Jet effects in high multiplicity pp events

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Work in collaboration with: Gyula Bencedi, Héctor Bello and Satyajit Jena
Outline

- Introduction
- Tools
- Particle production as a function of the event multiplicity and hardness
- Energy dependence
- Summary
INTRODUCTION
Introduction

- Small systems (like those produced in pp and p-Pb collisions) have attracted the attention of the heavy ion community because:
  - In high multiplicity events, sQGP-like signatures have been found (flow & long range azimuthal correlations)
  - The origin of such effects is still unknown
  - More differential studies are needed
A hydro-inspired model (Blast-Wave):

\[
\frac{1}{p_T} \frac{dN}{dp_T} \propto \int_0^R r dr m_T I_0 \left( \frac{p_T \sinh \rho}{T_{\text{kin}}} \right) K_1 \left( \frac{m_T \cosh \rho}{T_{\text{kin}}} \right)
\]

\[
\rho = \tanh^{-1} \beta_T = \tanh^{-1} \left( \left( \frac{r}{R} \right)^n \beta_S \right)
\]

Describes the \( p_T \) spectra of identified hadrons in:

- p-Pb and Pb-Pb data

ALICE, arXiv:1506.07287
Introduction

A hydro-inspired model (Blast-Wave):

\[
\frac{1}{p_T} \frac{dN}{dp_T} \propto \int_0^R r dr m_T I_0 \left( \frac{p_T \sinh \rho}{T_{\text{kin}}} \right) K_1 \left( \frac{m_T \cosh \rho}{T_{\text{kin}}} \right)
\]

\[\rho = \tanh^{-1} \beta_T = \tanh^{-1} \left( \left( \frac{r}{R} \right)^n \beta_S \right)\]

Describes the \(p_T\) spectra of identified hadrons in:
- p-Pb and Pb-Pb data
- Also the \(p_T\) distributions generated with Pythia (where no hydrodynamical evolution is assumed)

It has been discussed that color reconnection (CR) produces radial flow-like patterns due to boosted strings

G. Paić, E. Cuautle, P. Christiansen, I. Maldonado and A. O., PRL 111 (2013) 042001

ALICE, PLB 728 (2014) 25-38

Graph showing data points and fits for different collision conditions.
Introduction

Introduction

1\textsuperscript{st} partonic system

+2\textsuperscript{nd} partonic system

Introduction

Introduction

This was the focus of this work: PRL 111 (2013) 042001

- The more $N_{\text{MPI}}$ the higher the flow-like effect

Introduction

Due to the large $N_{\text{MPI}}$, a high $p_T$ jet in the event is expected (high probability):

- Can we quantify the effects of the high $p_T$ jets?
- I would expect a higher boost with increasing the parton $p_T$
In the CR model used in the tune Monash 2013 (Mo2013), an MPI system with a scale $p_T$ of the hard interaction (normally $2 \rightarrow 2$) can be merged with one of a harder scale with a probability that is:

$$P(p_T) = \frac{(RR \times p_{T0})^2}{(RR \times p_{T0})^2 + p_T^2}$$

Reconnection Range ($RR$): 0-10
Tune Monash 2013: $RRxp_{T0} \approx 3$

http://home.thep.lu.se/~torbjorn/pythia82html/Welcome.html

Introduction

In CR is activated

This work: study the properties of the pp events as a function of their multiplicity \( z = \frac{dN/d\eta}{<dN/d\eta>} \) & their jet content (leading jet \( p_T \))

Tools

- **Generator:** Pythia 8.212, T. Sjöstrand et. al, CPC191 (2005) 159
  - Tune Monash 2013, P. Skands, EPJC74 (2014) 8, 3024
  - 900M events
    - 7 TeV (reference), 0.9 TeV, 2.76 TeV and 13 TeV

- **Jet Finder:** FastJet 3.1.3, M. Cacciari et al., EPJC72(2012)1896
  - Anti-$k_T$ algorithm
  - R=0.4
  - $p_T^{\text{min}} = 5$ GeV
  - Visible particles (Pythia definition) are considered for the jet reconstruction

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A. Ortiz (MPI, Trieste, Italy)
INCLUSIVE PARTICLE PRODUCTION AS A FUNCTION OF THE EVENT MULTIPLICITY AND HARDNESS
INCLUSIVE PARTICLE PRODUCTION AS A FUNCTION OF THE EVENT MULTIPLICITY AND HARDNESS

The underlying event contribution to the jet $p_T$ was not studied, because we are only interested in the event classification.

