Long-range Correlations in Massive Jets

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Motivation

- People are looking for collectivity in pp and ee as a possible sign of QGP

- long range $\Delta Y$ correlations are the signal of collectivity

- Is the near-side ridge in high-multiplicity pp events due to QGP or massive jets?
Motivation

Long-range $\Delta Y$ correlations may emerge due to highly virtual partons (massive jets) in the hard process.
To get long range $\Delta Y$ correlations, we need massive jets

phasespace of hadrons in a jet initiated by a leading parton of momentum $P_\mu = (E_{jet}, \vec{P}_{jet})$ is an ellipsoid of width $M_{jet}$ and length $E_{jet}$
Motivation

To get long range $\Delta Y$ correlations, we need massive jets.

We can have hadrons with large $\Delta Y$ if $p_1$ and $p_2$ are small enough.
Motivation

To get long range $\Delta Y$ correlations, we need massive jets

But, the jet cone might exclude hadrons with large $\Delta Y$
Motivation

To get long range $\Delta Y$ correlations, we need massive jets.

(a) $pp \sqrt{s} = 7$ TeV, $N_{\text{thr}}^{\text{offline}} \geq 110$
How large $M_{\text{jet}}$ do we need?

Let's say, we calculate $v_2(p_T)$ from hadron pairs with $\Delta Y = 3$. 

![Diagram showing $M$ vs $p_T$ with different curves for $P = 50, 100, 200, 500$ GeV/c and labeling $\Delta Y$, $p_T$, and the edge of phasespace.](image)
Outline

- Off-shell fragmentation and scale evolution

- Long-range correlations of hadrons stemming from highly-virtual leading partons

- $v_2$ in fix multiplicity jets
Outline

- **Off-shell fragmentation and scale evolution**

- Long-range correlations of hadrons stemming from highly-virtual leading partons

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Off-shell fragmentation function

- Initial function at starting scale $Q_0$

- Scale evolution
Model for a jet at $Q_0$

- **Statistical model** for the initial FF at starting scale:

  The haron distribution in a jet of $n$ hadron with total momentum $P$

  \[ p_0 \frac{d\sigma}{d^3p} \propto (1 - x_1)^{n-3} \]

  \[ p_1 p_2 \frac{d\sigma}{d^3p_1 d^3p_2} \propto (1 - x_1 - x_2 + x_{12})^{n-4} \]

  \[ x_1 = 2 P_{\mu} p_1^\mu / M^2, \quad x_{12} = 2 p_{1\mu} p_2^\mu / M^2 \]

  \[ P(n) = \binom{n+r-1}{r-1} \tilde{p}^n (1 - \tilde{p})^r \]

- Averaging over multiplicity fluctuations of the form of

  results in an initial FF of the form of

  \[ p_0 \frac{d\sigma}{d^3p} = A \left[ 1 + \frac{q-1}{\tau} x \right]^{-1/(q-1)} \]

**Off-shell Scale-evolution** (in the $\varphi^3$ theory)

Difference from the standard way: the leading parton is off-shell
Thus, the **fragmentation scale** is the jet mass

Hadron spectrum: leading parton (of momentum $P$) emits on-shell daughter partons (of momentum $k$) that fragment to hadrons at low virtuality $m_0$

$$D(x, P^2) = \int \frac{dz}{z} \left[ \delta(1-z) + g^2 A(z, P^2) \right] D_0 \left( \frac{x}{z}, m_0^2 \right)$$

Which can be inverted (up to $O(g^2)$)

$$D_0(x, m_0^2) = \int \frac{dz}{z} \left[ \delta(1-z) - g^2 A(z, P^2) \right] D \left( \frac{x}{z}, P^2 \right)$$

