



# Charged-particle multiplicity distribution in high energy p-O collisions

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Presentation for the **IX Reunião Geral - Projeto Especial FAPESP**  
São Paulo, 26th May 2026

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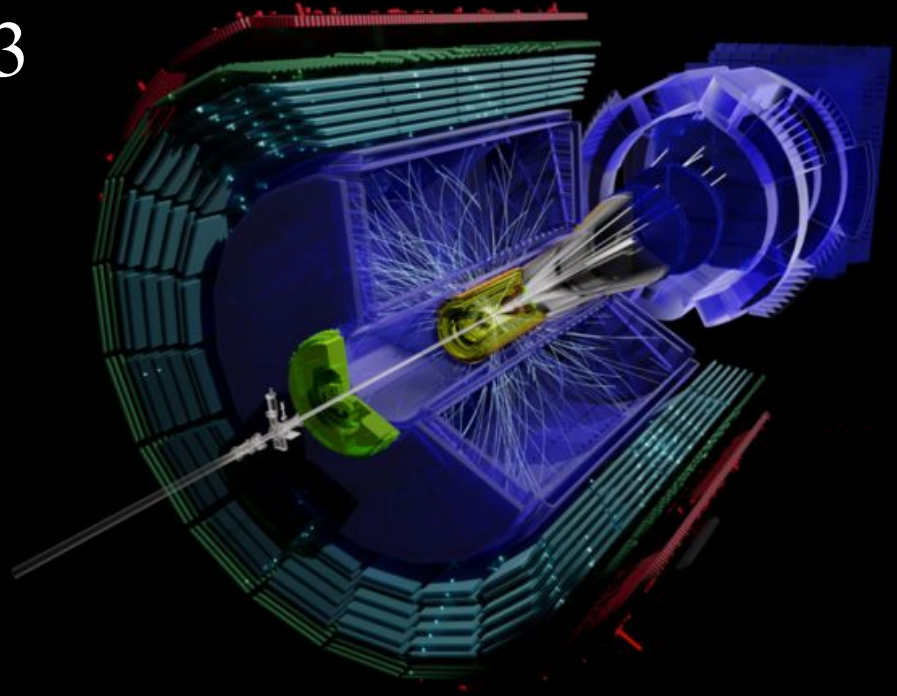
\* ylima@if.usp.br

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- Motivation
- Fundamentals
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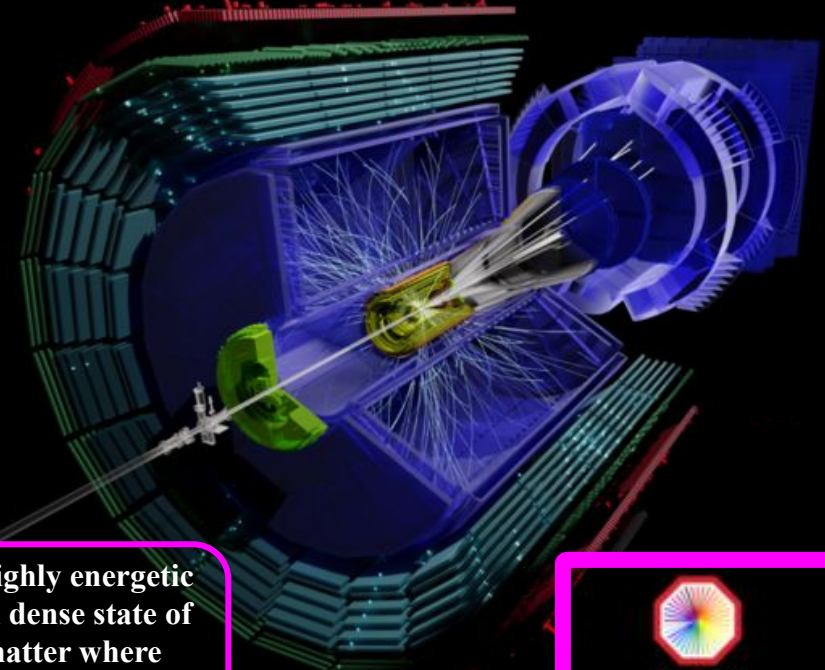
# Oxygen beams into Run 3

- The recent introduction of oxygen beams into Run 3 of the Large Hadron Collider (LHC), presents new opportunities to examine particle production from smaller systems within a previously unstudied energy domain.



# Oxygen beams into Run 3

- The recent introduction of oxygen beams into Run 3 of the Large Hadron Collider (LHC), presents new opportunities to examine particle production from smaller systems within a previously unstudied energy domain.
- Traditionally, **lead ions** have been utilized at the LHC for heavy ion collisions, as they are believed to create the optimal **conditions for Quark-Gluon Plasma (QGP) formation**. In contrast, oxygen nuclei are significantly smaller than lead nuclei, offering valuable comparative insights when studying nuclear collisions in relation to the size of the colliding nuclei.



A highly energetic and dense state of matter where quarks and gluons can move freely.



