\[ E \frac{d\sigma}{d^3p} (pp \rightarrow HX) = \frac{F(x_T, \theta_{CM})}{p_{T}^{n_{eff}}} \]

Trend consistent with RHIC at small \( x_T \)

\[ E \frac{d\sigma}{d^3p} (pp \rightarrow pX) = \frac{F(x_T, \theta_{CM})}{p_{T}^{12}} \]

\[ E \frac{d\sigma}{d^3p} (pp \rightarrow pX) = \frac{F(x_T, \theta_{CM})}{p_{T}^{8}} \]

Stan Brodsky, SLAC
\[ \sqrt{s_{NN}} = 130 \text{ and } 200 \text{ GeV} \]

Proton power changes with centrality!

Stan Brodsky, SLAC
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Peripheral

Central
Baryon can be made directly within hard subprocess

Coalescence within hard subprocess

\[ b_\perp \simeq 1 / p_T \]

\[ uu \rightarrow p \bar{d} \]

\[ \phi_p(x_1, x_2, x_3) \propto \Lambda_{QCD}^2 \]

Collision can produce 3 collinear quarks

Small color-singlet

Color Transparent

Minimal same-side energy

\[ n_{\text{active}} = 6 \]
\[ n_{\text{eff}} = 2n_{\text{active}} - 4 \]
\[ n_{\text{eff}} = 8 \]
Baryon made directly within hard subprocess

\[ b_\perp \simeq 1 \text{ fm} \]

Formation Time proportional to Energy

Small color-singlet
Color Transparent
Minimal same-side energy

\[ b_\perp \simeq 1/p_T \]

\[ uu \rightarrow p \bar{d} \]

\[ n_{\text{active}} = 6 \]
\[ n_{\text{eff}} = 2n_{\text{active}} - 4 \]
\[ n_{\text{eff}} = 8 \]

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Stan Brodsky, SLAC
Dimensional counting rules provide a simple rule-of-thumb guide for the power-law fall-off of the inclusive cross section in both $p_T$ and $(1 - x_T)$ due to a given subprocess:

$$E \frac{d\sigma}{d^3p} (AB \to CX) \propto \frac{(1 - x_T)^{2n_{\text{spectator}}-1}}{p_T^{2n_{\text{active}}-4}}$$

where $n_{\text{active}}$ is the “twist”, i.e., the number of elementary fields participating in the hard subprocess, and $n_{\text{spectator}}$ is the total number of constituents in $A, B$ and $C$ not participating in the hard-scattering subprocess. For example, consider $pp \to pX$. The leading-twist contribution from $qq \to qq$ has $n_{\text{active}} = 4$ and $n_{\text{spectator}} = 6$. The higher-twist subprocess $qq \to p\bar{q}$ has $n_{\text{active}} = 6$ and $n_{\text{spectator}} = 4$. This simplified model provides two distinct contributions to the inclusive cross section

$$\frac{d\sigma}{d^3p/E} (pp \to pX) = A \frac{(1 - x_T)^{11}}{p_T^4} + B \frac{(1 - x_T)^7}{p_T^8}$$

and $n = n(x_T)$ increases from 4 to 8 at large $x_T$. 

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**Stan Brodsky, SLAC**

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**sjb: RHIC News 1-15-08**

Small color-singlet
Color Transparent
Minimal same-side energy
Power-law exponent $n(x_T)$ for $\pi^0$ and $h$ spectra in central and peripheral Au+Au collisions at $\sqrt{s_{NN}} = 130$ and 200 GeV


Proton production dominated by color-transparent direct high $n_{\text{eff}}$ subprocesses
Particle ratio changes with centrality!

Protons less absorbed in nuclear collisions than pions because of dominant color transparent higher twist process.
Proton production more dominated by color-transparent direct high-$n_{\text{eff}}$ subprocesses.

