CGC, Glasma, RHIC and LHC
NFQCD, Kyoto December 2013

What is the high energy limit for strongly interacting particles?

What are the possible forms of high energy density matter?

How might such matter be produced and studied?

Color Glass Condensate:

Very High Density States of Gluons in High Energy Hadron Wavefunction

Quark Gluon Plasma:

Glasma: Highly Coherent Gluonic Matter Produced in Collisions of High Energy Hadrons

Thermalized Quark Gluon Plasma

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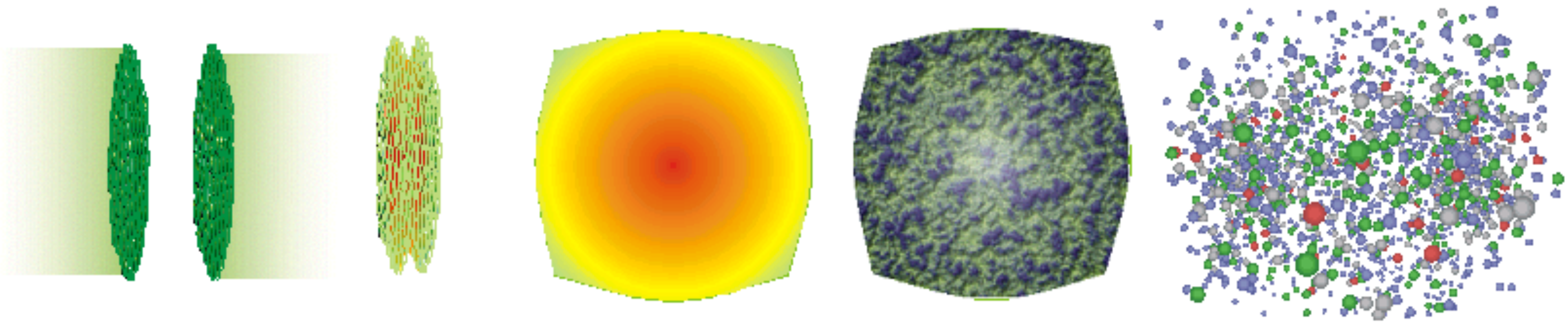
HUAZHONG UNIVERSITY

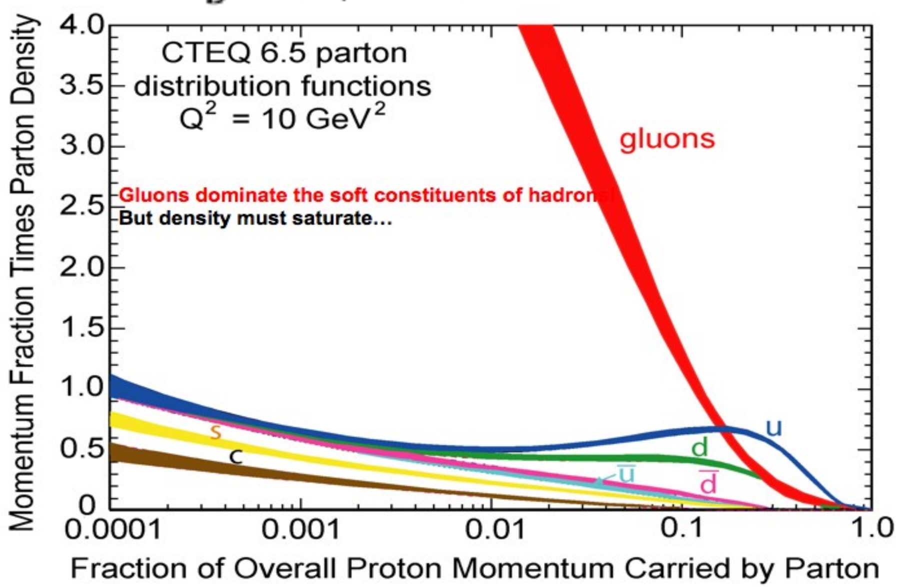
Matter as it Appears in High Energy Collisions



CGC | Initial Singularity | Glasma | Thermalized QGP | Hadron Gas

← Strongly Interacting QGP →

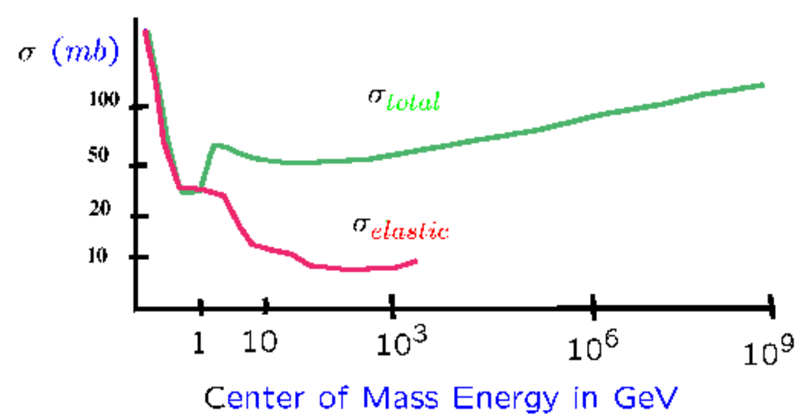
$$x = E_{gluon}/E_{hadron}$$



Gluons dominate the proton wavefunction

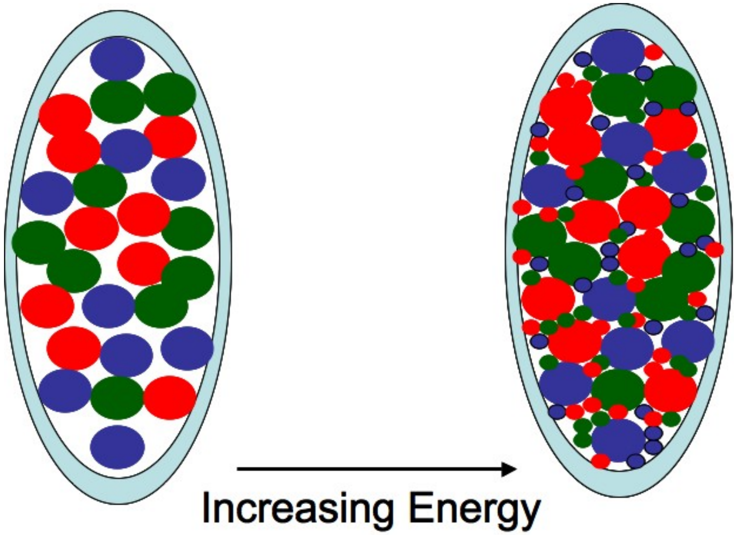
$$x_{min} \sim \Lambda_{QCD}/E_{hadron}$$

The total hadronic cross section:



Proton size grows slowly

High Energy Limit is High Gluon Density Limit!



