• Scaling behavior for large $Q^2$: $Q^4 F_1^n(Q^2) \rightarrow \text{constant}$  

\[
\tau = 3
\]  

Dirac Neutron Form Factor (Valence Approximation)

\[ Q^4 F_1^n(Q^2) \ [\text{GeV}^4] \]

Prediction for \( Q^4 F_1^n(Q^2) \) for \( \Lambda_{QCD} = 0.21 \ \text{GeV} \) in the hard wall approximation. Data analysis from Diehl (2005).
Spacelike Pauli Form Factor

From overlap of $L = 1$ and $L = 0$ LFWFs

Harmonic Oscillator Confinement
Normalized to anomalous moment

$$F_2^p(Q^2)$$

$$\kappa = 0.49 \text{ GeV}$$
\[
\left[ -\frac{d^2}{d\zeta^2} + V(\zeta) \right] \phi(\zeta) = M^2 \phi(\zeta)
\]

\[\zeta = \sqrt{x(1-x)b_{\perp}^2}\]

\[-\frac{d}{d\zeta^2} \equiv \frac{k_{\perp}^2}{x(1-x)}\]

Assume LFWF is a dynamical function of the quark-antiquark invariant mass squared

\[-\frac{d}{d\zeta^2} \rightarrow -\frac{d}{d\zeta^2} + \frac{m_1^2}{x} + \frac{m_2^2}{1-x} \equiv \frac{k_{\perp}^2 + m_1^2}{x} + \frac{k_{\perp}^2 + m_2^2}{1-x}\]
\[ J/\psi \]

**LFWF peaks at**

\[ x_i = \frac{m_{\perp i}}{\sum_j^n m_{\perp j}} \]

where

\[ m_{\perp i} = \sqrt{m^2 + k_{\perp}^2} \]

**minimum of LF energy denominator**

\[ \kappa = 0.375 \text{ GeV} \]

\[ m_a = m_b = 1.25 \text{ GeV} \]
\[|\pi^+ > = |u\bar{d} >\]
\[m_u = 2 \text{ MeV}\]
\[m_d = 5 \text{ MeV}\]

|\[\text{[Image]}|K^+ > = |u\bar{s} >\]
\[m_s = 95 \text{ MeV}\]

|\[\text{[Image]}|D^+ > = |c\bar{d} >\]
\[m_c = 1.25 \text{ GeV}\]

|\[\text{[Image]}|\eta_c > = |c\bar{c} >\]

|\[\text{[Image]}|B^+ > = |u\bar{b} >\]
\[m_b = 4.2 \text{ GeV}\]

|\[\text{[Image]}|\eta_b > = |b\bar{b} >\]
\[\kappa = 375 \text{ MeV}\]
First Moment of Kaon Distribution Amplitude

$$<\xi> = \int_{-1}^{1} d\xi \; \xi \; \phi(\xi)$$

$$\xi = 1 - 2x$$

$$<\xi>_K = 0.04 \pm 0.02$$

$$\kappa = 375 \; MeV$$

Range from $$m_s = 65 \pm 25 \; MeV$$ (PDG)

$$<\xi>_K = 0.029 \pm 0.002$$

Donnellan et al.

$$<\xi>_K = 0.0272 \pm 0.0005$$

Braun et al.

LBNL

April 7, 2009

Light-Front Holography

87

Stan Brodsky

SLAC
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
Light-Front QCD

Heisenberg Equation

\[
H_{LC}^{QCD} |\Psi_h\rangle = \mathcal{M}_h^2 |\Psi_h\rangle
\]

Use AdS/QCD basis functions

LBNL
April 7, 2009

Light-Front Holography
89

Stan Brodsky
SLAC
\[ \pi N \rightarrow \mu^+ \mu^- X \text{ at high } x_F \]

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

Entire pion \(\pi\) wave function contributes to hard process

Virtual photon is longitudinally polarized

“Direct” Subprocess

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

LBNL
April 7, 2009

Light-Front Holography
90

Stan Brodsky
SLAC
\( \pi^- N \rightarrow \mu^+ \mu^- X \) at 80 GeV/c

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

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

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

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

Example of a higher-twist direct subprocess

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

Chicago-Princeton Collaboration

Stan Brodsky
SLAC

LBNL
April 7, 2009

Light-Front Holography
91
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:** $n_{eff} = 2n_{active} - 4$
\[ \sqrt{s^n} E \frac{d\sigma}{d^3p} (pp \rightarrow \gamma X) \text{ at fixed } x_T \]

