Higher-twist dynamics in large $p_\perp$ hadron production

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LAPTH, Annecy

Moriond QCD 2010
Outline

- Motivations
  - Scaling laws in inclusive processes

- Data analysis
  - hadron, photon, and jet scaling properties from fixed-target to colliders
  - comparing with NLO expectations
  - interpretations

- Phenomenology
  - predictions in p p collisions at RHIC and LHC

Reference

FA, Brodsky, Hwang, Sickles, arXiv:0910.4604
Scattering amplitude $1 \ 2 \cdots \to \ldots \ n$ has dimension

$$\mathcal{M} \sim [\text{length}]^{n-4}$$

**Consequence**

In a *conformal* theory (no intrinsic scale), scaling of inclusive particle production

$$E \ \frac{d\sigma}{d^3p}(A \ B \to C \ X) \sim \frac{|\mathcal{M}|^2}{s^2} = \frac{F(x_\perp, \vartheta^{\text{cm}})}{p_{\perp}^{2n_{\text{active}}-4}}$$

where $n_{\text{active}}$ is the number of fields participating to the hard process

$x_\perp = 2p_\perp / \sqrt{s}$ and $\vartheta^{\text{cm}}$: ratios of invariants
Scattering amplitude $1\ 2\ \cdots \rightarrow \ldots n$ has dimension

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$$E \ \frac{d\sigma}{d^3 p} (A\ B \rightarrow C\ X) \sim \frac{|\mathcal{M}|^2}{s^2} = \frac{F(x_\perp, \vartheta_{cm})}{p_\perp^{2n_{active}-4}}$$

where $n_{active}$ is the number of fields participating to the hard process

$x_\perp = 2p_\perp/\sqrt{s}$ and $\vartheta_{cm}$: ratios of invariants

Let’s take the inclusive pion production as an example...
Conventional pQCD picture (leading twist): $2 \rightarrow 2$ process followed by fragmentation into a pion on long time scales

$n_{\text{active}} = 4 \rightarrow n = 4 \left(= 2 \times 4 - 4\right)$

$$E \frac{d\sigma}{d^3p} (p\ p \rightarrow \pi\ X) \sim \frac{F(x_\perp, \vartheta_{\text{cm}})}{p_\perp^4}$$
Scaling laws in inclusive pion production

- **Conventional pQCD picture** (leading twist): 2 → 2 process followed by fragmentation into a pion on long time scales

\[ n_{\text{active}} = 4 \rightarrow n = 4 \quad (= 2 \times 4 - 4) \]

\[ E \frac{d\sigma}{d^3p}(p \ p \rightarrow \pi \ X) \sim \frac{F(x_\perp, \vartheta_{\text{cm}})}{p_{\perp}^4} \]

- **Direct higher-twist picture**: pion produced directly in the hard process

\[ n_{\text{active}} = 5 \rightarrow n = 6 \quad (= 2 \times 5 - 4) \]

\[ E \frac{d\sigma}{d^3p}(p \ p \rightarrow \pi \ X) \sim \frac{F'(x_\perp, \vartheta_{\text{cm}})}{p_{\perp}^6} \]
Scaling laws in inclusive pion production

- **Conventional pQCD picture** (leading twist): $2 \rightarrow 2$ process followed by fragmentation into a pion on long time scales

- **Direct higher-twist picture**: pion produced directly in the hard process

**Remarks**

- $F(x_\perp)$ falls faster than $F'(x_\perp)$ with $x_\perp$ from the larger number of spectator partons

  \[ F(x_\perp) \sim (1 - x_\perp)^{2n_{\text{spectator}} - 1 + 2\Delta s} \]

  [ Brodsky Burkardt Schmidt 1995 ]

- Higher-twist processes naturally suppressed at large $p_\perp$

  Higher-twist contributions possible at high $x_\perp$ and not too large $p_\perp$

  [ Sivers Brodsky Blankenbecler 1975 ]
Scaling violations

QCD is not conformal

Scaling violations expected from

- running coupling
- evolution of parton densities and fragmentation functions

Scaling exponent greater than 4 even in leading-twist QCD
Slight increase of $n^h$ with $x_\perp$ from $n^h \approx 5$ to 6

Smaller exponent in the photon sector: $n^\gamma \approx n^h - 1$
  - lesser scaling violations due to (almost) no fragmentation component

Almost no difference between hadron species
QCD is not conformal

Scaling violations expected from

- running coupling
- evolution of parton densities and fragmentation functions

Scaling exponent greater than 4 even in leading-twist QCD

This analysis: systematic comparison between data and NLO expectations
Scaling exponent extracted by comparing \( x_\perp \) spectra at two \( \sqrt{s} \) within the same experiment in order to reduce systematic errors.

