One Phenomenological Formula for Transverse Momentum Hadrons Produced at LHC?

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in collaboration with

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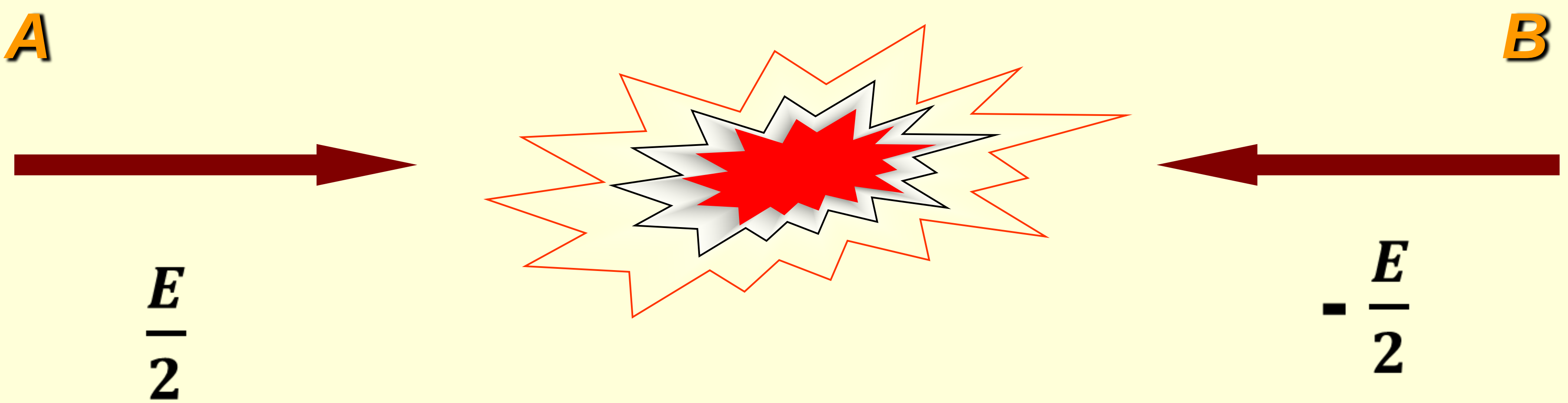
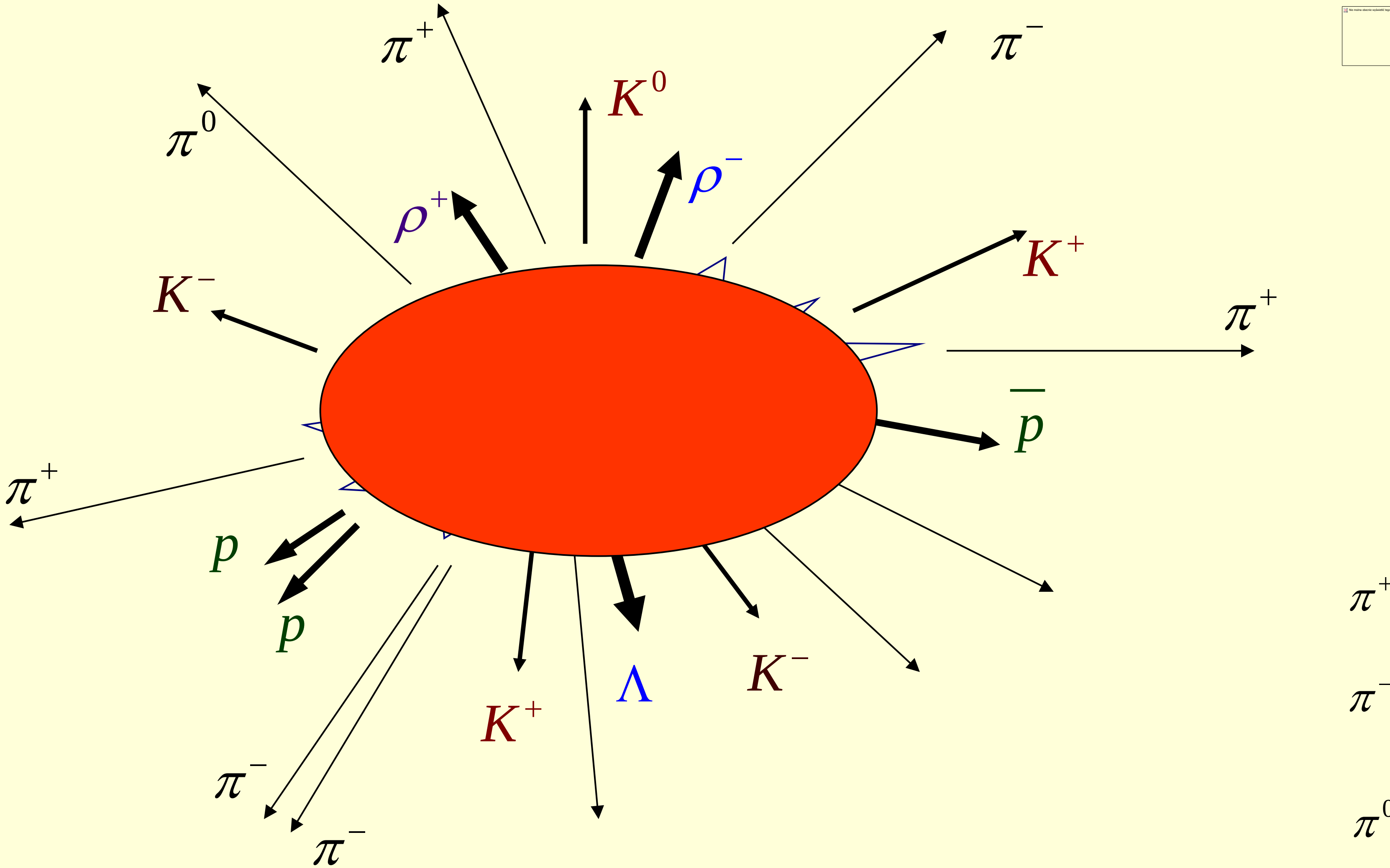
Multiparticle production at high energies:

Total energy available: $E=\sqrt{s}$ (~ 100 − 10000 GeV)