**Multiplicity $p_T$ spectra**

**Jet $p_T$**

-1 1 $\eta$
$p_T^{\text{jet}}$ vs. multiplicity

The higher the event multiplicity the higher the average $p_T^{\text{jet}}$.
$p/\pi$ vs. $\rho_T$ (low multiplicity)

**With Color Reconnection**

- $|\eta_{\text{jet}}| < 1$, $0 < z < 1$
  - w/o jets ($p_T^{\text{jet}} > 5$ GeV, $|\eta| < 1$)
  - $5 < p_T^{\text{jet}} < 10$ GeV
  - $10 < p_T^{\text{jet}} < 15$ GeV
  - $15 < p_T^{\text{jet}} < 20$ GeV
  - $20 < p_T^{\text{jet}} < 25$ GeV

**Without Color Reconnection**

- $|\eta_{\text{jet}}| < 1$, $0 < z < 1$
  - w/o jets ($p_T^{\text{jet}} > 5$ GeV, $|\eta| < 1$)
  - $5 < p_T^{\text{jet}} < 10$ GeV
  - $10 < p_T^{\text{jet}} < 15$ GeV
  - $15 < p_T^{\text{jet}} < 20$ GeV
  - $20 < p_T^{\text{jet}} < 25$ GeV

Pythia 8.212 Mo13 pp $\sqrt{s} = 7$ TeV
\( p/\pi \) vs. \( \rho_T \) (low multiplicity)

- **With Color Reconnection**
  - \( |\eta_{\text{jet}}| < 1, 0 < z < 1 \)
  - w/o jets (\( \rho_T^{\text{jet}} > 5 \text{ GeV}, |\eta|<1 \))
  - \( 5 < \rho_T^{\text{jet}} < 10 \text{ GeV} \)
  - \( 10 < \rho_T^{\text{jet}} < 15 \text{ GeV} \)
  - \( 15 < \rho_T^{\text{jet}} < 20 \text{ GeV} \)
  - \( 20 < \rho_T^{\text{jet}} < 25 \text{ GeV} \)
  - Inclusive

- **Without Color Reconnection**
  - \( |\eta_{\text{jet}}| < 1, 0 < z < 1 \)
  - w/o jets (\( \rho_T^{\text{jet}} > 5 \text{ GeV}, |\eta|<1 \))
  - \( 5 < \rho_T^{\text{jet}} < 10 \text{ GeV} \)
  - \( 10 < \rho_T^{\text{jet}} < 15 \text{ GeV} \)
  - \( 15 < \rho_T^{\text{jet}} < 20 \text{ GeV} \)
  - \( 20 < \rho_T^{\text{jet}} < 25 \text{ GeV} \)
  - Inclusive

- CR effects are observed for \( \rho_T^{\text{jet}} < 10 \text{ GeV} \)
\( \frac{p/\pi}{\rho_T} \) vs. \( \rho_T \) (low multiplicity)

- CR effects are observed for \( \rho_T^{\text{jet}} < 10 \) GeV
- The position of the peak is shifted to higher \( \rho_T \) when \( \rho_T^{\text{jet}} \) increases. The shift is accompanied by an increase of \( <\beta_T> \)
p/π vs. $p_T$ (low multiplicity)

- CR effects are observed for $p_T^{\text{jet}} < 10$ GeV
- The position of the peak is shifted to higher $p_T$ when $p_T^{\text{jet}}$ increases. The shift is accompanied by an increase of $<\beta_T>$ (from Blast-Wave analysis)
- The effect is very small for $p_T^{\text{jet}} > 15$ GeV
This is a FF effect ($p/\pi$ vs. $p_T/\rho_T^{\text{jet}}$ is $\approx \rho_T^{\text{jet}}$ independent)

