Single-spin asymmetries

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

\textbf{Pseudo-}T\textbf{-}Odd

\textbf{Light-Front Wavefunction}
\textbf{S and P- Waves}

Leading-Twist Sivers Effect

QCD S- and P- Coulomb Phases

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

Stan Brodsky, SLAC

\textbf{AdS/QCD} 139
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
Final-State Interactions Produce Pseudo T-Odd (Sivers Effect)

• Leading-Twist Bjorken Scaling!

• Requires nonzero orbital angular momentum of quark! $\mathbf{i} \, \vec{S} \cdot \vec{p}_{jet} \times \vec{q}$

• 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: $B(\sigma) = 0$)
In the context of the quark-parton model, the virtual-photon asymmetry $A_{U \perp T}$ can be represented in terms of parton distributions at the parton level with PYTHIA6 Monte Carlo simulation. The figure was taken from Ref.[9].

Sivers asymmetry from HERMES

- 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
The differential cross section is written as

\[ \frac{d^2 \sigma}{d^2 \mathbf{t}} = \text{terms involving } \hat{P} \cos 2\phi \]

We assume that this process is suppressed by Sudakov effects. In the next-to-leading order, similar terms can be expected to be small.

In the leading order, the dependence on the momentum transfer squared \( t \) and the twist of the relevant operators are expected to be small. We will discuss these terms in more detail later.

The dependence on the azimuthal angle of the outgoing particles, which arises in the calculation of the lepton asymmetry, is an important aspect of the process.

Anomaly extractions at RHIC and the Fermilab Tevatron on single-spin asymmetries can be explained by the QCD factorization-breaking effects. In the case of SIDIS, this can imply significant enhancements.

These expectations are in good agreement with the recent NA10 data.

The interplay between the Sudakov effects, the transverse momentum dependence, and the small angles at which these interactions occur, is expected to lead to very clean dependencies of the data on the twist of the interactions.

The systematic effects of the twist are expected to be small.

In the framework of the AdS/QCD approach, calculations of the Drell-Yan process with nonzero transverse momentum can be performed for a single lepton direction, which is in good agreement with the experimental data.

Furthermore, for two lepton directions, systematic effects of twist are expected to be small. However, the dependence on the momentum transfer squared \( t \) and the twist of the relevant operators is expected to be small. We will discuss these terms in more detail later.

In the framework of this approach, the dependence on the azimuthal angle of the outgoing particles, which arises in the calculation of the lepton asymmetry, is an important aspect of the process.

The interplay between the Sudakov effects, the transverse momentum dependence, and the small angles at which these interactions occur, is expected to lead to very clean dependencies of the data on the twist of the interactions. This is in good agreement with the recent NA10 data.

In the framework of the AdS/QCD approach, calculations of the Drell-Yan process with nonzero transverse momentum for a single lepton direction can be performed, which is in good agreement with the experimental data.

Furthermore, for two lepton directions, systematic effects of twist are expected to be small. However, the dependence on the momentum transfer squared \( t \) and the twist of the relevant operators is expected to be small. We will discuss these terms in more detail later.

In the framework of this approach, the dependence on the azimuthal angle of the outgoing particles, which arises in the calculation of the lepton asymmetry, is an important aspect of the process.
**Anomalous effect from Double ISI in Massive Lepton Production**

Boer, Hwang, sjb

\[
\cos 2\phi \ \text{correlation}
\]

- 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
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): $1 - \lambda - 2\nu = 0$

\[ \frac{\nu}{2} \propto h_1^\perp (\pi) h_1^\perp (N) \]

\[ \pi N \rightarrow \mu^+ \mu^- X \quad NA10 \]

---

**Violates Lam-Tung relation!**

**INT**
March 28, 2008

**AdS/QCD**

**Stan Brodsky, SLAC**
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 $Q_{\text{DA}}^2$ 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 \textit{rapidity gap} between the proton and the produced particles.

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

**DDIS**

**Diffractive Deep Inelastic Lepton-Proton Scattering**
Diffractive Structure Function $F_2^D$

**Diffractive inclusive cross section**

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

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

**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

INT
March 28, 2008

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

Hoyer, Marchal, Peigne, Sannino, sjb
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
Physics of Rescattering

- 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

INT March 28, 2008

AdS/QCD

158

Stan Brodsky, SLAC
“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
\[ |p, S_z > = \sum_{n=3}^{\infty} \Psi_n(x_i, \vec{k}_\perp i, \lambda_i) |n; \vec{k}_\perp i, \lambda_i > \]

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

The Light Front Fock State Wavefunctions
\[ \Psi_n(x_i, \vec{k}_\perp i, \lambda_i) \]
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.

