Fig: Light baryon orbital spectrum for $\Lambda_{QCD} = 0.25$ GeV in the HW model. The 56 trajectory corresponds to $L$ even $P = +$ states, and the 70 to $L$ odd $P = -$ states.
Non-Conformal Extension of Algebraic Structure (Soft Wall Model)

- We write the Dirac equation
  \[(\alpha \Pi(\zeta) - \mathcal{M}) \psi(\zeta) = 0,\]
  in terms of the matrix-valued operator \(\Pi\)
  \[\Pi_\nu(\zeta) = -i \left( \frac{d}{d\zeta} - \frac{\nu + \frac{1}{2}}{\zeta} \gamma_5 - \kappa^2 \zeta \gamma_5 \right),\]
  and its adjoint \(\Pi^\dagger\), with commutation relations
  \[\left[ \Pi_\nu(\zeta), \Pi^\dagger_\nu(\zeta) \right] = \left( \frac{2\nu + 1}{\zeta^2} - 2\kappa^2 \right) \gamma_5.\]

- Solutions to the Dirac equation
  \[\psi_+(\zeta) \sim z^{1+\nu} e^{-\kappa^2 \zeta^2/2} L_n^\nu(\kappa^2 \zeta^2),\]
  \[\psi_-(\zeta) \sim z^{3+\nu} e^{-\kappa^2 \zeta^2/2} L_n^{\nu+1}(\kappa^2 \zeta^2).\]

- Eigenvalues
  \[\mathcal{M}^2 = 4\kappa^2(n + \nu + 1).\]

\[
\frac{\omega_B}{\omega_M} = \frac{5}{8}
\]

\[
\kappa^2 \text{ for } \Delta n = 1
\]

\[
4\kappa^2 \text{ for } \Delta L = 1
\]

\[
2\kappa^2 \text{ for } \Delta S = 1
\]

\[M^2 \]

Parent and daughter 56 Regge trajectories for the \( N \) and \( \Delta \) baryon families for \( \kappa = 0.5 \text{ GeV} \).
E. Klempt et al.: $\Delta^*$ resonances, quark models, chiral symmetry and AdS/QCD

<table>
<thead>
<tr>
<th>$SU(6)$</th>
<th>$S$</th>
<th>$L$</th>
<th>Baryon State</th>
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<td>56</td>
<td>$\frac{1}{2}$</td>
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<td>$N_{\frac{1}{2}}^{1+}(939)$</td>
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<td>$\frac{3}{2}$</td>
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<td>$\Delta_{\frac{3}{2}}^{3+}(1232)$</td>
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<td>$N_{\frac{1}{2}}^{1-}(1650)$ $N_{\frac{3}{2}}^{3-}(1700)$ $N_{\frac{5}{2}}^{5-}(1675)$</td>
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<td>$\Delta_{\frac{5}{2}}^{5-}(1930)$ $\Delta_{\frac{7}{2}}^{7-}$</td>
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<td>56</td>
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<td>$N_{\frac{7}{2}}^{7-}$ $N_{\frac{9}{2}}^{9-}$ $N_{\frac{11}{2}}^{11-}$ $N_{\frac{13}{2}}^{13-}$</td>
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</tbody>
</table>
Space-Like Dirac Proton Form Factor

- Consider the spin non-flip form factors

\[
F_+(Q^2) = g_+ \int d\zeta J(Q, \zeta)|\psi_+(\zeta)|^2, \\
F_-(Q^2) = g_- \int d\zeta J(Q, \zeta)|\psi_-(\zeta)|^2,
\]

where the effective charges \(g_+\) and \(g_-\) are determined from the spin-flavor structure of the theory.

- Choose the struck quark to have \(S^z = +1/2\). The two AdS solutions \(\psi_+(\zeta)\) and \(\psi_-(\zeta)\) correspond to nucleons with \(J^z = +1/2\) and \(-1/2\).

