Topology and entanglement in the baryon structure at small x

Adrien Florio[1], **David Frenklakh**[2] and Dmitri Kharzeev[1,2,3]

[1]Department of Physics, Brookhaven National Laboratory, Upton, New York 11973-5000, USA
[2]Center for Nuclear Theory, Department of Physics and Astronomy, Stony Brook University, Stony Brook, New York 11794-3800, USA
[3]Co-design Center for Quantum Advantage, Department of Physics and Astronomy, Stony Brook University, Stony Brook, New York 11794-3800, USA

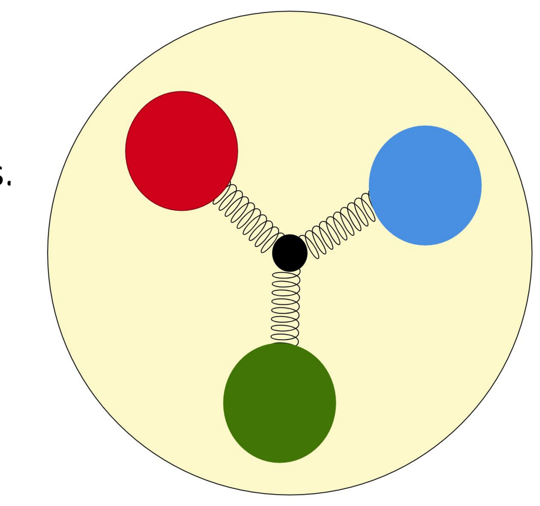
Introduction: baryon junctions

It has been suggested [1] that baryon number is carried by a gluonic string junction. It ensures gauge invariance of the operator containing three quark fields at different points.

Gauge-invariant baryon operator:

$$B(x_1,x_2,x_3)\sim q(x_1)q(x_2)q(x_3) \xrightarrow{\text{Gauge inv.}} B(x_1,x_2,x_3,x)=\epsilon^{ijk}[P\exp(ig\int_x^{x_1} A_\mu dx^\mu)q(x_1)]_i[P\exp(ig\int_x^{x_2} A_\nu dx^\nu)q(x_2)]_j[P\exp(ig\int_x^{x_3} A_\rho dx^\rho)q(x_3)]_k$$

If a string breaks, the baryon is restored around the junction. **Does the junction carry the baryon number?**



A schematic illustration of the baryon junction structure

Theory

Phenomenology

(1+1)-dimensional QCD

QCD in (1+1) is similar to (3+1): confinement, chiral symmetry breaking and mass gap in meson and baryon spectrum **and** is exactly solvable in the large N_c limit.

Bosonization → sine-Gordon model:

$$\mathcal{L}=\frac{1}{2}(\partial_\mu\phi)^2 - m'^2\cos\left(2\sqrt{\frac{\pi}{N_c}}\phi\right)$$

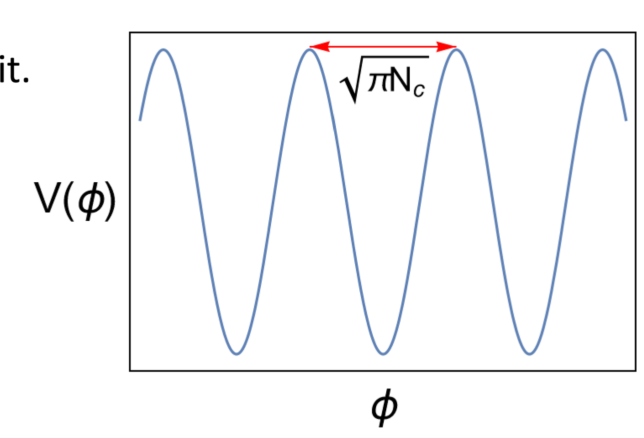


Fig.1 Potential of the sine-Gordon field

Baryon is represented by a topological kink (see Figure 2).

Baryon number is naturally topological charge.

Quantum state of a baryon is a particular coherent state [2]:

$$|B\rangle=\bigotimes_k|\alpha_k\rangle,\qquad |\alpha_k\rangle=e^{-|\alpha_k|^2/2}\sum_{n=0}^{\infty}\frac{\alpha_k^n}{n!}(a_k^\dagger)^n|0\rangle$$

where $a_k^\dagger$ create soliton constituents, not free quanta.

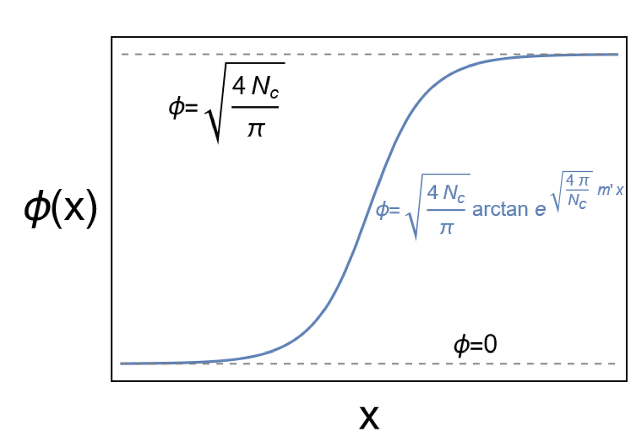


Fig. 2 Sine-Gordon kink field profile

α_k are Fourier coefficients of the classical kink profile:

$$\alpha_k=t_kc_k,\quad t_k=-\frac{i}{2k},\quad c_k=\sqrt{2\sqrt{2\pi}N_c|k|}\frac{1}{\cosh\left(\sqrt{\frac{N_c}{4\pi}}\frac{\pi k}{2m'}\right)}$$

leading to a natural decomposition of the coherent state into topology and "energy":

$$|\alpha_k\rangle=e^{-\frac{1}{2}|t_k|^2|c_k|^2}\sum_{n_k=0}^{\infty}\frac{t_k^{n_k}c_k^{n_k}}{\sqrt{n_k!}}|n_k\rangle_t\otimes|n_k\rangle_c$$

Reduced density matrix after tracing over the topological degrees of freedom:

$$\rho_{red}=\bigotimes_k\rho_k=\bigotimes_k e^{-|\alpha_k|^2}\sum_{n_k=0}^{\infty}\frac{|\alpha_k|^{2n_k}}{n_k!}|n_k\rangle_c\langle n_k|_c$$

Compute the entanglement entropy:

$$S_k=-\mathrm{Tr}(\rho_k\log\rho_k)=|\alpha_k|^2(1-\log|\alpha_k|^2)+e^{-|\alpha_k|^2}\sum_{n=2}^{\infty}|\alpha_k|^2\frac{\log n!}{n!}$$

Estimate the asymptotic behavior at small and large k analytically;
the rest can be computed numerically. Results are shown on Fig. 3

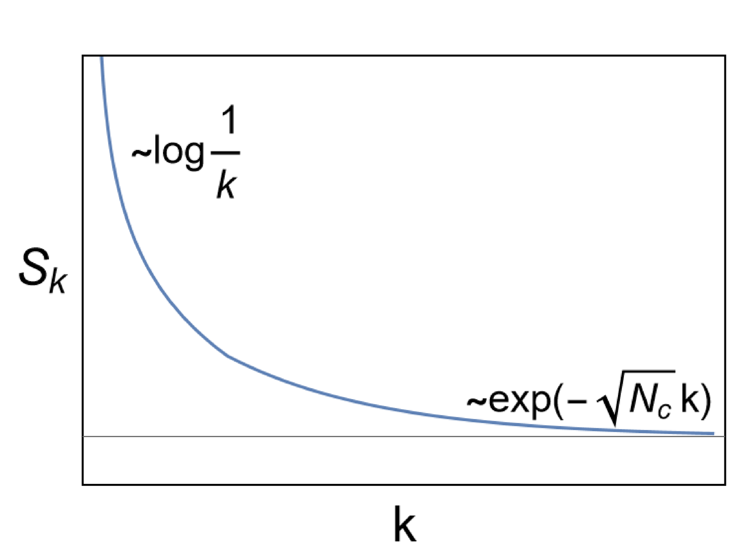


Fig. 3 Entanglement entropy as a function of momentum. Most entanglement is concentrated near zero momentum which corresponds to small x.

- We find entanglement between topological degrees of freedom (carrying the baryon number) and the rest of the baryon wavefunction.
- Entanglement is strongly enhanced at small momentum (fraction).

Proposal: semi-inclusive *ep*-collision tagging a forward baryon

A mature idea: junctions should lead to baryon stopping at heavy ion collisions [1].

Has been tested several times including by STAR with isobars recently: see e.g. the talk by C.Y. Tsang

A new idea: can we study junctions in ep-collisions? Yes!

- Tag a baryon in the virtual photon fragmentation region.
- Junction goes forward along with 2, 1 or 0 valence quarks (as shown on Fig. 4a-6a).
- The rest of the valence quarks break away from the junction producing unobserved mesons.
- The asymptotic s-dependence of the cross-sections estimated using optical theorem and Regge theory:
  $$\sigma\propto s^{\alpha(0)-1}$$
  where $\alpha(0)$ is the intercept of the state exchanged in the t-channel of squared diagram.
- For the states M_4^J, M_2^J, M_0^J (shown on Fig. 4b-6b) the intercepts are estimated as [3]:
  $$\alpha_{2k}^J=2\alpha_B(0)-1+(3-k)(1-\alpha_R(0))$$
  for k=0, 1, 2. $\alpha_B(0)$ and $\alpha_R(0)$ are the baryon and reggeon intercepts respectively.
- M_0^J has the largest intercept so the corresponding process dominates at large s.
- Rapidity dependence estimated (see Fig. 7)

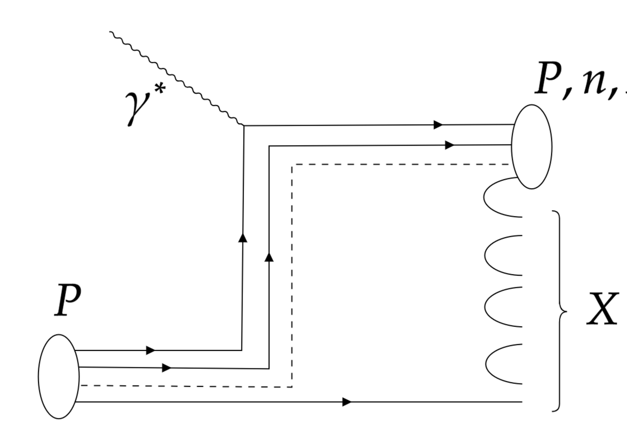


Fig. 4a The junction and two valence quarks in the forward direction. One string breaks producing unobserved X.

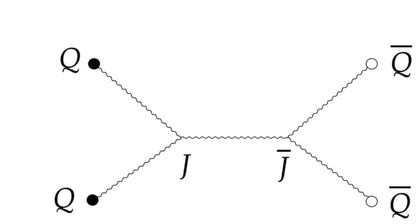


Fig. 4b M_4^J state exchanged in the t-channel of squared amplitude of Fig. 4a.

$$\alpha_4^J\approx-\frac{1}{2}$$

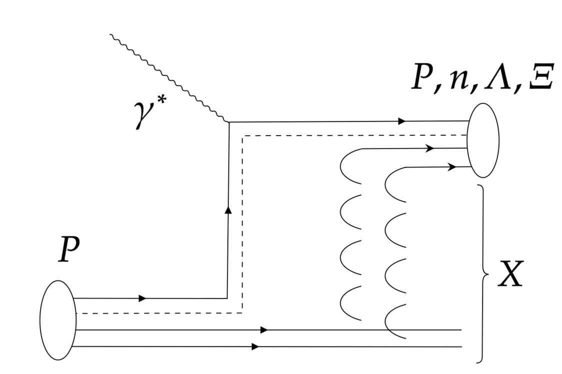


Fig. 5a The junction and one valence quark in the forward direction. Two strings break producing unobserved X.

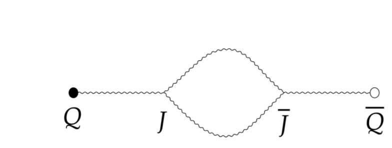


Fig. 5b M_2^J state exchanged in the t-channel of squared amplitude of Fig. 5a.

$$\alpha_2^J\approx 0$$

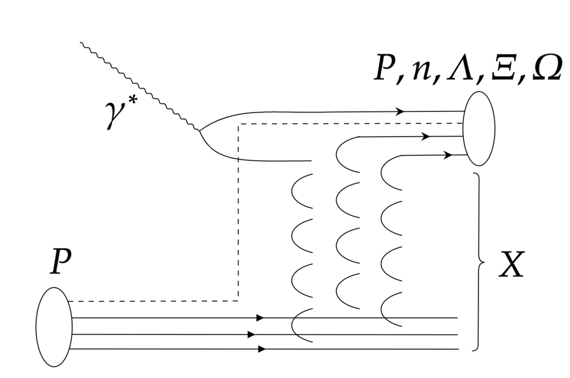


Fig. 6a Only the junction without valence quarks in the forward direction. Three strings break producing unobserved X.

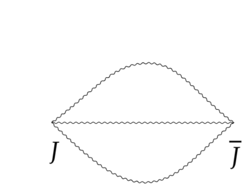


Fig. 6b M_0^J state exchanged in the t-channel of squared amplitude of Fig. 6a.

$$\alpha_0^J\approx\frac{1}{2}$$

- Flavor-independent forward baryon production rate since no valence quarks remain with the junction
- Large flavor-independent meson multiplicity
- Characteristic rapidity dependence (see Figure 7), decreasing in the forward direction slower than naively expected

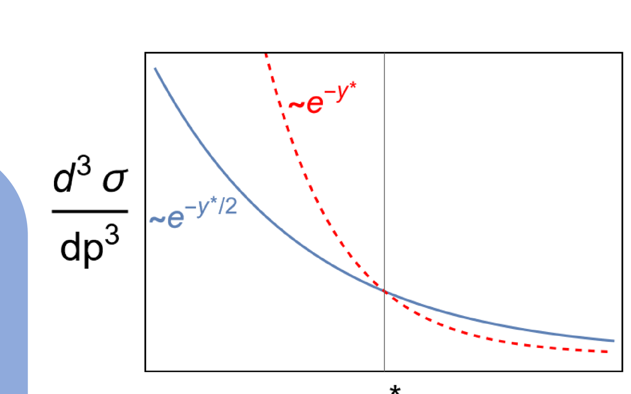


Fig. 7 Differential cross-section as a function of produced baryon COM rapidity y^*. Solid blue line: leading M_0^J exchange. Dashed red: subleading exchange or a naïve expectation with baryon exchange.

Conclusion

Bibliography

[1] D. Kharzeev, Phys. Lett. B 378, 238 (1996)
[2] A. Florio, D. Frenklakh, D. Kharzeev, Phys.Rev.D 106 (2022)
[3] G.C. Rossi, G. Veneziano Nucl.Phys.B 123 (1977)