QCD in heavy-ion collisions

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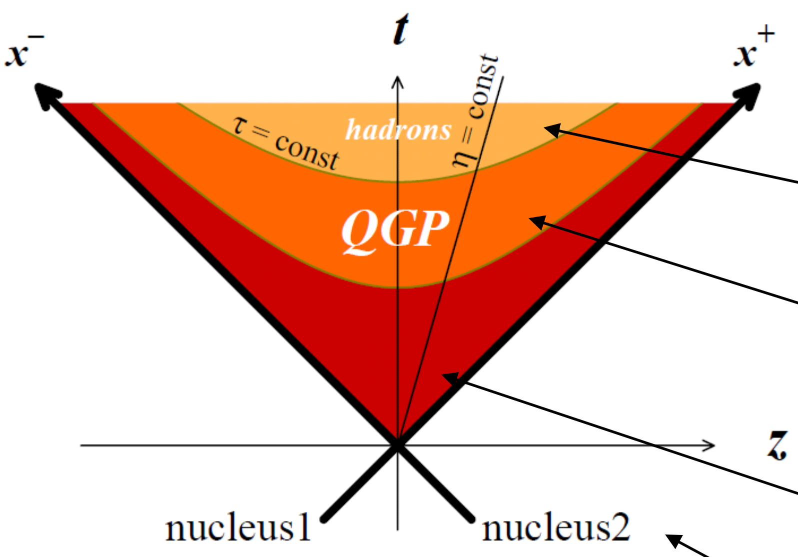
CERN TH retreat

Relativistic Heavy-Ion Collisions

main goal: produce and study the quark-gluon-plasma



space-time picture of heavy-ion collisions

5. Individual hadrons

freeze out

4. Hadron gas

cooling with expansion

3. Quark Gluon Plasma

thermalization, expansion

2. Pre-equilibrium state

collision

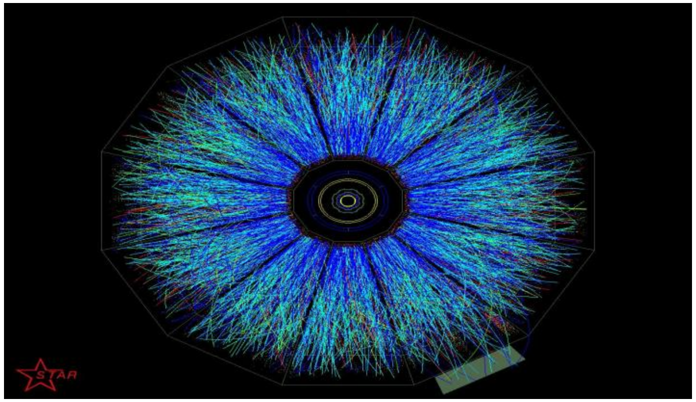
1. Nuclei (initial condition)

however, one observes the system after it has gone through a complicated evolution involving different aspect of QCD

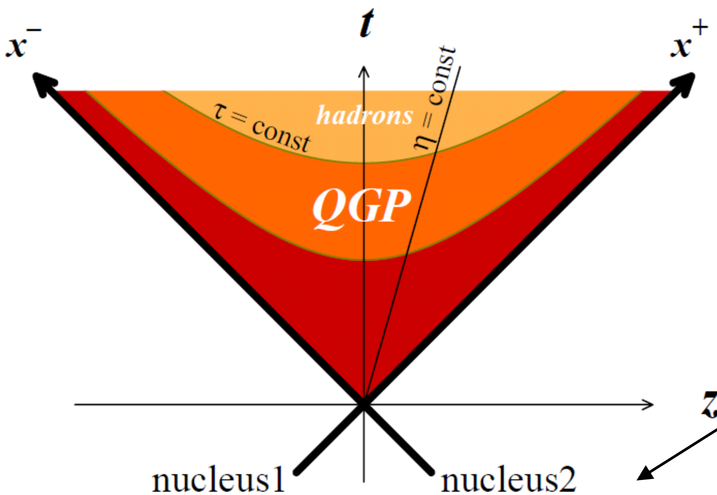
to understand each stage and the transition between them has been challenging

Relativistic Heavy-Ion Collisions

this is the result of a central Au+Au collision at RHIC



at the moment, our understanding of QCD is not good enough to unfold the whole time evolution



such multi-particle production involves low-energy (small-x) partons in the nuclear wave functions

this is the first thing to understand

I will discuss semi-classical weak coupling methods to describe the early stages of the collision

