1st International Workshop on a 2nd detector for the EIC

Temple University, Philadelphia, PA, USA, May 17-19, 2023

Quantum entanglement and saturation at the EIC

Dmitri Kharzeev

Center for Nuclear Theory

C2QA Co-design Center for Quantum Advantage

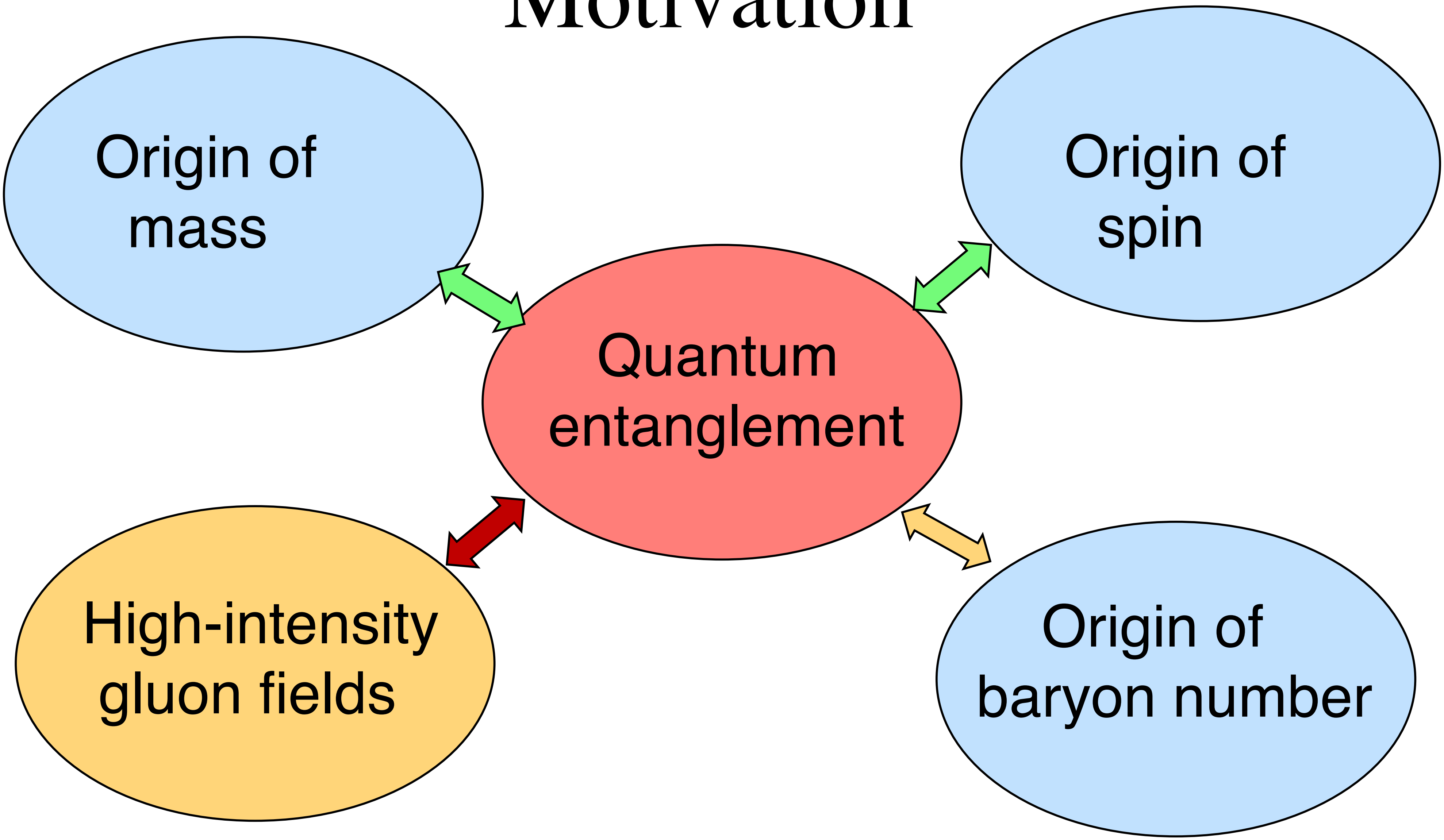
U.S. DEPARTMENT OF ENERGY Office of Science

Stony Brook University

Center for Frontiers in Nuclear Science

Brookhaven National Laboratory

Motivation


Origin of mass
Origin of spin
Quantum entanglement
High-intensity gluon fields
Origin of baryon number

Outline

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 at LHC, HERA and **EIC**

5. Outlook

Based on:

Entanglement in DIS: Maximally entangled state

DK, E. Levin, Phys Rev D 95 (2017) 114008 + PRD 104 (2021) 3

DK, Phil. Trans. Royal Soc A 380 (2021) 5

M. Hentschinski, DK, K. Kutak, Z. Tu, arXiv:2305.03069

Entanglement and integrability in DIS

K. Hao, DK, V. Korepin, Int J Mod Phys A34 (2019) 1950197

K. Zhang, K. Hao, DK, V. Korepin, Phys Rev D 105 (2022) 1

Based on:

Entanglement in real time processes + quantum simulations

DK, Y. Kikuchi, Phys. Rev. Res. 2 (2020) 2, 023342

A. Florio, DK, Phys Rev D 104 (2021) 5, 056021

D. Frenklakh, A. Florio, DK, Phys Rev D 106 (2022) 056021

A. Florio, D. Frenklakh, K. Ikeda, DK, V. Korepin, S. Shi, K. Yu, arXiv:2301.11991

K. Ikeda, DK, R. Meyer, S. Shi, arXiv:2305.00996

K. Ikeda, DK, S. Shi, arXiv:2305.05685

S. Grieninger, DK, I. Zahed, arXiv:2305.07121

S. Grieninger, K. Ikeda, DK, to appear

Based on:

Entanglement in high energy hadron collisions

O.K. Baker, DK, Phys Rev D 98 (2018) 054007

Z. Tu, DK, T. Ullrich, Phys Rev Lett 124 (2020) 6, 062001

Related work on entanglement in DIS:

Maximally entangled state at small x, link to black holes:

G. Dvali, R. Venugopalan, Phys Rev D 105 (2022) 5, 056026
Y. Liu, M. Nowak, I. Zahed, Phys.Rev.D 105 (2022) 11, 114028; …

