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):

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

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

Boer, Hwang, sjb

$\nu$ $\propto h_1^+(\pi) h_1^+(N)$

Violates Lam-Tung relation!

$\pi N \rightarrow \mu^+ \mu^- X$ NA10

$Q = 8 \text{ GeV}$

Model: Boer, Stan Brodsky, SLAC
Important Corrections from Initial and Final State Corrections

Sivers & Collins Odd-\(T\) Spin Effects, Co-planarity Correlations
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.
$\cos 2\phi$ correlation for quarkonium production at leading twist from double ISI
Enhanced by gluon color charge
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 *rapidity gap* between the proton and the produced particles.

The $t$-channel exchange must be *color singlet* $\rightarrow$ a pomeron??

**Diffractive Deep Inelastic Lepton-Proton Scattering**
Remarkable observation at HERA

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.

Diffractive Structure Function $F_2^D$

Diffractive inclusive cross section

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

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

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 (BHMPS)

Enberg, Hoyer, Ingelman, SJB

Hwang, Schmidt, SJB

Low-Nussinov model of Pomeron
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

\( q^+ = 0 \)

\( \gamma^* \)

\( X_g \)

\( \beta X_g \)

\( (1-\beta) X_g \)

\( \delta x \approx \frac{1}{v} \)

Rap Gap

Missouri S&T  Feb. 24, 2011  Novel Hadron Phenomena  Stan Brodsky, SLAC
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 and DDIS

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

Physics of FSI not in Wavefunction of Target
Nuclear Shadowing in QCD

Shadowing depends on understanding leading twist-diffraction in DIS

Nuclear Shadowing not included in nuclear LFWF!

Dynamical effect due to virtual photon interacting in nucleus
Anti-Shadowing

\[ F_2^{\text{Ca}}/F_2^{\text{D}} \]

\[ Q^2 = 5 \, \text{GeV}^2 \]


Missouri S&T   Feb. 24, 2011   Novel Hadron Phenomena   Stan Brodsky, SLAC
Anti-Shadowing

\[ F_2^{Ca/F_2} \]

\( Q^2 = 5 \text{ GeV}^2 \)

- EMC
- E136
- NMC
- E665

The one-step and two-step processes in DIS on a nucleus.

Coherence at small Bjorken $x_B$:
\[ \frac{1}{M x_B} = 2 \nu / Q^2 \geq L_A. \]

If the scattering on nucleon $N_1$ is via pomeron exchange, the one-step and two-step amplitudes are opposite in phase, thus diminishing the $\bar{q}$ flux reaching $N_2$.

→ Shadowing of the DIS nuclear structure functions.

**Observed HERA DDIS produces nuclear shadowing**
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

Antishadowing (Reggeon exchange) is not universal!

Schmidt, Yang, sjb
The one-step and two-step processes in DIS on a nucleus.

Coherence at small Bjorken $x_B$:

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**Anti-** Shadowing of the DIS nuclear structure functions.
Non-singlet Reggeon Exchange

Kuti-Weisskopf behavior
Origin of Regge Behavior of Deep Inelastic Structure Functions

$$F_{2p}(x) - F_{2n}(x) \propto x^{1/2}$$

Antiquark interacts with target nucleus at energy $$\hat{s} \propto \frac{1}{x_{bj}}$$

Regge contribution: $$\sigma_{\bar{q}N} \sim \hat{s}^{\alpha_R - 1}$$

Nonsinglet Kuti-Weisskoff $$F_{2p} - F_{2n} \propto \sqrt{x_{bj}}$$ at small $$x_{bj}$$.

Shadowing of $$\sigma_{\bar{q}M}$$ produces shadowing of nuclear structure function.
Reggeon Exchange

Phase of two-step amplitude relative to one step:

\[ \frac{1}{\sqrt{2}} (1 - i) \times i = \frac{1}{\sqrt{2}} (i + 1) \]

Constructive Interference

Depends on quark flavor!

Thus antishadowing is not universal

Different for couplings of \( \gamma^*, Z^0, W^\pm \)

Critical test: Tagged Drell-Yan
The one-step and two-step processes in DIS on a nucleus.

Coherence at small Bjorken $x_B$:
$$ \frac{1}{M x_B} = 2 \nu/Q^2 \geq L_A. $$

If the scattering on nucleon $N_1$ is via pomeron exchange, the one-step and two-step amplitudes are opposite in phase, thus diminishing the $\bar{q}$ flux reaching $N_2$.

Shadowing of the DIS nuclear structure functions.
$Q^2 = 5 \text{ GeV}^2$

**Extrapolations from NuTeV**

**SLAC/NMC data**

Scheinbein, Yu, Keppel, Morfin, Olness, Owens

Missouri S&T Feb. 24, 2011 Novel Hadron Phenomena Stan Brodsky, SLAC
Schmidt, Yang; sjb

Nuclear Antishadowing not universal!