The total particle multiplicity

the evolution of the total particle multiplicity with energy is driven by the *x* evolution of the nuclear wave functions

this is something we think we understand, we will know very soon

- about p+p collisions at the LHC

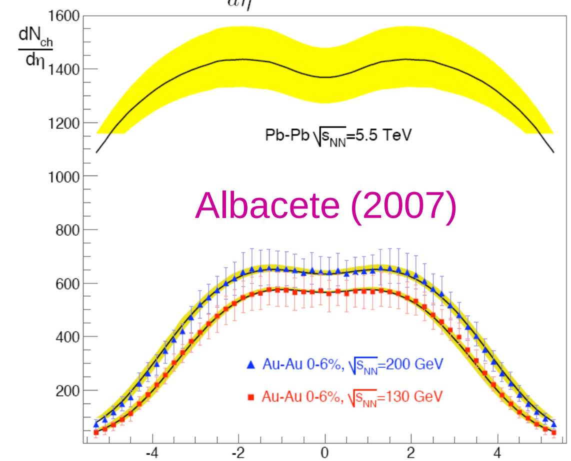
the multiplicity in 2.36TeV collisions couldn't be predicted with standard tools

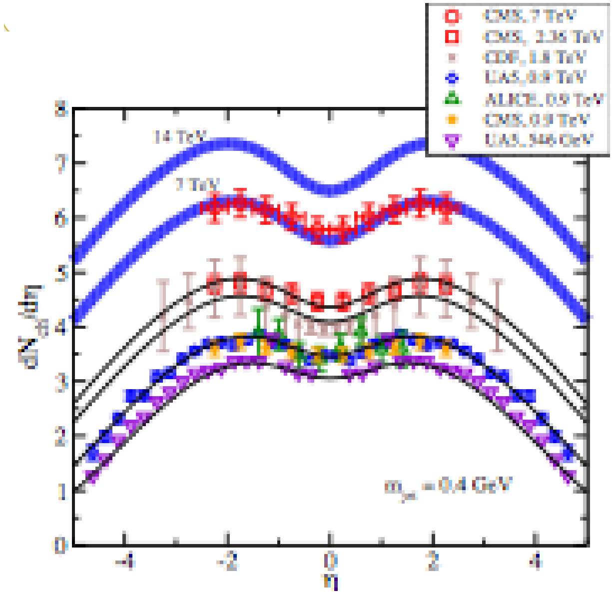
applying tools developed in the context of heavy-ion collisions, the 7 TeV multiplicity was predicted correctly

Levin and Rezaeian (2010)

LHC results already made an impact on our field

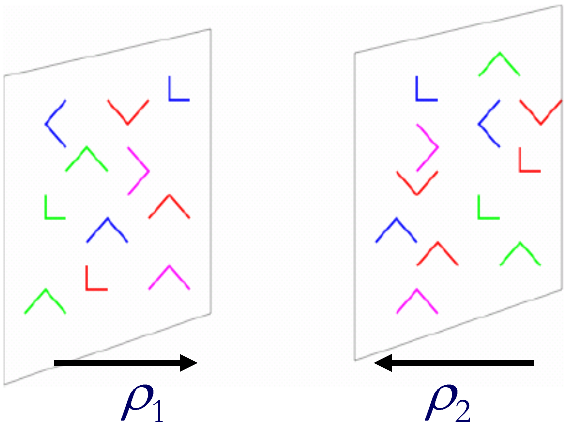
$$\frac{dN_{ch}^{Pb-Pb}(\sqrt{s}=5.5\,\mathrm{TeV},\eta=0)}{d\eta} \approx 1290 \div 1480$$





Classical-field description of HIC

- the initial condition for the time evolution in heavy-ion collisions



before the collision:

$$J^\mu = \delta^{\mu +}\delta(x^-)\rho_1(x_\perp) + \delta^{\mu -}\delta(x^+)\rho_2(x_\perp)$$

$$\rho_1 \sim 1/g \qquad \rho_2 \sim 1/g$$

the distributions of ρ contain the small-x evolution of the nuclear wave functions

$$|\Phi_{x_1}[\rho_1]|^2 \qquad |\Phi_{x_2}[\rho_2]|^2$$

that such a description of the small-*x* part of the nuclear wave function can provide a good approximation of QCD was not obvious at the beginning

