Quenching of hadron spectra
in heavy ion collisions at the LHC

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Context

Over the last decade, tremendous development on jet quenching

Experiment

- First reconstruction of jets in heavy ion collisions
- Jet substructure
- Fragmentation functions
- Jet-tagged and photon-tagged correlations, etc.

Phenomenology

- Monte-Carlo event generators in heavy-ion collisions
- Gluon emission off multi-particle antennas
- Jet fragmentation in a realistic medium, etc.
This talk

Here, looking for simpler things

I discuss a simple analytic model based on a single process – radiative energy loss – to describe the quenching of single hadrons at large $p_{\perp}$.

1. Why hadron quenching?

- hadrons = particles
  - in a sense much simpler than jets
- very precise data at the LHC
Here, looking for simpler things

I discuss a simple analytic model based on a single process – radiative energy loss – to describe the quenching of single hadrons at large $p_{\perp}$.

2. Why large transverse momentum?
   - cold nuclear matter effects weaken/vanish when $p_{\perp} \gg Q_s$
   - other hot medium effects only play a role at not too large $p_{\perp}$
   - radiative energy loss likely to be the only (or dominant) physical process at work
   - pp cross section has simple power-law behavior $\sigma^{pp} \propto p_{\perp}^{-n}$
The model

Take the simplest energy loss model for production of particle $i$

$$\frac{d\sigma^i_{AA}}{dy \, d\rho_\perp} = A^2 \int_0^{\infty} d\epsilon \frac{d\sigma^i_{pp}(p_\perp + \epsilon)}{dy \, d\rho_\perp} P_i(\epsilon)$$
The model

Take the simplest energy loss model for production of particle i

\[
\frac{d\sigma^i_{AA}}{dy \, dp_\perp} = A^2 \int_0^\infty d\epsilon \int_0^\infty d\sigma^i_{pp}(p_\perp + \epsilon) \frac{d\hat{\sigma}_{pp}(p_\perp + \epsilon)}{dy \, dp_\perp} P_i(\epsilon)
\]

Hadronization

- Particle losing energy \(\neq\) detected particle
- Introducing FF \(D^h_k\) and summing over partonic channels:

\[
\frac{d\sigma^h_{AA}}{dy \, dp_\perp} = A^2 \sum_k \int_0^1 dz D^h_k(z) \int_0^\infty d\epsilon \frac{d\hat{\sigma}_{pp}(p_\perp/z + \epsilon/z)}{dy \, dp_\perp} \frac{1}{z} P_k(\epsilon/z)
\]

- Assume that only one parton flavour to fragment (e.g. \(g \rightarrow h^{\pm}\))
- Approximate \(1/z \, P(\epsilon/z) \simeq 1/\langle z \rangle \, P(\epsilon/\langle z \rangle)\) and swapping integrals
The model

Take the simplest energy loss model for production of particle i

\[
\frac{d\sigma^h_{AA}}{dy \, dp_\perp} = A^2 \int_0^\infty d\epsilon \frac{d\sigma^h_{pp}(p_\perp + \langle z \rangle \epsilon)}{dy \, dp_\perp} P_i(\epsilon)
\]

Quenching weight

- In BDMPS, the quenching weight depends on a single energy loss scale \( \omega_c = 1/2 \hat{q} L^2 \) at high parton energy

\[
P(\epsilon) = \frac{1}{\omega_c} \bar{P} \left( \frac{\epsilon}{\omega_c} \right)
\]

- Computed numerically from the BDMPS (and GLV) gluon spectrum
- Due to hadronization, scale accessible from data is \( \bar{\omega}_c \equiv \langle z \rangle \omega_c \)
The model

Take the **simplest energy loss model** for production of particle $i$

$$\frac{d\sigma^h_{AA}}{dy \, dp_{\perp}} \simeq A^2 \int_0^\infty dx \frac{d\sigma^h_{pp}(p_{\perp} + \bar{\omega}_c x)}{dy \, dp_{\perp}} \bar{P}(x)$$

