Hadronization at the Amplitude Level

\[ \tau = x^+ \]

Capture if \( \zeta^2 = x(1-x)b^2_\perp > \frac{1}{\Lambda^2_{QCD}} \)

i.e.,

\[ M^2 = \frac{k^2_\perp}{x(1-x)} < \Lambda^2_{QCD} \]
Baryons in AdS/CFT

- Baryons Spectrum in "bottom-up" holographic QCD

- 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:
  $$\left( i \Gamma^{\ell} D_{\ell} - \mu \right) \Psi(x, z) = 0$$
  $$\left[ i \left( z \eta^{\ell m} \Gamma_{\ell} \partial_m + \frac{d}{2} \Gamma_z \right) + \mu R \right] \Psi(x^\ell) = 0.$$
Baryons

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 $\Pi_L(\zeta)$ satisfy the commutation relations

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

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

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

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

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

• Solution to Dirac eigenvalue equation with UV matching boundary conditions

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

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

• Hadronic mass spectrum determined from IR boundary conditions

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

given by

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

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>
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<tr>
<td>56</td>
<td>$\frac{1}{2}$</td>
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<td>$N^{\frac{1}{2}+}(939)$</td>
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<td>$N^{\frac{1}{2}-}(1650)$ $N^{\frac{3}{2}-}(1700)$ $N^{\frac{5}{2}-}(1675)$</td>
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<tr>
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<td>$\Delta^{\frac{1}{2}-}(1620)$ $\Delta^{\frac{3}{2}-}(1700)$</td>
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<tr>
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<td>2</td>
<td>$N^{\frac{3}{2}+}(1720)$ $N^{\frac{5}{2}+}(1680)$</td>
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<td>$\Delta^{\frac{1}{2}+}(1910)$ $\Delta^{\frac{3}{2}+}(1920)$ $\Delta^{\frac{5}{2}+}(1905)$ $\Delta^{\frac{7}{2}+}(1950)$</td>
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<td>$N^{\frac{3}{2}-}$ $N^{\frac{5}{2}-}$ $N^{\frac{7}{2}-}(2190)$ $N^{\frac{9}{2}-}(2250)$</td>
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<td>$\Delta^{\frac{5}{2}-}(1930)$ $\Delta^{\frac{7}{2}-}$</td>
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<tr>
<td>56</td>
<td>$\frac{1}{2}$</td>
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<td>$N^{\frac{7}{2}+}$ $N^{\frac{9}{2}+}(2220)$</td>
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<td>$N^{\frac{9}{2}-}$ $N^{\frac{11}{2}-}(2600)$</td>
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<td>$N^{\frac{7}{2}-}$ $N^{\frac{9}{2}-}$ $N^{\frac{11}{2}-}$ $N^{\frac{13}{2}-}$</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

\[\psi_+(\zeta) \sim z^{\frac{1}{2} + \nu} e^{-\kappa^2 \zeta^2 / 2} L_n^\nu(\kappa^2 \zeta^2),\]

\[\psi_-(\zeta) \sim z^{\frac{3}{2} + \nu} e^{-\kappa^2 \zeta^2 / 2} L_n^{\nu+1}(\kappa^2 \zeta^2).\]

- Eigenvalues

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

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

- 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 $Q^2$: $Q^4 F_1^p(Q^2) \rightarrow$ constant

Proton $\tau = 3$

Dirac Neutron Form Factor
(Valence Approximation)

\[ Q^4 F^n_1(Q^2) \] [GeV^4]

Prediction for \( Q^4 F^n_1(Q^2) \) for \( \Lambda_{QCD} = 0.21 \) GeV in the hard wall approximation. Data analysis from Diehl (2005).
Scaling behavior for large $Q^2$: $Q^4 F_1^n(Q^2) \rightarrow \text{constant}$  

