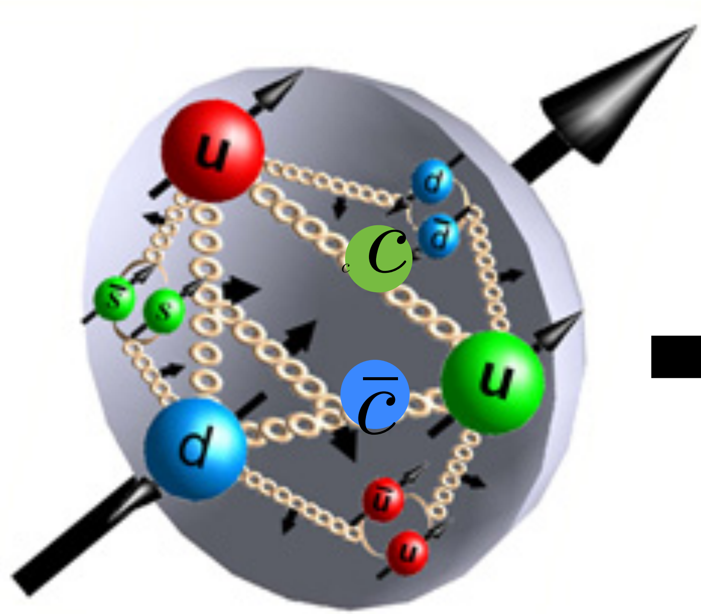
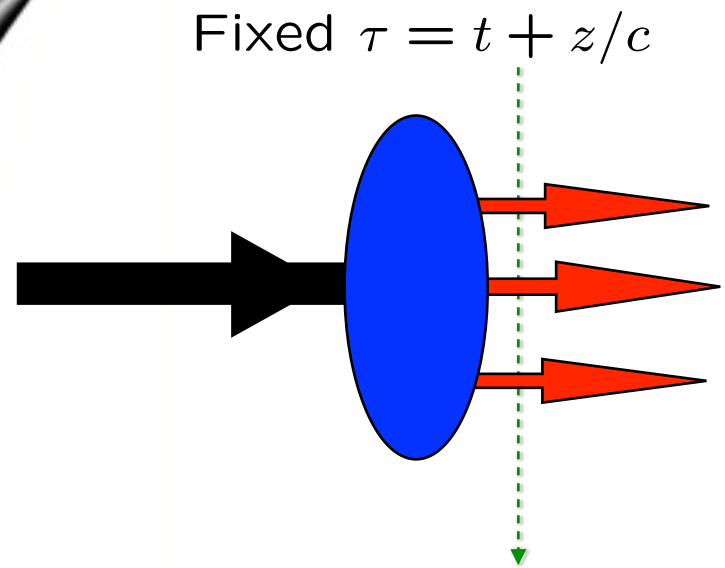
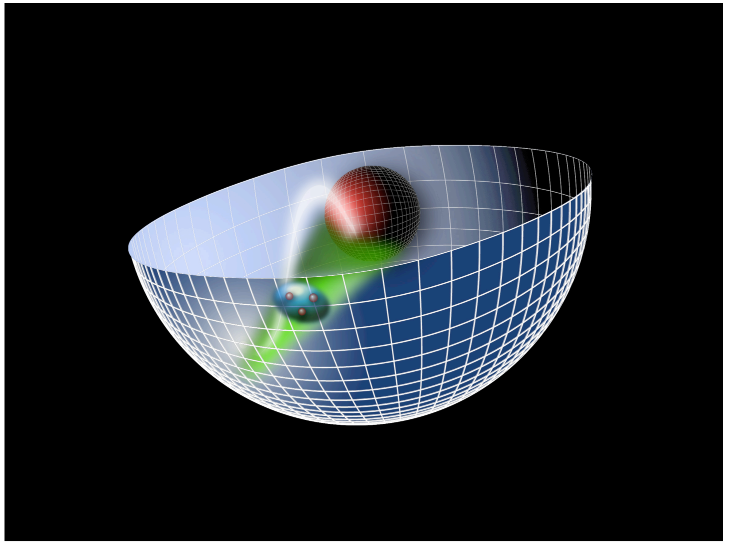
Novel QCD Features of Hadrons and Nuclei







Stan Brodsky

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GGI School

Frontiers in Nuclear and Hadronic Physics

February 25 - March 8, 2019

References

Light-Front Holographic QCD and Emerging Confinement
Stanley J. Brodsky (SLAC), Guy F. de Teramond (Costa Rica U.), Hans Gunter Dosch (U. Heidelberg, ITP), Joshua Erlich (William-Mary Coll.). Jul 30, 2014. 105 pp.
Published in **Phys.Rept. 584 (2015) 1-105**
SLAC-PUB-15972
DOI: 10.1016/j.physrep.2015.05.001
e-Print: **arXiv:1407.8131 [hep-ph] | PDF**

Meson/Baryon/Tetraquark Supersymmetry from Superconformal Algebra and Light-Front Holography
Stanley J. Brodsky (SLAC), Guy F. de Téramond (Costa Rica U.), Hans Günter Dosch (U. Heidelberg, ITP), Cédric Lorcé (Ecole Polytechnique, CPHT). Jun 15, 2016. 27 pp.
Published in **Int.J.Mod.Phys. A31 (2016) no.19, 1630029**
SLAC-PUB-16545
DOI: 10.1142/S0217751X16300295
Conference: C16-02-29.1
e-Print: **arXiv:1606.04638 [hep-ph] | PDF**

Remarkable, Fundamental Features of Hadrons, Nuclei

- *Color confinement: Quarks and Gluons permanently confined in hadrons!*
- *Origin of the hadron mass scale: what determines the proton mass?*
- *Pion is a quark-antiquark bound state, but it is massless if the quark mass is zero!*
- *The QCD coupling at all scales, beyond asymptotic freedom*
- *How does one set the renormalization scale? QCD —> QED if Nc —> 0*
- *Poincare invariance: Physics independent of observer motion — no Lorentz contraction!*
- *Causality: No correlations exceeding the speed of light*
- *Relativity: Relativistic Bound State Dynamics*
- *Mesons and Baryons display supersymmetry!*
- *Exotic Phenomena: Color Transparency, Intrinsic Charm, Hidden Color, Exotic Hadrons (Octoquark)*
- *Cosmological Constant is Zero!*

Light-Front Dynamics

Foundations of Light-Front Holography

- ***The QCD Lagrangian for m_q =0 has no mass scale.***
- ***What determines the hadron mass scale?***
- ***DAFF principle: add terms linear in D and K to Conformal Hamiltonian: Mass scale κ appears, but action remains scale invariant —> unique harmonic oscillator potential***
- ***Apply DAFF to the Poincare' invariant LF Hamiltonian: Unique color-confining potential***
- ***Fixes AdS_5 dilaton: predicts Spin and Spin-Orbit Interactions***
- ***Apply DAFF to Superconformal representation of the Lorentz group***
- ***Predicts Meson, Baryon, Tetraquark spectroscopy, dynamics***
- ***Supersymmetric Features of Spectrum***

An analytic first approximation to QCD

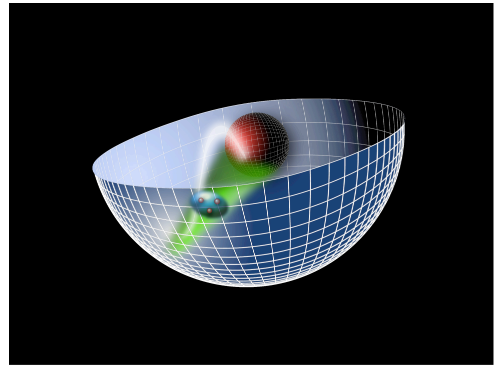
AdS/QCD + Light-Front Holography

- **As Simple as Schrödinger Theory in Atomic Physics**
- **LF radial variable ζ conjugate to invariant mass squared**
- **Relativistic, Frame-Independent, Color-Confining**
- **Unique confining potential!**
- **QCD Coupling at all scales: Essential for Gauge Link phenomena**
- **Hadron Spectroscopy and Dynamics from one parameter**
- **Wave Functions, Form Factors, Hadronic Observables, Constituent Counting Rules**
- **Insight into QCD Condensates: Zero cosmological constant!**
- **Systematically improvable with DLCQ-BLFQ Methods**

de Tèramond, Dosch, Lorcè, sjb

AdS/QCD Soft-Wall Model

$$e^{\varphi(z)} = e^{+\kappa^2 z^2}$$



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

Light-Front Holography

$$\left[-\frac{d^2}{d\zeta^2} + \frac{4L^2-1}{4\zeta^2} + U(\zeta^2)\right]\psi = M^2\psi$$

Light-Front Schrödinger Equation

$$U(\zeta) = \kappa^4\zeta^2 + 2\kappa^2(L+S-1)$$

Unique Confinement Potential!

Conformal Symmetry of the action

Single variable ζ

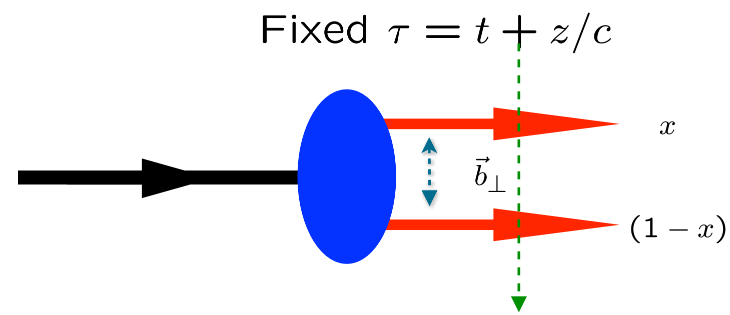
Confinement scale: $\kappa \simeq 0.5\ GeV$

- **de Alfaro, Fubini, Furlan:**
- **Fubini, Rabinovici**

Scale can appear in Hamiltonian and EQM without affecting conformal invariance of action!

Underlying Principles

- *Poincarè Invariance: Independent of the observer's Lorentz frame*



- *Quantization at Fixed Light-Front Time* τ
- *Causality: Information within causal horizon*
- *Light-Front Holography: AdS₅ = LF (3+1)*

$$\zeta^2 = x(1-x)b_\perp^2$$

$$z \leftrightarrow \zeta \text{ where } \zeta^2 = b_\perp^2 x(1-x)$$

- *Single fundamental hadronic mass scale κ: but retains the Conformal Invariance of the Action (dAFF)!*

$$U(\zeta^2) = \kappa^4 \zeta^2$$

- *Unique dilaton and color-confining LF Potential!*

$$e^{+\kappa^2 z^2}$$

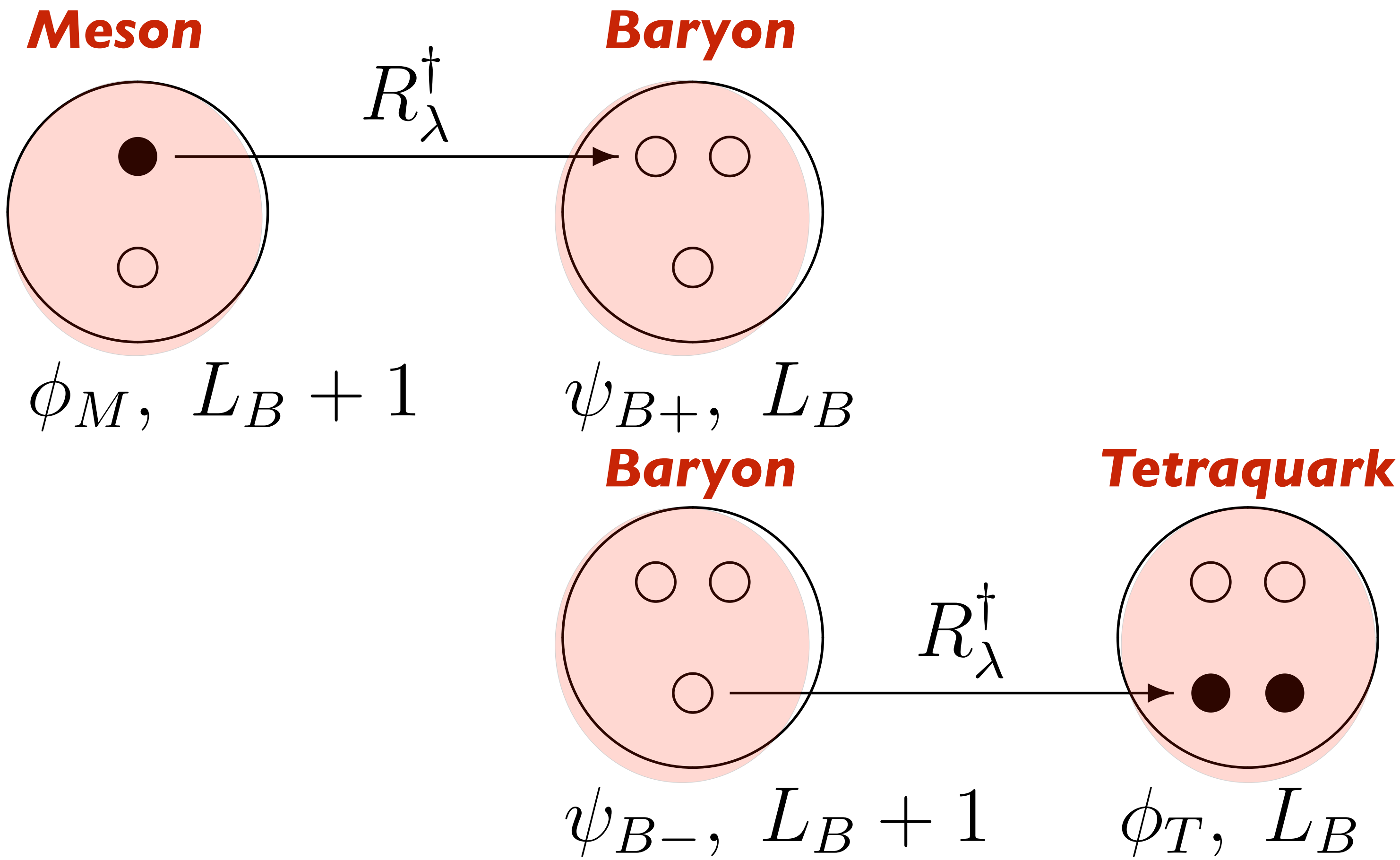
- *Superconformal Algebra: Mass Degenerate 4-Plet:*

$$\text{Meson } q\bar{q} \leftrightarrow \text{Baryon } q[qq] \leftrightarrow \text{Tetraquark } [qq][\bar{q}\bar{q}]$$

Superconformal Algebra

2X2 Hadronic Multiplets

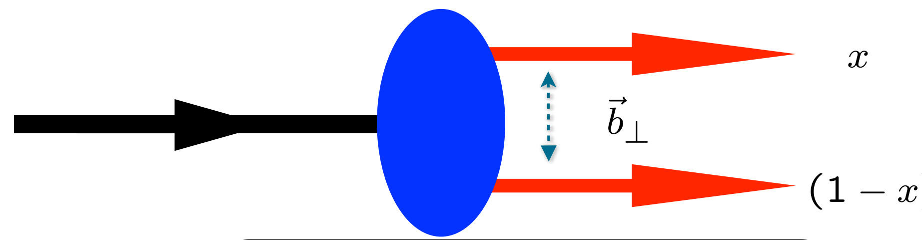
Bosons, Fermions with Equal Mass!



Proton: quark + scalar diquark $|q(qq)>$
(Equal weight: $L = 0, L = 1$)

Light-Front QCD

Fixed $\tau = t + z/c$



$$\zeta^2 = x(1-x) b_\perp^2$$

$\mathcal{L}_{QCD}$ → H^{LF}_{QCD}

$$(H^0_{LF} + H^I_{LF})|\Psi> = M^2 |\Psi>$$

Coupled Fock states

Eliminate higher Fock states and retarded interactions

$$[\frac{\vec{k}_\perp^2 + m^2}{x(1-x)} + V^{LF}_{\text{eff}}]\ \psi_{LF}(x, \vec{k}_\perp) = M^2\ \psi_{LF}(x, \vec{k}_\perp)$$

Effective two-particle equation

$$[-\frac{d^2}{d\zeta^2} + \frac{m^2}{x(1-x)} + \frac{-1+4L^2}{4\zeta^2} + U(\zeta, S, L)]\ \psi_{LF}(\zeta) = M^2\ \psi_{LF}(\zeta)$$

Azimuthal Basis

ζ, ϕ

AdS/QCD:

$$U(\zeta) = \kappa^4 \zeta^2 + 2\kappa^2(L+S-1)$$

Confining AdS/QCD potential!

Sums an infinite # diagrams

Semiclassical first approximation to QCD

Derivation of the Light-Front Radial Schrodinger Equation directly from LF QCD

$$\mathcal{M}^2 = \int_0^1 dx \int \frac{d^2\vec{k}_\perp}{16\pi^3} \frac{\vec{k}_\perp^2}{x(1-x)} \left|\psi(x,\vec{k}_\perp)\right|^2 + \text{interactions}$$

$$= \int_0^1 \frac{dx}{x(1-x)} \int d^2\vec{b}_\perp \, \psi^*(x,\vec{b}_\perp) \left(-\vec{\nabla}^2_{\vec{b}_{\perp\ell}}\right) \psi(x,\vec{b}_\perp) + \text{interactions.}$$

Change variables $(\vec{\zeta},\varphi)$, $\vec{\zeta} = \sqrt{x(1-x)}\vec{b}_\perp$: $\quad \nabla^2 = \frac{1}{\zeta}\frac{d}{d\zeta}\left(\zeta\frac{d}{d\zeta}\right) + \frac{1}{\zeta^2}\frac{\partial^2}{\partial\varphi^2}$

$$\mathcal{M}^2 = \int d\zeta \, \phi^*(\zeta)\sqrt{\zeta}\left(-\frac{d^2}{d\zeta^2} - \frac{1}{\zeta}\frac{d}{d\zeta} + \frac{L^2}{\zeta^2}\right)\frac{\phi(\zeta)}{\sqrt{\zeta}}$$

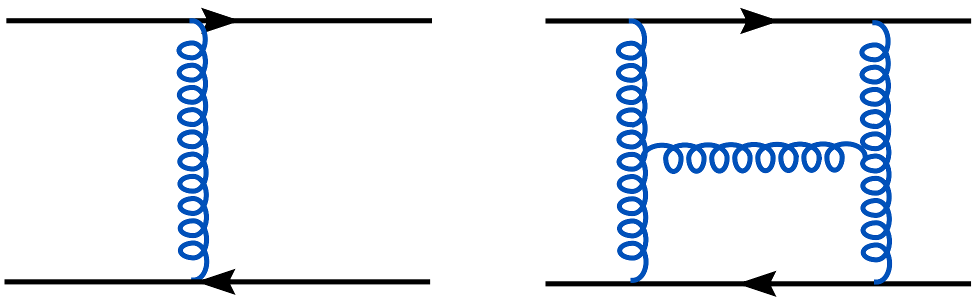
$$+ \int d\zeta \, \phi^*(\zeta) U(\zeta) \phi(\zeta)$$

$$= \int d\zeta \, \phi^*(\zeta)\left(-\frac{d^2}{d\zeta^2} - \frac{1 - 4L^2}{4\zeta^2} + U(\zeta)\right)\phi(\zeta)$$

Static Heavy Quark Potential is IR Divergent in QCD

$$V(Q^2) = -\frac{(4\pi)^2 C_F}{Q^2} a(Q^2) \Big[1 + (c_{2,0} + c_{2,1} N_f) a(Q^2) + (c_{3,0} + c_{3,1} N_f + c_{3,2} N_f^2) a(Q^2)^2$$
$$+ (c_{4,0} + c_{4,1} N_f + c_{4,2} N_f^2 + c_{4,3} N_f^3) a(Q^2)^3 + \boxed{8\pi^2 C_A^3 \ln \frac{\mu_{IR}^2}{Q^2} a(Q^2)^3} \Big]$$

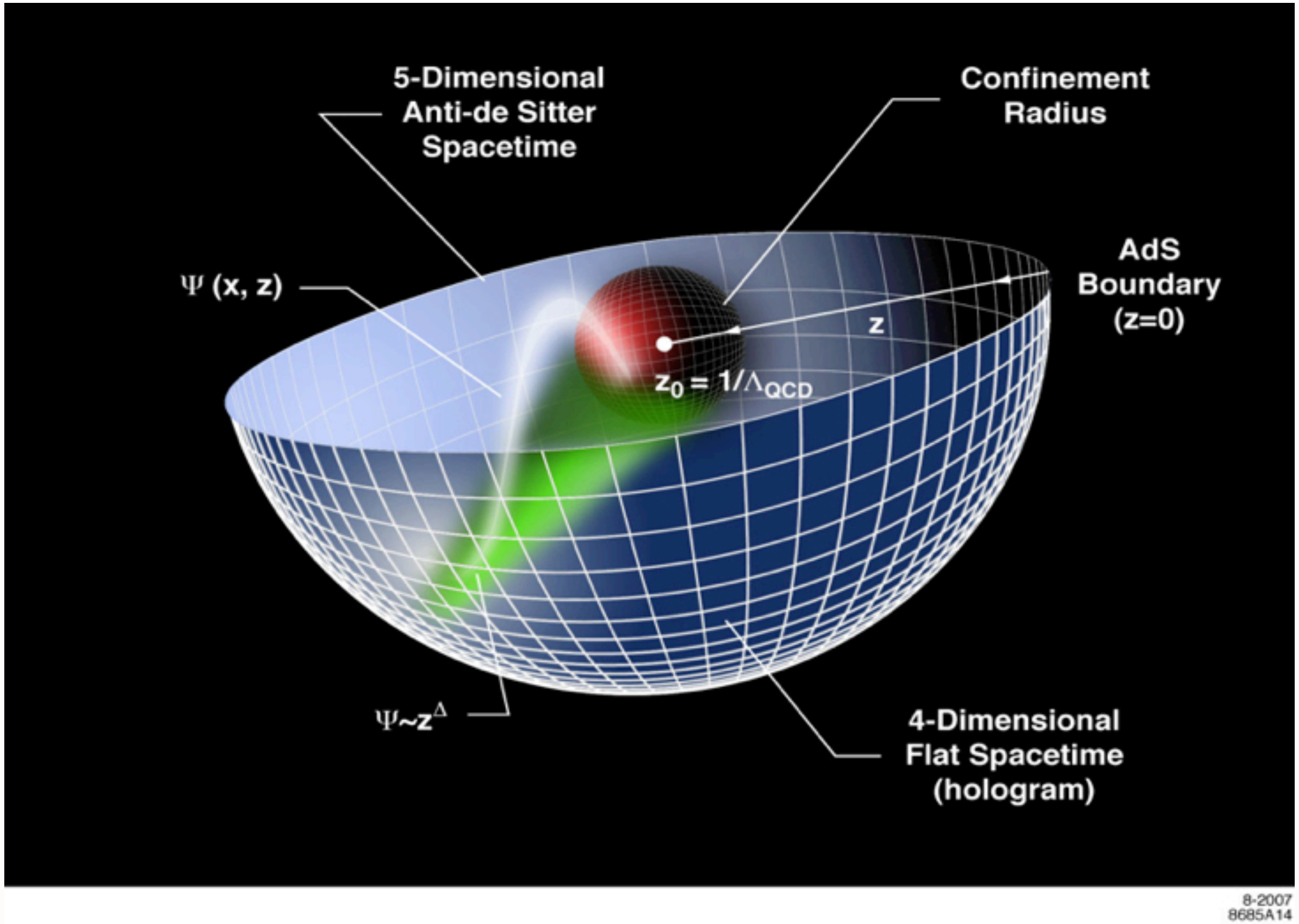
Smirnov, Smirnov, Steinhauser, 2010



$$\log \kappa^2 \zeta^2$$

Summation of H graphs: confining potential? $U(\zeta^2) = \kappa^4 \zeta^2$

Confinement eliminates IR divergences
Self-consistent mass scale?



Changes in physical length scale mapped to evolution in the 5th dimension z

- Truncated AdS/CFT (Hard-Wall) model: cut-off at $z_0 = 1/\Lambda_{\rm QCD}$ breaks conformal invariance and allows the introduction of the QCD scale (Hard-Wall Model) Polchinski and Strassler (2001).
- Smooth cutoff: introduction of a background dilaton field $\varphi(z)$ – usual linear Regge dependence can be obtained (Soft-Wall Model) Karch, Katz, Son and Stephanov (2006).

AdS/CFT

- 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.

Dilaton-Modified AdS/QCD

$$ds^2 = e^{\varphi(z)} \frac{R^2}{z^2}(\eta_{\mu\nu} x^\mu x^\nu - dz^2)$$

- **Soft-wall dilaton profile breaks conformal invariance** $e^{\varphi(z)} = e^{+\kappa^2 z^2}$
- **Color Confinement**
- **Introduces confinement scale** κ
- **Uses AdS_5 as template for conformal theory**

$$e^{\varphi(z)} = e^{+\kappa^2 z^2}$$

Positive-sign dilaton

- Dosch, de Teramond, sjb

AdS Soft-Wall Schrodinger Equation for bound state of two scalar constituents:

$$[-\frac{d^2}{dz^2} - \frac{1-4L^2}{4z^2} + U(z)]\Phi(z) = \mathcal{M}^2\Phi(z)$$

$$U(z) = \kappa^4 z^2 + 2\kappa^2(L+S-1)$$

Derived from variation of Action for Dilaton-Modified AdS_5

Identical to Light-Front Bound State Equation!

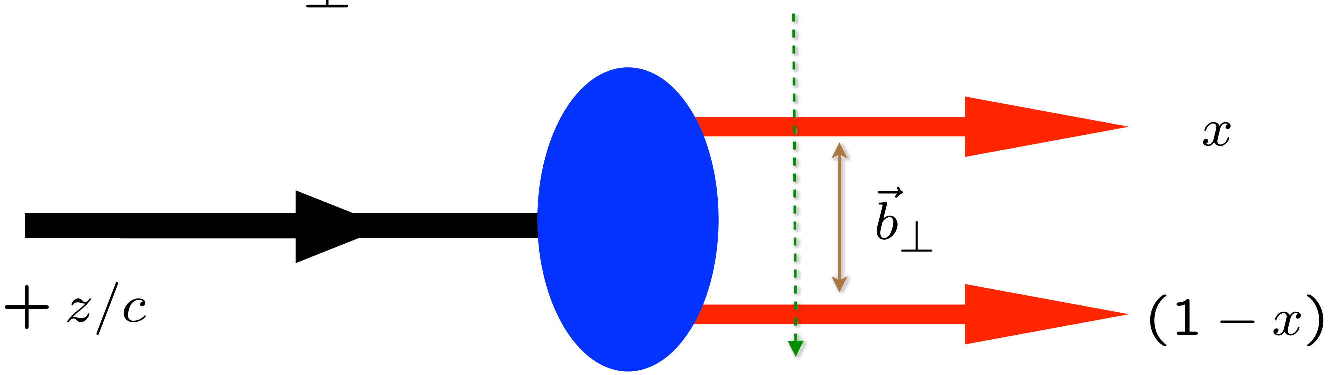
$$z \longleftrightarrow \zeta = \sqrt{x(1-x)\vec{b}_\perp^2}$$

de Teramond, sjb

$LF(3+1) \longleftrightarrow AdS_5$

$$\psi(x, \vec{b}_\perp) \longleftrightarrow \phi(z)$$

$$\zeta = \sqrt{x(1-x)\vec{b}_\perp^2} \longleftrightarrow z$$

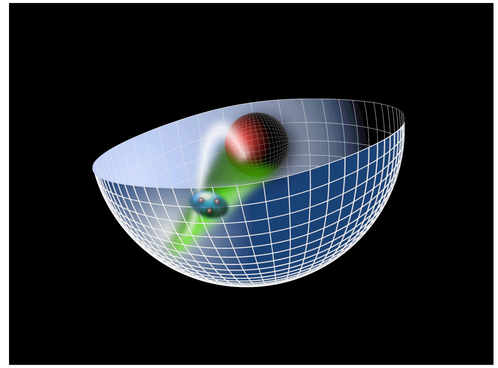


Fixed $\tau = t + z/c$

$$\psi(x, \zeta) = \sqrt{x(1-x)}\,\zeta^{-1/2}\phi(\zeta)$$

$$(\mu R)^2 = L^2 - (J-2)^2$$

Light-Front Holography: Unique mapping derived from equality of LF and AdS formula for EM and gravitational current matrix elements and identical equations of motion *de Tèramond, Dosch, Lorcè, sjb*



AdS/QCD
Soft-Wall Model

$$e^{\varphi(z)} = e^{+\kappa^2 z^2}$$

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

Light-Front Holography

$$[-\frac{d^2}{d\zeta^2} + \frac{4L^2-1}{4\zeta^2} + U(\zeta^2)]\psi = M^2\psi$$

Light-Front Schrödinger Equation

$$U(\zeta) = \kappa^4\zeta^2 + 2\kappa^2(L+S-1)$$

Unique Confinement Potential!

Conformal Symmetry of the action

Single variable ζ

Confinement scale: $\kappa \simeq 0.5 \; GeV$

- **de Alfaro, Fubini, Furlan:**
- **Fubini, Rabinovici**

Scale can appear in Hamiltonian and EQM without affecting conformal invariance of action!

Meson Spectrum in Soft Wall Model

Pion: Negative term for J=0 cancels positive terms from LFKE and potential

- Effective potential: $U(\zeta^2) = \kappa^4 \zeta^2 + 2\kappa^2 (J-1)$
- LF WE

$$\left(-\frac{d^2}{d\zeta^2} - \frac{1-4L^2}{4\zeta^2} + \kappa^4\zeta^2 + 2\kappa^2(J-1)\right)\phi_J(\zeta) = M^2\phi_J(\zeta)$$

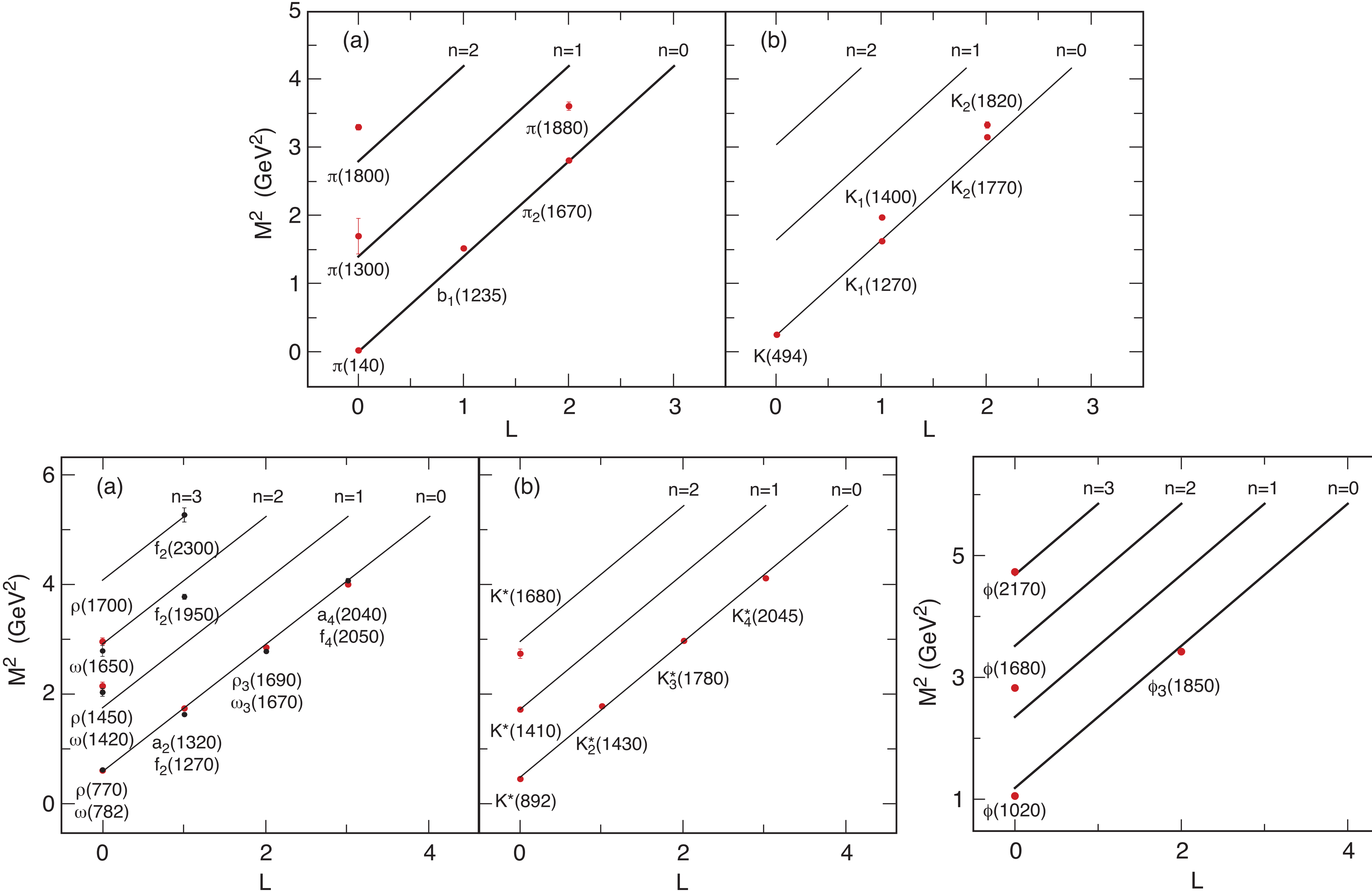
- Normalized eigenfunctions $\langle\phi|\phi\rangle = \int d\zeta \, \phi^2(z)^2 = 1$

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

- Eigenvalues

$$\mathcal{M}^2_{n,J,L} = 4\kappa^2\left(n + \frac{J+L}{2}\right)$$

G. de Teramond, H. G. Dosch, sjb



$$M^2(n, L, S) = 4\kappa^2(n + L + S/2)$$

Orbital and Radial Pseudoscalar and Vector Meson Excitations

Universal Hadronic Features

- **Universal quark light-front kinetic energy**

$$\Delta\mathcal{M}^2_{LFKE} = \kappa^2(1 + 2n + L)$$

Equal: Virial Theorem!

