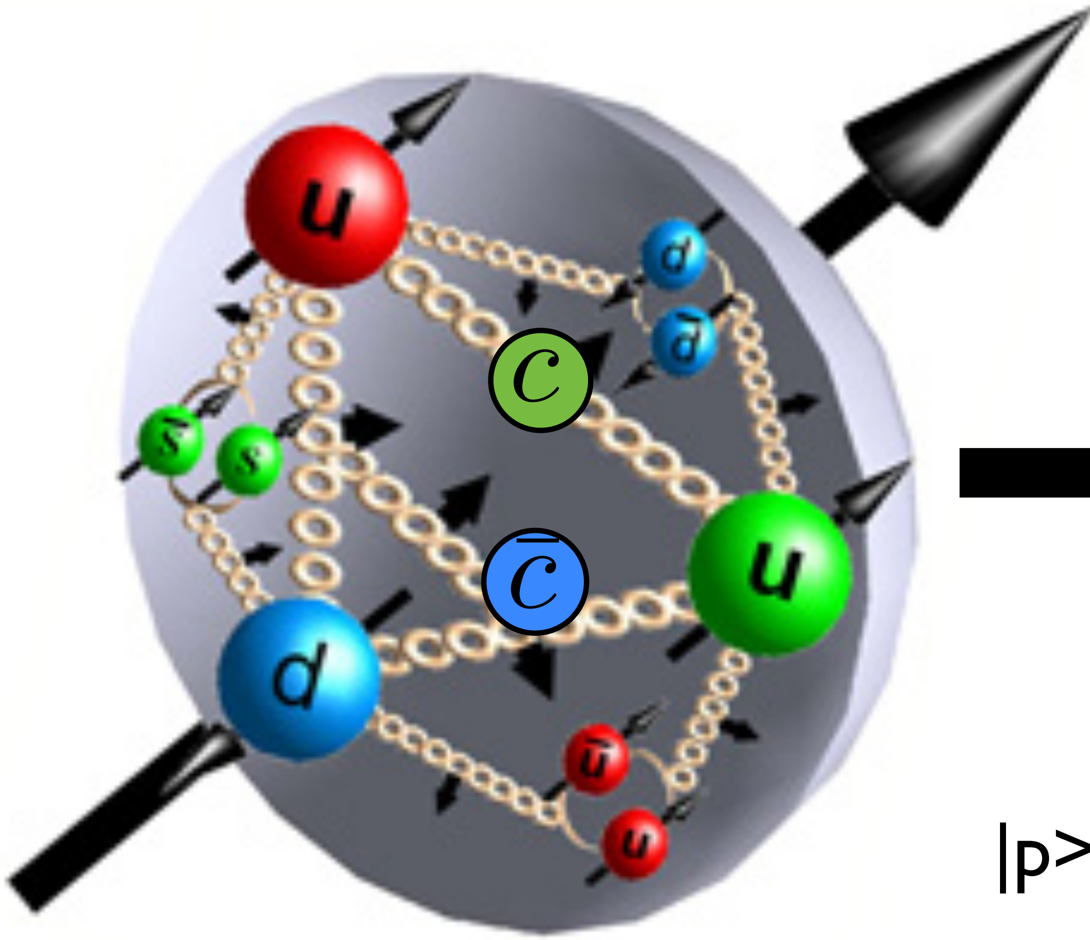
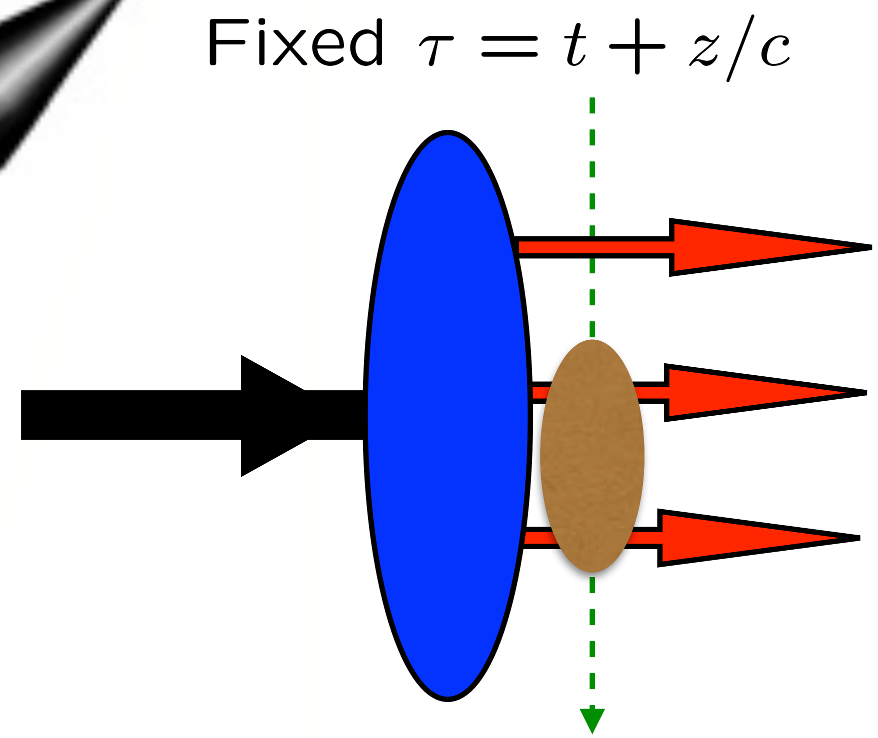
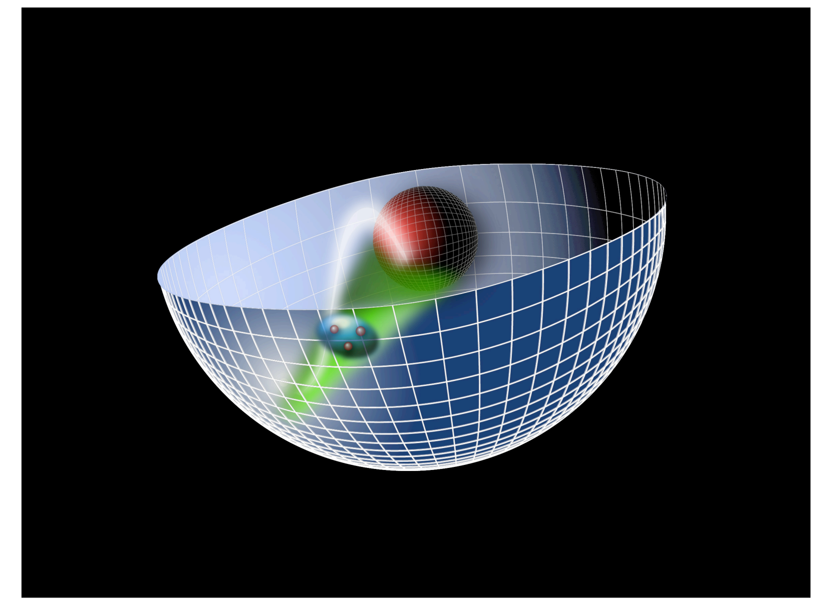
New Perspectives for Hadron Spectroscopy and Dynamics and the Running QCD Coupling from Color-Confining Holographic Light-Front QCD





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



with Guy de Tèramond, Hans Günter Dosch, Cèdric Lorcè, Alexandre Deur, and Joshua Erlich

A.N. Mitra Memorial Symposium April 15, 2025

Stan Brodsky

SLAC NATIONAL ACCELERATOR LABORATORY

A.N. Mitra

QCD at the amplitude level
Factorization Theorems,
Counting Rules,
Light-Front Theory
Nuclear Amplitudes

Spin dynamics of qqq wave function on light front in high momentum limit of QCD: Role of qqq force

A.N. Mitra

Annals Phys. 323 (2008) 845-865

Meson-Baryon Couplings in a Quark Mod

A.N. Mitra
Delhi U.
,
Marc Ross
Michigan U.

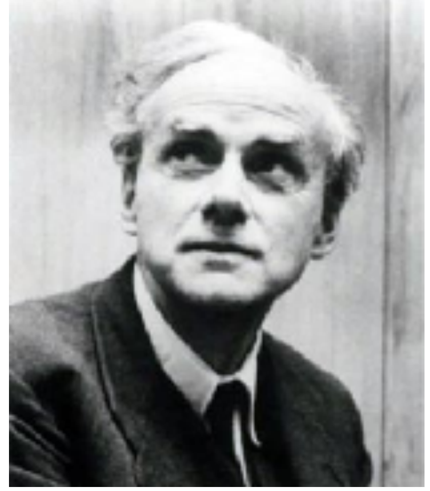
Published in:
Phys.Rev. 158 (1967) 1630-1638

Relativistic Form-Factors for Clusters with Nonrelativistic Wave Functions

Asoke N. Mitra
SLAC
,
Indra Kumari
Delhi U.

Phys.Rev.D 15 (1977) 261

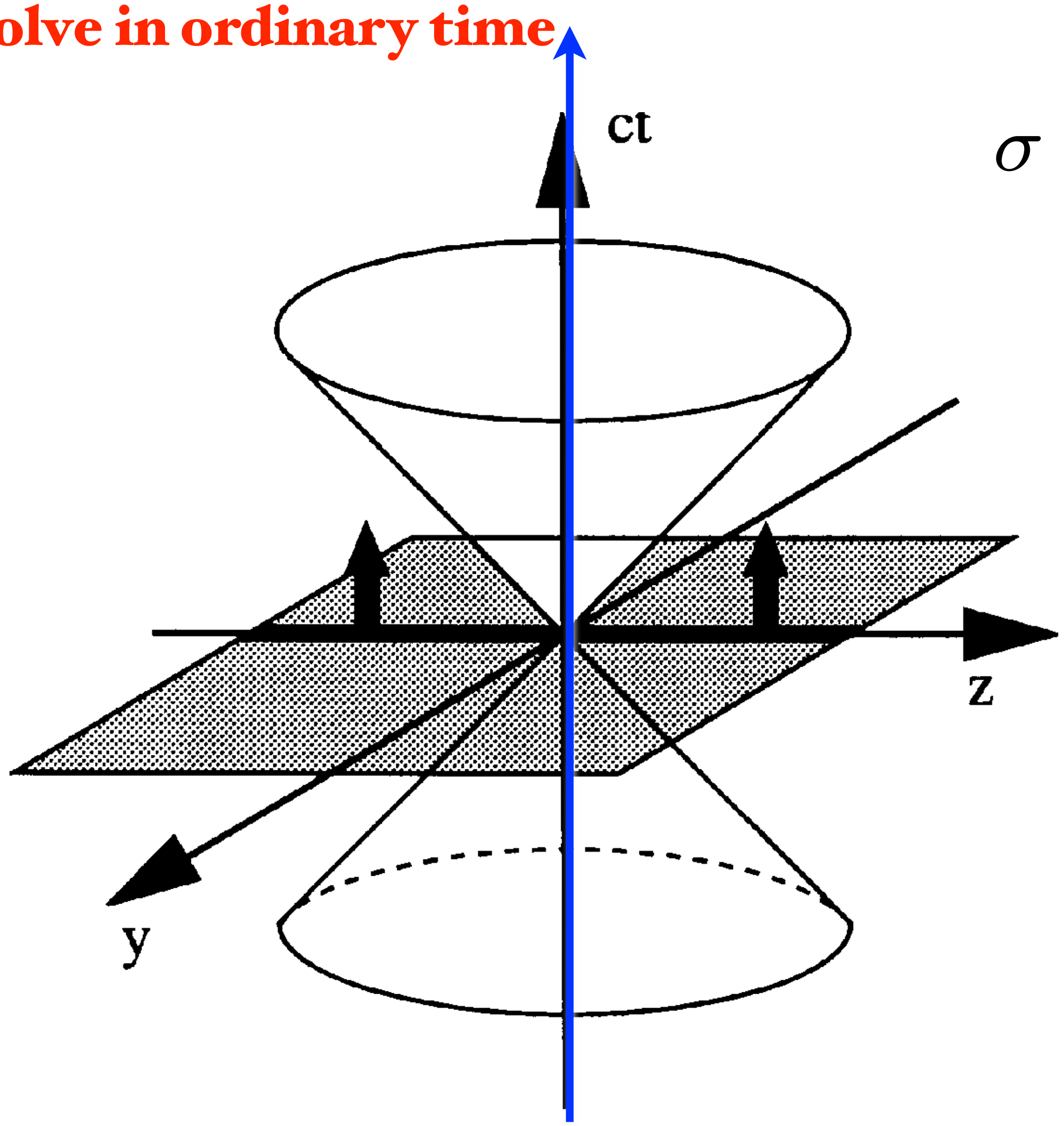
Light-Front Quantization



P.A.M Dirac, Rev. Mod. Phys. 21, 392 (1949)

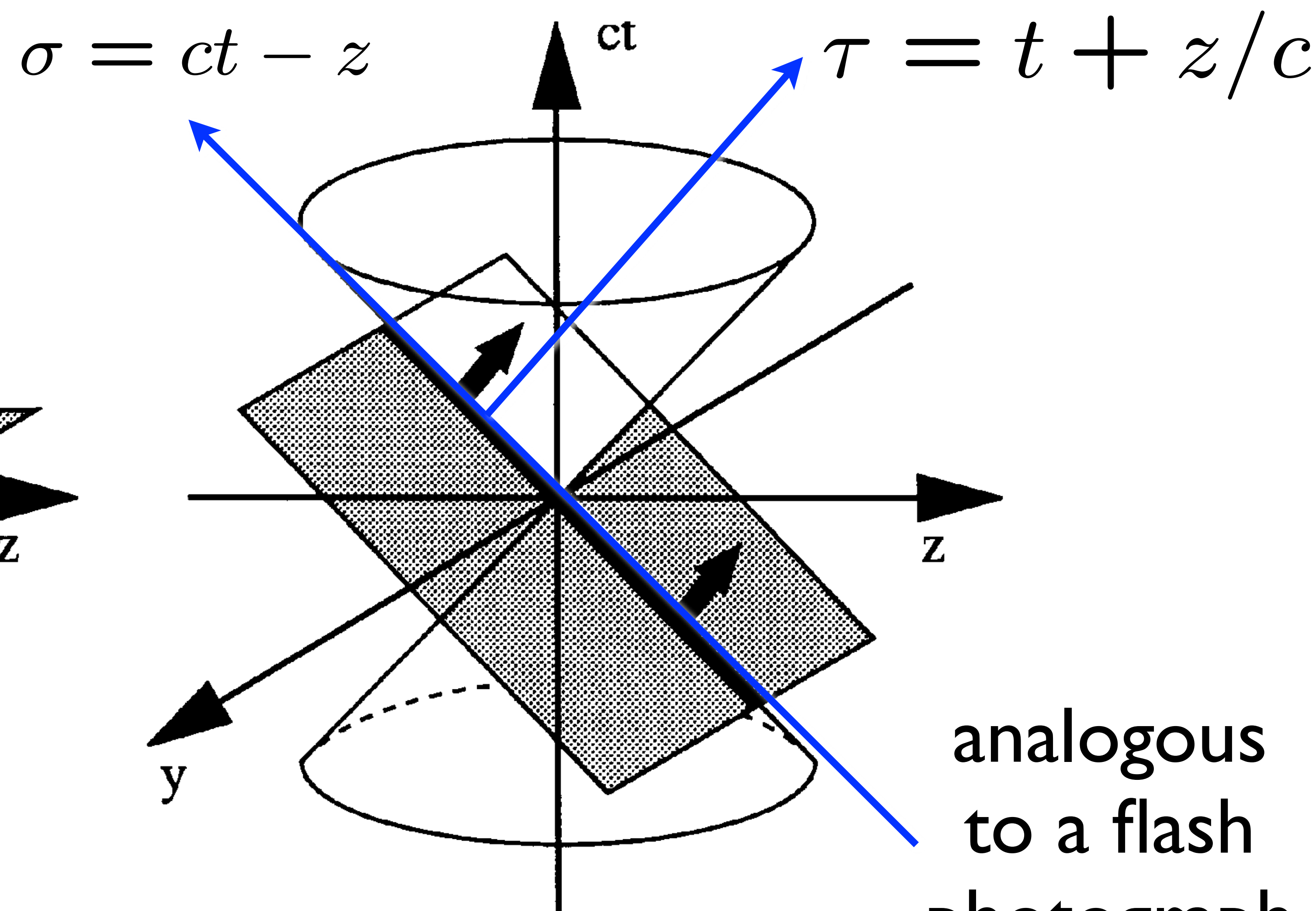
Dirac's Amazing Idea:
The "Front Form"

Evolve in ordinary time



Instant Form

Evolve in light-front time!



Front Form

analogous to a flash photograph

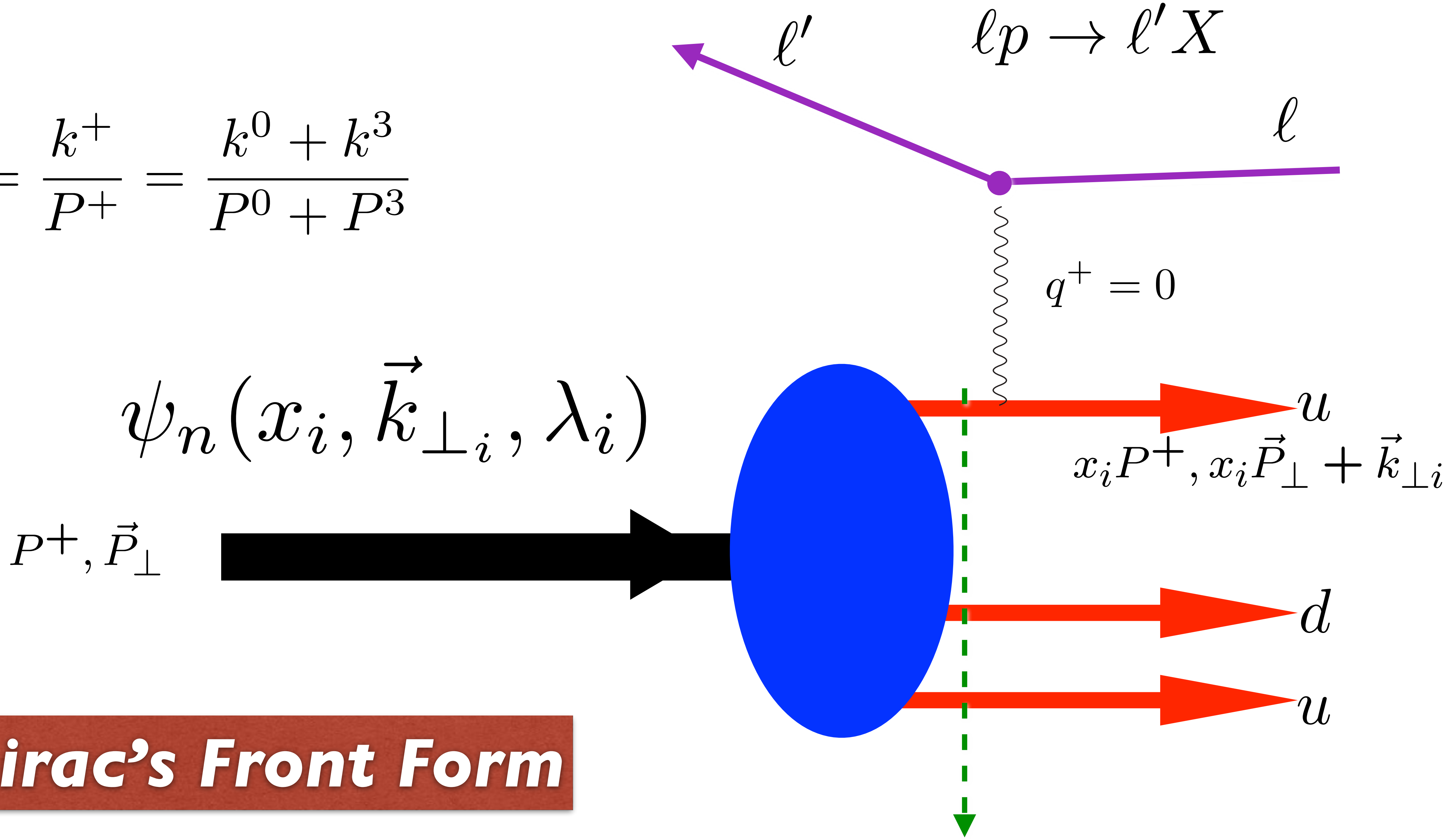
Causal, Boost Invariant!

Comparing light-front quantization with instant-time quantization
Philip D. Mannheim(Connecticut U.),
Peter Lowdon(Ecole Polytechnique, CPHT),
Stanley J. Brodsky(SLAC)

- e-Print: 2005.00109 [hep-ph]

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

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



Dirac's Front Form

Measurements of hadron LF wavefunction are at fixed LF time

Fixed $\tau = t + z/c$

Like a flash photograph

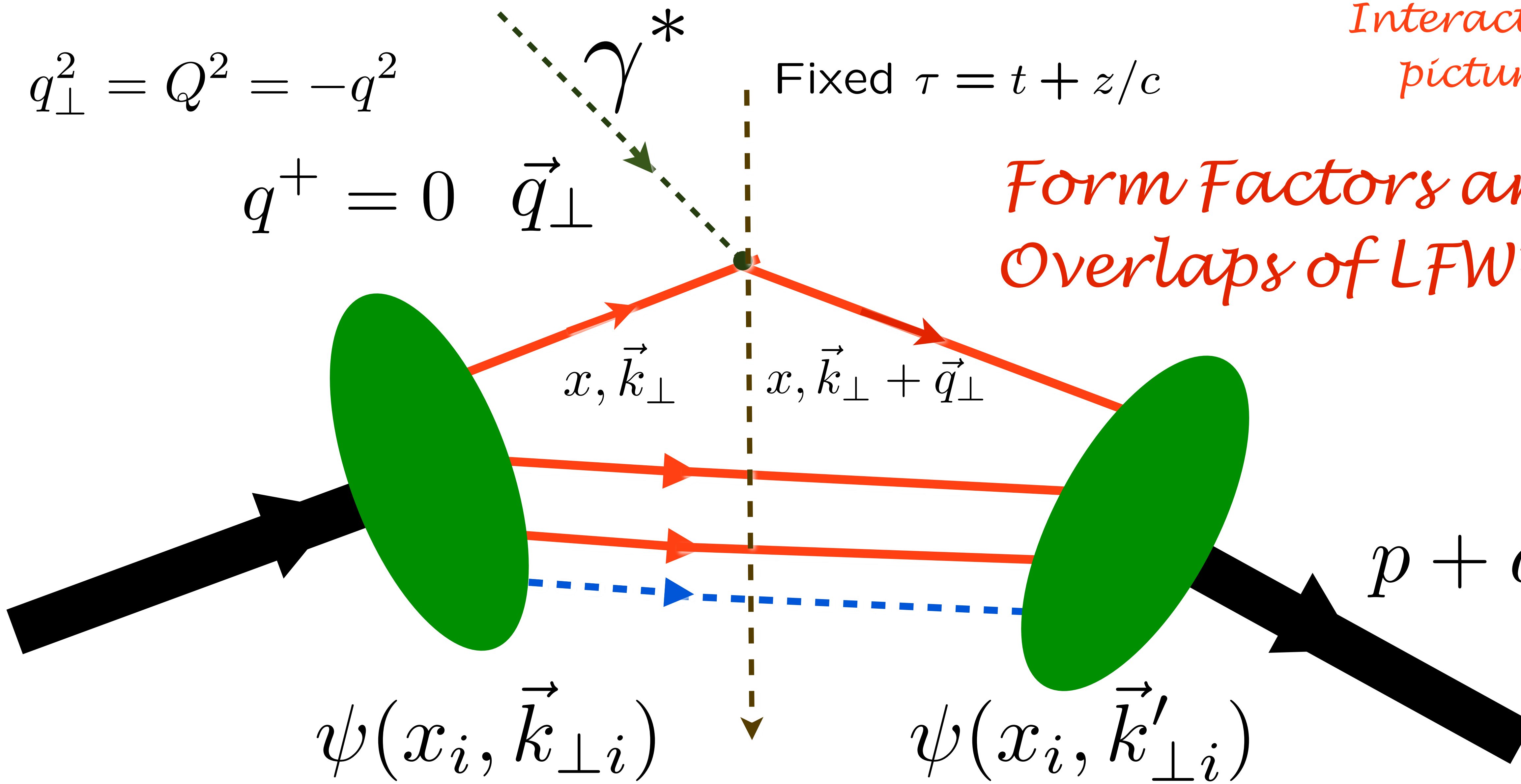
$$x_{bj} = x = \frac{k^+}{P^+}$$

Invariant under boosts! Independent of P^μ

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

Front Form

Interaction picture



Form Factors are Overlaps of LFWFs

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

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

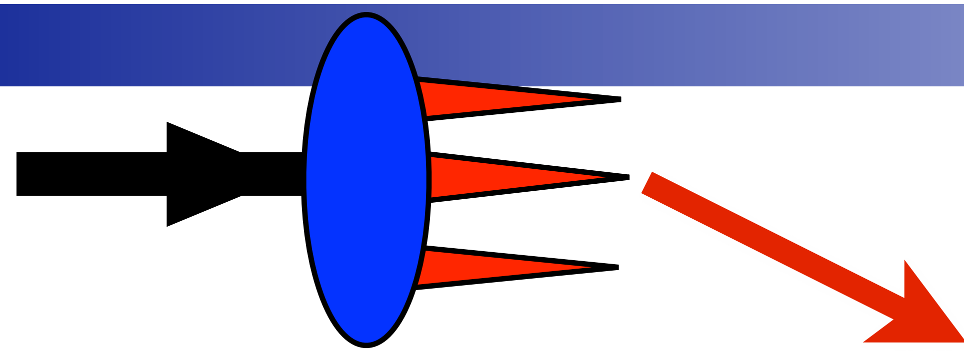
Drell &Yan, West
Exact LF formula!

Drell, sjb

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

Light-Front Wavefunctions underly hadronic observables

Lorce, Pasquini



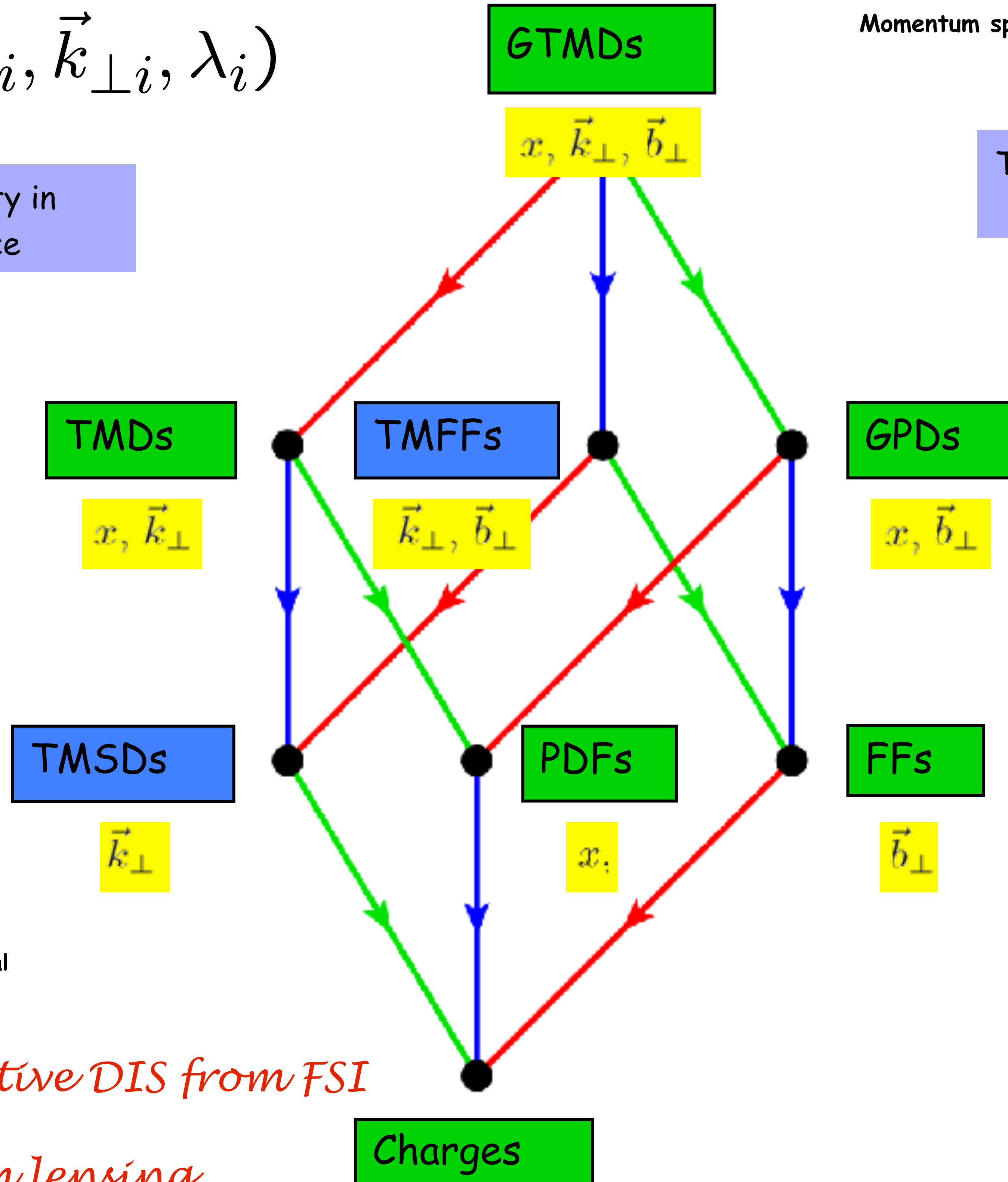
$$\Psi_n(x_i, \vec{k}_{\perp i}, \lambda_i)$$

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

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

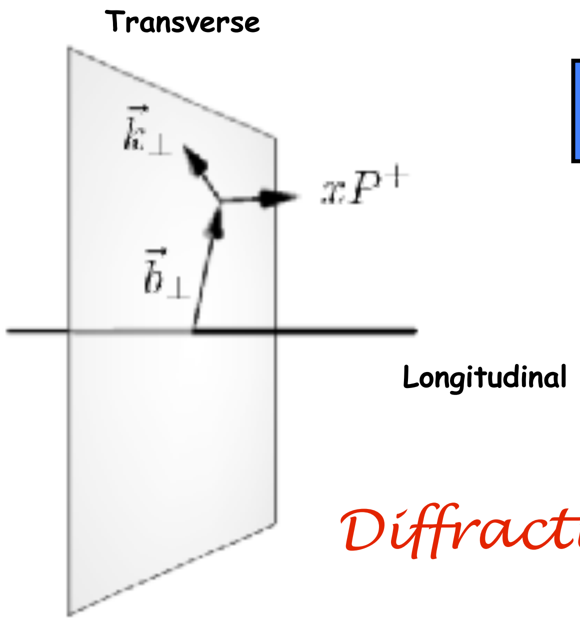
Transverse density in momentum space

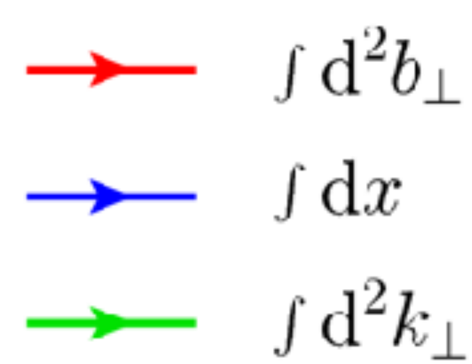
Transverse density in position space



Weak transition form factors

DGLAP, ERBL Evolution Factorization Theorems





Diffractive DIS from FSI

Sivers, T-odd from lensing

PHYSICAL REVIEW D VOLUME 22, NUMBER 9 1 NOVEMBER 1980

Exclusive processes in perturbative quantum chromodynamics

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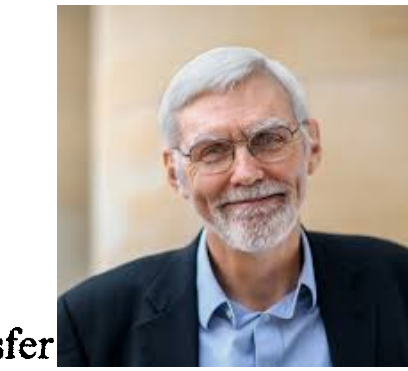
(Received 27 May 1980)



We present a systematic analysis in perturbative quantum chromodynamics (QCD) of large-momentum-transfer exclusive processes. Predictions are given for the scaling behavior, angular dependence, helicity structure, and normalization of elastic and inelastic form factors and large-angle exclusive scattering amplitudes for hadrons and photons. We prove that these reactions are dominated by quark and gluon subprocesses at short distances, and thus that the dimensional-counting rules for the power-law falloff of these amplitudes with momentum transfer are rigorous predictions of QCD, modulo calculable logarithmic corrections from the behavior of the hadronic wave functions at short distances. These anomalous-dimension corrections are determined by evolution equations for process-independent meson and baryon "distribution amplitudes" $\phi(x_i,Q)$ which control the valence-quark distributions in high-momentum-transfer exclusive reactions. The analysis can be carried out systematically in powers of $\alpha_s(Q^2)$, the QCD running coupling constant. Although the calculations are most conveniently carried out using light-cone perturbation theory and the light-cone gauge, we also present a gauge-independent analysis and relate the distribution amplitude to a gauge-invariant Bethe-Salpeter amplitude.

