Scaling properties of large $p_\perp$ hadron production at hadronic colliders

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Winter Workshop on Recent QCD Advances at the LHC

Les z'Houches – February 2011

Outline

- Motivations
  - Scaling laws in inclusive processes
  - Leading-twist vs. higher-twist hadron production
- World-data analysis
  - hadron, photon, and jet scaling properties from fixed-target to colliders, in comparison to NLO expectations
  - Interpretation
- Hadron production at the LHC
  - Testing leading-twist QCD NLO
  - Data-theory comparison
  - Data-driven predictions using $x_\perp$ scaling

References

FA, Brodsky, Hwang, Sickles, Phys. Rev. Lett. 105 (2010) 062002 [arXiv:0910.4604]

FA, D. d'Enterria, A. Yoon, JHEP 06 (2010) 035 [arXiv:1003.2963]

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

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

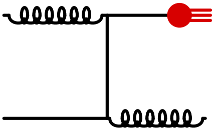
where n_{active} is the number of fields participating to the hard process

$x_\perp = 2p_\perp/\sqrt{s}$ 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): $2 \to 2$ process followed by fragmentation into a pion on long time scales



$$n_{\mathrm{active}} = 4 \to n = 4 \ (= 2 \times 4 - 4)$$

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

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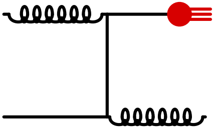

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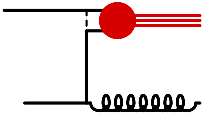
$$E \frac{d\sigma}{d^3p}(p\, p \to \pi\, X) \sim \frac{F(x_\perp, \vartheta^{\rm cm})}{p_\perp^4}$$

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



$$n_{\rm active} = 5 \to n = 6 \; (= 2 \times 5 - 4)$$

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

Scaling laws in inclusive pion production

- Conventional pQCD picture (leading twist): $2 \to 2$ 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]

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

- 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

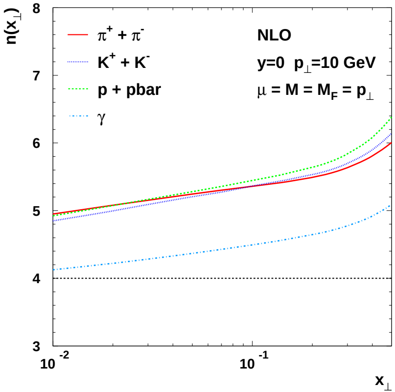
QCD is not conformal

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
- Almost no difference between hadron species

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

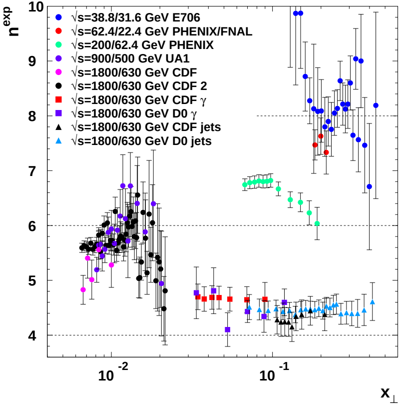
Data analysis

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

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

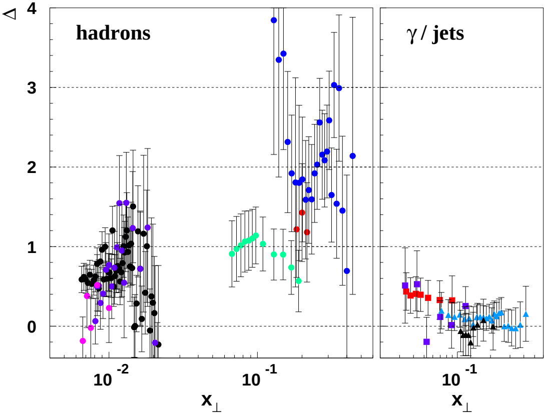
  within the same experiment in order to reduce systematic errors
- Particle production at mid-rapidity
  - hadrons (π and $h^\pm$), prompt photons, jets
- Data sets
  - most recent measurements: CDF, D0, E706, PHENIX
  - ... as well as older ISR data