- after the collision

the gluon field is a complicated function of the two classical color sources

the field decays, once it is no longer strong (classical)
a particle description is again appropriate

The field/particle composition

- the field after the collision is non trivial — Lappi and McLerran (2006)

it has a strong component $A^\mu \sim 1/g_s$, a particle-like component $A^\mu \sim 1$ and components of any strength in between

- the decay of the gluon field

right after the collision, the strong component contains all modes
then modes with $p_T > 1/\tau$ are not part of the strong component anymore

- thermalization is still an outstanding problem

glasma: $T^{\mu\nu} = \frac{1}{4} g^{\mu\nu} F^{\lambda\sigma} F_{\lambda\sigma} - F^{\mu\lambda} F^{\nu}_{\lambda}$

$$T^{\mu\nu}(\tau = 0^+) = \begin{pmatrix} \epsilon & & & \\ & \epsilon & & \\ & & \epsilon & \\ & & & -\epsilon \end{pmatrix} \qquad T^{\mu\nu}_{hydro} = \begin{pmatrix} \epsilon & & & \\ & p & & \\ & & p & \\ & & & p \end{pmatrix}$$

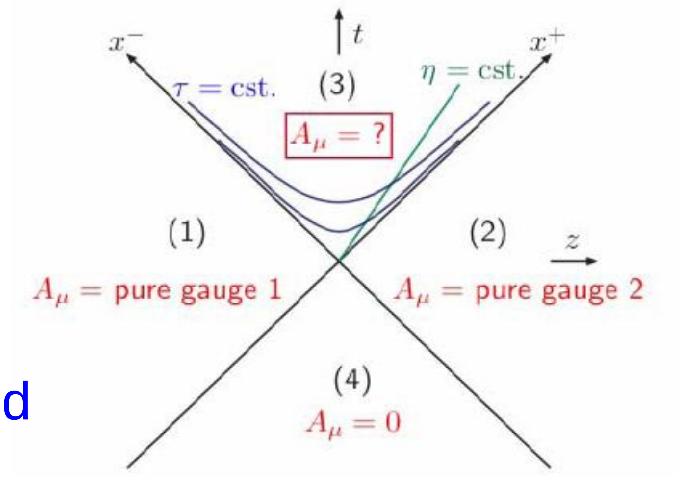
how does the transition happens ? in a scalar theory: Dusling et al (2010)

A new QCD factorization

- solve Yang-Mills equations

$$[D_\mu, F^{\mu\nu}] = J^\nu \longrightarrow \mathcal{A}_\mu[\rho_1, \rho_2]$$

this is done numerically (it can be done analytically in the p+A case)



- express observables in terms of the field

determine $O[\mathcal{A}_\mu]$, in general a non-linear function of the sources

examples later : single- and double-inclusive gluon production

- perform the averages over the color charge densities

$$\langle O \rangle = \int D\rho_1 D\rho_2 |\Phi_{x_1}[\rho_1]|^2 |\Phi_{x_2}[\rho_2]|^2 O[\mathcal{A}_\mu]$$

rapidity factorization proved recently at leading-order for (multi-)gluon production

Gelis, Lappi and Venugopalan (2008)

The Color Glass Condensate

- the CGC: an effective theory to describe the small-x gluons

McLerran and Venugopalan (1994)

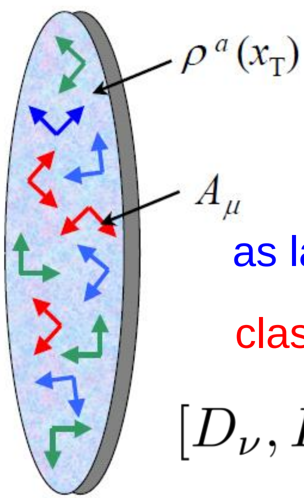
lifetime of the partons in the wave function ~ $xP^+/k_\perp^2$ $\Rightarrow$ $\begin{cases} \text{high-x partons} \equiv \text{static sources } \rho \\ \text{low-x partons} \equiv \text{dynamical fields } \mathcal{A} \end{cases}$

short-lived fluctuations

$$|\text{hadron}\rangle = |qqq\rangle + |qqqg\rangle + \ldots + |qqq \ldots\ldots ggggg\rangle \;\Rightarrow\; |\text{hadron}\rangle = \int D\rho\, \Phi_x[\rho]\, |\rho\rangle \equiv |\text{CGC}\rangle$$

effective wave function for the dressed hadron

separation between the long-lived high-x partons and the short-lived low-x gluons



valence partons as static random color source

small x gluons as large classical fields

classical Yang-Mills equations

$$[D_\nu, F^{\nu\mu}]^a = \delta^{\mu +}\delta(x^-)\rho^a(x_\perp)$$

the evolution of $|\Phi_x[\rho]|^2$ with x is a renormalization group which sums both $\begin{cases} \alpha_s^n \ln^n(1/x) \\ g_s^n \mathcal{A}^n \end{cases}$

this effective description of the hadronic wave function applies only to the small-x part

