Ivan Vitev

Hard probes in heavy ion collisions: current status and prospects for application of QCD evolution techniques

QCD Evolution Workshop, Santa Fe, NM 2014
Outline of the talk

- Motivation for studying hard probes in heavy ion collisions at RHIC and the LHC
- The physics of inclusive particle quenching. Interpretation of the RHIC and LHC results
- Directions for improvement in leading particle phenomenology in A+A at RHIC and the LHC
- From leading particles to jets. New LHC discoveries
- Resummation and possible directions for improvement in jet substructure phenomenology in heavy ion reactions
The phase diagram of QCD

**Big Bang**

- **Quark-Gluon Plasma**
  \[ \langle \bar{\psi} \psi \rangle = 0, \langle \psi \bar{\psi} \rangle = 0 \]

- **Hadron Gas**
  \[ \langle \bar{\psi} \psi \rangle \neq 0, \langle \psi \bar{\psi} \rangle = 0 \]

- **Color Superconductor**
  \[ \langle \bar{\psi} \psi \rangle = 0, \langle \psi \bar{\psi} \rangle \neq 0 \]

- **Chiral symmetry braking**
- **Quark pairing**

**Axes:**
- \( T [\text{MeV}] \)
- \( \mu_B [\text{MeV}] \)

**Institutions:**
- CERN-SPS
- RHIC
- LHC
- SPS

**People:**
- M. Stephanov et al. (2009)

**Additional Notes:**
- Chandra X-ray telescope
- Magnetic field \( \mu_B \)
Jet quenching in A+A collisions has been regarded as one of the most important discoveries at RHIC.

- Tested against alternative suggestions: CGC and hadronic transport models ✓
- Phenomenologically very successful ✓

\[ R_{AA}(I_{AA \ldots}) = \frac{\text{Yield}_{AA}}{\langle N_{\text{binary}} \rangle_{AA}} = \frac{1}{\langle N_{\text{binary}} \rangle_{\text{AuAu}}} \frac{d\sigma_{\text{AuAu}}}{dp_T dy} = \frac{d\sigma_{\text{pp}}}{dp_T dy} \]

PHENIX Au+Au (central collisions):
- Direct γ
- π^0 Preliminary
- η
- GlV parton energy loss (dN^0/dy = 1200)

Adams, J. et al. (2003)
The suppression of inclusive particle production in A+A is exclusively driven by final-state interactions. It is quite remarkable how small CNM effects are.
An operator approach to multiple scattering in QCD

- A general approach

- Can be applied to various collinear parton systems: 1 parton broadening, 2 partons [3],[8] medium induced splitting, meson dissociation [1]

$$k^+ \frac{dN^n}{dk^+ d^2k_\perp} \propto Tr \sum_{i_1...i_n} \overline{A}^{i_1...i_n} A_{i_1...i_n} = \overline{A}^{i_1...i_{n-1}} \left(D^+ D + V^+ + V\right) A_{i_1...i_{n-1}} = \overline{A}^{i_1...i_{n-1}} \hat{R} A_{i_1...i_{n-1}}$$

M. Gyulassy et al., (2001)

An operator that evolves suitably chosen initial conditions, discrete steps. Encodes the pole, phase and color structure

$$M_{2,0,3}^c \approx J(p) e^{ipz_0} e^{-i q_1 \cdot b_1} \int \frac{d^2q_1}{(2\pi)^2} v(0,q_1) e^{-i k_\perp \cdot q_1} \int \frac{d^2q_2}{(2\pi)^2} v(0,q_2) e^{-i k_\perp \cdot q_2} \times \frac{1}{2} (2ig_s) \epsilon \cdot (k - q_1 - q_2) e^{i \omega_0 z_1} \left(1 - e^{-i \omega (z_1 - z_0)}\right) \left[[c, a_2], a_1\right] (T_{a_2} T_{a_1})$$
In the soft gluon emission limit

\[
k^+ \frac{dN_g}{dk^+ d^2k_\perp} = \sum_{n=1}^{\infty} k^+ \frac{dN^n_g}{dk^+ d^2k_\perp} = \sum_{n=1}^{\infty} \frac{C_R \alpha_s}{\pi^2} \left[ \prod_{i=1}^{n} \int_0^{L-\sum_{j=i+1}^{n} \Delta z_j} \frac{d\Delta z_i}{\lambda_g(z_i)} \right] \int d^2 q_i \left( \frac{1}{\sigma_{el}} d\sigma_{el} - \delta^2(q_i) \right)
\]

\[
\times \left[ -2C_{(1...n)} \cdot \sum_{m=1}^{n} B_{(m+1...n)(m...n)} \left( \cos \left( \sum_{k=2}^{m} \omega_{(k...n)} \Delta z_k \right) - \cos \left( \sum_{k=1}^{m} \omega_{(k...n)} \Delta z_k \right) \right) \right]
\]

