Jet quenching: future experiments and ‘End Game’

Marco van Leeuwen, Nikhef, CERN

JETSCAPE Workshop, 5-7 January 2018
LBNL, Berkeley
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Disclaimer:
We are (I am) not in a position yet to design the End Game yet, but will try to do the next best thing....
The physics of parton energy loss — what do want/can we aim to learn?

Two broad categories: nature of energy loss mechanism and nature of the medium

Nature of the energy loss mechanism

Nature of the medium

Plus a host of technical questions, e.g. role of event-by-event/geometry fluctuations
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**Nature of the energy loss mechanism**
- Flavour dependence of energy loss
- Path length dependence of energy loss
- Interference: do jets lose energy as a single parton?
  - Also formation time effects
- Transverse broadening: relate transverse and longitudinal dynamics
  - Testing our understanding of the medium/dominant process

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Nature of the medium
- Density of the medium/value of qhat (vs temperature)
- Distribution of radiated energy; approach to thermalisation?
- Nature of the scattering centers?
  - Large angle deflection

Plus a host of technical questions, e.g. role of event-by-event/geometry fluctuations
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**Goal of the field:** answer as many of these questions as we can, as well as we can
- Technical questions have lower priority, but some may need answers to get to the interesting ones!
- Corollary: connections — Need coherent modeling of multiple observables

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Plus a host of technical questions, e.g. role of event-by-event/geometry fluctuations
Part I: basic observables
‘the bread and butter’
Simple observables; program and plan

• Observables/measurements:
  • Single particle $R_{AA}$, $v_n$
  • Di-hadron, recoil suppression $I_{AA}$
  • Heavy flavor $R_{AA}$, $v_n$

Address an important subset of the questions raised in the intro
• Density of the medium: value, time evolution of qhat
• Path length dependence of energy loss
• Heavy flavour energy loss:
  dead cone effect, importance of elastic scattering vs radiation
• Scale dependence of energy loss, medium properties?

Progress to be made by:
- Coherent modeling of multiple observables
- Improving precision, $p_T$ reach, comparing RHIC+LHC
Example of a systematic exploration: RHIC and LHC

Systematic comparison of energy loss models with data
Medium modelled by Hydrodynamics (2+1D, 3+1D)

$p_T$ dependence matches reasonably well
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**RHIC:** \[ \hat{q} = 1.2 \pm 0.3 \text{ GeV}^2/\text{fm} \] \( (T_i = 370 \text{ MeV}) \)

**LHC:** \[ \hat{q} = 1.9 \pm 0.7 \text{ GeV}^2/\text{fm} \] \( (T_i = 470 \text{ MeV}) \)
What do we learn from ‘knowing’ qhat?

RHIC: $\hat{q} = 1.2 \pm 0.3 \ \text{GeV}^2/fm \quad (T_i = 370 \ \text{MeV})$

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i.e. \[ \frac{\hat{q}}{T^3} \approx \begin{cases} 
4.6 \pm 1.2 & \text{at RHIC}, \\
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HTL expectation:

\[ \hat{q} = 2\pi C_R \alpha_S^2 N \ln \left( \frac{q_{\text{max}}^2}{m_D^2} \right) \]

\[ N = \frac{\zeta(3)}{\zeta(2)} \left( 1 + \frac{1}{4} N_f \right) T^3 \]

relation qhat - T depends on number of degrees of freedom, \( \alpha_s \)
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Conclusion for now: values are in the right ballpark — we semi-quantitatively understand parton energy loss

Arnold and Xiao, arXiv:0810.1026

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Future direction: can we make this quantitative?
E.g. determine number of degrees of freedom with a meaningful uncertainty?
Or constrain T-dependence of qhat?
What do we learn II: transport coefficient and viscosity

Parton gas expectation:
\[ \frac{\eta}{s} \approx 1.25 \frac{T^3}{q} \]

Elliptic flow

(Scaled) viscosity slightly larger at LHC

Transport coefficient from \( R_{AA} \)

Hints of increase of \( \eta/s \) and decrease of \( q/T^3 \) could have a common origin?

NB: effects not significant (yet); can we narrow down the uncertainties?

