Tsallis fitting of the CMS data

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Introduction

- p-p analyses
  - spectra of charged hadrons in p-p at $\sqrt{s} = 0.9$, 2.36, and 7 TeV
    JHEP 02 (2010) 041 Phys Rev Lett 105 (2010) 022002
  - spectra of charged hadrons in p-p up to high p_T at $\sqrt{s} = 0.9$ and 7 TeV
    JHEP 08 (2011) 086
  - spectra of identified neutral hadrons in p-p at $\sqrt{s} = 0.9$ and 7 TeV
    JHEP 05 (2011) 064
  - spectra of identified charged hadrons in p-p at $\sqrt{s} = 0.9$, 2.76, and 7 TeV
    Eur Phys J C 72 (2012) 2164

- Why Tsallis?
  - empirically describes both the low-p_T exponential
    and the high-p_T power-law behaviors
  - flexible enough, still with only two parameters
  - has a physics-motivated origin

All shown results are from **p-p collisions**

Tsallis-Pareto-type distributions

By now a well known functional form, success at RHIC – LHC:

$$\frac{d^2N}{dy dp_T} = \frac{dN}{dy} \cdot C \cdot p_T \left[1 + \frac{(m_T - m)}{nT}\right]^{-n}$$

where

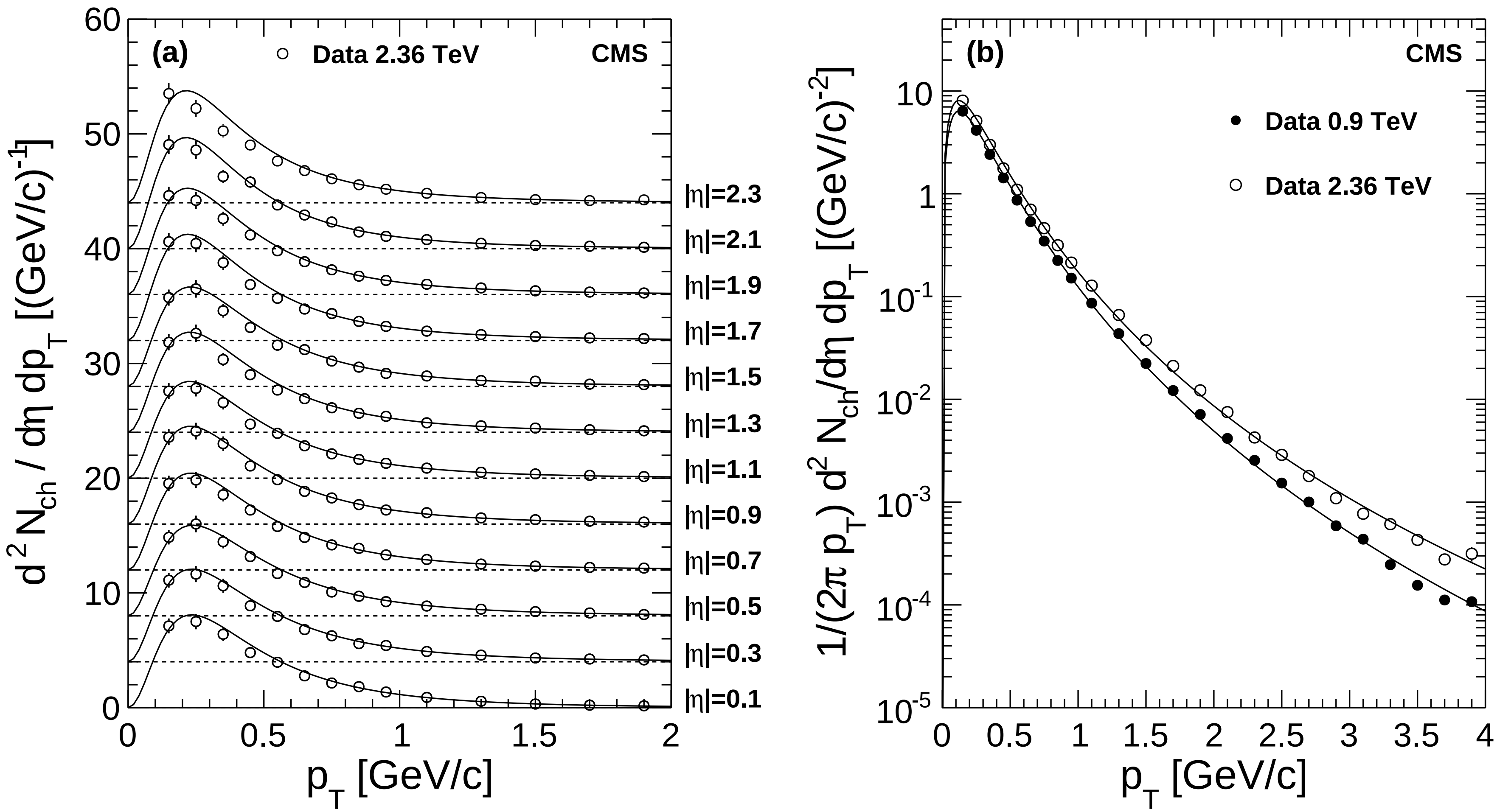
$$C = \frac{(n-1)(n-2)}{nT[nT + (n-2)m]}, \qquad m_T = \sqrt{m^2 + p_T^2}.$$

With roots in non-extensive statistics; a Lévy function

n – exponent, T – inverse slope parameter, m – particle mass
$\langle p_T \rangle$ is calculable with Monte Carlo integration

– T is determined by the low p_T part, while n is by the tail
– n and T can be highly correlated, especially if we don't have enough p_T range

