THE proton-proton collisions in all their splendor at high multiplicity

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Plan of the talk:

- Intriguing similarities at large p_T in pp and PbPb collisions

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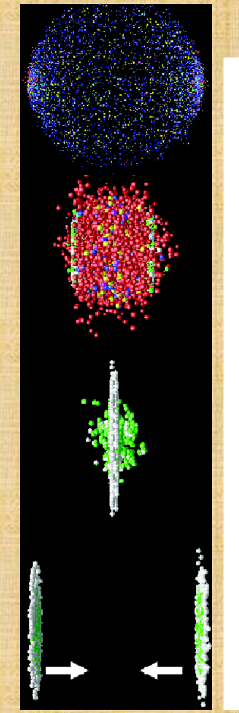
- Parton energy loss at very high-multiplicity

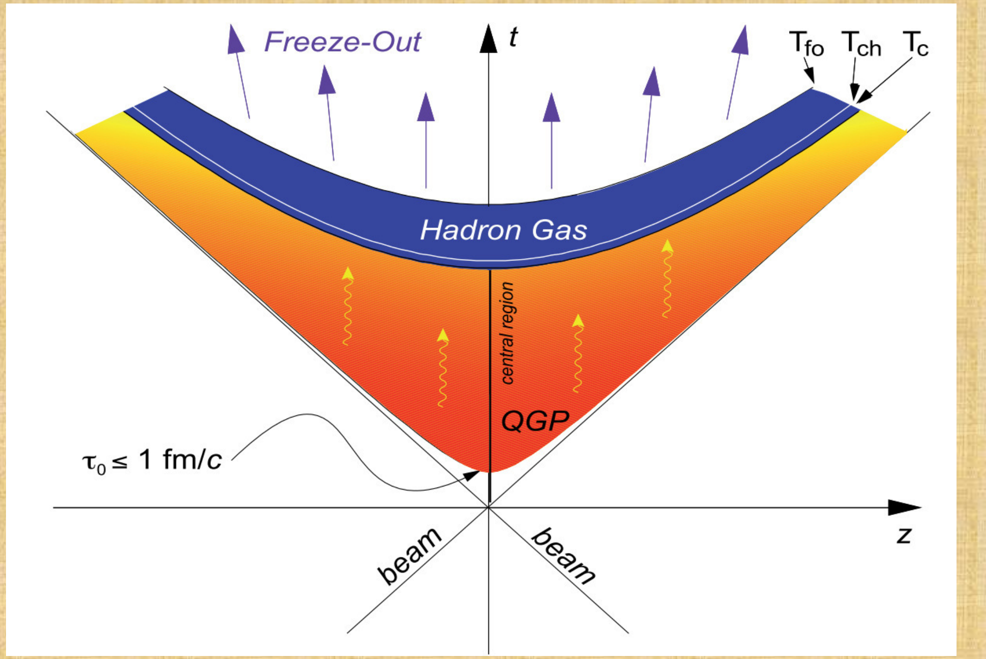
arXiv:1905.06918 (2019)

Intriguing similarities at large p_T in pp and PbPb collisions

Is the energy density playing an important role in pp and PbPb collision for the rising in R_{AA} and p_T?

High Energy Nucleus-Nucleus Collisions





- Lorentz Contraction
- Strongly-interacting matter is formed: this is the non-perturbative regime of QCD.
- If interactions are strong enough, it may reach local thermal equilibrium. Then, it expands like a fluid.

Introduction:

- Expected to have a medium in heavy-ion collisions.
- This created medium can cause of the parton energy loss in heavy-ion collisions.
- Experimentally, the medium effects are extracted by means of the nuclear modification factor:

$$\mathbf{R_{AA}(p_T)} = \frac{\mathbf{1}}{\mathbf{< T_{AA} >}} \frac{\mathbf{dN_{AA}/dp_T}}{\mathbf{d\sigma_{pp}/dp_T}}$$

$$< \mathbf{T_{AA}} >= \frac{< \mathbf{N_{coll}} >}{\sigma^{\mathrm{NN}}_{\mathrm{INEL}}}$$

Accounting for the flux of partons per collision.
determined from the Glauber model.

In the absence of Nuclear Effects : R_{AA} = 1.

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Yield in PbPb

$$\mathbf{R_{AA}(p_T) = \frac{1}{< T_{AA} >} \frac{dN_{AA}/dp_T}{d\sigma_{pp}/dp_T}}$$

Nuclear Thickness Function

Yield in Minimum Bias pp

$$\mathbf{< T_{AA} > = \frac{< N_{coll} >}{\sigma_{INEL}^{NN}}}$$

Accounting for the flux of partons per collision.
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In the absence of Nuclear Effects : R_{AA} = 1.

Introduction:

$$R_{AA}(p_T) = \frac{1}{< T_{AA} >} \frac{dN_{AA}/dp_T}{d\sigma_{pp}/dp_T}$$

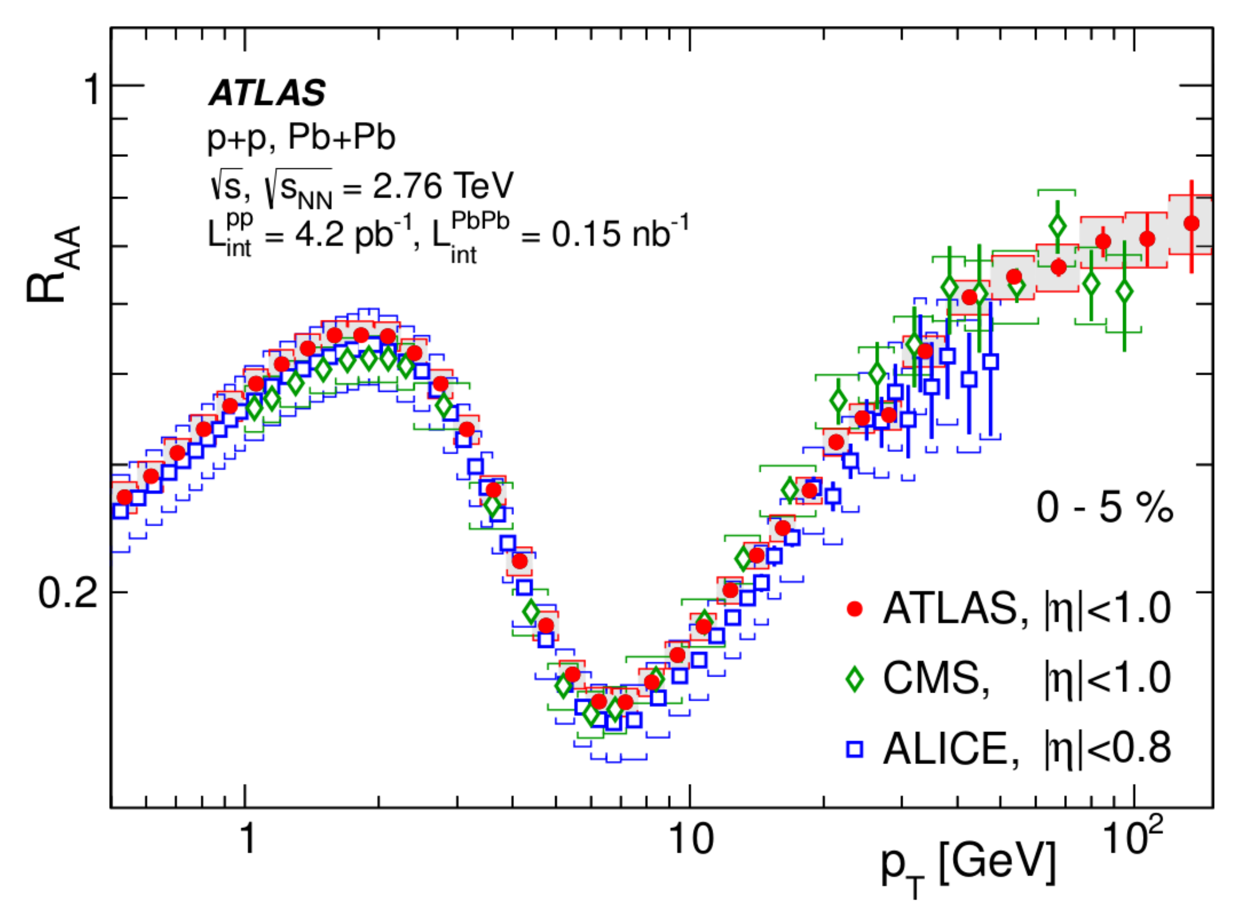
shape of R_{AA} *vs* p_T gives information about the parton energy loss.

BUT

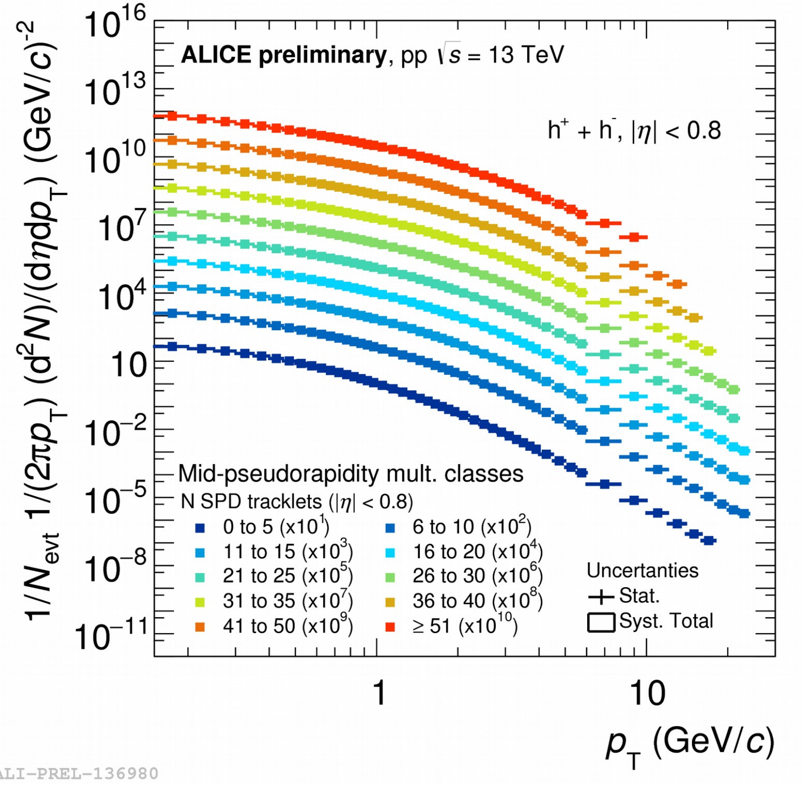
At High p_T (p_T > 8 GeV./C): shape of R_{AA} for high-*pT* particles is not fully attributed to the parton energy loss.

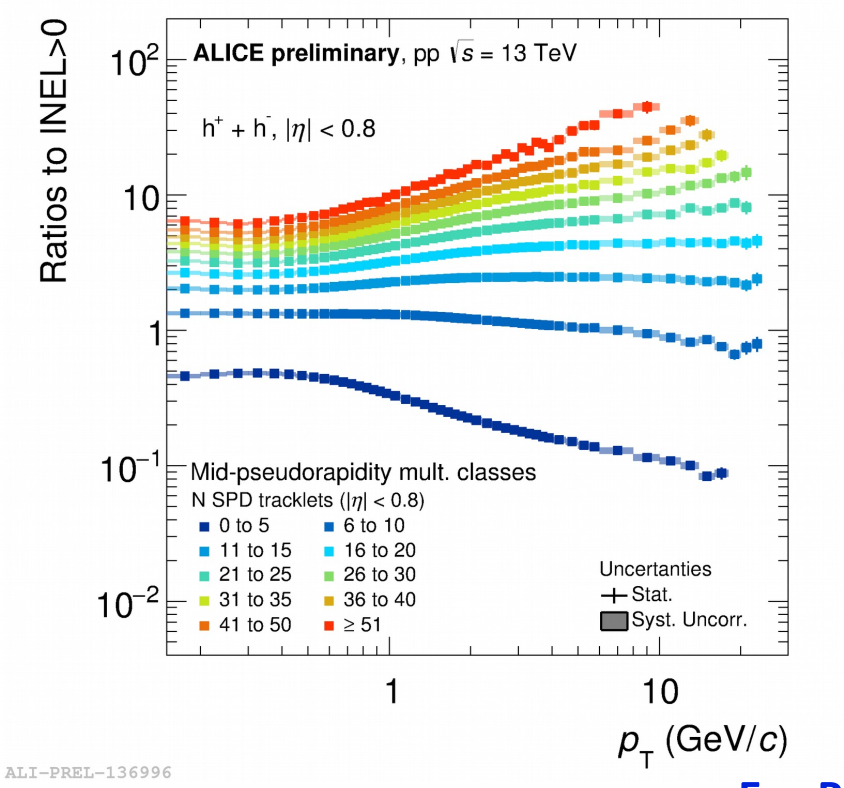
Because

I will demonstrate here, **a similar shape is observed for the analogous ratios in *pp* collisions, i.e., high-multiplicity p_T spectra normalized to that for minimum-bias events**.



