Why is Conformal Theory Relevant?

- Dimensional scaling of exclusive processes implies QCD is approximately conformal
- PQCD is conformal when $\beta = 0$
- Evaluate gluon exchange at small effective scales where α_s is approximately constant: IR fixed point
- Apply AdS/CFT

Define QCD Coupling from Observable

Grunberg

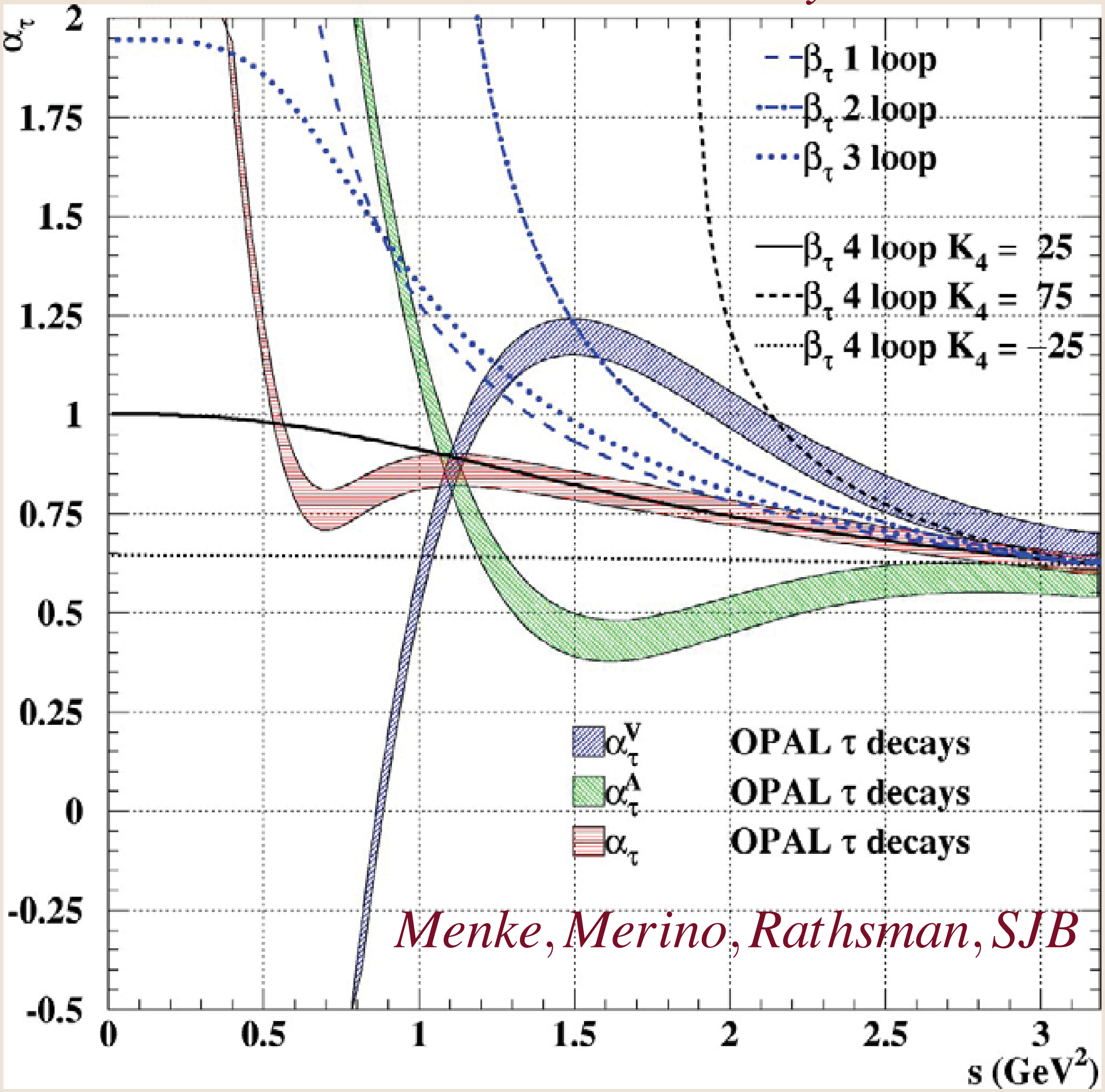
$$R_{e^+e^-\to X}(s) \equiv 3\Sigma_q e_q^2 \; [1 + \frac{\alpha_R(s)}{\pi}]$$

$$\Gamma(\tau \to X e\nu)(m_\tau^2) \equiv \Gamma_0(\tau \to u\bar{d}e\nu) \times [1 + \frac{\alpha_\tau(m_\tau^2)}{\pi}]$$

Relate observable to observable at commensurate scales

H.Lu, sjb

QCD Effective Coupling from *hadronic τ decay*



Conformal symmetry: Template for QCD

- Initial approximation to PQCD; correct for non-zero beta function
- Commensurate scale relations: relate observables at corresponding scales
- Infrared fixed-point for α_s
- Effective Charges: analytic at quark mass thresholds
- Eigensolutions of Evolution Equations

Strongly Coupled Conformal QCD and Holography

- Conformal Theories are invariant under the Poincaré and conformal transformations with $M^{\mu\nu}$, P^μ, D, K^μ, the generators of $SO(4,2)$.

- QCD appears as a nearly-conformal theory in the energy regimes accessible to experiment. Invariance of conformal QCD is broken by quark masses and quantum loops. For $\beta = d\alpha_s(Q^2)/dQ^2$, QCD is a conformal theory: Parisi, Phys. Lett. B **39**, 643 (1972).

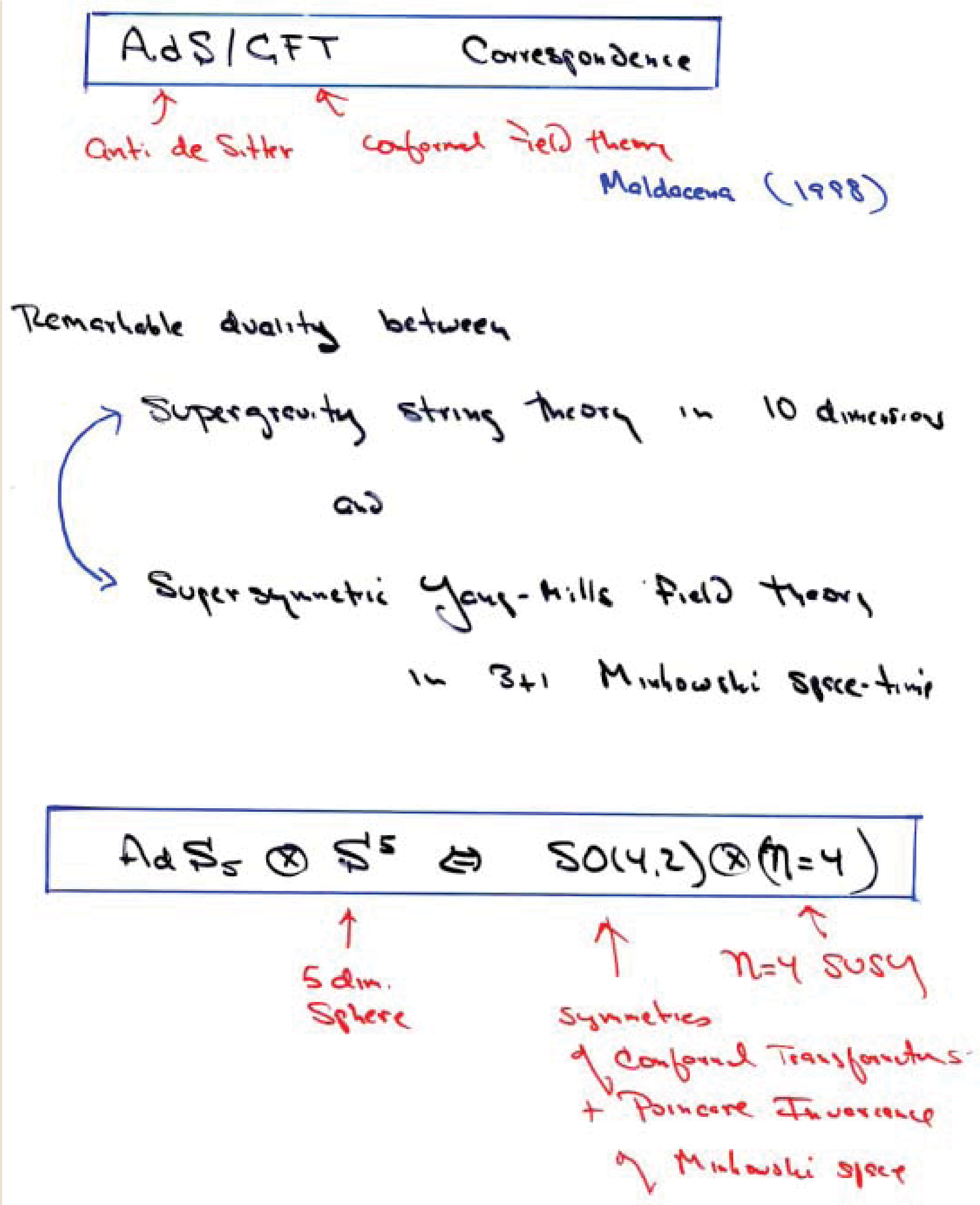
- Growing theoretical and empirical evidence that $\alpha_s(Q^2)$ has an IR fixed point: von Smekal, Alkofer and Hauck, arXiv:hep-ph/9705242; Alkofer, Fischer and Llanes-Estrada, hep-th/0412330; Deur, Burkert, Chen and Korsch, hep-ph/0509113 . . .

- Phenomenological success of dimensional scaling laws for exclusive processes

$$d\sigma/dt \sim 1/s^{n-2}, \quad n = n_A + n_B + n_C + n_D,$$

implies QCD is a strongly coupled conformal theory at moderate but not asymptotic energies Brodsky and Farrar, Phys. Rev. Lett. **31**, 1153 (1973); Matveev *et al.*, Lett. Nuovo Cim. **7**, 719 (1973).

Duality between strongly coupled conformal theory and weakly coupled type IIB string theory



Scale Transformations

- Isomorphism of $SO(4,2)$ of conformal QCD with the group of isometries of AdS space $SO(1,5)$

$$ds^2 = \frac{R^2}{z^2}(\eta_{\mu\nu}dx^\mu dx^\nu - dz^2),$$

$x^\mu \to \lambda x^\mu,\ z \to \lambda z$, maps scale transformations into the holographic coordinate z.

- AdS mode in z is the extension of the hadron wf into the fifth dimension.

- Different values of z correspond to different scales at which the hadron is examined.

$$x^2 \to \lambda^2 x^2, \quad z \to \lambda z.$$

$x^2 = x_\mu x^\mu$: invariant separation between quarks

- The AdS boundary at $z \to 0$ correspond to the $Q \to \infty$, UV zero separation limit.

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.

- 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 . . .

- Polchinski & Strassler: AdS/CFT builds in conformal symmetry at short distances, counting, rules for form factors and hard exclusive processes; non-perturbative derivation

- Goal: Use AdS/CFT to provide models of hadron structure: confinement at large distances, near conformal behavior at short distances

- Holographic Model: Initial "classical" approximation to QCD: Remarkable agreement with light hadron spectroscopy

- Use AdS/CFT wavefunctions as expansion basis for diagonalizing H^{LF}_{QCD} ; variational methods

AdS/CFT

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- Use mapping of conformal group SO(4,2) to AdS5
- Scale Transformations represented by wavefunction $\psi(z)$ in 5th dimension $x_\mu^2 \to \lambda^2 x_\mu^2$ $z \to \lambda z$
- Holographic model: Confinement at large distances and conformal symmetry in interior $0 < z < z_0$
- Match solutions at large r to conformal dimension of hadron wavefunction at short distances $\psi(z) \sim z^\Delta$ at $z \to 0$
- Truncated space simulates "bag" boundary conditions

$$\psi(z_0) = 0$$

$$z_0 = \frac{1}{\Lambda_{QCD}}$$

Match fall-off at small z to Conformal Dimension of State at short distances

- Pseudoscalar mesons: $\mathcal{O}_{3+L} = \overline{\psi}\gamma_5 D_{\{\ell_1} \dots D_{\ell_m\}}\psi$ ($\Phi_\mu = 0$ gauge).
- 4-d mass spectrum from boundary conditions on the normalizable string modes at $z = z_0$, $\Phi(x, z_o) = 0$, given by the zeros of Bessel functions $\beta_{\alpha,k}$: $\mathcal{M}_{\alpha,k} = \beta_{\alpha,k}\Lambda_{QCD}$
- Normalizable AdS modes $\Phi(z)$

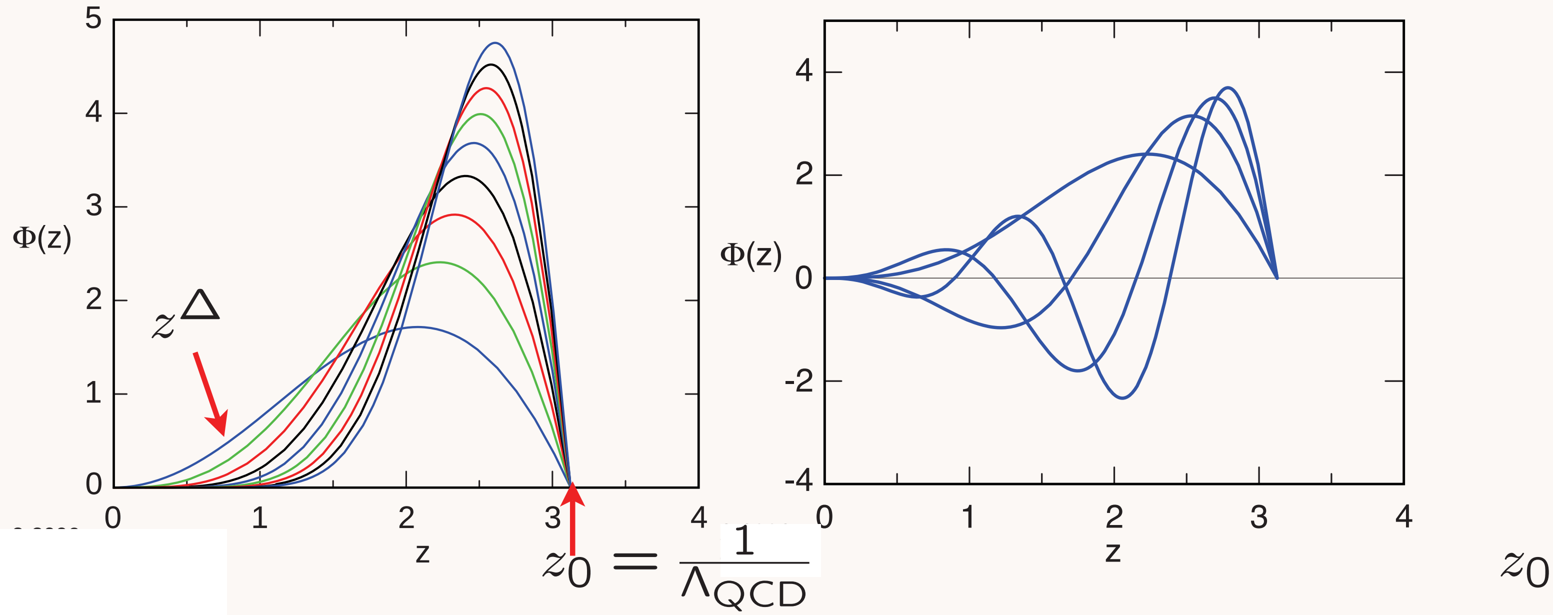

Fig: Meson orbital and radial AdS modes for $\Lambda_{QCD} = 0.32$ GeV.

