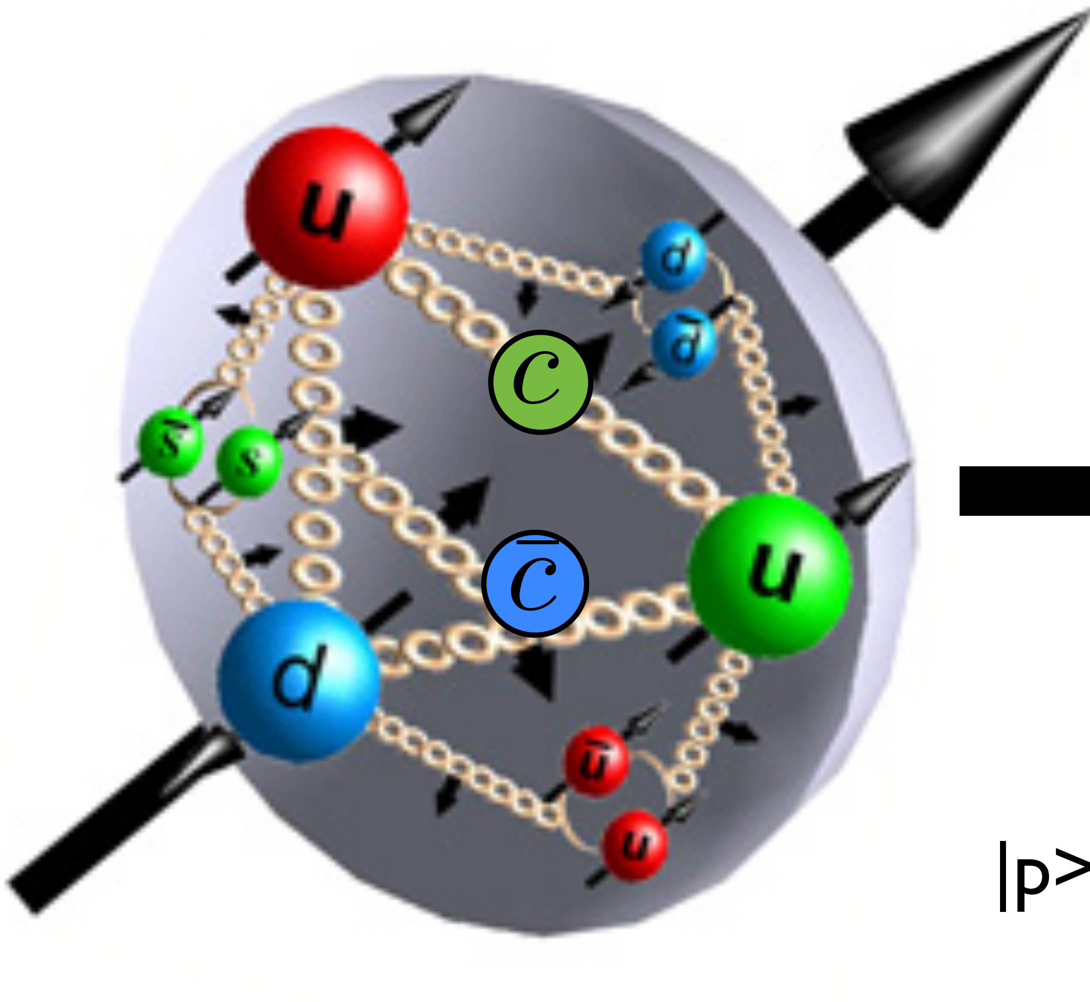
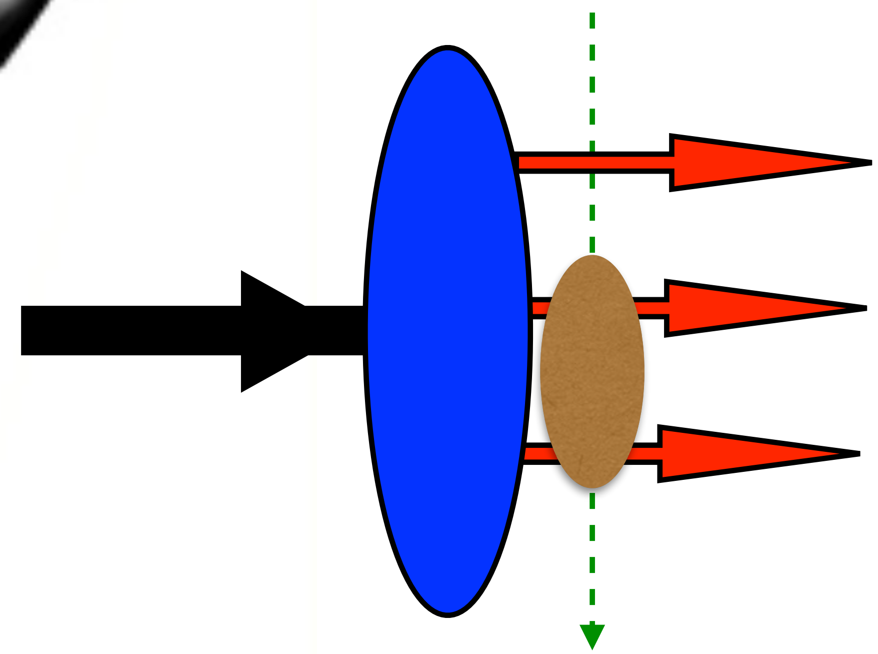
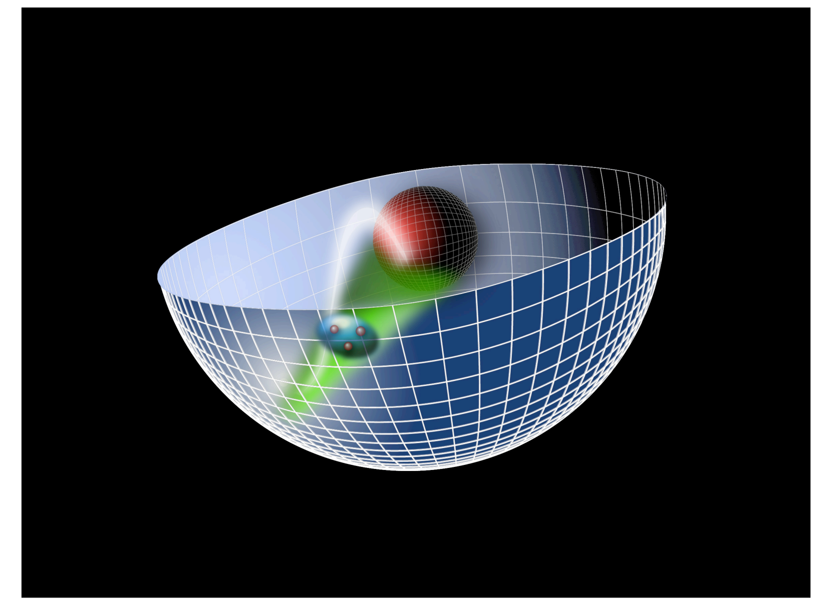
Light-Front Holographic QCD: A Novel Nonperturbative Approach to Color Confinement, Hadron Spectroscopy, and Dynamics



Fixed $\tau = t + z/c$





|p>=|u[ud]> quark-diquark cluster

with Guy de Tèramond, Hans Günter Dosch, Alexandre Deur, Raza Sabbir Sufian, Cedric Lorcè, Tianmbo Liu, Jennifer Rittenhouse West, and Marina Nielsen

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SLAC NATIONAL ACCELERATOR LABORATORY

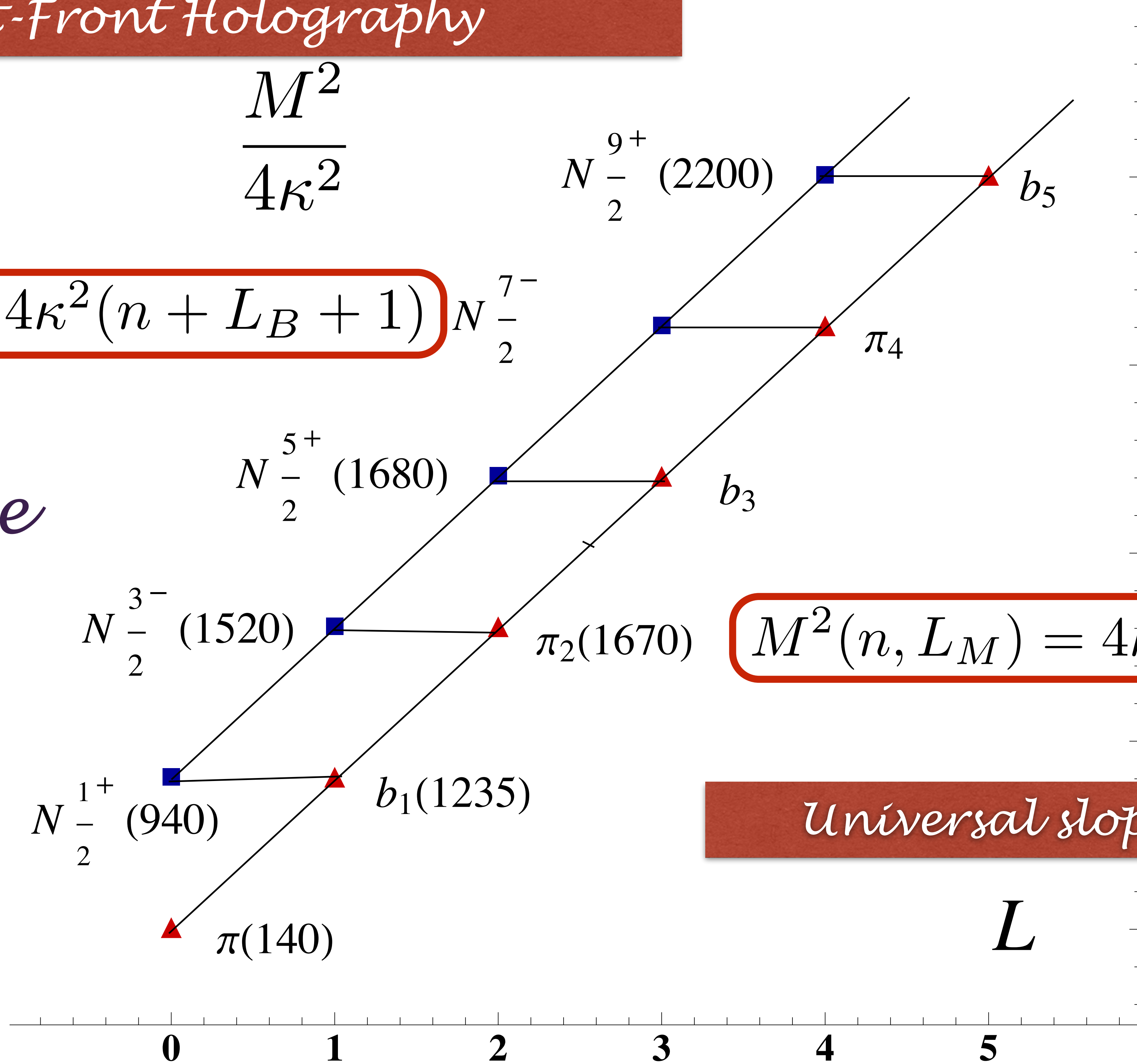
INT March 23, 2023

Challenge: Compute Hadron Structure, Spectroscopy, and Dynamics from QCD!

- *Color Confinement*
- *Origin of the QCD Mass Scale*
- *Meson and Baryon Spectroscopy:* Hadronic Supersymmetry
- *Exotic States: Tetraquarks, Pentaquarks, Gluonium,*
- *Universal Regge Slopes: n, L, Mesons and Baryons*
- *Almost Massless Pion: GMOR Chiral Symmetry Breaking*
  $M_\pi^2 f_\pi^2 = -\frac{1}{2}(m_u+m_d)\langle\bar{u}u+\bar{d}d\rangle+\mathcal{O}\big((m_u+m_d)^2\big)$
- *QCD Coupling at all Scales* $\alpha_s(Q^2)$
- *Eliminate Scale Uncertainties and Scheme Dependence: Principle of Maximum Conformality (PMC)*

Superconformal Quantum Mechanics
Light-Front Holography

de Téramond, Dosch, Lorcé, sjb



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

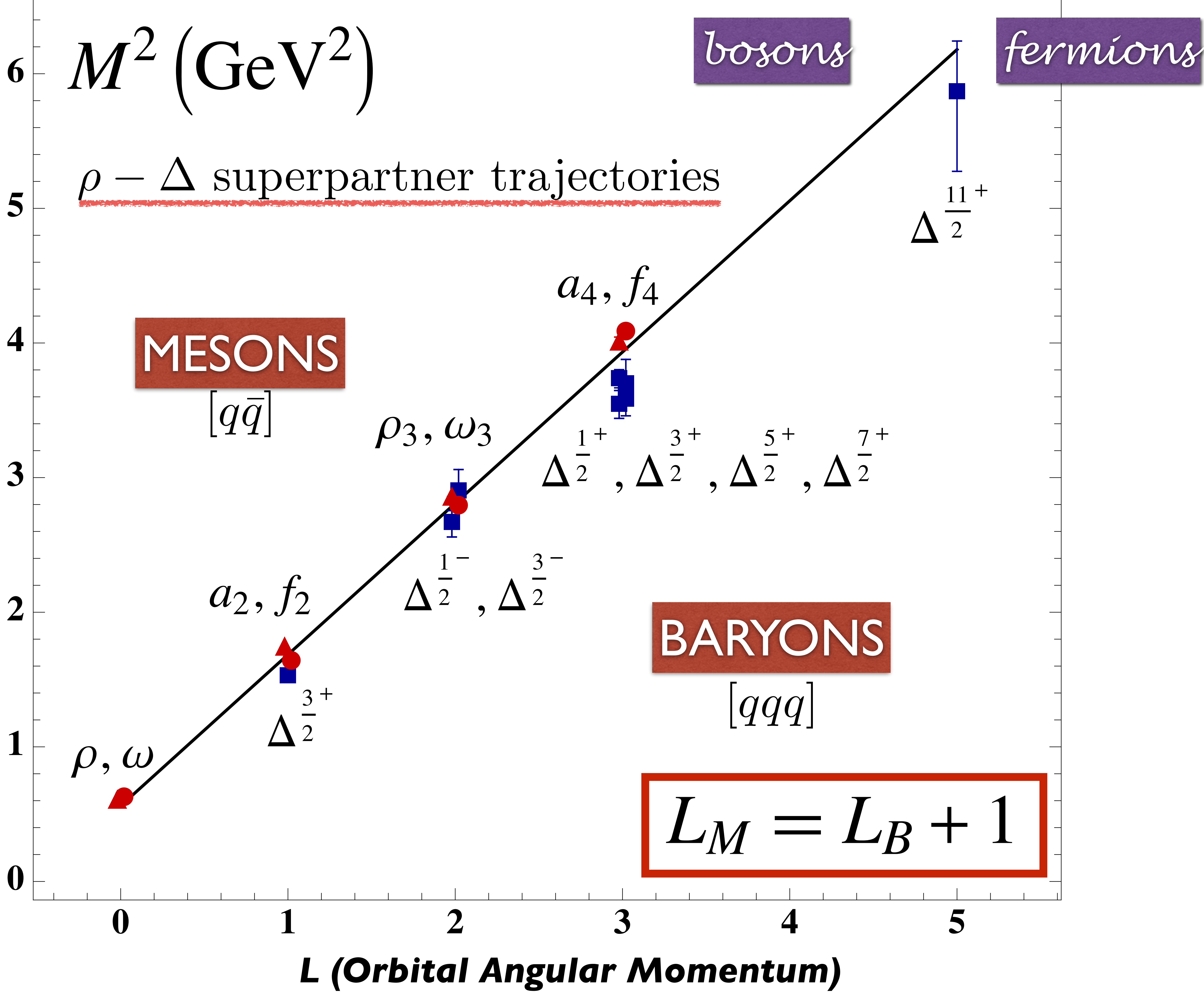
Same slope

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

Universal slopes in n, L

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

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

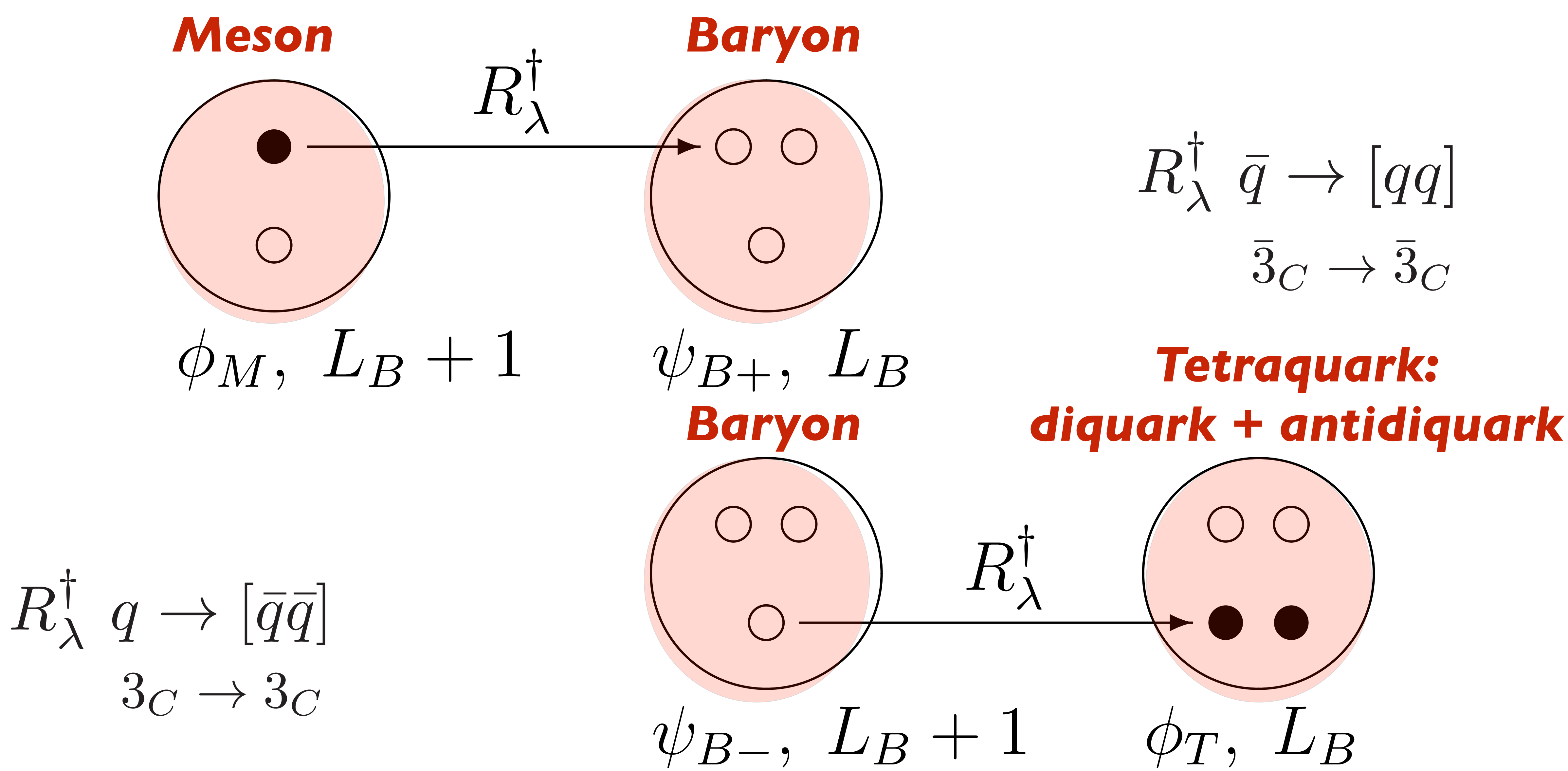


$M^2\,(\mathrm{GeV}^2)$
bosons
fermions
$\rho-\Delta$ superpartner trajectories
MESONS
$[q\bar{q}]$
BARYONS
$[qqq]$
ρ,ω
a_2, f_2
ρ_3,ω_3
a_4, f_4
$\Delta_{\frac{3}{2}^+}$
$\Delta_{\frac{1}{2}^-}, \Delta_{\frac{3}{2}^-}$
$\Delta_{\frac{1}{2}^+}, \Delta_{\frac{3}{2}^+}, \Delta_{\frac{5}{2}^+}, \Delta_{\frac{7}{2}^+}$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

Superconformal Algebra

2X2 Hadronic Multiplets

Bosons, Fermions with Equal Mass!

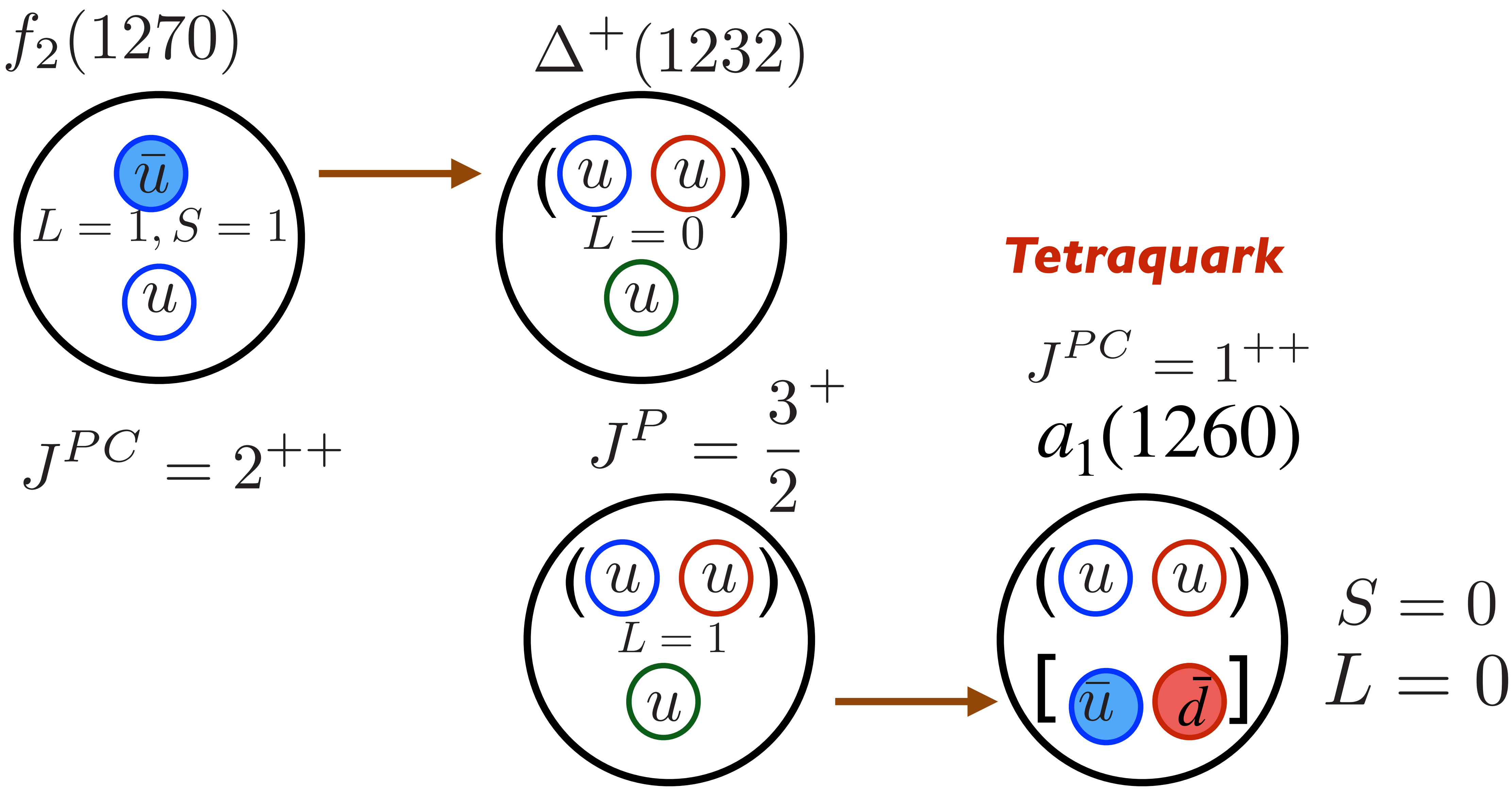


Proton: |u[ud]> Quark + Scalar Diquark
Equal Weight: L=0, L=1

Superconformal Algebra 4-Plet

$$R^\dagger_\lambda \quad \bar{q} \to (qq) \quad S = 1$$
$$\bar{3}_C \to \bar{3}_C$$

Vector ()+ Scalar [] Diquarks



Meson **Baryon**

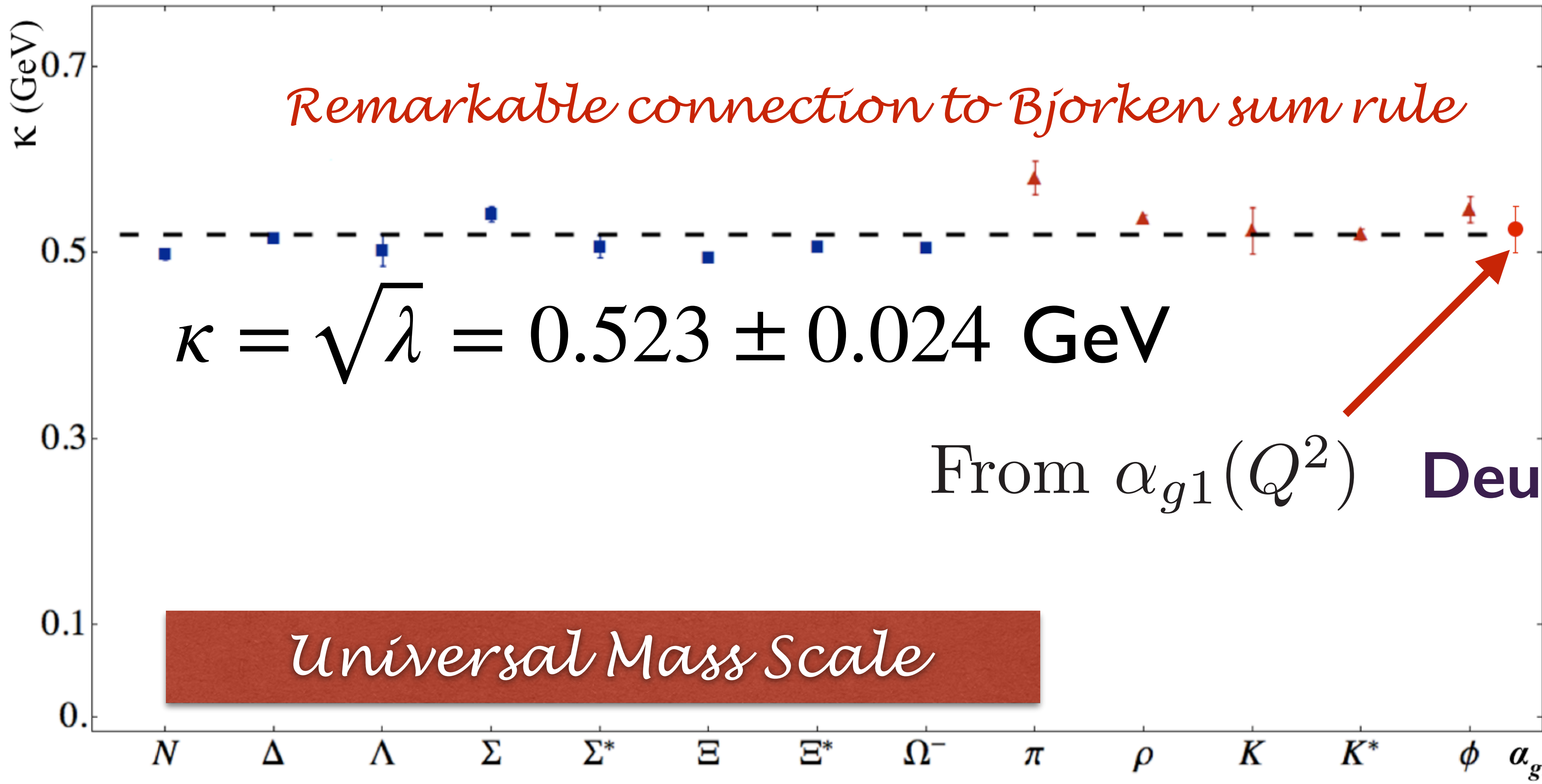
$$R^\dagger_\lambda \quad q \to [\bar{q}\bar{q}]$$
$$3_C \to 3_C$$

$\lambda = \kappa^2$

de Tèramond, Dosch, Lorce', sjb

$$m_u = m_d = 46 \text{ MeV}, \; m_s = 357 \text{ MeV}$$

κ

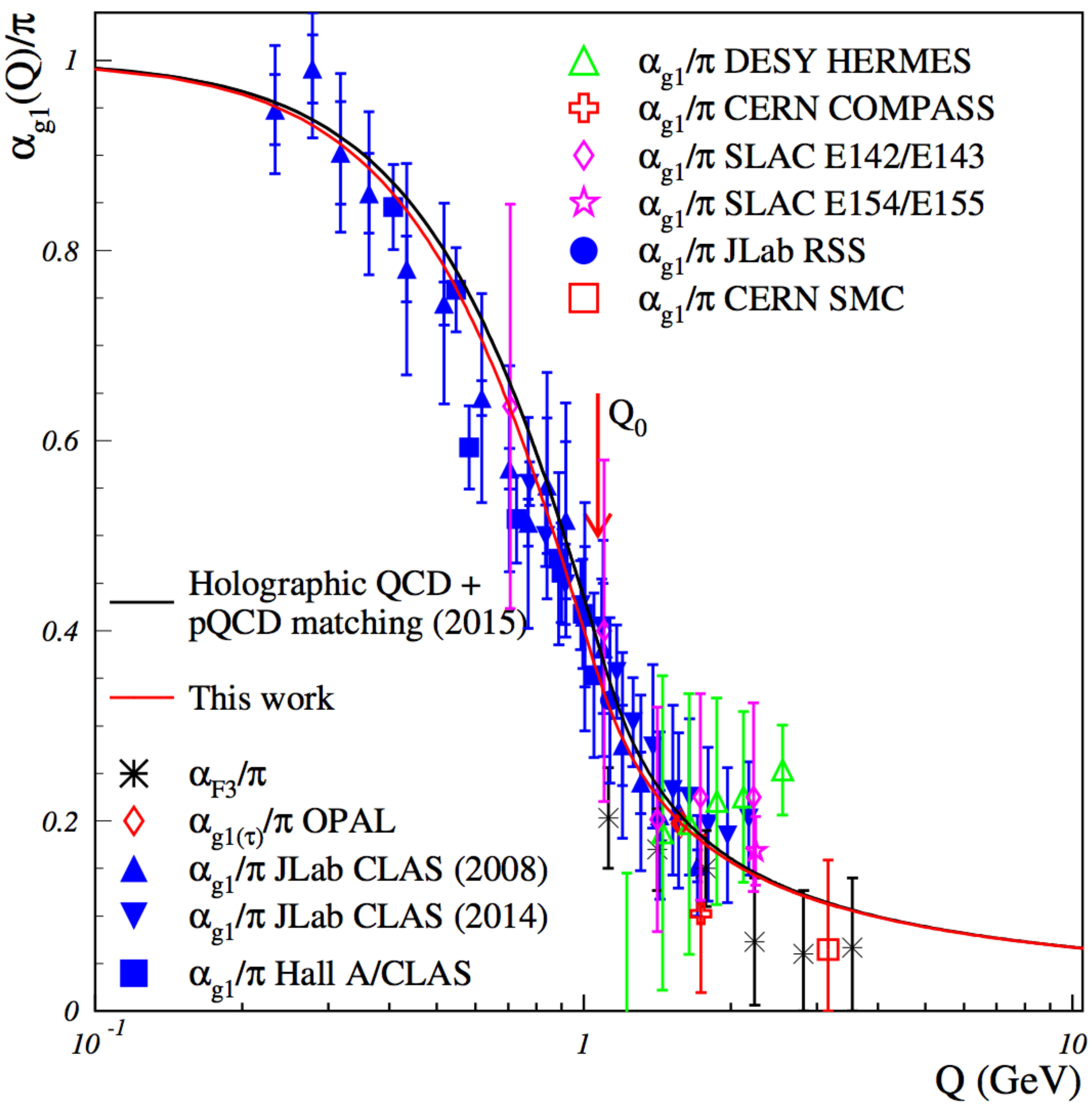


Deur, et al.

Fit to the slope of Regge trajectories, including radial excitations

Same Regge Slope for Meson, Baryons: Supersymmetric feature of hadron physics

Running QCD Coupling from AdS/QCD



Bjorken sum rule:

$$\frac{\alpha_{g_1}(Q^2)}{\pi} = 1 - \frac{6}{g_A}\int_0^1 dx\, g_1^{p-n}(x, Q^2)$$

Effective coupling in LFHQCD (valid at low-Q^2)

$$\alpha_{g_1}^{AdS}(Q^2) = \pi \exp\left(-Q^2/4\kappa^2\right)$$

Imposing continuity for α and its first derivative

A. Deur, S.J. Brodsky, G.F. de Téramond, Phys. Lett. B 750, 528 (2015); J. Phys. G 44, 105005 (2017).

Analytic, defined at all scales, IR Fixed Point

Light-Front QCD

Physical gauge: $A^+ = 0$

Exact frame-independent, causal formulation of nonperturbative QCD!

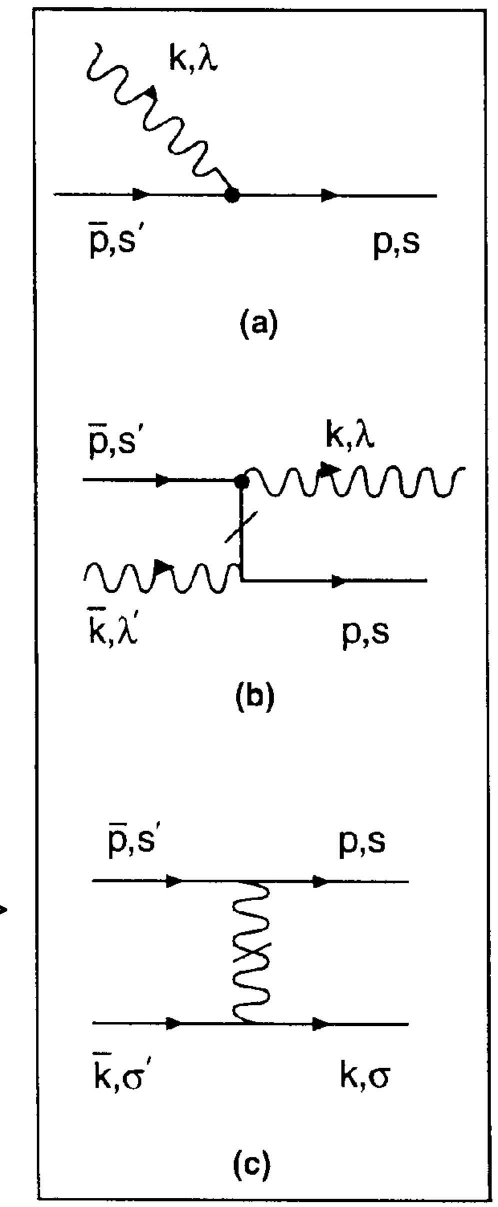
$$L^{QCD} \rightarrow H^{QCD}_{LF}$$

$$H^{QCD}_{LF} = \sum_i [\frac{m^2 + k^2_\perp}{x}]_i + H^{int}_{LF}$$

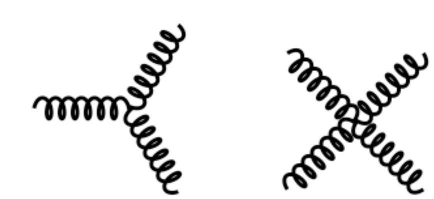
H^{int}_{LF}: Matrix in Fock Space

$$H^{QCD}_{LF} |\Psi_h> = \mathcal{M}^2_h |\Psi_h>$$

$$|p, J_z> = \sum_{n=3} \psi_n(x_i, \vec{k}_{\perp i}, \lambda_i) |n; x_i, \vec{k}_{\perp i}, \lambda_i>$$



Eigenvalues and Eigensolutions give Hadronic Spectrum and Light-Front wavefunctions



$$H^{int}_{LF}$$

LFWFs: Off-shell in P- and invariant mass

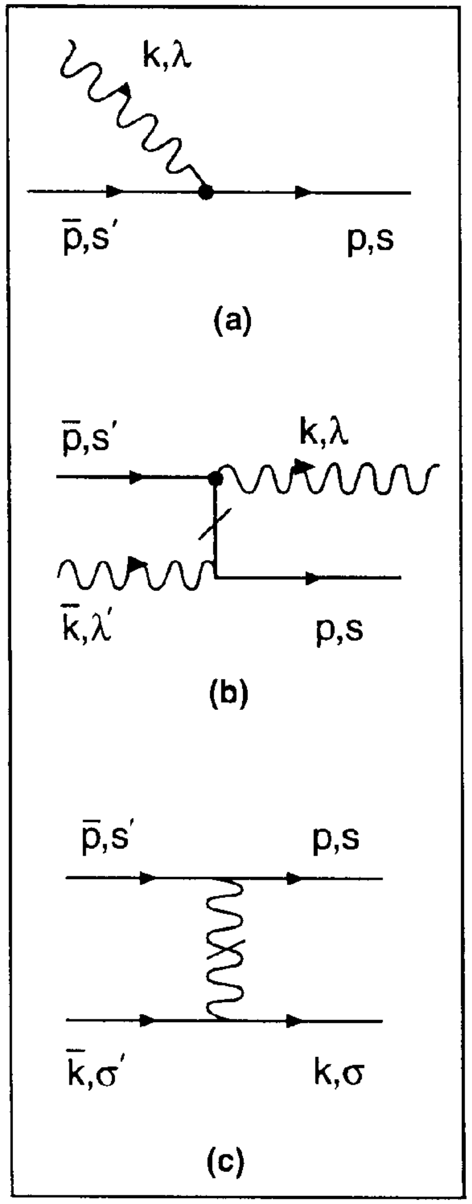
Light-Front QCD

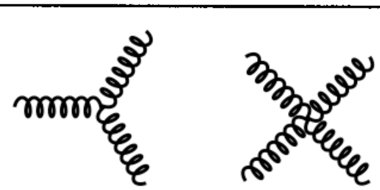
Heisenberg Equation

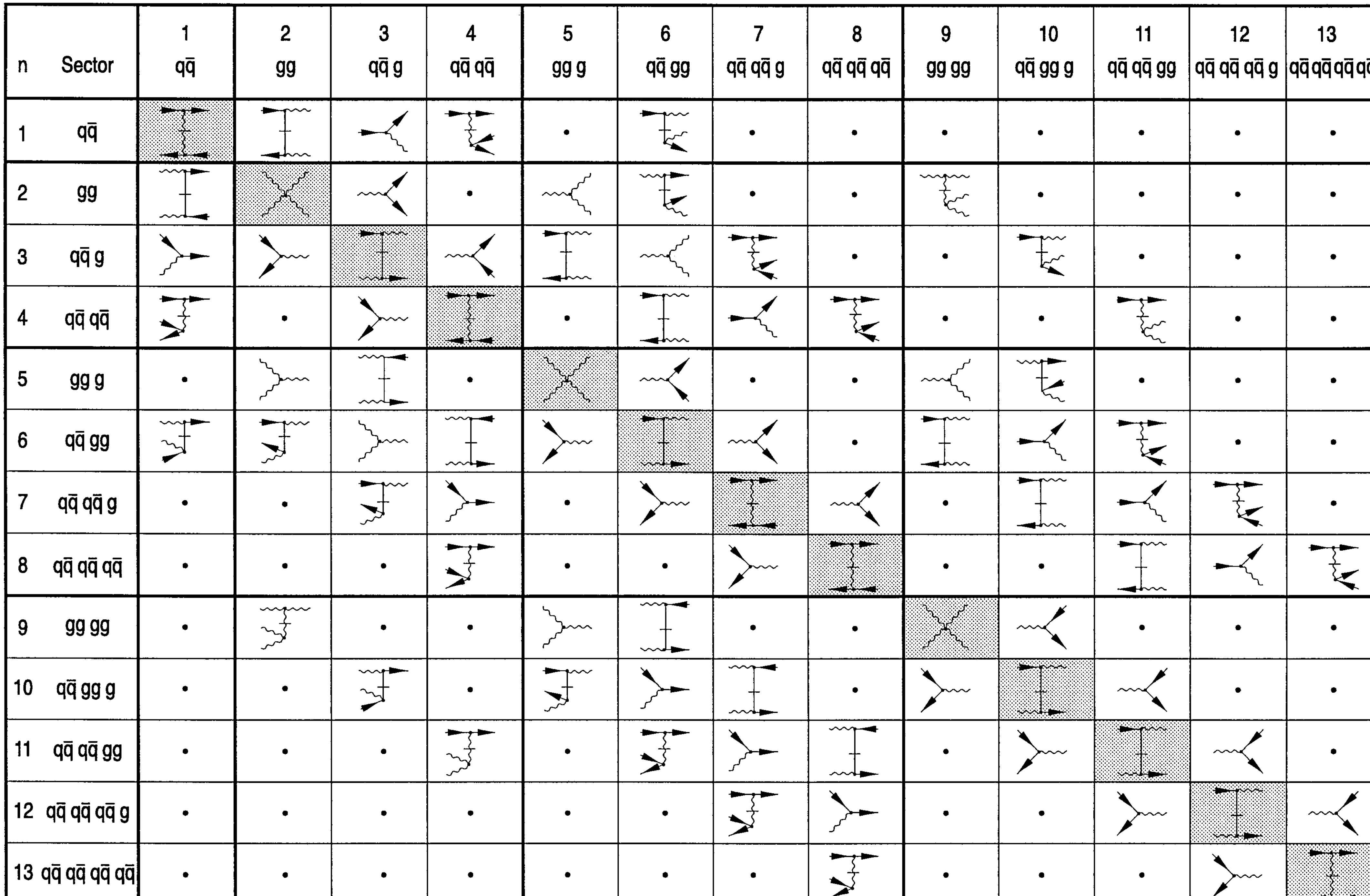
$$H_{LC}^{QCD}|\Psi_h\rangle = \mathcal{M}_h^2\,|\Psi_h\rangle$$

DLCQ: Solve QCD(1+1) for any quark mass and flavors

Hornbostel, Pauli, sjb







Minkowski space; frame-independent; no fermion doubling; no ghosts

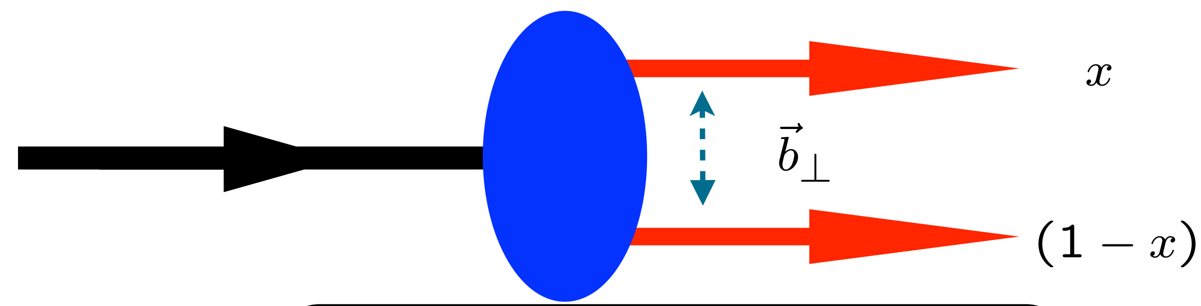
trivial vacuum

BLFQ (Vary et al)

Use LF Holographic Basis

Light-Front QCD

Fixed $\tau = t + z/c$



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

$$\mathcal{L}_{QCD} \rightarrow H^{LF}_{QCD}$$

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

Coupled Fock states

Eliminate higher Fock states
and retarded interactions

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

Effective two-particle equation

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

Azimuthal Basis ζ, ϕ

Single variable Equation

$m_q = 0$

AdS/QCD:

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

Confining AdS/QCD
potential!

