Gluon production in high-energy proton-nucleus and nucleus-nucleus collisions

Gabriele Parisi

Dipartimento di Fisica e Astronomia "Ettore Majorana"

UNIVERSITÀ degli STUDI di CATANIA

Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali del Sud

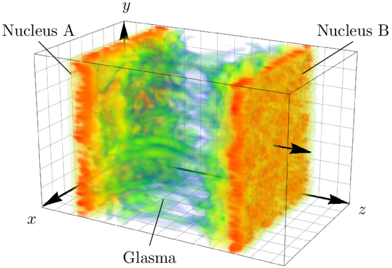
TNPI 2023

Collaborators: Marco Ruggieri, Vincenzo Greco

At energies as high as the ones reached in LHC, an Heavy Ion Collision occurs among *dense gluon distributions*.

↓

Emergence of a *saturation scale*: **Glasma** (*M. Ruggieri's talk*).



D. Muller (2019)

Glasma

Effective theory for high energy collisions

- High gluon densities $\implies$ Classical dynamics, **Yang Mills equations**:

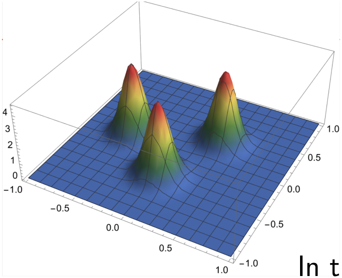
$$\mathcal{D}_\mu F^{\mu\nu} = 0$$

- Static sources due to time dilation $\implies$ **MV initial conditions** (McLerran and Venugopalan, 1996):

$$\langle \rho^a(\mathbf{x}_T) \rangle = 0,$$

$$\langle \rho^a(\mathbf{x}_T)\rho^b(\mathbf{y}_T) \rangle = (g\mu)^2 \delta^{ab}\delta^{(2)}(\mathbf{x}_T - \mathbf{y}_T),$$

where μ is the *MV parameter* (it can be $\mathbf{x}_T$-dependent).



In the pA case:
we sample the three hotspots $\bar{\mathbf{x}}_T^i$,
then

$$\mu(\mathbf{x}_T) \propto \frac{1}{3}\sum_{i=1}^{3}\frac{1}{2\pi B_q}\exp\left[-\frac{(\mathbf{x}_T-\bar{\mathbf{x}}_T^i)^2}{2B_q}\right]$$

Lattice Calculations

At $\tau = 0$, the Yang Mills equations in the covariant gauge and in light-cone coordinates reduce to:

$$-\Delta_T A_a^+(\mathbf{x}_T) = \rho_a(\mathbf{x}_T).$$

Calculations carried out in the gauge-invariant formalism of lattice gauge theory.

- Gauge links:

$$V^{\dagger}(\mathbf{x}_T, x^-) = \mathcal{P} \exp\left[-ig \int_{-\infty}^{x^-} dz^- A^+(z^-, \mathbf{x}_T)\right]$$

- Wilson Lines:

$$U_{\mathbf{x}_T, i} = V(\mathbf{x}_T) V^{\dagger}(\mathbf{x}_T + \Delta x_i)$$

- Plaquettes:

$$U_{x,\mu\nu} = U_{x,\mu} U_{x+\mu,\nu} U_{x+\mu+\nu,-\mu} U_{x+\nu,\nu}$$

In this formalism the evolution of the electric fields and of the plaquettes is then performed with a *leap-frog algorithm*.

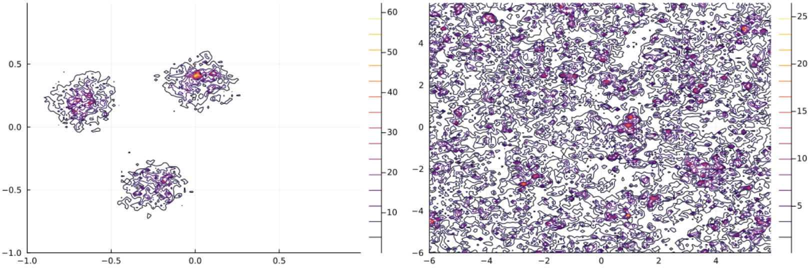
$$E^i(\tau+\Delta\tau) = E^i(\tau-\Delta\tau) + 2\Delta\tau\frac{i}{2g\tau}[U_{\eta i}(x) + U_{-\eta i}(x) - h.c.]_\tau +$$
$$+2\Delta\tau\frac{i\tau}{2g}\sum_{j\neq i}[U_{ji}(x) + U_{-ji}(x) - h.c.]_\tau$$

