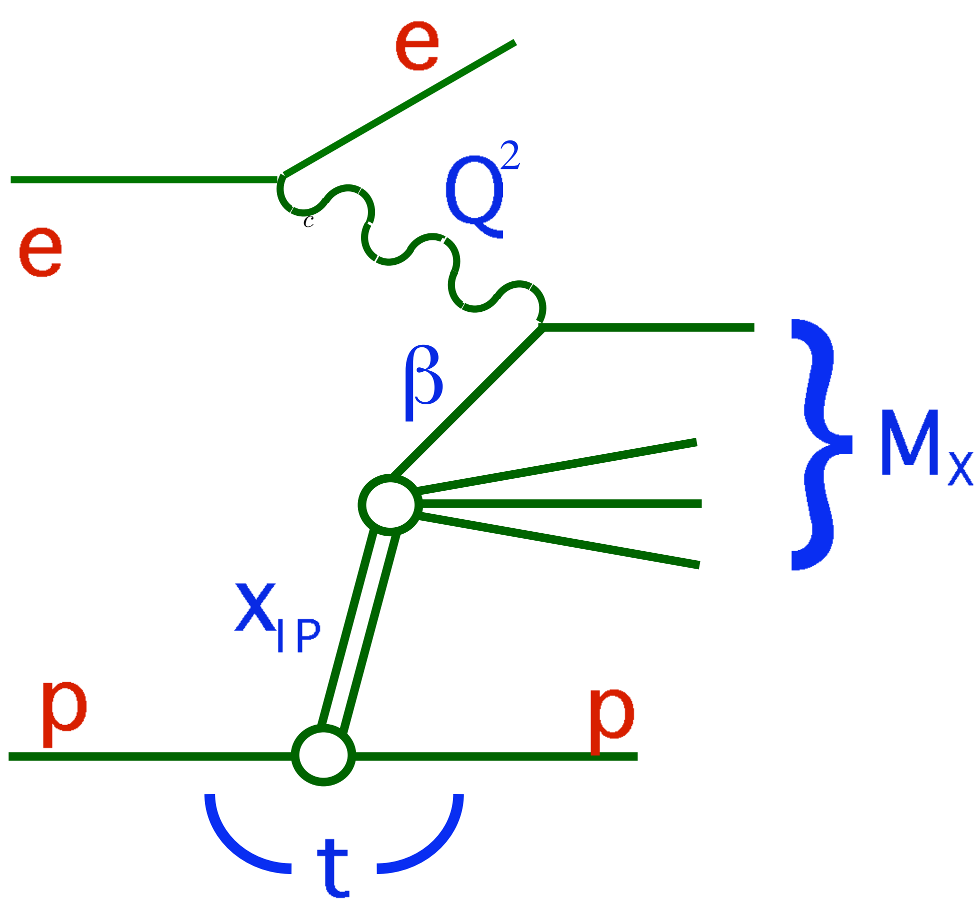
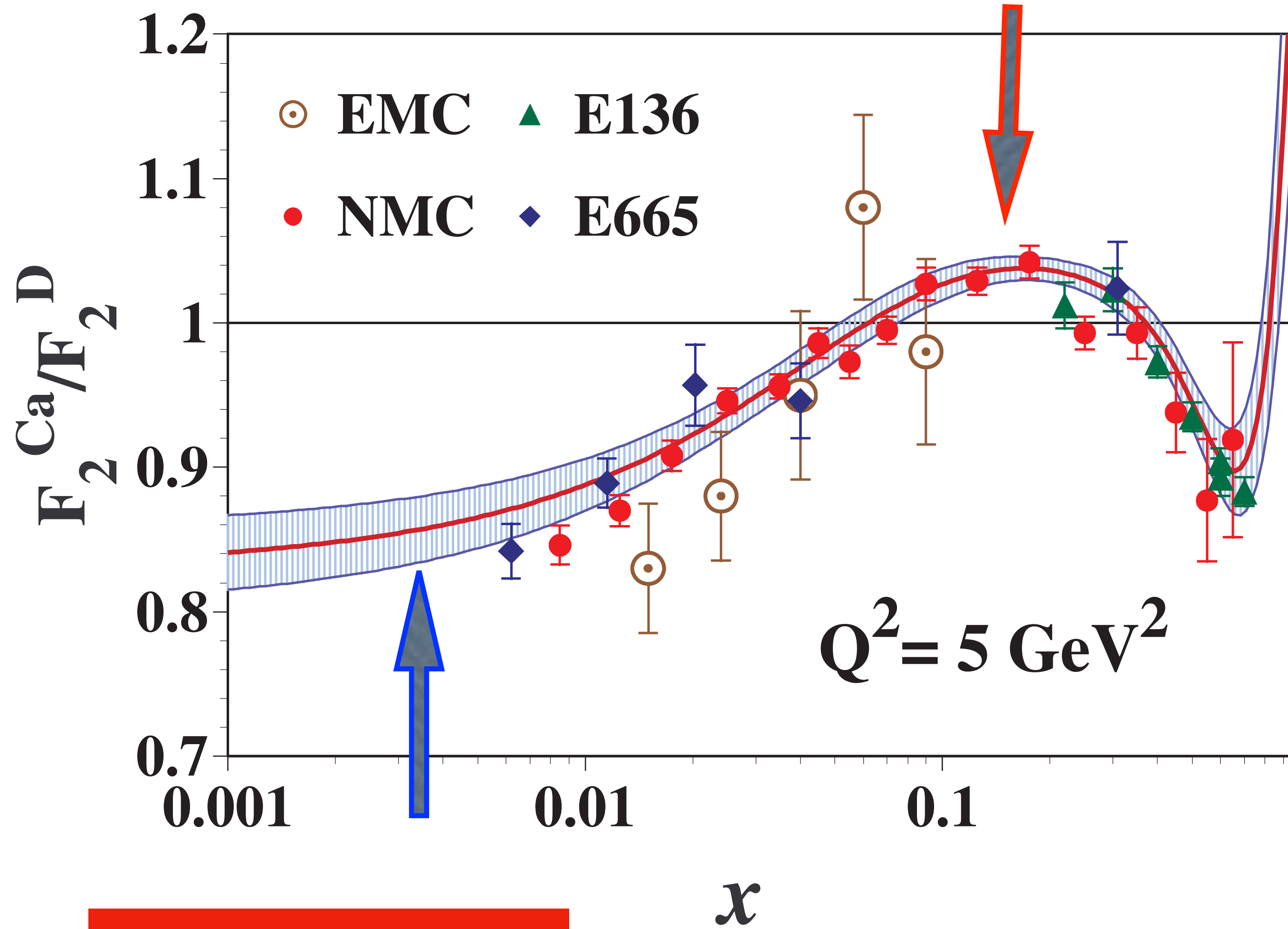
Diffractive Contribution to Deep Inelastic Scattering: Implications for QCD Sum Rules and Nuclear Parton Distributions

Anti-Shadowing





Diffractive DIS (DDIS)

Shadowing

Stan Brodsky

SLAC NATIONAL ACCELERATOR LABORATORY

Low-x 2021

Elba, September 27, 2021

The Diffractive Contribution to Deep Inelastic Lepton-Proton Scattering: Implications for QCD Momentum Sum Rules and Parton Distributions

Stanley J. Brodsky,[1] Valery E. Lyubovitskij,[2,3] and Ivan Schmidt[3]

[1]*SLAC National Accelerator Laboratory, Stanford University, Stanford, CA 94309, USA*
[2]*Institut für Theoretische Physik, Universität Tübingen,*
Kepler Center for Astro and Particle Physics, Auf der Morgenstelle 14, D-72076 Tübingen, Germany
[3]*Departamento de Física y Centro Científico Tecnológico de Valparaíso-CCTVal,*
Universidad Técnica Federico Santa María, Casilla 110-V, Valparaíso, Chile

Is the Momentum Sum Rule Valid for Nuclear Structure Functions ?