- For \(SU(6)\) spin-flavor symmetry

\[
F_1^p(Q^2) = \int d\zeta J(Q, \zeta)|\psi_+(\zeta)|^2, \\
F_1^n(Q^2) = -\frac{1}{3} \int d\zeta J(Q, \zeta) \left[|\psi_+(\zeta)|^2 - |\psi_-(\zeta)|^2\right],
\]

where \(F_1^p(0) = 1, \ F_1^n(0) = 0\).
• Scaling behavior for large $Q^2$: $Q^4 F_1^p(Q^2) \to$ constant

Proton $\tau = 3$

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

\[
\tau = 3
\]

Spacelike Pauli Form Factor

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

$F^p_2(Q^2)$

Harmonic Oscillator
Confinement
Normalized to anomalous moment

$\kappa = 0.49$ GeV

G. de Teramond, sjb

$F_2(Q^2) = 1 + O \frac{Q^2}{m_\pi m_p}$
in chiral perturbation theory

Preliminary

AdS/QCD No chiral divergence!
Non-Perturbative Running Coupling from Modified AdS/QCD

Deur, de Teramond, sjb

Five dimensional action in presence of dilaton background

\[ S = -\frac{1}{4} \int d^4 x dz \sqrt{g} \ e^{\phi(z)} \frac{1}{g_5^2} G^2 \]

where \( \sqrt{g} = \left(\frac{R}{z}\right)^5 \) and \( \phi(z) = +\kappa^2 z^2 \)

Define an effective coupling \( g_5(z) \)

\[ S = -\frac{1}{4} \int d^4 x dz \sqrt{g} \frac{1}{g_5^2(z)} G^2 \]

Thus \( \frac{1}{g_5^2(z)} = e^{\phi(z)} \frac{1}{g_5^2(0)} \) or \( g_5^2(z) = e^{-\kappa^2 z^2} g_5^2(0) \)

Light-Front Holography:

\[ z \to \zeta = b_\perp \sqrt{x(1-x)} \]

\[ \alpha_s(q^2) \propto \int_0^\infty d\zeta J_0(\zeta Q) \alpha_s(\zeta) \]

where \( \alpha_s(\zeta) = e^{-\kappa^2 \zeta^2} \alpha_s(0) \)
Running Coupling from AdS/QCD

\[ \frac{\alpha_s(Q)}{\pi} \]

\[ \alpha_s^{AdS}(Q)/\pi = e^{-Q^2/4\kappa^2} \]

\[ \kappa = 0.54 \text{ GeV} \]

Deur, de Teramond, sjb, (preliminary)
\[ \frac{\alpha_{s,g1}}{\pi} \]

- **GDH limit**
- **Burkert-Ioffe**
- **Cornwall**
- **Godfrey-Isgur**
- **Bloch et al.**
- **Lattice QCD**
- **AdS/CFT** (norm. to \( \pi \), \( \kappa=0.54 \))

**Legend:**
- Blue: Fit
- Cyan: pQCD evol. eq.

Q (GeV)
Diffractive Dissociation of Pion into Quark Jets

$M \propto \frac{\partial^2}{\partial^2 k_{\perp}} \psi_\pi(x, k_{\perp})$

Measure Light-Front Wavefunction of Pion

Minimal momentum transfer to nucleus

Nucleus left Intact!

E791 Ashery et al.
Key Ingredients in E791 Experiment

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

QCD COLOR Transparency

\[ M_A = A M_N \]

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

Target left intact

Diffraction, Rapidity gap

Purdue October 29, 2009

AdS/QCD

Stan Brodsky, SLAC
Measure pion LFWF in diffractive dijet production
Confirmation of color transparency

A-Dependence results: \( \sigma \propto A^\alpha \)

<table>
<thead>
<tr>
<th>( k_t ) range (GeV/c)</th>
<th>( \alpha )</th>
<th>( \alpha ) (CT)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.25 &lt; ( k_t &lt; 1.5 )</td>
<td>1.64 ( +0.06 ) -0.12</td>
<td>1.25</td>
</tr>
<tr>
<td>1.5 &lt; ( k_t &lt; 2.0 )</td>
<td>1.52 ( \pm 0.12 )</td>
<td>1.45</td>
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<tr>
<td>2.0 &lt; ( k_t &lt; 2.5 )</td>
<td>1.55 ( \pm 0.16 )</td>
<td>1.60</td>
</tr>
</tbody>
</table>

\( \alpha \) (Incoh.) = \( 0.70 \pm 0.1 \)

Conventional Glauber Theory Ruled Out!