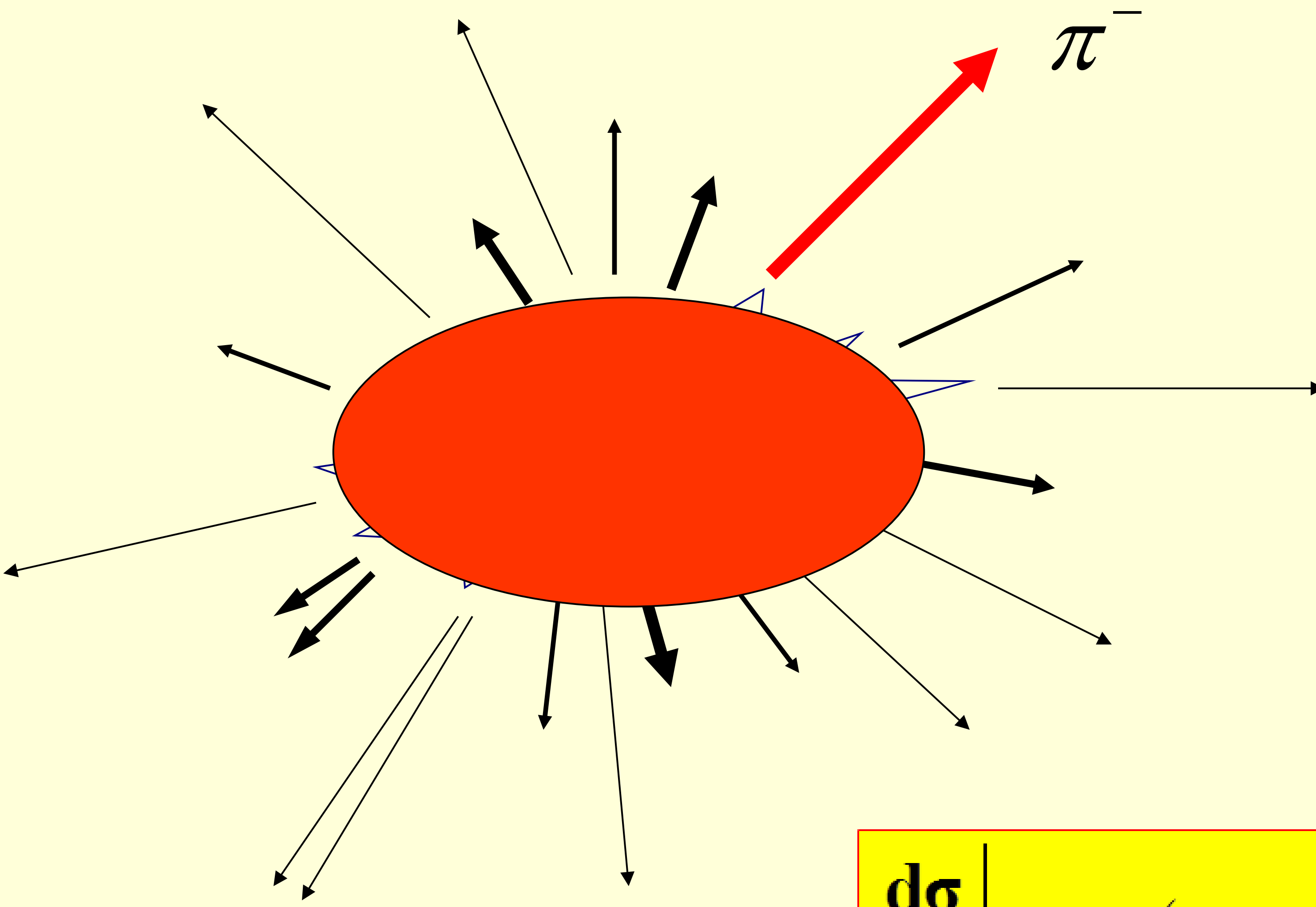


Multiparticle production at high energies



…large number <N> ~ 100 – 1000 secondaries is produced

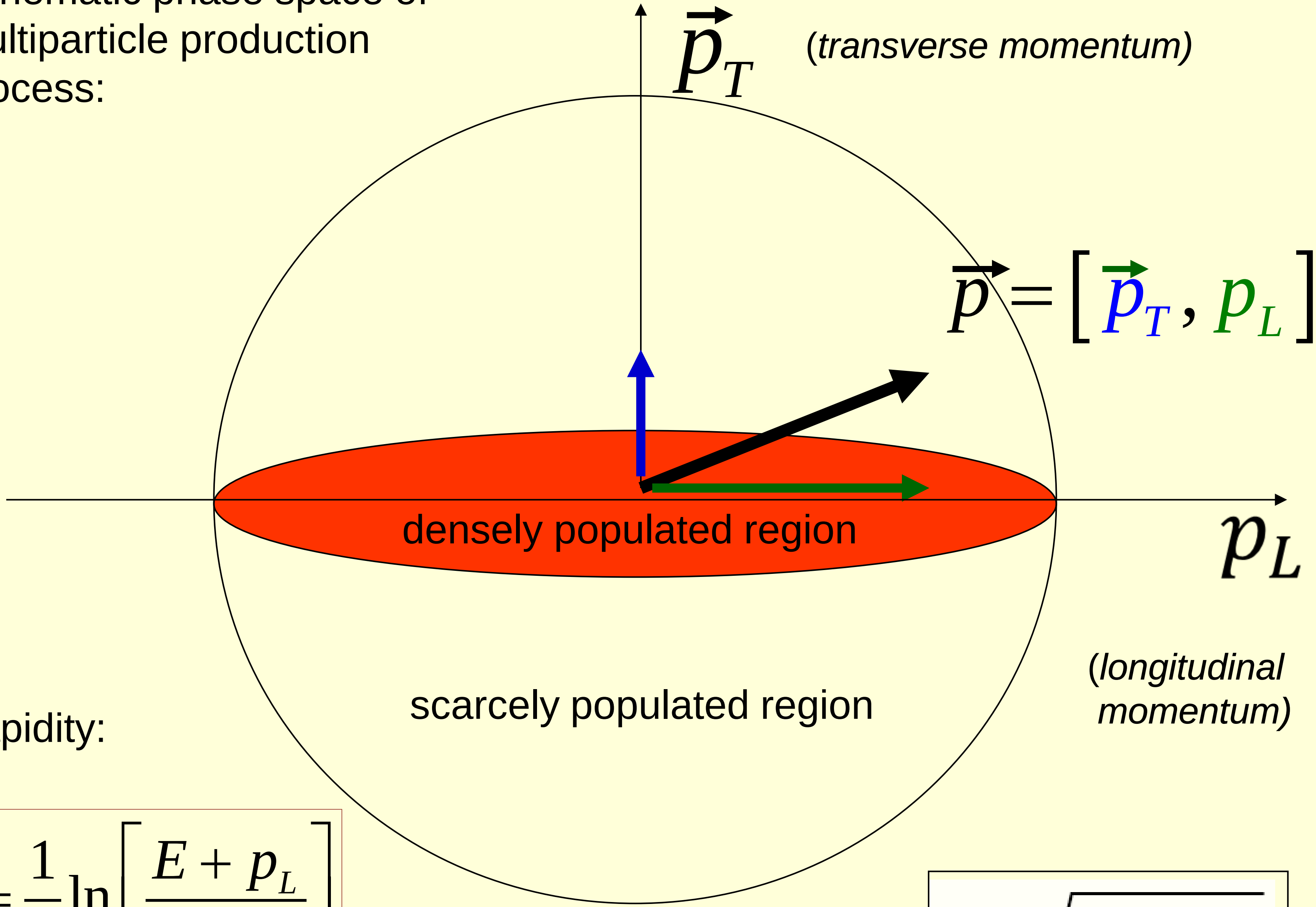
Multiparticle production at high energies



$$\left.\frac{d\sigma}{d^3p}\right|_{\pi^+} = f\left(\vec{p}_T, p_L\right)$$

... but usually only one of them is observed
-> single particle distributions

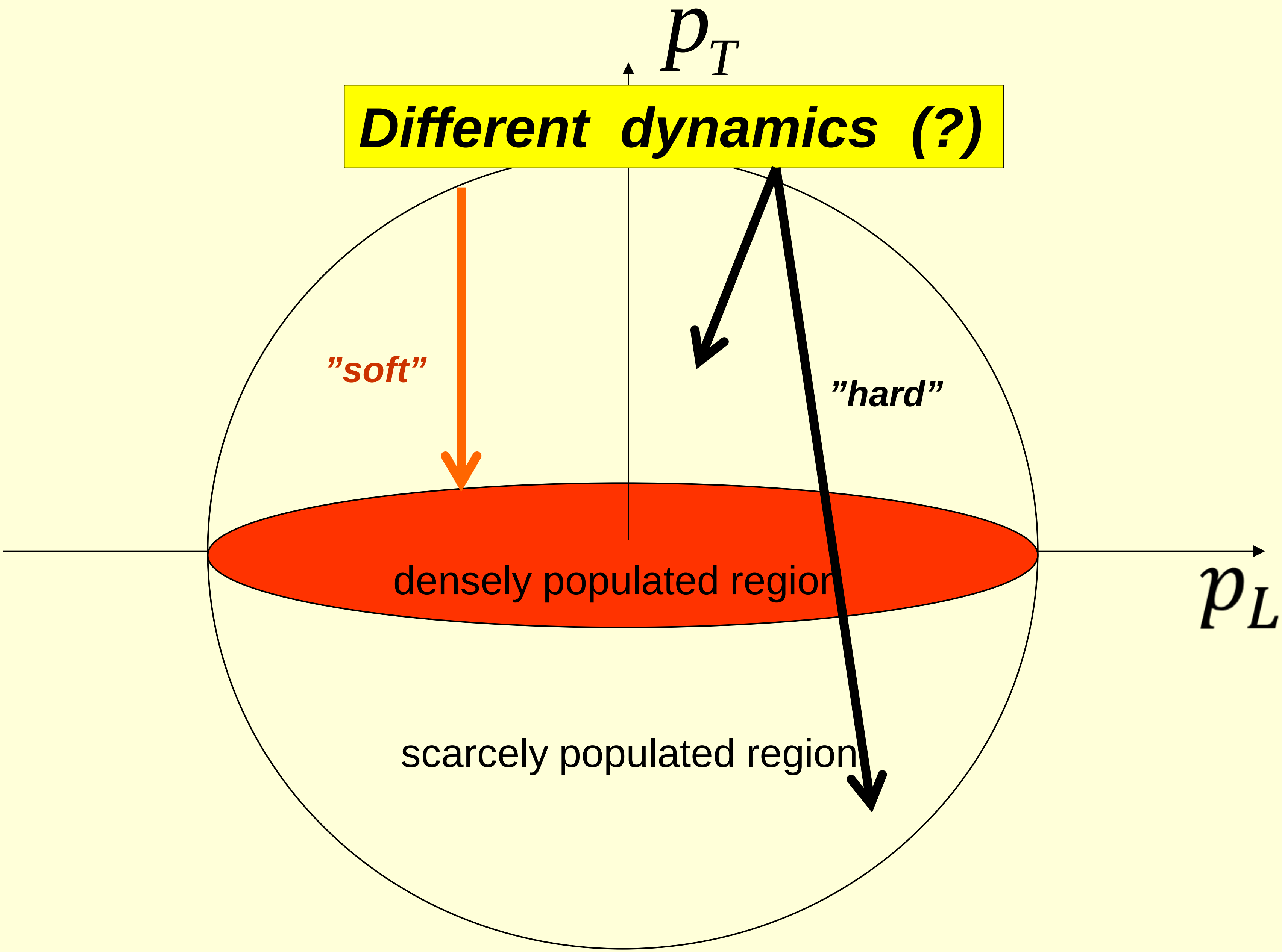
Schematic phase space of multiparticle production process:

