Introduction to the theory of the QGP and the CGC

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Outline

- **Quark Gluon Plasma (QGP)**
  - Basic features of QCD
  - Deconfinement phase transition
  - Physics of the quark gluon plasma
  - Signatures of the QGP

- **Color Glass Condensate (CGC)**
  - Parton model
  - Saturation
  - Color Glass Condensate
  - Signatures of the CGC
Quarks and gluons

- Electromagnetic interaction: Quantum electrodynamics
  - Matter: electron, interaction carrier: photon
  - Interaction:

- Strong interaction: Quantum chromodynamics
  - Matter: quarks, interaction carriers: gluons
  - Interactions:

- $i, j$: colors of the quarks (3 possible values)
- $a, b, c$: colors of the gluons (8 possible values)
- $(t^a)_{ij}: 3 \times 3$ matrix, $(T^a)_{bc}: 8 \times 8$ matrix
Quark confinement

- The quark potential increases linearly with distance
- Quarks are confined into color singlet hadrons
Asymptotic freedom

- Running coupling: \( \alpha_s = \frac{g^2}{4\pi} \)

\[
\alpha_s(r) = \frac{2\pi N_c}{(11N_c - 2N_f) \log\left(\frac{1}{r\Lambda_{QCD}}\right)}
\]

- The effective charge seen at large distance is screened by fermionic fluctuations (as in QED)
Asymptotic freedom

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- The effective charge seen at large distance is screened by fermionic fluctuations (as in QED)

- But gluonic vacuum fluctuations produce an anti-screening (because of the non-abelian nature of their interactions)

- As long as \( N_f < 11N_c / 2 = 16.5 \), the gluons win...
Asymptotic freedom

- The coupling constant is small at short distances
- At high density, a hadron gas may undergo deconfinement
  - quark gluon plasma
Fast increase of the pressure:

- at $T \sim 270$ MeV, if there are only gluons
- at $T \sim 150–170$ MeV, depending on the number of light quarks
Deconfinement

When the nucleon density increases, they merge, enabling quarks and gluons to hop freely from a nucleon to its neighbors.

This phenomenon extends to the whole volume when the phase transition ends.

Note: if the transition is first order, it goes through a mixed phase containing a mixture of nucleons and plasma.
Deconfinement

3-flavour phase diagram

\[ T_{c}^{n_f=2} \sim 175 \text{ MeV} \]

\[ T_{c}^{n_f=3} \sim 155 \text{ MeV} \]

\[ T_{d} \sim 270 \text{ MeV} \]

\[ m_{PS}^{c_{it}} \sim 2.5 \text{ GeV} \]

\[ m_{PS}^{c_{it}} \sim 200 \text{ MeV} \]
QCD phase diagram

- temperature
- chemical potential
- nuclei
- neutron stars
- hadronic phase
- quark gluon plasma
- color supraconductor

Basic features of QCD
- Deconfinement
- QCD phase diagram
- Early universe
- Heavy ion collisions

Physics of the QGP
- QGP signatures

CGC
- Parton model
- Saturation
- Color Glass Condensate
- CGC signatures
The QGP in the early universe

- Temperature
- Expansion of the early universe
- Quark gluon plasma
- Hadronic phase
- Color supraconductor
- Nuclei
- Neutron stars
- Chemical potential

The QGP in the early universe

- Formation of atoms
- Nucleosynthesis
- Confinement
- EW transition
- End of inflation
- Big bang

Timeline:
- $10^{-32}$ sec: Big bang
- $10^{-10}$ sec: QGP + electrons + photons
- $10^{-5}$ sec: Confinement
- $10^{+2}$ sec: EW transition
- $10^{+12}$ sec: Formation of atoms

Key events:
- Deconfinement
- QCD phase diagram
- Early universe
- Heavy ion collisions

