Hadrons and Multiquark States in Holographic QCD

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We discuss hadrons and multiquark states in holographic QCD. This approach is based on an action which describes hadron structure with broken conformal and chiral invariance and incorporates confinement through the presence of a background dilaton field. According to the gauge/gravity duality the five-dimensional boson and fermion fields propagating in AdS space are dual to four-dimensional fields leaving on the surface of AdS sphere, which correspond to hadrons. In this picture hadronic wave functions — basics blocks of hadronic properties — are dual to the profiles of AdS fields in the fifth (holographic) dimension, which is identified with scale variable. As applications we consider properties of hadrons and multiquark states from unified point of view: mass spectrum, form factors, parton, transverse momentum, Wigner and Husimi distributions.

1 Introduction

Recent decades have been marked by significant progress in derivation and application of holographic QCD approaches based on the gauge/gravity duality [1]. The duality has several manifistations. Two most important of them are: 1) matching between partion functions in two approaches gives relation between parameters of string and $SU(N)$ Yang-Mills (YM) theories; 2) conformal group acting in the boundary theory is isomorphic to $SO(4,2)$ group, which is the isometry group of the AdS_5 space. In particular, the string parameters g_s - coupling, l_s - length, and R - the AdS radius are related to the YM theory parameters g_{YM} - coupling, 't Hooft coupling $\lambda = g_{YM}^2 N$ as $2\pi g_s = g_{_{YM}}^2$ and $\frac{R^4}{l_s^4} = 2\, g_{_{YM}}^2\, N$. There are two imporant limits in case of dual theories: 1) 't Hooft limit (large N at λ fixed) $g_{YM} = \frac{\lambda}{N} \ll 1$, which corresponds to $g_s \ll 1$ (tree-level perturbative string theory). In this case we say that the "Conformal Field side" of duality works; 2) Strong coupling limit $\lambda \gg 1$, which means $l_s \ll R$. In this case we say that "String Theory side" of the duality works. AdS/QCD approaches are derived from AdS/CFT ones upon breaking of conformal invariance. According to the dictionary, the AdS/QCD or holographic QCD (HQCD) is an approximation to QCD attempting to model hadronic physics in terms of fields/strings living in extra dimensions - AdS space. HQCD models reproduce main features of QCD at low and high energies: chiral symmetry, confinement, power scaling of hadron form factors. One should stress that the extra 5th dimension has clear physical interpretation as the scale. AdS/QCD approaches are divided on two types: 1) top-down approaches – low-energy approximation of string theory trying to find a gravitational background with features similar to QCD (e.g. Sakai-Sugimoto model); 2) bottom-up approaches – more phenomenological ones, using the features of QCD to construct 5d dual theory including gravity on AdS space. In order to go towards to QCD one should: i) break conformal invariance and generate mass gap, ii) via Kaluza-Klein decomposition of the five-dimensional AdS fields introduce a tower of normalized bulk fields (Kaluza-Klein modes) dual to hadronic wave functions. Bottom-up AdS/QCD approaches have two main realizations of breaking of conformal invariance and introducing confinement — hard-wall and soft-wall versions. In the hard-wall approach the AdS geometry is cutted by two branes — ultraviolet (UV) ($z = \epsilon \to 0$) and infrared (IR) ($z = z_{\rm IR}$). Hard-wall model gives incorrect linear dependence of hadron masses on angular momentum. This approach is analogue of the quark bag model [2] and similar to the covariant constituent quark model with infrared confinement developed in Ref. [3]. In the soft-wall model the soft cutoff of the AdS space is introduced via background dilaton field [4]-[10]. The advantage of this approach is that it gives analytical solution of equation of motion for the bulk profiles of AdS fields and produces Regge behavior of hadronic masses: $M_H^2 \sim J(L)$.

In this paper we consider holographic approach based on soft-wall approach developed by us in Refs. [5]-[10]. We report the applications of our approach to the properties of hadrons and multiquark states. In particular, we present results for hadronic mass spectra, form factors and parton, transverse momentum, Wigner and Husimi distributions [5]-[10].