$$E^\eta(\tau+\Delta\tau) = E^\eta(\tau-\Delta\tau)+2\Delta\tau\frac{i}{2g\tau}\sum_{j=x,y}[U_{j\eta}(x)+U_{-j\eta}(x)-h.c.]_\tau$$

$$U_i(\tau + 2\Delta\tau) = \exp\left[-2ig\Delta\tau \cdot \frac{E^i(\tau + \Delta\tau)}{\tau + \Delta\tau}\right] U_i(\tau)$$

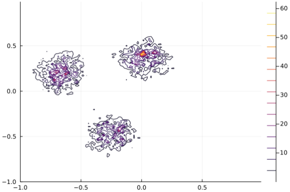
$$U_\eta(\tau + 2\Delta\tau) = \exp\left[-2ig\Delta\tau \cdot (\tau + \Delta\tau) \cdot E^\eta(\tau + \Delta\tau)\right] U_\eta(\tau)$$

Energy density (in GeV^4) vs transverse plane (in fm) at $\tau = 0^+$.

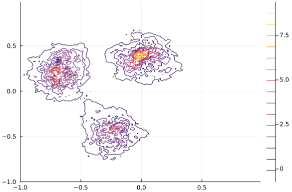


pA AA

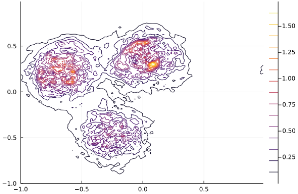
Energy density evolution



$\tau = 0.002$ fm



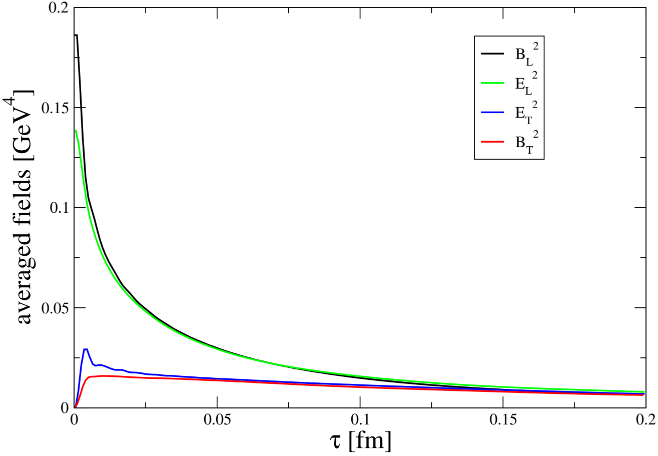
$\tau = 0.05$ fm



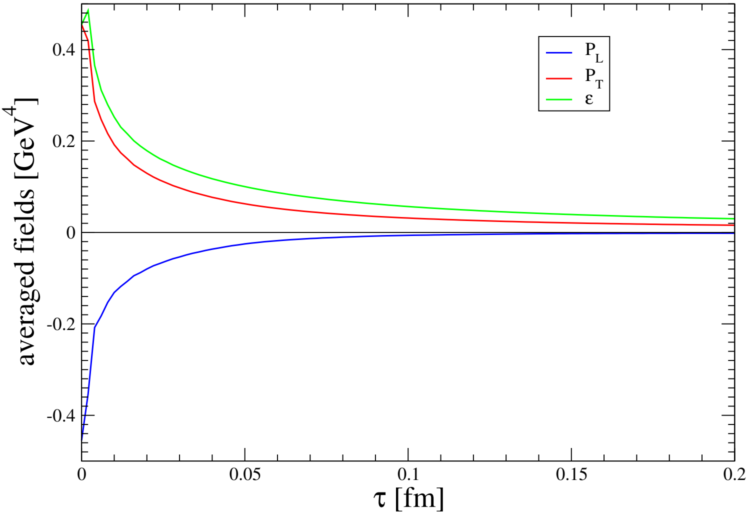
$\tau = 0.15$ fm

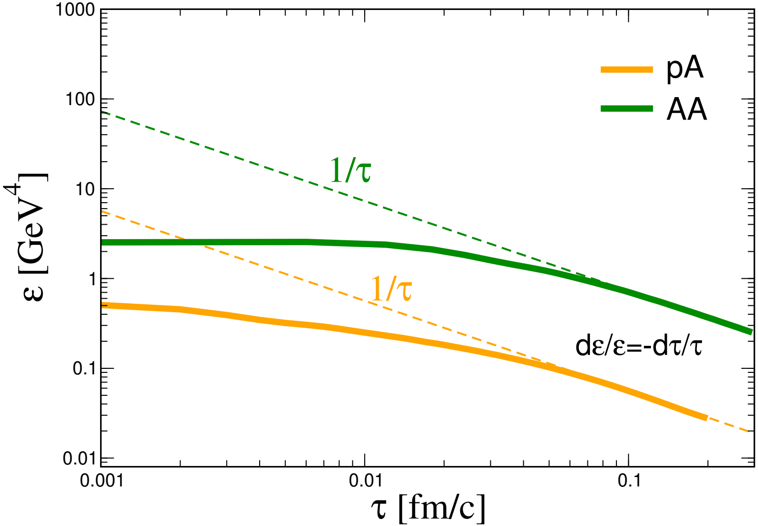
pA fields

