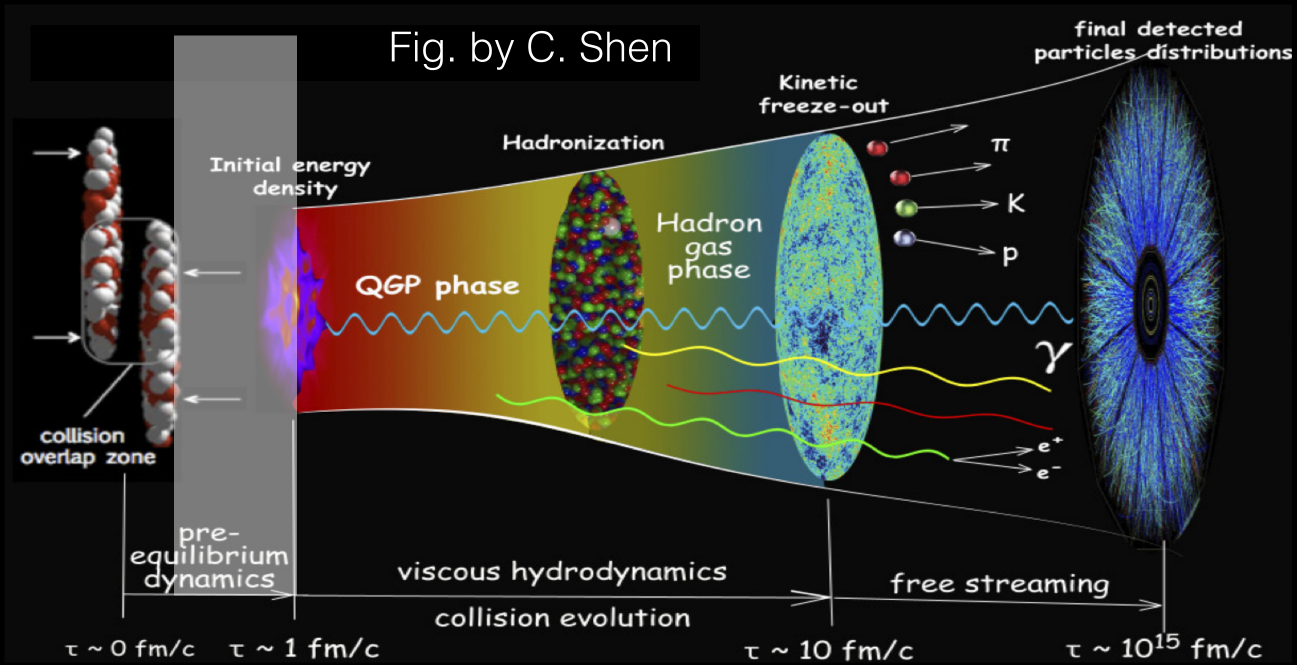
Standard model of heavy-ion collision

Despite very successful heavy-ion phenomenology insufficient understanding of early time dynamics



Questions we would like to understand better

— How is QGP created from the collision of heavy-nuclei?

— On what time & length scales does the system behave hydrodynamically?

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Non-equilibrium QCD dynamics

Generally there is no exact way to study non-equilibrium dynamics in a generic QFT (e.g. a la euclidean lattice techniques)

In high-energy QCD first principles studies are feasible in two limiting cases

- Strong coupling limit ($g^2N_c >> 1$) in related theories

  - Description in terms of shock-wave collision via gauge/gravity duality (e.g. in N=4 SYM)

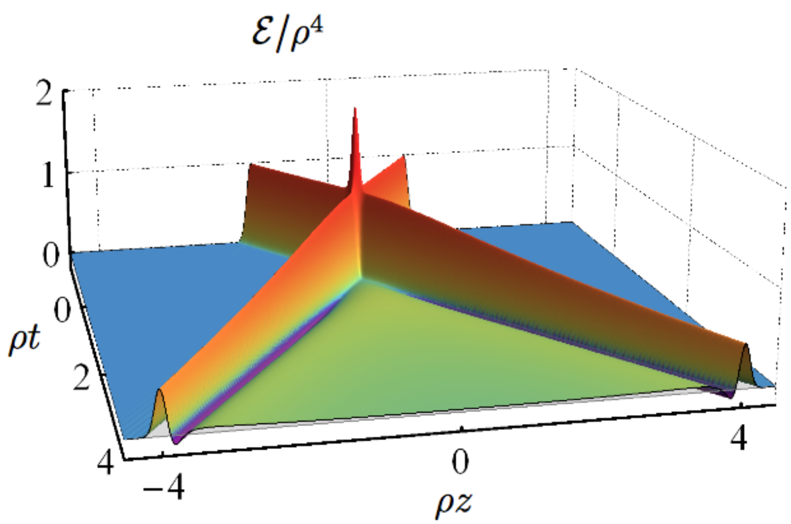
- QCD in weak-coupling limit ($g^2 << 1$)

  - Description of nuclei in Color Glass Condensate (CGC), early stages in classical Yang-Mills theory and equilibration in effective kinetic description

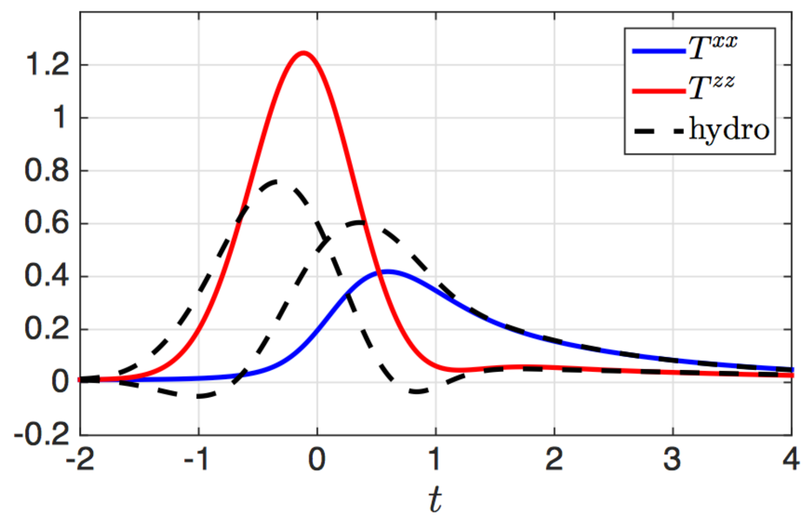
Strong-coupling picture

Description based on gauge/gravity duality

- Nucleus-nucleus collision modeled as collision of gravitational shock waves



(Casalderrey-Solana, Heller, Mateos, v.d.Schee PRL 111 (2013) 181601)



(Chesler, Yaffe JHEP 1510 (2015) 070)

Strong-coupling framework provides access to longitudinal dynamics

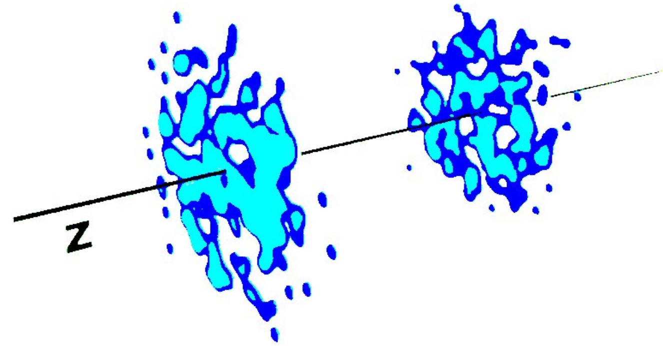
(c.f. talk by v.d. Schee)

-> Isotropization takes a long time. However, viscous hydrodynamics applicable already for large pressure anisotropies.

