Light-Front Holography: Hadronic Wavefunctions from AdS/QCD

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Goal:

- Use AdS/CFT to provide an approximate, covariant, and analytic model of hadron structure with confinement at large distances, conformal behavior at short distances

- Analogous to the Schrodinger Theory for Atomic Physics

- AdS/QCD Light-Front Holography

- Hadronic Spectra and Light-Front Wavefunctions
Applications of AdS/CFT to QCD

Changes in physical length scale mapped to evolution in the 5th dimension $z$

in collaboration with Guy de Teramond

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SLAC & IPPP
We will consider both holographic models:

- Truncated AdS/CFT (Hard-Wall) model: cut-off at $z_0 = 1/\Lambda_{\text{QCD}}$ breaks conformal invariance and allows the introduction of the QCD scale (Hard-Wall Model) Polchinski and Strassler (2001).

- Smooth cutoff: introduction of a background dilaton field $\varphi(z)$ – usual linear Regge dependence can be obtained (Soft-Wall Model) Karch, Katz, Son and Stephanov (2006).
Conformal Theories are invariant under the Poincare and conformal transformations with

\[ M^{\mu\nu}, P^\mu, D, K^\mu, \]

the generators of SO(4,2)

SO(4,2) has a mathematical representation on AdS5
Scale Transformations

• Isomorphism of $SO(4,2)$ of conformal QCD with the group of isometries of AdS space

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

invariant measure

$x^\mu \to \lambda x^\mu$, $z \to \lambda z$, maps scale transformations into the holographic coordinate $z$.

• AdS mode in $z$ is the extension of the hadron wf into the fifth dimension.

• Different values of $z$ correspond to different scales at which the hadron is examined.

$$x^2 \to \lambda^2 x^2, \quad z \to \lambda z.$$  

$x^2 = x_\mu x^\mu$: invariant separation between quarks

• The AdS boundary at $z \to 0$ correspond to the $Q \to \infty$, UV zero separation limit.
QCD is not conformal; however, it has manifestations of a scale-invariant theory: Bjorken scaling, dimensional counting for hard exclusive processes

Conformal window: \( \alpha_s(Q^2) \approx \text{const at small } Q^2 \)

Use mathematical mapping of the conformal group \( SO(4,2) \) to AdS5 space
\[ \Gamma_{\frac{p^-}{b_j}}(Q^2) \equiv \frac{g_A}{6} [1 - \frac{\alpha_s g_1(Q^2)}{\pi}] \]
Deur, Korsch, et al.

\[ \alpha_s g_{I}/\pi JLab \quad \text{GDH limit} \]

\[ \text{Fit} \quad pQCD \text{ evol. eq.} \]

- Cornwall
- Burkert-Ioffe
- Bloch et al.
- Godfrey-Isgur
- Bhagwat et al.
- Maris-Tandy
- Fischer et al.
- Lattice QCD

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IR Conformal Window for QCD?

- **Dyson-Schwinger Analysis:** QCD Coupling has IR Fixed Point

- **Evidence from Lattice Gauge Theory**

- Define coupling from observable: indications of IR fixed point for QCD effective charges

- Confined gluons and quarks have maximum wavelength: **Decoupling of QCD vacuum polarization at small \( Q^2 \) ** Serber-Uehling

\[
\Pi(Q^2) \rightarrow \frac{\alpha}{15\pi} \frac{Q^2}{m^2} \quad Q^2 \ll 4m^2
\]

- **Justifies application of AdS/CFT in strong-coupling conformal window**

Shrock, de Teramond, sjb

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Constituent Counting Rules

\[
\frac{d\sigma}{dt}(s, t) = \frac{F(\theta_{cm})}{s[n_{tot}^{-2}]} \quad s = E_{cm}^2
\]

\[
F_H(Q^2) \sim \left[\frac{1}{Q^2}\right]^{n_H-1}
\]

\[
n_{tot} = n_A + n_B + n_C + n_D
\]

Fixed \(t/s\) or \(\cos \theta_{cm}\)

**Conformal symmetry and PQCD predict leading-twist scaling behavior of fixed-CM angle exclusive amplitudes**

**Characteristic scale of QCD: 300 MeV**

**Many new J-PARC, GSI, J-Lab, Belle, Babar tests**

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Phenomenological success of dimensional scaling laws for exclusive processes

\[ \frac{d\sigma}{dt} \sim \frac{1}{s^{n-2}}, \quad n = n_A + n_B + n_C + n_D, \]

implies QCD is a strongly coupled conformal theory at moderate but not asymptotic energies

Farrar and sjb (1973); Matveev et al. (1973).