$$\varepsilon = \mathrm{Tr}[E_L^2 + E_T^2 + B_L^2 + B_T^2]$$

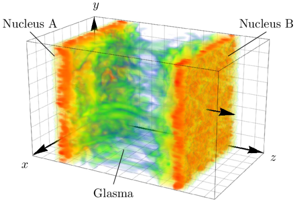


pA fields

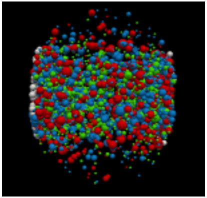



1000
100
10
1
0.1
0.01
0.001
0.01
0.1
ε [GeV^4]
τ [fm/c]
pA
AA
1/τ
1/τ
dε/ε=-dτ/τ

The previous graphs show that right after $\tau \sim 0.1$ fm we can employ a description in terms of "particles", of which we can evaluate the spectrum.



$\Longleftrightarrow$



D. Muller (2019)

MADAI collaboration

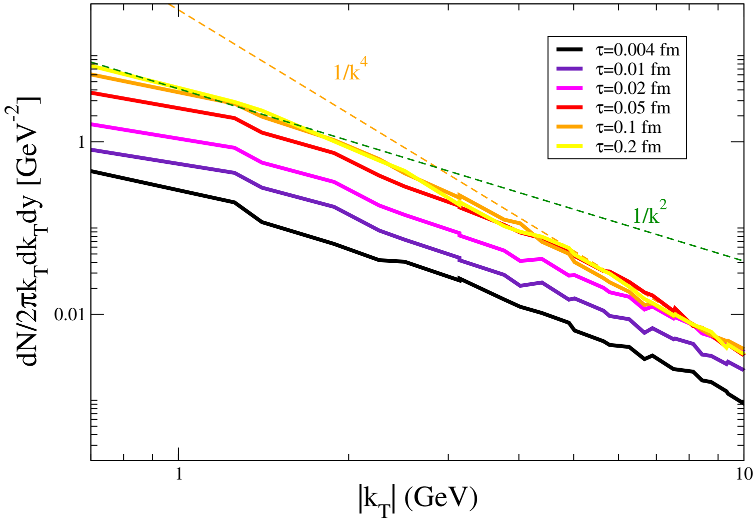
- A calculation of the gluon spectrum in this framework can be suitably used as a initial condition in a relativistic transport approach.
- We have just seen that our system is both out-of-equilibrium and anisotropic, therefore this could be an improvement with respect to previous approaches based on Hydro (e.g. IP-Glasma).

