High $p_T$ spectra and anisotropy of light and heavy hadrons

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Outline

• Motivation
• The work done to constrain the energy loss in a data driven way
  – Using elliptic flow to fix path length and vary the medium density (Phys. Rev. C 89, 034912, 2014)
    • Together with Vytautas Vislavicius and Konrad Tywoniuk
  – Using Event Shape Engineering to keep the medium density fixed while varying the path length
    • PC, J. Phys. Conf. Ser. 736 (2016) no.1, 012023
• I will interleave some questions and comments
• Jacquelyn Noronha-Hostler will give a theory driven discussion of this in the afternoon

Difficult for models to describe $R_{AA}$ and $v_2$ at the same time

PHENIX: PRL 105, 142301 (2010)
CMS $v_2$ compared to CUJET3

CUJET 3.0: J. Xu, J. Liao, and M. Gyulassy, JHEP 02 (2016) 169
Still an issue for some models to describe both $R_{AA}$ and $v_2$
$v_2$ comparison to SHEE

Results – Compare to Models

- CUJET3.0 fails over full $p_T$ and centrality dependence
  - JHEP 02 (2016) 169
- SHEE with linear energy loss has good agreement
  - arXiv:1609.05171

Jacquelyn Noronha-Hostler will show more results in the afternoon!
A data driven approach
LHC data is surprisingly simple (1/4)

ALICE 0-5% Pb-Pb \(s_{\text{NN}}=2.76\text{ TeV}\)

- \(\pi^+ + \pi^-\)
- \(K^+ + K^-\)
- \(\rho + \bar{\rho}\)

\(R_{\text{AA}}\)

\(p_T\) (GeV/c)
LHC data is surprisingly simple (2/4)


![Graph showing $v_2$ and $v_3$ as functions of $p_T$](image)

- ALICE
- $h^+h^-$ (10-50%)
- $\pi^+\pi^-$ (10-50%)
- $p\bar{p}$ (10-50%)
- $\pi^0$ PHENIX (10-50%)
- $\pi^0$ WHDG LHC Extrapolation (20-50%)

High $p_T$ spectra and anisotropy (P. Christiansen, Lund)
LHC data is surprisingly simple (3/4)

CMS-HIN-15-014

CMS Preliminary
PbPb $\sqrt{s_{NN}} = 5.02$ TeV

$v_2(\text{SP})$

$v_3(\text{SP})$
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 first 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
  - $R_{AA,\text{in}} \sim (1+2v_2)R_{AA}$
  - $R_{AA,\text{out}} \sim (1-2v_2)R_{AA}$

- Find centrality classes where the path length in and out matches (to fix it) and compare $R_{AA,\text{in}}$ and $R_{AA,\text{out}}$
  - Assumption: we can neglect the transverse expansion (study here also tests this assumption)
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 energy density (per rapidity) by \( dN_{\text{ch}}/d\eta \)
- Approximate area by \( 4\pi L_{\text{in}} L_{\text{out}} \)
- We use
  \[
  \rho = \frac{dN_{\text{ch}}/d\eta}{4\pi L_{\text{in}} L_{\text{out}}}
  \]
  (this density is of course not meaningful in itself, but here we are only interested in relative densities)
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:

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

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

Just a shift (PHENIX)

Compression of $p_T$ spectrum (here)
Testing hypotheses with $p_T$ loss

We observe that the scaling relation in which the $p_T$ loss is linear is:

$$\rho^{3/4}L^2$$

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

Scaling works even there are large flow differences between in and out (and the actual flow is centrality dependent) =>

Suggests that transverse expansion does not affect quenching (?)
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

![Graph showing $R_{AA}$ vs. $\sqrt{\rho L}$]
What about RHIC?
(PHENIX $\pi^0$, Phys. Rev. C 87, 034911)

- Pathlengths are similar, $\frac{dN}{d\eta}(\text{RHIC}) \sim \frac{1}{2} \frac{dN}{d\eta}(\text{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)

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!?
Should RHIC and LHC follow the same scaling relation

- Shouldn’t there be more gluon jets at LHC?
  - Gluons are expected to lose 2 times (color factor) more energy than quarks in the medium

- And shouldn’t they lose more energy?
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?
Question: is the naive perturbative picture true?

• Is quenching a perturbative process?
  – Quenched di-jets are back-to-back: no indication of deflection caused by large momentum transfers

• Can non-perturbative energy loss be similar for quarks and gluons?
Can start to do similar analyses for heavy hadrons soon

But not so easy how to interpret the results? One would have to understand the difference between light and heavy quark fragmentation.

But maybe there is another way, see next.
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 $\varepsilon_2 \left( \nu_2(p_T) = k_{\text{flow}}(p_T) \varepsilon_2 \right)$

- So one can vary the path length while keeping the average medium properties approximately fixed
  - One can therefore constrain the path length!
ESE calculation (1/2)

- 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:
  \[
  \frac{v_2 \text{ (high } \varepsilon_2 \text{)}}{v_2 \text{ (MB)}} = \frac{\langle \varepsilon_2 \text{(high } \varepsilon_2 \text{)} \rangle}{\langle \varepsilon_2 \text{(MB)} \rangle}
  \]

\[
\Delta p_T/p_T
\]

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

Low $p_T$: $v_2(pT) = k_{\text{flow}}(p_T) \varepsilon_2$

An example of real model calculations can be found in:
(they also get a linear relation!)
Light vs heavy quark energy loss


• 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
Talk this meeting

Soft-heavy event shape engineering

Keep centrality fixed, though fluctuations $\to v_2^{\text{heavy}} \sim c v_2^{\text{soft}}$

Approximate linear response !!