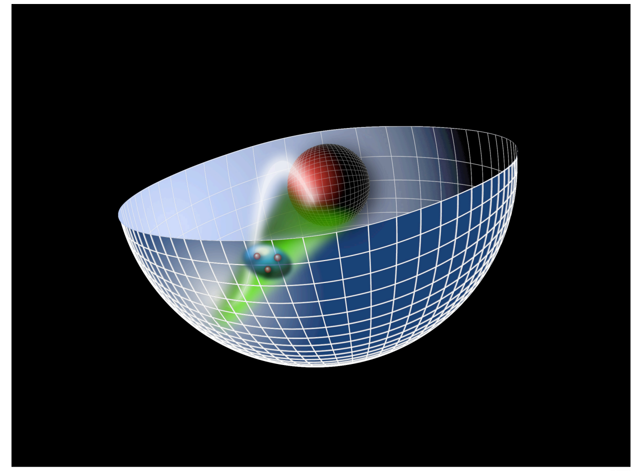
Semiclassical first approximation to QCD

Sums an infinite # diagrams

de Tèramond, Dosch, sjb

AdS/QCD
Soft-Wall Model

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



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

Light-Front Holography

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

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: $\kappa \simeq 0.5\ GeV$

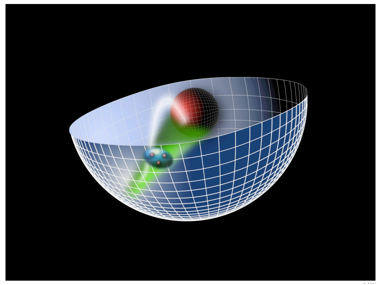
- **de Alfaro, Fubini, Furlan:**
- **Fubini, Rabinovici:**

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

GeV units external to QCD: Only Ratios of Masses Determined

Dilaton-Modified AdS

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



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

Introduce "Dilaton" to simulate confinement analytically

- Nonconformal metric dual to a confining gauge theory

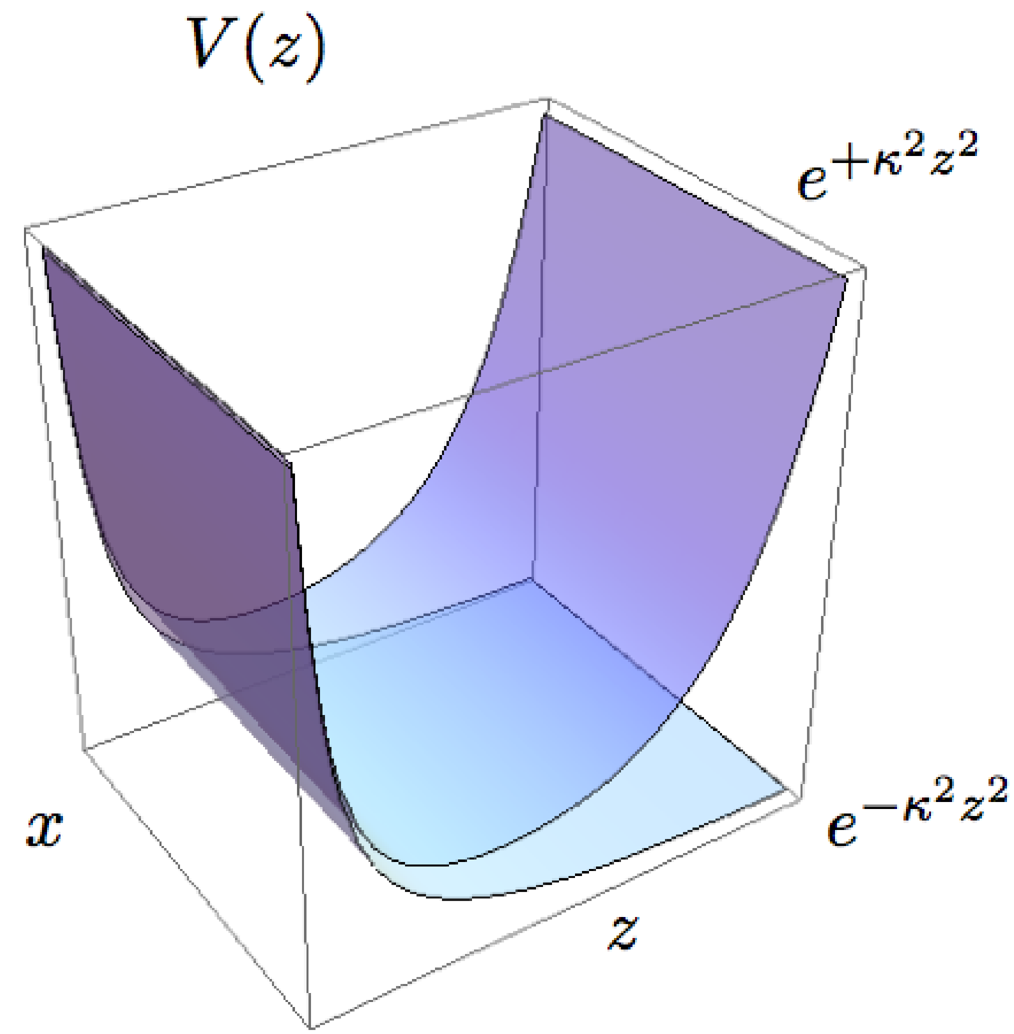
$$ds^2 = \frac{R^2}{z^2} e^{\varphi(z)} \left(\eta_{\mu\nu} dx^\mu dx^\nu - dz^2\right)$$

where $\varphi(z) \to 0$ at small z for geometries which are asymptotically AdS_5

- Gravitational potential energy for object of mass m

$$V = mc^2 \sqrt{g_{00}} = mc^2 R \frac{e^{\varphi(z)/2}}{z}$$

- Consider warp factor $\exp(\pm \kappa^2 z^2)$
- Plus solution: $V(z)$ increases exponentially confining any object in modified AdS metrics to distances $\langle z \rangle \sim 1/\kappa$



Klebanov and Maldacena

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

Positive-sign dilaton

- de Teramond, sjb

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

Positive-sign dilaton

de Téramond, Dosch, sjb

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

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

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

Derived from variation of Action for Dilaton-Modified AdS_5

Identical to Single-Variable Light-Front Bound State Equation in ζ!

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

Light-Front Holography

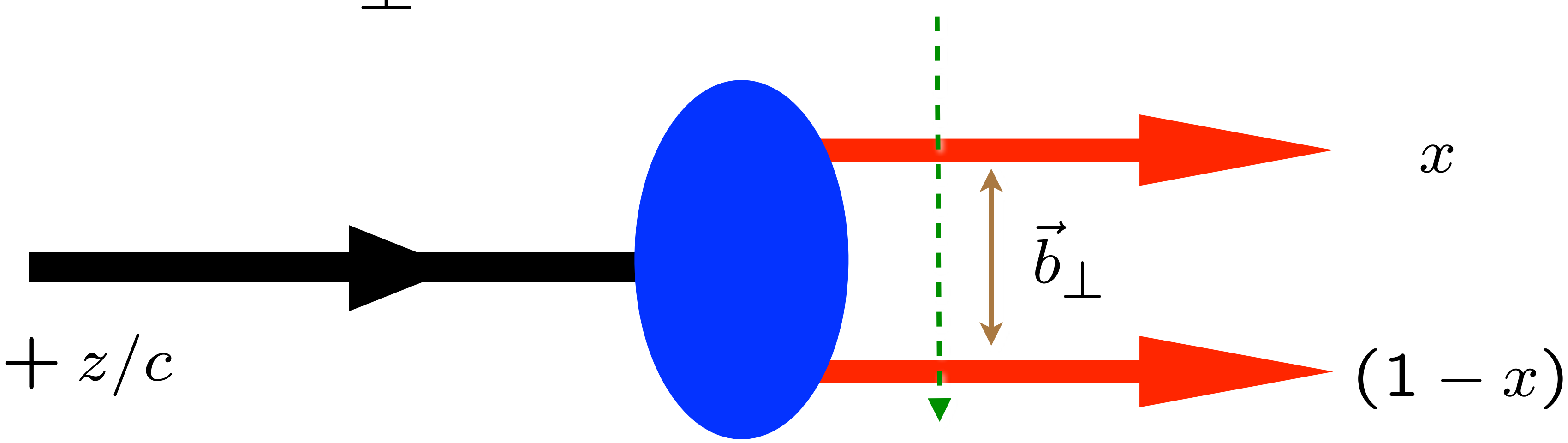
$LF(3+1) \longleftrightarrow AdS_5$

HLFQCD
de Téramond, Dosch, Lorcé, sjb

Light-Front Holographic Dictionary

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

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



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*

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 $J(Q,\zeta) = \zeta Q K_1(\zeta Q)$!

Identical to Polchinski-Strassler Convolution of AdS Amplitudes

de Téramond, sjb

de Téramond, Dosch, Lorcé, sjb

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=+

Meson Equation

$$\lambda = \kappa^2$$

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

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

S=0, P=+

Same κ!

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

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

Universal Hadronic Decomposition

$$\frac{\mathcal{M}_H^2}{\kappa^2} = (1 + 2n + L) + (1 + 2n + L) + (2L + 4S + 2B - 2)$$

- **_Universal quark light-front kinetic energy_**

Equal: Virial Theorem

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

- **_Universal quark light-front potential energy_**

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

- **_Universal Constant Contribution from AdS and Superconformal Quantum Mechanics_**

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

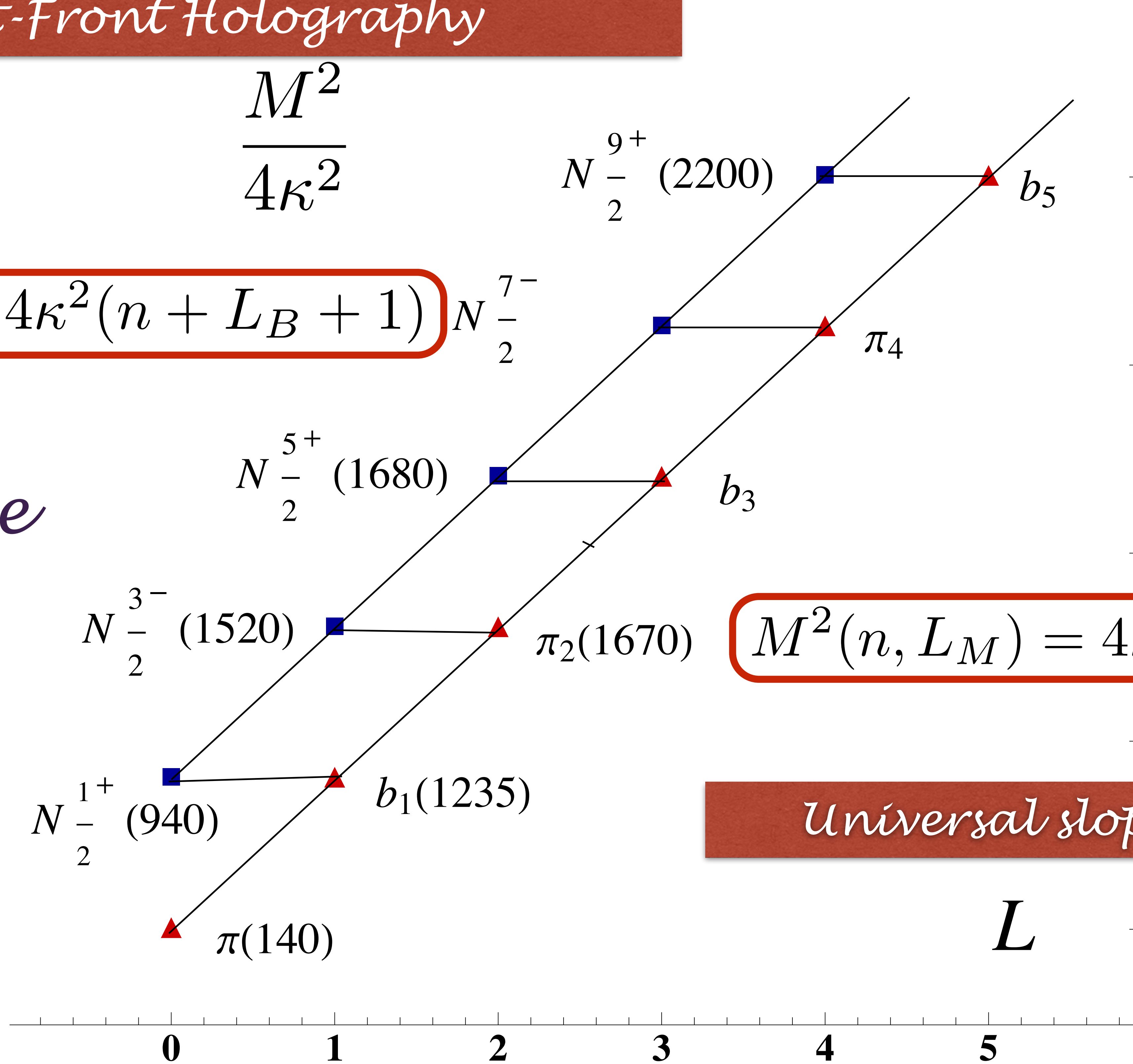
hyperfine spin-spin

Superconformal Quantum Mechanics
Light-Front Holography

de Téramond, Dosch, Lorcé, sjb

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

Same slope

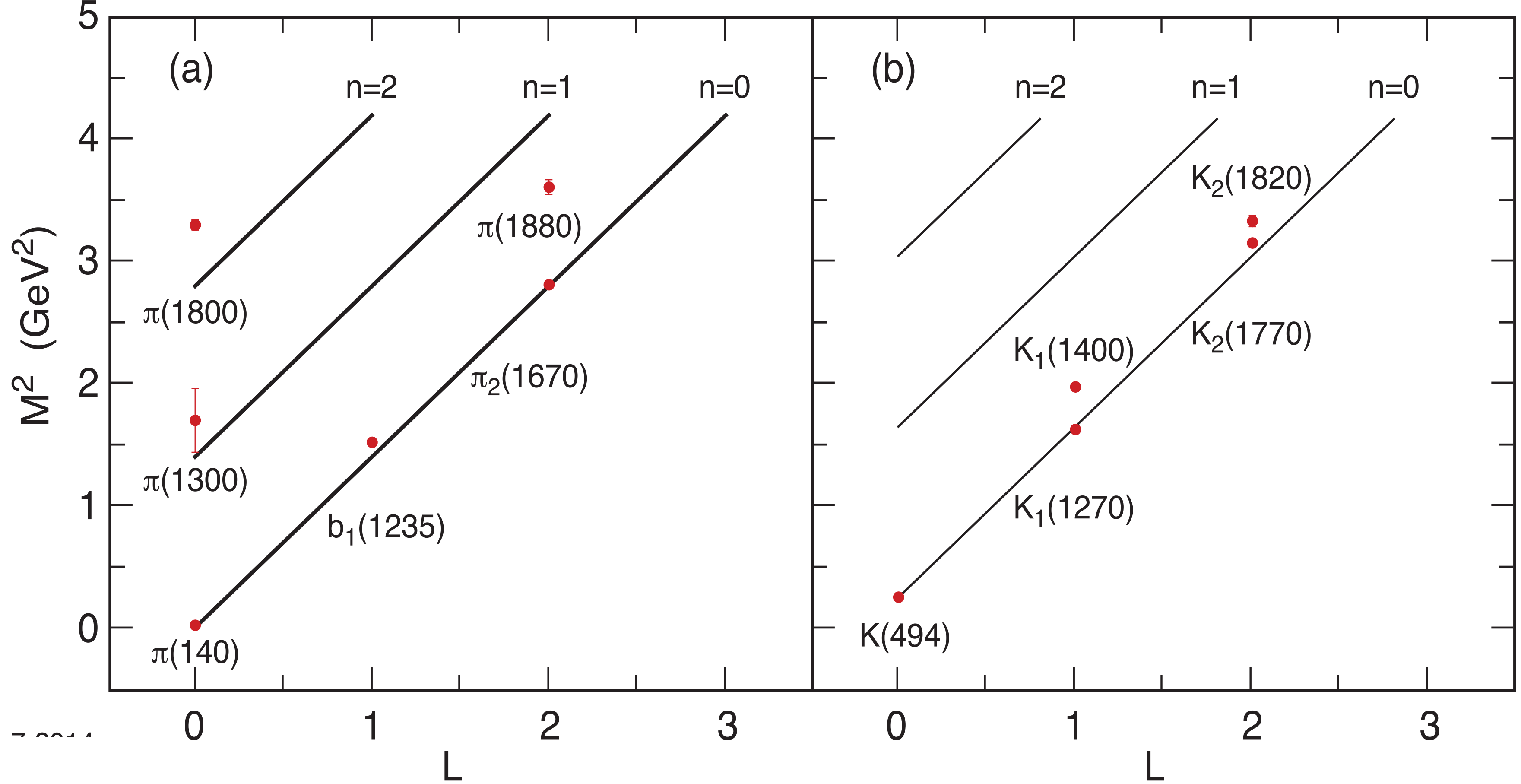


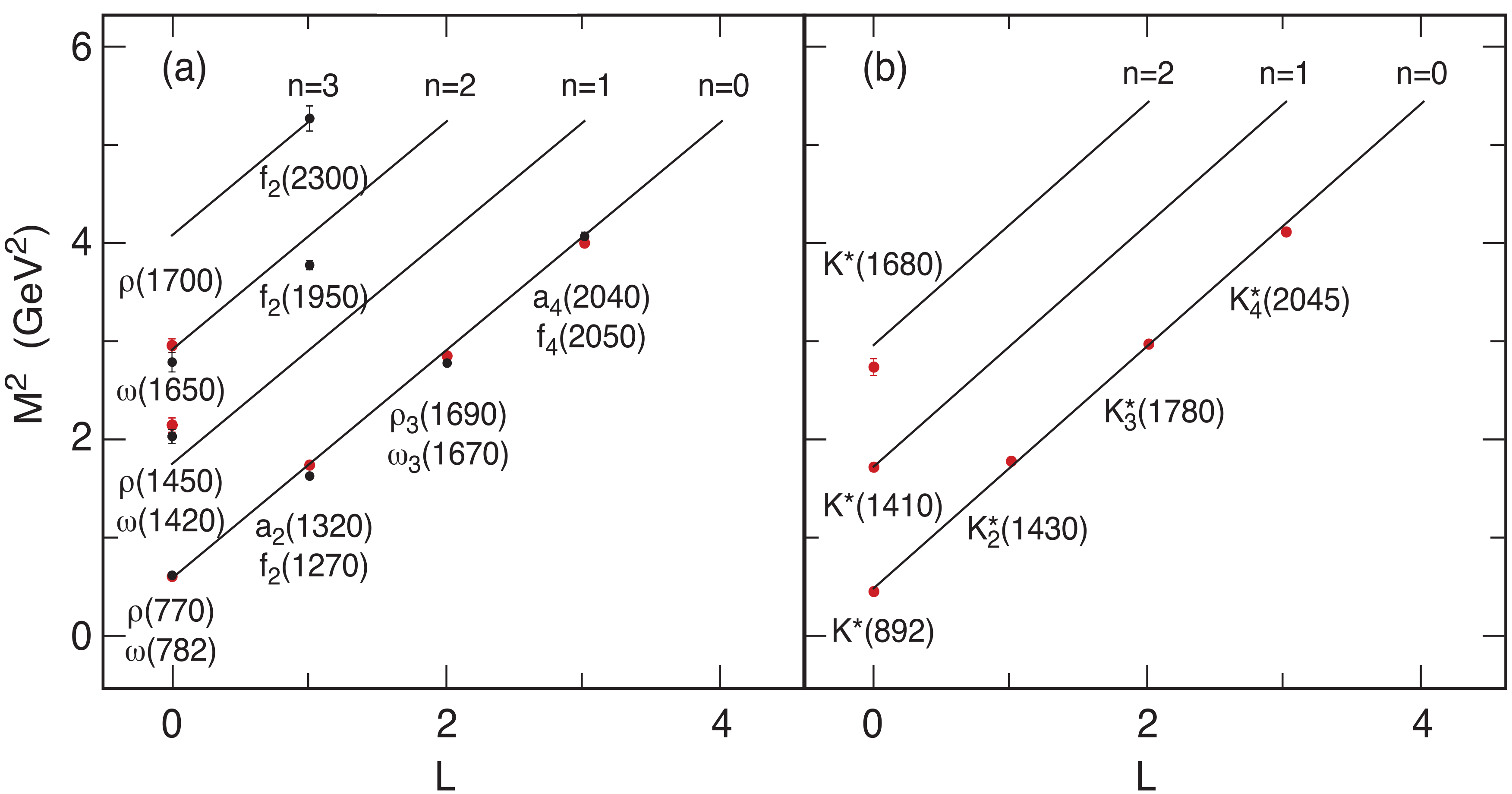
$$M^2(n, L_M) = 4\kappa^2(n + L_M)$$

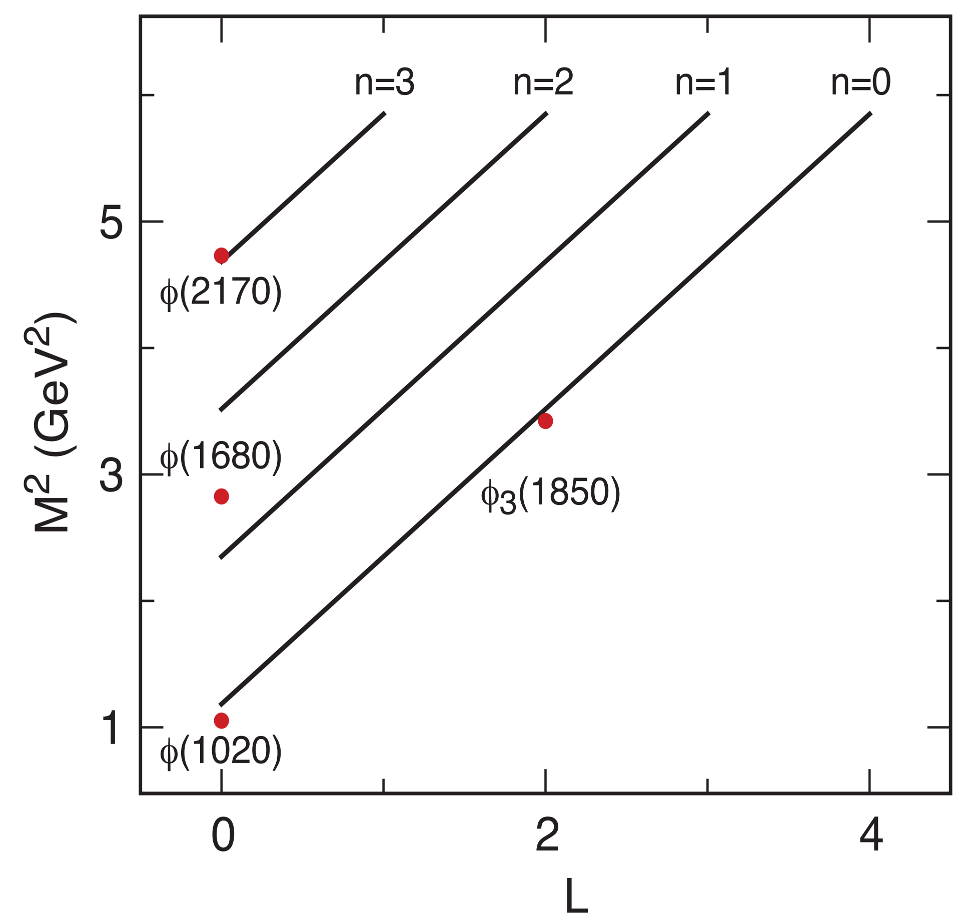
Universal slopes in n, L

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

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







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

Equal Slope in n and L

Quark separation increases with L

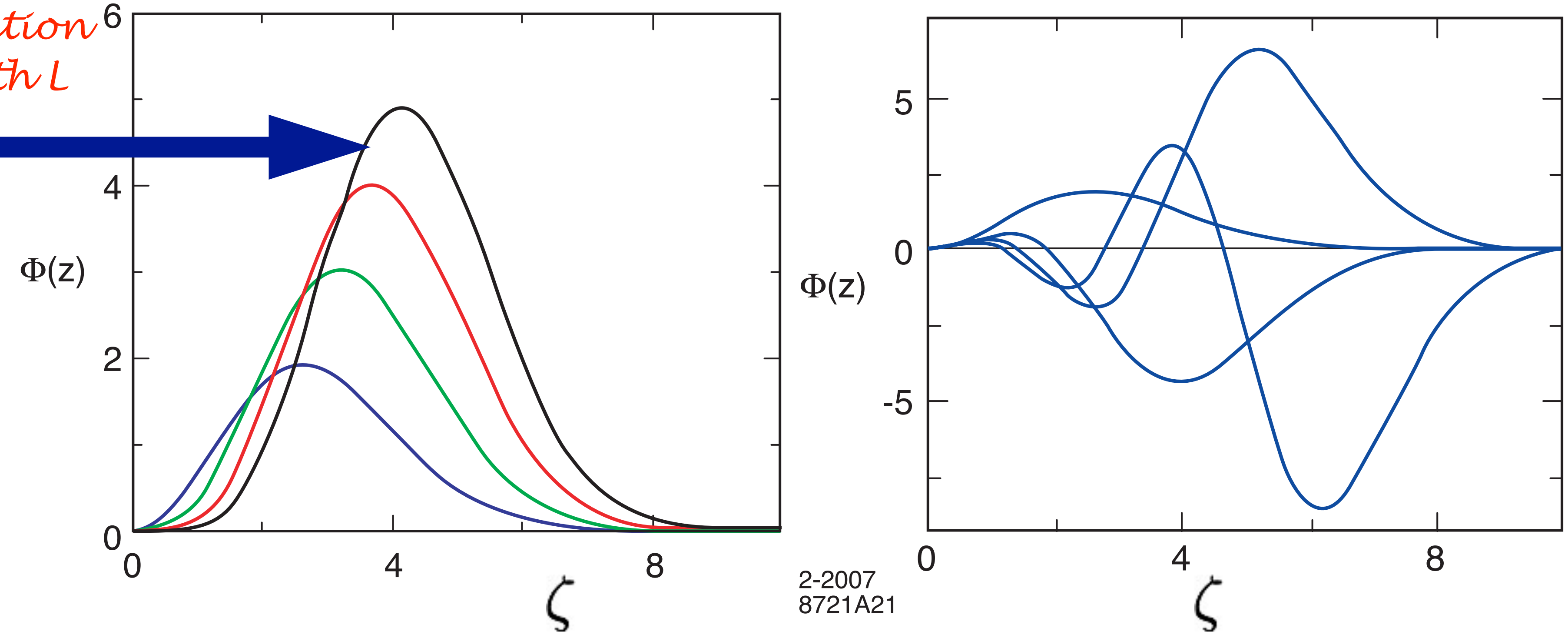
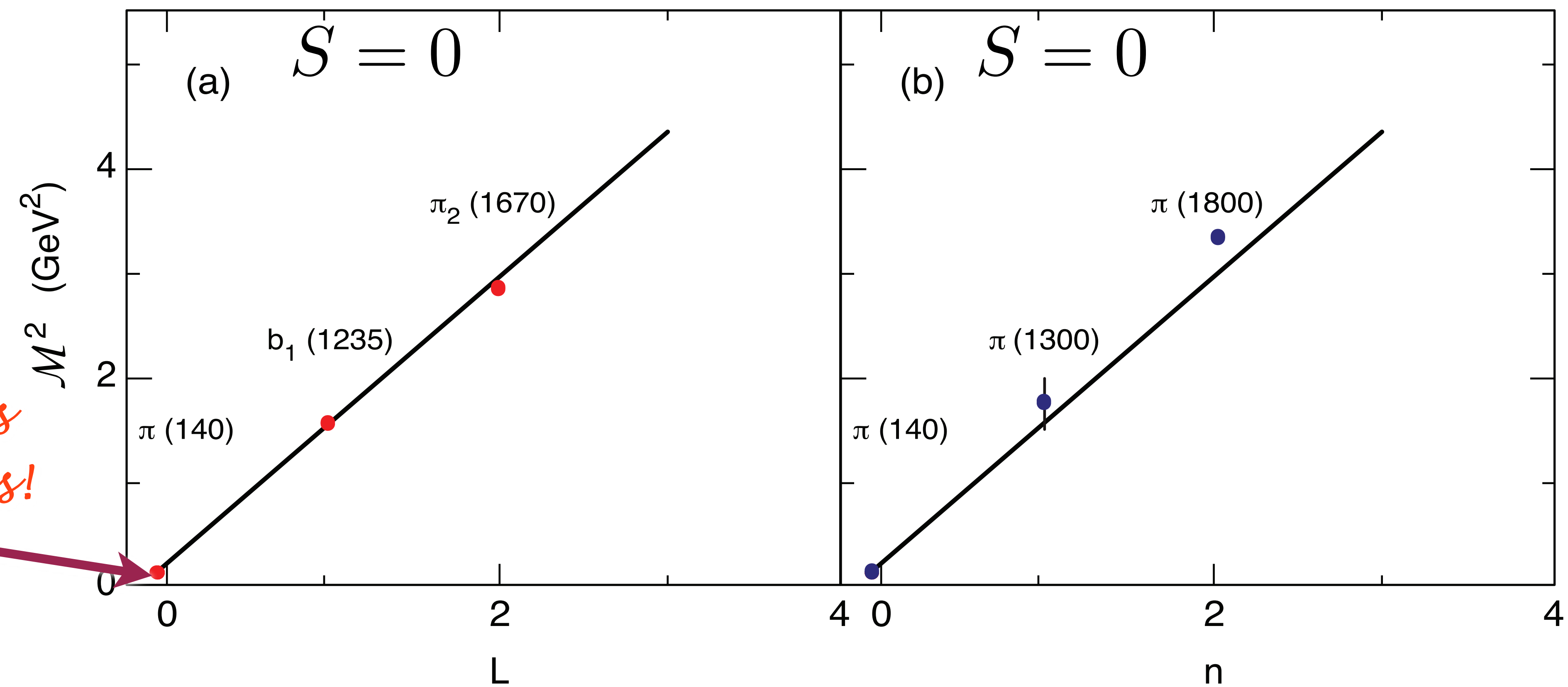


Fig: Orbital and radial AdS modes in the soft wall model for κ = 0.6 GeV .

Soft Wall Model

Same slope in n and L!

Pion has zero mass!



$$m_q = 0$$

Light meson orbital (a) and radial (b) spectrum for $\kappa = 0.6$ GeV.

Massless pion!

