Exploring the Thermodynamic and Transport Properties of Hadron Spectra in proton–proton collisions at $\sqrt{s}$ = 13 TeV

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Why study hadron spectra in small collision systems?

Transverse-momentum distributions connect particle production to the evolving medium.

THE MEDIUM

High-energy collisions create hot, short-lived matter. Its final-state hadrons retain information about the conditions at kinetic freeze-out.

THE SMALL-SYSTEM QUESTION

High-multiplicity pp events show several features also studied in larger systems, motivating tests of collective and thermodynamic behavior.

THE SPECTRAL HANDLE

Identified π, K and p spectra probe the interplay of soft production at low pT and hard partonic processes at high pT.

Central motivation

Can one consistent, thermodynamically grounded description of the spectra be used to track how effective freeze-out and transport properties change with event multiplicity?

The extracted quantities are effective, model-dependent characterizations—not direct measurements of a common thermal source.

Research objectives

A species-by-species analysis across ten event-activity classes.

01

Fit identified spectra

Describe $\pi^{+}+\pi^{-}$, $K^{+}+K^{-}$ and $p+\bar{p}$ transverse-momentum spectra with the thermodynamically consistent Tsallis form.

02

Extract freeze-out parameters

Determine effective temperature $T_{e}ff$, non-extensive shape parameter q and effective normalization volume V.

03

Derive response and transport quantities

Calculate α, λ, Kn and κT from the fitted parameters and thermodynamic integrals.

04

Track multiplicity evolution

Compare mass ordering and trends from high-multiplicity MC-1 to low-multiplicity MC-10.

Experimental data and collision system

ALICE identified-particle spectra from the 2016 LHC pp run.

√s

13 TeV

EVENT SAMPLE

≈143 million

RAPIDITY

$|y| < 0.5$

MULTIPLICITY

10 classes

PARTICLE SPECIES

$\pi^+ + \pi^-$ • charged pions
$K^+ + K^-$ • charged kaons
$p + \bar{p}$ • protons and antiprotons

TRANSVERSE-MOMENTUM COVERAGE

Pions: approximately 0.1–20 GeV/c
Kaons: approximately 0.2–20 GeV/c
Protons: approximately 0.3–20 GeV/c

Mean charged-particle multiplicity density ⟨dNch/dη⟩ spans approximately 2.55–26.02 across the ten V0M classes.

Thermodynamically consistent Tsallis distribution

A compact parametrization captures an exponential-like soft region and a power-law high-pT tail.

SPECTRAL FORM (μ = 0)

$$\frac{d^2N}{dp_T dy} = C p_T m_T \cosh y \left[1 + (q-1)\frac{m_T \cosh y - \mu}{T_{eff}}\right]^{-q/(q-1)}$$

KEY LIMIT

$q \to 1$

Boltzmann–Gibbs form

$q > 1$ produces a harder power-law tail.

Fit parameters

$T_e$ff

Effective spectral temperature (GeV)

q

Phenomenological spectral-shape parameter

V

Effective normalization volume (fm^3)

$T_e$ff and q are fitted independently for each hadron species; no common temperature or q is imposed.

Parameter extraction and derived quantities

Maximum-likelihood fits are performed separately for each species and multiplicity class.

01 INPUT

Published ALICE pT spectra and uncertainties

02 FIT

Tsallis model
$\theta = (q, T_e ff, V)$

03 DERIVE

Thermodynamic integrals and response functions

04 COMPARE

Species ordering and MC-1 → MC-10 trends

TRANSPORT ESTIMATES

$\lambda = 1/(n\sigma)$, with hard-sphere radius rh = 0.3 fm
Kn = λ/R, where R = (3V/4π)^(1/3)

