

# Particle production and entropy measurements in ALICE

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for the ALICE Collaboration

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A complex visualization of particle tracks, likely from a heavy-ion collision. Numerous colored lines (red, green, blue, yellow) radiate from a central point, representing the paths of various particles. The background is dark, and the tracks are dense and overlapping, creating a web-like structure.

## Particle Production

- Multiplicity measurements are made to better understand the nature of the proton's structure and the mechanisms underlying particle production.
- Charged particle multiplicity was measured at  $\sqrt{s} = 13.6$  TeV using the ALICE detector at the Large Hadron Collider during Run 3.

# Introduction

- A new mechanism for how these particles may be generated using entanglement has been proposed. We test this approach by making a comparison between entropy in the initial state and entropy in the final state.
- Entanglement in the initial state may be what gives rise to the thermal like behavior of larger systems.





# Particle Production

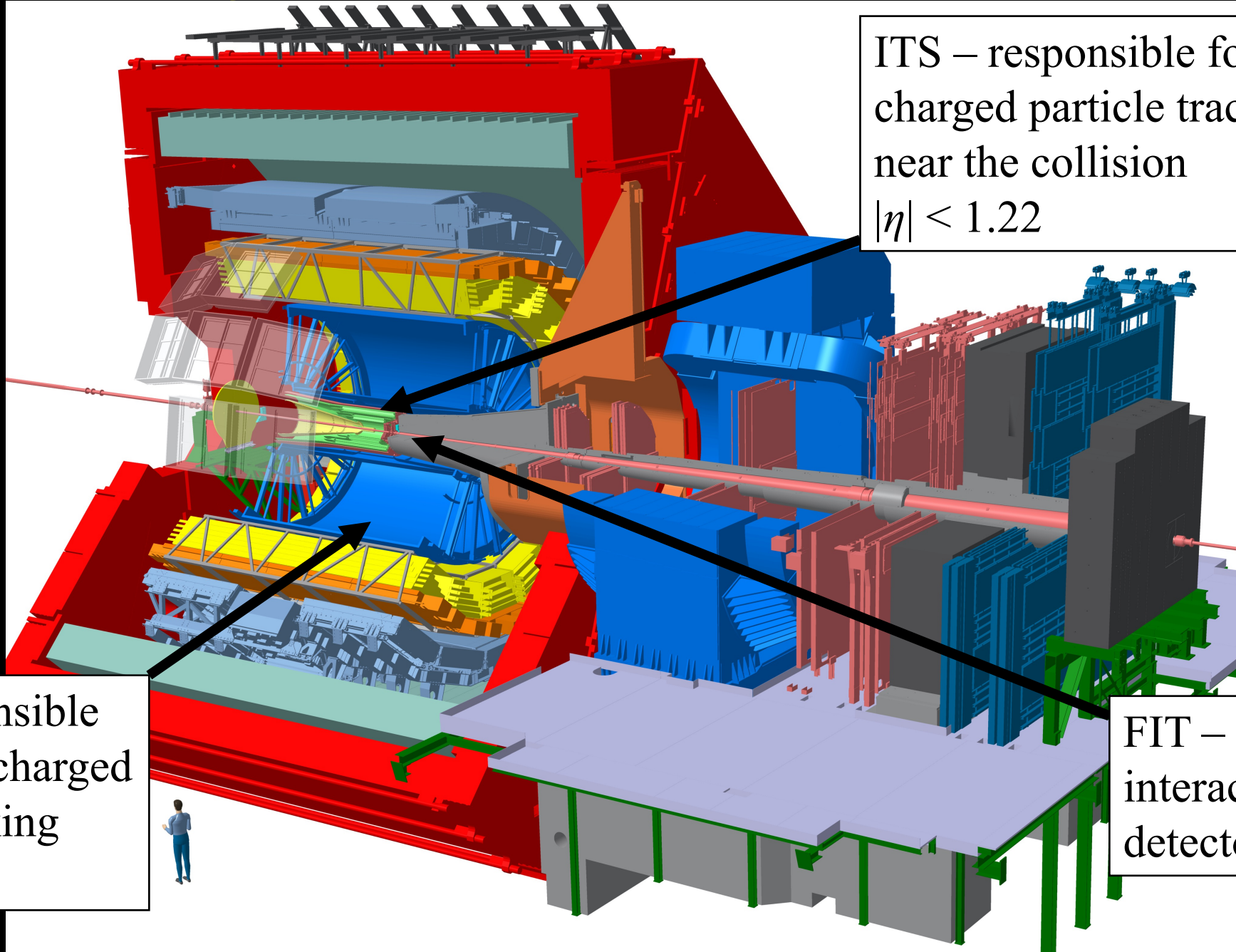
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## Entanglement Entropy

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- Entanglement in the initial state may be what gives rise to the thermal like behavior of larger systems.



# A Large Ion Collider Experiment (ALICE)



ITS – responsible for  
charged particle tracking  
near the collision  
 $|\eta| < 1.22$

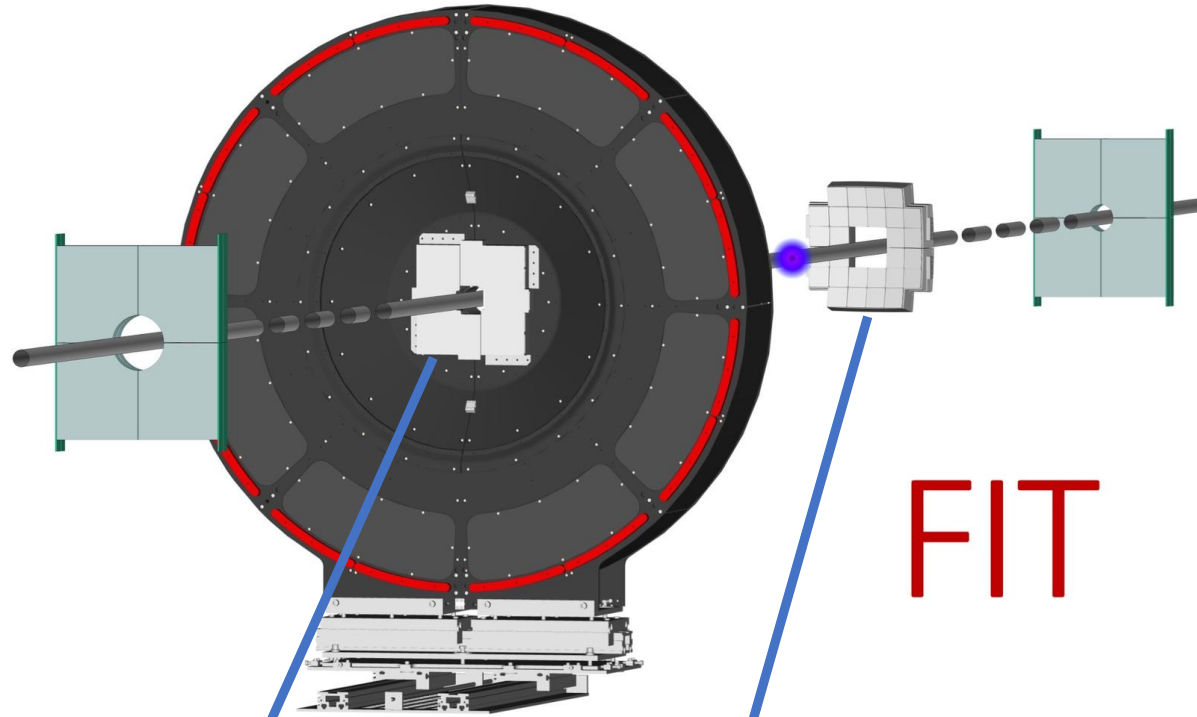
TPC – responsible  
for PID and charged  
particle tracking  
 $|\eta| < 0.9$

FIT – Fast  
interaction trigger  
detectors

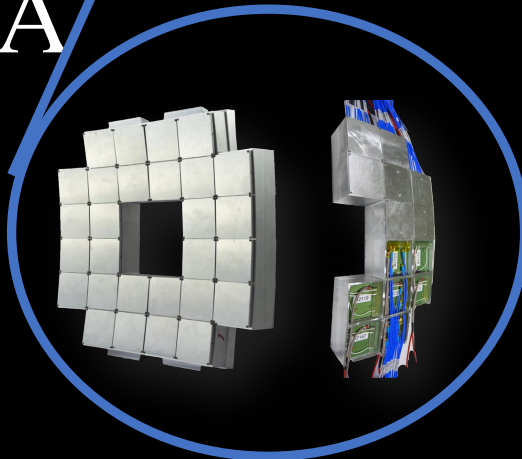


# Fast Interaction Trigger

- $\sim 0.8$  m and  $\sim 3$  m from IP
- 24 and 28 Cherenkov modules
- $3.8 < \eta < 5.0$  and  $-3.4 < \eta < -2.3$
- Time resolution:  $\sim 33$  ps
- Min. bias trigger, used to ensure collisions are close enough in time to filled bunch crossings



