QCD Phenomenology
and
Nucleon Structure

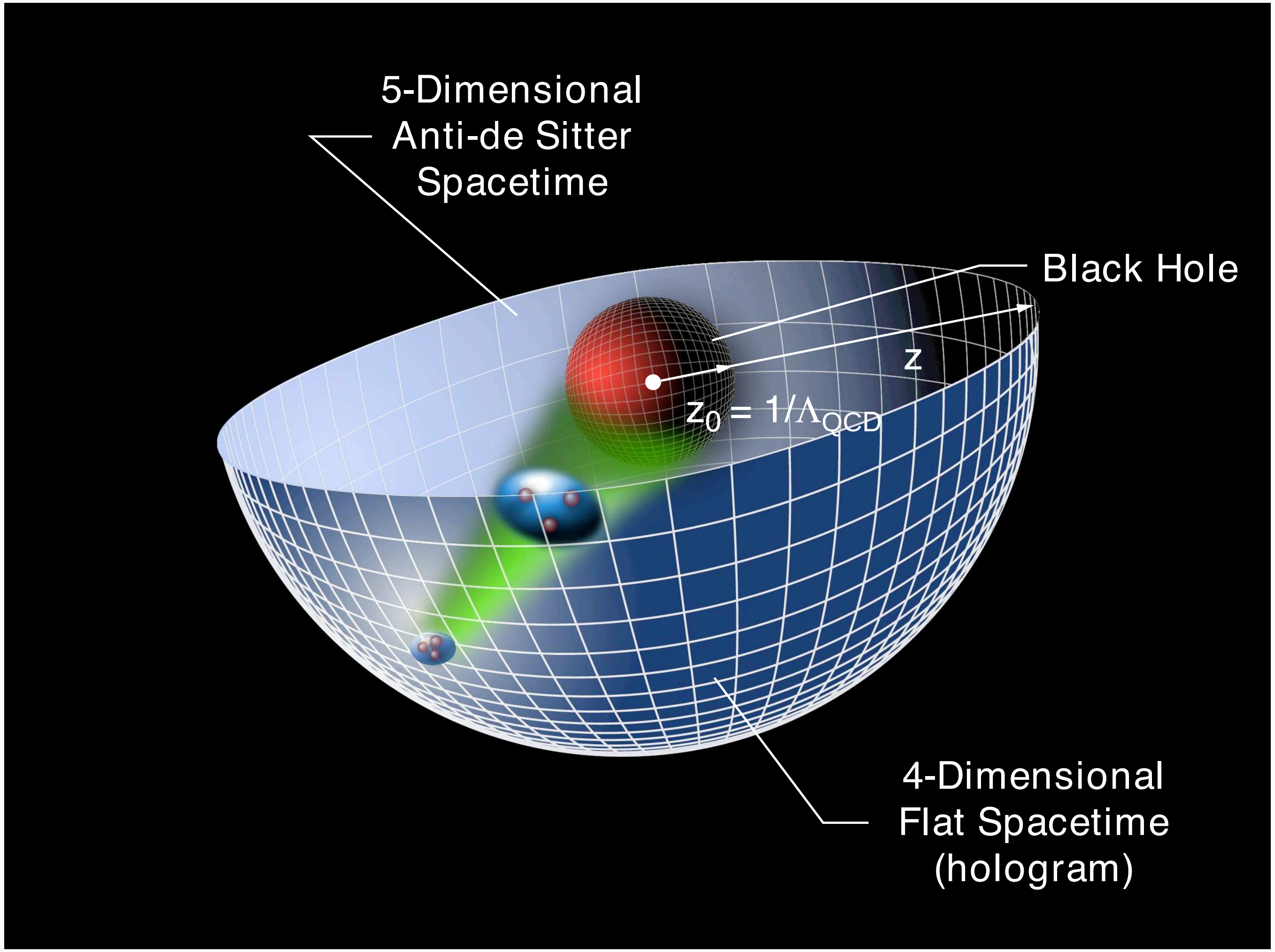
Stan Brodsky, SLAC

Lecture III

National Nuclear Physics Summer School

Impact of AdS/CFT on QCD

in collaboration with Guy de Teramond



AdS/CFT and QCD

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

- Representation of Semi-Classical QCD
- Confinement at Long Distances and Conformal Behavior at short distances
- Non-Perturbative Derivation of Dimensional Counting Rules (Strassler and Polchinski)
- Hadron Spectra, Regge Trajectories, Light-Front Wavefunctions
- Goal: A first approximant to physical QCD

Predictions of AdS/CFT

Only one parameter!

Entire light quark baryon spectrum

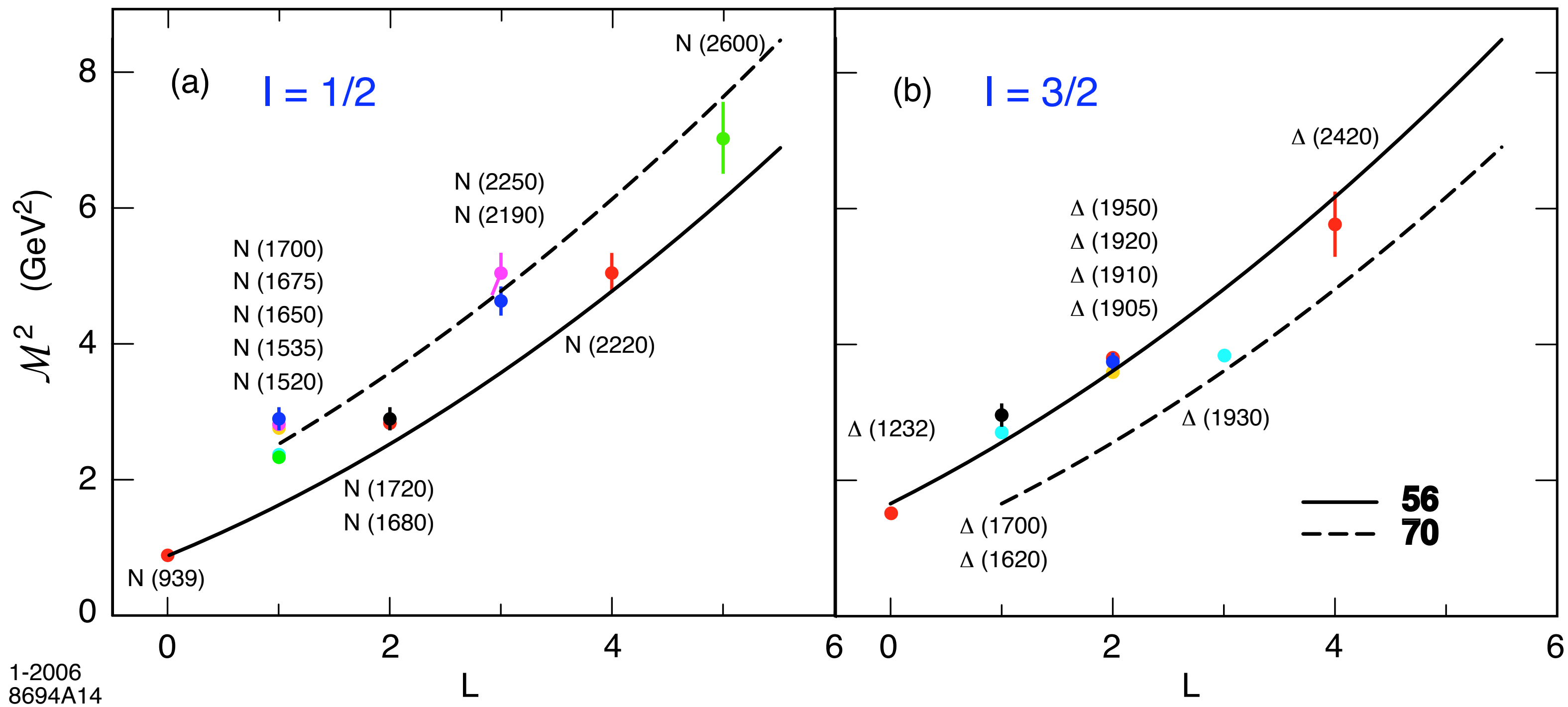


Fig: Predictions for the light baryon orbital spectrum for Λ_{QCD} = 0.25 GeV. The **56** trajectory corresponds to L even $P = +$ states, and the **70** to L odd $P = -$ states.

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SJB

- $SU(6)$ 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	$N\frac{7}{2}^-$ $N\frac{9}{2}^-$ $N\frac{11}{2}^-(2600)$ $N\frac{13}{2}^-$

AdS/CFT Holographic Model

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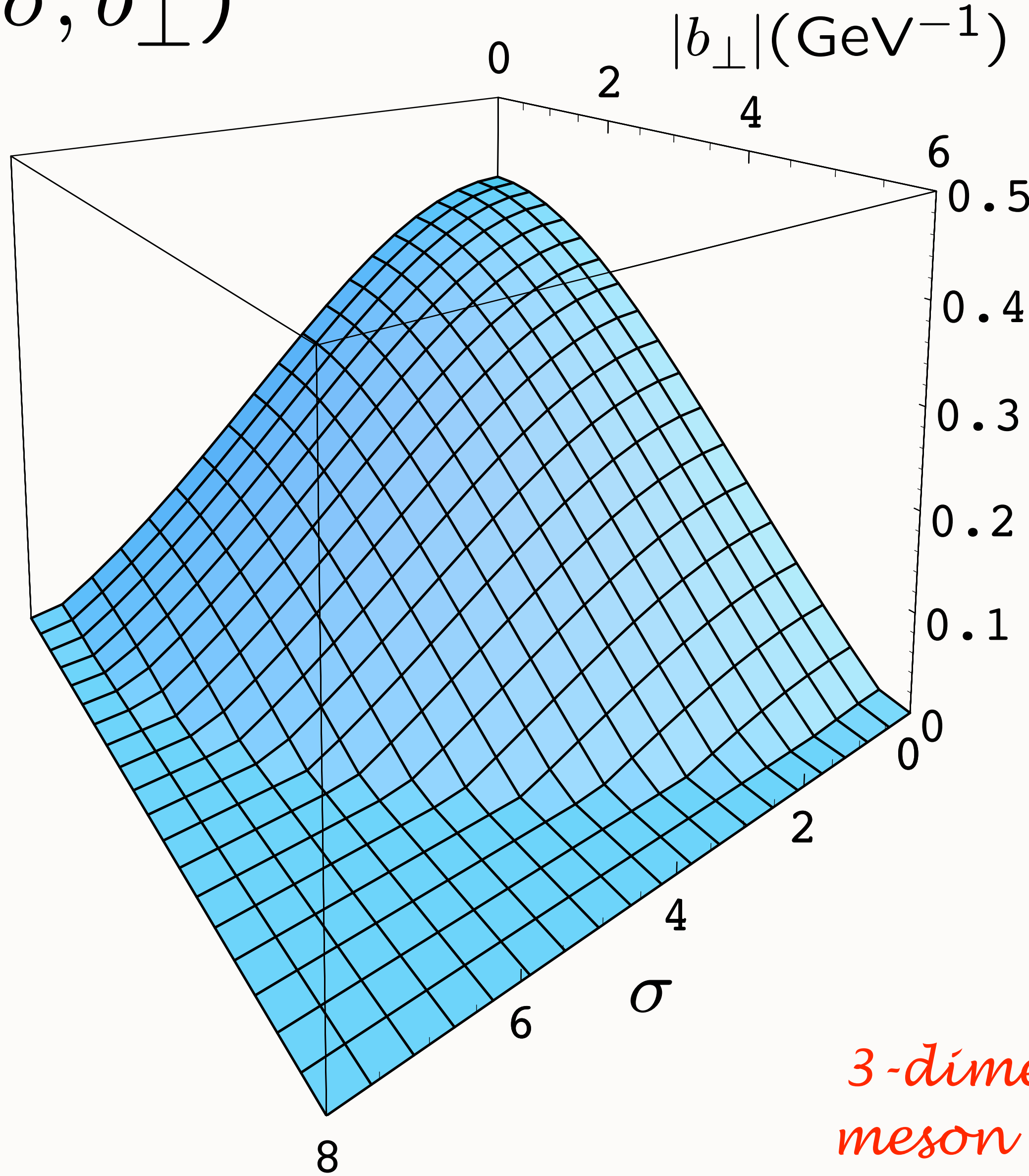
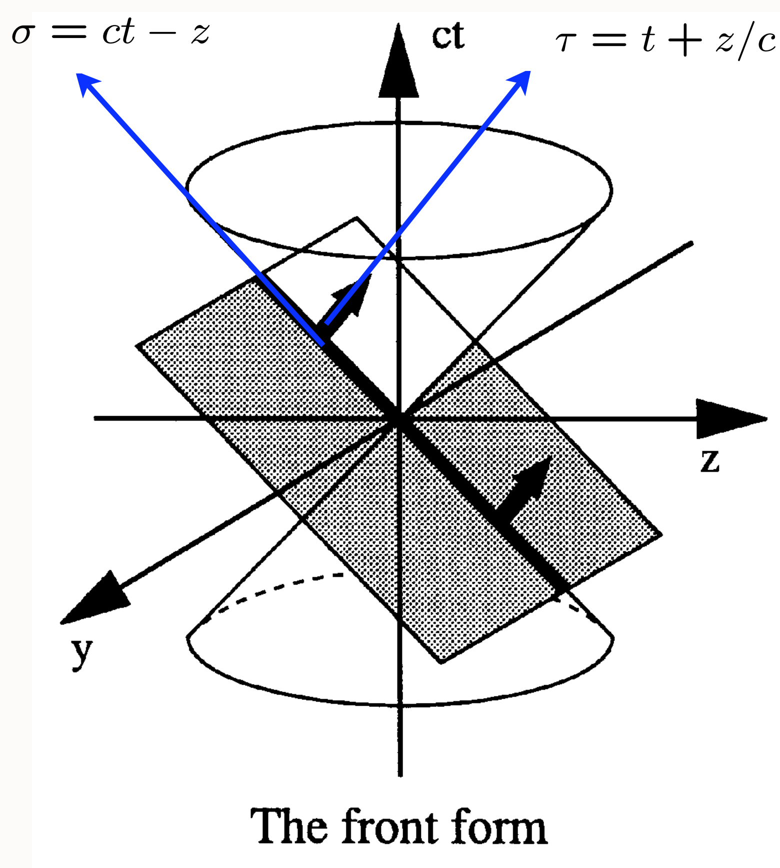
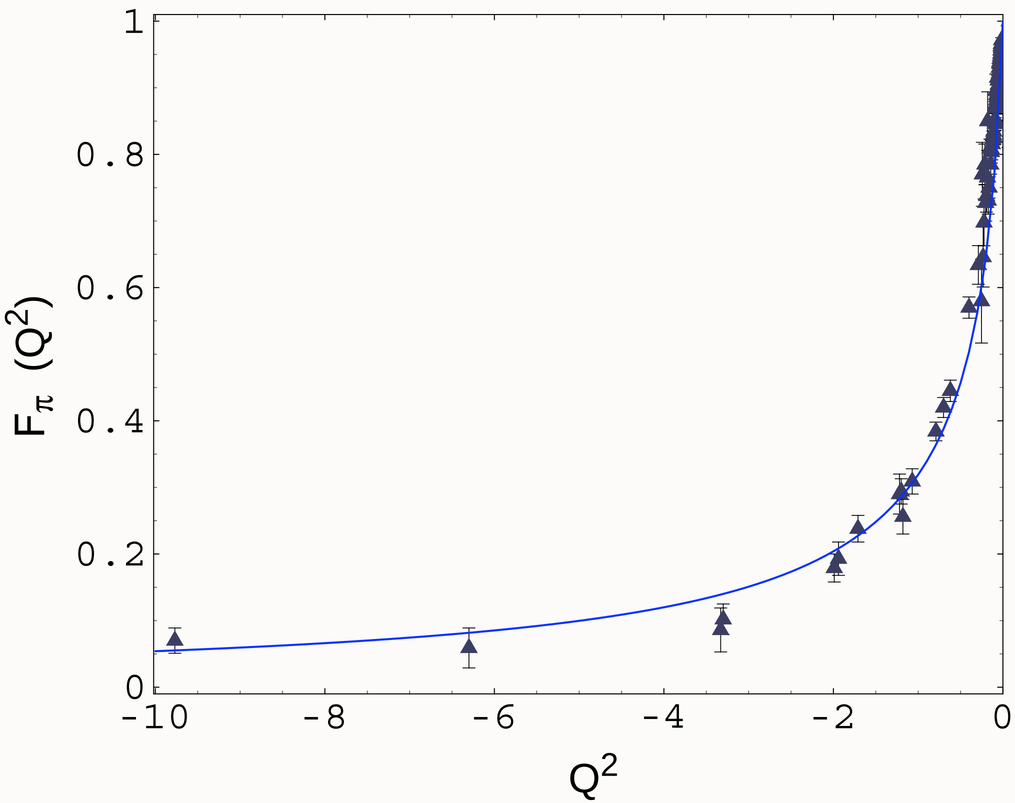
$\psi(\sigma, b_\perp)$



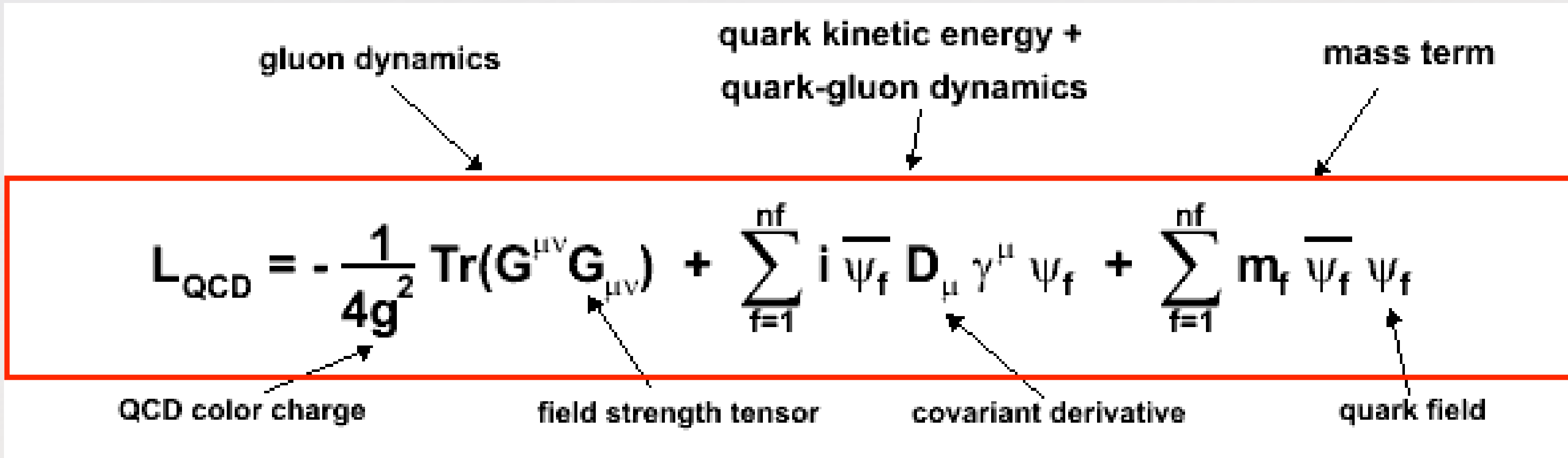


3-dimensional photograph: meson LFWF at fixed LF Time



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

QCD Lagrangian



$$L_{QCD} = -\frac{1}{4g^2} Tr(G^{\mu\nu} G_{\mu\nu}) + \sum_{f=1}^{nf} i \overline{\psi_f} D_\mu \gamma^\mu \psi_f + \sum_{f=1}^{nf} m_f \overline{\psi_f} \psi_f$$

QCD: $N_C = 3$ Quarks: 3_C Gluons: 8_C.

$\alpha_s = \frac{g^2}{4\pi}$ is dimensionless

Classical Lagrangian is scale invariant for massless quarks

If $\beta = \frac{d\alpha_s(Q^2)}{d \log Q^2} = 0$ then QCD is invariant under conformal transformations:

Parisi

- 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 "semi-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/QCD

- Semi-Classical approximation to massless QCD
- No particle creation, absorption
- Coupling is constant, $\beta = 0$
- Conformal symmetry broken by confinement

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).

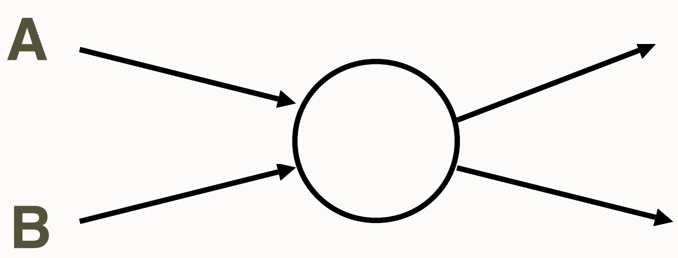
- Growing theoretical and empirical evidence that $\alpha_s(Q^2)$ has an IR fixed point: von Smekal, Alkofer and Hauck, arXiv:hep-ph/9705242; Alkofer, Fischer and Llanes-Estrada, hep-th/0412330; Deur, Burkert, Chen and Korsch, hep-ph/0509113 . . .

- 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).

