High $p_T$ hadron spectra and anisotropies - scaling relations and questions

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MOTIVATION
Why study $R_{AA}$ and $v_2$ together?

- $R_{AA}$ at a fixed $p_T$ is a monotonically decreasing function of centrality (density and path length both increases)
  - Can’t separate density and path-length dependence

- When we study
  
  $R_{AA,\text{in}} \approx R_{AA} (1+2v_2)$ and $R_{AA,\text{out}} \approx R_{AA} (1-2v_2)$

  together, the $R_{AA,\text{in}}$ can be larger than the $R_{AA,\text{out}}$ for a more peripheral class
  - Can separate density and path length dependence!

If we can understand the effect of the expanding medium
The hydro expansion

- Calculation by J. Nagle using P. Romatschke's SONIC for Au+Au @ 200 GeV collision with b = 6.5 fm
- Both partons start exactly in the center. One might assume that the parton moving up is seeing a lot more matter, but with the expanding medium that is not really the case.
Difficult for models to describe $R_{AA}$ and $v_2$ at the same time.

PHENIX: PRL 105, 142301 (2010)
CMS $v_2$ compared to CUJET 3.0 and SHEE


CUJET 3.0: J. Xu, J. Liao, and M. Gyulassy, JHEP 02 (2016) 169


“SHEE includes initial-state geometry fluctuations, while CUJET3.0 uses a smooth hydrodynamic background.”
Still an issue for some models to describe both $R_{AA}$ and $v_2$

JHEP 04 (2017) 039

CUJET 3.0: J. Xu, J. Liao, and M. Gyulassy, JHEP 02 (2016) 169

(and what about $p_T$ spectra?)

So in my mind this dead horse is still very much alive!
Outline

- Present scaling model analysis of $R_{AA,in}$ and $R_{AA,out}$
  - Work done with V. Vislavicius (Lund) and K. Tywoniuk (CERN)
  - Illustrates also how model results could be presented in a clearer way 😊

- Use scaling results to motivate questions:
  - Quark vs gluon energy loss
    - Perturbative or non-perturbative QCD
  - Non-linearity of energy loss with density (screening in the QGP)
    - Affects how the expansion interplay with quenching
  - Path length dependence of the energy loss
    - What is the effect of the transverse expansion?
A DATA DRIVEN APPROACH
LHC data is surprisingly simple

(1/4)

$R_{AA}$

ALICE 0-5% Pb-Pb $s_{NN}=2.76$ TeV

- $\pi^+\pi^-$
- $K^+K^-$
- $\rho + \bar{\rho}$

$\rho_T$ (GeV/c)

PLB 736 (2014) 196-207
LHC data is surprisingly simple (2/4)


\begin{figure}
\centering
\includegraphics[width=\textwidth]{v2_v3}
\caption{ALICE Pb-Pb $\sqrt{s}_{NN} = 2.76$ TeV
$V_2$ and $V_3$ for different collision systems and particle species.

- $h^+h^-$ (10-50%)
- $\pi^+\pi$ (10-50%)
- $p\bar{p}$ (10-50%)
- $\pi^0$ PHENIX (10-50%)
- $\pi^0$ WHDG LHC Extrapolation (20-50%)
\end{figure}
LHC data is surprisingly simple
(3/4)

CMS-HIN-15-014 (shown at LHCP)
LHC data is surprisingly simple (4/4)

It appears that at least the hard core of the jet is unmodified even for very asymmetric, $A_j > 0.35$, quenched subleading jets.
Data is surprisingly simple

• No particle species dependence of $R_{AA}$ and $v_2$ for $p_T > 10$ GeV/c
  – Assumption: at high $p_T$ we observe pure quenching and can neglect collective flow

• The leading particles in quenched jets looks like the leading particles in pp jets
  – Assumption: high $p_T$ particles are good proxies for jets (very important since it is the jets that are quenched)

• This allows for a simple data driven approach to understand jet quenching
The underlying idea