Stanley J. Brodsky

SLAC National Accelerator Laboratory, Stanford University

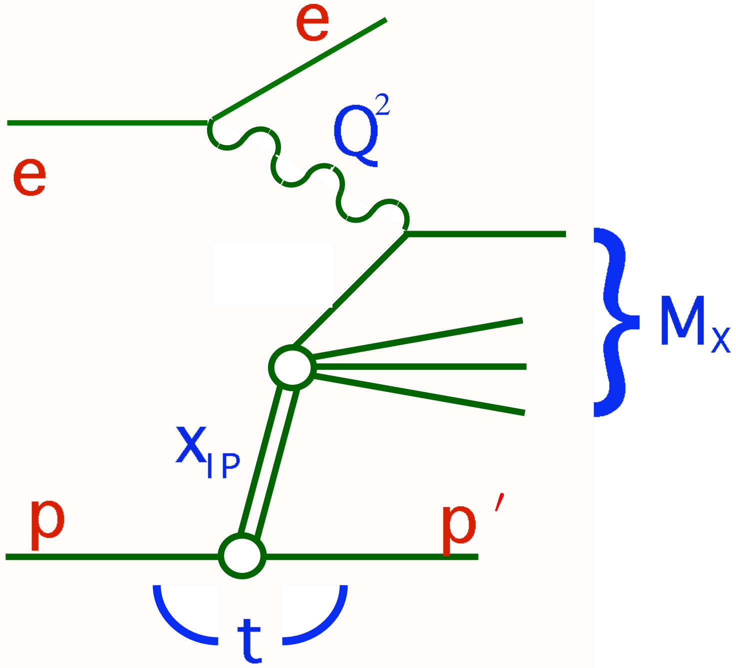
Ivan Schmidt

Departamento de Física y Centro Científico Tecnológico de Valparaíso-CCTVal
Universidad Técnica Federico Santa María, Casilla 110-V, Valparaíso, Chile

Simonetta Liuti*

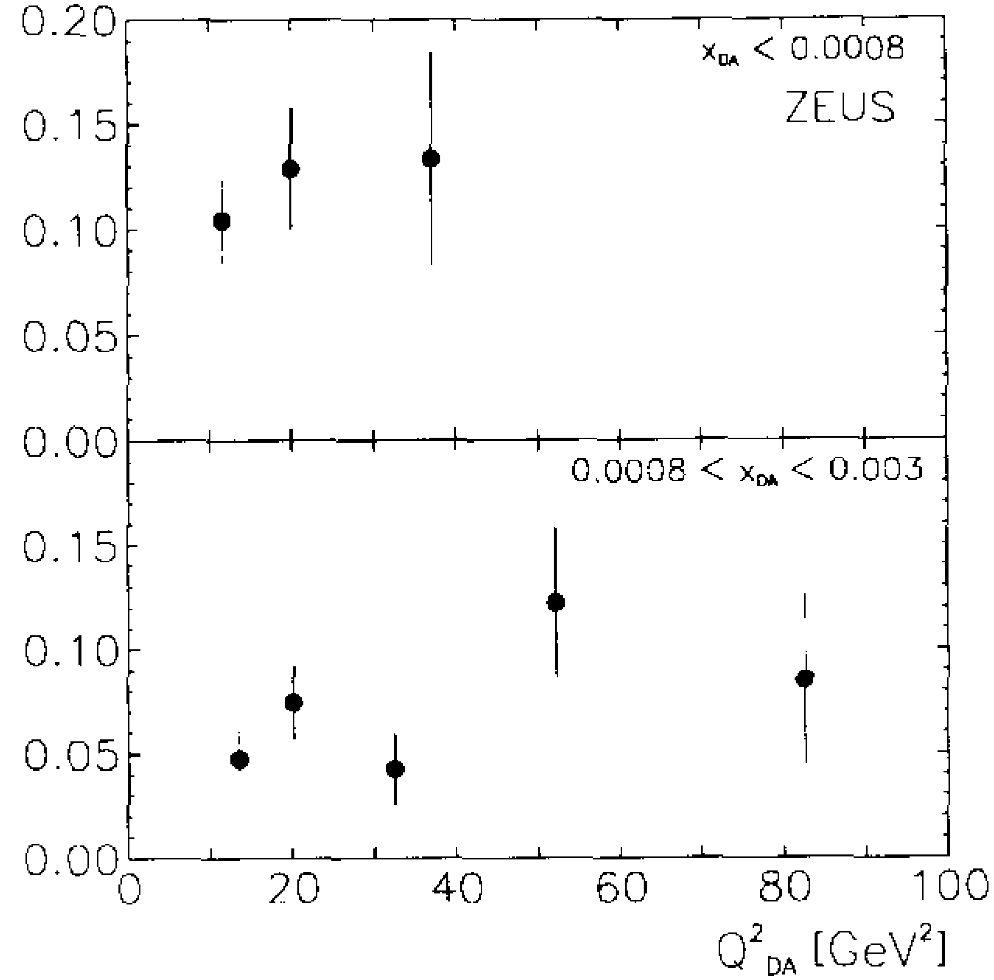
Department of Physics, University of Virginia, Charlottesville, VA 22904, USA.
(Dated: August 20, 2019)

Remarkable observation at HERA



10% to 15% of DIS events are diffractive !

ratio: DDIS/DIS

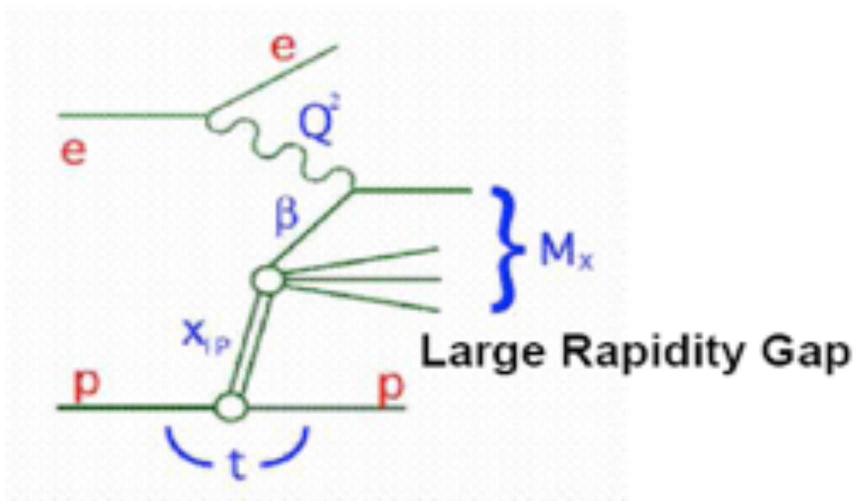


. Fraction r of events with a large rapidity gap, $\eta_{max} < 1.5$, as a function of Q^2_{DA} for two ranges of x_{DA}. No acceptance corrections have been applied.

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

DDIS is leading twist , Bjorken scaling

Diffractive Structure Function F_2^D



Diffractive inclusive cross section

$$\frac{d^3\sigma_{NC}^{diff}}{dx_{I\!P}\, d\beta\, dQ^2} \propto \frac{2\pi\alpha^2}{xQ^4} F_2^{D(3)}(x_{I\!P}, \beta, Q^2)$$