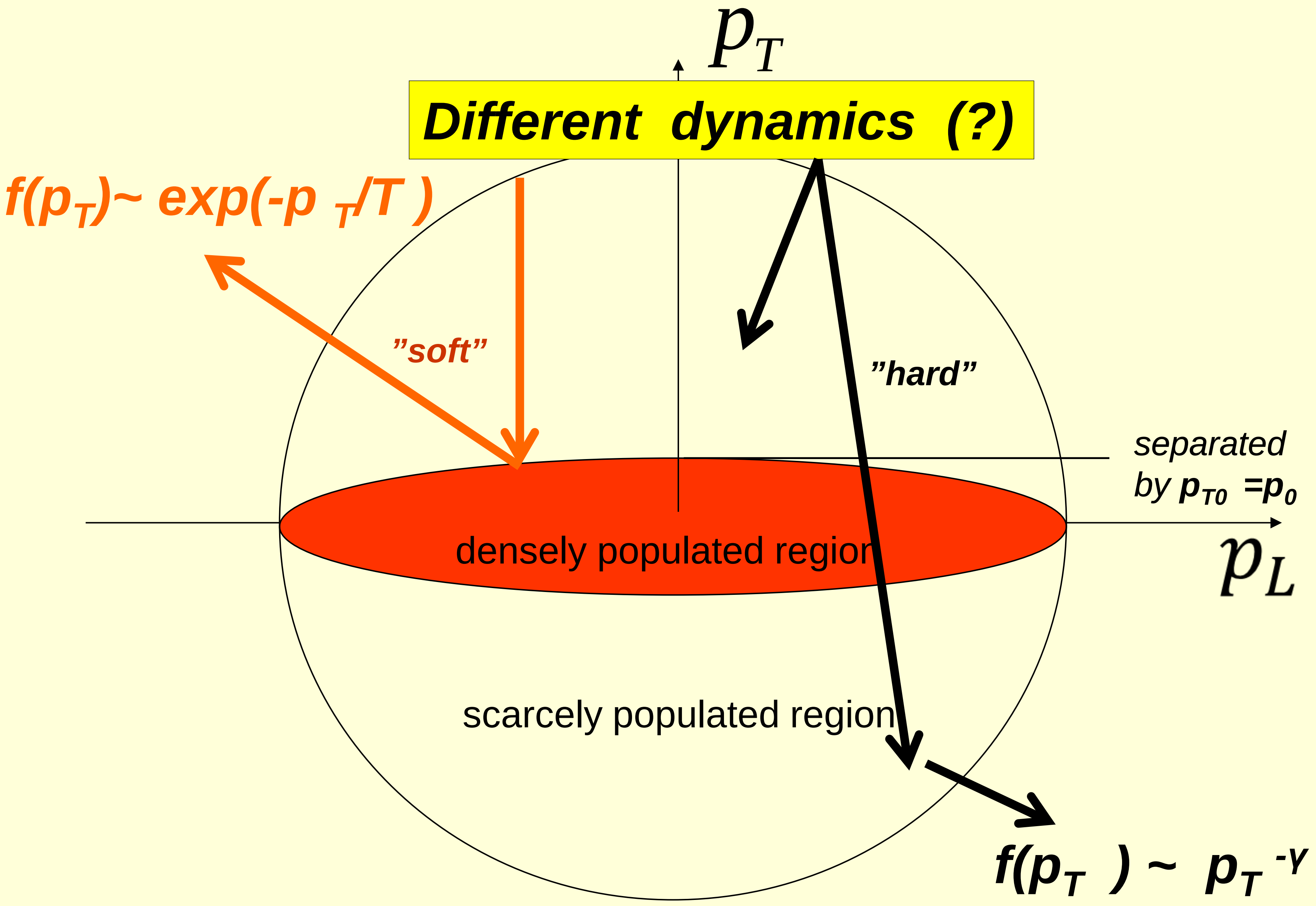


Rapidity:

$$y = \frac{1}{2}\ln\left[\frac{E + p_L}{E - p_L}\right]$$

$$E = \sqrt{m^2 + \vec{p}^{\,2}}$$


p_T
Different dynamics (?)
"soft"
"hard"
densely populated region
scarcely populated region
p_L



p_T
Different dynamics (?)
$f(p_T)\sim \exp(-p_T/T)$
"soft"
"hard"
separated by $p_{T0} = p_0$
p_L
densely populated region
scarcely populated region
$f(p_T) \sim p_T^{-\gamma}$

p_T

Different dynamics (?)

$f(p_T) \sim \exp(-p_T/T)$

However: One can describe both regions at the same time using a single formula interpolating between both regimes (and getting rid of separation parameter p_o):

„Hagedorn" (1977-1984) $$h(p_T) = C\left(1 + \frac{p_T}{mT}\right)^{-m}$$

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Tsallis (1988- …) $$f(p_T) = C\left[1 - (1-q)\frac{p_T}{T}\right]^{\frac{1}{1-q}}$$

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Tsallis (1988- …) $$f(p_T) = C\left[1 - (1-q)\frac{p_T}{T}\right]^{\frac{1}{1-q}}$$

Notice: $h(p_T) = f(p_T)$ for $m = \frac{1}{q-1}$

L

$f(p_T) \sim p_T^{-\gamma}$

Example
-small and medium p_T

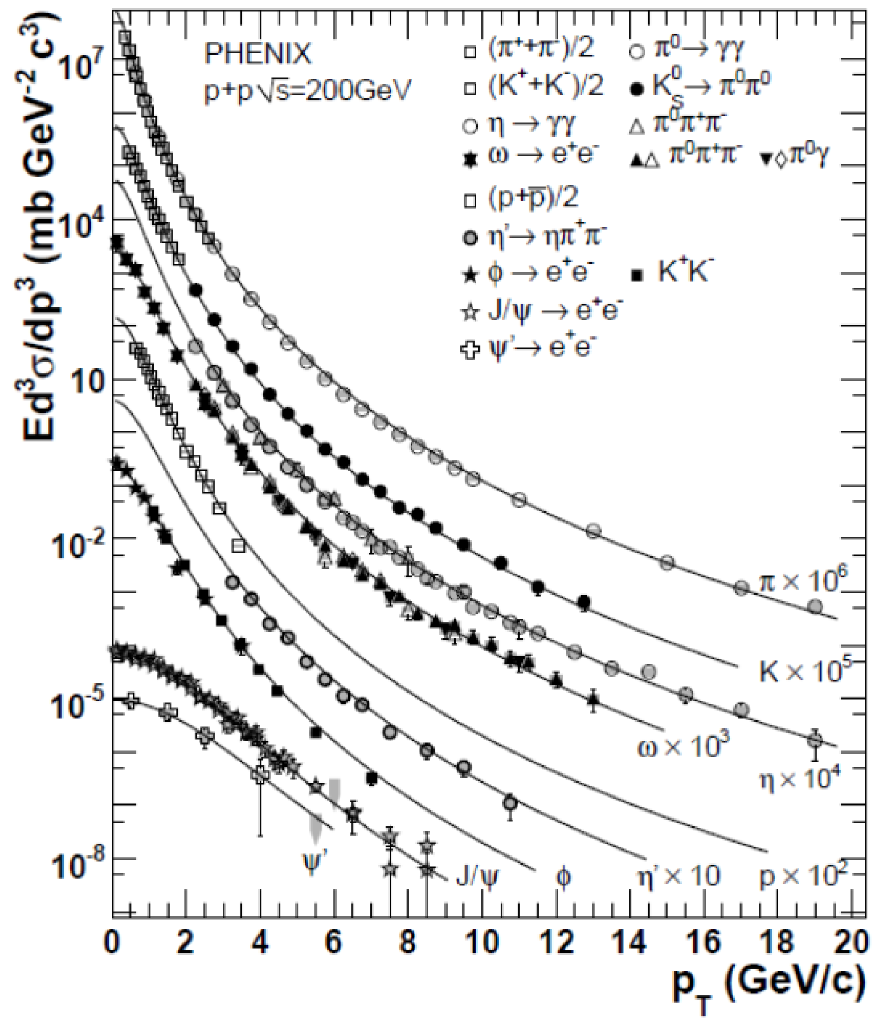
$$E\frac{d\sigma}{d^3p} = \frac{A}{\left(1+\frac{m_T - m}{nT}\right)^n};$$

$$n = \frac{1}{q-1}$$

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.

