Jet quenching and LHC data

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Jets in medium
Jet quenching

Hard scattering
Parton shower + color structure
Identify leading behavior

Non-perturbative hadronization

HADRONS
Jets in medium
Jet quenching

Put now a medium here

Hard scattering

Parton shower + color structure

Identify leading behavior

Non-perturbative hadronization

HADRONS
Vacuum: from parton splitting to parton shower

Soft and collinear divergencies in the gluon radiation

\[
\frac{dN}{dzdk_{\perp}^2} \sim \alpha_s C_R \frac{1}{z} \frac{1}{k_{\perp}^2}
\]

Resummation of splittings needed when

\[
\alpha_s \log^2 \frac{M_\perp}{Q_0} \sim 1
\]

[DGLAP, DLA, MLLA, ...]

Color coherence important: the antenna as a laboratory

- Take a pair (e.g. q-qbar) in a given color configuration \(a\) and compute soft gluon emission

\[
\omega \frac{dN}{d^3k} \sim \frac{\alpha_s}{\omega^2} \left[ C_F (R_q - \mathcal{J}) + C_F (R_{\bar{q}} - \mathcal{J}) + C_a \mathcal{J} \right]
\]

- \(C_a = 0\) if \(a\) is a photon
- \(C_a = C_A = N_c\) if \(a\) is a gluon

Out-of-cone radiation with the total charge
Vacuum: from parton splitting to parton shower

Soft and collinear divergencies in the gluon radiation

\[ \frac{dN}{dzdk^2} \sim \alpha_s \, C_R \frac{1}{z} \frac{1}{k^2} \]

Resummation of splittings needed when

\[ \alpha_s \log^2 \frac{M_\perp}{Q_0} \sim 1 \]

Medium induces additional radiation

[DGLAP, DLA, MLLA, ....]

Color coherence important: the antenna as a laboratory

- Take a pair (e.g. q-qbar) in a given color configuration \( a \) and compute soft gluon emission

\[ \omega \frac{dN}{d^3k} \sim \frac{\alpha_s}{\omega^2} \left[ C_F (R_q - J) + C_F (R_{\bar{q}} - J) + C_a J \right] \]

- \( C_a = 0 \) if \( a \) is a photon
- \( C_a = C_A = N_c \) if \( a \) is

Medium induces decoherence

Out-of-cone radiation with the total charge

$\text{Jet quenching and LHC data}$
Eikonal propagation

$E \gg k_1 \gg \mu$

Straight lines
Need color correlations in transverse plane - eikonal & recoilless approx.

- A dipole measures the color correlations in transverse plane

\[ W(x) = \mathcal{P} \exp \left[ i \int dx^- A^+(x_\perp, x^-) \right] \]

So that the S-matrix is

\[ |\alpha'; \beta'\rangle \equiv S_{\alpha' \beta' \alpha \beta} |\alpha; \beta\rangle = W_{\alpha' \alpha}(x_\perp) W_{\beta' \beta}^\dagger(y_\perp) |\alpha; \beta\rangle \]

and the survival probability for the initial color (singlet) configuration

\[ S(x_\perp, y_\perp) = \frac{1}{N_c} \text{tr} \left[ W(x_\perp) W^\dagger(y_\perp) \right] \]
Survival probability & antenna radiation

A simple application is the in-medium antenna radiation for soft gluons

\[
S(x_\perp, x_\perp) = 1 \quad S(x_\perp, y_\perp) \equiv 1 - \Delta_{\text{med}}(x_\perp, y_\perp)
\]

\[
\omega \frac{dN}{d^3 k} \sim \frac{\alpha_s}{\omega^2} \left[ C_F (R_q - S(x_\perp, y_\perp)J) + C_F (R_{\bar{q}} - S(x_\perp, y_\perp)J) + C_a S(x_\perp, y_\perp)J \right]
\]

The medium can break the color correlation between emitters

- Effect controlled by the survival probability

\[
S(x_\perp, y_\perp) \equiv 1 - \Delta_{\text{med}}(x_\perp, y_\perp) \simeq \exp \left\{ -\frac{1}{4} \int d\xi \hat{q}(\xi) (x_\perp(\xi) - y_\perp(\xi))^2 \right\}
\]

- Other medium-averages possible, but general discussion unchanged
Antenna coherence - qualitative discussion