Meson Spectrum in Soft Wall Model

$$m_\pi = 0 \text{ if } m_q = 0$$

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

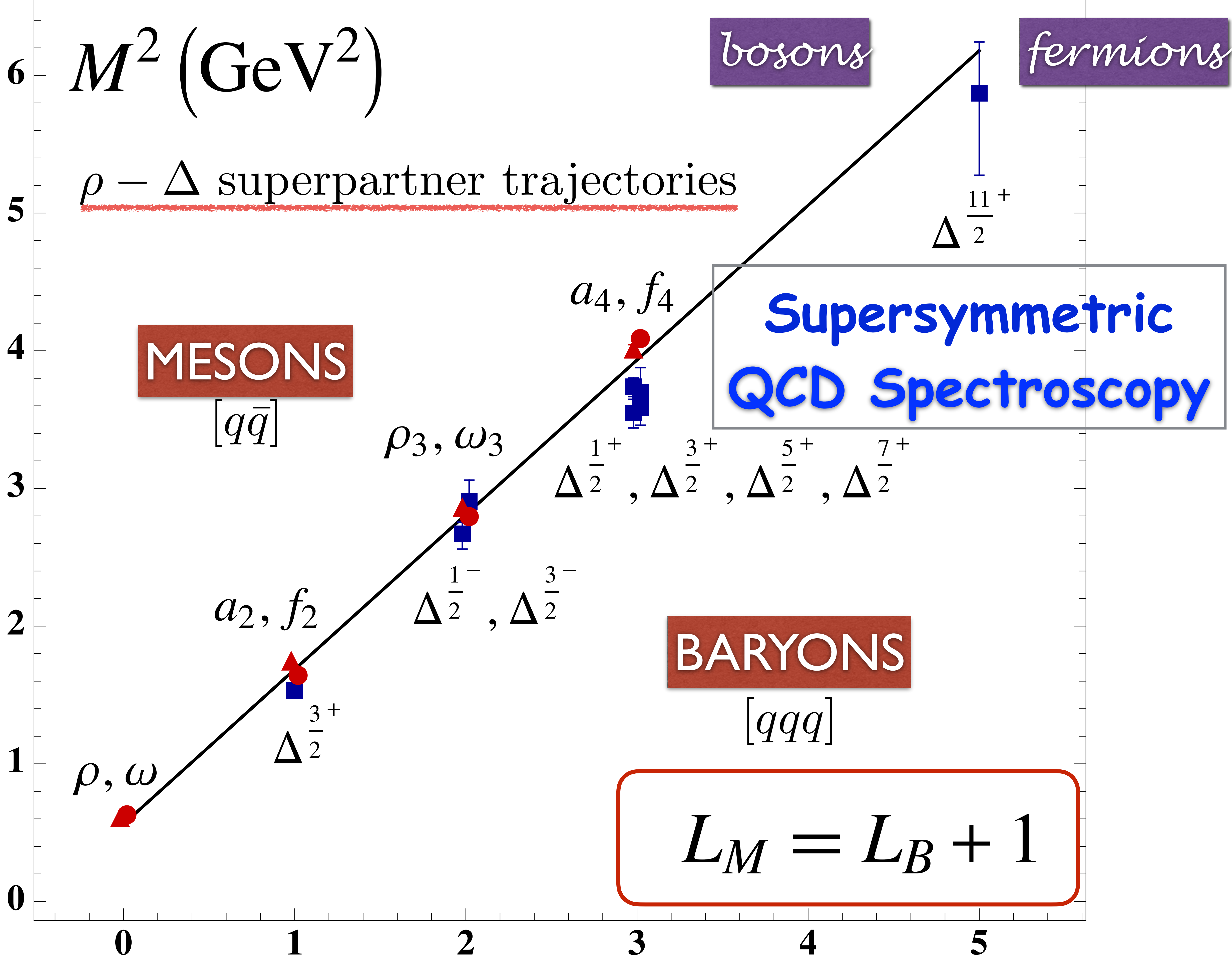
$$\phi_{n,L}(\zeta) = \kappa^{1+L}\sqrt{\frac{2n!}{(n+L)!}}\,\zeta^{1/2+L}e^{-\kappa^2\zeta^2/2}L_n^L(\kappa^2\zeta^2)$$

- Eigenvalues

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

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

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



de Téramond, Dosch, Lorcé, sjb

Supersymmetry in QCD

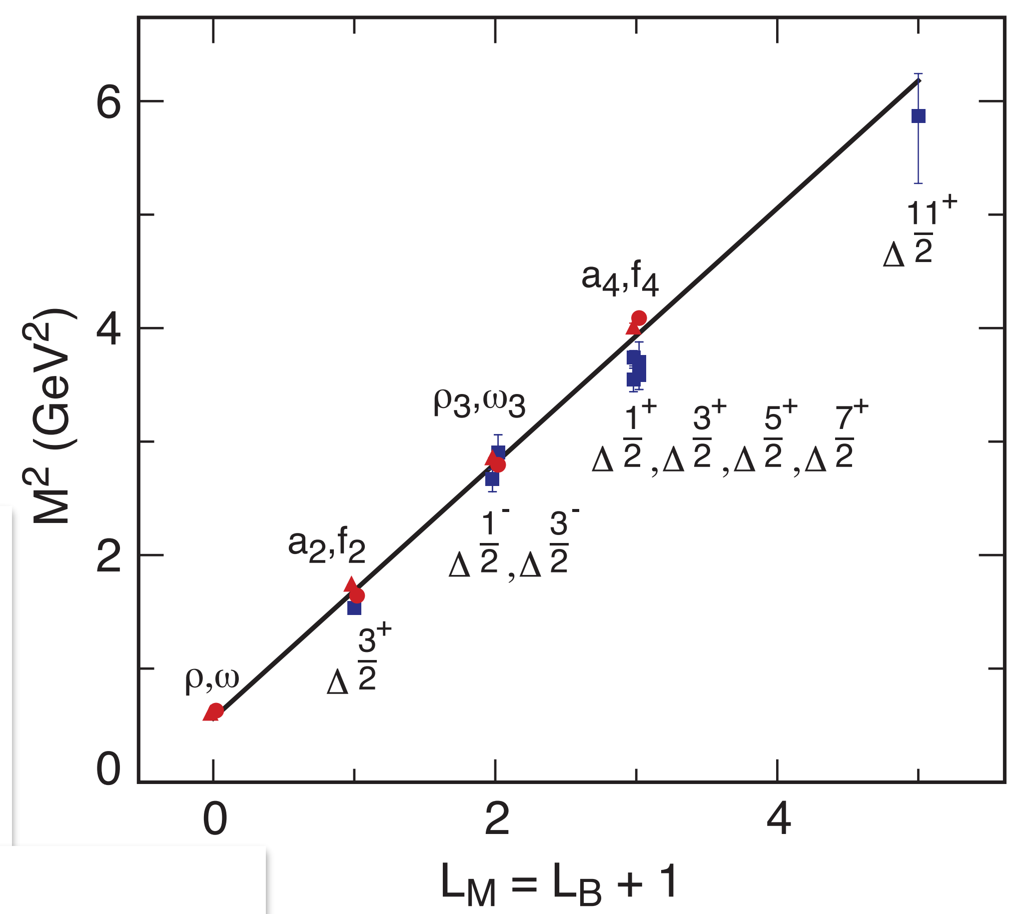
- A hidden symmetry of Color $SU(3)_C$ in hadron physics:
- Relates meson and baryon spectroscopy
- QCD: No squarks or gluinos!
- Emerges from Light-Front Holography and Super-Conformal Algebra
- Color Confinement

de Téramond, Dosch, Lorcé, sjb

Input: one fundamental mass scale

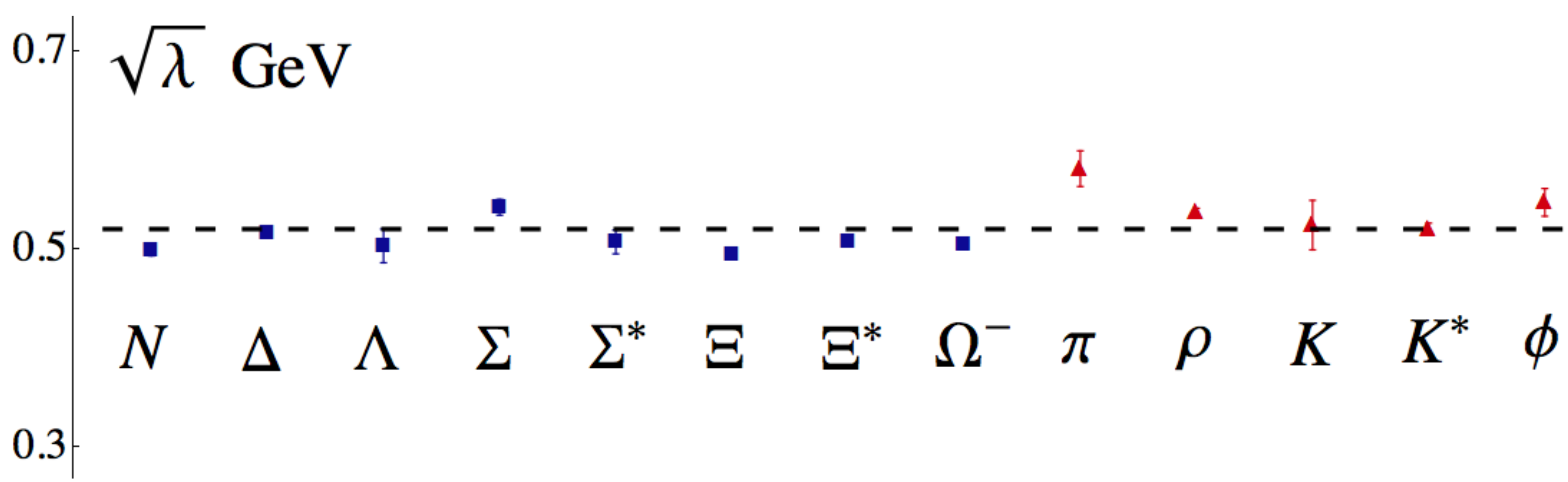
$$\kappa = \sqrt{\lambda} = 0.523 \pm 0.024 \text{ GeV}$$

Universal Regge Slope in L and n
Mesons and Baryons



$$\kappa = \sqrt{\lambda} = 0.523 \pm 0.024$$

- How universal is the semiclassical approximation based on superconformal LFHQCD ?



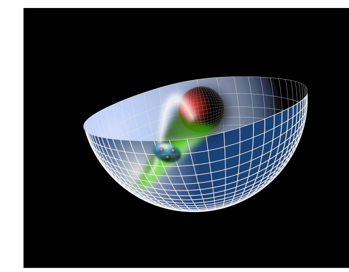
Best fit for hadronic scale $\sqrt{\lambda}$ from different light hadron sectors including radial and orbital excitations

LFHQCD: 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***

- ***Light-Front Holography: AdS_5 = LF (3+1)***



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

- ***Introduce Mass Scale κ while retaining the Conformal Invariance of the Action (dAFF)***

- ***Unique Dilaton in AdS_5:*** $e^{+\kappa^2 z^2}$

- ***Unique color-confining LF Potential*** $U(\zeta^2) = \kappa^4 \zeta^2$

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

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

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***

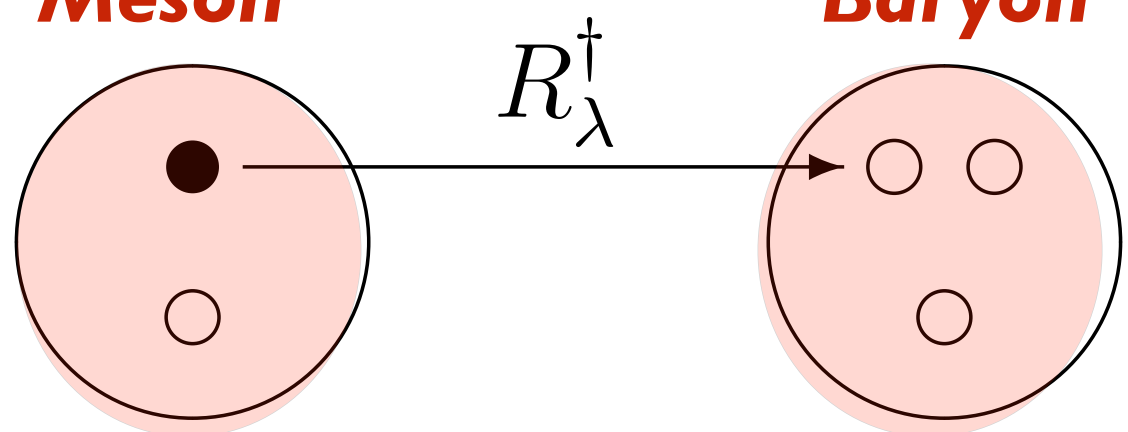
$$U(\zeta) = \kappa^4 \zeta^2 + 2\kappa^2 (L + S - 1)$$

Superconformal Algebra

Four-Plet Representations

Bosons, Fermions with Equal Mass!

Meson **Baryon**



$\phi_M, \;\; L_B + 1$ $\psi_{B+}, \;\; L_B$

$R^\dagger_\lambda \; \bar{q} \to [qq]$

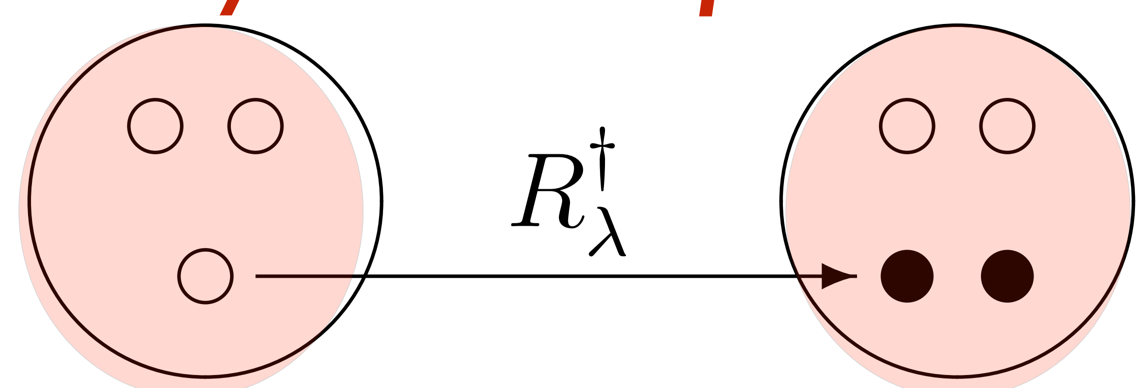
$\bar{3}_C \to \bar{3}_C$

Baryon

Tetraquark: diquark + antidiquark

$R^\dagger_\lambda \; q \to [\bar{q}\bar{q}]$

$3_C \to 3_C$

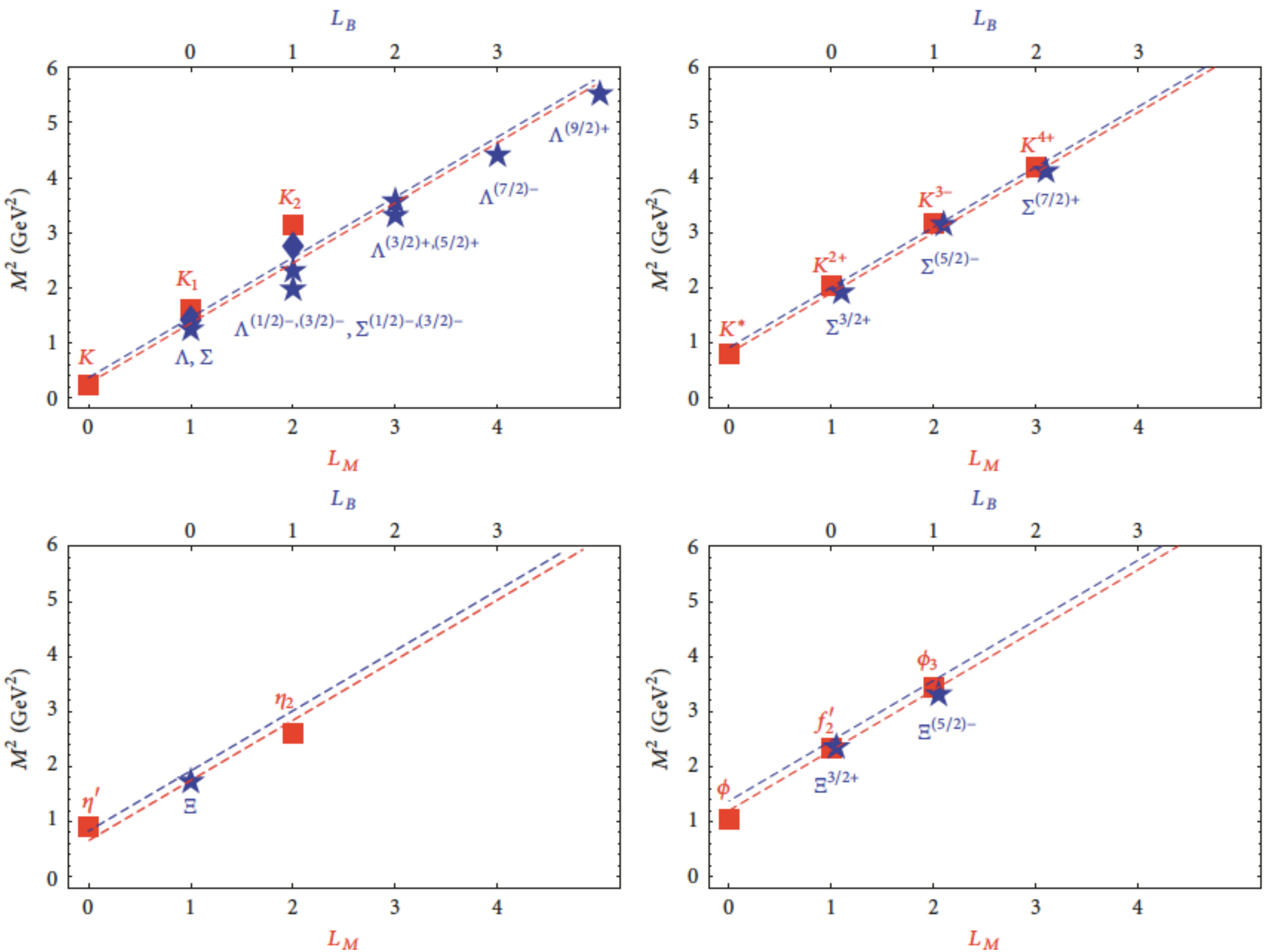


$\psi_{B-}, \;\; L_B + 1$ $\phi_T, \;\; L_B$

Proton: |u[ud]> Quark + Scalar Diquark
Equal Weight: L=0, L=1

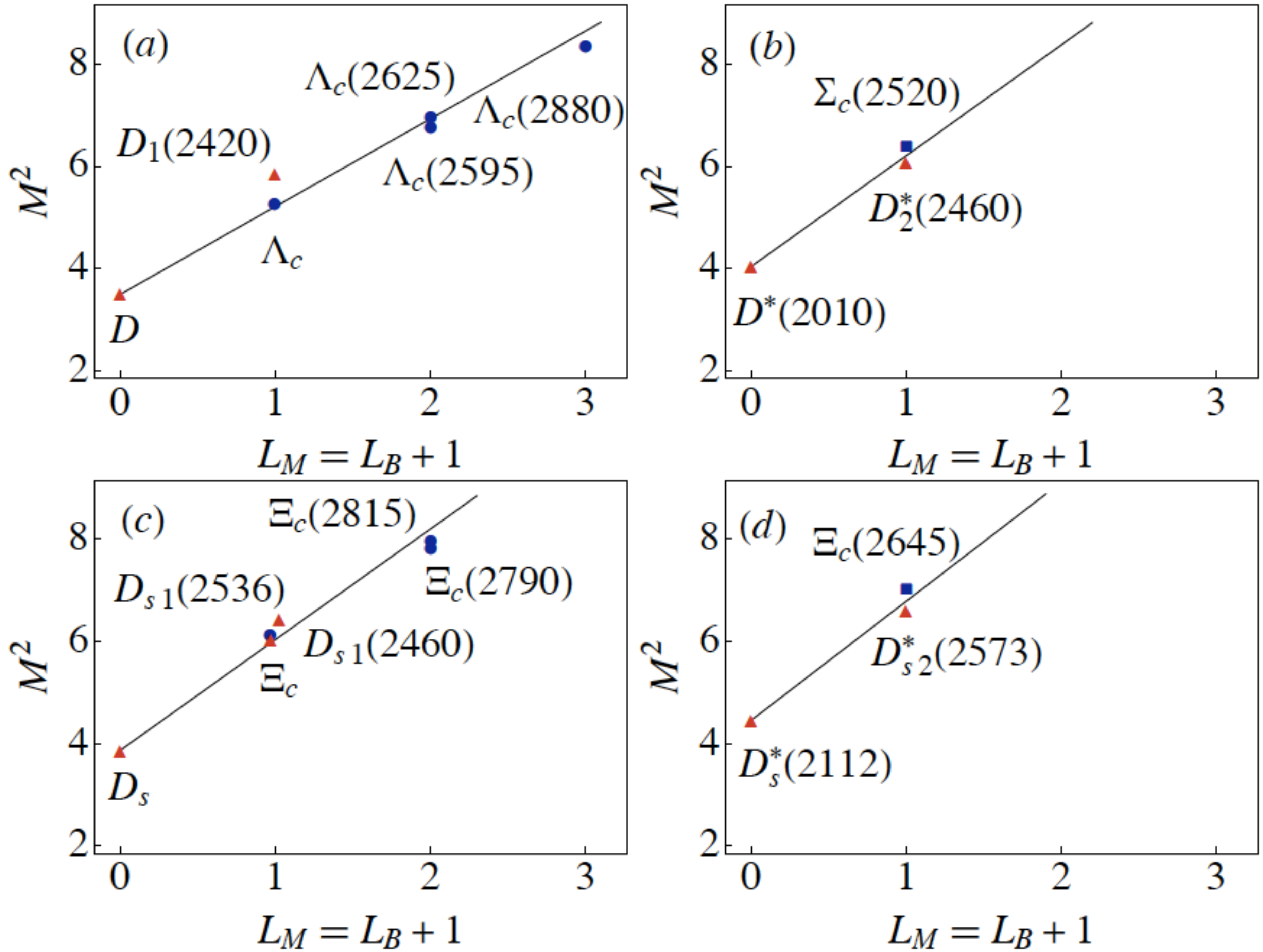
de Téramond, Dosch, Lorcé, sjb

Supersymmetry across the light and heavy-light spectrum



de Téramond, Dosch, Lorcé, sjb

Supersymmetry across the light and heavy-light spectrum



Heavy charm quark mass does not break supersymmetry

Heavy-light and heavy-heavy hadronic sectors

- Extension to the heavy-light hadronic sector

  [H. G. Dosch, GdT, S. J. Brodsky, PRD **92**, 074010 (2015), PRD **95**, 034016 (2017)]

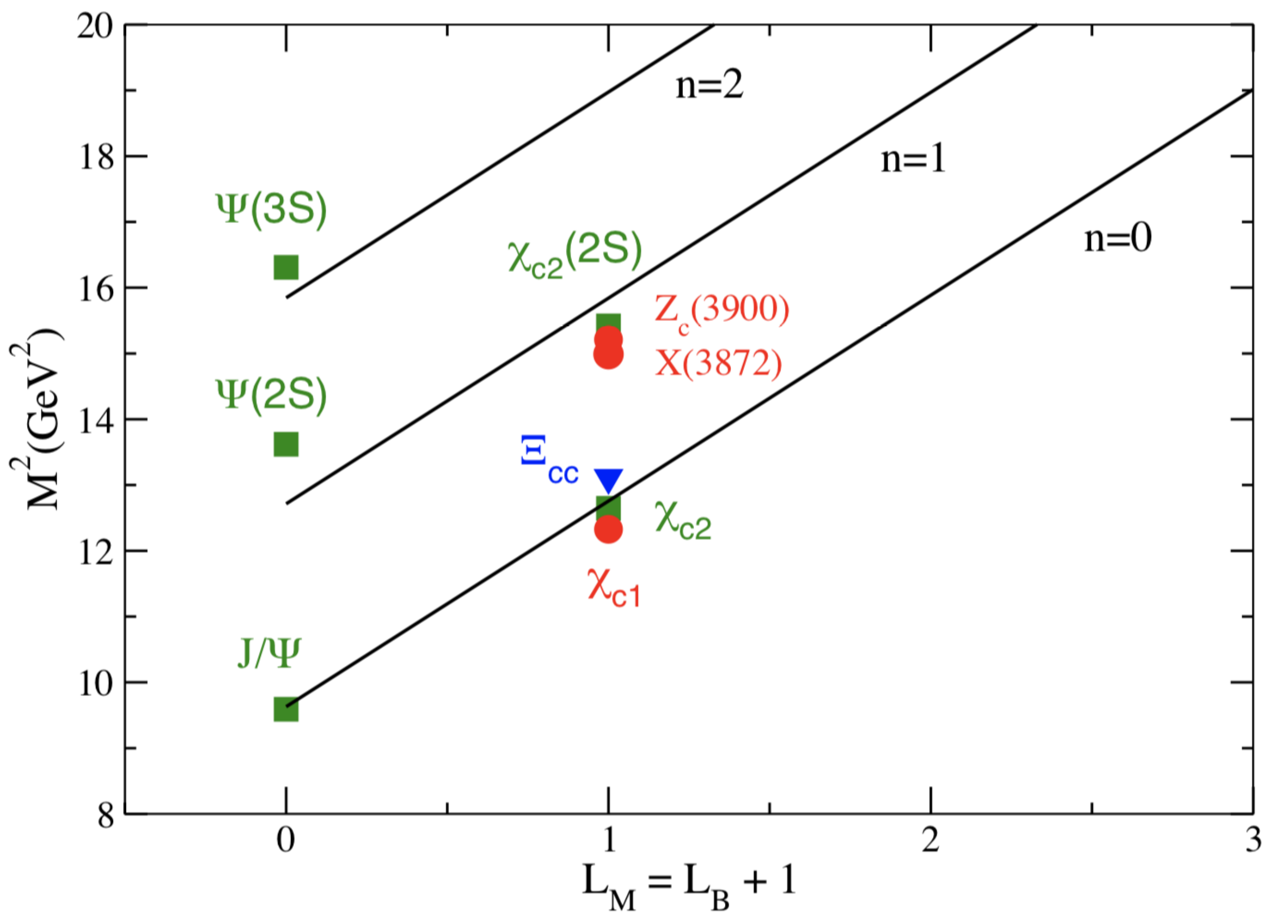
- Extension to the double-heavy hadronic sector

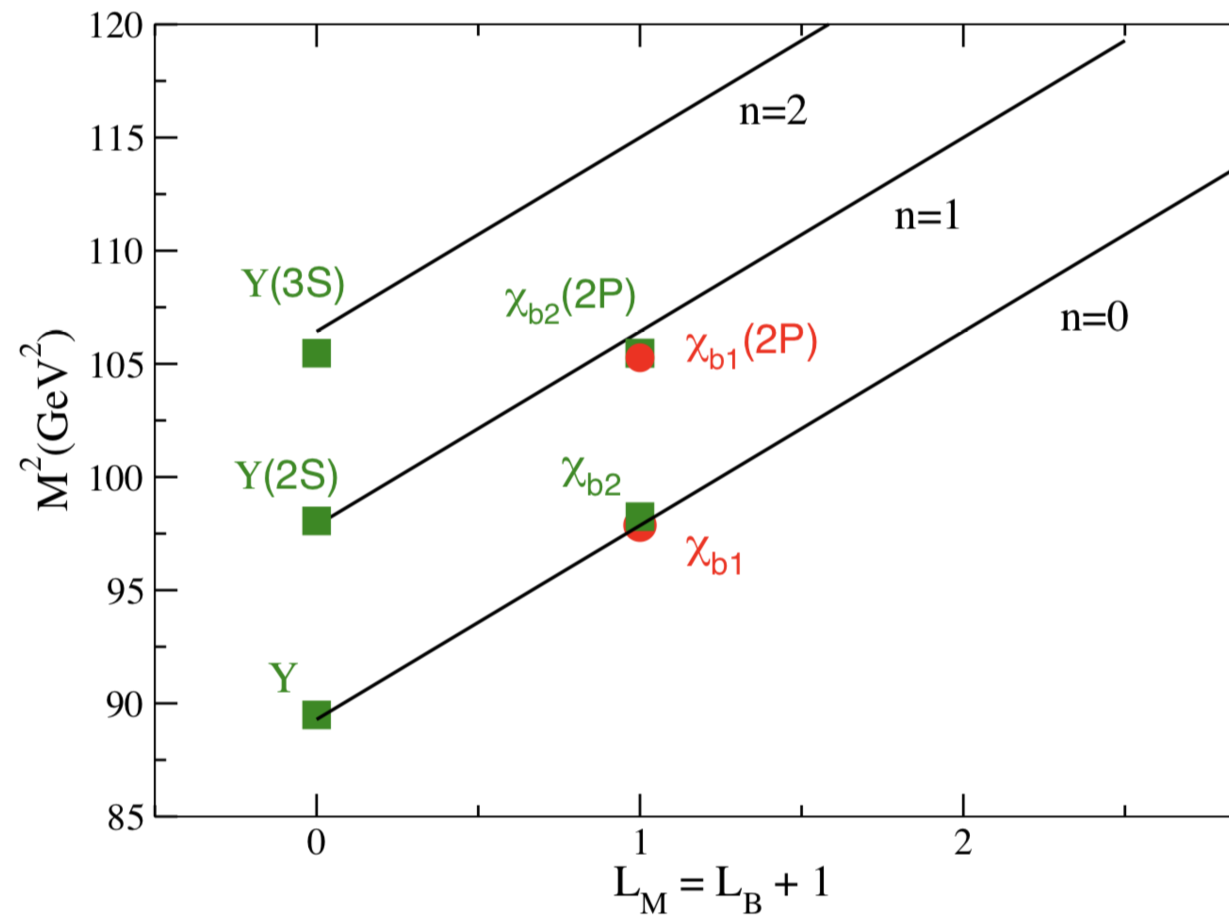
  [M. Nielsen and S. J. Brodsky, PRD, 114001 (2018)]

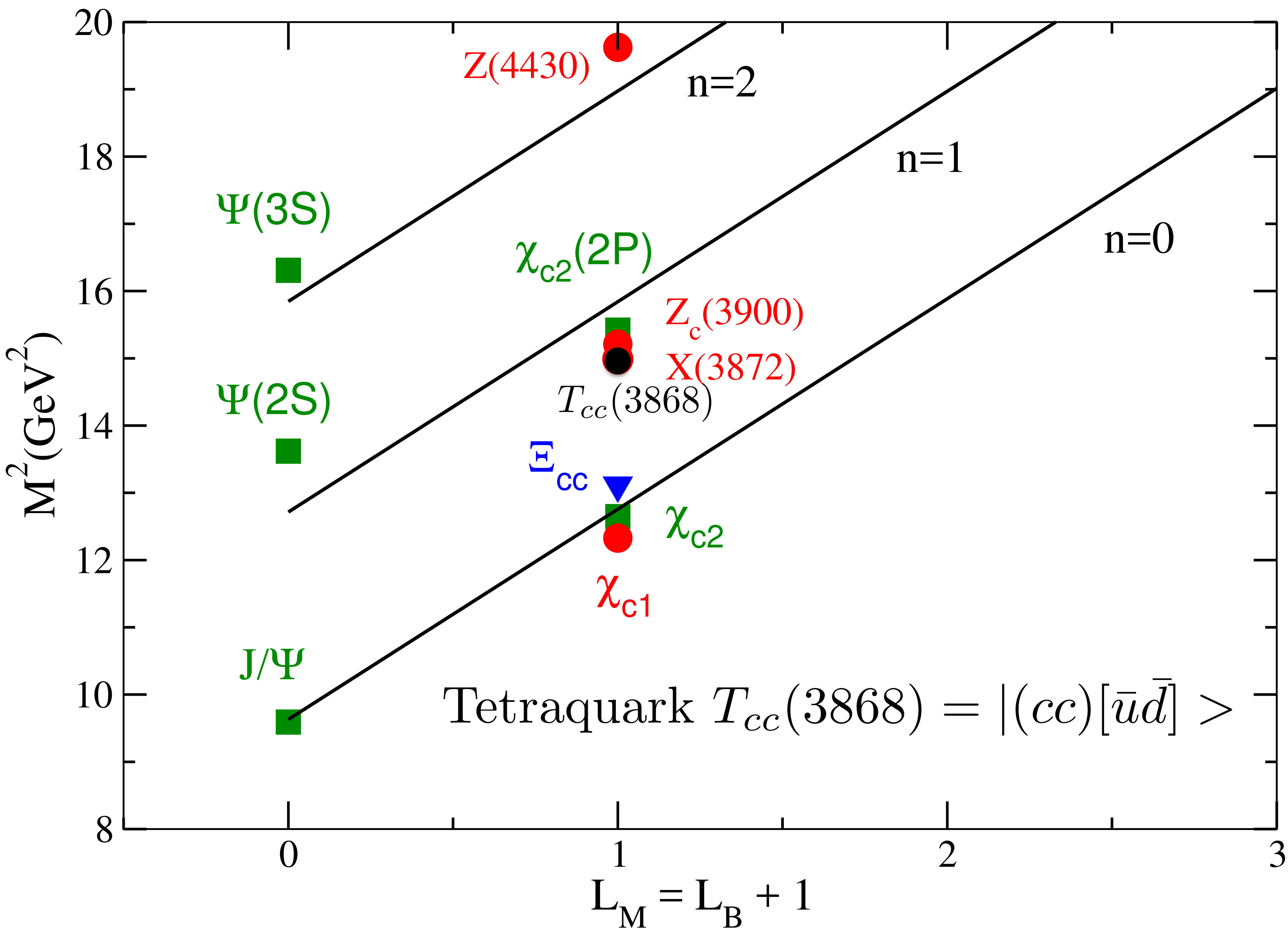
  [M. Nielsen, S. J. Brodsky, GdT, H. G. Dosch, F. S. Navarra, L. Zou, PRD **98**, 034002 (2018)]

- Extension to the isoscalar hadronic sector

  [L. Zou, H. G. Dosch, GdT,S. J. Brodsky, arXiv:1901.11205 [hep-ph]]







$Mesons : GreenSquare, Baryons(BlueTriangle), Tetraquarks(RedCircle)$

Connection to the Linear Instant-Form Potential

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

$\Updownarrow$

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 *de Tèramond, Dosch, Lorce, sjb*

New World of Tetraquarks

Complete Regge spectrum in n, L

$$3_C \times 3_C = \bar{3}_C + 6_C$$

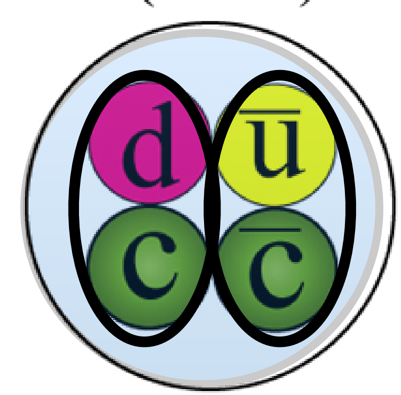
Bound!

- Diquark Color-Confined Constituents: Color $\bar{3}_C$
- Diquark-Antidiquark bound states
- Confinement Force Similar to quark-antiquark mesons $\bar{3}_C \times 3_C = 1_C$
- Isospin $I = 0, \pm 1, \pm 2$ Charge $Q = 0, \pm 1, \pm 2$

$uu\bar{d}\bar{d}$ $\quad$ $uu\bar{s}\bar{d}$ $\quad$ $uu\bar{s}\bar{s}$

Q= +2

Z(4430)



Q= - 1

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^{+-}	$b_1(1235)$	$[ud]q$	$(1/2)^+$	$N(940)$	$[ud][\bar u\bar d]$	0^{++}	$f_0(980)$
$\bar q q$	2^{-+}	$\pi_2(1670)$	$[ud]q$	$(1/2)^-$	$N_{\frac{1}{2}^-}(1535)$	$[ud][\bar u\bar d]$	1^{-+}	$\pi_1(1400)$
				$(3/2)^-$	$N_{\frac{3}{2}^-}(1520)$			$\pi_1(1600)$
$\bar q q$	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^{--}	$\rho_3(1690),\ \omega_3(1670)$	$[qq]q$	$(1/2)^-$	$\Delta_{\frac{1}{2}^-}(1620)$	$[qq][\bar u\bar d]$	2^{--}	$\rho_2(\sim 1700)?$
				$(3/2)^-$	$\Delta_{\frac{3}{2}^-}(1700)$			
$\bar q q$	4^{++}	$a_4(2040),\ f_4(2050)$	$[qq]q$	$(7/2)^+$	$\Delta_{\frac{7}{2}^+}(1950)$	$[qq][\bar u\bar d]$	3^{++}	$a_3(\sim 2070)?$
$\bar q s$	$0^{-(+)}$	$\bar K(495)$	—	—	—	—	—	—
$\bar q s$	$1^{+(-)}$	$\bar K_1(1270)$	$[ud]s$	$(1/2)^+$	$\Lambda(1115)$	$[ud][\bar s\bar q]$	$0^{+(+)}$	$\bar K_0^*(1430)$
$\bar q s$	$2^{-(+)}$	$\bar K_2(1770)$	$[ud]s$	$(1/2)^-$	$\Lambda(1405)$	$[ud][\bar s\bar q]$	$1^{-(+)}$	$\bar K_1^*(\sim 1700)?$
				$(3/2)^-$	$\Lambda(1520)$			
$\bar s q$	$0^{-(+)}$	$K(495)$	—	—	—	—	—	—
$\bar s q$	$1^{+(-)}$	$K_1(1270)$	$[sq]q$	$(1/2)^+$	$\Sigma(1190)$	$[sq][\bar s\bar q]$	0^{++}	$a_0(980)$
								$f_0(980)$
$\bar s q$	$1^{-(-)}$	$K^*(890)$	—	—	—	—	—	—
$\bar s q$	$2^{+(+)}$	$K_2^*(1430)$	$[sq]q$	$(3/2)^+$	$\Sigma(1385)$	$[sq][\bar q\bar q]$	$1^{+(+)}$	$K_1(1400)$
$\bar s q$	$3^{-(-)}$	$K_3^*(1780)$	$[sq]q$	$(3/2)^-$	$\Sigma(1670)$	$[sq][\bar q\bar q]$	$2^{-(-)}$	$K_2(\sim 1700)?$
$\bar s q$	$4^{+(+)}$	$K_4^*(2045)$	$[sq]q$	$(7/2)^+$	$\Sigma(2030)$	$[sq][\bar q\bar q]$	$3^{+(+)}$	$K_3(\sim 2070)?$
$\bar s s$	0^{-+}	$\eta(550)$	—	—	—	—	—	—
$\bar s s$	1^{+-}	$h_1(1170)$	$[sq]s$	$(1/2)^+$	$\Xi(1320)$	$[sq][\bar s\bar q]$	0^{++}	$f_0(1370)$
								$a_0(1450)$
$\bar s s$	2^{-+}	$\eta_2(1645)$	$[sq]s$	$(?)^?$	$\Xi(1690)$	$[sq][\bar s\bar q]$	1^{-+}	$\Phi'(1750)?$
$\bar s s$	1^{--}	$\Phi(1020)$	—	—	—	—	—	—
$\bar s s$	2^{++}	$f_2'(1525)$	$[sq]s$	$(3/2)^+$	$\Xi^*(1530)$	$[sq][\bar s\bar q]$	1^{++}	$f_1(1420)$
$\bar s s$	3^{--}	$\Phi_3(1850)$	$[sq]s$	$(3/2)^-$	$\Xi(1820)$	$[sq][\bar s\bar q]$	2^{--}	$\Phi_2(\sim 1800)?$
$\bar s s$	2^{++}	$f_2(1950)$	$[ss]s$	$(3/2)^+$	$\Omega(1672)$	$[ss][\bar s\bar q]$	$1^{+(+)}$	$K_1(\sim 1700)?$

Meson Baryon Tetraquark

New Organization of the Hadron Spectrum

M. Nielsen, sjb

Superpartners for states with one c quark

Meson			Baryon			Tetraquark		
q-cont	$J^{P(C)}$	Name	q-cont	J^P	Name	q-cont	$J^{P(C)}$	Name
$\bar{q}c$	0^-	$D(1870)$	—	—	—	—	—	—
$\bar{q}c$	1^+	$D_1(2420)$	$[ud]c$	$(1/2)^+$	$\Lambda_c(2290)$	$[ud][\bar{c}\bar{q}]$	0^+	$\bar{D}_0^*(2400)$
$\bar{q}c$	2^-	$D_J(2600)$	$[ud]c$	$(3/2)^-$	$\Lambda_c(2625)$	$[ud][\bar{c}\bar{q}]$	1^-	—
$\bar{c}q$	0^-	$\bar{D}(1870)$	—	—	—	—	—	—
$\bar{c}q$	1^+	$\bar{D}_1(2420)$	$[cq]q$	$(1/2)^+$	$\Sigma_c(2455)$	$[cq][\bar{u}\bar{d}]$	0^+	$D_0^*(2400)$
$\bar{q}c$	1^-	$D^*(2010)$	—	—	—	—	—	—
$\bar{q}c$	2^+	$D_2^*(2460)$	$(qq)c$	$(3/2)^+$	$\Sigma_c^*(2520)$	$(qq)[\bar{c}\bar{q}]$	1^+	$D(2550)$
$\bar{q}c$	3^-	$D_3^*(2750)$	$(qq)c$	$(3/2)^-$	$\Sigma_c(2800)$	$(qq)[\bar{c}\bar{q}]$	—	—
$\bar{s}c$	0^-	$D_s(1968)$	—	—	—	—	—	—
$\bar{s}c$	1^+	$D_{s1}(2460)$	$[qs]c$	$(1/2)^+$	$\Xi_c(2470)$	$[qs][\bar{c}\bar{q}]$	0^+	$\bar{D}_{s0}^*(2317)$
$\bar{s}c$	2^-	$D_{s2}(\sim 2860)?$	$[qs]c$	$(3/2)^-$	$\Xi_c(2815)$	$[sq][\bar{c}\bar{q}]$	1^-	—
$\bar{s}c$	1^-	$D_s^*(2110)$	—	—	—	—	—	—
$\bar{s}c$	2^+	$D_{s2}^*(2573)$	$(sq)c$	$(3/2)^+$	$\Xi_c^*(2645)$	$(sq)[\bar{c}\bar{q}]$	1^+	$D_{s1}(2536)$
$\bar{c}s$	1^+	$D_{s1}(\sim 2700)?$	$[cs]s$	$(1/2)^+$	$\Omega_c(2695)$	$[cs][\bar{s}\bar{q}]$	0^+	??
$\bar{s}c$	2^+	$D_{s2}^*(\sim 2750)?$	$(ss)c$	$(3/2)^+$	$\Omega_c(2770)$	$(ss)[\bar{c}\bar{s}]$	1^+	??

predictions

beautiful agreement!