Differentiate wrt $\ln(P^2)$ \( \rightarrow \) **DGLAP equation**

$$\frac{\partial}{\partial \ln P^2} D(x, P^2) = \int \frac{dz}{z} D \left( \frac{x}{z}, P^2 \right) g^2 \frac{\partial}{\partial \ln P^2} A(z, P^2)$$

$$\frac{\partial}{\partial \ln P^2} \tilde{D}(\omega, P^2) = \tilde{D}(\omega, P^2) g^2 \tilde{P}(\omega)$$

$$\tilde{D}(\omega, P^2) = \tilde{D}_0(\omega, m_0^2) \exp \left[ \tilde{P}(\omega) b(P^2) \right]$$

\( \tilde{f}(\omega) = \int_0^1 dx x^{\omega-1} f(x) \)
**Model for a jet**

- **Scale evolution of the parameters of the model:**

  - **approximation:**

  \[
  D(x, t) = \int_x^1 \frac{dz}{z} f(z, t) \left(1 + \frac{q_0 - 1}{\tau_0} \frac{x}{z}\right)^{1/(q_0 - 1)} \neq \left(1 + \frac{q(t) - 1}{\tau(t)} \frac{x}{z}\right)^{1/(q(t) - 1)}
  \]

- **Prescription for a few moments of D:**

  \[
  \int D_{apx}(x, t) = \int D(x, t)
  \]

  \[
  \int x D_{apx}(x, t) = \int x D(x, t) = 1 \quad \text{(by definition)}
  \]

  \[
  \int x^2 D_{apx}(x, t) = \int x^2 D(x, t)
  \]

  \[
  t = \ln \left( \frac{M_{jet}^2}{\Lambda^2} \right)
  \]

  \[
  q(t) = \frac{\alpha_1 (t/t_0)^{a_1} - \alpha_2 (t/t_0)^{-a_2}}{\alpha_3 (t/t_0)^{a_1} - \alpha_4 (t/t_0)^{-a_2}}
  \]

  \[
  \tau(t) = \frac{\tau_0}{\alpha_4 (t/t_0)^{-a_2} - \alpha_3 (t/t_0)^{a_1}}
  \]

  \[
  a_1 = \frac{\tilde{P}(1)}{\beta_0}, \quad a_2 = \frac{\tilde{P}(3)}{\beta_0}
  \]

Scale = jet mass!!!

Inside light jets

\[ M_1 \]

\[ D(x) \approx \exp\left\{-\frac{x}{\tau}\right\} \]

\[ P(n) \approx \frac{(1/\tau)^n}{n!} e^{-1/\tau} \]

The fragmentation function:

Inside heavy jets

\[ M_2 \]

\[ D(x) \approx \left(1 + \frac{q-1}{\tau} x\right)^{-1/(q-1)} \]

\[ P(n) \approx \binom{n+r-1}{r-1} \tilde{p}^n (1-\tilde{p})^r \]

\[ \tilde{p} = \frac{(q-1)}{\tau + q-1} \]

\[ r = 1/(q-1) - 3 \]
Evolution of the mean \textit{multiplicity} and its \textit{dispersion}:

\[ \langle n \rangle = \frac{4 - 3q_0}{\tau_0} (t/t_0)^{-a^2} \sim \ln^a(M_{\text{jet}}) \]

\[ \langle n^2 \rangle - \langle n \rangle^2 = \langle n \rangle \left[ \frac{3 - 2q_0}{\tau_0} (t/t_0)^{a^1} + 1 - \langle n \rangle \right] \]
The model works for longitudinal and transverse momentum distributions in jets.

