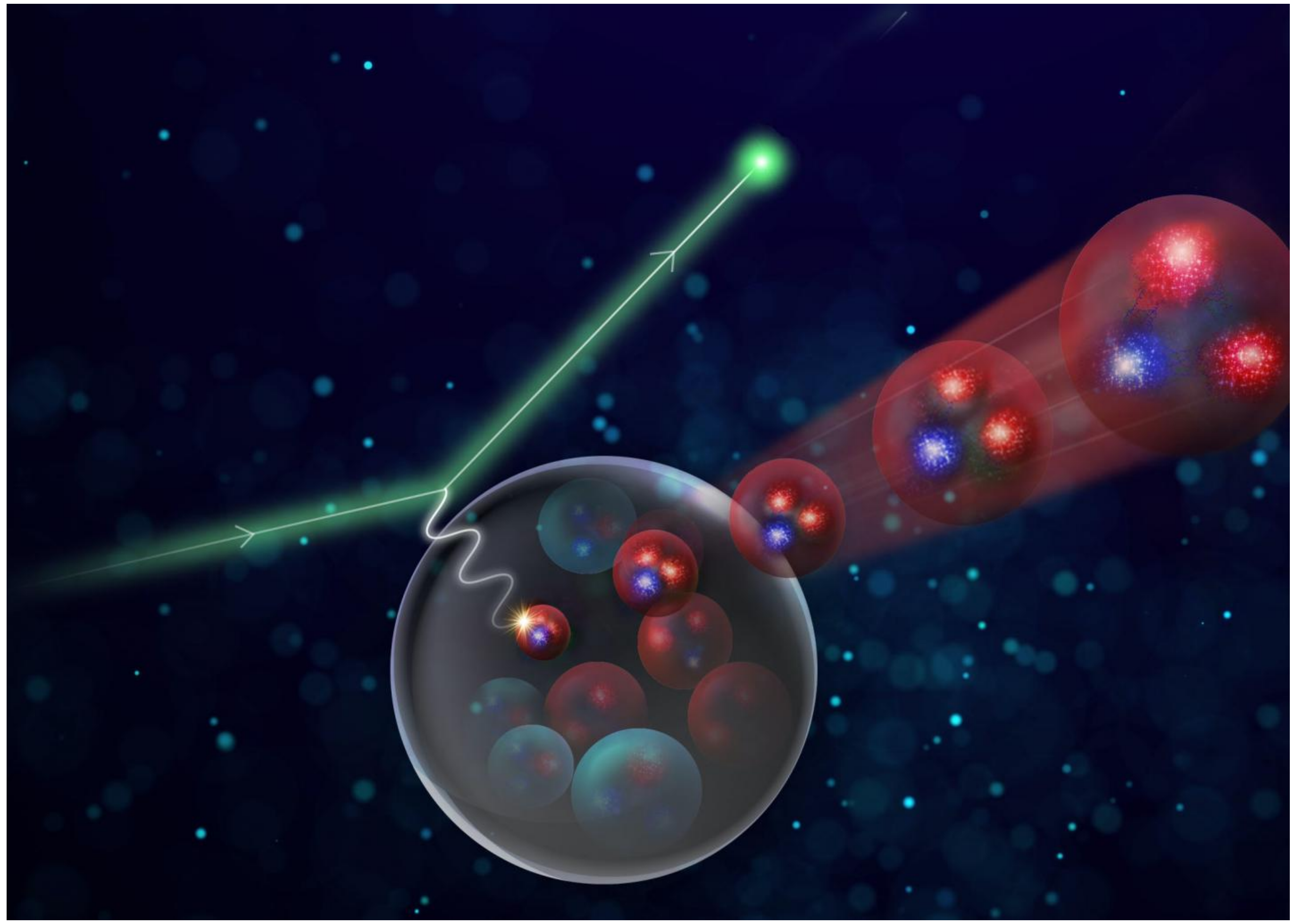
# The Onset of Color Transparency in Holographic Light-Front QCD



with Guy F. de Téramond

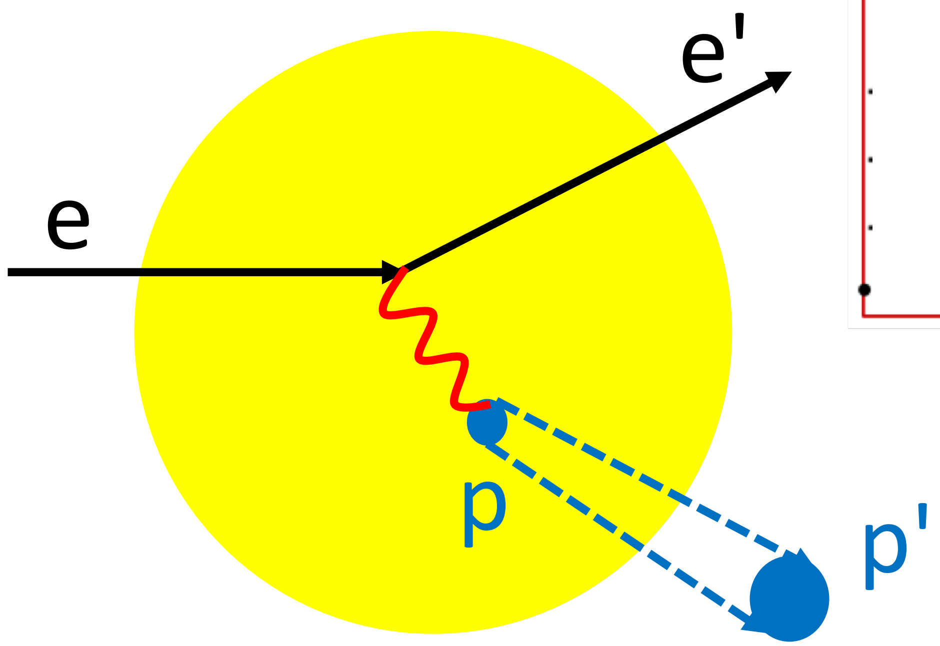
Future of Color Transparency and Hadronization Studies at JLab and Beyond

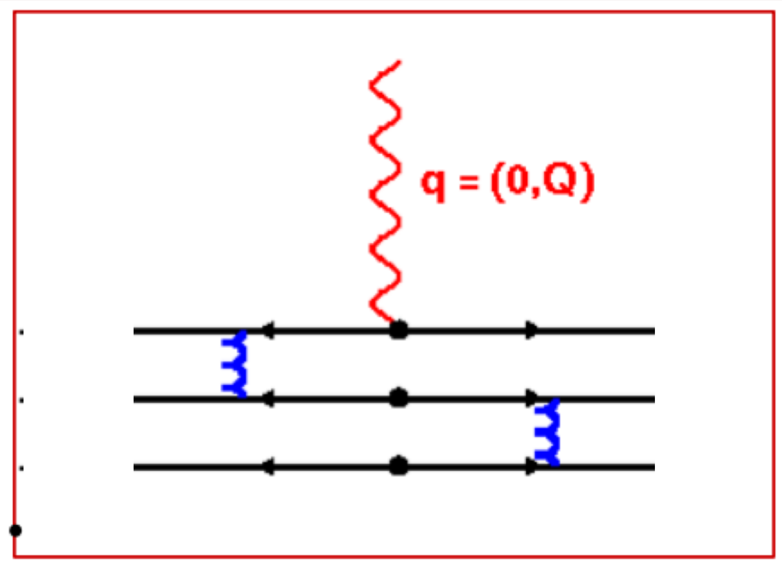

Stan Brodsky

SLAC NATIONAL ACCELERATOR LABORATORY


June 7, 2021

# Color transparency fundamental prediction of QCD




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

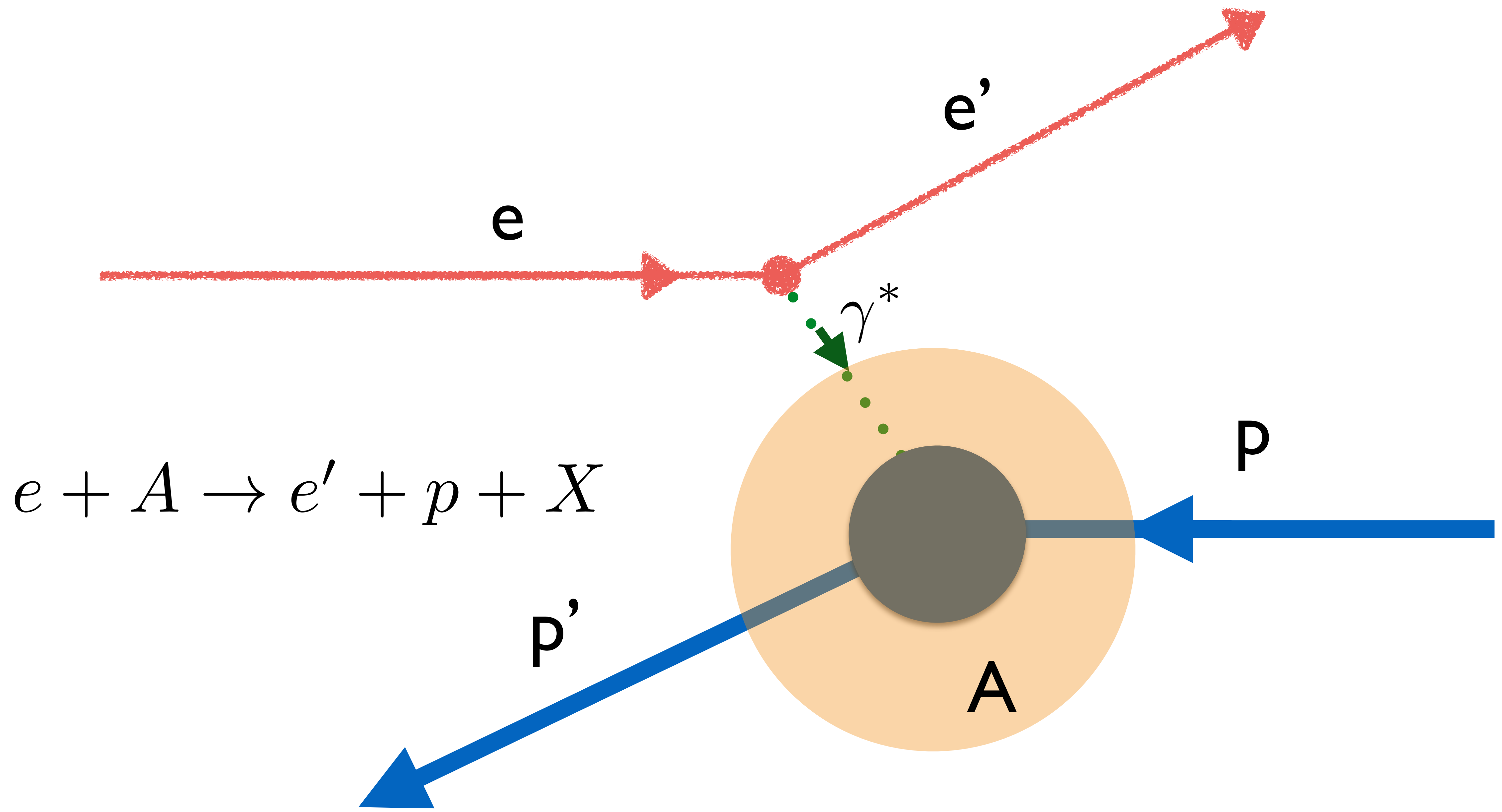
- Introduced by Mueller and Brodsky, 1982
- Vanishing of initial/final state interaction of hadrons with nuclear medium in exclusive processes at high momentum transfer

- 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

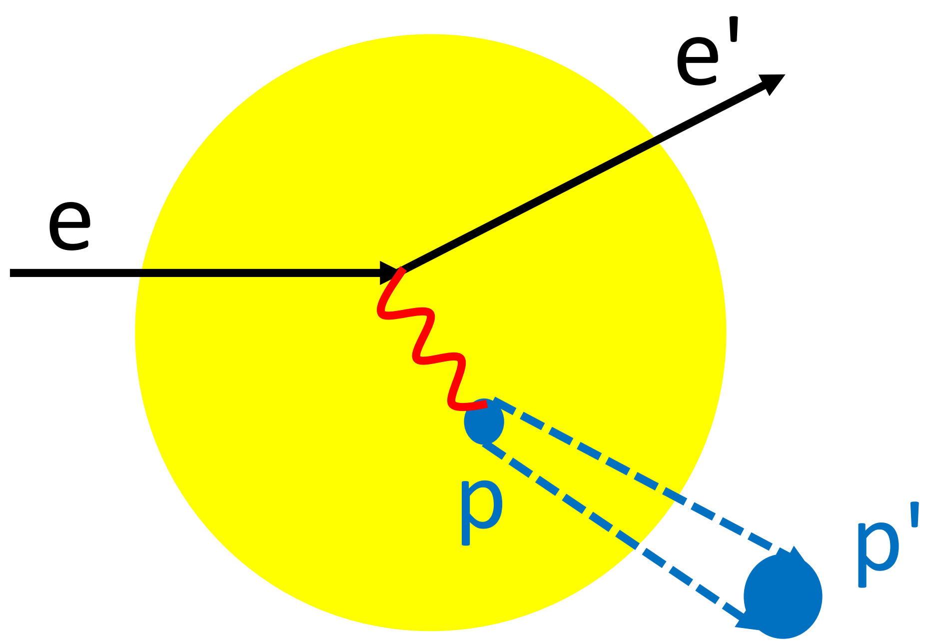
$$\boxed{\sigma(e + A \to e' + p + X) \to Z\frac{d\sigma}{dt}(ep \to e'p')}$$ at high $Q^2$



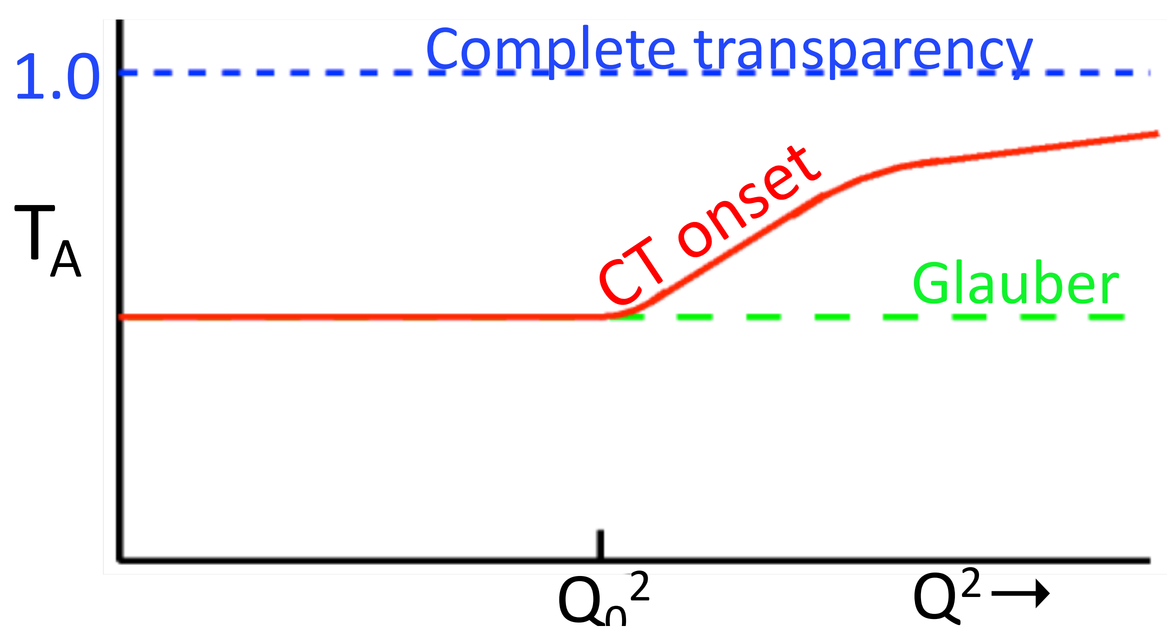

- **QCD: Gauge theory properties and quantum coherence**
- **Small-size color dipole moment interacts weakly in nuclei**

# Color transparency fundamental prediction of QCD

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




- 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, $Q^2$




$$T_A = \frac{\sigma_A}{A\,\sigma_N}$$

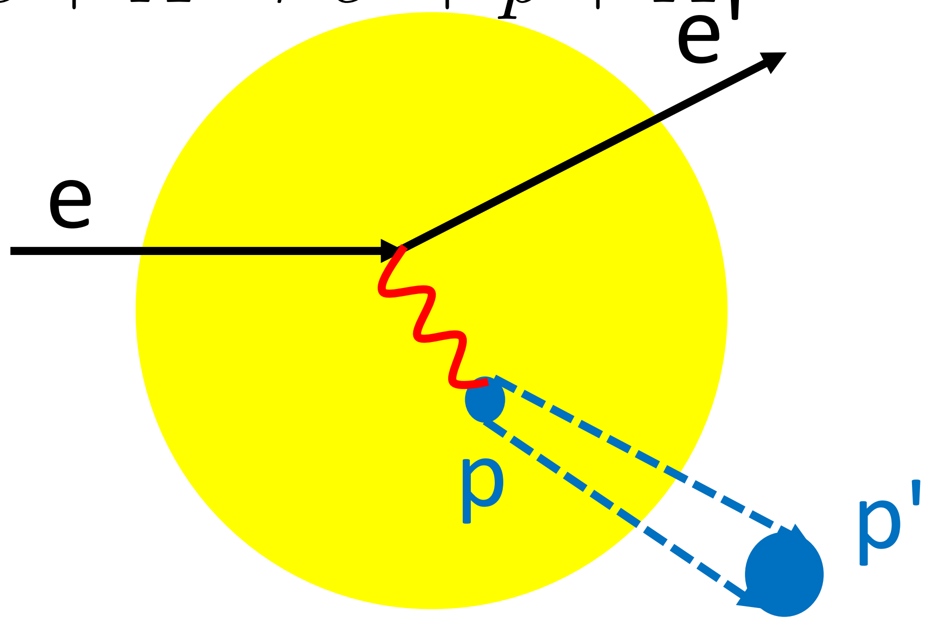
$\sigma_A$ (nuclear cross section)

$\sigma_N$ (free nucleon cross section)

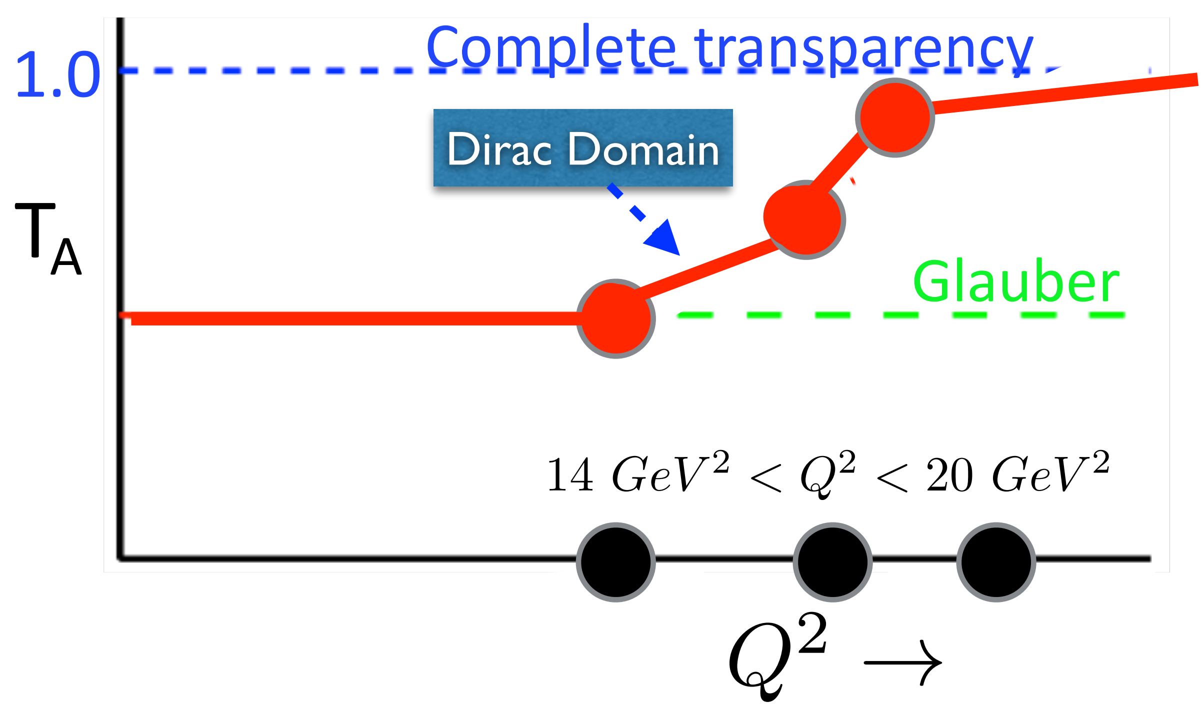
Holly Suzmila-Vance

# 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, $Q^2$




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

Holly Suzmila-Vance

Two-Stage Color Transparency for Proton

# Color Transparency

Mueller, sjb

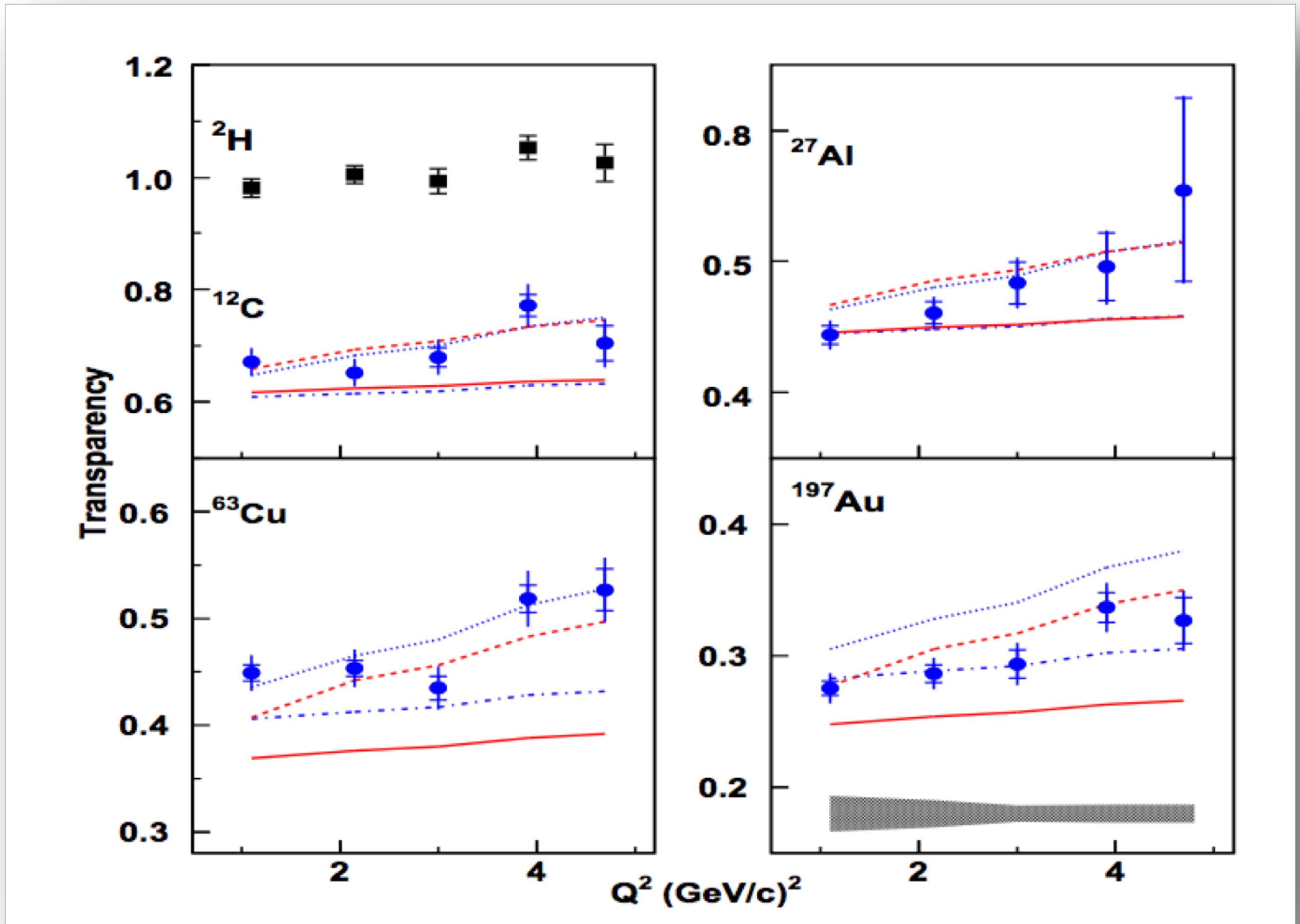
Bertsch, Gunion, Goldhaber, sjb

$$\frac{d\sigma}{dt}(eA \to ep(A-1)) = Z\frac{d\sigma}{dt}(ep \to ep)$$ 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'$\pi^+$)

