Jet fragmentation in heavy ion collisions

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* Work in progress, in collaboration with Sony Martins
Outline

- Motivation
- Baseline: hadron production in pp collisions
- Production of neutral and charged hadrons in heavy ion collisions - most central collisions
- Present some approaches for jet energy loss
- Fragmentation functions modified by the medium (quenching weights approach)
- Estimates of the nuclear modification factor $R_{AA}$
  - $\pi^0$ @ RHIC
  - $\pi^\pm$, $K^\pm$, $p$, $\bar{p}$: $h^\pm$ @ LHC
- Conclusions
Suppression of high $p_T$ jets is one of the signals of the formation of the Quark-Gluon Plasma (QGP) in heavy ion collisions.

Medium induced gluon radiation is claimed to be the dominant mechanism underlying the jet quenching phenomenon observed in heavy ion collisions.

In this contribution, we study the production of neutral and charged hadrons in ultrarelativistic heavy ion collisions - a scenario to test the properties of the hot and dense medium.

Consider some approaches to jet quenching and jet fragmentation.

Present estimates for the nuclear rates $R_{AA}$ at RHIC and LHC.

Infer some properties of the created quark gluon plasma - opacity, transport coefficient $\hat{q}$, etc.

Comment on how to include the hydrodynamic expansion of the QGP.
Hadron production in pp collisions

(LO) contributions: all $2 \rightarrow 2$ QCD processes: $ab \rightarrow cd, \ c \rightarrow h$

$$\frac{d\sigma_{pp\rightarrow h+X}}{dp_T^2dy} = J(m_T, y) \sum_{abcd} \int \frac{dz}{z^2} dy_2 x_a f_{a/p} (x_a, Q^2) x_b f_{b/p} (x_b, Q^2) \frac{d\hat{\sigma}}{d\hat{t}} \left(\frac{ab\rightarrow cd}{D_{h/c} (z, \mu_f^2)} \right)$$

- $f_{a,b/p}$: CTEQ6L parton distributions
- $x_{a,b} = \frac{q_T}{\sqrt{s}} \left(e^{\pm y_f} + e^{\pm y_2}\right)$, where $y_f$ and $y_2$ are the rapidity of the produced partons.
- $\frac{d\hat{\sigma}}{d\hat{t}}$: LO partonic cross sections (all $2 \rightarrow 2$ QCD processes)
- $D_{h/c}(z, \mu_f^2)$: KKP fragmentation functions

$z$: energy fraction of the parton carried by the hadron  

$$p_T = z q_T \quad \text{produced hadron } h \quad \text{fragmenting parton } c$$

$$J(m_T, y) = \left(1 - \frac{m^2}{m_T^2 \cosh^2 y}\right)^{1/2}, \ y = \sinh^{-1} \left(\frac{p_T}{m_T} \sinh y_f\right)$$
Production of charged particles @ LHC

\[ \pi^\pm, K^\pm, p \text{ and } \bar{p} \text{ produced in } pp \text{ collisions at } \sqrt{s} = 7 \text{ TeV} \]

In the plot, the invariant differential yield is well described with LO calculation, CTEQ6L parton distributions and KKP fragmentation functions.

The pp baseline calculation, to be compared with AA collisions.
Hadron production in heavy ion collisions

First estimates: obtain $\sigma_{AA}$ from $\sigma_{pp}$ and some minimal modifications:

$$
\frac{d\sigma_{AA \rightarrow h+X}}{dp_T dy} = J(m_T, y) \sum_{abcd} \int \frac{dz}{z^2} dy_2 x_a f_{a/A} (x_a, Q^2) x_b f_{b/A} (x_b, Q^2) \frac{d\hat{\sigma}}{dt}^{ab\rightarrow cd} D_{h/c} (z^*, \mu_f^2)
$$

$f_{a,b/A}$: parton distributions in the nuclei (EPS09, nDS, nCTEQ)

$D_{h/c}(z^*, \mu_f^2)$: fragmentation functions

jet (leading parton) produced in central region looses energy, $\Delta E$, in the medium $\rightarrow$ shift in the $z$ variable.

$q_T \rightarrow (q_T - \Delta E) \rightarrow p_T$

$$z^* = \frac{\Delta E}{q_T}$$

There are several models to consider the non-abelian energy loss of the jet propagating in the medium (quark gluon plasma)

$\rightarrow$ Here we consider a simplified form of some models
Parton energy loss in the medium (QGP)

