Probing QCD at High Energy:

predictions for single hadron production at LHC

Jamal Jalilian-Marian
Baruch College

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Radiated gluons have the same size \(1/Q^2\) - the number of partons increase due to the increased longitudinal phase space: nucleus becomes a dense system of gluons.

QCD in the strong color field limit novel universal properties of theory.
A New Paradigm of QCD: CGC

Saturation: dense system of gluons (all twist)

Extended scaling: dilute system - anomalous dimension

Double Log: BFKL meets DGLAP

DGLAP: collinearly factorized pQCD
**pA as a probe of high energy QCD**

- Multiplicities (dominated by $p_t < Q_s$):
  - energy, rapidity, centrality dependence

- Single particle production: hadron, photon, dilepton
  - rapidity, $p_t$, centrality dependence

- ★ Fixed $p_t$: vary rapidity (evolution in $x$)

- ★ Fixed rapidity: vary $p_t$ (transition from dense to dilute)
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**Average $P_t$**
Classical (multiple elastic scattering):

\[ p_t \gg Q_s : \text{enhancement (Cronin effect)} \]

\[ R_{pA} = 1 + \left( \frac{Q_s^2}{p_t^2} \right) \log \frac{p_t^2}{\Lambda^2} + \ldots \]

\[ R_{pA} (p_t \sim Q_s) \sim \log A \]

position and height of enhancement are increasing with centrality

Evolution in x:

can show analytically the peak disappears as energy/rapidity grows

and levels off at \( R_{pA} \sim A^{-1/6} < 1 \)

These expectations are confirmed at RHIC
CGC vs. RHIC
**CGC vs. RHIC**

- **suppression**
- **enhancement**

**BRAHMS**
Single Hadron Production in pA

\[
\frac{d\sigma^{pA\rightarrow hX}}{dY \ d^2P_t \ d^2b} = \frac{1}{(2\pi)^2} \int_{x_F}^{1} dx \ \frac{x}{x_F}
\]

\[
\begin{cases}
    f_{q/p}(x, Q^2) \ N_F\left[\frac{x}{x_F} P_t, b, y\right] \ D_{h/q}\left(\frac{x_F}{x}, Q^2\right) \\
    f_{g/p}(x, Q^2) \ N_A\left[\frac{x}{x_F} P_t, b, y\right] \ D_{h/g}\left(\frac{x_F}{x}, Q^2\right)
\end{cases}
\]

\(N_F, N_A\) are dipoles in fundamental and adjoint representation and satisfy the JIMWLK evolution equation.

Baier, Mehtar-Tani, Schiff NPA764 (2006) 515
Models of Dipole Cross Section

\[
\mathcal{N}(r_t, Y) = 1 - e^{-\frac{1}{4} \left[ \frac{C_F}{N_c} r_t^2 Q_s^2 \right] \gamma(r_t, Y)}
\]

\[
\gamma(r_t, Y) = \gamma_s + \Delta\gamma(r_t, Y)
\]

\[
\Delta\gamma = (1 - \gamma_s) \frac{\log(1/r_t^2 Q_s^2)}{\lambda Y + \log(1/r_t^2 Q_s^2) + d\sqrt{Y}}
\]

Dumitru, Hayashigaki, Jalilian-Marian (DHJ), NPA 2006
Hadron production: rapidity and $p_t$ dependence

What we see is a transition from DGLAP to BFKL to CGC kinematics

Dumitru, Hayashigaki, Jalilian-Marian, NPA 2006
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- Different K factor at different rapidities
- Average $P_t$
- Average $p_t$ in total multiplicities
- Low $p_t$: frag. functions?
- Average $p_t$ with a cutoff $\langle p_t \rangle \equiv \frac{\int_{p_t_{\min}} d^2 p_t p_t \frac{d\sigma_{pA \rightarrow \pi^0(p_t,y_h)}}{d^2 p_t dy_h} \times}{\int_{p_t_{\min}} d^2 p_t \frac{d\sigma_{pA \rightarrow \pi^0(p_t,y_h)}}{d^2 p_t dy_h}}$
Pion production in pp at LHC

Neutral pion production invariant cross section in pp

\( p_t \)

\( y = 3 \)
\( y = 4 \)
\( y = 5 \)
\( y = 6 \)
\( y = 8 \)

arXiv:0704.2628
Neutral pion production invariant cross section in pA

- $y = 0$
- $y = 2$
- $y = 4$
- $y = 6$
- $y = 8$
Pion average $p_t$ in pp at LHC

$<p_t>$ in GeV ($\pi^0$, pp at LHC)

Rapidity

$<p_t>$ in GeV ($\pi^0$, pp at LHC)

Rapidity

$p_t^{\text{min}} = 1.25$ GeV
Pion average $p_t$ in pA at LHC

\[ <p_t> \text{ in GeV (π^0, min. bias pA at LHC)} \]

- $p_t^{\text{min}} = 1.25 \text{ GeV}$
- $p_t^{\text{min}} = 4 \text{ GeV}$
- $p_t^{\text{min}} = 10 \text{ GeV, no DGLAP}$
- $p_t^{\text{min}} = 10 \text{ GeV}$
Looking forward to LHC
Mid rapidity: anomalous dimension
Hadron production in dA collisions at RHIC

Particle production at forward rapidity is dominated by quark scattering. Both DGLAP and CGC are important.
Application to dA at RHIC

BRAHMS data / Theory

K = 1.6

dAu BRAHMS data: minimum bias, h^-, y = 3.2
Theory: dAu[CTEQ-LO + CGC + KKP-LO[(h^++h^-)/2]], minimum bias, y = 3.2
BK = B-JIMWLK (mean field + large $N_c$)

A closed form equation

$$\partial_Y \langle T_{xy} \rangle = \frac{\bar{\alpha}}{2\pi} \int d^2 z \frac{(x - y)^2}{(x - z)^2(z - y)^2} \left[ \langle T_{xz} \rangle + \langle T_{zy} \rangle - \langle T_{xy} \rangle - \langle T_{xz}\rangle\langle T_{zy} \rangle \right]$$

The simplest equation to include unitarity: $T < 1$

Exhibits extended (geometric) scaling

$$T(x, r_t) \rightarrow T[r_t Q_s(x)]$$

for

$$Q_s < Q < \frac{Q_s^2}{\Lambda_{QCD}}$$