Novel Anti-Proton QCD Physics and New Insights from AdS/QCD

Stan Brodsky, SLAC

Panda Workshop, Turin, June 15-19, 2009
Mass range of PANDA

- Production of open charm
- Charmed hybrids
- Glueballs
- Charmonium
Search for exotic states

Naive Quark Model:
- Mesons (Resonances) = $qq$-states
- Baryons (Resonances) = $qqq$-states

LQCD + Model calculations:
- Existence of exotic states

$$\bar{p}p \rightarrow \gamma + X[q\bar{q}qq]$$

<table>
<thead>
<tr>
<th>Glue-Balls</th>
<th>Soliton-Type States (Without Quarks)</th>
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<tr>
<td>(gg), (ggg)</td>
<td>(qq) (qqâ­­) Penta Quark States</td>
</tr>
<tr>
<td>(qâ­­qg)</td>
<td>(qq) (qqqq) Dibaryons</td>
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<td>(qâ­­q) (qâ­­q)</td>
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<tr>
<td>(qqq) (qâ­­qq)</td>
<td>Quark-Molecules</td>
</tr>
</tbody>
</table>

New feature:
- Spin-exotic quantum numbers possible, not allowed in $qq$ ($J^{PC} = 0^{-}, 1^{+}, ...$)
New Charmonium Resonances

- **X(3872), Belle 09’2003, 1++, \( \chi_{c1} \) or \( D^0D^* \) molecule**
  - decays into \( J/\psi\pi^+\pi^- \), \( J/\psi\pi^+\pi^-\pi^0 \), \( J/\psi\gamma \), \( D^0D^* \)

- **Y(3940), Belle 09’2004, JP+, \( 2^3P_1 \) or Hybrid??**
  - decays into \( J/\psi\omega \)

- **Y(4260), BaBar 06’2005, 1--, \( 2^3D_1 \) (BaBar) or \( 4^3S_1 \) (CLEO) or Hybrid**
  - decays into \( e^+e^- \), \( J/\psi\pi^+\pi^- \), \( J/\psi\pi^0\pi^0 \), \( J/\psi K^+K^- \)

- **X(3943), Belle 07’2005, 0++, \( \eta_c \)´**
  - decays into \( D^0D^* \)

- **Z(3934), Belle 07’2005, 2++, \( \chi_{c2} \)´**
  - decays into \( \gamma\gamma \), \( DD \)

- **\( \psi(4320) \), BaBar 06’2006, ?, Hybrid**
Merits of antiprotons in hadron spectroscopy
High Resolution of $M$ and $\Gamma$

- Crystal Ball: typical resolution $\sim$ 10 MeV
- Fermilab: 240 keV
- PANDA: ~20 keV

Michael Düren
Deep Inelastic Electron-Proton Scattering

Conventional wisdom:
Final-state interactions of struck quark can be neglected
Single-spin asymmetries

Leading Twist Sivers Effect

Hwang, Schmidt, sjb

Collins, Burkardt Ji, Yuan

QCD S- and P-Coulomb Phases --Wilson Line

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

Pseudo-\( T \)-Odd

Light-Front Wavefunction S and P- Waves

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First evidence for non-zero Sivers function!

⇒ 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
Large 2005 data set still to be added!

Effect about equal for $K^- = s\bar{u}$ and $\pi^- = d\bar{u} \rightarrow$ note: same antiquark ...

Effect seems larger for $K^+ = u\bar{s}$ than $\pi^+ = u\bar{d}$ at $x \approx 0.1 \ldots !$
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
- Relate to the quark contribution to the target proton anomalous magnetic moment and final-state QCD phases
- QCD phase at soft scale: IR Fixed Point?
- New window to QCD coupling and running gluon mass in the IR
- QED $S$ and $P$ Coulomb phases infinite — difference of phases finite

\[ i \mathbf{S} \cdot \mathbf{p}_{jet} \times \mathbf{q} \]
Conformal window
Infrared fixed-point

\[ \beta(Q^2) = \frac{d\alpha_s(Q^2)}{d \log Q^2} \to 0 \]

Deur, Korsch, et al.

