Surprisingly Close Tsallis Fits to High Transverse Momentum Hadrons Produced at LHC

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(*) Introduction (Tsallis fits to hadron p_T spectra ,power laws and power index)

(*) Relativistic hard-scattering model

(*) Extraction of the power index n from experimental jet and hadron p_T distributions

(*) Phenomenological input necessary to get the low p_T limit

(*) Conclusions

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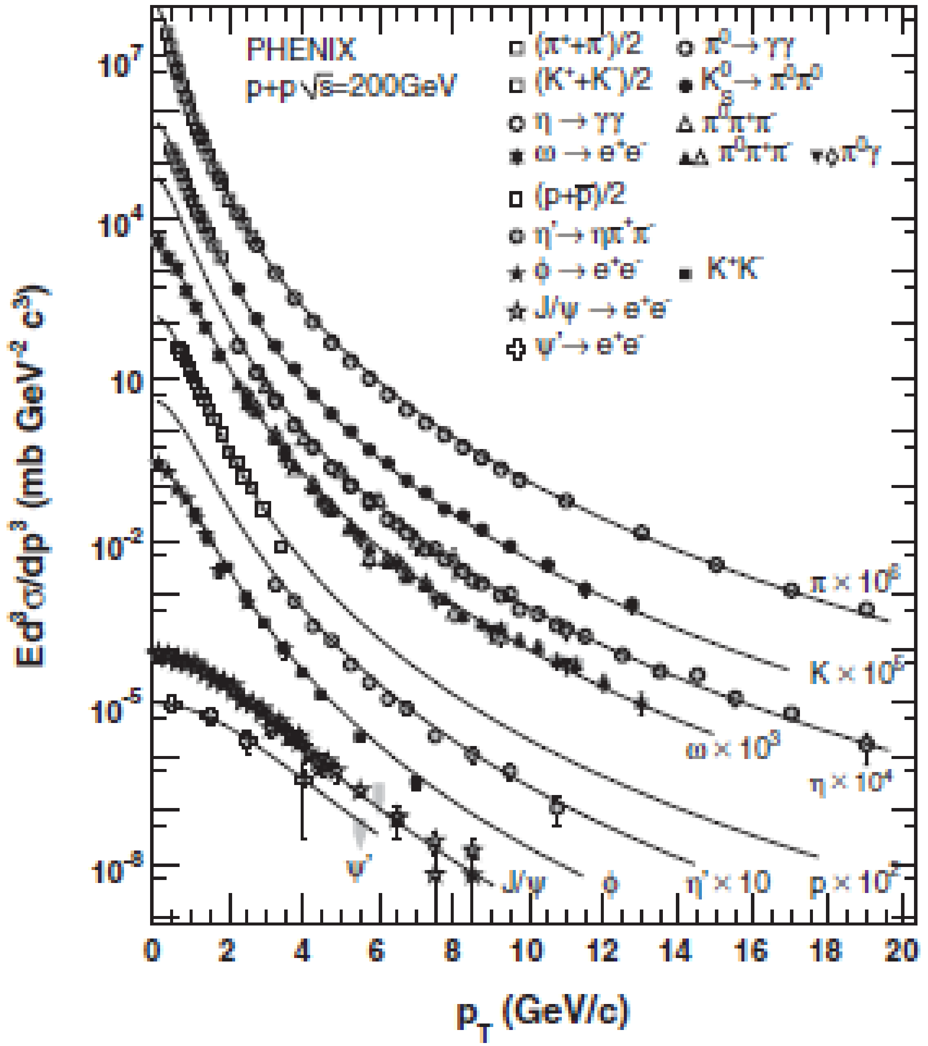
- Phys. Rev. D87 (2013) 114007
- arxiv: 1309.7330v1 [hep-ph] – proc.of Low-X 2013
The Open Nuclear & Particle Physics Journal, in press

Example of Tsallis distribution: application to PHENIX data

$$E\frac{d\sigma}{d^3p} = \frac{A}{\left(1 + \frac{m_T - m}{nT}\right)^n}; \quad n = \frac{1}{q-1}$$



Phenix Coll., PRD 83, 052004 (2011)

Fig. 12
Invariant differential cross sections of different particles measured in p p collisions at √s = 200 GeV in various decay modes.