Weak-coupling picture

Gluon saturation (color glass condensate)

- High-energy nuclei feature a large number of small-x gluons with typical momentum $Q_s(s)$ such that



$$f(p\sim Q_s) \sim 1/\alpha_s$$

-> At high energies $Q_s(s) >> \Lambda_{QCD}$ such that $\alpha_s(Q_s) << 1$ is small

-> Even though the relevant coupling $\alpha_s(Q_s) << 1$ is small the system is strongly correlated because of high gluon density

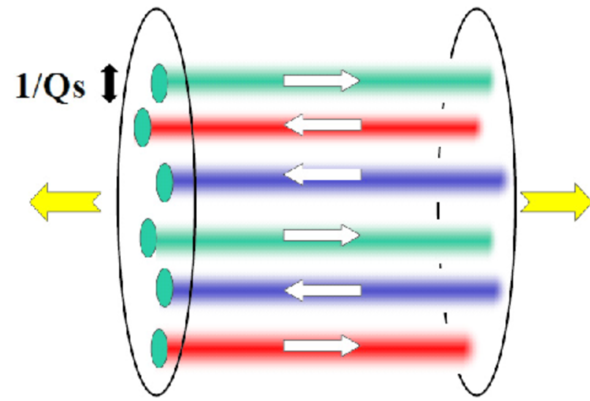
- Small-x gluons are liberated from the nuclear wave-functions during the collision, leading to a far from equilibrium 'Glasma' state

- Early-time dynamics is described by classical Yang-Mills equations (to leading order in α_s)

$$D_\mu F^{\mu\nu} = J^\nu$$

Early time dynamics at LO

Classical Yang-Mills dynamics leads to (2+1) D boost-invariant solution
(c.f. talk by R. Fries)



-> Naturally leads to approximately boost invariant properties at mid-rapidity

-> No thermalization to leading order in α_s

Next-to-leading order quantum fluctuations break boost invariance and thermalization becomes possible

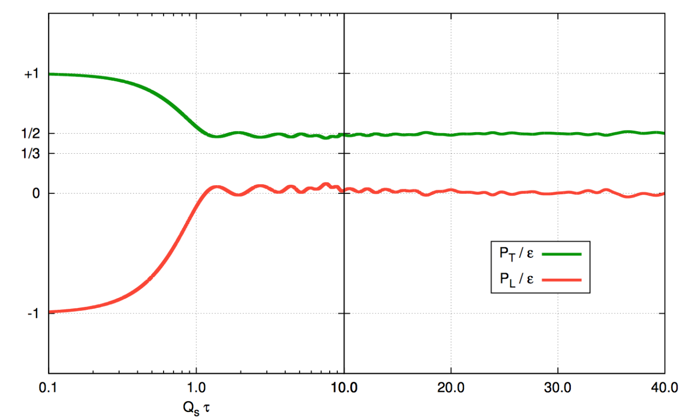
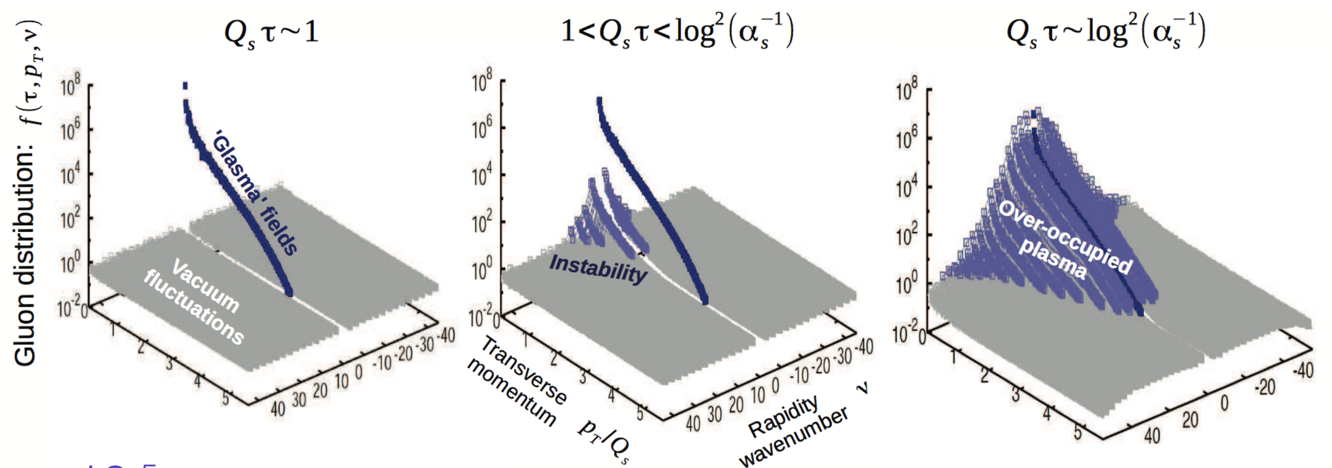


Fig by T. Epelbaum

- NLO correction is semi-classical with spectrum of fluctuations derived within CGC formalism (Epelbaum,Gelis)

Early time dynamics at NLO

Qualitative change of the dynamics as plasma instabilities lead to an exponential growth of quantum fluctuations



$\alpha_S \sim 10^{-5}$ Berges, Schenke, SS, Venugopalan NPA 931 (2014) 348-353

-> ***Subset of corrections*** becomes as important as the leading order.

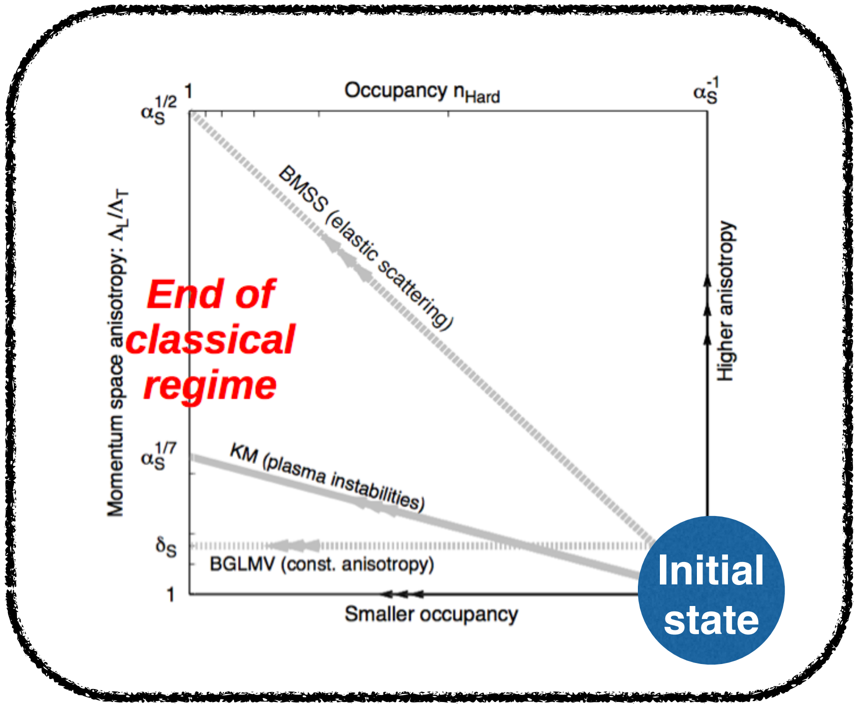
Breakdown of the naive power-counting.