Meson Spectrum

- Vector meson interpolating operator with twist-dimension minus spin-two, and conformal dimension $\Delta = 3 + L$

$$\mathcal{O}^{\mu}_{3+L} = \overline{\psi}\gamma^{\mu} D_{\{\ell_1} \dots D_{\ell_m\}}\psi.$$

$z \to 0$

$x^2 \to 0$

- AdS wave equation with effective 5-dim mass μ. Solution is a vector field Φ_μ with polarization along Poincaré coordinates:

$$\left[z^2\,\partial_z^2 - (d-1)z\,\partial_z + z^2\,\mathcal{M}^2 - (\mu R)^2 + d - 1\right] f_\mu(z) = 0,$$

with $\Phi_\mu(x,z) = e^{-iP\cdot x}\, f_\mu(z)$ and $P_\mu P^\mu = \mathcal{M}^2$ ($\Phi_z = 0$ gauge).

$d = 4$

- Normalizable AdS vector mode:

$$\Phi_\mu(x,z) = C e^{-iP\cdot x} z^{\frac{d}{2}} J_{\Delta - \frac{d}{2}}(z\mathcal{M})\,\epsilon_\mu.$$

$\sim z^{\Delta}$ at $z \to 0$

with $\Delta = d - 1 + L$ and $(\mu R)^2 = L(L + d - 2)$.

(Casimir)

Confinement

- QCD is a confining theory in the infrared with mass gap Λ_{QCD} and a well-defined spectrum of color-singlet states.
- There is a maximum separation of quarks and a maximum value of z.
- AdS space should end at a finite value $z_0 = 1/\Lambda_{\rm QCD}$.
- Cutoff at z_0 breaks conformal invariance and allows the introduction of the QCD scale.
- Non-conformal metric dual to a confining gauge theory (Polchinski and Strassler):

$$ds^2 = \frac{R^2}{z^2} e^{2A(z)} \left(\eta_{\mu\nu} dx^\mu dx^\nu - dz^2\right) + ds^2_X,$$

where $A(z) \to 0$ as $z \to 0$. Asymptotically: $AdS \times X$.

(X is a 5-dim compact manifold if 4-dim gauge theory is dual to a critical (10-dim) string)

- Simplified model: metric factor $e^{2A(z)}$ is a step function. Analog to the MIT bag model, but with boundary conditions on the holographic coordinate. Alternative: z^2 Potential
- Truncated AdS/CFT model: conformal behavior at short distances and confinement at large distances.

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AdS solution:

$$\Phi(z) = Ce^{-iP\cdot x} z^2 J_\alpha(zM)$$

At large argument of the Bessel function

$$\Phi(x,z) = Ce^{-iP\cdot x} z^{\frac{d}{2}} \sqrt{\frac{2}{\pi z \mathcal{M}}} \cos\left(z\mathcal{M} - \frac{\pi}{4}\sqrt{d^2 + 4l(l+4)} - \frac{\pi}{4}\right).$$

Dirichlet boundary condition:

$$\Phi(x, z = z_0 = \frac{1}{\Lambda_{QCD}}) = 0$$

$$M(n,l) = \frac{\pi}{2}\left[\frac{1}{2}\left(1 + \sqrt{d^2 + 4\ l(l+d)}\right) + (2n+1)\right]\ \Lambda_{QCD}$$

Quadratic Regge Relation

In the large ℓ limit:
$M^2 = \frac{\pi^2}{4}\ell^2 \Lambda^2_{QCD}$

Independent of n, d

Introduction of Twist (Spin 0 and 1 AdS Modes)

- For spin-carrying constituents: $\Delta \to \tau = \Delta - \sigma, \;\; \sigma = \sum_{i=1}^{n} \sigma_i.$
- For a two quark state $\Delta \to \Delta - 1$. Change compensated in μ by the shift $L \to L - 1.$
- Lowest state corresponds to $(\mu R)^2 = -1$. Thus $-1 \leq (\mu R)^2$: Breitenlohner-Freedman stab
  bound for a 1-form.
- Two-quark vector meson described by wave equation (d=4)

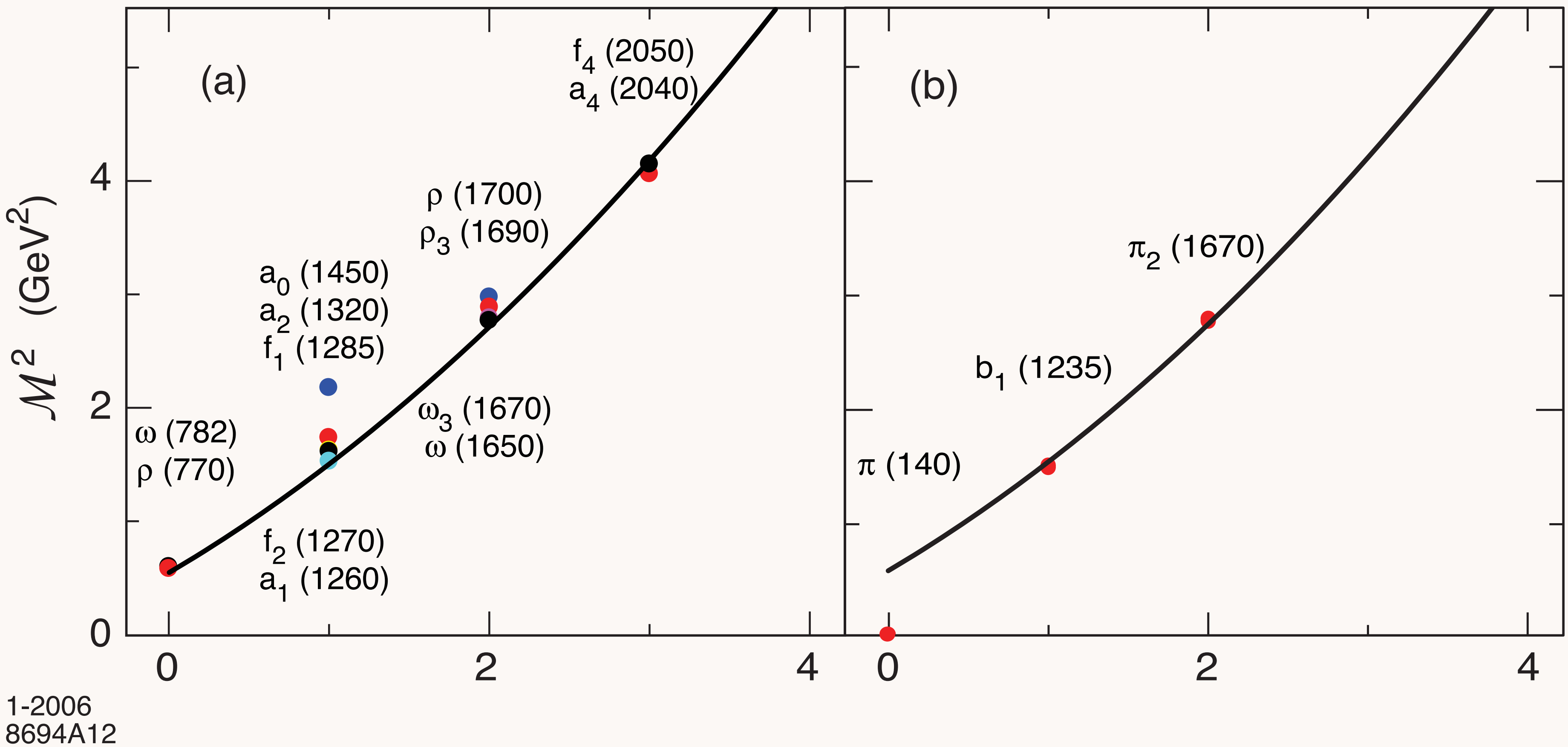
$$\boxed{\left[z^2 \, \partial_z^2 - 3z \, \partial_z + z^2 \mathcal{M}^2 - L^2 + 4\right] f_\mu(z) = 0}$$

with solution

$$\Phi_\mu(x, z) = C e^{-iP \cdot x} z^2 J_L(z\mathcal{M}) \, \epsilon_\mu.$$

- Same equation for $\Delta = 4$, $\tau = 2$ glueball 0-form with $-4 \leq (\mu R)^2$ and solution

$$\Phi(x, z) = C e^{-iP \cdot x} z^2 J_L(z\mathcal{M}).$$



Light meson orbital spectrum $\Lambda_{QCD} = 0.32 \text{ GeV}$

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Baryon Spectrum

- Baryon: twist-three, dimension $\Delta = \frac{9}{2} + L$

$$\mathcal{O}_{\frac{9}{2}+L} = \psi D_{\{\ell_1} \dots D_{\ell_q} \psi D_{\ell_{q+1}} \dots D_{\ell_m\}} \psi, \qquad L = \sum_{i=1}^{m} \ell_i .$$

- Solve full 10-dim Dirac Eq., $\not{D}\hat{\Psi} = 0$, since baryons are charged under $SU(4) \sim SO(6)$. Baryon number conservation?

- $\hat{\Psi}$ is expanded in terms of eigenfunctions $\eta_\kappa(y)$ of the Dirac operator on compact space X with eigenvalues λ_κ:

$$\hat{\Psi}(x, z, y) = \sum_\kappa \Psi_\kappa(x, z) \eta_\kappa(y).$$

- From the 10-dim Dirac equation, $\not{D}\hat{\Psi} = 0$:

$$\left[z^2\, \partial_z^2 - d\, z\, \partial_z + z^2 \mathcal{M}^2 - (\lambda_\kappa + \mu)^2 R^2 + \frac{d}{2}\left(\frac{d}{2} + 1\right) + (\lambda_\kappa + \mu) R\, \hat{\Gamma} \right] f(z) = 0,$$

$$i\not{D}_X \eta(y) = \lambda\, \eta(y),$$

where $\Psi(x, z) = e^{-iP\cdot x}\, f(z)$, $P_\mu P^\mu = \mathcal{M}^2$ and $\hat{\Gamma} u_\pm = \pm u_\pm$.

See: Muck and Viswanathan, hep-ph/9805945.

- Normalizable AdS baryon mode:

$$\Psi(x,z) = Ce^{-iP\cdot x} z^{\frac{d+1}{2}} \Big[J_{(\mu+\lambda_\kappa)R-\frac{1}{2}}(z\mathcal{M})\, u_+(P) + J_{(\mu+\lambda_\kappa)R+\frac{1}{2}}(z\mathcal{M})\, u_-(P) \Big].$$

  with $\Delta = \frac{d}{2} + |(\mu + \lambda_\kappa)R|$.

- For $d = 4$, $\hat{\Gamma} = \gamma_5$ and spinors $u_\pm(P)$ are defined along 4-dim coordinates.

- μ determined asymptotically by spectral comparison with orbital excitations in the boundary: $\mu = L/R$ and λ_κ are the eigenvalues of the Dirac equation on S^{d+1}:

$$\lambda_\kappa R = \pm \left(\kappa + \frac{d}{2} + \frac{1}{2} \right), \quad \kappa = 0, 1, 2...$$

  See: Camporesi and Higuchi: gr-gc/9505009.

- Spin-$\frac{3}{2}$ Rarita-Schwinger eq. in AdS similar to spin-$\frac{1}{2}$ in the $\Psi_z = 0$ gauge for polarization along Minkowski coordinates, Ψ_μ. See: Volovich, hep-th/9809009.

Introduction of Twist (Spin $\frac{1}{2}$ and $\frac{3}{2}$ AdS Modes)

- For spin-carrying constituents: $\Delta \to \tau = \Delta - \sigma, \ \ \sigma = \sum_{i=1}^{n} \sigma_i$.

- For a three quark state $\Delta \to \Delta - 3/2$. Change compensated in μ by the shift $L \to L - 1$ and $\Psi(z) \to z^{-\frac{1}{2}} \Psi(z)$.

- Three-quark baryon described by wave equation ($d = 4$, $\kappa = 0$)

$$\boxed{\left[z^2 \, \partial_z^2 - 3z \, \partial_z + z^2 \mathcal{M}^2 - \mathcal{L}_\pm^2 + 4\right] f_\pm(z) = 0}$$

with $\mathcal{L}_+ = L + 1$, $\mathcal{L}_- = L + 2$, and solution

$$\Psi(x, z) = C e^{-iP \cdot x} z^2 \Big[J_{1+L}(z\mathcal{M}) \, u_+(P) + J_{2+L}(z\mathcal{M}) \, u_-(P) \Big].$$

- 4-d mass spectrum $\Psi(x, z_o)^\pm = 0 \quad \Longrightarrow$ parallel Regge trajectories for baryons !

$$\mathcal{M}_{\alpha,k}^{+} = \beta_{\alpha,k} \Lambda_{QCD}, \quad \mathcal{M}_{\alpha,k}^{-} = \beta_{\alpha+1,k} \Lambda_{QCD}.$$

- Ratio of eigenvalues determined by the ratio of zeros of Bessel functions !

Predictions of AdS/CFT

Only one parameter!

Entire light quark baryon spectrum

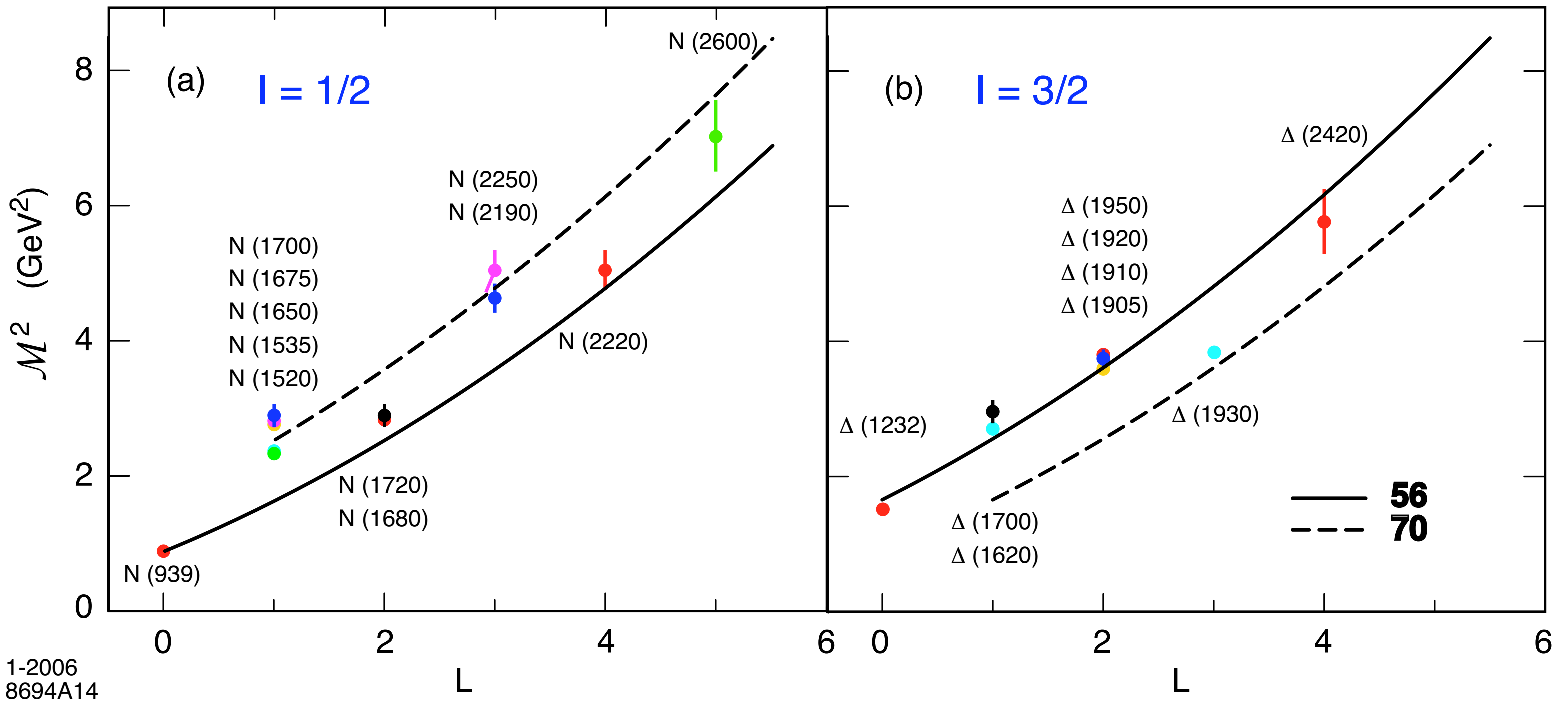

Fig: Predictions for the light baryon orbital spectrum for Λ_{QCD} = 0.25 GeV. The $\mathbf{56}$ trajectory corresponds to L even $P = +$ states, and the $\mathbf{70}$ to L odd $P = -$ states.

