Uncovering New Laws of Nature at the EIC, BNL, November 20-22, 2024

Quantum entanglement as a probe of strong interactions at the EIC

Google AI

Dmitri Kharzeev

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Office of Science

Center for Nuclear Theory
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Brookhaven National Laboratory

Disclaimer: this talk is not a review of the QIS/NP/HEP interface, but just a personal view.

Recent reviews:

PRX QUANTUM **4,** 027001 (2023)

Roadmap

Quantum Simulation for High-Energy Physics

Christian W. Bauer,[1,*] Zohreh Davoudi,[2,†] A. Baha Balantekin,[3] Tanmoy Bhattacharya,[4] Marcela Carena,[5,6,7,8] Wibe A. de Jong,[1] Patrick Draper,[9] Aida El-Khadra,[9] Nate Gemelke,[10] Masanori Hanada,[11] Dmitri Kharzeev,[12,13] Henry Lamm,[5] Ying-Ying Li,[14,15] Junyu Liu,[16,17] Mikhail Lukin,[18] Yannick Meurice,[19] Christopher Monroe,[20,21,22,23] Benjamin Nachman,[1] Guido Pagano,[24] John Preskill,[25] Enrico Rinaldi,[26,27,28] Alessandro Roggero,[29,30] David I. Santiago,[31,32] Martin J. Savage,[33] Irfan Siddiqi,[31,32,34] George Siopsis,[35] David Van Zanten,[5] Nathan Wiebe,[36,37] Yukari Yamauchi,[2] Kübra Yeter-Aydeniz,[38] and Silvia Zorzetti[6]

Quantum Information Science and Technology for Nuclear Physics

Input into U.S. Long-Range Planning, 2023

arXiv:2303.00113

A lot of exciting ongoing work!

(just a tiny sample of very recent papers)

Probing Celestial Energy and Charge Correlations through Real-Time Quantum Simulations: Insights from the Schwinger Model

João Barata[1,*] and Swagato Mukherjee[1]

[1] *Physics Department, Brookhaven National Laboratory, Upton, NY 11973, USA*

Spin-orbit entanglement in the Color Glass Condensate

Shohini Bhattacharya,[1,*] Renaud Boussarie,[2,†] and Yoshitaka Hatta[3,4,‡]

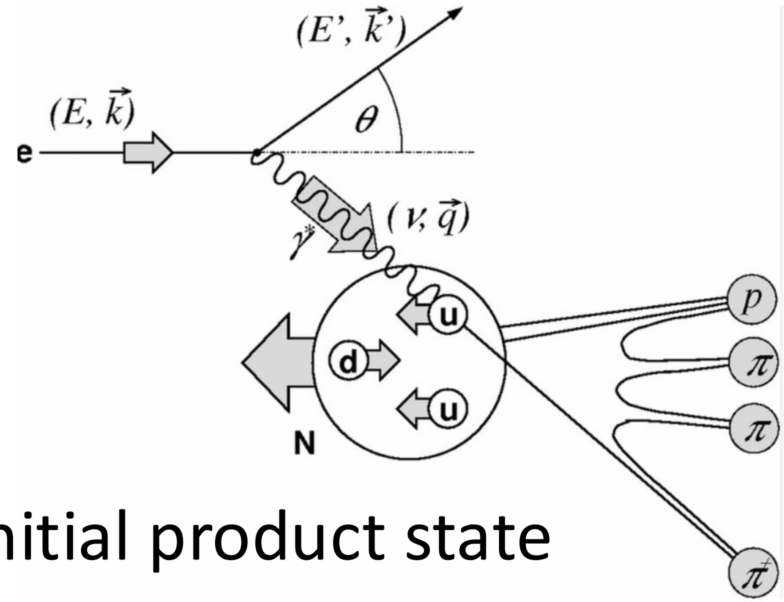
[1] *Theoretical Division, Los Alamos National Laboratory, Los Alamos, New Mexico 87545, USA*
[2] *CPHT, CNRS, Ecole Polytechnique, Institut Polytechnique de Paris, 91128 Palaiseau, France*
[3] *Physics Department, Brookhaven National Laboratory, Upton, NY 11973, USA*
[4] *RIKEN BNL Research Center, Brookhaven National Laboratory, Upton, NY 11973, USA*

Entanglement entropy of a color flux tube in (2+1)D Yang-Mills theory

Rocco Amorosso,[1] Sergey Syritsyn,[1] and Raju Venugopalan[2,3]

[1] *Department of Physics and Astronomy, Stony Brook University, Stony Brook, NY 11794, USA*
[2] *Physics Department, Brookhaven National Laboratory, Upton, NY 11973, USA*
[3] *CFNS, Department of Physics and Astronomy, Stony Brook University, Stony Brook, NY 11794, USA*

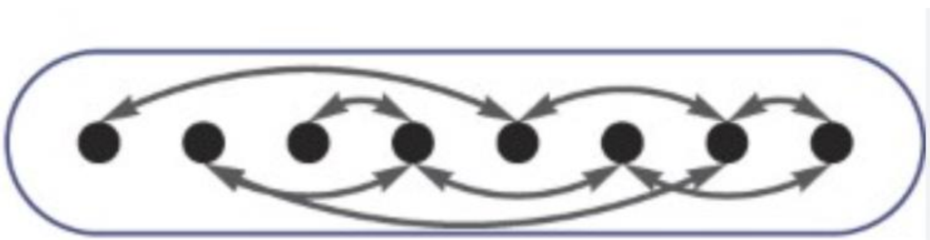
Deep-inelastic scattering from the QIS perspective



Rapid transition from the pure initial product state

$$|p> \bigotimes |e>$$

with zero (von Neumann) entropy to a final multi-hadron state with a large (Gibbs) entropy, and entanglement.



Can QIS tools and ideas help us understand better DIS?

QIS 4 DIS:

1. The puzzle of the parton model

2. Quantum entanglement and decoherence in high energy interactions

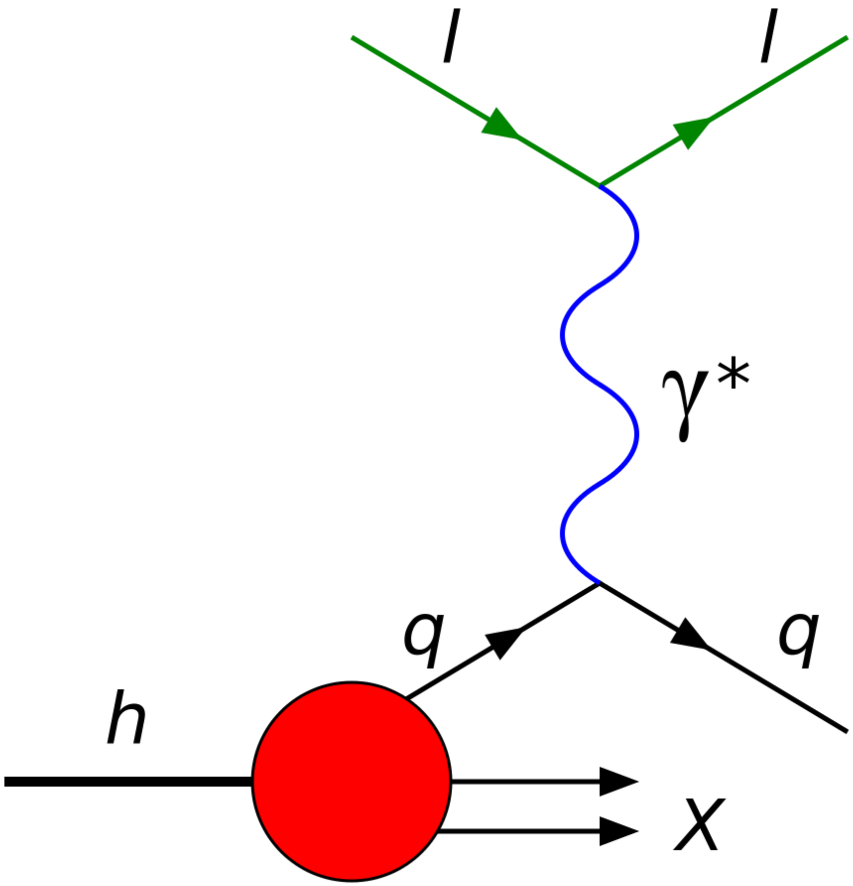
3. Maximally entangled state at small x

4. Experimental tests

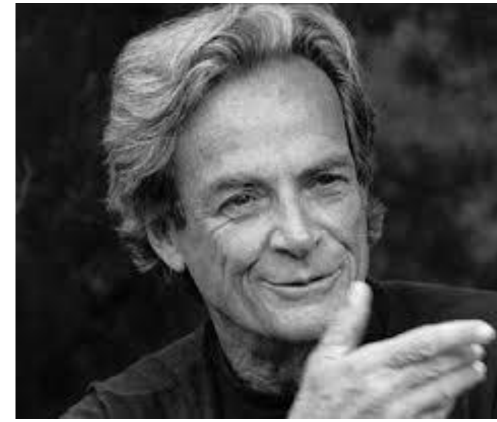
5. Entanglement from quantum simulations

6. Outlook

The parton model: 50 years of success



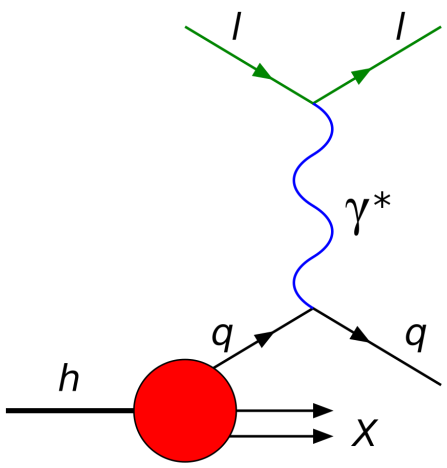

J. Bjorken


R. Feynman


V. Gribov

In fifty years that have ensued after the birth of the parton model, it has become an indispensable building block of high energy physics – so we have to understand it

