**Holography:**

**Map AdS/CFT to 3+1 LF Theory**

Relativistic LF radial equation

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

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

**Effective conformal potential:**

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

**Confining potential:**

Frame Independent

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AdS/QCD

Stan Brodsky, SLAC
Consider the $AdS_5$ metric:

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

$ds^2$ invariant if $x^\mu \rightarrow \lambda x^\mu$, $z \rightarrow \lambda z$,

Maps scale transformations to scale changes of the the holographic coordinate $z$.

We define light-front coordinates $x^\pm = x^0 \pm x^3$.

Then $\eta_{\mu \nu} dx^\mu dx^\nu = dx_0^2 - dx_3^2 - dx_\perp^2 = dx^+ dx^- - dx_\perp^2$

and

$$ds^2 = -\frac{R^2}{z^2} (dx_\perp^2 + dz^2) \text{ for } x^+ = 0.$$

- $ds^2$ is invariant if $dx_\perp^2 \rightarrow \lambda^2 dx_\perp^2$, and $z \rightarrow \lambda z$, at equal LF time.

- Maps scale transformations in transverse LF space to scale changes of the holographic coordinate $z$.

- Holographic connection of $AdS_5$ to the light-front.

- The effective wave equation in the two-dim transverse LF plane has the Casimir representation $L^2$ corresponding to the $SO(2)$ rotation group [The Casimir for $SO(N) \sim S^{N-1}$ is $L(L+N-2)$].
• Light-front Hamiltonian equation

\[ H_{LF} |\phi\rangle = M^2 |\phi\rangle, \]

leads to effective LF Schrödinger wave equation (KKSS)

\[
\left[ -\frac{d^2}{d\zeta^2} - \frac{1 - 4L^2}{4\zeta^2} + \kappa^4 \zeta^2 + 2\kappa^2 (L - 1) \right] \phi(\zeta) = M^2 \phi(\zeta)
\]

with eigenvalues \( M^2 = 4\kappa^2 (n + L) \) and eigenfunctions

\[
\phi_L(\zeta) = \kappa^{1+L} \sqrt{\frac{2n!}{(n+L)!}} \zeta^{1/2+L} e^{-\kappa^2 \zeta^2/2} L_n^{L} (\kappa^2 \zeta^2). \]

• Transverse oscillator in the LF plane with \( SO(2) \) rotation subgroup has Casimir \( L^2 \) representing rotations for the transverse coordinates \( b_\perp \) in the LF.

• SW model is a remarkable example of integrability to a non-conformal extension of AdS/CFT [Chim and Zamolodchikov (1992) - Potts Model.]
Example: Pion LFWF

- Two parton LFWF bound state:

\[
\tilde{\psi}^{HW}_{qq/\pi}(x, b_\perp) = \frac{\Lambda_{QCD}\sqrt{x(1-x)}}{\sqrt{\pi}J_{1+L}(\beta_{L,k})} J_L \left( \sqrt{x(1-x)} |b_\perp| \beta_{L,k}\Lambda_{QCD} \right) \theta \left( b_\perp^2 \leq \frac{\Lambda_{QCD}^{-2}}{x(1-x)} \right),
\]

\[
\tilde{\psi}^{SW}_{qq/\pi}(x, b_\perp) = \kappa^{L+1} \sqrt{\frac{2n!}{(n+L)!}} [x(1-x)]^{\frac{1}{2}+L} |b_\perp|^L e^{-\frac{1}{2}\kappa^2 x(1-x)} b_\perp^2 L_n^L (\kappa^2 x(1-x) b_\perp^2).
\]

Fig: Ground state pion LFWF in impact space. (a) HW model \( \Lambda_{QCD} = 0.32 \) GeV, (b) SW model \( \kappa = 0.375 \) GeV.
Prediction from AdS/CFT: Meson LFWF

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

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

“Soft Wall” model

\( \kappa = 0.375 \text{ GeV} \)

massless quarks

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Stan Brodsky, SLAC
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

\[ \phi_M(x, Q) = \int_0^Q d^2 \vec{k} \psi_{q\bar{q}}(x, \vec{k}_\perp) \]

