Jet (de)coherence in PbPb collisions at the LHC

Konrad Tywoniuk

21 May 2014, QM2014, Darmstadt, Germany
Jets

- physically: sprays of particles in the detector — probing partonic degrees of freedom
- well defined objects in perturbation theory*
- ideal hard probes for extracting properties of the medium!

* free from problems related to hadronic fragmentation functions…
QCD jet in vacuum

\[ M_\perp \equiv E \theta_{\text{jet}} \]

\[ l = \ln \left( \frac{1}{x} \right) \]

\[ x \frac{dN_g}{dx dM_\perp} \equiv G(l, y) \]

\[ t_{\text{hadr}} \approx \frac{k_{||}}{\Lambda_{QCD}^2} \]

\[ t_{\text{form}} \approx \frac{k_{||}}{k_{\perp}^2} \]

- probabilistic picture, factorization
- jet scales — perturbative evolution
- angular ordering — essential for small \( x \)
- MLLA + Local-Parton-Hadron-Duality

OPAL data, \( Q = 90 \text{ GeV} \)
ALEPH data, \( Q = 130 \text{ GeV} \)
QCD jet in medium

\[ M_\perp \equiv E \theta_{jet} \]

\[ Q_0 \sim \Lambda_{QCD} \]

New scales:

\[ M_\perp \equiv E \theta_{jet} \]

\[ Q_s \equiv \sqrt{\hat{q}L} \equiv m_D \sqrt{N_{\text{scat}}} \]

\[ r_{\perp jet}^{-1} \equiv (\theta_{jet} L)^{-1} \]

Casalderrey-Solana, Mehtar-Tani, Salgado, KT 1210.7765
Counting sources

**One emitter**

\[
\frac{1}{Q_s}
\]

jet remains coherent

**Two emitters**

\[
\frac{1}{Q_s}
\]

subjets decohere

The scale \( Q_s^{-1} \) determines the **number of independent color sources** that can are resolved by the medium.

:: medium induced radiation (BDMPS spectrum)

Mehtar-Tani, Salgado, KT 1009.2965; 1102.4317; 1112.5031; 1205.57397; Casalderrrey-Solana, lancu 1105.1760
Resolving jet substructure

Coherence survival prob.

\[ \Delta_{\text{med}} = 1 - e^{-\frac{\Theta_{\text{jet}}^2}{\theta_c^2}} \]

\[ \theta_c = \frac{1}{\sqrt{\hat{q}L^3}} \]

jet definition (\( \Theta_{\text{jet}} = R \))!

Coherent inner ‘core’

- branchings occurring inside the medium with \( \theta < \theta_c \) — hard modes
- the core interacts w/ medium coherently
- induces radiation — loses energy

A large fraction of the jets contain 90% of their energy within \( \Theta \sim 0.1 \)!

Casalderrrey-Solana, Mehtar-Tani, Salgado, KT 1210.7765
Perez-Ramos, Mathieu PLB 718 (2013) 1421 [arXiv:1207.2854]; Perez-Ramos, Renk arXiv:1401.5283
The evolution takes place between the jet subsequent emissions which is a manifestation of color set of single logarithmic corrections. One of the key features, logarithmic contributions SuLrT as well as the full evolution equations \[\text{bd}\] which take into account the double logarithmic approximations SMLLrT. The hadron and parton energies to the jet energy are related to the cone energy flow for dijets where it was observed that the medium parameters within the uncertainty due to the jet reconstruction angles using the previously extracted details in a forthcoming work. See also \[\text{bh}\].

The description of broadening will be discussed in more detail in a forthcoming work. See also \[\text{bh}\].

The evolution takes place between the jet subsequent emissions which is a manifestation of color set of single logarithmic corrections. One of the key features, logarithmic contributions SuLrT as well as the full evolution equations \[\text{bd}\] which take into account the double logarithmic approximations SMLLrT. The hadron and parton energies to the jet energy are related to the cone energy flow for dijets where it was observed that the medium parameters within the uncertainty due to the jet reconstruction angles using the previously extracted details in a forthcoming work. See also \[\text{bh}\].

The results obtained here agree qualitatively with the observation that the energy is still missing. This confirms that multiple medium parameters within the uncertainty due to the jet reconstruction angles using the previously extracted details in a forthcoming work. See also \[\text{bh}\].

The description of broadening will be discussed in more detail in a forthcoming work. See also \[\text{bh}\].
Nuclear modification factor

- assuming quark jets (n=5.6)
- allows to fix medium scales (fixing $L = 2.5$ fm)
- high-$p_T$ jets are the most reliable probe for $\bar{q}$!

