

Higher-twist contributions to large p_{\perp} hadron production in hadronic collisions

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The scaling behavior of large- p_{\perp} hadron production in hadronic collisions is investigated. A significant deviation from the NLO QCD predictions is reported, especially at high values of $x_{\perp} = 2p_{\perp}/\sqrt{s}$. In contrast, the prompt photon and jet production data prove in agreement with leading-twist expectations. These results are interpreted as coming from a non-negligible contribution of higher-twist processes, where the hadron is produced directly in the hard subprocess. Predictions for scaling exponents at RHIC are successfully compared to PHENIX preliminary measurements. We suggest to trigger on *isolated* large- p_{\perp} hadron production to enhance higher-twist processes, and point that the use of isolated hadrons as a signal for new physics at colliders can be affected by the presence of direct hadron production processes.

1 Introduction

The most important discriminant of the twist of a perturbative QCD subprocess in a hard hadronic collision is the scaling of the inclusive invariant cross section[?],

$$\sigma^{\text{inv}} \equiv E \frac{d\sigma}{d^3p}(A B \rightarrow C X) = \frac{F(x_{\perp}, \vartheta)}{p_{\perp}^n}, \quad (1)$$

at fixed $x_{\perp} = 2p_{\perp}/\sqrt{s}$ and center-of-mass (CM) angle ϑ . In the original parton model the power fall-off is simply $n = 4$ since the underlying $2 \rightarrow 2$ subprocess amplitude for point-like partons is scale invariant, and there is no dimensionful parameter as in a conformal theory. However, in general additional higher-twist (HT) contributions involving a larger number of elementary fields contributing to the hard subprocess, $n_{\text{active}} > 4$, are also expected. For example, the detected hadron C can be produced directly in the hard subprocess as in an exclusive reaction. Unlike quark or gluon fragmentation, the direct processes do not waste same-side energy, thus involving minimal values of the momentum fractions x_1 and x_2 where parton distributions are maximal. Neglecting scaling violations in QCD, the scaling exponent n is given by $n = 2n_{\text{active}} - 4$.

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The idea of direct hadron production was considered in the 1970's to explain the large fixed x_{\perp} scaling exponents reported at ISR and fixed target FNAL energies[?]. However, there has been no comprehensive and quantitative analysis of the data up to now which could bring compelling evidence for such higher-twist effects. In these proceedings, we summarize the novel aspects discussed in our recent analysis[?], namely:

- (i) a dedicated analysis of the most recent FNAL, RHIC and Tevatron data on large- p_{\perp} hadrons, prompt photons and jets;
- (ii) the systematic comparison of the experimental scaling exponents with NLO QCD expectations;
- (iii) predictions for the top RHIC energy and at the LHC.

2 Analysis

The exponent n^{NLO} of mid-rapidity particle production has been computed in QCD at next-to-leading order (NLO) accuracy from Ref.[?]. The x_{\perp} -dependence of n^{NLO} at fixed p_{\perp} has been determined for various hadron species (π , K , p/\bar{p}). At $p_{\perp} = 10$ GeV the exponents increase slowly from $n^{\text{NLO}} \simeq 5$ at small values of x_{\perp} ($x_{\perp} = 10^{-2}$) up to $n^{\text{NLO}} \simeq 6$ at $x_{\perp} = 0.5$ with almost no dependence on the specific hadron species. Remarkably, the exponent extracted in the prompt photon channel is below those of hadrons, by roughly one unit, close to the conformal limit, $n = 4$, at the smallest values of x_{\perp} . This observation is understood from the (relative) absence of fragmentation processes and one less power in α_s , leading to less scaling violation in this channel.

On the experimental side, the exponent n^{exp} has been systematically extracted from measurements in hadronic collisions, from fixed-target to collider experiments. It is deduced from the comparison of x_{\perp} -spectra at different CM energies,

$$n^{\text{exp}}(x_{\perp}) \equiv -\frac{\ln(\sigma^{\text{inv}}(x_{\perp}, \sqrt{s_1})/\sigma^{\text{inv}}(x_{\perp}, \sqrt{s_2}))}{\ln(\sqrt{s_1}/\sqrt{s_2})} \quad (2)$$

which is equivalent to (??) at fixed x_{\perp} . The data sets include π^0 measurements by the E706 at FNAL[?] and by the PHENIX collaboration at RHIC[?]. At higher energies, the measurements of charged hadrons (or charged tracks) in $p\text{-}\bar{p}$ collisions at $\sqrt{s} = 630, 1800$ GeV by CDF[?] and $\sqrt{s} = 500, 900$ GeV by UA1[?] are included in the analysis. Also considered are prompt photon[?] and jet[?] data obtained by CDF and D0 at $\sqrt{s} = 546, 630, 1800$ GeV.