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

**Intrinsic heavy quarks**
\[ \bar{u}(x) \neq \bar{d}(x) \]
\[ \bar{s}(x) \neq s(x) \]

**Mueller: BFKL DYNAMICS**

**AdS/QCD**

**Fixed LF time**

*Stan Brodsky, SLAC*
Light Antiquark Flavor Asymmetry

- Naïve Assumption from gluon splitting:

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

- E866/NuSea (Drell-Yan)
|uudc\bar{c} > Fluctuation in Proton
QCD: Probability $\sim \frac{\Lambda_{QCD}^2}{M_Q^2}$

|e^+e^-\ell^+\ell^- > Fluctuation in Positronium
QED: Probability $\sim \left(\frac{m_e\alpha}{M^4_\ell}\right)$

OPE derivation - M.Polyakov et al.

\[ < p | \frac{G_{\mu\nu}}{m_Q^2} | p > \text{ vs. } < p | \frac{F_{\mu\nu}}{m_\ell^4} | p > \]

\[ c\bar{c} \text{ in Color Octet} \]

Distribution peaks at equal rapidity (velocity)
Therefore heavy particles carry the largest momentum fractions

\[ \hat{x}_i = \frac{m_{\perp i}}{\sum_j^n m_{\perp j}} \]

**High x charm!**

Hoyer, Peterson, Sakai, sbj
**Intrinsic Heavy-Quark Fock States**

- Rigorous prediction of QCD, OPE
- Color - Octet + Color - Octet Fock State!
- Probability \( P_{Q\bar{Q}} \propto \frac{1}{M_Q^2} \) \( P_{Q\bar{Q}Q\bar{Q}} \sim \alpha_s^2 P_{Q\bar{Q}} \) \( P_{c\bar{c}/p} \approx 1\% \)
- Large Effect at high \( x \)

- Greatly increases kinematics of colliders such as Higgs production (Kopeliovich, Schmidt, Soffer, sjb)

- Severely underestimated in conventional parameterizations of heavy quark distributions (Pumplin, Tung)

- Many empirical tests
Measure $c(x)$ in Deep Inelastic Lepton-Proton Scattering

Hoyer, Peterson, SJB

INT
March 28, 2008

AdS/QCD

Stan Brodsky, SLAC
First Evidence for Intrinsic Charm


DGLAP / Photon-Gluon Fusion: factor of 30 too small

Measurement of Charm Structure Function
• EMC data: \( c(x, Q^2) > 30 \times \text{DGLAP} \)
  \[ Q^2 = 75 \text{ GeV}^2, \; x = 0.42 \]

• High \( x_F \) pp \( \rightarrow \) J/\(\psi\)X

• High \( x_F \) pp \( \rightarrow \) J/\(\psi\)J/\(\psi\)X

• High \( x_F \) pp \( \rightarrow \) \(\Lambda_c\)X

• High \( x_F \) pp \( \rightarrow \) \(\Lambda_b\)X

• High \( x_F \) pp \( \rightarrow \) \(\Xi(c\bar{c}d)\)X (SELEX)
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
String Theory

AdS/CFT

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

AdS/QCD

Conformal behavior at short distances + Confinement at large distance

Semi-Classical QCD / Wave Equations

Holography

Boost Invariant 3+1 Light-Front Wave Equations

Integrable!

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

Hadron Spectra, Wavefunctions, Dynamics

Goal: First Approximant to QCD

Counting rules for Hard Exclusive Scattering Regge Trajectories
QCD at the Amplitude Level

Stan Brodsky, SLAC

March 28, 2008
Light-Front Quantization of the Standard Model

\[ \phi(x) = \frac{1}{\sqrt{2}} \nu + \varphi = \frac{1}{\sqrt{2}} \left( [\nu + h(x)] + i\eta(x) \right) \]

No Higgs VEV!

Goldstone field

\[ k^+ = 0 \text{ zero mode} \]

A Unitary and renormalizable theory of the standard model in ghost free light cone gauge.

P. Srivastava and sjb  
hep-ph/0202141

Decoupling of gravity to the Higgs zero mode
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.
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, Mihailescu 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)  

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

INT  
March 28, 2008  
AdS/QCD  
176  
Stan Brodsky, SLAC
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

INT
March 28, 2008

AdS/QCD

Stan Brodsky, SLAC