Results – charged hadrons

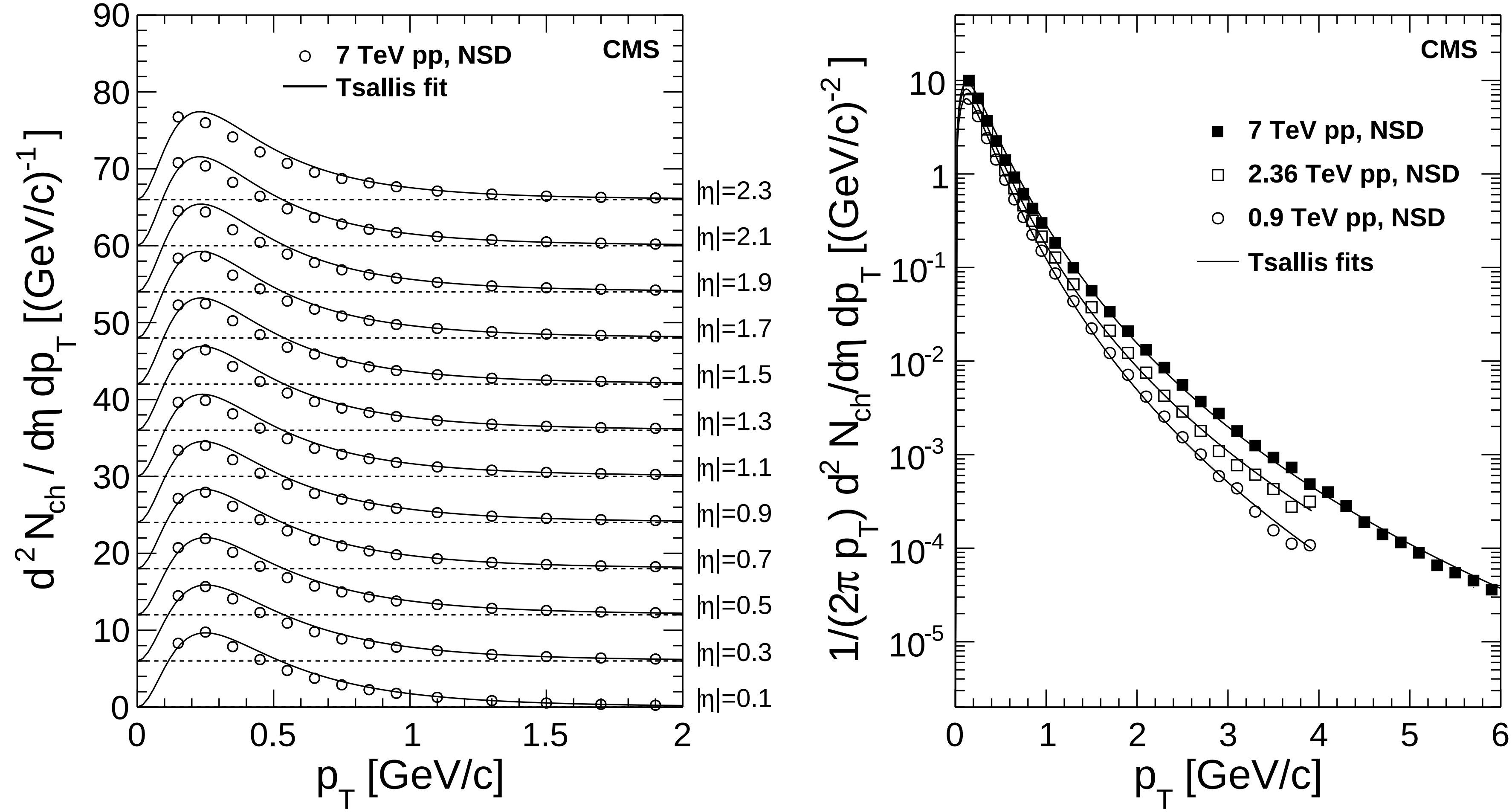


Unidentified charged hadrons, both charges

Fits in narrow $|\eta|$ bins at 0.9 and 2.36 TeV

Good fits

Results – charged hadrons



Unidentified charged hadrons, both charges

Right plot, p-p at 0.9, 2.36, and 7 TeV

Results – charged hadrons

$$E\frac{d^3N_{\rm ch}}{dp^3} = \frac{1}{2\pi p_T}\frac{E}{p}\frac{d^2N_{\rm ch}}{d\eta dp_T} = C(n,T,m)\frac{dN_{\rm ch}}{dy}\left(1+\frac{E_T}{nT}\right)^{-n}$$