The puzzle of the parton model



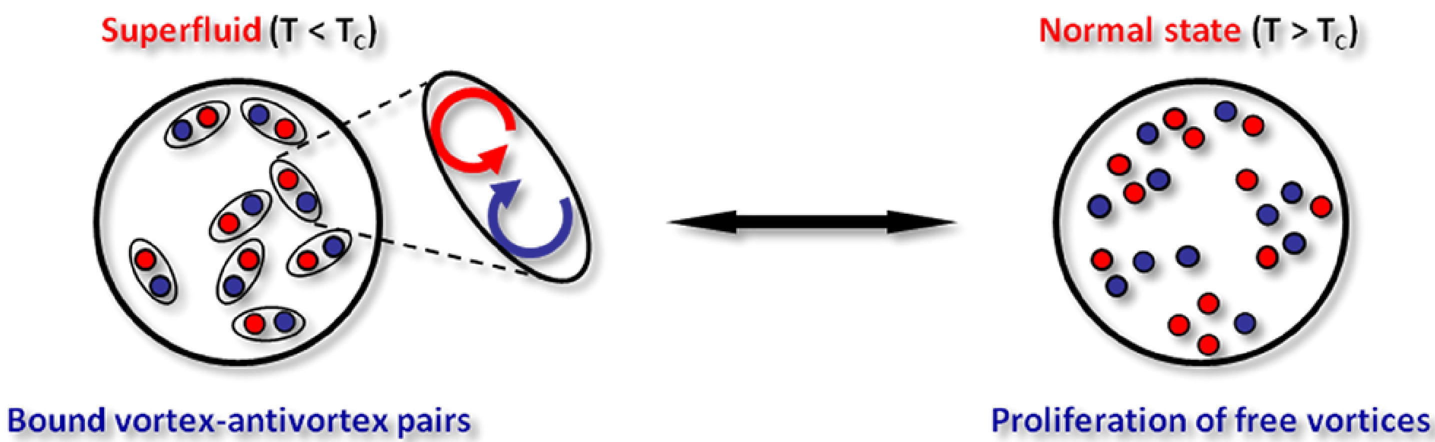
In parton model, the proton is pictured as a collection of point-like quasi-free partons that are frozen in the infinite momentum frame due to Lorentz dilation.

The DIS cross section is given by the incoherent sum of cross sections of scattering off individual partons.

How to reconcile this with quantum mechanics?

The puzzle of the parton model

In quantum mechanics, the proton is a pure state with zero entropy. Yet, a collection of free partons does possess entropy… Boosting to the infinite momentum frame does not help, as a Lorentz boost cannot transform a pure state into a mixed one.



The crucial importance of entropy in (2+1)D systems: BKT phase transition (Nobel prize 2016)

PHYSICAL REVIEW D **95,** 114008 (2017)

Deep inelastic scattering as a probe of entanglement

Dmitri E. Kharzeev[1,2,*] and Eugene M. Levin[3,4,†]

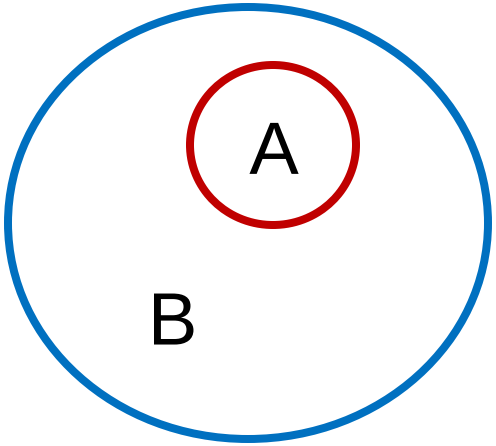
Our proposal: the key to solving this apparent paradox is entanglement.

DIS probes only a part of the proton's wave function (region A). We sum over unobserved region B;
in quantum mechanics, this corresponds to accessing the density matrix of a mixed state

$$\hat{\rho}_A = \mathrm{tr}_{\mathrm{B}}\hat{\rho}$$

with a non-zero entanglement entropy

$$S_A = -\mathrm{tr}\left[\hat{\rho}_{\mathrm{A}} \ln \hat{\rho}_{\mathrm{A}}\right]$$



The quantum mechanics of partons and entanglement

What is “region B” in DIS? It may be the phase!

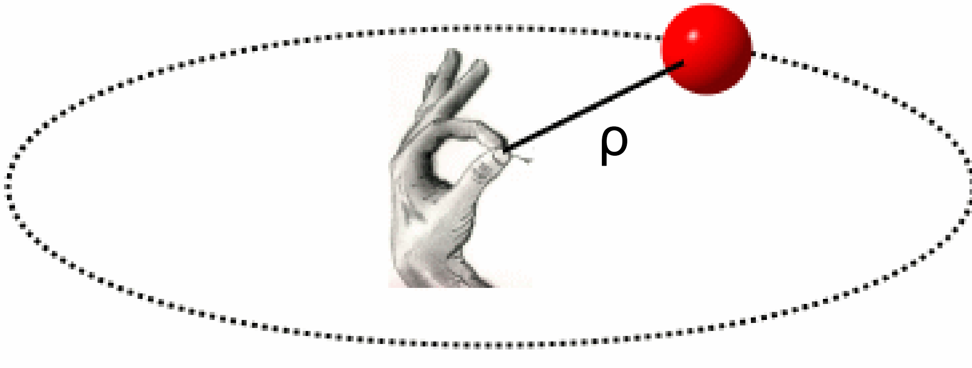
DK, Phil. Trans. Royal Soc (2022); arXiv:2108.08792

DIS takes an instant snapshot of the proton’s wave function. This snapshot cannot measure the phase of the wave function.

Classical analogy:

$$z = \rho \ \exp(i\omega t)$$

Instant snapshot can measure the amplitude ρ, but not the angular velocity ω !



The quantum mechanics of partons and entanglement

A simple quantum mechanical model:

DK, Phil. Trans. Royal Soc (2022); arXiv:2108.08792

Expand the proton's w.f. in oscillator Fock states:

$$|n\rangle = \frac{1}{\sqrt{n!}} \prod_i^n a_i^\dagger |0\rangle,$$

$$|\Psi\rangle = \sum_n \alpha_n |n\rangle,$$

The density matrix:

$$\hat{\rho} = |\Psi\rangle\langle\Psi\rangle = \sum_{n,n'} \alpha_n\, \alpha_{n'}^*\, |n\rangle\langle n'|,$$

depends on time:

$$\hat{\rho}(t) = \sum_{n,n'} e^{i(n'-n)\omega t}\, \hat{\rho}(t=0).$$

But this time dependence cannot be measured by a light front – it crosses the hadron too fast, at time $t_{light} = R,$

Decoherence in high energy interactions

DK, Phil. Trans. Royal Soc (2022)

Therefore, the observed density matrix is a trace over an unobserved phase:

$$\hat{\rho}_{parton} = \mathrm{Tr}_{\varphi}\hat{\rho} = \sum_{n,n'} \int_0^{2\pi} \frac{d\varphi}{2\pi} e^{i(n'-n)\varphi}\, \alpha_n\, \alpha^*_{n'}\, |n\rangle\langle n'| = \sum_n |\alpha_n|^2\, |n\rangle\langle n|.$$

U(1) Haar measure

"Haar scrambling" = decoherence
Y.Sekino, L.Susskind '08

After "Haar scrambling", the density matrix becomes diagonal in parton basis (Schmidt basis) –

Probabilistic parton model!

This is a density matrix of a mixed state, with non-zero entanglement entropy!

The quantum mechanics of partons and entanglement

The parton model density matrix:

$$\hat{\rho}_{parton} = \sum_n p_n \, |n\rangle\langle n|$$

is mixed, with purity

$$\gamma_{parton} = \mathrm{Tr}(\rho^2_{parton}) = \sum_n p_n^2 < 1.$$

entanglement entropy

$$S_E = -\sum_n p_n \ln p_n$$

Parton model expressions
for expectation values
of operators:

$$\langle \hat{O} \rangle = \mathrm{Tr}(\hat{O}\hat{\rho}_{parton}) = \sum_n p_n \langle n|\hat{O}|n\rangle;$$

The quantum mechanics of partons and entanglement on the light cone

The density matrix on the light cone:

$$\hat{\rho} = |\Psi\rangle\langle\Psi| = \sum_{n,n'}^{\infty} \int d\Gamma_n \, d\Gamma_{n'} \, \Psi^*_{n'}(x_{i'}, \vec{k}_{\perp i'}) \Psi_n(x_i, \vec{k}_{\perp i}) |n\rangle\langle n'|.$$

Haar scrambling: on the light cone, $t_i - z_i = x_i^- = 0,$

but t, z and $x^+ = z + t$ cannot be independently determined:

$$\int \frac{dx^+}{2\pi} e^{i(P_n^- - P_{n'}^-)x^+} = \delta(P_n^- - P_{n'}^-),$$

$$\hat{\rho}_{parton} = \mathrm{Tr}_{x^+} |\Psi\rangle\langle\Psi| = \sum_{n}^{\infty} \int d\Gamma_n \, |\Psi_n(x_i, \vec{k}_{\perp i})|^2 |n\rangle\langle n|,$$

Phase-occupation number uncertainty relation and parton model

$$\Delta\phi\Delta n \geq \tfrac{1}{2}\left|\langle\Psi|[\hat{\phi},\hat{n}]|\Psi\rangle\right|$$

