Energy loss models and jet measurements with ALICE

Marta Verweij
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Outline

- In-medium energy loss models
  - Parton energy loss in realistic geometry
  - Systematic comparison of models

- Jets with ALICE in Pb-Pb collisions
  - Jet spectra
  - Jet suppression
  - Jet broadening
Hard Probes in QCD matter

Heavy-ion collisions produce dense QCD matter
- Dominated by soft partons
  \( p \sim T \sim 100-300 \text{ MeV} \)

Hard-scatterings produce high energetic partons
\[ \Rightarrow \text{Initial-state production known from pQCD} \]
\[ \Rightarrow \text{Probe medium through energy loss} \]

Use hard partons to explore QCD matter

Sensitive to properties of the medium
Schematic picture of energy loss mechanism in hot dense matter

- Energy loss due to gluon bremsstrahlung in a hot dense medium
- What can we learn from Pb-Pb measurements & comparison to models?

Outgoing quark

\[ x_E = (1-x)E \]

Radiated energy

\[ \Delta E = xE \]
Comparison of energy loss models with data
$R_{AA}$ at RHIC

$$R_{AA} = \frac{dN / dp_T \big|_{Au+Au}}{N_{\text{coll}} dN / dp_T \big|_{p+p}}$$

- Common input parameter for all models: medium temperature
- All models can be fitted to $R_{AA}$

<table>
<thead>
<tr>
<th>Model</th>
<th>$\hat{q}_0$ (GeV/fm$^2$)</th>
<th>$T_0$ (MeV)</th>
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<tbody>
<tr>
<td>ASW-MS</td>
<td>$20.3^{+0.6}_{-5.1}$</td>
<td>$973^{+6}_{-90}$</td>
</tr>
<tr>
<td>WHDG rad</td>
<td>$5.7^{+0.3}_{-1.9}$</td>
<td>$638^{+11}_{-81}$</td>
</tr>
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<td>ASW-SH</td>
<td>$3.2^{+0.3}_{-0.3}$</td>
<td>$524^{+17}_{-18}$</td>
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Factor 4-5 difference in estimated medium density between different models

Path length bias for di-hadrons

- $p_T^\text{Trigger} > p_T^\text{Assoc}$
- For $R_{AA}$ and $I_{AA}$ different mean path length.
- **Trigger**: bias towards smaller $L$
- **Associate**: bias towards longer $L$
What is the difference between $R_{AA}$ and $l_{AA}$?

Different part of the parton spectrum is probed.

Original parton spectra resulting in hadrons with $8 < p_{t}^{\text{hadron}} < 15$ GeV for without (vacuum) and with (ASW-MS/WHDG) energy loss.
Calibrate density using $R_{AA}$

Most models underestimate $I_{AA}$

$z_t = \frac{p_{t}^{\text{assoc}}}{p_{t}^{\text{trig}}}$
Brick Problem

Goal: understand discrepancy in estimated medium density by models
Brick Problem

TECHQM: Theory-Experiment Collaboration on Hot Quark Matter

Compare energy loss models in a well-defined system:
- Fixed medium length $L$ and temperature $T$ (or $q_{\text{hat}}$)
- Parton (quark) propagates through brick, $E_{\text{parton}} = 10, 20$ GeV

Compare outgoing radiated gluon and parton distributions
2 cases: same density, same suppression
Four formalisms

- **Hard Thermal Loops (AMY)**
  - Dynamical (HTL) medium
  - Single gluon spectrum: BDMPS-Z like path integral
  - No vacuum radiation

- **Multiple soft scattering (BDMPS-Z, ASW-MS)**
  - Static scattering centers
  - Gaussian approximation for momentum kicks
  - Full LPM interference and vacuum radiation

- **Opacity expansion ((D)GLV, ASW-SH)**
  - Static scattering centers, Yukawa potential
  - Expansion in opacity $L/\lambda$
    (N=1, interference between two centers default)
  - Interference with vacuum radiation

- **Higher Twist (Guo, Wang, Majumder)**
  - Medium characterised by higher twist matrix elements
  - Radiation kernel similar to GLV
  - Vacuum radiation in DGLAP evolution

*Hard Probes 2010, M. van Leeuwen*
Four formalisms

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Today focus on these two models
Single gluon spectrum
fixed medium temperature