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Frishman, Lepage, Sachrajda, sjb

Peskin Braun

Efremov, Radyushkin Chernyak etal

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Second Moment of Pion Distribution Amplitude

\[ < \xi^2 > = \int_{-1}^{1} d\xi \; \xi^2 \phi(\xi) \]

\[ \xi = 1 - 2x \]

\[ < \xi^2 > = 1/5 \quad \phi_{asympt} \propto x(1 - x) \]

\[ < \xi^2 > = 1/4 \quad \phi_{AdS/QCD} \propto \sqrt{x(1 - x)} \]

Sachrajda Lattice: \[ < \xi^2 > = 0.28 \pm 0.02 \]
Spacelike pion form factor from AdS/CFT

$F_\pi(q^2)$

Data Compilation from Baldini, Kloe and Volmer

SW: Harmonic Oscillator Confinement

HW: Truncated Space Confinement

One parameter - set by pion decay constant.

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Note: Contributions to Mesons Form Factors at Large $Q$ in AdS/QCD

• Write form factor in terms of an effective partonic transverse density in impact space $b_\perp$

$$F_\pi(q^2) = \int_0^1 dx \int db^2 \tilde{\rho}(x, b, Q),$$

with $\tilde{\rho}(x, b, Q) = \pi J_0 [b Q (1 - x)] |\tilde{\psi}(x, b)|^2$ and $b = |b_\perp|$.

• Contribution from $\rho(x, b, Q)$ is shifted towards small $|b_\perp|$ and large $x \to 1$ as $Q$ increases.

Fig: LF partonic density $\rho(x, b, Q)$: (a) $Q = 1$ GeV/c, (b) very large $Q$. 
Example: Evaluation of QCD Matrix Elements

- Pion decay constant $f_\pi$ defined by the matrix element of EW current $J^+_W$:

\[ \langle 0 | \bar{\psi}_u \gamma^+ \frac{1}{2} (1 - \gamma_5) \psi_d | \pi^- \rangle = i \frac{P^+ f_\pi}{\sqrt{2}} \]

with

\[ |\pi^-\rangle = |d\bar{u}\rangle = \frac{1}{\sqrt{N_C}} \frac{1}{\sqrt{2}} \sum_{c=1}^{N_C} (b^\dagger_c d_{c\downarrow} \psi_{d\uparrow} - b^\dagger_c d_{c\uparrow} \psi_{d\downarrow}) |0\rangle. \]

- Find light-front expression (Lepage and Brodsky '80):

\[ f_\pi = 2 \sqrt{N_C} \int_0^1 dx \int \frac{d^2 k_\perp}{16\pi^3} \psi_{\bar{q}q/\pi}(x, k_\perp). \]

- Using relation between AdS modes and QCD LFWF in the $\zeta \to 0$ limit

\[ f_\pi = \frac{1}{8} \sqrt{\frac{3}{2}} R^{3/2} \lim_{\zeta \to 0} \frac{\Phi(\zeta)}{\zeta^2}. \]

- Holographic result ($\Lambda_{QCD} = 0.22$ GeV and $\kappa = 0.375$ GeV from pion FF data): Exp: $f_\pi = 92.4$ MeV

\[ f^{HW}_\pi = \frac{\sqrt{3}}{8J_1(\beta_0, k)} \Lambda_{QCD} = 91.7 \text{ MeV}, \quad f^{SW}_\pi = \frac{\sqrt{3}}{8} \kappa = 81.2 \text{ MeV}, \]

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Diffractive Dissociation of Pion into Quark Jets

Measure Light-Front Wavefunction of Pion

Minimal momentum transfer to nucleus

Nucleus left Intact!

