Entanglement As a Probe of Hadronization

[arXiv:2410.22331, accepted at PRL]

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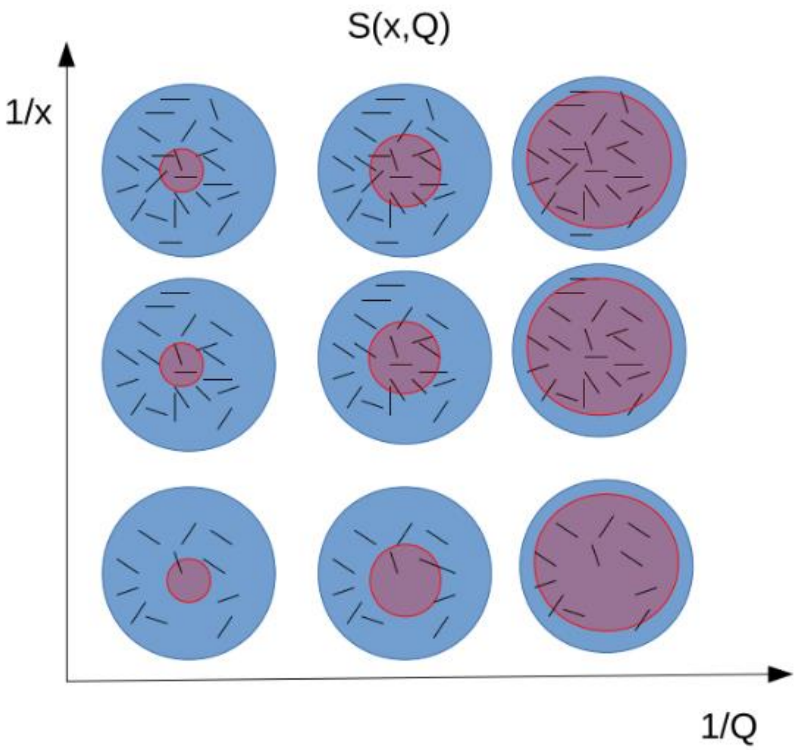
Quantum Entanglement and Entanglement Entropy

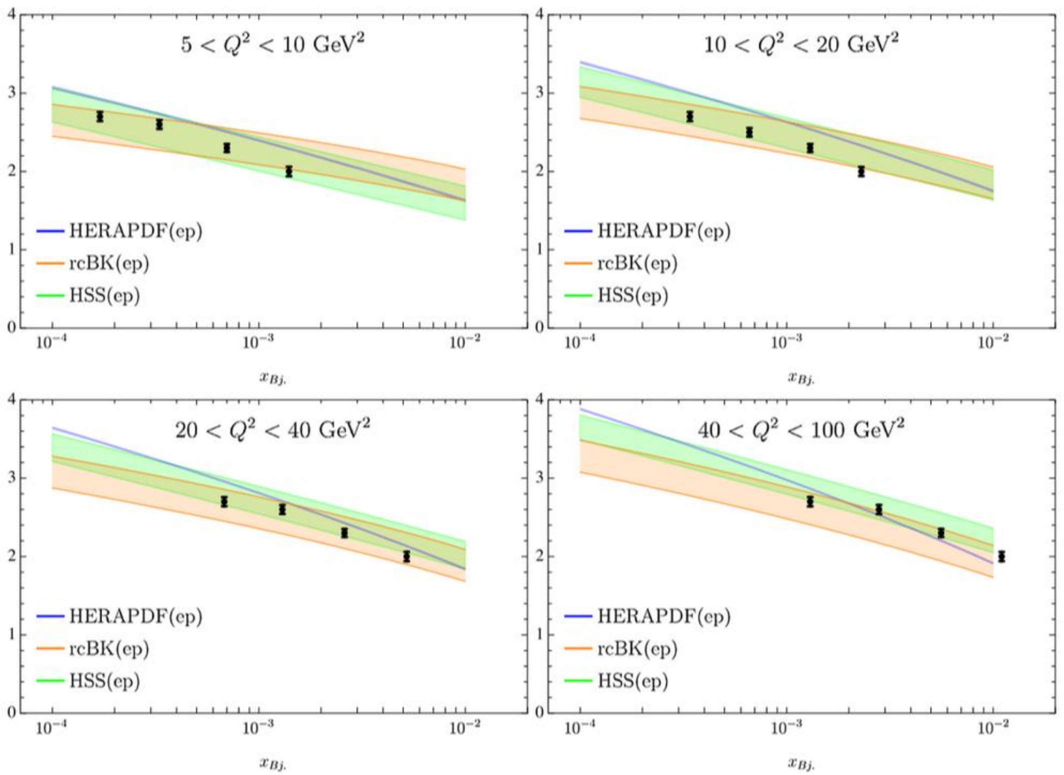
- Two systems S_1 and S_2 are entangled with respect to a certain degree of freedom if their total state $|\psi\rangle_{12}$ relative to that degree of freedom, cannot be written in factorized form as a product $|\psi\rangle_1 \otimes |\psi\rangle_2$