2 Approach

Here we briefly review our approach. First, we specify the five-dimensional AdS metric:

$$\begin{aligned} ds^2 = g_{MN} dx^M dx^N &= \eta_{ab}\, e^{2A(z)}\, dx^a dx^b = e^{2A(z)}\,(\eta_{\mu\nu} dx^\mu dx^\nu - dz^2)\,, \\ \eta_{\mu\nu} &= \mathrm{diag}(1,-1,-1,-1,-1)\,, \end{aligned} \tag{1}$$

where M and $N = 0, 1, \cdots, 4$ are the space-time (base manifold) indices, $a = (\mu, z)$ and $b = (\nu, z)$ are the local Lorentz (tangent) indices, and g_{MN} and η_{ab} are curved and flat metric tensors, respectively, which are related by the vielbein $\epsilon^a_M(z) = e^{A(z)}\,\delta^a_M$ as $g_{MN} = \epsilon^a_M \epsilon^b_N \eta_{ab}$. Here z is the holographic coordinate, R is the AdS radius, and $g = |\mathrm{det} g_{MN}|$. In the following we restrict ourselves to a conformal-invariant metric with $A(z) = \log(R/z)$.

The relevant AdS/QCD actions for the boson and fermion field of spin J are [5]-[7]

$$\begin{aligned} S_B &= \int d^4x dz\, \sqrt{g}\, e^{-\varphi(z)} \Big[\mathcal{D}_M \Phi_{M_1\cdots M_J}(x,z) \mathcal{D}^M \Phi^{M_1\cdots M_J}(x,z) \\ &- \Big((\mu_J^B)^2 + U_J^B(z) \Big)\, \Phi_{M_1\cdots M_J}(x,z) \Phi^{M_1\cdots M_J}(x,z) \Big]\,, \end{aligned} \tag{2}$$

$$\begin{aligned} S_F &= S_F^+ + S_F^-\,, \quad S_F^\pm \;=\; \int d^4x dz\, \sqrt{g}\, e^{-\varphi(z)} \sum_{i=+,-} \Big[\bar\Psi^\pm_{M_1\cdots M_J}(x,z) i \mathcal{D}^\pm_M \Psi^{\pm\, M_1\cdots M_J}(x,z) \\ &\mp\; \bar\Psi^\pm_{M_1\cdots M_J}(x,z) \Big((\mu_J^F)^2 + U_J^F(z) \Big) \Psi^{\pm\, M_1\cdots M_J}(x,z) \end{aligned} \tag{3}$$

where $\mathcal{D}_M$ and $\mathcal{D}^{\pm}_M$ are the covariant derivative (including external vector and axial fields) acting on boson $\Phi_{M_1\cdots M_J}$ and fermion $\Psi^{\pm}_{M_1\cdots M_J}$ fields, respectively. $\Psi^{\pm}_{M_1\cdots M_J}$ is the pair of bulk fermion fields, which are the holographic analogues of the left- and right-chirality fermion operators in the 4D theory. $\varphi(z) = \kappa^2 z^2$ is the dilaton field with κ being a free scale parameter. The quantities μ^B_J and μ^F_J are the bulk boson and fermion masses related to the conformal dimensions (Δ^B_J, Δ^F_J) of the spin-J AdS boson and fermion fields, respectively

$$(\mu^B_J R)^2 = \Delta^B_J(\Delta^B_J - 4)\,, \quad \mu^F_J R = \Delta^F_J - 2 \tag{4}$$

As was shown in Refs. [11] and [6] the field dimensions Δ^B_J and Δ^F_J are related to twist-dimension $\tau_{B/F}$ of hadronic operators as

$$\Delta^B_J = \tau_B = 2 + L\,, \quad \Delta^F_J = \tau_F + \frac{1}{2} = \frac{7}{2} + L\,. \tag{5}$$

where $L = \max|L_z|$ is the maximal value of the z component of the quark orbital angular momentum in hadron [11]: $U^B_J(z) = 4\varphi(z)(J-1)/R^2$ and $U^F_J(z) = \varphi(z)/R$ are the effective dilaton potentials. Note the choice of quadratic dilaton profile and potentials $U^B_J(z)$ and $U^F_J(z)$ is necessary in order to guarantee correct Regge behavior of hadronic mass spectra and asymptotic power scaling of hadronic factors at large momenta transfer in agreement with quark counting rules [5]-[10].

