Investigating the soft and hard limits in transverse momentum spectra and exploring isotropic events in pp collisions

Leonid Serkin

Facultad de Ciencias
Universidad Nacional Autónoma de México

In collaboration with: Guy Paic, Gabor Biro, Gergely Barnaföldi, arXiv:2403.07512 [hep-ph]

XV Latin American Symposium on High Energy Physics, Mexico City, 8 November 2024

Collective effects in proton-proton collisions?

- Collective effects in proton-proton collisions has been a highly active area of research over the past decade: production of **hot QCD matter in small systems**?

Physics Letters B 765 (2017) 193–220

Contents lists available at ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

ELSEVIER

Evidence for collectivity in pp collisions at the LHC

CrossMark

The CMS Collaboration *

CERN, Switzerland

A R T I C L E   I N F O

Article history:
Received 20 June 2016
Received in revised form 3 December 2016
Accepted 5 December 2016
Available online 13 December 2016
Editor: M. Doser

Keywords:
CMS
Physics
Heavy ion
Ridge
Correlation
pp

A B S T R A C T

Measurements of two- and multi-particle angular correlations in pp collisions at $\sqrt{s} = 5$, 7, and 13 TeV are presented as a function of charged-particle multiplicity. The data, corresponding to integrated luminosities of 1.0 pb^{-1} (5 TeV), 6.2 pb^{-1} (7 TeV), and 0.7 pb^{-1} (13 TeV), were collected using the CMS detector at the LHC. The second-order (v_2) and third-order (v_3) azimuthal anisotropy harmonics of unidentified charged particles, as well as v_2 of K^0_S and $\Lambda/\overline{\Lambda}$ particles, are extracted from long-range two-particle correlations as functions of particle multiplicity and transverse momentum. For high-multiplicity pp events, a mass ordering is observed for the v_2 values of charged hadrons (mostly pions), K^0_S, and $\Lambda/\overline{\Lambda}$, with lighter particle species exhibiting a stronger azimuthal anisotropy signal below $p_T \approx 2$ GeV/c. For 13 TeV data, the v_2 signals are also extracted from four- and six-particle correlations for the first time in pp collisions, with comparable magnitude to those from two-particle correlations. These observations are similar to those seen in pPb and PbPb collisions, and support the interpretation of a collective origin for the observed long-range correlations in high-multiplicity pp collisions.

Physics Letters B 789 (2019) 444–471

Contents lists available at ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

ELSEVIER

Correlated long-range mixed-harmonic fluctuations measured in *pp*, *p*+Pb and low-multiplicity Pb+Pb collisions with the ATLAS detector

Check for updates

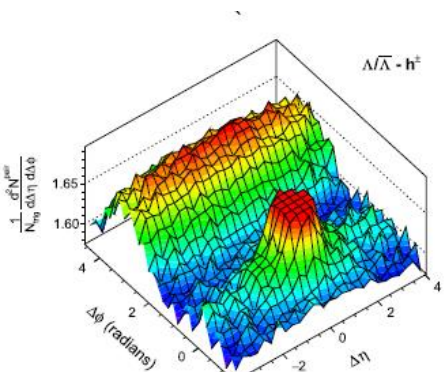
The ATLAS Collaboration *

A R T I C L E   I N F O

Article history:
Received 6 July 2018
Received in revised form 7 October 2018
Accepted 13 November 2018
Available online 2 January 2019
Editor: D.F. Geesaman

A B S T R A C T

Correlations of two flow harmonics v_n and v_m via three- and four-particle cumulants are measured in 13 TeV *pp*, 5.02 TeV *p*+Pb, and 2.76 TeV peripheral Pb+Pb collisions with the ATLAS detector at the LHC. The goal is to understand the multi-particle nature of the long-range collective phenomenon in these collision systems. The large non-flow background from dijet production present in the standard cumulant method is suppressed using a method of subevent cumulants involving two, three and four subevents separated in pseudorapidity. The results show a negative correlation between v_2 and v_3 and a positive correlation between v_2 and v_4 for all collision systems and over the full multiplicity range. However, the magnitudes of the correlations are found to depend on the event multiplicity, the choice of transverse momentum range and collision system. The relative correlation strength, obtained by normalisation of the cumulants with the $\langle v_n^2 \rangle$ from a two-particle correlation analysis, is similar in the three collision systems and depends weakly on the event multiplicity and transverse momentum. These results based on the subevent methods provide strong evidence of a similar long-range multi-particle collectivity in *pp*, *p*+Pb and peripheral Pb+Pb collisions.



nature physics

LETTERS

PUBLISHED ONLINE: 24 APRIL 2017 | DOI: 10.1038/NPHYS4111

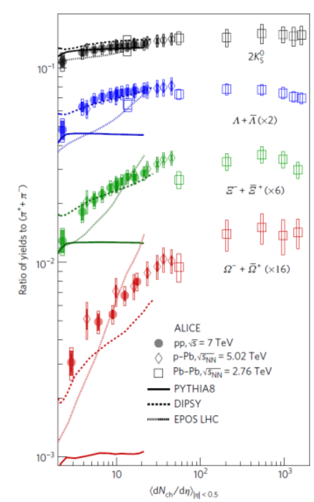
OPEN

Enhanced production of multi-strange hadrons in high-multiplicity proton–proton collisions

ALICE Collaboration†

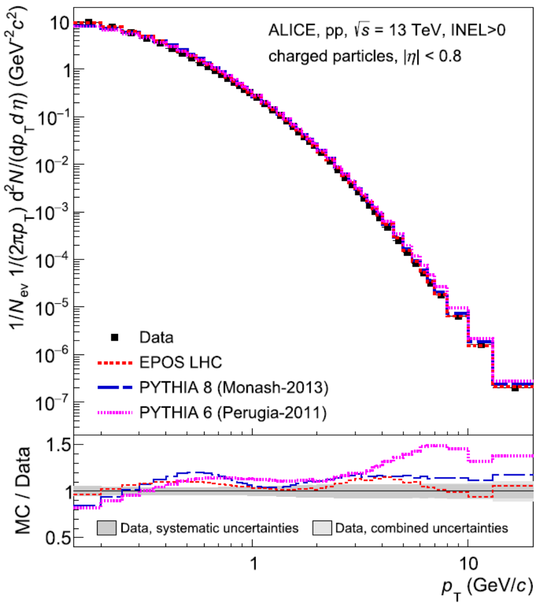
At sufficiently high temperature and energy density, nuclear matter undergoes a transition to a phase in which quarks and gluons are not confined: the quark–gluon plasma (QGP)[1]. Such an exotic state of strongly interacting quantum chromodynamics matter is produced in the laboratory in heavy nuclei high-energy collisions, where an enhanced production of strange hadrons is observed[2–6]. Strangeness enhancement, originally proposed as a signature of QGP formation in nuclear collisions[7], is more pronounced for multi-strange baryons. Several effects typical of heavy-ion phenomenology have been observed in high-multiplicity proton–proton (pp) collisions[8,9], but the enhanced production of multi-strange particles has not been reported so far. Here we present the first observation of strangeness enhancement in high-multiplicity proton–proton collisions. We find that the integrated yields of strange and multi-strange particles, relative to pions, increases significantly with the event charged-particle multiplicity. The measurements are in remarkable agreement with the p–Pb collision results[10,11], indicating that the phenomenon is related to the final system created in the collision. In high-multiplicity events strangeness production reaches values similar to those observed in Pb–Pb collisions, where a QGP is formed.

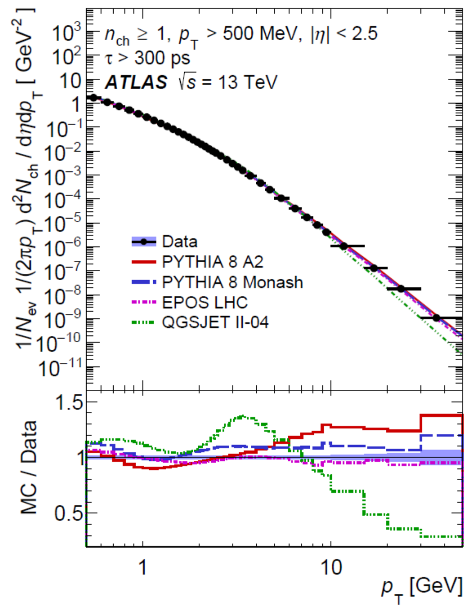
equilibrium and can be described using a grand-canonical statistical model[12,13]. In peripheral collisions, where the overlap of the colliding nuclei becomes very small, the relative yields of strange particles to pions decrease and tend toward those observed in pp collisions, for which a statistical-mechanics approach can also be applied[14,15]. Extensions of a pure grand-canonical description of particle production, such as statistical models implementing strangeness canonical suppression[16] and core–corona superposition[17,18] models, can effectively produce a suppression of strangeness production in small systems. However, the microscopic origin of enhanced strangeness production is not known, and the measurements presented in this Letter may contribute to its understanding. Several effects, such as azimuthal correlations and mass-dependent hardening of p_T distributions, which in nuclear collisions are typically attributed to the formation of a strongly interacting quark–gluon medium, have been observed in high-multiplicity pp and proton–nucleus collisions at the LHC[8–11,19–25]. Yet, enhanced production of strange particles as a function of the charged-particle multiplicity density ($dN_{ch}/d\eta$) has so far not been observed in pp collisions. The study of pp collisions at high multiplicity is thus of considerable interest as it opens the exciting possibility of a microscopic understanding of phenomena known from nuclear reactions.

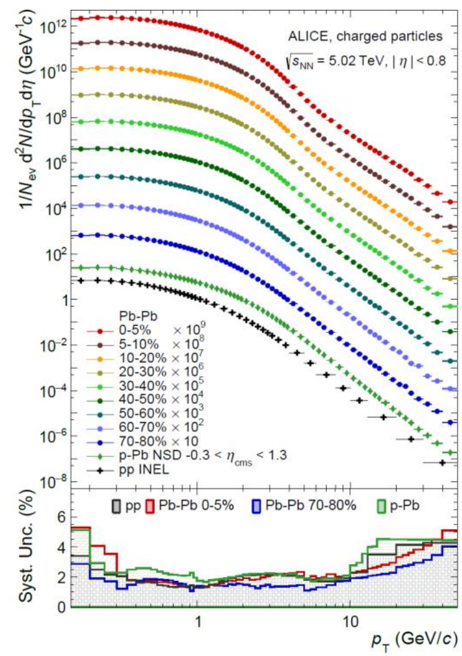


The pT spectra

- Transverse momentum (pT) spectra of identified particles are fundamental physical observables in high-energy collisions
- The evolution of the pT distribution with multiplicity in pp collisions is remarkably similar to the evolution observed in larger colliding systems







- Can be interpreted as originating from the hydrodynamical radial expansion of the produced medium
- **Thermal description:** final state particles are stemming from a system in thermal and chemical equilibrium in the hadronic phase

The pT spectra fitting

- The hadronic pT spectra can be described by exponential distributions based on the **Boltzmann-Gibbs** statistics-based effective models :

$$f(E) \sim \exp\left(-\frac{E-\mu}{T}\right)$$

where μ is chemical potential and T is the associated temperature, or simplified to:

$$f(p_T) = A\exp\left(-\frac{p_T}{T}\right)$$

- The main assumption is that the hadron production is governed by physically different, non-thermal and non-equilibrium perturbative QCD processes at low and high pT values

The pT spectra fitting

- In order to connect these two parts in a meaningful way, an improvement in the statistical picture is the generalization of the Boltzmann-Gibbs theory using a particular generalization of the exponential and logarithm functions:

$$\exp_q(x) = [1 + (1-q)x]^{1/(1-q)}$$

- The distributions with this form are usually called **Tsallis-Pareto** distributions, and they connect the powerlaw tailed and exponential-like (i.e. Boltzmann-Gibbs) distributions in a smooth way, simplified to:

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

The pT spectra fitting

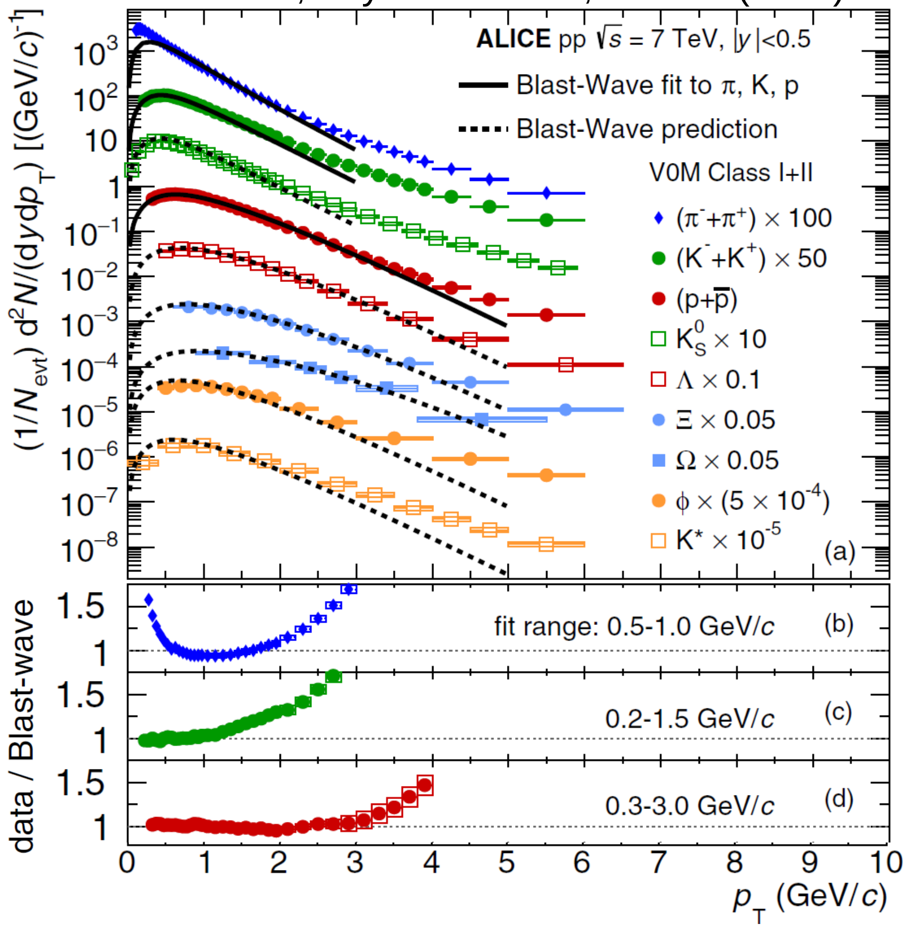
- The hadronic pT spectra can also be studied by means of the Boltzmann-Gibbs blast-wave model in terms of a few collective variables, in particular temperature, longitudinal, and transverse flow:

$$\frac{dN}{p_T\ dp_T} \propto \int_0^R r\ dr\ m_T\ I_0\left(\frac{p_T \sinh\rho}{T_{kin}}\right) K_1\left(\frac{m_T \cosh\rho}{T_{kin}}\right)$$

where $\rho = \tanh^{-1}(\beta_T)$

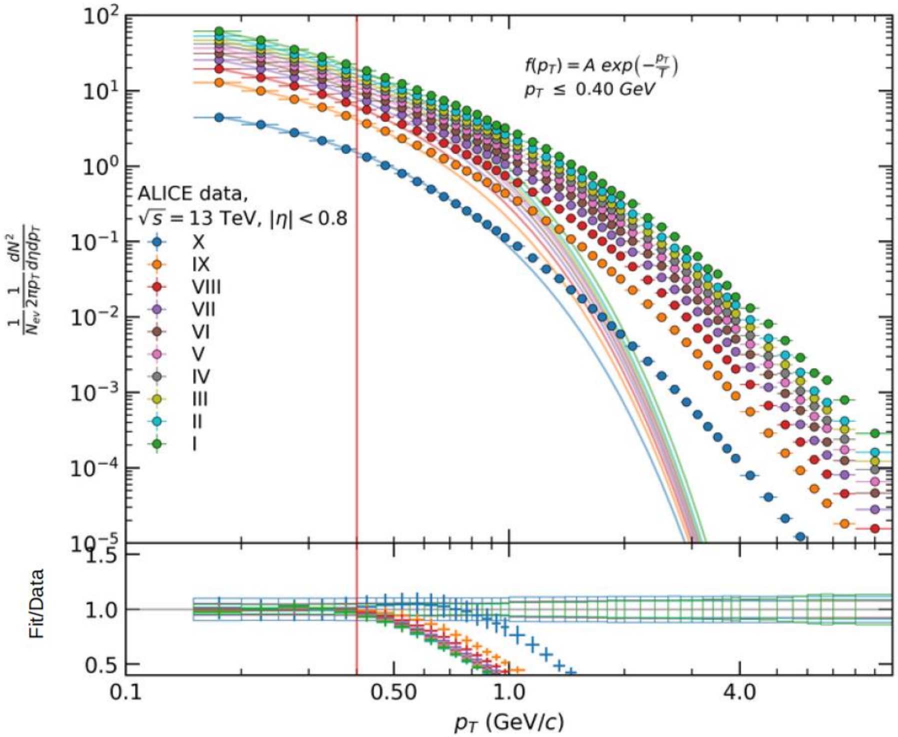
But the temperature is related to the mean transverse momentum...
and to the **fit range**

ALICE, Phys. Rev. C 99, 024906 (2019)

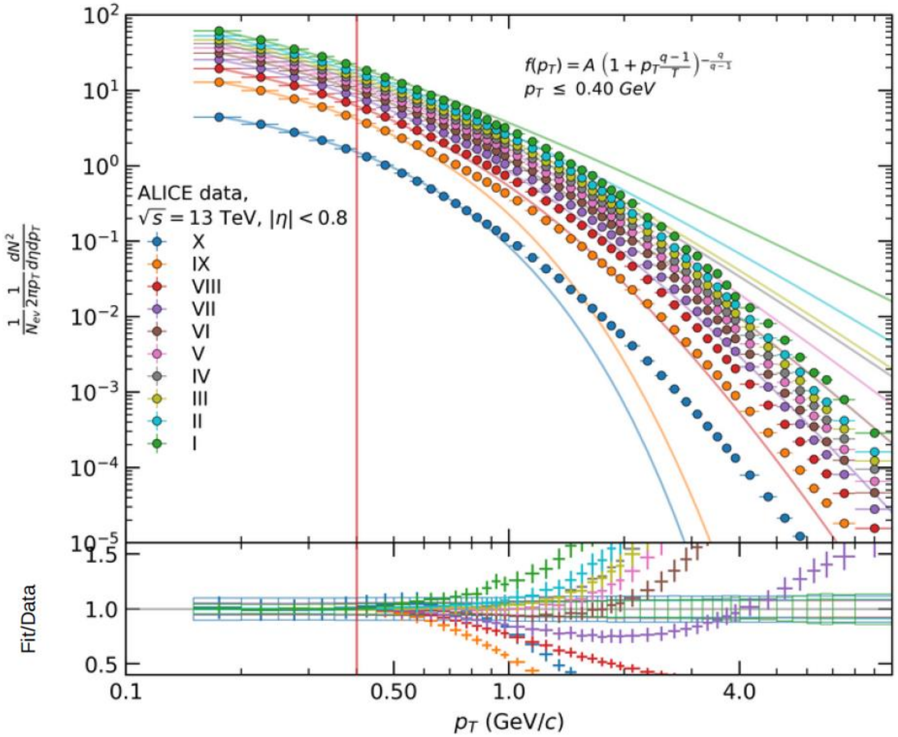


Study of fit ranges

Boltzmann



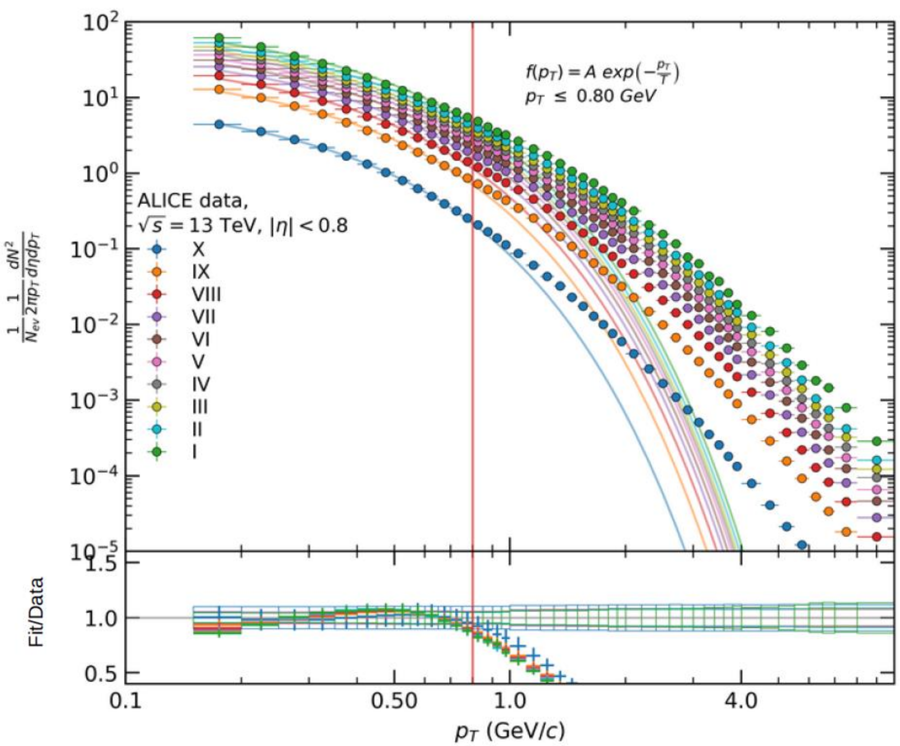
Tsallis



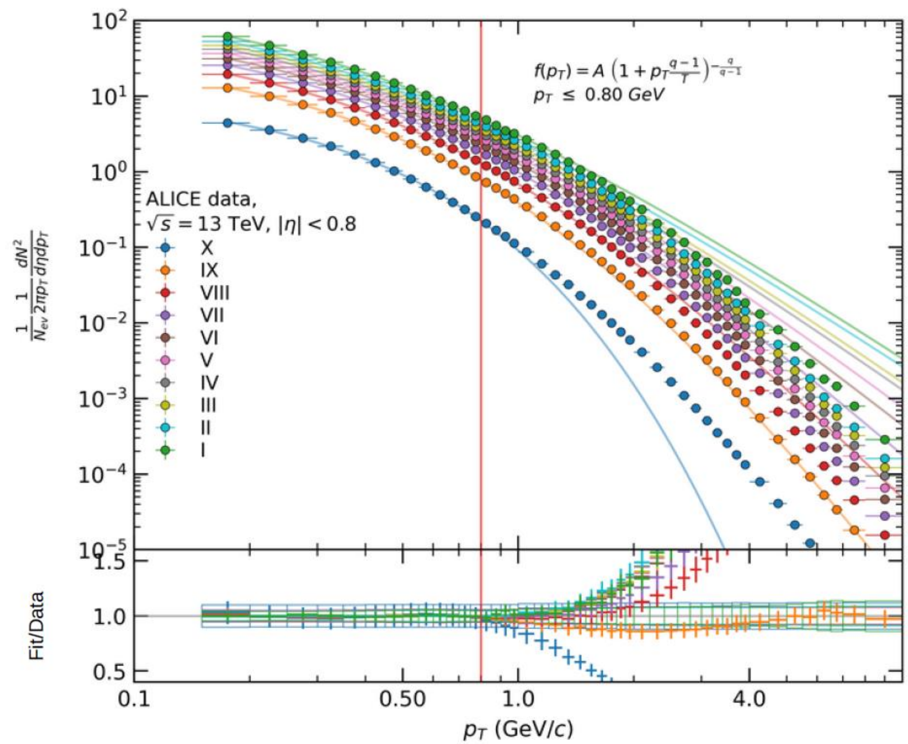
ALICE data in different event multiplicity classes: I – highest, X – lowest class.

Study of fit ranges

Boltzmann



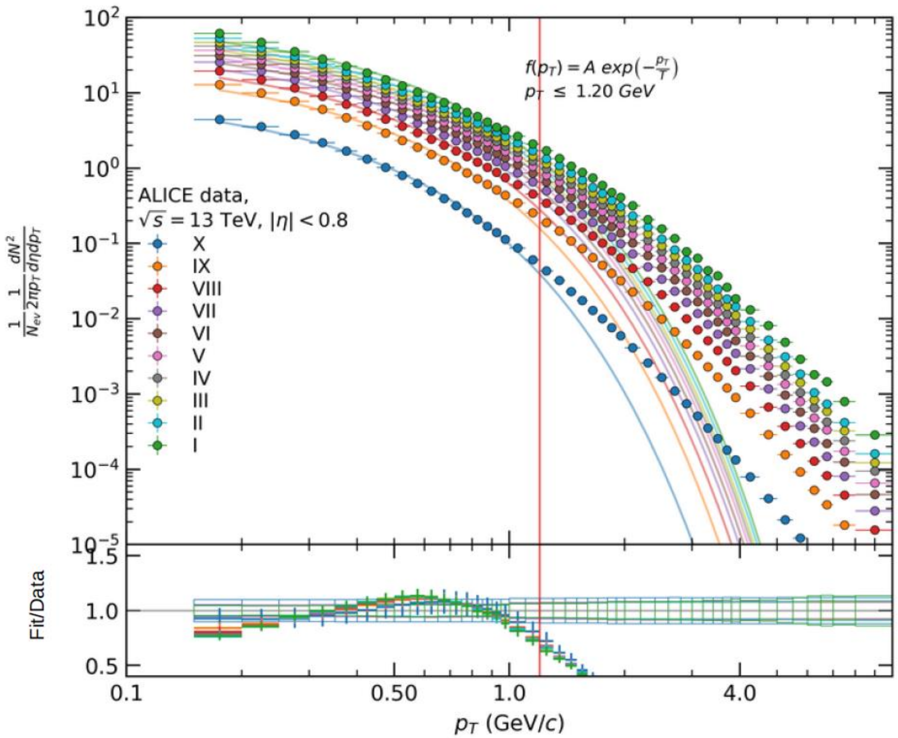
Tsallis



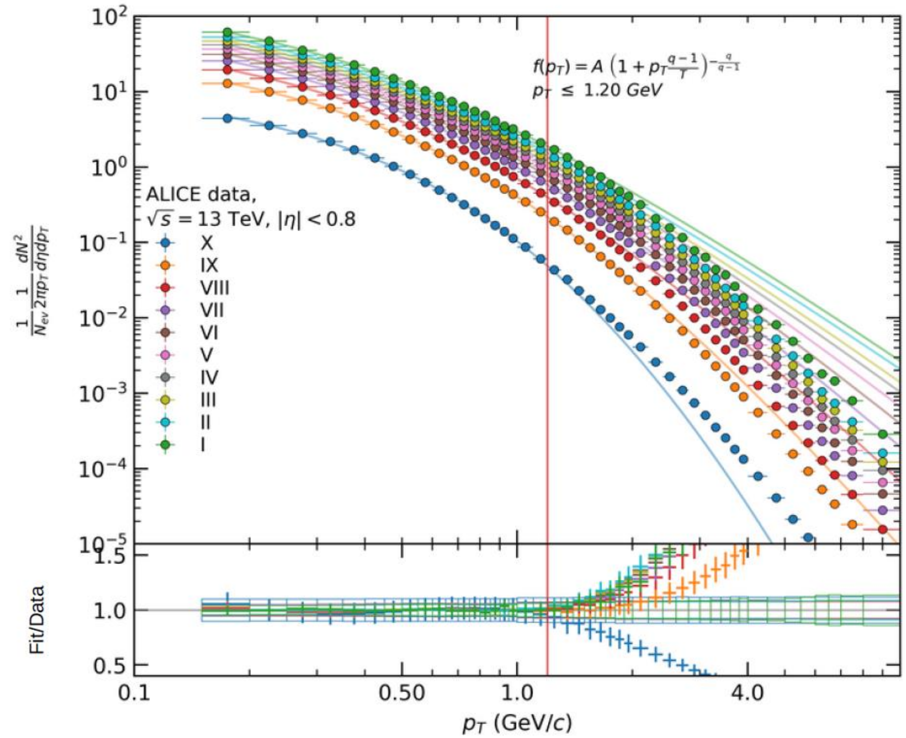
ALICE data in different event multiplicity classes: I – highest, X – lowest class.