Rigorous QCD analysis of exclusive reactions
Hadron Distribution amplitudes
ERBL Evolution

Also: Efremov and Radyshkin

Fixed $\tau = t + z/c$

Light-Front QCD

Physical gauge: $A^+ = 0$

Exact frame-independent formulation of nonperturbative QCD!

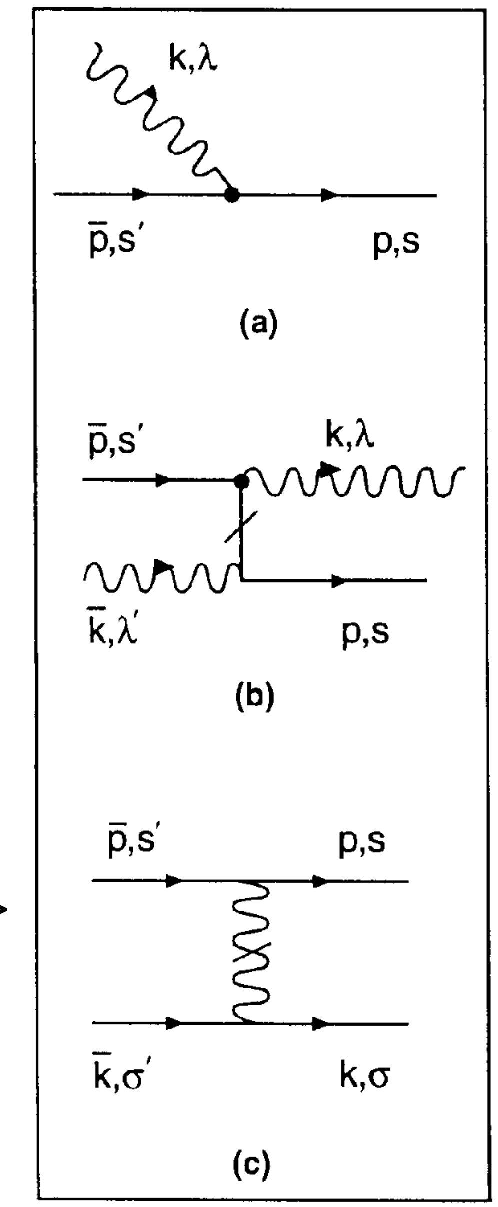
$$L^{QCD} \rightarrow H^{QCD}_{LF}$$

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

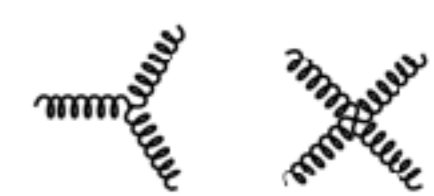
H^{int}_{LF}: Matrix in Fock Space

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

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



Eigenvalues and Eigensolutions give Hadronic Spectrum and Light-Front wavefunctions



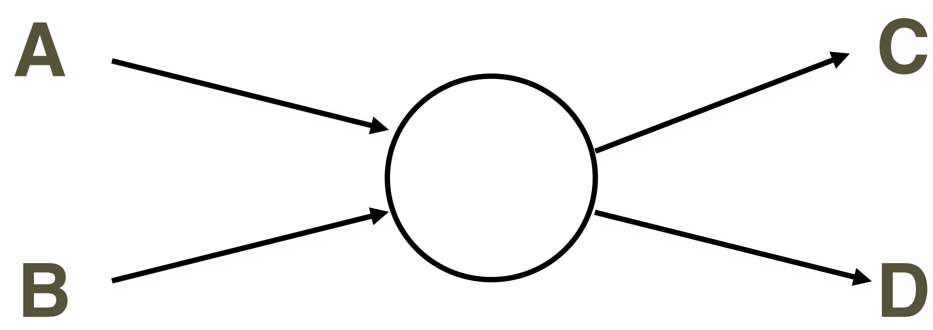
H^{int}_{LF}

LFWFs: Off-shell in P- and invariant mass

Solve nPQCD by matrix diagonalization: Hornbostel, Pauli, sjb

Scaling: manifestation of asymptotically free hadronic interactions

From dimensional arguments at high energies in binary reactions:



CONSTITUENT COUNTING RULE

Brodsky and Farrar, Phys. Rev. Lett. 31 (1973) 1153
Matveev et al., Lett. Nuovo Cimento, 7 (1973) 719

helicity conservation

Counting Rules:

$$q(x) \sim (1-x)^{2n_{spect}-1} \text{ for } x \to 1$$

$$F(Q^2) \sim \left(\frac{1}{Q^2}\right)^{(n-1)}$$

$$\frac{d\sigma}{dt}(AB \to CD) \sim \frac{F(t/s)}{s^{(n_{participants}-2)}}$$

$$n_{participants} = n_A + n_B + n_C + n_D$$

$$\frac{d\sigma}{d^3p/E}(AB \to CX) \sim F(\hat{t}/\hat{s}) \times \frac{(1-x_R)^{(2n_{spectators}-1)}}{(p_T^2)^{(n_{participants}-2)}}$$

Farrar, Jackson; Lepage, sjb; Burkardt, Schmidt, Sjb

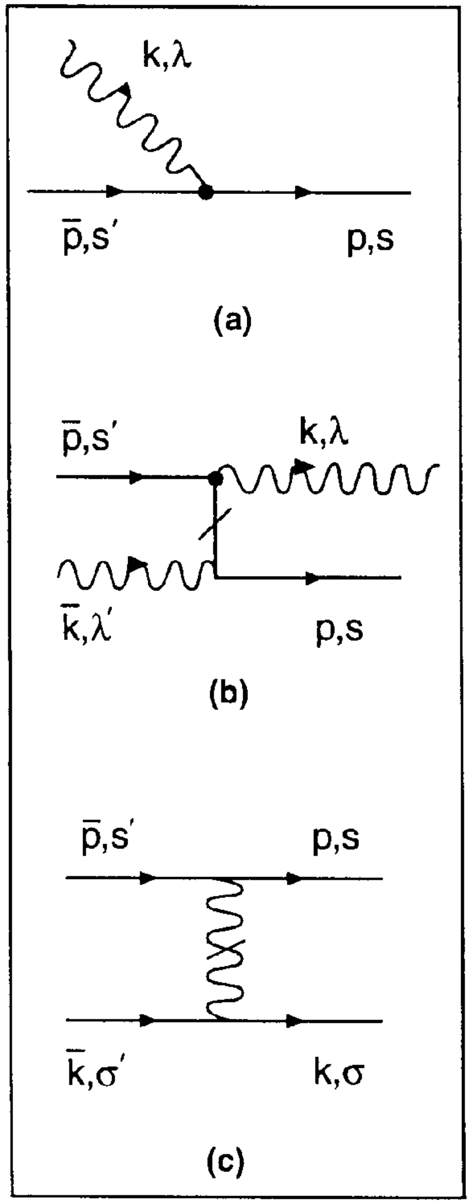
Light-Front QCD

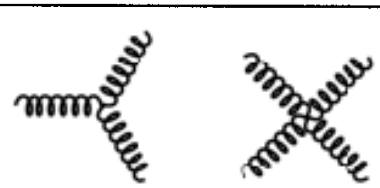
Heisenberg Equation

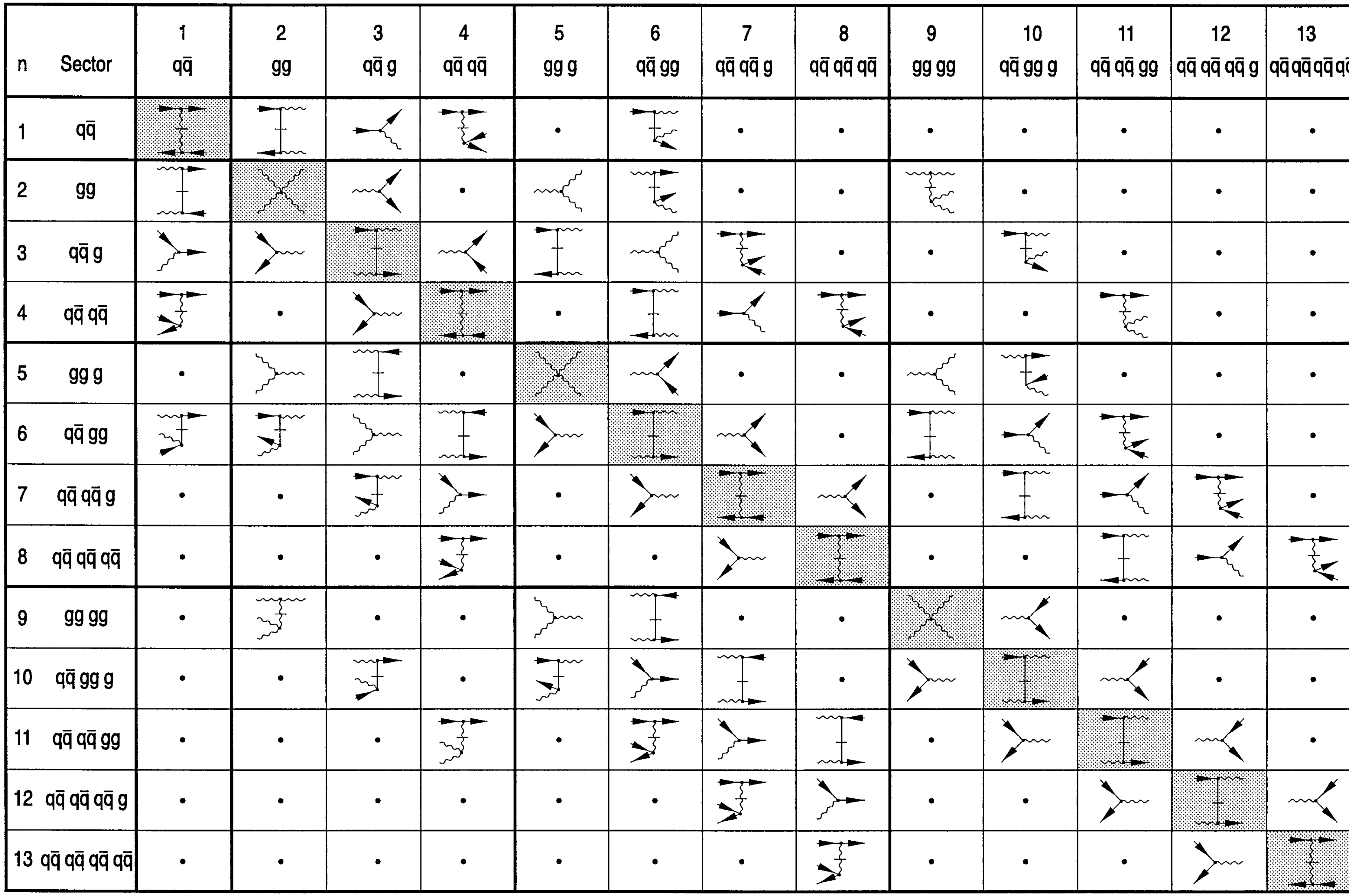
$$H_{LC}^{QCD} |\Psi_h\rangle = \mathcal{M}_h^2 \, |\Psi_h\rangle$$

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

Hornbostel, Pauli, sjb







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

Discretized LF Quantization

DLCQ: Diagonalize QCD Hamiltonian, periodic LF BC

BLFQ (Vary et al)
Use LF Holographic Basis

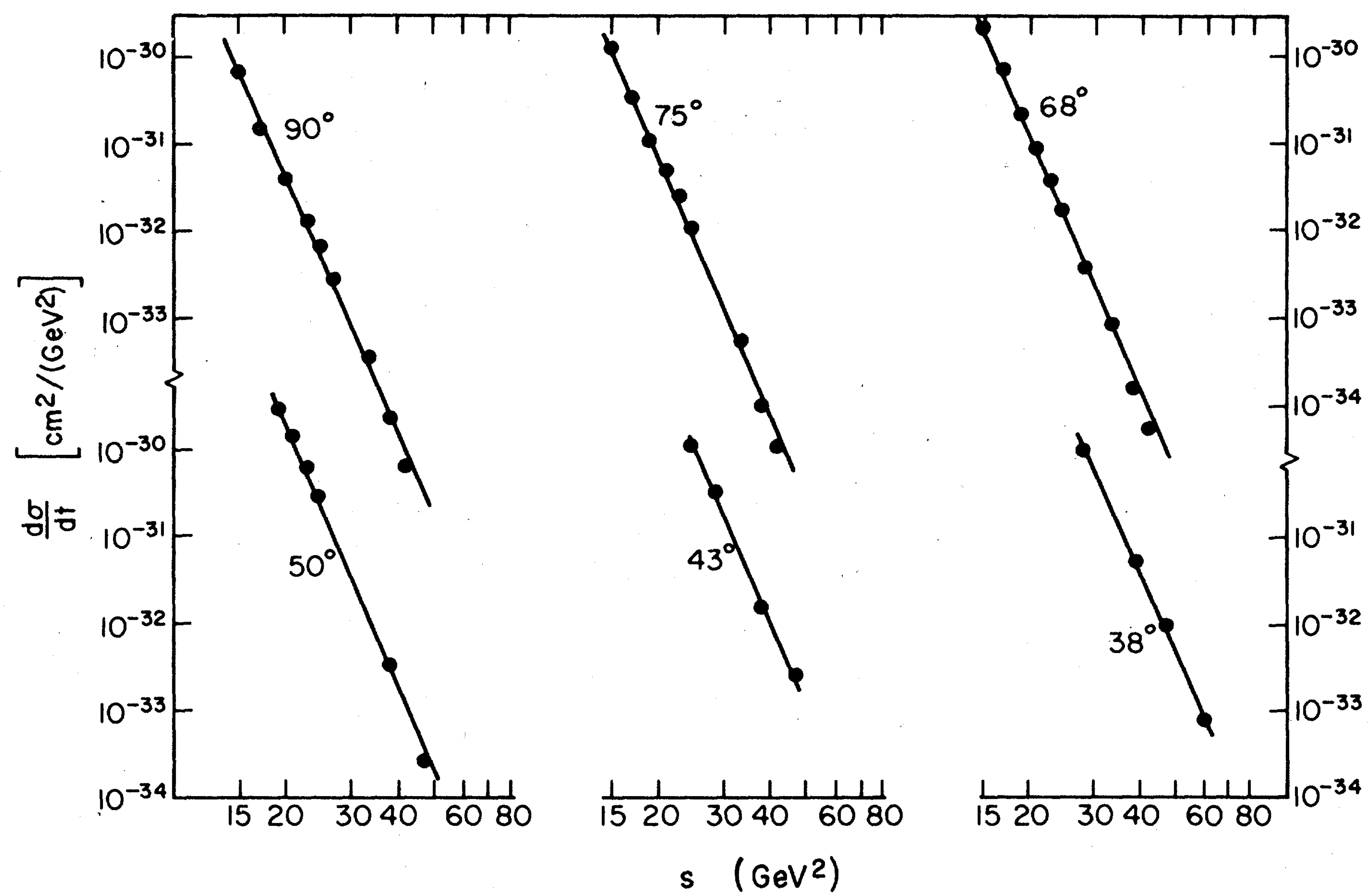
Solve QCD by Matrix Diagonalization

Diagonalize the LF Hamiltonian on an Orthonormal Basis
Lorentz Frame-Independent,
Minkowski Causal LF Time
Compute Hadron masses, LF Wavefunctions
Successful applications to QCD(1+1)
Use advanced computer resources
Competitive with LGTh?

H. C. Pauli, K. Hornbostel, sjb

Scaling of Hard Exclusive reactions: Fixed t/s

EXCLUSIVE PROCESSES IN PERTURBATIVE QUANTUM...

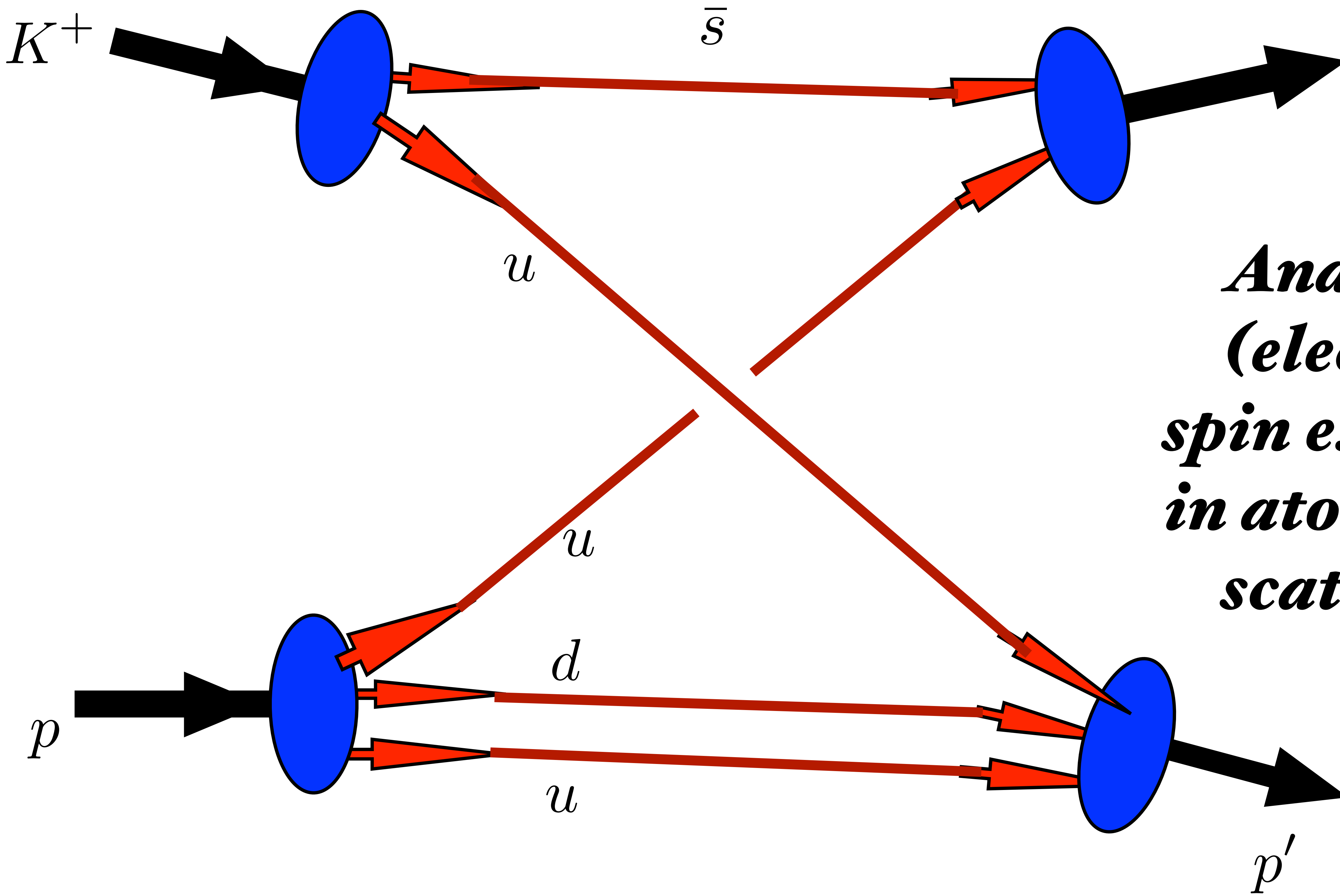


Cross sections for $pp \to pp$ at wide angles. The straight lines correspond to a falloff of $1/s^{10}$.

$$\frac{d\sigma}{dt}(p+p \to p+p) = \frac{F(\theta_{CM})}{s^{10}}$$

Manifestation of Asymptotic Freedom

$$K^+ p \to K^+ p$$

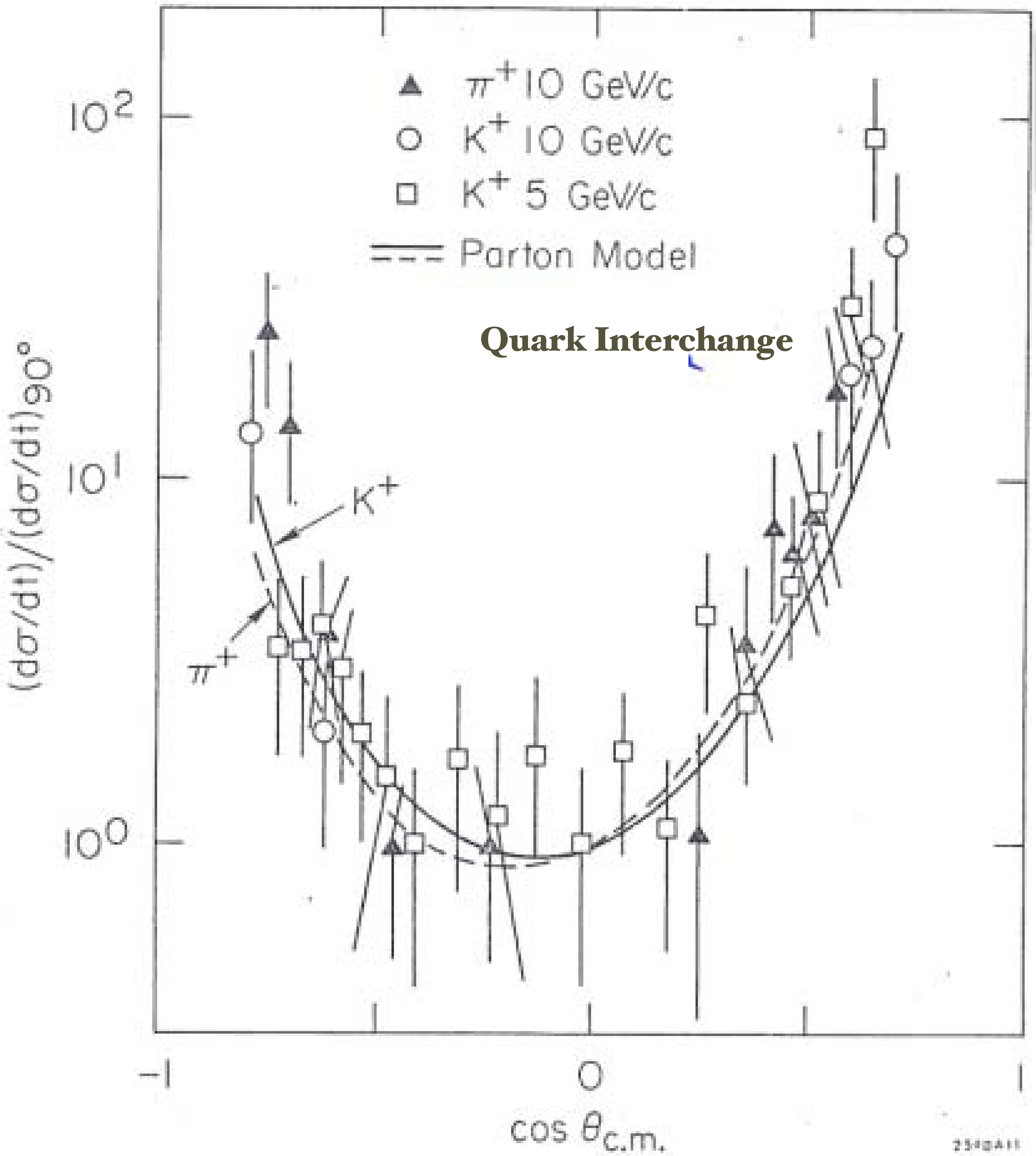


Analog of (electron) spin exchange in atom-atom scattering

Quark Interchange

Blankenbecler, Gunion, sjb

Interactions between exchanged quarks suppressed at high momentum transfer



Quark Interchange
Blankenbecler, Gunion, sjb

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

$$\frac{d\sigma}{dt}(K^+p \to K^+p) = \frac{F(t/s)}{s^8}$$

Non-linear Regge behavior:

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

$$\frac{d\sigma}{dt} = \frac{f(t/s)}{s^{N-2}}$$

N-2 =# fundamental constituents -2 = 2+3+2 +3- 2=8

"Counting Rules" *Farrar and sjb; Muradyan, Matveev, Tavkelidze*

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

- *Color Confinement*
- *Origin of the QCD Mass Scale*
- *Meson and Baryon Spectroscopy*
- *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: BLM/PMC (Principle of Maximum Conformality)*

Need a First Approximation to QCD

Comparable in simplicity to Schrödinger Theory in Atomic Physics

Relativistic, Frame-Independent, Color-Confining

Origin of hadronic mass scale if $m_q=0$

Semi-Classical Approximation to QCD

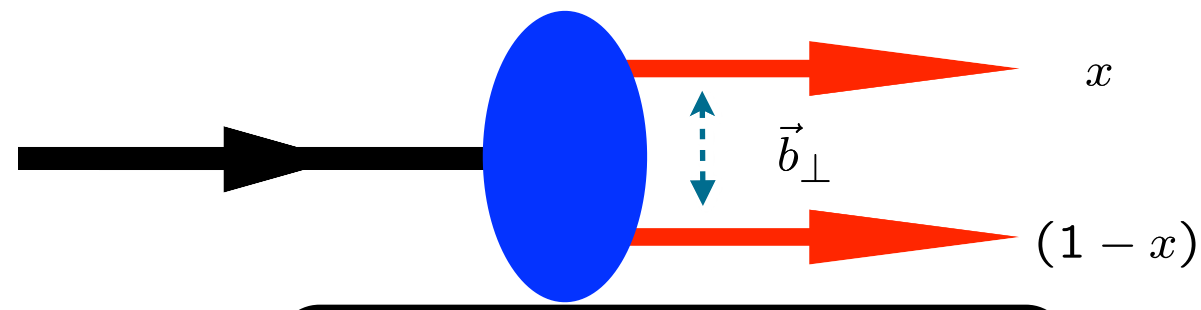
de Téramond, Dosch, Lorcé, sjb

AdS/QCD
Light-Front Holography

Light-Front QCD

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

Fixed $\tau = t + z/c$



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

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

Coupled Fock states

Eliminate higher Fock states and retarded interactions

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

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: LF Holography

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

Confining AdS/QCD potential!

Sums an infinite # diagrams

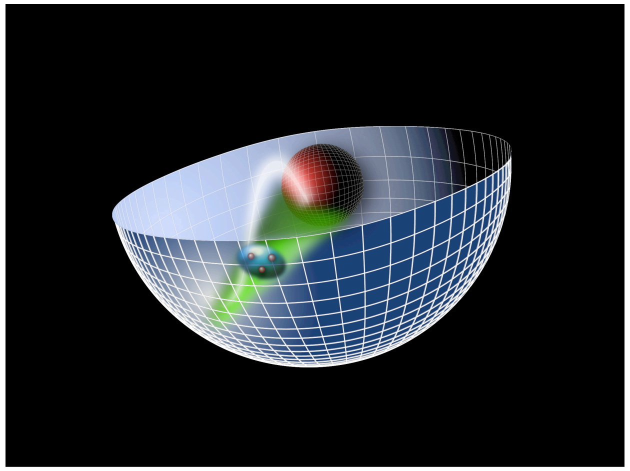
Semiclassical first approximation to QCD

de Téramond, Dosch, Lorcé, sjb

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

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

Single variable ζ

Unique Confinement Potential!

Conformal Symmetry of the AdS action

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 AdS action!

