Some Hadronic Properties with Light Front Holography

Alfredo Vega

Departamento de Física
y
Centro Científico Tecnológico de Valparaíso (CCTVal)
UTFSM

Work done in collaboration with
I. Schmidt, T. Gutsche,
T. Branz and V. Lyubovitskij
Outline

Introduction

Mesonic Phenomenology.

Generalized Parton Distributions in a Holographical Model

Conclusions
Introduction
Applicability to QCD.

- \( N=4 \) SYM is different to QCD, but we can argue that in some situations both are closer. Ej: Heavy Ion Collisions.
- Gauge / Gravity ideas can be expanded in several directions. This give us a possibility to get a field theory similar to QCD with gravity dual.
- You can use Gauge / Gravity as a nice frame to built phenomenological models with extra dimensions that reproduce some QCD facts.
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Extensions of AdS / CFT to QCD, are related at two approaches:

- **Top - Down approach.**
  You start from a string theory on $AdS_{d+1} \times C$, and try to get at low energies a theory similar to QCD in the border.

- **Bottom - Up approach.**
  Starting from QCD in 4d we try to build a theory with higher dimensions (not necessarily a string theory).
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**Dictionary.**

This tells us how are related elements involved in both sides of Gauge / Gravity duality.

<table>
<thead>
<tr>
<th>QCD (4d)</th>
<th>Gravity (5d)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operator ($O$)</td>
<td>Normalizable Modes ($\Phi$)</td>
</tr>
<tr>
<td>Hadron Mass ($M$)</td>
<td>Eigenvalues of $\Phi$</td>
</tr>
<tr>
<td>Twist Dimension ($[O] - S$)</td>
<td>Conformal Dimension ($\Delta$)</td>
</tr>
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Table: Summary of dictionary considered here.

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</tr>
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</tbody>
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Introduction

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</tr>
</tbody>
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Mesonic Phenomenology. ²

Mesonic Phenomenology.

Light Front: \[ F(q^2) = 2\pi \int_0^1 dx \frac{(1-x)}{x} \int d\zeta \zeta J_0(\zeta q \sqrt{\frac{1-x}{x}}) \left| \psi_{q_1 \bar{q}_2} \right|^2 \frac{1}{(1-x)^2}, \]

AdS: \[ F(q^2) = \int_0^\infty dz \Phi(z) J(q^2, z) \Phi(z), \]

where \( \Phi(z) \) correspond to modes that represent hadrons and \( J(q^2, z) \) represent electromagnetic current.

Notice that if we consider \( z = \zeta \), and if we can write \( J(q^2, z) \) as

\[ J(q^2, \zeta) = \int_0^1 dx f(x) J_0(\zeta q \sqrt{\frac{1-x}{x}}), \]

Relationship between Mesonic Wave Function and AdS Modes.

\[ |\psi(x, \zeta)|^2 = A \frac{1}{\zeta} x (1-x) f(x)|\Phi(\zeta)|^2, \]
**Dual modes to Mesons.**

\[ S_\Phi = \left(\frac{-1}{2}\right)^J \int d^d x dz \sqrt{g} e^{-\phi(z)} \left( \partial_N \phi_J \partial^N \phi_J - \mu_J^2(z) \phi_J \phi_J \right), \]

\[ ds^2 = \left(\frac{R}{z}\right)^2 (\eta_{\mu\nu} dx^\mu dx^\nu - dz^2) \quad \text{and} \quad \phi(z) = \kappa^2 z^2 \]

\[ \left[ - \frac{d^2}{dz^2} + U_J(z) \right] \Phi_nJ(z) = M_{nJ}^2 \Phi_nJ(z) \]

where \( U_J(z) \) is an effective potential given by

\[ U_J(z) = \kappa^4 z^2 + \frac{4a_J^2 - 1}{4z^2} + 2\kappa^2 \left( b_J - 1 \right) \]

\[ a_J = \frac{1}{2} \sqrt{(d - 2J)^2 + 4(\mu_J R)^2}, \quad b_J = \frac{1}{2} \left( g_J R^2 + d - 2J \right) \quad \text{and} \quad g_J R^2 = 4(J - 1) \]

Wave Function in momentum space

\[ \psi_{q_1 \bar{q}_2}(x, k) = \frac{4\pi A}{\kappa \sqrt{x(1-x)}} \exp \left( - \frac{k^2}{2\kappa^2_1 x(1-x)} \right). \]
Model Extension.