- $R_{AA}$ (ALICE, Phys. Lett. B 720, 52, 2013) and $v_2$ (ATLAS, Phys. Lett. B 707, 330, 2012) can be combined to get $R_{AA}$ in and out of plane
  - $R_{AA,in} \approx (1+2v_2)R_{AA}$
  - $R_{AA,out} \approx (1-2v_2)R_{AA}$

- Find centrality classes where the path length in and out matches (to fix it) and compare $R_{AA,in}$ and $R_{AA,out}$
  - Assumption: we can neglect the transverse expansion (study here also tests this assumption)
Example

The suppression in the most central events is larger. This could reflect that the medium density is larger. We can use this method to test different hypotheses.
How to determine the density

- Approximate density (per rapidity) by $dN_{\text{ch}}/d\eta$
- Approximate area by $4\pi L_{\text{in}} L_{\text{out}}$
- We use $\rho = dN_{\text{ch}}/d\eta / (4\pi L_{\text{in}} L_{\text{out}})$

(this density is of course not meaningful in itself, but here we are only interested in relative densities)

Question 1: is $dN/d\eta$ or $dE_T/d\eta$ the best estimator for the medium density?
Testing hypotheses

Too little information in RAA, because any scaling relation to some power will also be a scaling relation.

Need to demand something more: Here we demand that energy loss is linear in the scaling variable.
We use the $p_T$ loss by PHENIX

2 solutions for power law spectrum:

\[
\frac{\Delta p_T}{p_{T0}} = 1 - R_{AA}^{-1/b}
\]

Just a shift (PHENIX)

\[
\frac{\Delta p_T}{p_{T0}} = 1 - R_{AA}^{-1/(b+1)}
\]

Compression of $p_T$ spectrum (here)
We observe that the scaling relation in which the $p_T$ loss is linear is:

$$\sqrt{\rho L}$$

This is the scaling relation we will always use in the following

Question 2: why is quenching non-linear in the medium density?
We can now go back and select comparable event classes

For the event classes where $\sqrt{\rho L}$ are similar, we in general observe good agreement between the $R_{AA}$s.
What about the transverse expansion?

Question 3: what is the effect of the transverse expansion on the energy loss

Scaling works even there are large flow differences between in and out of plane.
Future: high precision data

Future: high precision data

- It is critical that data is published in fine binning and made available via HepData
- Also very nice 5 TeV data and D meson $R_{AA}$ & $v_2$
What about RHIC?
(PHENIX $\pi^0$, Phys. Rev. C 87, 034911)

- Pathlengths are similar, $dN/d\eta(\text{RHIC}) \sim \frac{1}{2} dN/d\eta(\text{LHC}) \Rightarrow \sqrt{2}$ less energy loss

\[ R_{AA} \]

RAA is different
What about RHIC?
(PHENIX $\pi^0$, Phys. Rev. C 87, 034911)

- Pathlengths are similar, $dN/d\eta(RHIC) \sim \frac{1}{2} dN/d\eta(LHC) \Rightarrow \sqrt{2}$ less energy loss

RAA is different
But the $p_T$ loss is following the same scaling at RHIC and LHC
(pp $p_T$ spectrum has different exponent)

Question 4: does quarks (RHIC) and gluons (LHC) quench the same
QUESTIONs

Question 1: is $dN/d\eta$ or $dE_T/d\eta$ the best estimator for the medium density?

Question 2: why is quenching non-linear in the medium density?

Question 3: what is the effect of the transverse expansion on the energy loss?

Question 4: does quarks (RHIC) and gluons (LHC) quench the same
Question 1: is \( \frac{dN}{d\eta} \) or \( \frac{dE_T}{d\eta} \) the best estimator for the medium density?

Question 2: what is the effect of the transverse expansion on the energy loss?

Question 3: does quarks (RHIC) and gluons (LHC) quench the same?