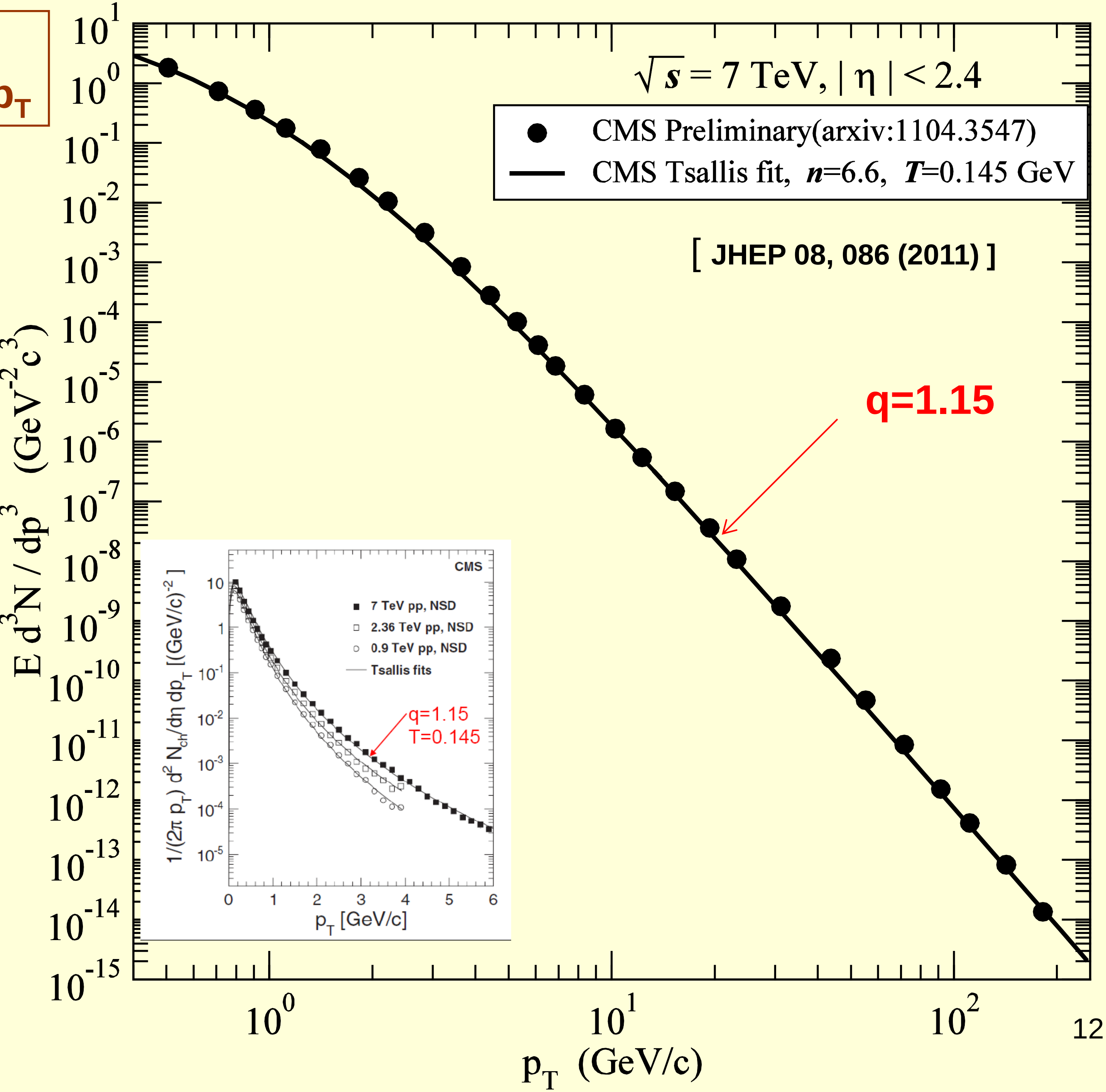
q=1.1 n=10

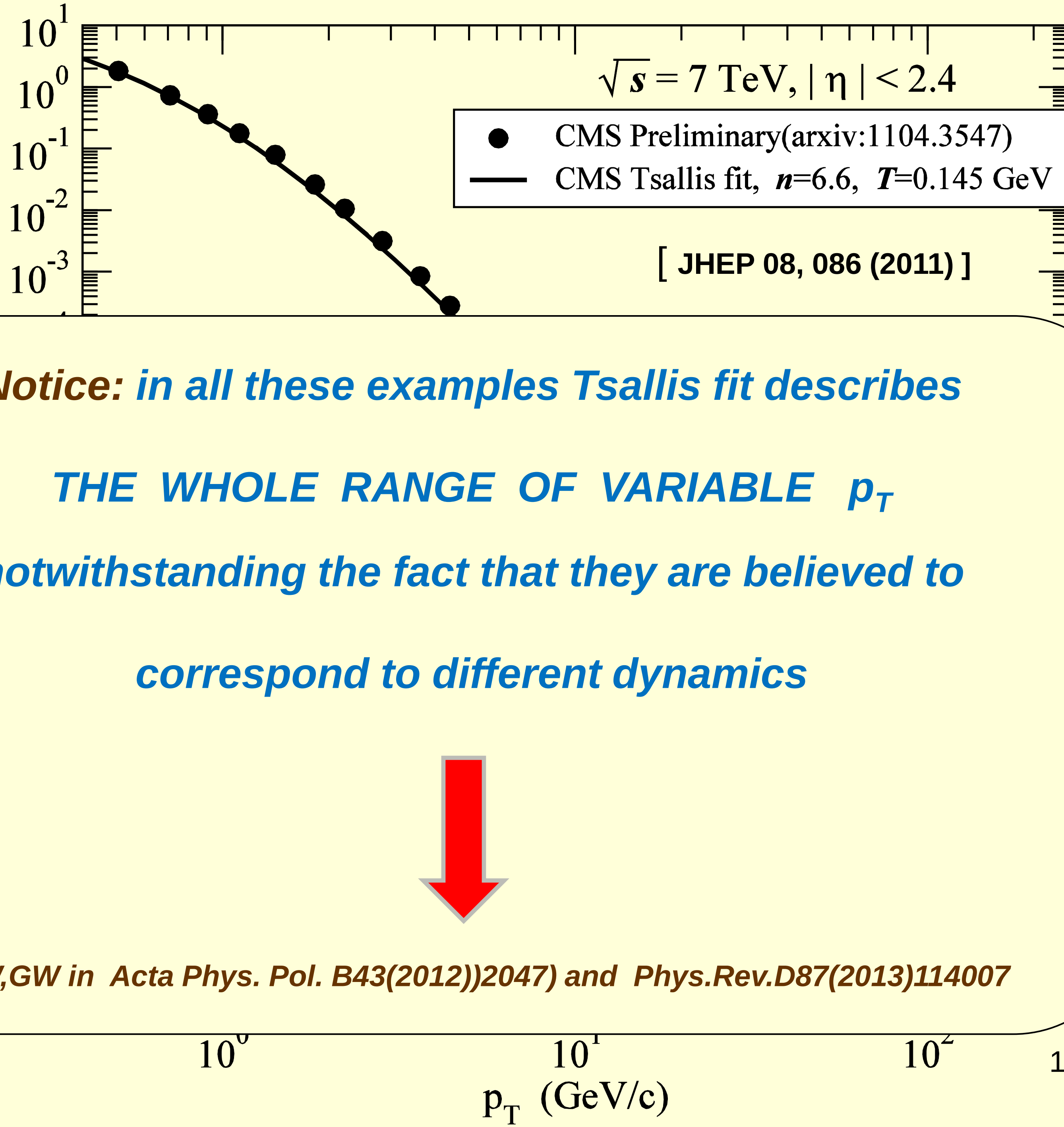


$q \simeq 1.10$

FIG. 12: Invariant differential cross sections of different particles measured in $p + p$ collisions at $\sqrt{s}$ =200 GeV in various decay modes. The spectra published in this paper are shown with closed symbols, previously published results are shown with open symbols. The curves are the fit results discussed in the text.

