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
### 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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AdS/QCD

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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)

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

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

Gluon Exchange
(Van der Waal -- Landshoff)

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

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

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AdS/QCD

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

Quark Interchange

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

Non-linear Regge behavior:

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

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

Exchange of common $u$ quark

$$M_{QIM} = \int d^2 k_\perp dx \, \psi_C^\dagger \psi_D^\dagger \Delta \psi_A \psi_B$$

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)

University of Minnesota, Minneapolis, Minnesota 55455

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.: $\pi^\pm p \rightarrow p\pi^\pm, \rho^\pm, \pi^+\Delta^\pm, K^+\Sigma^\pm, (\Lambda^0/\Sigma^0)K^0, K^\pm p \rightarrow pK^\pm; p^\pm p \rightarrow pp^\pm$. 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.

\[ \pi^\pm p \rightarrow p\pi^\pm, \]
\[ K^\pm p \rightarrow pK^\pm, \]
\[ \pi^\pm p \rightarrow \rho^\pm, \]
\[ \pi^\pm p \rightarrow \pi^+\Delta^\pm, \]
\[ \pi^\pm p \rightarrow K^+\Sigma^\pm, \]
\[ \pi^- p \rightarrow \Lambda^0K^0, \Sigma^0K^0, \]
\[ p^\pm p \rightarrow pp^\pm. \]
Light-Front Wavefunctions

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

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

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
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$^{e,a,f}$
Hadron Optics

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

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

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

DVCS Amplitude using holographic QCD meson LFWF

\[ \Lambda_{QCD} = 0.32 \]

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S. J. Brodsky\textsuperscript{a}, D. Chakrabarti\textsuperscript{b}, A. Harindranath\textsuperscript{c}, A. Mukherjee\textsuperscript{d}, J. P. Vary\textsuperscript{e, a, f}
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
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 sum rules

• Exclusive weak decay amplitudes

• Single spin asymmetries: Role if 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.
Single-spin asymmetries

Pseudo-\(T\)-Odd

\[ i \vec{S}_p \cdot \vec{q} \times \vec{p}_q \]

Leading-Twist Sivers Effect

Light-Front Wavefunction

\(S\) and \(P\)-Waves

D. S. Hwang, I. A. Schmidt, sjb

Stan Brodsky, SLAC

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Final-State Interactions Produce T-Odd (Sivers Effect)

- Bjorken Scaling!
- Arises from Interference of Final-State Coulomb Phases in S and P waves
- Relate to the quark contribution to the target proton anomalous magnetic moment

$\vec{S} \cdot \vec{p}_{jet} \times \vec{q}$

Hwang, Schmidt, sjb; Burkardt

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Final-State Interactions Produce Pseudo $T$-Odd (Sivers Effect)

- Leading-Twist Bjorken Scaling!
- Requires nonzero orbital angular momentum of quark! $i \vec{S} \cdot \vec{p}_{jet} \times \vec{q}$
- Arises from the interference of Final-State QCD Coulomb phases in $S$- and $P$- waves; Wilson line effect; gauge independent
- Unexpected QCD Effect -- thought to be zero!
- Relate to the quark contribution to the target proton anomalous magnetic moment and final-state QCD phases
- QCD Coulomb phase at soft scale
- Measure in jet trigger or leading hadron
- Sum of Sivers Functions for all quarks and gluons vanishes. (Zero gravito-anomalous magnetic moment: $B(\alpha) = 0$)
First evidence for non-zero Sivers function!

$\Rightarrow$ presence of non-zero quark orbital angular momentum!

Positive for $\pi^+$...
Consistent with zero for $\pi^-$...

Gamberg: Hermes data compatible with BHS model

Schmidt, Lu: Hermes charge pattern follow quark contributions to anomalous moment

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Single Spin Asymmetry In the Drell Yan Process
\[ \vec{S}_p \cdot \vec{p} \times \vec{q}_{\gamma^*} \]
Quarks Interact in the Initial State
Interference of Coulomb Phases for \( S \) and \( P \) states
Produce Single Spin Asymmetry [Siver’s Effect]Proportional to the Proton Anomalous Moment and \( \alpha_s \).
Opposite Sign to DIS! No Factorization

Collins; Hwang, Schmidt. sjb
DY $\cos 2\phi$ correlation at leading twist from double ISI
DY $\cos 2\phi$ correlation at leading twist from double ISI
Anomalous effect from Double ISI in Massive Lepton Production

- Leading Twist, valence quark dominated
- Violates Lam-Tung Relation!
- Not obtained from standard PQCD subprocess analysis
- Normalized to the square of the single spin asymmetry in semi-inclusive DIS
- No polarization required
- Challenge to standard picture of PQCD Factorization

\[ \cos 2\phi \text{ correlation} \]
Double Initial-State Interactions generate anomalous $\cos 2\phi$:

Drell-Yan planar correlations

$$\frac{1}{\sigma} \frac{d\sigma}{d\Omega} \propto \left( 1 + \lambda \cos^2 \theta + \mu \sin 2\theta \cos \phi + \frac{\nu}{2} \sin^2 \theta \cos 2\phi \right)$$

PQCD Factorization (Lam Tung): $1 - \lambda - 2\nu = 0$

$$\frac{\nu}{2} \propto h_1^+(\pi) h_1^+(N) .$$

\(\pi N \rightarrow \mu^+ \mu^- X\) NA10

Violates Lam-Tung relation!