Neutron $\tau = 3$

Spacelike Pauli Form Factor

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

Harmonic Oscillator
Confinement
Normalized to anomalous moment

$F_2^p(Q^2)$

$\kappa = 0.49 \text{ GeV}$

G. de Teramond, sjb

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AdS/CFT and Integrability

- Generate eigenvalues and eigenfunctions using Ladder Operators
- Apply to Covariant Light-Front Radial Dirac and Schrodinger Equations
Algebraic Structure, Integrability and Stability Conditions (HW Model)

- If $L^2 > 0$ the LF Hamiltonian, $H_{LF}$, can be written as a bilinear form

$$H_{LF}^L(\zeta) = \Pi_L^\dagger(\zeta)\Pi_L(\zeta)$$

in terms of the operator

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

and its adjoint

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

with commutation relations

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

- For $L^2 \geq 0$ the Hamiltonian is positive definite

$$\langle \phi | H_{LF}^L | \phi \rangle = \int d\zeta \left| \Pi_L \phi(z) \right|^2 \geq 0$$

and thus $M^2 \geq 0$. 

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Ladder Construction of Orbital States

- Orbital excitations constructed by the $L$-th application of the raising operator
  \[ a_L^\dagger = -i\Pi_L \]
  on the ground state:
  \[ a_L^\dagger |L\rangle = c_L |L + 1\rangle. \]

- In the light-front $\zeta$-representation
  \[
  \phi_L(\zeta) = \langle \zeta | L \rangle = C_L \sqrt{\zeta} (-\zeta)^L \left( \frac{1}{\zeta} \frac{d}{d\zeta} \right)^L J_0(\zeta M) = C_L \sqrt{\zeta} J_L(\zeta M).
  \]

- The solutions $\phi_L$ are solutions of the light-front equation ($L = 0, \pm 1, \pm 2, \cdots$)
  \[
  \left[ -\frac{d^2}{d\zeta^2} - \frac{1 - L^2}{4\zeta^2} \right] \phi(\zeta) = M^2 \phi(\zeta),
  \]

- Mode spectrum from boundary conditions: $\phi(\zeta = 1/\Lambda_{QCD}) = 0$. 
Non-Conformal Extension of Algebraic Integrability (SW Model)

- Soft-wall model [Karch, Katz, Son and Stephanov (2006)] retain conformal AdS metrics but introduce smooth cutoff which depends on the profile of a dilaton background field $\varphi(z)$.

- Consider the generator (short-distance Coulombic and long-distance linear potential)

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

and its adjoint

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

with commutation relations

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

- The LF Hamiltonian

$$H_{LF} = \Pi_L^\dagger \Pi_L + C$$

is positive definite $\langle \phi | H_{LF} | \phi \rangle \geq 0$ for $L^2 \geq 0$, and $C \geq -4\kappa^2$.

- Orbital and radial excited states are constructed from the ladder operators from the $L = 0$ state.
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
New Perspectives for QCD from AdS/CFT

- LFWFs: Fundamental frame-independent description of hadrons at amplitude level

- Holographic Model from AdS/CFT: Confinement at large distances and conformal behavior at short distances

- Model for LFWFs, meson and baryon spectra: many applications!

- New basis for diagonalizing Light-Front Hamiltonian

- Physics similar to MIT bag model, but covariant. No problem with support $0 < x < 1$.

- Quark Interchange dominant force at short distances
Quark Interchange
(Spin exchange in atom-atom scattering)

\[ \frac{d\sigma}{dt} = |M(s,t)|^2 \]

\[ M(t, u)_{\text{interchange}} \propto \frac{1}{ut^2} \]

Gluon Exchange
(Van der Waal -- Landshoff)

\[ M(s, t)_{\text{gluon exchange}} \propto s F(t) \]

MIT Bag Model (de Tar), large \( N_c \), ('t Hooft), AdS/CFT all predict dominance of quark interchange:

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AdS/CFT explains why quark interchange is dominant interaction at high momentum transfer in exclusive reactions.

\[ M(t, u)_{\text{interchange}} \propto \frac{1}{ut^2} \]

Non-linear Regge behavior:

\[ \alpha_R(t) \rightarrow -1 \]
Why is quark-interchange dominant over gluon exchange?