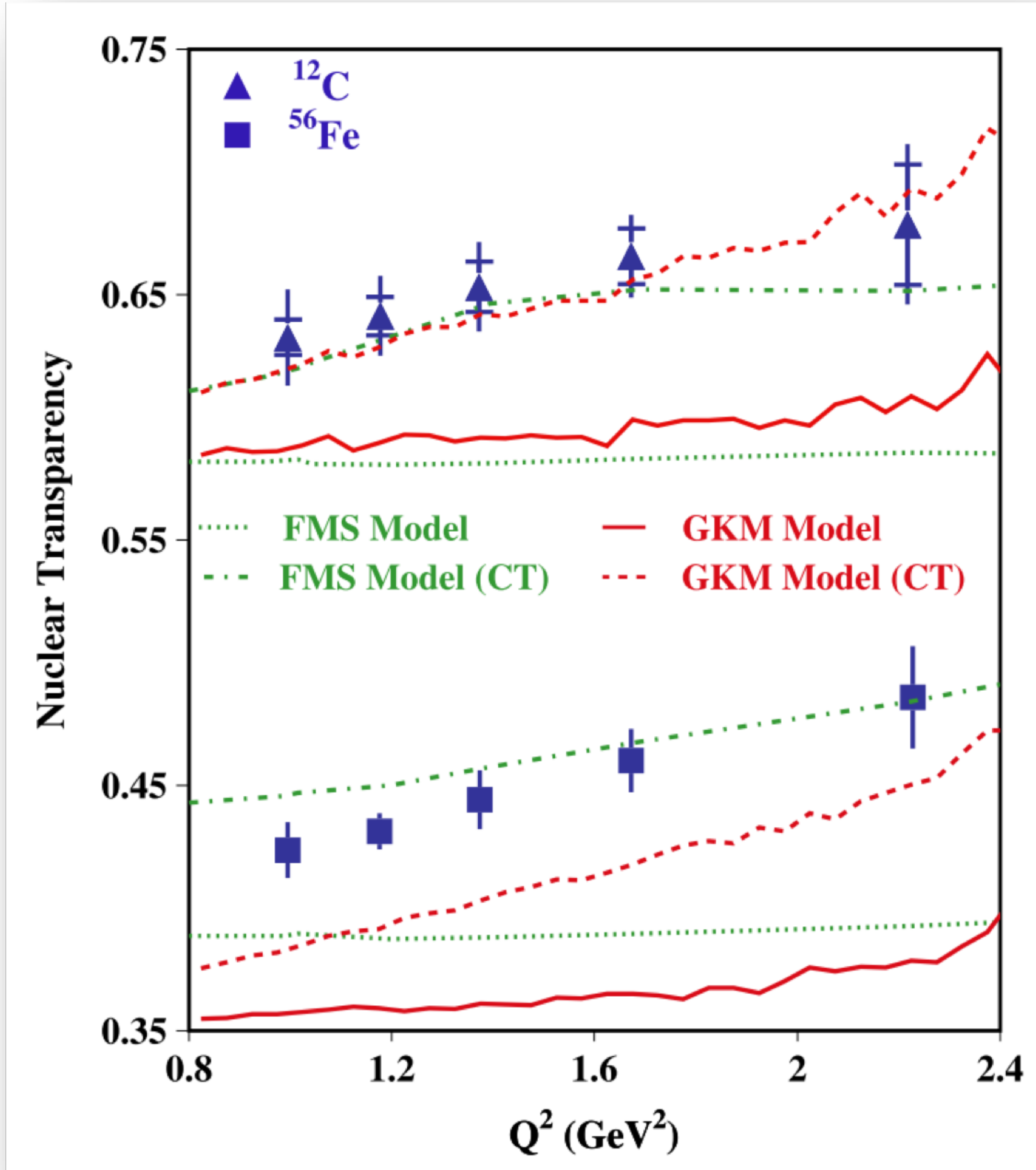



B.Clasie *et al.* PRL 99:242502 (2007)

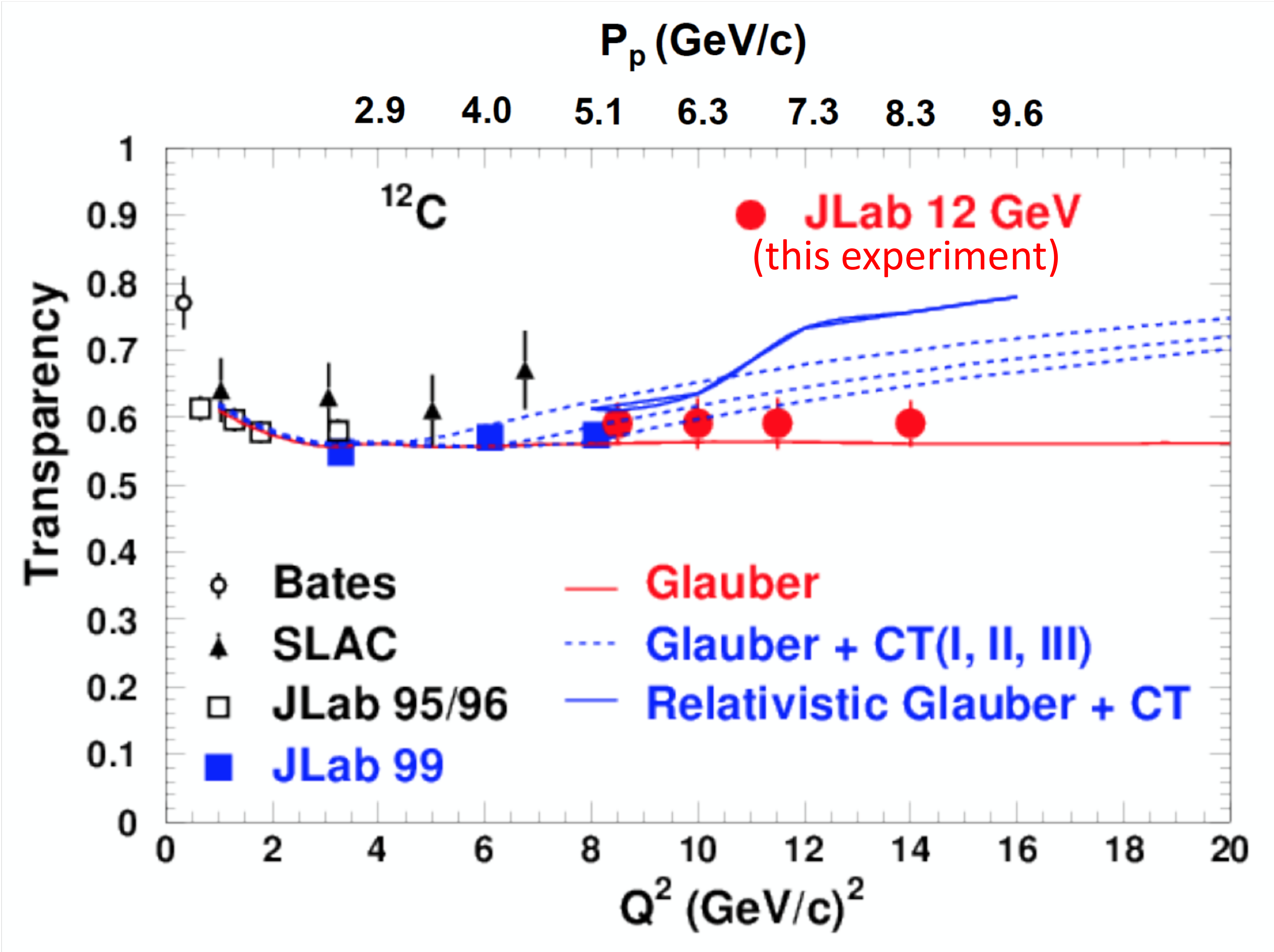
X. Qian *et al.* PRC81:055209 (2010)

CLAS E02-110 rho electro-production

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




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



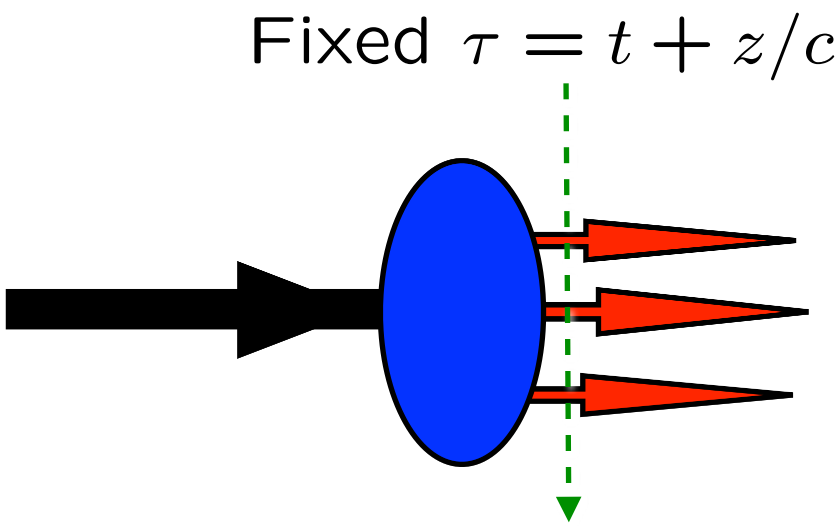

**Ruling out color transparency in quasi-elastic $^{12}$C(e,e$'$p) up to $Q^2$ of 14.2 (GeV/c)$^2$**

Hall C Collaboration

## 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 $P^\mu$***

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

**Direct connection to QCD Lagrangian**

## *LF Wavefunction: off-shell in invariant mass*

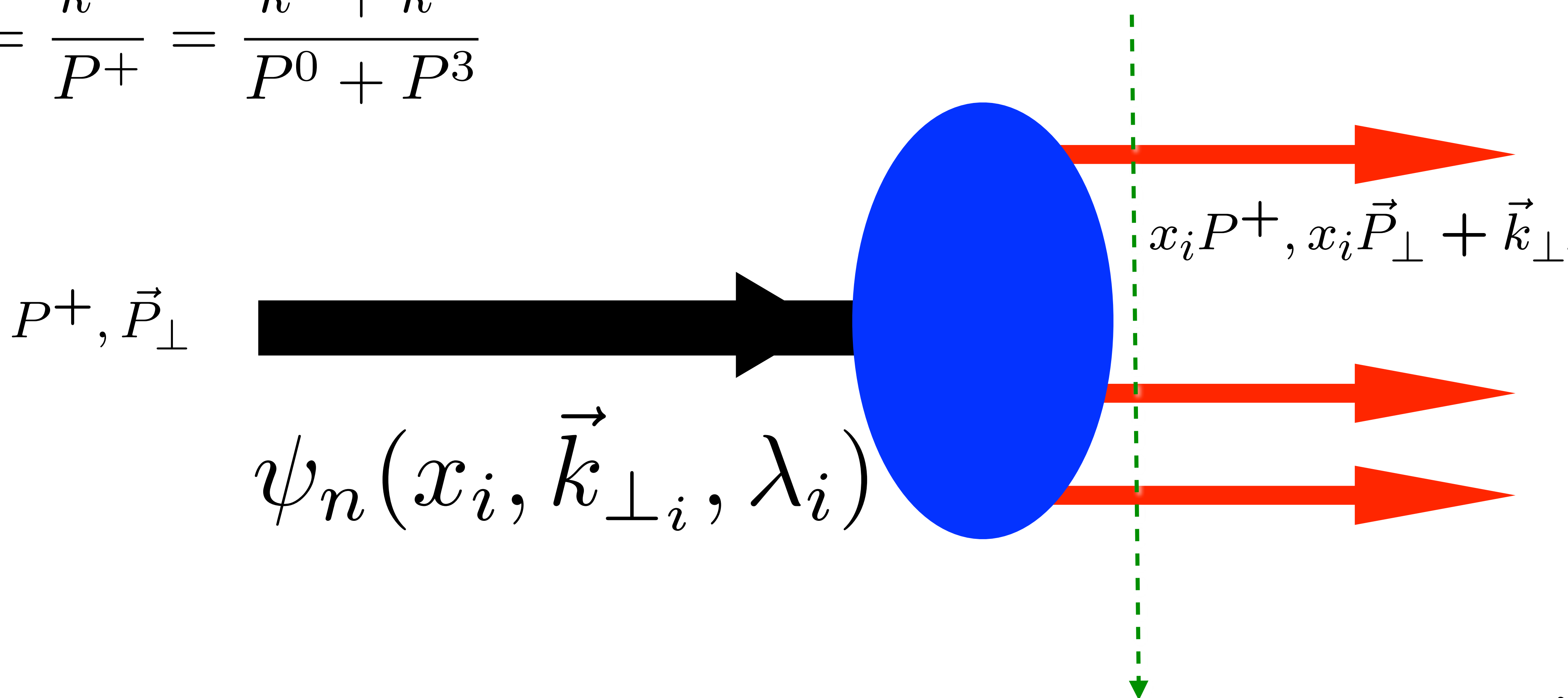
*Remarkable new insights from AdS/CFT, the duality between conformal field theory and Anti-de Sitter Space*

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

*Eigenstate of LF Hamiltonian*

Fixed $\tau = t + z/c$

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




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

$\sum_i^n x_i = 1$

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

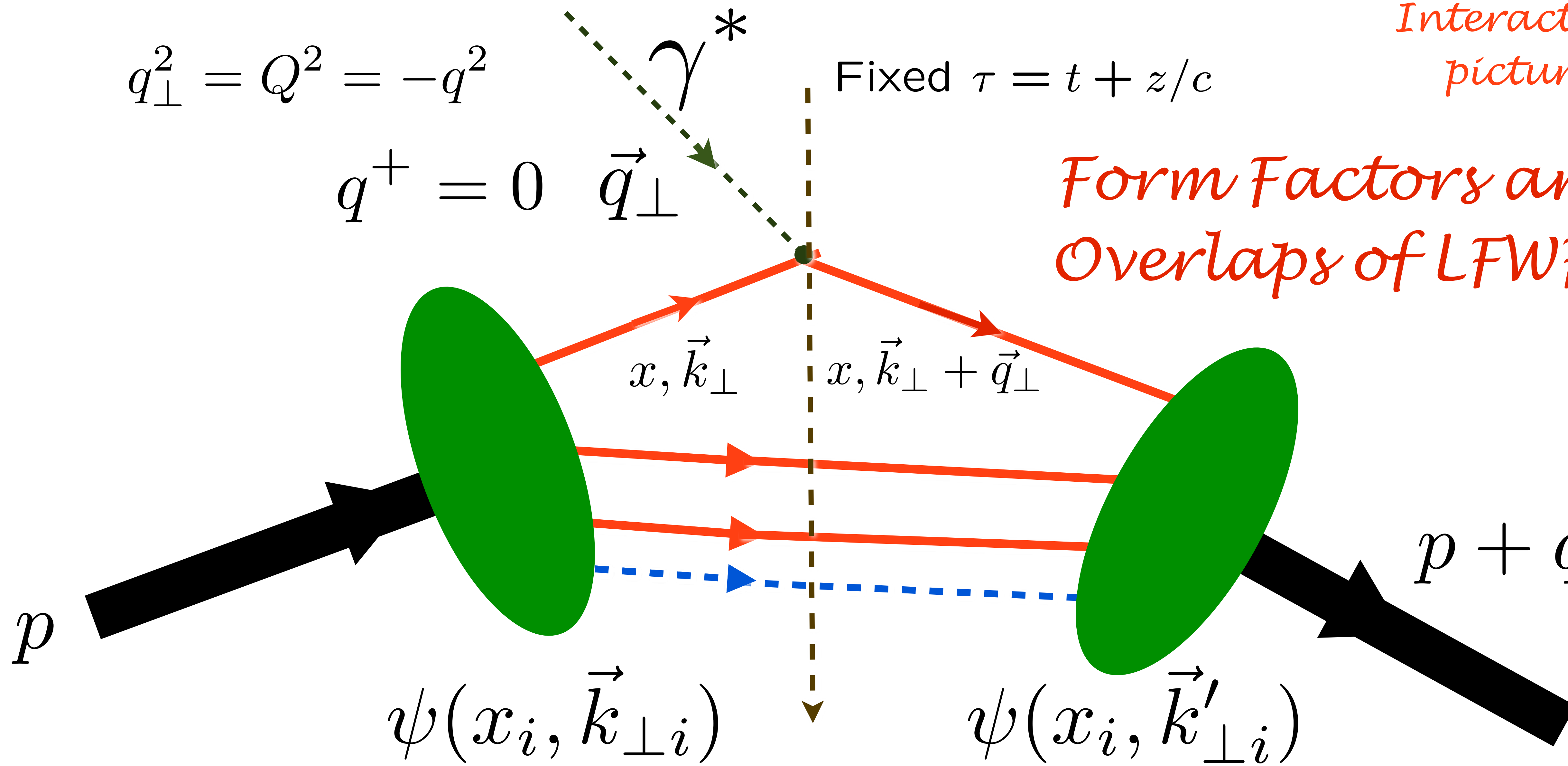
*Invariant under boosts! Independent of $P^\mu$*

***Causal, Frame-independent. Creation Operators on Simple Vacuum, Current Matrix Elements are Overlaps of LFWFS***

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

**Front Form**

*Interaction picture*



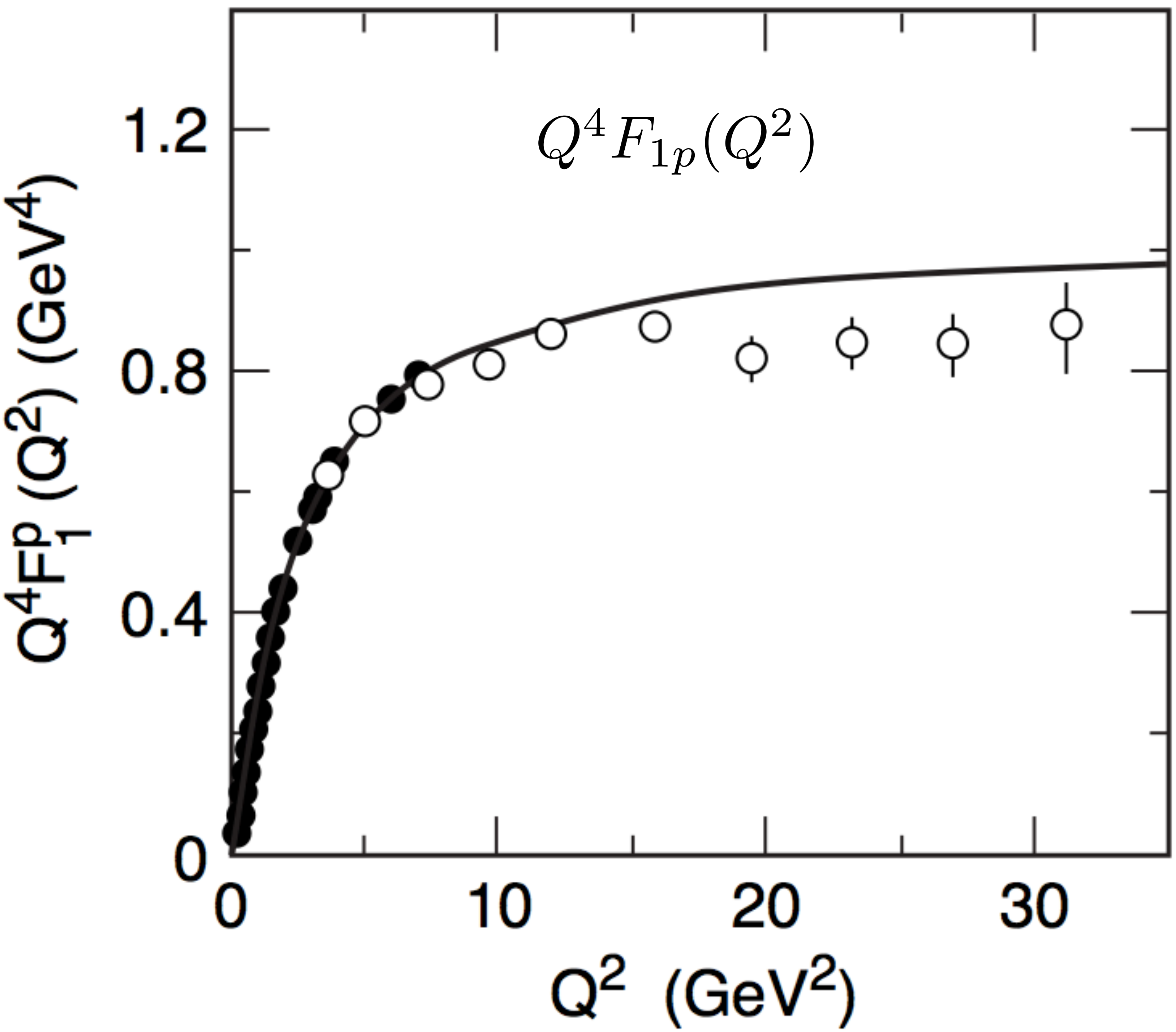

*Form Factors are Overlaps of LFWFs*

*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!**

G. de T`eramond, sjb




*Light-Front Holography Prediction*

# Exact LF Formula for Pauli Form Factor

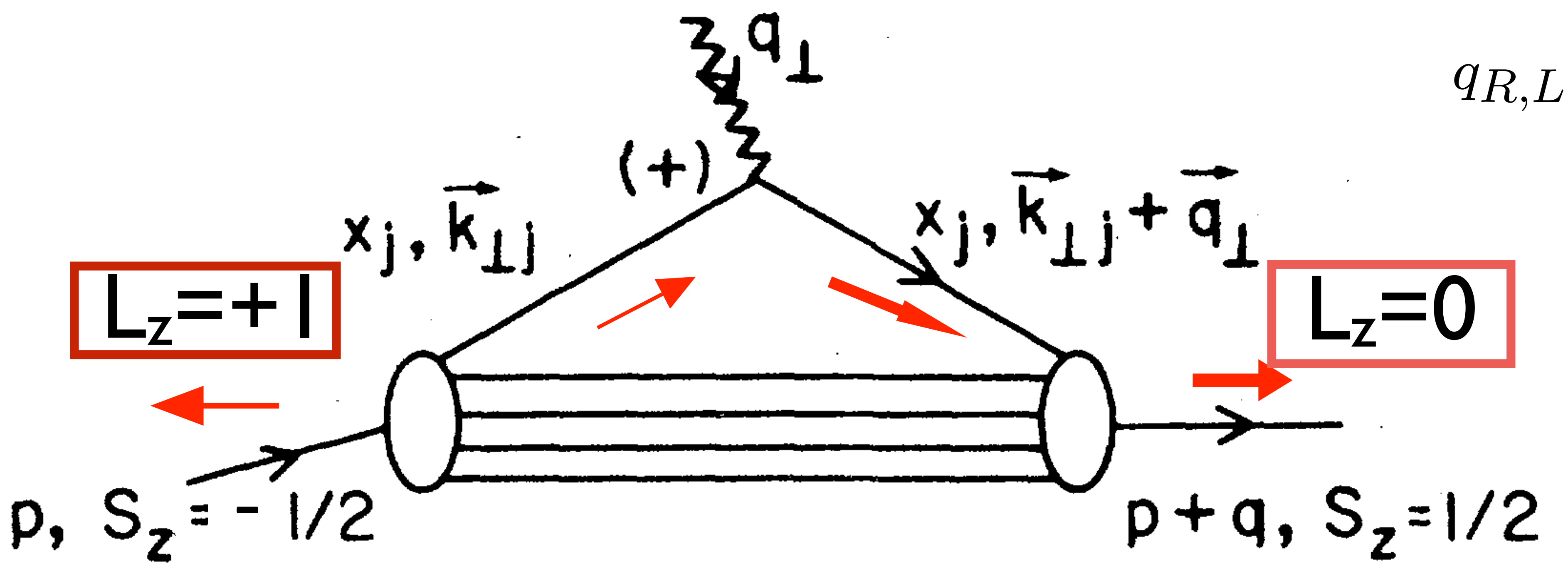
$$\frac{F_2(q^2)}{2M} = \sum_a \int [\mathrm{d}x][\mathrm{d}^2\mathbf{k}_\perp] \sum_j e_j \, \frac{1}{2} \, \times$$