Derivation of counting rules for gauge theories with mass gap dual to string theories in warped space
**Quark-Counting**:

\[
\frac{d\sigma}{dt} (pp \rightarrow pp) = \frac{F(\theta_{CM})}{s^{10}}
\]

\[n = 4 \times 3 - 2 = 10\]

**Best Fit**

\[n = 9.7 \pm 0.5\]

Reflects underlying conformal scale-free interactions
Conformal Invariance:

\[
\frac{d\sigma}{dt} \left( \gamma p \rightarrow MB \right) = \frac{F(\theta_{cm})}{s^7}
\]
String Theory

AdS/CFT

AdS/QCD

Semi-Classical QCD / Wave Equations

Boost Invariant 3+1 Light-Front Wave Equations

Hadron Spectra, Wavefunctions, Dynamics

Mapping of Poincare' and Conformal SO(4,2) symmetries of 3+1 space to AdS5 space

Conformal Invariance + Confinement at large distances

Light Front Holography

Goal: First Approximant to QCD
Counting rules for Hard Exclusive Scattering Regge Trajectories
QCD at the Amplitude Level

J = 0, 1, 1/2, 3/2 plus L

Integrable!

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Dirac’s Amazing Idea: The Front Form

Evolve in ordinary time

Evolve in light-front time!

\[ \tau = t + \frac{z}{c} \]

\[ \sigma = ct - z \]

\[ \chi \]

Instant Form

Front Form

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Each element of flash photograph illuminated at same LF time

\[ \tau = t + z/c \]
Calculation of Form Factors in Equal-Time Theory

**Instant Form**:  
\[ \sum \]  
Need vacuum-induced currents

Calculation of Form Factors in Light-Front Theory

**Front Form**:  
\[ \sum \]  
Absent for \( q^+ = 0 \) \( \text{zero} \)!!
Calculation of Hadron Form Factors

Instant Form

- Current matrix elements of hadron include interactions with vacuum-induced currents arising from infinitely-complex vacuum.
- Pair creation from vacuum occurs at any time before probe acts -- acausal.
- Knowledge of hadron wavefunction insufficient to compute current matrix elements.
- Requires dynamical boost of hadron wavefunction -- unknown except at weak binding.
- Complex vacuum even for QED.
- None of these complications occur for quantization at fixed LF time (front form).
Light-Front Wavefunctions: rigorous representation of composite systems in quantum field theory

\[ x = \frac{k^+}{P^+} = \frac{k^0 + k^3}{P^0 + P^3} \]

\[ P^+, \vec{P}_\perp \]

\[ \Psi_n(x_i, \vec{k}_\perp i, \lambda_i) \]

Fixed \( \tau = t + z/c \)

\[ \sum_i^n x_i = 1 \]

\[ \sum_i^n \vec{k}_\perp i = \vec{0}_\perp \]

Invariant under boosts! Independent of \( P^\mu \)

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Angular Momentum on the Light-Front

\[ J^z = \sum_{i=1}^{n} s^z_i + \sum_{j=1}^{n-1} l^z_j. \]

Conserved LF Fock state by Fock State

\[ l^z_j = -i(k_{1j} \frac{\partial}{\partial k_{2j}^2} - k_{2j}^2 \frac{\partial}{\partial k_{1j}^1}) \]

n-1 orbital angular momenta

Nonzero Anomalous Moment --> Nonzero orbital angular momentum

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\[
\frac{F_2(q^2)}{2M} = \sum_a \int [dx][d^2k_\perp] \sum_j e_j \frac{1}{2} \times \\
\left[ -\frac{1}{q_L} \psi_a^\dagger(x_i, k_{\perp i}, \lambda_i) \psi_a(x_i, k_{\perp i}, \lambda_i) + \frac{1}{q_R} \psi_a^\dagger(x_i, k_{\perp i}, \lambda_i) \psi_a(x_i, k_{\perp i}, \lambda_i) \right] \\
k'_{\perp i} = k_{\perp i} - x_i q_\perp \\
k'_{\perp j} = k_{\perp j} + (1 - x_j) q_\perp \\
q^2 = -q_\perp^2 \\
q^+ = 0
\]

