"Forward physics and instrumentation: from colliders to cosmic rays"

October 17-19, CFNS, Stony Brook University

Electron and neutrino interactions at high energies

D. Kharzeev

Big questions
to address at EIC and elsewhere:

- the mechanism of **color confinement**
- the origin of the nucleon's **mass**
- the origin of the nucleon's **spin**
- the structure of **strong color fields**

How some of these questions will be addressed in this talk:

1. color confinement is an ultimate example of **quantum entanglement**;

   can this be used to formulate a new approach to parton structure functions?

   how can this picture be tested in experiment using forward (backward) region measurements?

DK, E. Levin, Phys. Rev. D95 (2017) 114008;
O.K. Baker, DK, Phys. Rev. D98 (2018) 054007; + in progress

2. color confinement can be probed in high energy, large impact parameter, interactions

Probing QCD string in elastic and diffractive scattering at high energies

DK, E. Shuryak, I. Zahed, Phys. Rev. D97 (2018) 016008

Probing the QCD string (the Reggeon) by strong EM field in e-nucleus scattering

G. Basar, DK, H.U. Yee, I. Zahed, Phys. Rev. D95(2017)126005

2. Probing QCD string in elastic and diffractive scattering at high energies

High energy elastic and diffractive scattering allows to probe the dynamics of QCD strings, in particular higher order corrections to the Nambu-Goto action

$$S = -\sigma_T \int_M d^2x \,(1 + \partial_\alpha X^i \partial^\alpha X_i)$$

resulting from Polyakov terms:

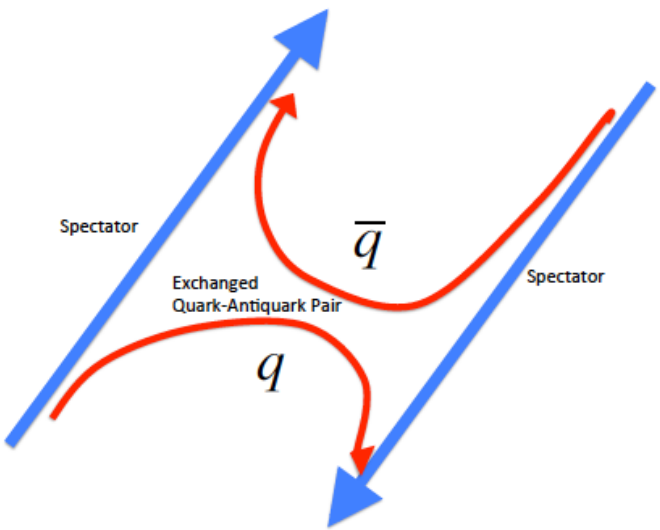
$$+\frac{1}{\kappa}\int d^2x \left(\dot{\dot{X}}^\mu \dot{\dot{X}}_\mu + 2\dot{X}'^\mu \dot{X}'_\mu + X''^\mu X''_\mu\right)$$

Observable effects in differential cross section and the phase of the scattering amplitude – LHC, EIC

DK, E. Shuryak, I. Zahed, Phys. Rev. D97 (2018) 016008

2. Probing the QCD string (the Reggeon) by strong EM field in e-nucleus scattering

Strong EM fields affect the propagation of quarks – Reggeon exchange amplitudes can be modified!



$$\mathcal{T}^{pp,p\bar{p}}_{\text{Reggeon}}(s,t) \sim i\, s^{\alpha_0+\alpha' t}\,,$$

$$\mathcal{T}^{Ap,A\bar{p}}_{\text{Reggeon}}(s,t) \sim i\, e^{\alpha'(Z)t\,(\ln s)^2}$$

EM fields suppress the Reggeon amplitude in eA, pA scattering at high energies (holography)

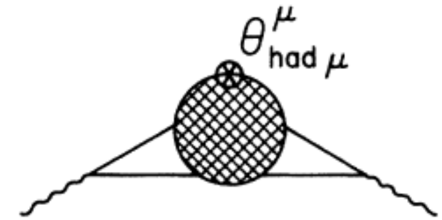
G. Basar, DK, H.U. Yee, I. Zahed, Phys. Rev. D95(2017)126005

3. How can we test the origin of nucleon's mass, and the mass distribution, in electron/photon scattering experiments?

threshold electro/photo production of heavy quarkonia as a probe of the nucleon's mass fraction carried by gluons

DK, nucl-th/9601029;
DK, H. Satz, A. Syamtomov, G. Zinovjev, Eur.Phys.J. C9(1999)459
+ in progress

Scale anomaly in QCD



The quantum effects (loop diagrams) modify the expression for the trace of the energy-momentum tensor:

$$\Theta^{\alpha}_{\alpha} = \frac{\beta(g)}{2g} G^{\alpha\beta a} G^{a}_{\alpha\beta} + \sum_{l=u,d,s} m_l (1+\gamma_{m_l}) \bar{q}_l q_l + \sum_{h=c,b,t} m_h (1+\gamma_{m_h}) \bar{Q}_h Q_h,$$