ALICE

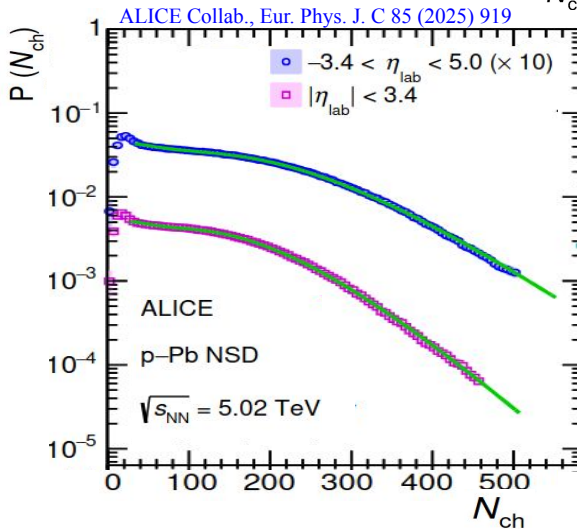
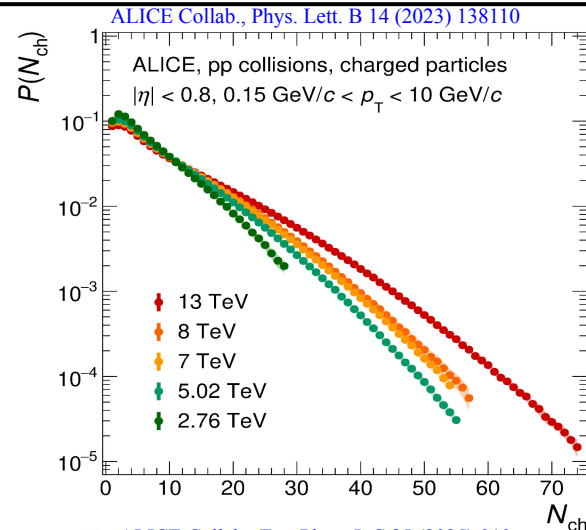
LHC Run3  
proton-Oxygen  
1 July 2025

# Particle multiplicity distribution

- **Multiplicity distributions** are among the most fundamental observables in hadronic collisions and are defined as the probability distribution  $P(N)$  which describes the probability of observing a specific number  $N$  of particles produced within a particular phase space.
- The multiplicity of charged particles is a fundamental observable for understanding the production of multiple particles in high-energy hadron collisions. The probability  $P(N)$  of producing  $N$  charged particles in the final state is related to the particle production mechanism.
- In recent years, a large body data and theoretical studies on multiplicity distribution, especially for charged particles, have been measured and made available by various collaborations.

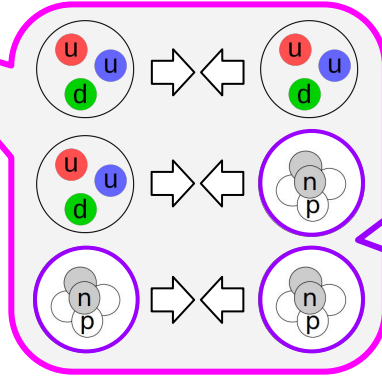
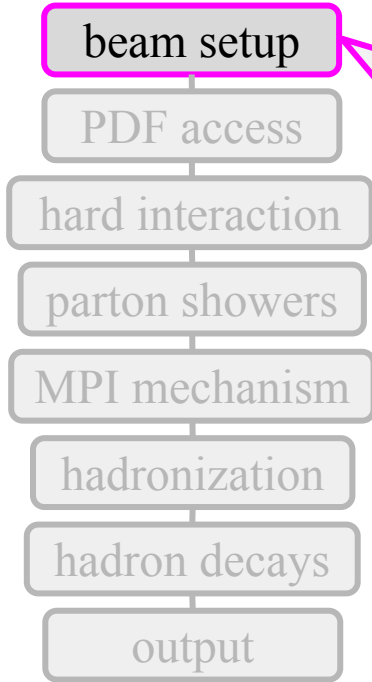
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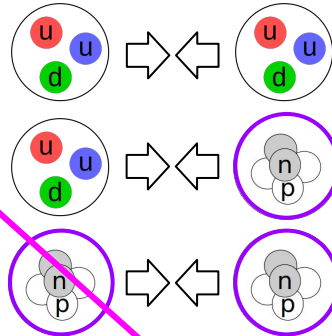
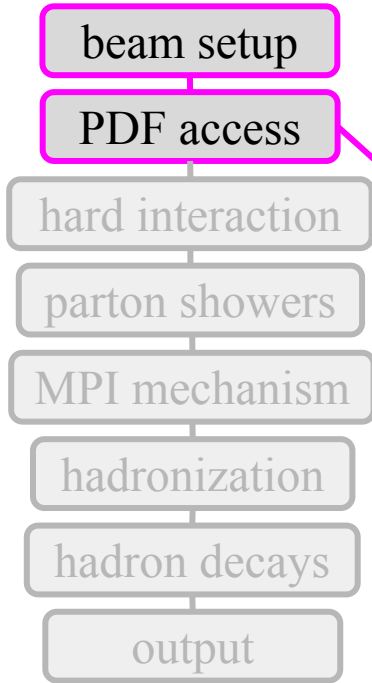
# PYTHIA event generator



**Angantyr** model generalizes the pp collision scheme to a nuclear collision as a superposition of multiple sub-collisions between pairs of nucleons from the projectile and target nuclei. By default: Glauber's model is used to calculate the probability of interaction between the two nuclei, employing the Woods-Saxon model to determine the spatial distribution of nucleons within each nucleus.