Asymptotic Freedom: High density systems are weakly coupled because typical distances are short

$$\alpha_S << 1$$

Each gluon interacts with strength α_s

$1/\alpha_s$ gluons act like a hard sphere

Size of gluons ~ 1/p_T

First fill up hadron with gluons of large size because it costs less energy, and then once these are filled, put in gluons of smaller size

$$\frac{dN}{d^2p_T dy d^2x_T} \sim \frac{1}{\alpha_s} \quad \text{for} \quad p_T < Q_{sat}(E)$$

This is a classical phase space density, which quantum mechanically is interpreted as an occupation number of quantum mechanical states. When much larger than one, occupation numbers are large and one can use classical dynamics.

The gluons can therefore be described by classical fields!

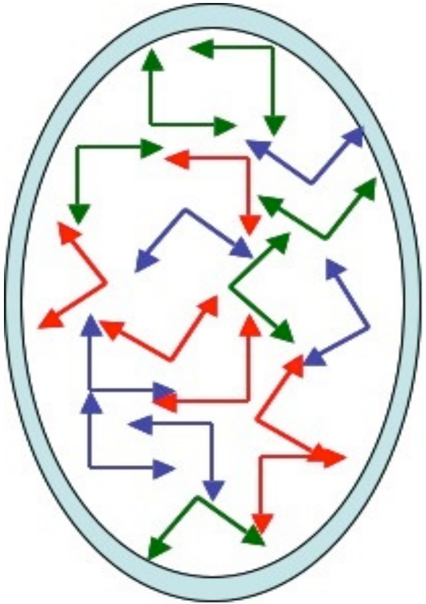
Color Glass Condensate

Color:
Gluons are colored

Condensate:
Gluon occupation number $1/\alpha_s$ is as large as can be, like Higgs condensate or superconductor
High density of gluons is self generated

Glass:
The sources of gluon field are static, evolving over much longer time scales than natural one
Resulting theory of classical field and real distribution of stochastic source is similar to spin glass

$$\frac{dN}{dy d^2 r_T d^2 p_T} \sim \frac{1}{\alpha_s}$$

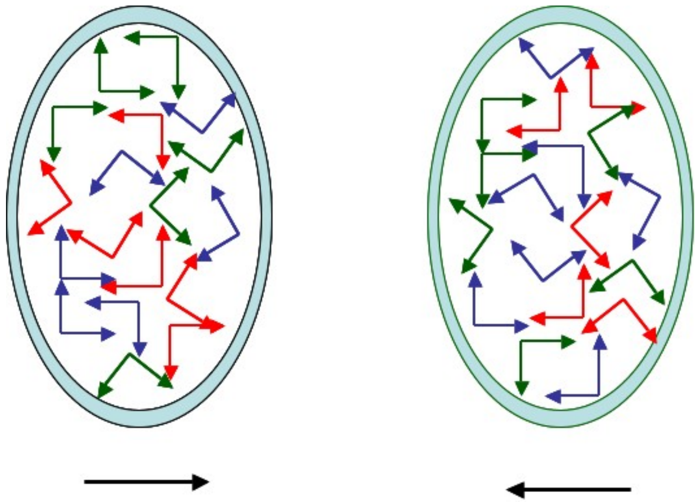


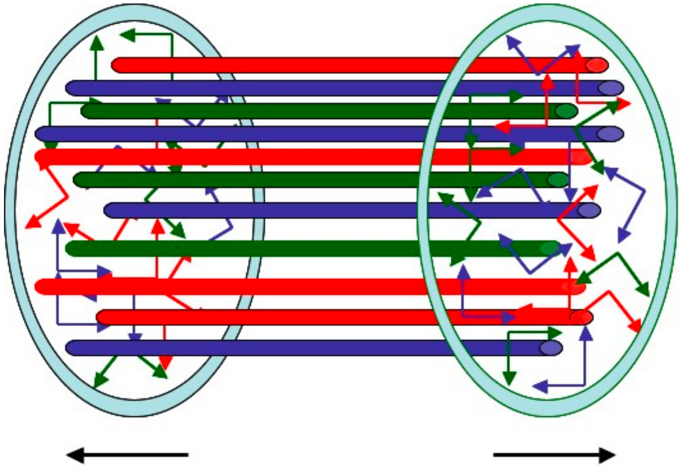
Parton distributions replaced by ensemble of coherent classical fields
Renormalization group equations for sources of these fields

$$Q^2_{sat} >> \Lambda^2_{QCD}$$

Collisions of two sheets of colored glass

Sheets get dusted with color electric and color magnetic fields





Long range color fields form in very short time

Maximal local density of topological charge:
Large local fluctuations in CP violating

$$\vec{E} \cdot \vec{B}$$

Glasma: Matter making the transition for Color Glass Condensate to Quark Gluon Plasma

The initial conditions for a Glasma evolve classically and the classical fields radiate into gluons
Longitudinal momentum is red shifted to zero by longitudinal expansion

But the classical equations are chaotic:
Small deviations grow exponentially in time

Chaos and Turbulence:

CGC field is rapidity independent => occupies restricted range of phase space
Wiggling strings have much bigger classical phase space
A small perturbation that has longitudinal noise grows exponentially

$$A_{classical} \sim 1/g$$

$$A_{quantum} \sim 1$$

After a time $t \sim \frac{ln^p(1/g)}{Q_{sat}}$ system isotropizes,

But it has not thermalized!

$$\Lambda_{IR}(t_0) = \Lambda_{UV}(t_0) = Q_{sat}$$

Evolve as powers of time

$$\Lambda_{IR}(t_{th}) = \alpha_s \Lambda_{UV}(t_{th})$$

Recent results of Gelis and Eppelbaum using spectrum of initial fluctuations derived from QCD:

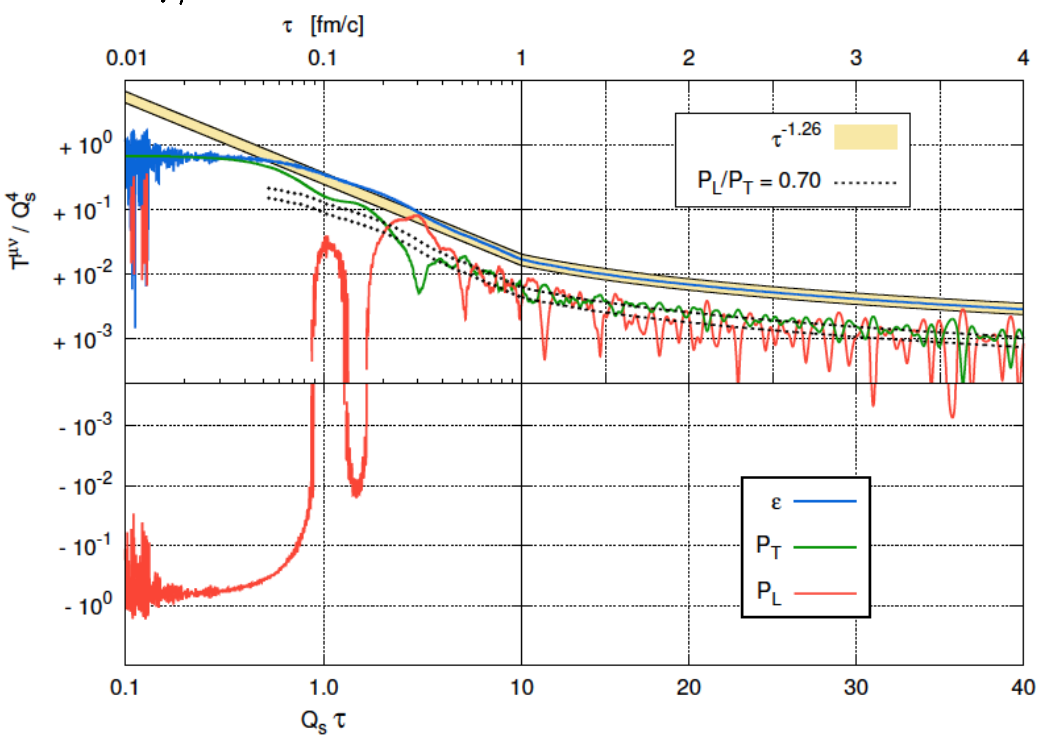
Find hydrodynamic behaviour a good approximation as coupling constant gets bigger, but even for

$$\alpha_S \sim 1/50$$

It is a good approximation.

For RHIC and LHC energy the coupling is even larger

$$\eta/S \sim 0.25 \qquad t_{hydro} \sim 3/Q_{sat}$$



The perfect fluid might not be a thermally equilibrated system!

Previous computations used different set of initial conditions,
Epelbaum and Gelis are the first to use initial fluctuation spectra derived from QCD
In scalar theory it takes times of order (100-1000)/Q_sat for these solutions to focus on the same behavior
However when

$$t \sim (1/\alpha)^a 1/Q_{sat}$$

The system will approach a thermal fixed point which is controlled by quantum corrections (classical thermal distribution functions must be replaced by Bose-Einstein distributions and this requires quantum mechanics)

Although there may be a universal scaling fixed point for asymptotically large times, this can only be approached for **VERY** small coupling since otherwise one goes to a thermal equilibration fixed point first.

Berges, Boguslavski, Schlichting and Venugopalan

For realistic coupling in QCD this probably happens in a few Fm/c.

Note also that the running of the coupling constant will force one to approach such a fixed point as the coupling becomes of order 1, that is at a temperature scale of the order of the QCD scale . Thermalization fixed point probably should be at temperature above the confinement transition

Fixed Momentum Space Asymmetry is Expected

Near a thermal fixed point t_scat << t_exp

Away from the thermal fixed point t_scat is of the order of t_exp

In !=! D expansion

$$\left(\frac{\mathcal{P}_L}{\mathcal{P}_T}\right)_{\rm NS} = \frac{P_{\rm eq} + \pi^{zz}_{\rm NS}}{P_{\rm eq} + \pi^{xx}_{\rm NS}} = \frac{\tau T - 16\bar{\eta}}{\tau T + 8\bar{\eta}}$$

$$\bar{\eta} = \frac{\eta}{\mathcal{S}}$$

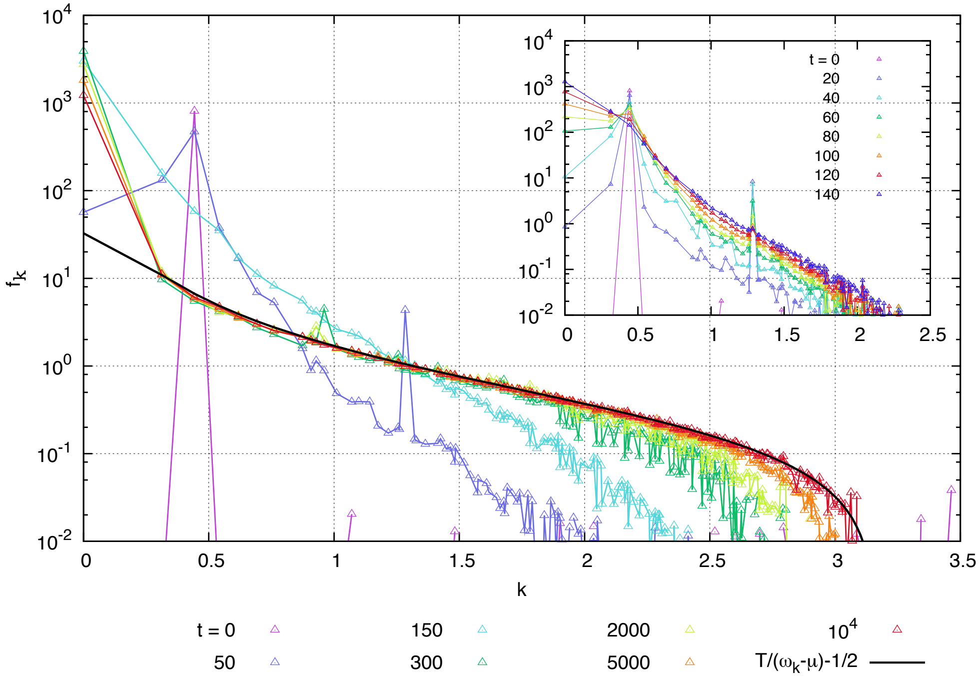
$$\eta/S \sim \tau_{scat} T \sim \tau T$$

$$P_L/P_T \sim cons$$

Strickland, Florkowski

The highly occupied initial conditions for the gluons is similar to studies of cold bosonic atomic gasses

One cools the gas by removing the high energy tail of a thermal distribution so that the low energy distribution is over occupied relative to a Bose Einstein distribution
When one tries to over occupy a bosonic system one has Bose condensation



This condensation occurs in scalar theory simulations, and in simulations of the Abelian Higgs model.