$$\int d^2\mathbf{x}_T\,\varepsilon = \int d^2\mathbf{x}_T\,\mathrm{Tr}[E_L^2+E_T^2+B_L^2+B_T^2] = \int \frac{d^2\mathbf{k}_T}{(2\pi)^2}\omega(\mathbf{k}_T)\frac{dN}{d^2\mathbf{k}_T},$$

with $\omega(\mathbf{k}_T) = |\mathbf{k}_T|$, namely a massless dispersion relation.
Therefore:

$$\frac{dN}{d^2\mathbf{k}_T} = \frac{2}{|\mathbf{k}_T|}\mathrm{Tr}[E_L(\mathbf{k}_T)E_L(-\mathbf{k}_T) + E_T(\mathbf{k}_T)E_T(-\mathbf{k}_T)]$$

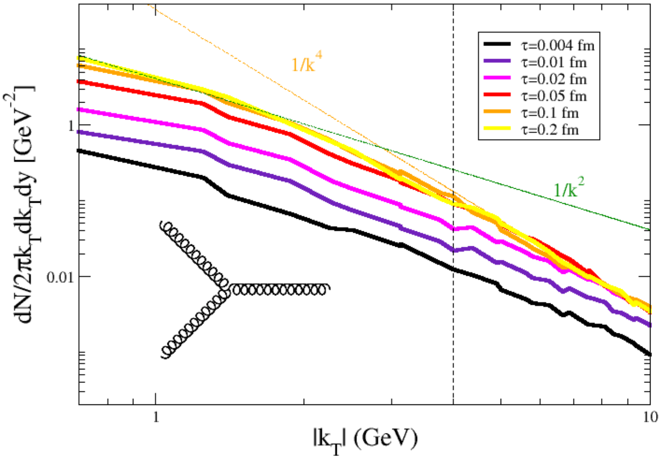
pA spectrum



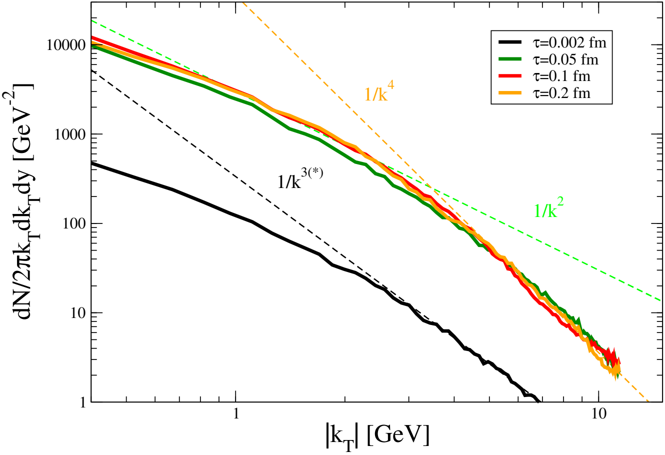
τ=0.004 fm
τ=0.01 fm
τ=0.02 fm
τ=0.05 fm
τ=0.1 fm
τ=0.2 fm
1/k^4
1/k^2
1
0.01
1
10
|k_T| (GeV)
dN/2πk_Tdk_Tdy [GeV^-2]

pA spectrum

For $|\mathbf{k}_T| \lesssim Q_s$ we see the effect of *recombination*!



AA spectrum



(*)K. Fukushima and F. Gelis, 2011

Summary

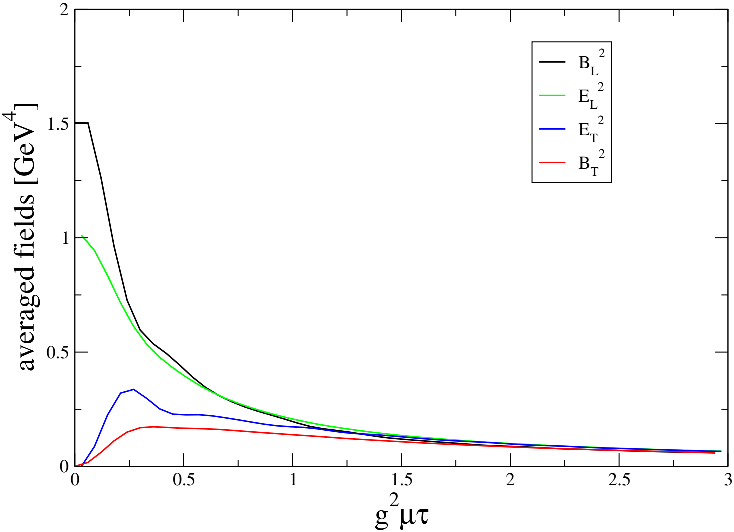
- The system is non-isotropic, since $P_L \neq P_T$.
- It has been shown a particle-like behaviour for $\tau \gtrsim 1/Q_s$
- The gluonic spectra, for both the pA and the AA case, show qualitative similarities.
- These spectra are manifestly *non-thermal*, since they exhibit a power-law behaviour instead of a exponential decay: physics of out of equilibrium, anisotropic systems.