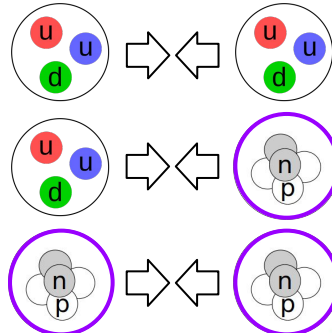
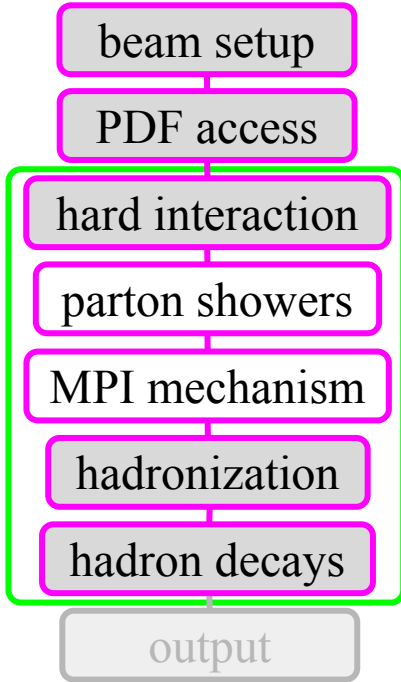
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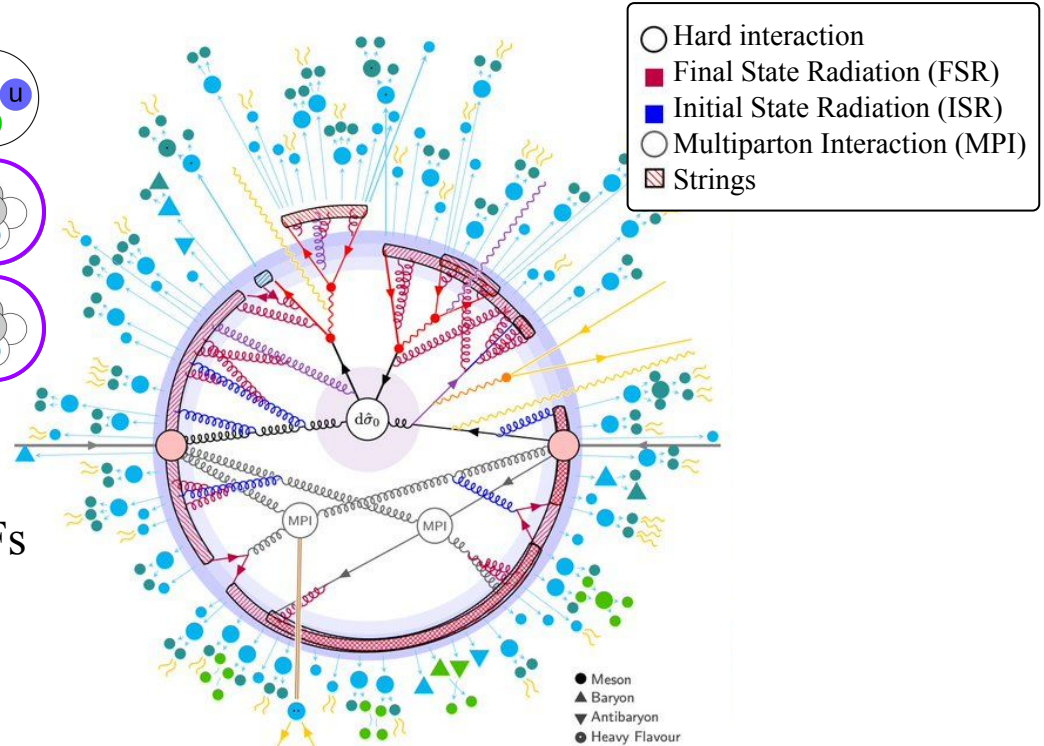
In hadronic collisions, PDFs determine the interacting partons



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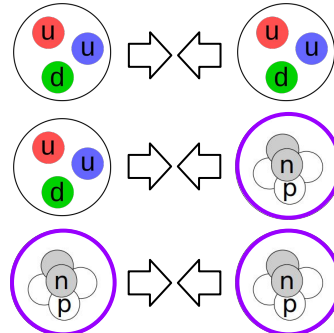
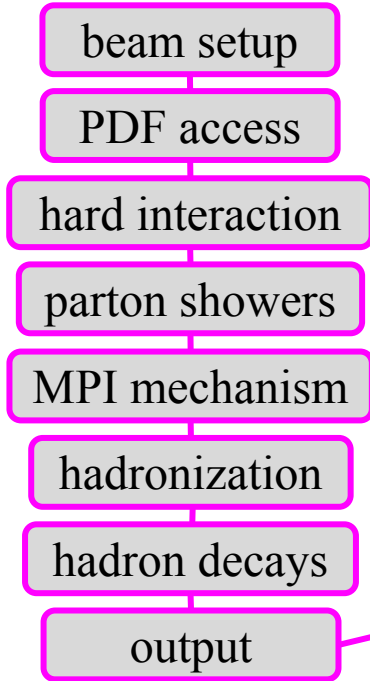
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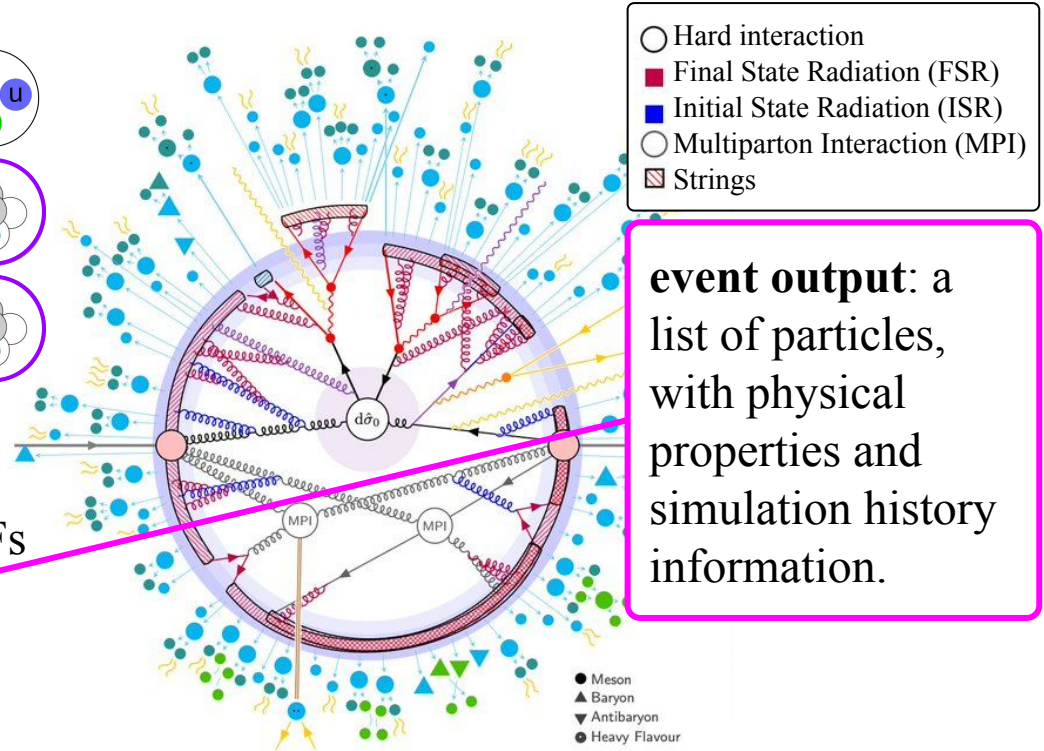
B. Christian and others, SciPost Phys. Codeb. 2022 (2022) 8



