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

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LAPTH, Annecy

Elastic and Diffractive Scattering 2009

CERN – June 2009

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 at RHIC and LHC

References

Brodsky, Sickles, Phys. Lett. B668 (2008) 111

FA, Brodsky, Hwang, Sickles, in preparation

Dimensional analysis

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

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

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

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

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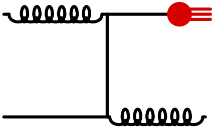
$x_\perp = 2p_\perp/\sqrt{s}$ and ϑ^{cm}: ratios of invariants

Let's take the inclusive pion production as an example...

Scaling laws in inclusive pion production

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



$n_{\mathrm{active}} = 4$

$$E\,\frac{d\sigma}{d^3p}(p\ p\ \to \pi\ X) \sim \frac{F(x_\perp, \vartheta^{\mathrm{cm}})}{p_\perp^4}$$

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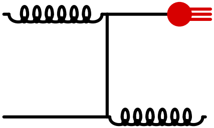

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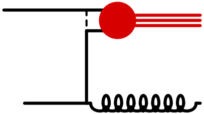
$$E\,\frac{d\sigma}{d^3p}(p\;p\;\to\pi\;X) \sim \frac{F(x_\perp,\vartheta^{\rm cm})}{p_\perp^4}$$

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



$n_{\rm active} = 5$

$$E\,\frac{d\sigma}{d^3p}(p\;p\;\to\pi\;X) \sim \frac{F'(x_\perp,\vartheta^{\rm cm})}{p_\perp^6}$$

Scaling laws in inclusive pion production

- Conventional pQCD picture (leading twist): 2 → 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 [Brodsky Burkardt Schmidt 1995]

$$F(x_\perp) \sim (1 - x_\perp)^{2n_{\rm spectator}-1+2\Delta s}$$

- 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

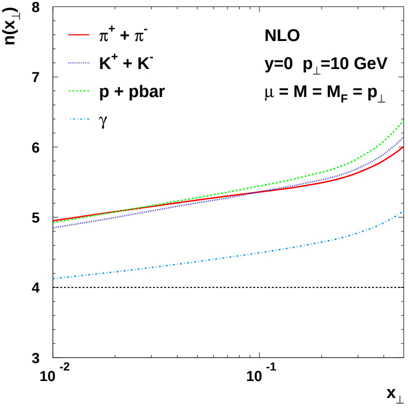
QCD is not conformal

Scaling violations expected from

- running coupling
- evolution of parton densities and fragmentation functions

Scaling exponent greater than 4 even in leading-twist QCD

Scaling violations



- Slight increase of n^h with $x_\perp$ from $n^h \simeq 5$ to 6
- Smaller exponent in the photon sector: $n^\gamma \simeq n^h - 1$
  - lesser scaling violations due to (almost) no fragmentation component

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

This analysis: systematic comparison between data and NLO expectations

Data analysis

- Scaling exponent extracted by comparing $x_\perp$ spectra at two $\sqrt{s}$

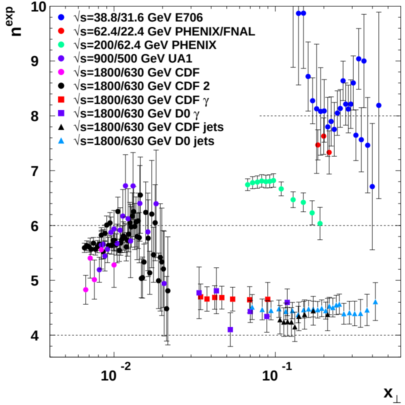
$$n^{\text{exp}}(x_\perp) \equiv -\frac{\ln\left[\sigma^{\text{inv}}(x_\perp, \sqrt{s_1}) \big/ \sigma^{\text{inv}}(x_\perp, \sqrt{s_2})\right]}{\ln\left(\sqrt{s_1} \big/ \sqrt{s_2}\right)}$$

  within the same experiment in order to reduce systematic errors
- Particle production at mid-rapidity
  - hadrons (π and $h^\pm$), prompt photons, jets
- Data sets
  - most recent measurements: CDF, D0, E706, PHENIX
  - ...as well as older ISR data

