

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

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Mini-workshop “Five topics in QCD phenomenology”

Nantes – January 2013

- **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 $1\ 2 \cdots \rightarrow \dots n$ has dimension

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

Consequence

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

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

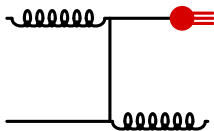
where n_{active} is the number of fields participating to the hard process

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

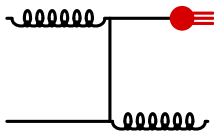


$$n_{\text{active}} = 4 \rightarrow n = 4 \quad (= 2 \times 4 - 4)$$

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

Scaling laws in inclusive pion production

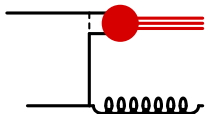
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- **Direct higher-twist picture**: pion produced directly in the hard process



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

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

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 [Brodsky Burkardt Schmidt 1995]

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

- 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

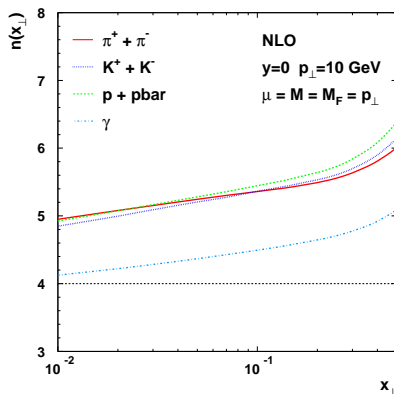
QCD is not conformal

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

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

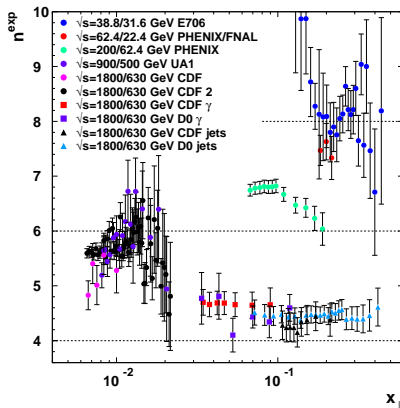
This analysis: systematic comparison between data and NLO expectations

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

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

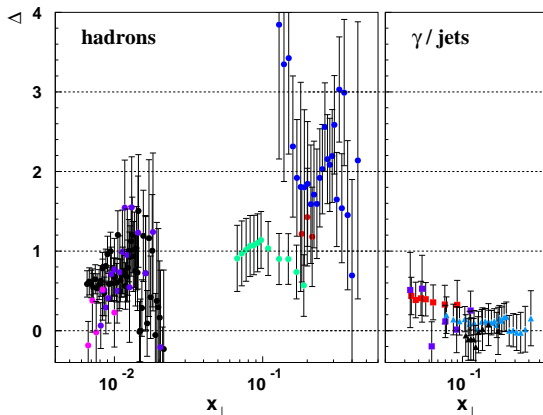
within the **same** experiment in order to reduce systematic errors

- 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



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

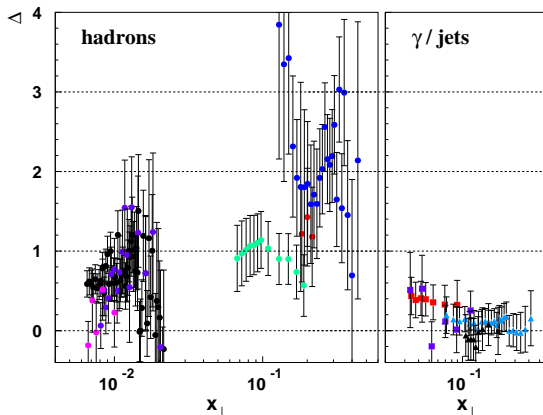
Comparing to QCD



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

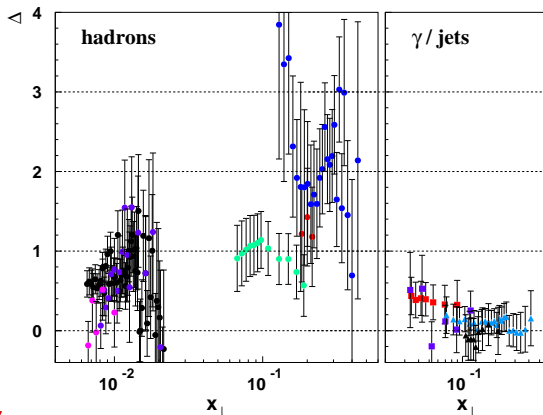
$$\Delta(x_{\perp}) \equiv n^{\text{exp}} - n^{\text{NLO}}$$