- With Color Reconnection
  - $|\eta^{\text{jet}}| < 1$, $0 < z < 1$
  - w/o jets ($p_T^{\text{jet}} > 5$ GeV, $|\eta| < 1$)
  - $5 < p_T^{\text{jet}} < 10$ GeV
  - $10 < p_T^{\text{jet}} < 15$ GeV
  - $15 < p_T^{\text{jet}} < 20$ GeV
  - $20 < p_T^{\text{jet}} < 25$ GeV

- Without Color Reconnection
  - $|\eta^{\text{jet}}| < 1$, $0 < z < 1$
  - w/o jets ($p_T^{\text{jet}} > 5$ GeV, $|\eta| < 1$)
  - $5 < p_T^{\text{jet}} < 10$ GeV
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  - $15 < p_T^{\text{jet}} < 20$ GeV
  - $20 < p_T^{\text{jet}} < 25$ GeV

CR effects are observed for $p_T^{\text{jet}} < 10$ GeV

The position of the peak is shifted to higher $p_T^{\text{jet}}$ when $p_T^{\text{jet}}$ increases. The shift is accompanied by an increase of $<\beta_T>$.

The effect is very small for $p_T^{\text{jet}} > 15$ GeV (saturation of $<\beta_T>$).
$p/\pi$ vs. $\rho_T$ (high multiplicity)

- Larger enhancement with respect to the case without CR
- With CR, jet effects (peak position) are smaller than in the low $N_{ch}$ case
  - Dominated by underlying event
$p/\pi$ vs. $p_T$ (high multiplicity)

Without CR: $p/\pi$ vs. $p_T/p_T^{\text{jet}}$ is $\approx p_T^{\text{jet}}$ independent (FF)

With Color Reconnection

Without Color Reconnection

- Larger enhancement with respect to the case without CR
- With CR, jet effects (peak position) are smaller than in the low $N_{\text{ch}}$ case

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Study of the inclusive light flavored hadron production

Results from the Blast-Wave analysis are presented, for this a simultaneous fit of the BW function to the the $p_T$ spectra is performed in order to extract $<\beta_T>$. The fitting ranges are the following:

<table>
<thead>
<tr>
<th>Particle</th>
<th>$p_T$ range (GeV/c)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\pi$</td>
<td>0.5-1.0</td>
</tr>
<tr>
<td>$K$</td>
<td>0.3-1.5</td>
</tr>
<tr>
<td>$K^0_S$</td>
<td>0.3-1.5</td>
</tr>
<tr>
<td>$\rho$</td>
<td>0.8-2.0</td>
</tr>
<tr>
<td>$\phi$</td>
<td>0.8-2.0</td>
</tr>
<tr>
<td>$\Lambda$</td>
<td>1.0-2.1</td>
</tr>
<tr>
<td>$\Xi$</td>
<td>1.2-2.6</td>
</tr>
<tr>
<td>$\Omega$</td>
<td>1.3-2.8</td>
</tr>
</tbody>
</table>

(Same $p_T$ ranges as in: G. Paić, E. Cuautle and A. O. NPA 941 (2015) 78-86, where the $p_T$ spectra in high multiplicity events were described by BW model within 10%)
Without Jets

MC / Fit

Pythia 8.212 (Mo2013)

〈 p_{T} 〉 = 0.29, T_{kin} = 0.14 GeV, n=3.68

〈 p_{T} 〉 = 0.37, T_{kin} = 0.14 GeV, n=2.62

〈 p_{T} 〉 = 0.37, T_{kin} = 0.14 GeV, n=2.54

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Without Jets

\[ <\beta_T> \approx 0.34, \quad <T_{\text{kin}}> \approx 0.14, \quad <n> \approx 2.94 \]

\[ \langle N_{\text{ch}} \rangle_{|\eta|<1} \approx 16.23 \quad \langle N_{\text{ch}} \rangle_{|\eta|<1} \approx 38.02 \quad \langle N_{\text{ch}} \rangle_{|\eta|<1} \approx 59.58 \]
Without Jets

$\langle \beta_T \rangle \approx 0.34$, $\langle T_{\text{kin}} \rangle \approx 0.14$, $\langle n \rangle \approx 2.94$

At high multiplicity, BW still describes the spectra within 10%, however:

- Smaller $\langle \beta_T \rangle$ is obtained than in the case without any selection on the hardness
- No strong multiplicity dependence is observed as in the more inclusive case
- Opposite behavior to that expected from hydro.