High energies – phase cannot be measured, number is fixed:

parton model applies

Low energies - phase shifts can be measured, number is uncertain:

parton model does not apply

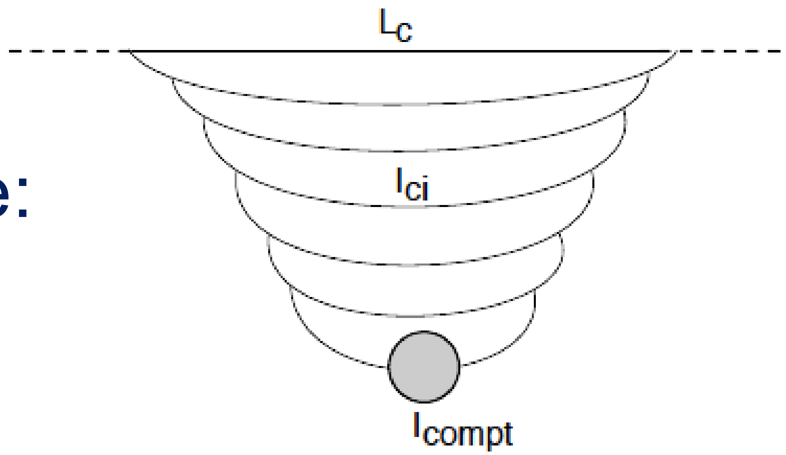
PHYSICAL REVIEW A VOLUME 48, NUMBER 4 OCTOBER 1993

Measurement of number-phase uncertainty relations of optical fields

D. T. Smithey, M. Beck, J. Cooper,* and M. G. Raymer

The entanglement entropy from QCD evolution

Space-time picture
in the proton's rest frame:



The evolution equation:

$$\frac{dP_n(Y)}{dY} = -\Delta\, n\, P_n(Y) + (n-1)\Delta P_{n-1}(Y)$$

The entanglement entropy from QCD evolution

$$\frac{dP_n(Y)}{dY} = -\Delta\, n\, P_n(Y) + (n-1)\Delta P_{n-1}(Y)$$

Solve by using the generating function method

(A.H. Mueller '94; E. Levin, M. Lublinsky '04):

$$Z(Y,u) = \sum_n P_n(Y) u^n.$$

Solution:

$$P_n(Y) = e^{-\Delta Y}(1 - e^{-\Delta Y})^{n-1}.$$

The resulting von Neumann entropy is

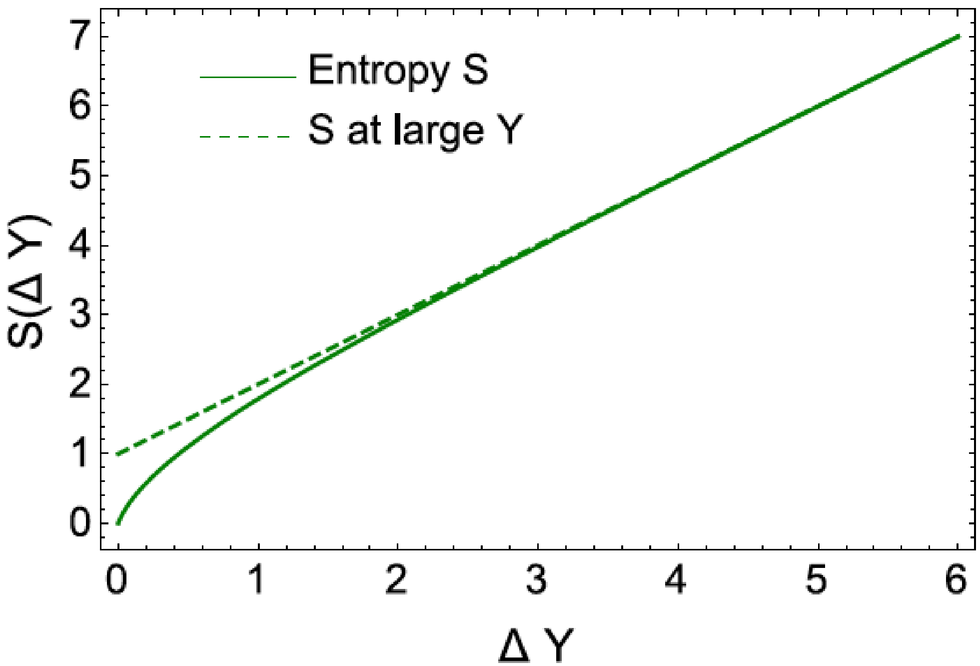
$$S(Y) = \ln(e^{\Delta Y} - 1) + e^{\Delta Y} \ln\left(\frac{1}{1 - e^{-\Delta Y}}\right)$$

DK, E. Levin, arXiv:1702.03489; PRD

The entanglement entropy from QCD evolution

At large ΔY, the entropy becomes

$$S(Y) \to \Delta Y$$



This "asymptotic" regime starts rather early, at

$$\Delta Y \simeq 2$$

DK, E. Levin, arXiv:1702.03489; PRD

Linear dependence on rapidity is a consequence of (approximate) conformal invariance:

PHYSICAL REVIEW D **110**, 074008 (2024)

Universal rapidity scaling of entanglement entropy inside hadrons from conformal invariance

Umut Gürsoy,[1] Dmitri E. Kharzeev,[2,3] and Juan F. Pedraza[4]

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[2]*Center for Nuclear Theory, Department of Physics and Astronomy, Stony Brook University, Stony Brook, New York 11794-3800, USA*

[3]*Department of Physics, Brookhaven National Laboratory, Upton, New York 11973-5000, USA*

[4]*Instituto de Física Teórica UAM/CSIC, Calle Nicolás Cabrera 13-15, Madrid 28049, Spain*

description. In this paper, we use an effective conformal field theoretic description of hadrons on the light cone to show that the linear dependence of the entanglement entropy on rapidity found in parton description is a general consequence of approximate conformal invariance and does not depend on the assumption of weak coupling. Our result also provides further evidence for a duality between the parton and string descriptions of hadrons.

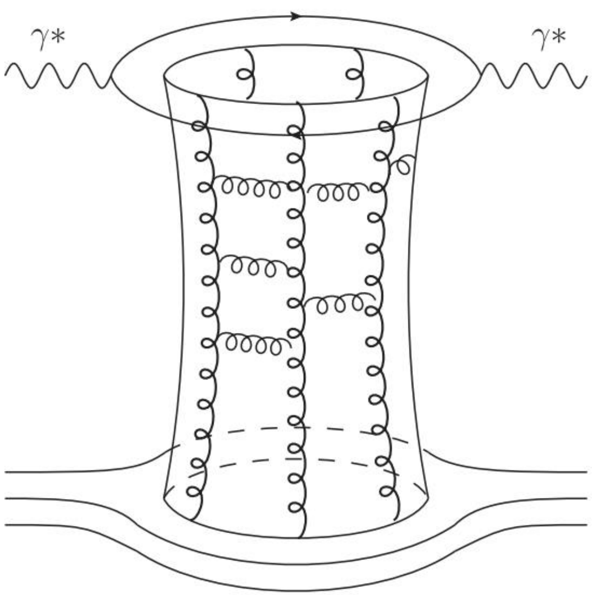
$$S_A = \frac{c}{6}\Delta\eta + \ldots,$$

Another evidence for linear growth of EE: Lipatov's effective theory of high energy QCD

PHYSICAL REVIEW D **105,** 014002 (2022)

Entanglement entropy production in deep inelastic scattering

Kun Zhang,[1] Kun Hao,[2,3,*] Dmitri Kharzeev,[4,5,†] and Vladimir Korepin[3,6,‡]



$$H_L = \sum_{k=1}^{L} H_{k,k+1},$$

$$\begin{aligned} H_{j,k} &= P_j^{-1}\ln(z_{jk})P_j + P_k^{-1}\ln(z_{jk})P_k + \ln(P_jP_k) + 2\gamma_E \\ &= 2\ln(z_{jk}) + (z_{jk})\ln(P_jP_k)(z_{jk})^{-1} + 2\gamma_E, \end{aligned} \qquad (2)$$

The entanglement entropy from QCD evolution

At large ΔY (x ~ 10^{-3}) the relation between the entanglement entropy and the structure function

$$xG(x) = \langle n \rangle = \sum_n n P_n(Y) = \left(\frac{1}{x}\right)^{\Delta}$$

becomes very simple:

$$S = \ln[xG(x)]$$

DK, E. Levin, arXiv:1702.03489; PRD 95 (2017)

The entanglement entropy from QCD evolution

What is the physics behind this relation?

$$S = \ln[xG(x)]$$

It signals that all $\exp(\Delta Y)$ partonic states have about equal probabilities $\exp(-\Delta Y)$ – in this case the **entanglement entropy is maximal**, and the proton is a **maximally entangled state** (a new look at the parton saturation and CGC?)

DK, E. Levin, arXiv:1702.03489; PRD 95 (2017)

Maximally entangled states

Consider the entanglement entropy

$$S = -\mathrm{tr}\rho \ln \rho = -\sum_n p_n \ln p_n$$

for the case of N states with equal probabilities

$$p_n = 1/N$$

Then $$S = -N \frac{1}{N} \ln(1/N) = \ln N$$

This looks like the Boltzmann formula!


S = k. log W

Experimental tests

What is the relation between the parton and hadron multiplicity distributions?