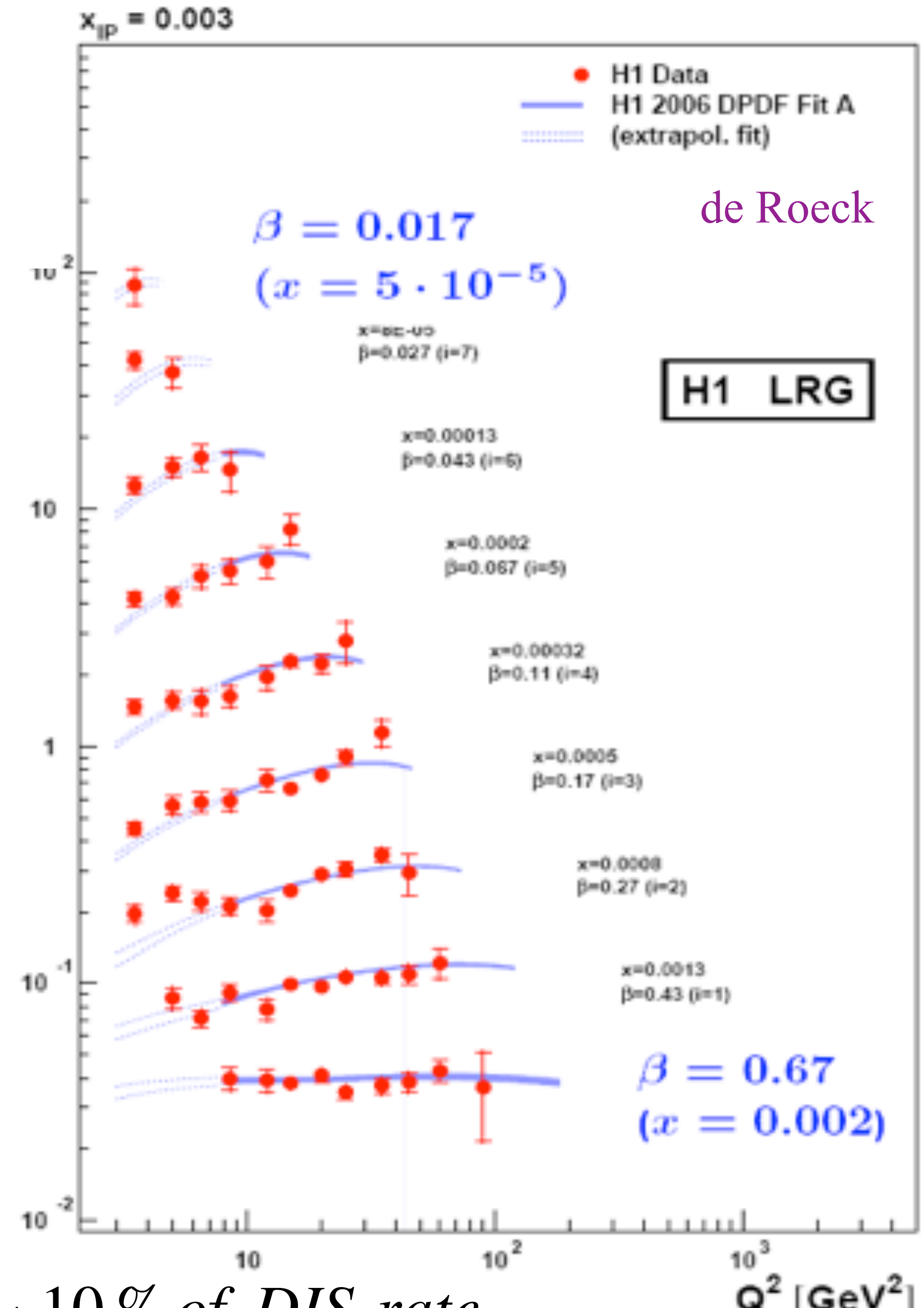
$$F_2^D(x_{I\!P}, \beta, Q^2) = f(x_{I\!P}) \cdot F_2^{I\!P}(\beta, Q^2)$$

extract DPDF and $xg(x)$ from scaling violation

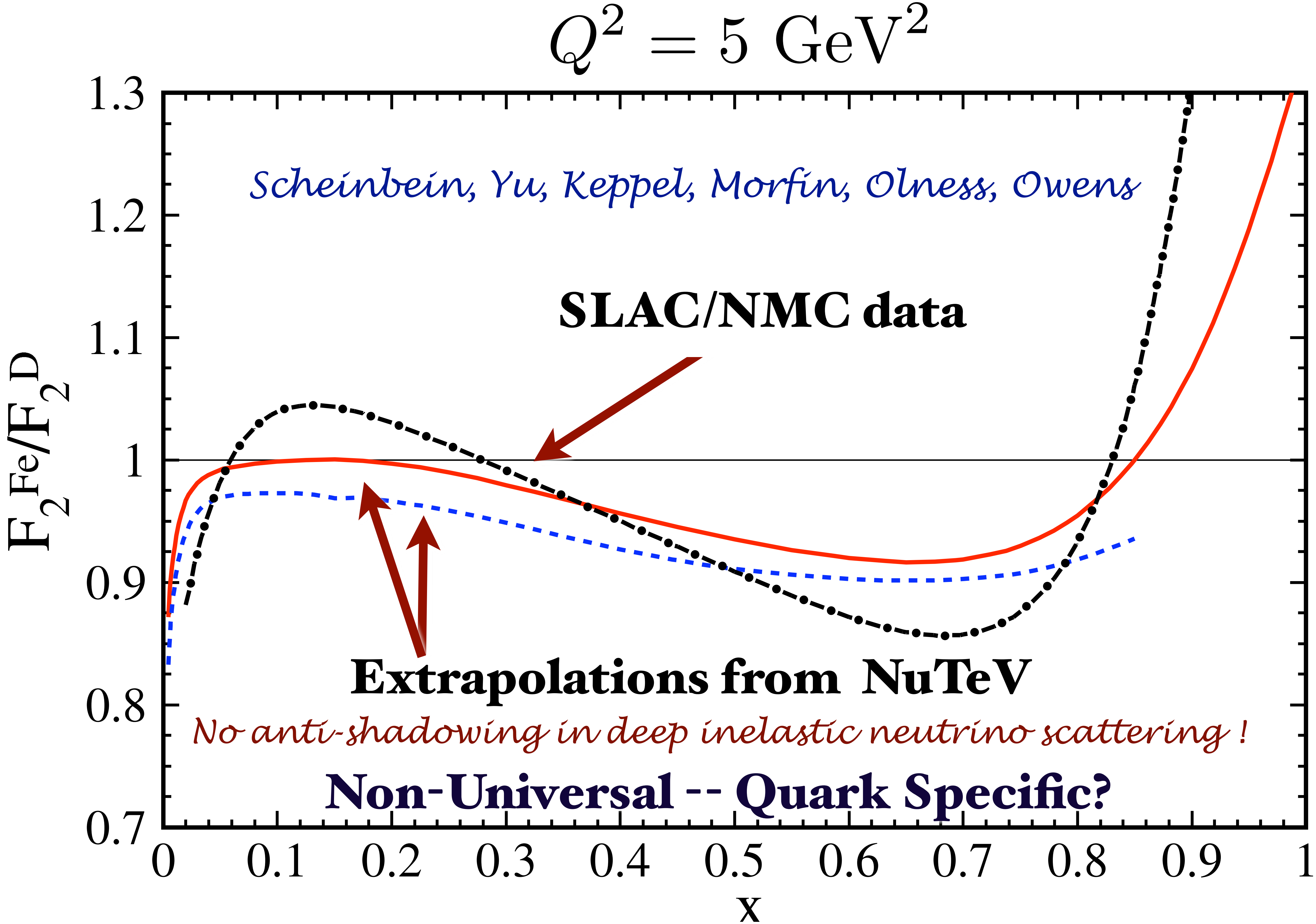
Large kinematic domain $3 < Q^2 < 1600\ \mathrm{GeV}^2$