Can we use this tool to try to rule out models?

$\langle N_{\text{ch}} \rangle_{|\eta|<1} \approx 16.23$ $\langle N_{\text{ch}} \rangle_{|\eta|<1} \approx 38.02$ $\langle N_{\text{ch}} \rangle_{|\eta|<1} \approx 59.58$

Pythia 8.212 (Mo2013)
$15 < p_T^{\text{Jet}} < 20$ GeV

$\langle \beta_T \rangle \approx 0.48, \quad \langle T_{\text{kin}} \rangle \approx 0.12, \quad \langle n \rangle \approx 1.94$

$\langle N_{\text{ch}} \rangle_{|\eta|<1} \approx 16.23 \quad \langle N_{\text{ch}} \rangle_{|\eta|<1} \approx 38.02 \quad \langle N_{\text{ch}} \rangle_{|\eta|<1} \approx 59.58$
15 < $p_T^{\text{Jet}}$ < 20 GeV

$\langle \beta_T \rangle \approx 0.48$, $\langle T_{\text{kin}} \rangle \approx 0.12$, $\langle n \rangle \approx 1.94$

When a high $p_T$ jet is required:

- BW model describes the spectra even in low multiplicity events. In the inclusive case (w/o selection on hardness), low multiplicity events are very soft -> BW can not fit the spectra
- $\langle \beta_T \rangle$ is $\approx$ independent of multiplicity when $p_T^{\text{jet}}$ and multiplicity are fixed

$\langle N_{\text{ch}} \rangle_{|n|<1} \approx 16.23$  
$\langle N_{\text{ch}} \rangle_{|n|<1} \approx 38.02$  
$\langle N_{\text{ch}} \rangle_{|n|<1} \approx 59.58$
$15 < p_T^{\text{Jet}} < 20$ GeV

Smaller $\langle \beta_T \rangle \approx 0.32$ & larger $n \approx 3.7$

Without Color Reconnection

Slight increase of $\langle \beta_T \rangle$
ENERGY DEPENDENCE
15 < \rho_T^{\text{Jet}} < 20 \text{ GeV}

Similar \langle N_{\text{ch}} \rangle \text{ and } \langle N_{\text{MPI}} \rangle \text{ gives similar parameters: } \langle \beta_T \rangle \approx 0.47, \quad \langle T_{\text{kin}} \rangle \approx 0.12, \quad \langle n \rangle \approx 2.18

\begin{align*}
\langle N_{\text{ch}} \rangle_{|\eta| < 1} & \approx 15.65 \\
\langle N_{\text{MPI}} \rangle & \approx 3.53
\end{align*}

\begin{align*}
\langle N_{\text{ch}} \rangle_{|\eta| < 1} & \approx 17.72 \\
\langle N_{\text{MPI}} \rangle & \approx 4.14
\end{align*}

\begin{align*}
\langle N_{\text{ch}} \rangle_{|\eta| < 1} & \approx 18.35 \\
\langle N_{\text{MPI}} \rangle & \approx 4.26
\end{align*}
Spectral shapes

Proton-to-pion ratio show little or no dependence with $\sqrt{s}$ ($p_T$ position of the peak is the same for the three colliding systems)
Spectral shapes

\[ \ln|\eta^{\text{jet}}| < 1, \left\langle N_{\text{ch}}\right\rangle_{|\eta|<1} \approx 17.24 \]

- TeV: 0.9
  - $15 < p_T^{\text{jet}} < 20$ GeV
- TeV: 7
  - $15 < p_T^{\text{jet}} < 20$ GeV
- TeV: 13
  - $15 < p_T^{\text{jet}} < 20$ GeV

Without the jet requirement, the ratios look more different due to the different jet biases.
Summary

- In Pythia, MPI (semi-hard and hard partonic scatterings) and CR produce flow-like effects.

- The result of the interaction between the soft and hard component could be used as a tool to validate or rule out models which produce flow(-like) effects in small systems, e.g. hydro vs. color reconnection (important for HI physics).