Majumder, Muller and Wang, PRL99, 192301
More systematics: compare soft scattering formalism

Similar fit to the data, as the JET paper, but using multiple-soft equations

Energy loss: BDMPS-ASW multiple soft scattering
Medium: Hydrodynamics; Hirano, Luzum & Romatschke

\[ \hat{q} = 2K \epsilon^{3/4} \]

pQCD expectation:
\( K = 1 \) (by definition)

Large difference (factor \( \sim 2 \)) between scale factor at RHIC and LHC

Conclusion seems different from JET collaboration work
Should follow up to find out what drives this
Points to modeling uncertainties? Can we reduce those?
High-\(p_T\) \(v_2\), \(R_{AA}\) in and out of plane

Current state: Hydro+E-loss models do not produce enough \(v_2\)

Various points under discussion:
- Effect of fluctuations
- HT gets higher \(v_2\)?
  Qin and Majumder, arXiv:0910.3016

Potential with more precise data, and some effort:
Use high-\(p_T\) data to co-validate/constrain medium evolution (models)
Another handle on path length dependence: di-hadrons

Near side trigger, biases to small E-loss

Away-side large L

Away-side (recoil) suppression $I_{AA}$
samples longer path-lengths than inclusive $R_{AA}$

Can be modelled with the same tools as inclusive particle production
I\textsubscript{AA} modeling

Medium model: Glauber profile  
Energy loss: Higher Twist

Medium model: (ideal) Hydro  
Energy loss: BDMPS-ASW multiple soft

R\textsubscript{AA} and I\textsubscript{AA} fit with similar density

Confirms \(\sim L^2\) dependence  
Calculations with elastic loss give too little suppression

T. Renk, PRC, arXiv:1106.1740
I_{AA} modeling

So far, model calculations only exist for RHIC:
- Would like to see LHC calculations to put modeling to the test
- Experimentally: extend p_{T} range

R_{AA} and I_{AA} fit with similar density

Confirms $\sim L^{2}$ dependence

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T. Renk, PRC, arXiv:1106.1740

Armesto et al, J.Phys. G37, 025104

H Zhang et al, PRL 98, 212301
I\_AA at the LHC

Data already exist — it’s really ‘just’ a matter of running the models/calculations!

Transition enhancement → suppression @ p\_T ~ 2 GeV
Heavy flavour $R_{AA}$; mass dependence

Compare beauty: non-prompt $J/\psi$
charm: D-mesons

Recent radiative (+coll) energy loss models agree well with HF data

Similarity of D meson and light hadron $R_{AA}$ ‘understood’

IMHO: importance of collisional energy loss not fully quantified

Medium model: PQM (static/expanding Glauber)

Several groups involved with different calculations approached; rough agreement between groups
Relating heavy and light flavor modeling: $D_s$ and $\hat{q}$

Cao, Qin, Bass, PRC 88, 044907

$$2 \pi T D_s = 8\pi \frac{C_F}{C_A} \frac{T^3}{\hat{q}}$$

(approximate relation; $D_s$ and $q\hat{q}$ are different regimes)

$D_s = 6/2 \pi T$

Trying out some numbers:

$q\hat{q}(T=400 \text{ MeV}) = 3 \text{ GeV}^2/\text{fm}$

However, perturbative estimate $D_s = 30/2 \pi T \rightarrow q\hat{q} \sim 0.6 \text{ GeV}^2/\text{fm}$

Should connect heavy and light flavor phenomenology

E.g.: Why is the perturbative estimate of $D_s$ so large?

LO: Svetitsky, PRD 37, 2484
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LO: Svetitsky, PRD 37, 2484
Jets: multi-parton states
High-p$_T$ jets vs hadrons

### Charged particle $R_{AA}$

$p_T$-dependence driven by energy dependence of E-loss

Single particles: consistent with expected constant (log $E$) dependence

Jets suggest increase of $\Delta E$ vs $E$

Tentative interpretation: in jets, multiple partons lose energy; more partons in high-$E$ jets $\rightarrow$ more E-loss

### Jet $R_{AA}$

Preliminary

ATLAS, $\sqrt{s_{NN}} = 5.02$ TeV, this analysis

ATLAS, $\sqrt{s_{NN}} = 2.76$ TeV, arXiv: 1411.2357

Jets: $R_{AA} < 1$ out to high $p_T$

Different for single particles and jets!?
High-p_T jets vs hadrons

Charged particle $R_{AA}$

Jet $R_{AA}$

First glimpse of jets as scale-dependent probes!
Opens up a field of study: p_T-dependence of jet modifications

$R_{AA}$-dependence driven by energy dependence of E-loss
Different for single particles and jets! ?

Single particles: consistent with expected constant (log E) dependence
Jets suggest increase of $\Delta E$ vs $E$

Tentative interpretation: in jets, multiple partons lose energy; more partons in high-E jets $\rightarrow$ more E-loss
First look at the models

JEWEL seems to capture the trends quite well

Some quantitative questions to be worked out;
e.g. increase of hadron R_{AA} too slow at 5 TeV?