Study of fit ranges

Boltzmann



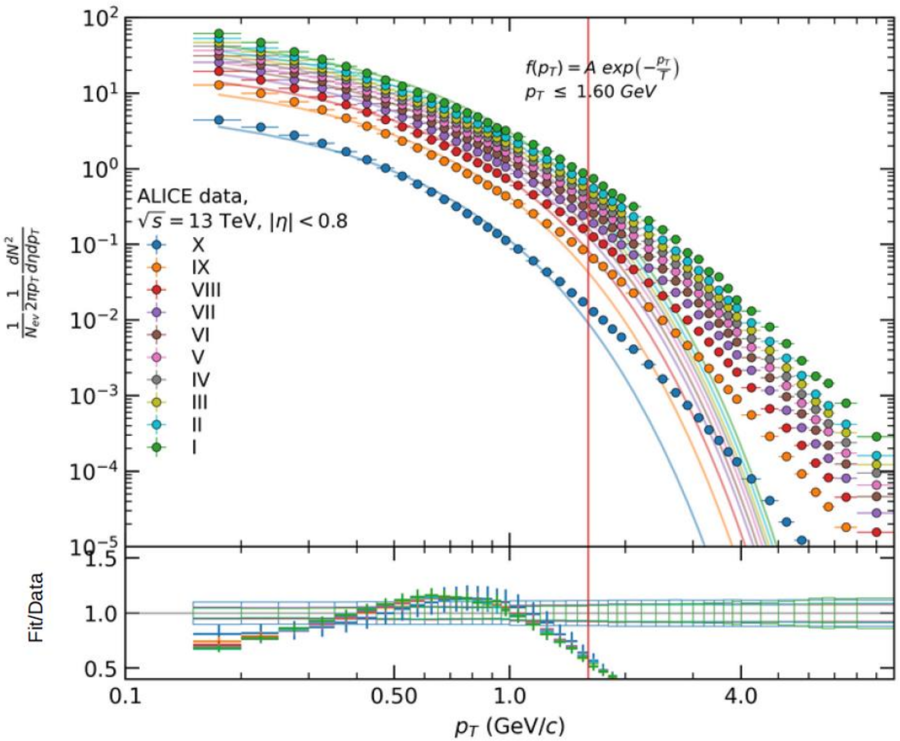
Tsallis



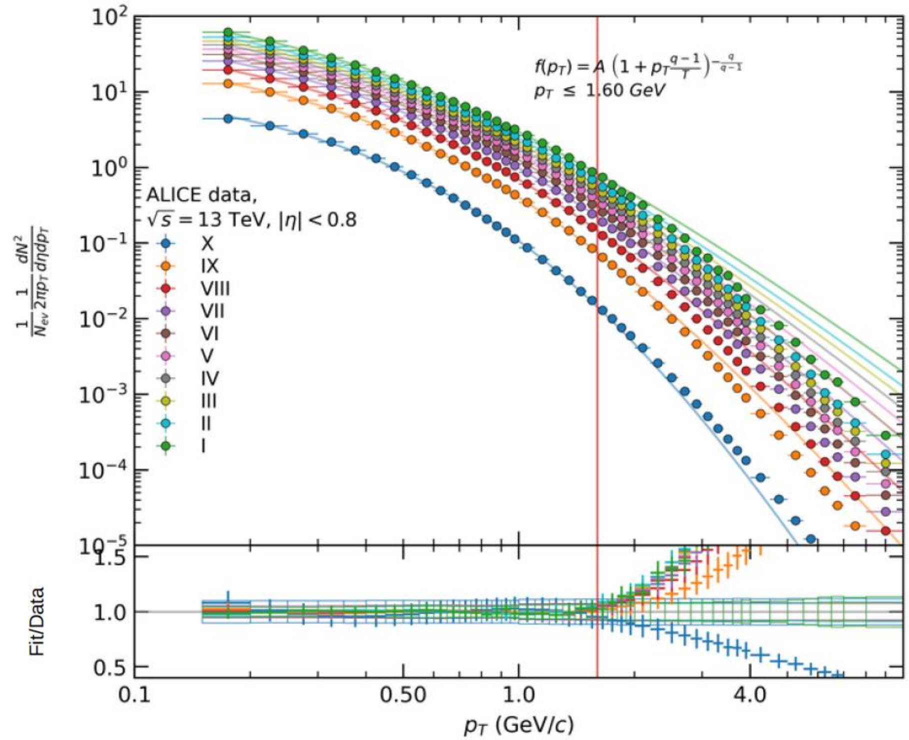
ALICE data in different event multiplicity classes: I – highest, X – lowest class.

Study of fit ranges

Boltzmann



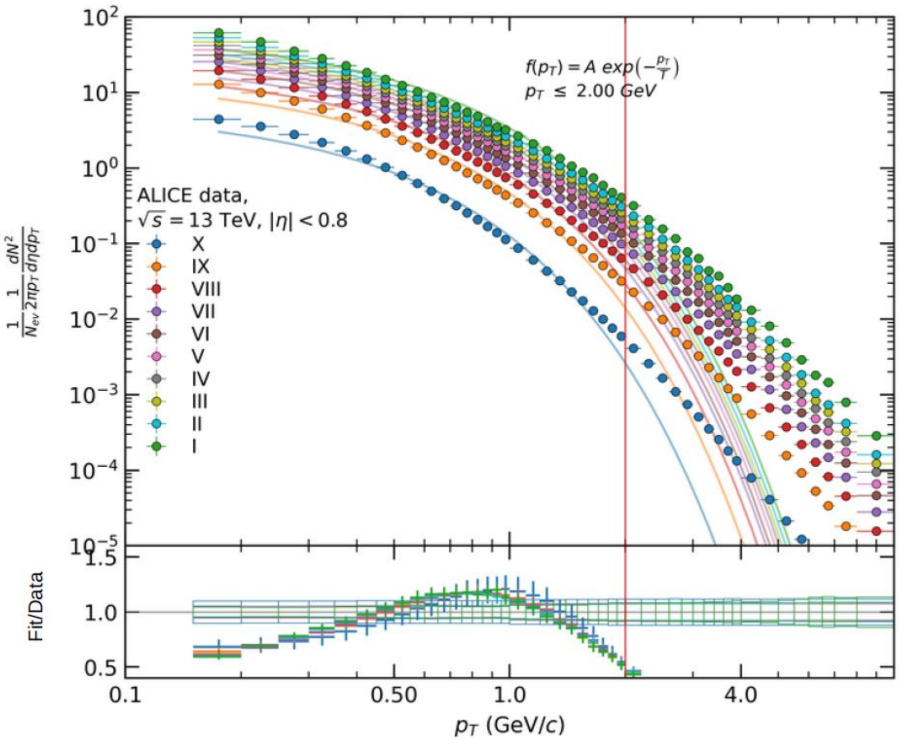
Tsallis



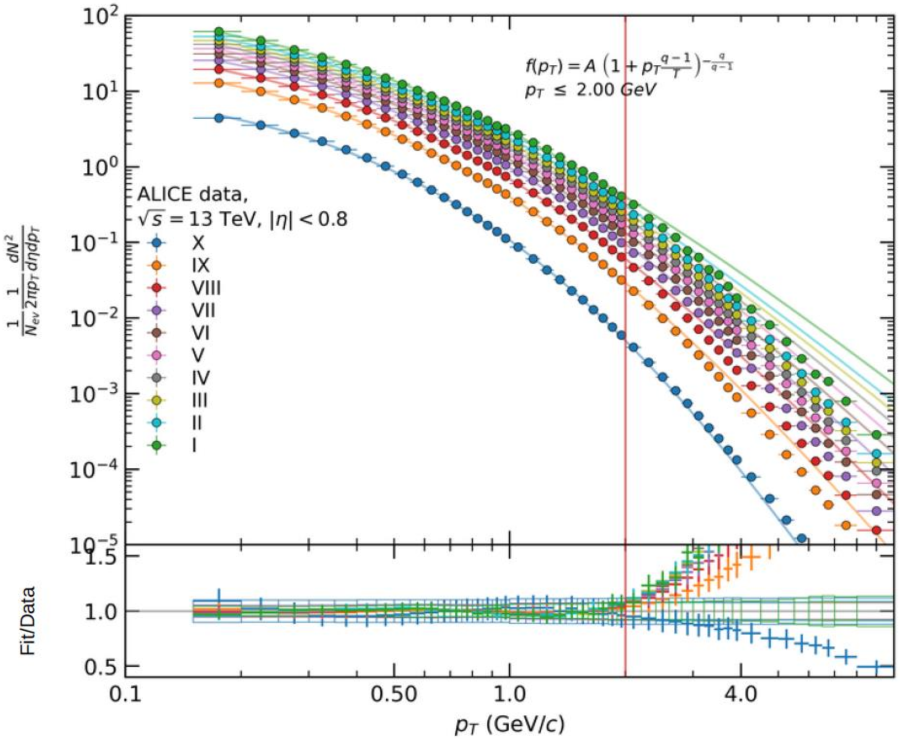
ALICE data in different event multiplicity classes: I – highest, X – lowest class.

Study of fit ranges

Boltzmann



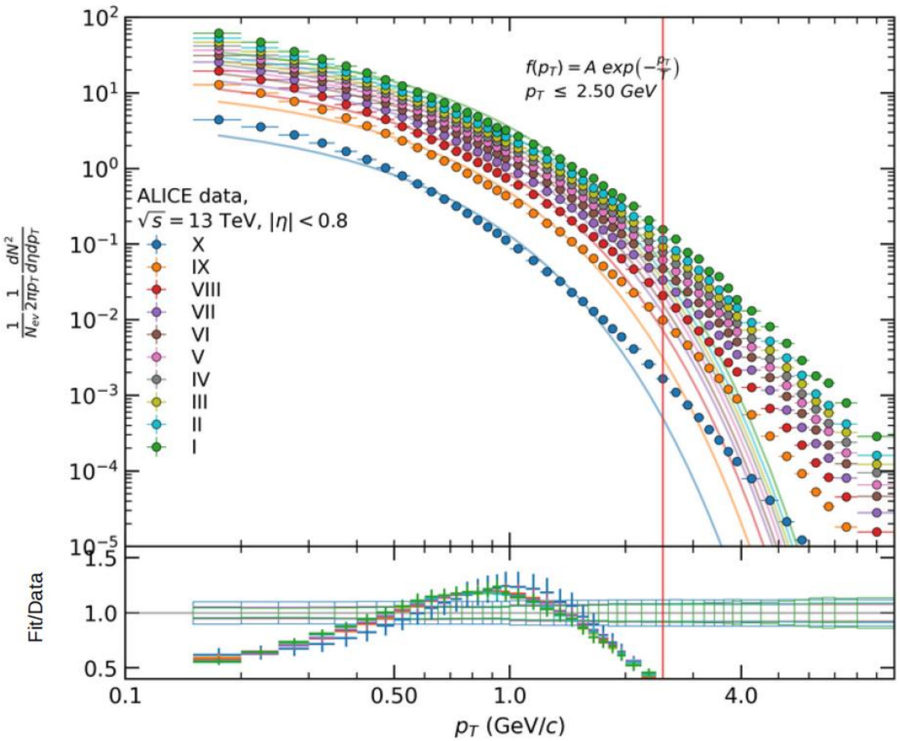
Tsallis



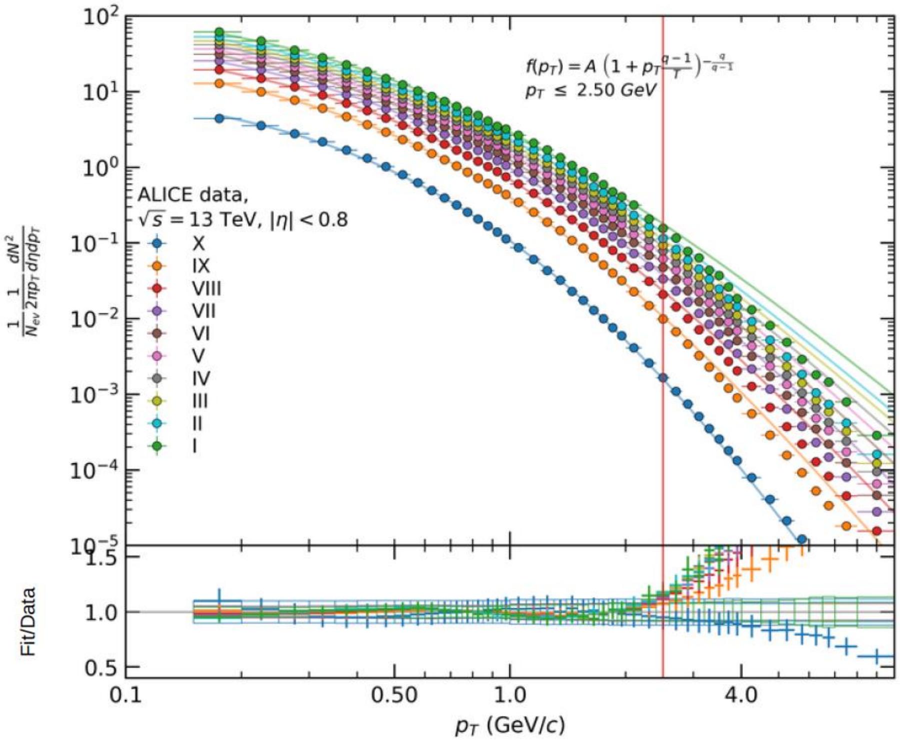
ALICE data in different event multiplicity classes: I – highest, X – lowest class.

