# Multiplicity Dependence of Non-extensive Parameters for Strange and Multi-Strange Particles in Proton-Proton Collisions at $\sqrt{s}$ = 7 TeV at the LHC

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*(Based on ALICE Nature Physics(2017))*

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# OUTLINE

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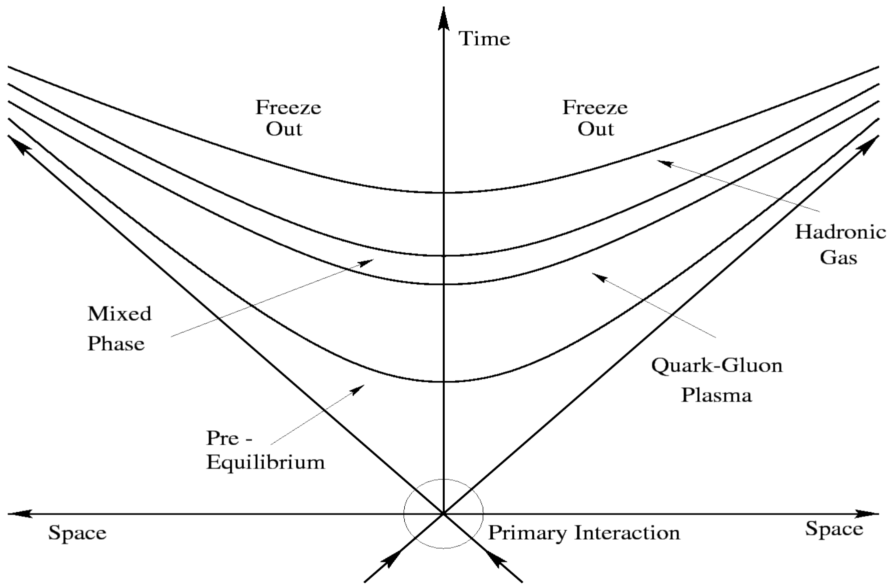
- Motivation
- Tsallis Non-extensive statistics in high energy collisions
- Particle Spectra in high energy collisions
- Multiplicity  dependence of thermodynamic parameters
- Summary

# Introduction

High energy collision → QGP → Hadron




- **Transverse momentum spectra of hadrons are important tools to understand the dynamics of high energy collisions.**

- **The produced hadrons from the collisions may carry information about the collision dynamics and the subsequent space-time evolution of the system till the occurrence of the final freeze-out.**

# Motivation

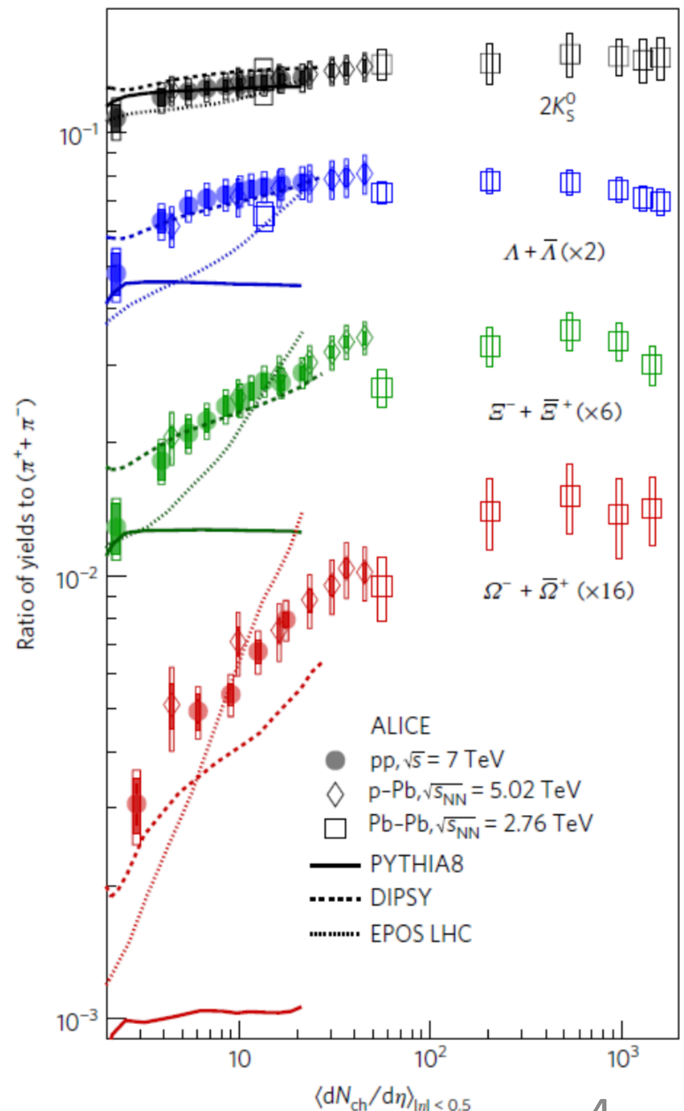
## Why is high multiplicity pp interesting?