Particle production at mid-rapidity
- hadrons (\( \pi \) and \( h^{\pm} \)), prompt photons, jets

Data sets
- most recent measurements: CDF, D0, E706, PHENIX
- ...as well as older ISR data
Significant increase of the hadron $n^{\exp}$ with $x_{\perp}$

- $n^{\exp} \simeq 8$ at large $x_{\perp}$

Huge contrast with photons and jets!

- $n^{\exp}$ constant and slight above 4 at all $x_{\perp}$
Comparing to QCD

NLO calculations carried out within the experimental kinematics ($p_\perp$, $\sqrt{s}$)

\[ \Delta(x_\perp) \equiv n^{\text{exp}} - n^{\text{NLO}} \]
Comparing to QCD

\[ \Delta_h \simeq 0.5 - 2 \text{ from small to large } x_{\perp} \]

\[ \Delta \gamma/\text{jets} \text{ consistent with } 0 \]

Error bars include theoretical uncertainty \( \mu = p_{\perp}/2 \) to \( 2p_{\perp} \)
Comparing to QCD

Clear hierarchy

**Tevatron**  \[ x_\perp \sim 10^{-2} \] \[ \Delta \sim 0.5 \]
**RHIC**  \[ x_\perp \sim 10^{-1} \] \[ \Delta \sim 1 \]
**fixed target**  \[ x_\perp \sim \text{few times } 10^{-1} \] \[ \Delta \sim 2 \]
Interpretations

Resumation of large “threshold” logs $\ln(1 - x_\perp)$ could explain part of the data. However, data – theory discrepancy even at small $x_\perp \sim 10^{-2}$

Most natural explanation

Higher-twist contributions: $q \bar{q} \rightarrow g \pi$ and $q g \rightarrow q \pi$

- HT effects absent in photon and jet production
- scale dependence
- meson vs. baryon behavior
Scale dependence

Pion scaling exponent extracted vs. $p_\perp$ at fixed $x_\perp$

- QCD slowly approaches $n = 4$ in the Bjorken limit ($s \to \infty$, fixed $x_\perp$)
- Data – theory discrepancy larger at smaller $p_\perp$
Scale dependence

Pion scaling exponent extracted vs. $p_\perp$ at fixed $x_\perp$

2-component toy-model

$$\sigma^\text{model}(pp \rightarrow \pi X) \propto \frac{A(x_\perp)}{p_\perp^4} + \frac{B(x_\perp)}{p_\perp^6}$$

Define effective exponent

$$n_{\text{eff}}(x_\perp, p_\perp, B/A) \equiv -\frac{\partial \ln \sigma^\text{model}}{\partial \ln p_\perp} + n^{\text{NLO}}(x_\perp, p_\perp) - 4$$

$$= \frac{2B/A}{p_\perp^2 + B/A} + n^{\text{NLO}}(x_\perp, p_\perp)$$
Scale dependence

Pion scaling exponent extracted vs. $p_\perp$ at fixed $x_\perp$

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$$= \frac{2B/A}{p_\perp^2 + B/A} + n^{\text{NLO}}(x_\perp, p_\perp)$$

Limits

$$n_{\text{eff}}(x_\perp, p_\perp) = n^{\text{NLO}}(x_\perp, p_\perp) \quad \text{for} \; B \ll A \times p_\perp^2$$

$$n_{\text{eff}}(x_\perp, p_\perp) = n^{\text{NLO}}(x_\perp, p_\perp) + 2 \quad \text{for} \; B \gg A \times p_\perp^2$$
Fit gives $[B(x_\perp)/A(x_\perp)]^{1/2} \simeq 4 - 7$ GeV