Notice that the fermion masses and the effective potentials corresponding to the fields Ψ^+ and Ψ^- have opposite signs according to the P-parity transformation. The absolute sign of the fermion mass is related to the chirality of the boundary operator. According to our conventions the QCD operators $\mathcal{O}_R$ and $\mathcal{O}_L$ have positive and negative chirality, and therefore the mass terms of the bulk fields Ψ^+ and Ψ^- have absolute signs "plus" and "minus", respectively.

One of the main advantages of the soft-wall AdS/QCD model is that the most of the calculations can be done analytically. In a first step, we show how in this approach the hadron wave functions and spectrum are generated. We follow the procedure pursued in Refs. [5]-[7]. We drop the external vector and axial fields in covariant derivatives, turn to the tangent space with Lorentz signature, where the AdS fields are rescaled as

$$\Phi_{\mu_1\cdots\mu_J} = e^{\varphi(z)/2 + A(z)J}\phi_{\mu_1\cdots\mu_J}\,, \quad \Psi^{\pm}_{\mu_1\cdots\mu_J} = e^{\varphi(z)/2 + A(z)(J-1/2)}\psi^{\pm}_{\mu_1\cdots\mu_J}\,. \tag{6}$$

Next we split the fermion field into left- and right-chirality components

$$\psi^{\pm}_{\mu_1\cdots\mu_J}(x,z) = \psi^{\pm\,L}_{\mu_1\cdots\mu_J}(x,z) + \psi^{\pm\,R}_{\mu_1\cdots\mu_J}(x,z) \tag{7}$$

and perform Kaluza-Klein (KK) expansion for $\phi_{\mu_1\cdots\mu_J}(x,z)$ and $\psi^{\pm\,L/R}_{\mu_1\cdots\mu_J}(x,z)$

$$\begin{aligned} \phi_{\mu_1\cdots\mu_J}(x,z) &= \sum_n \phi_{n\,\mu_1\cdots\mu_J}(x)\,F_{n\tau}(z)\,, \\ \psi^{\pm\,L/R}_{\mu_1\cdots\mu_J}(x,z) &= \frac{1}{\sqrt{2}}\sum_n \psi^{L/R}_{n\,\mu_1\cdots\mu_J}(x)\,G^{\pm\,L/R}_{n\tau}(z)\,, \end{aligned} \tag{8}$$

where the tower of the KK fields $\phi_{n\,\mu_1\cdots\mu_J}(x)$ is dual to four-dimensional fields describing mesons with spin J, while KK fields $\psi^{L/R}_{n\,\mu_1\cdots\mu_J}(x)$ are dual left/right-chirality fermion fields describing baryons with spin J. The number n corresponds to the radial quantum number. The set of functions $F_{n\tau}(z)$ are the profiles of boson AdS fields in holographic direction, which are dual to the mesonic wave functions with twist τ and radial quantum number n. In case of baryon we have four sets of such profiles dual to baryonic wave functions, which satisfy to the following relation (due P- and C-invariance) $G^{\pm R}_{n\tau}(z) = \mp G^{\mp L}_{n\tau}(z)$. Then it is convenient to rescale the boson and fermion profiles as

$$F_{n\tau}(z) = e^{-3/2A(z)}\, f_{n\tau}(z)\,, \quad G^{\pm R/L}_{n\tau}(z) = e^{-2A(z)}\, g^{\pm R/L}_{n\tau}(z) \tag{9}$$

in order derive the Schrödinger-type equation of motions (EOMs) for the wave functions $f_{n\tau}$ and $g^{\pm L/R}_{n\tau}(z)$

$$\Big[-\partial_z^2 + \frac{4L^2-1}{4z^2} + \kappa^4 z^2 + 2\kappa^2(J-1)\Big]\, f_{n\tau}(z) \;=\; M^2_{B,n\tau J}\, f_{n\tau}(z) \tag{10}$$