Model: Boer, Hwang, sjb

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Problem for factorization when both ISI and FSI occur
Factorization is violated in production of high-transverse-momentum particles in hadron-hadron collisions


The exchange of two extra gluons, as in this graph, will tend to give non-factorization in unpolarized cross sections.
Remarkable observation at HERA

10% to 15% of DIS events are diffractive!

Fraction $r$ of events with a large rapidity gap, $\eta_{\text{max}} < 1.5$, as a function of $Q^2_{\text{DA}}$ for two ranges of $x_{\text{DA}}$. No acceptance corrections have been applied.

In a large fraction ($\sim 10-15\%$) of DIS events, the proton escapes intact, keeping a large fraction of its initial momentum.

This leaves a large rapidity gap between the proton and the produced particles.

The $t$-channel exchange must be color singlet $\rightarrow$ a pomeron??
Diffractive Structure Function $F_2^D$

Diffractive inclusive cross section

$$
\frac{d^3 \sigma_{NC}^{diff}}{dx_P \, d\beta \, dQ^2} \propto \frac{2\pi \alpha_s^2}{xQ^4} \, F_2^D(3) (x_P, \beta, Q^2)
$$

$$
F_2^D (x_P, \beta, Q^2) = f(x_P) \cdot F_2^{IP} (\beta, Q^2)
$$

extract DPDF and $xg(x)$ from scaling violation

Large kinematic domain $3 < Q^2 < 1600 \text{ GeV}^2$
Precise measurements sys 5%, stat 5–20%
Final-State Interaction Produces Diffractive DIS

Quark Rescattering

Hoyer, Marchal, Peigne, Sannino, SJB (BHM Enberg, Hoyer, Ingelman, SJB
Hwang, Schmidt, SJB

Low-Nussinov model of Pomeron

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QCD Mechanism for Rapidity Gaps

Wilson Line: $\Psi(y) \int_0^y dx \, e^{iA(x) \cdot dx} \Psi(0)$

Reproduces lab-frame color dipole approach
Final State Interactions in QCD

Feynman Gauge

Light-Cone Gauge

Result is Gauge Independent
Integration over on-shell domain produces phase $i$

Need Imaginary Phase to Generate Pomeron

Need Imaginary Phase to Generate T-Odd Single-Spin Asymmetry

Physics of FSI not in Wavefunction of Target
Physics of Rescattering

- Sivers Asymmetry and Diffractive DIS: New Insights into Final State Interactions in QCD
- Origin of Hard Pomeron
- Structure Functions not Probability Distributions!
- T-odd SSAs, Shadowing, Antishadowing
- Diffractive dijets/ trijets, doubly diffractive Higgs
- Novel Effects: Color Transparency, Color Opaqueness, Intrinsic Charm, Odderon
• Diffractive DIS

• Non-Unitary Correction to DIS: Structure functions are not probability distributions

• Nuclear Shadowing, Antishadowing -- Not in Target WF

• Single Spin Asymmetries -- opposite sign in DY and DIS

• DY $\cos 2\phi$ distribution at leading twist from double ISI -- not given by PQCD factorization -- breakdown of factorization!

• Wilson Line Effects not 1 even in LCG

• Must correct hard subprocesses for initial and final-state soft gluon attachments

• Corrections to Handbag Approximation in DVCS!
“Dangling Gluons”

- Diffractive DIS
- Non-Unitary Correction to DIS: Structure functions are not probability distributions
- Nuclear Shadowing, Antishadowing
- Single Spin Asymmetries -- opposite sign in DY and DIS
- DY $\cos 2\phi$ correlation at leading twist from double ISI--not given by standard PQCD factorization
- Wilson Line Effects persist even in LCG
- Must correct hard subprocesses for initial and final-state soft gluon attachments -- Ji gauge link, Kovchegov gauge
Light-Front QCD Phenomenology

• Hidden color, Intrinsic glue, sea, Color Transparency

• Near Conformal Behavior of LFWFs at Short Distances; PQCD constraints

• Vanishing anomalous gravitomagnetic moment

• Relation between edm and anomalous magnetic moment

• Cluster Decomposition Theorem for relativistic systems

• OPE: DGLAP, ERBL evolution; invariant mass scheme
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**
Outlook