FT0-A

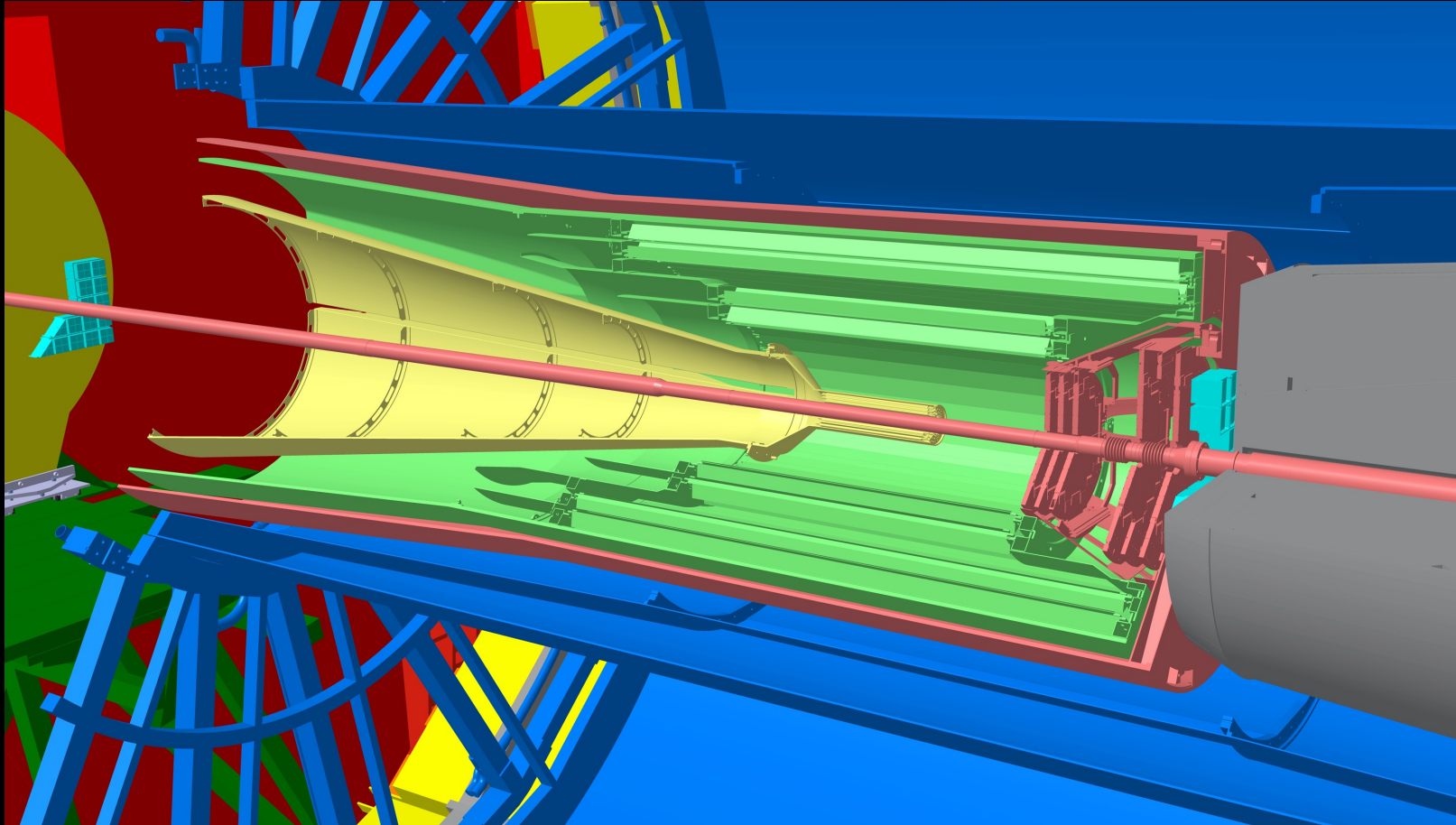


FT0-C





# Inner Tracking System (ITS)



- A key element of the Run 3 upgrade was the addition of the new ITS, which provides improved impact parameter resolution, readout-rate, and tracking efficiency.
- 7 layers of highly granulated silicon pixel detectors improve tracking efficiency especially for low- $p_T$  particles.
- The ITS is an important subsystem in particle tracking near the interaction point. We require at least one hit in the ITS for all tracks.

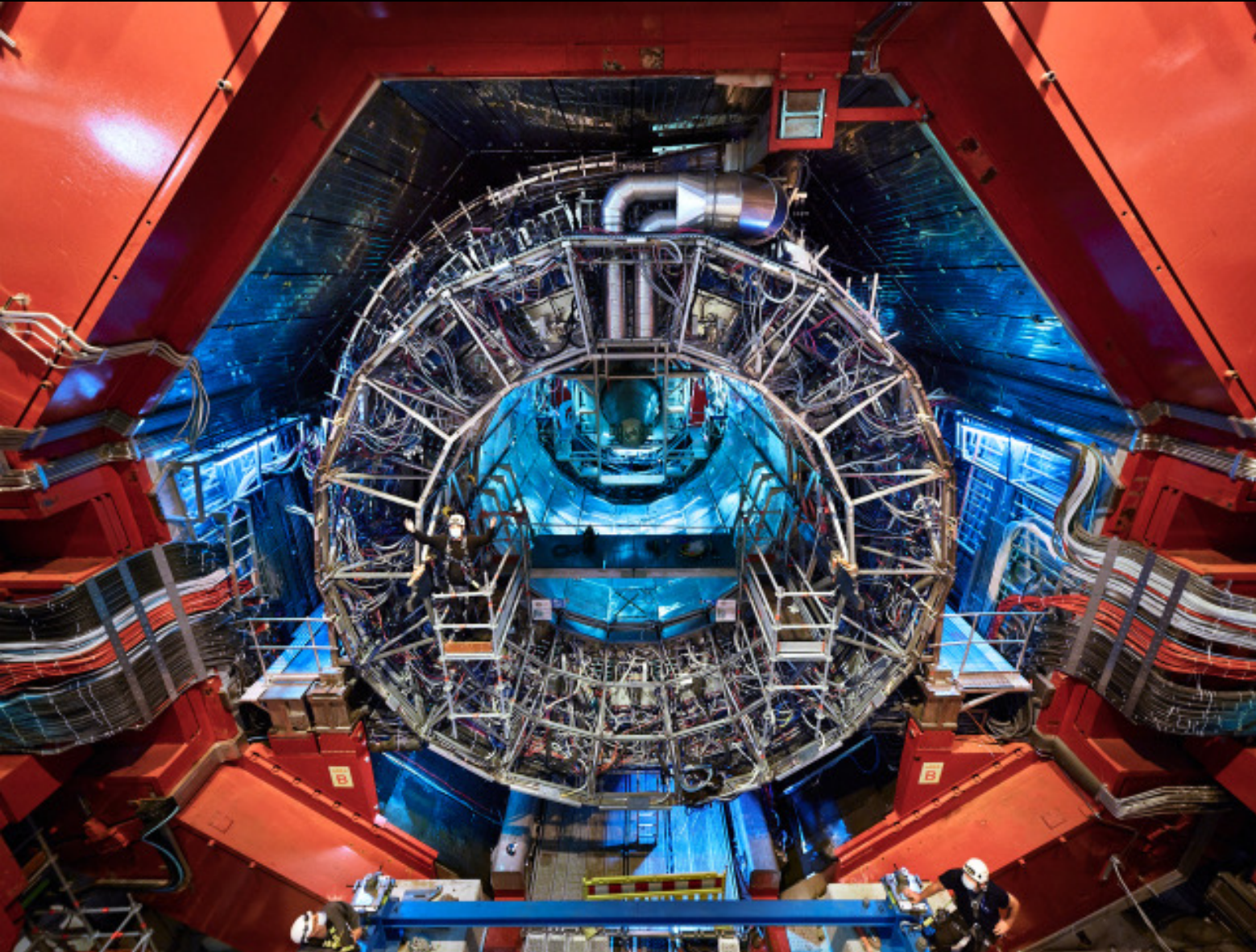
Pseudorapidity coverage:  $|\eta| < 1.22$

Pixels:  $12.5 \times 10^9$  MAPS (spatial resolution of  $5 \mu\text{m}$ )

Readout rate (pp): 500 kHz up to 1 MHz



# Time Projection Chamber (TPC)



- The TPC is the primary subsystem used for particle tracking in the central barrel.
- As charged particles traverse the TPC clusters of electrons from the ionized gas drift to the edge of the chamber.
- For the Run 3 upgrade Multi-Wire Proportional Chambers (MWPC) were replaced with Gas Electron Multipliers (GEM), thus removing rate restrictions, reducing ion backflow, and minimizing space-charge distortions



A 3D schematic diagram of the ALICE detector at the Large Hadron Collider. The diagram shows the central barrel region with various subdetectors labeled: ITS (Inner Tracking System) in yellow, TPC (Time Projection Chamber) in blue, TRD (Transition Radiation Detector) in green, and TOF (Time-of-Flight) in grey. Red lines represent particle tracks originating from the center and passing through these layers. The text "Multiplicity Measurements" is overlaid in large white letters.

