Holographic Truncated Space Model: Baryons

$$\alpha\Pi(\zeta)\psi(\zeta) = \mathcal{M}\psi(\zeta)$$

$$\Pi_\nu(\zeta) = -i\left(\frac{d}{d\zeta} - \frac{\nu+\frac{1}{2}}{\zeta}\gamma_\zeta\right)$$

$$\alpha^\dagger = \alpha, \quad \alpha^2 = 1,$$
$$\gamma_\zeta^\dagger = \gamma_\zeta, \quad \gamma_\zeta^2 = 1,$$
$$\{\alpha, \gamma_\zeta\} = 0.$$

$$\begin{pmatrix} 0 & -\frac{d}{d\zeta} \\ \frac{d}{d\zeta} & 0 \end{pmatrix}\begin{pmatrix} \psi_+ \\ \psi_- \end{pmatrix} - \begin{pmatrix} 0 & \frac{\nu+\frac{1}{2}}{\zeta} \\ \frac{\nu+\frac{1}{2}}{\zeta} & 0 \end{pmatrix}\begin{pmatrix} \psi_+ \\ \psi_- \end{pmatrix} = \mathcal{M}\begin{pmatrix} \psi_+ \\ \psi_- \end{pmatrix},$$

Frame-Independent LF Dirac Equation

Holographic Harmonic Oscillator Model: Baryons

$$(\alpha\Pi(\zeta) - \mathcal{M})\,\psi(\zeta) = 0,$$

Frame-Independent LF Dirac Equation

$$\Pi_\nu(\zeta) = -i\left(\frac{d}{d\zeta} - \frac{\nu+\frac{1}{2}}{\zeta}\gamma_5 - \kappa^2\zeta\gamma_5\right)$$

$$\Pi_\nu^\dagger(\zeta) = -i\left(\frac{d}{d\zeta} + \frac{\nu+\frac{1}{2}}{\zeta}\gamma_5 + \kappa^2\zeta\gamma_5\right)$$

Coupled Equations

$$\begin{pmatrix} 0 & -\frac{d}{d\zeta} \\ \frac{d}{d\zeta} & 0 \end{pmatrix}\begin{pmatrix}\psi_+ \\ \psi_-\end{pmatrix} - \begin{pmatrix} 0 & \frac{\nu+\frac{1}{2}}{\zeta} + \kappa^2\zeta \\ \frac{\nu+\frac{1}{2}}{\zeta} + \kappa^2\zeta & 0 \end{pmatrix}\begin{pmatrix}\psi_+ \\ \psi_-\end{pmatrix} = \mathcal{M}\begin{pmatrix}\psi_+ \\ \psi_-\end{pmatrix}$$

$$-\frac{d}{d\zeta}\psi_- - \frac{\nu+\frac{1}{2}}{\zeta}\psi_- - \kappa^2\zeta\psi_- = \mathcal{M}\psi_+,$$

$$\frac{d}{d\zeta}\psi_+ - \frac{\nu+\frac{1}{2}}{\zeta}\psi_+ - \kappa^2\zeta\psi_+ = \mathcal{M}\psi_-.$$

HO due to Linear Potential!

$$V = -\beta\kappa^2\zeta$$

Holographic Harmonic Oscillator Model: Baryons

$$(\alpha\Pi(\zeta) - \mathcal{M})\,\psi(\zeta) = 0,$$

$$\Pi_\nu(\zeta) = -i\left(\frac{d}{d\zeta} - \frac{\nu+\frac{1}{2}}{\zeta}\gamma_5 - \kappa^2\zeta\gamma_5\right)$$

$$\Pi_\nu^\dagger(\zeta) = -i\left(\frac{d}{d\zeta} + \frac{\nu+\frac{1}{2}}{\zeta}\gamma_5 + \kappa^2\zeta\gamma_5\right)$$

$$\left(H_{LF} - \mathcal{M}^2\right)\psi(\zeta) = 0, \qquad H_{LF} = \Pi^\dagger\Pi$$

Uncoupled Schrodinger Equations

Harmonic Oscillator Potential!

$$\left(\frac{d^2}{d\zeta^2} + \frac{1-4\nu^2}{4\zeta^2} - \kappa^4\zeta^2 - 2(\nu+1)\kappa^2 + \mathcal{M}^2\right)\psi_+(\zeta) = 0,$$

$$\left(\frac{d^2}{d\zeta^2} + \frac{1-4(\nu+1)^2}{4\zeta^2} - \kappa^4\zeta^2 - 2\nu\kappa^2 + \mathcal{M}^2\right)\psi_-(\zeta) = 0,$$

Solution

$$\psi_+(\zeta) \sim z^{\frac{1}{2}+\nu} e^{-\kappa^2\zeta^2/2} L_n^\nu(\kappa^2\zeta^2),$$

$$\psi_-(\zeta) \sim z^{\frac{3}{2}+\nu} e^{-\kappa^2\zeta^2/2} L_n^{\nu+1}(\kappa^2\zeta^2),$$

Same eigenvalue!

$$\mathcal{M}^2 = 4\kappa^2(n+\nu+1)$$

Holographic Baryon Spectrum

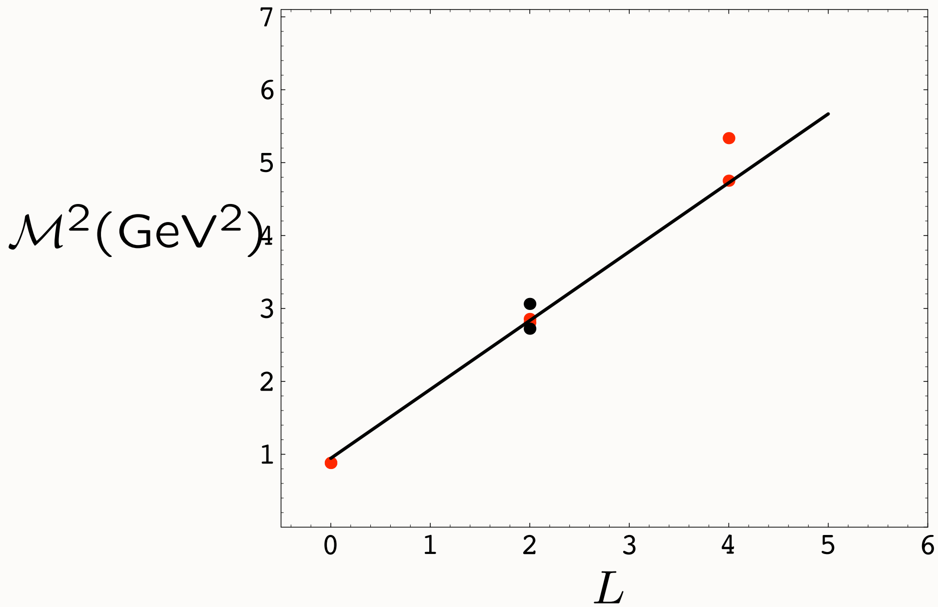
$$\psi(\zeta) = \kappa^{2+L}\sqrt{\frac{n!}{(n+L+2)!}}\zeta^{\frac{3}{2}+L}e^{-\kappa^2\zeta^2/2}\left[L_n^{L+1}\left(\kappa^2\zeta^2\right)u_+ + \frac{\kappa\zeta}{\sqrt{n+L+2}}L_n^{L+2}\left(\kappa^2\zeta^2\right)u_-\right]$$

$$\mathcal{M}^2 = 4\kappa^2(n+L+2).$$

Vacuum Energy Shift?

$$\mathcal{M}^2 \to \mathcal{M}^2 - 4\kappa^2,$$

$$\mathcal{M}^2 = 4\kappa^2(n+L+1).$$



$J = L + 1/2$ Regge trajectory

$\kappa \simeq 0.49$ GeV

Same slope in L and n

Example: Evaluation of QCD Matrix Elements

Pion decay constant f_π defined by the matrix element of EW current J^+_W:

$$\left\langle 0 \left| \overline{\psi}_u \gamma^+ (1-\gamma_5) \psi_d \right| \pi^- \right\rangle = i\sqrt{2} P^+ f_\pi,$$

with

$$\left|\pi^-\right\rangle = |d\overline{u}\rangle = \frac{1}{\sqrt{N_C}} \frac{1}{\sqrt{2}} \sum_{c=1}^{N_C} \left(b^\dagger_{c\, d\downarrow} d^\dagger_{c\, u\uparrow} - b^\dagger_{c\, d\uparrow} d^\dagger_{c\, u\downarrow} \right) |0\rangle.$$

Use light-cone expression:

$$f_\pi = 2\sqrt{N_C} \int_0^1 dx \int \frac{d^2\vec{k}_\perp}{16\pi^3}\, \psi_{\overline{q}q/\pi}(x, k_\perp).$$

Lepage and Brodsky '80

Find:

$$f_\pi = \frac{\sqrt{3}\Lambda_{\rm QCD}}{8 J_1(\beta_{0,1})} = 83.4 \,\text{Mev},$$

for $\Lambda_{\rm QCD} = 0.2$ GeV (fixed from the pion FF).

Experiment: $f_\pi = 92.4$ Mev.

Pion Decay Constant in HO Model

$$f_\pi = 2\sqrt{N_C}\int_0^1 dx \int \frac{d^2\vec{k}_\perp}{16\pi^3}\,\psi_{\overline{q}q/\pi}(x,\vec{k}_\perp)$$
$$= 2\sqrt{N_C}\int_0^1 dx\ \phi(x, Q^2 \to \infty),$$

$$\phi(x,Q^2) = \int^{Q^2} \frac{d^2\vec{k}_\perp}{16\pi^3}\psi(x,\vec{k}_\perp)$$

$$\psi_{\overline{q}q/\pi}(x,\vec{k}_\perp) = \frac{4\pi}{\kappa\sqrt{x(1-x)}}\, e^{-\frac{\vec{k}_\perp^2}{2\kappa^2 x(1-x)}}$$

$$f_\pi = \frac{\sqrt{3}\kappa}{8} = 86.6 \text{ MeV}$$ $$\kappa = 0.4 \text{ GeV}.$$

$$f_\pi = 92.4 \quad \text{MeV}$$ Exp.

$$F(Q^2) = R^3 \int_0^\infty \frac{dz}{z^3} \Phi_{P'}(z) J(Q,z) \Phi_P(z).$$

$$\Phi(z) = \frac{\sqrt{2}\kappa}{R^{3/2}} z^2 e^{-\kappa^2 z^2/2}. \qquad J(Q,z) = zQK_1(zQ).$$

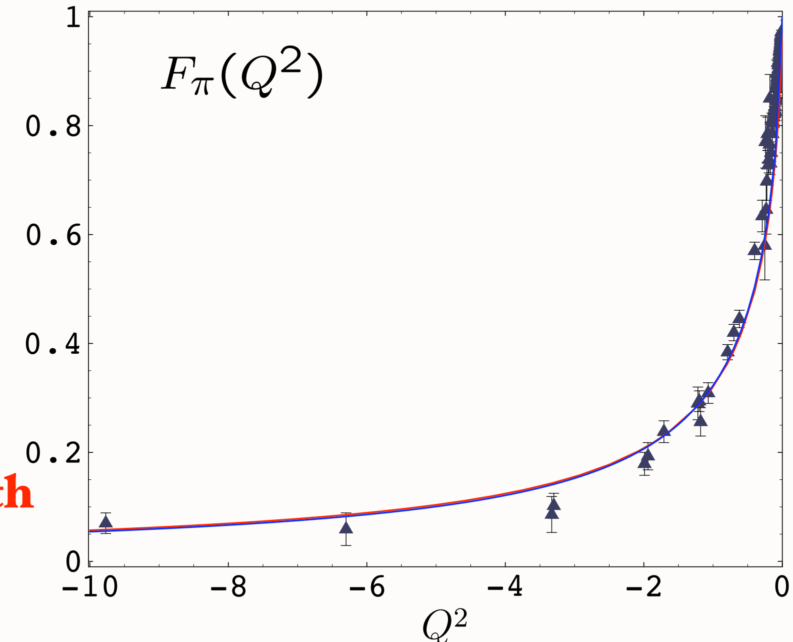
$$F(Q^2) = 1 + \frac{Q^2}{4\kappa^2} \exp\left(\frac{Q^2}{4\kappa^2}\right) Ei\left(-\frac{Q^2}{4\kappa^2}\right) \qquad Ei(-x) = \int_\infty^x e^{-t} \frac{dt}{t}.$$

Space-like Pion Form Factor

$\kappa = 0.4$ GeV

$\Lambda_{QCD} = 0.2$ GeV.