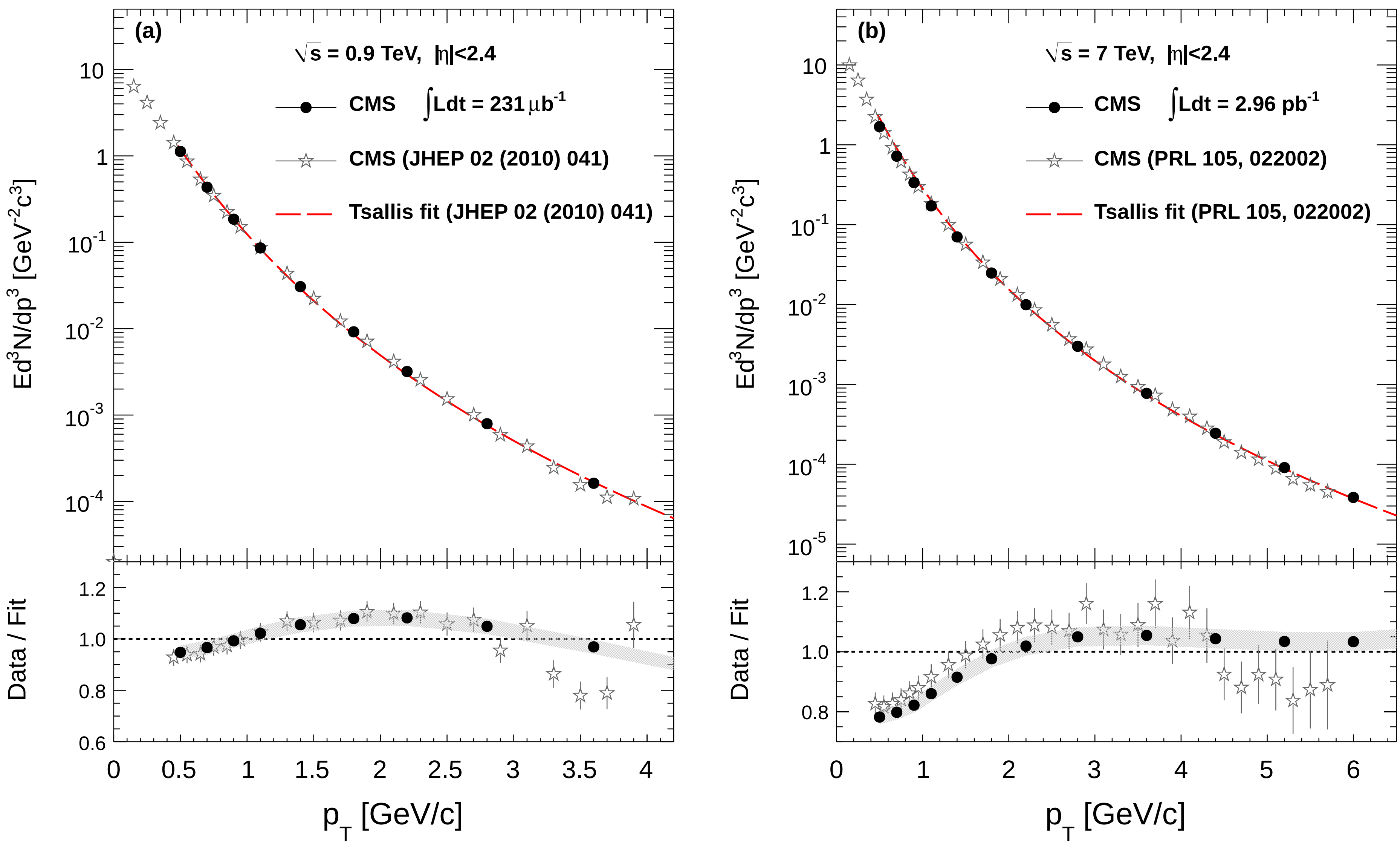
$$E_{\rm T} = \sqrt{m^2+p_{\rm T}^2} - m$$

The (y, p_T) plan was transformed to (η, p_T), taking m the charged pion mass

0.9 TeV	T $= 0.13 \pm 0.01$	GeV	n $= 7.7 \pm 0.2$
2.36 TeV	T $= 0.14 \pm 0.01$	GeV	n $= 6.7 \pm 0.2$
7 TeV	T $= 0.145 \pm 0.005$	GeV	n $= 6.6 \pm 0.2$