Even though plasma instabilities isotropize the plasma to some extent, the system is still far from equilibrium

Equilibration process?

- Different scenarios developed for the subsequent equilibration process based on kinetic theory

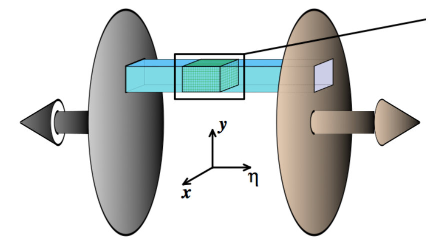
  - Baier et al. (BMSS), PLB 502 (2001) 51-58
  - Kurkela, Moore (KM), JHEP 1111 (2011) 120
  - Blaizot et al. (BGLMV), Nucl. Phys. A 873 (2012) 68-80



- Difference arises due to treatment of soft (non-perturbative) physics

  -> Non-perturbative simulations can decide which (if any) of the scenarios is realized

Qualitative description of equilibration process



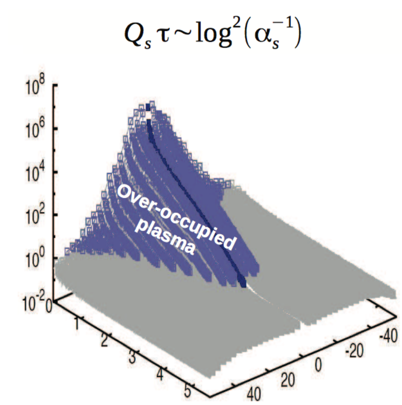
- Neglect the transverse expansion of the system during the early stages and consider longitudinal expansion only

- Characterize the initial state at $\tau_0 \sim 1/Q_s$ in terms of the initial gluon distribution

initial occupancy

$$f(p_T, p_z, \tau_0) = \frac{n_0}{\alpha_s}\,\Theta\left(Q - \sqrt{p_T^2 + (\xi_0 p_z)^2}\right)$$

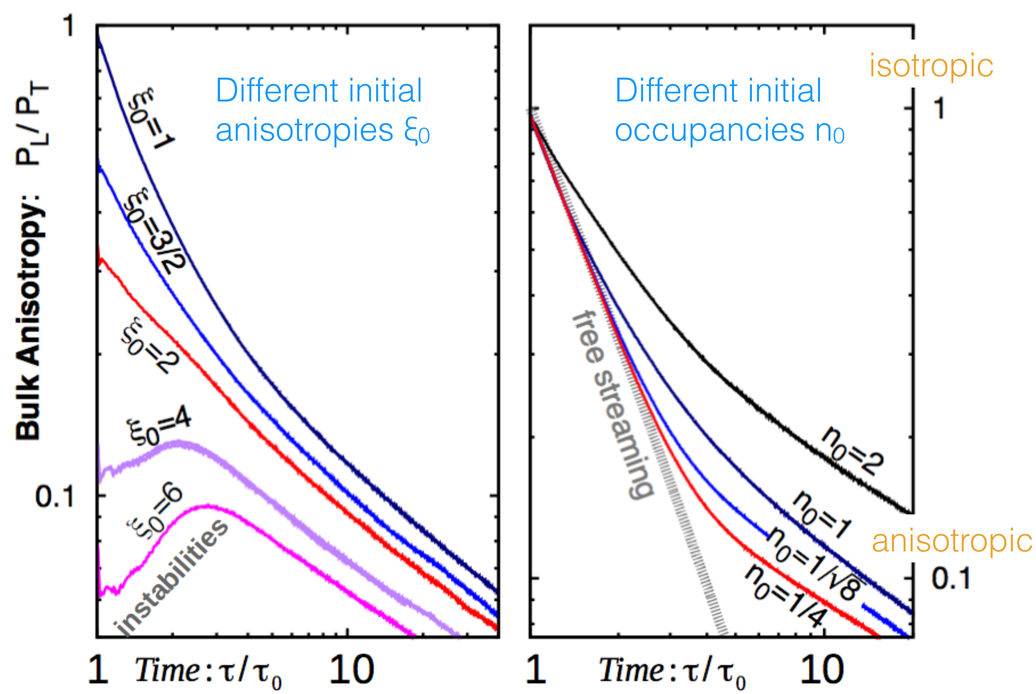
initial anisotropy



-> High gluon densities allow for an effectively classical description of the early stages of the thermalization process

Bulk anisotropy

Classical Yang-Mills simulations for different initial conditions



- Early time dynamics depends on initial conditions and ranges from plasma instabilities to free streaming
- Universal scaling behavior emerges at late times
- Described in terms of

$$f(p_T, p_z, \tau) = (Q\tau)^{\alpha} f_S\left((Q\tau)^{\beta} p_T, (Q\tau)^{\gamma} p_z\right)$$

with universal scaling exponents $\alpha=-2/3$, $\beta=0$, $\gamma=1/3$ and scaling function f_S *also* extracted from simulations

(Berges, Boguslavski, SS, Venugopalan PRD 89 (2014) 074011; 89 (2014) 114007)

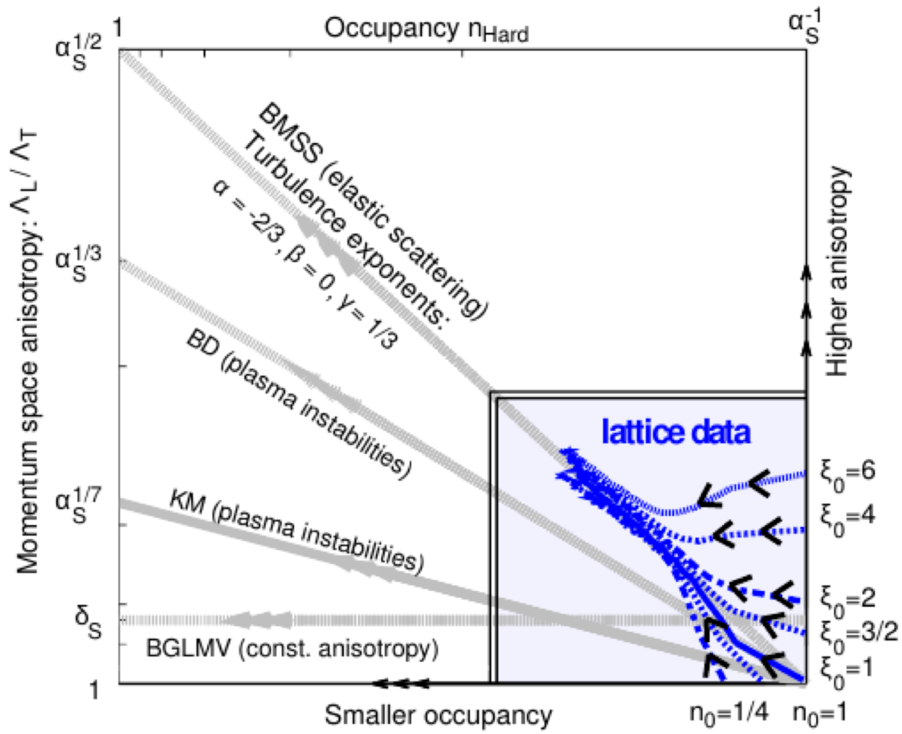
Kinetic theory comparison

- Effective memory loss at early times, where different initial conditions lead to universal attractor

