Fock States in AdS / QCD models to describe Nucleons

Alfredo Vega

In collaboration with
I. Schmidt, T. Gutsche and V. Lyubovitskij

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- Within the phenomenological models used recently in hadronic physics, some are based on the gauge/gravity duality.
- They suppose the existence of a gravity theory dual to QCD, and are divided into two classes: the Top-Down approach and the Bottom-Up models.
- The Bottom-Up models have proven to be quite useful because they are simple, and they have been used in different examples.

QCD

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AdS / QCD

⋆ **Dictionary.**

In our model for nucleons, 5d Dirac fields with different dimensions are duals to different Fock components with specific number of partons in nucleons.

◇ **Brief (and incomplete) list of uses of Bottom - Up models in hadron physics.**

- **DIS at high x** [Polchinski and Strassler; Ballon - Ballona, Boschi and Braga; Braga and A. V].
- **DIS at low x** [Brower, Polchinski, Strassler and Tan; Watanabe and Suzuki].
- **GPSs** [A.V, Schmidt, Gutsche and Lyubovitskij].
- **Hadronic wave functions** [Brodsky and de Teramond; Gutsche, Lyubovitskij, Schmidt and A.V].
- **Hadronic spectrum** [Brodsky and de Teramond; A.V and Schmidt; Gutsche, Lyubovitskij, Schmidt and A.V; Braga and Boschi; Forkel, Beyer and Frederico].
- **Transition form factors** [Brodsky, Cao and de Teramond; Gutsche, Lyubovitskij, Schmidt and A.V].

AdS / QCD Models with several Fock States [1]

[1] Thomas Gutsche, Valery E. Lyubovitskij, Ivan Schmidt y A. V, Phys. Rev. D86 (2012) 036007; Phys. Rev. D **87**, 016017 (2013).

The basic ingredients are

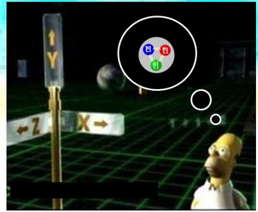
$$S = \int d^{d+1}x \sqrt{g}\, e^{-\Phi(z)} \left(\mathcal{L}_{\psi} + \mathcal{L}_{V} + \mathcal{L}_{int} \right),$$

where

$$ds^2 = \frac{1}{z^2}\left(\eta_{\mu\nu} dx^{\mu} dx^{\nu} - dz^2\right),$$

⋆ Hard Wall case: $\Phi(z) = Cte$ y z between 0 and z_0.

⋆ Soft Wall case: $\Phi(z) = \kappa^2 z^2$ and z between 0 and ∞.



To include several Fock states we consider

$$S_\psi = \sum_\tau c_\tau S_\tau,$$

where c_τ are a set of parameters.

If we integrate over z and we consider normalizations conditions for $f^{L/R}$

$$S = \int dx^4 \bar{\psi}_n(x)[\sum_\tau c_\tau i \not\partial - \sum_\tau c_\tau M_{n\tau}]\psi_n(x),$$

then

$$\sum_\tau c_\tau = 1 \quad , \quad \sum_\tau c_\tau M_{n\tau} = M_n,$$

NOTE: We consider $\tau = 3\ (3q),\ 4\ (3q+g)$ *and* $5\ (3q+q\bar{q}$ *or* $3q+2g)$.