Introduction: P_T distribution in function of multiplicity in pp collisions at 13 TeV





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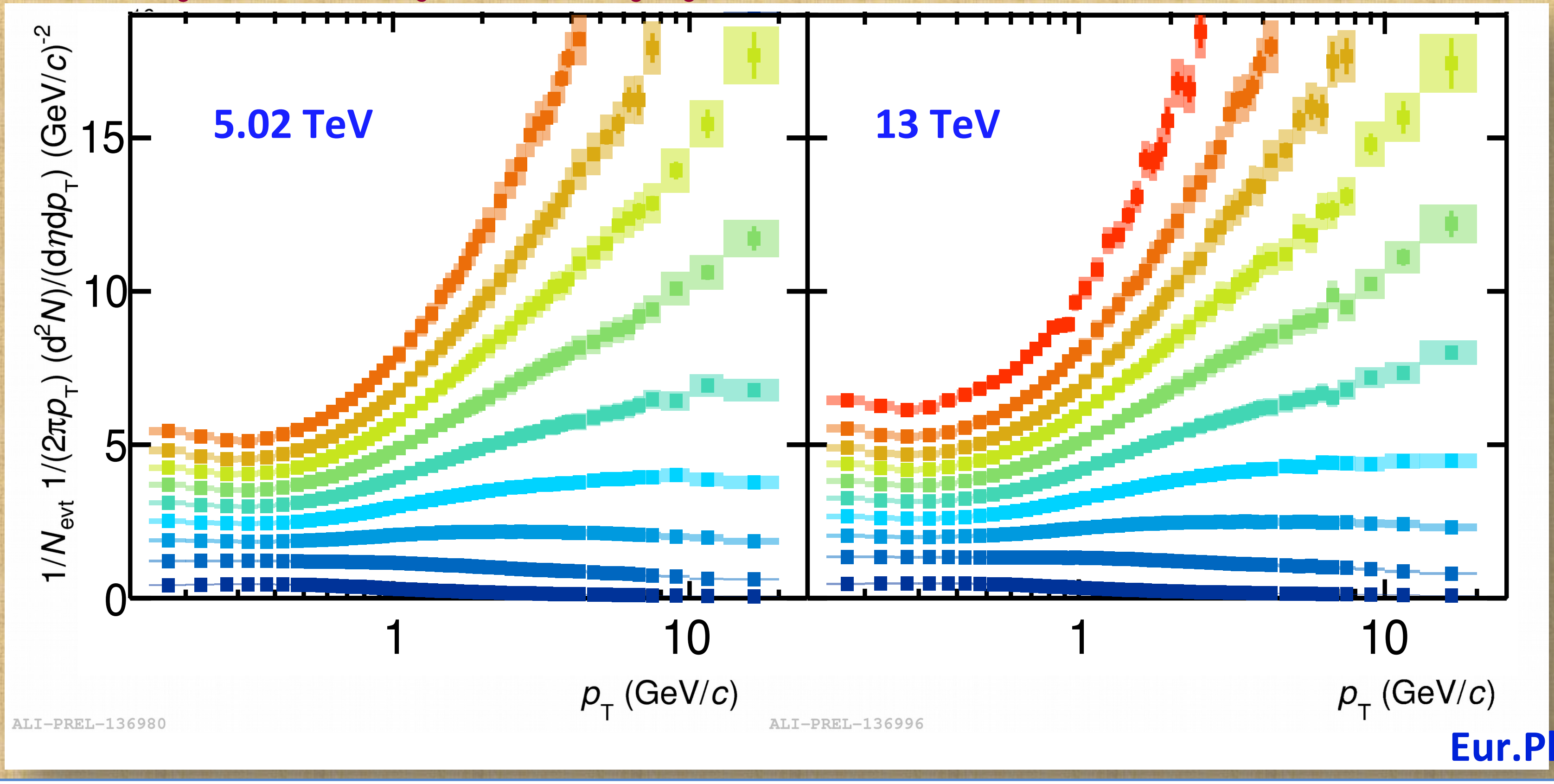
Within a limited multiplicity reach, the **ALICE Collaboration** has shown that such a ratio in pp collisions at 13 TeV exhibits a nonlinear increase with p_T.

Introduction: P_T distribution in function of multiplicity in pp collisions at 13 TeV

Rather perturbing evolution with multiplicity!?
Nonlinear!



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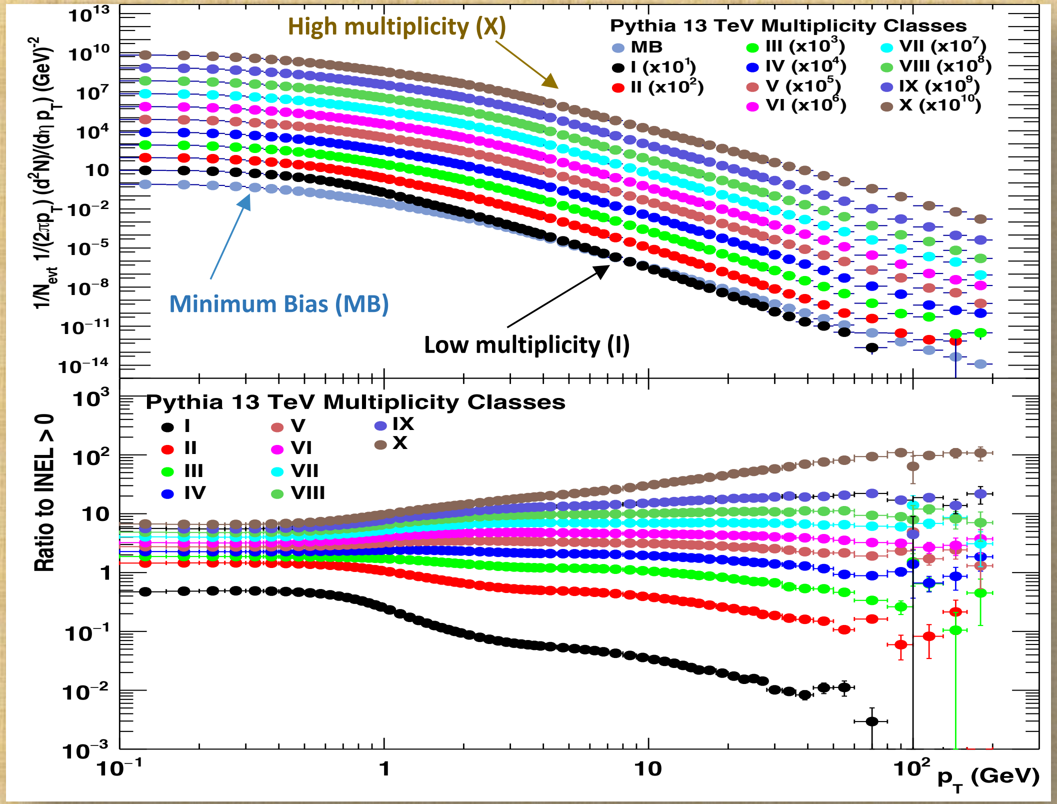
PYTHIA Simulations: Multiplicity classes for pp collisions at 13 TeV

- The multiplicity classes are defined based on the number of primary charged particles *N*ch within |η| < 0.8.
- The different event classes and their corresponding contributions to the inelastic cross section
- Multiplicity classes are similar to ALICE for direct comparison.

Class name	I	II	III	IV	V
N_{ch}	0–5	6–10	11–15	16–20	21–25
fraction	10.45%	15.68%	14.79%	13.78%	12.34%
Class name	VI	VII	VIII	IX	X
N_{ch}	26–30	31–35	36–40	41–50	$\geqslant$51
fraction	10.39%	8.08%	5.78%	6.09%	2.61%

Introduction: P_T distribution in function of multiplicity in pp collisions at 13 TeV

We have simulated pp collisions data at 13 TeV using PYTHIA 8.212 (tune Monash 2013) within ALICE acceptance and calculated the ratios.



For p_T > 8 GeV/c the spectra **become harder with increasing multiplicity**, such a hardening is a feature of hard processes.

$$\textbf{Ratio} = \frac{[\mathbf{p_T\ spectra}]_{\mathbf{Mult.Class}}}{[\mathbf{p_T\ spectra}]_{\mathbf{MB}}}$$

The ratios of the p_T spectra exhibit an **important increase with p_T.**

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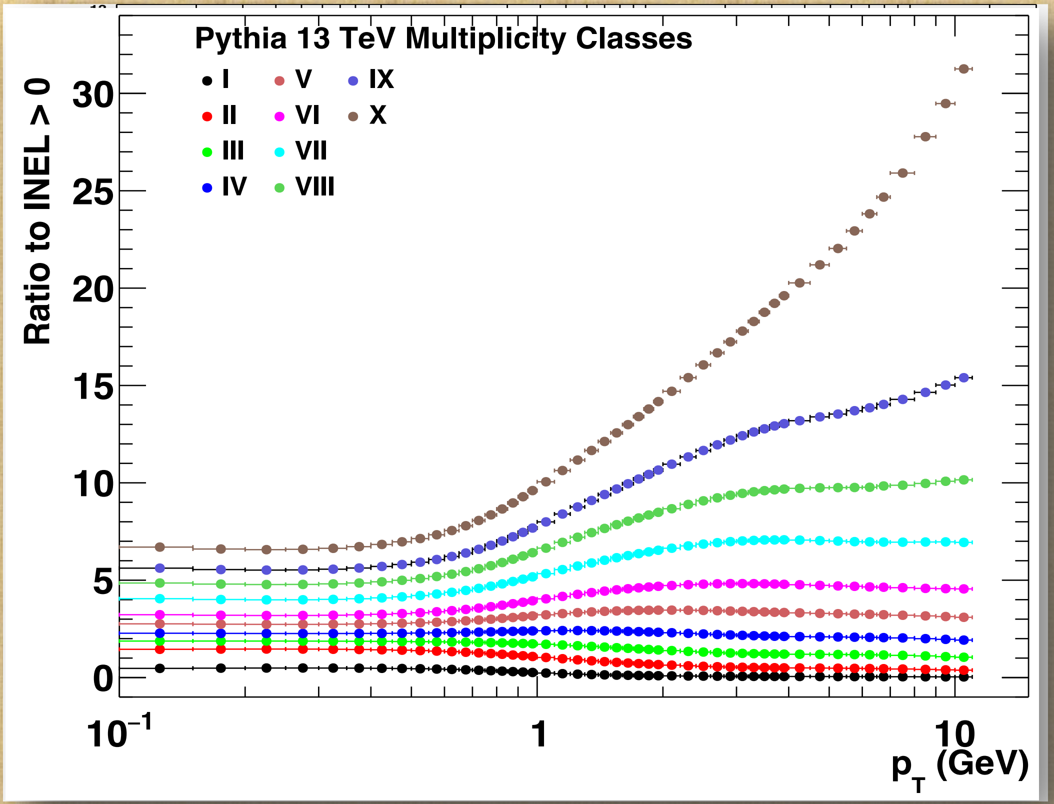

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The ratios of the p_T spectra exhibit an **important increase with p_T.**

Visible in Nonlinear scale!

Similar to the ALICE recent result.

Similar to the one observed in the RAA measured in Pb-Pb collision!!!

How to characterise the p_T spectra in a model independent way

- We believe the best (unbiased) way is to extract the shape of the spectra using the power law exponent where the transverse momentum probability is given to be

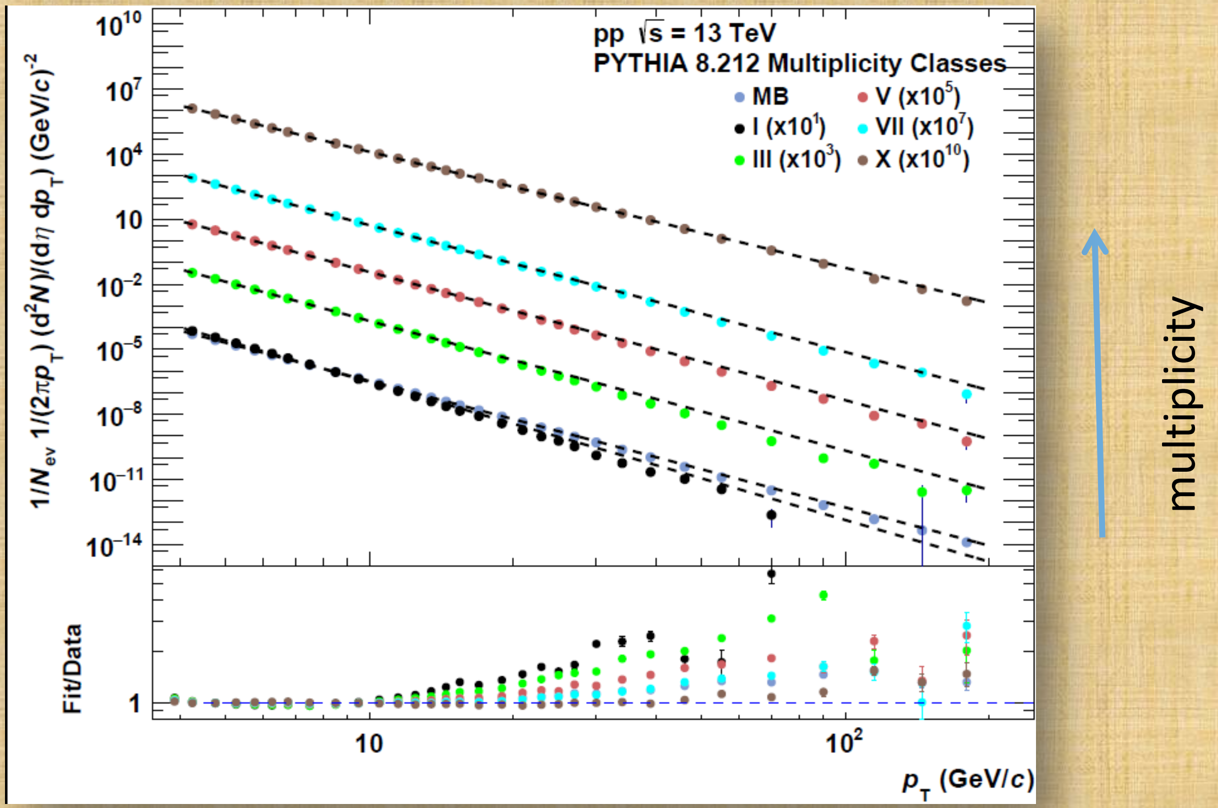
$$\propto p_T^{-n}$$

Above a certain value of transverse momentum. (in our case 6 GeV/c)