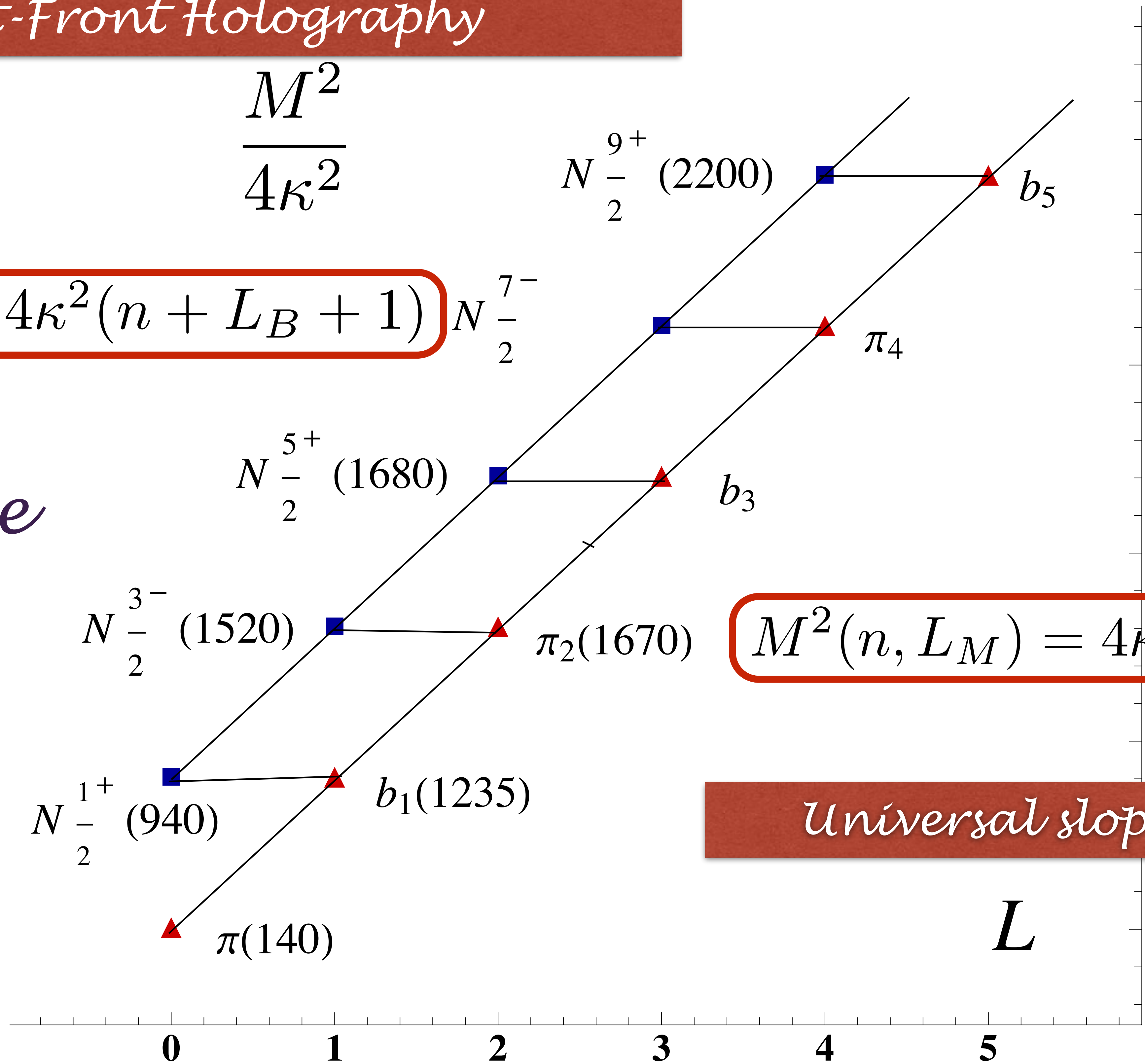
GeV units external to QCD: Ratios of Masses Determined

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

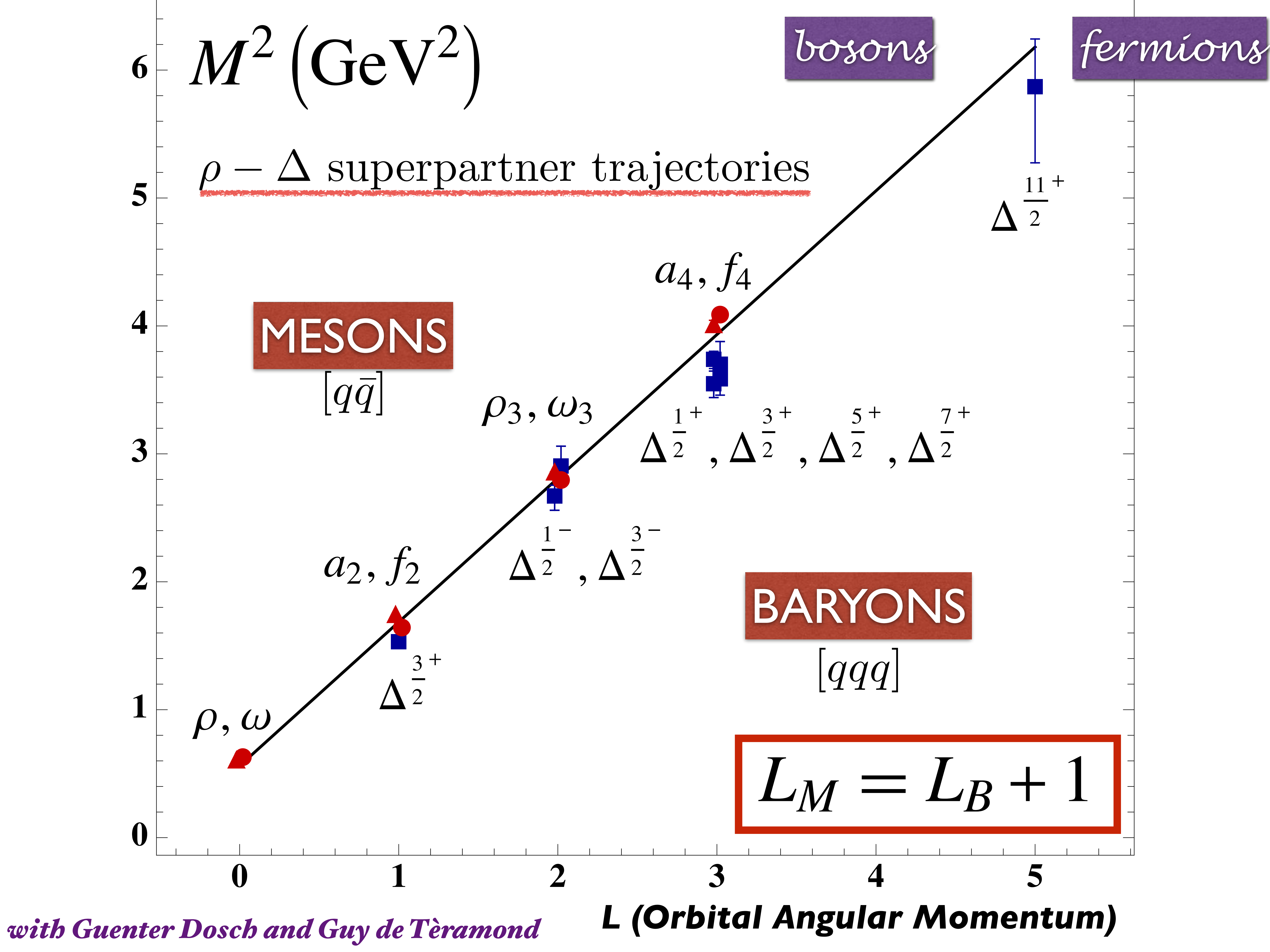


$$M^2(n, L_M) = 4\kappa^2(n + L_M)$$

Universal slopes in n, L

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

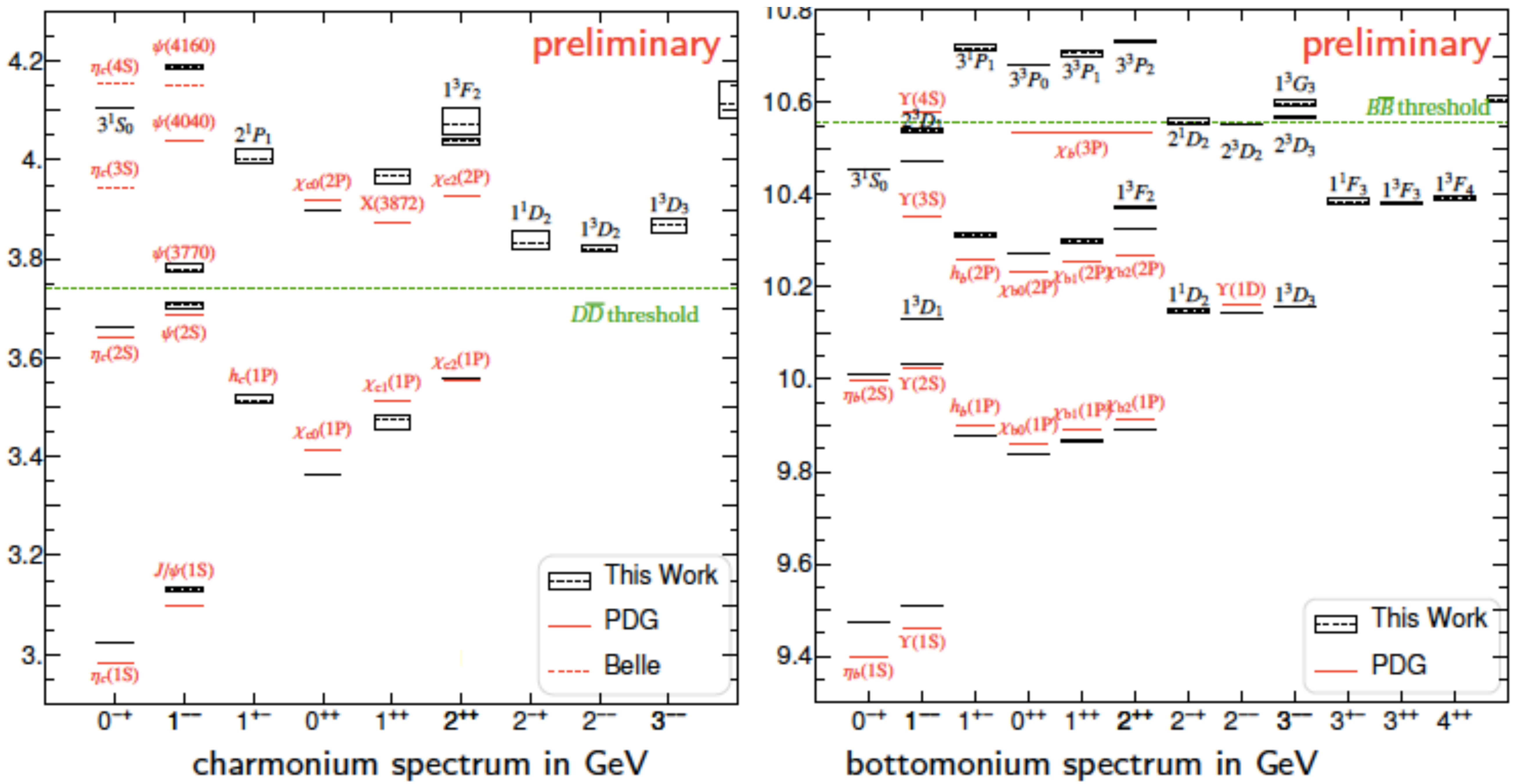
Meson-Baryon Mass Degeneracy for $L_M = L_B + 1$



$M^2\,(\mathrm{GeV}^2)$
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
L (Orbital Angular Momentum)
with Guenter Dosch and Guy de Tèramond

Heavy Quarkonium in a Light-Front Holographic Basis

BLFQ using AdS/QCD

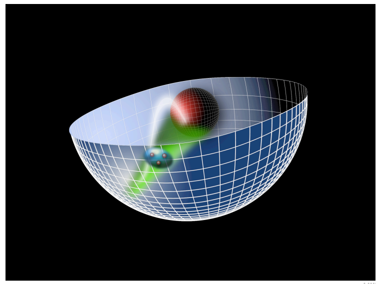


Yang Li , Pieter Maris Xingbo Zhao, James P. Vary   ***PLB 758, 116 (2016)***

$$H_{\rm eff} = \underbrace{\frac{\vec{k}_\perp^2 + m_q^2}{x} + \frac{\vec{k}_\perp^2 + m_{\bar{q}}^2}{1-x}}_{\text{LF kinetic energy}} + \underbrace{\kappa^4 \zeta_\perp^2 - \frac{\kappa^4}{(m_q + m_{\bar{q}})^2}\partial_x\left[x(1-x)\partial_x\right]}_{\text{confinement}} - \underbrace{\frac{C_F 4\pi\alpha_s}{Q^2}\bar{u}_{s'}(k')\gamma_\mu u_s(k)\bar{v}_{\bar{s}}(\bar{k})\gamma^\mu v_{\bar{s}'}(\bar{k}')}_{\text{one-gluon exchange}}$$

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***
- ***Color Confinement in z***
- ***Introduces confinement scale κ***
- ***Uses AdS_5 as template for conformal theory***

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

AdS/CFT

D. Gross: duality of QCD with string theory

Introduce "Dilaton" to simulate confinement analytically

- Nonconformal metric dual to a confining gauge theory

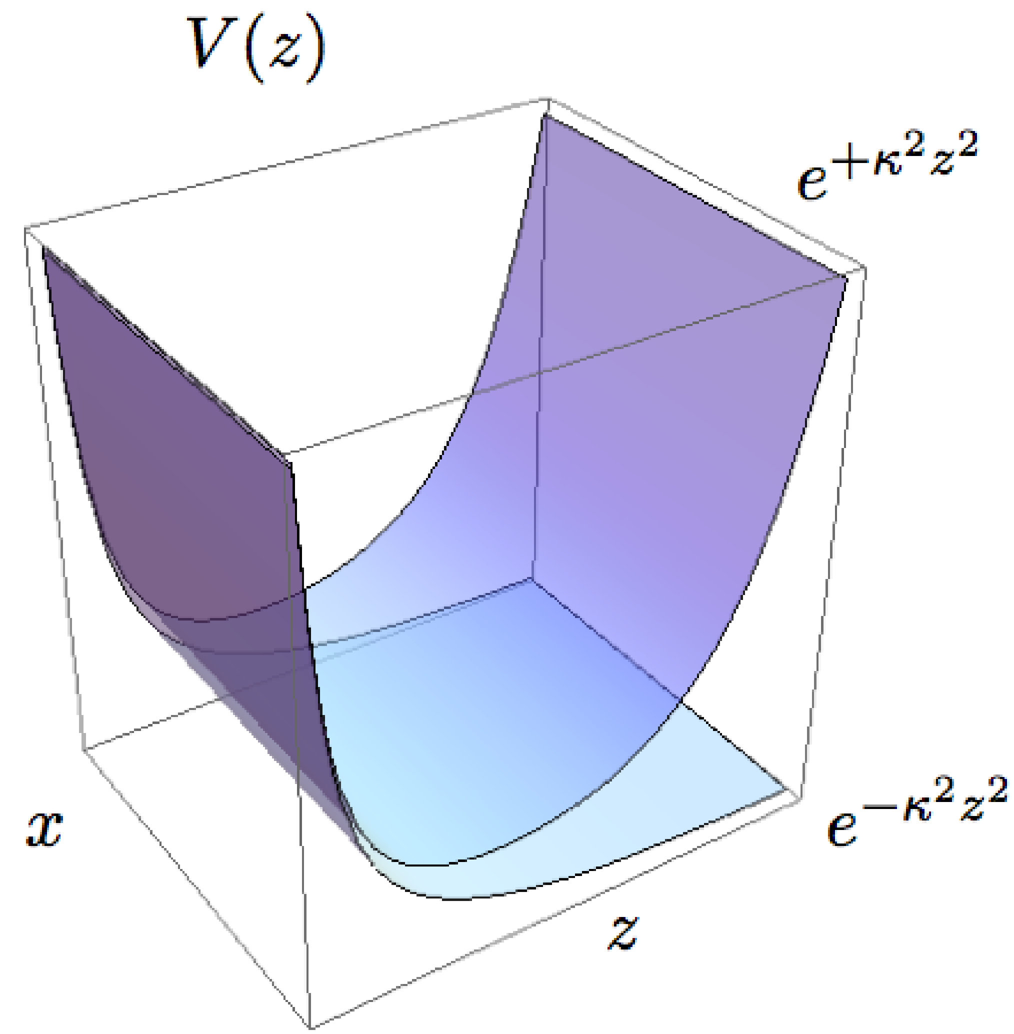
$$ds^2 = \frac{R^2}{z^2} e^{\varphi(z)} \left(\eta_{\mu\nu} dx^\mu dx^\nu - dz^2\right)$$

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 Te'ramond, sjb

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

Positive-sign dilaton

- de Teramond, 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!

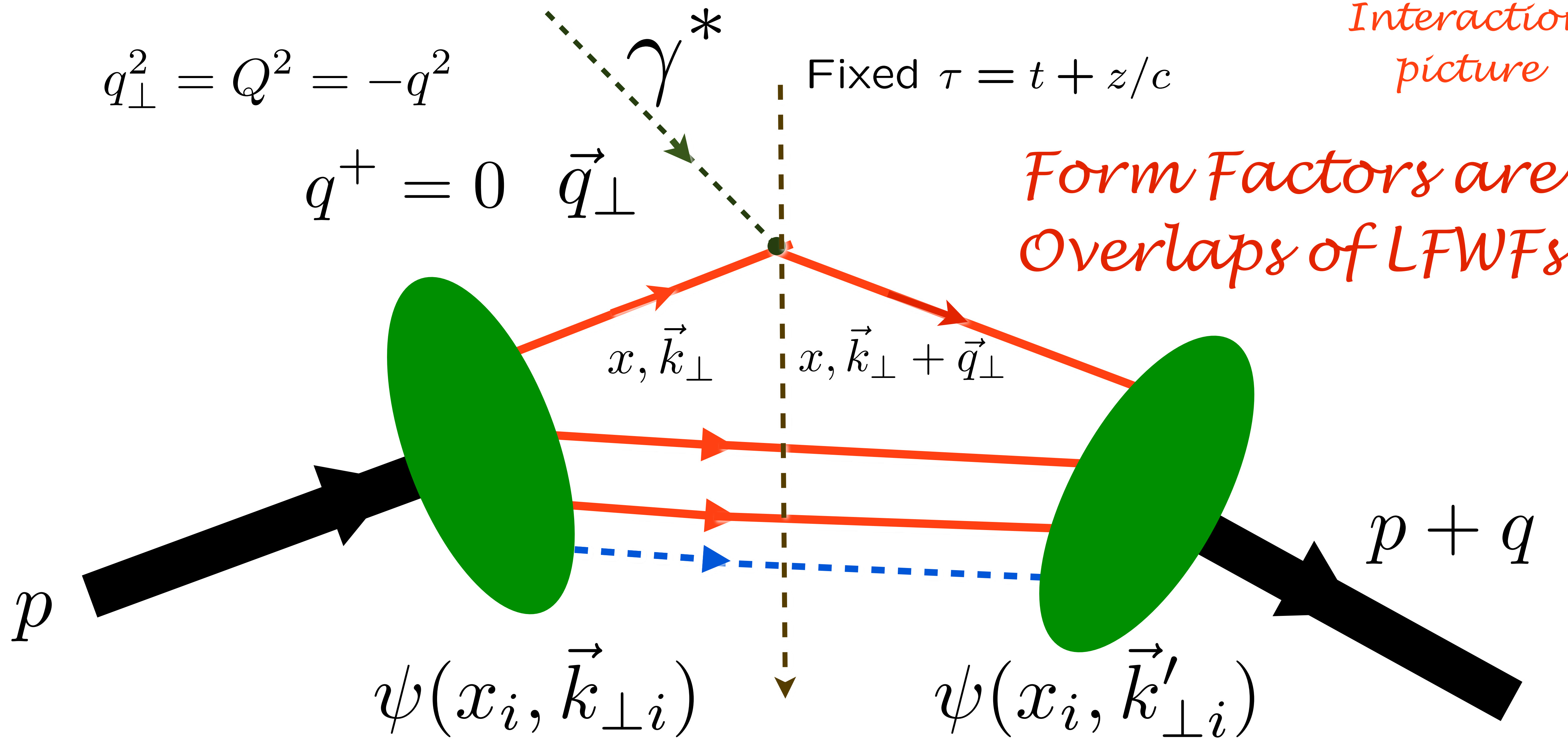
$$z \longleftrightarrow \zeta = \sqrt{x(1-x)\vec{b}_\perp^2}$$

Light-Front Holography

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

Front Form

Interaction picture



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

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 Te'ramond, sjb

Identical to Polchinski-Strassler Convolution of AdS Amplitudes

LF(3+1) ⟷ AdS_5

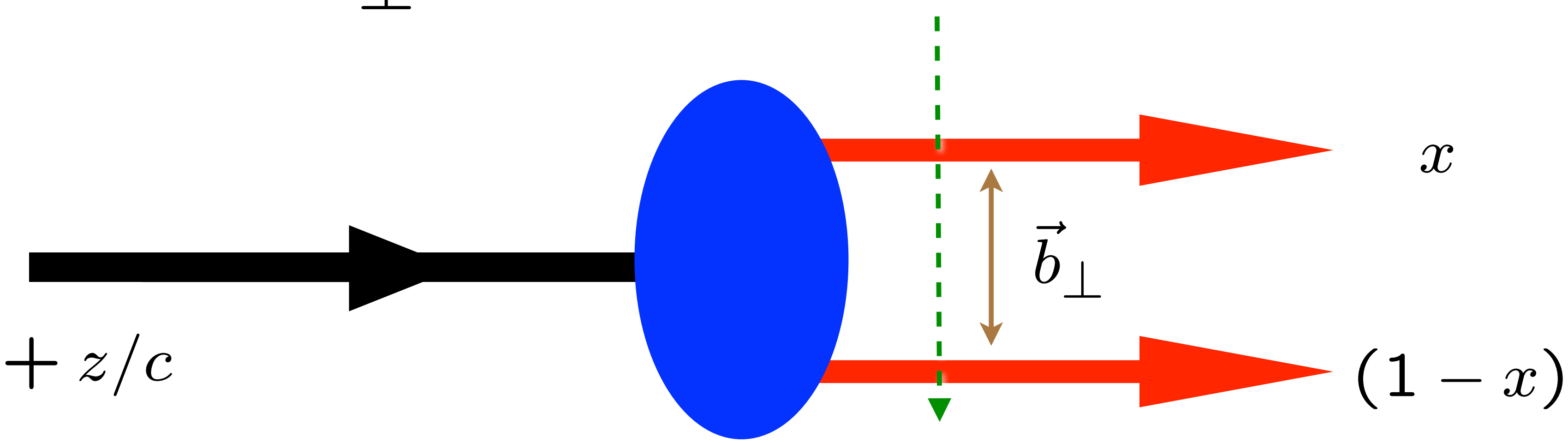
de Te'ramond, sjb

LF(3+1) ⟷ AdS_5

Light-Front Holographic Dictionary

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

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

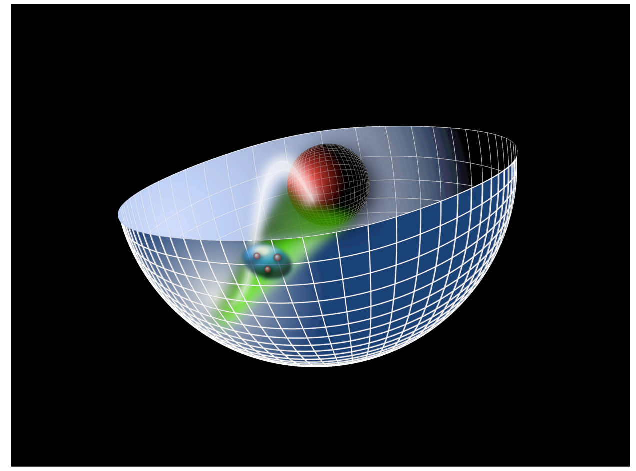


Fixed $\tau = t + z/c$

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

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

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* 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

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

Single variable ζ

Unique
Confinement Potential!

Conformal Symmetry
of the action

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: Ratios of Masses Determined

de Téramond, Dosch, Lorcé, sjb

LF Holography

Baryon Equation

Superconformal Quantum Mechanics

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

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

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

S=1/2, P=+

Meson Equation

$$\lambda = \kappa^2$$

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

S=0, P=+

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

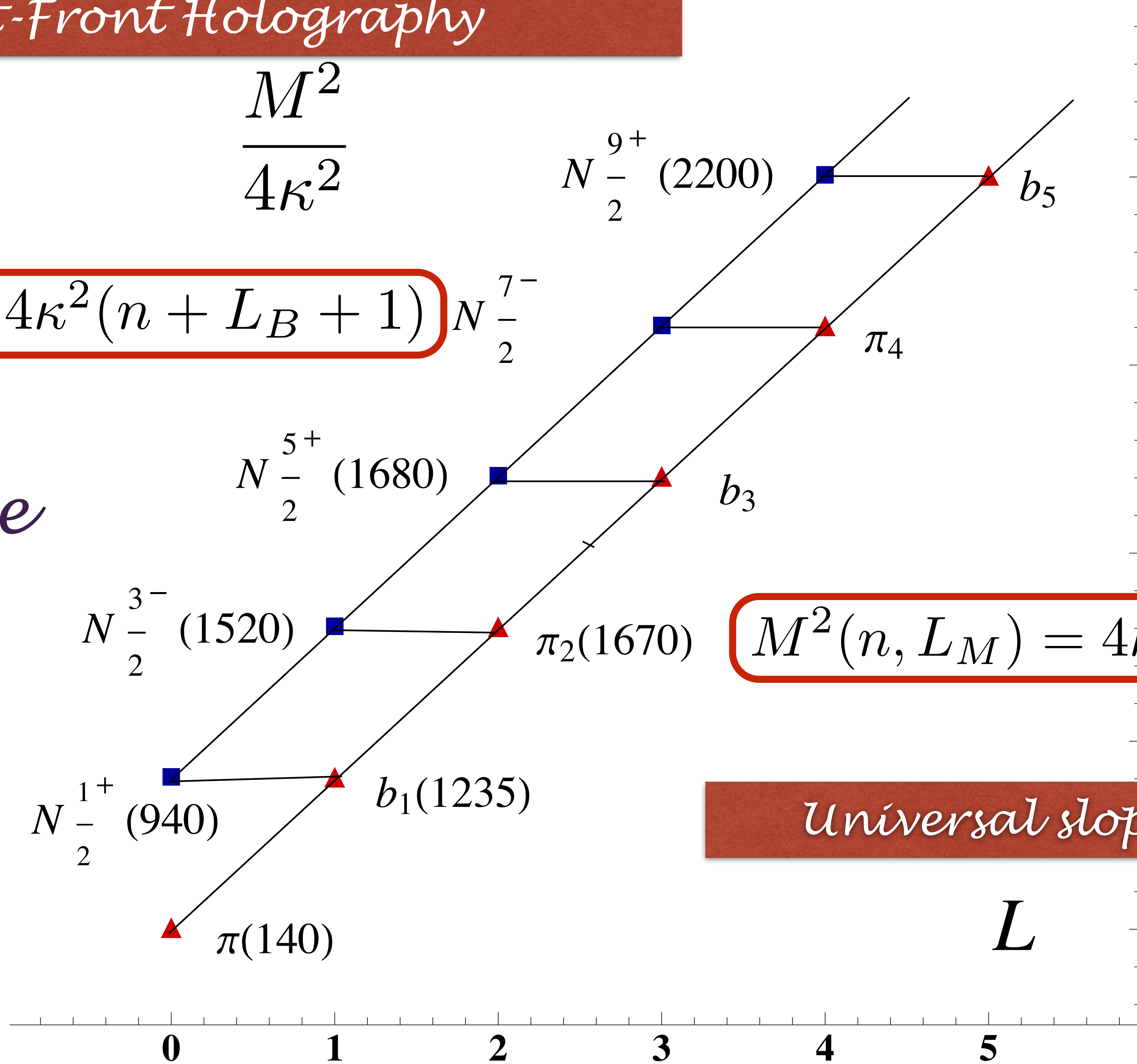
Same κ *!*

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

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

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 $L_M = L_B + 1$

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

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

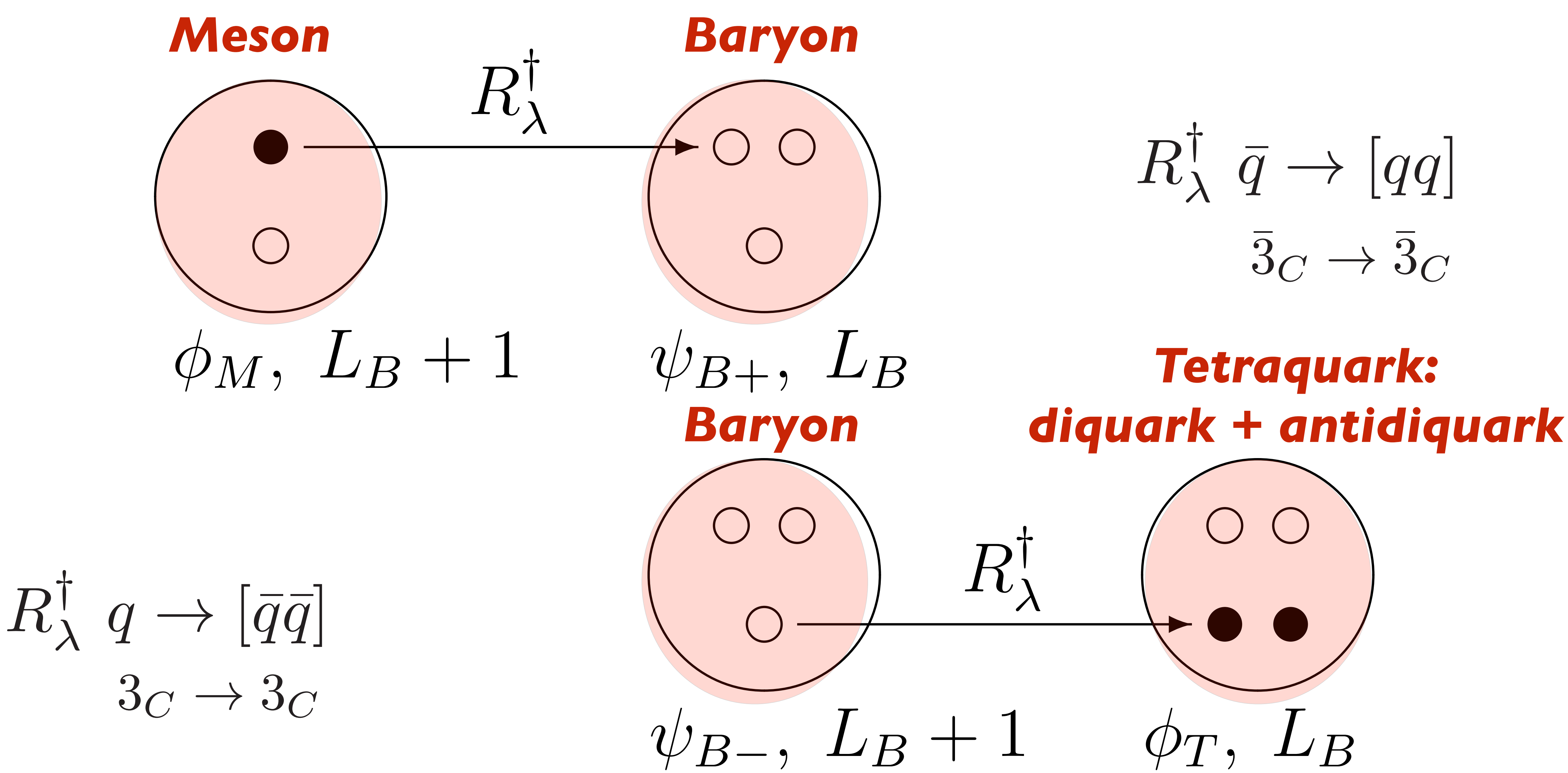
$$\vec{\zeta}^2 = \vec{b}^2_\perp x(1-x)$$

G. de Te'ramond, H. G. Dosch, sjb

Superconformal Algebra

Four-Plet Representations

Bosons, Fermions with Equal Mass!