Modifies NuTeV extraction of $\sin^2 \theta_W$

Test in flavor-tagged lepton-nucleus collisions
Predicted nuclear shadowing and antishadowing at $Q^2 = 1$ GeV$^2$

Shadowing and Antishadowing in Lepton-Nucleus Scattering

- Shadowing: **Destructive Interference** of Two-Step and One-Step Processes
  *Pomeron Exchange*

- Antishadowing: **Constructive Interference** of Two-Step and One-Step Processes!
  *Reggeon and Odderon Exchange*

- Antishadowing is Not Universal!
  Electromagnetic and weak currents: different nuclear effects!

**Can explain NuTeV result**
\[ Q^2 = 5 \text{ GeV}^2 \]

Extrapolations from NuTeV

SLAC/NMC data

\[ F_2^{\text{HeHe}}/F_2^{\text{D}} \]

Scheinbein, Yu, Keppel, Morfin, Olness, Owens
**LHC \( p-A \) Collisions**

**Leading-Twist Contribution to Hadron Production on Nuclei**

\[
G_{q/p}(x_1, p_\perp^2) \\
G_{q/A}(x_2, p_\perp^2) \simeq A^{\alpha(x_2)} G_{q/N}(x_2, p_\perp^2) \\
\]

\[
\frac{d\sigma}{d^3p/E}(pA \rightarrow \pi X) = A^{\alpha(x_2)} \frac{d\sigma}{d^3p/E}(pN \rightarrow \pi X)
\]

**Anti-shadowing is quark specific**

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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! *Not square of LFWFs*
- T-odd SSAs, Shadowing, Antishadowing
- Diffractive dijets/trijets, doubly diffractive Higgs
- Novel Effects: Color Transparency, Color Opaqueness, Intrinsic Charm, Odderon
<table>
<thead>
<tr>
<th><strong>Static</strong></th>
<th><strong>Dynamic</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>• Square of Target LFWFs</td>
<td>Modified by Rescattering: ISI &amp; FSI</td>
</tr>
<tr>
<td>• No Wilson Line</td>
<td>Contains Wilson Line, Phases</td>
</tr>
<tr>
<td>• Probability Distributions</td>
<td>No Probabilistic Interpretation</td>
</tr>
<tr>
<td>• Process-Independent</td>
<td>Process-Dependent - From Collision</td>
</tr>
<tr>
<td>• T-even Observables</td>
<td>T-Odd (Sivers, Boer-Mulders, etc.)</td>
</tr>
<tr>
<td>• No Shadowing, Anti-Shadowing</td>
<td>Shadowing, Anti-Shadowing, Saturation</td>
</tr>
<tr>
<td>• Sum Rules: Momentum and $J^z$</td>
<td>Sum Rules Not Proven</td>
</tr>
<tr>
<td>• DGLAP Evolution; mod. at large $x$</td>
<td>DGLAP Evolution</td>
</tr>
<tr>
<td>• No Diffractive DIS</td>
<td>Hard Pomeron and Odderon Diffractive DIS</td>
</tr>
</tbody>
</table>

\[
\Psi_{n}(x_i, \vec{k}_\perp i, \lambda_i) \quad 2
\]

**Image:** Diagram of particle interactions in static and dynamic processes.
Formation of Relativistic Anti-Hydrogen

Measured at CERN-LEAR and FermiLab

Munger, Schmidt, sjb

Coalescence of off-shell co-moving positron and antiproton.

Wavefunction maximal at small impact separation and equal rapidity

“Hadronization” at the Amplitude Level
Hadronization at the Amplitude Level

Construct helicity amplitude using Light-Front Perturbation theory; coalesce quarks via LFWFs

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Hadronization at the Amplitude Level

\[ \tau = x^+ \]

**Construct helicity amplitude using Light-Front Perturbation theory; coalesce quarks via LFWFs**

Baryon Production

\[ \psi(x, \vec{k}_\perp, \lambda_i) \]
Features of LF T-Matrix Formalism

“Event Amplitude Generator”

- Same principle as antihydrogen production: off-shell coalescence
- Coalescence to hadron favored at equal rapidity, small transverse momenta
- Leading heavy hadron production: D and B mesons produced at large z
- Hadron helicity conservation if hadron LFWF has \( L_z = 0 \)
- Baryon AdS/QCD LFWF has aligned and anti-aligned quark spin

\[ x_i P^+, x_i \vec{P}_\perp + \vec{k}_\perp i \]

\[ P^+ = P^0 + P^z \]

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Hadronization at the Amplitude Level

\[ \tau = x^+ \]