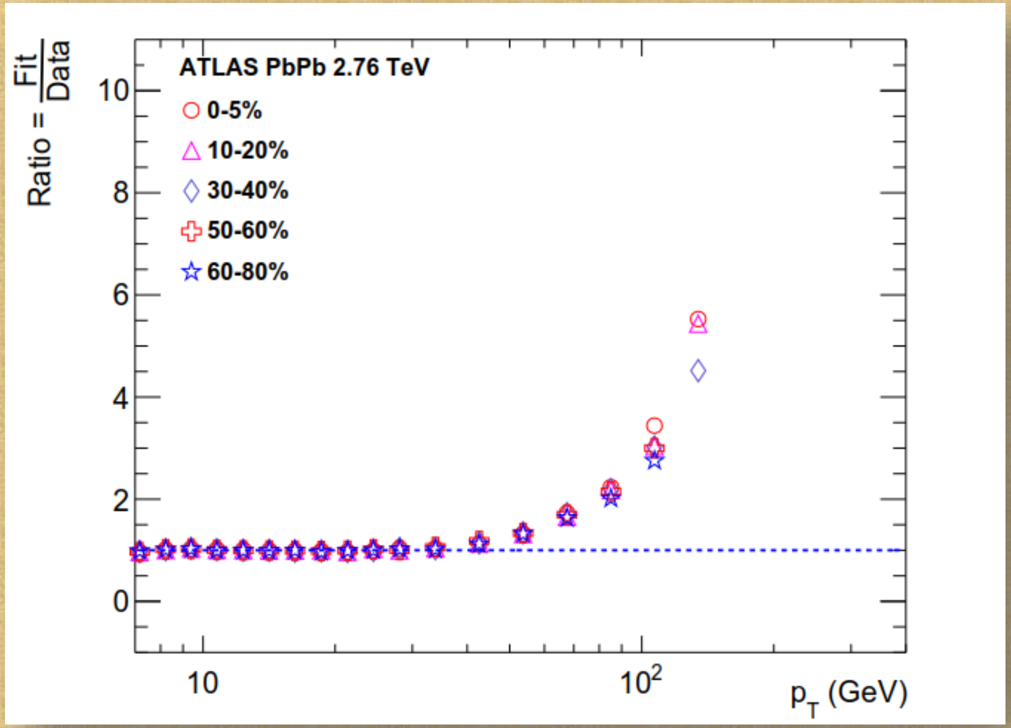
- it is obvious that the p_T spectra cannot be represented by a **single** exponent in a large p_T range so we determined a tangent at every point of the spectra

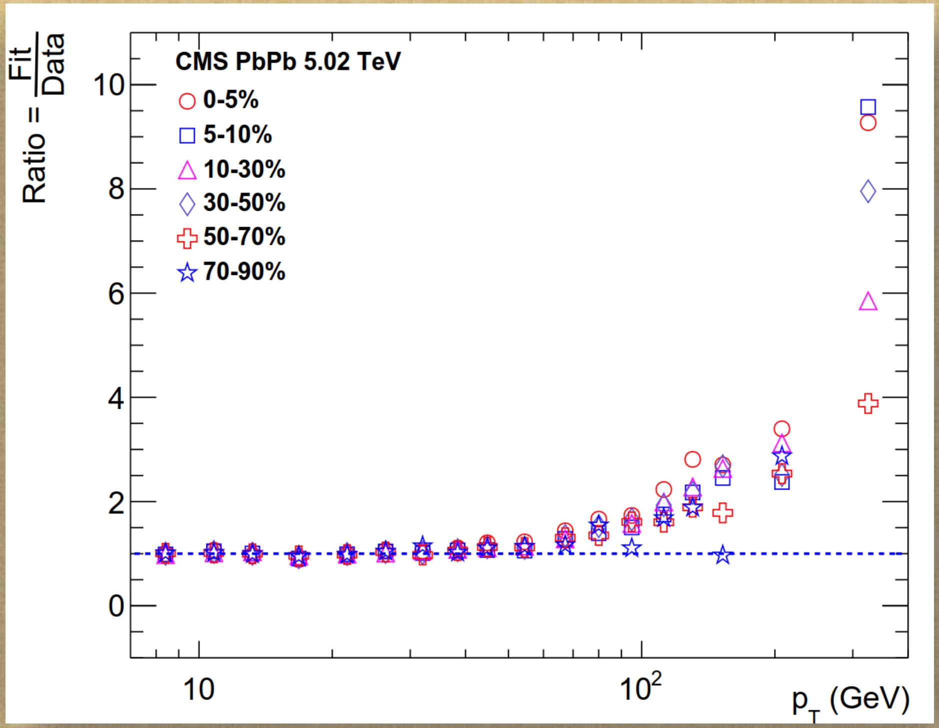
The spectra cannot be fitted with a single exponent !

- **Transverse momentum distributions of charged particles for different multiplicity classes in pp 13 TeV** (simulated with PYTHIA 8.212)