And Form Factors are generated by interaction terms in action.

$$S^V_{int} = \int d^4x dz \sqrt{g} e^{-\phi(z)} \mathcal{L}^V_{int}(x,z).$$

◇ **Mass Spectrum.**

$$M_n = \sum_\tau c_\tau M_{n\tau} \quad \rightarrow \quad M_n = 2\kappa \sum_\tau c_\tau \sqrt{n+\tau-1}$$

◇ **Electromagnetic Form Factors.**

Expressions for Dirac and Pauli Form Factors are given by

$$F_1^p(Q^2) = C_1(Q^2) + g_V C_2(Q^2) + \eta_V^p C_3(Q^2). \quad F_2^p(Q^2) = \eta_V^p C_4(Q^2).$$

$$F_1^n(Q^2) = -g_V C_2(Q^2) + \eta_V^n C_3(Q^2). \quad F_2^n(Q^2) = \eta_V^n C_4(Q^2).$$

where

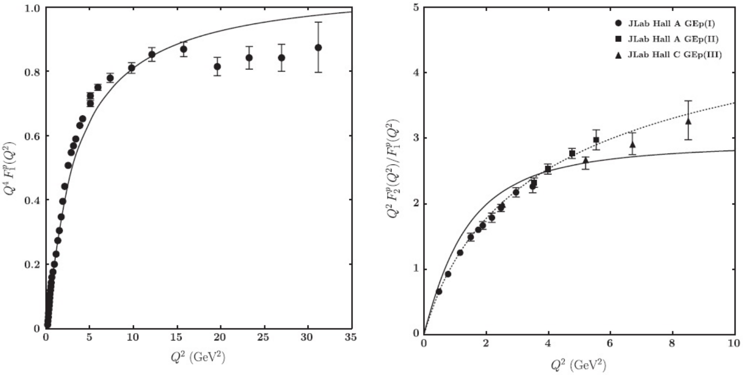
$$C_1(Q^2) = \frac{1}{2} \int_0^\infty dz \ V(Q,z) \sum_\tau c_\tau ([f_\tau^L(z)]^2 + [f_\tau^R(z)]^2).$$

$$C_2(Q^2) = \frac{1}{2} \int_0^\infty dz \ V(Q,z) \sum_\tau c_\tau ([f_\tau^R(z)]^2 - [f_\tau^L(z)]^2).$$

$$C_3(Q^2) = \frac{1}{2} \int_0^\infty dz \ z(\partial_z V(Q,z)) \sum_\tau c_\tau ([f_\tau^L(z)]^2 - [f_\tau^R(z)]^2).$$

$$C_4(Q^2) = 2m_N \int_0^\infty dz \ zV(Q,z) \sum_\tau c_\tau f_\tau^L(z) f_\tau^R(z).$$

AdS / QCD Models with several Fock States



Light Front Wave Functions

◇ **Basic Idea.** [2]

Comparison of Form Factors in light front and in AdS side, offer us a possibility to relate AdS modes that describe hadrons with LFWF.

- In Light Front (for hadrons with two partons),

$$F(q^2) = 2\pi \int_0^1 dx \frac{(1-x)}{x} \int d\zeta \; \zeta J_0(\zeta q \sqrt{\tfrac{1-x}{x}}) \frac{|\widetilde{\psi}(x,\zeta)|^2}{(1-x)^2}.$$

- In AdS

$$F(q^2) = \int_0^\infty dz \; \Phi(z) J(q^2, z) \Phi(z),$$

where $\Phi(z)$ correspond to AdS modes that represent hadrons, $J(q^2, z)$ it is dual to electromagnetic current.

[2] S. J. Brodsky and G. F. de Teramond, Phys. Rev. Lett. **96**, 201601 (2006); Phys. Rev. D **77**, 056007 (2008).

Light Front Wave Functions

Considering a soft wall model with a cuadratic dilaton, Brodsky and de Teramond found [3]

$$\psi(x, \mathbf{b}_\perp) = A\sqrt{x(1-x)}\; e^{-\frac{1}{2}\kappa^2 x(1-x)\mathbf{b}_\perp^2},$$

and in momentum space

$$\psi(x, \mathbf{k}_\perp) = \frac{4\pi A}{\kappa\sqrt{x(1-x)}}\exp\left(-\frac{\mathbf{k}_\perp^2}{2\kappa_1^2 x(1-x)}\right).$$

[3] S. J. Brodsky and G. F. de Teramond, Phys. Rev. Lett. **96**, 201601 (2006); Phys. Rev. D **77**, 056007 (2008).