- **Universal quark light-front potential energy**

$$\Delta\mathcal{M}^2_{LFPE} = \kappa^2(1 + 2n + L)$$

- **Universal Constant Term**

$$\mathcal{M}^2_{spin} = 2\kappa^2(S + L - 1 + 2n_{diquark})$$

$$M^2 = \Delta\mathcal{M}^2_{LFKE} + \Delta\mathcal{M}^2_{LFPE} + \Delta\mathcal{M}^2_{spin}$$

$$+ < \sum_i \frac{m_i^2}{x_i} >$$

Remarkable Features of Light-Front Schrödinger Equation

Dynamics + Spectroscopy!

- ***Relativistic, frame-independent***
- ***QCD scale appears - unique LF potential***
- ***Reproduces spectroscopy and dynamics of light-quark hadrons with one parameter***
- ***Zero-mass pion for zero mass quarks!***
- ***Regge slope same for n and L -- not usual HO***
- ***Splitting in L persists to high mass -- contradicts conventional wisdom based on breakdown of chiral symmetry***
- ***Phenomenology: LFWFs, Form factors, electroproduction***
- ***Extension to heavy quarks***

$$U(\zeta) = \kappa^4 \zeta^2 + 2\kappa^2 (L + S - 1)$$

Connection to the Linear Instant-Form Potential

Linear instant nonrelativistic form $V(r) = Cr$ for heavy quarks

↕

Harmonic Oscillator $U(\zeta) = \kappa^4 \zeta^2$ LF Potential for relativistic light quarks

A.P. Trawinski, S.D. Glazek, H. D. Dosch, G. de Teramond, sjb

Connection to the Linear Instant-Form Potential

- Compare invariant mass in the instant-form in the hadron center-of-mass system $\mathbf{P} = 0$,

$$M^2_{q\bar{q}} = 4\,m_q^2 + 4\mathbf{p}^2$$

with the invariant mass in the front-form in the constituent rest frame, $\mathbf{k}_q + \mathbf{k}_{\overline{q}} = 0$

$$M^2_{q\bar{q}} = \frac{\mathbf{k}^2_\perp + m_q^2}{x(1-x)}$$

obtain

$$U = V^2 + 2\sqrt{\mathbf{p}^2 + m_q^2}\,V + 2\,V\sqrt{\mathbf{p}^2 + m_q^2}$$

where $\mathbf{p}^2_\perp = \frac{\mathbf{k}^2_\perp}{4x(1-x)}$, $p_3 = \frac{m_q(x-1/2)}{\sqrt{x(1-x)}}$, and V is the effective potential in the instant-form

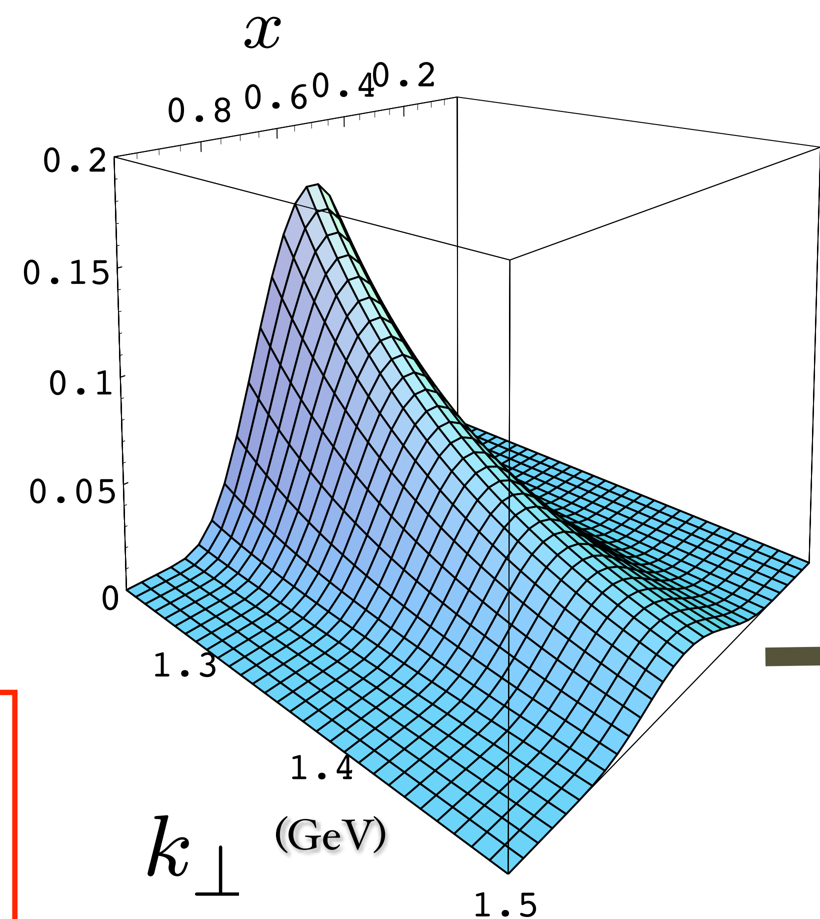
- For small quark masses a linear instant-form potential V implies a harmonic front-form potential U and thus linear Regge trajectories

A.P. Trawinski, S.D. Glazek, H. D. Dosch, G. de Teramond, sjb

Prediction from AdS/QCD: Meson LFWF

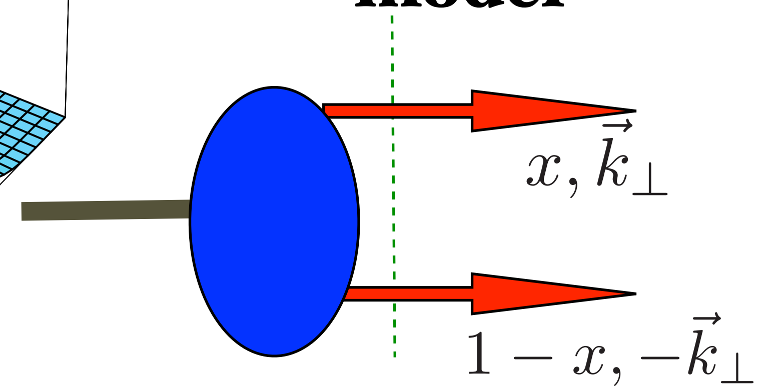
$$e^{\varphi(z)} = e^{+\kappa^2 z}$$

$$\psi_M(x, k_\perp^2)$$



de Teramond, Cao, sjb

"Soft Wall" model



massless quarks

Note coupling

$k_\perp^2, x$

$$\psi_M(x, k_\perp) = \frac{4\pi}{\kappa\sqrt{x(1-x)}} e^{-\frac{k_\perp^2}{2\kappa^2 x(1-x)}}$$

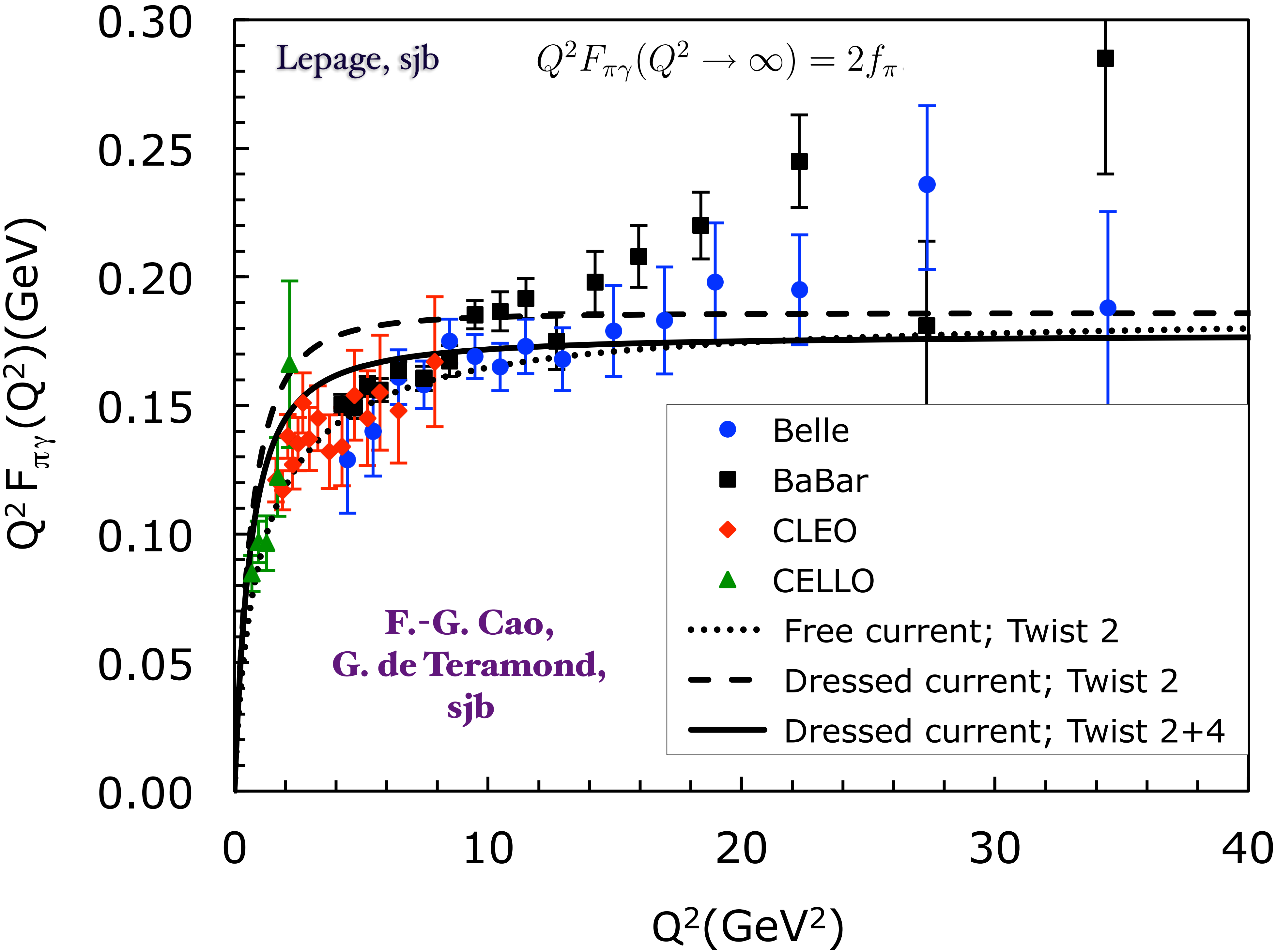
$$\phi_\pi(x) = \frac{4}{\sqrt{3}\pi} f_\pi \sqrt{x(1-x)}$$

$$f_\pi = \sqrt{P_{q\bar{q}}}\frac{\sqrt{3}}{8}\kappa = 92.4 \text{ MeV}$$

Same as DSE! **C. D. Roberts et al.**

Provides Connection of Confinement to Hadron Structure

Photon-to-pion transition form factor



$|\pi^+ >= |u\bar{d} >$

$m_u = 2\ MeV$
$m_d = 5\ MeV$

$|K^+ >= |u\bar{s} >$

$m_s = 95\ MeV$

$|D^+ >= |c\bar{d} >$

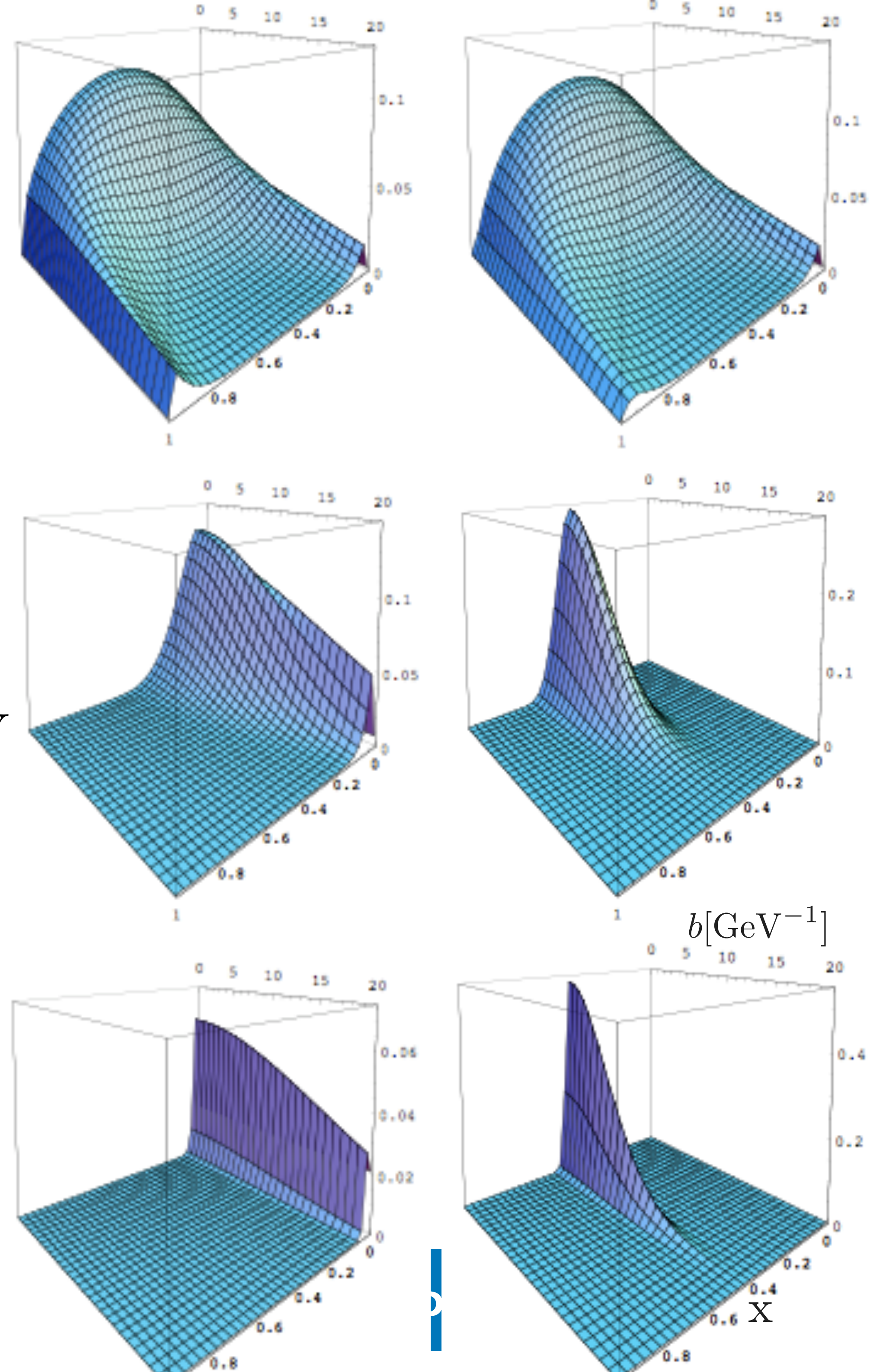
$m_c = 1.25\ GeV$

$|\eta_c >= |c\bar{c} >$

$|B^+ >= |u\bar{b} >$

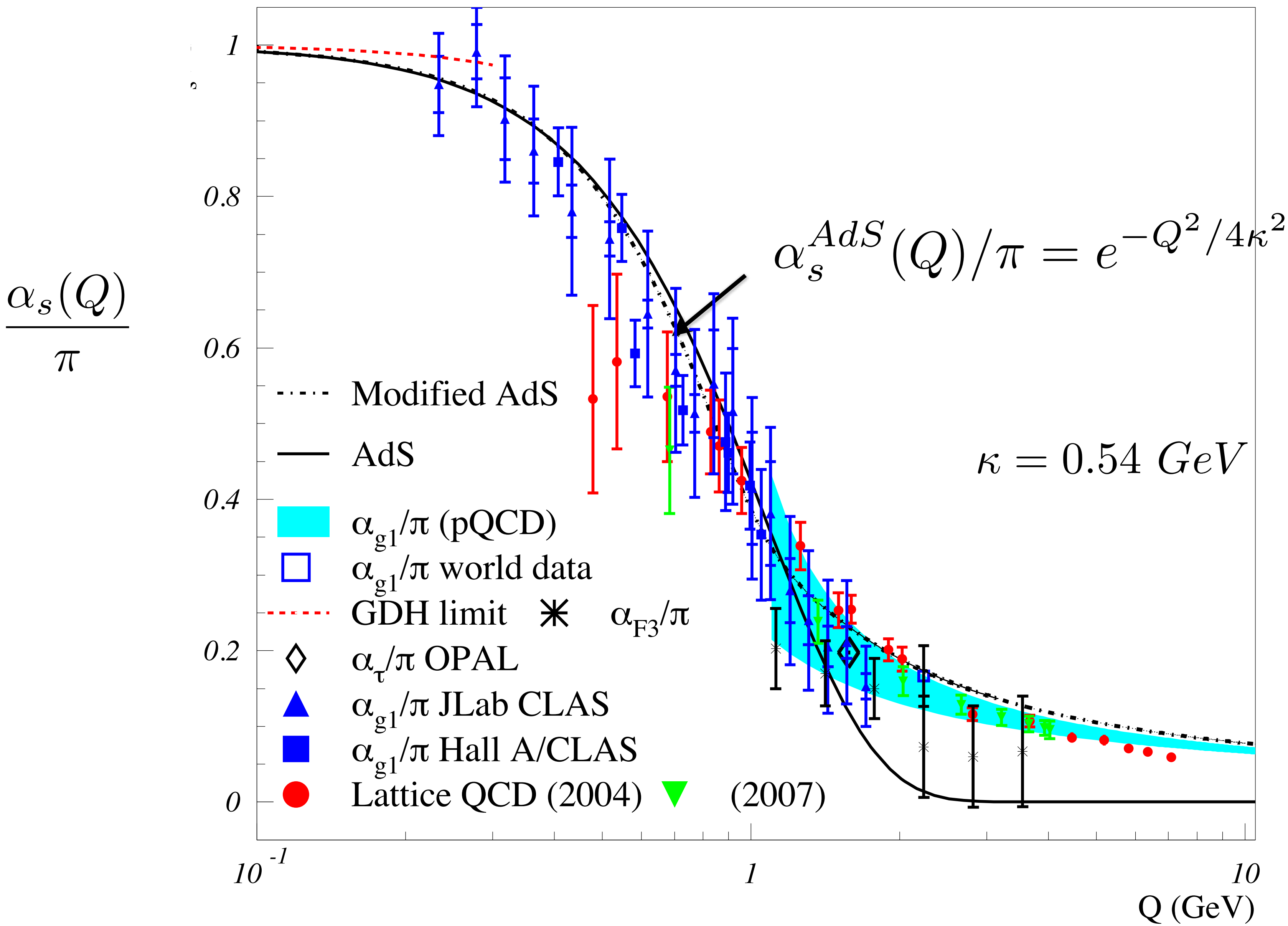
$m_b = 4.2\ GeV$

$|\eta_b >= |b\bar{b} >$



$\kappa = 375\ MeV$

Analytic, defined at all scales, IR Fixed Point



AdS/QCD dilaton captures the higher twist corrections to effective charges for Q < 1 GeV

$$e^{\varphi} = e^{+\kappa^2 z^2}$$

Deur, de Teramond, sjb

Deur, de Tèramond, sjb

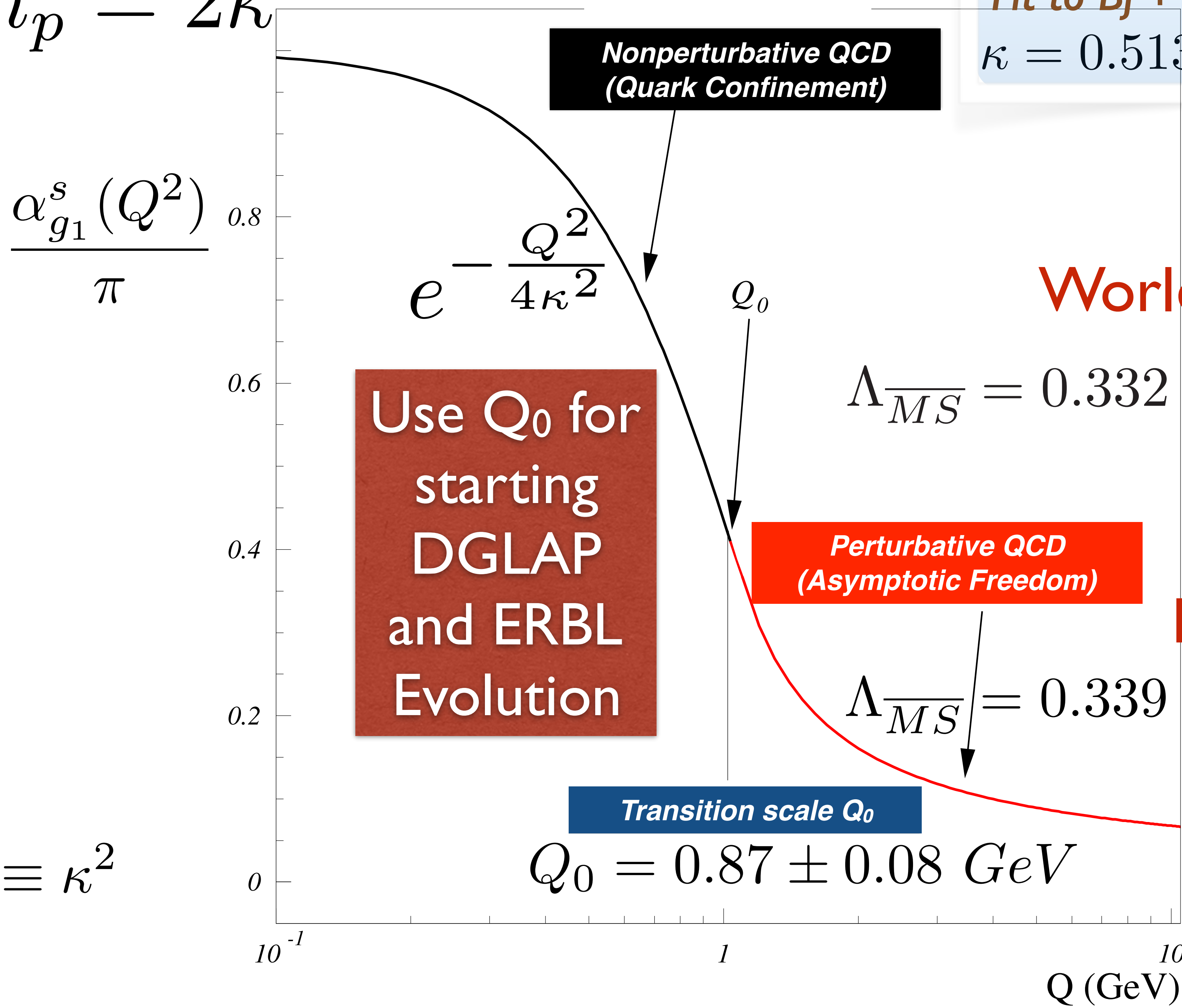
$$m_\rho = \sqrt{2}\kappa$$

$$m_p = 2\kappa$$

All-Scale QCD Coupling

Fit to Bj + DHG Sum Rules:

$$\kappa = 0.513 \pm 0.007\ GeV$$



World Data:

$$\Lambda_{\overline{MS}} = 0.332 \pm 0.017\ \text{GeV}$$

Prediction

$$\Lambda_{\overline{MS}} = 0.339 \pm 0.019\ GeV$$

$$\lambda \equiv \kappa^2$$

$$Q_0 = 0.87 \pm 0.08\ GeV$$

$\overline{MS}$ scheme

Holographic Mapping of AdS Modes to QCD LFWFs

Drell-Yan-West: Form Factors are Convolution of LFWFs

- Integrate Soper formula over angles:

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

with $\widetilde{\rho}(x, \zeta)$ QCD effective transverse charge density.

- Transversality variable

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

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

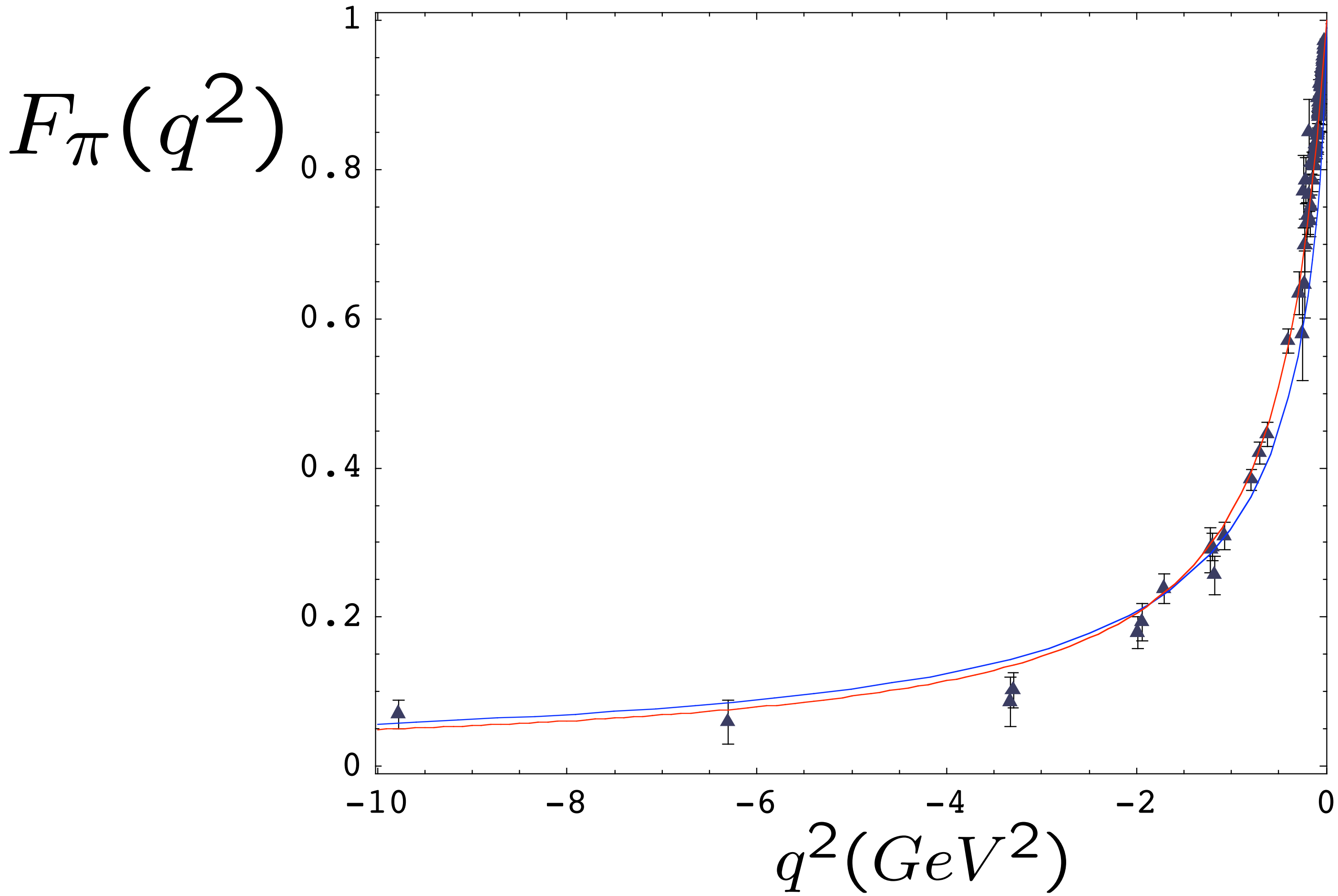
$$\int_0^1 dx J_0\left(\zeta Q \sqrt{\frac{1-x}{x}}\right) = \zeta Q K_1(\zeta Q),$$

the solution for $J(Q, \zeta) = \zeta Q K_1(\zeta Q)$!

de Teramond, sjb

Identical to Polchinski-Strassler Convolution of AdS Amplitudes

Spacelike pion form factor from AdS/CFT



Data Compilation
Baldini, Kloe and Volmer

Soft Wall: Harmonic Oscillator Confinement

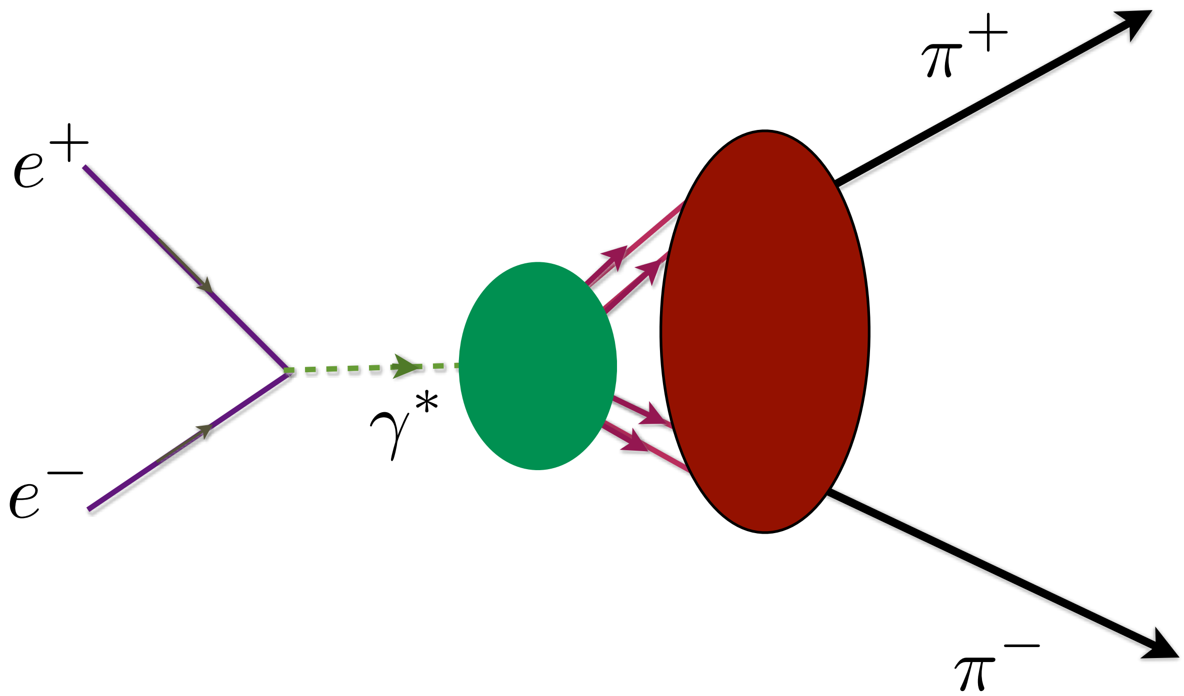
Hard Wall: Truncated Space Confinement

One parameter - set by pion decay constant

de Teramond, sjb
See also: Radyushkin

Time-like pion form factor from AdS/CFT

Dressed soft-wall current brings in higher Fock states and more vector meson poles



Current Matrix Elements in AdS Space (SW)

- Propagation of external current inside AdS space described by the AdS wave equation

$$\left[z^2\partial_z^2 - z\left(1 + 2\kappa^2 z^2\right)\partial_z - Q^2 z^2\right] J_\kappa(Q, z) = 0.$$

- Solution bulk-to-boundary propagator

$$J_\kappa(Q, z) = \Gamma\left(1 + \frac{Q^2}{4\kappa^2}\right) U\left(\frac{Q^2}{4\kappa^2}, 0, \kappa^2 z^2\right),$$

where $U(a, b, c)$ is the confluent hypergeometric function

$$\Gamma(a)U(a, b, z) = \int_0^\infty e^{-zt} t^{a-1}(1+t)^{b-a-1} dt.$$

Dressed Current in Soft-Wall Model

- Form factor in presence of the dilaton background $\varphi = \kappa^2 z^2$

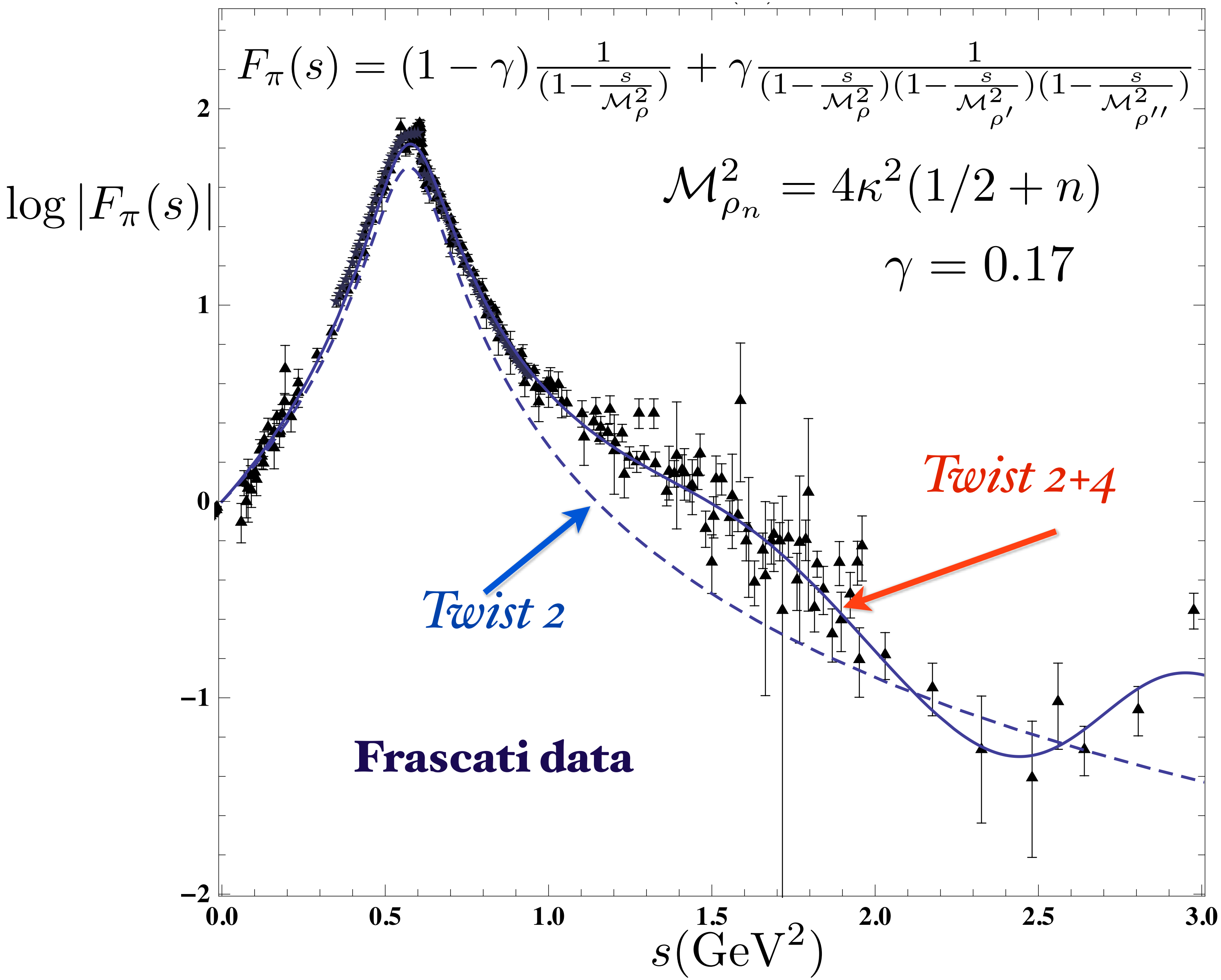
$$F(Q^2) = R^3 \int \frac{dz}{z^3}\, e^{-\kappa^2 z^2} \Phi(z) J_\kappa(Q, z) \Phi(z).$$

- For large $Q^2 \gg 4\kappa^2$

$$J_\kappa(Q, z) \to zQK_1(zQ) = J(Q, z),$$

the external current decouples from the dilaton field.