Drell, sjb

Must have $\Delta \ell_z = \pm 1$ to have nonzero $F_2(q^2)$
**Anomalous gravitomagnetic moment \( B(0) \)**

Okun, Kobzarev, Teryaev: \( B(0) \) Must vanish because of Equivalence Theorem

\[
q^2 = -q_\perp^2
\]

\[\begin{align*}
&x_j, \, \vec{k}_\perp j \\
&\text{(+) sum over constituents}
\end{align*}\]

Hwang, Schmidt, sjb; Holstein et al

\( B(0) = 0 \)

Each Fock State
Holography: Unique mapping derived from equality of LF and AdS formula for current matrix elements: **em and gravitational!**

\[ \psi(x, \zeta) = \sqrt{x(1-x)\zeta^{-1/2}} \phi(\zeta) \]
Light-Front Holography: Map AdS/CFT to 3+1 LF Theory

Relativistic LF radial equation

Frame Independent

\[
\left[ -\frac{d^2}{d\zeta^2} + V(\zeta) \right] \phi(\zeta) = M^2 \phi(\zeta)
\]

\[
\zeta^2 = x(1-x)b_{\perp}^2.
\]

Effective conformal potential:

\[
V(\zeta) = -\frac{1 - 4L^2}{4\zeta^2} + \kappa^4 \zeta^2.
\]

Confining potential:

\[
\text{G. de Teramond, sjb}
\]

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\text{Stan Brodsky}\quad \text{SLAC & IPPP}
\]
Prediction from AdS/CFT: Meson LFWF

\[ \psi_M(x, k_{\perp}^2) \]

"Soft Wall" model

de Teramond, sjb

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Prediction from AdS/CFT: Meson LFWF

\[ \psi_M(x, k_\perp^2) \]

\[ \psi_M(x, k_\perp) = \frac{4\pi}{\kappa \sqrt{x(1-x)}} e^{-\frac{k_\perp^2}{2\kappa^2 x(1-x)}} \]

\[ \phi_M(x, Q_0) \propto \sqrt{x(1-x)} \]

“Soft Wall” model

\[ \kappa = 0.375 \text{ GeV} \]

massless quarks

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Hadron Distribution Amplitudes

\[ \phi_H(x_i, Q) \]

\[ \sum_i x_i = 1 \]

- Fundamental gauge invariant non-perturbative input to hard exclusive processes, heavy hadron decays. Defined for mesons, baryons

- Evolution Equations from PQCD, OPE, Conformal Invariance

- Compute from valence light-front wavefunction in light-cone gauge

\[ \phi_M(x, Q) = \int^Q d^2 \vec{k} \psi_{q\bar{q}}(x, \vec{k}_\perp) \]

Lepage, sjb

Frishman, Lepage, Sachrajda, sjb

Peskin Braun

Efremov, Radyushkin Chernyak etal

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Spacelike pion form factor from AdS/CFT

\[ F_\pi(q^2) \]

-10 -8 -6 -4 -2 0

0 0.2 0.4 0.6 0.8 1

\( q^2 (GeV^2) \)

Data Compilation
Baldini, Kloe and Volmer

Soft Wall: Harmonic Oscillator Confinement
Hard Wall: Truncated Space Confinement

One parameter - set by pion decay constant.

de Teramond, sb
See also: Radyushkin

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\[ |p, S_z > = \sum_{n=3} \Psi_n(x_i, \vec{k}_\perp, \lambda_i) |n; \vec{k}_\perp, \lambda_i > \]

**sum over states with \( n=3, 4, \ldots \) constituents**

The Light Front Fock State Wavefunctions

\[ \Psi_n(x_i, \vec{k}_\perp, \lambda_i) \]

are boost invariant; they are independent of the hadron’s energy and momentum \( P^\mu \).