Example
- very large p_T





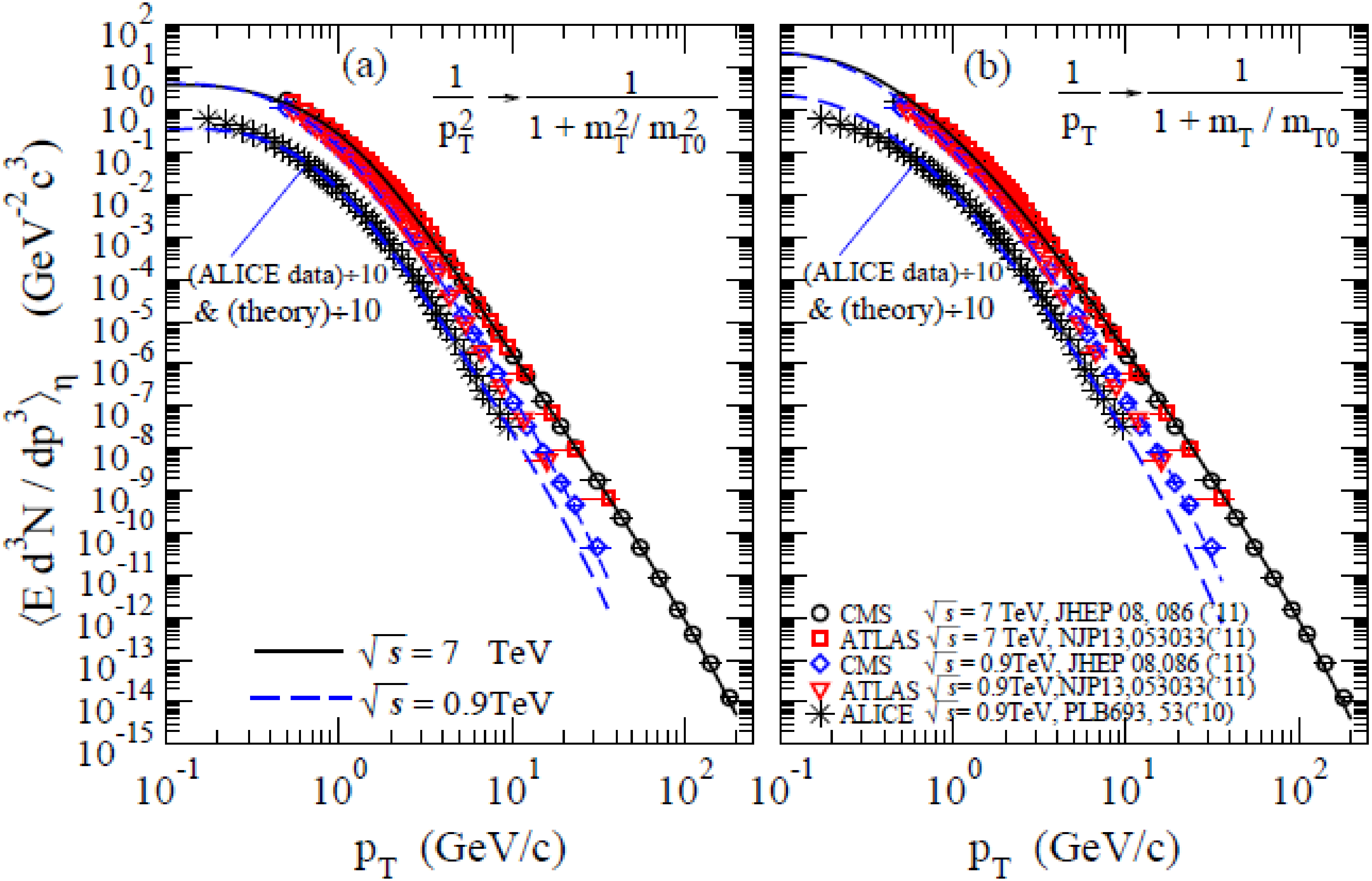
Notice: ***in all these examples Tsallis fit describes***

THE WHOLE RANGE OF VARIABLE p_T

notwithstanding the fact that they are believed to

correspond to different dynamics

CYW,GW in Acta Phys. Pol. B43(2012))2047) and Phys.Rev.D87(2013)114007

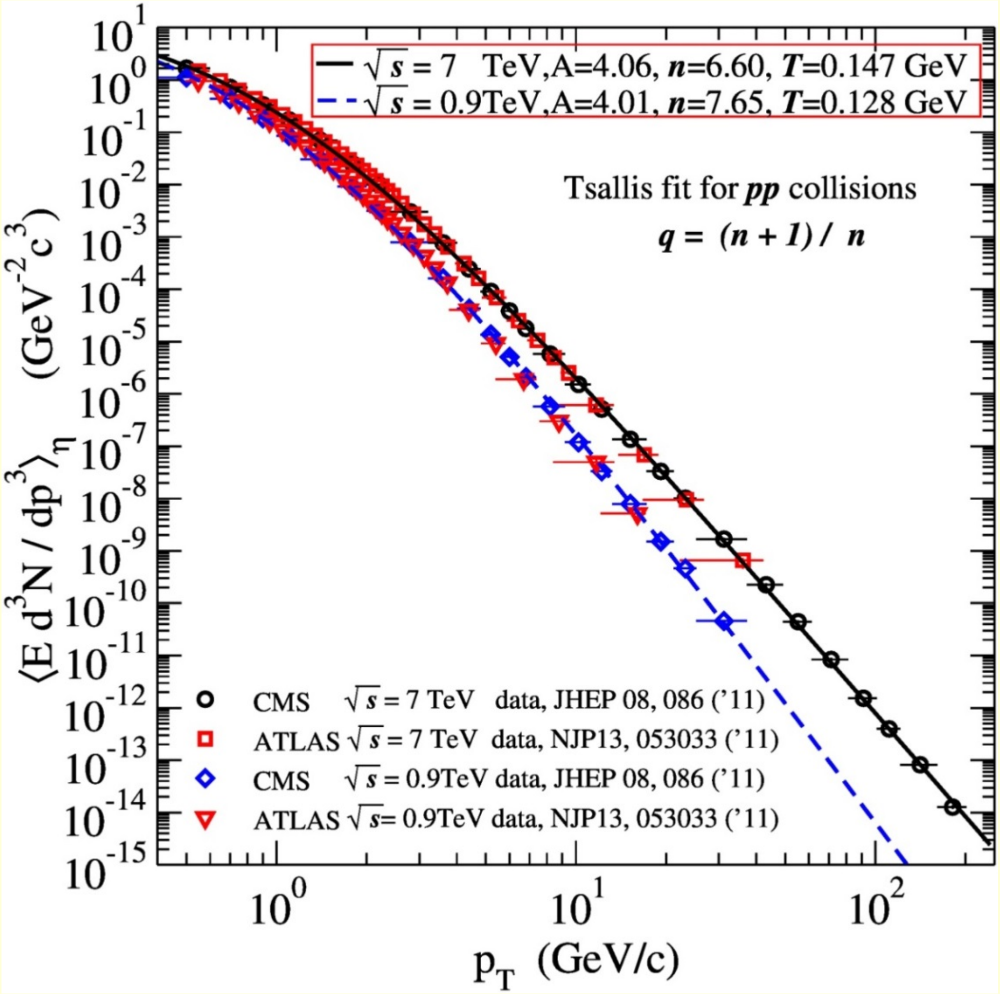


Comparison of the experimental data for hadron production in pp collisions at the LHC with the relativistic hard scattering model results (solid and dashed curves) (a) using Eq. (25), with a quadratic m_T dependence of the regulating function, and (b) using Eq. (24), with a linear m_T dependence of the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

How these results were obtained:

(*) Prompted by CMS fits recovered in our APPB43(2012)2047:

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



Good Tsallis fits have been obtained

for $\sqrt{s} = 7$ TeV, $n = 6.60$, $q = 1.15$

for $\sqrt{s} = 0.9$ TeV, $n = 7.65$, $q = 1.13$

Questions can be asked:

- 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 ?

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

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Parton Multiple Scattering:

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

However,

(*) 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).

Relativistic Hard Scattering Model:

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

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

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

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

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

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

The Power Index in Jet Production

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

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 $c \to p$ and introduce power index n

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

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

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

How to get n from data ?