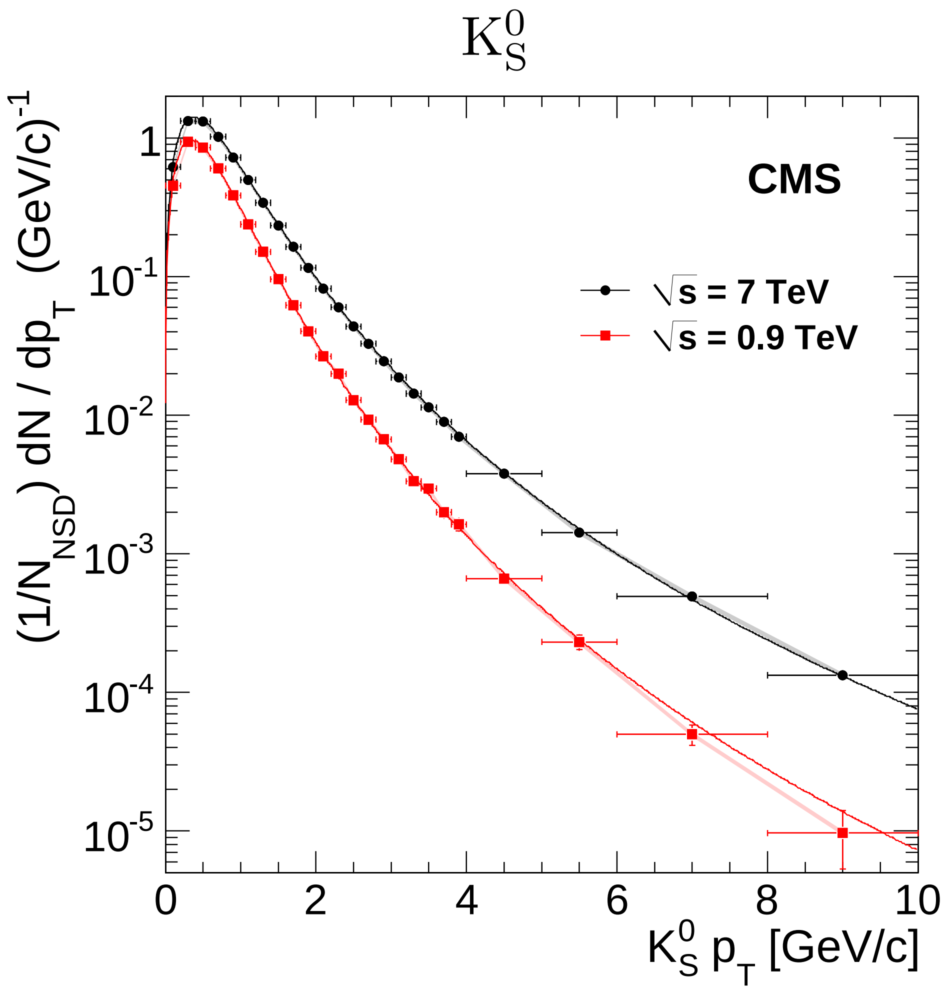
Slow evolution with $\sqrt{s}$

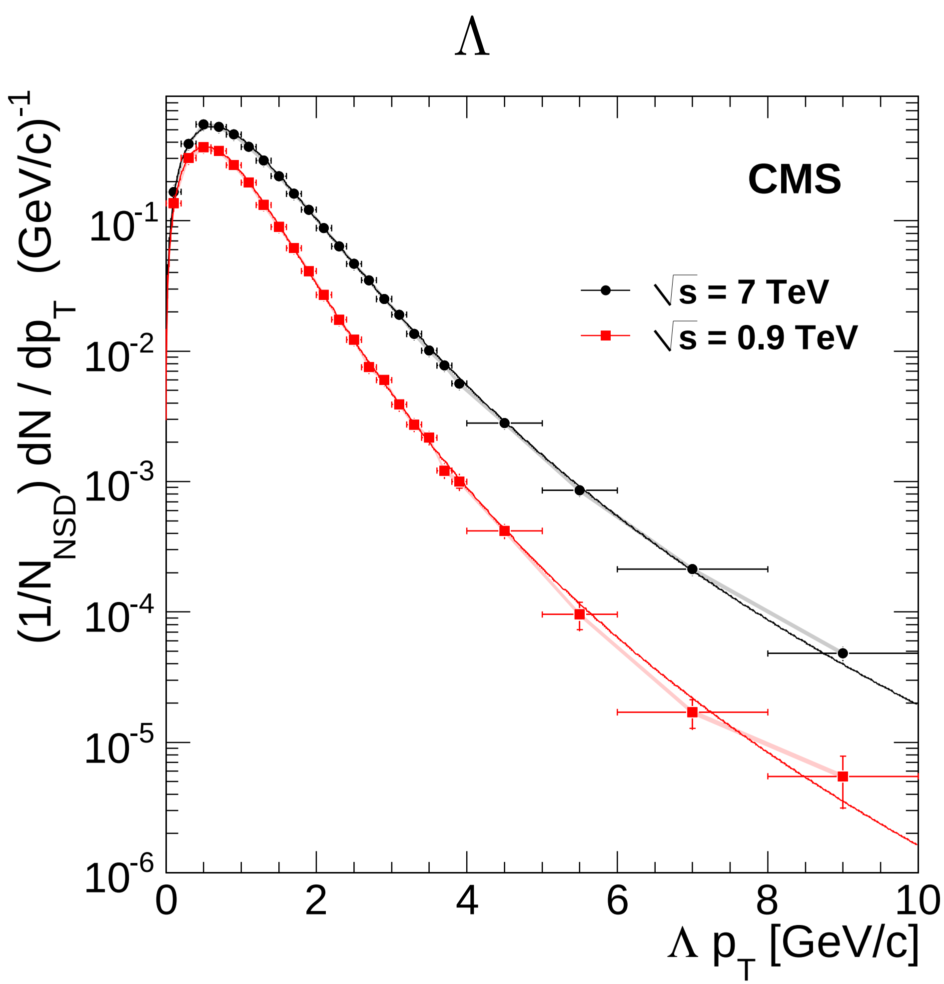
Results – high-p_T charged hadrons



Comparison; good match with the Tsallis fit obtained for $p_T \approx 0 - 4$ GeV/c