- Introduction of massive quarks:

\[
\frac{k^2}{x(1-x)} \rightarrow K = \frac{k^2}{x(1-x)} + m_{12}^2, \quad m_{12}^2 = \frac{m_1^2}{x} + \frac{m_2^2}{1-x}.
\]

Equivalent to the following change of the kinetic term in the Schrödinger EOM:

\[
-\frac{d^2}{d\zeta^2} \rightarrow -\frac{d^2}{d\zeta^2} + m_{12}^2.
\]

Wave Function in momentum space

\[
\psi_{q_1 \bar{q}_2}(x, k) = \frac{4\pi}{\kappa \sqrt{x(1-x)}} f(x, m_1, m_2) \exp\left(-\frac{k^2}{2\kappa_1^2 x(1-x)}\right). \quad \text{with} \quad f(x, m_1, m_2) = A f(x) e^{-\frac{m_{12}^2}{2\lambda^2}}
\]

- Extending the effective potential \( U \rightarrow U + U_C + U_{HF} \), where \( U_C \) and \( U_{HF} \) are the contributions of the color Coulomb and hyperfine (HF) potentials.

\[
M_{nJ}^2 = 4\kappa^2 \left( n + \frac{L+J}{2} \right) + \int_0^1 dx \left( \frac{m_1^2}{x} + \frac{m_2^2}{1-x} \right) f^2(x, m_1, m_2) - \frac{64\alpha_s^2 m_1 m_2}{9(n+L+1)^2} + \frac{32\pi\alpha_s}{9} \frac{\beta_S \nu}{\mu_{12}}.
\]
Choice of parameters.

- Constituent quark masses:
  \[ m = 420\,\text{MeV}, \quad m_s = 570\,\text{MeV}, \quad m_c = 1.6\,\text{GeV}, \quad m_b = 4.8\,\text{GeV} \]
- Dilaton Parameter: \( \kappa = 550\,\text{MeV} \)
- Hiperfine Parameter: \( \nu = 10^{-4}\,\text{GeV}^3 \)
- Constant Coupling with IR freezing.

\[
\alpha_s(\mu^2) = \frac{12\pi}{33 - 2N_f} \frac{1}{\ln\left(\frac{\mu^2 + M_B^2}{\Lambda^2}\right)}
\]

With \( M_B = 854\,\text{MeV} \) and \( \Lambda = 420\,\text{MeV} \).

- \( \lambda_{qq} = 0.63\,\text{GeV} \), \( \lambda_{qs} = 1.20\,\text{GeV} \), \( \lambda_{ss} = 1.68\,\text{GeV} \),
  \( \lambda_{qc} = 2.50\,\text{GeV} \), \( \lambda_{sc} = 3.00\,\text{GeV} \), \( \lambda_{qb} = 3.89\,\text{GeV} \),
  \( \lambda_{sb} = 4.18\,\text{GeV} \), \( \lambda_{cc} = 4.04\,\text{GeV} \), \( \lambda_{cb} = 4.82\,\text{GeV} \), \( \lambda_{bb} = 6.77\,\text{GeV} \).
Results.