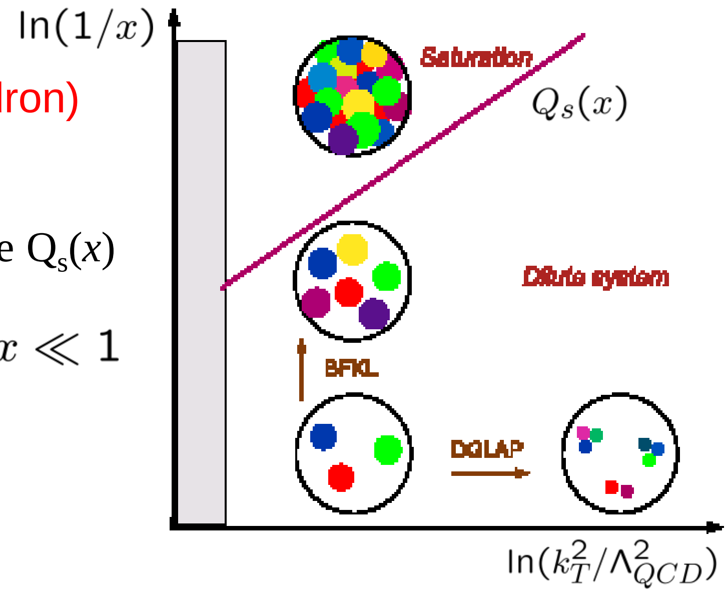
Parton saturation

- a regime of the hadronic/nuclear wave function predicted in QCD

x : parton longitudinal momentum fraction

k_T : parton transverse momentum

the distribution of partons as a function of x and k_T :



QCD linear evolutions: $k_T \gg Q_s$

DGLAP evolution to larger k_T (and a more dilute hadron)

BFKL evolution to smaller x (and denser hadron)

dilute/dense separation characterized by the saturation scale $Q_s(x)$

QCD non-linear evolution: $k_T \sim Q_s$ meaning $x \ll 1$

$\rho \sim \frac{xf(x,k_\perp^2)}{\pi R^2}$ gluon density per unit area; it grows with decreasing x

$\sigma_{rec} \sim \alpha_s/k^2$ recombination cross-section

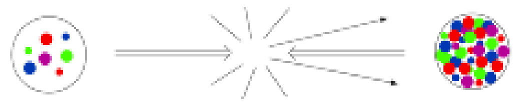
recombinations important when $\rho\ \sigma_{rec} > 1$

the saturation regime: for $k^2 < Q_s^2$ with $Q_s^2 = \frac{\alpha_s x f(x,Q_s^2)}{\pi R^2}$