Results – strange hadrons



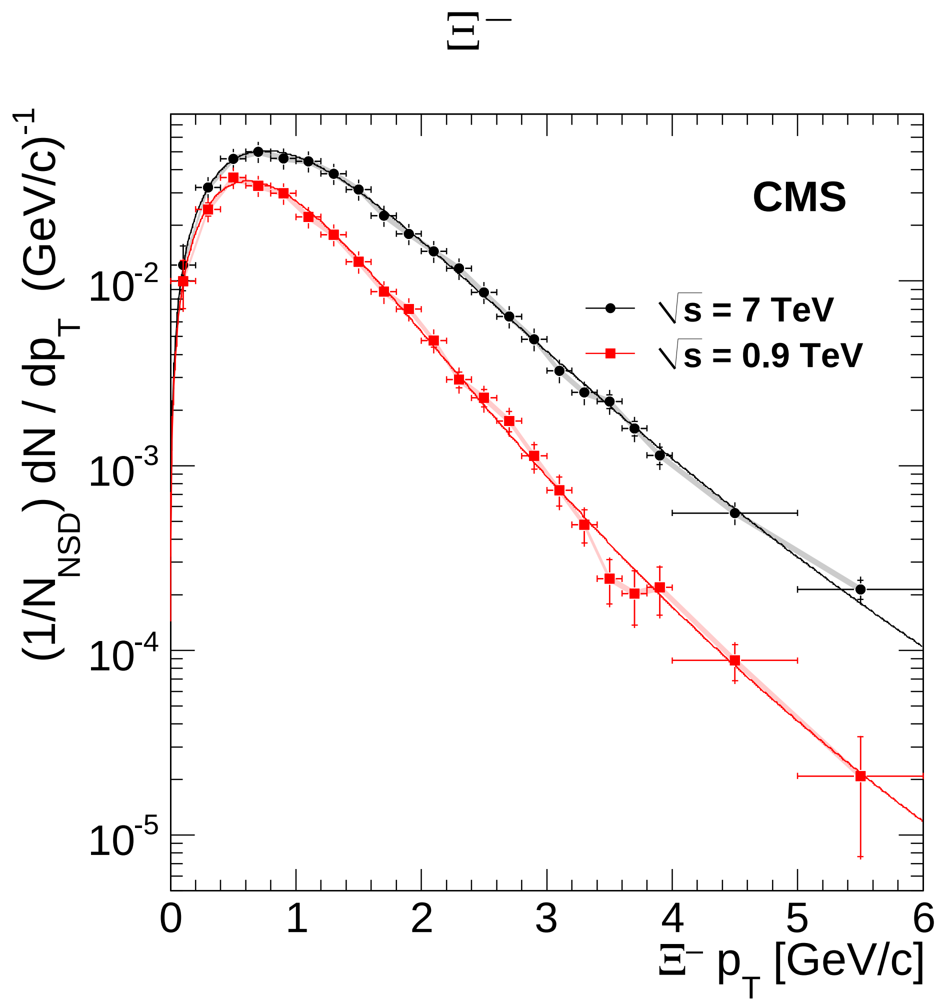


Particle production per NSD event

The (correlated) normalization uncertainty is shown as a band

Good fits to most of the samples

Results – strange hadrons



Particle production per NSD event

The (correlated) normalization uncertainty is shown as a band

Results – strange hadrons

$$\frac{1}{N_{\mathrm{NSD}}}\frac{dN}{dp_{\mathrm{T}}} = C\frac{(n-1)(n-2)}{nT[nT+m(n-2)]}p_{\mathrm{T}}\left[1+\frac{\sqrt{p_{\mathrm{T}}^2+m^2}-m}{nT}\right]^{-n}$$

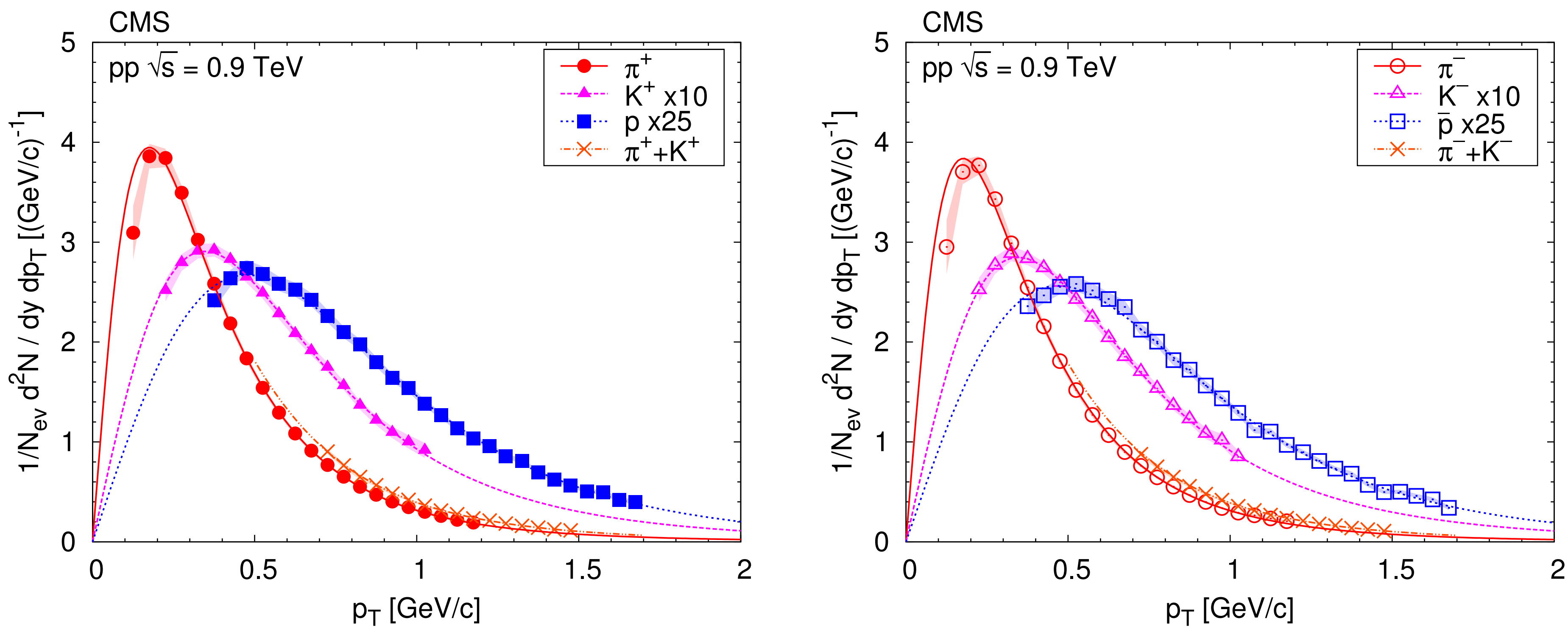
Particle	$\sqrt{s}$ (TeV)	C	T (MeV)	n	χ^2/NDF
$\mathrm{K^0_S}$	0.9	$0.776 \pm 0.002 \pm 0.042$	$187 \pm 1 \pm 4$	$7.79 \pm 0.07 \pm 0.26$	19/21
Λ	0.9	$0.395 \pm 0.002 \pm 0.041$	$216 \pm 2 \pm 11$	$9.3 \pm 0.2 \pm 1.1$	32/21
Ξ^-	0.9	$0.043 \pm 0.001 \pm 0.006$	$250 \pm 8 \pm 48$	$10.1 \pm 0.9 \pm 4.7$	19/19
$\mathrm{K^0_S}$	7	$1.329 \pm 0.001 \pm 0.062$	$220 \pm 1 \pm 3$	$6.87 \pm 0.02 \pm 0.09$	50/21
Λ	7	$0.696 \pm 0.002 \pm 0.058$	$292 \pm 1 \pm 10$	$9.3 \pm 0.1 \pm 0.5$	128/21
Ξ^-	7	$0.080 \pm 0.001 \pm 0.012$	$361 \pm 7 \pm 72$	$11.2 \pm 0.7 \pm 4.9$	21/19

Table 2. Results of fitting the Tsallis function to the data. In the C, T, and n columns, the first uncertainty is statistical and the second is systematic. The parameter values and χ^2/NDF are obtained from fits to the data with only the statistical uncertainty included.