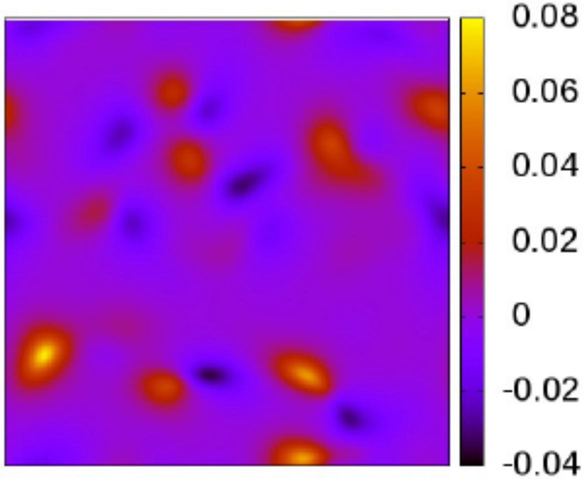
Unknown whether or not this might occur in the Glasma

Blaizot, Gelis,Liao, LDM, and Venugopalan

Glasma in the Abelian Higgs Model

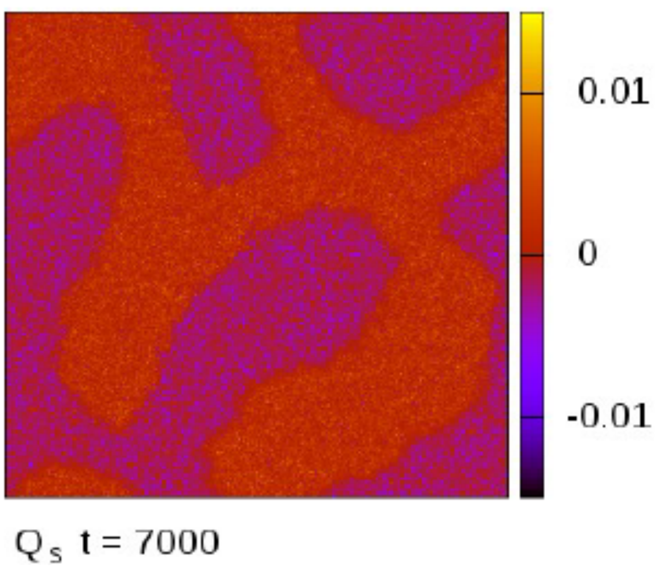
3 phases:
Normal
Type I Superconductor
Type II Superconductor

Scalar field is gauge variant but can define a gauge invariant scalar field correlation function and behavior is remarkably similar for gauged and non-gauged theories