- Beyond very early times evolution described by “bottom-up” thermalization scenario* (2<->2 and 2<->1)

(*Baier et al. PLB 502 (2001) 51-58)

-> Identification of a valid kinetic description



Berges,Boguslavski,SS,Venugopalan PRD 89 (2014) 074011)

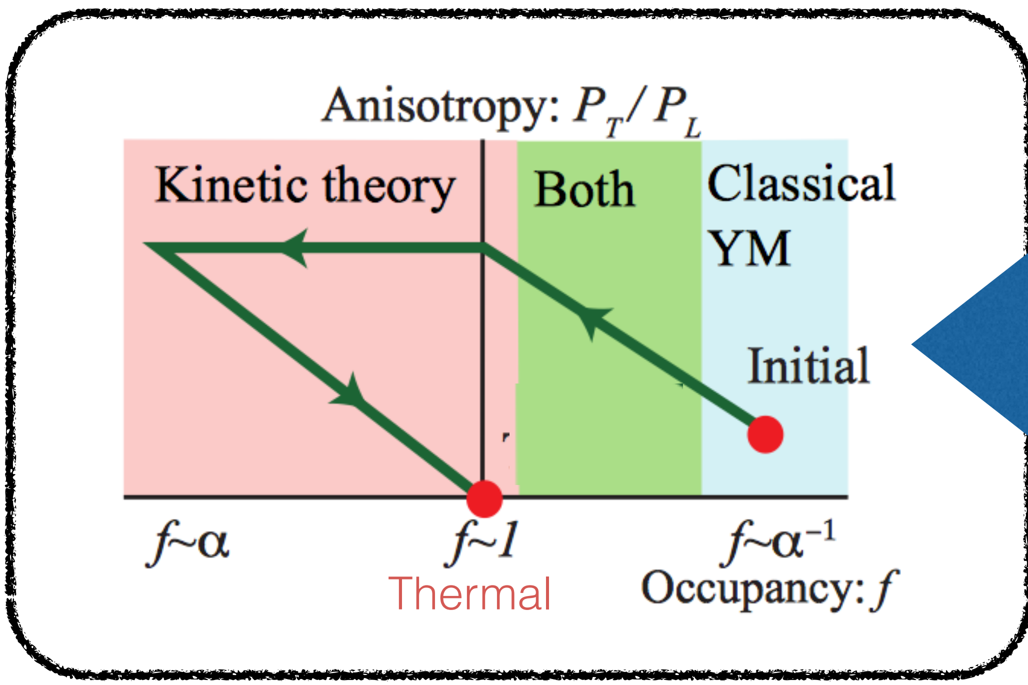
- Surprisingly, no signs of plasma instabilities affecting the late time evolution of hard excitations

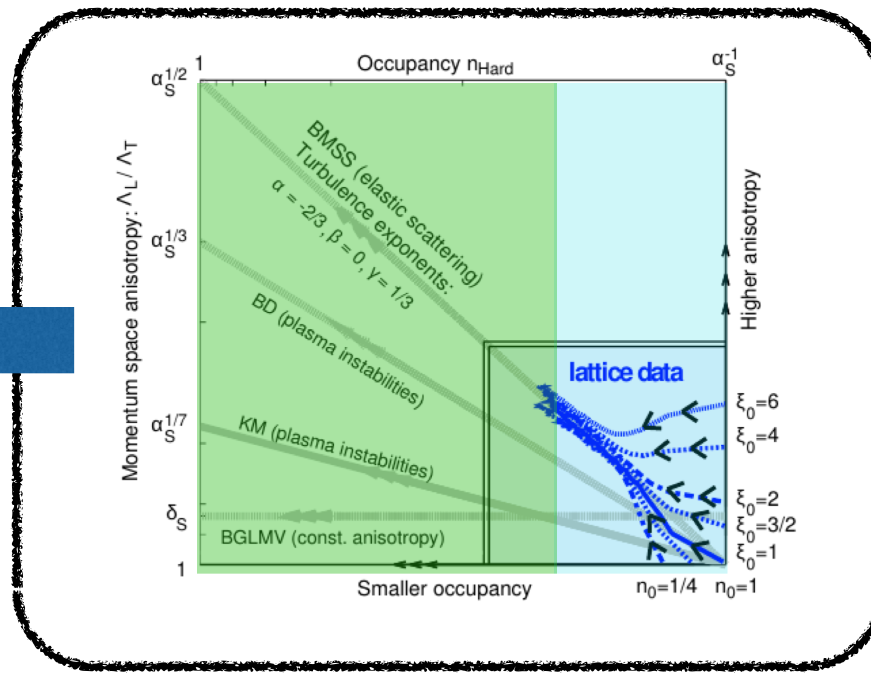
Equilibration process

- Even at end of the classical regime the system is still far from equilibrium and highly anisotropic

-> Genuine quantum description needed for approach to equilibrium

- Since classical-statistical simulations and effective kinetic description agree within their common range of validity one can now extend the kinetic treatment towards the quantum regime