Timelike Pion Form Factor from AdS/QCD and Light-Front Holography



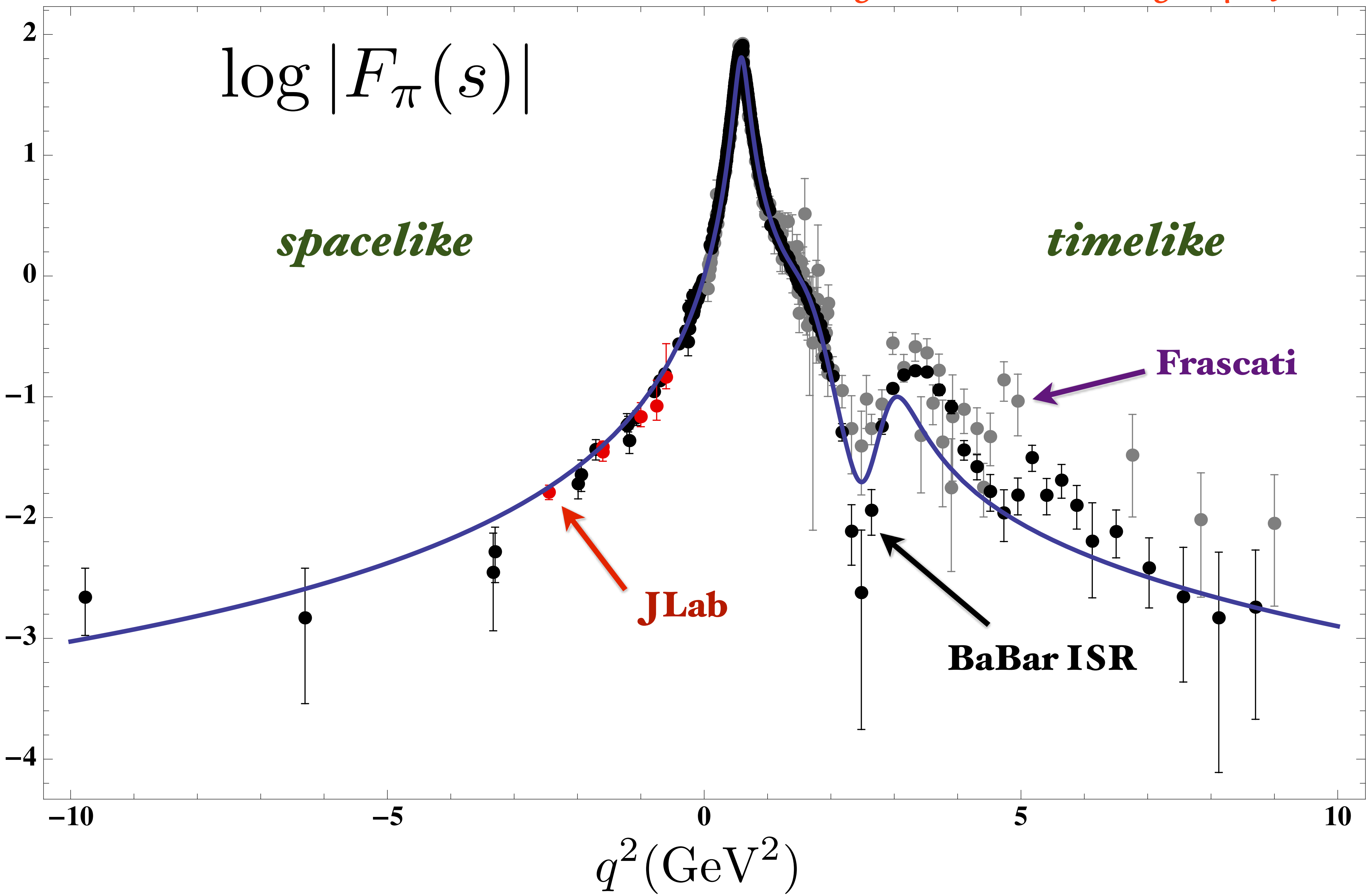
Prescription for Timelike poles :

$$\frac{1}{s - M^2 + i\sqrt{s}\Gamma}$$

14% four-quark probability

G. de Teramond & sjb

Pion Form Factor from AdS/QCD and Light-Front Holography



Form Factors in AdS/QCD

$$F(Q^2) = \frac{1}{1+\frac{Q^2}{\mathcal{M}_\rho^2}}, \quad N=2,$$

$$F(Q^2) = \frac{1}{\left(1+\frac{Q^2}{\mathcal{M}_\rho^2}\right)\left(1+\frac{Q^2}{\mathcal{M}_{\rho'}^2}\right)}, \quad N=3,$$

$$\cdots$$

$$F(Q^2) = \frac{1}{\left(1+\frac{Q^2}{\mathcal{M}_\rho^2}\right)\left(1+\frac{Q^2}{\mathcal{M}_{\rho'}^2}\right)\cdots\left(1+\frac{Q^2}{\mathcal{M}^2_{\rho^{N-2}}}\right)}, \quad N,$$

Positive Dilaton Background $\exp\left(+\kappa^2 z^2\right)$ $\quad \mathcal{M}_n^2 = 4\kappa^2\left(n+\frac{1}{2}\right)$

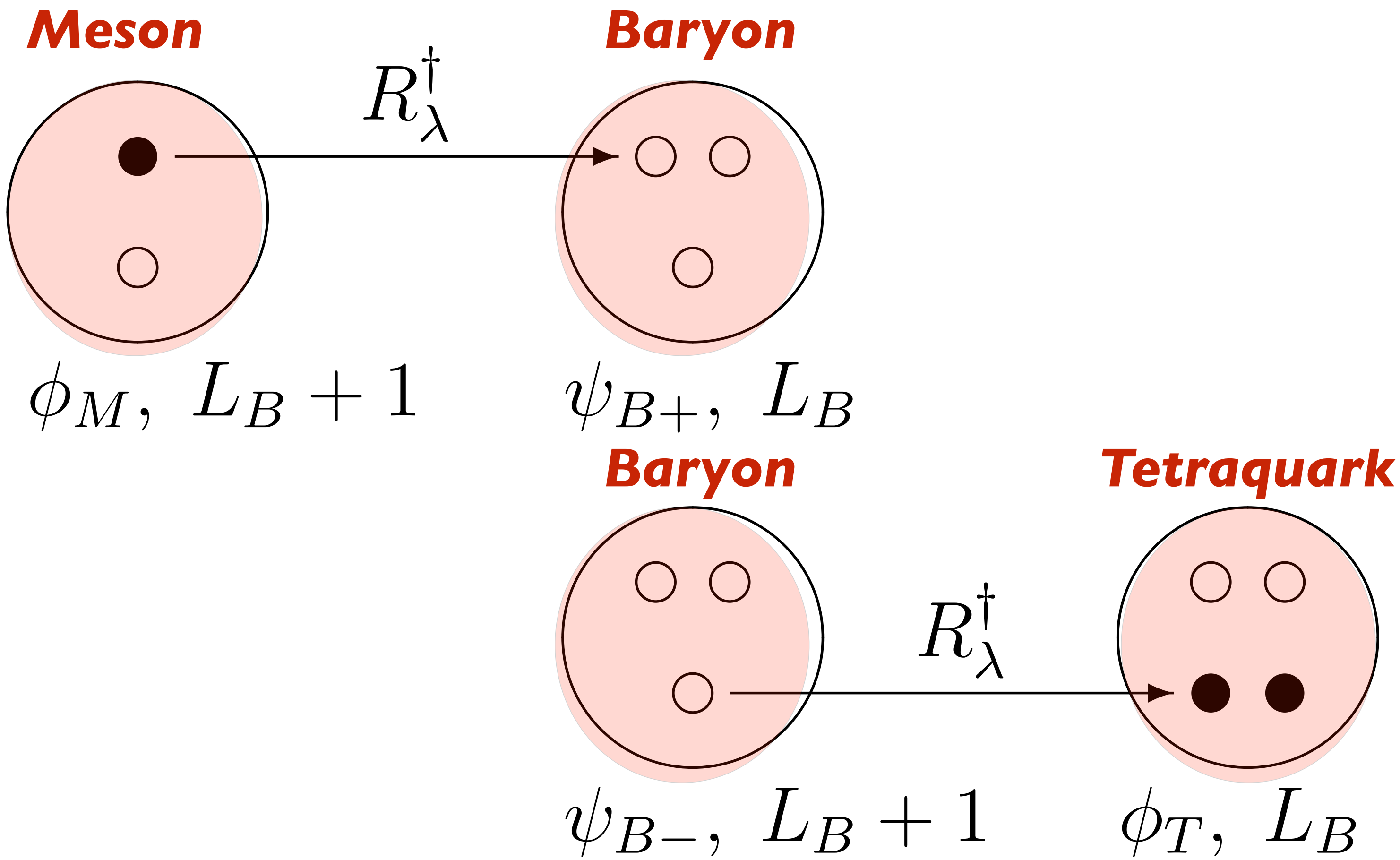
$$F(Q^2) \to (N-1)!\left[\frac{4\kappa^2}{Q^2}\right]^{(N-1)} \qquad Q^2 \to \infty$$

Constituent Counting

Superconformal Algebra

2X2 Hadronic Multiplets

Bosons, Fermions with Equal Mass!



Proton: quark + scalar diquark $|q(qq) >$
(Equal weight: $L = 0, L = 1$)

Superconformal Quantum Mechanics

Fubini and Rabinovici

Baryon Equation

$Q \simeq \sqrt{H}, \quad S \simeq \sqrt{K}$

Consider $R_w = Q + wS;$

w: dimensions of mass squared

$$G = \{R_w, R_w^+\} = 2H + 2w^2 K + 2wfI - 2wB$$

$$2B = \sigma_3$$

Retains Conformal Invariance of Action

Fubini and Rabinovici

New Extended Hamiltonian G is diagonal:

$$G_{11} = \big(-\partial_x^2 + w^2 x^2 + 2wf - w + \frac{4(f+\frac{1}{2})^2 - 1}{4x^2} \big)$$

$$G_{22} = \big(-\partial_x^2 + w^2 x^2 + 2wf + w + \frac{4(f-\frac{1}{2})^2 - 1}{4x^2} \big)$$

Identify $f - \frac{1}{2} = L_B \;, \quad w = \kappa^2$

Eigenvalue of G: $M^2(n, L) = 4\kappa^2(n + L_B + 1)$

LF Holography

Baryon Equation

Superconformal Quantum Mechanics

$$\left(-\partial_\zeta^2 + \kappa^4\zeta^2 + 2\kappa^2(L_B+1) + \frac{4L_B^2-1}{4\zeta^2}\right)\psi_J^+ = M^2\psi_J^+$$

$$\left(-\partial_\zeta^2 + \kappa^4\zeta^2 + 2\kappa^2 L_B + \frac{4(L_B+1)^2-1}{4\zeta^2}\right)\psi_J^- = M^2\psi_J^-$$

$$M^2(n, L_B) = 4\kappa^2(n + L_B + 1)$$

S=1/2, P=+

both chiralities

Meson Equation

$$\left(-\partial_\zeta^2 + \kappa^4\zeta^2 + 2\kappa^2(J-1) + \frac{4L_M^2-1}{4\zeta^2}\right)\phi_J = M^2\phi_J$$

$$M^2(n, L_M) = 4\kappa^2(n + L_M)$$

Same κ!

S=0, I=1 Meson is superpartner of S=1/2, I=1 Baryon

Meson-Baryon Degeneracy for $L_M=L_B+1$

- We write the Dirac equation

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

in terms of the matrix-valued operator Π

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

and its adjoint $\Pi^\dagger$, with commutation relations

$$\left[\Pi_\nu(\zeta), \Pi_\nu^\dagger(\zeta)\right] = \left(\frac{2\nu+1}{\zeta^2} - 2\kappa^2\right)\gamma_5.$$

- Solutions to the Dirac equation

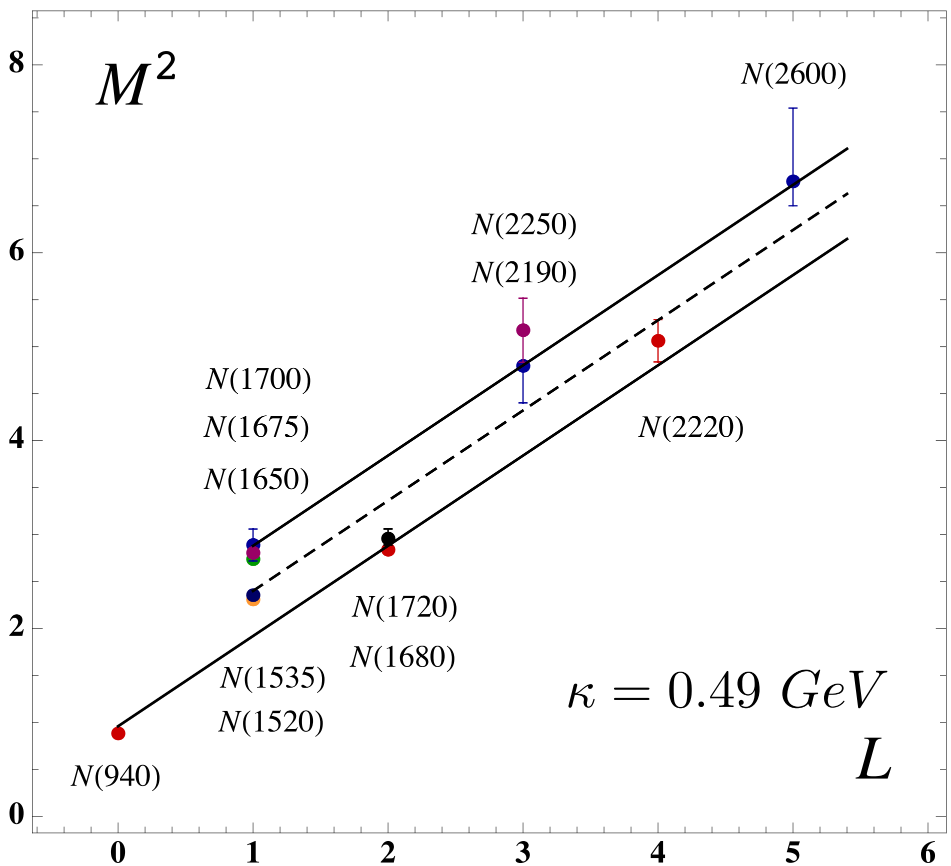
$$\psi_+(\zeta) \sim z^{\frac{1}{2}+\nu} e^{-\kappa^2\zeta^2/2} L_n^\nu(\kappa^2\zeta^2),$$
$$\psi_-(\zeta) \sim z^{\frac{3}{2}+\nu} e^{-\kappa^2\zeta^2/2} L_n^{\nu+1}(\kappa^2\zeta^2).$$

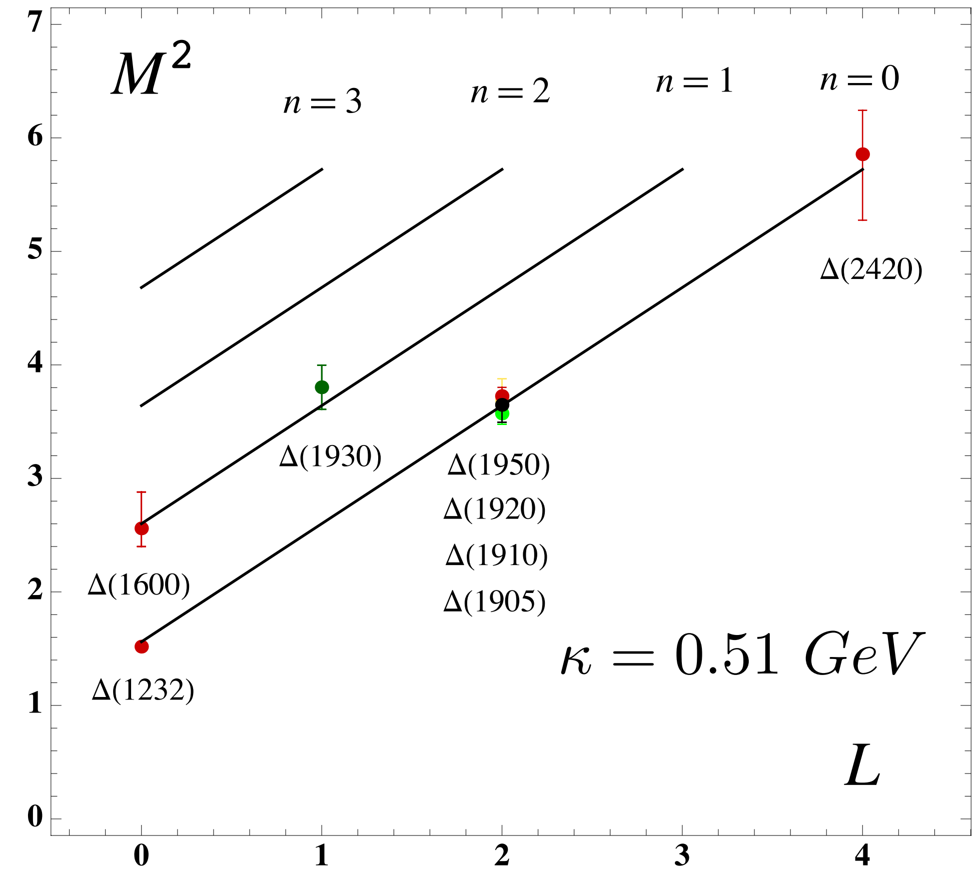
$$\nu = L + 1$$

- Eigenvalues

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

Baryon Spectroscopy from AdS/QCD and Light-Front Holography





de Teramond, sjb

$$\mathcal{M}^{2\,(+)}_{n,L,S} = 4\kappa^2\left(n + L + \frac{S}{2} + \frac{3}{4}\right), \quad \textbf{positive parity}$$

$$\mathcal{M}^{2\,(-)}_{n,L,S} = 4\kappa^2\left(n + L + \frac{S}{2} + \frac{5}{4}\right), \quad \textbf{negative parity}$$

All confirmed resonances from PDG 2012

See also Forkel, Beyer, Federico, Klempt

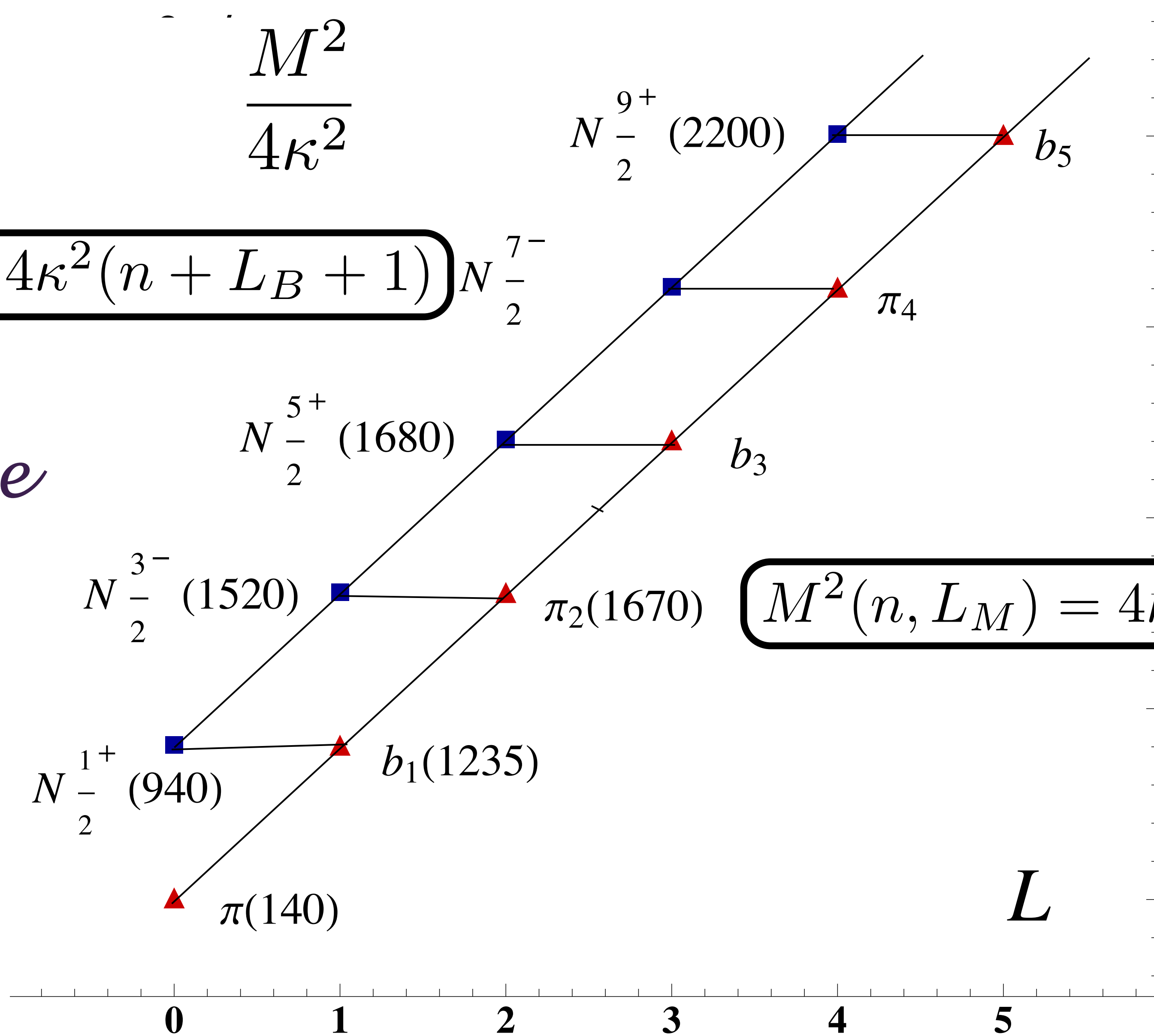
Superconformal Quantum Mechanics

de Tèramond, Dosch, sjb

$$M^2(n, L_B) = 4\kappa^2(n + L_B + 1)$$

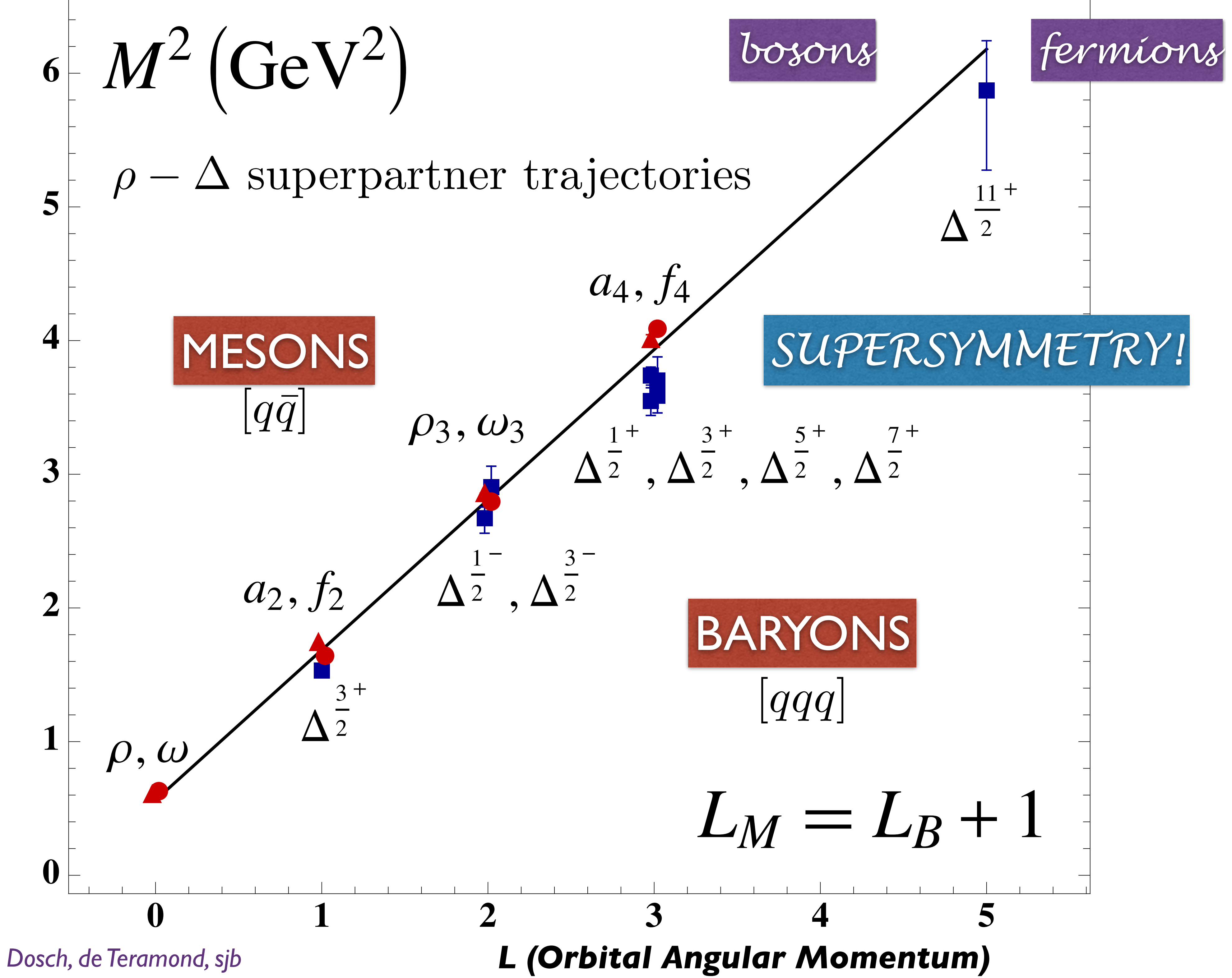
$$M^2(n, L_M) = 4\kappa^2(n + L_M)$$

Same slope



$$\frac{M^2_{meson}}{M^2_{nucleon}} = \frac{n + L_M}{n + L_B + 1}$$

Meson-Baryon Mass Degeneracy for $L_M=L_B+1$



$M^2\,(\mathrm{GeV}^2)$
bosons
fermions
$\rho - \Delta$ superpartner trajectories
$\Delta^{\frac{11}{2}^+}$
a_4, f_4
MESONS
$[q\bar{q}]$
SUPERSYMMETRY!
ρ_3, ω_3
$\Delta^{\frac{1}{2}^+}, \Delta^{\frac{3}{2}^+}, \Delta^{\frac{5}{2}^+}, \Delta^{\frac{7}{2}^+}$
$\Delta^{\frac{1}{2}^-}, \Delta^{\frac{3}{2}^-}$
a_2, f_2
BARYONS
$[qqq]$
$\Delta^{\frac{3}{2}^+}$
ρ, ω
$L_M = L_B + 1$
0
1
2
3
4
5
6
L (Orbital Angular Momentum)
Dosch, de Teramond, sjb

Meson			Baryon			Tetraquark		
q-cont	$J^{P(C)}$	Name	q-cont	J^P	Name	q-cont	$J^{P(C)}$	Name
$\bar{q}q$	0^{-+}	$\pi(140)$	—	—	—	—	—	—
$\bar{q}q$	1^{+-}	$h_1(1170)$	$[ud]q$	$(1/2)^+$	$N(940)$	$[ud][\bar{u}\bar{d}]$	0^{++}	$\sigma(500)$
$\bar{q}q$	2^{-+}	$\eta_2(1645)$	$[ud]q$	$(3/2)^-$	$N_{\frac{3}{2}^-}(1520)$	$[ud][\bar{u}\bar{d}]$	1^{-+}	—
$\bar{q}q$	1^{--}	$\rho(770),\ \omega(780)$	—	—	—	—	—	—
$\bar{q}q$	2^{++}	$a_2(1320),\ f_2(1270)$	$(qq)q$	$(3/2)^+$	$\Delta(1232)$	$(qq)[\bar{u}\bar{d}]$	1^{++}	$a_1(1260)$
$\bar{q}q$	3^{--}	$\rho_3(1690),\ \omega_3(1670)$	$(qq)q$	$(3/2)^-$	$\Delta_{\frac{3}{2}^-}(1700)$	$(qq)[\bar{u}\bar{d}]$	1^{-+}	$\pi_1(1600)$
$\bar{q}q$	4^{++}	$a_4(2040),\ f_4(2050)$	$(qq)q$	$(7/2)^+$	$\Delta_{\frac{7}{2}^+}(1950)$	$(qq)[\bar{u}\bar{d}]$	—	—
$\bar{q}s$	0^-	$K(495)$	—	—	—	—	—	—
$\bar{q}s$	1^+	$\bar{K}_1(1270)$	$[ud]s$	$(1/2)^+$	$\Lambda(1115)$	$[ud][\bar{s}\bar{q}]$	0^+	$K_0^*(1430)$
$\bar{q}s$	2^-	$K_2(1770)$	$[ud]s$	$(3/2)^-$	$\Lambda(1520)$	$[ud][\bar{s}\bar{q}]$	1^-	—
$\bar{s}q$	0^-	$K(495)$	—	—	—	—	—	—
$\bar{s}q$	1^+	$K_1(1270)$	$[sq]q$	$(1/2)^+$	$\Sigma(1190)$	$[sq][\bar{s}\bar{q}]$	0^{++}	$a_0(980)$
								$f_0(980)$
$\bar{s}q$	1^-	$K^*(890)$	—	—	—	—	—	—
$\bar{s}q$	2^+	$K_2^*(1430)$	$(sq)q$	$(3/2)^+$	$\Sigma(1385)$	$(sq)[\bar{u}\bar{d}]$	1^+	$K_1(1400)$
$\bar{s}q$	3^-	$K_3^*(1780)$	$(sq)q$	$(3/2)^-$	$\Sigma(1670)$	$(sq)[\bar{u}\bar{d}]$	2^-	$K_2(1820)$
$\bar{s}q$	4^+	$K_4^*(2045)$	$(sq)q$	$(7/2)^+$	$\Sigma(2030)$	$(sq)[\bar{u}\bar{d}]$	—	—
$\bar{s}s$	0^{-+}	$\eta'(958)$	—	—	—	—	—	—
$\bar{s}s$	1^{+-}	$h_1(1380)$	$[sq]s$	$(1/2)^+$	$\Xi(1320)$	$[sq][\bar{s}\bar{q}]$	0^{++}	$f_0(1370)$
								$a_0(1450)$
$\bar{s}s$	2^{-+}	$\eta_2(1870)$	$[sq]s$	$(3/2)^-$	$\Xi(1620)$	$[sq][\bar{s}\bar{q}]$	1^{-+}	—
$\bar{s}s$	1^{--}	$\Phi(1020)$	—	—	—	—	—	—
$\bar{s}s$	2^{++}	$f_2'(1525)$	$(sq)s$	$(3/2)^+$	$\Xi^*(1530)$	$(sq)[\bar{s}\bar{q}]$	1^{++}	$f_1(1420)$
								$a_1(1420)$
$\bar{s}s$	3^{--}	$\Phi_3(1850)$	$(sq)s$	$(3/2)^-$	$\Xi(1820)$	$(sq)[\bar{s}\bar{q}]$	—	—
$\bar{s}s$	2^{++}	$f_2(1640)$	$(ss)s$	$(3/2)^+$	$\Omega(1672)$	$(ss)[\bar{s}\bar{q}]$	1^+	$K_1(1650)$