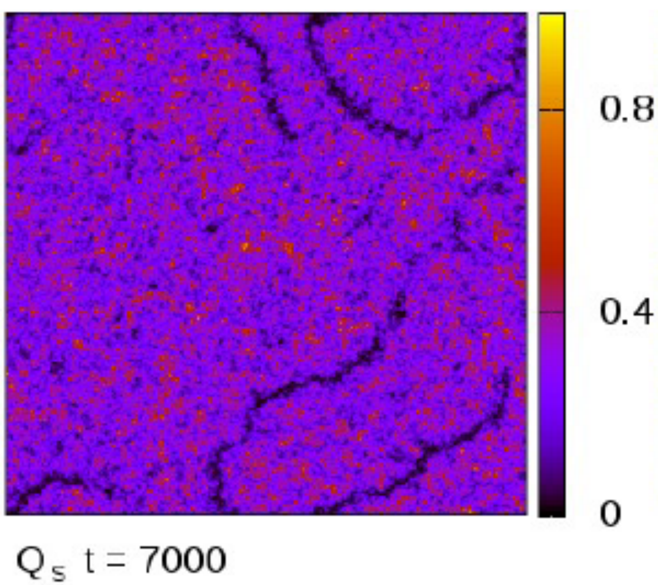
Vortices

Find interesting structures forming:
Vortices
Domain walls
Charged domains

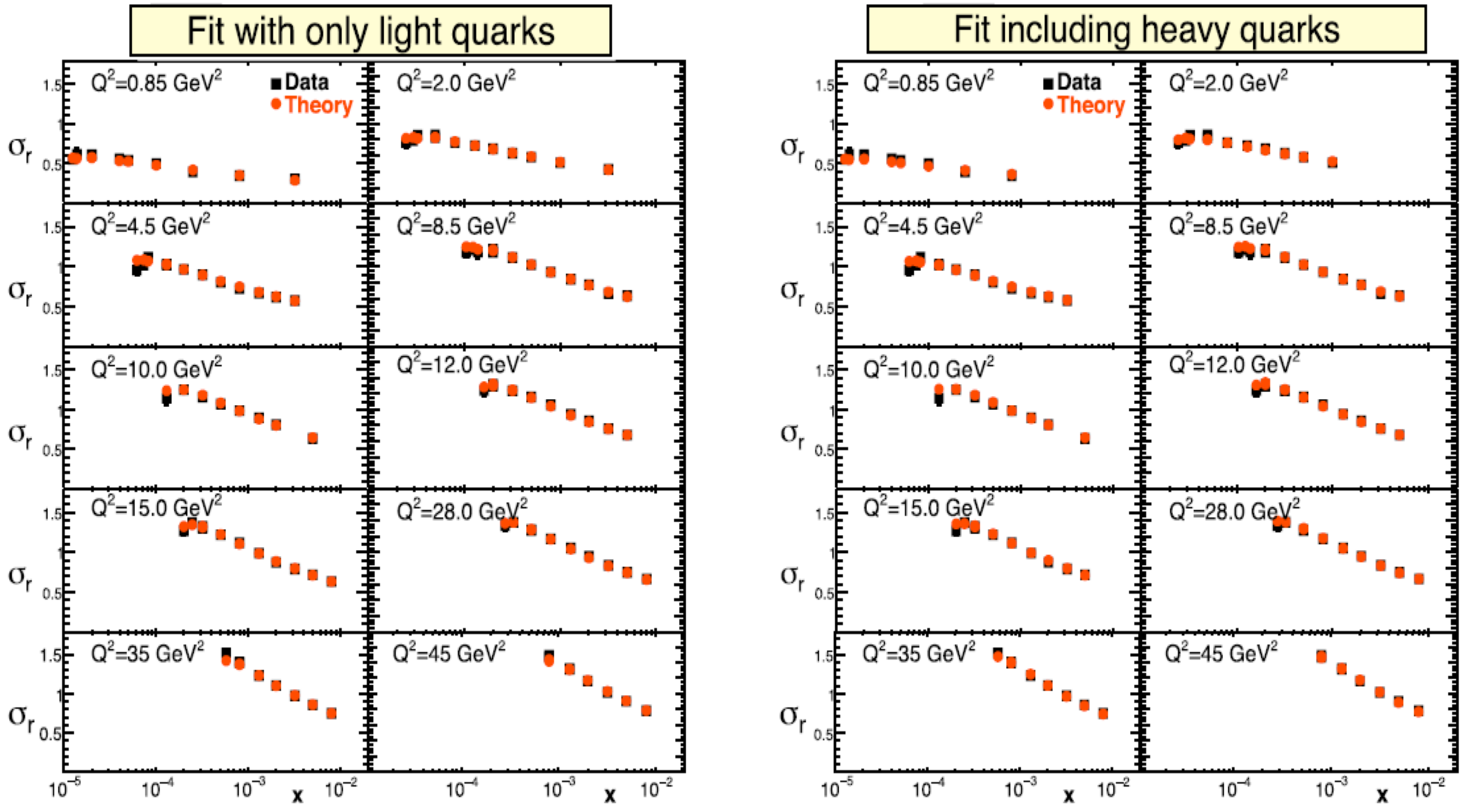


Charged domains and domain walls

Gassenzer, LDM, Pawlowski, Sexty



eA Collisions



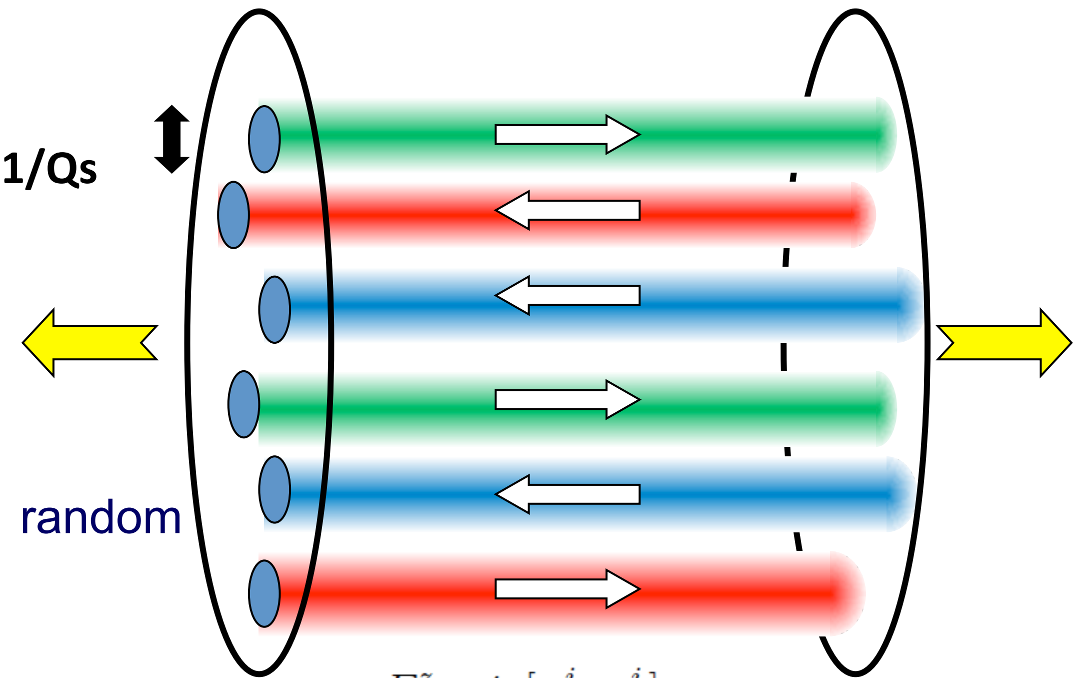
The CGC was motivated from ep studies

It provides a simple and good description of both deep inelastic and diffractive scattering at HERA

An eA collider at moderate energy can probe very high gluon densities

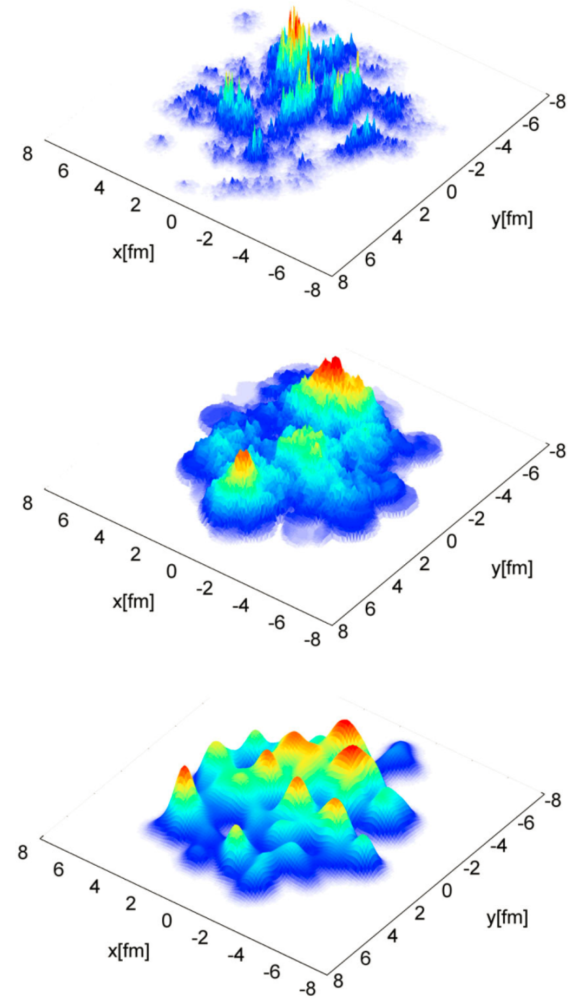
One can probe the degree of saturation as a function of transverse size scale with diffractive scattering: The diffractive cross section (no nuclear breakup) should be about ½ the total when the matter is saturated.

Heavy Ion Collisions



$$E^z = ig[\alpha_1^i, \alpha_2^i]$$
$$B^z = ig\epsilon^{ij}[\alpha_1^i, \alpha_2^j].$$