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- $SU(6)$ multiplet structure for N and Δ orbital states, including internal spin S and L.

$SU(6)$	S	L	Baryon State
56	$\frac{1}{2}$	0	$N\frac{1}{2}^+(939)$
	$\frac{3}{2}$	0	$\Delta\frac{3}{2}^+(1232)$
70	$\frac{1}{2}$	1	$N\frac{1}{2}^-(1535)$ $N\frac{3}{2}^-(1520)$
	$\frac{3}{2}$	1	$N\frac{1}{2}^-(1650)$ $N\frac{3}{2}^-(1700)$ $N\frac{5}{2}^-(1675)$
	$\frac{1}{2}$	1	$\Delta\frac{1}{2}^-(1620)$ $\Delta\frac{3}{2}^-(1700)$
56	$\frac{1}{2}$	2	$N\frac{3}{2}^+(1720)$ $N\frac{5}{2}^+(1680)$
	$\frac{3}{2}$	2	$\Delta\frac{1}{2}^+(1910)$ $\Delta\frac{3}{2}^+(1920)$ $\Delta\frac{5}{2}^+(1905)$ $\Delta\frac{7}{2}^+(1950)$
70	$\frac{1}{2}$	3	$N\frac{5}{2}^-$ $N\frac{7}{2}^-$
	$\frac{3}{2}$	3	$N\frac{3}{2}^-$ $N\frac{5}{2}^-$ $N\frac{7}{2}^-(2190)$ $N\frac{9}{2}^-(2250)$
	$\frac{1}{2}$	3	$\Delta\frac{5}{2}^-(1930)$ $\Delta\frac{7}{2}^-$
56	$\frac{1}{2}$	4	$N\frac{7}{2}^+$ $N\frac{9}{2}^+(2220)$
	$\frac{3}{2}$	4	$\Delta\frac{5}{2}^+$ $\Delta\frac{7}{2}^+$ $\Delta\frac{9}{2}^+$ $\Delta\frac{11}{2}^+(2420)$
70	$\frac{1}{2}$	5	$N\frac{9}{2}^-$ $N\frac{11}{2}^-$
	$\frac{3}{2}$	5	$N\frac{7}{2}^-$ $N\frac{9}{2}^-$ $N\frac{11}{2}^-(2600)$ $N\frac{13}{2}^-$

Features of HolographicModel

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- Ratio of proton to Delta trajectories= ratio of zeroes of Bessel functions.

- One scale Λ_{QCD} determines hadron spectrum (slightly different for mesons and baryons)

- Only quark-antiquark, qqq, and g g hadrons appear at classical level

- Covariant version of bag model: confinement+conformal symmetry

Glueball Regge trajectories from gauge/string duality and the Pomeron

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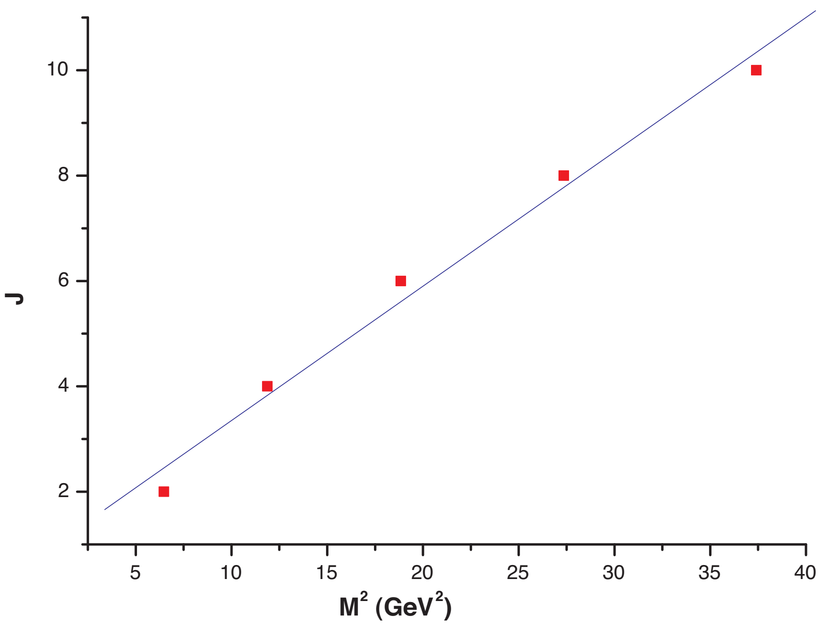
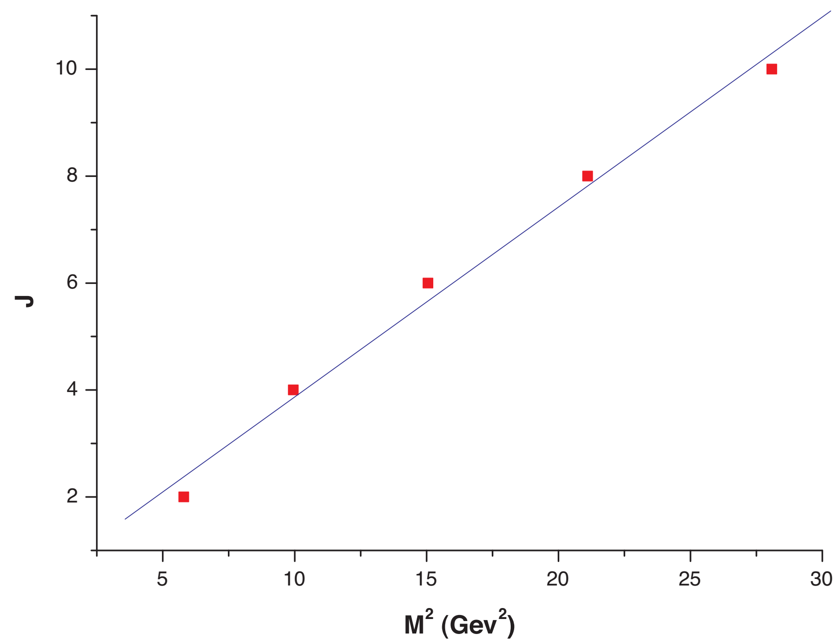
Instituto de Física, Universidade Federal do Rio de Janeiro,



Neumann Boundary Conditions



Dirichlet Boundary Conditions

- 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.

- D3/D7 branes (top-bottom):

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- Other aspects of high energy scattering in warped spaces:

  S. B. Giddings, hep-th/0203004; Andreev and Siegel, arXiv:hep-th/0410131; Kang and Nastase, hep-th/0410173; Nastase, hep-th/0501039; hep-th/0501068.

- Branes in Minkowski space:

  Siopsis, hep-th/0503245.

Hadronic Form Factor in Space and Time-Like Regions

- The form factor in AdS/QCD is the overlap of the normalizable modes dual to the incoming and outgoing hadron Φ_I and Φ_F and the non-normalizable mode J, dual to the external source (hadron spin σ):

$$F(Q^2)_{I\to F} = R^{3+2\sigma}\int_0^\infty \frac{dz}{z^{3+2\sigma}}\, e^{(3+2\sigma)A(z)}\Phi_F(z)\, J(Q,z)\, \Phi_I(z)$$
$$\simeq R^{3+2\sigma}\int_0^{z_o} \frac{dz}{z^{3+2\sigma}}\, \Phi_F(z)\, J(Q,z)\, \Phi_I(z),$$

- $J(Q,z)$ has the limiting value 1 at zero momentum transfer, $F(0)=1$, and has as boundary limit the external current, $A^\mu = \epsilon^\mu e^{iQ\cdot x} J(Q,z)$. Thus:

$$\lim_{Q\to 0} J(Q,z) = \lim_{z\to 0} J(Q,z) = 1.$$

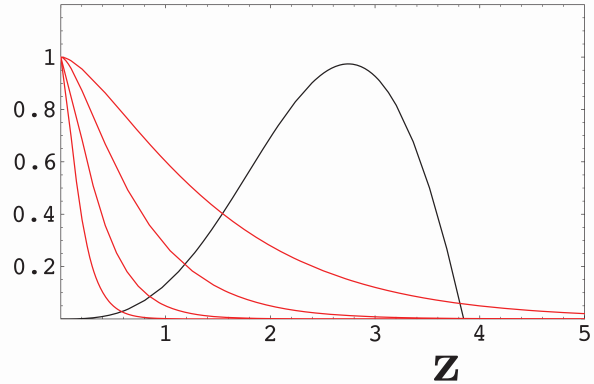
- Solution to the AdS Wave equation with boundary conditions at $Q=0$ and $z\to 0$:

$$J(Q,z) = zQK_1(zQ).$$

Polchinski and Strassler, hep-th/0209211; Hong, Yong and Strassler, hep-th/0409118.

- Propagation of external perturbation suppressed inside AdS.
- At large enough $Q \sim r/R^2$, the interaction occurs in the large-r conformal region. Important contribution to the FF integral from the boundary near $z \sim 1/Q$.

$\mathbf{J(Q, z)}, \quad \mathbf{\Phi(z)}$

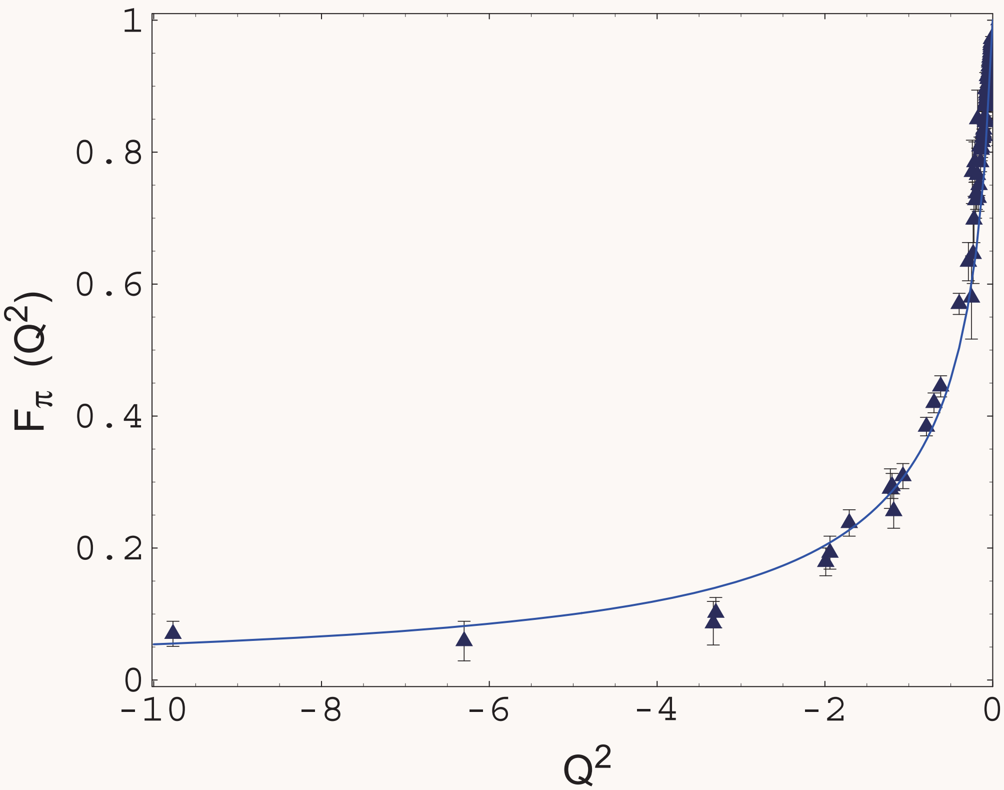


- Consider a specific AdS mode $\Phi^{(n)}$ dual to an n partonic Fock state $|n\rangle$. At small z, $\Phi^{(n)}$ scales as $\Phi^{(n)} \sim z^{\Delta_n}$. Thus:

$$F(Q^2) \to \left[\frac{1}{Q^2}\right]^{\tau-1},$$

General result from AdS/CFT

where $\tau = \Delta_n - \sigma_n$, $\sigma_n = \sum_{i=1}^{n} \sigma_i$. The twist is equal to the number of partons, $\tau = n$.



Space-like pion form factor in holographic model for $\Lambda_{QCD} = 0.2$ GeV.

Drell-Yan West formula for Form Factor of meson

$$F(q^2) = \sum_q e_q \int_0^1 dx \int \frac{d^2\vec{k}_\perp}{16\pi^3}\, \psi^*_{P'}(x, \vec{k}_\perp + (1-x)\vec{q}_\perp)\, \psi_P(x, \vec{k}_\perp).$$

In Impact Space:

$$F(q^2) = 4\pi \int_0^1 dx \int d^2\vec{b}_\perp\ e^{i\vec{b}_\perp\cdot\vec{q}_\perp} \left|\widetilde{\psi}(x,b)\right|^2$$

$$= 8\pi^2 \int_0^1 dx \int_0^\infty b\ db\ J_0\,(bqx)\ \left|\widetilde{\psi}(x,b)\right|^2,$$

For a two-parton state, the light-front wave function is effectively cutoff at

$$\vec{b}_\perp^2 \simeq \frac{1}{x(1-x)\Lambda^2_{\rm QCD}},$$

Change Integration variable to: $\zeta = |\vec{b}_\perp|\sqrt{x(1-x)}$

$$F_{IS}(Q^2) = 8\pi^2 \int_0^1 \frac{dx}{x(1-x)} \int_0^{\Lambda^{-1}_{\rm QCD}} \zeta\ d\zeta\ J_0\left(\frac{\zeta Q x}{\sqrt{x(1-x)}}\right)\ \left|\widetilde{\psi}(x,\zeta)\right|^2,$$

- Change the integration variable $\zeta = |\vec{b}_\perp|\sqrt{x(1-x)}$

$$F(Q^2) = 2\pi \int_0^1 \frac{dx}{x(1-x)} \int_0^{\zeta_{max}=\Lambda^{-1}_{\rm QCD}} \zeta \, d\zeta \, J_0\left(\frac{\zeta Q x}{\sqrt{x(1-x)}}\right) \left|\widetilde{\psi}(x,\zeta)\right|^2,$$

- Compare with AdS form factor for arbitrary Q. Find:

$$J(Q,\zeta) = \int_0^1 dx J_0\left(\frac{\zeta Q x}{\sqrt{x(1-x)}}\right) = \zeta Q K_1(\zeta Q),$$

the solution for the electromagnetic potential in AdS space, and

$$\boxed{\widetilde{\psi}(x,\vec{b}_\perp) = \frac{\Lambda_{\rm QCD}}{\sqrt{\pi} J_1(\beta_{0,1})} \sqrt{x(1-x)} J_0\left(\sqrt{x(1-x)}|\vec{b}_\perp|\beta_{0,1}\Lambda_{QCD}\right) \theta\left(\vec{b}_\perp^{\,2} \le \frac{\Lambda^{-2}_{\rm QCD}}{x(1-x)}\right)}$$

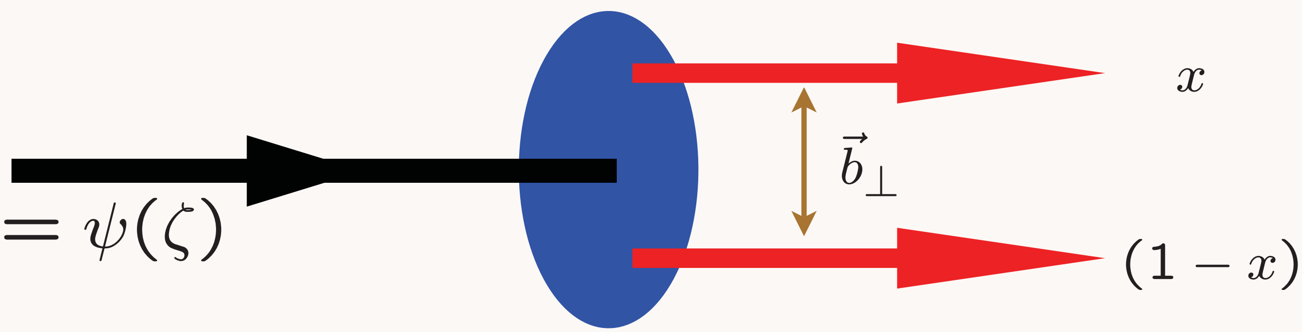
the holographic LFWF for the valence Fock state of the pion $\psi_{\overline{q}q/\pi}$.