T increases with particle mass and centre-of-mass energy

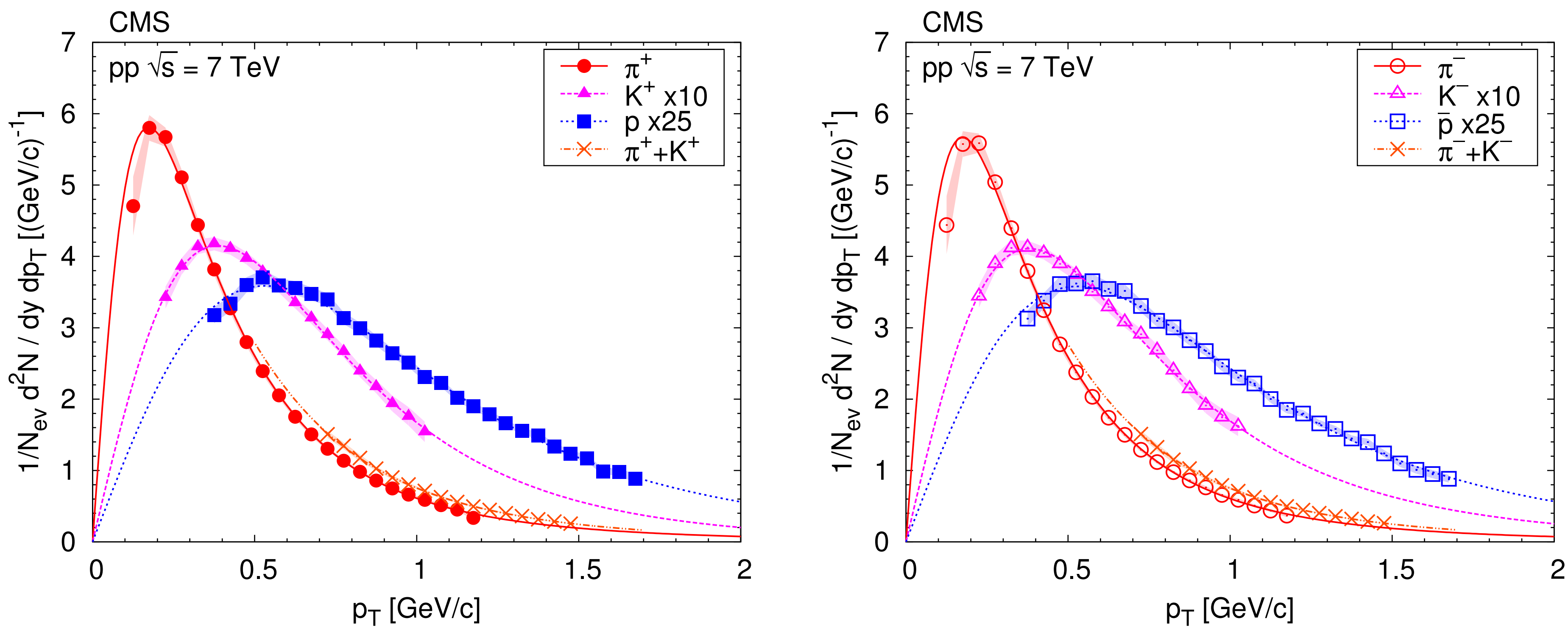
Much steeper fall off (n) for the two baryons than for the $\mathrm{K^0_S}$

Results – $\pi/\mathrm{K}/\mathrm{p}$ spectra



Results are corrected to a double-sided selection (DS):
at least one particle with E $>$ 3 GeV on both sides
$(-5 < \eta < -3$ and $3 < \eta < 5)$