this regime is non-linear yet weakly coupled $\alpha_s(Q_s^2) \ll 1$

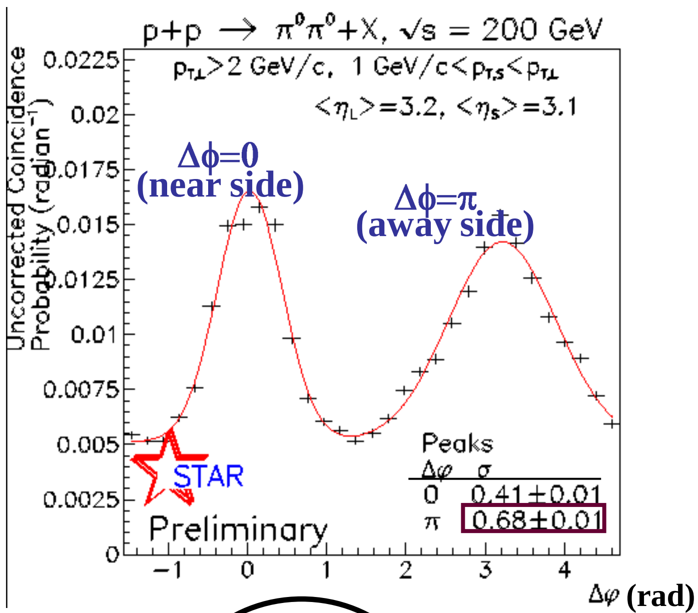
Forward monojet production

$$x_A = \frac{k_1\, e^{-y_1} + k_2\, e^{-y_2}}{\sqrt{s}} << 1$$

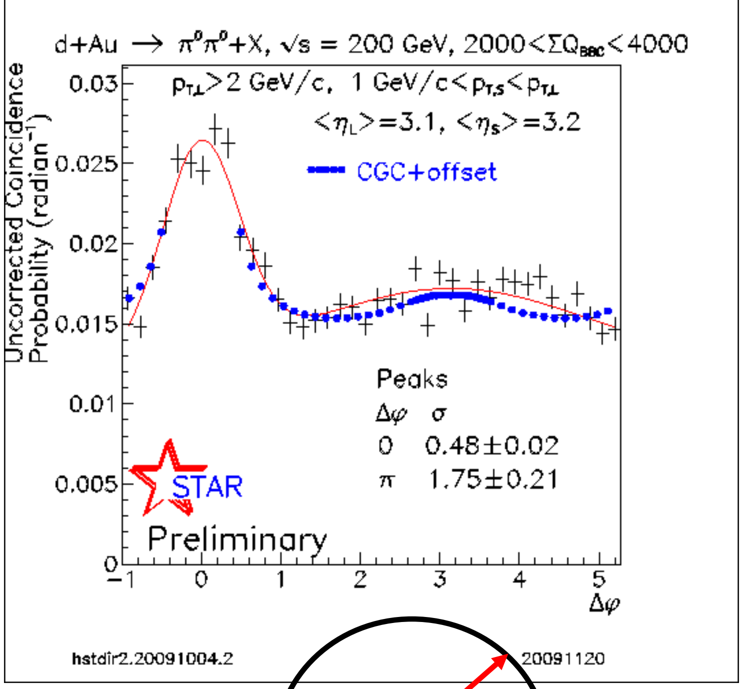


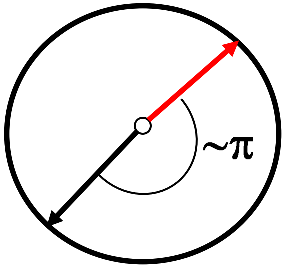
Albacete and CM (2010)