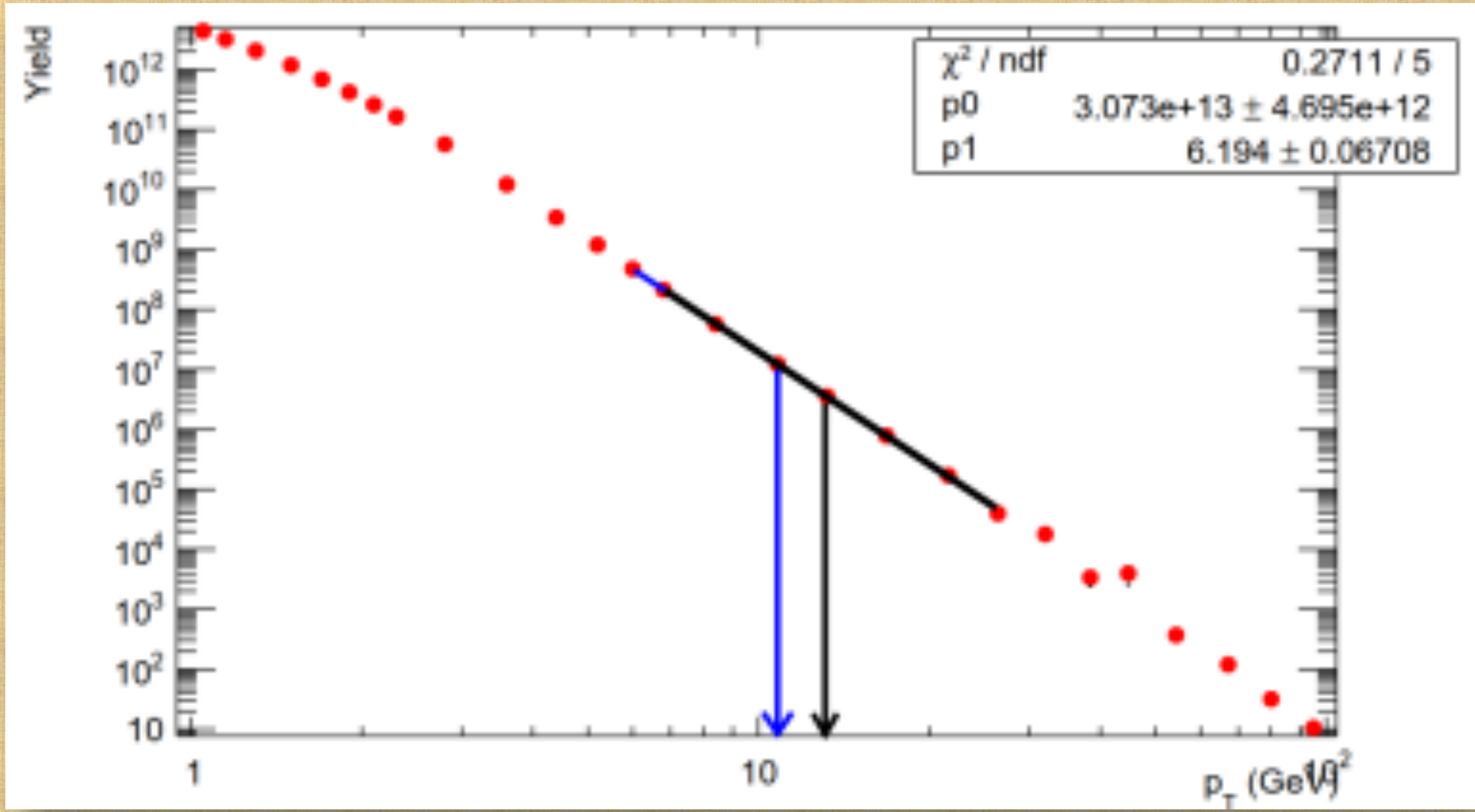


P_T-distribution in PbPb collisions

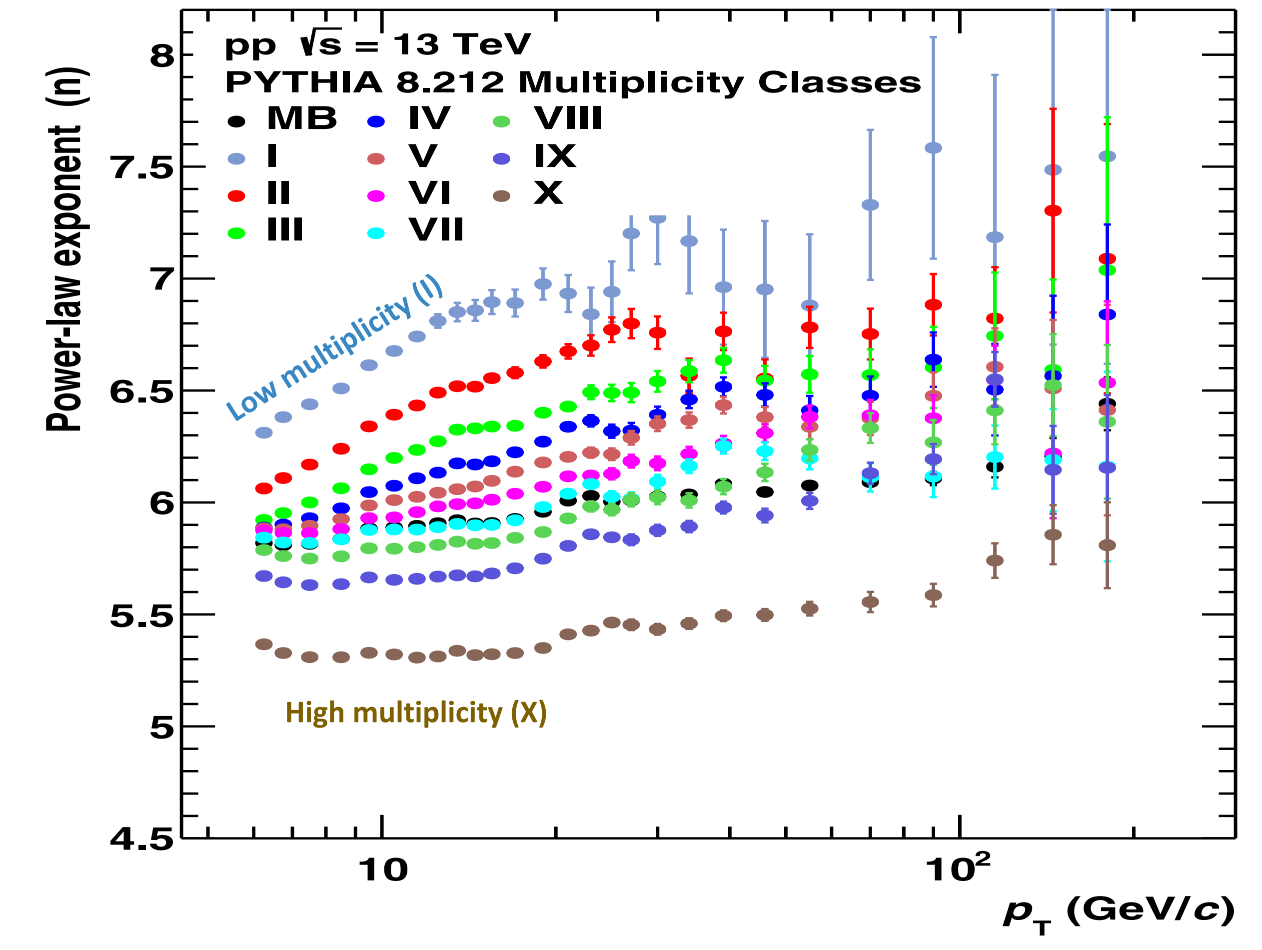




Use a sliding tangent in p_T bins to extract the exponent

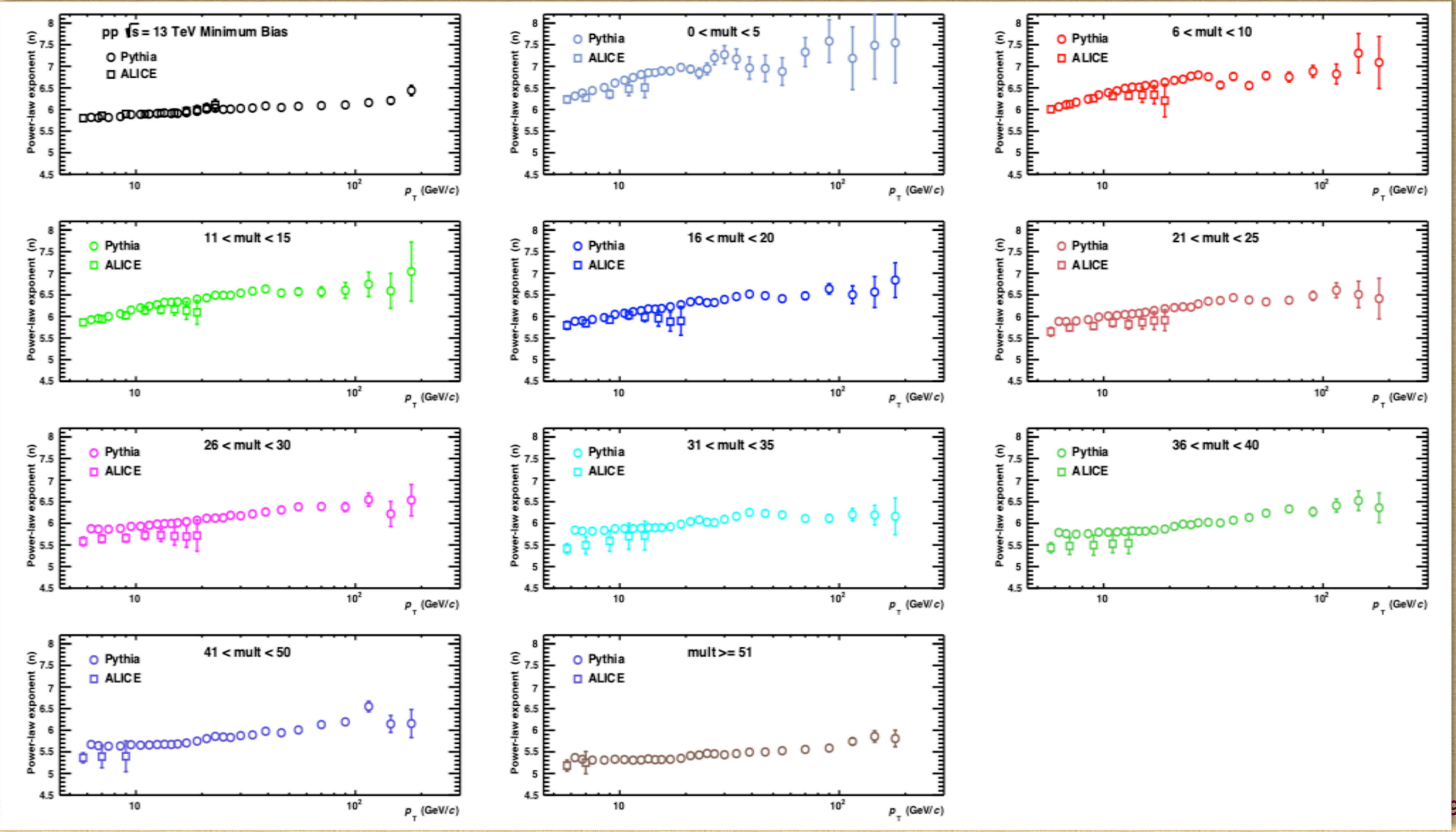


Power-law exponents vs pT for multiplicity classes



- The power-law exponents extracted from the fits
- The exponent has an important dependence on p_T
- At low multiplicities the exponents rise more rapidly than the MB one.
- Above multiplicity ~25 , the spectra tend to have exponents that are smaller than observed for MB.
- All multiplicity classes show tendency to have smaller exponents **(softening of the spectra)** at higher momenta, the tendency getting smaller for high multiplicities

Comparison of exponents obtained from ALICE data and PYTHIA 8.212 in pp 13 TeV



Bjorken x_T scaling

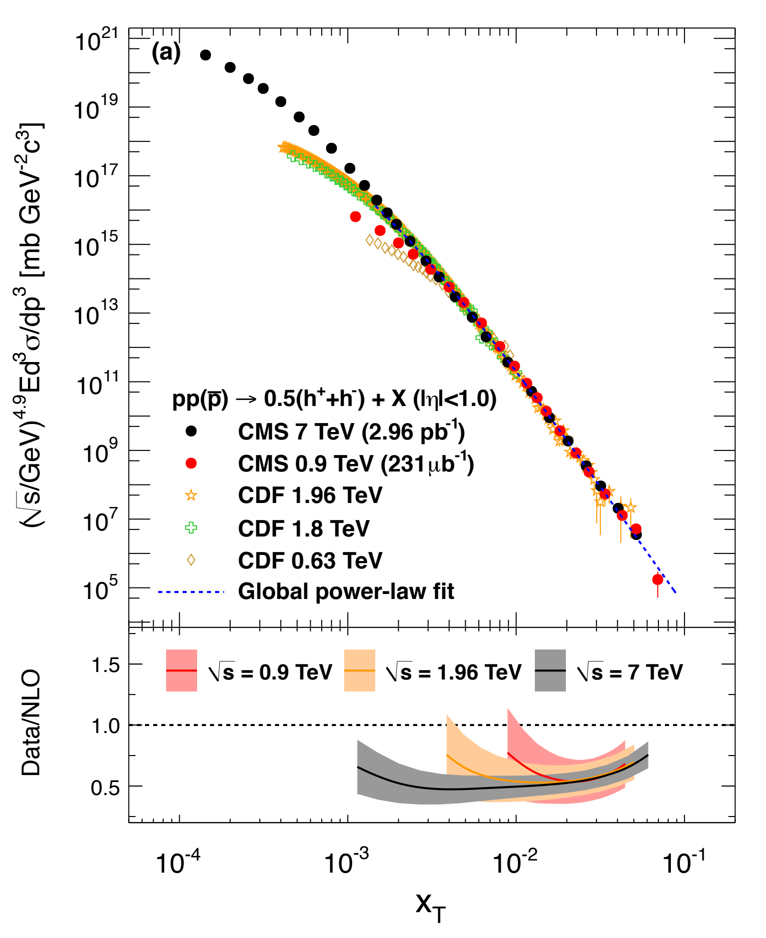
Theoretically p_T can have range from 0 to half of the center-of-mass energy, √s/2, of the collision. Therefore, the distribution can also be represented in as a function of the dimensionless variable

Bjorken $x_T = 2pT/\sqrt{s}$

x_T varies between 0 and 1

Experimentally it has been shown that the data show power-law scaling in terms of x_T

Energy Independent!



Power-law exponents (n) versus p_T and x_T for different energies

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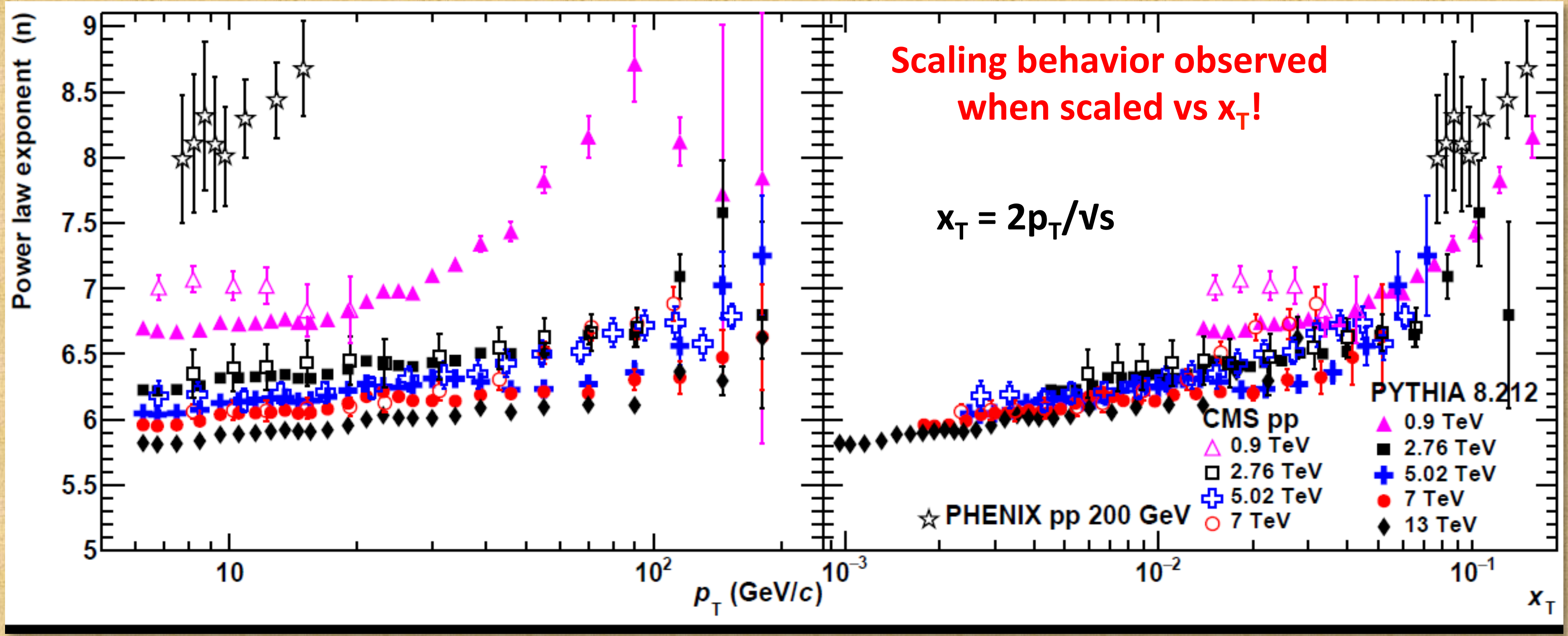

- The power law exponent (n) decreases in both data and PYTHIA with increasing energy.
- The power law exponent is presented as a function of x_T .
- Within 10%, All data fall now nicely on an universal curve.
- The approximate scaling property is well reproduced by PYTHIA.