Identical Results for both confinement models



$F(Q^2) \to \frac{4\kappa^2}{Q^2}$

$\kappa = 2\Lambda_{QCD}$

High Q^2 from short distances

$z^2 = \zeta^2 = b_\perp^2 x(1-x)$
$= \mathcal{O}(\frac{1}{Q^2})$

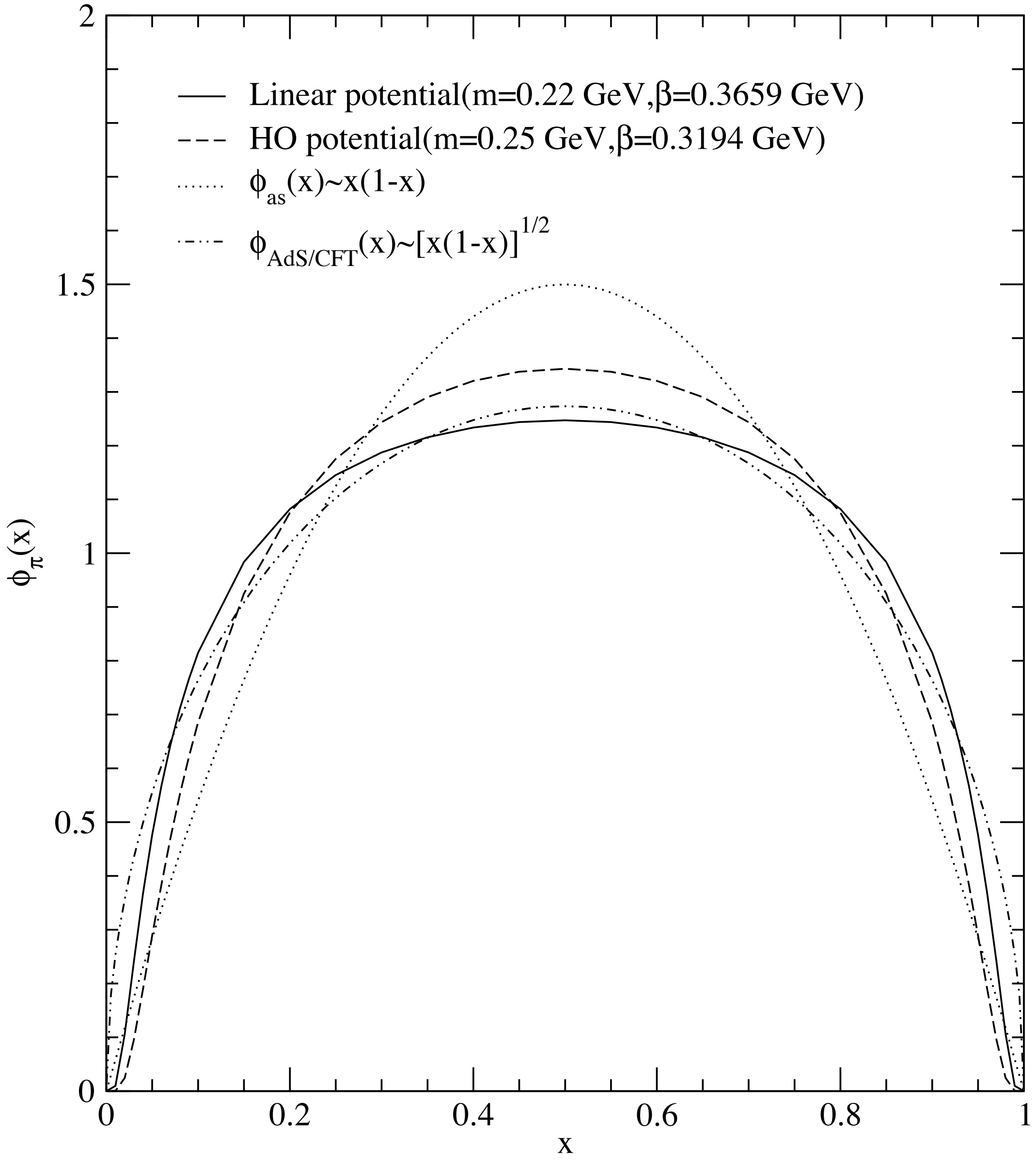
AdS/QCD

Hadron Distribution Amplitudes

$$\phi(x_i, Q) \equiv \Pi_{i=1}^{n-1} \int^Q d^2\vec{k}_\perp \; \psi_n(x_i, \vec{k}_{\perp i})$$

Lepage, SJB

- Fundamental measure of valence wavefunction
- Gauge Invariant (includes Wilson line)
- Evolution Equations, OPE
- Conformal Expansion
- Hadronic Input in Factorization Theorems



AdS/CFT:

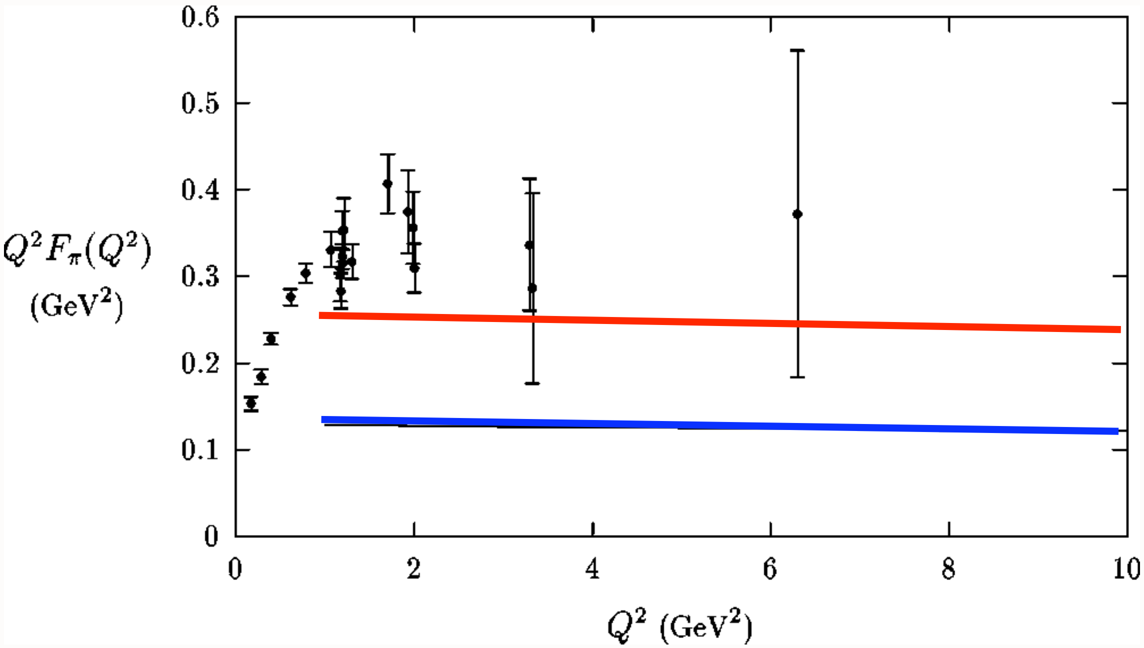
$$\phi(x, Q_0) \propto \sqrt{x(1-x)}$$

Increases PQCD leading twist prediction for $F_\pi(Q^2)$ by factor 16/9

Lepage, sjb

C. Ji, A. Pang, D. Robertson, sjb

$$F_\pi(Q^2) = \int_0^1 dx\, \phi_\pi(x) \int_0^1 dy\, \phi_\pi(y) \frac{16\pi C_F \alpha_V(Q_V)}{(1-x)(1-y)Q^2}$$



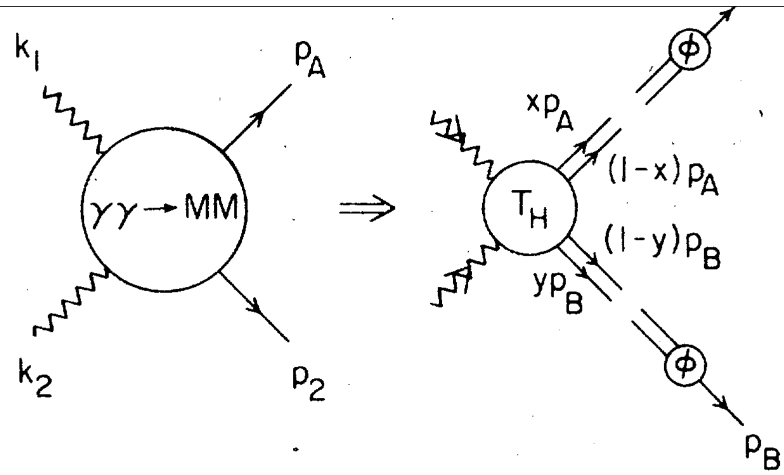
$\phi(x, Q_0) \propto \sqrt{x(1-x)}$

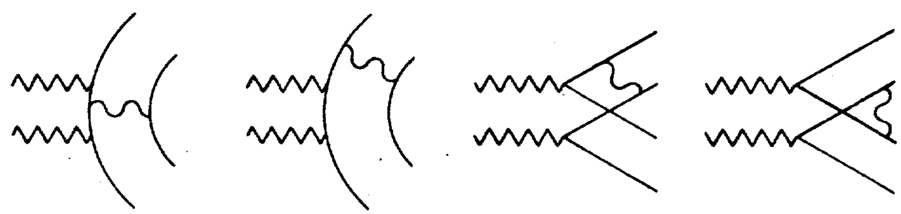
$\phi_{asymptotic} \propto x(1-x)$

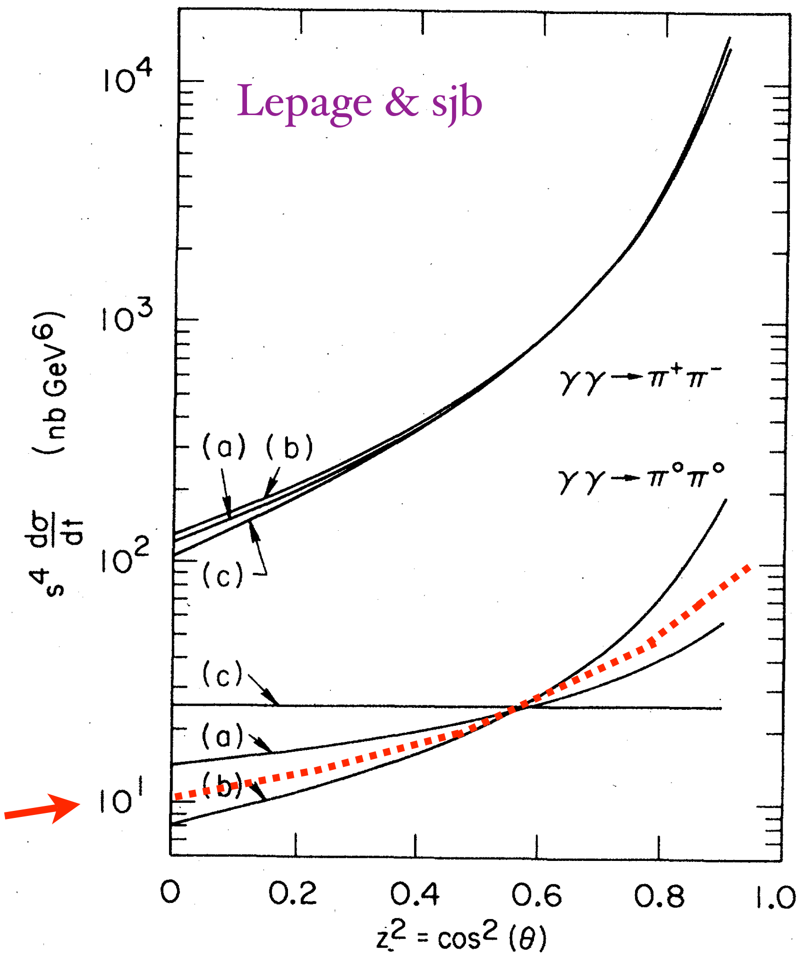
Normalized to f_π

AdS/CFT: Increases PQCD leading twist prediction for $F_\pi(Q^2)$ by factor 16/9

AdS/QCD







Neutral pair angular distribution sensitive to AdS/CFT distribution!

$$\phi_\pi^{AdS/QCD}(x) \propto [x(1-x)]^{1/2}$$

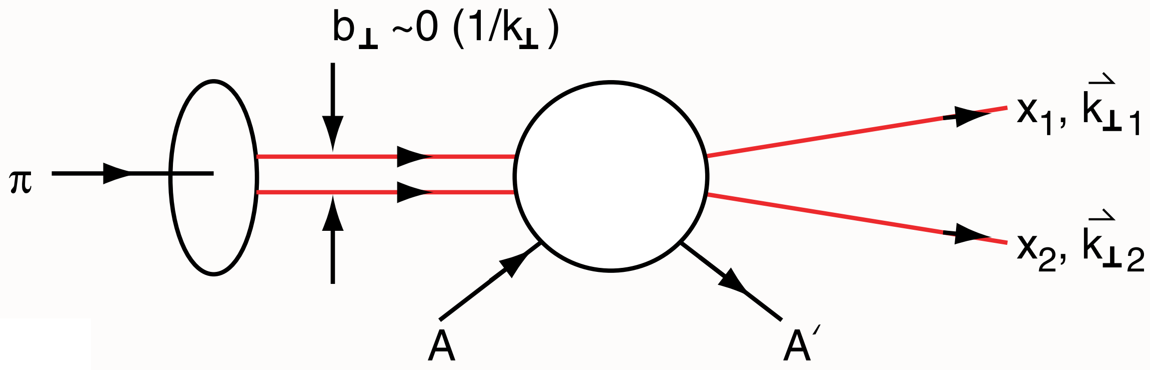
(a): $\phi_\pi(x) \propto x(1-x)$

(b): $\phi_\pi(x) \propto [x(1-x)]^{1/4}$

(c): $\phi_\pi(x) \propto \delta(x-1/2)$

Diffractive Dissociation of Pion into Quark Jets

E791 Ashery et al.