- The von-neumann entropy or entanglement entropy tells us, the amount of available information about an entangled system.

Entanglement in Protons



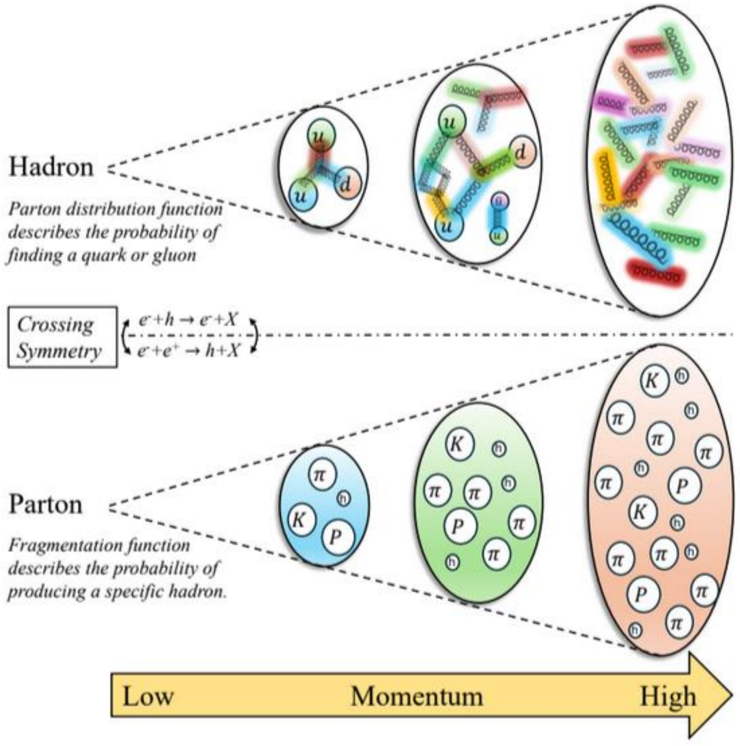
Generation of entanglement in DIS [Eur. Phys. J. C (2022) 82:1147]



Partonic entropy corrected for charged hadrons and compared with data of H1. [Eur. Phys. J. C (2022) 82:1147]

Entanglement in Jets

- The parton distribution functions and fragmentation functions (FF) are related by crossing symmetry [Phys. Lett. B 37, 78 (1971)].
- So it could be expected that jet state is also maximally entangled and the entanglement entropy of the produced hadrons is related to the fragmentation functions.
- The relation between entanglement entropy and fragmentation function has not yet been explored.
- We extend the idea of entanglement entropy to relate the jet fragmentation function to the entropy of the final hadron state.