Higher Fock State Coalescence

| \( uuds \bar{s} \rangle \)

Asymmetric Hadronization!

\[ D_{s \to p}(z) \neq D_{s \to \bar{p}}(z) \]

B-Q Ma, sbj

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Crucial Test of Leading-Twist QCD: Scaling at fixed $x_T$

$$x_T = \frac{2p_T}{\sqrt{s}}$$

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

**Parton model:** $n_{eff} = 4$

*As fundamental as Bjorken scaling in DIS*

**Conformal scaling:** $n_{eff} = 2n_{active} - 4$
Dimensional analysis

Scattering amplitude $1 \ 2 \cdots \rightarrow \ldots n$ has dimension

$$\mathcal{M} \sim [\text{length}]^{n-4}$$

Consequence

In a conformal theory (no intrinsic scale), scaling of inclusive particle production

$$E \frac{d\sigma}{d^3p} (A \ B \rightarrow C \ X) \sim \frac{|\mathcal{M}|^2}{s^2} = \frac{F(x_\perp, \vartheta_{\text{cm}})}{p_{\perp}^{2n_{\text{active}}} - 4}$$

where $n_{\text{active}}$ is the number of fields participating to the hard process

$x_\perp = 2p_\perp / \sqrt{s}$ and $\vartheta_{\text{cm}}$: ratios of invariants

$$n_{\text{active}} = 4 \rightarrow n_{\text{eff}} = 4$$
$pp \rightarrow \gamma X$

\[ E \frac{d\sigma}{d^3p} (pp \rightarrow \gamma X) = \frac{F(\theta_{cm}, x_T)}{p_T^4} \]

$gu \rightarrow \gamma u$

$n_{active} = 4$

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

$n_{eff} = 4$
\[ \sqrt{s^n} E \frac{d\sigma}{d^3p} (pp \rightarrow \gamma X) \text{ at fixed } x_T \]

\[ (\sqrt{s})^n E d^3\gamma d\sigma (pb GeV^{-2}c^2) \]

\( n = 5 \)

**x_T-scaling of direct photon production:** consistent with PQCD
Leading-Twist Contribution to Hadron Production

\[ \frac{d\sigma}{d^3p/E} = \alpha_s^2 \frac{F(x_\perp, y)}{p_\perp^4} \]

Parton model and Conformal Scaling:

\[ G_{q/p}(x_1, p_\perp^2) \]
\[ G_{q/p}(x_2, p_\perp^2) \]
\[ D_{\pi/q}(z, p_\perp^2) \]
QCD prediction: Modification of power fall-off due to DGLAP evolution and the Running Coupling

\[ \frac{d\sigma}{d^3p/E} = \frac{F(x_\perp, y)}{p_{\perp}^n(x_\perp)} \]

\[ pp \to \pi X \]
\[ pp \to \gamma X \]

Key test of PQCD: power-law fall-off at fixed \( x_T \)

5 < \( p_{\perp} < 20 \text{ GeV} \)

70 GeV < \( \sqrt{s} < 4 \text{ TeV} \)
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.

**Continuous rise of $n_{eff}$ with $x_T$.**

**Leading twist:**

$$E \frac{d\sigma}{d^3p} (pN \rightarrow pX) = \frac{F(x_T, \theta_{CM})}{p_T^{n_{eff}}} x_T$$
\[
[\sqrt{s}]^n \frac{d\sigma}{d^3p/E} (pp \rightarrow \pi^0 X) \text{ at fixed } x_T = \frac{2p_T}{\sqrt{s}}
\]
Jet-triggered charged particle transverse momentum spectra in pp collisions at 7 TeV

The CMS Collaboration

\[ \int L dt = 10.2 \text{ nb}^{-1} \]

Inclusive invariant cross sections, scaled by \( \sqrt{s}^{5.1} \)
Clear evidence for higher-twist contributions

J. W. Cronin, SSI 1974

Chicago-Princeton FNAL

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

$x_T = \frac{2p_T}{\sqrt{s}}$
$E \frac{d\sigma}{d^3p}(pp \to HX) = \frac{F(x_T, \theta_{CM} = \pi/2)}{p_T^{n_{eff}}}$

- $\sqrt{s}=38.8/31.6$ GeV E706
- $\sqrt{s}=62.4/22.4$ GeV PHENIX/FNAL
- $\sqrt{s}=62.8/52.7$ GeV R806
- $\sqrt{s}=52.7/30.6$ GeV R806
- $\sqrt{s}=200/62.4$ GeV PHENIX
- $\sqrt{s}=500/200$ GeV UA1
- $\sqrt{s}=900/200$ GeV UA1
- $\sqrt{s}=1800/630$ GeV CDF
- $\sqrt{s}=1800/630$ GeV CDF jets
- $\sqrt{s}=1800/630$ GeV D0 jets

$\pi$

$\gamma$, jets

$\gamma$

Leading-Twist PQCD

$x_T = 2p_T / \sqrt{s}$
Significant increase of the hadron $n^{\text{exp}}$ with $x_\perp$

- $n^{\text{exp}} \simeq 8$ at large $x_\perp$

Huge contrast with photons and jets!