Meson

Baryon

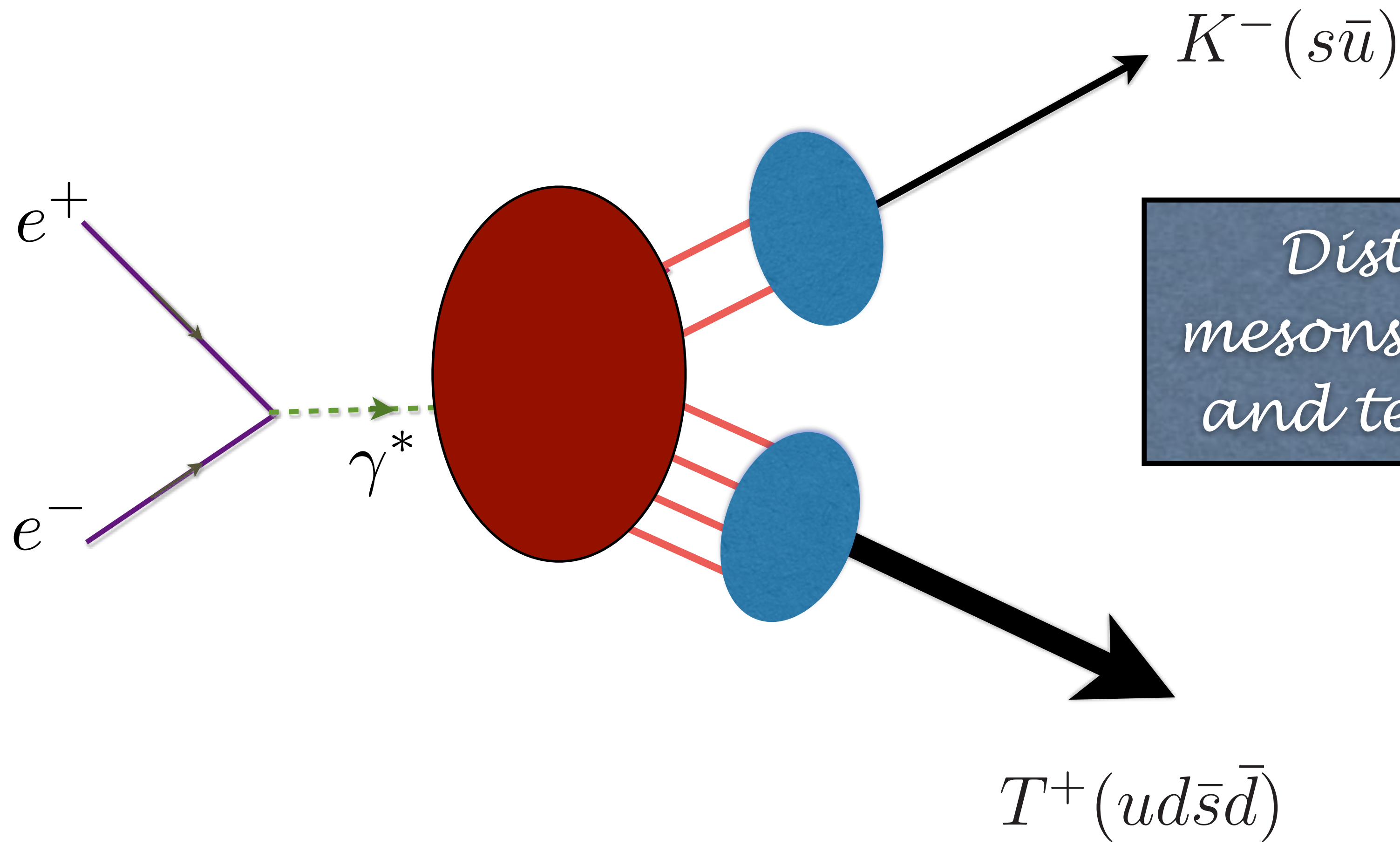
Tetraquark

New Organization of the Hadron Spectrum

M. Nielsen, sjb

Use Counting Rules to Verify Composition of Tetraquark

$$\mathcal{A}(e^+e^- \to \bar{M}(q\bar{q}) + T([qq][\bar{q}\bar{q}]) \sim \frac{1}{\sqrt{s}^{(2+4-1-1)}} = \frac{1}{s^2}$$



Distinguish mesons, glueballs, and tetraquarks

Same fall-off as $\mathcal{A}(e^+e^- \to \bar{B}(q[qq]) + B(q[\bar{q}\bar{q}]) \sim \frac{1}{\sqrt{s}^{(3+3-1-1)}} = \frac{1}{s^2}$

- Compute Dirac proton form factor using SU(6) flavor symmetry

$$F_1^p(Q^2) = R^4 \int \frac{dz}{z^4} V(Q,z) \Psi_+^2(z)$$

- Nucleon AdS wave function

$$\Psi_+(z) = \frac{\kappa^{2+L}}{R^2} \sqrt{\frac{2n!}{(n+L)!}} z^{7/2+L} L_n^{L+1}\left(\kappa^2 z^2\right) e^{-\kappa^2 z^2/2}$$

- Normalization $\quad (F_1{}^p(0) = 1, \quad V(Q=0,z) = 1)$

$$R^4 \int \frac{dz}{z^4} \Psi_+^2(z) = 1$$

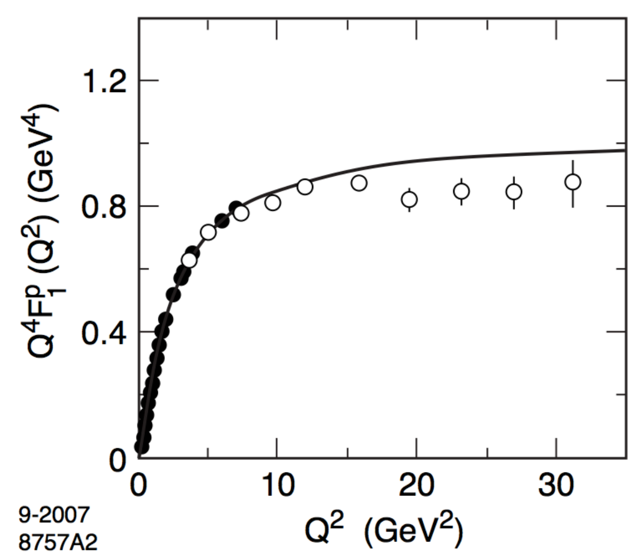
- Bulk-to-boundary propagator [Grigoryan and Radyushkin (2007)]

$$V(Q,z) = \kappa^2 z^2 \int_0^1 \frac{dx}{(1-x)^2} \, x^{\frac{Q^2}{4\kappa^2}} e^{-\kappa^2 z^2 x/(1-x)}$$

- Find

$$F_1^p(Q^2) = \frac{1}{\left(1+\frac{Q^2}{\mathcal{M}_\rho^2}\right)\left(1+\frac{Q^2}{\mathcal{M}_{\rho'}^2}\right)}$$

with $\mathcal{M}_{\rho_n}^2 \to 4\kappa^2(n+1/2)$



Space-Like Dirac Proton Form Factor

- Consider the spin non-flip form factors

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

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

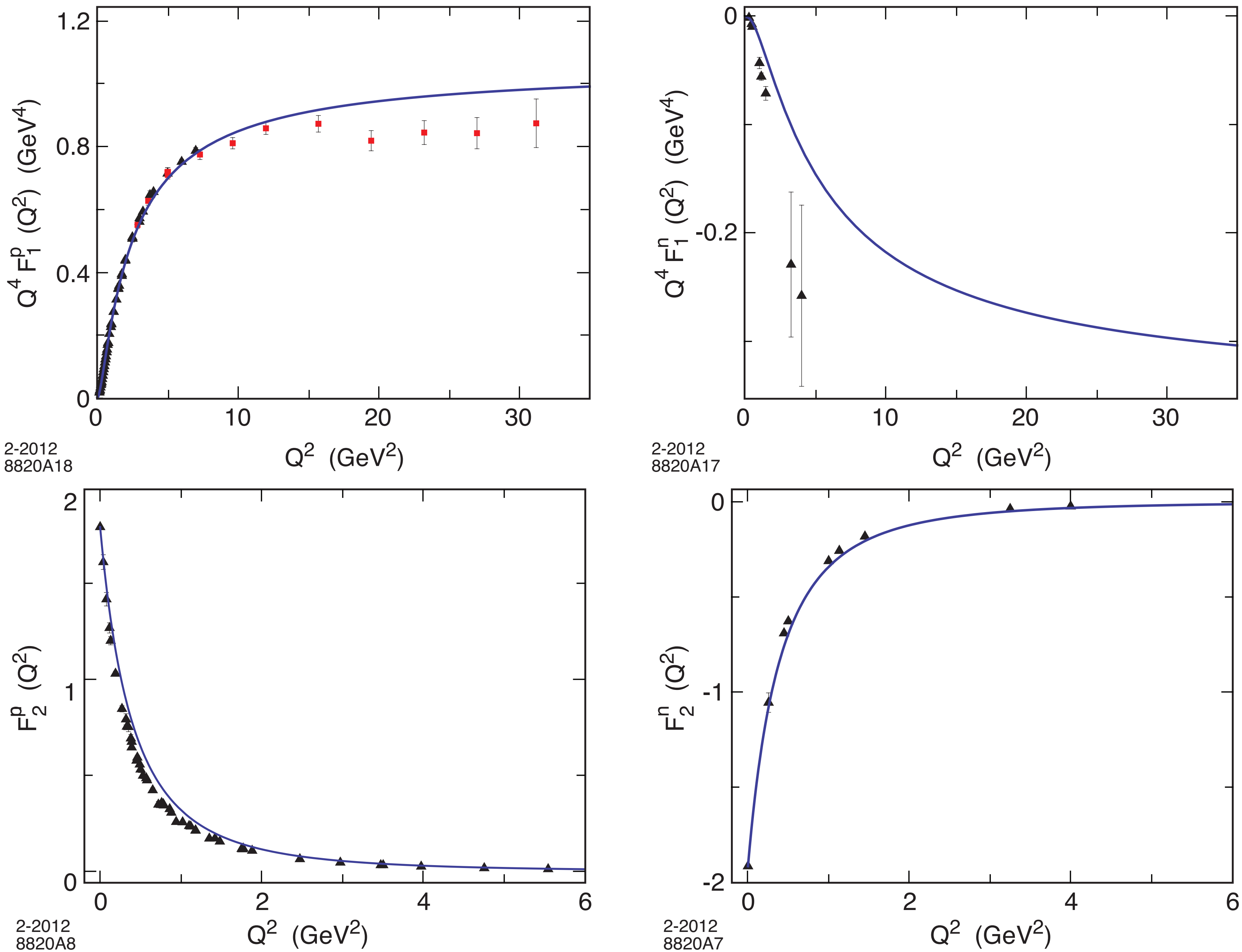
- Choose the struck quark to have $S^z = +1/2$. The two AdS solutions $\psi_+(\zeta)$ and $\psi_-(\zeta)$ correspond to nucleons with $J^z = +1/2$ and $-1/2$.

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

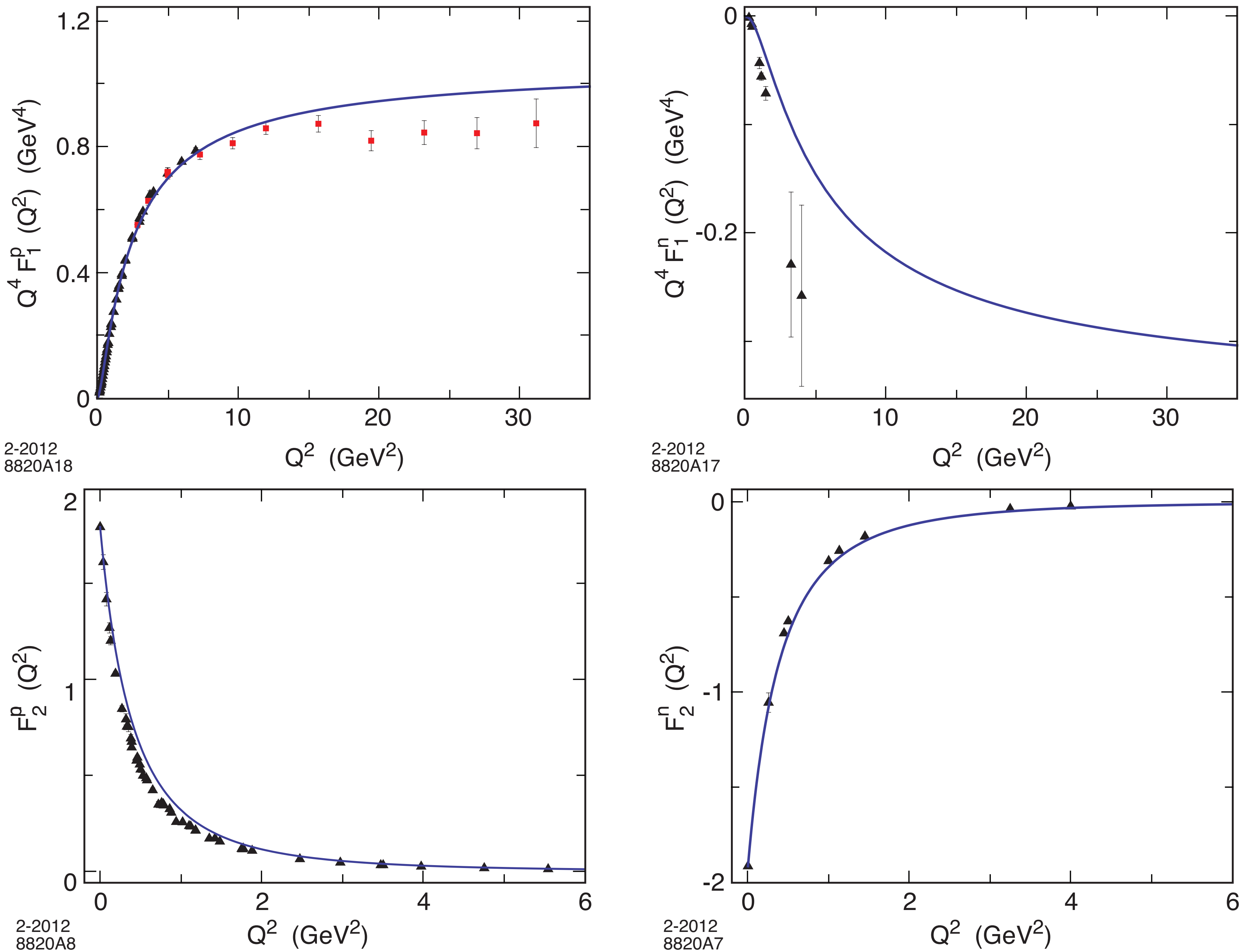
$$F_1^p(Q^2) = \int d\zeta\, J(Q,\zeta) |\psi_+(\zeta)|^2,$$
$$F_1^n(Q^2) = -\frac{1}{3} \int d\zeta\, J(Q,\zeta) \left[|\psi_+(\zeta)|^2 - |\psi_-(\zeta)|^2\right],$$

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

Using $SU(6)$ flavor symmetry and normalization to static quantities

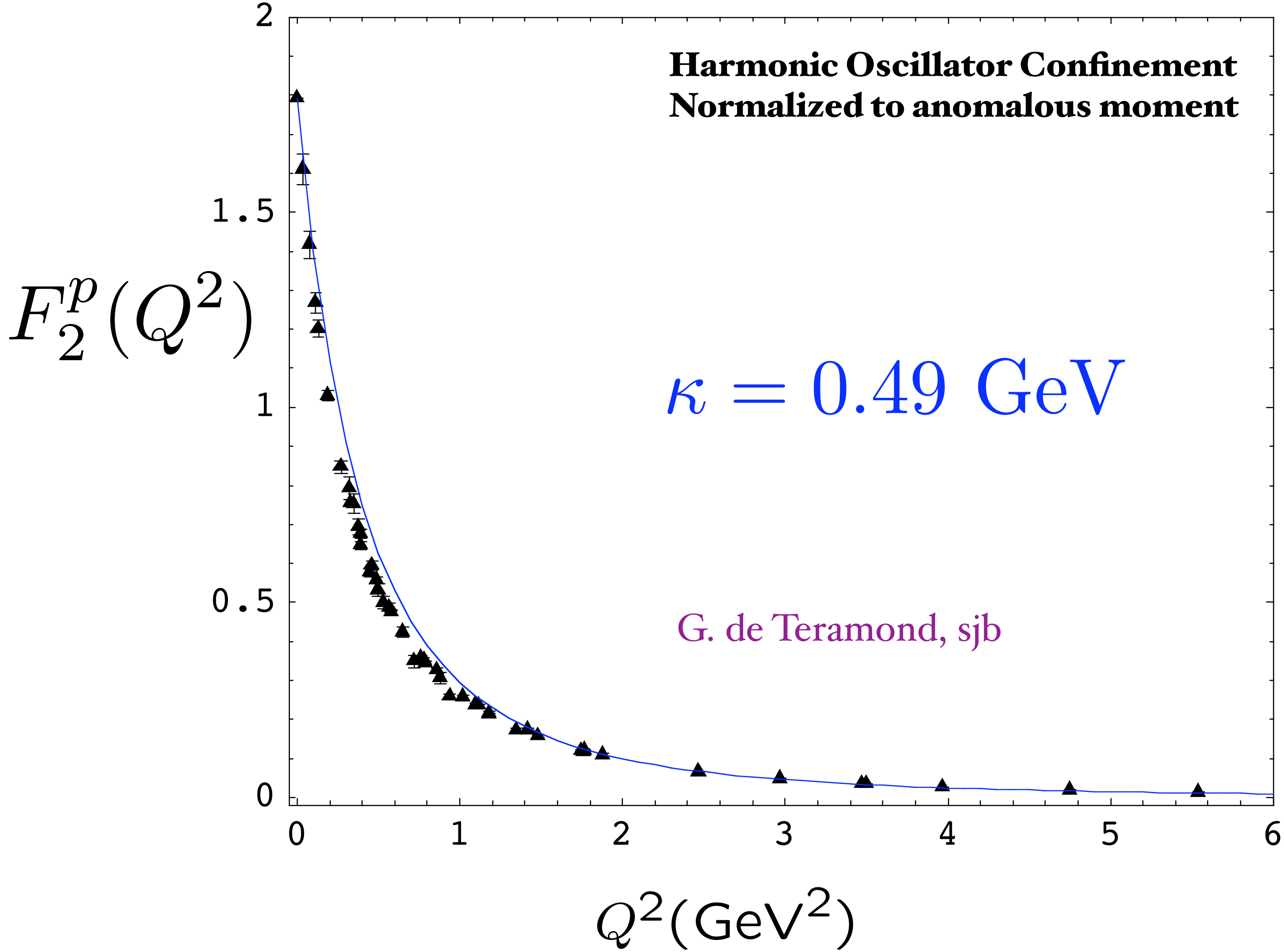


Using $SU(6)$ flavor symmetry and normalization to static quantities



Spacelike Pauli Form Factor

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



Nucleon structure in a light-front quark model consistent with quark counting rules and data

Gutsche, Lyubovitskij, Schmidt Vega

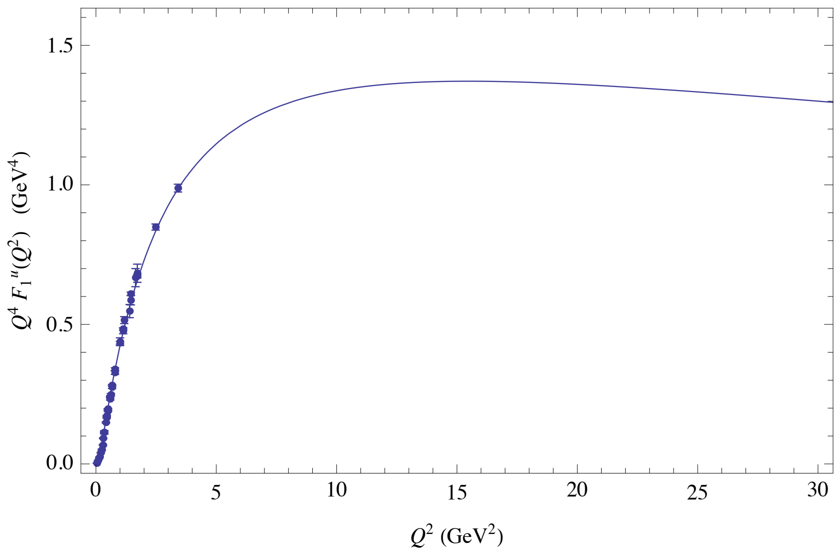


FIG. 9: Dirac u quark form factor multiplied by Q^4.

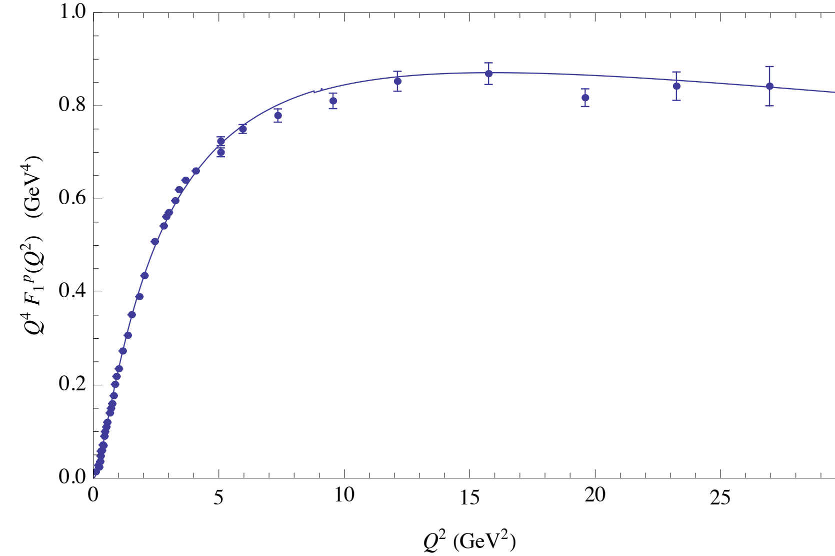


FIG. 13: Dirac proton form factor multiplied by Q^4.

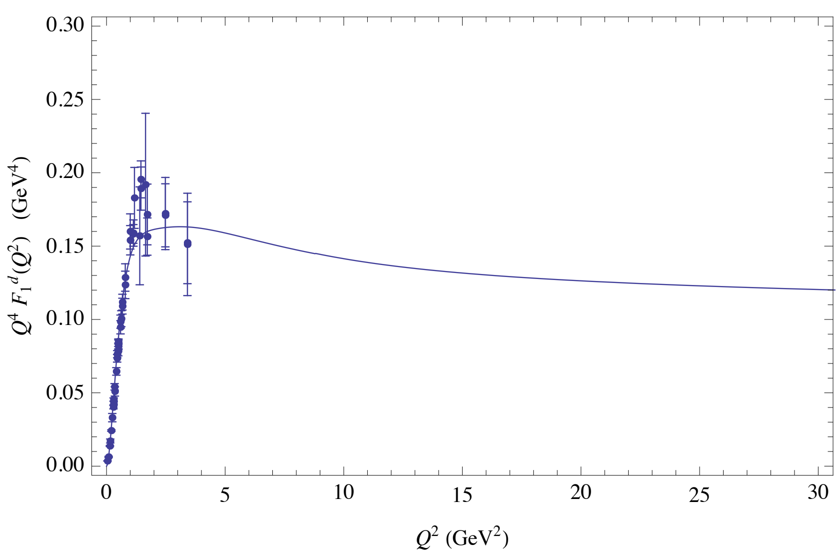


FIG. 10: Dirac d quark form factor multiplied by Q^4.

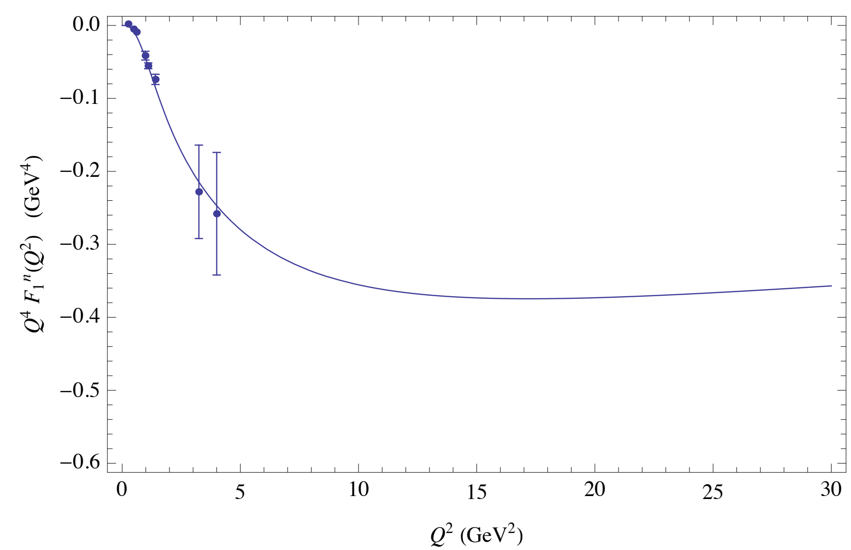
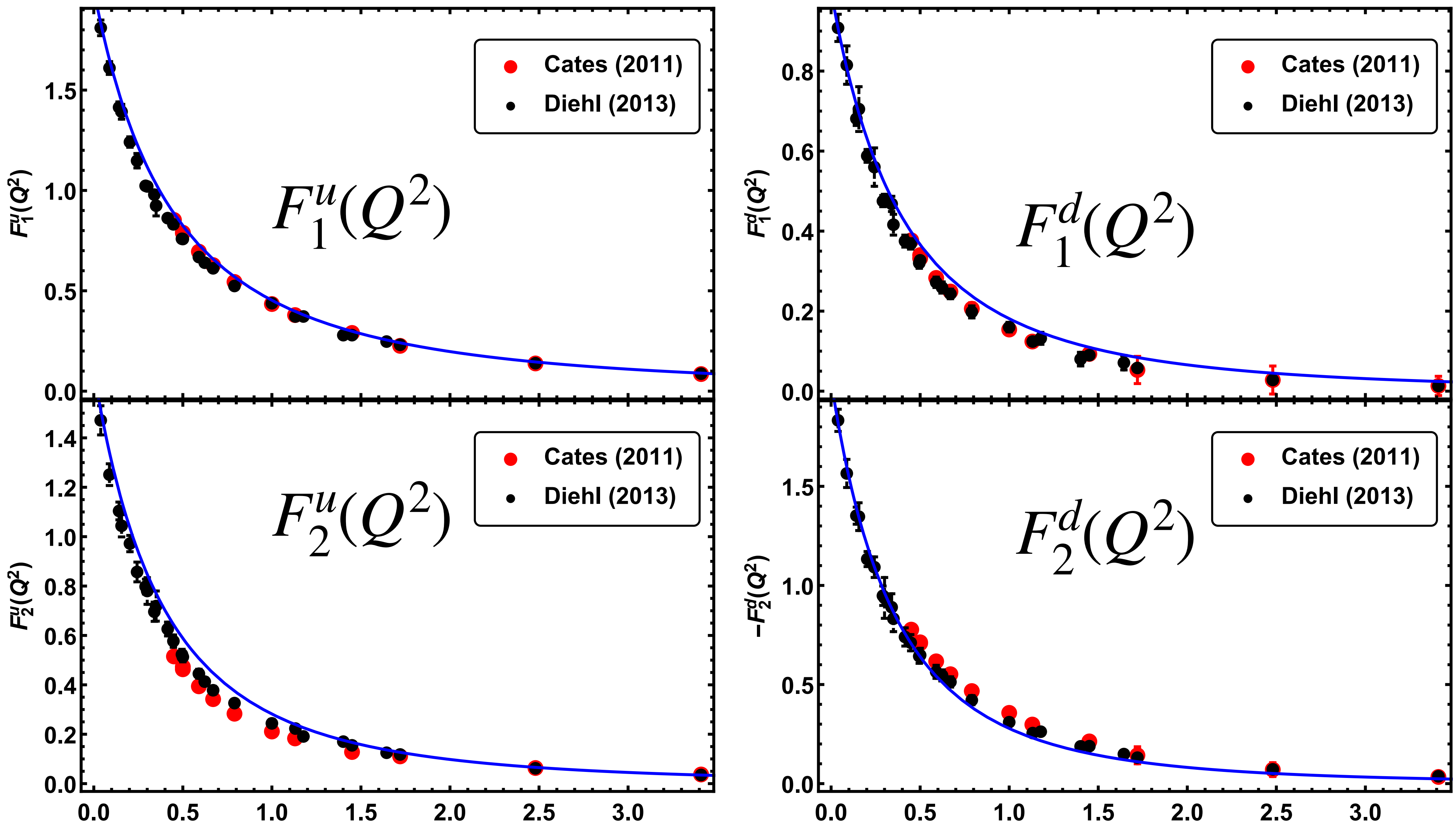


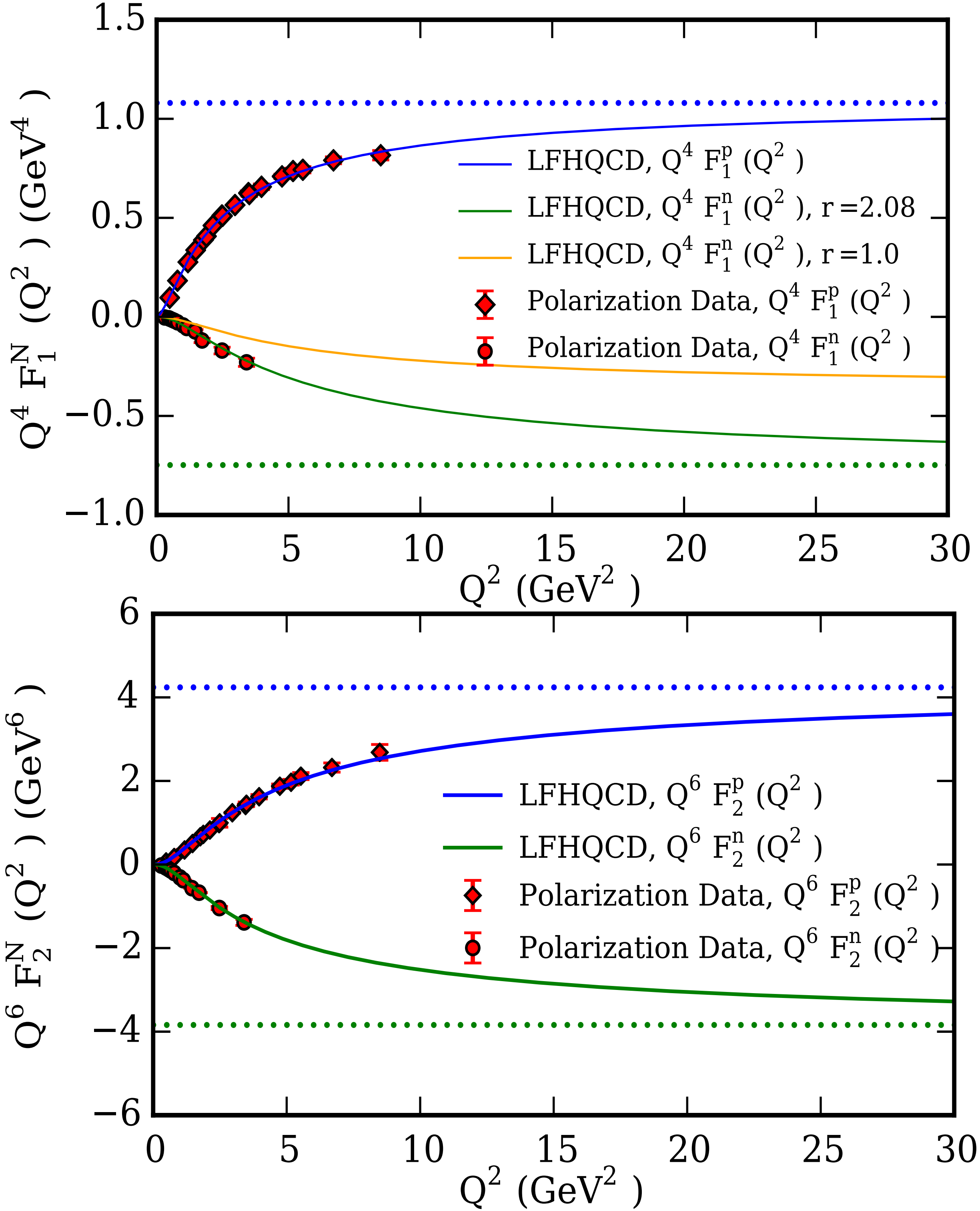
FIG. 14: Dirac neutron form factor multiplied by Q^4.