Power-law exponents (n) versus p_T and x_T for different energies

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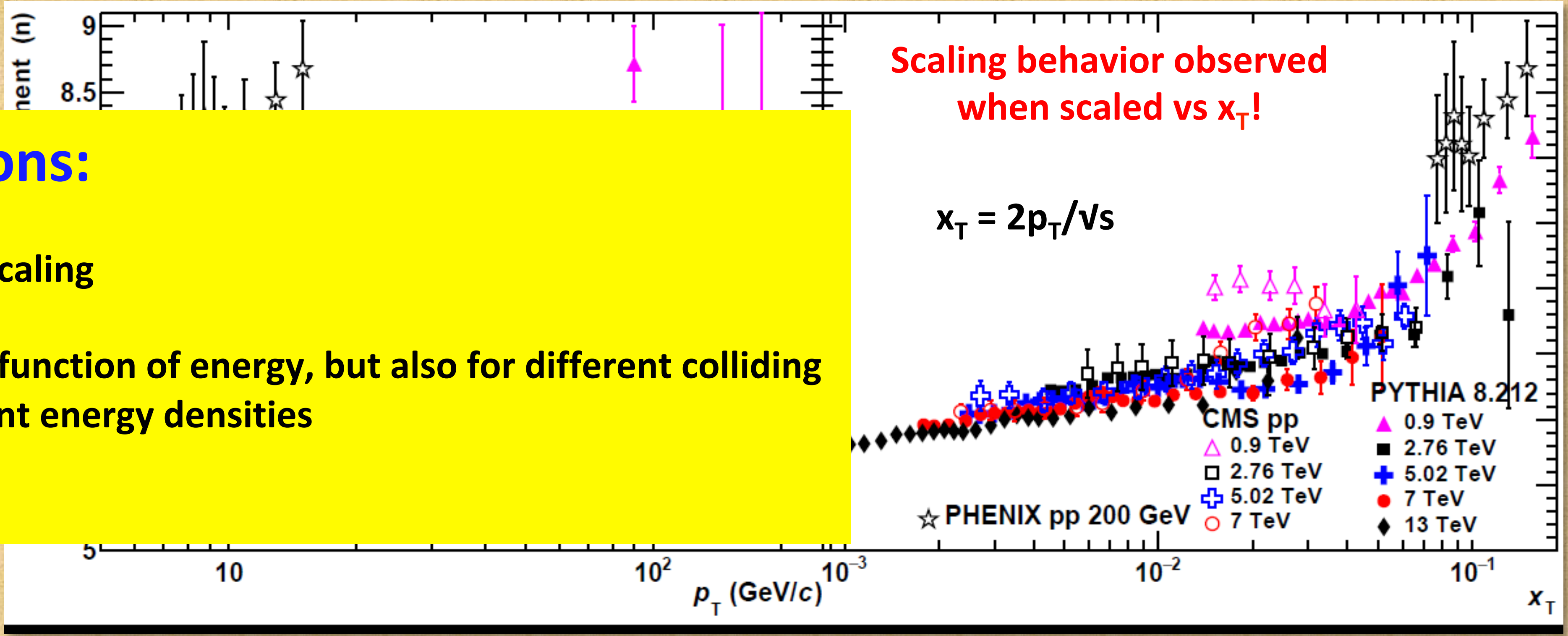

Striking observations:

- Data show a power-law scaling
- Universality not just as a function of energy, but also for different colliding systems that have different energy densities

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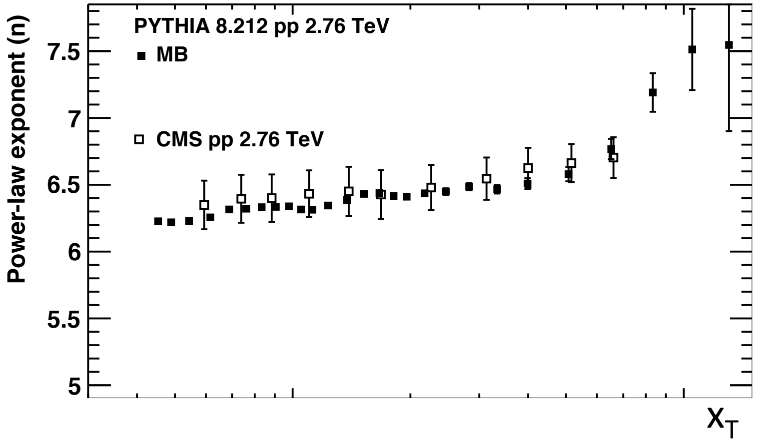
Comparison of PbPb and pp spectra (2.76 TeV)

- PYTHIA explain CMS Minimum Bias data very well.



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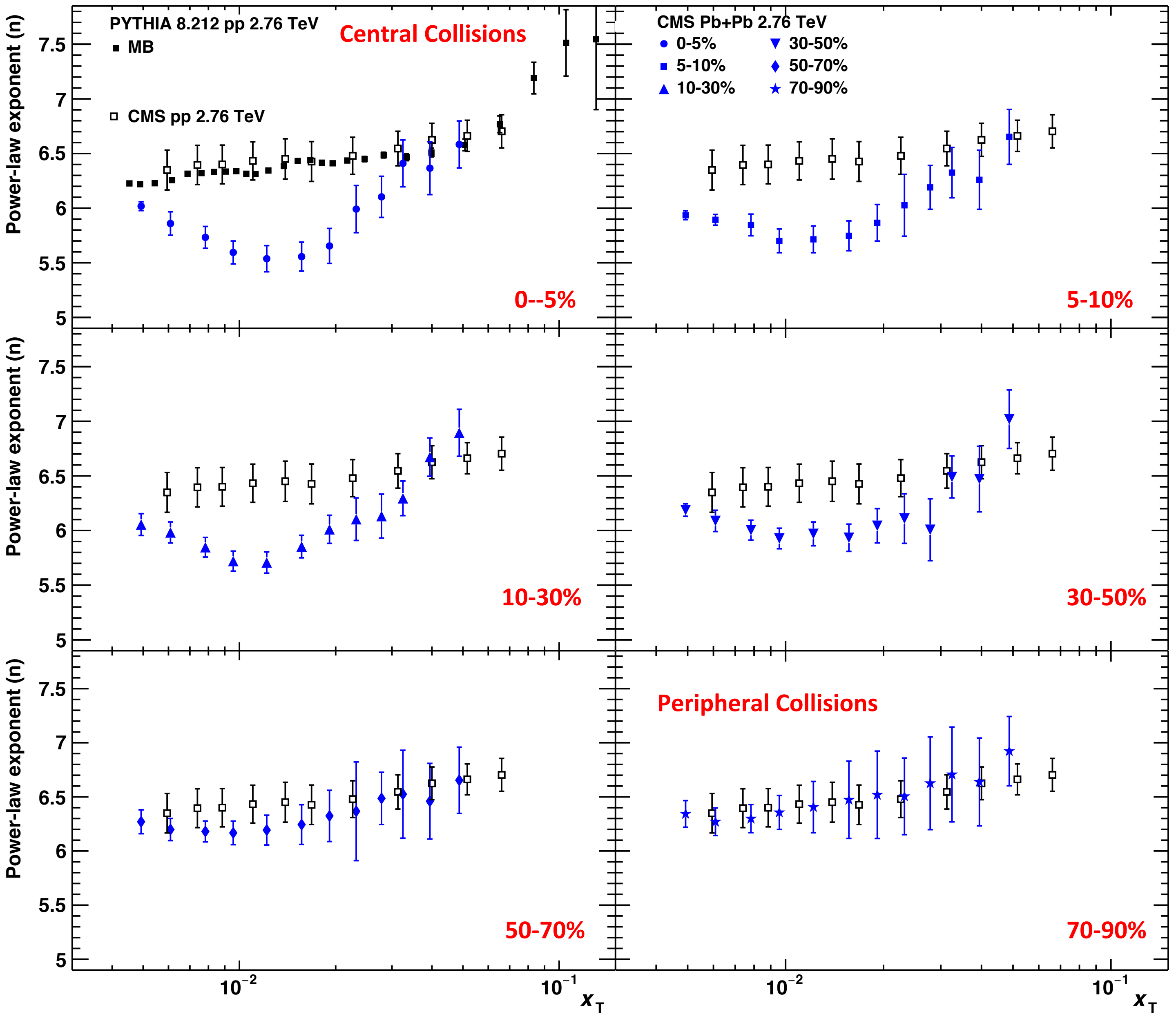
Comparison of PbPb and pp spectra (2.76 TeV)

- **PYTHIA explain CMS Minimum Bias data very well.**
- **Pb+Pb spectra have a drastic evolution with centrality.**
- **Most peripheral Pb+Pb spectra has exponents similar to pp MB.**
- **Going towards Most Central collision spectra needs other multiplicity class of pp collisions.**



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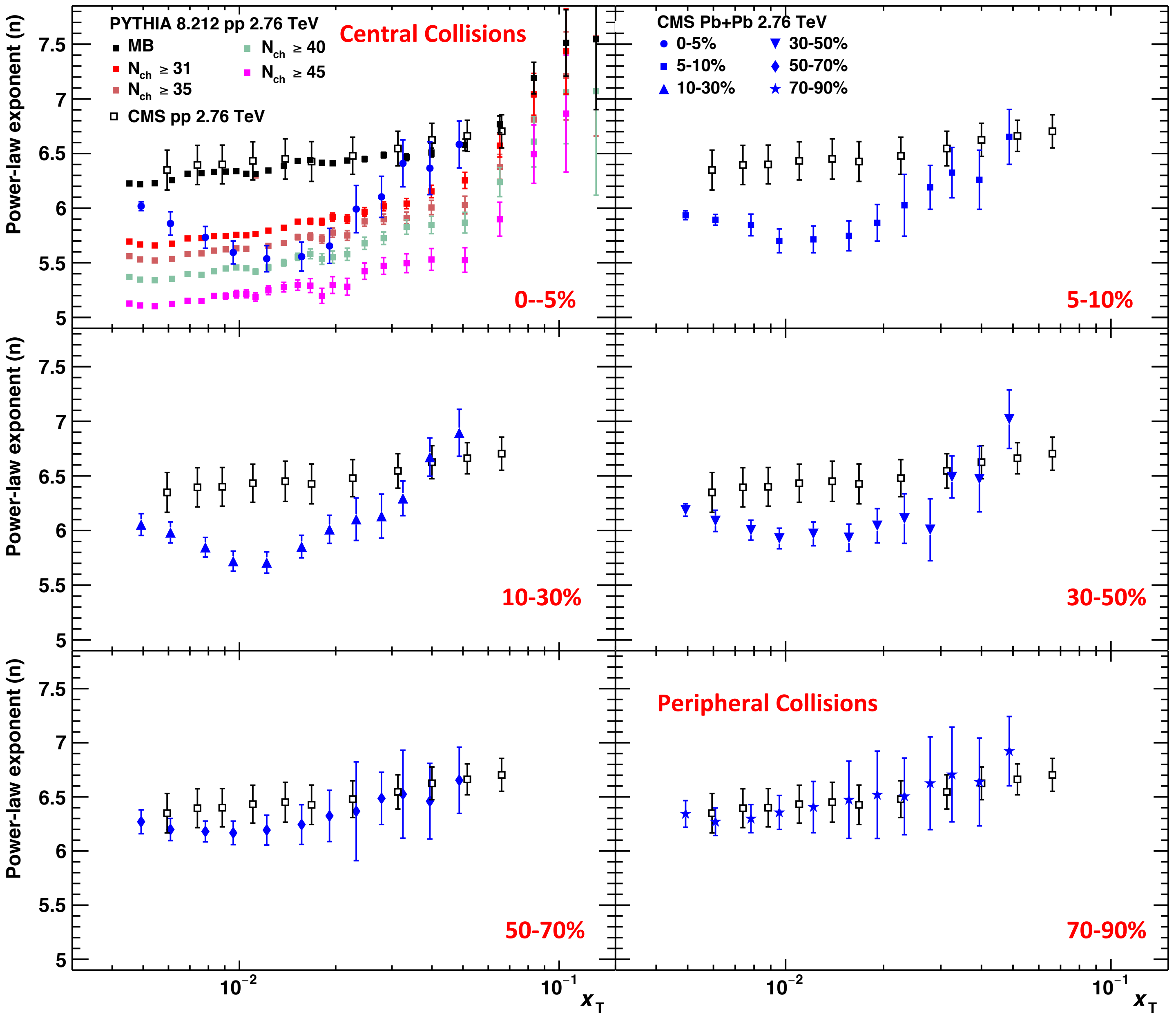
- **Pb+Pb spectra have a drastic evolution with centrality.**
- **Most peripheral Pb+Pb spectra has exponents similar to pp MB.**
- **Going towards Most Central collision spectra needs other multiplicity class of pp collisions.**
- **For each centrality in PbPb, there is a multiplicity class in pp, which has similar exponents.**

The particle production doesn't know about the colliding species: It only cares about the "ENERGY DENSITY" of the system.