**pp production cross section**

- Power-law behavior expected at high $p_{\perp} \gg \Lambda_{QCD}$
  $$\frac{d\sigma_{pp}^i}{dy \, dp_{\perp}} \propto p_{\perp}^{-n}$$

- Power law index $n(h, \sqrt{s}) \simeq 5 - 6$ fitted from pp data

- Absolute magnitude of cross section irrelevant to compute $R_{AA}$
Nuclear modification factor $R_{AA}$

$$R_{AA}^h(p_\perp) = \int_0^\infty dx \left(1 + x \frac{\bar{\omega}_c}{p_\perp}\right)^{-n} \tilde{P}(x) \simeq \int_0^\infty dx \exp\left(-x \frac{n \bar{\omega}_c}{p_\perp}\right) \tilde{P}(x)$$

- $R_{AA}$ uniquely predicted once the only parameter $\bar{\omega}_c$ is known
  - determined from a fit to $R_{AA}$
- Approximate scaling: $R_{AA}(p_\perp, \bar{\omega}_c, n) = f(p_\perp / n \bar{\omega}_c)$
- **Universal shape** of $R_{AA}(p_\perp)$ for all centralities, collision energies, hadron species
Nuclear modification factor $R_{AA}$

$$R_{AA}^h(p_\perp) = \int_0^\infty dx \left( 1 + x \frac{\bar{\omega}_c}{n} \right)^{-n} \bar{P}(x) \simeq \int_0^\infty dx \exp \left( -x \frac{n \bar{\omega}_c}{p_\perp} \right) \bar{P}(x)$$

- $R_{AA}$ unique
  - determined from a fit to $R_{AA}$
- Approximate scaling:
  $$R_{AA}(p_\perp, \bar{\omega}_c, n) = f\left( \frac{p_\perp}{n \bar{\omega}_c} \right)$$
- Universal shape of $R_{AA}(p_\perp)$ for all centralities, collision energies, hadron species

$\bar{\omega}_c = \omega_{cGLV}$
$\omega_{cGLV}$

![Graph showing the nuclear modification factor $R_{AA}$ with different curves for $n = 3, 4, 6, 8, 10$. The graph illustrates the quenching of hadrons at LHC with Hard Probes 2018.](image)
Strategy

- Model with least number of assumptions and parameters
- Check universality of quenching
- Extract robust and ideally model-independent estimates of parton energy loss in a data-driven approach
- Start with charged hadrons $R_{AA}$ at $\sqrt{s} = 5 \text{ TeV}$
Charged hadron quenching in PbPb at $\sqrt{s} = 5$ TeV
Scaling

Charged hadron quenching in PbPb at $\sqrt{s} = 5$ TeV

$R_{\text{PbPb}}$

$\hat{\omega}_c$ (GeV) = 23.4 ± 1.2 ($\chi^2$/ndf = 0.34)

CMS PbPb(5.02) 5-10%

BDMPS spectrum

Franois Arleian (LLR) Quenching of hadrons at LHC Hard Probes 2018 7 / 15
Scaling

Charged hadron quenching in PbPb at $\sqrt{s} = 5$ TeV

$R_{\text{PbPb}}$

- $\hat{\omega}_c$ (GeV) = 17.7 ± 1.0 ($\chi^2$/ndf = 0.22)

- CMS PbPb(5.02) 10-30%

BDMPS spectrum

Franc¸ois Arleian (LLR)
Charged hadron quenching in PbPb at $\sqrt{s} = 5$ TeV

Scaling

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Scaling

Charged hadron quenching in PbPb at $\sqrt{s} = 5$ TeV

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Scaling

Charged hadron quenching in PbPb at $\sqrt{s} = 5$ TeV

![Graph showing charged hadron quenching in PbPb at $\sqrt{s} = 5$ TeV.]

...now adding PbPb CMS data at $\sqrt{s} = 2.76$ TeV
Predicted scaling nicely observed at 2 energies and in 5 centrality bins

Shape of $R_{AA}$ consistent with BDMPS model ($\chi^2/\text{ndf} \simeq 1$)

Scaling violations at low $p_\perp \lesssim 10$ GeV (other process at work?)