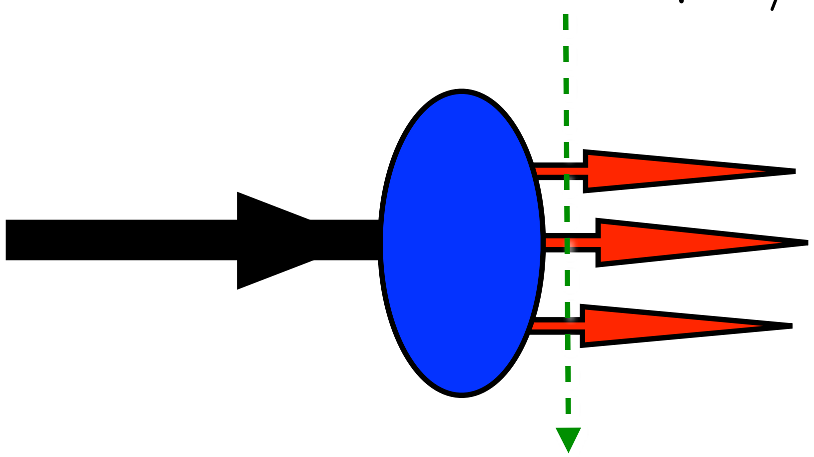
M. Nielsen, sjb

Bound States in Relativistic Quantum Field Theory:

Light-Front Wavefunctions

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

Fixed $\tau = t + z/c$



Boost invariant, Lorentz frame independent, Causal

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

$$x = \frac{k^+}{P^+} = \frac{k^0 + k^3}{P^0 + P^3}$$

Invariant under boosts. Independent of P^μ

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

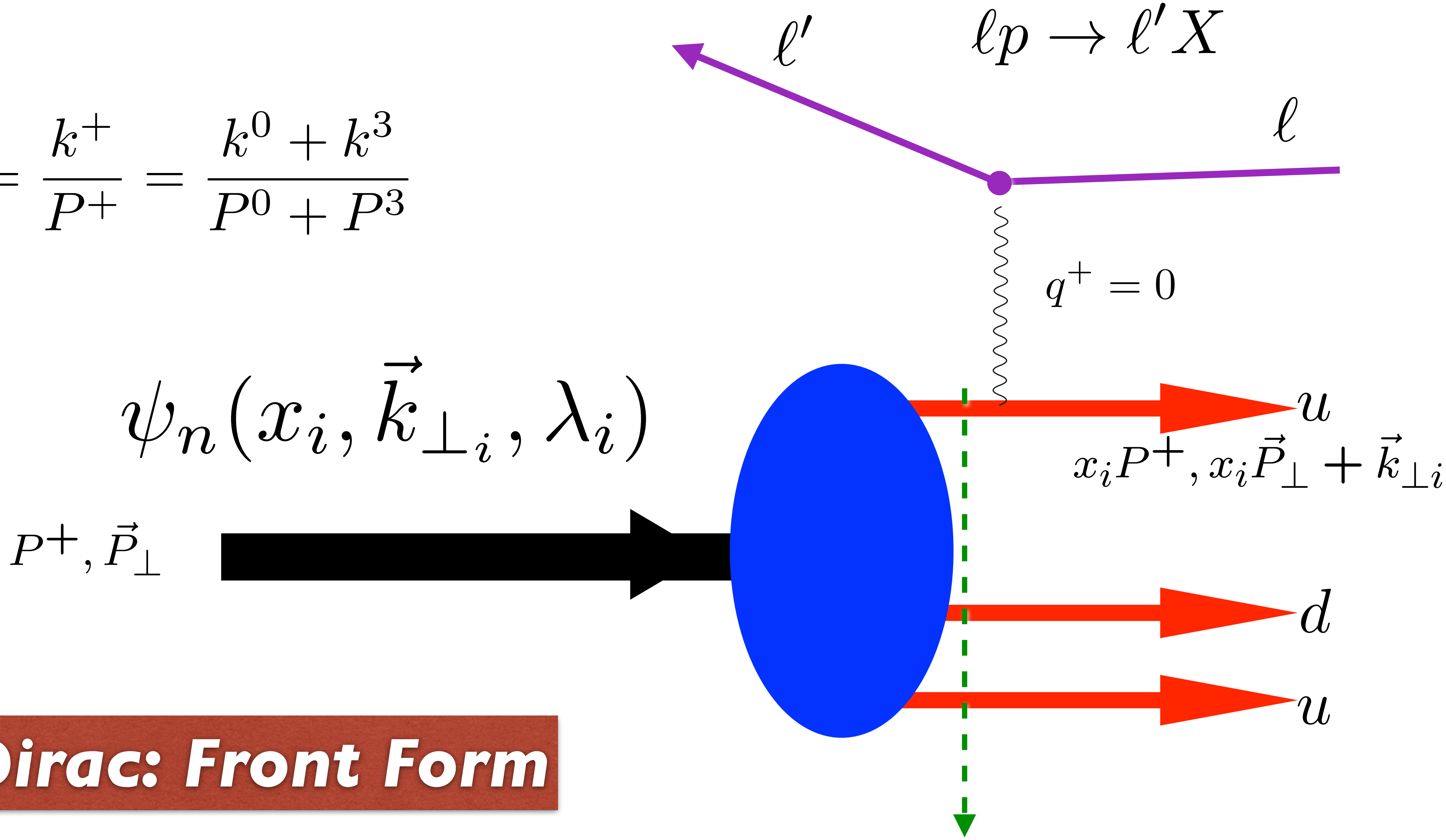
Direct connection to QCD Lagrangian

LF Wavefunction: off-shell in invariant mass

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

$$x = \frac{k^+}{P^+} = \frac{k^0 + k^3}{P^0 + P^3}$$

$$\psi_n(x_i, \vec{k}_{\perp_i}, \lambda_i)$$



Dirac: Front Form

Measurements of hadron LF wavefunction are at fixed LF time

Fixed $\tau = t + z/c$

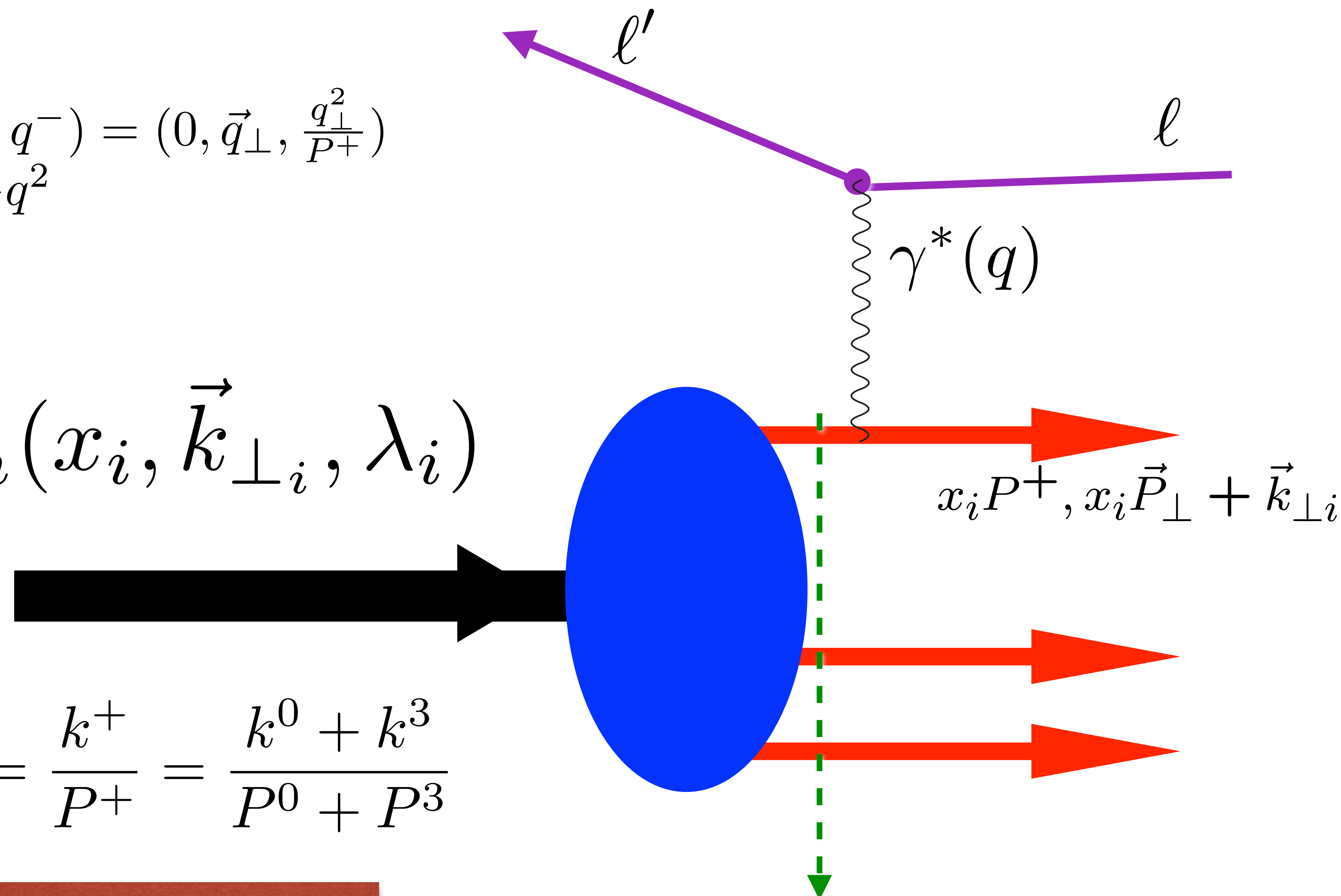
Like a flash photograph

$$x_{bj} = x = \frac{k^+}{P^+}$$

Invariant under boosts! Independent of P^μ

$$q^\mu = (q^+, \vec{q}_\perp, q^-) = (0, \vec{q}_\perp, \frac{q_\perp^2}{P^+})$$
$$q_\perp^2 = Q^2 = -q^2$$

$$\psi_n(x_i, \vec{k}_{\perp_i}, \lambda_i)$$



$$x = \frac{k^+}{P^+} = \frac{k^0 + k^3}{P^0 + P^3}$$

Dirac: Front Form

Fixed $\tau = t + z/c$

1912.08911 [hep-ph]

$$x_{bj} = x = \frac{k^+}{P^+}$$

G. A. Miller, sjb:

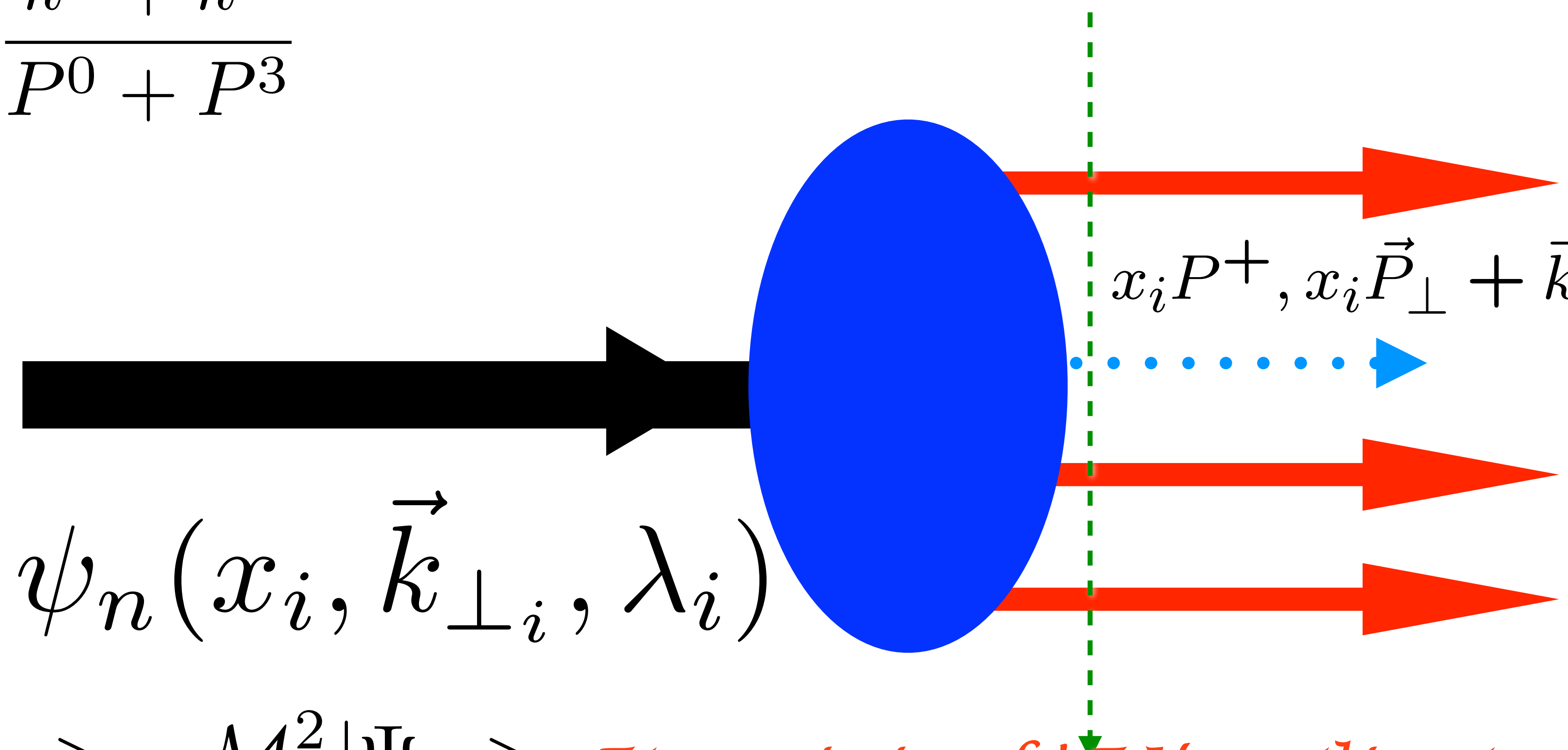
Ioffe Time: $\tilde{z}$ Third spatial LF coordinate.

Fourier Transform of x in LFWFs

Light-Front Wavefunctions: rigorous representation of composite systems in quantum field theory

Fixed $\tau = t + z/c$

$$x = \frac{k^+}{P^+} = \frac{k^0 + k^3}{P^0 + P^3}$$



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

$x_i P^+, x_i \vec{P}_\perp + \vec{k}_{\perp i}$

$\sum_i^n x_i = 1$

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

$$\psi_n(x_i, \vec{k}_{\perp_i}, \lambda_i)$$

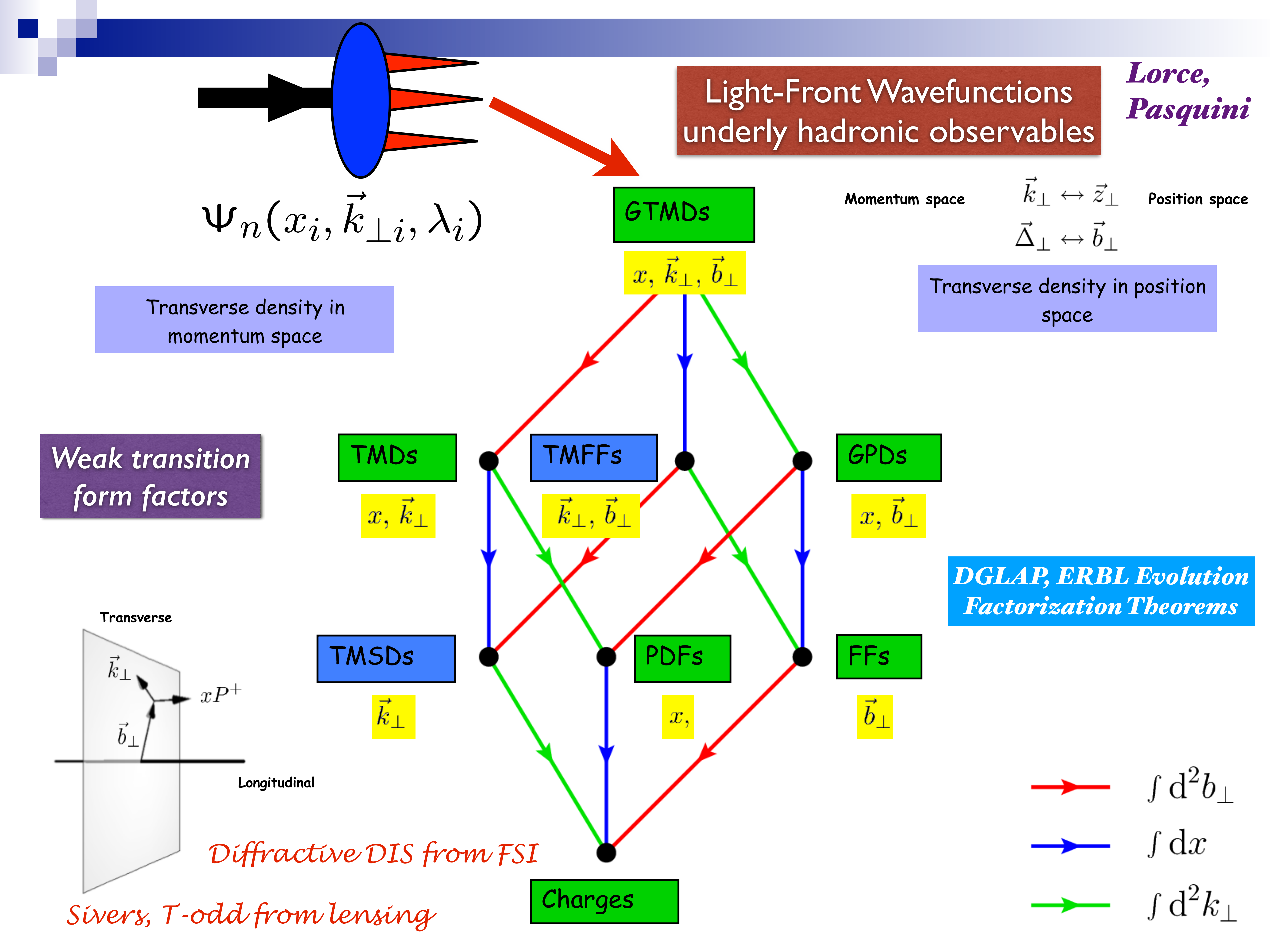
$$H^{QCD}_{LF} |\Psi_h> = \mathcal{M}^2_h |\Psi_h>$$ *Eigenstate of LF Hamiltonian*

$$|p, J_z> = \sum_{n=3} \psi_n(x_i, \vec{k}_{\perp i}, \lambda_i) |n; x_i, \vec{k}_{\perp i}, \lambda_i>$$

LFWF: Projection on free Fock state: $\Psi_n(x_i, \vec{k}_{\perp i}, \lambda_i) = < p|n >$

Invariant under boosts! Independent of P^μ

Structure Function is square of LFWFs, summed over all Fock states. Causal, Frame-independent. Creation Operators on Simple Vacuum, Current Matrix Elements are Overlaps of LFWFS



Light-Front Wavefunctions underly hadronic observables
Lorce, Pasquini
$\Psi_n(x_i, \vec{k}_{\perp i}, \lambda_i)$
Momentum space
$\vec{k}_\perp \leftrightarrow \vec{z}_\perp$
$\vec{\Delta}_\perp \leftrightarrow \vec{b}_\perp$
Position space
GTMDs
$x, \vec{k}_\perp, \vec{b}_\perp$
Transverse density in momentum space
Transverse density in position space
Weak transition form factors
TMDs
$x, \vec{k}_\perp$
TMFFs
$\vec{k}_\perp, \vec{b}_\perp$
GPDs
$x, \vec{b}_\perp$
DGLAP, ERBL Evolution Factorization Theorems
Transverse
$\vec{k}_\perp$
xP^+
$\vec{b}_\perp$
Longitudinal
TMSDs
$\vec{k}_\perp$
PDFs
$x,$
FFs
$\vec{b}_\perp$
$\int d^2 b_\perp$
$\int dx$
$\int d^2 k_\perp$
Diffractive DIS from FSI
Charges
Sivers, T-odd from lensing

$$< p+q|j^+(0)|p >= 2p^+ F(q^2)$$

Front Form

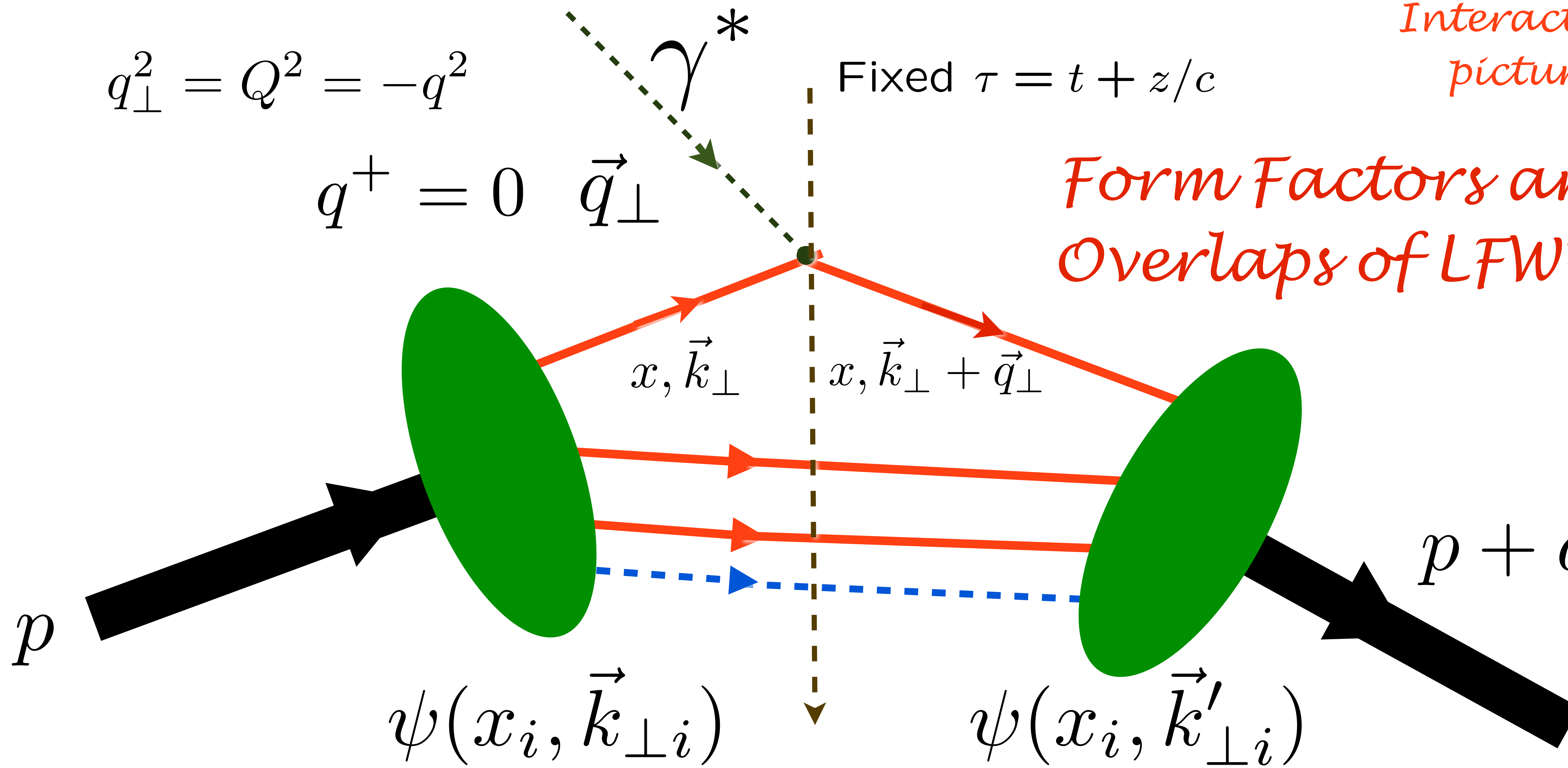
Interaction picture

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

$$q^+ = 0 \quad \vec{q}_\perp$$

Fixed $\tau = t + z/c$

Form Factors are Overlaps of LFWFs



struck $\vec{k}'_{\perp i} = \vec{k}_{\perp i} + (1 - x_i)\vec{q}_\perp$

spectators $\vec{k}'_{\perp i} = \vec{k}_{\perp i} - x_i \vec{q}_\perp$

Drell & Yan, West
Exact LF formula!

Drell, sjb

Transverse size $\propto \frac{1}{Q}$

Exact LF Formula for Pauli Form Factor

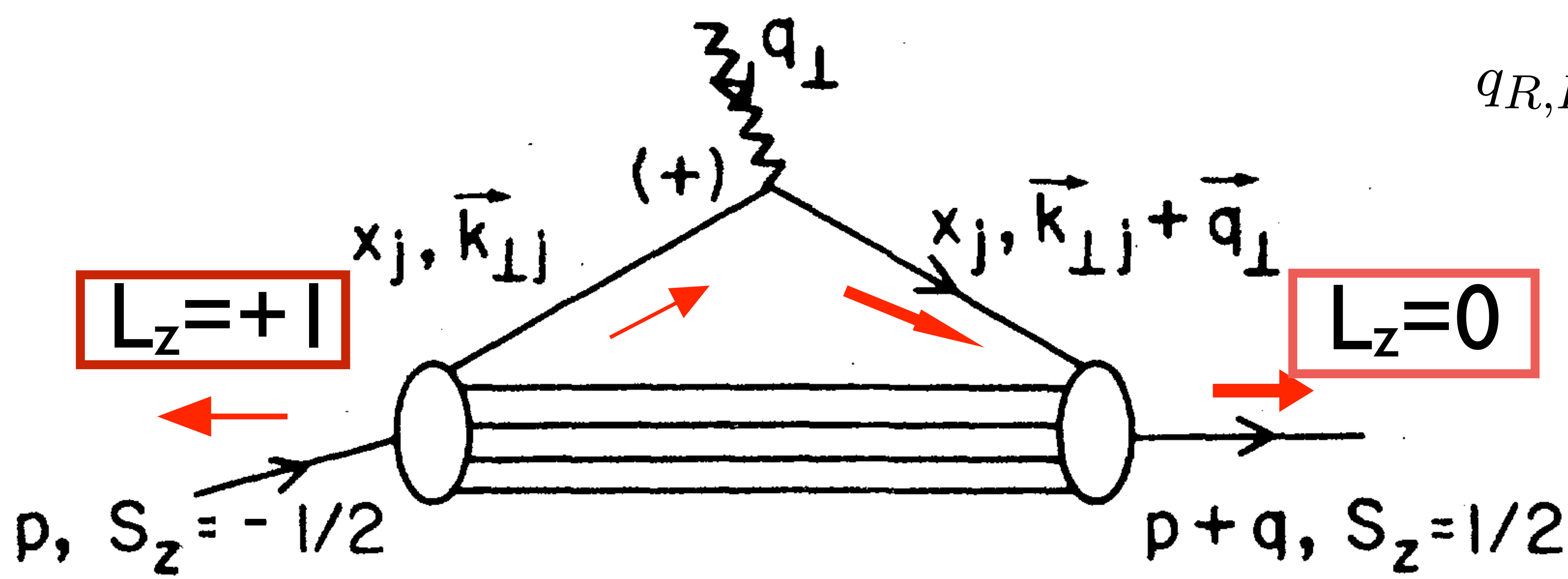
Drell, sjb

$$\frac{F_2(q^2)}{2M} = \sum_a \int [\mathrm{d}x][\mathrm{d}^2\mathbf{k}_\perp] \sum_j e_j \, \frac{1}{2} \times$$

$$\Big[-\frac{1}{q^L}\psi_a^{\uparrow *}(x_i, \mathbf{k}'_{\perp i}, \lambda_i)\, \psi_a^{\downarrow}(x_i, \mathbf{k}_{\perp i}, \lambda_i) + \frac{1}{q^R}\psi_a^{\downarrow *}(x_i, \mathbf{k}'_{\perp i}, \lambda_i)\, \psi_a^{\uparrow}(x_i, \mathbf{k}_{\perp i}, \lambda_i) \Big]$$

$$\mathbf{k}'_{\perp i} = \mathbf{k}_{\perp i} - x_i \mathbf{q}_\perp \qquad \mathbf{k}'_{\perp j} = \mathbf{k}_{\perp j} + (1 - x_j)\mathbf{q}_\perp$$

$$q_{R,L} = q^x \pm i q^y$$



Must have $\Delta\ell_z = \pm 1$ to have nonzero $F_2(q^2)$

Nonzero Proton Anomalous Moment -->
Nonzero orbital quark angular momentum

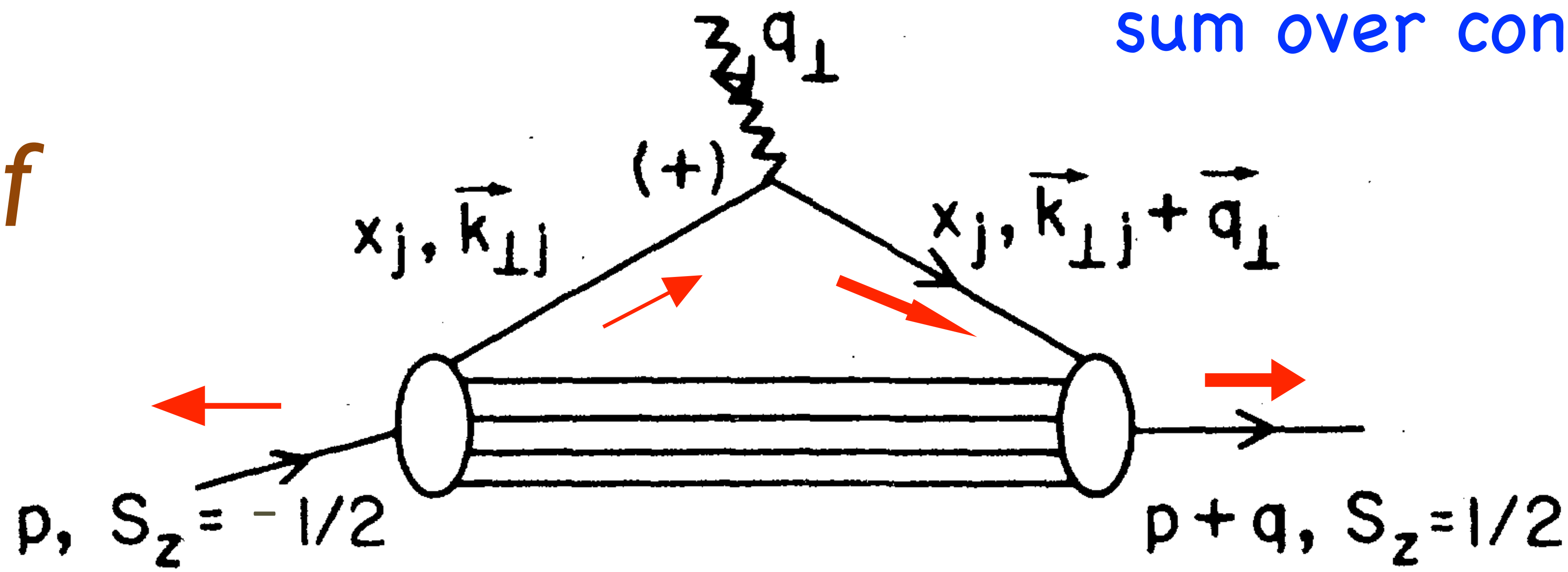
Dae Sung Hwang, Bo-Qiang Ma, Ivan Schmidt, sjb

Terayev, Okun: *B(0) Must vanish because of Equivalence Theorem*

graviton

sum over constituents

LF Proof



B(0) = 0

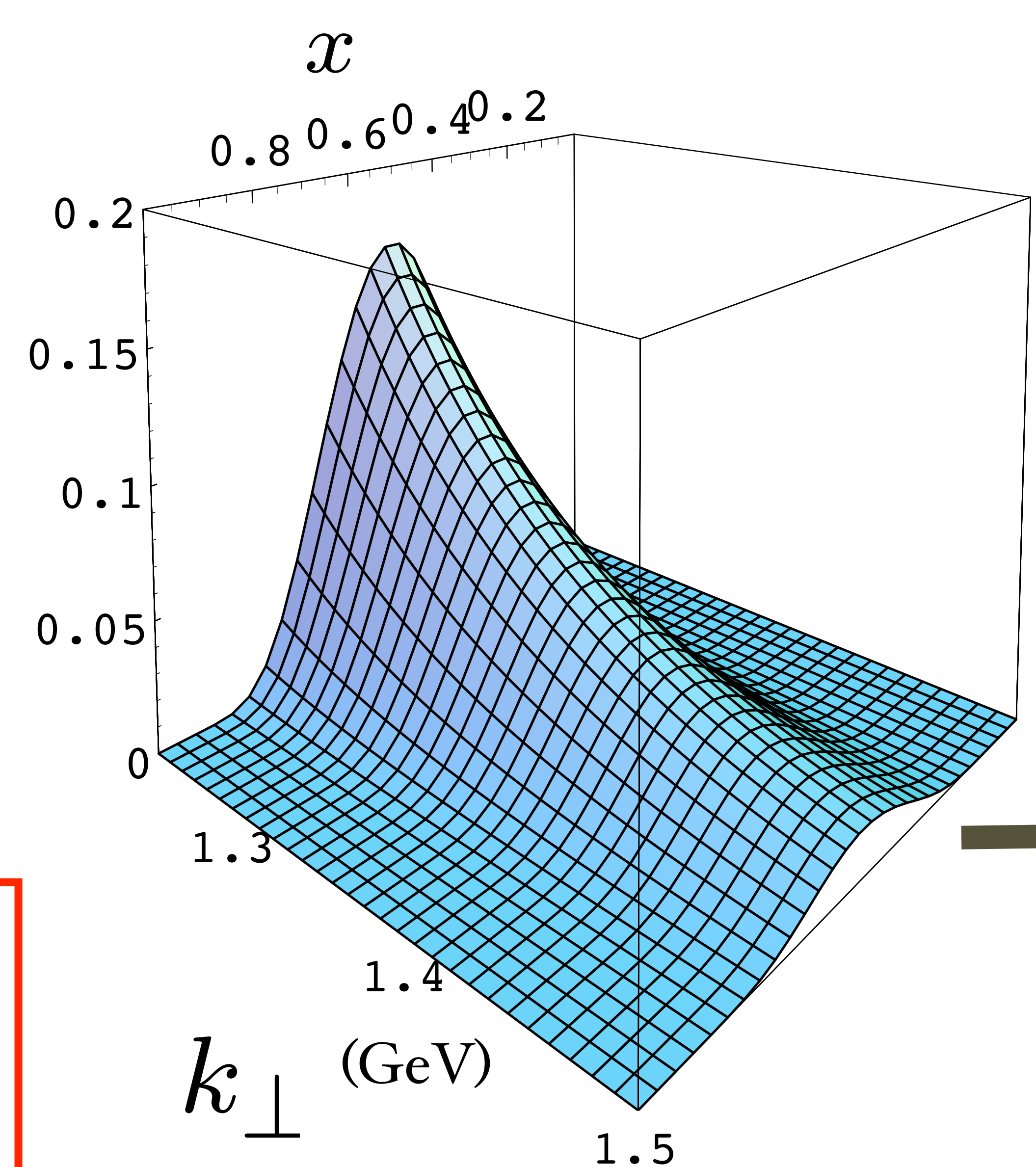
Each Fock State

Vanishing Anomalous gravitomagnetic moment B(0)

Prediction from AdS/QCD: Meson LFWF

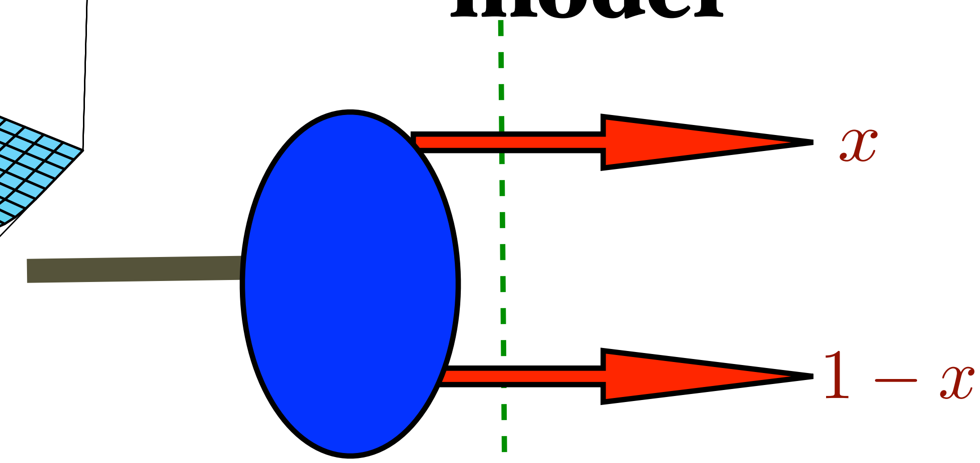
$$e^{\varphi(z)} = e^{+\kappa^2 z}$$

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



de Teramond, Cao, sjb

"Soft Wall" model



massless quarks

Note coupling

$$k_\perp^2, x$$

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

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

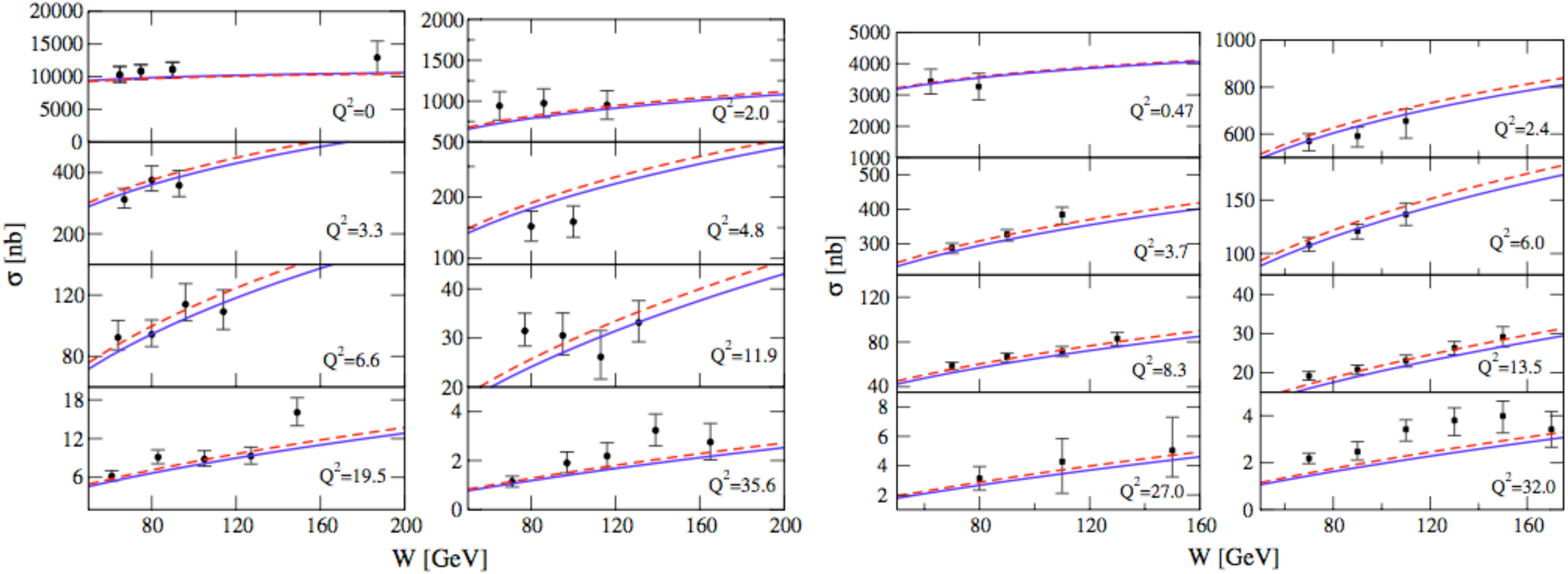
$$f_\pi = \sqrt{P_{q\bar{q}}}\frac{\sqrt{3}}{8}\kappa = 92.4 \text{ MeV}$$

