Jet quenching and energy loss models at RHIC

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- Leading particle observables
- Full jet and hard-soft correlation observables
Jet-medium interaction

- Learn about energy loss mechanism
  - Probe the effective DOF and transport properties of medium

- Interested in
  - Leading parton energy loss distributions: \( P(\Delta E) \)
    - Leading particle observables, \( R_{AA}, v_2, I_{AA} \) etc.
  - Parton shower and medium response:
    \[
    \frac{dN^g}{d\omega d^2k_{\perp}}
    \]

**Correlation and full jet observables**

Parton shower
Medium response
Leading particle
De-convolution, De-convolution, De-convolution

“Calibrated” input

Geometry

physics

Fluctuating, varying L

measured observables

Steeply falling spectra

Initial state effect

Ambiguity with medium

Varying definitions

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Leading particle observables

- Leading single particle observables: $R_{AA}$, $v_2$
- Leading hadron-hadron correlation observables: $I_{AA}$, $V_{2}^{IAA}$

\[
R_{AA} \quad L_1 \quad \left( \propto \frac{1}{p_T^8} \right) \quad L_2
\]

\[
I_{AA} \quad L_1 \quad \left( \propto \frac{1}{p_T^n}, n < 8 \right) \quad L_1
\]

\[
V_{2} \quad R_{AA}(\Delta \phi) \quad L_1 \quad L_2
\]

\[
V_{2}^{IAA} \quad I_{AA}(\Delta \phi) \quad L_1 \quad L_2
\]
How to study quenching via leading particles?

- $p_T$ dependence, $\sqrt{s}$ dependence, centrality and collision species dependence of given observable (e.g. $R_{AA}$).
  
  **Sensitive to all ingredients**

- Multiple observables of the same probe
  
  **De-convolute the geometry and input spectral shape.**

- Varying the probe
  
  **Changing interaction strength**
$p_T$ dependence of $R_{AA}$

- Increase of $R_{AA}$ vs $p_T$ is a generic feature of radiative $\Delta E$-$\log(E)$ or $\sqrt{E}$
  
- Complicated by the cold nuclear effects at RHIC and lack of $p_T$ lever arm
$p_T$ and $\sqrt{s}$ dependence

- Increase of $R_{AA}$ vs $p_T$ is a generic feature of radiative energy loss $\Delta E \sim \log(E)$ or $\sqrt{E}$

- Complicated by bigger CNM at RHIC, which is compressed in small $p_T$ range. Complicates the energy scan of jet quenching at RHIC.

- Clear advantage of going to higher beam energy

Cronin effect, PDF, CNM energy loss etc, higher twist effect…
$p_T$ and $\sqrt{s}$ dependence

- Increase of $R_{AA}$ vs $p_T$ is a generic feature of radiative eloss $\Delta E \sim \log(E)$ or $\sqrt{E}$
  - Complicated by bigger CNM at RHIC, which is compressed in small $p_T$ range
    Complicates the energy scan of jet quenching at RHIC.
  - Clear rise with $p_T$ at higher beam energy $\Rightarrow$ soft-hard transition around 7 GeV
**p_T and √s dependence**

- Increase of $R_{AA}$ vs $p_T$ is a generic feature of radiative eloss $\Delta E \sim \log(E)$ or $\sqrt{s}$
  - Complicated by bigger CNM at RHIC, which is compressed in small $p_T$ range
  - Clear rise with $p_T$ at higher beam energy $\rightarrow$ soft-hard transition around 7 GeV
  - Better constraint on medium properties by combining RHIC and LHC results

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Surprising transparency of the sQGP at LHC (WHDG). Also observed in HT (XinNian, Abjit)

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Horowitz 2011
Influence of spectral shape

- RHIC: Increase of local slope $n(p_T)$ make the $R_{AA}(p_T)$ flatter.
- Situation cleaner at LHC

\[
n^h(x_\perp) \equiv \left| \frac{d \ln N_{pp}^h(p_\perp)}{d \ln p_\perp} \right|, \quad R_{AA}^h(p_\perp) \approx 1 - \frac{\langle \epsilon \rangle(p_\perp)}{p_\perp} n^h(x_\perp)
\]
Sensitivity to fixed power law shape

- A simple check: shift the power law spectra via a $e^{-loss}$ formula

- Once overall suppression is fixed, $R_{AA}(p_T)$ not sensitive to overall magnitude of $n$?