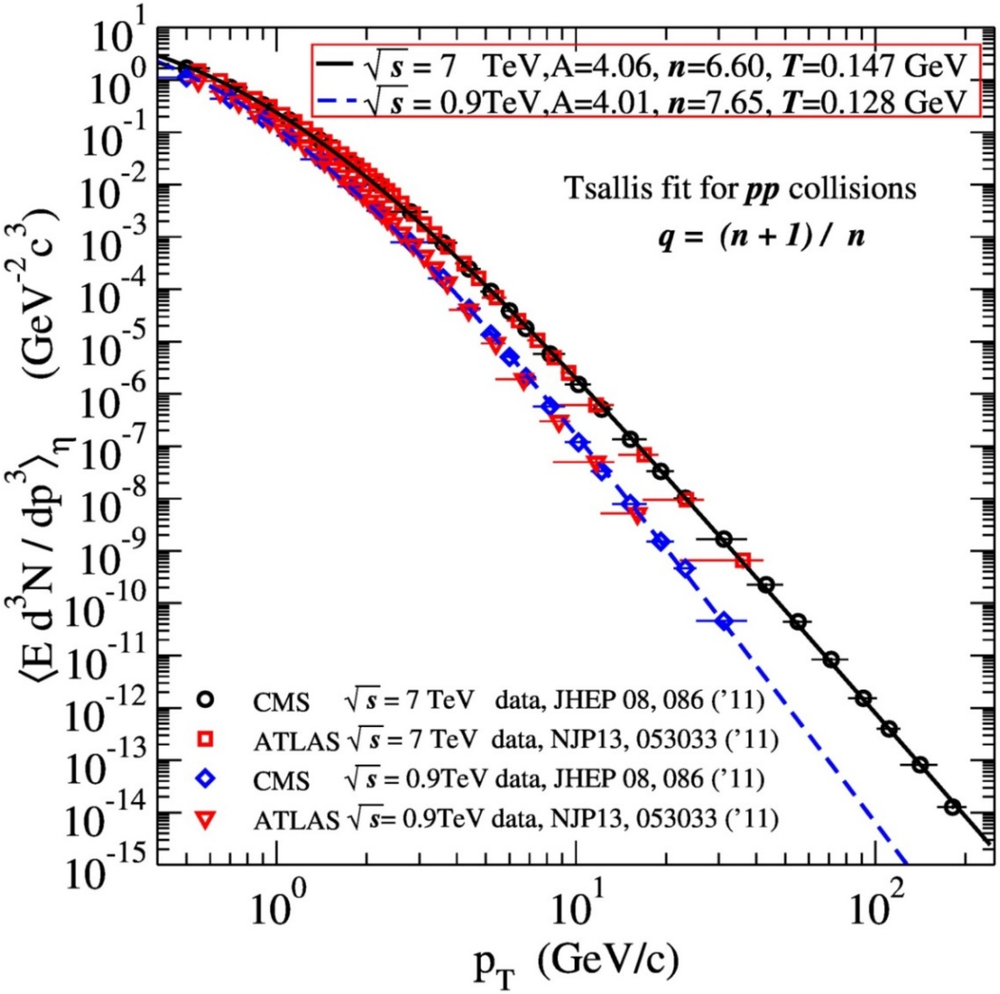
q=1.1 n=10

Tsallis distribution can describe LHC p_T distributions

$$E\frac{d\sigma}{d^3p} = \frac{A}{\left(1+\frac{m_T - m}{nT}\right)^n}; \quad n = \frac{1}{q-1}$$

Good Tsallis fits have been obtained

$$\begin{cases} \text{for } \sqrt{s} = 7 \text{ TeV}, & n = 6.60 \\ & q = 1.15 \\ \text{for } \sqrt{s} = 0.9 \text{ TeV}, & n = 7.65 \\ & q = 1.13 \end{cases}$$



Wong and Wilk, ActaPhysPol.B43,2047(2012)

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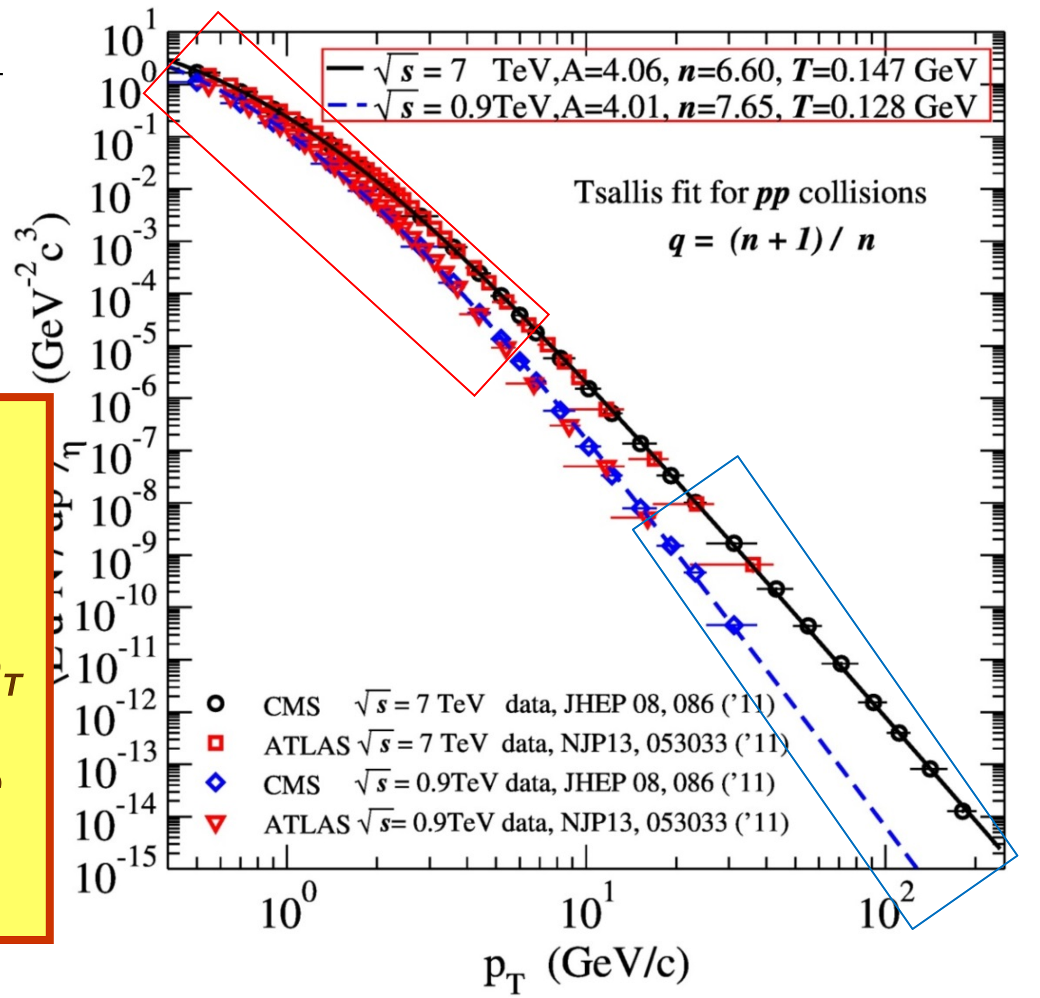
Good Tsallis fits have been

Notice that:

Tsallis fit describes

THE WHOLE RANGE OF VARIABLE p_T

notwithstanding the fact that they are believed to correspond to different dynamics



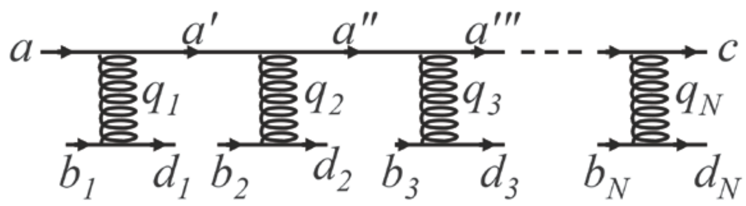
Wong and Wilk, ActaPhysPol.B43,2047(2012)

Good Tsallis p_T fits raise questions

- What is the physical meaning of *n* ?
- If *n* is the power index of $1/p_T^n$, then why is $n \sim 7$, whereas pQCD predicts $n \sim 4$?
- Why are there only few degrees of freedom over such a large p_T domain ?
- Do multiple parton collisions play any role in modifying the power index *n*?
- Does the hard scattering process contribute significantly to the production of low-p_T hadrons?
- What is the origin of low-p_T part of Tsallis fits ?
- ……………………………………………………………………….

