Nuclear modification factors for jet fragmentation

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Talk based on arXiv:2005.05852
A pQCD picture for jet evolution in the QGP  

**Parton showers from pQCD:** factorization between vacuum-like emissions (bremsstrahlung) and medium-induced ones (BDMPS-Z).

- **Vetoed region** for VLEs inside the medium.

- VLEs $\Rightarrow$ sources for energy loss via MIEs.

- **Angular ordering** violation for the 1\textsuperscript{st} emission outside the medium.

**This talk:**

First Monte-Carlo results based on this factorized picture (including coherence effects) for the fragmentation function.
**Fragmentation function (FF): definition**

- Energy ($\sim$ transverse momentum) distribution of particles within jets.

$$D(x) = \frac{1}{N_{\text{jets}}} \frac{dN}{dx}$$

with

$$x = \frac{p_T \cos(\Delta R)}{p_{T,\text{jet}}} \sim \frac{p_T}{p_{T,\text{jet}}}$$

N.B. $x$ often denoted as $z$ in experimental plots →

- Nuclear modification of the jet fragmentation function:

$$R(x) = \frac{D_{PbPb}(x)}{D_{pp}(x)}$$

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**ATLAS Collaboration, Phys. Rev. C98, 2018**
FF is not infrared and collinear safe

\[ xD_{pp}(x) \overset{\text{DLA}}{=} 2\tilde{\alpha}_s \int_{k_{\perp \min}/(xp_T)}^{R} \frac{d\theta}{\theta} I_0 \left( 2\tilde{\alpha}_s \sqrt{2 \log(1/x) \log(R/\theta)} \right) \]

\[ \Rightarrow \textbf{strong} \ \text{dependence upon} \ k_{\perp \min}. \]

Two ways out:

- focus on the ratio \( \mathcal{R}(x) \),
- replace FF with better behaved (IRC-safe) observables.

\[ \begin{align*}
200 < p_{T,\text{jet}} < 251 \text{ GeV}, \ R = 0.4, \ |\eta_{\text{jet}}| < 2.1 \\
\hat{q} = 1.5 \text{ GeV}^2/\text{fm}, \ L = 4 \text{ fm}, \ \alpha_{s,\text{med}} = 0.24 \\
k_{\perp, \min} = 0.15, 0.25, 0.5 \text{ GeV} \\
\theta_{\max} = 0.75, 1, 1.5
\end{align*} \]
Monte-Carlo results and discussion

Fragmentation function from subjets

Our Monte-Carlo calculations

Sets of parameters describing $R_{AA}$
($R_{AA}$ controlled by $\alpha_{s,med}^2 \hat{q} L^2$)

3 medium parameters: $\hat{q}$, $L$, and $\alpha_{s,med}$ (vertex for MIEs).
Our Monte-Carlo calculations

Sets of parameters describing $R_{AA}$
($R_{AA}$ controlled by $\alpha_s^{2,med} \hat{q} L^2$)

| ATLAS       | $q = 2.0$ GeV$^2$/fm, $L = 4$ fm, $\alpha_{s,med} = 0.20$ |
|-------------|-----------------------------------------------------------|
| $\alpha_s = 0.20$, $\gamma = 0.20$ | $\alpha_s = 0.30$, $\gamma = 0.29$ |
| $\alpha_s = 0.20$, $\gamma = 0.20$ | $\alpha_s = 0.30$, $\gamma = 0.29$ |
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Two regimes

Nuclear **enhancement** at large $x$ and low $x$: same behaviour seen in the data.
Large-x behaviour: bias towards “hard-branching” jets

- Not a nuclear change in the fragmentation pattern, but in the statistics of hard-fragmenting jets.

- Hard-fragmenting jets have less structure, hence they lose less energy.