- The variable ζ, $0 \le \zeta \le \Lambda^{-1}_{QCD}$, represents the scale of the invariant separation between quarks and is also the holographic coordinate $\zeta = z$!

Mapping between LF(3+1) and AdS₅

LF(3+1)		AdS₅
$\psi(x, \vec{b}_\perp)$	↔	$\phi(z)$
$\zeta = \sqrt{x(1-x)\vec{b}_\perp^2}$	↔	z

$$\psi(x, \vec{b}_\perp) = \psi(\zeta)$$



G. de Teramond and sjb

Map AdS/CFT to 3+1 LF Theory

Effective radial equation:

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

$$\zeta^2 = x(1-x)\mathbf{b}_\perp^2.$$

Effective conformal potential:

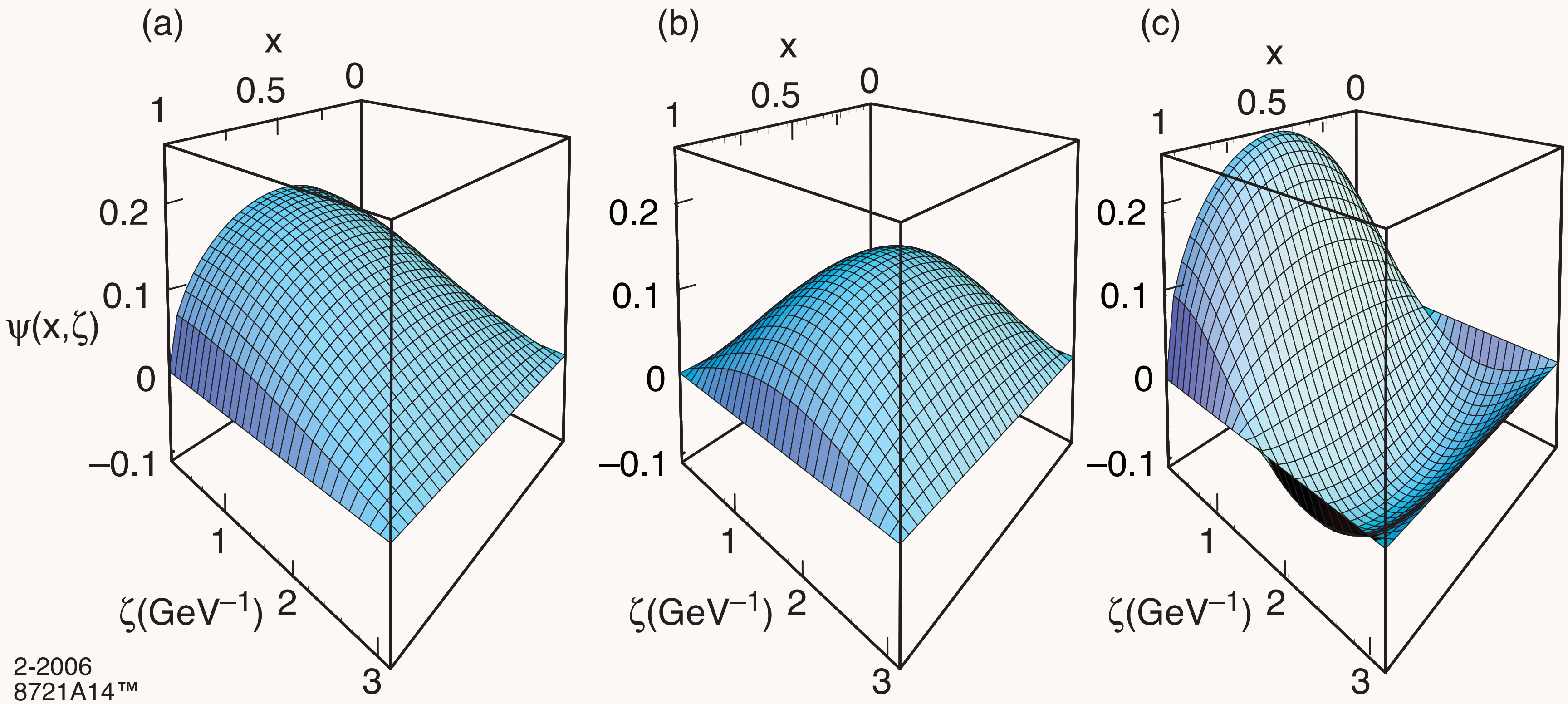
$$V(\zeta) = -\frac{1-4L^2}{4\zeta^2}.$$

General solution:

$$\widetilde{\psi}_{L,k}(x,\vec{b}_\perp) = B_{L,k}\sqrt{x(1-x)}$$

$$\mathbf{X} \quad J_L\left(\sqrt{x(1-x)}|\vec{b}_\perp|\beta_{L,k}\Lambda_{QCD}\right)\theta\left(\vec{b}_\perp^{\,2} \le \frac{\Lambda_{QCD}^{-2}}{x(1-x)}\right),$$

AdS/CFT Prediction for Meson LFWF



Two-parton holographic LFWF in impact space $\widetilde{\psi}(x,\zeta)$ for $\Lambda_{QCD} = 0.32$ GeV: (a) ground state $L=0,\ k=1$; (b) first orbital exited state $L=1,\ k=1$; (c) first radial exited state $L=0,\ k=2$. The variable ζ is the holographic variable $z = \zeta = |b_\perp|\sqrt{x(1-x)}$.

Evaluation of QCD Matrix Elements: Example f_π

- Pion decay constant 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, Phys. Rev. D **22**, 2157 (1980)

- 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.

Experiment: $f_\pi = 92.4$ Mev.

- Define effective single particle transverse density by (Soper, Phys. Rev. D **15**, 1141 (1977))

$$F(q^2) = \int_0^1 dx \int d^2\vec{\eta}_\perp e^{i\vec{\eta}_\perp \cdot \vec{q}_\perp} \tilde{\rho}(x, \vec{\eta}_\perp)$$

- From DYW expression for the FF in transverse position space:

$$\tilde{\rho}(x, \vec{\eta}_\perp) = \sum_n \prod_{j=1}^{n-1} \int dx_j \, d^2\vec{b}_{\perp j} \, \delta(1 - x - \sum_{j=1}^{n-1} x_j) \, \delta^{(2)}(\sum_{j=1}^{n-1} x_j \vec{b}_{\perp j} - \vec{\eta}_\perp) |\psi_n(x_j, \vec{b}_{\perp j})|^2$$

- Compare with the the form factor in AdS space for arbitrary Q:

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

- Holographic variable z is expressed in terms of the average transverse separation distance of the spectator constituents $\vec{\eta} = \sum_{j=1}^{n-1} x_j \, \vec{b}_{\perp j}$

$$\boxed{z = \sqrt{\frac{x}{1-x}} \, \Big| \sum_{j=1}^{n-1} x_j \, \vec{b}_{\perp j} \Big|}$$

- Our final result: hadronic QCD transverse density $\tilde{\rho}$ is determined by the modes Φ in AdS space!

$$\boxed{\tilde{\rho}(x,\zeta) = \frac{R^3}{2\pi}\,\frac{x}{1-x}\,e^{3A(\zeta)}\,\frac{|\Phi(\zeta)|^2}{\zeta^4}}$$

- The variable ζ, $0 \le \zeta \le \Lambda^{-1}_{\rm QCD}$, is related to the average transverse separation between spectator constituents, and it is also the holographic variable z, $\zeta = z$.

- For the two-particle case

$$\tilde{\rho}(x,\zeta) = \frac{1}{(1-x)^2}\,|\psi\,(x,\zeta)|^2\,,$$

and we recover our previous results

$$|\psi(x,\zeta)|^2 \simeq \frac{R^3}{2\pi}\,x(1-x)\,\frac{|\Phi(\zeta)|^2}{\zeta^4}\theta\left(\zeta^2 \le \Lambda^{-2}_{\rm QCD}\right).$$

- Consider the spin non-flip form factors in the infinite wall approximation

$$F_+(Q^2) = g_+ R^3 \int \frac{dz}{z^3} J(Q,z)\,|\psi_+(z)|^2,$$
$$F_-(Q^2) = g_- R^3 \int \frac{dz}{z^3} J(Q,z)\,|\psi_-(z)|^2,$$

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 $\psi_+(z)$ and $\psi_-(z)$ correspond to nucleons with $J^z = +1/2$ and $-1/2$.

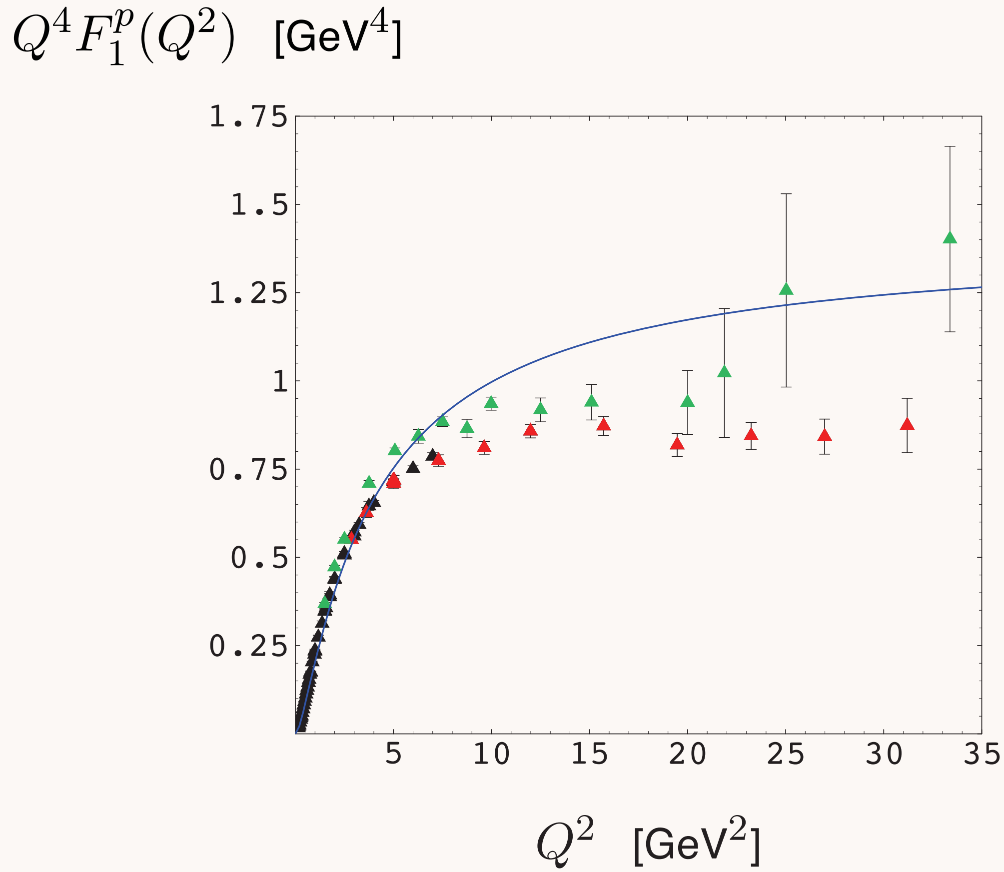
- For $SU(6)$ spin-flavor symmetry

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

where $F_1^p(0) = 1,\; F_1^n(0) = 0$.

- Large Q power scaling: $F_1(Q^2) \to \left[1/Q^2\right]^2$.

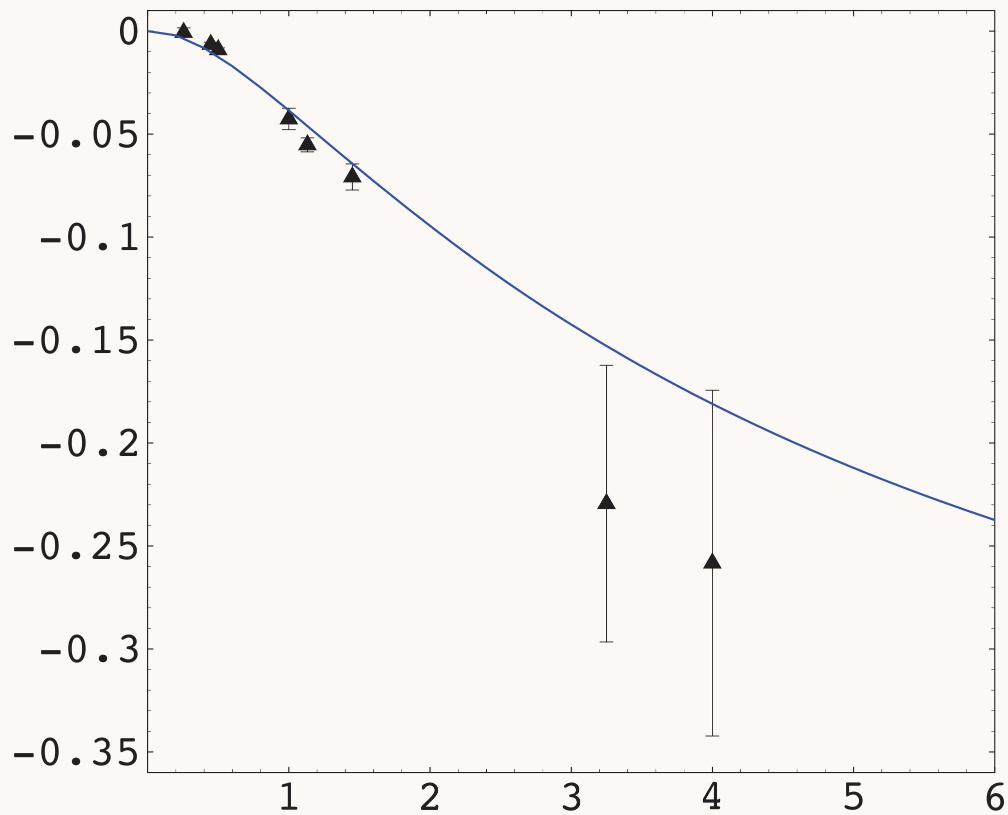
Dirac Proton Form Factor F_1^p



Prediction for $Q^4 F_1^p(Q^2)$ for $\Lambda_{\rm QCD} = 0.21$ GeV in the infinite wall approximation includding the data from Kirk (superimposed green points assuming $G_E^p = G_M^p$): P. N. Kirk *et al.*, Phys. Rev. D **8** (1973) 63.

$Q^4 F_1^n(Q^2)$ [GeV^4]

Dirac Neutron Form Factor F_1^n



Q^2 [GeV^2]

Prediction for $Q^4 F_1^n(Q^2)$ for $\Lambda_{\mathrm{QCD}} = 0.21$ GeV in the infinite wall approximation.