$M \propto \frac{\partial^2}{\partial^2 k_\perp} \psi_\pi(x, k_\perp)$

E791 Ashery et al.
Two-gluon exchange measures the second derivative of the pion light-front wavefunction:

$$M \propto \frac{\partial^2}{\partial^2 k_{\perp}} \psi_{\pi}(x, k_{\perp})$$
Key Ingredients in E791 Experiment

Small color-dipole moment pion not absorbed; interacts with each nucleon coherently

QCD COLOR Transparency

\[ M_A = A \cdot M_N \]

\[ \frac{d\sigma}{dt} (\pi A \rightarrow q\bar{q}A') = A^2 \frac{d\sigma}{dt} (\pi N \rightarrow q\bar{q}N') \cdot F_A^2(t) \]

Target left intact
Diffraction, Rapidity gap
Color Transparency

- Fundamental test of gauge theory in hadron physics
- Small color dipole moments interact weakly in nuclei
- Complete coherence at high energies
- Clear Demonstration of CT from Diffractive Di-Jets
**Measure pion LFWF in diffractive dijet production**

**Confirmation of color transparency**

**A-Dependence results:** \[ \sigma \propto A^\alpha \]

<table>
<thead>
<tr>
<th>( k_t ) range (GeV/c)</th>
<th>( \alpha )</th>
<th>( \alpha ) (CT)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.25 &lt; ( k_t ) &lt; 1.5</td>
<td>1.64 ±0.06 -0.12</td>
<td>1.25</td>
</tr>
<tr>
<td>1.5 &lt; ( k_t ) &lt; 2.0</td>
<td>1.52 ± 0.12</td>
<td>1.45</td>
</tr>
<tr>
<td>2.0 &lt; ( k_t ) &lt; 2.5</td>
<td>1.55 ± 0.16</td>
<td>1.60</td>
</tr>
</tbody>
</table>

\[ \alpha \text{ (Incoh.)} = 0.70 ± 0.1 \]

**Conventional Glauber Theory Ruled Out!**

*Ashery E791*

*Factor of 7*

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**AdS/QCD**

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**Stan Brodsky, SLAC**
- Fully coherent interactions between pion and nucleons.
- Emerging Di-Jets do not interact with nucleus.

\[ \mathcal{M}(A) = A \cdot \mathcal{M}(N) \]

\[ \frac{d\sigma}{dq_t^2} \propto A^2 \cdot q_t^2 \sim 0 \]

\[ \sigma \propto A^{4/3} \]
E791 Diffractive Di-Jet transverse momentum distribution

Two Components

High Transverse momentum dependence $k_T^{-6.5}$ consistent with PQCD, ERBL Evolution

Gaussian component similar to AdS/CFT HO LFWF

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Narrowing of $x$ distribution at higher jet transverse momentum

$x$: distribution of diffractive dijets from the platinum target for $1.25 \leq k_t \leq 1.5$ GeV/c (left) and for $1.5 \leq k_t \leq 2.5$ GeV/c (right). The solid line is a fit to a combination of the asymptotic and CZ distribution amplitudes. The dashed line shows the contribution from the asymptotic function and the dotted line that of the CZ function.

**Possibly two components:**
Nonperturbative (AdS/CFT) and Perturbative (ERBL)
Evolution to asymptotic distribution

$$\phi(x) \propto \sqrt{x(1-x)}$$

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\( \phi_{asympt} \sim x(1 - x) \)

**AdS/CFT:**

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

Increases PQCD leading twist prediction for \( F_\pi(Q^2) \) by factor \( 16/9 \).
\[ F_\pi(Q^2) = \int_0^1 dx \phi_\pi(x) \int_0^1 dy \phi_\pi(y) \frac{16\pi C_F\alpha_V(Q_V)}{(1-x)(1-y)Q^2} \]

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

\[ \phi_{asymptotic} \propto x(1-x) \]

**AdS/CFT:** Increases PQCD leading twist prediction for \( F_\pi(Q^2) \) by factor 16/9

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AdS/QCD

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Higher Spin Bosonic Modes HW

• Each hadronic state of integer spin $S \leq 2$ is dual to a normalizable string mode

$$\Phi_{\mu_1 \mu_2 \ldots \mu_S}(x, z) = \epsilon_{\mu_1 \mu_2 \ldots \mu_S} e^{-iP \cdot x} \Phi_S(z).$$

with four-momentum $P_\mu$ and spin polarization indices along the 3+1 physical coordinates.