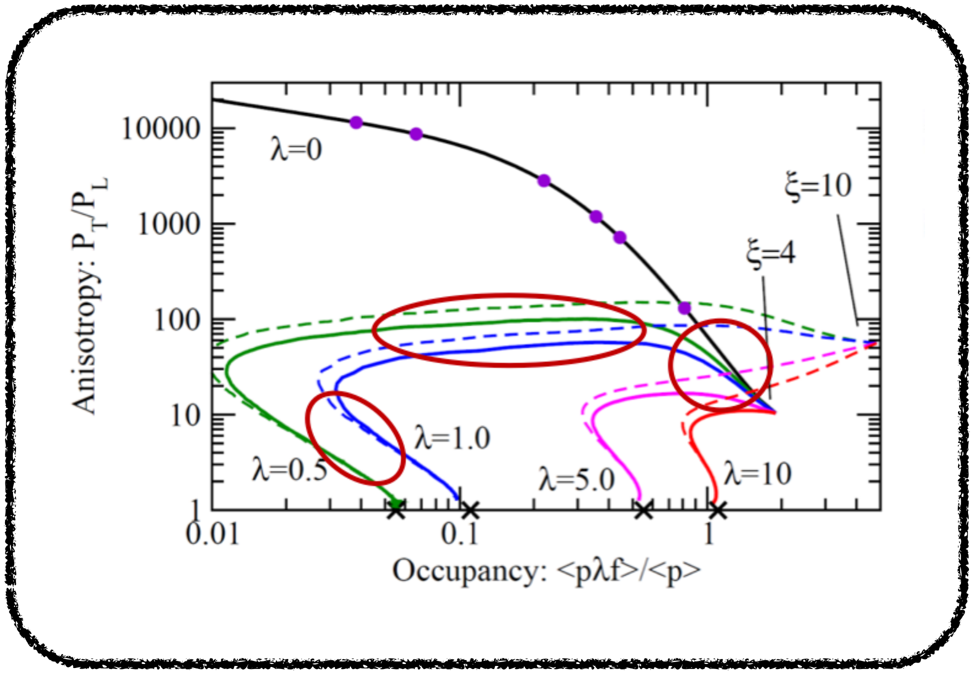




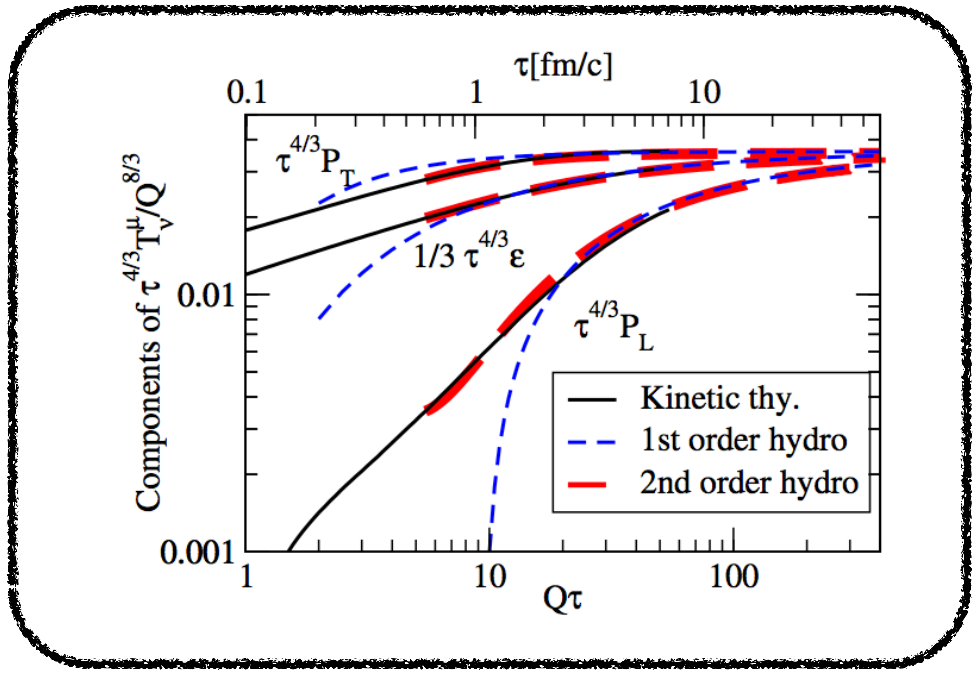
Quantum regime

- Numerical study of effective kinetic description (AMY 2<->2 + eff. coll. 1<->2)

Kurkela & Zhu PRL 115 (2015) 18, 182301



Clear observation of the three distinct stages of “bottom up” scenario

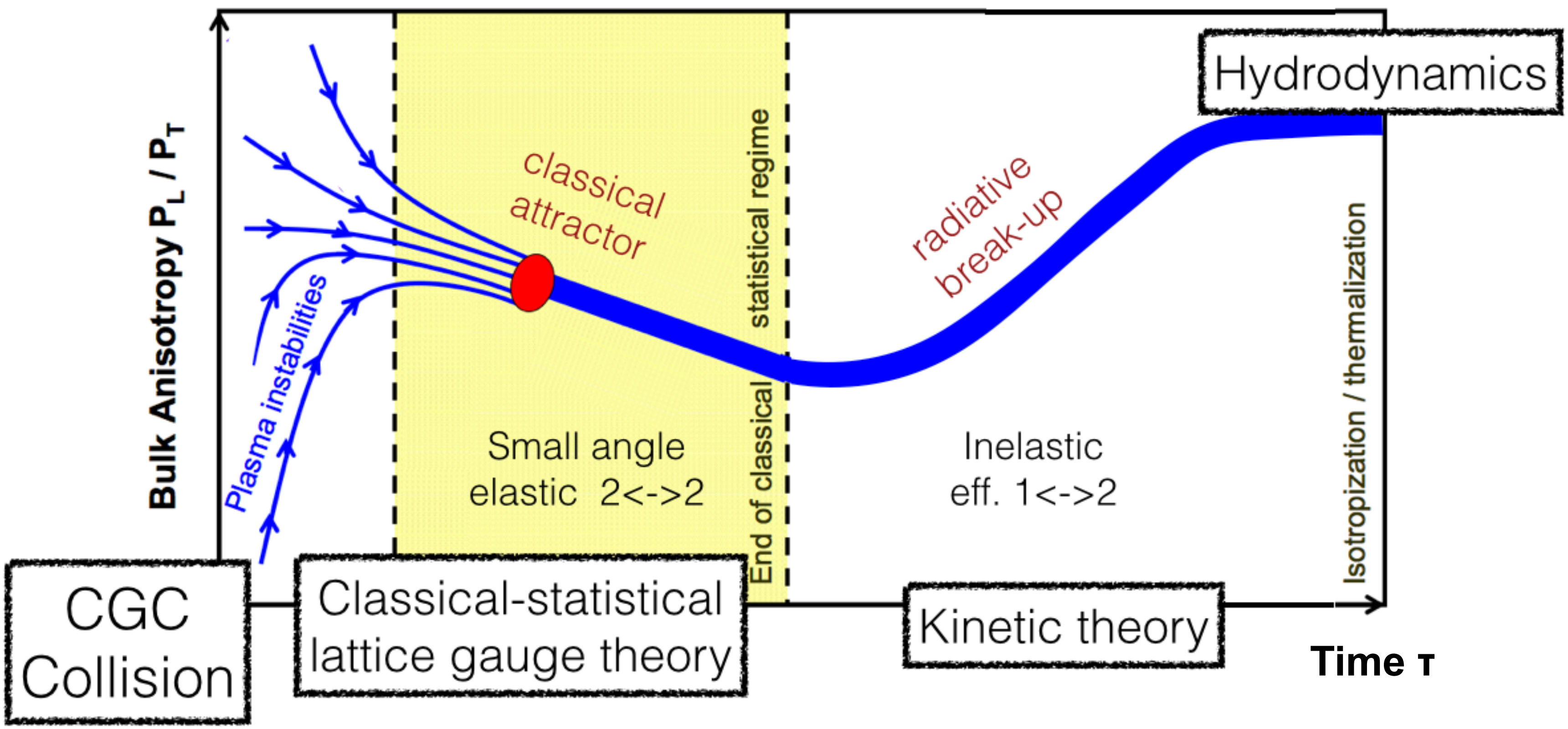


Hydrodynamic behavior on time scales ~1 fm/c when extrapolating weak coupling description to α_s =0.3