- Only one scale $\Lambda_{QCD}$ determines hadronic spectrum (slightly different for mesons and baryons).
- Ratio of Nucleon to Delta trajectories determined by zeroes of Bessel functions.
- String modes dual to baryons extrapolate to three fermion fields at zero separation in the AdS boundary.
- Only dimension 3, $\frac{9}{2}$ and 4 states $\bar{q}q$, $qqq$, and $gg$ appear in the duality at the classical level!
- Non-zero orbital angular momentum and higher Fock-states require introduction of quantum fluctuations.
- Simple description of space and time-like structure of hadronic form factors.
- Dominance of quark-interchange in hard exclusive processes emerges naturally from the classical duality of the holographic model. Modified by gluonic quantum fluctuations.
- Covariant version of the bag model with confinement and conformal symmetry.
Novel Heavy Flavor Physics

- LFWFS -- remarkable model from AdS/CFT
- AdS/CFT: Hadron Spectra and Dynamics, Counting Rules
- Intrinsic Charm and Bottom: rigorous prediction of QCD
- B decays: Many Novel QCD Effects
- Exclusive Channels: QCD at Amplitude Level
- Test B-analyses in other hard exclusive reactions, such as two-photon reactions
- Initial and Final State QCD Interactions -- Breakdown of QCD Factorization in Heavy Quark Hadroproduction!
- Renormalization scale not arbitrary
A Few References: Bottom-up-Approach

- Derivation of dimensional counting rules of hard exclusive glueball scattering in AdS/CFT:
  Polchinski and Strassler, hep-th/0109174.

- Deep inelastic scattering in AdS/CFT:
  Polchinski and Strassler, hep-th/0209211.

- Unified description of the soft and hard pomeron in AdS/CFT:
  Brower, Polchinski, Strassler and Tan, hep-th/0603115.

- Hadron couplings and form factors in AdS/CFT:
  Hong, Yoon and Strassler, hep-th/0409118.

- Low lying meson spectra, chiral symmetry breaking and hadron couplings in AdS/QCD (Emphasis on axial and vector currents)
  Erlich, Katz, Son and Stephanov, hep-ph/0501128,
• Gluonium spectrum (top-bottom):
  Csaki, Ooguri, Oz and Terning, hep-th/9806021; de Mello Kock, Jevicki, Mihaiescu and Nuñez, hep-th/9806125; Csaki, Oz, Russo and Terning, hep-th/9810186; Minahan, hep-th/9811156; Brower, Mathur and Tan, hep-th/0003115, Caceres and Nuñez, hep-th/0506051.

• D3/D7 branes (top-bottom):

• Other aspects of high energy scattering in warped spaces:
  Giddings, hep-th/0203004; Andreev and Siegel, hep-th/0410131; Siopsis, hep-th/0503245.

• Strongly coupled quark-gluon plasma ($\eta/s = 1/4\pi$):
Counting rules, low lying meson and baryon spectra and form factors in AdS/CFT, holographic light front representation and mapping of string amplitudes to light-front wavefunctions, integrability and stability of AdS/CFT equations (Emphasis on hadronic quark constituents)

1. “Light-Front Dynamics and AdS/QCD: The Pion Form Factor in the Space- and Time-Like Regions”  
S. J. Brodsky and G. F. de Teramond  

2. “AdS/CFT and QCD”  
S. J. Brodsky and G. F. de Teramond  
arXiv:hep-th/0702205  
SLAC-PUB-12361(2007)  
*Invited talk at 2006 International Workshop on the Origin of Mass and Strong Coupling Gauge Theories (SCGT 06), Nagoya, Japan, 21-24 Nov 2006*

3. “Hadronic spectra and light-front wavefunctions in holographic QCD”  
S. J. Brodsky and G. F. de Teramond  

4. “Advances in light-front quantization and new perspectives for QCD from AdS/CFT”  
S. J. Brodsky and G. F. de Teramond  
*Invited talk at Workshop on Light-Cone QCD and Nonperturbative Hadron Physics 2005 (LC 2005), Cairns, Queensland, Australia, 7-15 Jul 2005*

5. “Hadron spectroscopy and wavefunctions in QCD and the AdS/CFT correspondence”  
S. J. Brodsky and G. F. de Teramond  
*Invited talk at 11th International Conference on Hadron Spectroscopy (Hadron05), Rio de Janeiro, Brazil, 21-26 Aug 2005*
6. “Applications of AdS/CFT duality to QCD”
S. J. Brodsky and G. F. de Teramond
Invited talk at International Conference on QCD and Hadronic Physics, Beijing, China, 16-20 Jun 2005

7. “Nearly conformal QCD and AdS/CFT”
G. F. de Teramond and S. J. Brodsky
SLAC-PUB-11375(2005)
Presented at 1st Workshop on Quark-Hadron Duality and the Transition to pQCD, Frascati, Rome, Italy, 6-8 Jun 2005

8. “The hadronic spectrum of a holographic dual of QCD”
G. F. de Teramond and S. J. Brodsky

9. “Baryonic states in QCD from gauge / string duality at large N(c)”
G. F. de Teramond and S. J. Brodsky
arXiv:hep-th/0409074
Presented at ECT* Workshop on Large Nc QCD 2004, Trento, Italy, 5-9 Jul 2004

10. “Light-front hadron dynamics and AdS/CFT correspondence”
S. J. Brodsky and G. F. de Teramond