• Wave equation for spin $S$-mode

$$\left[ z^2 \partial_z^2 - (d+1-2S)z \partial_z + z^2 \mathcal{M}^2 - (\mu R)^2 \right] \Phi_S(z) = 0,$$

• Solution

$$\tilde{\Phi}(z)_S = \left( \frac{z}{R} \right)^S \Phi(z)_S = C e^{-iP \cdot x} z^{d/2} J_{\Delta - d/2}(z \mathcal{M}) \epsilon(P)_{\mu_1 \mu_2 \ldots \mu_S},$$

• We can identify the conformal dimension:

$$\Delta = \frac{1}{2} \left( d + \sqrt{(d - 2S)^2 + 4\mu^2 R^2} \right).$$

• Normalization:

$$R^{d - 2S - 1} \int_0^{\Lambda_{QCD}^{-1}} \frac{dz}{z^{d - 2S - 1}} \Phi_S^2(z) = 1.$$
Baryons in “bottom-up” approach to holographic QCD: { GdT and SJB (2004)}. 

“Top-down” Sakai-Sugimoto model: { Hong, Rho, Yee and Yi (2007); Hata, Sakai, Sugimoto, Yamato (2007)}. 

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• Baryons Spectrum in "bottom-up" holographic QCD

Baryons in Ads/CFT

• Action for massive fermionic modes on AdS_{d+1}:

\[ S[\bar{\Psi}, \Psi] = \int d^{d+1}x \sqrt{g} \bar{\Psi}(x, z) \left( i\Gamma^{\ell} D_\ell - \mu \right) \Psi(x, z). \]

• Equation of motion:

\[ (i\Gamma^{\ell} D_\ell - \mu) \Psi(x, z) = 0 \]

\[ \left[ i \left( z\eta^{\ell m} \Gamma_\ell \partial_m + \frac{d}{2} \Gamma_z \right) + \mu R \right] \Psi(x^\ell) = 0. \]
Holographic Light-Front Integrable Form and Spectrum

- In the conformal limit fermionic spin-$\frac{1}{2}$ modes $\psi(\zeta)$ and spin-$\frac{3}{2}$ modes $\psi_\mu(\zeta)$ are two-component spinor solutions of the Dirac light-front equation

$$\alpha \Pi(\zeta) \psi(\zeta) = M \psi(\zeta),$$

where $H_{LF} = \alpha \Pi$ and the operator

$$\Pi_L(\zeta) = -i \left( \frac{d}{d\zeta} - \frac{L + \frac{1}{2}}{\zeta} \gamma_5 \right),$$

and its adjoint $\Pi_L^\dagger(\zeta)$ satisfy the commutation relations

$$\left[ \Pi_L(\zeta), \Pi_L^\dagger(\zeta) \right] = \frac{2L + 1}{\zeta^2} \gamma_5.$$

- Supersymmetric QM between bosonic and fermionic modes in AdS?
• Note: in the Weyl representation \((i\alpha = \gamma_5\beta)\)

\[
\begin{align*}
  i\alpha &= \begin{pmatrix} 0 & I \\ -I & 0 \end{pmatrix}, \\
  \beta &= \begin{pmatrix} 0 & I \\ I & 0 \end{pmatrix}, \\
  \gamma_5 &= \begin{pmatrix} I & 0 \\ 0 & -I \end{pmatrix}.
\end{align*}
\]

• Baryon: twist-dimension \(3 + L\) \((\nu = L + 1)\)

\[
\mathcal{O}_{3+L} = \psi D_{\ell_1} \ldots D_{\ell_q} \psi D_{\ell_{q+1}} \ldots D_{\ell_m} \psi, \quad L = \sum_{i=1}^{m} \ell_i.
\]

• Solution to Dirac eigenvalue equation with UV matching boundary conditions

\[
\psi(\zeta) = C \sqrt{\zeta} \left[ J_{L+1}(\zeta \mathcal{M}) u_+ + J_{L+2}(\zeta \mathcal{M}) u_- \right].
\]

Baryonic modes propagating in AdS space have two components: orbital \(L\) and \(L + 1\).

