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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AdS/QCD

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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
Measurement of Nuclear Transparency for the $A(e, e'\pi^+)\,\text{Reaction}$

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

B. Clasie, et al., Jlab

PRL 99, 242502 (2007)

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GPDs & Deeply Virtual Exclusive Processes
- New Insight into Nucleon Structure

Deeply Virtual Compton Scattering (DVCS)

\[ \frac{1}{2} - J^G = \frac{1}{2} \int_{-1}^{1} x dx \left[ H^q(x, \xi, 0) + E^q(x, \xi, 0) \right] \]

The position of the struck quark differs by $x^-$ in the two wave functions.

**Space-time picture of DVCS**

Measure $x$-distribution from DVCS:
Take Fourier transform of skewness, the longitudinal momentum transfer

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

$$x^+ = x^\perp = 0$$

$$\zeta = \frac{Q^2}{2 p \cdot q}$$

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

\[ \psi(\sigma, b_{\perp}) \]

3-dimensional photograph: meson LFWF at fixed LF Time

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\[ \sigma = x^- = ct - x^3 \]
\[ x^+ = ct + x^3 \]

G. de Teramond
SJB

Stan Brodsky, SLAC
The Fourier Spectrum of the DVCS amplitude in $\sigma$ space for different fixed values of $|b_\perp|$.

$$A(\sigma, b_\perp) = \frac{1}{2\pi} \int d\zeta e^{i\sigma\zeta} \tilde{A}(b_\perp, \zeta)$$

$$\sigma = \frac{1}{2} x^- P^+ \quad \zeta = \frac{Q^2}{2p \cdot q}$$

$\Lambda_{QCD} = 0.32$

**DVCS Amplitude using holographic QCD meson LFWF**
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)

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

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

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\[ \boxed{AdS/QCD} \]

Stan Brodsky, SLAC
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:

\[ \alpha_R(t) \rightarrow -1 \]
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.: $\pi^\pm p \rightarrow p\pi^\pm$, $p\rho^\pm$, $\pi^\pm \Delta^\pm$, $K^+\Sigma^\pm$, $(\Lambda^0/\Sigma^0)K^0$, $K^\pm p \rightarrow pK^\pm$; $p^\pm p \rightarrow pp^\pm$. 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.
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.
$pp \rightarrow HX$ at high $p_T$

Hadron created from jet fragmentation

$E \frac{d\sigma}{d^3p}(pN \rightarrow \pi X) = \frac{F(x_T, \theta_{CM})}{p_T^{n_{eff}}} n_{active} = 4$

$n_{eff} = 2n_{active} - 4$

$n_{eff} = 4$
Particle ratio changes with centrality!

Protons less absorbed in nuclear collisions than pions!


Ratio

proton/pion

$\pi^\pm / \pi^0$

$\sqrt{s} = 53$ GeV, ISR

Peripheral

Central

Au+Au 0-10%

Au+Au 20-30%

Au+Au 60-92%

p+p,

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\[ \text{Ratio} \]

\[ \text{proton/pion} \]

\[ \pi^\pm / \pi^0 \]

\[ \text{Central} \]

\[ \text{Peripheral} \]

\[ \text{Protons less absorbed in nuclear collisions than pions!} \]
$pp \rightarrow HX$ at high $p_T$

Hadron created from jet fragmentation

PQCD Factorization: $p/\pi$ ratio universal. Same as $e^+e^- \rightarrow HX$. 

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Particle ratios change with centrality!

PQCD Factorization: $p/\pi$ ratio universal. Same as $e^+e^- \rightarrow HX$.

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Baryon can be made directly within hard subprocess

Coalescence within hard subprocess

Collision can produce 3 collinear quarks

Small color-singlet
Color Transparent
Minimal same-side energy

Bjorken
Blankenbecler, Gunion, sjb
Berger, sjb
Hoyer, et al: Semi-Exclusive

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Clear evidence for higher-twist contributions

\[ E \frac{d\sigma}{d^3p} (pp \rightarrow HX) = \frac{F(x_T, \theta_{cm} = \pi/2)}{p_T^n} \]

\[ x_T = 2p_T/\sqrt{s} \]

J. W. Cronin, SSI 1974

\[ p \quad \bar{p} \quad \text{elastic} \]

\[ \pi \]

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AdS/QCD

Stan Brodsky, SLAC
Protons produced in AuAu collisions at RHIC do not exhibit clear scaling properties in the available \( p_T \) range. Shown are data for central (0 – 5%) and for peripheral (60 – 90%) collisions.