New Perspectives for QCD from AdS/CFT

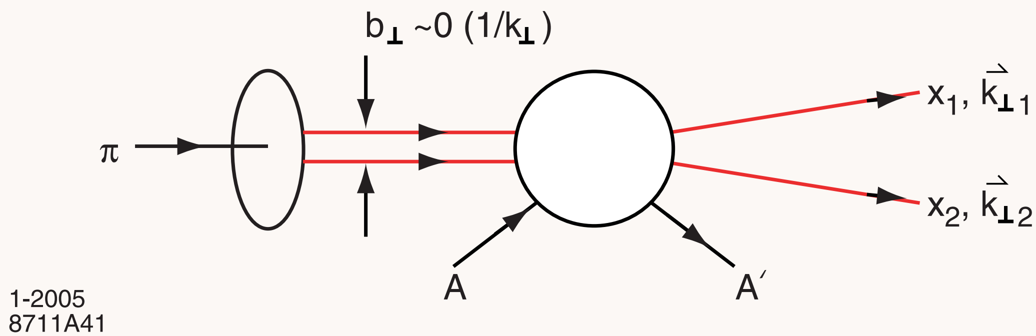
- LFWFs: Fundamental description of hadrons at amplitude level
- Holographic Model from AdS/CFT : Confinement at large distances and conformal behavior at short distances
- Model for LFWFs, meson and baryon spectra: many applications!
- New basis for diagonalizing Light-Front Hamiltonian
- Physics similar to MIT bag model, but covariant. No problem with support $0 < x < 1$.
- Quark Interchange dominant force at short distances

Use Diffraction to Resolve Hadron Substructure

- Measure Light-Front Wavefunctions
- Test AdS/CFT predictions
- Novel Aspects of Hadron Wavefunctions: Intrinsic Charm, Hidden Color, Color Transparency/Opaqueness
- Diffractive Di-Jet Production
- Nuclear Shadowing and Antishadowing
- New Mechanism for Higgs Production

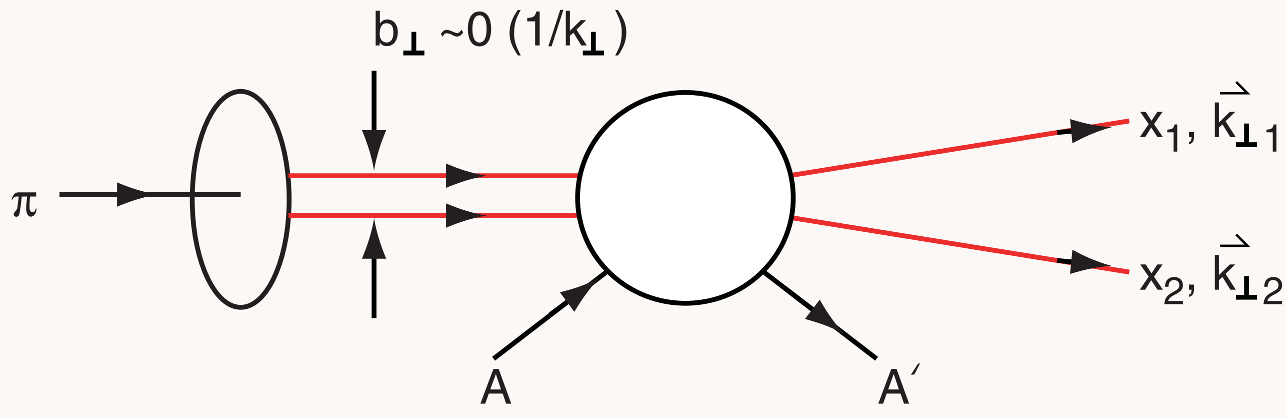
Diffractive Dissociation of Pion

E791 Ashery et al.

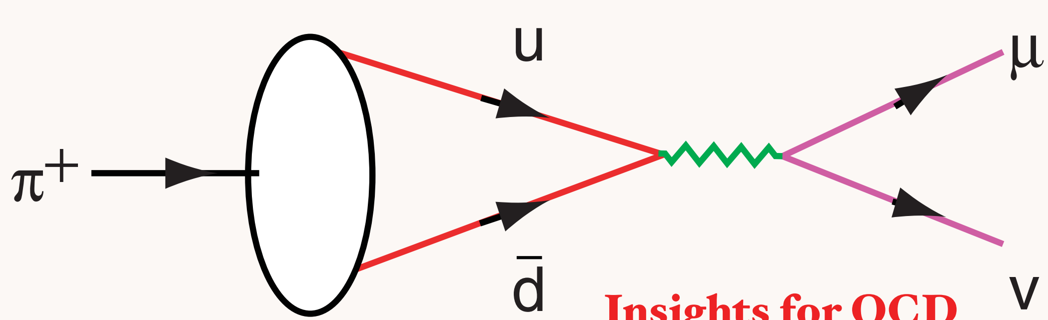


Measure Light-Front Wavefunction of Pion
Two-gluon Exchange
Minimal momentum transfer to nucleus
Nucleus left Intact

Fluctuation of a Pion to a Compact Color Dipole State



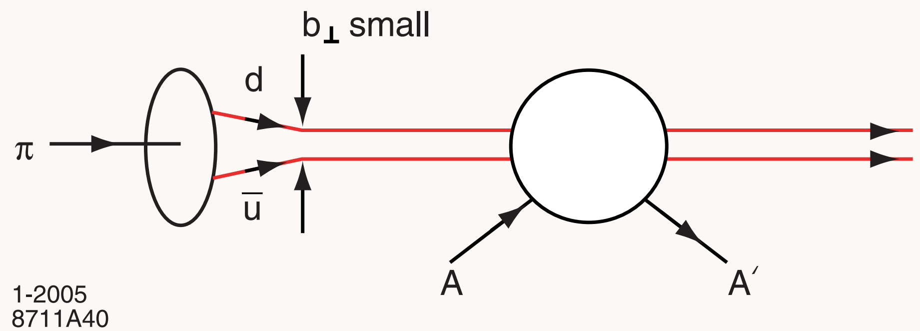
Color-Transparent Fock State For High Transverse Momentum Di-Jets



Same Fock State Determines Weak Decay

Fluctuation of a Pion to a Compact Color Dipole State

Small Size Pion Can Interact Coherently on Each Nucleon of Nucleus



Diffractive Dijet Cross Section Color Transparent

$$M(\pi A \to Jet Jet A') = A^1 M(\pi N \to Jet Jet N') F_A(t)$$
$$d\sigma/dt(\pi A \to Jet Jet A') =$$
$$A^2 d\sigma/dt(\pi N \to Jet Jet N') |F_A(t)|^2$$
$$\sigma \propto \frac{A^2}{R_A^2} \sim A^{4/3}$$

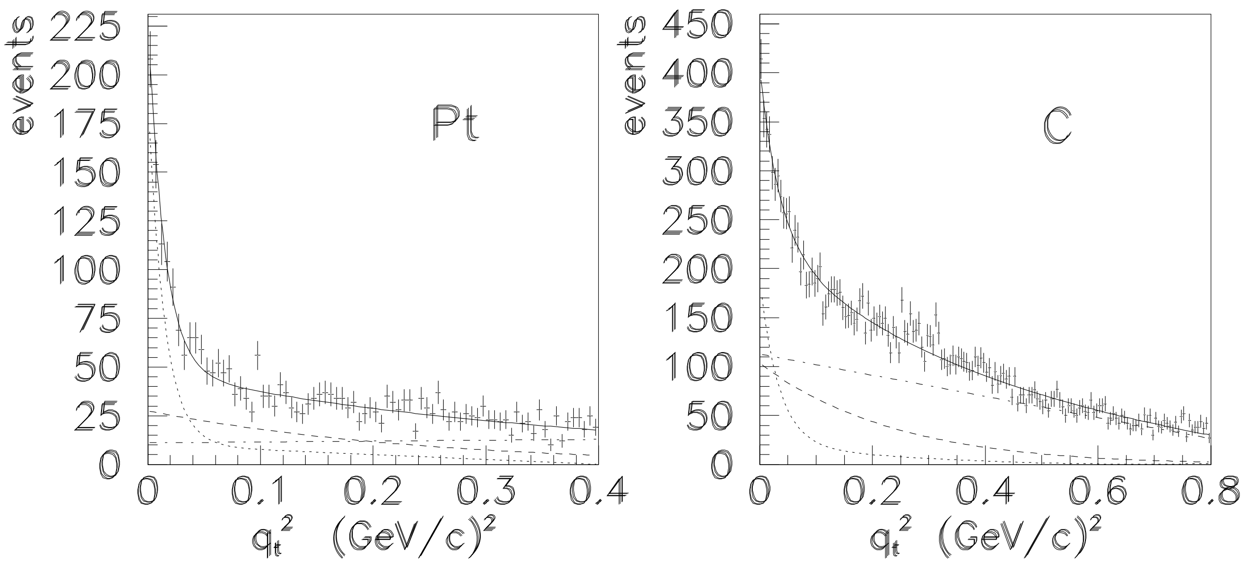
- Fully coherent interactions between pion and nucleons.
- Emerging Di-Jets do not interact with nucleus.

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

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

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

E791 Collaboration, E. Aitala *et al.*, Phys. Rev. Lett. 86, 4773 (2001)



Ashery E791:
Measure pion LFWF in diffractive dijet production
Confirms color transparency !

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 !

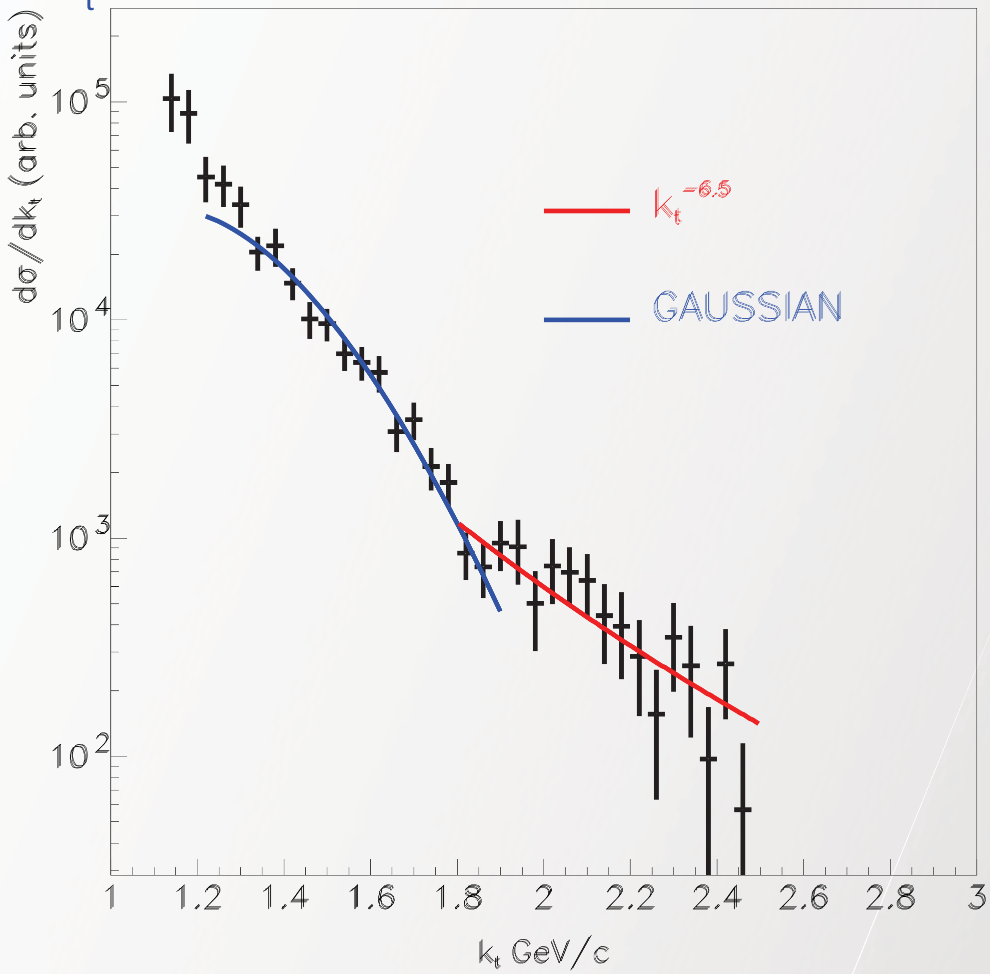
Factor of 7

FermiLab E791
Ashery et al

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** $G(x, k_t^2) \sim k_t^{1/2}$: $\frac{d\sigma}{dk_t} \sim k_t^{-6}$



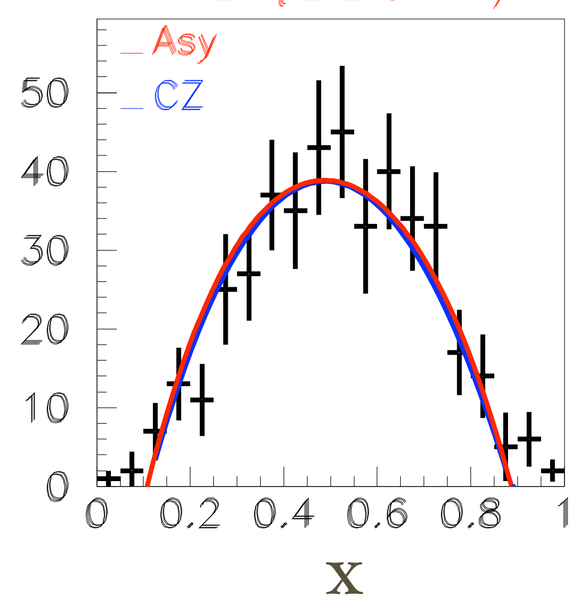
High Transverse momentum dependence consistent with PQCD/ AdS/CFT

Diffractive Dissociation of a Pion into Dijets

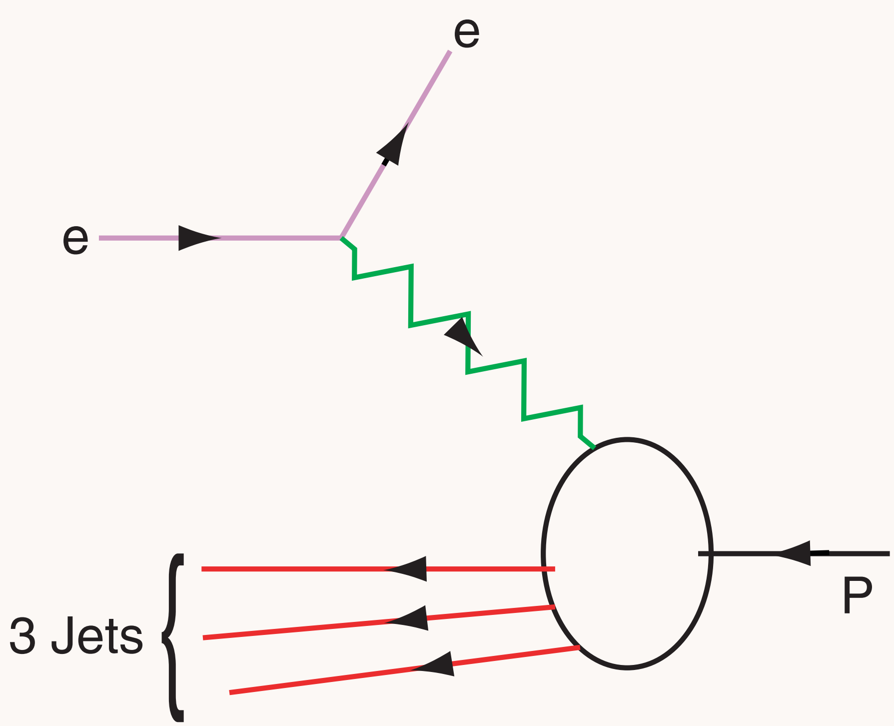
$$\pi A \rightarrow Jet\,Jet\,A'$$

- 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

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



Coulomb-Dissociate Proton to Three Jets at HERA



Frankfurt
Strikman
Miller

Measure $\Psi_{qqq}(x_i, \vec{k}_{\perp i})$ valence wavefunction of proton

New Perspectives on QCD from AdS/CFT

- Holographic Model from AdS/CFT : Confinement at large distances and conformal behavior at short distances
- AdS/CFT predicts Light-front wavefunctions: Fundamental description of hadrons at amplitude level
- AdS/CFT: gluonium (gg) , meson ($q \bar{q}$), and baryon (qqq) spectra
- Quark-interchange dominates scattering amplitudes
- No ggg bound states

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.