BOTH CHARM AND BOTTOM COUPLE STRONGLY TO MEDIUM
So what is the problem? (my understanding)

PHENIX: PRL 105, 142301 (2010)
The initial energy loss in and out of plane must be the same.

The jets going in and out of plane will initially experience the same density.

- Most simplifications we have done will make it more difficult for a real model calculation.
  - Any transverse hydro-expansion will tend to make the path lengths similar -> reduce $v_2$.
The effect of the hydro expansion

- Calculation by Jamie Nagle using Paul Romatschke's SONIC with smooth initial conditions for a Au+Au @ 200 GeV collision with $b = 6.5$ fm.
- Both partons start exactly in the center - one moving straight up and one moving straight to the right. Naively from the initial hydrodynamic picture, 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.
What could be done with real models

• If you have a full model then you can track the time dependence of the energy loss in and out of plane
  – Better understanding of how $v_2$ is generated in the model

• Analyze theoretical models in a similar way to understand what the scaling variables are and how they are affected by different processes

• I would personally be very interested to see such studies
Questions

• Scaling relations have many issues in that they are not hypothesis based, but they can guide our curiosity!
  – Are gluons and quarks quenched similarly?
  – Does the transverse expansion affect quenching?
  – Why should quenching depend on $dN/d\eta$ and not $E_T$, and why as $\sqrt{dN/d\eta}$?

Thank you!
Backup slides
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.
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

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

- Because the medium is diluted the path length dependence needs to be increased
What about intermediate $p_T$?

- This is also likely where we have to look for the reason that the FFs have had some issues to describe LHC data.
Similar $p_T$ regions are seen for all systems!

**Question:** what is the origin of the intermediate $p_T$ physics?

Rephrase: Are the protons enhanced (e.g. “pushed” / “recombined” out also to these large $p_T$)? Or are the pions suppressed?
Looking at the ratio of spectra for different pp multiplicity classes

The slope of proton spectra for $4 < p_T < 10$ GeV/c are independent of the multiplicity in pp collisions (“more of the same”)
For pions the slope changes! (not just “more of the same”????)
In general it seems that baryon ratios are flat at intermediate $p_T$ while meson ratios rise.

The experimental results show a surprising and interesting trend that IMO should be further investigated. (Could also play a role for $v_2$)
What is high $p_T$? (1/2)

• The partonic cross section scales as:
  \[
  \frac{d\hat{\sigma}}{dp_T^2} \propto \frac{\alpha_s(p_T^2)}{p_T^4}
  \]

• In PYTHIA it is regularized via a $p_{T,0}$ of order $\sim 2$ GeV/c

• The interpretation of this scale is that the proton appears to be color neutral on scales larger than $\sim 0.1$ fm (whereas they expected $\Lambda_{QCD} \sim 1$ fm)

• Toy model study by Johann Dischler and Torbjörn Sjöstrand (Eur. Phys. J. direct C3 (2001) 2) where they evolve a proton ($uud + 2g$) to a new scale and then, randomly fixing the position of the partons, resolves it with a gluon
What is high $p_T$? (2/2)

Coherent / incoherent partonic Xsection

$$A = \frac{|\sum_k q_k e^{i r_k P_{\perp}}|^2}{\sum_k |q_k|^2}$$

- To get hard scatterings we need to have momentum transfers that are $>> 2$ GeV/c
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?
ESE: low $p_T$ ($p_T < 2$ GeV/c)

The flow region

- ESE is based on the nearly ideal flow
  \[ \nu_2(pT) = k_{\text{flow}}(p_T) \varepsilon_2 \]
  so $\nu_2$ and $\varepsilon_2$ are directly proportional

- If one has 2 ESE classes, a and b, we can take the ratio
  \[ R_{\text{flow}} = \frac{\langle \nu_2 \rangle_a}{\langle \nu_2 \rangle_b} = \frac{\langle \varepsilon_2 \rangle_a}{\langle \varepsilon_2 \rangle_b} \]
  In this way one can experimentally determine the ratio of eccentricities without any need for theoretical modelling
  
  + ESE predicts that this ratio is independent of $p_T$
Even experimentally detector effects smear the results we still have a very good handle on the relative initial geometry variation (but larger fluctuations for imprecise estimators)

– Also for comparisons to models
ESE: high $p_T$ ($p_T > 10 \text{ GeV/c}$)  
The quenching region  

- In the following I will try to argue that at high $p_T$ we likely have that the medium and path-length dependence factorizes 

$$v_2(pT) \approx k_{\text{medium}}(\text{probe}, pT) \cdot k_{\text{pathlegth}}(\text{probe}, \varepsilon_2)$$

If we now have 2 ESE classes, a and b, we can take the ratio

$$R_{\text{quenching}}(\text{probe}) = \frac{\langle v_2 \rangle_a}{\langle v_2 \rangle_b} = \frac{k_{\text{pathlegth}}(\text{probe}, \langle \varepsilon_2 \rangle_a)}{k_{\text{pathlegth}}(\text{probe}, \langle \varepsilon_2 \rangle_b)}$$

And so at least naively it seems that we are mainly sensitive to the path-length dependence
Is this factorization reasonable?


- There is clearly a $p_T$/energy dependence of energy loss but as long as the path-length dependence is the same my naïve expectation is that you mainly change the scale, i.e., the absolute $v_2$, but not the relative fluctuations so that the ESE ratio to first order is the same (caveats on next slide)
Caveats

• $R_{AA}$ and $v_2$ are not linear in energy loss and so this is just a first order approximation

• The relative amount of radiative and collision energy loss will also depend on $pT \rightarrow$ break factorization
  – But putting on positive glasses it means we are likely sensitive to this change using ESE

• These are of course things where a real model could deliver much more insight