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

Provides Connection of Confinement to Hadron Structure

PRL **109,** 081601 (2012) PHYSICAL REVIEW LETTERS week ending 24 AUGUST 2012

AdS/QCD Holographic Wave Function for the ρ Meson and Diffractive ρ Meson Electroproduction

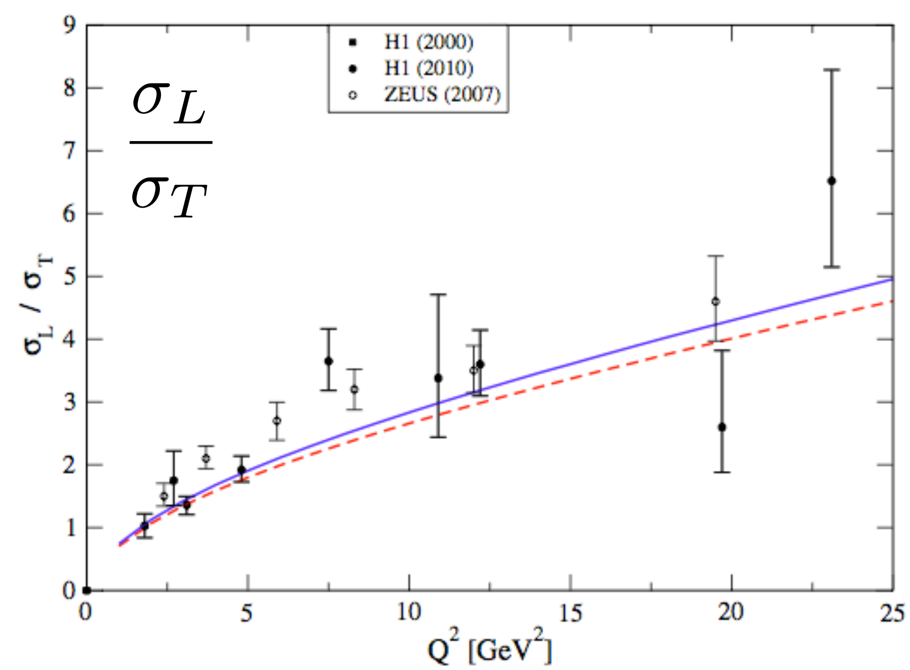


(a) H1

(b) ZEUS

J. R. Forshaw, R. Sandapen

$$\gamma^* p \to \rho^0 p'$$



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

The Pion's Valence Light-Front Wavefunction

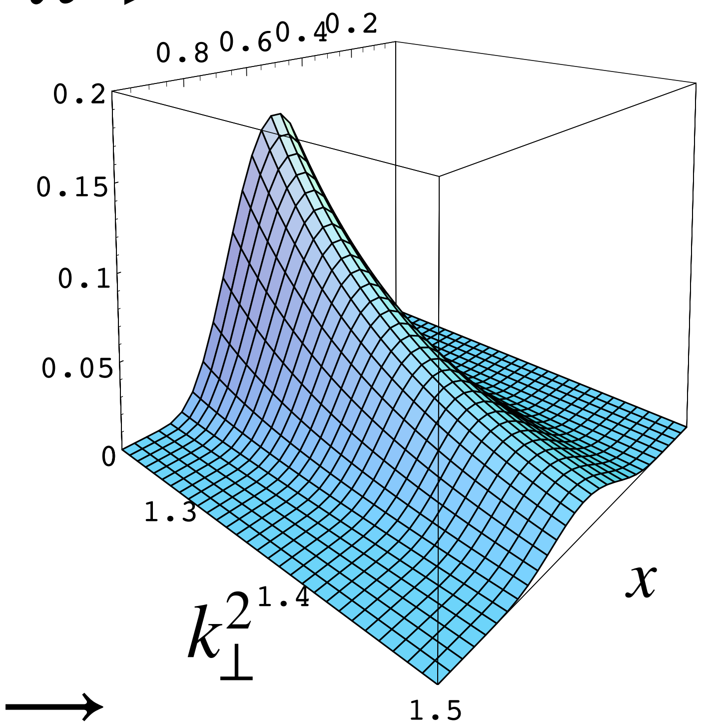
- Relativistic Quantum-Mechanical Wavefunction of the pion eigenstate $H_{LF}^{QCD} | \pi > = m_\pi^2 | \pi >$

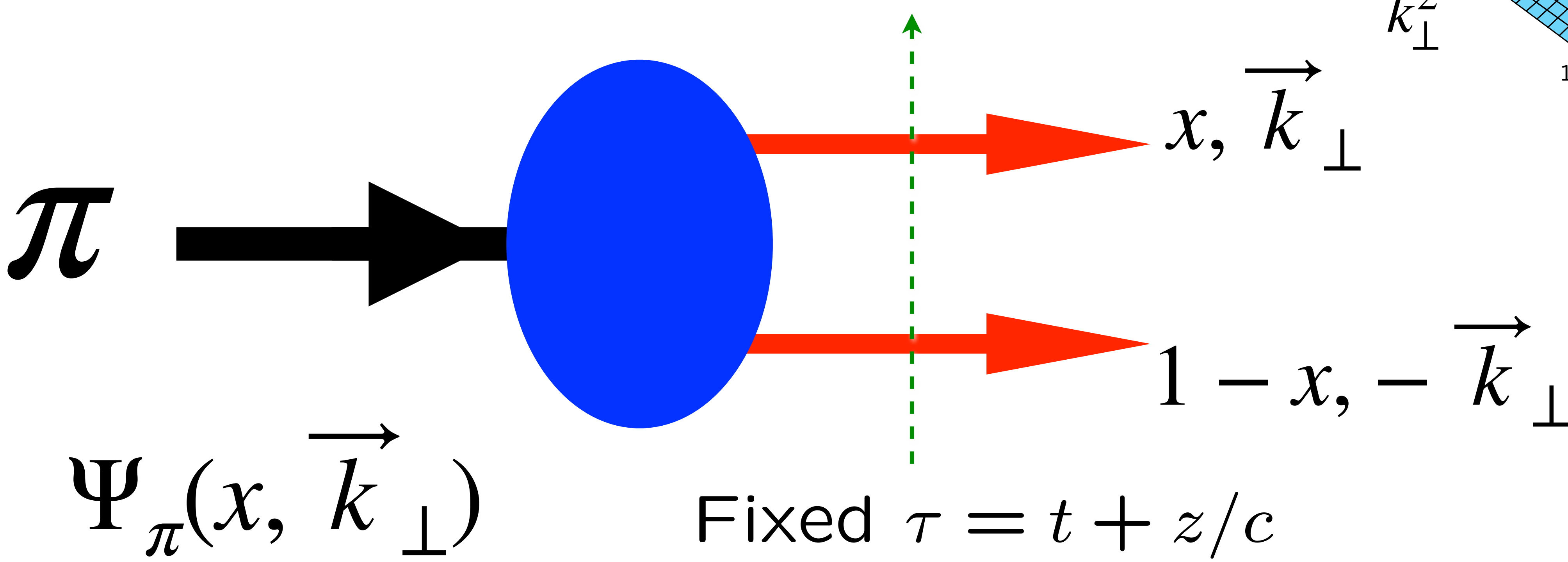
$$\Psi_\pi(x, \overrightarrow{k}_\perp) = < q(x, \overrightarrow{k}_\perp) \bar{q}(1-x, -\overrightarrow{k}_\perp) | \, \pi >$$

- Independent of the observer's or pion's motion

- No Lorentz contraction; causal

- ***Confined*** quark-antiquark bound state





Universality of Generalized Parton Distributions in Light-Front Holographic QCD

Guy F. de Te´ramond, Tianbo Liu, Raza Sabbir Sufian, Hans Günter Dosch, Alexandre Deur, SJB

(HLFHS Collaboration)

$$F_\tau(t) = \frac{1}{N_\tau} B\left(\tau - 1, \frac{1}{2} - \frac{t}{4\lambda}\right),$$

$$N_\tau = B(\tau - 1, 1 - \alpha(0))$$

$$B(u, v) = \int_0^1 dy y^{u-1} (1 - y)^{v-1} = [\Gamma(u)\Gamma(v)/\Gamma(u + v)]$$

$$F_\tau(Q^2) = \frac{1}{\left(1 + \frac{Q^2}{M_0^2}\right)\left(1 + \frac{Q^2}{M_1^2}\right) \cdots \left(1 + \frac{Q^2}{M_{\tau-2}^2}\right)}$$

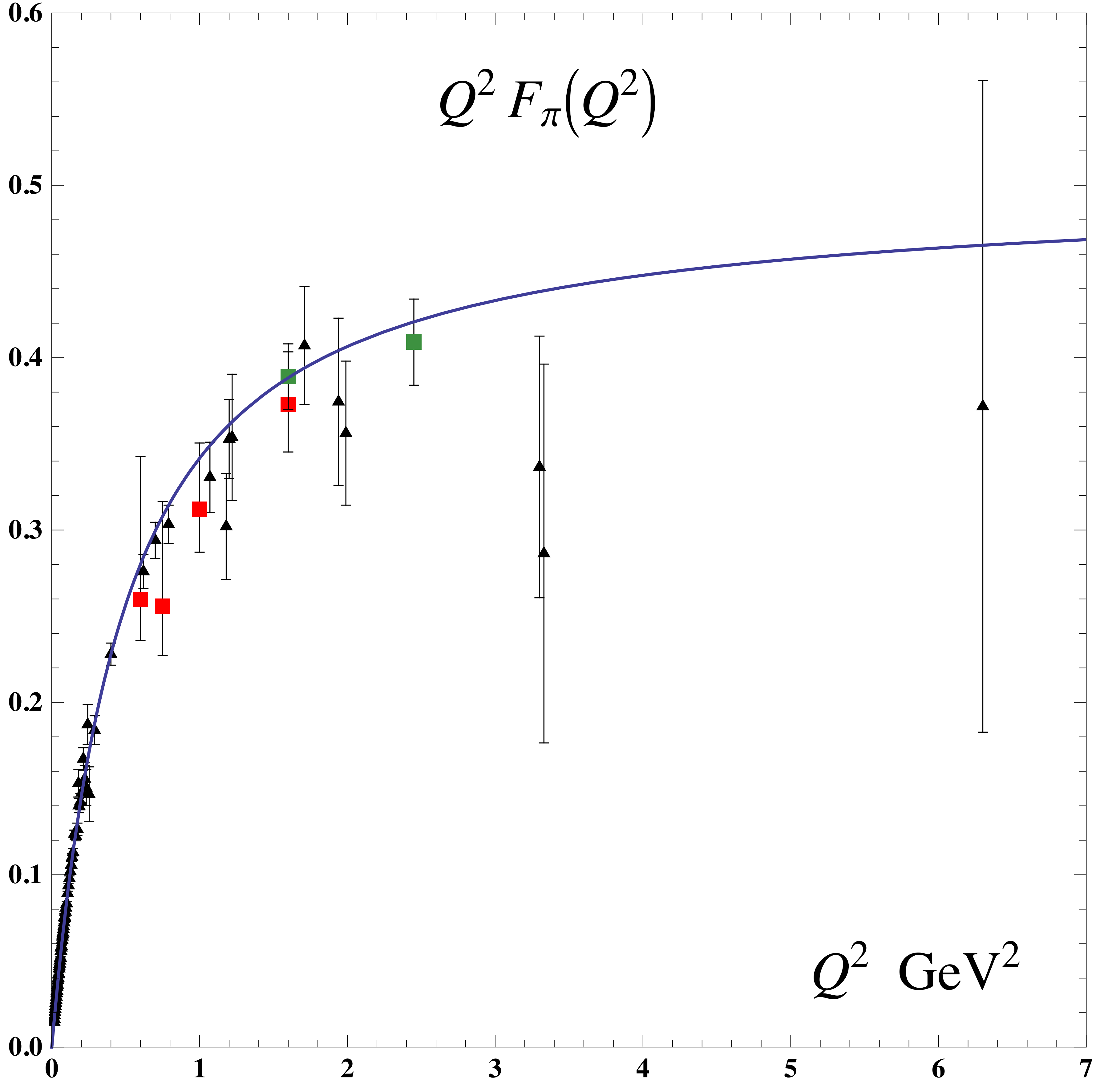
$$F_\tau(Q^2) \sim \left(\frac{1}{Q^2}\right)^{\tau-1}$$

$$M_n^2 = 4\lambda(n + \tfrac{1}{2}), n = 0, 1, 2, \ldots, \tau - 2, \qquad M_0 = m_\rho$$

$$\sqrt{\lambda} = \kappa = \frac{m_\rho}{\sqrt{2}} = 0.548\ GeV \qquad \frac{1}{2} - \frac{t}{4\lambda} = 1 - \alpha_R(t)$$

Consistent with QCD counting rules

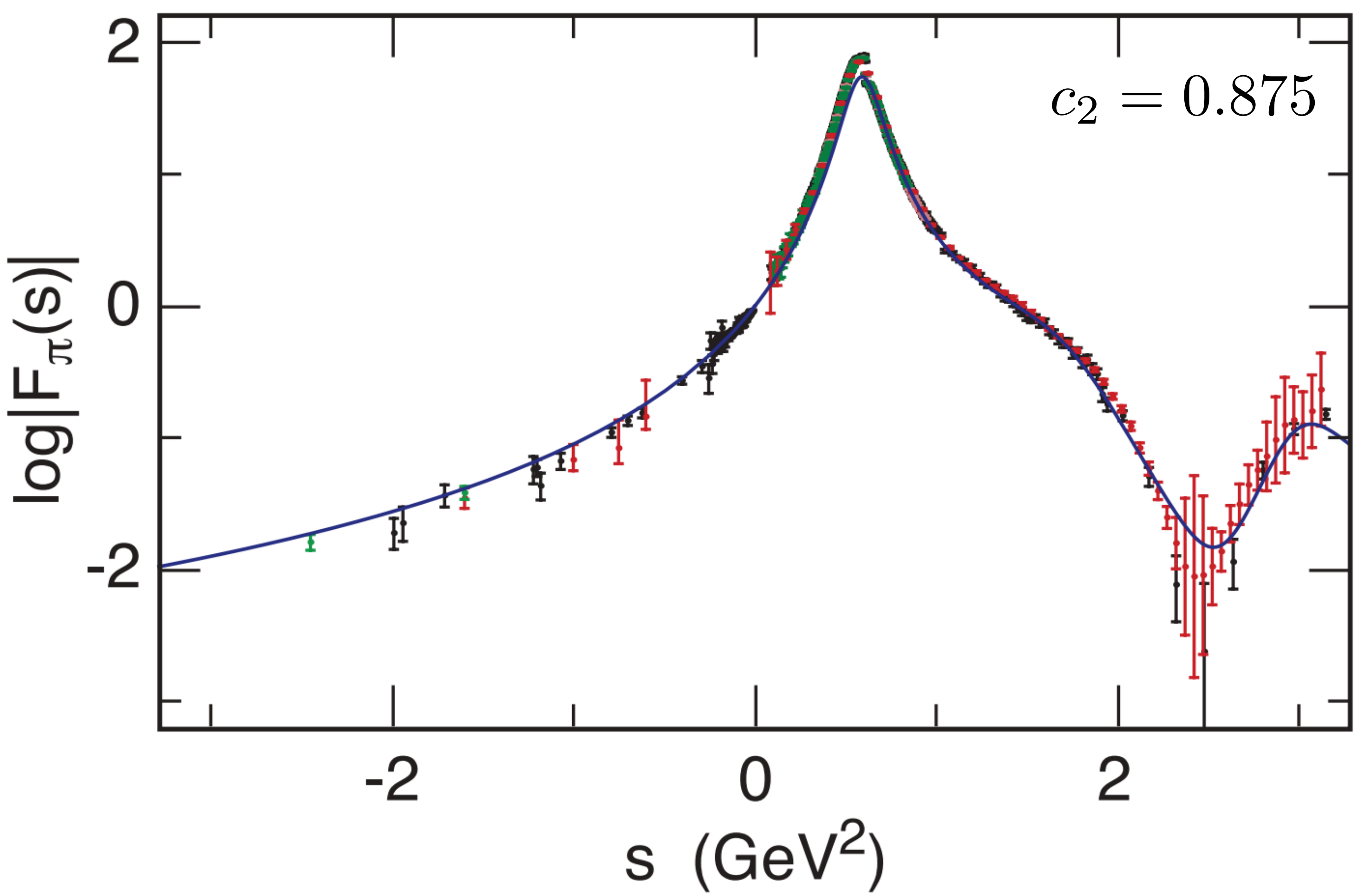
$\alpha_R(t) = \rho$ Regge Trajectory



$Q^2 F_\pi(Q^2)$
Q^2 GeV^2
0.6
0.5
0.4
0.3
0.2
0.1
0.0
0
1
2
3
4
5
6
7

Pion EM Form Factor

Pion form factor compared with data



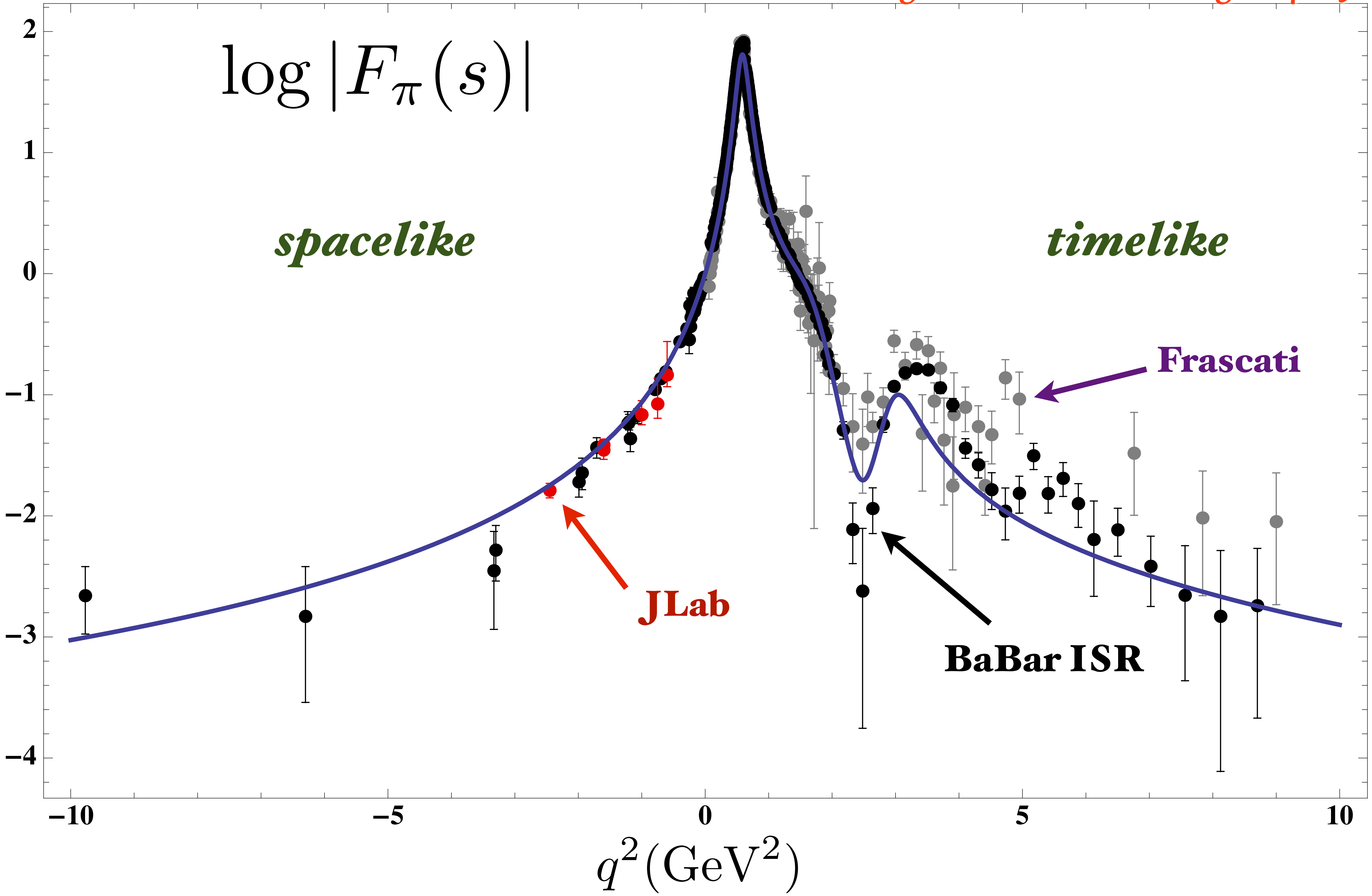
$$F_\pi(t) = \sum_\tau P_\tau F_\tau(t) \qquad \sum_\tau P_\tau = 1$$

Truncated at twist-τ = 4

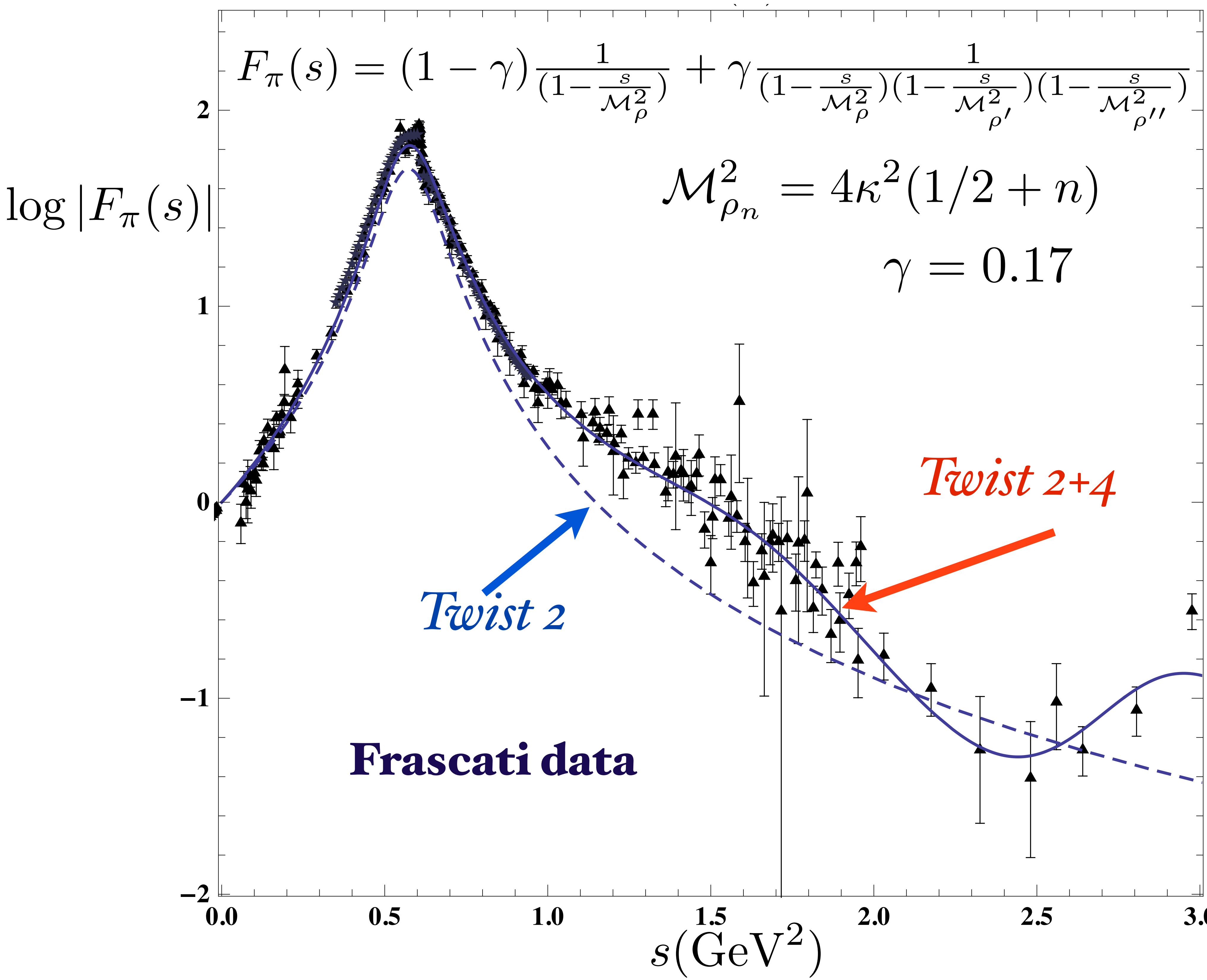
$$F_\pi(t) = c_2 F_{\tau=2}(t) + (1 - c_2) F_{\tau=4}(t)$$

G.F. de Téramond and S.J. Brodsky, Proc. Sci. LC2010 (2010) 029.
S.J. Brodsky, G.F. de Téramond, H.G. Dosch, J. Erlich, Phys. Rep. 584, 1 (2015). [Sec. 6.1.5]

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



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

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

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

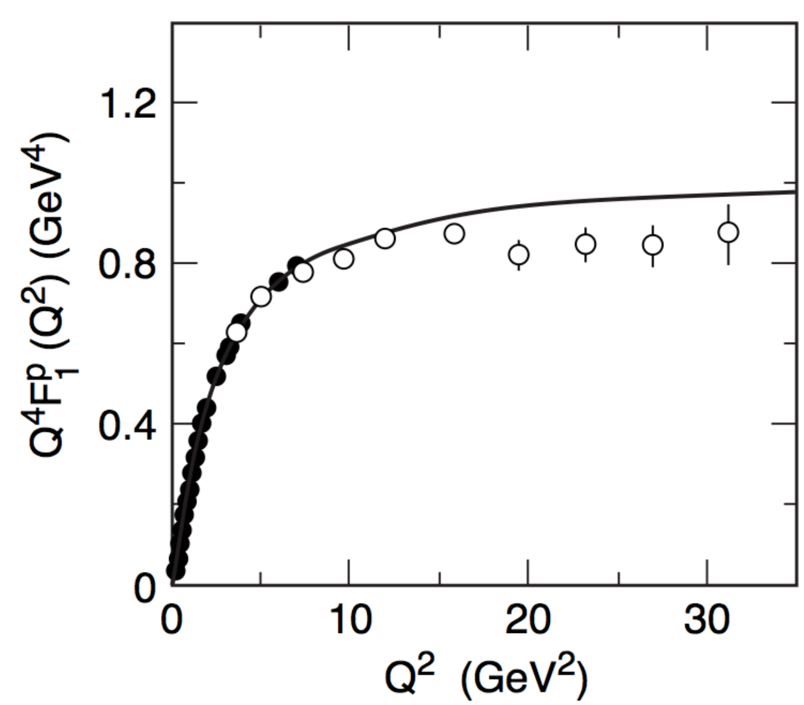
- Bulk-to-boundary propagator [Grigoryan and Radyushkin (2007)]