Constituent Counting Rules



$$\frac{d\sigma}{dt}(s,t) = \frac{F(\theta_{\rm cm})}{s^{[n_{\rm tot}-2]}} \qquad s = E^2_{\rm cm}$$

$$F_H(Q^2) \sim [\frac{1}{Q^2}]^{n_H - 1} \qquad -t = Q^2$$

- Point-like quark and gluon constituents plus scale-invariant interactions

  Farrar, sjb; Matveev et al

- Fall-off of Amplitude measures degree of compositeness (twist)

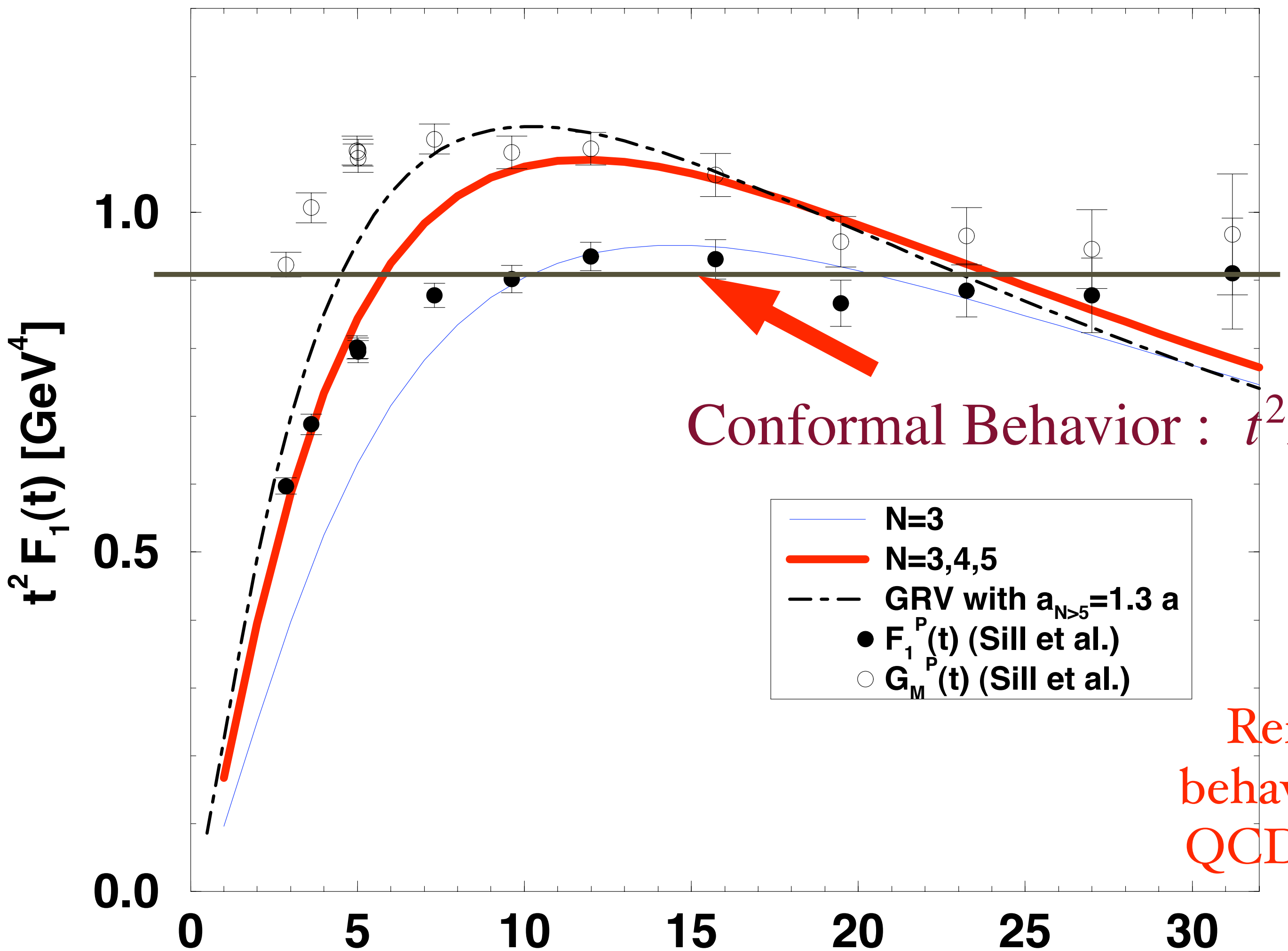
- Reflects near-Conformal Invariance of QCD

- PQCD: Logarithmic Modification by running coupling and Evolution Equations

  Lepage, sjb; Efremov, Radyushkin

- Angular and Spin Dependence -- Fundamental Wavefunctions: Hadron Distribution Amplitudes $\phi_H(x_i, Q)$

Proton Form Factor



-t (GeV^2)

Conformal Behavior : $t^2 F_1(t) = \text{const}$

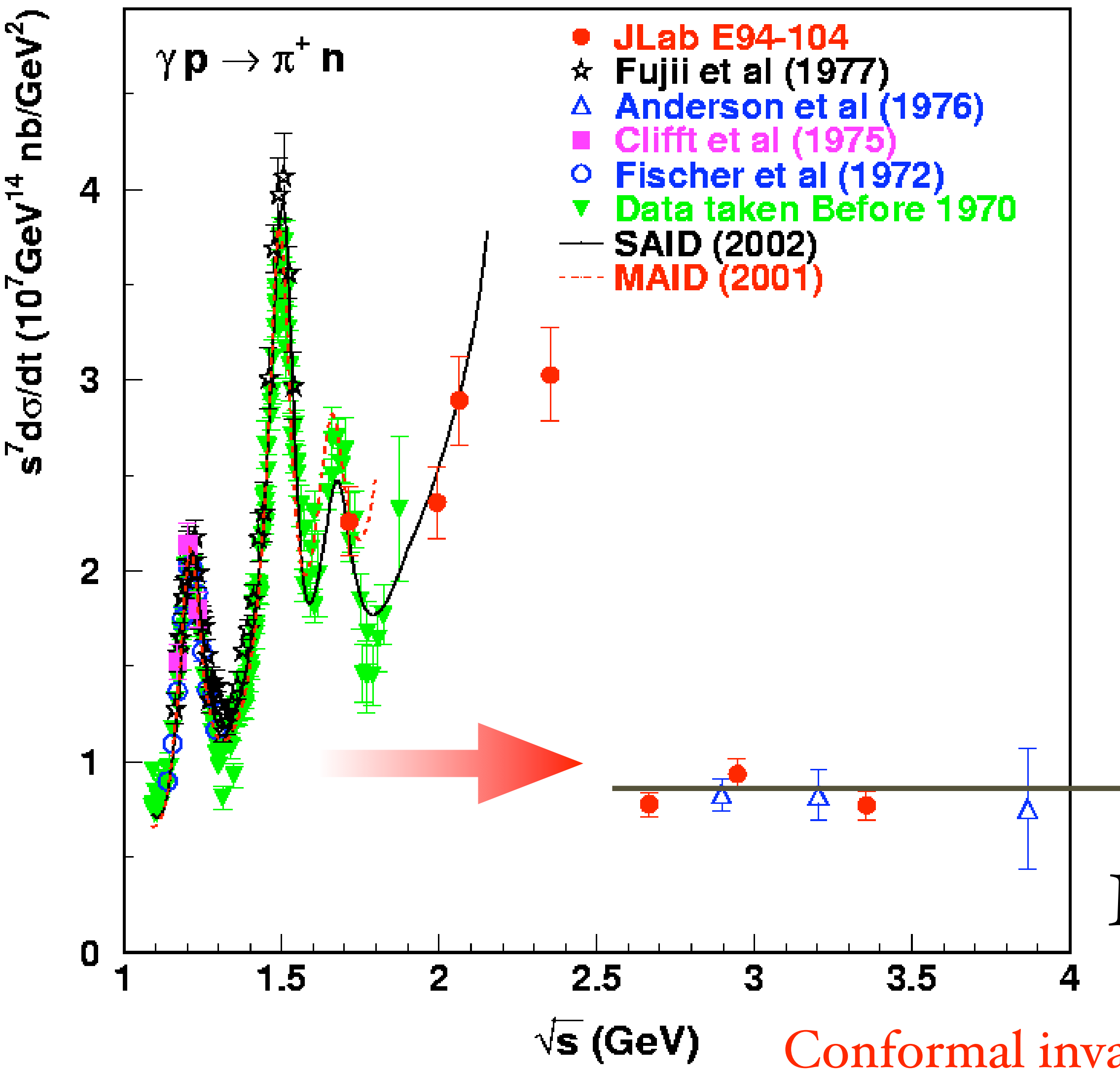
Remarkable scaling behavior -- no signal for QCD running coupling

Non-perturbative model: Diehl, Kroll

Test of PQCD Scaling

Constituent counting rules

Farrar, sjb; Muradyan, Matveev, Taveklidze



$s^7 d\sigma/dt(\gamma p \to \pi^+ n) \sim const$

fixed θ_{CM} scaling

PQCD and AdS/CFT:

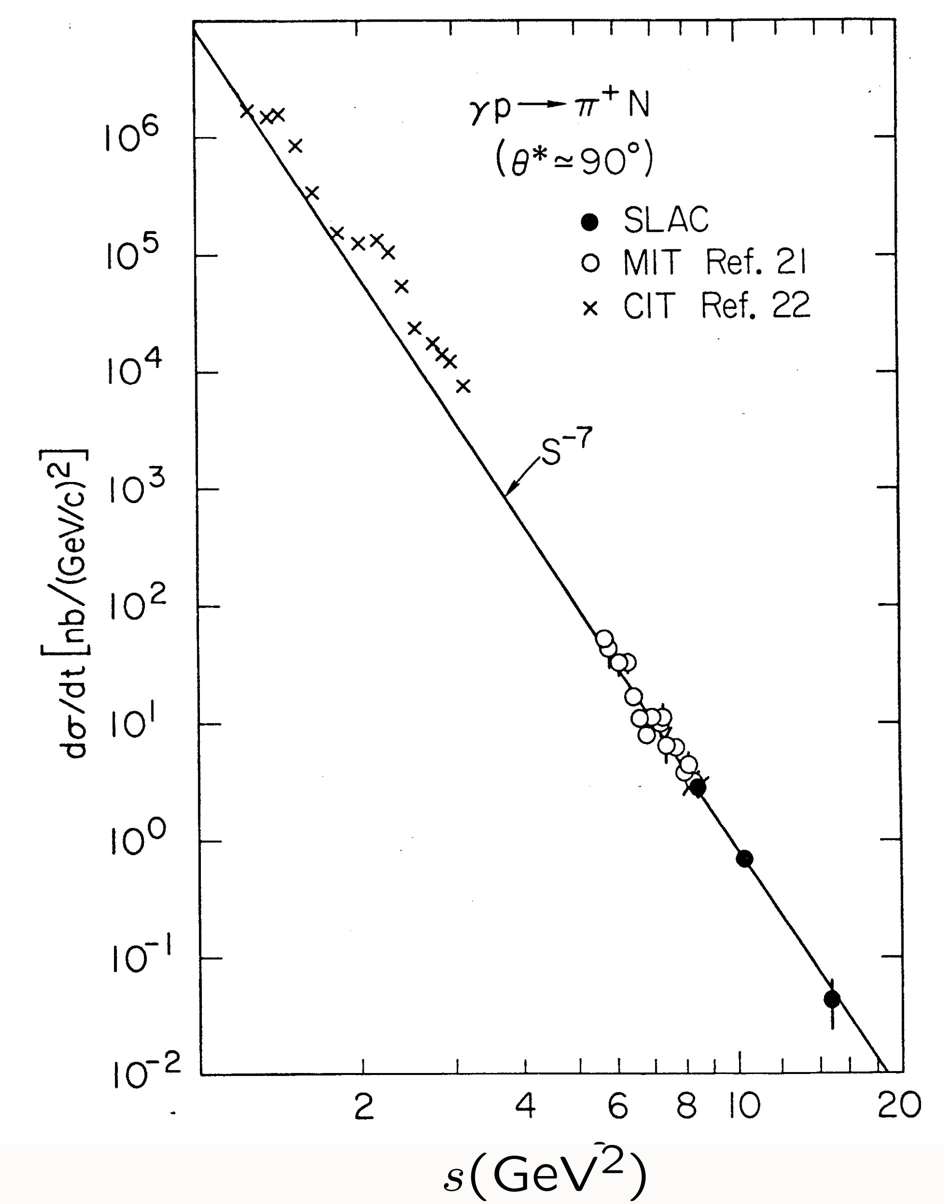
$$s^{n_{tot}-2}\frac{d\sigma}{dt}(A+B \to C+D) = F_{A+B\to C+D}(\theta_{CM})$$

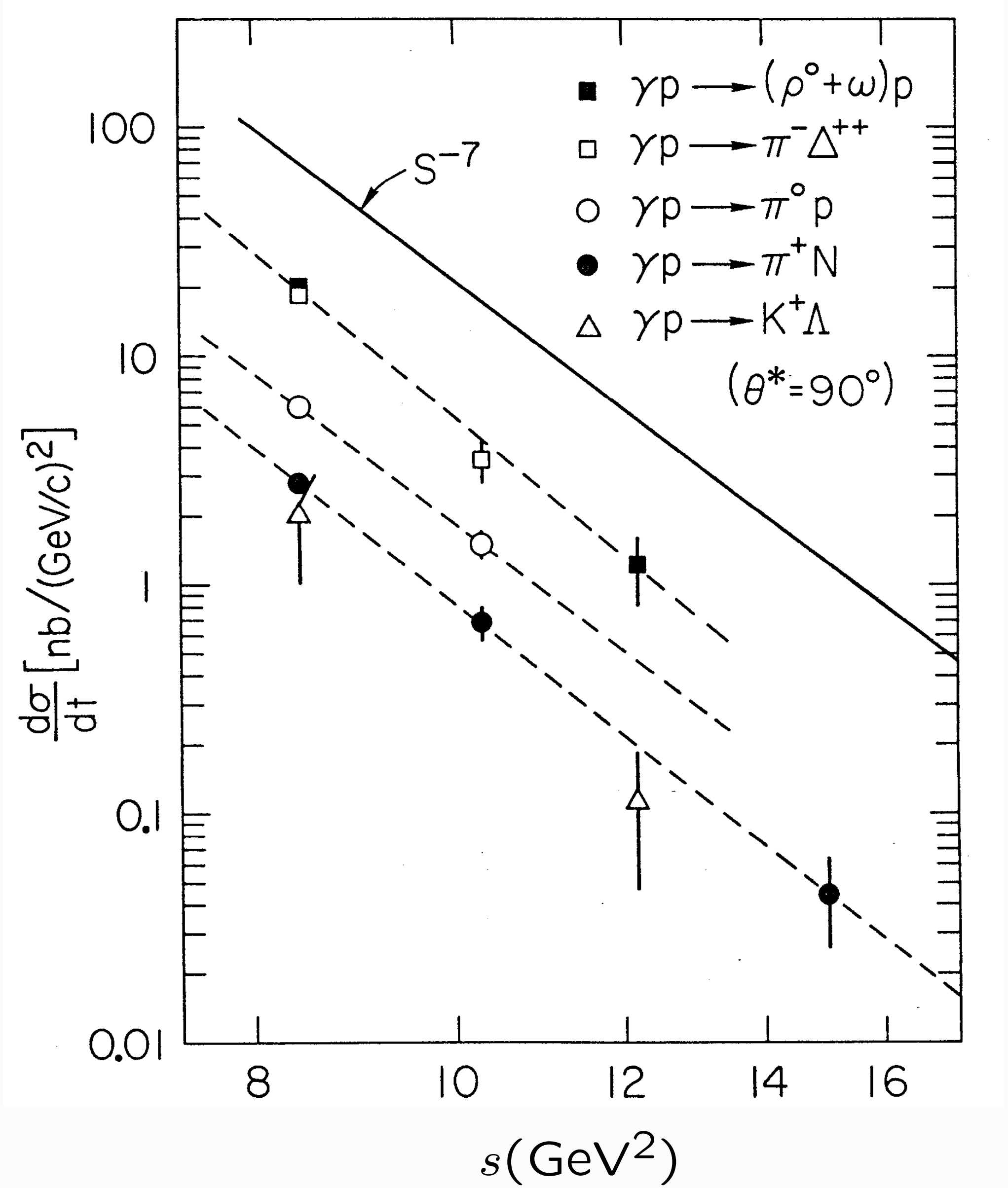
$$s^7\frac{d\sigma}{dt}(\gamma p \to \pi^+ n) = F(\theta_{CM})$$

$$n_{tot} = 1+3+2+3 = 9$$

No sign of running coupling

Conformal invariance at high momentum transfer!

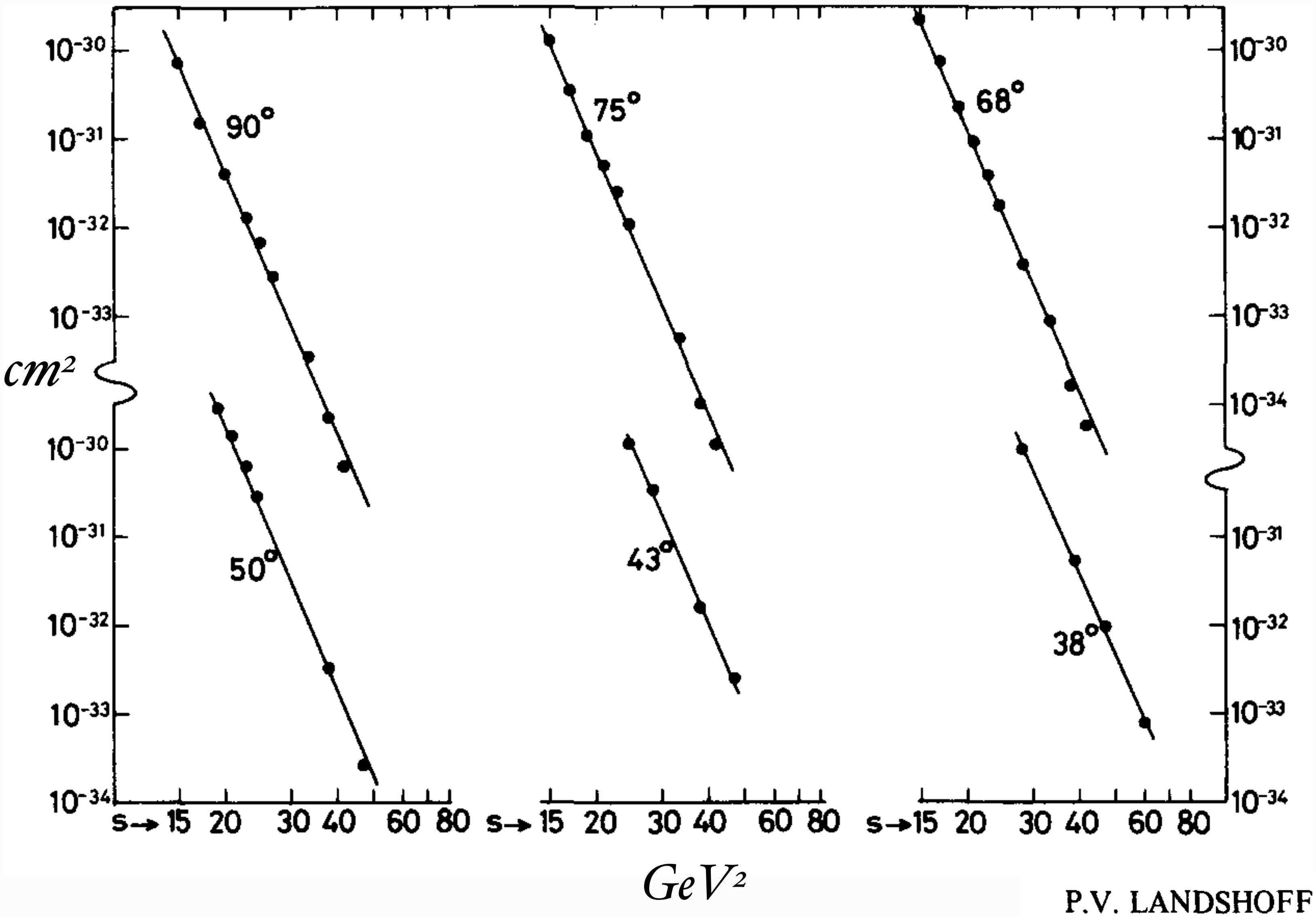




Conformal Invariance:

$$\frac{d\sigma}{dt}(\gamma p \to MB) = \frac{F(\theta_{cm})}{s^7}$$

Quark-Counting : $\frac{d\sigma}{dt}(pp \to pp) = \frac{F(\theta_{CM})}{s^{10}}$ $n = 4 \times 3 - 2 = 10$



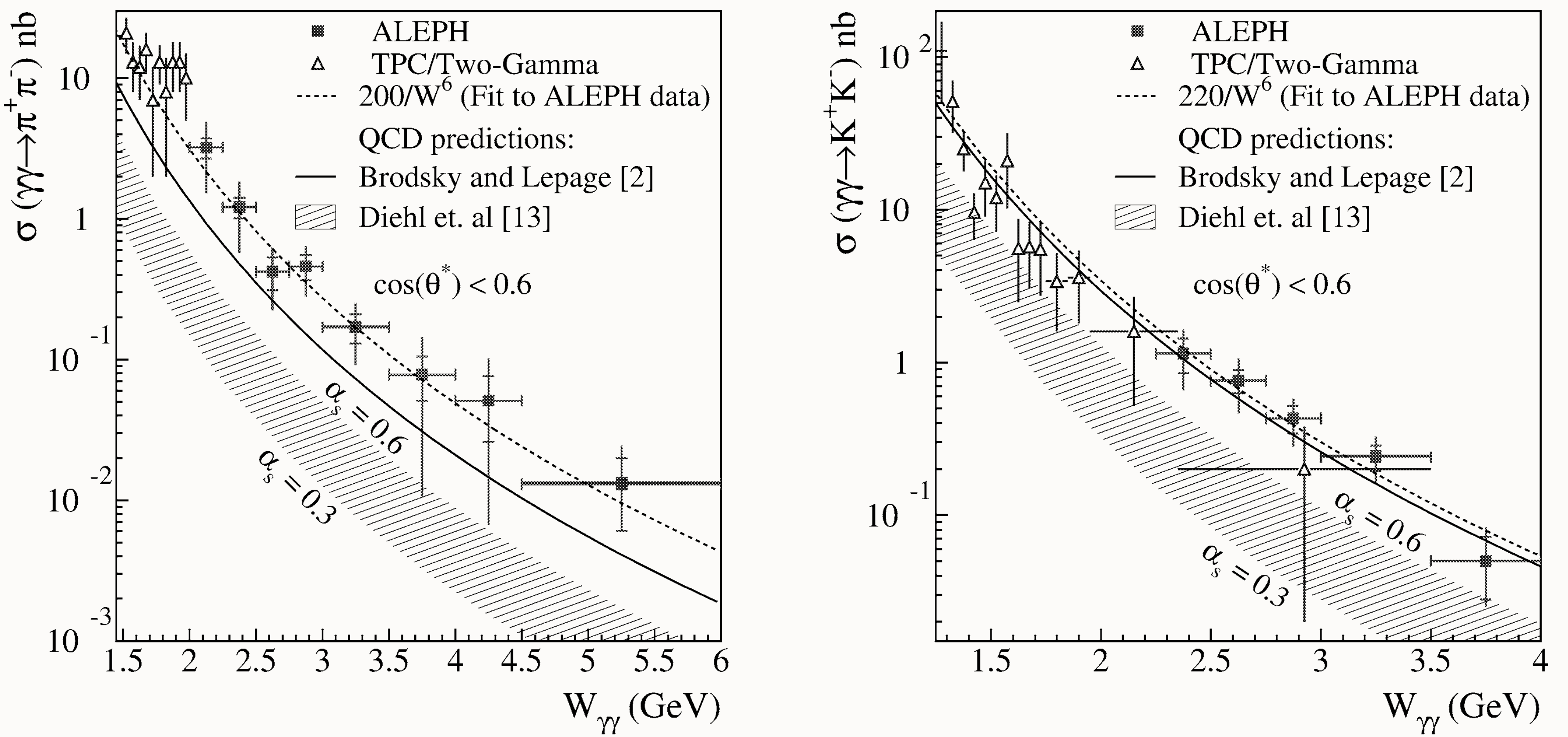
Best Fit

$n = 9.7 \pm 0.5$

Reflects underlying conformal scale-free interactions

P.V. LANDSHOFF and J.C. POLKINGHORNE

ALEPH Collaboration / Physics Letters B 569 (2003) 140–150



Measured distribution for $\gamma\gamma \to \pi^+\pi^-$ (left) and $\gamma\gamma \to \mathrm{K}^+\mathrm{K}^-$ (right) as a function of $W_{\gamma\gamma}$. Also shown are results from TPC/Two-Gamma [ ], the result of a fit to the ALEPH data and a leading twist QCD calculation with two alternative normalizations as described in the text.