Drell, sjb

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

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

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

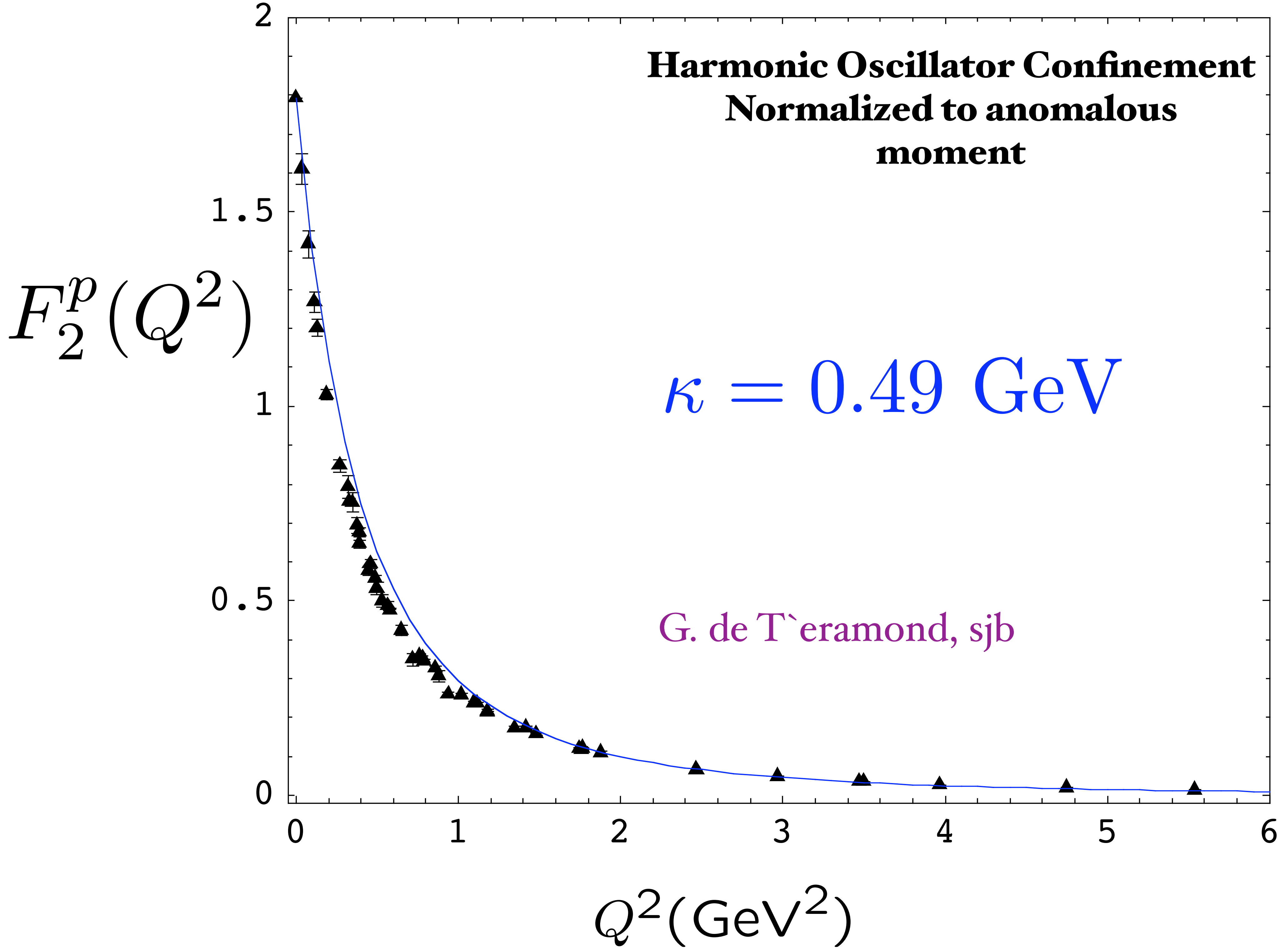



Must have $\Delta \ell_z = \pm 1$ to have nonzero $F_2(q^2)$

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

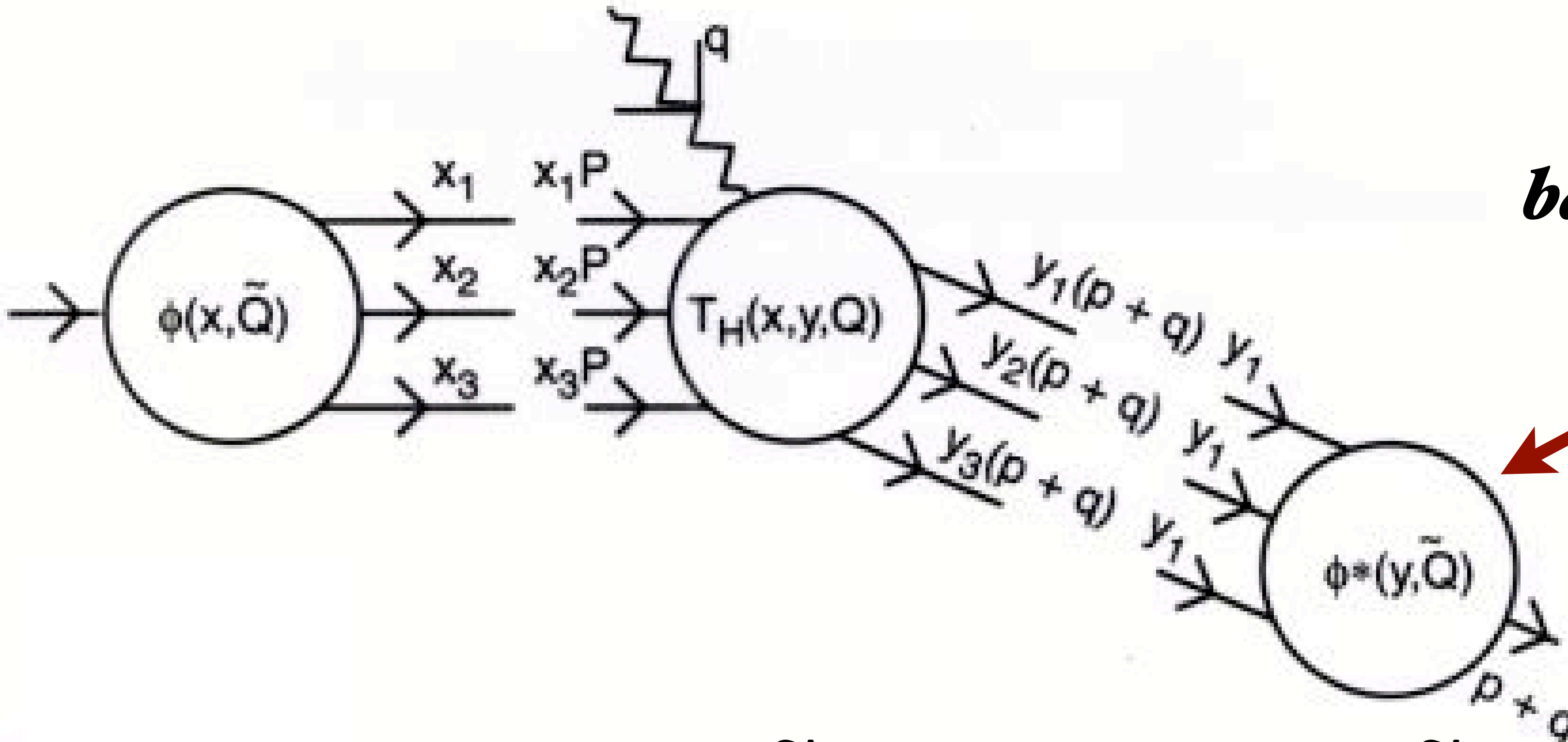
# Spacelike Pauli Form Factor

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



# Leading-Twist PQCD Factorization for form factors, exclusive amplitudes

**Lepage, sjb**



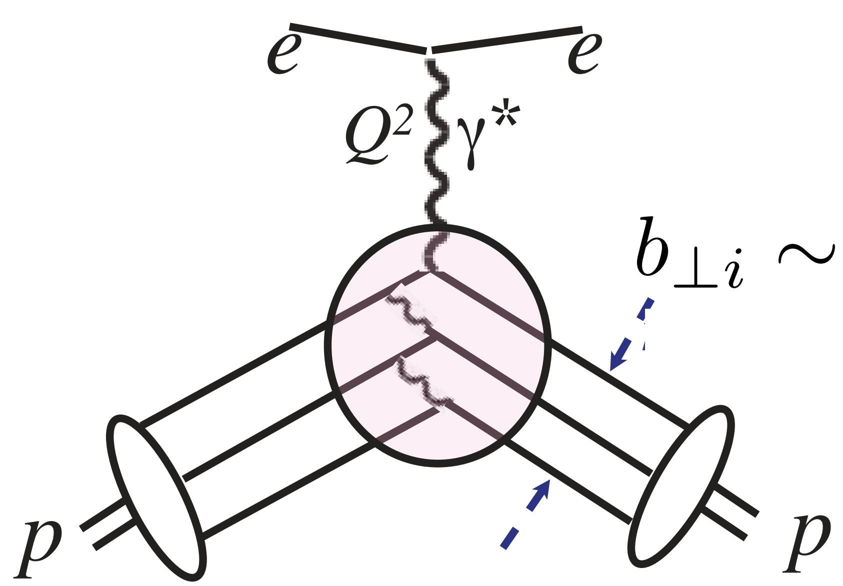

***baryon distribution amplitude***

*ERBL Evolution*

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

Exclusive

*Scaling Laws*
*Counting Rules*



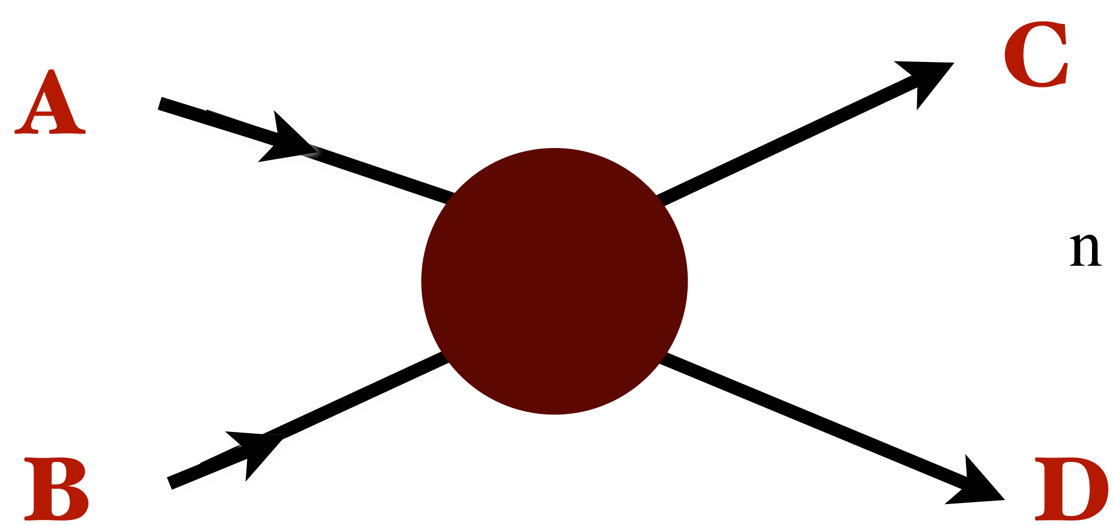

$b_{\perp i} \sim \frac{1}{x_i Q}$

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

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

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

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

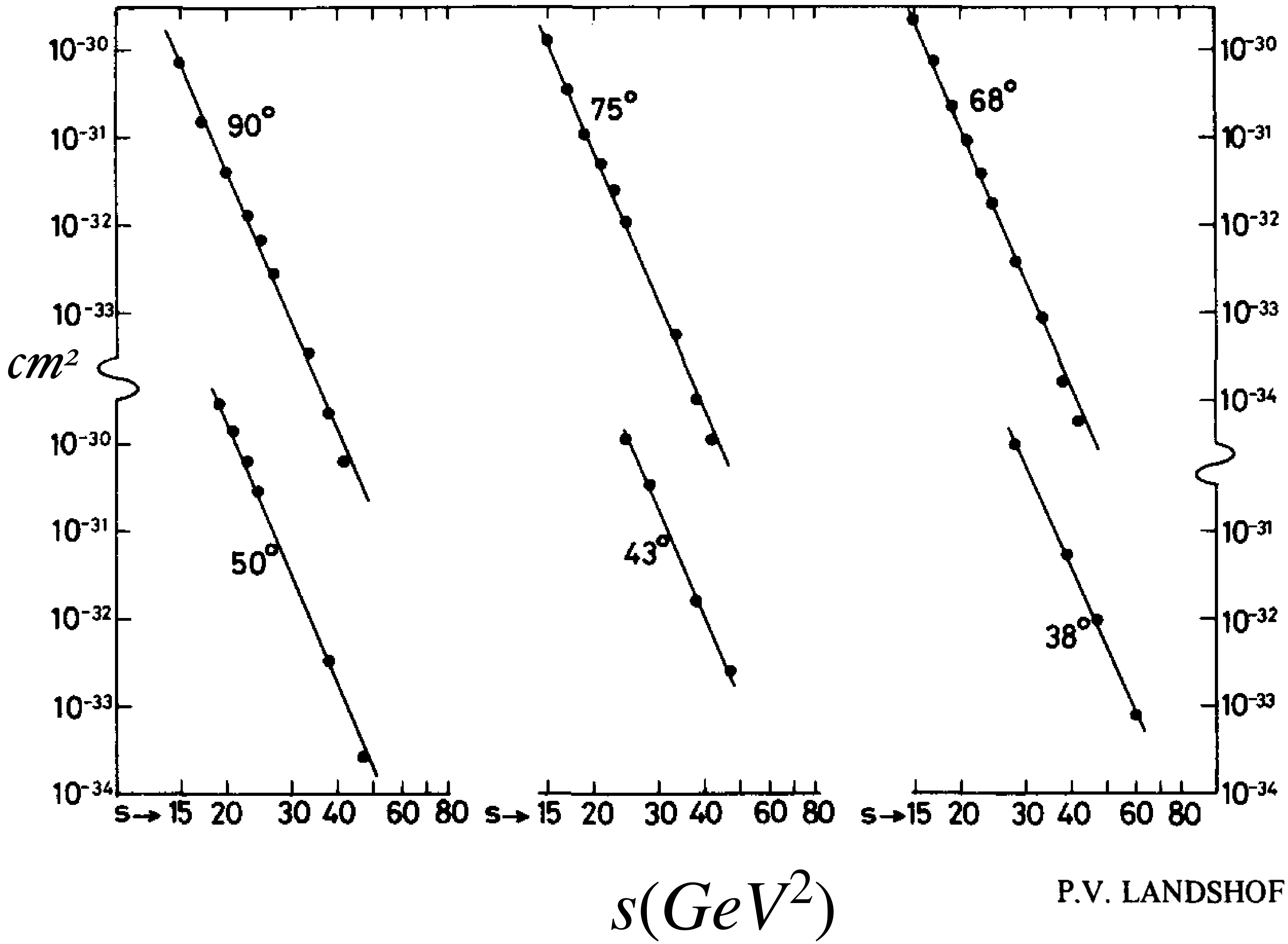



n = twist τ = dimension - spin

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



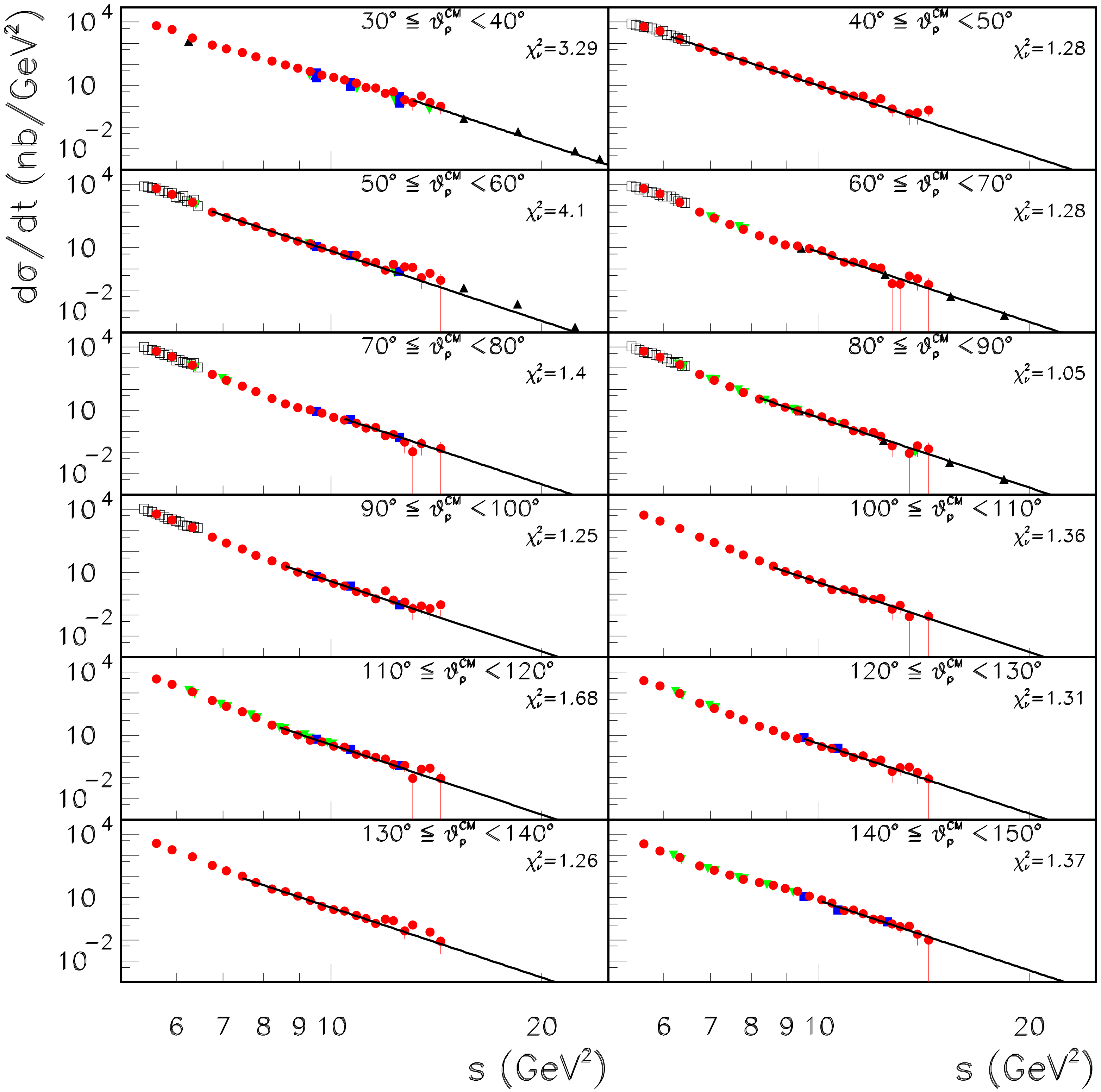

Best Fit

$n = 9.7 \pm 0.5$

Reflects underlying conformal, scale-free interactions

P.V. LANDSHOFF and J.C. POLKINGHORNE

# Deuteron Photodisintegration & Dimensional Counting Rules




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

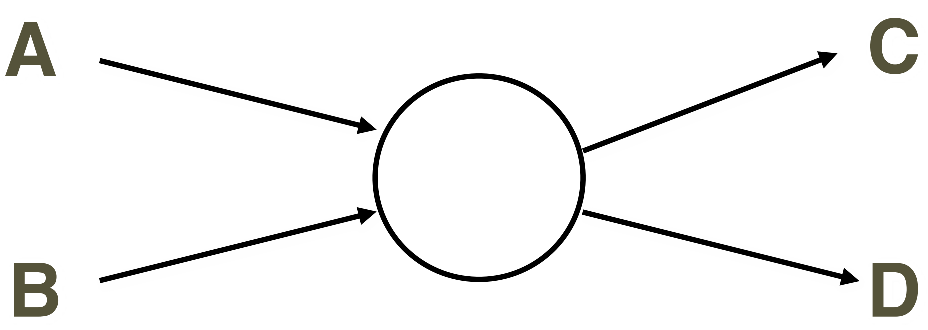
$$s^{11}\frac{d\sigma}{dt}(\gamma d\to np)=F(\theta_{CM})$$