- **Probability to have more than one hard scattering is more → leads to high multiplicity**

**Recent results in pp:**
In high-multiplicity events strangeness production reaches values similar to those observed in Pb–Pb collisions, where a QGP is formed [1] .

- **Does the high multiplicity lead to thermalisation in pp collisions?**

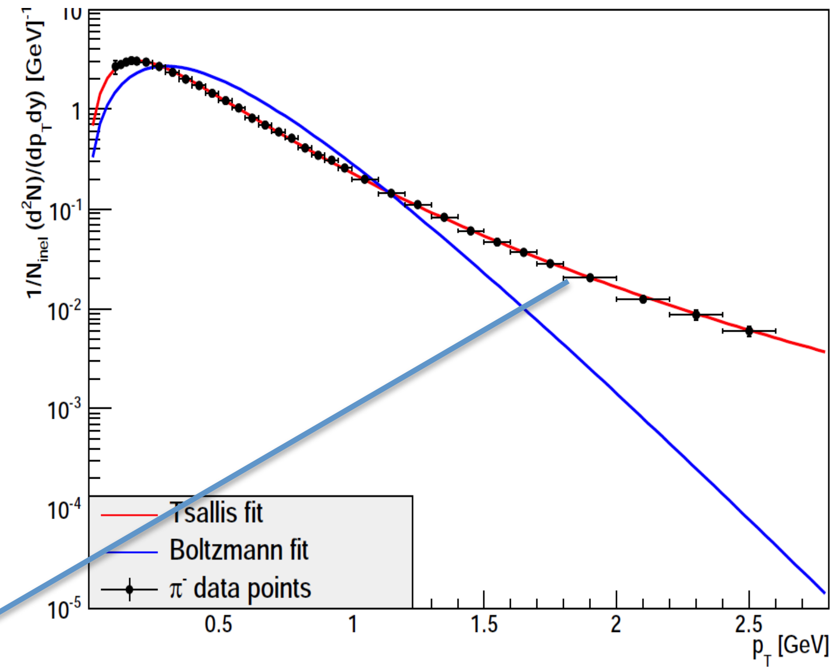
[1] Nature Physics 13, 535–539 (2017)



# Transvers Momentum Spectra in High Energy Collisions

- **Long back a statistical description of transverse momenta of final state particles produced in high energy collision have been proposed to follow a thermalized Boltzmann type of distribution**

$$E\frac{d^3\sigma}{d^3p} \simeq C\exp\left(-\frac{p_T}{T}\right).$$

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- **Experiments at RHIC and LHC observe non-exponential behavior at large transverse momenta**