• Hadronic mass spectrum determined from IR boundary conditions

\[
\psi_\pm (\zeta = 1/\Lambda_{\text{QCD}}) = 0,
\]

given by

\[
\mathcal{M}^+_{\nu,k} = \beta_{\nu,k} \Lambda_{\text{QCD}}, \quad \mathcal{M}^-_{\nu,k} = \beta_{\nu+1,k} \Lambda_{\text{QCD}},
\]

with a scale independent mass ratio.
Fig: Light baryon orbital spectrum for $\Lambda_{QCD} = 0.25$ GeV in the HW model. The 56 trajectory corresponds to $L$ even $P = +$ states, and the 70 to $L$ odd $P = -$ states.
<table>
<thead>
<tr>
<th>$SU(6)$</th>
<th>$S$</th>
<th>$L$</th>
<th>Baryon State</th>
</tr>
</thead>
<tbody>
<tr>
<td>56</td>
<td>( \frac{1}{2} )</td>
<td>0</td>
<td>$N_{\frac{1}{2}}^1$ (939)</td>
</tr>
<tr>
<td>3/2</td>
<td>0</td>
<td>$\Delta_{\frac{3}{2}}^3$ (1232)</td>
<td></td>
</tr>
<tr>
<td>70</td>
<td>( \frac{1}{2} )</td>
<td>1</td>
<td>$N_{\frac{1}{2}}^1$ (1535) $N_{\frac{3}{2}}^3$ (1520)</td>
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<tr>
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<td>$N_{\frac{1}{2}}^1$ (1650) $N_{\frac{3}{2}}^3$ (1700) $N_{\frac{5}{2}}^5$ (1675)</td>
<td></td>
</tr>
<tr>
<td>1/2</td>
<td>1</td>
<td>$\Delta_{\frac{1}{2}}^1$ (1620) $\Delta_{\frac{3}{2}}^3$ (1700)</td>
<td></td>
</tr>
<tr>
<td>56</td>
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<td>2</td>
<td>$N_{\frac{3}{2}}^3$ (1720) $N_{\frac{5}{2}}^5$ (1680)</td>
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<td>2</td>
<td>$\Delta_{\frac{1}{2}}^1$ (1910) $\Delta_{\frac{3}{2}}^3$ (1920) $\Delta_{\frac{5}{2}}^5$ (1905) $\Delta_{\frac{7}{2}}^7$ (1950)</td>
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</tr>
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<td>( \frac{1}{2} )</td>
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</tr>
<tr>
<td>3/2</td>
<td>3</td>
<td>$N_{\frac{3}{2}}^3$ $N_{\frac{5}{2}}^5$ $N_{\frac{7}{2}}^7$ (2190) $N_{\frac{9}{2}}^9$ (2250)</td>
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<tr>
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</tr>
<tr>
<td>3/2</td>
<td>4</td>
<td>$\Delta_{\frac{5}{2}}^5$ $\Delta_{\frac{7}{2}}^7$ $\Delta_{\frac{9}{2}}^9$ $\Delta_{\frac{11}{2}}^9$ (2420)</td>
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<tr>
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</tr>
<tr>
<td>3/2</td>
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<td>$N_{\frac{7}{2}}^7$ $N_{\frac{9}{2}}^9$ $N_{\frac{11}{2}}^{11}$ $N_{\frac{13}{2}}^{13}$</td>
<td></td>
</tr>
</tbody>
</table>
Non-Conformal Extension of Algebraic Structure (Soft Wall Model)

