A light-front AdS/QCD quark-diquark nucleon model in proton-proton and heavy-ion collisions

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Overview

- Light-front AdS/QCD
- The light-front AdS/QCD quark-diquark nucleon model
- Diquark PDFs from light-front holography
- Approach to diquark cross-sections
- Probing the model on proton-proton collisions
- Probing the model on heavy-ion collisions

Three behaviours are possible for $\beta(\mathrm{g})$:

1. $\beta(\mathrm{g}) > 0$: Electromagnetism.
2. $\beta(\mathrm{g}) = 0$: CFTs.
3. $\beta(\mathrm{g}) < 0$: QCD.

It has been pointed out that QCD could have an infrared fixed point, around which it behaves as a CFT [1] leading to the idea of apply the AdS/CFT correspondence conjecture to QCD.

The AdS/CFT correspondence relates inverse coupling regimes, the non-perturbative regime of the Conformal Field Theory corresponds to the small coupling regime of gravity theories on AdS spacetime.

The light-front AdS/QCD quark-diquark nucleon model

The light-front wave functions (LFWF) of bound states in QCD are relativistic generalizations of the Schrödinger wavefunctions at fixed light-cone time $\tau = x^0 + x^3$.

The light-front QCD Hamiltonian equation for a relativistic bound state $|\Psi\rangle$:

$$H_{LF}^{QCD}|\Psi(P)\rangle = P^{\mu}P_{\mu}|\Psi(P)\rangle = M^2|\Psi(P)\rangle. \quad (1)$$

Baryons are described as a composed quark-diquark state. Under a spin-flavor SU(4) symmetry, the possible diquark states for nucleons are:

the isoscalar-scalar diquark singlet state ud_0,
the isoscalar-vector diquark state ud_1,
the isovector-vector diquark state uu_1 (protons) and dd_1 (neutrons).

The proton state can be written as

$$|P;\pm\rangle = C_S|u\,S^0\rangle^{\pm} + C_V|u\,A^0\rangle^{\pm} + C_{VV}|d\,A^1\rangle^{\pm}, \tag{2}$$

S and A represent the scalar and axial-vector diquark. The neutron state is given by the isospin symmetry $u \leftrightarrow d$.

It has been proposed a generalized form to the Hamiltonian eigen-function ϕ_i^{ν} by matching the results in soft-wall AdS/QCD and light-front holography [1, 2] for $\nu = u, d$,

$$\phi_i^{(\nu)}(x, p_\perp) = \frac{4P}{\kappa}\sqrt{\frac{\log(1/x)}{1-x}}\, x^{a_i^{\nu}}(1-x)^{b_i^{\nu}} \exp\left[-\delta^{\nu}\frac{p_\perp^2}{2\kappa^2}\frac{\log(1/x)}{(1-x)^2}\right], \tag{3}$$

where $x = p^+/P^+$ is the longitudinal momentum fraction carried by the struck parton and $p_\perp$ the transverse momentum. κ is a scale parameter from the soft-wall AdS/QCD model.

By using the DGLAP equation, at a scale μ, the expressions for the PDFs are given as[3]

$$f^{(S)}(x,\mu) = N_S^2(\mu)\Big[\frac{1}{\delta^u(\mu)} x^{2a_1^u(\mu)}(1-x)^{2b_1^u(\mu)+1} + x^{2a_2^u(\mu)-2}(1-x)^{2b_2^u(\mu)+3}\frac{\kappa^2}{(\delta^u(\mu))^2 M^2 \ln(1/x)}\Big], \tag{4}$$

$$f^{(A)}(x,\mu) = \Big(\frac{1}{3}N_0^{(\nu)2}(\mu) + \frac{2}{3}N_1^{(\nu)2}(\mu)\Big) \times \Big[\frac{1}{\delta^\nu(\mu)} x^{2a_1^\nu(\mu)}(1-x)^{2b_1^\nu(\mu)+1} + x^{2a_2^\nu(\mu)-2}(1-x)^{2b_2^\nu(\mu)+3}\frac{\kappa^2}{(\delta^\nu(\mu))^2 M^2 \ln(1/x)}\Big]. \tag{5}$$