Typical configuration of a single event
just after the collision

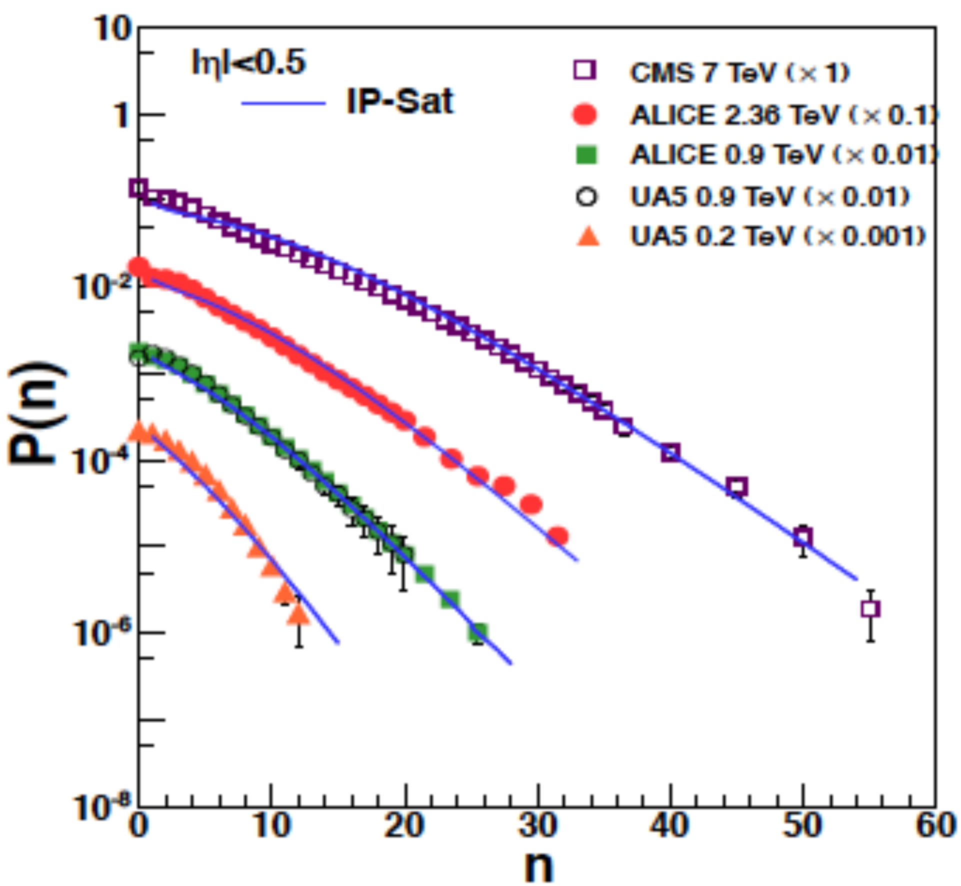


Highly coherent colored fields:
Stringlike in longitudinal direction
Stochastic on scale of inverse saturation momentum in transverse direction
Multiplicity fluctuates as negative binomial distribution

Good description, when combined, with hydro of bulk properties of heavy ion collisions

A Sub-Nucleonic description such as the CGC-Glasma is **absolutely necessary** for a well motivated description of pp and pA

Transverse size scales are less than a Fermi
Glauber at the nucleon level is certainly not applicable for pp or high multiplicity pA events



Including fluctuations and better positioning of matter produced makes a big difference:

Size of region is

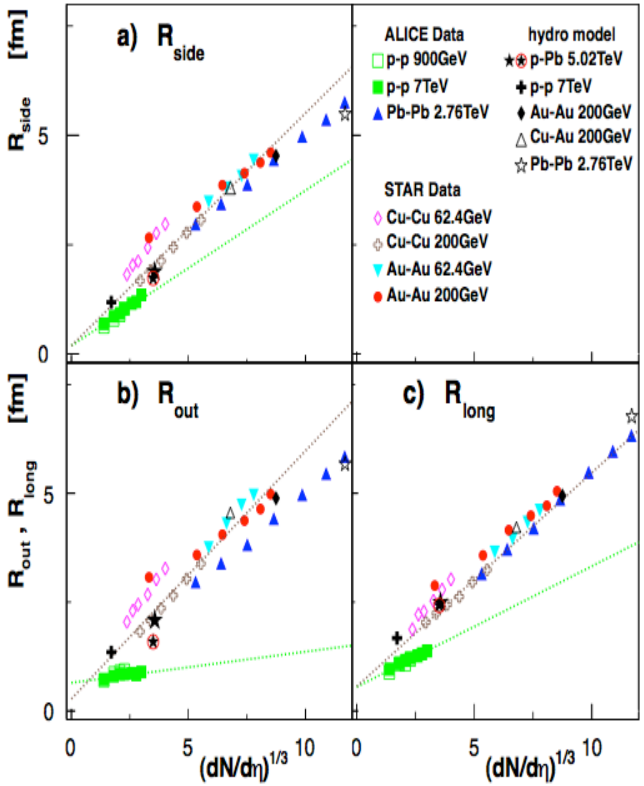
dN/dy ~ 30-50

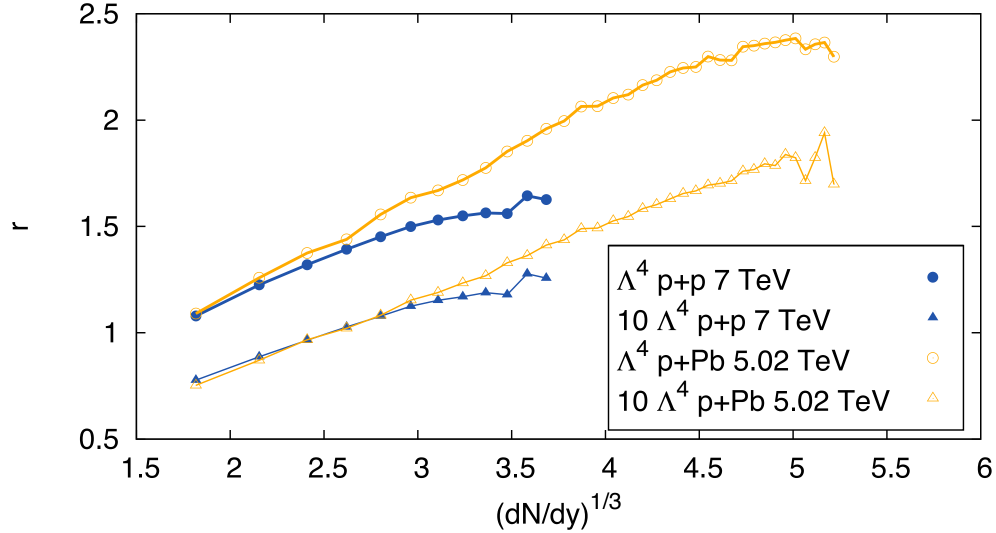
Since the ridge appears in pp collisions, there must be a sub nucleonic component