Hybrid model: similar conclusion at first sight:
increase of jet R_{AA} less steep than hadron R_{AA}
Also consistent with energy shift + small corrections?

Take home message: need large p_{T} range to draw strong conclusions
small range: flat vs increase hard to disentangle; limited precision of models and data
Results clearly show that lost energy goes to large angle and soft particles.

Should try to go beyond this qualitative statement:

- Is the transport to large-angle consistent with expectations from pQCD?
- Does it require ‘thermalisation’?
- Can we learn more about coherence effects?

Several studies exist: JEWEL, Hybrid model, CCNU give partial answers…

Requires careful modeling of soft physics ― not easy and exploration of model uncertainties.
**High-z**: hadron vs jet R\(_{AA}\); scale dependence of energy loss

**Low-z**: mechanism of thermalisation in the medium vs soft fragmentation

Effects tend to be small:
- Experimentally: need good precision and study \( p_T \) dependence
- Models: need to consider systematic uncertainties on models/missing physics
Jet acoplanarity

Gaussian width: sensitive to momentum broadening

Relation momentum broadening - energy loss depends on nature of medium

\[ \langle q_{\perp}^2 \rangle = \hat{q}L \quad \hat{q} = KT^3 \]

K = 2-5 in QCD

larger in strong coupling

Tails: ‘Rutherford scattering’

Potential for direct sensitivity to scattering centers in the medium
Competing effects for acoplanarity: Sudakov broadening and E loss

Natural width of h-jet, jet-jet distributions

\[ \langle q^2 \rangle = (2 - 5 \text{ GeV})^2 \]
Putting things together: dialing the biases

Leveraging the differences in geometric and energy loss bias in observables

Conceptually powerful, but needs simultaneous modeling of geometry, energy loss, and experimental selection
Main ingredients: surface bias vs fluctuations

**h-h**

**jet-h**

**jet-jet (A_{ij})**

Surface bias differs between probes: largest for hadrons and energy/collider: stronger at RHIC

T. Renk, arXiv:1212.0646
Using biases: examples/ideas

• Disentangle geometric effects and fluctuations
  • Inclusive vs recoil
  • gamma-jet (or EW boson-jet) vs di-jets

• Select quark/heavy quark jets

• Dial the biases to tease out the small acoplanarity signals?

• Select jets that experience a large energy loss to increase ‘signal’
  • ‘Natural’ fluctuations from geometry and the intrinsic process are very large; ‘average’ not always useful

• Explicitly study energy loss dependence on e.g. opening angle?

Needs development/study: ideally have two classes of variables:
  • Variable(s) that preserve properties of the ‘vacuum jet’, i.e. not (much) affected by energy loss
  • Variable(s) that are explicitly sensitive to energy loss
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This is where jet shape variables have great potential!
Many options under study; unfortunately no time to review…
Observation: di-jet imbalance small at RHIC when selecting ‘hard-core jets’

Is this driven by the hard core selection?
→ Hard core selects jet (pairs) that lose little energy
Can be tested at LHC

What about other biases/effects:
- Steeper spectrum at RHIC
- Smaller overall energy loss at RHIC vs LHC?
- Quark vs gluon jets?

Promising avenue, needs follow-up to extract the physics
Example II: compare $\gamma$-jet and jet-jet

Comparing $\gamma$-jet and jet-jet changes:
- Energy loss bias
  reco jet energy is ‘after energy loss’
- Flavour content
  quark vs gluon jets

Leads to difference in frag function modification

Leverage this with models + increasing data precision to extract the physics
Example III: h-jet at RHIC and LHC

LHC: recoil jet suppression
\[ \Delta I_{AA} \sim 0.5 \] with \( R = 0.2 \)

RHIC: recoil jet suppression
\[ \Delta I_{AA} \sim 0.3 \] with \( R = 0.2 \)

Suppression numerically quite different at RHIC and LHC.