Parton Multiple Scattering

For the collision of a parton ***a*** with a target of **A** partons in sequence without centrality selection, the differential c_T distribution is given by



$$\frac{d\sigma_H(aA \to cX)}{d\vec{c}_T} = A\frac{\alpha_s^2}{c_T^4}\int d\vec{b}\,T(b)$$

$$+\frac{A(A\text{-}1)}{2}\frac{16\pi\alpha_s^4}{c_T^6}\ln\left(\frac{c_T}{2p_0}\right)\int d\vec{b}[T(b)]^2$$

$$+\frac{A(A\text{-}1)(A-2)}{6}\frac{936\pi^2\alpha_s^4}{c_T^8}\left[\ln\left(\frac{c_T}{2p_0}\right)\right]^2\int d\vec{b}[T(b)]^3$$

The contribution from the single collision dominates, but high multiple collisions comes in at lower $\mathbf{p_T}$ and for more central collisions

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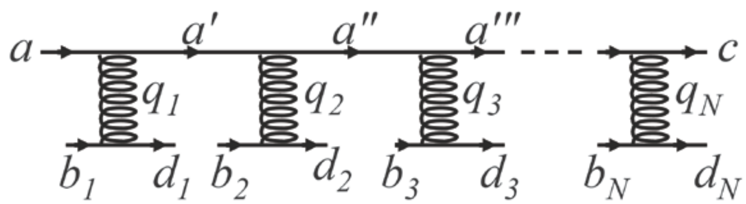

One expects then that for more and more central collisions, contributions with a greater number of multiple parton collisions gains in importance. As a consequence, the power index n is expected to become greater when we select more central collisions (subject to experimental verification).

The contribution from the single collision dominates, but high multiple collisions comes in at lower $\mathbf{p_T}$ and for more central collisions

Good Tsallis p_T fits raise questions

- What is the physical meaning of n ?
- If n is the power index of $1/p_T^n$, then why is $n \sim 7$,

We seek answers to these questions from the

relativistic hard-scattering (RHS) model

[Blankebecler, Brodsky et al., PRD10(1974)2973; D12(1975)3469; D15(1977)3321]

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-
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of low-p_T hadrons?

- What is the origin of low-p_T part of Tsallis fits ?
- ....

Relativistic Hard-Scattering (RHS) Model

- Approximate Hard-Scattering Integral -

$$E_p \frac{d\sigma(AB \to cX)}{d^3p} = \sum_{ab} \int dx_a dx_b G_{a/A}(x_a) G_{b/B}(x_b)\, E_c \frac{d\sigma(ab \to cd)}{d^3p}$$

The basic differential cross section is

$$E_c \frac{d\sigma(ab \to cd)}{d^3p} = \frac{\hat{s}}{\pi} \frac{d\sigma(ab \to cd)}{dt} \delta(\hat{s} + \hat{t} + \hat{u}).$$

We assume: $x_a G_{a/A}(x_a) = A_a (1 - x_a)^g,$

For central rapidity, $|\eta| \approx 0,$ we obtain

$$E_p \frac{d^3\sigma(AB \to cX)}{d^3c} = \sum_{ab} \frac{A_a A_b}{\sqrt{\pi g}} (1 - x_{a0})^g (1 - x_{b0})^g \times$$

$$\times \frac{1}{\sqrt{\tau_c}} \left\{ \frac{1 - x_c}{1 - \tau_c^2 / x_c} \right\}^{1/4} \sqrt{\frac{(1 - x_{b0})}{1 - (x_{b0} + \tau_c^2 / x_c)/2}} \frac{d\sigma(ab \to cd)}{dt}$$

$$x_c = \frac{c_0 + c_z}{\sqrt{s}}, \quad \tau_c = \frac{c_T}{\sqrt{s}}, \quad x_{a0} = x_c + \tau_c \sqrt{\frac{1 - \tau_c^2 / x_c}{1 - x_c}}, \quad x_{b0} = \frac{\tau_c^2}{x_c} + \tau_c \sqrt{\frac{1 - \tau_c^2 / x_c}{1 - x_c}}$$

RHS Model - The Power Index in Jet Production

For $gg \to gg, qq' \to qq'$, and $qg \to qg$, $\quad \frac{d\sigma(ab \to cd)}{dt} \propto \frac{\alpha_s^2(c_T)}{c_T^4}$

The analytical formula is

$$E_c \frac{d\sigma(AB \to cX)}{d^3c} \propto \frac{1}{(c_T/\sqrt{s})^{1/2}} \frac{\alpha_s^2(c_T)}{c_T^4} (1 - x_{a0}(c_T))^g (1 - x_{b0}(c_T))^g$$

For $\eta \sim 0$, $x_{a0}(c_T) = x_{b0}(c_T) = 2x_c(c_T) = 2c_T/\sqrt{s}$, the analytical formula is

$$E_c \frac{d\sigma(AB \to cX)}{d^3c} \propto \frac{\alpha_s^2(c_T)\ (1-2x_c(c_T))^g (1-2x_c(c_T))^g}{c_T^{4+1/2}/(\sqrt{s})^{1/2}}$$

We change notations $\quad c \to p \quad$ and introduce power index n

$$E_p \frac{d\sigma(AB \to pX)}{d^3p} \propto \frac{\alpha_s^2(p_T)\ (1-2x_c(p_T))^g (1-2x_c(p_T))^g}{p_T^n/(\sqrt{s})^{1/2}}$$

where $\quad n = 4 + 1/2 \quad$ for LO pQCD. $\quad g_{a,b} = g = 6 - 10 \quad$ (we take g = 6 [18])

[18] D. W. Duke and J. F. Owens, Phy. Rev D30, 49 (1984).

How to get n from data ?