Why do dimensional counting rules work so well?

- PQCD predicts log corrections from powers of α_s, logs, pinch contributions
- QCD coupling evaluated in intemediate regime.
- IR Fixed point! DSE: Alkofer, von Smekal et al.
- QED, EW -- define coupling from observable, predict other observable
- Underlying Conformal Symmetry of QCD Lagrangian

Define QCD Coupling from Observable

Grunberg

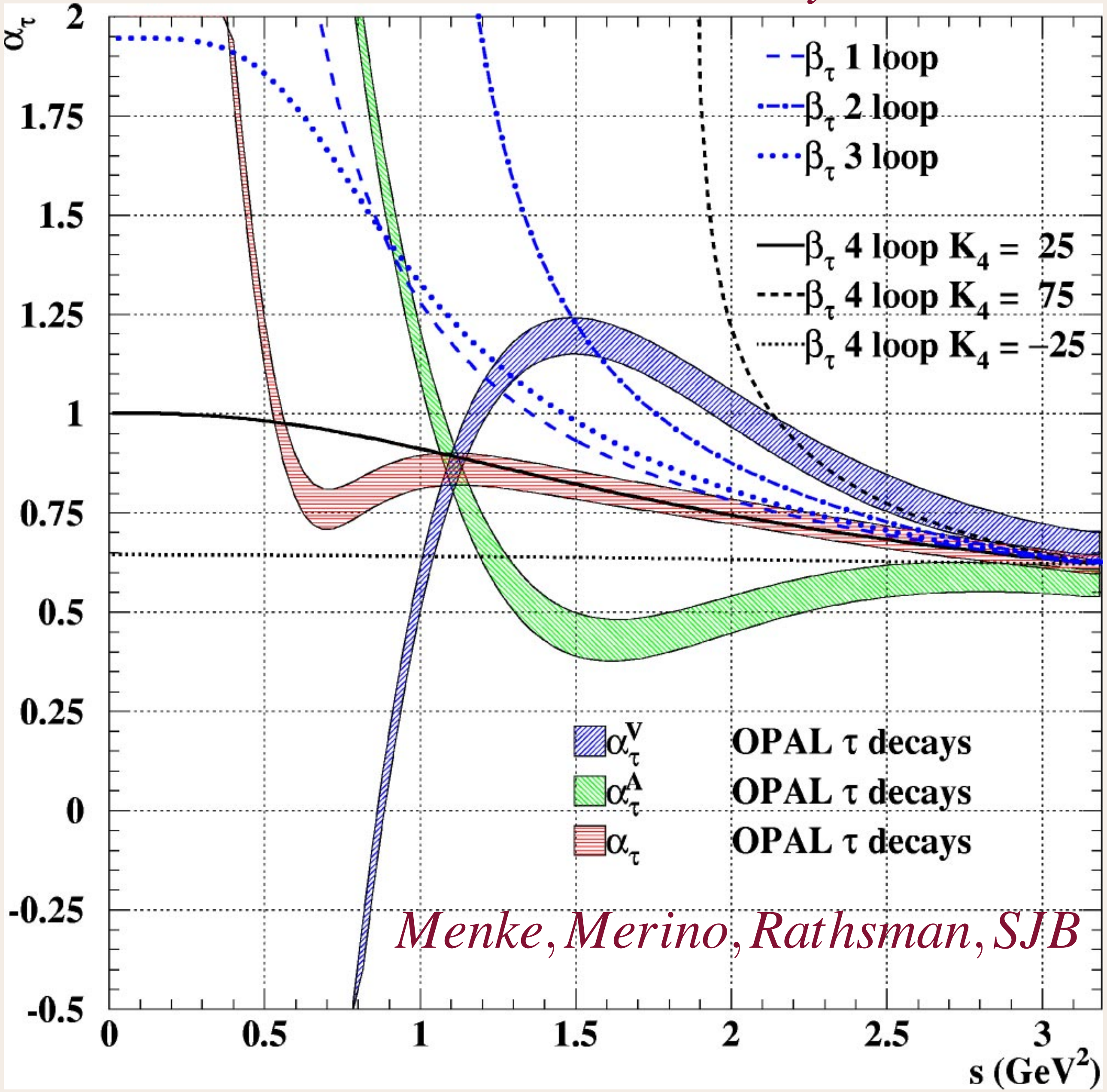
$$R_{e^+e^-\to X}(s) \equiv 3\Sigma_q e_q^2 \; [1 + \frac{\alpha_R(s)}{\pi}]$$

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

Relate observable to observable at commensurate scales

H.Lu, sjb

QCD Effective Coupling from *hadronic τ decay*



Scale Transformations

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

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

invariant measure

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

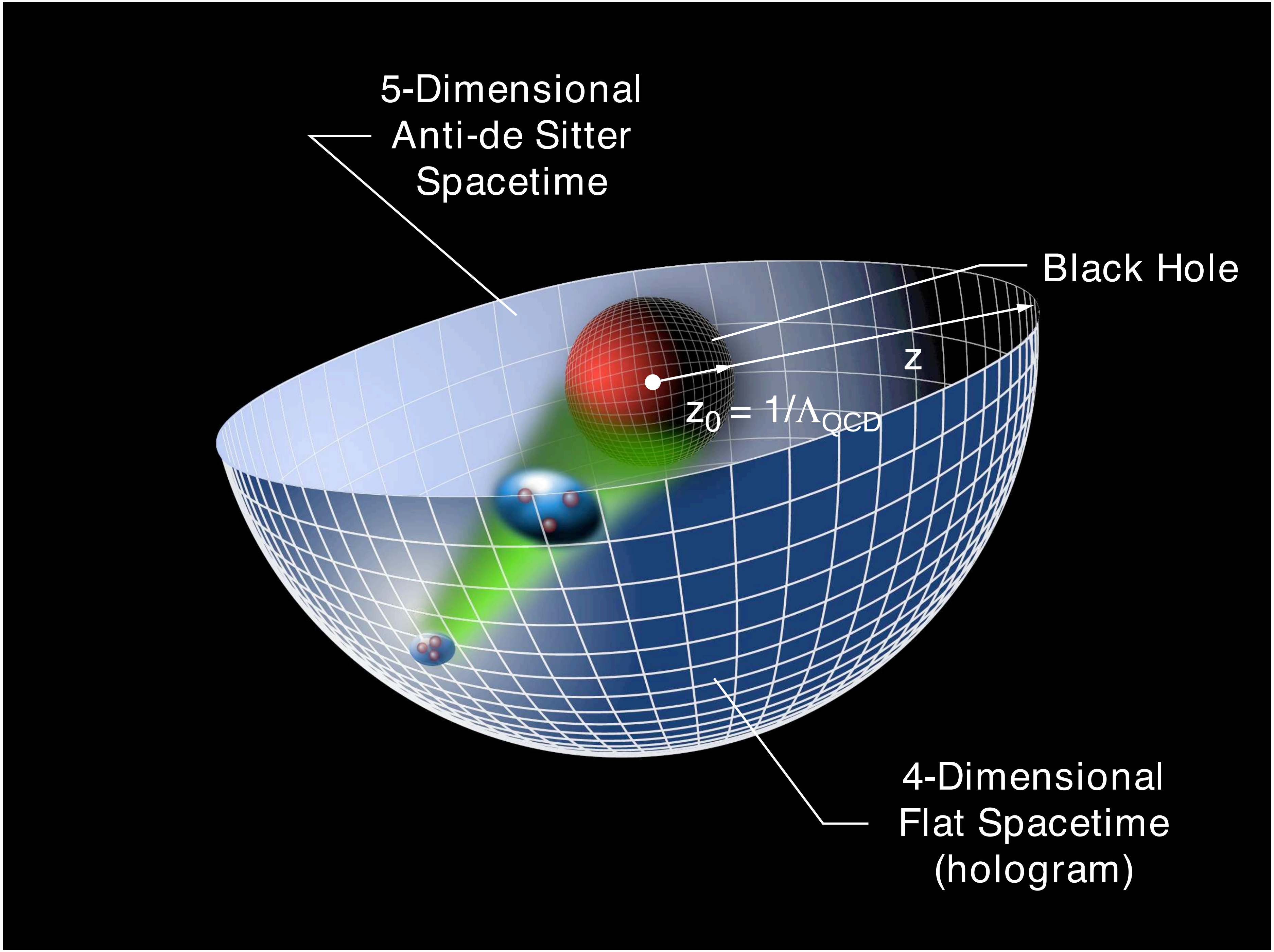
- AdS mode in z is the extension of the hadron wf into the fifth dimension.

- 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.



5-Dimensional
Anti-de Sitter
Spacetime
Black Hole
z
$z_0 = 1/\Lambda_{QCD}$
4-Dimensional
Flat Spacetime
(hologram)

AdS/CFT

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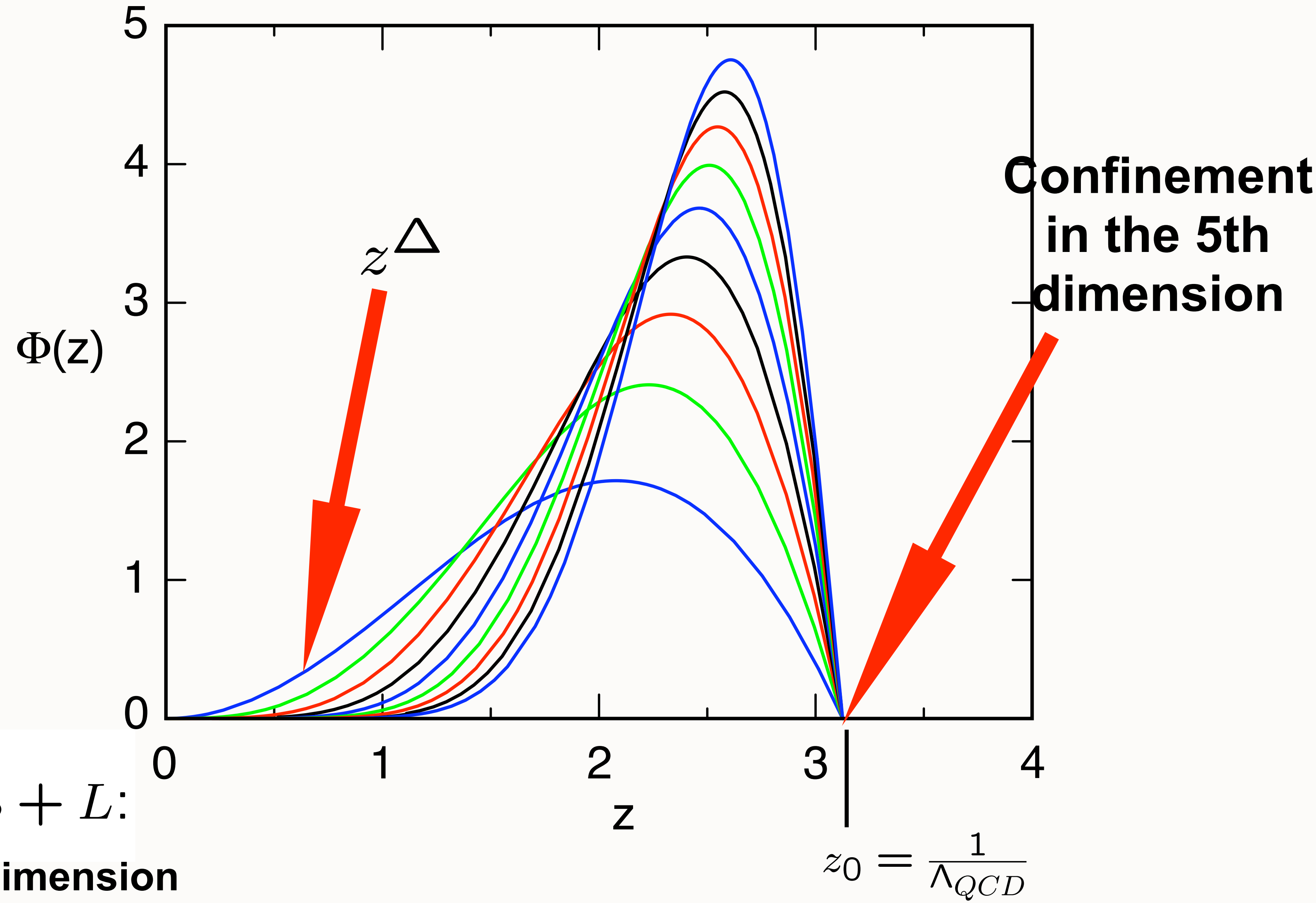
- Use mapping of conformal group SO(4,2) to AdS5
- Scale Transformations represented by wavefunction $\psi(z)$ in 5th dimension $x_\mu^2 \to \lambda^2 x_\mu^2$ $z \to \lambda z$
- Holographic model: Confinement at large distances and conformal symmetry in interior $0 < z < z_0$
- Match solutions at small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

$$\psi(z_0) = 0$$

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

Identify hadron by its interpolating operator at z → 0



$\Delta = 3 + L$:

Twist dimension of baryon

de Teramond, sjb

Predictions of AdS/CFT

Only one parameter!

Entire light quark baryon spectrum

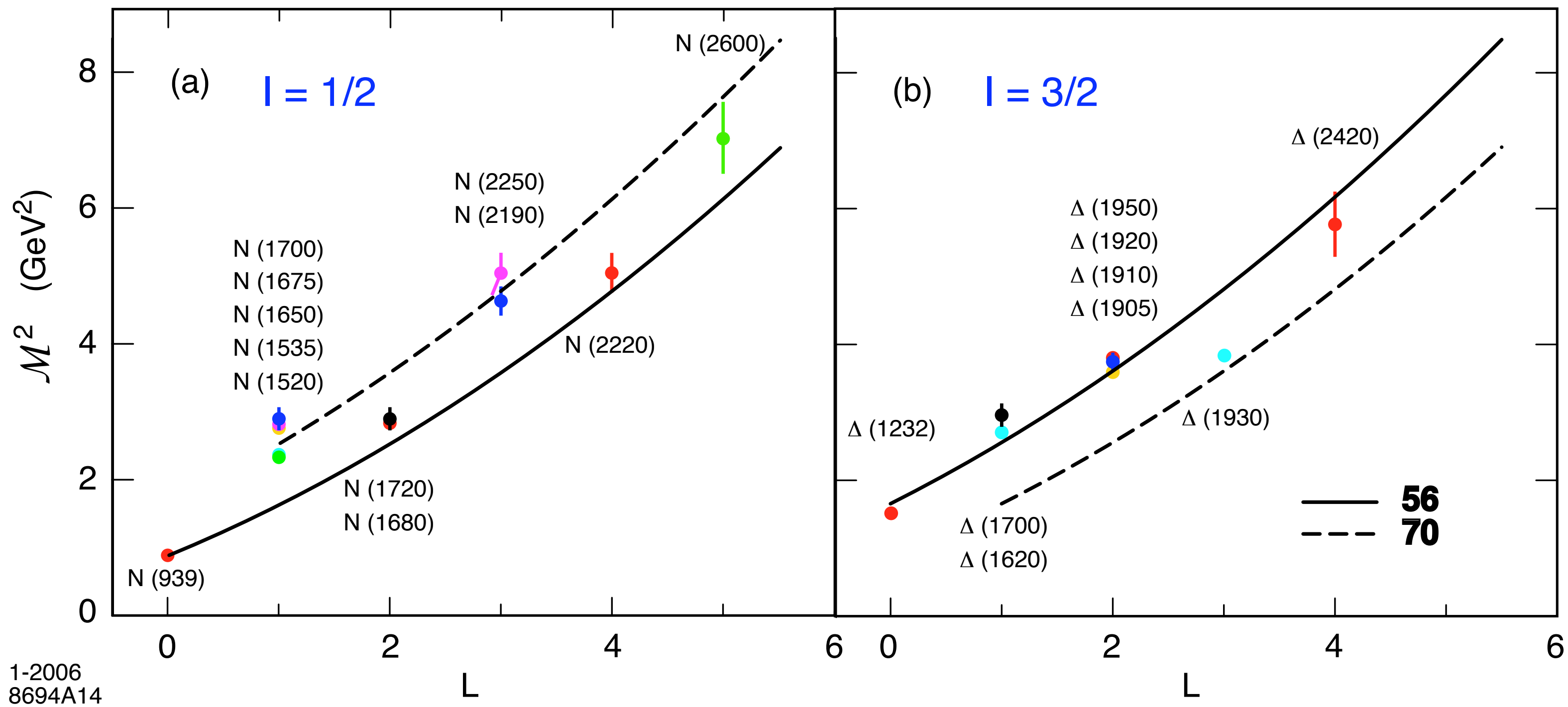


Fig: Predictions for the light baryon orbital spectrum for Λ_{QCD} = 0.25 GeV. The **56** trajectory corresponds to L even $P = +$ states, and the **70** to L odd $P = -$ states.

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Action for scalar field in AdS_5

$$S[\Phi] = \kappa' \int d^4x dz \sqrt{g} \left[g^{\ell m} \partial_\ell \Phi^* \partial_m \Phi - \mu^2 \Phi^* \Phi \right]$$

where $[\kappa'] = L^{-2}$ $\quad g^{\ell m} = \frac{z^2}{R^2} \eta^{\ell m} \quad \sqrt{g} = R^5/z^5$

Action is invariant under scale transformations

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

$$\Phi(x^\ell) = \Phi(\lambda x^\ell)$$

Variation wrt Φ

$$\frac{1}{\sqrt{g}} \frac{\partial}{\partial x^\ell} \left(\sqrt{g}\, g^{\ell m} \frac{\partial}{\partial x^m} \Phi \right) + \mu^2 \Phi = 0$$

Solutions of form: $\Phi(x,z) = e^{-iP\cdot x} f(z)$ $P_\mu P^\mu = \mathcal{M}^2$

$$S = -\kappa R^3 \int \frac{dz}{z^3}\left[(\partial_z f)^2 - \mathcal{M}^2 f^2 + \frac{(\mu R)^2}{z^2} f^2\right]$$

Variation of S wrt f :

$$z^5 \partial_z \left(\frac{1}{z^3}\partial_z f\right) + z^2 \mathcal{M}^2 f - (\mu R)^2 f = 0.$$

$$\left[z^2\partial_z^2 - 3z\partial_z + z^2\mathcal{M}^2 - (\mu R)^2\right] f = 0,$$

Introduce confinement, break conformal invariance

P-S Boundary Condition $f(z = \frac{1}{\Lambda_{QCD}}) = 0$

Normalization in truncated space $R^3 \int_0^{\Lambda_{\rm QCD}^{-1}} \frac{dz}{z^3}\, f^2(z) = 1$

Classical solution

$$f(z) = \frac{\sqrt{2}\Lambda_{\rm QCD}}{R^{3/2} J_{\alpha+1}(\beta_{\alpha,k})} z^2 J_\alpha(z\beta_{\alpha,k}\Lambda_{\rm QCD}),$$

where $\alpha = \sqrt{4 + (\mu R)^2}.$

$$S = -\kappa R^3 \int_0^{\Lambda_{\rm QCD}^{-1}} \frac{dz}{z^5} f \left[-z^5 \partial_z \left(\frac{1}{z^3} \partial_z \right) - z^2 \mathcal{M}^2 + (\mu R)^2 \right] f$$
$$+ \kappa R^3 \lim_{z \to 0} \frac{1}{z^3} f \partial_z f$$

First term vanishes leaving $S_{class} = \kappa R^3 \lim_{z \to 0} \frac{1}{z^3} f \partial_z f.$

Breitenlohner - Freedman bound $\alpha \geq 0$

Identify $\alpha = L$ *Orbital Angular Momentum* $(\mu R)^2 = -4 + L^2$

- Wave equation in AdS for bound state of two scalar partons with conformal dimension $\Delta = 2 + L$

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

with solution

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

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

- The twist τ is equal to the number of partons $\tau = n$.