Running coupling -> dimensional transmutation -> mass scale

Gross, Wilczek; Politzer

$$\beta(g) = -b\frac{g^3}{16\pi^2} + \ldots, \;\; b = 9 - \frac{2}{3} n_h,$$

Ellis, Chanowitz; Crewther; Collins, Duncan, Joglecar; …

At small momentum transfer, heavy quarks decouple:

$$\sum_h m_h \bar{Q}_h Q_h \rightarrow -\frac{2}{3}\, n_h\, \frac{g^2}{32\pi^2} G^{\alpha\beta a} G^{a}_{\alpha\beta} + \ldots$$

SVZ ’78

so only light quarks enter the final expression

$$\Theta^{\alpha}_{\alpha} = \frac{\tilde{\beta}(g)}{2g} G^{\alpha\beta a} G^{a}_{\alpha\beta} + \sum_{l=u,d,s} m_l \bar{q}_l q_l,$$

The proton mass

At zero momentum transfer, the matrix elements of the energy-momentum tensor are

$$\langle P|\theta^{\mu\nu}|P\rangle = 2P^\mu P^\nu$$

so that the trace of the energy-momentum tensor defines the masses of hadrons:

$$\langle P|\theta^\mu_\mu|P\rangle = 2M^2$$

$$\Theta^\alpha_\alpha = \frac{\tilde{\beta}(g)}{2g} G^{\alpha\beta a} G^a_{\alpha\beta} + \sum_{l=u,d,s} m_l \bar{q}_l q_l ,$$

In the chiral limit, the entire mass is from gluons!

Probing the proton mass

How do we probe the distribution of mass inside the proton?

Need a dilaton source… closest approximation: the heavy quarkonium

The scattering amplitude

$$F_{\Phi h} = r_0^3 \epsilon_0^2 \sum_{n=2}^{\infty} d_n \langle h | \frac{1}{2} G^a_{0i} (D^0)^{n-2} G^a_{0i} | h \rangle$$

Wilson coefficients

The Wilson coefficients

$$d_n^{(1S)} = \left(\frac{32}{N}\right)^2 \sqrt{\pi}\,\frac{\Gamma(n+\frac{5}{2})}{\Gamma(n+5)}$$

M.Peskin '78

$$d_n^{(2S)} = \left(\frac{32}{N}\right)^2 4^n \sqrt{\pi}\,\frac{\Gamma(n+\frac{5}{2})}{\Gamma(n+7)}(16n^2+56n+75)$$

$$d_n^{(2P)} = \left(\frac{15}{N}\right)^2 4^n 2\sqrt{\pi}\,\frac{\Gamma(n+\frac{7}{2})}{\Gamma(n+6)}$$

DK, nucl-th/9601029

Quarkonium-proton interaction

$$F_{\Phi h} = r_0^3 \epsilon_0^2 \sum_{n=2}^{\infty} d_n \langle h | \frac{1}{2} G_{0i}^a (D^0)^{n-2} G_{0i}^a | h \rangle$$

1. Interaction is attractive (VdW force of QCD)

S.Brodsky, I.Schmidt, G. de Teramond ‘90

2. For n=2 (low energy) the amplitude is proportional to the trace of the energy-momentum tensor

M.Luke, A.Manohar, M.Savage ’92

Quarkonium-proton interaction at low energy probes the distribution of mass inside the proton

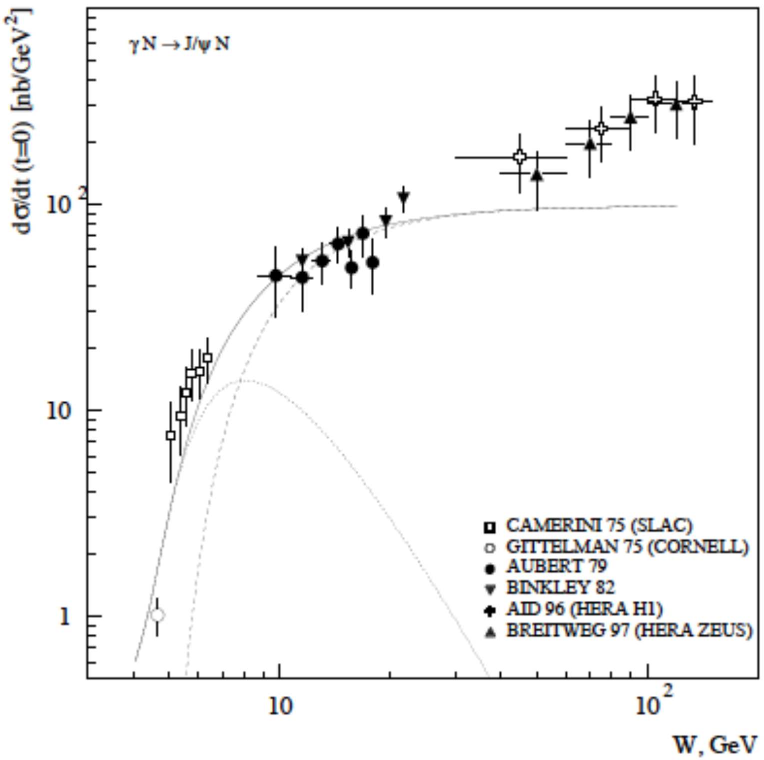


Figure 1: Forward J/ψ photoproduction data compared to our results with (solid line) and without (dashed line) the real part of the amplitude. The curves were obtained using a scaling PDF [4]

The real part of the amplitude is crucially important, directly probes the gluon contribution to the mass of the proton. The plot assumes 80% contribution.