Factor of 7

Purdue October 29, 2009

\( AdS/QCD \)

Stan Brodsky, SLAC

Mueller, sjb; Bertsch et al; Frankfurt, Miller, Strikman
Color Transparency

Bertsch, Gunion, Goldhaber, sjb
A. H. Mueller, sjb

- 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.

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

\[ \frac{d\sigma}{dq_t^2} \propto A^2 \quad q_t^2 \sim 0 \]

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

Nuclear coherence

\[ F_A^2(q_{\perp}^2) \sim e^{-\frac{1}{3} R_A^2 q_{\perp}^2} \]
A(π,dijet) data from FNAL

Conventional Glauber Theory Ruled Out!

Fit to $\sigma = \sigma_0 A^\alpha$

$\alpha > 0.76$ from pion-nucleus to cross-section.

Coherent $\pi^+$ diffractive dissociation with 500 GeV/c pions on Pt and C.


Aitala et al., PRL 86 4773 (2001)

Factor of 7
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
Two-gluon exchange measures the second derivative of the pion light-front wavefunction

\[ M \propto \frac{\partial^2}{\partial^2 k_{\perp}} \psi_\pi(x, k_{\perp}) \]
**E-791** Diffractive Di-Jet transverse momentum distribution

**Two Components**

High Transverse momentum dependence consistent with $k_T^{-6.5}$

PQCD, ERBL Evolution

Gaussian component similar to AdS/CFT HO LFWF

---

*Purdue October 29, 2009*

*AdS/QCD*
Narrowing of $x$ distribution at higher jet transverse momentum

- $x$: distribution of diffractive dijets from the platinum target for $1.25 \leq k_t \leq 1.5$ GeV/c (left) and for $1.5 \leq k_t \leq 2.5$ 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**

\[
\phi(x) \propto \sqrt{x(1-x)}
\]
Narrowing of $x$ distribution at higher jet transverse momentum

$x$: distribution of diffractive dijets from the platinum target for $1.25 \leq k_t \leq 1.5$ GeV/c (left) and for $1.5 \leq k_t \leq 2.5$ 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

$$\phi(x) \propto \sqrt{x(1-x)}$$

Purdue October 29, 2009

AdS/QCD

Stan Brodsky, SLAC
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)

Transparency vs. $Q^2 (\text{GeV}/c)^2$ for various nuclei:
- $^2H$
- $^{12}C$
- $^{63}Cu$
- $^{27}Al$
- $^{197}Au$

Color Transparency Prediction

Glauber

AdS/QCD
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)

\[ M(t, u)_{\text{interchange}} \propto \frac{1}{ut^2} \]

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:

\[ \frac{d\sigma}{dt} = \left| M(s,t) \right|^2 \]
AdS/CFT explains why quark interchange is dominant interaction at high momentum transfer in exclusive reactions.

$$M(t, u)_{	ext{interchange}} \propto \frac{1}{ut^2}$$

Non-linear Regge behavior:

$$\alpha_R(t) \to -1$$
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.: $\pi^\pm p \rightarrow p\pi^\pm, p\rho^\pm, \pi^+\Delta^\pm, K^+\Sigma^\pm, (\Lambda^0/\Sigma^0)K^0, K^\pm p \rightarrow pK^\pm; p^\pm p \rightarrow pp^\pm$. 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

\[ M_{QIM} = \int d^2k_\perp dx \quad \psi_C^\dagger \psi_D^\dagger \Delta \psi_A \psi_B \]

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.
Particle ratio changes with centrality!