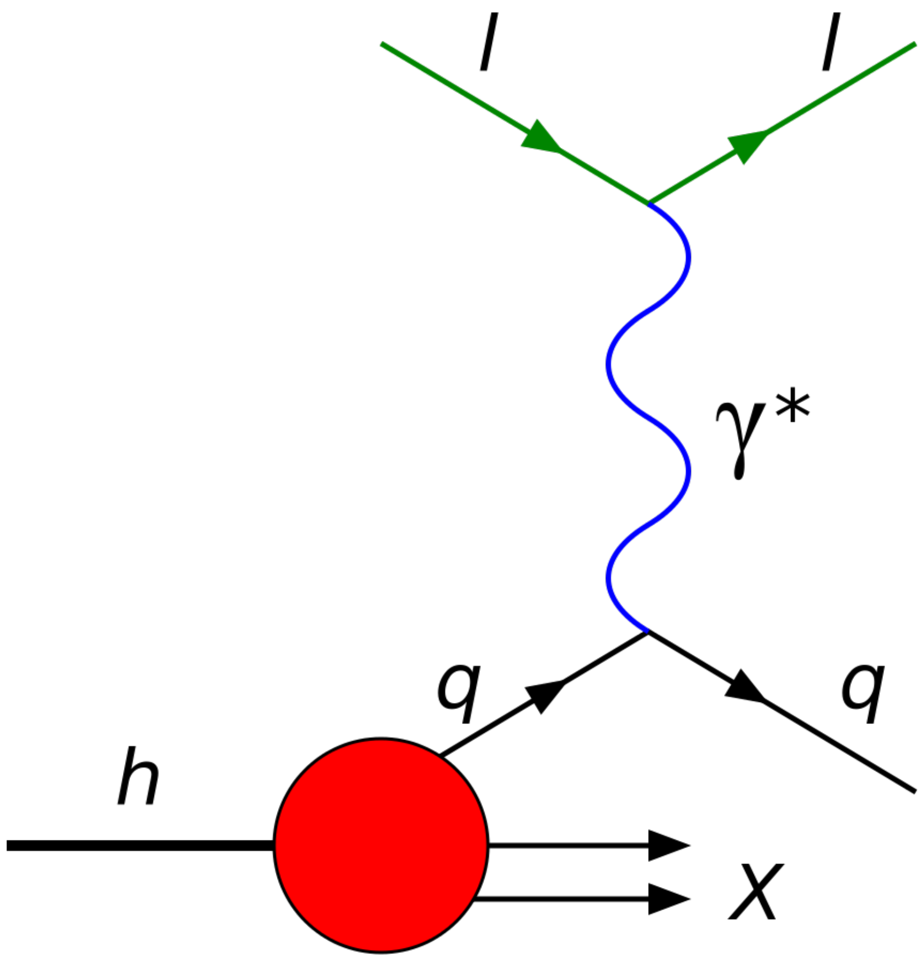
Maximally entangled state at small x:

M. Hentschinski, K. Kutak, Eur.Phys.J.C 82 (2022) 2, 111; ….

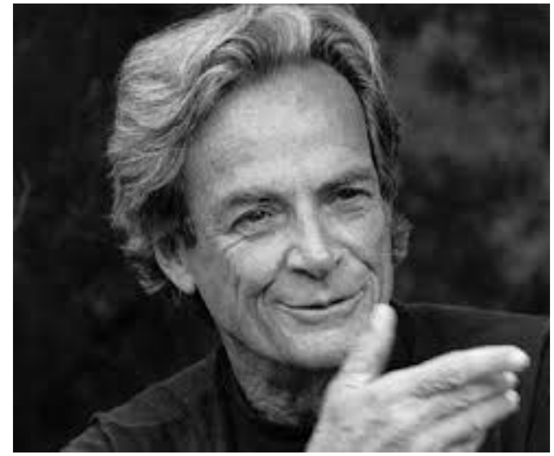
Momentum space entanglement and RG evolution:

A. Kovner, M. Lublinsky Phys Rev D 92 (2015) 3, 034016;
A. Kovner, M. Lublinsky, M. Serino, Phys Lett B 792 (2019) 4;
N. Armesto, F. Dominguez, A. Kovner, M. Lublinsky, V. Skokov, JHEP 05(2019) 025; ….