$Q_s = 3.6 \text{ GeV}$
Nuclear modification factor

- assuming quark jets (n=5.6)
- allows to fix medium scales (fixing L = 2.5 fm)
- high-\(p_{\perp}\) jets are the most reliable probe for \(\bar{q}\)!

\[ Q_s = 3.6 \text{ GeV} \]

Jet deflection :: \(\Delta \Theta \sim Q_s/E \sim 0.04\)
Nuclear modification factor

- assuming quark jets (n=5.6)
- allows to fix medium scales (fixing $L = 2.5$ fm)
- high-$p_T$ jets are the most reliable probe for $\bar{q}!$

$$Q_s = 3.6 \text{ GeV}$$

Jet deflection :: $\Delta \Theta \sim Q_s/E \sim 0.04$

| Missing pt in dijet events | $\Theta$ | $\bar{\Theta}$ |
|----------------------------|---------|---------------|
| missing energy at $\theta < \Theta$ | 14 - 19 % | 9 - 15 % |

$\omega_c = 60$-$100$ GeV, $\omega_{BH} = 1.5$ GeV
$\omega_c = 80$ GeV, $\omega_{BH} = 0.5$-$2.5$ GeV

CMS Prelim.

Mehtar-Tani, KT 1401.8293
Soft gluons in the cone

Going beyond the inclusive jet spectrum, the assumption of fully coherent jets marginal

\[ \Theta_{\text{jet}} = 0.3 \]

\[ \Theta_c = 0.08 \]

Contribution from 2nd emission in DLA w/ running coupling.

\[ D_{\text{med}}^{\text{jet}}(x; Q, L) = D_{\text{med}}^{\text{coh}}(x; Q, L) + \Delta D_{\text{med}}^{\text{decoh}}(x; Q, L) \]
Fragmentation function

- vacuum baseline reproduced by MLLA :: valid close to the humpbacked plateau
- allow the jet energy to vary (due to energy loss)
- coherent jet quenching important for intermediate \( l \)
- decoherence plays main role at large \( l \) (small \( x \))
Summary

- jet quenching is a powerful tool to access properties (e.g. $\hat{q}$, $\hat{\varepsilon}$ etc.) of the hot and dense QGP
  - resolved sub-jets are a consequence of color transparency (perturbative QCD)

- separation of scales (angles)
  - jet ‘core’ :: energy loss
  - jet ‘edge’ :: modification of fragmentation function
  - large angle :: transport in the medium
backup
Resolving jet substructure

\[ \Delta_{\text{med}} = 1 - e^{-\Theta_{\text{jet}}^2 / \theta_c^2} \]

Coherence survival prob.

‘Soft edge’ of the jet

- softer components of the jet occupy the full angular range
  - do not carry a large energy fraction!
- sensitive to effects of decoherence
- modification of jet fragmentation function
  - sensitive to the critical angle \( \Theta_c \)

Mehtar-Tani, KT 1401.8293
Induced radiation

Multiple induced gluon radiation (BDMPS) resummed in a rate equation in “time”

\[ \tau = \frac{\alpha_s N_c}{\pi} \sqrt{\frac{\hat{q} L^2}{E}} \]

• probabilistic interpretation
• turbulent flow: no intrinsic accumulation of energy
• effective in transporting sizable energy to large angles

Jeon, Moore hep-ph/0309332; Baier, Mueller, Schiff, Son hep-ph/0009237; Blaizot, Iancu, Mehtar-Tani 1301.6102
Transparency vs decoherence

• $r_\perp < Q_s^{-1}$ (Dipole regime)

\[
\Delta_{\text{med}} \approx \frac{1}{12} Q_s^2 r_\perp^2
\]

• $r_\perp > Q_s^{-1}$ (Decoh. regime)

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

$k_\perp < Q_{\text{hard}}$

hardest scale determines phase space for radiation

Mehtar-Tani, Salgado, KT 1009.2965; 1102.4317; 1112.5031; 1205.57397; Casalderrey-Solana, lancu 1105.1760
Induced radiation

Multiple scattering in the medium:

\[
\begin{align*}
  t_{br} &= \lambda_{mfp} N_{coh} \\
  k_{br}^2 &= \mu^2 N_{coh} \\
  t_{br} &= \sqrt{\omega/\hat{q}} \\
  k_{br}^2 &= \sqrt{\hat{q}\omega}
\end{align*}
\]

\[\lambda_{mfp} \rightarrow t_{br} \quad \text{:: Landau-Pomeranchuk-Migdal effect}\]

**Bethe-Heitler regime**

\[
t_{br} \sim \lambda_{mfp} \\
\omega_{BH} = \lambda^2 \hat{q} \sim \lambda m_D^2
\]

**Factorization regime**

\[
t_{br} \sim L \\
\omega_c = \hat{q} L^2
\]

**LPM regime**

\[
\omega_{BH} \ll \omega \ll \omega_c
\]

Baier, Dokshitzer, Mueller, Peigné, Schiff (1997-2000), Zakharov (1996), Wiedemann (2000), Gyulassy, Levai, Vitev (2000), Arnold, Moore, Yaffe (2001)