Method (I),

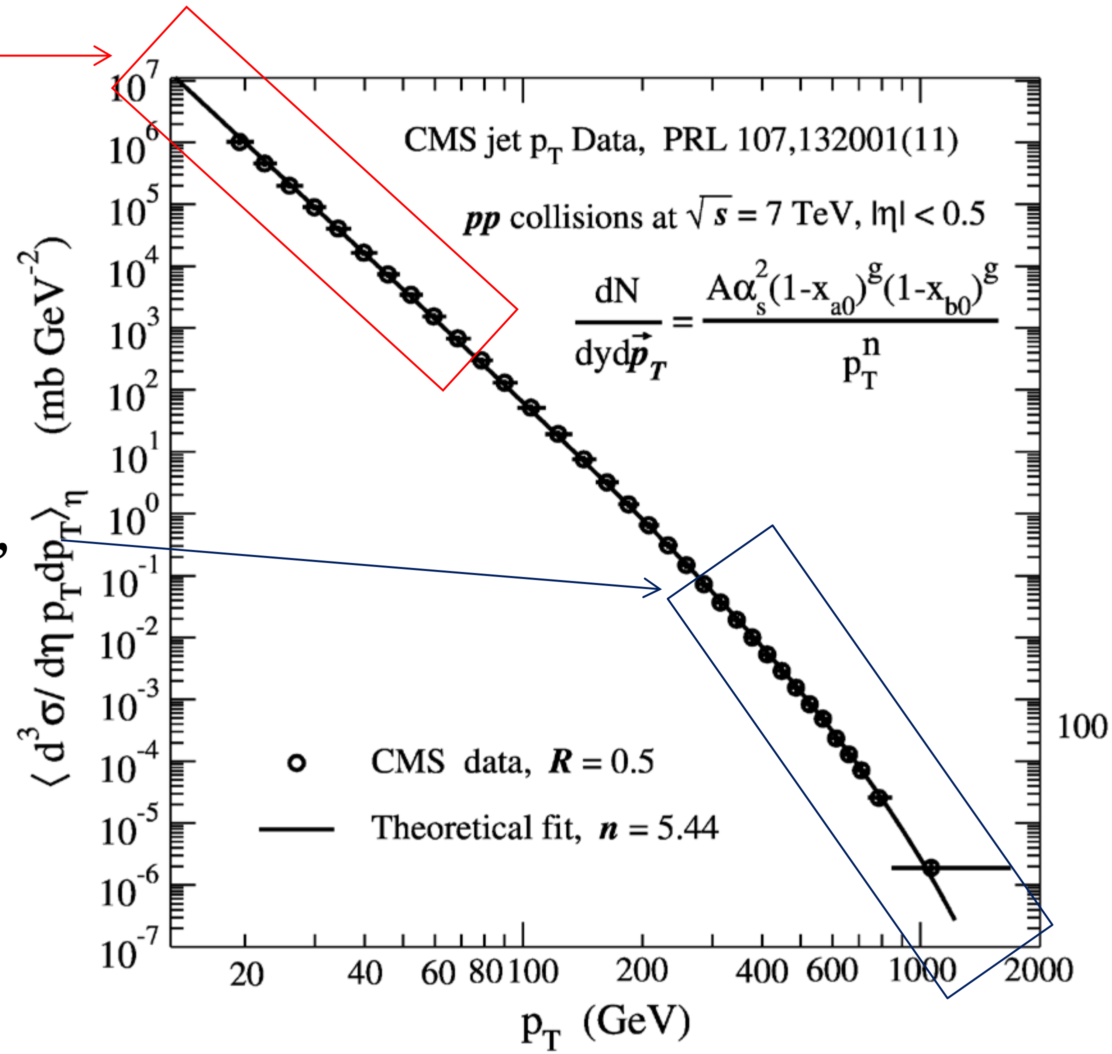
Work at a fixed $\sqrt{s}$, and make a log-log plot of σ_{inv} and p_T

(i) in the lower p_T region, the slope gives n,

$$\frac{d(\ln \sigma_{\text{inv}})}{d(\ln p_T)} = -n,$$

(ii) in the very high p_T region, the bending of the curve gives g,

$$\frac{d(\ln p_T^n \sigma_{\text{inv}})}{d(\ln (1-2x_c))} = g.$$



How to get n from data ?

Method (II) [10]

Write the analytical formula

$$E_p \frac{d\sigma(AB \to pX)}{d^3p} \propto \frac{\alpha_s^2(p_T)\ (1-2x_c(p_T))^g (1-2x_c(p_T))^g}{p_T^n / (\sqrt{s})^{1/2}}$$

with $x_c = p_T/\sqrt{s}$ as

$$\sigma_{\text{inv}}(\sqrt{s}, x_c) = E_p \frac{d\sigma(AB \to pX)}{d^3p} \propto \frac{\alpha_s^2(p_T)\ (1-2x_c(p_T))^g (1-2x_c(p_T))^g}{(x_c\sqrt{s})^n / (\sqrt{s})^{1/2}}$$

At a fixed x_c, we look at two different energies, $\sqrt{s_1}$ and $\sqrt{s_2}$,

$$\frac{\ln[\sigma_{\text{inv}}(\sqrt{s_1}, x_c)/\sigma_{\text{inv}}(\sqrt{s_2}, x_c)]}{\ln[\sqrt{s_2}/\sqrt{s_1}]} \approx n(x_c) - \frac{1}{2}$$

[10] F. Arleo, S. Brodsky, D. S. Hwang, and A. M. Sickles, Phys. Rev. Lett. 105, 062002 (2010).

How to get n from data ?

Method (III)

At a fixed $\sqrt{s}$, consider running coupling constant

$$\boldsymbol{\alpha_s(Q(c_T)) = \frac{12\pi}{27\ln(C + Q^2/\Lambda^2_{QCD})}},$$

$$\Lambda_{\mathrm{QCD}} = 0.25\,\mathrm{GeV} \Rightarrow \alpha_S\left(M_Z^2\right) = 0.1184;$$

$$C = 10 \Rightarrow \alpha_S\left(Q \propto \Lambda_{QCD}\right) \approx 0.6 \text{ in hadron spectroscopy studies [17]}$$