  This is clear for exponential spectra (also see previous formula)
Sensitivity to fixed power law shape

- A simple check: shift the power law spectra via a eloss formula

- Once overall suppression is fixed, $R_{AA}(p_T)$ not sensitive to overall magnitude of $n$?
  
  This is clear for exponential spectra (also see previous formula)

- Same is true for a different eloss formula (but $R_{AA}$ shape changed)

- Advantage of LHC is from increased lever arm, constant $n$, reduced $p_T$ dependence of CNM (measurement needed), **but not from smallness of $n$!!**
Constraint of a single observable

- Not calculated from first principle, but from model dependent fit
  - Calculate $R_{AA}$ for one parameter
  - Minimize $\chi^2$ wrt data
- Other ingredients (parameters) are fixed by hand

\[
\begin{align*}
\text{PQM} & \quad \langle q \rangle = 13.2^{+2.1}_{-3.2} \text{ GeV}^2/\text{fm} \\
\text{GLV} & \quad dN_g/dy = 1400^{+270}_{-150} \\
\text{WHDG} & \quad dN_g/dy = 1400^{+200}_{-375} \\
\text{ZOWW} & \quad \varepsilon_0 = 1.9^{+0.2}_{-0.5} \text{ GeV/fm}
\end{align*}
\]
**Constraining P(ΔE) from \( R_{AA} \)**

- \( R_{AA} \) alone cannot constrain \( P(\Delta E) \).

T. Renk hep-ph/0607166
See also 0711.1030
Combining multiple observables

- Multiple observables of the same probe allow us to de-convolute the geometry and input spectral shape.
Combining $R_{AA}$ and $I_{AA}$

- Better constraint on $q$ in a given model.
- Expose limitations of the model, i.e. ASW tends to predict smaller $I_{AA}$ and larger $R_{AA}$.

Similar comparisons done for other models, see also T. Renk talk in QM2011

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Combining $R_{AA}$ and $\gamma$-h $I_{AA}$

- Theory has been tuned to $R_{AA}$.
- Current error is too large to unfold $P(\Delta E)$, probably this is also true for h-h $I_{AA}$.
Combining $R_{AA}$ and $v_2$

- In general, pQCD models under-shoots the $v_2$ in 6-10 GeV region
pQCD calculation is applicable only at $p_T > 10$-12 GeV?
Correlations between the $R_{AA}$ and $v_2$

- Present experimental data as direct correlation between observables
  - As function of centrality, e.g. $R_{AA}$ vs $v_2$
- $R_{AA}$ vs $v_2/\varepsilon$ is better: stronger suppression $\Rightarrow$ larger $v_2/\varepsilon$
  - Disentangle geometry, spectral shape and L dependence.

![Diagram of $R_{AA}$ vs $v_2$ and $v_2/\varepsilon$](image)
At high trigger and assoc. $p_T$, $I_{AA} > R_{AA}$

- away-side input spectrum harder than single inclusive hadron → smaller suppression for same amount energy loss.

See discussion of trigger bias in Renk 1106.1740
Correlations between $R_{AA}$ and $I_{AA}$

- Calculation without (left) and with (right) spectral shape taken into account
  - Pure absorption picture (left): $R_{AA} < I_{AA}$.
  - Including flatter spectral shape for PTY (right): $R_{AA} > I_{AA}$.

$R_{AA}$ and $I_{AA}$ correlation has additional sensitivity to L dependence!

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Varying the probes

- Significantly change the jet-medium interaction but with same geometry

*PHENIX Au+Au (central collisions):*
- Direct $\gamma$
- $\pi^0$ Preliminary
- $\eta$
- GLV parton energy loss ($dN^0/dy = 1200$)

Heavy quark suppression puzzle

- Remain unsolved, need direct separation of c and b mesons

Wicks et al., NPA784, 2007
Updated calculation including dynamical scattering potential, and high order opacity corrections etc…

- Split between heavy and light at $p_T<10$ GeV at RHIC remains, however Djordjevic 1105.6082 claim otherwise
- The hierarchy of ordering strongly depends on $p_T$ & $\sqrt{s}$

The importance of experimentally isolating and observing charged heavy mesons cannot be overstated since the mass splitting between c and b jets is a particularly robust prediction of pQCD in a deconfined QGP medium.
Part II
Full jet and hard-soft correlation observables
Parton shower and medium response

- Full jet observables: jet and di-jet, FF, $j_T$ etc.