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

Measure Light-Front Wavefunction of Pion

Minimal momentum transfer to nucleus

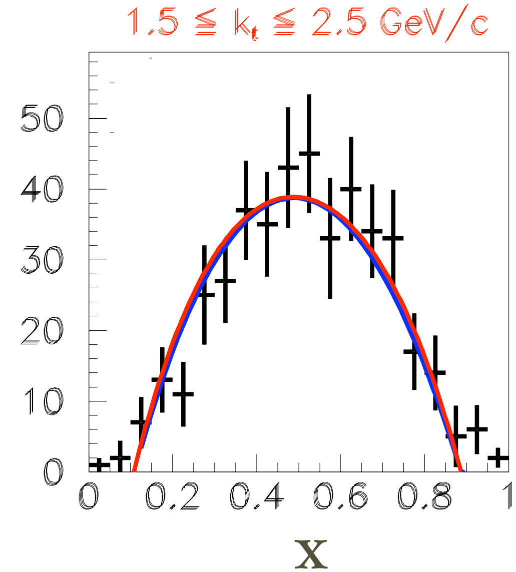
Nucleus left Intact!

Diffractive Dissociation of a Pion into Dijets

$$\pi A \rightarrow Jet\,Jet\,A'$$

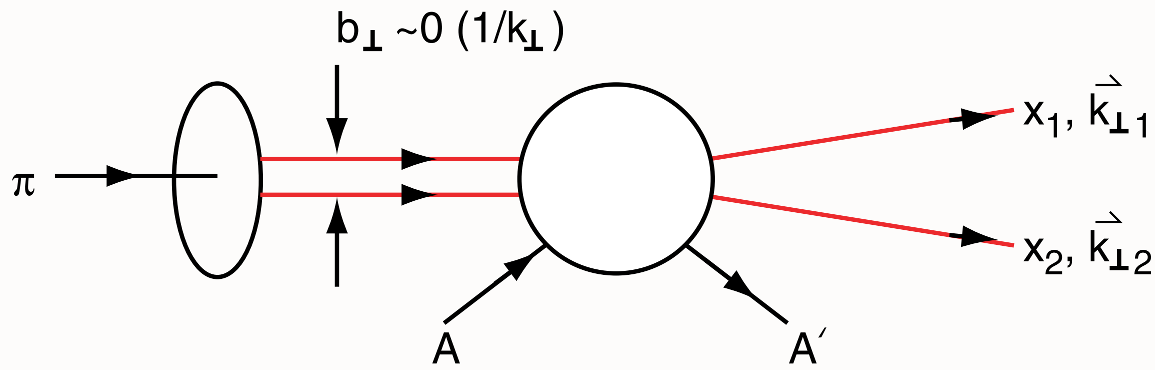
- E789 Fermilab Experiment Ashery et al
- 500 GeV pions collide on nuclei keeping it intact
- Measure momentum of two jets
- Study momentum distributions of pion LF wavefunction

$$\psi^{\pi}_{q\bar{q}}(x, \vec{k}_{\perp})$$

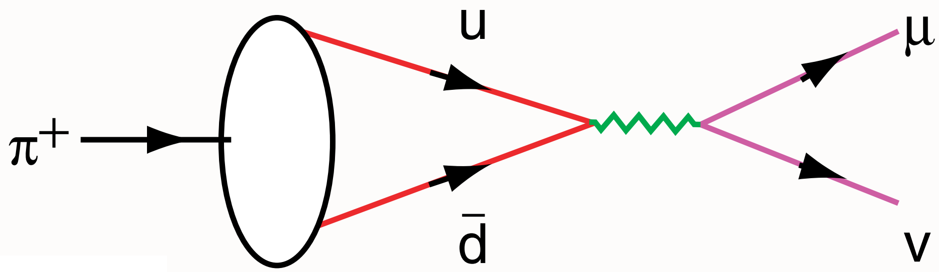


AdS/QCD

Fluctuation of a Pion to a Compact Color Dipole State



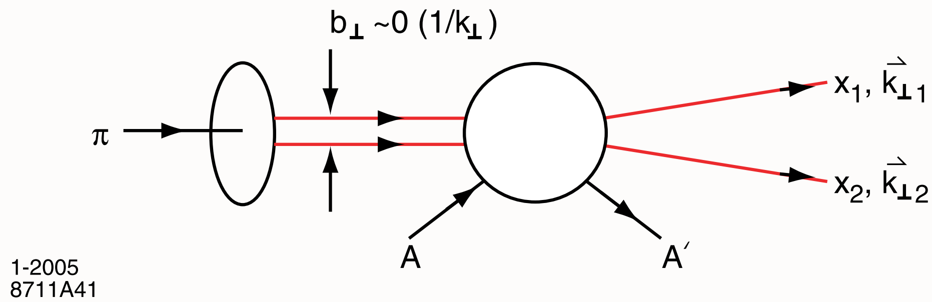
Color-Transparent Fock State For High Transverse Momentum Di-Jets