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

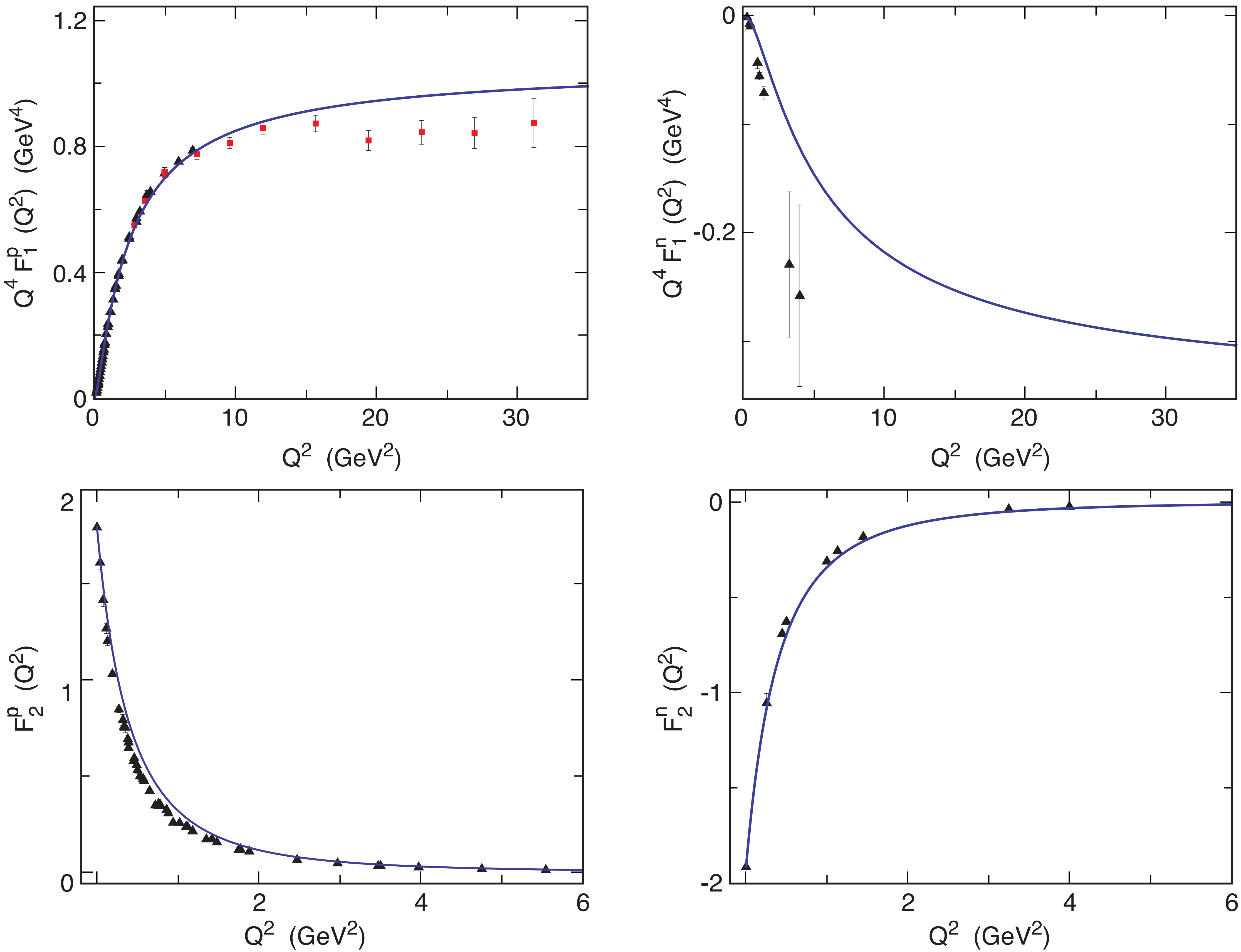
- Find

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

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

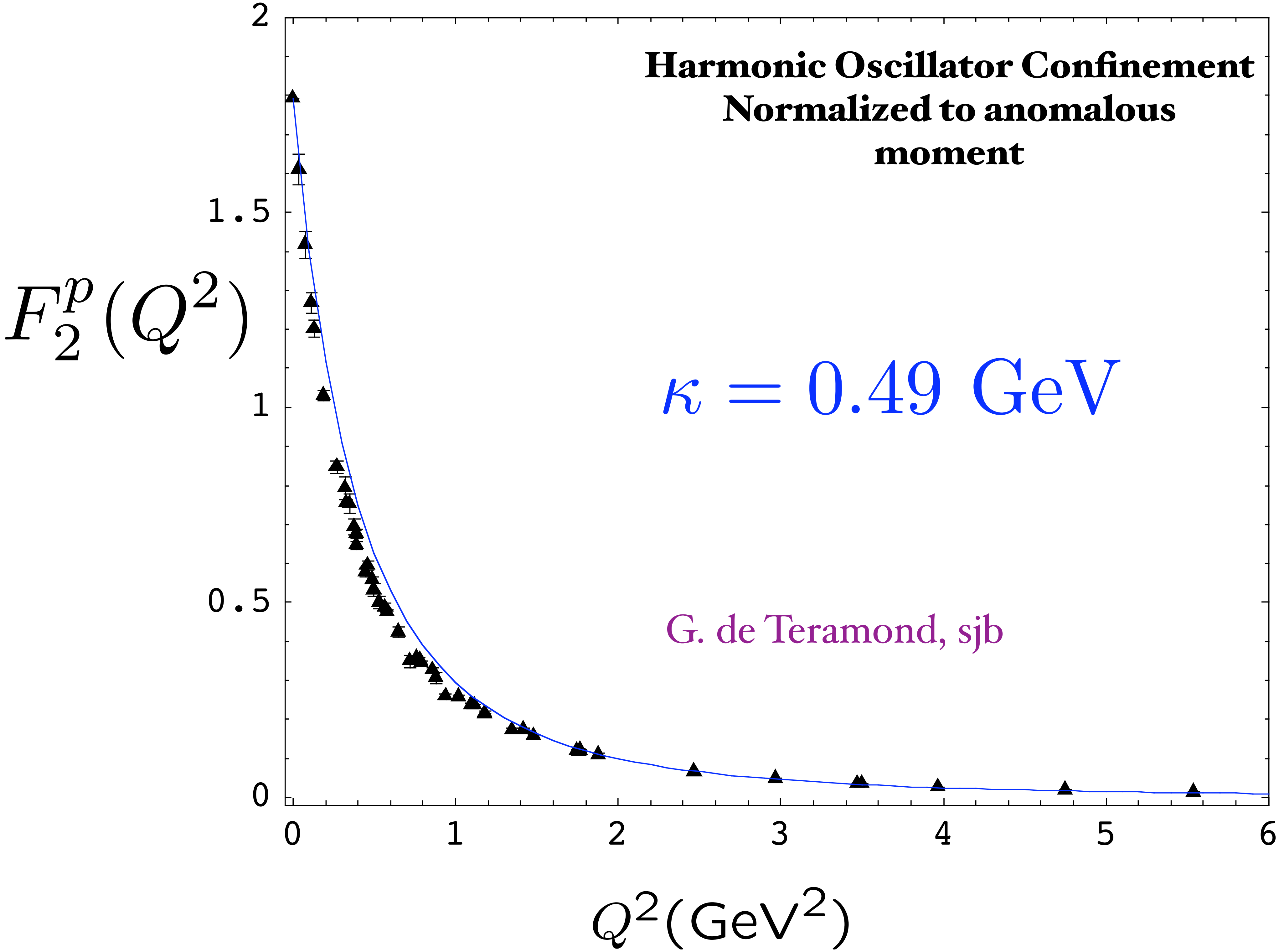


Using $SU(6)$ flavor symmetry and normalization to static quantities

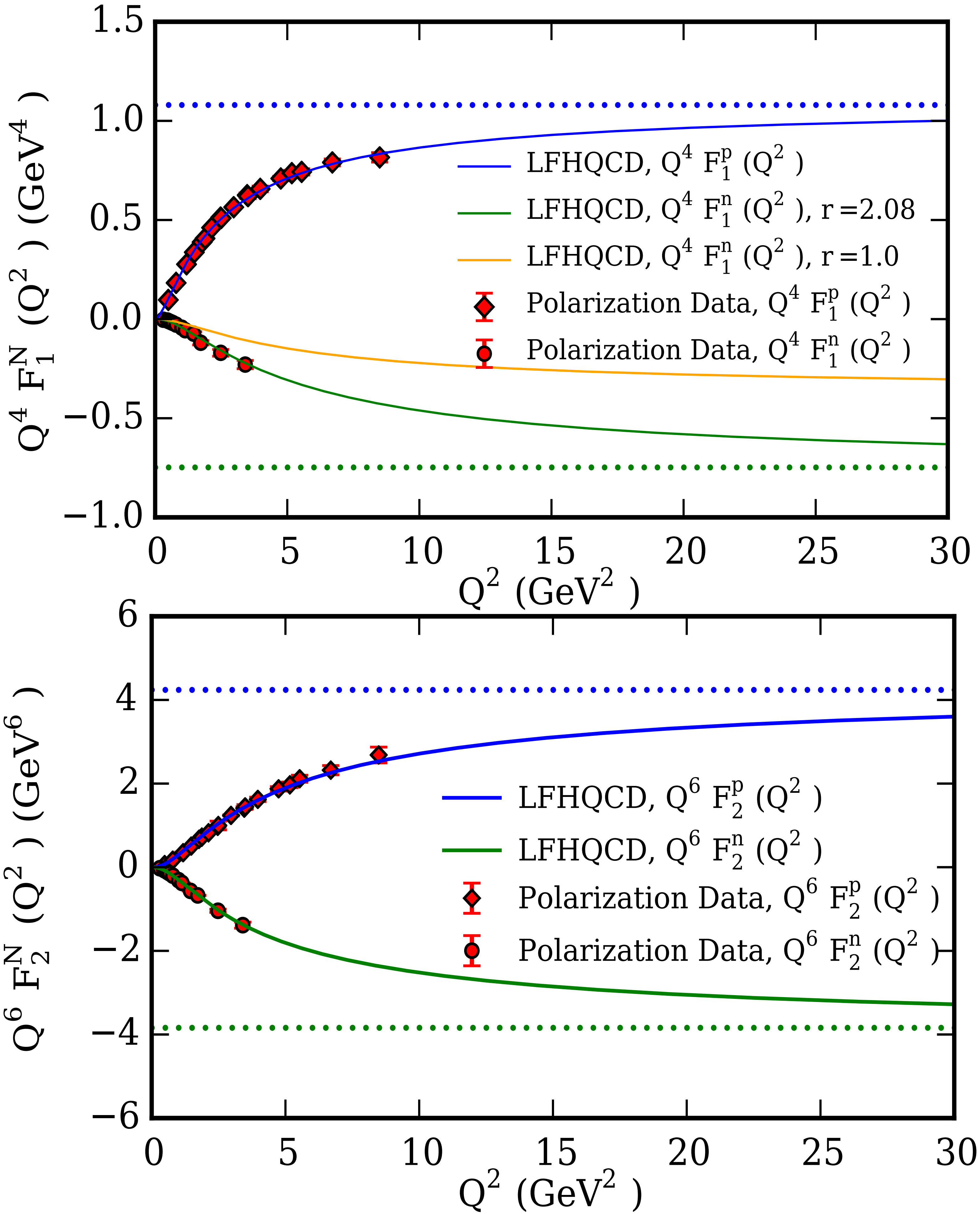


Spacelike Pauli Form Factor

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



Sufian, de Teramond, Deur, Dosch, sjb



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

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

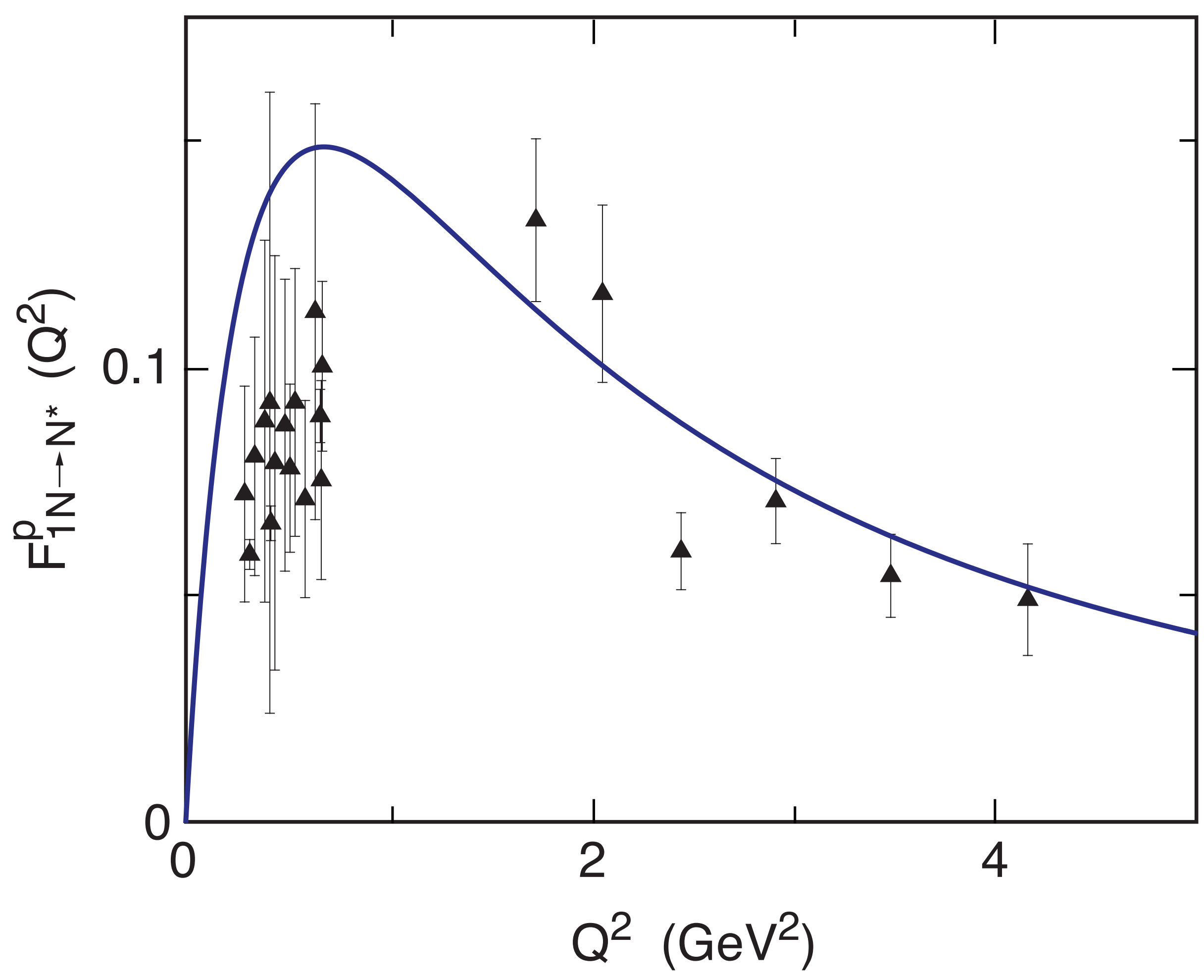
Includes 5-quark Fock states

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

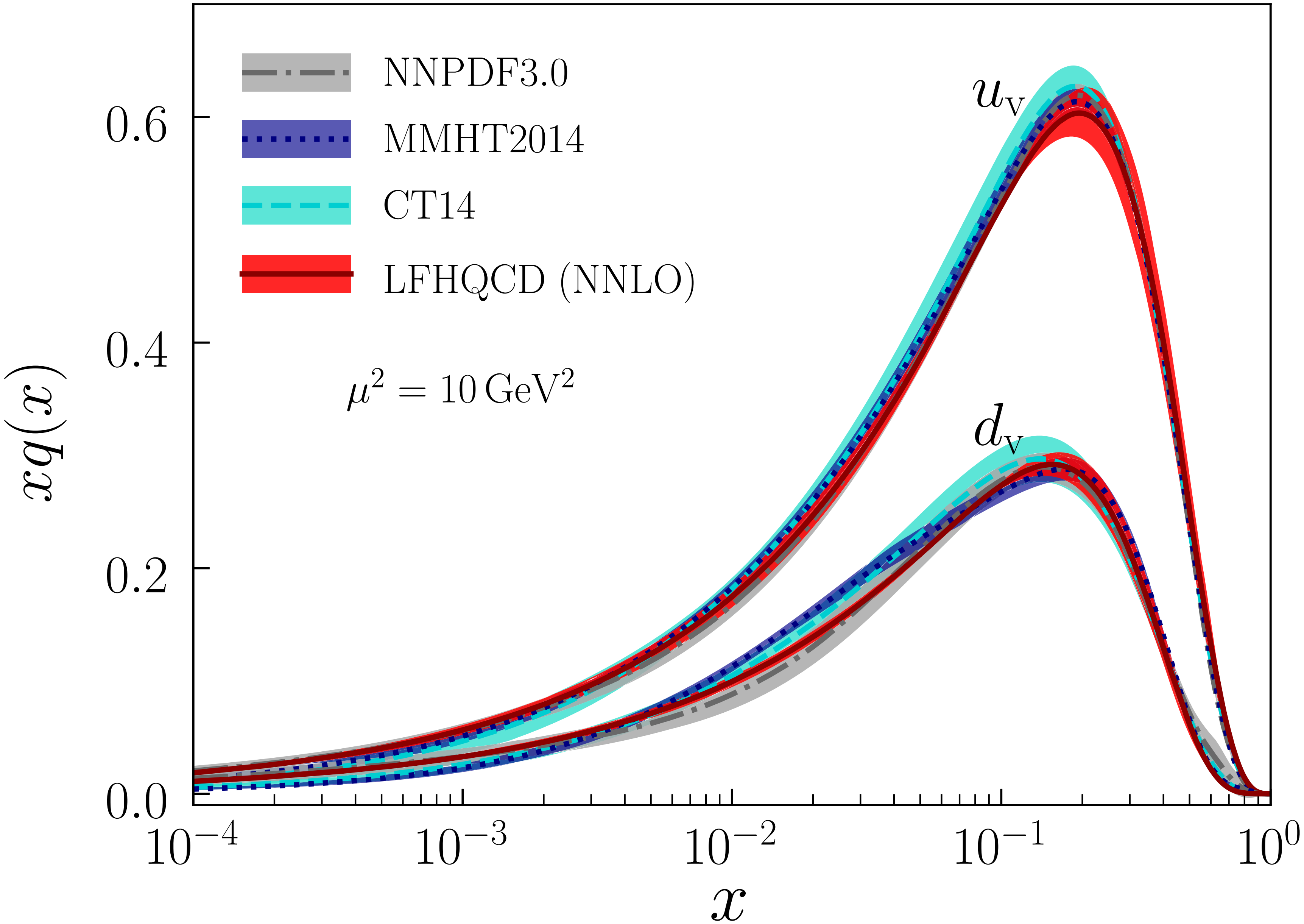
$Q^6 F_2^n(Q^2)$

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



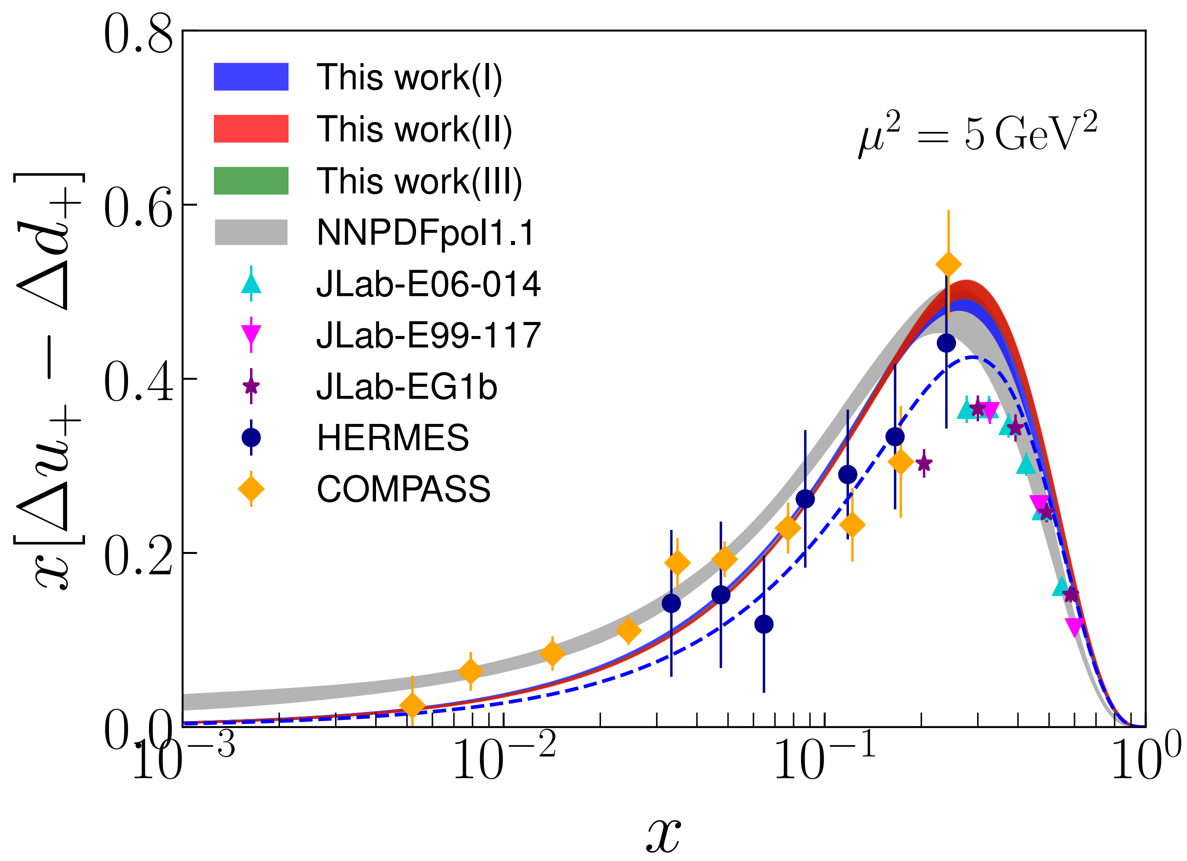
Comparison for $xq(x)$ in the proton from LFHQCD (red bands) and global fits: MMHT2014 (blue bands) [5], CT14 [6] (cyan bands), and NNPDF3.0 (gray bands) [77]. LFHQCD results are evolved from the initial scale $\mu_0 = 1.06 \pm 0.15$ GeV.

Universality of Generalized Parton Distributions in Light-Front Holographic QCD

Guy F. de Te´ramond, Tianbo Liu, Raza Sabbir Sufian, Hans Günter Dosch, Stanley J. Brodsky, and Alexandre Deur

PHYSICAL REVIEW LETTERS 120, 182001 (2018)

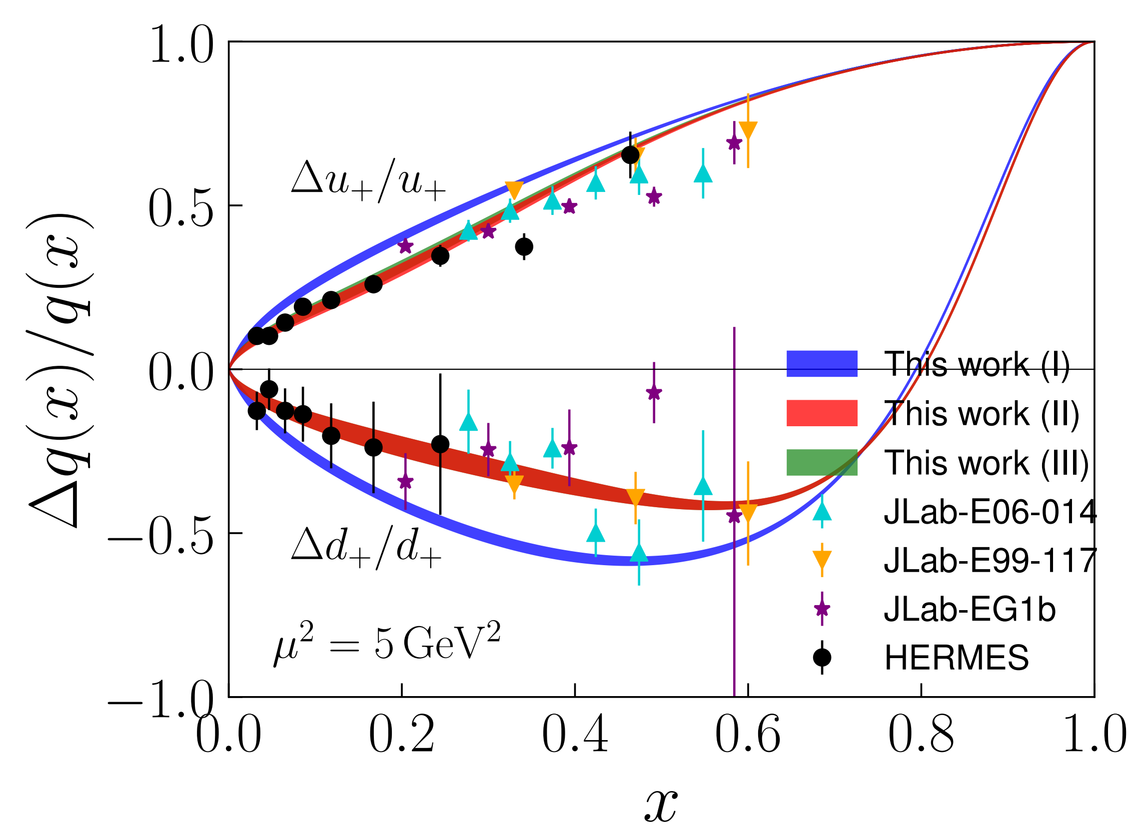
Tianbo Liu, Raza Sabbir Sufian, Guy F. de T´eramond, Hans Gunter Dösch, Alexandre Deur, sjb

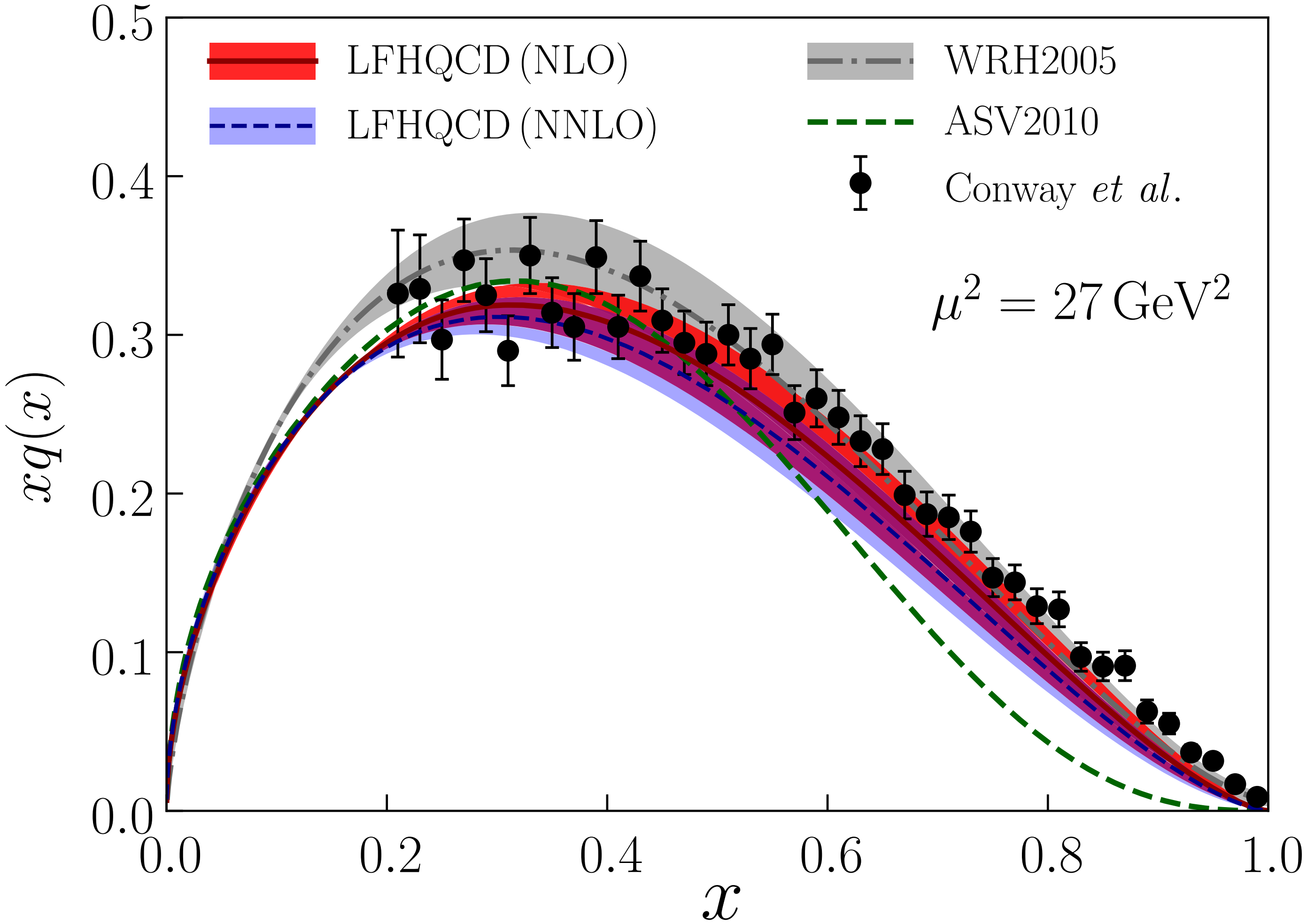


Polarized distributions for the isovector combination $x[\Delta u_+(x) - \Delta d_+(x)]$

$$d_+(x) = d(x) + \bar{d}(x) \qquad u_+(x) = u(x) + \bar{u}(x)$$

$$\Delta q(x) = q_\uparrow(x) - q_\downarrow(x)$$





Comparison for $xq(x)$ in the pion from LFHQCD (red band) with the NLO fits [82,83] (gray band and green curve) and the LO extraction [84]. NNLO results are also included (light blue band). LFHQCD results are evolved from the initial scale $\mu_0 = 1.1 \pm 0.2$ GeV at NLO and the initial scale $\mu_0 = 1.06 \pm 0.15$ GeV at NNLO.

Universality of Generalized Parton Distributions in Light-Front Holographic QCD

Guy F. de Te´ramond, Tianbo Liu, Raza Sabbir Sufian, Hans Günter Dosch, Stanley J. Brodsky, and Alexandre Deur *PHYSICAL REVIEW LETTERS 120, 182001 (2018)*

Deur, de Tèramond, sjb

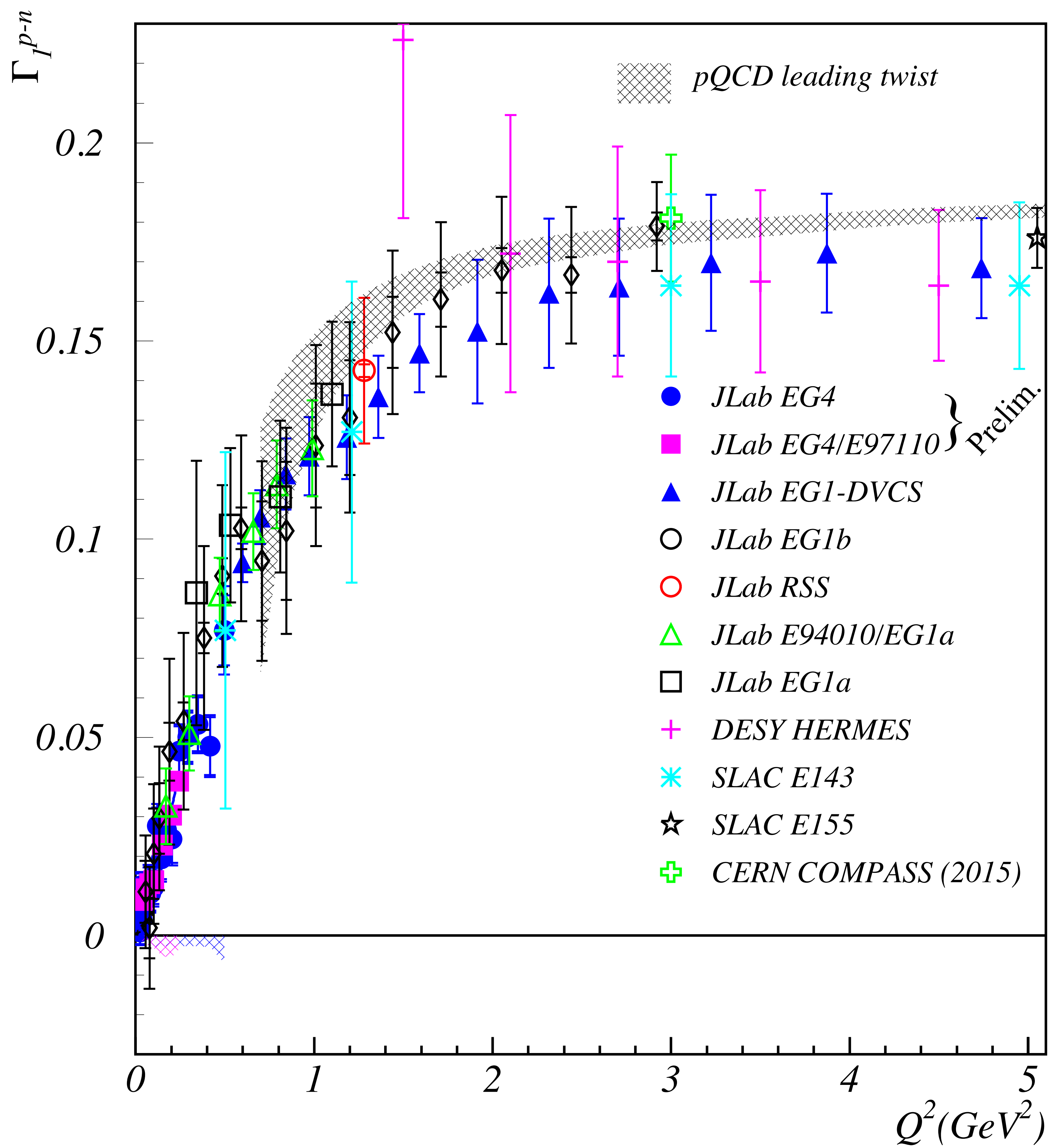
Bjorken sum rule defines effective charge: $\alpha_{g1}(Q^2)$

$$\int_0^1 dx[g_1^{ep}(x,Q^2) - g_1^{en}(x,Q^2)] \equiv \frac{g_a}{6}[1 - \frac{\alpha_{g1}(Q^2)}{\pi}]$$

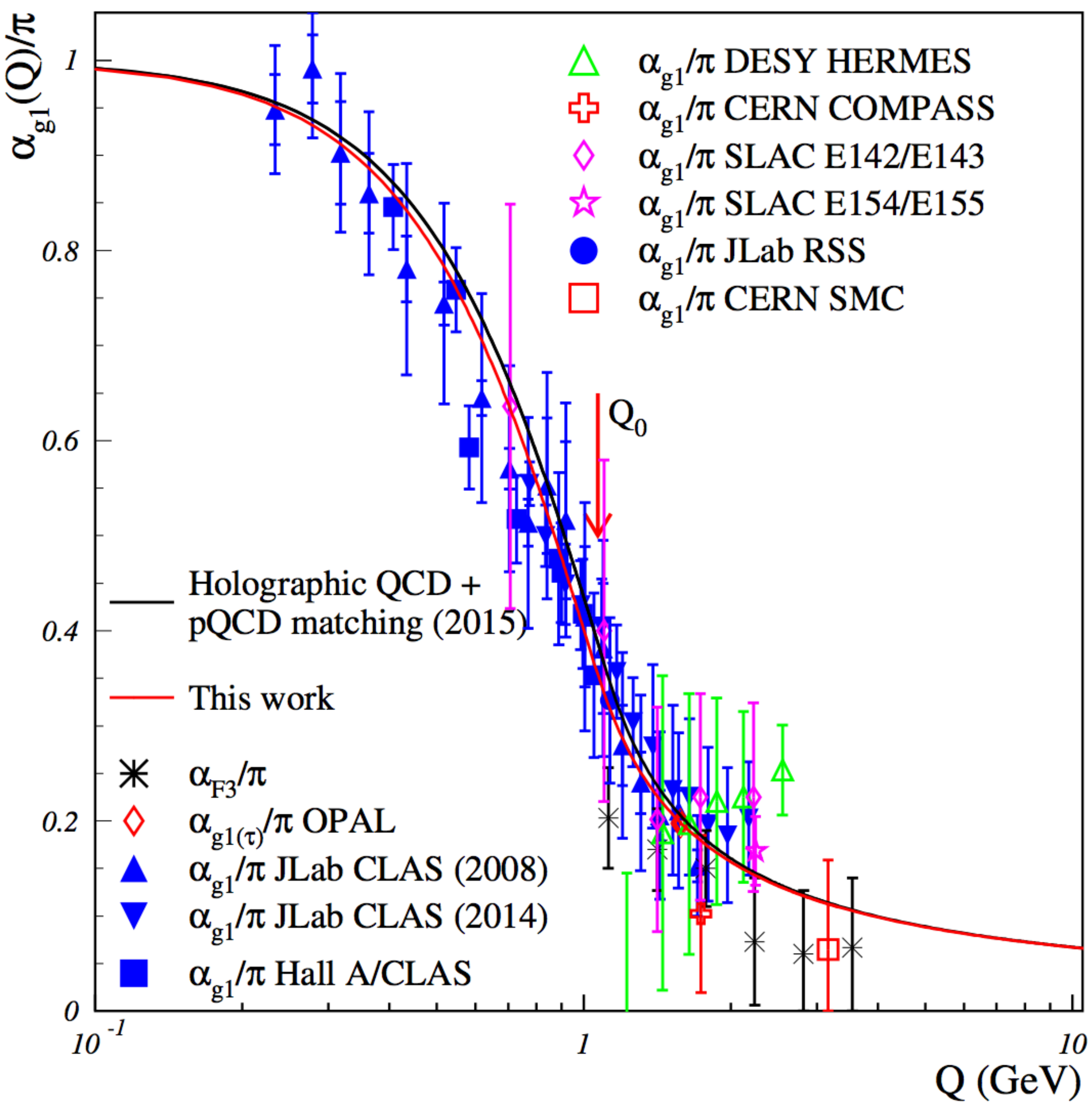
- ***Can be used as standard QCD coupling***
- ***Well measured***
- ***Asymptotic freedom at large Q^2***
- ***Computable at large Q^2 in any pQCD scheme***
- ***Universal β_0, β_1***
- ***Analytic connection to other schemes:***

Commensurate scale relations

Bjorken sum Γ_1^{p-n} measurements



Running QCD Coupling from AdS/QCD



Bjorken sum rule:

$$\frac{\alpha_{g_1}(Q^2)}{\pi} = 1 - \frac{6}{g_A}\int_0^1 dx\, g_1^{p-n}(x, Q^2)$$

Effective coupling in LFHQCD (valid at low-Q^2)

$$\alpha_{g_1}^{AdS}(Q^2) = \pi \exp\left(-Q^2/4\kappa^2\right)$$

Imposing continuity for α and its first derivative

A. Deur, S.J. Brodsky, G.F. de Téramond,
Phys. Lett. B 750, 528 (2015); J. Phys. G 44, 105005 (2017).

Analytic, defined at all scales, IR Fixed Point

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

$m_p = 2\kappa$

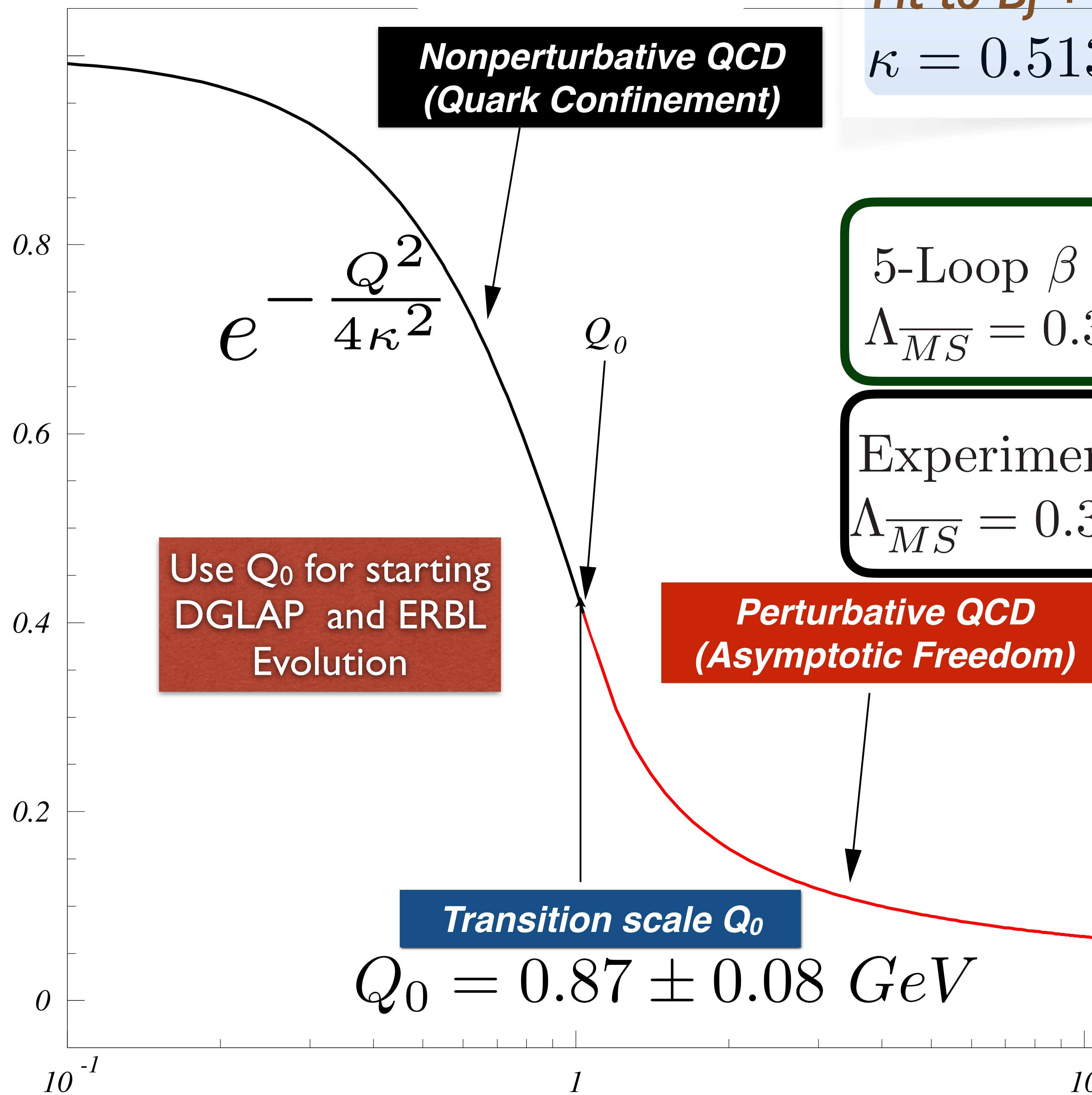
All-Scale QCD Coupling

Deur, de Tèramond, sjb

Fit to Bj + DHG Sum Rules:

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

$$\frac{\alpha^s_{g_1}(Q^2)}{\pi}$$



5-Loop β Prediction:

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

Experiment:

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

$\lambda \equiv \kappa^2$

$\overline{MS}$ scheme

PMC Renormalization Scale Setting, Commensurate Scale Relations

Light-Front Holography Model of the EMC Effect

Dmitriy N. Kim and Gerald A. Miller
Department of Physics, University of Washington, Seattle, WA 98195-1560, USA
(Dated: December 12, 2022)

A new two-component model of the EMC effect based on Light-Front Holographic QCD (LFHQCD) is presented. The model suggests the EMC effect is the result of the nuclear potential breaking SU(6) symmetry. The model separates the F_2^A nuclear structure function into two parts: a free contribution, involving the addition of proton and neutron structure functions weighted by the number of protons and neutrons respectively, and a nuclear/medium modified contribution that involves nucleus independent universal function. Further, the model displays a correlation between the size of the EMC effect and the SRC pair density, a_2 - extracted from kinematic plateaus at around $x > 1$ in inclusive quasi-elastic (QE) scattering.

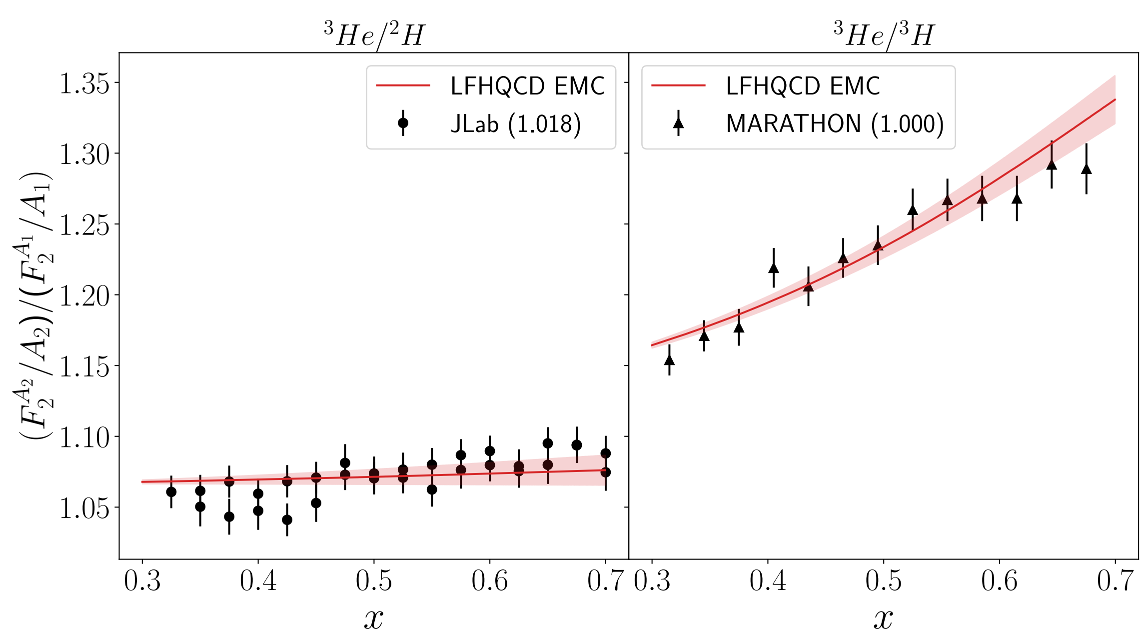


FIG. 3: EMC ratio comparisons between the LFHQCD model (red line) and published experimental data (removed isoscalar corrections) obtained from JLab (solid points) and MARATHON (solid triangles). The red bands display 1σ uncertainties for the LFHQCD EMC model. The number in parenthesis next to the experiment name in the legend is the normalization factor that multiplies all the data points, η_{exp} in Eq. (61).

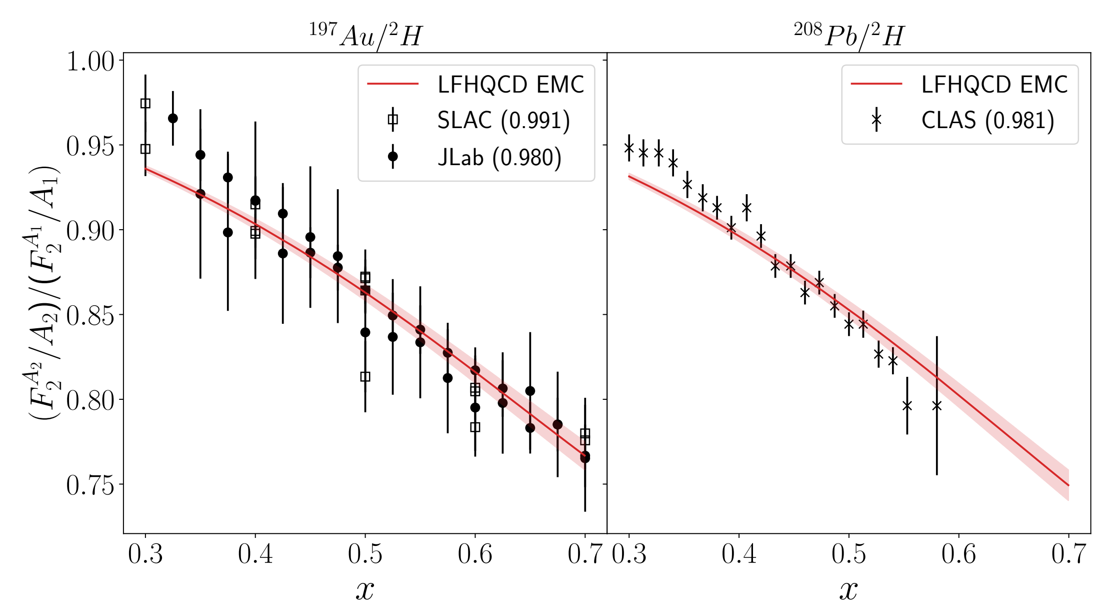
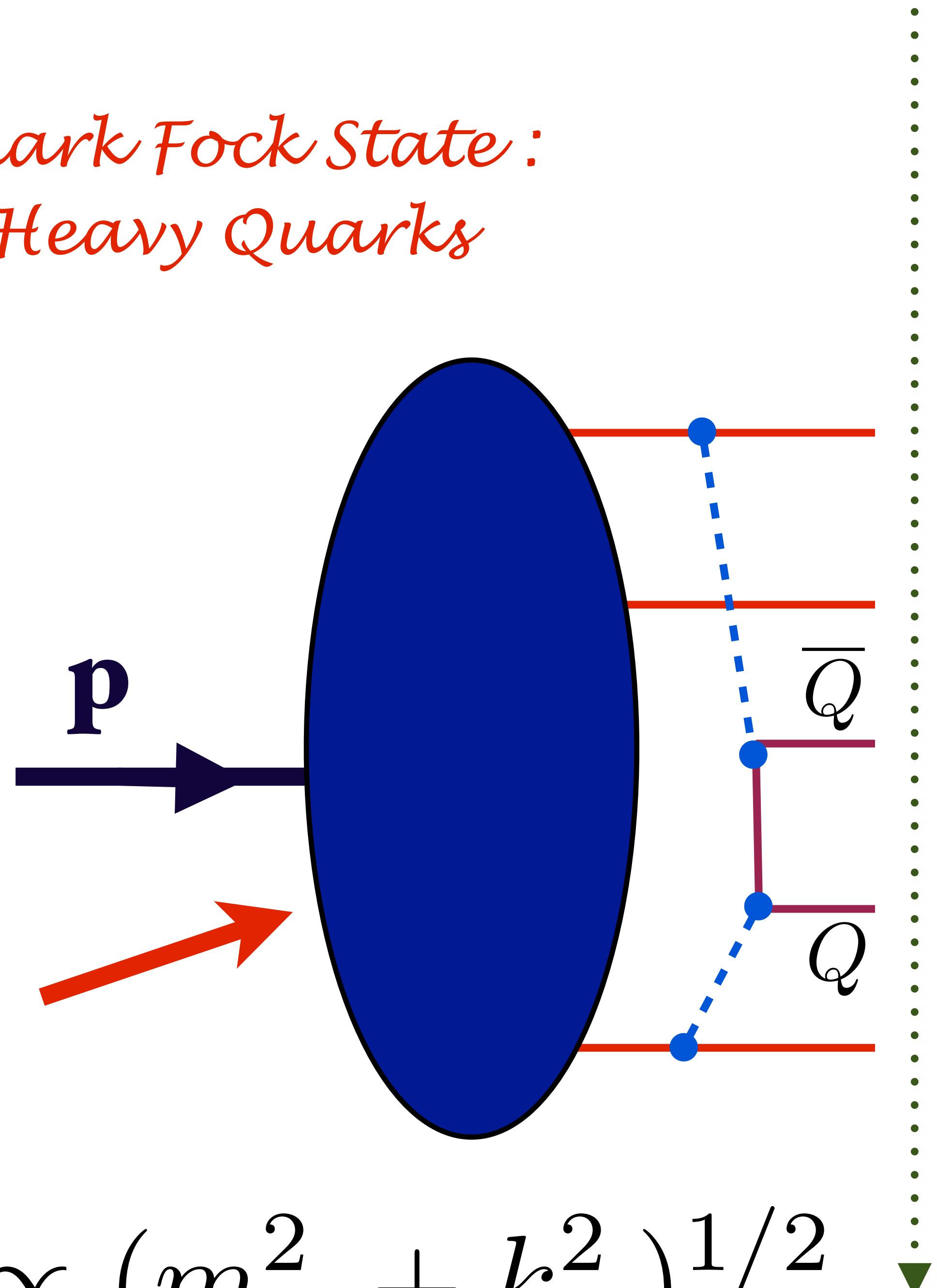


FIG. 6: EMC ratio comparisons between the LFHQCD model (red line) and published experimental data (removed isoscalar corrections) obtained from SLAC (open boxes), JLab (solid points), and CLAS (crosses). The red bands display 1σ uncertainties for the LFHQCD EMC model. The number in parenthesis next to the experiment name in the legend is the normalization factor that multiplies all the data points, η_{exp} in Eq. (61).