and

$$\left[-\partial_z^2 + \kappa^4 z^2 + 2\kappa^2\Big(m \mp \frac{1}{2}\Big) + \frac{m(m\pm 1)}{z^2}\right] g^{L/R}_{n\tau}(z) \;=\; M^2_{F,n\tau}\, g^{L/R}_{n\tau}(z)\,, \tag{11}$$

where $m = \tau - 3/2$; $M_{B,n\tau J}$ and $M_{F,n\tau}$ are the masses of bosons and fermions dual to corresponding hadrons (mesons and baryons) with specific values of quantum numbers.

Above EOMs have analytical solutions for both wave functions

$$\begin{aligned}
f_{n\tau}(z) &= \sqrt{\frac{2\Gamma(n+1)}{\Gamma(n+\tau-1)}}\; \kappa^{\tau-1}\; z^{\tau-3/2}\; e^{-\kappa^2 z^2/2}\; L_n^{\tau-2}(\kappa^2 z^2)\,, \\
g^L_{n\tau}(z) &= \sqrt{\frac{2\Gamma(n+1)}{\Gamma(n+\tau)}}\; \kappa^{\tau}\; z^{\tau-1/2}\; e^{-\kappa^2 z^2/2}\; L_n^{\tau-1}(\kappa^2 z^2)\,, \\
g^R_{n\tau}(z) &= \sqrt{\frac{2\Gamma(n+1)}{\Gamma(n+\tau-1)}}\; \kappa^{\tau-1}\; z^{\tau-3/2}\; e^{-\kappa^2 z^2/2}\; L_n^{\tau-2}(\kappa^2 z^2)
\end{aligned} \tag{12}$$

and mass spectrum $M^2_{B,n\tau J} = 4\kappa^2\Big(n + \frac{\tau+J}{2} - 1\Big)$ and $M^2_{F,n\tau} = 4\kappa^2\Big(n + \tau - 1\Big)$. Therefore, our main idea is to find the solutions for the bulk profiles of the AdS field in the z–direction, and then calculate the physical properties of hadrons in terms of the bulk profiles of AdS fields dual to hadronic wave functions. In this way both mass spectrum and dynamical hadronic properties like form factors and parton distributions will be calculated from a unified point of view based on the solutions of the Schrödinger-type EOMs (12). One can see that the bulk profiles of AdS fields have the correct scaling behavior for small z, which leads to correct power behavior of calculated hadronic form factors at large Q^2. Another important property of the bulk profiles is that they vanish at large z (confinement). Up to now we discussed the solutions of EOMs for the bulk profiles on its mass shell $p^2 = M^2$. In case when we go beyond mass shell, we can calculate so-called bulk-to-boundary propagators describing the behavior of bulk profiles at arbitrary p^2, which are necessary for calculation of momentum dependence of matrix elements in our approach. In particular, the bulk-to-boundary propagator for the vector AdS field dual to electromagnetic field is given in analytical form in terms of the Gamma $\Gamma(n)$ and Tricomi $U(a,b,z)$ functions: $V(Q,z) = \Gamma\Big(1 + \frac{Q^2}{4\kappa^2}\Big) U\Big(\frac{Q^2}{4\kappa^2}, 0, \kappa^2 z^2\Big)$. The bulk-to-boundary propagator $V(Q,z)$ obeys the normalization condition $V(0,z)=1$ consistent with gauge invariance and fulfils the following ultraviolet (UV) and infrared (IR) boundary conditions: $V(Q,0)=1\,, \quad V(Q,\infty)=0$. The UV boundary condition corresponds to the local (structureless) coupling of the electromagnetic field to matter fields, while the IR boundary condition implies that the vector field vanishes at $z=\infty$. E.g. a generic expression for the meson form factor is given in the form integral over z variable of the product of $V(Q,z)$ and bulk profiles corresponding to the wave functions of initial (in) and final (fin) meson

$$F_M(Q^2) = \int\limits_0^\infty dz V(Q,z) f_{\rm in}(z) f_{\rm fin}(z)\,. \tag{13}$$

Another advantage of our approach is a possibility to constraint the form of light-front wave functions (see detailed discussion in Refs. [5]-[10]) from matching of matrix elements of physical processes in AdS/QCD and Light-Front QCD. The idea of such matching was proposed in Ref. [11]. Next step is inclusion of effects of quark masses in agreement with constraints imposed by chiral symmetry and heavy quark effective theory.