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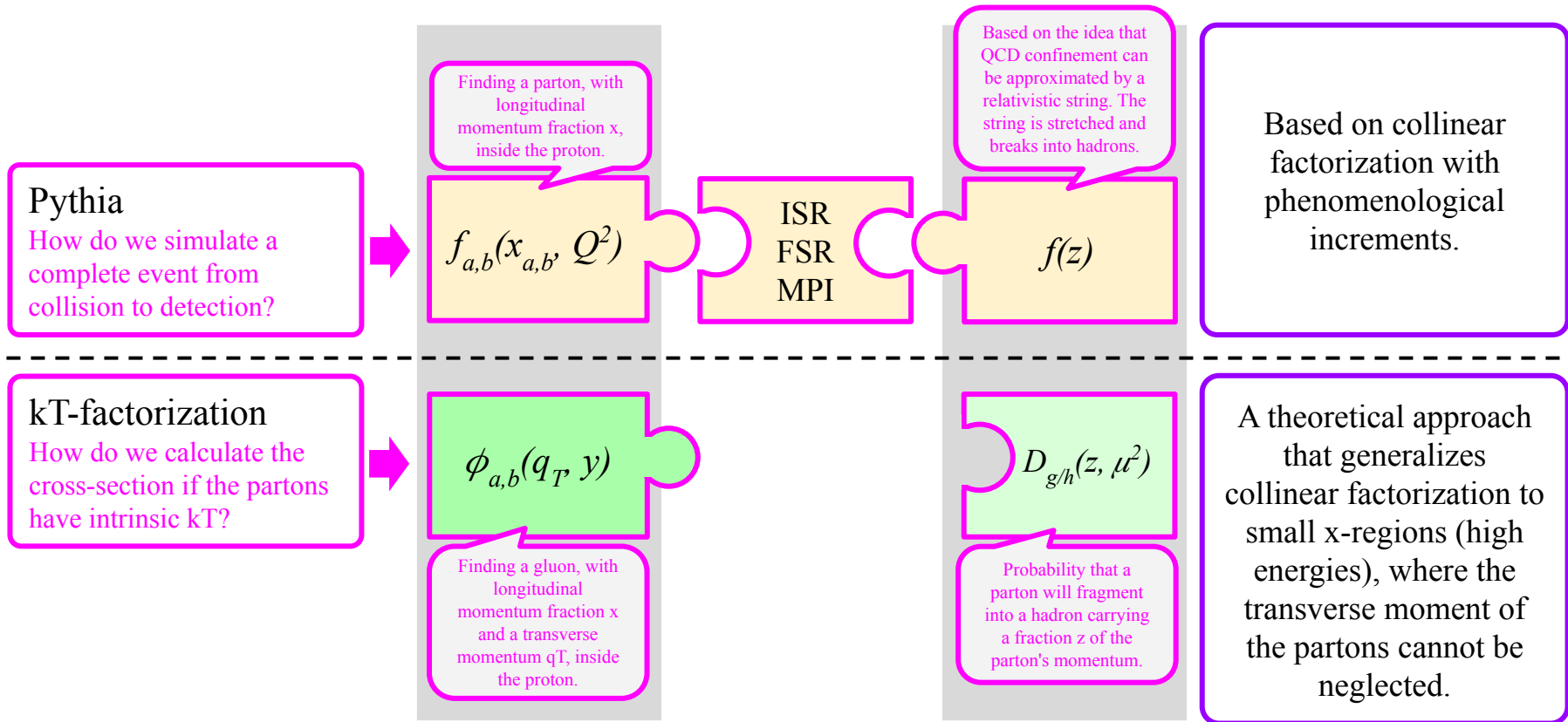


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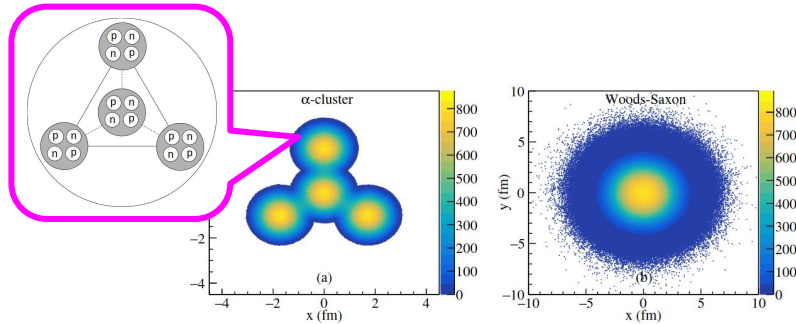
B. Christian and others, SciPost Phys. Codeb. 2022 (2022) 8