$N_S = 2.0191,\ N_0^{(u)} = 3.2050,\ N_0^{(d)} = 5.9423,\ N_1^{(u)} = 0.9895,\ N_1^{(d)} = 1.1616$, And $\kappa = 0.4$ GeV (parameters proposed in [3])

$$a_i^\nu(\mu) = a_i^\nu(\mu_0) + A_i^\nu(\mu), \tag{6}$$

$$b_i^\nu(\mu) = b_i^\nu(\mu_0) - B_i^\nu(\mu)\frac{4C_F}{\beta_0}\ln\left(\frac{\alpha_s(\mu^2)}{\alpha_s(\mu_0^2)}\right), \tag{7}$$

$$\delta^\nu(\mu) = \exp\left[\delta_1^\nu\left(\ln(\mu^2/\mu_0^2)\right)^{\delta_2^\nu}\right], \tag{8}$$

where the $a_i^\nu(\mu_0)$ and $b_i^\nu(\mu_0)$ are the parameters at $\mu = \mu_0$.

The scale dependent parts $A_i^\nu(\mu)$ and $B_i^\nu(\mu)$ evolve as

$$P_i^\nu(\mu) = \alpha_{P,i}^\nu \, \mu^{2\beta_{P,i}^\nu} \left[\ln\left(\frac{\mu^2}{\mu_0^2}\right)\right]^{\gamma_{P,i}^\nu} \Bigg|_{i=1,2}, \tag{9}$$

where the subscript P in the right hand side stands for $P = A, B$ corresponding to $P_i^\nu(\mu) = A_i^\nu(\mu), B_i^\nu(\mu)$.

The flavour decomposed PDFs are given as,

$$f^u(x,\mu) = C_S^2 f^{(S)}(x,\mu) + C_V^2 f^{(V)}(x,\mu), \tag{10}$$

$$f^d(x,\mu) = C_{VV}^2 f^{(VV)}(x,\mu). \tag{11}$$

$C_S^2 = 1.3872, C_V^2 = 0.6128, C_{VV}^2 = 1$. So, it is possible to find the evolution parameters by fitting the functions $f^{(S)}$ and $f^{(A)}$ with data of quark PDFs. Then, it is possible to know the PDFs of diquarks. **Here we show our results [4] using data from NNPDF2.3 QCD+QED NNLO**[5].

PDF data

Fitted parameters:

$P_i^\nu(\mu)$	α_i^ν	β_i^ν	γ_i^ν	χ^2/d.o.f
A_1^u	-0.196314 ± 0.002266	-0.197209 ± 0.010210	0.927163 ± 0.036270	0.09
B_1^u	6.4894 ± 0.0459	0.161127 ± 0.006494	-0.910813 ± 0.021850	0.17
A_2^u	-0.441651 ± 0.002674	-0.038950 ± 0.005802	0.306214 ± 0.019020	0.995
B_2^u	2.58149 ± 0.26410	-0.054837 ± 0.078060	-0.80730 ± 0.27790	1.54
A_1^d	-0.119059 ± 0.002517	-0.124819 ± 0.018800	0.95291 ± 0.06010	0.27
B_1^d	12.84810 ± 0.09134	0.097661 ± 0.006134	-0.80035 ± 0.01510	0.53
A_2^d	-0.514816 ± 0.000724	-0.001555 ± 0.001244	0.171831 ± 0.003307	0.41
B_2^d	1.10727 ± 0.00703	0.084447 ± 0.005591	-0.57190 ± 0.01486	0.03

Table 1: PDF evolution parameters with 95% confidence bounds. Using data from NNPDF2.3 QCD+QED NNLO

$\delta^\nu(\mu)$	δ_1^ν	δ_2^ν	χ^2/d.o.f
δ^u	0.35074 ± 0.03009	0.48314 ± 0.06732	10.5
δ^d	0.406762 ± 0.007024	0.46990 ± 0.01275	3.79

Table 2: PDF evolution parameter δ_1^ν and δ_2^ν for $\nu = u, d$. Using data from NNPDF2.3 QCD+QED NNLO