<table>
<thead>
<tr>
<th>Meson</th>
<th>$n$</th>
<th>$L$</th>
<th>$S$</th>
<th>Mass [MeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\pi$</td>
<td>0</td>
<td>0,1,2,3</td>
<td>0</td>
<td>140</td>
</tr>
<tr>
<td>$\pi$</td>
<td>0,1,2,3</td>
<td>0</td>
<td>0</td>
<td>140</td>
</tr>
<tr>
<td>$K$</td>
<td>0</td>
<td>0,1,2,3</td>
<td>0</td>
<td>496</td>
</tr>
<tr>
<td>$\eta$</td>
<td>0,1,2,3</td>
<td>0</td>
<td>0</td>
<td>544</td>
</tr>
<tr>
<td>$f_0[\bar{n}n]$</td>
<td>0,1,2,3</td>
<td>1</td>
<td>1</td>
<td>1114</td>
</tr>
<tr>
<td>$f_0[\bar{s}s]$</td>
<td>0,1,2,3</td>
<td>1</td>
<td>1</td>
<td>1304</td>
</tr>
<tr>
<td>$a_0(980)$</td>
<td>0,1,2,3</td>
<td>1</td>
<td>1</td>
<td>1114</td>
</tr>
<tr>
<td>$\rho(770)$</td>
<td>0,1,2,3</td>
<td>0</td>
<td>1</td>
<td>804</td>
</tr>
<tr>
<td>$\rho(770)$</td>
<td>0</td>
<td>0,1,2,3</td>
<td>1</td>
<td>804</td>
</tr>
<tr>
<td>$\omega(782)$</td>
<td>0,1,2,3</td>
<td>0</td>
<td>1</td>
<td>804</td>
</tr>
<tr>
<td>$\omega(782)$</td>
<td>0</td>
<td>0,1,2,3</td>
<td>1</td>
<td>804</td>
</tr>
<tr>
<td>$\phi(1020)$</td>
<td>0,1,2,3</td>
<td>0</td>
<td>1</td>
<td>1019</td>
</tr>
<tr>
<td>$a_1(1260)$</td>
<td>0,1,2,3</td>
<td>1</td>
<td>1</td>
<td>1358</td>
</tr>
</tbody>
</table>
### Mesons Phenomenology

#### Masses of Heavy-Light Mesons

<table>
<thead>
<tr>
<th>Meson</th>
<th>$J^P$</th>
<th>$n$</th>
<th>$L$</th>
<th>$S$</th>
<th>Mass [MeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D(1870)$</td>
<td>0$^-$</td>
<td>0</td>
<td>0,1,2,3</td>
<td>0</td>
<td>1857</td>
</tr>
<tr>
<td>$D^*(2010)$</td>
<td>1$^-$</td>
<td>0</td>
<td>0,1,2,3</td>
<td>1</td>
<td>2015</td>
</tr>
<tr>
<td>$D_s(1969)$</td>
<td>0$^-$</td>
<td>0</td>
<td>0,1,2,3</td>
<td>0</td>
<td>1963</td>
</tr>
<tr>
<td>$D_s^*(2107)$</td>
<td>1$^-$</td>
<td>0</td>
<td>0,1,2,3</td>
<td>1</td>
<td>2113</td>
</tr>
<tr>
<td>$B(5279)$</td>
<td>0$^-$</td>
<td>0</td>
<td>0,1,2,3</td>
<td>0</td>
<td>5279</td>
</tr>
<tr>
<td>$B^*(5325)$</td>
<td>1$^-$</td>
<td>0</td>
<td>0,1,2,3</td>
<td>1</td>
<td>5336</td>
</tr>
<tr>
<td>$B_s(5366)$</td>
<td>0$^-$</td>
<td>0</td>
<td>0,1,2,3</td>
<td>0</td>
<td>5360</td>
</tr>
<tr>
<td>$B_s^*(5413)$</td>
<td>1$^-$</td>
<td>0</td>
<td>0,1,2,3</td>
<td>1</td>
<td>5416</td>
</tr>
</tbody>
</table>
### Masses of heavy quarkonia $c\bar{c}$, $b\bar{b}$ and $c\bar{b}$

<table>
<thead>
<tr>
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<th>$J^P$</th>
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<th>$L$</th>
<th>$S$</th>
<th>Mass [MeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\eta_c(2986)$</td>
<td>$0^-$</td>
<td>0,1,2,3</td>
<td>0</td>
<td>0</td>
<td>2997</td>
</tr>
<tr>
<td>$\psi(3097)$</td>
<td>$1^-$</td>
<td>0,1,2,3</td>
<td>0</td>
<td>1</td>
<td>3097</td>
</tr>
<tr>
<td>$\chi_{c0}(3414)$</td>
<td>$0^+$</td>
<td>0,1,2,3</td>
<td>1</td>
<td>1</td>
<td>3635</td>
</tr>
<tr>
<td>$\chi_{c1}(3510)$</td>
<td>$1^+$</td>
<td>0,1,2,3</td>
<td>1</td>
<td>1</td>
<td>3718</td>
</tr>
<tr>
<td>$\chi_{c2}(3555)$</td>
<td>$2^+$</td>
<td>0,1,2,3</td>
<td>1</td>
<td>1</td>
<td>3798</td>
</tr>
<tr>
<td>$\eta_b(9300)$</td>
<td>$0^-$</td>
<td>0,1,2,3</td>
<td>0</td>
<td>0</td>
<td>9428</td>
</tr>
<tr>
<td>$\Upsilon(9460)$</td>
<td>$1^-$</td>
<td>0,1,2,3</td>
<td>0</td>
<td>1</td>
<td>9460</td>
</tr>
<tr>
<td>$\chi_{b0}(9860)$</td>
<td>$0^+$</td>
<td>0,1,2,3</td>
<td>1</td>
<td>1</td>
<td>10160</td>
</tr>
<tr>
<td>$\chi_{b1}(9893)$</td>
<td>$1^+$</td>
<td>0,1,2,3</td>
<td>1</td>
<td>1</td>
<td>10190</td>
</tr>
<tr>
<td>$\chi_{b2}(9912)$</td>
<td>$2^+$</td>
<td>0,1,2,3</td>
<td>1</td>
<td>1</td>
<td>10219</td>
</tr>
<tr>
<td>$B_c(6276)$</td>
<td>$0^-$</td>
<td>0,1,2,3</td>
<td>0</td>
<td>0</td>
<td>6276</td>
</tr>
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</table>
### Decay constants $f_P$ (MeV) of pseudoscalar mesons