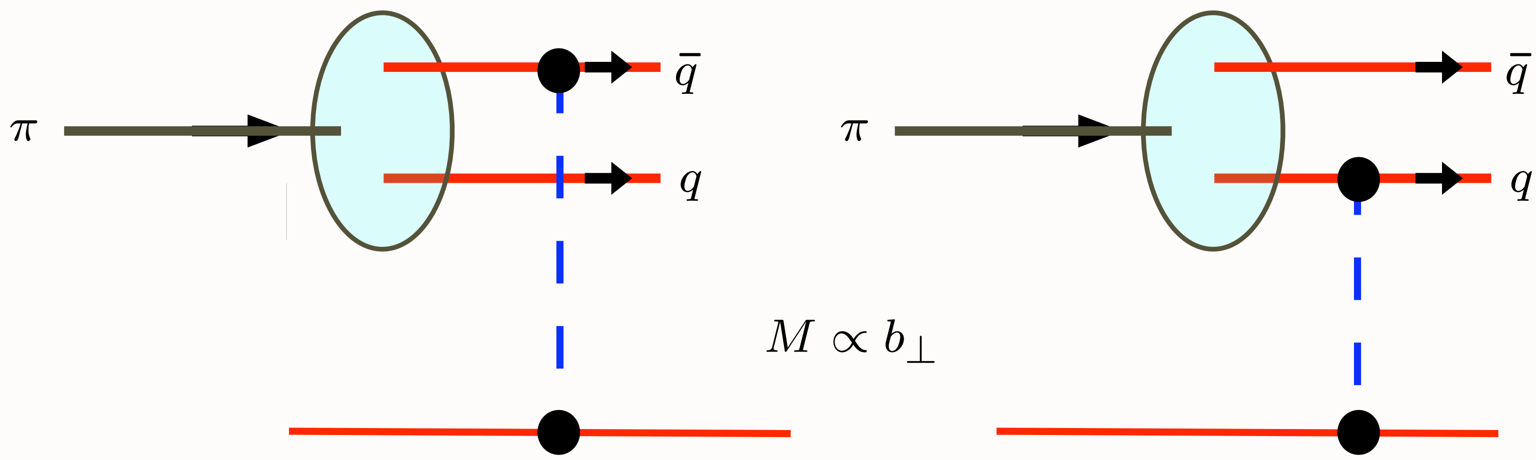
Same Fock State Determines Weak Decay

AdS/QCD

Key Ingredients in Ashery Experiment

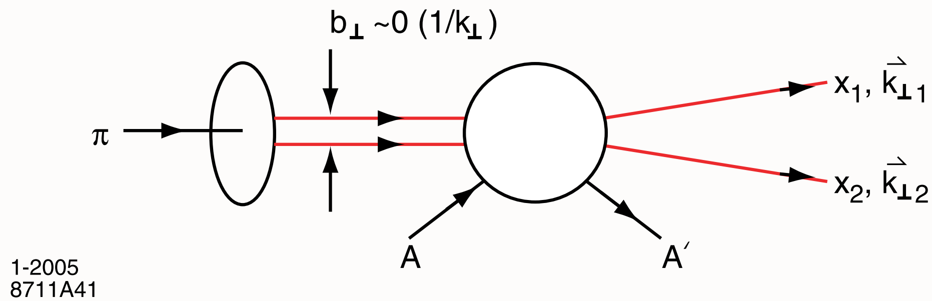


Local gauge-theory interactions
measure transverse size of color dipole



AdS/QCD

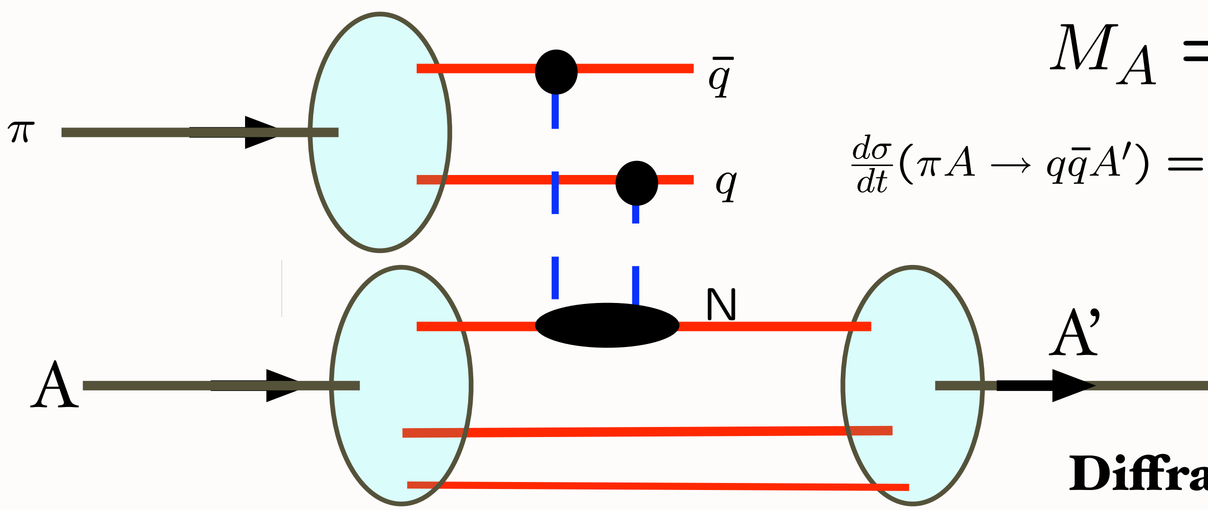
Key Ingredients in Ashery Experiment



Brodsky Mueller
Frankfurt Miller Strikman

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

QCD COLOR Transparency



$$M_A = A\ M_N$$

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

Target left intact

Diffraction, Rapidity gap

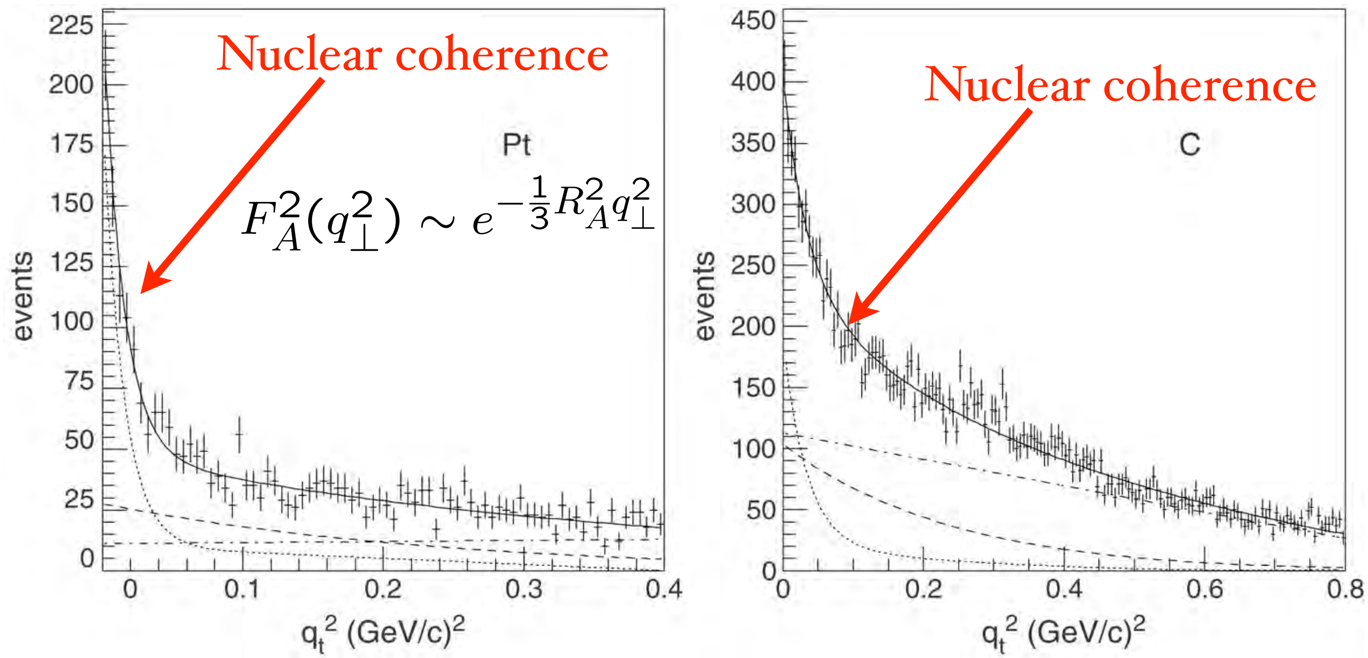
AdS/QCD

- Fully coherent interactions between pion and nucleons.
- Emerging Di-Jets do not interact with nucleus.

$$\mathcal{M}(\mathcal{A}) = \mathcal{A} \cdot \mathcal{M}(\mathcal{N})$$

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

$$\sigma \propto A^{4/3}$$



AdS/QCD

Ashery E791:
Measure of pion LFWF in diffractive dijet production
Confirmation of color transparency, gauge theory of strong interactions

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

A-Dependence results: $\sigma \propto A^{\alpha}$

k_t range (GeV/c)	α	α (CT)
$1.25 < k_t < 1.5$	1.64 +0.06 -0.12	1.25
$1.5 < k_t < 2.0$	1.52 ± 0.12	1.45
$2.0 < k_t < 2.5$	1.55 ± 0.16	1.60

α (Incoh.) $= 0.70 \pm 0.1$

Conventional Glauber Theory Ruled Out !

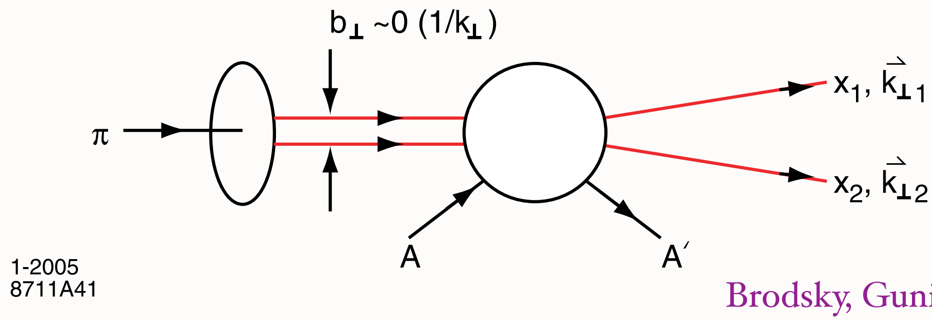
Factor of 7

Color Transparency

A. H. Mueller, sjb
Bertsch, Gunion, Goldhaber, sjb
Frankfurt, Miller, Strikman

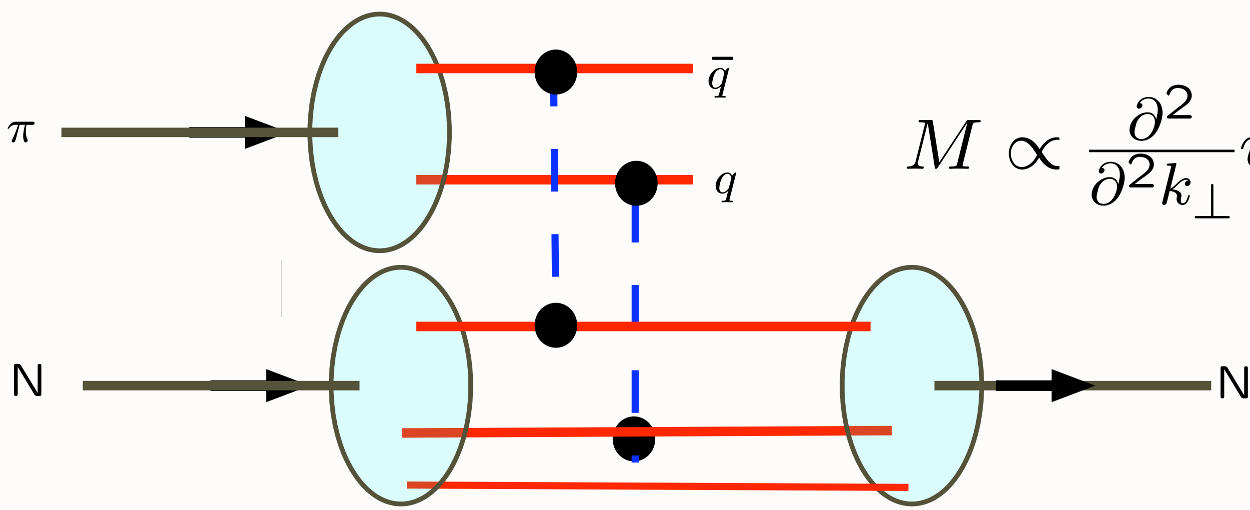
- Fundamental test of gauge theory in hadron physics
- Small color dipole moments interact weakly in nuclei
- Complete coherence at high energies
- Clear Demonstration of CT from Diffractive Di-Jets

Key Ingredients in Ashery Experiment



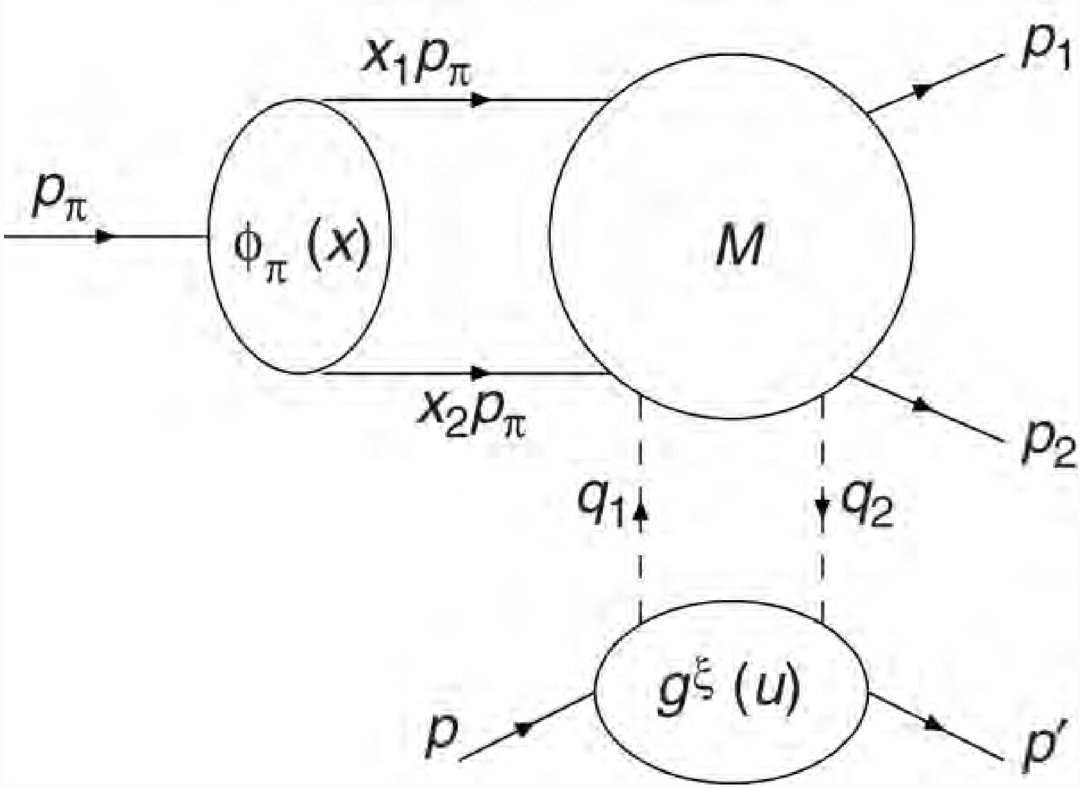
Brodsky, Gunion, Frankfurt, Mueller, Strikman
Frankfurt, Miller, Strikman

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



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

AdS/QCD



x

1-x

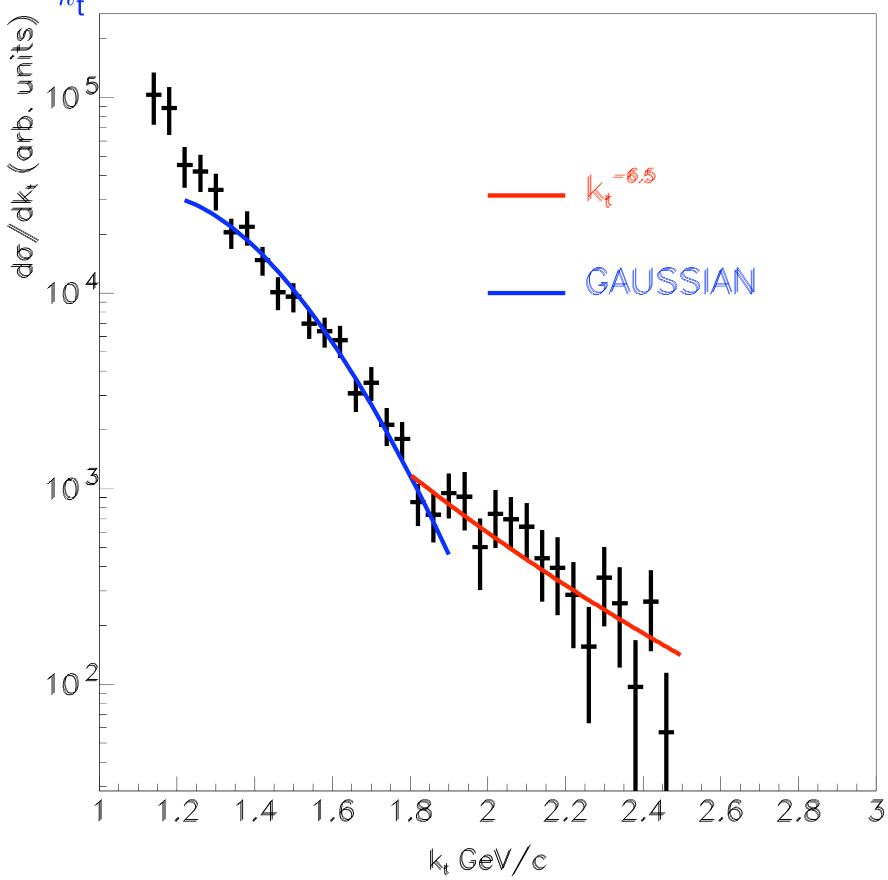
gluons measure size of color dipole

$$\frac{d\sigma}{dk_t^2} \propto |\alpha_s(k_t^2) x_N G(u, k_t^2)|^2 \left| \frac{\partial^2}{\partial k_t^2} \psi(x, k_t) \right|^2$$