- Two-quark vector meson described by wave equation

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

with solution

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

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

- Pseudoscalar mesons: $\mathcal{O}_{3+L} = \overline{\psi}\gamma_5 D_{\{\ell_1} \ldots D_{\ell_m\}}\psi$ ($\Phi_\mu = 0$ 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 $\Phi(z)$

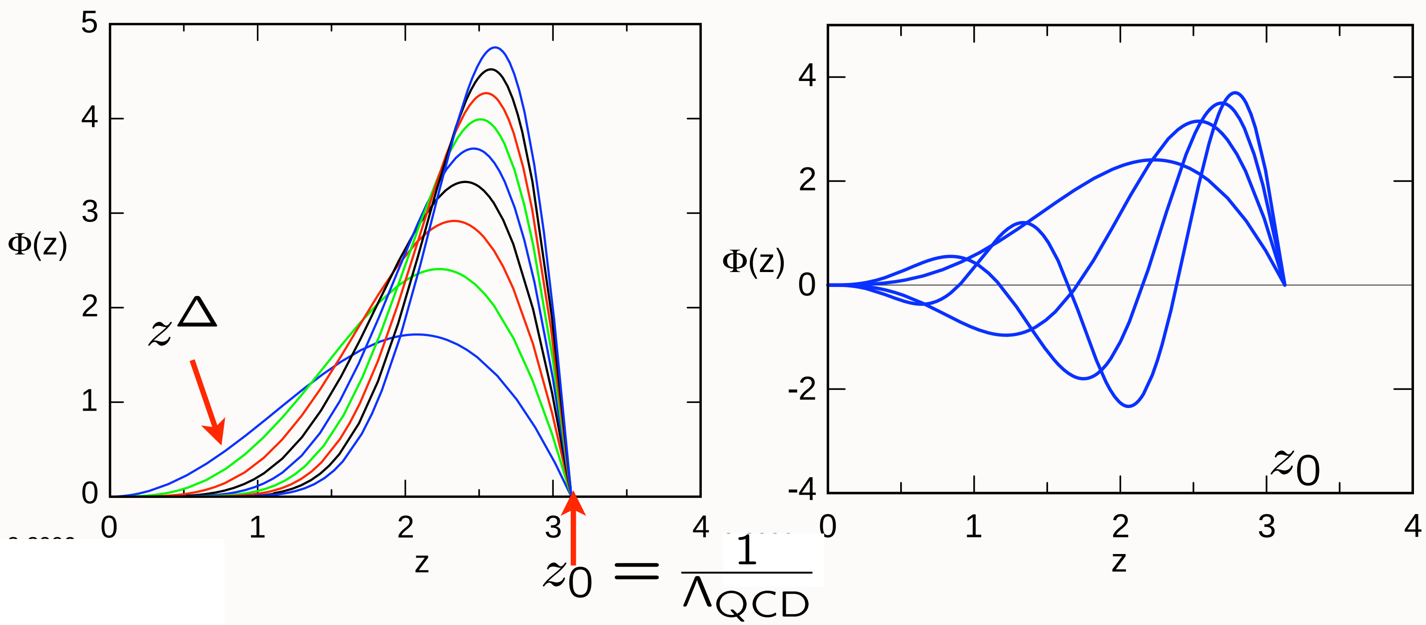
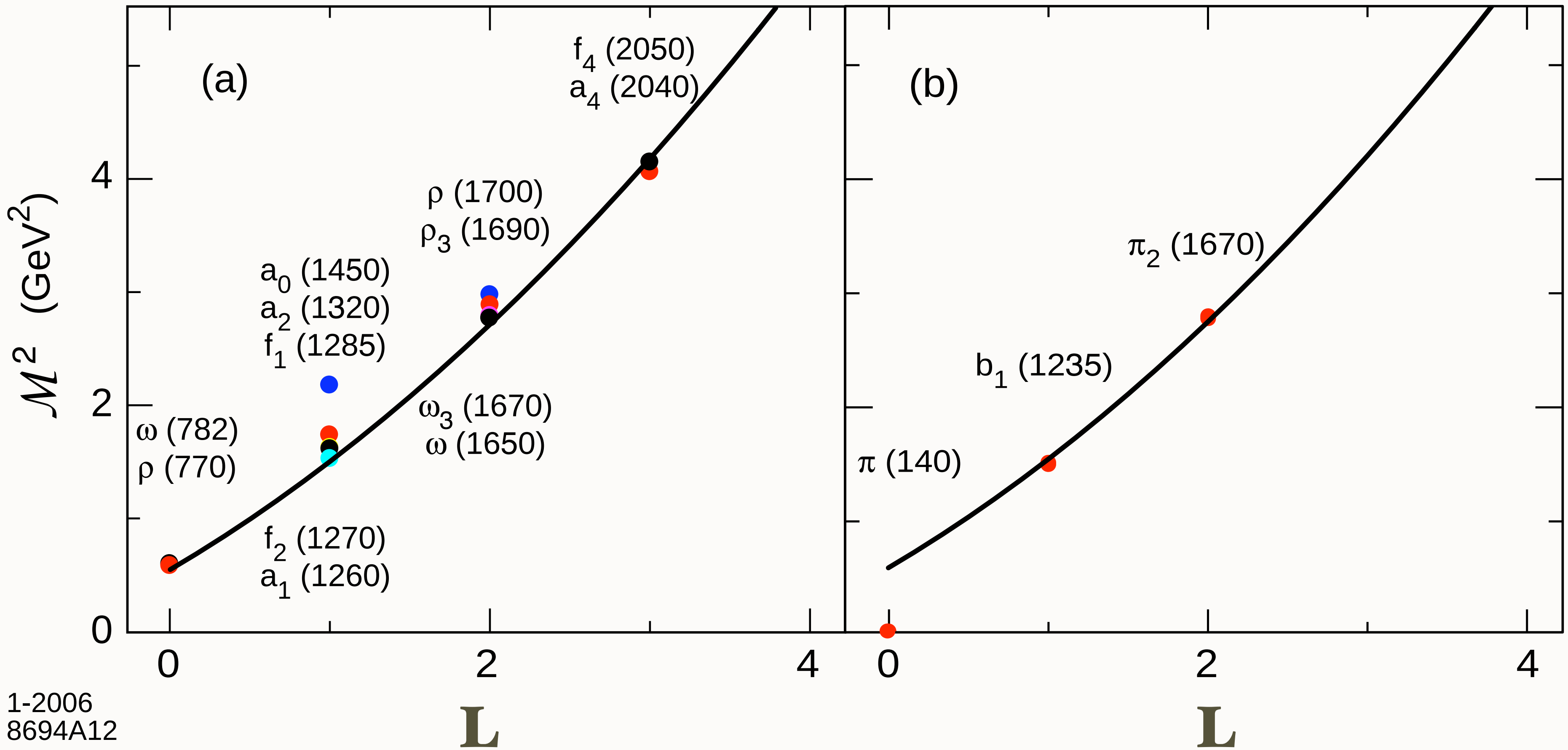


Fig: Meson orbital and radial AdS modes for $\Lambda_{QCD} = 0.32$ GeV.



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

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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

Baryon Spectrum

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

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

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

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

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

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

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

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

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

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

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

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

- Normalizable AdS fermion mode (lowest KK-mode $\kappa = 0$:

$$\Psi_{\alpha,k}(x, z) = C_{\alpha,k} e^{-iP\cdot x} z^{\frac{5}{2}} \Big[J_\alpha(z\beta_{\alpha,k}\Lambda_{QCD})\, \mu_+(P) + J_{\alpha+1}(z\beta_{\alpha,k}\Lambda_{QCD})\, \mu_-(P) \Big].$$

where $\mu^- = \frac{\gamma^\mu P_\mu}{P} \mu^+$, $\alpha = 2 + L$ and $\Delta = \frac{9}{2} + L$.

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

$$\mathcal{M}^+_{\nu,n} = \alpha_{\nu,n} \Lambda_{QCD}, \qquad \mathcal{M}^-_{\nu,n} = \alpha_{\nu+1,n} \Lambda_{QCD}$$

- 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.

Predictions of AdS/CFT

Only one parameter!

Entire light quark baryon spectrum

PARITY DOUBLING

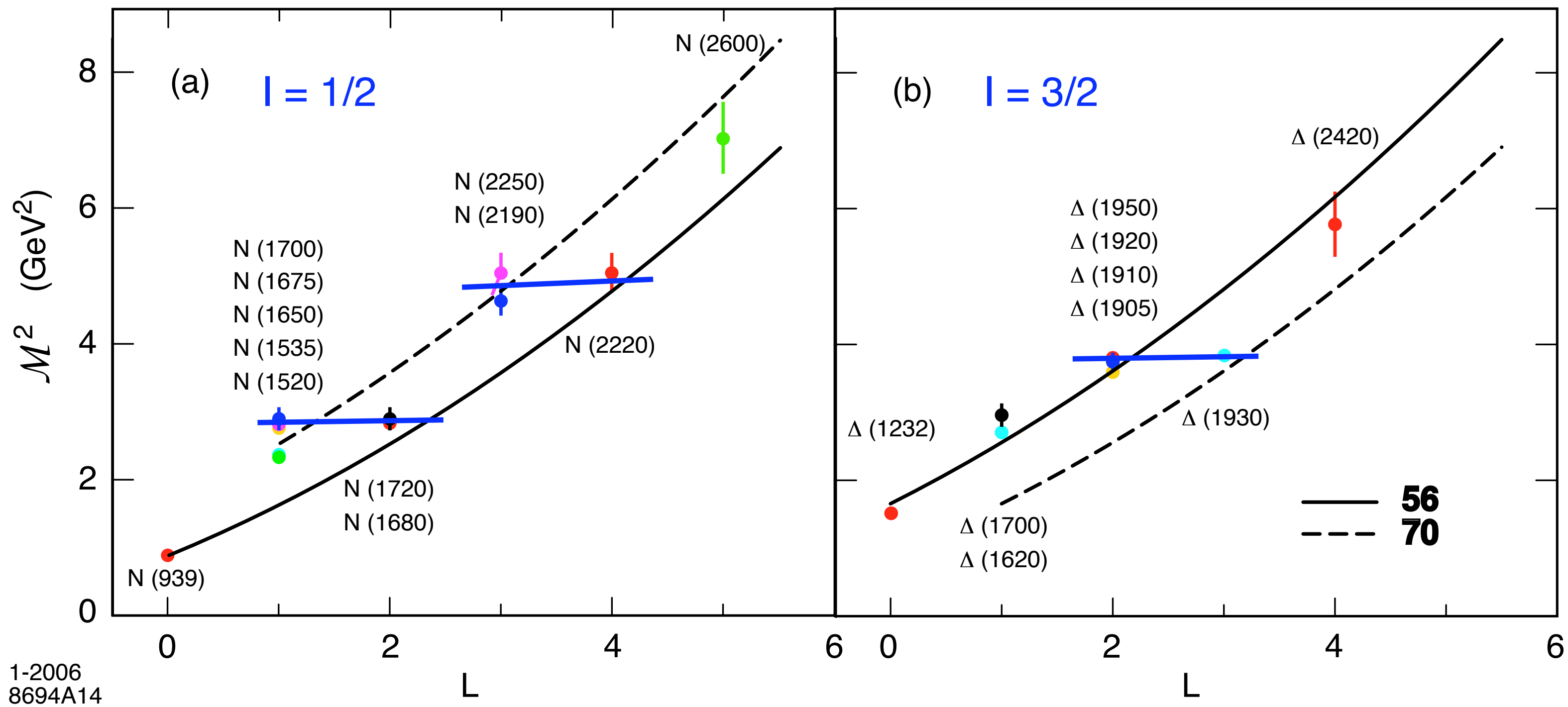

Fig: Predictions for the light baryon orbital spectrum for Λ_{QCD} = 0.25 GeV. The **56** trajectory corresponds to L even $P = +$ states, and the **70** to L odd $P = -$ states.

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Glueball Spectrum

- AdS wave function with effective mass μ:

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

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

- Glueball interpolating operator with twist -dimension minus spin- two, and conformal dimension $\Delta = 4 + L$

$$\mathcal{O}_{4+L} = F D_{\{\ell_1} \dots D_{\ell_m\}} F,$$

where $L = \sum_{i=1}^{m} \ell_i$ is the total internal space-time orbital momentum.

- Normalizable scalar AdS mode (d = 4):

$$\Phi_{\alpha,k}(x,z) = C_{\alpha,k} e^{-iP\cdot x} z^2 J_\alpha\left(z\,\beta_{\alpha,a}\Lambda_{QCD}\right)$$

with $\alpha = 2 + L$ and scaling dimension $\Delta = 4 + L$.

Glueball Regge trajectories from gauge/string duality and the Pomeron

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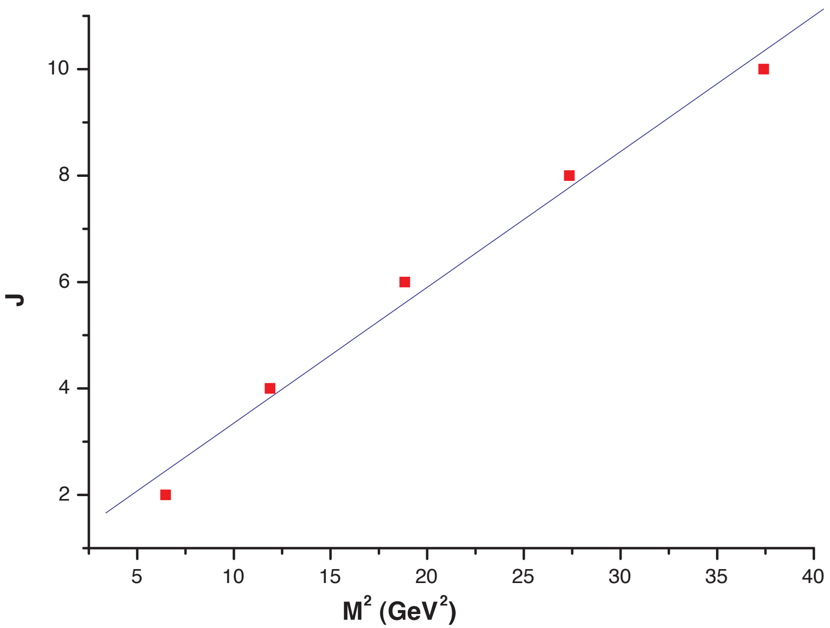
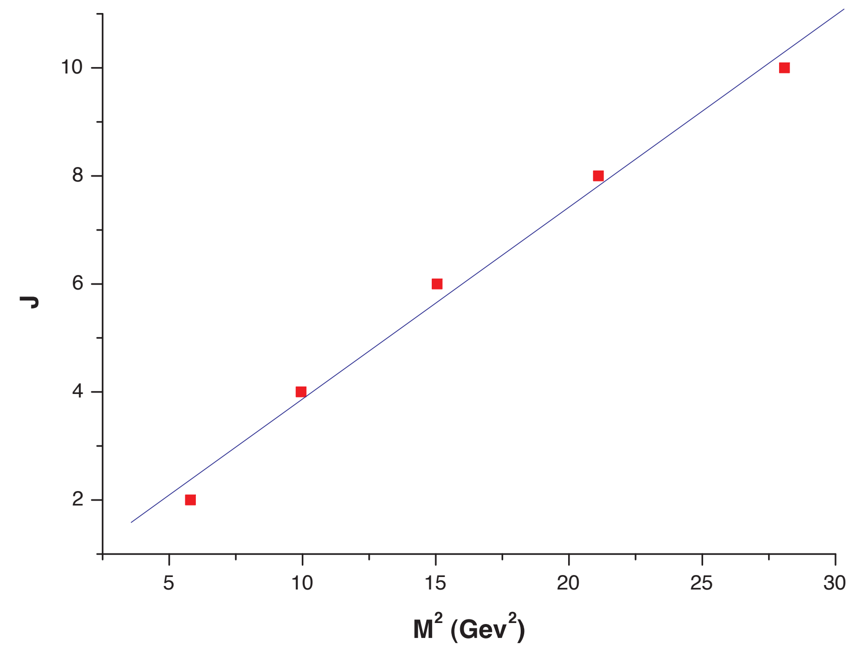


Neumann Boundary Conditions



Dirichlet Boundary Conditions

Substitute $$f(z) = (\frac{z}{R})^{\frac{3}{2}} \ \phi(z)$$

$$[-\frac{d^2}{dz^2} + V(z)]\phi(z) = \mathcal{M}^2\phi(z)$$

Conformal Kernel $$V(z) = -\frac{1-4\alpha^2}{4z^2}$$ de Teramond , sjb

HO Kernel $$V(z) = -\frac{1-4\alpha^2}{4z^2} + \kappa^4 z^2$$ Karch, et al.

Solutions:

$$\phi_\alpha(z) = \kappa^{\alpha+1} \sqrt{\frac{2n!}{(n+\alpha)!}} \ z^{1/2+\alpha} \ e^{-\kappa^2 z^2/2} \ L_n^\alpha(\kappa^2 z^2)$$

Why is α quantized?

$$S = \lambda \int_0^\infty d\zeta \left[(\partial_\zeta \phi)^2 - \mathcal{M}^2 \phi^2 - \frac{1-4\alpha^2}{4\zeta^2} \phi^2 + \kappa^4 z^2 \phi^2 \right]$$

$$S[\phi] = S_{class}[\phi] + S_{fluct}[\phi]$$

$\alpha \neq 0$ solutions

$$S_{fluct} = \lambda \alpha^2 \int_0^\infty \frac{d\zeta}{\zeta^2} \phi^2 = \lambda \kappa^2 \alpha$$

Semi-classical quantization:
Fluctuations should leave Z unchanged

$$Z[\phi] \sim e^{iS[\phi]} = e^{iS_{class}[\phi]}.$$

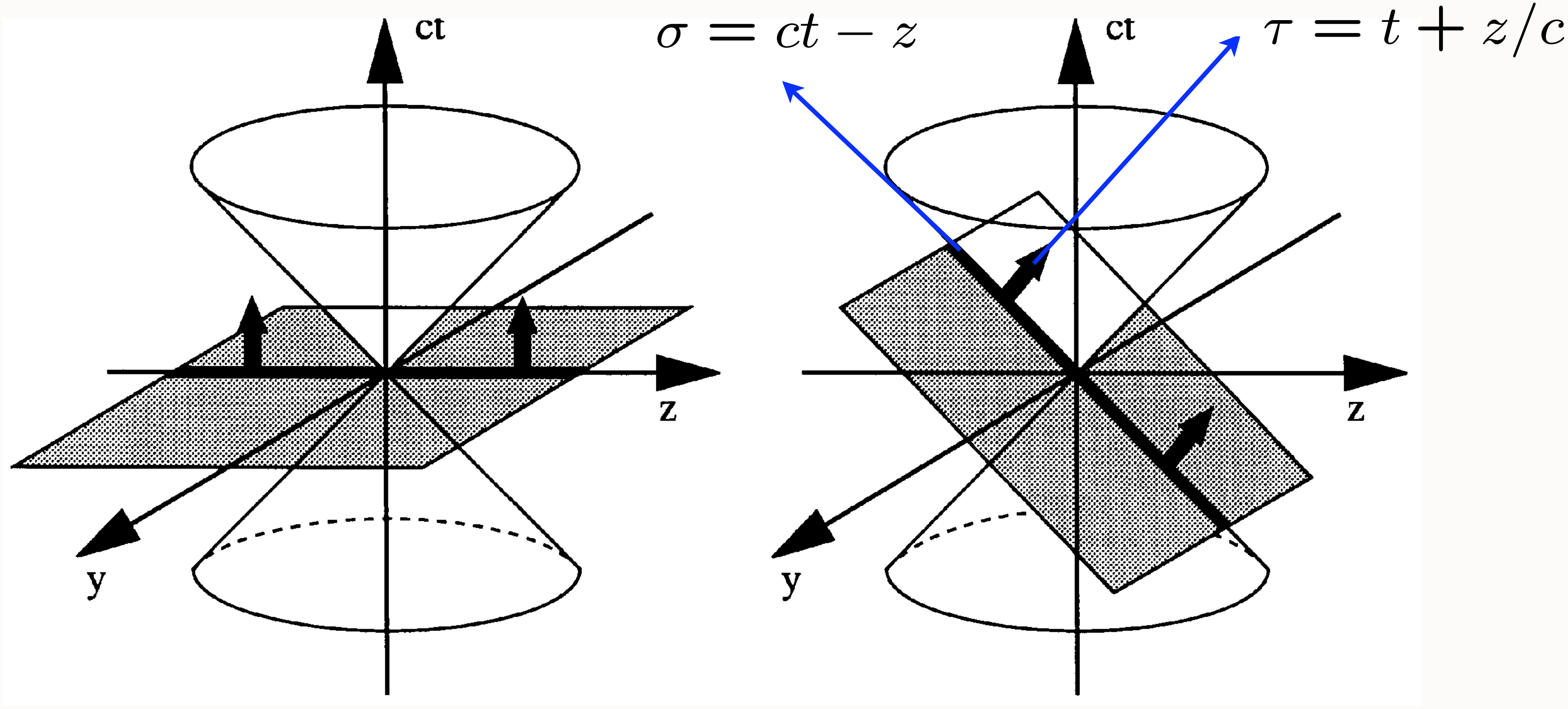
$$S_{fluct} = 2\pi\alpha = 2\pi L$$

Thus $\alpha = L$ is integer $\quad \lambda = 2\pi/\kappa^2$ (Heuristic argument)

Matches integral twist-dimension of state

Dirac's Amazing Idea: The "Front Form"

Evolve in light-front time!