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Conformal window
Infrared fixed-point

\[ \beta(Q^2) = \frac{d\alpha_s(Q^2)}{d \log Q^2} \rightarrow 0 \]

Non-perturbative comparison of QCD effective charges

A. C. Aguilar, D. Binosi, J. Papavassiliou, and J. Rodríguez-Quintero
Single-spin asymmetries

Leading Twist Sivers Effect

Hwang, Schmidt, sjb

Collins, Burkardt Ji, Yuan

QCD S- and P- Coulomb Phases --Wilson Line

Pseudo-$T$-Odd

Light-Front Wavefunction

S and P- Waves

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Light-Front Wavefunctions: rigorous representation of composite systems in quantum field theory

\[ x = \frac{k^+}{P^+} = \frac{k^0 + k^3}{P^0 + P^3} \]

Fixed \( \tau = t + z/c \)

\[ \Psi_n(x_i, \vec{k}_{\perp i}, \lambda_i) \]

Invariant under boosts! Independent of \( P^\mu \)

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

\[ \sum_{i}^{n} \vec{k}_{\perp i} = \vec{0}_{\perp} \]
\[ |p, S_z > = \sum_{n=3}^{\infty} \Psi_n(x_i, \vec{k}_\perp, \lambda_i) |n; \vec{k}_\perp, \lambda_i > \]

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

The Light Front Fock State Wavefunctions

\[ \Psi_n(x_i, \vec{k}_\perp, \lambda_i) \]

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.

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

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

**Fixed LF time**

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QCD and the LF Hadron Wavefunctions

- AdS/QCD
  - Light-Front Holography
  - LF Schrödinger Eqn

- Heavy Quark Fock States
  - Intrinsic Charm

- Coordinate space representation

- Quark & Flavor Structure

- J=0 Fixed Pole
  - DVCS, GPDs, TMDs
  - LF Overlap, incl ERBL

- Initial and Final State Rescattering
  - DDIS, DDIS, T-Odd
  - Non-Universal Antishadowing

- Gluonic properties
  - DGLAP

- Orbital Angular Momentum
  - Spin, Chiral Properties
  - Crewther Relation

- Hard Exclusive Amplitudes
  - Form Factors
  - Counting Rules

- Distribution amplitude
  - ERBL Evolution
  \[ \phi_p(x_1, x_2, Q^2) \]

- Nuclear Modifications
  - Baryon Anomaly
  - Color Transparency

- Hadronization at Amplitude Level

- Baryon Excitations

- Baryon Decay
\[
\frac{F_2(q^2)}{2M} = \sum_a \int [dx][d^2k_\perp] \sum_j e_j \frac{1}{2} \times \\
\left[ - \frac{1}{q_L} \psi_\alpha^\dagger(x_i, k'_\perp, \lambda_i) \psi_\alpha(x_i, k_\perp, \lambda_i) + \frac{1}{q_R} \psi_\alpha^\dagger(x_i, k'_\perp, \lambda_i) \psi_\alpha(x_i, k_\perp, \lambda_i) \right] \\
k'_\perp = k_\perp - x_i q_\perp \\
k'_\perp = k_\perp + (1 - x_j) q_\perp \\
q_{R,L} = q^x \pm iq^y
\]

Must have $\Delta \ell_z = \pm 1$ to have nonzero $F_2(q^2)$

Same matrix elements appear in Sivers effect
-- connection to quark anomalous moments
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 anomalous gavitomagnetic moment)

\[ \vec{S} \cdot \vec{p}_{jet} \times \vec{q} \]
Anomalous gravitomagnetic moment $B(0)$

Teryaev, Okun et al: $B(0)$ Must vanish because of Equivalence Theorem

$B(0) = 0$

Each Fock State

Hwang, Schmidt, sjb; Holstein et al
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
Measure single-spin asymmetry $A_N$ in Drell-Yan reactions

Leading-twist Bjorken-scaling $A_N$ from $S, P$-wave initial-state gluonic interactions

Predict: $A_N(DY) = -A_N(DIS)$

Opposite in sign!

$Q^2 = x_1 x_2 s$

$Q^2 = 4 \text{ GeV}^2, s = 80 \text{ GeV}^2$

$x_1 x_2 = .05, x_F = x_1 - x_2$

\[ \bar{p} p \uparrow \rightarrow \ell^+ \ell^- X \]

\[ \vec{S} \cdot \vec{q} \times \vec{p} \text{ correlation} \]
Initial-state interactions and single-spin asymmetries in Drell–Yan processes

Stanley J. Brodsky\textsuperscript{a}, Dae Sung Hwang\textsuperscript{a,b}, Ivan Schmidt\textsuperscript{c}


\[
P_y = -\frac{e_1 e_2}{8\pi} \frac{2(\Delta M + m)r_1^1}{[(\Delta M + m)^2 + \vec{r}_\perp^2]} \left[ \vec{r}_\perp^2 + \Delta(1 - \Delta) \left( -\frac{M^2}{\Delta} + \frac{m^2}{1 - \Delta} + \frac{\lambda^2}{1 - \Delta} \right) \right]
\]

\[
\times \frac{1}{\vec{r}_\perp^2} \ln \frac{\vec{r}_\perp^2 + \Delta(1 - \Delta)(-M^2 + \frac{m^2}{\Delta} + \frac{\lambda^2}{1 - \Delta})}{\Delta(1 - \Delta)(-M^2 + \frac{m^2}{\Delta} + \frac{\lambda^2}{1 - \Delta})}.
\]