# PYTHIA × kT-factorization



# Oxygen clustering

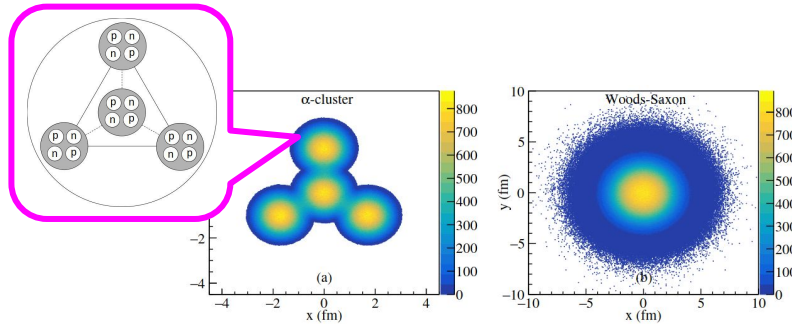
- The oxygen is a light nucleus composed of 8 protons and 8 neutrons, being a natural candidate for a  $\alpha$ -clustered nucleus
- The geometric configuration of the oxygen nucleus, whether represented by a continuous Woods-Saxon distribution or as a compact array of tetrahedral  $\alpha$ -clusters, plays a significant role in final-state particle production



S. Prasad, et al, Phys. Lett. B 860 (2025) 139145

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S. Prasad, et al, Phys. Lett. B 860 (2025) 139145

Nuclear charge density at a radial distance  $r$  from the center of nucleus, via the 3pF distribution:

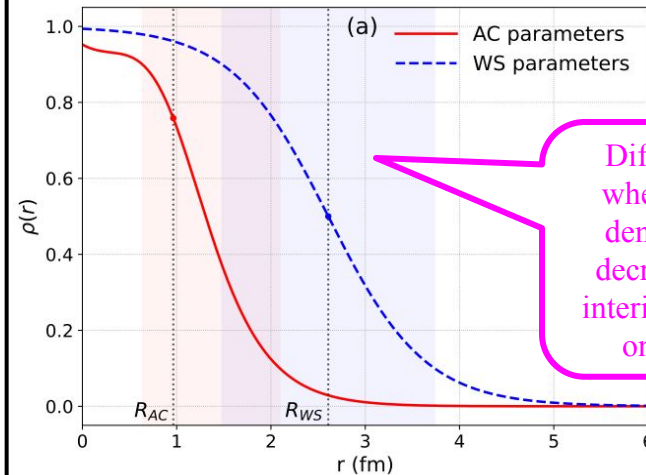
$$\rho(r) = \frac{\rho_0 [1 + w(r/R)]}{1 + \exp [(r - R)/a]}$$

$R$  - nuclear radius;

$a$  - diffuseness parameter;

$w$  - skin thickness parameter.

For each cluster, the positions of the nucleons are randomized by applying three successive Euler rotations.



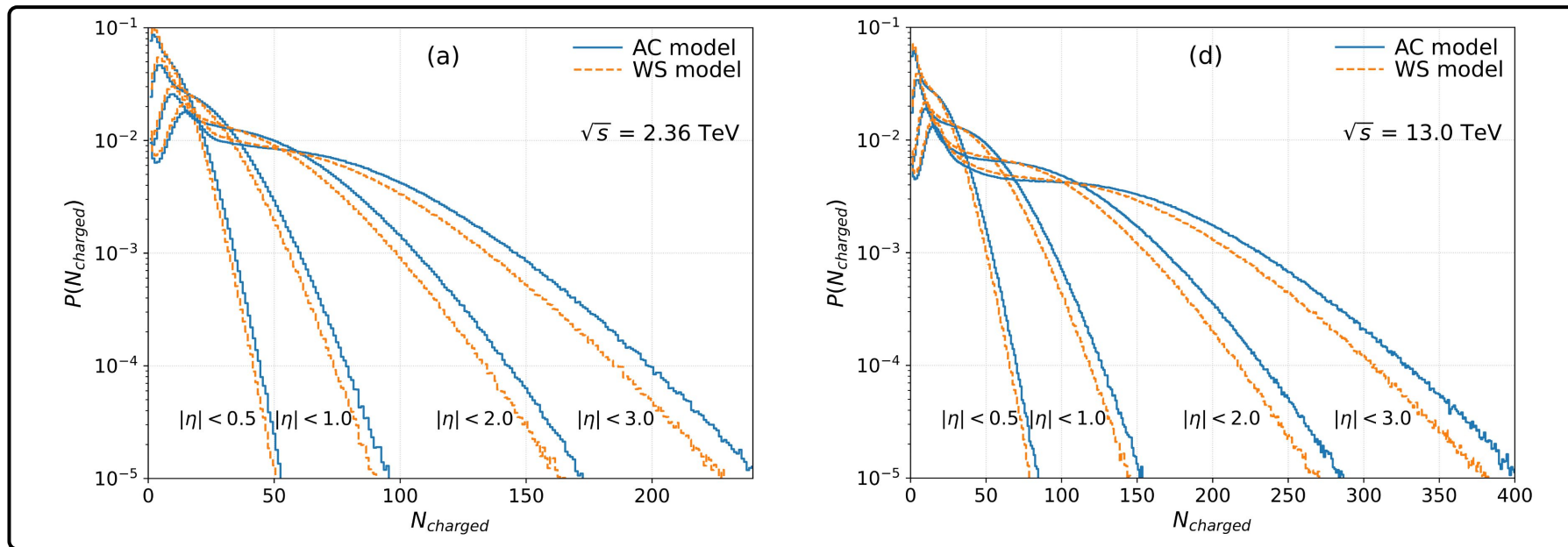
Diffusion region:  
where the nuclear  
density gradually  
decreases from the  
interior value to zero  
on the exterior