- Non-Abelian energy loss in hot matter: Induced gluon radiation in the QGP
  - BDMPS (Baier, Dokshitzer, Mueller, Peigne, Schiff)
    - In thick plasmas, for a great number of jet scatterings, $L/\lambda \gg 1$
      \[
      \Delta E_{BDMPS} = \frac{C_R \alpha_s}{4} \frac{L^2 \mu^2}{\lambda_g} \bar{\nu}
      \]
    - $\lambda_g = (C_A/C_R)\lambda$: radiated gluon mean free path
  - Non-Abelian Energy Loss at Finite Opacity (Gyulassy, Leval, Vitev): reaction operator approach to opacity expansion
    - In thin plasmas, the mean number of jet scatterings, $\bar{n} = L/\lambda$, is small $\rightarrow$ opacity expansion
    - $\bar{n}$: measure of the opacity or geometrical thickness of the medium
    - Energy loss in first order in opacity:
      \[
      \Delta E_{GLV}^{(1)} \approx \frac{C_R \alpha_s}{4} \frac{L^2 \mu^2}{\lambda_g} \log \frac{E}{\mu}
      \]
    - $\mu$: screening scale from color Yukawa potential
    - QGP: $\lambda_g = 1 \text{fm}$, $\mu = 0.5 \text{GeV}$, $\alpha_s = 0.3$
Neutral $\pi$ production @ RHIC

$R_{AA} = \frac{d^2\sigma(AA)}{d\eta d^p_T} |_{|\eta| \leq 0.35} / \frac{A^2 d^2\sigma(pp)}{d\eta d^p_T} |_{|\eta| \leq 0.35}$

Energy loss models: fair description of RHIC $\pi^0$ data

estimates of the QGP opacity at RHIC:

- BDMPS: $L/\lambda = 2.9$
- GLV: $L/\lambda = 2.65$

Somewhat larger opacities have been previously reported, in different implementation of the same effects

(Levai, NPA 862 (2011) 146)
Charged hadron production @ LHC

\[
R_{AA} = \frac{\frac{d^2\sigma(AA)}{d\eta dp_T}|_{|\eta| \leq 0.8}}{\frac{A^2 d^2\sigma(pp)}{d\eta dp_T}|_{|\eta| \leq 0.8}}
\]

\[\AA \text{ collisions, } \sqrt{s} = 2.76 \text{ TeV} \]

- \(\pi^\pm, K^\pm, p, \bar{p}\)
- Energy loss models: fair description of higher-\(p_T\) LHC data
- Not expected to describe low \(p_T\) data
- Estimates of the QGP opacity at LHC:
  - BDMPS: \(L/\lambda = 3.8\)
  - GLV: \(L/\lambda = 3.25\)
  \(\Rightarrow\) larger than in RHIC
- Somewhat larger opacities have been previously reported, in different implementation of the same effects
  \((\text{Levai, NPA 862 (2011) 146})\)
Jet Energy Loss - Quenching Weights formalism

(Salgado, Wiedemann)

- Medium induced gluon radiation
- Produced parton loses with probability $P(\epsilon)$ an additional fraction of its energy, $\epsilon = \frac{\Delta E}{E_q}$
- $\Rightarrow$ Medium modified fragmentation function

$$D_{h/q}^{(med)}(z, Q^2) = \int_0^1 d\epsilon \frac{P(\epsilon)}{1-\epsilon} D_{h/q} \left( \frac{z}{1-\epsilon}, Q^2 \right)$$

Quenching weights (energy loss probabilities):

$$P(\Delta E) = p_0 \sum_{k=0}^{\infty} \frac{1}{k!} \int \left[ \prod_{i=1}^{k} d\omega_i \int_0^{\omega_i} dk_\perp \frac{dI^{med}(\omega_i)}{d\omega dk_\perp} \right] \delta \left( \sum_{j=1}^{k} \omega_j - \Delta E \right) = p_0 \delta(\Delta E) + p(\Delta E)$$

$p_0$: probability of no energy loss ($\neq 0$ for finite medium)

$\frac{dI^{med}}{d\omega dk_\perp}$: spectrum of medium-induced gluons (path integral approach to opacity expansion)

- $P(\Delta E)$ available in two approximations:
  - Multi soft scattering approximation
  - Single hard scattering approximation ($\approx$ GLV)
Quenching Weights - limiting cases

Multi soft scattering approximation:
- Partonic projectile performs a Brownian motion in transverse momentum (due to multi soft scatterings)
- \( \hat{q} \): transport coefficient, measures the scattering power of the medium (momentum broadening per unit length)
- Dimensionless parameter \( R = \omega_c L \leftarrow \) kinematic constraint restricting \( p_T \) of radiated gluons (BDMPS: \( R \to \infty \))
- \( \omega_c \): characteristic gluon frequency: set scale of energy-loss probability distribution

Single hard scattering approximation:
- Incoherent superposition of very few \( n_0 L \) single hard scattering processes in path length \( L \)
- Single scatterer: Yukawa potential with Debye screening mass \( \mu \)
- Kinematic constraint \( \bar{R} = \bar{\omega}_c L \)
Quenching Weights & model parameters