p+p

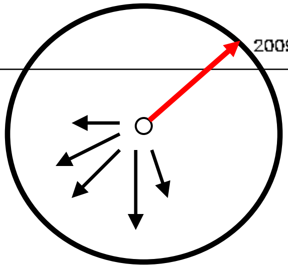


d+Au central

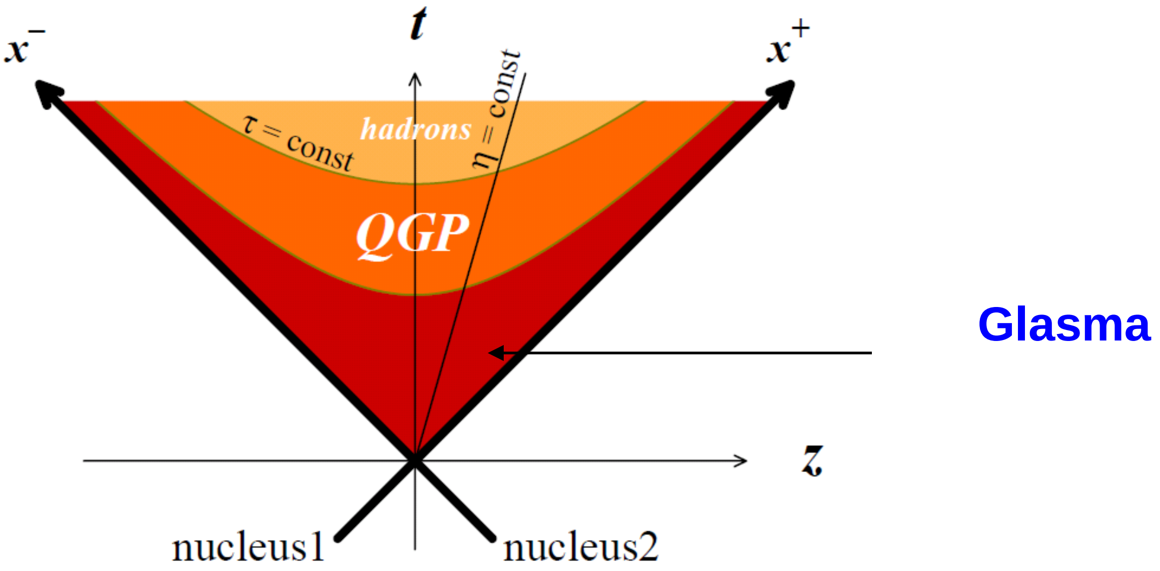




this happens at forward rapidities,
but at central rapidities, the p+p and
d+Au signal are almost identical



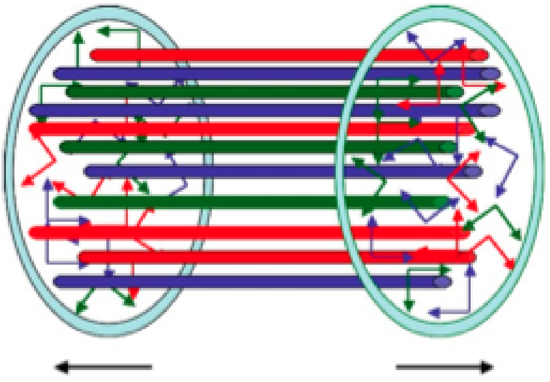
The Glasma



t
x^-
x^+
$\eta = \text{const}$
$\tau = \text{const}$
hadrons
QGP
Glasma
z
nucleus1
nucleus2

Probing features of the Glasma

- features of the Glasma fields



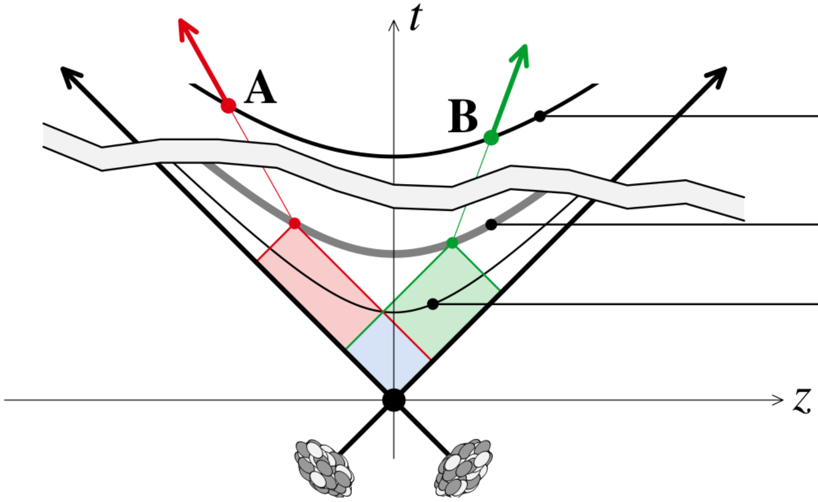
in general, the following phases (QGP, …) destroy the information coming from the glasma

HICs are not great probes of parton saturation

nevertheless, some observables are still sensitive to the physics of the early stages

- long-range rapidity correlations

$$\tau < \tau_{freezeout} \; \exp(-\Delta\eta/2)$$



Particle production in the glasma

- single gluon production

Krasnitz and Venugopalan (1998)

$$\frac{dN}{d^3p}[\mathcal{A}] = \frac{1}{16\pi^3}\int_{x,y} e^{ip.(x-y)} \sum_\lambda \varepsilon^\mu_\lambda \varepsilon^\nu_\lambda A_\mu(x) A_\nu(y)$$

