High-$p_T$ physics at RHIC and prospects for LHC

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High transverse momentum physics in heavy-ion collisions

- A 5-plot overview of high-$p_T$ results from RHIC
- Radiative vs. collisional energy loss
- Models of radiative energy loss
  - energy loss due to the (non-Abelian) LPM effect
  - opacity expansion
  - medium-modified MLLA
- (Models of collisional energy loss)
- “Predictions” for LHC
High transverse momentum physics in heavy-ion collisions

Prediction (Bjorken, 1984): a high-$p_T$ parton traversing a dense colored medium loses energy.

proton-proton:

nucleus-nucleus:

The “jet” is quenched and does not escape the medium (a photon, a $W^\pm$ or a $Z^0$ boson are not affected)
High transverse momentum physics in heavy-ion collisions

To quantify the amount of jet quenching, compare the yield in high-$p_T$ particles in nucleus-nucleus with that in proton-proton collision:

"nuclear modification factor" $R_{AB} \equiv \frac{\text{yield in } AB}{N_{\text{coll.}} \times \text{yield in } pp}$

number of binary collisions

If the nucleus-nucleus collision amounts to the superposition of independent nucleon-nucleon collisions, $R_{AB} = 1$. 
For photons, $R_{AuAu} \approx 1$ at high $p_T$: no medium effect (and $N_{coll}$ is calculated properly).
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In contrast, high-momentum $\pi^0$ and $\eta$ are suppressed by a factor $\approx 5$. 
Nuclear modification factor at RHIC

High-\(p_T\) charged hadrons are suppressed in central Au-Au collisions as well, by the same amount (≠ no suppression in d-Au).

The more peripheral the collision (the smaller the medium size), the smaller the suppression.
Two-particle correlations

Count, as a function of the angular separation $\Delta \phi$, the multiplicity of particles (above a given $p_T$ cut) “associated” with the particle with highest transverse momentum in the event (“trigger particle”).

In central Au-Au collisions, the back jet at 180° disappears ≠ in pp or in d-Au collisions

When increasing the transverse momentum threshold (= triggering on jets of increasing energy), the back jet reappears.
Models of high-$p_T$ parton energy loss

Two different “categories” of models of parton energy loss, depending on the basic underlying process:

“radiative” process (Bremsstrahlung)

also “in vacuum”, but controlled by the presence of a medium

“collisional” process
Models of high-$p_T$ parton energy loss

Two different “categories” of models of parton energy loss, depending on the basic underlying process:

- inelastic
  - "radiative" process (Bremsstrahlung)
  - also “in vacuum”, but controlled by the presence of a medium collisions!

- elastic
  - "collisional" process
The spectrum of (mostly) gluons radiated by a fast parton is modified by the presence of the medium:

\[ dI^{\text{tot}} = dI^{\text{vac}} + dI^{\text{med}} \]

given by the normal DGLAP evolution

depends on the modeling of the medium
Inelastic energy loss

Models based on the Landau-Pomeranchuk-Migdal effect [1/4]

The propagating high-$p_T$ parton traverses a thick target. It radiates soft gluons, which scatter coherently on independent color charges in the medium, resulting in a medium-modified gluon energy spectrum.

Multiple soft scattering limit
Inelastic energy loss

Models based on the Landau-Pomeranchuk-Migdal effect [2/4]

Coherent scatterings: \( \ell_{\text{coh}} \sim \frac{2\omega}{k_\perp^2} \leq L \) (medium length)

LPM only affects gluons with \( \omega \lesssim \omega_c \equiv \frac{1}{2} \hat{q} L^2 \)

Medium characterized by the transport coefficient \( \hat{q} \equiv \frac{\mu^2}{\lambda} \)

\[ \ell_{\text{coh}} = \sqrt{\frac{2\omega \lambda}{\mu^2}} \]

Baier, Dokshitzer, Mueller, Peigné, Schiff (BDMPS); Zakharov

Coherence length of the emitted gluon

\( \ell_{\text{coh}} = \sqrt{\frac{2\omega \lambda}{\mu^2}} \)
Inelastic energy loss


Gluon coherence length \( \ell_{\text{coh}} = \sqrt{\frac{2\omega \lambda}{\mu^2}} \)

\( \Rightarrow \) gluon energy spectrum per unit path length \( \omega \frac{dI}{d\omega d\zeta} \approx \frac{\alpha_s}{\ell_{\text{coh}}} \approx \alpha_s \sqrt{\hat{q} \omega} \)

For a path length \( L \): \( \omega \frac{dI}{d\omega} \approx \alpha_s \sqrt{\frac{\hat{q} L^2}{\omega}} \)

Average medium-induced energy loss: \( \Delta E = \int \omega \frac{dI}{d\omega} d\omega \approx \alpha_s \omega_c \propto \alpha_s \hat{q} L^2 \)

- BDMPS-Z, only two parameters: \( \hat{q} \) & \( L \)
Inelastic energy loss

Models based on the Landau-Pomeranchuk-Migdal effect [4/4]

BDMPS-Z approach gives a good description of the data:

\[ R_{AA} = \text{fragile} \] (Eskola, Honkanen, Salgado, Wiedemann):

\[ \text{data cannot allow to distinguish between } \hat{q} = 5 \text{ or } 15 \text{ GeV}^2/\text{fm}. \]
Inelastic energy loss