Protons less absorbed in nuclear collisions than pions!


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 $e^+e^- \rightarrow HX$. 
Particle ratios change with centrality!

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

Stan Brodsky, SLAC
Purdue October 29, 2009
High centrality 0 – 10% $p + \bar{p}$

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

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

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

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

*As fundamental as Bjorken scaling in DIS*

**Conformal scaling:** $n_{eff} = 2n_{active} - 4$
$pp \rightarrow \gamma X$

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

$gu \rightarrow \gamma u$

$n_{active} = 4$

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

$n_{eff} = 4$
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:

\[ G_{q/p}(x_1, p_{\perp}^2) \]

\[ D_{\pi/q}(z, p_{\perp}^2) \]
\[ \sqrt{s^n} E \frac{d\sigma}{d^3p} (pp \rightarrow \gamma X) \] at fixed \( x_T \)

\( x_T \)-scaling of direct photon production is consistent with PQCD
$pp \rightarrow HX$ at high $p_T$

Hadron created from jet fragmentation

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

$n_{active} = 4$

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

$n_{eff} = 4$
QCD prediction: Modification of power fall-off due to DGLAP evolution and the Running Coupling

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

\[ pp \rightarrow \pi X \]

\[ pp \rightarrow \gamma X \]

Key test of PQCD: power-law fall-off at fixed $x_T$

5 < $p_\perp$ < 20 GeV

70 GeV < $\sqrt{s}$ < 4 TeV

DSS
(De Florian-Sassot-Stratmann)

Arleo, Aurenche
Hwang, Sickles, sjb

Pirner, Raufefisen, sjb

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

INCLNLO
\[ \sqrt{s}^n E \frac{d\sigma}{d^3p} (pp \rightarrow \pi^0 X) \text{ at fixed } x_T = \frac{2p_T}{\sqrt{s}} \]

\( n = 6.38 \)

\( n^0 \text{ from } p+p \)

M. J. Tannenbaum

PHENIX 62.4 and 200 GeV data
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

AdS/QCD

Stan Brodsky, SLAC

Purdue October 29, 2009
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 $x_T$.**

$n_{eff} = 4$
Clear evidence for higher-twist contributions

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

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

J. W. Cronin, SSI 1974
\[ E \frac{d\sigma}{d^3p}(pp \to HX) = \frac{F(x_T, \theta_{CM} = \pi/2)}{p_{T}^{n_{eff}}} \]

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

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

Arleo, Aurenche, Hwang, Sickles, sjb

\textit{AdS/QCD}
Baryon can be made directly within hard subprocess

Coalescence within hard subprocess

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

AdS/QCD

Stan Brodsky, SLAC
Baryon made directly within hard subprocess

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

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

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

Formation Time proportional to Energy

Small color-singlet
Color Transparent
Minimal same-side energy

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

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

\[ n_{\text{eff}} = 8 \]
Proton production more dominated by color-transparent direct high-\( n_{eff} \) subprocesses
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 $n_{eff}$ subprocesses
Particle ratio changes with centrality!

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

Central

Peripheral

Tannenbaum: “Baryon Anomaly”


Purdue October 29, 2009

AdS/QCD

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 $x_T = 1$
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

$\bar{s}$ produced on away side

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

Purdue October 29, 2009

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\( \pi N \rightarrow \mu^+ \mu^- X \) at high \( x_F \)

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

Entire pion wave function contributes to hard process

Virtual photon is longitudinally polarized

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

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

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

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

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

Example of a higher-twist direct subprocess

Chicago-Princeton Collaboration

Purdue October 29, 2009

AdS/QCD

Stan Brodsky, SLAC
String Theory

AdS/CFT

AdS/QCD

Semi-Classical QCD / Wave Equations

Boost Invariant 3+1 Light-Front Wave Equations

Hadron Spectra, Wavefunctions, Dynamics

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

Holography

Integrable!
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, sbj
Vary, Harinandrath, Maris, sbj
Chiral Symmetry Breaking in AdS/QCD