3 Applications

One of the nice features of our approach is that we can derive effective light-front wave functions (LFWFs) using matrix elements for physical processes calculated in AdS/QCD. In particular, the nucleon LFWFs are set up as

$$\begin{aligned}
\psi^+_{+q}(x,\mathbf{k}_\perp) &= \varphi_q^{(1)}(x,\mathbf{k}_\perp)\,, \quad \psi^+_{-q}(x,\mathbf{k}_\perp) \; = \; -\frac{k^1+ik^2}{xM_N}\,\varphi_q^{(2)}(x,\mathbf{k}_\perp)\,,\\
\psi^-_{+q}(x,\mathbf{k}_\perp) &= \frac{k^1-ik^2}{xM_N}\,\varphi_q^{(2)}(x,\mathbf{k}_\perp)\,, \quad \psi^-_{-q}(x,\mathbf{k}_\perp) \; = \; \varphi_q^{(1)}(x,\mathbf{k}_\perp)\,,\\
\varphi_q^{(1)}(x,\mathbf{k}_\perp) &= \frac{4\pi}{M_N}\sqrt{\frac{q_v(x)+\delta q_v(x)}{2}}\,\sqrt{D_q^{(1)}(x)}\exp\biggl[-\frac{\mathbf{k}_\perp^2}{2M_N^2}D_q^{(1)}(x)\biggr]\,,\\
\varphi_q^{(2)}(x,\mathbf{k}_\perp) &= \frac{4\pi}{M_N}\sqrt{\frac{q_v(x)-\delta q_v(x)}{2}}\,D_q^{(2)}(x)\exp\biggl[-\frac{\mathbf{k}_\perp^2}{2M_N^2}D_q^{(2)}(x)\biggr]\,.
\end{aligned} \tag{14}$$

Here M_N is the nucleon mass.

Our functions $\varphi_q^{(1)}$ and $\varphi_q^{(2)}$ are normalized as

$$\begin{aligned}
\int\frac{d^2\mathbf{k}_\perp}{16\pi^3}\Bigl[\varphi_q^{(1)}(x,\mathbf{k}_\perp)\Bigr]^2 &= \frac{q_v(x)+\delta q_v(x)}{2}\,,\\
\int\frac{d^2\mathbf{k}_\perp}{16\pi^3}\,\frac{\mathbf{k}_\perp^2}{M_N^2}\Bigl[\varphi_q^{(2)}(x,\mathbf{k}_\perp)\Bigr]^2 &= \frac{q_v(x)-\delta q_v(x)}{2}\,,\\
\int\limits_0^1 dx\int\frac{d^2\mathbf{k}_\perp}{16\pi^3}\Bigl[\varphi_q^{(1)}(x,\mathbf{k}_\perp)\Bigr]^2 &= \frac{n_q+g_A^q}{2}\,,\\
\int\limits_0^1 dx\int\frac{d^2\mathbf{k}_\perp}{16\pi^3}\,\frac{\mathbf{k}_\perp^2}{M_N^2}\Bigl[\varphi_q^{(2)}(x,\mathbf{k}_\perp)\Bigr]^2 &= \frac{n_q-g_A^q}{2}\,,
\end{aligned} \tag{15}$$

where n_q is the number of u or d valence quarks in the proton and g_A^q is the axial charge of a quark with flavor $q = u$ or d.