  Systematic study of jet yield and jet shape

- Correlation observables: hard-soft correlation such as $h-h$, $\gamma-h$, and jet-$h$.

  Systematic study of jet modification at large angle and low $p_T$. 

Leading particle

Parton shower & medium response
Smaller jet definition produces more suppression?

Approaching the $R_{AA}$ of single particles?
LHC jet $R_{cp}$ not changing with cone size??

Difference of $\text{d}E/\text{d}x$ between soft (RHIC) and hard jet (LHC)?
Or due to different spectra shape?

B. Cole QM2011
Relation between $R_{AA}^{jet}$ and $R_{AA}$

- $R_{AA}^{Jet}$ depends on jet shapes in both AuAu and pp.
- Medium modification can lead to complicated feeding and feedout.

\[ \Delta E = \int \omega d\omega dk^2_\perp \left[ f_g(\omega, k^2_\perp, t_i) - f_g(\omega, k^2_\perp, t_f) \right] \]
\[ + \int \omega d\omega dk^2_\perp dt \frac{dN_{med}^g}{d\omega dk^2_\perp dt} + \int_{t_i}^{t_f} \hat{e}(t) dt. \] (9)

Qin Muller 1012.5280

Radiative

Collisional

Leading parton e-loss

e.g. leading hadron unmodified, but soft fragments to large angle: $R_{AA}^{jet} < R_{AA} = 1$
- ATLAS Jet $R_{cp}$ seems to agree with CMS single $R_{AA}$ at high $p_T$
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- But CMS single $R_{AA}$ above 50 GeV has little centrality dependence
Compare $R_{AA}^{jet}$ with $R_{AA}$

- ATLAS Jet $R_{cp}$ seems to agree with CMS single $R_{AA}$
- But CMS single $R_{AA}$ above 50 GeV has little centrality dependence
- Similar observation seem in ALICE, but also a change in magnitude
Theory calculations on full jet observables

- **Qin and Muller 1012.5280, Qin QM 2011 talk**
  - HT formulism, elastic and radiative, rate equation for feedin and feedout
  - Schematic modeling of geometry.
  - Toy jet finding without fluctuation
  - Only calculated di-jet asymmetry $A_j$. No jet and single $R_{AA}$

- **Lokhtin, Belyaev and Snigirev 1103.1853**
  - PyQuen MC model (BDMS), elastic and radiative, simplistic parameterization of radiation angular distribution. collisional knockout
  - Toy jet finding without bg fluctuation
  - Simultaneous description of single $R_{AA}$ and $A_j$. No Jet $R_{AA}$.

- **Young, Schenke, Jeon and Gale 1103.5769**
  - MARTINI MC model (AMY), elastic and radiative, ideal hydro
  - Anti-kt algorithm, but no EbE background fluctuation
  - Only calculated di-jet asymmetry $A_j$. No jet and single $R_{AA}$

- **He, Vitev, Zhang 1105.2566, Vitev QM2011 talk**
  - GLV formulism, elastic and radiative.
  - Toy jet finding, schematic estimation of fluctuation
  - Simultaneous description of jet $R_{AA}$ and $A_j$.

Clear need for a full event by event MC generator with hydro and fluctuations! Most calculations were done for LHC, is theory community interested in RHIC?
Comparison to results at RHIC energy

- Calculation include soft fragments down to 0 $p_T$
  - How can one separate medium from radiation?
- CNM much stronger $p_T$ dependence, $d+A$ measurement is crucial for RHIC future jet program.
  - Potential ambiguity in separating cold and hot nuclear effect for jet observable at NLO level

In the kinematic region of interest, $10 \text{GeV} \leq E_T \leq 50 \text{GeV}$ around midrapidity at RHIC, the EMC effect and initial-state energy loss play a dominant role. I. Vitev

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- Significant initial state effects for direct $\gamma R_{AA}$.
  - Plus jet flavor conversion

- Significant suppression of d+Au jet $R_{cp}$ above 15 GeV

- They complicate jet measurements at RHIC
Correlation observables

- Hard-soft correlation to capture parton shower and medium response
  - Distinction between parton shower and medium become ambiguous at low $p_T$ and large angle on a particle by particle level.
  - But can still study the energy/momentum flow

$h-h, \gamma-h$, and jet-$h$ correlations
- Hard-soft correlation are sensitive to parton shower and medium response.