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

$$\boldsymbol{\alpha}_s(\mathbf{Q}(\mathbf{c}_T)) = \frac{12\pi}{27\ln(C + Q^2/\Lambda^2_{QCD})},$$

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

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

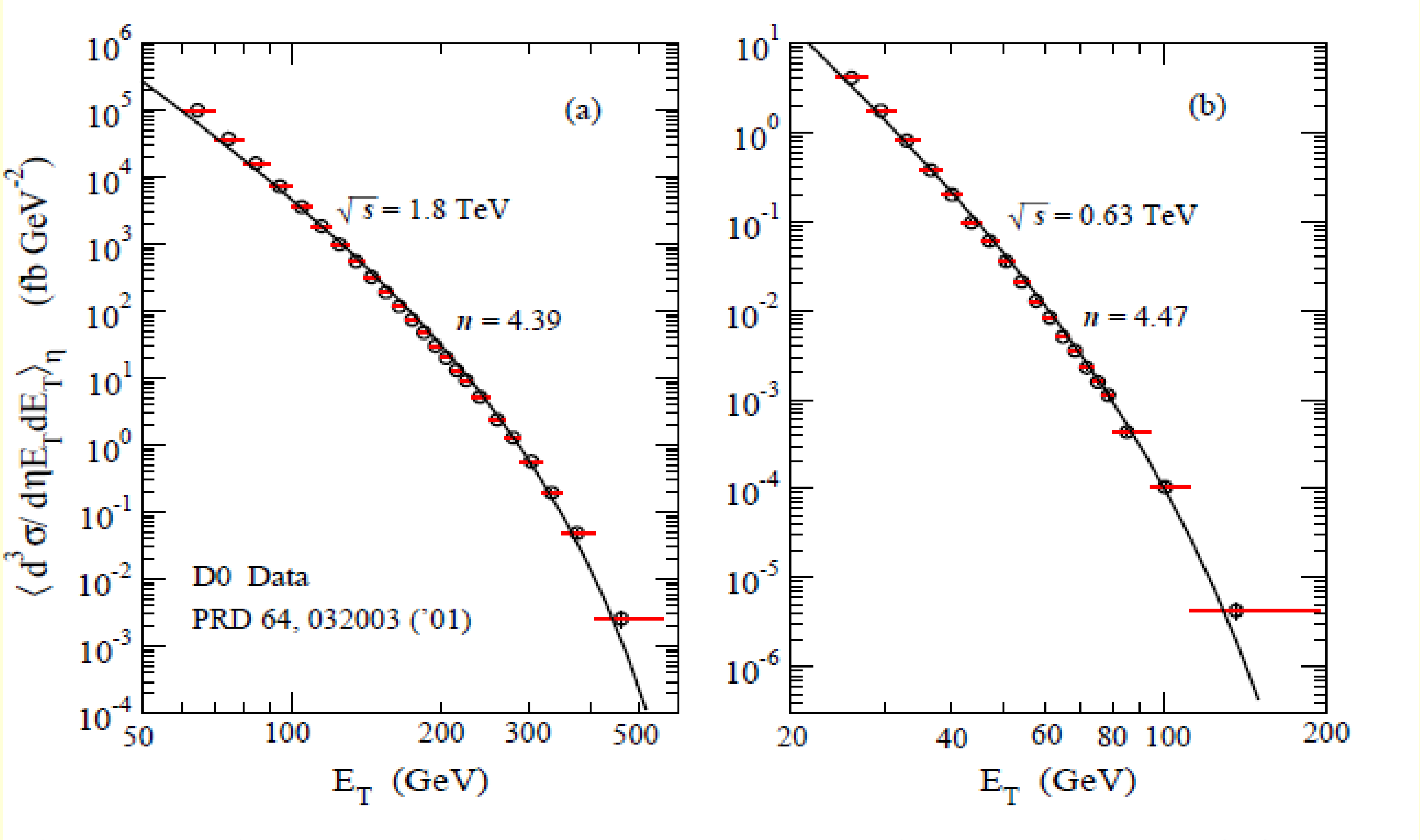
For $Q = c_T$ search for n by fitting experimental data at $\eta \approx 0$

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

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

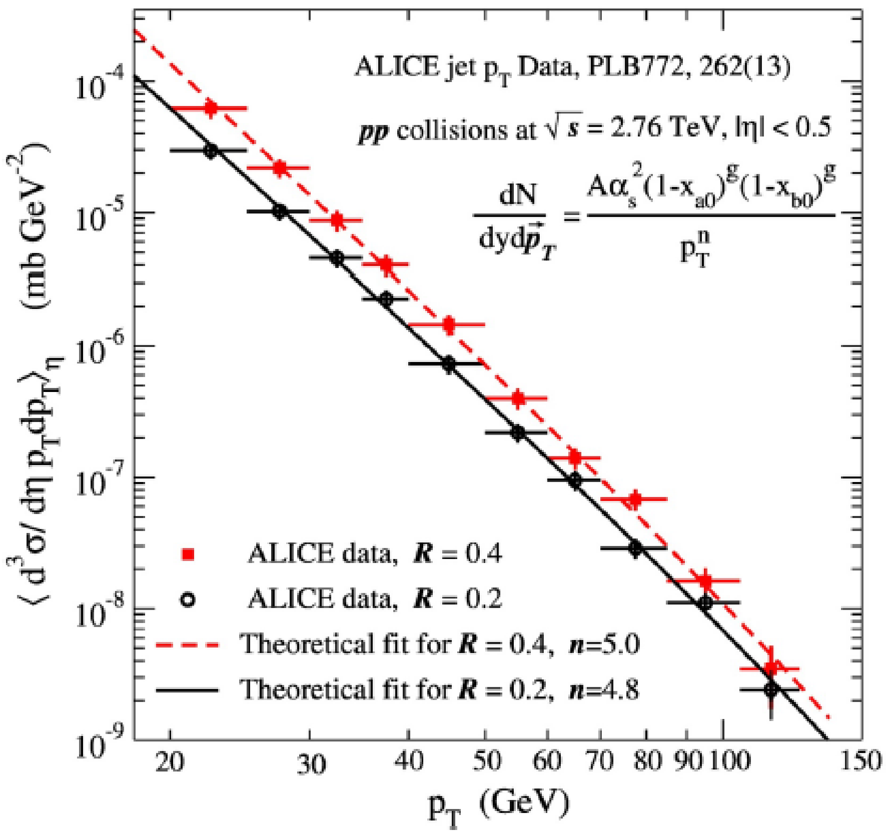
[17] C. Y. Wong, E. S. Swanson, and T. Barnes, Phy. Rev. C, 65, 014903 (2001).

Fits to D0 jet data

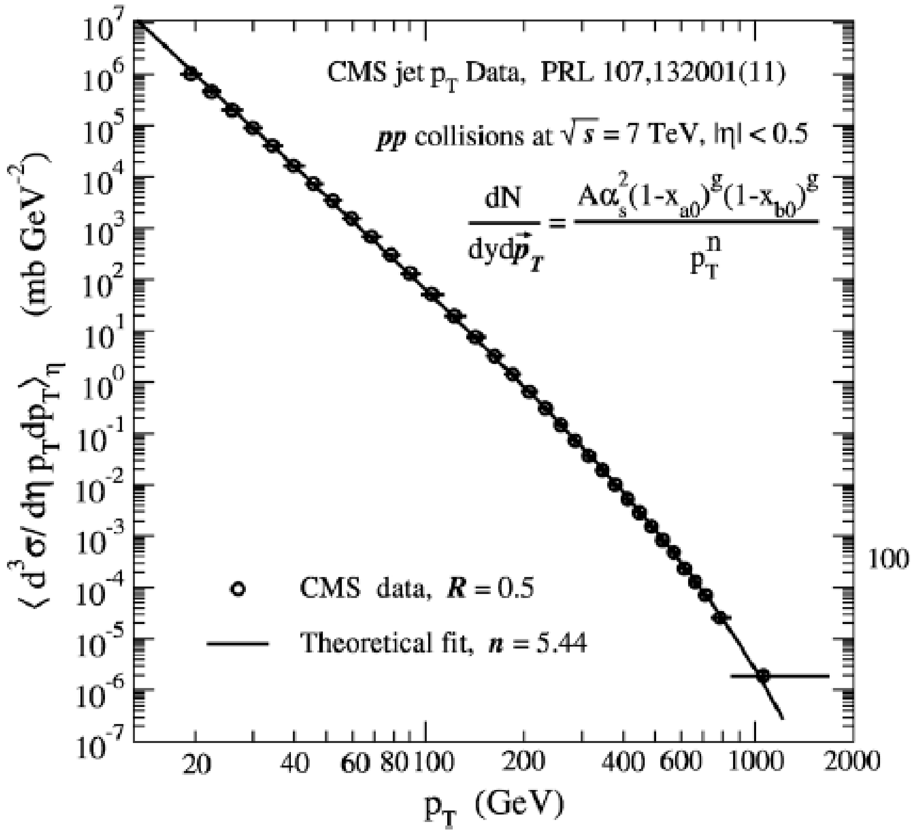


Comparison of the relativistic hard-scattering model results for jet production, Eq. (22) (solid curves), with experimental $d\sigma/d\eta\, E_T\, dE_T$ data from the D0 Collaboration, for hadron jet production within $|\eta|<0.5$, in $\bar{p}p$ collision at (a) $\sqrt{s}$=1.80 TeV, and (b) $\sqrt{s}$=0.63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