DK, Satz, Syamtomov, Zinovjev EPJ '99

Also:
Y.Hatta, D.-L.Yang, PRD98(2018)074003

4. How can we test the origin of nucleon's spin, using the forward/backward region measurements in polarized electron or neutrino scattering experiments?

measurements of Λ polarization in the target fragmentation region in polarized DIS
(spin entanglement)

J. Ellis, DK, A. Kotzinian, Z. Phys. C69 (1996) 467
+ in progress

4. Λ polarization in the target fragmentation region in polarized DIS (spin entanglement)

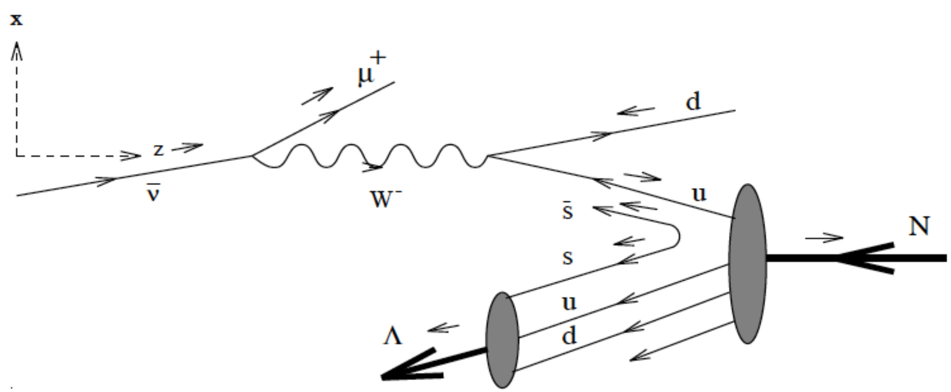


Figure 1: *Dominant diagram for Λ production in the target fragmentation region due to scattering on a valence u quark. Each small arrow represent the longitudinal polarization*

x range	$0 < x < 1$	$0 < x < 0.2$	$0.2 < x < 1$
P_Λ in WA59 experiment	-0.63 ± 0.13	-0.46 ± 0.19	-0.85 ± 0.19
P_s in our model	-0.86	-0.84	-0.94
Dilution factor D_F	0.73 ± 0.15	0.55 ± 0.23	0.90 ± 0.20

Table 1: *Λ polarization in the target fragmentation region* ($x_F < 0$).

J. Ellis, DK, A. Kotzinian, Z. Phys. C69 (1996) 467
\+ in progress

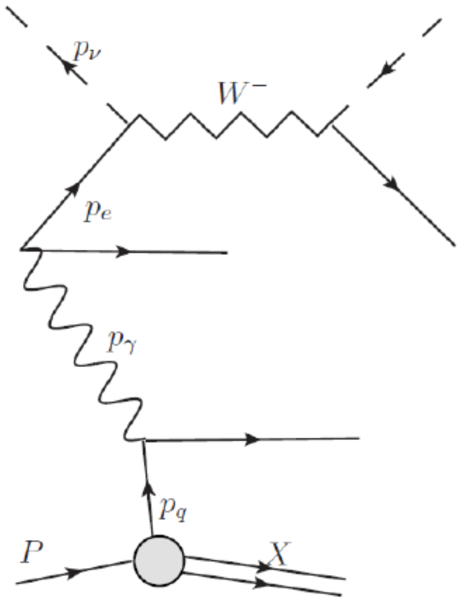
Measurements of Λ polarization in the target FR in polarized DIS and neutrino scattering probe the **spin entanglement** between the struck quark and the sea around it.

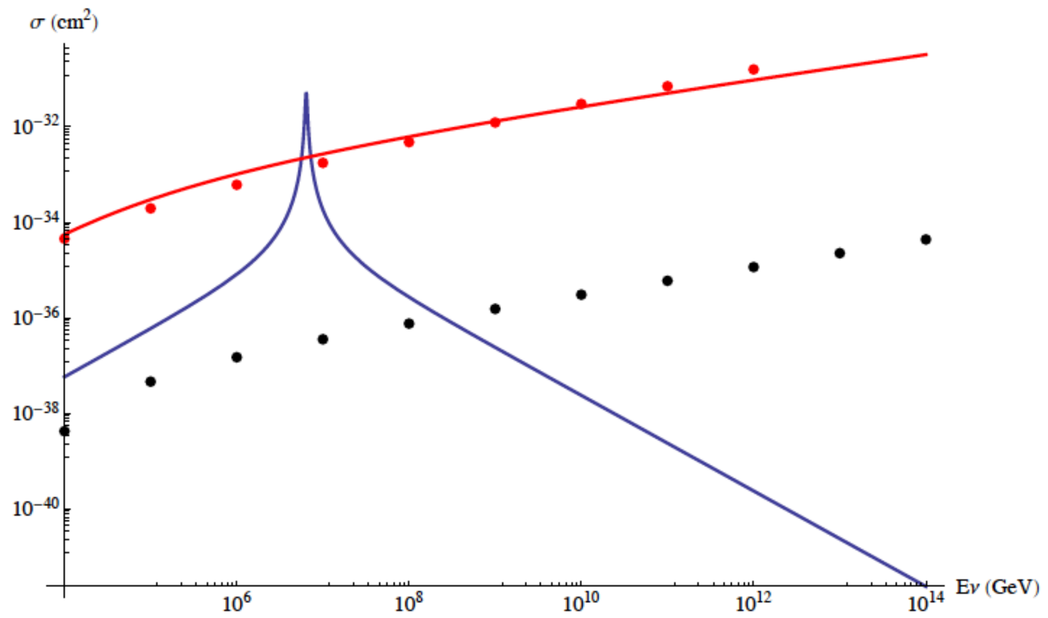
The existing data suggest strong negative correlation. The proton spin puzzle!