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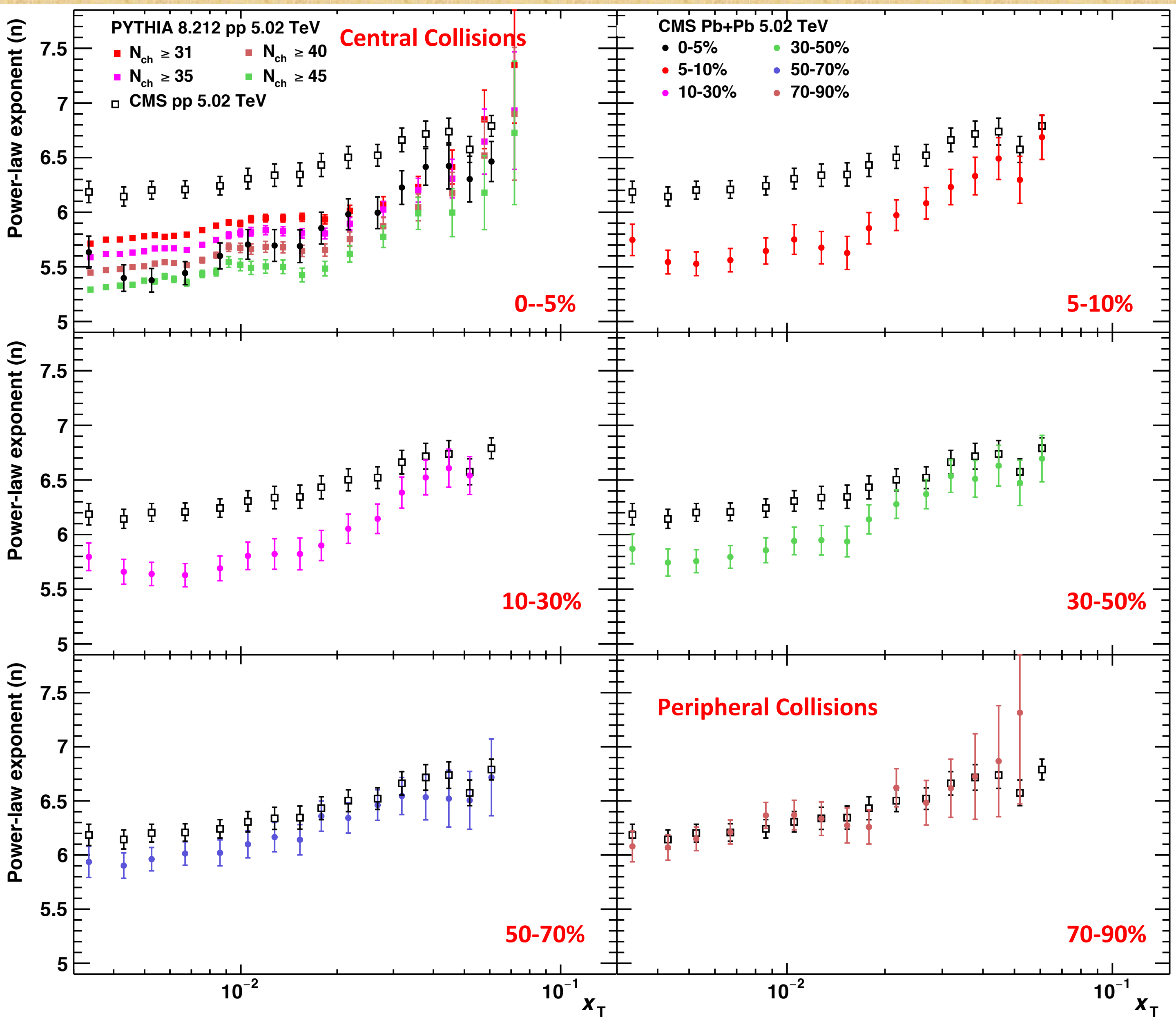
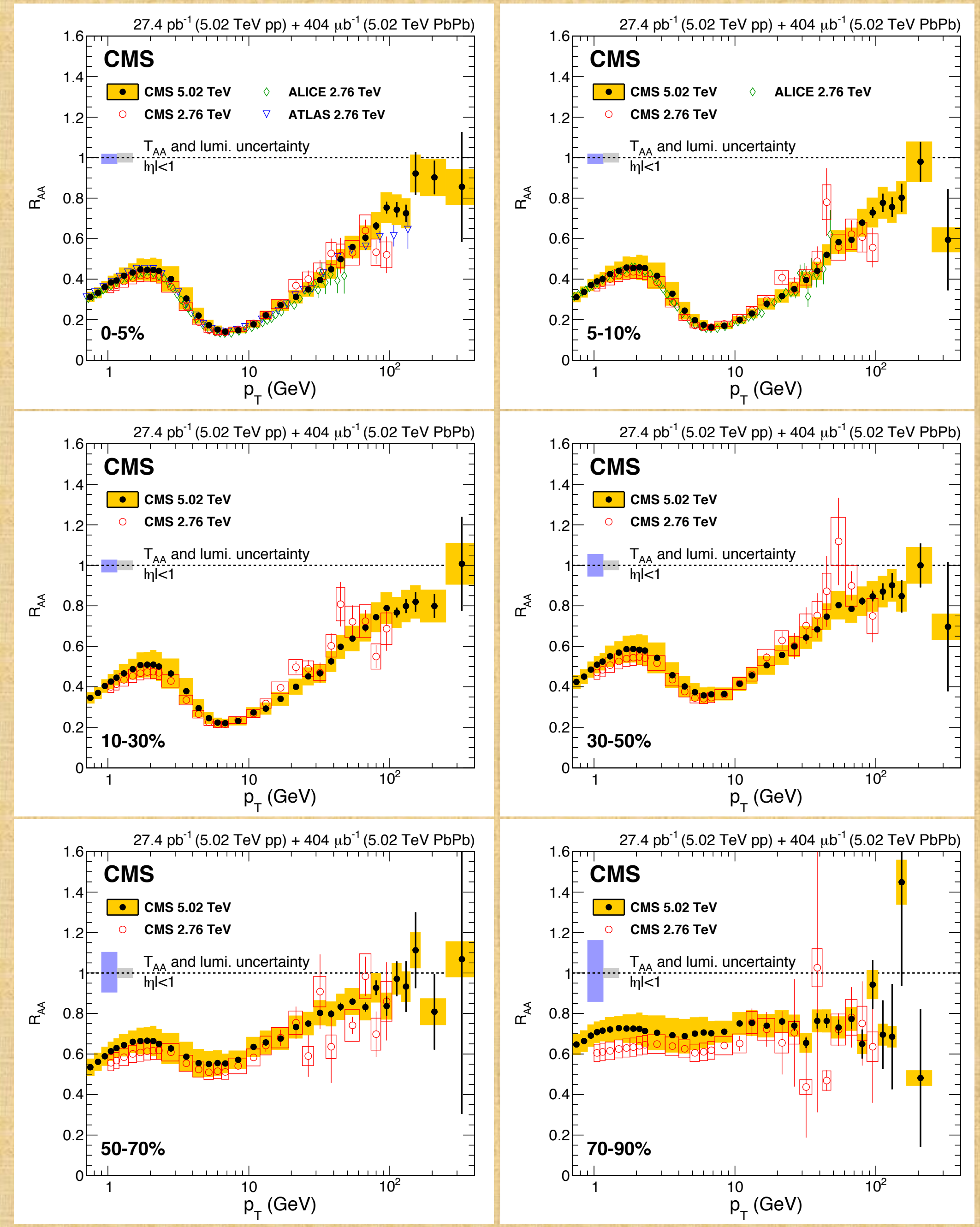
Comparison of PbPb and pp spectra (5.02 TeV)

Similar behavior found for the latest Pb+Pb collisions @ 5.02 TeV



consequences:

The slope of the nuclear modification factor exhibit at high momenta exactly the same behavior observed for pp high energy divided by the pp Minimum bias



JHEP 04 (2017) 039

Question arises: Can we have a QGP like medium in pp collisions??

ENERGY DENSITY can give answer!!

QGP phase transition:

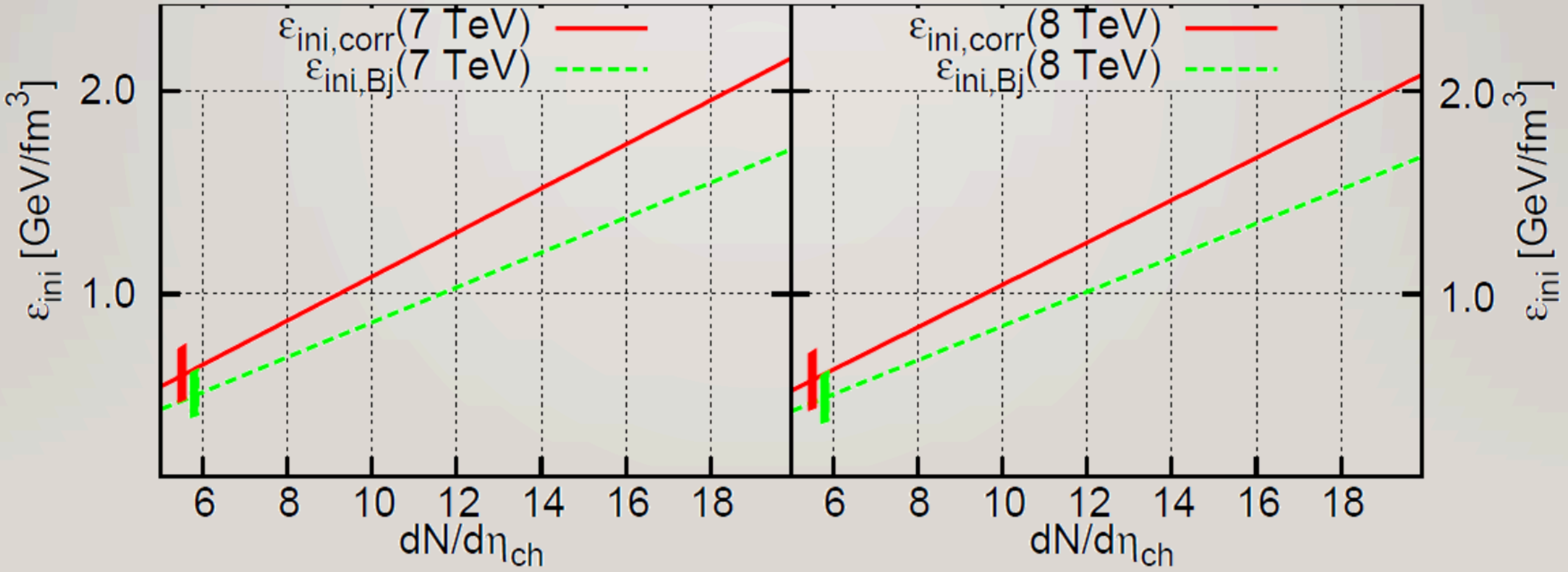
- The original idea: energy density based on dE/dy

- QGP critical $\epsilon_c \sim 1$ GeV/fm^3

This is very easy to achieve even in pp collisions

Energy Density vs Multiplicity

- Initial energy density estimate above 1 GeV/fm^3, if:
  - Bjorken estimate: $dN_{ch}/d\eta > 12$
  - Corrected estimate: $dN_{ch}/d\eta > 9$



In high-multiplicity pp collisions, we reach high energy densities

https://indico.cern.ch/event/684046/contributions/2809620/attachments/1572015/2480526/csanad_zimanyi17_dndeta.pdf

Conclusions:

- The slopes of the p_T spectra have a marked dependence **on the multiplicity and energy** in pp collisions and on the centrality in heavy ion collisions.
- For every centrality of AA collisions, one may find a multiplicity class in pp collisions which has a the same exponent.
- Similar behavior is observed in PbPb and pp when one studies the centrality (multiplicity) dependent particle production and similar values of the exponents in pp and Pb-Pb collisions.
- It has been demonstrated that the characterization of the spectra in function of x_T and of the power law exponent offers interesting observation (scaling behavior).
- The effect of the rise of the RAA at high momenta **is not due to an increased transparency of the hot system**. The behavior of the rise is solely due to the evolution of the p_T spectra. Rather then working with the ratio of two spectra we should carefully analyse the spectra of each collision system.
- The similarities between pp and PbPb suggest that the high-p_T production in both systems have a common origin, namely, the **density of the system.**

Parton energy loss at very high-multiplicity

We get some exciting features if one give closer look to the high-multiplicity pp events.

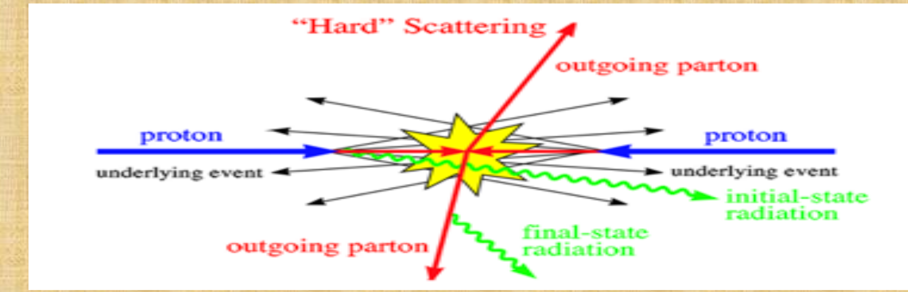
Introduction:

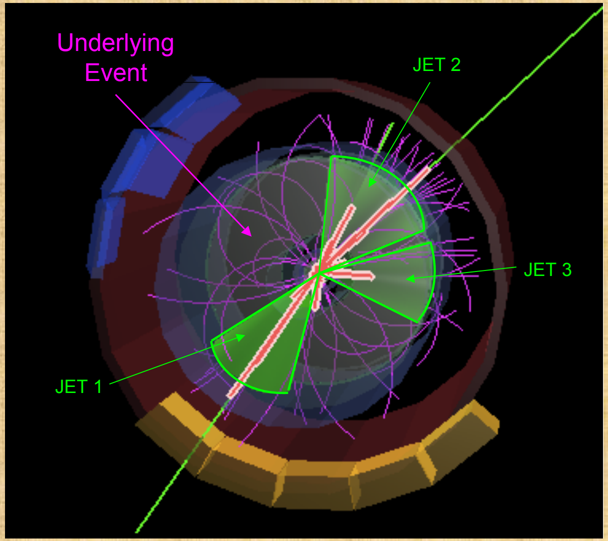
Leading Particle:

Particle with highest p_T in the particular event is assigned as a leading pT of the event. The azimuthal angle with the leading particle will be the new reference for other particles belonging to the event.