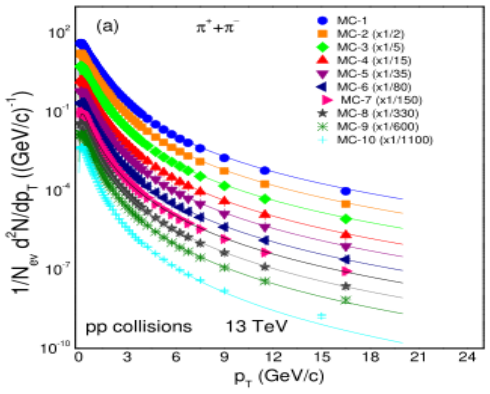
IMPORTANT FIT CAVEAT

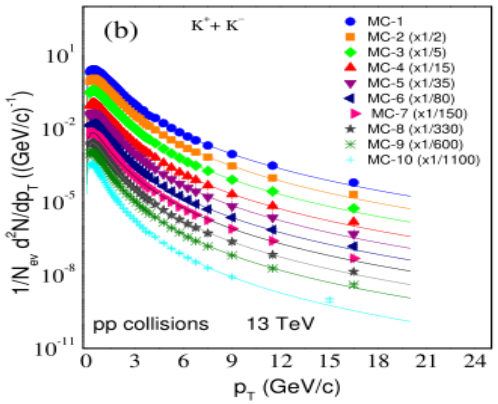
Published full covariance matrices are unavailable. The baseline fit treats pT-bin uncertainties as uncorrelated; systematic shifts are tested by coherent ±1σ refits.

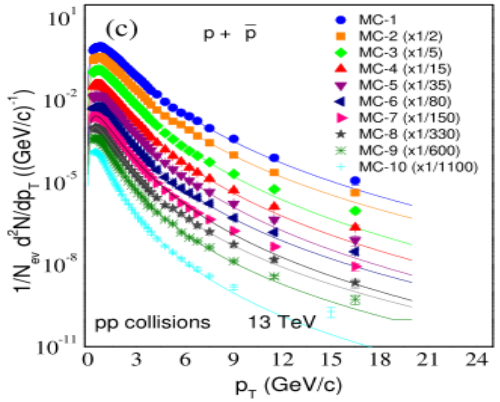
The same hard-sphere cross section is used for all three species; species dependence enters through fitted densities and effective radii.

Identified-hadron transverse-momentum spectra

Tsallis fits describe the spectra across ten multiplicity classes, with weaker agreement at very low pT.







OVERALL DESCRIPTION

Reasonable agreement over most of the measured pT range and multiplicity classes.

LOW-pT REGION

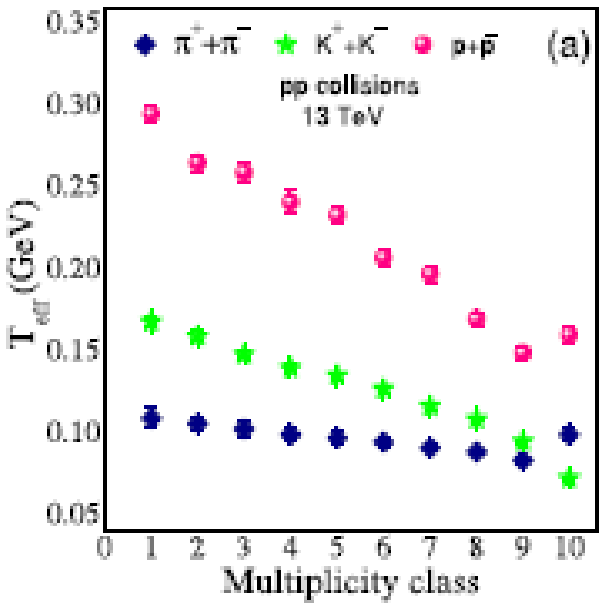
Discrepancies below roughly 0.5 GeV/c are expected; resonance-decay contributions are not explicitly modeled.