The light-cone momentum fraction

\[ x_i = \frac{k_i^+}{p^+} = \frac{k_i^0 + k_i^z}{P^0 + P^z} \]

are boost invariant.

\[ \sum_i^n k_i^+ = P^+, \sum_i^n x_i = 1, \sum_i^n \vec{k}_i^\perp = \vec{0}^\perp. \]

**Intrinsic heavy quarks**

\[ \bar{u}(x) \neq \bar{d}(x) \]

\[ \bar{s}(x) \neq s(x) \]

**Mueller: BFKL DYNAMICS**

**AdS/QCD**

**Fixed LF time**

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\( L^{QCD} \rightarrow H_{LF}^{QCD} \)

\[ H_{LF}^{QCD} = \sum_{i} \left[ \frac{m^2 + k_{\perp}^2}{x} \right] i + H_{LF}^{int} \]

\( H_{LF}^{int} \): Matrix in Fock Space

\[ H_{LF}^{QCD} | \Psi_h > = \mathcal{M}_h^2 | \Psi_h > \]

Eigenvalues and Eigensolutions give Hadron Spectrum and Light-Front wavefunctions

DLCQ: Periodic BC in \( x^- \). Discrete \( k^+ \); frame-independent truncation
Light-Front QCD

Heisenberg Matrix Formulation

\[ H_{LF}^{QCD} |\Psi_h > = M_h^2 |\Psi_h > \]

DLCQ

Discretized Light-Cone Quantization

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Eigenvalues and Eigensolutions give Hadron Spectrum and Light-Front wavefunctions

H.C. Pauli & sbj

DLCQ: Frame-independent, No fermion doubling; Minkowski Space
\[
\left( M_{\pi}^2 - \sum_i \frac{\tilde{m}_i^2}{x_i} \right) \begin{bmatrix}
\psi_{q\bar{q}/\pi} \\
\psi_{q\bar{g}/\pi} \\
\vdots
\end{bmatrix} = \begin{bmatrix}
\langle q\bar{q} | V | q\bar{q} \rangle & \langle q\bar{g} | V | q\bar{g}g \rangle & \cdots \\
\langle q\bar{g} | V | q\bar{q} \rangle & \langle q\bar{g}g | V | q\bar{g}g \rangle & \cdots \\
\vdots & \vdots & \ddots
\end{bmatrix} \begin{bmatrix}
\psi_{q\bar{q}/\pi} \\
\psi_{q\bar{g}/\pi} \\
\vdots
\end{bmatrix}
\]

\[A^+ = 0\]

G.P. Lepage, sjb

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Use AdS/CFT orthonormal LFWFs as a basis for diagonalizing the QCD LF Hamiltonian

- Good initial approximant
- Better than plane wave basis
- DLCQ discretization -- highly successful 1+1
- Use independent HO LFWFs, remove CM motion
- Similar to Shell Model calculations

Pauli, Hornbostel, Hiller, McCartor, sjb
Vary, Harinandrath, Maris, sjb
Light-Front QCD
Heisenberg Equation

\[
H_{LC}^{QCD} |\psi_h\rangle = M_h^2 |\psi_h\rangle
\]

Use AdS/QCD basis functions

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A Unified Description of Hadron Structure

\[ \Psi_n(x_i, k_{\perp i}, \lambda_i) \]

- Elastic form factors
- B-Decays
- Real Compton scattering at high $Q^2$
- GPDs
- Deeply Virtual Compton Scattering
- Deeply Virtual Meson production
- Distribution Amplitudes
- Hadronization at the amplitude level
- Parton momentum distributions

Trieste ICTP
May 12, 2008

AdS/QCD

Stan Brodsky
SLAC & IPPP
Hadron Dynamics at the Amplitude Level

• LFWFS are the universal hadronic amplitudes which underlie structure functions, GPDs, exclusive processes, distribution amplitudes, direct subprocesses, hadronization.

• Relation of spin, momentum, and other distributions to physics of the hadron itself.

• Connections between observables, orbital angular momentum

• Role of FSI and ISIs--Sivers effect