Example: \( M(K^+ p \rightarrow K^+ p) \propto \frac{1}{ut^2} \)

Exchange of common \( u \) quark

\[
M_{QIM} = \int d^2k_\perp dx \; \psi_C^\dagger \psi_D^\dagger \Delta \psi_A \psi_B
\]

Holographic model (Classical level):

Hadrons enter 5th dimension of \( AdS_5 \)

Quarks travel freely within cavity as long as separation \( z < z_0 = \frac{1}{\Lambda_{QCD}} \)

LFWFs obey conformal symmetry producing quark counting rules.
Comparison of Exclusive Reactions at Large $t$

B. R. Baller, (a) G. C. Blazey, (b) H. Courant, K. J. Heller, S. Heppelmann, (c) M. L. Marshak, E. A. Peterson, M. A. Shupe, and D. S. Wahl (d)

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D. S. Barton, G. Bunce, A. S. Carroll, and Y. I. Makdisi

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(Received 28 October 1987; revised manuscript received 3 February 1988)

Cross sections or upper limits are reported for twelve meson-baryon and two baryon-baryon reactions for an incident momentum of 9.9 GeV/c, near 90° c.m.: $\pi^\pm p \to p\pi^\pm, p\rho^\pm, \pi^+\Delta^\pm, K^+\Sigma^\pm, (\Lambda^0/\Sigma^0)K^0, K^\pm p \to pK^\pm; p^\pm p \to pp^\pm$. By studying the flavor dependence of the different reactions, we have been able to isolate the quark-interchange mechanism as dominant over gluon exchange and quark-antiquark annihilation.

\[ \begin{align*}
\pi^\pm p &\to p\pi^\pm, \\
K^\pm p &\to pK^\pm, \\
\pi^\pm p &\to p\rho^\pm, \\
\pi^\pm p &\to \pi^+\Delta^\pm, \\
\pi^\pm p &\to K^+\Sigma^\pm, \\
\pi^- p &\to \Lambda^0K^0, \Sigma^0K^0, \\
p^\pm p &\to pp^\pm.
\end{align*} \]
New Perspectives on QCD Phenomena from AdS/CFT

- **AdS/CFT**: Duality between string theory in Anti-de Sitter Space and Conformal Field Theory

- New Way to Implement Conformal Symmetry

- Holographic Model: Conformal Symmetry at Short Distances, Confinement at large distances

- Remarkable predictions for hadronic spectra, wavefunctions, interactions

- AdS/CFT provides novel insights into the quark structure of hadrons
Light-Front Wavefunctions

Dirac’s Front Form: Fixed $\tau = t + z/c$

$$\psi(x, k_\perp)$$

$$x_i = \frac{k_i^+}{P^+}$$

Invariant under boosts. Independent of $P^\mu$

$$H_{LF}^{QCD} |\psi > = M^2 |\psi >$$

Remarkable new insights from AdS/CFT, the duality between conformal field theory and Anti-de Sitter Space
Some Applications of Light-Front Wavefunctions

- Exact formulae for form factors, quark and gluon distributions; vanishing anomalous gravitational moment; edm connection to anm
- Deeply Virtual Compton Scattering, generalized parton distributions, angular momentum sum rules
- Exclusive weak decay amplitudes
- Single spin asymmetries: Role of ISI and FSI
- Factorization theorems, DGLAP, BFKL, ERBL Evolution
- Quark interchange amplitude
- Relation of spin, momentum, and other distributions to physics of the hadron itself.
The position of the struck quark differs by $x^-$ in the two wave functions

Measure $x^{-}$ distribution from DVCS:
Take Fourier transform of skewness, $\xi = \frac{Q^2}{2p.q}$
the longitudinal momentum transfer

S. J. Brodsky$^a$, D. Chakrabarti$^b$, A. Harindranath$^c$, A. Mukherjee$^d$, J. P. Vary$^{e,a,f}$

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Hadron Optics

\[ A(\sigma, \vec{b}_\perp) = \frac{1}{2\pi} \int d\xi e^{i\frac{\xi}{2} \sigma} \tilde{A}(\xi, \vec{b}_\perp) \]

\[ \sigma = \frac{1}{2} x^- P + \xi = \frac{Q^2}{2p.q} \]

The Fourier Spectrum of the DVCS amplitude in \( \sigma \) space for different fixed values of \( |b_\perp| \).