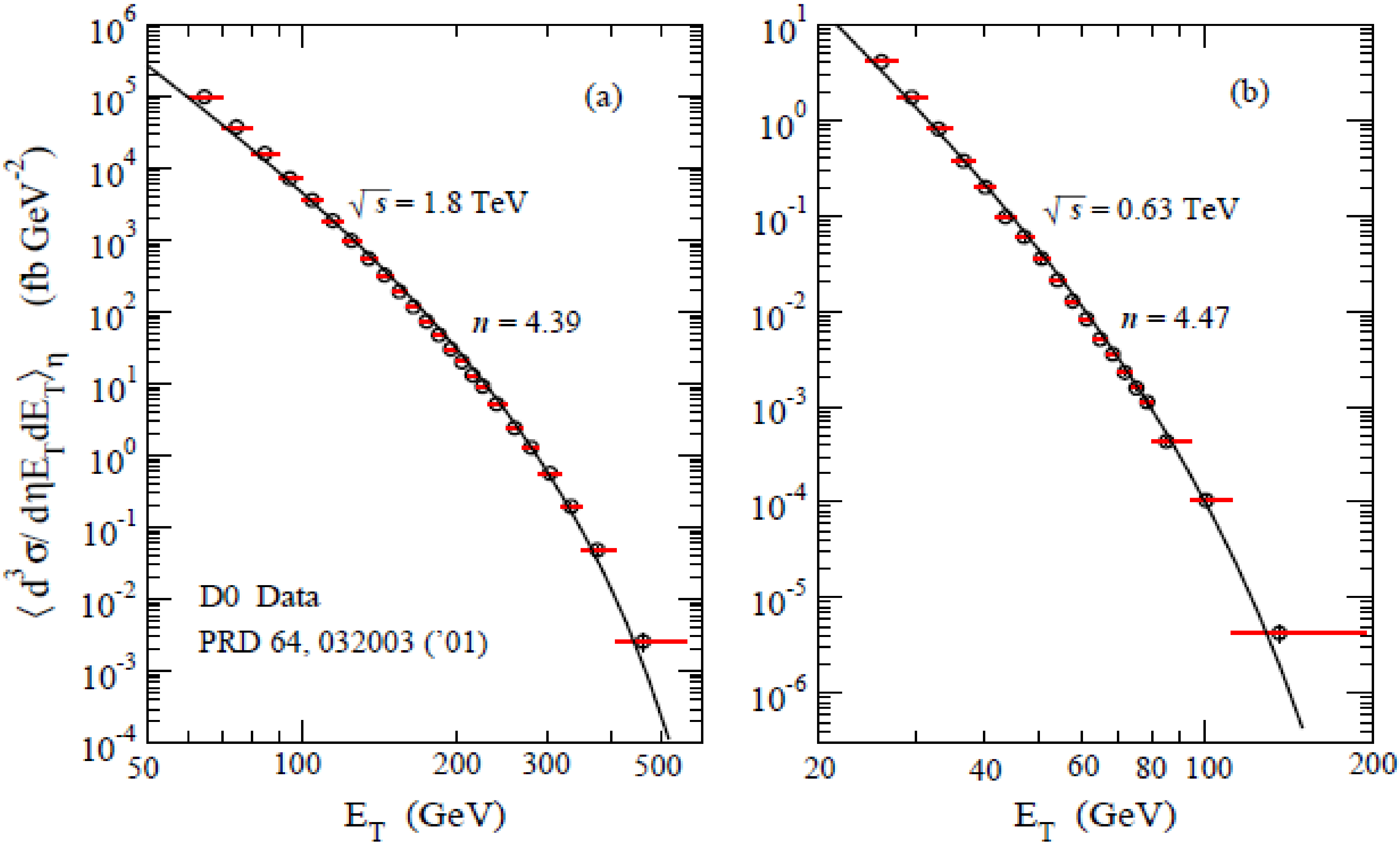
For $Q = c_T$ search for n by fitting experimental data at $\eta \approx 0$

$$E_c \frac{d\sigma^3(AB \to cX)}{dc^3} = \frac{A\alpha_s^2(Q^2(c_T))\ (1-x_{a0})^{g_a + \frac{1}{2}}(1-x_{b0})^{g_b + \frac{1}{2}}}{c_T^n \sqrt{1-x_c}}$$

Notice: parameter C regularizes the coupling constant for small values of $Q(c_T)$.

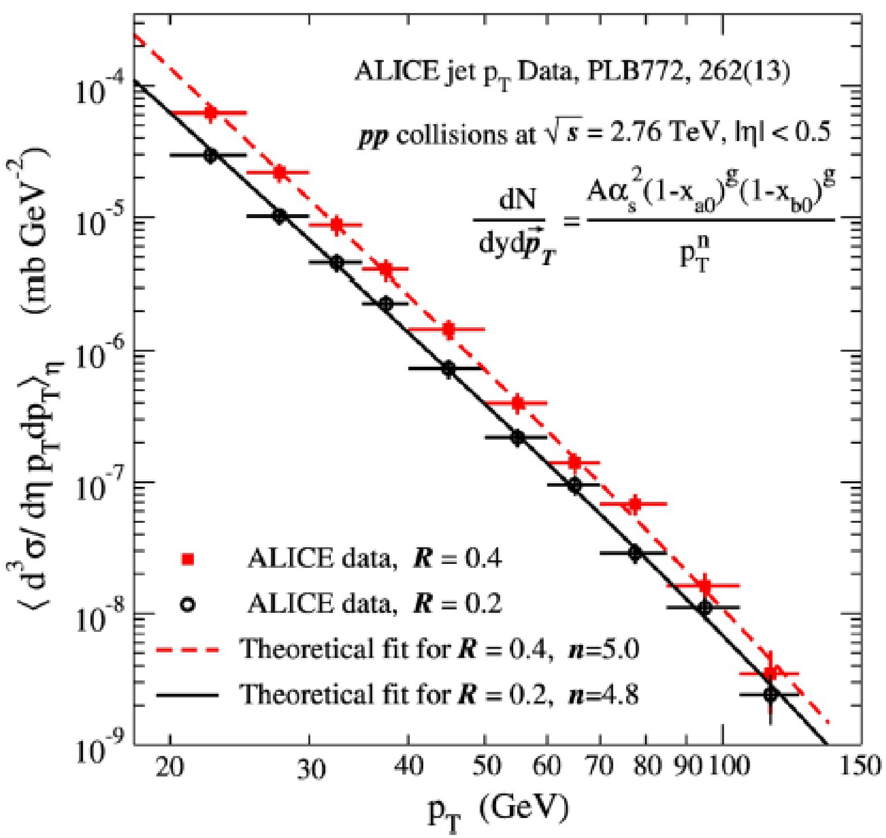
[17] C. Y. Wong, E. S. Swanson, and T. Barnes, Phy. Rev. C, 65, 014903 (2001).