Let us assume they are the same ("EbyE parton-hadron duality"); then the hadron multiplicity distribution should be given by

$$P_n(Y) = e^{-\Delta Y}(1 - e^{-\Delta Y})^{n-1}.$$

Consider moments

$$C_q = < n^q > / < n >^q$$

Fluctuations in hadron multiplicity

The moments can be easily computed by using the generating function

$$C_q = \left(u \frac{d}{du} \right)^q Z\left(Y, u\right) \Bigg|_{u=1}$$

We get

$$C_2 = 2 - 1/\bar{n}; \quad C_3 = \frac{6(\bar{n}-1)\bar{n}+1}{\bar{n}^2};$$

$$C_4 = \frac{(12\bar{n}(\bar{n}-1)+1)(2\bar{n}-1)}{\bar{n}^3}; \quad C_5 = \frac{(\bar{n}-1)(120\bar{n}^2(\bar{n}-1)+30\bar{n})+1}{\bar{n}^4}.$$

Fluctuations in hadron multiplicity

Numerically, for $\bar{n} = 5.8 \pm 0.1$ at |η|<0.5, E_{cm}=7 TeV we get:

theory	exp (CMS)	theory, high energy limit
C_2 = 1.83	C_2 = 2.0+-0.05	C_2 = 2.0
C_3 = 5.0	C_3 = 5.9+-0.6	C_3 = 6.0
C_4 = 18.2	C_4 = 21+-2	C_4 = 24.0
C_5 = 83	C_5 = 90+-19	C_5 = 120

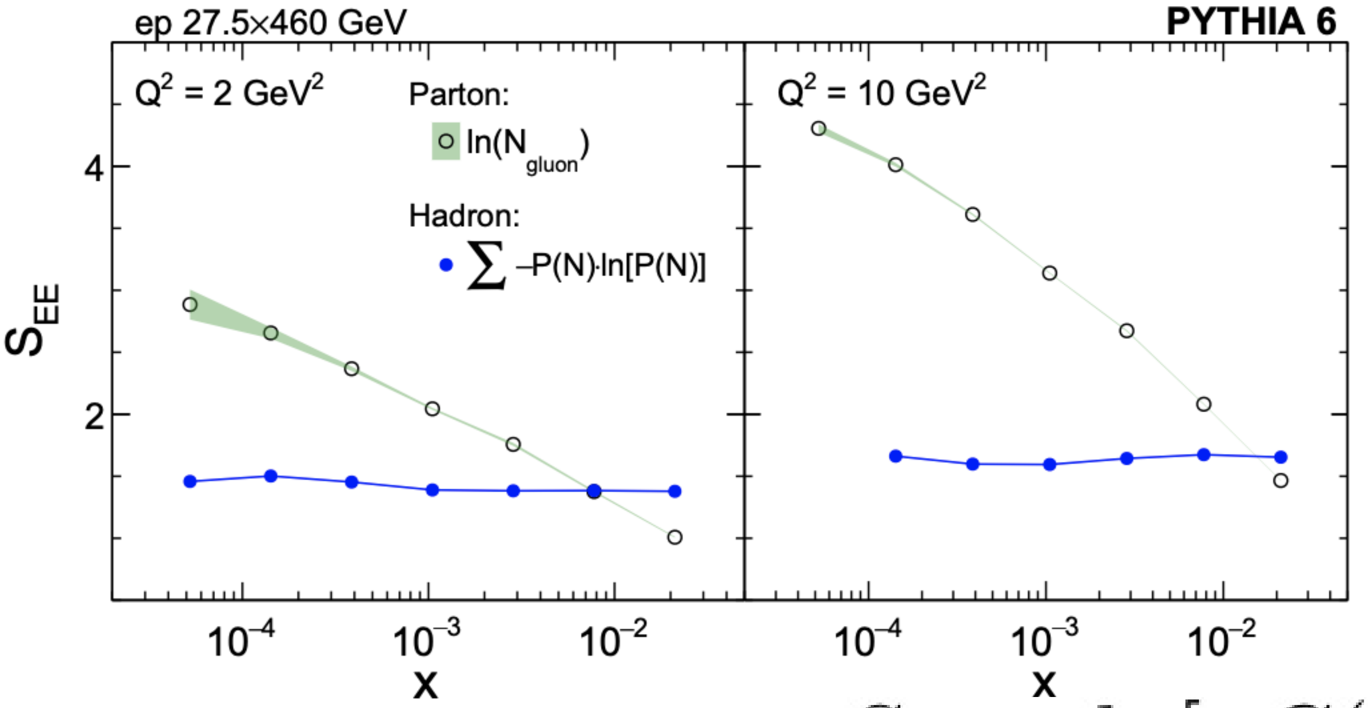
It appears that the multiplicity distributions of final state hadrons are very similar to the parton multiplicity distributions – this suggests that the entropy is close to the entanglement entropy

Test of the entanglement at the LHC

PHYSICAL REVIEW LETTERS **124**, 062001 (2020)

Einstein-Podolsky-Rosen Paradox and Quantum Entanglement at Subnucleonic Scales

Zhoudunming Tu,[1,*] Dmitri E. Kharzeev,[2,3] and Thomas Ullrich[1,4]



MC generator PYTHIA: $S = \ln[xG(x)]$

is not satisfied at small x (no entanglement)

Test of the entanglement at the LHC

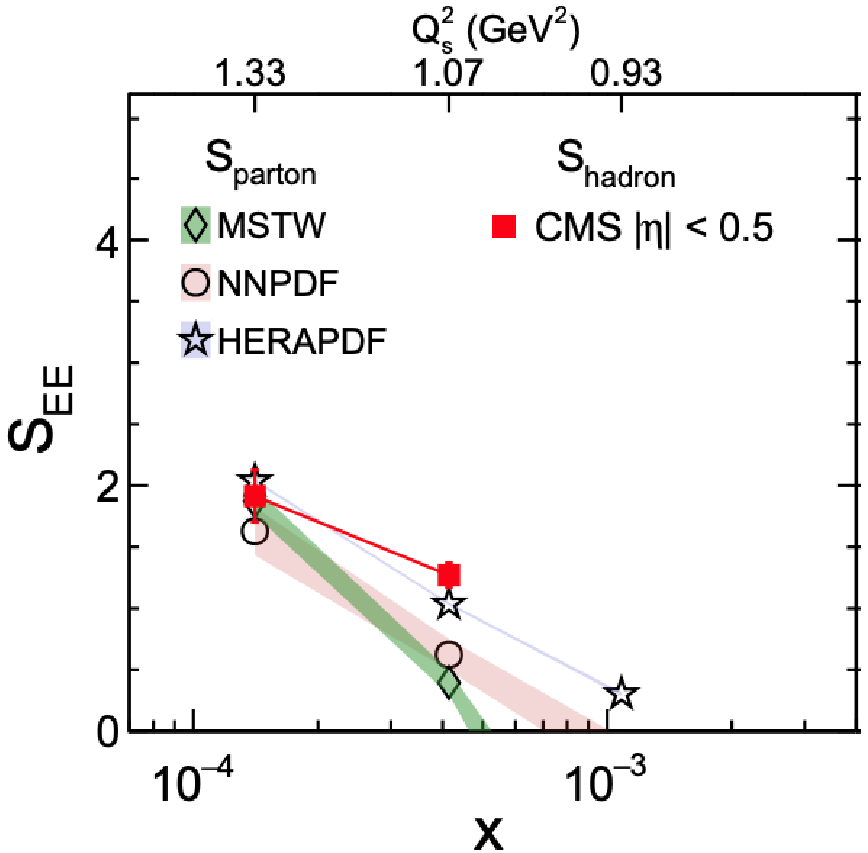
LHC data:

arXiv:1904.11974

$$S = \ln[xG(x)]$$

is satisfied at small x (**entanglement?!**)

K. Tu, DK, T. Ullrich,
arXiv:1904.11974;
PRL (2020)



Test of the entanglement in DIS

H1 Coll. test of

$$S = \ln[xG(x)]$$

using DIS data (current fragmentation region)

H1 Coll.,
arXiv:2011.01812;
EPJC81(2021)3, 212

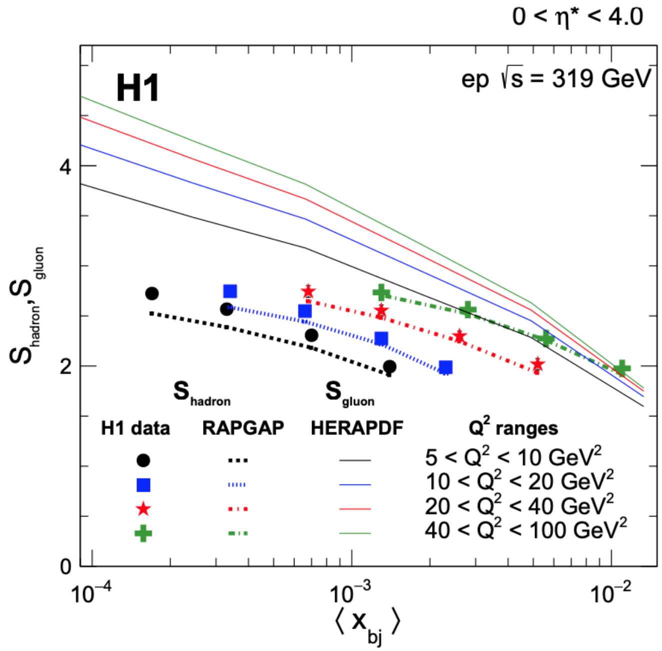


Figure 12: Hadron entropy S_{hadron} derived from multiplicity distributions as a function of $\langle x_{\text{bj}} \rangle$ measured in different Q^2 ranges, measured in $\sqrt{s} = 319\,\text{GeV}$ ep collisions. Here, a restriction to the current hemisphere $0 < \eta^* < 4$ is applied. Further phase space restrictions are given in Table 1. Predictions for S_{hadron} from the RAPGAP model and for the entanglement entropy S_{gluon} based on an entanglement model are shown by the dashed lines and solid lines, respectively. For each Q^2 range, the value of the lower boundary is used for predicting S_{gluon}. The total uncertainty on the data is represented by the error bars.

Poor agreement is found!

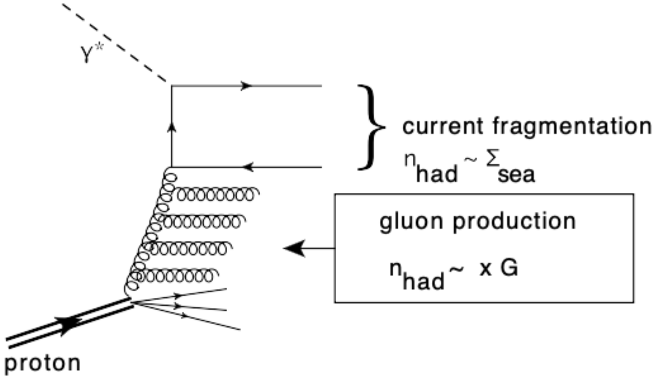
Failure of the entanglement-based picture?