THE k_t DEPENDENCE OF DI-JETS YIELD

$$\frac{d\sigma}{dk_t^2} \propto \left|\alpha_s(k_t^2)G(x,k_t^2)\right|^2 \left|\frac{\partial^2}{\partial k_t^2}\psi(u,k_t)\right|^2$$

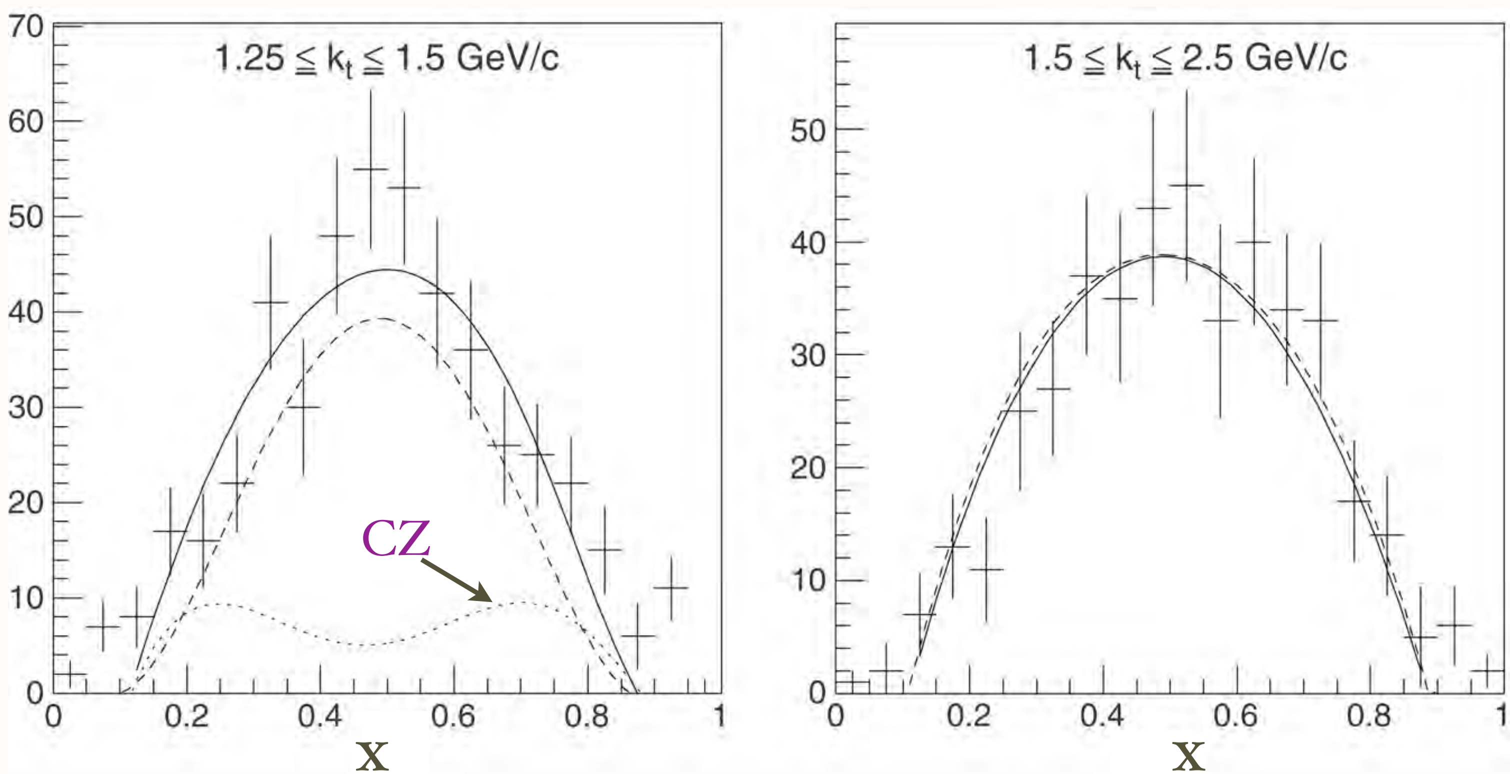
With $\psi \sim \frac{\phi}{k_t^2}$, weak $\phi(k_t^2)$ and $\alpha_s(k_t^2)$ dependences and $G(x,k_t^2) \sim k_t^{1/2}$: $\frac{d\sigma}{dk_t} \sim k_t^{-6}$



High Transverse momentum dependence consistent with PQCD, ERBL Evolution

Two Components?

AdS/QCD



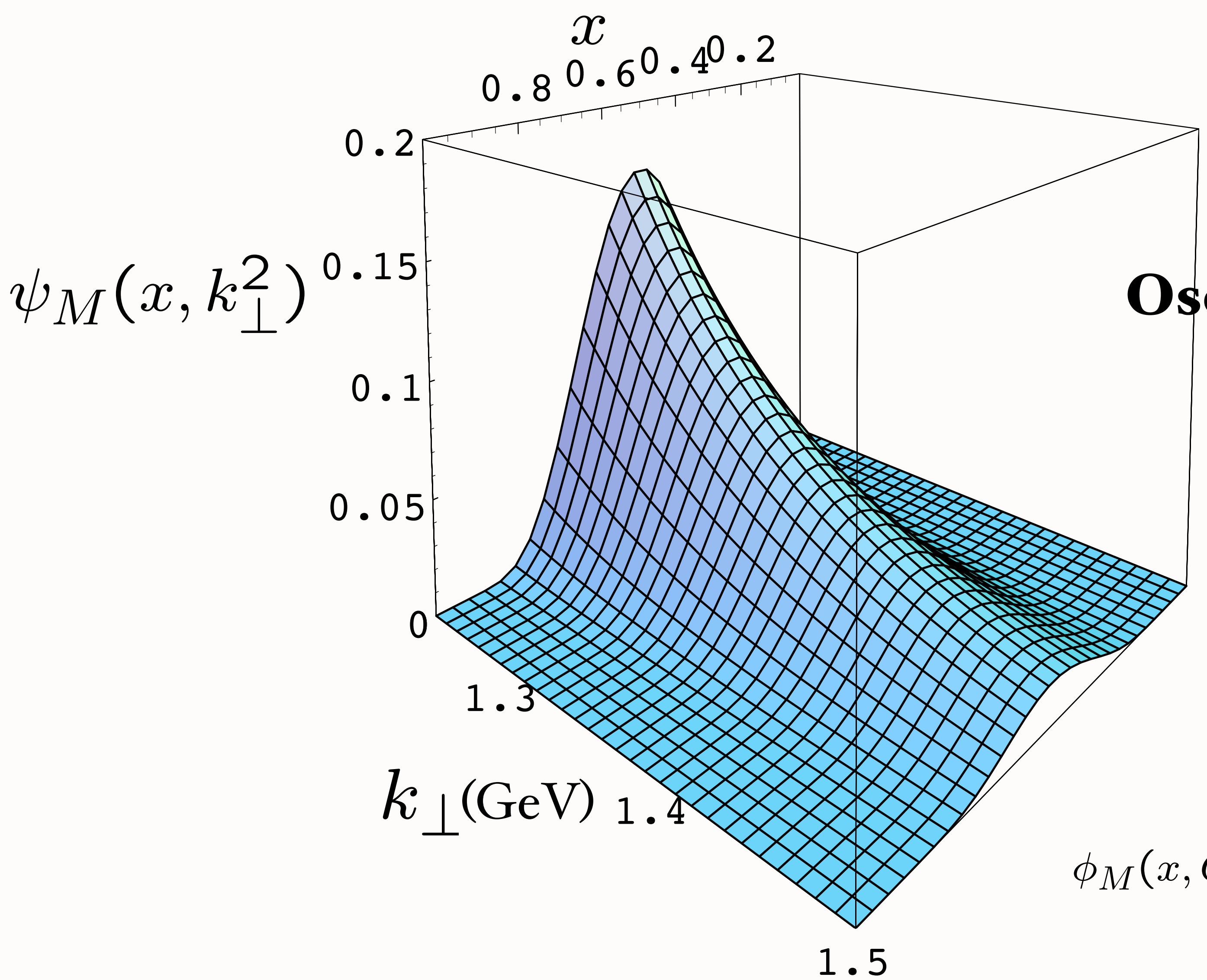
Narrowing of x distribution at higher jet transverse momentum

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

AdS/QCD

Prediction from AdS/CFT: Meson LFWF



Harmonic Oscillator model

$\kappa = 0.77\text{GeV}$

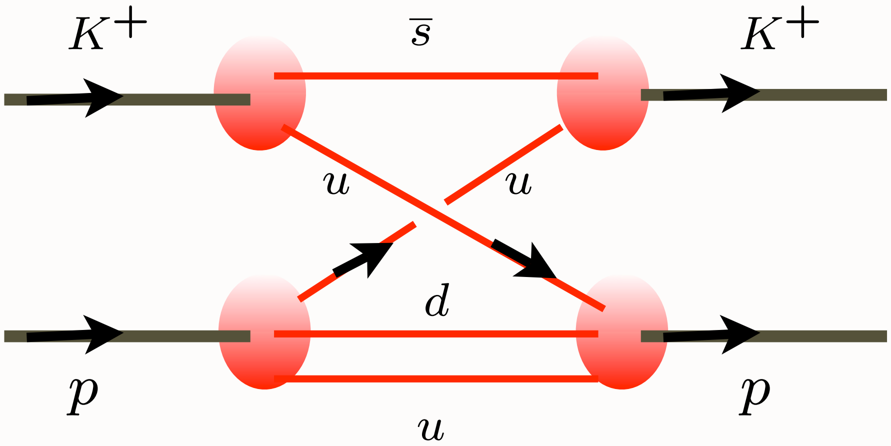
de Teramond, sjb

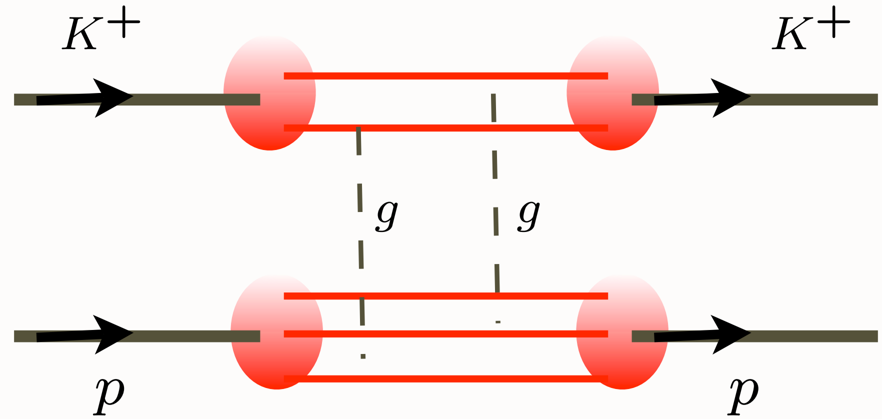
$\phi_M(x, Q_0) \propto \sqrt{x(1-x)}$

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

CIM: Blankenbecler, Gunion, sjb





Quark Interchange
(Spin exchange in atom-atom scattering)

