A simultaneous description of jet suppression and hadron suppression

Daniel Pablos

in collaboration with J. Casalderrey, Z. Hulcher, G. Milhano & K. Rajagopal

McGill

WAYNE STATE

Quark Matter 2018

Venezia

15th May 2018
Motivation

How to understand high momentum behaviour?

Different asymptotic trend for jets than for hadrons?

What can we learn from a simultaneous fit to jet and hadron data?

Precise data available up to very high momentum

ATLAS Preliminary
anti-κ, $R = 0.4$ jets

ATLAS, $\sqrt{s_{NN}} = 5.02$ TeV, this analysis
ATLAS, $\sqrt{s_{NN}} = 2.76$ TeV, arXiv: 1411.2357

2015 Pb+Pb data, 0.49 nb$^{-1}$
2015 pp data, 25 pb$^{-1}$
Jet FFs count the number of hadrons, per jet, with an energy fraction \( z \)

**Soft particle enhancement w.r.t. pp jets**

Medium back-reaction to deposited energy & momentum  
Antenna decoherence breaks angular ordering

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**Jet Fragmentation Functions (FFs)**

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see C. Park’s talk on Wednesday

see E. Iancu’s talk on Wednesday

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Jet Fragmentation Functions (FFs)

Jet FFs count the number of hadrons, per jet, with an energy fraction $z$

Hard particle enhancement w.r.t. pp jets

Steeply falling jet spectrum → High $p_T$ hadron spectrum dominated by leading tracks (from hard fragmenting jets)
Jet Fragmentation Functions (FFs)

Jet FFs count the number of hadrons, per jet, with an energy fraction $z$

Hard particle enhancement w.r.t. pp jets

High $z$ region of jet FFs closely related to hadronic spectrum
How do jet FFs affect the hadron spectrum?

Hybrid Model

Jet FFs and hadrons

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Jets, their FFs, and hadrons

In preparation

Hybrid Model

**Graph:**
- **Y-axis:** $R_{AA}$
- **X-axis:** Hadron or Jet $p_T$ [GeV]
- **Legend:**
  - Hadrons
  - Jets $R = 0.4$
  - Jets $\otimes FF^{actual}$

**Inset:**
- **Label:** Actual jet FFs
- **Graph:**
  - **Y-axis:** $\ln(1/z)$
  - **X-axis:** 0.5 to 4
  - Plot of jet FFs for high z enhancement

**Data Points:**
- **Hadrons:**
  - $R_{AA}$ values for different $p_T$ values.
- **Jets $R = 0.4$:**
  - $R_{AA}$ values for different $p_T$ values.
- **Jets $\otimes FF^{actual}$:**
  - $R_{AA}$ values for different $p_T$ values.

**Notes:**
- **High z enhancement:**
  - Indicated in the inset graph.
- **PbPb jet FFs:**
  - Highlighted in the main graph.

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Jets, their FFs, and hadrons

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Hybrid Model

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High z enhancement
Flat FFs ratio
High z suppression

Inverted jet FFs
Vacuum jet FFs
PbPb jet FFs

Hybrid Model

Hadrons
Jets $R = 0.4$

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Jet narrowing: a selection bias

**Wider, more active jets lose more energy than narrower, hard fragmenting ones**

Steeply falling jet spectrum -> bias inclusive jet sample to narrower ones, explains high z enhancement

High $p_T$ hadrons belong to such subsample of narrow jets, which get less quenched, and so $R_{AA}^{had} > R_{AA}^{jet}$

(Effect seen in the literature, for different models, on different observables - see backup)
The hybrid strong/weak coupling model

*Basis: exploit scale separation*

High energy jet starts with a high virtuality, much greater than medium scale

→ Parton shower well approximated by vacuum-like splittings (late stages?)
The hybrid strong/weak coupling model

*Basis: exploit scale separation*

High energy jet starts with a **high virtuality**, much greater than medium scale

→ Parton shower well approximated by **vacuum-like** splittings (late stages?)