The parton model: 50 years of success



J. Bjorken

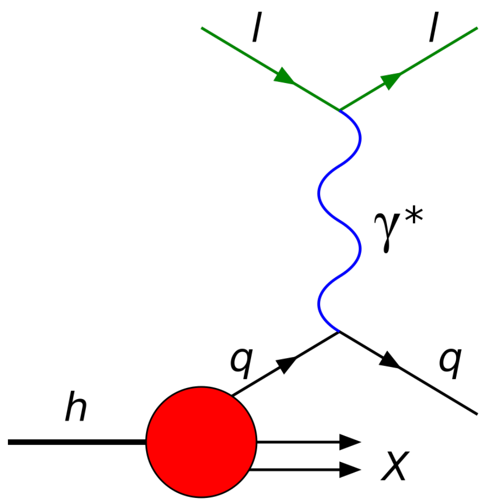


R. Feynman

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



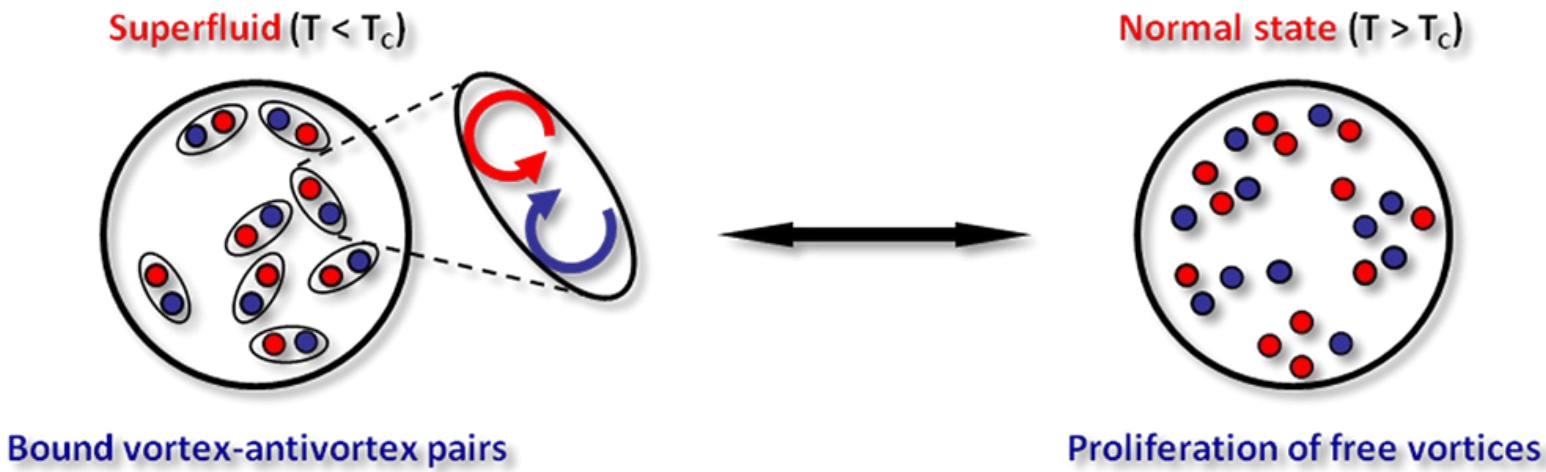
In parton model, the proton is pictured as a collection of point-like quasi-free partons that are frozen in the infinite momentum frame due to Lorentz dilation.

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)

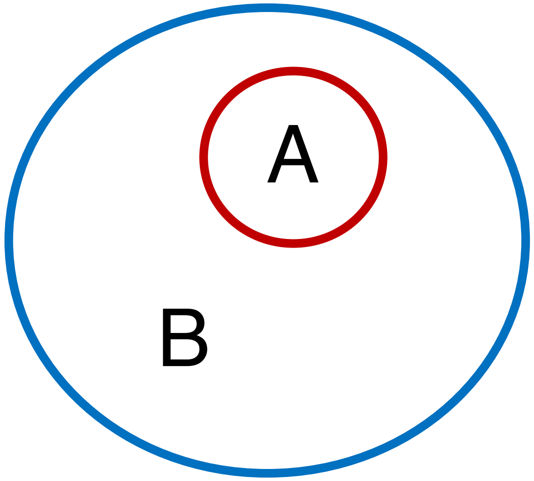
The quantum mechanics of partons and entanglement

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

DK, E. Levin, arXiv:1702.03489; PRD

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 <u>mixed state</u>

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



with a non-zero <u>entanglement entropy</u>

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

The quantum mechanics of partons and entanglement

Another (more general?) argument:

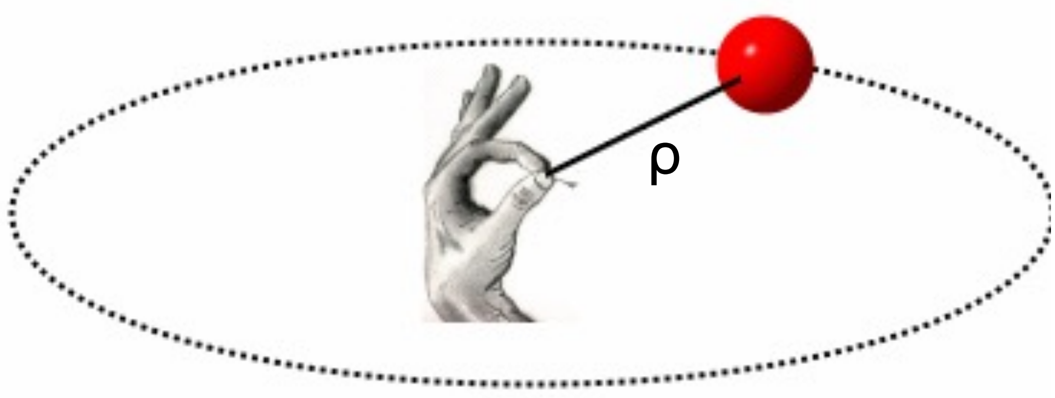
DK, Phil. Trans. Royal Soc (2022); arXiv:2108.08792

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 (proton rest frame):

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:

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

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

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

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:

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

The quantum mechanics of partons and entanglement on the light cone

The density matrix on the light cone:

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

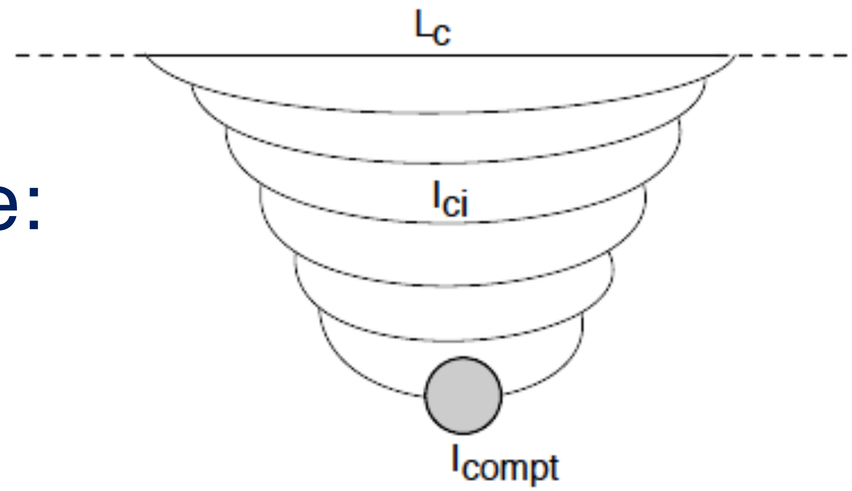
Haar scrambling: on the light cone, $t_i - z_i = x_i^- = 0,$
but t, z and $x^+ = z + t$ cannot be independently determined:

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

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

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

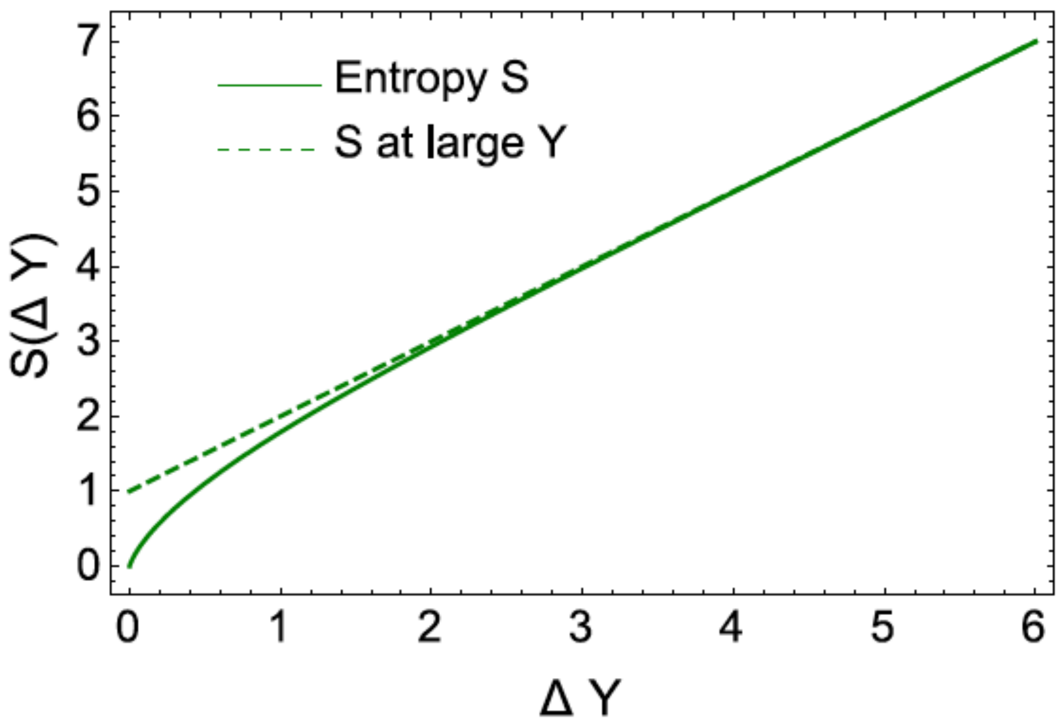
$$S(Y) = \ln(e^{\Delta Y} - 1) + e^{\Delta Y} \ln\left(\frac{1}{1 - e^{-\Delta Y}}\right)$$

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

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

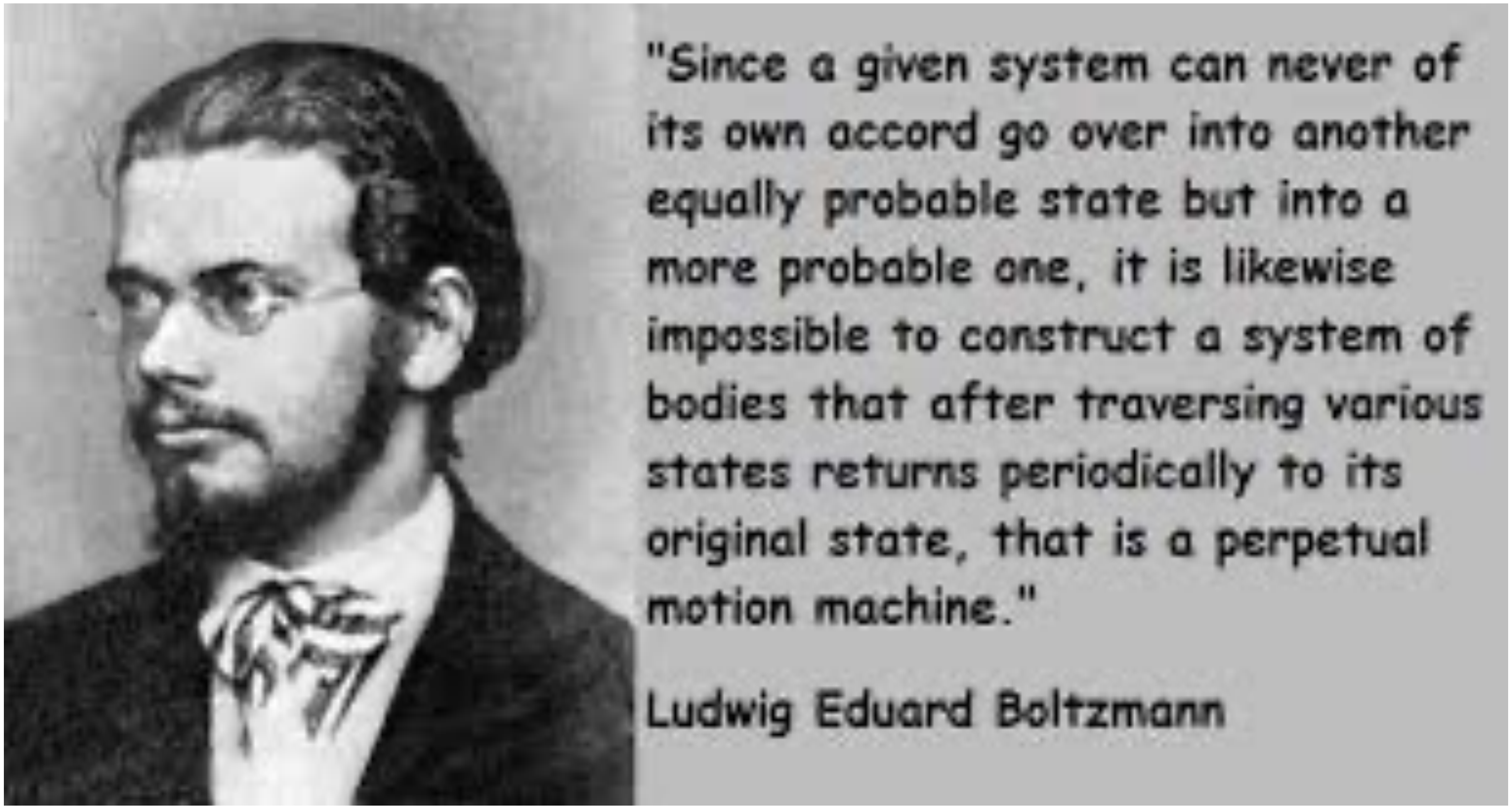
$$p_n = 1/N$$

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

This looks like the Boltzmann formula!


S = k. log W

L. Boltzmann:



the system is driven to the most probable state with the largest entropy

Why does the entanglement entropy of a maximally entangled quantum state have the same form as a classical entropy of an equilibrated system?

Perhaps, what we perceive as ``classical equilibrium" is a maximally entangled quantum state in which some information has been scrambled?