Results



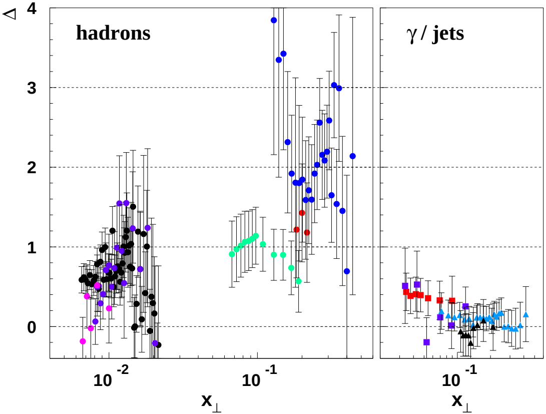
- Significant increase of the hadron $n^{\rm exp}$ with $x_\perp$
  - $n^{\rm exp} \simeq 8$ at large $x_\perp$
- Huge contrast with photons and jets !
  - $n^{\rm exp}$ constant and slight above 4 at all $x_\perp$

Comparing to QCD



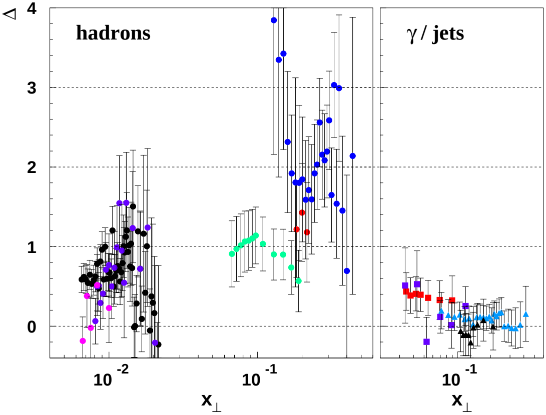
NLO calculations carried out within the experimental kinematics ($p_\perp$, $\sqrt{s}$)

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



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

Comparing to QCD



Clear hierarchy

Tevatron	$x_\perp \sim 10^{-2}$	$\Delta \simeq 0.5$
RHIC	$x_\perp \sim 10^{-1}$	$\Delta \simeq 1$
fixed target	$x_\perp \sim$ few times 10^{-1}	$\Delta \simeq 2$

Interpretations

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

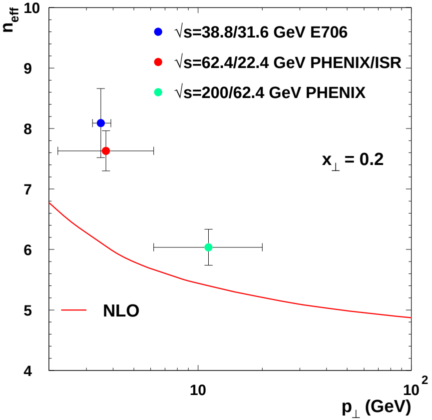
Most natural explanation

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

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

Define effective exponent

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

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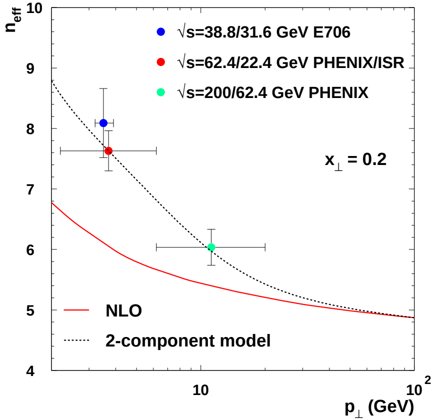
Limits

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

$n_{\rm eff}(x_\perp, p_\perp) = n^{\rm NLO}(x_\perp, p_\perp) + 2$ for $B \gg A \times p_\perp^2$

Scale dependence

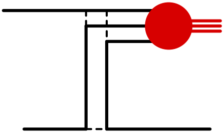


- Fit gives $[B(x_\perp)/A(x_\perp)]^{1/2} \simeq 4 - 7$ GeV
- Significantly reduced because of trigger bias effect
  - $[B(x_\perp)/A(x_\perp)]^{1/2} \simeq 1$ GeV

Baryon vs. meson production

Which scaling behavior for higher-twist baryon production?