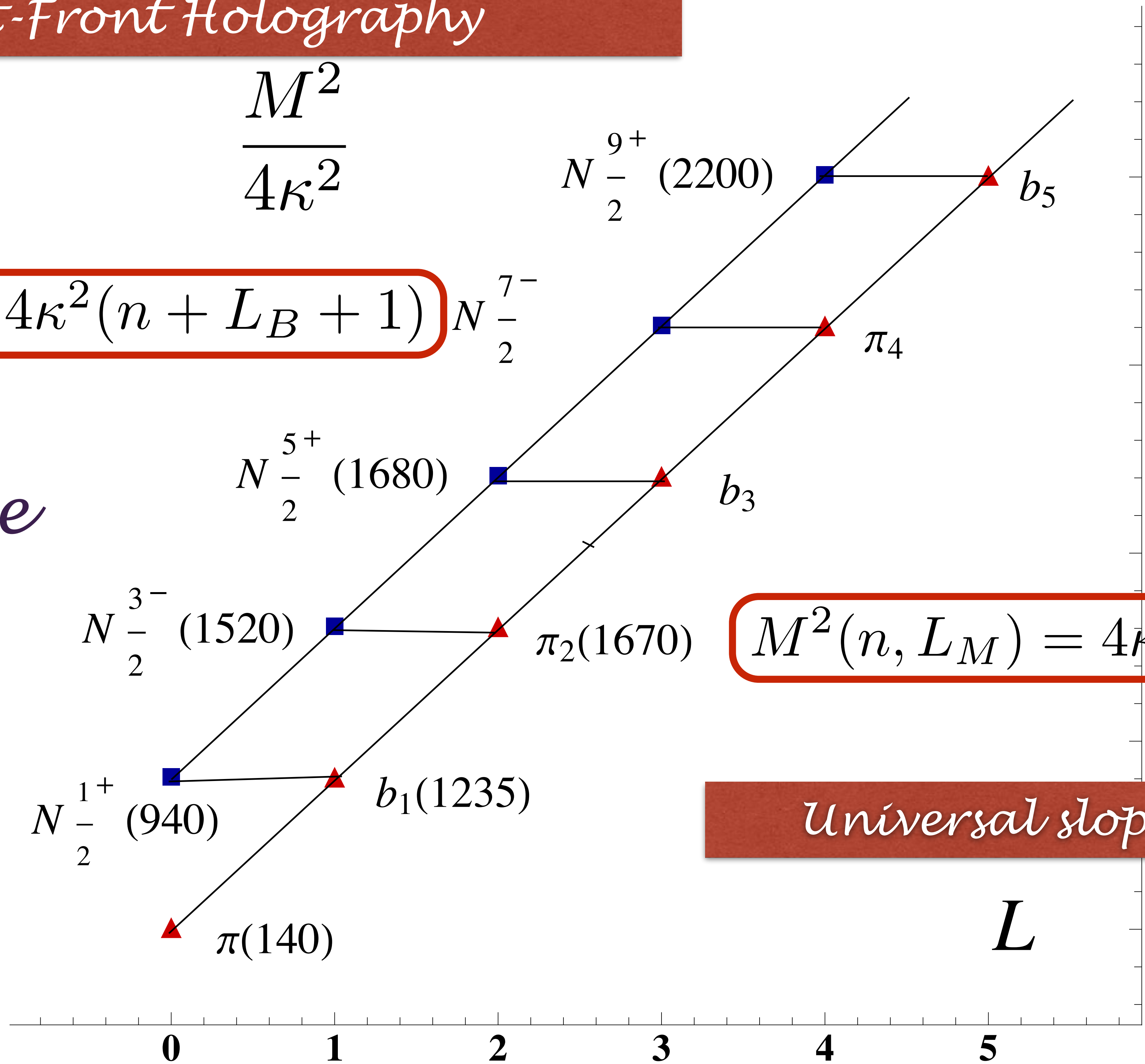
Proton: |u[ud]> Quark + Scalar Diquark
Equal Weight: L=0, L=1

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

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

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

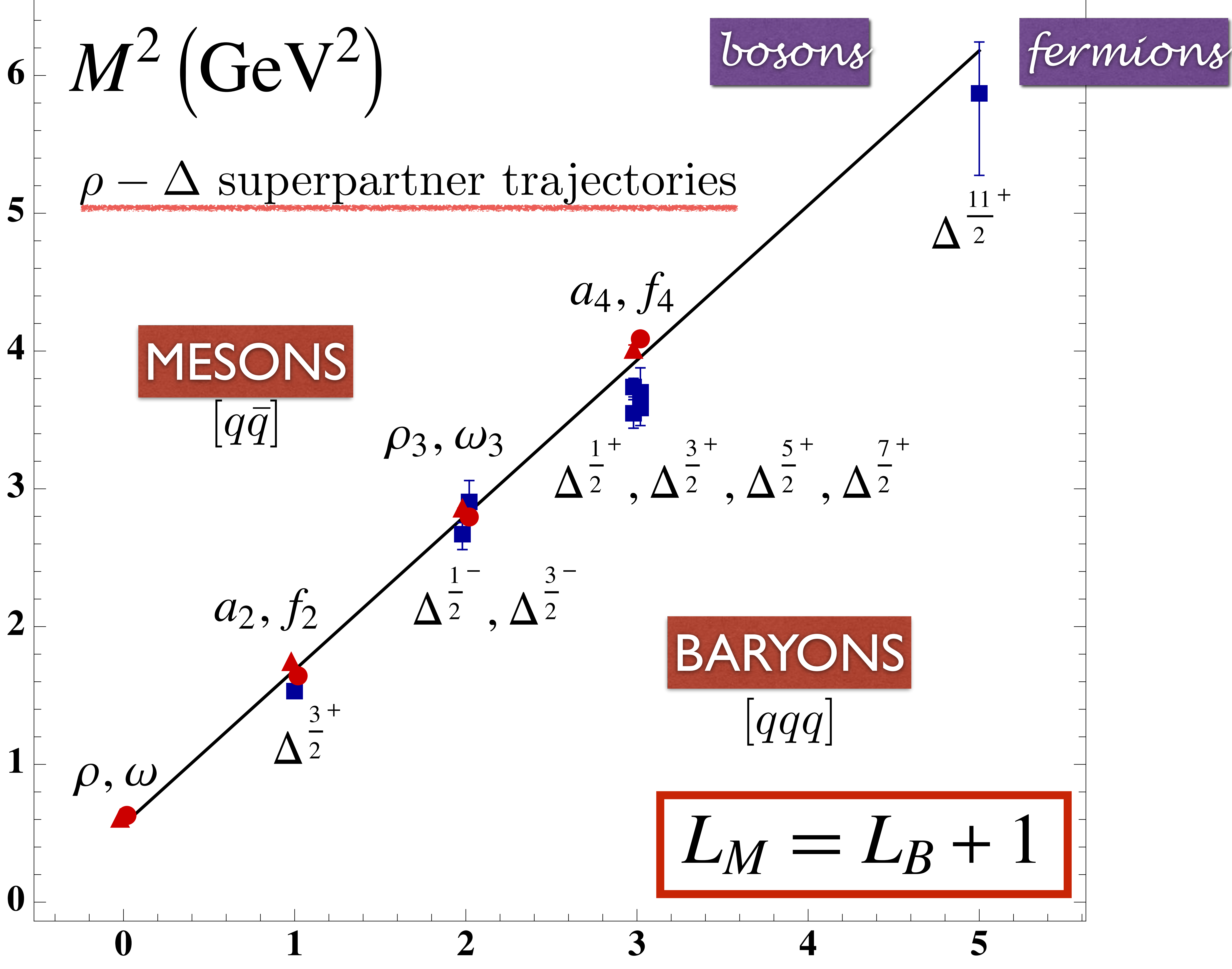
$$\phi_{n,L}(\zeta) = \kappa^{1+L} \sqrt{\frac{2n!}{(n+L)!}}\, \zeta^{1/2+L} e^{-\kappa^2\zeta^2/2} L_n^L(\kappa^2\zeta^2)$$

- 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

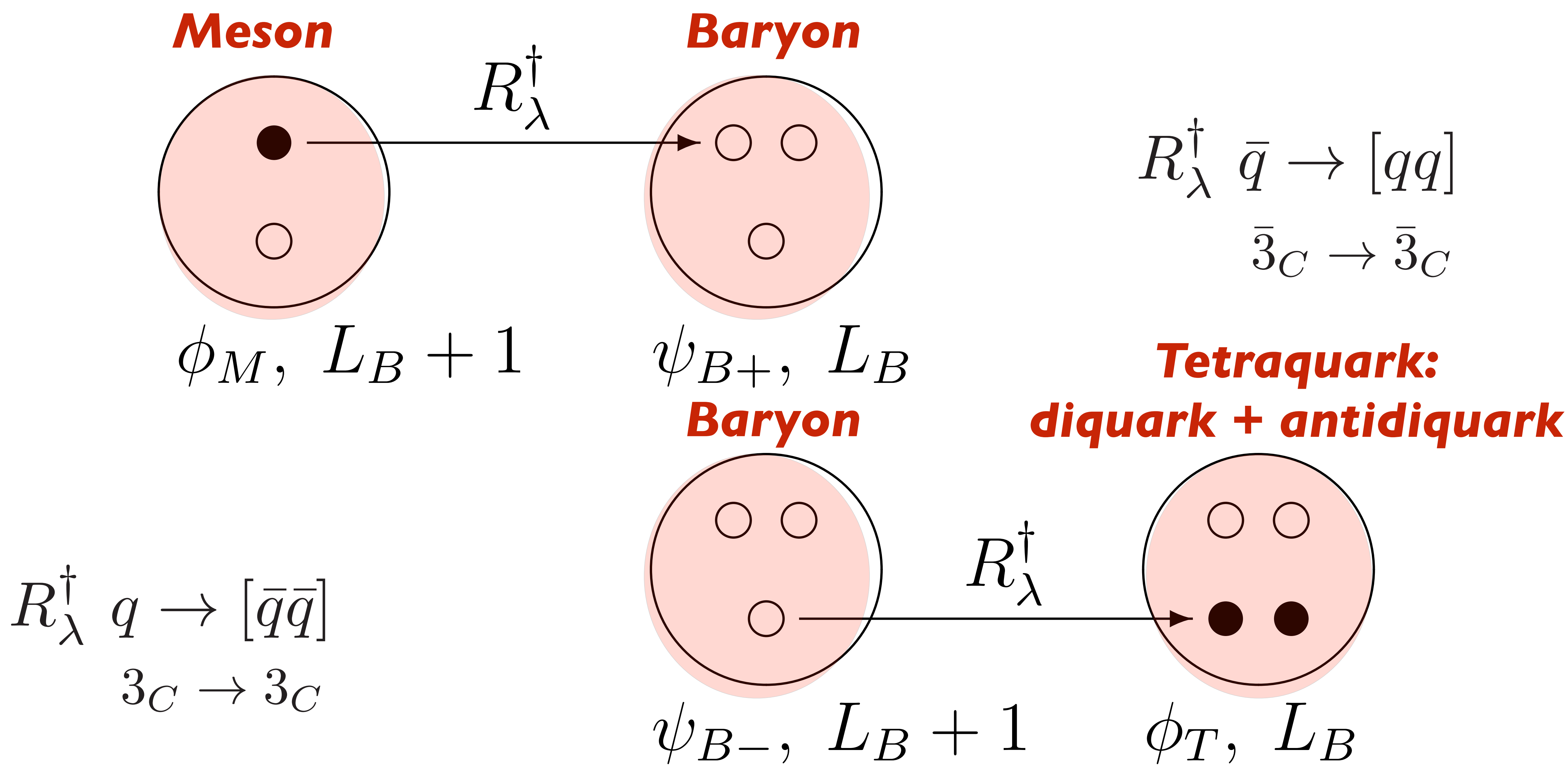


with Guenter Dosch and Guy de Tèramond

Superconformal Algebra

Four-Plet Representations

Bosons, Fermions with Equal Mass!



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

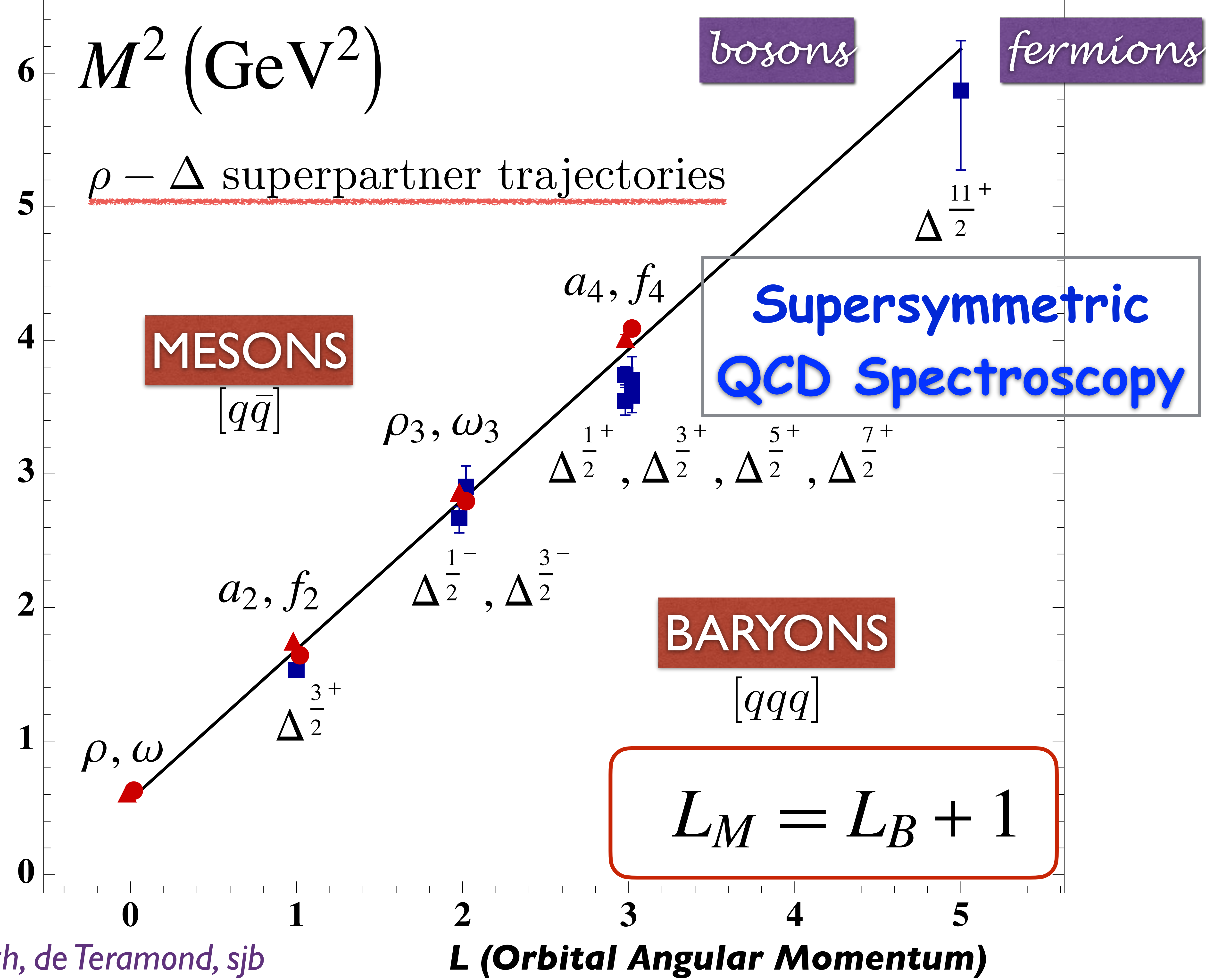
Supersymmetry in QCD

- 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

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



Dosch, de Teramond, sjb

Remarkable Features of Light-Front Schrödinger Equation

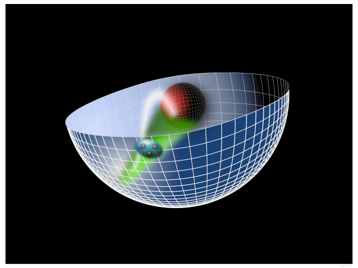
Dynamics + Spectroscopy!

- ***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***

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

LFHQCD: Underlying Principles

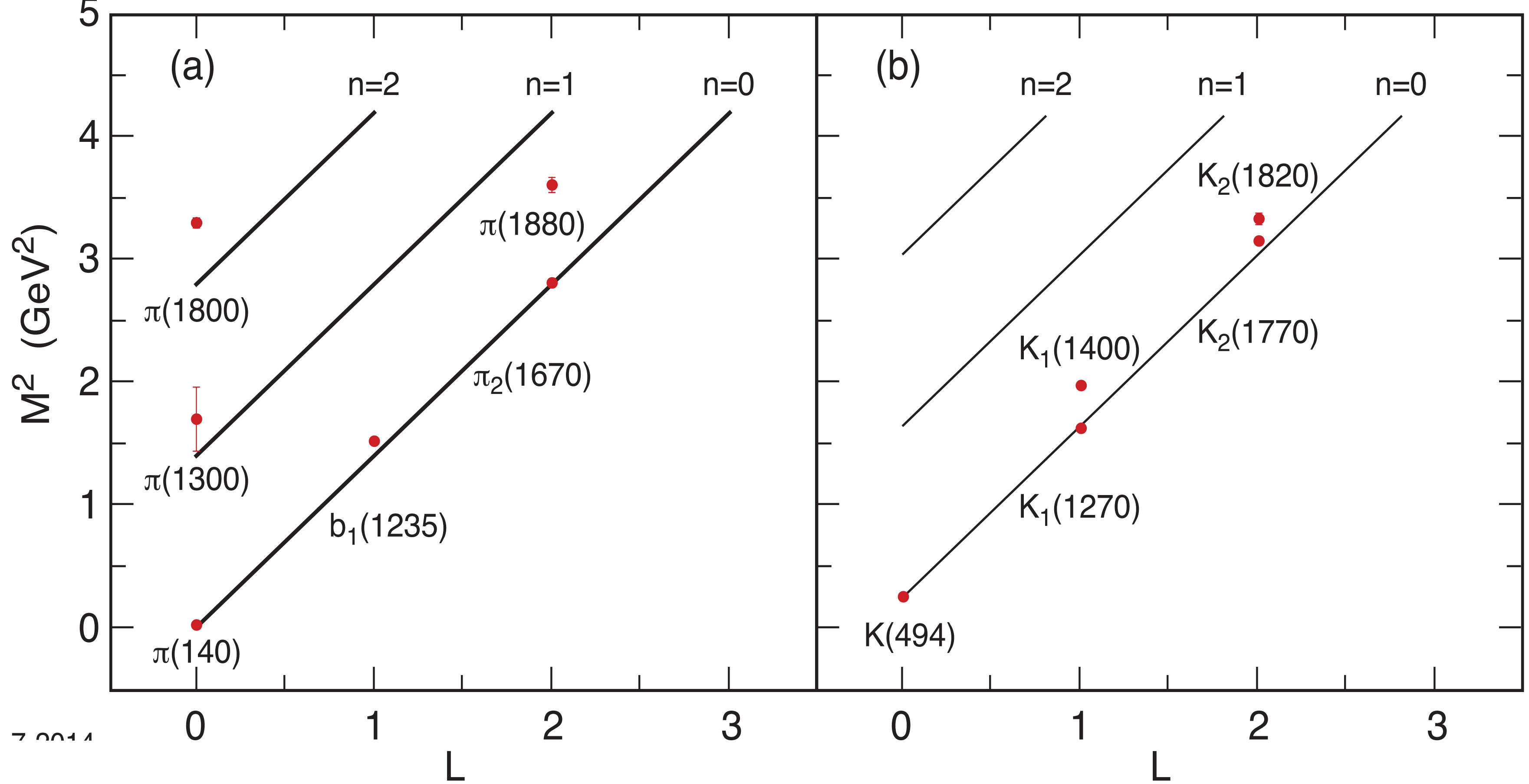
- ***Poincarè Invariance: Independent of the observer's Lorentz frame: Quantization at Fixed Light-Front Time τ***
- ***Causality: Information within causal horizon: Light-Front***
- ***Light-Front Holography: AdS_5 = LF (3+1)***

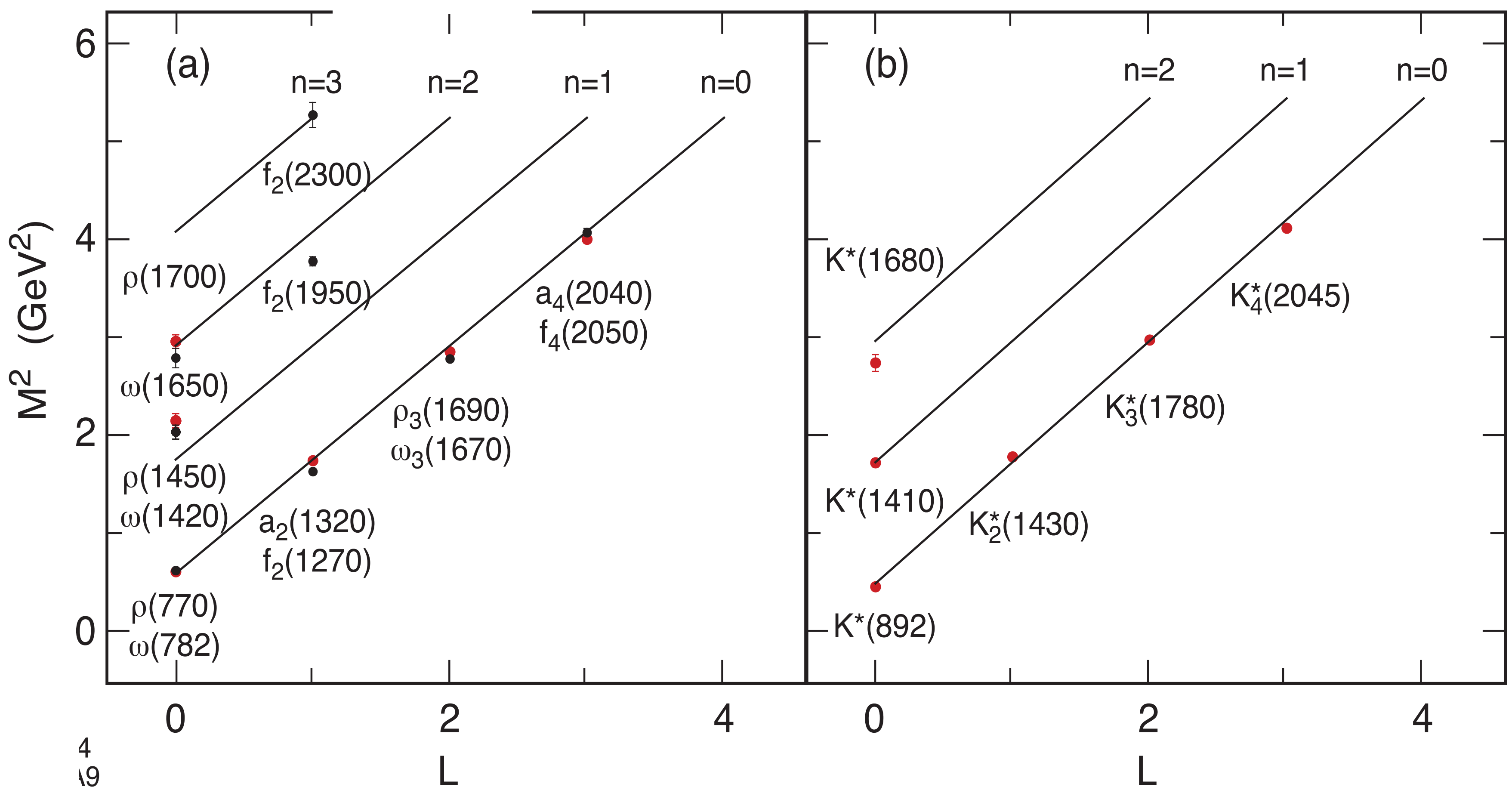


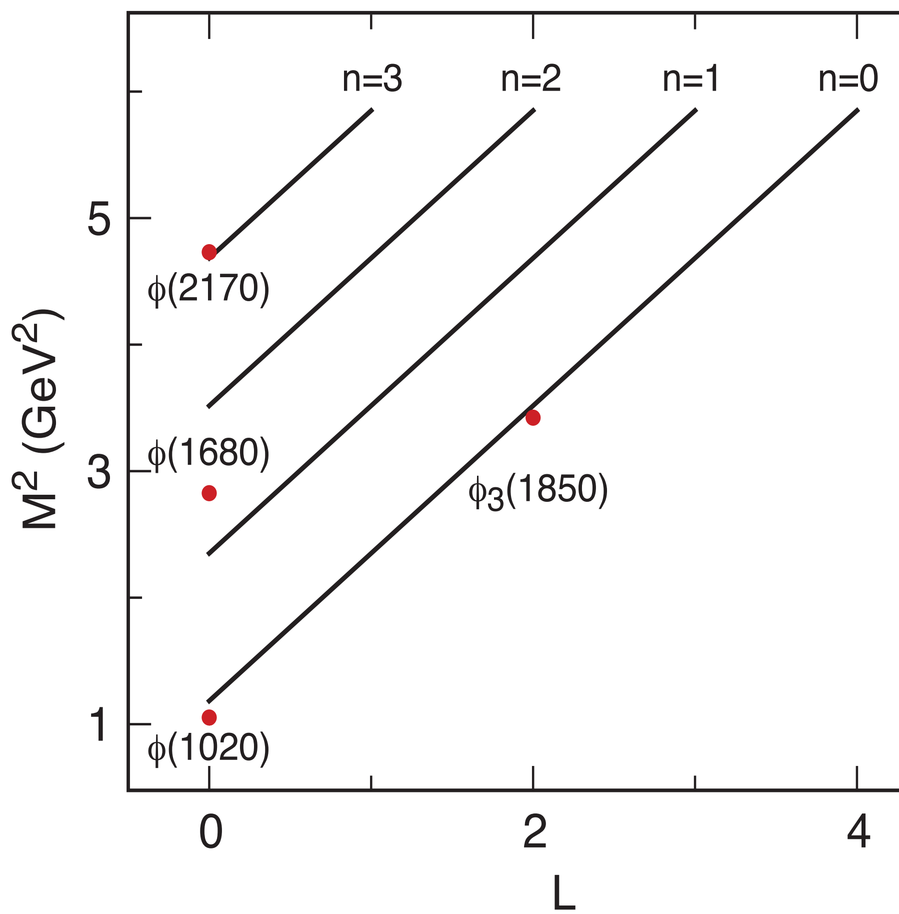
$$z \leftrightarrow \zeta \text{ where } \zeta^2 = b_\perp^2 x(1-x)$$

- ***Introduce Mass Scale κ while retaining the Conformal Invariance of the AdS 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:***

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







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

Equal Slope in n and L

Quark separation increases with L

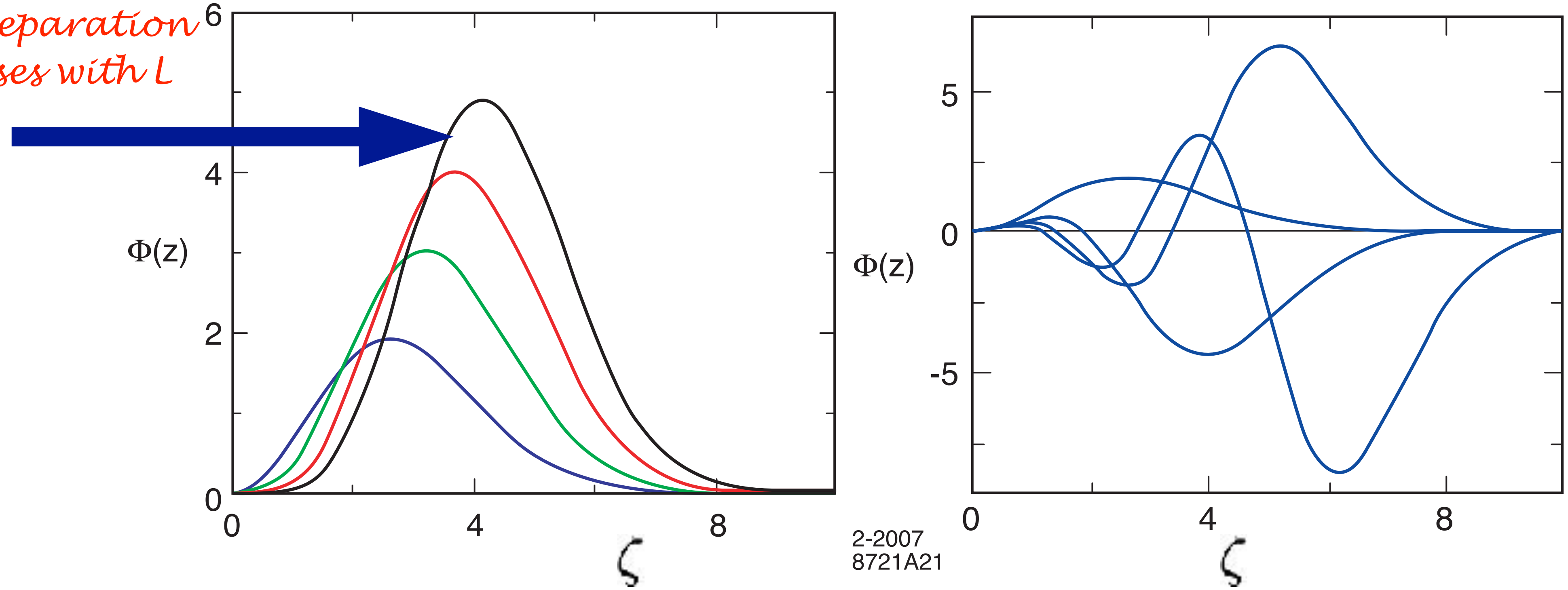
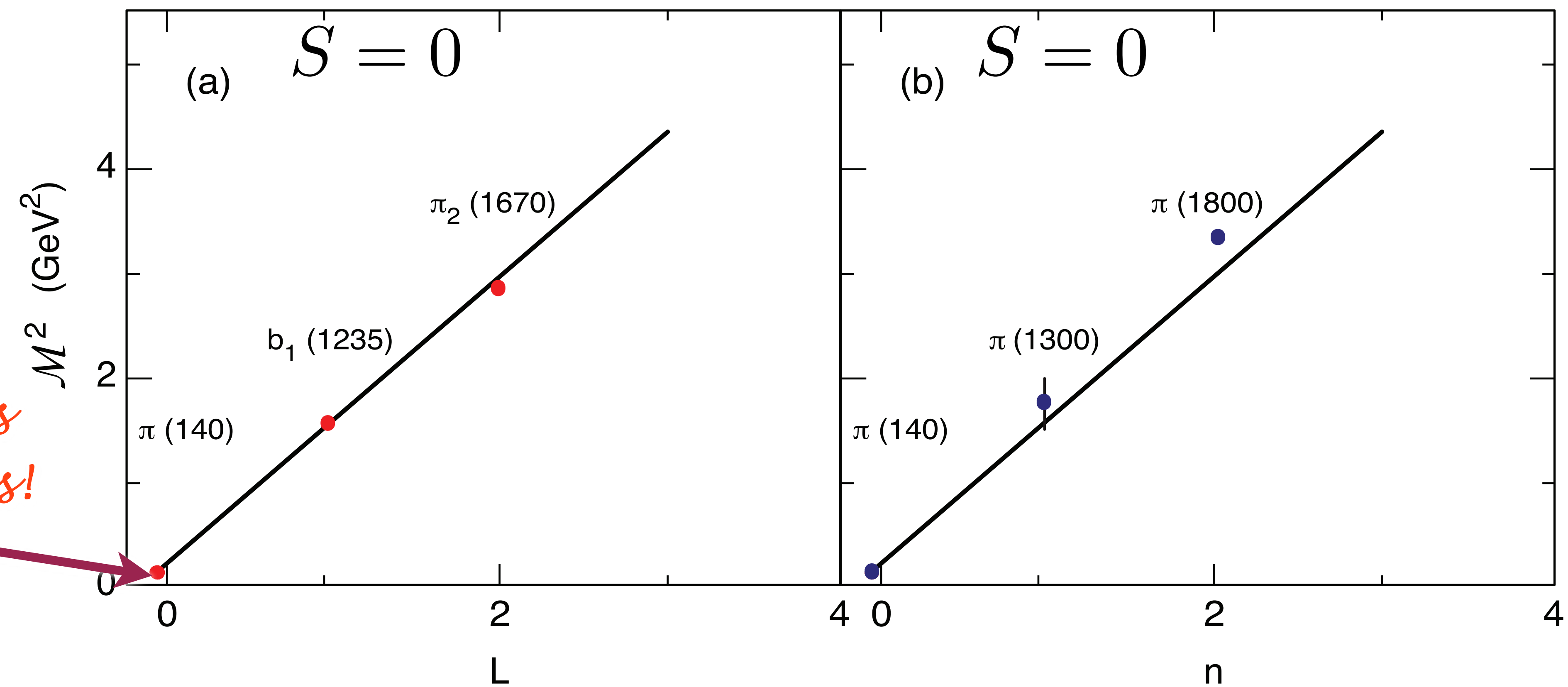


Fig: Orbital and radial AdS modes in the soft wall model for κ = 0.6 GeV .

Soft Wall Model

Same slope in n and L!