Here $\Delta = \frac{q^z}{2P_{q'}} = \frac{q^z}{2M_\nu}$ where $\nu$ is the energy of the lepton pair in the target rest frame.
Drell-Yan angular distribution

Unpolarized DY

- Experimentally, a violation of the Lam-Tung sum rule is observed by sizeable $\cos^2\Phi$ moments
- Several model explanations
  - Higher twist
  - Spin correlation due to non-trivial QCD vacuum
  - Non-zero Boer Mulders function

Lam – Tung SR: $1 - \lambda = 2\nu$

NLO pQCD: $\lambda \approx 1, \mu \approx 0, \nu \approx 0$

Experiment: $\nu \approx 0.3$

$$\frac{1}{\sigma} \frac{d\sigma}{d\Omega} = \frac{3}{4\pi} \frac{1}{\lambda + 3} \left( 1 + \lambda \cos^2\theta + \mu \sin2\theta \cos\phi + \frac{\nu}{2} \sin^2\theta \cos2\phi \right)$$

B. Seitz
Measurement of Angular Distributions of Drell-Yan Dimuons in $p + d$ Interaction at 800 GeV/c

(FNAL E866/NuSea Collaboration)

Parameter $\nu$ vs. $p_T$ in the Collins-Soper frame for three Drell-Yan measurements. Fits to the data using Eq. 3 and $M_C = 2.4$ GeV/$c^2$ are also shown.

Huge Effect in $\pi W \rightarrow \mu^+\mu^- X$
Negligible Effect $pd \rightarrow \mu^+\mu^- X$
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

Product of Boer-Mulders Functions

$$h_1^{\perp}(x_1, p_\perp^2) \times \bar{h}_1^{\perp}(x_2, k_\perp^2)$$
Sivers Function

Boer-Mulders Function

Unpolarized Distribution

Bj Sum Rule

Transversity

$T$-Odd: Require ISI or FSI

$\mathrm{Unpolarized\ Distribution}$

$\mathrm{Bj\ Sum\ Rule}$

$\mathrm{Transversity}$

$\mathrm{Sivers\ Function}$

$\mathrm{Boer-Mulders\ Function}$

$T_1 = \begin{array}{c}
\text{Boer-Mulders Function} \\
\text{Sivers Function}
\end{array}$

$g_{1L} = \begin{array}{c}
\text{Boer-Mulders Function} \\
\text{Sivers Function}
\end{array}$

$h_{1T} = \begin{array}{c}
\text{Boer-Mulders Function} \\
\text{Sivers Function}
\end{array}$

$f_{1T} = \begin{array}{c}
\text{Boer-Mulders Function} \\
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$\text{Turin June 17, 2009}$

$\text{Stan Brodsky}$

$\text{SLAC}$
Double Initial-State Interactions generate anomalous $\cos 2\phi$; Boer, Hwang, sjb

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

$$\frac{\nu}{2} \propto h_{1}^{\perp}(\pi) h_{1}^{\perp}(N)$$

$$\pi N \rightarrow \mu^+ \mu^- X \text{ NA10}$$

Violates Lam-Tung relation!

Model: Boer, Stan Brodsky

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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

Boer, Hwang, sjb

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

We show that initial-state interactions contribute to the $\cos 2\phi$ distribution in unpolarized Drell-Yan lepton pair production $pp$ and $p\bar{p} \rightarrow \ell^+\ell^- X$, without suppression. The asymmetry is expressed as a product of chiral-odd distributions $h^1_1(x_1, p^2_{1\perp}) \times \overline{h}^1_1(x_2, k^2_{1\perp})$, where the quark-transversity function $h^1_1(x, p^2_{1\perp})$ is the transverse momentum dependent, light-cone momentum distribution of transversely polarized quarks in an unpolarized proton. We compute this (naive) $T$-odd and chiral-odd distribution function and the resulting $\cos 2\phi$ asymmetry explicitly in a quark-scalar diquark model for the proton with initial-state gluon interaction. In this model the function $h^1_1(x, p^2_{1\perp})$ equals the $T$-odd (chiral-even) Sivers effect function $f^1_T(x, p^2_{1\perp})$. This suggests that the single-spin asymmetries in the SIDIS and the Drell-Yan process are closely related to the $\cos 2\phi$ asymmetry of the unpolarized Drell-Yan process, since all can arise from the same underlying mechanism. This provides new insight regarding the role of quark and gluon orbital angular momentum as well as that of initial- and final-state gluon exchange interactions in hard QCD processes.
$\cos 2\phi$ correlation for charm pair production at leading twist from double ISI
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
Also possible FSI
\[ \pi N \rightarrow \mu^+ \mu^- X \text{ at high } x_F \]