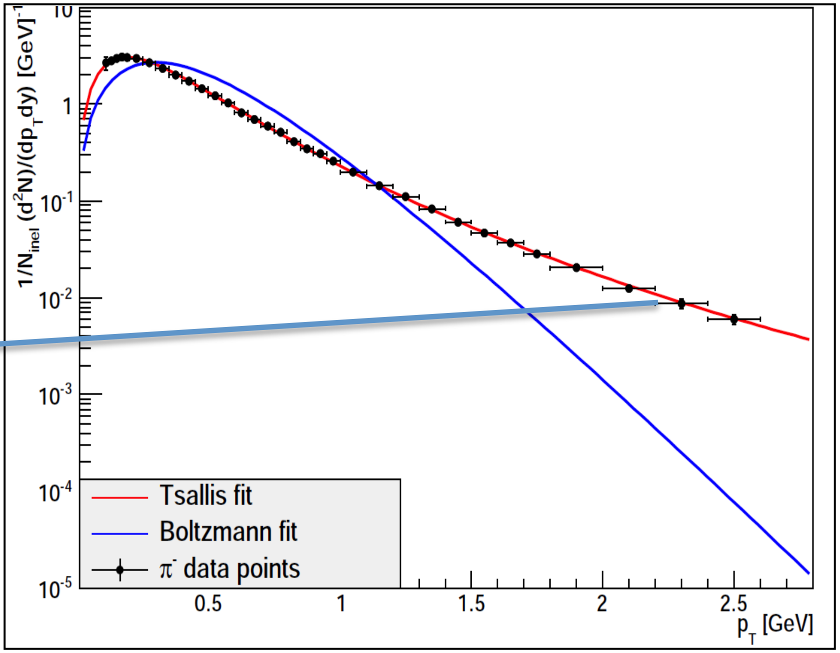
# Transverse Momentum Spectra in High Energy Collisions

To account for this non-exponential behaviour, Hagedorn proposed an empirical formula which is given by,

$$E\frac{d^3\sigma}{d^3p} = C\left(1+\frac{p_T}{p_0}\right)^{-n} \longrightarrow \begin{cases} \exp\left(-\frac{np_T}{p_0}\right) & \text{for } p_T \to 0, \\ \left(\frac{p_0}{p_T}\right)^{n} & \text{for } p_T \to \infty, \end{cases}$$

However, the Tsallis formula based on non-extensive entropy, accounts for the high-energy behaviour of the observed spectra and is given by,

$$f(p_T) = C_q\left[1+(q-1)\frac{p_T}{T}\right]^{-\frac{1}{q-1}}$$

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# The Tsallis Non-extensive Statistics

The thermodynamically consistent Tsallis-Boltzmann distribution function is given by,

$$f = \left[1 + (q-1)\frac{E-\mu}{T}\right]^{-\frac{1}{q-1}} \xrightarrow{(q \to 1)} e^{-(E-\mu)/T}$$

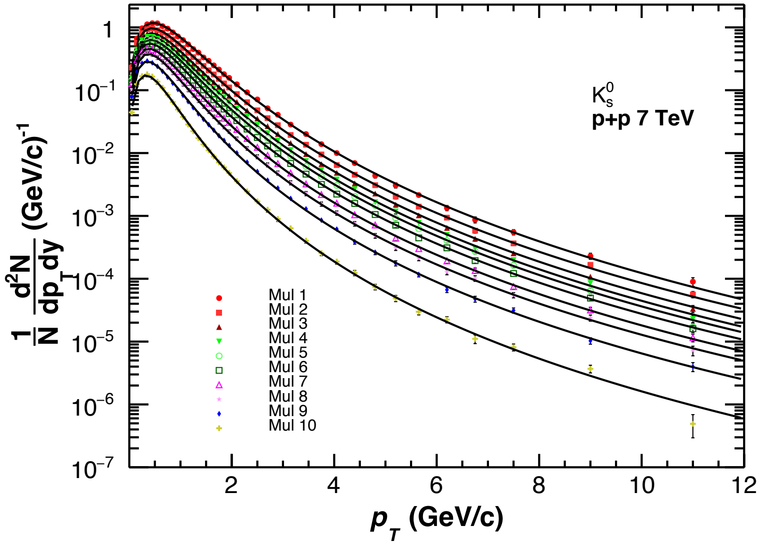
The invariant yield at mid-rapidity is given by,