Most peripheral data do not follow the systematics
Heavy hadrons into the game

At large $p_\perp \gg M$, production of heavy hadrons (D/B, heavy quarkonia) should also proceed from the collinear fragmentation of a single parton.

- Fit to D & $J/\psi$ using the same BDMPS (massless) quenching weight
- $R_{AA}$ of heavy hadrons follow the same trend
  - need for more precise data, more centrality & even larger $p_\perp$
Energy loss possibly only process relevant for $J/\psi$ with $p_\perp \gtrsim 10$ GeV
▶ maybe not for excited states?
Mean energy loss

Fits allow for computing $\langle \bar{\epsilon} \rangle = \langle z \rangle \times \langle \epsilon \rangle$

- ...and $\langle \epsilon \rangle$ if $\langle z \rangle$ is known
  - NLO pQCD indicates $\langle z \rangle \simeq 0.5$ for $h^\pm$, larger for D & $J/\psi$
  - could be computed from the (fractional) moments of the FF

- $\langle \epsilon \rangle = \text{mean energy loss of the fragmenting parton, averaged over geometry}$
  - could be computed e.g. from hydrodynamics
Drop from $\langle \bar{\epsilon} \rangle \simeq 7$ GeV to 1 GeV, from central to peripheral

$\langle \bar{\epsilon} \rangle \simeq 4$–5 GeV from D & J/$\psi$ in min bias collisions
  - need to analyze same centralities for better comparison with $h^\pm$

10–20% increase of $\langle \bar{\epsilon} \rangle$ from 2.76 to 5 TeV
  - consistent with the increase of particle multiplicity measured by ALICE
Towards a purely data driven approach

- Still some model dependence because a specific quenching weight is assumed
- **Taylor expansion** of the pp production cross section in $\epsilon/p_\perp$ leads to

$$R_{AA}(p_\perp) = 1 - n \frac{\langle \epsilon \rangle}{p_\perp} + \frac{n(n+1)}{2} \frac{\langle \epsilon^2 \rangle}{p_\perp^2} + \ldots$$

Idea: take the first moments $\langle \bar{\epsilon}^j \rangle$ as **free** parameters!

**Procedure**

Generate pseudo-data according to the known quenching weight and check that the **first moments can be retrieved** from a fit to the pseudo-data
Extracting first moment

- First moment $\langle \epsilon \rangle$ can be extracted reliably if the $p_\perp$ range is large
- Larger uncertainties expected with 3rd order fits
Extracting moments from data

Testing the procedure with charged hadron CMS data

- Good fits at all centralities
• Good agreement between the BDMPS and the ‘agnostic’ estimates
• Larger uncertainties because of the 3 parameters
Summary

- **Simple energy loss model revisited** in light of the recent LHC data

- Measured $R_{AA}$ exhibit a universal shape (scaling)
  - at different centralities and at both energies
  - D and $J/\psi$ follow the same behavior
  - scaling violations below $p_\perp \lesssim 10$ GeV

- Energy loss scales extracted for all centralities
  - 10%–20% increase from 2.76 to 5 TeV

- Data-driven procedure to extract moments of the quenching weight
  - results consistent with estimates from the BDMPS model
Viens voir les physiciens

Charles Aznavour (1924-2018)

Thanks for your attention (and thank you Charles!)
What about jets?

Perhaps the most natural observable to test the model is $R_{AA}$ of jets, 

*but...*
What about jets?

Perhaps the most natural observable to test the model is $R_{AA}$ of jets, but...

How to understand this?

- Rather flattish $R_{AA}$
- $R_{AA}$ never reaches unity even at extremely large energies!
What about jets?

How to understand this? No clue!

Bias in the measurement

- All measurements have been carefully cross-checked... so almost 1 TeV jets indeed seem significantly quenched!

Physical origin

- Energy lost by a jet in a medium should not necessarily be that of a single parton, nor that of a hadron
- Different scaling property of medium-induced energy loss for a jet? Should $\langle \epsilon \rangle \propto \hat{q}L^2$ hold there too? If not, why?
Peripheral collisions

![Graphs showing CMS data on R_AA as a function of p_T for different luminosities and pseudorapidity ranges.](image)