Formula for quark interchange using LFWFs

Blankenbecler, Gunion, sjb; Sivers

$$M_{FI} = \langle \psi_F | E - K | \psi_I \rangle$$

$$\equiv \langle \psi_F | \Delta | \psi_I \rangle$$

$$= \frac{1}{2(2\pi)^3} \int d^2k \int_0^1 \frac{dx}{x^2(1-x)^2} \Delta \psi_C(\vec{k}_\perp - x\vec{r}_\perp, x) \psi_D(\vec{k}_\perp + (1-x)\vec{q}_\perp, x) \psi_A(\vec{k}_\perp - x\vec{r}_\perp + (1-x)\vec{q}_\perp, x) \psi_B(\vec{k}_\perp, x)$$

where

$$\Delta = s - M_A{}^2 - M_B{}^2 - K_a - K_b - K_c - K_d$$

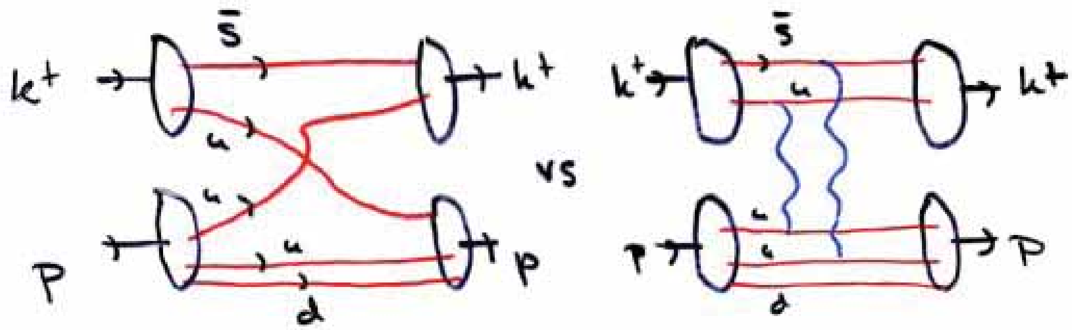
$$= M_A{}^2 + M_B{}^2 - S_A(\vec{k}_\perp + (1-x)\vec{q}_\perp - x\vec{r}_\perp, x) - S_B(\vec{k}_\perp, x)$$

$$= M_C{}^2 + M_D{}^2 - S_C(\vec{k}_\perp - x\vec{r}_\perp, x) - S_D(\vec{k}_\perp + (1-x)\vec{q}_\perp, x) .$$

Angular Distribution $-t/s = \frac{1}{2}(1-\cos\theta_{cm})$

$$\frac{d\sigma}{dt} = \frac{1}{s^{n_{TOT}-2}} F(t/s)$$

determined by scattering mechanism



Quark Interchange | gluon exchange

analogous to spin exchange in atom-atom scattering

Van der Waals

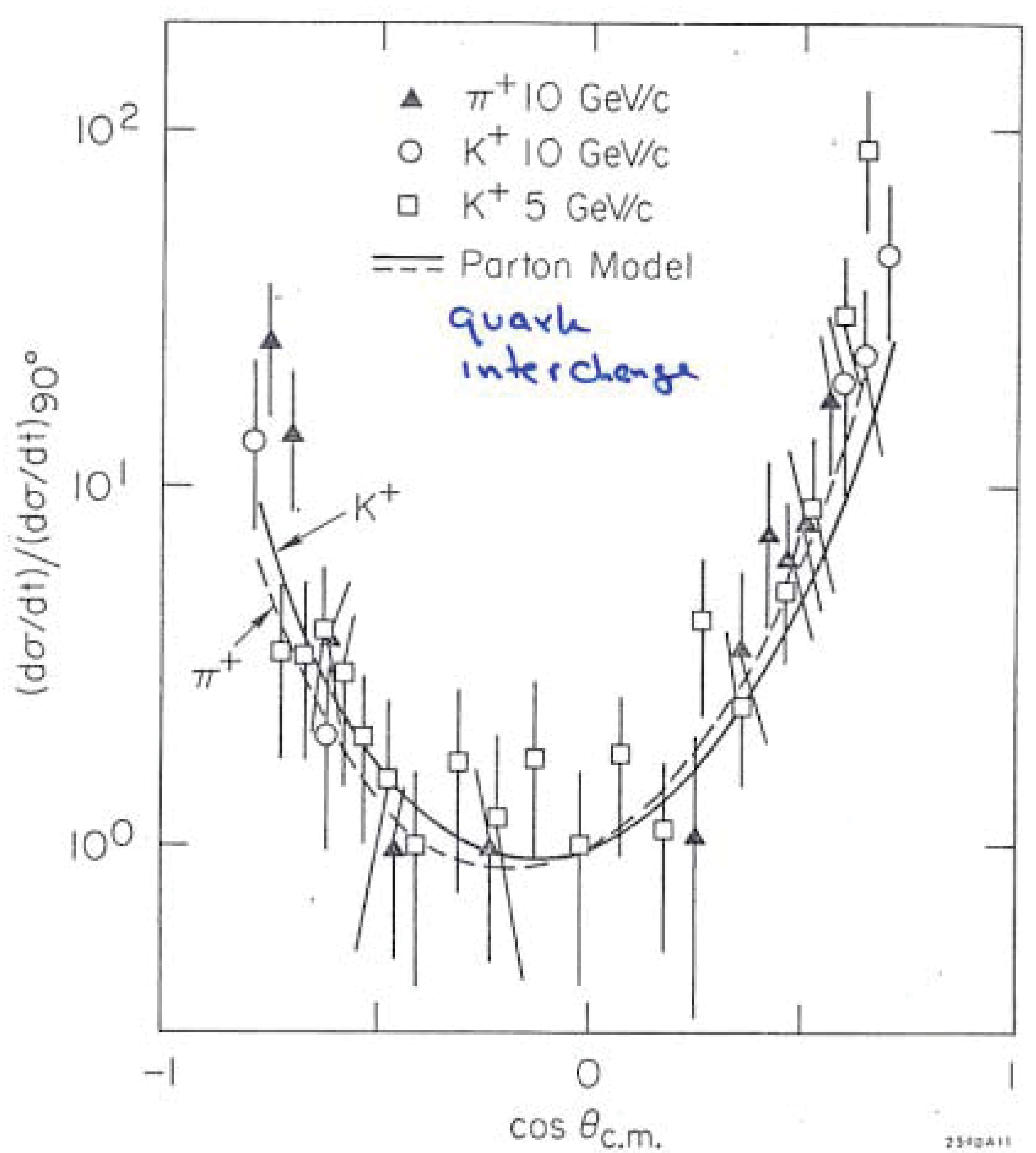
Large N_c: Quark Interchange Dominant

$$M \sim \frac{1}{u}\frac{1}{t^2}$$

t' Hooft limit, AdS/CFT

Blankenbecler, Gunion, sjb

MIT Bag Model predicts dominance of quark interchange: deTar

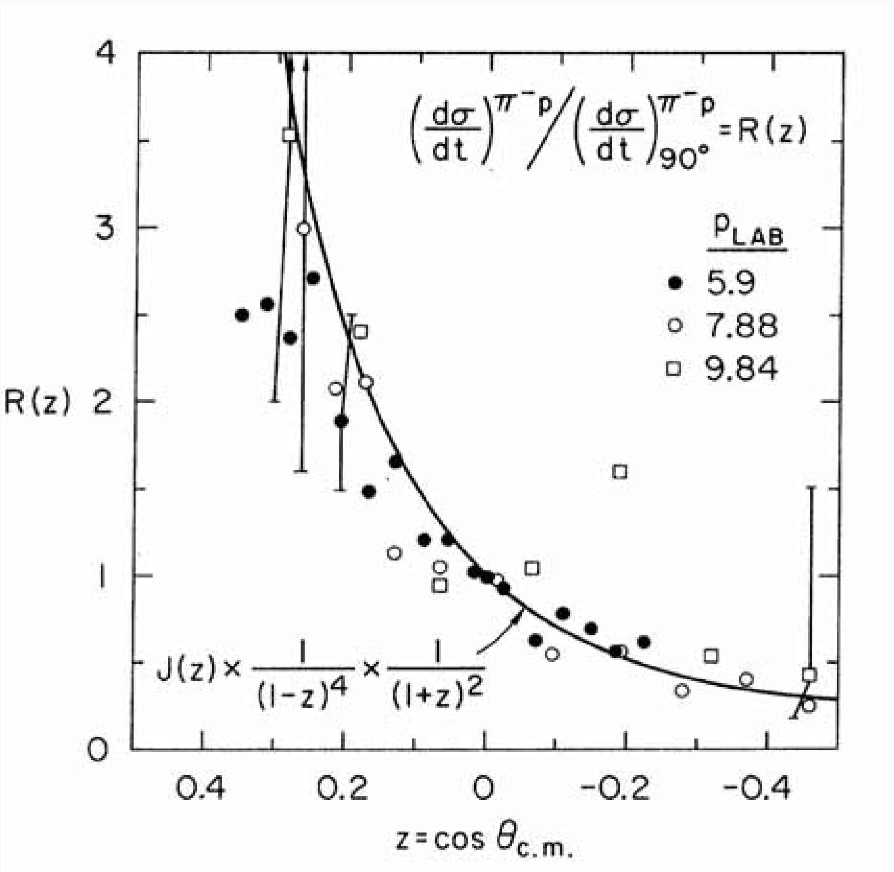


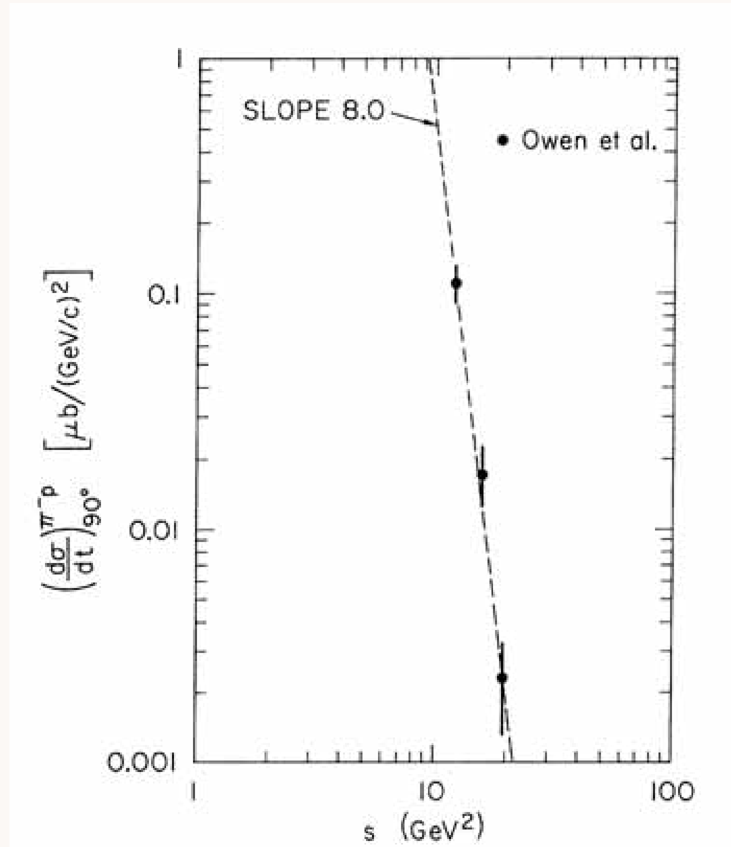
AdS/CFT explains why quark interchange is dominant interaction at high momentum transfer in exclusive reactions

$$M_{FI} = \langle \psi_F | E - K | \psi_I \rangle$$
$$\equiv \langle \psi_F | \Delta | \psi_I \rangle$$
$$= \frac{1}{2(2\pi)^3} \int d^2k \int_0^1 \frac{dx}{x^2(1-x)^2} \Delta \psi_C(\vec{k}_\perp - x\vec{r}_\perp, x)\psi_D(\vec{k}_\perp + (1-x)\vec{q}_\perp, x)\psi_A(\vec{k}_\perp - x\vec{r}_\perp + (1-x)\vec{q}_\perp, x)\psi_B(\vec{k}_\perp, x),$$

where

$$\Delta = s - M_A{}^2 - M_B{}^2 - K_a - K_b - K_c - K_d$$
$$= M_A{}^2 + M_B{}^2 - S_A(\vec{k}_\perp + (1-x)\vec{q}_\perp - x\vec{r}_\perp, x) - S_B(\vec{k}_\perp, x)$$
$$= M_C{}^2 + M_D{}^2 - S_C(\vec{k}_\perp - x\vec{r}_\perp, x) - S_D(\vec{k}_\perp + (1-x)\vec{q}_\perp, x) .$$





Outlook

- Only one scale Λ_{QCD} determines hadronic spectrum (slightly different for mesons and baryons).
- Light-cone frame is the natural frame to establish the AdS/QCD holographic duality.
- Ratio of Nucleon to Delta trajectories determined by zeroes of Bessel functions.
- AdS modes dual to hadrons extrapolate to valence constituents at zero separation in the AdS boundary.
- Non-zero orbital angular momentum and higher Fock-states require introduction of quantum fluctuations.
- Initial good approximation for description of the structure of hadronic form factors and other observables, but disagreement with data at very high Q^2 may indicate shortcomings of the hard wall approximation.

Features of Holographic Model

- Use of holographic light-front wave functions to compute hadronic matrix elements and other observables.
- 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.
- Precise mapping of string modes to partonic states. String modes inside AdS represent the probability amplitude for the distribution of quarks at a given scale.
- Exact holographic mapping for n-parton state determines effective QCD transverse charge density in terms of modes in AdS space.
- Holographic mapping allows deconstruction: express the eigenvalue problem in terms of 3+1 QCD degrees of freedom.

Light-Front QCD Phenomenology

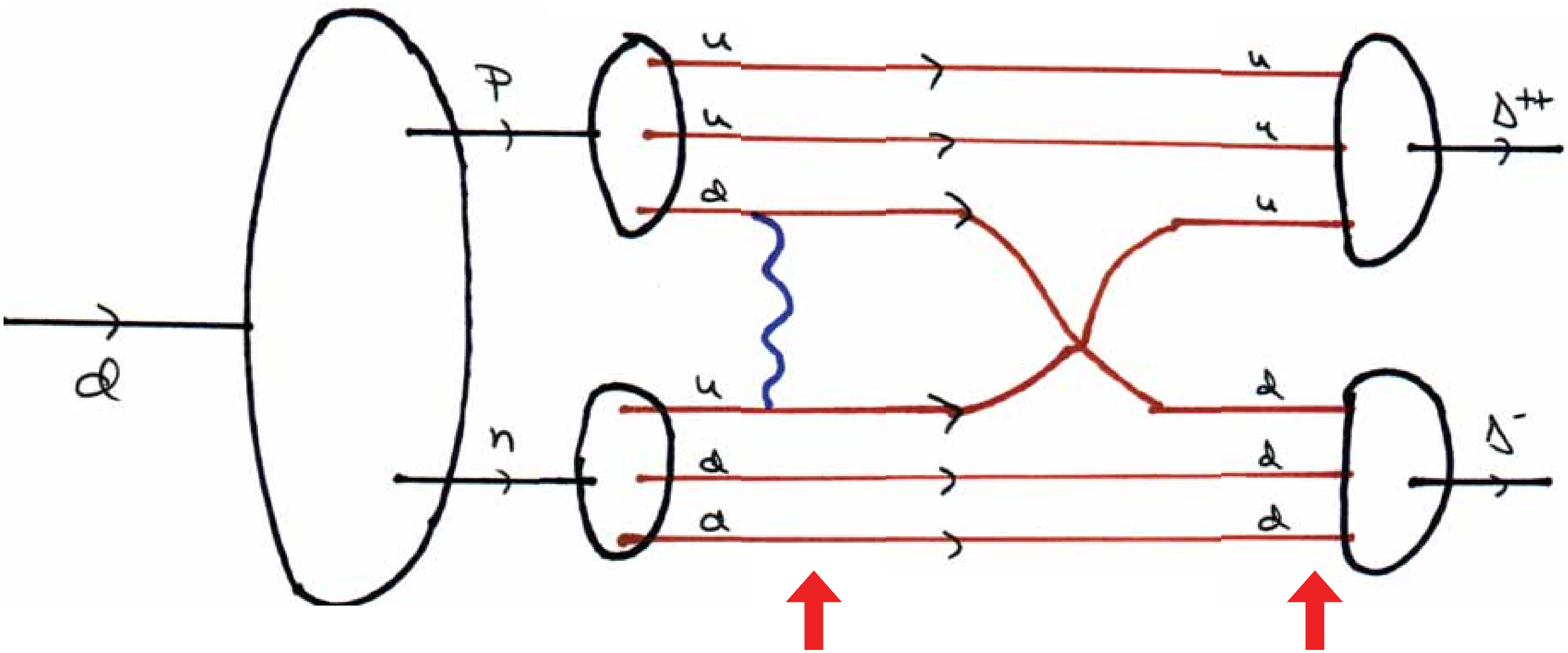
- Hidden color, Intrinsic glue, sea, Color Transparency
- Near Conformal Behavior of LFWFs at Short Distances; PQCD constraints
- Vanishing anomalous gravitomagnetic moment
- Relation between edm and anomalous magnetic moment
- Cluster Decomposition Theorem for relativistic systems
- OPE: DGLAP, ERBL evolution; invariant mass scheme