Test of the entanglement in DIS

DK, E. Levin,
arXiv:2102.09773, PRD

It appears that in H1 kinematics
(current fragmentation region),
the assumptions used to derive the formula

$$S \ = \ \ln[xG(x)]$$



do not apply:

1. The quark structure function is not proportional to the gluon one, so need to use the quark distribution explicitly

$$x\Sigma(x,Q^2) \ = \ \frac{C_F\,\alpha_s}{2\,\pi}\int_0^{\xi} d\xi' \int_x^1 dz\,P_{qG}\,(z)\left(\frac{x}{z}G\left(\frac{x}{z},\xi'\right)\right) \qquad \textbf{with} \quad P_{qG}\,(z) = \frac{1+(1-z)^2}{z}$$

2. Multiplicity N is not large, so need to take into account 1/N corrections

Test of the entanglement in DIS

The result: good agreement with H1 data

DK, E. Levin, arXiv:2102.09773; PRD

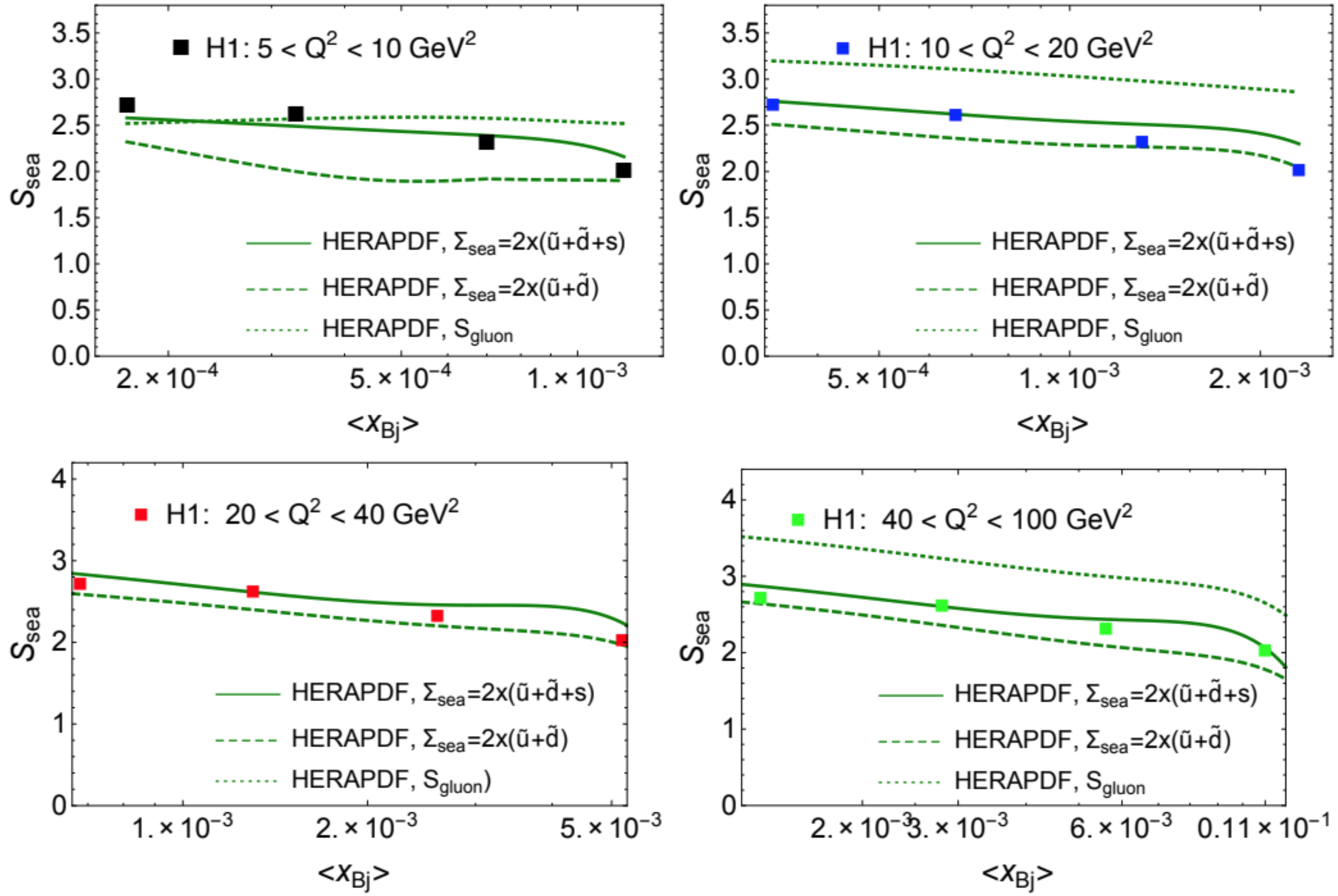


FIG. 1: Comparison of the experimental data of the H1 collaboration [6] on the entropy of produced hadrons in DIS [6] with our theoretical predictions, for which we use the sea quark distributions from the NNLO fit to the combined H1-ZEUS data.

Evidence for the maximally entangled low x proton in Deep Inelastic Scattering from H1 data

Martin Hentschinski[1] and Krzysztof Kutak[2]

[1]Departamento de Actuaria, Física y Matemáticas, Universidad de las Americas Puebla, San Andrés Cholula, 72820 Puebla, Mexico

[2] Institute of Nuclear Physics, Polish Academy of Sciences, ul. Radzikowskiego 152, 31-342, Kraków, Poland

December 14, 2021

Abstract

We investigate the proposal by Kharzeev and Levin of a maximally entangled proton wave function in Deep Inelastic Scattering at low x and the proposed relation between parton number and final state hadron multiplicity. Contrary to the original formulation we determine partonic entropy from the sum of gluon and quark distribution functions at low x, which we obtain from an unintegrated gluon distribution subject to next-to-leading order Balitsky-Fadin-Kuraev-Lipatov evolution. We find for this framework very good agreement with H1 data. We furthermore provide a comparison based on NNPDF parton distribution functions at both next-to-next-to-leading order and next-to-next-to-leading with small x resummation, where the latter provides an acceptable description of data.

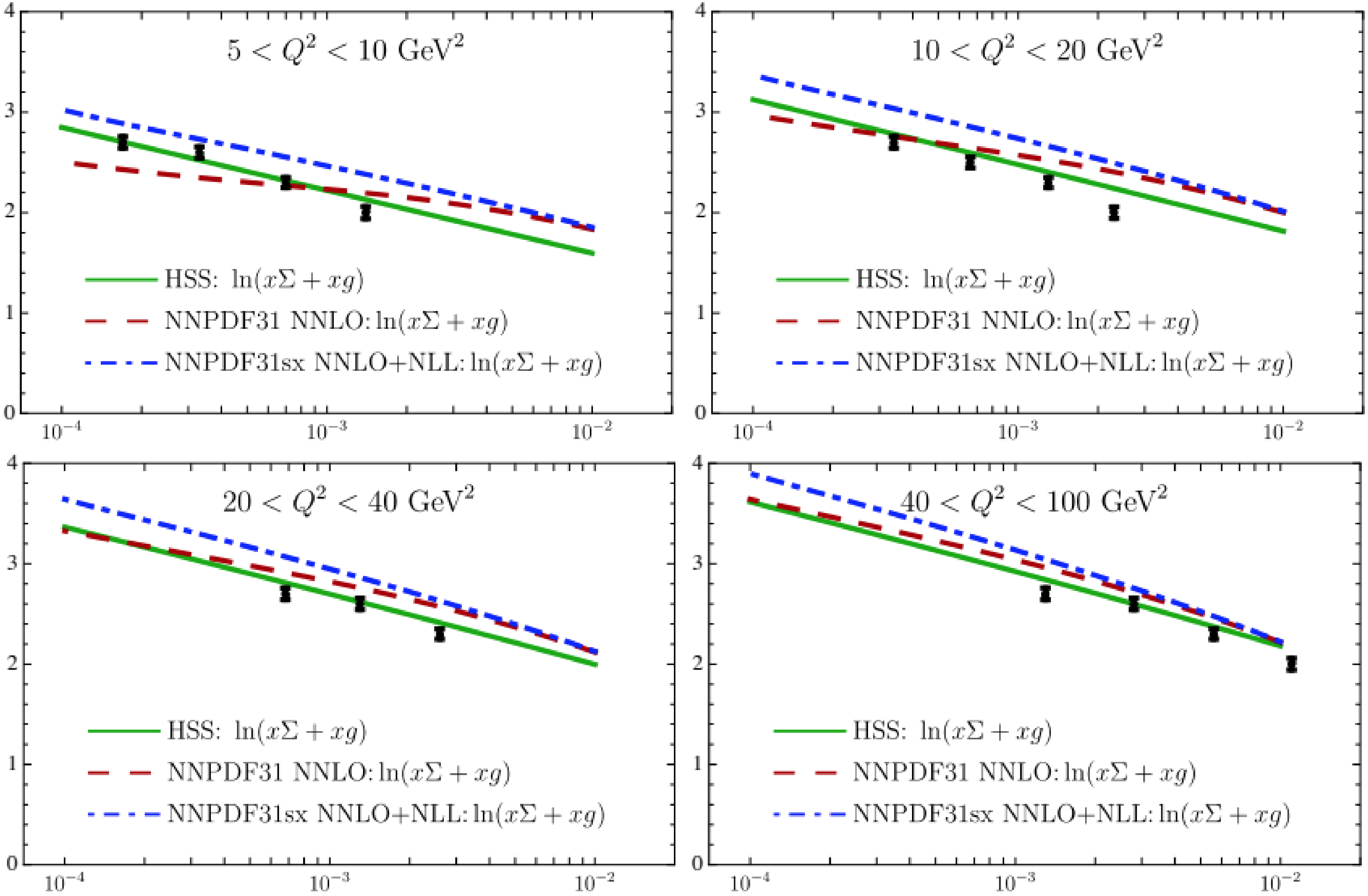


Figure 1: *Partonic entropy versus Bjorken x, as given by Eq. (1) and Eq. (2). We furter show results based on the gluon distribution only as well as a comparison to NNPDFs. Results are compared to the final state hadron entropy derived from the multiplicity distributions measured at H1 [19]*

PHYSICAL REVIEW LETTERS **131,** 241901 (2023)

Probing the Onset of Maximal Entanglement inside the Proton in Diffractive Deep Inelastic Scattering

Martin Hentschinski,[1,*] Dmitri E. Kharzeev,[2,3,†] Krzysztof Kutak,[4,‡] and Zhoudunming Tu[3,§]

Main idea: requirement of rapidity gap Δy "delays" the evolution inside the proton by Δy,

See e.g. A.D.Le, A.H.Mueller, S. Munier, PRD 104 (2021) 034026

so we can study the onset of maximal entanglement!