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

**Light-Front Wavefunctions from AdS/CFT**

Entire pion wf contributes to hard process

Virtual photon is longitudinally polarized

**"Direct" Subprocess**

Berger, sjb
Khoze, Brandenburg, Muller, sjb
Hoyer Vanttinenen

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\pi^- N \rightarrow \mu^+ \mu^- X \text{ at 80 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 $x_T$

Example of a higher-twist direct subprocess

Direct Subprocess Prediction.

\begin{align*}
\text{Chicago-Princeton Collaboration} \\
\end{align*}
$\pi q \rightarrow \gamma^* q$

**Initial State**

**Interaction**

**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
\[ A(1 - x)^3(1 + \cos^2 \theta) + B \frac{(1 - x) \sin^2 \theta}{Q^2} + C \frac{(1 + \cos^2 \theta)}{(1 - x)Q^4} \]

Diquark appears directly in subprocess

All of the diquark's momentum is transferred to the lepton pair

Lepton Pair is produced longitudinally polarized

Key Panda Experiment.

\[ [\bar{q}q]q \rightarrow \gamma^* \bar{q} \]
Remarkable observation at HERA

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.

**Profound effect:** target stays intact despite production of a massive system X.
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: \( \overline{\psi}(y) \int_0^y dx \, e^{iA(x) \cdot dx} \, \psi(0) \)

Reproduces lab-frame color dipole approach
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
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<th><strong>Static</strong></th>
<th><strong>Dynamic</strong></th>
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<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>
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<tr>
<td>- Probability Distributions</td>
<td>No Probabilistic Interpretation</td>
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<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>
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<tr>
<td>- Sum Rules: Momentum and $J^z$</td>
<td>Sum Rules Not Proven</td>
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<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>

$$\psi_n(x_i, \vec{k}_\perp i, \lambda_i)^2$$

![Diagram of e^{-}e^{-} interaction](image)
Double-Diffractive Drell-Yan

\[
\bar{p}p \rightarrow \bar{p} + \ell^+\ell^- + p
\]

Large-Mass Timelike Muon Pairs in Hadronic Interactions
S. M. Berman*, D. J. Levy, and T. L. Neff§


Prototype for exclusive Higgs production
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.

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

**Intrinsic heavy quarks,**

\[ \bar{s}(x) \neq s(x) \]
\[ \bar{u}(x) \neq \bar{d}(x) \]

**Fixed LF time**
Intrinsic Heavy-Quark Fock States

- Rigorous prediction of QCD, OPE
- Color-Octet Color-Octet Fock State!
- Probability \( P_{Q \bar{Q}} \propto \frac{1}{M_Q^2} \) \( P_{Q \bar{Q} Q \bar{Q}} \) \( \sim \alpha_s^2 P_{Q \bar{Q}} \) \( P_{c \bar{c}/p} \sim 1\% \)
- 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
Measurement of Charm Structure Function


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 $x_F \ pp \rightarrow \Xi(ccd) X \ (\text{SELEX})$

C.H. Chang, J.P. Ma, C.F. Qiao and X.G. Wu,
Leading Hadron Production from Intrinsic Charm

Coalescence of Comoving Charm and Valence Quarks
Produce $J/\psi$, $\Lambda_c$ and other Charm Hadrons at High $x_F$
Production of a Double-Charm Baryon

SELEX high $x_F$  $< x_F > \geq 0.33$
Measurement of $\gamma + b + X$ and $\gamma + c + X$ Production Cross Sections
in $p\bar{p}$ Collisions at $\sqrt{s} = 1.96$ TeV

$\Delta \sigma(\bar{p}p \rightarrow \gamma cX) / \Delta \sigma(\bar{p}p \rightarrow \gamma bX)$

Ratio insensitive to gluon PDF, scales

Signal for significant IC at $x > 0.1$?
Excitation of Intrinsic Heavy Quarks in Proton