Take for instance proton production



$n_{\rm active} = 6$

$$E\,\frac{d\sigma}{d^3p}(p\ p\ \to p\ X) \sim \frac{F(x_\perp, \vartheta^{\rm cm})}{p_\perp^{8}}$$

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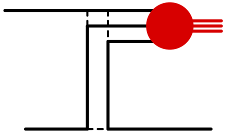
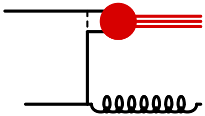


$n_{\text{active}} = 6$

$$E \frac{d\sigma}{d^3p}(p\ p\ \to p\ X) \sim \frac{F(x_\perp, \vartheta^{\text{cm}})}{p_\perp^8}$$

... which contrasts with pion scaling exponents



$n_{\text{active}} = 5$

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

Baryon vs. meson production

Protons minus pions results

	$n^p - n^\pi$
QCD NLO	$\simeq 0$
Higher-twist picture	$\simeq 2$
Experiment (ISR)	$\simeq 1$

Results consistent with a mixture of LT and HT "direct" components

Baryon vs. meson production

Protons minus pions results

	$n^p - n^\pi$
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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 (π, K, p) at the LHC !

RHIC/LHC predictions

Global fit

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

$$\Delta^{\rm fit}(x_\perp, p_\perp) \quad = \quad (-\log x_\perp)^{p_3} \times \frac{2 \; p_1 (1 - x_\perp)^{p_2}}{{p_\perp}^2 + p_1 (1 - x_\perp)^{p_2}}$$

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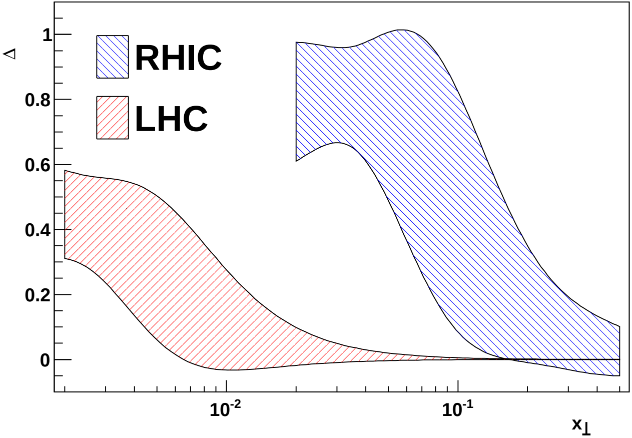
Predictions at RHIC and LHC

	$\sqrt{s_1}$	$\sqrt{s_2}$
RHIC	500 GeV	200 GeV
LHC	7 TeV	1.8 TeV

RHIC/LHC predictions



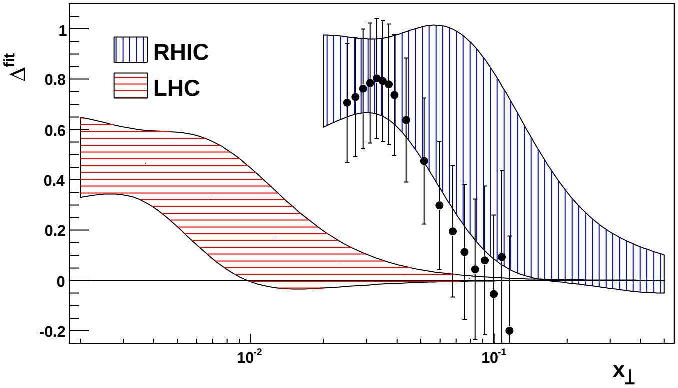
- $\Delta \lesssim 1$ at RHIC, $\Delta \lesssim 0.5$ at LHC
- Deviation from NLO visible below $x_\perp = 10^{-1}/10^{-2}$ at RHIC/LHC

RHIC/LHC predictions

PHENIX results

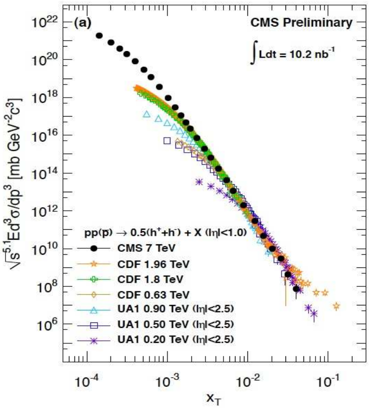
Scaling exponents from $\sqrt{s} = 500$ GeV preliminary data