Scaling of direct photon production consistent with PQCD
$pp \rightarrow \gamma X$

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

$gu \rightarrow \gamma u$

$n_{active} = 4$

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

$n_{eff} = 4$
Higher-Twist Contribution to Hadron Production

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

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

No Fragmentation Function
Clear evidence for higher-twist contributions

Fermilab, ISR data

Continuous Rise of \( n_{\text{eff}} \)

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

\[
x_T = \frac{2p_T}{\sqrt{s}}
\]
QCD prediction: Modification of power fall-off due to DGLAP evolution and the Running Coupling

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

\[ n(x_{\perp}) \]

- photon
- pion

**INCLNLO**

**CTEQ6.6 PDF**

**DSS/BFG FF**

**scales=p_{\perp}**

**y=0**

\[ pp \rightarrow \pi X \]

\[ pp \rightarrow \gamma X \]

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

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

**LBNL**

**April 7, 2009**

**Light-Front Holography**

**97**

**Stan Brodsky**

**SLAC**
\[ 5 < p_\perp < 20 \text{ GeV} \quad 70 \text{ GeV} < \sqrt{s} < 4 \text{ TeV} \]

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

\[ x_\perp = \frac{2p_\perp}{\sqrt{s}} \]

- **pions**
- **proton**
- **anti-proton**

CTEQ6.6 PDF
DSS FF
scales=p_\perp
y=0

Arleo, Aurenche

LBNL
April 7, 2009

Light-Front Holography
98

Stan Brodsky
SLAC
\[ E \frac{d\sigma}{d^3p}(pp \rightarrow HX) = \frac{F(x_T, \theta_{CM} = \pi/2)}{p_T^{n_{eff}}} \]
Baryon Anomaly: Particle ratio changes with centrality!

Protons less absorbed in nuclear collisions than pions


**Ratio**

Proton/pion

**$p_T$ (GeV/c)**

Central

Peripheral

LBNL
April 7, 2009

Light-Front Holography

Stan Brodsky
SLAC
$\sqrt{s_{NN}} = 130$ and 200 GeV

Proton power changes with centrality!
$pp \rightarrow HX$ at high $p_T$

Proton created from jet fragmentation

Color Opaque

$n = 2n_{active} - 4$

$n = 4$

$n_{active} = 4$
Baryon can be made directly within hard subprocess

Coalescence within hard subprocess

\[ b_\perp \simeq \frac{1}{p_T} \]

Collision can produce 3 collinear quarks

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

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

Small color-singlet
Color Transparent
Minimal same-side energy

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

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

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

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

\[ n_{\text{active}} = 6 \]

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

\[ n_{\text{eff}} = 8 \]

Formation Time proportional to Energy

Small color-singlet

Color Transparent

Minimal same-side energy

QGP

LBNL April 7, 2009

Light-Front Holography

105

Stan Brodsky

SLAC
Particle ratio changes with centrality!

Protons less absorbed in nuclear collisions than pions because of dominant color transparent higher twist process.

Central

Peripheral

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

trigger: $2.5 < p_T < 4.0$ GeV/c
associated: $1.8 < p_T < 2.5$ GeV/c

# same-side particles decreases with centrality
Central Au+Au: PHENIX

Central Au+Au: STAR

p+p NSD: STAR

e^+e^- \rightarrow ggg: ARGUS

\Lamda_{K_S}^{0}/2

\bar{p}/\pi

Baryon to Meson Ratios

Transverse Momentum \( p_T \) (GeV/c)

Central Au+Au: STAR

40%-60% central: STAR

200 GeV p+p: STAR

630 GeV p+p: UA1

LBNL
April 7, 2009

Light-Front Holography

108

Stan Brodsky
SLAC
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
Lambda can be made directly within hard subprocess

Coalescence within hard subprocess

ud → Λatars

Small color-singlet
Color Transparent
Minimal same-side energy

Λs produced on away side

nactive = 6
n_{eff} = 2n_{active} - 4
n_{eff} = 8

Sickles, sjb

LBNL
April 7, 2009

Light-Front Holography
110

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 $x_T = 1$
\[ |p, S_z > = \sum_{n=3} \Psi_n(x_i, \vec{k}_{\perp i}, \lambda_i) |n; \vec{k}_{\perp i}, \lambda_i > \]

**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.

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

**Intrinsic heavy quarks,**

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

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

**Fixed LF time**
E866/NuSea (Drell-Yan)

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

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

Intrinsic glue, sea, heavy quarks
Remarkable Features of Hadron Structure

• Valence quark helicity represents less than half of the proton’s spin and momentum

• Non-zero quark orbital angular momentum!