# Work in progress...

Yuri N. Lima, Lucas J. F. Silva, André V. Giannini, Marcelo G. Munhoz,  
[arXiv:2602.11452](https://arxiv.org/abs/2602.11452)

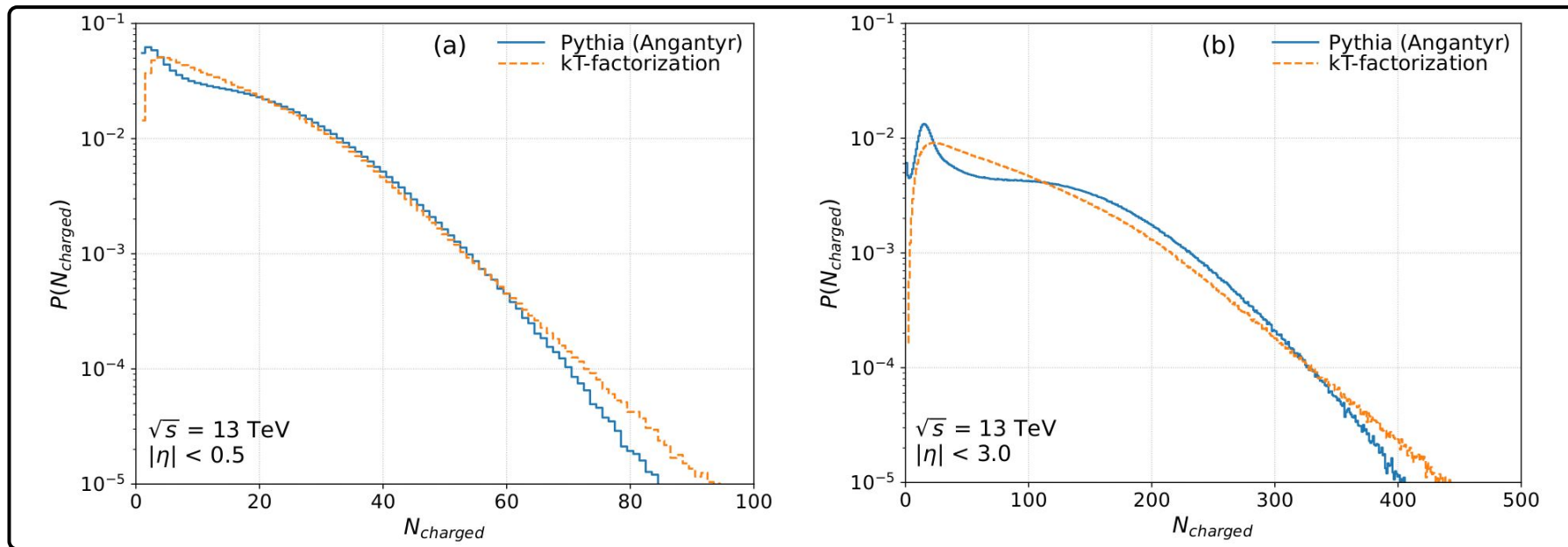


# Charged-particle multiplicity distribution



We can see a difference between the models across the entire observed spectrum; this difference gradually increases as we consider higher values of  $N$ .

# Charged-particle multiplicity distribution



We can see that there are significant differences between the results obtained with Pythia and with the kT-factorization.

# KNO scaling

Koba-Nielsen-Olesen (KNO) scaling is a fundamental feature of multiplicity distributions, suggests that at sufficiently high energies the multiplicity exhibits universal scaling behavior.

In a given collision, the probability of producing  $n$  particles can be written a

$$P_n(s) = \frac{1}{\langle n(s) \rangle} \Psi \left( \frac{n}{\langle n(s) \rangle} \right)$$

$\langle n(s) \rangle$  - average particle multiplicity at a given center-of-mass value.

$\psi(z)$  - represents the universal form of the multiplicity distribution.

# KNO scaling

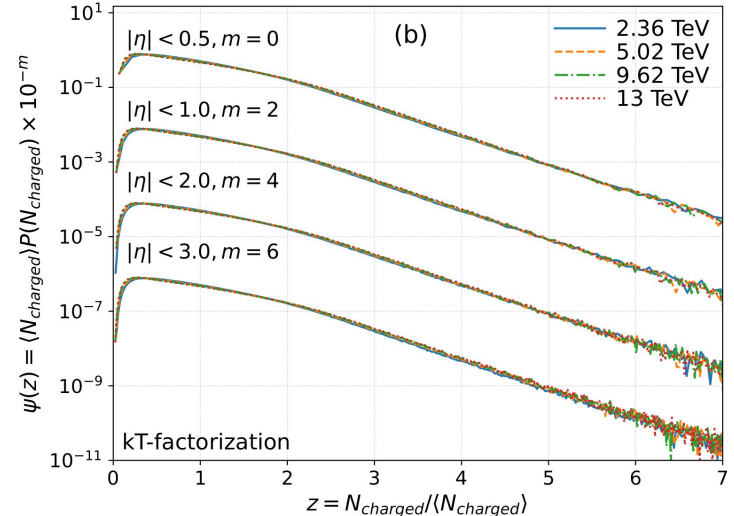
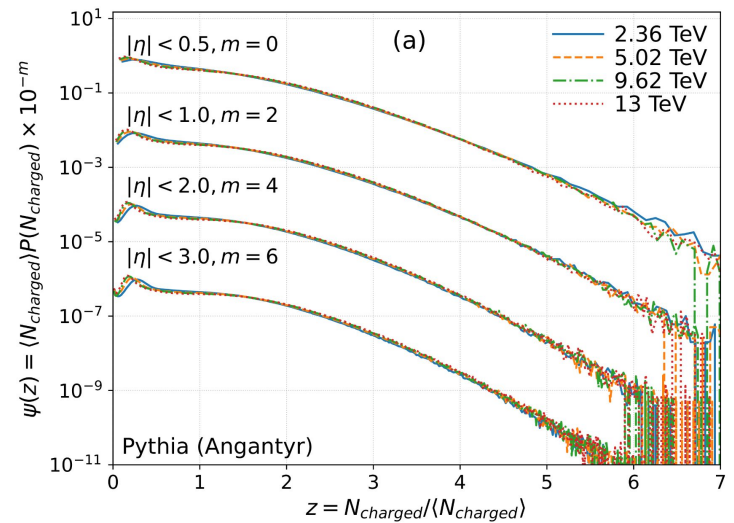
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# Double NBD

