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

Hwang, Schmidt. sjb; Burkardt
Final-State Interactions Produce Pseudo $T$-Odd (Sivers Effect)

- Leading-Twist Bjorken Scaling!

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

- 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: $B(0) = 0$)
First evidence for non-zero Sivers function!

• \( L_z \neq 0 \) is also needed to produce a T-odd effect!

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
DY $\cos 2\phi$ correlation at leading twist from double ISI

Boer, Hwang, sjb
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
Double Initial-State Interactions

generate anomalous \( \cos 2\phi \) : 

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

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

Double Initial-State Interactions (ISI) 

\( \frac{\nu}{2} \propto h^\perp_1(\pi) h^\perp_1(N) \).

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

NA10

\( \nu(Q_T) \)

Violates Lam-Tung relation!

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AdS/QCD

Boer, Hwang, sjb

Stan Brodsky, SLAC & IPPP
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.
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 $Q^2_{DA}$ for two ranges of $x_{DA}$. 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 $F_2^D$

**Large Rapidity Gap**

Diffractive inclusive cross section

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

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

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

Large kinematic domain $3 < Q^2 < 1600 \text{ GeV}^2$

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: \( \bar{\psi}(y) \int_0^y dx e^{iA(x) \cdot dx} \psi(0) \)

Reproduces lab-frame color dipole approach

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Final State Interactions in QCD

\[ \gamma^* \]

\[ q \]

\[ k_1 \]

\[ k_2 \]

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

• $\cos 2\phi$ 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
“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

Bodwin, Lepage, sjb
Hoyer, Marchal, Peigne, Sannino, sjb
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
\[ |p, S_z \rangle = \sum_{n=3} \Psi_n(x_i, \vec{k}_{\perp i}, \lambda_i) |n; \vec{k}_{\perp i}, \lambda_i \rangle \]

**sum over states with n=3, 4, ...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.

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

**Intrinsic heavy quarks**

\( \bar{u}(x) \neq \bar{d}(x) \)

\( \bar{s}(x) \neq s(x) \)

**Mueller: BFKL DYNAMICS**

**Fixed LF time**

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**AdS/QCD**

**Stan Brodsky, SLAC & IPPP**
• Naïve Assumption from gluon splitting:

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

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

Fluctuation in Positronium
QED: Probability $\sim \frac{(m_\ell \alpha)^4}{M_\ell^4}$

OPE derivation - M. Polyakov et al.

$\langle p\frac{G^{\mu\nu}}{m_Q^2}|p\rangle \text{ vs. } \langle p\frac{F^{\mu\nu}}{m_\ell^4}|p\rangle$

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

$\hat{x}_i = \frac{m_{\perp i}}{\sum_j n_j m_{\perp j}}$

High $x$ charm!

Hoyer, Peterson, Sakai, sjb
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

First Evidence for Intrinsic Charm

DGLAP / Photon-Gluon Fusion: factor of 30 too small
- 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 \( x_F \) \( pp \rightarrow \Xi(c\bar{c}d)X \ (\text{SELEX}) \)
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
Goal: First Approximant to QCD
Counting rules for Hard
Exclusive Scattering
Regge Trajectories
QCD at the Amplitude Level

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

Conformal behavior at short
distances
+ Confinement at large
distance

Holography
Integrable!

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

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AdS/QCD
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r66
Light-Front Quantization of the Standard Model

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

No Higgs VEV!

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


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 $\bar qq, qqq$, 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.
Light-Front Holography and AdS/QCD Correspondence.

Light-Front Dynamics and AdS/QCD Correspondence: Gravitational Form Factors of Composite Hadrons.

AdS/CFT and Light-Front QCD.

AdS/CFT and Exclusive Processes in QCD.

Light-Front Dynamics and AdS/QCD Correspondence: The Pion Form Factor in the Space- and Time-Like Regions.
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
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  
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)