Maximally entangled state at small x

In the maximally entangled regime at small x, it appears that the behavior of the gluon structure function becomes universal;

[it is determined by the central charge of the corresponding CFT, and not by its anomalous dimension]

Analogy to statistical mechanics:

in thermal equilibrium (maximal entropy), the equation of state is determined by temperature (1/x)

and

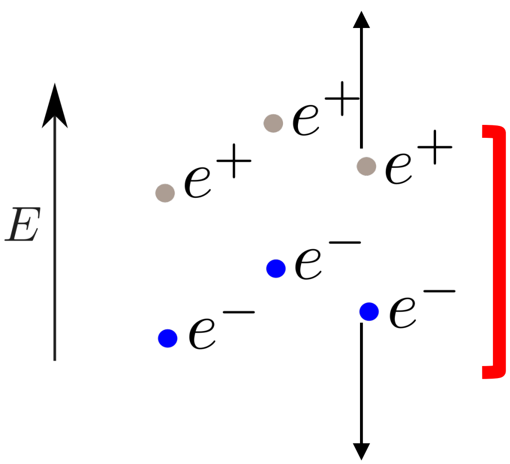
the effective number of degrees of freedom (central charge).

From entanglement entropy to statistical entropy: a simple example

A. Florio, DK, PRD (2021)

Study of real-time evolution of entanglement between the left- and right-movers in Schwinger pair production by electric pulses

$$S_G = \int \mathrm{d}k_1 \Big[\left(1 - |\beta_{k_1,t^*}|^2\right) \log\left(1 - |\beta_{k_1,t^*}|^2\right) + |\beta_{k_1,t^*}|^2 \log\left(|\beta_{k_1,t^*}|^2\right) \Big] \ ,$$



entanglement

Gibbs entropy

$$|\alpha_{k_1,t^*}|^2 = 1 - |\beta_{k_1,t^*}|^2$$

Entanglement entropy

$$S_E = - \int \mathrm{d}k_1 \Big[|\alpha_{k_1,t^*}|^2 \log\left(|\alpha_{k_1,t^*}|^2\right) + |\beta_{k_1,t^*}|^2 \log\left(|\beta_{k_1,t^*}|^2\right) \Big]$$

Real-time dynamics: from entanglement entropy to Boltzmann entropy

Entanglement entropy can be reconstructed from the moments of multiplicity distribution:

A. Florio, DK, PRD (2021)

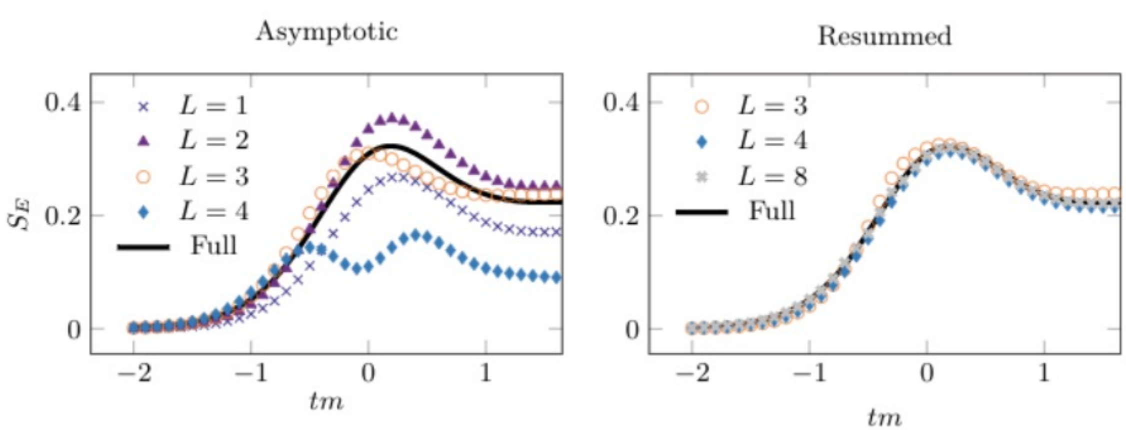
$$S_E = \sum_{l=1}^{\infty} \frac{C_{2l}}{(2l)!}(2\pi)^{2l}|B_{2l}|$$

Bernoulli numbers

Derived first for shot noise in Quantum Point Contacts:

I. Klich, L. Levitov, PRL (2009)

An efficient way to resum this series is found, using Pade-Borel methods:



The effect of radiation on quantum entanglement:

S. Grieninger, DK, I. Zahed, arXiv:2305.07121

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

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

We get

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

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

DK, E. Levin, arXiv:1702.03489; PRD

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

DK, E. Levin, arXiv:1702.03489; PRD

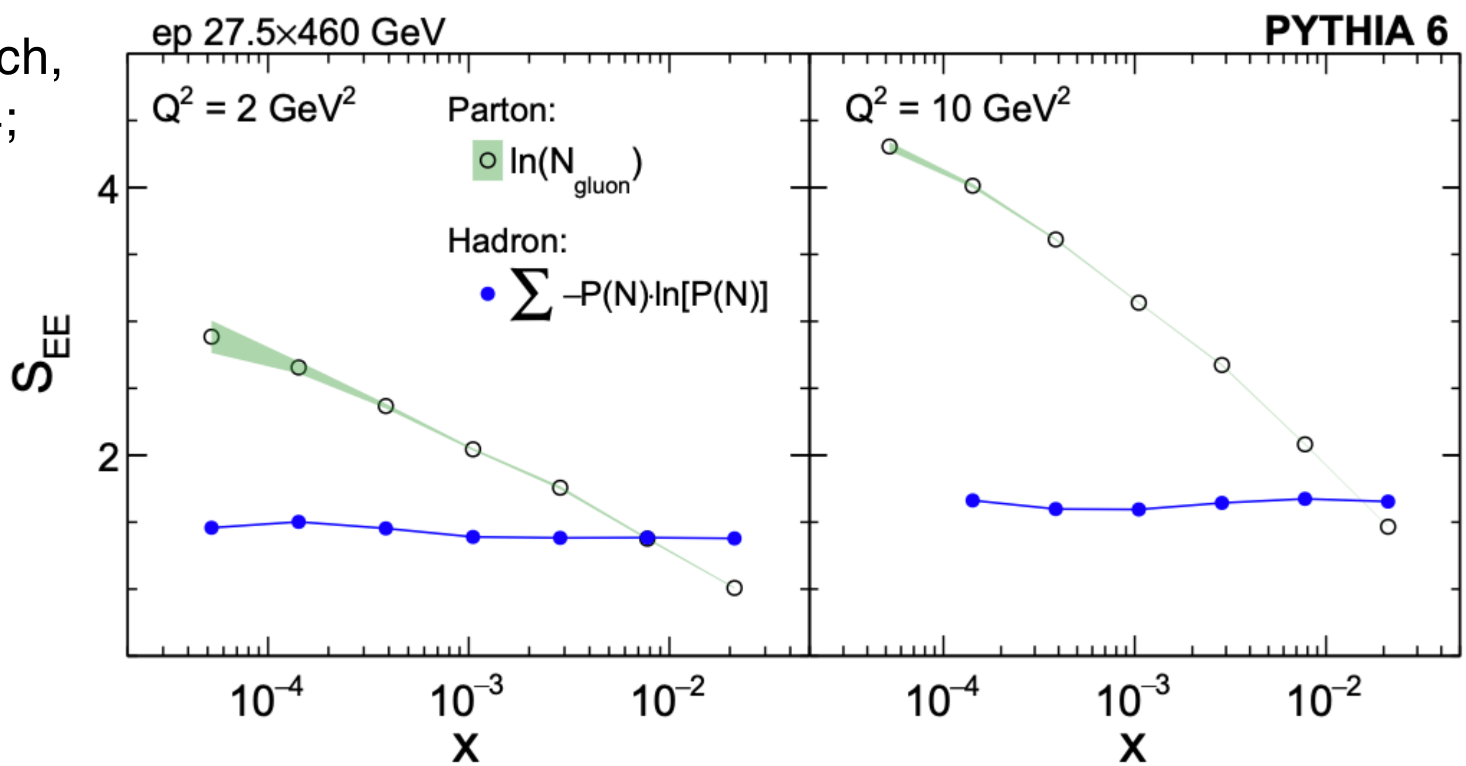
Test of the entanglement at the LHC

MC generator PYTHIA:

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

is not satisfied at small x (no entanglement)

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



Test of the entanglement at the LHC

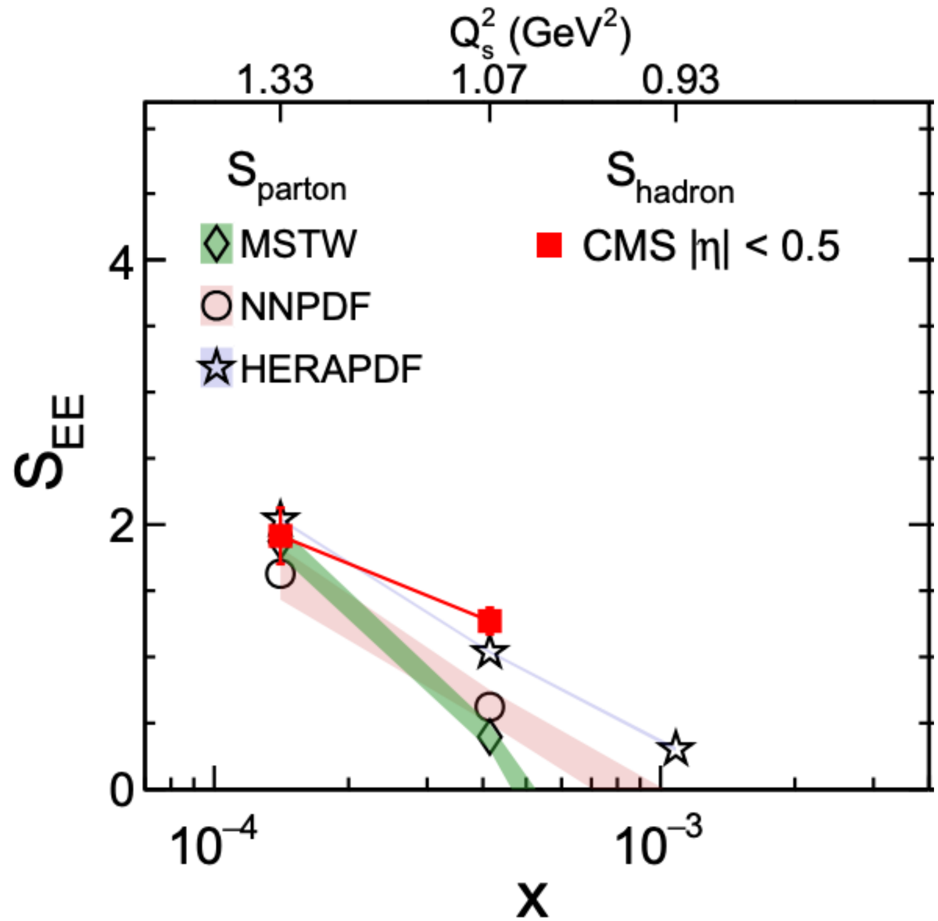
LHC data:

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

H1 Coll. test of

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

using DIS data (current fragmentation region)

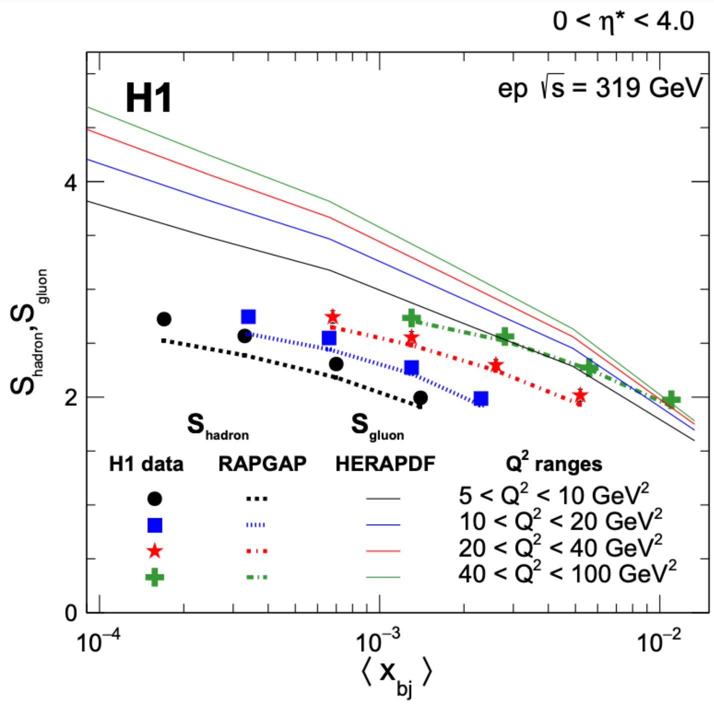


Figure 12: Hadron entropy S_{hadron} derived from multiplicity distributions as a function of $\langle x_{\mathrm{bj}} \rangle$ measured in different Q^2 ranges, measured in $\sqrt{s} = 319$ GeV ep collisions. Here, a restriction to the current hemisphere $0 < \eta^* < 4$ is applied. Further phase space 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?