Proton 5-quark Fock State :
Intrinsic Heavy Quarks



$$x_Q \propto (m_Q^2 + k_\perp^2)^{1/2}$$

QCD predicts Intrinsic Heavy Quarks at high x!

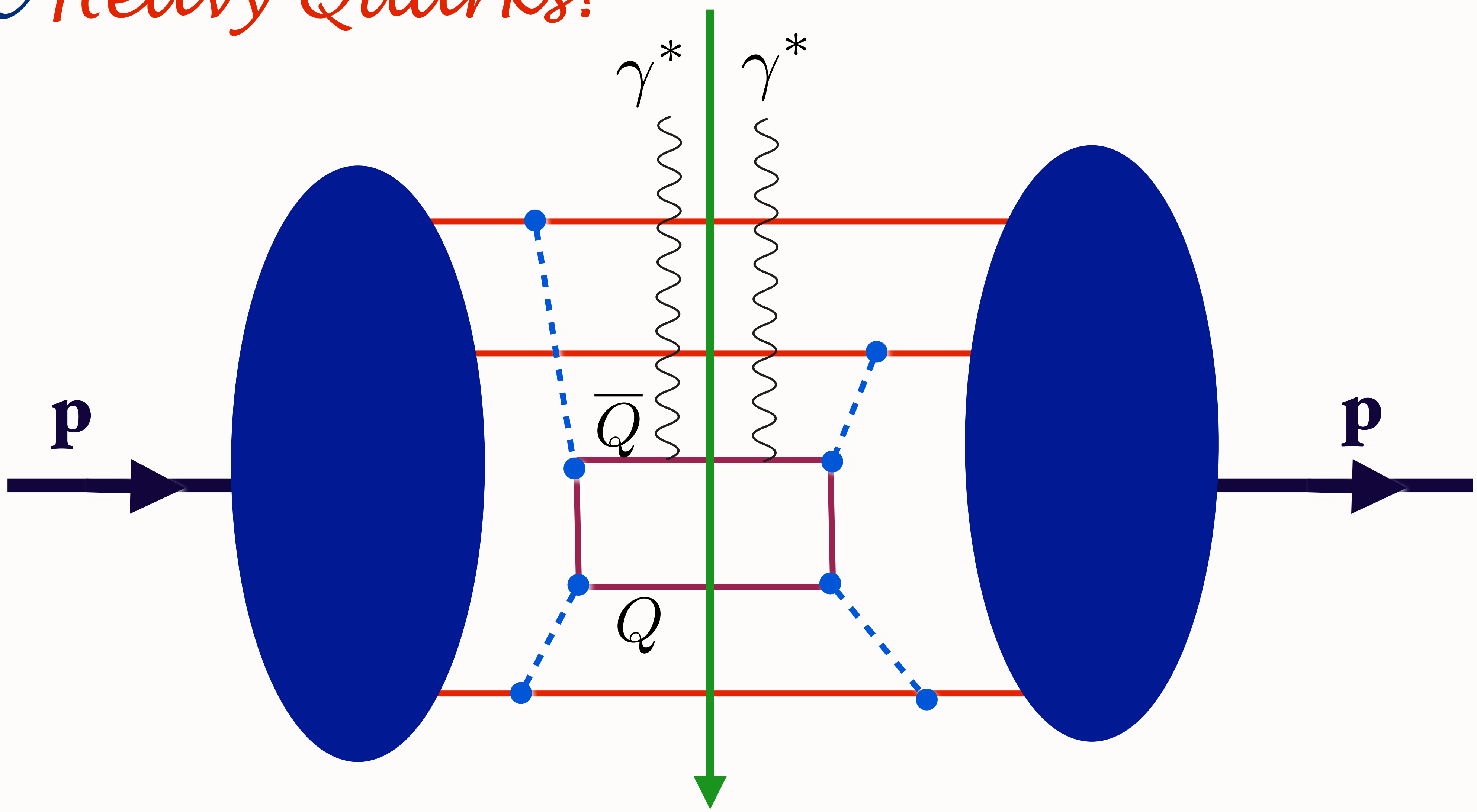
Minimal off-shellness!

Probability (QED) $\propto \frac{1}{M_\ell^4}$

Probability (QCD) $\propto \frac{1}{M_Q^2}$

Hoyer, Peterson, Sakai, Collins, Ellis, Gunion, Mueller, sjb
Polyakov, et al.

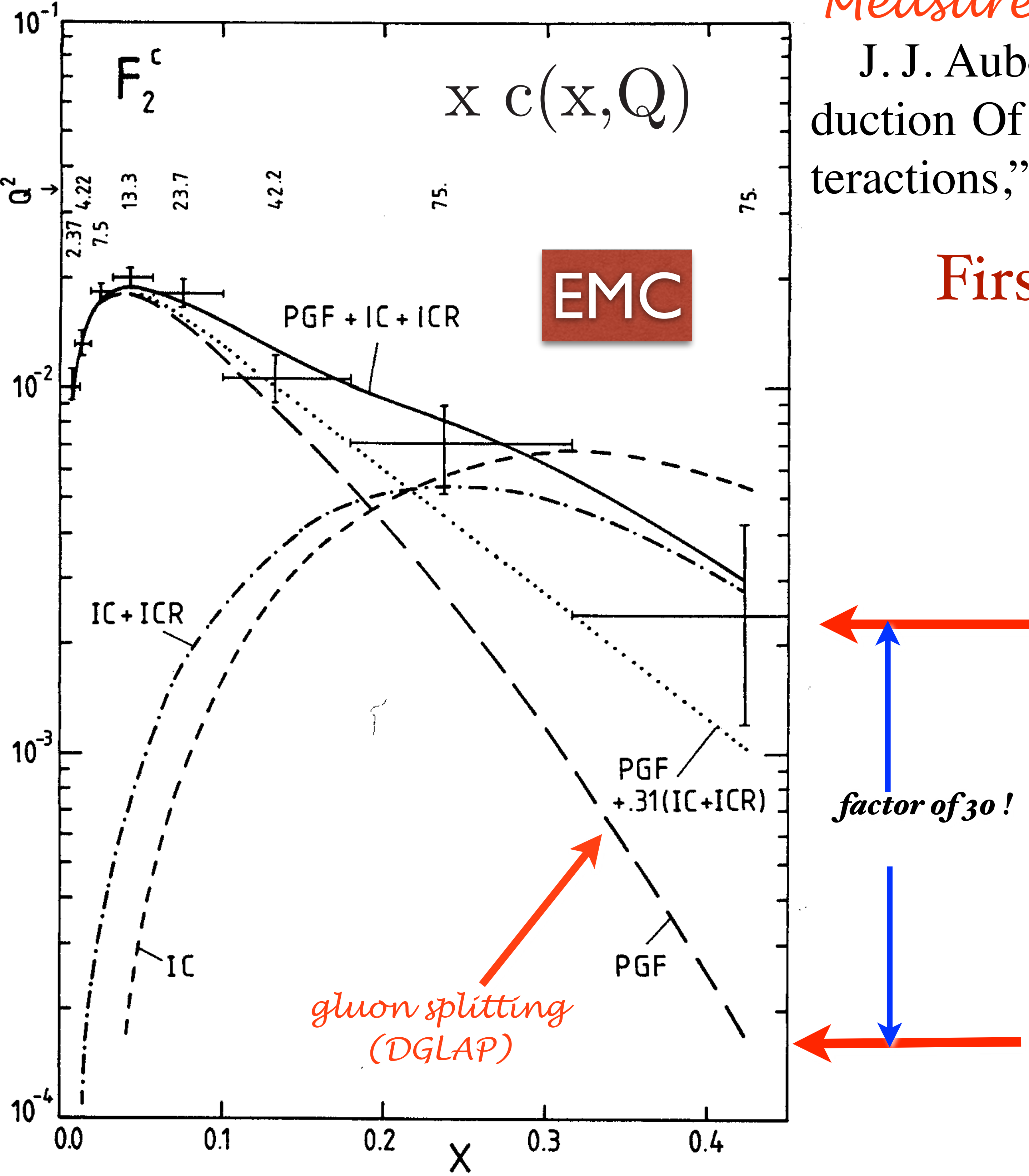
Cut of Proton Self Energy:
QCD predicts
Intrinsic Heavy Quarks!



Probability (QED) $\propto \frac{1}{M_\ell^4}$ Probability (QCD) $\propto \frac{1}{M_Q^2}$

$$x_Q \propto (m_Q^2 + k_\perp^2)^{1/2}$$

Hoyer, Peterson, Sakai, Collins, Ellis, Gunion, Mueller, sjb
Polyakov, et al.



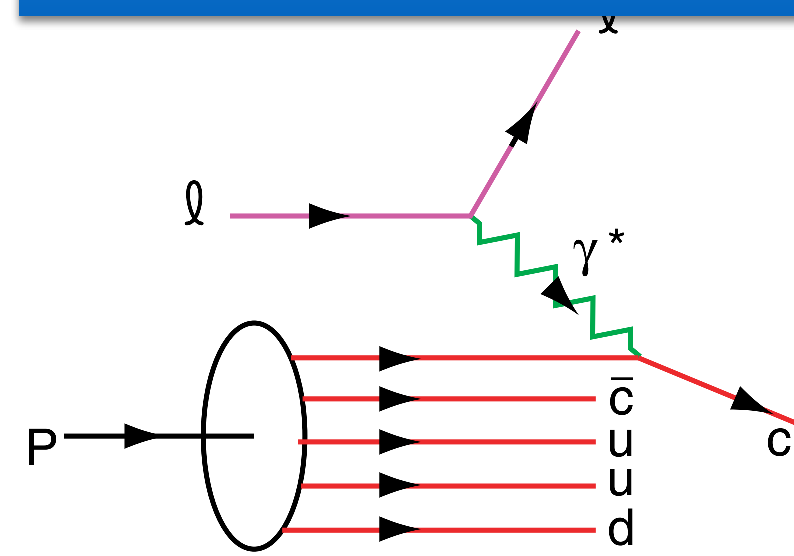
Measurement of Charm Structure Function!

J. J. Aubert et al. [European Muon Collaboration], "Production Of Charmed Particles In 250-Gev Mu+ - Iron Interactions," Nucl. Phys. B 213, 31 (1983).

First Evidence for Intrinsic Charm

$$< x_{c\bar{c}} >_p \simeq 1\%$$

New Analysis:
R.D. Ball, et al. [NNPDF Collaboration], "A Determination of the Charm Content of the Proton," arXiv:1605.06515 [hep-ph].



DGLAP / Photon-Gluon Fusion: factor of 30 too small

Two Components (separate evolution):

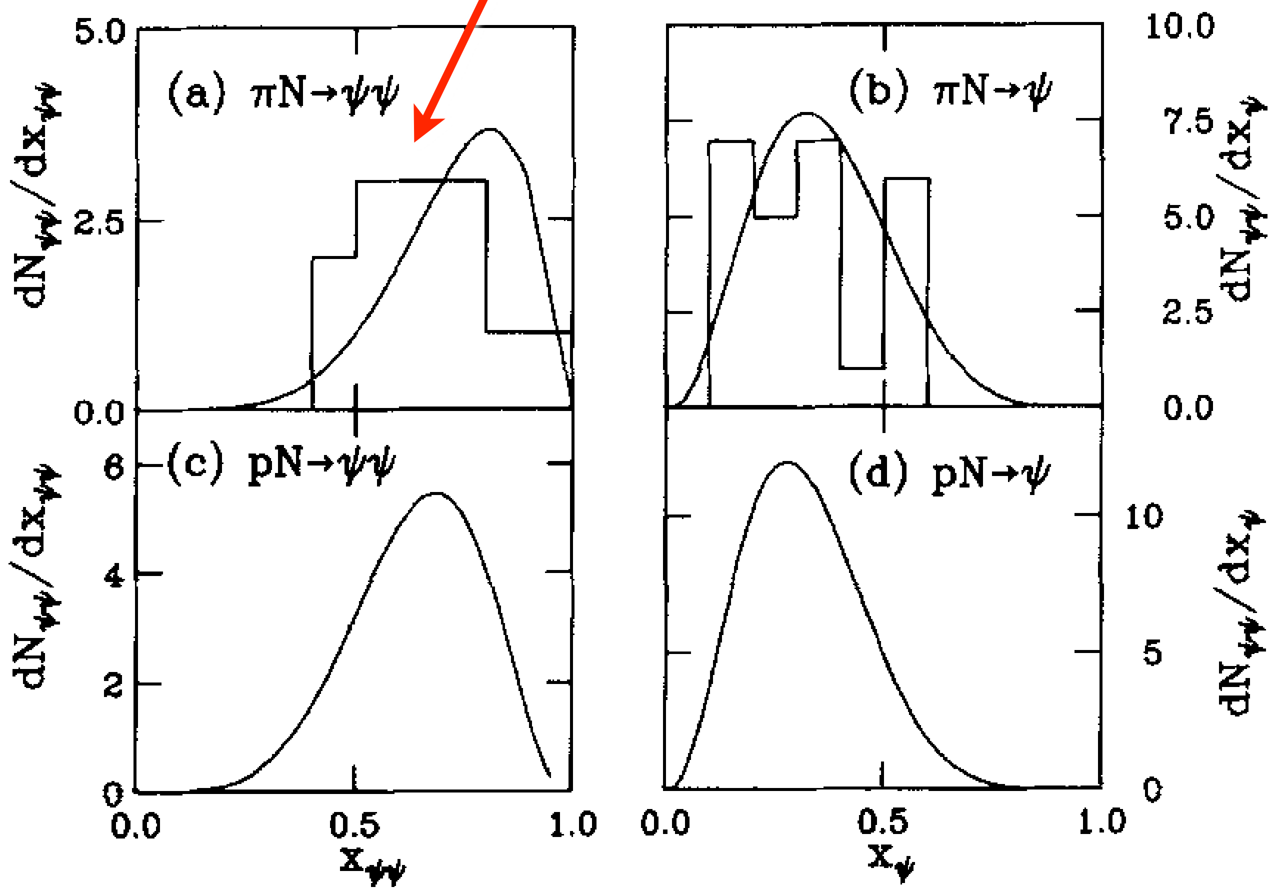
$$c(x, Q^2) = c(x, Q^2)_{\text{extrinsic}} + c(x, Q^2)_{\text{intrinsic}}$$

All events have $x^F_{\psi\psi} > 0.4$!

Double J/ψ Production

$\pi A \to J/\psi J/\psi X$

R. Vogt, sjb



. The $\psi\psi$ pair distributions are shown in (a) and (c) for the pion and proton projectiles. Similarly, the distributions of J/ψ's from the pairs are shown in (b) and (d). Our calculations are compared with the $\pi^- N$ data at 150 and 280 GeV/c [1]. The $x_{\psi\psi}$ distributions are normalized to the number of pairs from both pion beams (a) and the number of pairs from the 400 GeV proton measurement (c). The number of single J/ψ's is twice the number of pairs.

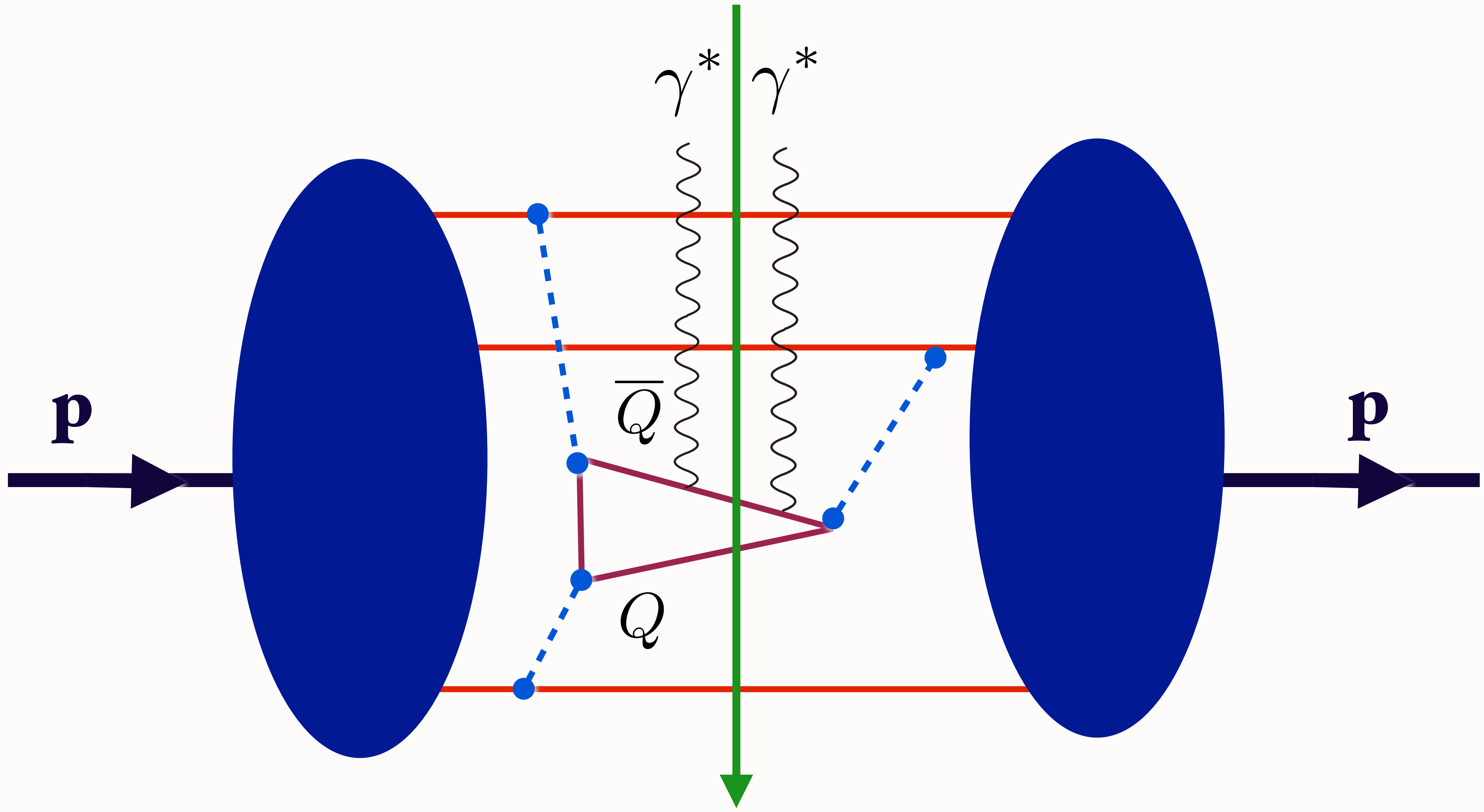
NA3 Data

The probability distribution for a general n-particle intrinsic $c\bar{c}$ Fock state as a function of x and $\boldsymbol{k}_T$ is written as

$$\frac{dP_{\rm ic}}{\prod_{i=1}^n dx_i d^2k_{T,i}} = N_n \alpha_s^4(M_{c\bar{c}}) \frac{\delta(\sum_{i=1}^n \boldsymbol{k}_{T,i})\delta(1-\sum_{i=1}^n x_i)}{(m_h^2 - \sum_{i=1}^n (m_{T,i}^2/x_i))^2} ,$$

I.A. Schmidt, V. Lyubovitskij, sjb

Interference of Intrinsic and Extrinsic Heavy Quark Amplitudes



Interference predicts $Q(x) \neq \bar{Q}(x)$

$$\frac{d\sigma}{dy dp_T^2}(pp \to D^+ c\bar{d}X) \neq \frac{d\sigma}{dy dp_T^2}(pp \to D^- \bar{c}dX)$$

QED Analog: J. Gillespie, sjb (1968)

Constraints on charm-anticharm asymmetry in the nucleon from lattice QCD

Raza Sabbir Sufian[a], Tianbo Liu[a], Andrei Alexandru[b,c], Stanley J. Brodsky[d], Guy F. de Téramond[e], Hans Günter Dosch[f], Terrence Draper[g], Keh-Fei Liu[g], Yi-Bo Yang[h]

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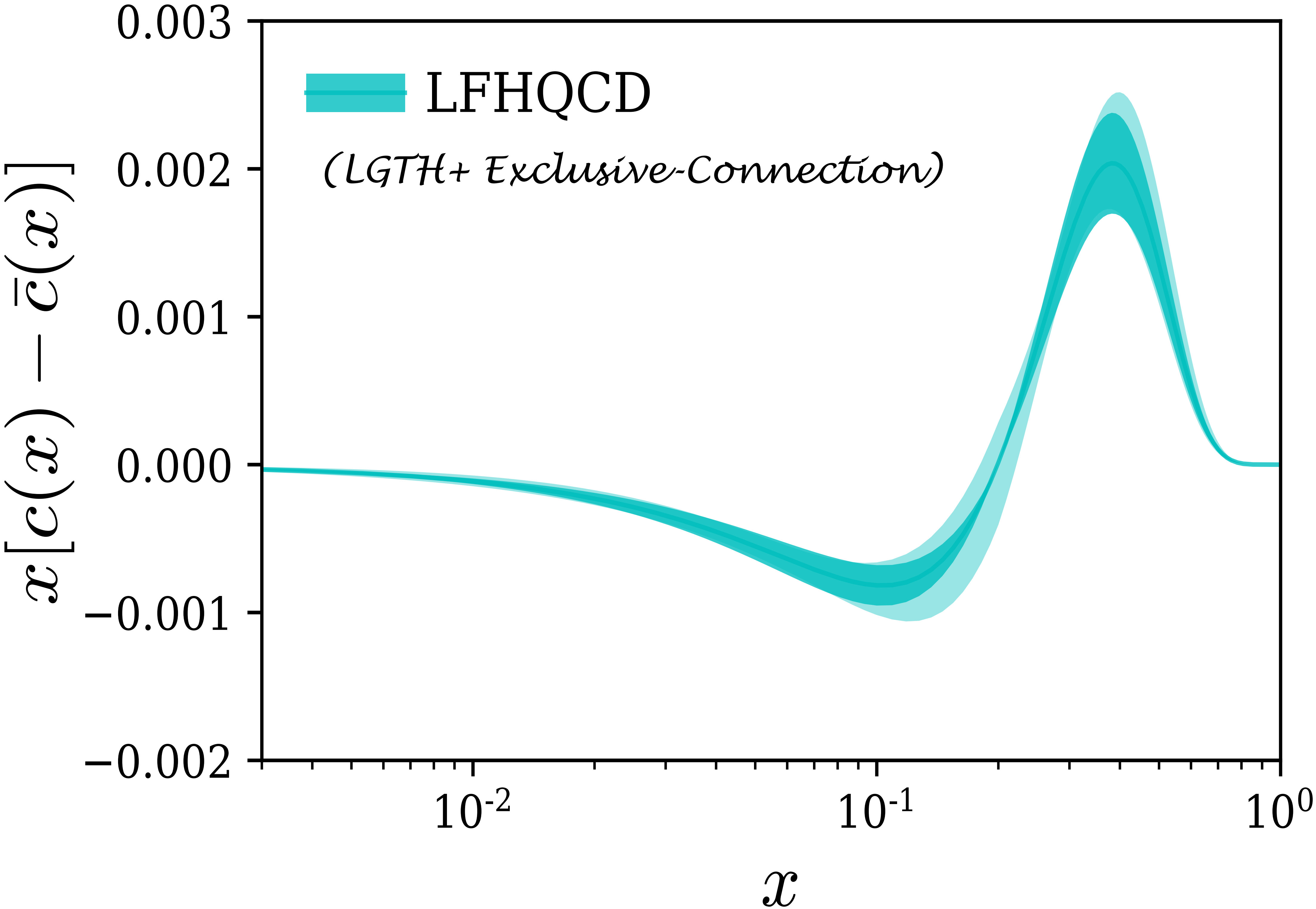
[g] *Department of Physics and Astronomy, University of Kentucky, Lexington, Kentucky 40506, USA*
[h] *CAS Key Laboratory of Theoretical Physics, Institute of Theoretical Physics, Chinese Academy of Sciences, Beijing 100190, China*

Abstract

We present the first lattice QCD calculation of the charm quark contribution to the nucleon electromagnetic form factors $G^c_{E,M}(Q^2)$ in the momentum transfer range $0 \leq Q^2 \leq 1.4\ \mathrm{GeV}^2$. The quark mass dependence, finite lattice spacing and volume corrections are taken into account simultaneously based on the calculation on three gauge ensembles including one at the physical pion mass. The nonzero value of the charm magnetic moment $\mu^c_M = -0.00127(38)_{\rm stat}(5)_{\rm sys}$, as well as the Pauli form factor, reflects a nontrivial role of the charm sea in the nucleon spin structure. The nonzero $G^c_E(Q^2)$ indicates the existence of a nonvanishing asymmetric charm-anticharm sea in the nucleon. Performing a nonperturbative analysis based on holographic QCD and the generalized Veneziano model, we study the constraints on the $[c(x) - \bar{c}(x)]$ distribution from the lattice QCD results presented here. Our results provide complementary information and motivation for more detailed studies of physical observables that are sensitive to intrinsic charm and for future global analyses of parton distributions including asymmetric charm-anticharm distribution.

Keywords: Intrinsic charm, Form factor, Parton distributions, Lattice QCD, Light-front holographic QCD,
JLAB-THY-20-3155, SLAC-PUB-17515



The distribution function $x[c(x) - \bar{c}(x)]$ obtained from the LFHQCD formalism using the lattice QCD input of charm electromagnetic form factors $G^{c}_{E,M}(Q^2)$. The outer cyan band indicates an estimate of systematic uncertainty in the $x[c(x) - \bar{c}(x)]$ distribution obtained from a variation of the hadron scale κ_c by 5%.

Intrinsic charm-anticharm asymmetry in the proton

Sufian, T. Liu, Alexandru, Brodsky, GdT, Dosch, Draper, K. F. Liu and Y. B. Yang (2020)

Intrinsic charm in the proton introduced by Brodsky, Hoyer, Peterson and Sakai (1980)

Charm FF normalization computed with with three gauge ensembles in LGTH (one at the physical pion mass)

Intrinsic charm asymmetry $c(x) - \bar{c}(x)$,

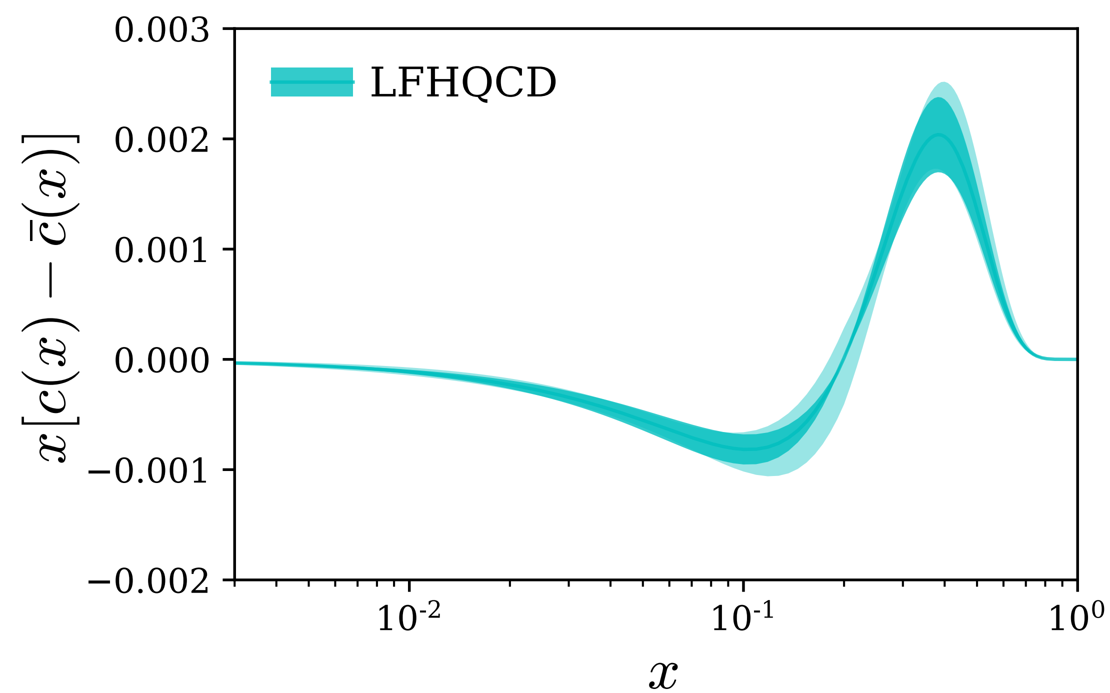
$$c(x) - \bar{c}(x) = \sum_{\tau} c_\tau \left(q_\tau(x) - q_{\tau+1}(x) \right)$$

with $\int_0^1 dx [c(x) - \bar{c}(x)] = 0$, from HLFQCD

J/Ψ Regge trajectory

$$\alpha(t)_{J/\Psi} = -2.066 + \frac{t}{4\lambda_c}, \quad \lambda_c = 0.874 \text{ GeV}^2$$

from HLFQCD and HQET

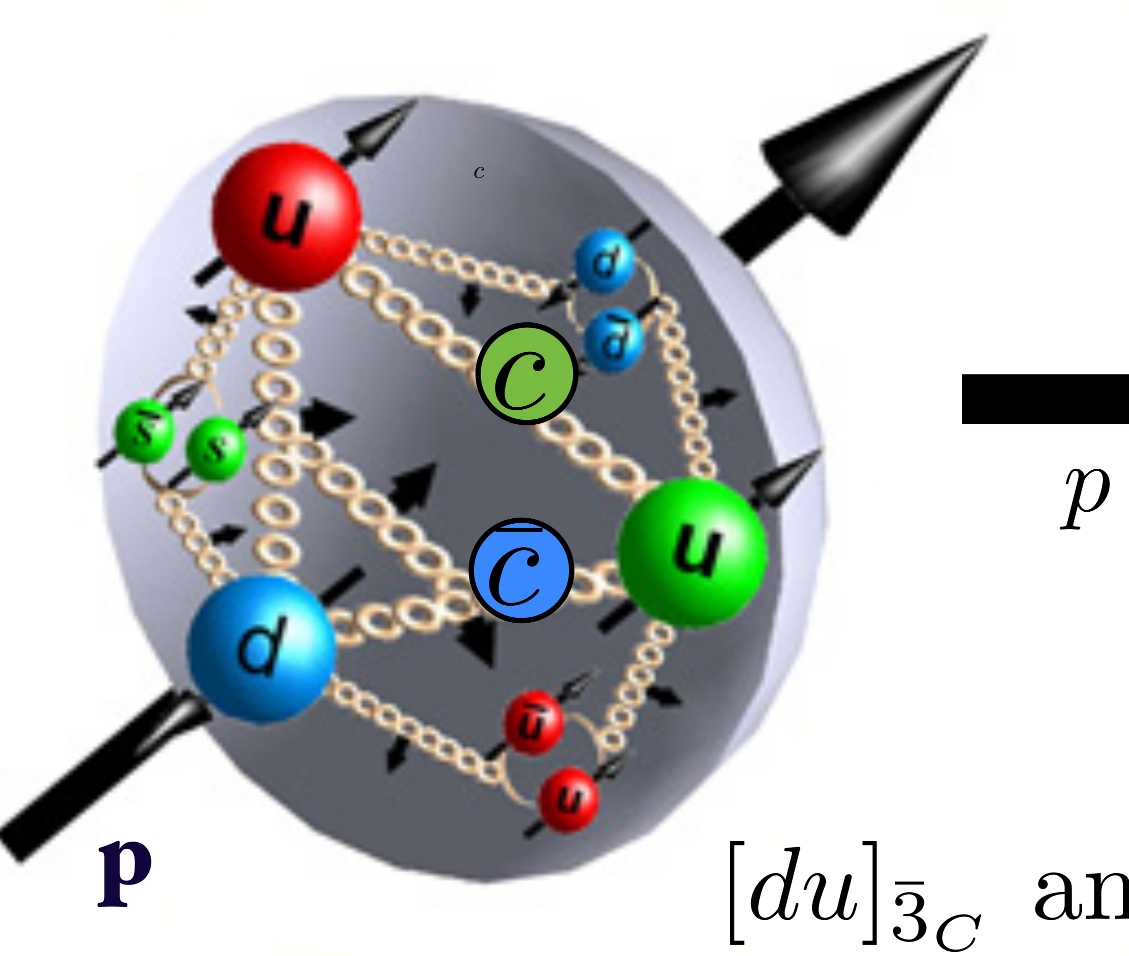


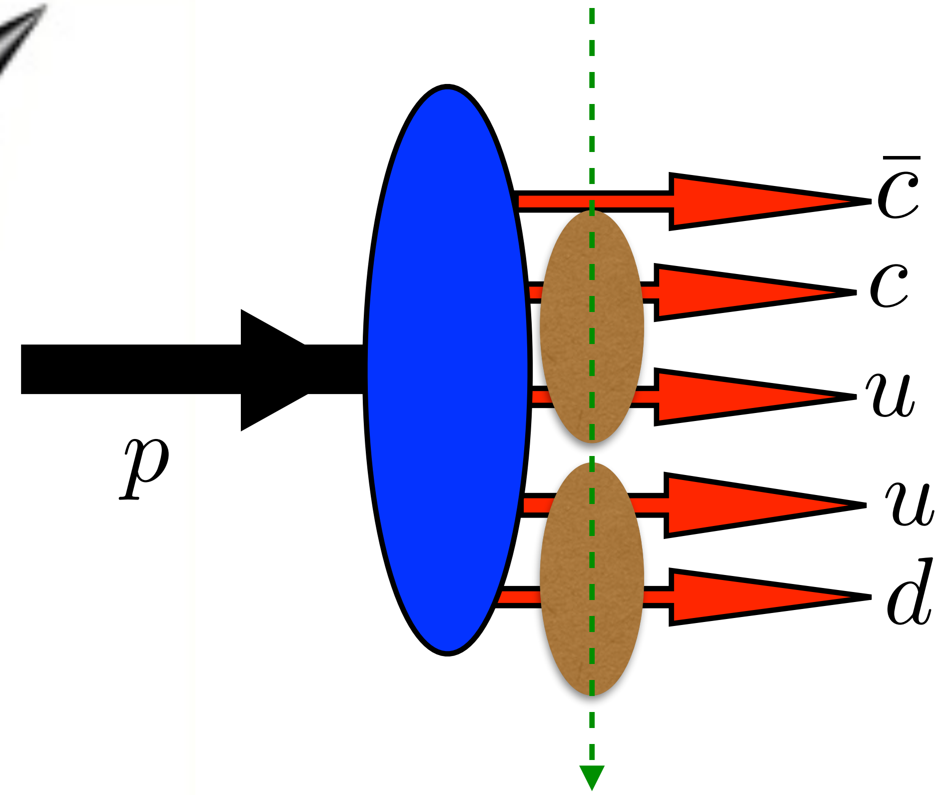
Nielsen, Brodsky, GdT, Dosch, Navarra and Zou (2018)

Color confinement potential from AdS/QCD

$$U(\zeta^2) = \kappa^4 \zeta^2, \zeta^2 = b_\perp^2 x(1-x)$$

Fixed $\tau = t + z/c$





Intrinsic Charm

$|\bar{c}[cu][ud]>$

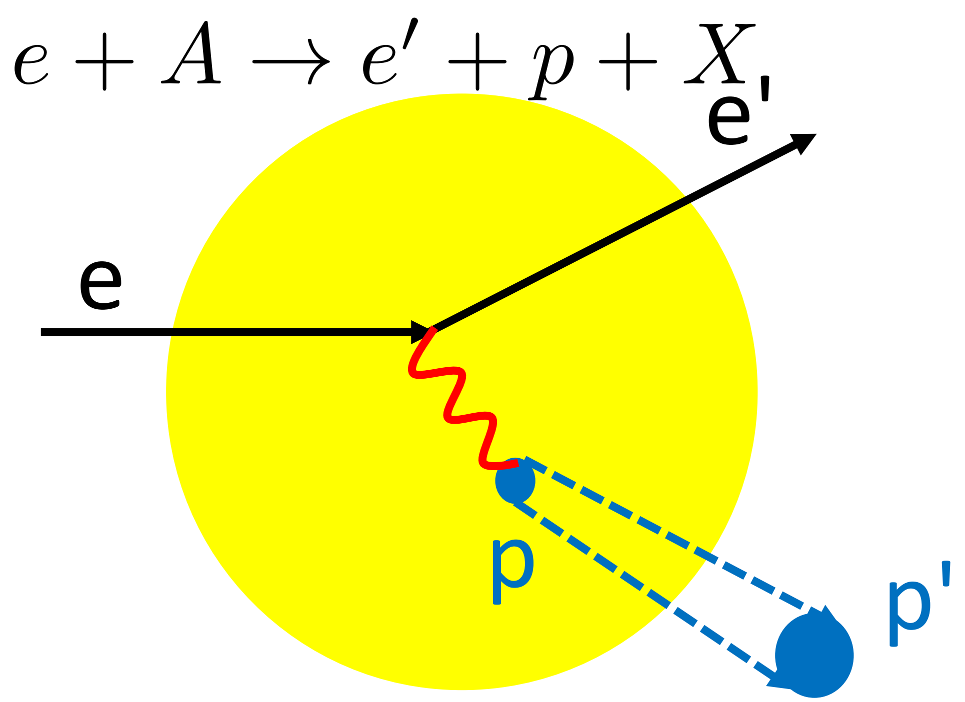
$[du]_{\bar{3}_C}$ and $[cu]_{\bar{3}_C}$ $J=0$ diquark dominance

$$\psi_n(\vec{k}_{\perp i}, x_i) \propto \frac{1}{\kappa^{n-1}} \, e^{-\mathcal{M}_n^2/2\kappa^2} \, \Pi_{j=1}^{n} \frac{1}{\sqrt{x_j}}$$