- Same physics is obtained when a selection on multiplicity and hardness is implemented.
Guy Paić, Peter Christiansen, Andreas Morsch and Eleazar Cuautle are acknowledged for the useful discussions
With CR
HADRONIZATION IN A CLEAN PARTONIC CONFIGURATION
$p_T^g = 5 \text{ GeV}$

- $\pi^+ + \pi^-$ (100.00x)
- $K^+ + K^-$ (50.00x)
- $K_S^0$ (25.00x)
- $p + \bar{p}$ (1.00x)
- $\phi$ (0.50x)
- $\Lambda + \bar{\Lambda}$ (0.10x)
- $\Xi + \bar{\Xi}$ (0.05x)
- $\Omega + \bar{\Omega}$ (0.01x)

- Blast-Wave (global)

MC / Fit

$\langle \beta_T \rangle = 0.46$, $T_{\text{kin}} = 0.13 \text{ GeV}$, $n=1.96$

**Parton-level configurations as direct input for hadronization**

Instituto de Ciencias Nucleares UNAM
$p_T^g = 10 \text{ GeV}$

- $\pi^+ + \pi^-$ (100.00x)
- $K^+ + K^-$ (50.00x)
- $K^0_S$ (25.00x)
- $p + \bar{p}$ (1.00x)
- $\phi$ (0.50x)
- $\Lambda + \bar{\Lambda}$ (0.10x)
- $\Xi^- + \bar{\Xi}^+$ (0.05x)
- $\Omega^- + \bar{\Omega}^+$ (0.01x)
- Blast-Wave (global)

Parton-level configurations as direct input for hadronization

$\langle \beta_T \rangle = 0.59, \quad T_{\text{kin}} = 0.10 \text{ GeV}, \quad n=1.35$
$p_T^g = 80 \text{ GeV}$

- $\pi^+ + \pi^-$ (100.00x)
- $K^+ + K^-$ (50.00x)
- $K_S^0$ (25.00x)
- $p + \bar{p}$ (1.00x)
- $\phi$ (0.50x)
- $\Lambda + \bar{\Lambda}$ (0.10x)
- $\Xi^+ + \bar{\Xi}^+$ (0.05x)
- $\Omega^- + \bar{\Omega}^+$ (0.01x)

Blast-Wave (global)

Parton-level configurations as direct input for hadronization

$\langle \beta_T \rangle = 0.58$, $T_{\text{kin}} = 0.16 \text{ GeV}$, $n=1.41$

MC / Fit

Pythia 8.212
OTHER APPROACHES
Jet effects can be also seen in a more inclusive analysis

No second rise is observed
Notice that the second rise has been reported by ALICE

ALICE PLB 727 (2013) 371-380

pp $\sqrt{s} = 5.02$ TeV, Pythia 8.201 (4C)

$dN_{ch}/d\eta (p_T > 0 \text{ GeV}/c)$

- $<p_T>$ was computed with charged particles within $|\eta|<0.3$
- $dN_{ch}/d\eta$ was computed using different $\eta$ windows
Jet effects can be also seen in a more inclusive analysis

\[ \langle \beta_T \rangle \]

\[ \text{pp } \sqrt{s} = 5.02 \text{ TeV, Pythia 8.201 (4C)} \]

- \( |\eta| < 5.0 \)
- \( |\eta| < 2.5 \)
- \( |\eta| < 1.0 \)
- \( |\eta| < 0.3 \)

Higher \( \langle \beta_T \rangle \) when the jet bias is stronger

Similar effect has been reported using event shapes


- \( \langle \beta_T \rangle \) was computed with charged particles within \( |\eta| < 0.3 \)
- \( dN_{\text{ch}}/d\eta \) was computed using different \( \eta \) windows
PID in charged jets

Xianguo Lu, for the ALICE Collaboration, NPA 00 (2014), 1-4

\[
\frac{K^+ + K^-}{\pi^+ + \pi^-}
\]

\[
\frac{p + \bar{p}}{\pi^+ + \pi^-}
\]

anti-\(k_T\)

\[R = 0.4; |\eta^{\text{jet}}| < 0.5\]

\[p_T^{\text{track}} > 0.15 \text{ GeV/c}\]

\[|\eta^{\text{track}}| < 0.9\]

pp \(\sqrt{s} = 7\) TeV

ALICE Preliminary

- 5-10 GeV/c
- 10-15 GeV/c
- 15-20 GeV/c

scaled to 5-10 GeV/c