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

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

## 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:

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

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

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

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

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

Exclusive-Inclusive Connection
Gribov-Lipatov crossing

Counting Rules: Asymptotic Freedom and Underlying Conformal Symmetry of QCD

# 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*

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

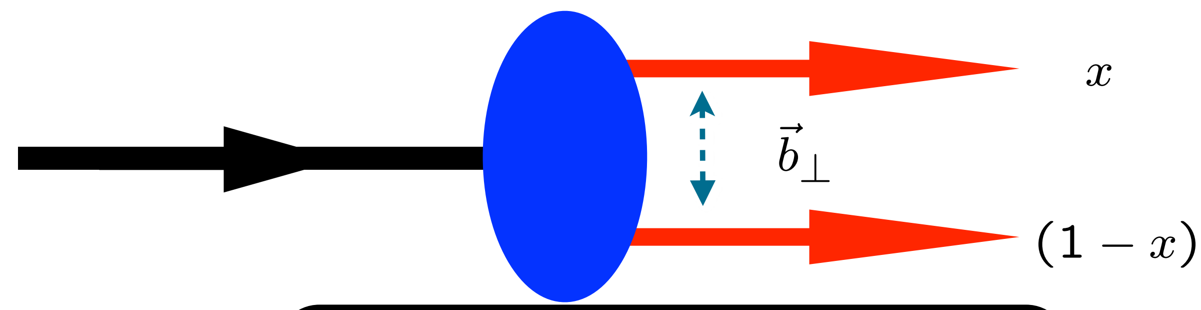
- *QCD Coupling at all Scales* $\alpha_s(Q^2)$
- *Eliminate Scale Uncertainties and Scheme Dependence*

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

# Light-Front QCD

Fixed $\tau = t + z/c$

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




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

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

*Coupled Fock states*

*Eliminate higher Fock states and retarded interactions*

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

*Effective two-particle equation*

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

*Azimuthal Basis* $\zeta, \phi$

**Single variable Equation**

$m_q = 0$

**AdS/QCD:**

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

*Confining AdS/QCD potential!*

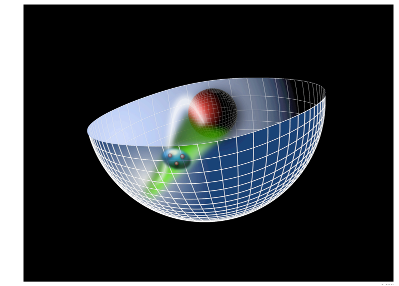
*Semiclassical first approximation to QCD*

***Sums an infinite # diagrams***

Maldacena

# 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***

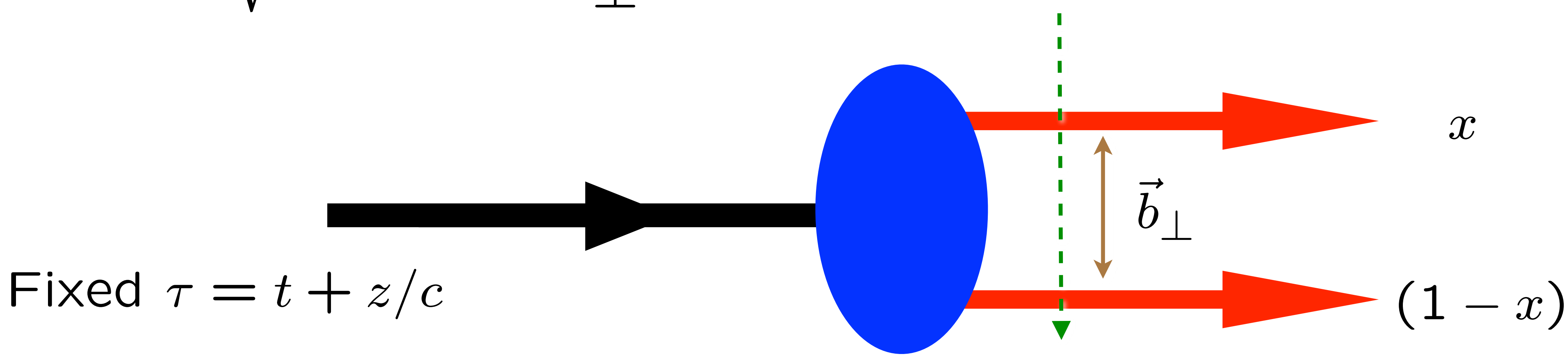
de Teramond, sjb

LF(3+1) $\longleftrightarrow$ AdS$_5$

# *Light-Front Holographic Dictionary*

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

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



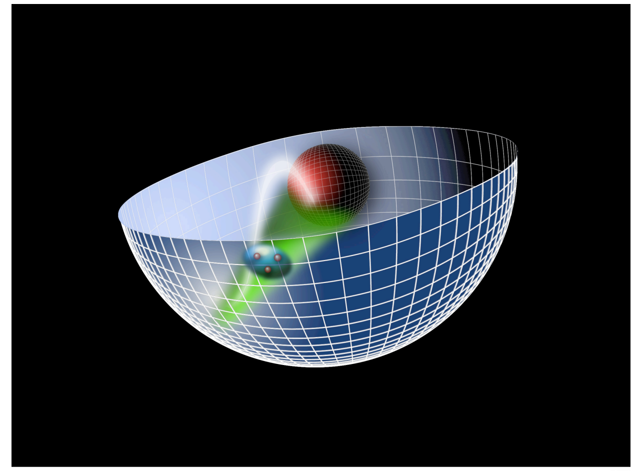

$$\psi(x, \zeta) = \sqrt{x(1-x)}\zeta^{-1/2}\phi(\zeta)$$

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

***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

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



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

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 $\zeta$

***Unique Confinement Potential!***

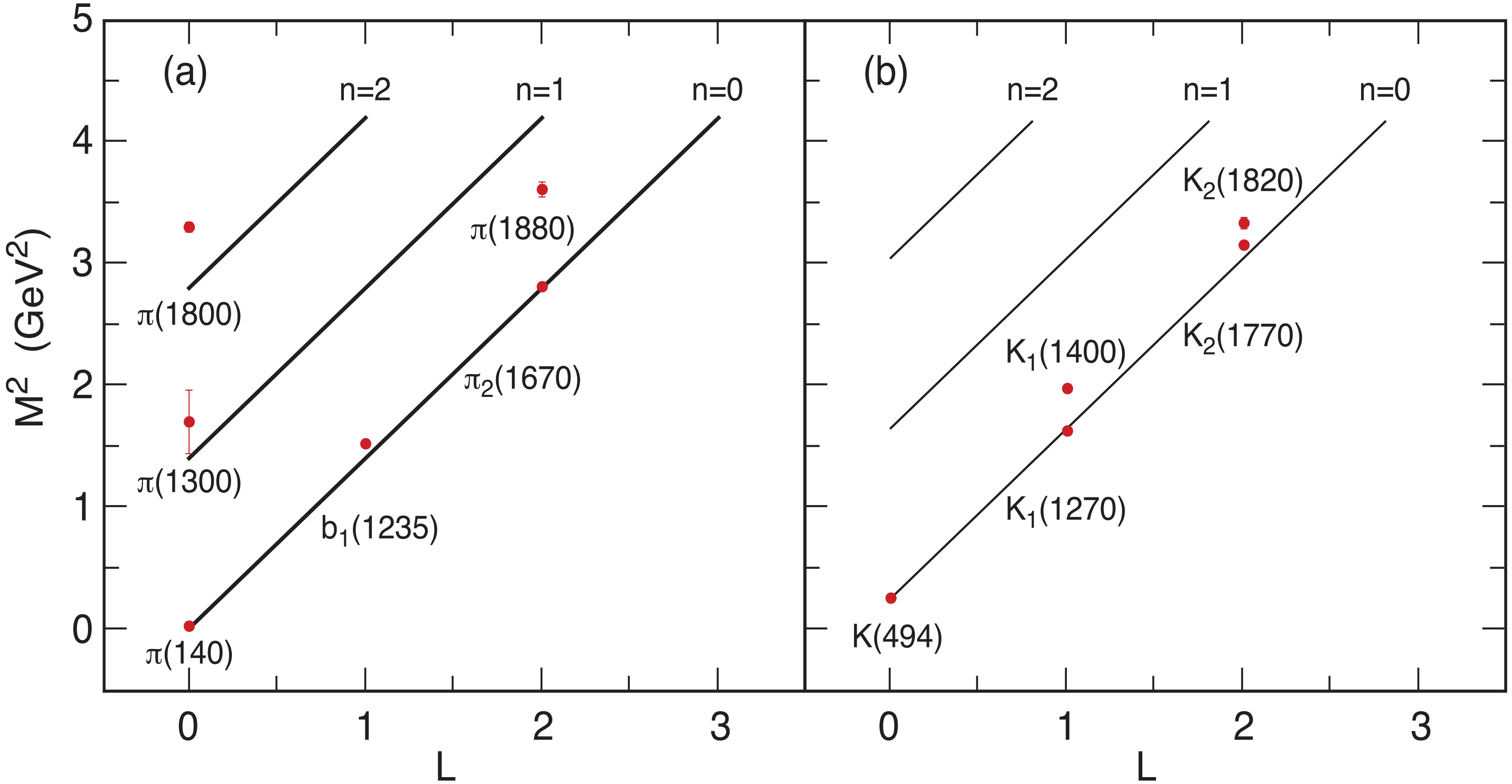
Conformal Symmetry of the action

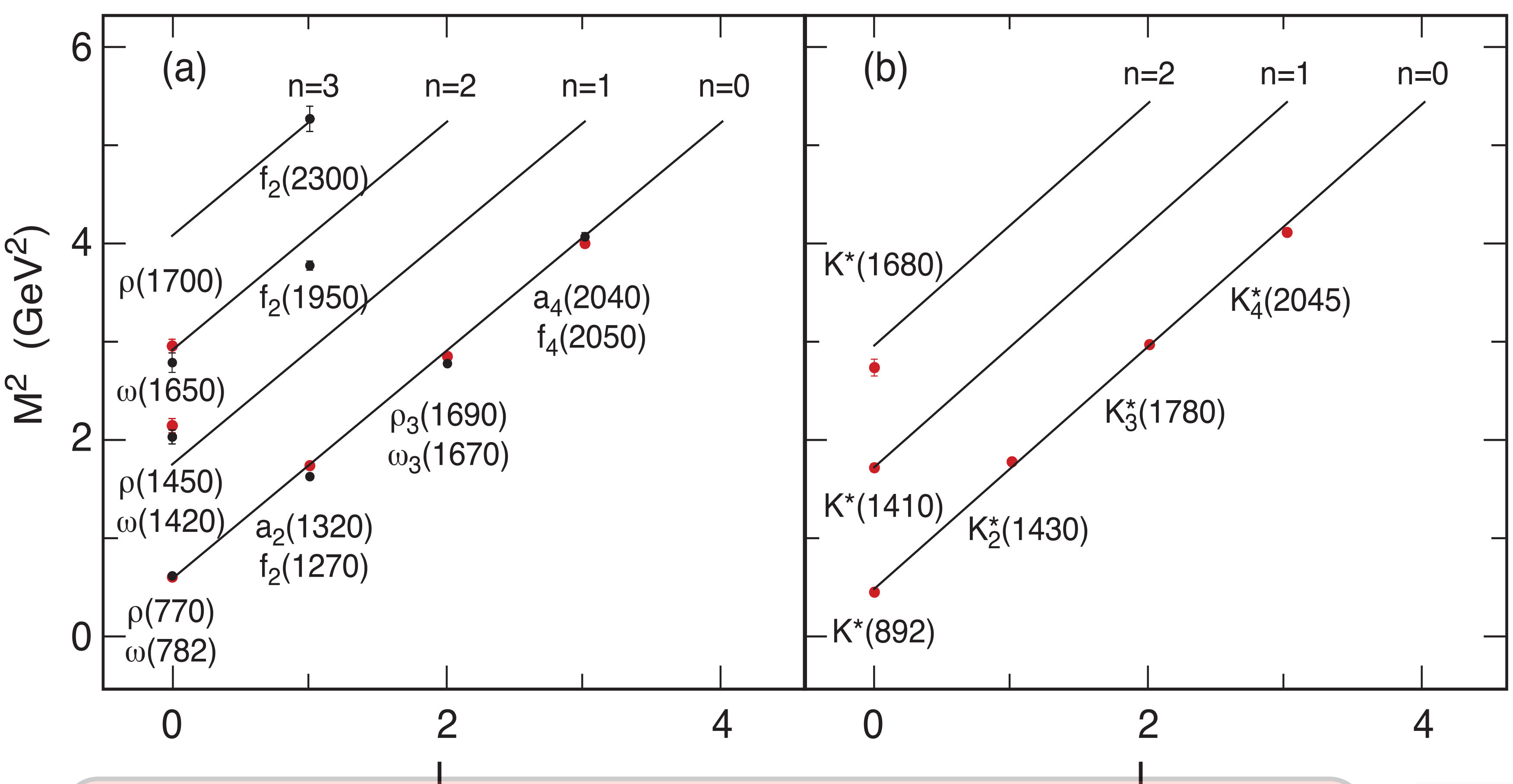
***Confinement scale:*** $\kappa \simeq 0.5\ GeV$

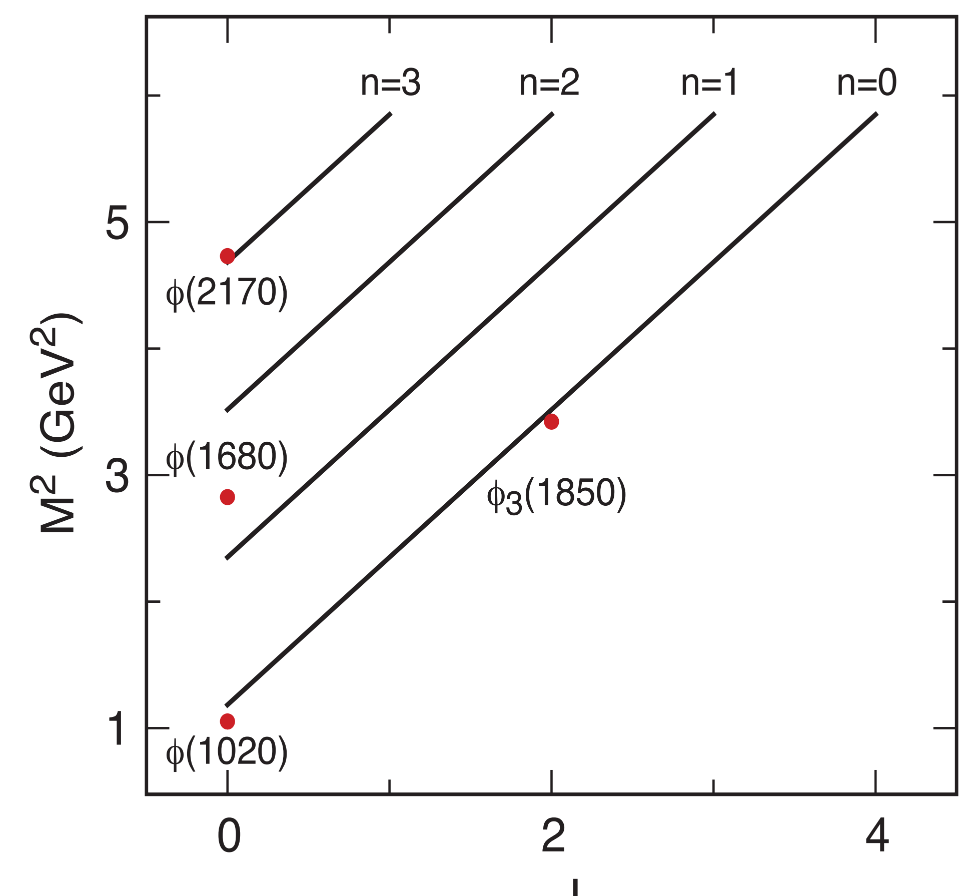
- **de Alfaro, Fubini, Furlan:**
- **Fubini, Rabinovici:**

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

GeV units external to QCD: Only Ratios of Masses Determined



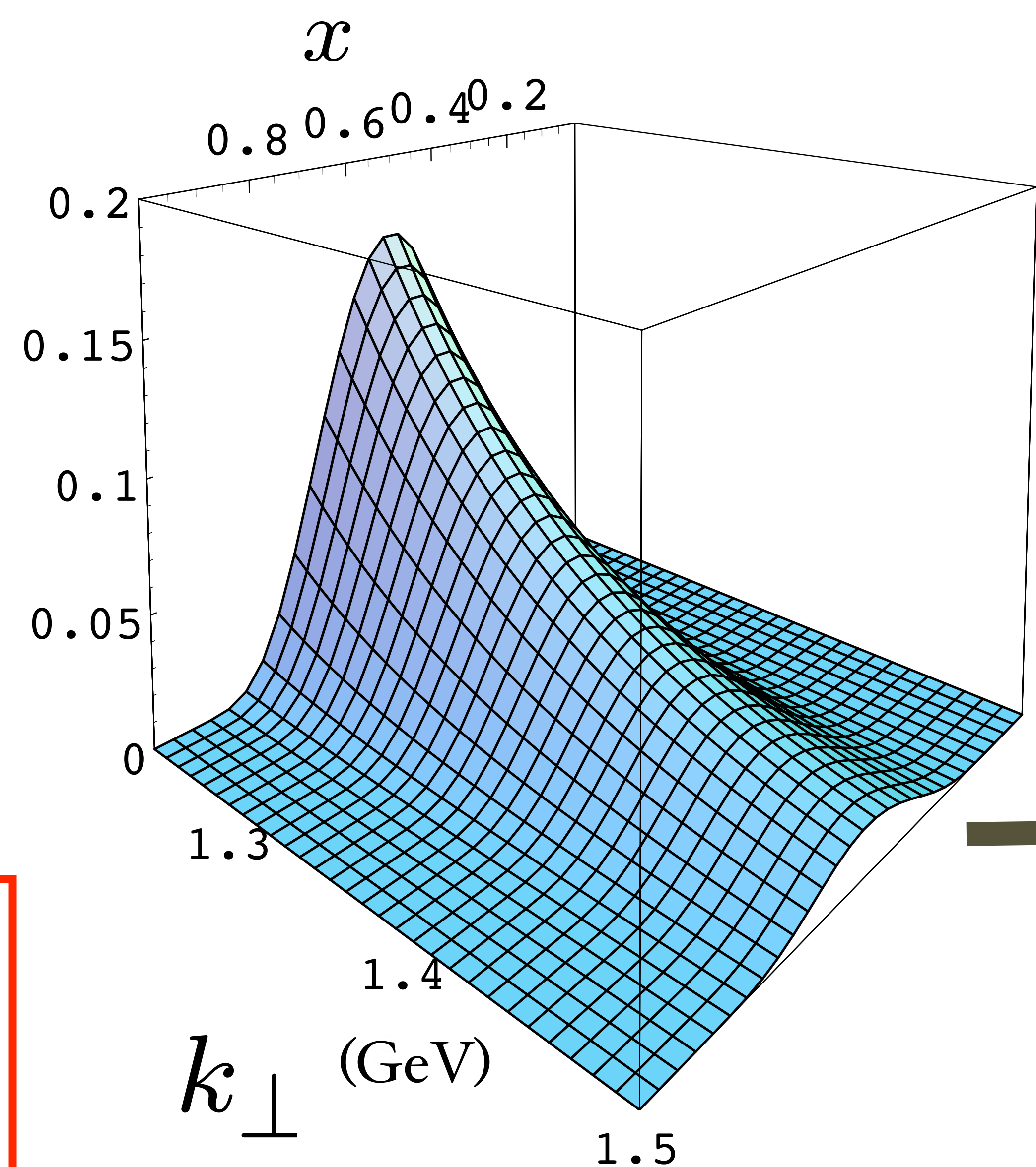

$$M^2(n, L, S) = 4\kappa^2(n + L + S/2)$$

Equal Slope in n and L

# Prediction from AdS/QCD: Meson LFWF

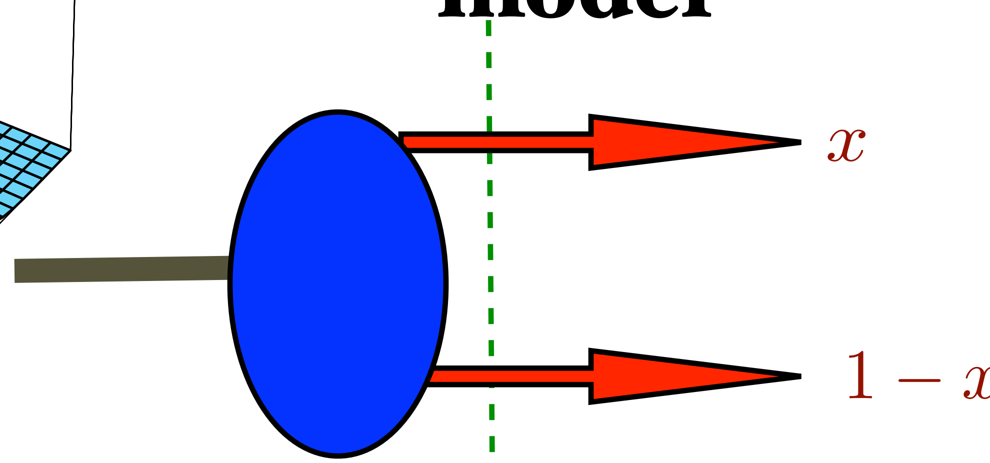
$$e^{\varphi(z)} = e^{+\kappa^2 z}$$

$$\psi_M(x, k^2_\perp)$$




**de T`eramond, Cao, sjb**

**"Soft Wall" model**




massless quarks

**Note coupling**
$k^2_\perp, x$

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

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

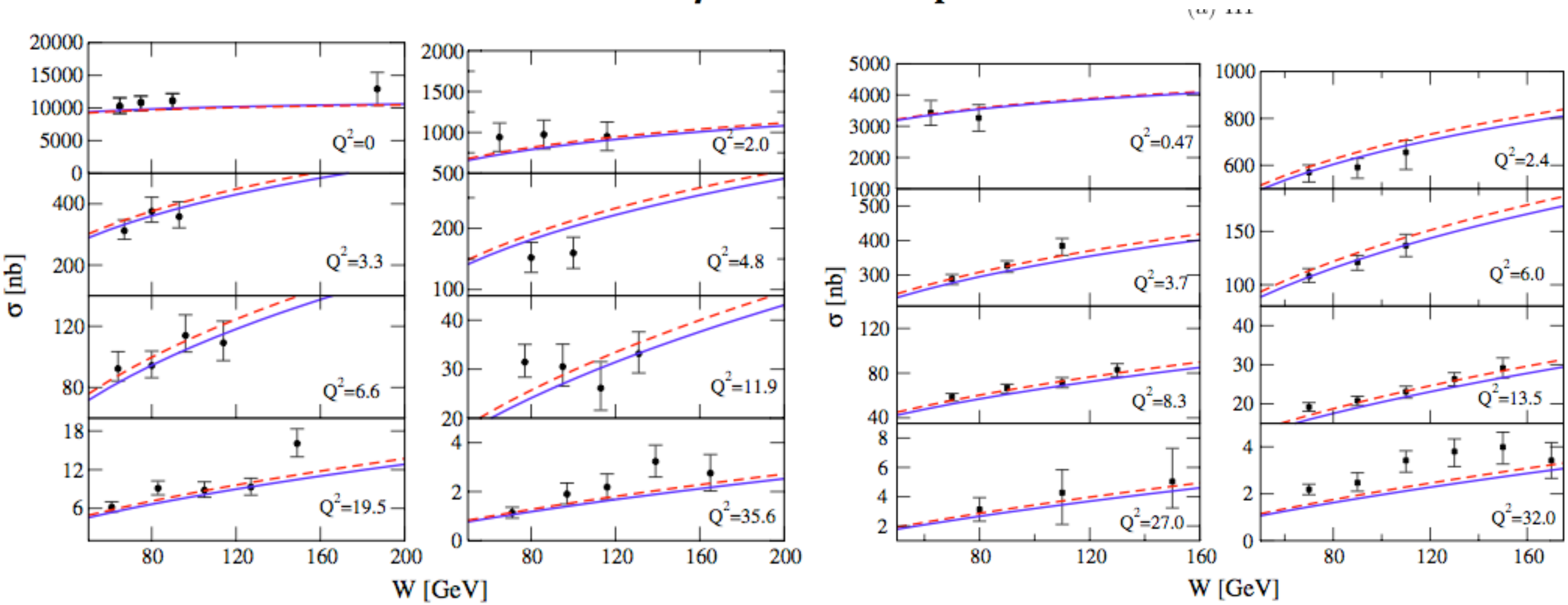
$$f_\pi = \sqrt{P_{q\bar{q}}}\frac{\sqrt{3}}{8}\kappa = 92.4 \text{ MeV}$$