Instant Form

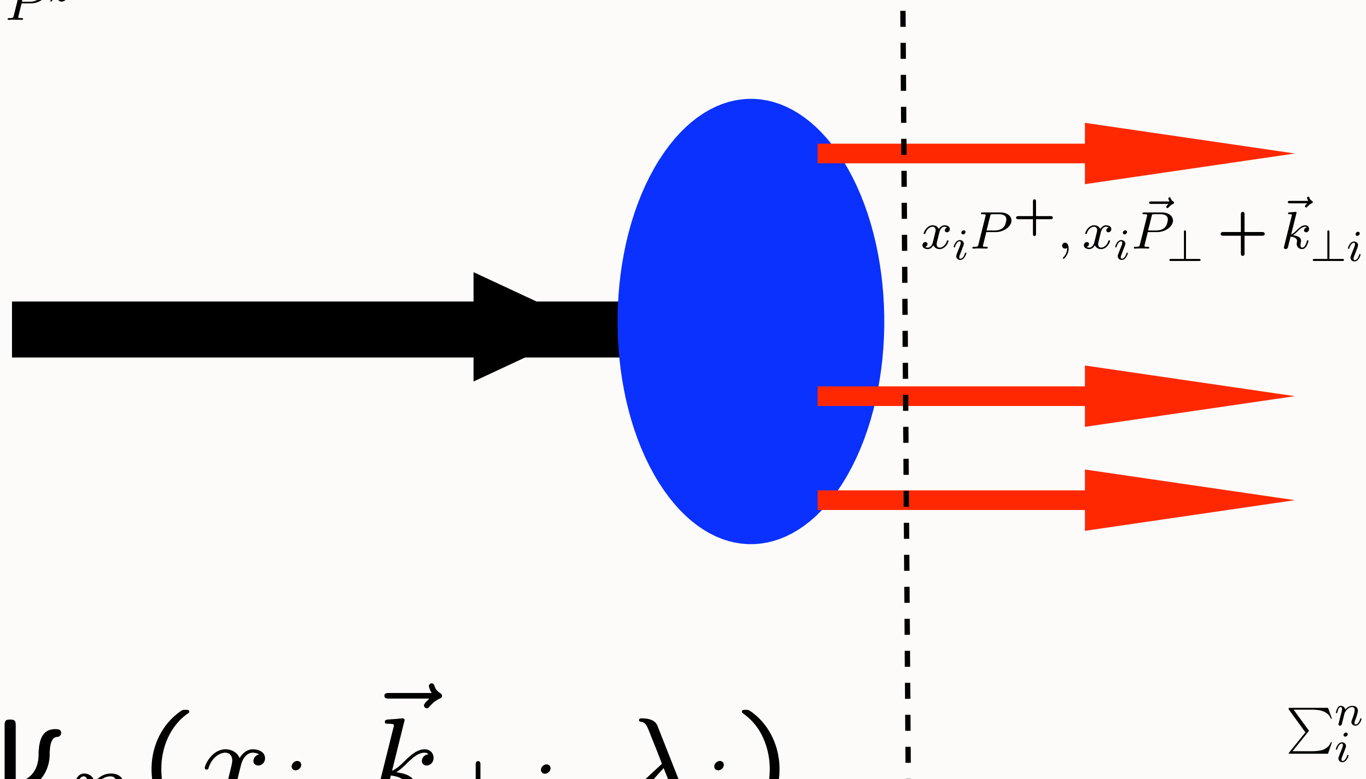
Front Form

Light-Front Wavefunctions

Fixed $\tau = t + z/c$

$P^+ = P^0 + P^z$

$P^+, \vec{P}_\perp$



$$\Psi_n(x_i, \vec{k}_{\perp i}, \lambda_i)$$

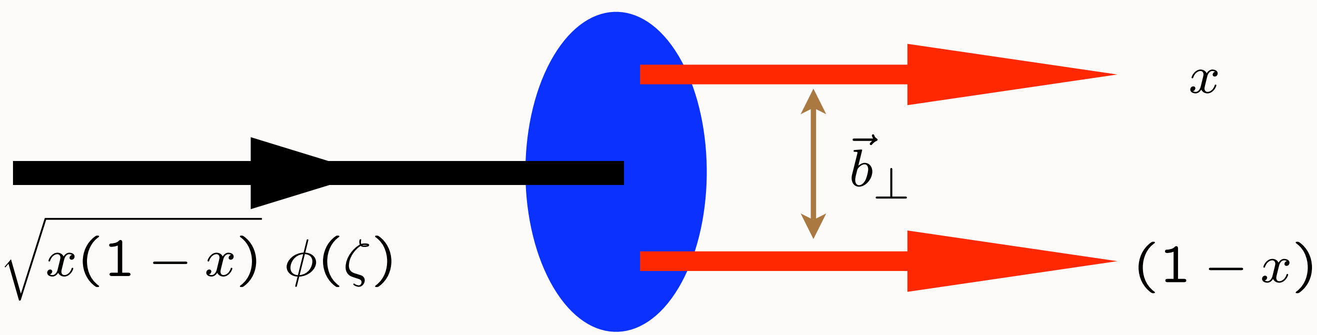
$\sum_i^n x_i = 1$

$\sum_i^n \vec{k}_{\perp i} = \vec{0}_\perp$

Invariant under boosts! Independent of P^μ

Mapping between LF(3+1) and AdS_5

LF(3+1)		AdS_5
$\psi(x, \vec{b}_\perp)$	$\longleftrightarrow$	$\phi(z)$
$\zeta = \sqrt{x(1-x)\vec{b}_\perp^2}$	$\longleftrightarrow$	z



$$\psi(x, \vec{b}_\perp) = \sqrt{x(1-x)}\ \phi(\zeta)$$

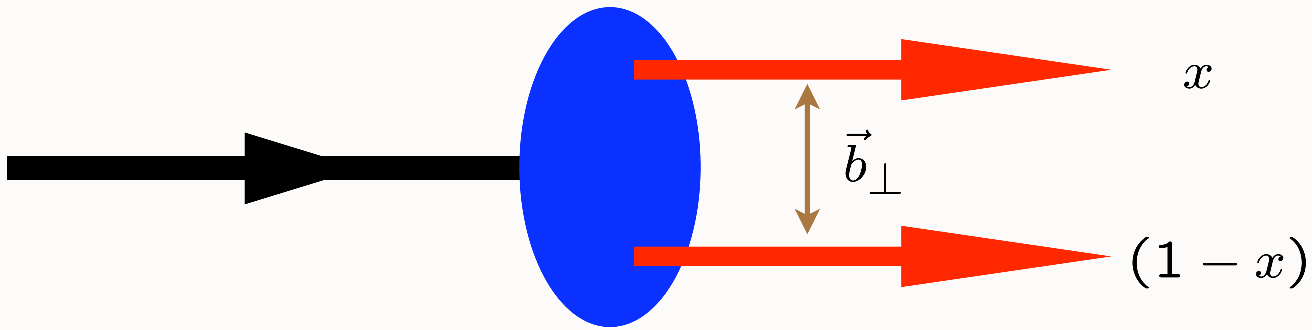
Holography: Map AdS/CFT to 3+1 LF Theory

Relativistic radial equation: *Frame Independent*

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

G. de Teramond, sjb

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



Effective conformal potential:

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

The Form Factor in AdS Space

- Non-conformal metric dual to a confining gauge theory

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

where $A(z) \to 0$ as $z \to 0$ (Polchinski and Strassler, hep-th/0109174).

- Hadronic matrix element for EM coupling with string mode $\Phi(x, z)$, $x^\ell = (x^\mu, z)$

$$ig_5 \int d^4x \, dz \, \sqrt{g} \, A^\ell(x, z) \Phi^*_{P'}(x, z) \overleftrightarrow{\partial}_\ell \Phi_P(x, z).$$

- Electromagnetic probe polarized along Minkowski coordinates,

$$A_\mu = \epsilon_\mu e^{-iQ\cdot x} J(Q, z), \quad A_z = 0,$$

with

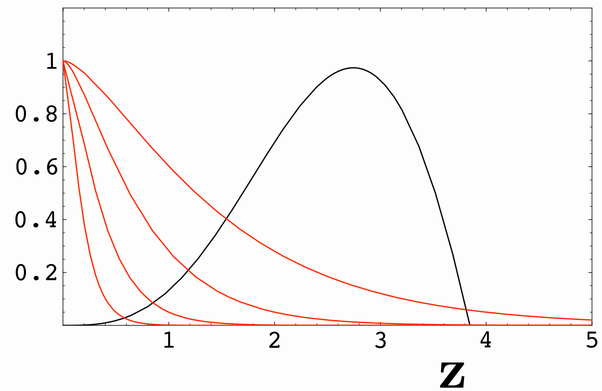
$$J(Q, z) = zQK_1(zQ), \quad J(Q = 0, z) = J(Q, z = 0) = 1$$

- Hadronic modes are plane waves along the Poincaré coordinates with four-momentum P^μ and invariant mass $P_\mu P^\mu = \mathcal{M}^2$

$$\Phi(x, z) = e^{-iP\cdot x} f(z), \quad f(z) \to z^\Delta, \quad z \to 0.$$

- 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 $z \sim 1/Q$.

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

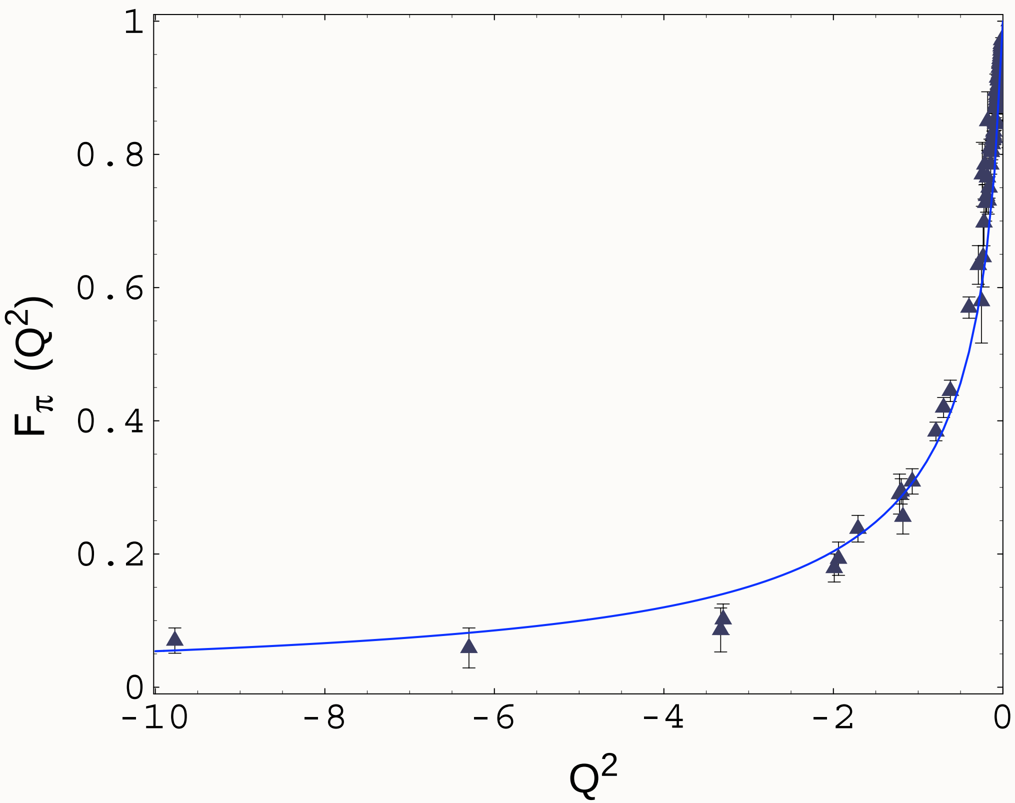


- Consider a specific AdS mode $\Phi^{(n)}$ dual to an n partonic Fock state $|n\rangle$. At small z, $\Phi^{(n)}$ scales as $\Phi^{(n)} \sim z^{\Delta_n}$. Thus:

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

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.

Contributions from Feynman large-x
and high transverse momenta regimes

Holographic Model for QCD Light-Front Wavefunctions

- Drell-Yan-West form factor

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

- Fourrier transform to impact parameter space $\vec{b}_\perp$

$$\psi(x, \vec{k}_\perp) = \sqrt{4\pi} \int d^2\vec{b}_\perp\, e^{i\vec{b}_\perp \cdot \vec{k}_\perp} \widetilde{\psi}(x, \vec{b}_\perp)$$

- Find $(b = |\vec{b}_\perp|)$:

$$\begin{aligned} F(q^2) &= \int_0^1 dx \int d^2\vec{b}_\perp\, e^{ix\vec{b}_\perp \cdot \vec{q}_\perp} \left|\widetilde{\psi}(x, b)\right|^2 \\ &= 2\pi \int_0^1 dx \int_0^\infty b\, db\, J_0(bqx)\, \left|\widetilde{\psi}(x, b)\right|^2, \end{aligned}$$

Soper

Two parton case

- 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

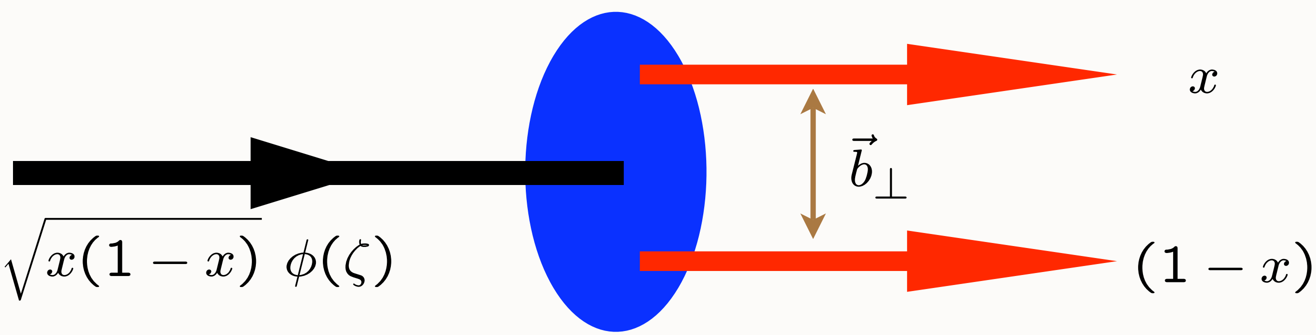
$$\boxed{\widetilde{\psi}(x,\vec{b}_\perp) = \frac{\Lambda_{\rm QCD}}{\sqrt{\pi} J_1(\beta_{0,1})} \sqrt{x(1-x)} J_0\left(\sqrt{x(1-x)}|\vec{b}_\perp|\beta_{0,1}\Lambda_{QCD}\right) \theta\left(\vec{b}_\perp^{\,2} \le \frac{\Lambda^{-2}_{\rm QCD}}{x(1-x)}\right)}$$

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 AdS_5

LF(3+1)	AdS_5
$\psi(x, \vec{b}_\perp)$	$\phi(z)$
$\zeta = \sqrt{x(1-x)\vec{b}_\perp^2}$	z



$$\psi(x, \vec{b}_\perp) = \sqrt{x(1-x)}\ \phi(\zeta)$$

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:

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

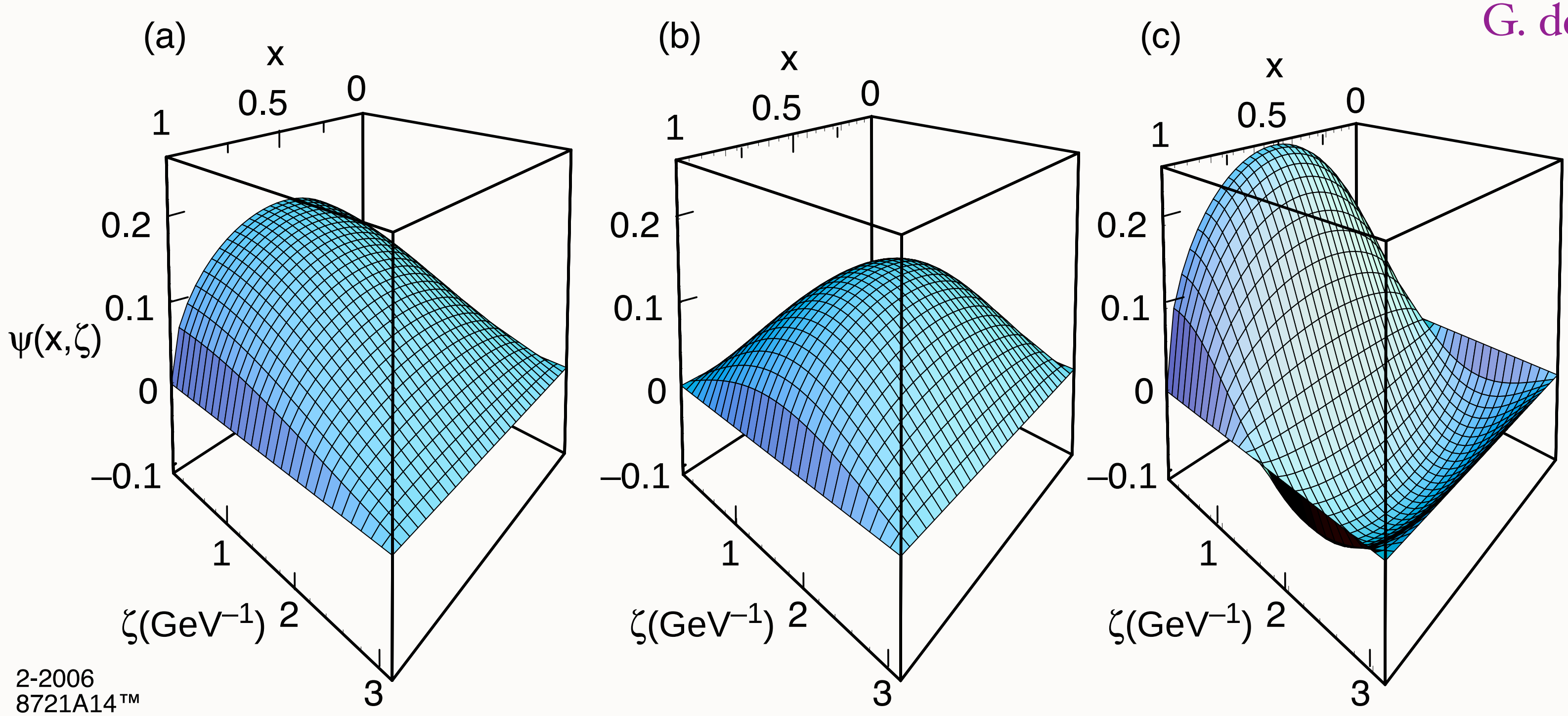
General solution:

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

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

AdS/CFT Prediction for Meson LFWF

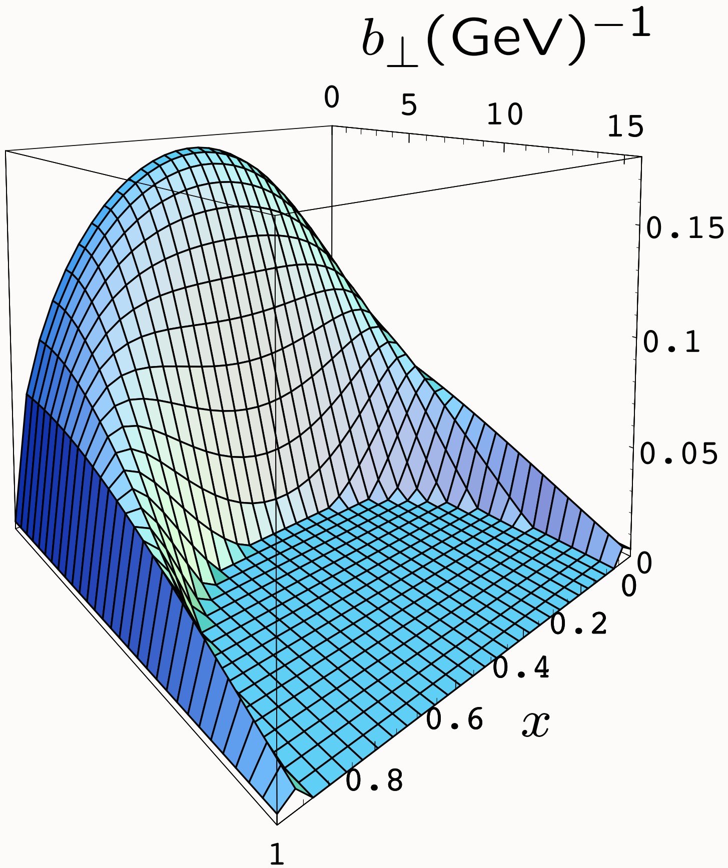
G. de Teramond
SJB



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 $z = \zeta = |b_\perp|\sqrt{x(1-x)}$.

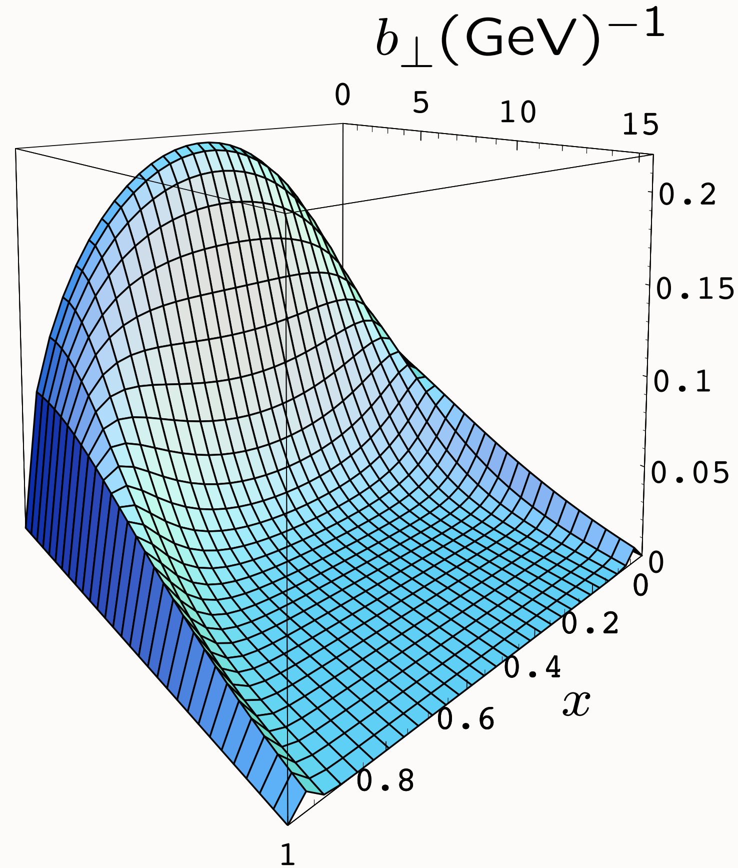
$$\widetilde{\psi}(x,\zeta) = \frac{\Lambda_{\rm QCD}}{\sqrt{\pi}J_1(\beta_{0,1})}\sqrt{x(1-x)}J_0\left(\zeta\beta_{0,1}\Lambda_{QCD}\right)\theta\left(z \le \Lambda_{\rm QCD}^{-1}\right)$$