LFHQCD predictions for Nucleon Form Factors



From Neetika Sharma

Sufian, de Teramond, Deur, Dosch, sjb



$Q^4 F_1^p(Q^2)$

$Q^4 F_1^n(Q^2)$

Includes 5-quark Fock states

$Q^6 F_2^p(Q^2)$

$Q^6 F_2^n(Q^2)$

Form Factors in AdS/QCD

$$F(Q^2) = \frac{1}{1 + \frac{Q^2}{\mathcal{M}_\rho^2}}, \quad N = 2,$$

$$F(Q^2) = \frac{1}{\left(1 + \frac{Q^2}{\mathcal{M}_\rho^2}\right)\left(1 + \frac{Q^2}{\mathcal{M}_{\rho'}^2}\right)}, \quad N = 3,$$

$$\cdots$$

$$F(Q^2) = \frac{1}{\left(1 + \frac{Q^2}{\mathcal{M}_\rho^2}\right)\left(1 + \frac{Q^2}{\mathcal{M}_{\rho'}^2}\right)\cdots\left(1 + \frac{Q^2}{\mathcal{M}_{\rho^{N-2}}^2}\right)}, \quad N,$$

Positive Dilaton Background $\exp\left(+\kappa^2 z^2\right)$ $\qquad \mathcal{M}_n^2 = 4\kappa^2\left(n + \frac{1}{2}\right)$

$$F(Q^2) \to (N-1)!\left[\frac{4\kappa^2}{Q^2}\right]^{(N-1)} \qquad Q^2 \to \infty$$

Constituent Counting

Nucleon Transition Form Factors

- Compute spin non-flip EM transition $N(940) \to N^*(1440)$: $\Psi_+^{n=0,L=0} \to \Psi_+^{n=1,L=0}$

- Transition form factor

$$F_{1\,N\to N^*}^{\,p}(Q^2) = R^4 \int \frac{dz}{z^4}\, \Psi_+^{n=1,L=0}(z) V(Q,z) \Psi_+^{n=0,L=0}(z)$$

- Orthonormality of Laguerre functions $\left(F_{1\,N\to N^*}^{\,p}(0) = 0, \quad V(Q=0,z) = 1\right)$

$$R^4 \int \frac{dz}{z^4}\, \Psi_+^{n',L}(z) \Psi_+^{n,L}(z) = \delta_{n,n'}$$

- Find

$$F_{1\,N\to N^*}^{\,p}(Q^2) = \frac{2\sqrt{2}}{3} \frac{\frac{Q^2}{M_P^2}}{\left(1+\frac{Q^2}{\mathcal{M}_\rho^2}\right)\left(1+\frac{Q^2}{\mathcal{M}_{\rho'}^2}\right)\left(1+\frac{Q^2}{\mathcal{M}_{\rho''}^2}\right)}$$

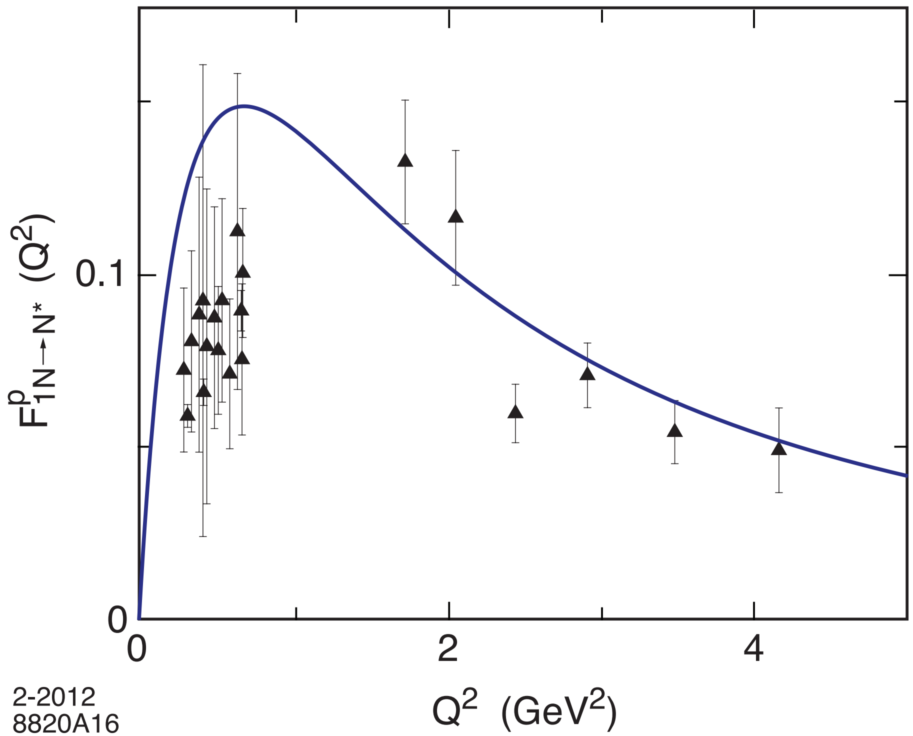
with ${\mathcal{M}_{\rho_n}}^2 \to 4\kappa^2(n+1/2)$

de Teramond, sjb

Consistent with counting rule, twist 3

Nucleon Transition Form Factors

$$F^{p}_{1\,N\to N^*}(Q^2) = \frac{\sqrt{2}}{3} \frac{\frac{Q^2}{\mathcal{M}_\rho^2}}{\left(1+\frac{Q^2}{\mathcal{M}_\rho^2}\right)\left(1+\frac{Q^2}{\mathcal{M}_{\rho'}^2}\right)\left(1+\frac{Q^2}{\mathcal{M}_{\rho''}^2}\right)}.$$

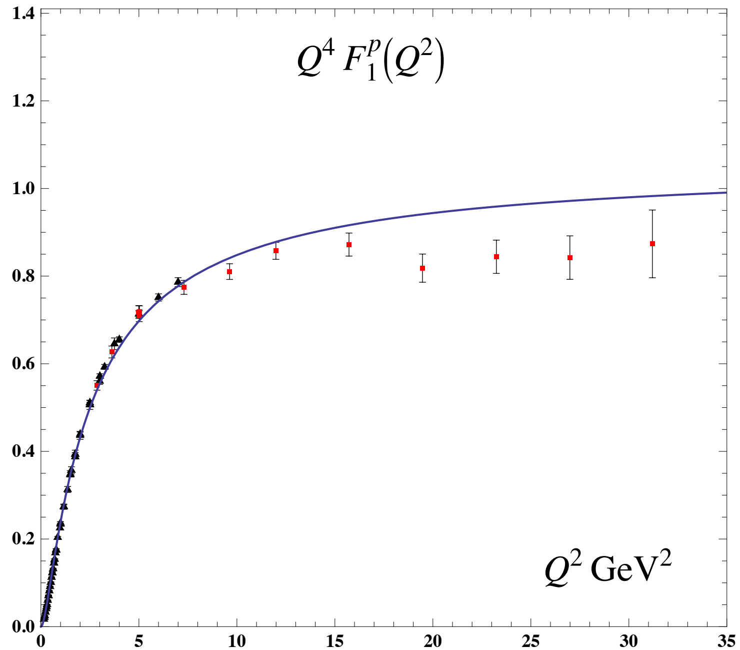


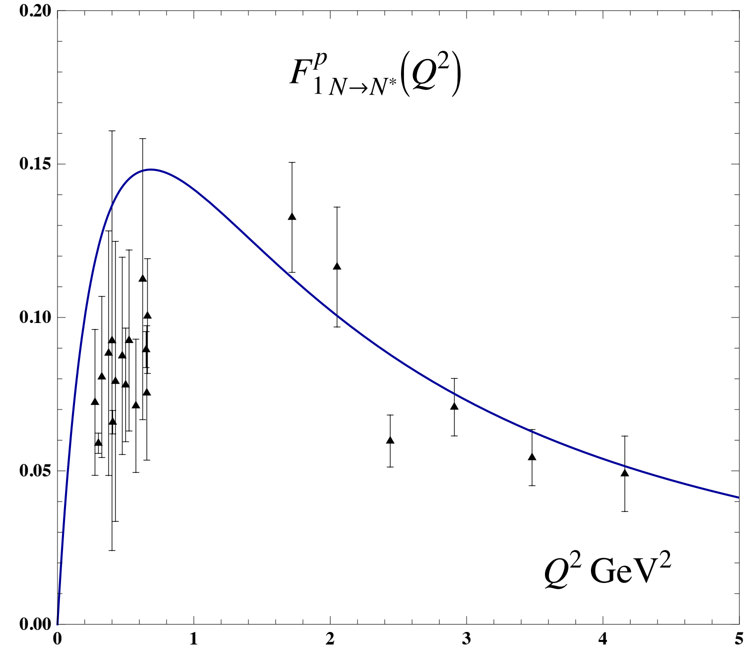
Proton transition form factor to the first radial excited state. Data from JLab

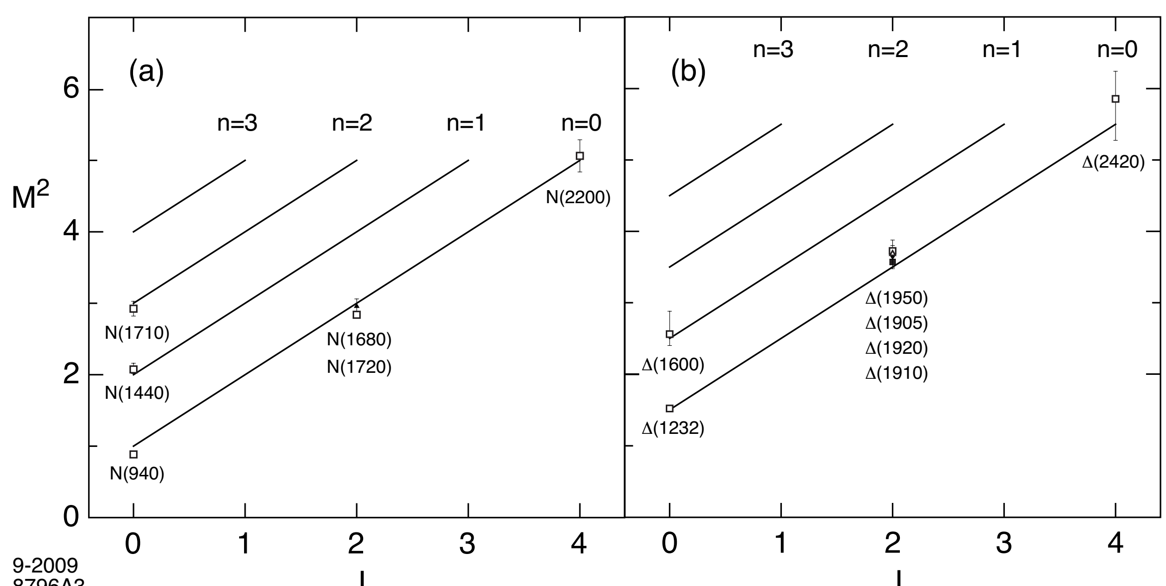
Predict hadron spectroscopy and dynamics

Excited Baryons in Holographic QCD

G. de Teramond & sjb



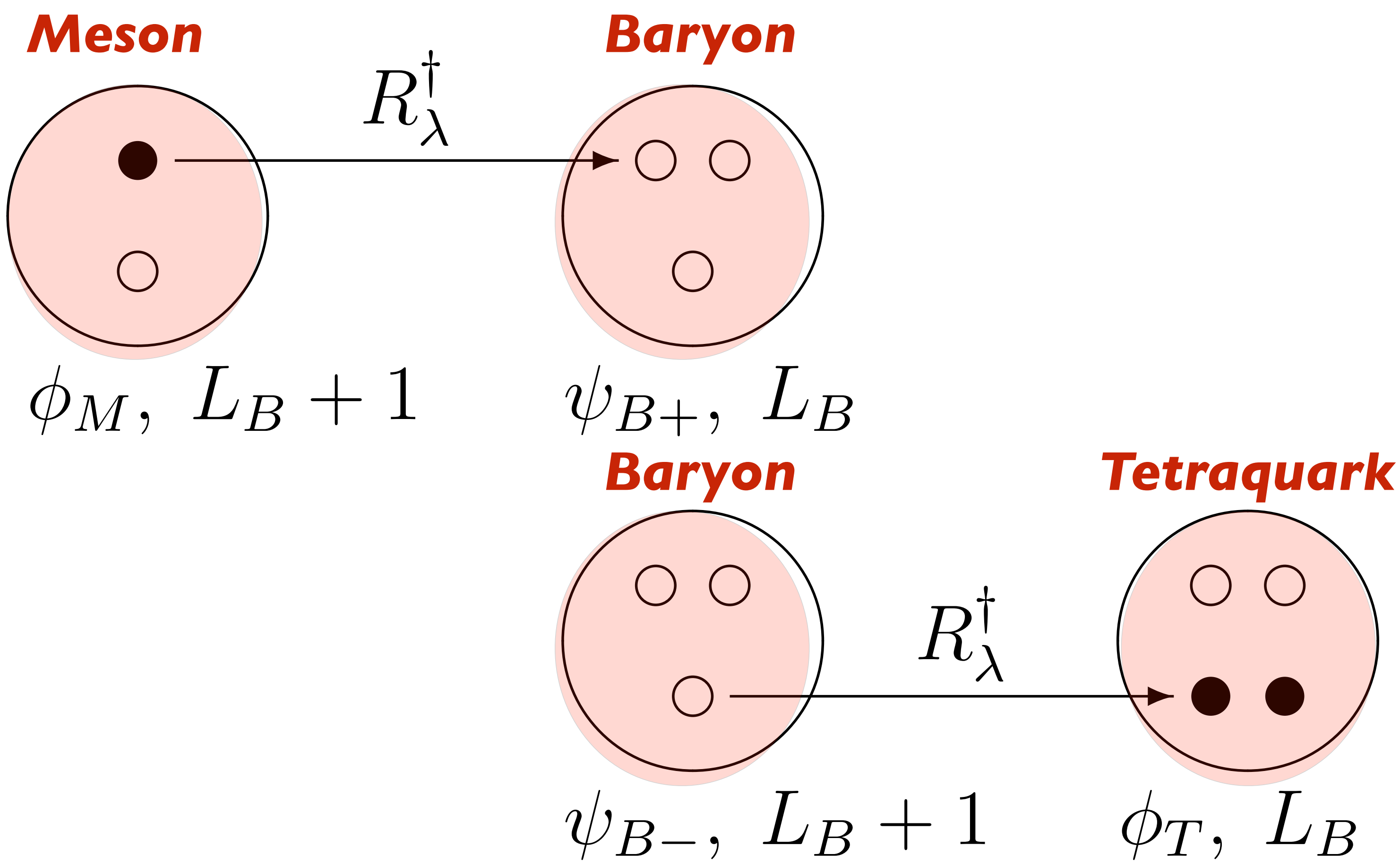




Superconformal Algebra

2X2 Hadronic Multiplets

Bosons, Fermions with Equal Mass!



Proton: quark + scalar diquark $|q(qq) >$
(Equal weight: $L = 0, L = 1$)

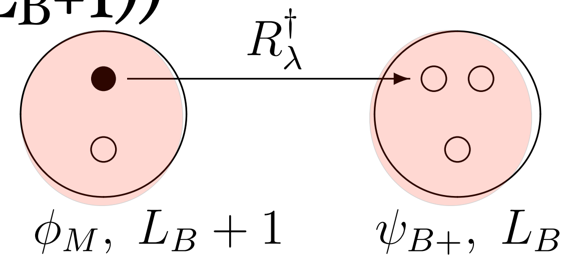
de Tèramond, Dosch, Lorce, sjb

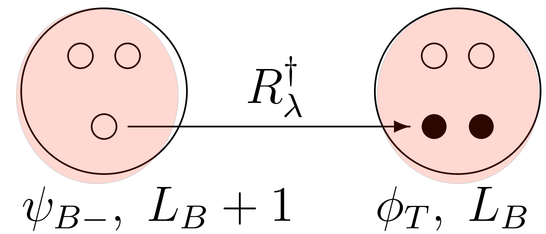
Superconformal Algebra

2X2 Hadronic Multiplets

$$\begin{pmatrix} \phi_M(L_M = L_B + 1) & \psi_{B-}(L_B + 1) \\ \psi_{B+}(L_B) & \phi_T(L_T = L_B) \end{pmatrix}$$

- quark-antiquark meson ($L_M = L_{B+1}$))
- quark-diquark baryon (L_B)
- quark-diquark baryon (L_{B+1})
- diquark-antidiquark tetraquark ($L_T = L_B$)
- Universal Regge slopes $\lambda = \kappa^2$





$$M_H^2/\lambda = \overbrace{\underbrace{(2n + L_H + 1)}_{kinetic} + \underbrace{(2n + L_H + 1)}_{potential}}^{contribution\ from\ 2\text{-}dim\ light\text{-}front\ harmonic\ oscillator} + \overbrace{2(L_H + s) + 2\chi}^{contribution\ from\ AdS\ and\ superconformal\ algebra} + < \sum_i \frac{m_i^2}{x_i} >$$

$\chi(mesons) = -1 \qquad \chi(baryons, tetraquarks) = +1$

Features of Supersymmetric Equations

- J =L+S baryon simultaneously satisfies both equations of G with L , L+1 with same mass eigenvalue
- $J^z = L^z + 1/2 = (L^z + 1) - 1/2$ $\qquad S^z = \pm 1/2$
- Proton spin carried by quark L^z

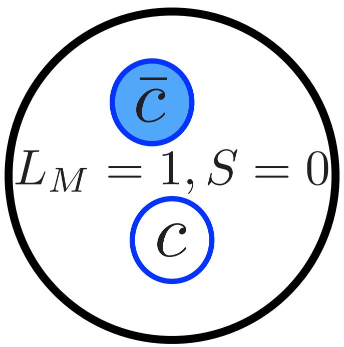
$$< J^z >= \frac{1}{2}(S_q^z = \frac{1}{2}, L^z = 0) + \frac{1}{2}(S_q^z = -\frac{1}{2}, L^z = 1) =< L^z >= \frac{1}{2}$$

- Mass-degenerate meson "superpartner" with $L_M = L_B + 1$. *"Shifted meson-baryon Duality"*
- Mesons and baryons have same κ !

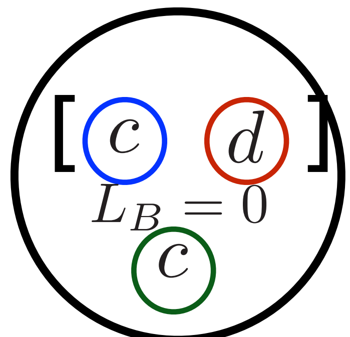
Double-Charm Baryon (SELEX)

$$S = 0$$
$$R_\lambda^\dagger \ \bar{q} \to [qq]$$
$$\bar{3}_C \to \bar{3}_C$$

$h_c(3525)$



$\Xi_{CC}^{+}(3520)$



Predict Tetraquark $T_{c\bar{c}q\bar{q}}$

$M_T \sim 3520 \ MeV$

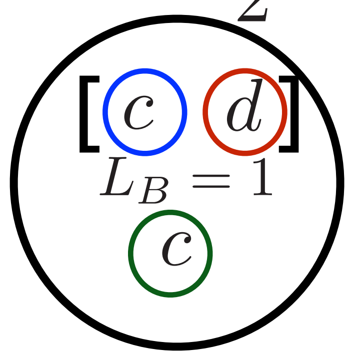
Scalar Diquarks

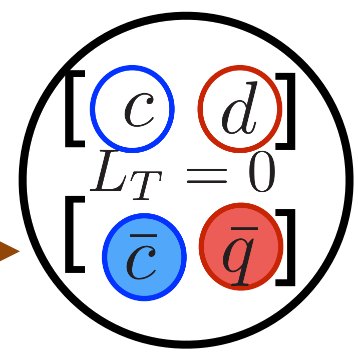
$$J^P = \frac{1}{2}^+$$

$$J^{PC} = 0^{++}$$

η_c'

$$J^{PC} = 1^{+-}$$



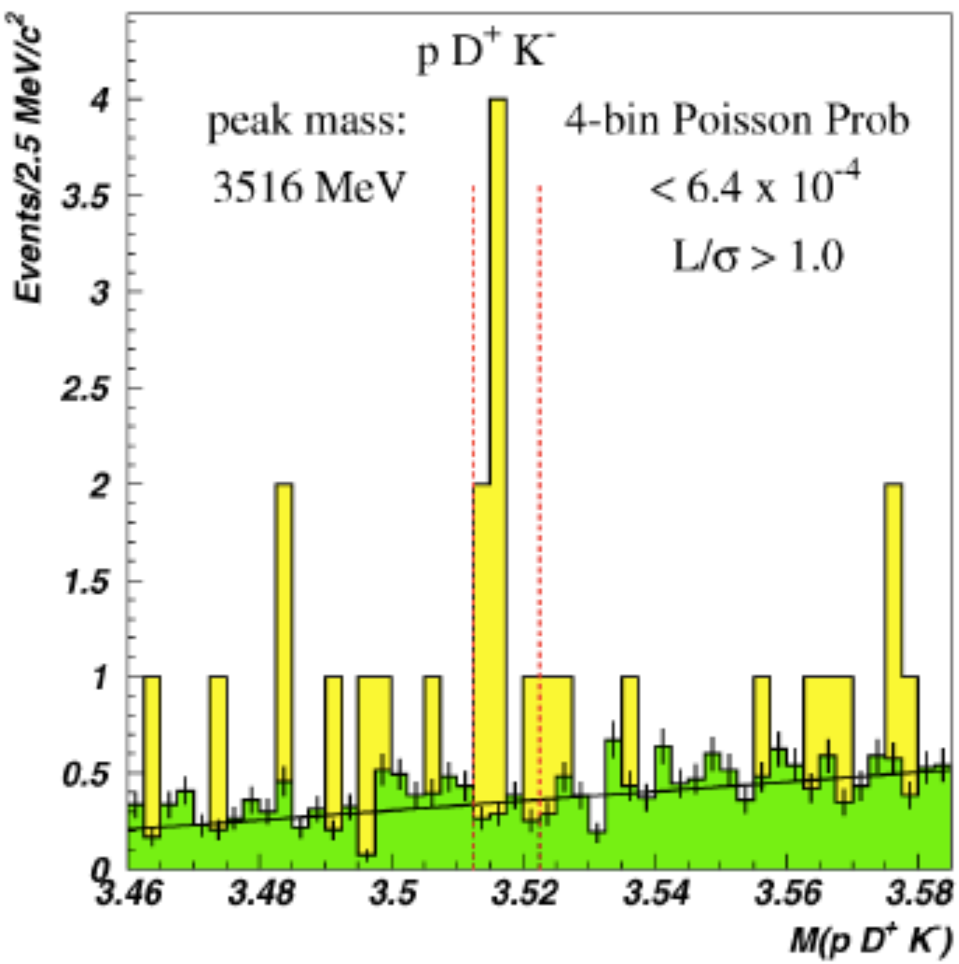


$$R_\lambda^\dagger \ q \to [\bar{q}\bar{q}] \qquad S = 0$$
$$3_C \to 3_C$$

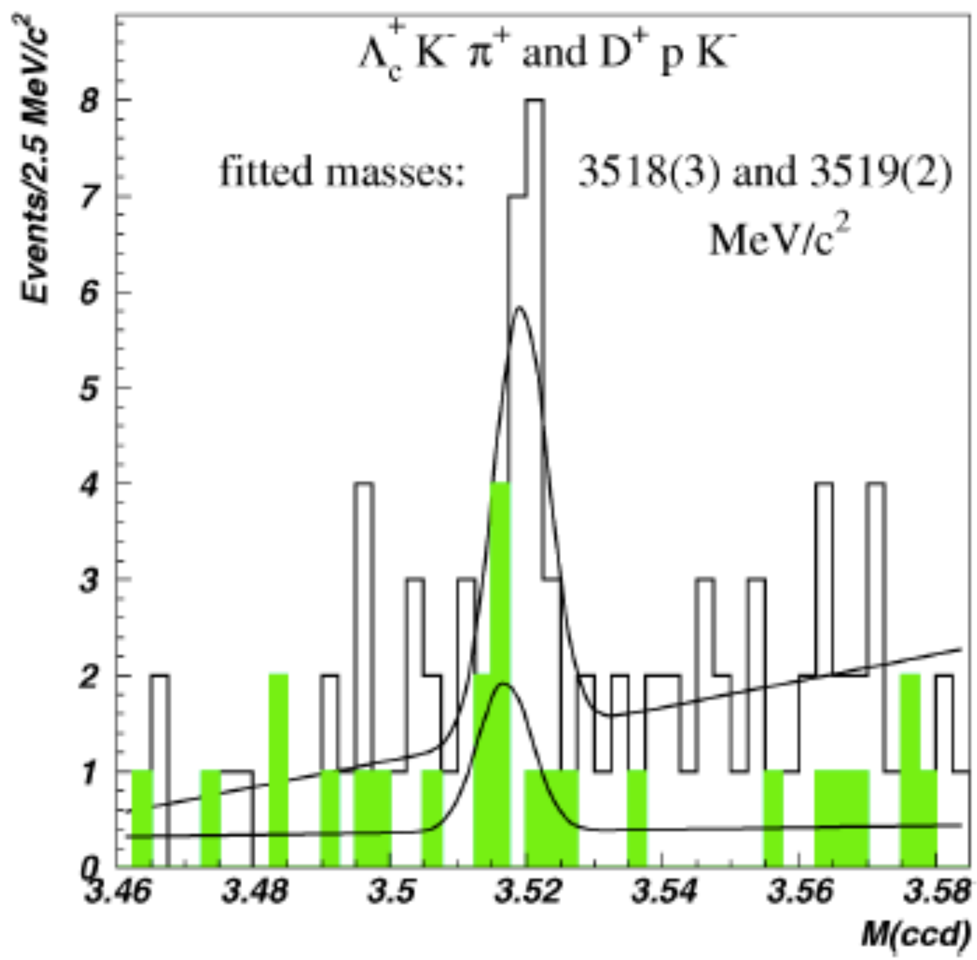
SELEX ($3520 \pm 1\ MeV$) $J^P = \frac{1}{2}^-$ $|[cd]c>$

Two decay channels: $\Xi_{cc}^+ \to \Lambda_c^+ K^- \pi^+, pD^+K^-$

SELEX Collaboration / Physics Letters B 628 (2005) 18–24



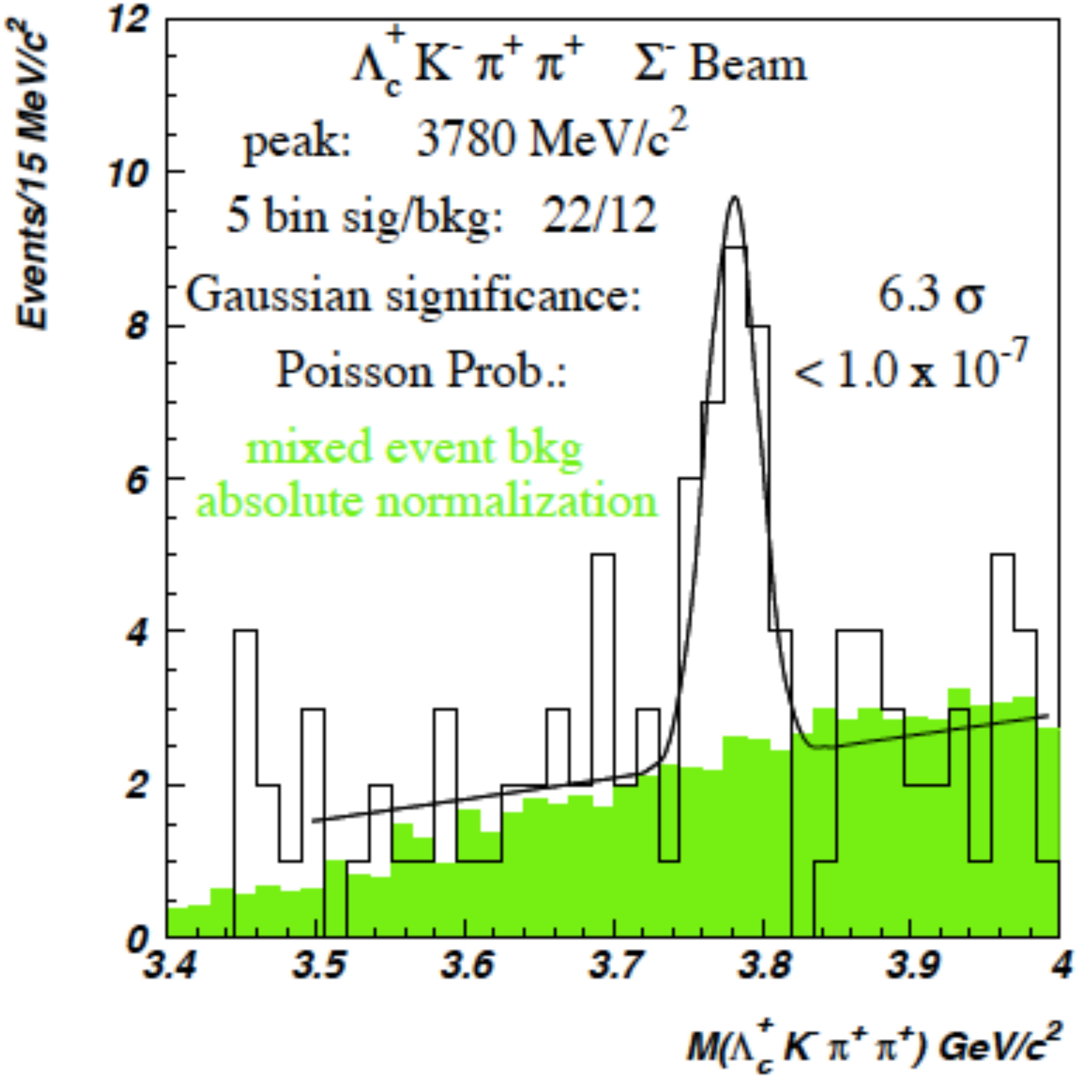
$\Xi_{cc}^+ \to pD^+K^-$ mass distribution from Fig. 2(a) with high-statistics measurement of random combinatoric background computed from event-mixing.



Gaussian fits for $\Xi_{cc}^+ \to \Lambda_c^+ K^- \pi^+$ and $\Xi_{cc}^+ \to pD^+K^-$ (shaded data) on same plot.

UASLP–IF–07–001
FERMILAB–Conf–07/029–E

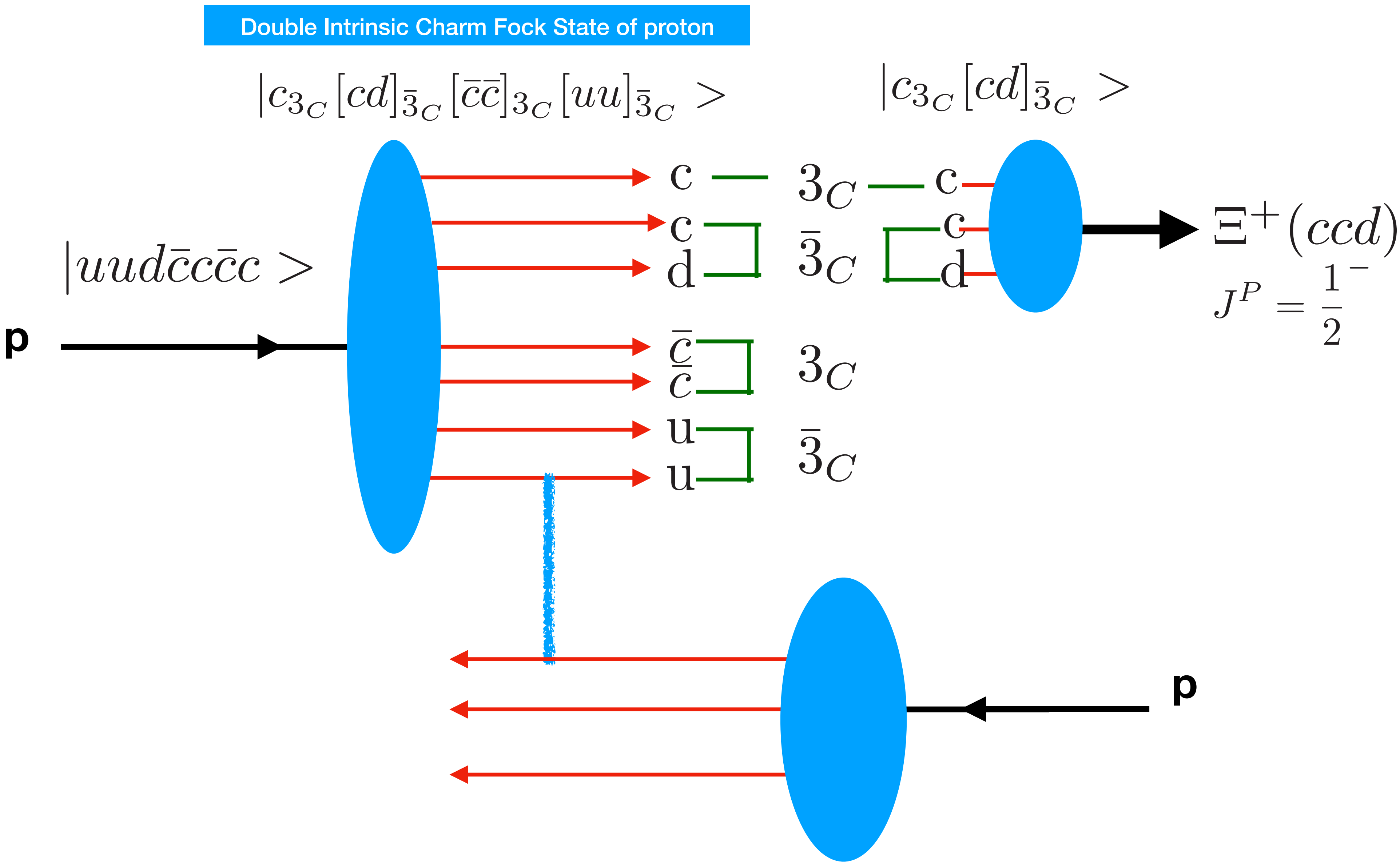
SELEX: Recent Progress in the Analysis of Charm-Strange and Double-Charm Baryons



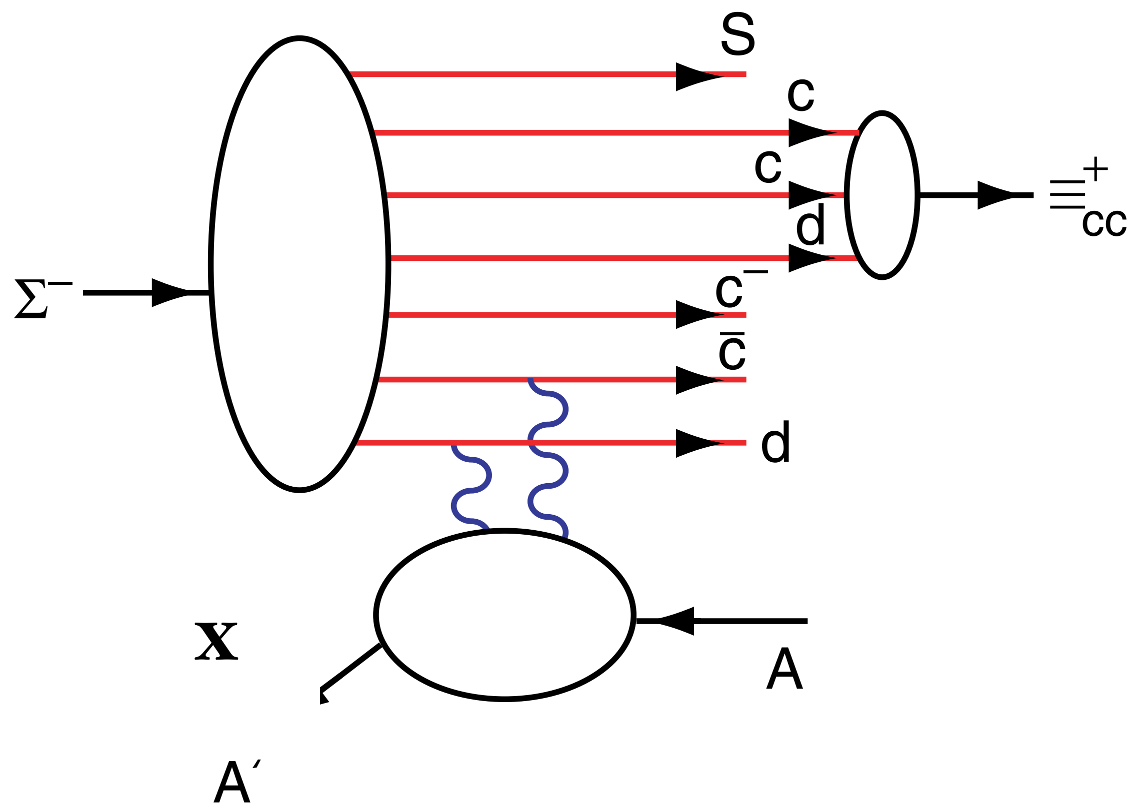
The $\Lambda_c^+ K^- \pi^+ \pi^+$ invariant mass distribution, for Σ^- beam only.