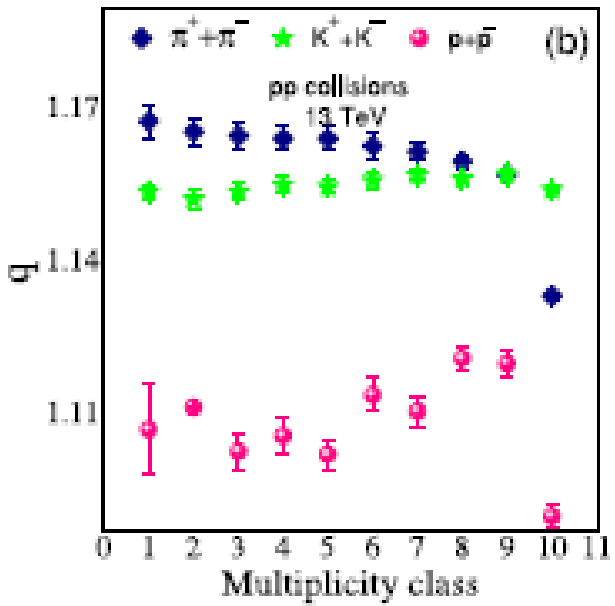
FIT QUALITY

Proton spectra—especially MC-10—are less accurately described.

Effective temperature and non-extensivity

The fitted parameters exhibit distinct mass ordering and multiplicity dependence.





TEMPERATURE ORDERING

$T_e ff(p) > T_e ff(K) > T_e ff(\pi)$

MC-1 → MC-9: $T_e ff$ decreases for all species.

q ORDERING

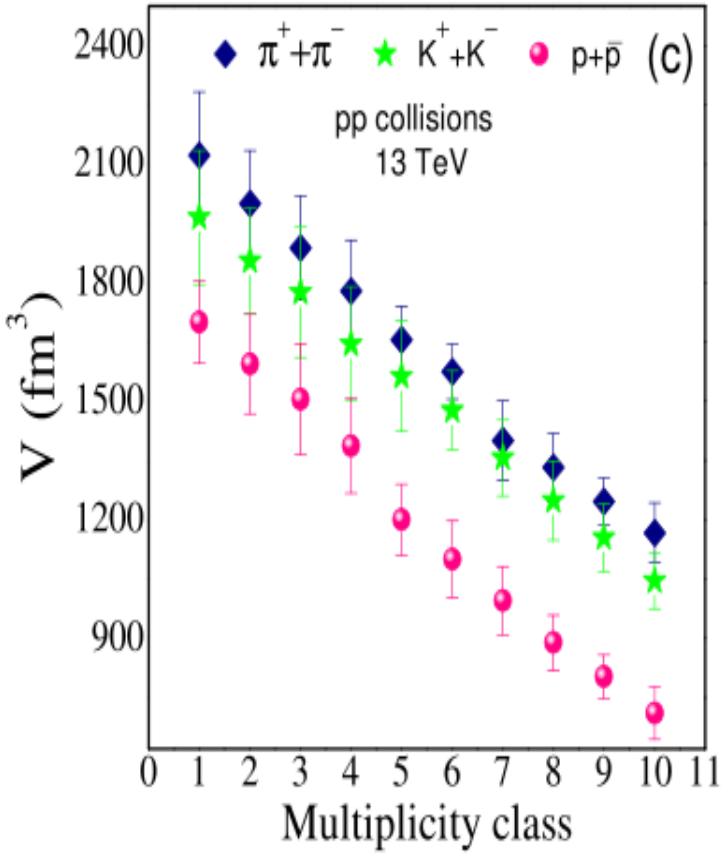
$q\pi > qK > qp$

Pion q decreases; kaon and proton q are comparatively stable through most classes.

Interpretation: these are independent species-specific fits. The hierarchy reflects different spectral shapes and does not establish one common thermal source.

Freeze-out volume decreases with decreasing multiplicity

The fitted normalization volume is monotonic for all three species.