• Asymmetric sea: $\bar{u}(x) \neq \bar{d}(x)$ relation to meson cloud

• Non-symmetric strange and antistrange sea $\bar{s}(x) \neq s(x)$

• Intrinsic charm and bottom at high $x$

• Hidden-Color Fock states of the Deuteron
Light-Front QCD Phenomenology

- Hidden color, Intrinsic glue, sea, Color Transparency
- Physics of spin, orbital angular momentum
- 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
Deep Inelastic Electron-Proton Scattering

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

Pseudo- $T$-Odd

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

Light-Front Wavefunction

$S$ and $P$-Waves

Leading Twist Sivers Effect

Hwang, Schmidt, sjb

Collins, Burkardt Ji, Yuan

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

--Wilson Line

Moreno

LBNL
April 7, 2009

Light-Front Holography

117

Stan Brodsky
SLAC
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
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.

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
QCD Mechanism for Rapidity Gaps

Wilson Line: \( \overline{\Psi}(y) \int_{0}^{y} dx \, e^{iA(x) \cdot dx} \psi(0) \)

Origin of Diffractive DIS
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_
Final State Interactions in QCD

Feynman Gauge

Light-Cone Gauge

Result is Gauge Independent
DY $\cos 2\phi$ correlation at leading twist from double ISI

Product of Boer-Mulders Functions

$$h_{1}^{\perp}(x_1, p_{\perp}^2) \times \bar{h}_{1}^{\perp}(x_2, k_{\perp}^2)$$
Drell-Yan Lepton Pair Azimuthal Asymmetry in Hadronic Processes

Jian Zhou,¹,² Feng Yuan,²,³ and Zuo-Tang Liang¹

¹School of Physics, Shandong University, Jinan, Shandong 250100, China
²Nuclear Science Division, Lawrence Berkeley National Laboratory, Berkeley, CA 94720
³RIKEN BNL Research Center, Building 510A, Brookhaven National Laboratory, Upton, NY 11973

Abstract

We study the azimuthal asymmetry (cos 2φ) in the Drell-Yan lepton pair production in hadronic scattering processes at moderate transverse momentum region, taking into account the contributions from the twist-three quark-gluon correlations from the unpolarized hadrons. The contributions are found to dominate the asymmetry, and are not power suppressed by q⊥/Q at small q⊥ where q⊥ and Q are the transverse momentum and invariant mass of the lepton pair. Accordingly, the Lam-Tung relation will be violated at this momentum region, and its violation depends on the twist-three functions. However, at large transverse momentum q⊥ ∼ Q, the Lam-Tung relation still holds because all corrections are power suppressed by Λ²/q² ∼ Λ²/Q² where Λ is the typical nonperturbative scale.
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): $1 - \lambda - 2\nu = 0$

$$\frac{\nu}{2} \propto h_1^+(\pi) h_1^+(N).$$

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

Violates Lam-Tung relation!
Problem for factorization when both ISI and FSI occur
Physics of Rescattering

- Diffractive DIS: New Insights into Final State Interactions in QCD
- Origin of Hard Pomeron
- Structure Functions not Probability Distributions!
- T-odd single-spin asymmetries,
- Nuclear Shadowing, Non-Universal Antishadowing
- Diffractive dijets/ trijets, doubly diffractive Higgs
- Novel Effects: Color Transparency, Color Opaqueness, Intrinsic Charm, Odderon

Schmidt, Yang, sjb
Factorization is violated in production of high-transverse-momentum particles in hadron-hadron collisions


Implications for QCD at the LHC

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
$\cos 2\phi$ correlation for quarkonium production at leading twist from double ISI
Enhanced by gluon color charge
Anti-Shadowing