Proton trigger: $2.5 < p_T < 4.0$ GeV/c

Associated: $1.8 < p_T < 2.5$ GeV/c

Anne Sickles
Baryon to Meson Ratios

Transverse Momentum $p_T$ (GeV/c)

Central Au+Au: PHENIX
Central Au+Au: STAR
$p+p$ NSD: STAR
e$^+e^- \rightarrow ggg$: ARGUS
e$^+e^- \rightarrow q\bar{q}$: ARGUS

$\frac{\bar{p}}{\pi}$

$\frac{\Lambda}{2K_S}$
Lambda can be made directly within hard subprocess

Coalescence within hard subprocess

\[ ud \rightarrow \Lambda \bar{s} \]

Small color-singlet
Color Transparent
Minimal same-side energy

\[ \bar{s} \text{ produced on away side} \]

Active quark numbers:
\[ n_{\text{active}} = 6 \]
\[ n_{\text{eff}} = 2n_{\text{active}} - 4 \]
\[ n_{\text{eff}} = 8 \]

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Stan Brodsky, SLAC
**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 $x_T = 1$
Role of higher twist in hard inclusive reactions

- Hadron can be produced directly in hard subprocess as in exclusive reactions
- Sum over reactions
- Trigger bias: No wasted same-side energy
- Exclusive -inclusive connection important at high $x_T$
- Explanation of $n_{\text{eff}} = 8, 12$ observed at ISR, Fermilab: Chicago-Princeton experiments
- Direct Hadron Production -- color transparency and reduced same side absorption
- Critical to plot data at fixed $x_T$
- Interpretation of RHIC data is modified if higher twist subprocesses play an important role
Holographic Connection between LF and AdS/CFT

• Predictions for hadronic spectra, light-front wavefunctions, interactions

• Deduce meson and baryon wavefunctions, distribution amplitude, structure function from holographic constraint

• Identification of Orbital Angular Momentum Casimir for SO(2): LF Rotations

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

**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.

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

**Intrinsic heavy quarks**

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

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

**Mueller: BFKL DYNAMICS**

**Fixed LF time**

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• Naïve Assumption from gluon splitting:

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

- E866/NuSea (Drell-Yan)
Evolution of 5 color-singlet Fock states

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

\[ \Phi_n(x_i, Q) = \int k_{\perp i}^2 <Q^2 \prod' d^2 k_{\perp j} \psi_n(x_i, \vec{k}_{\perp j}) \]

5 X 5 Matrix Evolution Equation for deuteron distribution amplitude
Interaction of $a$ and $b$ when $\vec{r}_\perp a \simeq \vec{r}_\perp b$ and $\sigma_a \simeq \sigma_b$

Universal Light Front Wavefunctions independent of $P^+, \ell_\perp$

\[ \Psi_A(x_a, \vec{k}_\perp a) \]

\[ \Psi_B(x_b, \vec{k}_\perp b) \]

\[ \vec{r}_\perp a = \text{conj} \left[ x_a \ell_\perp + \vec{k}_\perp a \right] \]

\[ \sigma_a = \text{conj} \left[ x_a \right] \]
\[ p_A = (P^+, \frac{M_A^2 + \ell_{\perp}^2}{P^+}, \vec{\ell}_{\perp}) \]

\[ p_B = (P^+, \frac{M_B^2 + \ell_{\perp}^2}{P^+}, -\vec{\ell}_{\perp}) \]

Both beams move along the positive \( z \) direction, and \( s = (p_A + p_B)^2 = 2M_A^2 + 2M_B^2 + 4\ell_{\perp}^2 \) is represented by the oppositely directed transverse momenta \( \pm \vec{\ell}_{\perp} \) of the colliding nuclei.

Note that the value of \( P^+ \) is irrelevant.

As \( \tau \) progresses, the constituents from A and B each interact as their coordinates \( \sigma_i \) and \( \vec{b}_{\perp i} \) overlap.
What is the dynamical mechanism which creates the QGP?

• How do the parameters of the QGP depend on the initial and final state conditions?

• A dynamical model: “Gluonic Laser”
Gluonic Laser

Gluonic bremsstrahlung from initial hard scattering backscatters on nuclear ""mirrors"

\[ gq \rightarrow \gamma q \]

QCD cascade mechanism for forming quark-gluon plasma inside overlap ellipse

energy loss from stimulated radiation of away-side jet.