Significantly reduced because of trigger bias effect

$[B(x_\perp)/A(x_\perp)]^{1/2} \simeq 1$ GeV
Global fit

\[ \Delta^{\text{fit}}(x_\perp, p_\perp) \] extracted from a fit to Tevatron, PHENIX, and E706 data

\[ \Delta^{\text{fit}}(x_\perp, p_\perp) = (-\log x_\perp)^{p_3} \times \frac{2 \ p_1 (1 - x_\perp)^{p_2}}{p_\perp^2 + p_1 (1 - x_\perp)^{p_2}} \]
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Predictions at RHIC and LHC

<table>
<thead>
<tr>
<th></th>
<th>(\sqrt{s_1})</th>
<th>(\sqrt{s_2})</th>
</tr>
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<tbody>
<tr>
<td>RHIC</td>
<td>500 GeV</td>
<td>200 GeV</td>
</tr>
<tr>
<td>LHC</td>
<td>14 TeV</td>
<td>10 TeV</td>
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</tbody>
</table>
\[ \Delta \lesssim 1 \text{ at RHIC, } \Delta \approx 0.5 \text{ at LHC} \]

Deviation from NLO visible below \( x_\perp = 10^{-1}/10^{-2} \) at RHIC/LHC
RHIC/LHC predictions

PHENIX results

Scaling exponents from $\sqrt{s} = 500$ GeV preliminary data

Magnitude of $\Delta$ and its $x_\perp$-dependence consistent with predictions
Isolated hadrons

**Leading twist**

Hadrons accompanied by a significant hadronic activity ⇒ inside jets

**Higher twist**

Color-singlet produced in the hard process ⇒ “isolated” hadrons
Isolated hadrons

Leading twist

Hadrons accompanied by a significant hadronic activity ⇒ inside jets

Higher twist

Color-singlet produced in the hard process ⇒ “isolated” hadrons

Idea: use isolation criteria to filter the leading twist component

\[
E_{\text{had}}^\perp \leq E_{\text{max}}^\perp = \varepsilon p_{\perp}^h
\]

for particles inside a cone

\[
(\eta - \eta_\gamma)^2 + (\phi - \phi_\gamma)^2 \leq R^2
\]

\[
R = \sqrt{\Delta \eta^2 + \Delta \phi^2}
\]
Isolated hadrons

Leading twist

Hadrons accompanied by a significant hadronic activity $\Rightarrow$ inside jets

Higher twist

Color-singlet produced in the hard process $\Rightarrow$ “isolated” hadrons

Idea: use isolation criteria to filter the leading twist component

$$E_{\text{had}}^\perp \leq E_{\text{max}}^\perp = \varepsilon P_{\perp}$$

for particles inside a cone

$$(\eta - \eta_\gamma)^2 + (\phi - \phi_\gamma)^2 \leq R^2$$

Consequence

Enhanced scaling exponent for isolated hadrons

$$n_{\text{isolated}}^h > n_{\text{inclusive}}^h$$
Summary

Scaling laws
- powerful probe of hadron production dynamics

Analysis
- exponents systematically extracted from hadron, photon and jet data
- significant discrepancy in the hadron sector, esp. at large $x_\perp$
- supports a non-negligible higher-twist contribution in large $p_\perp$ hadron production (first seen at ISR)

Phenomenology
- possible breakdown of NLO QCD could also be seen at these energies
- ratio of $x_\perp$ spectra predicted in pp collisions at RHIC and LHC
- predictions in good agreement with preliminary data at 500 GeV
Which scaling behavior for higher-twist baryon production?
Take for instance proton production

\[ n_{\text{active}} = 6 \]

\[ E \frac{d\sigma}{d^3p} (p \ p \rightarrow p \ X) \sim \frac{F(x_\perp, \mathcal{y}_{\text{cm}})}{p_\perp^8} \]
Which scaling behavior for higher-twist baryon production?