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

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

Extrapolations from NuTeV

SLAC/NMC data

Scheinbein, Yu, Keppel, Morfin, Olness, Owens
Static vs. Dynamic Structure Functions

Static

- Square of Target LFWFs
- No Wilson Line
- Probability Distributions
- Process-Independent
- $T$-even Observables
- No Shadowing, Anti-Shadowing
- Sum Rules: Momentum and $J^z$
- DGLAP Evolution; mod. at large $x$
- No Diffractive DIS

Dynamic

- Modified by Rescattering: ISI & FSI
- Contains Wilson Line, Phases
- No Probabilistic Interpretation
- Process-Dependent - From Collision
- $T$-Odd (Sivers, Boer-Mulders, etc.)
- Shadowing, Anti-Shadowing, Saturation
- Not Proven
- DGLAP Evolution
- Hard Pomeron and Odderon: DDIS
Deur, Korsch, et al: Effective Charge from Bjorken Sum Rule

\[ \Gamma_{p^-n}^{bj} (Q^2) \equiv \frac{g_A}{6} \left[ 1 - \frac{\alpha_s g_1(Q^2)}{\pi} \right] \]
Deur, Korsch, et al.

\[ \alpha_s/g_1/\pi \text{ JLab} \quad \text{GDH limit} \]

\[ \text{Fit} \quad \text{pQCD evol. eq.} \]

\[ \alpha_s/g_1 \quad \text{Burkert-Ioffe} \]

\[ \text{Bloch et al.} \quad \text{Godfrey-Isgur} \]

\[ \text{Cornwall} \quad \text{Bhagwat et al.} \quad \text{Maris-Tandy} \]

\[ \text{DSE gluon couplings} \]

\[ \text{Lattice QCD} \]

\[ Q \quad (\text{GeV}) \]
**IR Conformal Window for QCD?**

- **Dyson-Schwinger Analysis:** QCD gluon coupling has IR Fixed Point

- **Evidence from Lattice Gauge Theory**

- Define coupling from observable: **indications of IR fixed point for QCD effective charges**

- Confined gluons and quarks have maximum wavelength: **Decoupling of QCD vacuum polarization at small Q^2**

- Justifies application of AdS/CFT in strong-coupling conformal window

\[
\Pi(Q^2) \rightarrow \frac{\alpha}{15\pi m^2} \frac{Q^2}{m^2} \quad Q^2 << 4m^2
\]
QED One-Loop Vacuum Polarization

\[ \Pi(Q^2) = \frac{\alpha(0)}{3\pi} \left[ \frac{5}{3} - \frac{4m^2}{Q^2} - (1 - \frac{2m^2}{Q^2}) \sqrt{1 + \frac{4m^2}{Q^2}} \log \frac{1 + \sqrt{1 + \frac{4m^2}{Q^2}}}{1 - \sqrt{1 + \frac{4m^2}{Q^2}}} \right] \]

\[ \Pi(Q^2) \simeq \frac{\alpha(0)}{3\pi} \log \frac{Q^2}{m^2} \quad Q^2 \gg 4m^2 \]

\[ \beta = \frac{d(\frac{\alpha}{4\pi})}{d \log Q^2} = \frac{4}{3} \left( \frac{\alpha}{4\pi} \right)^2 n_\ell > 0 \]

\[ \Pi(Q^2) = \frac{\alpha(0) Q^2}{15\pi m^2} \quad Q^2 << 4m^2 \quad \text{Serber-Uehling} \]

\[ \beta \propto \frac{Q^2}{m^2} \quad \text{vanishes at small momentum transfer} \]
Lesson from QED: 
Lamb Shift in Hydrogen

$$\Delta E \sim \alpha (Z\alpha)^4 \ln (Z\alpha)^2 m_e$$

Infrared divergence of free electron propagator removed because of atomic binding

Maximum wavelength of bound electron

Lamb shift in hydrogen
Lesson from QED and Lamb Shift:

maximum wavelength of bound quarks and gluons

\[ k > \frac{1}{\Lambda_{QCD}} \]

\[ \lambda < \Lambda_{QCD} \]

---

B-Meson
Shrock, sjb

gluon and quark propagators cutoff in IR
because of color confinement
Consequences of Maximum Quark and Gluon Wavelength