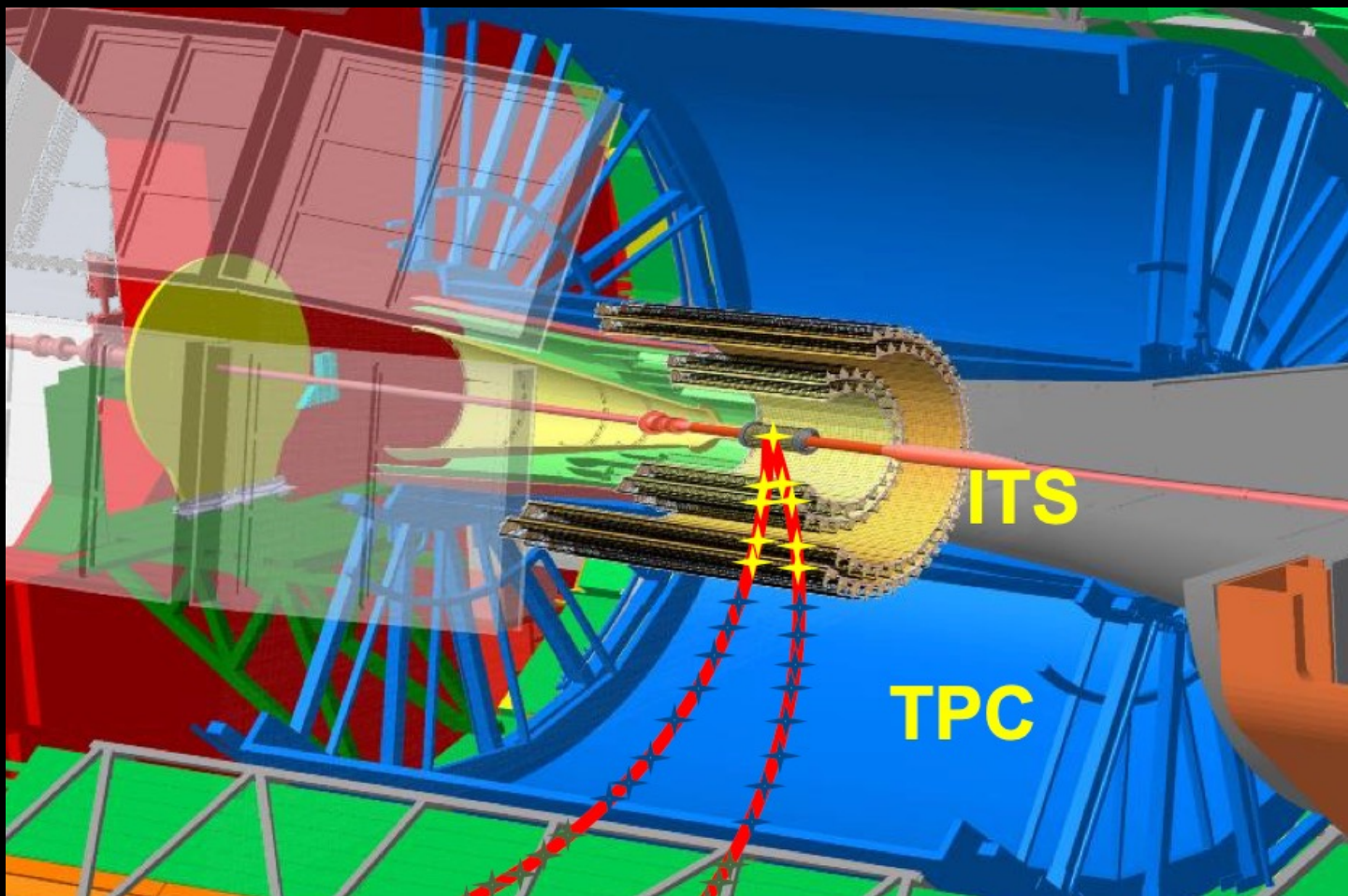
# Multiplicity Measurements

## Track Counting

- ITSTPC global tracks are used for particle counting, they have at least one hit in the ITS and a matching TPC track.
- Standard cuts are made on the tracks (e.g. minimum # of TPC clusters) to ensure high quality tracks are used.



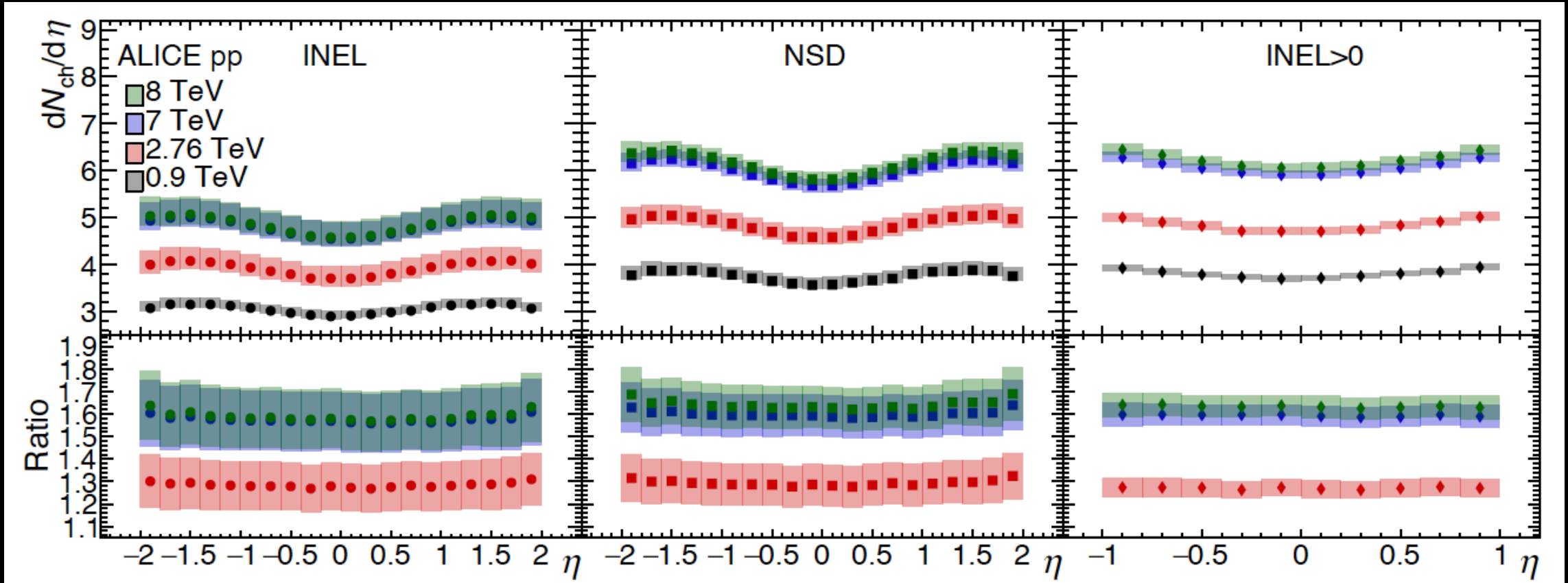
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# Previous Measurements