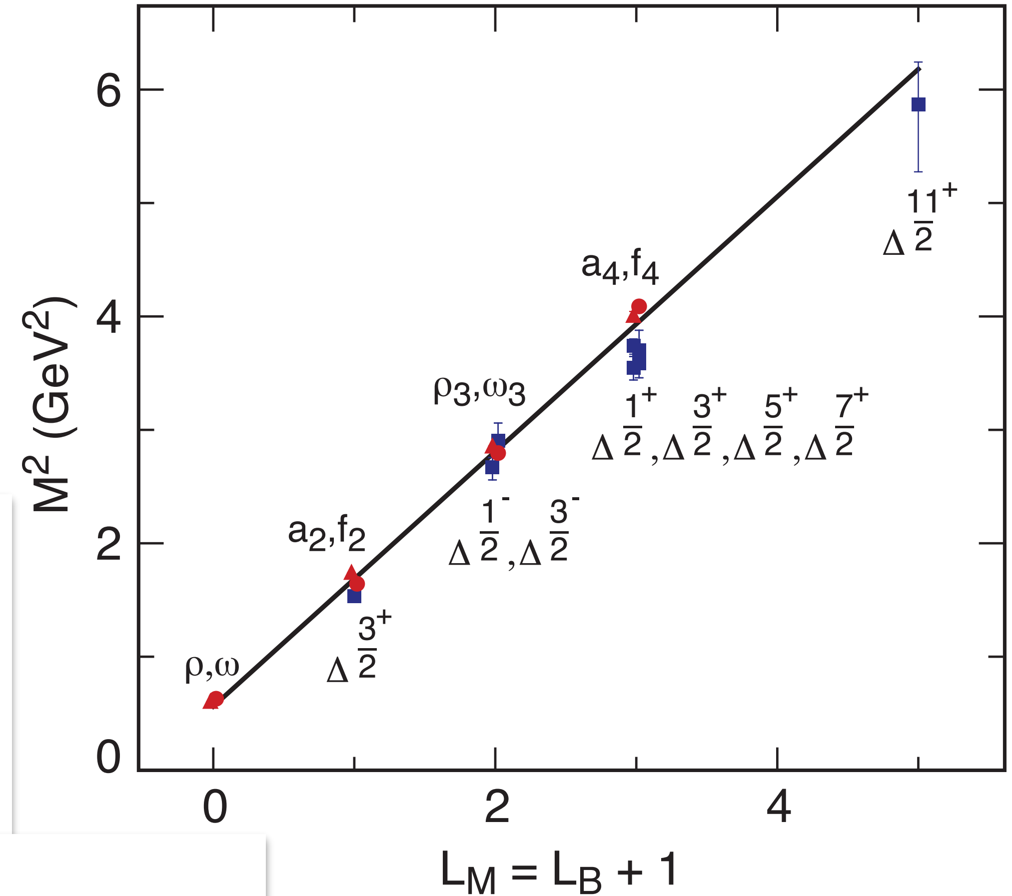


Pion has zero mass!

$m_q = 0$

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

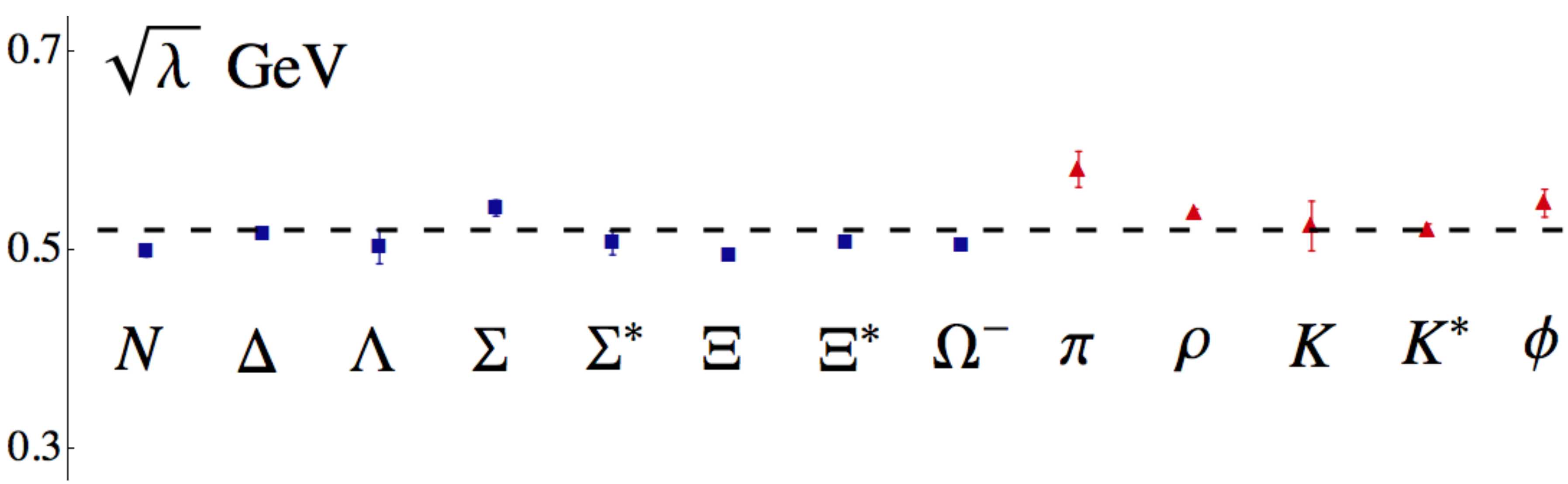
Universal Regge Slope in L and n



- (

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

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

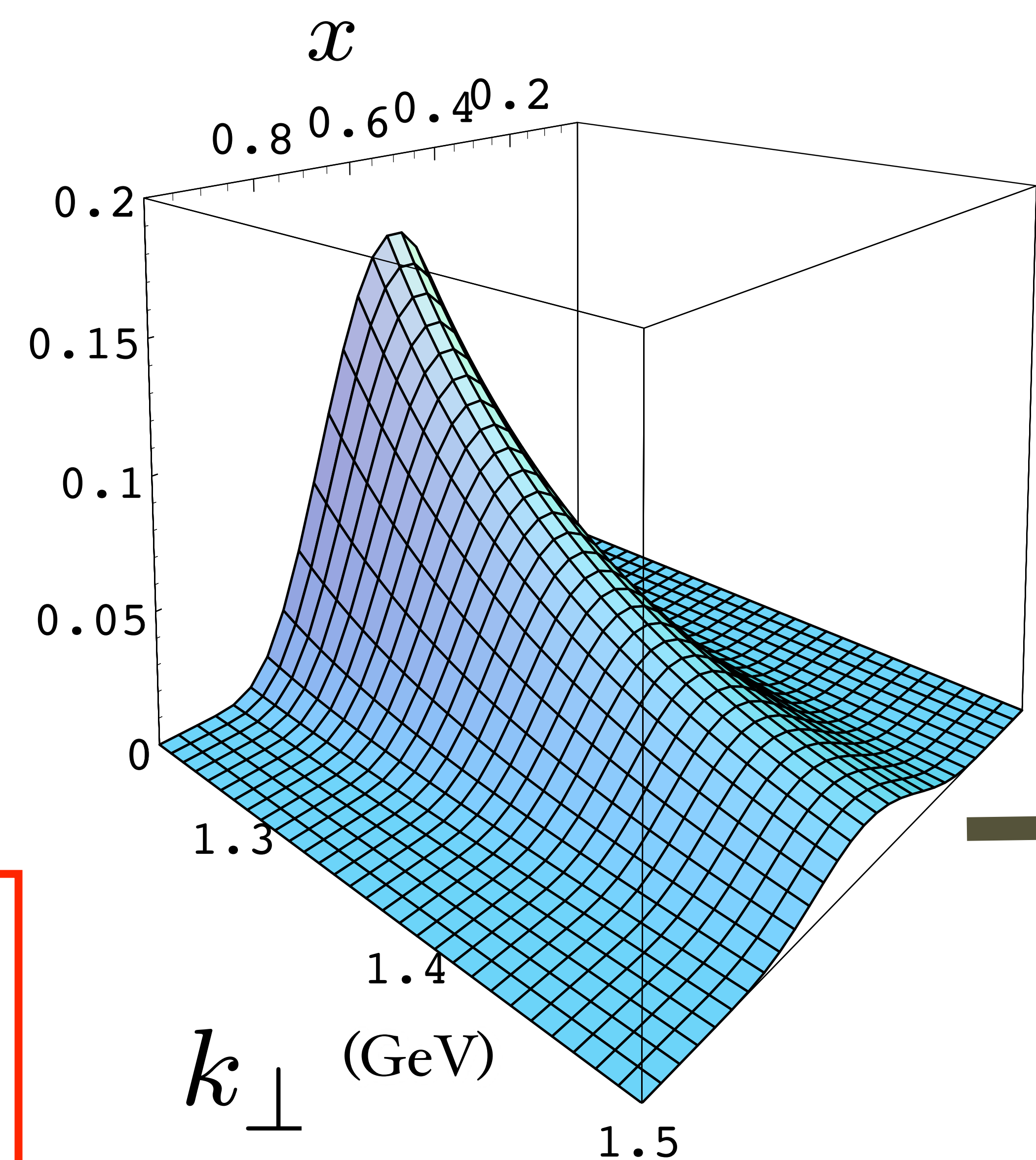


Best fit for hadronic scale $\sqrt{\lambda}$ from different light hadron sectors including radial and orbital excitations

Prediction from AdS/QCD: Meson LFWF

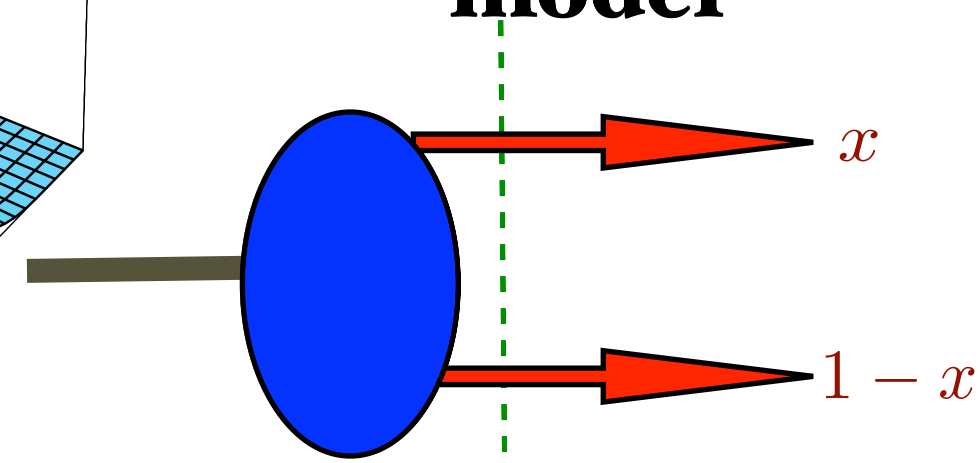
$$e^{\varphi(z)} = e^{+\kappa^2 z}$$

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



de Teramond, Cao, sjb

"Soft Wall" model



massless quarks

Note coupling

$$k_\perp^2, x$$

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

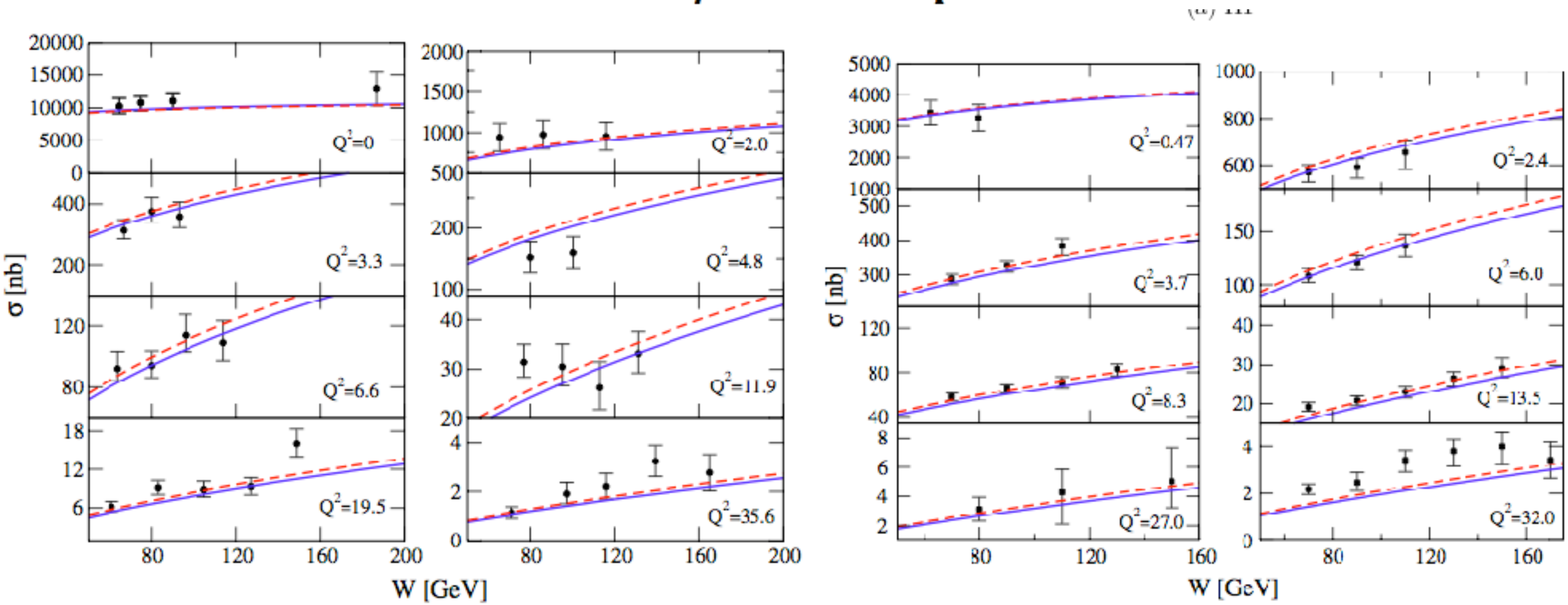
$$\phi_\pi(x) = \frac{4}{\sqrt{3}\pi} f_\pi \sqrt{x(1-x)}$$

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

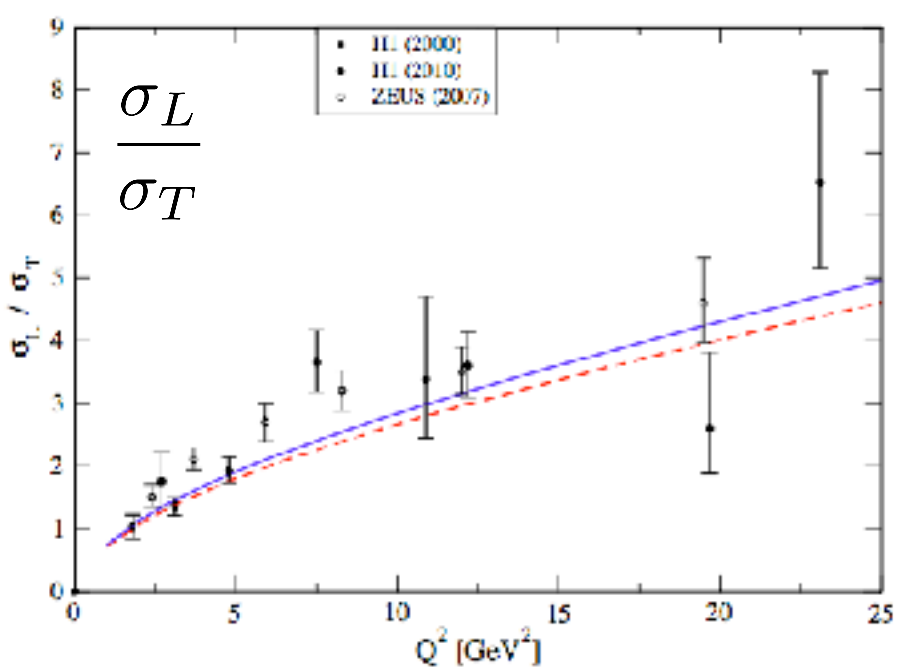
Same as DSE! **C. D. Roberts et al.**

Provides Connection of Confinement to Hadron Structure

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



(a) H1 (b) ZEUS



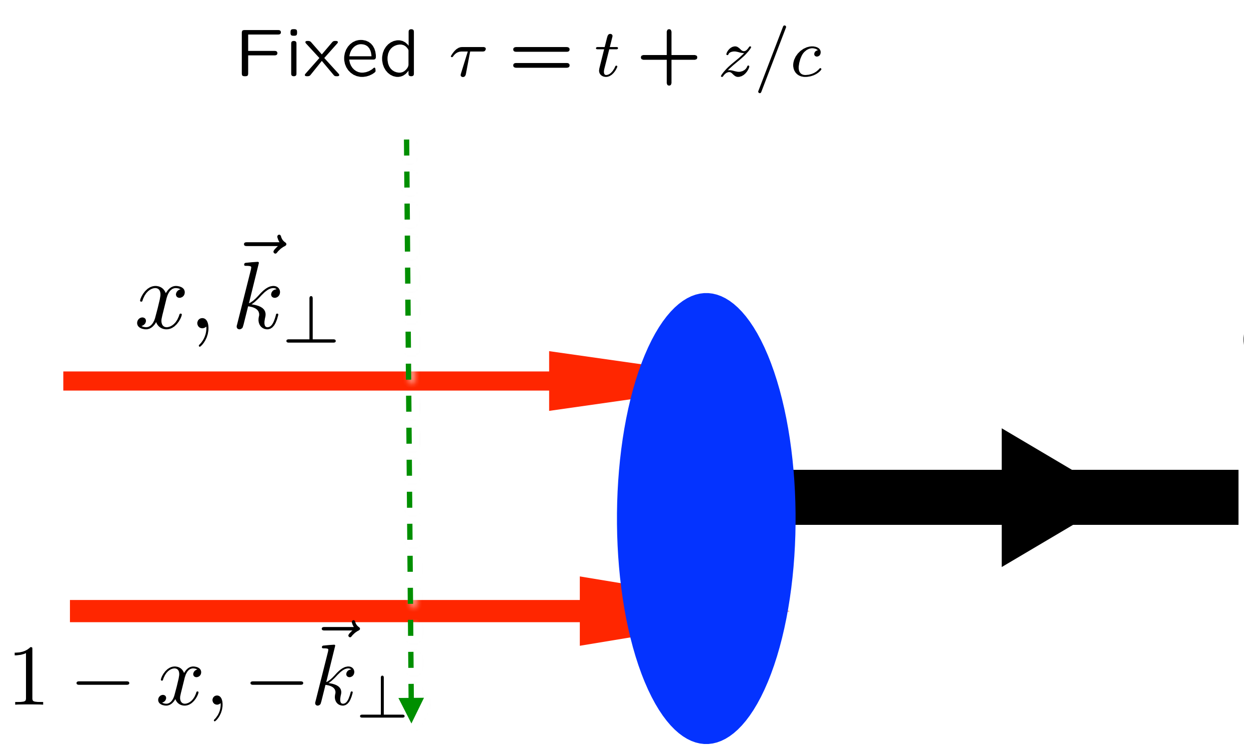
J. R. Forshaw, R. Sandapen

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

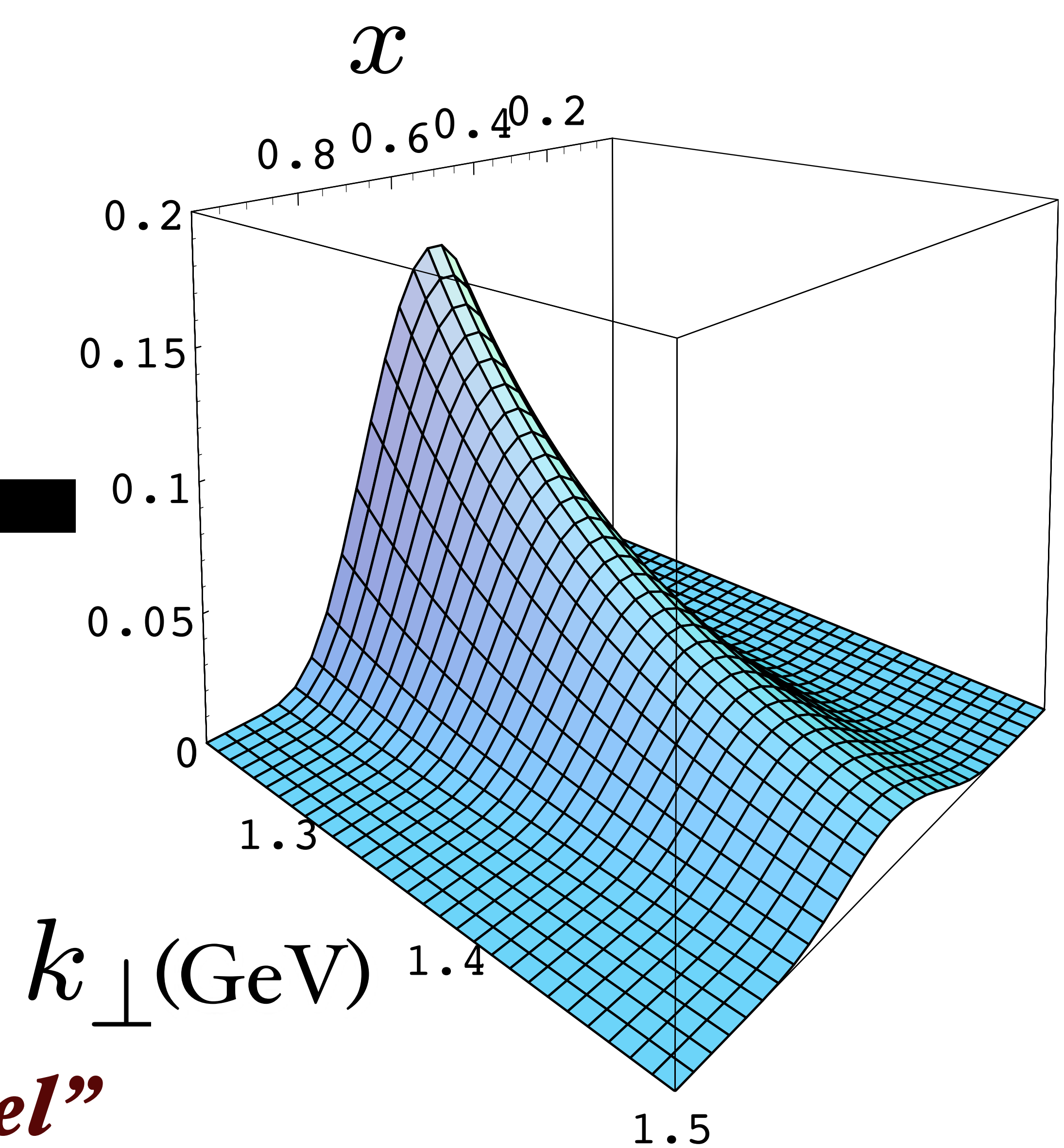
$$\psi_M(x, k_\perp) = \frac{4\pi}{\kappa\sqrt{x(1-x)}} e^{-\frac{k_\perp^2}{2\kappa^2 x(1-x)}}$$

- *Light Front Wavefunctions:* $\Psi_n(x_i, \vec{k}_{\perp i}, \lambda_i)$

off-shell in P^- and invariant mass $\mathcal{M}^2_{q\bar{q}}$



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



"Hadronization at the Amplitude Level"

Boost-invariant LFWF connects confined quarks and gluons to hadrons

Light-Front Holography: First Approximation to QCD

- **Color Confinement, Analytic form of confinement potential**

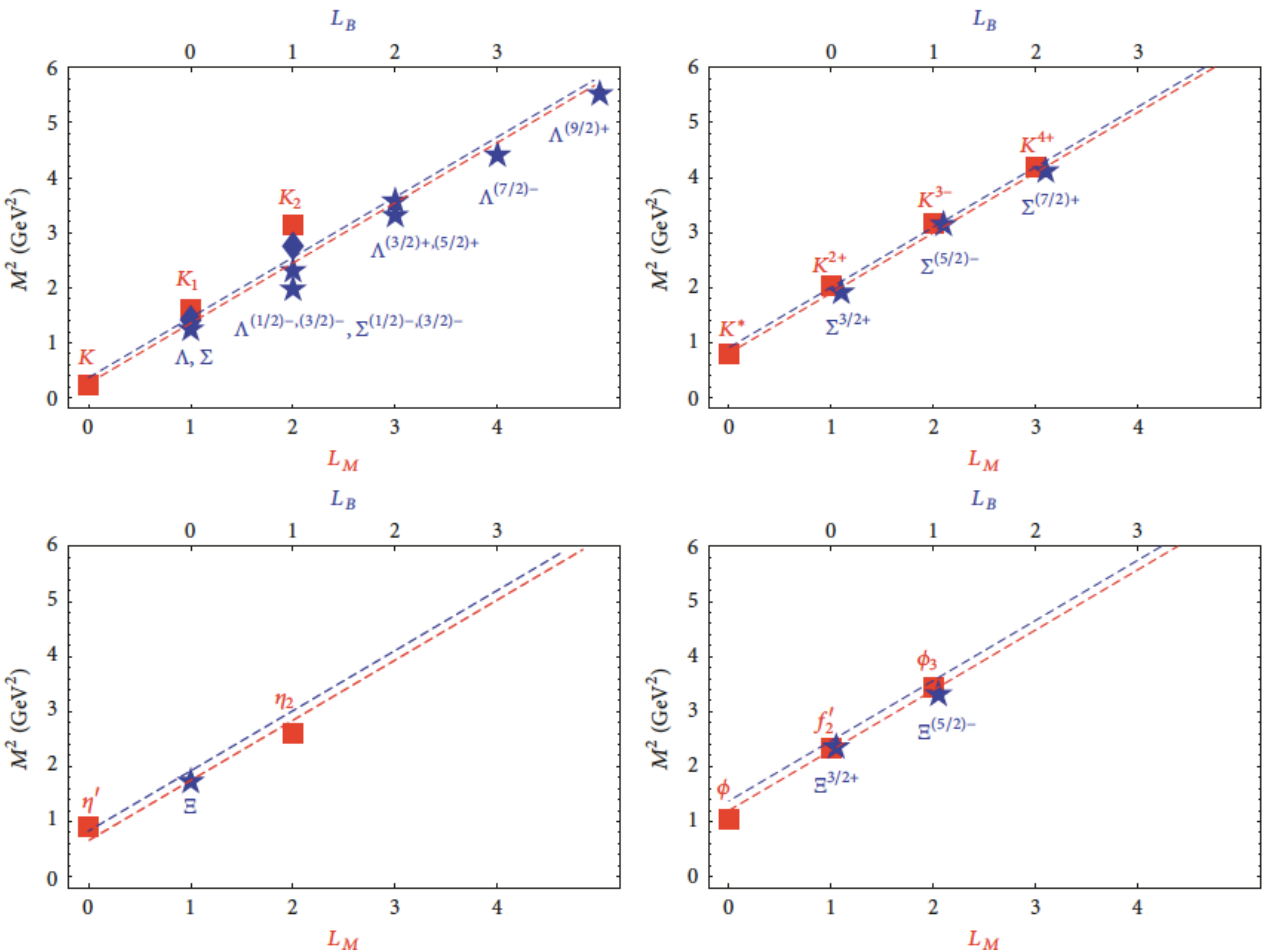
de Téramond, Dosch, Lorcé, sjb

- **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**
- **Hadron Spectroscopy-Regge Trajectories with universal slopes in n, L**
- **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