Study of fit ranges

Boltzmann



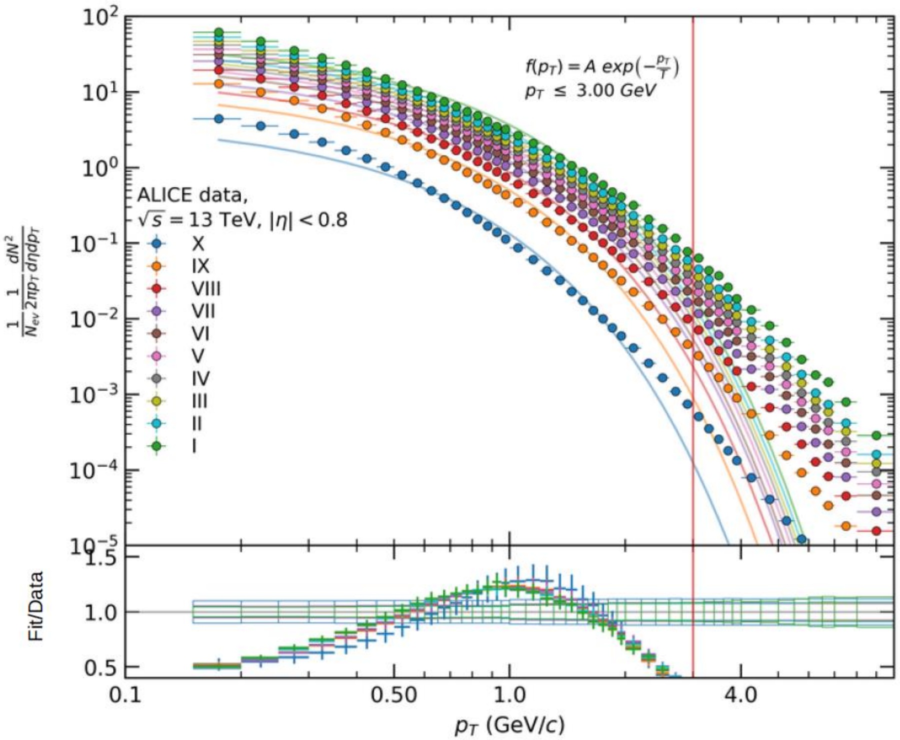
Tsallis



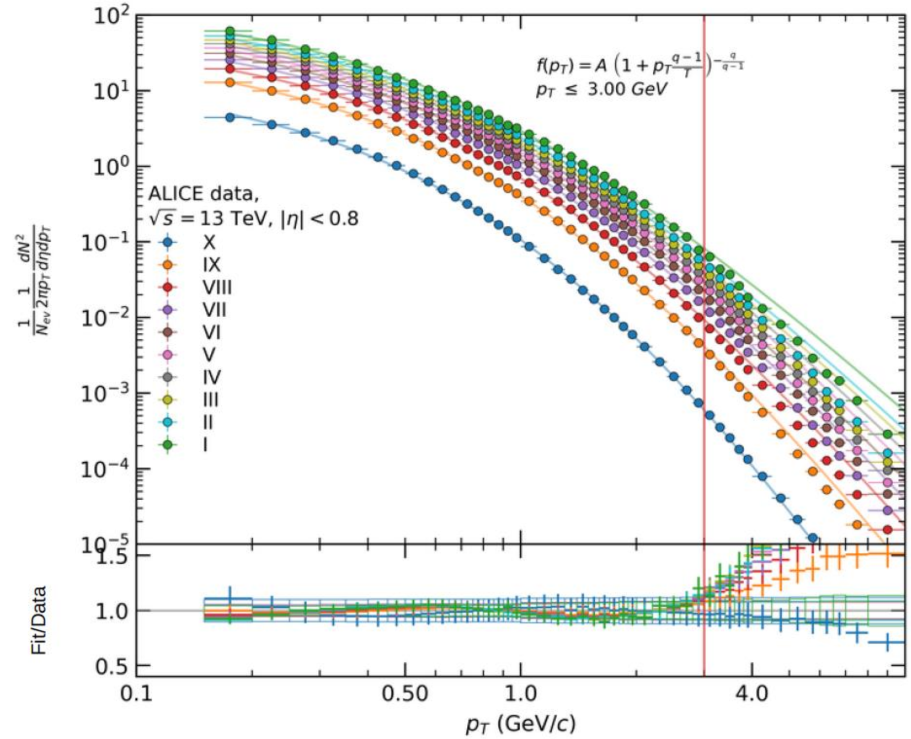
ALICE data in different event multiplicity classes: I – highest, X – lowest class.

Study of fit ranges

Boltzmann



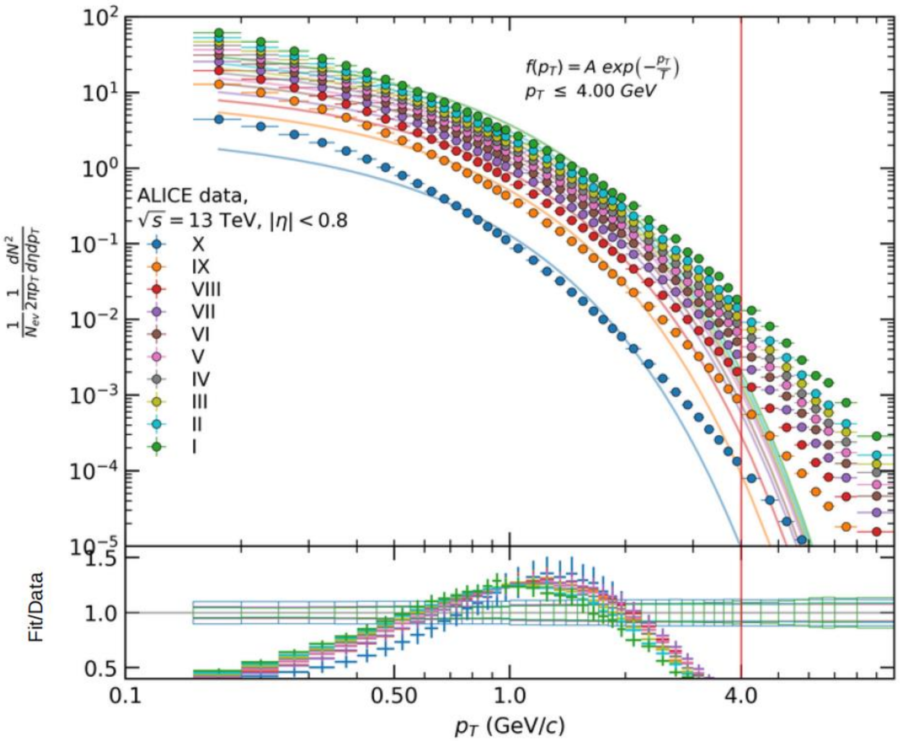
Tsallis



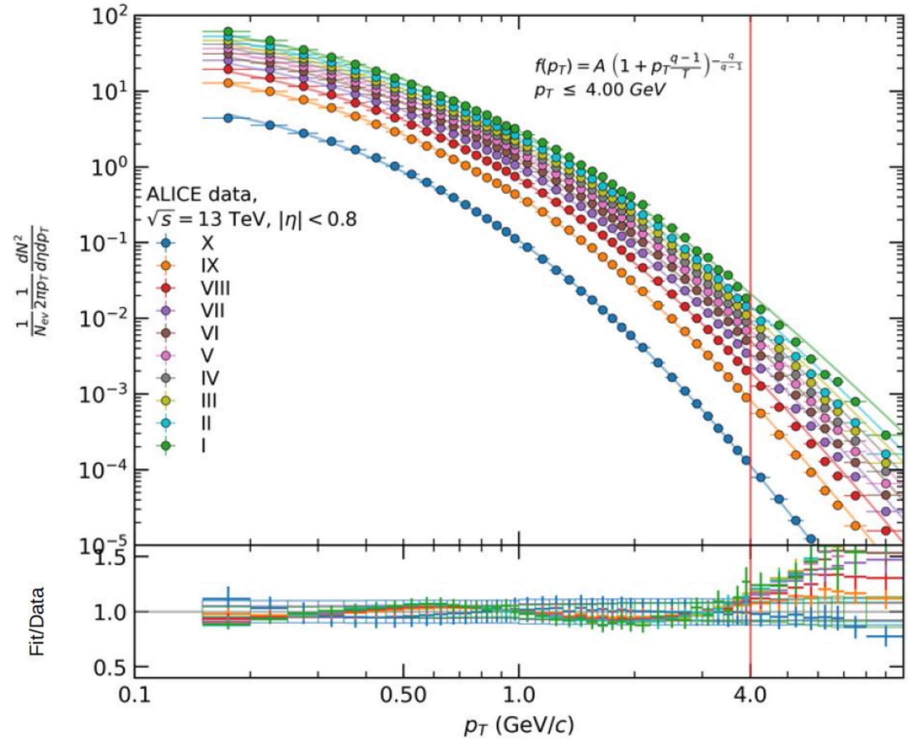
ALICE data in different event multiplicity classes: I – highest, X – lowest class.

Study of fit ranges

Boltzmann

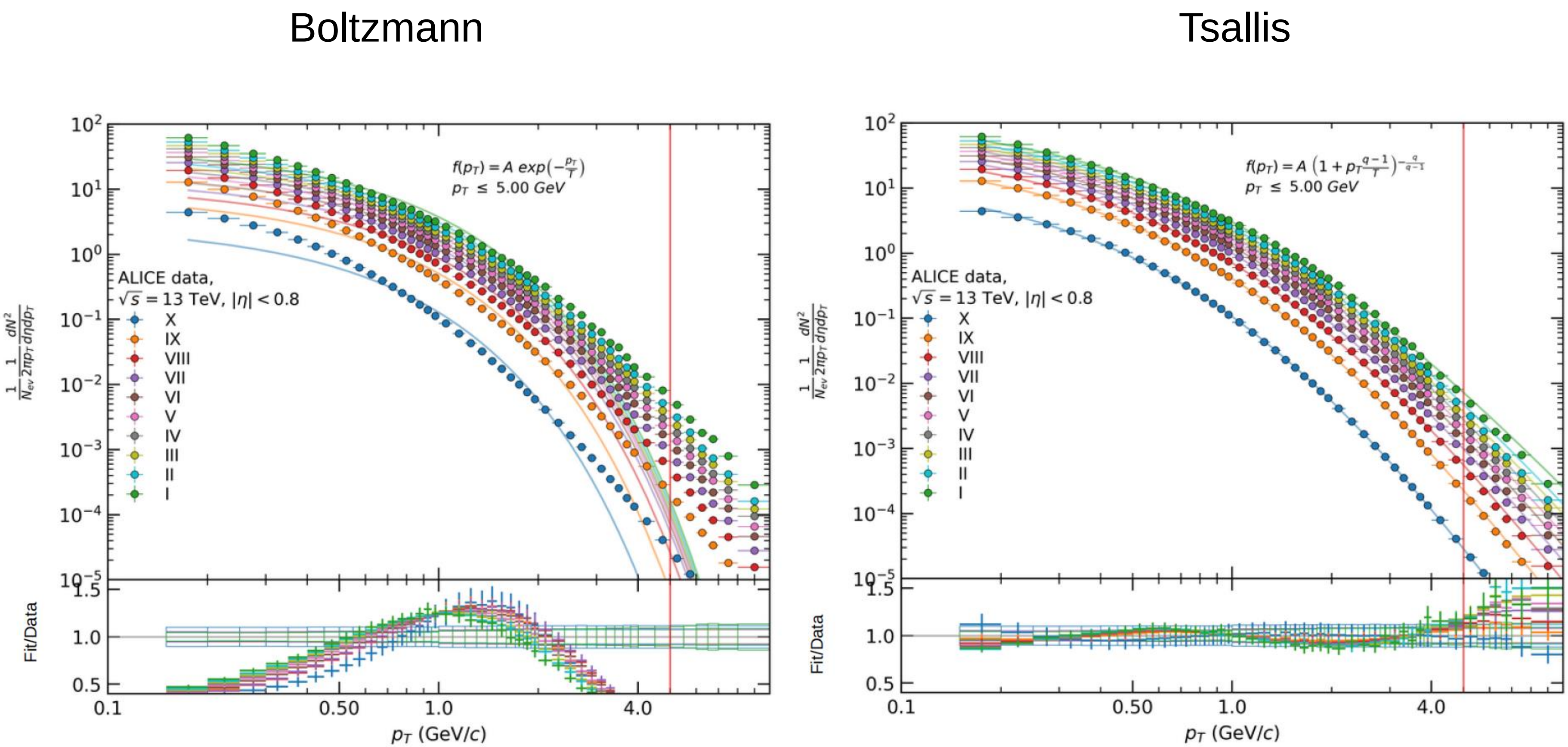


Tsallis



ALICE data in different event multiplicity classes: I – highest, X – lowest class.

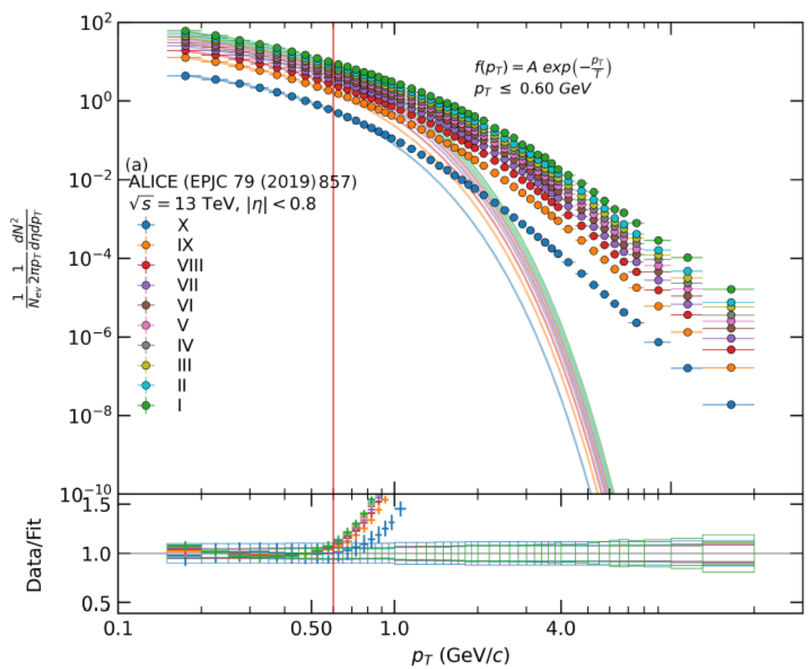
Study of fit ranges



ALICE data in different event multiplicity classes: I – highest, X – lowest class.