ALICE, Eur. Phys. J. C, vol. 77 (2017)1

INEL

All inelastic events

NSD

Inelastic events  
excluding single  
diffractive events

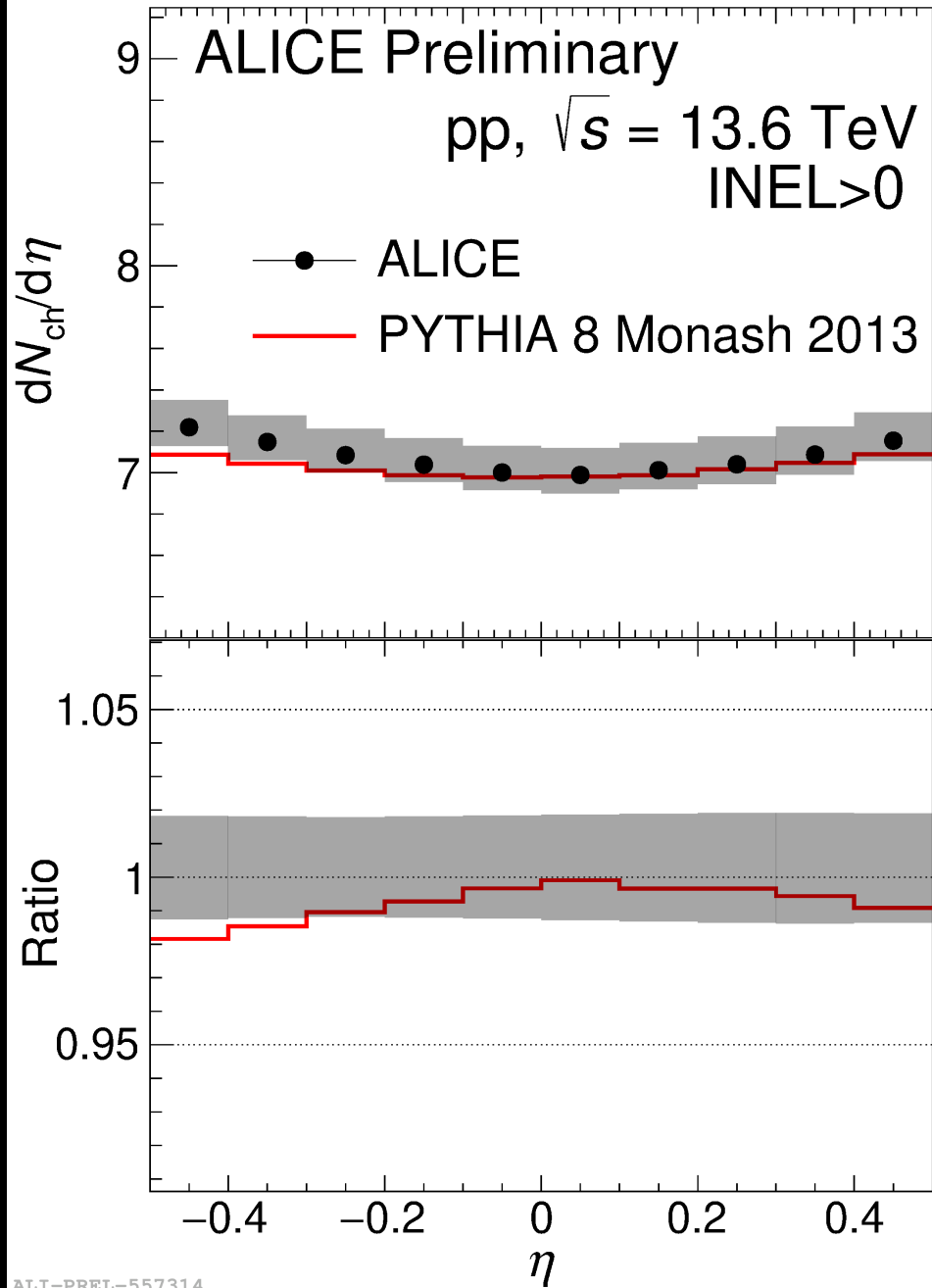
INEL>0

Inelastic events with at  
least one charged particle  
produced in  $|\eta|<1$



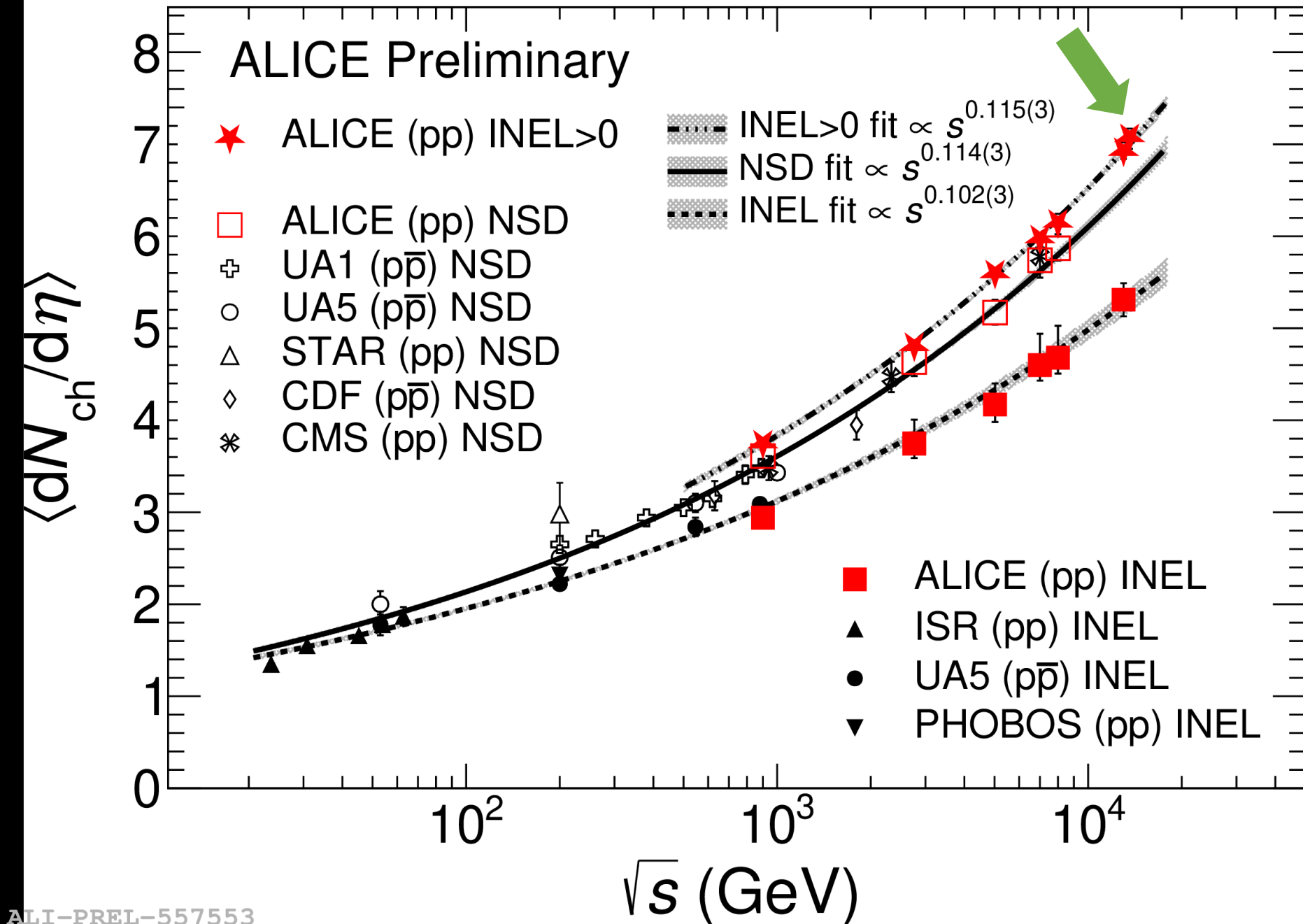
# New results in Run 3

$dN_{ch}/d\eta$  vs.  $\eta$



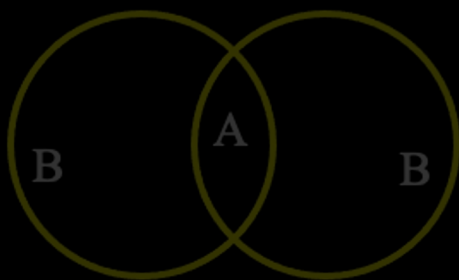
- Data sample: 13.6 TeV
- Event selection: INEL > 0
- Pseudorapidity coverage:  $-0.5 < \eta < 0.5$
- We observe good agreement between data and PYTHIA.





# New results In Run 3 $\langle dN_{ch}/d\eta \rangle$ vs. $\sqrt{s}$

- New results at 13.6 TeV are compatible with expected values from power law fitting.



## Entanglement Entropy (initial-state)

- Entanglement entropy quantifies the degree of correlation or amount of information shared between two or more quantum systems.
- A proton represents a pure state; meaning the partons are fully correlated and maximally entangled.
- The interacting proton can be segmented into an interaction region (A) and a region that remains unprobed (B). Entanglement entropy arises between these two regions.

$$S_A = -tr[\hat{\rho}_A \ln \hat{\rho}_A] = S_B = -tr[\hat{\rho}_B \ln \hat{\rho}_B]$$

## Gibbs Entropy (final-state)

- Gibbs entropy is a thermodynamic quantity that measures the degree of disorder, or randomness, in a system.
- This is calculated using a probability distribution of the number of microstates. In this case the number of hadrons

While the Gibbs entropy is defined under different contexts than entanglement entropy, each of these definitions attempts to quantify the disorder of the system.

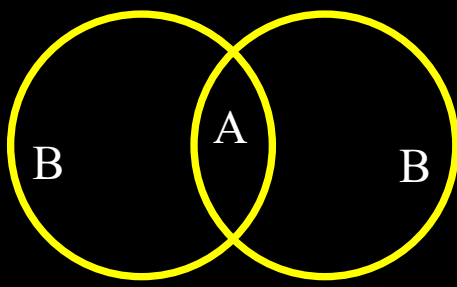
$$S_{\text{Gibbs}} = - \sum P(N) \ln P(N)$$

## Ongoing work at the University of Houston

QM poster #1077

The goal of this analysis is to show that entanglement survives the system evolution, and these two entropies can be related, even to the extent that their values should be equal. This would demonstrate that we are not dealing with a thermal system but rather a quantum many body system that appears thermal.





