Imaging the RHIC medium with hard probes
— systematics, results and potentials

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Introduction
Pathlength dependence
- what the data show about energy loss physics
Geometry of the evolution model
- what the data show about hydrodynamical evolution
Jets and energy redistribution
- perturbative vs. non-perturbative mechanisms
Measuring $\hat{q}$
- why this is beyond our grasp
Conclusions
The 'standard' jet quenching picture

pQCD radiative energy loss for hard partons interacting with the medium

What is perturbative here?

1) the hard process? — almost certainly
2) the radiation of gluons from a hard parent parton? — quite possibly
3) the re-interaction of radiated gluons (the shower) with the medium? — maybe
4) the medium degrees of freedom? — almost certainly not

⇒ there is a zoo of pictures!
Which is correct?
The zoo of bulk evolution pictures

- viscous vs. ideal hydro
  - due to viscous entropy production, viscous IS contains (up to 50%) less entropy
  ⇒ how does this influence hard probes?

- Glauber vs. CGC initial state
  - 'sharpness' of the initial state influences the average pathlength at given angle
  ⇒ is this seen in $R_{AA}(\phi)$?

- early freeze-out vs. late freeze-out
  - when is the ability of the medium to modify hard probes no longer significant?
  ⇒ is there a hard probe which is sensitive to the question?

- 'black' vs. 'grey' medium
  - some models predict a complete quenching of jets in the QGP
  ⇒ can we tell a core/corona picture from a partially transparent medium?

Which is the correct model?
**The strategy**

Test systematically for pathlength dependence and correlation properties!

- test combinations of hydro and parton-medium interaction models
- require that the same model describes bulk, $R_{AA}$ and $I_{AA}$
- study several differential observables within *the same* hydro framework

Various experimental handles on interesting parameters:

  - centrality dependence $\Leftrightarrow$ in-medium pathlength and medium density
  - reaction plane angle $\Leftrightarrow$ in-medium pathlength
  - dihadron correlations $\Leftrightarrow$ in-medium pathlength and trigger bias, correlation width
  - energy ($\sqrt{s}$) dependence $\Leftrightarrow$ medium density, kinematics
  - hadron species $\Leftrightarrow$ parton type

It is absolutely crucial to dispense with toy medium models (static cylinders, Bjorken cylinders, hard sphere overlap...). It is known now that high $P_T$ observables using the same jet quenching model may come out a factor two (!) different between constrained hydro models. This indicates that any result for an unconstrained bulk model are essentially a random number.
**Energy loss vs. in-medium shower**

Conceptual model difference: energy loss vs. medium modified fragmentation function

Single inclusive hard hadron production:
- dominated by showers in which a single parton carries most of the momentum
  - ![Diagram 1](image1.png)
  - unbiased hard jet events — multiple low $p_T$ hadron production
    - ![Diagram 2](image2.png)

For single inclusive hard hadron production:
\[ \Rightarrow \text{fragmentation function} \approx \text{hadronization of leading parton} \]
\[ \Rightarrow \text{medium effect} \approx \text{reduction of leading parton energy} \]
\[ \Rightarrow \text{if hadronization happens outside the medium, the two factorize!} \]

\[ \Rightarrow \text{Medium-induced energy loss good concept to describe leading hadron only} \]
1) medium-induced energy loss for the leading parton, then vacuum fragmentation

\[ P(E, \Delta E) \otimes D_{\text{vac}}(z, Q_i \rightarrow Q_h) \otimes D_{\text{vac}}(z, Q_h) \]

(BDMPS, ASW, (D)GLV, AMY, some HT results)

2) in-medium shower, followed by hadronization in vacuum

\[ D_{\text{med}}(z, Q_i \rightarrow Q_h) \otimes D_{\text{vac}}(z, Q_h) \]

(recent HT, JEWEL, YaJEM, Q-PYTHIA, Q-HERWIG)
The toolkit

- Duke 3+1 d hydrodynamical model

- Jyväskylä 2+1 d hydrodynamical model

- VISH2+1 2+1 d viscous hydrodynamical model
  H. Song and U. W. Heinz, 0709.0742; 0712.3715; 0805.1756

- ASW radiative energy loss formulation

- parametric elastic energy loss modelling

- AdS/CFT - pQCD hybrid model

- elastic MC (pQCD interactions)
  J. Auvinen, K. J. Eskola and T. Renk, 0912.2265 [hep-ph].