- Energy spectrum for 1 radiated gluon: for all models this is the starting point
- Clear hierarchy between models. Radiation AMY > GLV > ASW-MS
- Average number of emitted gluons:

\[
\langle N_g \rangle = \int d\omega \frac{dI}{d\omega}.
\]
Outgoing quark spectrum

Same temperature

Energy fraction of quark after leaving the medium.
Fixed length, fixed temperature for all models

- $x_E = 1 - \Delta E/E$
- $x_E = 0$: Absorbed quarks
- $x_E = 1$: No energy loss

For fixed temperature:
- $<N_{\text{gluons}}>$ larger for opacity expansion than multiple soft scattering approximation
- Suppression: AMY > DGLV > ASW-MS
Suppression in a brick vs qhat

Temperature $T$ is the common variable in all models.

$R_7 = \text{approximation for } R_{AA}$

$$R_n = \int_0^1 d\epsilon (1 - \epsilon)^{n-1} P(\epsilon)$$

$$\epsilon = \Delta E / E$$

Gluon gas $N_f = 0$

**In simple geometry:**

Large differences in medium density for $R_7 = 0.25$
Outgoing quark spectrum

Same suppression

- Fixed suppression: $N_{\text{gluons}}$ similar, but different mean energy loss

For detailed discussion, see brick report arXiv:1106.1106
Validity of models

Gluon radiation rate vs $\tau (=L)$

<table>
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<tr>
<th>Model</th>
<th>Description</th>
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<tbody>
<tr>
<td>Full</td>
<td>GLV N=1</td>
</tr>
<tr>
<td>N=1</td>
<td>Too much radiation at large $L$ (no interference between scattering centers)</td>
</tr>
<tr>
<td>AMY</td>
<td>Too little radiation at small $L$ (ignores 'hard tail' of scattering potential)</td>
</tr>
<tr>
<td>H.O.</td>
<td>AMY, small $L$, no $L^2$, no vacuum interference</td>
</tr>
</tbody>
</table>

**H.O.** = ASW/BDMPS like (harmonic oscillator)

Each model is valid for different medium lengths
Jets with ALICE in Pb-Pb collisions
Jets in Heavy Ion Collisions

- Probes to study properties of medium
- Due to interaction of the jet with the medium, the jet is modified:
  **Jet Quenching**

Experimental challenge in HI collisions:

**Separate jet signal from large soft background originating from bulk**
Jet Reconstruction

  - anti-$k_T$ for signal (stable area)
  - $k_T$ to estimate background density
  - Boost invariant $p_T$ recombination scheme
  - Transverse momentum track cut-off $p_T > 0.15$ GeV/c

- Charged jet reconstruction with tracks reconstructed in tracking detectors:
  - High precision on particle level
  - Uniform $\eta$-$\varphi$ acceptance
  - Neutral energy missing, eg. $\pi^0$, n, $\gamma$
Centrality of HI collisions

Peripheral collisions

Central collisions
Jets in HI events: background

- Jet sits on top of a soft background
- 2 step procedure to correct for UE contaminating the jet:

  1) Background density $\rho$: $k_T$ algorithm excluding the 2 leading clusters.

  2) Background fluctuations: inhomogeneous structure of events. Quantified by embedding high $p_T$ probes on top of the measured PbPb events.
Jets in HI events: background

Event-by-event subtraction of average background momentum density $\rho$.

Background fluctuations quantified by embedding high $p_T$ probes in Pb-Pb events

Width of fluctuations for jets with constituent $p_T > 150$ MeV/c:

$\sigma(\delta p_T, R=0.2) = 4.5$ GeV

$\sigma(\delta p_T, R=0.3) = 7.1$ GeV

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Uncorrected Jet Spectrum

- Average background subtraction: event-by-event background density for central events $\sim 140$ GeV/c/A
- Low $p_T$ jets collect a lot of background energy and appear at very high $p_T$ after clustering

**Pb-Pb $\sqrt{s_{NN}} = 2.76$ TeV**

Charged Jets
- $R = 0.4$
- $p_{T,\text{track}} > 0.15$ GeV/c
- Area $> 0.4$

$N_{\text{coll}}/N_{\text{evts}} dp_T/dN$
Jets in HI events: background

Combinatorial jets: clusters which do not originate from a hard process. Reduced by triggering jets with a leading track of $p_T > 5$ and 10 GeV/c.