[A. Bazilevsky, APS Meeting]



- Magnitude of Δ and its $x_\perp$-dependence consistent with predictions

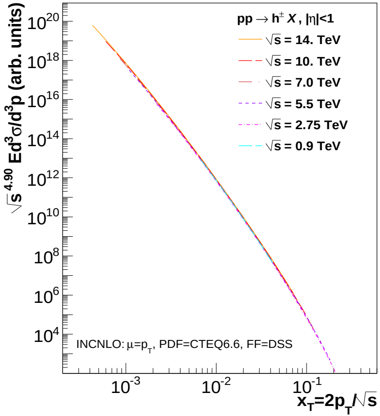
CMS preliminary measurements



[CMS, PAS QCD-10-008]

- CMS preliminary data suggest $n = 5.1$

CMS preliminary measurements



[FA, D. d'Enterria, A. Yoon, 1003.2963]

- CMS preliminary data suggest $n = 5.1$
- Slightly above (but not much) QCD NLO predictions $n \simeq 4.9$

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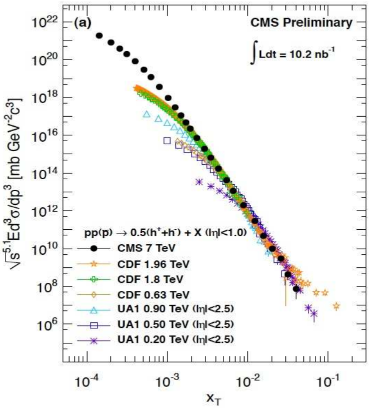


[CMS, PAS QCD-10-008]

- CMS preliminary data suggest $n = 5.1$
- Slightly above (but not much) QCD NLO predictions $n \simeq 4.9$
- Bin-to-bin ($p_\perp$-dependent) extraction of n would be ideal

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

Isolated hadrons

Leading twist

Hadrons accompanied by a significant hadronic activity ⇒ inside jets

Higher twist

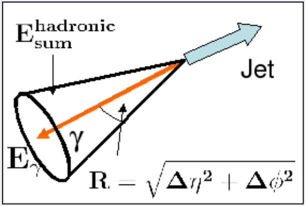
Color-singlet produced in the hard process ⇒ "isolated" hadrons

Idea: use isolation criteria to filter the leading twist component

$$E_\perp^{\rm had} \le E_\perp^{\rm max} = \varepsilon \; p_\perp^h$$

for particles inside a cone

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



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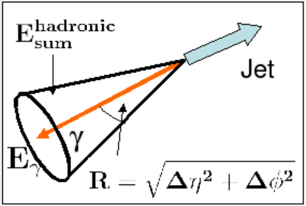


Consequence

Enhanced scaling exponent for isolated hadrons

$$n^h_{\rm isolated} > n^h_{\rm inclusive}$$

Hadron spectra at the LHC

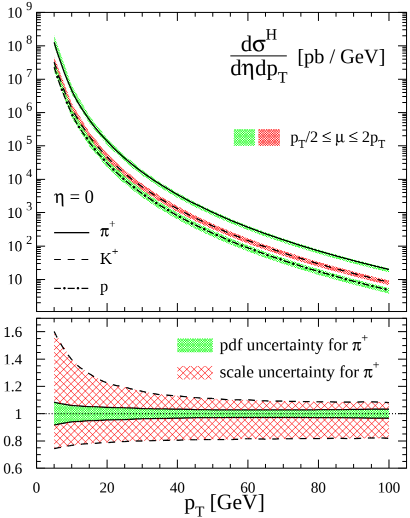
At large enough transverse momentum, higher-twist "direct" hadron production should be completely suppressed

Hadron spectra at LHC interesting playground for testing

(leading-twist) QCD NLO predictions

- Test of parton distribution functions (PDF)
- Test of fragmentation functions (FF)

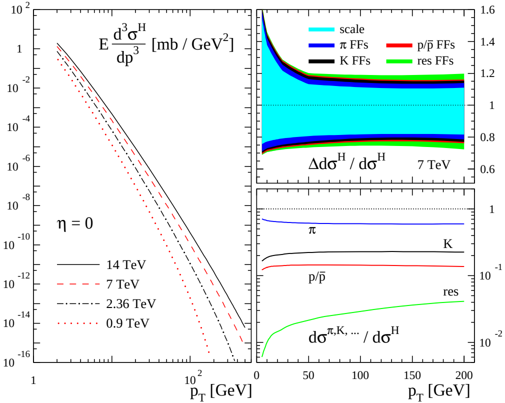
π, K, $p/\bar{p}$ spectra at $\sqrt{s} = 7$ TeV