Precise measurements *sys 5%, stat 5–20 %*

Bjorken Scaling, Leading Twist



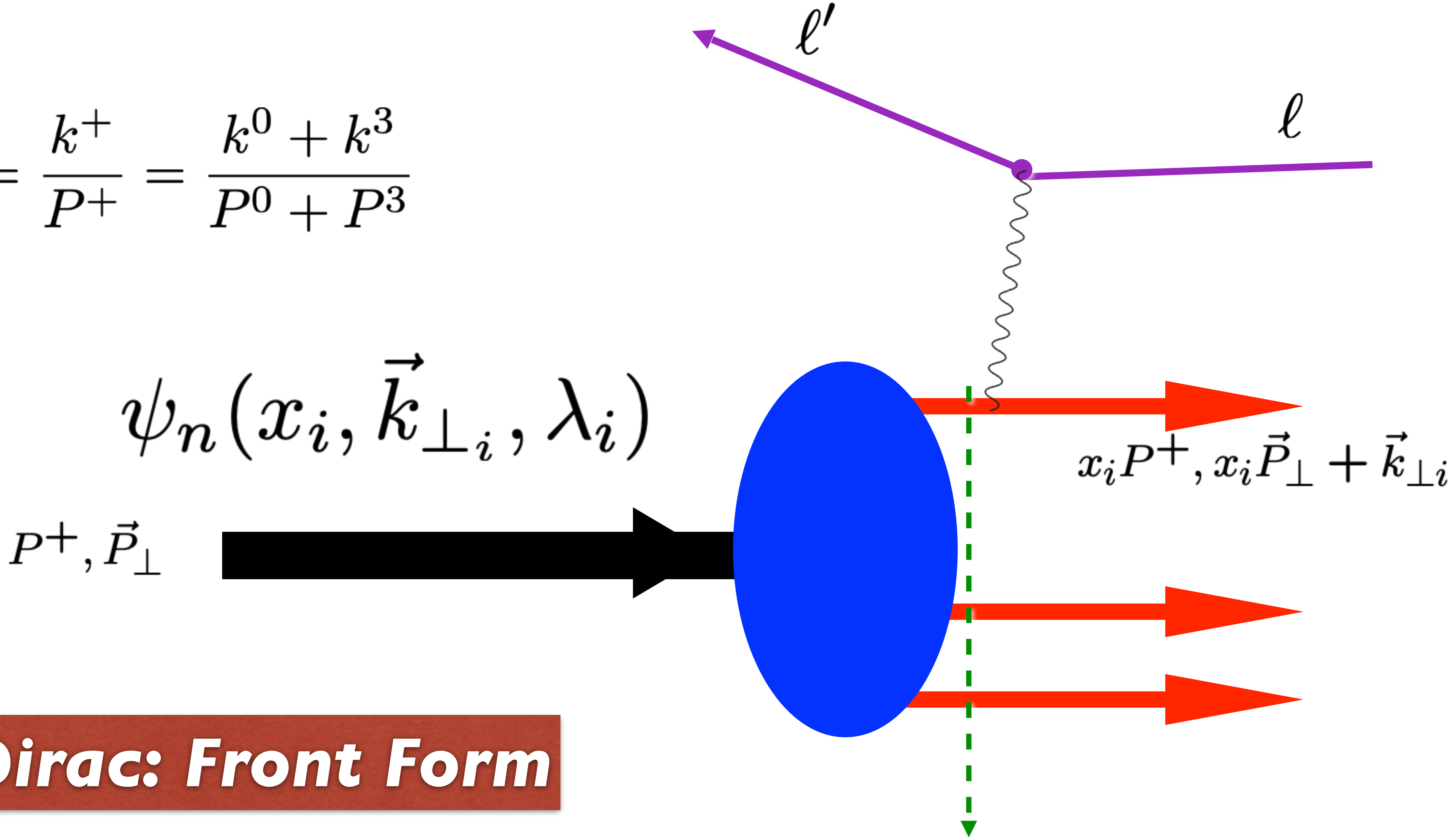
$DDIS \sim 10\,\%$ *of DIS rate*



Nuclear Shadowing and Anti-Shadowing

Can the Momentum Sum Rule be applied?

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



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

Light-Front QCD

Physical gauge: $A^+ = 0$

Exact frame-independent formulation of nonperturbative QCD!

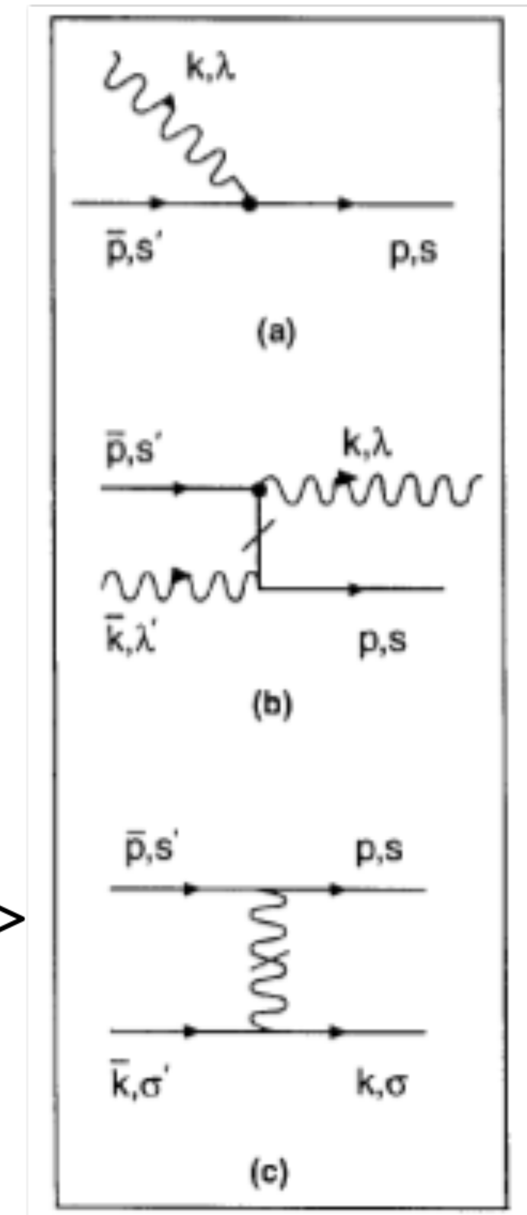
$$L^{QCD} \rightarrow H^{QCD}_{LF}$$

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

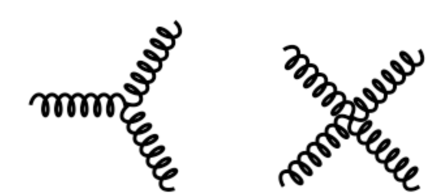
H^{int}_{LF}: Matrix in Fock Space

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

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



Eigenvalues and Eigensolutions give Hadronic Spectrum and Light-Front wavefunctions



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

LFWFs: Off-shell in P- and invariant mass

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

$$x_i = \frac{k_i^+}{P^+}, \sum_i k_i^+ = P^+$$

$$\sum_{i=1}^n x_i = 1, \sum_{i=1}^n \vec{k}_{\perp i} = 0$$

Light-Front Wavefunctions $\psi(x_i, k_{\perp i}, \lambda_i)$
obey charge and momentum sum rules

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

sum over states with n=3, 4, ...constituents

The Light Front Fock State Wavefunctions

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

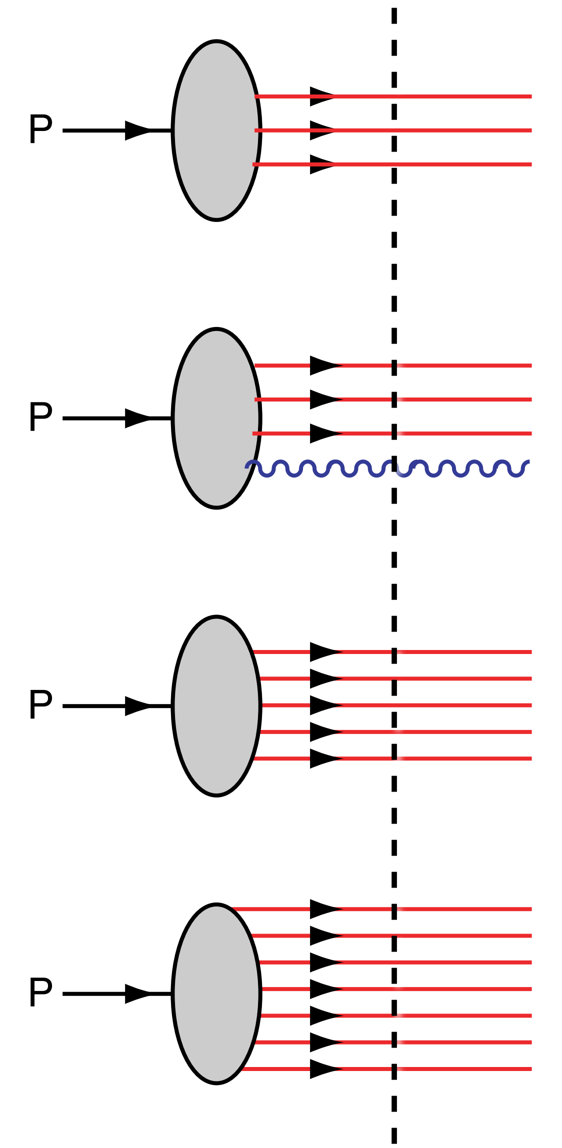
are boost invariant; they are independent of the hadron's energy and momentum P^μ.

The light-cone momentum fractions

$$x_i = \frac{k_i^+}{p^+} = \frac{k_i^0 + k_i^z}{P^0 + P^z}$$

are boost invariant.

$$\sum_i^n k_i^+ = P^+, \ \sum_i^n x_i = 1, \ \sum_i^n \vec{k}_i^\perp = \vec{0}^\perp.$$



Fixed LF time

Intrinsic heavy quarks

s(x), c(x), b(x) at high x !