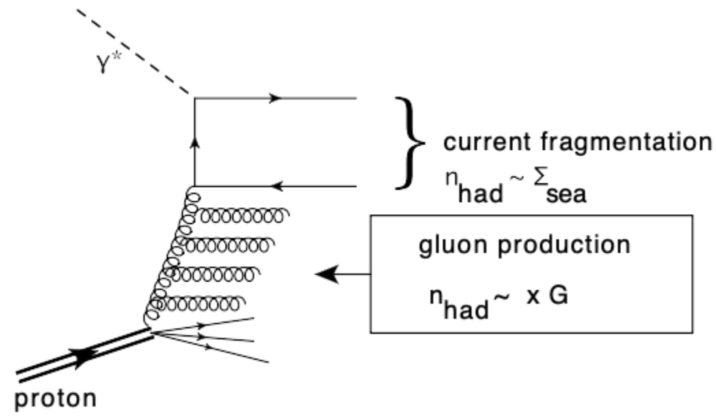
Test of the entanglement in DIS

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

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

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

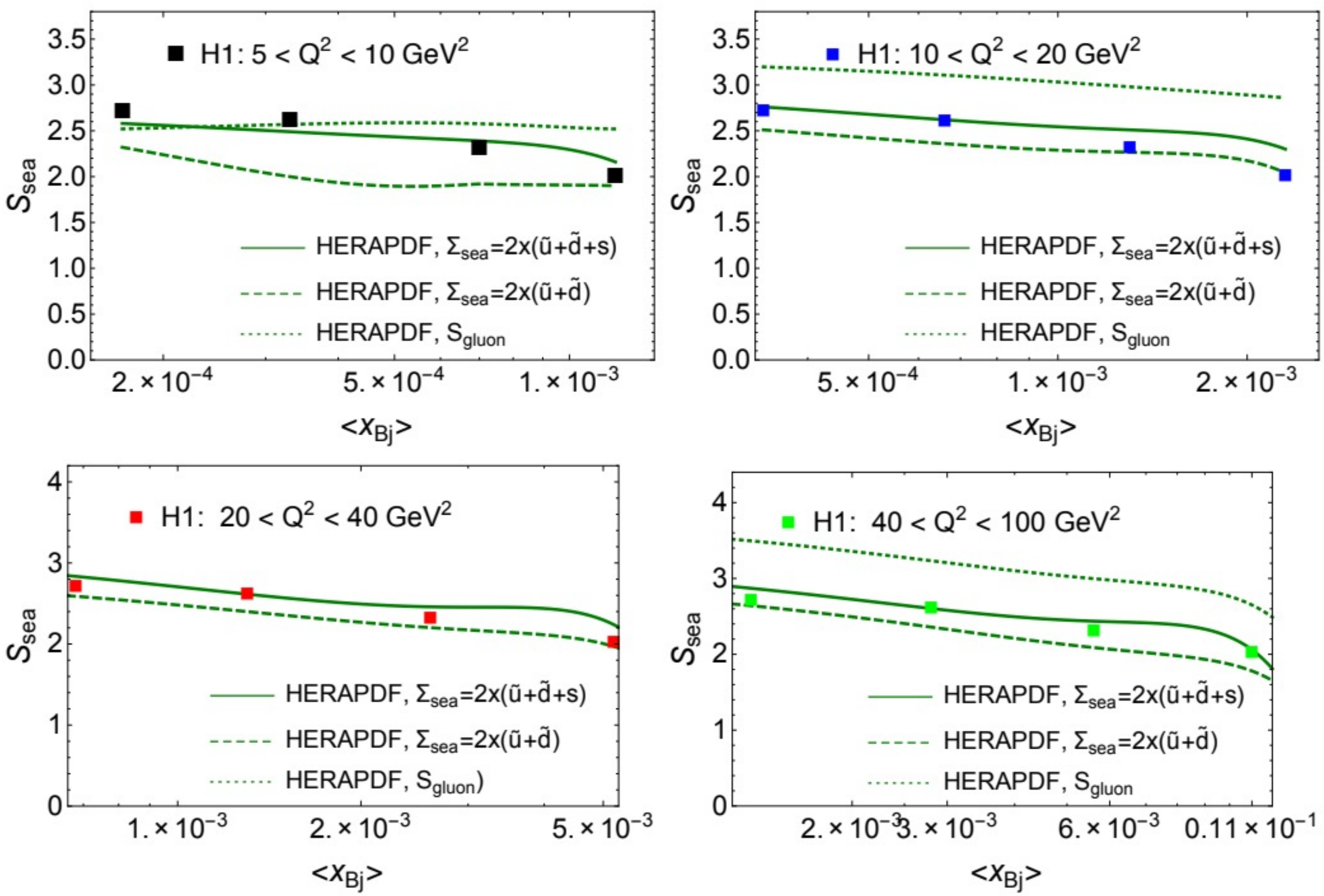


FIG. 1: Comparison of the experimental data of the H1 collaboration [6] on the entropy of produced hadrons in DIS [6] with our theoretical predictions, for which we use the sea quark distributions from the NNLO fit to the combined H1-ZEUS data.

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.