Combinatorial / fake jets

Jets reconstructed from charged particles with $p_T > 150$ MeV/c.
Background Fluctuations

- Background fluctuations estimated by studying the response of embedded high $p_T$ probe in heavy ion event.
- Data driven approach to estimate influence of background fluctuations on jet reconstruction.
- We embed different kind of probes:
  - Random cones
  - Single tracks
  - Jets from full detector simulation pp @ 2.76 TeV
- Response is quantified by comparing the reconstructed jet to the embedded probe:

\[ \delta p_T = p_{T,\text{jet}}^{\text{rec}} - \rho A - p_T^{\text{probe}} \]
Background Fluctuations

Comparison of Probes

Random Cones
Single Tracks
Pythia jets

- No dependence on fragmentation pattern observed
  - Small back-reaction effect
- Fluctuations reduced by increasing minimum particle $p_T$
- High $p_T$ tail same shape as jet spectrum
  - Challenging for unfolding

arXiv:1201.2423v1
Background Fluctuations
Comparison of jet radii

Reduced background fluctuation for smaller jet areas
Measured $\sigma(\delta p_T)$ larger than naive expectation from only statistical fluctuations
Unfolding the background

- Need to **unfold** measured jet spectrum to obtain 'real' jet spectrum (Truth)
- Refolded = unfolded jet spectrum smeared with background fluctuations

Assume:

\[
\left. \frac{dN}{dp_T} \right|_{meas} = P(\delta p_T) \otimes \left. \frac{dN}{dp_T} \right|_{jet}
\]

Unfolding done with \( \chi^2 \) minimization

\[
\chi^2 = \sum_{\text{refolded}} \left( \frac{y_{\text{refolded}} - y_{\text{measured}}}{\sigma_{\text{measured}}} \right)^2 + \beta \sum_{\text{unfolded}} \left( \frac{d^2 \log y_{\text{unfolded}}}{d \log p_T^2} \right)^2
\]

\( \chi^2 \)-term  Regularization/penalty
Background and detector corrections

Raw jet spectra need to be corrected for background fluctuations

Background fluctuations shift low $p_T$ jets to high $p_T$
Background and detector corrections

Raw jet spectra need to be corrected for background fluctuations and detector effects.

Background fluctuations shift low $p_T$ jets to high $p_T$.

Detector effects shift jets to lower $p_T$. 

Fake jets go here.
Jet spectra have been measured for 2 cone radii and 4 centrality bins. 

**R=0.2**

Centrality
- 0-10%
- 10-30%
- 30-50%
- 50-80%

Charged Jets
Anti-\(k_t\) R = 0.2
\(p_t^{\text{track}} > 0.15\) GeV/c

**R=0.3**

Centrality
- 0-10%
- 10-30%
- 30-50%
- 50-80%

Charged Jets
Anti-\(k_t\) R = 0.3
\(p_t^{\text{track}} > 0.15\) GeV/c
Jet $R_{CP}$

$R=0.2$

$R=0.3$

Strong suppression for jets
No strong $p_T$ dependence
Similar suppression for jet radii $R=0.2$ and $R=0.3$

Central events jet $R_{CP} \sim 0.5$
Peripheral closer to 1
Jet Suppression

- Leading track requirement → fragmentation bias at low $p_T$ → potentially modified by jet quenching

Fragementation bias the same for central and peripheral events.
Jet $R_{AA}$ vs Hadron $R_{AA}$

Jet $R_{AA}^{\text{Pythia}}_{\alpha}$ vs Hadron $R_{AA}$

Jet $R_{AA}^{\text{Pythia}}_{\alpha} = 0.3$

Charged Jets

$\text{Anti-}k_{t} R = 0.3$

$p_{T}^{\text{track}} > 0.15 \text{ GeV/c}$

Centrality
- 0-10%
- 10-30%
- 30-50%
- 50-80%

$\text{Pb-Pb } \sqrt{s_{NN}} = 2.76 \text{ TeV}$

Charged Particle $R_{AA}$

ALICE, charged particles, Pb-Pb

$\sqrt{s_{NN}} = 2.76 \text{ TeV, } |\eta| < 0.8$

Jet $R_{AA}^{\text{Pythia}} \leq$ Hadron $R_{AA}$
**Model Comparison**

Jet $R_{AA}$: ALICE vs JEWEL

JEWEL (radiative + elastic energy loss MC) reproduces

→ Hadron $R_{AA}$ (Zapp, Krauss, Wiedemann arXiv:1111.6838)

→ Charged jet $R_{AA}$ for R=0.2 and R=0.3  

**JEWEL jet results: private communication**
Ratio of jet cross sections

$R=0.2/R=0.3$

$\sigma(R=0.2)/\sigma(R=0.3)$ consistent with vacuum jets for peripheral and central collisions
→ no sign of jet broadening

Good agreement with energy loss MC JEWEL.