Diquark PDFs

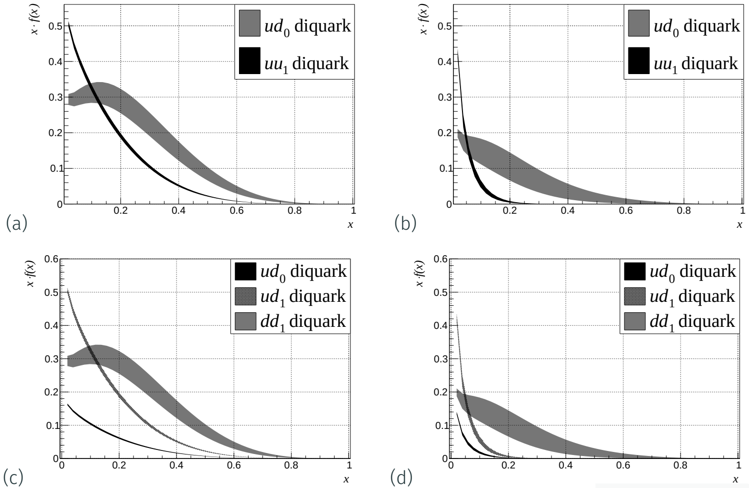


Figure 1: Graphs of $x \cdot f(x)$ at scale energies $\mu^2 = 10$ and 10^4 GeV^2 in protons, (a) and (b), as well as in neutrons, (c) and (d). For protons, gray bands show the case of the isoscalar-scalar diquark and black bands are for the isovector-vector diquark; the isoscalar-vector diquark and isoscalar-scalar have a similar behaviour since $\frac{1}{3}\mathrm{N}_0^{(u)2} + \frac{2}{3}\mathrm{N}_1^{(u)2} \approx \mathrm{N}_\mathrm{S}^2$. In neutrons, black bands are for scalar diquarks, gray bands for isovector-vector diquarks and checkered bands for isoscalar-vector diquarks.

By taking diquarks as anticolor particles, the diquark-gluon, diquark-quark and diquark-diquark differential cross sections are found as

$$\frac{\mathrm{d}\hat{\sigma}}{\mathrm{d}\hat{t}}(\mathrm{dg} \to \mathrm{dg}) = \frac{\pi\alpha_{\mathrm{s}}}{\hat{s}}\left(\frac{(\hat{s}-\hat{u})^2}{2\hat{t}^2} - \frac{7}{18}\right), \tag{12}$$

$$\frac{\mathrm{d}\hat{\sigma}}{\mathrm{d}\hat{t}}(\mathrm{dq} \to \mathrm{dq}) = \frac{\pi\alpha_{\mathrm{s}}}{\hat{s}}\left(-\frac{8\hat{s}\hat{u}}{9\hat{t}^2}\right), \tag{13}$$

$$\frac{\mathrm{d}\hat{\sigma}}{\mathrm{d}\hat{t}}(\mathrm{dd} \to \mathrm{dd}) = \frac{\pi\alpha_{\mathrm{s}}}{\hat{s}}\frac{2}{9}\left(\frac{(\hat{s}-\hat{u})^2}{\hat{t}^2} + \frac{(\hat{s}-\hat{t})^2}{\hat{u}^2} - \frac{2}{3}\left(1 + \frac{2\hat{s^2}}{\hat{u}\hat{t}}\right)\right). \tag{14}$$

And diquark form factors approached to the pion form factor as the general form

$$\mathrm{F}(\mu^2) = \frac{1}{1 + \frac{\mu^2}{\mathrm{M}^2}}, \tag{15}$$

where M is known as *scale form factor*.

Thus, it is possible to assemble the light-front AdS/QCD quark-diquark nucleon model to be used in simulations of nucleon collisions. We implemented such a model to the HardQCD processes in the PYTHIA8303 simulation package to take advantage of the hadronization processes existing in it[1].

[1] Details on paper.