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

*Provides Connection of Confinement to Hadron Structure*

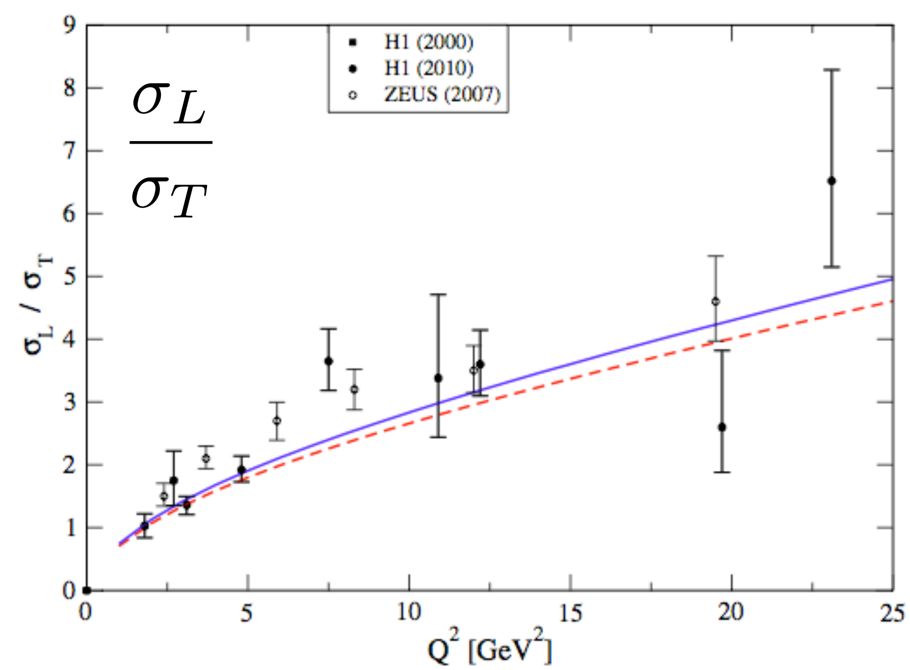
PRL 109, 081601 (2012) PHYSICAL REVIEW LETTERS week ending 24 AUGUST 2012

# AdS/QCD Holographic Wave Function for the $\rho$ Meson and Diffractive $\rho$ Meson Electroproduction




(a) H1

(b) ZEUS




$$\frac{\sigma_L}{\sigma_T}$$

**J. R. Forshaw, R. Sandapen**

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

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

# 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)

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

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

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

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

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

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

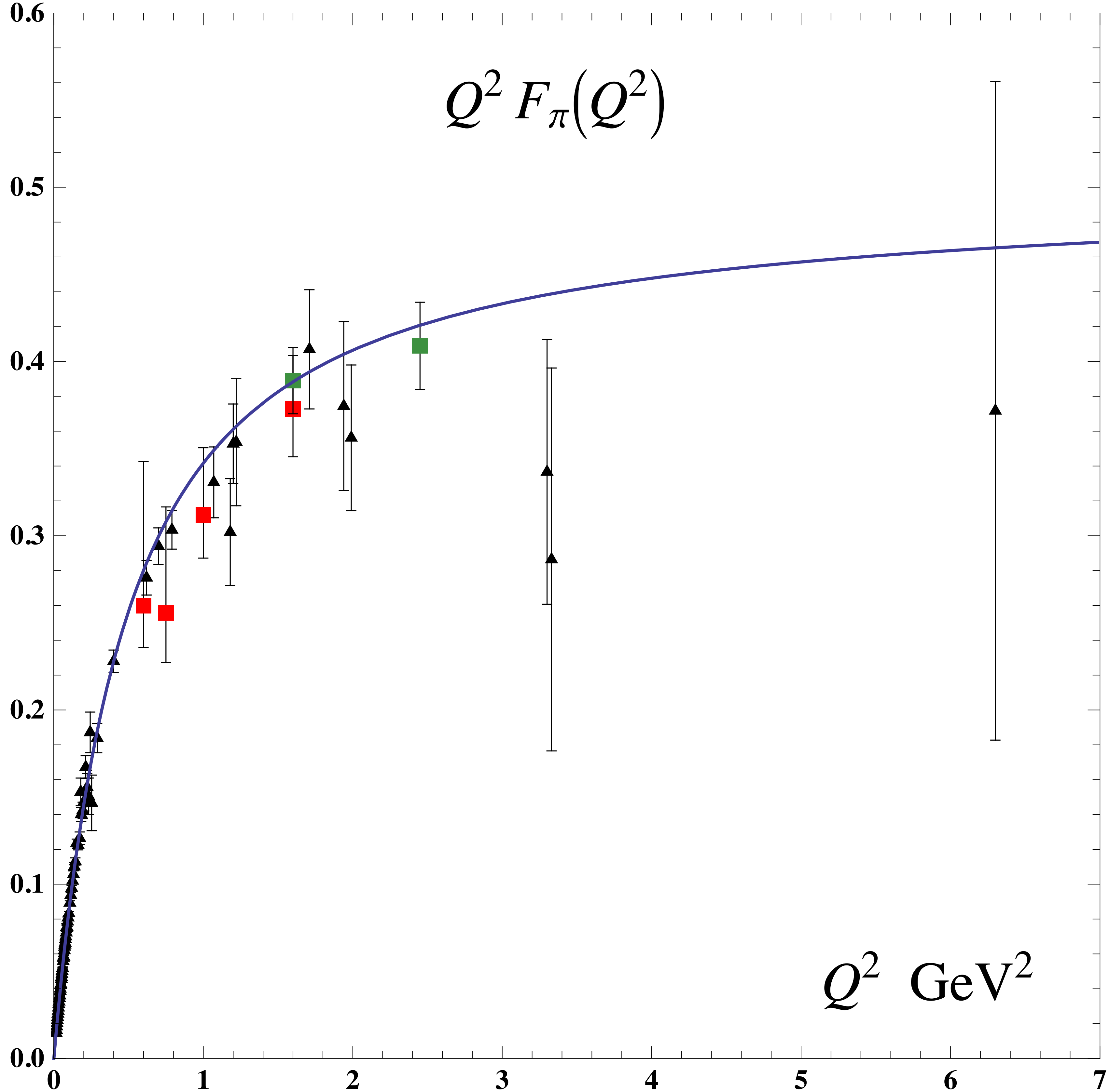
$$M_0 = m_\rho$$

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

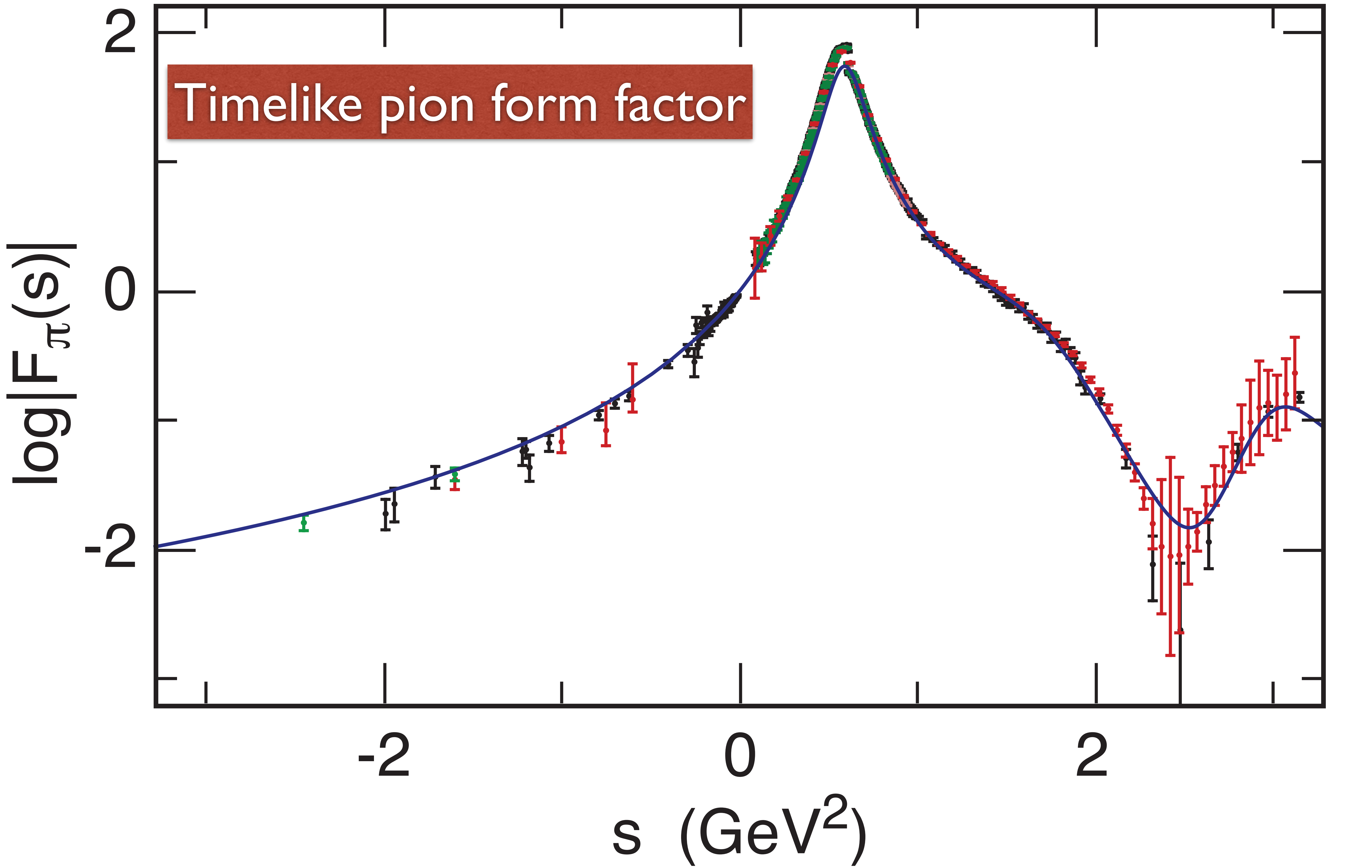
$$\frac{1}{2} - \frac{t}{4\lambda} = 1 - \alpha_R(t)$$

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

# Spacelike Pion Form Factor




*de Téramond, Dosch, sjb*



Timelike pion form factor
log|F_π(s)|
2
0
-2
-2
0
2
s (GeV²)

# 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, sjb***

*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* $\kappa$ *!*

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

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

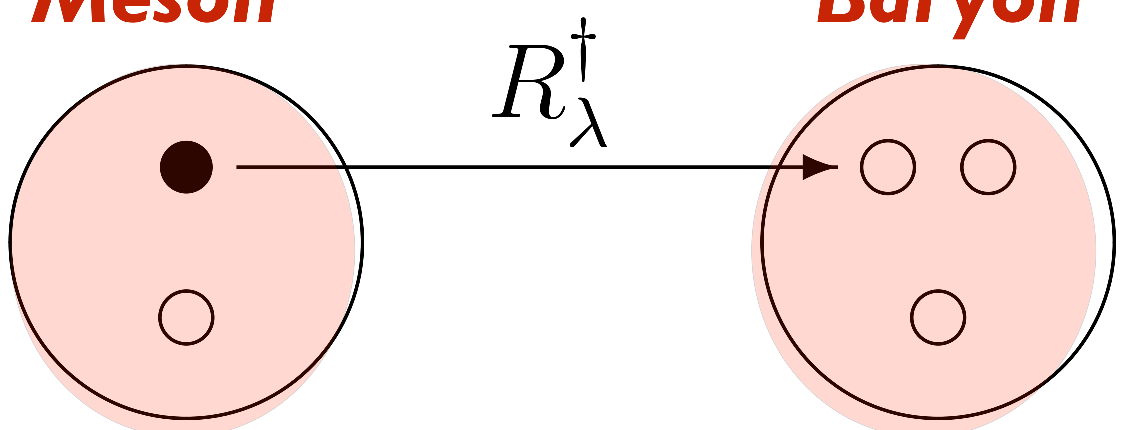
# Superconformal Algebra

de Téramond, Dosch, sjb

## 2X2 Hadronic Multiplets

### Bosons, Fermions with Equal Mass!

**Meson** **Baryon**



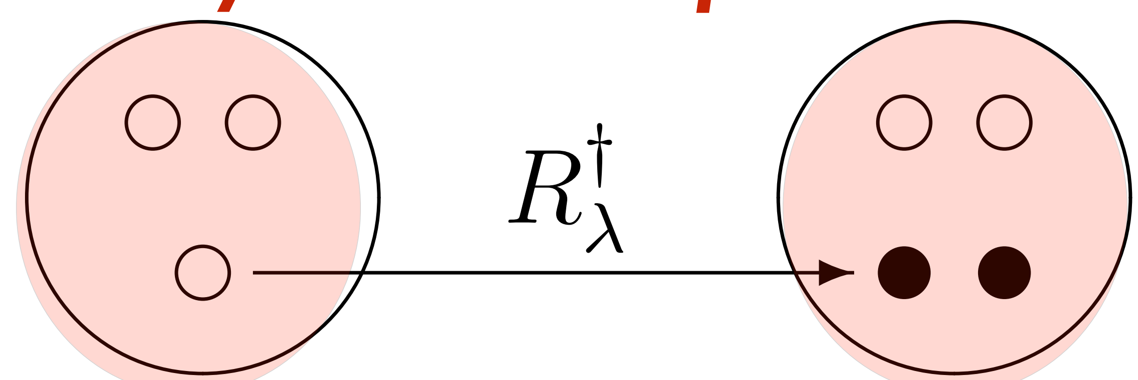

$\phi_M,\ L_B + 1$ $\psi_{B+},\ L_B$

$R_\lambda^\dagger\ \bar{q} \to [qq]$

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

**Baryon**

**Tetraquark: diquark + antidiquark**




$R_\lambda^\dagger\ q \to [\bar{q}\bar{q}]$

$3_C \to 3_C$

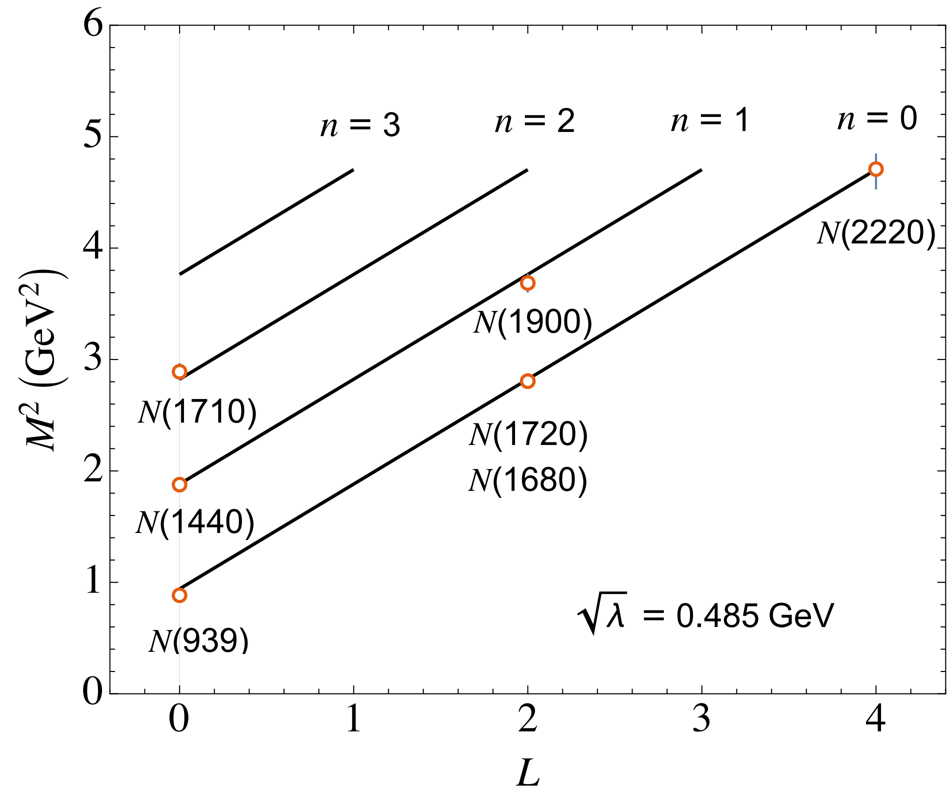
$\psi_{B-},\ L_B + 1$ $\phi_T,\ L_B$

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

# Baryon Spectroscopy from LF Holography

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

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




- Eigenvalues

$$M^2 = 4\lambda(n+L+1)$$

- Eigenfunctions

$$\psi_+(\zeta) \sim \zeta^{\frac{1}{2}+L} e^{-\lambda\zeta^2/2} L_n^L(\lambda\zeta^2), \quad \psi_-(\zeta) \sim \zeta^{\frac{3}{2}+L} e^{-\lambda\zeta^2/2} L_n^{L+1}(\lambda\zeta^2)$$

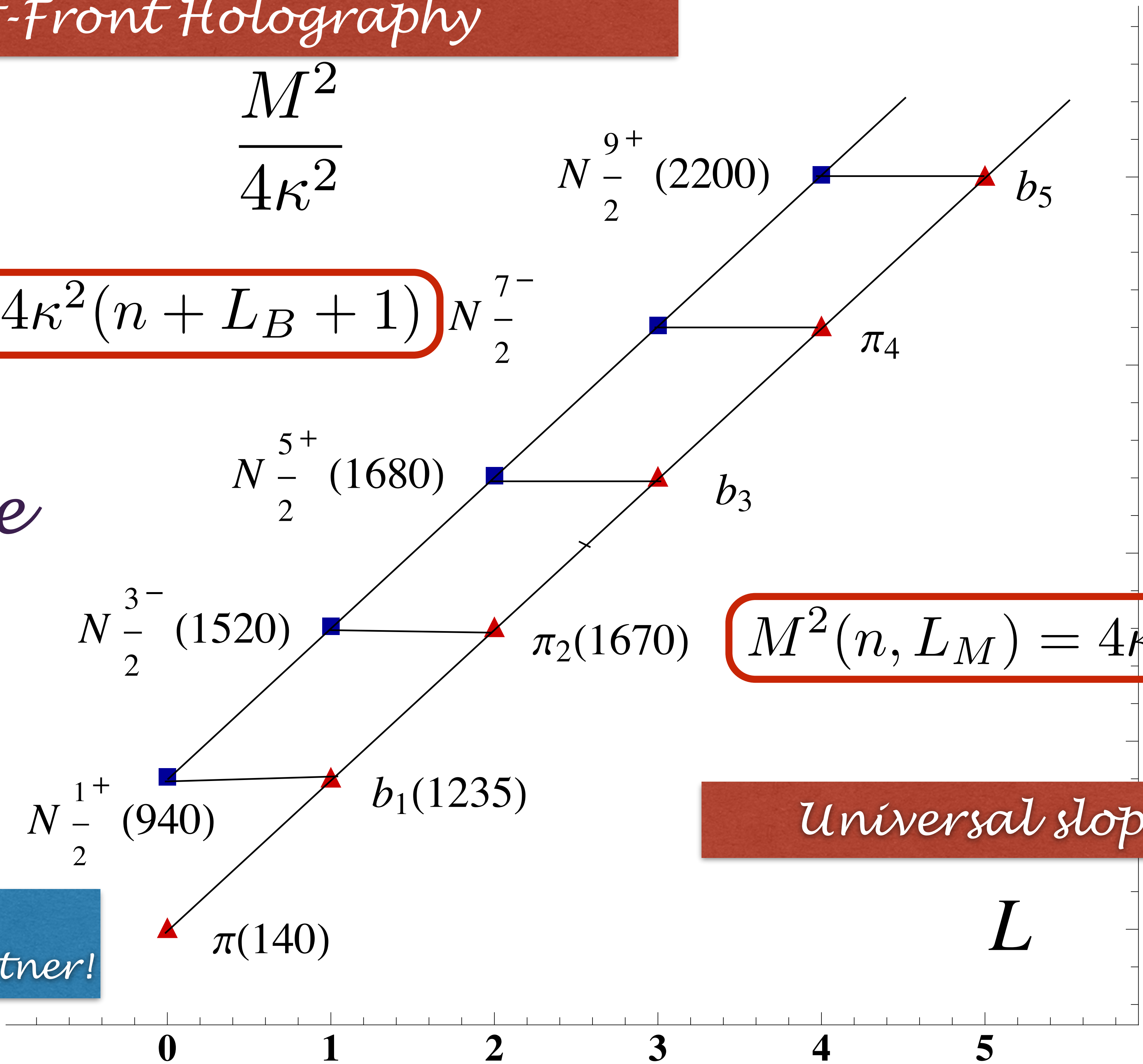
## Same slope in n and L!