Medium transverse color resolution vs jet typical size

\[ \Delta_{\text{med}} = 1 - \exp \left[ -\frac{1}{12} \frac{r_{\perp}^2}{\Lambda_{\text{med}}^2} \right] \]

\[ r_{\perp} \sim \Theta L \quad \Lambda_{\text{med}} \sim \frac{1}{\sqrt{qL}} \]

Coherence maintained

Coherence broken

Same reasoning applies to the medium-induced gluon radiation with the changes

\[ \mathcal{R}_q \longrightarrow \mathcal{R}_q^{\text{vac}} + \mathcal{R}_q^{\text{med}} \]

\[ \mathcal{J} \longrightarrow \mathcal{J}^{\text{vac}} + \mathcal{J}^{\text{med}} \]

So, for example, for a gluon splitting into a qqbar pair in the coherent case:

\[ \omega \frac{dN}{d^3k} \sim \frac{\alpha_s}{\omega^2} \left[ C_F \left( \mathcal{R}_q^{\text{vac}} - \mathcal{J}^{\text{vac}} \right) + C_F \left( \mathcal{R}_q^{\text{med}} - \mathcal{J}^{\text{med}} \right) + C_A \mathcal{J}^{\text{vac}} + C_A \mathcal{J}^{\text{med}} \right] \]

(vacuum) angular ordered, collinear

Medium-induced
A new picture of jet quenching

The parton shower is composed of **un-modified subjets** (vacuum-like)
- **With a typical radius given by the medium scale**
- For medium-induced radiation each subject is one single emitter

Also, 1st calculation of 1->3 splitting performed in SCET and 1st order in opacity expansion
- [Fickinger, Ovanesyan, Vitev] - [also Arnold, Iqbal 2015; Casalderrey-Solana, Pablos, Tywoniuk 2015]
Let us consider now the case of three emitters (two hard splittings inside the medium)

Large-\(N_c\) limit

The soft gluon is emitted by one antenna with **same rules for decoherence**

\[
\sim 1 \quad \sim S(t, L) \quad \sim S_1(0, t) S_2(t, L)
\]

[Dominguez, Salgado, Vila, in preparation]
Non-eikonal propagation

\[ E \gg k_L \gg \mu \]

Brownian motion in \( L \)-plane

(Broadened)
Medium-induced gluon radiation - BDMPS limit

Computed in the mid-90’s for very energetic quarks emitting soft gluons

\[
\omega \frac{dI}{d\omega dk} \sim \alpha_s C_R \int dy \int dy' \int du e^{ik \cdot u} \partial_u \cdot \partial_y \mathcal{K}(y', u; y, y) \bigg|_{y=0} \tilde{P}(L, y'; u)
\]

\[\mathcal{K}(y', u; y, y) = \int_{y(y')}^u Dr \exp \left\{ \frac{i}{2} \int d\xi \left( \frac{dr(\xi)}{d\xi} \right)^2 \right\} \tilde{P}(y', y, r)\]

\[\{\text{Zakharov, Baier, Dokshitzer, Mueller, Peigne, Schiff, Wiedemann, Gyulassy, Levai, Vitev, and many others...}\]
Medium-induced gluon radiation - BDMPS limit

Computed in the mid-90's for very energetic quarks emitting soft gluons

\[ \omega \frac{dI}{d\omega dk} \sim \alpha_s C_R \int dy \int dy' \int du e^{i k \cdot u} \partial_u \cdot \partial_y K(y', u; y, y) \bigg|_{y=0} \tilde{P}(L, y'; u) \]

\[ K(y', u; y, y) = \int_{y(y')}^{u(y')} Dr \exp \left\{ i \frac{\omega}{2} \int d\xi \left( \frac{dr(\xi)}{d\xi} \right)^2 \right\} \tilde{P}(y', y, r) \]

\[ \tilde{P} \approx \langle W_A(r_g) W_A(0) \rangle \quad (\text{survival probability}) \]

\[ \tilde{P} \approx \langle W_A(r_g) W_A(r) \rangle \quad (\text{classical broadening}) \]

\[ \left\{ \text{harov, Baier, Dokshitzer, Mueller, Peigne, Schiff, Wiedemann, Gyulassy, Levai, Vitev, and many others...} \right\} \]

