Exploring Quantum Entanglement in Heavy Ion Collisions

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Perturbative QCD

Recent studies established the relation between entanglement entropy $S(x)$ and parton densities for small Bjorken-x, large rapidity regime

$$S_{parton} = \ln(xG(x;Q^2) + x\Sigma(x;Q^2))$$

initial state

[1] Phys. Rev. D 95, 114008. D. Kharzeev and E. Levin (2017)
[2] Phys. Rev. D 104, 031503. D. Kharzeev and E. Levin (2021)

Entanglement Entropy

Entanglement entropy (EE) applies to both perturbative and non-perturbative regimes

→ EE can connect initial and final state of high-energy reactions

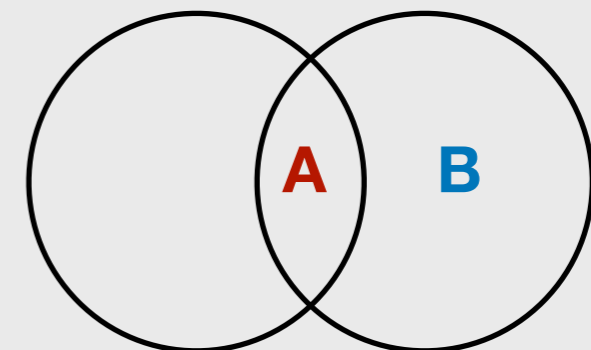$$S_{hadron} = -\sum P(N)\ln P(N)$$

final state

High Energy Processes

Try to verify the relation: $S_{parton} \leq S_{hadron}$

1. Deep Inelastic Scattering [3] arXiv:2207.09430v1. M. Hentschinski et al (2022)
2. Proton-proton collisions [4] Phys. Rev. Lett. 124, 062001. Z. Tu et al (2020)

Our proposal: entanglement in proton-nucleus collisions with ALICE

A   B

# Entanglement in proton-proton collisions

Charged-particle multiplicity distributions

- *Multiplicity distribution* is the probability distribution $P(N_{ch})$ of a collision event to have N_{ch} particles produced

- [4]: proton-proton (pp) collisions with center-of-mass energies $\sqrt{s} = 0.9$, 2.36, and 7 TeV at different pseudo-rapidity ranges $|\eta| < 0.5$, 1.0, and 1.5 of the CMS experiment

- Using Negative Binomial Distribution (NBD) and double NBD to fit the data, we take as our distribution $P(N)$ half of the average to account for one proton distribution

Parton Distribution Functions

- The measurable cross-section can be factorized in a short-distance interaction — the partonic cross-section — and in a function containing the long-distance interactions, the Parton Distribution Functions (PDFs)

- PDFs cannot be derived from first principles → global QCD analysis procedure

- pp analysis: used HERAPDF, NNPDF, and MSTW sets to calculate S_{parton} for d, u, s, and the gluon distribution

Entanglement entropies for pp collisions
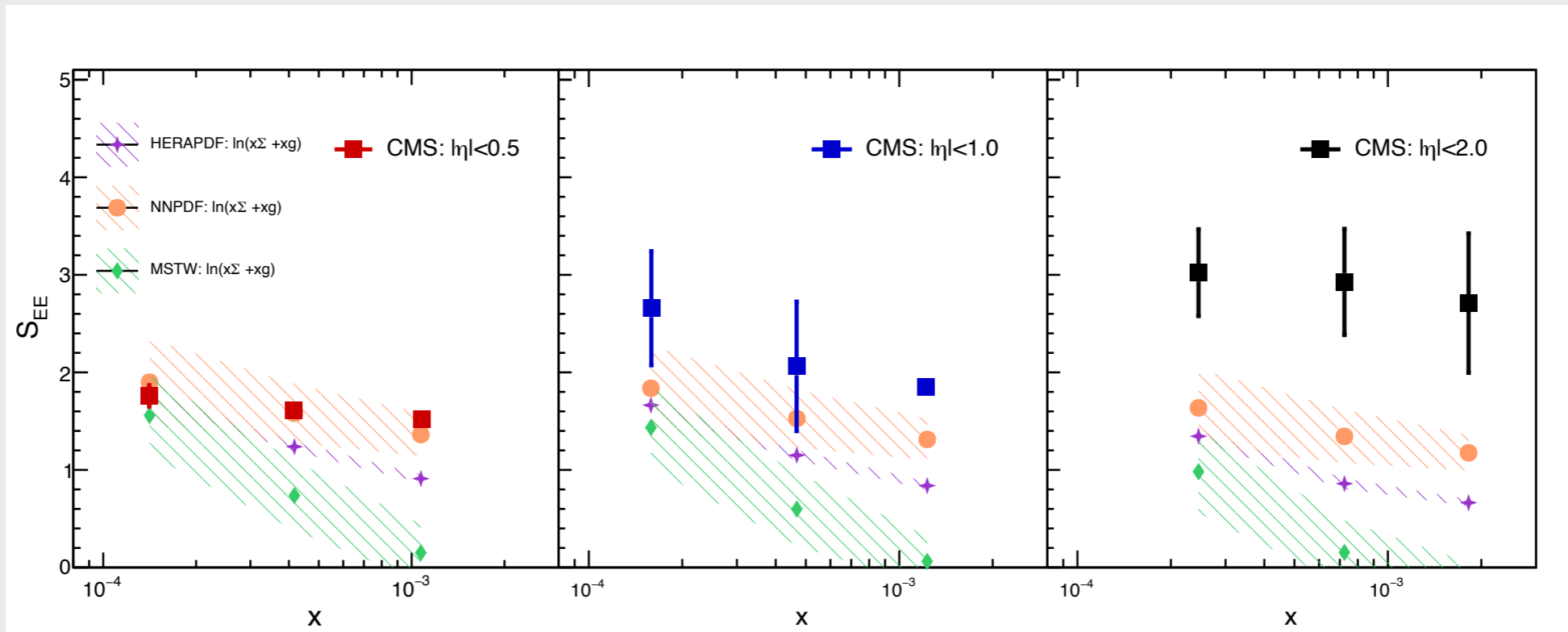
What about proton-nucleus collisions?

- **Final state entropy** Currently working on the data analysis of charged-particle distributions of proton-Lead collisions with ALICE [PAG-MM: https://indico.cern.ch/event/1214899/]

- **Initial state entropy** nPDFs: Fewer data constraints lead to parametrization bias → new approaches for S_{parton}