**Single-spin asymmetries**

**Pseudo-\(T\)-Odd**

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

**Leading-Twist Sivers Effect**

**QCD \(S\)- and \(P\)-Coulomb Phases**

**Light-Front Wavefunction**

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

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

Stan Brodsky, SLAC

BNL
March 7, 2007

AdS/QCD
132
Final-State Interactions Produce $T$-Odd (Sivers Effect) $i \vec{S} \cdot \vec{p}_{jet} \times \vec{q}$

- 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
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: $B(\alpha) = 0$)

BNL
March 7, 2007

AdS/QCD

Stan Brodsky, SLAC
• 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

Stan Brodsky, SLAC
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
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

Boer, Hwang, sjb

- 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

$\cos 2\phi$ correlation
Double Initial-State Interactions generate anomalous $\cos 2\phi$:

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

Drell-Yan planar correlations

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

\[ \nu(Q_T) \]

Violates Lam-Tung relation!
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.
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.
Remarkable observation at HERA

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

This leaves a large \textit{rapidity gap} between the proton and the produced particles.

The \textit{t}-channel exchange must be \textit{color singlet} $\rightarrow$ a 
\textit{pomeron}??

\section*{Diffractive Deep Inelastic Lepton-Proton Scattering}
Diffractive Structure Function $F_2^D$

Diffractive inclusive cross section

$$\frac{d^3 \sigma^{diff}}{dx_{IP} \, d\beta \, dQ^2} \propto \frac{2\pi \alpha^2}{xQ^4} \, F_2^D(x_{IP}, \beta, Q^2)$$

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

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

Large kinematic domain $3 < Q^2 < 1600$ 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

BNL
March 7, 2007

AdS/QCD
Stan Brodsky, SLAC
QCD Mechanism for Rapidity Gaps

Wilson Line:

\[
\overline{\psi}(y) \int_0^y dx \ e^{iA(x) \cdot dx} \ \psi(0)
\]

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

\[ \gamma^* \rightarrow q + k_1 + k_2 \]

**Feynman Gauge**

**Light-Cone Gauge**

Result is Gauge Independent

--

BNL
March 7, 2007

AdS/QCD

Stan Brodsky, SLAC
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
• 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!

Hoyer, Marchal, Peigne, Sannino, sjb
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!

\[ p \ A \rightarrow \text{jet jet jet jet } A' \text{ at RHIC} \]
Two-gluon exchange measures the second derivative of the pion light-front wavefunction

\[ b_\perp \sim 0 \left( \frac{1}{k_\perp} \right) \]

\[ \pi \rightarrow q, \bar{q} \]

\[ \pi \rightarrow q, \bar{q} \]

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

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

**QCD COLOR Transparency**

$$M_A = A \ M_N$$

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

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
• Fully coherent interactions between pion and nucleons.

• Emerging Di-Jets do not interact with nucleus.

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

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

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

Nuclear coherence

\[ F^2_A(q^2_{\perp}) \sim e^{-\frac{1}{3}R_A^2 q^2_{\perp}} \]
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>$1.64 \pm 0.06$</td>
<td>$1.25$</td>
</tr>
<tr>
<td>$1.5 &lt; k_t &lt; 2.0$</td>
<td>$1.52 \pm 0.12$</td>
<td>$1.45$</td>
</tr>
<tr>
<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!

Ashery E791

Factor of 7
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

BNL
March 7, 2007

AdS/QCD
158

Stan Brodsky, SLAC
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

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

Ashery E791

BNL
March 7, 2007
Linear potential \((m=0.22 \text{ GeV}, \beta=0.3659 \text{ GeV})\)

HO potential \((m=0.25 \text{ GeV}, \beta=0.3194 \text{ GeV})\)

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

\(\phi_{AdS/CFT} \sim [x(1-x)]^{1/2}\)

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

**AdS/CFT:**

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

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

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

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

Normalized to \(f_\pi\)

---

**BNL**
March 7, 2007

**AdS/QCD**

**Stan Brodsky, SLAC**
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)

BNL
March 7, 2007

AdS/QCD

Stan Brodsky, SLAC
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)

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

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

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:
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:

\[ \alpha_R(t) \to -1 \]
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

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

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

Brookhaven National Laboratory, Upton, New York 11973

and

S. Gushue (e) and J. J. Russell

Southeastern Massachusetts University, North Dartmouth, Massachusetts 02747

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

\[
\begin{align*}
\pi^\pm p & \rightarrow p\pi^\pm, \\
K^\pm p & \rightarrow pK^\pm, \\
\pi^\pm p & \rightarrow p\rho^\pm, \\
\pi^\pm p & \rightarrow \pi^\pm\Delta^\pm, \\
\pi^\pm p & \rightarrow K^\pm\Sigma^\pm, \\
\pi^- p & \rightarrow \Lambda^0K^0, \Sigma^0K^0, \\
p^\pm p & \rightarrow pp^\pm.
\end{align*}
\]
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.

**Space-time picture of DVCS**

\[ \sigma = \frac{1}{2} x^- P^+ \]

\[ x^+ = x_\perp = 0 \]

**Measure $x^-$ distribution from DVCS:**

**Take Fourier transform of skewness,**

\[ \xi = \frac{Q^2}{2 p.q} \]

**the longitudinal momentum transfer**

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

---

**BNL**
March 7, 2007

**AdS/QCD**

169

**Stan Brodsky, SLAC**
Hadron Optics

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

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

DVCS Amplitude using holographic QCD meson LFWF

\[ \Lambda_{QCD} = 0.32 \]

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

GeV units

BNL
March 7, 2007

AdS/QCD

Stan Brodsky, SLAC
• LFWFS -- remarkable model from AdS/CFT

• AdS/CFT: Hadron Spectra and Dynamics, Counting Rules

• Intrinsic Charm and Bottom: rigorous prediction of QCD

• Heavy Hadron decays: Many Novel QCD Effects

• Exclusive Channels: QCD at Amplitude Level

• Initial and Final State QCD Interactions -- Breakdown of QCD Factorization in Heavy Quark Hadroproduction!

• Renormalization scale not arbitrary
Challenging Conventional Wisdom

- Renormalization scale **is not arbitrary; multiple scales, unambiguous at given order**

- Heavy quark distributions **do not derive exclusively from DGLAP or gluon splitting -- component intrinsic to hadron wavefunction**

- Initial and final-state interactions **are not always power suppressed in a hard QCD reaction**

- LFWFS are universal, but measured nuclear parton distributions **are not universal -- antishadowing is flavor dependent**

- Hadroproduction at large transverse momentum **does not derive exclusively from 2 to 2 scattering subprocesses**
AdS/CFT and QCD

Bottom-Up Approach

- Nonperturbative derivation of dimensional counting rules of hard exclusive glueball scattering for gauge theories with mass gap dual to string theories in warped space:
  Polchinski and Strassler, hep-th/0109174.

- Deep inelastic structure functions at small $x$:
  Polchinski and Strassler, hep-th/0209211.

- Derivation of power falloff of hadronic light-front Fock wave functions, including orbital angular momentum, matching short distance behavior with string modes at AdS boundary:
  Brodsky and de Téramond, hep-th/0310227.

- Low lying hadron spectra, chiral symmetry breaking and hadron couplings in AdS/QCD:

E. van Beveren et al.