• We write the Dirac equation

\[(\alpha \Pi(\zeta) - \mathcal{M}) \psi(\zeta) = 0,\]

in terms of the matrix-valued operator \(\Pi\)

\[\Pi_\nu(\zeta) = -i \left( \frac{d}{d\zeta} - \frac{\nu + \frac{1}{2}}{\zeta} \gamma_5 - \kappa^2 \zeta \gamma_5 \right),\]

and its adjoint \(\Pi^\dagger\), with commutation relations

\[\left[ \Pi_\nu(\zeta), \Pi^\dagger_\nu(\zeta) \right] = \left( \frac{2\nu + 1}{\zeta^2} - 2\kappa^2 \right) \gamma_5.\]

• Solutions to the Dirac equation

\[\psi_+(\zeta) \sim z^{1+\nu} e^{-\kappa^2 \zeta^2 / 2} L^\nu_n(\kappa^2 \zeta^2),\]
\[\psi_-(\zeta) \sim z^{3+\nu} e^{-\kappa^2 \zeta^2 / 2} L^{\nu+1}_n(\kappa^2 \zeta^2).\]

• Eigenvalues

\[\mathcal{M}^2 = 4\kappa^2 (n + \nu + 1).\]
- Baryon: twist-dimension $3 + L$ ($\nu = L + 1$)

\[ O_{3+L} = \psi D_{\{\ell_1 \ldots D_{\ell_q} \psi D_{\ell_{q+1}} \ldots D_{\ell_m}\}} \psi, \quad L = \sum_{i=1}^{m} \ell_i. \]

- Define the zero point energy (identical as in the meson case)

\[ \mathcal{M}^2 \rightarrow \mathcal{M}^2 - 4\kappa^2: \]

\[ \mathcal{M}^2 = 4\kappa^2(n + L + 1). \]
Space-Like Dirac Proton Form Factor

• Consider the spin non-flip form factors

\[ F_+(Q^2) = g_+ \int d\zeta \ J(Q, \zeta) |\psi_+(\zeta)|^2, \]
\[ F_-(Q^2) = g_- \int d\zeta \ J(Q, \zeta) |\psi_-(\zeta)|^2, \]

where the effective charges \( g_+ \) and \( g_- \) are determined from the spin-flavor structure of the theory.

• Choose the struck quark to have \( S^z = +1/2 \). The two AdS solutions \( \psi_+(\zeta) \) and \( \psi_-(\zeta) \) correspond to nucleons with \( J^z = +1/2 \) and \( -1/2 \).

• For \( SU(6) \) spin-flavor symmetry

\[ F_1^p(Q^2) = \int d\zeta \ J(Q, \zeta) |\psi_+(\zeta)|^2, \]
\[ F_1^n(Q^2) = -\frac{1}{3} \int d\zeta \ J(Q, \zeta) \left[ |\psi_+(\zeta)|^2 - |\psi_-(\zeta)|^2 \right], \]

where \( F_1^p(0) = 1, \ F_1^n(0) = 0. \)
- Scaling behavior for large $Q^2$: $Q^4 F^p_1(Q^2) \rightarrow \text{constant}$  

\[
\begin{array}{c}
\text{Proton } \tau = 3
\end{array}
\]

Dirac Neutron Form Factor
(Valence Approximation)

\[ Q^4 F^m_1(Q^2) \quad [\text{GeV}^4] \]

Prediction for \( Q^4 F^m_1(Q^2) \) for \( \Lambda_{\text{QCD}} = 0.21 \text{ GeV} \) in the hard wall approximation. Data analysis from Diehl (2005).
• Scaling behavior for large $Q^2$: $Q^4 F^n_1(Q^2) \rightarrow \text{constant}$  

Neutron $\tau = 3$

Spacelike Pauli Form Factor

From overlap of $L = 1$ and $L = 0$ LFWFs

Harmonic Oscillator Confinement
Normalized to anomalous moment

$F_2^p(Q^2)$

$k = 0.49$ GeV

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AdS/QCD

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Holographic Connection between LF and AdS/CFT

- Predictions for hadronic spectra, light-front wavefunctions, interactions

- Deduce meson and baryon wavefunctions, distribution amplitude, structure function from holographic constraint

- Identification of Orbital Angular Momentum Casimir for SO(2): LF Rotations

- Extension to massive quarks