3 Results

The hadron exponents plotted in Fig. ?? (left) exhibit a clear trend, with a significant rise of n^{exp} as a function of x_{\perp} . Typical values of n^{exp} are $n^{\text{exp}} \simeq 5\text{--}6$ at small $x_{\perp} \simeq 10^{-2}$ while PHENIX data point to a mean value $n^{\text{exp}} \simeq 6.7$ at an intermediate $x_{\perp} \simeq 10^{-1}$. At higher values of x_{\perp} , the measurements by PHENIX and E706 reveal an exponent even larger, $n^{\text{exp}} \simeq 8$, confirming the results reported long ago at the ISR. The exponents obtained in the photon and jet channels are strikingly different, showing almost no dependence on x_{\perp} . Importantly enough, the values obtained lie only slightly above the conformal limit, $n_{\gamma}^{\text{exp}} \simeq 4.6$ and $n_{\text{jets}}^{\text{exp}} \simeq 4.4$, i.e. several units smaller than the exponents observed for hadrons.

In order to compare properly data and theory, the *difference* between experimental and theoretical exponents, $\Delta(x_{\perp}) \equiv n^{\text{exp}} - n^{\text{NLO}}$, is plotted in the right panel of Fig. ?? for hadrons and photons/jets. Note that the error bars include both experimental *as well as* theoretical

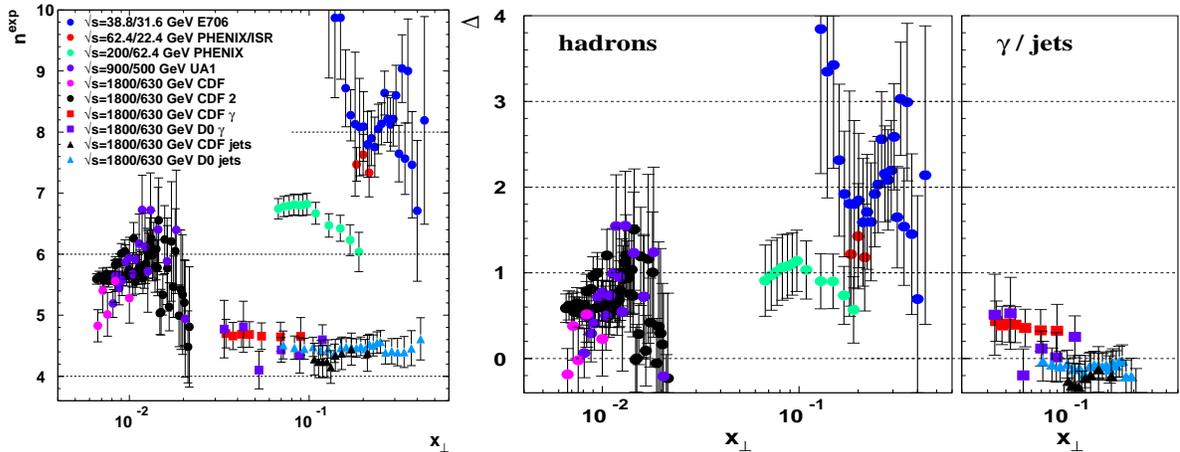


Figure 1: *Left:* Values of n^{exp} as a function of x_{\perp} for h^{\pm}/π^0 (circles), γ (squares) and jets (triangles). *Right:* $\Delta \equiv n^{\text{exp}} - n^{\text{NLO}}$ vs. x_{\perp} , error bars include the experimental and the theoretical uncertainties added in quadrature.

errors, added in quadrature. The theoretical uncertainty is estimated from the variation of renormalization/factorization scales from $p_{\perp}/2$ to $2p_{\perp}$. Fig. ?? (right) indicates that the hadronic exponents extracted experimentally prove significantly above the leading-twist (LT) predictions. The discrepancy is moderate at small $x_{\perp} \sim 10^{-2}$, $\Delta \simeq 0.5$, but becomes increasingly larger at higher values of x_{\perp} : $\Delta \simeq 1$ at $x_{\perp} = 10^{-1}$ and up to $\Delta \simeq 2$ in the largest x_{\perp} region. In contrast, the scaling behavior observed for photons and jets are in very good agreement with the NLO predictions ($\Delta \simeq 0$).

4 Discussion

Part of the discrepancy reported in hadron production data at large $x_{\perp} \sim 1$ could occur because of the appearance of large threshold logarithms, $\ln(1 - x_{\perp})$, which should be resummed to all orders in perturbation theory[?]. It would therefore be most interesting to investigate whether or not threshold resummation might bring data and theory in agreement. Note however that the discrepancy is also observed at small values of $x_{\perp} \sim 10^{-2}$, where such effects are usually expected to be small.

A natural explanation for the large exponents observed in the hadron channel is the presence of important HT contributions from processes in which the detected hadron is produced directly in the hard subprocess, because of the dimension of the hadron distribution amplitude. In contrast, particles having no hadronic structure like isolated photons and jets are much less sensitive to such HT contributions and should behave closer to LT expectations, as observed. Another piece of evidence for HT effects is the larger exponents for protons than for pions observed at the ISR. As discussed in[?], the difference between the *direct* proton and pion scaling exponent is $n_p - n_{\pi} = 2$ ($n_p = 8$, $n_{\pi} = 6$) instead of $n_p - n_{\pi} \simeq 0$ at LT. The experimental value obtained from the ISR, $n_p - n_{\pi} \simeq 1$, thus reflects the mixture of LT and HT contributions to the total cross section. It has also been noted[?] that the presence of color-transparent HT subprocesses can account for anomalous features of proton production in heavy ion collisions[?].