For high energies, the literature teaches that **we need a combination of two Negative Binomial Distribution (NBD)** to describe the multiplicity distribution, where **each NBD corresponds to a distinct class of events: “soft” and “semi-hard” processes**. The multiplicity distribution can be written in the form

$$P(n) = \lambda[\alpha_{soft}P_{NBD}(n, \langle n \rangle, k_1) + (1 - \alpha_{soft})P_{NBD}(m, \langle m \rangle, k_2)]$$

where

$$P_{NBD}(n, \langle n \rangle, k) = \frac{(n + k - 1)!}{n!(k - 1)!} (1 - \langle n \rangle)^k \langle n \rangle^n.$$

$k$  measures the degree of clustering: for  $k \rightarrow \infty$ , the NBD tends towards a Poisson distribution (processes with independent events); for  $k=1$ , the NBD becomes a Geometric distribution.

# Double NBD

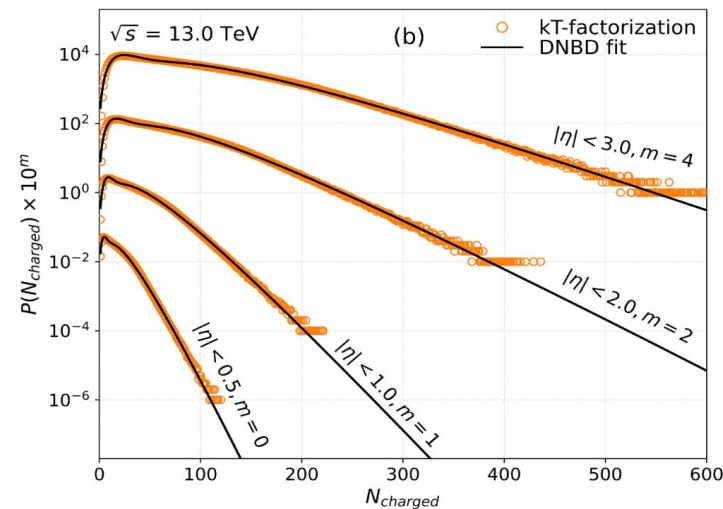
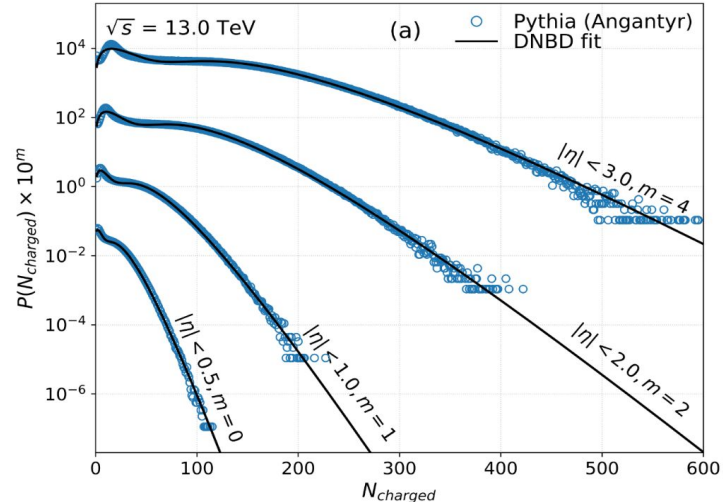
For high energies, the literature teaches that we need a combination of two Negative Binomial Distribution (NBD) to describe the multiplicity distribution, where each NBD corresponds to a distinct class of events: “soft” and “semi-hard” processes. The multiplicity distribution can be written in the form

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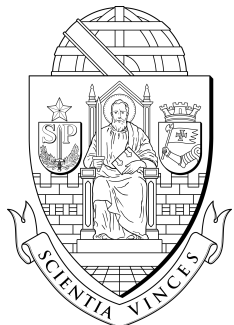
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# Summary

- The multiplicity of charged particles is strongly influenced by the initial geometry considered. The geometric description of the oxygen nucleus as being  $\alpha$ -clusters arranged at the vertices of a tetrahedron or a Woods-Saxon projects significantly different multiplicities, particularly for large  $N_{\text{charged}}$  and more expressively at higher pseudorapidity.
- The multiplicity of charged particles calculated with Pythia (Angantyr) reveals significantly different behavior from that calculated with kT-factorization. The characteristic peak-valley structure of Pythia at small  $N_{\text{charged}}$  does not appear in the kT-factorization calculations. Large  $N_{\text{charged}}$  also shows a large divergence between the models.
- We observed that in all cases there is universality in the behavior of the multiplicity, that is, the KNO scale is not violated.
- We also observed that the DNBD fit describes the projections well with Pythia (Angantyr) and also with kT - factorization

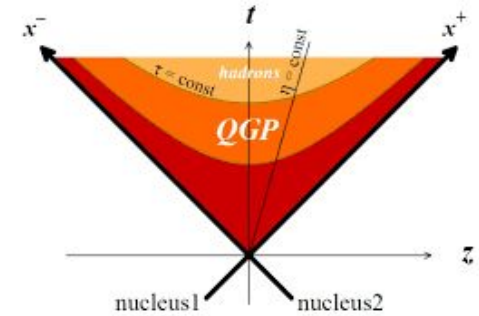


Thank you!