- two-gluon production

easily obtained from the single-gluon result

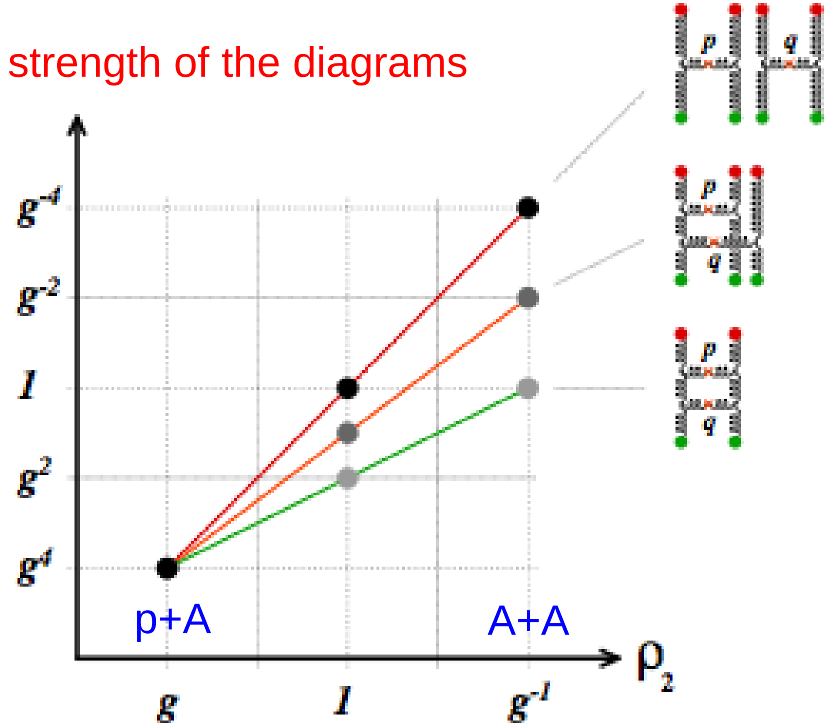
$$\frac{dN}{d^3p\,d^3q}[\mathcal{A}] = \frac{dN}{d^3p}[\mathcal{A}] \times \frac{dN}{d^3q}[\mathcal{A}]$$

in A+A collisions, disconnected diagrams dominate multi-gluon production

Gelis, Lappi and Venugopalan (2008)

the exact implementation of the small-x evolution is still not achieved as in the single-particle case

strength of the diagrams



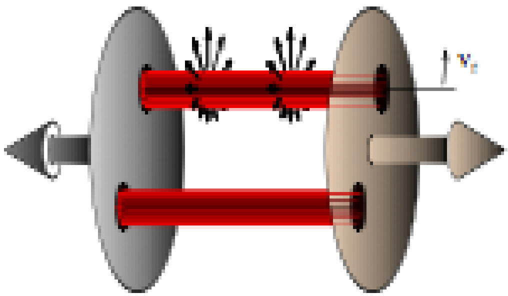
strength of the color charge of the projectile

the target is always dense $\rho_1 \sim 1/g$

The ridge in A+A collisions

- the ridge is qualitatively understood within the CGC framework

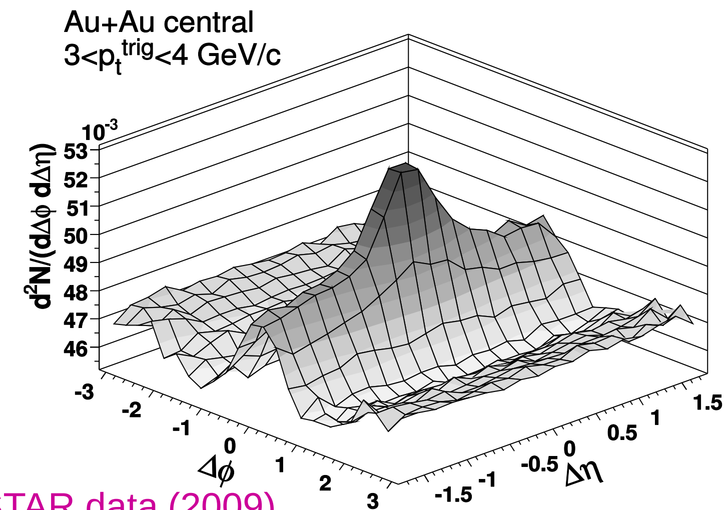
the $\Delta\phi$ collimation is due to the radial flow