AdS/CFT Predictions for Meson LFWF $\psi(x, b_\perp)$



$\Lambda_{\mathrm{QCD}} = 0.32$ GeV

Truncated Space

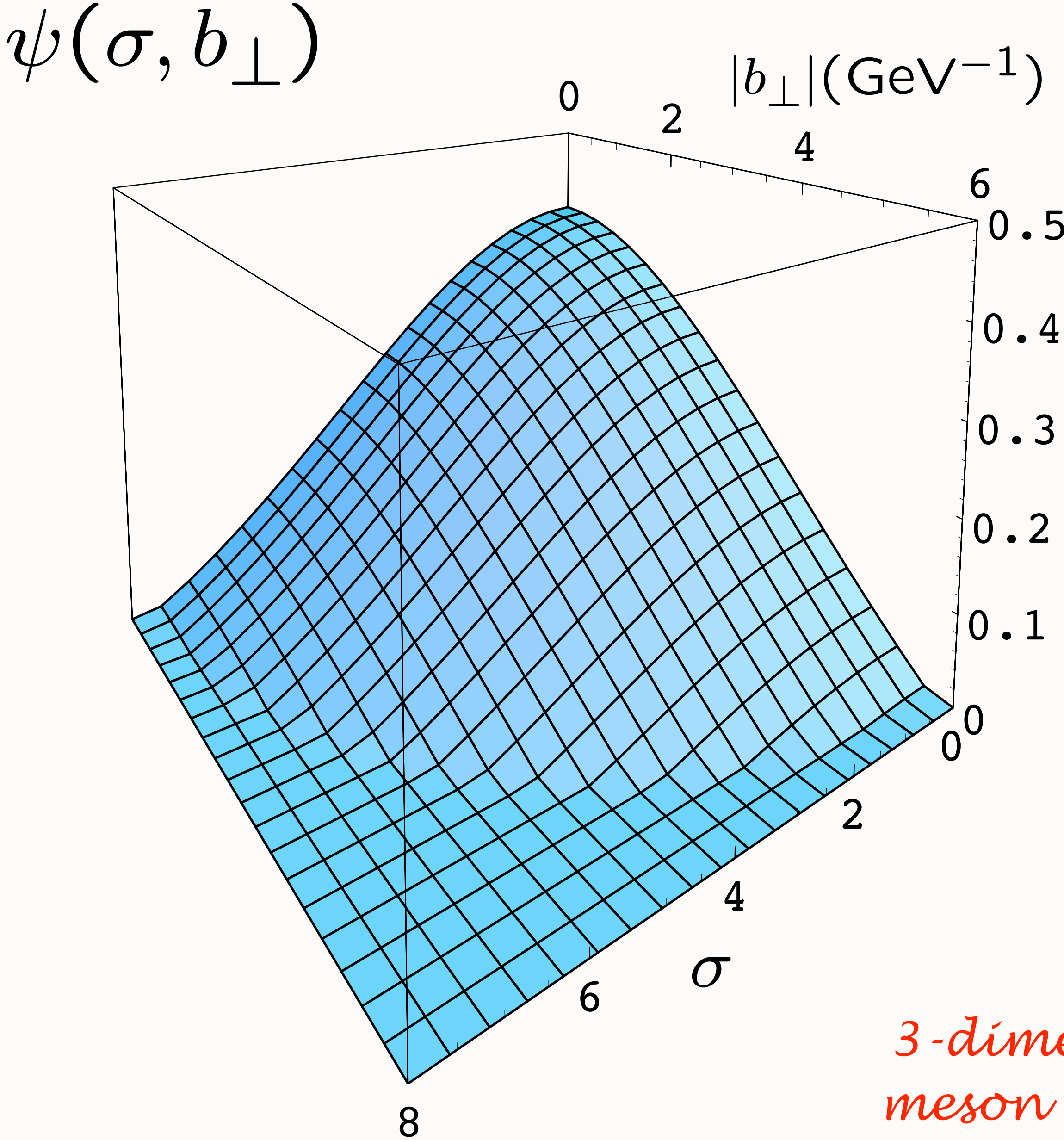


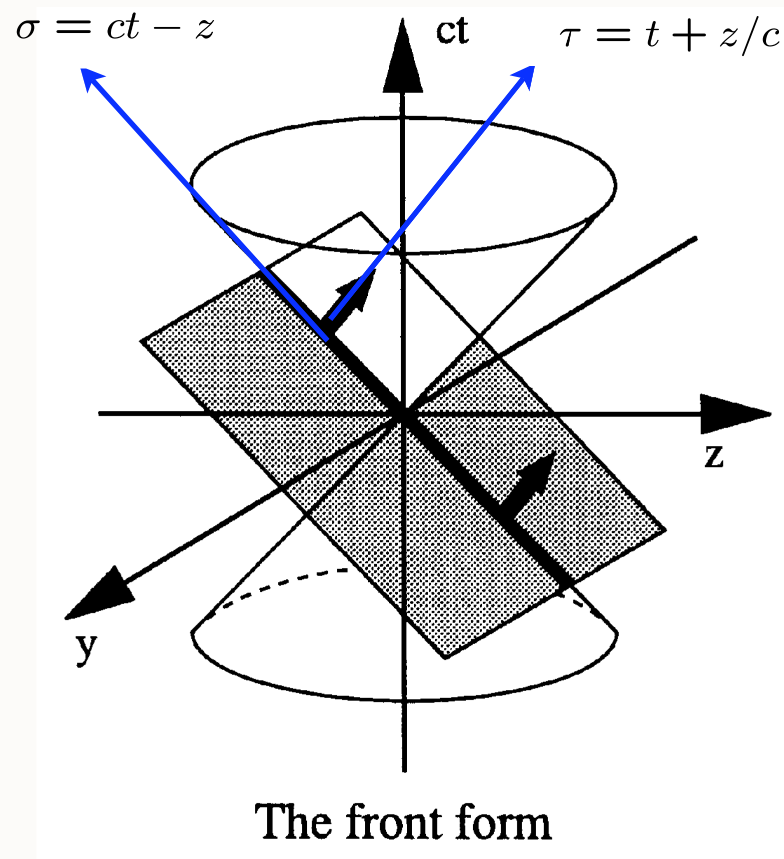
$\kappa = 0.76$ GeV.

Harmonic Oscillator

AdS/CFT Holographic Model

G. de Teramond
SJB





3-dimensional photograph: meson LFWF at fixed LF Time

General n-parton case

- Form factor in AdS is the overlap of normalizable modes dual to the incoming and outgoing hadrons Φ_P and $\Phi_{P'}$ with the non-normalizable mode $J(Q,z)$ dual to the external source

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

Polchinski and Strassler, hep-th/0209211

- Integrate Soper formula over angles:

$$F(q^2) = 2\pi \int_0^1 dx \frac{(1-x)}{x} \int \zeta d\zeta J_0\left(\zeta q \sqrt{\frac{1-x}{x}}\right) \tilde{\rho}(x,\zeta).$$

- Transversality variable

$$\zeta = \sqrt{\frac{x}{1-x}} \left| \sum_{j=1}^{n-1} x_j \mathbf{b}_{\perp j} \right|.$$

- Compare AdS and QCD expressions of FFs for arbitrary Q using identity:

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

the solution for $J(Q,\zeta)$!

- 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 $\vec{\eta} = \sum_{j=1}^{n-1} x_j\, \vec{b}_{\perp j}$

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

- Hadronic QCD transverse density $\tilde\rho$ is identified with the string mode density $|\Phi|^2$ 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 represents the invariant separation between point-like constituents and it is also the holographic variable: $\zeta = z$.

- For two-partons

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

- Two-parton bound state LFWF

$$\left|\widetilde\psi(x,\zeta)\right|^2 = \frac{R^3}{2\pi}\,x(1-x)\,e^{3A(\zeta)}\,\frac{|\Phi(\zeta)|^2}{\zeta^4}.$$

Brodsky and de Teramond, arXiv:hep-ph/0602252

- Short distance behavior of LFWF: $\widetilde\psi(x,\mathbf{b}_\perp) \sim (\mathbf{b}_\perp^2)^{\Delta-2}$.

- 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, $0 \leq \zeta \leq \Lambda_{\rm QCD}^{-1}$, 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

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

and we recover our previous results

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

Hadron Distribution Amplitudes

Lepage; SJB
Efremov, Radyuskin

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

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

AdS/CFT: $\quad \phi(x, Q_0) \propto \sqrt{x(1-x)}$

Baryon Form Factors

- Coupling of the extended AdS mode with an external gauge field $A^\mu(x,z)$

$$ig_5 \int d^4x\, dz\, \sqrt{g}\, A_\mu(x,z)\, \overline{\Psi}(x,z)\gamma^\mu\Psi(x,z),$$

where

$$\Psi(x,z) = e^{-iP\cdot x}\left[\psi_+(z)u_+(P) + \psi_-(z)u_-(P)\right],$$

$$\psi_+(z) = Cz^2 J_1(zM), \qquad \psi_-(z) = Cz^2 J_2(zM),$$

and

$$u(P)_\pm = \frac{1 \pm \gamma_5}{2}\, u(P).$$

$$\psi_+(z) \equiv \psi^\uparrow(z), \quad \psi_-(z) \equiv \psi^\downarrow(z),$$

the LC $\pm$ spin projection along $\hat{z}$.

- Constant C determined by charge normalization:

$$C = \frac{\sqrt{2}\Lambda_{\rm QCD}}{R^{3/2}\left[-J_0(\beta_{1,1})J_2(\beta_{1,1})\right]^{1/2}}.$$

- 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 (proton up)

$$N^{\uparrow}_{u\uparrow} = \frac{5}{3},\ N^{\uparrow}_{u\downarrow} = \frac{1}{3},\ N^{\uparrow}_{d\uparrow} = \frac{1}{3},\ N^{\uparrow}_{d\downarrow} = \frac{2}{3}.$$

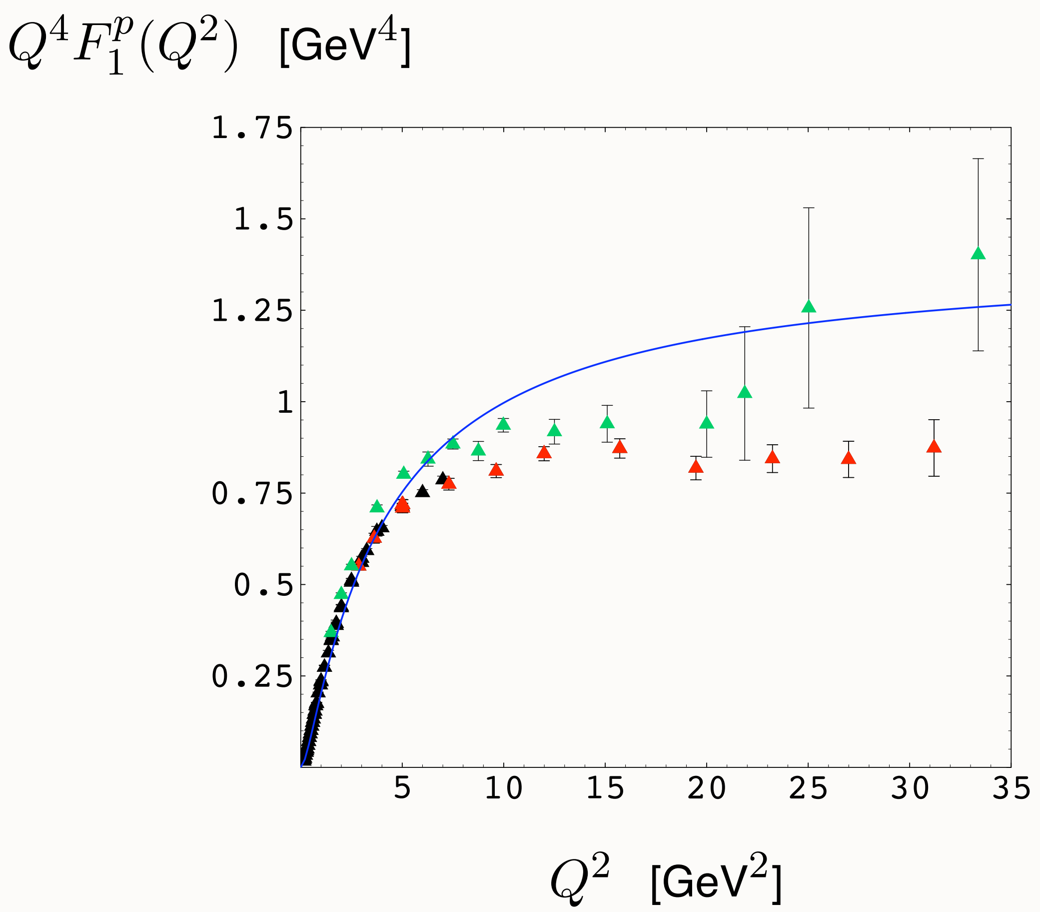
- Final result

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

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

Dirac Proton Form Factor

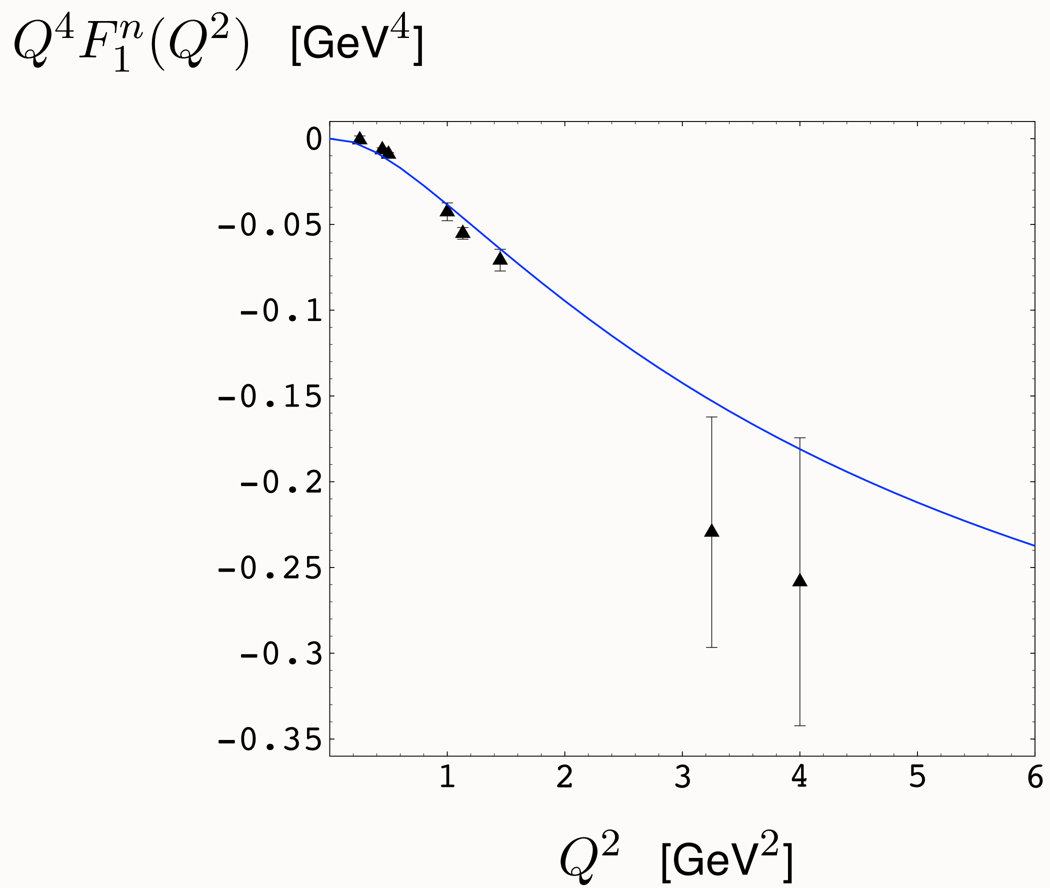
(Valence Approximation)



Prediction for $Q^4 F_1^p(Q^2)$ for $\Lambda_{\rm QCD} = 0.21$ GeV in the hard wall approximation. Analysis of the data is from Diehl (2005). Red points are from Sill (1993). Superimposed Green points are from Kirk (1973).

Dirac Neutron Form Factor

(Valence Approximation)



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

AdS/CFT and QCD

Implications for Exclusive Processes

- Meson distribution amplitude $\phi(x, Q_0) \propto \sqrt{x(1-x)}$
- Dominance of constituent interchange mechanism
- Power-law behavior from small impact separation $b_\perp$ high transverse momentum $k_\perp$ as well as x near 1
- High transverse momentum behavior matches PQCD LFWF with orbital: Belitsky, Ji, Yuan
- Perfect match of LF and AdS/CFT formulae for form factors

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
- Factorization theorems, DGLAP, BFKL, ERBL Evolution
- Quark interchange amplitude
- Relation of spin, momentum, and other distributions to physics of the hadron itself.

Advantages of Light-Front Formalism

- *Hidden Color* Of Nuclear Wavefunction
- *Color Transparency, Opaqueness*
- 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

Light-Front Wavefunctions

Dirac's Front Form: Fixed $\tau = t + z/c$

$$\psi(x, k_\perp)$$

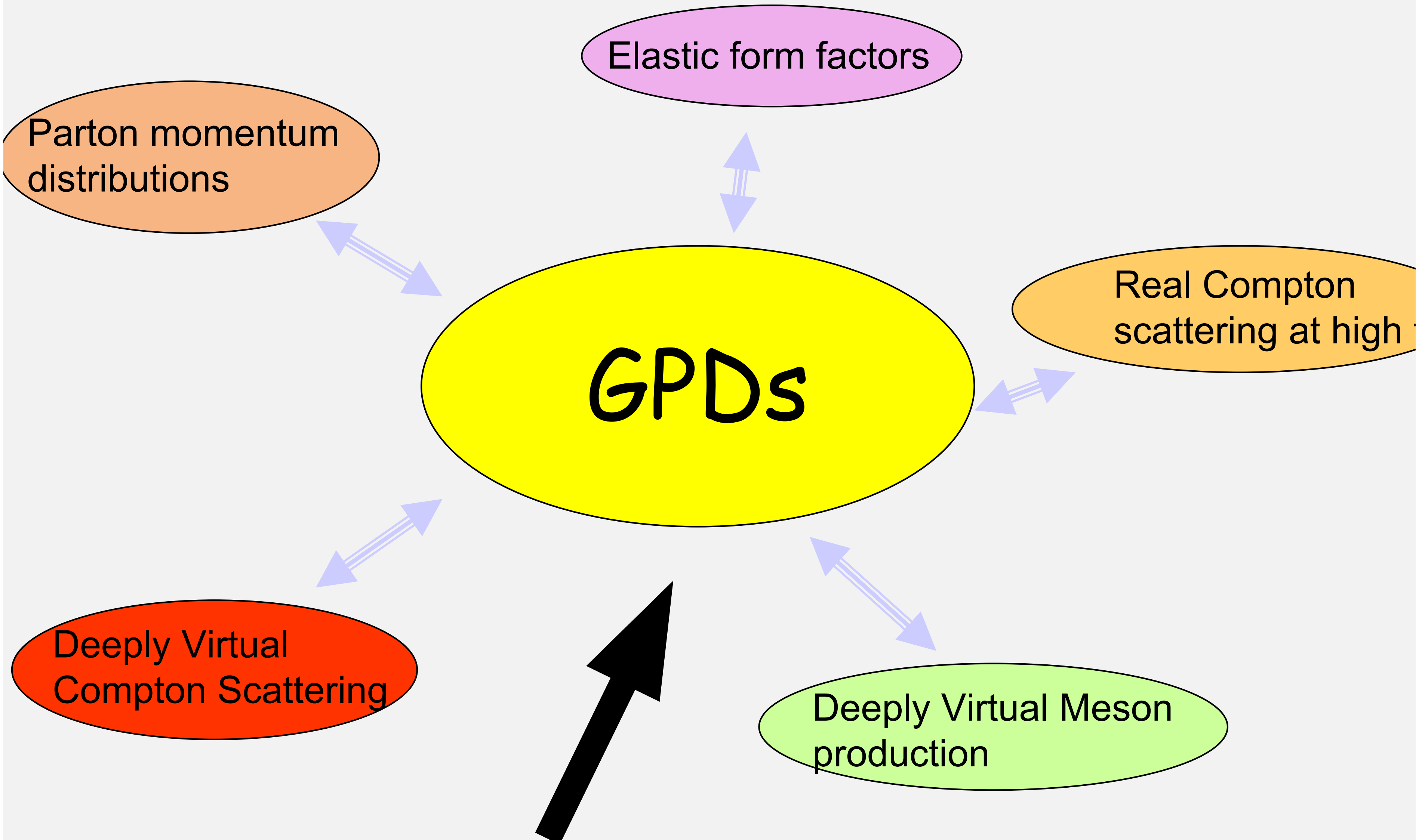
$$x_i = \frac{k_i^+}{P^+}$$

Invariant under boosts. Independent of P^μ

$$H_{LF}^{QCD} |\psi> = M^2 |\psi>$$

Remarkable new insights from AdS/CFT, the duality between conformal field theory and Anti-de Sitter Space