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Consequences of Gluon Laser Mechanism

Ridge created by trigger bias (Cronin effect)

Momenta of initial colored partons biased towards trigger

Soft gluon radiation from initial state partons emitted in plane of production; fills rapidity

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Possible time sequence of a RHIC Ion-Ion Collision

- Nuclei collide; nucleons overlap within an ellipse

- Initial hard collision between quarks and/or gluons producing high $p_T$ trigger hadron or photon

- Induced gluon radiation radiated from initial parton collision

- Collinear radiation back-scatters on other incoming partons

- Cascading gluons creates multi-parton quark-gluon plasma within ellipse, thermalization

- Stimulated radiation contributes to energy loss of away-side jet

- Sidewise pressure creates hadronic energy along minor axis -- yields planar $\cos 2\phi$ correlation: $v_2$

- Same final state for high $p_T$ direct photons and mesons

- Baryons formed in higher-twist double-scattering process at high $x_T$; double induced radiation and thus double $v_2$. 
\[ |p, S_z > = \sum_{n=3}^{\infty} \Psi_n(x_i, \bar{k}_\perp, \lambda_i) |n; \bar{k}_\perp, \lambda_i > \]

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

The Light Front Fock State Wavefunctions
\[ \Psi_n(x_i, \bar{k}_\perp, \lambda_i) \]
are boost invariant; they are independent of the hadron’s energy and momentum \( P^\mu \).

The light-cone momentum fraction
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are boost invariant.

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

**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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Fluctuation in Proton
QCD: Probability $\sim \frac{\Lambda_{QCD}^2}{M_Q^2}$

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

$|uudcc\bar{c}\rangle$ in Color Octet

OPE derivation - M. Polyakov et al.

$$\langle p \mid \frac{G^3_{\mu\nu}}{m_Q^2} \mid p \rangle \text{ vs. } \langle p \mid \frac{F^4_{\mu\nu}}{m_\ell^4} \mid p \rangle$$

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

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

**High x charm!**

Hoyer, Peterson, Sakai, sjb
Intrinsic Heavy-Quark Fock States

- Rigorous prediction of QCD, OPE
- Color - Octet + Color - Octet Fock State!
- Probability $P_{Q\bar{Q}} \propto \frac{1}{M_Q^2}$
- $P_{Q\bar{Q}Q\bar{Q}} \sim \alpha_s^2 P_{Q\bar{Q}}$
- $P_{c\bar{c}/p} \simeq 1\%$
- 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

Hoyer, Peterson, Sakai, sjb

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

Hoyer, Peterson, SJB

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Measurement of Charm Structure Function


First Evidence for Intrinsic Charm

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

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Stan Brodsky, SLAC
• 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)

Test intrinsic high-$x$ $c(x)$ and $b(x)$ at RHIC

$pp \rightarrow c, bX$ at high $p_T, x_F$
Leading Hadron Production from Intrinsic Charm

Coalescence of Comoving Charm and Valence Quarks Produce $J/\psi$, $\Lambda_c$ and other Charm Hadrons at High $x_F$
Remarkably Strong Nuclear Dependence for Fast Charmonium

Violation of PQCD Factorization!

800 GeV p-A (FNAL) \( \sigma_A = \sigma_p^* A^\alpha \)

PRL 84, 3256 (2000); PRL 72, 2542 (1994)

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

\[ \sigma_A = \sigma_p^* A^\alpha \]

open charm: no A-dep at mid-rapidity

Violation of factorization in charm hadroproduction.

$J/\psi$ nuclear dependence vrs rapidity, $x_{Au}$, $x_F$

PHENIX compared to lower energy measurements

Huge "absorption" effect

Violates PQCD factorization!

Hoyer, Sukhatme, Vanttinen

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Scattering on Nucleon via one Gluon

Production of Color-Octet IC Fock State

Coalescence of Color-Singlet Pair into Charmonium State

\[
\frac{d\sigma}{dx_F}(pA \rightarrow J/\psi X) = A^{2/3} \times \frac{d\sigma}{dx_F}(pN \rightarrow J/\psi X)
\]
Two Components

\[
\frac{d\sigma_1}{dx_F}(pA \rightarrow J/\psi X) = A \frac{d\sigma_1}{dx_F} + A^{2/3} \frac{d\sigma_2}{3dx_F}
\]

A\(^1\) component

Identify with Fusion

Conventional PQCD subprocesses
J. Badier et al, NA3

\[
\frac{d\sigma}{dx_F}(pA \rightarrow J/\psi X) = A_1 \frac{d\sigma_1}{dx_F} + A^{2/3} \frac{d\sigma_{2/3}}{dx_F}
\]

**A^{2/3} component**

**Identify with IC**

**High \(x_F\)**

**Remarkably Flat Distribution**

**Excess beyond conventional PQCD subprocesses**

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\[
\frac{d\sigma}{dx_F} (pA \rightarrow J/\psi X) = A^1 \frac{d\sigma_{\text{fusion}}}{dx_F} (pA \rightarrow J/\psi X) + A^{2/3} \frac{d\sigma_{\text{non-fusion}}}{dx_F} (pA \rightarrow J/\psi X)
\]
Production of a Double-Charm Baryon

SELEX high $x_F$  

$\langle x_F \rangle = 0.33$
Production of Two Charmonia at High $x_F$
All events have $x_{\psi\psi}^F > 0.4$!