<table>
<thead>
<tr>
<th>Meson</th>
<th>Data</th>
<th>Our</th>
</tr>
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<tbody>
<tr>
<td>$\pi^-$</td>
<td>130.4 ± 0.03 ± 0.2</td>
<td>131</td>
</tr>
<tr>
<td>$K^-$</td>
<td>156.1 ± 0.2 ± 0.8</td>
<td>155</td>
</tr>
<tr>
<td>$D^+$</td>
<td>206.7 ± 8.9</td>
<td>167</td>
</tr>
<tr>
<td>$D_s^+$</td>
<td>257.5 ± 6.1</td>
<td>170</td>
</tr>
<tr>
<td>$B^-$</td>
<td>193 ± 11</td>
<td>139</td>
</tr>
<tr>
<td>$B_s^0$</td>
<td>253 ± 8 ± 7</td>
<td>144</td>
</tr>
<tr>
<td>$B_c$</td>
<td>489 ± 5 ± 3</td>
<td>159</td>
</tr>
</tbody>
</table>

### Decay constants $f_V$ (MeV) of vector mesons with open and hidden flavor

<table>
<thead>
<tr>
<th>Meson</th>
<th>Data</th>
<th>Our</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\rho^+$</td>
<td>210.5 ± 0.6</td>
<td>170</td>
</tr>
<tr>
<td>$D^*$</td>
<td>245 ± 20$^{+3}_{-2}$</td>
<td>167</td>
</tr>
<tr>
<td>$D_s^*$</td>
<td>272 ± 16$^{+3}_{-20}$</td>
<td>170</td>
</tr>
<tr>
<td>$B^*$</td>
<td>196 ± 24$^{+39}_{-2}$</td>
<td>139</td>
</tr>
<tr>
<td>$B_s^*$</td>
<td>229 ± 20$^{+41}_{-16}$</td>
<td>144</td>
</tr>
</tbody>
</table>

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</tr>
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<tbody>
<tr>
<td>$\rho^0$</td>
<td>154.7 ± 0.7</td>
<td>120</td>
</tr>
<tr>
<td>$\omega$</td>
<td>45.8 ± 0.8</td>
<td>40</td>
</tr>
<tr>
<td>$\phi$</td>
<td>76 ± 1.2</td>
<td>66</td>
</tr>
<tr>
<td>$J/\psi$</td>
<td>277.6 ± 4</td>
<td>116</td>
</tr>
<tr>
<td>$\Upsilon(1s)$</td>
<td>238.5 ± 5.5</td>
<td>56</td>
</tr>
</tbody>
</table>
Generalized Parton Distributions in a Holographical Model

Generalized Parton Distributions in a Holographical Model

◊ General Ideas.