Color current propagators

Coherence phases (LPM effect)

- One can make a continuous approximation assuming that medium is infinite (BDMPS)
- In SIDIS one can replace the scattering lengths and momentum transfers with twist 4 quark-gluon correlation function. NLO calculation for the k_T-weighted cross section, evolution of the correlation function

See talk by H. Xing
Non-abelian energy loss

\[ \Delta E^{(1)} \approx \frac{C_R \alpha_s}{4} \frac{\mu^2}{\lambda_g} L^2 \log \frac{2E}{\mu^2 (L)L} + \ldots, \]

- Static medium

\[ \Delta E^{(1)} \approx \frac{9\pi C_R \alpha_s^3}{4} \frac{1}{L} \frac{dN^g}{dy} \log \frac{2E}{\mu^2 (L)L} + \ldots, \]

- 1+1D Bjorken

- Transport coefficient 
- Effective gluon rapidity density

- Difference between static and an expanding medium: SIDIS and A+A

- Numerical example relevant to the 62 GeV run at RHIC
Below $p_T = 10$ GeV important nuclear effects beyond energy loss contribute to the $R_{AA}$ shape: Cronin, power corrections, shadowing.

- Parton energy loss is relatively small and $R_{AA}$ is driven by its interplay with the power law parton spectrum.

- The number of emitted gluons is not small ($>10$ for g jet at LHC).
- Role of geometry is as expected.

I. V. et al. (2002)
What is the relevant regime of medium-induced radiative corrections (E-loss) incoherent Gunion-Bertsch or coherent Landau-Pomeranchuk-Migdal?

How do jets see the medium? Are they strongly coupled or are they weakly coupled to it?
Caveat: predictions are made at different C.M. energy.
Even if an error is added for this most calculations will be incompatible with data.

### Predictions for the LHC

![Graph](image)

<table>
<thead>
<tr>
<th>Authors</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zakharov</td>
<td>$\pi^0$, 5% (T_0=404 MeV=1.26 V_RHHC), rad.+coll.+1d exp., chadh.</td>
</tr>
<tr>
<td>Wang et al.</td>
<td>$\pi^0$, 5% ($\chi_0=3.3c_0^{RHHC}$), WW close+1d exp., shadowing</td>
</tr>
<tr>
<td>Vitov</td>
<td>$\pi^0$, 10%, GLV+g-fccdb.+cold close, $dN/d\eta=1.7$-3.3($dN/d\eta$) RHHC</td>
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<tr>
<td>Pantuč</td>
<td>charged, $N_{part}=350$, $v_{QGP}^2=4.2$ fm$^{-2}$, 0.5($v_{QGP}^2$) RHHC</td>
</tr>
<tr>
<td>Lokhtin et al.</td>
<td>charged, 10% ($dN/d\eta=2700$), rad.+coll. close in MC</td>
</tr>
<tr>
<td>Kopčičov</td>
<td>$\pi^0$, 10%, early hadronization</td>
</tr>
<tr>
<td>Liu et al.</td>
<td>$\pi^0$, $p_T^{beam}=40$, 10%, 2$&lt;\eta&lt;2$ w. conv., transv. exp.</td>
</tr>
<tr>
<td>Jeon et al.</td>
<td>$\pi^0$, $p_T^{beam}=40$, 10%, ($\chi_0=1$ fm), BH close+QW, $AE_{E}^{RHHC}$</td>
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<tr>
<td>Wiecko et al.</td>
<td>$\pi^0$, 10%, rad.+coll. close, $dN/d\eta=1.75$-2.9($dN/d\eta$) RHHC</td>
</tr>
<tr>
<td>Qin et al.</td>
<td>charged, 10% ($dN/d\eta=2500$), AMY+hydro, $\alpha_s=0.25$-0.33</td>
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<tr>
<td>Renk et al.</td>
<td>$\pi^0$, 10% ($dN/d\eta=2500$), BDMPs QW with hydro evol.</td>
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<tr>
<td>Dainese et al.</td>
<td>$\pi^0$, 10%, BDMPs QW with WS, $\alpha_2$-Tq</td>
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<tr>
<td>Cunqueiro et al.</td>
<td>$\pi^0$, 10% ($dN/d\eta=1500$), percolation</td>
</tr>
<tr>
<td>Capella et al.</td>
<td>$\pi^0$, 10% ($dN/d\eta=1000$), comovers, kinematics</td>
</tr>
<tr>
<td>Arleo et al.</td>
<td>charged, 10% ($dN/d\eta=1300$), $p_T=50$ GeV</td>
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N. Armesto (2009)
What did we learn?