Physics of the QGP

QGP signatures

CGC

Parton model

Saturation

Color Glass Condensate

CGC signatures
Heavy ion collisions
Heavy ion collisions

- $\tau \sim 0 \text{ fm/c}$
- Production of hard particles:
  - jets
  - heavy quarks
  - direct photons
- calculable with the tools of perturbative QCD
Heavy ion collisions

- $\tau \sim 0.2 \text{ fm/c}$
- Production of semi-hard particles:
  - gluons, light quarks
- relatively small momentum: $p_{\perp} \lesssim 1$–2 GeV
- make up for most of the multiplicity
- sensitive to the physics of saturation (CGC)
Heavy ion collisions

- $\tau \sim 1\text{–}2 \text{ fm/c}$

- **Thermalization**
  - experiments suggest a fast thermalization
  - but this is still not understood from QCD
Heavy ion collisions

- $2 \leq \tau \lesssim 10 \text{ fm/c}$
- Quark gluon plasma
Heavy ion collisions

- $10 \lesssim \tau \lesssim 20 \text{ fm/c}$
- Hot hadron gas
Heavy ion collisions

- **\( \tau \to +\infty \)**
- **Chemical freeze-out:**
  density too small to have inelastic interactions
- **Kinetic freeze-out:**
  no more elastic interactions
Degrees of freedom

**Quarks**

\[
\frac{dN_q}{d^3\vec{x}d^3\vec{k}} = \frac{1}{e^{\omega/T} + 1}
\]

\[(\text{Fermi-Dirac})\]

**Gluons**

\[
\frac{dN_g}{d^3\vec{x}d^3\vec{k}} = \frac{1}{e^{\omega/T} - 1}
\]

\[(\text{Bose-Einstein})\]

**Average energy per particle**

\[\langle \omega \rangle \sim T\]

**Particle density**

\[\rho \sim T^3\]

**Average distance between particles**

\[\ell \sim 1/T\]
Collective phenomena

- Phenomena involving many elementary constituents
- Large wavelength compared to the typical distance between constituents
- Small frequency or energy
- The quantum numbers of collective excitations may not be related to those of the elementary constituents

Major collective phenomena:
- Quasi-particles
- Debye screening
- Landau damping
- Collisional width
Quasi-particles

- Dispersion curves of particles in the plasma:

  \[ \omega \]

  \[ \omega \]

  \[ m_q \]

  \[ m_g \]

  quarks

  gluons

  \[ (+) \]

  \[ (-) \]

  \[ (T) \]

  \[ (L) \]

- Thermal masses due to interactions with the other particles in the plasma:

  \[ m_q \sim m_g \sim gT \]

- One needs a non-zero energy to make a particle of the plasma move.
Debye screening

- A test charge polarizes the particles of the plasma in its vicinity, in order to screen its charge:

\[ V(r) = \exp\left( -\frac{m_{\text{debye}}}{r} \right) \]

- The Coulomb potential of the test charge decreases exponentially at large distance. The effective interaction range is:

\[ \ell \sim \frac{1}{m_{\text{debye}}} \sim \frac{1}{gT} \]

- Note: static magnetic fields are not screened by this mechanism (they are screened over length-scales \( \ell_{\text{mag}} \sim \frac{1}{g^2T} \))
Landau damping

- A wave propagating through the plasma is damped because its quanta may be absorbed by particles of the plasma:

\[ \omega_c \sim gT \]
Collisional width

**Decay width:**

\[
\Gamma_{\text{decay}} = \frac{1}{\bar{\Gamma}_{\text{coll}}} = g^4 T
\]

**Collisional width:**

\[
\Gamma_{\text{coll}} = \frac{1}{\bar{\lambda}} = g^4 T^3 \int \frac{d^2 \vec{p}_\perp}{p_\perp^4} \sim g^2 T
\]

\[\lambda \equiv \frac{1}{\Gamma_{\text{coll}}} \text{ is the mean free path between two small angle scatterings (} \theta \sim g\)\]

\[\text{Note: the mean free path between two large angle scatterings (} \theta \sim 1\) is } \sim \frac{1}{g^4 T}\]
Length scales