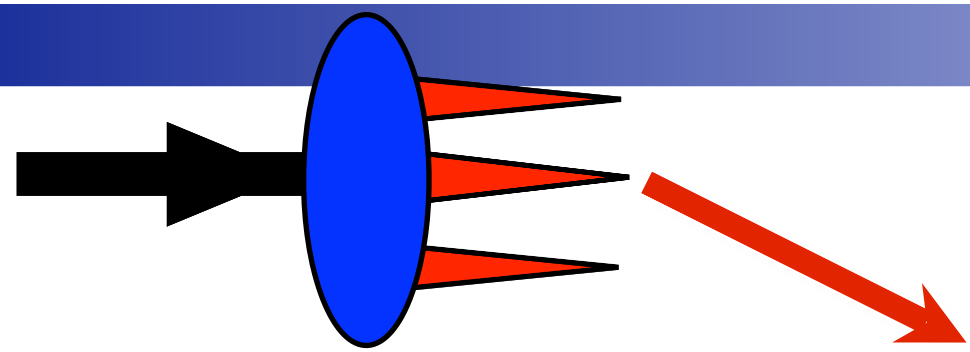
$\bar{s}(x) \neq s(x)$

$\bar{u}(x) \neq \bar{d}(x)$

Deuteron: Hidden Color

Light-Front Wavefunctions underly hadronic observables

Lorce, Pasquini



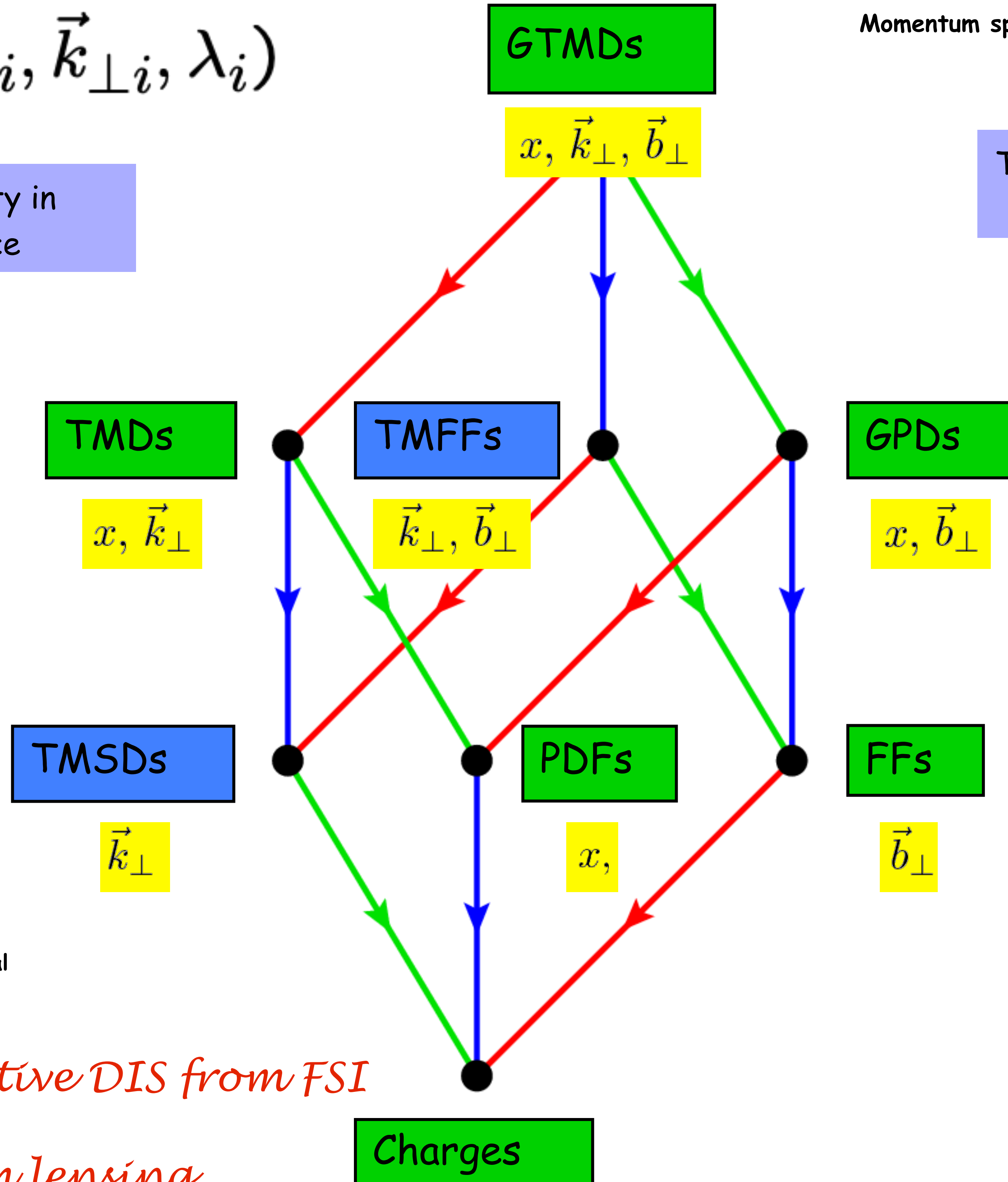
$$\Psi_n(x_i, \vec{k}_{\perp i}, \lambda_i)$$