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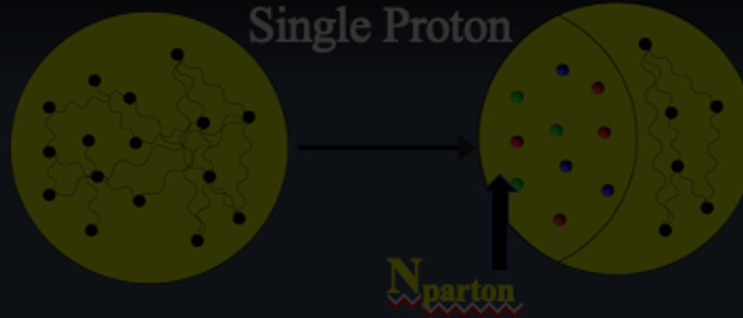
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$$S_{\text{hadron}} = - \sum P(N) \ln P(N)$$

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Proton before collision

- Pure quantum state
- Maximally entangled
- 0 von Neumann entropy



Coherence between the region probed by the other proton and the part left alone is lost. Giving rise to increase in entanglement entropy

In the region of low  $x$  where the proton can be described as a mass of indistinguishable gluons we estimate the entanglement entropy as:

Parton model places the proton in a Lorenz contracted high momentum frame where partons are seen as quasi-free by some external probe

# Initial State

$$S_{\text{parton}} = \ln(N_{\text{parton}})$$

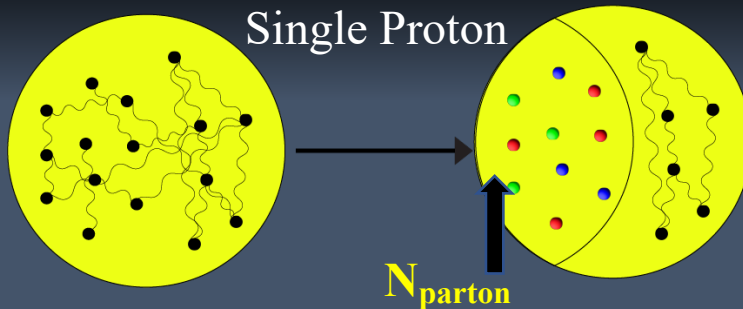
Non-uniform color fields generated by the interaction can lead to the formation of flux tubes, which are regions of high color field strength that extend between partons. These flux tubes can be thought of as one-dimensional objects, or strings.

String formation adds a third dimension thereby making entropy an extensive quantity. This approach only quantifies the transverse component of the entanglement entropy.



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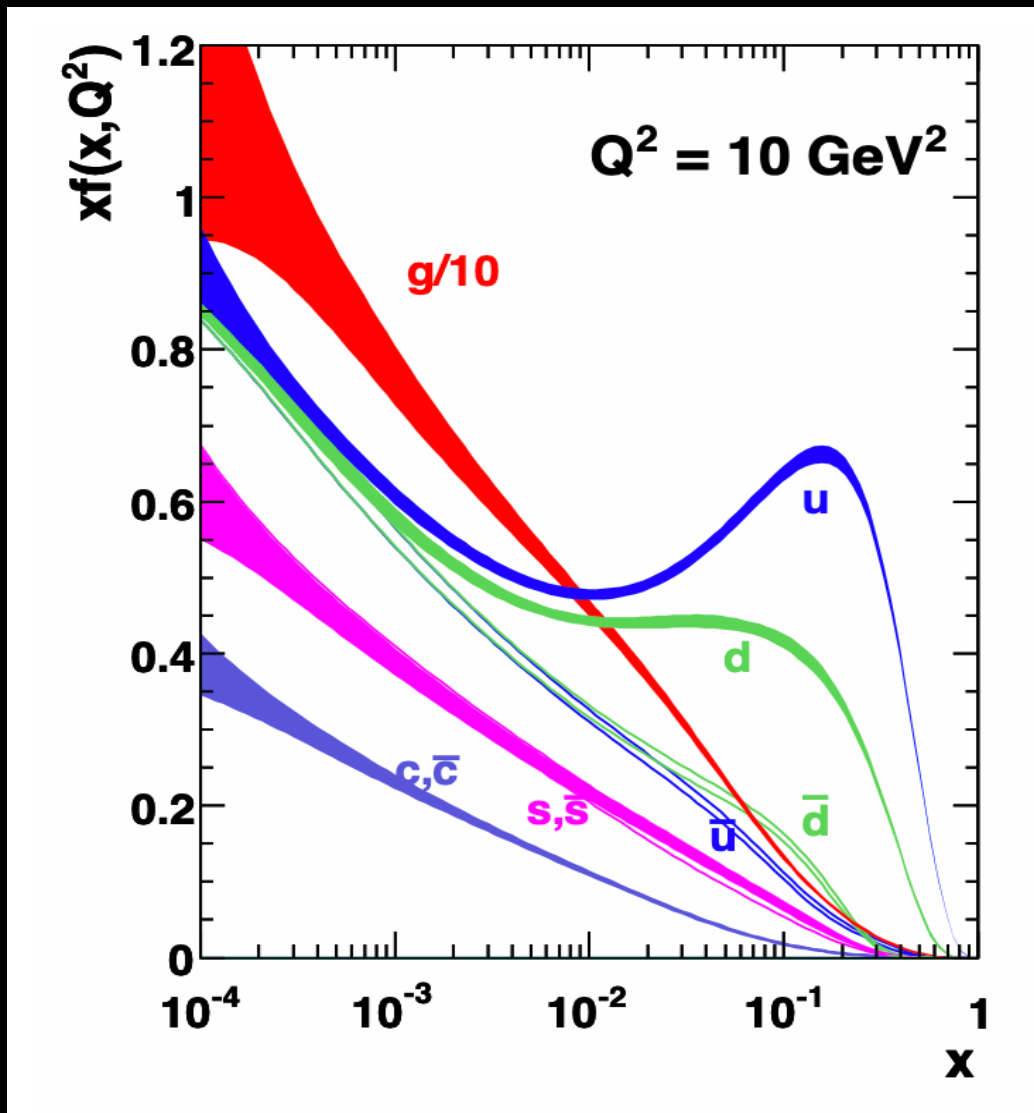
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# Parton Distribution Functions



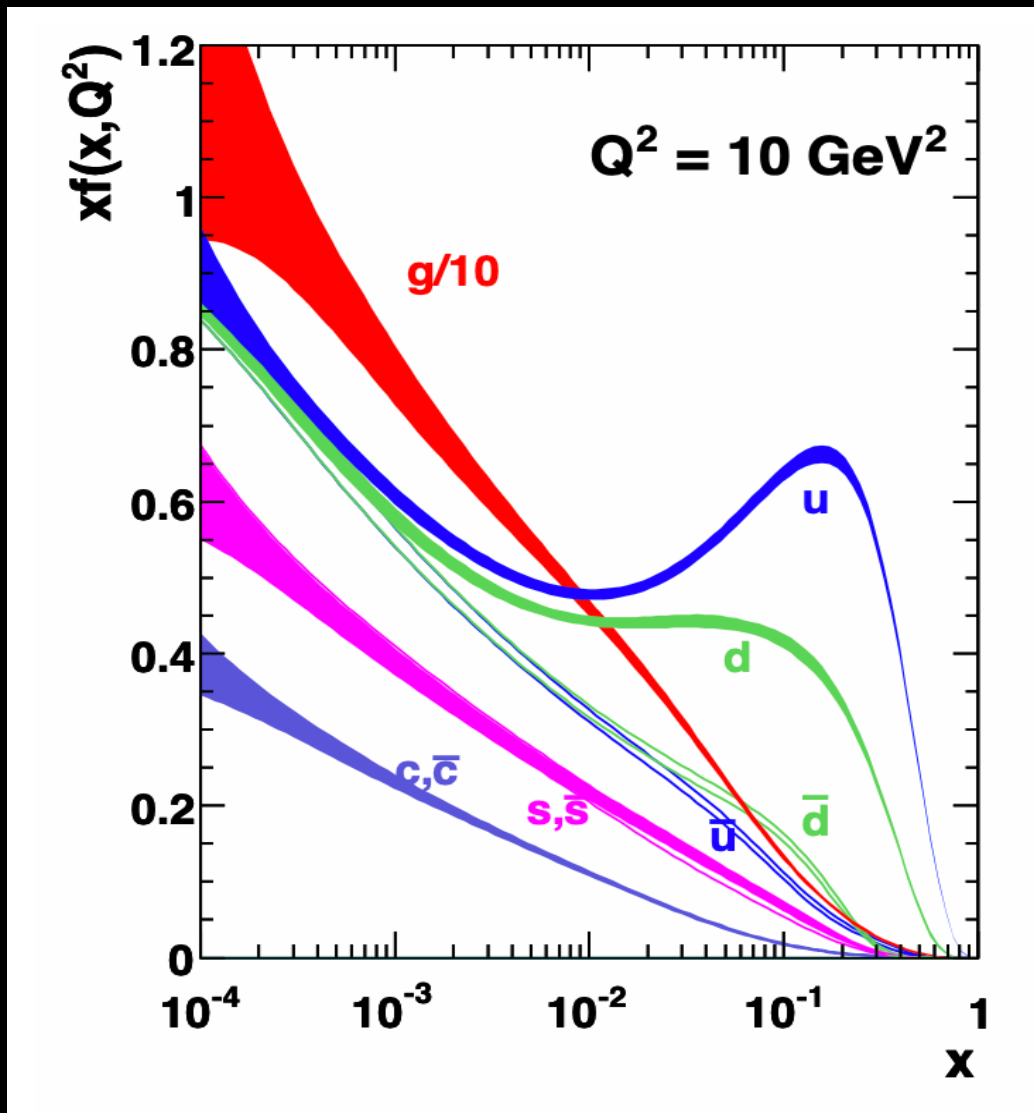
*A. D. Martin, W. J. Stirling, R. S. Thorne, and G. Watt, Eur. Phys. J. C63, 189 (2009)*