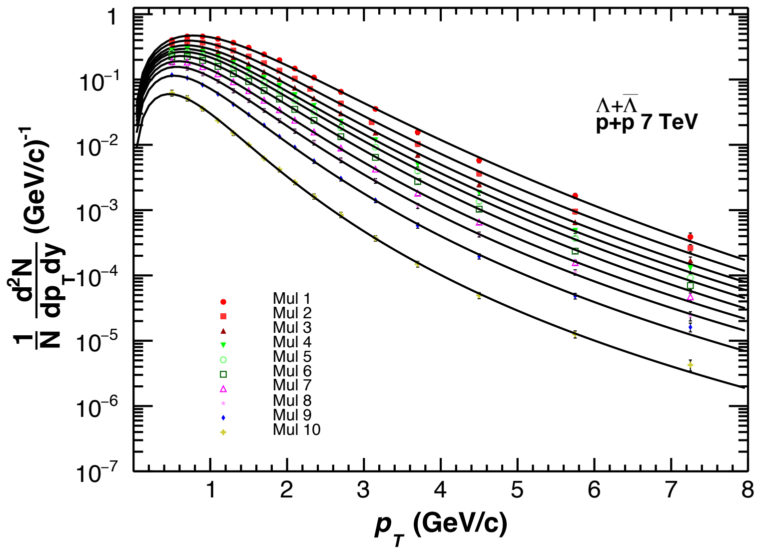
$$\left.\frac{1}{p_T}\frac{d^2N}{dp_T dy}\right|_{y=0} = \frac{gVm_T}{(2\pi)^2}\left[1 + (q-1)\frac{m_T - \mu}{T}\right]^{-\frac{q}{q-1}}$$

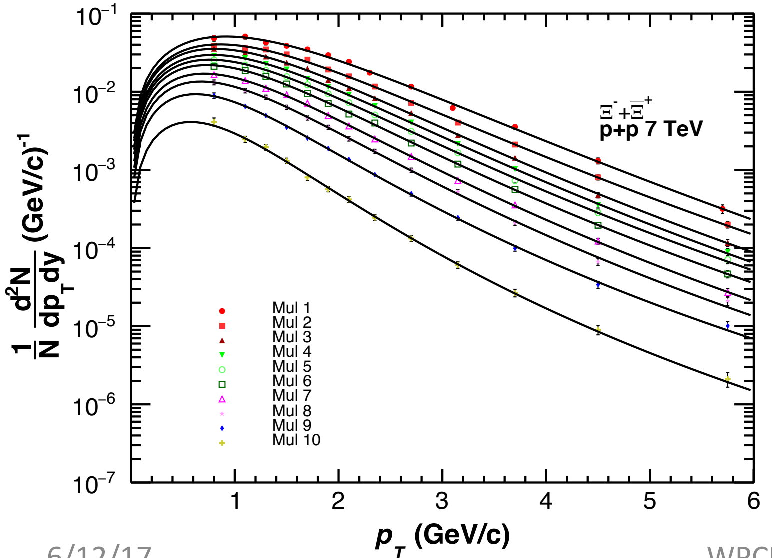
at LHC energies μ~0, so the invariant yield becomes

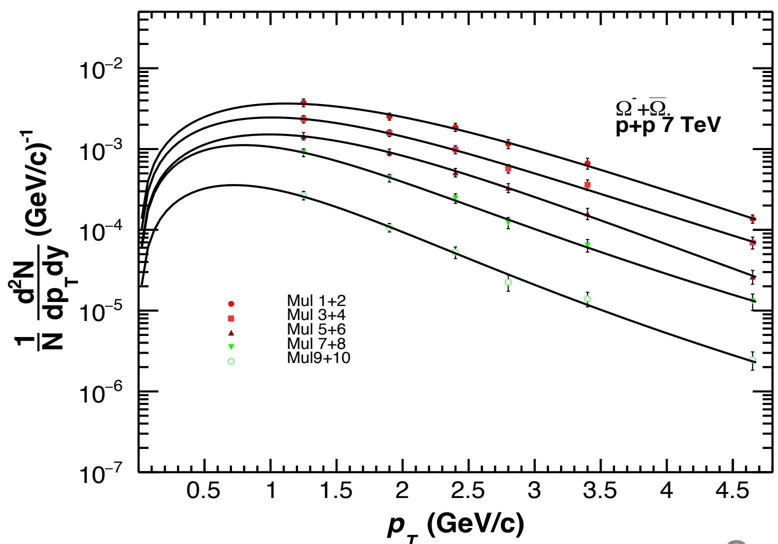
$$\left.\frac{1}{p_T}\frac{d^2N}{dp_T dy}\right|_{y=0} = \frac{gVm_T}{(2\pi)^2}\left[1 + (q-1)\frac{m_T}{T}\right]^{-\frac{q}{q-1}}$$