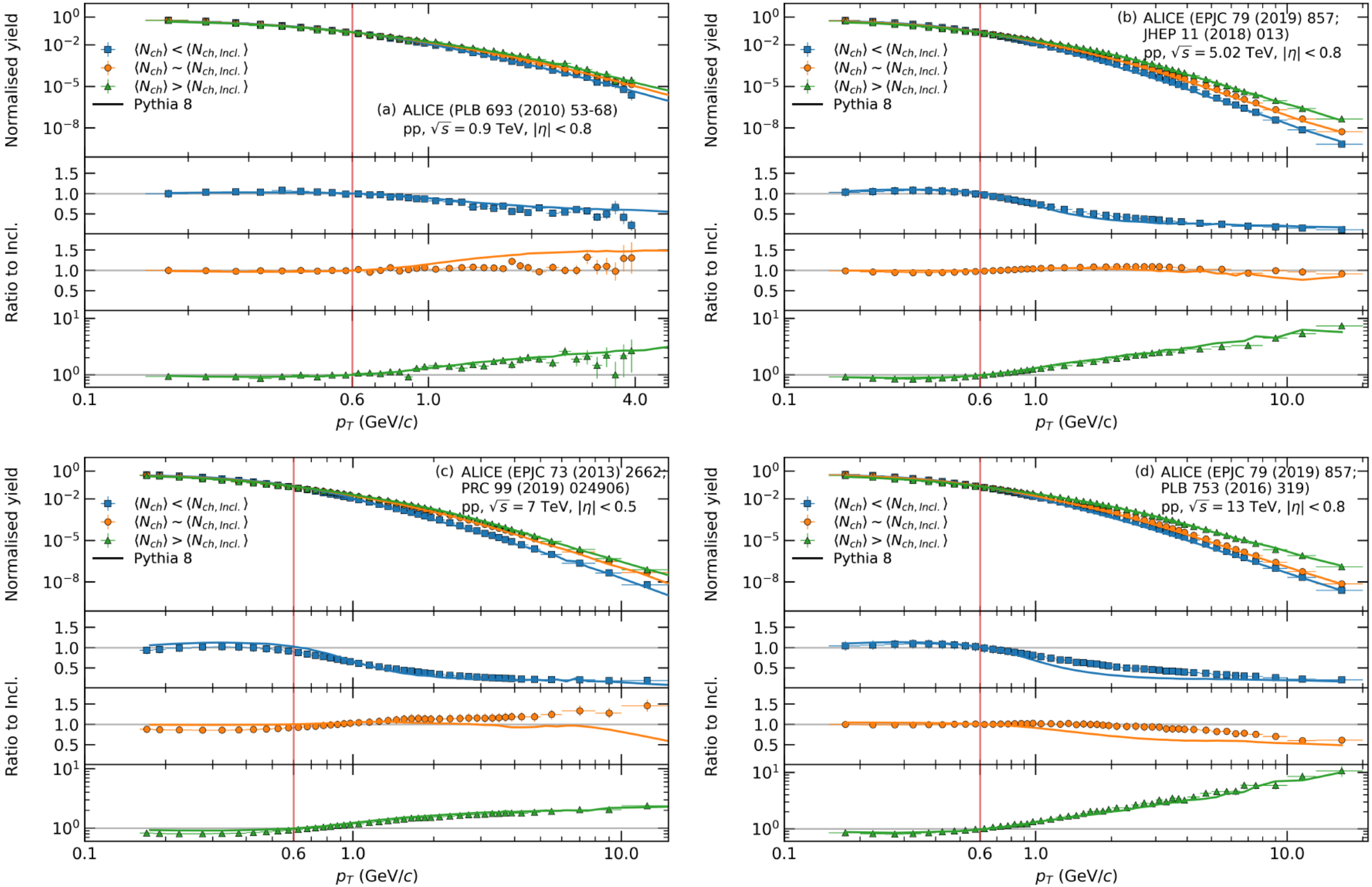
Soft interactions in the pT spectra

- Let's suppose that the region where a Boltzmannian fit gives a satisfactory fit correspond to soft interactions
- Then the pT-spectra may be roughly separated into three regions:
    1) low-pT part representing purely soft interaction
    2) intermediate part where the hard interactions get mixed with soft ones
    3) hard interactions beyond pT ~ 4 GeV



Universal crossing for all LHC energies

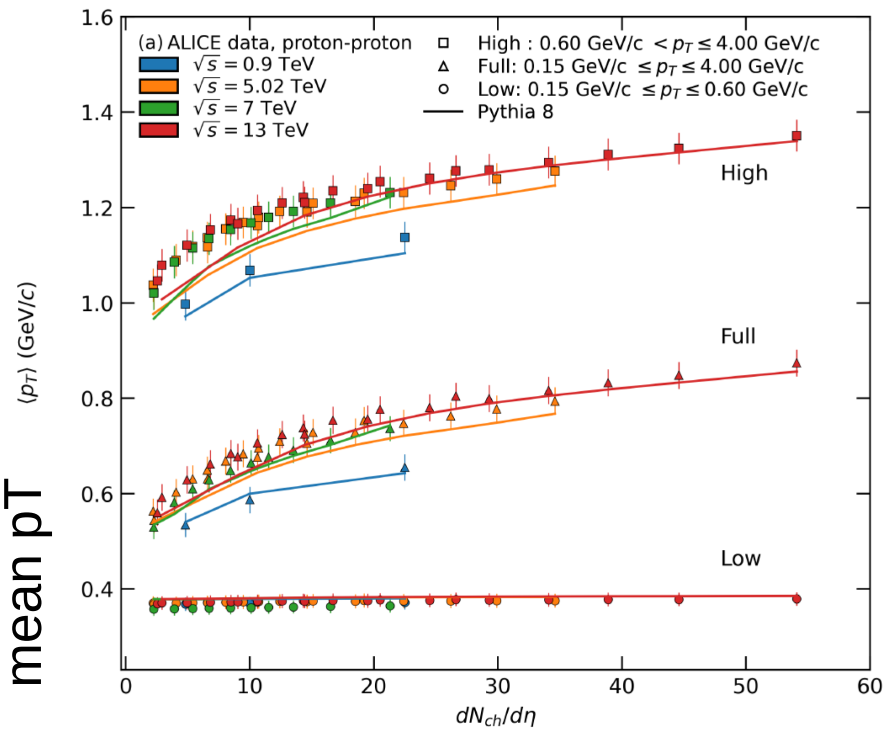
- Crossing at the unity value at ~0.6 GeV: **hint for soft limit?**

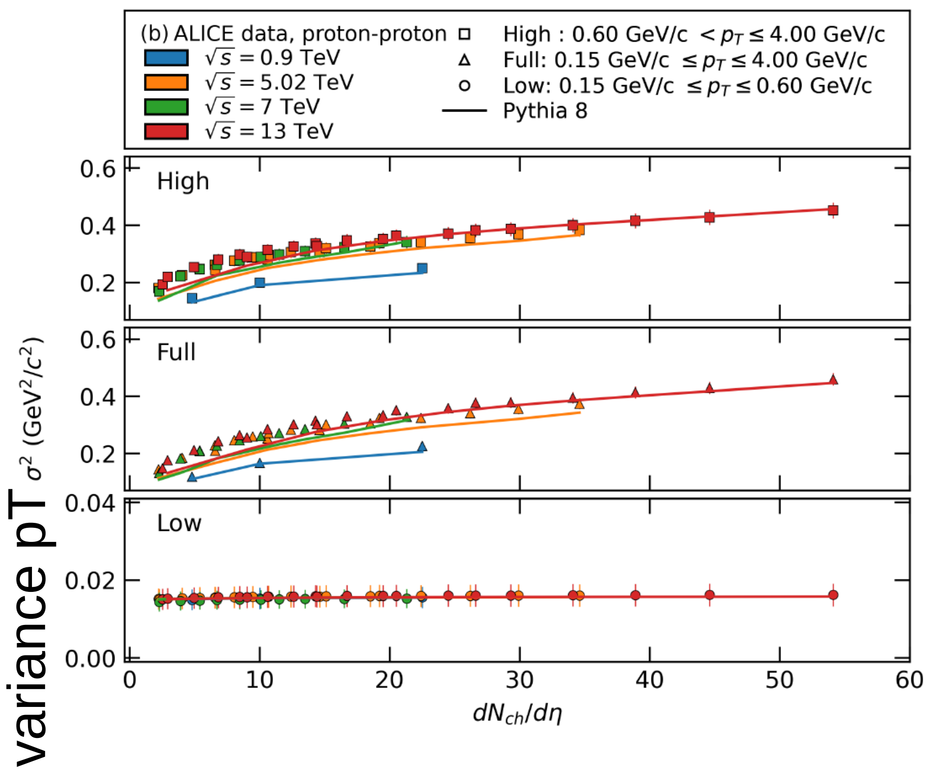


Soft/hard limit?

- Two different observations lead to the same conclusion: the pT-spectra in a given multiplicity class stems from at least two different processes:

1. Predominantly soft region (low-p_{T}): 0.15 GeV$/c \leq p_{\mathrm{T}} \leq 0.6$ GeV$/c$,
2. Mixed (soft and hard) region (higher-p_{T}): 0.6 GeV$/c < p_{\mathrm{T}} \leq 4$ GeV$/c$.



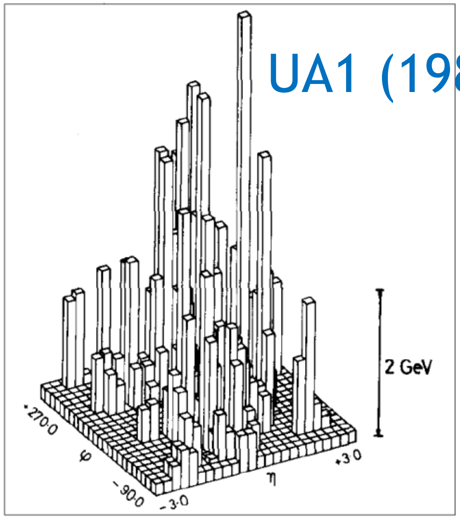


Hedgehogs (erizos) at the LHC?

Introduction to “hedgehog-like” events

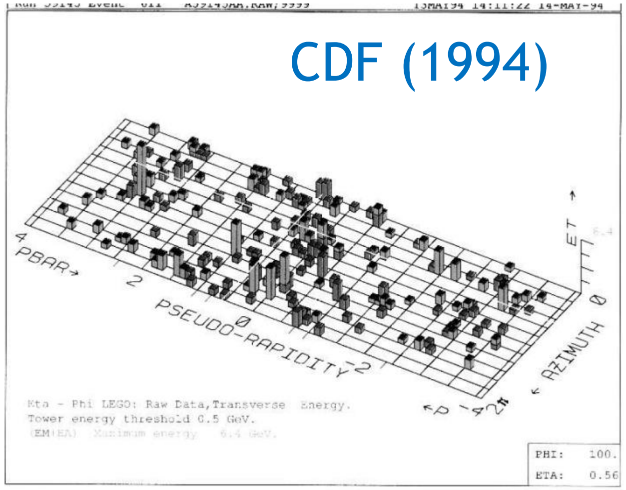
- Looking for the presence of events with a very **extended structure** of low momentum tracks filling in a **uniform way the pseudorapidity-azimuth** (η-φ) space.
- First dedicated analysis of highest transverse energy (E_T) events seen in the UA1 detector at the SppS collider at CERN in proton-antiproton collisions at $\sqrt{s}$ = 630 GeV
- Several isotropic events with E_T ~210 GeV in UA1 observed (even tested for top quark production), no evidence for non-QCD mechanism for these events.
- Similar unusual events observed in p-pbar collisions at $\sqrt{s}$ = 1.8 TeV by CDF’s Run 1 detector with more than 60 charged particles and E_T ~320 GeV
- Called “**hedgehog-like**” events by C. Quigg
- Taken for granted that in these events with high E_T perturbative aspects of QCD dominate the event properties: multi-jet events.