- Infrared integrations regulated by confinement
- Infrared fixed point of QCD coupling
  \[ \alpha_s(Q^2) \text{ finite, } \beta \to 0 \text{ at small } Q^2 \]
- Bound state quark and gluon Dyson-Schwinger Equation
- Quark and Gluon Condensates exist within hadrons

Casher, Susskind
Shrock, sjb
Lesson from QED and Lamb Shift:

maximum wavelength of bound quarks and gluons

\[ k > \frac{1}{\Lambda_{\text{QCD}}} \]

\[ \lambda < \Lambda_{\text{QCD}} \]

Use Dyson-Schwinger Equation for bound-state quark propagator: find confined condensate

\[ < \bar{b} | \bar{q} q | \bar{b} > \text{ not } < 0 | \bar{q} q | 0 > \]
Quark and Gluon condensates reside within hadrons, not vacuum.

- **Bound-State Dyson-Schwinger Equations**
- **LF vacuum trivial up to** $k^+ = 0$ **zero modes**
- **Analogous to finite size superconductor**
- **Usual picture for** $m_\pi \rightarrow 0$
- **Implications for cosmological constant -- reduction by 45 orders of magnitude!**
Determinations of the vacuum Gluon Condensate

\[ < 0 | \frac{\alpha_s}{\pi} G^2 | 0 > [\text{GeV}^4] \]

\[-0.005 \pm 0.003 \text{ from } \tau \text{ decay.} \quad \text{Davier et al.} \]

\[+0.006 \pm 0.012 \text{ from } \tau \text{ decay.} \quad \text{Geshkenbein, Ioffe, Zyablyuk} \]

\[+0.009 \pm 0.007 \text{ from charmonium sum rules} \quad \text{Ioffe, Zyablyuk} \]

Consistent with zero vacuum condensate
**AdS$_5$ Black hole simulation of temperature**

\[ ds^2 = \frac{R^2}{z^2} \left[ -f(z) \, dt^2 + d\vec{x}^2 + \frac{dz^2}{f(z)} \right] \]

- Hawking Temperature
  \[ f(z) = 1 - \frac{z^4}{z_0^4} \]
  \[ T_H = \frac{r_0}{\pi R^2} = \frac{\hbar c}{\pi z_0} \]
  \[ \hat{z} = \frac{R^2}{r} \]

D. T. Son, et al
Gauge/gravity duality provides unexpected tools to compute the viscosity of some strongly coupled theories.

The class of theories with gravity dual description is limited, but contains very interesting theories with infinite coupling.

The calculation of the viscosity is easy: viscosity $\propto$ absorption cross section of low-energy gravitons by the black hole.

In this class, the ratio $\eta/s$ is equal to a universal number $\hbar/4\pi$, much smaller than in any other system in Nature.

The ratio $\eta/s$ is the measure of perfectness of the QGP.

sjb: AdS/CFT gives a model of perfect quantum coherence. Temperature not due to classical heating.
• Large longitudinal coherence at high energies

• Coherence: LPM effect limits energy loss; Glauber theory of nuclear shadowing in DIS

• Color transparency in Diffractive dijets (Ashery)

• Laser cascade mechanism sets up coherent system in central heavy ion collisions

• Ridge: Coherence over large longitudinal momenta

• Large $v_2$: $\Delta p_x \sim \frac{\hbar}{\Delta x}$

• Small $\eta/s \sim \frac{\hbar}{4\pi}$
3 < p_{T,\text{trigger}} < 4 \text{ GeV/c}
Ridge created by DGLAP semihard radiation
Momenta of initial colored partons biased towards trigger

Soft gluon radiation from initial state partons emitted in plane of production; fills rapidity
Light-Front Description of Heavy Ion Collisions

- Nuclear LFWFs are momentum independent
- No effects on wavefunction from boost
- Process independent
- Three-dimensional
- Small x gluons and sea quarks in any frame
- Dynamical effects arise from interactions
- Wilson line give ISI and FSI
- Nuclear shadowing and antishadowing not in nuclear wavefunction -- Glauber multistep diffractive interactions
Interaction of $a$ and $b$ when $\mathbf{r}_\perp^a \simeq \mathbf{r}_\perp^b$ and $\sigma_a \simeq \sigma_b$.