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\( \Lambda_{QCD} = 0.32 \)

**DVCS Amplitude using holographic QCD meson LFWF**

\[ |b_\perp| = 0.1 \]
\[ |b_\perp| = 0.5 \]
\[ |b_\perp| = 1.0 \]
Diffractive Dissociation of Pion into Quark Jets

E791 Ashery et al.

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

Measure Light-Front Wavefunction of Pion

Minimal momentum transfer to nucleus

Nucleus left Intact!
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

\[ M_A = A \ M_N \]

\[ \frac{d\sigma}{dt}(\pi A \to q\bar{q}A') = A^2 \ \frac{d\sigma}{dt}(\pi N \to q\bar{q}N') \ F^2_A(t) \]

Target left intact

Diffraction, Rapidity gap

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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
• Fully coherent interactions between pion and nucleons.

• Emerging Di-Jets do not interact with nucleus.

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

\[ \frac{d\sigma}{dq_f^2} \propto A^2 \quad q_f^2 \sim 0 \]

\[ \sigma \propto A^{4/3} \]

Nuclear coherence

\[ F_A^2(q_{\perp}^2) \sim e^{-\frac{1}{3} R_A^2 q_{\perp}^2} \]
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>
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<tbody>
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<td>$1.25 &lt; k_t &lt; 1.5$</td>
<td>$1.64 \pm 0.06$ -0.12</td>
<td>1.25</td>
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<td>$2.0 &lt; k_t &lt; 2.5$</td>
<td>$1.55 \pm 0.16$</td>
<td>1.60</td>
</tr>
</tbody>
</table>

$\alpha$ (Incoh.) = $0.70 \pm 0.1$

Conventional Glauber Theory Ruled Out!

Factor of 7

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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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Fig. 22. The $u$ distribution of diffractive dijets from the platinum target for $1.25 \leq k_t \leq 1.5 \text{ GeV/c}$ (left) and for $1.5 \leq k_t \leq 2.5 \text{ GeV/c}$ (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.

Narrowing of $x$ distribution at higher jet transverse momentum

$x$ distribution of diffractive dijets from the platinum target for $1.25 \leq k_t \leq 1.5 \text{ GeV/c}$ (left) and for $1.5 \leq k_t \leq 2.5 \text{ GeV/c}$ (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 
\[ F_\pi(Q^2) \] by factor 16/9
\[ F_\pi(Q^2) = \int_0^1 dx \phi_\pi(x) \int_0^1 dy \phi_\pi(y) \frac{16\pi C_F \alpha_V(Q_V)}{(1-x)(1-y)Q^2} \]

Normalized to \( f_\pi \)

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

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

**AdS/CFT:** Increases PQCD leading twist prediction for \( F_\pi(Q^2) \) by factor 16/9
Measurement of Nuclear Transparency for the $A(e, e'\pi^+)$ Reaction

$$eA \rightarrow e'\pi^+ X$$

B. Clasie, et al, Jlab

PRL 99, 242502 (2007)

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Particle ratio changes with centrality!

Open (filled) points are for $\pi^{\pm}$ ($\pi^{\nu}$), respectively.
Baryon can be made directly within hard subprocess

Coalescence within hard subprocess

\[ uu \rightarrow p\bar{d} \]

\[ \phi_p(x_1, x_2, x_3) \propto \Lambda_{QCD}^2 \]

Collision can produce 3 collinear quarks

\[ qq \rightarrow B\bar{q} \]

Small color-singlet
Color Transparent
Minimal same-side energy

AdS/QCD

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Power-law exponent $n(x_T)$ for $\pi^0$ and $h$ spectra in central and peripheral Au+Au collisions at $\sqrt{s_{NN}} = 130$ and 200 GeV


Proton production dominated by color-transparent direct high $n_{\text{eff}}$ subprocesses