5. Neutrino interactions at ultra-high energies:

Glashow resonance in the presence of strong electromagnetic and color fields of the nuclei

S. L. Glashow, Phys. Rev. **118**, 316 (1960)





J. Kiryluk, F. Loshaj, DK, to appear

1. color confinement is an ultimate example of **quantum entanglement**;

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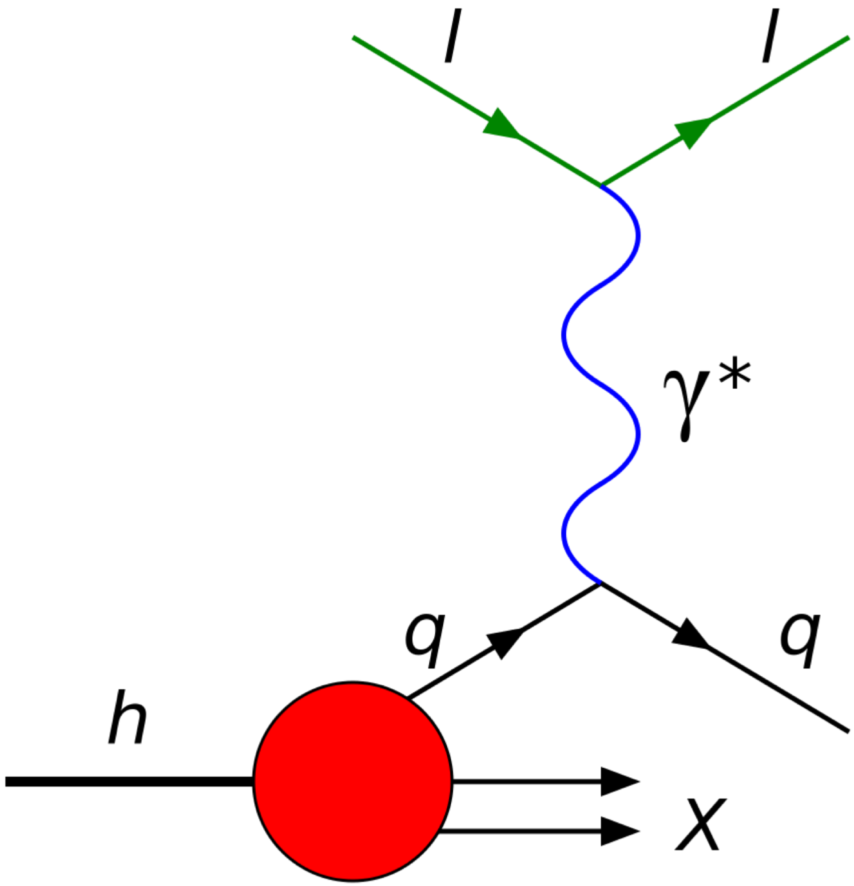
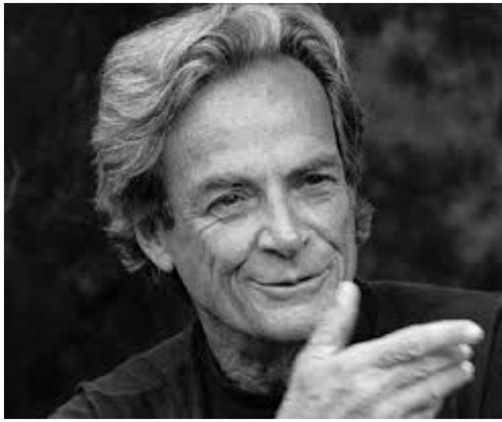
   DK, E. Levin, Phys. Rev. D95 (2017) 114008;
   O.K. Baker, DK, Phys. Rev. D98 (2018) 054007; + in progress

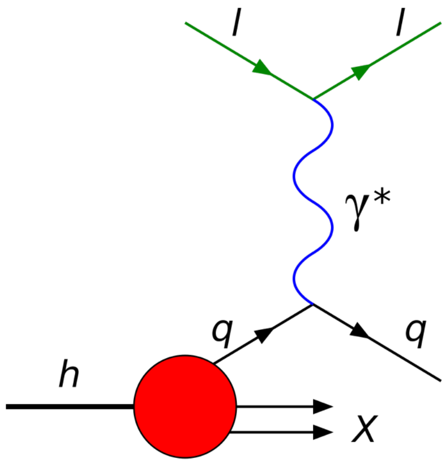
The parton model: 50 years of success





In almost fifty years that have ensued after the birth of the parton model, it has become an indispensable building block of high energy physics

The parton model: basic assumptions



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?