Fits to ALICE and CMS jet data



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	$\lvert\eta\rvert < 0.7$	4.39
D0	$\bar{p}p$ at 0.63 TeV	0.7	$\lvert\eta\rvert < 0.7$	4.47
ALICE	pp at 2.76 TeV	0.2	$\lvert\eta\rvert < 0.5$	4.78
ALICE	pp at 2.76 TeV	0.4	$\lvert\eta\rvert < 0.5$	4.98
CMS	pp at 7 TeV	0.5	$\lvert\eta\rvert < 0.5$	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

– one has to account for:

(i) showering (and/or fragmentation),

(ii) hadronization

Jet production →

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

.

hadrons

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

(*) 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 $\langle c_T \rangle = 2.3 p_T$

(*) The power law and power index are preserved under linear (p=zc) fragmentation

(*) 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 one can expect that

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

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 **c**$\to$ ***p***, the hard scattering cross section for $AB \to pX$ becomes:

$$\frac{\mathbf{d^3\sigma(AB \to pX)}}{\mathbf{dydp_T}} \propto \frac{\boldsymbol{\alpha}_\mathbf{S}^\mathbf{2}(\bar{\mathbf{c}}_\mathbf{T})(\mathbf{1} - \mathbf{x_{a0}}(\bar{\mathbf{c}}_\mathbf{T}))^{\mathbf{g_a}}(\mathbf{1} - \mathbf{x_{b0}}(\bar{\mathbf{c}}_\mathbf{T}))^{\mathbf{g_a}}}{\mathbf{p_T^{n'}}}$$

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

After all this one gets power-law behavior

but this is **not Tsallis formula**

because low p_T ibehaviour s not correct

$$\frac{d^3\sigma\left(AB \rightarrow pX\right)}{dy\,dp_T} \propto \frac{\alpha_S^2\left(\bar{c}_T\right)\left(1 - x_{a0}\left(\bar{c}_T\right)\right)^{g_a}\left(1 - x_{b0}\left(\bar{c}_T\right)\right)^{g_a}}{p_T^{n'}}$$

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

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 accordingly regularizing denominator,***

for example by using instead of:

$$\frac{d^3\sigma(AB \to pX)}{dy dp_T} \propto \frac{\alpha_S^2(\bar{c}_T)(1 - x_{a0}(\bar{c}_T))^{g_a}(1 - x_{b0}(\bar{c}_T))^{g_a}}{p_T^{n'}}$$

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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 accordingly regularizing denominator,

following formula:

$$\frac{d^3\sigma(AB \to pX)}{dy\,dp_T} \propto \frac{\alpha_S^2(\bar{c}_T)(1 - x_{a0}(\bar{c}_T))^{g_a}(1 - x_{b0}(\bar{c}_T))^{g_a}}{\left(1 + \frac{m_T}{m_{T0}}\right)^n}; \quad m_T = \sqrt{m^2 + p_T^2}$$

Notice:

that we have just assumed

the form of Tsallis/Hagedorn

formula showed at the beginning:

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

$$\frac{d^3\sigma(AB \to pX)}{dy\,dp_T} \propto \frac{\alpha_S^2(\bar{c}_T)\left(1 - x_{a0}(\bar{c}_T)\right)^{g_a}\left(1 - x_{b0}(\bar{c}_T)\right)^{g_a}}{\left(1 + \frac{m_T}{m_{T0}}\right)^n};\quad m_T = \sqrt{m^2 + p_T^2}$$

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)).

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

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

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

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

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

$$= \sqrt{1-\frac{m^2}{m_T^2\cosh^2 y}}\,A\,\alpha_S^2(\bar{\mathbf{c}}_{\mathbf{T}})\left(1-x_{a0}(\bar{\mathbf{c}}_{\mathbf{T}})\right)^{g_a}\left(1-x_{b0}(\bar{\mathbf{c}}_{\mathbf{T}})\right)^{g_a}\cdot$$

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

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

Looks like Tsallis

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$$=\sqrt{1-\frac{m^2}{m_T^2\cosh^2 y}}\,A\alpha_S^2(\bar{\mathbf{c}}_\mathbf{T})\left(1-x_{a0}(\bar{\mathbf{c}}_\mathbf{T})\right)^{g_a}\left(1-x_{b0}(\bar{\mathbf{c}}_\mathbf{T})\right)^{g_a}\cdot$$

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

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

… 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: $\quad p_T \to (m_{T0} + m_T)$

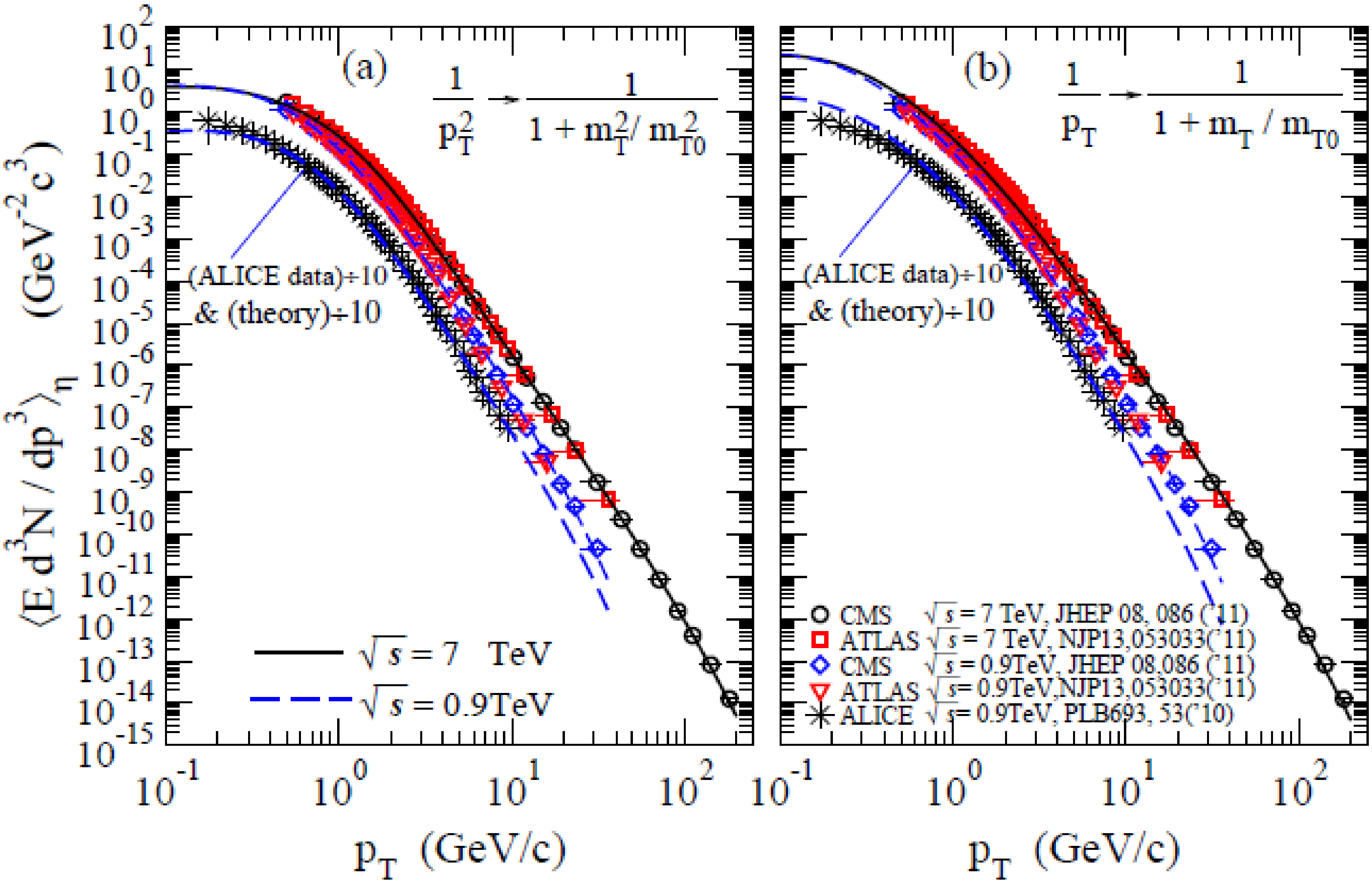
$$E_p \frac{d\sigma(AB \to pX)}{d^3p} = \frac{A\alpha_s^2(\bar{c}_T)\ (1-2x_c(\bar{c}_T))^g (1-2x_c(\bar{c}_T))^g}{(m_{T0}+m_T)^n}. \qquad (24)$$

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.