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



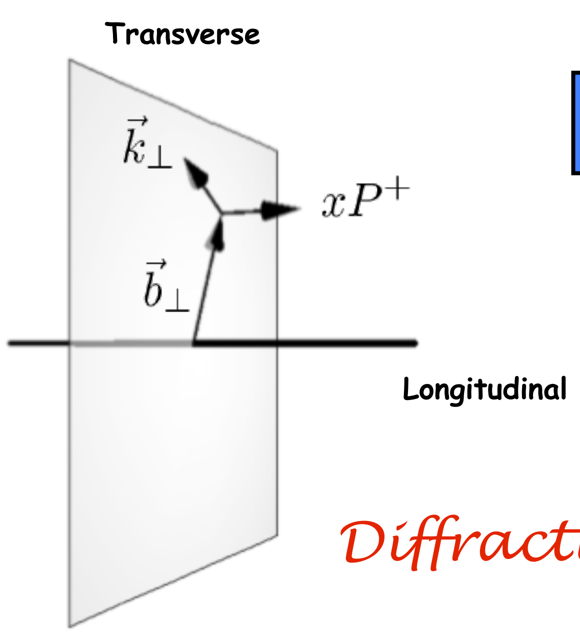
$\int d^2b_\perp$

$\int dx$

$\int d^2k_\perp$

Weak transition form factors

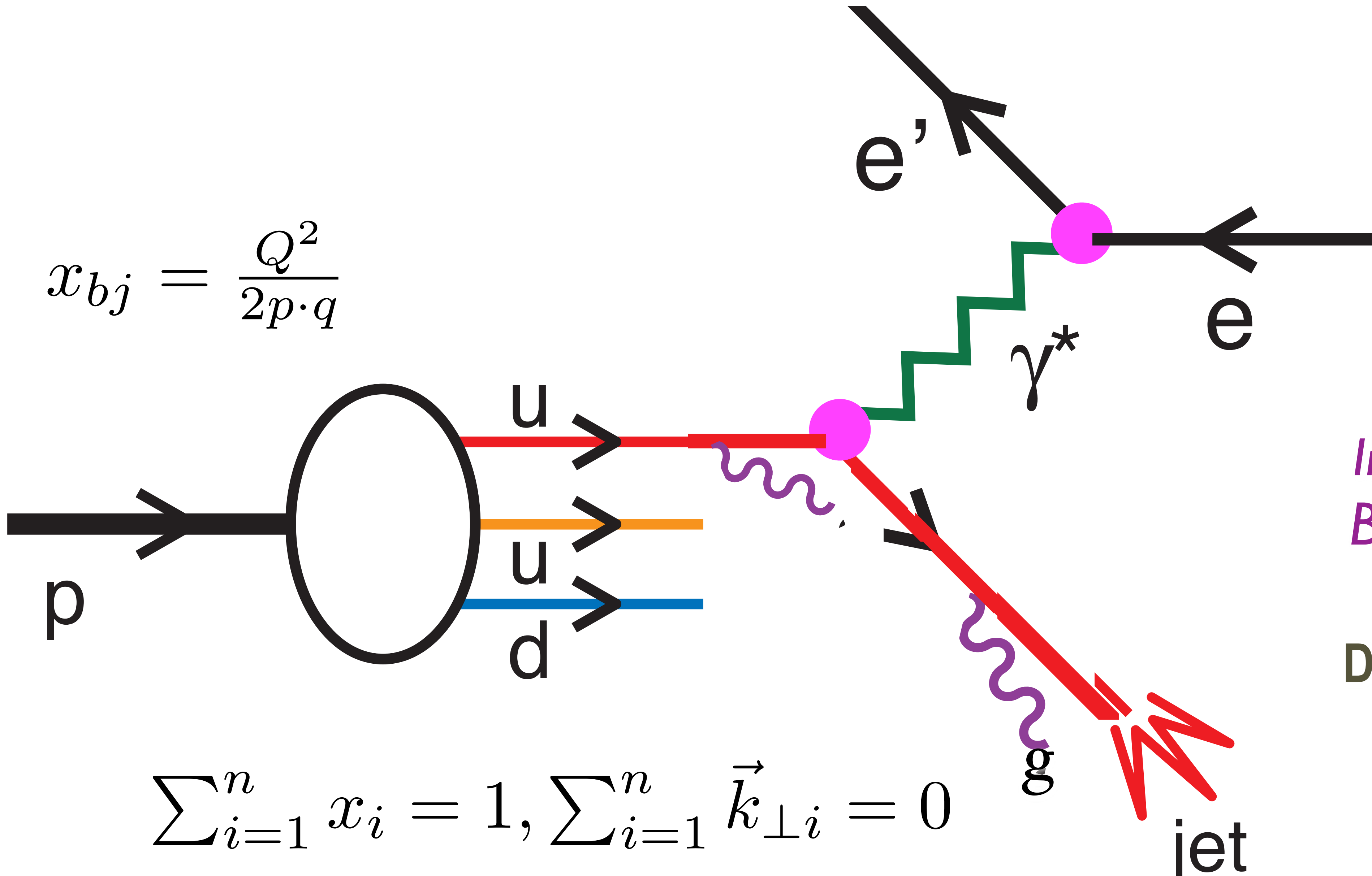
DGLAP, ERBL Evolution Factorization Theorems



Diffractive DIS from FSI

Sivers, T-odd from lensing

Deep Inelastic Electron-Proton Scattering



$x_{bj} = \frac{Q^2}{2p\cdot q}$

Includes Gluonic Bremsstrahlung

DGLAP Evolution

$$\sum_{i=1}^{n} x_i = 1, \sum_{i=1}^{n} \vec{k}_{\perp i} = 0$$

$$F_2(x_{bj}, Q^2) = \sum_{n\geq 3} \int_0^1 dx_i \int d^2k_{\perp_i} |\psi_n(x_i, \vec{k}_{\perp i})|^2 \delta(x_{struck} - x_{bj})$$

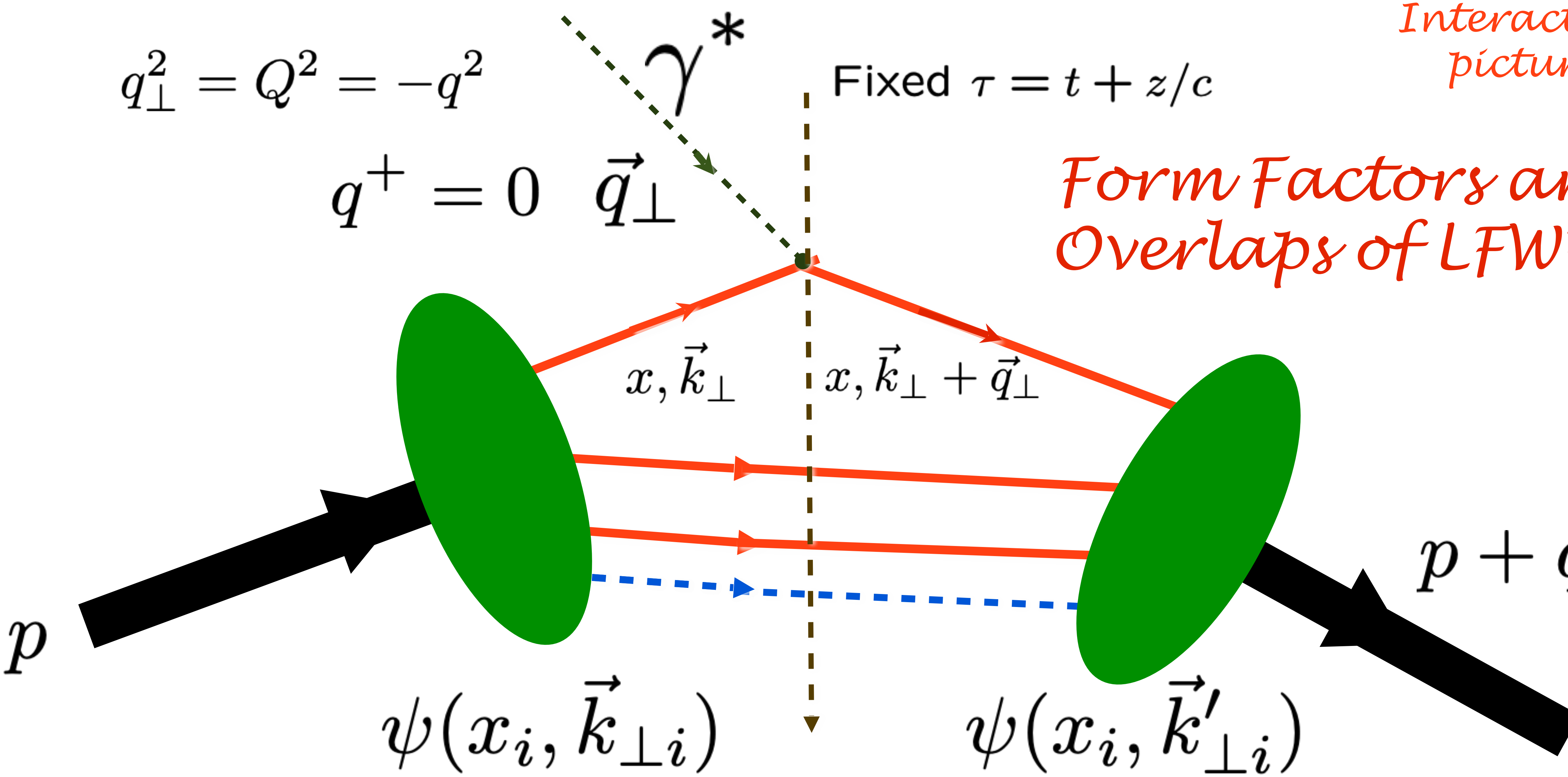
$$|p, J_z> = \sum_{n=3} \psi_n(x_i, \vec{k}_{\perp i}, \lambda_i)|n; x_i, \vec{k}_{\perp i}, \lambda_i>$$