- Chiral symmetry breaking effect in AdS/QCD depends on weighted $z^2$ distribution, not constant condensate

$$\delta M^2 = -2m_q \langle \bar{\psi} \psi \rangle \times \int dz \, \phi^2(z) z^2$$

- $z^2$ weighting consistent with higher Fock states at periphery of hadron wavefunction

- AdS/QCD: confined condensate

- Suggests "In-Hadron" Condensates

Erlich et al.
Chiral magnetism (or magnetohadrochironics)

Aharon Casher and Leonard Susskind

Tel Aviv University Ramat Aviv, Tel-Aviv, Israel
(Received 20 March 1973)

I. INTRODUCTION

The spontaneous breakdown of chiral symmetry in hadron dynamics is generally studied as a vacuum phenomenon.\(^1\) Because of an instability of the chirally invariant vacuum, the real vacuum is "aligned" into a chirally asymmetric configuration.

On the other hand an approach to quantum field theory exists in which the properties of the vacuum state are not relevant. This is the parton or constituent approach formulated in the infinite-momentum frame.\(^2\) A number of investigations have indicated that in this frame the vacuum may be regarded as the structureless Fock-space vacuum. Hadrons may be described as nonrelativistic collections of constituents (partons). In this framework the spontaneous symmetry breakdown must be attributed to the properties of the hadron’s wave function and not to the vacuum.\(^3\)
Use Dyson-Schwinger Equation for bound-state quark propagator:

\[
\begin{align*}
\langle \bar{b} | \bar{q} q | \bar{b} \rangle & \quad \text{not} \quad \langle 0 | \bar{q} q | 0 \rangle
\end{align*}
\]
Pion mass and decay constant.
e-Print: nucl-th/9707003

Pi- and K meson Bethe-Salpeter amplitudes.
e-Print: nucl-th/9708029

Concerning the quark condensate.
e-Print: nucl-th/0301024

“\textit{In-Meson Condensate}”

\[- \langle \bar{q}q \rangle_\zeta^\pi = f_\pi \langle 0 | \bar{q} \gamma_5 q | \pi \rangle .\]

Valid even for \( m_q \to 0 \)

\( f_\pi \) nonzero

Purdue October 29, 2009

AdS/QCD

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Stan Brodsky, SLAC
Quark and Gluon condensates reside within hadrons, not LF vacuum

- **Bound-State Dyson-Schwinger Equations**
- **Spontaneous Chiral Symmetry Breaking within infinite-component LFWFs**
- **Finite size phase transition - infinite # Fock constituents**
- **AdS/QCD Description -- CSB is in-hadron Effect**
- **Analogous to finite-size superconductor!**
- **Phase change observed at RHIC within a single-nucleus-nucleus collisions-- quark gluon plasma!**
- **Implications for cosmological constant -- reduction by 45 orders of magnitude!**

“Confined QCD Condensates”
“One of the gravest puzzles of theoretical physics”

DARK ENERGY AND
THE COSMOLOGICAL CONSTANT PARADOX

A. ZEE
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\[
(\Omega_\Lambda)_{QCD} \sim 10^{45} \quad \Omega_\Lambda = 0.76 (\text{expt})
\]

\[
(\Omega_\Lambda)_{EW} \sim 10^{56}
\]

QCD Problem Solved if Quark and Gluon condensates reside within hadrons, not LF vacuum

Shrock, sjb
• Color Confinement: Maximum Wavelength of Quark and Gluons

• Conformal symmetry of QCD coupling in IR

• Conformal Template (BLM, CSR, ...)

• Motivation for AdS/QCD

• QCD Condensates inside of hadronic LFWFs

• Technicolor: confined condensates inside of technihadrons -- alternative to Higgs

• Simple physical solution to cosmological constant conflict with Standard Model

Shrock and 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!