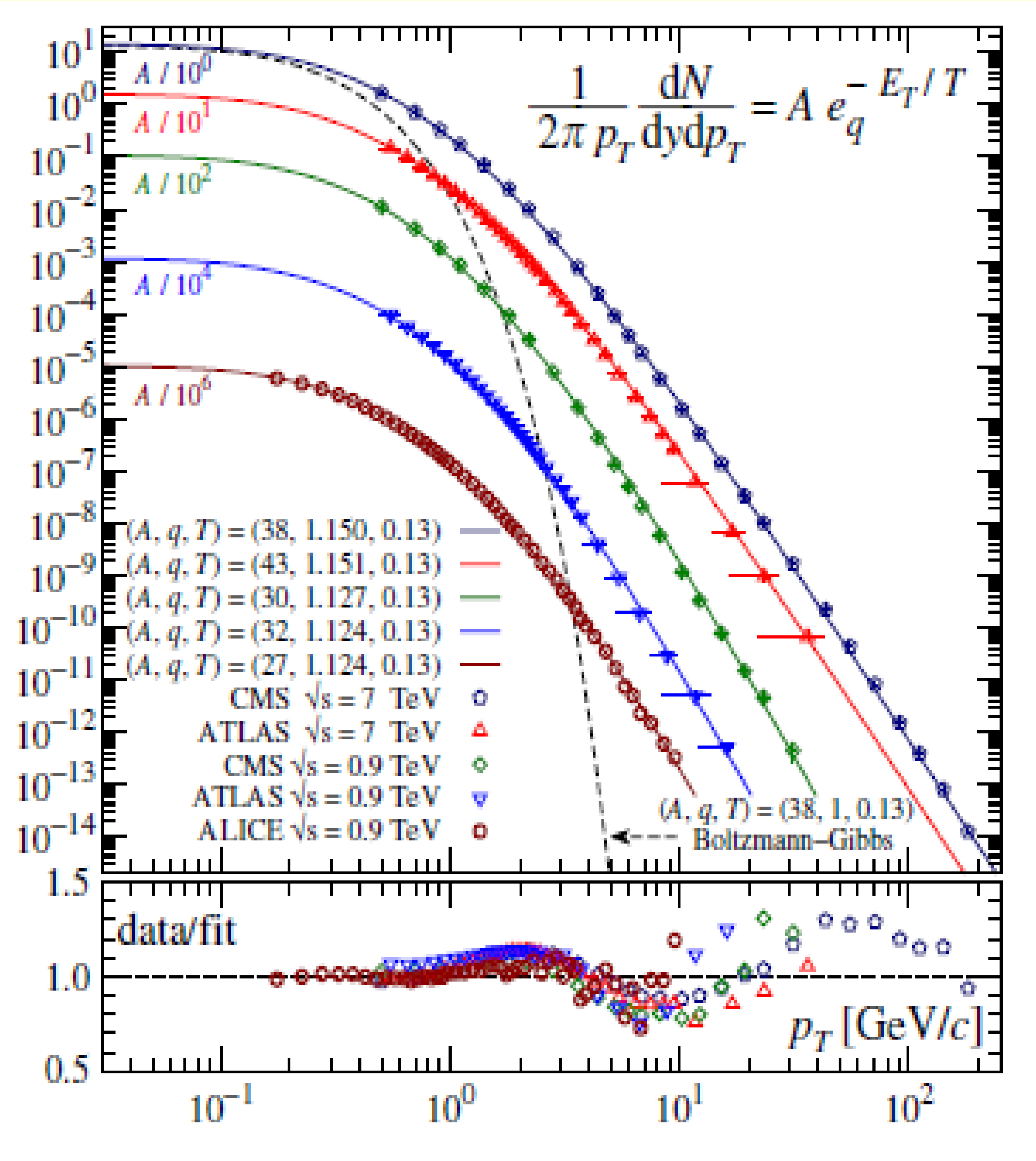
(*) Fragmentation and showering processes increase therefore slightly the value of the power index n of the transverse spectra.

To summarize this part:

- *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*
- *The success.of Tsallis fits to LHC high* $\boldsymbol{p_T}$ *spectra arises from the power law of jest production,* **~ $\boldsymbol{\alpha_S^2 / p_T^4}$,** *leading to* ***n=4.5***
- *Showering and hadronization increses* ***n*** *to* ***n~6****.*
- *Additionally,* $\boldsymbol{\alpha_S^2 (p_T)}$ *and* $\boldsymbol{(1\text{-}2x_C)^{2g}}$ *increases it furteher up to* ***~7.***

One Phenomenological Formula for Transverse Momentum Hadrons Produced at LHC?

Fits at midrapidity, one simple formula used, q~1.1, T=130 MeV (satisfactory compares with pion mass).



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$$e_q^z \equiv [1 + (1-q)\,z]^{1/(1-q)} \quad (e_1^z = e^z).$$

L.J.L.Cirto, C.Tsallis,
C-Y.Wong, G. Wilk, in preparation

(*) Transverse momentum spectrum from the very low energy regime of many tenths of a GeV to the very high energy regime of hundreds of GeV, in high-energy pp collisions at central rapidities, is characterized by a small number of degrees of freedom.

(*) However, one expects on physical grounds at least **three different physical** mechanisms contributing to the hadron production process:

- In the low p_T region at central rapidities **the mechanism of non-perturbative string-fragmentation** is expected to play an important role. In this mechanism, the hadron are produced from the string stretched between the colliding nucleon with a plateau structure in rapidity.

- In the low p_T region near the beam and target rapidities, **the mechanism of direct fragmentation** is expected to play a dominant role. In this mechanism, the produced hadron fragments directly from the nucleon without making a collision with the partons of the other colliding nucleon. The transverse spectrum then depends on the probability of the hadron fragmenting out of the nucleon.

- In the high p_T region, **the relativistic hard-scattering process** becomes important. In this mechanism, a parton from the projectile nucleon scatters elastically with a parton from the target nucleon, and the parton subsequently cascades and fragments into the produced hadrons.

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  In this mechanism, a parton from the projectile nucleon scatters elastically with a parton from the target nucleon, and the parton subsequently cascades and fragments into the produced hadrons. The transverse spectrum therefore depends on many factors, including the parton distribution in the nucleons, the parton-parton hard-scattering amplitude, the cascade and fragmentation of the scattered parton to the hadrons, as well as the running of the coupling constant, The three mechanisms mentioned above are expected to give rise to different shapes of the transverse distributions as they depend on the transverse momentum in different ways.

(*) The string fragmentation is associated with a flux tube and the transverse momentum distribution is limited by the flux tube dimension.

(*) The direct fragmentation is governed by the parton intrinsic p_T motion inside a nucleon and the gluon radiations

(*) The transverse momentum distribution in hard-scattering is governed by the law of parton-parton scattering, parton distribution, parton cascade, parton fragmentation, and the running of the coupling constant.

Therefore, one would normally expect that the three different production mechanisms will lead to different behaviors as functions of p_T , and there would consistently be a breakdown of a single description at some point of the complete spectrum.

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Therefore, one would normally expect that the three different production mechanisms will lead to different behaviors as functions of p_T , and there would consistently be a breakdown of a single description at some point of the complete spectrum.

apparently, nothing of this kind is observed !

What interestingly emerges:

(*) the good agreement of the present phenomenolocal fit extends to the whole p_T region where reliable experimental data are available.

(*) It is achieved with very few free parameters what implies the simplicity of the underlying structure and the dominance of one of the three mechanisms over virtually the whole p_T range in the central rapidity region.

(*) It is reasonable to consider the dominant mechanism to be the hard-scattering process because the other two mechanisms are unlikely to produce hadrons with high $p_{T.}$ Moreover, the dominance of hard-scattering also for the production of low-p_T hadron in the central rapidity region is supported by two-particle correlation data where the two-body correlations in minimum p_T biased data reveals that a produced hadron is correlated with a „ridge" of particles along a wide range of on the azimuthally away side centering around $\varphi=\pi$.

(*) While the basic hard-scattering process is relatively simple in the jet production level, there are many layers of stochastic processes in the production of hadrons from jets which mask this simplicity. The hard-scattering process exhibits the power-law behavior of the transverse momentum in its basic framework for jet production However, many other stochastic elements are involved in this process which definitively increase its complexity.

(*) It seems to be reasonable to assume, in the lowest-order description, a „no-hair" hypothesis of a statistical-mechanical approach for the transverse-momentum distribution in the p_T region above 0.5 GeV/c.

(*)The hadron production process appears to be well characterized by a single-particle statistical-mechanical description of QCD quanta in an relativistic d = 2 system.

(*) All other information about the produced hadron matter, such as the parton distribution, the hard-scattering mechanism of jet production, jet-parton cascade process followed by parton fragmentation, and the intermediary possible quark-gluon plasma, „disappear" behind the stochastic process.

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Tentative conclusions:

(*) What emerges from the analysis of the data in high-energy pp collisions is that the good agreement of the phenomenological fit of a single component extends to the whole p_T region.

(*) The few degrees of freedom implies the final simplicity of the underlying structure and the dominance of only one of the three (or more?) possible mechanisms over the whole range of p_T in the central rapidity region.

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Thank you