- The excess and broadening could well be result of local heating of bulk medium by quenched jet, intrinsically non-perturbative
  - Gluon feed back cannot be the full story

- Response of jet finder (designed for vacuum jet) to this stuff not under control?
Energy/momentum flow from high $p_T$ to low $p_T$.

$$D_{AA}(p_T^{assoc}) = Y_{AA}(p_T^{assoc}) \cdot p_{T,AA}^{assoc} - Y_{pp}(p_T^{assoc}) \cdot p_{T,pp}^{assoc}$$

$$\Delta B = \int dp_T^{assoc} D_{AA}(p_T^{assoc})$$

- Majority of high-$p_T^{assoc}$ suppression is balanced by low-$p_T^{assoc}$ enhancement for all $p_T^{jet}$.
Situation in A+A

matrix elements: unmodified due to high scale

final state parton shower: no general theory, only calculations for special cases
e.g. single gluon radiation spectrum in eikonal limit

initial state parton shower: found to be unmodified at RHIC except for pdf's

hadronisation: probably modified, no theoretical guidance

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Conclusions

- theoretical and experimental arguments for going from single-inclusive observables to jets
- raises important conceptual (and technical) issues
- theory tool: Monte Carlo generators
  - describe jets on basis of multi-particle final states
  - account dynamically for jet – medium interactions
  - versatile to explore conceptual issues
  - jet finders and entire analyses can run on MC events
  - have to rely on phenomenological modelling
- ultimately: unified description of jet & medium evolution
- expect major progress in next years
- and fruitful interaction between experimentalists and theorists
Summary

- **Leading particle observables to probe leading parton energy loss**
  - We are able to constrain $<\Delta E>$ thus $<q_{\text{hat}}>$ for given model setup
  - We are not yet able to obtain $P(\Delta E)$ without a priori assumed function form
  - Need to unfold influence of spectral shape, CNE, medium geometry & evolution, and hadronization, and address conceptual issues of pQCD.
    - Precision $p_T$ and $\sqrt{s}$ dependence (compare with LHC);
    - Simultaneous description of multiple observables;
    - Vary the energy loss processes with different probes;

- **Full jet and hard-soft correlation observables to probe the parton shower and medium response.**
  - Observed jets show a relatively unmodified core and a broad and soft corona.
    - So far no clear indication (yet) advantage for leading parton energy loss?
    - Clear energy/momentum flow from high $p_T$ to low $p_T$, boundary at 2 GeV
  - Full jet at RHIC need to properly address CNM and kinematic constrains
    - Need precision $p+p$ and $d+Au$ run to accompany jet program at RHIC
  - Theory side: need to develop MC models (for jet) and have unified description of jet and medium evolution (scale separation)– more difficult at RHIC
Is pQCD applicable 3-10 GeV?

- Jet production dominates at $p_T > 2-3$ GeV
- But spectra, $v_2$ and hadron chemistry suggests jet and medium difficult to separate up to 7-10 GeV (similar results from RHIC)
- Can one assume breaking of pQCD to depend on species? ($\pi$ but not $p$)
  - Recombination and flavor conversion etc
Where pQCD calculation can be trusted?

Non-pQCD effects only grows to lower $\sqrt{s}$
Complicates study the onset of jet quenching at RHIC via energy scan
Nuclear parton densities

\[ R_i^A(x, Q^2) = f_i^{p/A}(x, Q^2)/f_i^p(x, Q^2) \]

poorly constrained experimentally

Assuming collinear factorization:

\[ R_{AA}(p_\perp) \approx R_i^A(x_\perp, p_\perp^2) \times R_j^A(x_\perp, p_\perp^2) \]

- Dramatic uncertainties at low \( p_\perp^2 \) and small \( x_\perp \approx 2p_\perp/\sqrt{s} \)
- Better under control at larger \( p_\perp \), say \( p_\perp \gtrsim 10 \) GeV

Francois Arle (LAPTH)  Quenching from RHIC to LHC  Quark Matter 2011  10 / 36
Influence of Low-x to suppression

K. L. Tuchin

\[ R_{A}(p_T) \]

\[ \sqrt{s} = 200 \text{ GeV} \]

\[ \sqrt{s} = 5.5 \text{ TeV} \]

\[ p_T \text{ (GeV/c)} \]

\[ R_{pA} \]

Kopeliovich 2002

Pions (0-20%)

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- Weak cone size dependence at high $p_T$
- Some dependence on coupling constant,
- Some CNM effect (PDF and $e$loss)!