A Unified Description of Hadron Structure

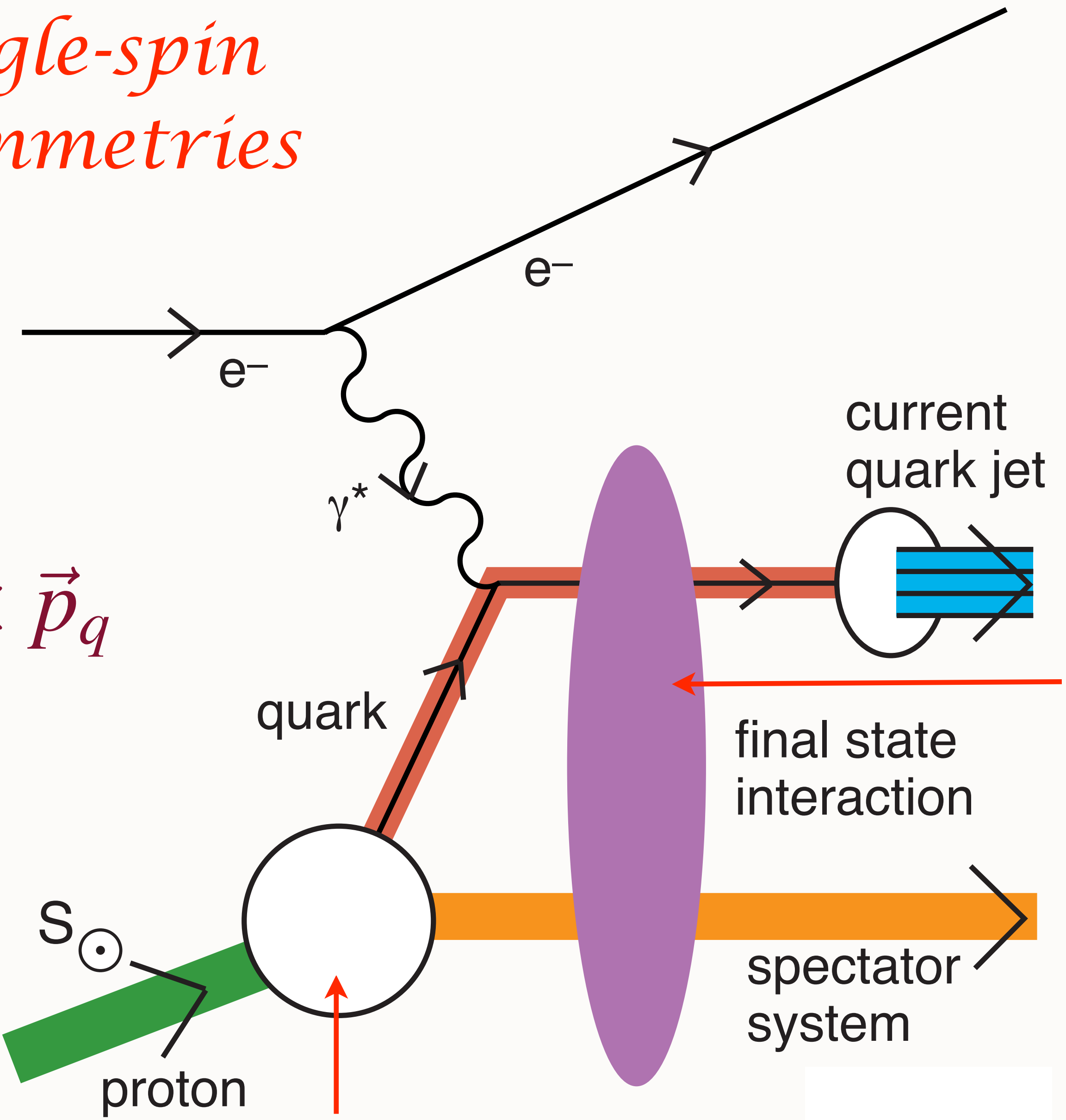


Light Front Wavefunctions

Single-spin asymmetries

Sivers Effect

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



QCD S- and P- Coulomb Phases

Light-Front Wavefunction S and P- Waves

Hwang, Schmidt.
sjb

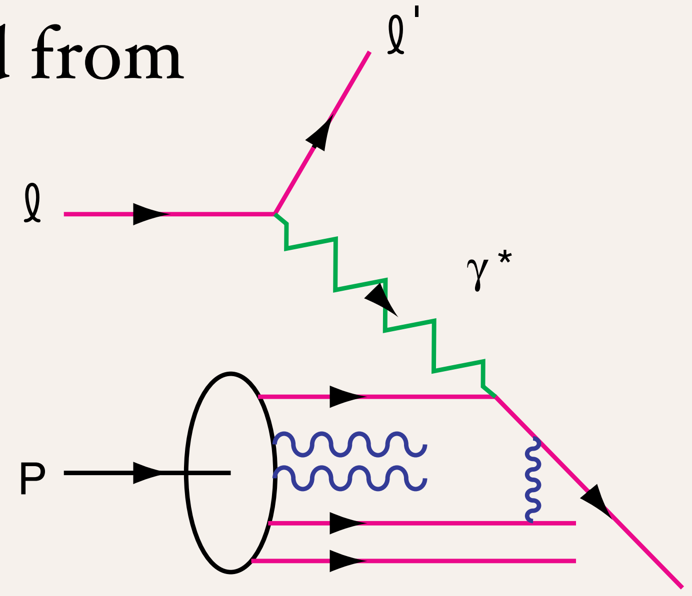
Final State Interactions Produce T-Odd (Sivers Effect)

- Bjorken Scaling!
- Arises from Interference of Final-State Coulomb Phases in S and P waves
- Relate to the quark contribution to the target proton anomalous magnetic moment
- Sum of Sivers Functions for all quarks and gluons vanishes. (Zero gravitoanomalous magnetic moment)

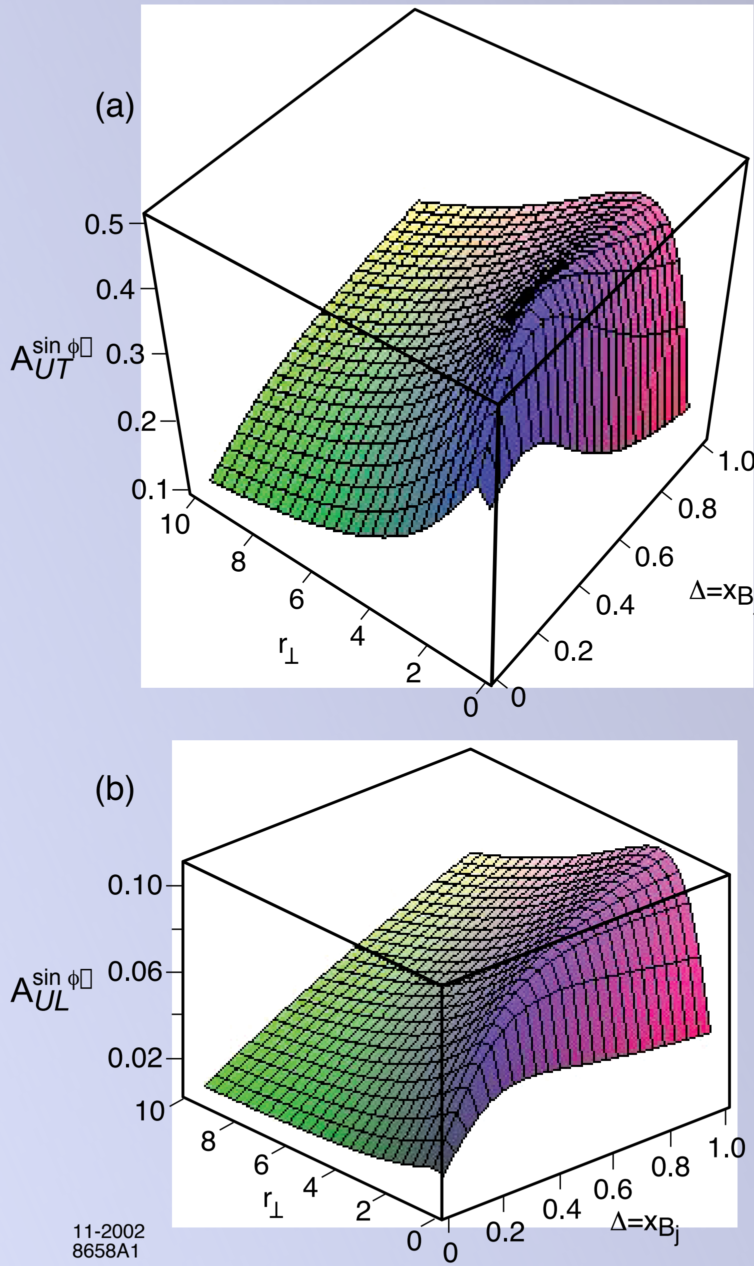
$$\vec{S} \cdot \vec{p}_{jet} \times \vec{q}$$

Hwang, Schmidt. sjb; Burkardt

- 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



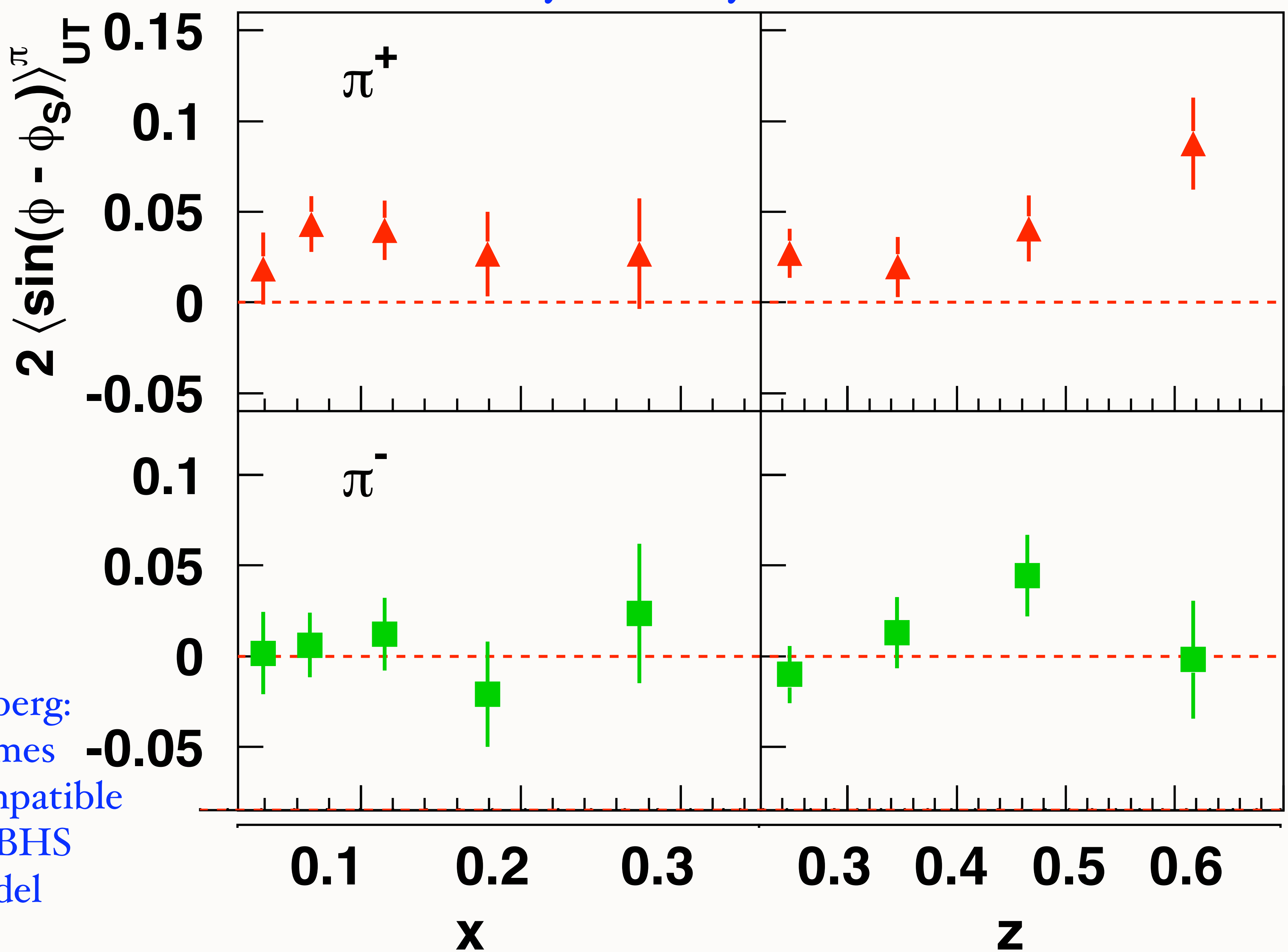
Prediction for Single-Spin Asymmetry



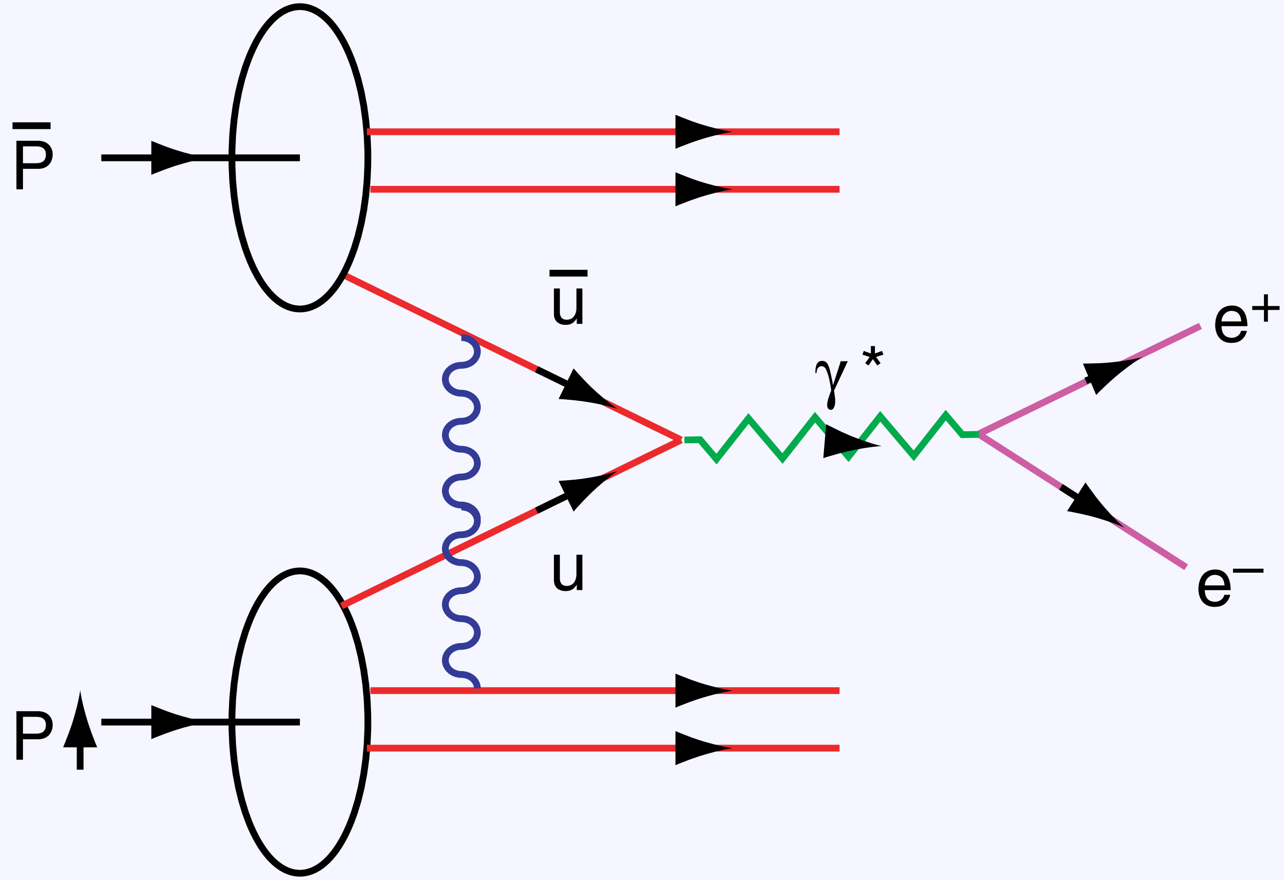
Hwang, Schmidt.
sjb

HERMES coll., A. Airapetian et al., Phys. Rev. Lett. 94 (2005) 012002.

Sivers asymmetry from HERMES



Gamberg: Hermes data compatible with BHS model



Single Spin Asymmetry In the Drell Yan Process
$\vec{S}_p \cdot \vec{\overline{p}} \times \vec{q}_{\gamma^*}$
Quarks Interact in the Initial State
Interference of Coulomb Phases for S and P states
Produce Single Spin Asymmetry [Siver's Effect]Proportional to the Proton Anomalous Moment and α_s.
Opposite Sign to DIS! No Factorization

Collins;
Hwang, Schmidt.
sjb

Key QCD Experiment at GSI

Measure single-spin asymmetry A_N
in Drell-Yan reactions

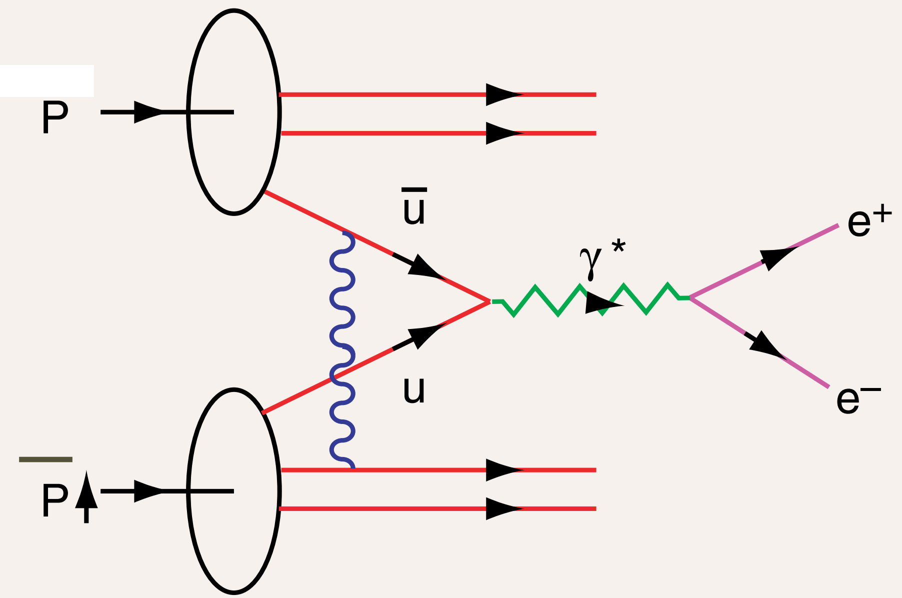
Leading-twist Bjorken-scaling A_N
from S, P-wave
initial-state gluonic interactions

Predict: $A_N(DY) = -A_N(DIS)$
Opposite in sign!

$$Q^2 = x_1 x_2 s$$

$$Q^2 = 4 \text{ GeV}^2, s = 80 \text{ GeV}^2$$

$$x_1 x_2 = .05, x_F = x_1 - x_2$$



$$p\bar{p}_\uparrow \to \ell^+ \ell^- X$$

$\vec{S} \cdot \vec{q} \times \vec{p}$ correlation

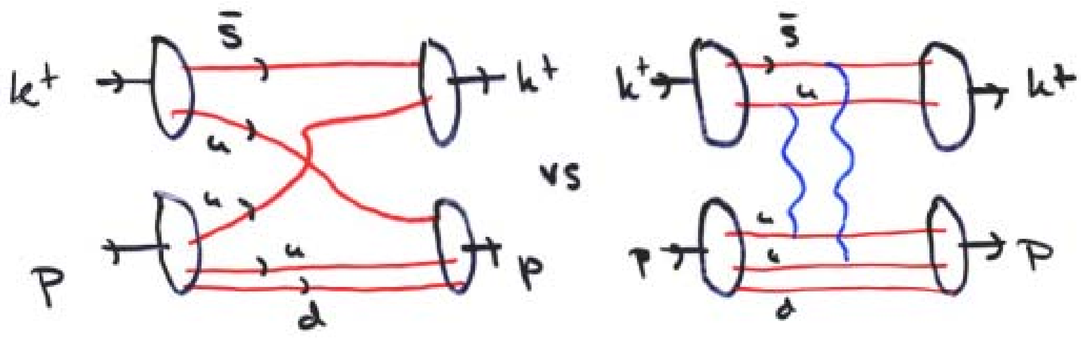
New Perspectives for QCD from AdS/CFT

- 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

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

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

determined by scattering mechanism



Quark Interchange $\qquad$ gluon exchange

↗ analogous to spin exchange in atom - atom scattering $\qquad$ Van der Waals

Large N_c: Quark Interchange Dominant

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

't Hooft limit, AdS/CFT

Blankenbecler, Gunion, sjb

MIT Bag Model predicts dominance of quark interchange:

C. de Tar

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

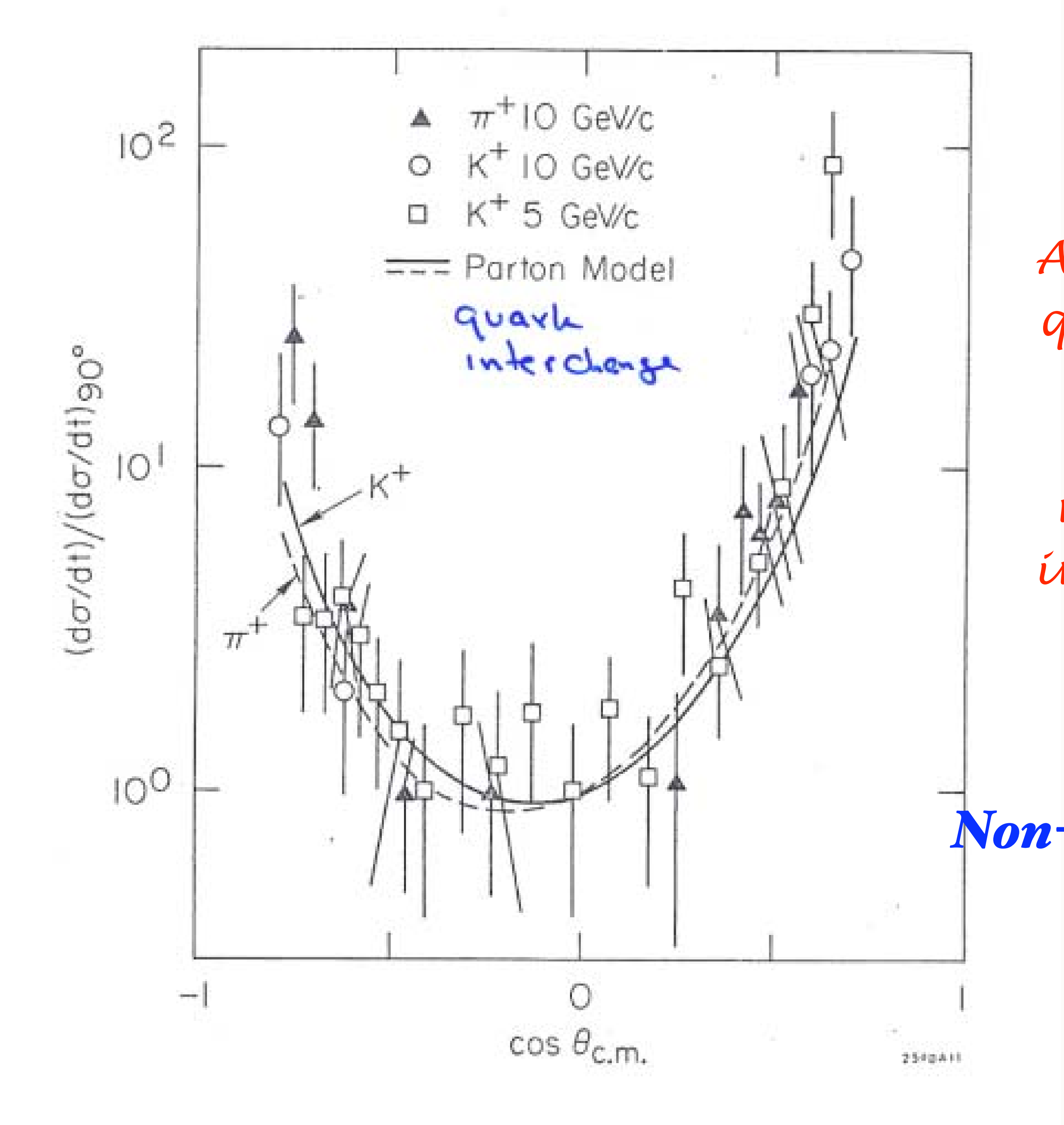
$M_{QIM} = \int d^2k_\perp dx\ \psi^\dagger_C \psi^\dagger_D \Delta \psi_A \psi_B$

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.