Underlying Event (UE):

In parton-parton scattering, the UE is usually defined to be everything except the two outgoing hard scattered partons:





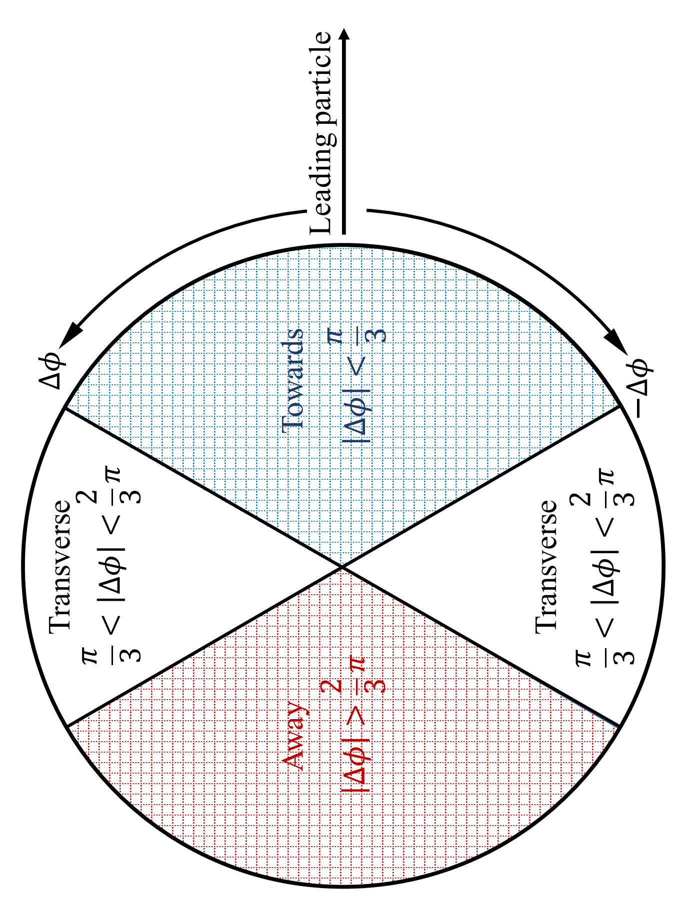
Introduction:

Traditional UE measurement: According to the azimuthal direction of leading charged particle, three distinct topological regions are defined:

- ➢ Near Side (NS): |ΔΦ| < π/3
- ➢ Away Side (AS): |ΔΦ| > 2π/3

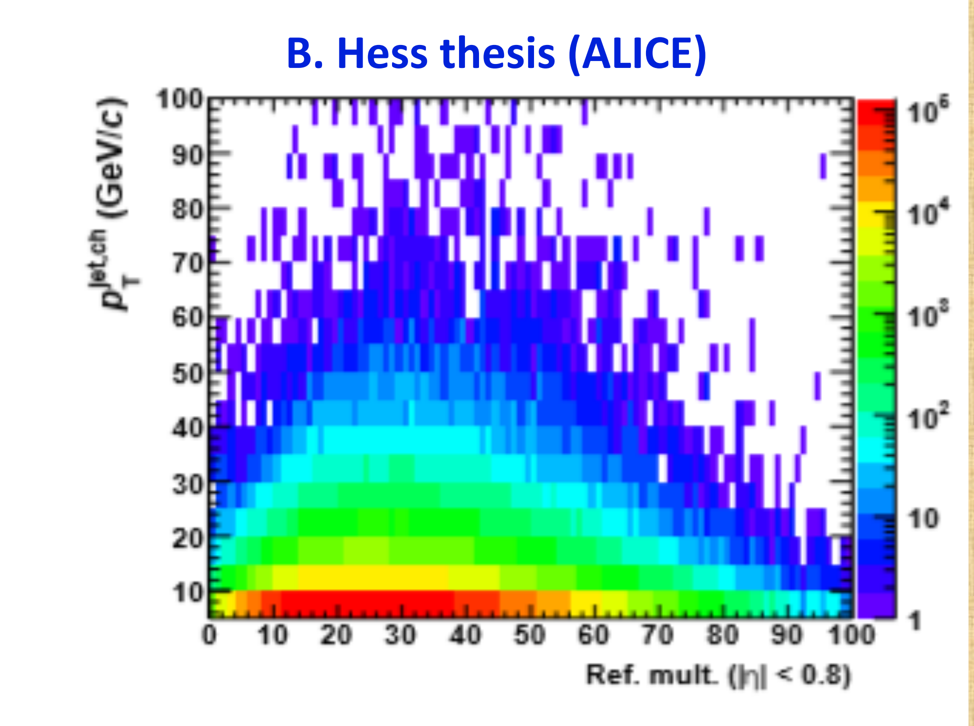
(sensitive to Jet fragmentation) [applies to NS and AS]

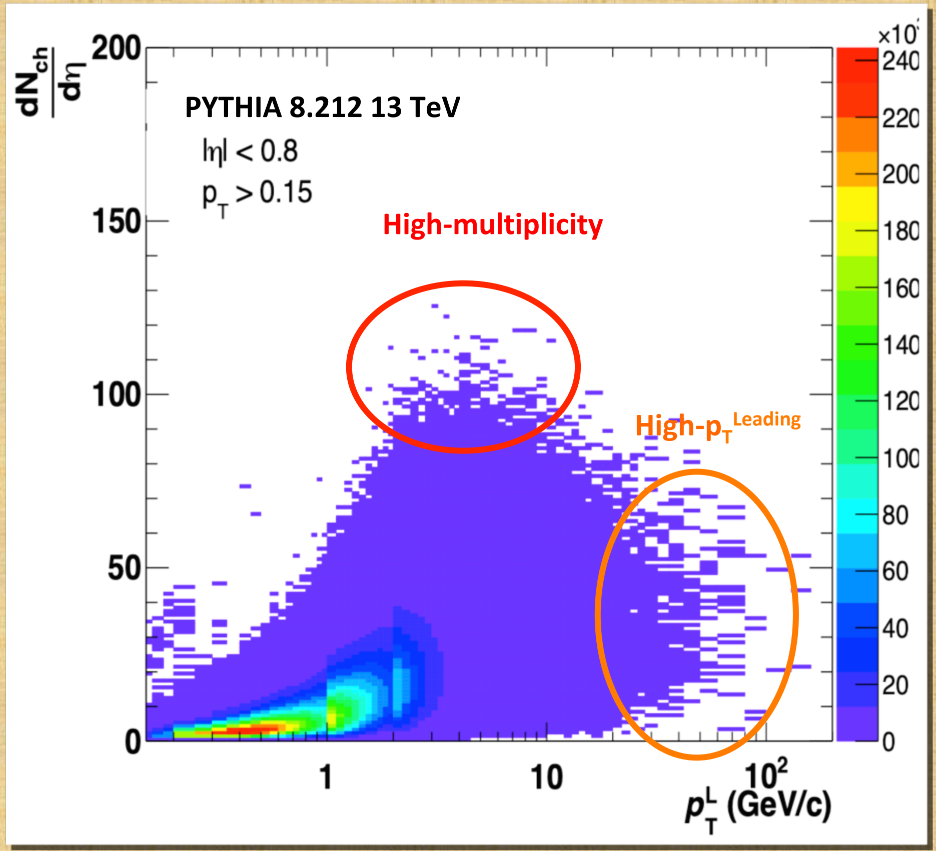
- ➢ Transverse Side (TS): π/3 < |ΔΦ| < 2π/3 (sensitive to UE)



Introduction:

- High multiplicity events have p_T leading ~ 6-10 GeV/c
- High p_T leading events have multiplicity ~ 30 - 50

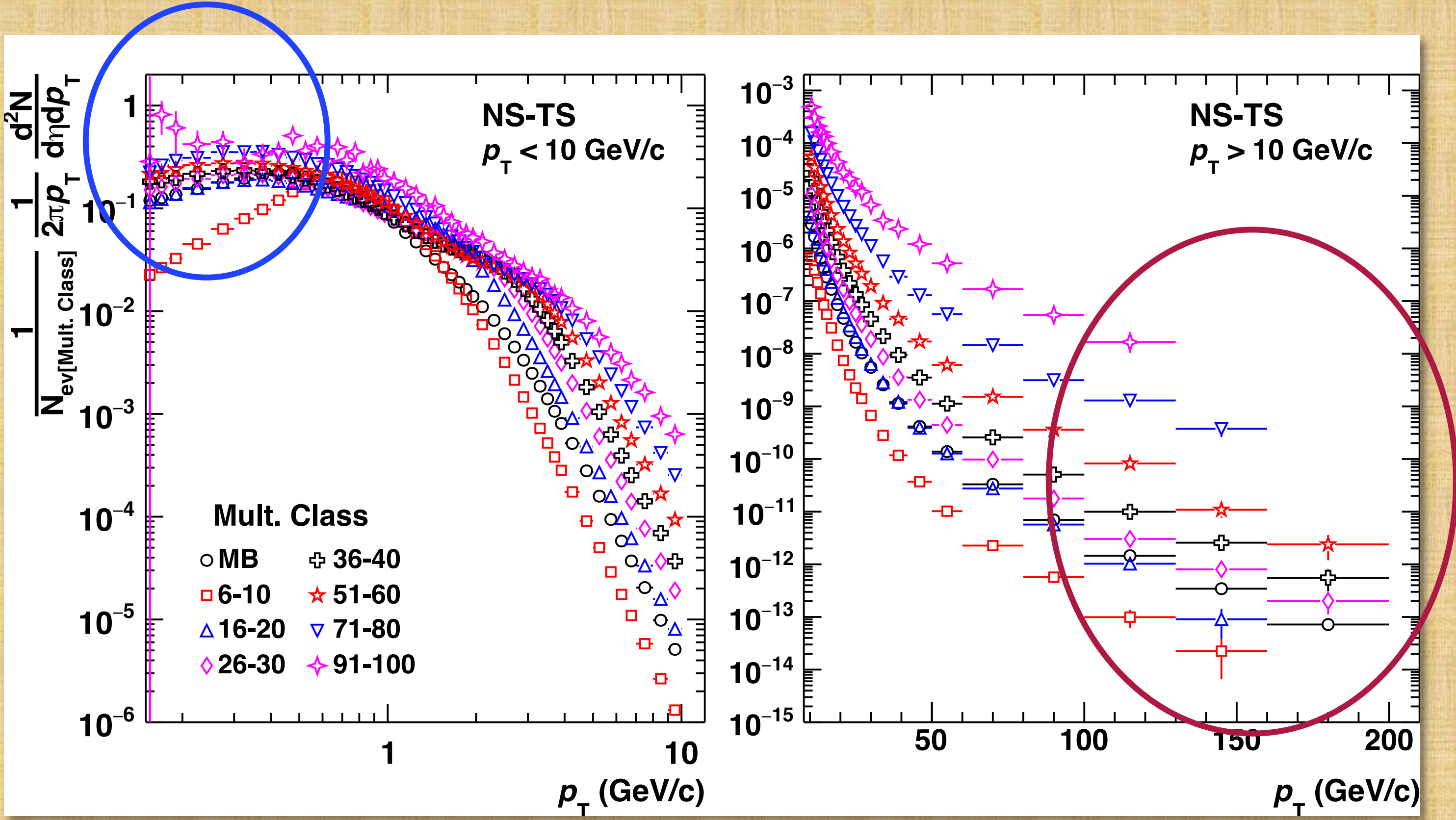




The highest multiplicities do not yield the maximum leading p_T!

Observation: Hard/Jetty spectra (NS-TS)

- The spectrum labeled NS-TS which is obtained by subtracting the TS spectrum from the NS spectrum.
- The spectra exhibit a hardening with multiplicity.
- At higher multiplicities the slope of the spectra continues decreasing without producing higher momentum particles!



arXiv:1905.06918 (2019)

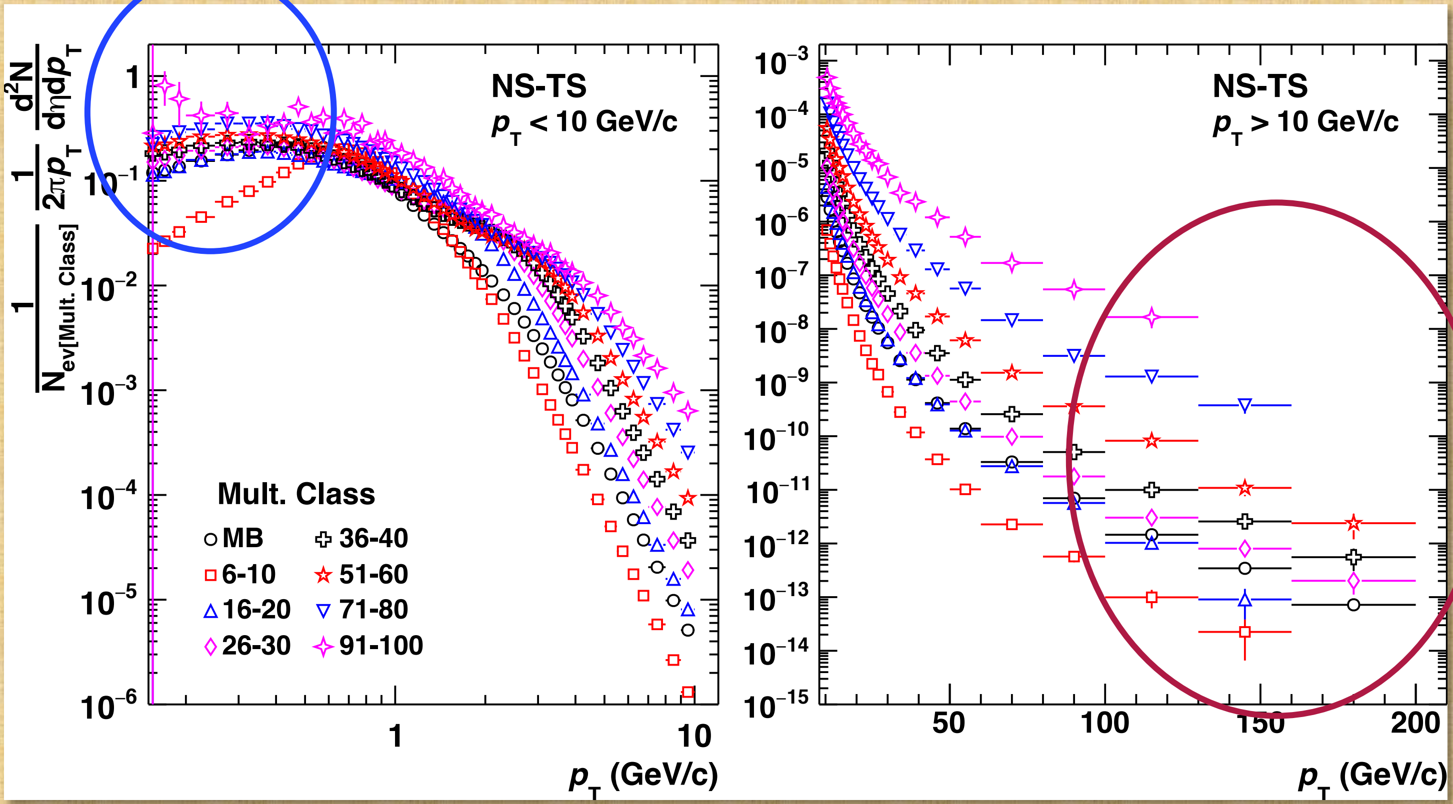
Missing high-pT particle and getting access of particles at low-pT is not a coincident!