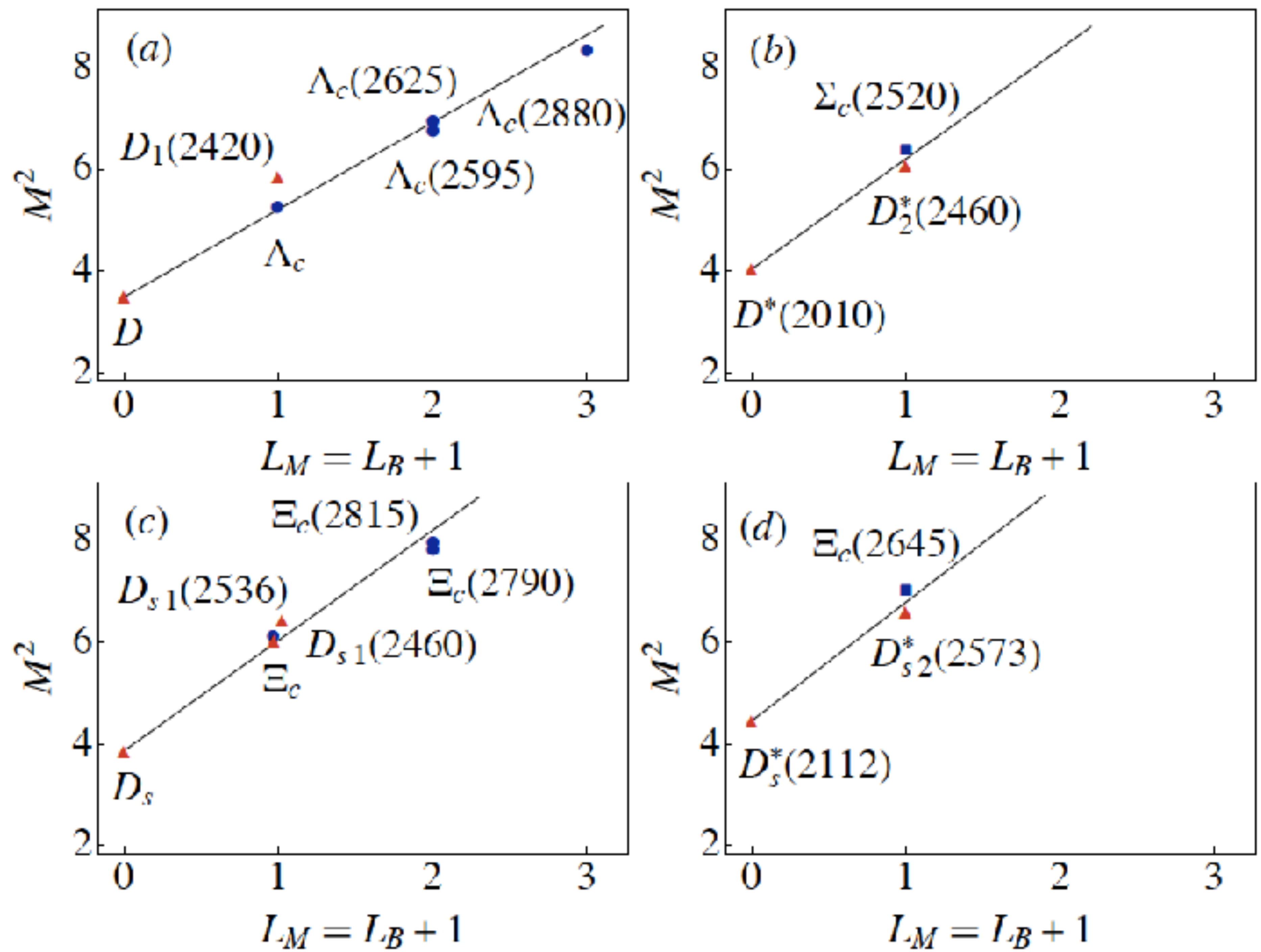
de Téramond, Dosch, Lorcé, sjb

Supersymmetry across the light and heavy-light spectrum



de Téramond, Dosch, Lorcé, sjb

Supersymmetry across the light and heavy-light spectrum

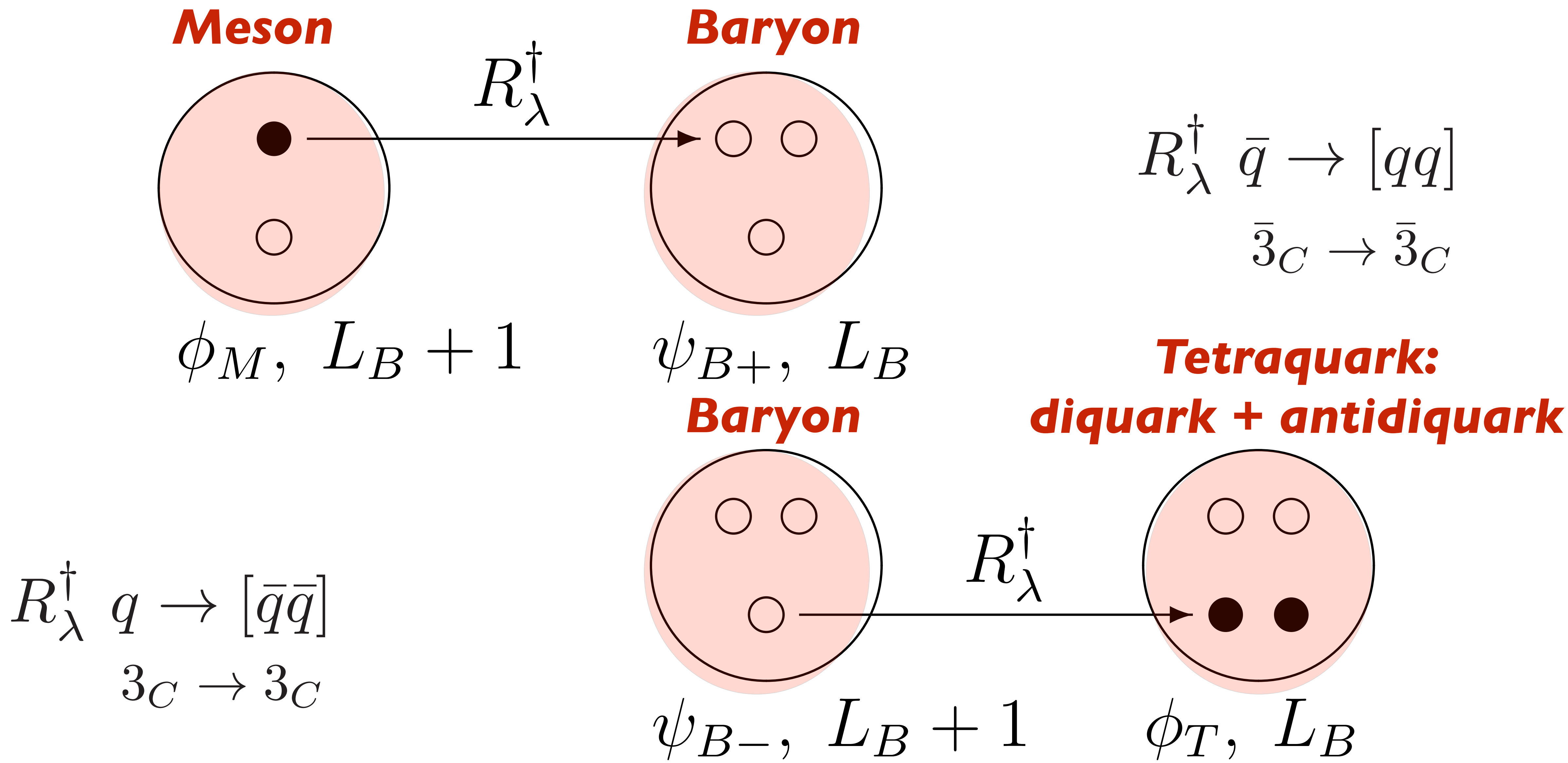


Heavy charm quark mass does not break supersymmetry

Superconformal Algebra

Four-Plet Representations

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

$f_2(1270)$

$\Delta^+(1232)$

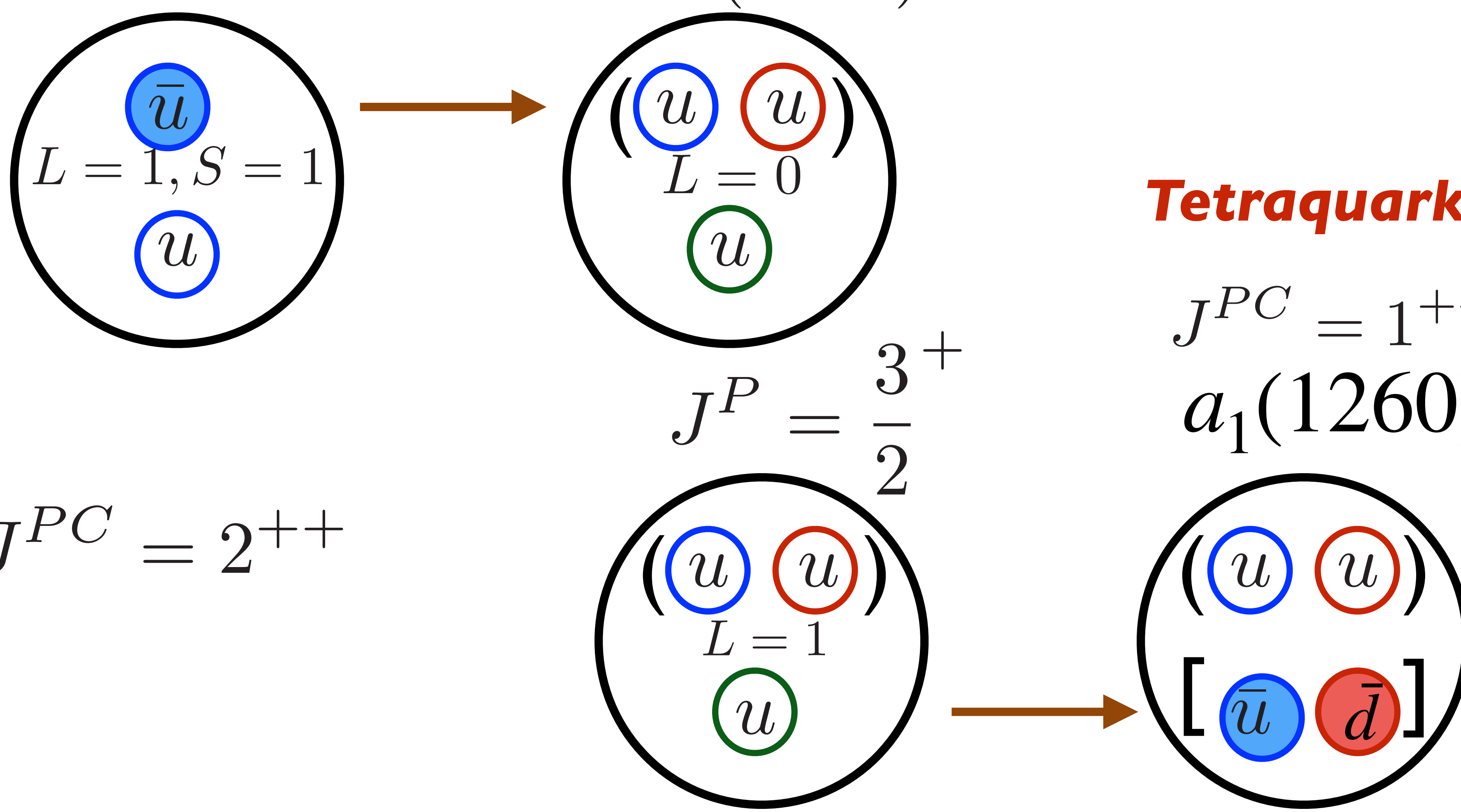
Tetraquark

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

$a_1(1260)$

$J^P = \frac{3}{2}^+$

$J^{PC} = 2^{++}$



$S=0$

$L=0$

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

$3_C \to 3_C$

Meson

Baryon

Superconformal meson-baryon-tetraquark symmetry

H. G. Dosch, G. d-Te'ramond, sjb, PRD 91, 085016 (2015)

Upon the substitution in the superconformal equations

$$x \mapsto \zeta, \quad E \mapsto M^2,$$

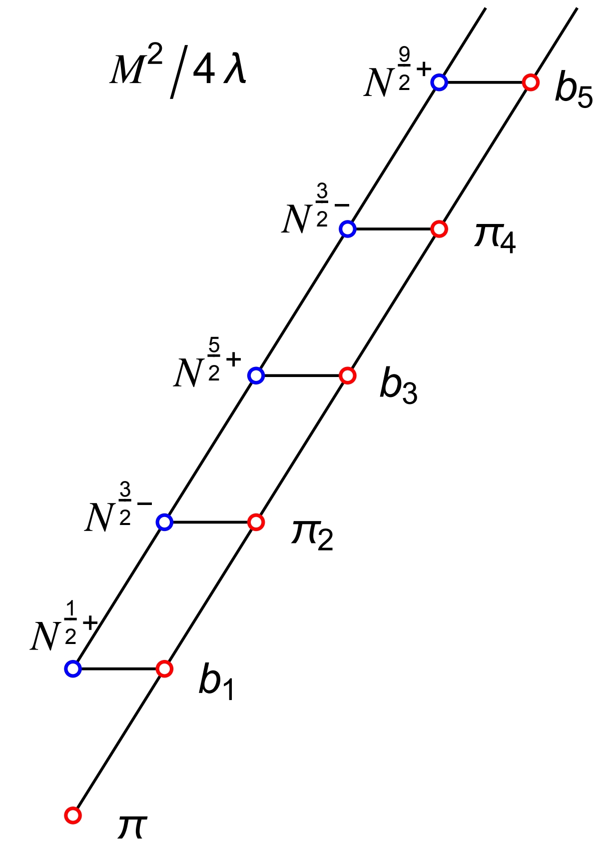
$$\lambda \mapsto \lambda_B = \lambda_M, \quad f \mapsto L_M - \tfrac{1}{2} = L_B + \tfrac{1}{2}$$

$$\phi_1 \mapsto \phi_M, \quad \phi_2 \mapsto \phi_B$$

we find the LF meson/baryon bound-state equations

$$\left(-\frac{d^2}{d\zeta^2} + \frac{4L_M^2 - 1}{4\zeta^2} + \lambda_M^2\,\zeta^2 + 2\lambda_M(L_M - 1)\right)\phi_M = M^2\,\phi_M$$

$$\left(-\frac{d^2}{d\zeta^2} + \frac{4L_B^2 - 1}{4\zeta^2} + \lambda_B^2\,\zeta^2 + 2\lambda_B(L_N + 1)\right)\phi_B = M^2\,\phi_B$$



$$\Phi = \begin{pmatrix} \phi_M & \phi_B^- \\ \phi_B^+ & \phi_T \end{pmatrix}$$

Superconformal QM imposes the condition $\lambda = \lambda_M = \lambda_B$ (equality of Regge slopes) and the remarkable relation $L_M = L_B + 1$

L_M is the LF angular momentum between the quark and antiquark in the meson and L_B between the active quark and spectator diquark cluster in the baryon

Full hadron 4-plet: meson-baryon-tetraquark

G d-Te'ramond, H. G. Dosch and C. Lorce, PLB 759, 171 (2016)

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^{++}	$a_3(\sim 2070)?$
$\bar q s$	$0^{-(+)}$	$K(495)$	—	—	—	—	—	—
$\bar q s$	$1^{+(-)}$	$\bar K_1(1270)$	$[ud]s$	$(1/2)^+$	$\Lambda(1115)$	$[ud][\bar s \bar q]$	$0^{+(+)}$	$K_0^*(1430)$
$\bar q s$	$2^{-(+)}$	$K_2(1770)$	$[ud]s$	$(1/2)^-$	$\Lambda(1405)$	$[ud][\bar s \bar q]$	$1^{-(+)}$	$K_1^*(\sim 1700)?$
				$(3/2)^-$	$\Lambda(1520)$			
$\bar s q$	$0^{-(+)}$	$K(495)$	—	—	—	—	—	—
$\bar s q$	$1^{+(-)}$	$K_1(1270)$	$[sq]q$	$(1/2)^+$	$\Sigma(1190)$	$[sq][\bar s \bar q]$	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

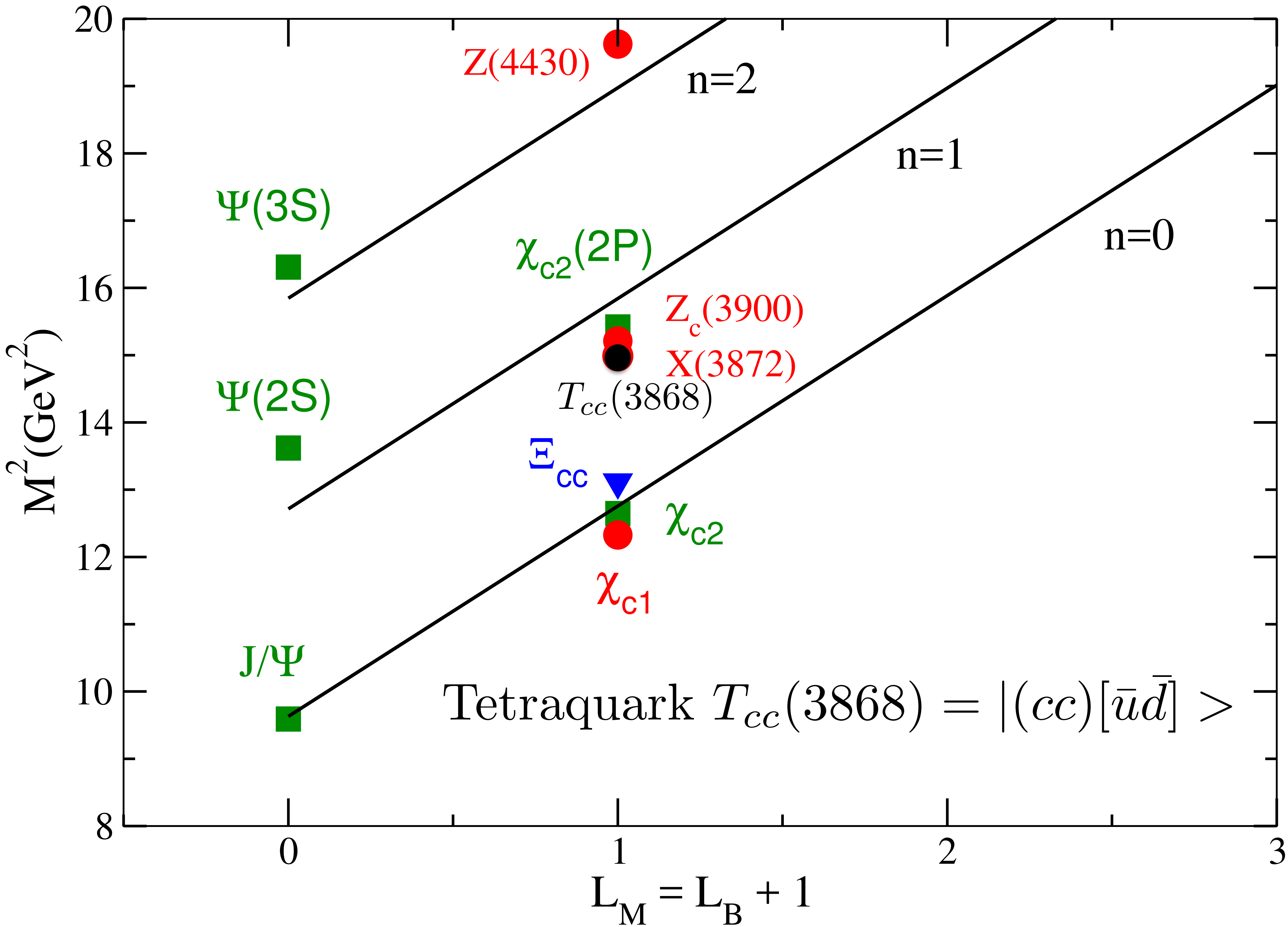
Superpartners for states with one c quark

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



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

Connection to the Linear Instant-Form Heavy Quark Potential

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

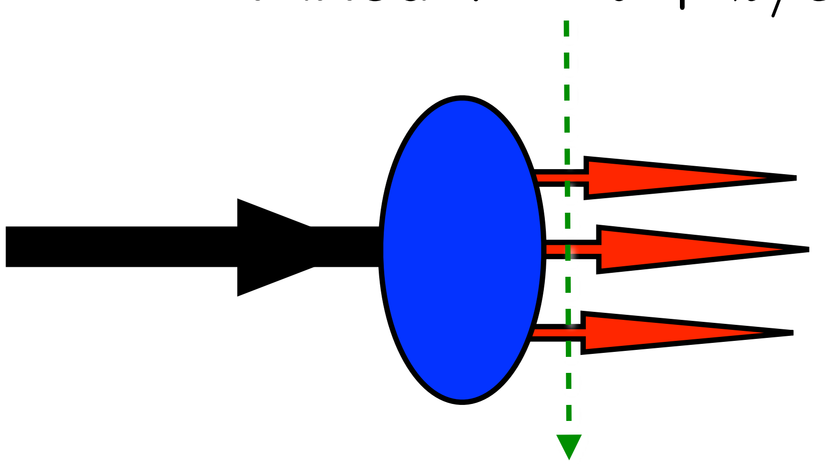
Linear instant nonrelativistic form $V(r) = Cr$ for heavy quarks

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

Bound States in Relativistic Quantum Field Theory:

Light-Front Wavefunctions

Dirac's Front Form: 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

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

Direct connection to QCD Lagrangian

LF Wavefunction: off-shell in invariant mass

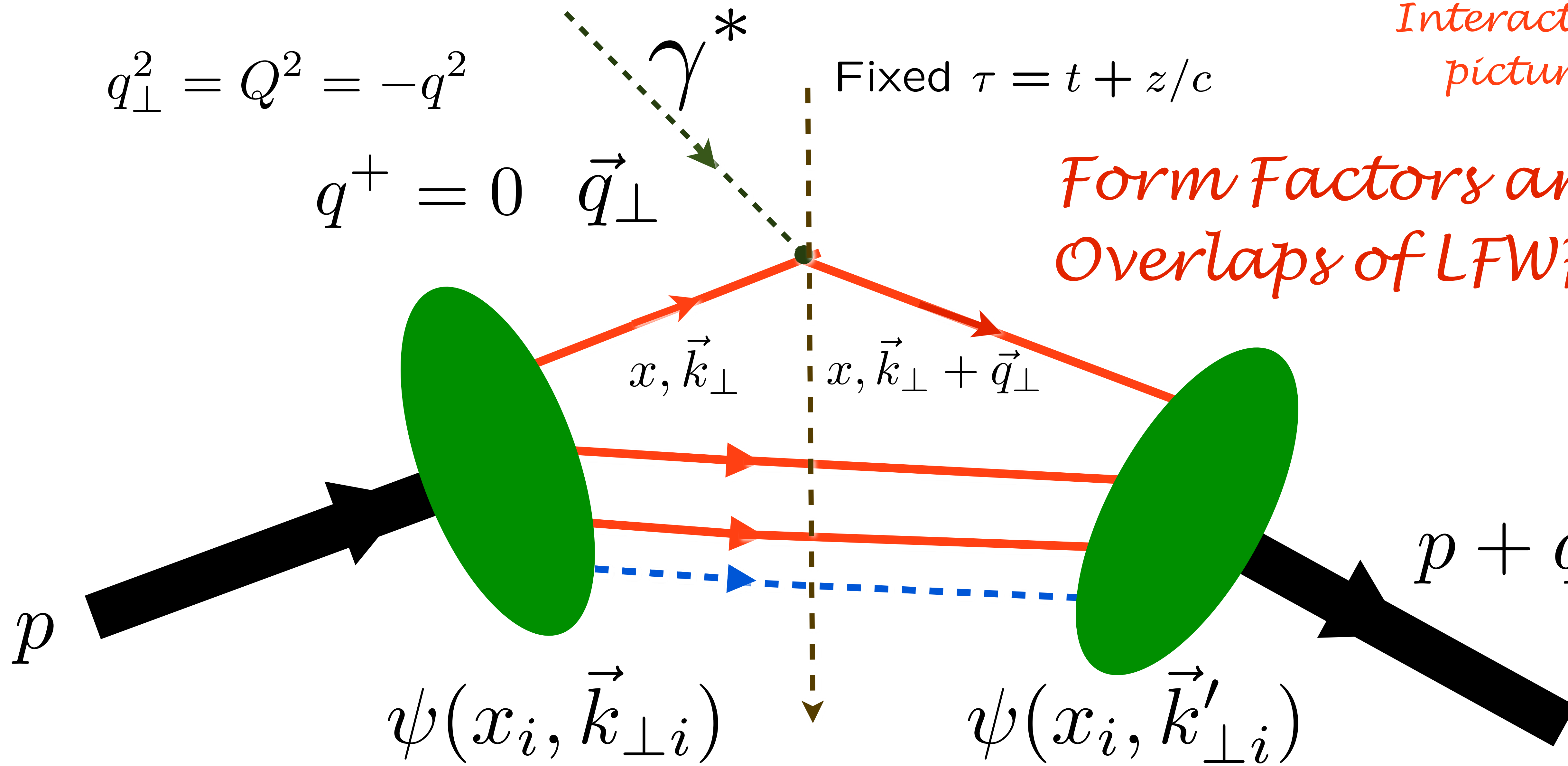
Remarkable new insights from AdS/CFT, the duality between conformal field theory and Anti-de Sitter Space

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

Front Form

Interaction picture

Form Factors are Overlaps of LFWFs



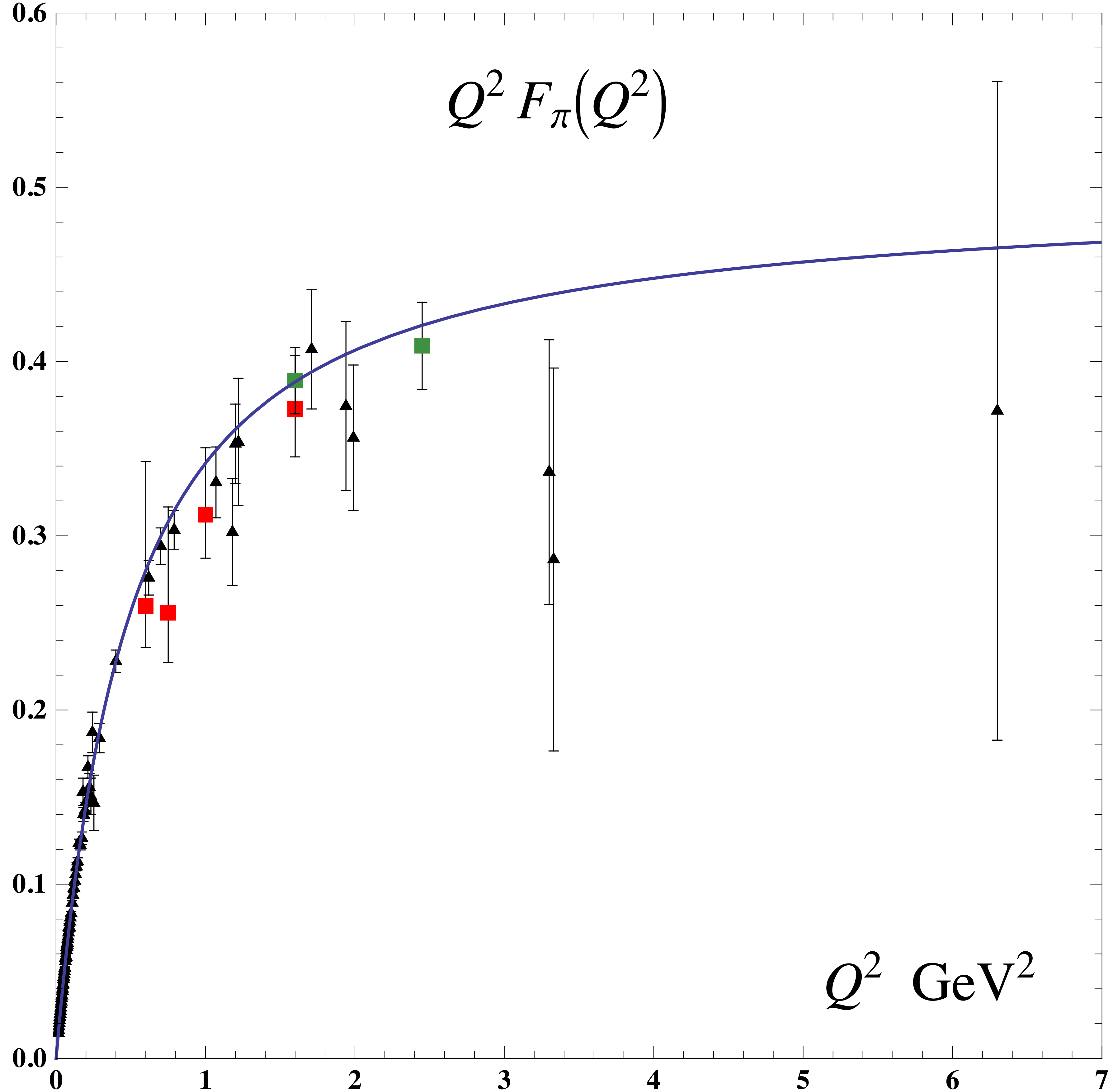
struck $\vec{k}'_{\perp i} = \vec{k}_{\perp i} + (1 - x_i)\vec{q}_\perp$

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

Drell &Yan, West
Exact LF formula!

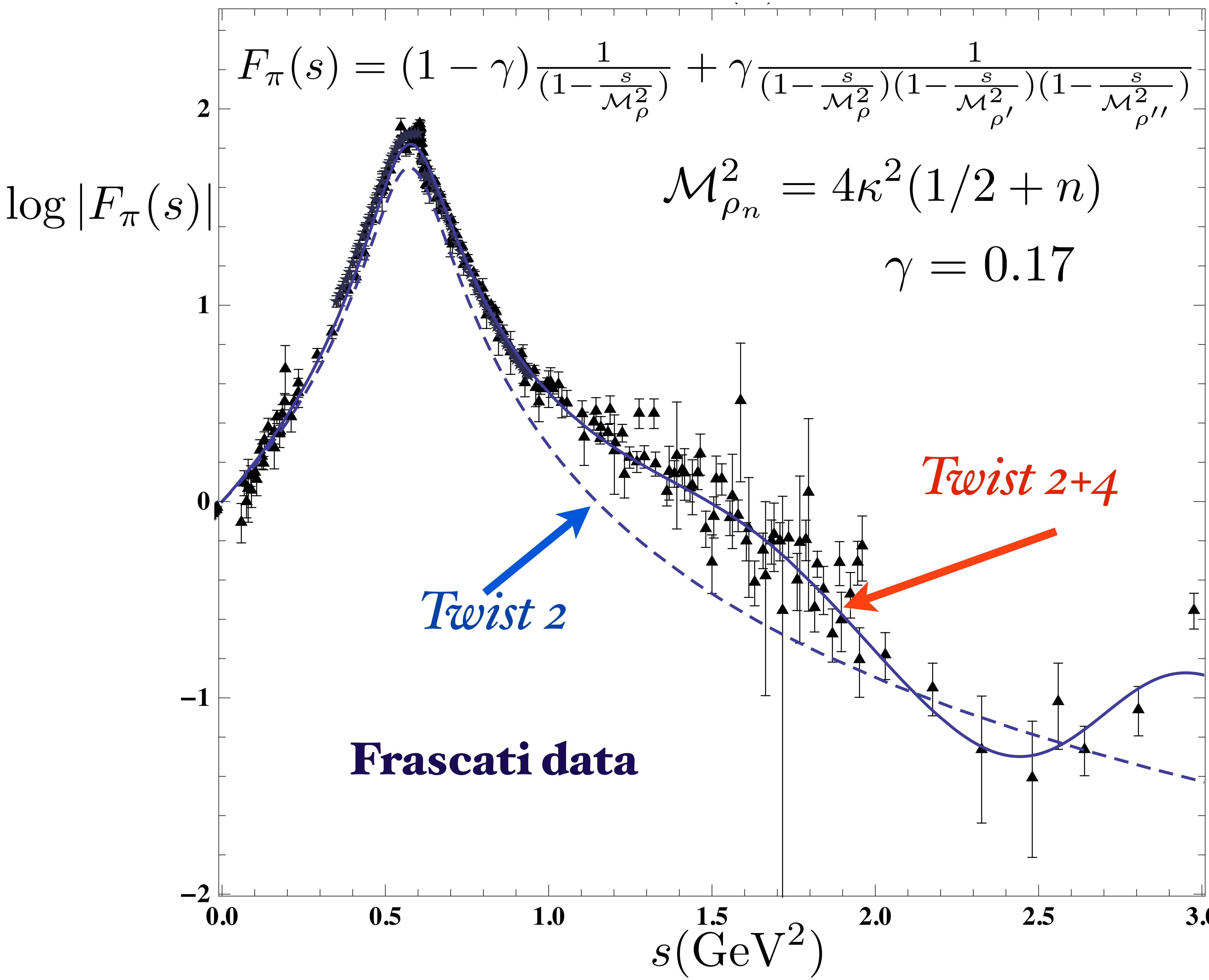
Drell, sjb

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



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

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



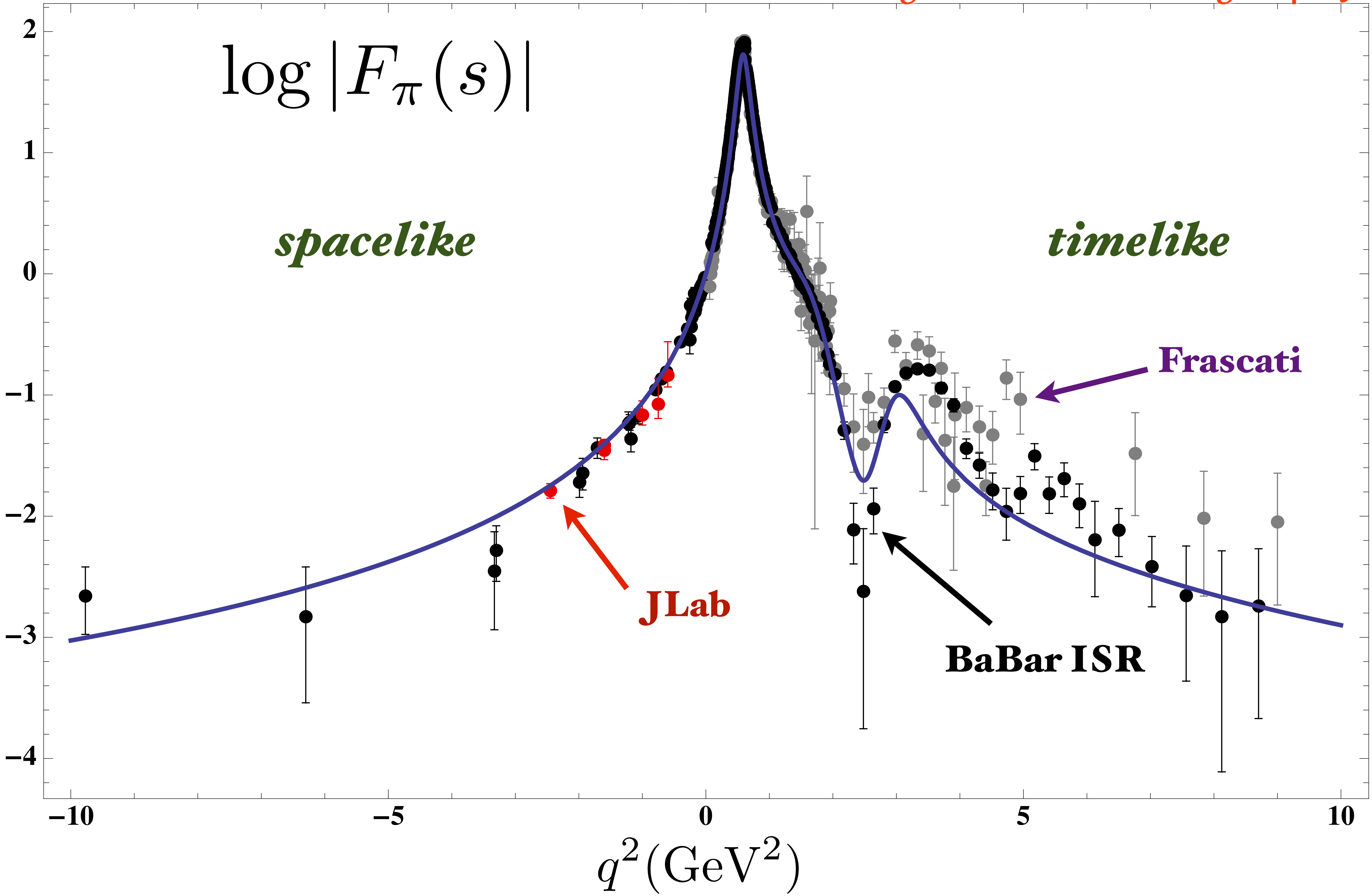
Prescription for Timelike poles :