- $1/T$: wavelength of particles in the plasma
- $1/gT$: typical distance for collective phenomena
  - Thermal masses of quasi-particles
  - Screening phenomena
  - Damping of waves
- $1/g^2T$: distance between two small angle scatterings
  - Color transport
  - Photon emission
- $1/g^4T$: distance between two large angle scatterings
  - Momentum, electric charge transport

In the weak coupling limit ($g \ll 1$), there is a clear hierarchy between these scales

Distinct effective theories according to the characteristic scale of the problem under study
Length scales

$1/gT$

$1/g^2T$

$1/g^4T$
The hydrodynamical regime is reached when one considers length scales that are much larger than the mean free path of the plasma constituents: $\lambda \ll R$.

In order to describe the system at such scales, one needs:

- Hydrodynamical equations (Euler, Navier-Stokes)
- Conservation equations for the various currents
- Equation of state, viscosity
In the real world, $\alpha_s \sim 0.2-0.3$ (i.e. $g \sim 2$). No clear hierarchy between the various length scales...

Lattice QCD:
very difficult to extract transport coefficients

Alternate approach: AdS/CFT correspondence

- Maldacena conjecture:
The strong coupling regime of a super-symmetric Yang-Mills theory (very complicated...) is equivalent to the weak coupling regime of a theory of super-gravity (calculable)

- Viscosity of a plasma in the super-YM theory:

\[ \frac{\eta}{s} = \frac{1}{4\pi} \]

- Major problem: Super-symmetric QCD $\neq$ QCD...
In non-central collisions, pressure turns a spatial anisotropy into an anisotropy of the momenta.

**Observable:** $2^{\text{nd}}$ harmonic of the azimuthal distribution

$$dN/d\varphi \sim 1 + 2v_1 \cos(\varphi) + 2v_2 \cos(2\varphi) + \cdots$$

**Note:** a large $v_2$ implies a strong transverse pressure, but says very little on the longitudinal degrees of freedom. It does not imply a tri-dimensional thermalization...
Strangeness enhancement

- In a nucleon, the distribution of strange quarks is smaller than that of $u, d$ quarks (valence) by a factor of the order of $\alpha_s \sim 0.2-0.3$
  - In $pp$ collisions, less strange particles are produced than non-strange particles

- In the QGP, the average energy of $u, d$ quarks and of the gluons is of the order of the temperature
  - if $T$ is large enough (compared to the mass of the strange quark), then the processes $u\bar{u}\rightarrow s\bar{s}$, $d\bar{d}\rightarrow s\bar{s}$, $gg\rightarrow s\bar{s}$ are not inhibited by the kinematical threshold due to the mass of the $s$ quark

- In this case, the population of strange quarks will become identical to that of light quarks
  - the production of strange hadrons will be enhanced compared to proton-proton collisions

- The interpretation of data based on statistical models works also for strange particles at RHIC
Statistical models

- One assumes that particles are produced by a thermalized system with temperature $T$ and baryon chemical potential $\mu_B$.

- The number of particles of mass $m$ per unit volume is:

$$\frac{dN}{d^3\mathbf{x}} = \int \frac{d^3\mathbf{p}}{(2\pi)^3} \frac{1}{e^{(\sqrt{p^2+m^2}-\mu_B Q)/T} \pm 1}$$

- These models reproduce the ratios of particle yields with only two parameters.

- The same models also work for $e^+e^-$ collisions:
  - Standard explanation: randomly filling a phase space leads to exponential distributions.
  - However, this argument alone does not explain why the value of $T$ that comes out is the same as in nucleus-nucleus collisions. Dynamical arguments (about the properties of the vacuum?) certainly play a role here...
Freeze-out parameters

\[
T_f \ [\text{MeV}] \quad \mu_B^f \ [\text{GeV}]
\]

\( \text{RHIC} \quad \text{SPS} \quad \text{AGS} \quad \text{LEP} \quad \text{SIS} \)

\[ \langle E \rangle / \langle N \rangle = 1 \ \text{GeV} \]
Debye screening prevents the $Q\bar{Q}$ pair from forming a bound state \cite{Matsui:1986dk}.