Front Form

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

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

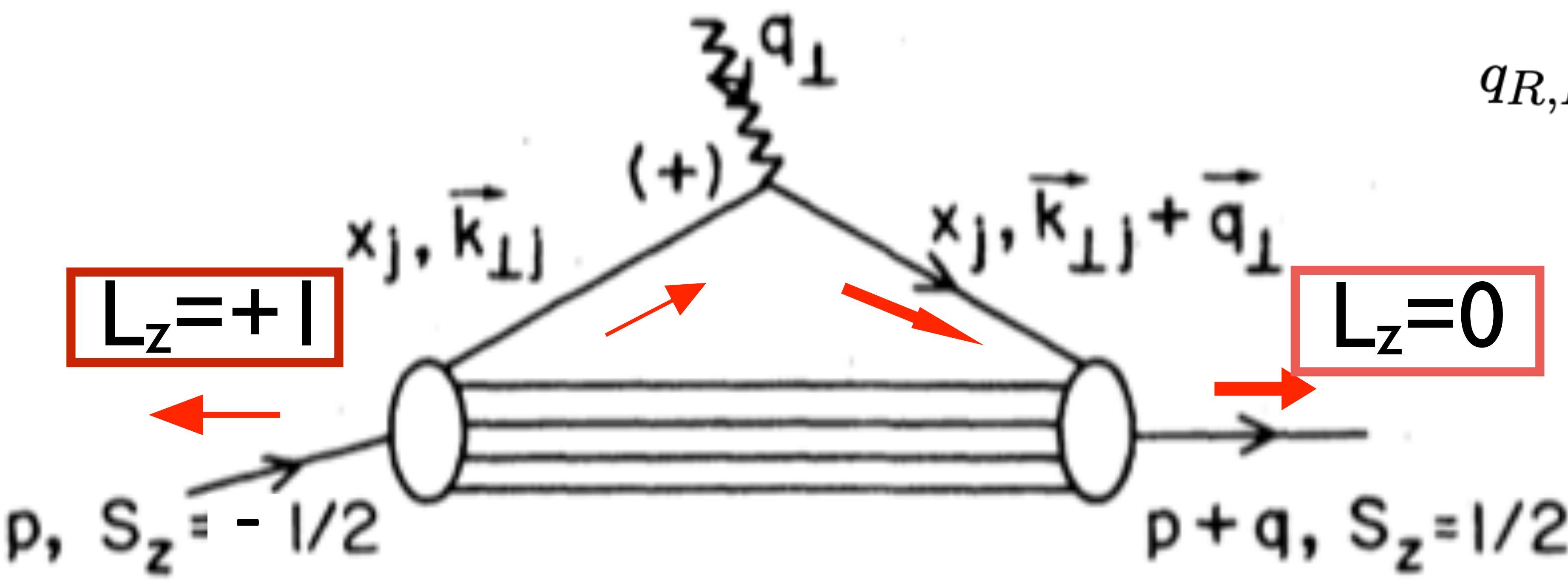
Drell, sjb

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

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

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

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



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

Nonzero Proton Anomalous Moment -->

Nonzero orbital quark angular momentum

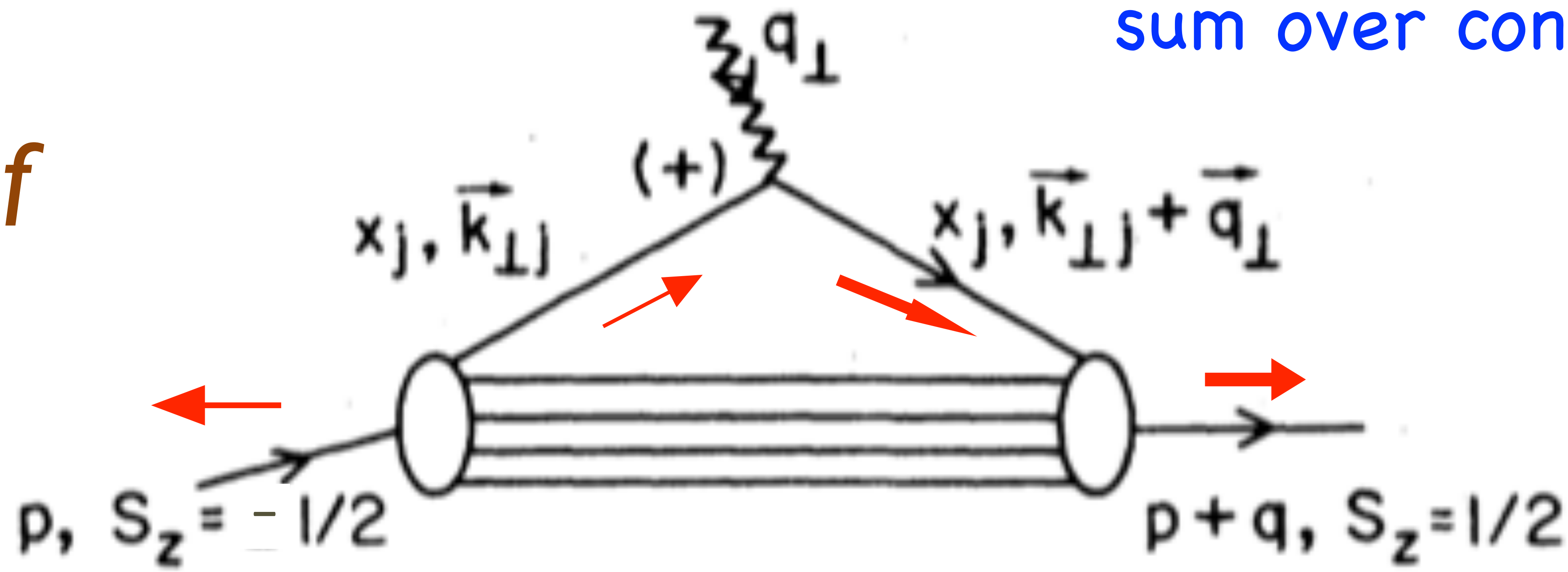
Dae Sung Hwang, Bo-Qiang Ma, Ivan Schmidt, sjb

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

graviton

sum over constituents

LF Proof



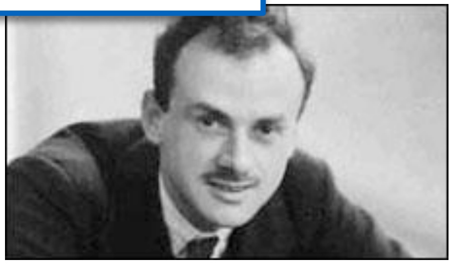
B(0) = 0

Each Fock State

Vanishing Anomalous gravitomagnetic moment B(0)

Advantages of the Dirac's Front Form for Hadron Physics
Poincare' Invariant

Physics Independent of Observer's Motion



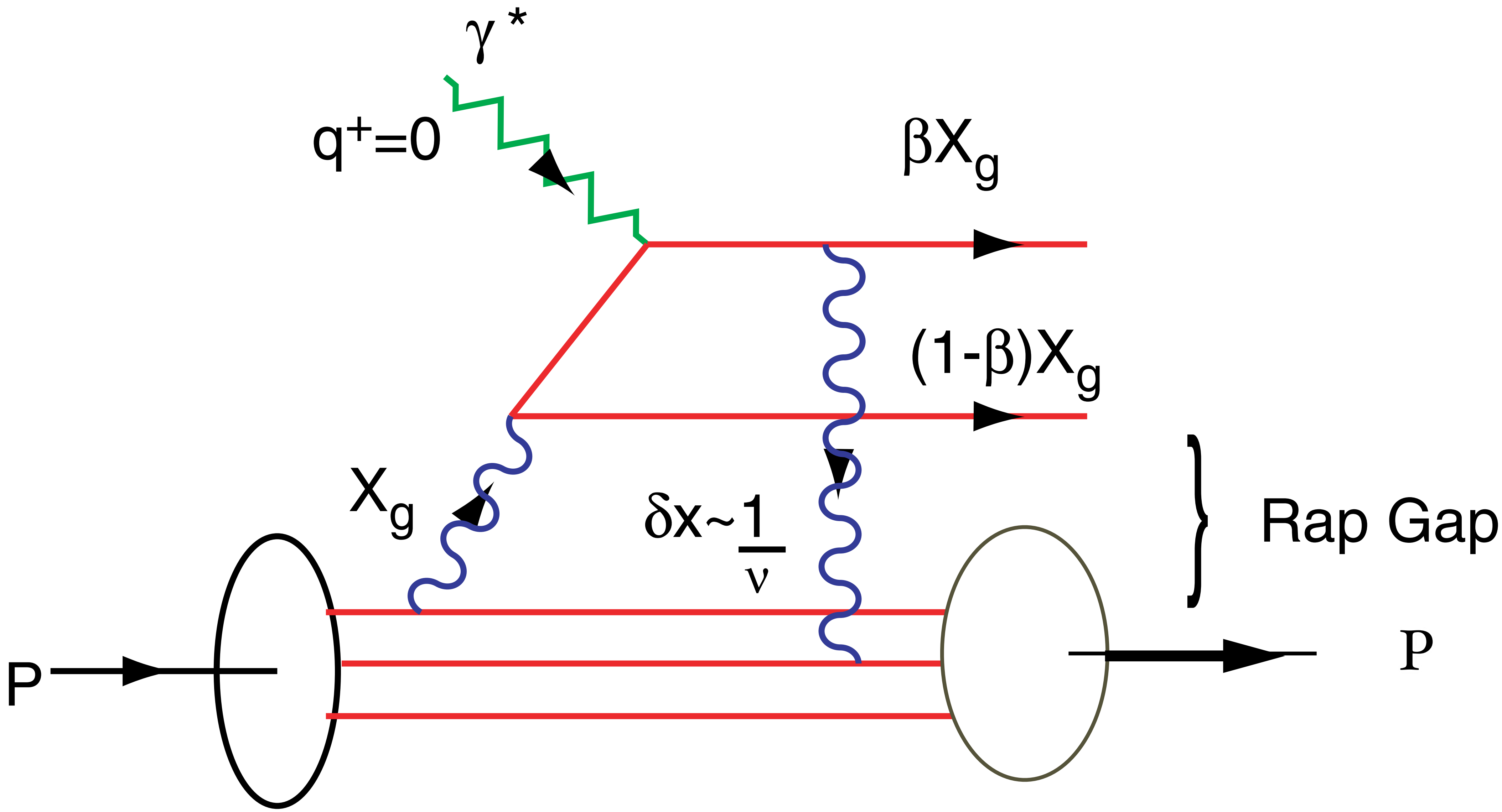
- Measurements are made at fixed τ
- Causality is automatic
- Structure Functions are squares of LFWFs
- Form Factors are overlap of LFWFs
- LFWFs are frame-independent: no boosts, no pancakes!