- PDF uncertainty rather small at all $p_\perp$: $\lesssim 10\%$
- Important scale dependence, especially at low $p_\perp$: 50%

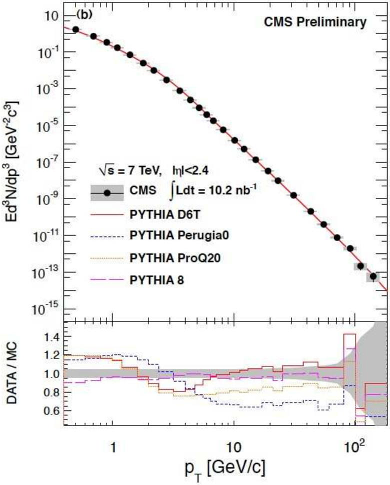
[Sassot Zurita Stratmann, 1008.0540]

Hadron spectra at the LHC



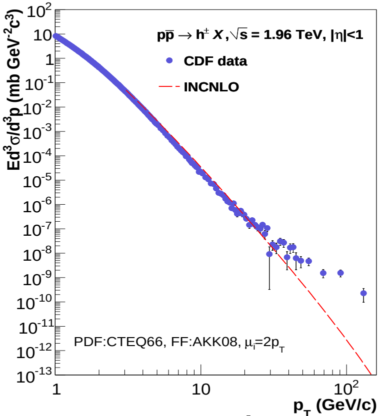
- FF uncertainty larger at large $p_\perp$ (i.e. large z), almost comparable in size to the scale dependence
- Chemical composition almost independent of $p_\perp$
  - pions (60%), kaons (25%), protons/antiprotons (15%), others ($\leq$ 4%)

Hadron spectra at the LHC



- CMS prel. data in good agreement with PYTHIA (various tunes)
- Need to compare to NLO QCD with various FF

What about CDF data vs. NLO predictions?



[FA, D. d'Enterria, A. Yoon, 1003.2963]

- Huge discrepancy above $p_{\perp} = 20$ GeV between CDF data and NLO reported last year [See also Albino, Kniehl, Kramer and Cacciari, Salam, Strassler]

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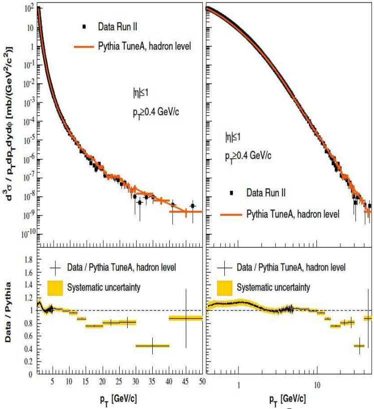


[Phys. Rev. D82 (2010) 119903(E)]

- Huge discrepancy above $p_\perp = 20$ GeV between CDF data and NLO reported last year [See also Albino, Kniehl, Kramer and Cacciari, Salam, Strassler]
- CDF erratum: corrected spectrum above $p_\perp = 20$ GeV in agreement with PYTHIA [Phys. Rev. D82 (2010) 119903(E)]

How to compare pp and Pb Pb spectra?

A crucial requirement for heavy-ion spectra

Need to compare precisely hadron spectra in pp and Pb Pb collisions at the same energy $\sqrt{s}$

Problem

- No pp data (yet) at $\sqrt{s} = 2.76$ and 5.5 TeV
- NLO QCD calculations are known within 20% accuracy at best

Prescription [FA, D. d'Enterria, A. Yoon, 1003.2963]

- Assume $x_\perp$ scaling in large $p_\perp$ hadron production
- Interpolate data from e.g. $\sqrt{s} = 1.96/2.36$ TeV to 7 TeV data

How to compare pp and Pb Pb spectra?