UA1 (1987)



UA1 Collaboration, Zeit. für Phys. C, V. 36, p. 33 (1987)

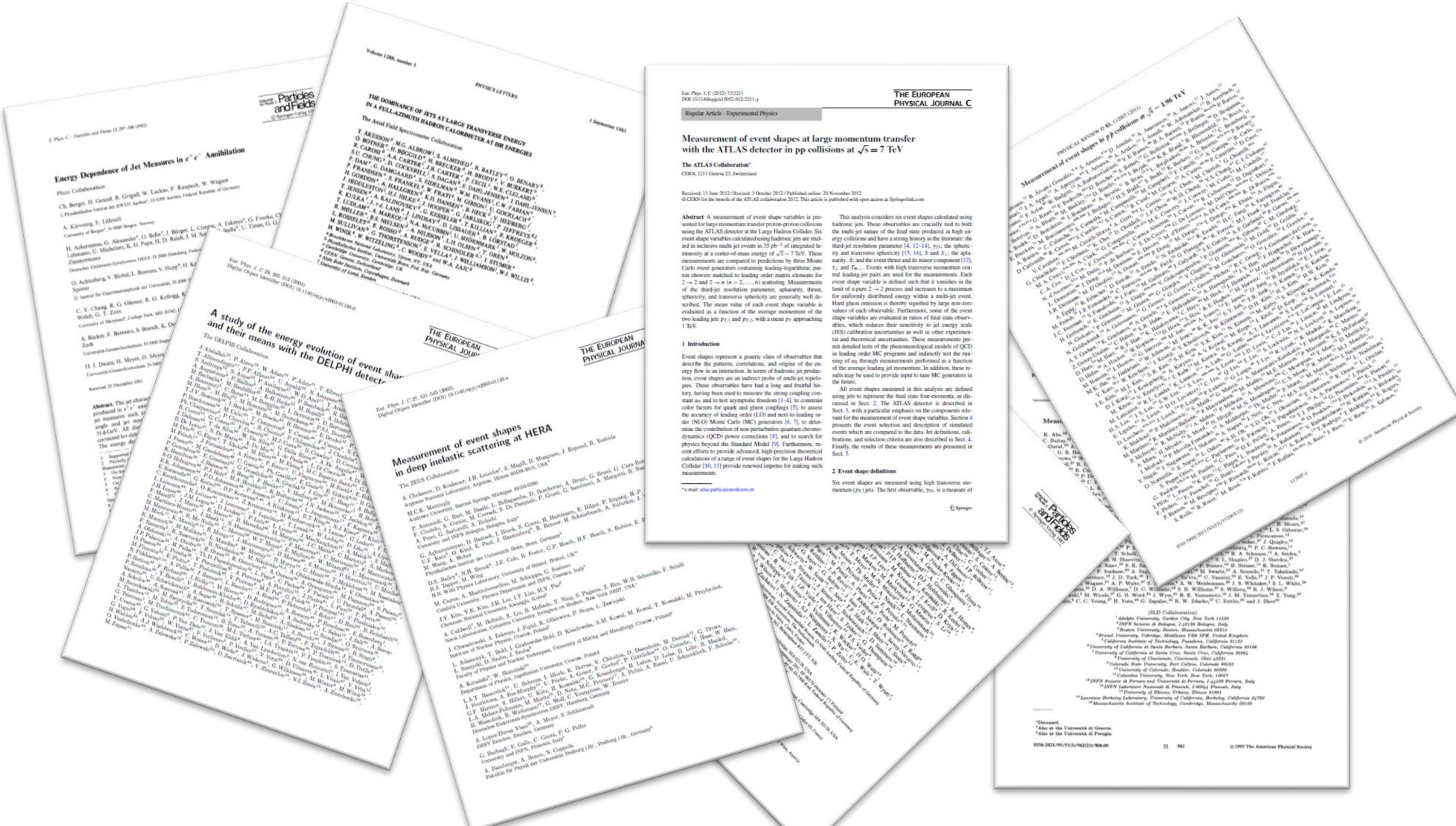
CDF (1994)



C. Quigg, Il Nuovo Cimento, V. 33C, N. 5 p. 327 (2010)

Geometry of the final state: event shapes

- Event shape variables: instrumental in classifying the **geometrical and topological configurations** of the final-state particles produced in high-energy collisions at PETRA, ISR, SppS, SLD, LEP, HERA, Tevatron and the LHC.



Commonly used event shape variables

- Study the isotropy of the final-state energy distribution by defining the **linearized sphericity tensor of the event**, where the Greek indices denote the x, y, and z components of the momentum of the charged particle *i*. The eigenvalues must satisfy the normalization condition: $\lambda_1 \geq \lambda_2 \geq \lambda_3$ and $\lambda_1 + \lambda_2 + \lambda_3 = 1$.

$$S^{\alpha\beta} = \frac{\sum_i p_i^\alpha p_i^\beta}{\sum_i |\vec{p}_i|^2},$$

$$A = \frac{3}{2}\lambda_3; \quad S = \frac{3}{2}(\lambda_2 + \lambda_3).$$

- **Aplanarity (A)** serves as a measure of how planar an event is. A balanced pencil-like event corresponds to A = 0, and an isotropic event corresponds to A = 1/2.

- **Sphericity (S)** quanties the isotropy of an event, representing the degree to which energy and momentum are evenly distributed in all directions. S= 0 denotes a balanced dijet event, and S = 1 for an isotropic event.

Commonly used event shape variables

• **Centrality**: a measure of how much of the event is contained within the central part of the detector; ranges between 0 and 1, where a pencil-like has C = 0 and a centrally contained event corresponds to C = 1.

$$C = \frac{\sum_i p_{T,i}}{\sum_i E_i},$$

$$T = 1 - \max_{\hat{n}} \frac{\sum_i |\vec{p}_{\mathrm{T},i} \cdot \hat{n}|}{\sum_i |\vec{p}_{\mathrm{T},i}|},$$

• **Transverse thrust**: a widely used event shape ranging from 0 for a pencil-like topology to 1/3 for a circularly symmetric distribution of particles in the transverse plane.

• **Transverse spherocity**: infrared and colliner safe event shape that ranges from S_0 = 0 for events with back-to-back multijet final states to S_0 = 1 for isotropic event topologies.

$$S_0 = \frac{\pi^2}{4} \min_{\hat{n}_s} \left(\frac{\sum_i |\vec{p}_{T,i} \times \hat{n}_s|}{\sum_i p_{\mathrm{T}_\mathrm{i}}} \right)^2 .$$

Characterisation of high-multiplicity events

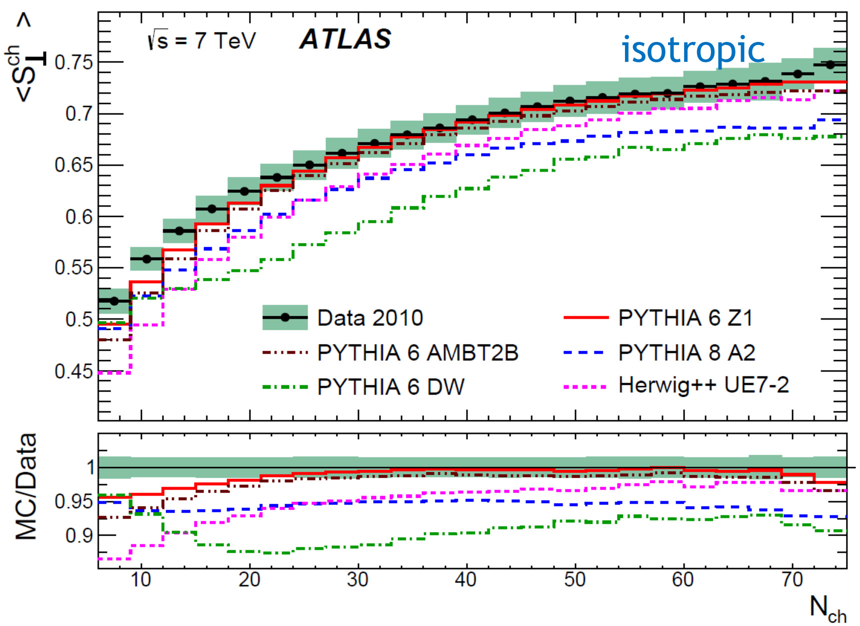
- Attempts to characterise these high-multiplicity events: use of event shapes, i.e. using **transverse sphericity:**

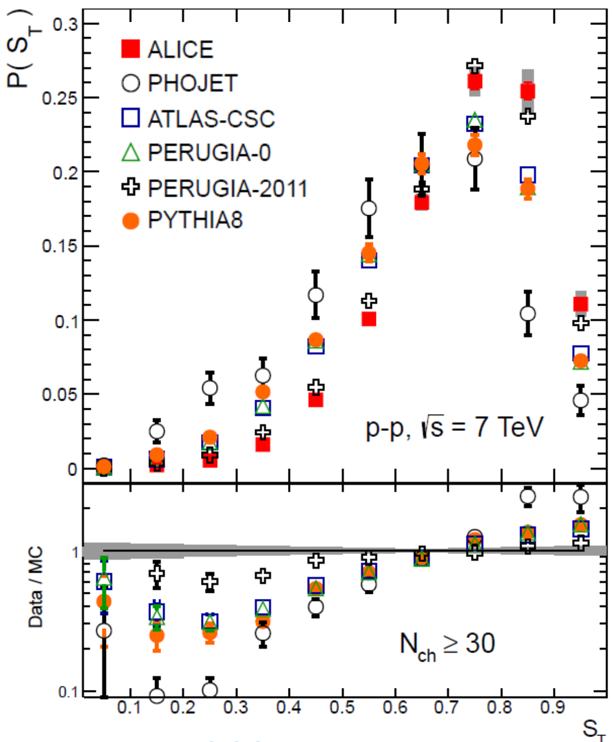
$$S_\perp = \frac{2\lambda_2^{xy}}{\lambda_1^{xy} + \lambda_2^{xy}}, \quad S^{xy} = \sum_i \frac{1}{|\vec{p}_{T,i}|^2} \begin{bmatrix} p_{x,i}^2 & p_{x,i}\,p_{y,i} \\ p_{x,i}\,p_{y,i} & p_{y,i}^2 \end{bmatrix}$$

- Both ALICE and ATLAS observed an **under-estimation of isotropic events by MC generators at high charged multiplicity** ($N_{ch} \geq 30$)

  ✓ Suggest that a very active underlying event (UE) is needed by the MC event generators in order to explain these high-multiplicity events

ATLAS Collaboration, Phys. Rev. D 88, 032004 (2013)





ALICE Collaboration, Eur. Phys. J. C 72 (2012) 2124

Characterisation of high-multiplicity events

- Attempts to characterise these high-multiplicity events: use of event shapes, i.e. using transverse sphericity:

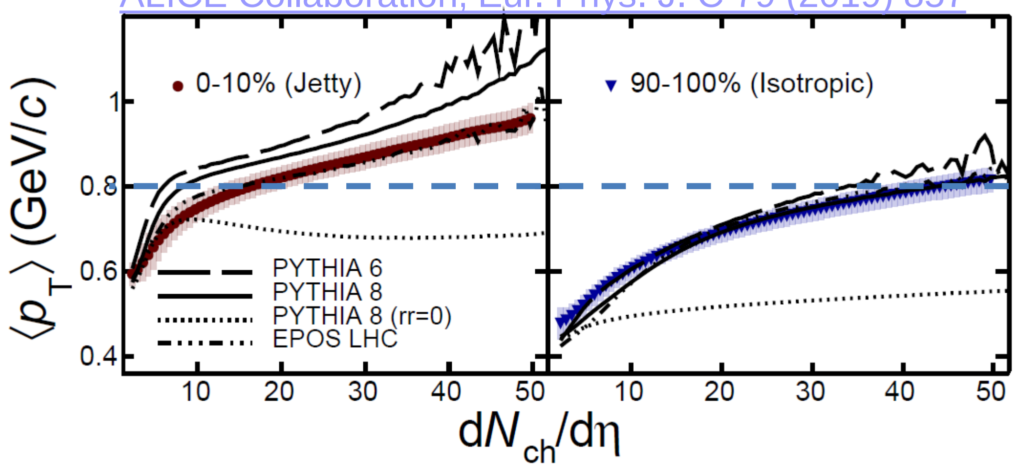
$$S_{\perp} = \frac{2\lambda_2^{xy}}{\lambda_1^{xy} + \lambda_2^{xy}} \; , \quad S^{xy} = \sum_i \frac{1}{|\vec{p}_{\mathrm{T},i}|^2} \begin{bmatrix} p_{x,i}^2 & p_{x,i}\, p_{y,i} \\ p_{x,i}\, p_{y,i} & p_{y,i}^2 \end{bmatrix}$$

- Both ALICE and ATLAS observed an under-estimation of isotropic events by MC generators at high charged multiplicity ($N_{ch} \geq 30$)

  ✓ Suggest that a very active underlying event (UE) is needed by the MC event generators in order to explain these high-multiplicity events

- ALICE measurement shows that $<p_T>$ as a function of N_{ch} in isotropic events was found to be smaller than that measured in jet-like events, and that **for jet-like events, the $<p_T>$ is over-estimated by PYTHIA 6 and 8 models.**

ALICE Collaboration, Eur. Phys. J. C 79 (2019) 857



Characterisation of high-multiplicity events

- Attempts to characterise these high-multiplicity events: use of event shapes, i.e. using transverse sphericity:

$$S_{\perp} = \frac{2\lambda_2^{xy}}{\lambda_1^{xy} + \lambda_2^{xy}} \,, \quad S^{xy} = \sum_i \frac{1}{|\vec{p}_{\mathrm{T},i}|^2} \begin{bmatrix} p_{x,i}^2 & p_{x,i}\,p_{y,i} \\ p_{x,i}\,p_{y,i} & p_{y,i}^2 \end{bmatrix}$$

- Both ALICE and ATLAS observed an under-estimation of isotropic events by MC generators at high charged multiplicity ($N_{ch} \geq 30$)

  ✓ Suggest that a very active underlying event (UE) is needed by the MC event generators in order to explain these high-multiplicity events

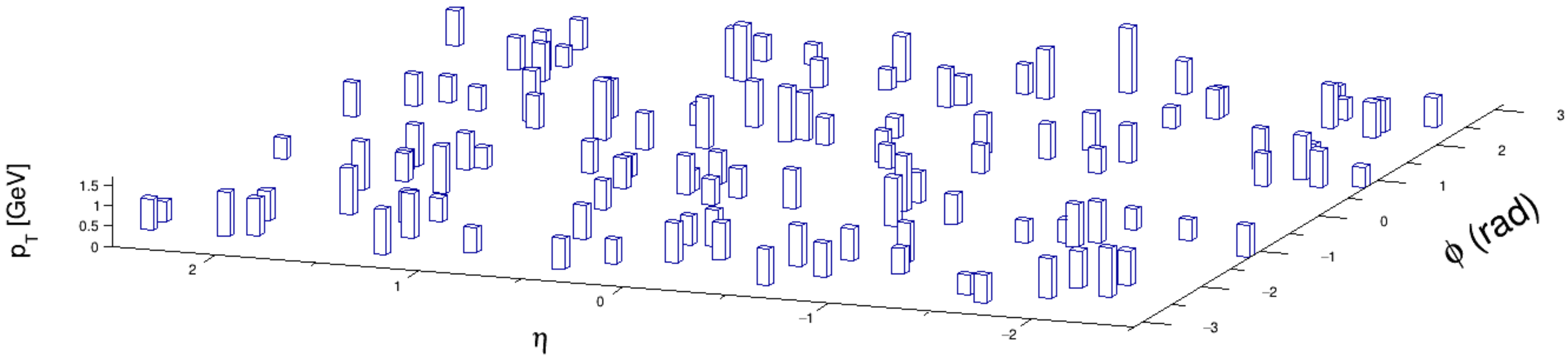
- ALICE measurement shows that $\langle p_T \rangle$ as a function of N_{ch} in isotropic events was found to be smaller than that measured in jet-like events, and that for jet-like events, the $\langle p_T \rangle$ is over-estimated by PYTHIA 6 and 8 models.