- energy loss from leading parton

- in-medium shower

- YaJEM (MC code for induced radiation and drag)
Outline of modelling:

- generate a hard back-to-back parton pair according to LO pQCD → take care of initial state effects (nPDFs), intrinsic $k_T$, . . .
- follow the path of each parton through the evolving hydrodynamical medium → in eikonal approximation, tests with eMC have shown that corrections are small
- compute gluon radiation from leading parton / shower evolution → different prescriptions, ASW, YaJEM, . . .
- hadronize the emerging partons, assuming it happens outside the medium → tested for leading hadron in YaJEM event by looking at complete branching chain → FFs for leading parton, Lund model for shower
- apply any experimental cuts → count yields of remaining hadrons
- model $\hat{q}, \hat{e}$ as functions of thermodynamics → one free parameter, adjusted to $R_{AA}$ in 200 AGeV central AuAu collisions → any other observable calculated without additional parameters

Needs substantial amount of CPU-time, but is easily doable on a grid facility.
• spread in-plane vs. out of plane in $R_{AA}(\phi)$ related to

![Diagram showing strong and weak surface bias](image)

• strong surface bias (medium very opaque for large pathlength/ high density regions) → more emission in-plane because the emitting surface is larger

• weak surface bias (emission also from the medium core) → more emission in plane because $\langle x \rangle < \langle y \rangle$

⇒ no clear signal
Pinning down pathlength

- normalization of $R_{AA}(b)$ increases for peripheral collisions due to

- drop in average density
  $\rightarrow$ this is seen for any scenario of parton-medium interaction

- drop in average pathlength
  $\rightarrow$ this probes pathlength dependence in a qualitatively characteristic way

$\Rightarrow$ expect $R_{AA}^{AdS} > R_{AA}^{rad} > R_{AA}^{rel}$ for non-central collisions

For increasing $b$, $R_{AA}$ rises and a spread between in-plane and out of plane emission opens:

  - normalization $\Leftrightarrow$ average density, average pathlength
  - spread $\Leftrightarrow$ hydro density profile, emission geometry, pathlength difference. . .
Pinning down pathlength

- advantage of back-to-back correlations

\[ L^2 \text{pathlength dependence} \quad \text{near side} \quad \text{near side} \]

\[ L \text{pathlength dependence} \]

- expect (due to surface bias of trigger) \( \sim \) factor 2 in away side pathlength \( \Rightarrow \) magnifies pathlength effects as compared to \( R_{AA}(\phi) \)

- Large difference in predicted away side per-trigger yield (or \( I_{AA} \))
- elastic fails completely to reproduce spread and normalization
  ⇒ large component of elastic energy loss (>10%) disfavoured by data
- AdS pQCD hybrid has largest spread and average for given hydro
  ⇒ dependent on the medium model, this is good or bad
- dependence on hydro model (3+1d hydro causes larger spread)
  ⇒ need to investigate systematically (⇒ later in this talk)
• MC simulations for $I_{AA}$ / away side per-trigger yield

• essentially same picture, just more pronounced
  ⇒ a large component of elastic $L$ pathlength dependence is ruled out

• no clear distinction between strong coupling and perturbative dynamics
Systematic study with different hydro codes/runs:

- **ideal 3+1 d**: $\tau_i = 0.6 \text{ fm/c}$, $T_F = 130 \text{ MeV}$, Glauber IC, only $b = 7.5 \text{ fm}$
- **ideal 2+1 d**: $\tau_i = 0.17 \text{ fm/c}$, $T_F = 160 \text{ MeV}$, Glauber initial condition
- **viscous 2+1 d Glauber**: $\tau_i = 0.4 \text{ fm/c}$, $T_F = 130 \text{ MeV}$, $\eta/s = 3/4\pi$, Glauber IC
- **viscous 2+1 d CGC**: $\tau_i = 0.4 \text{ fm/c}$, $T_F = 130 \text{ MeV}$, $\eta/s = 3/4\pi$, CGC IC

Also some runs (no full systematics) with:

- **ideal 2+1 d**: $\tau_i = 0.6 \text{ fm/c}$, $T_F = 160 \text{ MeV}$, Glauber initial condition
- **ideal 2+1 d**: $\tau_i = 0.17 \text{ fm/c}$, $T_F = 130 \text{ MeV}$, Glauber initial condition

$\Rightarrow$ very difficult to 'change only a single parameter in hydro to see what happens'
$\Rightarrow$ don’t run scenarios in obvious contradiction with bulk data
$\Rightarrow$ compromise between best fit to data and interesting parameter choice

Very difficult to systematically cover the hydro model space!
Pinning down geometry

20 - 30 %

PHENIX in plane
PHENIX out of plane
2+1d ideal
2+1d viscous CGC
2+1d viscous Glauber
3+1d ideal

20 - 30 %

PHENIX in plane
PHENIX out of plane
2+1d ideal
2+1d viscous CGC
2+1d viscous Glauber
3+1d ideal

30 - 40 %

PHENIX in plane
PHENIX out of plane
2+1d ideal
2+1d viscous CGC
2+1d viscous Glauber

30 - 40 %

PHENIX in plane
PHENIX out of plane
2+1d ideal
2+1d viscous CGC
2+1d viscous Glauber