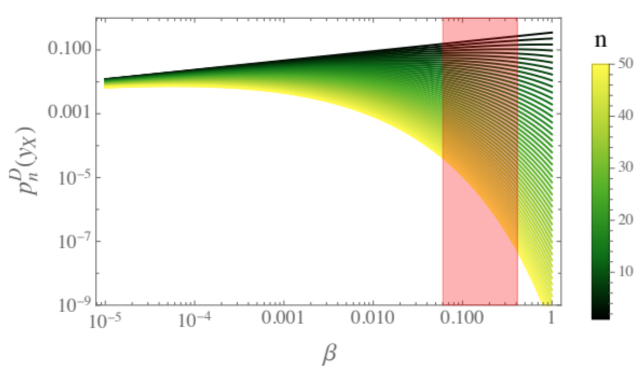


FIG. 2. Probabilities $p_n(y_X)$ with $y_X = \ln(1/\beta)$ as extracted from leading order diffractive PDFs for $n = 1, \ldots, 50$ for the charged hadron multiplicities. The shaded region indicates the region in β probed by the H1 data set.

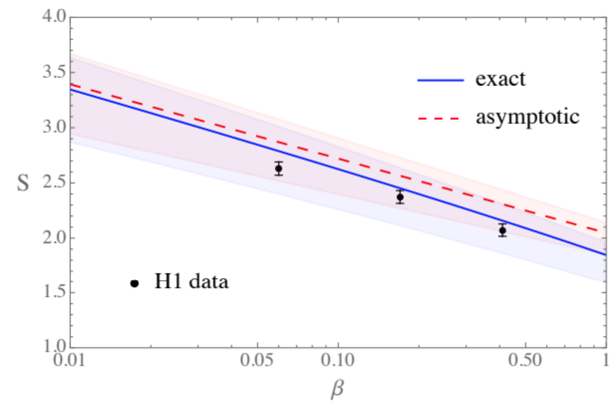
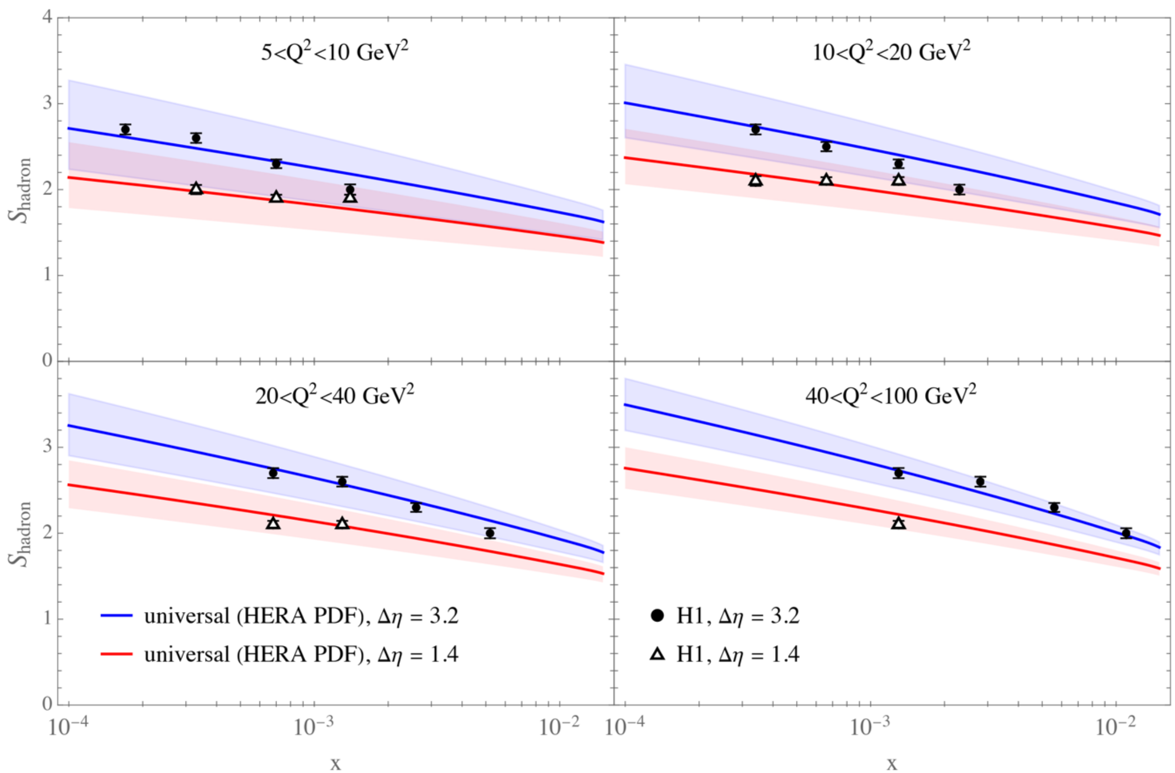


FIG. 3. Exact and asymptotic entropy as a function of β. H1 data [59] extracted from the multiplicity distributions are shown, where statistical and systematic uncertainty are added in quadrature and presented as error bars. The uncertainty bands correspond to a variation of the factorization scale of leading order diffractive PDFs in the range $\mu \to [Q/2, 2Q]$

QCD evolution of entanglement entropy

Martin Hentschinski[1], Dmitri E Kharzeev[2,3], Krzysztof Kutak[4] and Zhoudunming Tu[3,*]

arXiv: 2408.01259; Reports on Progress in Physics, 2024, in press



Maximal entanglement agrees with H1 measurements in different rapidity windows

Entanglement as a probe of hadronization

Jaydeep Datta,[1,*] Abhay Deshpande,[1,2,†] Dmitri E. Kharzeev,[3,4,‡] Charles Joseph Naïm,[1,§] and Zhoudunming Tu[5,¶]

[1] *Center for Nuclear Frontiers in Nuclear Science, Department of Physics and Astronomy, Stony Brook University, New York 11794-3800, USA*
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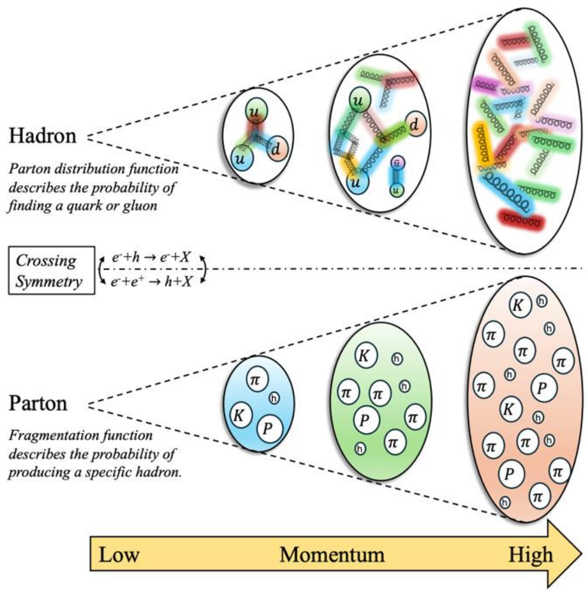
arXiv:2410.22331



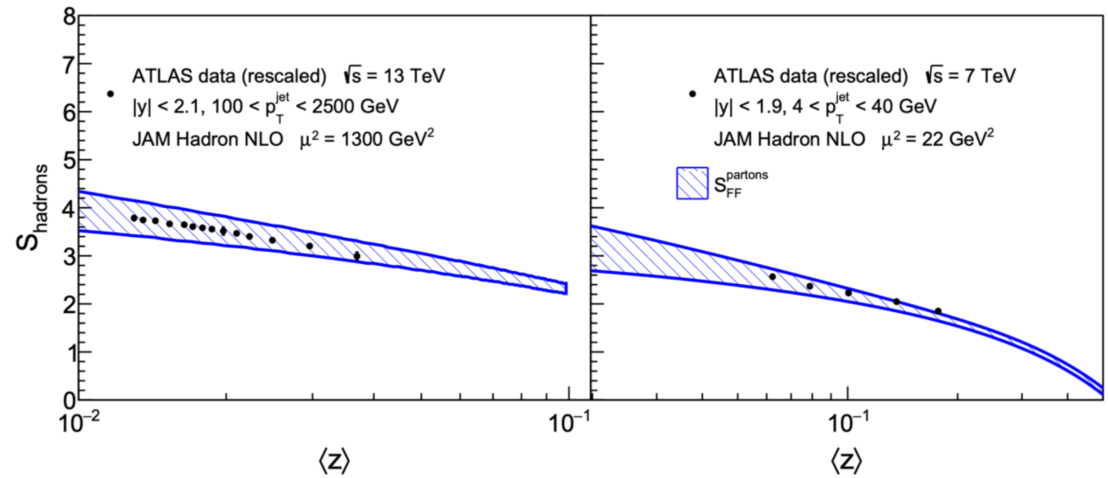


FIG. 3. The entropy S_{hadrons} as a function of $\langle z \rangle$ for $S_{\mathrm{FF}}^{\mathrm{partons}}$ — incorporating gluons, u-(anti)quarks, and d-(anti)quarks — is shown using JAM fragmentation functions at NLO for $\mu^2 = 1300$ GeV^2, compared with ATLAS data at $\sqrt{s} = 13$ TeV [45] (left). Additionally, the results at $\mu^2 = 22$ GeV^2 are compared with ATLAS data at $\sqrt{s} = 7$ TeV [43] (right). The uncertainties are calculated at the 1σ level. The total entropy $S_{\mathrm{FF}}^{\mathrm{partons}}$ is derived from the sum of the individual entropies of each parton, with each contribution normalized by the average fraction of jets produced by that parton from PYTHIA simulation.