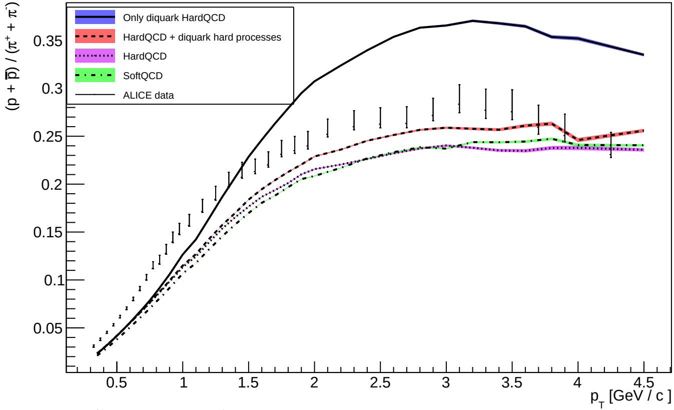
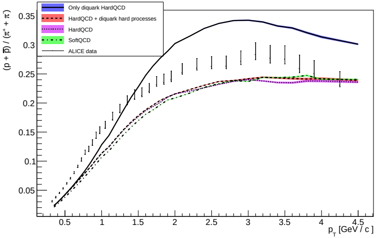
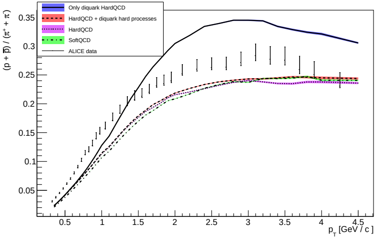


Figure 2: Comparison of the ratio proton-to-pion in dependence of the transverse momentum p_T between experimental data from Alice experiment [6] and different models performed in PYTHIA at $\sqrt{s} = 13$ TeV. In green bands are shown results using SoftQCD and in violet bands is shown the case using the usual HardQCD (quark+gluon hard processes) of PYTHIA. Red bands represent our results of hard processes of HardQCD including diquarks, while blue bands show hard processes only of diquarks. Diquark cross sections are approached as point-like anticolour particles times a form-factor.

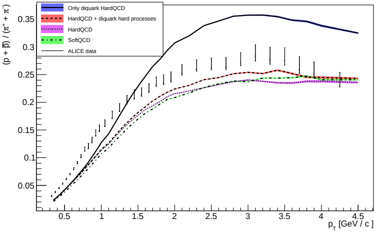
Proton-proton collisions at $\sqrt{s} = 13$ TeV, $M^2 = 3.22$, 5 and 12 GeV^2



(a)



(b)



(c)

Figure 3: Comparison of production of the ratio proton-to-pion with experimental data and different models for $M^2 = 3.22, 5$ and 12 GeV^2 for diquark form factors in (a), (b) and (c) respectively. The rations are in function of transverse momentum measured in pp collisions at $\sqrt{s} = 13$ TeV in the region $0 \lesssim p_T \leq 4.5$ GeV.

HeAu a $\sqrt{s} = 200$ GeV and $M^2 = 20$ GeV^2

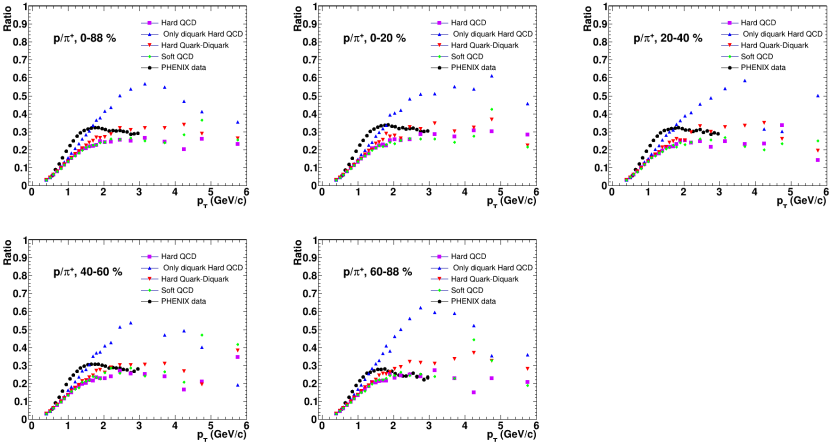


Figure 4: Comparison of results of the ratio p/P^{+} from simulations with experimental data at several centralities.

Summary

- The light-front holography provides a way to calculate some properties of nucleon structure. In particular, by introducing diquark correlations in the nucleon valence, it is possible to find the PDFs of quarks and diquarks.
- The isospin symmetry leads to an equivalency between the PDFs of isoscalar-vector diquarks in protons and isovector-vectors in neutrons (and vice versa).
- Diquark hard processes may explain some properties of scale symmetry breaking on protons over pions in the region $1 \lesssim p_T \lesssim 4$ GeV/c in hadron collisions and diquark PDFs found after light-front holography can fine-tune the accuracy of the simulations.

References

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