Comparing to QCD



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

Comparing to QCD



Clear hierarchy

Tevatron

RHIC

fixed target

$$x_{\perp} \sim 10^{-2}$$

$$x_{\perp} \sim 10^{-1}$$

$$x_{\perp} \sim \text{few times } 10^{-1}$$

$$\Delta \simeq 0.5$$

$$\Delta \simeq 1$$

$$\Delta \simeq 2$$

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

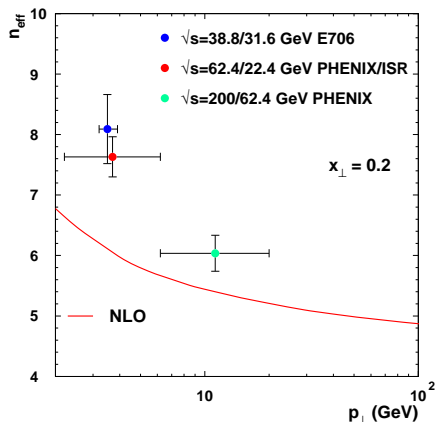
Most natural explanation

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 ($s \rightarrow \infty$, 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

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

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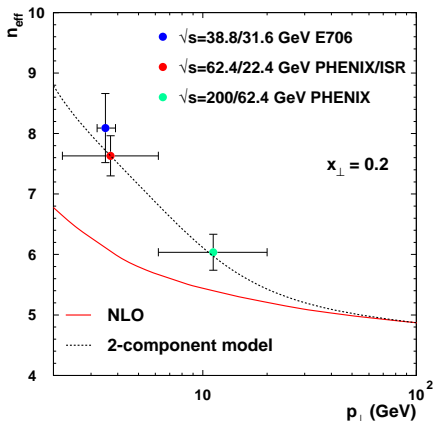
$$\begin{aligned} n_{\text{eff}}(x_{\perp}, p_{\perp}, B/A) &\equiv -\frac{\partial \ln \sigma^{\text{model}}}{\partial \ln p_{\perp}} + n^{\text{NLO}}(x_{\perp}, p_{\perp}) - 4 \\ &= \frac{2B/A}{p_{\perp}^2 + B/A} + n^{\text{NLO}}(x_{\perp}, p_{\perp}) \end{aligned}$$

Limits

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

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

Scale dependence

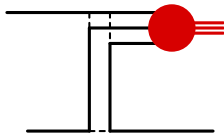


- Fit gives $[B(x_{\perp})/A(x_{\perp})]^{1/2} \simeq 4 - 7$ GeV
- Significantly reduced because of trigger bias effect
 - $[B(x_{\perp})/A(x_{\perp})]^{1/2} \simeq 1$ GeV

Baryon vs. meson production

Which scaling behavior for higher-twist baryon production?

Take for instance proton production



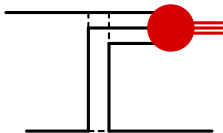
$$n_{\text{active}} = 6$$

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

Baryon vs. meson production

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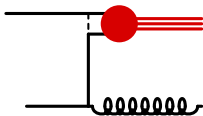
Take for instance proton production



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

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

... 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

	$n^p - n^\pi$
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

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

Need for good hadron identification capabilities (π , K , p) at the LHC !

Global fit

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

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

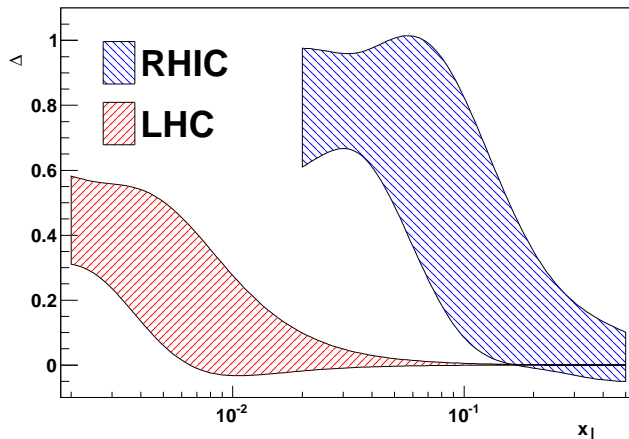
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Predictions at RHIC and LHC