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Computed in the mid-90’s for very energetic quarks emitting soft gluons

\[ \omega \frac{dI}{d\omega dk} \sim \alpha_s C_R \int dy \int dy' \int du \, e^{i \mathbf{k} \cdot \mathbf{u}} \partial_u \cdot \partial_y K(y', u; y, y) \bigg|_{y=0} \tilde{P}(L, y'; u) \]

\[ \mathcal{K}(y', u; y, y) = \int_{y(y)}^{u(y')} Dr \exp \left\{ \frac{i \omega}{2} \int d\xi \left( \frac{dr(\xi)}{d\xi} \right)^2 \right\} \tilde{P}(y', y, r) \]

\[ \langle W_A(r_g) W_A(0) \rangle \] (survival probability)

\[ \langle W_A(r_g) W_A(r_g) \rangle \] (classical broadening)

Harov, Baier, Dokshitzer, Mueller, Peigne, Schiff, Wiedemann, Gyulassy, Levai, Vitev, and many others...
Let now all partons be non-eikonal (finite energy corrections)

- The transverse position of the quark is now not fixed

\[ \left< U_q^+ U_g U_g^+ U_q^+ U_q U_q \right> \]
\[ \rightarrow \left< U_q^+ U_g \right> \times \left< U_q^+ U_q U_q U_g \right> \]
\[ \rightarrow [\times \left< U_q^+ U_q \right>]^2 \times \left< U_q^+ U_q \right> \Delta_{\text{coh}} \]

The quadrupole controls again the degree of decoherence

- Suppressed when quadrupole cannot be broken in two dipoles

\[ t_{\text{fam}} \sim \sqrt{\frac{g}{N_c}} \ll L \Rightarrow \Delta_{\text{coh}} \sim 1 \Rightarrow \text{Factorization} \]

izot, Dominguez, Iancu, Mehtar-Tani 2012-2014; Apolinario, Armesto, Milhano, Salgado 2014

Jet quenching and LHC data
The Wilson line of a massive quark comes with a phase \( \exp \left[ i \frac{M^2}{E_Q} y \right] \)

\[
\omega \frac{dI}{d\omega dk} \sim \alpha_s C_R \int dy \int dy' \int du e^{i k \cdot u} e^{i \frac{\omega}{2} \theta_{DC} (y' - y)} \partial_u \cdot \partial_y K(y', u; y, y) \bigg|_{y=0} \tilde{P}(L, y'; u)
\]

Where \( \theta_{DC} = M/E_Q \) suppresses the radiation in most of the phase space.

The same phase suppresses also the interferences.

In the coherent case, the quark and antiquark are not resolved and the system lose energy as a whole, but with dead-cone suppression.

[Calvo, Moldes, Salgado 2014]
Some phenomenology
Qualitative description: jet collimation

Lessons from experimental data on jet reconstruction

- Suppression similar to inclusive hadrons for similar pT
- Fragmentation functions are mildly modified - more in soft
- Jet shapes have mild modifications
- Azimuthal decorrelation of di-jets as in proton-proton
- Energy taken by soft particles at large angles
Extraction of the value of $q_{\text{hat}}$ - centrality

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Jet quenching and LHC data

Andres, Armesto, Luzum, Salgado, Zhu, in preparation

Taken at face value: why $K$ depends only on collision center of mass energy

- Needs clarification - what is the temperature dependence of $q_{\text{hat}}$?

[A study for central collisions: Jet Collaboration 2013]
**Idea:** to have color singlet (partonic) antenna propagating through the medium

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**Top Mass**

*PRELIMINARY* all quenched - leading quarks - antenna unquenched - unquenched

**W Mass**

*PRELIMINARY* all quenched - leading quarks - antenna unquenched - unquenched

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**Distance (fm)**

- Top decay distance
- W decay distance
- Coherence distance
- Average total decay distance

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*Apolinario, Milhano, Salam, Salgado, in preparation*
Summary

Color coherence, an essential ingredient in jet quenching

- Controls medium-induced gluon radiation (BDMPS, etc)
- Dictates a new picture of jet quenching in which the jet organizes in sub-structures (sub-jets) defined by the typical medium resolution length
- Each sub-jet loses energy with its total (color) charge

Some phenomenological consequences

- Qualitative agreement with observations in reconstructed jets
- Heavy quark jets - larger energy loss for octet (QQbar in same jet)
- Boosted tops and singlet objects
- Quenching weights - centrality dependence of qhat to be understood