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

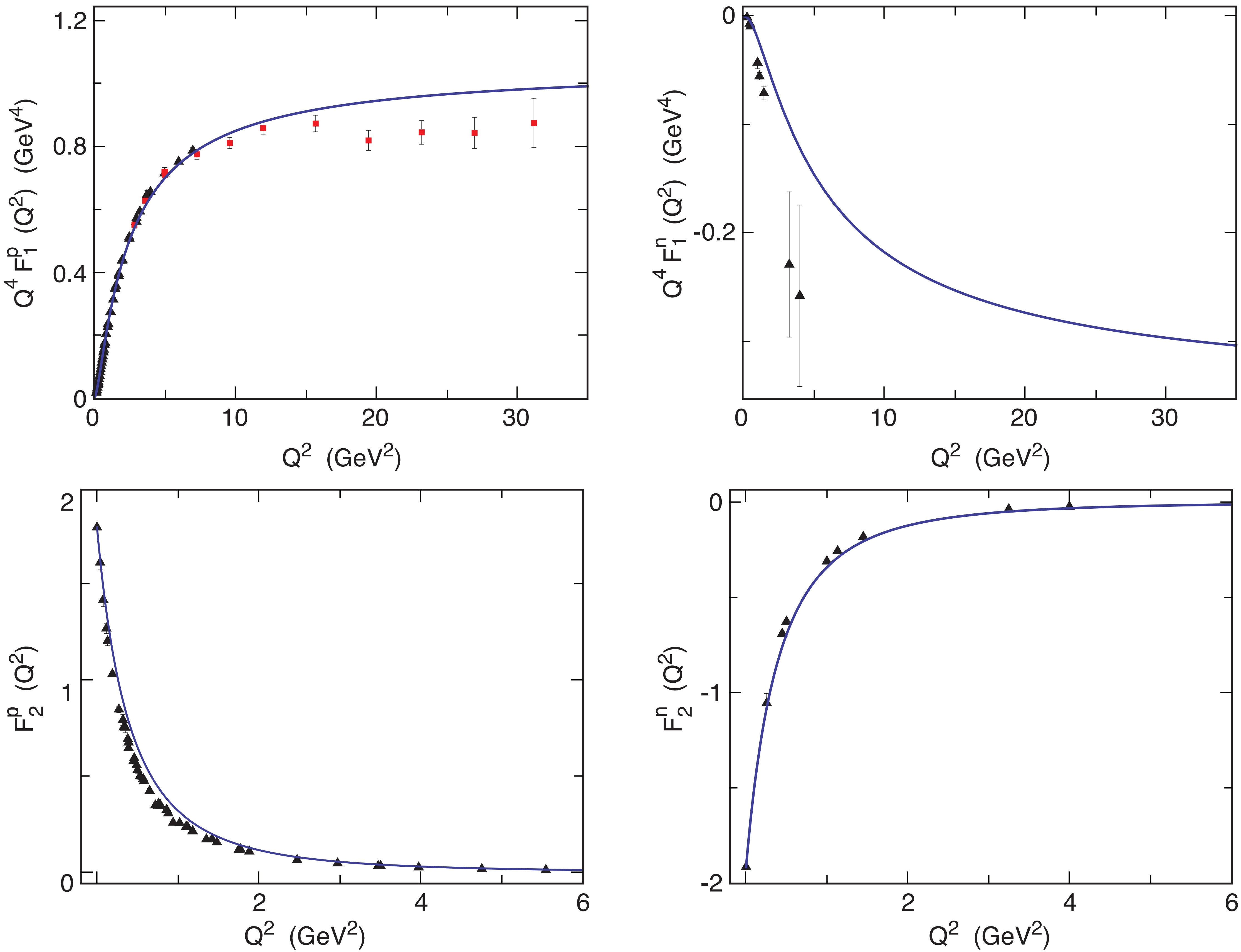
14% four-quark probability

G. de Teramond & sjb

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



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



Exact LF Formula for Pauli Form Factor

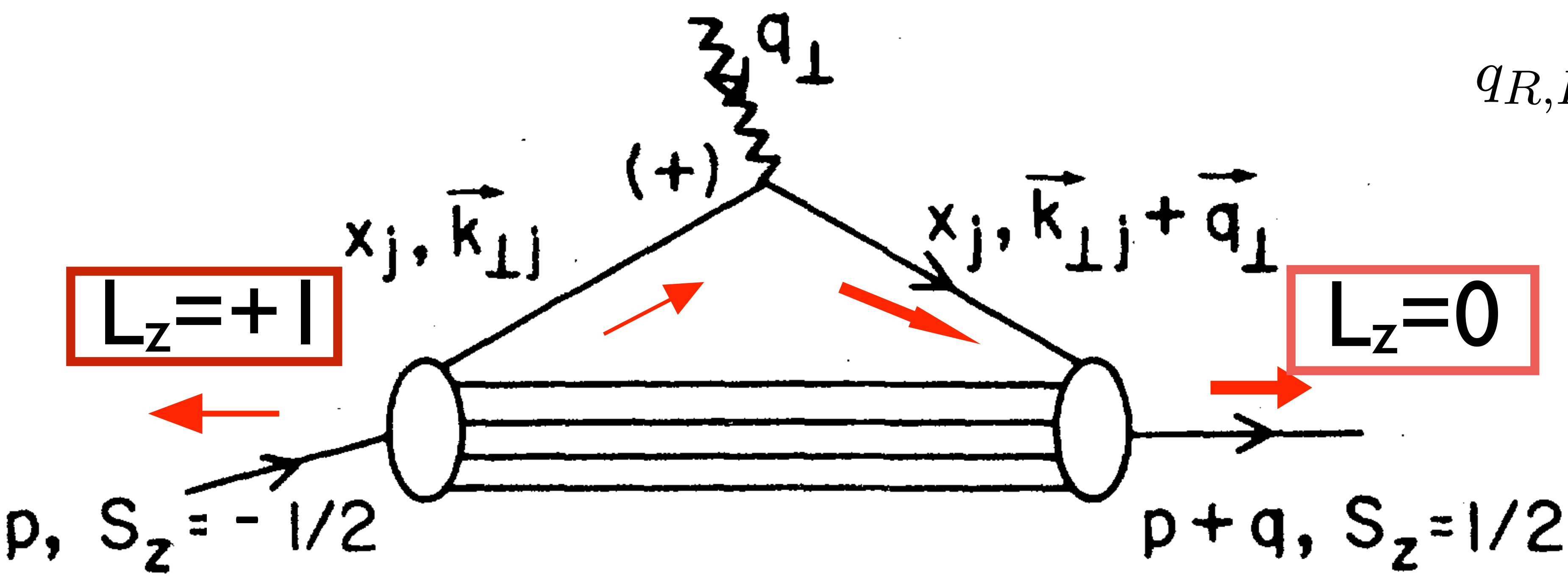
$$\frac{F_2(q^2)}{2M} = \sum_a \int [\mathrm{d}x][\mathrm{d}^2\mathbf{k}_\perp] \sum_j e_j \, \frac{1}{2} \times$$

Drell, sjb

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

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

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

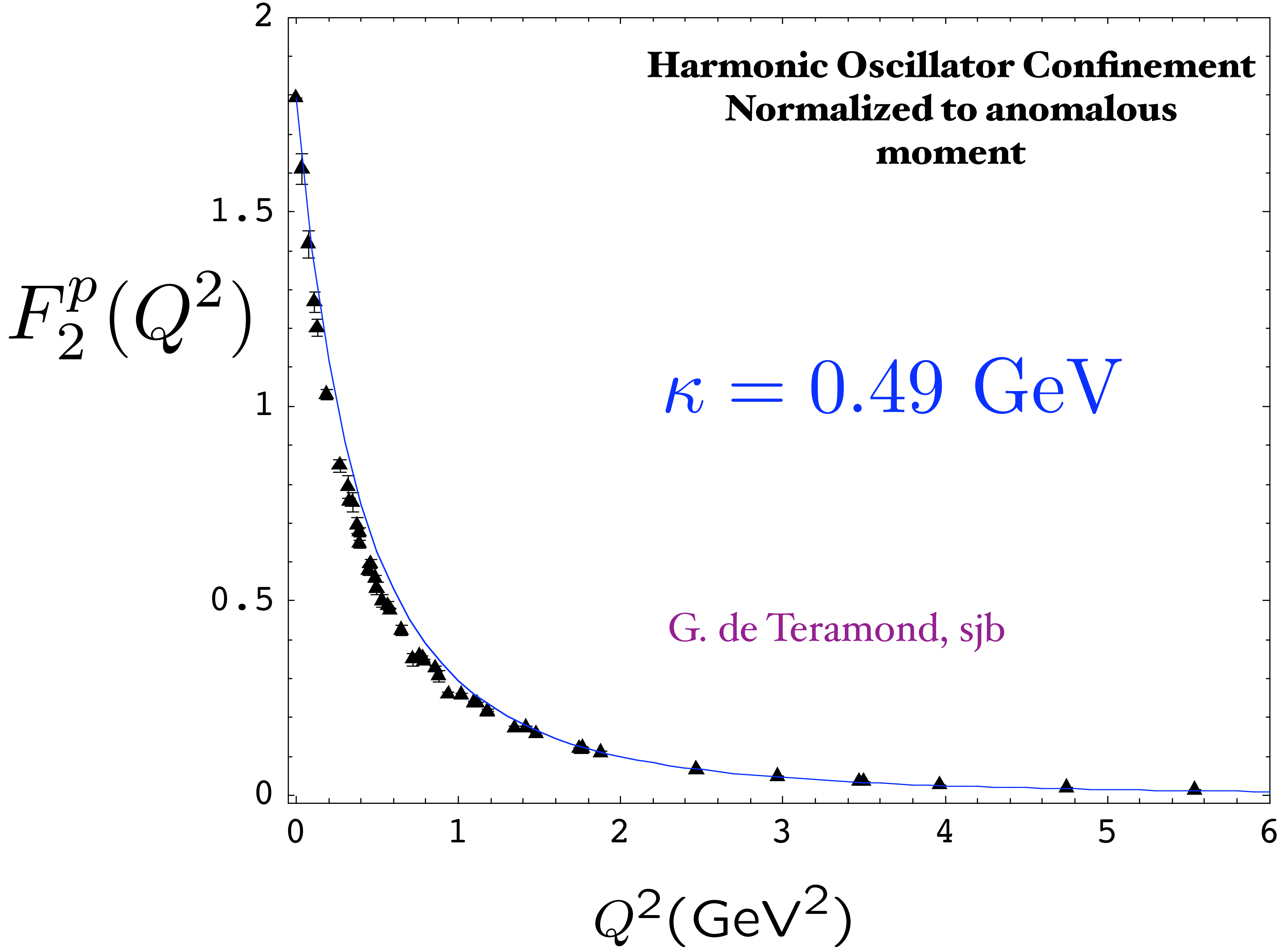


Must have $\Delta \ell_z = \pm 1$ to have nonzero $F_2(q^2)$

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

Spacelike Pauli Form Factor

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



Deur, de Tèramond, sjb

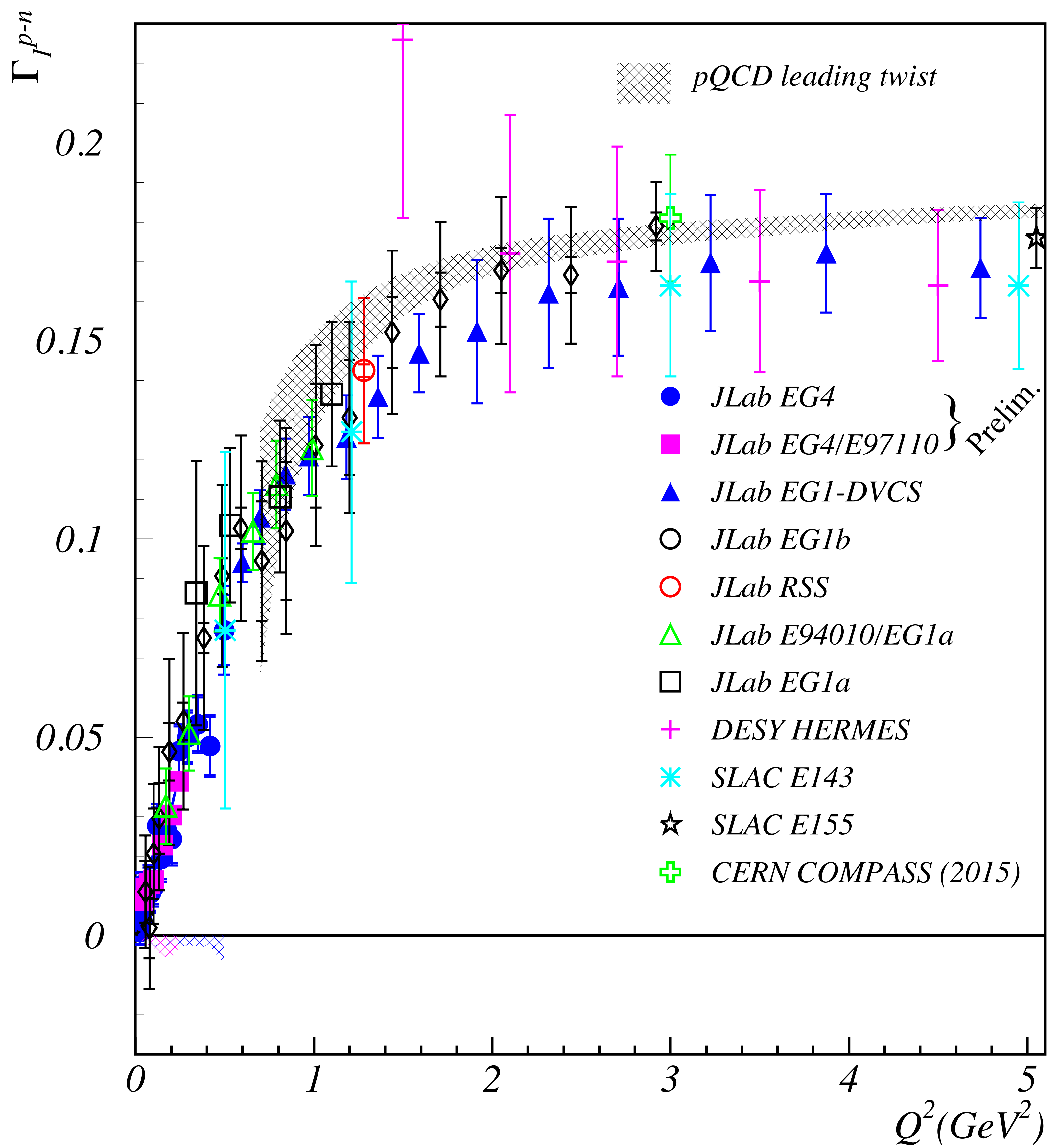
Bjorken sum rule defines effective charge: $\alpha_{g1}(Q^2)$

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

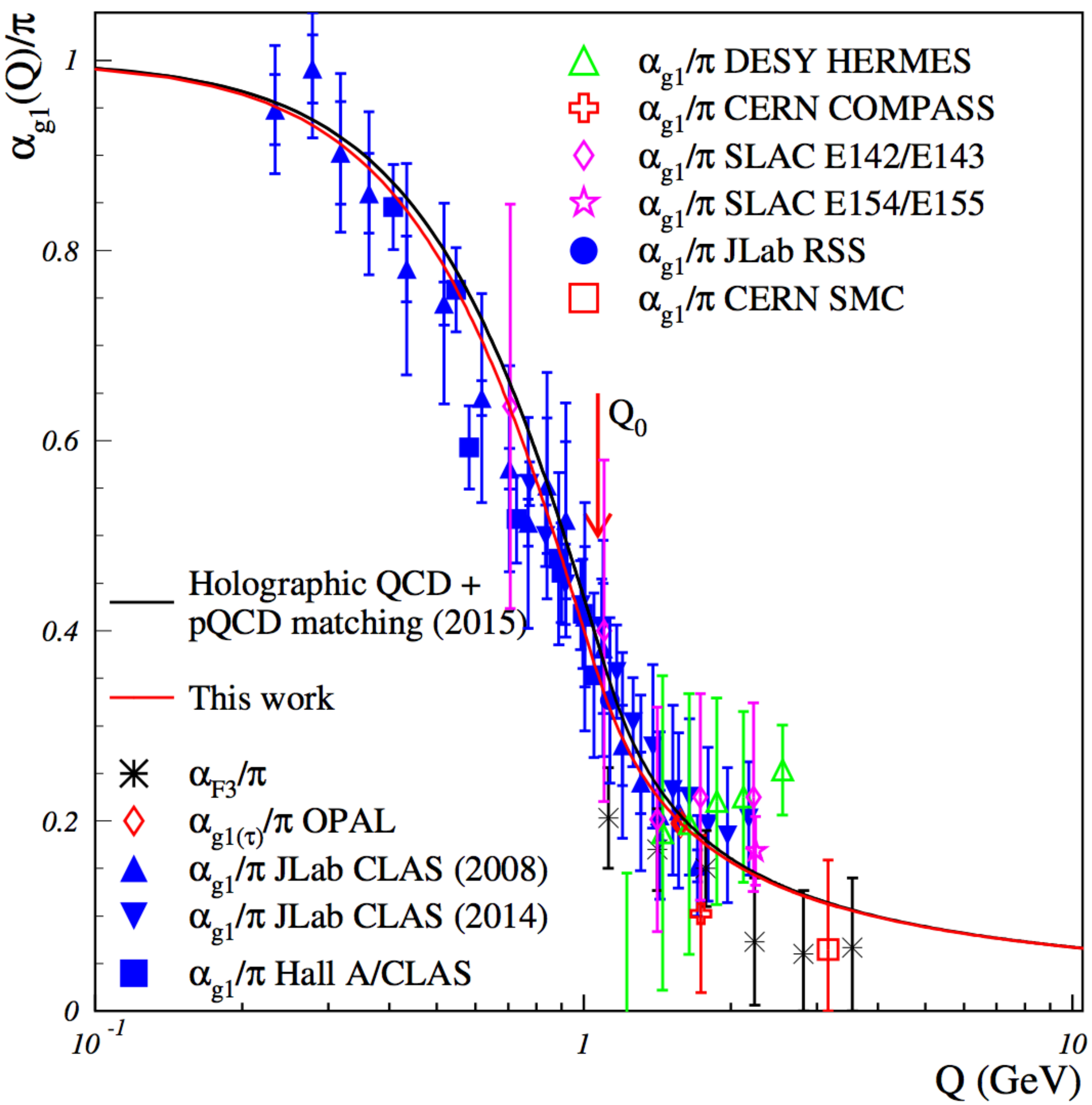
- ***Can be used as standard QCD coupling***
- ***Well measured***
- ***Asymptotic freedom at large Q^2***
- ***Computable at large Q^2 in any pQCD scheme***
- ***Universal β_0, β_1***
- ***Analytic connection to other schemes:***

Commensurate scale relations

Bjorken sum $\Gamma_1^{p\text{-}n}$ measurements



Running 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

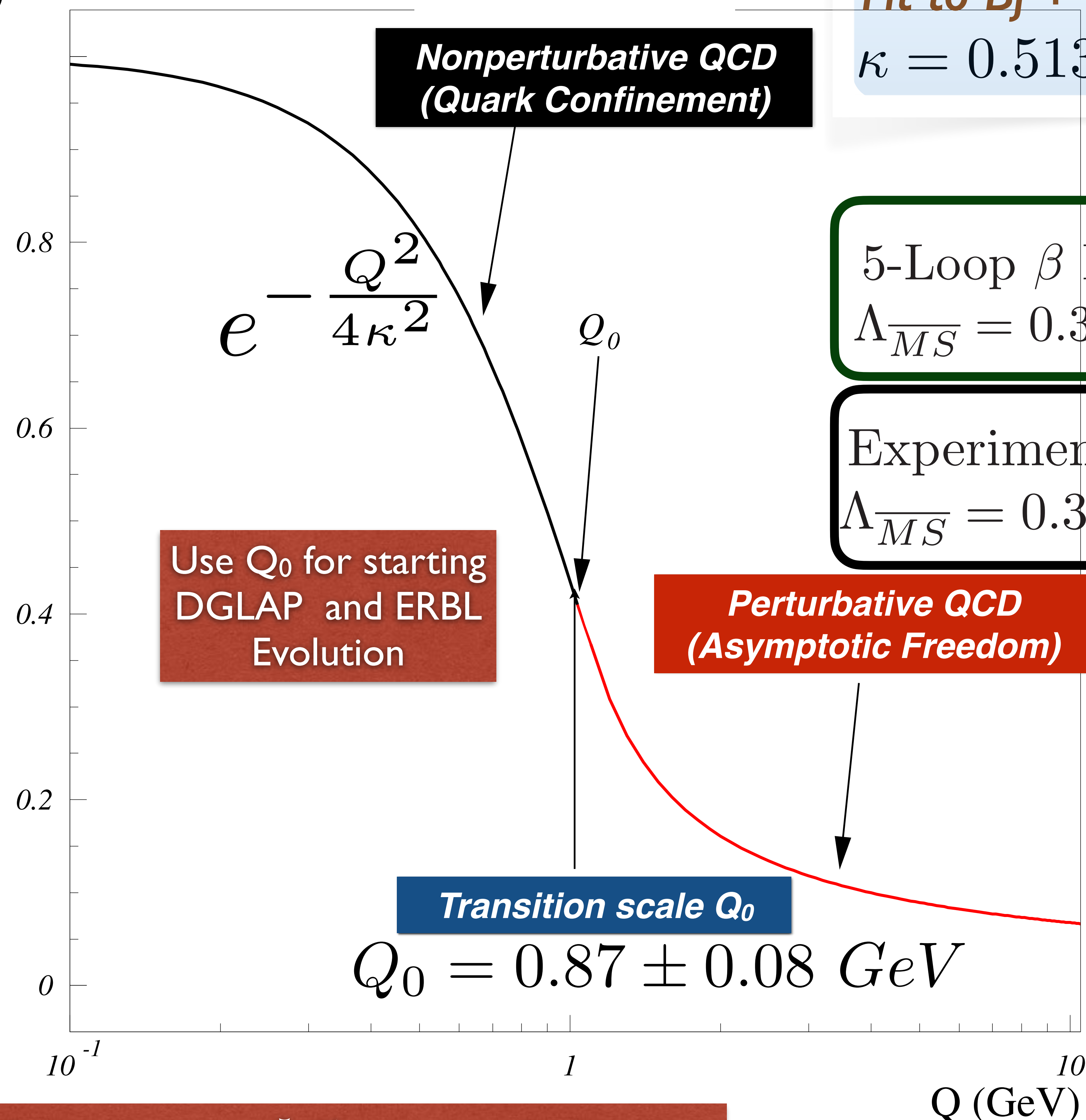
Deur, de Tèramond, sjb

Fit to Bj + DHG Sum Rules:
$\kappa = 0.513 \pm 0.007\ GeV$

5-Loop β Prediction:
$\Lambda_{\overline{MS}} = 0.339 \pm 0.019\ GeV$

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

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



$\lambda \equiv \kappa^2$

Reverse Dimensional Transmutation!

A. Deur, G. d T`eramond, sjb

Initial DGLAP evolution scale form IR-UV matching of QCD coupling

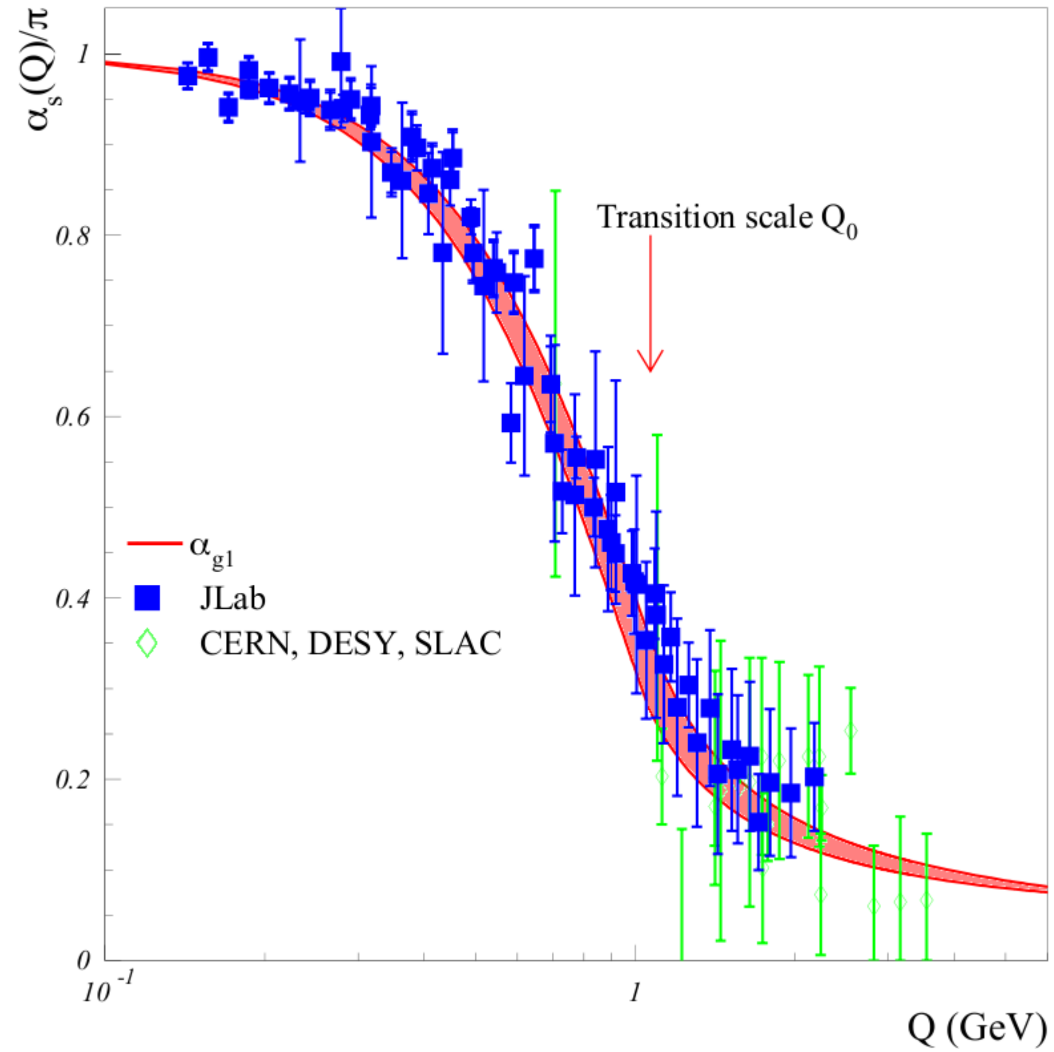
IR behavior of strong coupling in LFHQCD

$$\alpha_s^{IR}(Q^2) = \alpha_s^{IR}(0) e^{-Q^2/4\lambda}$$

Λ_{QCD} and transition scale Q_0 from matching perturbative (5-loop) and nonperturbative regimes for $\sqrt{\lambda} = 0.534 \pm 0.05$ GeV

Transition scale: $Q_0^2 \simeq 1$ GeV^2

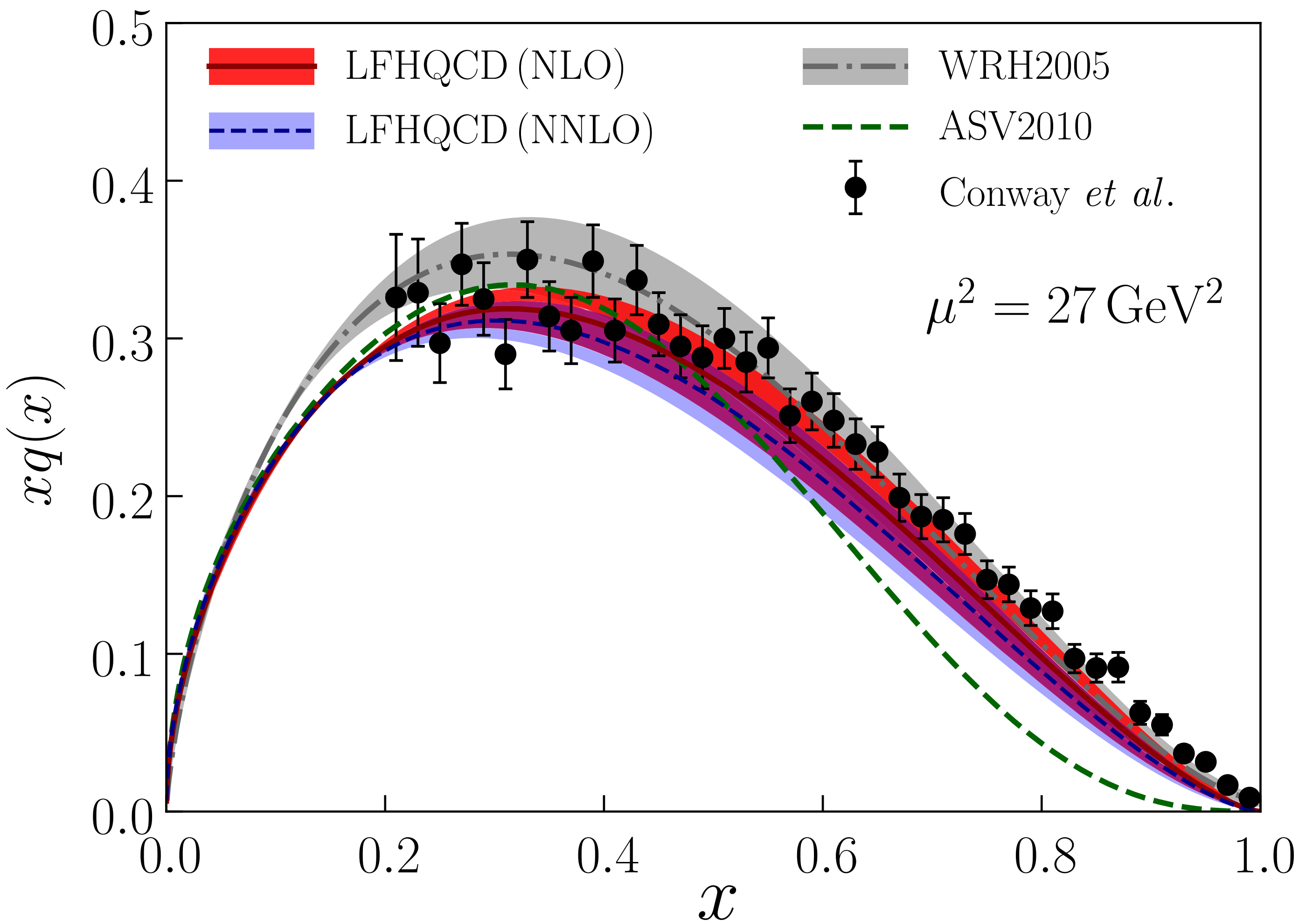
Connection between proton mass, $M_p^2 = 4\lambda$, the ρ mass, $M_\rho^2 = 2\lambda$, and the perturbative QCD scale Λ_{QCD} in any RS !