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

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

$$\sigma_a = \text{conj} \left[ x_a \right]$$

$$x_a \ell_\perp + \mathbf{k}_\perp^a$$

$$\Psi_A(x_a, \mathbf{k}_\perp^a)$$

$$\Psi_B(x_b, \mathbf{k}_\perp^b)$$
Light-Front Description of Heavy Ion Collisions

- Nuclear LFWFs are momentum independent
- No effects on wavefunction from boost
- Process independent
- Three-dimensional
- Small x gluons and sea quarks in any frame
- Dynamical effects arise from interactions
- Wilson line give ISI and FSI
- Nuclear shadowing and antishadowing not in nuclear wavefunction -- Glauber multistep diffractive interactions
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''

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

analog of laser backscattering in QED

\[ gq \rightarrow \gamma q \]
Diffractive Dissociation of Pion into Quark Jets

Measure Light-Front Wavefunction of Pion

Minimal momentum transfer to nucleus

Nucleus left Intact!

\[ M \propto \frac{\partial^2}{\partial^2 k_{\perp}} \psi_\pi(x, k_{\perp}) \]
Two-gluon exchange measures the second derivative of the pion light-front wavefunction

\[ M \propto \frac{\partial^2}{\partial^2 k_\perp} \psi_\pi(x, k_\perp) \]
Key Ingredients in E791 Experiment

Small color-dipole moment pion not absorbed; interacts with each nucleon coherently

QCD COLOR Transparency

\[ M_A = A \cdot M_N \]

\[ \frac{d\sigma}{dt}(\pi A \rightarrow q\bar{q}A') = A^2 \frac{d\sigma}{dt}(\pi N \rightarrow q\bar{q}N') \cdot F_A^2(t) \]

Target left intact

Diffraction, Rapidity gap
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
- Fully coherent interactions between pion and nucleons.

- Emerging Di-Jets do not interact with nucleus.

\[ \mathcal{M}(\mathcal{A}) = \mathcal{A} \cdot \mathcal{M}(\mathcal{N}) \]

\[ \frac{d\sigma}{dq_f^2} \propto A^2 \quad q_f^2 \sim 0 \]

\[ \sigma \propto A^{4/3} \]

Nuclear coherence

\[ F_A^2(q^2_\perp) \sim e^{-\frac{1}{3}R_A^2q^2_\perp} \]
E791 Diffractive Di-Jet transverse momentum distribution

Two Components

High Transverse momentum dependence $k_T^{-6.5}$ consistent with PQCD, ERBL Evolution

Gaussian component similar to AdS/CFT HO LFHWF
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

\[ \phi(x) \propto \sqrt{x(1-x)} \]
Possibly two components:
Perturbative (ERBL) + Nonperturbative (AdS/CFT)

\[ \phi(x) = A_{\text{pert}}(k^2_{\perp})x(1-x) + B_{\text{nonpert}}(k^2_{\perp})\sqrt{x(1-x)} \]

Narrowing of x distribution at high jet transverse momentum
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

- Coherence creates hadronic momentum along minor axis

- 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 $v_2$. 
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

- Higher Fock States give GMOR Relations, Chiral Symmetry Breaking
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
Features of Soft-Wall $\text{AdS/QCD}$

- Single-variable frame-independent radial Schrodinger equation
- Massless pion ($m_q = 0$)
- Regge Trajectories: universal slope in $n$ and $L$
- Valid for all integer $J$ & $S$. Spectrum is independent of $S$
- Dimensional Counting Rules for Hard Exclusive Processes
- Phenomenology: Space-like and Time-like Form Factors
- LF Holography: LFWFs; broad distribution amplitude
- No large $N_c$ limit
- Add quark masses to LF kinetic energy
- Systematically improvable -- diagonalize $H_{LF}$ on AdS basis
String Theory

AdS/CFT

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

AdS/QCD

Conformal behavior at short distances + Confinement at large distance

Semi-Classical QCD / Wave Equations

Holography

Boost Invariant 3+1 Light-Front Wave Equations

Integrable!

Hadron Spectra, Wavefunctions, Dynamics

Goal: First Approximant to QCD

Counting rules for Hard Exclusive Scattering
Regge Trajectories
QCD at the Amplitude Level