- each heavy quark pairs with a light quark in order to form a $D$ meson.

The inter-quark potential can be calculated using lattice QCD.

Possible observable: $[J/\psi] / [\text{Open charm}]$.

\[ \text{ complication: there is also a suppression in proton-nucleus collisions, due to multiple scattering} \]
J/Psi suppression

- The free energy of a $Q\bar{Q}$ pair can be calculated on the lattice, and then converted into a potential by taking into account the entropy:

$$F = U - TS, \quad S = -\frac{\partial F}{\partial T}$$

- Result for $T/T_c = 1.5$:
**J/Psi suppression**

- \( T \) dependence of the potential:

![Graph showing the dependence of \( U_1(r,T) \) on \( r \) and \( T \).](image)

- Data points for different temperatures: 1.95\( T_c \), 2.60\( T_c \), 4.50\( T_c \), 7.50\( T_c \).
J/Psi suppression

- What do we do with this potential?
  - Shröedinger equation for a $Q\bar{Q}$ bound state:
    \[
    \left[ 2m_Q + \frac{1}{m_Q} \vec{\nabla}^2 + U_1(r, T) \right] \Psi = M(T)\Psi
    \]
  - Non-relativistic
  - Assumes that there are only two-body interactions

- Dissociation temperatures:

<table>
<thead>
<tr>
<th>state $T_d/T_c$</th>
<th>$J/\psi$</th>
<th>$\chi_c$</th>
<th>$\psi'$</th>
<th>$\Upsilon$</th>
<th>$\chi_b$</th>
<th>$\Upsilon'$</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.0</td>
<td>1.1</td>
<td>1.1</td>
<td>4.5</td>
<td>2.0</td>
<td>2.0</td>
<td></td>
</tr>
</tbody>
</table>

- the $Q\bar{Q}$ states are not dissolved immediately above the critical temperature
... or enhancement?

- Many $Q\bar{Q}$ pairs may be produced in each $AA$ collision
  - Braun-Munzinger, Stachel (2000)
  - Thews, Schroedter, Rafelski (2001)
  - A $Q$ from one pair may recombine with a $\bar{Q}$ from another pair

- Avoids the conclusion of Matsui and Satz’s scenario, provided that the average distance between heavy quarks is smaller than the Debye screening length

- May lead to an enhancement of $J/\psi$ production
Coalescence models

- In proton-proton collisions, hadronization is described via fragmentation functions:

\[
\frac{dN_H}{d^3\vec{p}} = \sum_i \int_0^1 dz \ F_{i\rightarrow H}(z) \ \frac{dN_i}{d^3\vec{q}} \bigg|_{\vec{q}=\vec{p}/z}
\]

- \( F_{p\rightarrow H}(z) \) is the probability that a parton \( p \) gives the hadron \( H \) (accompanied by any other fragments), the hadron carrying the fraction \( z \) of the momentum of the parton.
- This formulation forbids that several partons combine into the same hadron.

- In an environment having a large parton density, hadronization can occur via the coalescence of several partons (Note: present models are very primitive, and take into account only the valence quark).

- These models can explain some differences between baryons and mesons observed in RHIC data.
Thermal photons

- Photons produced by the QGP:
  - Rate determined by physics at the scale $g^2 T$
  - Very sensitive to the temperature: $dN_\gamma/dt d^3 \vec{x} \sim T^4$
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  - Rate determined by physics at the scale $g^2 T$
  - Very sensitive to the temperature: $dN_\gamma/dt d^3 \vec{x} \sim T^4$

- But very important background...
  - initial photons
  - photons produced by in-medium jet fragmentation
  - photons produced by the hadron gas
  - meson decays
Thermal photons

Photon spectrum (arbitrary units)

- Initial photons
- Decays
- Thermal photons ($T_1$)
- Thermal photons ($T_2 = 2T_1$)

Energy (GeV)

Photon spectrum (arbitrary units)

- Initial photons
- Decays
- Thermal photons ($T_1$)
- Thermal photons ($T_2 = 2T_1$)

Energy (GeV)
Variant: thermal dileptons

- Look for virtual photons, in the channel $\ell^+\ell^-$
- Chose the invariant mass of the lepton pair in a region which is not too contaminated by resonance decays
- Note: if the invariant mass of the virtual photon is small, then the production mechanisms are the same as for the production of real photons
- Difficulty: the decay $\gamma^* \rightarrow \ell^+\ell^-$ brings another power of the electromagnetic coupling $\alpha_{em} \approx 1/137$ in the production rate $\triangleright$ problem of statistics
Jet quenching

- Jets are produced at the initial impact
  - Not very interesting by themselves...
Jet quenching

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  - Not very interesting by themselves...

- Radiative energy loss when they travel through the QGP
  - Sensitive to the energy density of the medium
  - Depends on the path length as $L^2$
  - Important modification of the azimuthal correlations
    (at RHIC, complete absorption of the opposite jet)
Jet quenching

- Photon-jet correlations:
  - At leading order, the photon and the jet have opposite $\vec{p}_\perp$'s.
  - The photon escapes without any energy loss, and gives a reference for the energy of the jet $\triangleright$ one can compare the properties of jet after going through the medium to those of a jet of the same $\vec{p}_\perp$ which has been produced in the vacuum.

- Complications due to higher order corrections:
  - Final state with photon + two jets
  - Photon produced by fragmentation of a quark $\triangleright$ in both cases, the momentum of the photon is not directly related to the initial momentum of a jet.
CGC
Where does the CGC stand?

- describes the content of nucleons and nuclei at small $x$
- framework to calculate the production of semi-hard particles
- provides initial conditions for the subsequent evolution
Nucleon at rest

- Very complicated non-perturbative object...
- Contains fluctuations at all space-time scales smaller than its own size
- Only the fluctuations that are longer lived than the external probe participate in the interaction process
- The only role of short lived fluctuations is to renormalize the masses and couplings
- Interactions are very complicated if the constituents of the nucleon have a non trivial dynamics over time-scales comparable to those of the probe
Nucleon at high energy

- **Dilation** of all internal time-scales of the nucleon
- Interactions among constituents now take place over time-scales that are longer than the characteristic time-scale of the probe
  - the constituents behave as if they were free
- Many fluctuations live long enough to be seen by the probe. The nucleon appears **denser at high energy** (it contains more gluons)
- Pre-existing fluctuations are totally frozen over the time-scale of the probe, and act as static sources of new partons
Parton model

- At the time of the interaction, the nucleon can be seen as a collection of free constituents, called partons.
- The nucleon content is described by parton distributions, that depend on the momentum fraction $x$ of the parton.
- One needs only to calculate the cross-section between the probe and the partons. If the parton density is low, only one parton interacts.
- One can separate the hard diffusion, perturbative, from the non-perturbative parton distributions, because the strong interactions responsible for these non-perturbative effects act on much longer time-scales ("factorization").
- Note: parton distributions also depend on a "transverse resolution scale", $Q$:

\[
Q^{-1}
\]
Saturation

at low energy, only valence quarks are present in the hadron wave function
Saturation

- when energy increases, new partons are emitted
- the emission probability is $\alpha_s \int \frac{dx}{x} \sim \alpha_s \ln\left(\frac{1}{x}\right)$, with $x$ the longitudinal momentum fraction of the gluon
- at small-$x$ (i.e. high energy), these logs need to be resummed
as long as the density of constituents remains small, the evolution is **linear**: the number of partons produced at a given step is proportional to the number of partons at the previous step (BFKL)
eventually, the partons start overlapping in phase-space
Saturation