Schenke, Tribedy, Venugopalan

HBT Radii are of order 1 Fm for pp at largish multiplicities

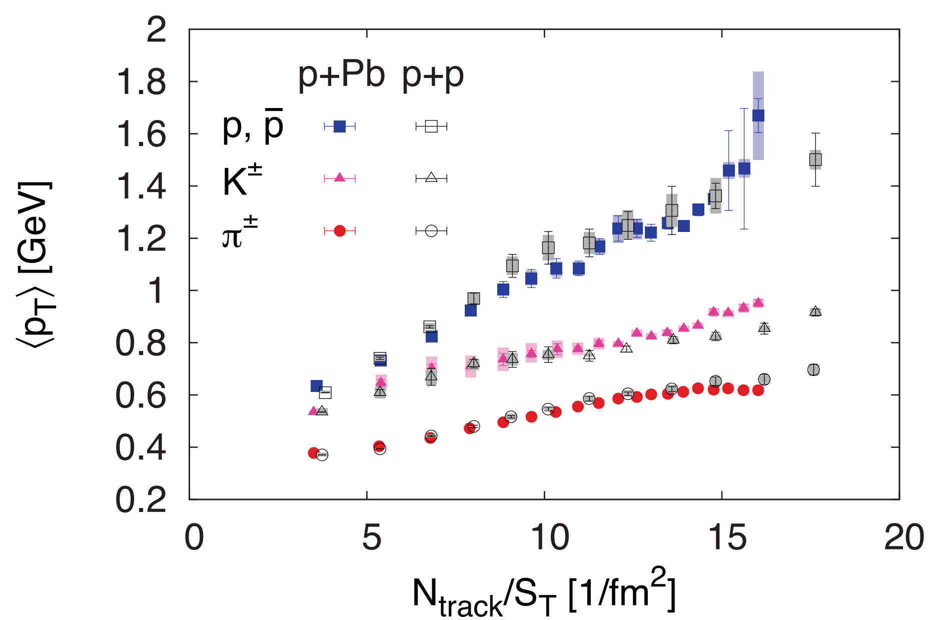
Bzdak, Schenke, Tribedy, Venugopalan





Radii computed in IP Sat Model

Geometric scaling maps pp data into pA in CMS identified particle data and for unidentified particles in ALICE



If true, low and high multiplicity data are related as well as pp and pA

Praszalowicz, LDM

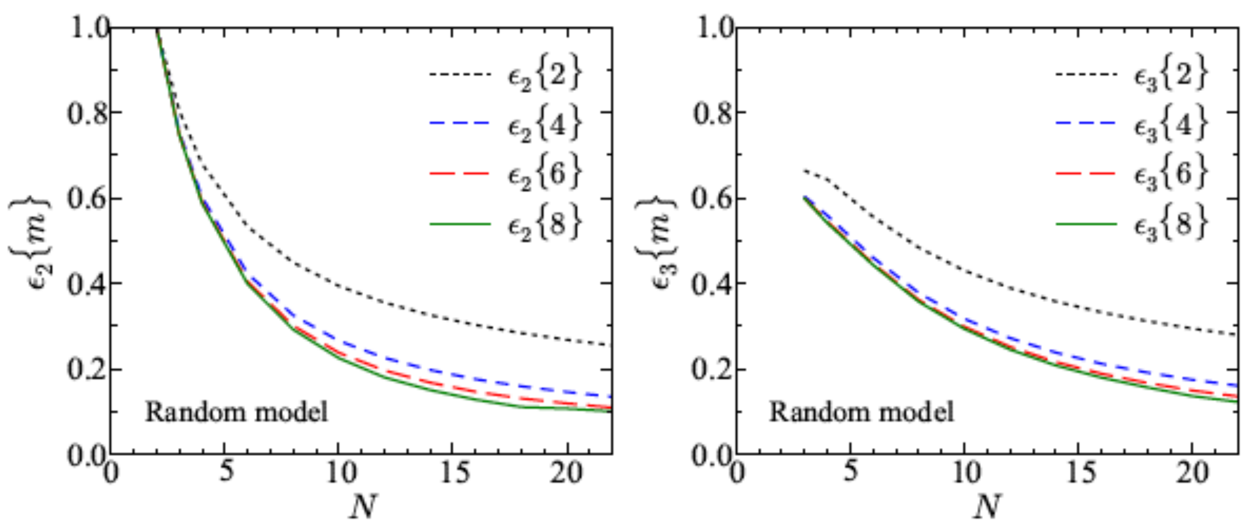
Flow in pA Collisions:

Initial State or Hydrodynamic or Both?

Collaborations with Dumitru and Lappi and with Bzdak and Bozek

$$\epsilon_n = \frac{1}{\langle r_T^n \rangle} \int d^2 r_T e^{in\phi} r_T^n \frac{dN}{dy d^2 r_T}$$

Define m particle cumulents: $\epsilon_n\{m\}$



Similar results for Glauber or Glauber plus Negative Binomial

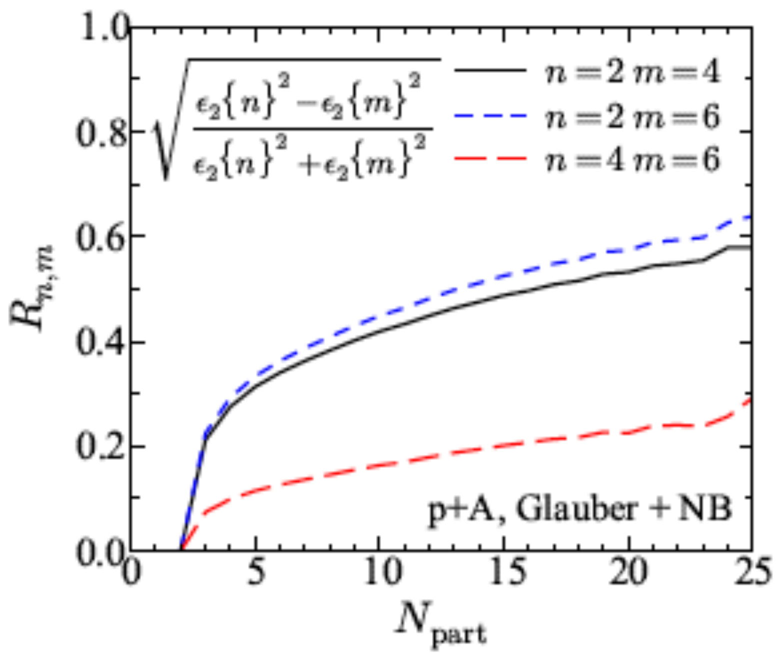
Fluctuation induced symmetry breaking

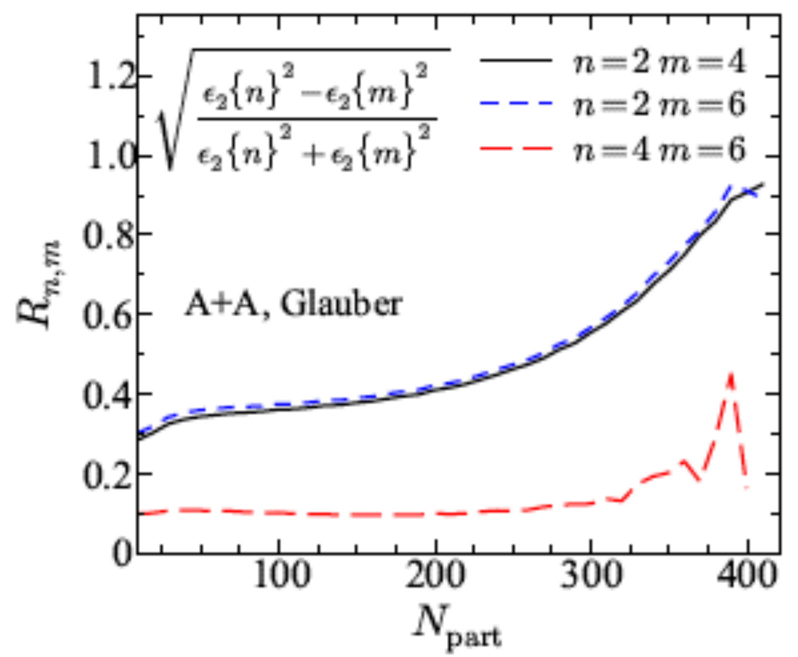
Can be generated by:

$$\langle|\epsilon_n|^m\rangle = \frac{\int dz d\bar{z} e^{-(z-z_n)(\bar{z}-\bar{z}_n)/\sigma_n^2}(z\bar{z})^{m/2}}{\int dz d\bar{z} e^{-(z-z_n)(\bar{z}-\bar{z}_n)/\sigma_n^2}}$$