R_AA

R_AA

p_T [GeV]

p_T [GeV]
Pinning down geometry

40 - 50%

50 - 60%

\begin{align*}
\text{PHENIX in plane} & \quad \text{PHENIX out of plane} \\
2+1d \text{ ideal} & \quad 2+1d \text{ viscous CGC} \\
2+1d \text{ viscous Glauber} & \\
\end{align*}
### Pinning down geometry

<table>
<thead>
<tr>
<th>hydro model</th>
<th>elastic $L$</th>
<th>radiative $L^2$</th>
<th>AdS/QCD $L^3$</th>
</tr>
</thead>
<tbody>
<tr>
<td>3+1d ideal</td>
<td>fails</td>
<td>works</td>
<td>marginal</td>
</tr>
<tr>
<td>2+1d ideal</td>
<td>fails</td>
<td>fails</td>
<td>fails</td>
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<td>2+1d viscous CGC</td>
<td>fails</td>
<td>marginal</td>
<td>works</td>
</tr>
<tr>
<td>2+1d viscous Glauber</td>
<td>fails</td>
<td>marginal</td>
<td>works</td>
</tr>
</tbody>
</table>

- low decoupling temperature (long thermal evolution) favoured
- ambiguity between geometry and AdS/QCD vs. radiative dynamics
- viscosity increases the spread
- initial state geometry is a small effect
  → not surprising for $L^2$ or $L^3$ weighting which suppress early times

Can we say still more?
Pinning down geometry

• How large is the degree of surface bias?

Qualitatively different expectations for $I_{AA}(\phi)$
Pinning down geometry

20-30%

20-30%, AdS

50-60%

50-60%, AdS
Pinning down geometry

- no geometry suggests a black core
- even theory statistics-limited... → results inconclusive at $b = 7.49$ fm
- trends as established already — AdS results show stronger effect for large $b$
- awaits comparison with new PHENIX data

More differential: Consider subleading hadrons
⇒ Jets!
Experimentally, jets are difficult to identify above background. Why bother?

- Jets involving multiple soft hadrons are frequent
  → higher statistics, reach to larger $P_T$

- Precise mechanism of energy loss difficult to study for leading hadron
  → but changes the subleading hadron distribution

- Jet evolution is usually computed in momentum space
  → the medium provides a 'meter-stick' and a 'clock' in position space

Additional non-trivial information from jets!
It is *hellishly* difficult to compute something that can be compared with data!

Problem 1: Cannot distinguish medium and jet at low $P_T$:

any low $P_T$ hadron correlated with the jet axis may be correlated because. . .

- it is part of the hadronization of the perturbative shower
- it is bulk medium recoiling from the jet-medium interaction
- it is, due to a similar bias, accidentally correlated
  (e.g. unmodified jets tend to emerge $\perp$ surface — direction of radial flow!)
- bias in jet-finding algorithms

Problem 2: The hadronization models may not be valid at low $P_T$ (in the medium)

- at present we can only compute reliably *above* a $P_T$ cut
  ⇒ need to worry about bias (excluding events with lots of soft production)

Jet expectations from MC code are proof of principle! Real calculations will require knowledge of experimental jet finding strategy — lots of issues hidden in the small print!
Jet finding

• standard jet finding algorithms search for jets with vacuum properties ⇒ they find **unmodified** jets

But: there is some control over the jet-finding bias - jet $R_{AA}$

• a (magical) ideal jet finder would find a jet no matter how modified ⇒ jet $R_{AA} \sim 1$
  → i.e. the whole shower evolution is modified

• a simplistic jet finder finds a jet when it essentially is like a single hadron ⇒ jet $R_{AA} \approx \text{hadron } R_{AA}$
  → i.e. the jet is dominated by a single leading parton (energy loss picture)

Thus, to get physics from jets which is not already in hadron $R_{AA}$

\[
1 > R_{AA}^{jets} > R_{AA}^{hadrons}
\]

is a necessary condition.

⇒ need dedicated in-medium jet finding!
• distinctive feature of jet MC codes: low $p_T$ hadron production

- medium-induced radiation as in RAD or FMED enhance the hump-backed plateau
- a drag force in which energy is transferred to the medium does not
- picture of RAD and FMED: 'lost' energy reappears in low $p_T$ hadron production
  → **perturbative** redistribution of energy in the jet cone

Jet shapes for typical medium path:

\[ \Psi_{int}(r, R) = \frac{\sum_i E_i \theta(r-R_i)}{\sum_i E_i \theta(R-R_i)} \]

⇒ the perturbative energy redistribution is a **small-angle** mechanism!