A generalizations of LFWF discused in previous section looks like

$$\psi(x, \mathbf{k}_\perp) = N \frac{4\pi}{\kappa\sqrt{x(1-x)}} g_1(x) \exp\left(-\frac{\mathbf{k}_\perp^2}{2\kappa_1^2 x(1-x)} g_2(x)\right).$$

You can found some examples in

- S. J. Brodsky and G. F. de Teramond, arXiv:0802.0514 [hep-ph].
- A. V, I. Schmidt, T. Branz, T. Gutsche and V. E. Lyubovitskij, PRD 80, 055014 (2009).
- S. J. Brodsky, F. G. Cao and G. F. de Teramond, PRD 84, 075012 (2011).
- J. Forshaw and R. Sandapen, PRL 109, 081601 (2012).
- S. Chabysheva and J. Hiller, Annals of Physics 337 (2013) 143 - 152.
- T. Gutsche, V. Lyubovitskij, I. Schmidt and A. V, PRD 87, 056001 (2013).

Recently we have suggested a LFWF at the initial scale μ_0 for hadrons with arbitrary number of constituents that looks like [4]

$$\psi_\tau(x,\mathbf{k}_\perp) = N_\tau \frac{4\pi}{\kappa}\sqrt{log(1/x)}(1-x)^{(\tau-4)/2} Exp\left[-\frac{\mathbf{k}_\perp^2}{2\kappa^2}\frac{log(1/x)}{(1-x)^2}\right]$$

The PDFs $q_\tau(x)$ and GPDs $H_\tau(x,Q^2)$ in terms of the LFWFs at the initial scale can be calculated.

Next we extend our LFWF to an arbitrary scale

$$\psi_\tau(x,\mathbf{k}_\perp,\mu) = N_\tau(\mu)\frac{4\pi}{\kappa}\sqrt{log(1/x)}x^{a_1(\tau,\mu)}(1-x)^{b_1(\tau,\mu)}$$

$$\times(1+c_1(\tau,\mu)\sqrt{x}+c_2(\tau,\mu)x)^{1/2} Exp\left[-\frac{\mathbf{k}_\perp}{2\kappa^2}\frac{log(1/x)}{x^{a_2(\tau,\mu)}(1-x)^{b_2(\tau,\mu)}}\right],$$

[4] Thomas Gutsche, Valery E. Lyubovitskij, Ivan Schmidt y A. V, Phys. Rev. D89 (2014) 054033.

Light Front Wave Functions

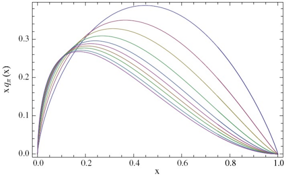


Figure: Hard evolution of the pion PDF for $\mu =$ 1,2,4,10,25,50,100,200,500 and 1000 *GeV*.

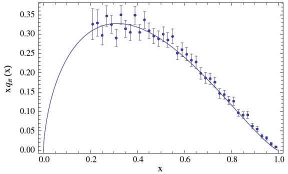


Figure: Comparison of the evolved pion PDF at the scale $\mu = 4$ *GeV* in our approach to the analysis of the E615 experiment.

Conclusions

- It is possible to use Gauge / Gravity ideas to study hadrons properties using a Fock expansion for hadrons.
- You can use soft wall models as in (Phys. Rev. D86 (2012) 036007) and (Phys. Rev. D **87**, 016017 (2013)) where some properties are calculated in de AdS side.
- Currently we have considered this model in the nucleonic sector to study electromagnetic form factors and some transition form factors, and we plan to extend the model to describe mesons and to study another hadronic properties.
- For other side we believe that it is possible to use the LFWF inspired by holography in a complementary way with models based in QCD that consider Fock expansions in hadrons.

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That's all Folks!