Evidence for maximal entanglement from jet fragmentation

Entanglement from quantum simulations

Quantum simulation of entanglement and hadronization in jet production: lessons from the massive Schwinger model

Adrien Florio,[1,2,*] David Frenklakh,[3,†] Kazuki Ikeda,[2,3,‡] Dmitri Kharzeev,[1,2,3,§] Vladimir Korepin,[2,4,¶] Shuzhe Shi,[3,5,**] and Kwangmin Yu[6,††]

arXiv:2404.00087 (submitted to PRX Quantum)

Real-Time Nonperturbative Dynamics of Jet Production in Schwinger Model: Quantum Entanglement and Vacuum Modification

Adrien Florio, David Frenklakh, Kazuki Ikeda, Dmitri Kharzeev, Vladimir Korepin, Shuzhe Shi, and Kwangmin Yu

Phys. Rev. Lett. **131**, 021902 – Published 13 July 2023

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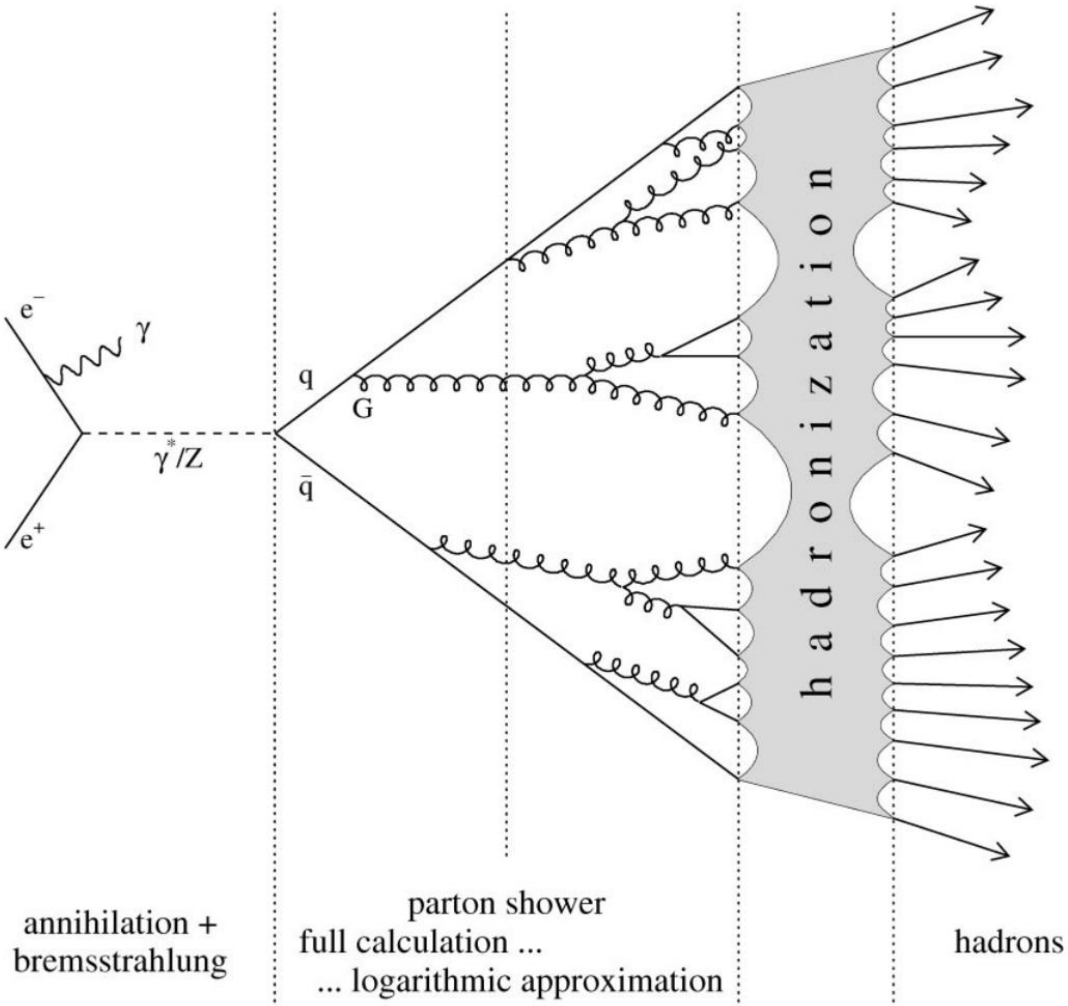
IBM
Quantum

NVIDIA

The setup

O. Biebel / Physics Reports 340 (2001) 165–289



PHYSICAL REVIEW D VOLUME 10, NUMBER 2 15 JULY 1974

Vacuum polarization and the absence of free quarks

A. Casher,* J. Kogut,† and Leonard Susskind‡
Tel Aviv University, Ramat-Aviv, Tel Aviv, Israel
(Received 29 June 1973; revised manuscript received 4 October 1973)

This paper is addressed to the question of why isolated quark partons are not seen. It is argued that in vector gauge theories it is possible to have the short-distance and light-cone behavior of quark fields without real quark production in deep-inelastic reactions. The physical mechanism involved is the flow of vacuum-polarization currents which neutralize any outgoing quarks. Our ideas are inspired by arguments due to Schwinger and an intuitive picture of Bjorken. Two-dimensional (1 space, 1 time) vector gauge field theories provide exactly soluble examples of this phenomenon. The resulting picture of deep-inelastic final states predicts jets of hadrons and logarithmically rising multiplicities as conjectured by Bjorken and Feynman.

Massless Schwinger model coupled to external sources:

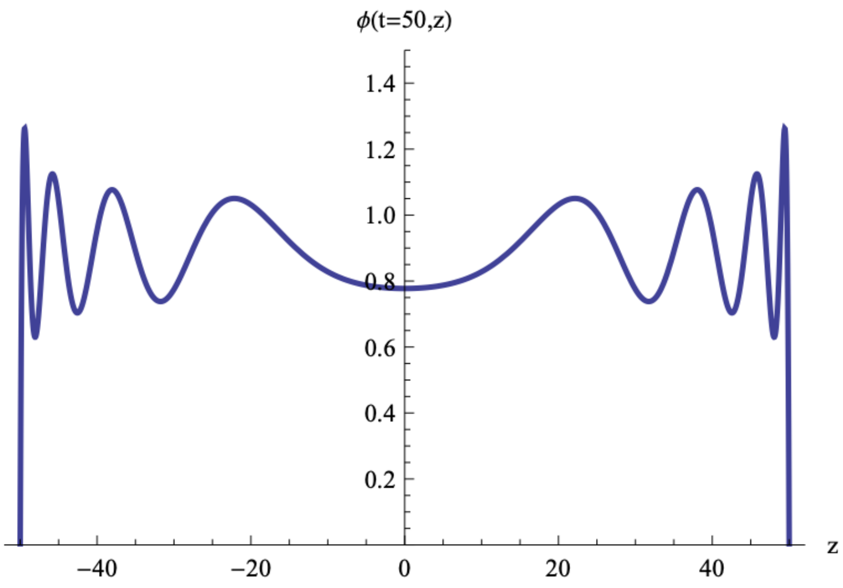
$$j_0^{\text{ext}} = g\delta(z-t), \quad j_1^{\text{ext}} = g\delta(z-t) \qquad \text{for } z>0,$$

$$j_0^{\text{ext}} = -g\delta(z+t), \quad j_1^{\text{ext}} = g\delta(z+t) \qquad \text{for } z<0,$$

In the massless case, can be solved exactly:

$$\phi(x) = \theta(t^2 - z^2)[1 - J_0(m\sqrt{t^2 - z^2})]$$

DK, F. Loshaj
Phys Rev D 87 (2013)



String breaking due to production of quark-antiquark pairs;
the produced mesons form a rapidity plateau

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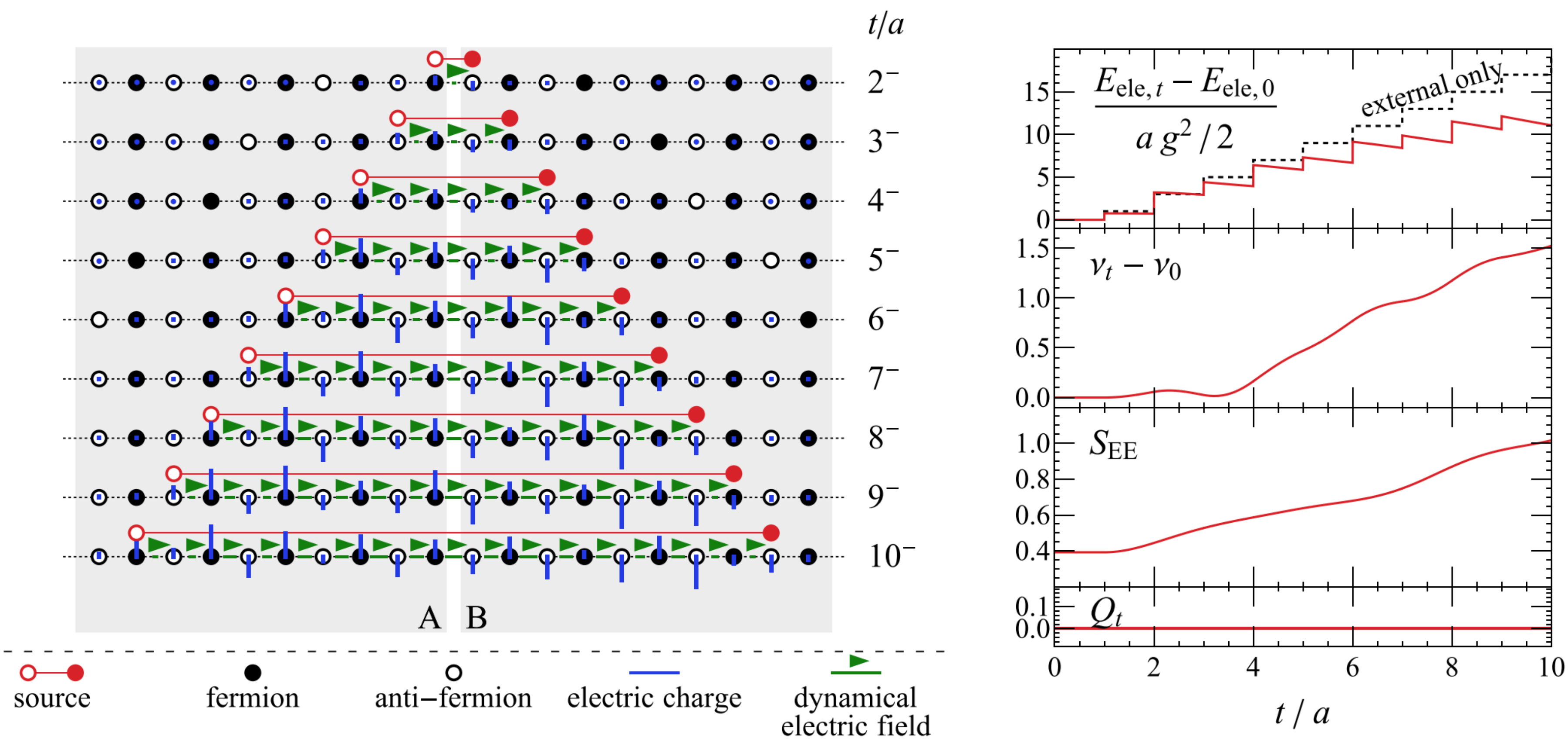
PHYSICAL REVIEW LETTERS **131,** 021902 (2023)