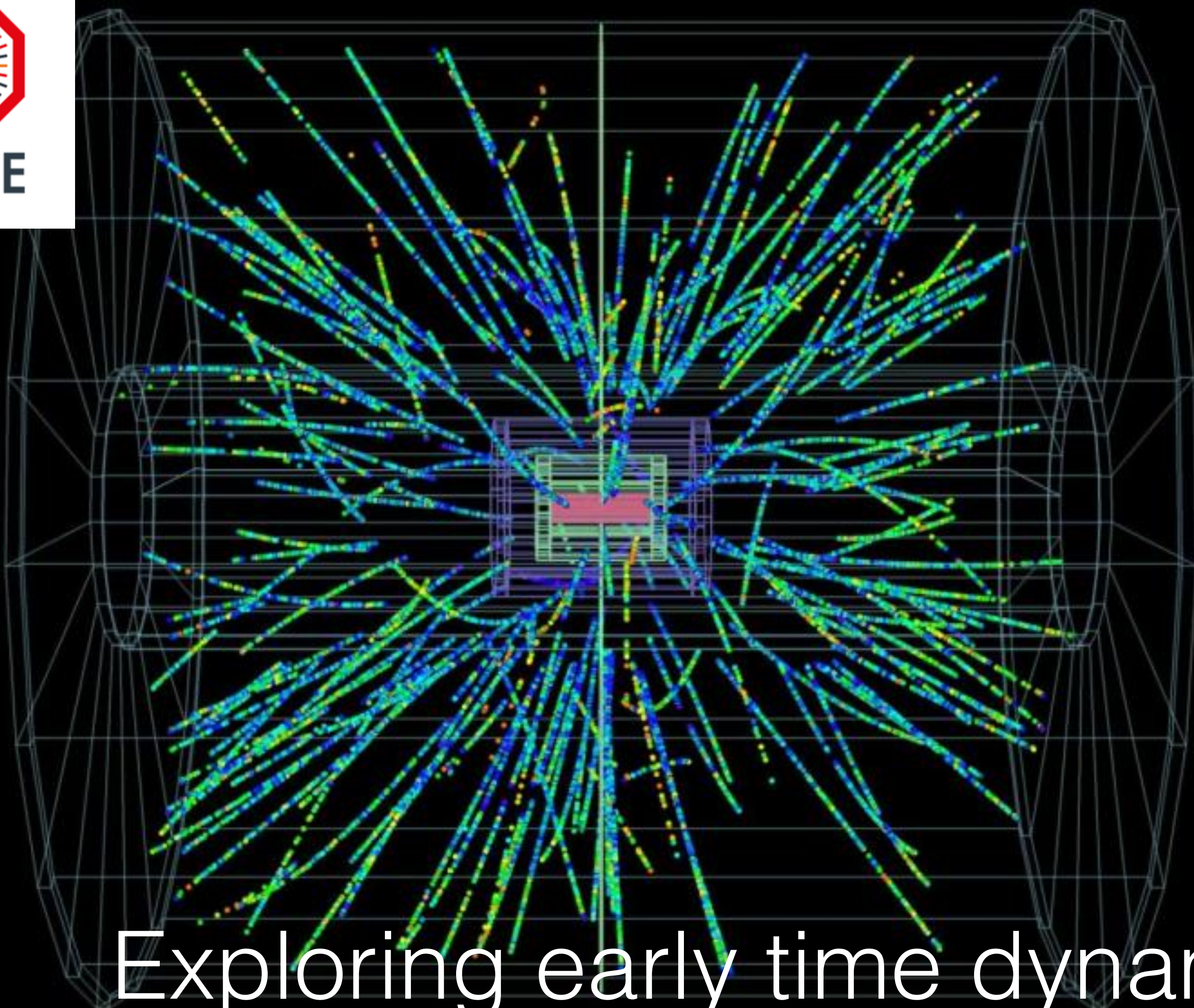
-> Viscous hydrodynamics applicable already for large pressure anisotropies

Isotropization at weak coupling

Evolution of the bulk anisotropy based on effective kinetic description a la “bottom-up” (Baier et al. PLB 502 (2001) 51-58)



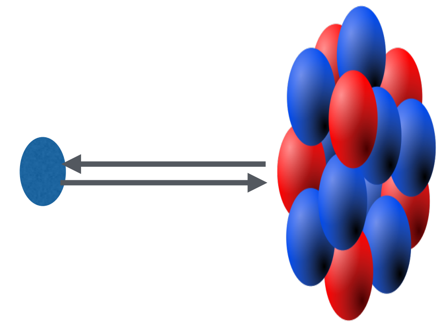
-> Can now describe entire process by interplay of weak-coupling methods



Exploring early time dynamics in small collision systems (p/d+A)

Small systems (p/d+A)

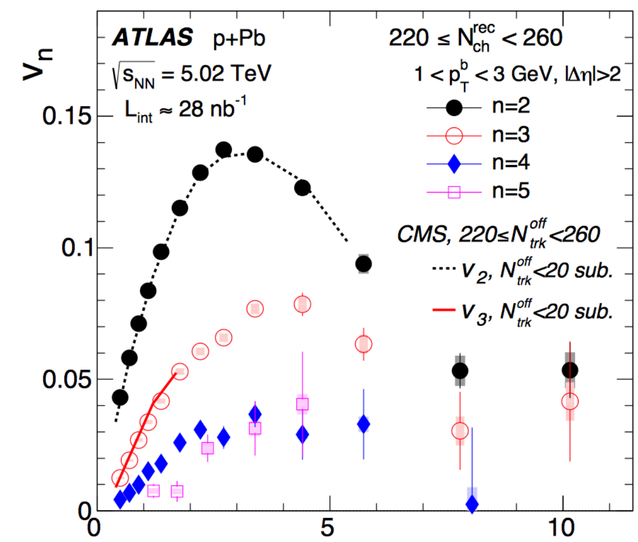
Conventional picture for a long time no QGP created in p+A collision system.



Instead useful as a reference probe to study "cold-nuclear matter effects"