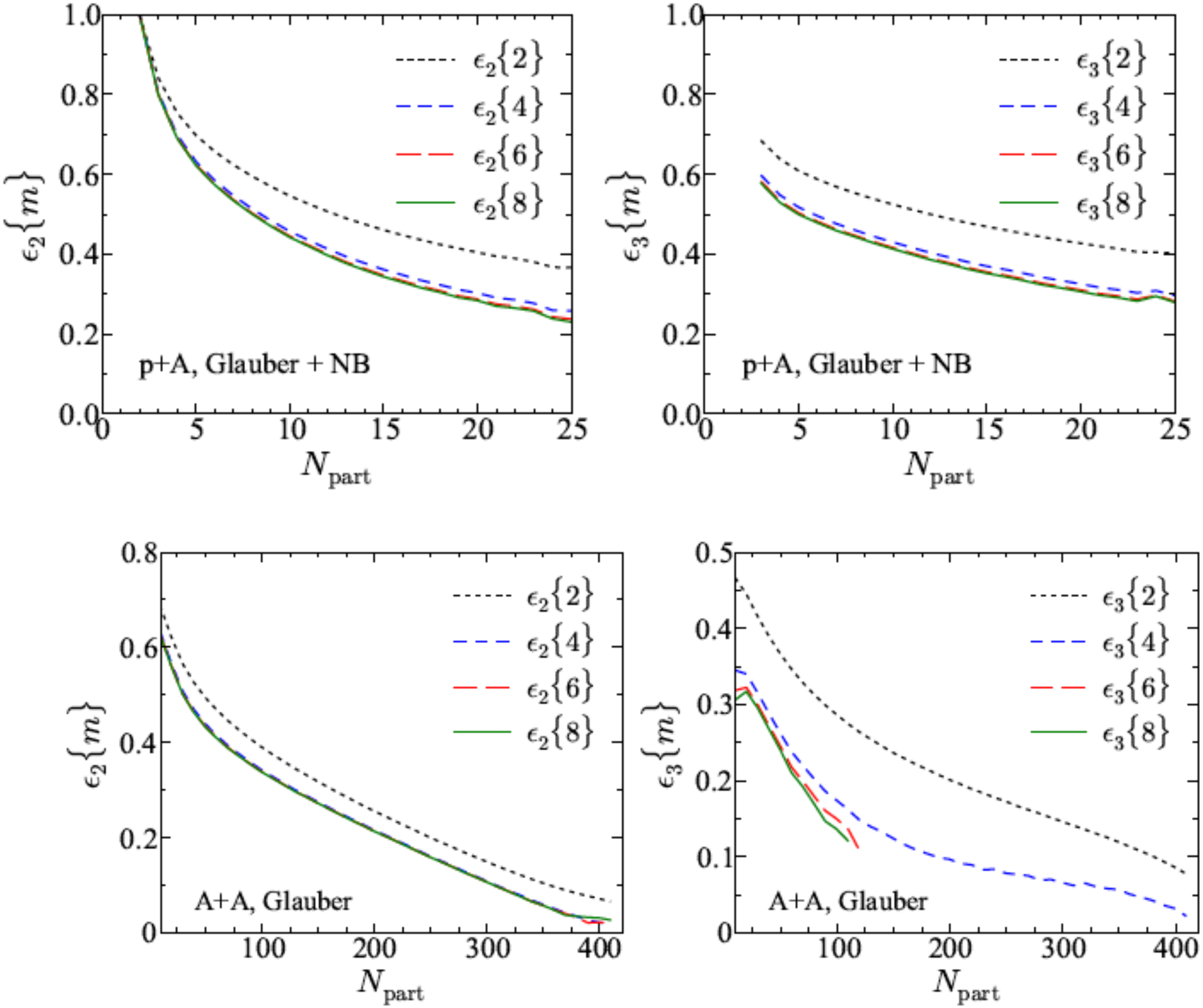
$$\epsilon_n\{2\} = \sqrt{|z_n|^2 + \sigma_n^2}$$

$$\epsilon_n\{m\} = |z_n|,$$





Multi-particle flow follows ellipticity in an linear response dynamics:
Hydro, Classical radiation



$\epsilon_2\{2\}$
$\epsilon_2\{4\}$
$\epsilon_2\{6\}$
$\epsilon_2\{8\}$
p+A, Glauber + NB
$\epsilon_3\{2\}$
$\epsilon_3\{4\}$
$\epsilon_3\{6\}$
$\epsilon_3\{8\}$
p+A, Glauber + NB
A+A, Glauber
A+A, Glauber
$\epsilon_2\{m\}$
$\epsilon_3\{m\}$
$N_{\rm part}$

Future Directions for Heavy Ions

There is now the framework for a more or less complete description of heavy ion collisions from beginning to end

CGC

Initial conditions can be computed from first principles, including non trivial flow like correlations from the initial state

Glasma

Has been shown to generate hydrodynamic behaviour:

Flow generation in glasma phase?

Viscosities?

Photons?

Turbulence?

Condensation?

Thermalization?

Thermalized QGP

Chemical abundances

Flow generation?

Late times, Edge Effects, Hadronization?

In pp and pA, small system size means hydro probably has large viscous correction. Glasma treatment may not suffer from treating viscous effects as an approximation.

CGC+Glasma+Hydro

Estimate limits of validity of various approaches

Determine contribution of various stages of evolution to quantities such as the ridge and photon production

Probably biggest uncertainty will be edge effects and hadronization

Summary:

If we accept that there is saturation, then we must conclude that interactions among the constituents within a single hadron are strong, then for some time in a collision of two hadrons there must also be strong interactions among these constituents. Perhaps in some situations initial state or final state effect may be more important, but both are present and must play important roles.

The scientific issue is how do we properly understand, compute and probe these interactions.

The Zen End