- Found using pQCD by fitting DIS cross sections from data, PDF's describe the probability to find a particular parton with some fraction of the protons momentum characterized by  $x$ .
- PDF's are dependent on the scale at which the proton is probed  $Q^2$  called the factorization scale.
- $x$  represents the fractional momentum carried by a struck parton. We can map  $x$  to pseudorapidity in the final state using:

$$x = e^{-y_p} e^{\eta_h}$$



# Parton Distribution Functions



*A. D. Martin, W. J. Stirling, R. S. Thorne, and G. Watt, Eur. Phys. J. C63, 189 (2009)*

- PDF's are integrated over to find the number of partons in the initial state.
- The limits of integration are defined by the pseudorapidity range over which we measure final state particles.

$$N_g = \int_{x_1}^{x_2} \frac{xG(x)dx}{x}$$

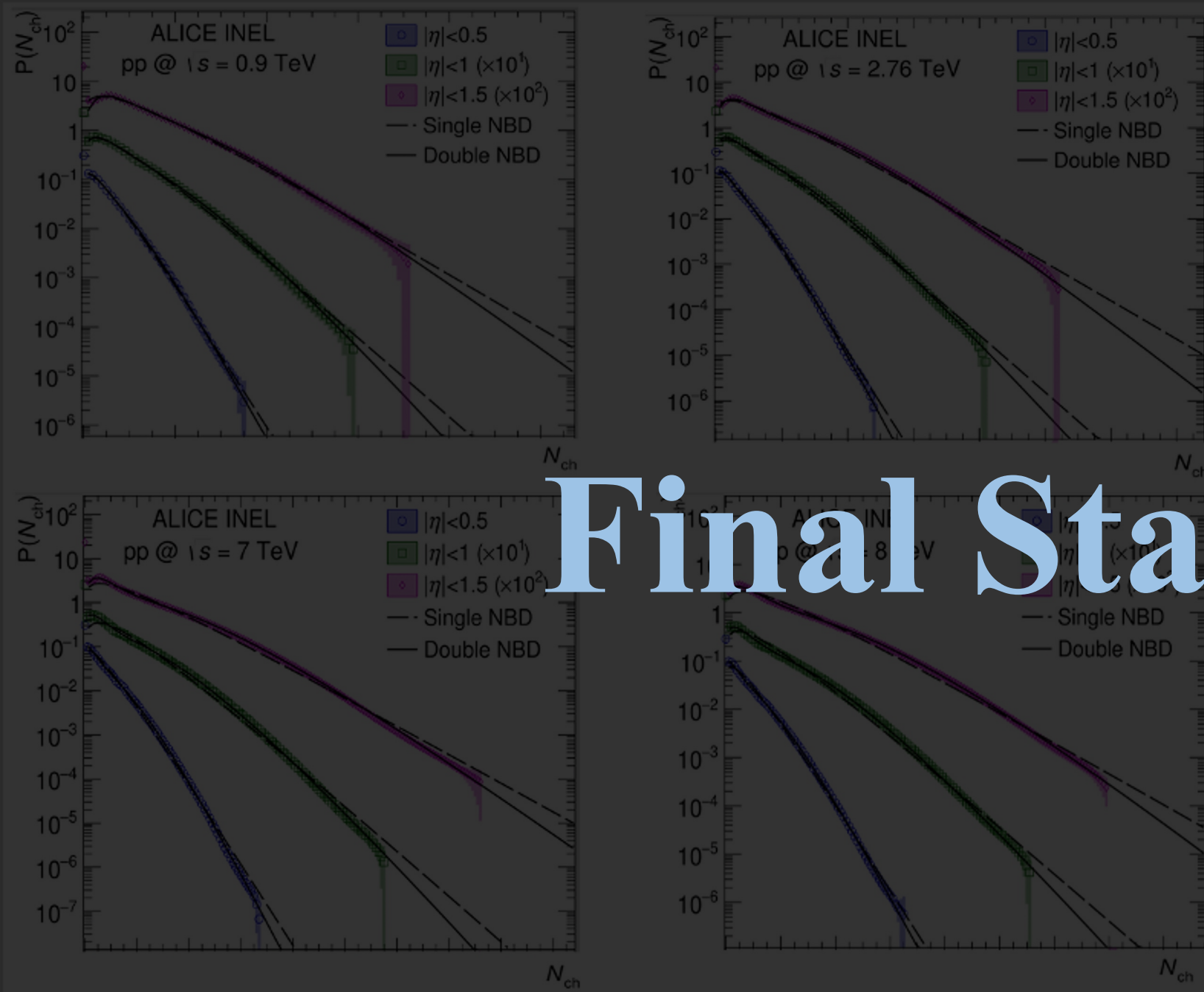
$$S_{\text{parton}} = \ln(N_{\text{parton}})$$

# Multiplicity Distributions

By summing over the final state multiplicity distributions for inelastic events we can calculate an entropy in the final state.

$$S_{final} \propto \sum P(N_h) \ln(P(N_h))$$

# Final State

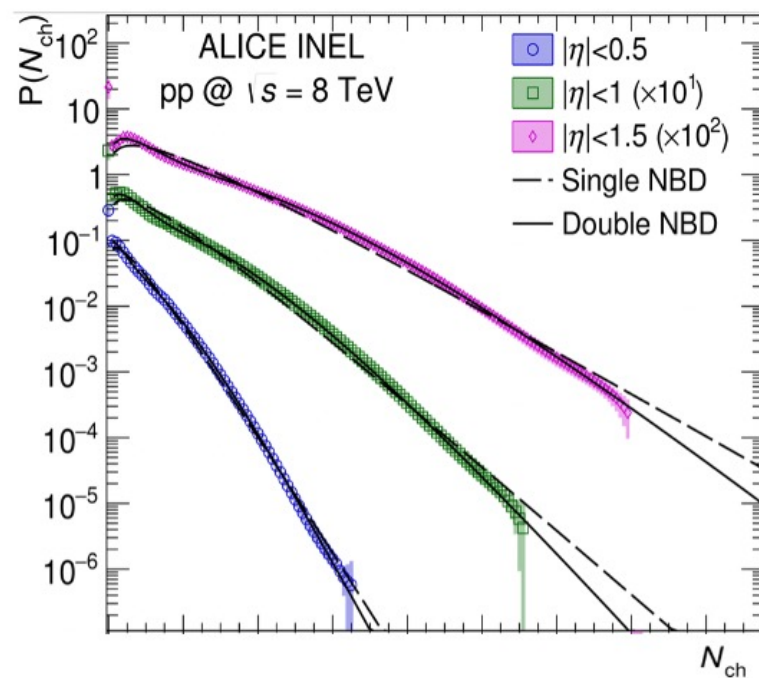
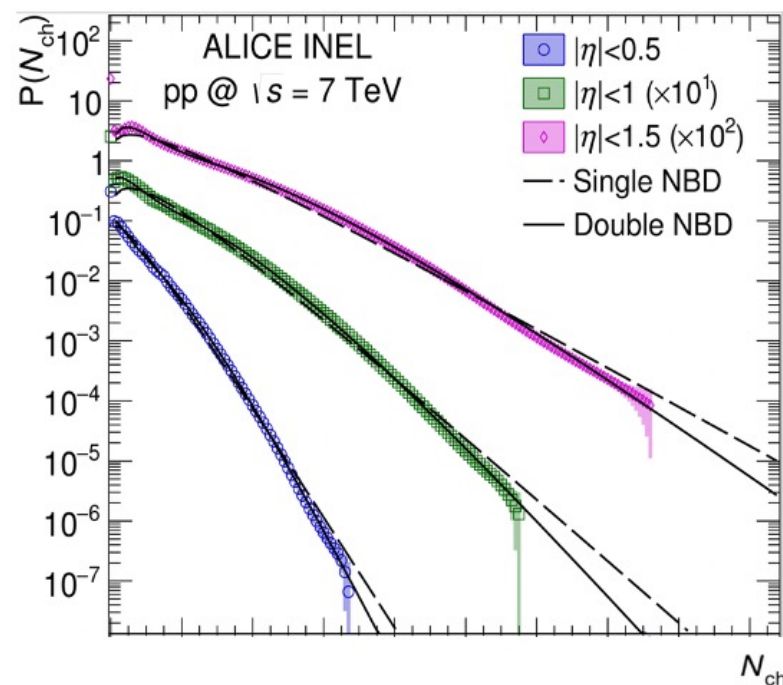
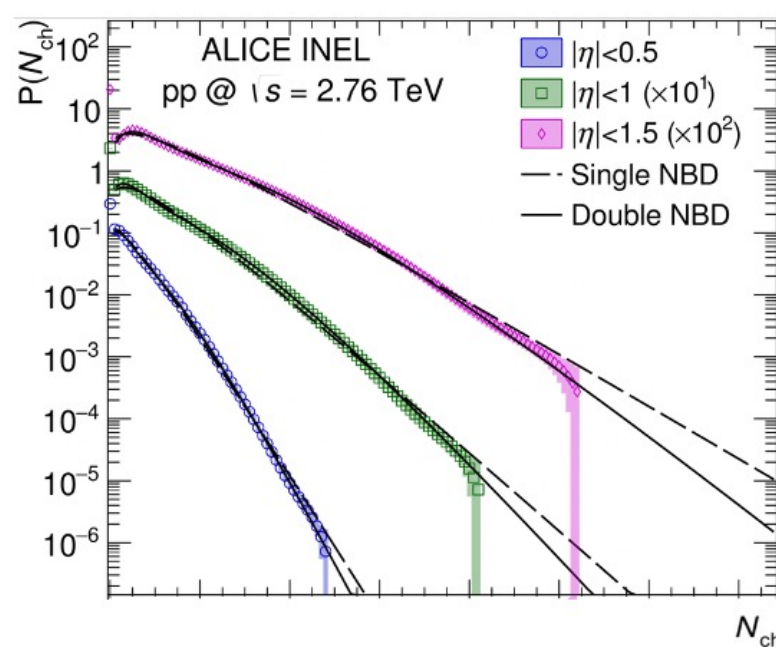
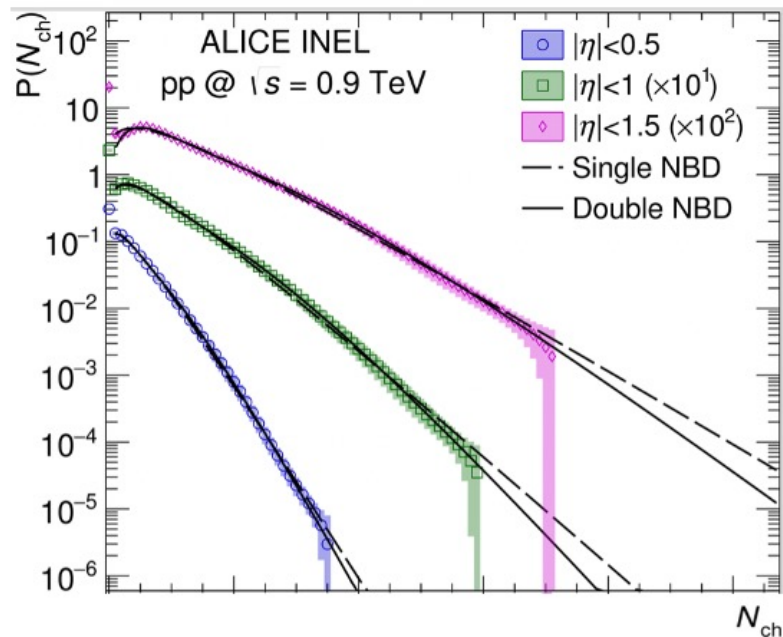