Plasma-jet interaction dominated by **temperature scale**, order $\Lambda_{QCD}$

→ Use non-perturbative **holographic** prescription for partonic energy loss

*Energy flowing into hydro modes:*

\[
\frac{1}{E_{in}} \frac{dE}{dx} = -\frac{4}{\pi} \frac{x^2}{x_{stop}^2} \frac{1}{\sqrt{x_{stop}^2 - x^2}}
\]

Chesler & Rajagopal - PRD '14, JHEP '16

\[
x_{\text{stop}} = \frac{1}{2} \frac{E_{in}^{1/3}}{\kappa_{SC} T^{4/3}}
\]

$O(1)$ free parameter
The hybrid strong/weak coupling model

**Basis: exploit scale separation**

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**Energy flowing into hydro modes:**

$$\frac{1}{E_{\text{in}}} \frac{dE}{dx} = -\frac{4}{\pi} \frac{x^2}{x_{\text{stop}}^2} \sqrt{x_{\text{stop}}^2 - x^2}$$

Estimate the hadronic spectra coming from medium response

(assume small perturbation, instantaneous hydrodynamization)

- Lost jet energy converted into soft particles at large angles (corr. bkgd.)

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Pablo et al. - JHEP '14, '16, '17

Chesler & Rajagopal - PRD '14, JHEP '16

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Finite resolution effects

**Weak coupling:**
- interplay between antenna angle, formation time and emission wavelength
- medium interactions can destroy antenna color correlations
  
  \[ \text{radiation from the global charge only if system not resolved by QGP} \]

**Strong coupling:**
- quark-gluon system emulated by string with kink
- stopping distance modulated by angular separation between endpoint & kink
  
  \[ \text{needs further study!} \]

**In Hybrid Model:**
- unresolved dipoles lose energy as a single effective excitation
- two partons are resolved if their separation is greater than resolution length \( L_{\text{res}} \sim \lambda_D \)

\[ \text{see Z. Hulcher’s poster later today} \]
Finite resolution effects have an impact on jet substructure, e.g. on jet FFs. They affect the relation between $R_{AA}^{jet}$ and $R_{AA}^{had}$ as well.

Hulcher et al. - JHEP '18
Model implementation & Fitting

**PDFs:** CTEQ6L1 (pp) & CTEQ6L1+EPS09 (AA)

**Jet Production:** PYTHIA 8.230 (kinematics) & MC Glauber (trans. position)

**Jet Branching:** PYTHIA 8.230. Space-time picture through $\tau_F$ argument

**Hydro Profile:** smooth profiles from C. Shen

**Energy Loss:** apply holographic dE/dx in between splittings

**Jet Hadronization:** Lund string model from PYTHIA (pp & AA)

**Medium Response:** Perturbed Cooper-Frye, 4-mom. cons. with Metropolis

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$\chi^2$ **Goodness of Fit Test**

- Find best $\kappa$ for a given value of $L_{res} = \{0, 2/\pi T, 5/\pi T\}$

**Data**

- ATLAS and CMS, jet & hadron ($p_T > 10$ GeV) most central data
- PHENIX, hadron ($p_T > 5$ GeV) most central data

- Consider different error nature (stat., syst. uncorr., syst. corr., norm.) (following PHENIX PRC 08 arXiv:0801.1665)
Results

Consistent, but some tension between hadrons & jets preferred value

\[ L_{res} = 0 \]

CMS Had 5.02
ATLAS Had 5.02
CMS Had 2.76
ATLAS Had 2.76
RHIC Had 0.20
CMS Jets R=0.2 2.76
CMS Jets R=0.3 2.76
CMS Jets R=0.4 2.76
ATLAS Jets R=0.4 2.76
ATLAS Jets R=0.5 2.76

* with LHC data only

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Results

With increasing $L_{res}$, hadrons & jets preferred value is more similar…

$L_{res} = 2/\pi T$

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* with LHC data only

Hadrons 0-5%  Jets 0-10%

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Results

\[ L_{res} = \frac{2}{\pi T} \]

Although quality of global fit stays roughly the same (see backup).

\[ L_{res} = \frac{5}{\pi T} \]

In the backup.
Extracted jet FFs

ATLAS Prelim. Data

\( L_{res} = 0 \)
\( L_{res} = \frac{2}{\pi T} \)

125 < \( p_T^{jet} \) < 160 GeV

\(|y| < 2.1, R = 0.4\)

\( \sqrt{s} = 5.02\) ATeV

\( \kappa \in \{0.395, 0.420\} \)
\( \kappa \in \{0.420, 0.445\} \)

(global fits)
Conclusions & Outlook

- Hybrid Model successfully describes central hadron & jet data, simultaneously!