Using these LFWFs one can calculate electromagnetic form factors, transverse momentum, Wigner and Husimi distributions, etc. Analytic experessions for these quantities can be found in Ref. [10]. In Figs. 1-4 we plot the results for the x-dependence of the unpolarized and polarized PDFs, TMDs, Wigner and Husimi distributions, and indicate selected results for the quark and nucleon electromagnetic form factors. We use the results for the NLO helicity-independent and helicity-dependent parton distributions at $\mu^2_{\rm NLO} = 0.40$ GeV^2 from Refs. [12] as input. Next in Figs. 5-7 we show our prediction for the deuteron electromagnetic form factors and structure functions.

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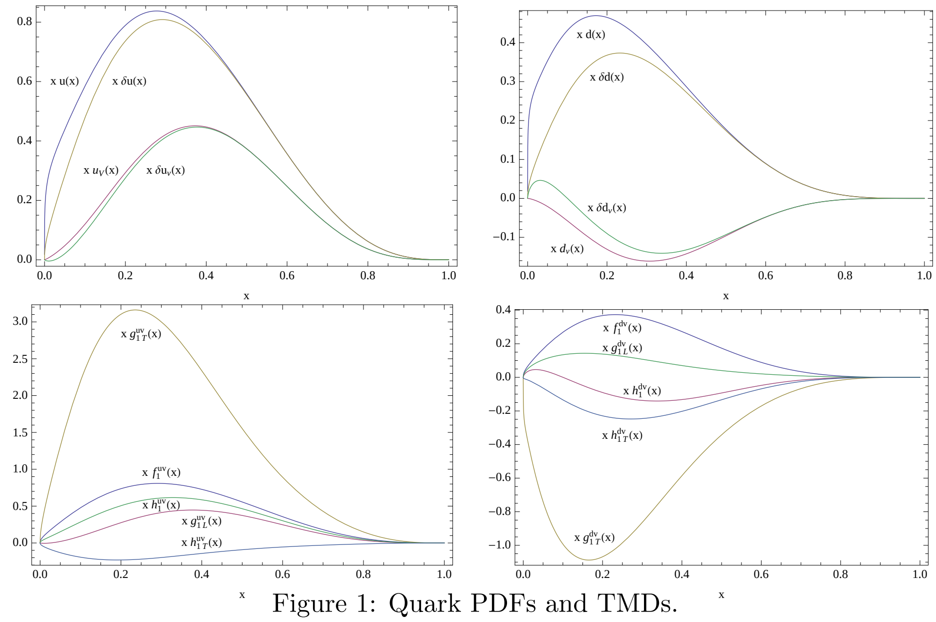

Figure 1: Quark PDFs and TMDs.

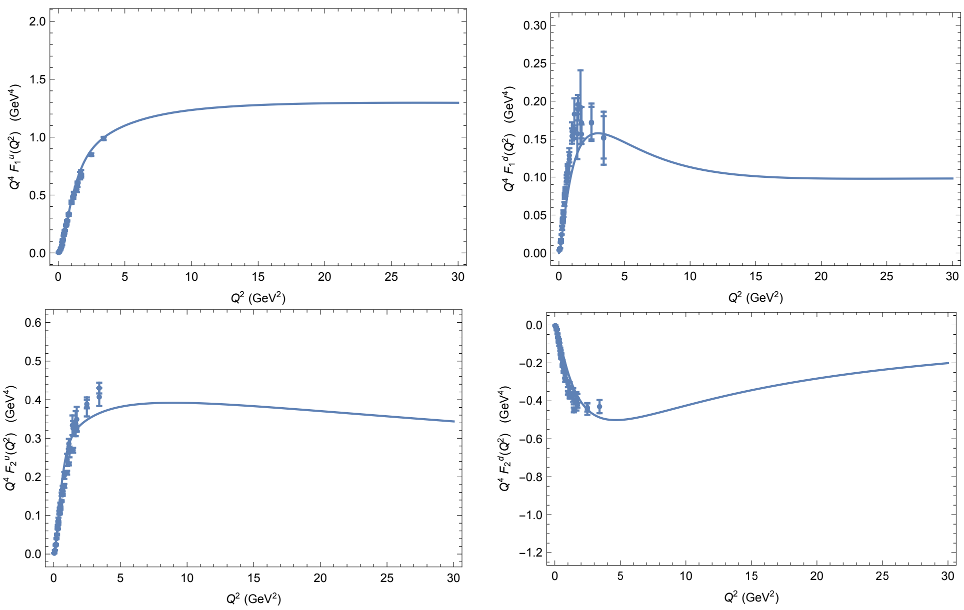

Figure 2: Dirac and Pauli Quark EM Form Factors multiplied by Q^4.