Observation: Hard/Jetty spectra (NS-TS)

At multiplicities above ≈ 50 the production of the highest momentum particles seems to be decreasing while the mean transverse momentum in the TS continues rising!

- T … with m …
- A … the sp … hout p … um p …

Are we observing some kind of **“melting”** of the highest p_T-particles at high multiplicities: producing particles at lower-p_T, increasing thus the **multiplicity and mean p_T**?



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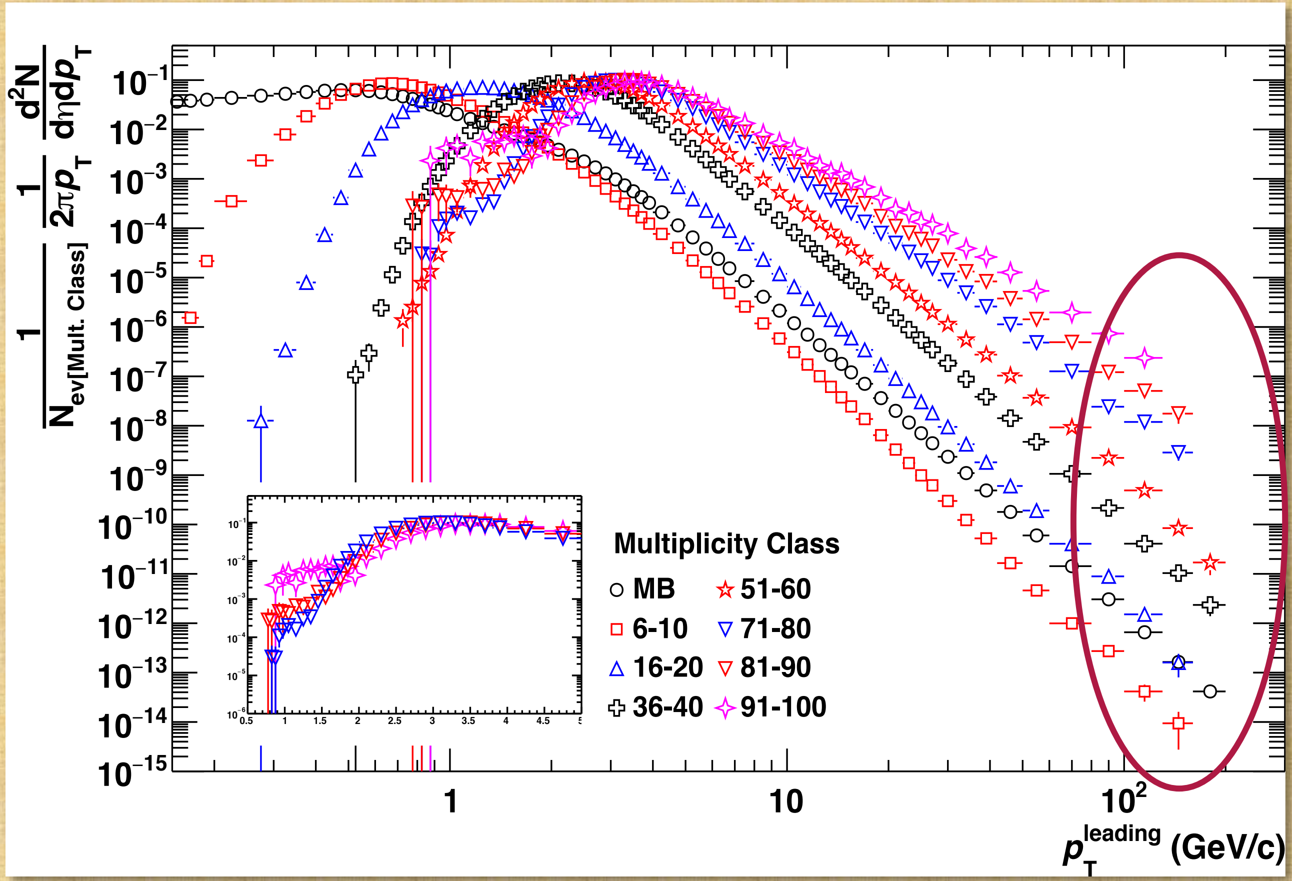
Missing high-pT particle and getting access of particles at low-pT is not a coincident!

Observation: Leading Particles Spectra

- The low pT-part of the highest multiplicity bins spectra develop a "kink" at around 1 GeV/c.
- **This supports the previous observation that the leading particles have been "degraded"?**



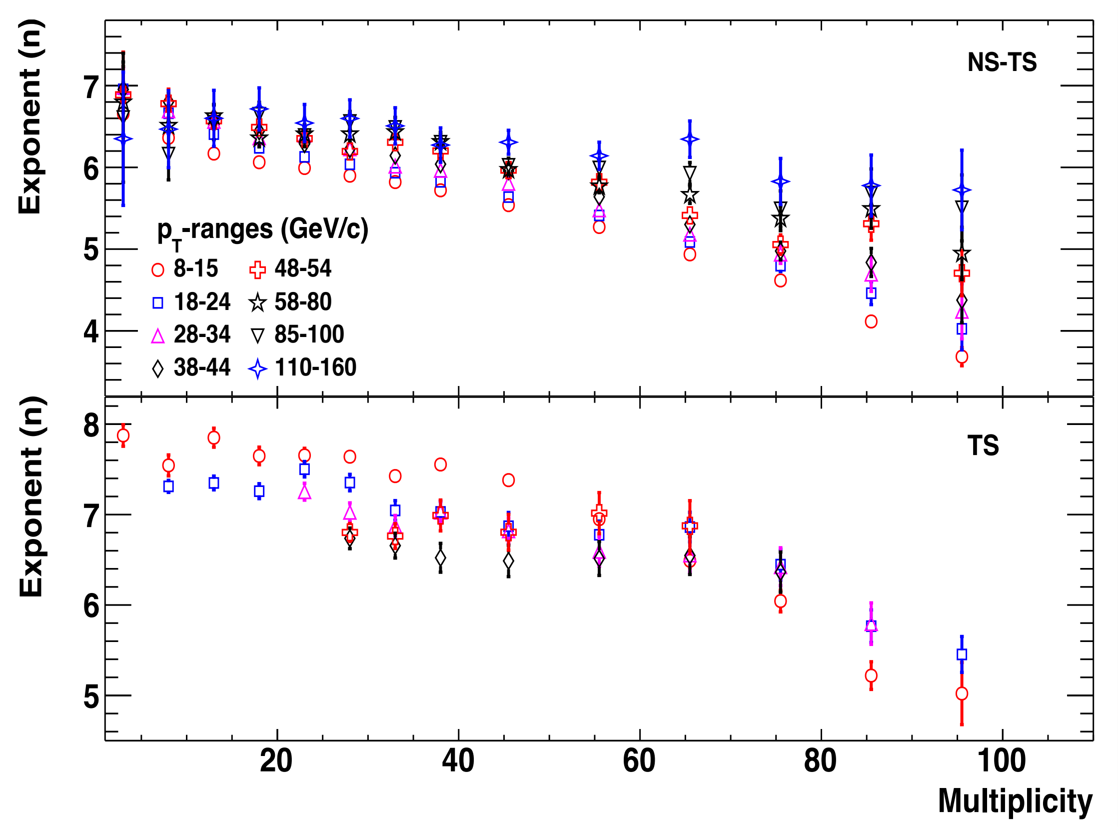
arXiv:1905.06918 (2019)

Observation: Exponents

- At multiplicity below ~ 50 the slopes of all the multiplicity bins are approximately equal while above the critical charged particle density the slopes gets gradually smaller.

- At multiplicities above ~ 50, the production of the highest momentum particles seems to be decreasing while the mean transverse momentum in the TS continues rising!

- We observe that in the low p_T region a rather important variation in the power-law exponent beyond the multiplicities corresponding to the maximum leading transverse momenta, while in the higher p_T bins this tendency is much smaller



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Conclusions:

- ☑ The maximum reachable multiplicities are not accompanied by an increase in the maximum leading particle momentum. The proportionality between maximum p_T and increasing multiplicity breaks down at multiplicity densities of around ~ 50.

- ☑ Beyond multiplicity density ~ 50, the NS-TS spectra continue to get flatter, increasing the mean transverse momentum, seemingly at the expense of the maximum reachable momentum

- ☑ Beyond the particle density corresponding to the maximum p_T reach both the TS and the NS-TS regions suffer a sudden hardening.

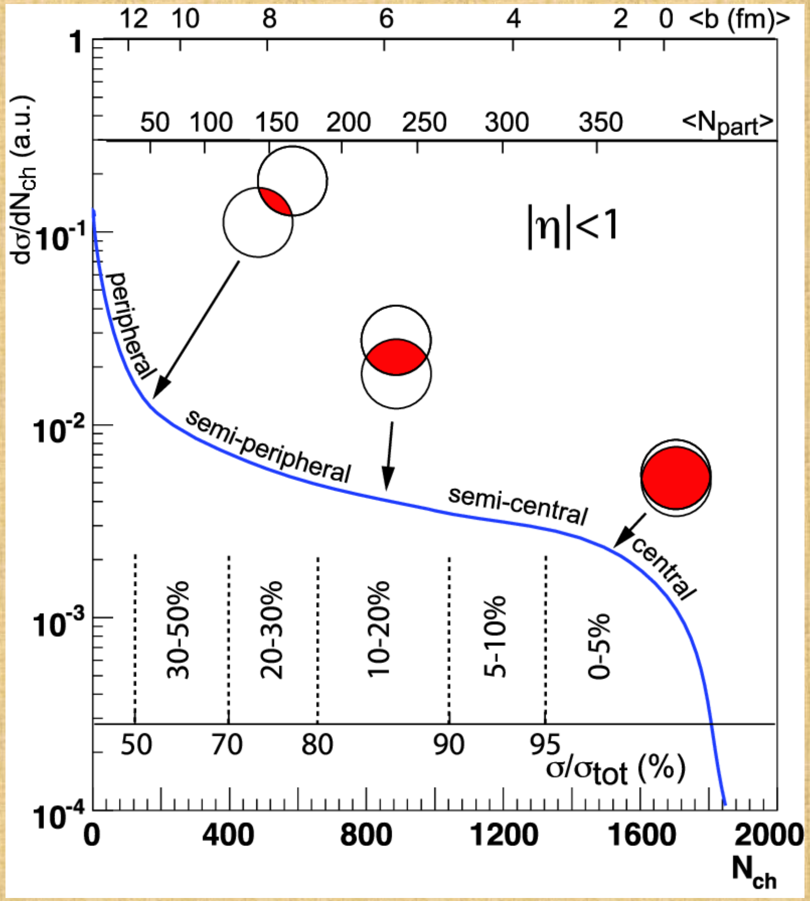
- ☑ At very low momenta the high multiplicity events present also a specific evolution by augmenting the yield of the smallest transverse momenta . The feature is observed both in the NS-TS spectra as well as in the leading particle spectra

- ☑ These results indicate a possible parton-energy loss at very high multiplicity by following observations:
  - Hardening of the spectra without high p_T particle production => Increase in mean p_T
  - Excess of particle production (a bump) at low p_T

Thank you very much for you kind attentions

Centrality in heavy-ion collisions:

arXiv:0910.4114



Adv. High Energy Phys. 2015 (2015) 612390