- **$L$:** medium length
- **$P(\Delta E)$** in two limiting cases:
  - **Multi soft scattering approximation:** $R = \hat{q}L^3/2$, $\omega_c = \hat{q}L^2/2$, $xx = \omega/\omega_c = \epsilon E_q L/R$
  - **Single hard scattering approximation:** $\bar{R} = \mu^2L^2/2$, $\bar{\omega}_c = \mu^2L/2$, $xx = \omega/\bar{\omega}_c = \epsilon E_q L/\bar{R}$

- $\mu^2$: Debye screening mass
- transport coefficient $\hat{q}$ for "static" medium: $\hat{q} = \frac{\langle q^2 \rangle_{med}}{\lambda}$
- ratio $R/\bar{R} = \frac{\hat{q}L^3}{\mu^2L^2} \frac{2}{\mu^2L^2} = \frac{\langle q^2 \rangle_{med}}{\lambda} \frac{L^2}{\mu^2} \approx \frac{L}{\lambda}$ ← a measure of the medium opacity
Quenching weights for an expanding medium

- Expansion in the multi soft scattering approximation: \( R = \hat{\varphi}L^3/2, \omega_c = \hat{\varphi}L^2/2 \)

- Transport coefficient \( \hat{\varphi} \)
  - for "static" medium: \( \hat{\varphi} = \frac{\langle q_\perp^2 \rangle_{med}}{\lambda} \)
  - for an expanding medium: assuming a scaling with the local energy density \( \varepsilon \)
    \[ \hat{\varphi} = 2K\varepsilon^{3/4}(\tau) \quad \Rightarrow \quad \hat{\varphi} = \hat{\varphi}_0 \left( \frac{\tau_0}{\tau} \right)^\alpha, \alpha \leq 3, \]
    \( (\alpha = 1: \text{longitudinal expansion}, 1 < \alpha \leq 3: \text{addit. transverse expansion}) \)

- Using a dynamical scaling law, \( \langle \hat{\varphi} \rangle \) and \( \bar{\omega}_c \) can be mapped onto an equivalent static scenario:
  \[
  \langle \hat{\varphi} \rangle = \frac{2}{L^2} \int_{\tau_0}^{L+\tau_0} d\tau (\tau - \tau_0) \hat{\varphi} \quad \bar{\omega}_c = \frac{\langle \hat{\varphi} \rangle L^2}{2}
  \]
  \[\Rightarrow\]  Using the rescaled kinematic constraint \( \langle R \rangle = \frac{1}{2} \langle \hat{\varphi} \rangle L^3 \), the dynamical QW agree with the static medium case

<table>
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<th>RHIC</th>
<th>LHC</th>
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<td>( L )</td>
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<td>7 fm</td>
</tr>
<tr>
<td>( \tau_0 )</td>
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<td>0.5 fm</td>
</tr>
<tr>
<td>( \hat{\varphi}_0 )</td>
<td>18.5 GeV²/fm</td>
<td>?</td>
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- There is an analogous dynamic scaling in the single hard scattering approximation
Neutral $\pi$ production @ RHIC

Preliminary results

Quenching weights: reasonable description of RHIC $\pi^0$ data for $\neq$ values of kinematic constraint $R$

- multi soft scattering approx: $R = 30000$
- single hard scattering approx: $R = 7000$

- different trend compared with previous energy loss approaches
- estimation of QGP opacity via ratio $L/\lambda \approx R/R = 4.3$
Charged hadron production @ LHC

Preliminary results

Quenching weights: reasonable description of higher $p_T$ LHC data for $\neq$ values of kinematic constraint $R$

- multi soft scattering approx: $R = 23000$
- single hard scattering approx: $R = 4500$

Not expected to describe low $p_T$ data. Hydro, Cronin effect, non-perturbative effects...?

- estimation of QGP opacity at LHC $L/\lambda \approx R/\bar{R} = 5.1 \leftarrow$ larger than in RHIC
- somewhat odd values for "best" $R$: smaller than in RHIC !?!?
- $\rightarrow$ still not reasonable to obtain the correct transport coefficient $\dot{q}$ ($\dot{q}_0$)
Conclusions and discussion

Assuming a certain model for energy loss, one may estimate some properties of the QGP, which reasonably describe RHIC and LHC heavy ion data on neutral and charged hadron production.

Model dependence of QGP properties not desirable...

Quenching weights; unified and easy-to-implement modification in the fragmentation functions...

Consider other nPDF’s (DS, HKN, nCTEQ) and FF’s

Generalize this study to several centrality classes, from central to more peripheral collisions (use the correct geometry)

Other approaches: medium modified splitting functions alter the evolution of fragmentation functions...

Considere more realistic hydrodynamical quantities: transversal expansion, $T$ and $\varepsilon$ dependency of transport coefficients, etc

Pin down the cold matter effects in pA collisions, where the QGP is not criated

Complement these studies with Monte Carlo implementations like QPythia and others...

Necessary to study other observables: dihadron correlations, two jet asymmetries, etc