Finally, we discuss the phenomenological consequences of possible HT contributions to hadron production in p - p collisions at RHIC and LHC. In order to obtain qualitative predictions, the difference Δ between the experimental and the NLO exponent has been fitted to the hadron data currently analyzed. The typical values of Δ^{fit} expected at RHIC (taking $\sqrt{s} = 200, 500$ GeV) and at LHC ($\sqrt{s} = 7$ TeV, compared to $\sqrt{s} = 1.8$ TeV at Tevatron) are

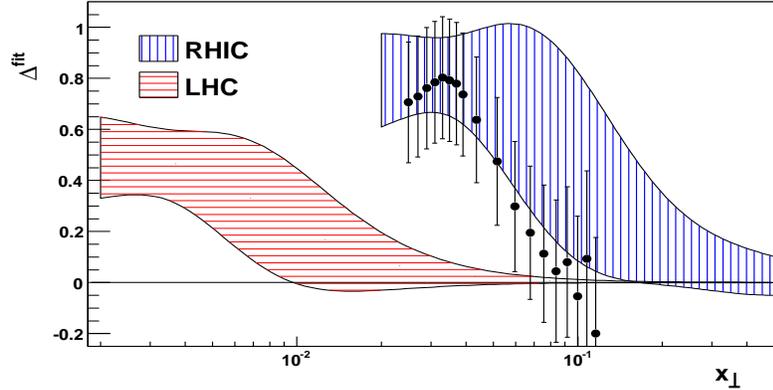


Figure 2: Predicted difference between the experimental and NLO scaling exponent at RHIC ($\sqrt{s} = 200, 500$ GeV) and the LHC ($\sqrt{s} = 7$ TeV as compared to $\sqrt{s} = 1.8$ TeV), compared to PHENIX preliminary measurements.

plotted as a function of x_{\perp} in Fig. ???. At RHIC, Δ^{fit} is slightly below 1 at small $x_{\perp} \lesssim 5 \cdot 10^{-2}$ but decreases towards zero at larger x_{\perp} . The predictions turn out to be in very good agreement, both in shape and magnitude, with the PHENIX preliminary measurements⁷ performed at $\sqrt{s} = 500$ GeV. At LHC, smaller deviations with NLO expectations are expected because of the large values of $\langle p_{\perp} \rangle$ probed at high energy: $\Delta^{\text{fit}} \simeq 0.5$ below $x_{\perp} = 5 \times 10^{-3}$ and smaller above. In order to enhance the HT contribution to hadron production, we suggest to trigger on *isolated* hadrons, i.e. with small hadronic activity in their vicinity. We also point that the use of isolation cuts, usually applied for prompt photons, will strongly suppress LT processes. Consequently, the scaling exponents of isolated hadrons are expected to be somewhat larger than those in the inclusive channel. The use of isolated hadrons as a signal for Higgs production or new physics scenarios⁷ might be confused by the presence of direct hadron production processes.

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1. See e.g. S. J. Brodsky, G. R. Farrar, Phys. Rev. Lett. **31** (1973) 1153
2. F. Arleo, S. J. Brodsky, D.S. Hwang, A. M. Sickles, arXiv:0911.4604, to appear in PRL
3. P. Aurenche *et al.*, Eur. Phys. J. C **9** (1999) 107; *ibid.*, Eur. Phys. J. C **13** (2000) 347; Z. Kunszt and D. E. Soper, Phys. Rev. D **46** (1992) 192
4. L. Apanasevich *et al.*, Phys. Rev. D **68** (2003) 052001
5. A. Adare *et al.*, Phys. Rev. D **76** (2007) 051106; *ibid.*, **79** (2009) 012003
6. F. Abe *et al.*, Phys. Rev. Lett. **61** (1988) 1819; D. E. Acosta *et al.*, Phys. Rev. D **65** (2002) 072005
7. C. Albajar *et al.*, Nucl. Phys. **B335** (1990) 261
8. D. E. Acosta *et al.*, Phys. Rev. D **65** (2002) 112003; B. Abbott *et al.*, Phys. Rev. Lett. **84** (2000) 2786; V. M. Abazov *et al.*, Phys. Rev. Lett. **87** (2001) 251805
9. F. Abe *et al.*, Phys. Rev. Lett. **70** (1993) 1376; B. Abbott *et al.*, Phys. Rev. D **64** (2001) 032003
10. See e.g. D. de Florian and W. Vogelsang, Phys. Rev. D **71** (2005) 114004.
11. S. J. Brodsky, A. Sickles, Phys. Lett. B **668** (2008) 111
12. S. S. Adler *et al.*, Phys. Rev. Lett. **91** (2003) 172301
13. A. Bazilevsky, talk at APS Meeting 2010, <http://meetings.aps.org/Meeting/APR10>
14. A. Nisati (ATLAS), and Y. Sirois (CMS), private communication.