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

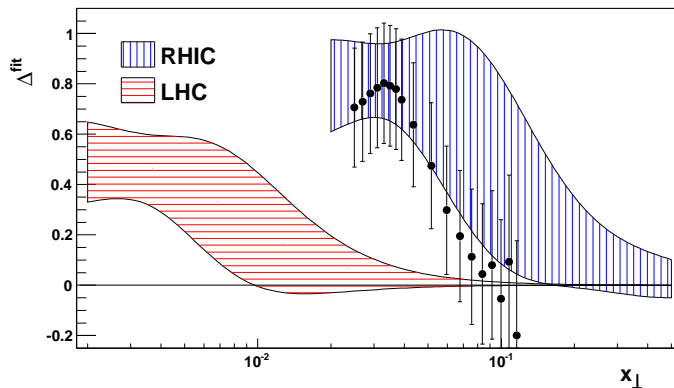


- $\Delta \lesssim 1$ at RHIC, $\Delta \lesssim 0.5$ at LHC
- Deviation from NLO visible below $x_{\perp} = 10^{-1}/10^{-2}$ at RHIC/LHC

PHENIX results

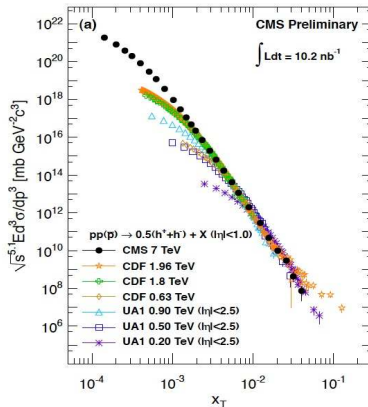
Scaling exponents from $\sqrt{s} = 500$ GeV preliminary data

[A. Bazilevsky, APS Meeting]



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

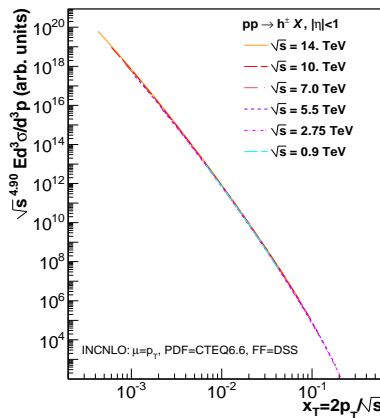
CMS preliminary measurements



[CMS, PAS QCD-10-008]

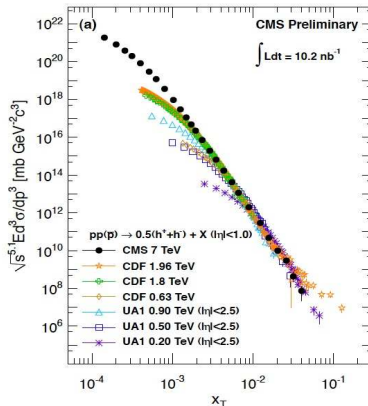
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[[FA, D. d'Enterria, A. Yoon, 1003.2963](#)]

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- Slightly above (but not much) QCD NLO predictions $n \simeq 4.9$



[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

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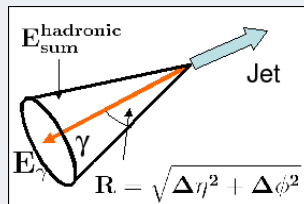
Color-singlet produced in the hard process \Rightarrow “isolated” hadrons

Idea: use isolation criteria to filter the leading twist component

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

for particles inside a cone

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



Isolated hadrons

Leading twist

Hadrons accompanied by a significant hadronic activity \Rightarrow inside jets

Higher twist

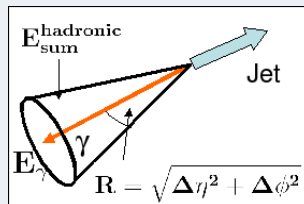
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Consequence

Enhanced scaling exponent for isolated hadrons

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

Hadron spectra at the LHC

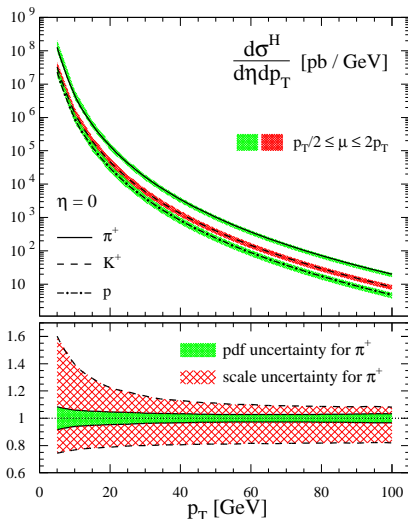
At large enough transverse momentum, higher-twist “direct” hadron production should be completely suppressed