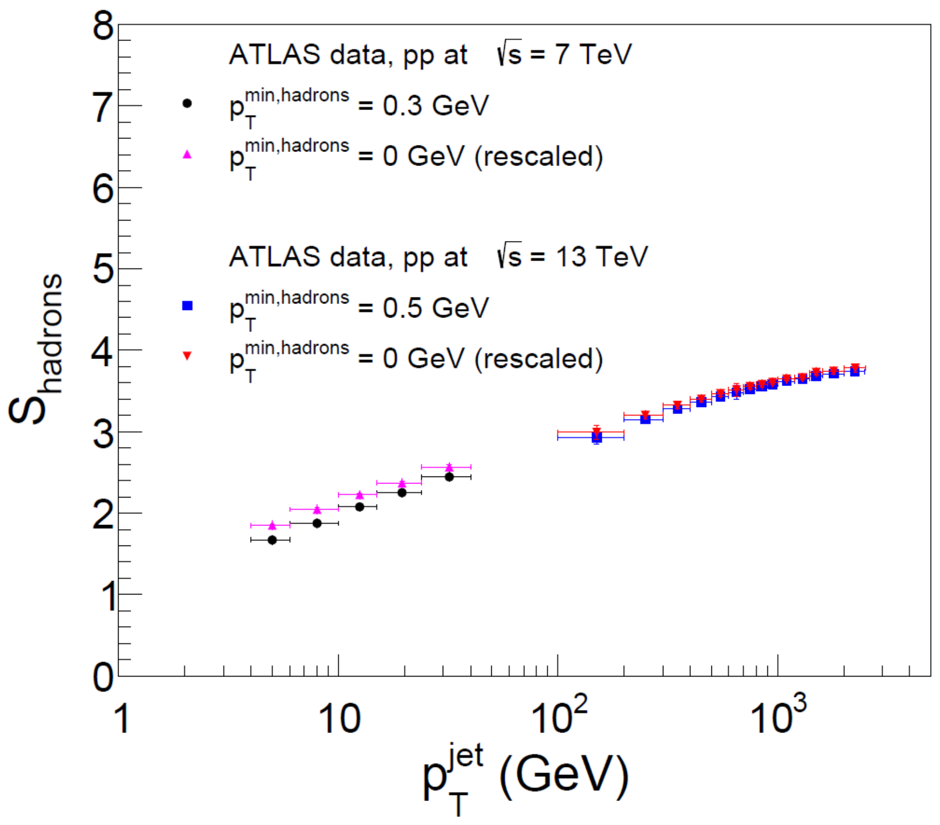


Theory

- The initial von Neumann entropy is not zero for parton fragmentation and is determined by the entanglement created in the production of the parton pair [arXiv:2404.00087].
- For "bare" parton-antiparton initial configuration, we get S_q = ln (Nc) and S_g = ln $(N_c^2 - 1)$, where N_c is 3
- The entropy of charged hadrons within jets is connected to their fragmentation functions for a maximally entangled hadronization process as follows:

$$S_{FF}^{q/g} = S_{q/g} + \ln\left[\int_{z_{\min p_T^{jet}}}^{1} dz\, D_{q/g}^{h}(z,\mu^2)\right]$$

Hadron entropy as function of p_T^{jet}



Hadron entropy calculated for jets at ATLAS

[arXiv:2410.22331, accepted at PRL]

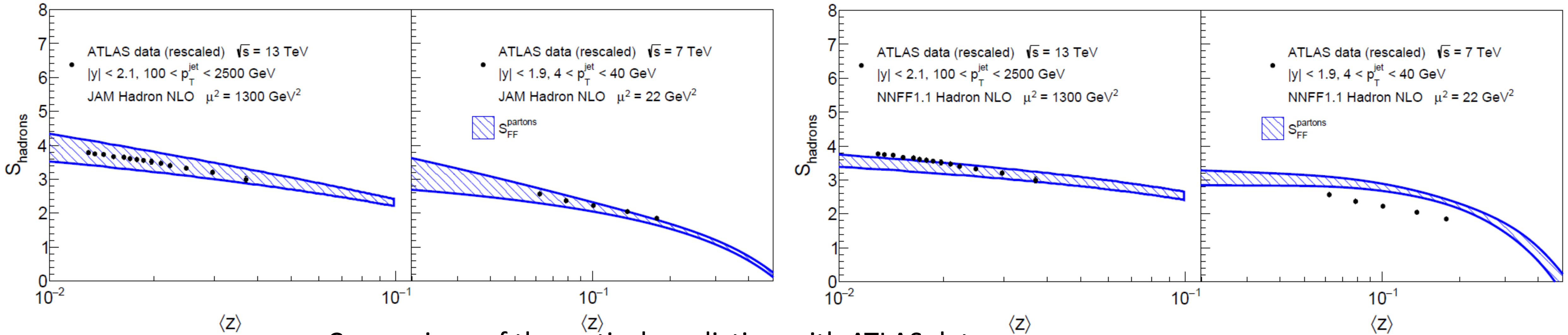
- The entropy S of all hadrons in jet is related to the number of charged hadrons produced in the final state and is defined as

$$S_{hadrons} = \sum_n P_n \ln(P_n)$$

P_n represents the probability of detecting n charged hadrons.