PIONS

2122 → 1167 fm^3

KAONS

1965 → 1045 fm^3

PROTONS

1700 → 711 fm^3

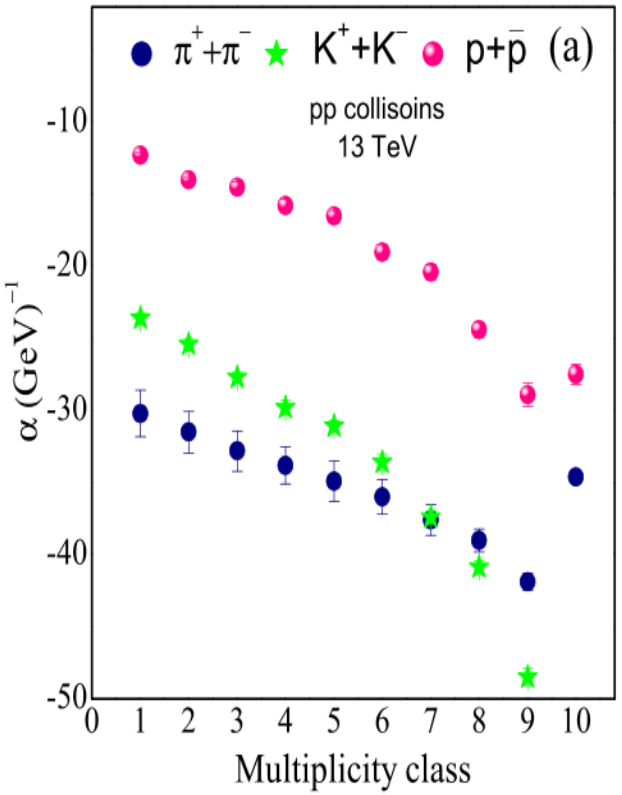
SPECIES HIERARCHY

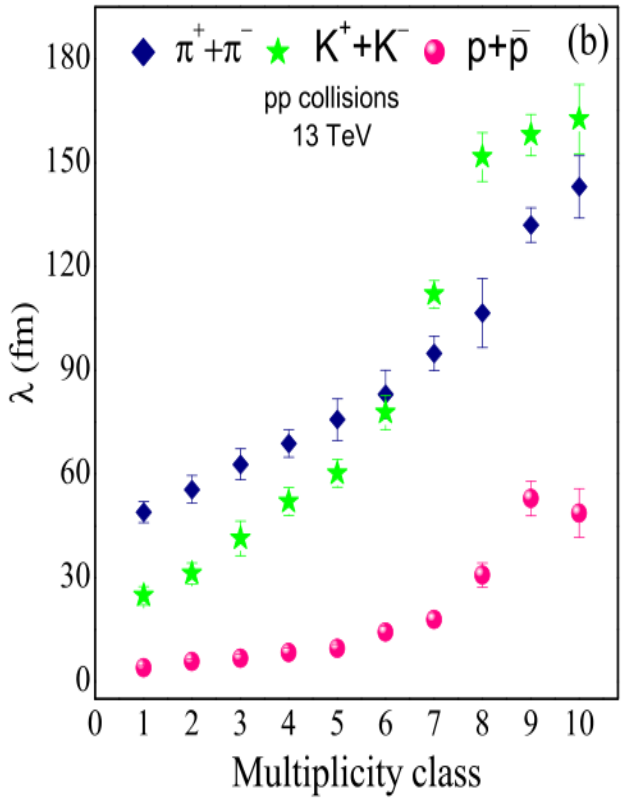
Vπ > VK > Vp across the multiplicity classes.

Caution: V is an effective, model-dependent normalization volume—not a direct geometric measurement. Its ordering is suggestive, not proof of sequential freeze-out.

Expansion coefficient and mean free path

Both quantities reflect the evolving density and show species-dependent behavior.





EXPANSION COEFFICIENT α

Generally becomes more negative from MC-1 to MC-9; MC-10 shows departures, including a pronounced kaon deviation.