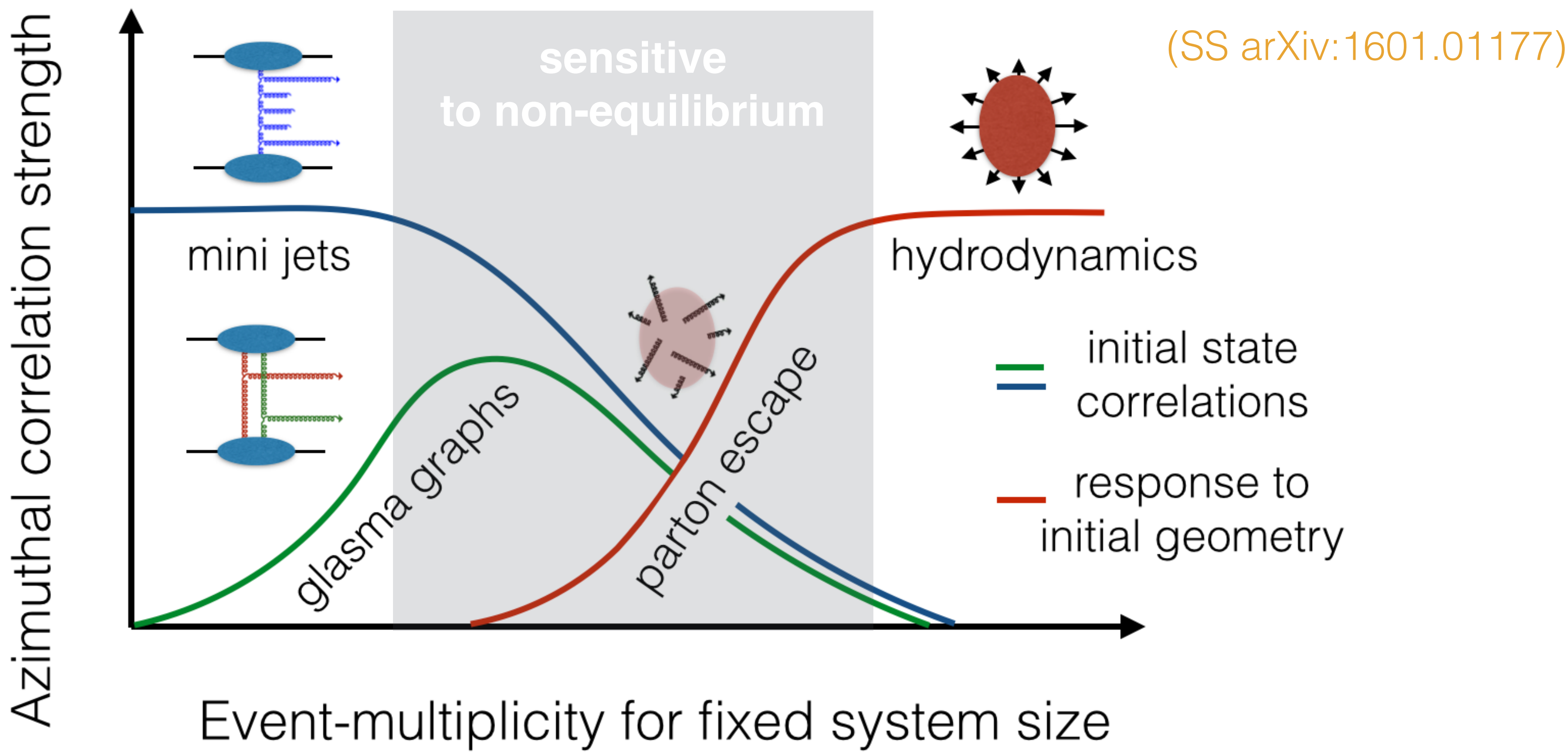
- Modification of nuclear PDF's
- Multi-parton interactions

Surprisingly high-multiplicity p+A collision at LHC reveal pronounced long-range azimuthal correlations, qualitative similar to A+A



hep-ex/1409.1792

Qualitative picture of correlations in small systems



-> Small systems provide a unique laboratory to probe early time dynamics.

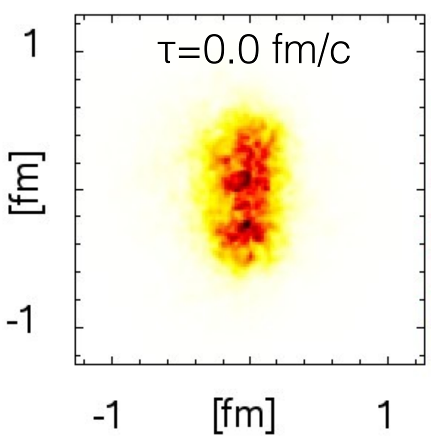
Early time dynamics in p+A

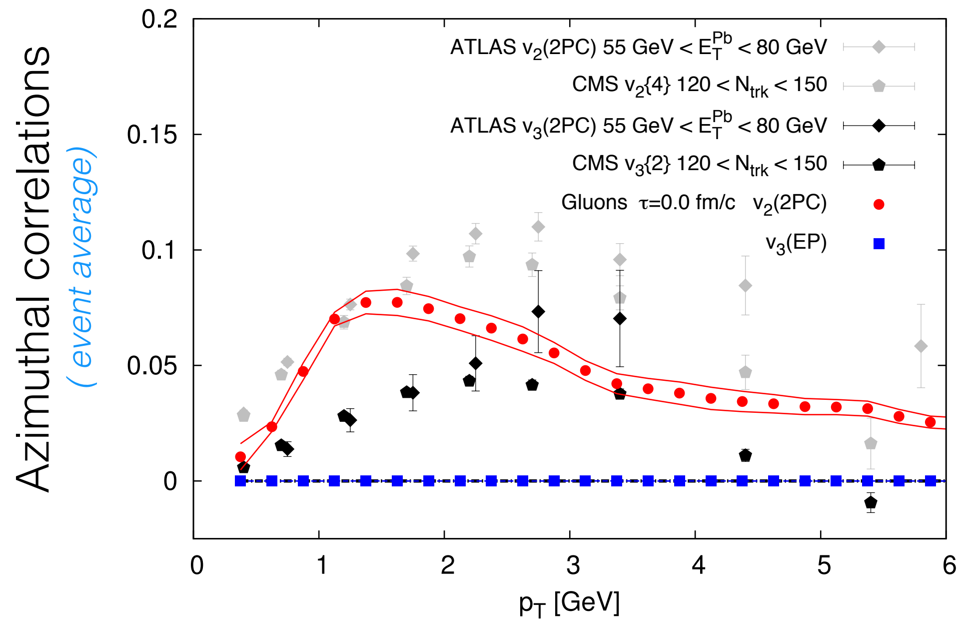
Initial state immediately after the collision ($\tau=0^+$)

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

Energy density profile

(single event)





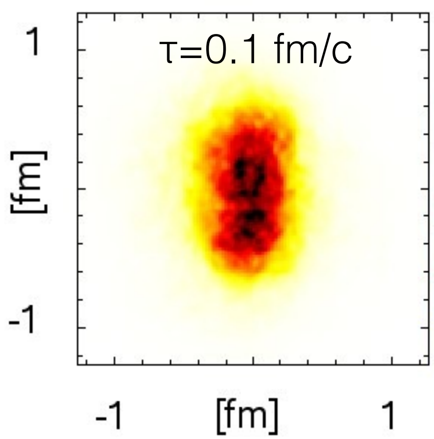
-> Significant momentum space correlations v_2 at $\tau=0$ due to production mechanism.

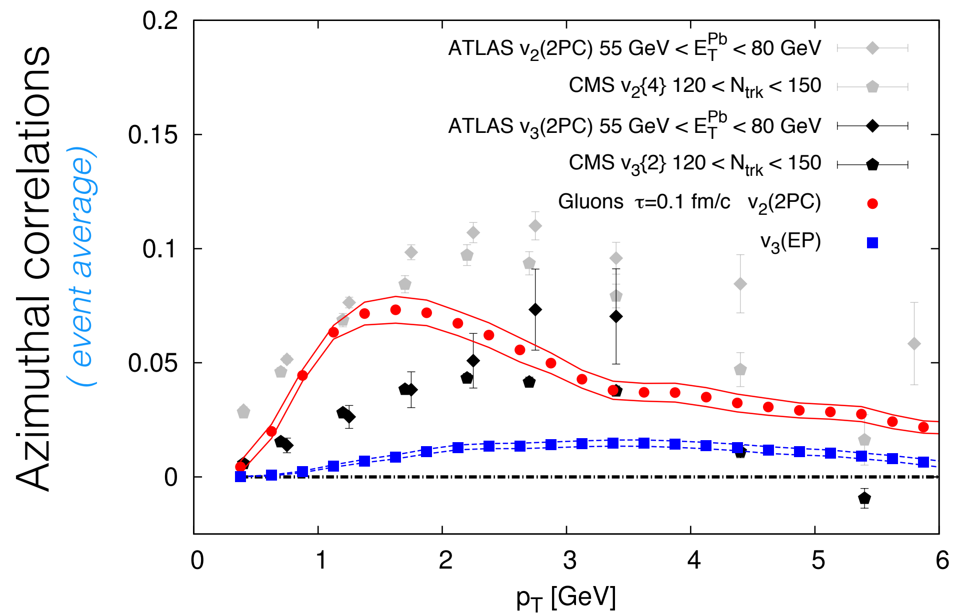
-> No odd harmonics for gluons without final-state interactions. Initial spectrum symmetric under $\mathbf{k}_T$<->-$\mathbf{k}_T$