- $n^{\text{exp}}$ constant and slight above 4 at all $x_\perp$

Photons and Jets agree with PQCD $x_T$ scaling

Hadrons do not!
\[ \Delta(x_\perp) = n^{\text{exp}}(x_\perp) - n^{\text{NLO}}(x_\perp) \]
RHIC/LHC predictions

PHENIX results
Scaling exponents from $\sqrt{s} = 500$ GeV preliminary data

- Magnitude of $\Delta$ and its $x_\perp$-dependence consistent with predictions

[A. Bezilevsky, APS Meeting]
Direct Higher Twist Processes

- QCD predicts that hadrons can interact directly within hard subprocesses
- Exclusive and quasi-exclusive reactions
- Form factors, deeply virtual meson scattering
- Controlled by the hadron distribution amplitude
  \[ \phi_H(x_i, Q) \]
- Satisfies ERBL evolution
Direct Contribution to Hadron Production

\[ \phi_\pi(x, p_{\perp}^2) \propto f_\pi \]

\[ \frac{d\sigma}{d^3p/E} = \alpha_s^3 f^2 \pi \frac{F(x_{\perp}, y)}{p_{\perp}^6} \]

No Fragmentation Function
Hadron Distribution Amplitudes

\[ \phi_M(x, Q) = \int^Q d^2 k \psi_{q\bar{q}}(x, \vec{k}_\perp) \]

\[ \sum_{i} x_i = 1 \]

\[ \text{Fixed } \tau = t + z/c \]

- Fundamental gauge invariant non-perturbative input to hard exclusive processes, heavy hadron decays. Defined for Mesons, Baryons

- Evolution Equations from PQCD, OPE,

- Conformal Invariance

- Compute from valence light-front wavefunction in light-cone gauge

Lepage, Huang, sjb
Efremov, Radyushkin

Sachrajda, Frishman Lepage, sjb
Braun, Gardi

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\[ \pi^- N \rightarrow \mu^+ \mu^- X \text{ at } 80 \text{ GeV/c} \]

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

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

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

\[ Q^2 = M^2 \]

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

\[ x_\pi = x_{\bar{q}} \]

Example of a higher-twist direct subprocess

\[ \text{Chicago-Princeton Collaboration} \]


Novel Hadron Phenomena

Stan Brodsky, SLAC
$\pi N \rightarrow \mu^+ \mu^- X$ at high $x_F$

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

Distribution amplitude from AdS/CFT

Entire pion wf contributes to hard process

Virtual photon is longitudinally polarized

"Direct" Subprocess

Similar higher twist terms in jet hadronization at large $z$

Berger, sjb
Khoze, Brandenburg, Muller, sjb
Hoyer Vanttinen

Novel Hadron Phenomena

Stan Brodsky, SLAC
Pion appears directly in subprocess at large $x_F$
All of the pion’s momentum is transferred to the lepton pair
Lepton Pair is produced longitudinally polarized

$\pi q \rightarrow \gamma^* q$
\[ \pi^- N \rightarrow \mu^+ \mu^- X \text{ at } 80 \text{ GeV/c} \]

\[ \frac{d\sigma}{d\Omega} \propto 1 + \lambda \cos^2\theta + \rho \sin2\theta \cos\phi + \omega \sin^2\theta \cos2\phi. \]

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

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

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

Example of a higher-twist direct subprocess

Direct Subprocess Prediction

Chicago-Princeton Collaboration

Scaling laws in inclusive pion production

- **Conventional pQCD picture** (leading twist): $2 \to 2$ process followed by fragmentation into a pion on long time scales

  \[
  n_{\text{active}} = 4 \to n = 4 \quad (\equiv 2 \times 4 - 4) \quad E \frac{d\sigma}{d^3p}(p\ p \rightarrow \pi\ X) \sim \frac{F(x_{\perp}, \theta_{\text{cm}})}{p^4_{\perp}}
  \]

- **Direct higher-twist picture**: pion produced directly in the hard process

  \[
  n_{\text{active}} = 5 \to n = 6 \quad (\equiv 2 \times 5 - 4) \quad E \frac{d\sigma}{d^3p}(p\ p \rightarrow \pi\ X) \sim \frac{F'(x_{\perp}, \theta_{\text{cm}})}{p^6_{\perp}}
  \]