Amplitude maximal at small invariant mass, equal rapidity

\[ x_i \sim \frac{m_{\perp i}}{\sum_j m_{\perp j}} \]

\[ \frac{d\sigma}{dy_{J/\psi}} (\bar{p}p \rightarrow J/\psi X) \]

Heavy Quarkonium produced in target rapidity region

\[ x_c \sim 0.4 \]
\[ x_{\bar{c}} \sim 0.4 \]

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Heavy Quarkonium produced in \textbf{TARGET} rapidity region

\begin{equation}
\frac{d\sigma}{dy_{J/\psi}} (\bar{p}p \rightarrow J/\psi X) \end{equation}

\textbf{Important Test of Intrinsic Charm.}
Measure diffractive hidden charm production at forward $x_F$

$$\frac{d\sigma}{dt_1 dt_2 dx_F} (\bar{p} p \rightarrow \bar{p} + J/\psi + p)$$

$$\frac{d\sigma}{dt dx_F} (\bar{p} p \rightarrow \bar{p} + J/\psi + X)$$

Anomalous nuclear dependence

$$\frac{d\sigma}{dx_F} (\bar{p} A \rightarrow J/\psi + X)$$

$A^\alpha(x_2)$ versus $A^\alpha(x_F)$

Important Tests of Intrinsic Charm
Open and Hidden Charm Production Near Threshold

\[ \bar{p}p \rightarrow J/\psi X \]
\[ \bar{p}p \rightarrow D \bar{D} X \]
\[ \bar{p}p \rightarrow \Lambda_c D X \]

- Several Mechanisms for Inclusive Production:

\[ gg \rightarrow c \bar{c} \quad q \bar{q} \rightarrow g \rightarrow c \bar{c} \]
\[ c_I + g \rightarrow cg \quad [c_I + \bar{c}_I] + g \rightarrow J/\psi \]

*ISI and FSI, Schwinger Sommerfeld Threshold Corrections*
Color-Opaque IC Fock state interacts on nuclear front surface

Scattering on front-face nucleon produces color-singlet $c \bar{c}$ pair

Octet-Octet IC Fock State

No absorption of small color-singlet

\[
\frac{d\sigma}{dx_F}(pA \rightarrow J/\psi X) = A^{2/3} \times \frac{d\sigma}{dx_F}(pN \rightarrow J/\psi X)
\]
Remarkably Strong Nuclear Dependence for Fast Charmonium

Violation of PQCD Factorization!

\[ \frac{d\sigma}{dx_F}(pA \rightarrow J/\psi X) \]

Violation of factorization in charm hadroproduction.

J/ψ nuclear dependence vrs rapidity, x_{Au}, x_{F}

PHENIX compared to lower energy measurements

Violates PQCD factorization!

Hoyer, Sukhatme, Vanttinen

$\frac{d\sigma}{dx_F}(pA \rightarrow J/\psi X)$

M. Leitch

Kopeliovich, NP A696:669,2001
\[ d\sigma_{dxF}(pA \rightarrow J/\psi X) = A^1 d\sigma_1 \frac{dx}{dx_F} + A^{2/3} d\sigma_{2/3} \frac{dx}{dx_F} \]

J. Badier et al, NA3

Excess beyond conventional PQCD subprocesses
\begin{itemize}
\item IC Explains Anomalous $\alpha(x_F)$ not $\alpha(x_2)$ dependence of $pA \rightarrow J/\psi X$ (Mueller, Gunion, Tang, SJB)
\item Color Octet IC Explains $A^{2/3}$ behavior at high $x_F$ (NA3, Fermilab) (Kopeliovitch, Schmidt, Soffer, SJB)
\item IC Explains $J/\psi \rightarrow \rho \pi$ puzzle (Karliner, SJB)
\item IC leads to new effects in $B$ decay (Gardner, SJB)
\end{itemize}

**Higgs production at $x_F = 0.8$**
Intrinsic Charm Mechanism for Exclusive Diffraction Production

\[ p \, p \rightarrow J/\psi \, p \, p \]
\[ x_{J/\psi} = x_c + x_{\bar{c}} \]

Kopeliovitch, Schmidt, Soffer, sjb

Intrinsic \( c\bar{c} \) pair formed in color octet \( 8_c \) in proton wavefunction

Large Color Dipole

Collision produces color-singlet \( J/\psi \) through color exchange

RHIC Experiment

PANDA Workshop Turin June 17, 2009

Novel Anti-Proton QCD Physics

Stan Brodsky SLAC
Anti-Shadowing

$F_2^{Ca/F_2} \times x$

$Q^2 = 5 \text{ GeV}^2$