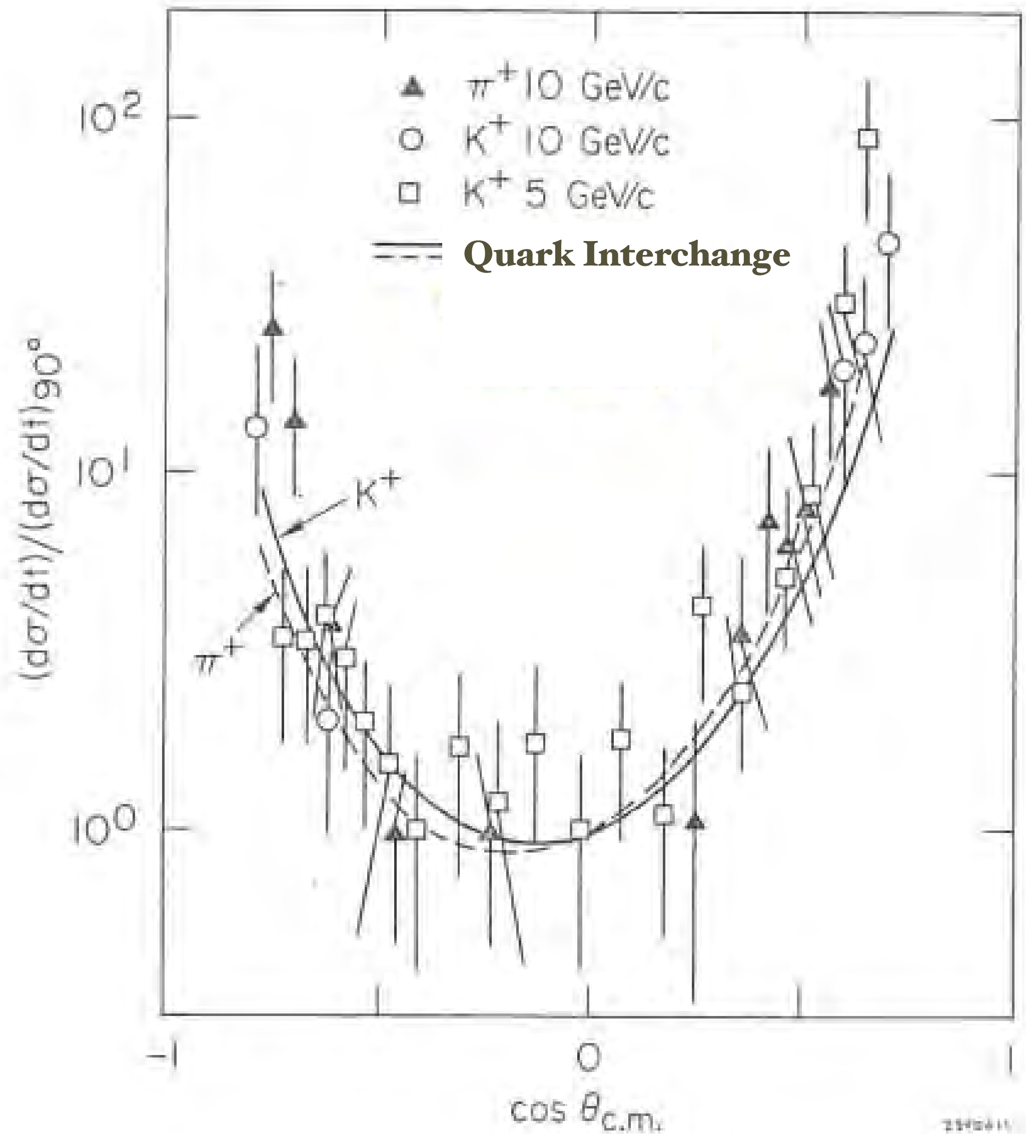
Gluon Exchange
(Van der Waal -- Landshoff)

$$\frac{d\sigma}{dt} = \frac{|M(s,t)|^2}{s^2}$$

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

$M(s,t)_{\text{gluonexchange}} \propto sF(t)$

MIT Bag Model (de Tar), large N_C, ('t Hooft), AdS/CFT all predict dominance of quark interchange:



AdS/CFT explains why quark interchange is dominant interaction at high momentum transfer in exclusive reactions

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

Non-linear Regge behavior:

$$\alpha_R(t) \to -1$$

Why is quark-interchange dominant over gluon exchange?

Example: $M(K^+p \to K^+p) \propto \frac{1}{ut^2}$

Exchange of common u quark

$M_{QIM} = \int d^2k_\perp dx\ \psi^\dagger_C \psi^\dagger_D \Delta \psi_A \psi_B$

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.

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]
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D. S. Barton, G. Bunce, A. S. Carroll, and Y. I. Makdisi
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and

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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.: $\pi^{\pm}p \to p\pi^{\pm}, p\rho^{\pm}, \pi^{+}\Delta^{\pm}, K^{+}\Sigma^{\pm}, (\Lambda^{0}/\Sigma^{0})K^{0}$; $K^{\pm}p \to pK^{\pm}$; $p^{\pm}p \to pp^{\pm}$. 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.

$\pi^{\pm}p \to p\pi^{\pm}$,

$K^{\pm}p \to pK^{\pm}$,

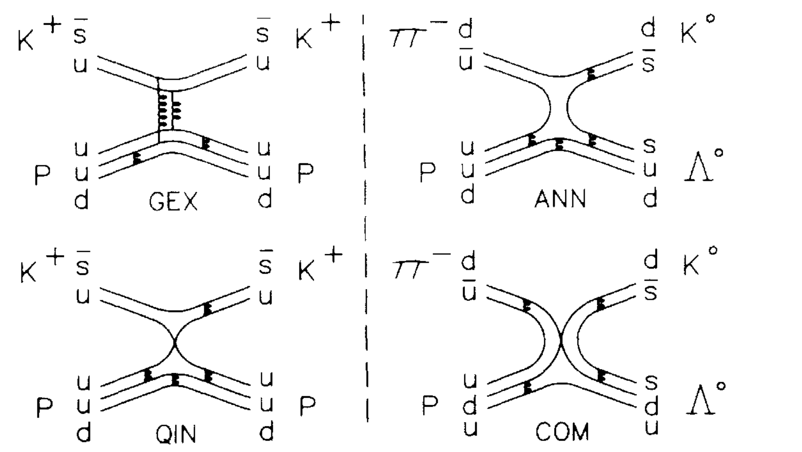
$\pi^{\pm}p \to p\rho^{\pm}$,

$\pi^{\pm}p \to \pi^{+}\Delta^{\pm}$,

$\pi^{\pm}p \to K^{+}\Sigma^{\pm}$,

$\pi^{-}p \to \Lambda^{0}K^{0}, \Sigma^{0}K^{0}$,

$p^{\pm}p \to pp^{\pm}$.



Hadron Dynamics at the Amplitude Level

- LFWFS are the universal hadronic amplitudes which underlie structure functions, GPDs, exclusive processes.

- Relation of spin, momentum, and other distributions to physics of the hadron itself.

- Connections between observables, orbital angular momentum

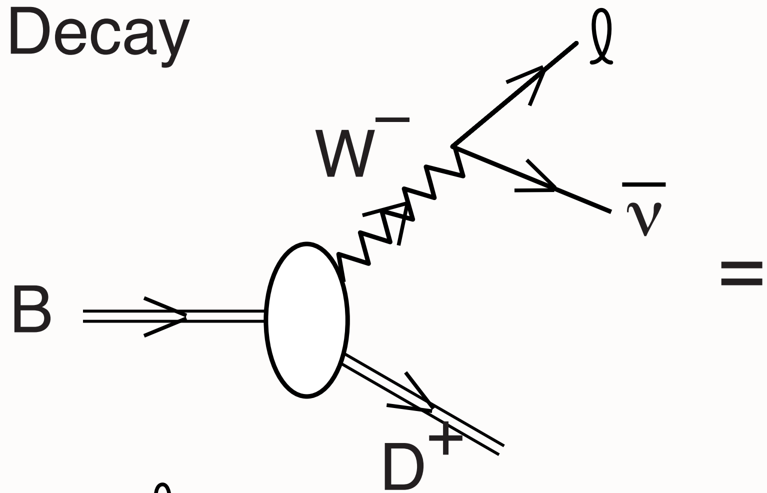
- Role of FSI and ISIs--Sivers effect

Some Applications of Light-Front Wavefunctions

- Exact formulae for form factors, quark and gluon distributions; vanishing anomalous gravitational moment; edm connection to anm
- Deeply Virtual Compton Scattering, generalized parton distributions, angular momentum sum rules
- Exclusive weak decay amplitudes
- Single spin asymmetries: Role if ISI and FSI
- Factorization theorems, DGLAP, BFKL, ERBL Evolution
- Quark interchange amplitude
- Relation of spin, momentum, and other distributions to physics of the hadron itself.