Assuming $x_\perp$ scaling only (value of exponent not necessary)

$$\sigma^{\rm inv}(\sqrt{s}, p_\perp = x_\perp \frac{\sqrt{s}}{2}) = \sigma^{\rm inv}(\sqrt{s_1}, x_\perp) \times \left[\frac{\sigma^{\rm inv}(\sqrt{s_2}, x_\perp)}{\sigma^{\rm inv}(\sqrt{s_1}, x_\perp)}\right]^\alpha$$

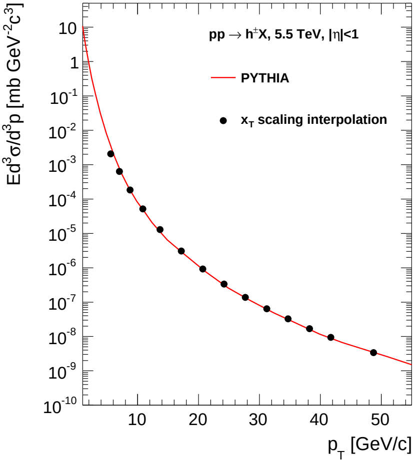
where $\alpha \equiv \ln(\sqrt{s}/\sqrt{s_1})/\ln(\sqrt{s_2}/\sqrt{s_1})$

Interpolation uncertainty

$$\frac{\delta\sigma^{\rm inv}(\sqrt{s}, x_\perp)}{\sigma^{\rm inv}(\sqrt{s}, x_\perp)} = \sqrt{(1-\alpha)^2 \left(\frac{\delta\sigma^{\rm inv}(\sqrt{s_1}, x_\perp)}{\sigma^{\rm inv}(\sqrt{s_1}, x_\perp)}\right)^2 + \alpha^2 \left(\frac{\delta\sigma^{\rm inv}(\sqrt{s_2}, x_\perp)}{\sigma^{\rm inv}(\sqrt{s_2}, x_\perp)}\right)^2}$$

possibly smaller than that of NLO QCD predictions

How to compare pp and Pb Pb spectra?



Checking the interpolation by comparing

- PYTHIA at $\sqrt{s} = 5.5$ TeV
- $x_\perp$-interpolation of PYTHIA at $\sqrt{s} = 1.96$ TeV and $\sqrt{s} = 14$ TeV

Agreement within less than 10% above $p_\perp = 10$ GeV

Summary

- Scaling laws
  - powerful probe of hadron production dynamics
- World-data analysis
  - exponents systematically extracted from hadron, photon and jet data
  - significant discrepancy in the hadron sector supports a non-negligible higher-twist contribution at not too large $p_\perp$ (first seen at ISR)
- Hadron production at LHC
  - scale dependence largest uncertainty (20% above $p_\perp = 20$ GeV)
  - good agreement with PYTHIA up to $p_\perp \simeq 100$ GeV
  - $x_\perp$-scaling procedure to interpolate pp data at heavy-ion c.m.s. energies

ISR data

Exp.	h	$\langle x_\perp \rangle$	$n_{\rm data}$	$\langle n_{\rm exp} \rangle$
ABCS	π^0	0.34 ± 0.05	5	5.7 ± 0.7
ABCSY	π^0	0.16 ± 0.04	15	8.1 ± 0.3
ACHM	π^0	0.20 ± 0.07	75	7.0 ± 0.1
BS 73	$\pi^\pm$	0.12 ± 0.02	5	9.0 ± 0.6
BS 75	$\pi^\pm$	0.15 ± 0.03	5	7.6 ± 0.2
	$K^\pm$	0.15 ± 0.03	5	7.2 ± 0.3
	$p/\bar{p}$	0.15 ± 0.03	5	8.4 ± 0.3
CCR	π^0	0.22 ± 0.07	45	8.2 ± 0.1
CCOR	π^0	0.31 ± 0.08	27	6.2 ± 0.1
CCRS	π^0,$\pi^\pm$	0.20 ± 0.06	157	8.5 ± 0.1
CP	$\pi^\pm$	0.36 ± 0.11	11	7.6 ± 0.2
	$K^\pm$	0.36 ± 0.11	11	7.6 ± 0.3
	$p/\bar{p}$	0.35 ± 0.11	10	8.8 ± 0.2
CSZ	π^0	0.28 ± 0.05	9	6.2 ± 0.7
R806	π^0	0.23 ± 0.08	30	8.0 ± 0.2

Results compatible with older ISR data