$\sqrt{s}$ TeV	|y| range	p_T^{jet} range in GeV	p_T^{jet} in GeV	Reference
7	< 1.9	4 $< p_T^{jet} <$ 40	> 0.3	Phys. Rev. D 84, 054001 (2011)
13	< 2.1	100 $p_T^{jet} <$ 2500	> 0.5	Phys. Rev. D 100, 052011 (2019)

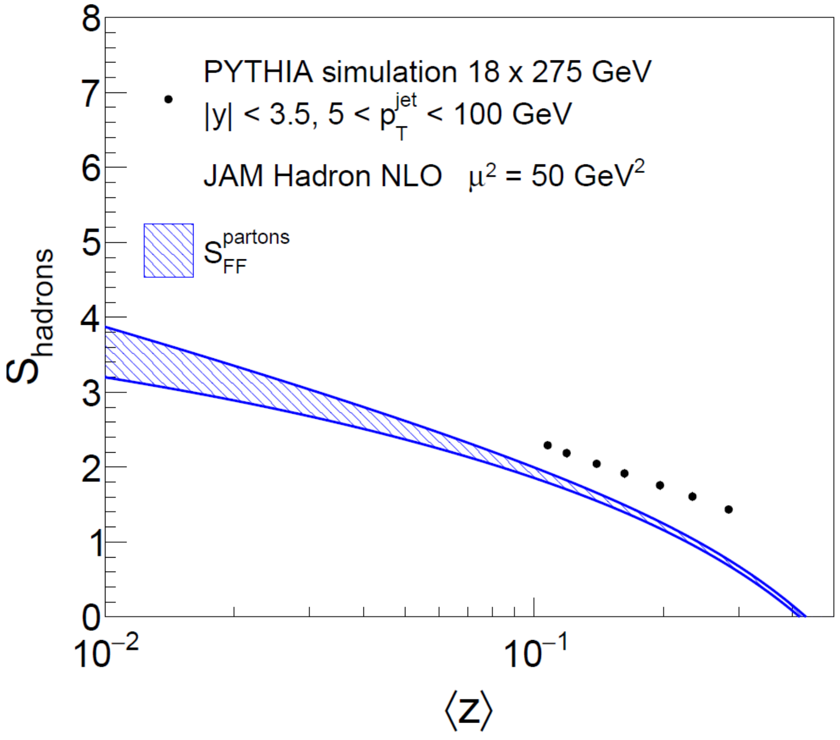
Comparison with ATLAS data



Comparison of theoretical prediction with ATLAS data [arXiv:2410.22331, accepted at PRL]

- ❖ For comparison between theoretical prediction and data, data is re-expressed in terms of the mean value ⟨z⟩ for each p_T^{jet} bin.
- ❖ The relationship between ⟨z⟩ and p_T^{jet} is determined through a PYTHIA simulation of pp collisions
- ❖ For each p_T^{jet} bin the from the z distribution the mean was found
- ❖ The limit for integration was defined that 50% of the distribution is included in the integration

Prediction for EIC



Comparison between simulated EIC data and theory [arXiv:2410.22331, accepted at PRL]

- ep collisions with 18 GeV electrons and 275 GeV protons
- Detector effects excluded
- Minimum Q^2 cut of 10 GeV^2
- Criteria to choose Jets
  - The radius parameter of 0.4
  - At least two particles in the jet
  - Transverse momentum in range of (5 GeV, 100 GeV)
  - Jets in pseudo- rapidity range of $-3.5 < \eta < 3.5$
- The contribution of the c-(anti)quarks included
- In ep collisions, processes like $\gamma g \rightarrow qq$ and $\gamma g \rightarrow q\bar{q}$ enhance quark jet contributions at lower ⟨z⟩ values, reducing gluon jet contribution.

Summary

- ❖ This work extends the idea of relation between proton's parton distribution and hadron entropy to jet production
- ❖ The maximal entanglement predicts a relation between the jet fragmentation function and the jet fragmentation.
- ❖ This relation is tested in ATLAS data
- ❖ A good correlation has been found
- ❖ First use of quantum entanglement framework in experimental study of the hadronization process

Acknowledgement

- The authors like to thank the organizers for this opportunity
- The authors like to thank their respective funding agencies for the support
- We thank Stony Brook University and Brookhaven National Laboratory for their help

THANK YOU