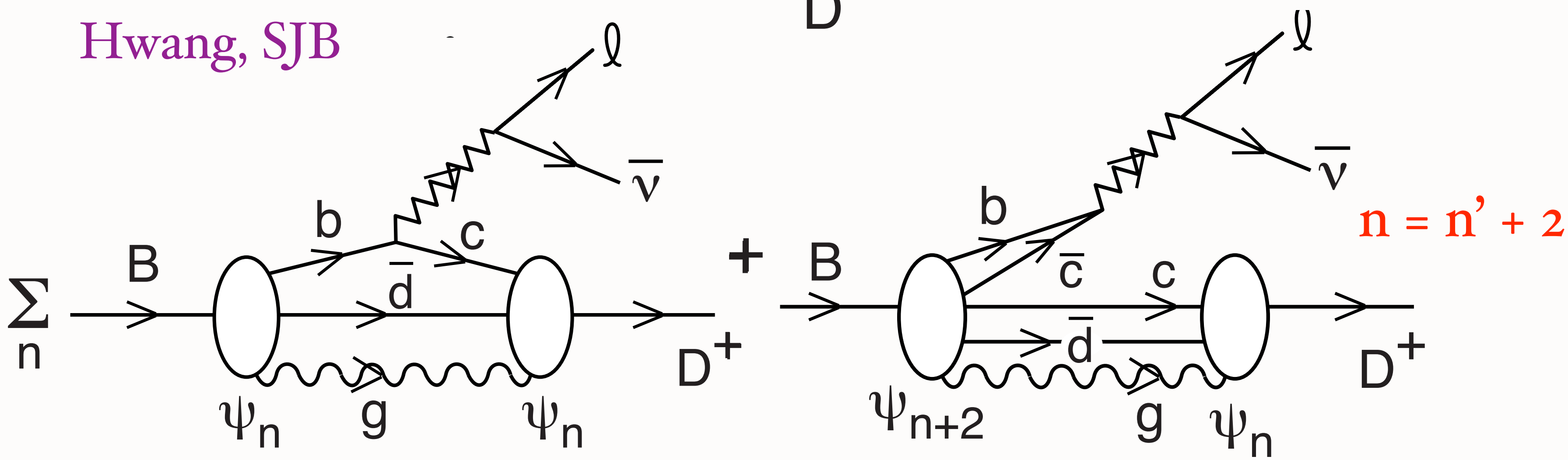
Weak Exclusive Decay

$\langle D | J^{+}(0) | B \rangle$



Exact Formula

Hwang, SJB

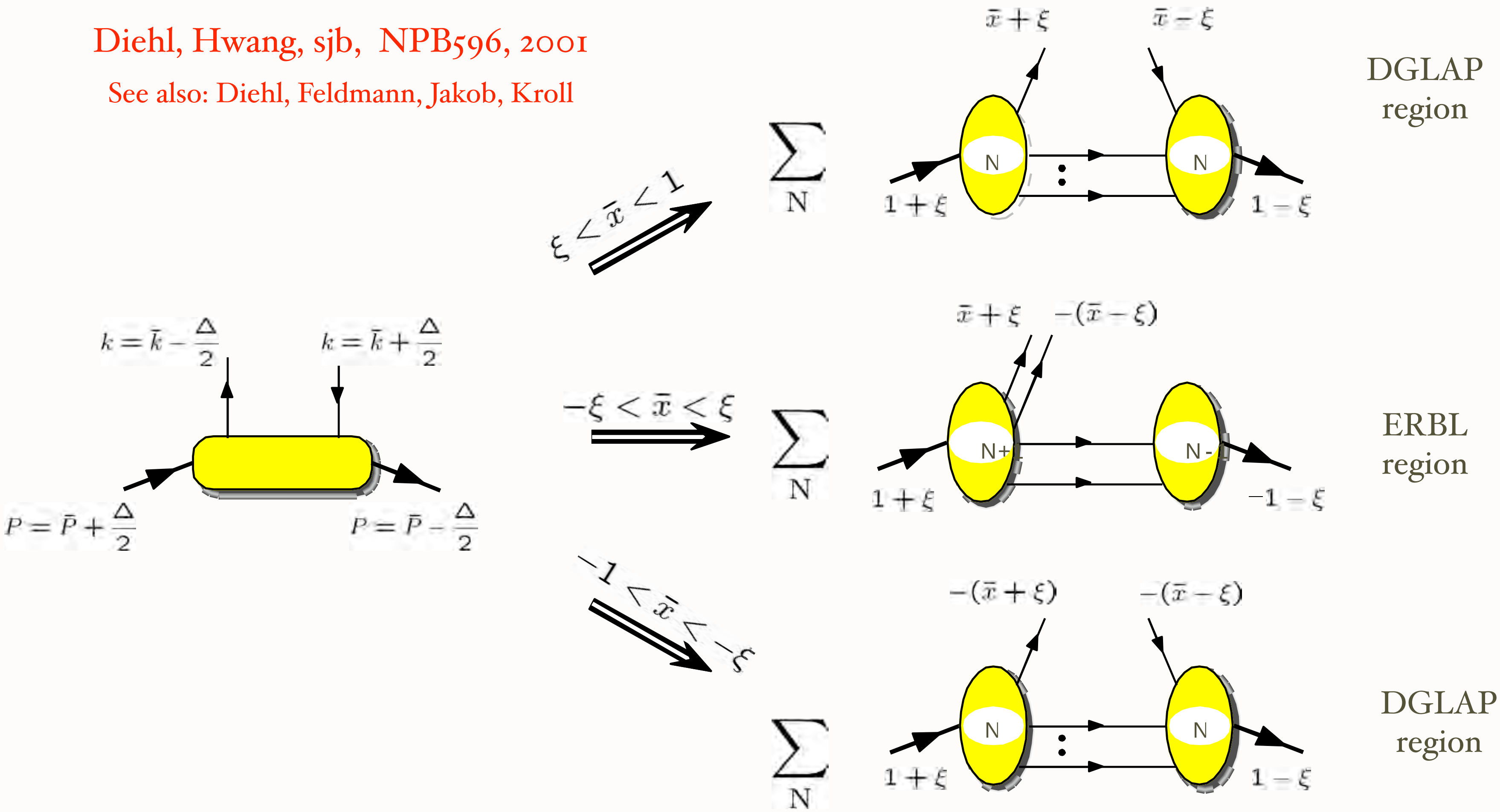


Annihilation amplitude needed for Lorentz Invariance

Light-Front Wave Function Overlap Representation

Diehl, Hwang, sjb, NPB596, 2001

See also: Diehl, Feldmann, Jakob, Kroll



N=3 VALENCE QUARK ⇒ Light-cone Constituent quark model

N=5 VALENCE QUARK + QUARK SEA ⇒ Meson-Cloud model

Pasquini

AdS/QCD

The Generalized Parton Distribution $E(x, \zeta, t)$

The generalized form factors in virtual Compton scattering $\gamma^*(q) + p(P) \to \gamma^*(q') + p(P')$ with $t = \Delta^2$ and $\Delta = P - P' = (\zeta P^+, \boldsymbol{\Delta}_\perp, (t + \boldsymbol{\Delta}_\perp^2)/\zeta P^+)$, have been constructed in the light-front formalism. [Brodsky, Diehl, Hwang, 2001]
We find, under $\boldsymbol{q}_\perp \to \boldsymbol{\Delta}_\perp$, for $\zeta \le x \le 1$,

$$\frac{E(x,\zeta,0)}{2M} = \sum_a (\sqrt{1-\zeta})^{1-n} \sum_j \delta(x - x_j) \int [\mathrm{d}x][\mathrm{d}^2\mathbf{k}_\perp] \times \psi_a^*(x_i', \mathbf{k}_{\perp i}, \lambda_i) \mathbf{S}_\perp \cdot \mathbf{L}_\perp^{\mathbf{q_j}} \psi_a(x_i, \mathbf{k}_{\perp i}, \lambda_i)\,,$$

with $x_j' = (x_j - \zeta)/(1-\zeta)$ for the struck parton j and $x_i' = x_i/(1-\zeta)$ for the spectator parton i.
The E distribution function is related to a $\mathbf{S}_\perp \cdot \mathbf{L}_\perp^{\mathbf{q_j}}$ matrix element at finite ζ as well.

Link to DIS and Elastic Form Factors

DIS at $\xi = t = 0$

$$H^q(x,0,0) = q(x), \quad -\bar{q}(-x)$$

$$\tilde{H}^q(x,0,0) = \Delta q(x), \quad \Delta\bar{q}(-x)$$

Form factors (sum rules)

$$\int^1 dx \sum_q \left[H^q(x,\xi,t)\right] = F_1(t) \quad \text{Dirac f.f.}$$

$$\int^1 dx \sum_q \left[E^q(x,\xi,t)\right] = F_2(t) \quad \text{Pauli f.f.}$$

$$\int_{-1}^1 dx\, \tilde{H}^q(x,\xi,t) = G_{A,q}(t), \quad \int_{-1}^1 dx\, \tilde{E}^q(x,\xi,t) = G_{P,q}(t)$$

Verified using LFWFs

Diehl,Hwang, sjb

$$H^q, E^q, \tilde{H}^q, \tilde{E}^q(x,\xi,t)$$

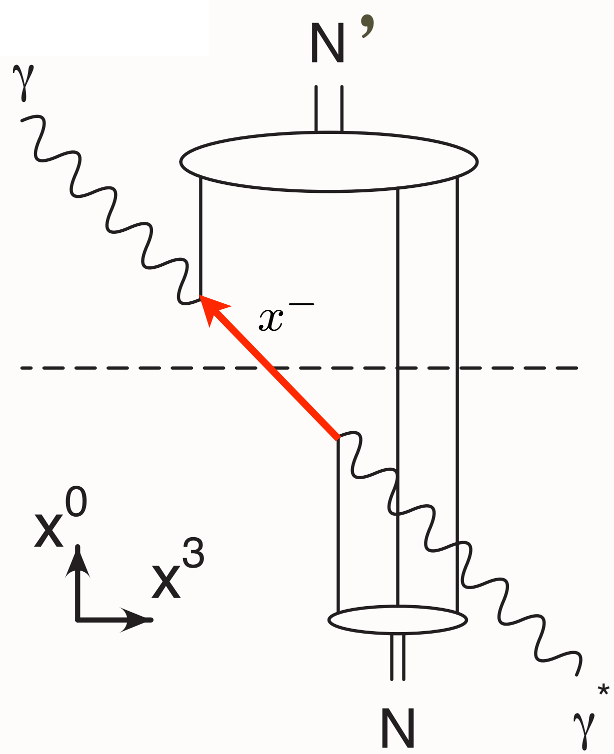
Quark angular momentum (Ji's sum rule)

$$J^q = \frac{1}{2} - J^G = \frac{1}{2}\int_{-1}^{1} x\,dx \left[H^q(x,\xi,0) + E^q(x,\xi,0)\right]$$

X. Ji, Phy.Rev.Lett.78,610(1997)

Space-time picture of DVCS

P. Hoyer



$\sigma = \frac{1}{2} x^- P^+$

$x^+ = \mathbf{x}_\perp = 0)$

The position of the struck quark differs by x^- in the two wave functions

Measure x- distribution from DVCS:
Use Fourier transform of skewness,
the longitudinal momentum transfer

$\zeta = \frac{Q^2}{2p \cdot q}$

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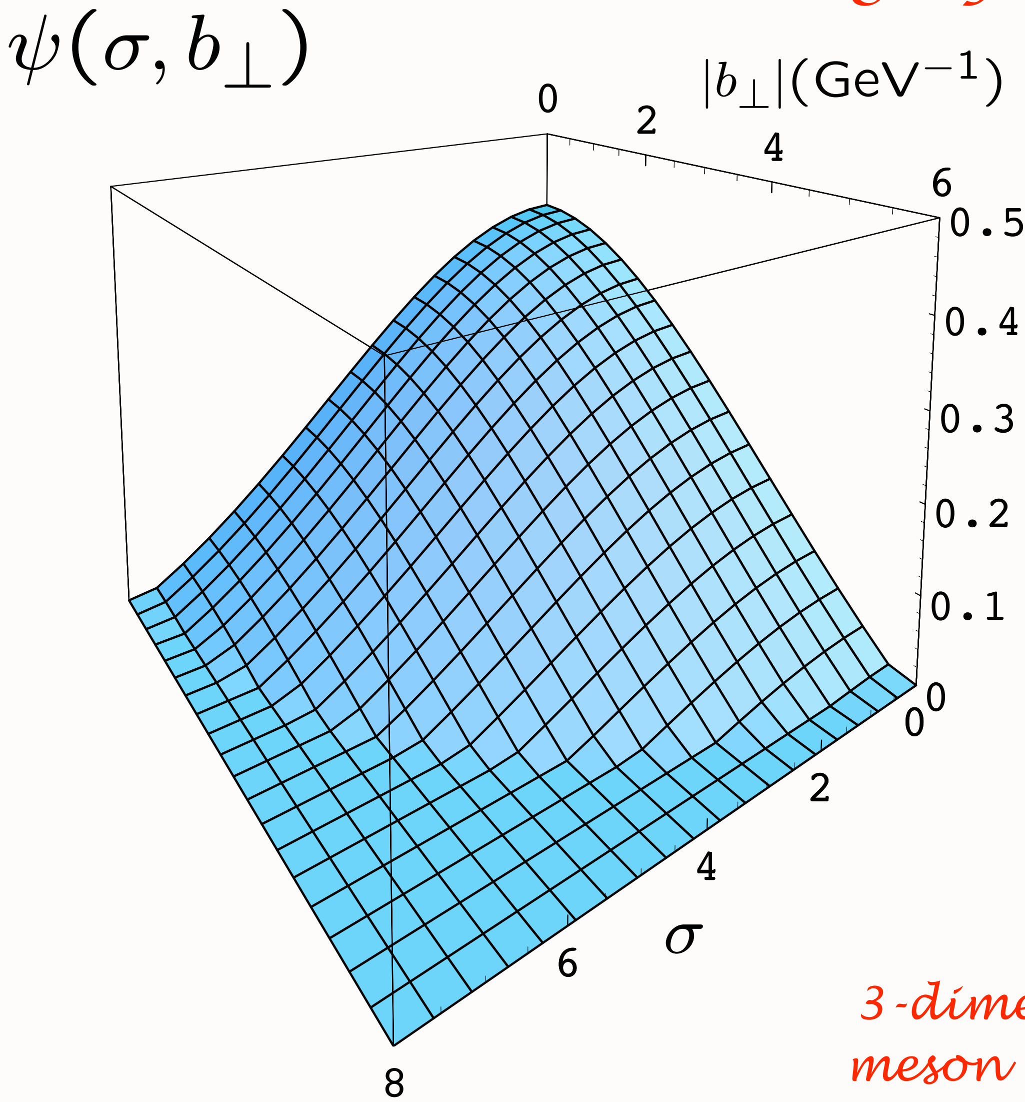
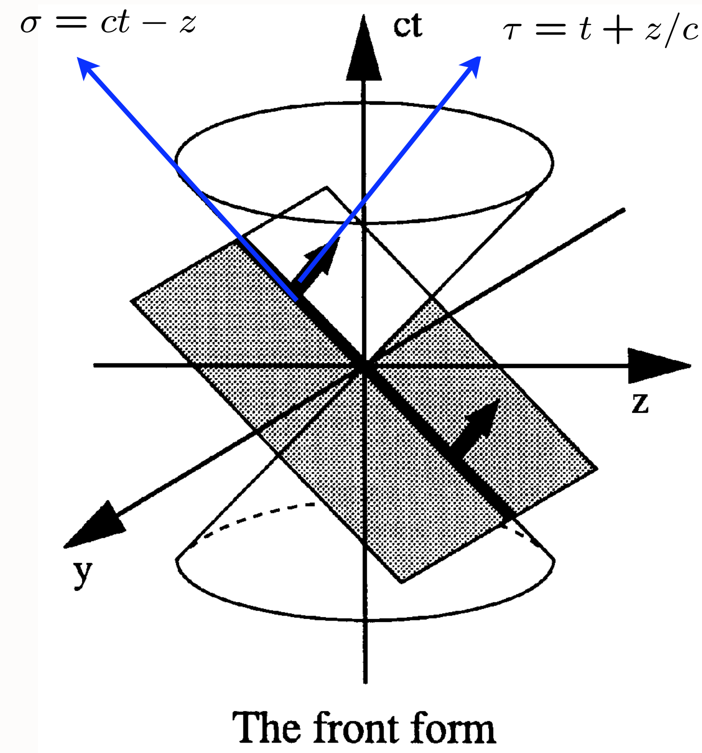
AdS/QCD

AdS/CFT Holographic Model

G. de Teramond
SJB





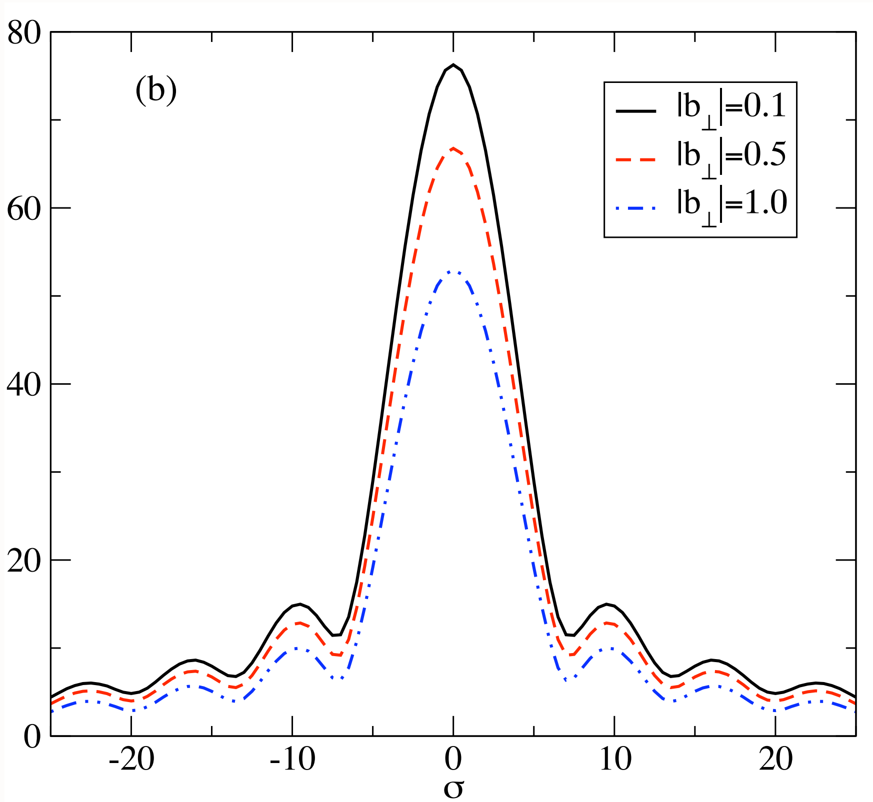
3-dimensional photograph: meson LFWF at fixed LF Time