# Backup

# Quark-Gluon Plasma

QGP is an extremely energetic and high-density state of matter in which quarks and gluons move freely in a macroscopically large volume. QGP can form in collisions that create a sufficiently large volume and a sufficiently high energy density to overcome confinement.



Under normal conditions, a QGP is not expected to form in pp collisions, because the volume and energy density are generally too small to sustain an extended thermalized state. However, in very high-multiplicity pp collisions signs of collectivity similar to those seen in the QGP are observed. This raises questions about whether a miniature QGP or other collective mechanism might be occurring even in these small systems.

An extensive review of the QGP can be found at [ALICE Collab., Eur. Phys. J. C 84 \(2024\) 813](#)

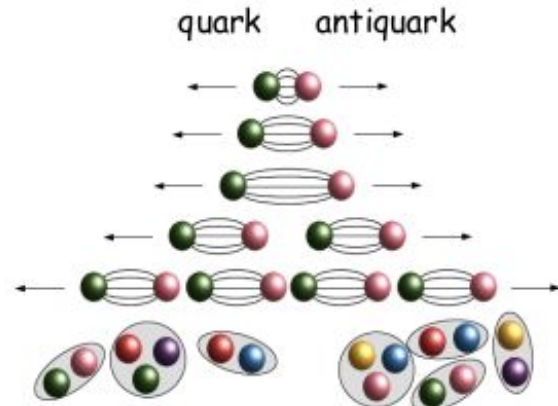
# Lund String Model

It is a non-perturbative part of QCD, based on empirical models fitted to experimental data.

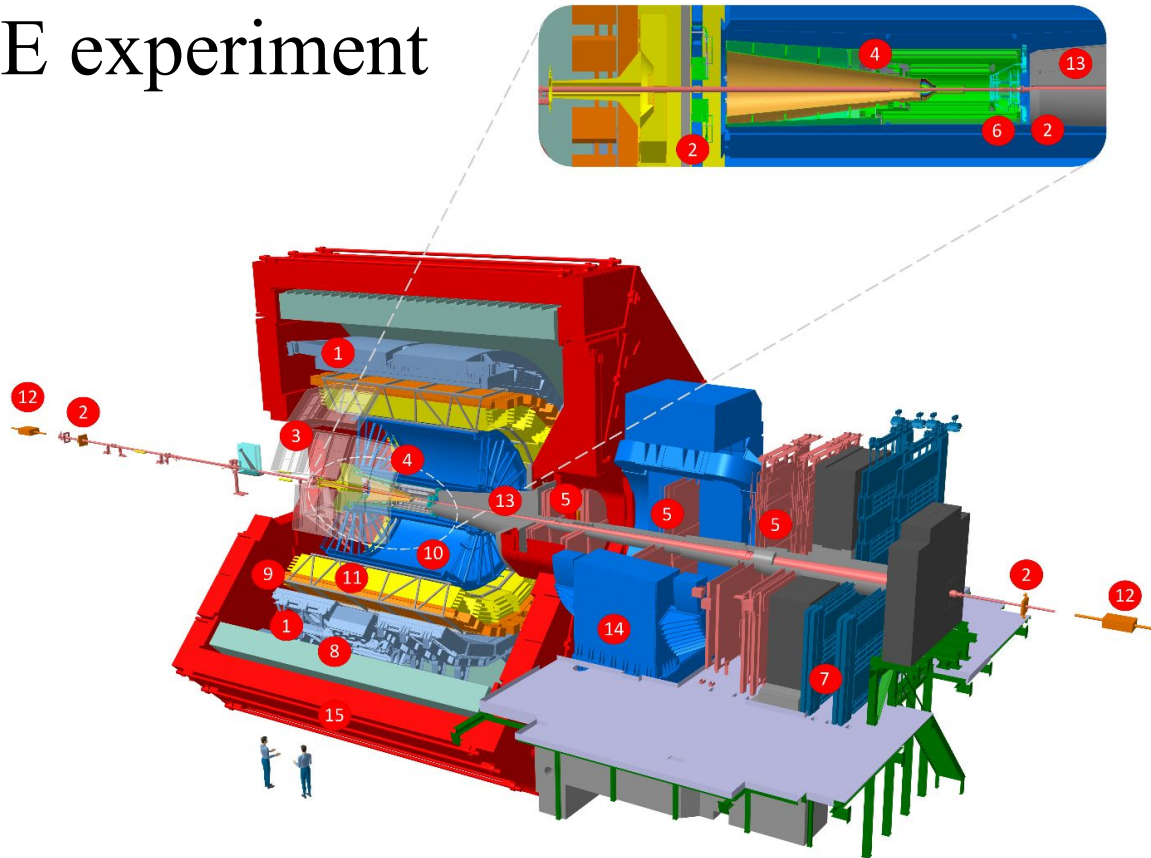
- The partons are connected by color field “strings.”
- As the strings stretch, they “break” and form qqbar pairs, resulting in hadrons.

Soft processes  $0 < p_T < 1 \text{ GeV}$

String formation and decay  
(non perturbative QCD)



# ALICE experiment



- 1 EMCAL | Electromagnetic Calorimeter
- 2 FIT | Fast Interaction Trigger
- 3 HMPID | High Momentum Particle Identification Detector
- 4 ITS | Inner Tracking System
- 5 MCH | Muon Tracking Chambers
- 6 MFT | Muon Forward Tracker
- 7 MID | Muon Identifier
- 8 PHOS/CPV | Photon Spectrometer
- 9 TOF | Time Of Flight
- 10 TPC | Time Projection Chamber
- 11 TRD | Transition Radiation Detector
- 12 ZDC | Zero Degree Calorimeter
- 13 Absorber
- 14 Dipole Magnet
- 15 L3 Magnet