Screening of electric field, modification of the vacuum, growth of entanglement entropy!

The entanglement spectrum

$$\rho(t) = \sum_{i=1}^{2^{N/2}} \lambda_i(t) |\psi_i(t)\rangle\langle\psi_i(t)|,$$

At late times, a huge number of entanglement eigenstates start to contribute, with comparable eigenvalues – approach to the maximal entanglement and thermalization?

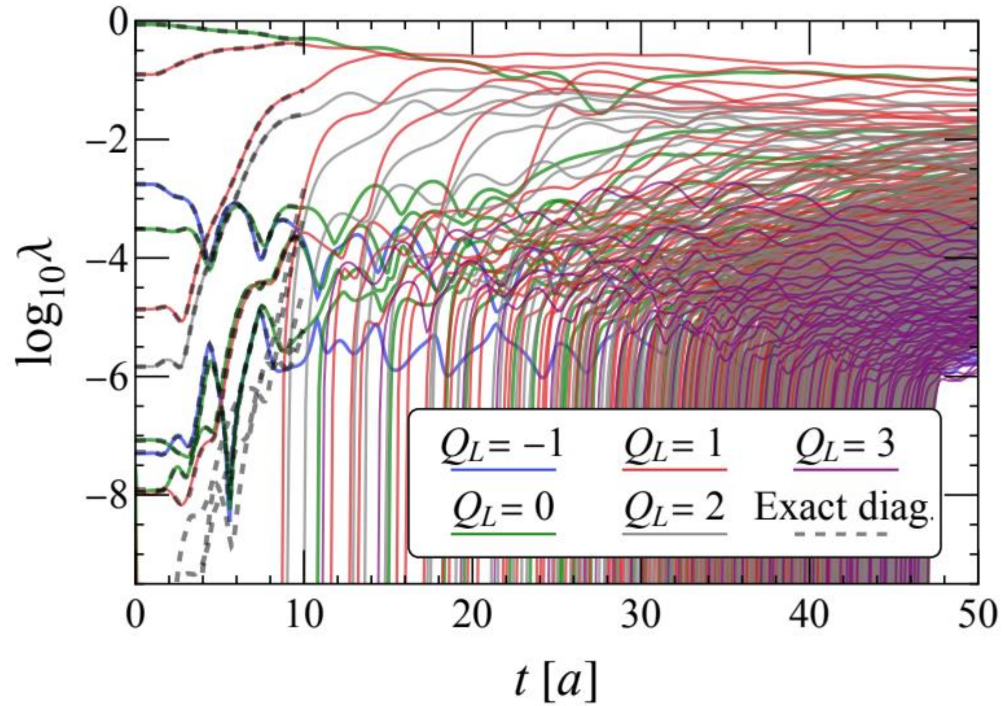


FIG. 2. Symmetry-resolved entanglement spectrum evolution for the lattice size $N = 100$, $m = 1/(4a), g = 1/(2a)$. For comparison the spectrum obtained with exact diagonalization for $N = 20$ at the same mass and coupling is shown as dashed curves.

Tests of maximal entanglement

Renyi entropy

$$S_\alpha(t) \equiv \frac{\ln \mathrm{Tr}_L(\rho_L(t)^\alpha)}{1-\alpha} = \frac{\ln \sum_{i=1}^{2^{N/2}} \lambda_i^\alpha}{1-\alpha}.$$

"Entangleness"

$$\mathcal{E} \equiv \frac{1-\mathrm{tr}\rho_L^2}{1-2^{-N/2}} = \frac{1-\sum_{i=1}^{2^{N/2}} \lambda^2}{1-2^{-N/2}}.$$

$$\mathcal{E}[\mathrm{MES}] = 1.$$

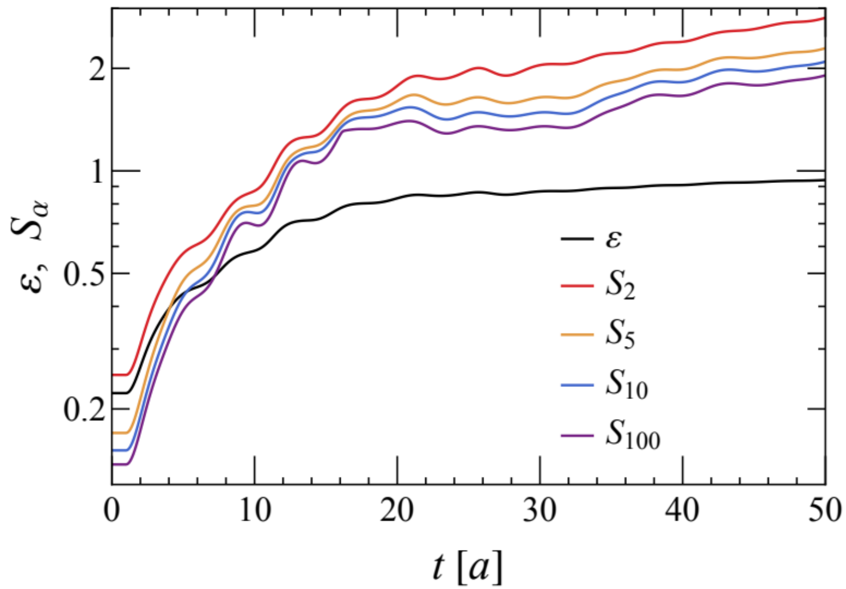


FIG. 3. Entangleness (black) and Rényi entropy with $\alpha = 2$ (red), 5 (gold), 10 (blue), and 100 (purple).

Approach to maximal entanglement!

The physical meaning of Schmidt states

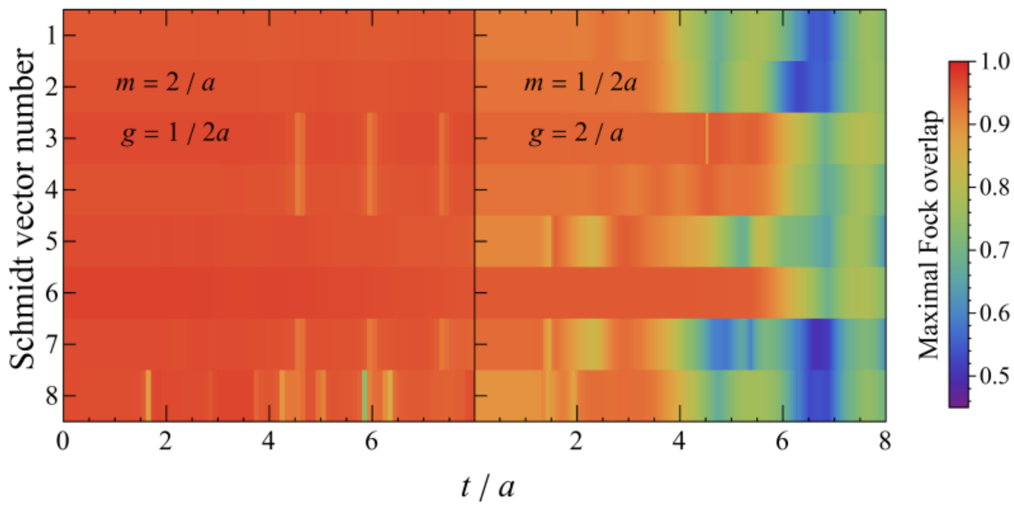


FIG. 5. Maximal overlap of each Schmidt vector with any Fock state. Comparison between $m = 2/a, g = 1/(2a)$ on the left panel and $m = 1/(2a), g = 2/a$ on the right panel is shown. In both cases, $N = 16$. To study continuous evolution, we choose to consider the 8 leading Schmidt vectors in the vacuum state at $t = 0$ and follow their evolution. Because of the level crossing in Schmidt spectrum, at later times these vectors are not necessarily the 8 leading Schmidt vectors.

Transition from "quark-antiquark" states at early times to "mesons" at late times –

Hadronization seen in real time!

Summary

1. Entanglement entropy (EE) provides a viable solution to the apparent contradiction between the parton model and quantum mechanics.

2. Indications from experiment that the link between EE and parton distributions is real, and proton at small x is a maximally entangled state.

   Further tests at RHIC and EIC, requirements for detector design (target fragmentation region, …)

3. Entanglement may provide a mechanism for thermalization in high-energy collisions. Need for further study of real-time dynamics!