Hadroproduction of the Double-Charm Baryon at High x_F

$$p + A \to \Xi(ccd)^+ + X$$



SELEX: $\Xi(ccd)^+(3510 \pm 2) \to \Lambda_c^+ K^- \pi^+$



Production of a Double-Charm Baryon

SELEX high x_F $< x_F >= 0.33$

SELEX $(3520 \pm 1\ MeV)$ $J^P = \frac{1}{2}^-$ $|[cd]c>$

Two decay channels: $\Xi_{cc}^+ \to \Lambda_c^+ K^- \pi^+, pD^+ K^-$

LHCb $(3621 \pm 1\ MeV)$ $J^P = \frac{1}{2}^-$ or $\frac{3}{2}^-$ $|(cu)c>$

$$\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+$$

Groote, Koshkarev, sjb: SELEX& LHCb could both be correct!

Very different production kinematics:

LHCb (central region)

SELEX (Forward, High x_F) where Λ_c , Λ_b were discovered

NA3: Double J/ψ Hadroproduction measured at High x_F

Radiative Decay:

LHCb(3621) $\to$ SELEX(3520) $+ \gamma$

strongly suppressed: $[\frac{100\ MeV}{M_c}]^7$

Also: Different diquark structure possible for LHCb: $|(cc)u>$

Karliner and Rosner

Rinaldi, Vento, Orava

Looking for pure glueball states

Matteo Rinaldi

Dipartimento di Fisica e Geologia. Università degli Studi di Perugia and INFN section of Perugia. Perugia Via A. Pascoli, I-06123,Italy

Vicente Vento

Departamento de Física Teórica-IFIC, Universidad de Valencia- CSIC, 46100 Burjassot (Valencia), Spain.

Risto Orava

University of Helsinki, Helsinki Institute of Physics and CERN-EP, CH-1211 Geneva 23, Switzerland

(Dated: February 8, 2019)

A phenomenological analysis of the scalar glueball and scalar meson spectra is carried out by using the AdS/QCD framework in the bottom-up approach. We make use of the relation between the mode functions in AdS/QCD and the wave functions in Light-Front QCD to discuss the mixing of glueballs and mesons.

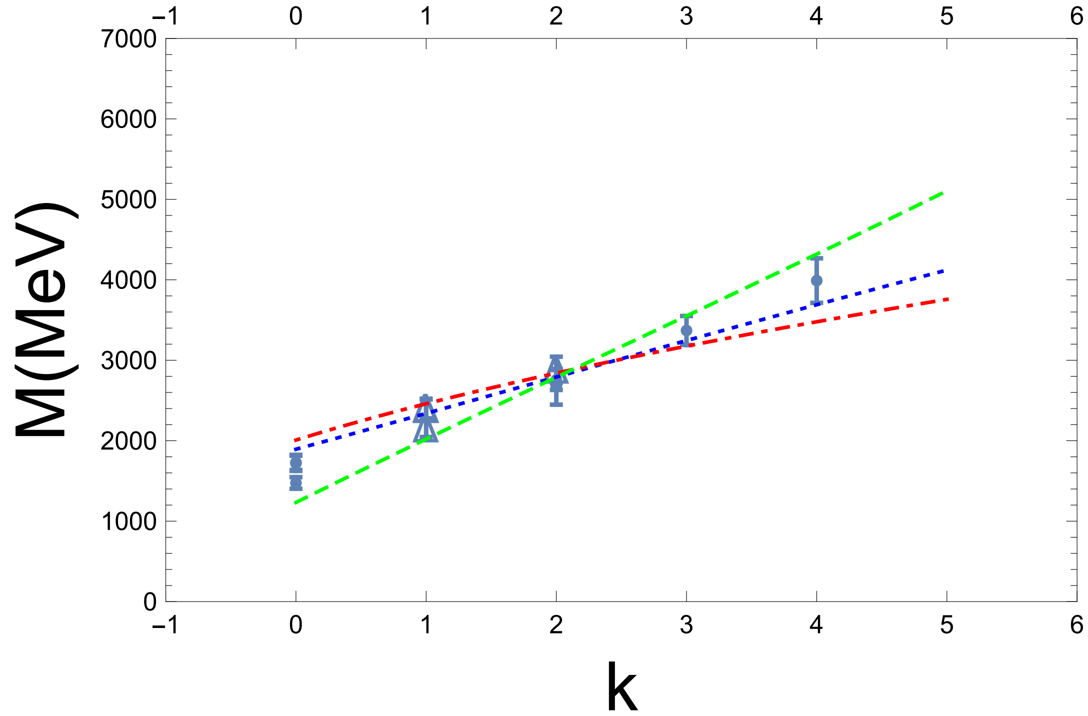


FIG. 1: Glueball spectrum obtained by the Dirichlet hard wall (dashed), a soft wall (dashed-dotted) and soft wall graviton (dotted) approaches. These calculations were reported in ref. [12]. The lattice data are from refs. [8–10] as shown in Table I. The dots label the scalar glueballs and the triangles the tensor glueballs.

$\omega_k^2 = (4k + 8)$, where $k = 0, 1, 2 \ldots$ is the mode number

Chiral Features of Soft-Wall AdS/QCD Model

- **Boost Invariant**
- **Trivial LF vacuum! No condensate, but consistent with GMOR**
- **Massless Pion**
- **Hadron Eigenstates (even the pion) have LF Fock components of different L^z**
- **Proton: equal probability** $S^z = +1/2, L^z = 0; S^z = -1/2, L^z = +1$

$$J^z = +1/2 :< L^z >= 1/2, < S^z_q >= 0$$

- **Self-Dual Massive Eigenstates: Proton is its own chiral partner.**
- **Label State by minimum L as in Atomic Physics**
- **Minimum L dominates at short distances**
- **AdS/QCD Dictionary: Match to Interpolating Operator Twist at z=0.**

No mass -degenerate parity partners!

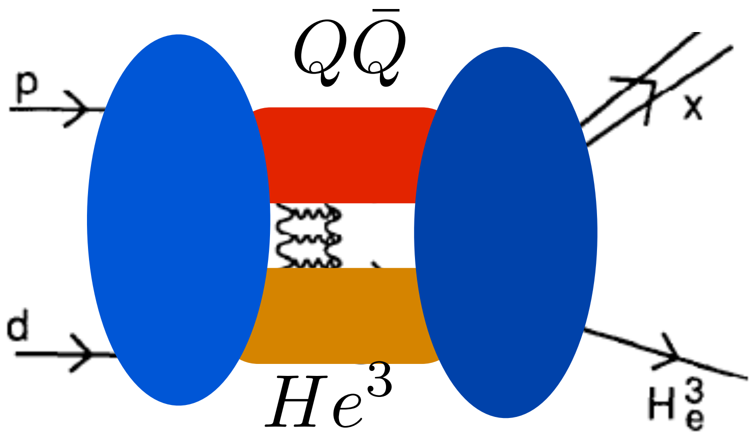
Remarkable Features of Light-Front Schrödinger Equation

Dynamics + Spectroscopy!

- ***Relativistic, frame-independent***
- ***QCD scale appears - unique LF potential***
- ***Reproduces spectroscopy and dynamics of light-quark hadrons with one parameter***
- ***Zero-mass pion for zero mass quarks!***
- ***Regge slope same for n and L -- not usual HO***
- ***Splitting in L persists to high mass -- contradicts conventional wisdom based on breakdown of chiral symmetry***
- ***Phenomenology: LFWFs, Form factors, electroproduction***
- ***Extension to heavy quarks***

$$U(\zeta) = \kappa^4 \zeta^2 + 2\kappa^2 (L + S - 1)$$

Nuclear-Bound Quarkonium $[(Q\bar{Q})A]$

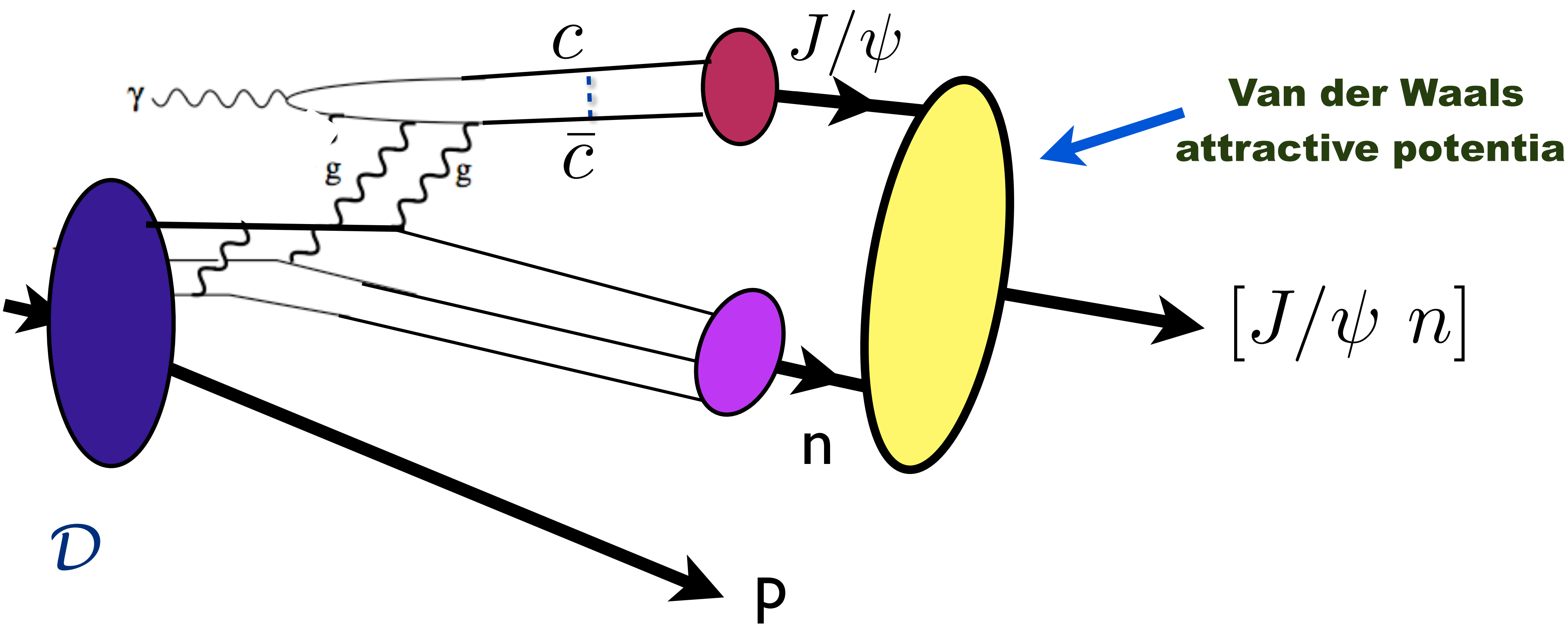


- Binding via QCD Van der Waals
- No valence quarks in common
- Guaranteed J/ψ-A binding for high A

Schmidt, de Teramond, sjb

Manohar

Charmonium Production at Threshold



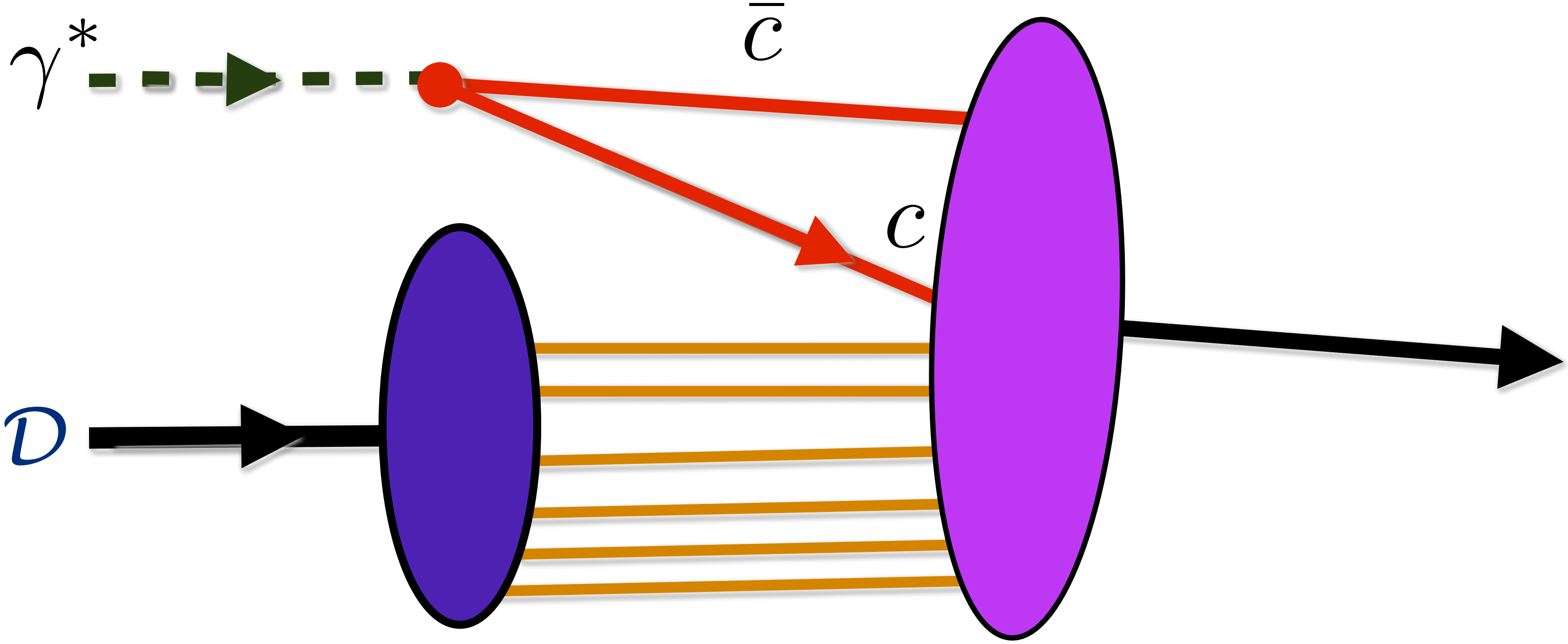
$$\gamma\ d \to [J/\psi\ n]\ p$$

$$\gamma\ d \to [J/\psi\ p]\ n$$

Form nucleon-charmonium bound state! $|uudc\bar{c}>$

Octoquark Production at Threshold

$$M_{\text{octoquark}} \sim 5 \text{ GeV}$$



$$\gamma^* \mathscr{D} \to |uududdc\bar{c}>$$

Explains Krisch Effect!

Produce Charge Q=4,I=3,B=2 Hidden-Color Dibaryon State at JLab

- **First suggested by F. Dyson and N-H Xuong (1964)**

"Hexaquark"

$$[B = 2, Q = +4] \leftrightarrow |u^{\uparrow}_R u^{\uparrow}_B u^{\uparrow}_Y u^{\downarrow}_R u^{\downarrow}_B u^{\downarrow}_Y >$$

- **Hidden-Color Six-Quark Configuration**
- **Decays to $\Delta^{++}\Delta^{++}$**

$$\gamma d \to [B = +2, Q = +4]\pi^- \pi^- \pi^-$$

Discover at JLab!

Bashkanov, Clement, sjb

"Exclusive Transversity"

A. Krisch, Sci. Am. 257 (1987)
"The results challenge the prevailing theory that describes the proton's structure and forces"

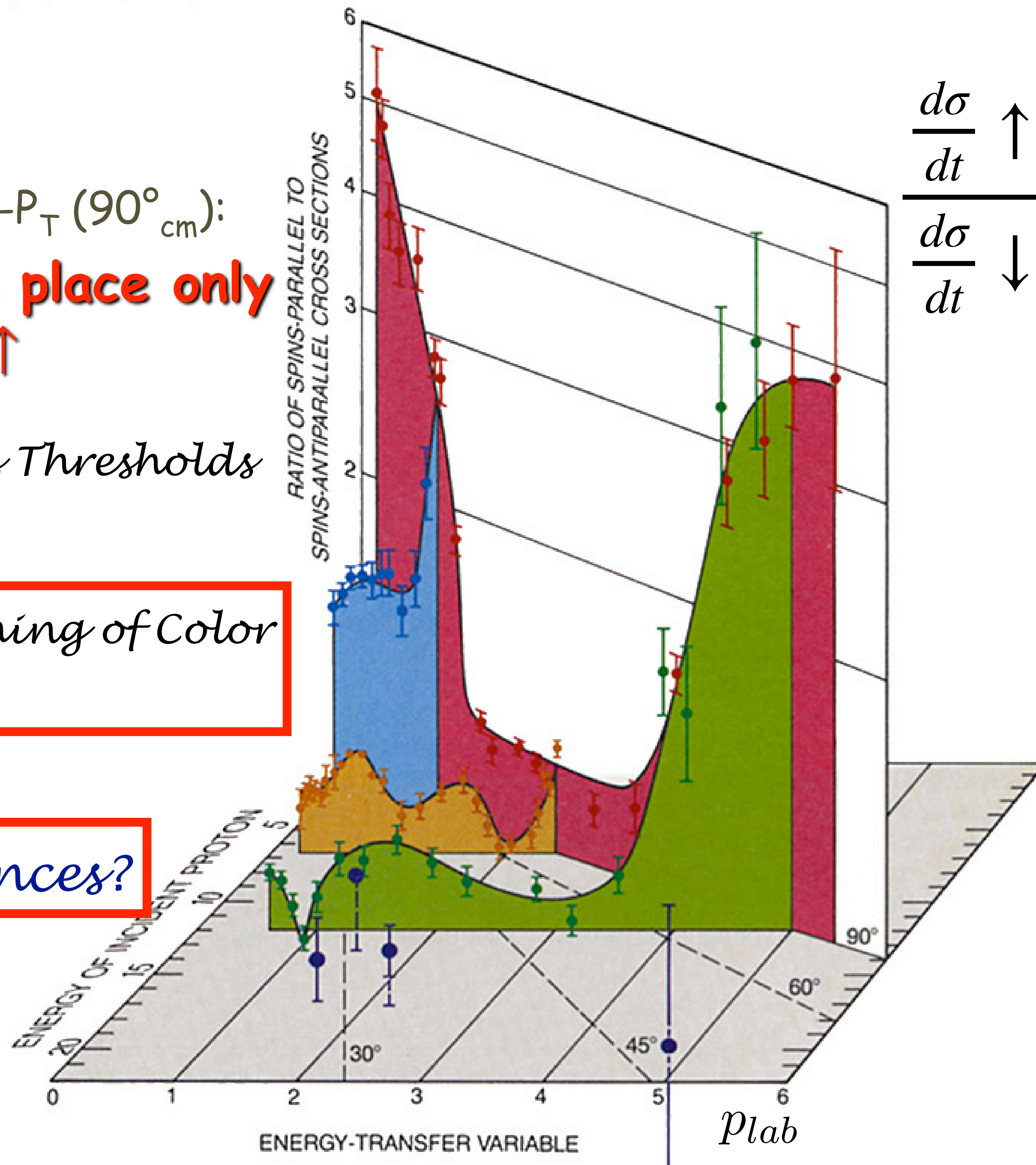
Spin-dependence at large-P_T ($90°_{cm}$):

Hard scattering takes place only with spins ↑↑

Charm and Strangeness Thresholds

Heppelmann et al: Quenching of Color Transparency

B=2 Octoquark Resonances?

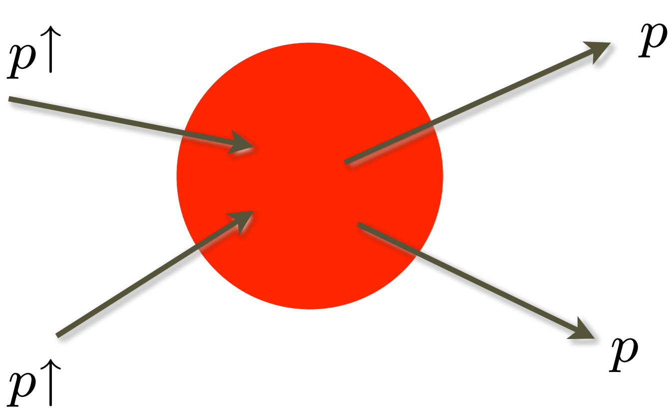


$$\frac{\frac{d\sigma}{dt}\uparrow\uparrow}{\frac{d\sigma}{dt}\downarrow\uparrow}$$

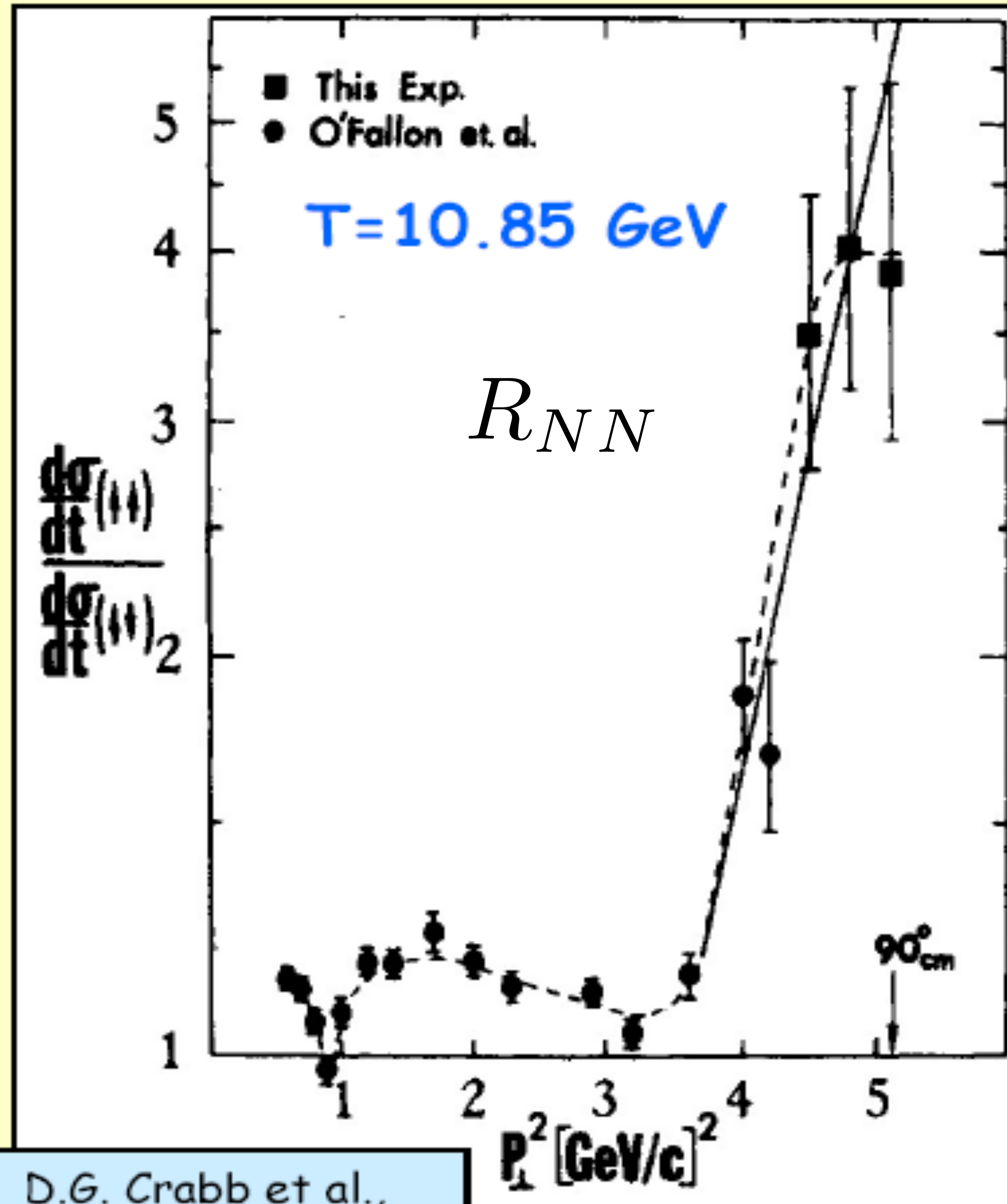
p_{lab}

Krisch, Crabb, et al

Unexpected spin-spin correlation in pp elastic scattering

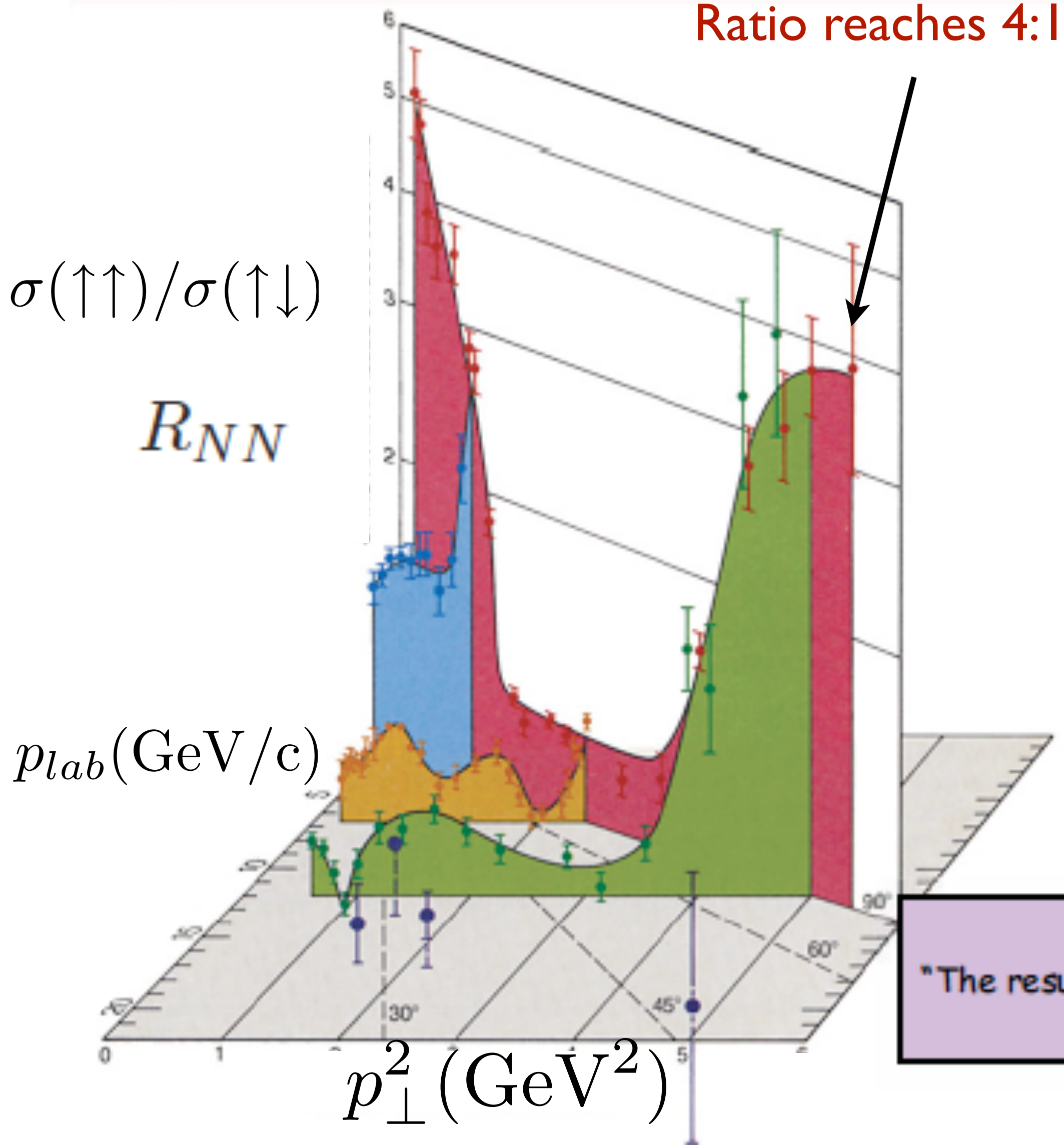


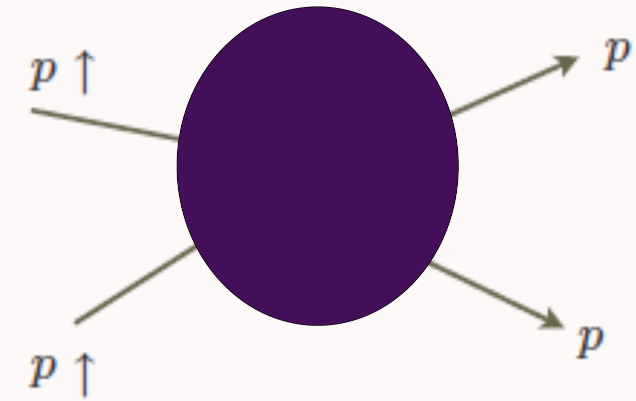
polarizations normal to scattering plane



D.G. Crabb et al., PRL 41, 1257 (1978)

Spin Correlations in Elastic $p-p$ Scattering





polarization normal to scattering plane

$$|uud\ uud\ c\bar{c}\rangle$$

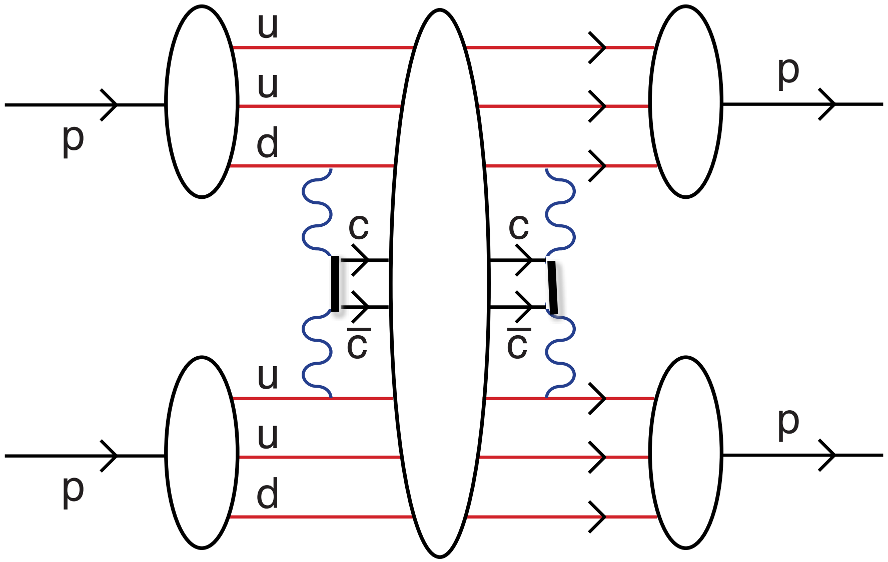
Dibaryon resonance?