Outlook

- This work paves the way to an improvement of the well-known IP-Glasma+Hydro.
- Every physical quantity in the early stage, e.g. the photon spectrum or the v_2, can be computed in this framework.
- Such formalism allows for the search of *attractors* in the initial stage (*V. Nugara's talk*).
- Gluons in the early stage can induce significant modifications to observables e.g. hadron multiplicities: more study needed.

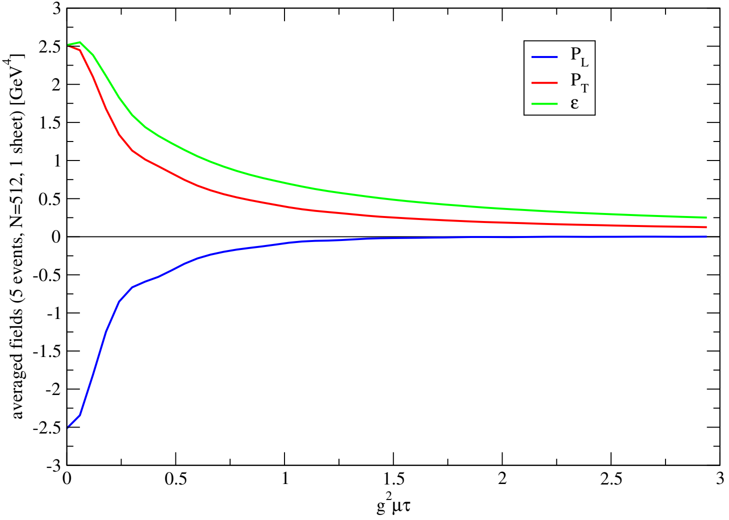
Thanks for your attention!

AA fields



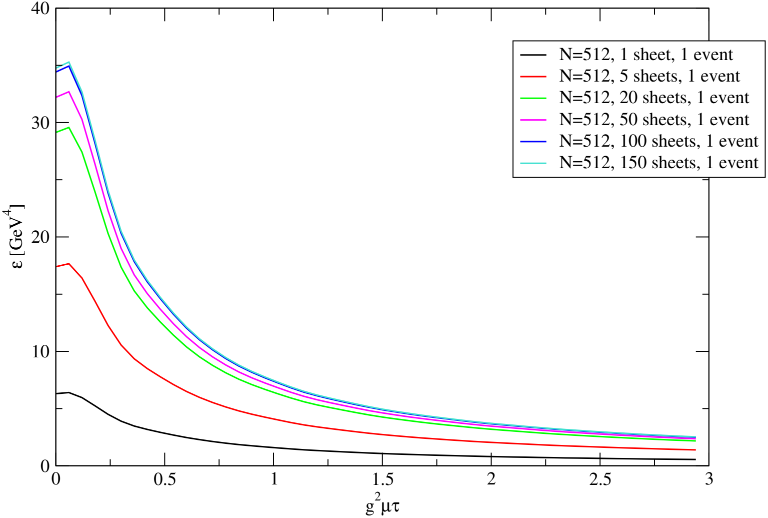
2
1.5
1
0.5
0
0
0.5
1
1.5
2
2.5
3
averaged fields [GeV^4]
g^2μτ
B_L^2
E_L^2
E_T^2
B_T^2

AA fields



averaged fields (5 events, N=512, 1 sheet) [GeV^4]
$g^2\mu\tau$
P_L
P_T
ε
3
2.5
2
1.5
1
0.5
0
-0.5
-1
-1.5
-2
-2.5
-3
0
0.5
1
1.5
2
2.5
3

AA sheet dependence



JIMWLK evolution