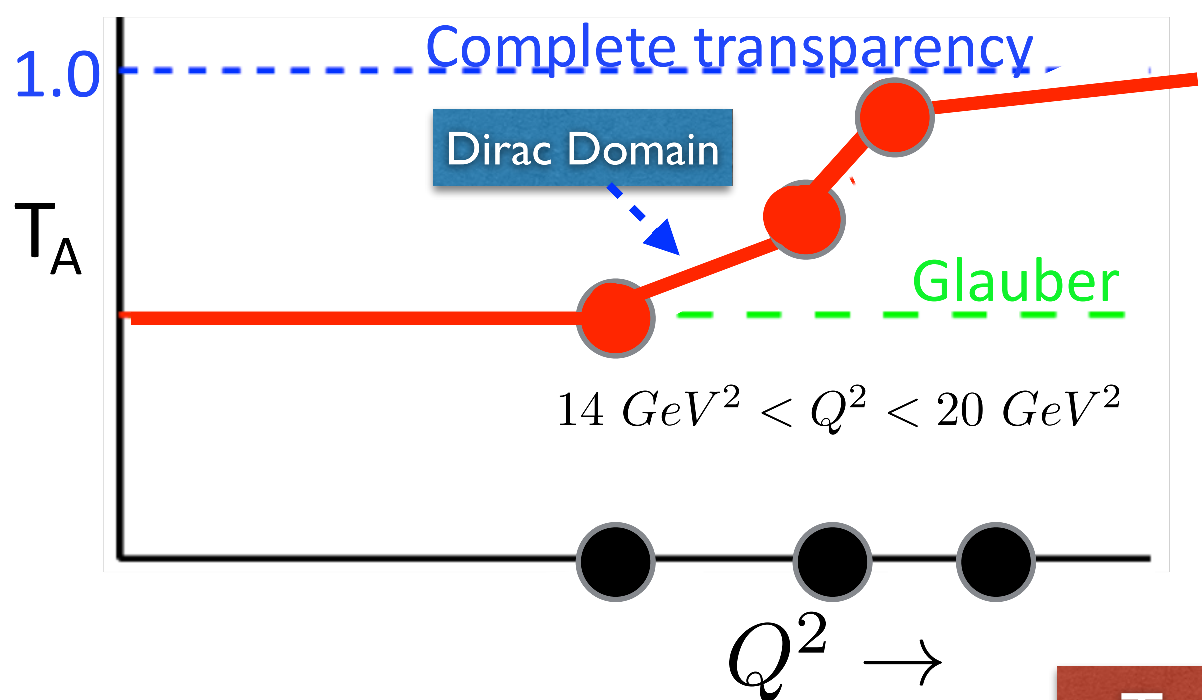
$$\mathcal{M}_n^2 = \sum_{i=1}^{n} \left(\frac{k_\perp^2 + m^2}{x}\right)_i$$

A.H. Mueller, sjb

Color transparency: fundamental prediction of QCD



- Not predicted by strongly interacting hadronic picture → arises in picture of quark-gluon interactions
- QCD: color field of singlet objects vanishes as size is reduced
- Signature is a rise in nuclear transparency, T_A, as a function of the momentum transfer, Q^2



$$T_A = \frac{\sigma_A}{A\,\sigma_N}$$
(nuclear cross section)
(free nucleon cross section)

G. de Teramond, sjb

Two-Stage Color Transparency for Proton

Drell-Yan-West Formula in Impact Space

$$F(q^2) = \sum_n \prod_{i=1}^{n} \int dx_i \int \frac{d^2\mathbf{k}_{\perp i}}{2(2\pi)^3} 16\pi^3 \, \delta\Big(1 - \sum_{j=1}^{n} x_j\Big) \, \delta^{(2)}\Big(\sum_{j=1}^{n} \mathbf{k}_{\perp j}\Big)$$

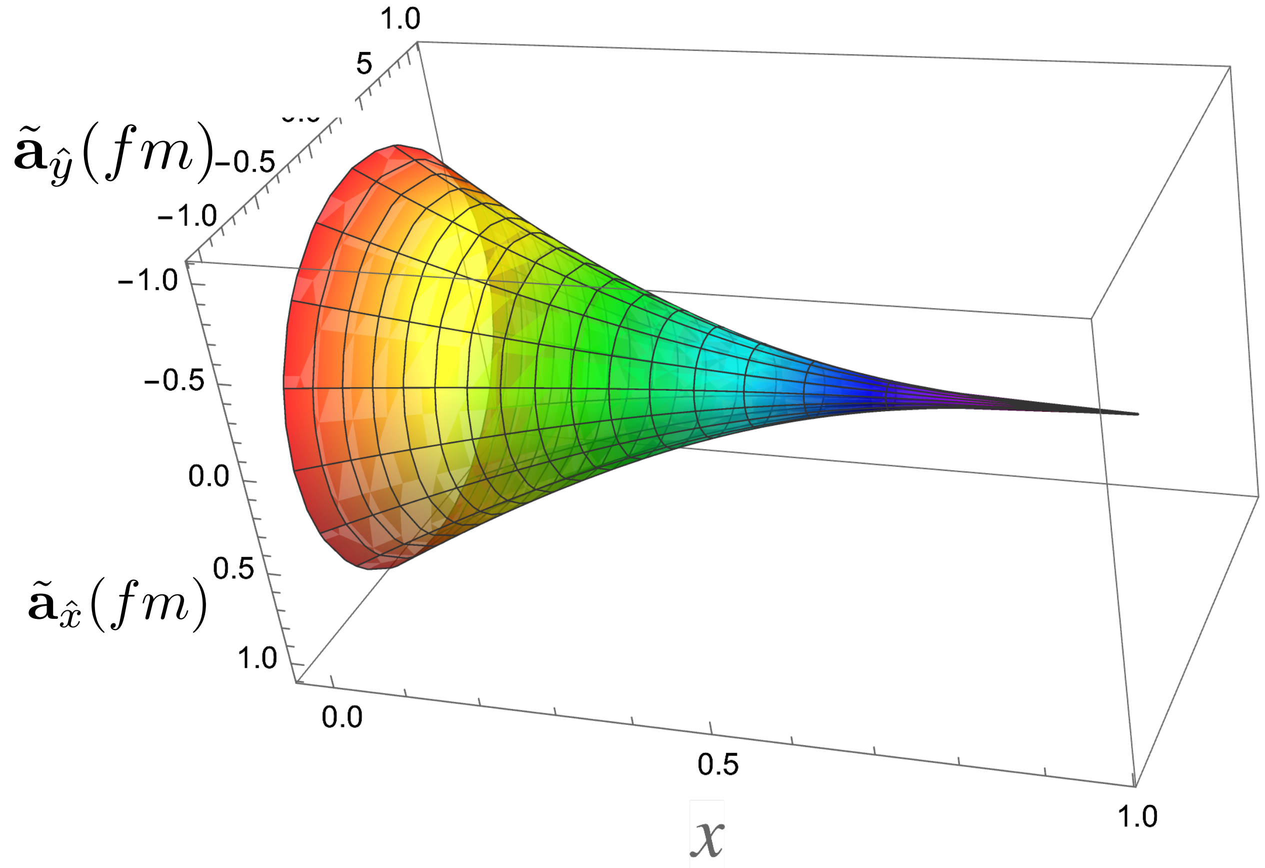
$$\sum_j e_j \psi_n^*(x_i, \mathbf{k}'_{\perp i}, \lambda_i) \psi_n(x_i, \mathbf{k}_{\perp i}, \lambda_i),$$

$$= \sum_n \prod_{j=1}^{n-1} \int dx_j \int d^2\mathbf{b}_{\perp j} \exp\Big(i\mathbf{q}_\perp \cdot \sum_{j=1}^{n-1} x_j \mathbf{b}_{\perp j}\Big) \left|\psi_n(x_j, \mathbf{b}_{\perp j})\right|^2$$

$$\textstyle\sum_{i=1}^{n} x_i = 1 \text{ and } \sum_{i=1}^{n} \mathbf{b}_{\perp i} = 0.$$

$$F(q^2) = \int_0^1 dx \int d^2\mathbf{a}_\perp e^{i\mathbf{a}_\perp \cdot \mathbf{q}_\perp} q(x, \mathbf{a}_\perp),$$

where $\mathbf{a}_\perp = \sum_{j=1}^{n-1} x_j \mathbf{b}_{\perp j}$ is the x-weighted transverse position coordinate of the $n-1$ spectators.



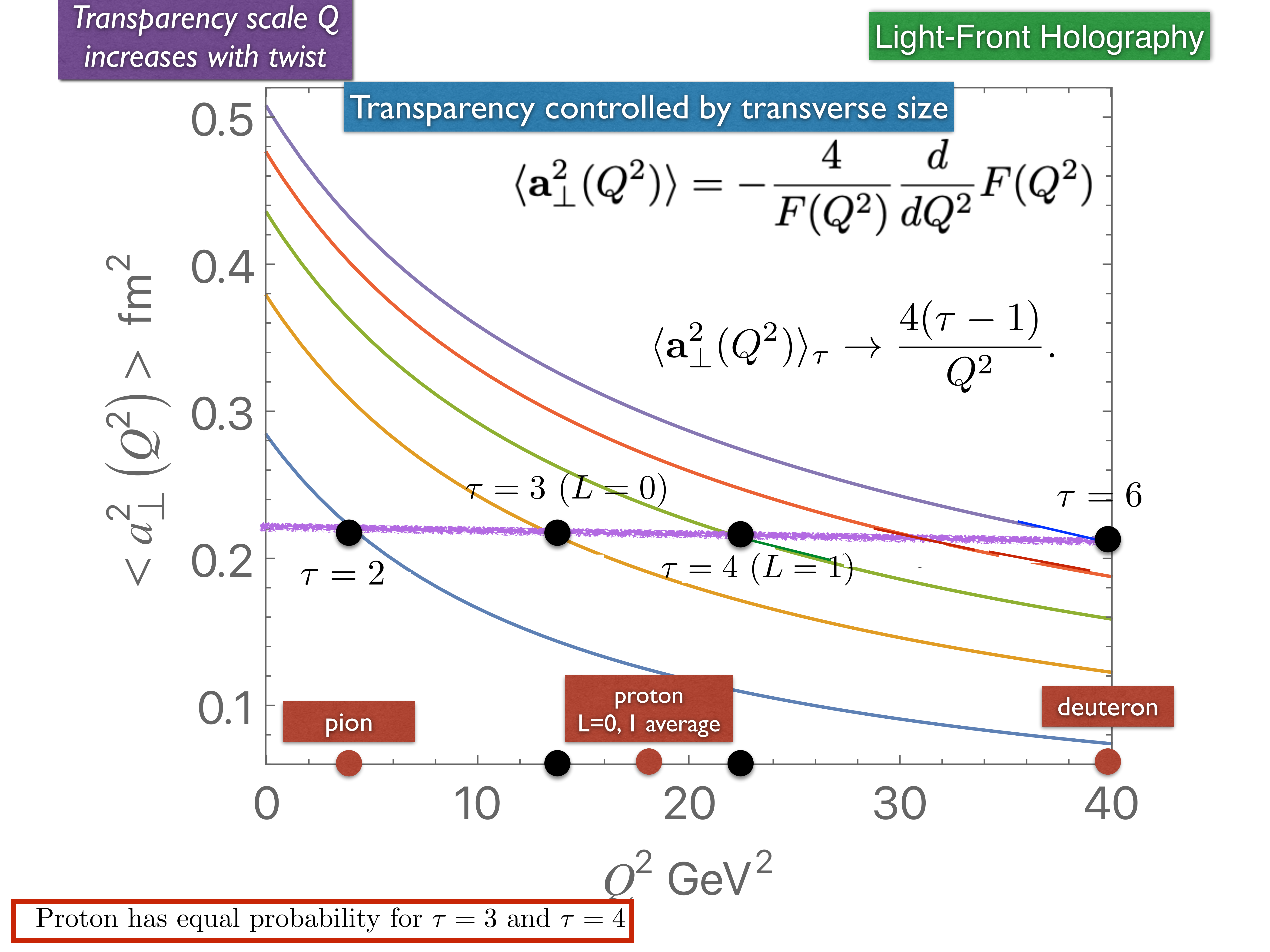
$$< \tilde{\mathbf{a}}_\perp^2(x) >= \frac{\int d^2\mathbf{a}_\perp \mathbf{a}_\perp^2 \, q(x,\mathbf{a}_\perp)}{\int d^2\mathbf{a}_\perp \, q(x,\mathbf{a}_\perp)}$$

At large light-front momentum fraction x, and equivalently at large values of Q^2, the transverse size of a hadron behaves as a point-like color-singlet object. This behavior is the origin of color transparency in nuclei.

Although the dependence of the transverse impact area as a function of x is universal, the behavior in Q^2 depends on properties of the hadron, such as its twist.

$$\langle \mathbf{a}_\perp^2(Q^2) \rangle_\tau \to \frac{4(\tau - 1)}{Q^2}.$$

Mean transverse size as a function of Q and Twist


Transparency scale Q increases with twist
Light-Front Holography
Transparency controlled by transverse size
$$\langle \mathbf{a}_\perp^2(Q^2)\rangle = -\frac{4}{F(Q^2)}\frac{d}{dQ^2}F(Q^2)$$
$$\langle \mathbf{a}_\perp^2(Q^2)\rangle_\tau \rightarrow \frac{4(\tau-1)}{Q^2}.$$
$\tau = 3\ (L=0)$
$\tau = 6$
$\tau = 2$
$\tau = 4\ (L=1)$
$< a_\perp^2(Q^2) >$ fm^2
0.5
0.4
0.3
0.2
0.1
pion
proton L=0, 1 average
deuteron
0
10
20
30
40
Q^2 GeV^2
Proton has equal probability for $\tau = 3$ and $\tau = 4$

$F(q^2) =$

G. de Teramond, sjb

$$\sum_n \prod_{j=1}^{n-1} \int dx_j \int d^2\mathbf{b}_{\perp j} \exp\left(i\mathbf{q}_\perp \cdot \sum_{j=1}^{n-1} x_j \mathbf{b}_{\perp j}\right) |\psi_n(x_j, \mathbf{b}_{\perp j})|^2$$

$$\sum_i x_i = 1$$

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

$$\vec{a}_\perp^2(Q^2) = -4 \frac{\frac{d}{dQ^2} F(Q^2)}{F(Q^2)}$$

Proton radius squared at $Q^2 = 0$

Color Transparency is controlled by the transverse-spatial size $\vec{a}_\perp^2$ and its dependence on the momentum transfer $Q^2 = -t$:

The scale Q^2_τ required for Color Transparency grows with twist τ

Light-Front Holography:

$$\langle \mathbf{a}_\perp^2(t) \rangle_\tau = \frac{1}{\lambda} \sum_{j=1}^{\tau-1} \frac{1}{j - \alpha(t)},$$

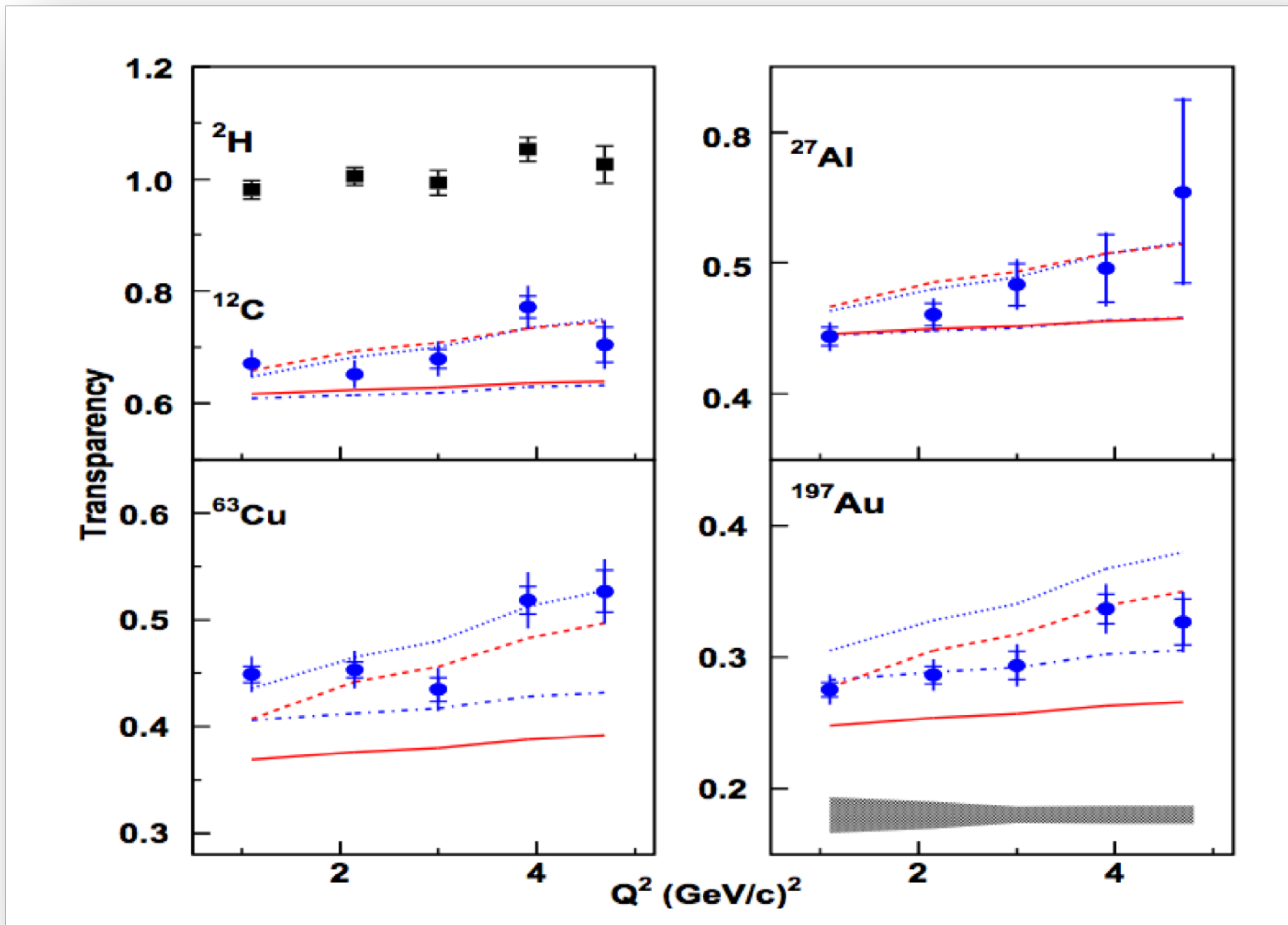
For large Q2 :

$$\langle \mathbf{a}_\perp^2(Q^2) \rangle_\tau \to \frac{4(\tau - 1)}{Q^2}.$$

Color Transparency verified for π^+ and ρ electroproduction

Hall C E01-107 pion electro-production

$A(e,e'\pi^+)$

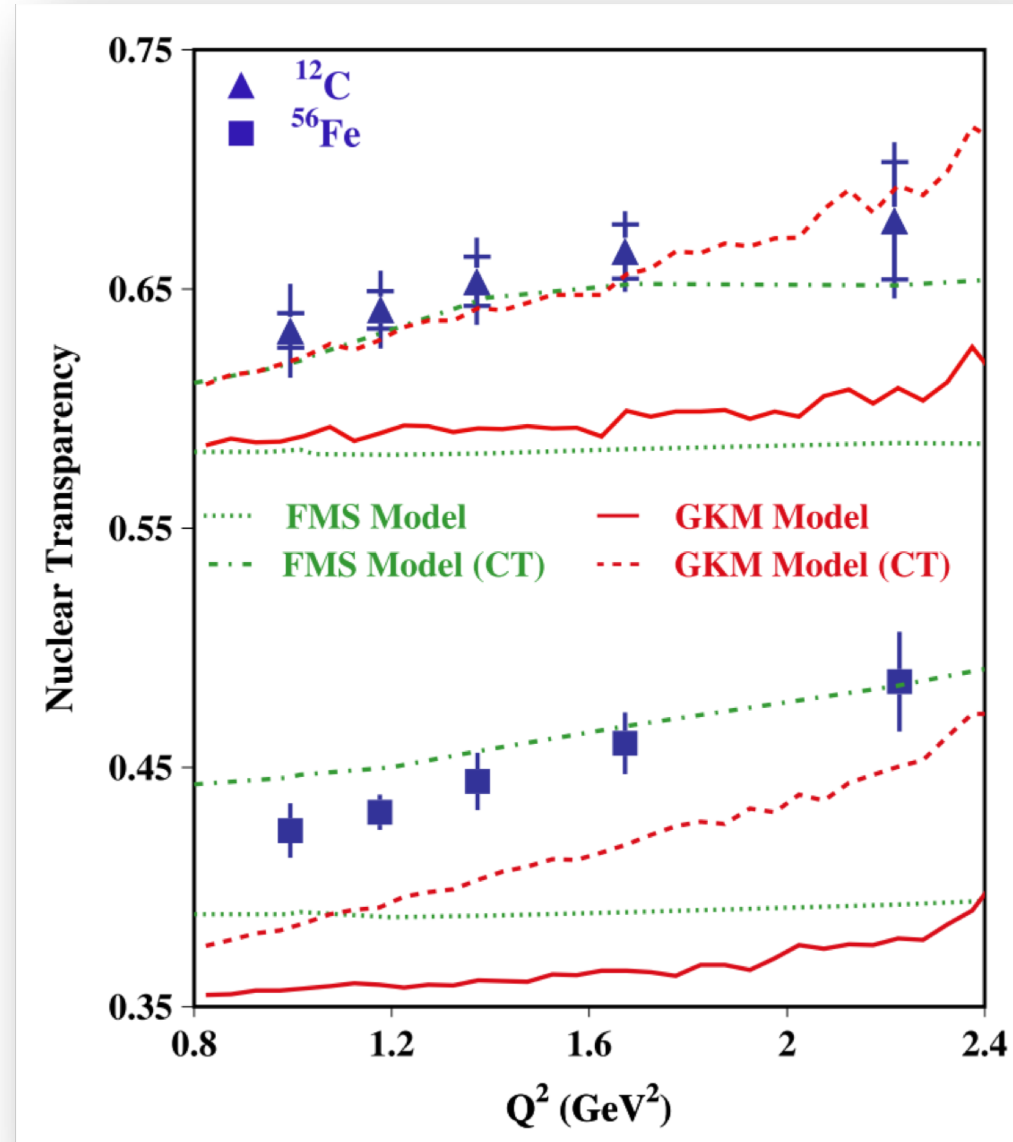


B.Clasie *et al.* PRL 99:242502 (2007)

X. Qian *et al.* PRC81:055209 (2010)

CLAS E02-110 rho electro-production

$A(e,e'\rho^0)$



L. El Fassi *et al.* PLB 712,326 (2012)

$$T_A = \frac{\frac{d\sigma}{dQ^2}(pA \to \pi^+ X)}{\frac{d\sigma}{dQ^2}(pp \to \pi^+ X)}$$

$$T_A = \frac{\frac{d\sigma}{dQ^2}(pA \to \rho^0 X)}{\frac{d\sigma}{dQ^2}(pp \to \rho^0 X)}$$

Two-Stage Color Transparency

$$14\ GeV^2 < Q^2 < 20\ GeV^2$$

If Q^2 is in the intermediate range, then the twist-3 state will propagate through the nuclear medium with minimal absorption, and the protons which survive nuclear absorption will only have L = 0 (twist-3).

The twist-4 L = 1 state which has a larger transverse size will be absorbed.

Thus 50% of the events in this range of Q^2 will have full color transparency and 50% of the events will have zero color transparency (T = 0).

The $ep \to e'p'$ cross section will have the same angular and Q^2 dependence as scattering of the electron on an unphysical proton which has no Pauli form factor.

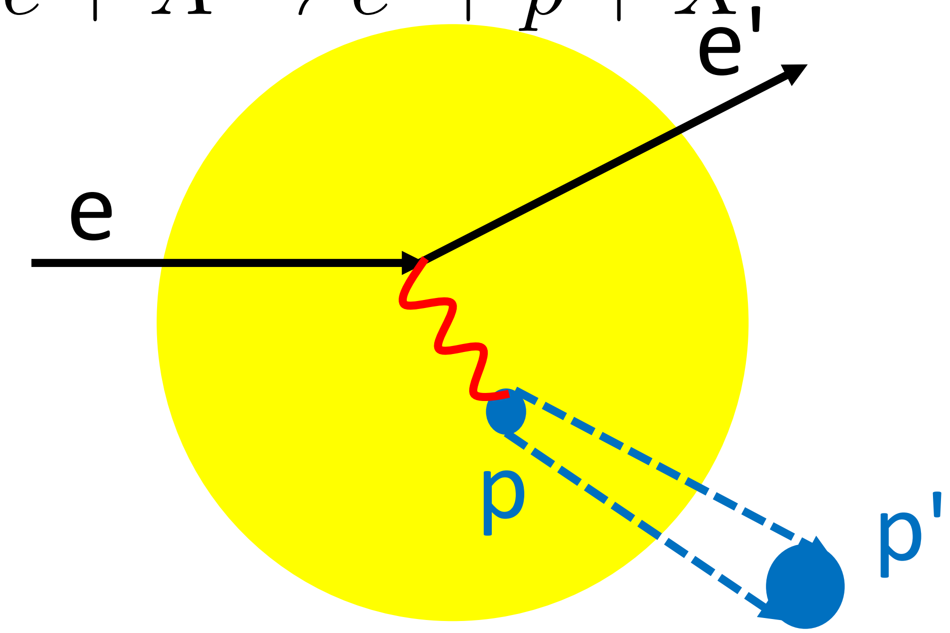
$$Q^2 > 20\ GeV^2$$

However, if the momentum transfer is increased to $Q^2 > 20\ GeV^2$, all events will have full color transparency, and the $ep \to e'p'$ cross section will have the same angular and Q^2 dependence as scattering of the electron on a physical proton eigenstate, with both Dirac and Pauli form factor components.

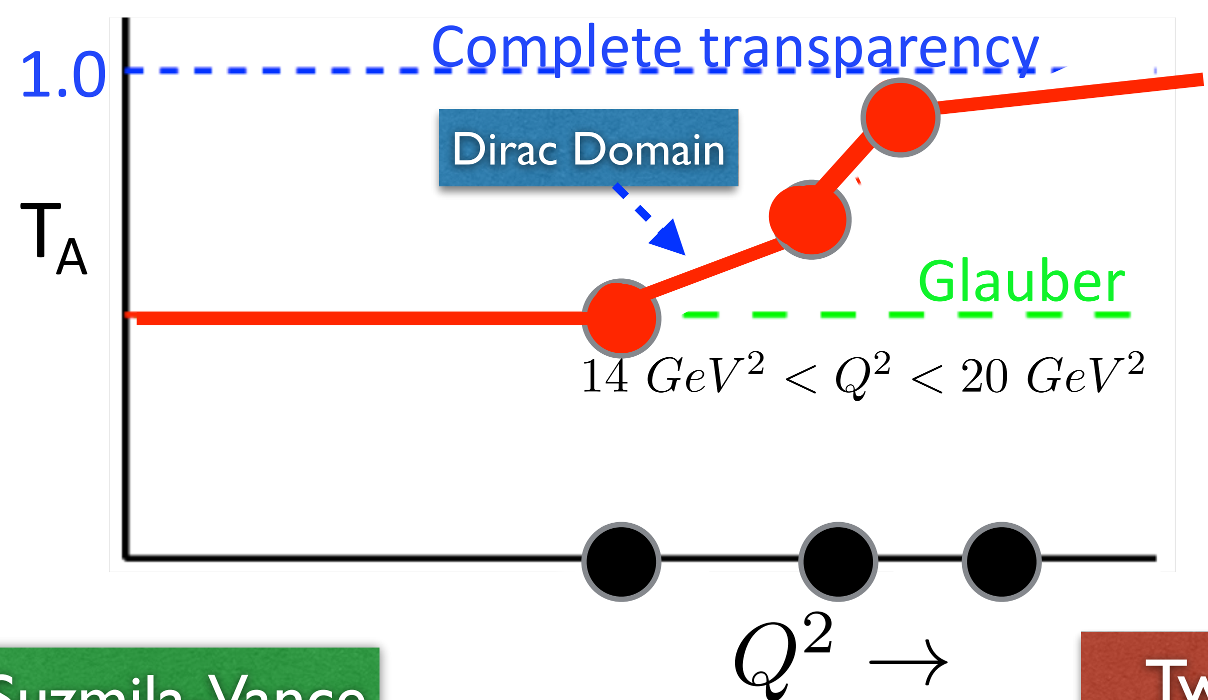
A.H. Mueller, sjb

Color transparency fundamental prediction of QCD

$$e + A \to e' + p + X$$



- Not predicted by strongly interacting hadronic picture → arises in picture of quark-gluon interactions
- QCD: color field of singlet objects vanishes as size is reduced
- Signature is a rise in nuclear transparency, T_A, as a function of the momentum transfer, Q^2



$$T_A = \frac{\sigma_A}{A\ \sigma_N}$$ (nuclear cross section) / (free nucleon cross section)

Holly Suzmila-Vance

Two-Stage Color Transparency for Proton

Color Transparency and Light-Front Holography

- Essential prediction of QCD
- LF Holography: Spectroscopy, dynamics, structure
- Transverse size predicted by LF Holography as a function of Q
- Q scale for CT increases with twist, number of constituents
- Two-Stage Proton Transparency: Equal probability L=0,1
- No contradiction with present experiments

$$Q_0^2(p) \simeq 18\ GeV^2 \text{ vs. } Q_0^2(\pi) \simeq 4\ GeV^2 \text{ for onset of color transparency in } {}^{12}C$$

Feynman domain also incorporated

Other Consequences of $[ud]_{\bar{3}_C, I=0, J=0}$ diquark cluster

QCD Hidden-Color Hexadiquark in the Core of Nuclei

J. Rittenhouse West, G. de Te'ramond, A. S. Goldhaber, I. Schmidt, sjb

$$|\Psi_{HDQ} >= |[ud][ud][ud][ud][ud][ud] >$$
mixes with
$$^4He|npnp >$$

Increases alpha binding energy, EMC effects

Diquarks Can Dominate Five-Quark Fock State of Proton

$$|p >= \alpha|[ud]u > + \beta|[ud][ud]\bar{d} >$$

Natural explanation why $\bar{d}(x) >> \bar{u}(x)$ in proton

Excitations and Decay of HdQ in Alpha-Nuclei
may explain ATOMKI X17 signal

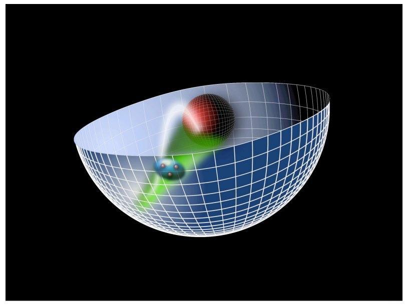
V. Kubarovsky, J. Rittenhouse West, sjb

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*

- *Light-Front Holography: AdS_5 = LF (3+1)*



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

- *Introduce mass scale* **κ** *while retaining conformal invariance of the Action (dAFF)*

"Emergent Mass"

- *Unique Dilaton in AdS_5:* $e^{+\kappa^2 z^2}$

- *Unique color-confining LF Potential* $U(\zeta^2) = \kappa^4 \zeta^2$

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

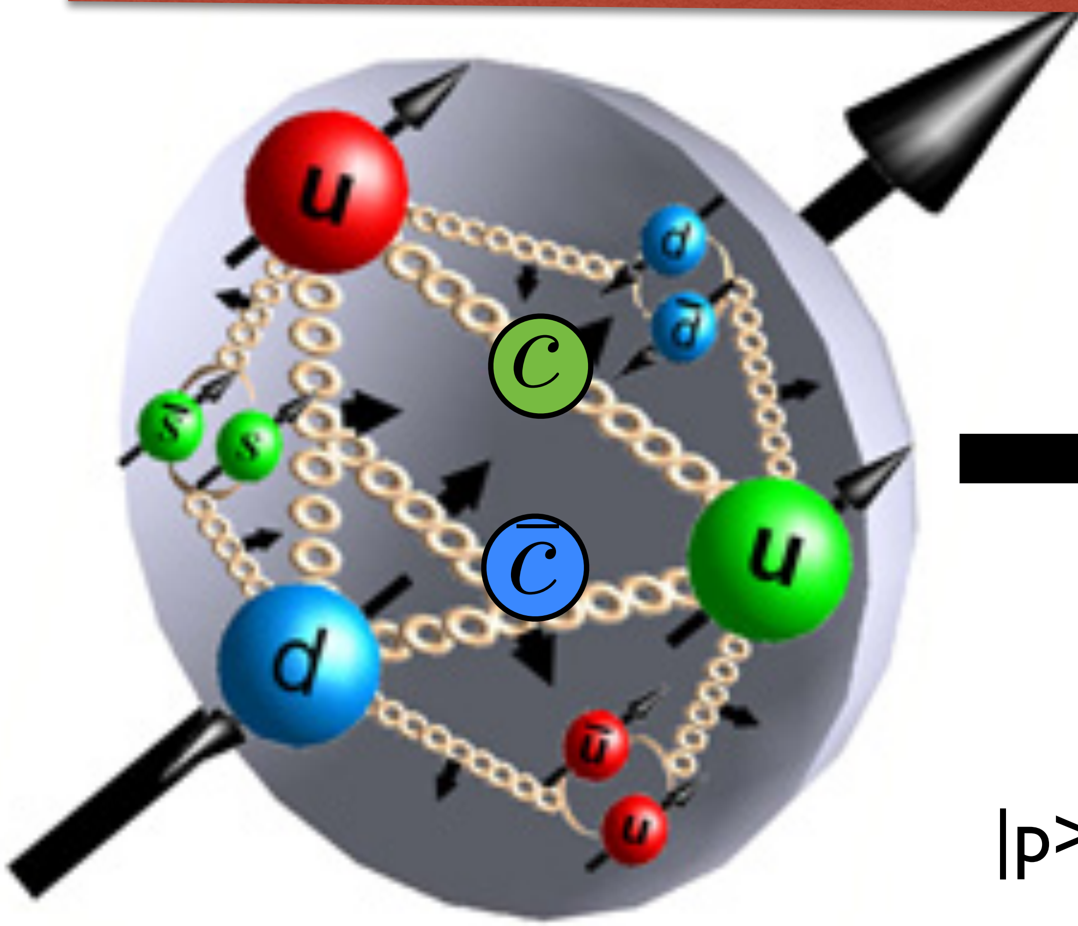
$$\text{Meson } q\bar{q} \leftrightarrow \text{Baryon } q[qq] \leftrightarrow \text{Tetraquark } [qq][\bar{q}\bar{q}]$$

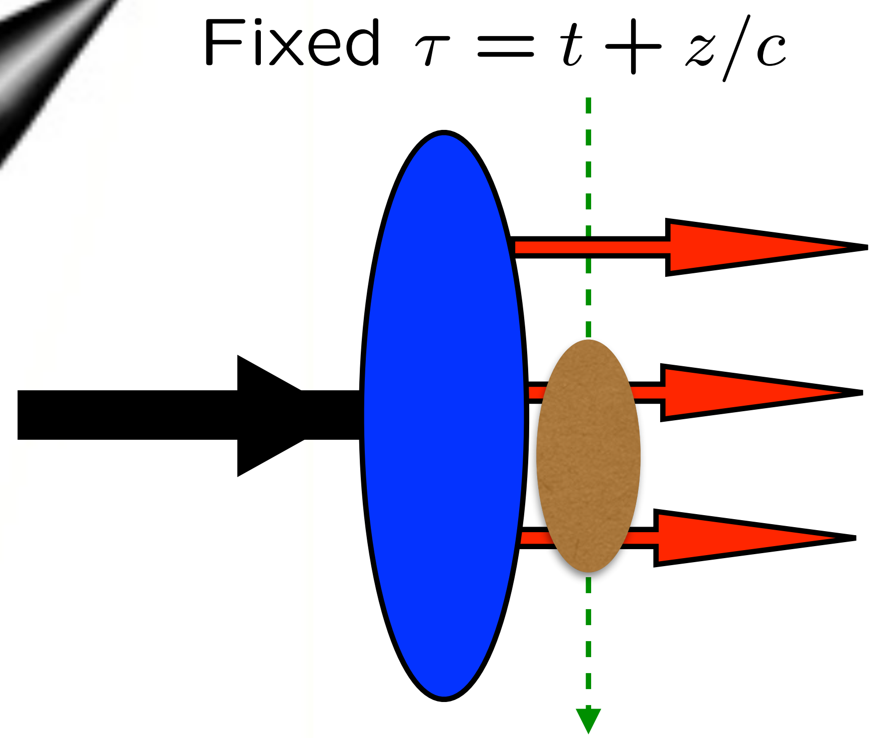
Light-Front Holography: First Approximation to QCD

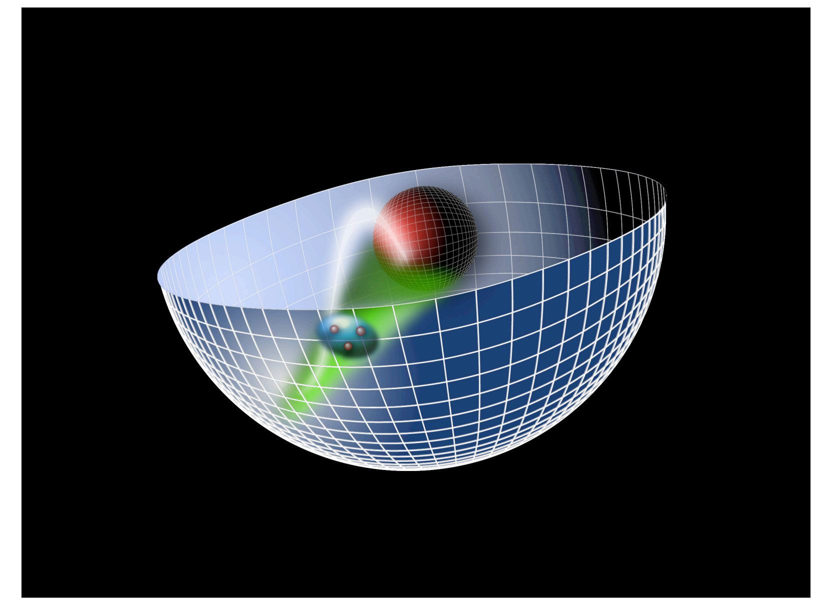
- **Color Confinement, Analytic form of confinement potential**
- **Retains underlying conformal properties of QCD despite mass scale (DeAlfaro-Fubini-Furlan Principle)**
- **Massless quark-antiquark pion bound state in chiral limit, GMOR**
- **QCD coupling at all scales**
- **Connection of perturbative and nonperturbative mass scales**
- **Poincarè Invariant, Frame Independent, Causal**
- **Hadron Spectroscopy-Regge Trajectories with universal slopes in n, L**
- **Incorporates features of Veneziano model**
- **Supersymmetric 4-Plet: Meson-Baryon -Tetraquark Symmetry**
- **Light-Front Wavefunctions**
- **Form Factors, Structure Functions, Hadronic Observables**
- **OPE: Constituent Counting Rules**
- **Hadronization at the Amplitude Level: Many Phenomenological Tests**
- **Systematically improvable: Basis LF Quantization (BLFQ)**

Supersymmetric Features of Hadron Physics from Superconformal Algebra and Light-Front Holography

Light-Front Holographic QCD: A Novel Nonperturbative Approach to Color Confinement, Hadron Spectroscopy, and Dynamics







|p>=|u[ud]> quark-diquark cluster

with Guy de Tèramond, Hans Günter Dosch, Alexandre Deur, Raza Sabbir Sufian, Cedric Lorcè, Tianbo Liu, Jennifer Rittenhouse West, and Marina Nielsen

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