A. Krisch, Sci. Am. 257 (1987)
"The results challenge the prevailing theory that describes the proton's structure and forces"

Large R_{NN} in $pp \to pp$ explained by
$B=2, J=L=1\ |uuduudc\bar{c}>$ resonance
at $\sqrt{s} \sim 5$ GeV

de Teramond and sjb

$$A_{nn} = 1!$$



Production of uud $\bar{c}$ c uud octoquark resonance

J=L=S=1, C=-, P=- state

QCD Schwinger-Sommerfeld Enhancement at Heavy Quark Threshold

Hebecker, Kuhn, sjb

8 quarks in S-wave: odd parity

$$\sqrt{s} \sim 5\ GeV$$

S. J. Brodsky and G. F. de Teramond, "Spin Correlations, QCD Color Transparency And Heavy Quark Thresholds In Proton Proton Scattering," Phys. Rev. Lett. **60**, 1924 (1988).

$\sigma(pp \to c\bar{c}X) \simeq 1\ \mu b$ at threshold $\qquad \sigma(\gamma p \to c\bar{c}X) \simeq 1\ nb$ at threshold

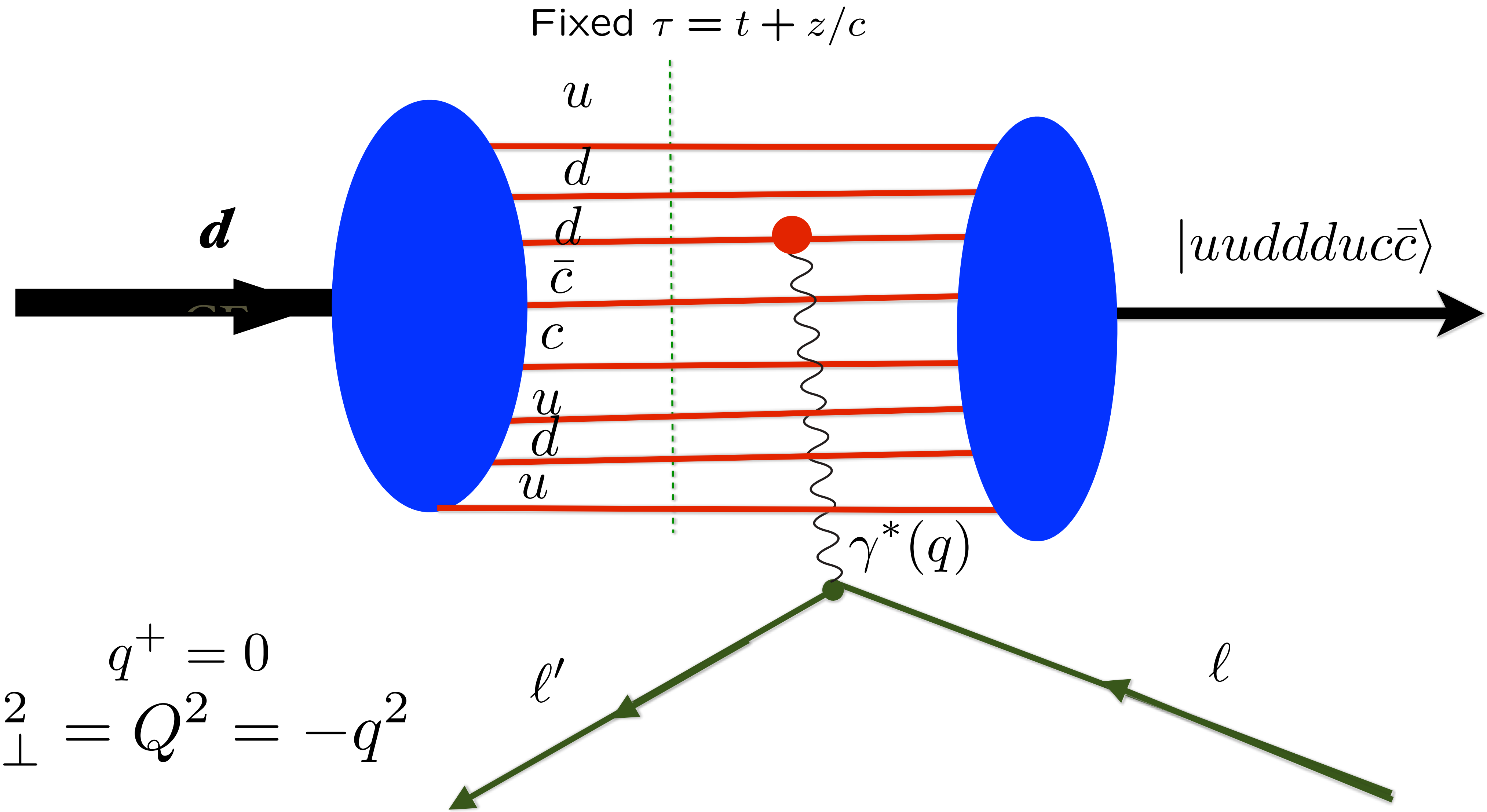
- New QCD physics in proton-proton elastic scattering at the charm threshold
- Anomalously large charm production at threshold!!?
- Octoquark resonances?
- Color Transparency disappears at charm threshold
- Key physics at GSI: second charm threshold

$$\bar{p}p \rightarrow \bar{p}pJ/\psi$$

$$\bar{p}p \rightarrow \bar{p}\Lambda_c D$$

Dramatic Spin Effects Possible at Threshold!

Light-Front Wavefunctions and Heavy-Quark Electroproduction



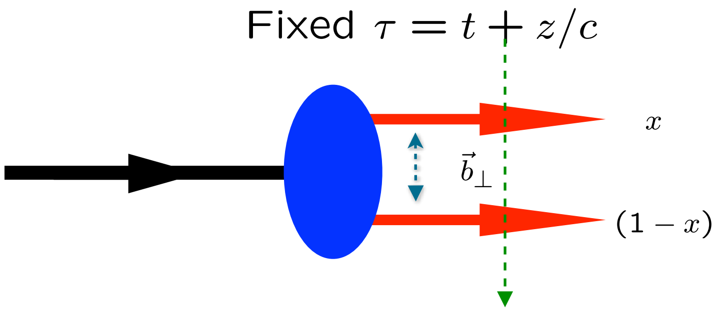
$$q^+ = 0$$
$$q_\perp^2 = Q^2 = -q^2$$

Coalescence of comovers can produce the $B = +2$ $Q = +1$ isospin partner of the $B = +2$ $Q = +2$ resonance $|uduudc\bar{c}\rangle$ which produces the large R_{NN} in p p elastic scattering

Threshold Production at JLab!

Underlying Principles

- *Poincarè Invariance: Independent of the observer's Lorentz frame*
- *Quantization at Fixed Light-Front Time* τ
- *Causality: Information within causal horizon*
- *Light-Front Holography: AdS_5 = LF (3+1)*



$$\zeta^2 = x(1-x)b^2_\perp$$

$$z \leftrightarrow \zeta \text{ where } \zeta^2 = b^2_\perp x(1-x)$$

- *Single fundamental hadronic mass scale κ: but retains the Conformal Invariance of the Action (dAFF)!*

$$U(\zeta^2) = \kappa^4 \zeta^2$$

- *Unique dilaton and color-confining LF Potential!*

$$e^{+\kappa^2 z^2}$$

- *Superconformal Algebra: Mass Degenerate 4-Plet:*

$$\text{Meson } q\bar{q} \leftrightarrow \text{Baryon } q[qq] \leftrightarrow \text{Tetraquark } [qq][\bar{q}\bar{q}]$$

Features of LF Holographic QCD

- *Regge spectroscopy—same slope in n,L for mesons, baryons*
- *Chiral features for m_q=0: m_π=0, chiral-invariant proton!*
- *Hadronic LFWFs*
- *Counting Rules*
- *Connection between hadron masses and* $\Lambda_{\overline{MS}}$

Superconformal AdS Light-Front Holographic QCD (LFHQCD)

Meson-Baryon Mass Degeneracy for $L_M=L_B+1$

Fundamental Hadronic Features

Virial Theorem

- Partition of the Proton's Mass: Potential vs. Kinetic Contributions

$$\Delta\mathcal{M}^2_{LFKE} = \kappa^2(1+2n+L)$$
$$\Delta\mathcal{M}^2_{LFPE} = \kappa^2(1+2n+L)$$

- Color Confinement $U(\zeta^2) = \kappa^4\zeta^2$
- Role of Quark Orbital Angular Momentum in the Proton

Equal L=0,1

- Quark-Diquark Structure
- Quark Mass Contribution $\Delta M^2 = < \frac{m_q^2}{x} >$

from the Yukawa coupling to the Higgs zero mode

- Baryonic Regge Trajectory $M^2_p(n, L_B) = 4\kappa^2(n + L_B + 1)$
- Mesonic Supersymmetric Partners $L_M = L_B + 1$
- Proton Light-Front Wavefunctions and Dynamical Observables

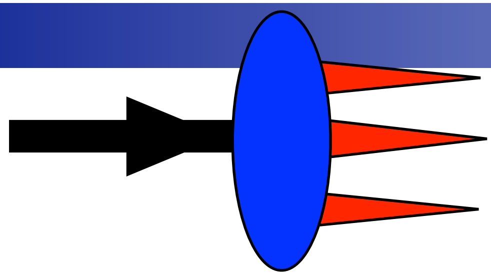
$$\psi_M(x, k_\perp) = \frac{4\pi}{\kappa\sqrt{x(1-x)}} e^{-\frac{k_\perp^2}{2\kappa^2 x(1-x)}}$$

- Form Factors, Distribution Amplitudes, Structure Functions
- Non-Perturbative - Perturbative QCD Transition $Q_0 = 0.87 \pm 0.08\ GeV\ \overline{MS}\ scheme$
- Dimensional Transmutation: $m_p \simeq 3.21\ \Lambda_{\overline{MS}}$ $m_\rho \simeq 2.2\ \Lambda_{\overline{MS}}$

Remarkable Advantages of the Front Form

- Light-Front Time-Ordered Perturbation Theory: Elegant, Physical
- Frame-Independent
- Few LF Time-Ordered Diagrams (not n!) -- all k^+ must be positive
- J^z conserved at each vertex
- Automatically normal-ordered; LF Vacuum trivial up to zero modes
- Renormalization: Alternate Denominator Subtractions: Tested to three loops in QED
- Reproduces Parke-Taylor Rules and Amplitudes (Stasto)
- Hadronization at the Amplitude Level with Confinement

- *Light Front Wavefunctions:*



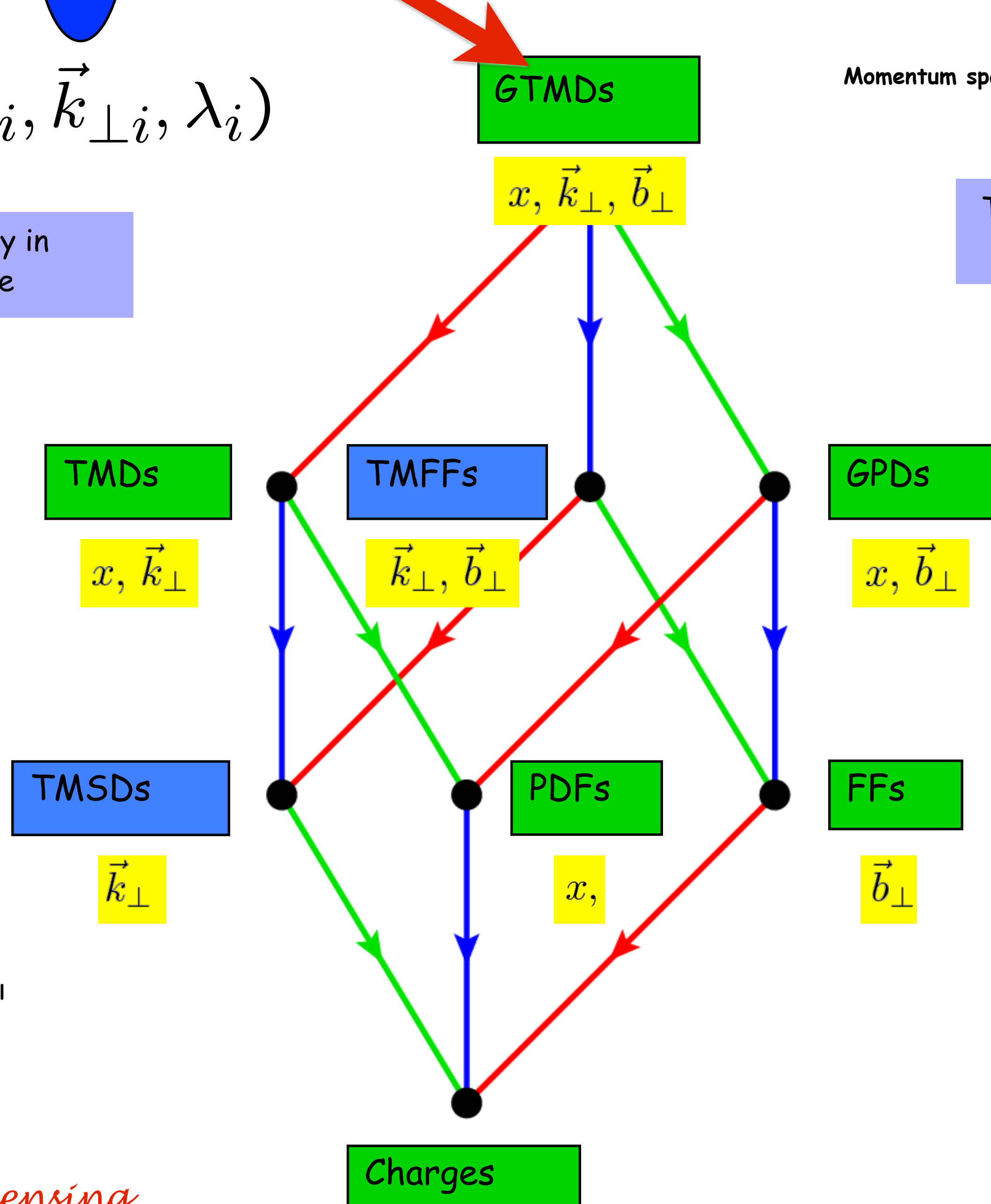
$$\Psi_n(x_i, \vec{k}_{\perp i}, \lambda_i)$$

Transverse density in momentum space

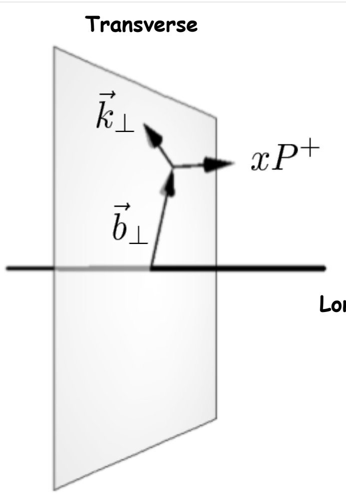
Momentum space $\vec{k}_\perp \leftrightarrow \vec{z}_\perp$ Position space

$\vec{\Delta}_\perp \leftrightarrow \vec{b}_\perp$

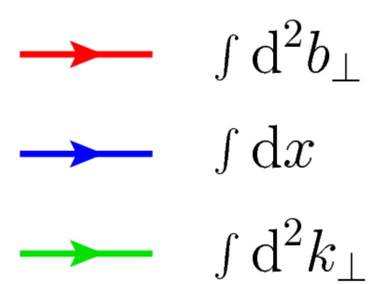
Transverse density in position space



Lorce, Pasquini

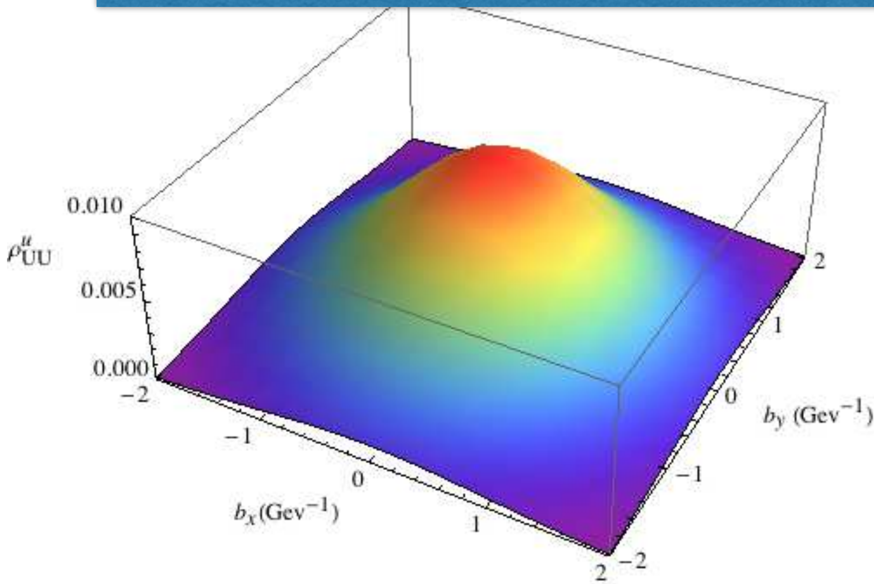


Sivers, T-odd from lensing

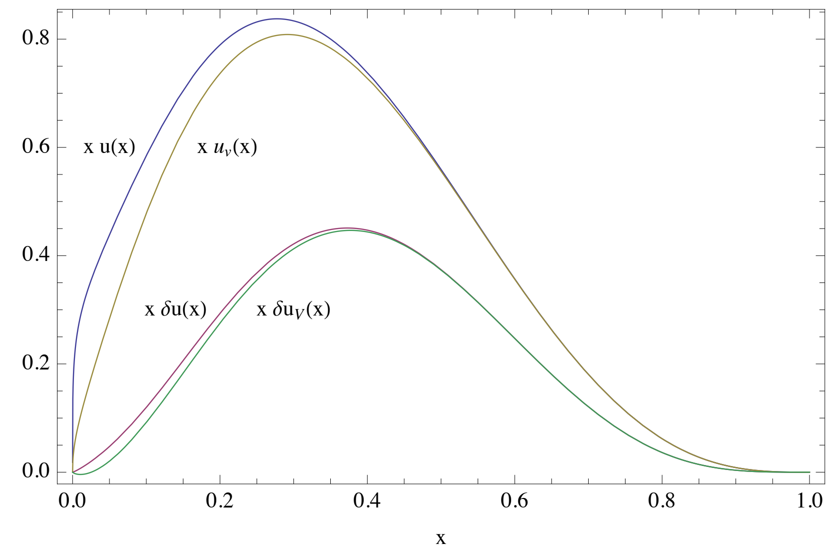


Nucleon parton distributions in a light-front quark model
Gutsche, Lyubovitskij, Schmidt

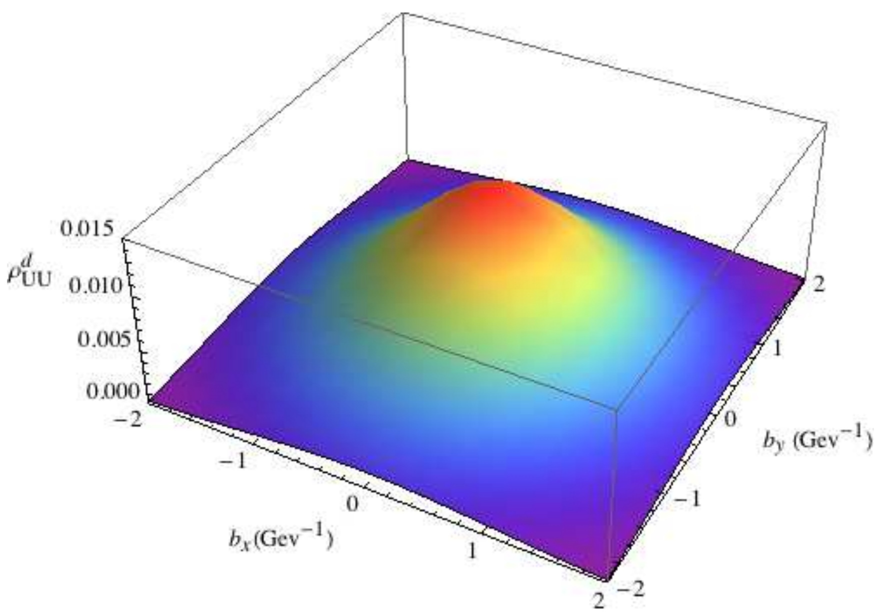
arXiv:1605.03526



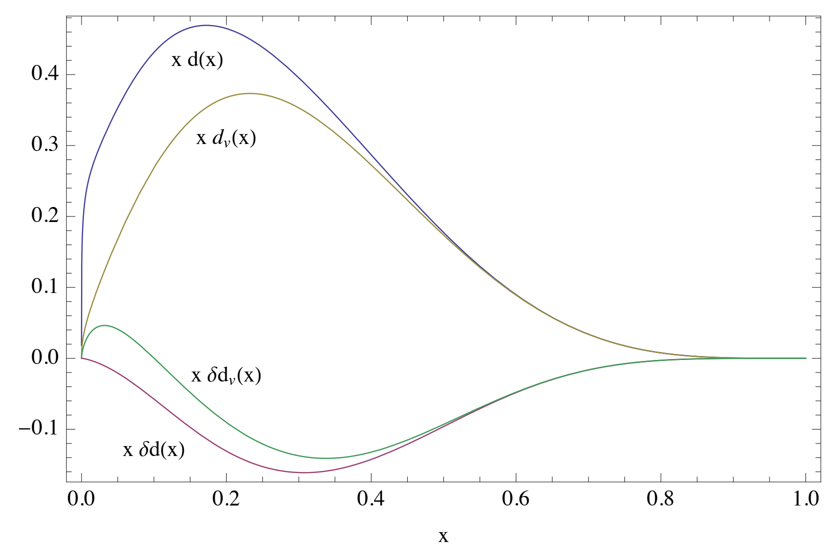
Wigner distribution $\rho^u_{UU}(x, \mathbf{b}_\perp, \mathbf{k}_\perp)$ at $x = 0.5$, $k_x = k_y = 0.5$ GeV.



u quark PDFs multiplied with x.



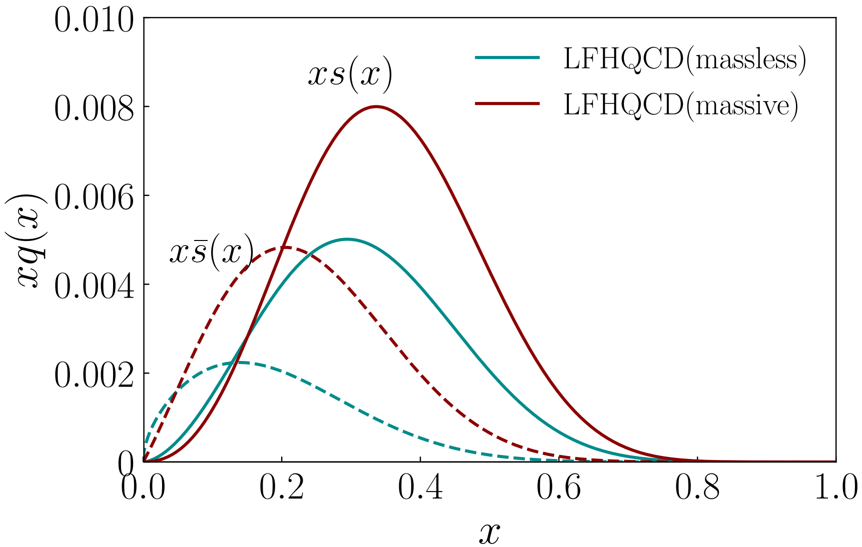
Wigner distribution $\rho^d_{UU}(x, \mathbf{b}_\perp, \mathbf{k}_\perp)$ at $x = 0.5$, $k_x = k_y = 0.5$ GeV.

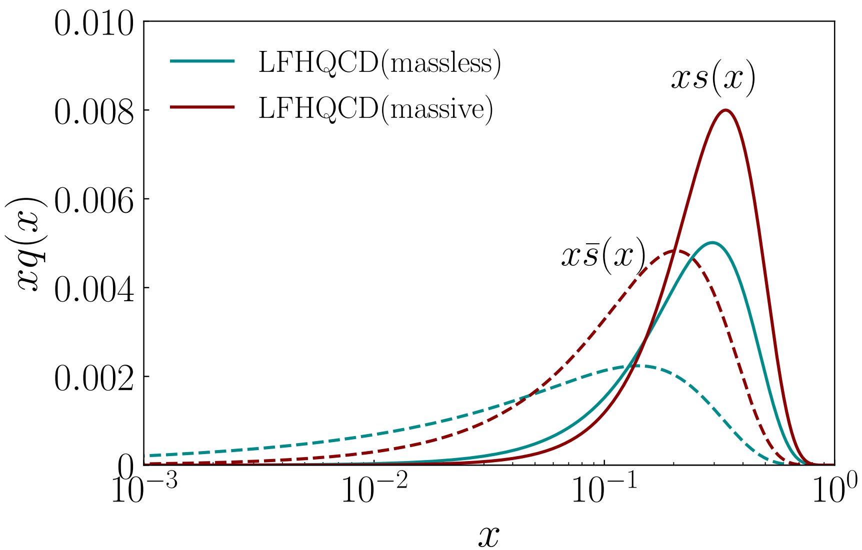


d quark PDFs multiplied with x.

Nonperturbative strange-quark sea from lattice QCD, light-front holography, and meson-baryon fluctuation models

Raza Sabbir Sufian,[1] Tianbo Liu,[1,2,*] Guy F. de Téramond,[3] Hans Günter Dosch,[4]
Stanley J. Brodsky,[5] Alexandre Deur,[1] Mohammad T. Islam,[6] and Bo-Qiang Ma[7,8,9]





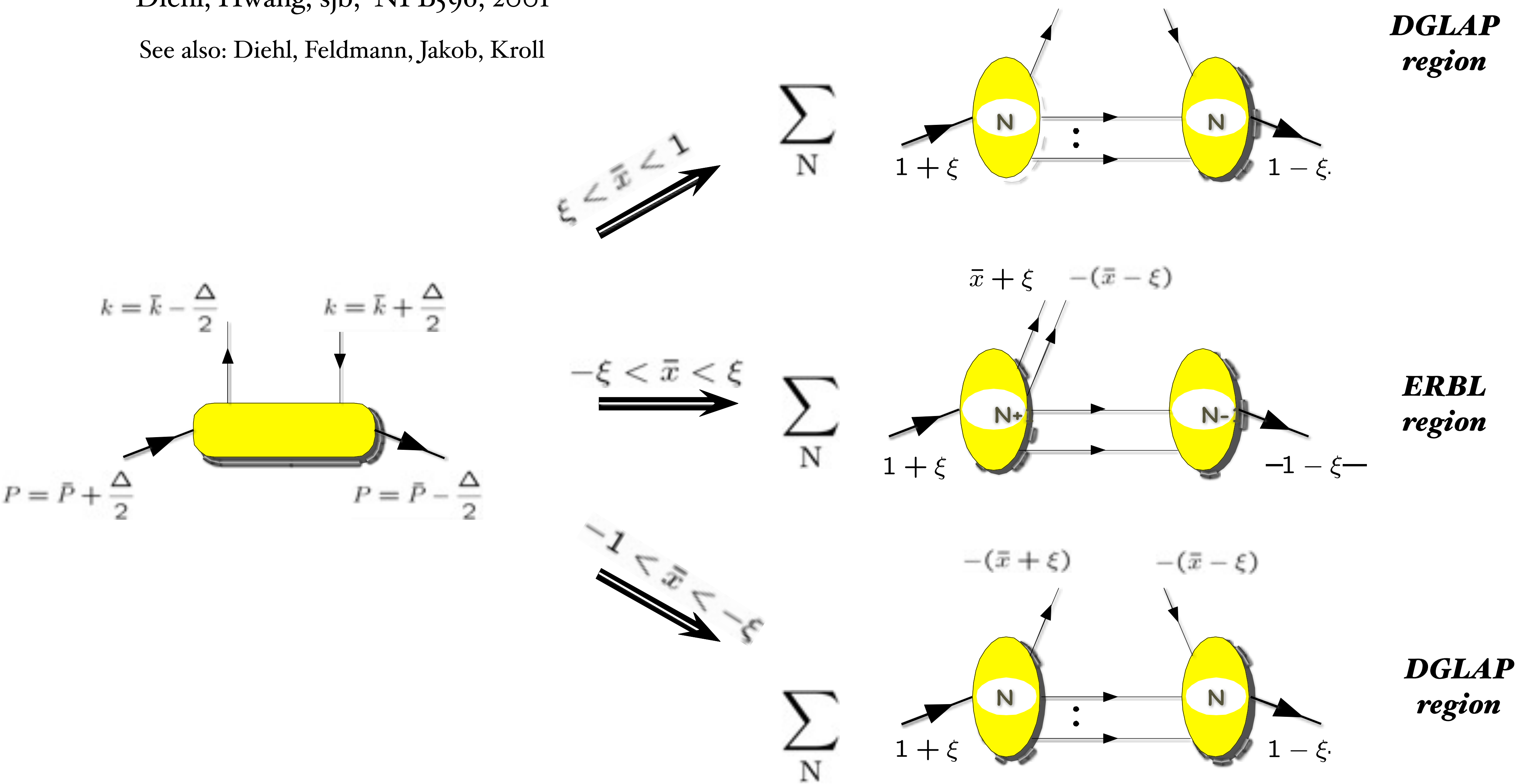
The distributions $xs(x)$ (continuous curves) and $x\bar{s}(x)$ (dashed curves) correspond to the minimum intrinsic strange probability $I_s = 0.2\, N_s$ with $N_s = 0.047$, $\sqrt{\lambda} = 0.534\,\mathrm{GeV}$, and $M_\phi^2 = 1.96\,\lambda$. The results with massless quarks are included for comparison.