Data analysis

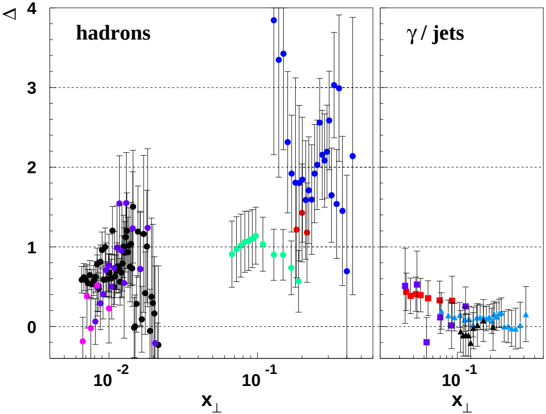
exp.	part.	$\sqrt{s}$	$p_\perp$	$x_\perp$	N
E706	π^0	31.6 / 38.8	2 – 9	10^{-1} – 4.10^{-1}	25
PHENIX/ISR	π^0	62.4 / 22.4	2 – 7	2.10^{-2} – 2.10^{-2}	3
PHENIX	π^0	62.4 / 200	2 – 19	7.10^{-2} – 2.10^{-1}	12
UA1	$h^\pm$	500 / 900	2 – 9	8.10^{-3} – 2.10^{-2}	18
CDF	$h^\pm$	630 / 1800	2 – 9	7.10^{-3} – 10^{-2}	5
CDF	tracks	630 / 1800	2 – 19	7.10^{-3} – 2.10^{-2}	52
CDF	γ	630 / 1800	11 – 81	3.10^{-2} – 9.10^{-2}	7
D0	γ	630 / 1800	11 – 107	3.10^{-2} – 10^{-1}	6
CDF	jets	546 / 1800	29 – 190	10^{-1} – 2.10^{-1}	9
D0	jets	630 / 1800	23 – 376	8.10^{-2} – 4.10^{-1}	23

Results



- Significant increase of the hadron n^{exp} with $x_\perp$
  - $n^{\mathrm{exp}} \simeq 8$ at large $x_\perp$
- Huge contrast with photons and jets!
  - n^{exp} constant and slight above 4 at all $x_\perp$

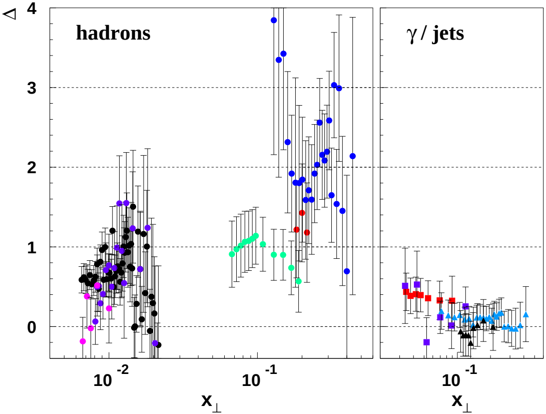
Comparing to QCD



NLO calculations carried out within the experimental kinematics

$$\Delta(x_\perp) \equiv n^{\rm exp} - n^{\rm NLO}$$

Comparing to QCD



- $\Delta^h \simeq 0.5 - 2$ from small to large $x_\perp$
- $\Delta^{\gamma/\text{jets}}$ consistent with 0
- Error bars include theoretical uncertainty $\mu = p_\perp/2$ to $2p_\perp$

Interpretations

Resumation of large "threshold" logs $\ln(1 - x_\perp)$ could explain part of the data. However,

- no effects in photons/jets despite the large $x_\perp$
- data – theory discrepancy even at small $x_\perp \sim 10^{-2}$

Most natural explanation

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

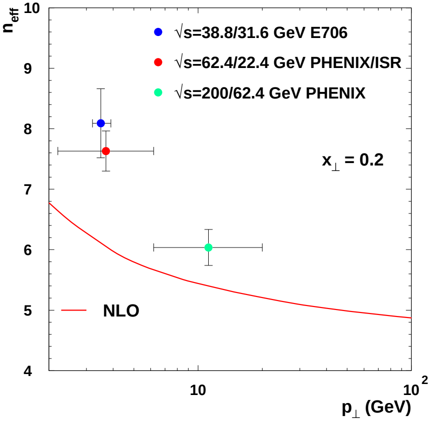
- HT effects absent in photon and jet production
- ISR data indicate a larger proton exponent: $n^p \simeq n^\pi + 1$

$$q\ q\ \to p\ \bar{q}\ (n = 6) \Rightarrow E\ \frac{d\sigma}{d^3p}(p\ p\ \to p\ X) \sim \frac{1}{p_\perp^8}$$