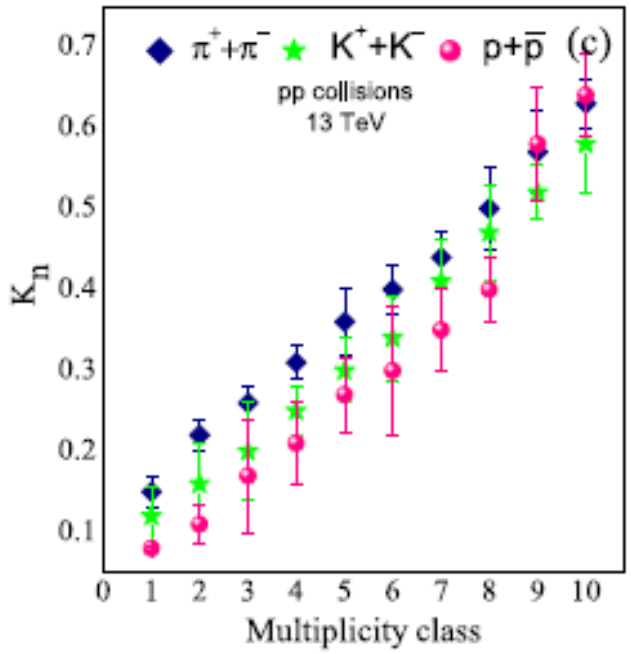
MEAN FREE PATH λ

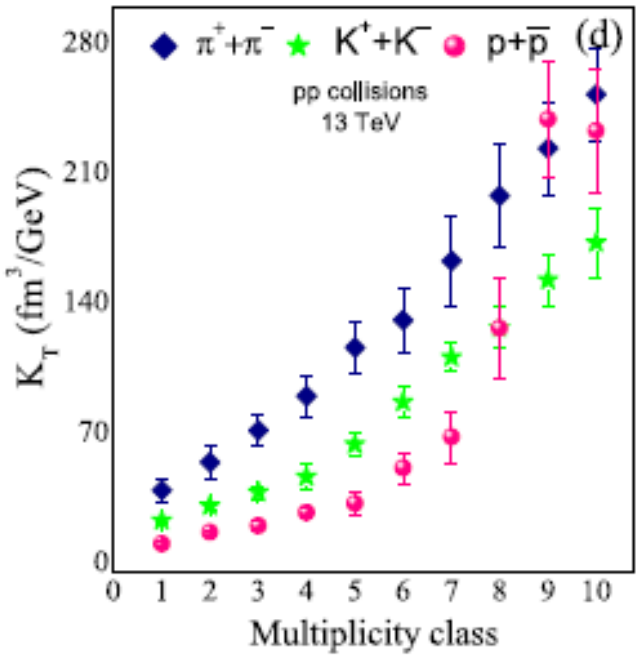
Increases toward lower multiplicity as the system becomes more dilute. Pions have the largest λ; protons the smallest.

λ is estimated using $\lambda = 1/(n\sigma)$, with $\sigma = 4\pi r_h^2$ and $r_h = 0.3$ fm.

Knudsen number and isothermal compressibility

The lower-multiplicity system becomes less collision-dominated, but does not reach free-streaming.





KNUDSEN NUMBER Kn

Increases toward MC-10; values remain below unity, reaching roughly 0.6.

ISOTHERMAL COMPRESSIBILITY κT

Generally grows as density falls; some non-monotonic behavior appears in the lowest-multiplicity classes.

Kn ≪ 1 indicates a collision-dominated regime; Kn ≫ 1 signals free-streaming. MC-10 weakens, but does not invalidate, the fluid-like description.

What do the trends tell us—and what remains uncertain?

ROBUST PATTERNS

- Clear species ordering in fitted parameters
- Effective volume falls from MC-1 to MC-10
- Transport quantities evolve toward a more dilute regime

MC-10 DEVIATIONS

- $T_e$ff upturn for pions and protons
- q drops for pions and protons
- Several derived quantities depart from smooth trends

POSSIBLE EXPLANATIONS

Growing hard-scattering contribution, limited statistics, or fit instability. These remain possibilities—not a firm transition claim.

KEY LIMITATIONS

Independent species fits; missing full covariance matrix; single-component Tsallis form; model-dependent effective volume.

A two-component soft-plus-hard analysis and improved treatment of correlated uncertainties would help test the MC-10 interpretation.

Conclusions

Thermodynamically consistent Tsallis fits describe most π, K and p spectra across ten multiplicity classes.

Fitted $T_e$ff and q show clear species ordering: $T_e$ff(p) > $T_e$ff(K) > $T_e$ff(π), while qπ > qK > qp.

The effective volume decreases toward lower multiplicity, with Vπ > VK > Vp.

α, λ, Kn and κT reveal a transition toward a more dilute, less collision-dominated regime.

MC-10 deviations are intriguing but require further study; the system remains far from free-streaming.

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Thank you

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