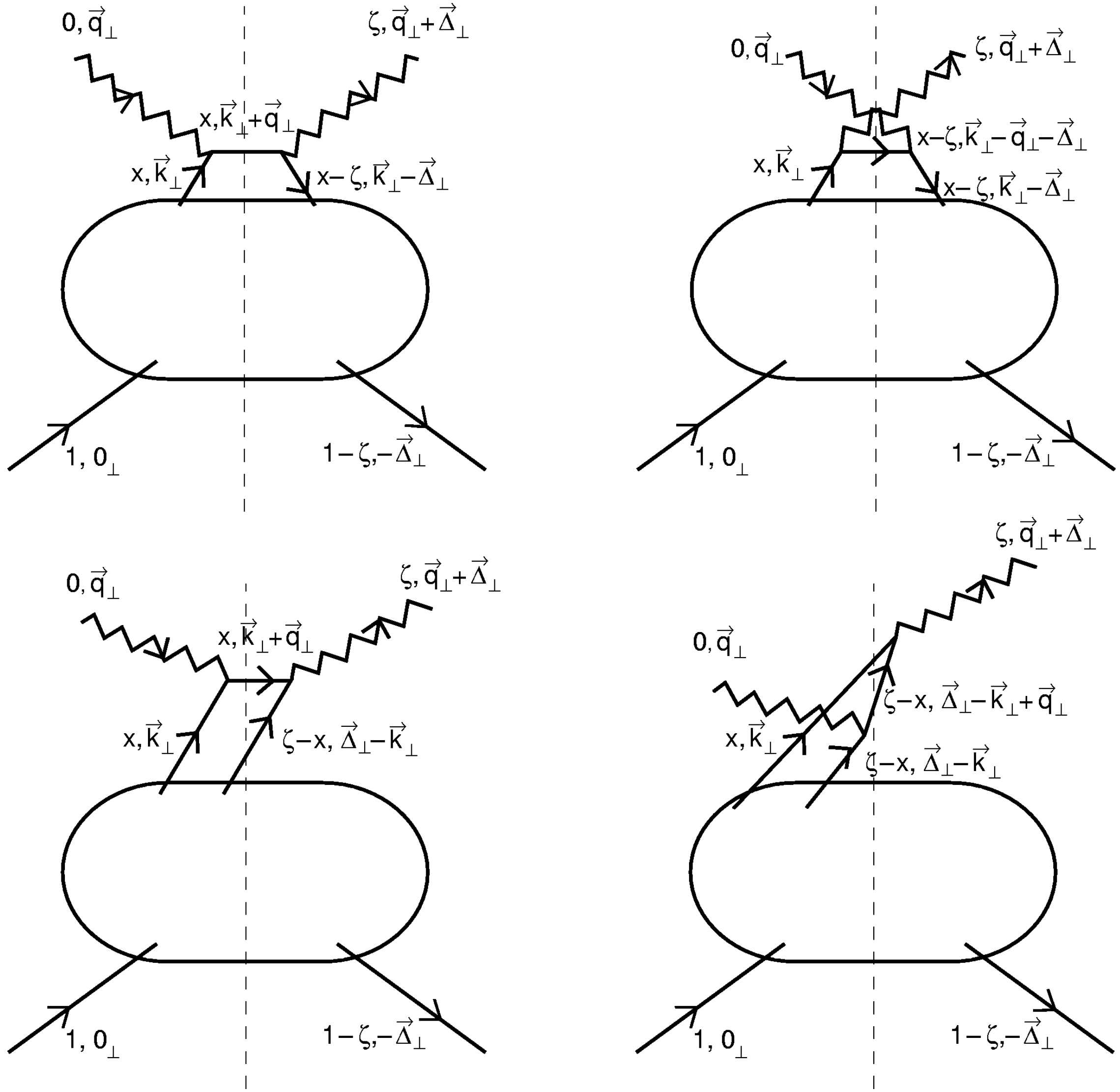
Light-Front Wave Function Overlap Representation

DVCS/GPD

Diehl, Hwang, sjb, NPB596, 2001

See also: Diehl, Feldmann, Jakob, Kroll





Coleman-Norton space-time amplitudes equivalent to LF T-Matrix

Light-front wavefunctions representation of deeply virtual Compton scattering

Stanley J. Brodsky [a], Markus Diehl [a,1], Dae Sung Hwang [b]

The GPD's are non-forward matrix elements of the PDF operator:

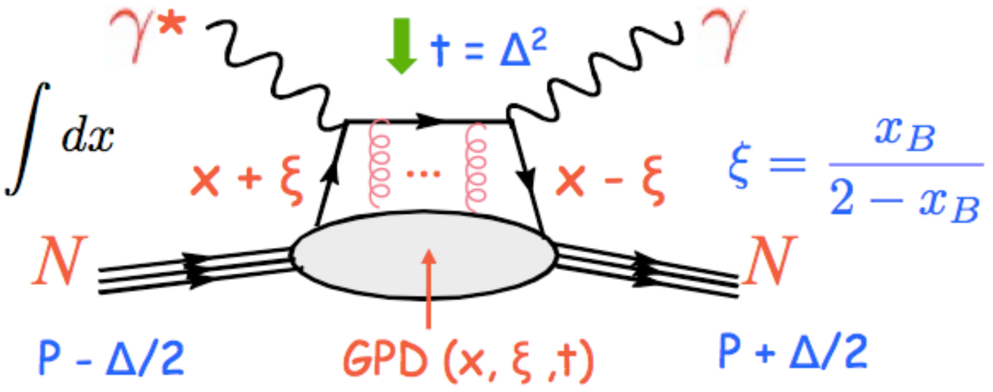
$$\frac{1}{8\pi}\int dr^- e^{imxr^-/2}\langle P+\tfrac{1}{2}\Delta|\bar{q}(-\tfrac{1}{2}r)\gamma^+ W[\tfrac{1}{2}r^-,-\tfrac{1}{2}r^-]q(\tfrac{1}{2}r)|P-\tfrac{1}{2}\Delta\rangle_{r^+=r_\perp=0}$$

$$=\frac{1}{2P^+}\bar{u}(P+\tfrac{1}{2}\Delta)\left[H(x,\xi,t)\gamma^+ + E(x,\xi,t)i\sigma^{+\nu}\frac{\Delta_\nu}{2m}\right]u(P-\tfrac{1}{2}\Delta)$$

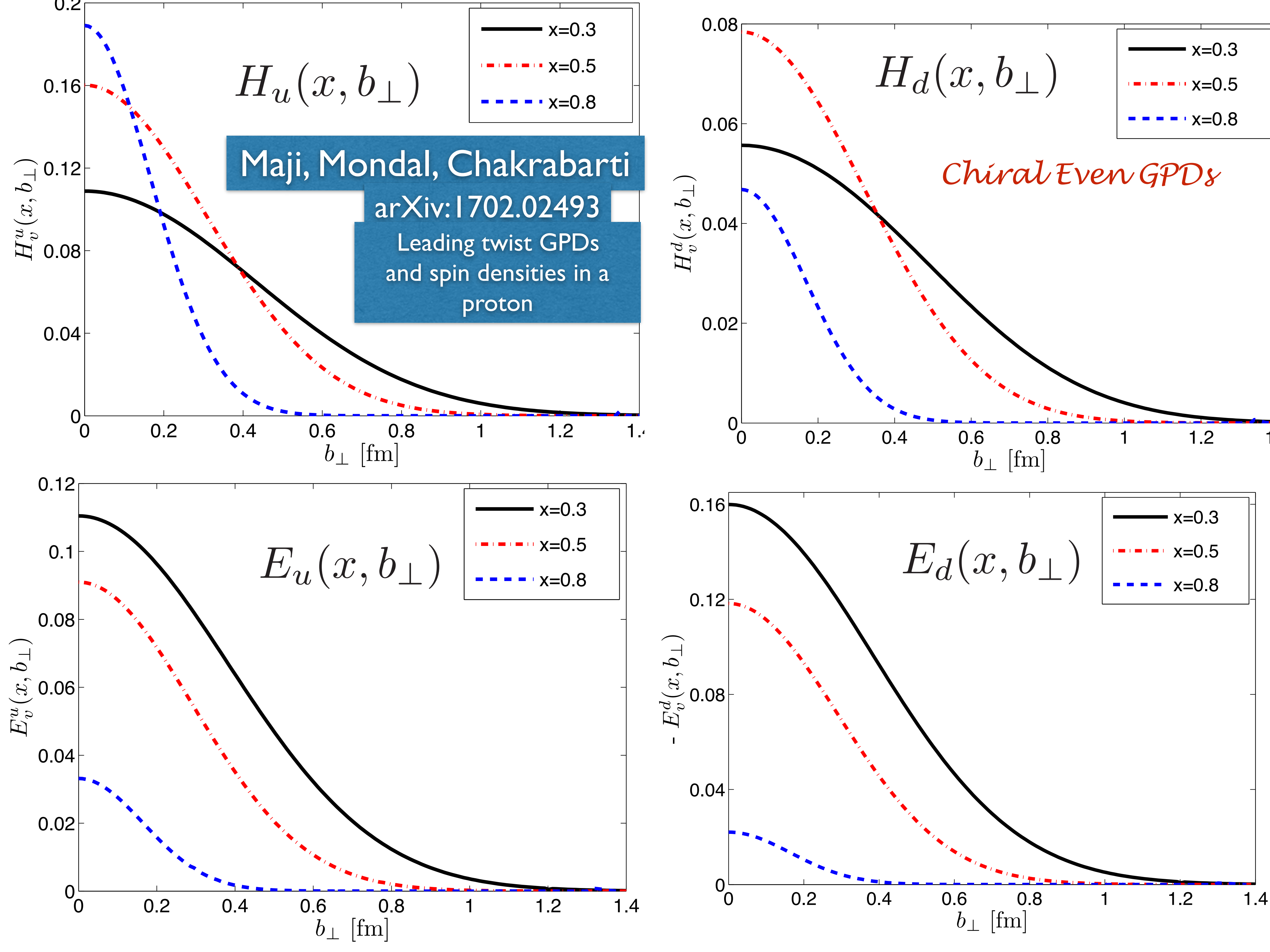
The GPD amplitudes can be accessed experimentally through the Deeply Virtual Compton Scattering cross section at leading twist: $Q^2 \to \infty$.

DVCS: $e\,N \to e' + \gamma + N$

Through $\Delta_\perp$, the GPD's contain information about the parton distributions in transverse space.



Handbag modified by leading-twist lensing!

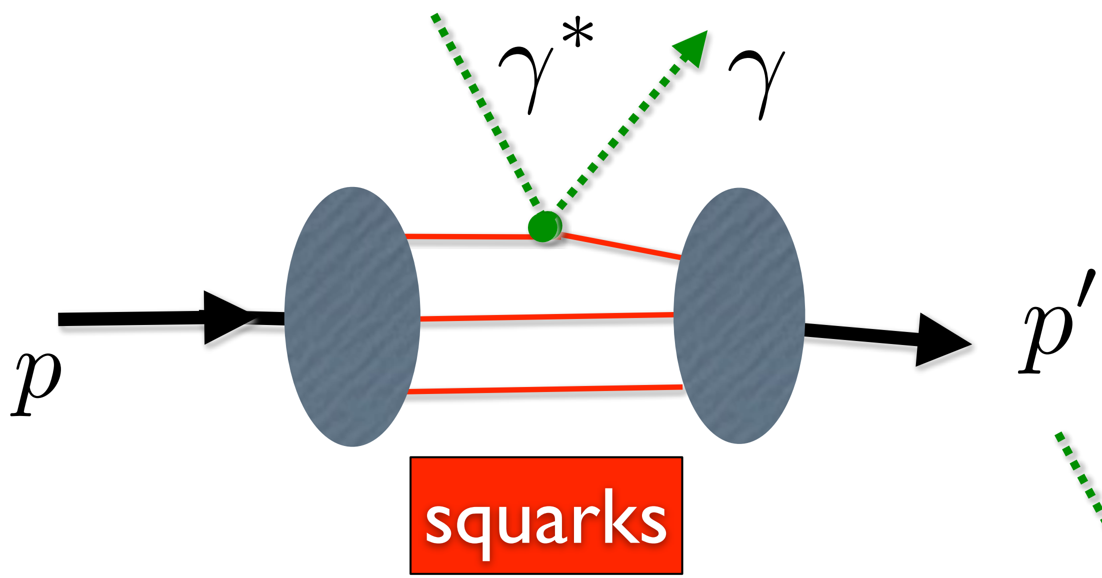


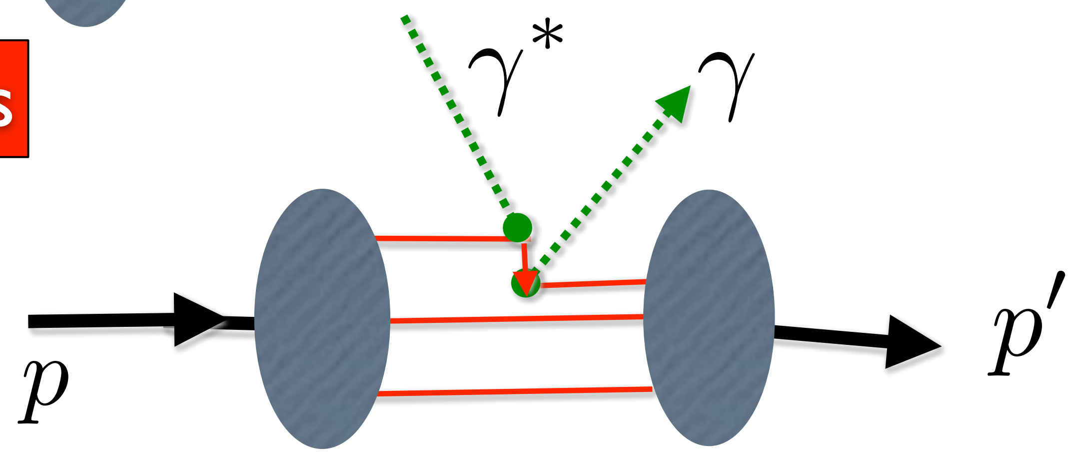
$H_u(x, b_\perp)$
Maji, Mondal, Chakrabarti
arXiv:1702.02493
Leading twist GPDs and spin densities in a proton
x=0.3
x=0.5
x=0.8
$H_v^u(x, b_\perp)$
$b_\perp$ [fm]
$H_d(x, b_\perp)$
Chiral Even GPDs
$H_v^d(x, b_\perp)$
$b_\perp$ [fm]
$E_u(x, b_\perp)$
$E_v^u(x, b_\perp)$
$b_\perp$ [fm]
$E_d(x, b_\perp)$
$-E_v^d(x, b_\perp)$
$b_\perp$ [fm]

J=0 Fixed Pole Contribution to DVCS

- J=0 fixed pole -- direct test of QCD locality -- from seagull or instantaneous contribution to Feynman propagator

Szczepaniak, Llanes-Estrada, sjb
Close, Gunion, sjb

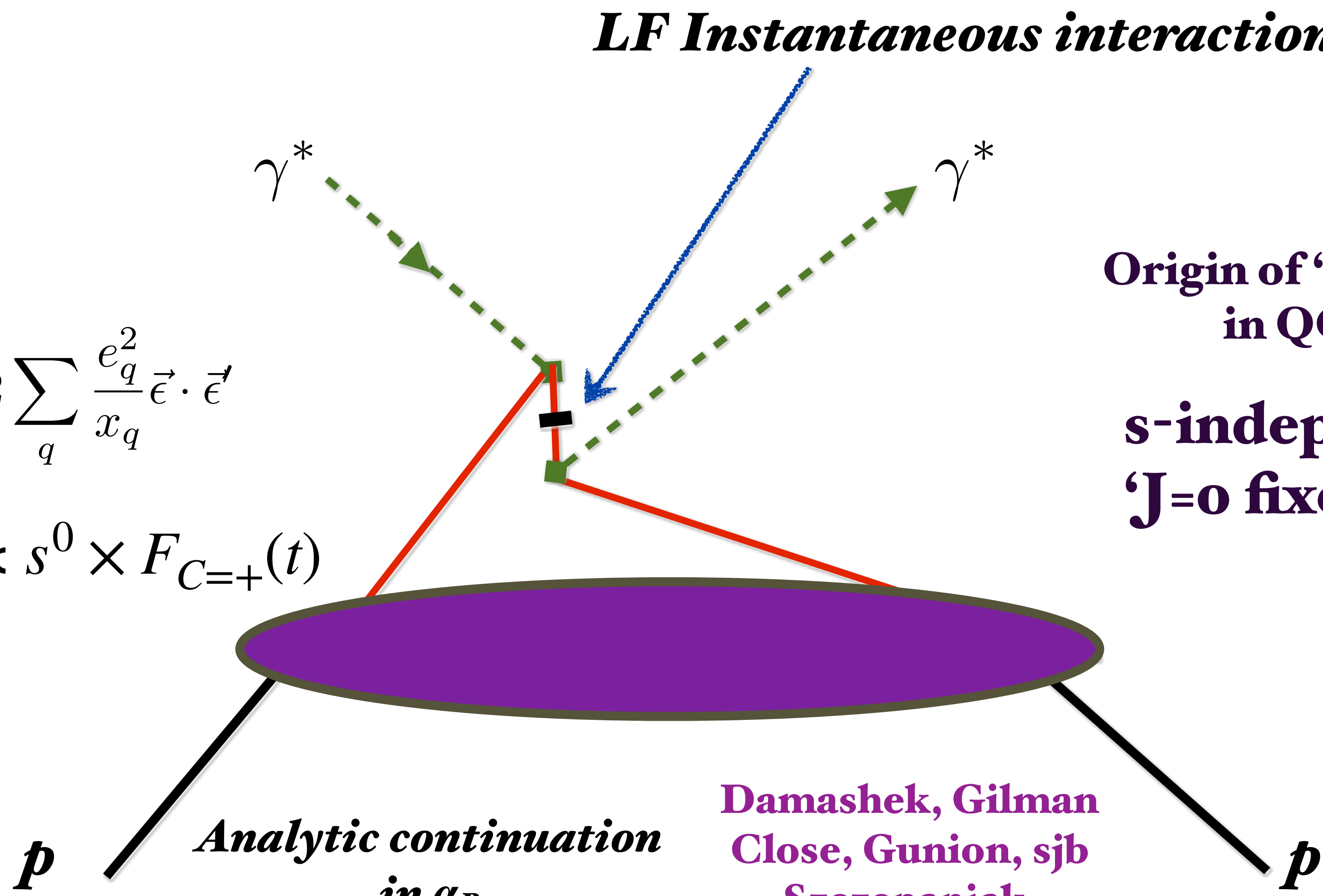




Real amplitude, independent of Q^2 at fixed t

quarks

Leading-Twist Contribution to Real Part of DVCS



$$T = -2 \sum_q \frac{e_q^2}{x_q} \vec{\epsilon} \cdot \vec{\epsilon}'$$

$$T(s,t) \propto s^0 \times F_{C=+}(t)$$

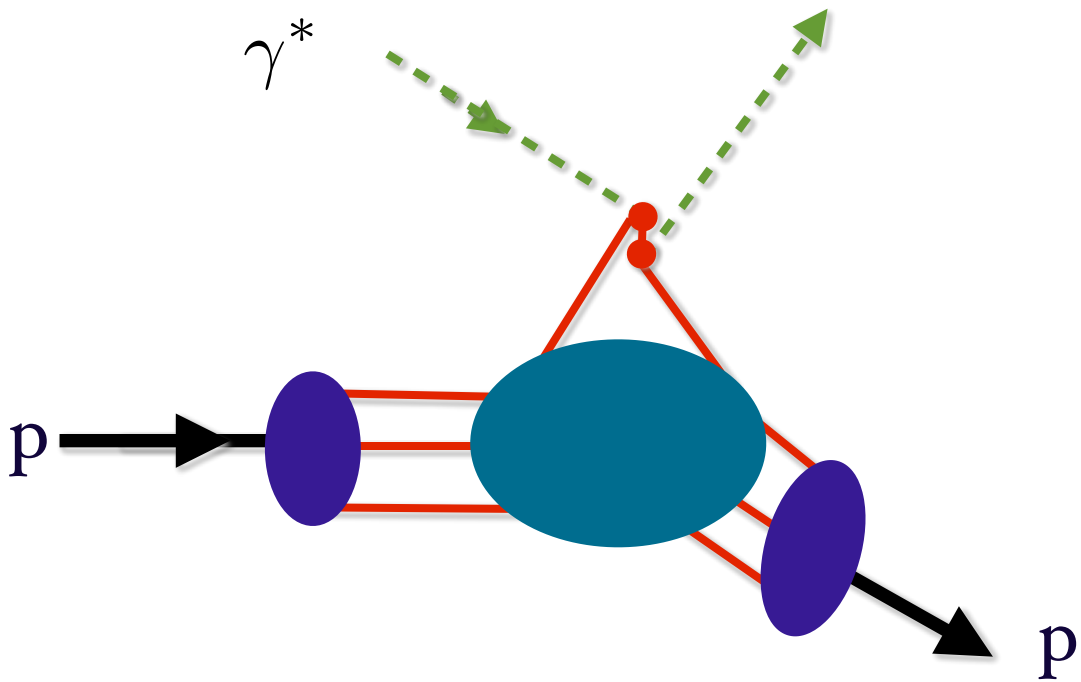
Origin of 'D-Term' in QCD

s-independent 'J=0 fixed pole'

Damashek, Gilman
Close, Gunion, sjb
Szczepaniak, Llanes Estrada, sjb

Deeply Virtual Compton Scattering

$$\gamma^* p \to \gamma p$$



Seagull interaction (instantaneous quark exchange or Z-graph)

$$s >> -t, Q^2 >> \Lambda^2_{QCD}$$

Hard Reggeon Domain

$$T(\gamma^*(q)p \to \gamma(k) + p) \sim \epsilon \cdot \epsilon' \sum_R s_R^{\alpha}(t)\beta_R(t)$$

$$\alpha_R(t) \to 0$$

Reflects elementary coupling of two photons to quarks

$$\beta_R(t) \sim \frac{1}{t^2}$$

$$\frac{d\sigma}{dt} \sim \frac{1}{s^2}\frac{1}{t^4} \sim \frac{1}{s^6} \text{ at fixed } \frac{Q^2}{s}, \frac{t}{s}$$

J=0 Fixed pole in real and virtual Compton scattering

Damashek, Gilman; Close, Gunion, sjb Llanes-Estrada, Szczepaniak, sjb

Effective two-photon contact term

Seagull for scalar quarks

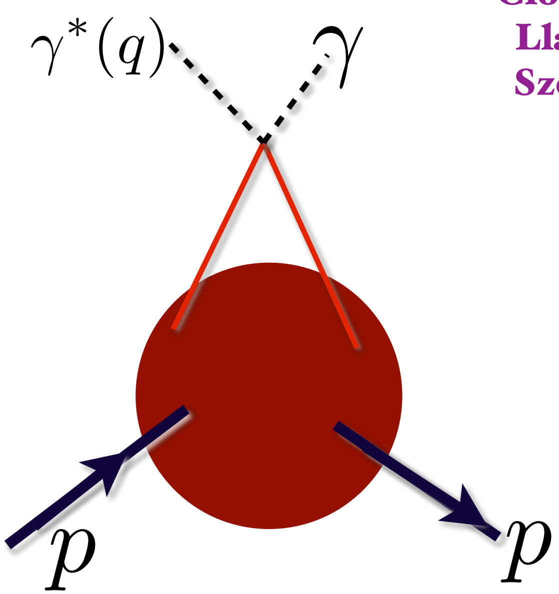
Real phase

$$M = s^0 \sum e_q^2 F_q(t)$$

Independent of Q^2 at fixed t

<1/x> Moment: Related to Feynman-Hellman Theorem

Fundamental test of local gauge theory



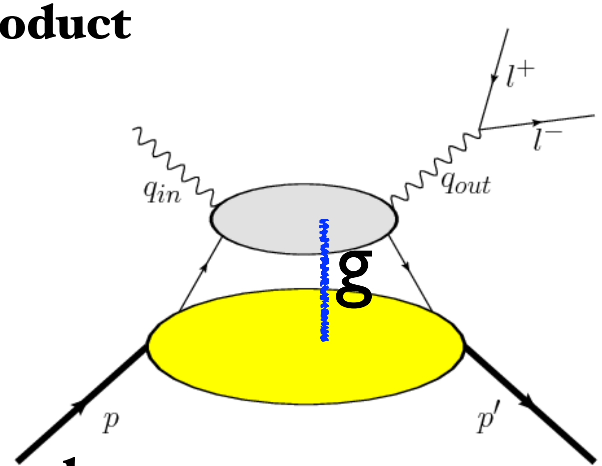
Q^2-independent contribution to Real DVCS amplitude

$$s^2 \frac{d\sigma}{dt}(\gamma^* p \to \gamma p) = F^2(t)$$

independent of s

"Handbag" Approximation

- **Parton model: assumes current-current correlator carried by single quark propagator at high photon virtuality**
- **Imaginary Part of Virtual Forward Compton Amplitude gives DIS structure Functions**
- **Leading-Twist Dominance — Motivated by the Operator Product Expansion**
- **Produces Momentum and Baryon Number Sum Rules**
- **Real Part: J=0 Fixed Pole from local two-photon operators**
- **Will show: Handbag Approximation invalid for DVCS on a nuclear target because of shadowing, antishadowing!**
- **Recall: Sivers Effect and Diffractive DIS are leading twist!**



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Light-front formulation of the standard model

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Light-front (LF) quantization in the light-cone (LC) gauge is used to construct a renormalizable theory of the standard model. The framework derived earlier for QCD is extended to the Glashow-Weinberg-Salam (GWS) model of electroweak interaction theory. The Lorentz condition is automatically satisfied in LF-quantized QCD in the LC gauge for the free massless gauge field. In the GWS model, with the spontaneous symmetry breaking present, we find that the 't Hooft condition accompanies the LC gauge condition corresponding to the massive vector boson. The two transverse polarization vectors for the massive vector boson may be chosen to be the same as found in QCD. The nontransverse and linearly independent third polarization vector is found to be parallel to the gauge direction. The corresponding sum over polarizations in the standard model, indicated by $K_{\mu\nu}(k)$, has several simplifying properties similar to the polarization sum $D_{\mu\nu}(k)$ in QCD. The framework is unitary and ghost free (except for the ghosts at $k^+=0$ associated with the light-cone gauge prescription). The massive gauge field propagator has well-behaved asymptotic behavior. The interaction Hamiltonian of electroweak theory can be expressed in a form resembling that of covariant theory, plus additional instantaneous interactions which can be treated systematically. The LF formulation also provides a transparent discussion of the Goldstone boson (or electroweak) equivalence theorem, as the illustrations show.

Standard Model on the Light-Front

- Same phenomenological predictions
- Higgs field has three components
- Real part creates Higgs particle
- Imaginary part (Goldstone) become longitudinal components of W, Z
- *Higgs VEV of instant form becomes k^+=0 LF zero mode!*
- Analogous to a background static classical Zeeman or Stark Fields
- Zero contribution to $T^\mu{}_\mu$; zero coupling to gravity

P. Srivastava, sjb

Abelian U(1) LF Model with Spontaneous Symmetry Breaking

$$\mathcal{L} = \partial_+ \phi^\dagger \partial_- \phi + \partial_- \phi^\dagger \partial_+ \phi - \partial_\perp \phi^\dagger \partial_\perp \phi - \mathcal{V}(\phi^\dagger \phi)$$

where $V(\phi^\dagger \phi) = \mu^2 \phi^\dagger \phi + \lambda (\phi^\dagger \phi)^2$ with $\lambda > 0, \ \mu^2 < 0$

Constraint equation: $\int d^2 x_\perp dx^- \left[\partial_\perp \partial_\perp \phi - \frac{\delta V}{\delta \phi^\dagger} \right] = 0$

$$\phi(\tau, x^-, x_\perp) = \omega(\tau, x_\perp) + \varphi(\tau, x^-, x_\perp)$$

$\omega(\tau, x_\perp)$ is a $k^+ = 0$ zero mode

$\omega = v/\sqrt{2}$ where $v = \sqrt{-\mu^2/\lambda}$

Thus a c-number in LF replaces conventional Higgs VEV

No coupling to gravity!

Possibility: $\partial_\perp \omega \neq 0$

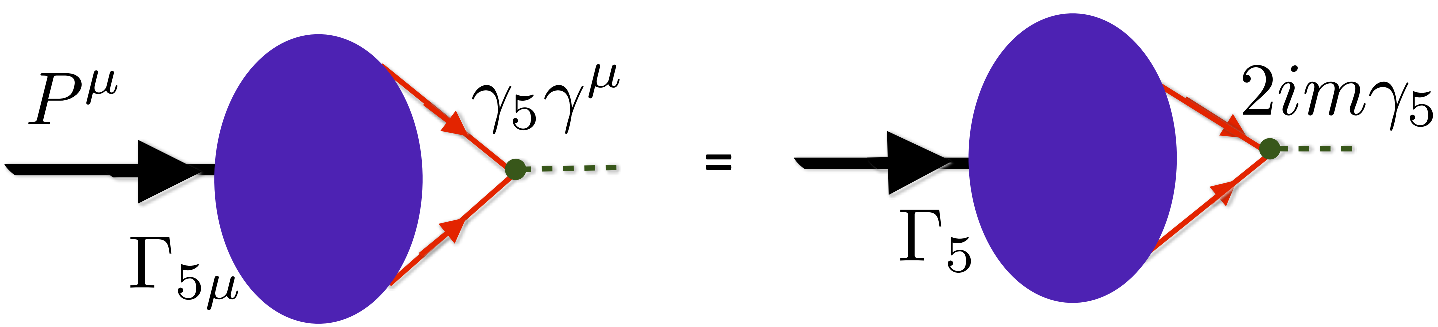
Light-Front Quantization of the Standard Model

- SU(2) X U(1) GWS Model of Weak Interactions
- Non-Abelian Higgs Model in LG Gauge
- Unitary, renormalizable, no Gupta-Bleuler, Fadeev-Popov ghosts
- SSB: Perturbative vacuum plus zero mode field
- t'Hooft conditions satisfied
- Higgs field: Real field creates Higgs particle; imaginary components identified with longitudinal components of W, Z
- Higgs VEV replaced by zero mode

Ward-Takahashi Identity for axial current

$$P^{\mu}\Gamma_{5\mu}(k,P) + 2im\Gamma_5(k,P) = S^{-1}(k+P/2)i\gamma_5 + i\gamma_5 S^{-1}(k-P/2)$$

$$S^{-1}(\ell) = i\gamma\cdot\ell A(\ell^2) + B(\ell^2) \qquad m(\ell^2) = \frac{B(\ell^2)}{A(\ell^2)}$$



plus non-pole

Identify pion pole at $P^2 = m_\pi^2$

$$P^{\mu} < 0|\bar{q}\gamma_5\gamma^{\mu}q|\pi >= 2m < 0|\bar{q}i\gamma_5 q|\pi >$$

$$f_\pi m_\pi^2 = -(m_u + m_d)\rho_\pi$$

Revised Gell Mann-Oakes-Renner Formula in QCD

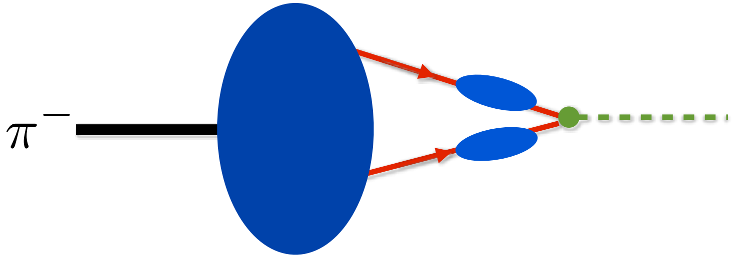
$$m_\pi^2 = -\frac{(m_u + m_d)}{f_\pi^2} < 0|\bar{q}q|0 >$$

current algebra: effective pion field

$$m_\pi^2 = -\frac{(m_u + m_d)}{f_\pi} < 0|i\bar{q}\gamma_5 q|\pi >$$

QCD: composite pion Bethe-Salpeter Eq.

vacuum condensate actually is an "in-hadron condensate"



$$< 0|\bar{q}\gamma_5 q|\pi >$$

Maris, Roberts, Tandy

“One of the gravest puzzles of theoretical physics”

**DARK ENERGY AND
THE COSMOLOGICAL CONSTANT PARADOX**

A. ZEE

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$$(\Omega_\Lambda)_{QCD} \sim 10^{45}$$

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

$$\Omega_\Lambda = 0.76(expt)$$

Extraordinary conflict between the conventional definition of the vacuum in quantum field theory and cosmology

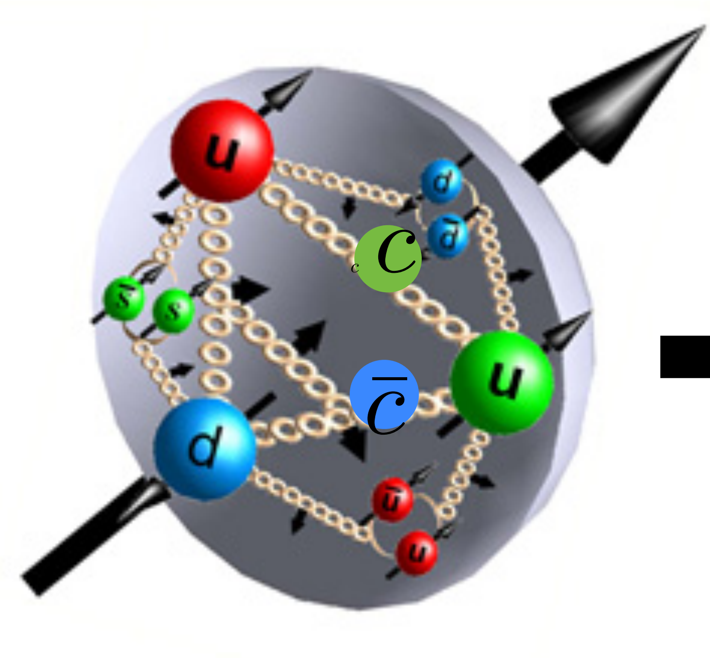
Elements of the solution:

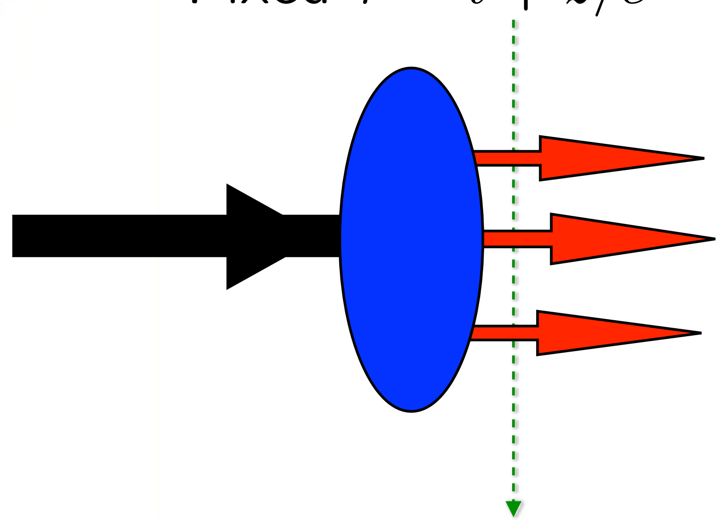
(A) Light-Front Quantization: causal, frame-independent vacuum

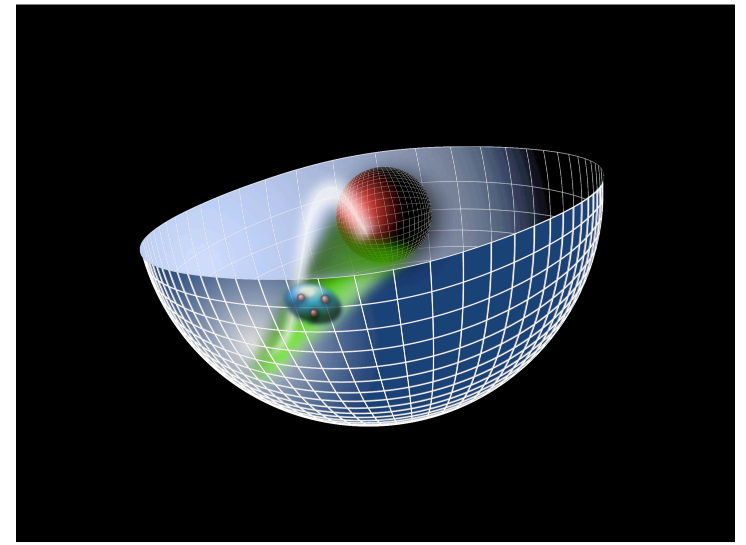
(B) New understanding of QCD “Condensates”

(C) Higgs Light-Front Zero Mode

Novel QCD Features of Hadrons and Nuclei







Stan Brodsky

SLAC NATIONAL ACCELERATOR LABORATORY

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GGI School   Frontiers in Nuclear and Hadronic Physics   February 25 - March 8, 2019