Take for instance proton production

\[ n_{\text{active}} = 6 \]

\[ E \frac{d\sigma}{d^3p} (p \ p \rightarrow p \ X) \sim \frac{F(x_\perp, \vartheta_{\text{cm}})}{p_\perp^8} \]

... which contrasts with pion scaling exponents

\[ n_{\text{active}} = 5 \]

\[ E \frac{d\sigma}{d^3p} (p \ p \rightarrow \pi \ X) \sim \frac{F'(x_\perp, \vartheta_{\text{cm}})}{p_\perp^6} \]
Baryon vs. meson production

Protons minus pions results

\[
np - n\pi
\]

<table>
<thead>
<tr>
<th></th>
<th>(\approx)</th>
</tr>
</thead>
<tbody>
<tr>
<td>QCD NLO</td>
<td>0</td>
</tr>
<tr>
<td>Higher-twist picture</td>
<td>2</td>
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<tr>
<td>Experiment (ISR)</td>
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</table>

Results consistent with a mixture of LT and HT “direct” components
<table>
<thead>
<tr>
<th>Event</th>
<th>QCD NLO</th>
<th>Higher-twist picture</th>
<th>Experiment (ISR)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$n^p - n^\pi$</td>
<td>$\sim 0$</td>
<td>$\sim 2$</td>
<td>$\sim 1$</td>
</tr>
</tbody>
</table>

Results consistent with a mixture of LT and HT “direct” components

Hadrochemistry as a useful probe of production dynamics at large $p_\perp$

Need for good hadron identification capabilities ($\pi$, $K$, $p$) at the LHC!
### ISR data

<table>
<thead>
<tr>
<th>Exp.</th>
<th>$h$</th>
<th>$\langle x_\perp \rangle$</th>
<th>$n_{\text{data}}$</th>
<th>$\langle n_{\text{exp}} \rangle$</th>
</tr>
</thead>
<tbody>
<tr>
<td>ABCS</td>
<td>$\pi^0$</td>
<td>0.34 ± 0.05</td>
<td>5</td>
<td>5.7 ± 0.7</td>
</tr>
<tr>
<td>ABCSY</td>
<td>$\pi^0$</td>
<td>0.16 ± 0.04</td>
<td>15</td>
<td>8.1 ± 0.3</td>
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<tr>
<td>ACHM</td>
<td>$\pi^0$</td>
<td>0.20 ± 0.07</td>
<td>75</td>
<td>7.0 ± 0.1</td>
</tr>
<tr>
<td>BS 73</td>
<td>$\pi^\pm$</td>
<td>0.12 ± 0.02</td>
<td>5</td>
<td>9.0 ± 0.6</td>
</tr>
<tr>
<td>BS 75</td>
<td>$\pi^\pm$</td>
<td>0.15 ± 0.03</td>
<td>5</td>
<td>7.6 ± 0.2</td>
</tr>
<tr>
<td></td>
<td>$K^\pm$</td>
<td>0.15 ± 0.03</td>
<td>5</td>
<td>7.2 ± 0.3</td>
</tr>
<tr>
<td></td>
<td>$p/\bar{p}$</td>
<td>0.15 ± 0.03</td>
<td>5</td>
<td>8.4 ± 0.3</td>
</tr>
<tr>
<td>CCR</td>
<td>$\pi^0$</td>
<td>0.22 ± 0.07</td>
<td>45</td>
<td>8.2 ± 0.1</td>
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<tr>
<td>CCOR</td>
<td>$\pi^0$</td>
<td>0.31 ± 0.08</td>
<td>27</td>
<td>6.2 ± 0.1</td>
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<tr>
<td>CCRS</td>
<td>$\pi^0,\pi^\pm$</td>
<td>0.20 ± 0.06</td>
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<td>8.5 ± 0.1</td>
</tr>
<tr>
<td>CP</td>
<td>$\pi^\pm$</td>
<td>0.36 ± 0.11</td>
<td>11</td>
<td>7.6 ± 0.2</td>
</tr>
<tr>
<td></td>
<td>$K^\pm$</td>
<td>0.36 ± 0.11</td>
<td>11</td>
<td>7.6 ± 0.3</td>
</tr>
<tr>
<td></td>
<td>$p/\bar{p}$</td>
<td>0.35 ± 0.11</td>
<td>10</td>
<td>8.8 ± 0.2</td>
</tr>
<tr>
<td>CSZ</td>
<td>$\pi^0$</td>
<td>0.28 ± 0.05</td>
<td>9</td>
<td>6.2 ± 0.7</td>
</tr>
<tr>
<td>R806</td>
<td>$\pi^0$</td>
<td>0.23 ± 0.08</td>
<td>30</td>
<td>8.0 ± 0.2</td>
</tr>
</tbody>
</table>

Results compatible with older ISR data