Early time dynamics in p+A

Classical Yang-Mills evolution after the collision
— includes re-scattering of produced gluons

Energy density profile
(single event)





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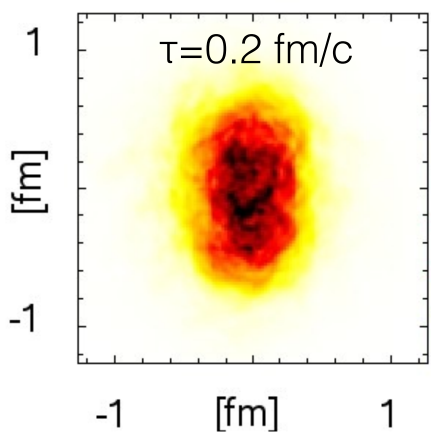

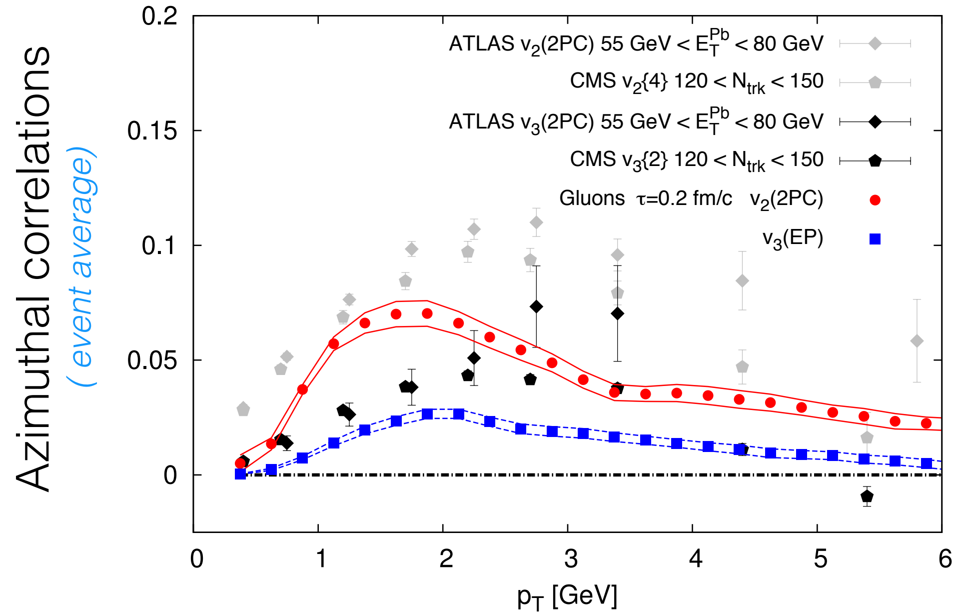

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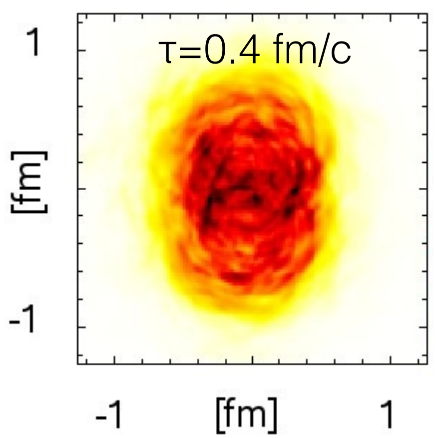
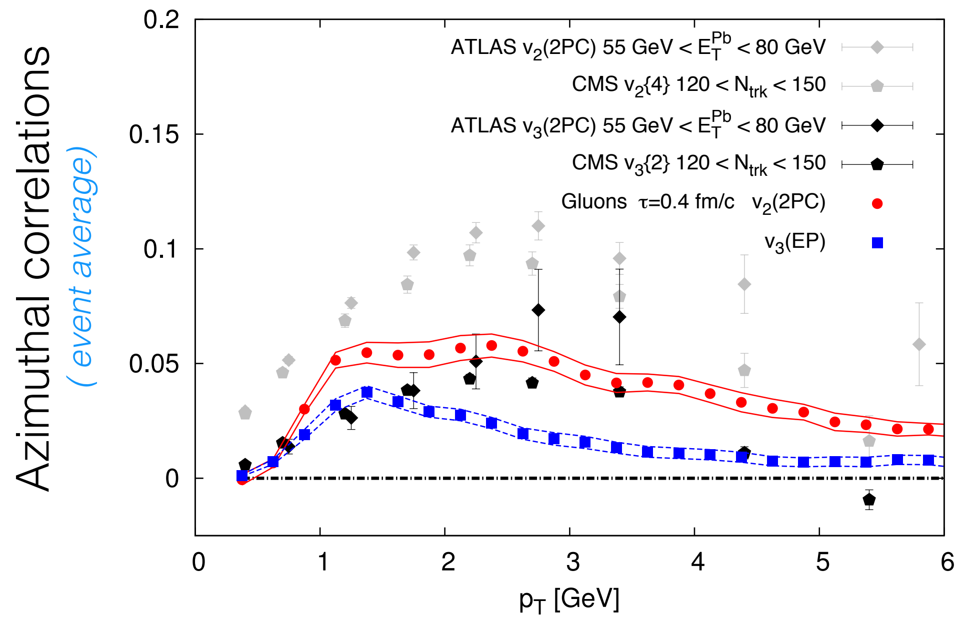


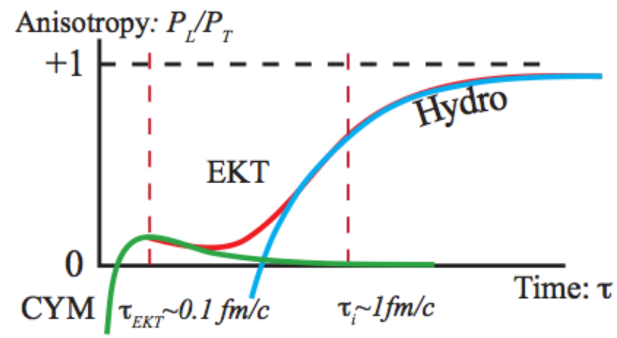


-> Clear modifications of correlations due to non-equilibrium dynamics on a time scale ~0.4 fm/c

Quantitative understanding requires consistent theoretical description consistently taking into account initial state and final state effects.

Conclusions & Outlook

- Qualitative understanding of the dynamics of the thermalization process in the strong and weak coupling limits



- Can now compute entire thermalization process from an interplay of different weak coupling methods

- Several applications beyond bulk phenomenology

— Small systems p/d+A

— Non-equilibrium photon production

— Sphaleron transitions & anomaly induced transport phenomena

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