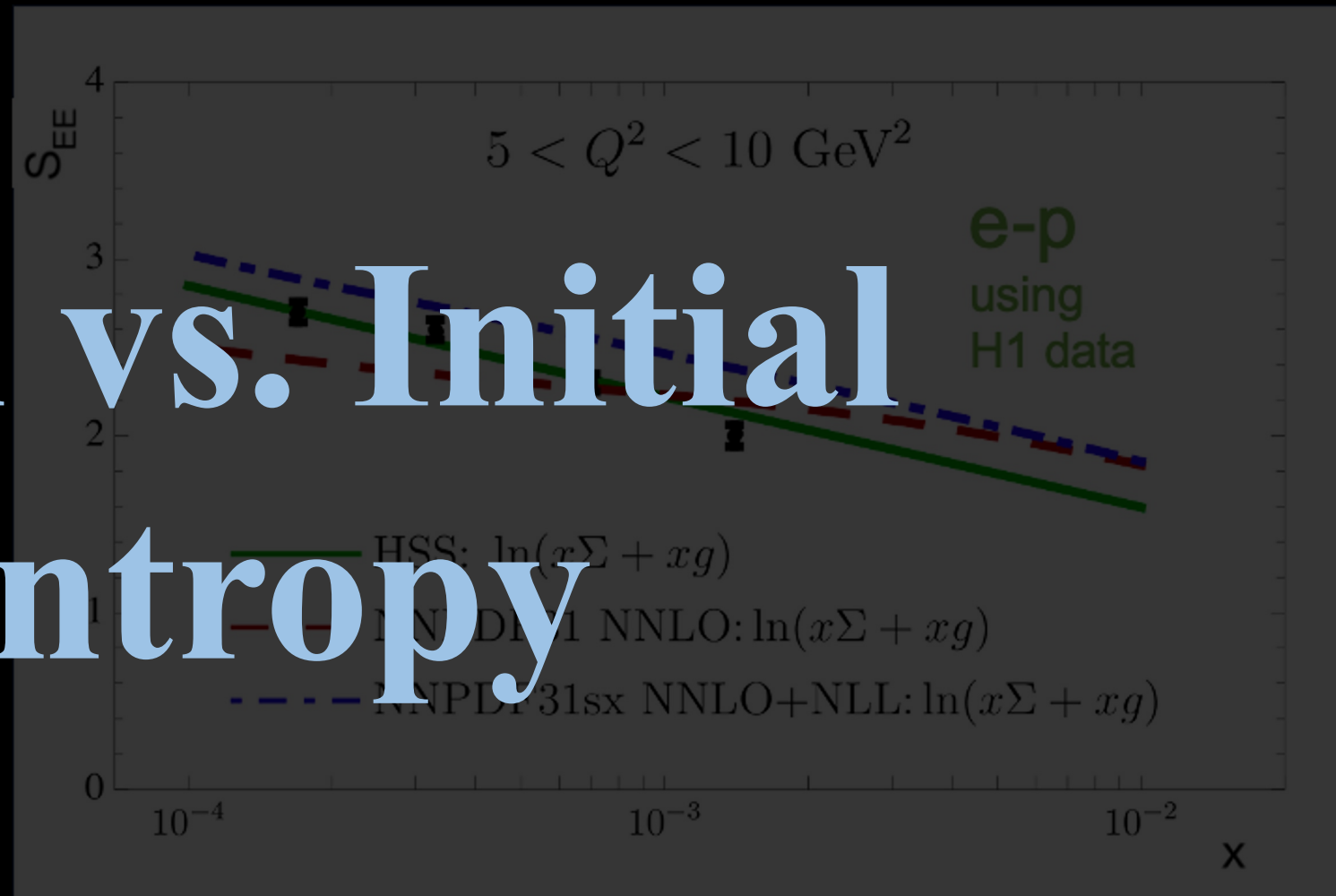
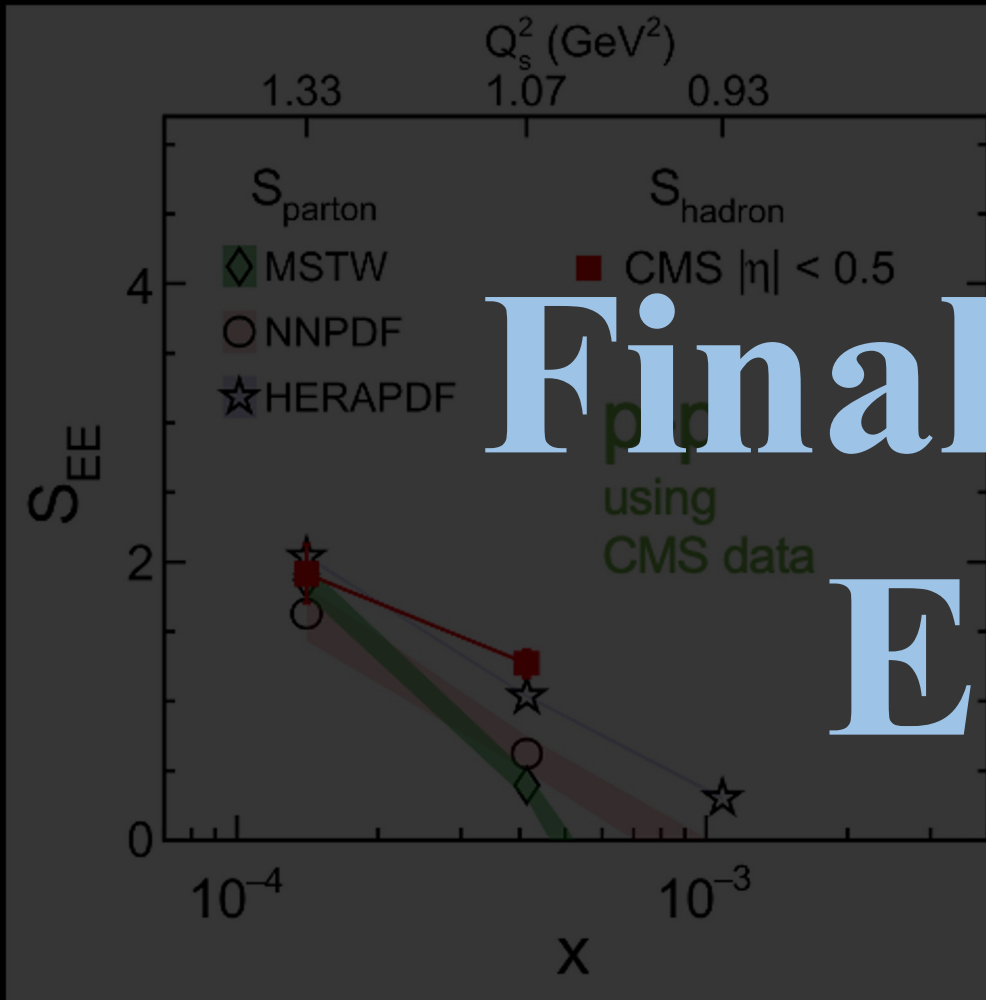
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# Previous Analysis