\( e^+P \rightarrow 2 \text{jets} \)

Scale evolution of the fit parameters

\[ q(t) = \frac{\alpha_1 (t/t_0)^{a_1} - \alpha_2 (t/t_0)^{-a_2}}{\alpha_3 (t/t_0)^{a_1} - \alpha_4 (t/t_0)^{-a_2}} \]

\[ \tau(t) = \frac{\tau_0}{\alpha_4 (t/t_0)^{-a_2} - \alpha_3 (t/t_0)^{a_1}} \]

\[ t = \ln \left( \frac{M_{jet}^2}{\Lambda^2} \right) \]
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- $v_2$ in fix multiplicity jets
Long-range correlations in fat jets

1-particle distribution

$E = 110 \text{ GeV}$
$P = 85 \text{ GeV/c}$
$M = 70 \text{ GeV/c}^2$
Long-range correlations in fat jets

away and near-side ridge-like structure
Long-range correlations in fat jets

Away and near-side ridge-like structure
$v^2$ from large $2 < |\Delta \eta| < 4$ correlations
\[ v_2 = \frac{\int_{-q_0}^{q_0} d\varphi f(\varphi) \cos(n\varphi)}{\int_{-q_0}^{q_0} d\varphi f(\varphi)} \rightarrow 1 \]

\text{edge of phasespace}

\[ v_2 \text{ increases} \]
$p^* = \frac{E_{JET} - P_{JET}}{2}$

edge of phasespace

position of this minimum

$E_p = 150 \quad E_m = 60 \quad E_3 = 10.5 \quad P_3 = 43 \quad M_3 = 94.868$
$v_2$ in 1 jet

Graphs showing $v_2$ as a function of $p_T$ for different $P_{\text{JET}}$ and $M_{\text{JET}}$. The graphs are for $P_{\text{JET}} = 50, 150, 250, 450$ GeV/c and $M_{\text{JET}}$ values from 20 to 200 GeV/c².
$v_2$ in 1 jet scaled by $p^* = \frac{E_{JET} - P_{JET}}{2}$
Averaging over jet mass fluctuations

\[ \rho(M_{\text{jet}}) \sim \ln^{b}(M_{\text{jet}}/M_0)/M_{\text{jet}}^c \]

Averaging reduces fluctuations in \( v_2 \)
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Fix Multiplicity
Events
Jet Mass dependence
Multiplicity dependence

![Graph showing multiplicity dependence with varying jet multiplicities and $p_T$ values.](image-url)
Fix multiplicity v2

„peripheral” pp
10 < N < 20

„central” pp
105 < N < 150

$P_{\text{jet}}^{1,2} = 40 \text{ GeV/c}$, $M_{\text{jet}}^{1,2} = 20, 25, 30 \text{ GeV/c}^2$

$N_{\text{jet}}^{1,2} = [5, 15]$; $N_{\text{jet}}^1 + N_{\text{jet}}^2 = [10, 20]$
Conclusions

We have a fragmentation function for highly virtual partons. The frag.scale is the jet mass

We have a FF for jets of fix multiplicity

v2 of large $\Delta Y$ hadrons seems to be discribable by fragmentation of off-shell leading partons
Back-up Slides
\[ v^2 \text{ from large } \Delta \eta \text{ correlations at } \phi = 0 \]
$v^2$ decreases near $\phi = 0$.

Correlations flatten near $\phi = 0$. 

$v^2$ decreases.
$v_2$ increases at $\phi = 0$
correlations decrease with increasing $p_T$ and flatten at $\phi = 0$. $v_2$ decreases as well.
At $\phi = 0$, $v_2$ increases and correlations steepen.
Particle Multiplicity fluctuates according to the **Negative-binomial distribution**

\[ e^+e^- \rightarrow h^\pm \]

**pp → jets @ 7 TeV**

**pp → h^± @ LHC**

**AuAu → h^± @RHIC**

Power-law **hadron spectra**

\[ e^-e^+ \rightarrow h^\pm \]

\[ pp \rightarrow \text{jets} @ 7 \text{ TeV} \]

\[ pp \rightarrow h^\pm @ \text{LHC} \]

\[ AuAu \rightarrow h^\pm @ \text{RHIC} \]

Urmossy et al., *PLB*, **701**: 111-116 (2011)


Spectrum and v2

PbPb

PP

$v_2$ in $pp$ and $PbPb$