# 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**



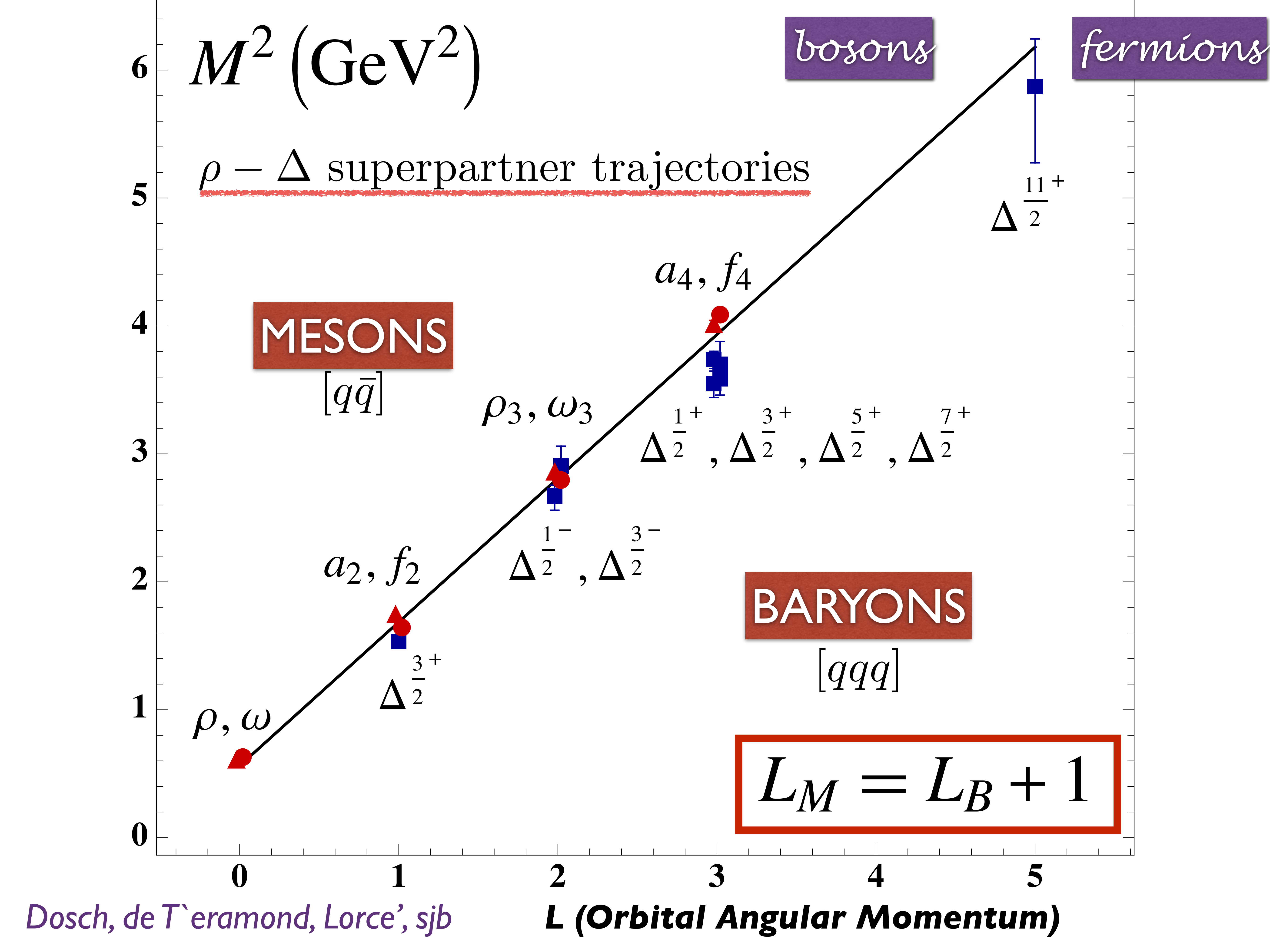

$$M^2(n, L_M) = 4\kappa^2(n + L_M)$$

Universal slopes in n, L

pion has no superpartner!

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

**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
$[qqq]$
$\rho, \omega$
$a_2, f_2$
$\rho_3, \omega_3$
$a_4, f_4$
$\Delta^{\frac{3}{2}^+}$
$\Delta^{\frac{1}{2}^-}, \Delta^{\frac{3}{2}^-}$
$\Delta^{\frac{1}{2}^+}, \Delta^{\frac{3}{2}^+}, \Delta^{\frac{5}{2}^+}, \Delta^{\frac{7}{2}^+}$
$\Delta^{\frac{11}{2}^+}$
$L_M = L_B + 1$
0
1
2
3
4
5
6
L (Orbital Angular Momentum)
Dosch, de T`eramond, Lorce', sjb

# 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

# 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

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

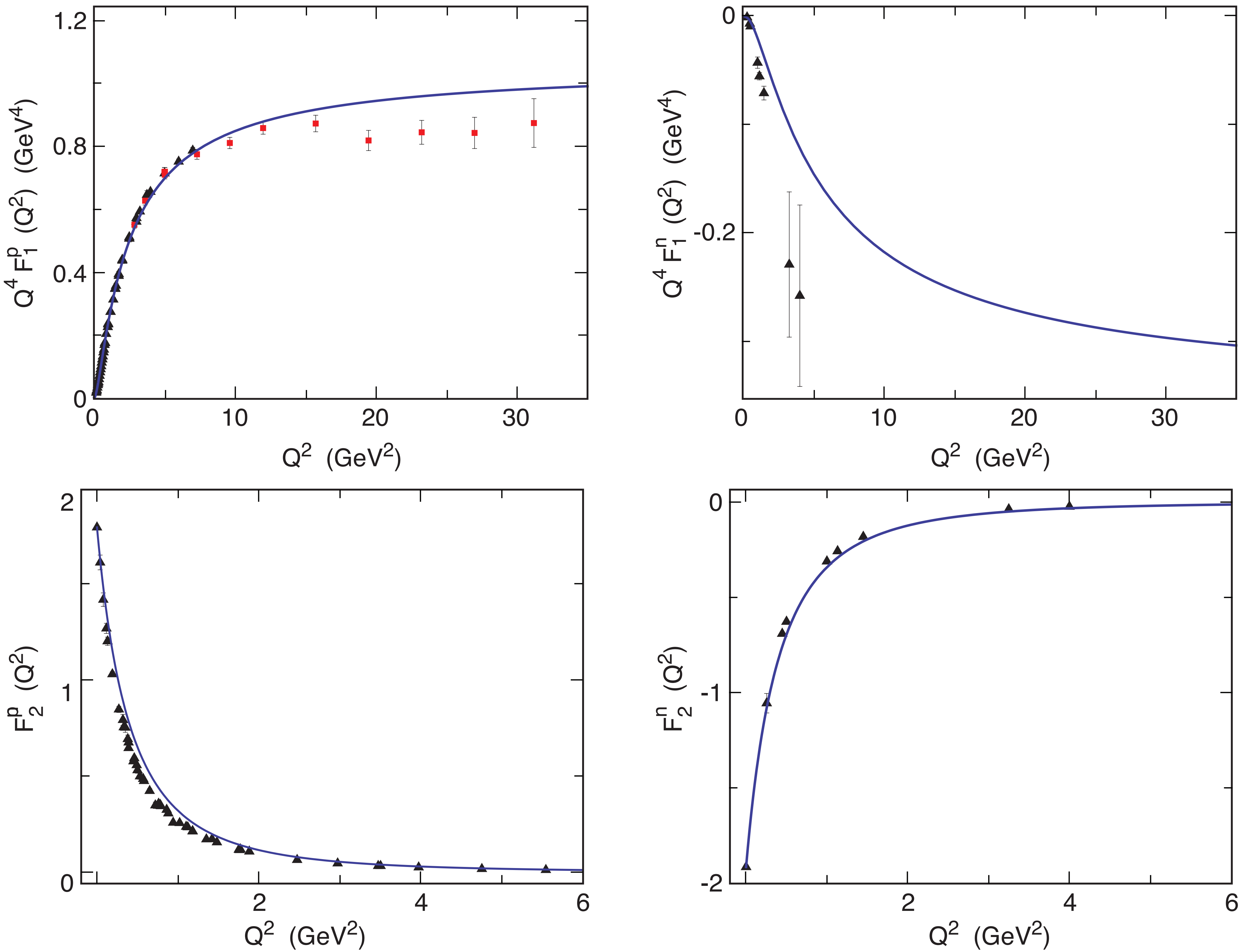
*Quark Chiral Symmetry of Eigenstate!*

**Nucleon: Equal Probability for L=0,1**

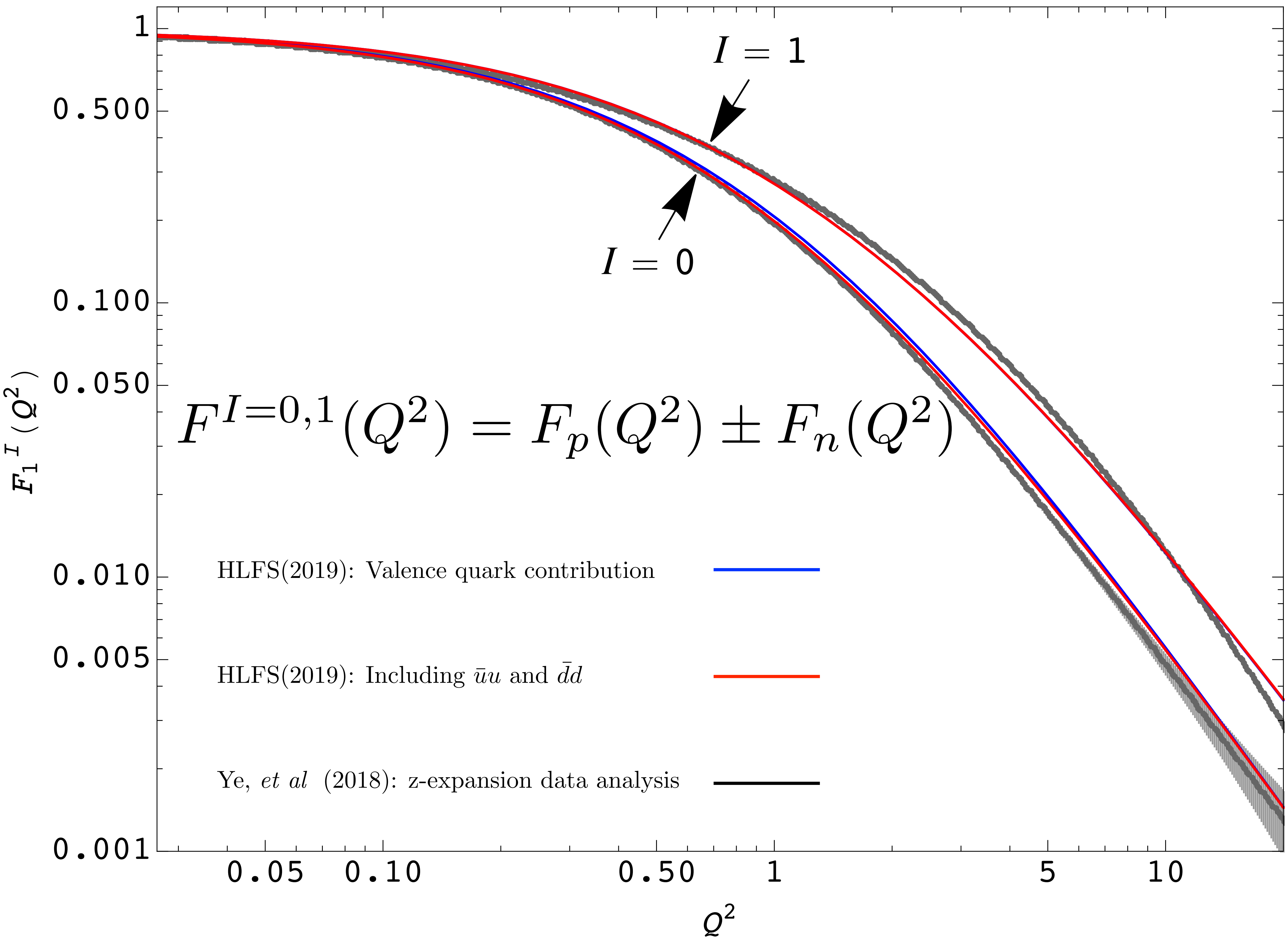
$$J^z = +1/2: \quad \frac{1}{\sqrt{2}}[\,|S_q^z = +1/2, L^z = 0 > + |S_q^z = -1/2, L^z = +1 >\,]$$

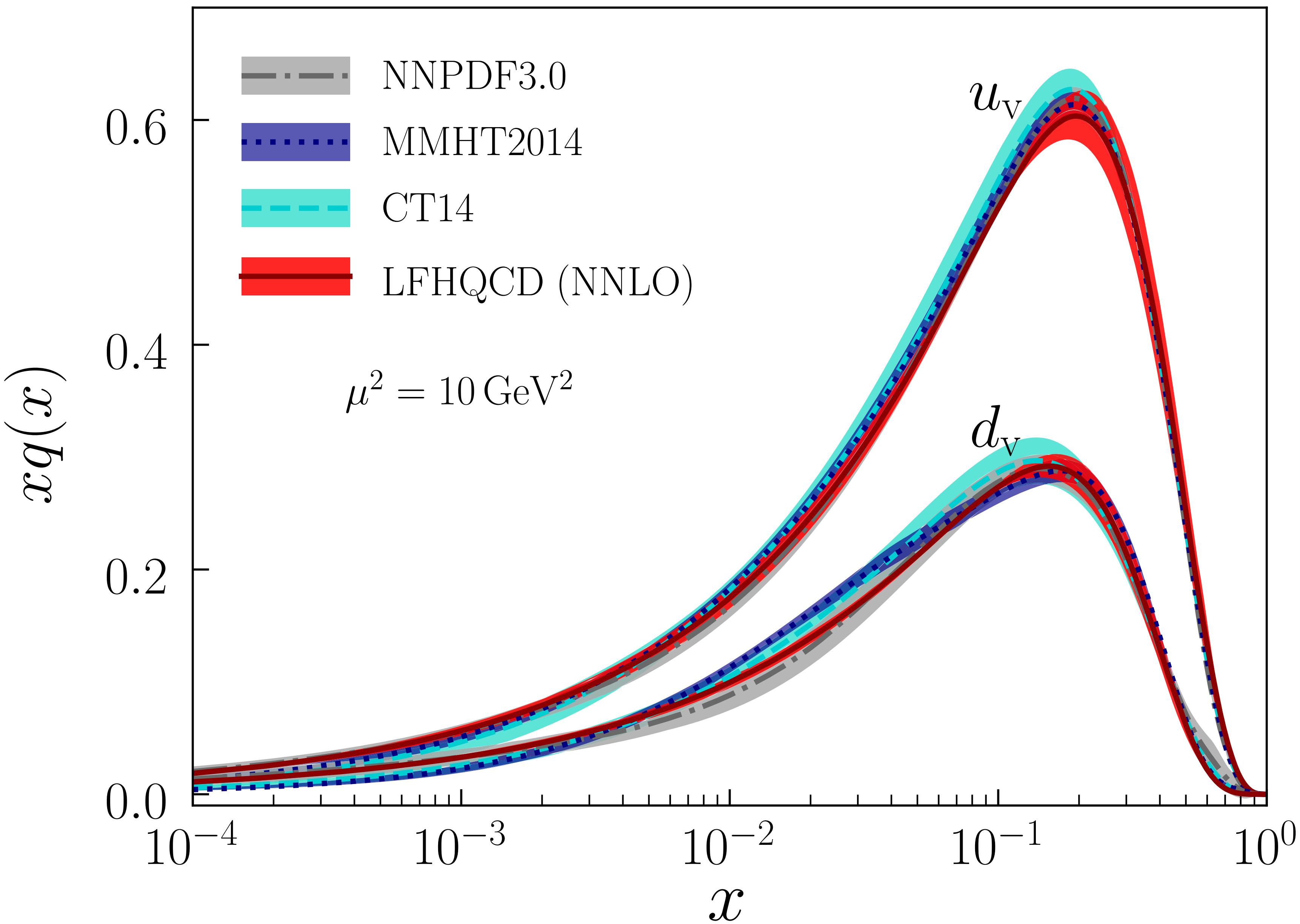
*Nucleon spin carried by quark orbital angular momentum*

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



# LF Holographic Nucleon Form Factors





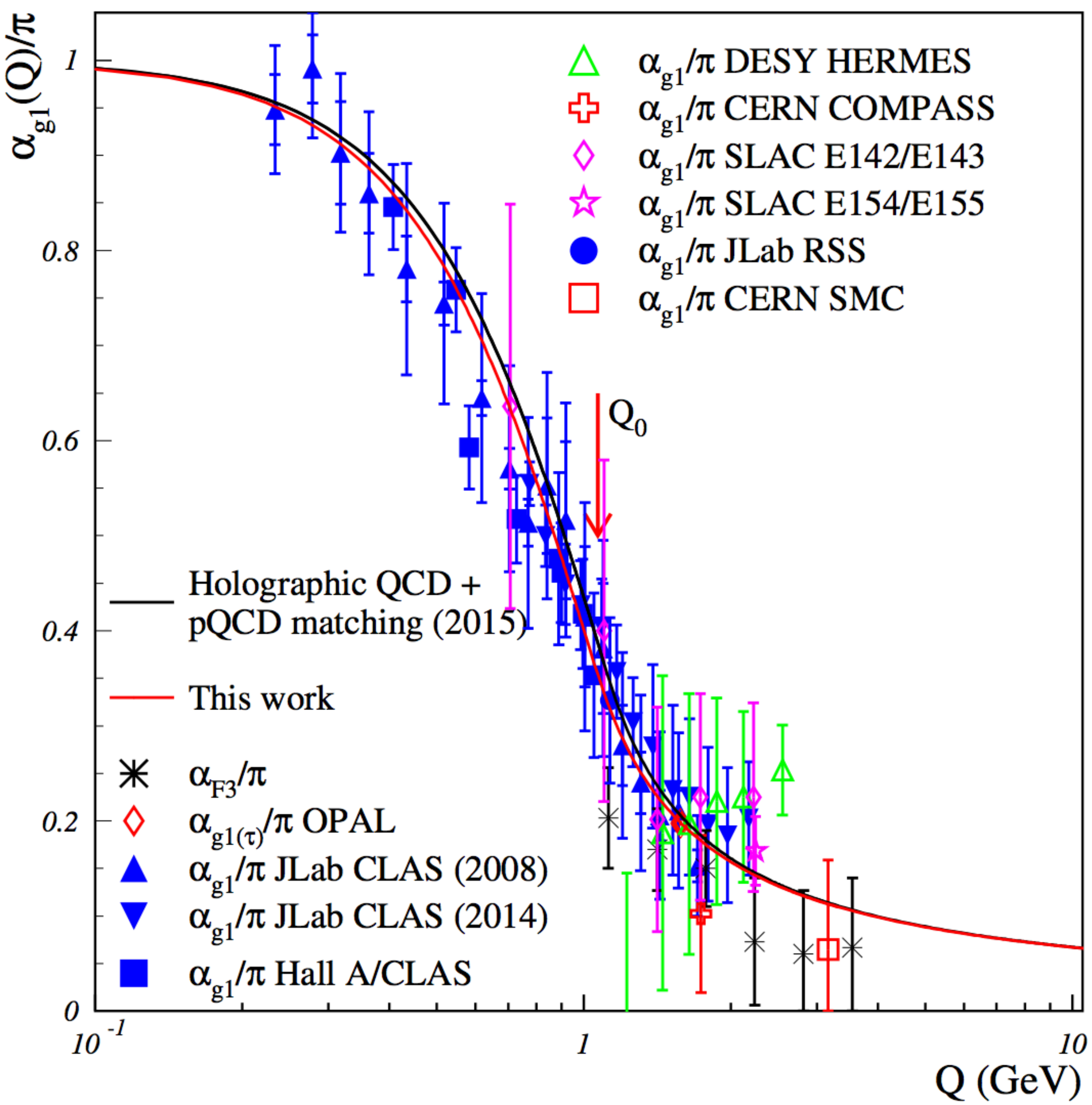

Comparison for $xq(x)$ in the proton from LFHQCD (red bands) and global fits: MMHT2014 (blue bands) [5], CT14 [6] (cyan bands), and NNPDF3.0 (gray bands) [77]. LFHQCD results are evolved from the initial scale $\mu_0 = 1.06 \pm 0.15$ GeV.

***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)***

# 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 $\alpha$ 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).**

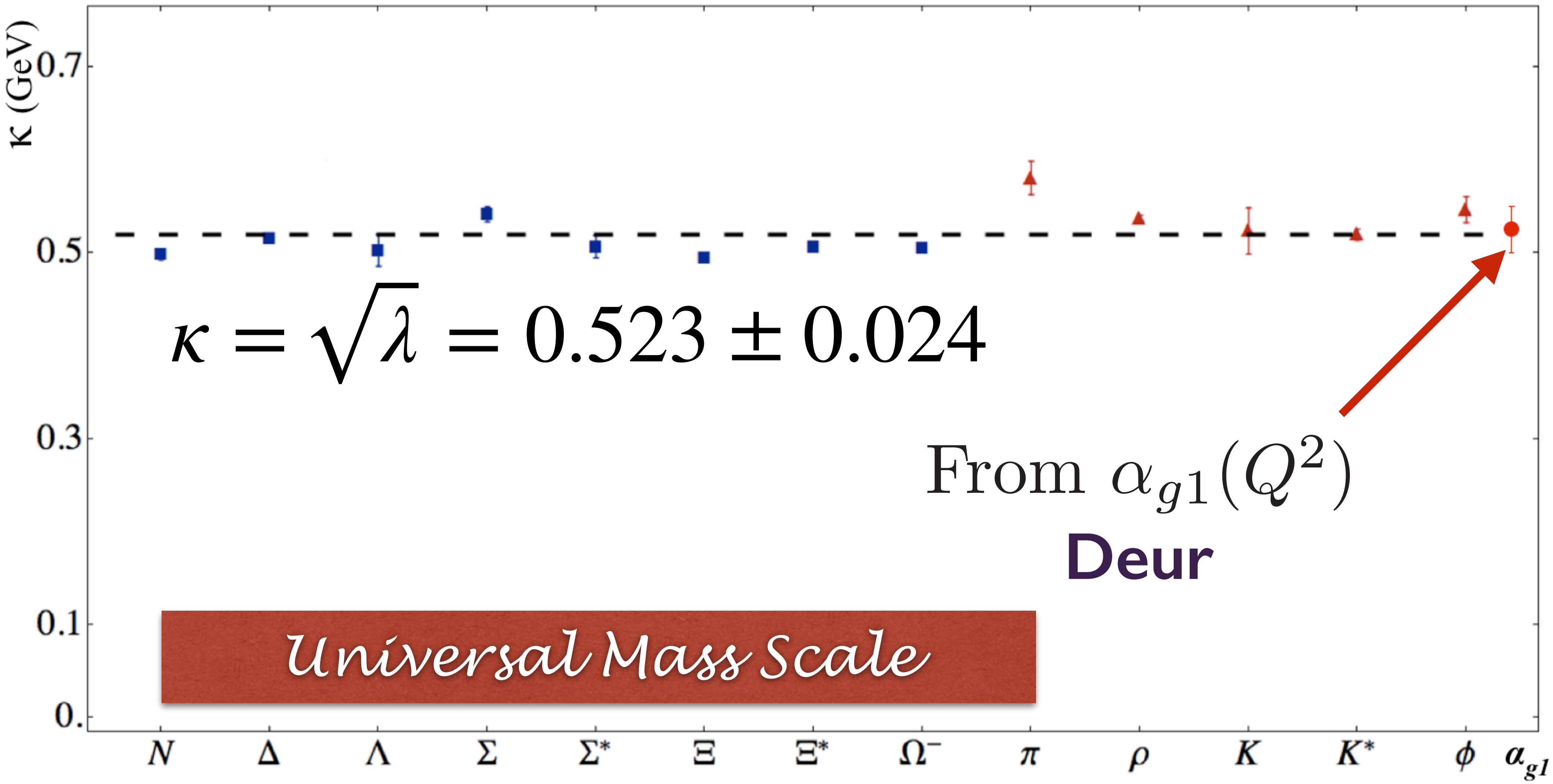
**Analytic, defined at all scales, IR Fixed Point**

$\lambda = \kappa^2$

*de Téramond, Dosch, Lorcé, sjb*

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

$\kappa$

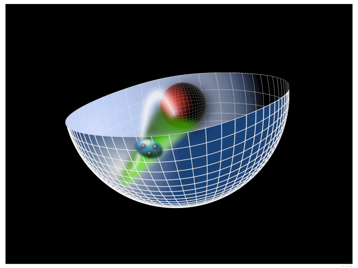



**Fit to the slope of Regge trajectories, including radial excitations**

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

# LFHQCD: Underlying Principles

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



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

- *Introduce Mass Scale **κ** while retaining the Conformal Invariance of the Action (dAFF)*
- *Unique Dilaton in $AdS_5$:* $e^{+\kappa^2 z^2}$
- *Unique color-confining LF Potential* $U(\zeta^2) = \kappa^4 \zeta^2$
- *Superconformal Algebra: Mass Degenerate 4-Plet:*

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

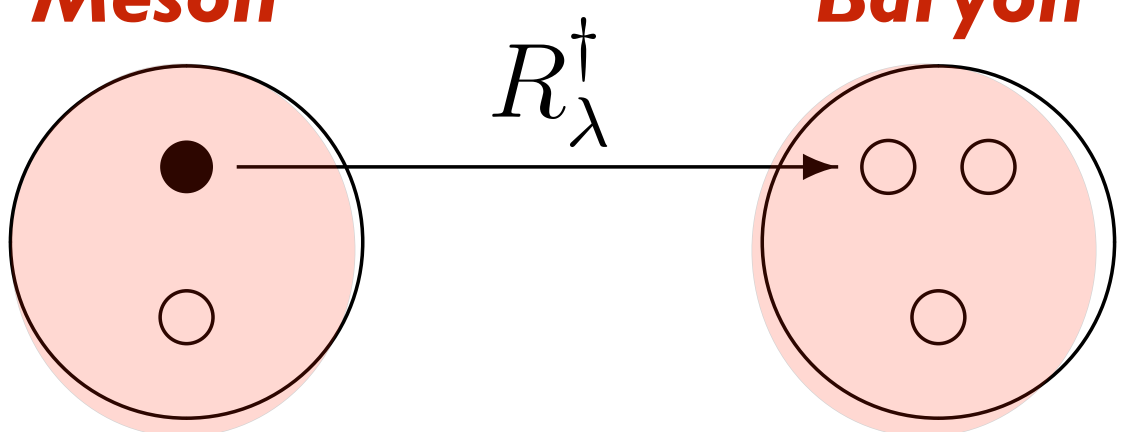
# Superconformal Algebra

de Téramond, Dosch, sjb

## 2X2 Hadronic Multiplets

Bosons, Fermions with Equal Mass!

**Meson** **Baryon**

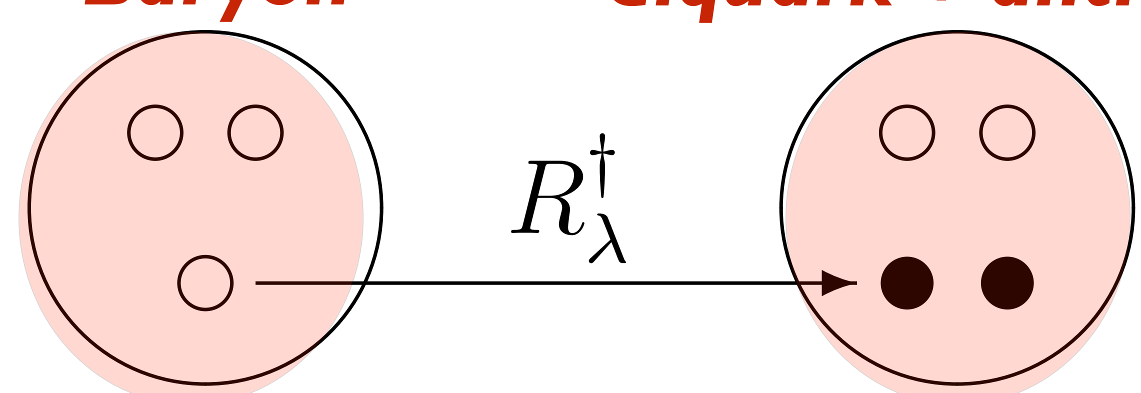



$\phi_M, \ L_B + 1$ $\psi_{B+}, \ L_B$

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

**Tetraquark: diquark + antidiquark**

**Baryon**




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

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

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

## Drell-Yan-West Formula in Impact Space

$$F(q^2) =$$

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

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

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

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

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

where $\boxed{\mathbf{a}_\perp = \sum_{j=1}^{n-1} x_j \mathbf{b}_{\perp j}}$ 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)

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

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

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

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

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

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

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

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

$$F(q^2) =$$

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

$$\sum_i x_i = 1$$

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

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

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:

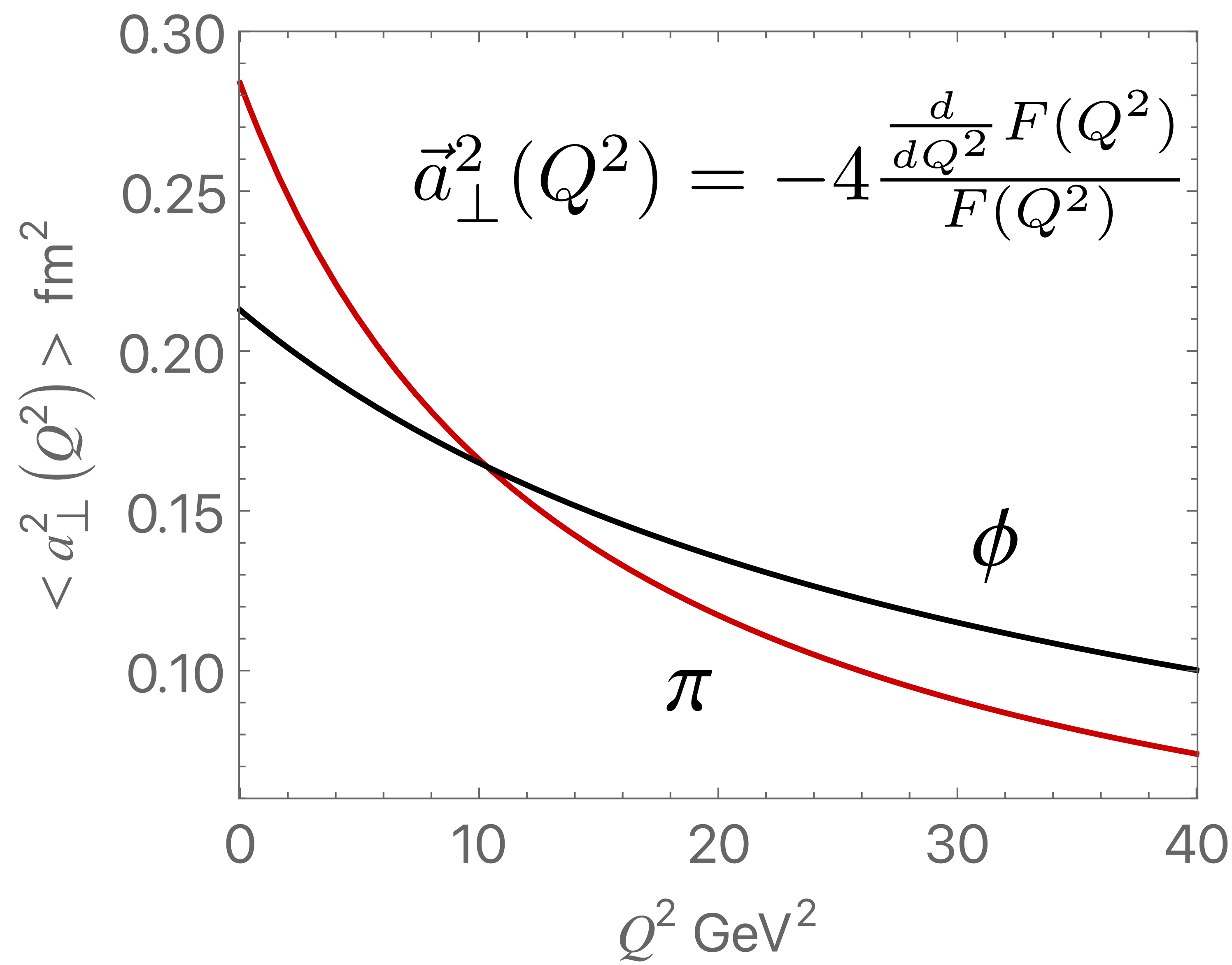
For large Q2 :

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

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

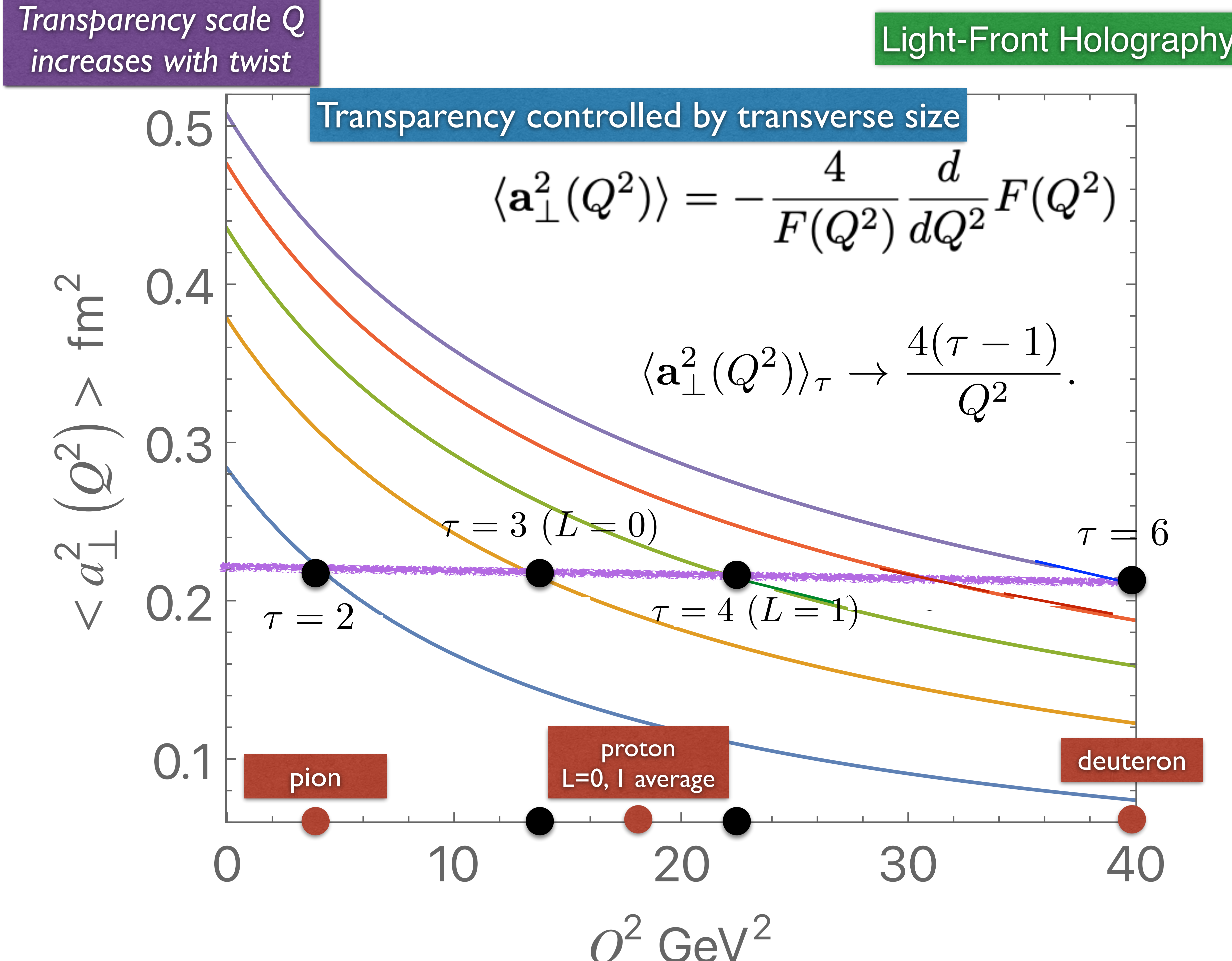
The scale $Q^2_\tau$ required for Color Transparency grows with twist $\tau$

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




Transverse size depends on internal dynamics

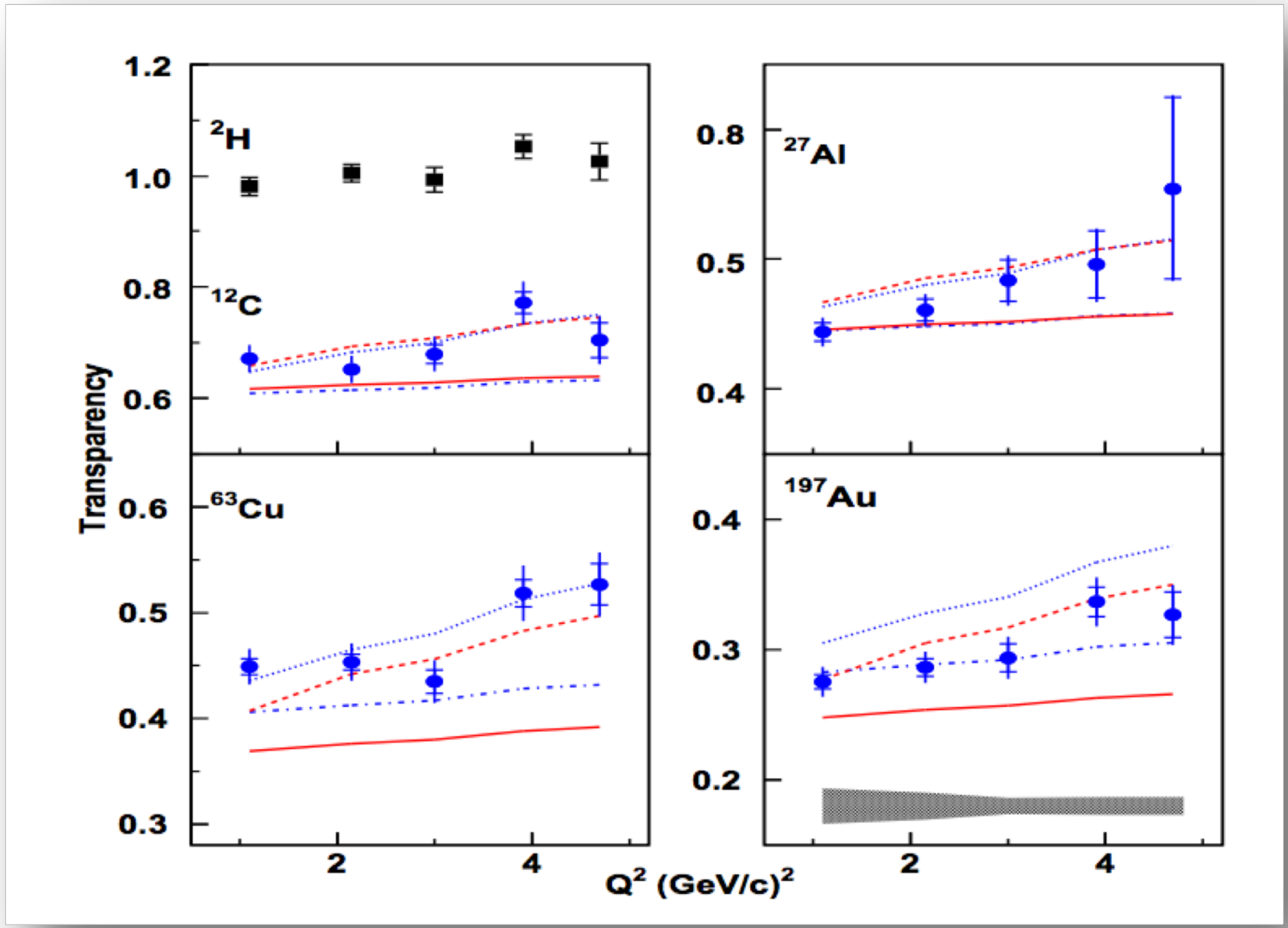
Transparency controlled by transverse size




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

Hall C E01-107 pion electro-production

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

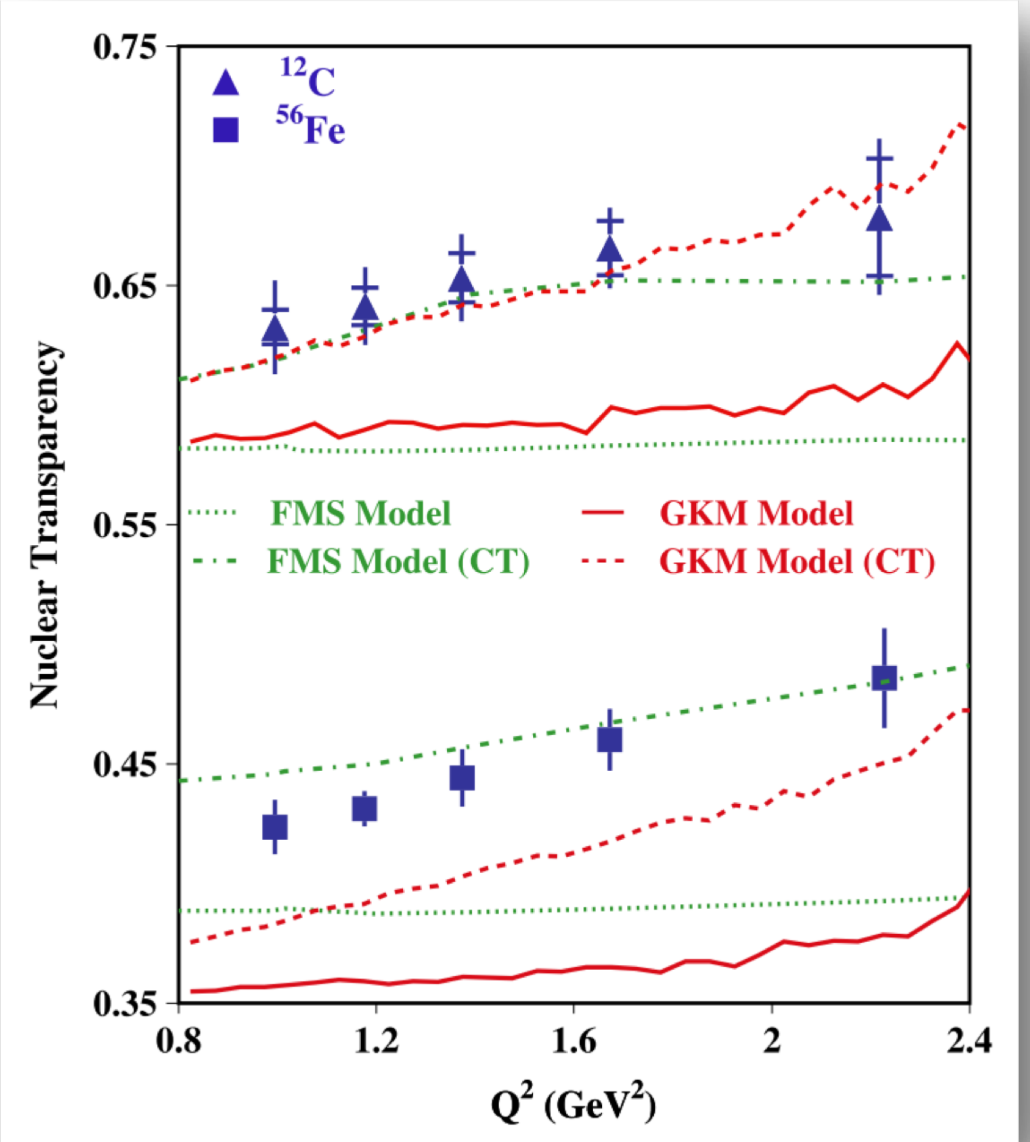



B.Clasie *et al.* PRL 99:242502 (2007)

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

CLAS E02-110 rho electro-production

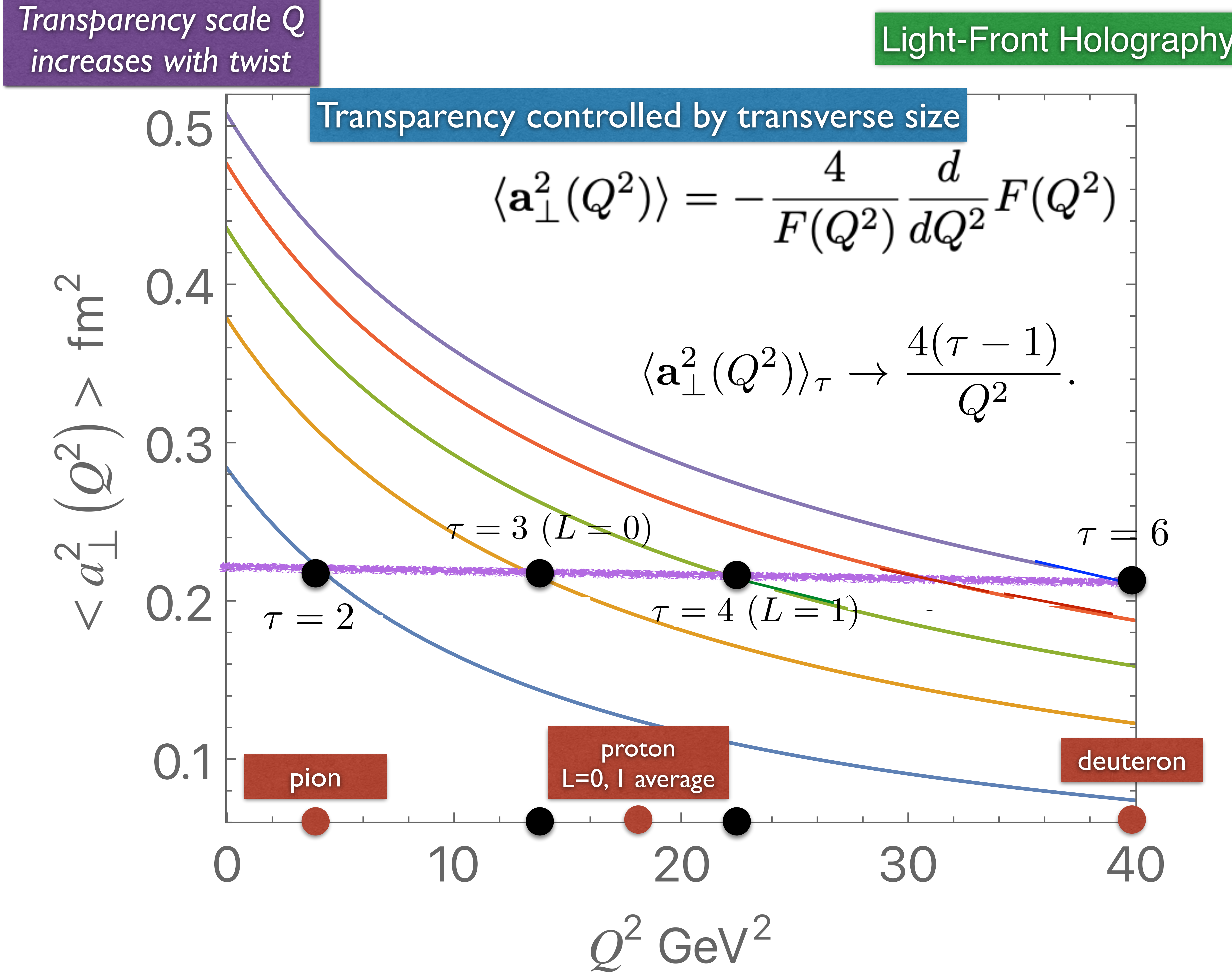
$A(e,e'\rho^0)$




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

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

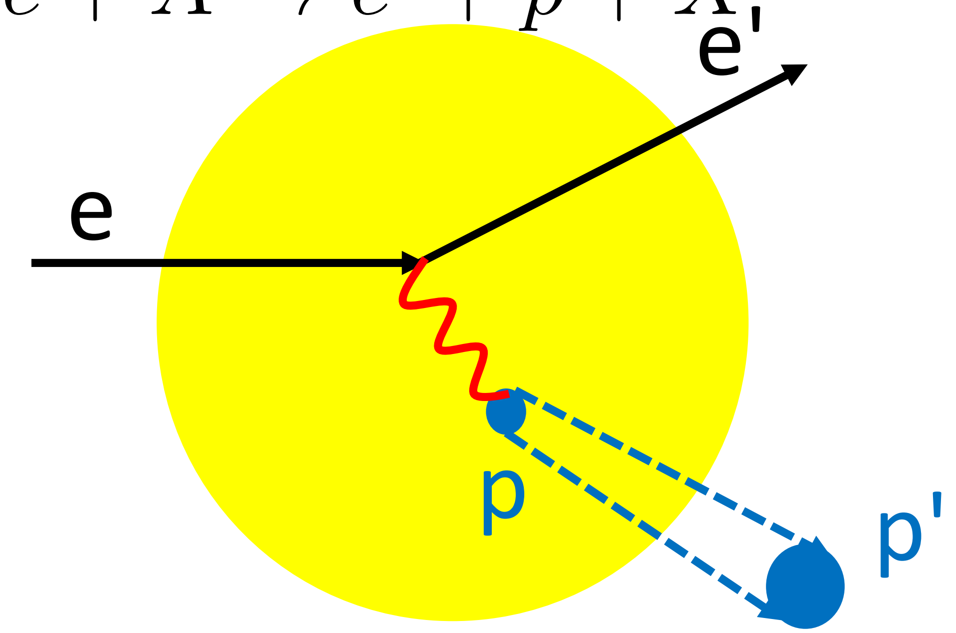
5% increase for $T_\pi$ in $^{12}C$ at $Q^2 = 4\ GeV^2$ implies 5% increase for $T_p$ at $Q^2 = 18\ GeV^2$




5% increase for $T_\pi$ 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

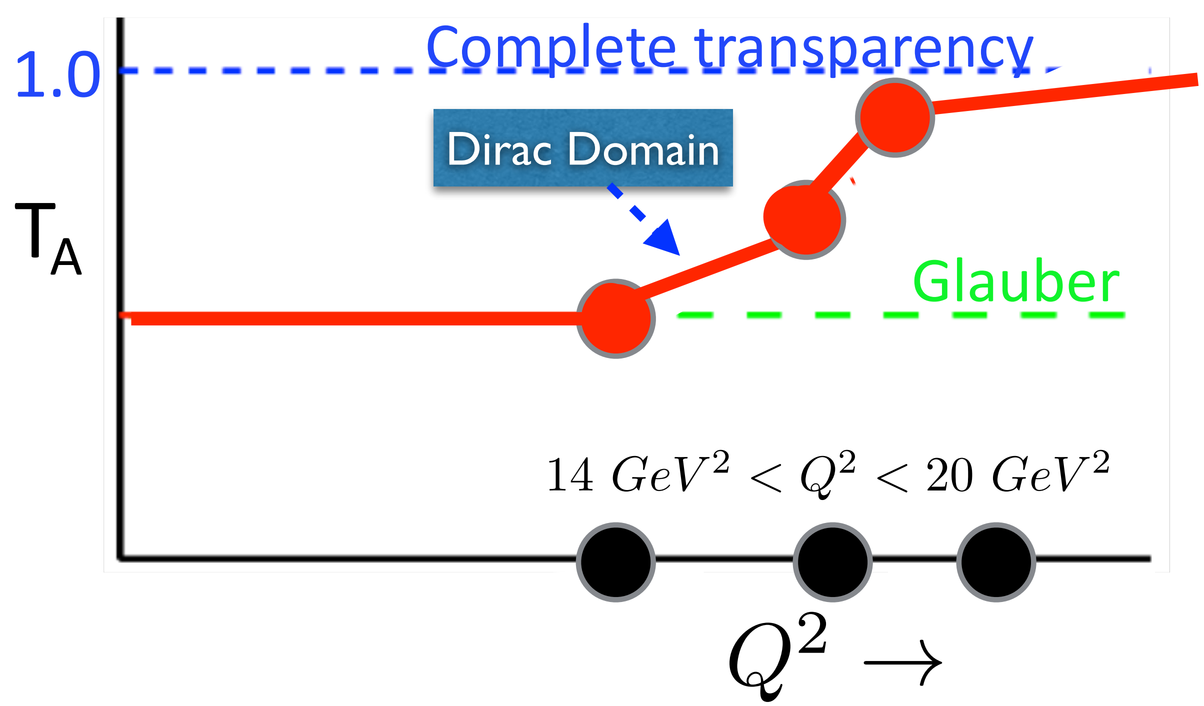
$$e + A \to e' + p + X$$




- 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)

# 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.

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

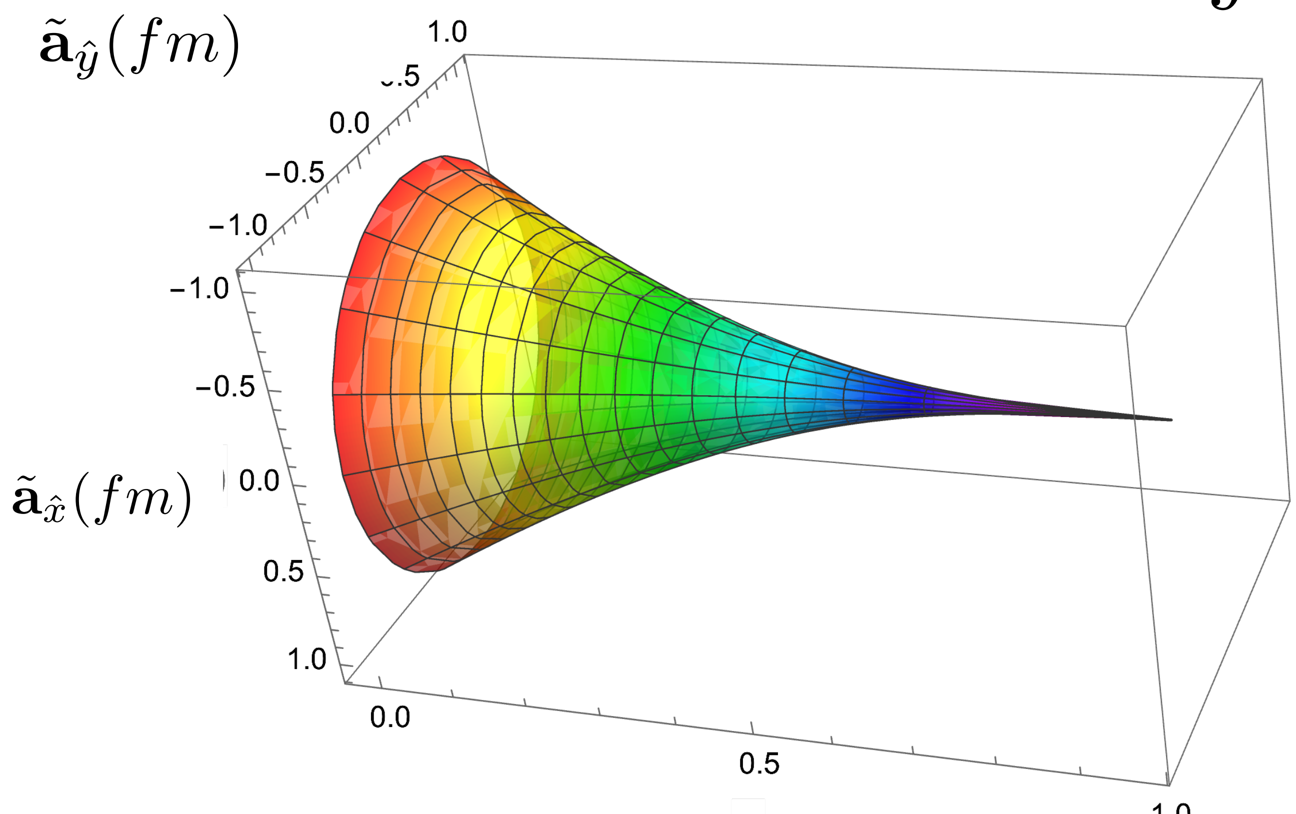
$$\boxed{\vec{a}_\perp \equiv \sum_{j=1}^{n-1} x_j \vec{b}_{\perp j}}$$

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

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

*Define mean transverse size as a function of x*

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




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

*Mean transverse size as a function of Q and Twist*

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

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

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

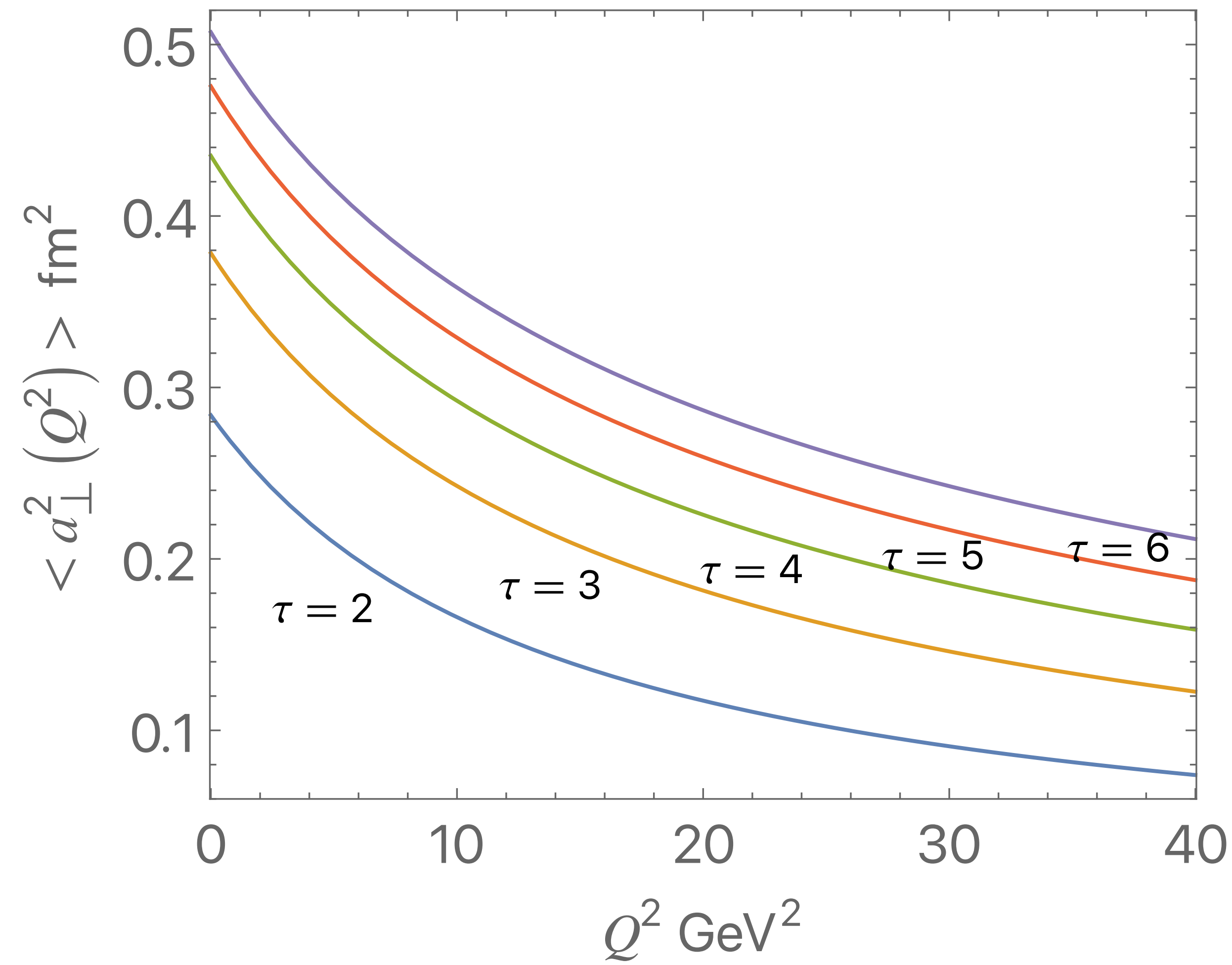
with $\psi$ the digamma function

- For integer twist $\tau = N$

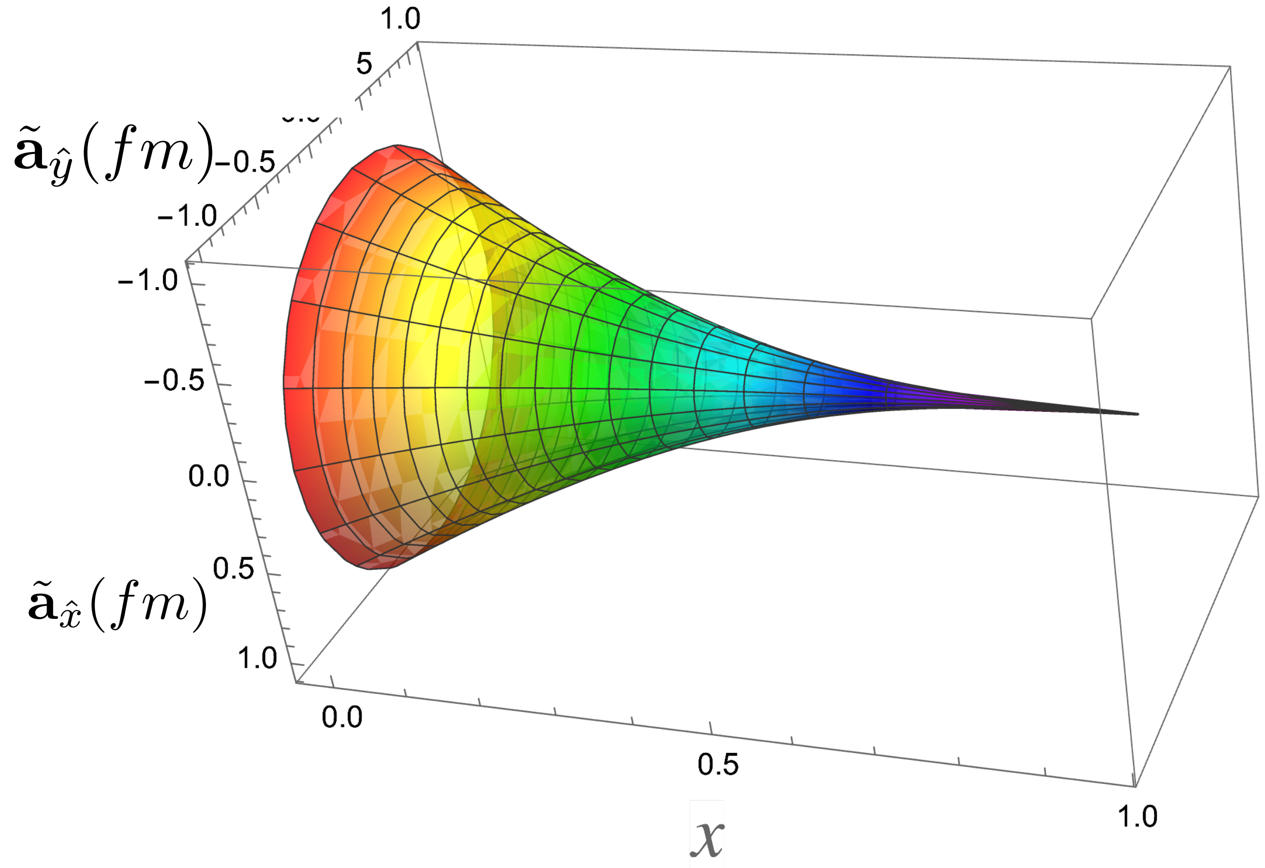
$$\langle a_\perp^2(t) \rangle_\tau \equiv 4 \langle \sigma(t) \rangle_\tau$$
$$= \frac{1}{\lambda} \sum_{j=1}^{\tau-1} \frac{1}{j - \alpha(t)}$$

- 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




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

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

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

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

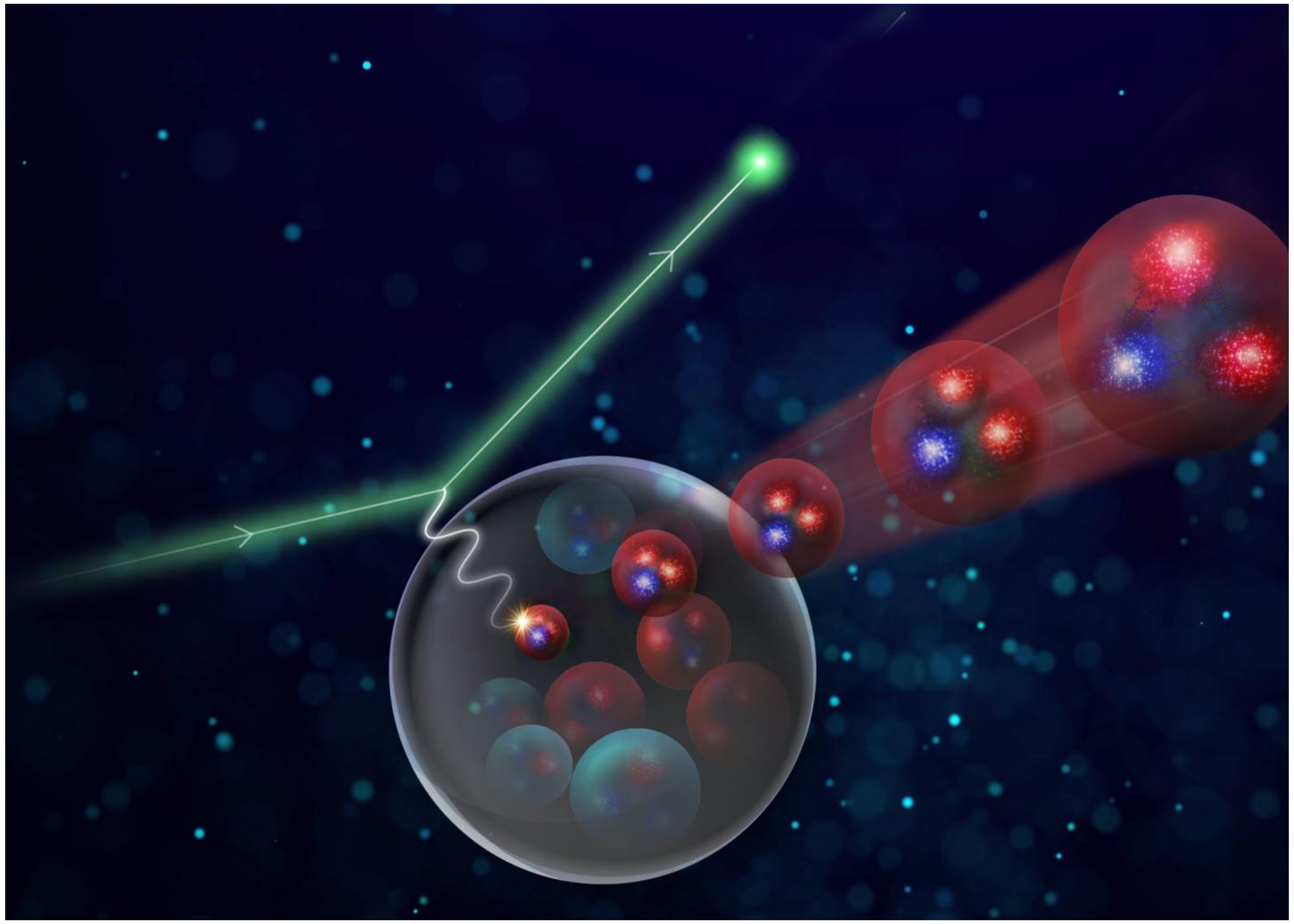
*Mean transverse size as a function of Q and Twist*

# *Color Transparency and Light-Front Holography*

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

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

# The Onset of Color Transparency in Holographic Light-Front QCD



with Guy F. de Téramond

Future of Color Transparency and Hadronization Studies at JLab and Beyond

Stan Brodsky

SLAC NATIONAL ACCELERATOR LABORATORY

June 7, 2021