Thermal Radiation and Entanglement in Antineutrino Scattering from Nuclei

George Iskander [1], Mojique Tyler [1], O. K. Baker [1]

[1]Department of Physics, Yale University, New Haven, CT

Introduction

- The transverse momentum distribution of pp collisions from ATLAS and CMS data has been observed to decompose into a power-law curve ("hard") and decaying exponential curve ("soft") [1].
- The hard-scattering curve arises from quark and gluon scattering; the soft-scattering component however, appears to be thermal in nature and is poorly understood
- Entanglement entropy thermalization between distinct regions of the colliding nucleons can potentially explain the origin of the soft-scattering component, evidenced by previous studies demonstrating how the exponential component disappears in diffractive events [2]
- We extend these principles to the weak sector by studying antineutrino-nucleus scattering on hydrocarbon and carbon using data from MINERvA and corroborate previous conclusions regarding entanglement entropy thermalization

Methodology

- Using the principles of entanglement entropy, we look for the following experimental signature in neutrino-nucleus scattering:
  - For an interaction that probes a subregion of the nucleus, there will be a thermal component in the momentum distribution of the produced pion
  - For an interaction that probes the entirety of the nucleus, the thermal component will be **absent**
- We use the two following datasets from MINERvA:
  - antineutrino induced π^0 production on hydrocarbon at $\langle E_\nu \rangle \approx 3.6$ GeV [3, 4]
  - antineutrino coherent π^- production on carbon at $\langle E_\nu \rangle = 3$ GeV [5]
- Three separate curve fits are made in CERN ROOT:
  - A decaying exponential curve
  - A power law curve
  - The sum of a decaying exponential curve and a power law curve
- We calculate R, a measure of the power law component in the combined fit, which ranges from 0 to 1.

Results & Analysis

Antineutrino Induced π^0 Production

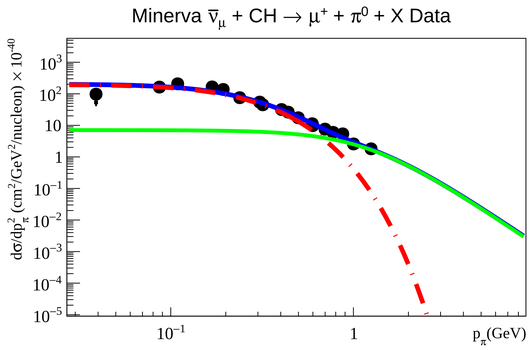

Figure 1. Antineutrino differential scattering cross section against hydrocarbon nuclei with charged current pion production. Red dashed line shows the thermal component and solid green line the hard component of the combined (solid blue line) best fit to the data. Data taken from [3, 4].

- The reduced chi square statistic is approximately 0.84, indicating excellent fit with the data
- The calculated value of R is 0.13 ± 0.03, in line with previous studies of pp collisions, in which $R = 0.16 \pm 0.05$ [2].

Antineutrino Coherent π^- Production

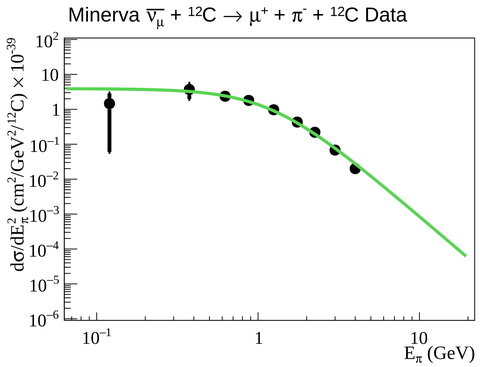

Figure 2. Antineutrino coherent scattering from the hydrocarbon scintillator nuclei. The differential cross section is well described by a hard-scattering component alone, as expected in the absence of entanglement. The reduced chi-squared fit is $\chi^2/\text{ndf} = 5.5/6$. Data taken from [5].

- $R = 1.00 \pm 0.08$, as expected in the absence of entanglement, indicating no thermal component

Results & Analysis (Cont.)

- Final state interactions (FSI) are large at low pion momenta
- However, due to large systematatic and statistical uncertainties, the effects of the FSI do not impact our analysis
- The value of R agrees with the value found in pp collisions

Conclusions

- **Results are in line with the hypothesis of entanglement entropy thermalization, namely that quantum entanglement in hadrons is responsible for observed thermal behavior**
- Thermal component is absent in coherent π^- production, but present in π^0 production
- Our study raises future questions. How does entanglement arise from QCD? Is it possible there may be additional experimental signatures?
- The future EIC at Brookhaven will provide valuable electron-proton data for these studies, allowing researchers to shed light on the connection between hadronic entanglement entropy and its relation to QCD.
- Future MINERvA runs can provide data with improved statistics, which would allow a more detailed analysis of entanglement entropy thermalization in the weak sector

References

[1] F. Becattini, P. Castorina, J. Manninen, and H. Satz, "The thermal production of strange and non-strange hadrons in e+e- collisions", Eur. Phys. J. C **56**, 493 (2008).

[2] O. K. Baker and D. E. Kharzeev, "Thermal radiation and entanglement in proton-proton collisions at the LHC", Phys. Rev. D **98**, 054007 (2018).

[3] T. Le et al., "Single neutral pion production by charged-current $\overline{\nu}_\mu$ interactions on hydrocarbon at $E_\nu = 3.6$ GeV", Physics Letters B **749**, 130 (2015).

[4] C. L. McGivern et al., "Cross sections for neutrino and antineutrino induced pion production on hydrocarbon in the few-GeV region using MINERvA", Physical Review D **94**, 052005 (2016).

[5] A. Mislivec et al., "Measurement of total and differential cross sections of neutrino and antineutrino coherent $\pi^\pm$ production on carbon", Physical Review D **97**, 032014 (2018).

[6] X. Feal, C. Pajares, and R. A. Vazquez, "Thermal behavior and entanglement in Pb-Pb and pp collisions", Physical Review C **99**, 015205 (2019).

[7] C. Andrés, A. Moscoso, and C. Pajares, "Universal geometrical scaling for hadronic interactions", en, Nuclear Physics A **901**, 14 (2013).

Acknowledgments

G. I. acknowledges the Yale STARS II Fellowship for their financial support.