JEWEL: Zapp, Krauss, Wiedemann arXiv:1111.6838
Summary

- TECHQM Brick: differences between formalisms identified. Not physics but approximations

- Jets with ALICE
  - Strong jet suppression in central events
  - No signs of modified jet structure observed in ratio of jet cross section $R=0.2/R=0.3$
  - $Jet \ R_{AA} \leq Hadron \ R_{AA}$
backup
Track Selection
Requirements for jet analysis

- Uniform acceptance in eta and phi
- Avoid outliers (tracks with low $p_T$ generated which are reconstructed at very high $p_T$)
- Track momentum resolution
- High tracking efficiency

Strategy for track selection:
Use the best available $\rightarrow$ hybrid tracks
Hybrid Tracks

- Hybrid tracks
  - Standard global tracks: w/ SPD & ITSrefit (82%)
  - Constrained global tracks: w/o SPD || w/o ITSrefit (12 + 6%)
- Constrained tracks fill the gaps in phi caused by missing SPD layers. Constrained to primary vertex to improve momentum resolution
- Tracking efficiency: 80-85% at high $p_T$. (~70% for global standard tracks)
Fluctuations vs reaction plane

Goal: estimate influence of region-to-region fluctuations of correlated background.

~5 GeV shift for in- and out-of-plane: $\propto v_2 \rho$

Collective effects ($v_n$) broaden background fluctuations
Suppression Factor
in a brick

• Hadron spectrum if each parton loses $\epsilon$ energy:

$$\frac{dN}{dp_t} = \frac{1}{(1 - \epsilon)p_t^n} \frac{dp_t}{dp'_t} = \frac{1}{(1 - \epsilon)^{n-1}p_t^n}$$

Weighted average energy loss:

$$R_n = \int_0^1 d\epsilon (1 - \epsilon)^{n-1} P(\epsilon)$$

For RHIC: $n=7$

• $R_7$ approximation for $R_{AA}$
Model input parameters

- Multiple soft scattering approximation (ASW-MS):

\[ N_{gluon} = \int d\omega \frac{dI}{d\omega}(\omega_c, R) = \int d\omega \frac{dI}{d\omega}(\hat{q}, L) \]

- Opacity expansion (GLV, etc.):

\[ N_{gluon} = \left( \frac{L}{\lambda} \right) \int d\omega \frac{dI}{d\omega}(\mu, L) \]

- No qhat for opacity expansions.

\[ \hat{q} = \frac{\langle q_{\perp}^2 \rangle}{\lambda} \sim \frac{\mu^2}{\lambda} \]

- In evolving medium: effective path averaged input parameters.

Common variable between models: medium temperature
Energy loss models in realistic geometry
Scattering rate in (D)GLV

\[ x \frac{dN_g}{dx} = \frac{C_R C g \pi^2}{2} \int \frac{d^2q}{(2\pi)^2} d^2k \ dz \ C(q, z) \times K(k, q, z) \]

\[ C(q, z)^{GLV} = \frac{(2\pi)^2}{\lambda C_R} \frac{1}{\pi} \frac{\mu^2}{(q^2 + \mu^2)^2} \rho(z) \]

- Normalized Yukawa potential and \( \rho(z) \)
- \( \rho(z) \) is the probability to have a scattering at position \( z \)
  \( \rightarrow \) \( \rho/\lambda = \) scattering rate per unit length
- Explore effect of constant \( C(q) \) (uniform medium, GLV default) vs position-dependent \( C(q) \) (non-uniform medium)

Medium as seen by parton

- **Exercise:**
  - Parton is created at $x_0$ and travels radially through the center of the medium until it leaves the medium or freeze-out has taken place.