IR QCD strong coupling from Bjorken sum-rule vs HLFQCD prediction (red)

Similar behavior of the IR coupling was obtained from the DSE

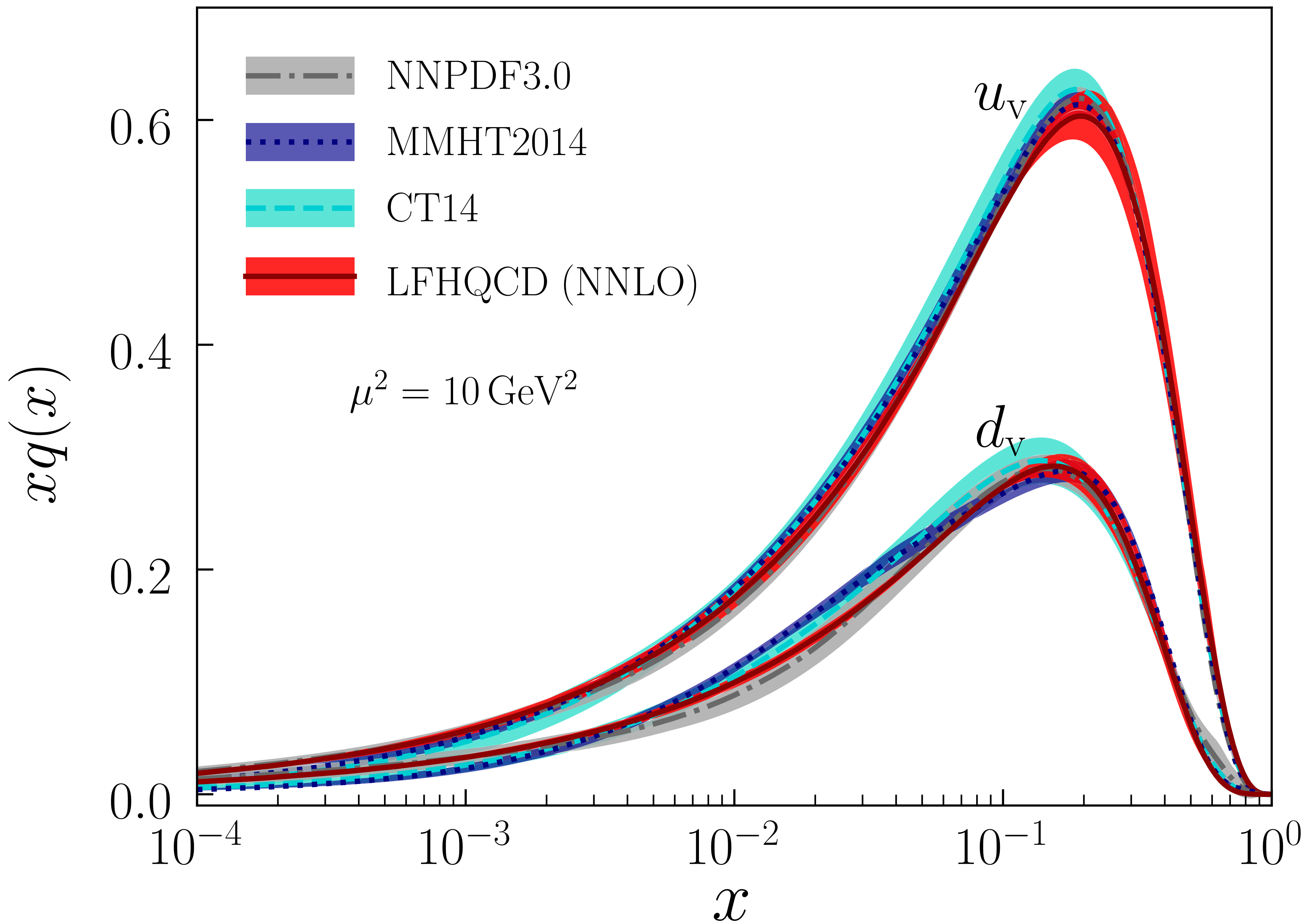
D. Binosi *et al.* (2017) and Z. F. Cui, et al. Chin. Phys. C **44**, 083102 (2020)



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)***



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

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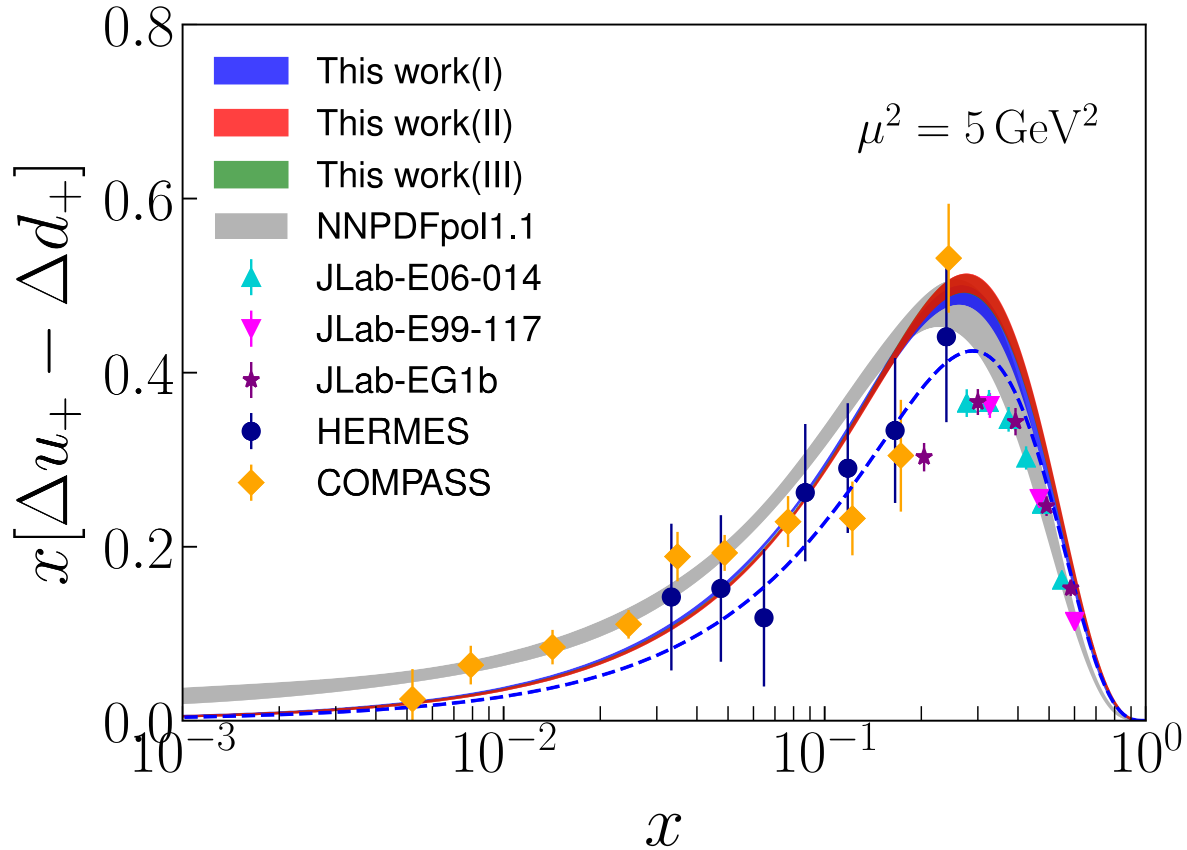
PHYSICAL REVIEW LETTERS 120, 182001 (2018)

Tianbo Liu, Raza Sabbir Sufian, Guy F. de Te'ramond, Hans Gunter Dösch, Alexandre Deur, sjb

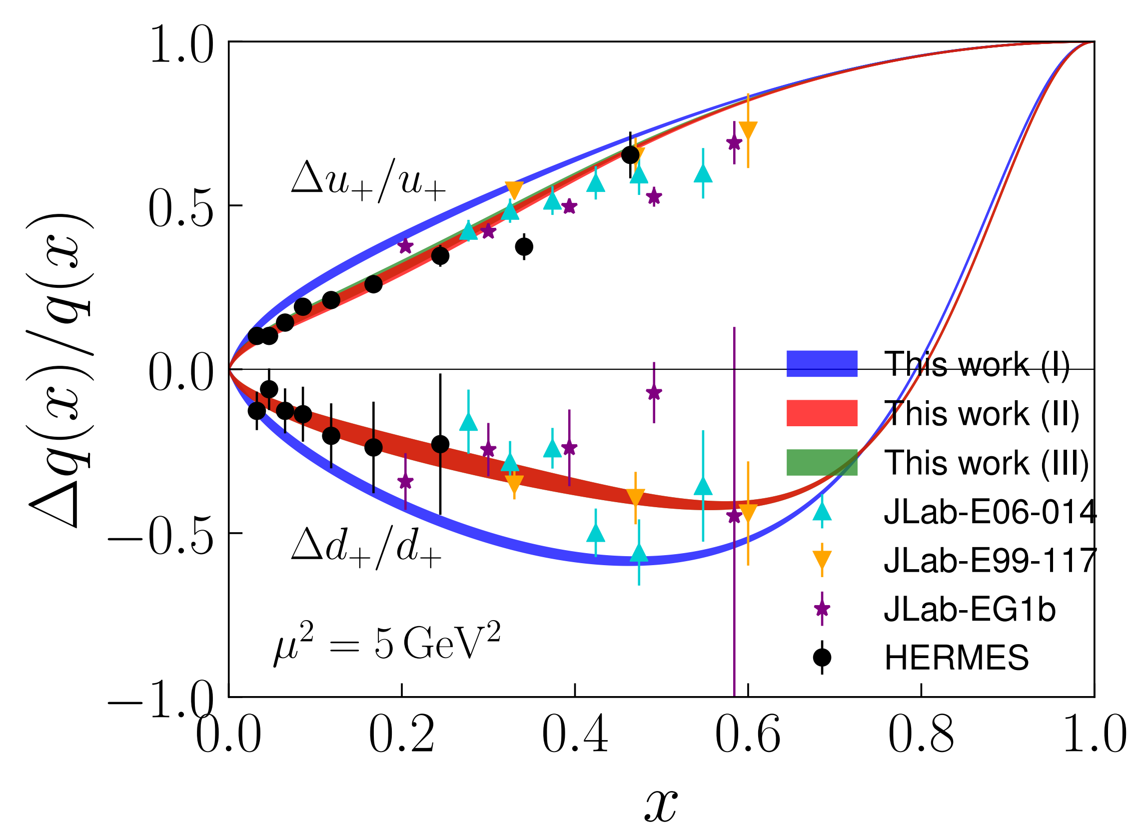


Polarized distributions for the

isovector combination $x[\Delta u_+(x) - \Delta d_+(x)]$

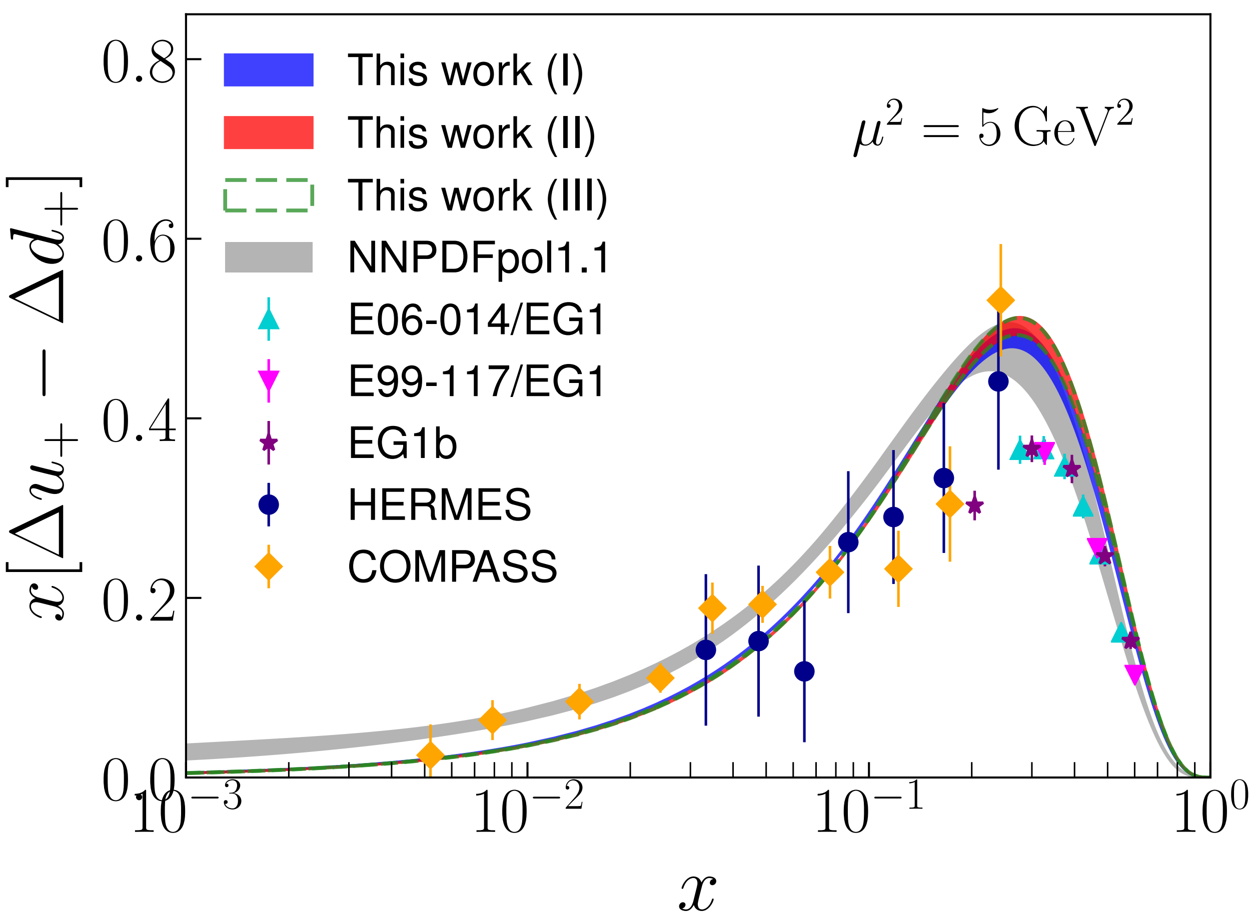
$$d_+(x) = d(x) + \bar{d}(x) \qquad u_+(x) = u(x) + \bar{u}(x)$$

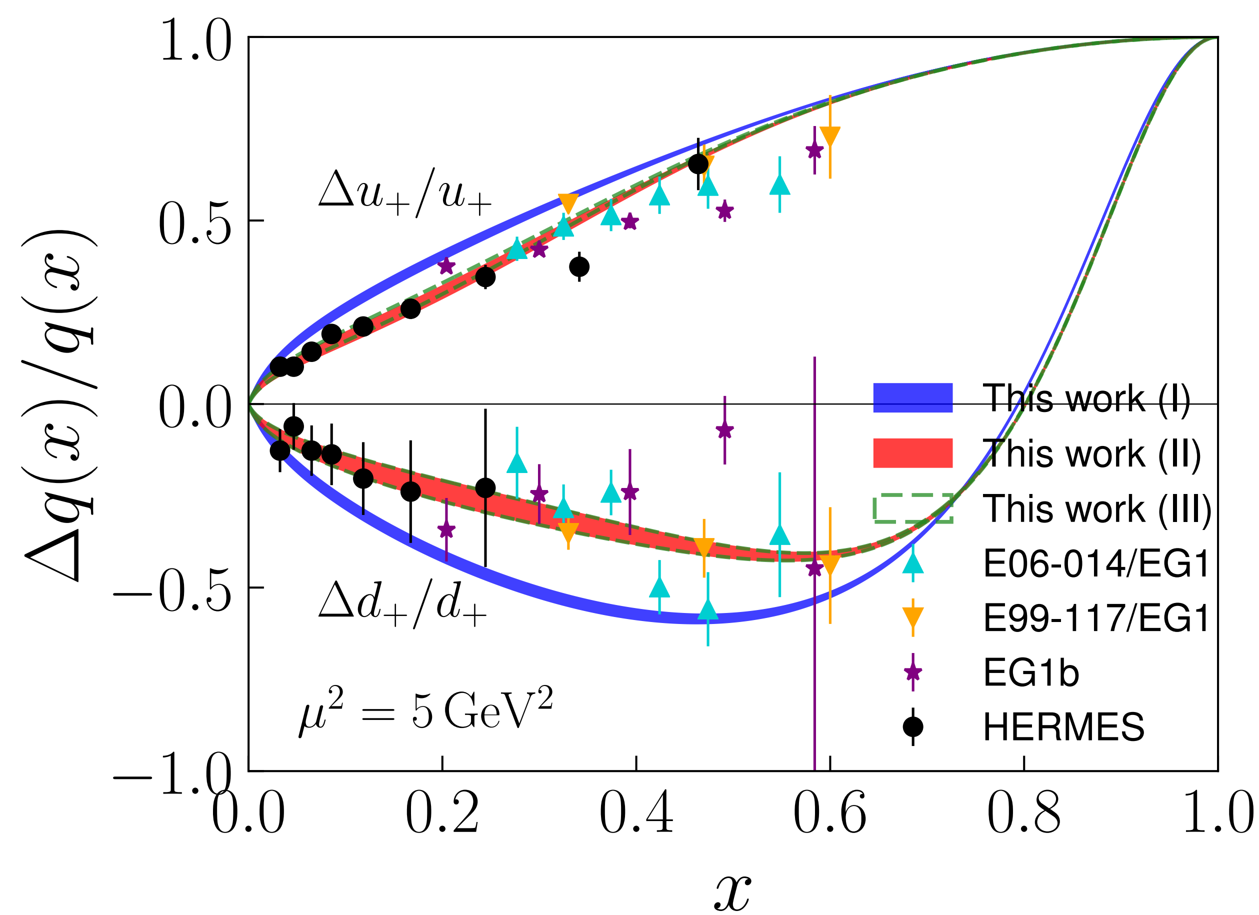
$$\Delta q(x) = q_\uparrow(x) - q_\downarrow(x)$$



Polarized GPDs and PDFs (HLFHS Collaboration, 2019)

- Separation of chiralities in the AdS action allows computation of the matrix elements of the axial current including the correct normalization, once the coefficients c_τ are fixed for the vector current
- Helicity retention between quark and parent hadron (pQCD prediction): $\lim_{x\to 1} \frac{\Delta q(x)}{q(x)} = 1$
- No spin correlation with parent hadron: $\lim_{x\to 0} \frac{\Delta q(x)}{q(x)} = 0$





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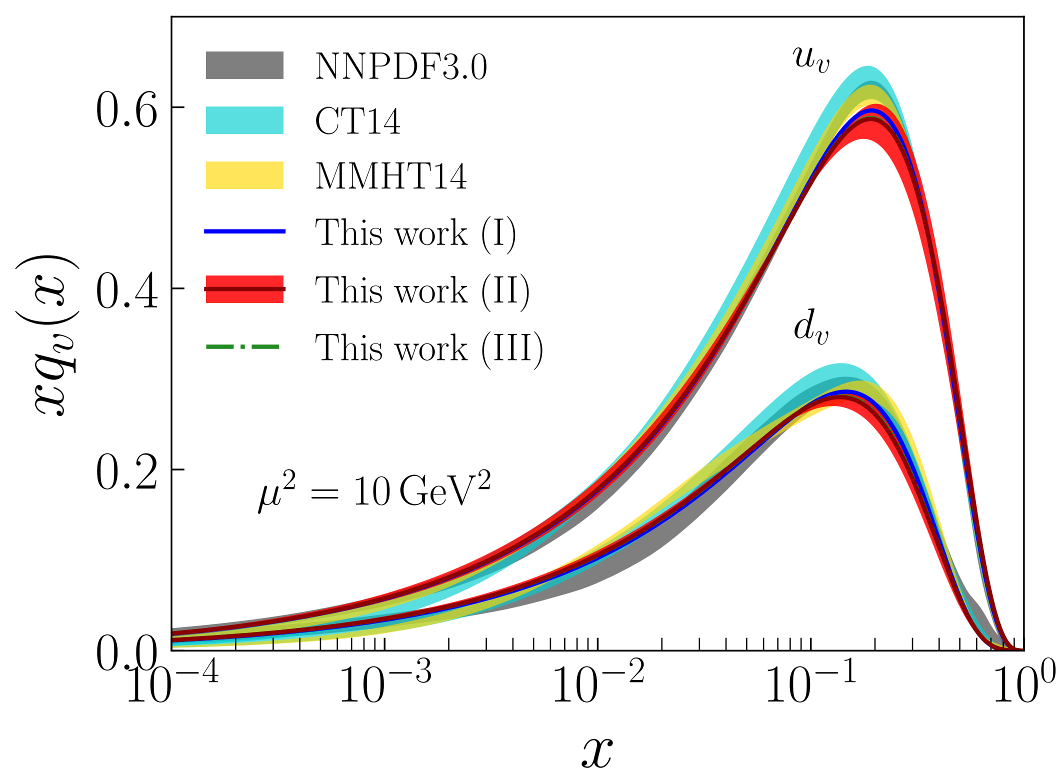
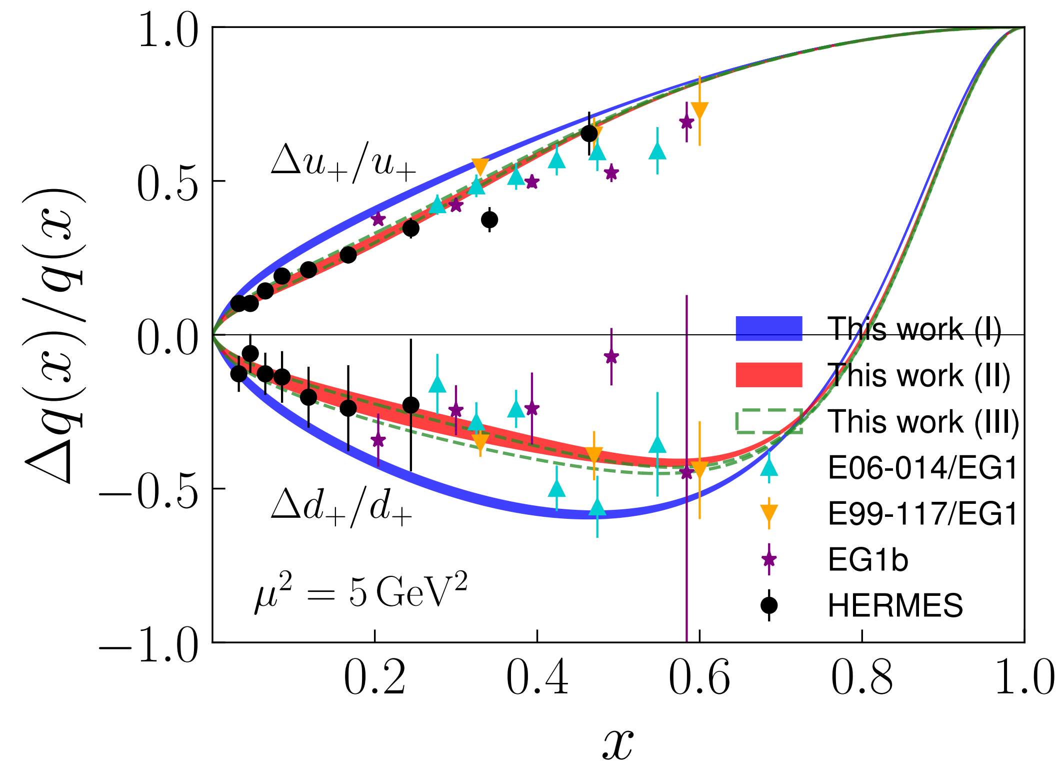
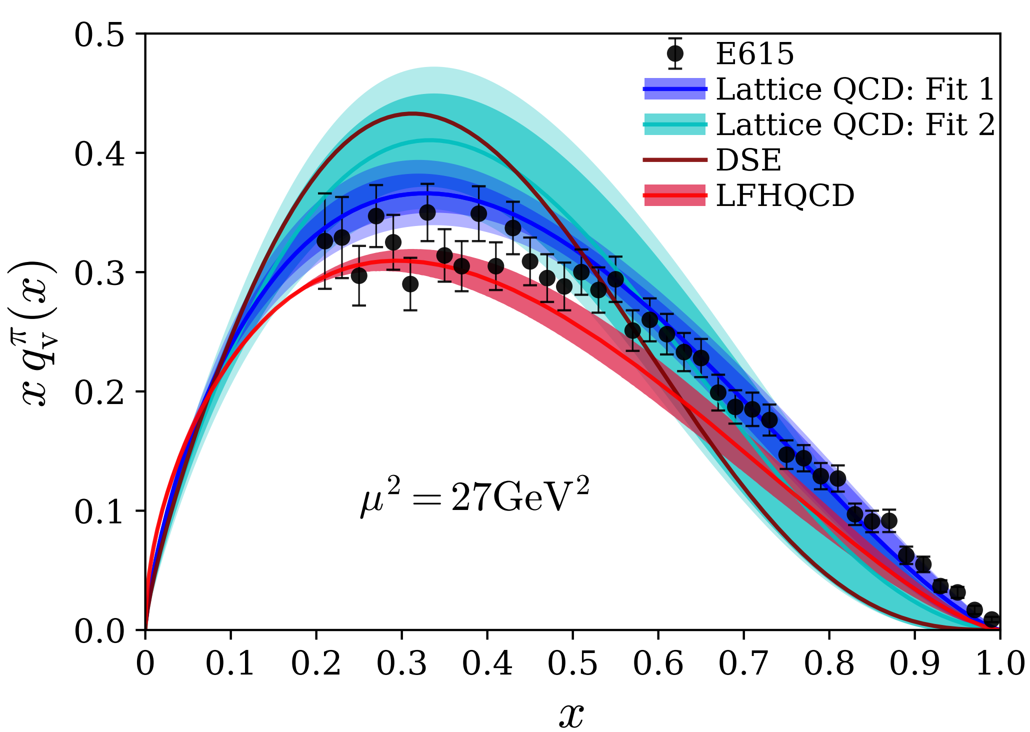






Separation of chiralities from the axial current
Coefficients c_τ are fixed from the vector current

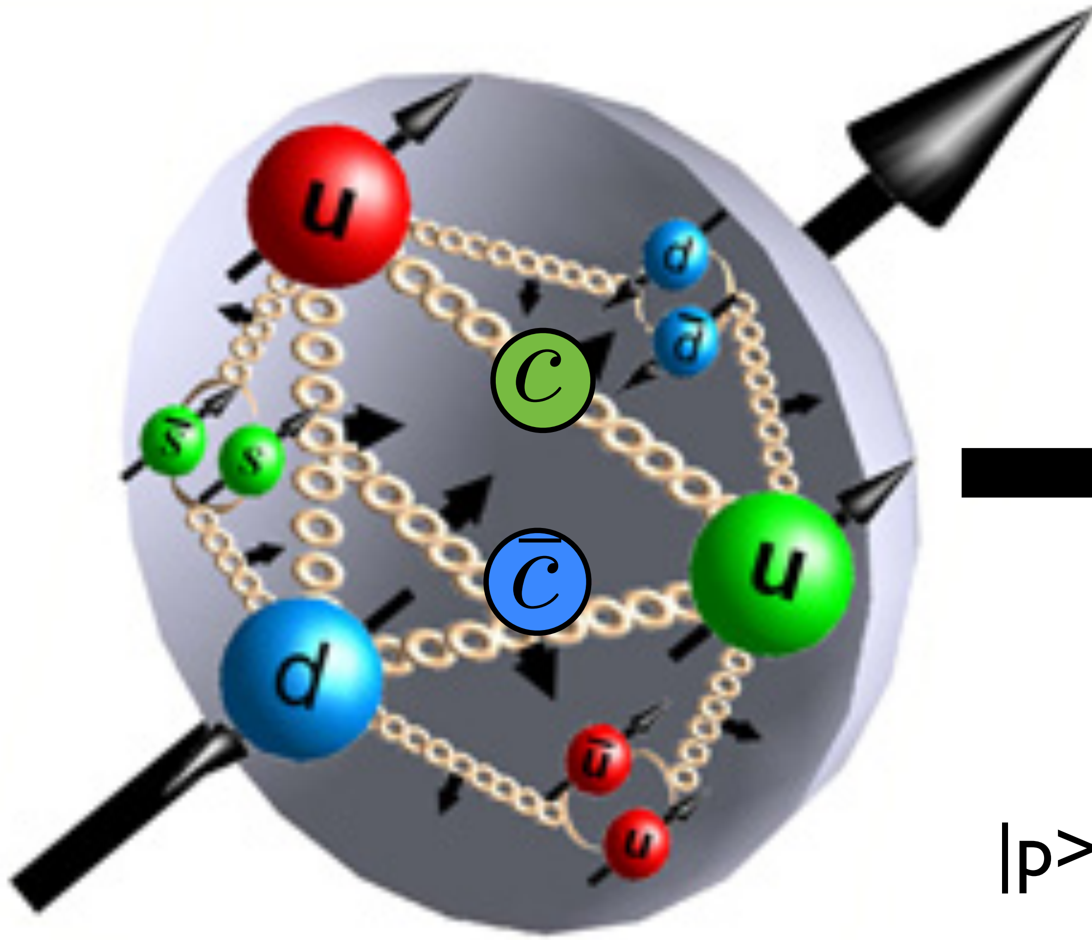
Regge trajectory from HLFQCD

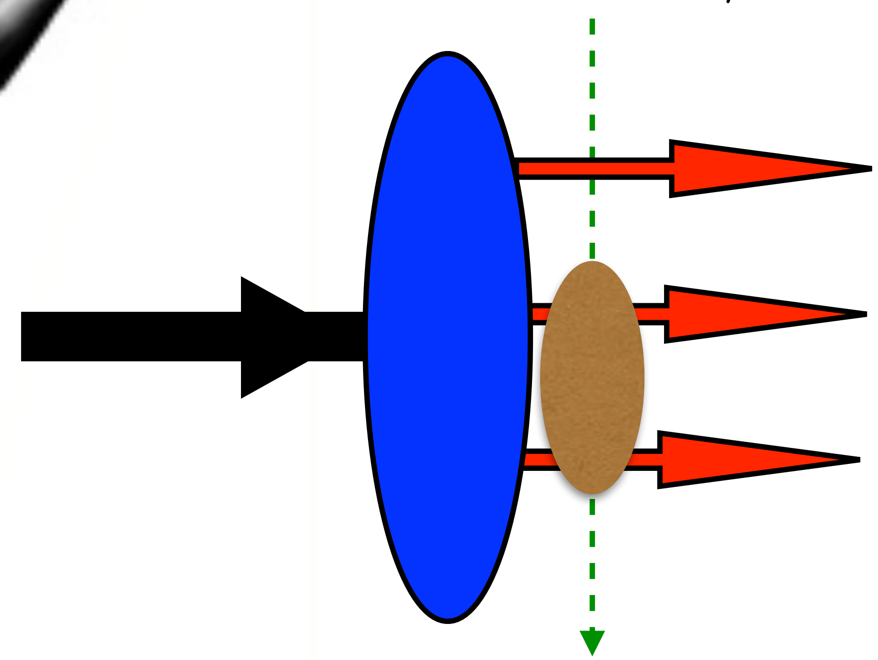
$$\alpha_A(t) = \frac{t}{4\lambda}$$

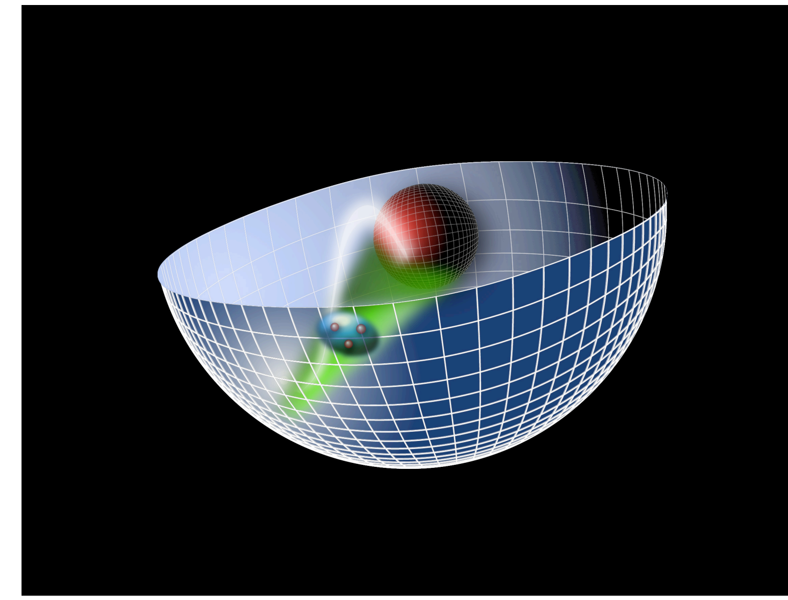
$$\lim_{x\to 1} \frac{\Delta q(x)}{q(x)} = 1, \quad \lim_{x\to 0} \frac{\Delta q(x)}{q(x)} = 0$$

DGLAP NNLO evolution from initial scale $\mu \simeq 1$ GeV from soft-hard matching in α_s

New Perspectives for Hadron Spectroscopy and Dynamics and the Running QCD Coupling from Color-Confining Holographic Light-Front QCD







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

with Guy de Tèramond, Hans Günter Dosch, Cèdric Lorcè, Alexandre Deur, and Joshua Erlich

A.N. Mitra Memorial Symposium
April 15, 2025

Stan Brodsky

SLAC NATIONAL ACCELERATOR LABORATORY