- Recently, **a new event shape parameter, flattenicity**, was proposed [A. Ortiz, G. Paic, Rev. Mex. Fis. Suppl. 3 (2022) 4, 040911] that allows one to identify and characterise high-multiplicity events with a quasi-isotropic distribution in a wide pseudorapidity range in proton-proton collisions.

- MC event generators are able to model “hedgehog” events, which opens the possibility to study their properties and find a potential way to experimentally trigger these events.

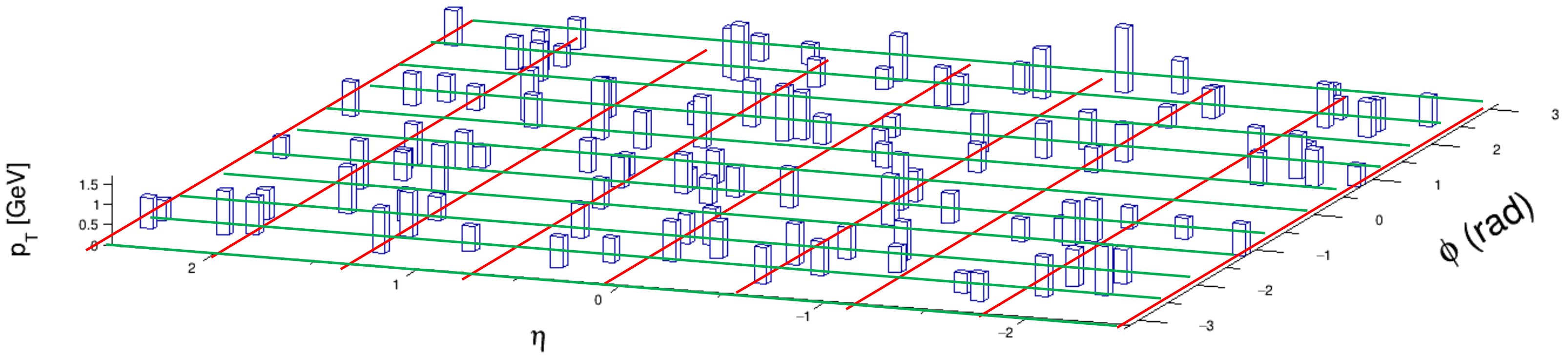
Calculating flattenicity

- The idea: find out how uniform the p_T of tracks is distributed in a given event!



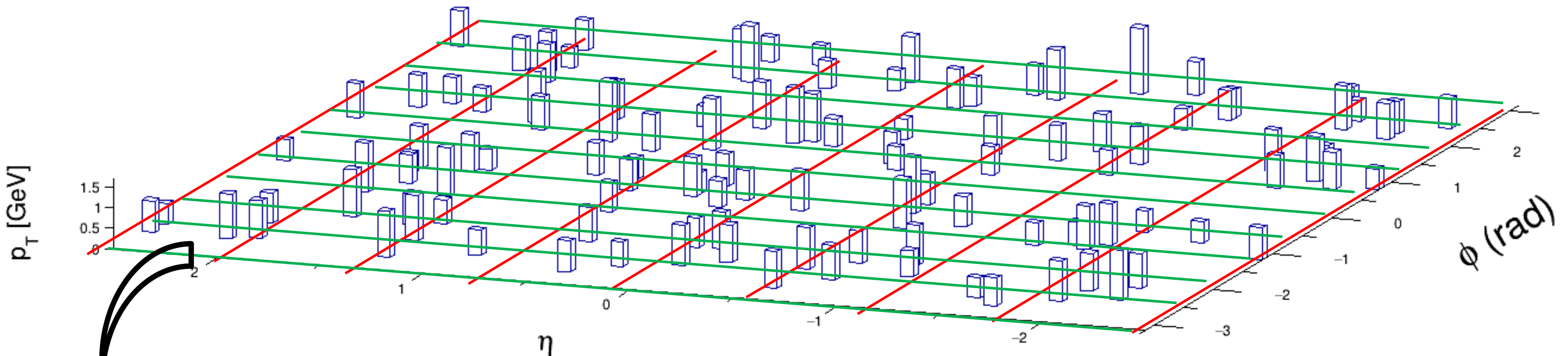
Calculating flattenicity

- Build 10 x 12 grid in (η-φ) space:



Calculating flattenicity

- Build **10** x **12** grid in (η-φ) space:



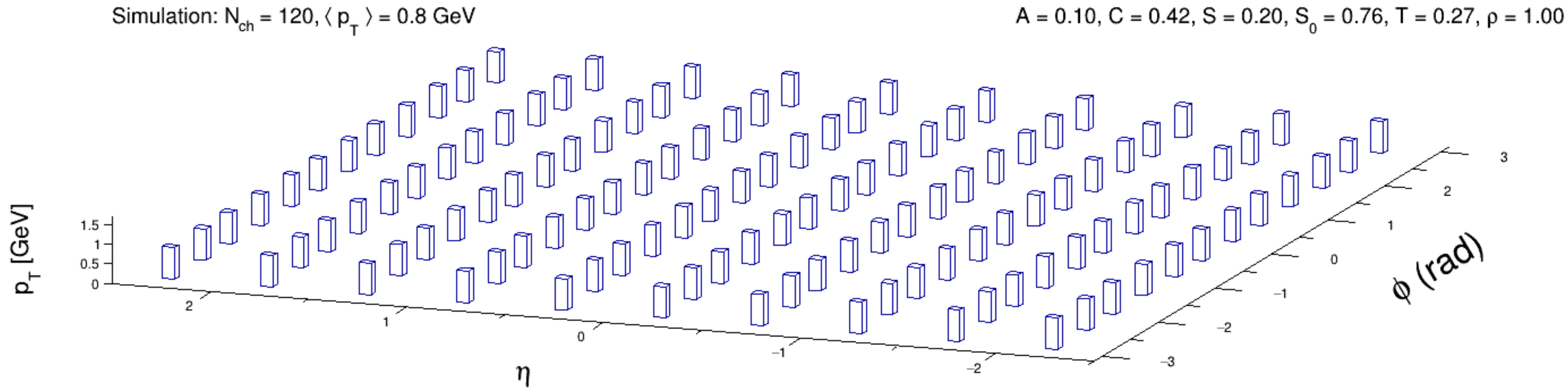
In each cell, the average transverse momentum is calculated: $p_{\mathrm{T}}^{\mathrm{cell}}$

- Event-by-event, the relative standard deviation of the $p_{\mathrm{T}}^{\mathrm{cell}}$ distribution is obtained.
- Events with isotropic distribution of particles ("**hedgehogs**") are expected to have ρ = 1.

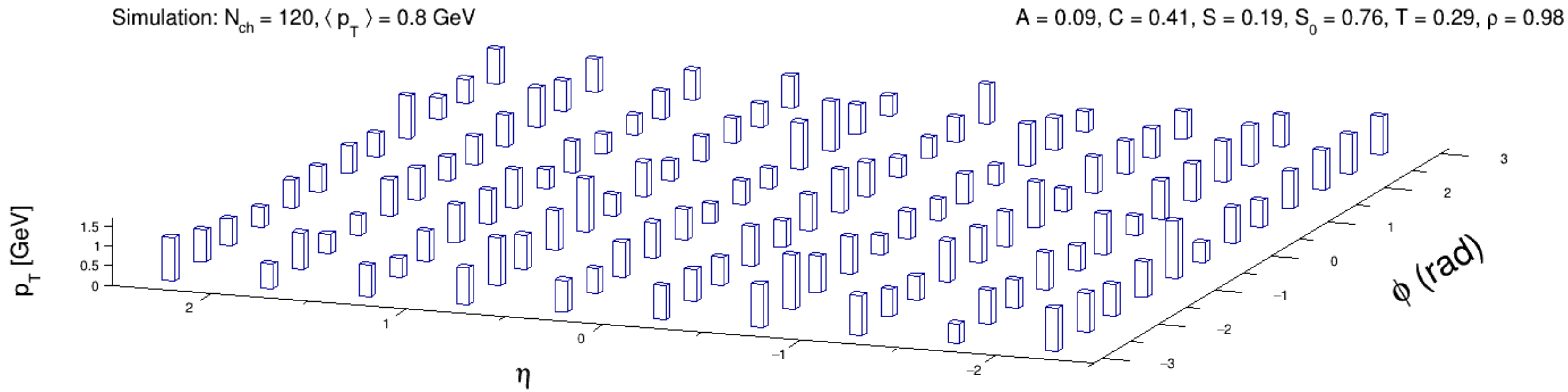
$$\rho = 1 - \frac{\sqrt{\sum_{i=1}^{i=120}\left(p_{\mathrm{T}}^{\mathrm{cell},i} - \langle p_{\mathrm{T}}^{\mathrm{cells}}\rangle\right)^2 / \mathrm{N}_{\mathrm{cell}}^2}}{\langle p_{\mathrm{T}}^{\mathrm{cells}}\rangle},$$

Benchmark hedgehog-like structures

ρ = 1

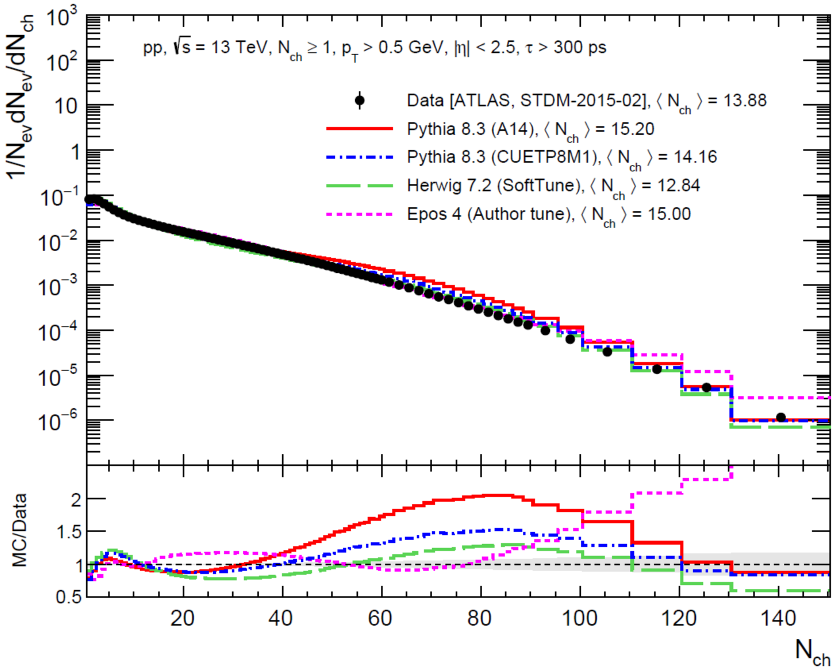


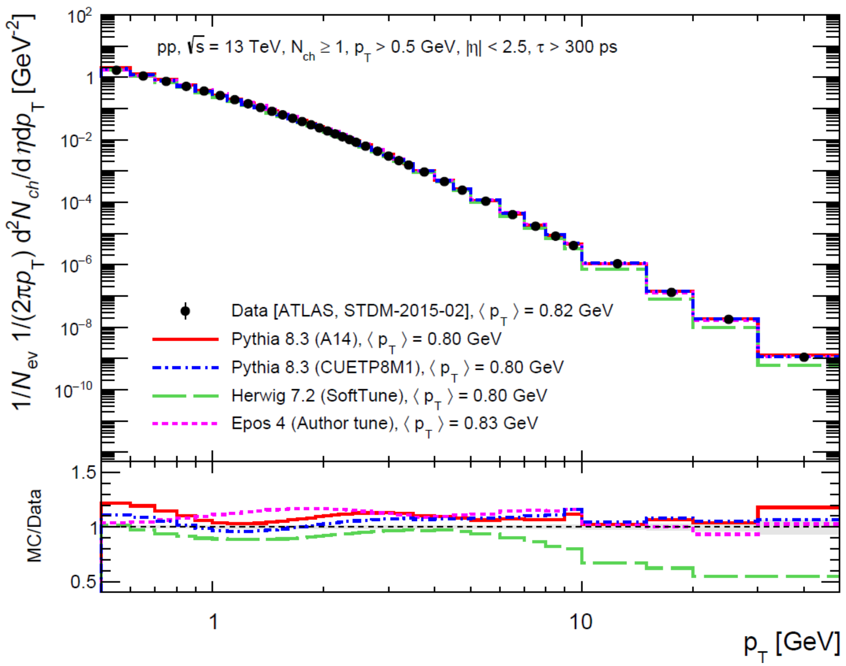
ρ = 0.98



Flattenicity using different MC generators

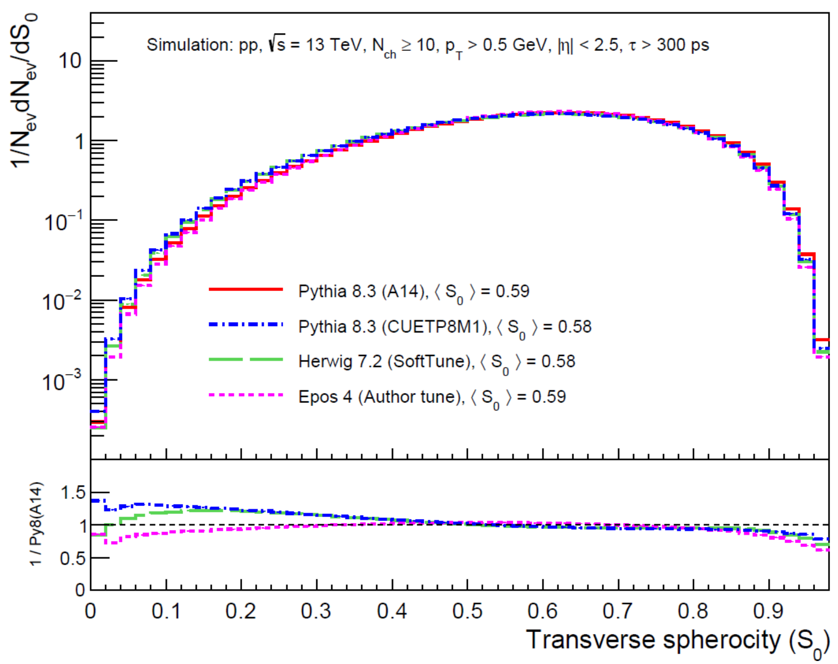
- Two sets of inelastic events, including non-diffractive and diffractive components, were simulated using **Pythia 8.309**: ATLAS A14 tune and CMS CUETP8M1 tune.
- **Herwig 7.2.0** with SoftTune based on the MMHT2014 LO PDF
- Recently released **EPOS 4.0.0** framework using authors tune
- First, **revise the performance** of these MC models in reproducing the 13 TeV pp collision data.