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

Non-linear Regge behavior

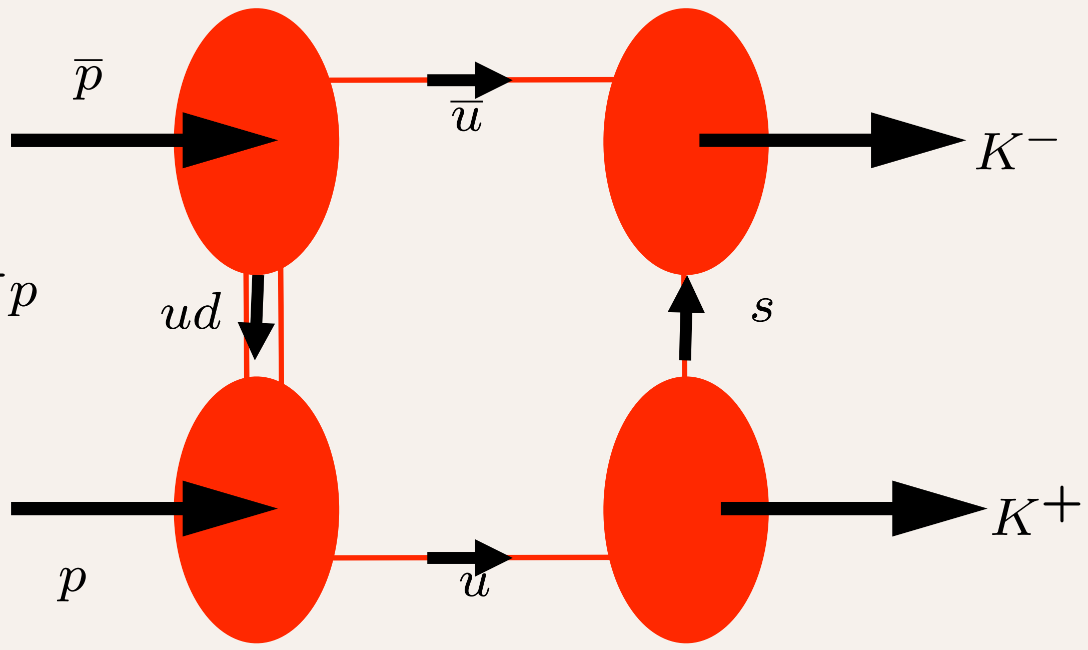
$$\alpha_R(t) \to -1$$

Key QCD Experiment at GSI

$$\bar{p}p \to K^+ K^-$$

$s \leftrightarrow t \;\; t \leftrightarrow u$ crossing of $K^+ p \to K^+ p$

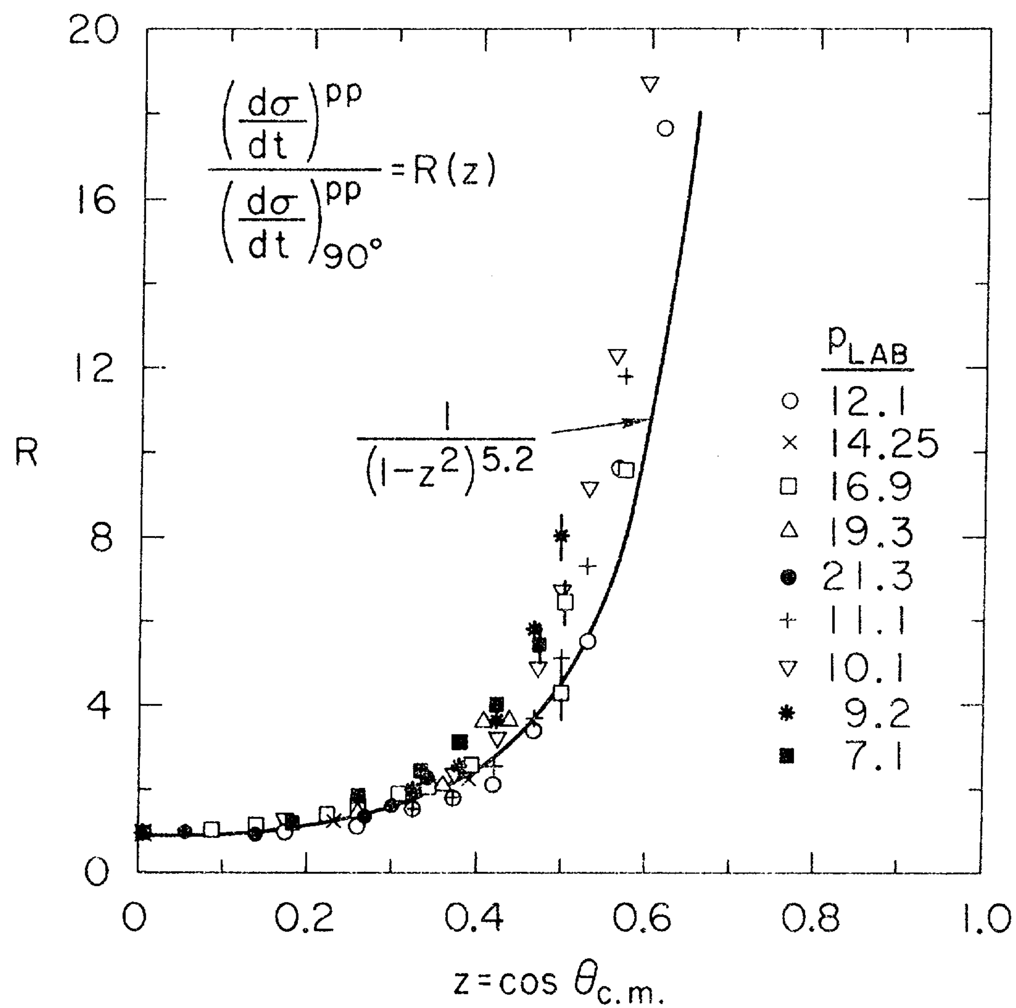
$$M(\bar{p}p \to K^+ K^-) \propto \frac{1}{ts^2}$$



$$\frac{d\sigma}{dt} \propto \frac{1}{s^6 t^2}$$

at large t, u

Test of Quark Interchange Mechanism in QCD



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

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

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

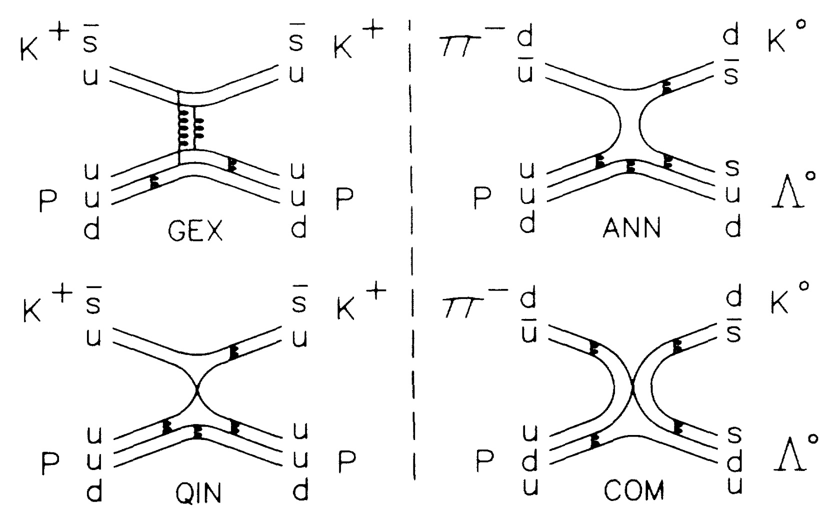
$\pi^{\pm}p \to p\rho^{\pm}$,

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

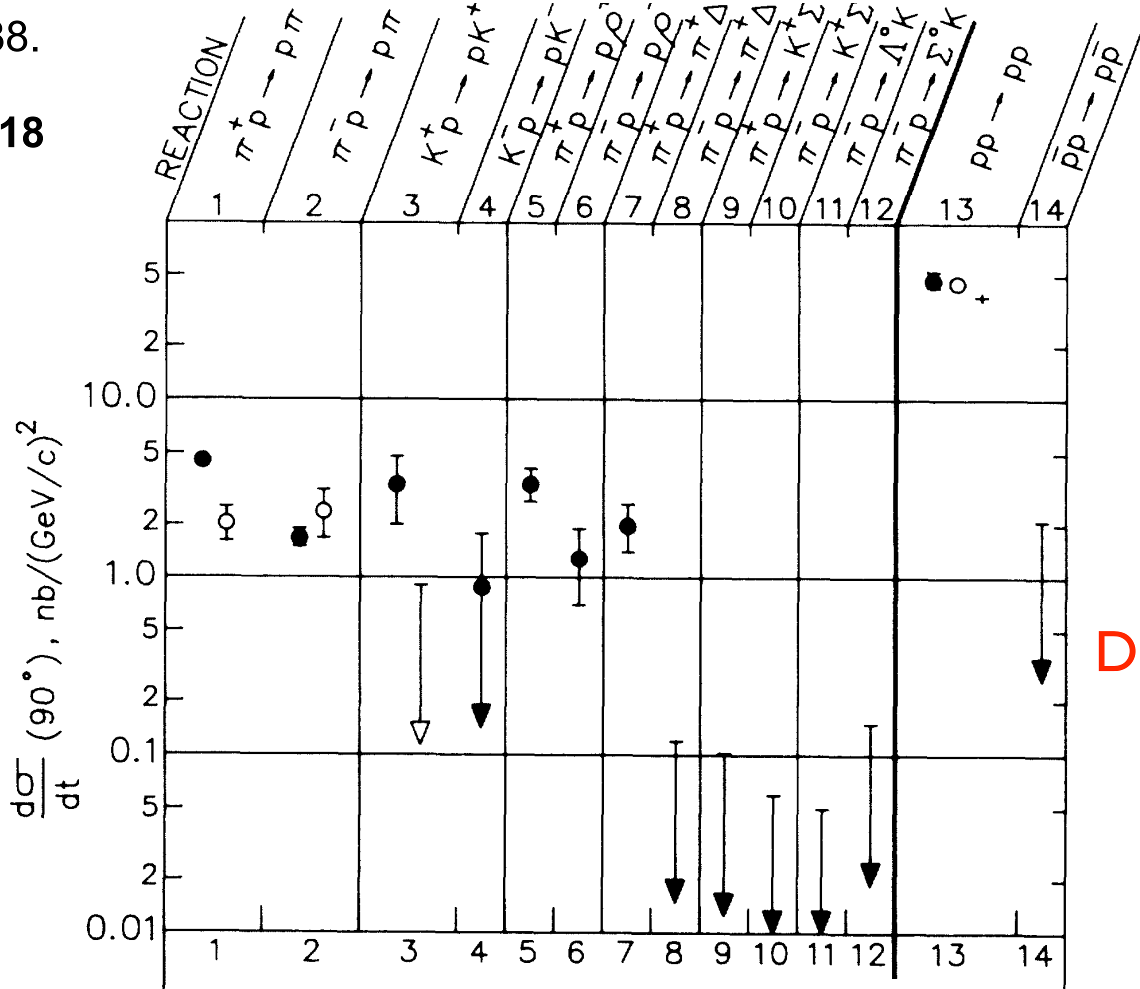
$\pi^{\pm}p \to K^{+}\Sigma^{\pm}$,

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

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



B.R. Baller *et al.*. 1988. Published in **Phys.Rev.Lett.60:1118 -1121,1988**



Comparison of Exclusive Reactions at Large *t*

The cross section and upper limits (90% confidence level) measured by this experiment are indicated by the filled circles and arrowheads. Values from this experiment and from previous measurements represent an average over the angular region of $-0.05 < \cos\theta_{\text{c.m.}} < 0.10$. The other measurements were obtained from the following references: $\pi^+ p$ and $K^+ p$ elastic, Ref. 5; $\pi^- p \to p\pi^-$, Ref. 6; $pp \to pp$, Ref. 7: Allaby, open circle; Akerlof, cross. Values for the cross sections [(Reaction), cross section in nb/(GeV/c)^2] are as follows: (1), 4.6 ± 0.3; (2), 1.7 ± 0.2; (3), 3.4 ± 1.4; (4), $0.9^{+0.7}_{-0.9}$; (5), 3.4 ± 0.7; (6), 1.3 ± 0.6; (7), 2.0 ± 0.6; (8), < 0.12; (9), < 0.1; (10), < 0.06; (11), < 0.05; (12), < 0.15; (13), 48 ± 5; (14), < 2.1.

Quark Interchange: Dominant Dynamics at large t, u

Relative Rates Correct

Formula for quark interchange using LFWFs

Blankenbecler, Gunion, sjb; Sivers

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

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

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

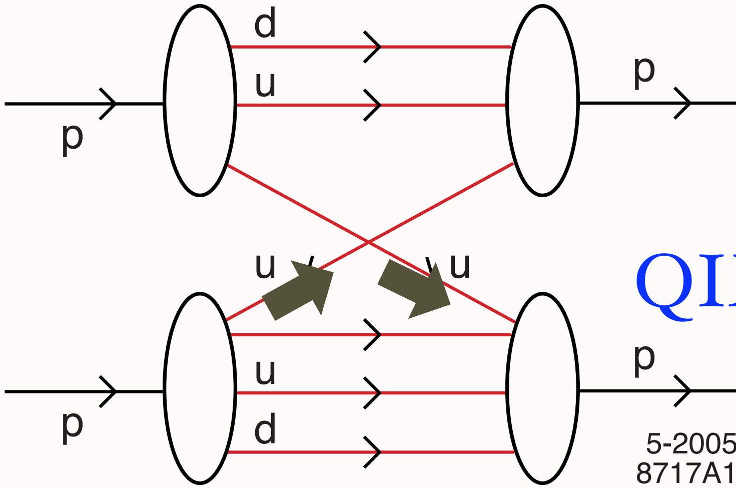
$($

here

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

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

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



QIM

$$\frac{d\sigma}{dt}(pp \to pp) = C\,\frac{F_p^{\,2}(t)F_p^{\,2}(u)}{s^2}$$

$$\frac{d\sigma}{dt} = \frac{1}{s^{10}} f(\theta_{\rm c.m.})\,, \quad f(\theta_{\rm c.m.}) \sim \left(\frac{1}{1-\cos^2\theta}\right)^4 .$$

N N Force at Short Distances

The biggest failure of the interchange mechanism is in the spin correlation. For all angles we predict from Table I

$$A_{nn} = \frac{1}{3}\,\frac{1-(\frac{3}{31})^2\chi^2}{1+\frac{1}{3}(\frac{3}{31})^2\chi^2}\,, \tag{3.11}$$

where

$$\chi = \frac{f(\theta)-f(\pi-\theta)}{f(\theta)+f(\pi-\theta)}\,.$$

Thus A_{nn} is predicted to be within 2% of $\frac{1}{3}$ even when $\chi = 1$ [$\chi = 0$ for the form in Eq. (3.6)]. The data clearly indicate that A_{nn} is not a constant near $\frac{1}{3}$.

Our expectation, then, is that there is an additional amplitude which strongly interferes with the quark-interchange contributions at Argonne energies; most plausibly, the quark-interchange contribution is dominant at asymptotic t and u, and the interfering amplitude is most important at low t and u. As we shall discuss below, the behavior of A_{ll} and A_{ss} in the interference region can play an important role in sorting out the possible subasymptotic contributions.

These results for the quark-interchange model have also been obtained by Farrar, Gottlieb, Sivers, and Thomas,[12] who also consider the possibility that nonperturbative effects (quark-quark scattering via instantons) can explain the data.

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

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.

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.

Use the AdS/CFT orthonormal LFWFs as a basis to diagonalize the QCD LF Hamiltonian

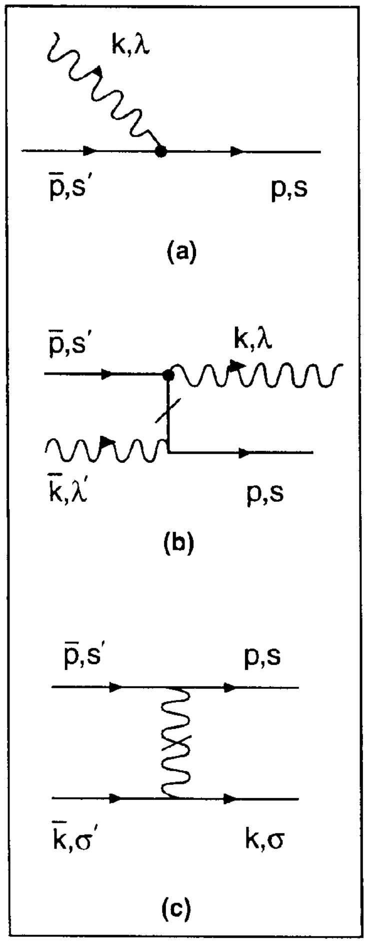
- Good initial approximant
- Better than plane wave basis
- DLCQ discretization
- Use independent HO LFWFs, remove CM motion
- Similar to Shell Model calculations

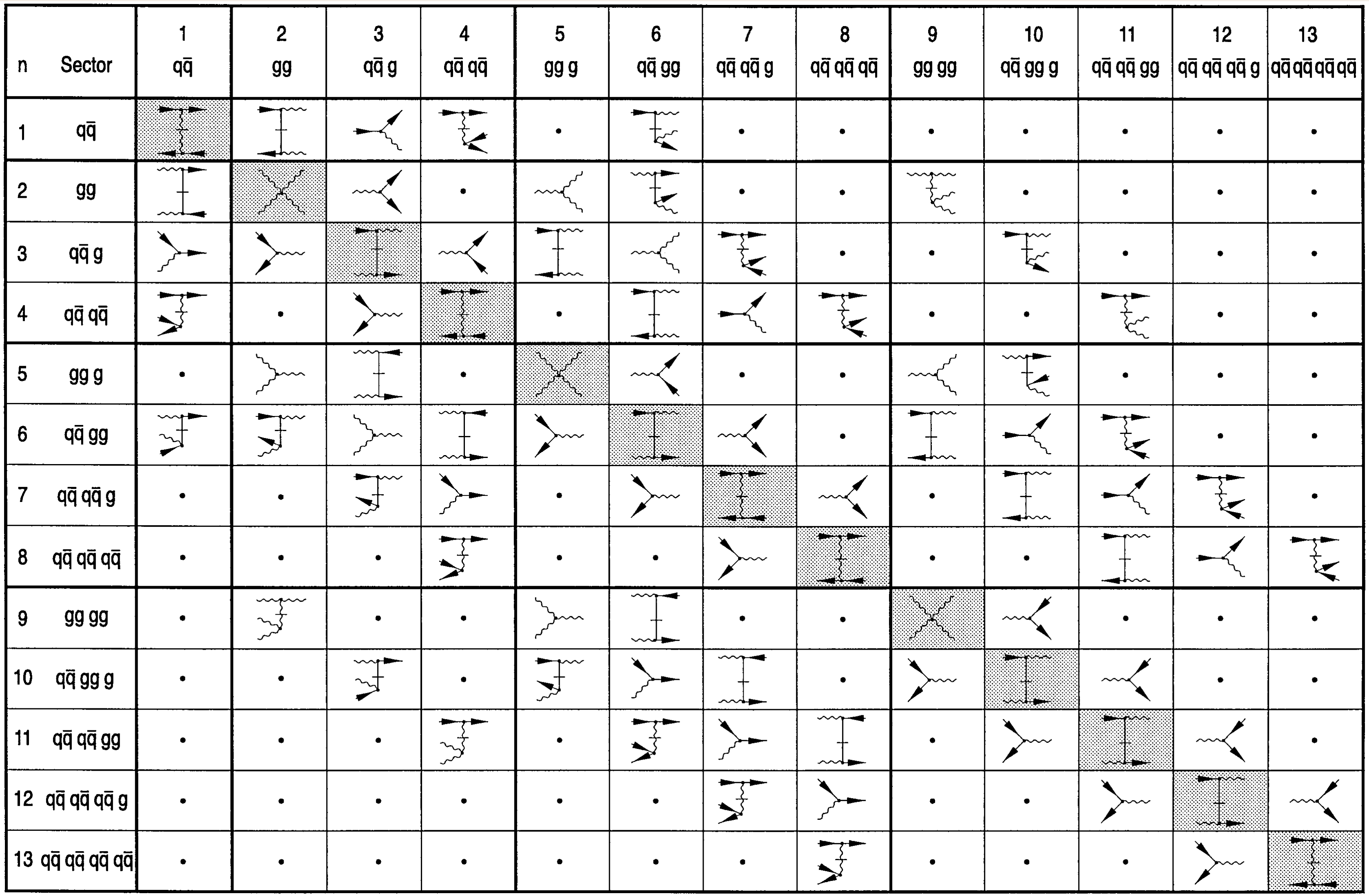
Vary, Harinandrath, sjb

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

Use AdS/QCD Basis functions to diagonalize the LF Hamiltonian

"…I will sum up by saying that light-front QCD is not for the faint of heart, but for a few good candidates it is a chance to be a leader in a much smaller community of researchers than one faces in the other areas of high-energy physics, with, I believe, unusual promise for interesting and unexpected results."

K.G. Wilson, "The Origins of Lattice Gauge Theory," Nuclear Physics B, Suppl., **140** (2005) p3

Conformal symmetry: Template for QCD

- Initial approximation to PQCD; then correct for non-zero beta function and quark masses
- Commensurate scale relations: relate observables at corresponding scales: Generalized Crewther Relation
- Arguments for Infrared fixed-point for α_s Alhofer, et al.
- Effective Charges: analytic at quark mass thresholds, finite at small momenta
- Eigensolutions of Evolution Equation of distribution amplitudes

New Perspectives on QCD from AdS/CFT

- LFWFs: Fundamental description of hadrons at amplitude level
- QCD is Nearly Conformal
- Holographic Model from AdS/CFT : Confinement at large distances and conformal behavior at short distances
- Model for LFWFs, meson and baryon spectra
- Quark-interchange dominates scattering amplitudes

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 . . .

SCIENCE VOL 265 15 SEPTEMBER 1995

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.

Frank and Ernest