- Additionally: bias towards quark-initiated jets.

  see also Casalderrey-Solana et al.(1808.07386) 2019, Spousta and Cole, (1504.05169) 2016

\[ R_{AA} \text{ for different bins of } x_{\text{max}} \]

\[ \hat{q} = 1.5 \text{ GeV}^2/\text{fm}, L = 4 \text{ fm} \]

\[ \alpha_{s, \text{med}} = 0.24 \]

\[ R_{AA} \text{ for different bins of } x_{\text{max}} \]

- all jets
- 0.0 < \( x_{\text{max}} \) < 0.5
- 0.5 < \( x_{\text{max}} \) < 0.9
- 0.9 < \( x_{\text{max}} \) < 1.0

\[ p_T, \text{jet} \text{ [GeV]} \]

\[ R_{AA}, \text{anti-}k_t (R = 0.4), |y_{\text{jet}}| < 2.8 \]

PC, Iancu, Mueller, Soyez (2005.05852), 2020
Large-\(x\) behaviour: bias towards “hard-branching” jets

- Strong correlation between \(R_{AA}\) and large \(x\) fragmentation function ratio.
- Mild effect coming from the medium fragmentation pattern itself. 

PC, Mueller, Iancu, Soyez, 2020
Enhancement at low $x$: colour decoherence and MIEs

**Colour decoherence**

$\Rightarrow$ **no angular ordering** for the first emission outside the medium,

$\Rightarrow$ **factorisation** between parton cascades inside & outside the medium.  

\[
xD_{\text{PbPb}}(x) \sim \frac{\sqrt{\alpha_s}}{4} \times \begin{cases} 
\text{number of "in" sources} \\
\text{outside DL cascade}
\end{cases} \times \frac{1}{N_{\text{med}}} 
\times \exp(\bar{\alpha}_s \log(2p_T/\Lambda^2 L))
\]

\[
x = 0.005, 0.01, 0.02, 0.05, 0.1, 0.2, 0.5
\]

$\omega$, $p_T$, $R$

$\theta_c$, $\hat{q}$

$\omega = 2\Lambda^2$, $\theta = 1$

$\omega = 2\Lambda^2$, $p_T < q$

$\omega = 2\Lambda^2$, $p_T \geq q$

$\omega = \Lambda^2$, $\hat{q} < q$

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$\omega = \Lambda^2$, $\hat{q} < q$

$\omega = \Lambda^2$, $\hat{q} \geq q$
Enhancement at low $x$: colour decoherence and MIEs

Monte Carlo tests of various mechanisms

- VLEs only: medium effect = vetoed region + colour decoherence,
- VLEs and MIEs: vetoed region, energy loss, but no colour decoherence,
- Full MC: no angular ordering for the first emission outside the medium.
IRC safe fragmentation function: FF from subjets

Definition

\[ D_{\text{sub}}(z) = \frac{1}{N_{\text{jets}}} \frac{dN_{\text{sub}}}{dz} \]

d\(N_{\text{sub}}\) number of primary subjets with \(k_\perp > k_\perp \text{cut}\) found after an iterative C/A declustering.

\[
\text{primary Lund declusterings}
\]

\[
\begin{align*}
\omega^3 \theta^4 &= 2^q \\
L^2 &= 2 \\
\omega \theta &= k_\perp, \text{min}
\end{align*}
\]
**DL result**

\[
\mathcal{D}_{\text{sub}}^{PbPb}(z) \sim \left[ \int_0^R d\theta \frac{2 \alpha_s(z \theta p_T)}{\theta \pi z} \Theta_{\text{cut}} \Theta_{\text{veto}} \right] \times \sum_{i=q,g} \frac{C_i \sigma_i(p_T + \mathcal{E}_i(z))}{\sigma_q(p_T + \mathcal{E}_q) + \sigma_g(p_T + \mathcal{E}_g)}
\]

- **Same physics** at play as for the FF.
- **Veto region** \( \Theta_{\text{cut}} \rightarrow \Theta_{\text{cut}} \Theta_{\text{veto}}(z, \theta) \)
- \( N_{\text{jets}} \) normalization effect: 
  energy loss \( \tilde{E} \) of the average jets < energy loss \( E_i(z) \) for 2 hard subjets

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**Fragmentation into subjets - analytic**