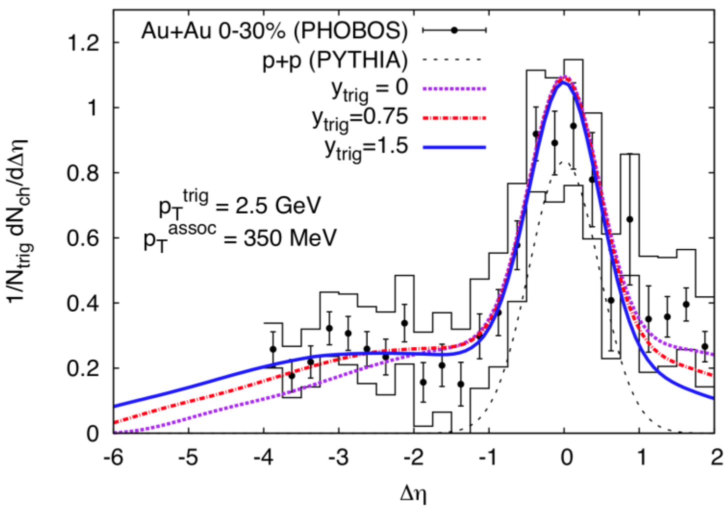
if it is very extended in rapidity, the ridge is a manifestation of early-time phenomena:

$$\tau < \tau_{\text{freezeout}} \exp(-\Delta\eta/2)$$

Dusling, Gelis, Lappi and Venugopalan (2009)



STAR data (2009)

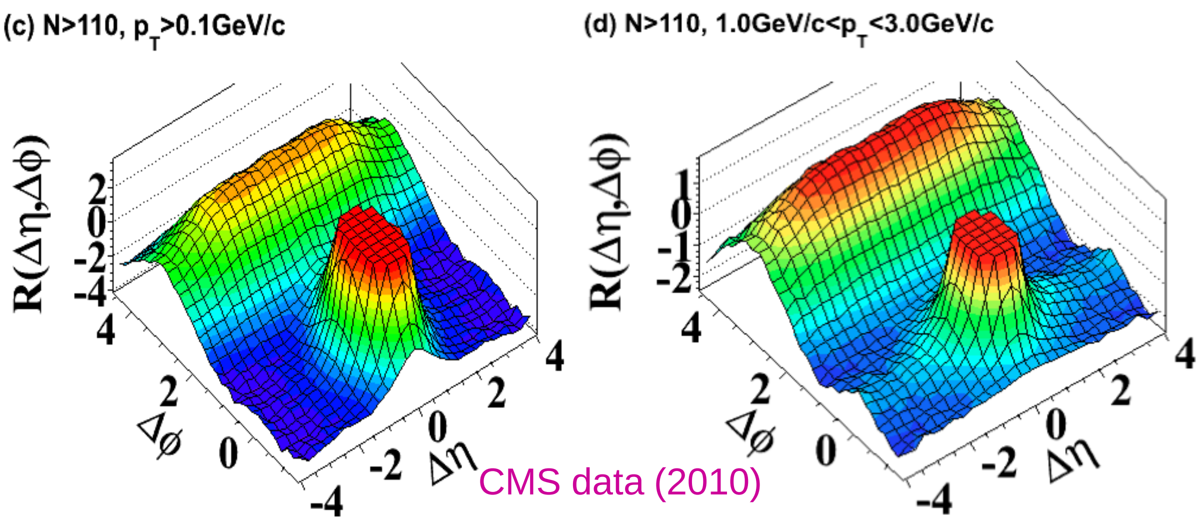


quantitative calculations are underway

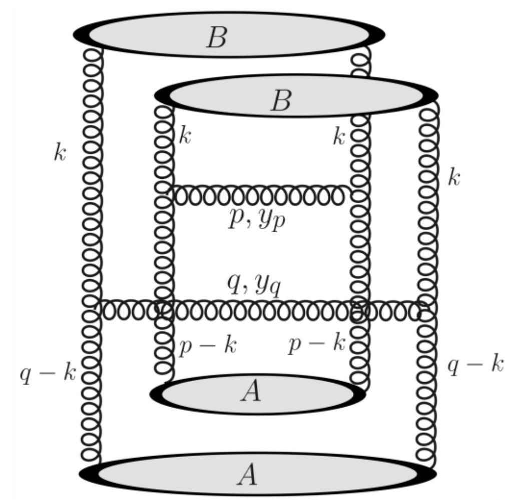
The ridge in p+p collisions

- in the absence of flow, the ridge reflect the actual momentum correlations of the early times

Dumitru, Dusling, Gélis, Jalilian-Marian, Lappi and Venugopalan (2010)



CMS data (2010)



no ridge at low p_T, there can't be much flow

ridge with p_T ~ Qs

diagram which gives the $\Delta\phi$ dependence

at the moment, the agreement is only qualitative

(some leading-Nc diagrams are notoriously difficult to include)