The Energy Dependence of $q$ and Parton Saturation in QGP

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Introduction

Broadening of a probe in the medium

\[ \langle p_{out}^2 \rangle = \hat{q} L \]

Jet transport parameter:
\( \hat{q} = \text{mean transferred momentum squared per unit length} \)

Fundamental medium property

Controls the (radiative) energy loss:
\[ \Delta E = \frac{\alpha_s N_c}{4} \hat{q}_R L^2 \]

LHC allows to study jets in a large energy range

Does \( \hat{q} \) depend on Energy?
Transverse broadening of the probe:
⇒ scattering with thermal particles

\[ \hat{q}_R = \rho \int d\mu^2 \frac{d\sigma_R}{dq_T^2} q_T^2 \]

A closer look leads to

\[ \hat{q}_R = \frac{4\pi^2 C_R}{N_c^2 - 1} \rho \int_0^{\mu^2} \frac{d^2q_T}{(2\pi)^2} \int dx \delta(x - \frac{q_T}{2p^- <k^+>}) \alpha_s(q_T^2) \phi(x, q_T^2) \]

The value of x decreases with the probe energy!

If the gluon distribution is independent of x

\[ \hat{q}_R \approx \frac{4\pi^2 C_R}{N_c^2 - 1} \rho \alpha_s(\mu^2) x G(x, \mu^2) \]

Gluon distribution per scattering center

Unintegrated gluon distribution function
Evolution

High Energy Jets

⇒ $x$ is small

Large momentum transfer

⇒ large scales $\mu^2$

The gluon distribution function grows = Evolution

Since both $x^{-1}$ and the scale are large

⇒ Evolution via the Double Logarithmic Approximation (DLA)

For scales $\mu >> \mu_D$ the medium effects on the evolution are small

⇒ We use vacuum DLA evolution

Initial condition for evolution deduced from HTL.
Saturation

Multiple coherent scattering  \[ \Rightarrow \text{saturation} \]

Maximum length for interference

\[ L_c = \frac{1}{q^+} = \frac{1}{xT} \approx \frac{6ET}{Q_s^2} \frac{1}{T} \]

Saturation scale is determined by:

\[ Q_s^2(x) = \frac{4\pi^2 N_c \alpha_s (Q_s^2)}{N_c^2 - 1} \rho x G(x, Q_s^2) \min(L, L_c) \]

The QGP density is much larger than nuclear density

Saturation sets at larger \( x \)

The saturation scale is larger

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Coherence Length

\( L_c \) is comparable to typical path length

\[ L_c = 5 \text{ fm} \quad \text{for } E=300 \text{ GeV and } T=0.6 \text{ GeV} \]

The effect of \( \Lambda_{\text{QCD}} \) leads to non trivial scale dependence
Saturation: Length Dependence

$Q_s$ grows with path length. Coherence length stops the growth.

The abrupt change for $L=L_c$ is a consequence of simplified treatment.

Evolutions leads to $Q_s^2 \sim L^p$, $p \approx 0.7$ (from numerics) slower than linear!
We obtain large values for the saturation scale (large density)

Significant energy dependence:

For $L > L_c$ fast grow \[ Q_s^2 \sim \frac{ET}{Q_s^2T} \Rightarrow Q_s^2 \sim \sqrt{E} \]
\( \hat{q} \) from the Thermal Gluon Distribution

Simplified treatment of the unintegrated gluon distribution

Constant for \( Q^2 < Q^2_s \)

Linear evolution for \( Q^2 > Q^2_s \)

We find

\[
\hat{q}_R = \frac{C_R}{N_c \min(L, L_c)} \frac{Q_s^2}{\ln \frac{1}{x_m} \ln \frac{Q_s^2(x_m)}{\Lambda^2}} \times \\
\left[ \sqrt{\pi \frac{b}{N_c}} \ln \frac{1}{x_m} \ln \left( \ln \frac{Q_s^2}{\Lambda^2} / \ln \frac{\mu^2}{\Lambda^2} \right) \right] + \ln \left( \ln \frac{Q_s^2}{\Lambda^2} / \ln \frac{\mu^2}{\Lambda^2} \right) \frac{1}{\ln(Q_s^2(x_m)/\Lambda^2)}
\]

The transport coefficient is determined by the saturation scale (as expected)
Evolution leads to energy dependence
Non trivial length dependence

Apparent divergence of $\hat{q}$ is due to $Q_s^2 \sim L^p$, $p \approx 0.7$ (from numerics)
Jet Acoplanarity

Look for $\gamma + \text{jet}$ events

$\gamma$ gives the initial direction

The back-jet broadens in its propagation

The jet acoplanarity is sensitive to the transferred momentum

Since $\gamma$ does not lose energy, the typical length is the average length

Cross check for the jet energy loss since it depends on the broadening
Large Vacuum Acoplanarity

Acoplanarity in p+p

\[ p_{out} = p_T^{max} \sin(\Delta \theta) \]

\[ \langle p_{out} \rangle = \sqrt{\frac{Q_s^2}{4\pi}} \approx \sqrt{\frac{35 \text{ GeV}^2}{4\pi}} \approx 1.3 \text{ GeV} \]

Thanks to: I. Dominguez Jimenez, G. Paic


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Conclusions

Ø $\hat{q}$ is determined from the unintegrated gluon distributions

  High energy jets probe the small x region

Ø The growth of the gluon distribution leads to saturation (in the plasma)

  Large densities lead to large $Q_s$

Ø $q$ depends on the saturation scale (as expected)

  Rapidity dependent $Q_s$ leads to energy dependent $\hat{q}$

Ø The energy and length dependence of $\hat{q}$ is significant in the kinematic range of LHC jets.
Back up
Large Vacuum Acoplanarity

Initial state radiation $\Rightarrow$ Large vacuum acoplanarity

(estimated via LO-PQCD: Davis, Webber and Stirling, 85)

\[
\langle p_{out}^2 \rangle_{vac} \approx 400 GeV^2
\]

Medium effect

$\Rightarrow$ gaussian broadening

\[
\langle p_{out}^2 \rangle_{me} \approx 35 GeV^2
\]

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Broadening of Thermal Particles

For thermal particles, $\hat{q}$ is computed via HTL

\[
\hat{q}_R = \frac{4\pi^2\alpha_s C_R}{N_c^2 - 1}\rho \int dx\frac{dq_T^2}{(2\pi)^2}\delta(x - \frac{q_T^2}{2p-\langle k^+ \rangle})2N_c\alpha_s \frac{\pi^2}{6\zeta(3)}q_T^2|\mathcal{M}_{Rb}|^2
\]

With the HTL propagator:

\[
\mathcal{M}_{Rb} \approx \left[\frac{1}{q^2 + \mu_D^2 \pi_L(x_q)} - \frac{(1 - x_q^2) \cos \phi}{q^2(1 - x_q^2) + \mu_D^2 \pi_T(x_q) + \mu_{mag}^2}\right] \quad x_q = \frac{\omega}{q} \approx \frac{3xT}{q_T}
\]

For a maximum momentum transfer of order $T$

\[
xG(x, \mu) = \int_{\mu} d^2q_T(2\pi)^2\phi(x, q_T^2)
\]

\[
xG(x, \mu^2) \approx C_A \frac{\alpha_s}{\pi} \frac{\pi^2}{6\zeta(3)} \frac{1}{2} \left[\frac{3}{2} \ln \frac{\mu^2}{\mu_D^2} + \frac{1}{3} \ln \frac{\mu_D}{xT}\right]
\]

We use this as initial condition at $\mu=T$