S. J. Brodsky[a], D. Chakrabarti[b], A. Harindranath[c], A. Mukherjee[d], J. P. Vary[e,a,f]

Hadron Optics

$$A(\sigma, b_\perp) = \frac{1}{2\pi}\int d\zeta e^{i\sigma\zeta}\tilde{A}(b_\perp, \zeta)$$

$$\sigma = \tfrac{1}{2}x^- P^+ \qquad \zeta = \frac{Q^2}{2p\cdot q}$$

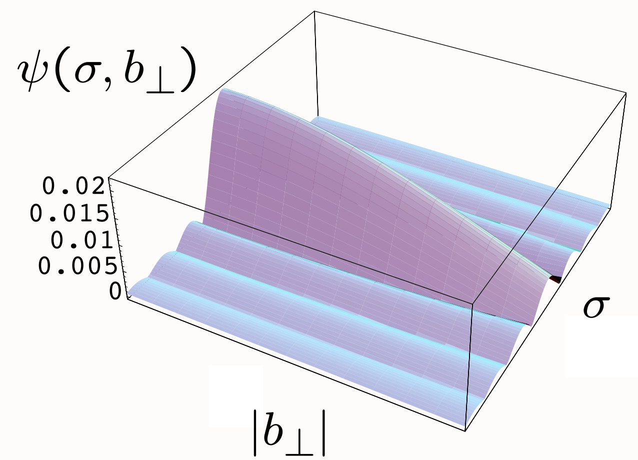


The Fourier Spectrum of the DVCS amplitude in σ space for different fixed values of $|b_\perp|$.

GeV units

DVCS Amplitude using holographic QCD meson LFWF

$$\Lambda_{QCD} = 0.32$$



AdS/QCD

Features of Light-Front Formalism

- *Hidden Color* Of Nuclear Wavefunction
- *Color Transparency, Opaqueness*
- *Intrinsic glue, sea quarks, intrinsic charm*
- Simple proof of Factorization theorems for hard processes (Lepage, sjb)
- *Direct mapping to AdS/CFT* (de Teramond, sjb)
- New Effective LF Equations (de Teramond, sjb)
- Light-Front Amplitude Generator

String Theory

↓

AdS/CFT

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

Goal: First Approximant to QCD
QCD at the Amplitude Level

↓

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!

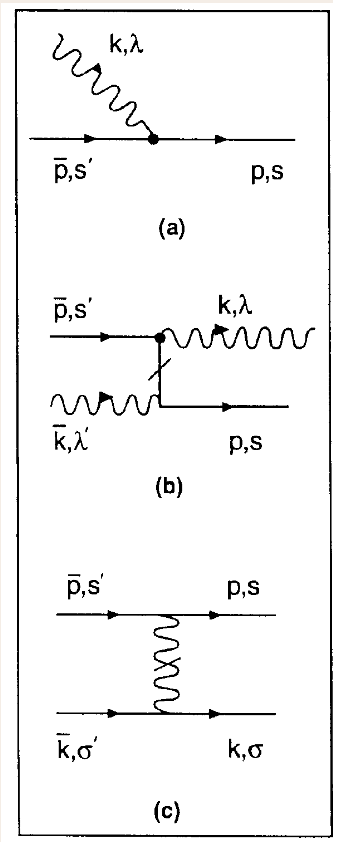
↓

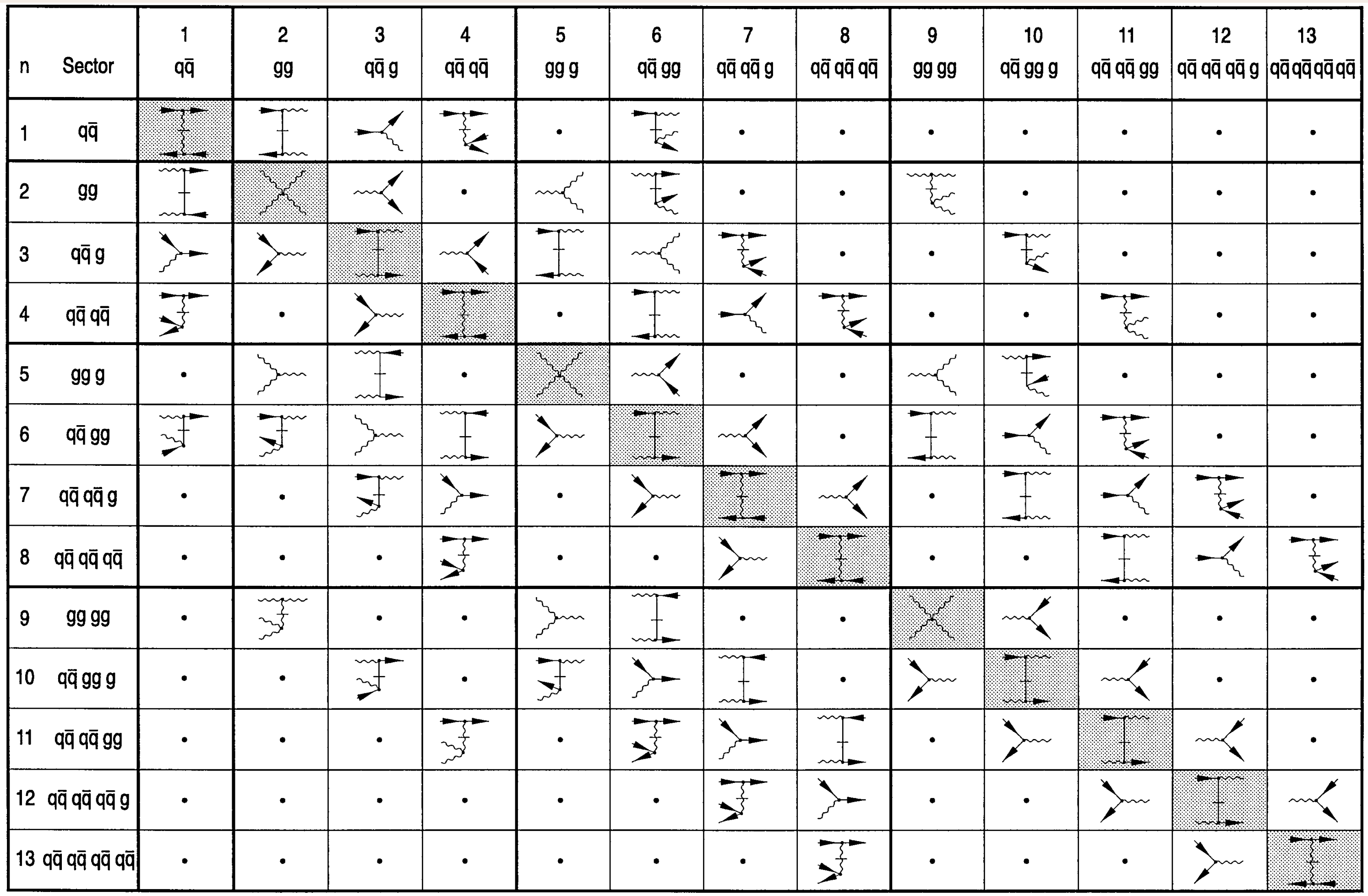
Hadron Spectra, Wavefunctions, Dynamics

Light-Front QCD Heisenberg Equation

$$H_{LC}^{QCD} |\Psi_h\rangle = \mathcal{M}_h^2 \; |\Psi_h\rangle$$

DLCQ





Use AdS/QCD basis functions

Pauli, Pinsky, sjb

AdS/QCD

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

Vary, Harinandrath, sjb

AdS/QCD

- New initial approximation to QCD based on conformal invariance, and confinement
- Underlying principle: Semi-Classical QCD
- AdS5: Mathematical representation of conformal gauge theory
- Challenges: chiral symmetry, heavy quark masses
- Systematically improve using DLCQ
- Successes: Hadron spectra, LFWFs, dynamics
- QCD at the Amplitude Level

Outlook

- Only one scale Λ_{QCD} determines hadronic spectrum (slightly different for mesons and baryons).
- Ratio of Nucleon to Delta trajectories determined by zeroes of Bessel functions.
- String modes dual to baryons extrapolate to three fermion fields at zero separation in the AdS boundary.
- Only dimension $3, \frac{9}{2}$ and 4 states $\overline{q}q$, qqq, and gg appear in the duality at the classical level!
- Non-zero orbital angular momentum and higher Fock-states require introduction of quantum fluctuations.
- Simple description of space and time-like structure of hadronic form factors.
- Dominance of quark-interchange in hard exclusive processes emerges naturally from the classical duality of the holographic model. Modified by gluonic quantum fluctuations.
- Covariant version of the bag model with confinement and conformal symmetry.

AdS/CFT and QCD

Bottom-Up Approach

- Nonperturbative derivation of dimensional counting rules of hard exclusive glueball scattering for gauge theories with mass gap dual to string theories in warped space:

  Polchinski and Strassler, hep-th/0109174.

- Deep inelastic structure functions at small x:

  Polchinski and Strassler, hep-th/0209211.

- Derivation of power falloff of hadronic light-front Fock wave functions, including orbital angular momentum, matching short distance behavior with string modes at AdS boundary:

  Brodsky and de Téramond, hep-th/0310227. E. van Beveren et al.

- Low lying hadron spectra, chiral symmetry breaking and hadron couplings in AdS/QCD:

  Boschi-Filho and Braga, hep-th/0212207; de Téramond and Brodsky, hep-th/0501022; Erlich, Katz, Son and Stephanov, hep-ph/0501128; Hong, Yong and Strassler, hep-th/0501197; Da Rold and Pomarol, hep-ph/0501218; Hirn and Sanz, hep-ph/0507049; Boschi-Filho, Braga and Carrion, arXiv:hep-th/0507063; Katz, Lewandowski and Schwartz, arXiv:hep-ph/0510388.

- Gluonium spectrum (top-bottom):

  Csaki, Ooguri, Oz and Terning, hep-th/9806021; de Mello Kock, Jevicki, Mihailescu and Nuñez, hep-th/9806125; Csaki, Oz, Russo and Terning, hep-th/9810186; Minahan, hep-th/9811156; Brower, Mathur and Tan, hep-th/0003115, Caceres and Nuñez, hep-th/0506051.

- D3/D7 branes (top-bottom):

  Karch and Katz, hep-th/0205236; Karch, Katz and Weiner, hep-th/0211107; Kruczenski, Mateos, Myers and Winters, hep-th/0311270; Sakai and Sonnenschein, hep-th/0305049; Babington, Erdmenger, Evans, Guralnik and Kirsch, hep-th/0312263; Nuñez, Paredes and Ramallo, hep-th/0311201; Hong, Yoon and Strassler, hep-th/0312071; hep-th/0409118; Kruczenski, Pando Zayas, Sonnenschein and Vaman, hep-th/0410035; Sakai and Sugimoto, hep-th/0412141; Paredes and Talavera, hep-th/0412260; Kirsh and Vaman, hep-th/0505164; Apreda, Erdmenger and Evans, hep-th/0509219; Casero, Paredes and Sonnenschein, hep-th/0510110.

- Other aspects of high energy scattering in warped spaces:

  Giddings, hep-th/0203004; Andreev and Siegel, hep-th/0410131; Siopsis, hep-th/0503245.

- Strongly coupled quark-gluon plasma ($\eta/s = 1/4\pi$):

  Policastro, Son and Starinets, hep-th/0104066; Kang and Nastase, hep-th/0410173 . . .

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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.