Question 4: why is quenching non-linear in the medium density?
For strangeness, \( \frac{dN}{d\eta} \) is a good scaling variable across system size

While \( \langle p_T \rangle \) does not scale

Is \( E_T \) reflecting the expansion and \( \frac{dN}{d\eta} \) reflecting medium?
Transverse expansion?
Not important in AMPT...

Anisotropic parton escape is the dominant source of azimuthal anisotropy in transport models

Liang He, Terrence Edmonds, Zi-Wei Lin, Feng Liu, Denes Molnar, Fuqiang Wang


“It is found that the majority of $v_n$ comes from the anisotropic escape probability of partons, with no fundamental difference at low and high transverse momenta. The contribution to $v_n$ from hydrodynamic-type collective flow is found to be small.”

???
Does gluon and quark jets quench differently?

- Shouldn’t there be more gluon jets at LHC?

- And shouldn’t they lose more energy?
  - Gluons are expected to lose \( \approx 2 \) times (color factor) more energy than quarks in the medium
So how much gluon contribution do we expect

Similar to calc. shown in d’Enterria et al., Nucl. Phys. B883. Thanks to Ilkka Helenius.

- So we would expect huge differences in quenching due to the different color factor of gluons and quarks!

  Caveat: is Kretzer really the best FF? Not at RHIC:
Is pQCD picture correct?

- We could maybe learn something very fundamental about the degrees of freedoms in the QGP if gluons and quarks would be quenched the same way!

- (Some ideas from that FF differences observed by ATLAS is due to q/g differences, M. Spousta, B. Cole, Eur. Phys.J. C76 (2016) 50 )
Why does the $p_T$ loss scale with $\sqrt{\rho}$ and not with $\rho$?

- From Debye screening we expect screening mass of order $gT$ (or $g^2T$)
  - Higher $T$ means more screening -> Non-linear effect on energy loss

- Similar screening is also known in initial state scatterings
  - In PYTHIA the cross section is regularized with a $p_{T0}$ which increase with $\sqrt{s}$
  - In CGC $Q_s$ scale at mid rapidity grows with $\sqrt{s}$
    - Higher $\sqrt{s}$ means higher $Q_s$ (at mid rapidity)

- Is there a relation between initial and final state screening?
Final “ramblings”

- Maybe in the end the goal is not just to extract the best $q\hat{\epsilon}$
- We know from flow measurements that the medium has an interesting structure
- Maybe we can learn precious things about the medium from how it couples to
  - If it expands? (anisotropic parton escape?)
  - Its structure (how it screens)
  - How it couples (to quark and gluons)
  - The dynamics of its constituents (how the longitudinal/transverse expansion affects them)

(P. Christiansen, arXiv:1709.03415)
Conclusions

• I have shown an example of how one can
  – Use elliptic flow to fix path length and vary the medium density
  – Not shown: One can also use Event Shape Engineering to keep the medium density fixed while varying the path length

• There seems to be some interesting relations in the data
  – Better tests can be done with new high precision data

• How well do we understand the jet quenching?
  – Several fundamental questions seem to remain
Backup slides
Comparison to recent PHENIX results (only $R_{AA}$)

- Looking at only $R_{AA}$:
  
  \[ L_{\text{in}} L_{\text{out}} \sim L^2 \Rightarrow \sqrt{\rho L} \propto \sqrt{dN/d\eta} \]
  
  no L dependence!

- Similar to what PHENIX has observed (but the L dependence is needed for $v_2$)

Suggests energy loss in pp and p-Pb collisions!?
The same Kretzer Fragmentation Functions (KRE) found to describe charged particle spectra the best (d’Enterria et al., Nucl.Phys.B883, (2014) 615-628) also describes best the identified spectra. Kaon spectra are better described by all sets of FFs. Protons have largest differences.