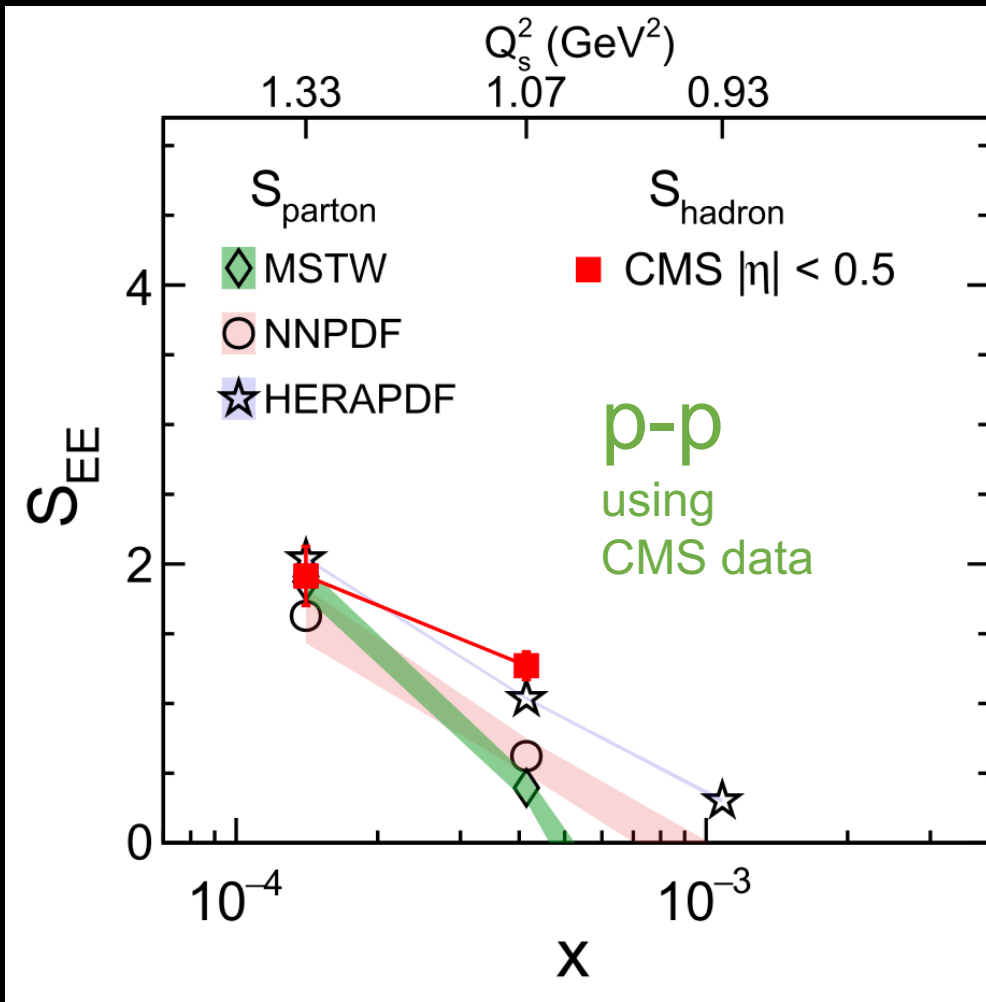
# Final vs. Initial Entropy

Tu, Z., [Kharzeev, D. E.](#), & Ullrich, T., Phys. Rev. Letters, 124(6) (2020)

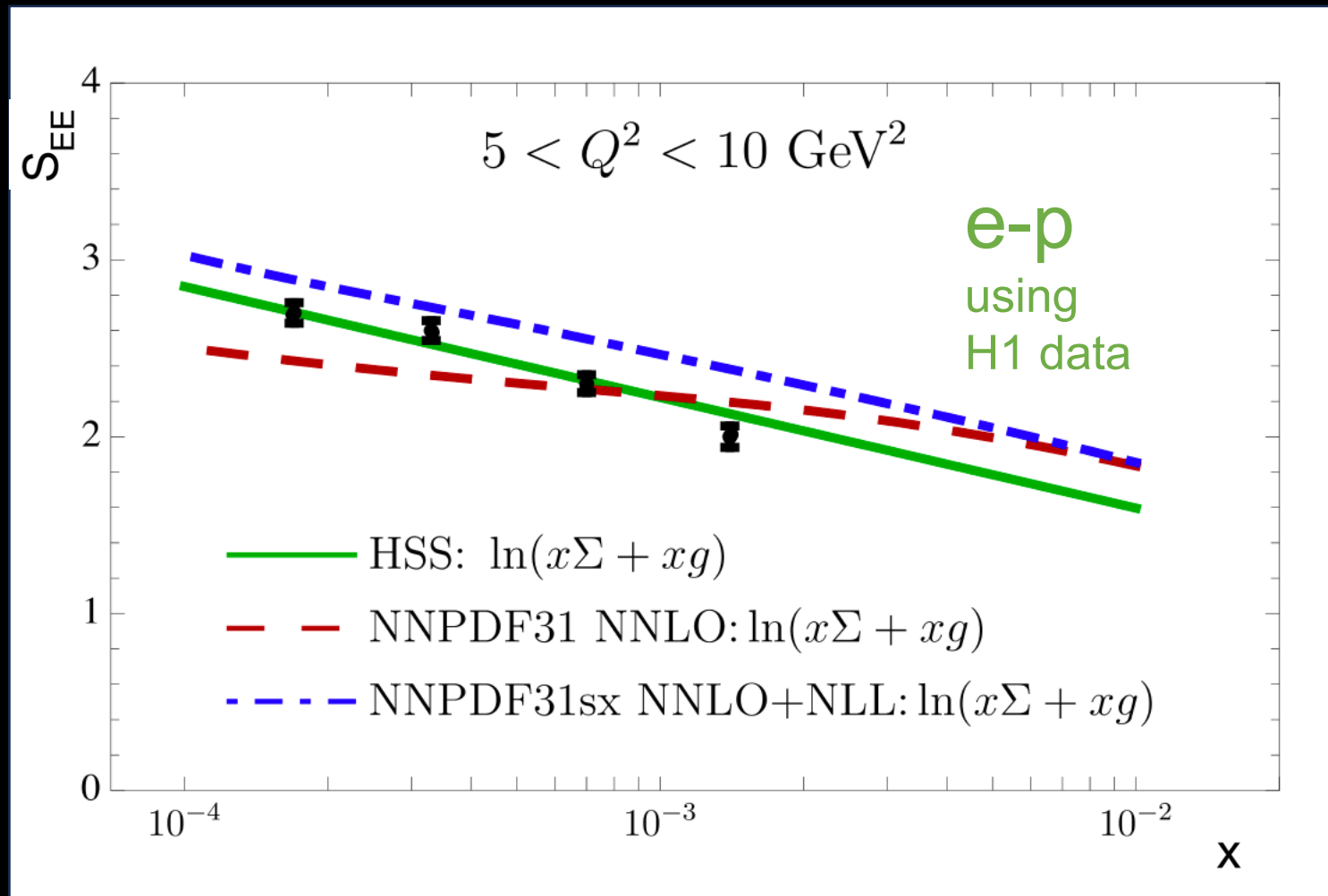
[Hentschinski, M.](#), & Kutak, K, Eur. Phys. J. C, 82(2) (2022)



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# Conclusions and Ongoing Work

- Multiplicity density as a function of pseudorapidity at 13.6 TeV was shown and has reasonable agreement with PYTHIA.
- Multiplicity density as a function of centre-of-mass energy follows the power-law trend extrapolated from lower collision energies.
- Multiplicity distributions for Run 3 are ongoing, will be completed with Pb-Pb multiplicity measurements from Run 3.
- Entropy measurements are ongoing using Run 2 and Run 3 data from ALICE.



# References

ALICE Collaboration, “*Charged-particle multiplicities in proton-proton collisions at  $\sqrt{s} = 0.9$  to 8 TeV*”, The European Physical Journal C, vol. 77, no. 1, January 2017

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A.D. Martin, W.J. Stirling, R.S. Thorne, G. Watt, “*Parton distributions for the LHC*”, The European Physical Journal C, vol. 63, no. 2, pp. 189-285, July 2009.

<https://arxiv.org/abs/0901.0002>

Zhoudunming Tu, Dmitri E. Kharzeev, Thomas Ullrich, “*Einstein-Podolsky-Rosen Paradox and Quantum Entanglement at Subnucleonic Scales*”, Physical Review Letters, vol. 124, no. 6, February 2019

<https://arxiv.org/abs/1904.11974>

Hentschinski, Martin, Krzysztof Kutak, and Robert Straka. "Maximally Entangled Proton and Charged Hadron Multiplicity in Deep Inelastic Scattering." The European Physical Journal C 82.12 (2022): DOI: 10.1140/epjc/s10052-022-11122-1.

<https://arxiv.org/abs/2207.09430>