Connection to $\gamma$-h correlations

- averaged over 3-d hydrodynamical medium evolution, $I_{AA}$ in $\gamma$-h:

![Graph showing $I_{AA}$ vs $z_T$ with different energy photons and models](image)

- lost energy in ASW nonperturbatively distributed in medium (large angle)
- perturbative small angle low $z$ hadron production in shower should be visible

• YaJEM: lost energy is perturbatively redistributed in a broadened cone
• ASW: lost energy is non-perturbatively redistributed in shockwaves

Correlation strength extracted in cone
• no low \( z \) enhancement seen
\[ \Rightarrow \text{energy is not redistributed in the cone} \]
• removing energy from the cone works fine
\[ \Rightarrow \text{indication for a non-perturbative fate of radiated gluons, large angle correlations} \]
• maybe perturbative mechanism observable at LHC

EXTRACTING TRANSPORT COEFFICIENTS

- \( \hat{q} \) usually determined from a model after fit to \( R_{AA}, I_{AA} \), but:

\( \hat{q} \) is not a number, it is a tensor \( \hat{q}_{\alpha\beta}(\eta_s, r, \phi, \tau) \)

Should it be quoted:
- at a single spacetime point?
- averaged at an instance in proper time?
- averaged over the evolution?
- for quarks or gluons?
- averaged over all emerging hadrons?
- . . . ?

This matters! For the same 3-d hydro and the same fit to \( R_{AA}, I_{AA} \)

<table>
<thead>
<tr>
<th>prescription</th>
<th>( \hat{q} ) [GeV(^2)/fm]</th>
<th>prescription</th>
<th>( \hat{q} ) [GeV(^2)/fm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>max. value</td>
<td>18.5</td>
<td>averaged at 1 fm/c</td>
<td>4.2</td>
</tr>
<tr>
<td>av. ( T_F = 130 ) MeV</td>
<td>0.82</td>
<td>av. ( T_F = 140 ) MeV</td>
<td>1.02</td>
</tr>
<tr>
<td>path averaged</td>
<td>3.4</td>
<td>path averaged w. bias</td>
<td>2.2</td>
</tr>
</tbody>
</table>

The notion of an averaged \( \hat{q} \) is not well defined!

(you wouldn’t ask a meteorologist to summarize the weather for the next 48 hours in a single number either. . . )

T. R.,1004.0809 [hep-ph]
Extracting transport coefficients

• extra complication: need a model to translate thermodynamics into $\hat{q}$

• from systematic study: ASW: 18.5 GeV$^2$/fm, HT: 1.5 GeV$^2$/fm
  $\Rightarrow$ ideal QGP estimate: 5.15 GeV$^2$/fm - is there an sQGP or a rwQGP?

• but: ASW assumed $\hat{q} \sim \epsilon^{3/4}$, HT assumed $\hat{q} \sim T^3$
  $\Rightarrow$ using $T^3$ ASW extracts $\sim 9$ GeV$^2$/fm

  Factor 2 difference in the outcome dependent on the scaling assumption!

• all assume $L^2$ pathlength dependence - what if it is really $L^3$?

• assuming $\hat{q} \sim K\epsilon^{3/4}$, $K$ in viscous hydro up to factor 2 larger than in ideal
  $\Rightarrow$ viscous reheating implies reduced entropy in initial state

• cutoff dependence in different models introduces large theoretical error

• meaningful measure of $\hat{q}$ requires good control over qualitative aspects first
  $\Rightarrow$ too early to provide numbers which mean anything!

Summary

• systematic comparison of models and data, aiming for:
  → pathlength dependence, medium geometry, energy redistribution

  Pathlength dependence

• $L$ dependence (elastic energy loss) not supported by the data
  → elastic component $\sim 10\%$ or less
  → but in pQCD calculations modelling the QGP as quasiparticle gas elastic is large
  ⇒ the DOF of the QGP are not a quasiparticle gas

• $L^2$ and $L^3$ both seem to work within systematical uncertainties
  ⇒ can't decide between pQCD and strong coupling dynamics yet

  Geometry

• a long hadronic evolution is preferred

• the medium core is not opaque

• not sensitive yet to initial state geometry or viscosity effects
Summary

Energy redistribution

• energy lost from leading hadron can be traced in $\gamma$-h and jets
  $\rightarrow$ part of the energy flows to large angles by a non-perturbative mechanism
  $\rightarrow$ part of the energy is perturbatively redistributed in the jet cone
  $\Rightarrow$ will be interesting at LHC to see the balance change with $E_{jet}$

Transport coefficients

• both conceptual and systematic difficulties in the definition and measurement
  $\rightarrow$ in my opinion, currently can’t seriously be done
  $\Rightarrow$ let’s settle qualitative questions first!

RHIC has shown that tomography with hard probes is doable - let’s wait for the much larger $p_T$ range at the LHC!
The normalization and split of $R_{AA}(\phi)$ using elastic energy loss is not an artefact of using a simple parametric model. A detailed MC simulation of elastic energy loss has the same outcome: