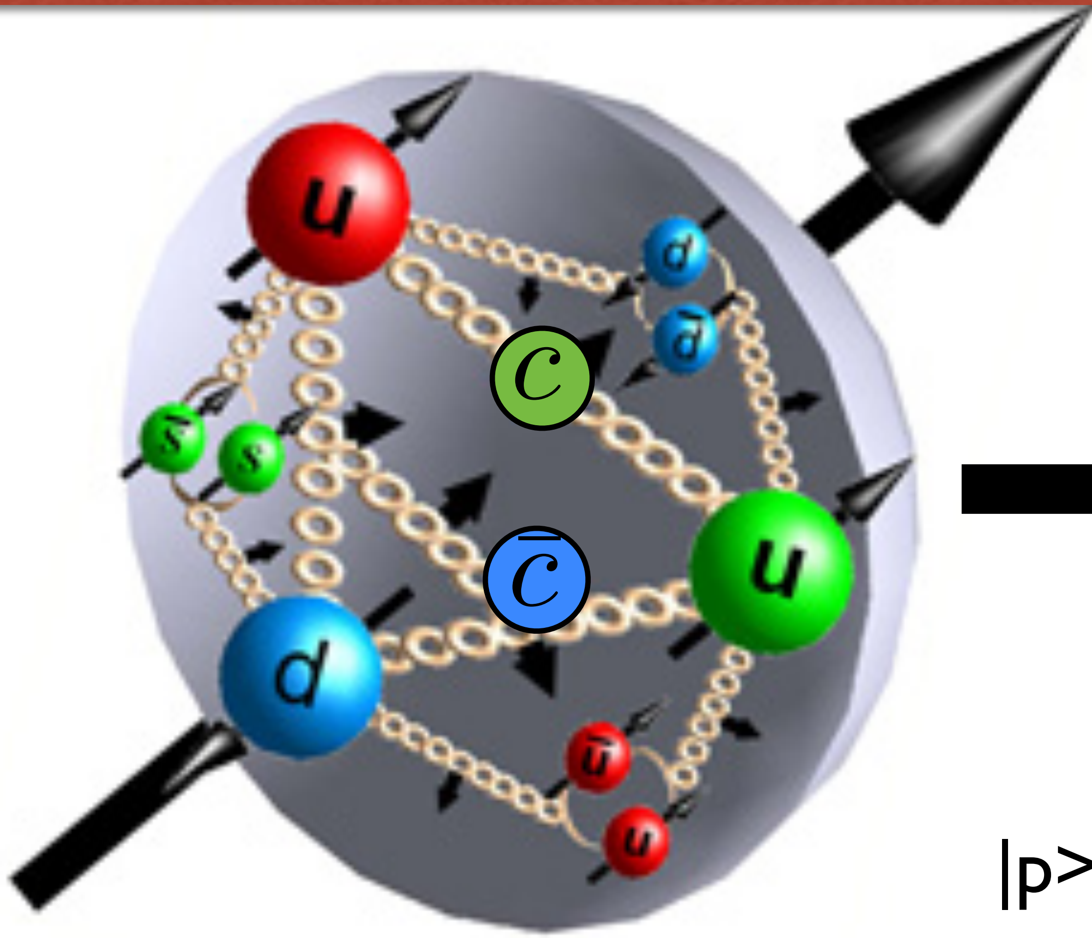
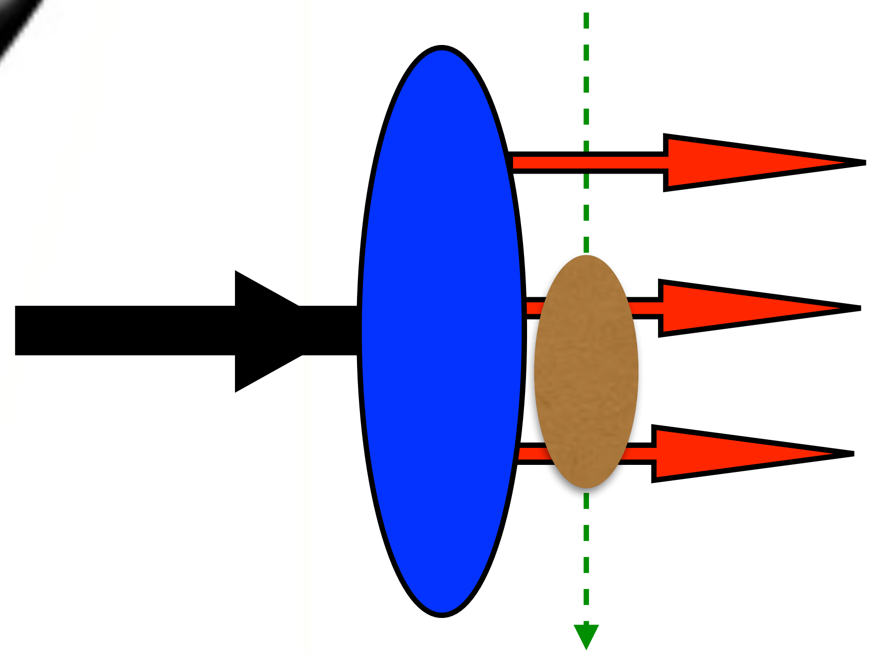
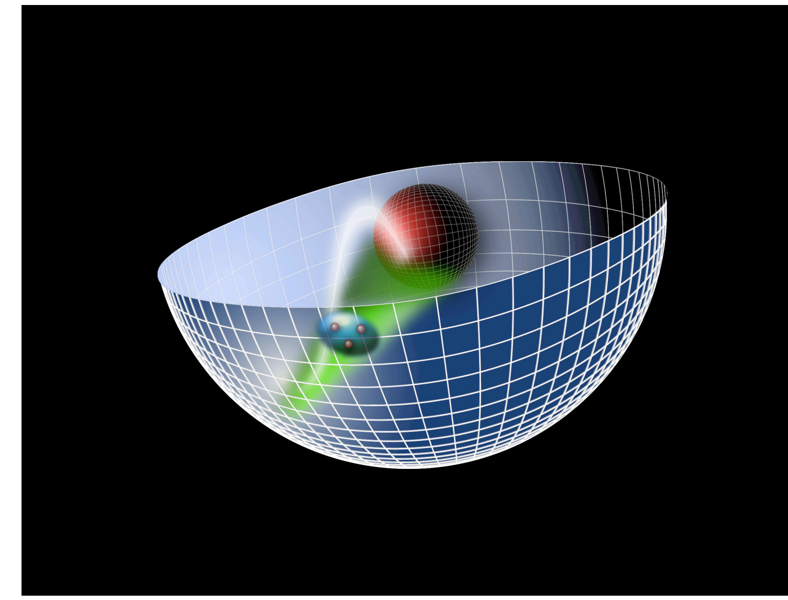
Color Confinement and Supersymmetric Features of Hadron Physics from Light-Front Holography and Novel Features of QCD from Light-Front Holography II



Fixed $\tau = t + z/c$





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

with Guy de Tèramond, Hans Günter Dosch, Alexandre Deur, Marina Nielsen, Ivan Schmidt, F. Navarra, Jennifer Rittenhouse West, G. Miller, Keh-Fei Liu, Tianbo LIu, Liping Zou, S. Groote, Joshua Erlich, S. Koshkarev, Xing-Gang Wu, Sheng-Quan Wang, Cedric Lorcè, R. S. Sufian, R. Vogt, G. Lykasov, S. Gardner, S. Liuti, V. Lyubovitskij, L. di Giustino

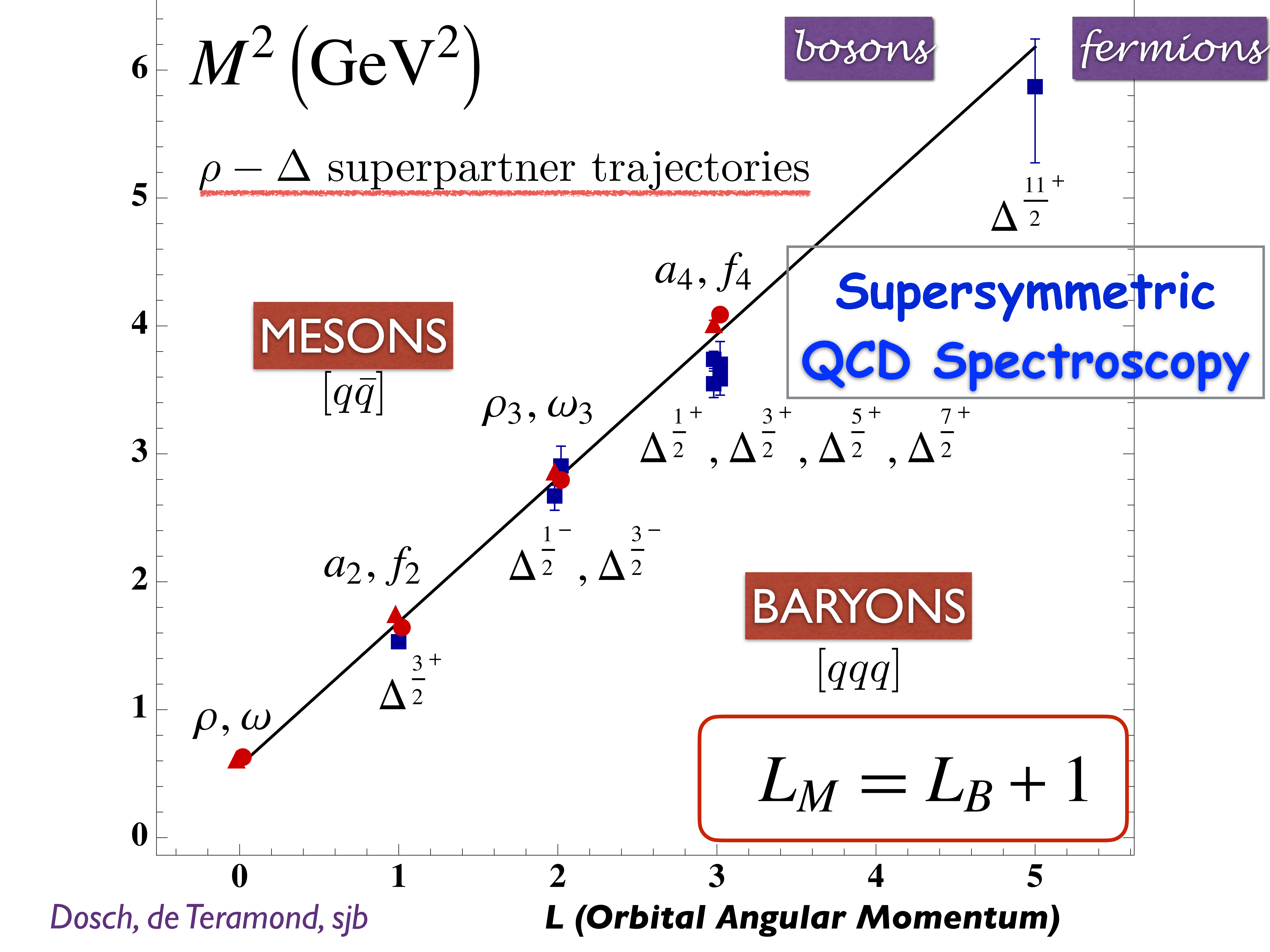
Bled Workshop

What Comes Beyond the Standard Models?

Stan Brodsky

SLAC NATIONAL ACCELERATOR LABORATORY

Talk II July 8, 2021

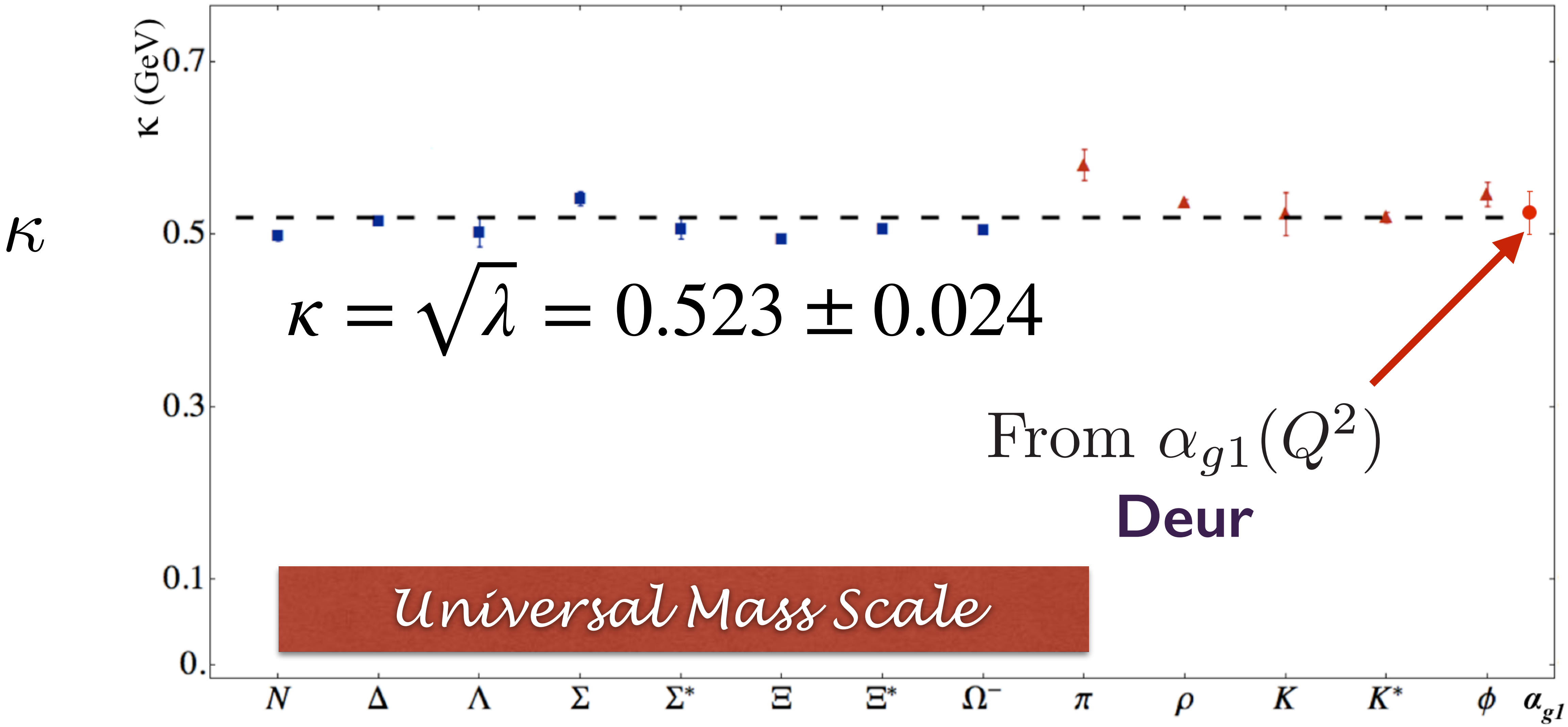


$M^2\ (\mathrm{GeV}^2)$
bosons
fermions
$\rho - \Delta$ superpartner trajectories
Supersymmetric QCD Spectroscopy
MESONS
$[q\bar{q}]$
BARYONS
$[qqq]$
ρ, ω
a_2, f_2
ρ_3, ω_3
a_4, f_4
$\Delta^{\frac{3}{2}^+}$
$\Delta^{\frac{1}{2}^-}, \Delta^{\frac{3}{2}^-}$
$\Delta^{\frac{1}{2}^+}, \Delta^{\frac{3}{2}^+},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

$\lambda = \kappa^2$

de Tèramond, Dosch, Lorce', sjb

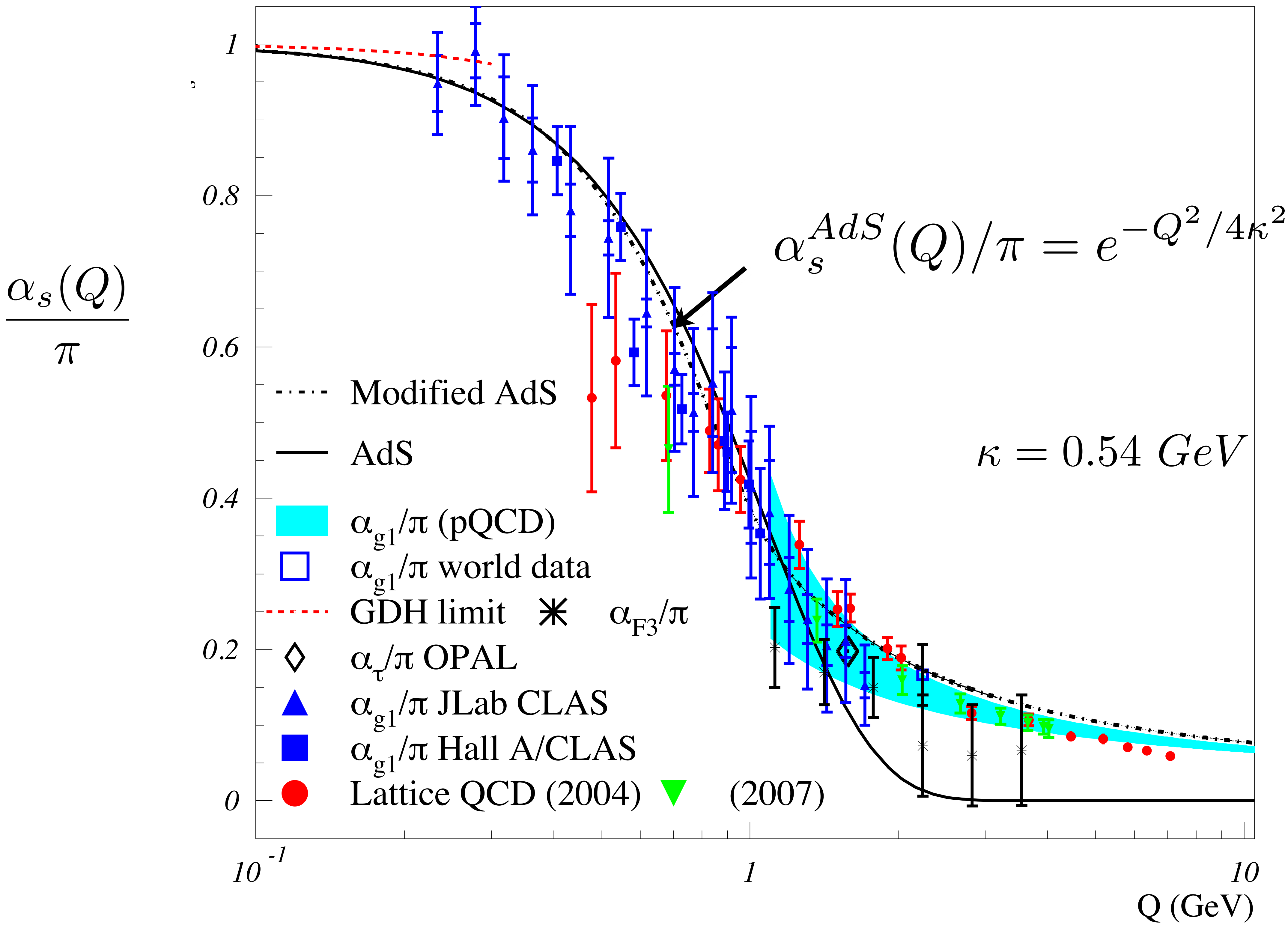
$$m_u = m_d = 46 \text{ MeV}, \; m_s = 357 \text{ MeV}$$



Fit to the slope of Regge trajectories, including radial excitations

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

Analytic, defined at all scales, IR Fixed Point



AdS/QCD dilaton predicts the nonperturbative corrections to the QCD running coupling

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

Deur, de Teramond, sjb

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

- ***Color Confinement***
- ***Origin of the QCD Mass Scale***
- ***Meson and Baryon Spectroscopy***
- ***Universal Regge Slopes: n and L for Mesons, Baryons, Tetraquarks***
- ***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***
- ***Heavy Quark Distributions***

$$\mathscr{L}_{QCD} \to \psi_n^H(x_i, \overrightarrow{k}_{\perp i}, \lambda_i)$$ *Valence and Higher Fock States*

Supersymmetry in QCD

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

de Téramond, Dosch, Lorcé, sjb

Need a First Approximation to QCD

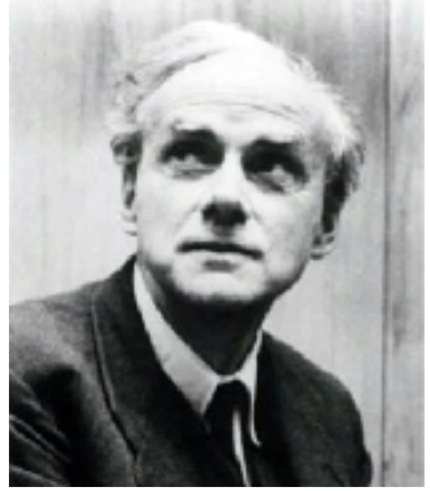
Comparable in simplicity to Schrödinger Theory in Atomic Physics

Relativistic, Frame-Independent, Color-Confining

Origin of hadronic mass scale

AdS/QCD
Light-Front Holography
Superconformal Algebra

No parameters except for quark masses!

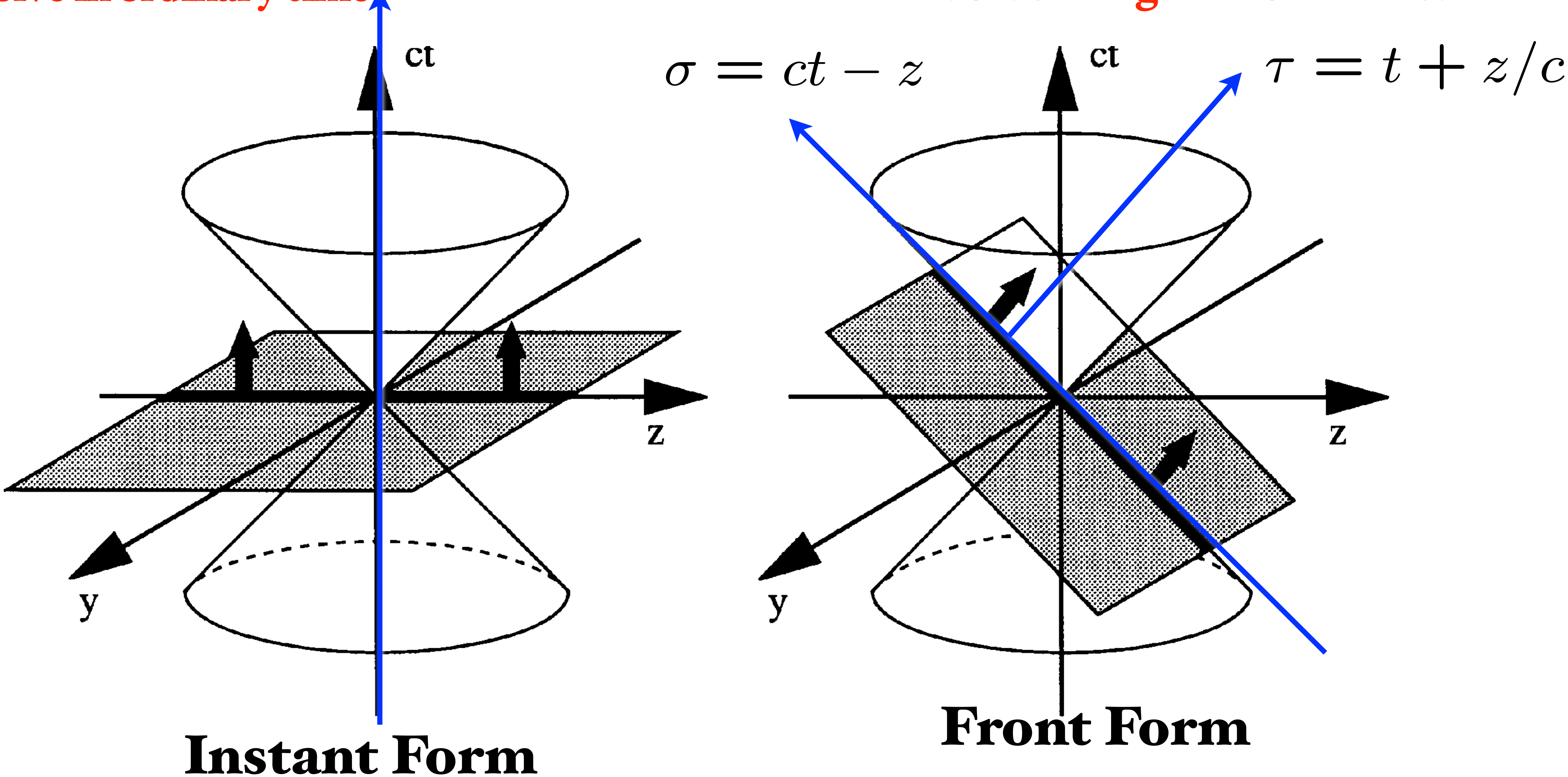


P.A.M Dirac, Rev. Mod. Phys. 21, 392 (1949)

Dirac's Amazing Idea: The "Front Form"

Evolve in ordinary time

Evolve in light-front time!



Casual, Boost Invariant!

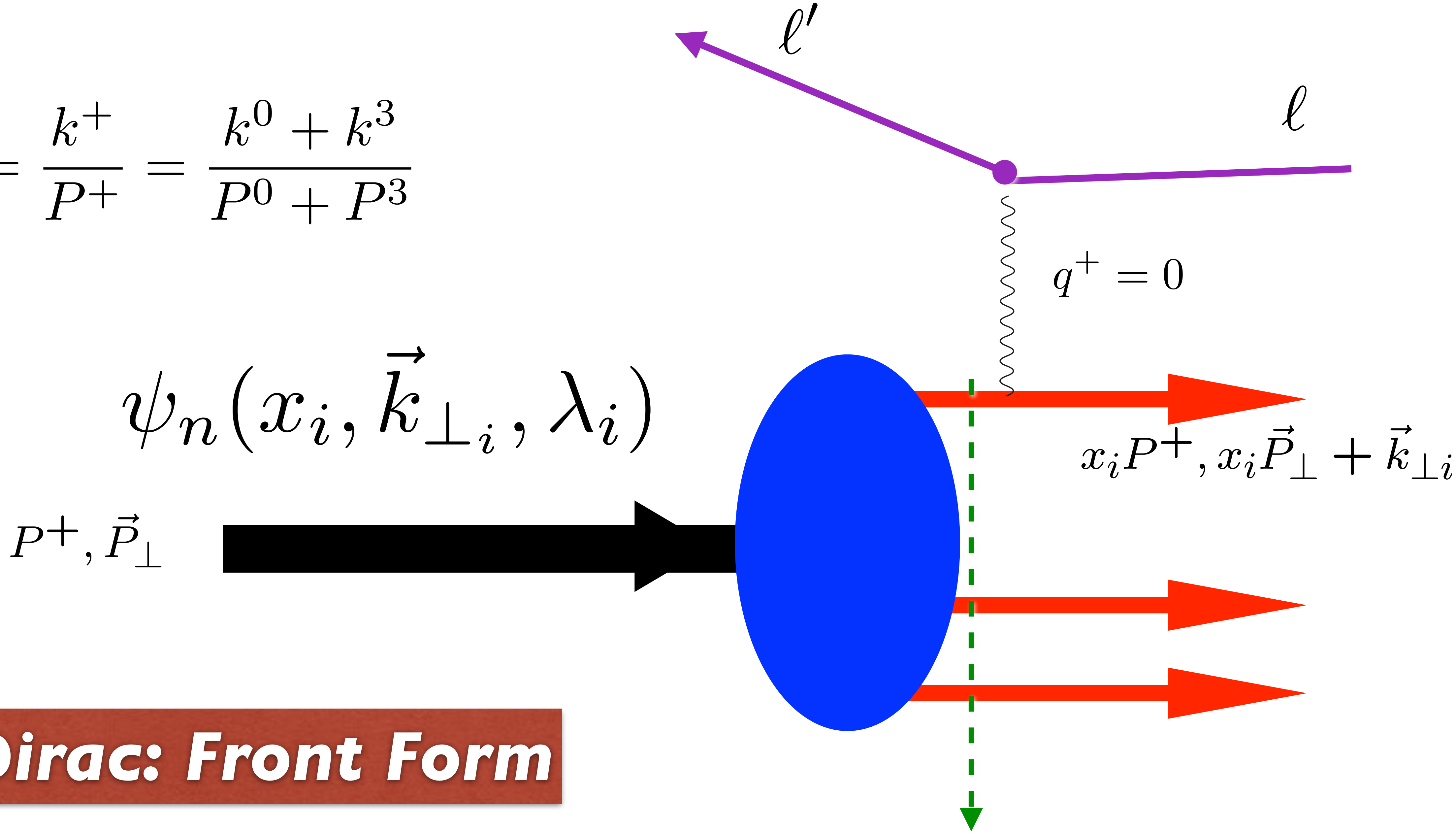
- ***Trivial LF Vacuum (up to zero modes)***

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: Front Form

Measurements of hadron LF wavefunction are at fixed LF time

Fixed $\tau = t + z/c$

Like a flash photograph

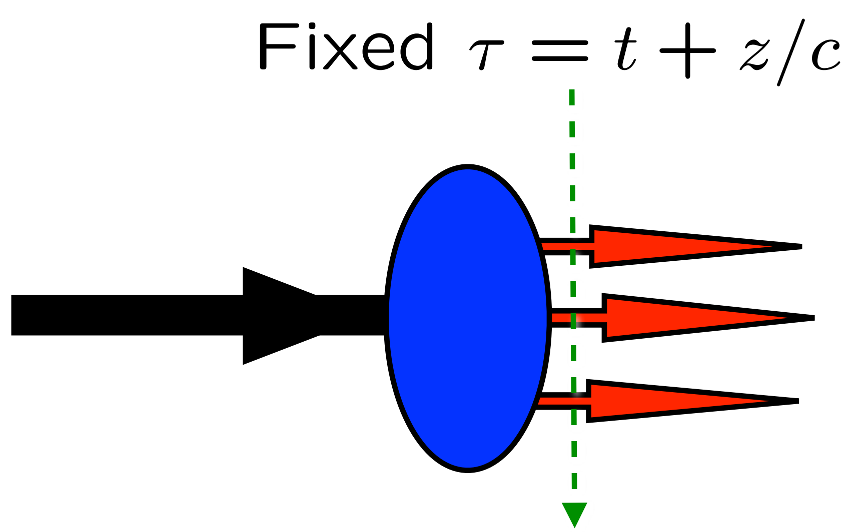
$$x_{bj} = x = \frac{k^+}{P^+}$$

Invariant under boosts! Independent of P^μ

Bound States in Relativistic Quantum Field Theory:

Light-Front Wavefunctions

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



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

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

Invariant under boosts. Independent of P^μ

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

Direct connection to QCD Lagrangian

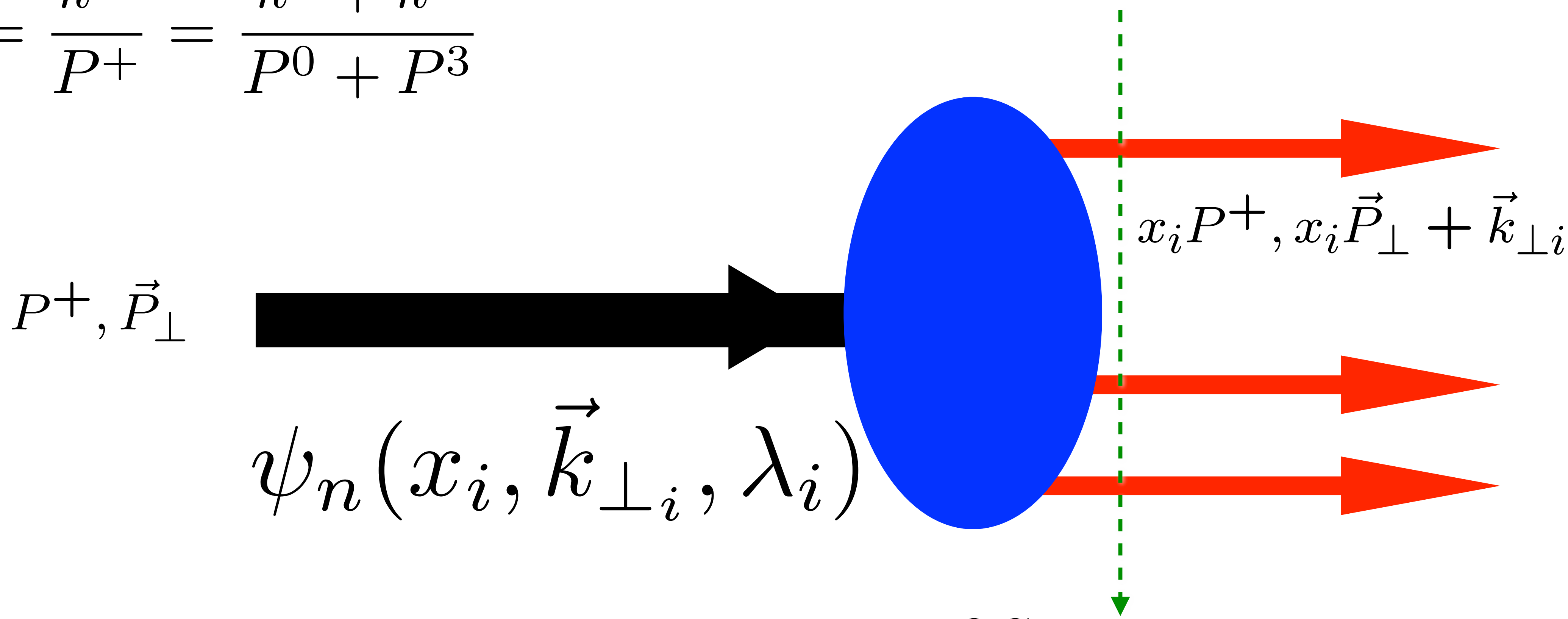
LF Wavefunction: off-shell in invariant mass

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

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

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

Fixed $\tau = t + z/c$



$\sum_i^n x_i = 1$

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

Eigenstate of LF Hamiltonian

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

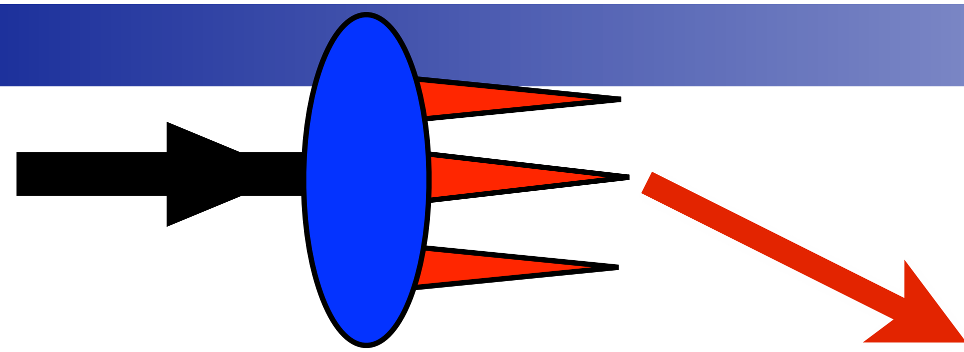
$$|p, J_z> = \sum_{n=3} \psi_n(x_i, \vec{k}_{\perp i}, \lambda_i) |n; x_i, \vec{k}_{\perp i}, \lambda_i>$$

Invariant under boosts! Independent of P^μ

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

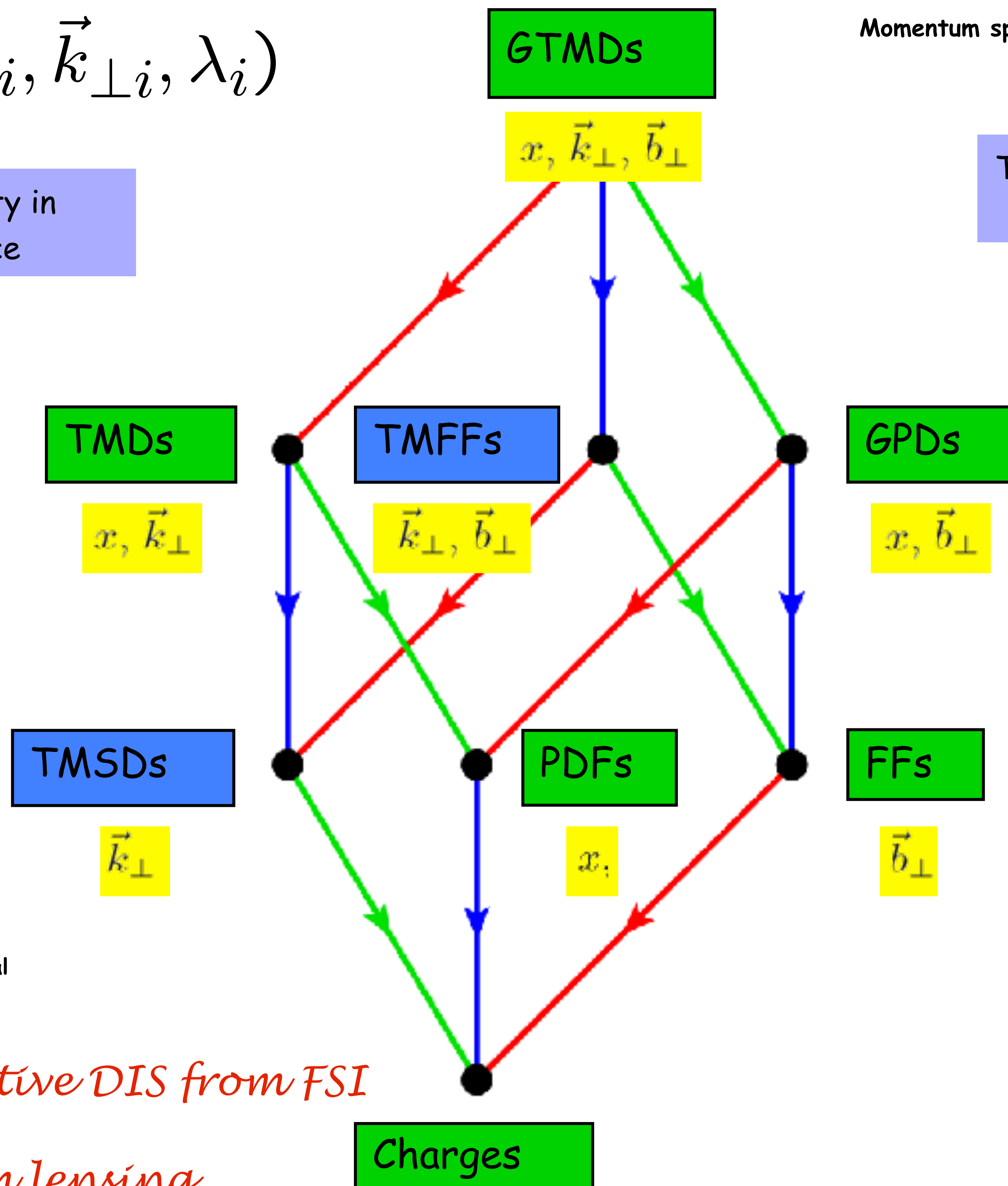
$\vec{\Delta}_\perp \leftrightarrow \vec{b}_\perp$

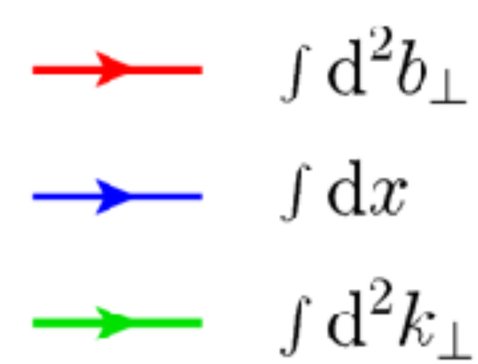
Transverse density in momentum space

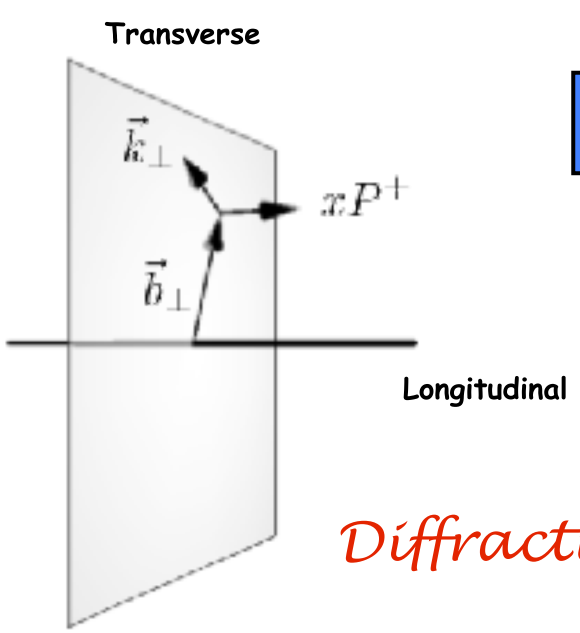
Transverse density in position space

Weak transition form factors

DGLAP, ERBL Evolution Factorization Theorems







Diffractive DIS from FSI

Sivers, T-odd from lensing

Two Definitions of Vacuum State

Instant Form: Lowest Energy Eigenstate of Instant-Form Hamiltonian

$$H|\psi_0> = E_0|\psi_0>, E_0 = min\{E_i\}$$

Eigenstate defined at one time t over all space; Acausal! Frame-Dependent

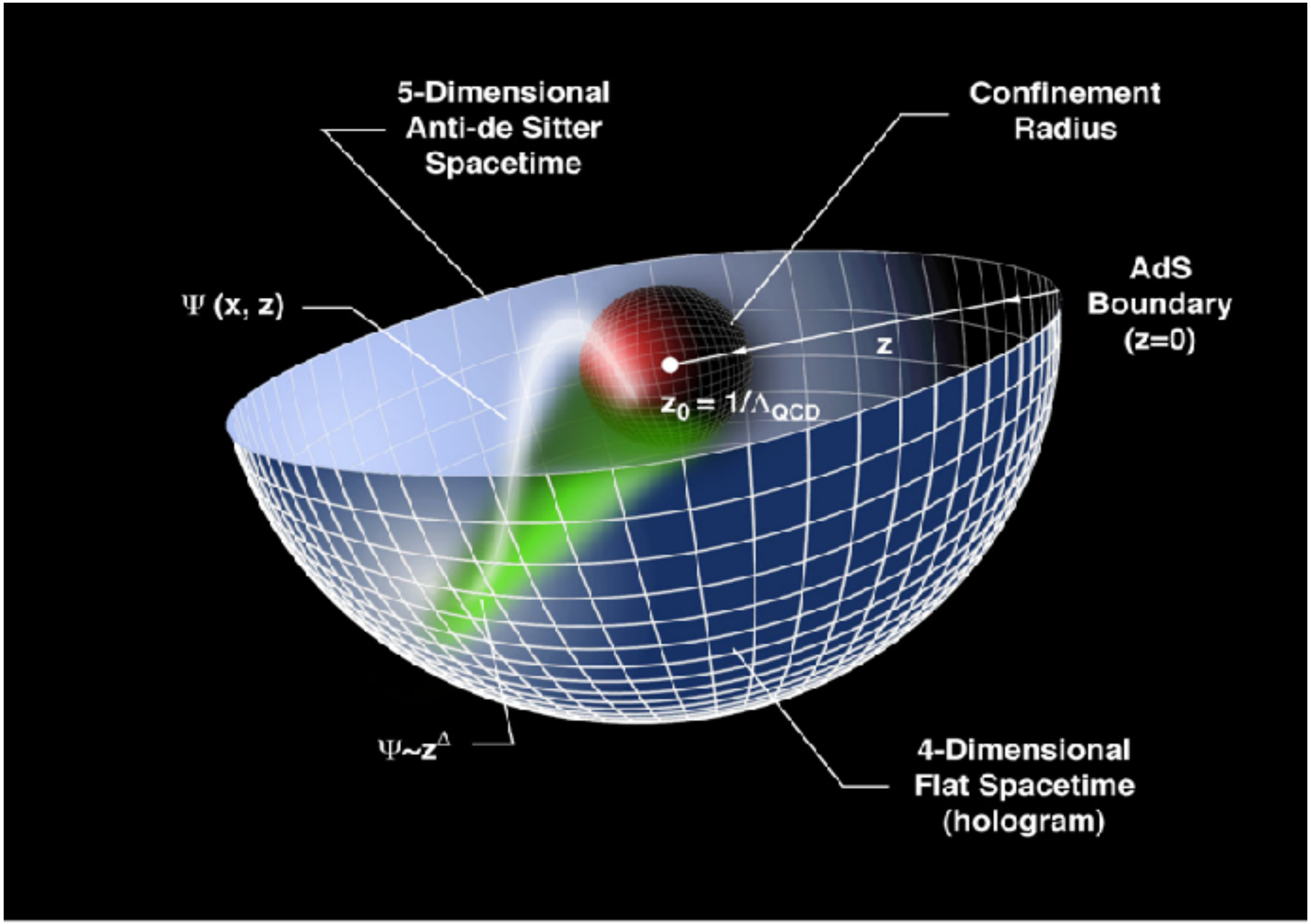
Front Form: Lowest Invariant Mass Eigenstate of Light-Front Hamiltonian

$$H_{LF}|\psi_0>_{LF} = M_0^2|\psi_0>_{LF}, M_0^2 = 0.$$

Frame-independent eigenstate at fixed LF time $\tau = t+z/c$ within causal horizon

Frame-independent description of the causal physical universe!

AdS_5

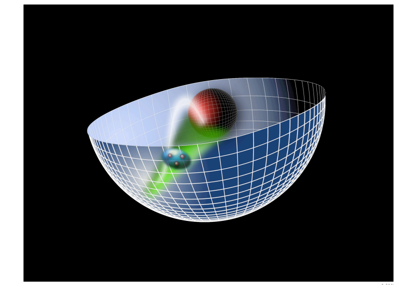


Changes in physical length scale mapped to evolution in the 5th dimension z

in collaboration with Guy de Teramond and H. Guenter Dosch

Dilaton-Modified AdS

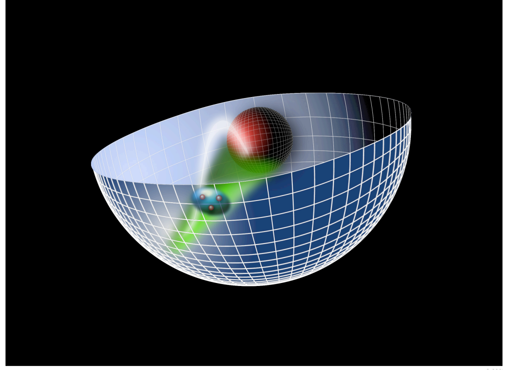
$$ds^2 = e^{\varphi(z)} \frac{R^2}{z^2} (\eta_{\mu\nu} x^\mu x^\nu - dz^2)$$



- **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**

Maldacena

AdS$_5$



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

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

invariant measure

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

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

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

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

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

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

AdS/CFT

Holographic Mapping of AdS Modes to QCD LFWFs

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

- Integrate Soper formula over angles:

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

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

- Transversality variable

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

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

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

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

de Teramond, sjb

Identical to Polchinski-Strassler Convolution of AdS Amplitudes

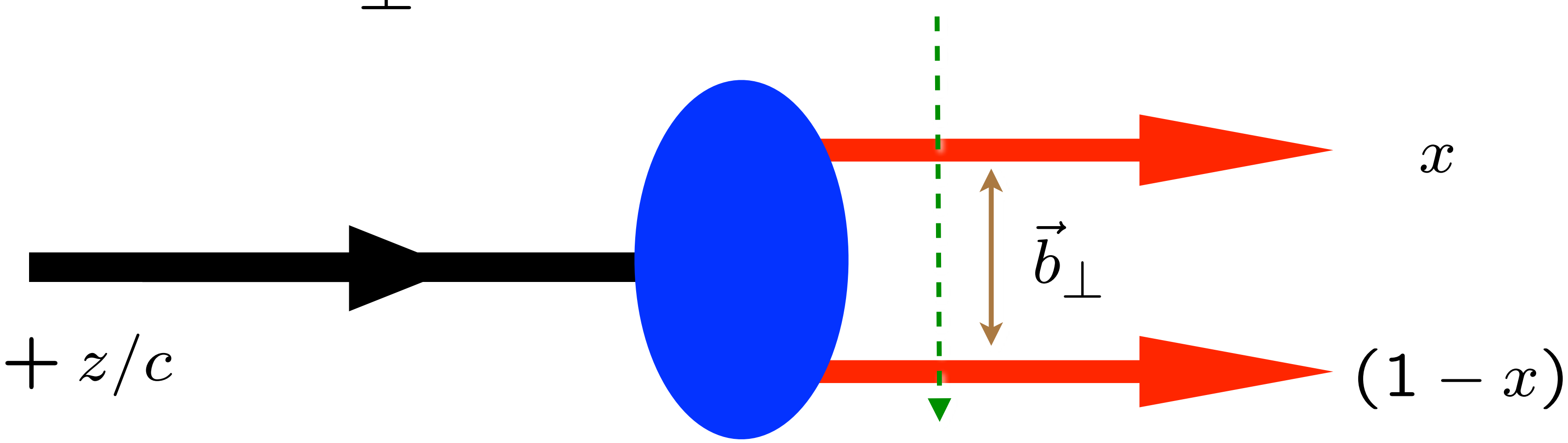
de Teramond, sjb

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*

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

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!

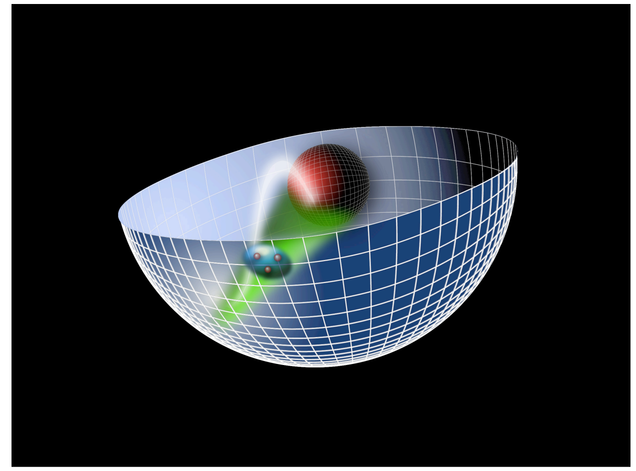
$$z \longleftrightarrow \zeta = \sqrt{x(1-x)\vec{b}_\perp^2}$$

Light-Front Holography

de Tèramond, Dosch, sjb

AdS/QCD
Soft-Wall Model

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



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

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: Only Ratios of Masses Determined

Massless pion!

Meson Spectrum in Soft Wall Model

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

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

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

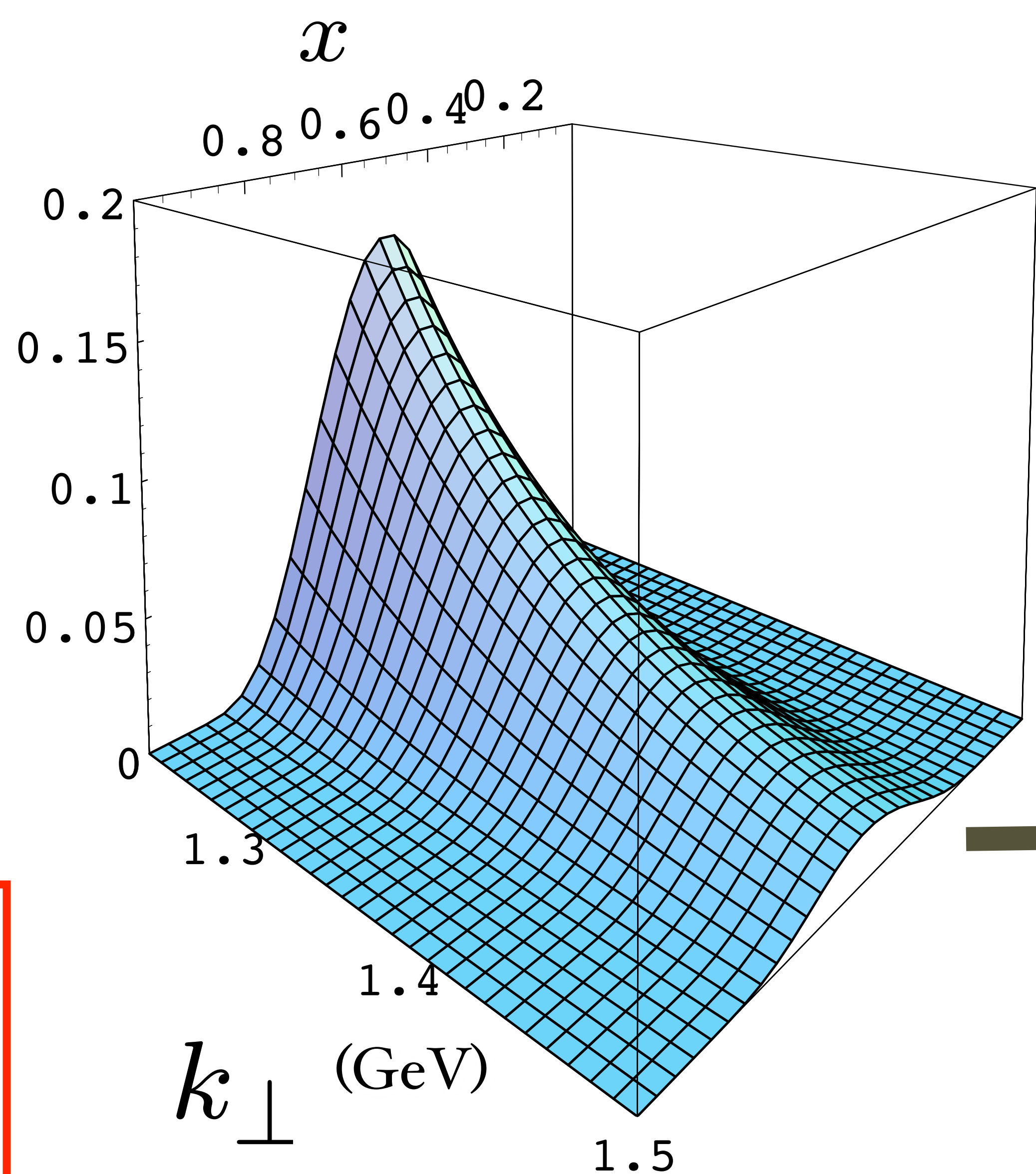
$$\vec{\zeta}^2 = \vec{b}^2_\perp x(1-x)$$

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

Prediction from AdS/QCD: Meson LFWF

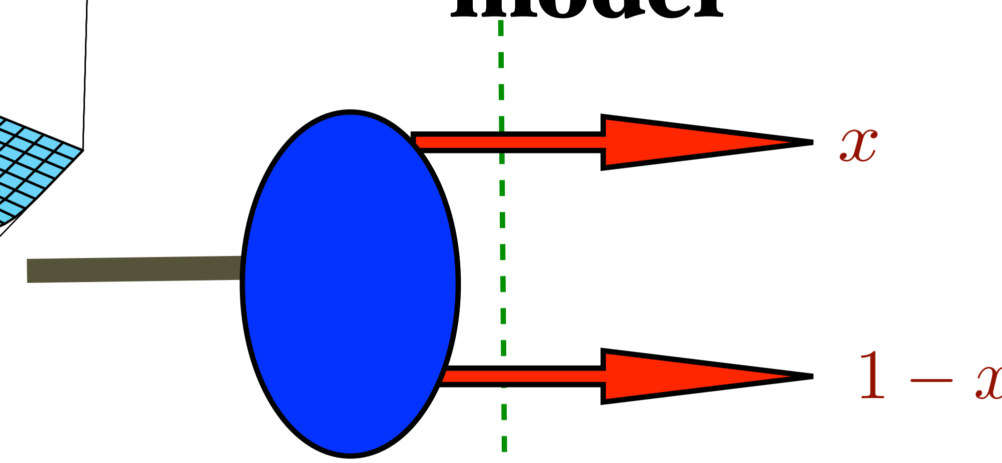
$$e^{\varphi(z)} = e^{+\kappa^2 z}$$

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



de Teramond, Cao, sjb

"Soft Wall" model



massless quarks

Note coupling

$$k_\perp^2, x$$

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

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

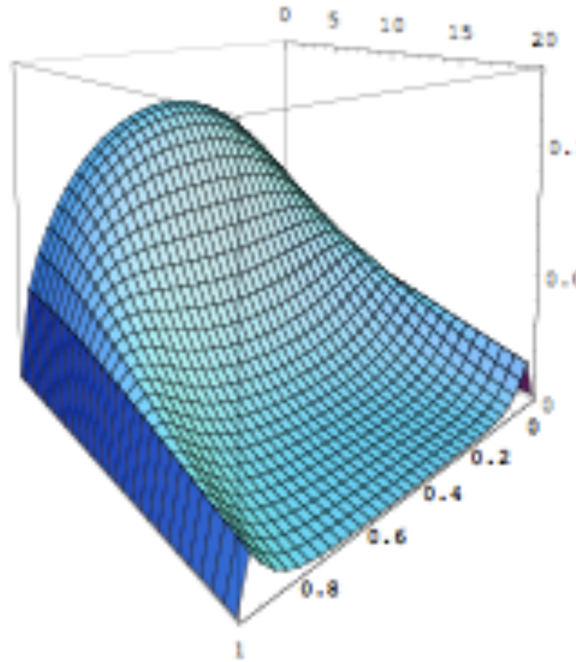
$$f_\pi = \sqrt{P_{q\bar{q}}}\frac{\sqrt{3}}{8}\kappa = 92.4 \text{ MeV}$$

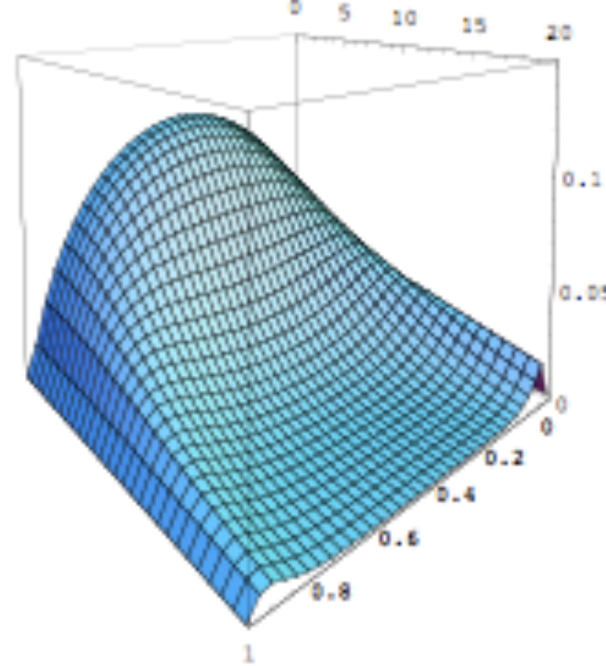
Same as DSE! **C. D. Roberts et al.**

Provides Connection of Confinement to Hadron Structure

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

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



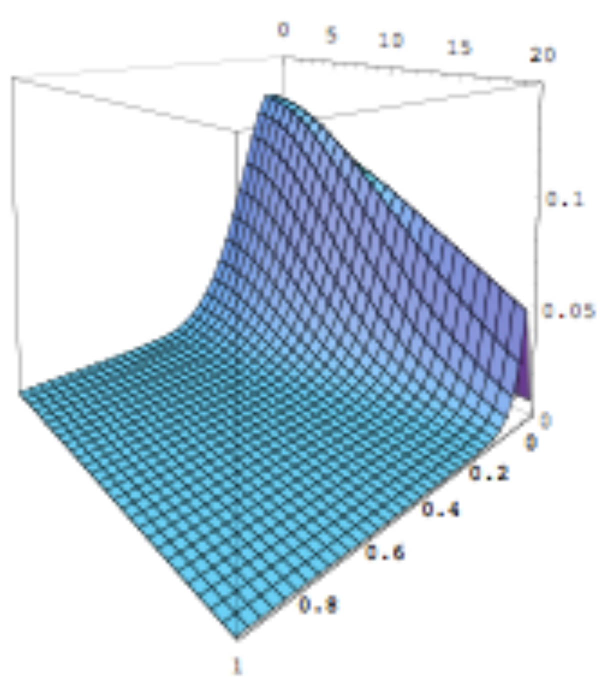


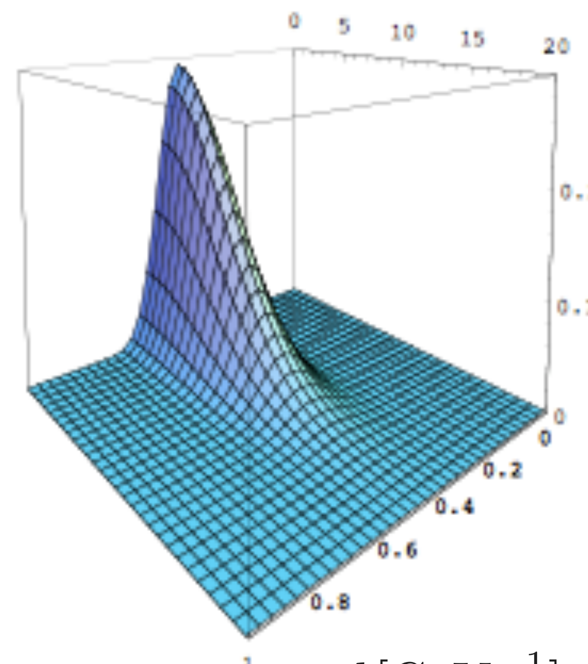
$|K^+ >= |u\bar{s} >$

$m_s = 95\ MeV$

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

$m_c = 1.25\ GeV$

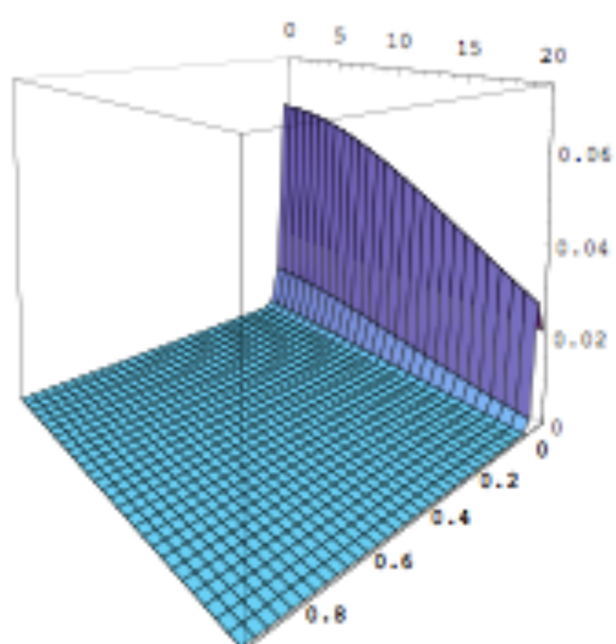


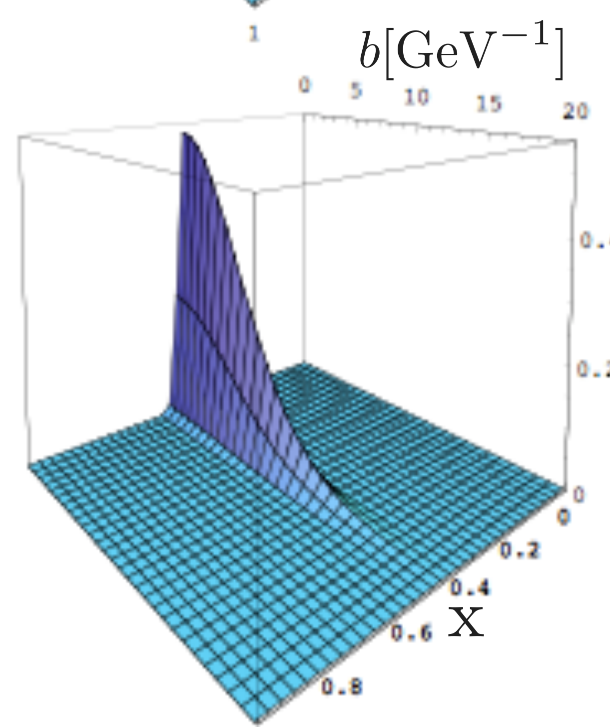


$|\eta_c >= |c\bar{c} >$

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

$m_b = 4.2\ GeV$

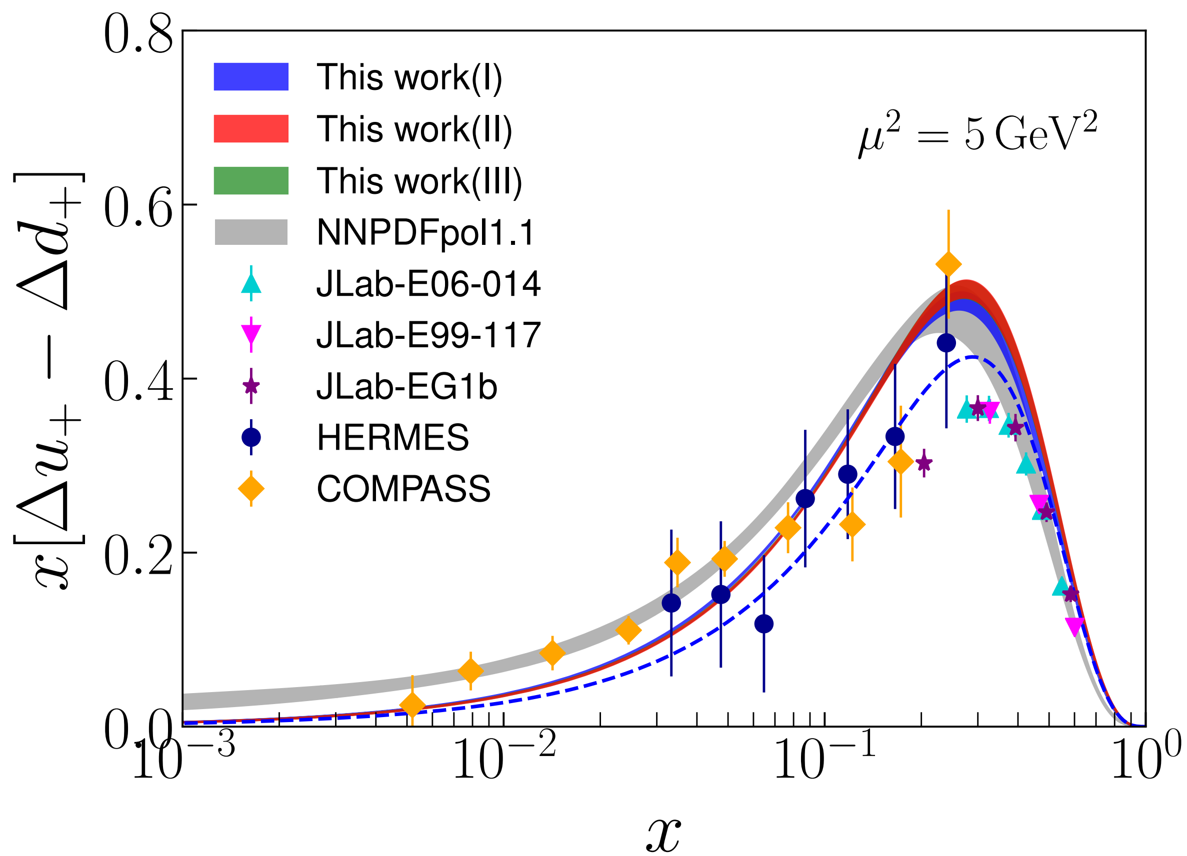




$|\eta_b >= |b\bar{b} >$

$\kappa = 375\ MeV$

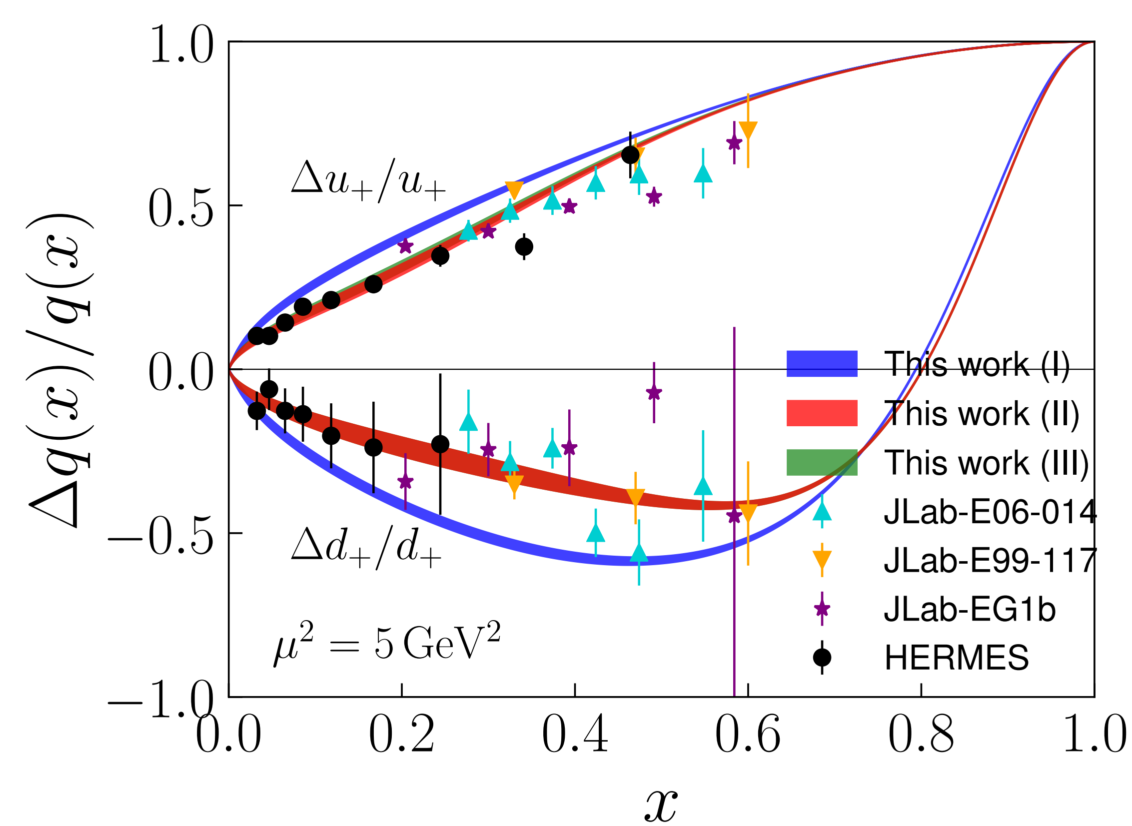
Tianbo Liu, Raza Sabbir Sufian, Guy F. de T´eramond, Hans Gunter Dösch, Alexandre Deur, sjb



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

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

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



Quark separation increases with L

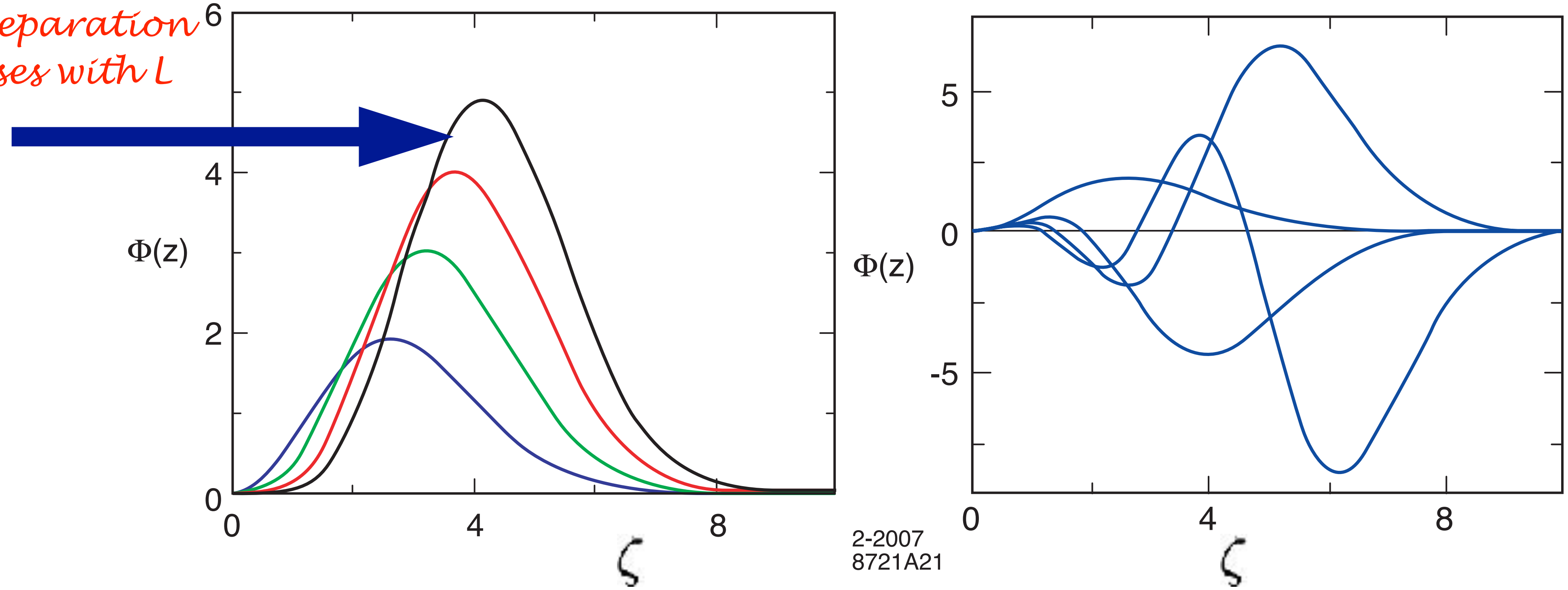
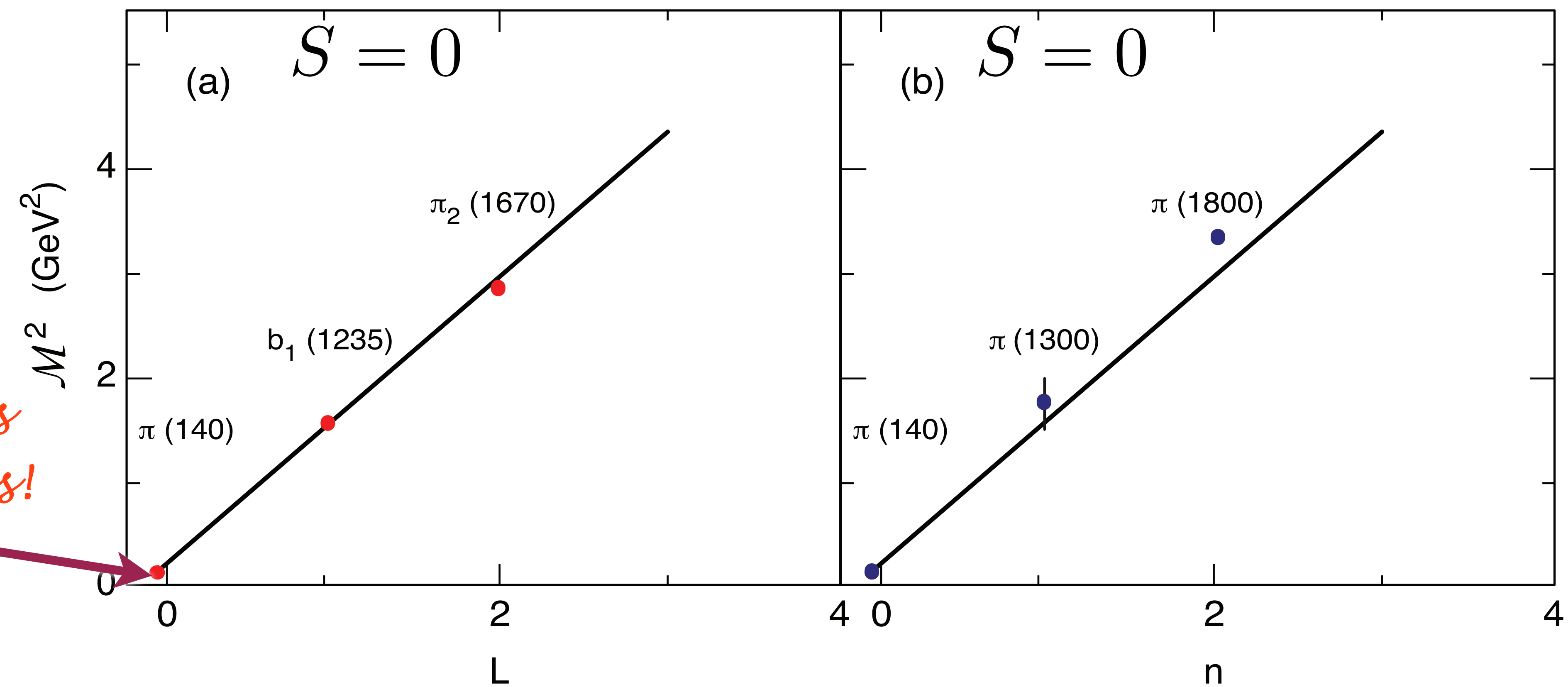


Fig: Orbital and radial AdS modes in the soft wall model for κ = 0.6 GeV .

Soft Wall Model

Same slope in n and L!

Pion has zero mass!



$\boxed{m_q = 0}$

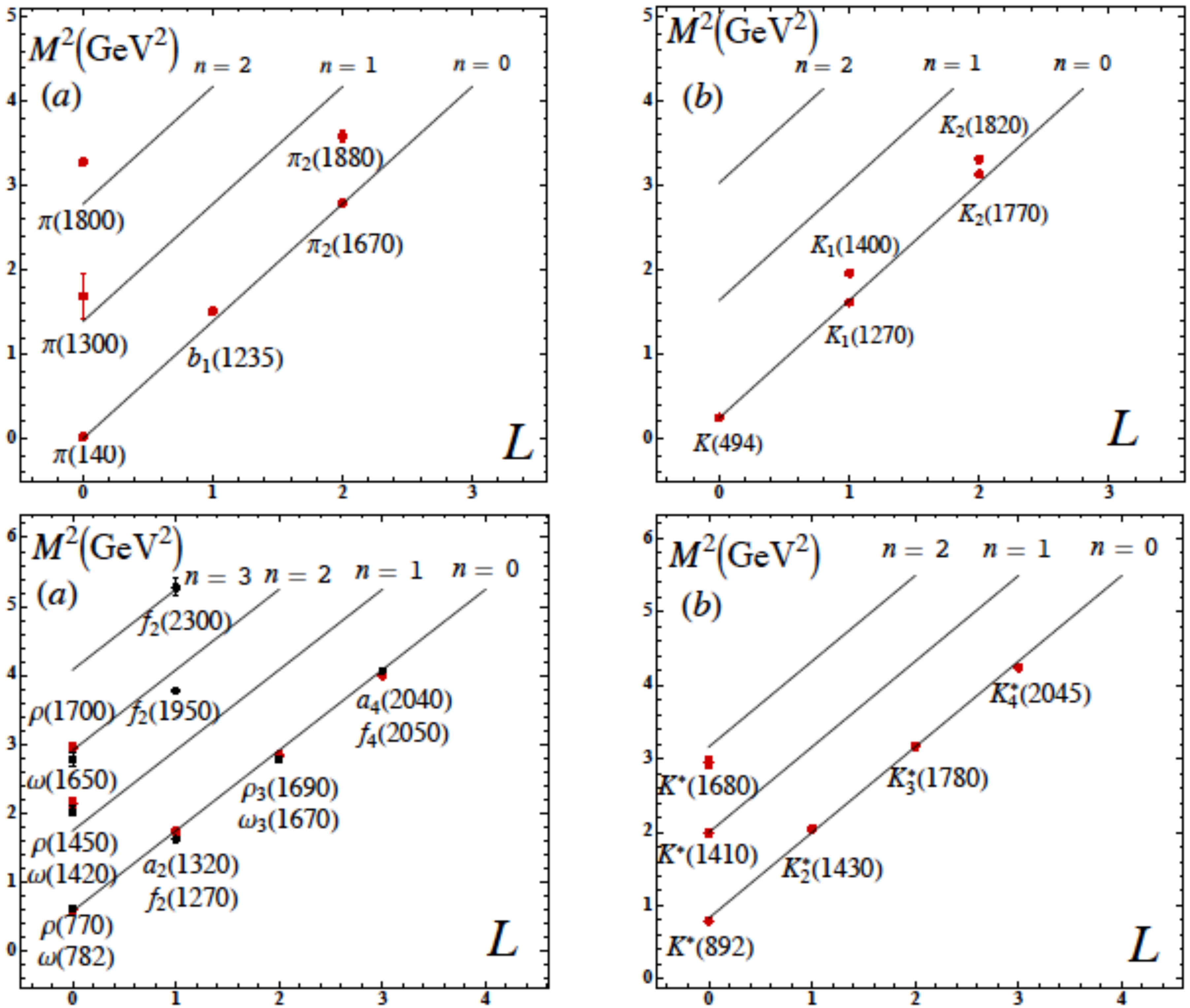
Light meson orbital (a) and radial (b) spectrum for $\kappa = 0.6$ GeV.

De Tèramond, Dosch, sjb

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

$$M^2 = M_0^2 + \left\langle X \left| \frac{m_q^2}{x} \right| X \right\rangle + \left\langle X \left| \frac{m_{\bar{q}}^2}{1-x} \right| X \right\rangle$$

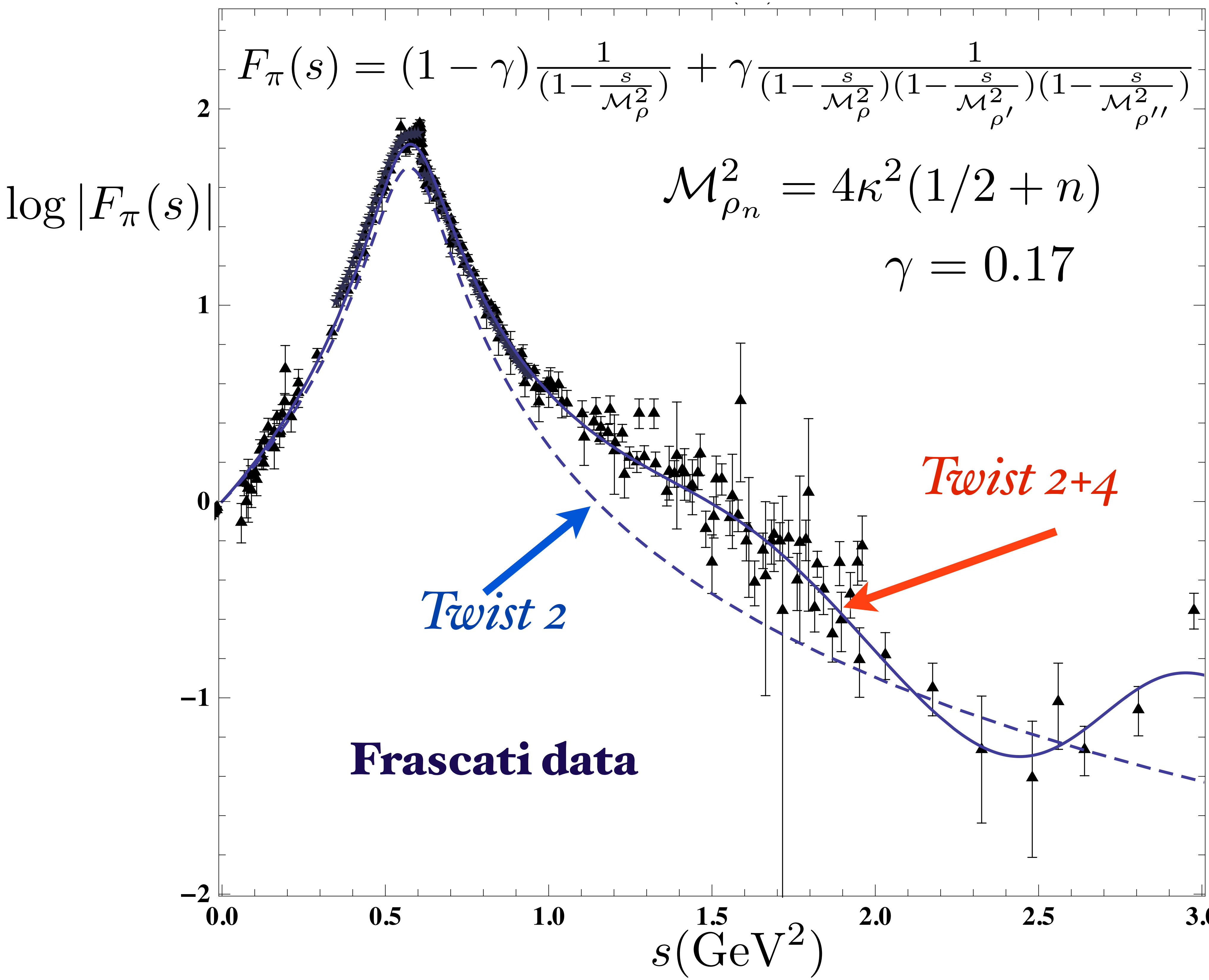
from LF Higgs mechanism



Effective mass from $m(p^2)$

Roberts, et al.

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

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

Remarkable Features of Light-Front Schrödinger Equation

Dynamics + Spectroscopy!

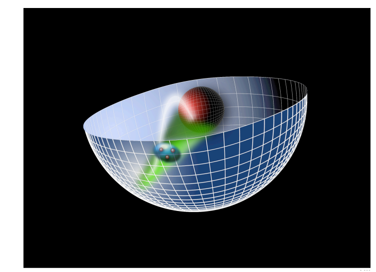
- ***Relativistic, frame-independent***
- ***QCD scale appears - unique LF potential***
- ***Reproduces spectroscopy and dynamics of light-quark hadrons with one parameter***
- ***Zero-mass pion for zero mass quarks!***
- ***Regge slope same for n and L -- not usual HO***
- ***Splitting in L persists 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)*

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



- *Introduces 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:*

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

Haag, Lopuszanski, Sohnius (1974)

Superconformal Quantum Mechanics

$$\{\psi, \psi^+\} = 1 \qquad B = \frac{1}{2}[\psi^+, \psi] = \frac{1}{2}\sigma_3$$

$$\psi = \frac{1}{2}(\sigma_1 - i\sigma_2), \quad \psi^+ = \frac{1}{2}(\sigma_1 + i\sigma_2)$$

$$Q = \psi^+[-\partial_x + \frac{f}{x}], \quad Q^+ = \psi[\partial_x + \frac{f}{x}], \qquad S = \psi^+ x, \quad S^+ = \psi x$$

$$\{Q, Q^+\} = 2H, \quad \{S, S^+\} = 2K$$

$$\{Q, S^+\} = f - B + 2iD, \quad \{Q^+, S\} = f - B - 2iD$$

generates conformal algebra

[H,D]= i H, [H, K] =2 i D, [K, D] = - i K

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

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

$$\lambda = \kappa^2$$

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

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

S=0, P=+

Same κ *!*

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

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

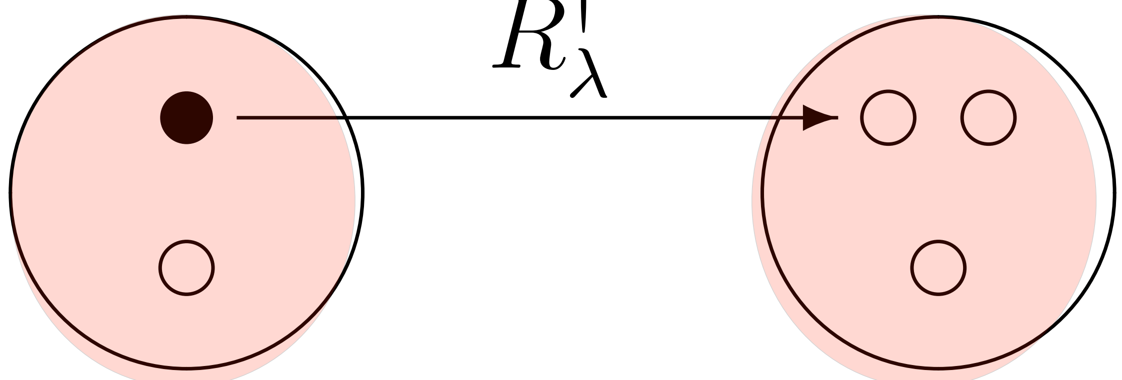
Superconformal Algebra

2X2 Hadronic Multiplets

Bosons, Fermions with Equal Mass!

Meson **Baryon**

$R^\dagger_\lambda$



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

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

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

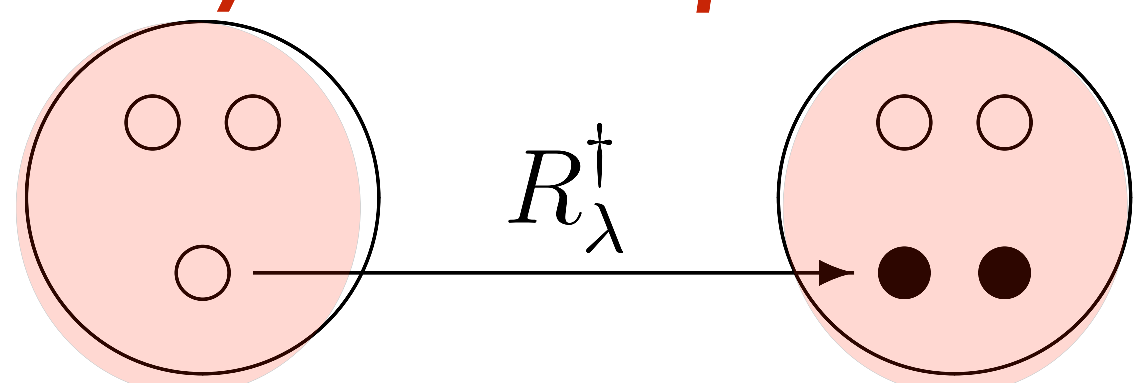
Tetraquark: diquark + antidiquark

Baryon

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

$3_C \to 3_C$

$R^\dagger_\lambda$



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

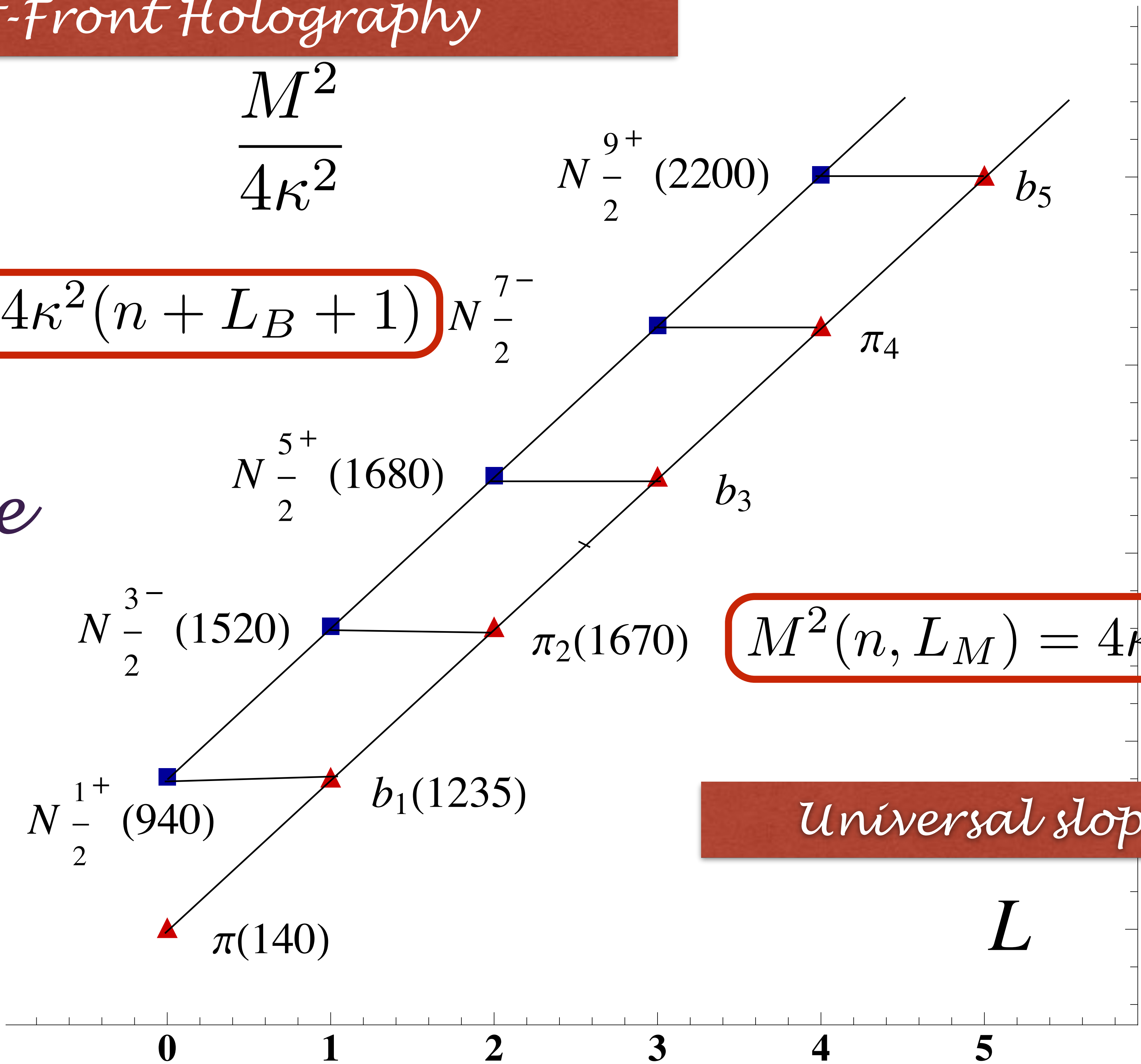
Proton: |u[ud]> Quark + Scalar Diquark
Equal Weight: L=0, L=1

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



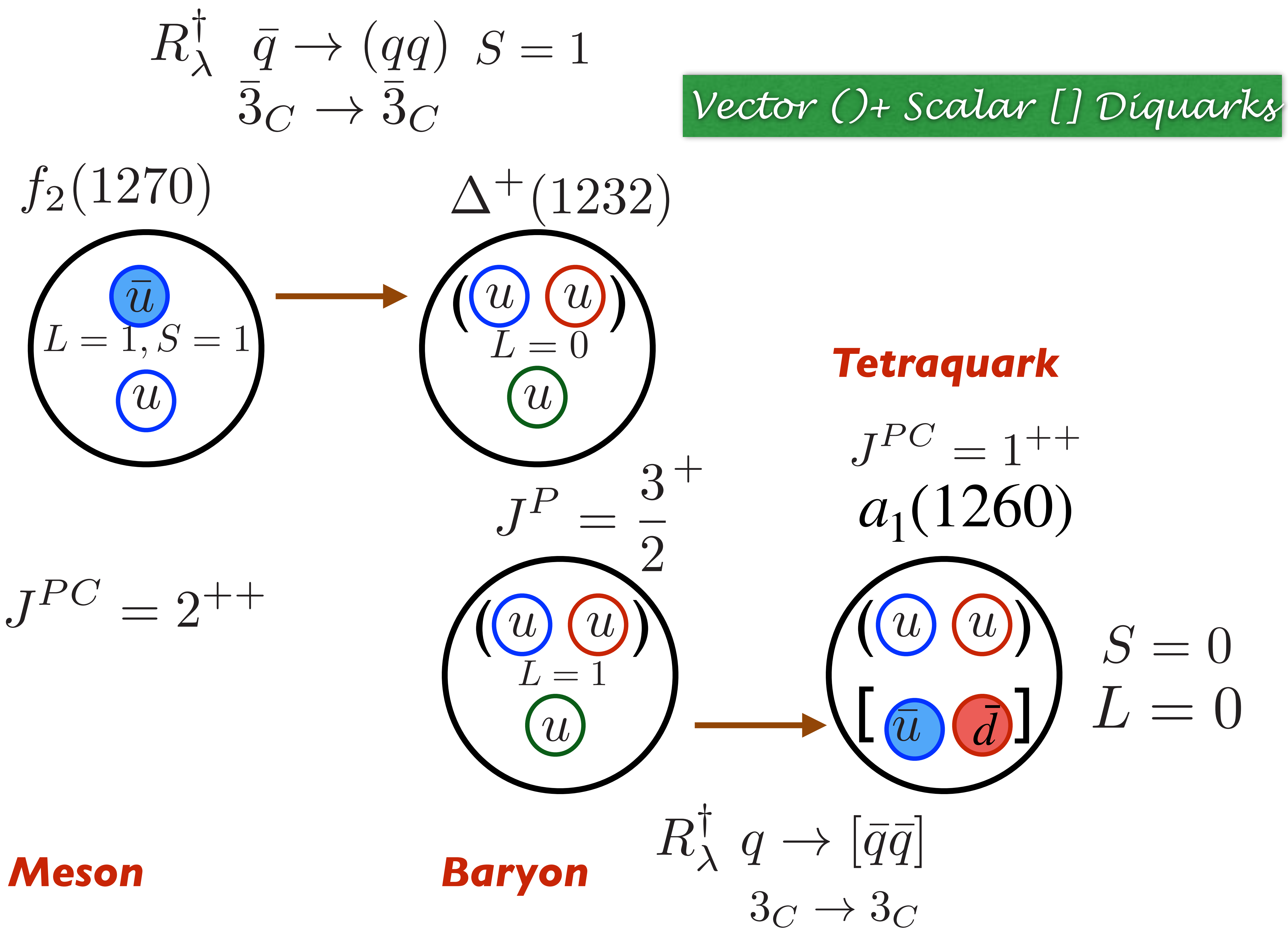
$$M^2(n, L_M) = 4\kappa^2(n + L_M)$$

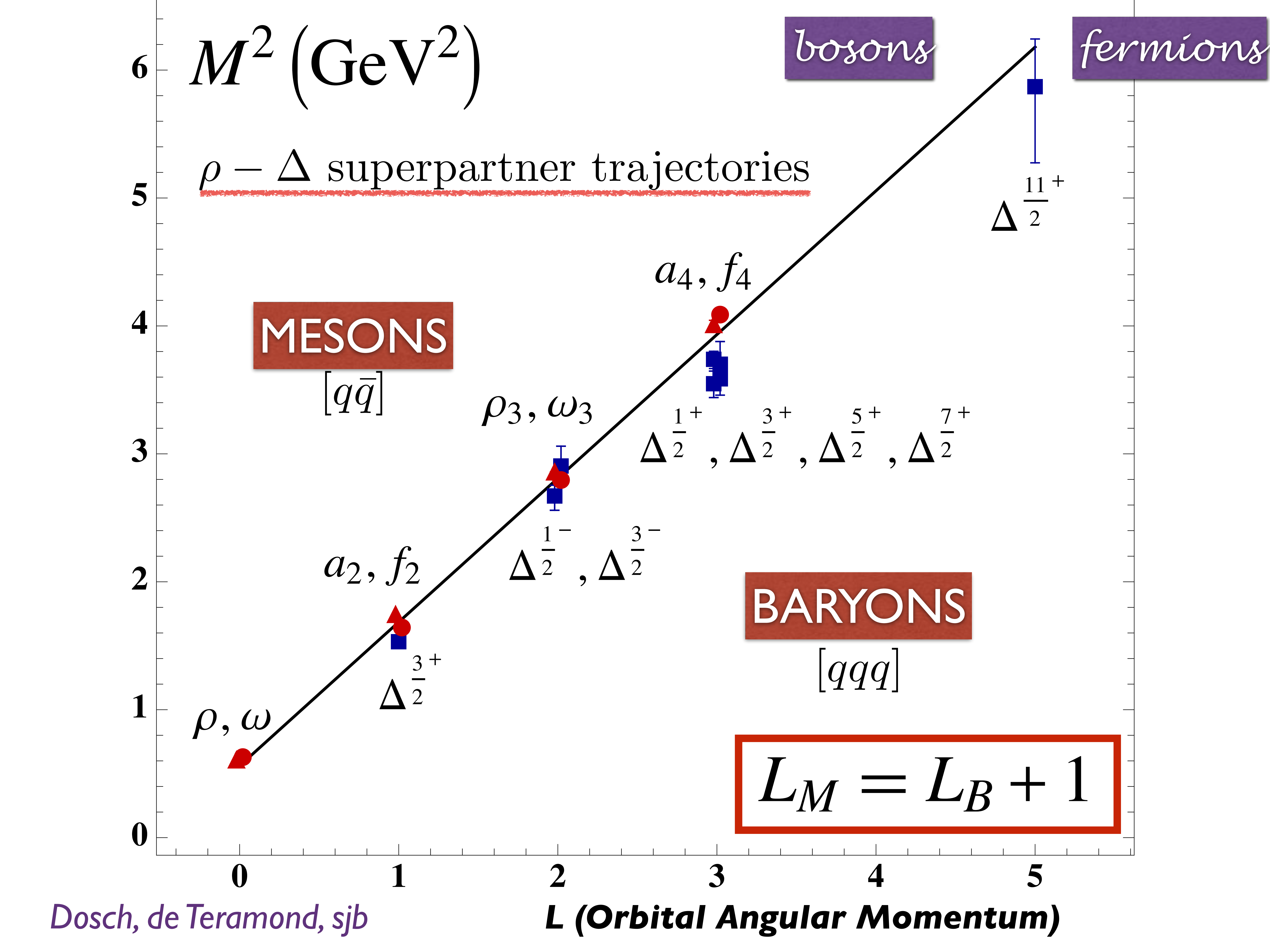
Universal slopes in n, L

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

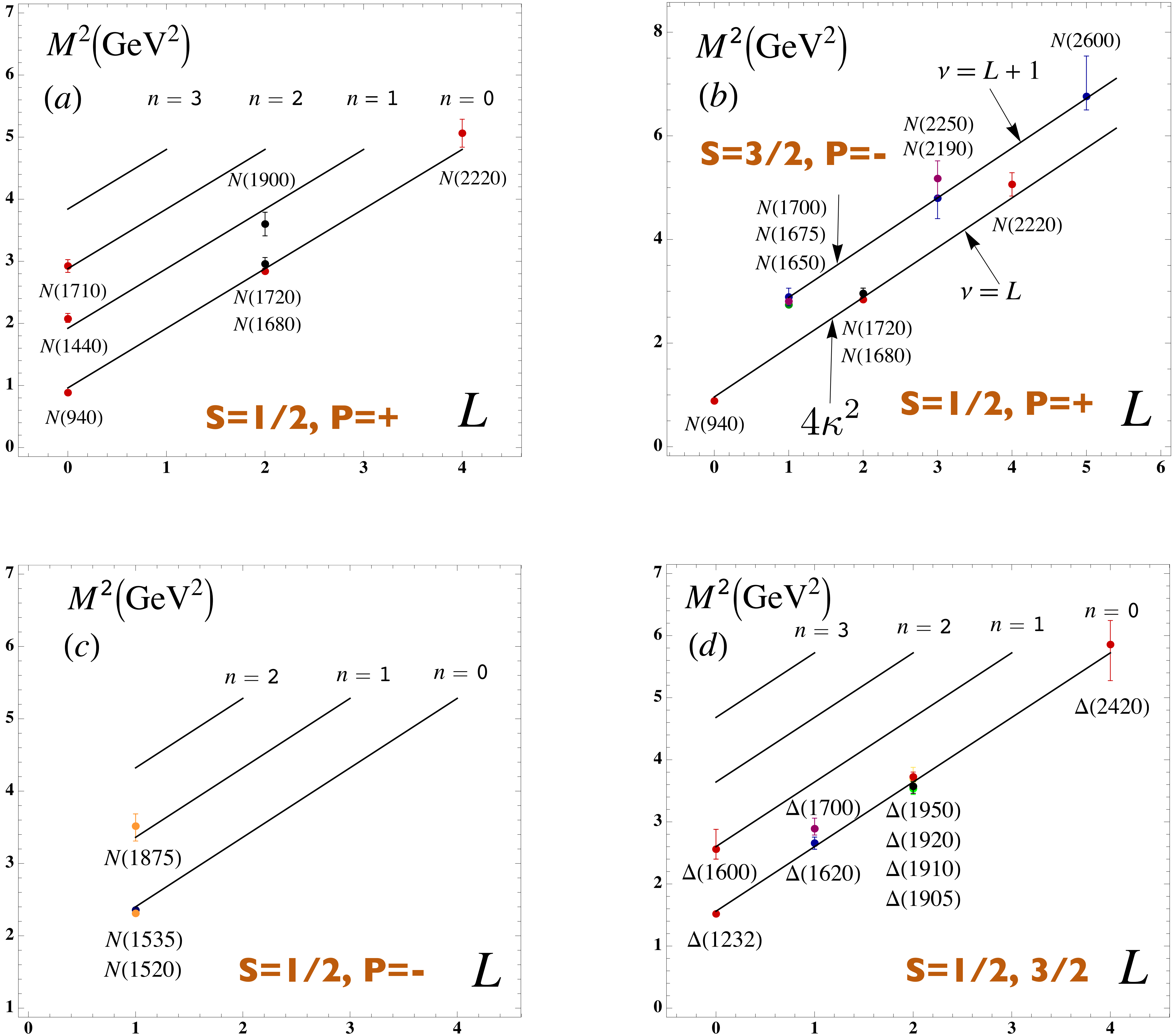
Meson-Baryon Mass Degeneracy for $L_M = L_B + 1$

Superconformal Algebra 4-Plet





$M^2\,(\mathrm{GeV}^2)$
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
$\Delta \frac{3}{2}^+$
$\Delta \frac{1}{2}^-, \Delta \frac{3}{2}^-$
$\Delta \frac{1}{2}^+, \Delta \frac{3}{2}^+, \Delta \frac{5}{2}^+, \Delta \frac{7}{2}^+$
$\Delta \frac{11}{2}^+$
$L_M = L_B + 1$
L (Orbital Angular Momentum)
Dosch, de Teramond, sjb



$M^2(\mathrm{GeV}^2)$
(a)
n = 3
n = 2
n = 1
n = 0
N(1900)
N(2220)
N(1710)
N(1440)
N(1720)
N(1680)
N(940)
S=1/2, P=+
L
$M^2(\mathrm{GeV}^2)$
(b)
N(2600)
$\nu = L + 1$
N(2250)
N(2190)
S=3/2, P=-
N(1700)
N(1675)
N(1650)
N(2220)
$\nu = L$
N(1720)
N(1680)
N(940)
$4\kappa^2$
S=1/2, P=+
L
$M^2(\mathrm{GeV}^2)$
(c)
n = 2
n = 1
n = 0
N(1875)
N(1535)
N(1520)
S=1/2, P=-
L
$M^2(\mathrm{GeV}^2)$
(d)
n = 3
n = 2
n = 1
n = 0
Δ(2420)
Δ(1700)
Δ(1950)
Δ(1920)
Δ(1910)
Δ(1905)
Δ(1600)
Δ(1620)
Δ(1232)
S=1/2, 3/2
L

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

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^{++}	$a_3(\sim 2070)?$
$\bar{q}s$	$0^{-(+)}$	$\bar{K}(495)$	—	—	—	—	—	—
$\bar{q}s$	$1^{+(-)}$	$\bar{K}_1(1270)$	$[ud]s$	$(1/2)^+$	$\Lambda(1115)$	$[ud][\bar{s}\bar{q}]$	$0^{+(+)}$	$K_0^*(1430)$
$\bar{q}s$	$2^{-(+)}$	$\bar{K}_2(1770)$	$[ud]s$	$(1/2)^-$	$\Lambda(1405)$	$[ud][\bar{s}\bar{q}]$	$1^{-(+)}$	$K_1^*(\sim 1700)?$
				$(3/2)^-$	$\Lambda(1520)$			
$\bar{s}q$	$0^{-(+)}$	$K(495)$	—	—	—	—	—	—
$\bar{s}q$	$1^{+(-)}$	$K_1(1270)$	$[sq]q$	$(1/2)^+$	$\Sigma(1190)$	$[sq][\bar{s}\bar{q}]$	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

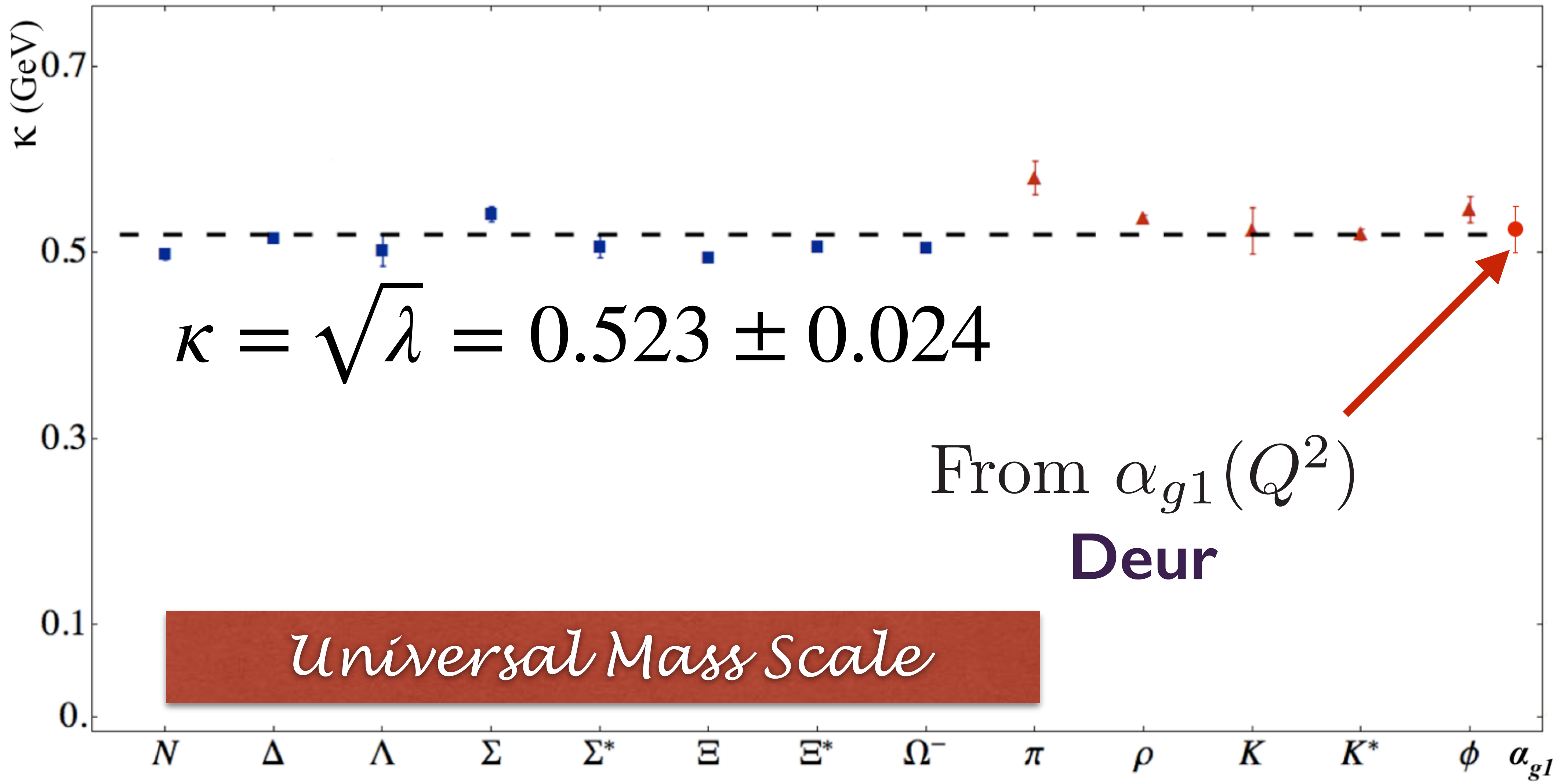
M. Nielsen, sjb

$\lambda = \kappa^2$

de Téramond, Dosch, Lorcé, sjb

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

κ



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

From $\alpha_{g1}(Q^2)$

Deur

Universal Mass Scale

Fit to the slope of Regge trajectories, including radial excitations

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

LF Holography

Baryon LFWFs

Superconformal Quantum Mechanics

- Nucleon LF modes

$$\psi_+(\zeta)_{n,L} = \kappa^{2+L}\sqrt{\frac{2n!}{(n+L)!}}\zeta^{3/2+L}e^{-\kappa^2\zeta^2/2}L_n^{L+1}\left(\kappa^2\zeta^2\right)$$

$$\psi_-(\zeta)_{n,L} = \kappa^{3+L}\frac{1}{\sqrt{n+L+2}}\sqrt{\frac{2n!}{(n+L)!}}\zeta^{5/2+L}e^{-\kappa^2\zeta^2/2}L_n^{L+2}\left(\kappa^2\zeta^2\right)$$

- Normalization

$$\int d\zeta\,\psi_+^2(\zeta) = \int d\zeta\,\psi_-^2(\zeta) = 1$$

- Eigenvalues

$$\int_0^\infty d\zeta \int_0^1 dx\psi_+^2(\zeta^2,x) = \int_0^\infty d\zeta \int_0^1 dx\psi_-^2(\zeta^2,x) = \tfrac{1}{2}$$

Quark Chiral Symmetry of Eigenstate!

Nucleon: Equal Probability for L=0,1

$$J^z = +1/2: \quad \frac{1}{\sqrt{2}}[\,|S_q^z = +1/2,\, L^z = 0 > + |S_q^z = -1/2,\, L^z = +1 >\,]$$

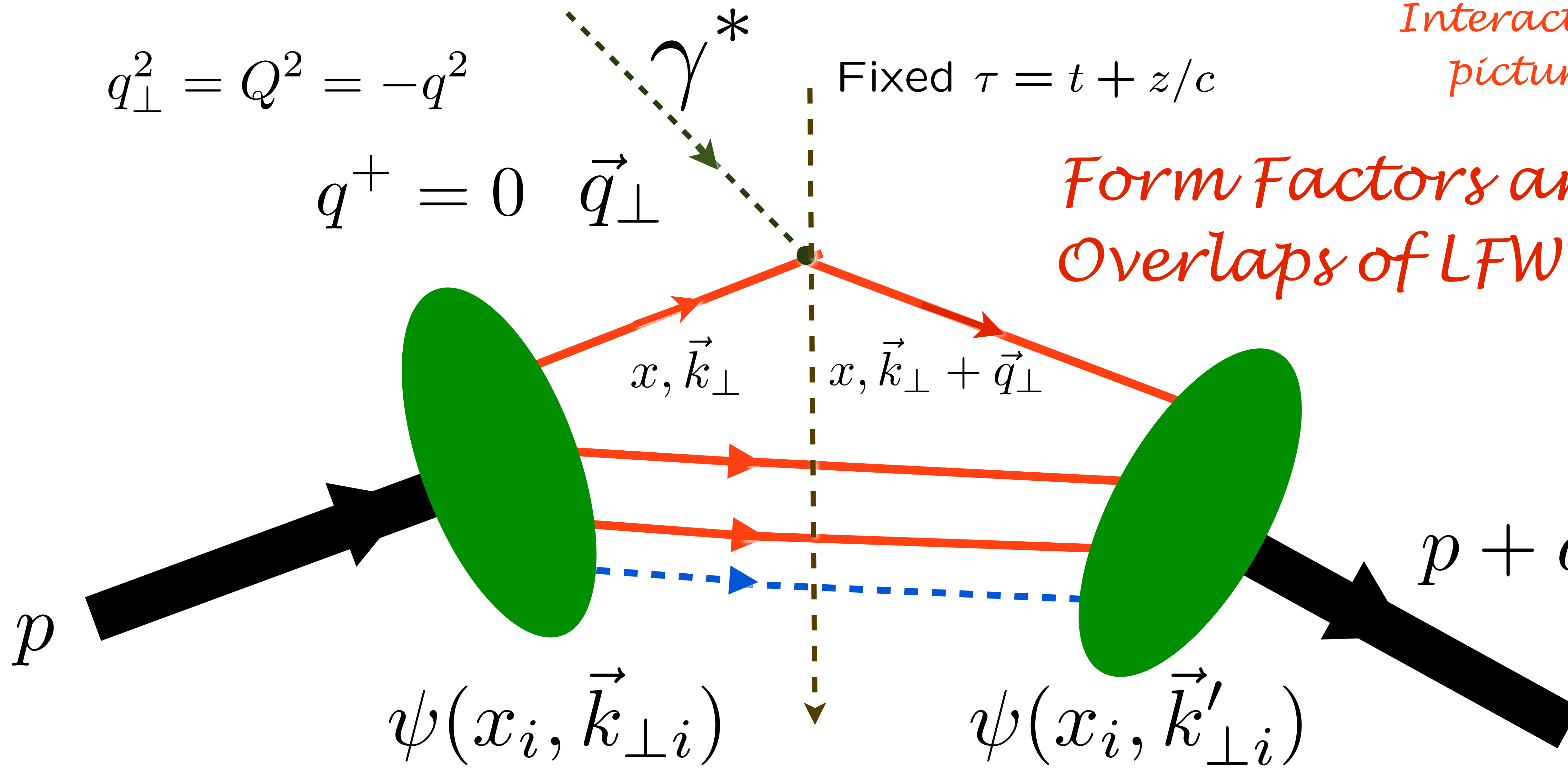
Nucleon spin carried by quark orbital angular momentum

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

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

Exact LF Formula for Pauli Form Factor

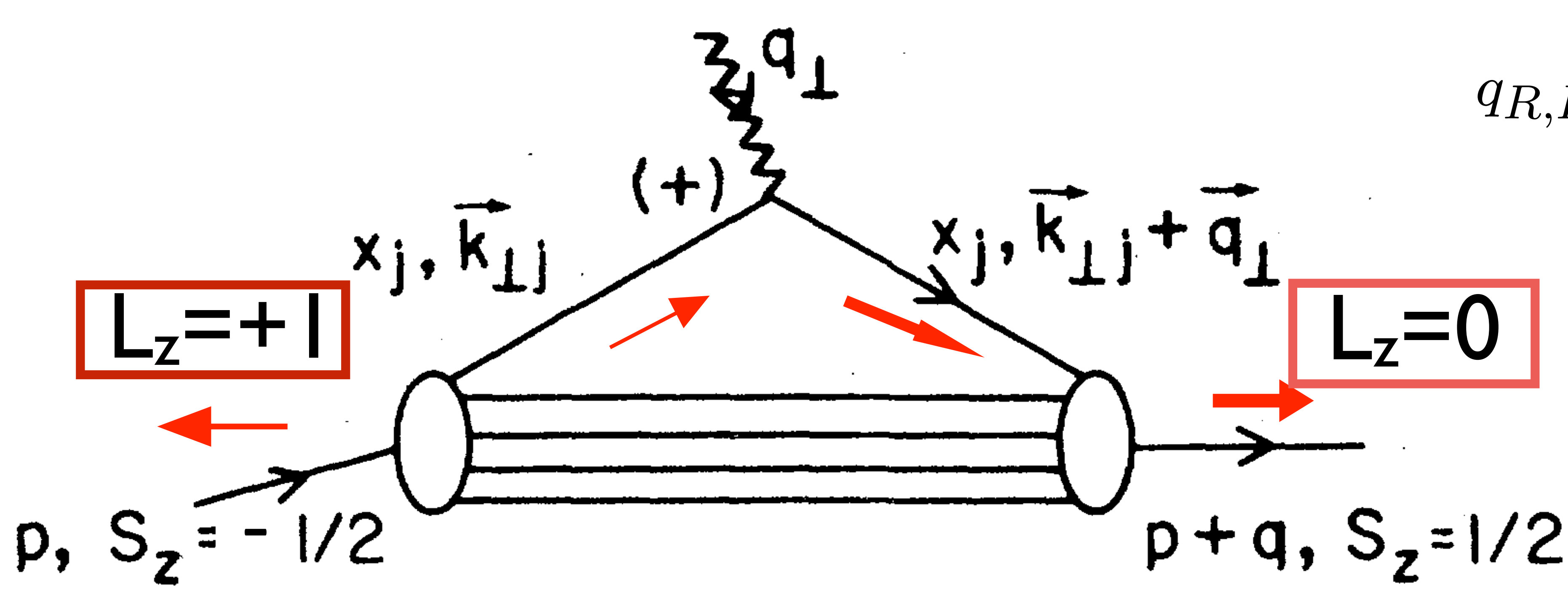
$$\frac{F_2(q^2)}{2M} = \sum_a \int [\mathrm{d}x][\mathrm{d}^2\mathbf{k}_\perp] \sum_j e_j \, \frac{1}{2} \times$$

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 $F_2(q^2)$

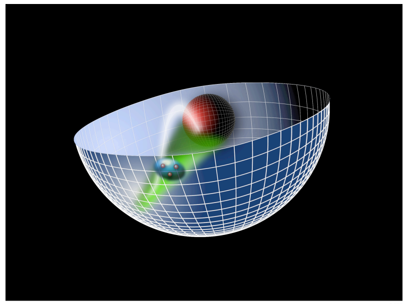
Nonzero Proton Anomalous Moment -->
Nonzero orbital quark angular momentum

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)*

"Emergent Mass"

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

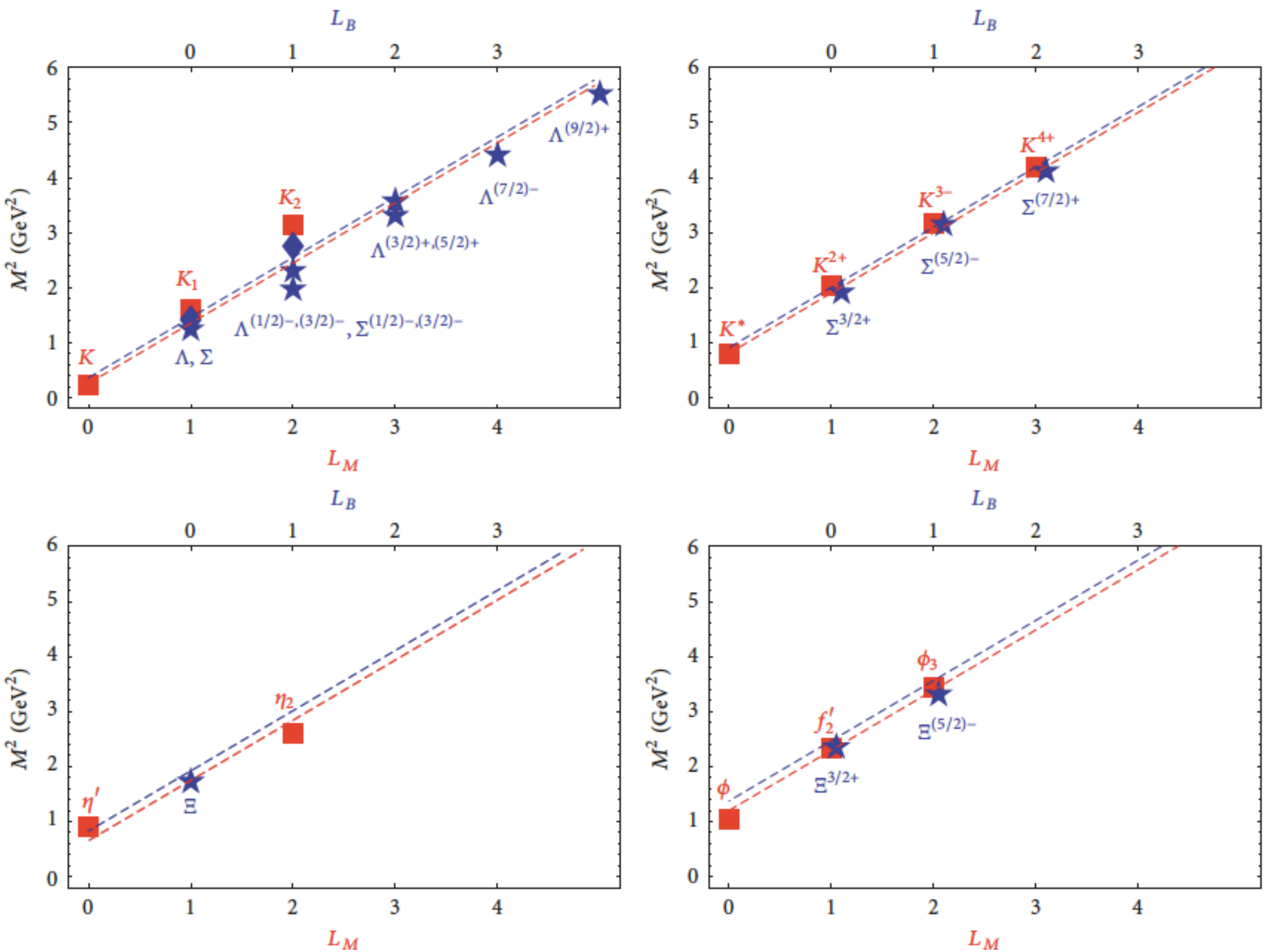
- *Unique color-confining LF Potential* $U(\zeta^2) = \kappa^4 \zeta^2$

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

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

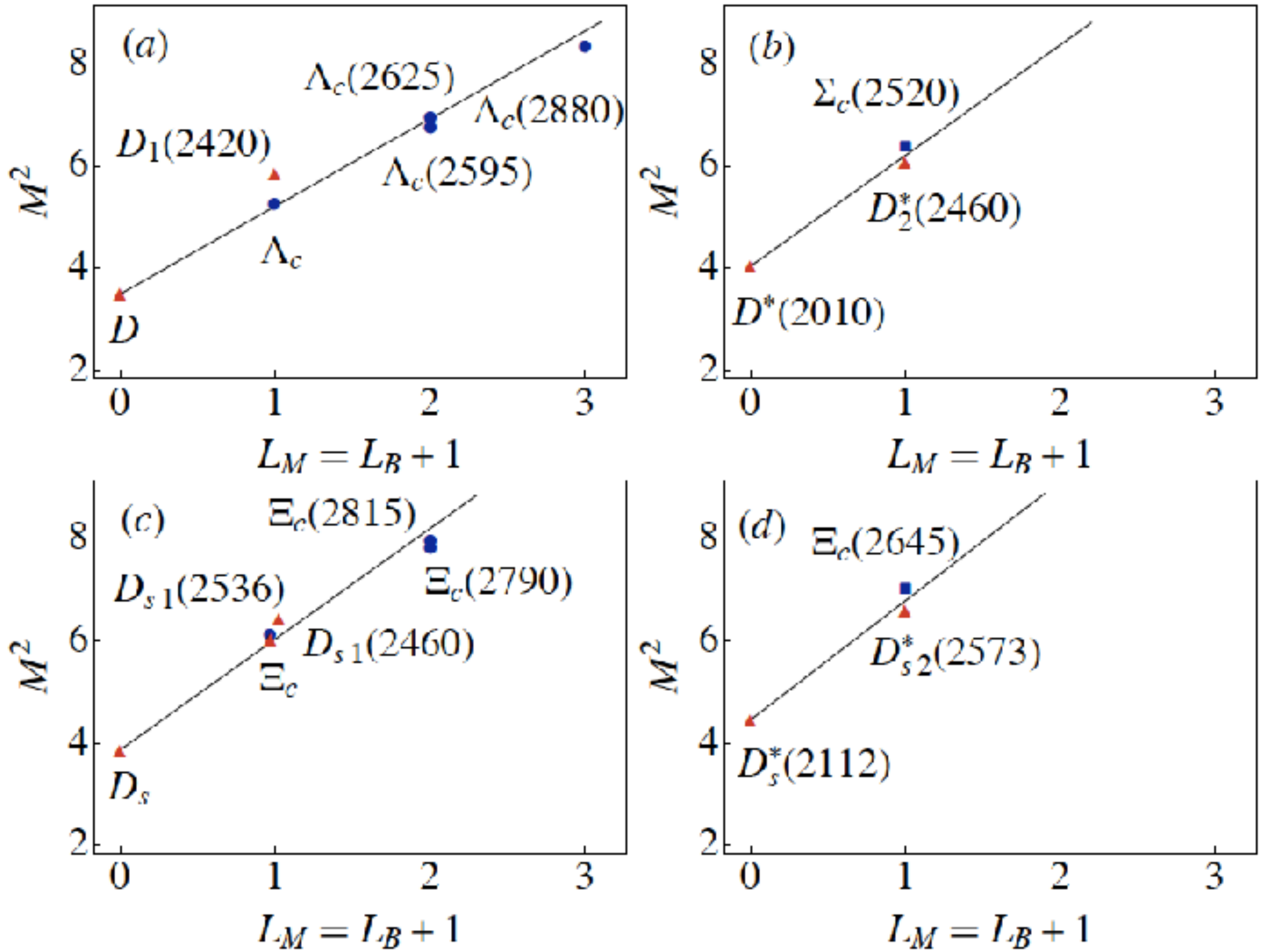
de Téramond, Dosch, Lorcé, sjb

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

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^+	??

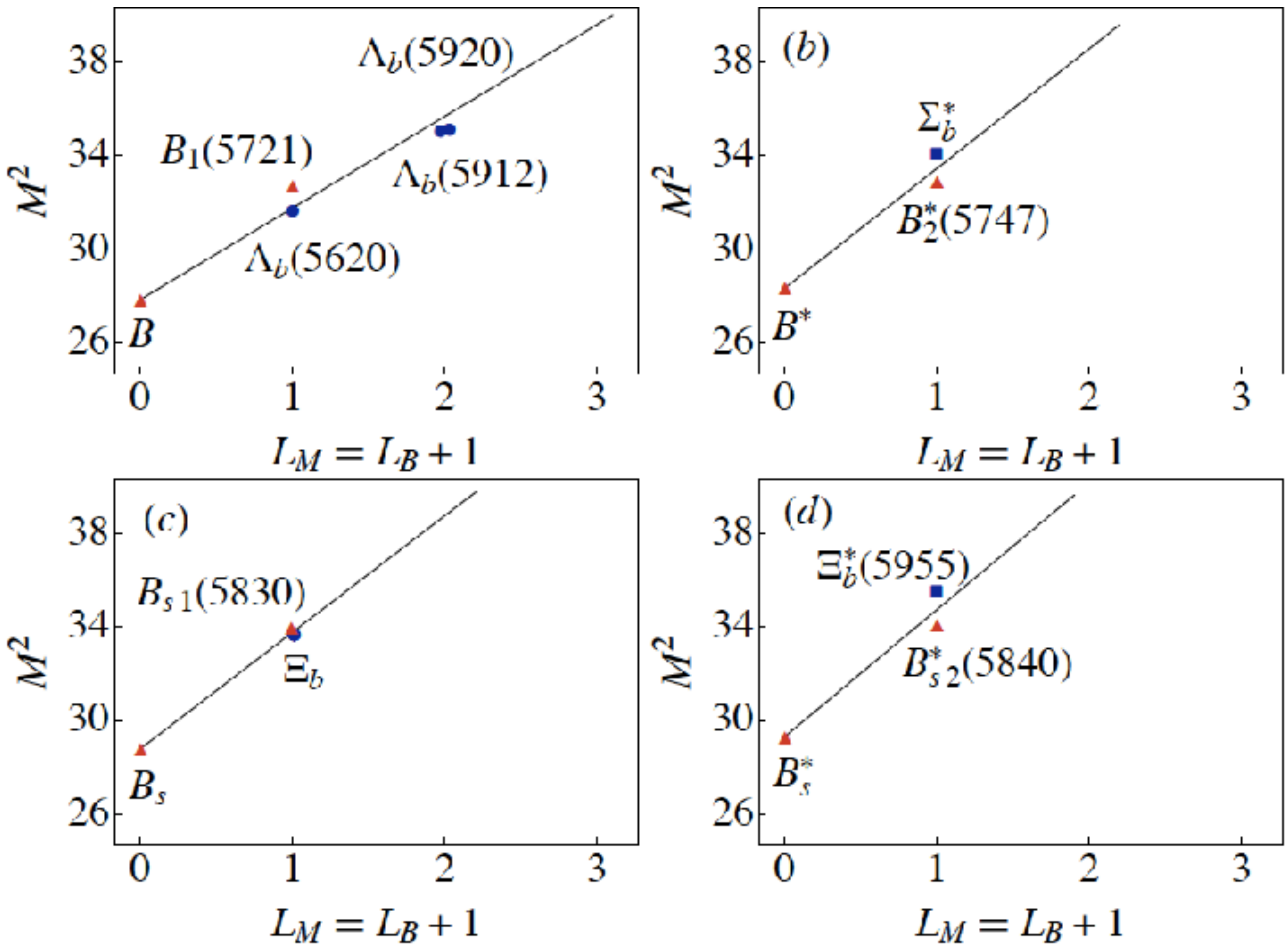
predictions

beautiful agreement!

M. Nielsen, sjb

de Téramond, Dosch, Lorcé, sjb

Supersymmetry across the light and heavy-light spectrum



Heavy bottom 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)]

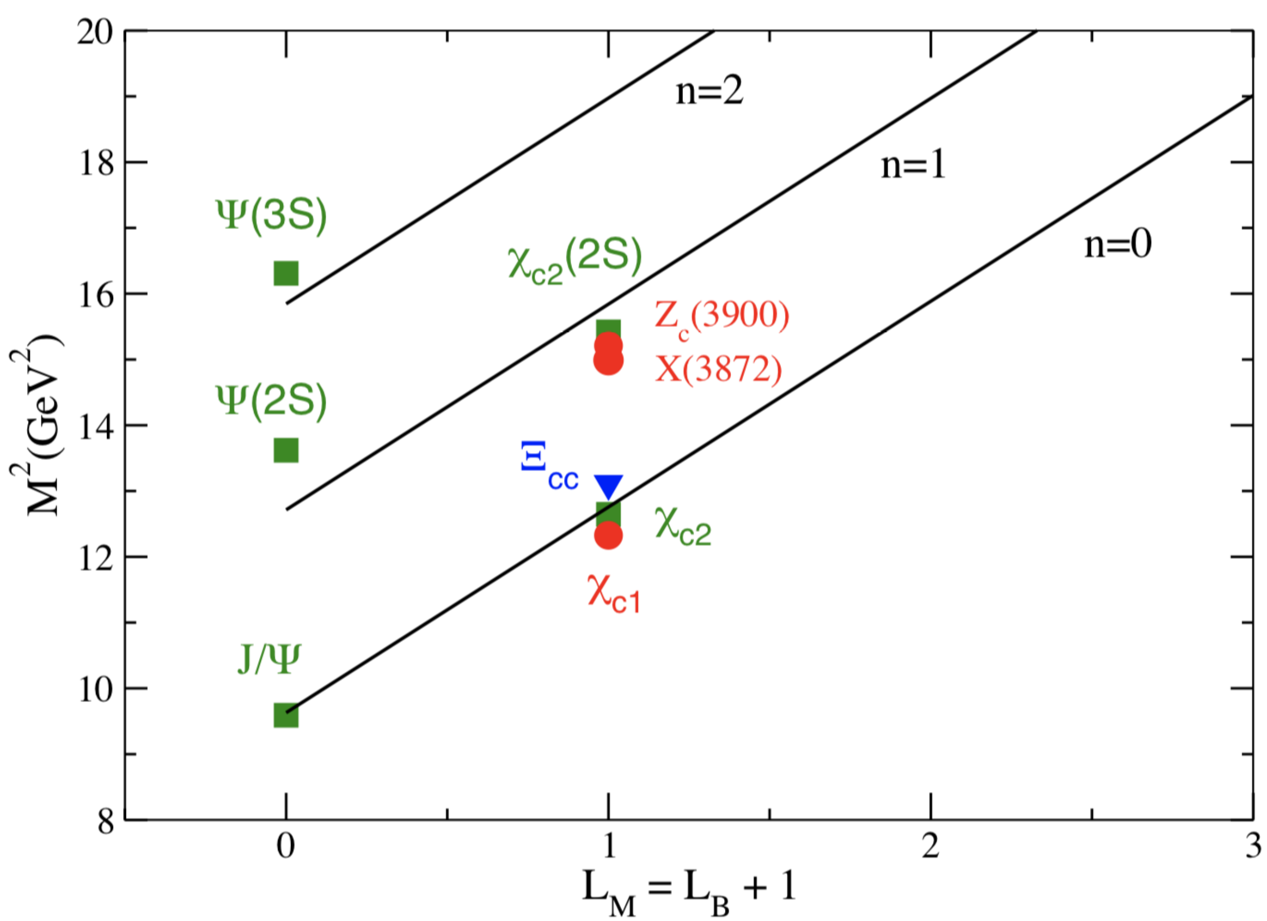
- Extension to the double-heavy hadronic sector

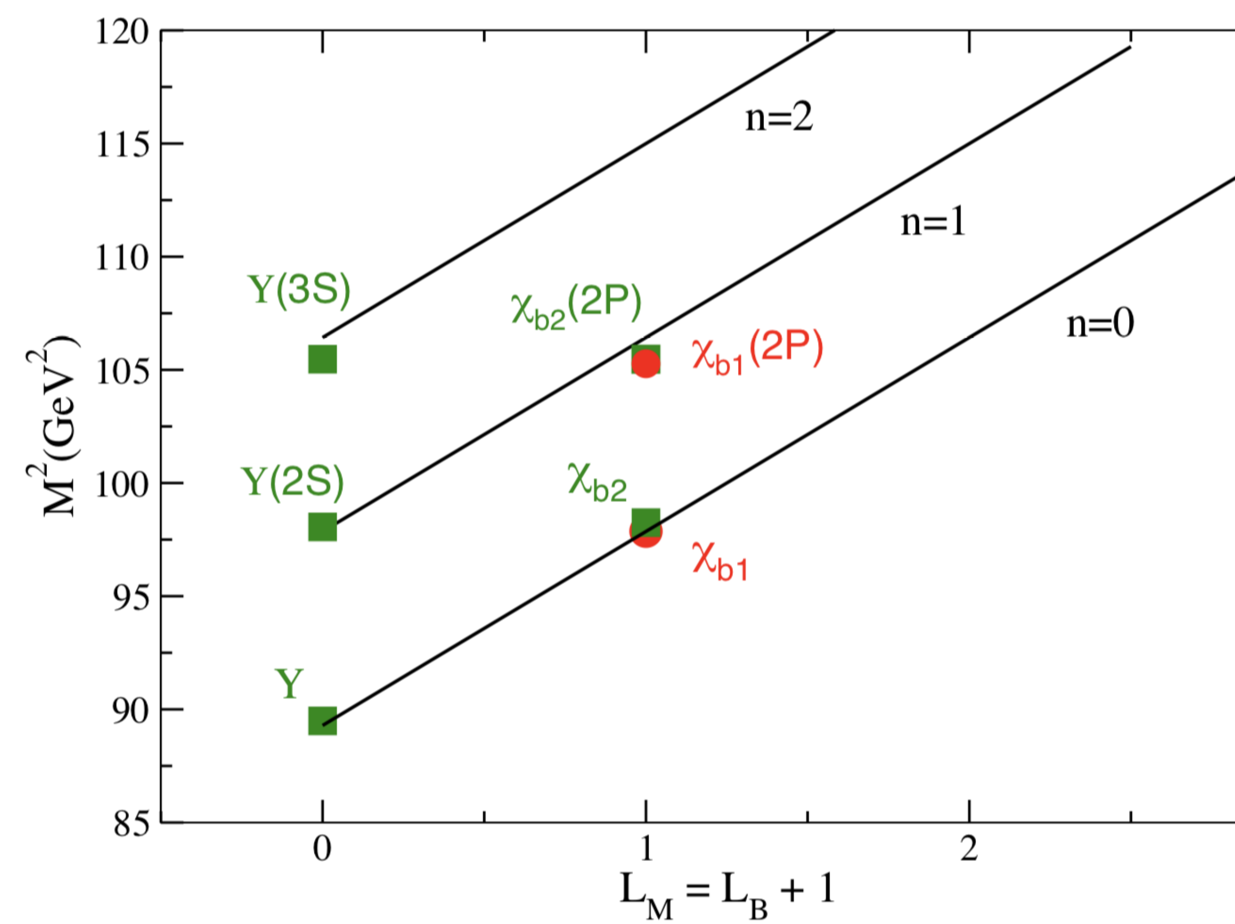
  [M. Nielsen and S. J. Brodsky, PRD, 114001 (2018)]

  [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]]





Running Coupling from Modified AdS/QCD

Deur, de Teramond, sjb

- Consider five-dim gauge fields propagating in AdS$_5$ space in dilaton background $\varphi(z) = \kappa^2 z^2$

$$e^{\phi(z)} = e^{+\kappa^2 z^2} \qquad S = -\frac{1}{4}\int d^4x\, dz\, \sqrt{g}\, e^{\varphi(z)}\, \frac{1}{g_5^2}\, G^2$$

- Flow equation

$$\frac{1}{g_5^2(z)} = e^{\varphi(z)} \frac{1}{g_5^2(0)} \quad \text{or} \quad g_5^2(z) = e^{-\kappa^2 z^2} g_5^2(0)$$

where the coupling $g_5(z)$ incorporates the non-conformal dynamics of confinement

- YM coupling $\alpha_s(\zeta) = g_{YM}^2(\zeta)/4\pi$ is the five dim coupling up to a factor: $g_5(z) \to g_{YM}(\zeta)$

- Coupling measured at momentum scale Q

$$\alpha_s^{AdS}(Q) \sim \int_0^\infty \zeta d\zeta J_0(\zeta Q)\, \alpha_s^{AdS}(\zeta)$$

- Solution

$$\boxed{\alpha_s^{AdS}(Q^2) = \alpha_s^{AdS}(0)\, e^{-Q^2/4\kappa^2}.}$$

where the coupling α_s^{AdS} incorporates the non-conformal dynamics of confinement

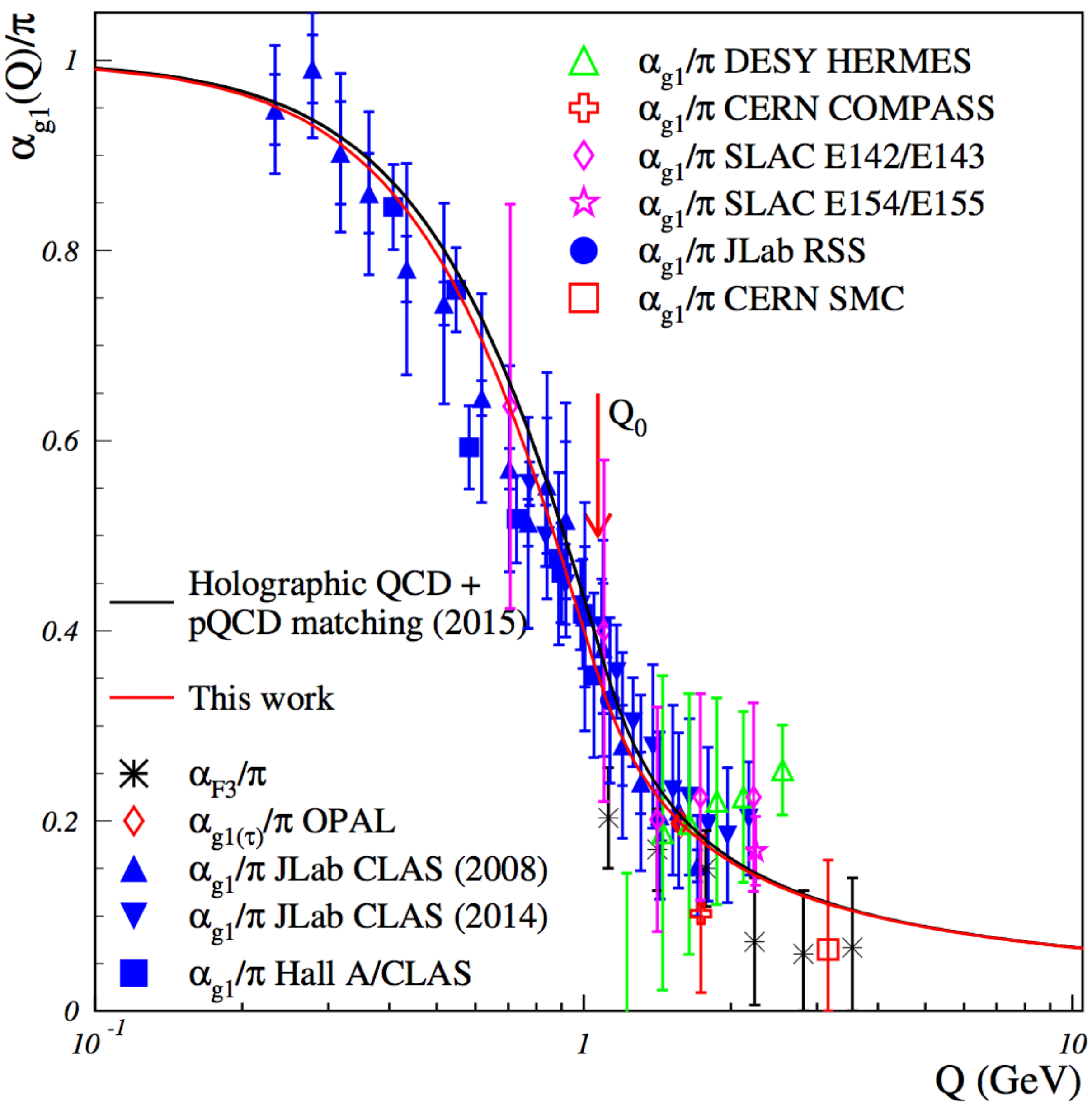
Bjorken sum rule defines effective charge

$\alpha_{g1}(Q^2)$

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

- ***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***

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)

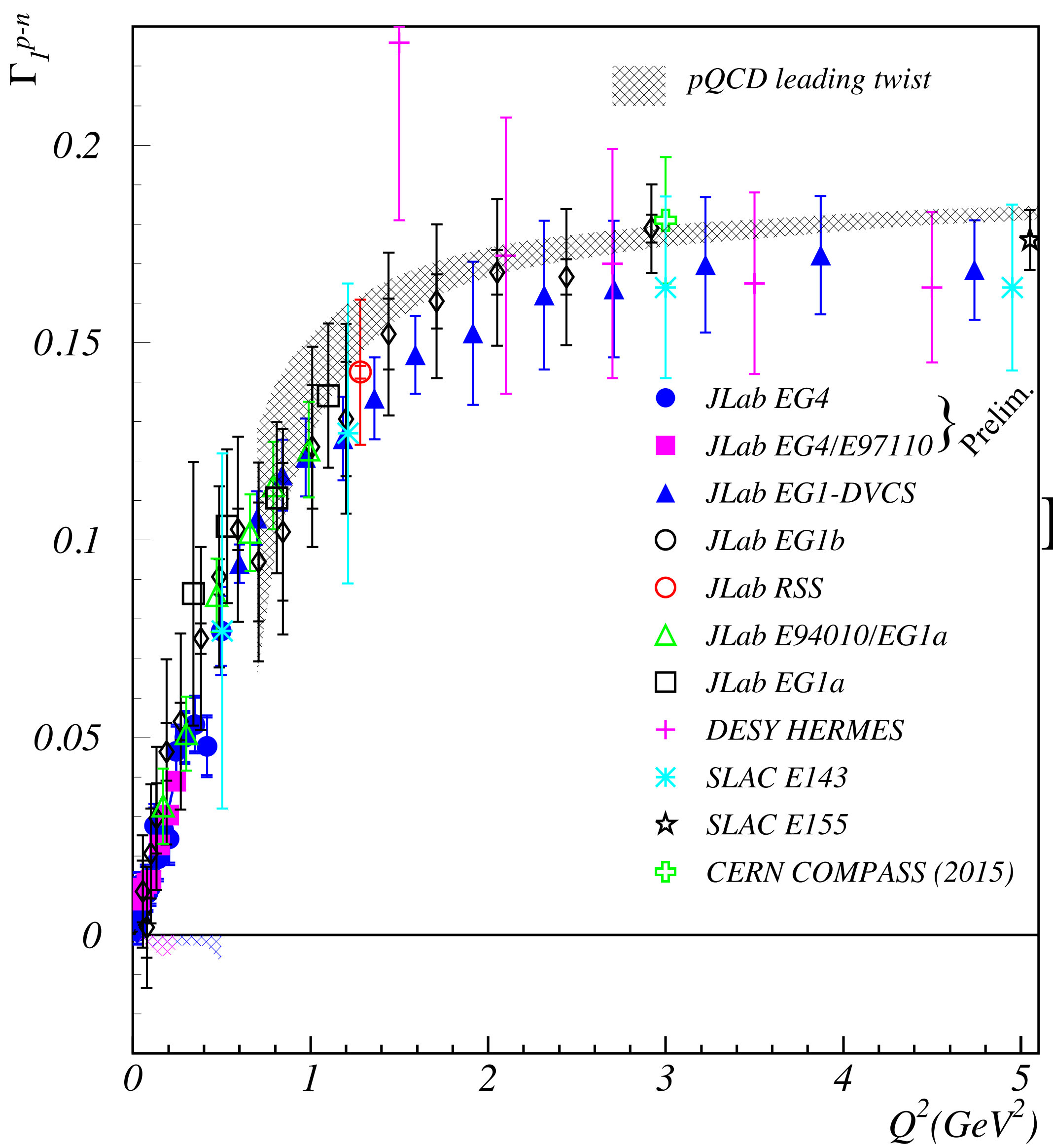
$$\alpha_{g_1}^{AdS}(Q^2) = \pi \exp\left(-Q^2/4\kappa^2\right)$$

Imposing continuity for α and its first derivative

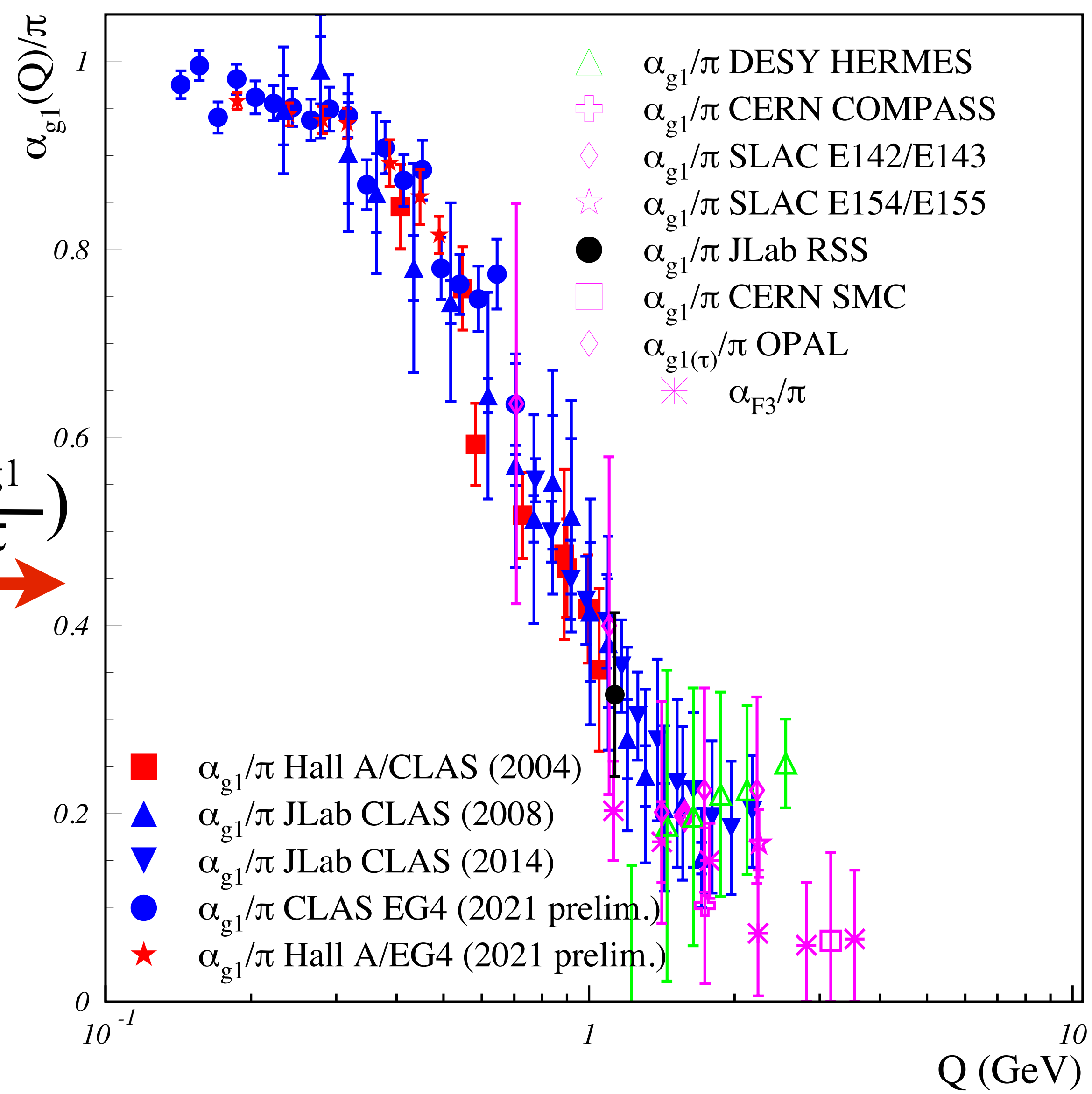
A. Deur, S.J. Brodsky, G.F. de Téramond,
Phys. Lett. B 750, 528 (2015); J. Phys. G 44, 105005 (2017).

Analytic, defined at all scales, IR Fixed Point

Bjorken sum Γ_1^{p-n} measurements



$$\Gamma_1^{p\text{-}n} \triangleq \frac{1}{6} g_A \left(1 - \frac{\alpha_{g1}}{\pi}\right)$$



Low Q^2 limit

A. Deur

At $Q^2 = 0$, a sum rule related to the Bjorken sum rule exists: the Gerasimov-Drell-Hearn (GDH) sum rule:

At $Q^2 = 0$, GDH sum rule:

$$\Gamma_1 = \frac{-\kappa^2 Q^2}{8M^2}$$

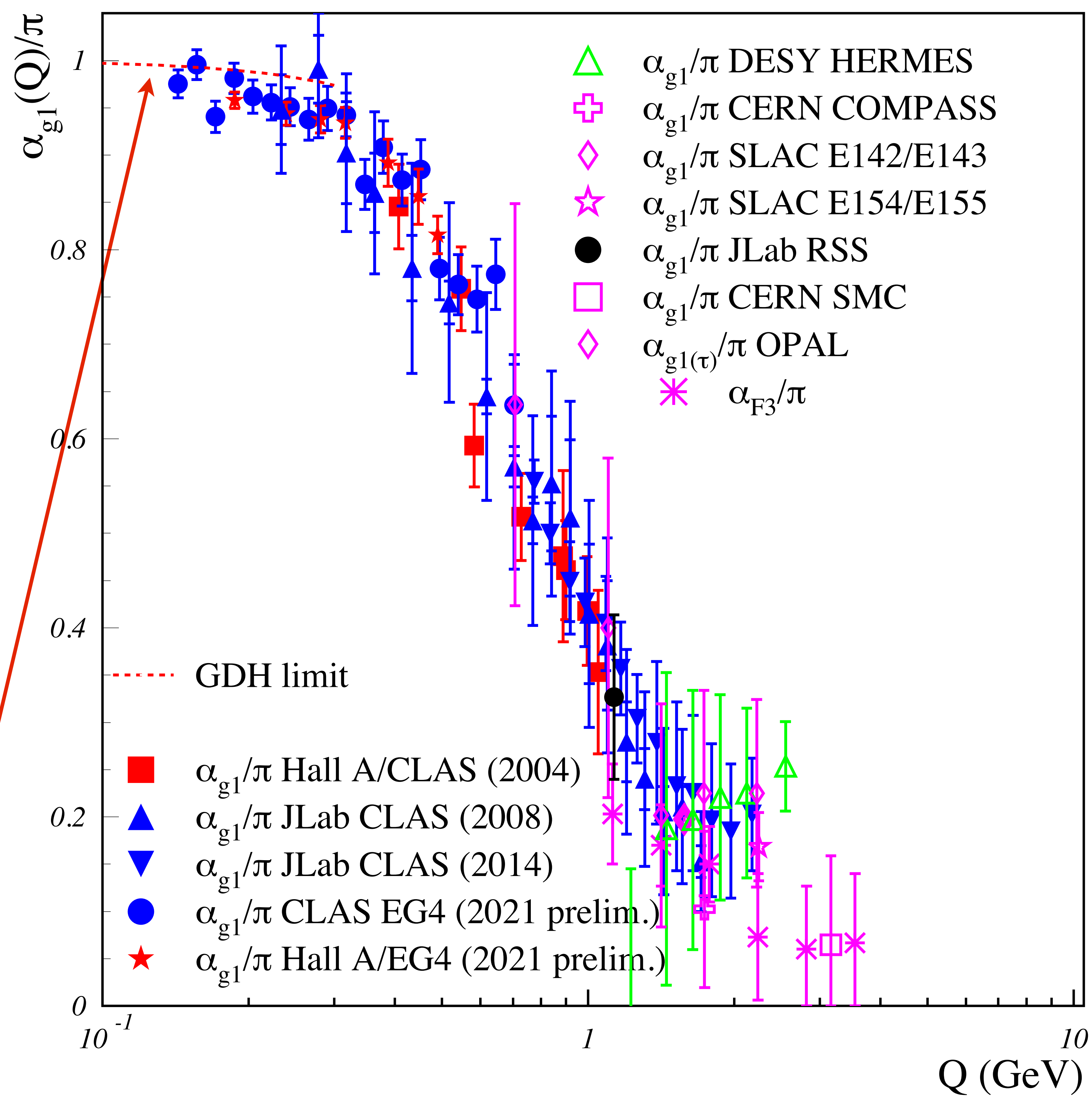
anomalous magnetic moment

Nucleon mass

$\Rightarrow Q^2 = 0$ constraints:

3.66 3.20

$$\Rightarrow \begin{cases} \alpha_{g1} = \pi \\ \dfrac{d\alpha_{g1}}{dQ^2} = \dfrac{3\pi}{4g_A}\left(\dfrac{\kappa_n^2}{M_n^2} - \dfrac{\kappa_p^2}{M_p^2}\right) \end{cases}$$



First experimental evidence of nearly *conformal behavior* (i.e. no Q^2-dependence) of QCD at low Q^2.

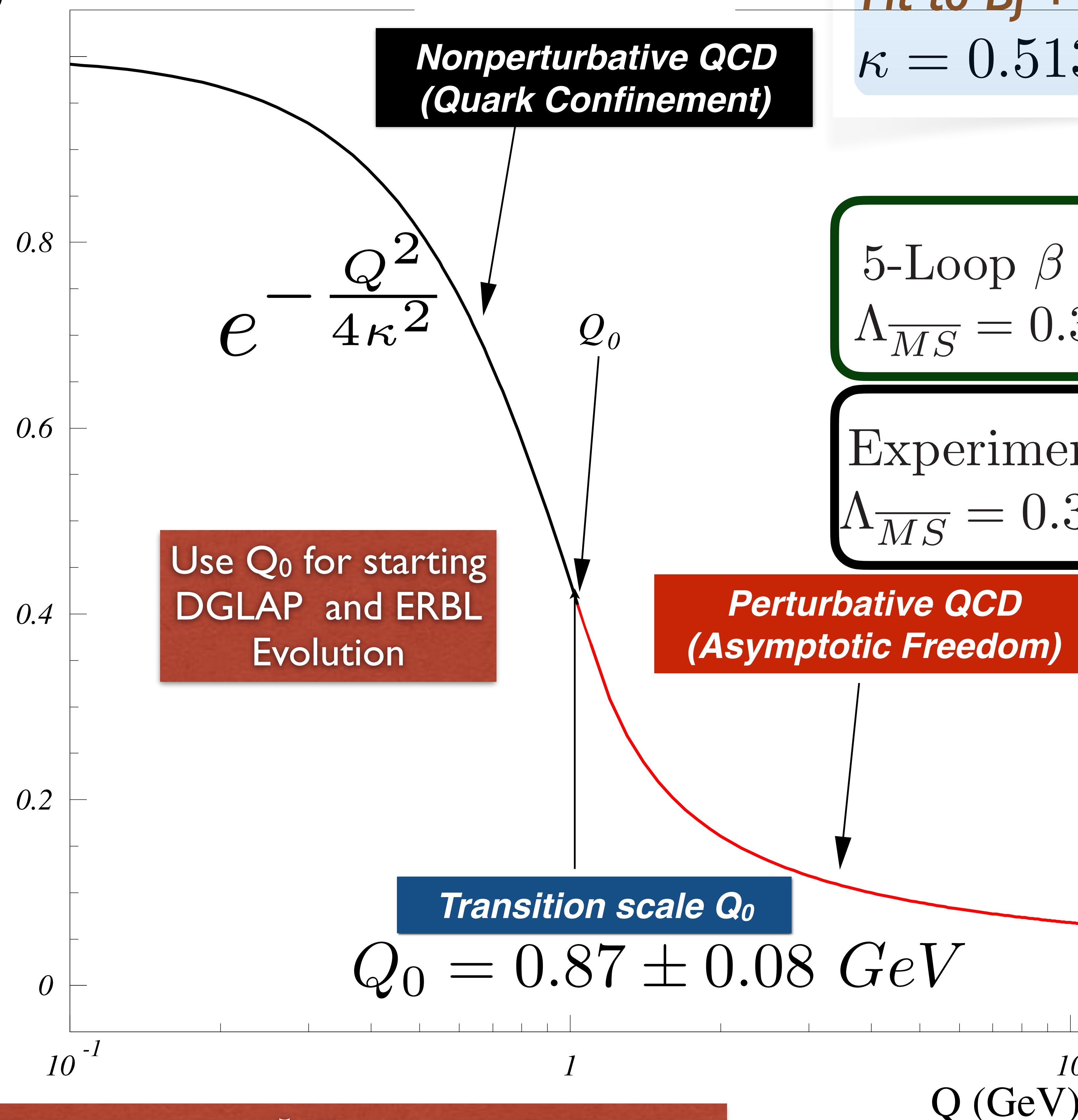
$$m_\rho = \sqrt{2}\kappa$$
$$m_p = 2\kappa$$

All-Scale QCD Coupling

Deur, de Tèramond, sjb

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

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



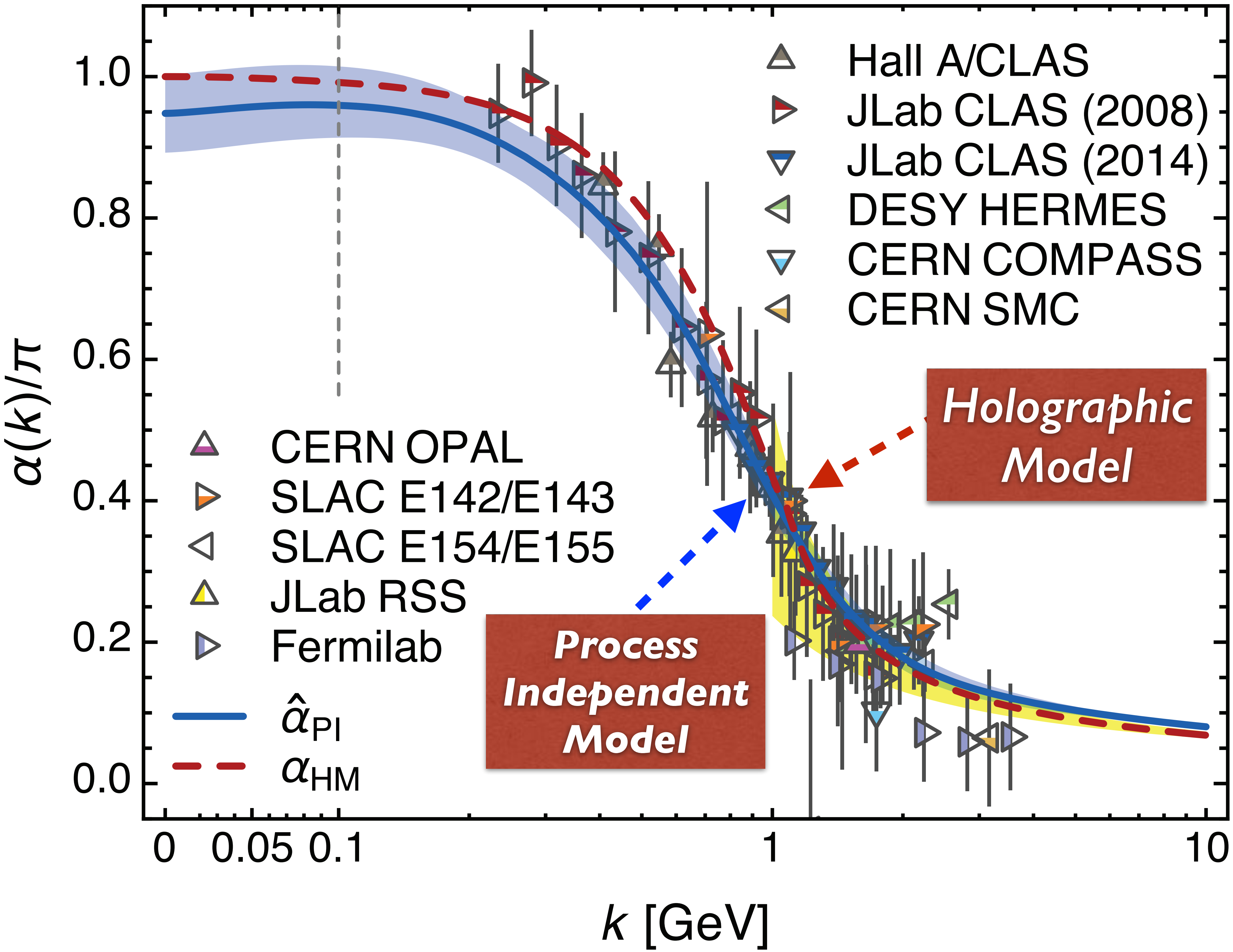
5-Loop β Prediction:
$\Lambda_{\overline{MS}} = 0.339 \pm 0.019 \ GeV$

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

$\lambda \equiv \kappa^2$

$\overline{MS}$ *scheme*

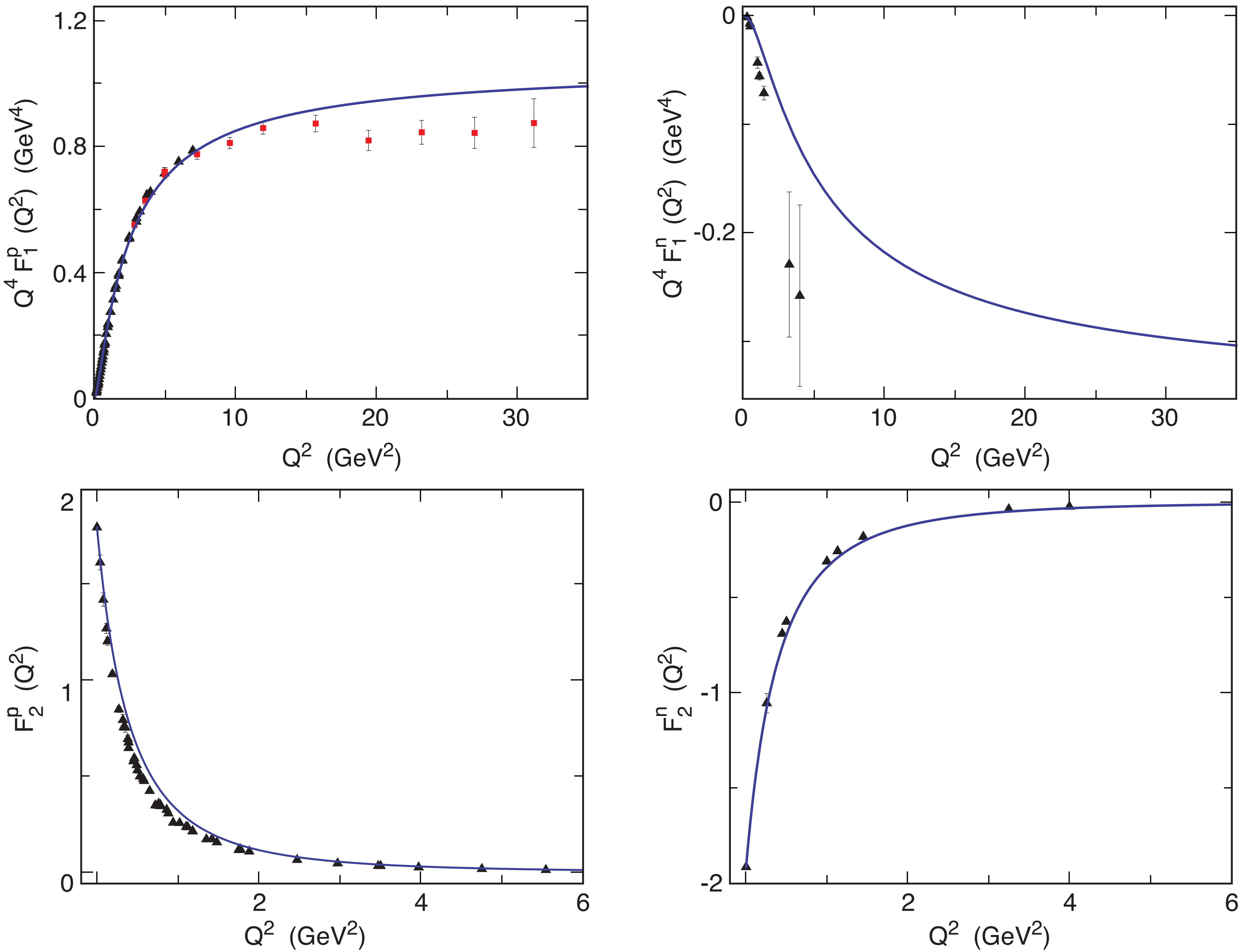
Reverse Dimensional Transmutation!



Process-independent strong running coupling

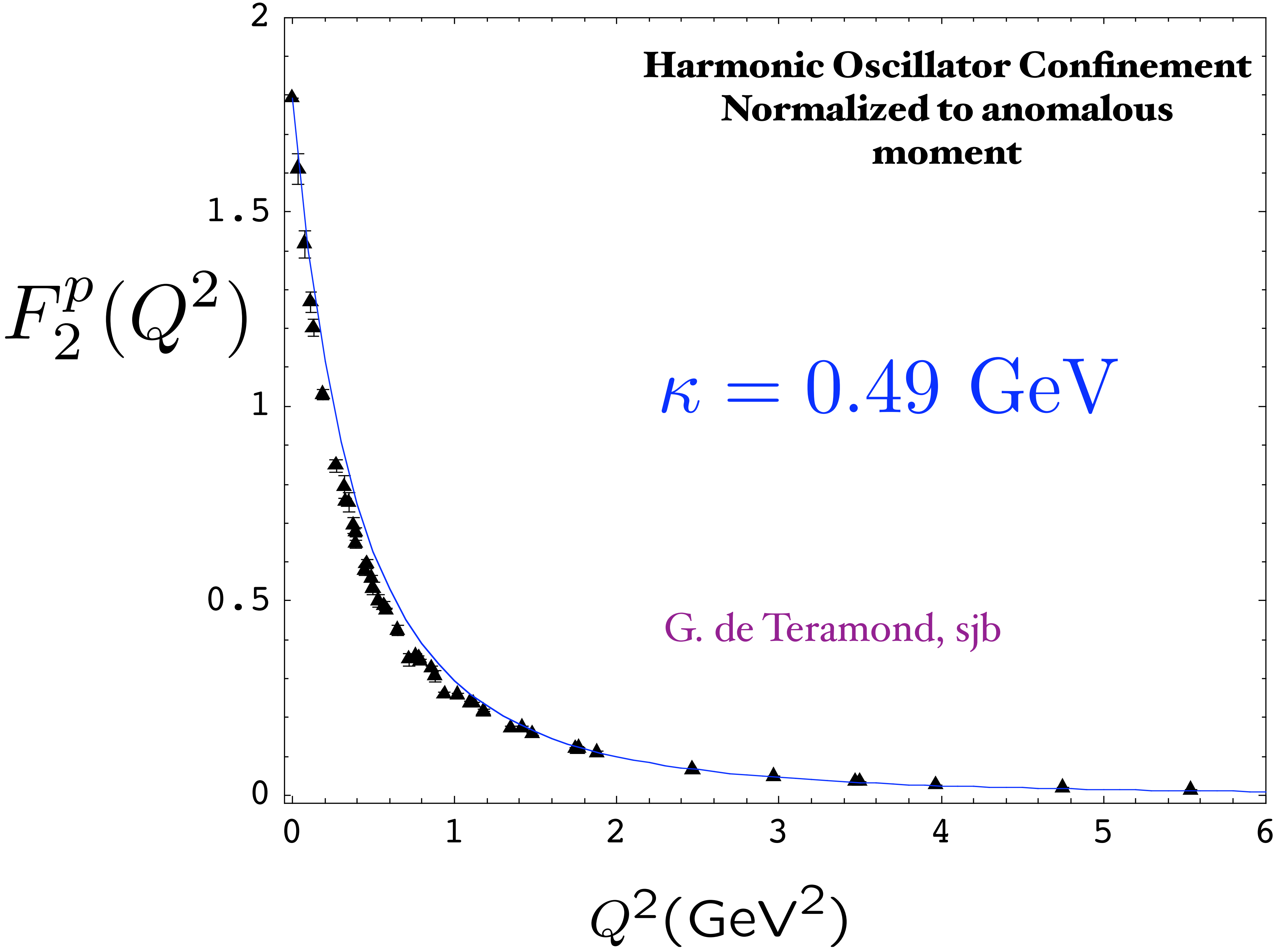
Daniele Binosi,[1] Cédric Mezrag,[2] Joannis Papavassiliou,[3] Craig D. Roberts,[2] and Jose Rodríguez-Quintero[4]

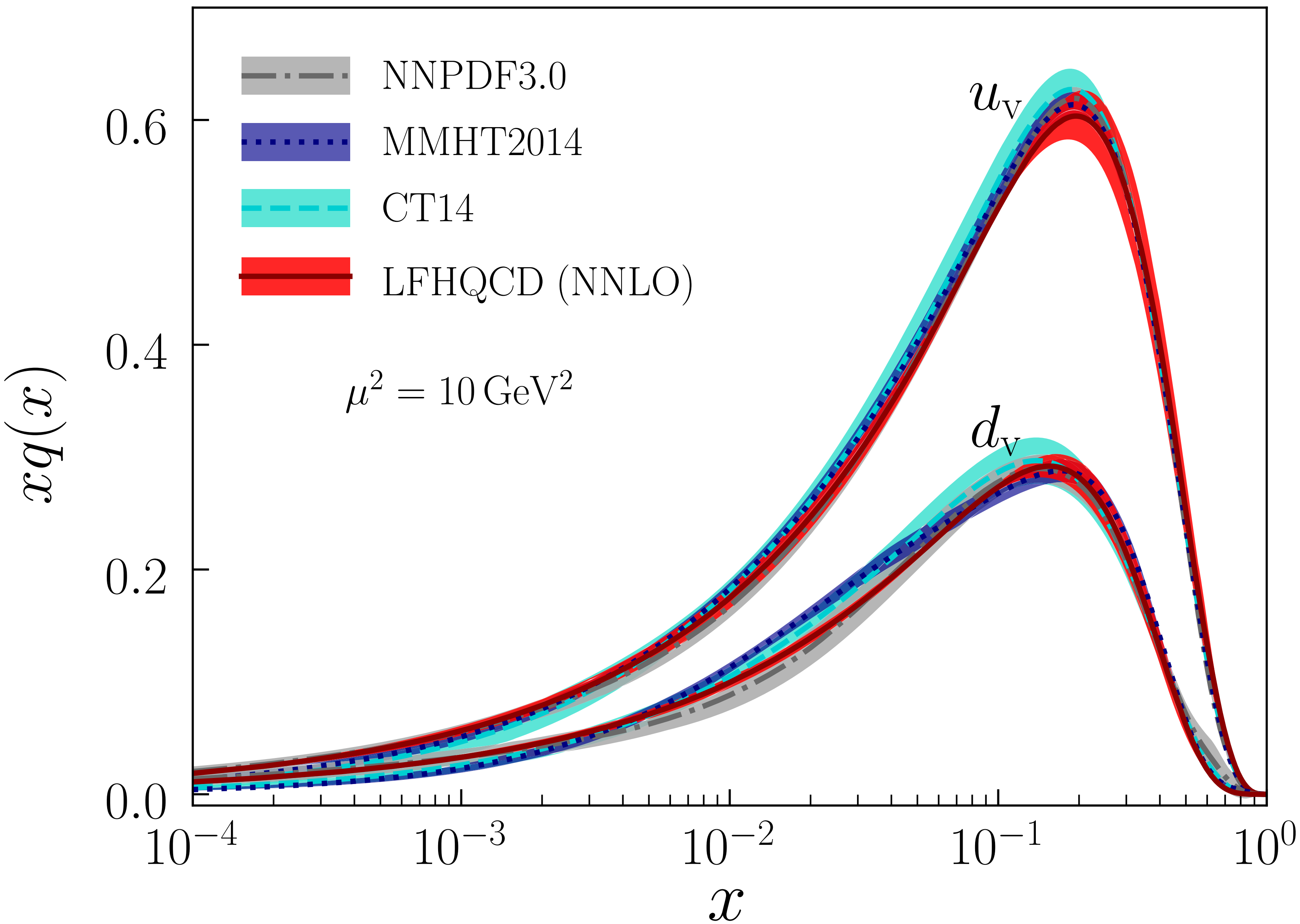
Using $SU(6)$ flavor symmetry and normalization to static quantities



Spacelike Pauli Form Factor

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





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.

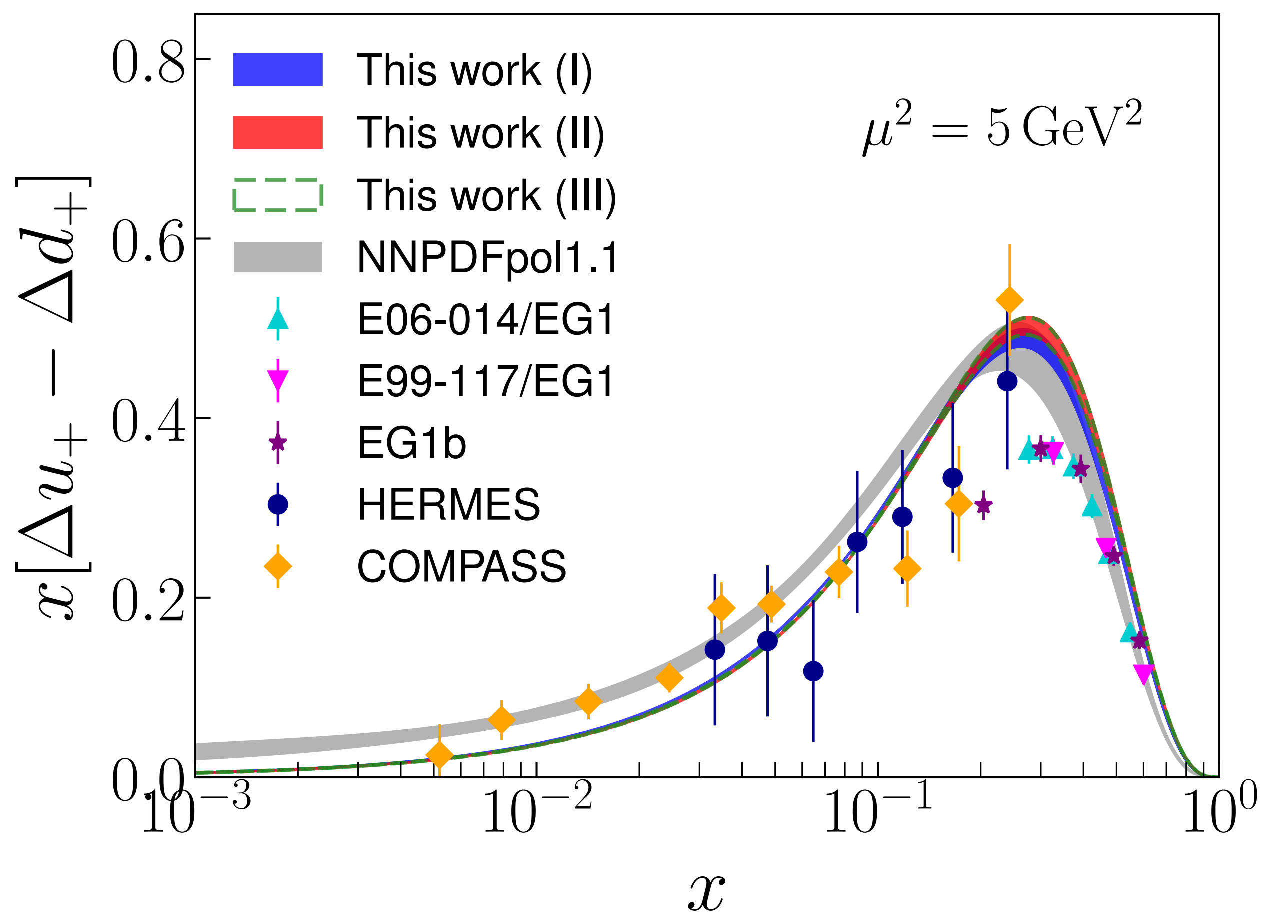
Universality of Generalized Parton Distributions in Light-Front Holographic QCD

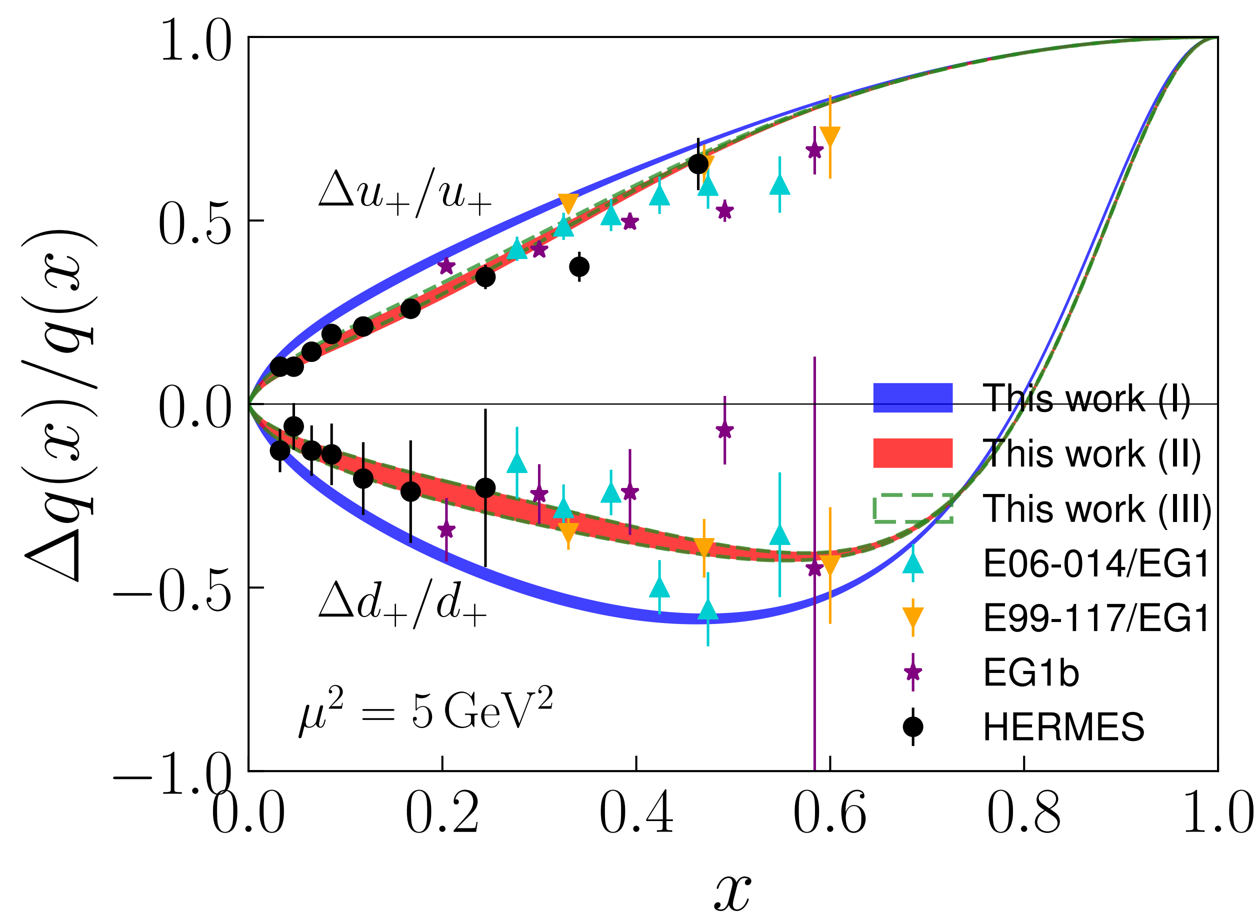
Guy F. de Te´ramond, Tianbo Liu, Raza Sabbir Sufian, Hans Günter Dosch, Stanley J. Brodsky, and Alexandre Deur

PHYSICAL REVIEW LETTERS 120, 182001 (2018)

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: $\lim_{x\to 0} \frac{\Delta q(x)}{q(x)} = 0$





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 Teramond, 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

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

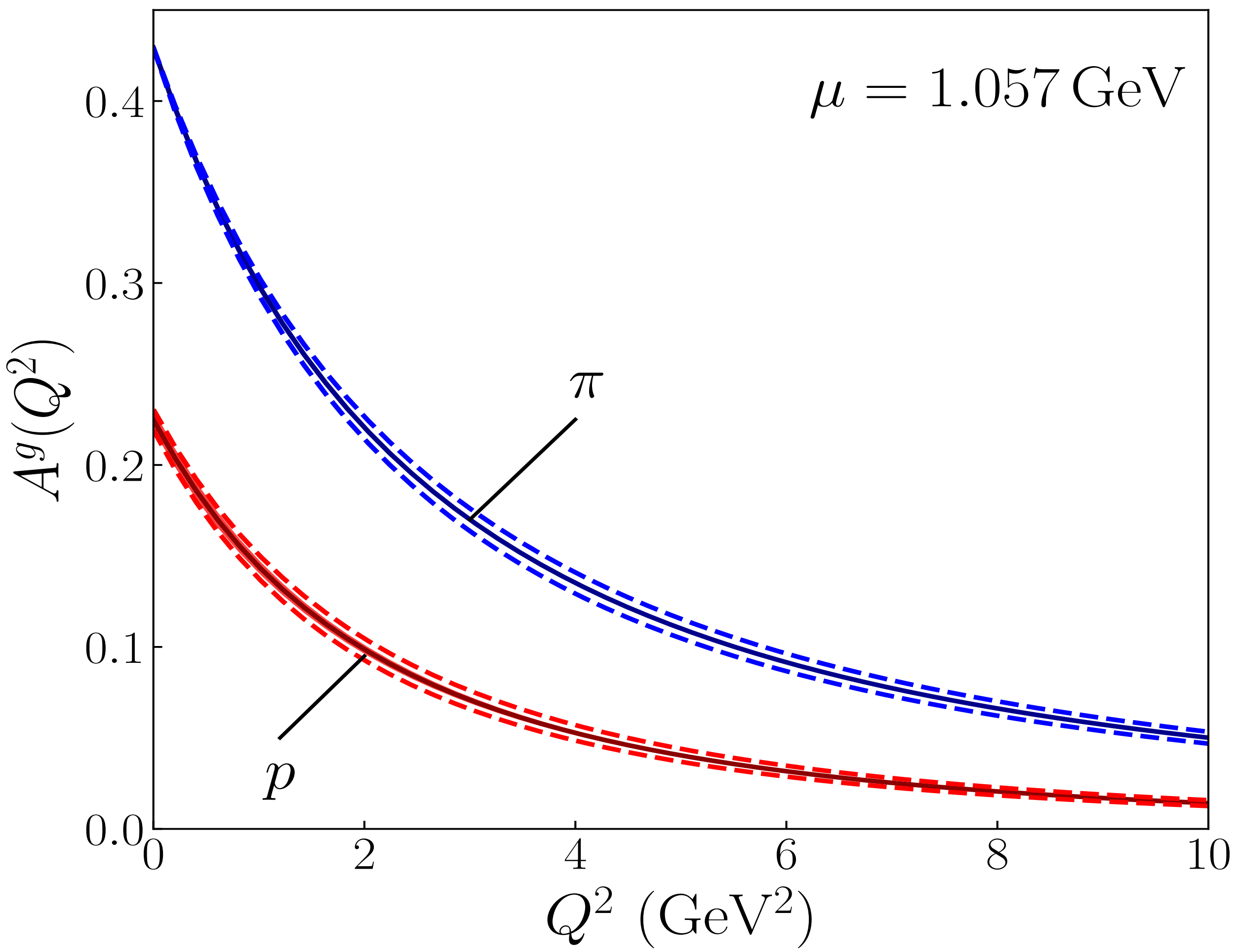
J. Rittenhouse West, sjb (to be published)

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

Gluon matter distribution in the proton and pion from extended holographic light-front QCD

Guy F. de Téramond,[1] H. G. Dosch,[2] Tianbo Liu,[3,*]
Raza Sabbir Sufian,[4,5,†] Stanley J. Brodsky,[6] and Alexandre Deur[5]
(HLFHS Collaboration)

$$\left\langle P' \left| T_{\mu}^{\ \nu} \right| P \right\rangle = \left(P^{\nu} P'_{\mu} + P_{\mu} P'^{\nu} \right) A(Q^2)$$



Gluon gravitational form factor $A^g(Q^2)$ of the proton (red) and the pion (blue). The dashed curves indicate the uncertainty from the variation of λ_g by $\pm 5\%$. The value $A^g(0)$ corresponds to the momentum fraction carried by gluons: 0.225 for the proton and 0.429 for the pion.

JLAB-THY-21-3454
SLAC-PUB-17612

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Guy F. de Téramond,[1] H. G. Dosch,[2] Tianbo Liu,[3,*]
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$$\langle r_g^2 \rangle = \frac{6}{A^g(0)} \frac{dA^g(t)}{dt}\Big|_{t=0},$$

$$< r_g >_p = 0.34\ fm \qquad < r_g >_\pi = 0.31\ fm$$

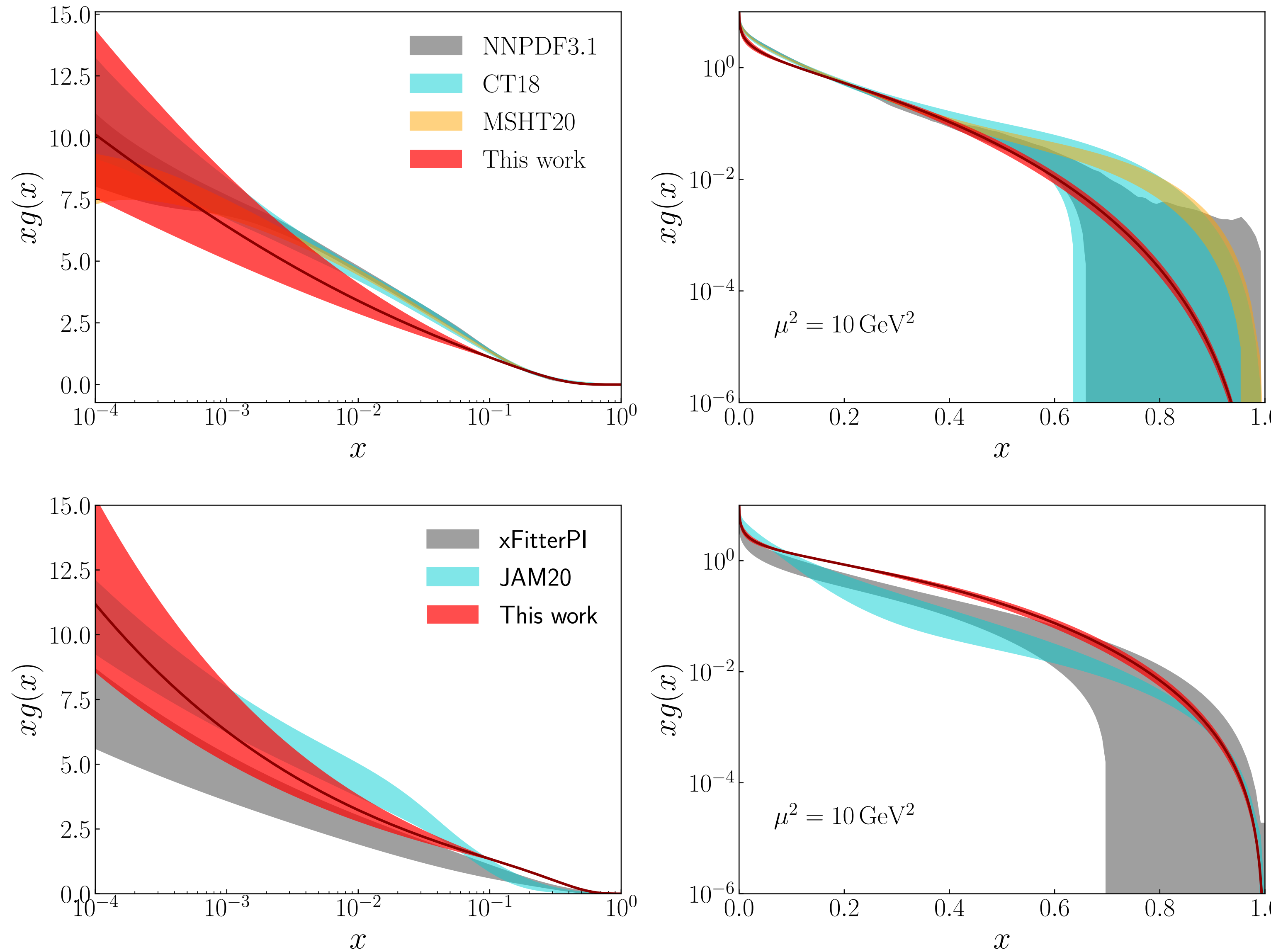
Momentum fraction carried by gluons in the proton:
$A^g(0)_p = 0.225$

Momentum fraction carried by gluons in the pion:
$A^g(0)_\pi = 0.429$

Compare with the gluonic radius

The pion's electromagnetic radius is 0.657 fm

The proton's electromagnetic radius is 0.833 fm



Unpolarized gluon distribution in the proton (top panel) and pion (bottom panel) from HLFQCD and comparison with global fits. The figures on left and right are the same distributions with different scales for $xg(x)$ and x to enhance the view of the small and large-x regions respectively.

JLAB-THY-21-3454
SLAC-PUB-17612

Gluon matter distribution in the proton and pion from extended holographic light-front QCD

Guy F. de Téramond,[1] H. G. Dosch,[2] Tianbo Liu,[3,*]
Raza Sabbir Sufian,[4,5,†] Stanley J. Brodsky,[6] and Alexandre Deur[5]
(HLFHS Collaboration)

Longitudinal dynamics and chiral symmetry breaking in holographic light-front QCD

Guy F. de Téramond[1,*] and Stanley J. Brodsky[2,†]

[1] *Laboratorio de Física Teórica y Computacional, Universidad de Costa Rica, 11501 San José, Costa Rica*
[2] *SLAC National Accelerator Laboratory, Stanford University, Stanford, CA 94309, USA*

(Dated: April 18, 2021)

The breaking of chiral symmetry in holographic light-front QCD is encoded in its longitudinal dynamics with its chiral limit protected by the superconformal algebraic structure which governs its transverse dynamics. The scale in the longitudinal light-front Hamiltonian determines the confinement strength in this direction: It is also responsible for most of the light meson ground state mass consistent with the Gell-Mann-Oakes-Renner constraint. Longitudinal confinement and the breaking of chiral symmetry are found to be different manifestations of the same underlying dynamics like in 't Hooft large N_C QCD$(1+1)$ model.

Transverse and Longitudinal LF Confinement

$$M_H^2 = M_{||}^2 + M_\perp^2$$

$$\left(-\frac{d^2}{d\zeta^2} - \frac{1-4L^2}{4\zeta^2} + U_\perp(\zeta)\right)\phi(\zeta) = M_\perp^2 \phi(\zeta),$$

$$\left(\frac{m_q^2}{x} + \frac{m_{\bar q}^2}{1-x} + U_{||}(x)\right)\chi(x) = M_{||}^2\,\chi(x),$$

Longitudinal contribution for nonzero quark mass

S. S. Chabysheva and J.R.Hiller,

Constraint: Rotational symmetry in non-relativistic heavy-quark limit.

Transverse Confinement

$$\left(-\frac{d^2}{d\zeta^2} - \frac{1-4L^2}{4\zeta^2} + U_\perp(\zeta)\right)\phi(\zeta) = M_\perp^2 \phi(\zeta),$$

$$U_\perp(\zeta) = \lambda^2\zeta^2 + 2\lambda(J-1). \qquad \zeta^2 = b_\perp^2 x(1-x)$$

$$M_\perp^2(n,J,L) = 4\lambda\left(n + \frac{J+L}{2}\right),$$

and eigenfunctions

de Teramond, Dosch, sjb

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

$$\boxed{M_\pi = 0 \text{ in chiral } (m_q = 0) \text{ limit}}$$

Longitudinal Confinement

$$\left(\frac{m_q^2}{x} + \frac{m_{\bar{q}}^2}{1-x} + U_\parallel(x) \right) \chi(x) = M_\parallel^2 \, \chi(x)$$

$$U_\parallel(x) = -\sigma^2 \partial_x \left(x(1-x) \, \partial_x \right)$$

Li, Maris, Zhao, Vary

$$U_{||} = \sigma^2 x(1-x) \tilde{z}^2$$

Ioffe length $\tilde{z}$: conjugate to LF $x = \frac{k^+}{P^+}$

G.A. Miller, sjb

$\frac{\gamma^+ \gamma^+}{k^{+2}}$ LF interaction in $A^+ = 0$ gauge

de Teramond, sjb

Same potential: t' Hooft Equation $\mathrm{QCD}(1+1)_{N_C \to \infty}$

Longitudinal Confinement

$$U_{||} = \sigma^2 x(1-x)\tilde{z}^2$$

$$\left(\frac{m_q^2}{x} + \frac{m_{\bar{q}}^2}{1-x}\right)\chi(x) + \frac{g^2 N_C}{\pi} P \int_0^1 dx' \frac{\chi(x) - \chi(x')}{(x-x')^2}$$

$$= M_{||}^2 \chi(x),$$

$$\sigma = g\sqrt{\pi N_C/3} = \text{const},$$

$$\chi(x) \sim x^{\frac{2m_q}{\sigma}}(1-x)^{\frac{2m_{\bar{q}}}{\sigma}}$$

$$M_\pi^2 = g\sqrt{\pi N_C/3}\,(m_u + m_d) + \mathcal{O}\big((m_u + m_d)^2\big)$$

GMOR relation

de Teramond, sjb

$$\boxed{M_\pi^2 = \sigma(m_u + m_d) + \mathcal{O}\big((m_u + m_d)^2\big)\,,}$$

in the limit $m_u, m_d \to 0$. It has the same linear dependence in the quark mass as the Gell-Mann-Oakes-Renner (GMOR) relation

$$\boxed{M_\pi^2 f_\pi^2 = -\tfrac{1}{2}(m_u + m_d)\langle \bar{u}u + \bar{d}d \rangle + \mathcal{O}\big((m_u + m_d)^2\big)}$$

where the "vacuum condensate" $\langle \overline{\psi}\psi \rangle \equiv \frac{1}{2}\langle \bar{u}u + \bar{d}d \rangle$ plays the role of a chiral order parameter. The same linear dependence arises for the $(3+1)$ effective LF Hamiltonian, since the constraints from the superconformal algebra require that the contribution to the pion mass from the transverse LF dynamics is identically zero.

Interpret $< \bar{\psi}\psi >$ as an *in-hadron condensate*

Roberts, Shrock, Tandy, sjb

Roberts, Richards, Horn, Chang

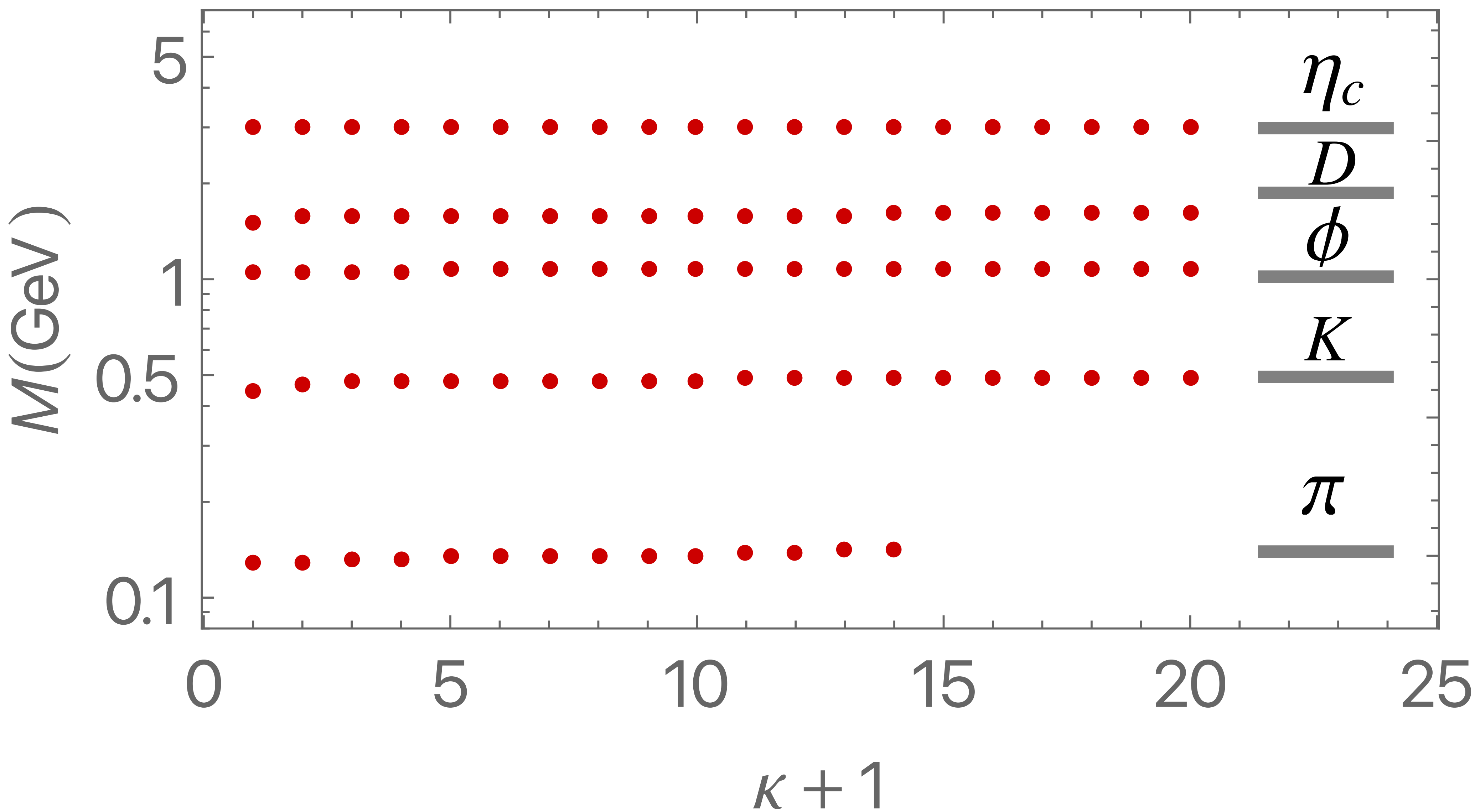
Expand in complete orthonormal basis

$$\chi_\kappa^{\alpha,\beta}(x) = N x^{\alpha/2}(1-x)^{\beta/2} P_\kappa^{(\alpha,\beta)}(1-2x).$$

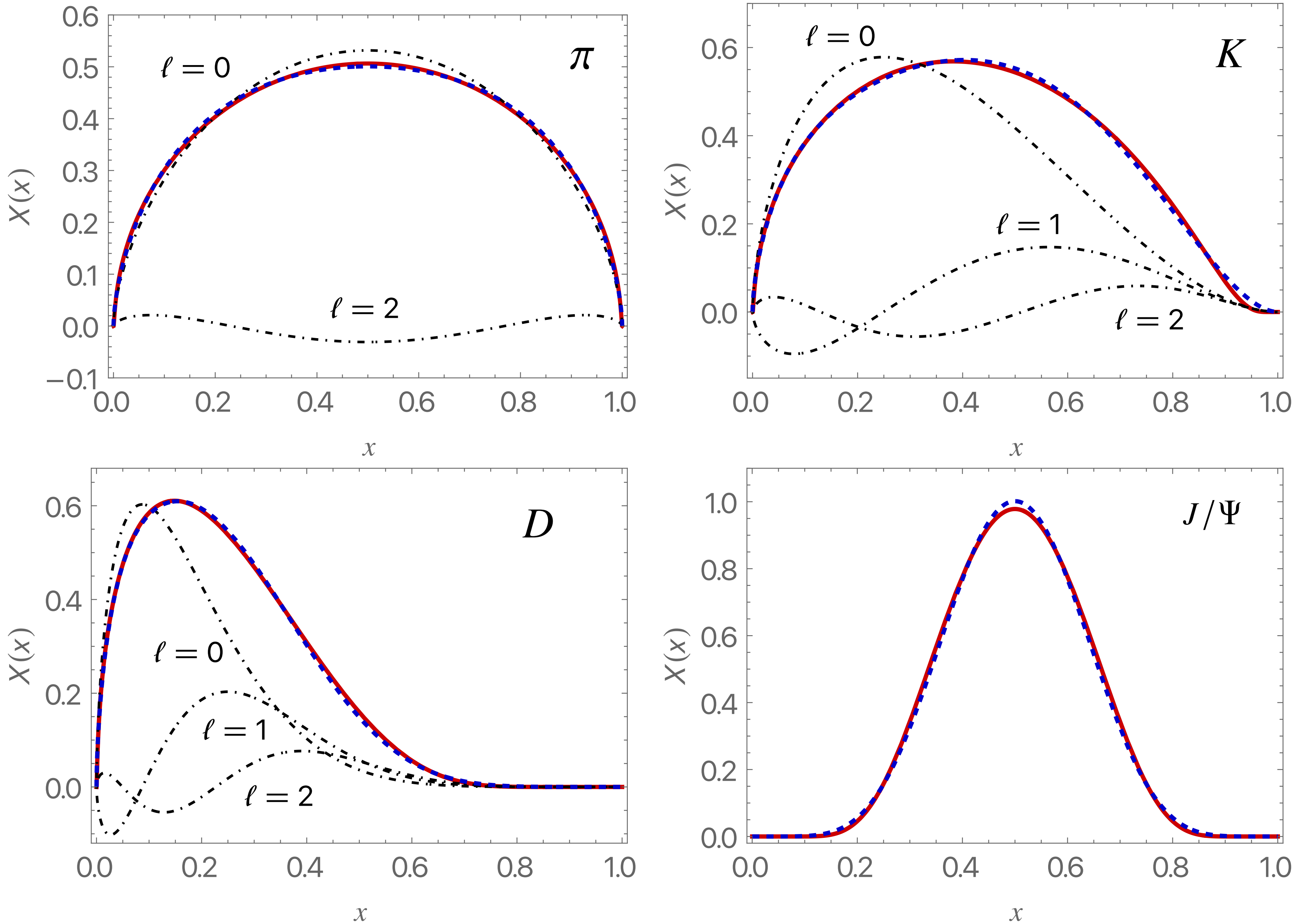
$$M_\parallel^2 = \sigma^2 \int_0^1 dx\, \chi(x) \Big(- \partial_x \left(x(1-x)\partial_x\right) + \frac{1}{4}\Big[\frac{\alpha^2}{x} + \frac{\beta^2}{1-x}\Big]\Big)\chi(x) = \sigma^2 \sum_\kappa C_\kappa^2\, \nu^2(\kappa,\alpha,\beta),$$

where $\nu^2(\kappa,\alpha,\beta) = \frac{1}{4}(\alpha+\beta+2\kappa)(2+\alpha+\beta+2\kappa)$, with $\alpha = 2m_q/\sigma$ and $\beta = 2m_{\bar{q}}/\sigma$.

Mode expansion



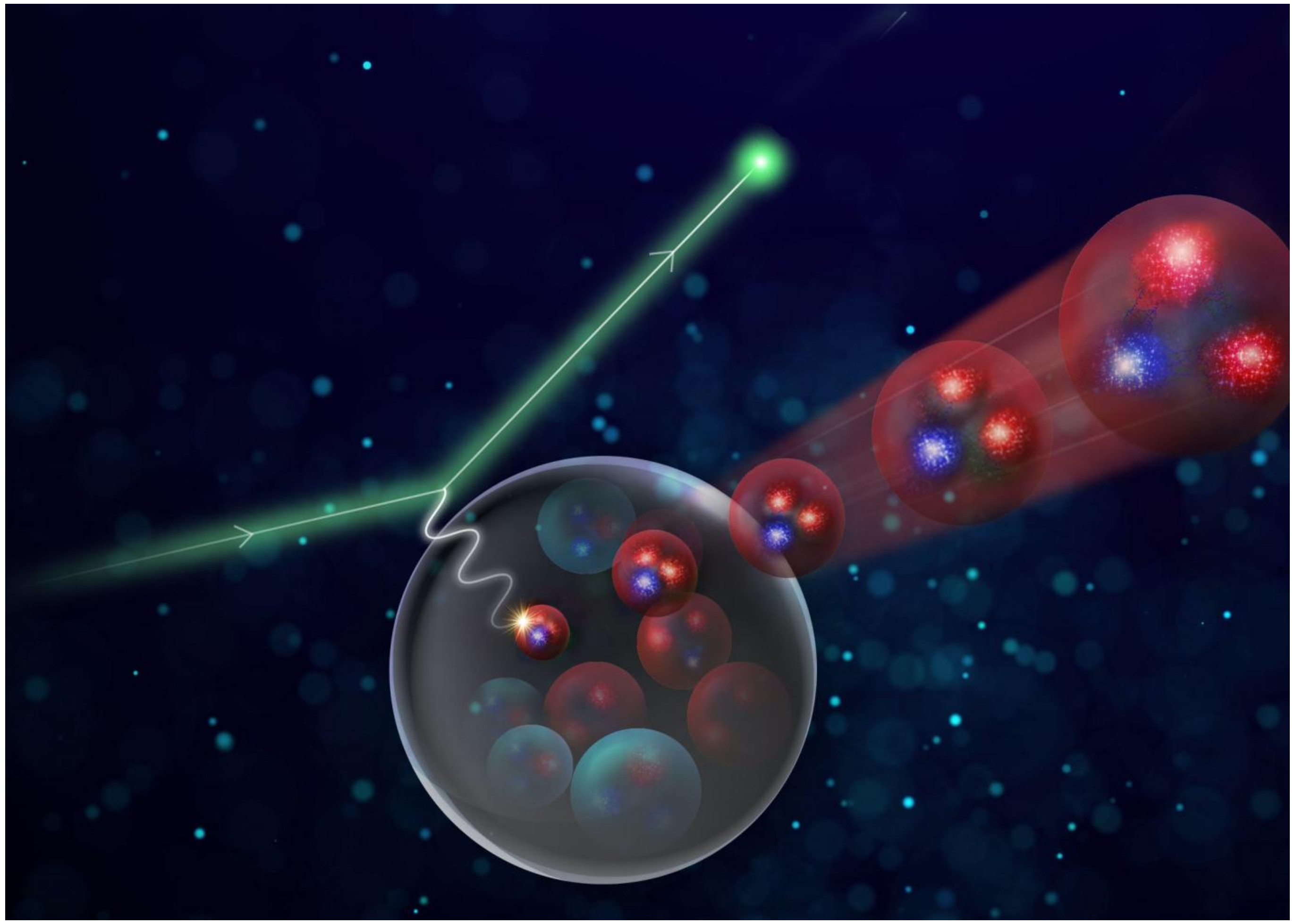
Convergence of ground state meson masses with increasing κ
The horizontal grey lines in the figure are the observed masses.



Light-front distribution amplitudes $X(x)$ for the π, K, D and J/Ψ mesons: the red curve is the invariant mass result, dot dashed black curves are individual modes in the expansion (16), dashed blue curve represent the sum of modes in the figure. Notice that the J/Ψ result is well described by the zero mode alone.

The Onset of Color Transparency in Holographic Light-Front QCD

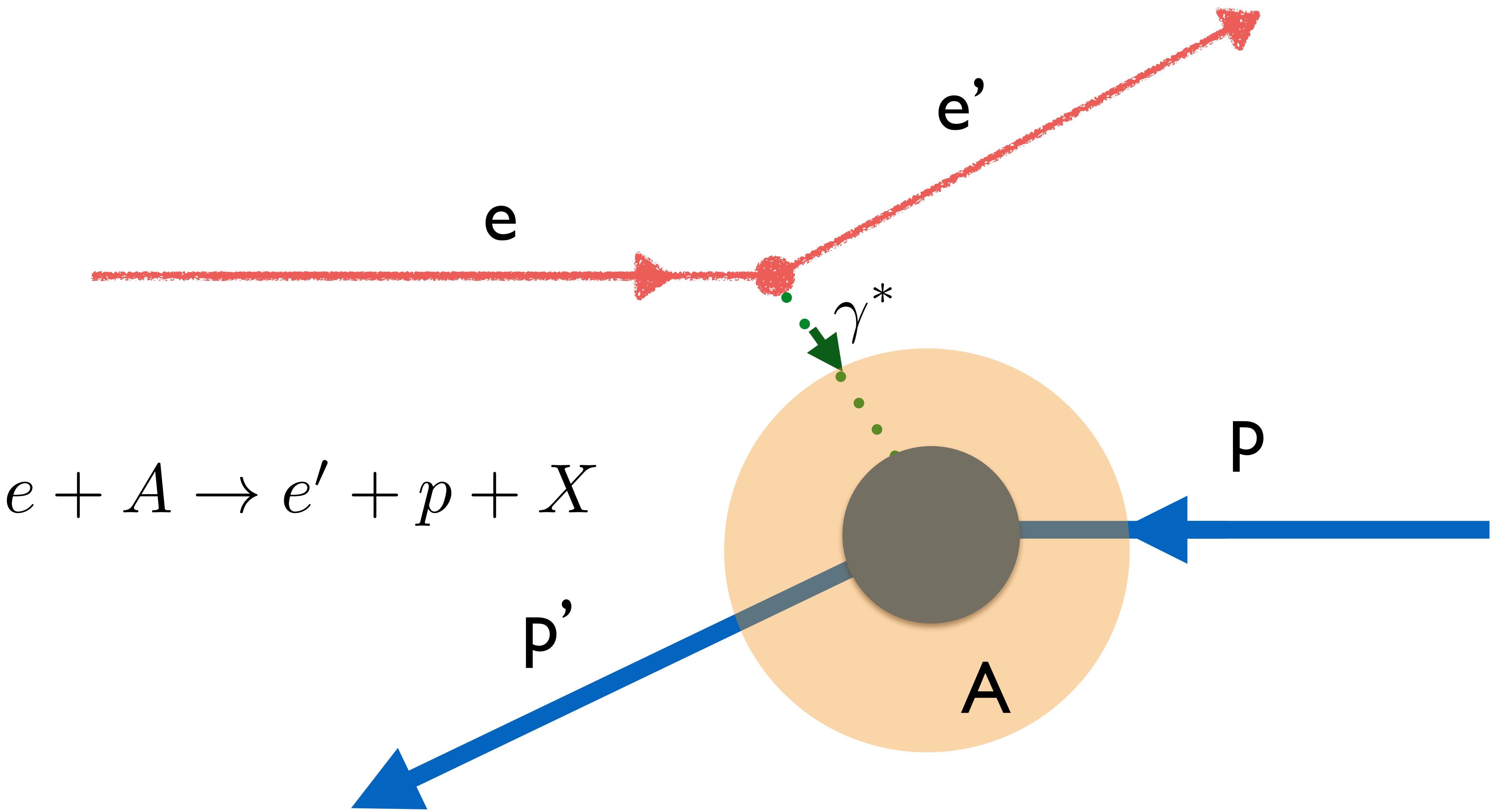
c



with Guy F. de Téramond

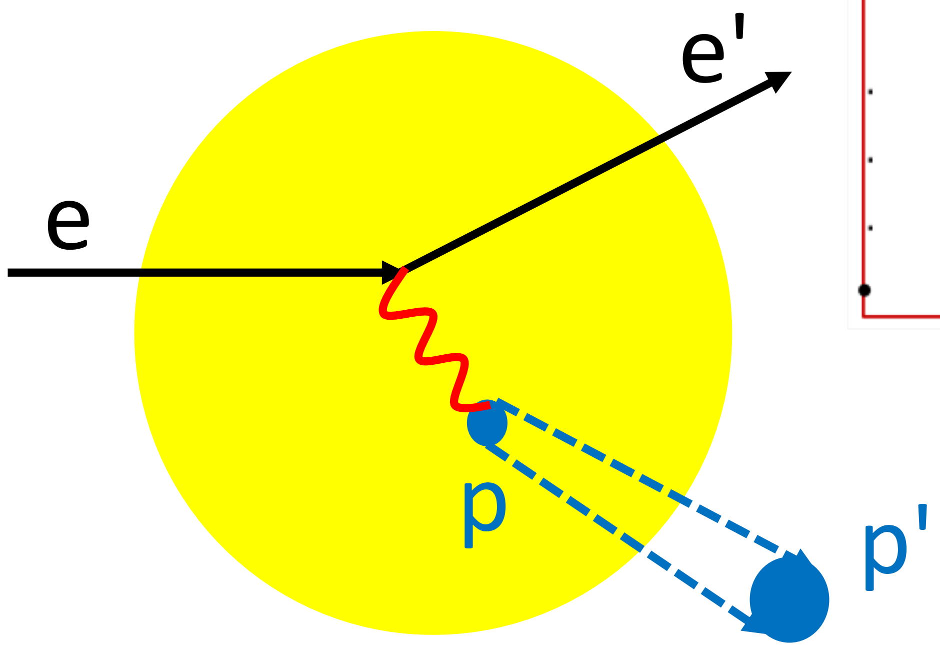
Color Transparency

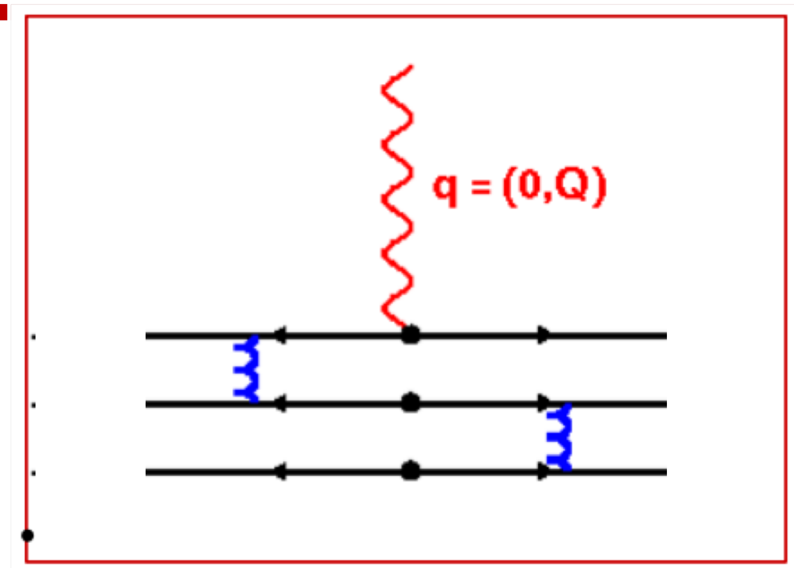
$$\boxed{\sigma(e + A \to e' + p + X) \to Z \frac{d\sigma}{dt}(ep \to e'p')}$$ at high Q^2



- **QCD: Gauge theory properties and quantum coherence**
- **Small-size color dipole moment interacts weakly in nuclei**

Color transparency fundamental prediction of QCD





- Introduced by Mueller and Brodsky, 1982
- Vanishing of initial/final state interaction of hadrons with nuclear medium in exclusive processes at high momentum transfer

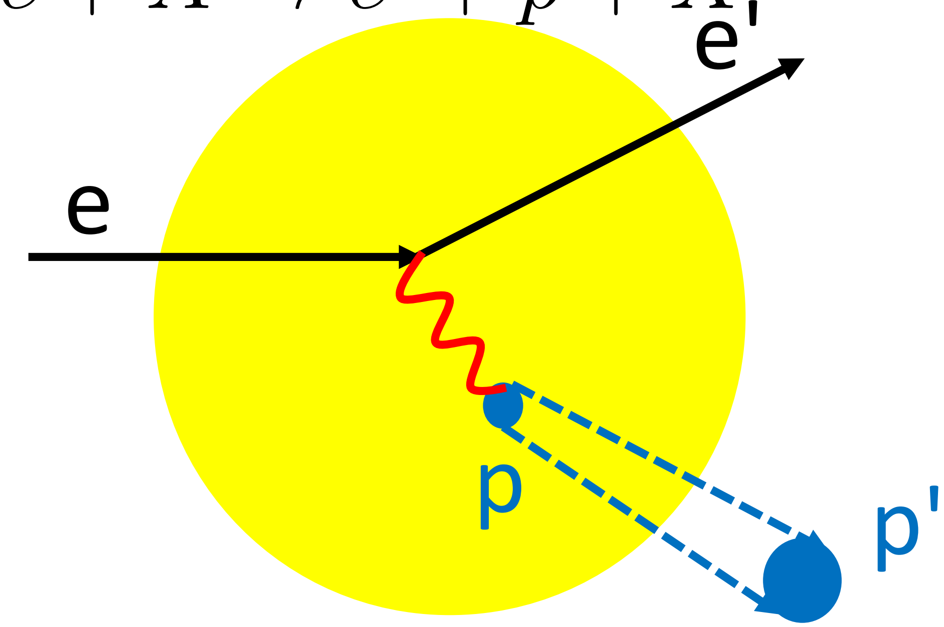
$$e + A \rightarrow e' + p + X$$

- Hadron fluctuates to small transverse size (quantum mechanics)
- Maintains this small size as it propagates out of the nucleus (relativity)
- Experiences reduced attenuation in nucleus, color screened (strong force)

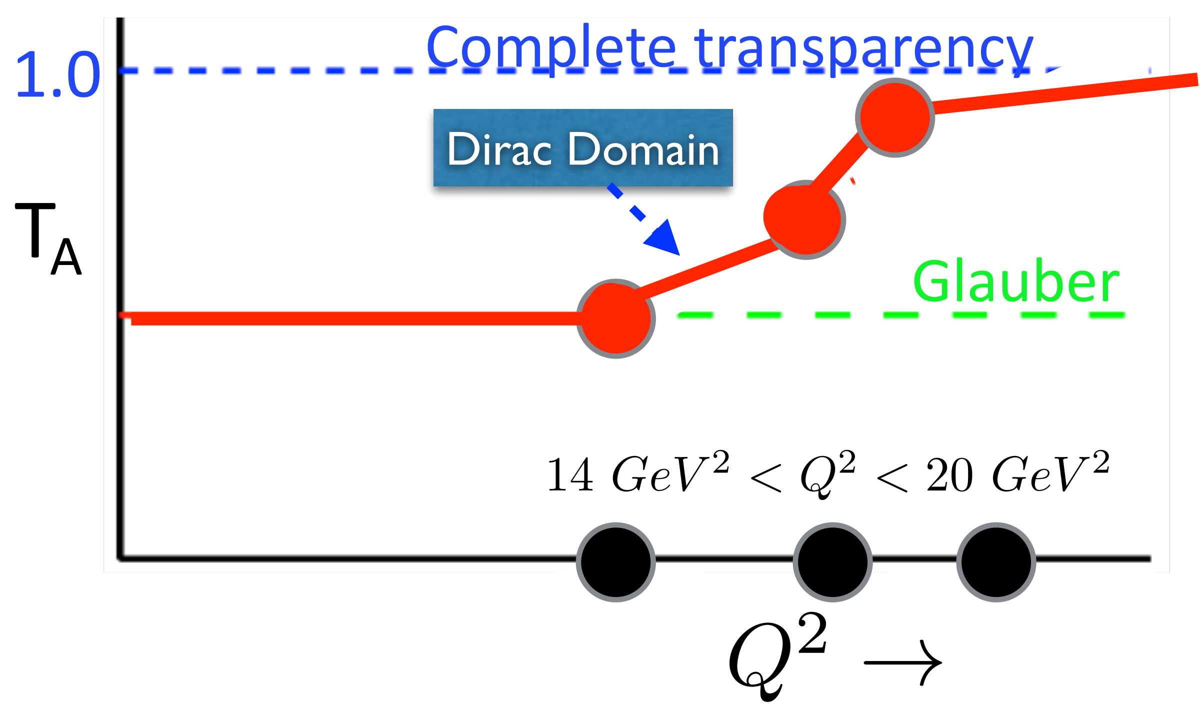
Holly Suzmila-Vance

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



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

Color Transparency

Mueller, sjb

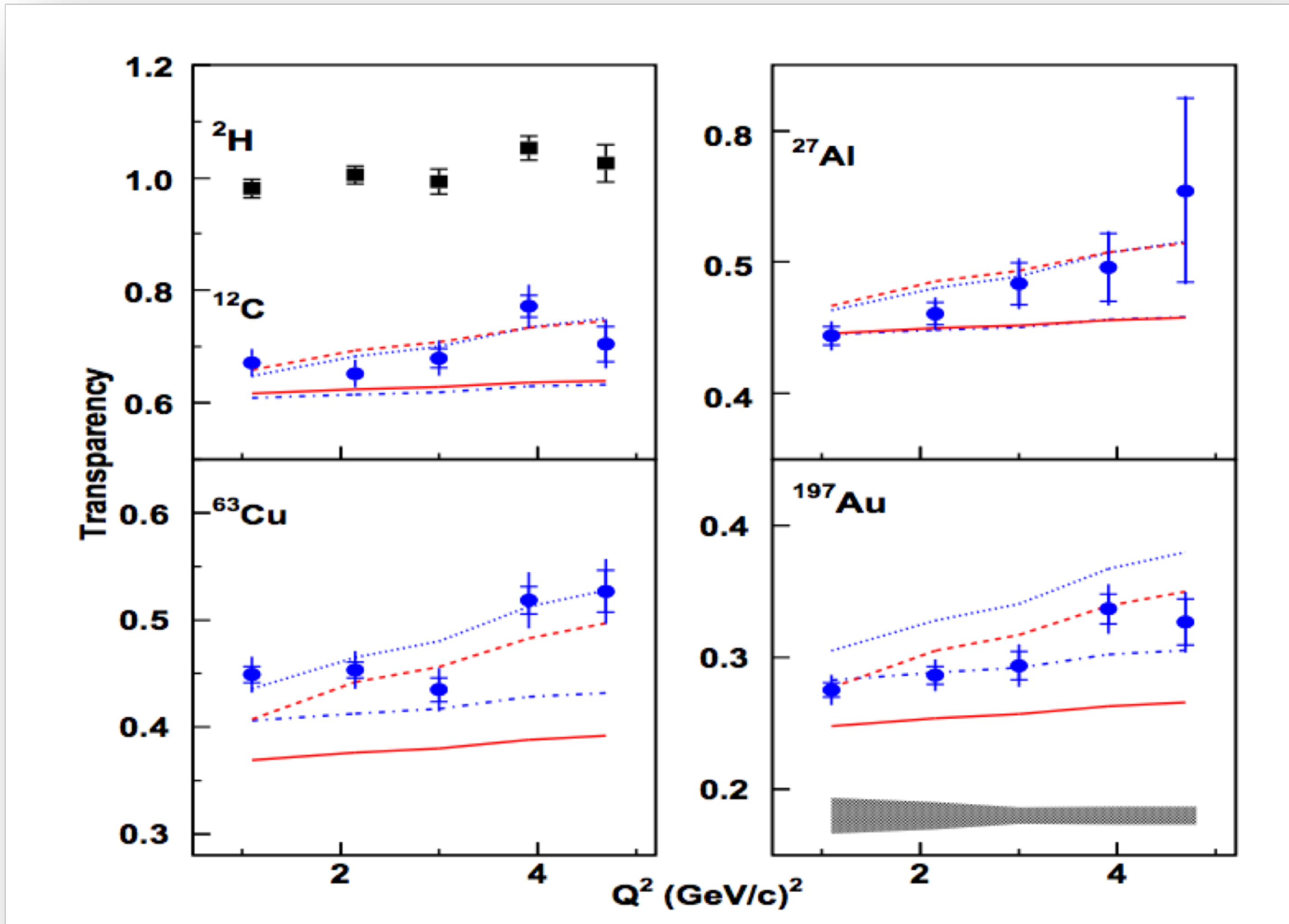
Bertsch, Gunion, Goldhaber, sjb

$$\frac{d\sigma}{dt}(eA \to ep(A-1)) = Z\frac{d\sigma}{dt}(ep \to ep)$$ at high momentum transfer

- **Fundamental test of gauge theory in hadron physics**
- **Small color dipole moment interacts weakly in nuclei**
- **Complete coherence at high energies**
- **Many tests in hard exclusive processes**
- **Clear Demonstration of CT from Diffractive Di-Jets**
- **Explains Baryon Anomaly at RHIC**
- **Small color dipole moment interacts weakly in nuclei**

Hall C E01-107 pion electro-production

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

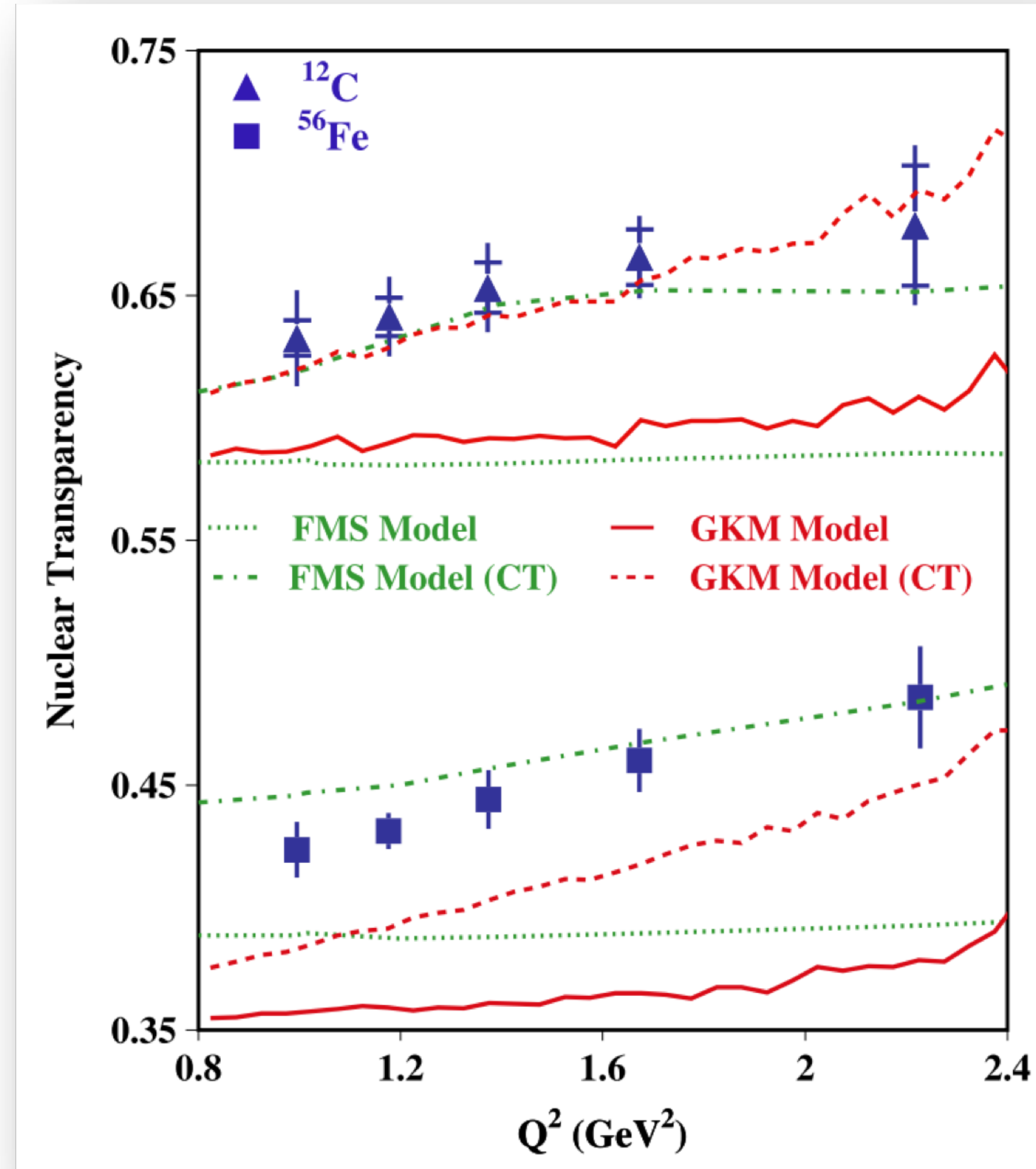


B.Clasie *et al.* PRL 99:242502 (2007)

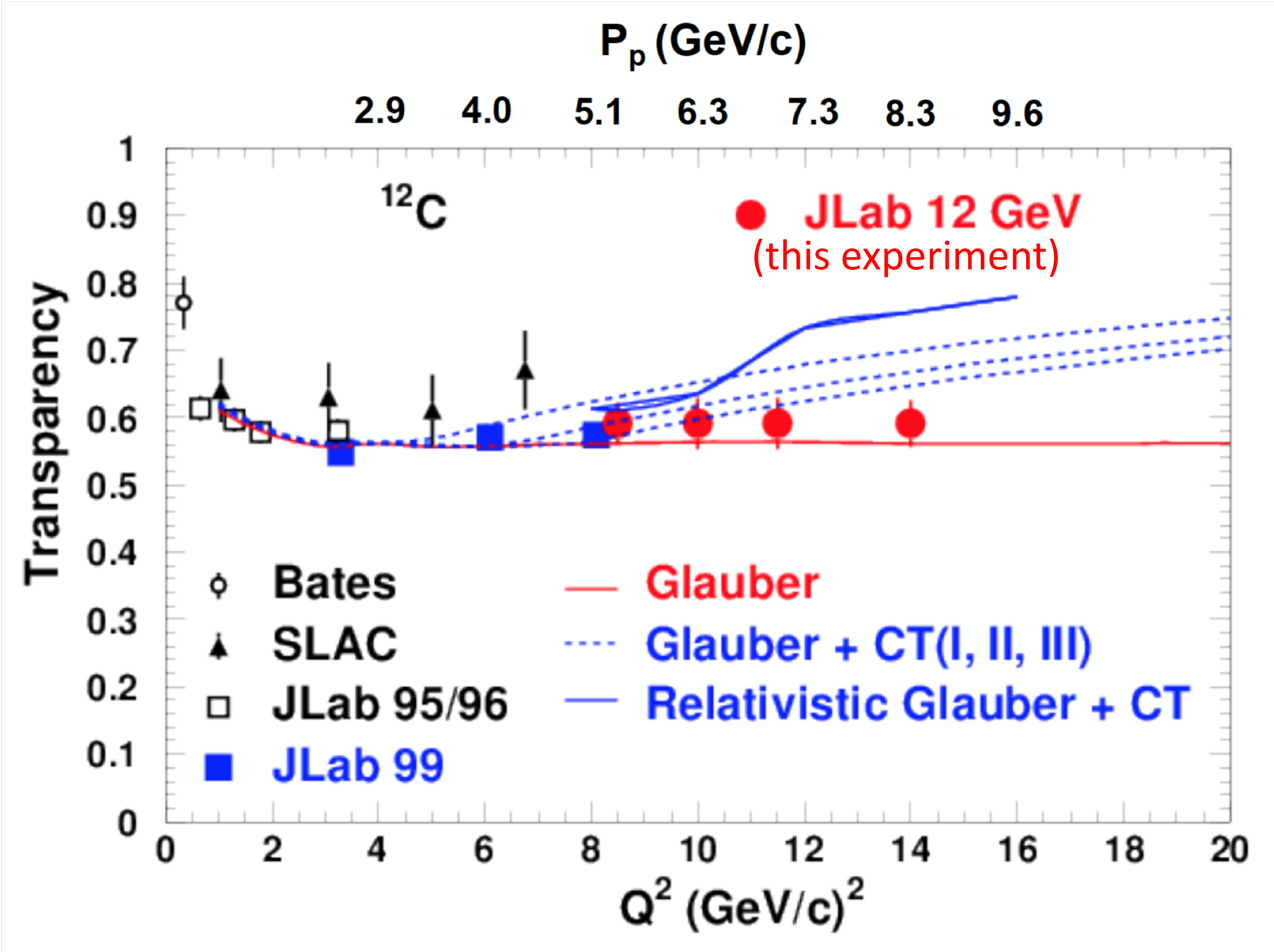
X. Qian *et al.* PRC81:055209 (2010)

CLAS E02-110 rho electro-production

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



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

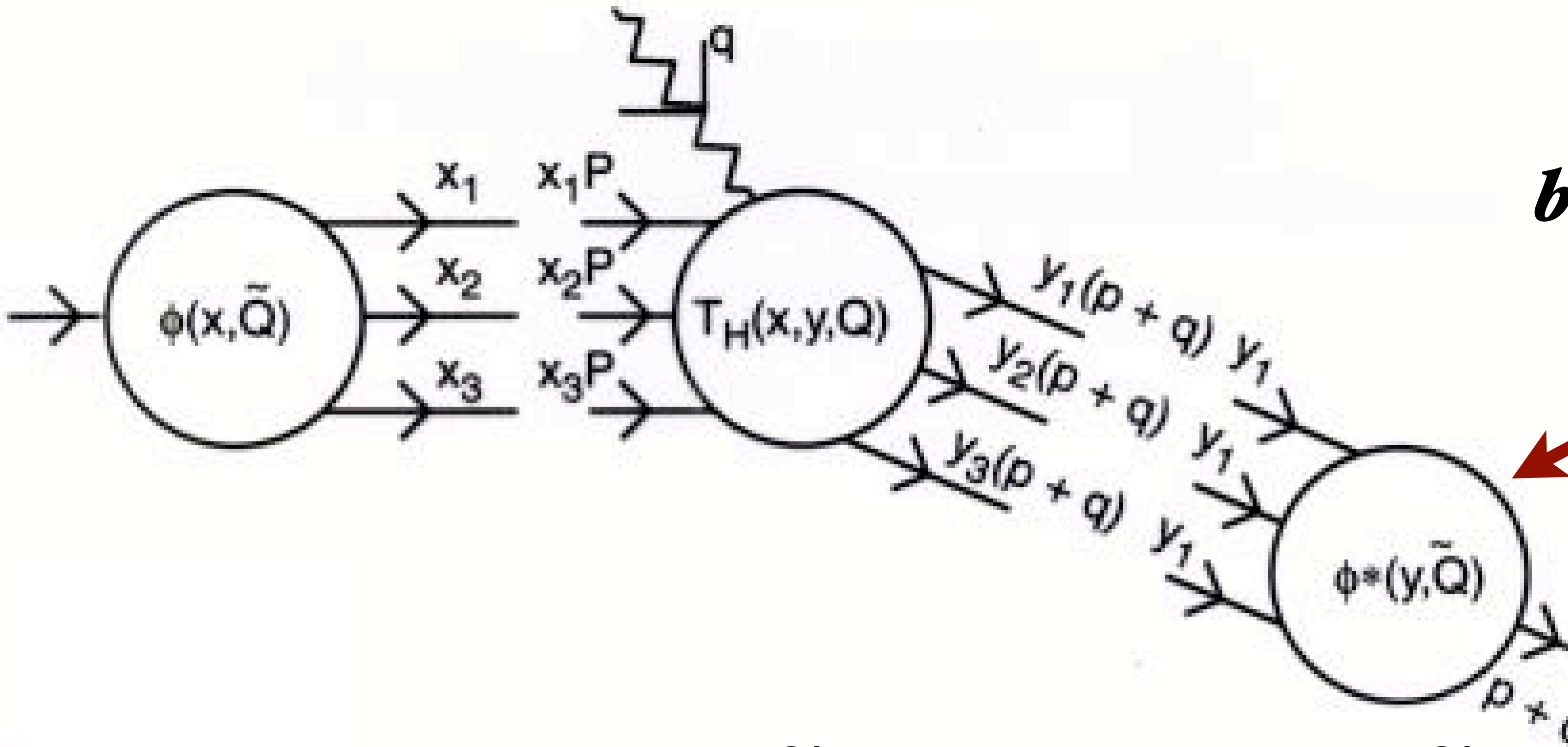


Ruling out color transparency in quasi-elastic ^{12}C(e,e$'$p) up to Q^2 of 14.2 (GeV/c)^2

Hall C Collaboration

Leading-Twist PQCD Factorization for form factors, exclusive amplitudes

Lepage, sjb



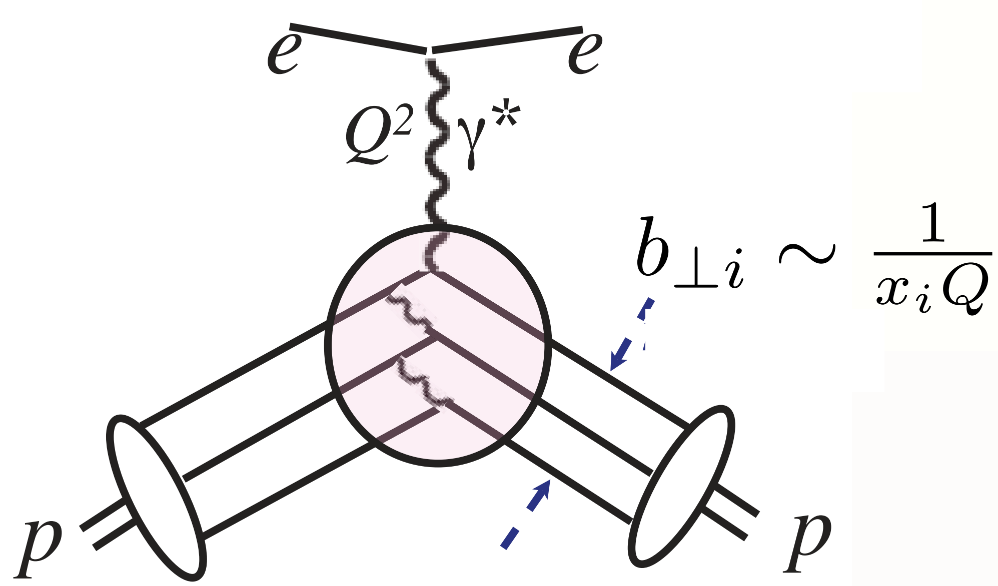
baryon distribution amplitude

ERBL Evolution

$$M = \int \Pi dx_i dy_i \phi_F(x_i,\tilde{Q}) \times T_H(x_i,y_i,\tilde{Q}) \times \phi_I(y_i,\tilde{Q})$$

Scaling Laws
Counting Rules

Exclusive

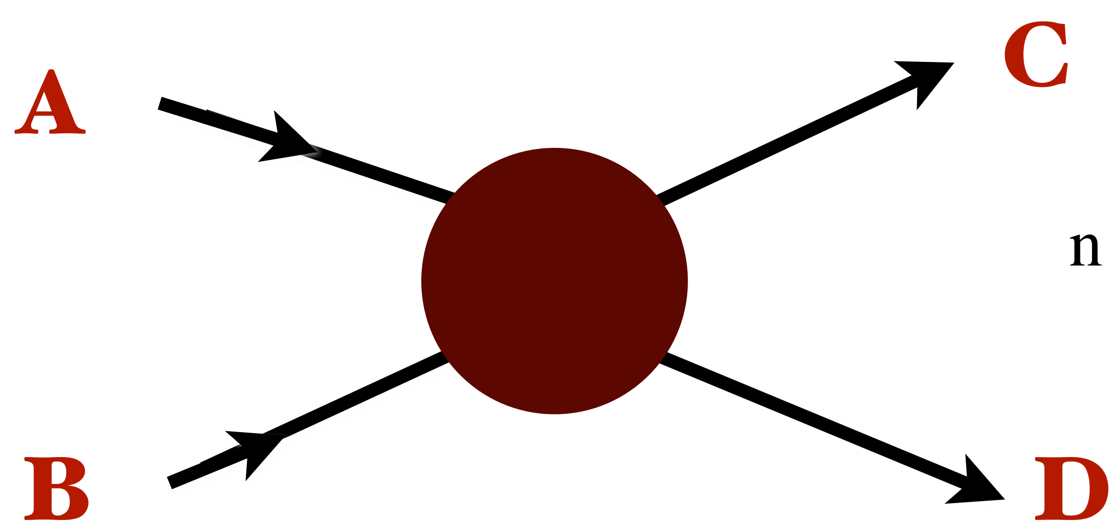


$$< x_i > \sim \frac{1}{n} = \frac{1}{twist\ \tau}$$

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

$$\frac{d\sigma}{dt}(A+B\to C+D)=\frac{F(t/s)}{s^{n_{tot}-2}}$$

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

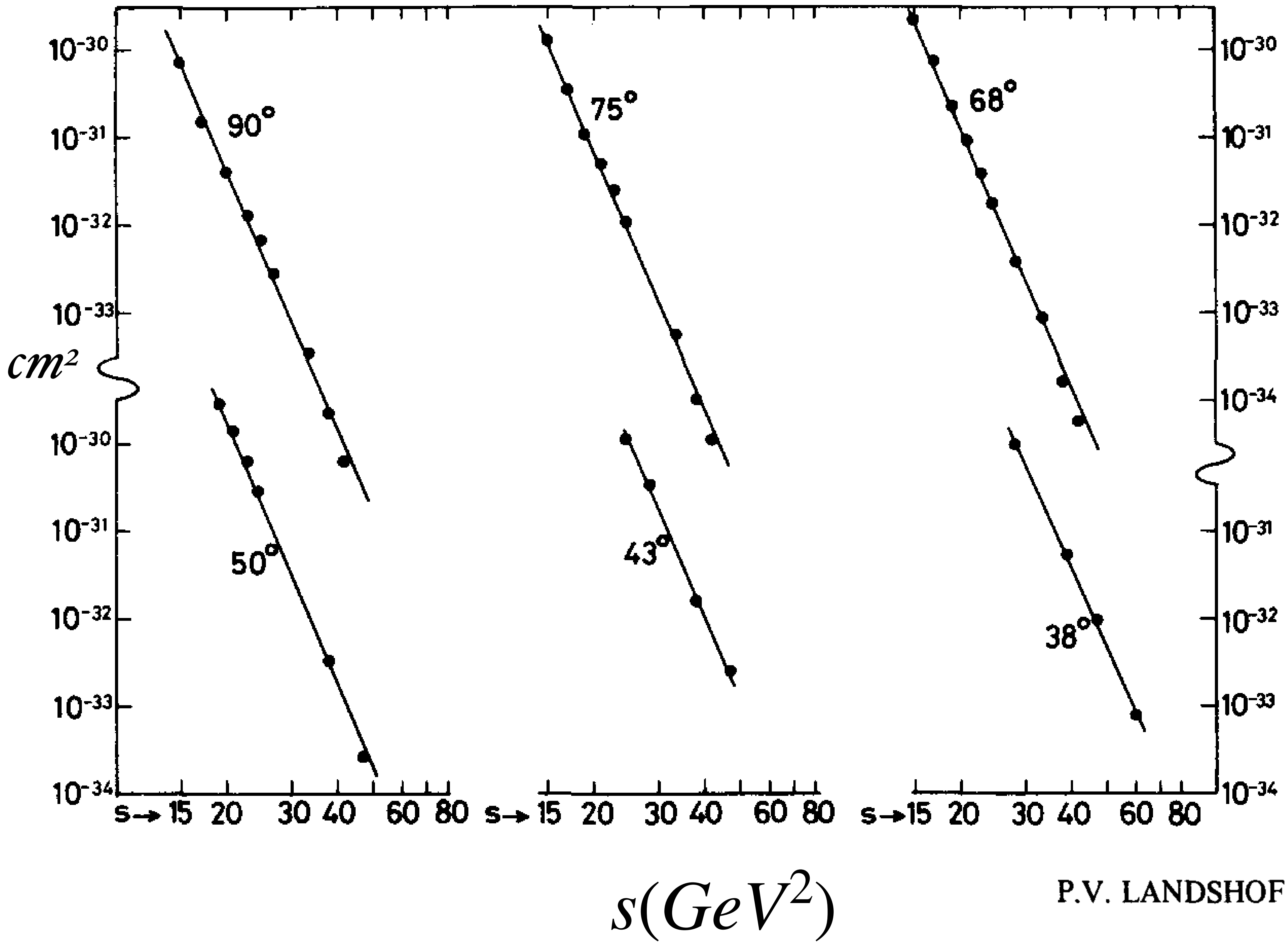


n = twist τ = dimension - spin

e.g. $n_{tot}-2=n_A+n_B+n_C+n_D-2=10$ for $pp\to pp$

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

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



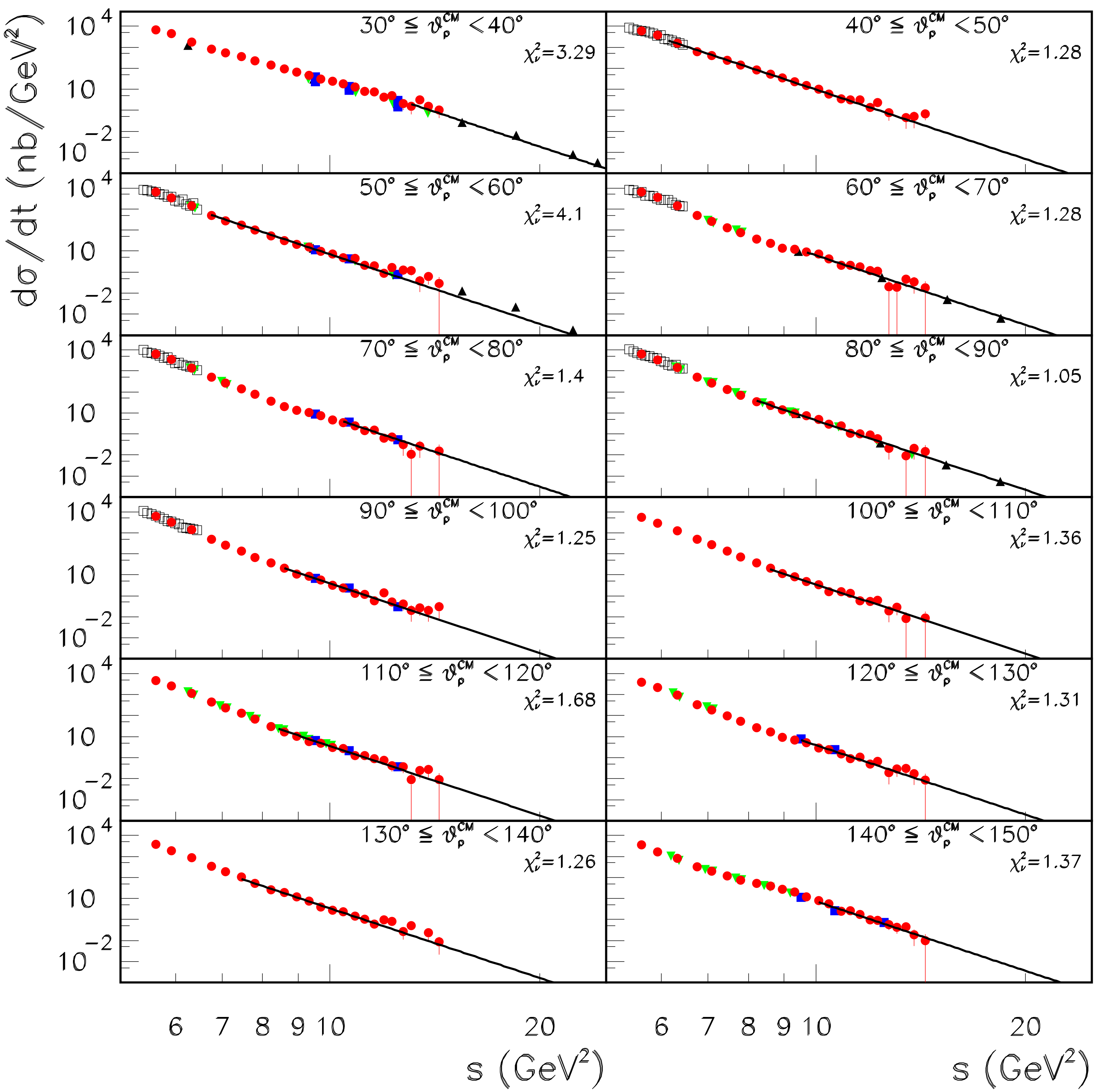
Best Fit

$n = 9.7 \pm 0.5$

Reflects underlying conformal, scale-free interactions

P.V. LANDSHOFF and J.C. POLKINGHORNE

Deuteron Photodisintegration & Dimensional Counting Rules



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

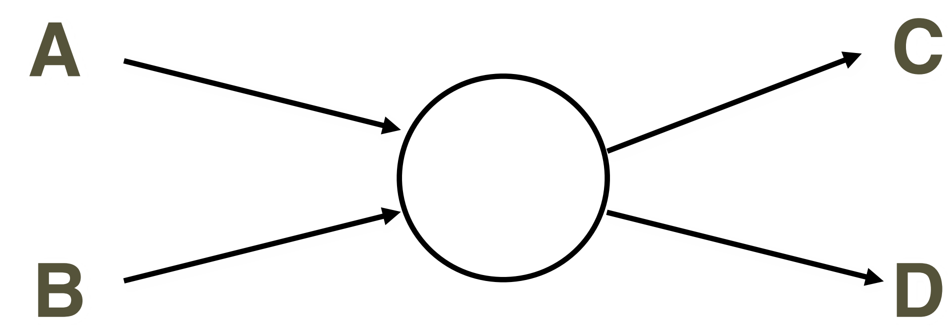
$$s^{11}\frac{d\sigma}{dt}(\gamma d\to np) = F(\theta_{CM})$$

$$n_{tot}-2 = (1+6+3+3)-2 = 11$$

$$F_D(Q^2) \sim [\frac{1}{Q^2}]^5$$

Scaling is a manifestation of asymptotically free hadron interactions

From dimensional arguments at high energies in binary reactions:



CONSTITUENT COUNTING RULES

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

Counting Rules:

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

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

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

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

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

Exclusive-Inclusive Connection
Gribov-Lipatov crossing

Counting Rules: Asymptotic Freedom and Underlying Conformal Symmetry of QCD

$F(q^2) =$ Drell-Yan-West Formula in Impact Space

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

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

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

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

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

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

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)

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

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

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

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

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

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

$$M_0 = m_\rho$$

$$\sqrt{\lambda} = \kappa = \frac{m_\rho}{\sqrt{2}} = 0.548\ GeV$$

$$\frac{1}{2} - \frac{t}{4\lambda} = 1 - \alpha_R(t)$$

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

$$F(q^2) =$$

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

$$\sum_i x_i = 1$$

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

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

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 $Q^2 = -t$:

Light-Front Holography:

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

For large Q2 :

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

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

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

Counting rules:

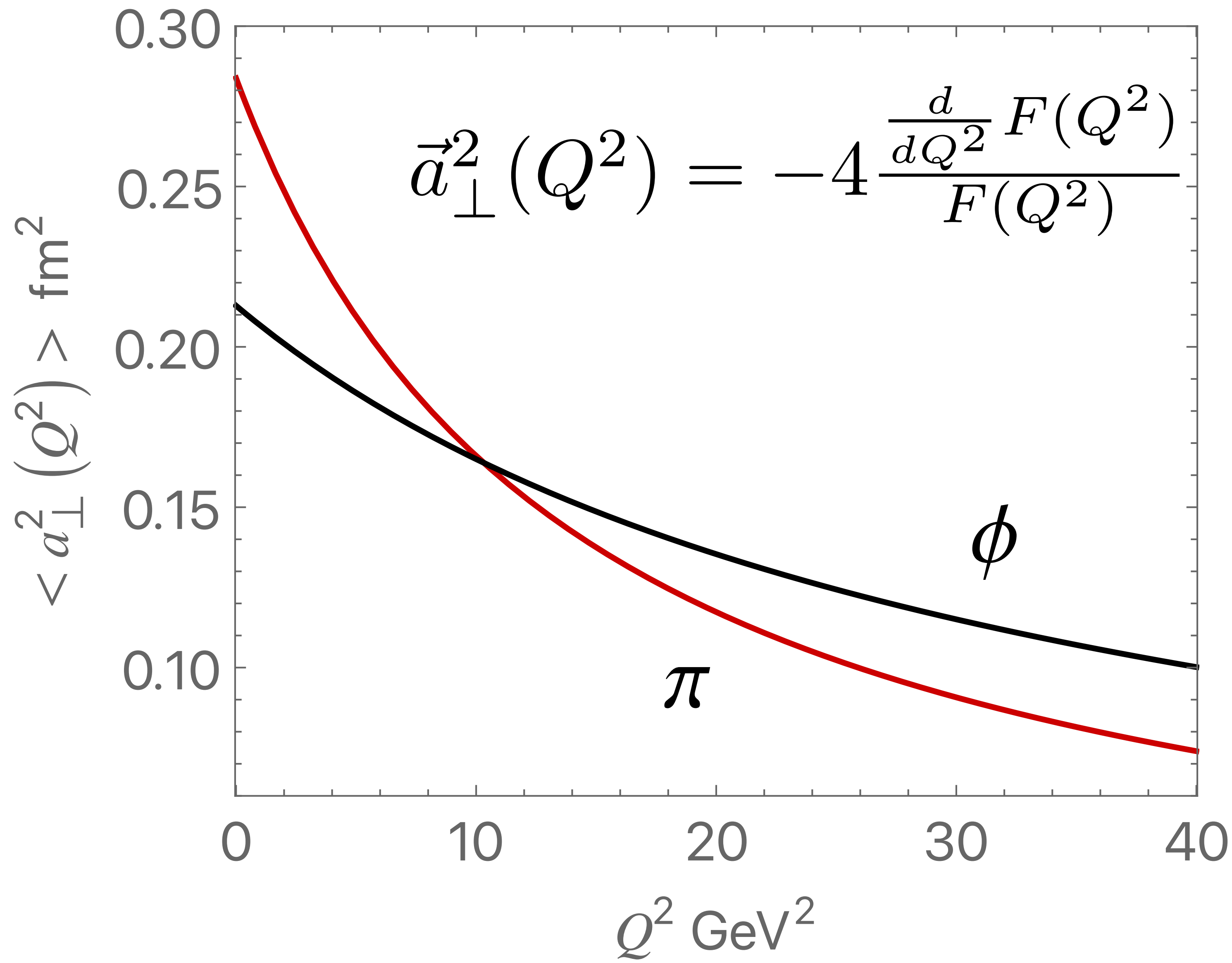
$$q_\tau(x) \propto (1-x)^{2n_s - 1} = (1-x)^{2\tau - 3}$$

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

Transverse size $a_\perp$ decreases with momentum transfer Q, grows with the number of spectators plus the internal orbital angular momentum L

Twist $\tau = n + L$

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



Transverse size depends on internal dynamics

Transparency controlled by transverse size

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

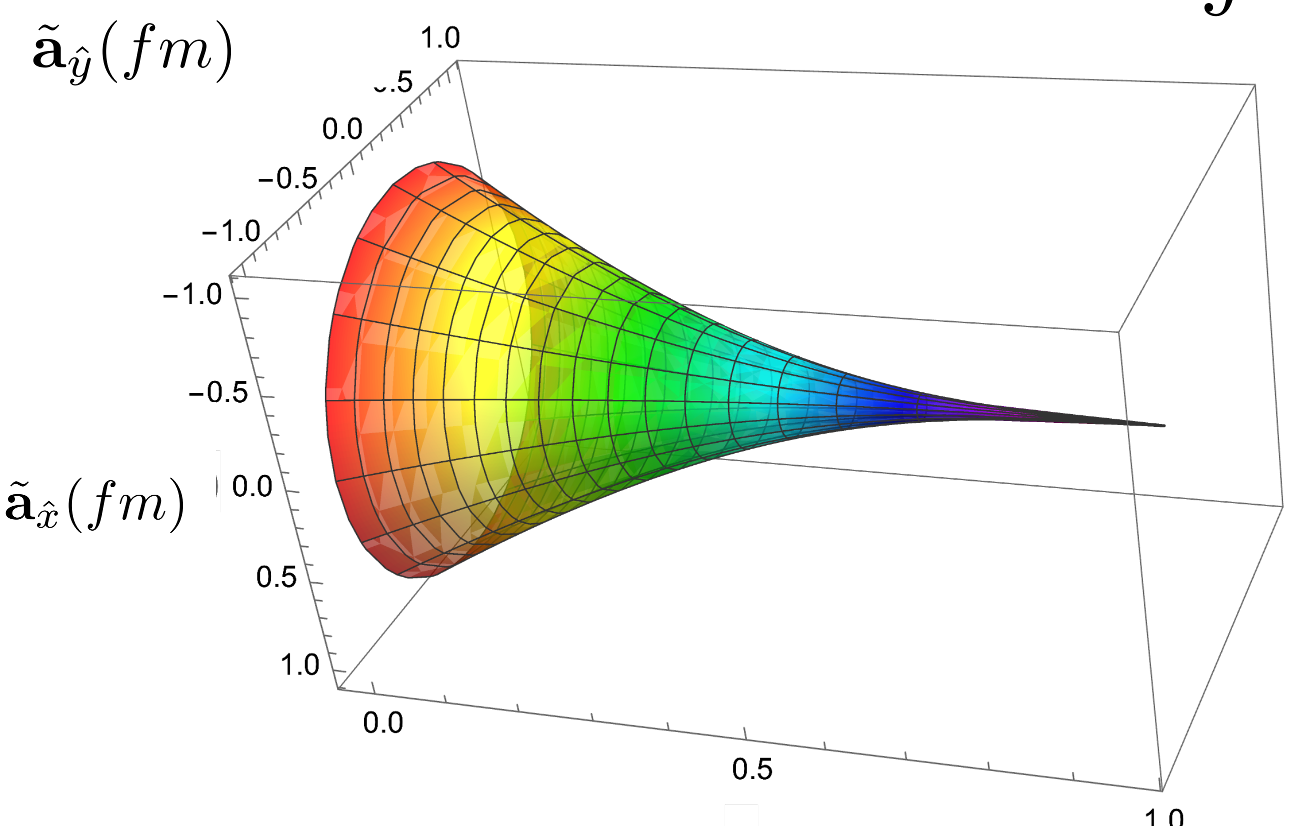
$$\boxed{\vec{a}_\perp \equiv \sum_{j=1}^{n-1} x_j \vec{b}_{\perp j}}$$

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

$$\boxed{x = 1 - \sum_{j=1}^{n-1} x_j}$$

Define mean transverse size as a function of x

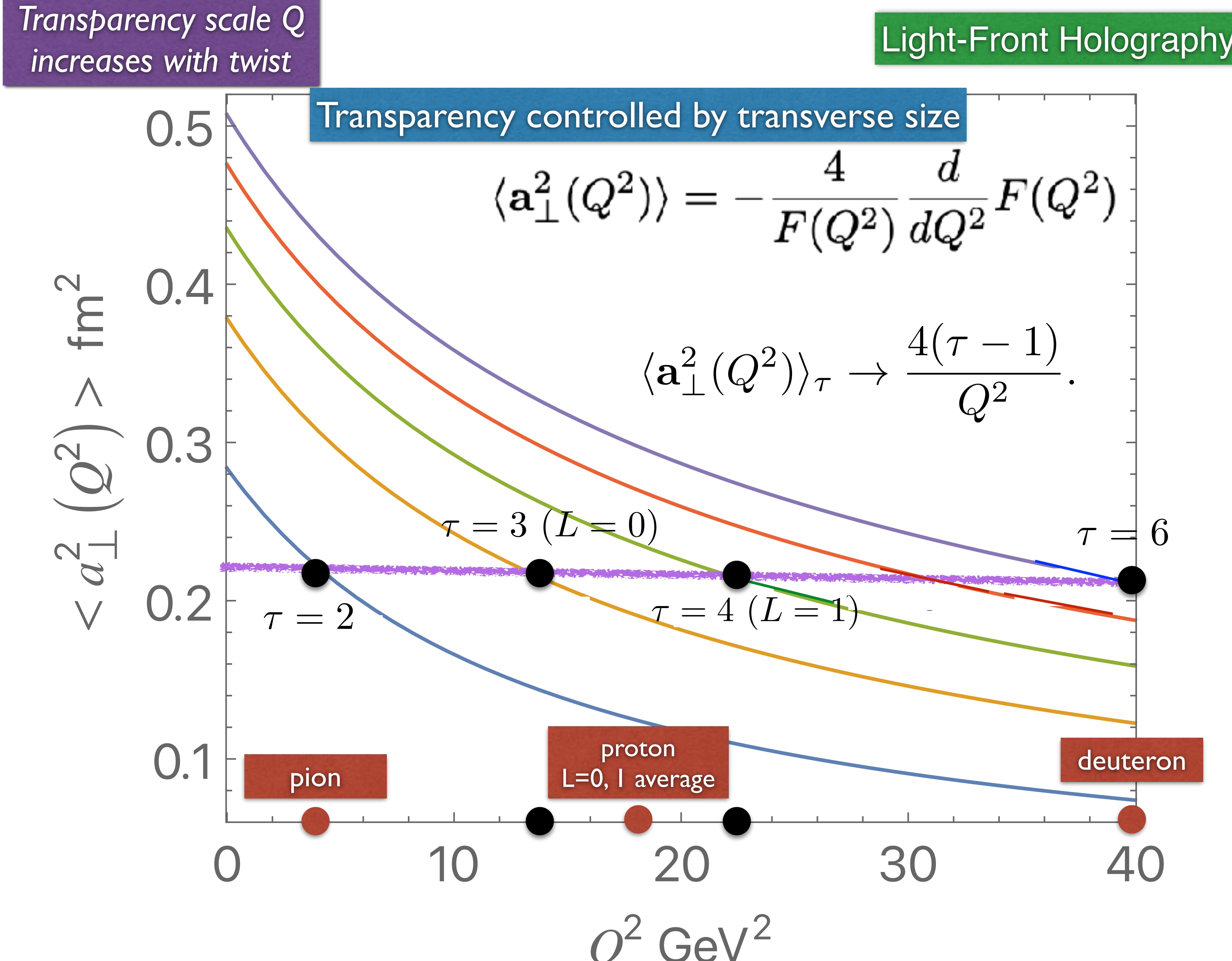
$$\sigma(x) = \ < \tilde{\mathbf{a}}_\perp^2(x) >= \frac{\int d^2\mathbf{a}_\perp \mathbf{a}_\perp^{\mathbf{2}} q(x,\mathbf{a}_\perp)}{\int d^2\mathbf{a}_\perp q(x,\mathbf{a}_\perp)}$$



$< \tilde{a}_\perp^2(x) >$: averaged over Q^2

Mean transverse size as a function of Q and Twist

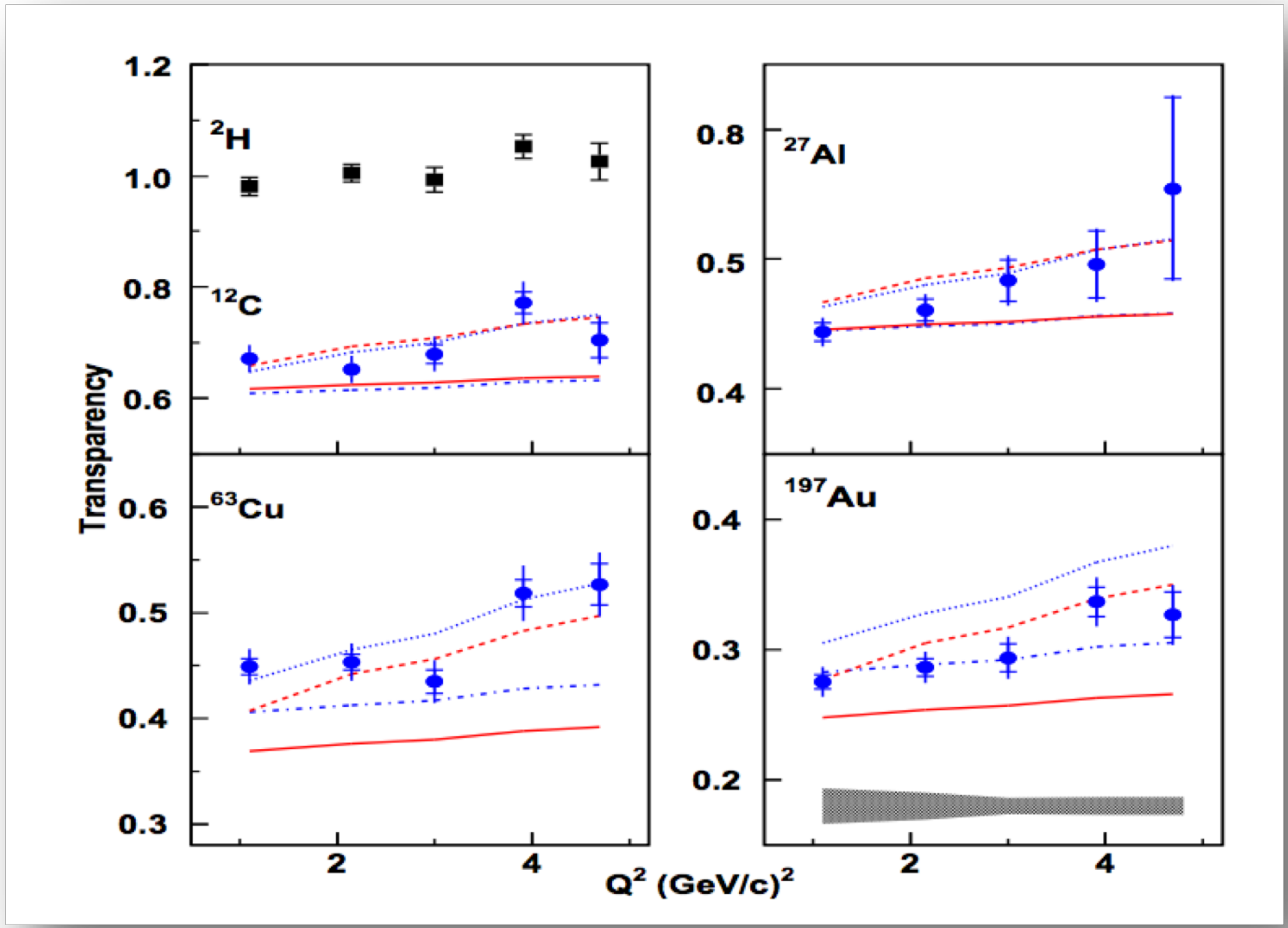
$$\boxed{\langle \mathbf{a}_\perp^2(Q^2) \rangle_\tau \to \frac{4(\tau - 1)}{Q^2}.}$$



Proton has equal probability for $\tau = 3$ and $\tau = 4$

Hall C E01-107 pion electro-production

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

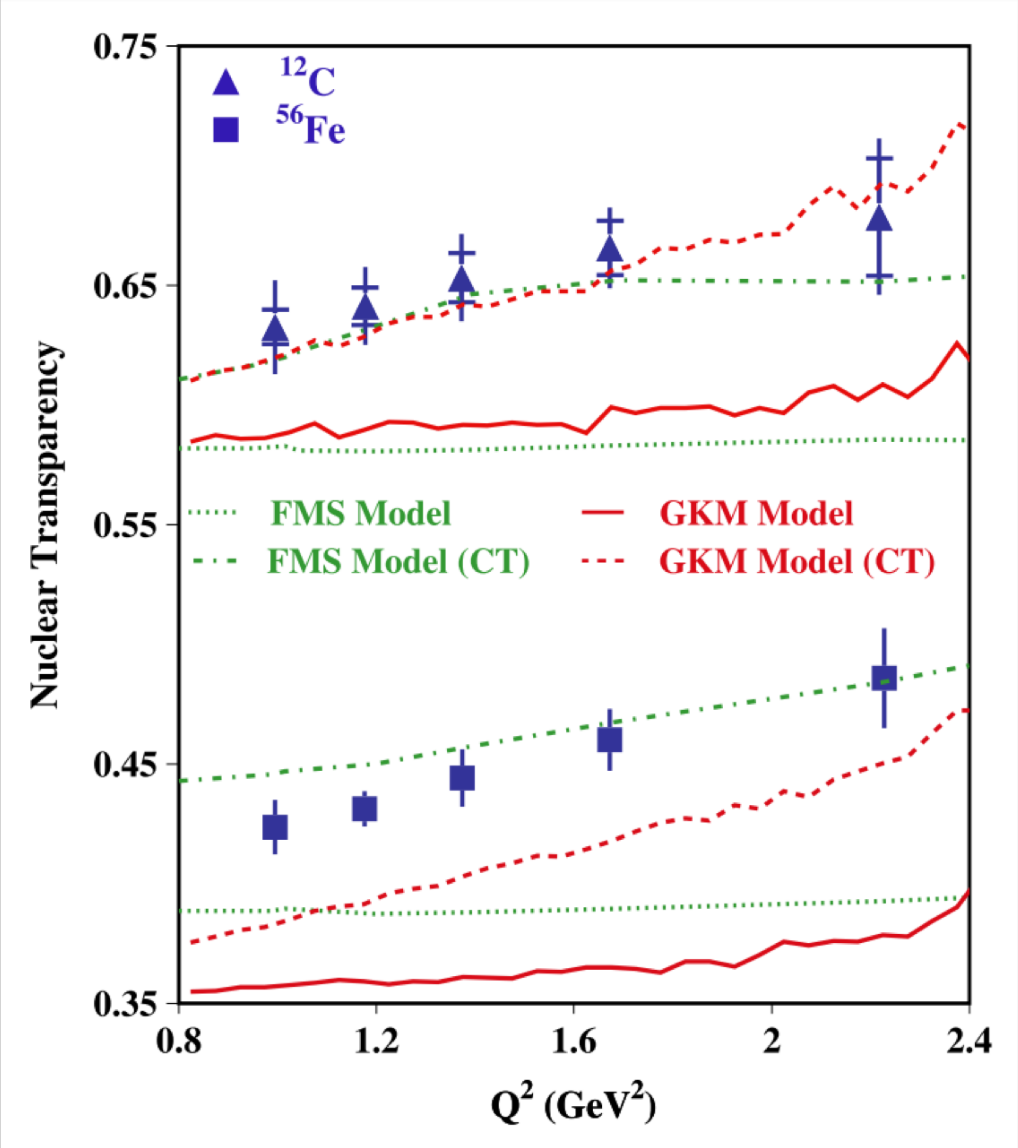


B.Clasie *et al.* PRL 99:242502 (2007)

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)

$$< a_\perp^2(Q^2 = 4\ GeV^2) >_{\tau=2} \simeq < a_\perp^2(Q^2 = 14\ GeV^2) >_{\tau=3} \simeq < a_\perp^2(Q^2 = 22\ GeV^2) >_{\tau=4} \simeq 0.24\ fm^2$$

5% increase for T_π in ^{12}C at $Q^2 = 4\ GeV^2$ implies 5% increase for T_p at $Q^2 = 18\ GeV^2$

- Transverse-impact size dependence on $t = -Q^2$ from expectation value of the profile function $\sigma(x)$

$$\langle \sigma(t) \rangle_\tau = \frac{\int dx\, \sigma(x) \rho_\tau(x,t)}{\int dx \rho_\tau(x,t)}$$
$$= \frac{1}{F_\tau(t)} \frac{d}{dt} F_\tau(t) = \frac{1}{4\lambda} \left[\psi\left(\tau - \alpha(t)\right) - \psi(1 - \alpha(t)\right]$$

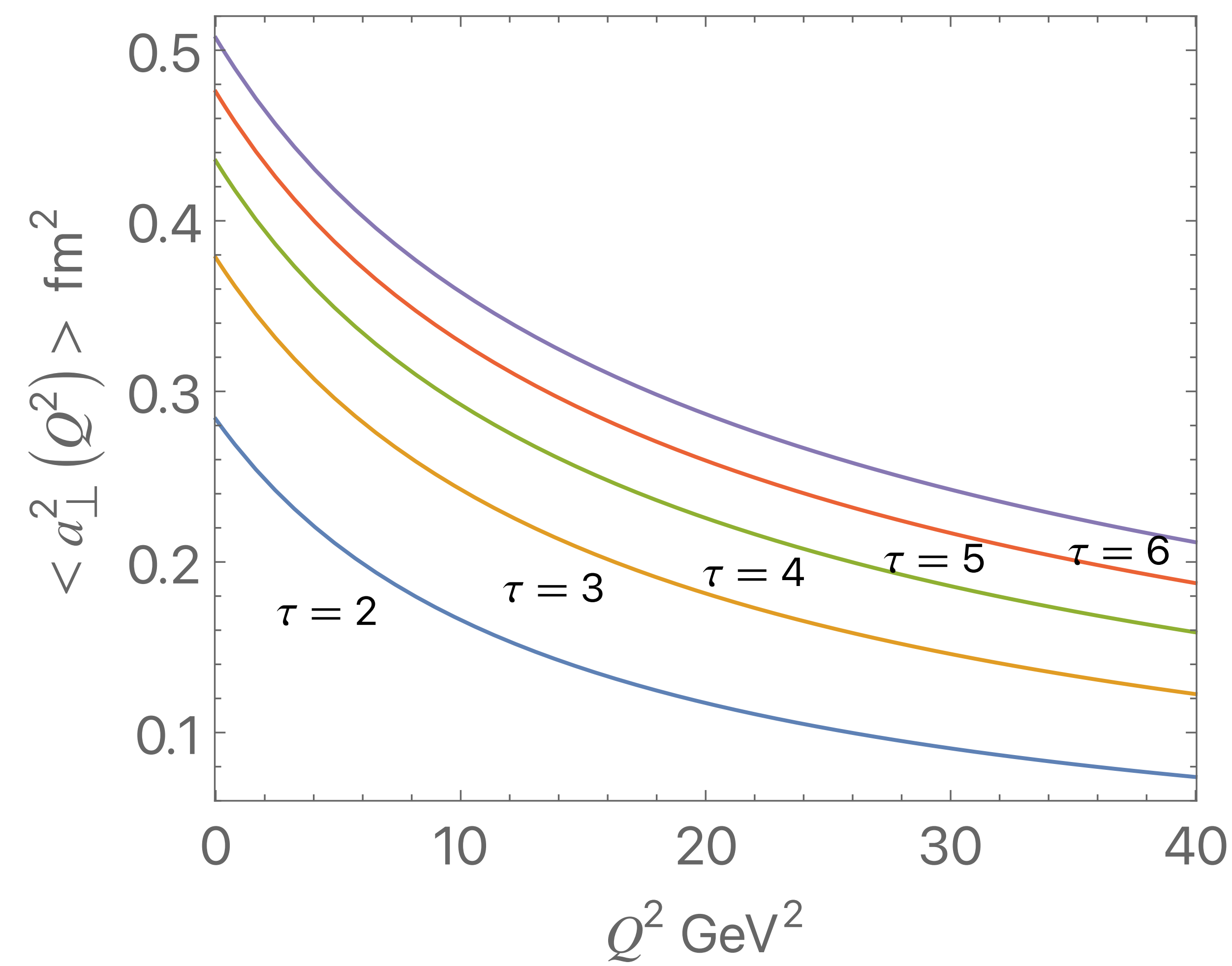
with ψ the digamma function

- For integer twist $\tau = N$

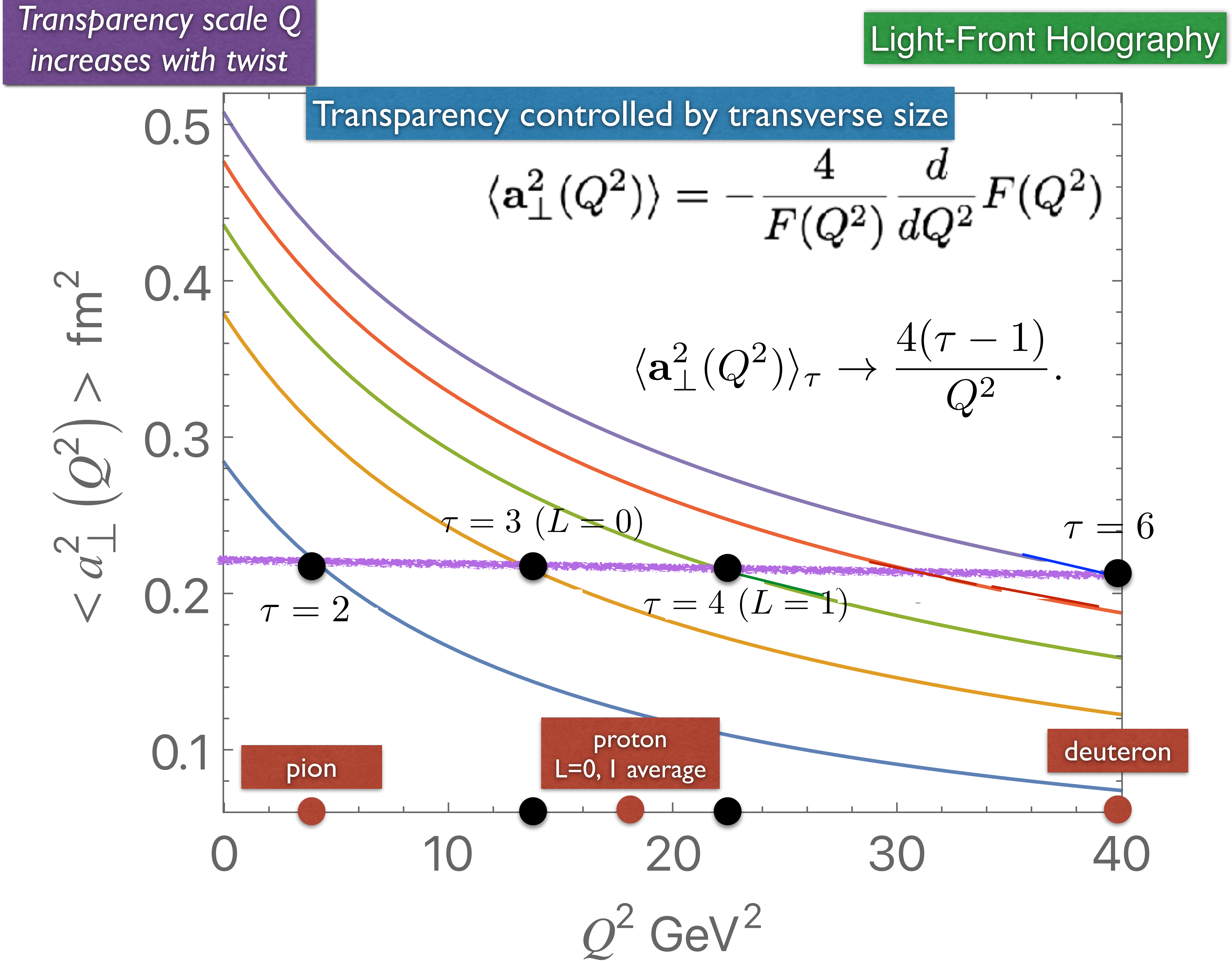
$$\langle a_\perp^2(t) \rangle_\tau \equiv 4 \langle \sigma(t) \rangle_\tau$$
$$= \frac{1}{\lambda} \sum_{j=1}^{\tau-1} \frac{1}{j - \alpha(t)}$$

- At large values $t = -Q^2$

$$\langle a_\perp^2(Q^2) \rangle_\tau \to \frac{4(\tau - 1)}{Q^2}$$



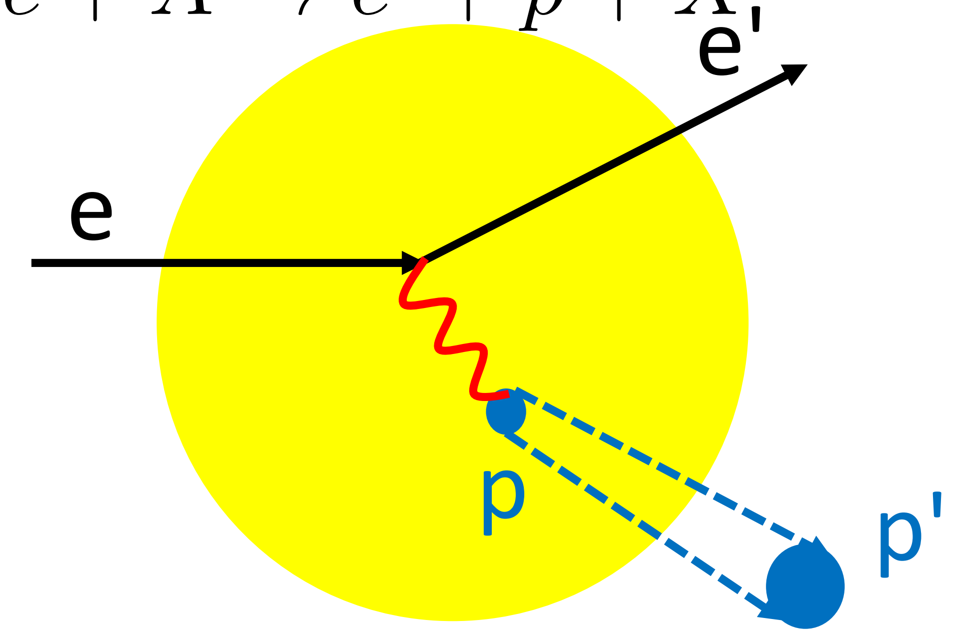
- The Q^2 required to contract all of the valence constituents of to a color-singlet domain of given transverse size, grows as the number of spectators and depends also on the properties of the quark current



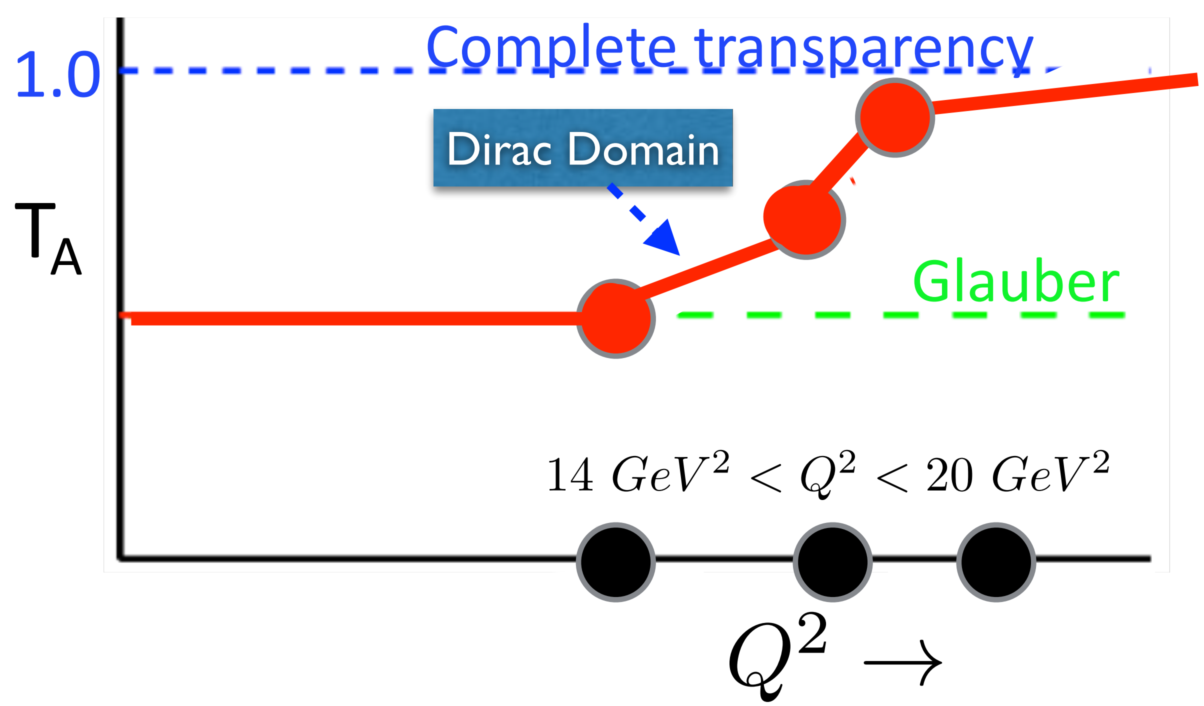
5% increase for T_π in ^{12}C at $Q^2 = 4\ GeV^2$ implies 5% increase for T_p at $Q^2 = 18\ GeV^2$

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

Two-Stage Color Transparency

$$\boxed{14\ GeV^2 < Q^2 < 20\ GeV^2}$$

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.

$$\boxed{Q^2 > 20\ GeV^2}$$

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.

Color Transparency and Light-Front Holography

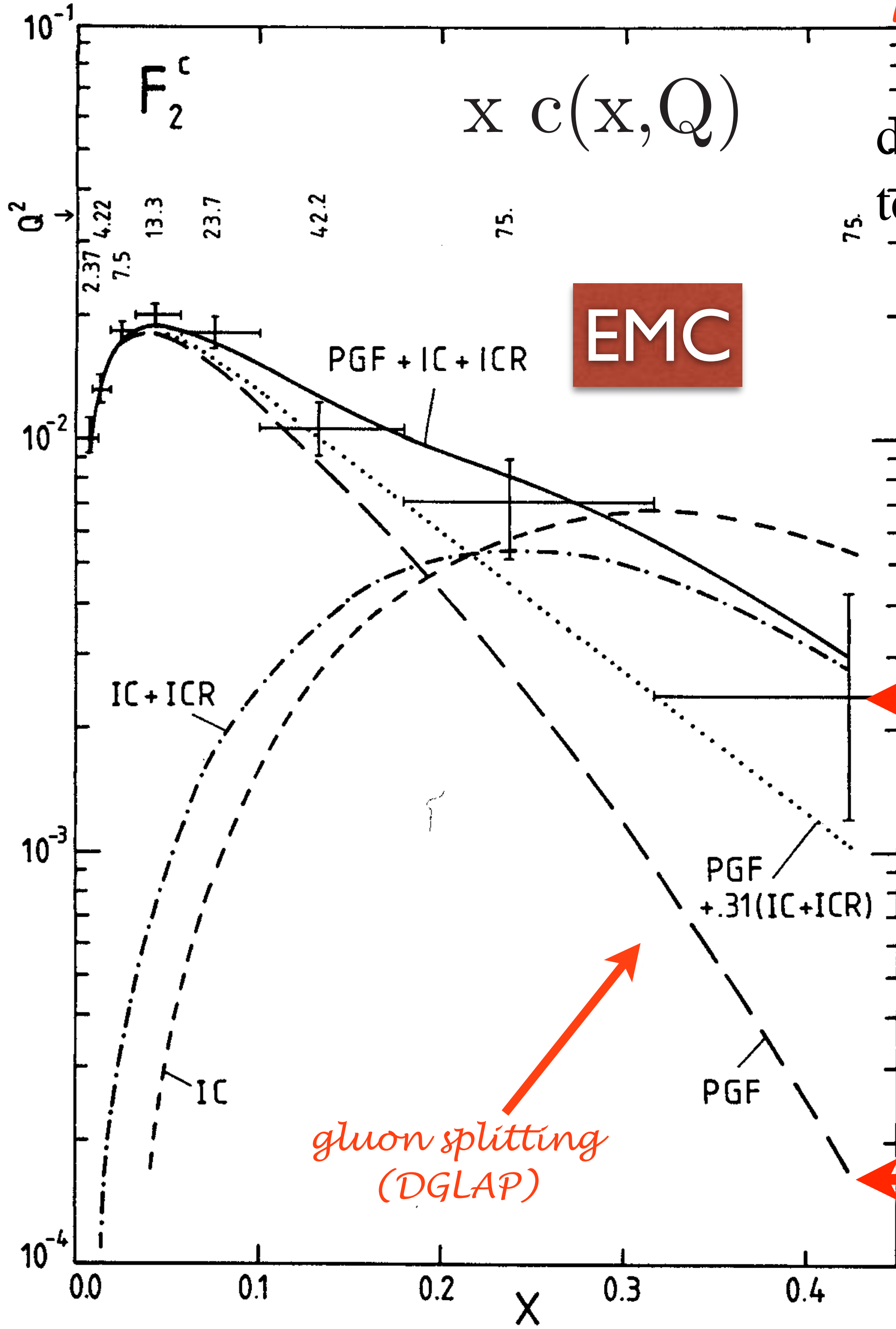
- Essential prediction of QCD
- LF Holography: Spectroscopy, dynamics, structure
- Transverse size predicted by LF Holography as a function of Q
- Q scale for CT increases with twist, number of constituents
- Two-Stage Proton Transparency: Equal probability L=0,1
- No contradiction with present experiments

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

$$Q_0^2(d) \simeq 40\ GeV^2$$

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).

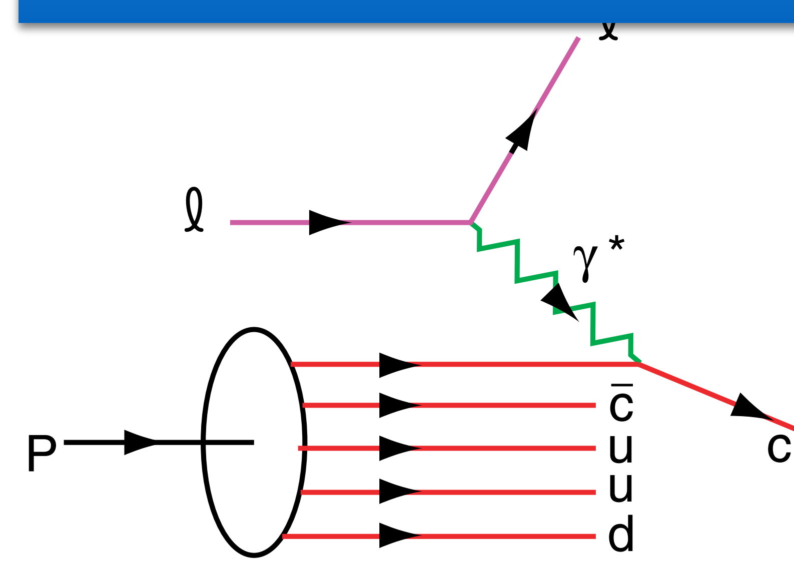


factor of 30 !

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

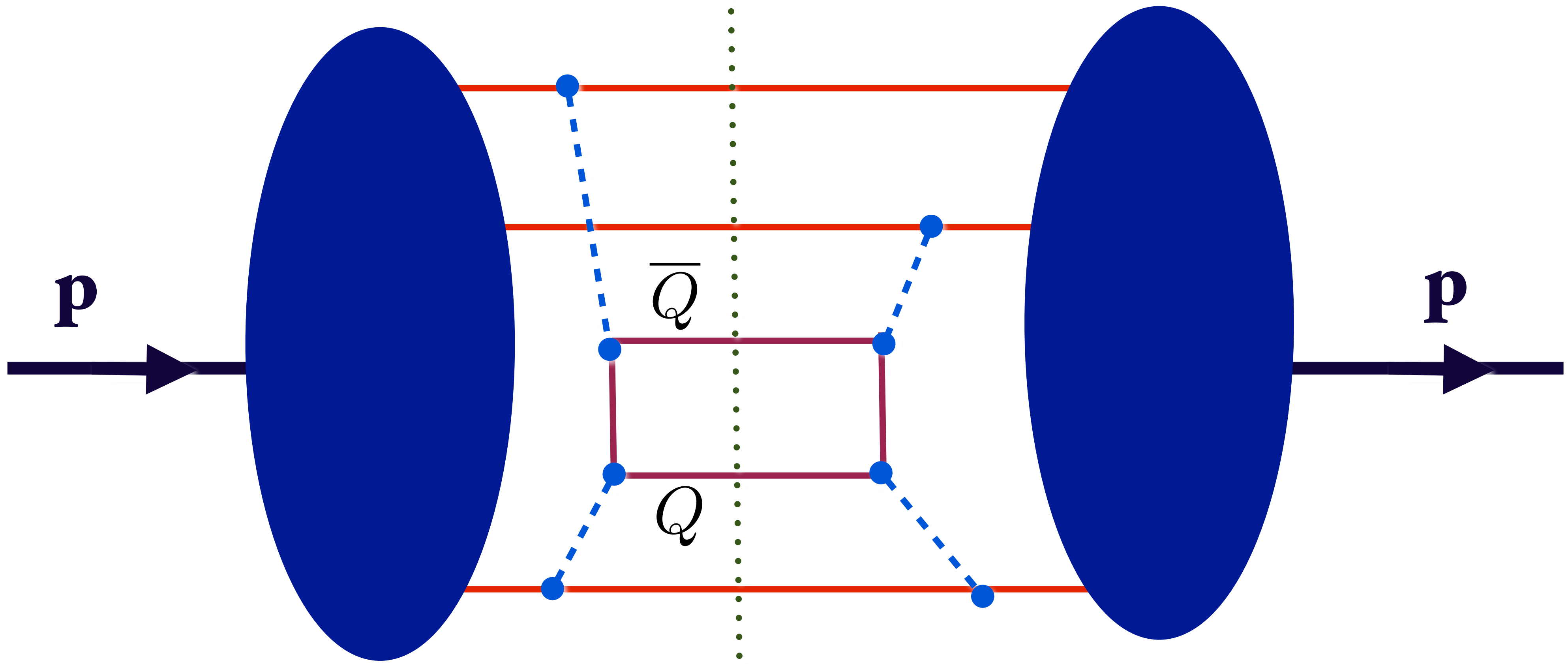
Two Components (separate evolution):

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

Hoyer, Peterson, Sakai, sjb
S. Gardner, sjb

Proton Self Energy
Intrinsic Heavy Quarks

Fixed LF time



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

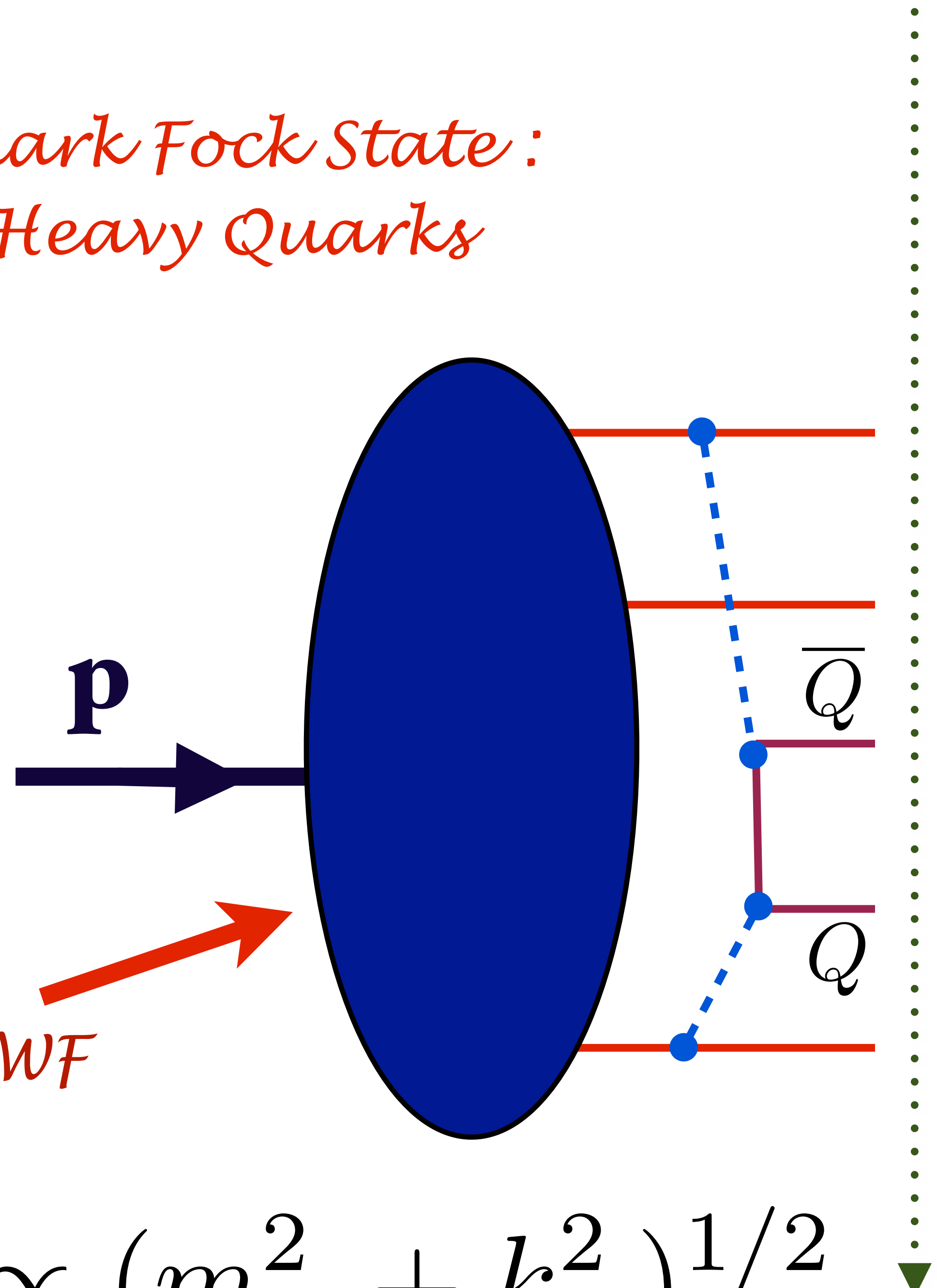
$\text{Probability (QCD)} \propto \frac{1}{M_Q^2}$

Rigorous OPE Analysis

Collins, Ellis, Gunion, Mueller, sjb
M. Polyakov, et al.

Proton 5-quark Fock State :
Intrinsic Heavy Quarks

$g \to Q\bar{Q}$ at low x: High $\mathcal{M}^2$



Use AdS/QCD LFWF

QCD predicts Intrinsic Heavy Quarks at high x!

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

Minimal off-shellness!

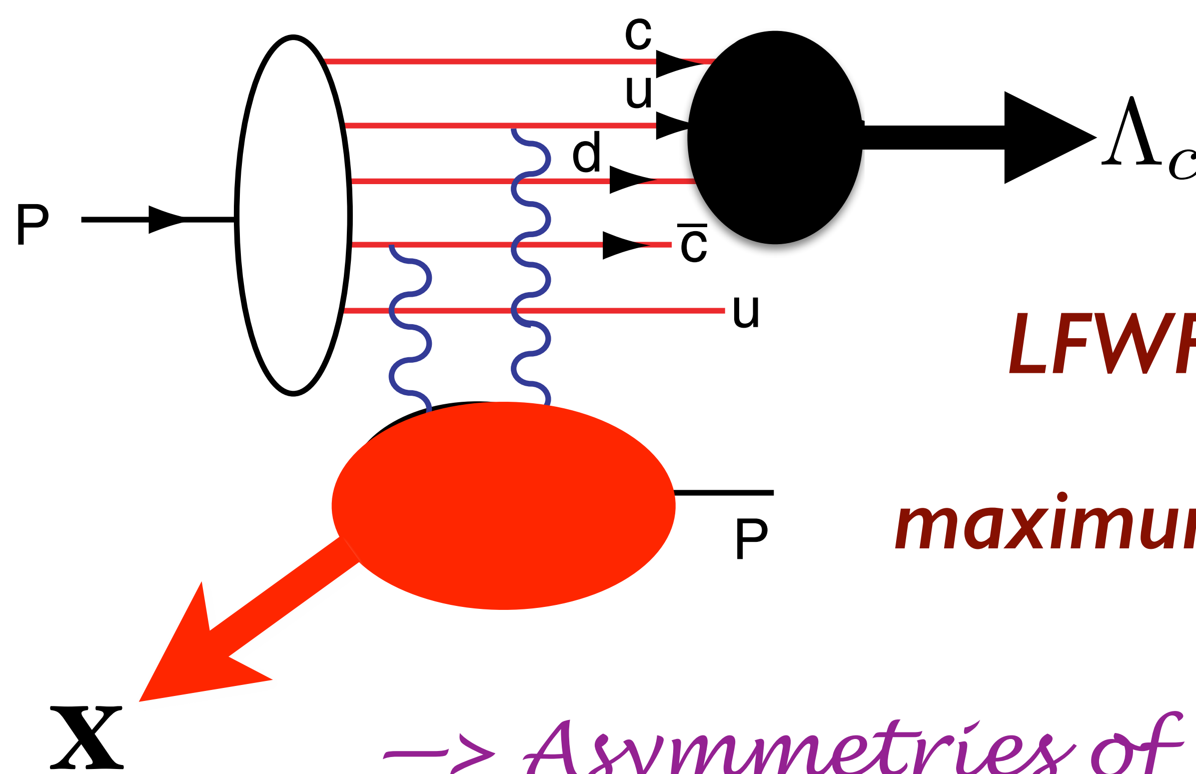
Probability (QED) $\propto \frac{1}{M_\ell^4}$

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

Collins, Ellis, Gunion, Mueller, sjb
Polyakov, et al.

Coalesece of comovers produces high x_F heavy hadrons

High x_F hadrons combine most of the comovers, fewest spectators



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

LFWF maximum at equal rapidity

maximum at minimal invariant mass

—> Asymmetries of leading hadrons

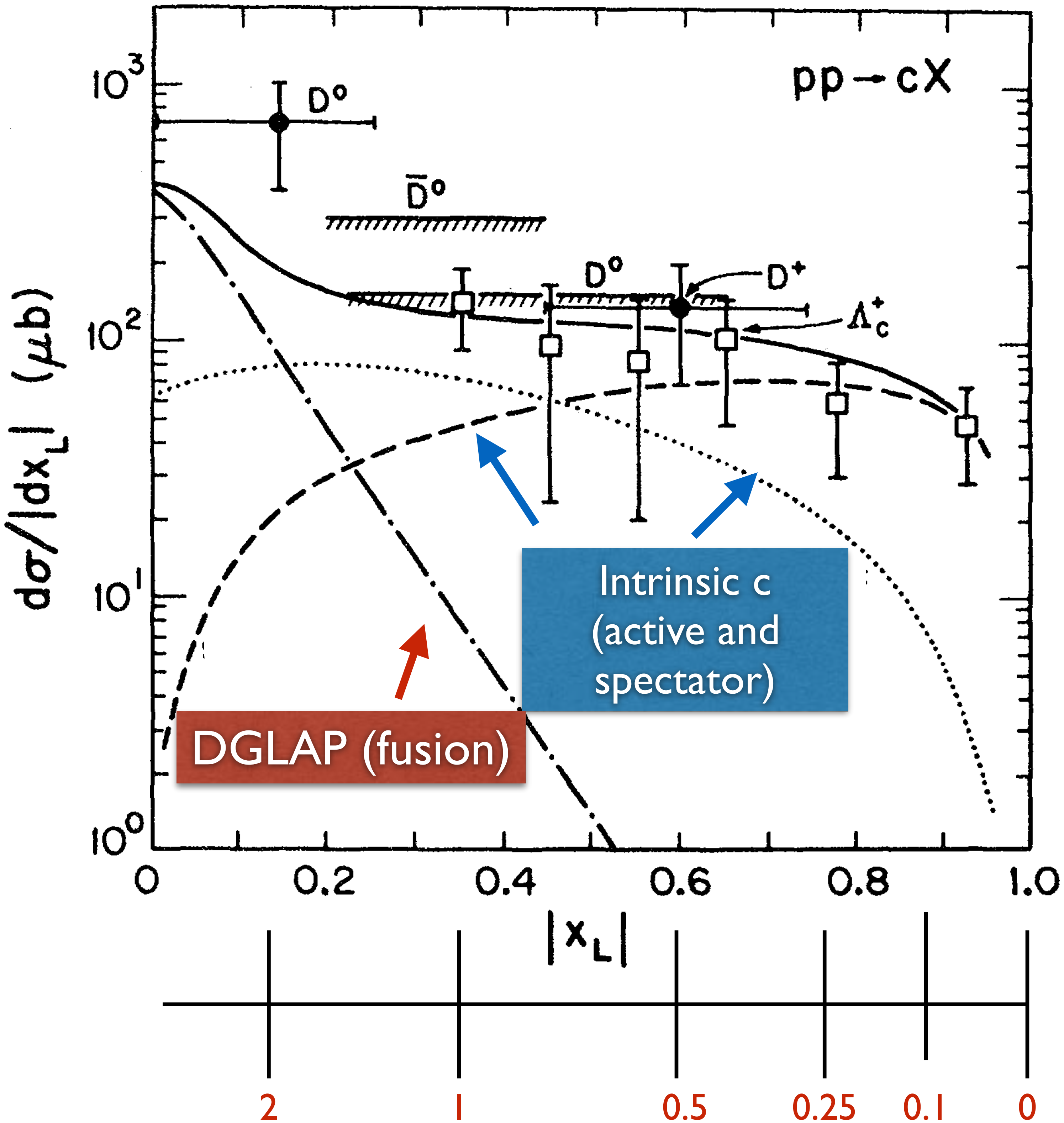
Spectator counting rules

$$\frac{dN}{dx_F} \propto (1 - x_F)^{2n_{spect}-1}$$

Coalescence of Comoving Charm and Valence Quarks Produce J/ψ, Λ_c and other Charm Hadrons at High x_F

Vogt, sjb

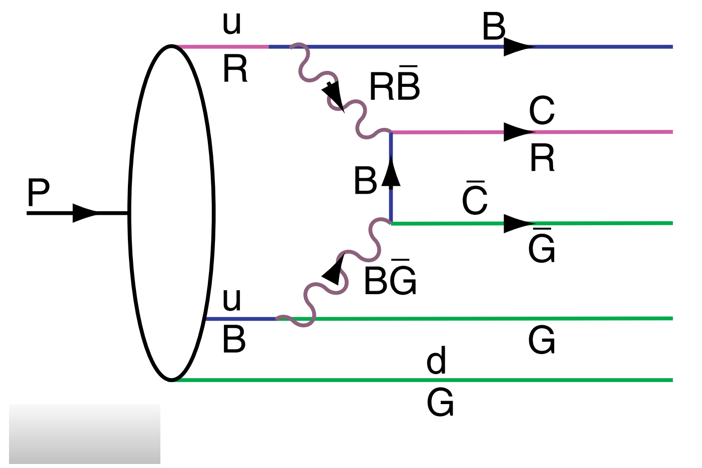
Barger, Halzen, Keung
PRD 25 (1981)



$\Delta y = \log x$

Hoyer, Peterson, Sakai, sjb
M. Polyakov, et. al

Intrinsic Heavy-Quark Fock States



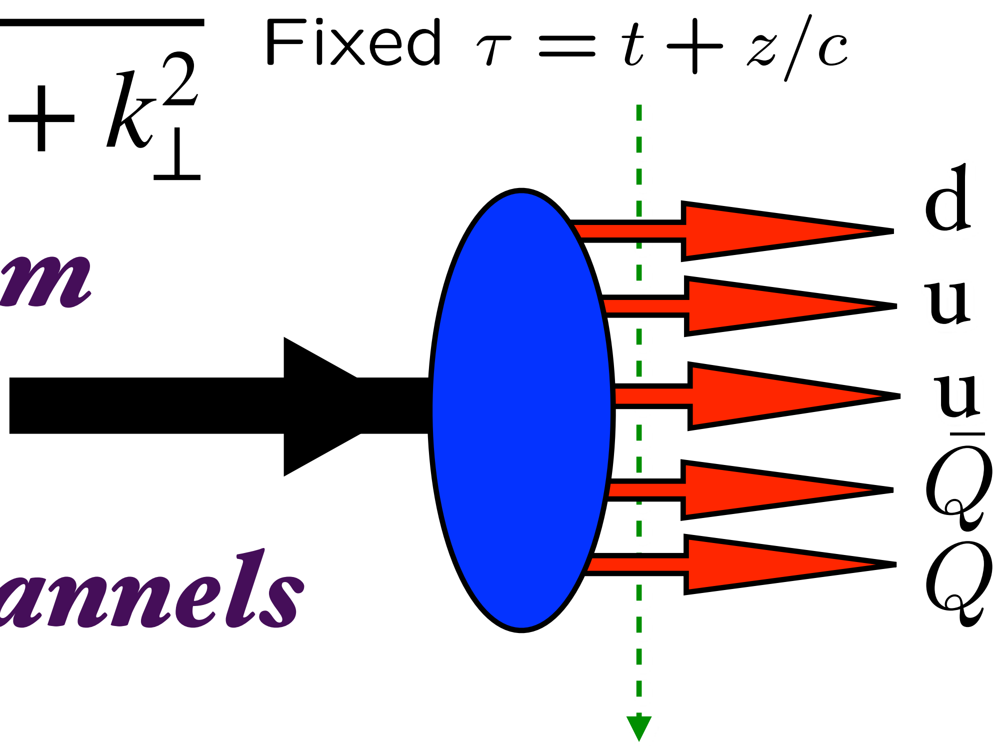
- Rigorous prediction of QCD, OPE
- Color-Octet Color-Octet Fock State!
- Probability $P_{Q\bar{Q}} \propto \frac{1}{M_Q^2}$ $P_{Q\bar{Q}Q\bar{Q}} \sim \alpha_s^2 P_{Q\bar{Q}}$ $P_{c\bar{c}/p} \simeq 1\%$
- Large Effect at high x
- Greatly increases kinematics of colliders such as Higgs production at high x_F (Kopeliovich, Schmidt, Soffer, Goldhaber, sjb)
- Severely underestimated in conventional parameterizations of heavy quark distributions (Pumplin, Tung)
- Many empirical tests (Gardener, Karliner, ..)

Review: G. Lykasov, et al

Properties of Non-Perturbative Five-Quark Fock-State

- ***Dominant configuration: mininum off-shell, same rapidity***
- ***Heavy quarks have most of the LF momentum***

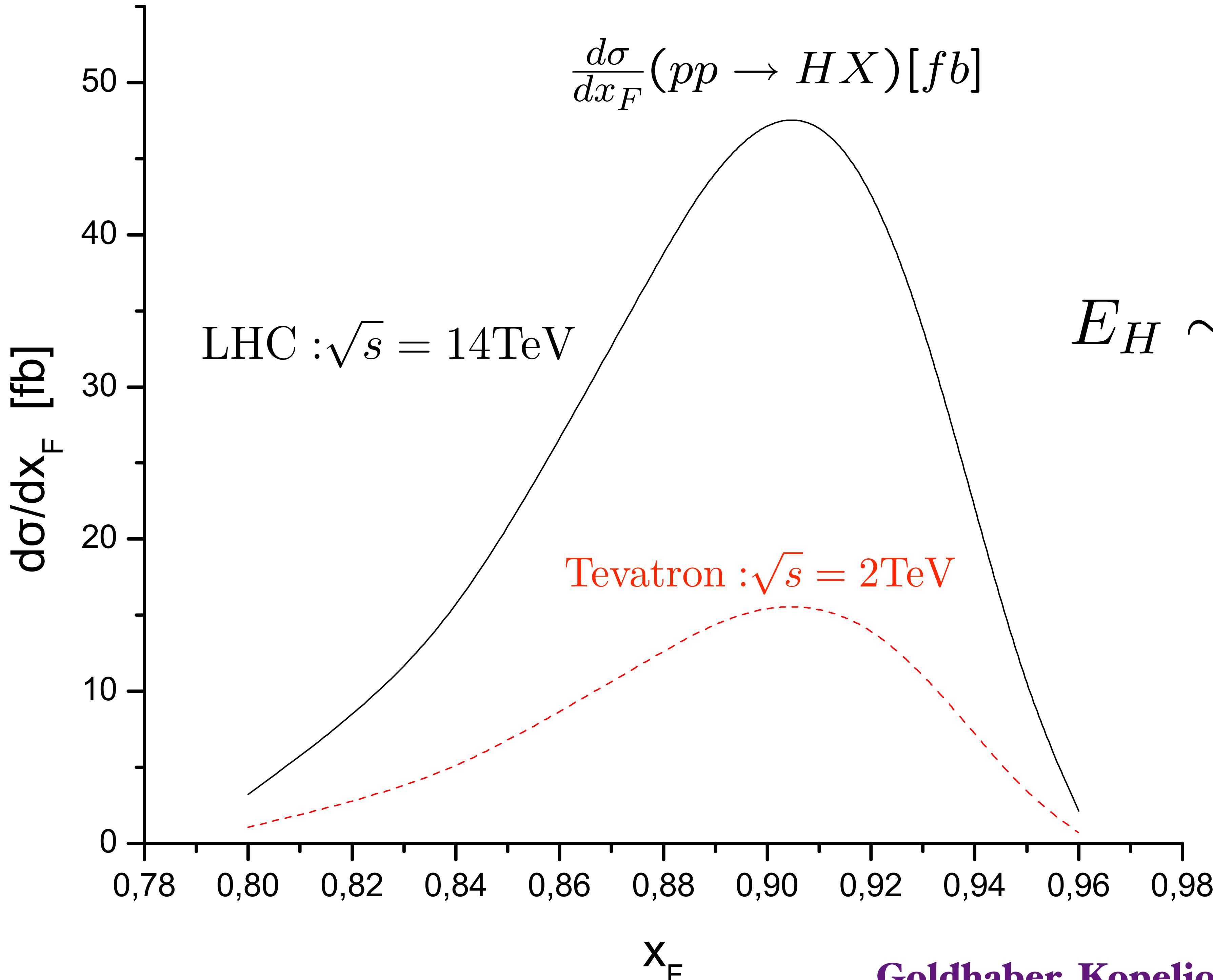
$$< x_Q > \propto \sqrt{m_Q^2 + k_\perp^2}$$



- ***Correlated with proton quantum numbers***
- ***Duality with meson-baryon channels***
- ***Strangeness, charm asymmetry at x > 0.1***

$$s_p(x) \neq \bar{s}_p(x) \quad c_p(x) \neq \bar{c}_p(x)$$

Intrinsic Heavy Quark Contribution to Inclusive Higgs Production



$E_H \sim 0.9 E_p$

Goldhaber, Kopeliovich, Schmidt, sjb

Measure $H \to ZZ^* \to \mu^+\mu^-\mu^+\mu^-$.

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

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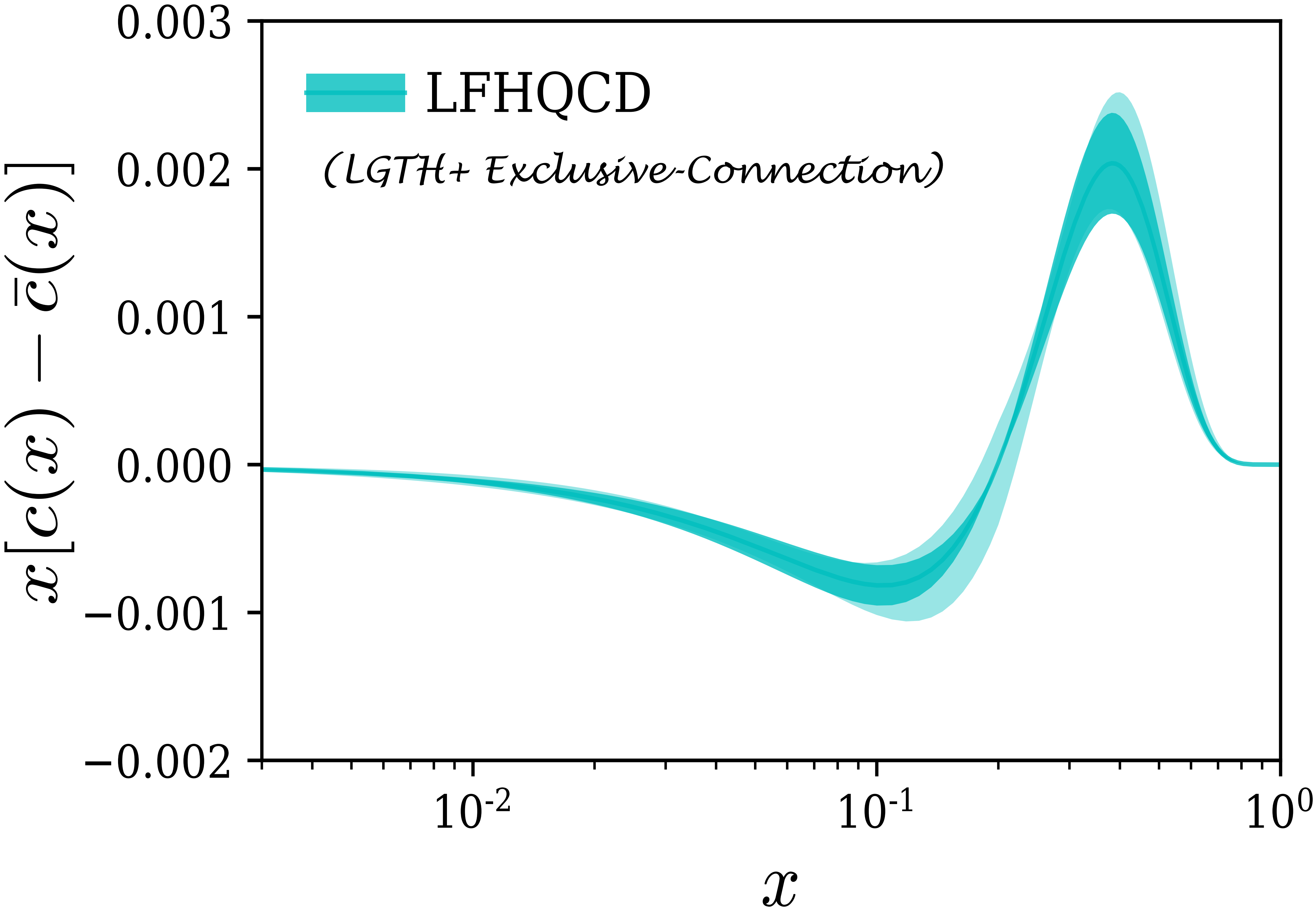
Abstract

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 $\mu^c_M = -0.00127(38)_{\mathrm{stat}}(5)_{\mathrm{sys}}$, 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

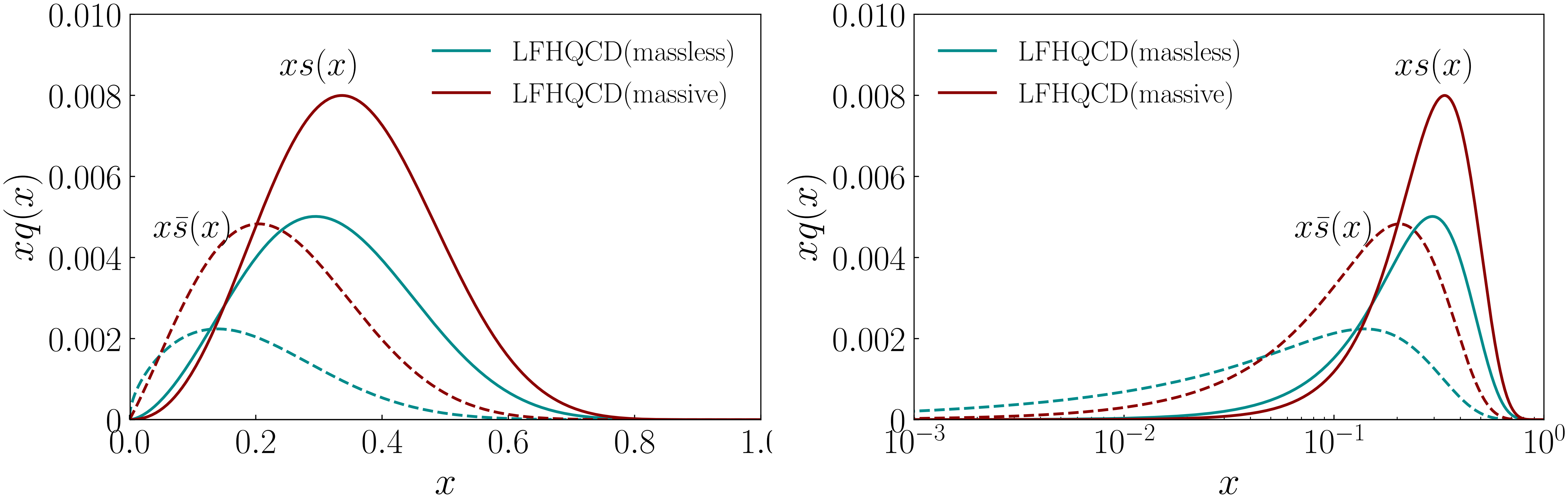


The distribution function $x[c(x) - \bar{c}(x)]$ obtained from the LFHQCD formalism using the lattice QCD input of charm electromagnetic form factors $G^c_{E,M}(Q^2)$. The outer cyan band indicates an estimate of systematic uncertainty in the $x[c(x) - \bar{c}(x)]$ distribution obtained from a variation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

Strange and Antistrange Distributions

Input: nonzero lattice axial form factor

Duality with $|K\Lambda>$ meson-nucleon fluctuations



Phys. Rev. D 98, 114004 (2018).

R. S. Sufian, T.Liu, de Teramond, Dosch, Deur, Islam, Ma, sjb

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*

$$M_\pi^2 f_\pi^2 = -\tfrac{1}{2}(m_u + m_d)\langle \bar{u}u + \bar{d}d\rangle + \mathcal{O}\big((m_u + m_d)^2\big)$$

- *QCD Coupling at all Scales* $\alpha_s(Q^2)$
- *Eliminate Scale Uncertainties and Scheme Dependence*

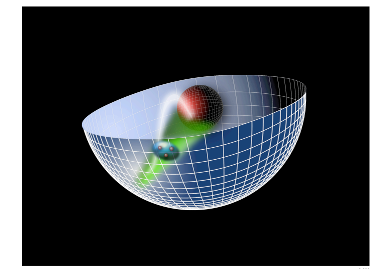
$\mathscr{L}_{QCD} \to \psi_n^H(x_i, \overrightarrow{k}_{\perp i}, \lambda_i)$ *Valence and Higher Fock States*

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-like relation
- QCD coupling at all scales
- Nonperturbative mass scale
- Hadron Spectroscopy-Regge Trajectories for mesons, baryons with universal slopes in n, L
- Supersymmetric 4-Plet: Meson-Baryon -Tetraquark Symmetry
- Light-Front Wavefunctions
- Form Factors, Quark and Gluon Structure Functions
- New Hadronic Observables; gluonic radii and gluonic momentum fraction
- OPE: Constituent Counting Rules
- Hadronization at the Amplitude Level: Many Phenomenological Tests
- Systematically improvable: Basis LF Quantization (BLFQ)

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:*

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

Invariance Principles of Quantum Field Theory

- *Polncarè Invariance: Physical predictions must be independent of the observer's Lorentz frame: Front Form*
- *Causality: Information within causal horizon: Front Form*
- *Gauge Invariance: Physical predictions of gauge theories must be independent of the choice of gauge*
- *Scheme-Independence: Physical predictions of renormalizable theories must be independent of the choice of the renormalization scheme — Principle of Maximum Conformality (PMC)*
- *Mass-Scale Invariance: Conformal Invariance of the Action (DAFF)*

Principle of Maximum Conformality (PMC)

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Systematic All-Orders Method to Eliminate Renormalization-Scale and Scheme Ambiguities in Perturbative QCD

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We introduce a generalization of the conventional renormalization schemes used in dimensional regularization, which illuminates the renormalization scheme and scale ambiguities of perturbative QCD predictions, exposes the general pattern of nonconformal $\{\beta_i\}$ terms, and reveals a special degeneracy of the terms in the perturbative coefficients. It allows us to systematically determine the argument of the running coupling order by order in perturbative QCD in a form which can be readily automatized. The new method satisfies all of the principles of the renormalization group and eliminates an unnecessary source of systematic error.

Set multiple renormalization scales -- Lensing, DGLAP, ERBL Evolution ...

$Choose\ renormalization\ scheme;\ e.g.\ \alpha_s^R(\mu_R^{\rm init})$

↓

$Choose\ \mu_R^{init};\ arbitrary\ initial\ renormalization\ scale$

↓

$Identify\ \{\beta_i^R\} - terms\ using\ n_f - terms$

$through\ the\ PMC - BLM\ correspondence\ principle$

↓

$Shift\ scale\ of\ \alpha_s\ to\ \mu_R^{\rm PMC}\ to\ eliminate\ \{\beta_i^R\} - terms$

↓

$Conformal\ Series$

$Result\ is\ independent\ of\ \mu_R^{\rm init}\ and\ scheme\ at\ fixed\ order$

PMC/BLM

No renormalization scale ambiguity!

Result is independent of Renormalization scheme and initial scale!

QED Scale Setting at N_C=0

Eliminates unnecessary systematic uncertainty

Scale fixed at each order

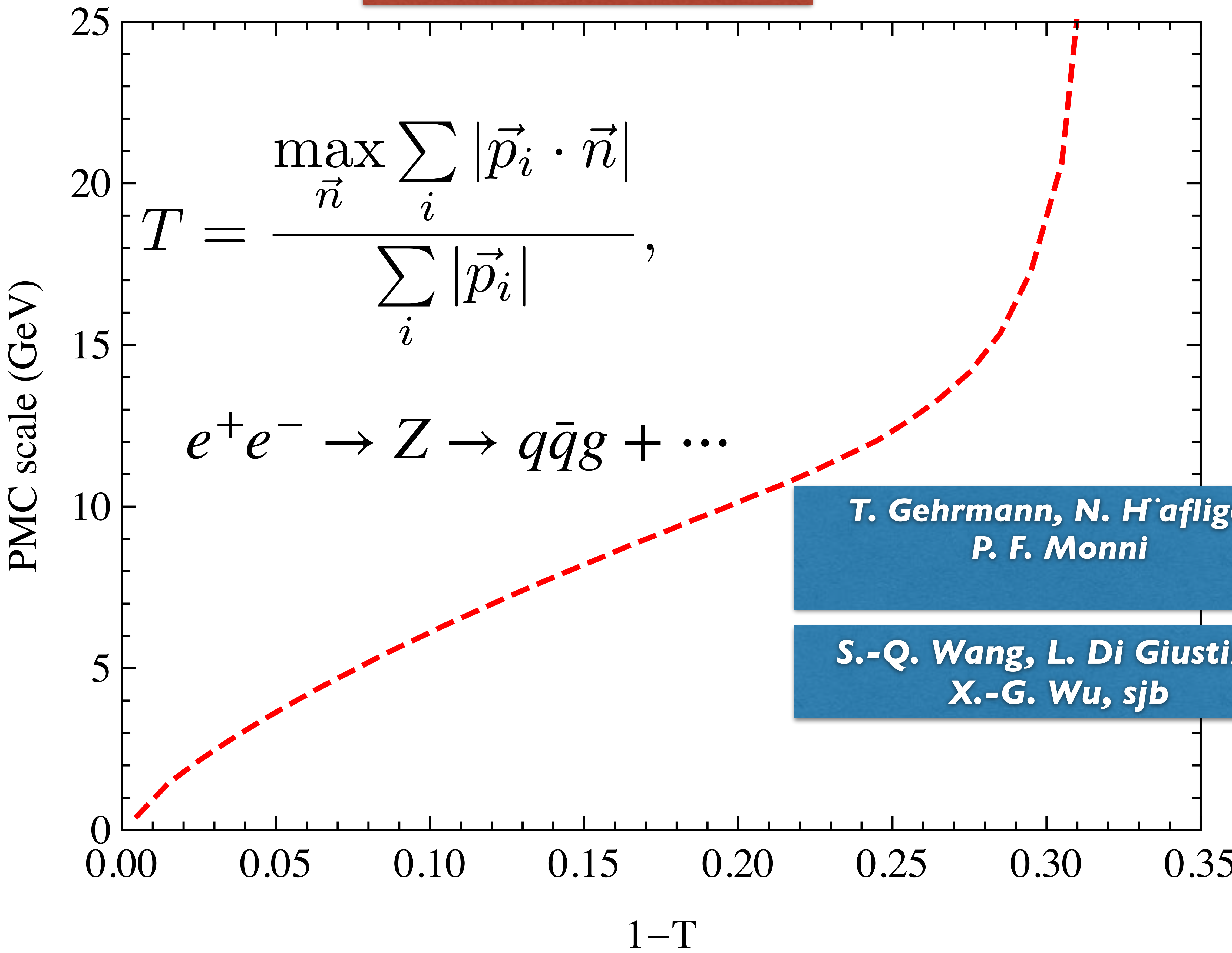
δ-Scheme automatically identifies β-terms!

Principle of Maximum Conformality

Xing-Gang Wu, Matin Mojaza Leonardo di Giustino, SJB

Renormalization scale depends on the thrust

Not constant !



T. Gehrmann, N. H˙afliger, P. F. Monni

S.-Q. Wang, L. Di Giustino, X.-G. Wu, sjb

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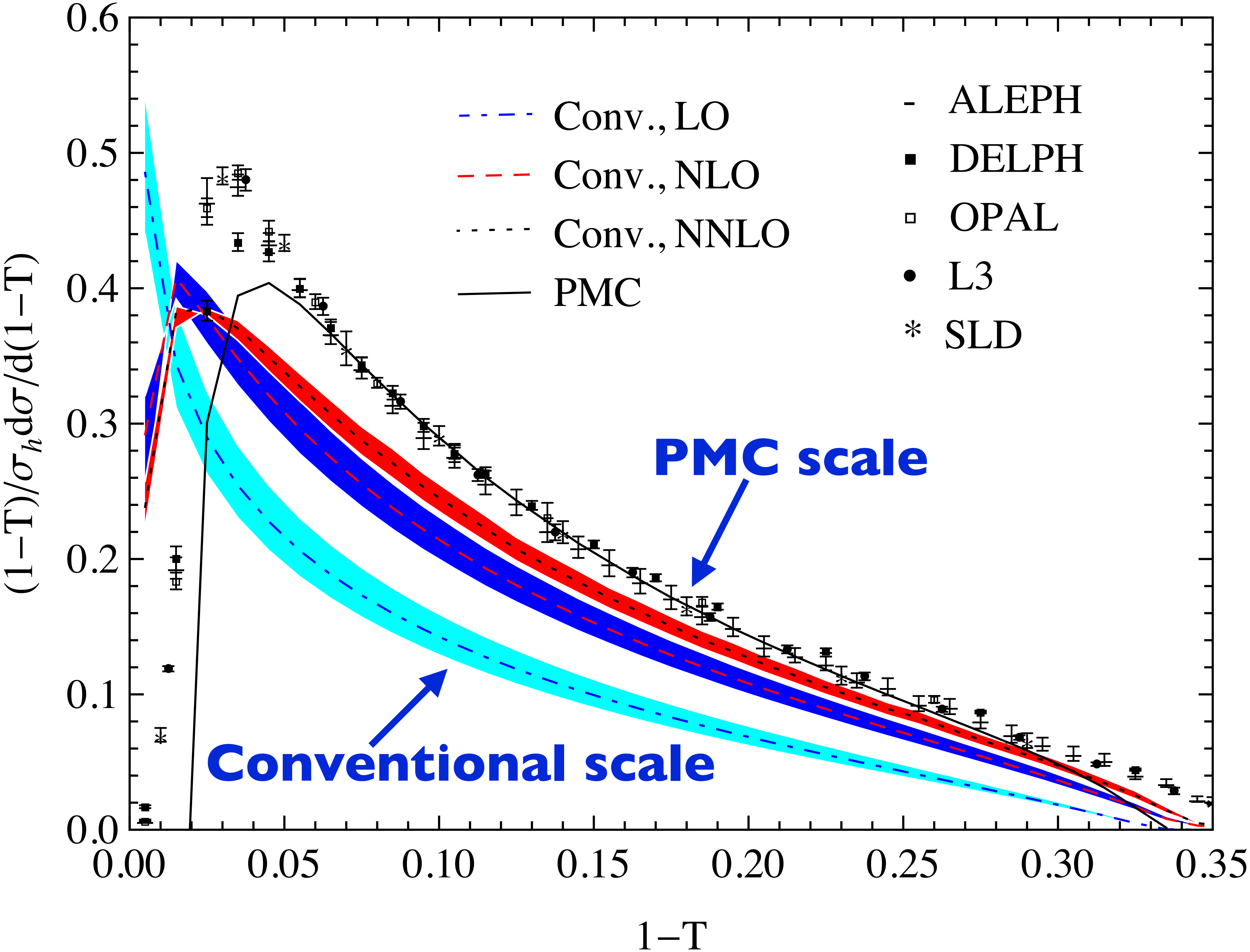
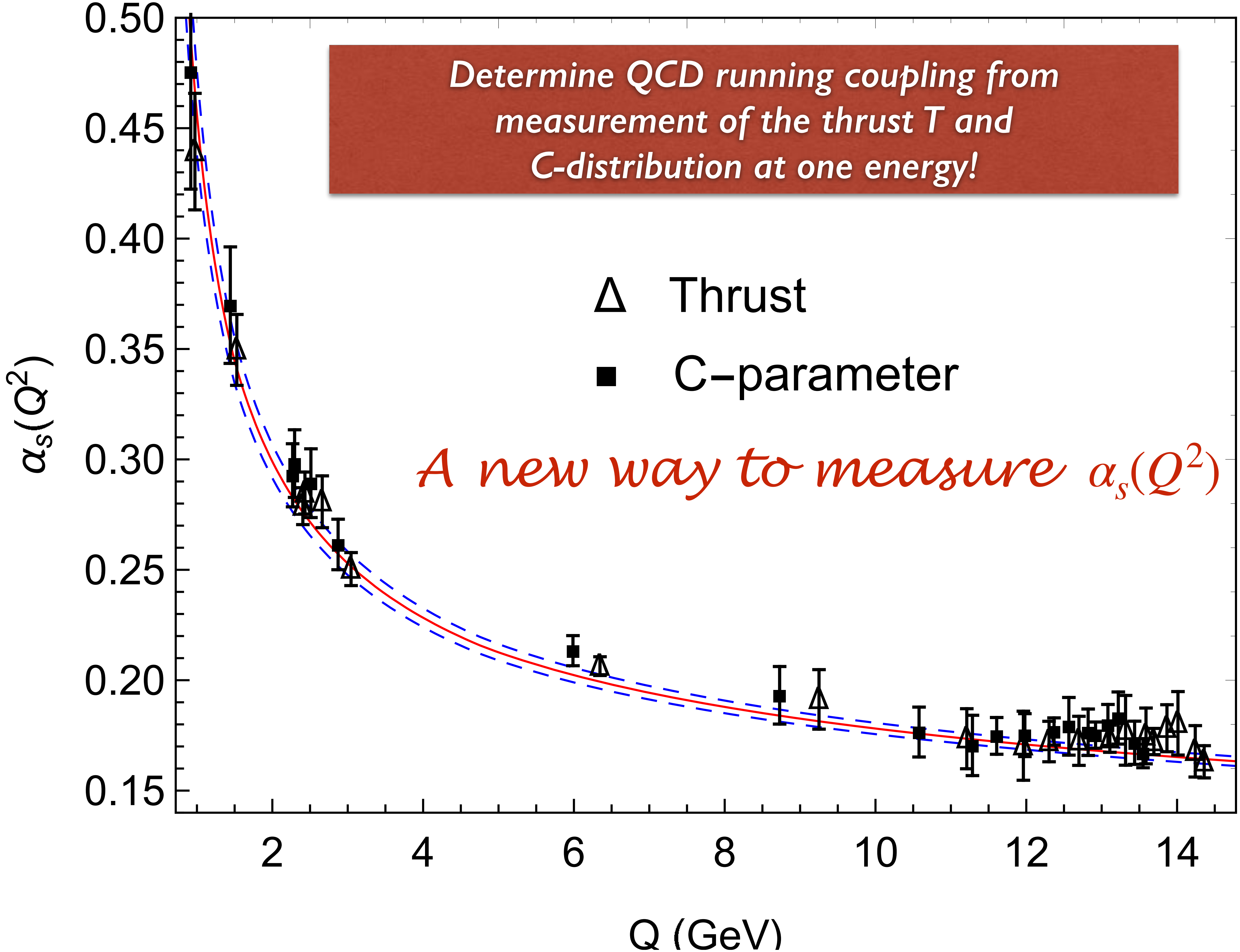


Principle of Maximum Conformality (PMC)

$e^+e^- \to Z^0 \to q\bar{q}g + \cdots \quad \alpha_s(Q^2)$ *in* $\overline{MS}$ *scheme*



S.-Q. Wang, L. Di Giustino, X.-G. Wu, SJB

Features of BLM/PMC

- ***Predictions are scheme-independent at every order***

- ***Matches conformal series***

- ***No n! Renormalon growth of pQCD series***

- ***New scale appears at each order; n_F determined at each order - matches virtuality of quark loops***

- ***Multiple Physical Scales Incorporated (Hoang, Kuhn, Tuebner, sjb)***

- ***Rigorous: Satisfies all Renormalization Group Principles***

- ***Realistic Estimate of Higher-Order Terms***

- ***Reduces to standard QED scale*** $N_C \to 0$

- ***GUT: Must use the same scale setting procedure for QED, QCD***

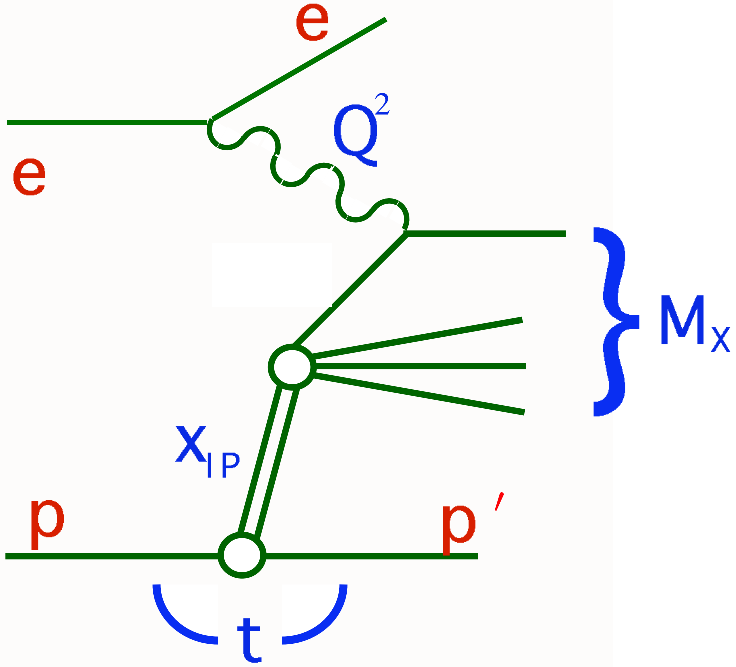
- ***Eliminates unnecessary theory error***

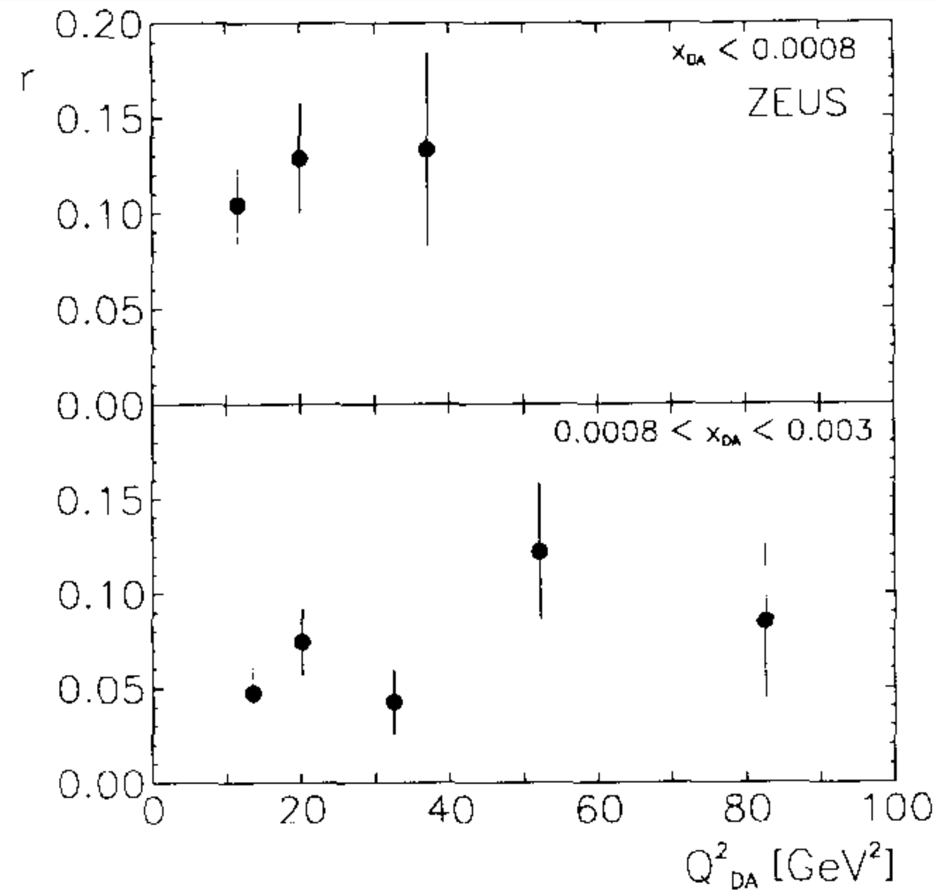
- ***Maximal sensitivity to new physics***

- ***Commensurate Scale Relations between observables: Generalized Crewther Relation (Kataev, Lu, Rathsman, sjb)***

- ***PMC Reduces to BLM at NLO: Example: BFKL intercept*** **(Fadin, Kim, Lipatov, Pivovarov, sjb)**

Remarkable observation at HERA



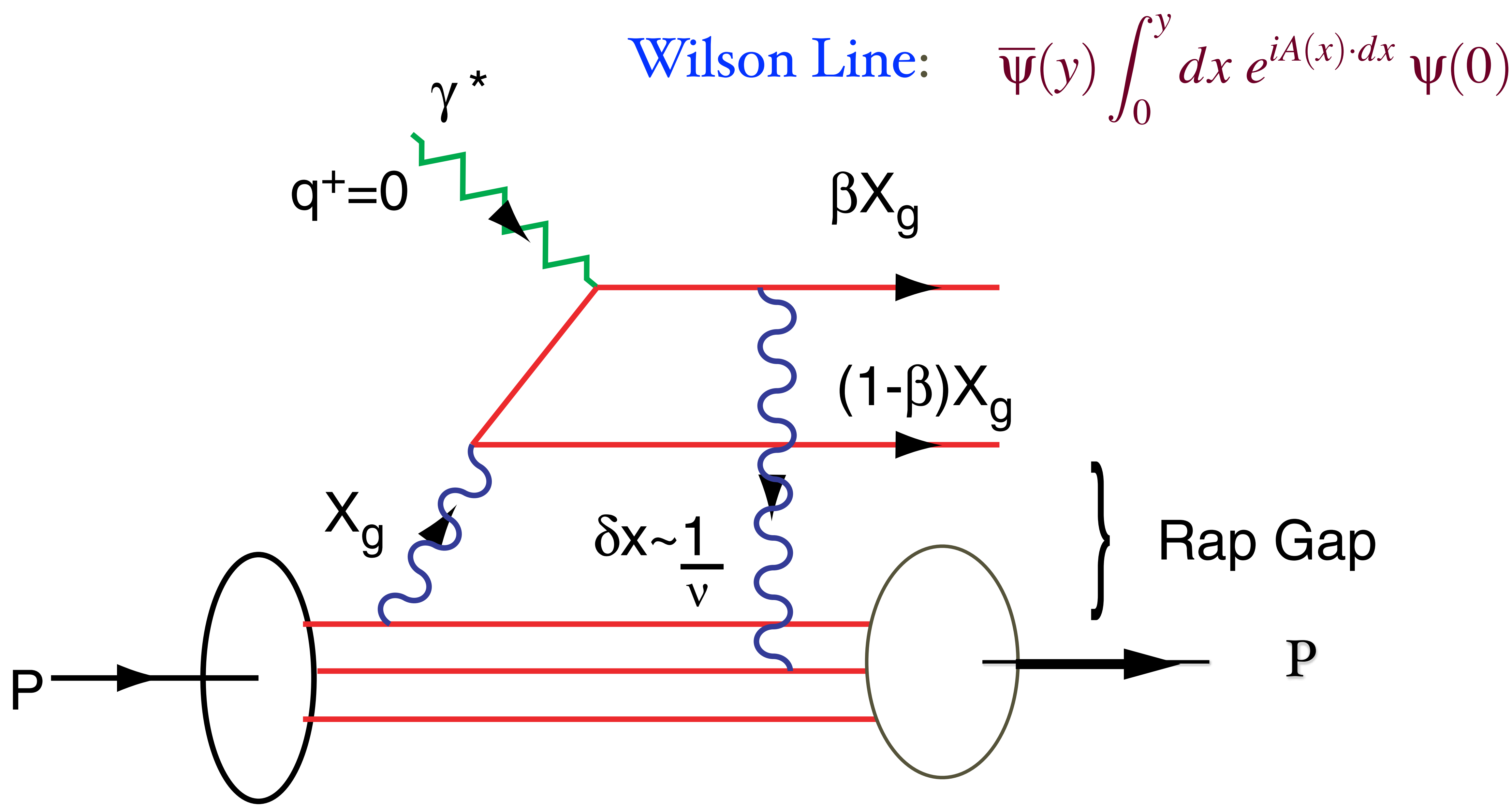


Fraction r of events with a large rapidity gap, $\eta_{\max} < 1.5$, as a function of Q^2_{DA} for two ranges of x_{DA}. No acceptance corrections have been applied.

10% to 15% of DIS events are diffractive !

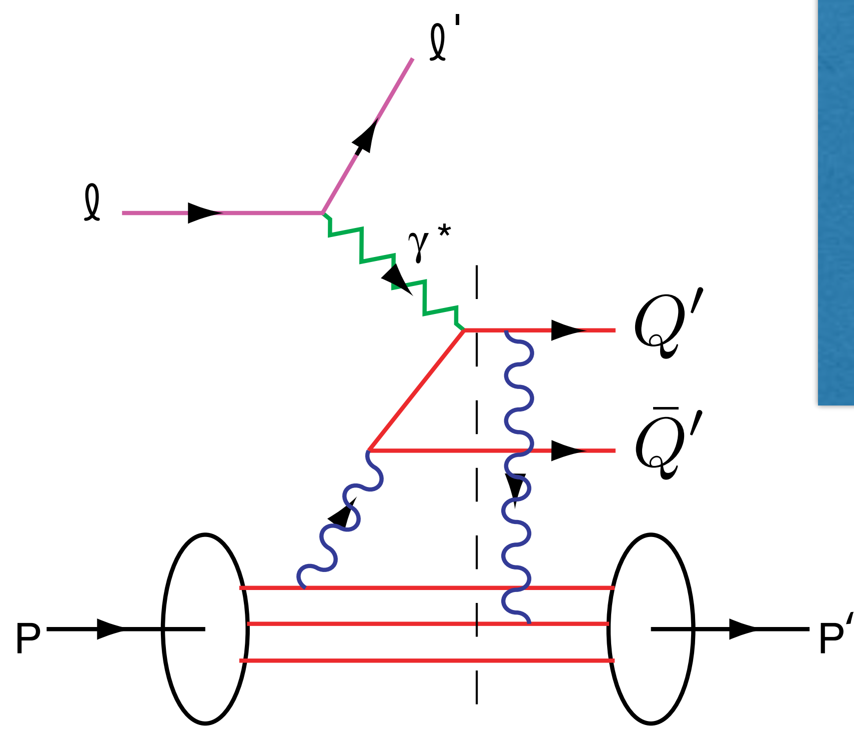
M. Derrick et al. [ZEUS Collaboration], Phys. Lett. B 315, 481 (1993)

QCD Mechanism for Rapidity Gaps



Reproduces lab-frame color dipole approach

DDIS: Input for leading twist nuclear shadowing



DDIS: Diffractive Deep Inelastic Scattering

90% of proton momentum carried off by final state p' in 15% of events!

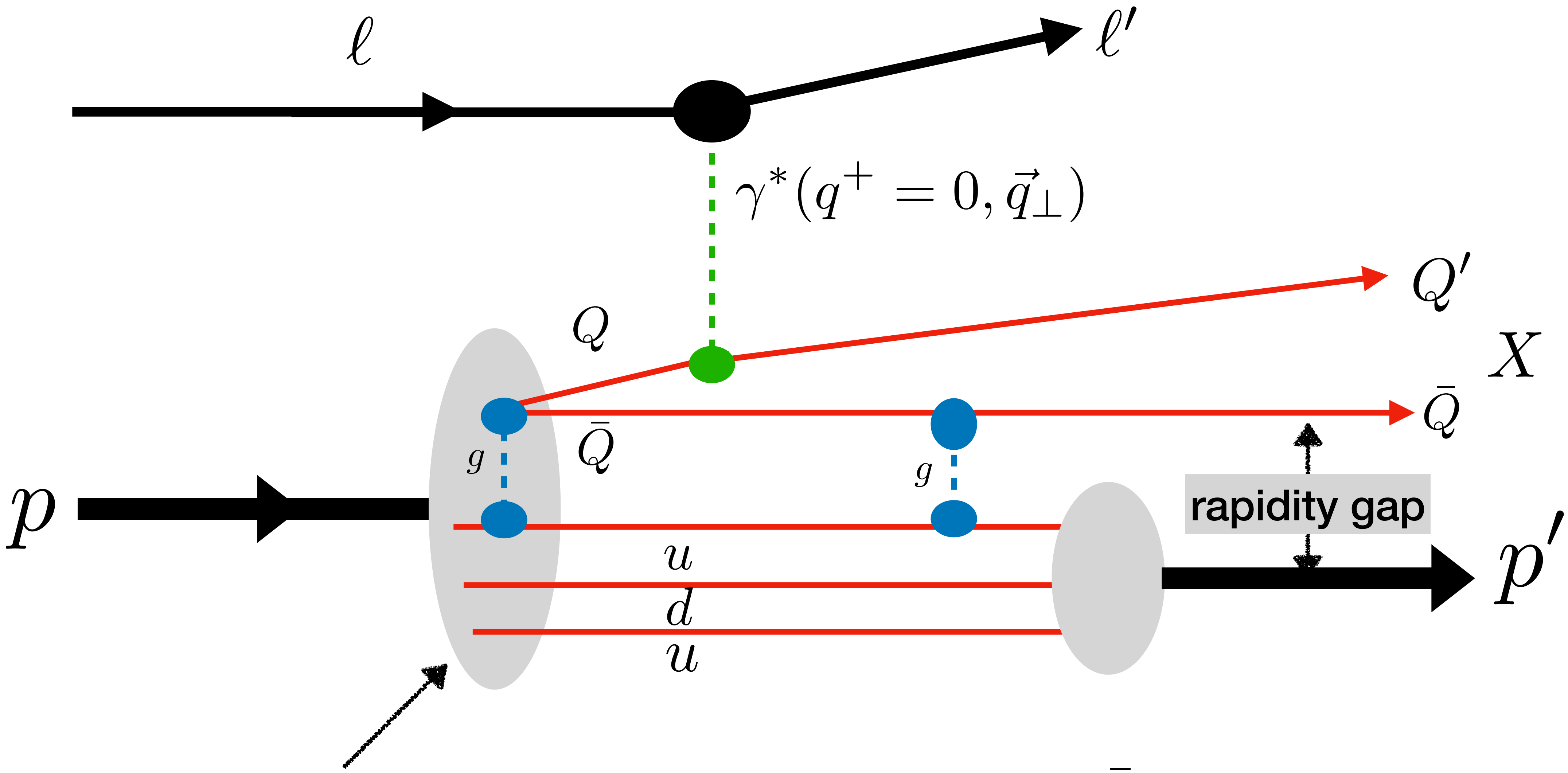
Gluon momentum fraction misidentified!

p' is measured in DDIS but escapes detectation in DIS events

Simplified Description of DDIS from two-gluon Pomeron exchange in the LF framework

Five-quark Fock State + final-state interaction produces rapidity gap

Diffractive DIS Event: $\gamma^* + p_{|uduQ\bar{Q}>} \to p' + X + (rapgap)$

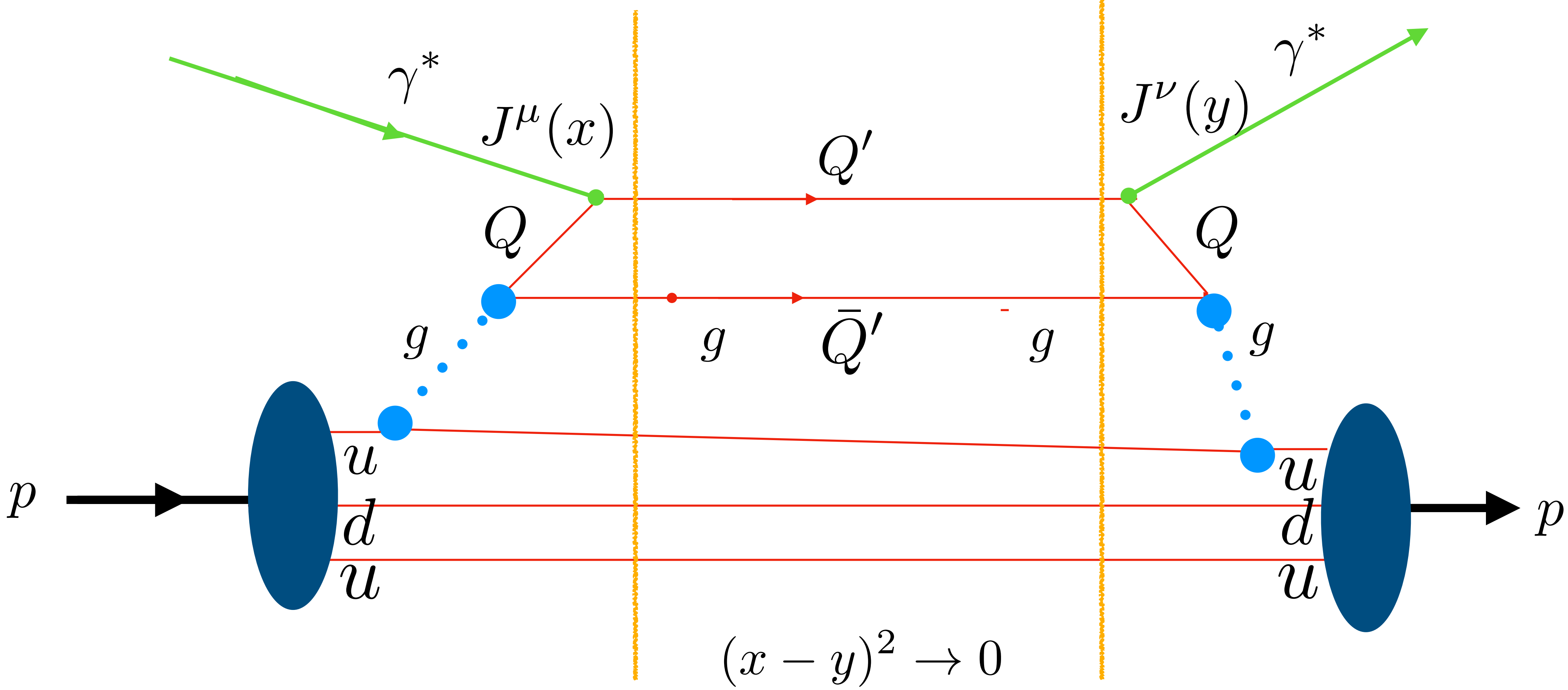


Five-quark Fock state of proton: $|\{udu\}_{8C}\{Q\bar{Q}\}_{8C} >$

Low-Nussinov Two-Gluon Model of Pomeron

Forward Virtual Compton scattering for a DIS event

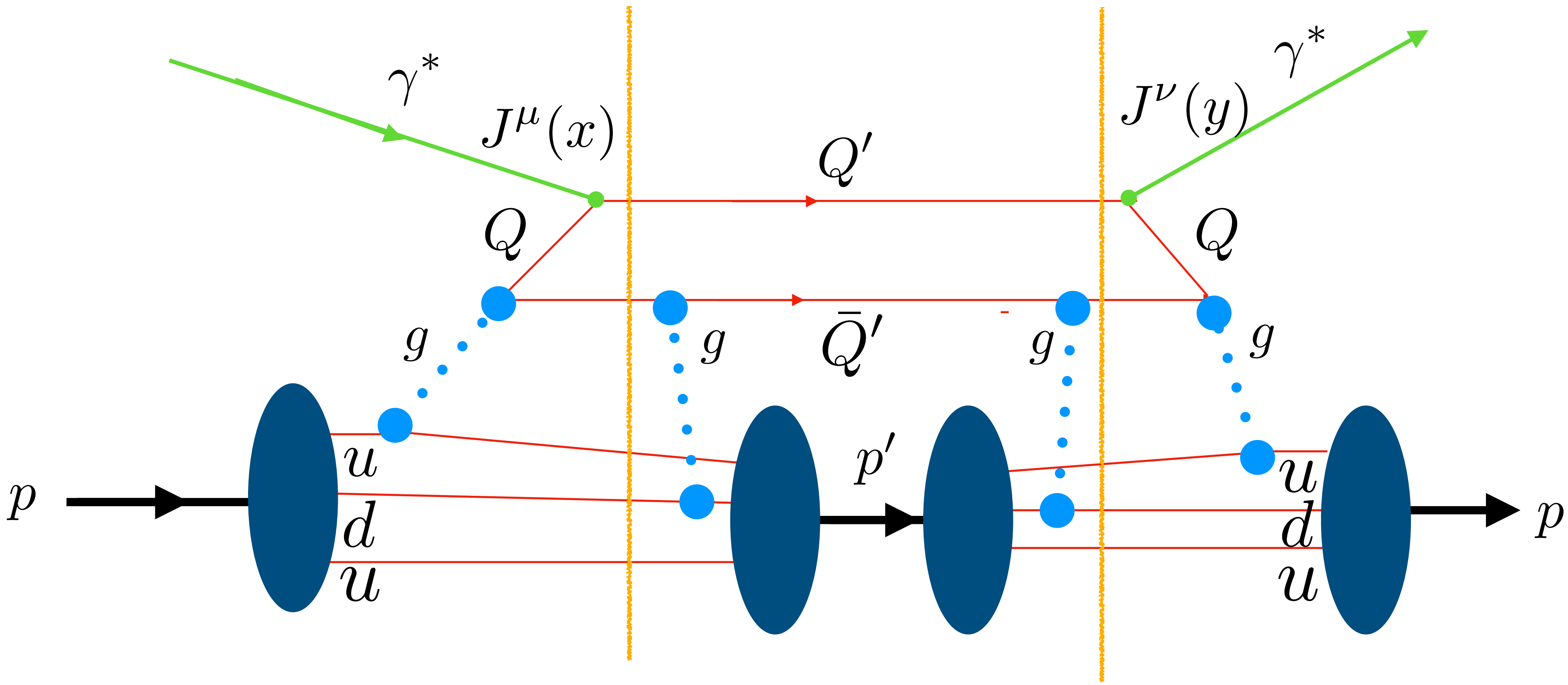
$$\gamma^* + p \to X \to \gamma^* + p$$



Vanishing LF time between currents of virtual photons at large q^2 : OPE!

Forward Virtual Compton scattering for a DDIS event

$$\gamma^* + p \to \{Q'\bar{Q}'\} + p' \to \gamma^* + p$$



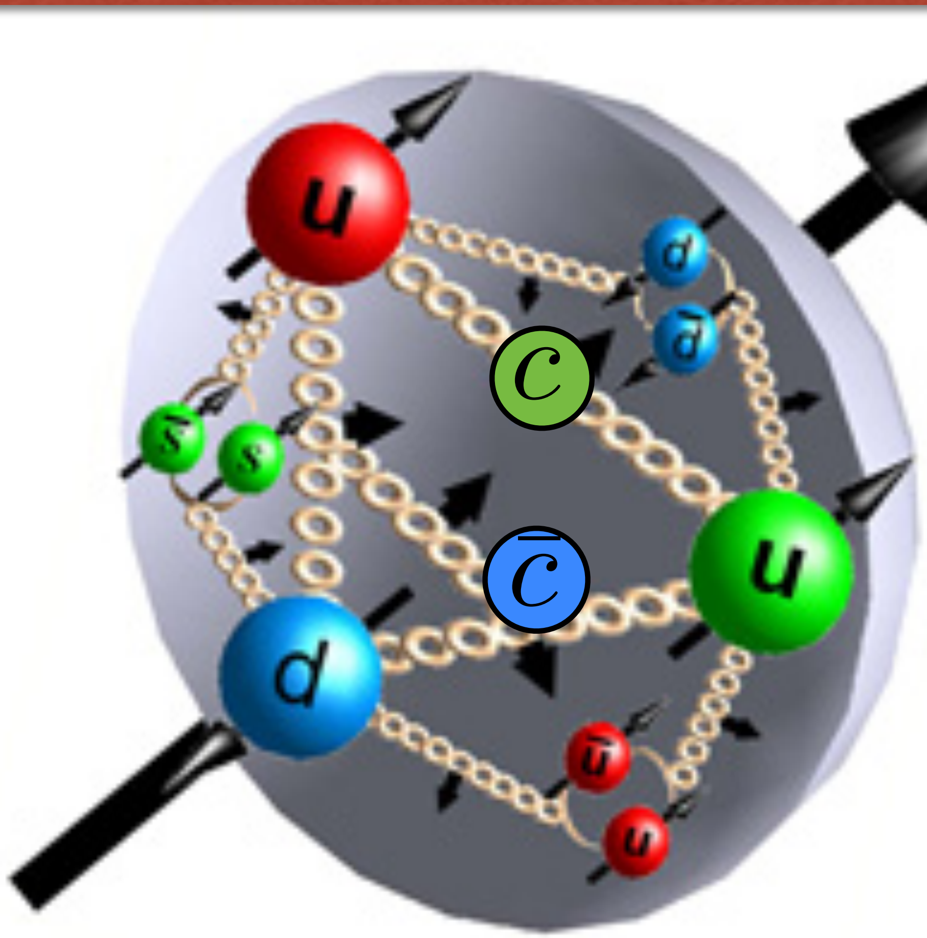
Nonzero LF propagation time between virtual photons: No OPE!

$$< p|J^\mu(x)|N >< N|J^\nu(y)|p >, (x-y)^2 \neq 0$$

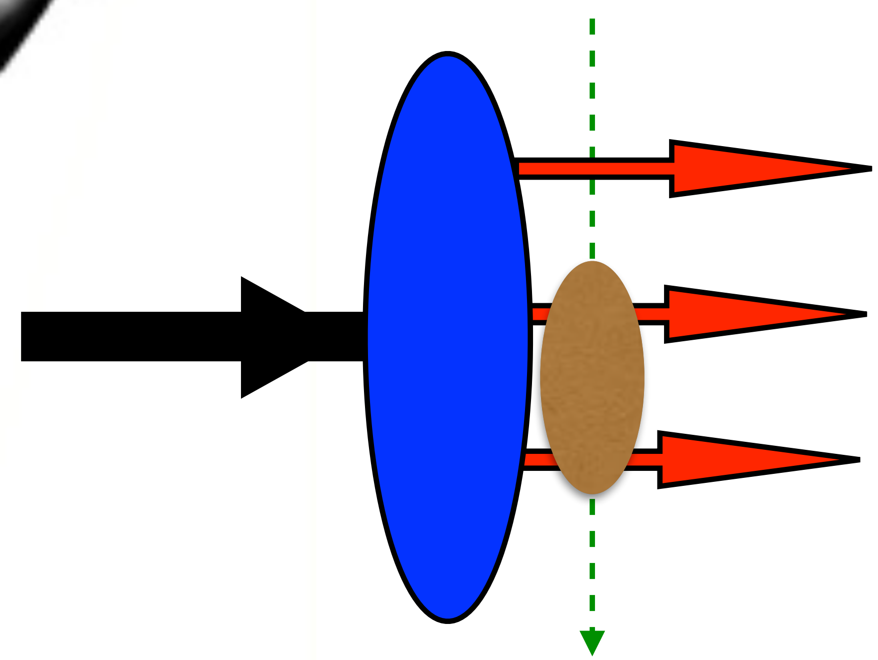
Cannot reduce to matrix element of local operator! No Sum Rules!

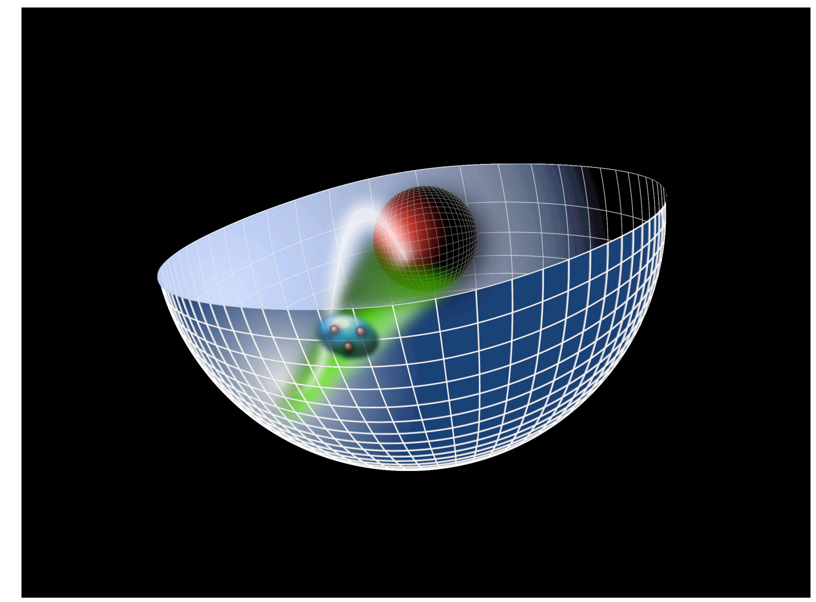
Liuti, Lubovitski, Schmidt, sjb

Color Confinement and Supersymmetric Features of Hadron Physics from Light-Front Holography and Novel Features of QCD from Light-Front Holography II



Fixed $\tau = t + z/c$





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

with Guy de Tèramond, Hans Günter Dosch, Alexandre Deur, Marina Nielsen, Ivan Schmidt, F. Navarra, Jennifer Rittenhouse West, G. Miller, Keh-Fei Liu, Tianbo LIu, Liping Zou, S. Groote, Joshua Erlich, S. Koshkarev, Xing-Gang Wu, Sheng-Quan Wang, Cedric Lorcè, R. S. Sufian, R. Vogt, G. Lykasov, S. Gardner, S. Liuti, V. Lyubovitskij, L. di Giustino

Bled Workshop

What Comes Beyond the Standard Models?

Stan Brodsky

SLAC NATIONAL ACCELERATOR LABORATORY

Talk II July 8, 2021