Results – $\pi/\mathrm{K}/\mathrm{p}$ spectra

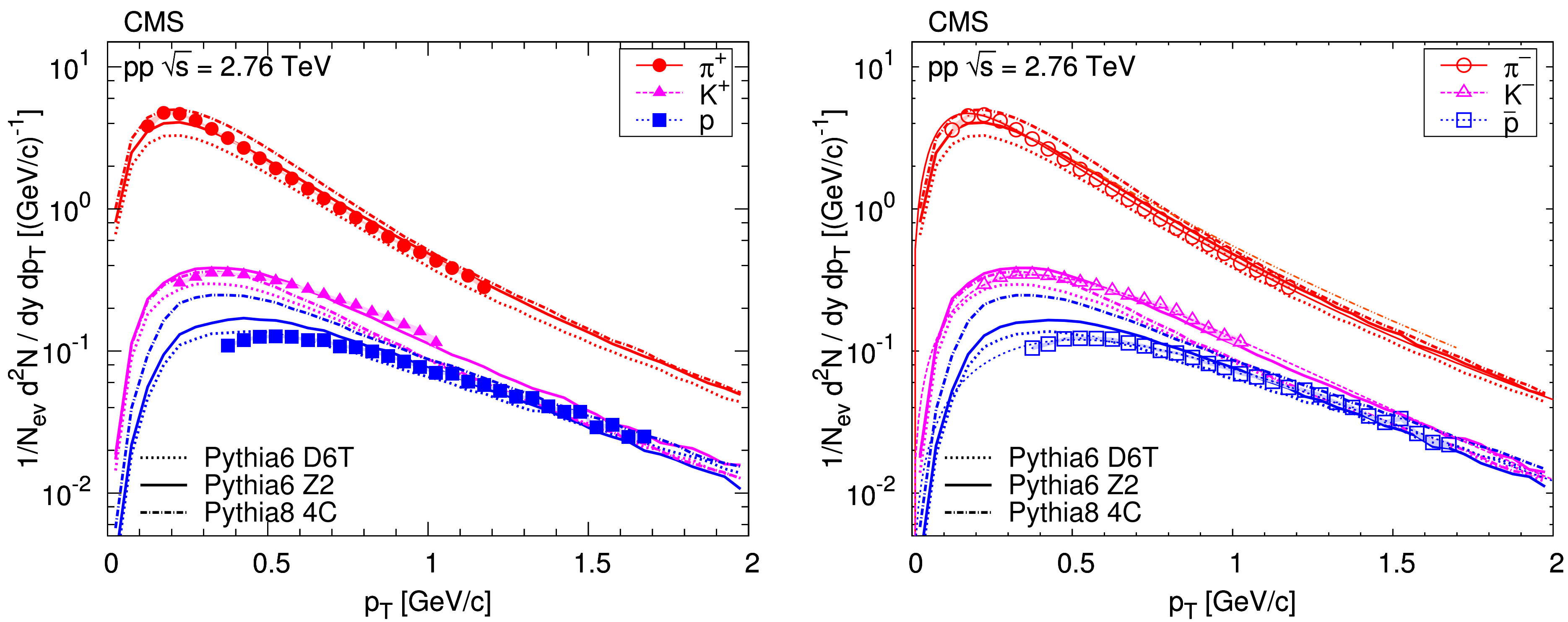


The fits are usually of good quality

With $\chi^2/$ndf values in the range 0.6-1.5 for pions, 0.6-2.1 for kaons, and 0.4-1.1 for protons

Some deviations for the lowest-p_T pions

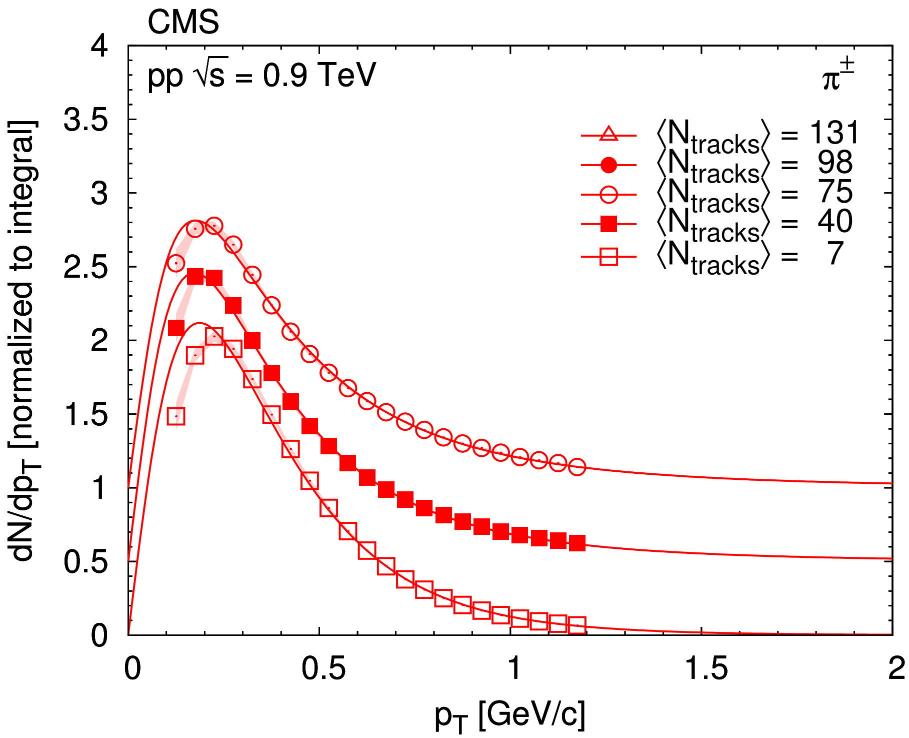
Results – $\pi/\mathrm{K}/\mathrm{p}$ spectra

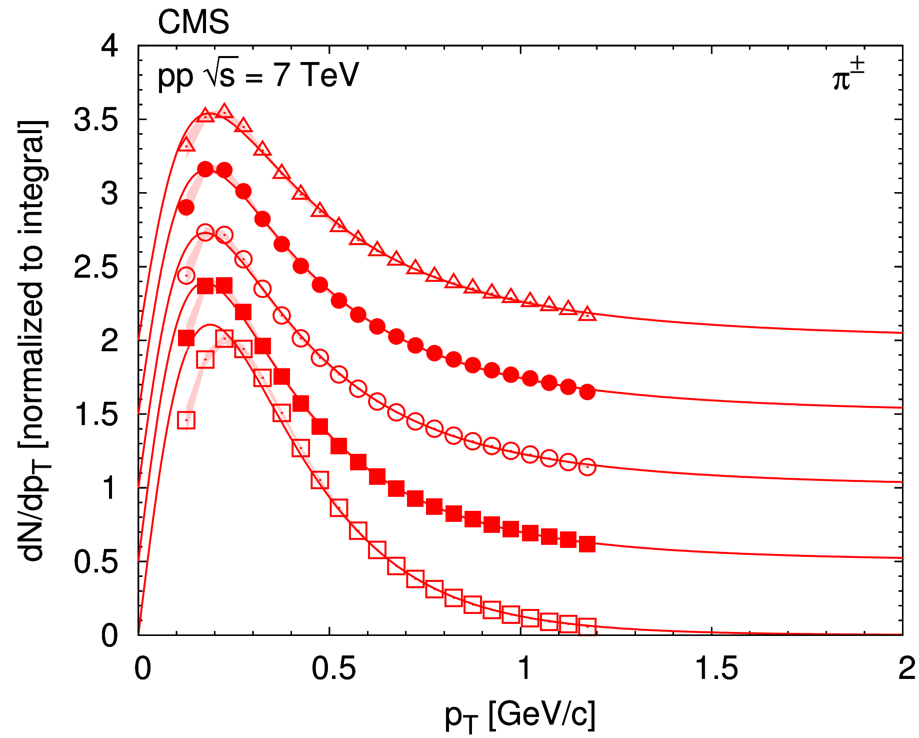


Logarithmic scale, comparison to models

Pythia6 D6T and Pythia8 4C tend to systematically under/overshoot the spectra
Pythia6 Z2 is generally closer to the measurements (except for low-p_T protons)