Models based on an opacity expansion [1/2]

The high-$p_T$ parton interacts with a thin target:

the energy loss results from an incoherent superposition of very few

χ ≡ L/λ → “opacity” (= number of collisions)

⇒ gluon energy spectrum per unit path length

\[ \omega \frac{dI}{d\omega \, dz} \sim \left( \frac{L}{\lambda} \right) \frac{\alpha_s}{\ell_{coh}} \sim \left( \frac{L}{\lambda} \right) \alpha_s \frac{\mu^2}{\omega} \neq \alpha_s \sqrt{\frac{q}{\omega}} \text{ within LPM} \]

leads to an average energy loss \( \Delta E \propto L^2 \) (for a static medium)

Gyulassy, Lévai, Vitev (GLV); Wiedemann

three parameters: \( \left( \frac{L}{\lambda} \right), \mu & L \)

⇒ the (linear) density of scattering centers
Inelastic energy loss

Models based on an opacity expansion [2/2]

GLV reproduce the data with \( \approx 1000-1200 \) gluons per rapidity unit:

\[
R_{AA}(p_T) = \frac{dN/dy_{AA}}{dN/dy_{pp}}
\]

![Graph showing the relationship between rapidity and gluon density](image)

Inelastic energy loss

A model based on modified parton splitting functions [1/3]

The above-mentioned approaches to inelastic energy loss are only applied to the leading parton. However, the parton virtuality does not enter present comparisons to experimental data. In addition, momentum conservation is not implemented at each parton splitting, but only globally.
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This can be remedied by replacing \( dI^{\text{vac}} \) by \( dI^{\text{tot}} \) everywhere in a "medium-modified parton shower"  ⇒ necessitates a Monte-Carlo.
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can be done analytically, modulo an extra approximation, namely neglecting the $\omega$-dependence of the medium-induced spectrum of radiated gluons:

$$\frac{dI^{\text{med}}}{d\omega} = f_{\text{med}}$$

(reasonable in the kinematic regime at RHIC).
Inelastic energy loss

A model based on modified parton splitting functions [2/3]

Assuming a constant medium-induced radiation spectrum amounts to modifying the Altarelli-Parisi parton splitting functions, e.g.

\[ P_{q\bar{q}}(z) = C_F \left( \frac{2(1 + f_{\text{med}})}{1 - z} - (1 + z) \right) \]

where \( f_{\text{med}} = 0 \) in the absence of a medium. \(( f_{\text{med}} \) only parameter)
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\( \Rightarrow \) modification of the “hump-backed plateau” of longitudinal particle distributions within a jet computed using MLLA.

NB, Wiedemann
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Modified Leading Logarithmic Approximation (of QCD)

NB, Wiedemann
Inelastic energy loss

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NB, Wiedemann

\[ \text{depletion at large } x \]

\[ \text{enhancement at small } x \]
Inelastic energy loss

A model based on modified parton splitting functions

The agreement with the data is also satisfactory:

However, several realistic features are not included in the calculation...
Inelastic energy loss

A few model-independent remarks [1/2]

actually also valid for models of elastic energy loss

Independent scattering centers: \( \lambda \gg 1/\mu \).

mean free path \( \longrightarrow \) screening mass

All partons do not lose the same amount of energy, even when they traverse the same in-medium path length \( L \)

\( \Rightarrow \) nuclear modification factor \( R_{AA} \) mostly reflects the few partons which have lost little energy.

use of “quenching weights” (= probability to lose a given energy)
A few model-independent remarks [2/2]

A model of partonic energy loss has to be supplemented by several other elements to allow comparison with the data:
- parton distribution functions inside the nuclei (shadowing, Cronin effect...);
- production cross-sections.

The medium traversed by the parton is not static, but in expansion!

Model-builders introduce dynamics (most often, à la Bjorken), which may lead to a redefinition ($\hat{q} \rightarrow \hat{q}_{\text{eff}}$) of the parameters, to the introduction of new ones ($\tau_0$, $T_0$), or to a change in scaling properties ($\Delta E_{\text{GLV}} \propto L$ instead of $L^2$).
Elastic energy loss

The elder (Bjorken, 1984), yet still in its infancy...

Until 2003, it was commonly accepted that the amount of energy dissipated by the fast parton through elastic processes

\[
\frac{dE_{\text{el.}}}{dz} \approx 0.3 - 0.5 \text{ GeV/fm}
\]

was negligible with respect to the inelastic energy loss.

Since then, many models are emerging, stating that it is actually sizable...

- because of the running of the coupling constant \( \alpha_s \);
- for heavy quarks only;
- for c quarks only;
- because of “soft QCD processes”.

Wait and see...
Should one anticipate that $R_{\text{PbPb}}$ remain constant at high $p_T$?
Nuclear modification factor at LHC…

Should one anticipate that $R_{\text{PbPb}}$ remain constant at high $p_T$?

Or rather, that it will increase?
(for instance, because virtuality effects kick in: a high-$Q$ parton will degrade its virtuality on a time scale $\sim E/Q^2$, so quick that it does not feel the presence of the medium.)

The answer comes in 2008!