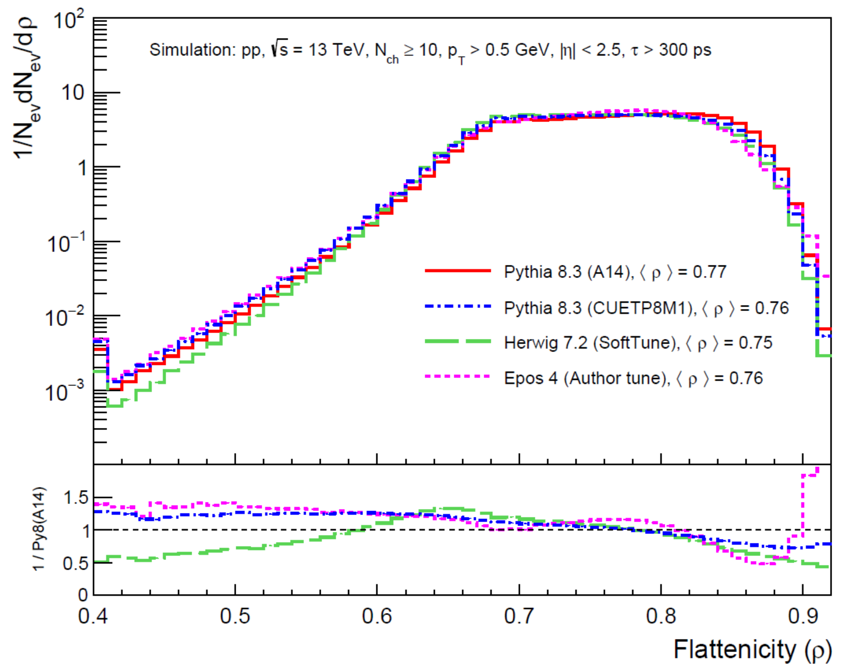




Flattenicity using different MC generators

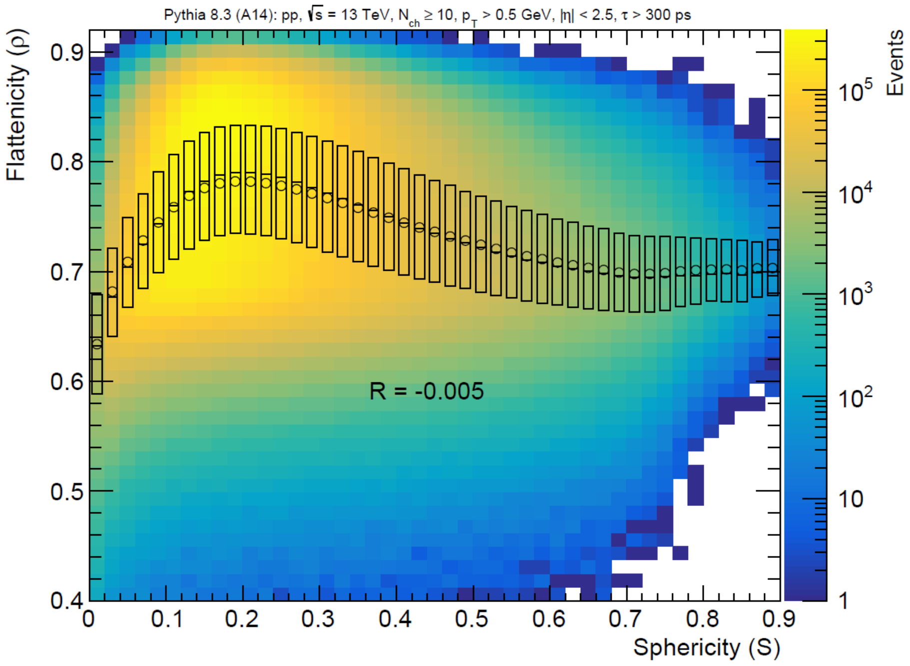
- Two sets of inelastic events, including non-diffractive and diffractive components, were simulated using **Pythia 8.309**: ATLAS A14 tune and CMS CUETP8M1 tune.
- **Herwig 7.2.0** with SoftTune based on the MMHT2014 LO PDF
- Recently released **EPOS 4.0.0** framework using authors tune
- Then, **compare transverse spherocity and flattenicity** for the 4 MC settings

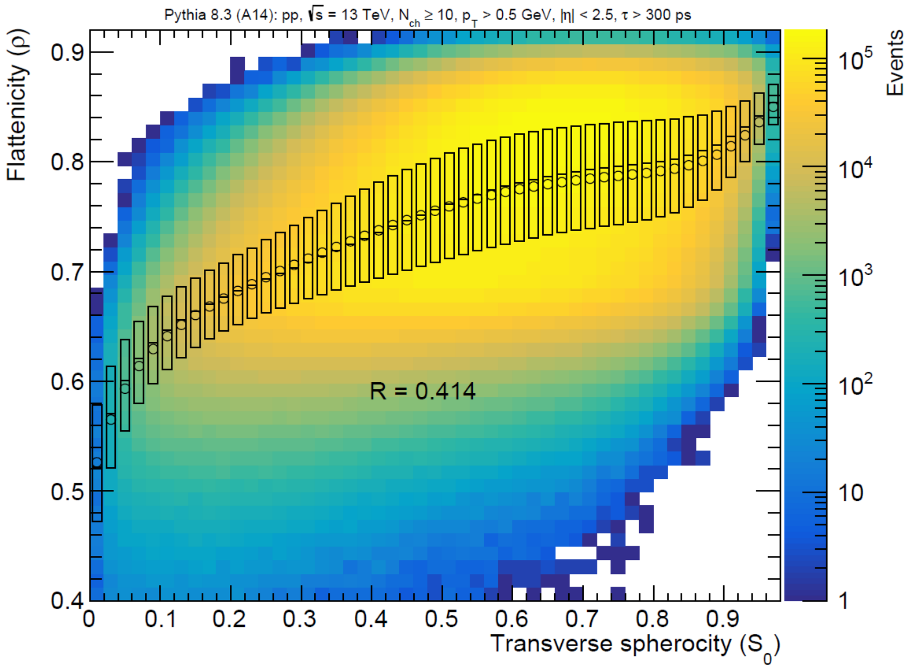




Flattenicity correlations

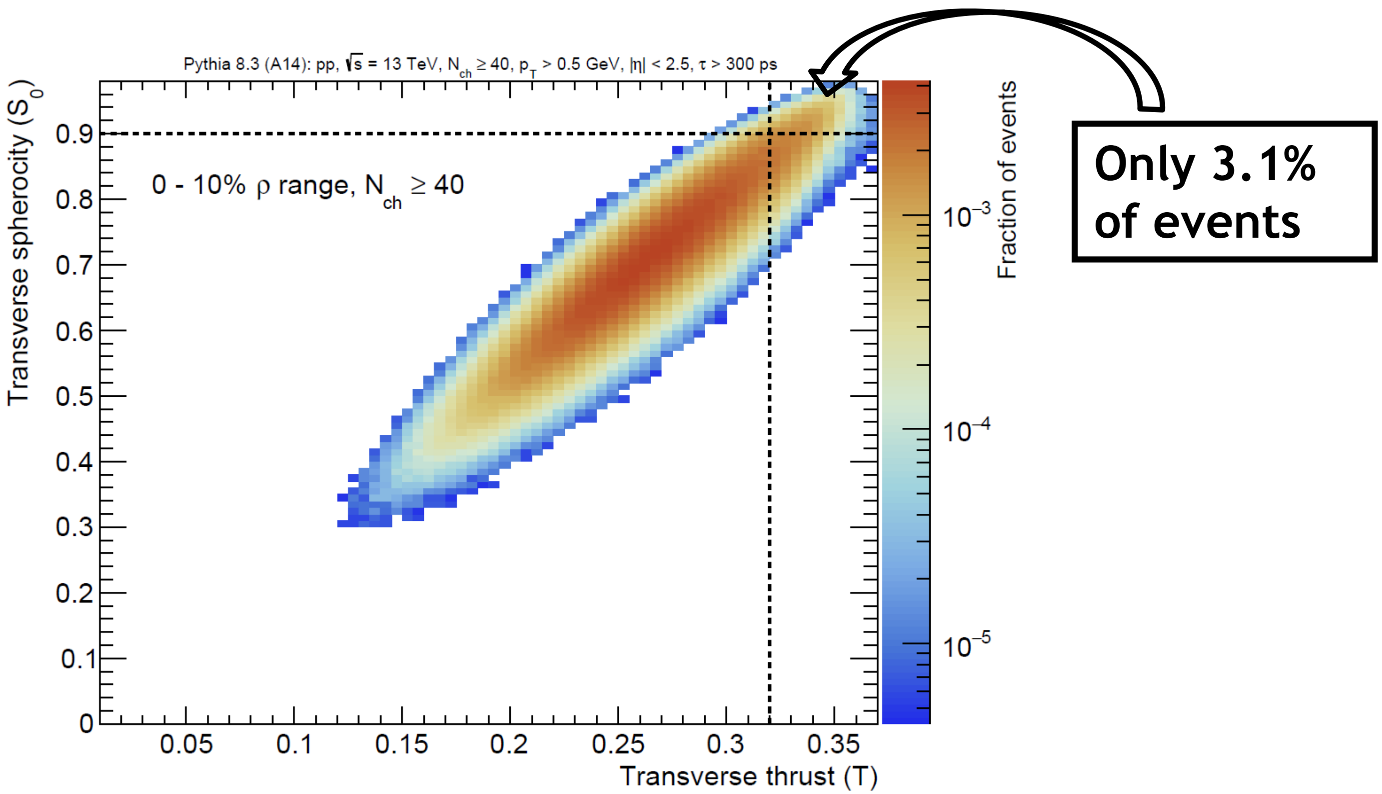
- To demonstrate flattenicity's value in identifying isotropic events and its complementary information about the global shape of an event, we study its correlation with other event shape variables.
- Overall, there is clear indication that while flattenicity is related to other event shape variables, it **provides distinct and complementary** info of the isotropy of events





Flattenicity correlations

- Classify the **top 10%** of events in the distributions of flattenicity, transverse spherocity, and transverse thrust for each multiplicity class as **isotropic events.**
- Our observation is that for the highest charged-particle multiplicity class, only 3.1% of events meet all the three criteria: clearly indicates that **flattenicity selects a different subset** of events as compared to widely used S_0 and T.



Conclusions

- We notice that, traditionally, collision data observables are presented as **mean values** of more differential distributions, such as mean charged-particle multiplicity ⟨Nch⟩, mean of transverse momentum ⟨pT⟩, mean values of anisotropic flow, etc.

- The agreement or disagreement *of the means of a model with the data* may not really point to the details of the result, given that different models may have the same means as the data but with different underlying assumptions.

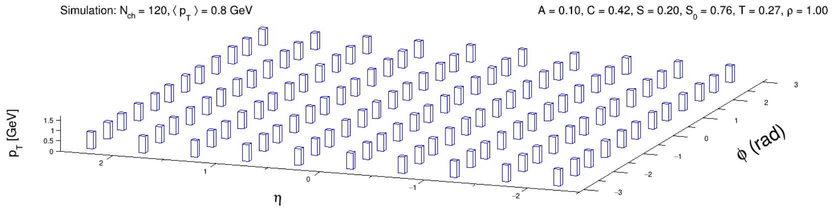
- We observe that the mean transverse momentum ⟨pT⟩ is highly sensitive to the selected pT range, and it is not sensitive within the soft region (low-pT) region studied of 0.15 GeV ≤ pT ≤ 0.6 GeV.

- **Universal crossing point** of the ratios to the inclusive spectrum at pT ≈ 0.6 GeV.

- We are in presence of two different QCD processes: when studying **collective effects**, it is important to notice that when extending the pT range above the 0.6 GeV, one risks important contributions of hard QCD nature.

Conclusions

- Hedgehog events **have never been seriously studied** in pp collisions at the LHC.
- Flattenicity - the new event structure parameter – allows one to identify the hedgehog events and observe the evolution of events from jetty to hedgehog type.
- pT spectra as a function of flattenicity already studied in ALICE, see Paola Vargas talk
- When compared to other event shape variables widely used in the literature, such as transverse spherocity, we found that flattenicity is able to **identify** a subset of isotropic events with **hedgehog-like structures**.
- More experimental measurements using flattenicity are needed! Look for “hedgehog” events in data!



Muchas gracias por su atención!