# Fitting with Tsallis Distribution Function

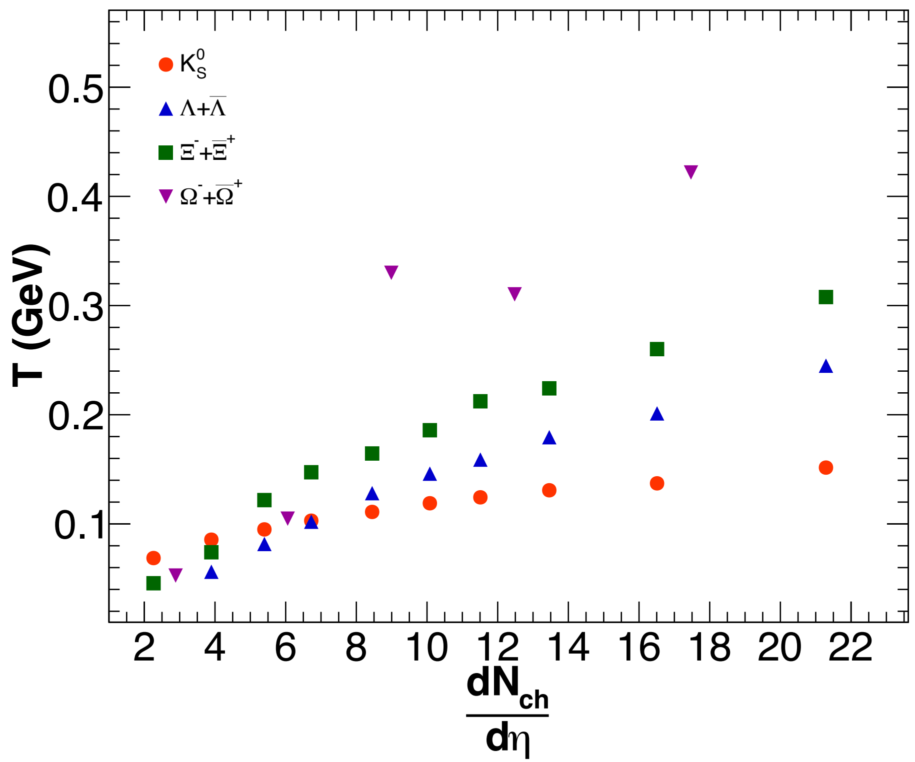


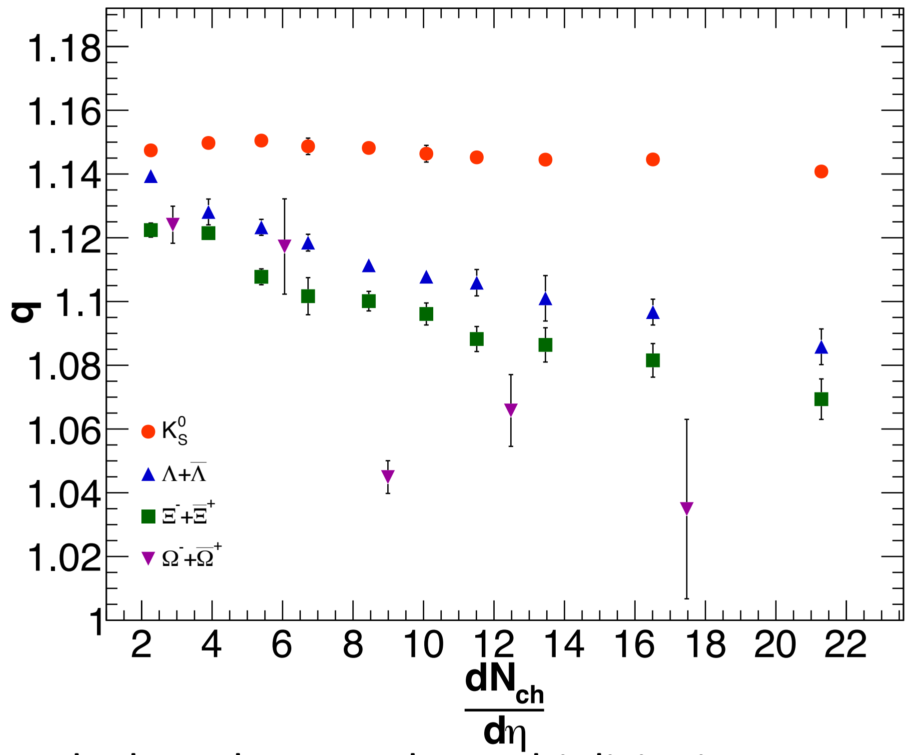



# Tsallis Temperature (T)




- The variable T shows a systematic increase with multiplicity, the heaviest baryons showing the steepest increase.
- This is an indication of a mass hierarchy in particle freeze-out: leading to a differential freeze-out scenario (D.Thakur, et al. Adv.High Energy Phys. (2016) 4149352)

# Tsallis Non-extensive Parameter (q)




- q decreases towards the value 1 as the multiplicity increases, except for the $K_s^0$ which shows no clear dependence.
- This shows the tendency of the produced system to equilibrate with higher multiplicities.
- This goes inline with the expected multipartonic interactions, which increase for higher multiplicities in p + p collisions and are thus responsible for bringing the system towards thermodynamic equilibrium.

# Summary

- Tsallis distribution provides a very good description of the transverse momentum distributions of strange and multi-strange particles produced in pp collisions at $\sqrt{s}$ = 7 TeV
- The variable *T* shows a systematic increase with multiplicity, the heaviest baryons showing the steepest increase
- *q* decreases towards the value 1 as the multiplicity increases, except for the $K_s^0$ which shows no clear dependence