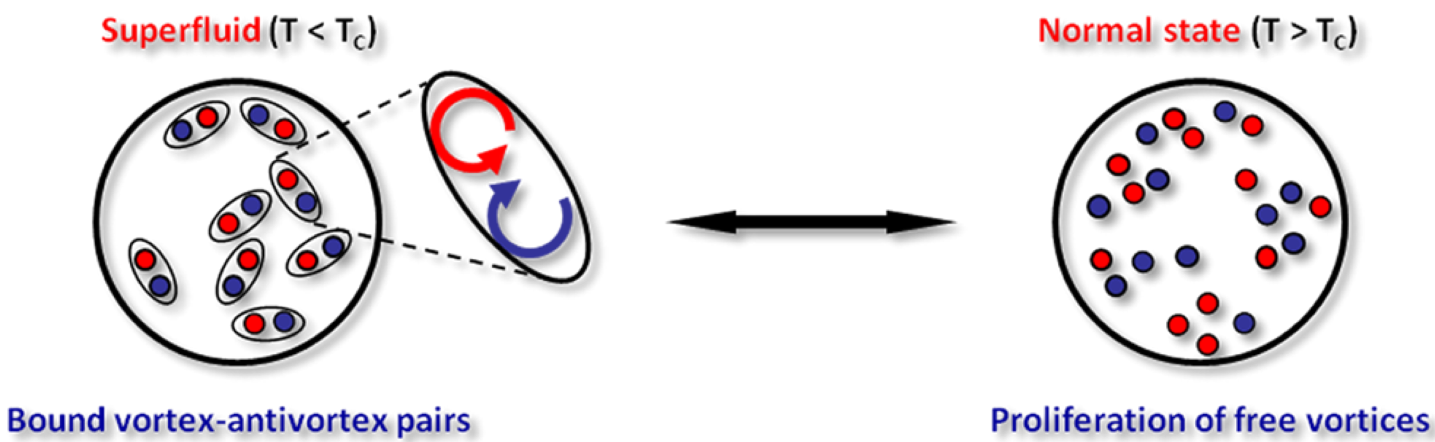
DIS and entanglement

"...we never experiment with just one electron or atom or (small) molecule. In thought experiments, we sometimes assume that we do; this invariably entails ridiculous consequences ... ."

Erwin Schrödinger, 1952

The puzzle of the parton model

In quantum mechanics, the proton is a <u>pure state</u> with <u>zero entropy</u>. 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.

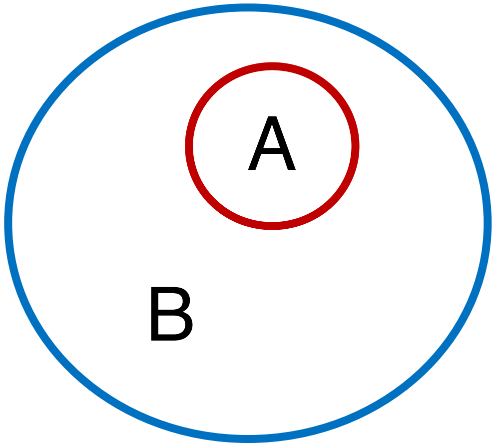
DK, E. Levin, arXiv:1702.03489

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

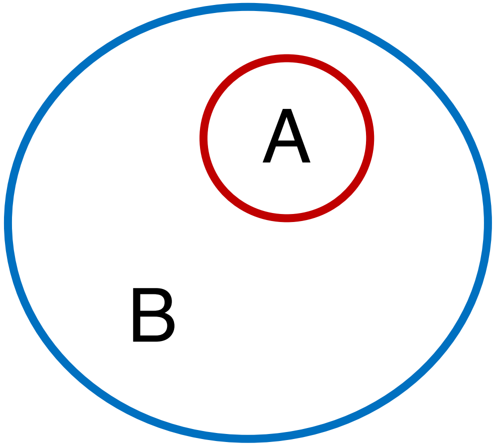
$$\hat{\rho}_A = \mathrm{tr}_{\mathrm{B}} \hat{\rho}$$

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



The proton is described by a vector

$$|\Psi_{AB}\rangle = \sum_{i,j} c_{ij} \; |\varphi_i^A\rangle \otimes |\varphi_j^B\rangle$$

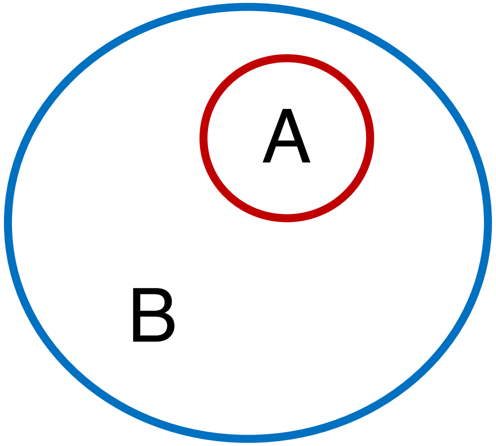
in Hilbert space $\mathcal{H}_A \otimes \mathcal{H}_B$

If $|\Psi_{AB}\rangle = |\varphi^A\rangle \otimes |\varphi^B\rangle$ only one term

contributes, then the state is separable (not our case!). Otherwise, the state is **entangled**.

The quantum mechanics of partons and entanglement

The Schmidt decomposition theorem:



$$|\Psi_{AB}\rangle = \sum_n \alpha_n |\Psi_n^A\rangle |\Psi_n^B\rangle$$

There exist the orthonormal states $|\Psi_n^A\rangle$ and $|\Psi_n^B\rangle$ for which the pure state can be represented as a <u>single</u> sum with real and positive coefficients α_n

If only one term (Schmidt rank one), then the state is separable. Otherwise, it is **entangled**; but no interference between different n's.

The quantum mechanics of partons and entanglement

We assume that the Schmidt basis $|\Psi_n^A\rangle|\Psi_n^B\rangle$ corresponds to the states with different numbers of partons n; since this decomposition represents a state in relativistic quantum field theory (QCD), the Schmidt rank is in general infinite.

The density matrix is now given by

$$\rho_A = \mathrm{tr_B}\ \rho_{\mathrm{AB}} = \sum_{\mathrm{n}} \alpha_{\mathrm{n}}^2\ |\Psi_{\mathrm{n}}^{\mathrm{A}}\rangle\langle\Psi_{\mathrm{n}}^{\mathrm{A}}|$$

where $\alpha_n^2 \equiv p_n$ is the probability of a state with n partons

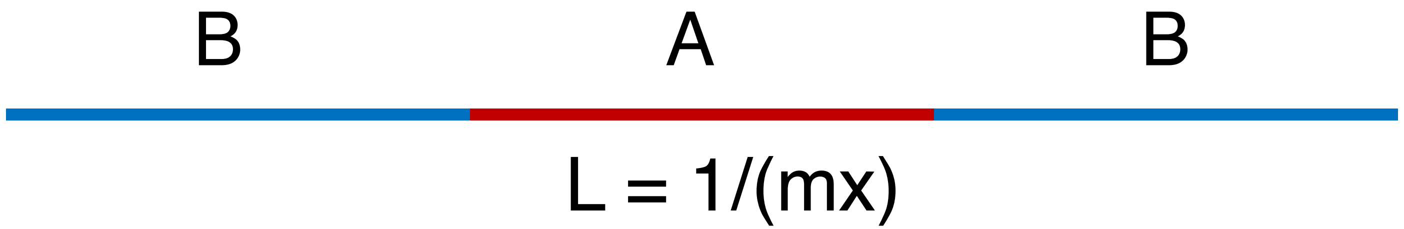
The entanglement entropy

The entanglement entropy is now given by the von Neumann's formula

$$S = -\sum_n p_n \ln p_n$$

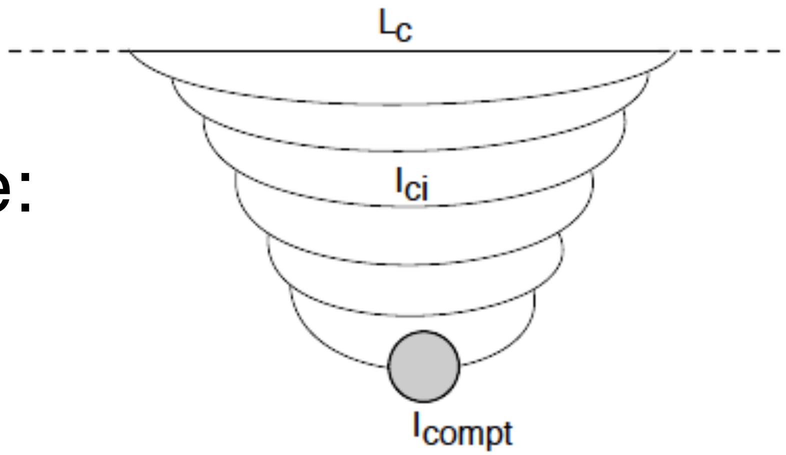
and can be evaluated by using the QCD evolution equations.

Let us start with a (1+1) case:



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:

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

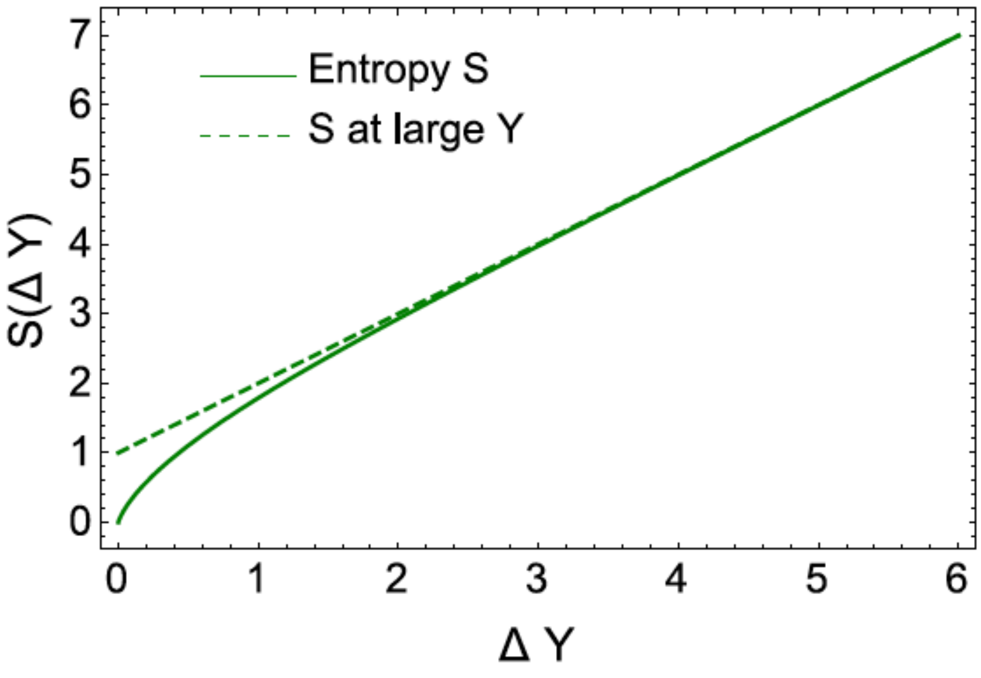
The resulting von Neumann entropy is

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

The entanglement entropy from QCD evolution

At large ΔY , the entropy becomes

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



This "asymptotic" regime starts rather early, at

$$\Delta Y \simeq 2$$

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:

$$\boxed{S = \ln[xG(x)]}$$

The entanglement entropy from QCD evolution

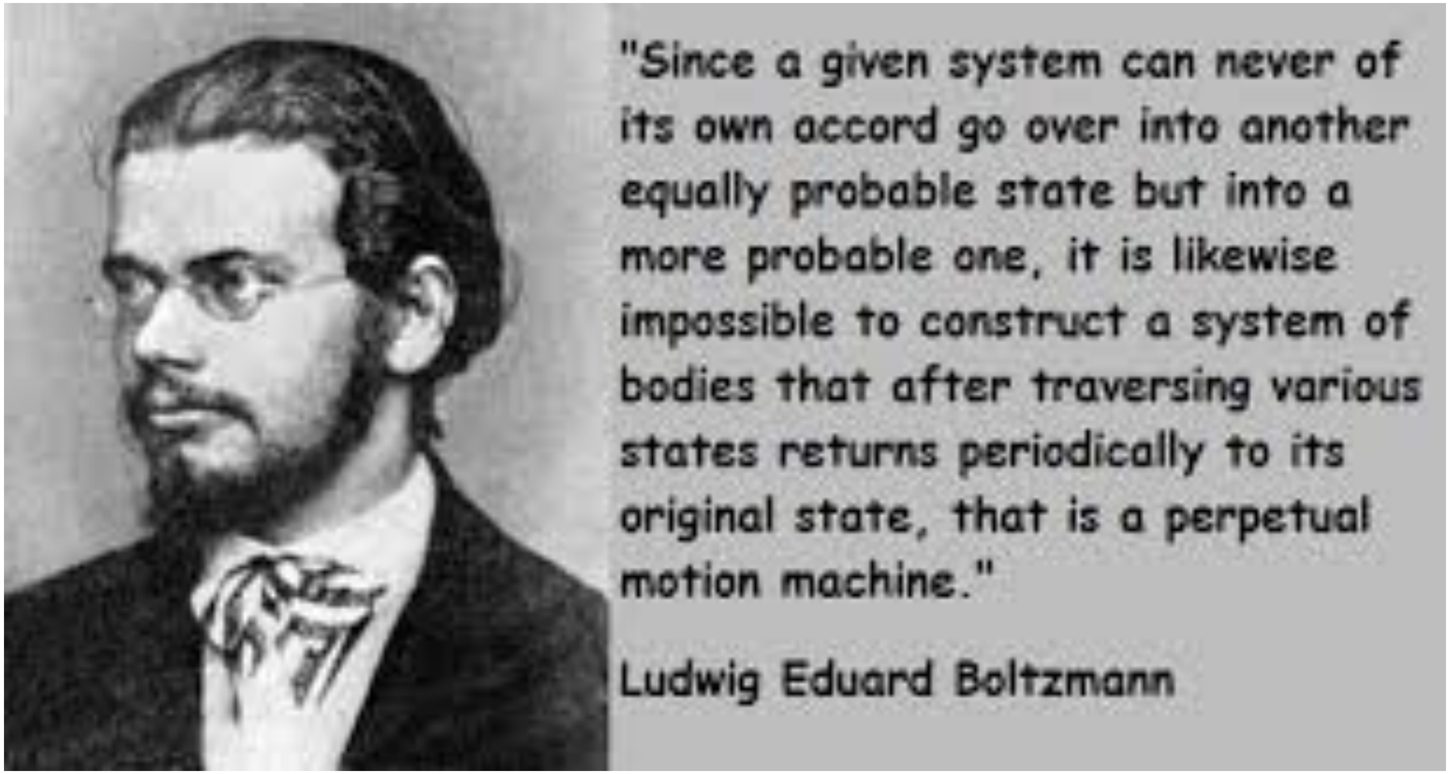
The (3+1) case is cumbersome, but the result is the same, with $\Delta = \bar{\alpha}_s \ln(r^2 Q_s^2)$

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?)

L. Boltzmann:



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

Fluctuations in hadron multiplicity

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

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

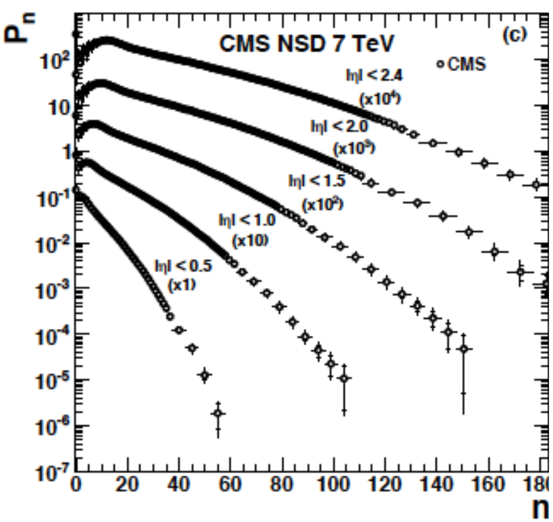
Consider moments

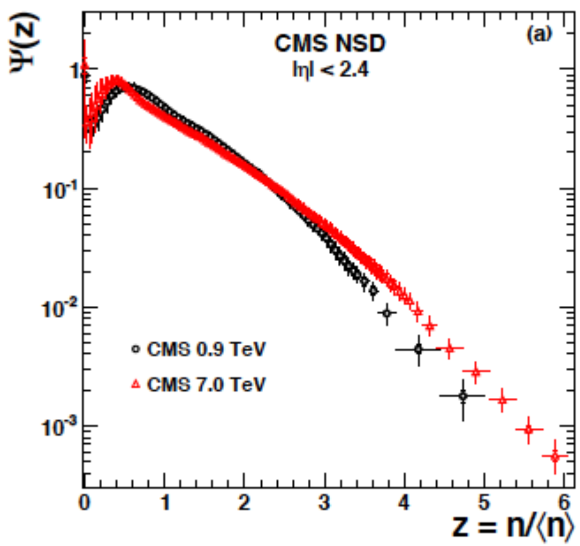
$$C_q = < n^q > / < n >^q$$

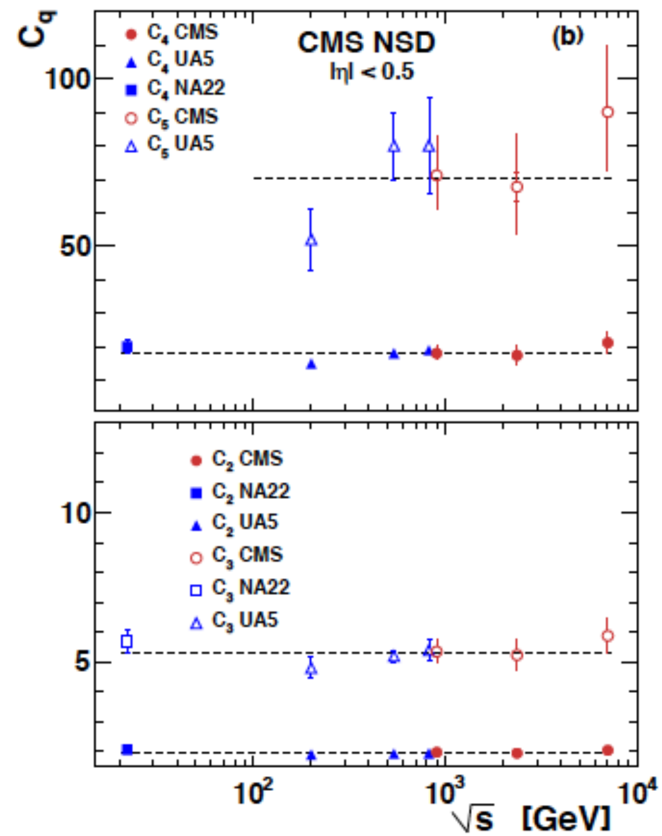
Fluctuations in hadron multiplicity

The CMS Coll., arXiv:1011.5531, JHEP01(2011)079

Charged particle multiplicities in pp interactions at $\sqrt{s} = 0.9, 2.36, \text{and } 7\text{ TeV}$







KNO scaling violated

Fluctuations in hadron multiplicity

The moments can be easily computed by using the generating function

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

We get

$$C_2 = 2 - 1/\bar{n}; \qquad C_3 = \frac{6(\bar{n}-1)\bar{n}+1}{\bar{n}^2};$$
$$C_4 = \frac{(12\bar{n}(\bar{n}-1)+1)(2\bar{n}-1)}{\bar{n}^3}; \qquad C_5 = \frac{(\bar{n}-1)(120\bar{n}^2(\bar{n}-1)+30\bar{n})+1}{\bar{n}^4}.$$

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

Physics at EIC:

supplement the measurements of structure functions by the studies of hadronic final state (especially in the target fragmentation region).

Testing the Second Law for the transformation of entanglement Entropy into the Boltzmann one is fundamentally important;

extracting the entropy of the final hadronic state will require event-by-event measurements.

This can be started at RHIC and LHC! Combine Measurements of “hard” cross sections with the e-by-e measurements of associated hadron multiplicity

The forward physics at colliders and cosmic rays allows to address questions of fundamental importance:

- the mechanism of **color confinement**
- the origin of the nucleon's **mass**
- the origin of the nucleon's **spin**
- the structure of **strong color fields**