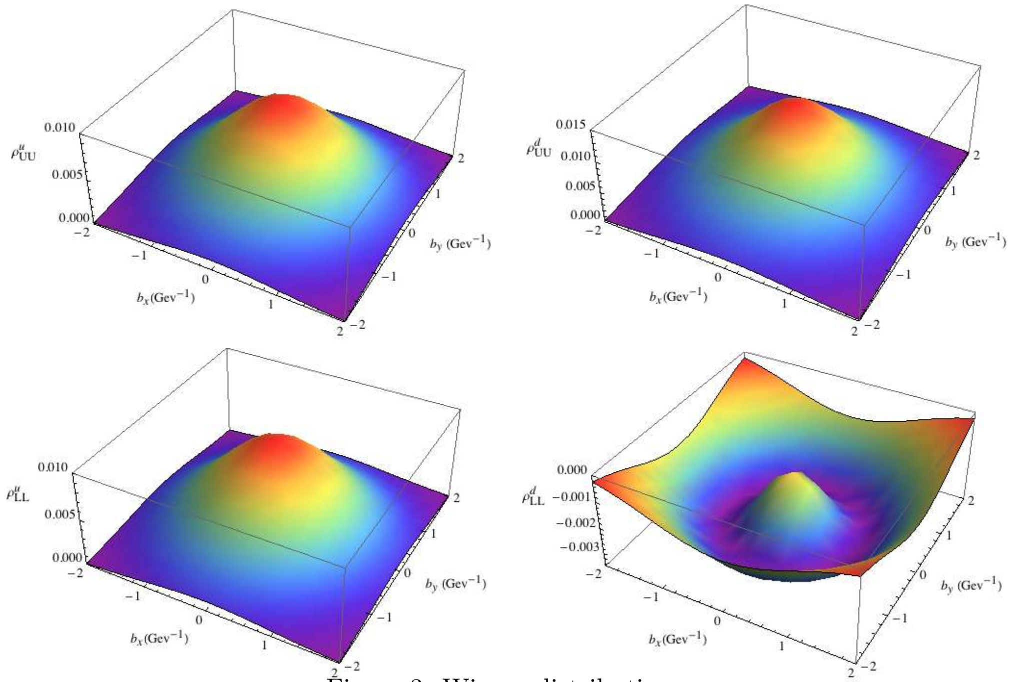

Figure 3: Wigner distributions.