Hidden Color

- Deuteron six quark wavefunction: Lepage, Ji, sjb
- 5 color-singlet combinations of 6 color-triplets -- one state is |n p>
- Components evolve towards equality at short distances
- Hidden color states dominate deuteron form factor and photodisintegration at high momentum transfer
- Predict $\frac{d\sigma}{dt}(\gamma d \to \Delta^{++}\Delta^{-}) \simeq \frac{d\sigma}{dt}(\gamma d \to pn)$ at high Q^2

Ratio = 2/5 for asymptotic wf

Structure of Deuteron in QCD



Hidden Color Fock State

Delta-Delta Fock State

The evolution equation for six-quark systems in which the constituents have the light-cone longitudinal momentum fractions x_i ($i=1,2,\ldots,6$) can be obtained from a generalization of the proton (three-quark) case.[2] A nontrivial extension is the calculation of the color factor, C_d, of six-quark systems[5] (see below). Since in leading order only pairwise interactions, with transverse momentum Q, occur between quarks, the evolution equation for the six-quark system becomes $\{[dy]=\delta(1-\sum_{i=1}^{6}y_i)\prod_{i=1}^{6}dy_i$, $C_F=(n_c^2-1)/2n_c=\frac{4}{3}$, $\beta=11-\frac{2}{3}n_f$, and n_f is the effective number of flavors$\}$

$$\prod_{k=1}^{6} x_k\left[\frac{\partial}{\partial\xi}+\frac{3C_F}{\beta}\right]\tilde{\Phi}(x_i,Q)=-\frac{C_d}{\beta}\int_0^1 [dy]\,V(x_i,y_i)\,\tilde{\Phi}(y_i,Q),$$

$$\xi(Q^2)=\frac{\beta}{4\pi}\int_{Q_0^2}^{Q^2}\frac{dk^2}{k^2}\alpha_s(k^2)\sim\ln\left(\frac{\ln(Q^2/\Lambda^2)}{\ln(Q_0^2/\Lambda^2)}\right).$$

$$V(x_i,y_i)=2\prod_{k=1}^{6}x_k\sum_{i\neq j}^{6}\theta(y_i-x_i)\prod_{l\neq i,j}^{6}\delta(x_l-y_l)\frac{y_j}{x_j}\left(\frac{\delta_{h_i\bar{h}_j}}{x_i+x_j}+\frac{\Delta}{y_i-x_i}\right)$$

where $\delta_{h_i\bar{h}_j}=1$ (0) when the helicities of the constituents $\{i,j\}$ are antiparallel (parallel). The infrared singularity at $x_i=y_i$ is cancelled by the factor $\Delta\tilde{\Phi}(y_i,Q)=\tilde{\Phi}(y_i,Q)-\tilde{\Phi}(x_i,Q)$ since the deuteron is a color singlet.

Quantum Chromodynamic Predictions for the Deuteron Form Factor

$$F_d(Q^2) = \int_0^1 [dx][dy]\varphi_d^\dagger(y,Q) \times T_H^{6q+\gamma^*\to 6q}(x,y,Q)\varphi_d(x,Q), \quad (1)$$

where the hard-scattering amplitude

$$T_H^{6q+\gamma^*\to 6q} = [\alpha_s(Q^2)/Q^2]^5 t(x,y) \times [1+O(\alpha_s(Q^2))] \quad (2)$$

gives the probability amplitude for scattering six quarks collinear with the initial to the final deuteron momentum and

$$\varphi_d(x_i,Q) \propto \int^{k_{\perp i}<Q}[d^2k_\perp]\psi_{qqq\,qqq}(x_i,\vec{k}_{\perp i}) \quad (3)$$

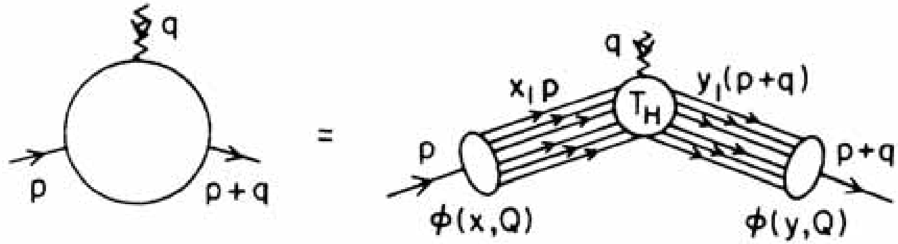


FIG. 1. The general structure of the deuteron form factor at large Q^2.

Ji, Lepage, sjb

QCD Prediction for Deuteron Form Factor

$$F_d(Q^2) = \left[\frac{\alpha_s(Q^2)}{Q^2}\right]^5 \sum_{m,n} d_{mn} \left(\ln\frac{Q^2}{\Lambda^2}\right)^{-\gamma_n^d - \gamma_m^d} \left[1 + O\left(\alpha_s(Q^2), \frac{m}{Q}\right)\right]$$

Define "Reduced" Form Factor

$$f_d(Q^2) \equiv \frac{F_d(Q^2)}{F_N{}^2(Q^2/4)}\,.$$

Same large momentum transfer behavior as pion form factor

$$f_d(Q^2) \sim \frac{\alpha_s(Q^2)}{Q^2}\left(\ln\frac{Q^2}{\Lambda^2}\right)^{-(2/5)\,C_F/\beta}$$

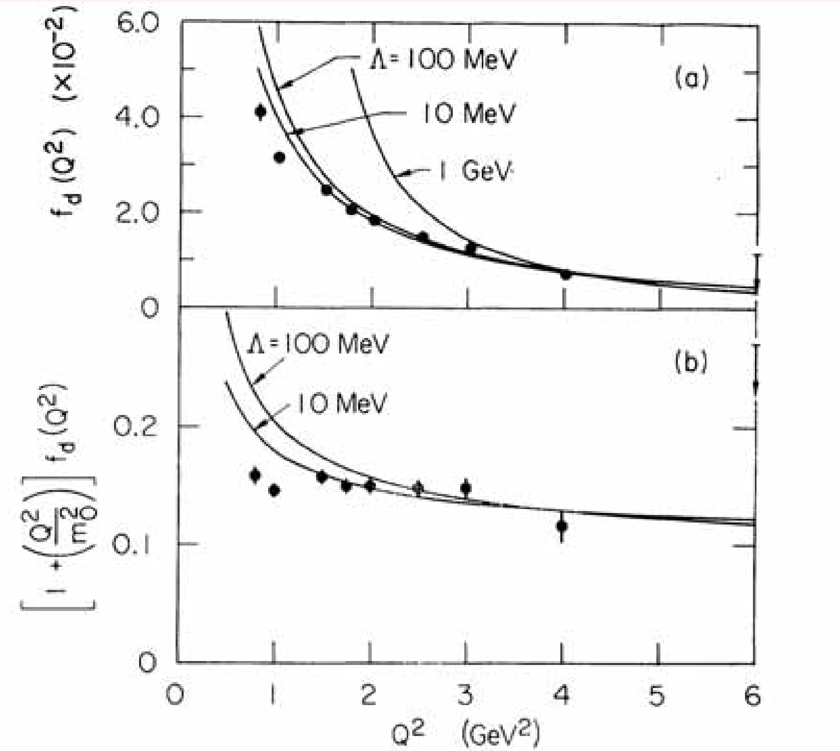
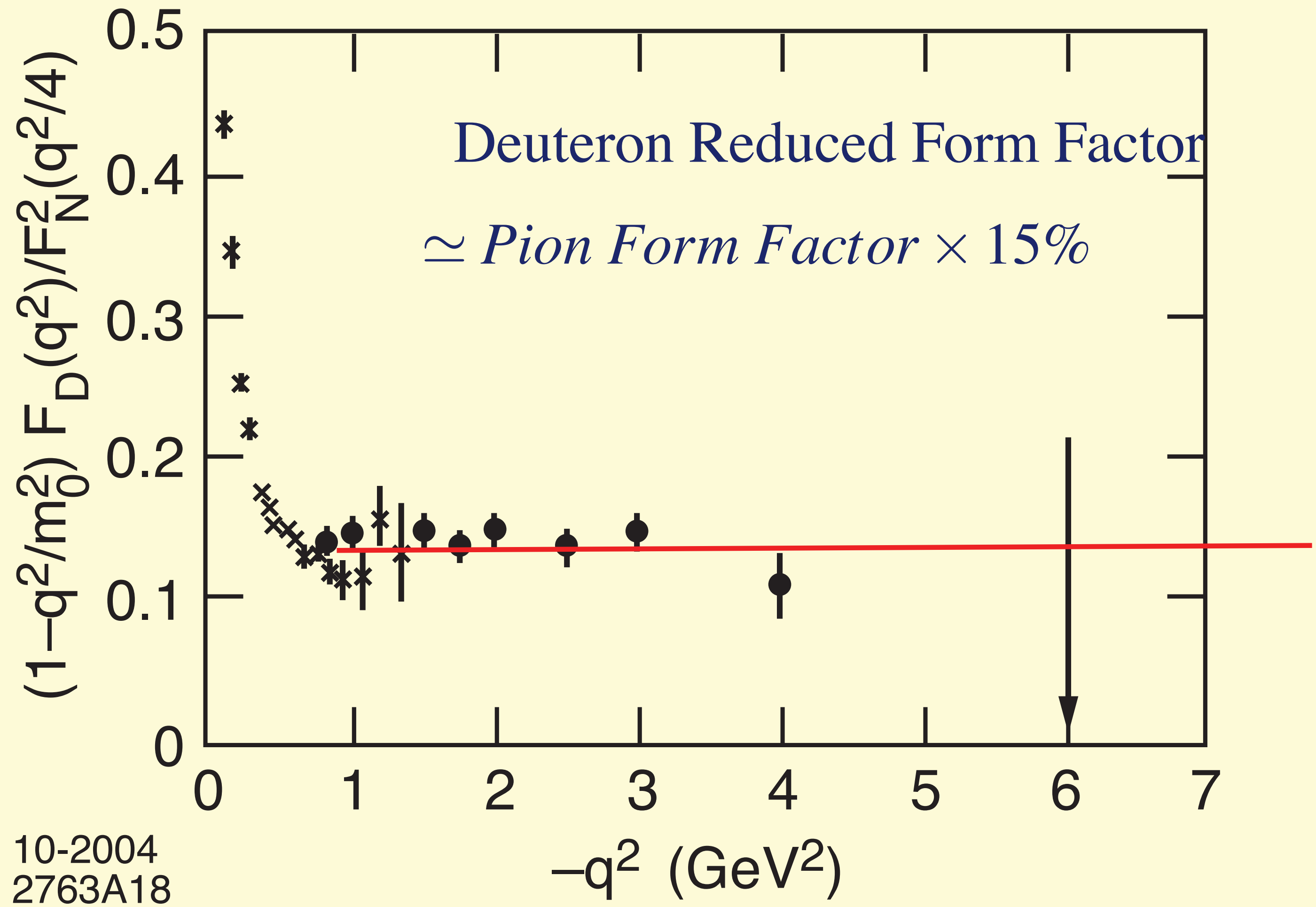


FIG. 2. (a) Comparison of the asymptotic QCD prediction $f_d(Q^2) \propto (1/Q^2)[\ln(Q^2/\Lambda^2)]^{-1-(2/5)C_F/\beta}$ with final data of Ref. 10 for the reduced deuteron form factor, where $F_N(Q^2) = [1 + Q^2/(0.71\ \text{GeV}^2)]^{-2}$. The normalization is fixed at the $Q^2 = 4$ GeV^2 data point. (b) Comparison of the prediction $[1 + (Q^2/m_0^2)]f_d(Q^2) \propto [\ln(Q^2/\Lambda^2)]^{-1-(2/5)C_F/\beta}$ with the above data. The value $m_0^2 = 0.28$ GeV^2 is used (Ref. 8).

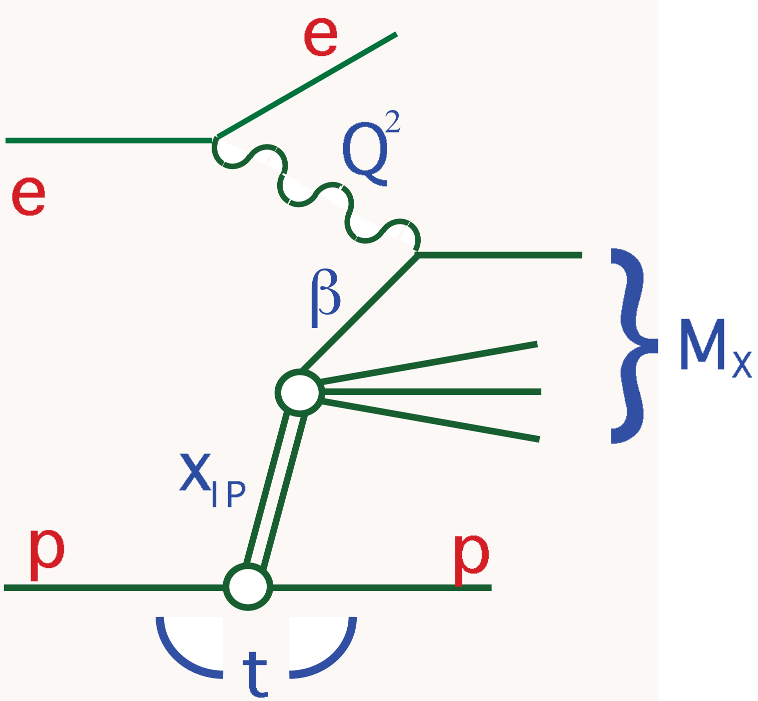


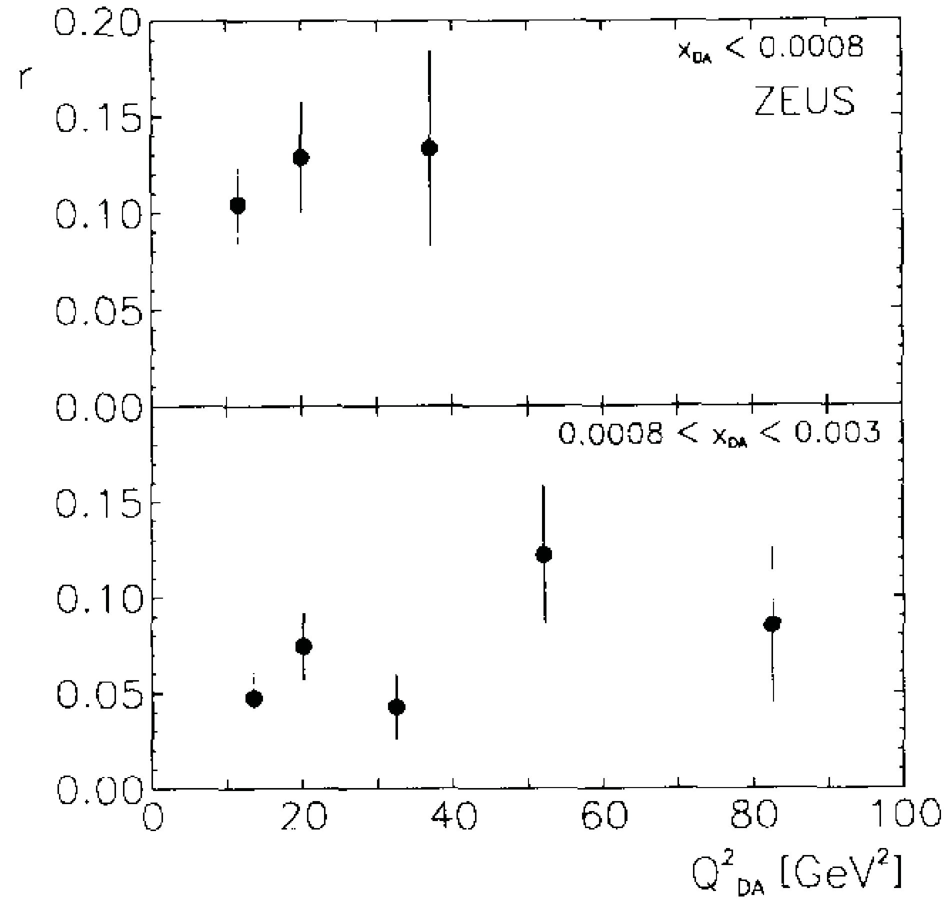
- 15% Hidden Color in the Deuteron

Test Hidden Color of Deuteron

- Diffractive, Coulomb Dissociation to $\Delta^{++}\,\Delta^{-}$
- Photodisintegration of Deuteron to $\Delta^{++}\,\Delta^{-}$
- Connection to EMC
- Deuteron not simply n + p

Remarkable observation at HERA





10% of DIS events are diffractive !