▷ parton recombination becomes favorable

▷ after this point, the evolution is non-linear:
the number of partons created at a given step depends non-linearly
on the number of partons present previously
Saturation criterion

**Gribov, Levin, Ryskin (1983)**

- Number of gluons per unit area:
  \[ \rho \sim \frac{x G(x, Q^2)}{\pi R^2} \]

- Recombination cross-section:
  \[ \sigma_{gg\rightarrow g} \sim \frac{\alpha_s}{Q^2} \]

- Recombination happens if \( \rho \sigma_{gg\rightarrow g} \gtrsim 1 \), i.e. \( Q^2 \lesssim Q_s^2 \), with:
  \[ Q_s^2 \sim \frac{\alpha_s x G(x, Q_s^2)}{\pi R^2} \]

- At saturation, the phase-space density is:
  \[ \frac{dN_g}{d^2 \vec{x}_\perp d^2 \vec{p}_\perp} \sim \frac{\rho}{Q^2} \sim \frac{1}{\alpha_s} \]
Saturation domain

Boundary defined by $Q^2 = Q_s^2(x)$
Degrees of freedom

McLerran, Venugopalan (1994)
Iancu, Leonidov, McLerran (2001)

- Small $x$ modes have a large occupation number
  - they can be described by a classical color field $A^\mu$

- Large $x$ modes, slowed down by time dilation, are described as static color sources $\rho$

- The classical field obeys Yang-Mills equations:
  \[
  D_\nu F^{\nu\mu} = J^\mu = \delta^\mu + \delta(x^-) \rho(\vec{x}_\perp)
  \]

- The color sources $\rho$ are random, and described by a statistical distribution $W_{x_0}[\rho]$, where $x_0$ is the separation between “small $x$” and “large $x$”

- An evolution equation (JIMWLK) controls the changes of $W_{x_0}[\rho]$ with $x_0$ (generalizes BFKL to the saturated regime)
A brief lesson of semantics...

McLerran (mid 2000)

- **Color**: more or less obvious...

- **Glass**: the system has degrees of freedom whose time-scale is much larger than the typical time-scales for interaction processes. Moreover, these degrees of freedom are stochastic variables, like in “spin glasses” for instance.

- **Condensate**: the soft degrees of freedom are as densely packed as they can (the density remains finite, of order $\alpha_s^{-1}$, due to repulsive interactions between gluons).
McLerran-Venugopalan model

- The JIMWLK equation must be completed by an initial condition, given at some $x_0$
- As with DGLAP, the initial condition is in general non-perturbative
- The McLerran-Venugopalan model is often used as an initial condition at moderate $x_0$ for a large nucleus:
  - partons are randomly distributed
  - many partons in each “tube”
  - absence of correlations at different $x_\perp$
- The MV model assumes that the density of color charges $\rho(x_\perp)$ has a gaussian distribution:
\[
W_{x_0}[\rho] = \exp \left[ - \int d^2 x_\perp \frac{\rho(x_\perp) \rho(x_\perp)}{2\mu^2(x_\perp)} \right]
\]
Correlation length

- In a nucleon at low energy, the typical correlation length among color charges is of the order of the nucleon size, i.e. $\Lambda_{QCD}^{-1} \sim 1 \text{ fm}$. Indeed, at low energy, color screening is due to confinement, controlled by the non-perturbative scale $\Lambda_{QCD}$.

- At high energy (small $x$), partons are much more densely packed, and it can be shown that color neutralization occurs in fact over distances of the order of $Q_s^{-1} \ll \Lambda_{QCD}^{-1}$.