D0 jet data can be described by RHS model

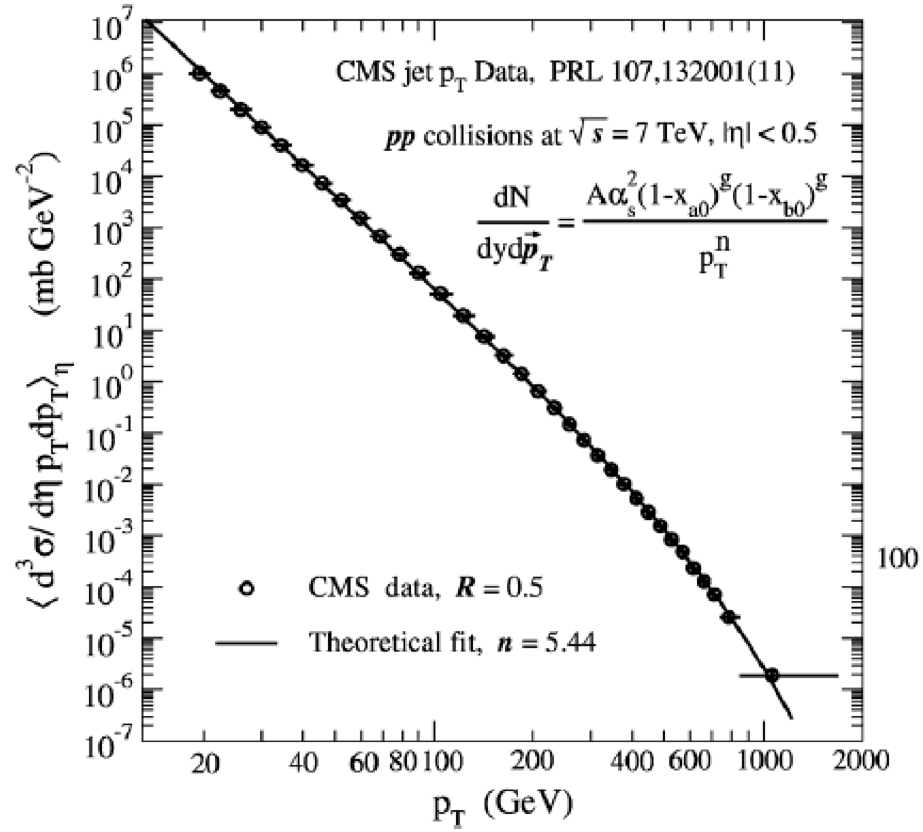


Comparison of the relativistic hard-scattering model results for jet production, Eq. (22) (solid curves), with experimental $d\sigma/d\eta\, E_T\, dE_T$ data from the D0 Collaboration, for hadron jet production within $|\eta|<0.5$, in $\bar{p}p$ collision at (a) $\sqrt{s}$=1.80 TeV, and (b) $\sqrt{s}$=0.63 TeV.

ALICE and CMS jet data can be described by RHS model



n predicted from pQCD is 4.5



n predicted from pQCD is 4.5

(without regularization of $\alpha(p_T)$; R is clustering parameter used in jet finding algorithms)

Except for the CMS data at 7 TeV that may need further re-examination, the power indices extracted for hadron jet production are in approximate agreement with the value of **n=4.5** in Eq. (19) and with previous analysis in [10], indicating the approximate validity of the hard scattering model for jet production in hadron-hadron collisions, with the predominant α^2_s / c^4_T parton-parton differential cross section as predicted by pQCD.

Collaboration	$\sqrt{s}$	R	η	n
D0	$\bar{p}p$ at 1.80 TeV	0.7	$\|\eta\| < 0.7$	4.39
D0	$\bar{p}p$ at 0.63 TeV	0.7	$\|\eta\| < 0.7$	4.47
ALICE	pp at 2.76 TeV	0.2	$\|\eta\| < 0.5$	4.78
ALICE	pp at 2.76 TeV	0.4	$\|\eta\| < 0.5$	4.98
CMS	pp at 7 TeV	0.5	$\|\eta\| < 0.5$	5.39

[10] F. Arleo, S. Brodsky, D. S. Hwang, and A. M. Sickles, Phys. Rev. Lett. 105, 062002 (2010).

Evolution from jet to hadrons

The evolution from a jet to hadrons passes through the stages of

(i) showering (and/or fragmentation),

(ii) hadronization.

Phenomenological Modifications for Hadron Production

Jet production →

$$E_c \frac{d\sigma^3(AB \to cX)}{dc^3} = \frac{A\alpha_s^2(Q^2(c_T))\ (1-x_{a0})^{g_a+\frac{1}{2}}(1-x_{b0})^{g_b+\frac{1}{2}}}{c_T^n \sqrt{1-x_c}}$$

hadrons

(*) For the case of hadron production, it is necessary to take into account additional effects. Jets undergoes fragmentation and hadronization to produce the observed hadrons.

(*) For example: from the fragmentation function for a parent parton jet to fragment into hadrons, an observed hadron **p** of transverse momentum p_T can be estimated to arise (on the average) from the fragmentation of a parent jet **c** with transverse momentum $\langle c_T \rangle = 2.3 p_T$ [11].

[11] C. Y. Wong and G. Wilk, Phys. Rev. D87, 114007 (2013).

Effects of showering (and/or fragmentation) on power law

If the fragmentation is such that $p = zc$,

$$E_p \frac{d\sigma(AB \to pX)}{d^3 p} = \int dz D_{p/c}(z) \int d^4 c \frac{d\sigma(AB \to cX)}{d^4 c} \delta^{(4)}(p - zc)$$

$$= \int \frac{dz}{z^2} D_{p/c}(z) z^{4+1/2} \frac{\alpha_s^2(c_T)(1-x_c(c_T))^g (1-x_c(c_T))^g}{p_T^{4+1/2}}$$

$$\approx \frac{\alpha_s^2(\bar{c}_T)(1-x_c(\bar{c}_T))^g (1-x_c(\bar{c}_T))^g}{p_T^{4+1/2}}$$

where $\bar{c}_T = p_T \left\langle \frac{1}{z} \right\rangle$

and $\left\langle \frac{1}{z} \right\rangle = \int \frac{dz}{z^2} D_{p/c}(z) z^{4+1/2} \left(\frac{1}{z} \right) \Big/ \int \frac{dz}{z^2} D_{p/c}(z) z^{4+1/2}$

The power law and power index are preserved under p=zc fragmentation

Showering and the power index

As a result of parton showering involving virtuality degradation, the leading hadron momentum ***p*** and the showering parton momentum **c** may not be linearly related and can expect that

$$\mathbf{p = z\, c^{1-\mu}}$$

where parameter **μ** describes details of virtuality degradation. As a consequence, the power index can be changed under parton showering.