- **VLEs only**
- **VLEs+large-angle \( E \)loss**
- **full**
**FF from subjets: leading order analysis**

### DL result

\[
D_{\text{sub}}^{PbPb}(z) \simeq \int_0^R d\theta \left[ \frac{1}{\theta} \frac{2\alpha_s(z\theta p_T)}{\pi z} \Theta_{\bar{q} \text{veto}} + \frac{d^2 N_{\text{mie}}}{dz d\theta} \right] \Theta_{\text{cut}} \times \sum_{i=q,g} \frac{C_i \sigma_i(p_T + E_i(z))}{\sigma_q(p_T + \bar{E}_q) + \sigma_g(p_T + \bar{E}_g)}
\]

#### Figure

- **Same physics** at play as for the FF.
- **Veto region** \( \Theta_{\text{cut}} \to \Theta_{\text{cut}} \Theta_{\bar{q} \text{veto}}(z, \theta) \)
- **\( N_{\text{jets}} \)** normalization effect:
  - energy loss \( \bar{E} \) of the average jets < energy loss \( E_i(z) \) for 2 hard subjets
- **Intrajet hard MIEs.**
Take-home messages

- IRC safe is ... safer!

- Standard FF (IRC unsafe):
  - large $x$ enhancement correlated with RAA,
  - small $x$ enhancement due to intrajet MIEs + decoherence,
  - large error bars (sensitivity to $k_{\perp\text{min}}$).

- FF from subjets (IRC safe): better control for the nuclear effects.

THANK YOU!
BACK-UP
FF from subjets: dependence on medium parameters

$p_{t, \text{jet}} = 500 \text{ GeV}, R = 0.4, k_t > 2.0 \text{ GeV}$

$z = \frac{p_t}{p_{t, \text{parent}}}$

primary Lund declusterings

- $\hat{q} = 1.5, L = 3, \alpha_s = 0.35$
- $\hat{q} = 1.5, L = 4, \alpha_s = 0.24$
- $\hat{q} = 2, L = 3, \alpha_s = 0.29$
- $\hat{q} = 2, L = 4, \alpha_s = 0.2$
Jet energy loss as function of $x_{\text{max}}$

![Diagram showing average energy loss vs. $x_{\text{max}}$](image)

- $\hat{q} = 1.5 \ \text{GeV/fm}^2$
- $L = 4 \ \text{fm}$
- $\alpha_s = 0.24$
- $\theta_{\text{max}} = R, \ k_{\perp,\text{min}} = 0.25 \ \text{GeV}$
FF: dependence on jet $p_T$

dependence of $\mathcal{R}$ on the jet $p_T$

$\hat{q} = 1.5$ GeV$^2$/fm, $L = 4$ fm, $\alpha_{s,med} = 0.24$

- 126 < $p_{T,\text{jet}}$ < 158 GeV
- 200 < $p_{T,\text{jet}}$ < 251 GeV
- 316 < $p_{T,\text{jet}}$ < 358 GeV

anti-$k_t (R = 0.4)$, 200 < $p_{T,\text{jet}}$ < 251 GeV, $|y_{\text{jet}}| < 2.1$
FF: disentangling statistical bias vs. in-medium fragmentation

Nuclear modification factor $R(x)$ - analytic

- VLEs only
- VLEs + $E_{\text{loss}}$
- VLEs + $E_{\text{loss}} + \text{MIEs}$
- full ($p_{T, \text{jet}} = p_{T0}$)

Nuclear modification factor $R(x)$ - Monte Carlo

- VLEs only
- VLEs + $E_{\text{loss}} + \text{MIEs}$
- full ($200 < p_{T, \text{jet}} < 251 \text{ GeV}, |y| < 2.1$)

**Legend:**
- **quark**
- anti-$k_t (R = 1)$, $p_{T0} = 200 \text{ GeV}, k_{\perp, \text{min}} = 0.25 \text{ GeV}$
- $\hat{q} = 1.5 \text{ ReV}^2/\text{fm}, L = 4 \text{ fm}, \alpha_s, \text{med} = 0.24$