Fig. 3. The $\psi\psi$ pair distributions are shown in (a) and (c) for the pion and proton projectiles. Similarly, the distributions of $J/\psi$'s from the pairs are shown in (b) and (d). Our calculations are compared with the $\pi^- N$ data at 150 and 280 GeV/c [1]. The $x_{\psi\psi}$ distributions are normalized to the number of pairs from both pion beams (a) and the number of pairs from the 400 GeV proton measurement (c). The number of single $J/\psi$'s is twice the number of pairs.

**Excludes `color drag' model**

$\pi A \rightarrow J/\psi J/\psi X$

Intrinsic charm contribution to double quarkonium hadroproduction

R. Vogt*, S.J. Brodsky

The probability distribution for a general $n$-parton intrinsic $c\bar{c}$ Fock state as a function of $x$ and $k_T$ written as

$$\frac{dP_{ic}}{\prod_{i=1}^{n} dx_i d^2k_{T,i}}$$

$$= N_n \alpha_s^4(M_{c\bar{c}}) \frac{\delta(\sum_{i=1}^{n} k_{T,i}) \delta(1 - \sum_{i=1}^{n} x_i)}{(m_{c\bar{c}}^2 - \sum_{i=1}^{n} (m_{T,i}^2/x_i))^2}.$$

**NA3 Data**

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**Stan Brodsky, SLAC**
Heavy Quark Anomalies

Nuclear dependence of $J/\psi$ hadroproduction

Violates PQCD Factorization: $A^\alpha(x_F)$ not $A^\alpha(x_2)$

Huge $A^{2/3}$ effect at large $x_F$
• IC Explains Anomalous $\alpha(x_F)$ not $\alpha(x_2)$ dependence of $pA \rightarrow J/\psi X$ (Mueller, Gunion, Tang, SJB)

• Color Octet IC Explains $A^{2/3}$ behavior at high $x_F$ (NA3, Fermilab) (Kopeliovitch, Schmidt, Soffer, SJB)

• Color Opaqueness

• IC Explains $J/\psi \rightarrow \rho\pi$ puzzle (Karliner, SJB)

• IC leads to new effects in $B$ decay (Gardner, SJB)

Higgs production at $x_F = 0.8$
SELEX $\Lambda_c^+$ Studies – $p_T$ Dependence

- $\Lambda_c^+$ production by $\Sigma^-$ vs $x_F$
- shows harder spectrum at low $p_T$ - consistent with an intrinsic charm picture.

Heavy Quark Anomalies

\[ J/\psi \rightarrow \rho \pi \] puzzle

\[ \text{BR} = 1.27 \pm 0.09 \% \]

Largest two-body decay channel

Violates hadron helicity conservation

\[ \psi' \text{ almost never decays to } \rho \ \pi \ < 8.3 \times 10^{-5} \]

Solution: Intrinsic charm Fock states in \( \rho, \pi \)

Karliner, sjb
Why is Intrinsic Charm Important for Flavor Physics?

- New perspective on fundamental nonperturbative hadron structure
- Charm structure function at high x
- Dominates high $x_F$ charm and charmonium production
- Hadroproduction of new heavy quark states such as $c\bar{c}u$, $c\bar{c}d$ at high $x_F$
- Intrinsic charm -- long distance contribution to penguin mechanisms for weak decay
- Novel Nuclear Effects from color structure of IC, Heavy Ion Collisions
- New mechanisms for high $x_F$ Higgs hadroproduction
- Dynamics of $b$ production: LHCb
- Fixed target program at LHC: produce $b\bar{b}b$ states
Hadron Dynamics at the Amplitude Level

• LFWFS are the universal hadronic amplitudes which underlie structure functions, GPDs, exclusive processes, distribution amplitudes, direct subprocesses, hadronization.

• 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