The pQCD understanding of particle spectra are also important for the relative importance of quark and gluon jets in energy loss calculations.
High $p_T$ spectra and anisotropy (P. Christiansen, Lund)

PHENIX pQCD comparisons
(PRL 241803, 2003)

- $E^2 d^3\sigma/dp^3$ (mb GeV$^{-2}$ c$^{-3}$)
- $\Delta\sigma/\sigma$ (%)
- (Data-QCD)/QCD

Graphs showing comparisons between PHENIX data and theoretical predictions from KKP FF and Kretzer FF models.
How can we take the longitudinal expansion into account

• As the jet parton propagates with the speed $c$ then $L=ct$, and if the longitudinal expansion delutes $\rho$ as $1/t$ then one needs to compensate by increasing the path length dependence

$$\sqrt{\rho_{static}} \ L \sim \sqrt{\rho_0 \ t_0/t} \ L^{3/2}$$

• Because the medium is diluted the path length dependence needs to be increased
Correlating the soft and hard $v_2$

**CMS-HIN-15-014**

- Clear demonstration that soft and hard $v_2$ probe the same initial geometry
- But not so easy to interpret because one both varies the geometry and the medium properties
  - Use Event Shape Engineering!
Event Shape Engineering and energy loss


- By cutting on the flow vector $Q_2$ one can select different eccentricity classes $\varepsilon_2$ ($v_2(p_T) = k_{\text{flow}}(p_T) \varepsilon_2$)

- So one can vary the path length while keeping the average medium properties approximately fixed

  – One can therefore constrain the path length!
• Use the same scaling relation but now the density is (essentially) fixed
ESE calculation (2/2)

- For 20-30% centrality we have 6 lengths (fm)
  - $L_{\text{in}}$, high $\varepsilon_2$: 1.78, MB: 2.10, low $\varepsilon_2$: 2.40
  - $L_{\text{out}}$, high $\varepsilon_2$: 2.89, MB: 2.75, low $\varepsilon_2$: 2.60

- For low $p_T$ flow:
  \[
  \frac{v_2 \text{ (high $\varepsilon_2$)}}{v_2 \text{ (MB)}} = \frac{\langle \varepsilon_2 \text{ (high $\varepsilon_2$)} \rangle}{\langle \varepsilon_2 \text{ (MB)} \rangle}
  \]

\[\Delta p_T/p_T\]
\[L\]

Prediction:
\[\frac{v_2 \text{ (high $\varepsilon_2$)}}{v_2 \text{ (MB)}} \text{ (quenching)} \sim 1.05 \quad \frac{v_2 \text{ (low $\varepsilon_2$)}}{v_2 \text{ (MB)}} \text{ (flow)}\]
\[\frac{v_2 \text{ (low $\varepsilon_2$)}}{v_2 \text{ (MB)}} \text{ (quenching)} \sim 0.97 \quad \frac{v_2 \text{ (low $\varepsilon_2$)}}{v_2 \text{ (MB)}} \text{ (flow)}\]
ATLAS ESE results on $v_2$ at high $p_T$

Low $p_T$: $v_2(pT) = k_{\text{flow}}(p_T) \epsilon_2$

An example of real model calculations can be found in:
(they also get a linear relation!)
- ESE is also a tool for constraining the initial geometry (similar to centrality)
- Is it possible to avoid model comparisons?
  - By comparing quenching of light and heavy quarks one could expect that if the path length dependence is the same, then
    \[
    \frac{\langle v_2 \rangle_a}{\langle v_2 \rangle_b} \text{ (light q)} = \frac{\langle v_2 \rangle_a}{\langle v_2 \rangle_b} \text{ (heavy q)}
    \]
even the elliptic flow would be different
- It would be interesting to understand with calculations if this idea is reasonable or not
The measured $v_2$ at high $p_T$ is consistent for all methods.
Large high $p_T$ $v_2$ even in peripheral collisions

- While $v_2$ at low $p_T$ seems to go down, $v_2$ at high $p_T$ goes up as we go more peripheral
  - Is jet quenching driving the $v_2$ in peripheral collisions?
  - Or is it a bias?