**Leading twist:**

\[
E \frac{d\sigma}{d^3p} (pN \rightarrow pX) = \frac{F(x_T, \theta_{CM})}{p_T^{n_{eff}}} x_T
\]

**Continuous rise of \( n_{eff} \) with \( x_T \).**

\( n_{eff} = 4 \)

**RHIC**

---

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AdS/QCD

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

Baryon Anomaly: Evidence for Direct, Higher-Twist Subprocesses

- Explains anomalous power behavior at fixed $x_T$
- Protons more likely to come from direct higher-twist subprocess than pions
- Protons less absorbed than pions in central nuclear collisions because of color transparency
- Predicts increasing proton to pion ratio in central collisions
- Proton power $n_{\text{eff}}$ increases with centrality since leading twist contribution absorbed
- Fewer same-side hadrons for proton trigger at high centrality
- Exclusive-inclusive connection at $x_T = 1$
\[ \pi N \rightarrow \mu^+ \mu^- X \text{ at high } x_F \]

In the limit where \((1-x_F)Q^2\) is fixed as \(Q^2 \rightarrow \infty\)

Entire pion wave function contributes to hard process

Virtual photon is longitudinally polarized

Berger and Brodsky, PRL 42 (1979) 940
\[ \pi^- N \rightarrow \mu^+ \mu^- X \text{ at } 80 \text{ GeV/c} \]

\[ \frac{d\sigma}{d\Omega} \propto 1 + \lambda \cos^2 \theta + \rho \sin 2\theta \cos \phi + \omega \sin^2 \theta \cos 2\phi. \]

\[ \frac{d^2\sigma}{dx_\pi d\cos \theta} \propto x_\pi \left( (1 - x_\pi)^2 (1 + \cos^2 \theta) + \frac{4}{9} \frac{\langle k_T^2 \rangle}{M^2} \sin^2 \theta \right) \]

\[ \langle k_T^2 \rangle = 0.62 \pm 0.16 \text{ GeV}^2/c^2 \]

Dramatic change in angular distribution at large \( x_T \)

Example of a higher-twist direct subprocess

Chicago-Princeton Collaboration

Hadron Dynamics at the Amplitude Level

- LFWFS are the universal hadronic amplitudes which underlie structure functions, GPDs, exclusive processes.

- 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
• Quarks Reinteract in Final State

• Analogous to Coulomb phases, but not unitary

• Observable effects: DDIS, SSI, shadowing, antishadowing

• Structure functions cannot be computed from LFWFs computed in isolation

• Wilson line not 1 even in lcg
Single-spin asymmetries

Pseudo-$T$-Odd

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

Light-Front Wavefunction
$S$ and $P$-Waves

Leading Twist Sivers Effect

QCD $S$- and $P$-Coulomb Phases

D. S. Hwang,
I. A. Schmidt,
spb
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
- Sum of Sivers Functions for all quarks and gluons vanishes. (Zero gravitoanomalous magnetic moment)

\[ \vec{S} \cdot \vec{p}_{jet} \times \vec{q} \]

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

- Leading-Twist Bjorken Scaling!
- Requires nonzero orbital angular momentum of quark!
- 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: $B(\alpha) = 0$)
Final State Interaction Produces Diffractive DIS

Quark Rescattering

Hoyer, Marchal, Peigne, Sannino, SJB (BHM

Enberg, Hoyer, Ingelman, SJB

Hwang, Schmidt, SJB

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10% 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.

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
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
Novel Diffractive Phenomena and New Insights Into QCD from AdS/CFT

- Initial-state and final-state interactions from gluon-exchange, neglected in the parton model, have a profound effect on QCD hard-scattering reactions

- Leading-twist single-spin asymmetries

- Diffractive deep inelastic scattering

- Diffractive hard hadronic reactions

- Nuclear shadowing and antishadowing

- New “Exclusive Diffractive Mechanism” for high $x_F$ Higgs Production
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

- \( \text{DY} \cos 2\phi \) 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
Features of Light-Front Formalism

• Hidden Color Nuclear Wavefunction

• Color Transparency, Opaqueness

• Intrinsic glue, sea quarks, intrinsic charm

• Simple proof of Factorization theorems for hard processes (Lepage, sjb)

• Direct mapping to AdS/CFT (de Teramond, sjb)

• New Effective LF Equations (de Teramond, sjb)

• Light-Front Amplitude Generator
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

Integrable!

Holography

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

Hadron Spectra, Wavefunctions, Dynamics

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AdS/QCD
Stan Brodsky, SLAC
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
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

Pauli, Hornbostel, Hiller, McCartor, sjb
Vary, Harinandrath, Maris, sjb
Future QCD Experimental Programs: Hadron and Nuclear Physics

- GSI antiproton storage ring
- JLab 12 GeV electrons
- J-PARC Protons
- e-RHIC: electron/positron - proton/ion collider
- LHC
- ILC
- Super B Factory
A Theory of Everything Takes Place

String theorists have broken an impasse and may be on their way to converting this mathematical structure -- physicists’ best hope for unifying gravity and quantum theory -- into a single coherent theory.

I thought I had discovered the Theory of Everything
But everything canceled out!
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. E. van Beveren et al.

- Low lying hadron spectra, chiral symmetry breaking and hadron couplings in AdS/QCD:
• 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 ($\eta/s = 1/4\pi$):
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

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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