Energy Dependence of the Jet Quenching Parameter $\hat{q}$

Jorge Casalderrey-Solana
Xin-Nian Wang
LBNL
Introduction

Transverse broadening of the probe:
⇒ scattering with thermal particles

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

A closer look leads to

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

The value of $x$ decreases with the probe energy!

If the gluon distribution is independent of $x$

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

Unintegrated gluon distribution function

Gluon distribution per scattering center
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 $\mu \gg \mu_D$ the medium effects on the evolution are small
⇒ We use vacuum DLA evolution
Initial Conditions

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

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

With the HTL propagator:

$$M_{Rb} \approx \left[ \frac{1}{q^2 + \mu_D^2 \pi_L(x_q)} - \frac{(1 - x_q^2) \cos \phi}{q^2(1 - x_q^2) + \mu_D^2 \pi_T(x_q) + \mu_{\text{mag}}^2} \right]$$

$$x_q = \frac{\omega}{q} \approx \frac{3xT}{q_T}$$

For a maximum momentum transfer of order $T$

$$xG(x, \mu) = \int_\mu^\infty \frac{d^2 q_T}{(2\pi)^2} \phi(x, q_T^2)$$

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

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

HIC at LHC

Jorge Casalderrey-Solana
Saturation in QGP

The growth of the gluon distribution is tamed by saturation effects

The saturation scale is estimated from the linearized evolution

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

The QGP density is much larger than the nuclear density

Saturation sets at larger \( x \)

The saturation scale is larger

Large \( Q_s^2 \Rightarrow \) the coherence length becomes smaller than in the nucleus

\[ L_c = \frac{1}{xT} \approx \frac{6ET}{Q_s^2} \frac{1}{T} \]
The coherence length, $L_c$, is comparable to typical path lengths:

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

The effect of $\Lambda_{QCD}$ leads to nontrivial scale dependence.
\( \hat{q} \) from the Thermal Gluon Distribution

Simplified treatment of the unintegrated gluon distribution

Linear evolution from initial condition for \( Q^2 > Q^2_s \)

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

\[ \phi(x, Q^2) = \phi(x, Q^2_s) \]

The integration of \( \phi \) over the \( x = q^2 T/Q^2_{\text{max}} \) is approximated by

\[
\hat{q}_R = \frac{C_R}{N_c \min(L, L_c)} \frac{Q^2_s}{\ln \left( \frac{Q^2_s}{\Lambda^2} \right)} \times \left[ \frac{\delta_L}{\sqrt{\pi} \frac{b}{N_c} \ln \frac{1}{x_m} \ln \left( \frac{Q^2_s}{\Lambda^2} / \ln \frac{\mu^2}{\Lambda^2} \right)} + \frac{1}{\ln \left( \frac{\ln Q^2_s / \ln \frac{\mu^2}{\Lambda^2}}{\ln Q^2_s (x_m) / \Lambda^2} \right)} \right]^{Q^2_{\text{max}} = 6ET}
\]

The transport coefficient is determined by the saturation scale (as expected)
We obtain large values for the saturation scale (large density)

For $L > L_c$ fast grow

$$Q_s^2 \sim \frac{ET}{Q_s^2 T} \implies Q_s^2 \sim \sqrt{E}$$

Significant energy dependence of the transport parameter.
Evolution leads to a non-trivial length dependence
The abrupt change for $L=L_c$ is a consequence of simplified treatment
Apparent divergence of $\hat{q}$ is due to $Q_s^2 \sim L^p$, $p \approx 0.7$ (from numerics)
Direct Measurement of $\hat{q}$

Look for $\gamma +$ jet events

$\gamma$ gives the initial direction

The back-jet broadens in its propagation

The jet acoplanarity gives the transferred momentum

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

Cross check for the jet energy loss since it depends on the broadening
Conclusions

- $\hat{q}$ is determined from the unintegrated gluon distributions
  - High energy jets probe the small $x$ region
- The growth of the gluon distribution leads to saturation (in the plasma)
  - Large densities lead to large $Q_s$
- $q$ depends on the saturation scale (as expected)
  - Rapidity dependent $Q_s$ leads to energy dependent $\hat{q}$
- The energy and length dependence of $\hat{q}$ is significant in the kinematic range of LHC jets.
Back up