Results – multiplicity dependence – pions



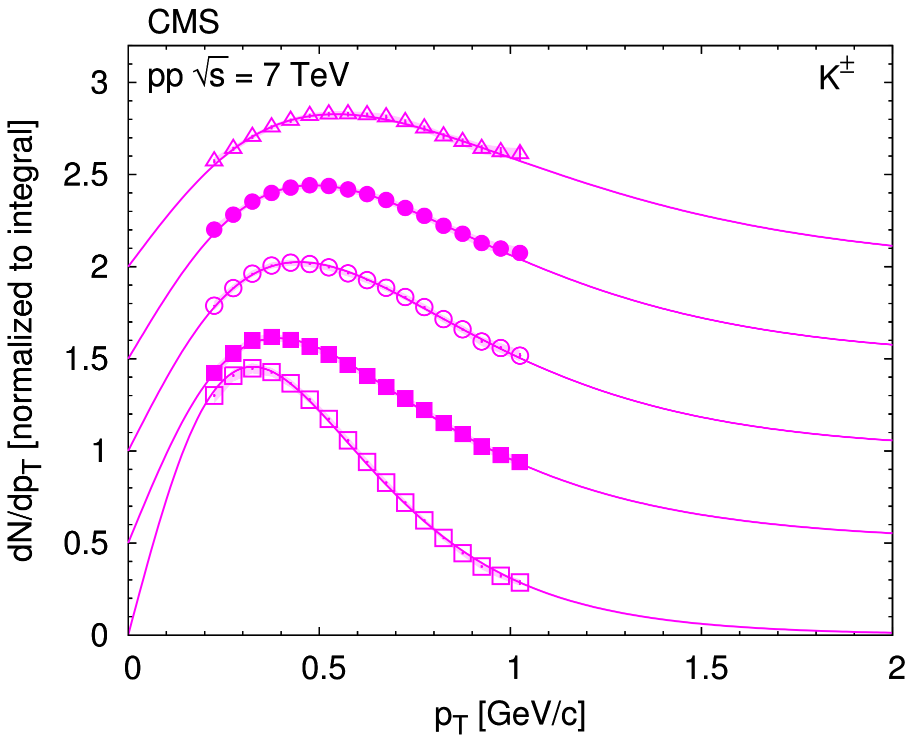


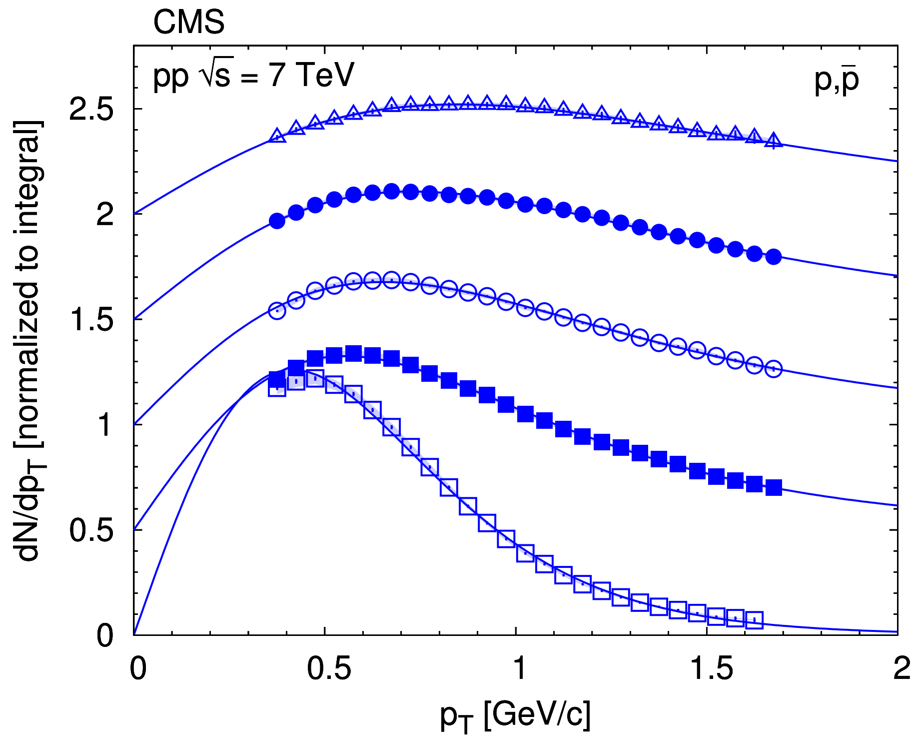
Multiplicity classes: relate measured N_{rec} to true $\langle N_{\text{tracks}} \rangle$ in $|\eta| < 2.4$

N_{rec}	0-9	10-19	20-29	30-39	40-49	50-59	60-69	70-79	80-89	90-99	100-109	110-119
$\langle N_{\text{tracks}} \rangle$	7	16	28	40	52	63	75	86	98	109	120	131

Shapes?

Results – multiplicity dependence – kaons and protons





Harder spectral shape with increasing multiplicity

Increasing $\langle p_T \rangle$ with increasing multiplicity

Summary

- CMS and Tsallis
  - Fits from very low to high p_T with only two parameters (T and n)
  - Used in all p-p spectra analyses

- Why so successful?
  - many applications in the natural and social sciences
  - physics origins? non-extensivity?
  - maybe the fractal structure and dynamic nature of particle production?
  - in p-p collisions the phase-space has to be filled with particles in a very short time