- scale dependence

Scale dependence

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



Scale dependence

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

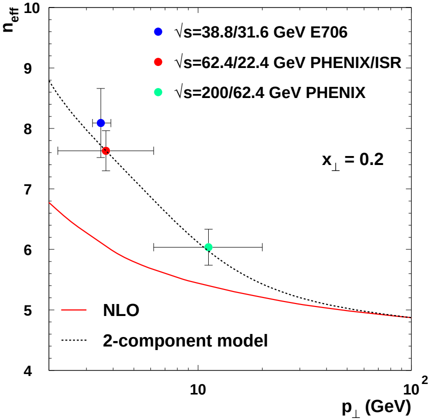
2-component toy-model

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

Define effective exponent

$$\begin{aligned} n_{\rm eff}(x_\perp, p_\perp, B/A) &\equiv -\frac{\partial \ln \sigma^{\rm model}}{\partial \ln p_\perp} + n^{\rm NLO}(x_\perp, p_\perp) - 4 \\ &= \frac{2B/A}{p_\perp^2 + B/A} + n^{\rm NLO}(x_\perp, p_\perp) \end{aligned}$$

Scale dependence



- Fit gives $[B(x_\perp)/A(x_\perp)]^{1/2} \simeq 4 - 7$ GeV
- Could be significantly reduced because of trigger bias effect

Phenomenology

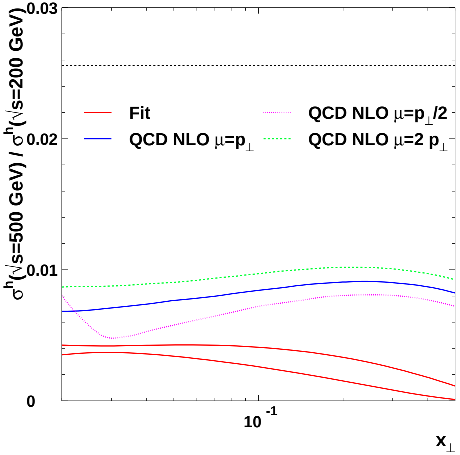
Predictions at RHIC and LHC

$$R_{\sqrt{s_1}/\sqrt{s_2}}(x_\perp) \equiv \left(\sqrt{s_2}/\sqrt{s_1}\right)^{n^{\mathrm{fit}}(x_\perp, p_\perp = x_\perp \sqrt{s}/2)}$$

with $n^{\mathrm{fit}}(x_\perp, p_\perp)$ extracted from a fit to Tevatron, PHENIX, and E706 data

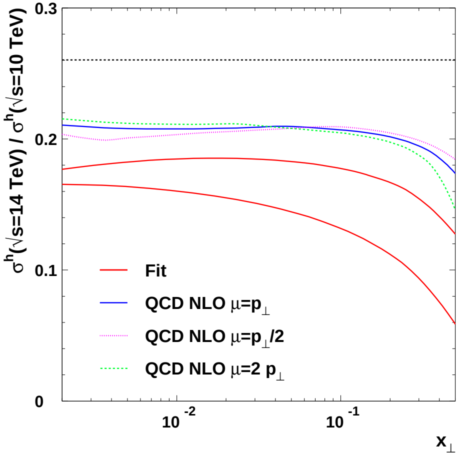
- RHIC: $\sqrt{s_1} = 500$ GeV vs. $\sqrt{s_2} = 200$ GeV
- LHC: $\sqrt{s_1} = 14$ TeV vs. $\sqrt{s_2} = 10$ TeV

Phenomenology



- Ratio well below the conformal limit expectation, even within NLO
- Possible breakdown of NLO visible also between 200 and 500 GeV

Phenomenology



- Differences also expected at the LHC

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
  - ratio of $x_\perp$ spectra predicted at RHIC and LHC
  - possible breakdown of NLO QCD could also be seen at these energies
  - important implications in heavy-ion collisions: color singlet states penetrate dense media due to color transparency

[Brodsky Pirner Raufeisen 2006, Brodsky Sickles 2008]