- **Characterize energy loss of parton with suppression factor $R_7$.**

- **More soft gluon radiation in case of inhomogeneous distribution of scattering centers.**
Medium as seen by parton

- **Exercise:**
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- **Characterize energy loss of parton with suppression factor $R_7$**

- **Large difference in energy loss for partons with long path lengths**
  - important for $I_{AA}$ calculations
Geometry of HI collision

- Woods-Saxon profile
- Wounded Nucleon Scaling with optical Glauber
- Medium formation time: $\tau_0 = 0.6$ fm
- Longitudinal Bjorken Expansion $1/\tau$
- Freeze out temperature: 150 MeV

\[
\frac{dN}{dp_{t, \text{hadr}}} = \frac{dN}{dp_{t, \text{parton}}} \circ P(\Delta E) \circ D\left(\frac{p_{t, \text{hadr}}}{p_{t, \text{parton}}}\right)
\]

Measurement

Input parton spectrum Known LO pQCD

Energy loss geometry medium

Fragmentation Function
Known from e+e-
Medium density profile

- Parton travels through evolving medium
- Parton sees different medium at each step in space and time
- Density of medium decreases as function of space and time
- In evolving medium: effective path averaged parameters which depend on $T^n$ → same treatment of geometry for different models (ASW-MS and GLV)

Local $q$ as function of space-time coordinate $x$ for different starting points
Medium as seen by parton

- Path average variables which characterize the energy loss.

\[ \langle \Delta E \rangle \propto \hat{q} L^2 \propto \omega_c \]

- Exercise:
  - Parton is created at \( x_0 \) and travels radially through the center of the medium until it leaves the medium or freeze out has taken place.
LHC estimates

\[ p_t^h = 50 \text{ GeV} \]

- ASW-MS
- ASW-SH
- WHDG rad

\[ R_{AA} \]

<table>
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<th>RHIC best fits</th>
<th>If [ \tau &lt; \tau_0 ] then [ \hat{q} = \hat{q}_0 ]</th>
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Opacity Expansion Single Gluon Spectrum

- General formula:

\[ x \frac{dN_g}{dx} = \frac{C_R C_g g^2}{2\pi^3} \int \frac{d^2q}{(2\pi)^2} d^2k \ dz \ C(q, z) \times K(k, q, z) \]

in which:

\[ K(k, q, z) = \frac{k \cdot q (k - q)^2 - \beta^2 q \cdot (k - q)}{[(k - q)^2 + \beta^2]^2(k^2 + \beta^2)} \times \left[ 1 - \cos \left( \frac{(k - q)^2 + \beta^2}{2Ex} \ z \right) \right] \]

\[ C(q) = \frac{1}{C_s (2\pi)^2} \frac{d^2\Gamma_{el}(q)}{d^2q} \]

- \(C(q)\) depends on medium properties.

- Explore effect of constant \(C(q)\) (uniform medium) vs position-dependent \(C(q)\) (non-uniform medium).

Local $\rho$ and $\mu$

- $\rho(z) = \text{medium density} = \mathcal{N}(z) \sim T^3$
- Differential cross-section temperature dependent while the parton propagates through the medium.

$$C(q,z) = \frac{g^4 \mathcal{N}(z)}{(q^2 + \mu(z)^2)^2}$$

$$\mathcal{N}(z) = \frac{\zeta(3)}{\zeta(2)} (1 + \frac{1}{4} N_f) T(z)^3$$

$$\mu(z)^2 = (1 + \frac{1}{6} N_f) g^2 T(z)^2$$

- Medium: participant scaling + Bjorken expansion + constant medium density prior to formation time
Single gluon spectrum (D)GLV

- Normalized $\rho(z)$ is varied and compared to the WHDG result.
- In WHDG radiative change of variables $q \rightarrow q+k$ is applied.
- Similar spectrum in case of exponentially decaying and uniform (brick) distribution of scattering centers.

\[ \int_0^\infty \rho(z) = 1 \]

\[ \text{Exponential} \]

\[ \text{Brick} \]
Opacity expansion + evolving participant scaling

- Parton starts at center of medium and moves radially outwards.
- More soft gluon radiation in case of inhomogeneous distribution of scattering centers.

Parton is absorbed by the medium

Outgoing quark spectrum

\[
\frac{dN}{dx_E} \quad \text{No energy loss}
\]

Single gluon spectrum

\[
\frac{dN}{dx} \quad \text{ \( L_{\text{eff}} = 6.35, \overline{\omega}_{\text{c,eff}} = 5.57 \text{ GeV} \)}
\]

\[
L_{\text{eff}} = 4.41 \text{ fm}
\]