What drives this? Kinematic selection, different surface bias, …
Future experiments: HL-LHC

https://indico.cern.ch/event/647676/timetable/

HL-LHC: expect factor ~3 increase of lumi; 2.8 nb⁻¹/year

Current target lumi: 10 nb⁻¹ in run 3 + 4 (2021-2029) (ALICE request)

Increase in statistics compared to run 1, 2:
- 5x for triggers in ATLAS+CMS
- 10x for triggers in ALICE
- 100x for MB-like in ALICE

LHC HI lumi over the years
Future experiments: HL-LHC

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The HI program for run 3, 4 and beyond is being discussed in a series of workshops → European Strategy for Particle Physics
Future experiments: sPHENIX at RHIC

Physics drives detector requirements

<table>
<thead>
<tr>
<th>Physics goal</th>
<th>Detector requirement</th>
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<tbody>
<tr>
<td>High statistics for rare probes</td>
<td>Accept/sample full delivered luminosity</td>
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<td>Full azimuthal and large rapidity acceptance</td>
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<td>Precision Upsilon spectroscopy</td>
<td>Hadron rejection &gt; 99% with good e+/μ acceptance</td>
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<td>Mass resolution 1% @ $m_Y$</td>
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<td>High jet efficiency and resolution</td>
<td>Full hadron and EM calorimetry</td>
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<td>Tracking from low to high pT</td>
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<tr>
<td>Control over parton mass</td>
<td>Precision vertexing for heavy flavor ID</td>
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<tr>
<td>Control over initial parton p_T</td>
<td>Large acceptance, high resolution photon ID</td>
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<td>Full characterization of jet final</td>
<td>High efficiency tracking for 0.2 &lt; p_T &lt; 40GeV</td>
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Planned start: 2022 ~ LHC run 3
Main directions

Experiment:
• Increased precision and $p_T$ reach
  Non-trivial improvement of physics potential!
• More differential studies
  Leveraging the biases
• Better overlap between RHIC and LHC

Theory/modeling:
• Need coherent/simultaneous description
  of multiple observables to constrain the physics
• Need competing/alternative models/mechanisms to compare and contrast
  Also within a single group/code!
Thanks for your attention!
More distant future: FCC and HE-LHC

FCC
Future Circular Collider
\[ \sqrt{s} = 100 \text{ TeV for pp, } \sqrt{s_{NN}} = 39.4 \text{ TeV for Pb-Pb} \]
very large project; requires new tunnel \( \sim 100 \text{ km} \)

HE-LHC
High-Energy LHC
\[ \sqrt{s} = 27 \text{ TeV pp, } \sqrt{s_{NN}} = 10.6 \text{ TeV Pb-Pb} \]
Earliest possible realisation 2040

More info: see HL-LHC workshops and FCC weeks, e.g.: http://fcw2018.web.cern.ch
Simple observables; how to model them?

• A lot of experience exists with simple modeling:
  • Production, energy loss, and fragmentation
  • Plus full hydro background or a good approximation in most cases
• Main advantage: keeps the model tractable (clear what is put in)
• Disadvantage: no natural extension to jet observable
  • Simple modeling may be good enough for single particle observables
  • Except, maybe via jet functions, but long and tedious road
• Also not always obvious how to implement path-length dependence in a non-uniform medium

Note: should not forget model uncertainties/freedoms
  • Important part of the story; may point to new questions/directions!
  • Several aspects have been explored; many connections still missing
Summary of transport coefficient study

**RHIC:**
\[ \hat{q} = 1.2 \pm 0.3 \text{ GeV}^2/fm \]
\( (T_i = 370 \text{ MeV}) \)

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Arnold and Xiao, arXiv:0810.1026

HTL expectation: \( \hat{q} \approx 24 \alpha_s^2 T^3 \approx 2 T^3 \)

Sizeable uncertainties from \( \alpha_s \), treatment of logs etc expected

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Values found are in the right ballpark compared (p)QCD estimate

Magnitude of parton energy loss is understood
Transport coefficient and viscosity

Transport coefficient:
momentum transfer per unit path length

\[ \hat{q} = \frac{\langle q_1^2 \rangle}{\lambda} = \rho \int dq_1 q_1^2 \frac{d^2 \sigma}{dq_1^2} \]

\[ \rho \propto T^3 \quad \hat{q} \text{ basically measures the density} \]
Transport coefficient and viscosity

Transport coefficient:
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\[ \rho \propto T^3 \quad \hat{q} \text{ basically measures the density} \]

Viscosity:

\[ \eta \propto \rho \langle p \rangle \lambda \]

General relation:

\[ \frac{\hat{q}}{T^3} \propto \left( \frac{\eta}{s} \right)^{-1} \]
Transport coefficient and viscosity

Transport coefficient:
momentum transfer per unit path length

\[
\hat{q} = \frac{\langle q^2 \rangle}{\lambda} = \rho \int dq^2_1 \frac{d^2 \sigma}{dq^2_1}
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\( \rho \propto T^3 \)  \( \hat{q} \) basically measures the density