- Surprisingly, we have learned a lot form the ALICE and CMS results in spite of the postdiction avalanche.

- Geometry is **not the driving factor** behind the shape and magnitude of jet and particle suppression.

- Energy loss models with large E-loss and large no-radiation probability are excluded.

- It is unlikely that the Bethe-Heitler / Bertsch-Gunion regime is relevant to final-state E-loss.

- The Landau-Pomeranchuk-Migdal (LPM) effect is **critical** to understand the suppression pattern of hadrons.
Directions for improvement

- Only in the soft gluon emission limit can the splitting processes be interpreted as energy loss.
- Need to go beyond the soft gluon approximation, obtain all one-loop medium-induced splitting kernels. Needs to unify the treatment of vacuum and medium-induced parton showers.
- First work was done for SIDIS where E-loss was used to set "quenched" initial conditions for the fragmentation functions.

Need to understand the connection between traditional energy loss approaches and the ECD evolution and resummation.

Deng et al. (2014)

See talk by G. Ovanesyan.
Interestingly, the first observation of jet quenching at the LHC was for approximately back-to-back jets.
Comparison to data

- Most recent experimental data form the LHC

- Both the predicted magnitude and $R$ dependence observed by experiment

Y. He et al. (2011)

The medium induced parton shower is not fully dissipated in the medium

ATLAS Collab. (2011)
Surprisingly, there is no big difference between the jet shape in vacuum and the total jet shape in the medium.

Take a ratio of the differential jet shapes.

\[ \Psi_{\text{int}}(r; R) = \frac{\sum_i (E_T)_i \Theta(r - (R_{\text{jet}})_i)}{\sum_i (E_T)_i \Theta(R - (R_{\text{jet}})_i)} \]

\[ \psi(r; R) = \frac{d\Psi_{\text{int}}(r; R)}{dr} \]

I.V. et al. (2008)
Directions for improvement

- Understand how the calculation has to be performed using the full medium-induced splitting functions
- Use SCET resummation techniques to improve the accuracy of the jet shape calculations

Talk was given by Y.T. Chien
Heavy ion physics has attracted attention from a large number of fields.

Hard particle and jet production are the ones most closely related to pQCD and SCET. The energy-loss jet quenching phenomenology (inclusive particle suppression) has been very successful at RHIC, LHC.

To make connection between the treatment of vacuum and the medium-induced parton shower one needs to go beyond the soft gluon approximation. Evolution, discussed in SIDIS and now in A+A. Also directly calculating medium induced radiative corrections.

The field is transitioning to understanding parton shower modification in the A+A and to study of jet observables that are sensitive to such modification. We already have results for inclusive jet production at the LHC, \( Z^0/\gamma \)-tagged jets and di-jets at the LHC in the soft gluon energy loss approximation.

The direction to improve is to use resummation and SCET techniques and to look into the jet substructure, jet shapes and jet fragmentation.
Understanding of inclusive particle suppression

- Problems are evident in extending the jet quenching calculations below 5 GeV-10 GeV at the LHC

\[ D_{h/c}(z) \approx \int_0^{1-z} d\epsilon \frac{1}{1-\epsilon} D_{h/c} \left( \frac{z}{1-\epsilon} \right) + \int_{z}^{1} d\epsilon \frac{dN^g}{d\epsilon}(\epsilon) \frac{1}{\epsilon} D_{h/g} \left( \frac{z}{\epsilon} \right) \]

- The radiative gluon contribution is important at the LHC (energy conservation)

- Not a proof that all important physics is considered / included physics is correct.
- As the only prediction that gave qualitative and even quantitative description at both high and low \( p_T \) it is strongly suggestive

I. V. (2006)
Current experimental results for jet $A_J$ and $R_{AA}$

- Significantly enhanced di-jet asymmetry in central Pb+Pb collisions. Suggests large energy loss of the subleading jet.