Hadron spectra at LHC interesting playground for testing
(leading-twist) QCD NLO predictions

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

Hadron spectra at the LHC

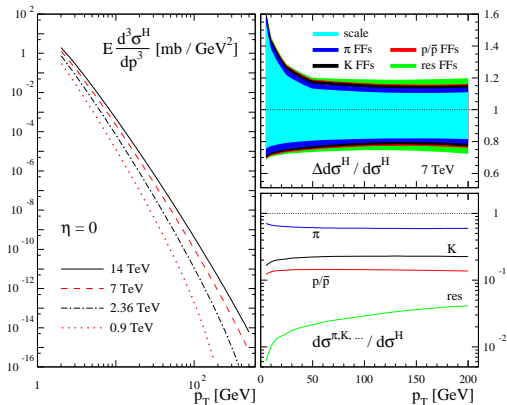
π , K , p/\bar{p} spectra at $\sqrt{s} = 7$ TeV



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

[[Sassot Zurita Stratmann, 1008.0540](#)]

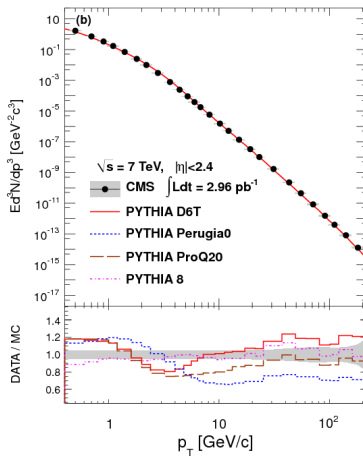
Hadron spectra at the LHC



- 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

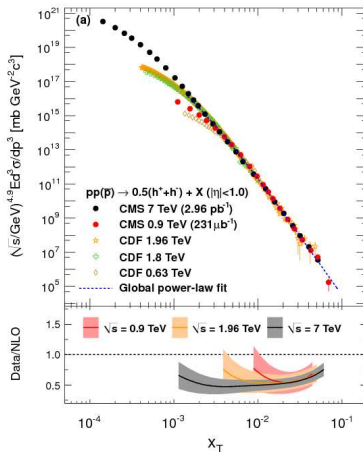
CMS 1104.3547



- Rather good agreement with PYTHIA (various tunes)

Hadron spectra at the LHC

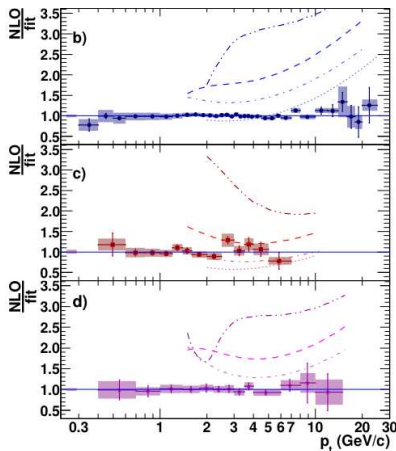
CMS 1104.3547



- Discrepancy between CMS and NLO!

Hadron spectra at the LHC

ALICE 1205.5724



- “NLO calculations **cannot provide a consistent description** of measured data at both beam energies”

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)

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

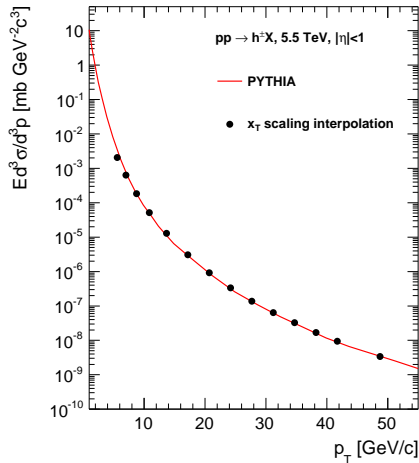
where $\alpha \equiv \ln(\sqrt{s}/\sqrt{s_1}) / \ln(\sqrt{s_2}/\sqrt{s_1})$

Interpolation uncertainty

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

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

- **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)
 - Discrepancy between data and NLO predictions from 0.9 to 7 TeV
 - x_{\perp} -scaling procedure to interpolate pp data at heavy-ion c.m.s. energies