After the fragmentation and showering of the parton c to hadron p, the hard-scattering cross section for the scattering in terms of hadron momentum p_T becomes

$$\frac{d^3\sigma(AB \to pX)}{dy\,d\mathbf{p}_T} = \frac{d^3\sigma(AB \to cX)}{dy\,d\bar{\mathbf{c}}_\mathbf{T}} \frac{d\bar{\mathbf{c}}_\mathbf{T}}{d\mathbf{p}_T}$$

$$\propto \frac{\alpha_S^2(\bar{\mathbf{c}}_\mathbf{T})(1 - x_{a0}(\bar{\mathbf{c}}_\mathbf{T}))^{g_a}(1 - x_{b0}(\bar{\mathbf{c}}_\mathbf{T}))^{g_a}}{c_T^{4+1/2}} \frac{d\bar{\mathbf{c}}_\mathbf{T}}{d\mathbf{p}_T}$$

where $$\frac{d\bar{\mathbf{c}}_\mathbf{T}}{d\mathbf{p}_T} = \frac{1}{1-\mu}\left(a\frac{p_T}{p_{T0}}\right)^{\frac{2\mu}{1-\mu}}$$

Here ***a*** is a constant relating the scales of virtuality and transverse momentum. Therefore under the fragmentation $\mathbf{c} \to p$, the hard scattering cross section for $AB \to pX$ becomes:

$$\frac{d^3\sigma(AB \to pX)}{dy\,d\mathbf{p}_T} \propto \frac{\alpha_S^2(\bar{\mathbf{c}}_\mathbf{T})(1 - x_{a0}(\bar{\mathbf{c}}_\mathbf{T}))^{g_a}(1 - x_{b0}(\bar{\mathbf{c}}_\mathbf{T}))^{g_a}}{p_T^{n'}}$$

$$n' = \left(\frac{n-2\mu}{1-\mu}\right) \quad \text{with} \quad \mathrm{n} = 4 + 1/2$$

After all this one gets power-law behavior but not Tsallis formula:

$$\frac{d^3\sigma(AB \to pX)}{dyd\mathbf{p}_T} \propto \frac{\alpha_S^2(\overline{\mathbf{c}}_{\mathbf{T}})(1-x_{a0}(\overline{\mathbf{c}}_{\mathbf{T}}))^{g_a}(1-x_{b0}(\overline{\mathbf{c}}_{\mathbf{T}}))^{g_a}}{p_T^{n'}} \qquad (*)$$

Low p_T is not correct.

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Low p_T is not correct. The proposed possible remedy is

to replace the usual parameter p_0 ($\sim 1\div 2\ GeV$) dividing phase space into part governed by „soft physics „ ($p_T < p_0$) from that governed by „hard physics" ($p_T \geq p_0$) by regularizing denominator in (*),

for example by using:

$$\frac{d^3\sigma(AB\to pX)}{dyd\mathbf{p}_T}\propto\frac{\alpha_S^2(\bar{\mathbf{c}}_\mathbf{T})(1-x_{a0}(\bar{\mathbf{c}}_\mathbf{T}))^{g_a}(1-x_{b0}(\bar{\mathbf{c}}_\mathbf{T}))^{g_a}}{\left(1+\frac{m_T}{m_{T0}}\right)^n} \qquad (\oplus)$$

$$m_T=\sqrt{m^2+p_T^2}$$

Notice that we have just assumed the form of Tsallis formula showed at the beginning:

$$\mathbf{E}\frac{\mathbf{d}\boldsymbol{\sigma}}{\mathbf{d}^3\mathbf{p}} = \frac{\mathbf{A}}{\left(\mathbf{1}+\frac{\mathbf{m_T}-\mathbf{m}}{\mathbf{nT}}\right)^{\mathbf{n}}}$$

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$$m_T = \sqrt{m^2 + p_T^2}$$

In addition to the replacement

$$(1/p_T)^n \rightarrow 1/(1 + p_T/p_0)^n$$

in actual calculations **we also regularize coupling constant for small values of p_T** (following method proposed in hadron spectroscopic studies by C. Y. Wong, E. S. Swanson, and T. Barnes, Phy. Rev. C, 65, 014903 (2001)).

$$\alpha_s(p_T) = \frac{12\pi}{27\ln(C + p_T^2/\Lambda_{QCD}^2)},$$

$$\Lambda_{QCD} = 0.25\,\mathrm{GeV} \Rightarrow \alpha_S\left(M_Z^2\right) = 0.1184;$$

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Experiments measure the differential yield in nonsingle-diffractive events, which in our case is

$$\frac{d^3N(AB\to pX)}{dyd\mathbf{p}_T}=\sqrt{1-\frac{m^2}{m_T^2\cosh^2 y}}A\frac{\alpha_S^2(\bar{\mathbf{c}}_\mathbf{T})(1-x_{a0}(\bar{\mathbf{c}}_\mathbf{T}))^{g_a}(1-x_{b0}(\bar{\mathbf{c}}_\mathbf{T}))^{g_a}}{\left(1+\frac{m_T}{m_{T0}}\right)^n}=$$

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$$\bullet\left[1-(1-q)\frac{m_T}{T}\right]^{\frac{1}{1-q}}$$

where $\mathrm{q}=1+\frac{1}{\mathrm{n}}$ and $T=\frac{m_{T0}}{q-1}$

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Looks like Tsallis

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$$\bullet\left[1-(1-q)\frac{m_T}{T}\right]^{\frac{1}{1-q}}$$

where $\quad \mathrm{q}=1+\frac{1}{\mathrm{n}} \quad$ and $\quad T=\frac{m_{T0}}{q-1}$

… but with quite complicated prefactor

Looks like Tsallis

Analysis of hadron p_T distributions

Two ways to regulate the cross sections at low p_T were used:

I. Linear m_T: $\quad p_T \to (m_{T0} + m_T)$

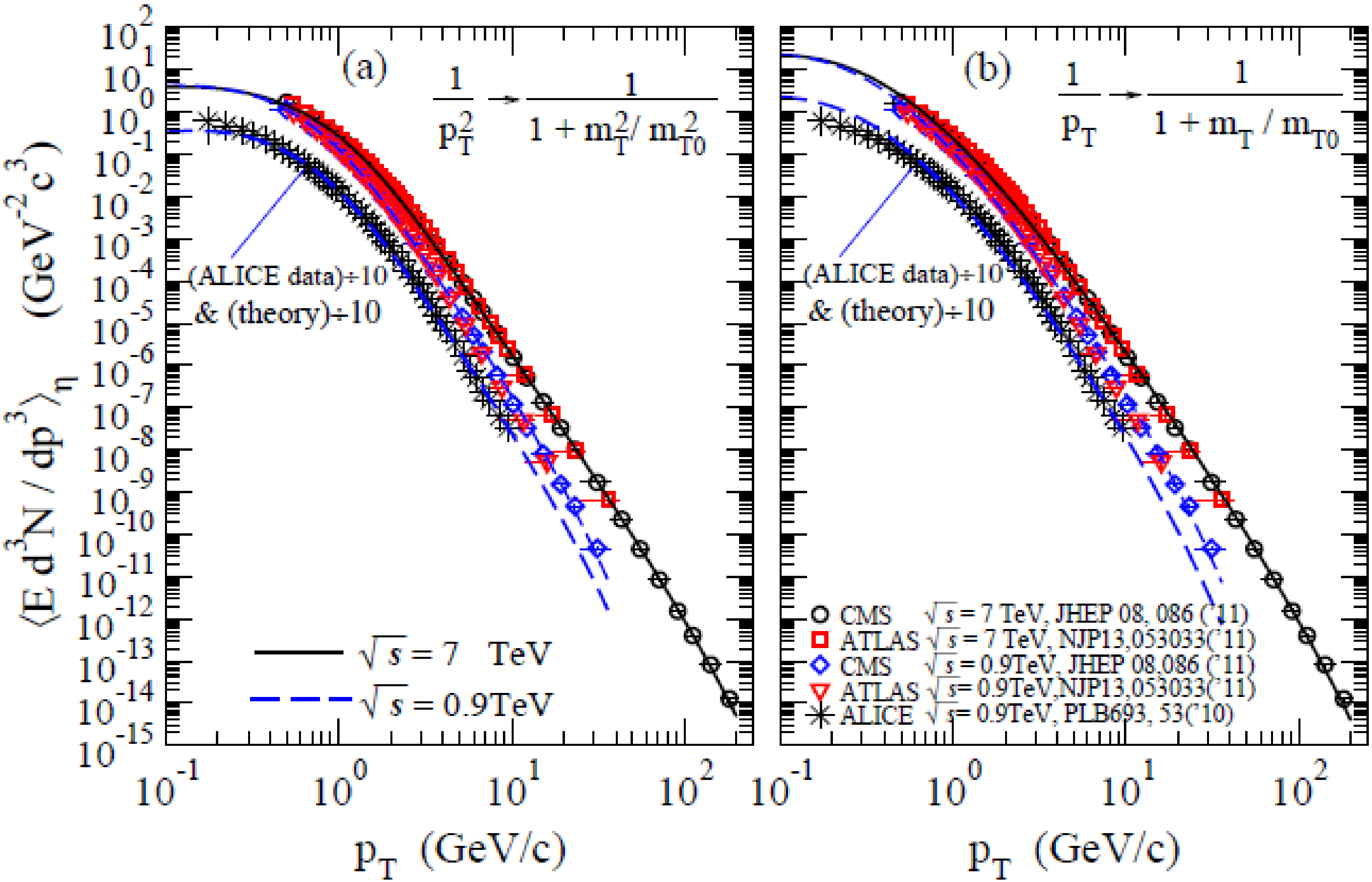
$$E_p \frac{d\sigma(AB \to pX)}{d^3p} = \frac{A\alpha_s^2(\bar{c}_T)\ (1-2x_c(\bar{c}_T))^g (1-2x_c(\bar{c}_T))^g}{(m_{T0}+m_T)^n}. \qquad (24)$$

II. Quadratic m_T: $\quad p_T^2 \to (m_{T0}^2 + m_T^2)$

$$E_p \frac{d\sigma(AB \to pX)}{d^3p} = \frac{A\alpha_s^2(\bar{c}_T)\ (1-2x_c(\bar{c}_T))^g (1-2x_c(\bar{c}_T))^g}{(m_{T0}^2+m_T^2)^{n/2}}. \qquad (25)$$

where $\quad \bar{c}_T = p_T \left\langle \frac{1}{z} \right\rangle; \quad \left\langle \frac{1}{z} \right\rangle = \int \frac{dz}{z^2} D_{p/c}(z) z^{4+1/2} \left(\frac{1}{z} \right) \Big/ \int \frac{dz}{z^2} D_{p/c}(z) z^{4+1/2} = 2.33$

We search for n that fits the hadron p_T spectra.



Comparison of the experimental data for hadron production in pp collisions at the LHC with the relativistic hard scattering model results (solid and dashed curves) (a) using Eq. (25), with a quadratic m_T dependence of the regulating function, and (b) using Eq. (24), with a linear m_T dependence of the regulating function. In both cases regularized coupling constant α_S was used.

	Linear m_T Eq. (24)		Quadratic m_T^2 Eq. (25)	
	$\sqrt{s}$=7TeV	$\sqrt{s}$=0.9TeV	$\sqrt{s}$=7TeV	$\sqrt{s}$=0.9TeV
n	5.69	5.86	5.45	5.49
m_{T0} (GeV)	0.804	0.634	1.09	0.837

(*) For pp collisions at the LHC the power index extracted from hadron spectra has the value of n~6 and is slightly greater than the power indices of n~4-5 extracted from jet transverse differential cross sections.

(*) Fragmentation and showering processes increase therefore slightly the value of the power index n of the transverse spectra.

Relevance to Tsallis fits to p_T spectra

- The sucesses of the Tsallis fits to LHC high-$\mathbf{p_T}$ spectra arises from the power law of $\boldsymbol{\alpha_s^2/p_T^4}$ for the production of jets, leading to $\mathbf{n = 4.5}$.
- Showering and hadronization changes $\mathbf{n}$ from $\mathbf{4.5}$ to $\mathbf{\sim 6}$.
- The additional $\boldsymbol{\alpha_s^2(p_T)}$ and $\mathbf{(1-2x_c)^{2g}}$ bring in additional $\mathbf{p_T}$ dependencies that lead to an increase of $\mathbf{n}$ from $\mathbf{\sim 6}$ to $\mathbf{\sim 7}$ in the Tsallis distribution for hadron production..

Conclusions

- A simple Tsallis formula can describe data with a power index of **n ~ 6.6 - 7.6**

- A power law with a power index of **n ~ 4 - 5** can describe the p_T spectra of jets.

- A regularized power law with a power index of **n ~ 5.5 - 6** can describe (together with regularized coupling constant) the p_T spectra of hadrons for all p_T .

- The power index *n* appears to become larger as a jet evolves into hadrons.

Thank you