- This shows the tendency of the produced system to equilibrate with higher multiplicities
- This goes inline with the expected multipartonic interactions, which increase for higher multiplicities in p + p collisions and are thus responsible for bringing the system towards thermodynamic equilibrium

**Thanks for your attention!**

# The Tsallis Non-extensive Statistics

**Thermodynamic consistency**

$$T = \left.\frac{\partial \epsilon}{\partial s}\right|_{n} \qquad \mu = \left.\frac{\partial \epsilon}{\partial n}\right|_{s}$$

$$n = \left.\frac{\partial P}{\partial \mu}\right|_{T} \qquad s = \left.\frac{\partial P}{\partial T}\right|_{\mu}$$

**Here**
**s = S/V (entropy density)**
**n = N/V (particle number density)**

$$\boxed{S_q(A,B) = S_q(A) + S_q(B) + (1-q)S_q(A)S_q(B)}$$

# Transvers Momentum Spectra in High Energy Collisions

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$$E\frac{d^3\sigma}{d^3p} \simeq C\exp\left(-\frac{p_T}{T}\right).$$

**Experiments observe non-exponential behavior at large transverse momenta.**

$$E\frac{d^3\sigma}{d^3p} = C\left(1+\frac{p_T}{p_0}\right)^{-n}$$

$$\longrightarrow \begin{cases} \exp\left(-\frac{np_T}{p_0}\right) & \text{for } p_T \to 0, \\ \left(\frac{p_0}{p_T}\right)^n & \text{for } p_T \to \infty, \end{cases}$$

$$f(p_T) = C_q\left[1+(q-1)\frac{p_T}{T}\right]^{-\frac{1}{q-1}}$$

$$S_q(A,B) = S_q(A)+S_q(B)+(1-q)S_q(A)S_q(B)$$

$$S_q = \frac{1-\sum {p_i}^q}{q-1}$$