- This implies that all hadrons, and nuclei, behave in the same way at high energy. In this sense, the small $x$ regime described by the CGC is universal.
Leading twist shadowing

- Interactions between the partons of the target:

  - At small $x$, the wave function of a parton “spreads” outside of the nucleon it belongs to, so that it can interact with partons from other nucleons. This implies:
    
    $$x G_{\text{noyau}}(x, Q^2) \prec A x G_{\text{nucleon}}(x, Q^2)$$

  - At small $x$, one has a suppression of cross-sections:
    
    $$\frac{d\sigma_{pA}}{d^2 \vec{p}_\perp} \sim A^\alpha \quad \text{with} \quad \alpha < 1$$

  - Note: these interactions are the same as those involved in saturation
Multiple scatterings

- Because of the large parton density at small $x$ in the target, the external probe can interact several times:

- One of the scatterings “produces” the final state, and the others merely change its momentum (“higher twist” shadowing)

- Each additional scattering brings a correction $\alpha_s A^{1/3} \Lambda^2 / p^2_\perp$
  - important effect at small $p_\perp$, despite the $\alpha_s$ suppression

- At leading order, multiple scattering only affect the momentum distribution of the final particles, but not their total number. The suppression at small $p_\perp$ is compensated by an increase at larger $p_\perp$ (Cronin effect)
Multiple scatterings

- At high $p_{\perp}$, a single scattering dominates:

  - Standard result for a random walk in an external potential, when the potential does not decrease fast at large momentum ("intermittency")
  - Differential cross-sections scale like the atomic number $A$ at high $p_{\perp}$

- Note: the MV model describes correctly multiple scatterings, but does not contain any "leading twist" shadowing at small $x$
Deep Inelastic Scattering

In a frame in which the virtual photon has a large energy:

$$ q \left( 1 - z \right) q $$

The structure function $F_2$ can be expressed in terms of the "dipole" cross-section:

$$ F_2 \sim \sigma_{\gamma^* p}(x, Q^2) = \int_0^\infty r \, dr \int_0^1 dz \, |\psi(z, r, Q^2)|^2 \sigma_{\text{dipole}}(x, r) $$
Deep Inelastic Scattering

“Geometrical” scaling: \[ F_2(x, Q^2) = F_2(\tau \equiv Q^2/Q_s^2(x)) \]
Deep Inelastic Scattering
Nucleus-nucleus collisions

- The major problem is that the CGC only describes the very first instants after the collision ($\tau \lesssim 0.2 \text{ fm/c}$), while most of the observables undergo important modifications due to their interactions with the plasma.

- In fact, by definition, \textit{thermalization} (if it happens) implies that the system “forgets” all about the details of its initial state...

- Only inclusive quantities, like the multiplicity, have a chance of staying unchanged until the end.

- The dependence of the total multiplicity at RHIC on the center of mass energy $\sqrt{s}$ and on the centrality of the collision is correctly predicted by the CGC.

- Some hydrodynamical descriptions of the evolution of the system have successfully used “CGC inspired” initial conditions.
Proton-nucleus collisions

- The produced particles escape without having to go through an extended dense medium
  - the phenomena predicted in the CGC framework can be measured rather directly
- The proton is much less dense than the nucleus, and can be described with the standard structure functions:
- The matrix elements that enter in cross-sections are directly calculable in the CGC framework (they are known for a number of processes, like gluon or quark production)
- Note: contrary to DIS, one does not know exactly the momentum of the incoming parton
Results of the BRAHMS experiment at RHIC for deuteron-gold collisions:

\[ R_{dAu} \equiv \frac{1}{N_{coll}} \left. \frac{dN}{dp_{\perp} d\eta} \right|_{dAu} - \left. \frac{dN}{dp_{\perp} d\eta} \right|_{pp} \]

- At small rapidity, suppression at low \( p_{\perp} \) and enhancement at high \( p_{\perp} \) (multiple scatterings – Cronin effect)
- At large rapidity, suppression at all \( p_{\perp} \)'s (shadowing)