S. Chatrchyan et al. (2011)

G. Aad et al. (2011)
These results are even more important since they give an independent observable and help understand what happens with the jet energy balance.
Both approaches include collisional and radiative energy loss contributions
Based upon the HT and AMY formalisms, respectively
The approaches can be tuned to the $A_J$ measurement
The second approach is presented as a part of the MARTINI Monte Carlo
III. Inclusive and di-jet cross sections at NLO and p+p results

- Includes 2- and 3-parton final states

\[ \frac{d\sigma_{\text{jet}}}{dE_T dy} = \frac{1}{2!} \int d\{E_T, y, \phi\}_2 \frac{d\sigma[2 \rightarrow 2]}{d\{E_T, y, \phi\}_2} S_2(\{E_T, y, \phi\}_2) + \frac{1}{3!} \int d\{E_T, y, \phi\}_3 \frac{d\sigma[2 \rightarrow 3]}{d\{E_T, y, \phi\}_3} S_3(\{E_T, y, \phi\}_3) \]

- At one loop – jet size/algorithm dep.

- Excellent description of the cross sections at RHIC and the LHC

Y.He et al. (2011)

S.D. Ellis et al. (1990)

Z. Kunszt et al. (1992)
III. Exploring the jet variables in heavy-ion collisions

- One can leverage the differences between the vacuum parton showers, the medium-induced showers and the medium response to jets to experimental signatures of parton interaction in matter

I. Vitev et al. (2008)

- Calculations at NLO

\[
R_{AA}^{jet}(E_T; R_{max}, \omega_{min}) = \frac{\frac{d\sigma^{AA}(E_T; R_{max}, \omega_{min})}{dyd^2E_T}}{\langle N_{bin} \rangle} \frac{d\sigma^{pp}(E_T; R_{max}, \omega_{min})}{dyd^2E_T}
\]

<table>
<thead>
<tr>
<th>Mechanism</th>
<th>Signature</th>
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<tbody>
<tr>
<td>Radiative</td>
<td>Continuous variation of ( R_{AA}^{jet} ) with ( R, \omega_{min} )</td>
</tr>
<tr>
<td>Collisional</td>
<td>(~ Constant \ R_{AA}^{jet} = R_{AA}^{particle} ) (Large suppression)</td>
</tr>
</tbody>
</table>
III. Inclusive jet cross sections in A+A reactions

- Jet cross sections with cold nuclear matter and final-state parton energy loss effect are calculated for different $R$

\[
\frac{\sigma^{AA}(R, \omega_{\text{min}})}{d^2 E_T dy} = \int_{\epsilon=0}^{1} d\epsilon \sum_{q,g} P_{q,g}(\epsilon) \frac{1}{(1 - (1 - f_{q,g}) \cdot \epsilon)^2} \frac{\sigma^{NN}(R, \omega_{\text{min}})}{d^2 E_T' dy}
\]

- Calculate in real time

Fraction of the energy redistributed inside the jet

\[
f(R_i, p_{T_{\text{min}}}^{\text{q,g}}) = \frac{\int_{R_i}^{R_i^0} dr \int_{p_{T_{\text{min}}}^{\text{q,g}}}^{E_T} d\omega \frac{d\sigma_{pp}(0)}{d\alpha d\omega}}{\int_{0}^{R_i^0} dr \int_{0}^{E_T} d\omega \frac{d\sigma_{pp}(0)}{d\alpha d\omega}}
\]

The probability to lose energy due to multiple gluon emission

\[
\int_{0}^{1} P_{q,g}(\epsilon_i) d\epsilon_i = 1, \quad \int_{0}^{1} \epsilon_i P_{q,g}(\epsilon_i) d\epsilon_i = \frac{\Delta E_{q,g,i}}{E_i}
\]

- Obtain