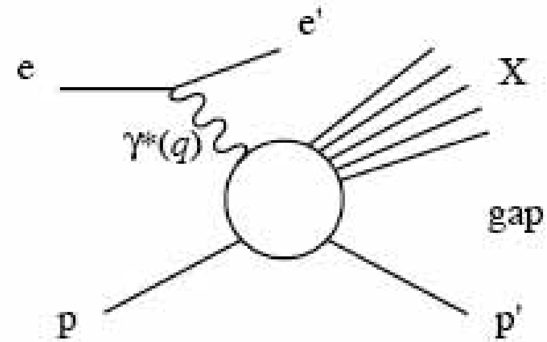
Fraction r of events with a large rapidity gap, $\eta_{max} < 1.5$, as a function of Q^2_{DA} for two ranges of x_{DA}. No acceptance corrections have been applied.

M. Derrick et al. [ZEUS Collaboration], Phys. Lett. B 315, 481 (1993).

Hard Diffraction from Rescattering

- Diffractive DIS: New Insight into Final State Interactions in QCD
- Origin of Hard Pomeron
- Structure Functions not Probability Distributions
- T-odd Single-Spin Asymmetries
- Diffractive dijets/ trijets
- Color Transparency, Color Opaqueness

DDIS

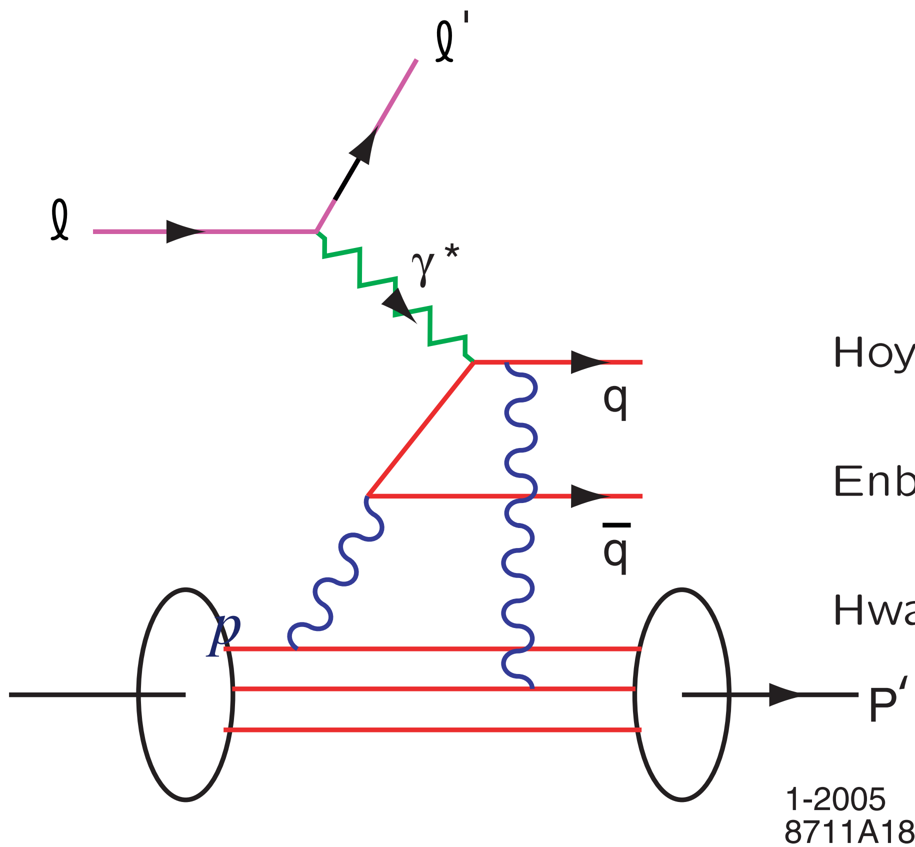


- In a large fraction ($\sim$ 10–15%) of DIS events, the proton escapes intact, keeping a large fraction of its initial momentum
- This leaves a large *rapidity gap* between the proton and the produced particles
- The t-channel exchange must be *color singlet* $\rightarrow$ a pomeron??

Enberg

Diffractive Deep Inelastic Lepton-Proton Scattering

Final State Interaction Produces Diffractive DIS

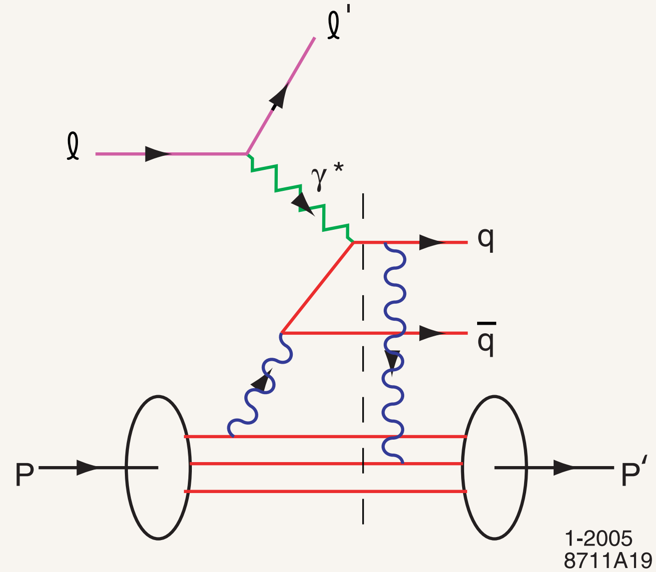


Quark Rescattering

Hoyer, Marchal, Peigne, Sannino, SJB (BHM

Enberg, Hoyer, Ingelman, SJB

Hwang, Schmidt, SJB



Integration over on-shell domain produces phase i

Need Imaginary Phase to Generate
Pomeron

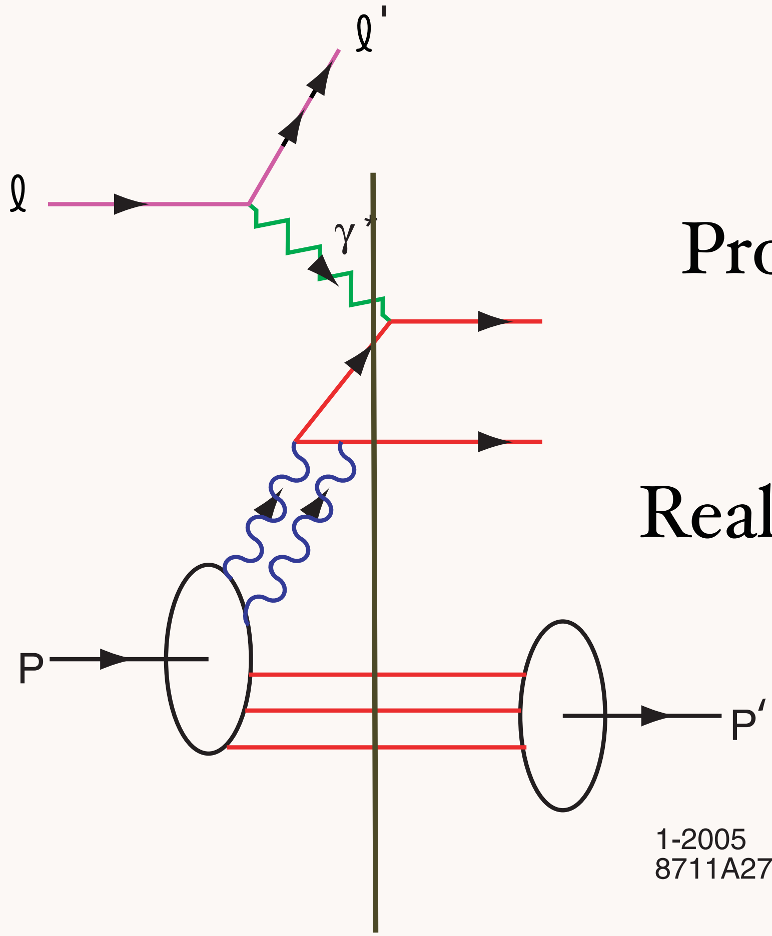
Need Imaginary Phase to Generate
T-Odd Single-Spin Asymmetry

Physics of FSI not in Wavefunction of Target

Problem: Wrong Phase

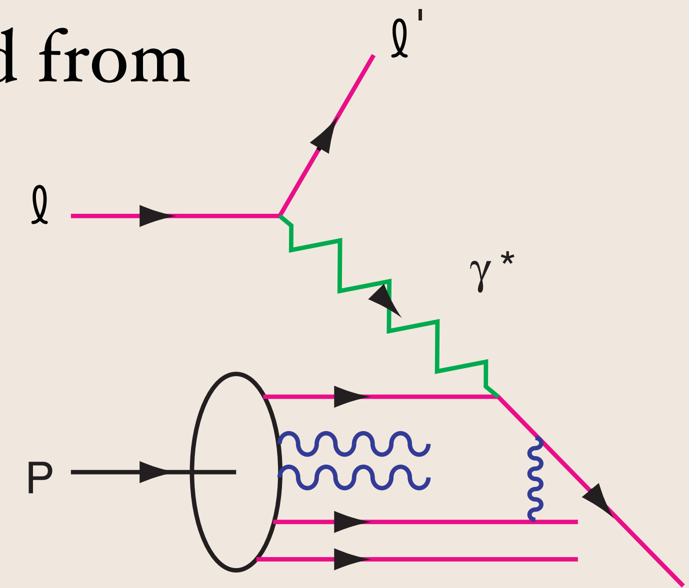
Real; should be imaginary

Pomeron is not a constituent of proton!



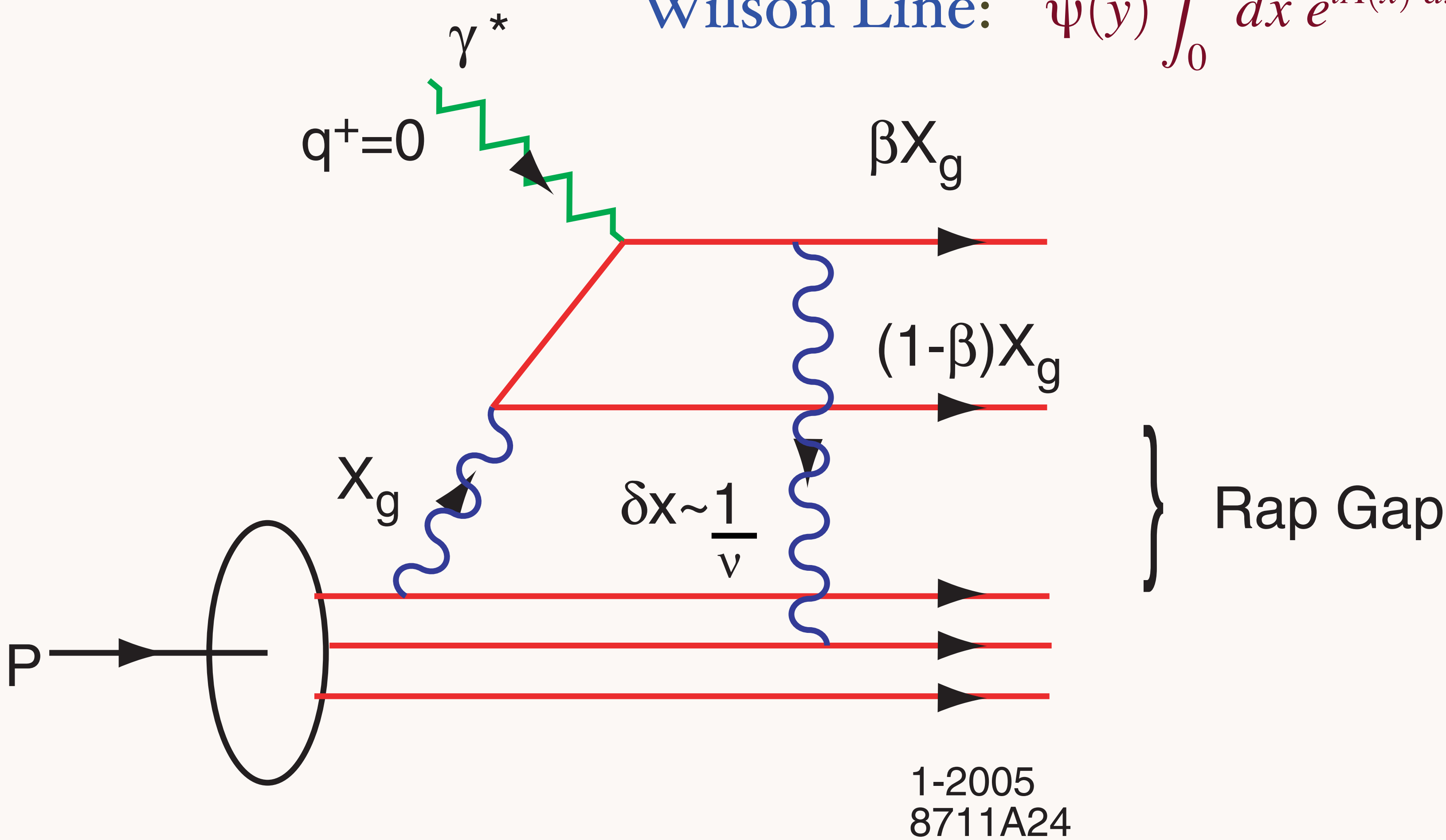
Need Final State Interactions !

- Quarks Reinteract in Final State
- Analogous to Coulomb phases, but not unitary
- Observable effects: DDIS, SSI, shadowing, antishadowing
- Structure functions cannot be computed from LFWFs computed in isolation
- Wilson line not 1 even in lcg



QCD Mechanism for Rapidity Gaps

Wilson Line: $\overline{\psi}(y) \int_0^y dx\, e^{iA(x)\cdot dx}\, \psi(0)$



Physics of Rescattering

- Diffractive DIS: New Insight into Final State Interactions in QCD
- Origin of Hard Pomeron
- Structure Functions not Probability Distributions
- T-odd SSAs, Shadowing, Antishadowing
- Diffractive dijets/ trijets, doubly diffractive Higgs
- Novel Effects: Color Transparency, Color Opaqueness, Intrinsic Charm, Odderon

New Perspectives for QCD from AdS/CFT

- LFWFs: Fundamental 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

QCD at The Amplitude Level

- Light-Front Fock Expansions
- LFWFs boost invariant
- Direct connection to form factors, structure functions, distribution amplitudes, GPDs
- Higher Twist Correlations
- Orbital Angular Momentum
- Validated in QED, Bethe-Salpeter
- AdS/CFT Holographic Model

Essential to test QCD

- GSI antiprotons
- 12 GeV Jlab
- J-PARC
- BaBar/Belle: ISR, two-gamma, timelike DVCS
- RHIC/LHC Nuclear Collisions; LHCb; forward heavy quarks, higgs
- photon-photon collider at the ILC
- electron-proton, electron-nucleus collisions