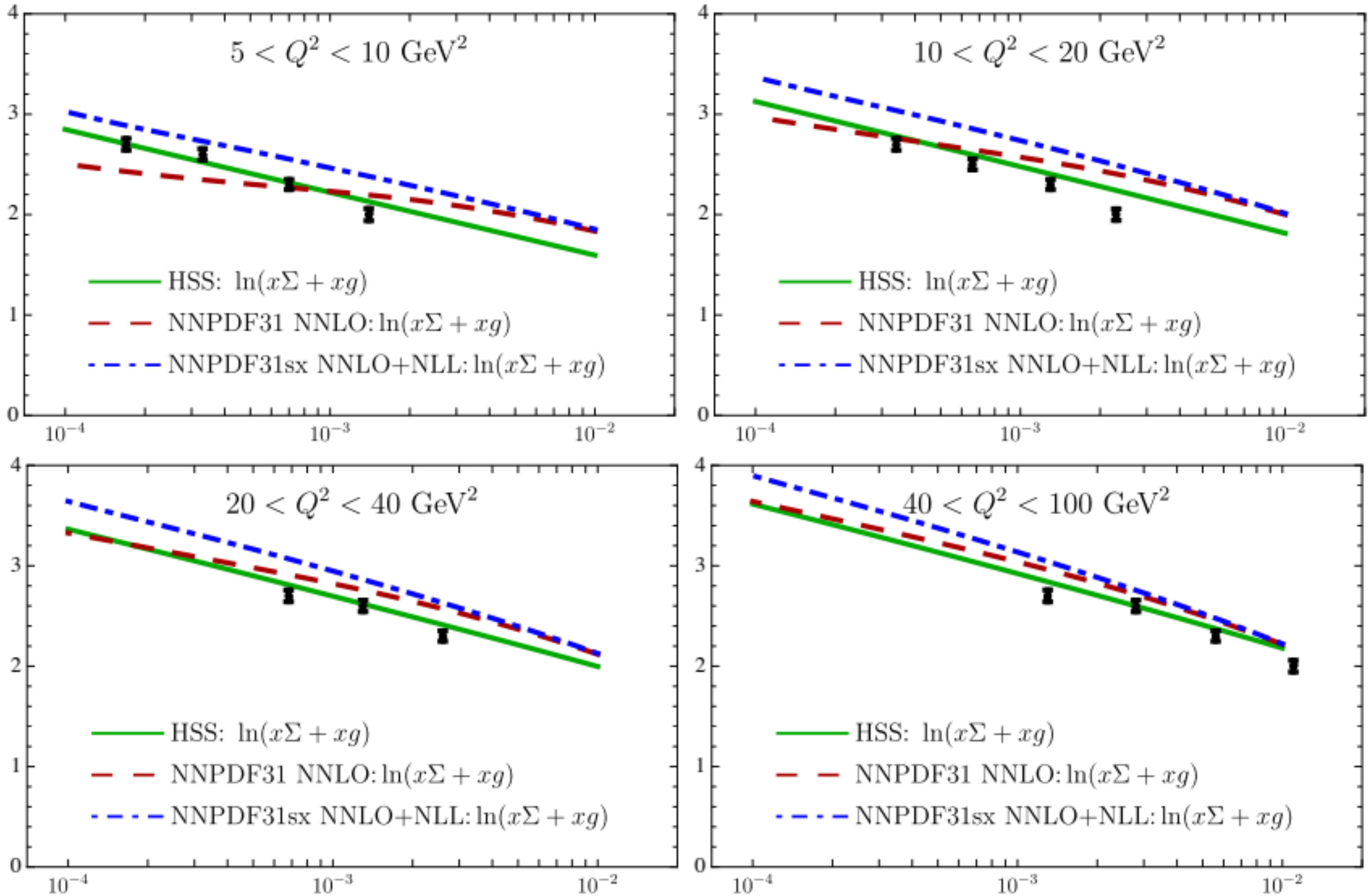


Figure 1: *Partonic entropy versus Bjorken x, as given by Eq. (1) and Eq. (2). We furter show results based on the gluon distribution only as well as a comparison to NNPDFs. Results are compared to the final state hadron entropy derived from the multiplicity distributions measured at H1 [19]*

The onset of maximal entanglement in diffractive DIS

M. Hentschinski, DK, K. Kutak, Z. Tu, arXiv:2305.03069

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

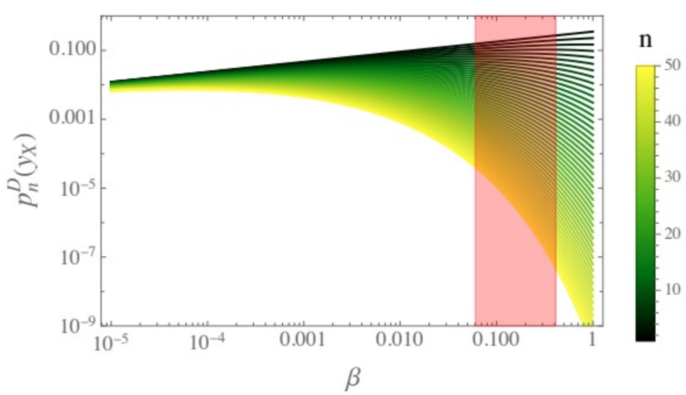


FIG. 2. Probabilities $p_n(y_X)$ with $y_X = \ln(1/\beta)$ as extracted from leading order diffractive PDFs for $n = 1, \ldots, 50$ for the charged hadron multiplicities. The shaded region indicates the region in β probed by the H1 data set.

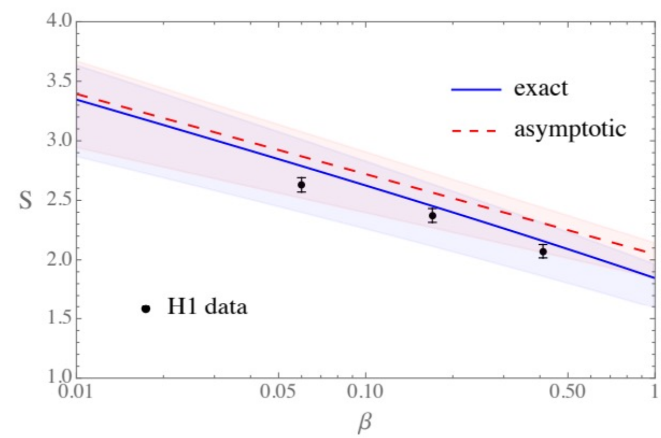


FIG. 3. Exact and asymptotic entropy as a function of β. H1 data [59] extracted from the multiplicity distributions are shown, where statistical and systematic uncertainty are added in quadrature and presented as error bars. The uncertainty bands correspond to a variation of the factorization scale of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

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 EIC, requirements for detector design:

- detect hadrons in a broad range of rapidity y, including target fragmentation region;
- hadron ID (mesons vs baryons – baryon transfer, …)
- detection of hadrons in diffractive DIS at different rapidity gaps