- There is some tension between RHIC and LHC data, pointing toward a larger $\kappa$ in the RHIC plasma, but the tension is only at the 3 $\sigma$ level.

- High $z$ region of jet FFs, which relates hadron with jet spectrum, shows an enhancement in AA/pp ratio:
  - wider jets lose more energy, final distribution biased toward narrow jets
  - inner jet structure important for jet quenching phenomenology

- Jet FFs are notably dependent on finite resolution effects, and so is the relation between hadron and jet suppression:
  - motivates introduction of such effects in other jet quenching MCs
  - can be specially constraining for pQCD
    (both suppression & coherence angle depend on $\hat{q}$)
\[ L_{res} = \frac{2}{\pi T} \]

\( \kappa \in \{0.420, 0.445\} \) (global fit)

\( \sqrt{s} = 5.02 \text{ ATeV} \)
\( \sqrt{s} = 2.76 \text{ ATeV} \)
Results

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Significance of results

\[ L_{res} = 0 \]
\[ L_{res} = \frac{2}{\pi T} \]
\[ L_{res} = \frac{5}{\pi T} \]

p-value \approx 0.03

CMS Had 5.02
ATLAS Had 5.02
CMS Had 2.76
ATLAS Had 2.76
RHIC Had 0.20
CMS Jets R=0.2 2.76
CMS Jets R=0.3 2.76
CMS Jets R=0.4 2.76
ATLAS Jets R=0.4 5.02
ATLAS Jets R=0.4 2.76

\[ \chi^2_{\min}/\nu \]

* with LHC data only
Wider, more active jets lose more energy than narrower, hard fragmenting ones

Effect seen in the literature, for different models, on different observables

- Holographic “jets”
- JEWEL
- Hybrid Model

Even though each individual jet widens, final distribution is narrower

Initial jet ensemble binned in energy and width

CMS’ jet shapes ratio

\[ \frac{\rho(t)}{\rho_{pp}} \]

Brewer et al. - JHEP ‘18
Wider jets lose more energy

*Wider, more active jets lose more energy than narrower, hard fragmenting ones*

Effect seen in the literature, for different models, on different observables

Holographic “jets”

JEWEL

Hybrid Model

Dijet asymmetry dominated by mass to momentum ratio, proxy for # vacuum splittings

Milhano & Zapp - EPJ ‘16
Wider jets lose more energy

*Wider, more active jets lose more energy than narrower, hard fragmenting ones*

Effect seen in the literature, for different models, on different observables

- Holographic “jets”
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Jet spectra ratio among different R

Larger R jets more quenched due to more energy loss sources

Pablos et al. - JHEP '17
Finite resolution effects

For a fixed $p_T$:

less quenching because
less # resolved charges
Finite resolution effects

As a function of $p_T$: steeper slope because additional partons not resolved

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Finite resolution effects

In other words: resolvable fluctuations induce additional quenching at high $p_T$

0-5% Centrality
$\sqrt{s} = 5.02$ ATeV
$\kappa = 0.42$

Hadrons $L_{res} = 0$
Hadrons $L_{res} \to \infty$
Jets $R=0.4$ $L_{res} = 0$
Jets $R=0.4$ $L_{res} \to \infty$

see K. Tywoniuk’s talk on Wed.
The effect of nuclear PDFs

\[ T_c = 145 \text{ MeV}, \quad L_{\text{res}} = \frac{2}{\pi T} \]

\[ \kappa_{SC} = 0.395 \]

0 – 5%

\[ \sqrt{s} = 5.02 \text{ ATeV} \]
Model improvements

Current medium response approximation cannot account for semi-hard regime (see CMS jet shapes, ATLAS & CMS jet FFs, CMS ‘missing-pt’)

Medium modified hadronization effects

Presence of rare, hard momentum transfers inducing extra splittings