★ Electromagnetic form factors and GPDs.

\[ F^p_1(t) = \int_0^1 dx \left( \frac{2}{3} H^u_v(x, t) - \frac{1}{3} H^d_v(x, t) \right) \]

\[ F^n_1(t) = \int_0^1 dx \left( \frac{2}{3} H^d_v(x, t) - \frac{1}{3} H^u_v(x, t) \right) \]

\[ F^p_2(t) = \int_0^1 dx \left( \frac{2}{3} E^u_v(x, t) - \frac{1}{3} E^d_v(x, t) \right) \]

\[ F^n_2(t) = \int_0^1 dx \left( \frac{2}{3} E^d_v(x, t) - \frac{1}{3} E^u_v(x, t) \right) \]

★ Form Factors in AdS / QCD.


\[ F^p_1(t) = C_1(Q^2) + \eta_p C_2(Q^2) , \ F^n_1(t) = \eta_p C_3(Q^2) \]

\[ F^p_2(t) = \eta_n C_2(Q^2) \text{ and } F^n_2(t) = \eta_n C_3(Q^2) \]

where

\[ C_1(Q^2) = \int dze^{-\Phi}(V(Q, z)/2z^3)(\psi^2_L(z) + \psi^2_R(z)) \]

\[ C_2(Q^2) = \int dze^{-\Phi}(V(Q, z)/2z^2)(\psi^2_L(z) - \psi^2_R(z)) \]

\[ C_3(Q^2) = \int dze^{-\Phi}(2m_N V(Q, z)/2z^3)(\psi^2_L(z)\psi^2_R(z)) \]

\[ V(Q, z) = \Gamma \left(1 + \frac{Q^2}{4\kappa^2} \right) U \left(\frac{Q^2}{4\kappa^2}, 0, \kappa^2 z^2 \right) = \kappa^2 z^2 \int_0^1 \frac{dx}{(1-x)^2} \frac{Q^2}{4\kappa^2} e^{-\kappa^2 z^2 x} \]
**Summary of Results**

The GPDs obtained look like.

\[
H^q_v(x, Q^2) = q(x)x^a \quad \text{and} \quad E^q_v(x, Q^2) = e(x)x^a,
\]

where

\[
a = \frac{Q^2}{4\kappa^2}; \quad q(x) = \alpha^q \gamma_1 + \beta^q \gamma_2; \quad e(x) = \beta^q \gamma_3,
\]

and

\[
\alpha^u = 2, \quad \alpha^d = 1, \quad \beta^u = 2\eta_p + \eta_n, \quad \beta^d = \eta_p + 2\eta_n
\]

\[
\gamma_1 = \frac{1}{2}(5 + 8x + 3x^2) \quad \gamma_1 = 1 - 10x + 21x^2 - 12x^3 \quad \gamma_1 = \frac{6m_N\sqrt{2}}{\kappa}(1 - x)^2
\]

**Parameters involved.**

\[
\kappa = 350\text{MeV}, \quad \eta_p = 0.224, \quad \eta_n = -0.239
\]

fixed to reproduce nucleon mass and anomalous magnetic moment of the nucleon.
Generalized Parton Distributions in a Holographical Model

◊ Nucleon GPDs Plots.
Generalized Parton Distributions in a Holographical Model

◇ **Nucleon GPDs in impact space.**

\[ q(x, b_\perp) = \int \frac{d^2 k_\perp}{(2\pi)^2} H_q(x, k_\perp^2) e^{-ib_\perp k_\perp} \quad \text{and} \quad e^q(x, b_\perp) = \int \frac{d^2 k_\perp}{(2\pi)^2} E_q(x, k_\perp^2) e^{-ib_\perp k_\perp} \]

Figure: Plots for \( q(x, b) \). The upper panels correspond to \( u(x, b) \) and the lower to \( d(x, b) \). Both cases are taken for \( x = 0.1 \).
Generalized Parton Distributions in a Holographical Model

● Parton charge and magnetization densities in transverse impact space.

\[ \rho_E^N(b_\perp) = \sum q \int_0^1 dx \ q(x, b_\perp) \quad \text{and} \quad \rho_M^N(b_\perp) = \sum q \int_0^1 dx \ e^q(x, b_\perp) \]
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- In a phenomenological way we extended Brodsky and de Teramonds ideas to map AdS modes with mesonic wave functions with massive quarks, considering additional potentials.
- These ingredients let us describe several mesons.
- For other side we determined the nucleon GPDs using a similar procedure used in some applications of light front holography.
- The nucleon GPDs obtained have an exponential form, as in several phenomenological approaches.
- As in hadronic physics the mesonic wave function and GPDs are very important, we can see that Gauge / Gravity can be considered as a useful tool in some QCD applications.
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That’s all Folks !