Viscosity:
\( \eta \propto \rho \langle p \rangle \lambda \)

General relation:
\[
\frac{\hat{q}}{T^3} \propto \left( \frac{\eta}{s} \right)^{-1}
\]

Expect \( \frac{\eta}{s} \approx 1.25 \frac{T^3}{\hat{q}} \) for a QCD medium

Majumder, Muller and Wang, PRL99, 192301
Elastic+radiative energy loss; follows BDMPS-Z in appropriate limits
Medium: Bjorken-expanding Glauber overlap

\( T_i = 350 \text{ MeV} \@ \tau_0 = 0.8 \text{ fm/c} \)

\( T_i = 530 \text{ MeV} \@ \tau_0 = 0.5 \text{ fm/c} \)

Good agreement with JET collaboration values
$T$ vs $t$ in EPOS/MC@HQ

Medium parameters in MC@HQ agree well with light flavour fits

Q: how does the relation $\Delta E(T)$ compare?
Model(ing) uncertainties for high-\(p_T\) \(v_2\)

- Initial time/treatment
- Freeze-out temperature/treatment
- Length sampling in a non-uniform medium
- Event-by-event fluctuations

When reporting a model/calculation; make sure to specify these things
Observation: high-$p_T$ $v_2$ is measured wrt to low $p_T$ $v_2$

Basically, measure $\left< v_2^2 \right>$

Fluctuations bias $v_2$

NB: no energy loss fluctuations; not so clear how geometry was implemented (L)
$v_2$ in CUJET

GLV-based E-loss

as runs, with cut-off at low $Q$

$$\alpha_s \rightarrow \alpha_s(Q^2) = \begin{cases} \frac{2\pi}{\alpha_{max} \log(Q/\Lambda_{QCD})} & \text{if } Q \leq Q_{min} \\ \frac{2\pi}{9 \log(Q/\Lambda_{QCD})} & \text{if } Q > Q_{min} \end{cases}$$

Cut-off is the main model parameter

Standard settings underpredict $v_2$

Black dashed line: $\alpha_{max}$ depends on $\phi - \Psi$

Add $v_2$ ‘by hand’

However, see also: CUJET3.0

Xu et al, arXiv:1509.00552
$v_2$ in Higher Twist

Qin and Majumder, arXiv:0910.3016
Relating qhat to medium density, or $T$

There are sizeable factors of uncertainty in relation $\hat{q}(T)$

- $\alpha_s$
- degrees of freedom
- $q_T$ cut-off

Some of these are intrinsic uncertainties, some are convenience

When comparing values from different authors, need to check what was used

Ideally: use same convention when comparing calculations
Comparison to LBT


Factor \(~1.5\) between LBT fits and JET values; probably within uncertainties

Heavy+light energy loss
Di-hadrons and single hadrons at LHC

Need simultaneous comparison to several measurements to constrain geometry and E-loss

Here: $R_{AA}$ and $I_{AA}$

Three models:
- **ASW**: radiative energy loss
- **YaJEM**: medium-induced virtuality
- **YaJEM-D**: YaJEM with $L$-dependent virtuality cut-off (induces $L^2$)
Di-hadron modeling

Model ‘calibrated’ on single hadron $R_{AA}$

$L^2$ (ASW) fits data
$L^3$ (AdS) slightly below

Clear sensitivity to $L$ dependence

$L$ (YaJEM): too little suppression
$L^2$ (YaJEM-D) slightly above

Modified shower generates increase at low $z_T$
Di-hadron with high-$p_T$ trigger

$p_{t,\text{trig}}$ (GeV):

- 19.2 - 24.0 GeV
- 14.0 - 28.8 GeV
- 28.8 - 35.2 GeV
- 35.2 - 48.0 GeV

$p_{t,\text{trig}} > 20$ GeV at LHC: strong signals even at low $p_T^{\text{assoc}}$ 1-3 GeV
CMS di-hadrons: near side

Transition enhancement → suppression @ $p_T \sim 3$ GeV

also compatible with $I_{AA}=1$ at $p_T > 3$ GeV?
Some open and partially-answered questions

Energy loss mechanism
physics of hard partons in a plasma

Flavor dependence of energy loss

Role of interference effects
Do all partons in a jet lose energy?

Scale dependence of energy loss?

Path length dependence of energy loss
—> tomography of the medium

Thermalisation of the lost energy

Angular broadening
large-angle scattering

Nature of the medium
density, character of constituents