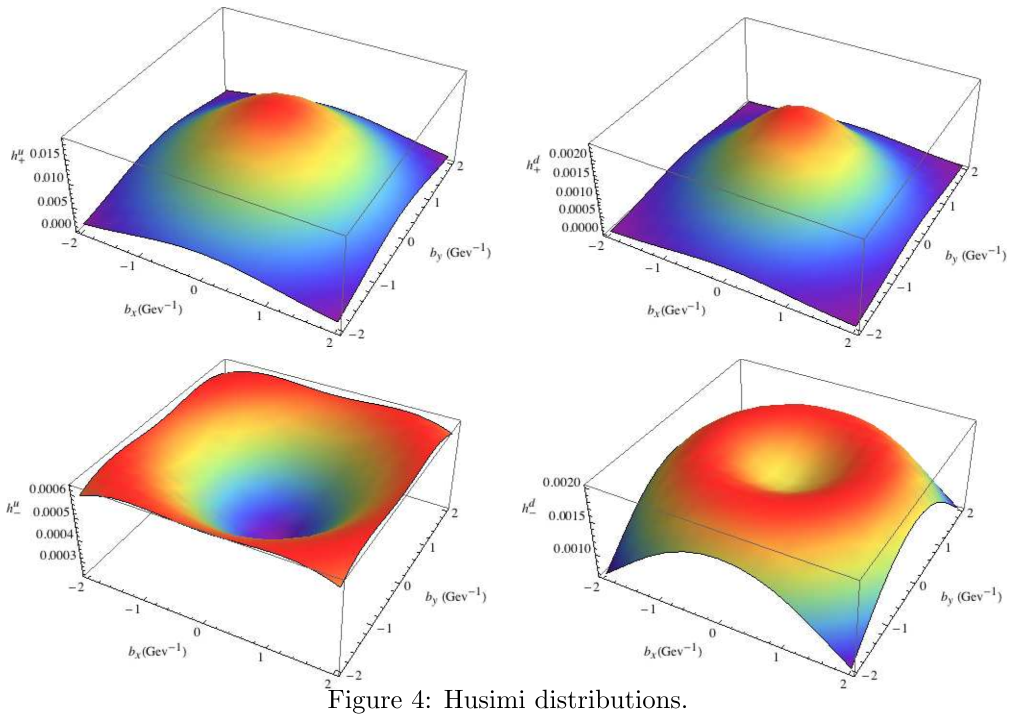

Figure 4: Husimi distributions.

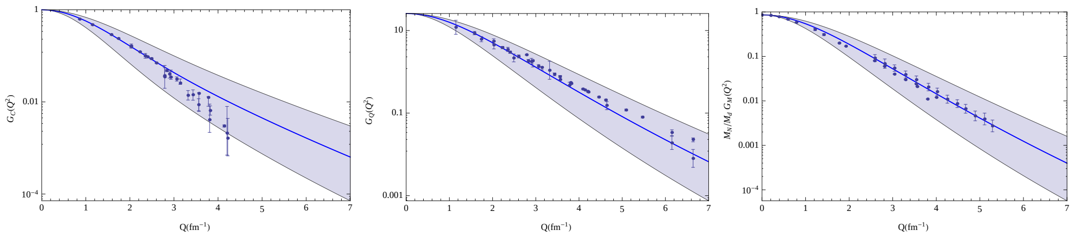

Figure 5: Deuteron charge G_C, quadrupole G_Q and magnetic G_M form factors.

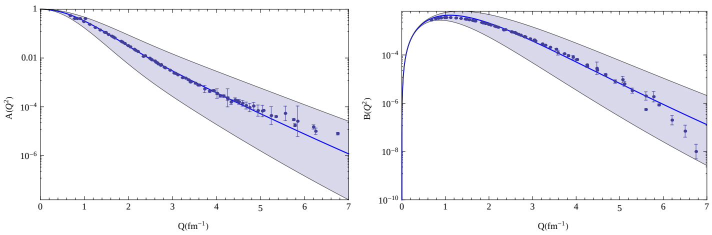

Figure 6: Deuteron structure functions A and B.

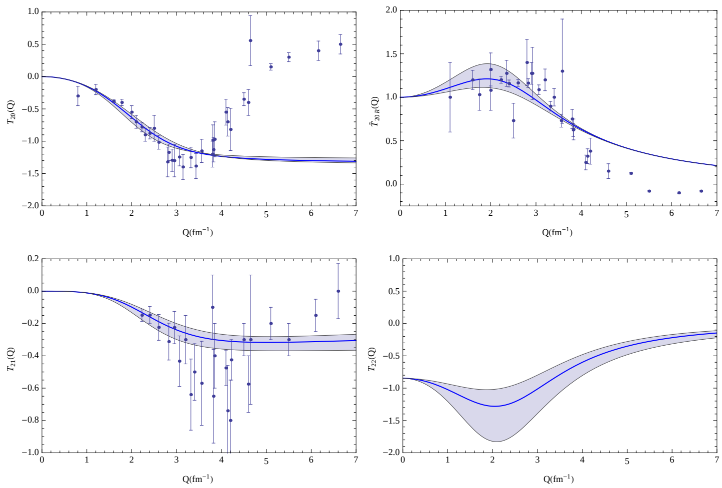

Figure 7: Deuteron tensor-polarized structures T_{20}, $\tilde{T}_{20R}$, T_{21} and T_{22}.

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