Penrose, Terrell, Weisskopf

- Same structure function measured at an e p collider and the proton rest frame
- No dependence of hadron structure on observer's frame
- LF Holography: Dual to AdS space
- LF Vacuum trivial up to zero modes
- Implications for Cosmological Constant

Hoyer, Marchal, Peigne, Sannino, sjb

QCD Mechanism for DDIS and Rapidity Gaps

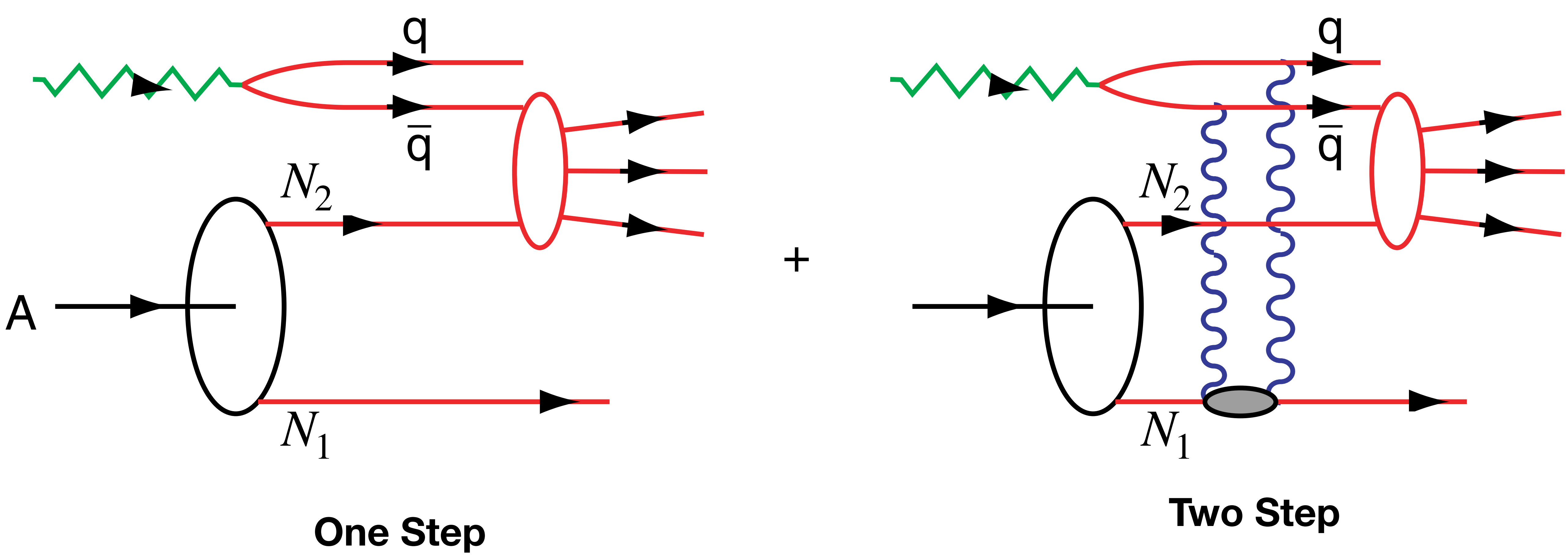


Reproduces lab-frame color dipole approach
DDIS: Input for leading twist nuclear shadowing

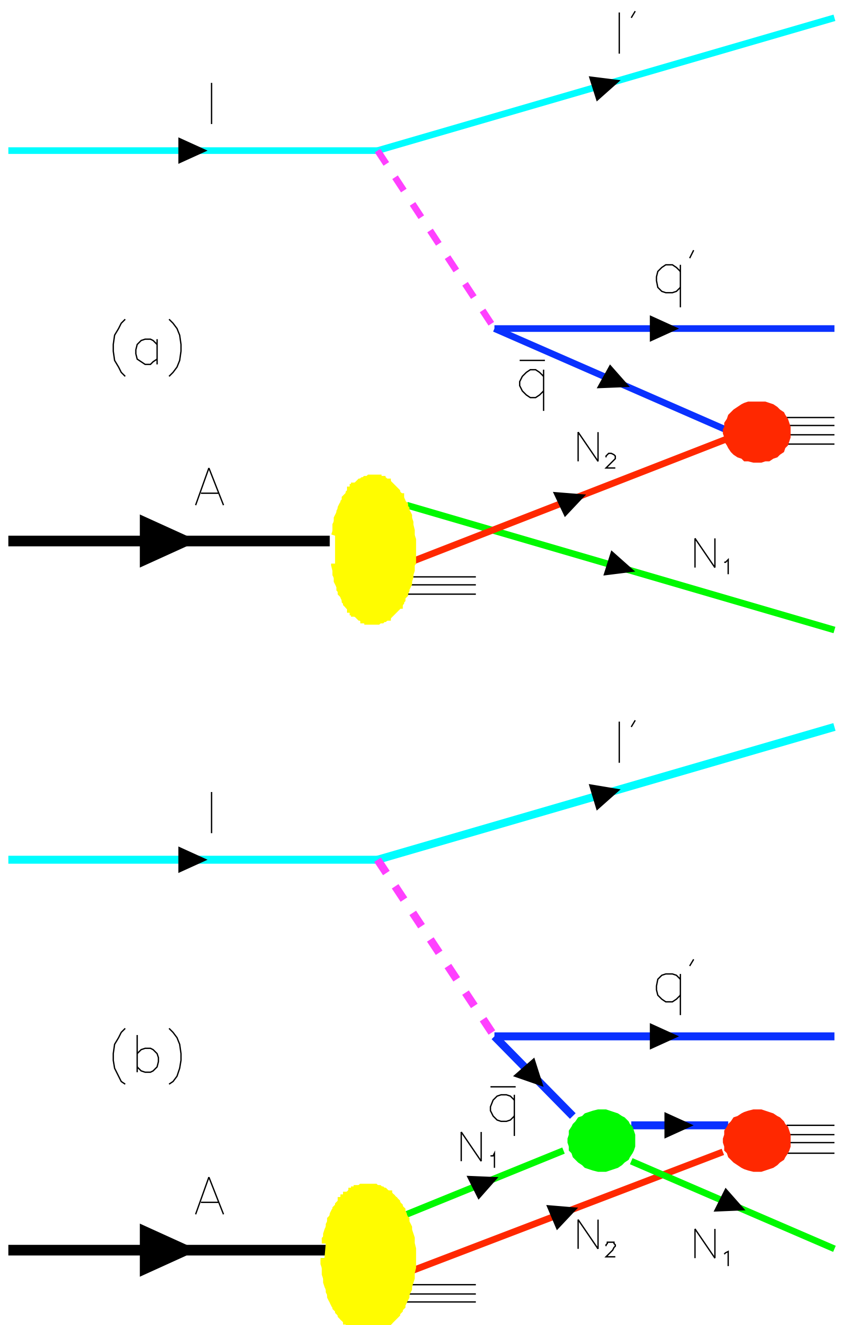
DDIS: Diffractive Deep Inelastic Scattering

Stodolsky
Pumplin, sjb
Gribov

Theory of Nuclear Shadowing in DIS



Shadowing depends on understanding leading twist-diffraction in DIS



The one-step and two-step processes in DIS on a nucleus.

Coherence at small Bjorken x_B : $1/Mx_B = 2\nu/Q^2 \geq L_A$.

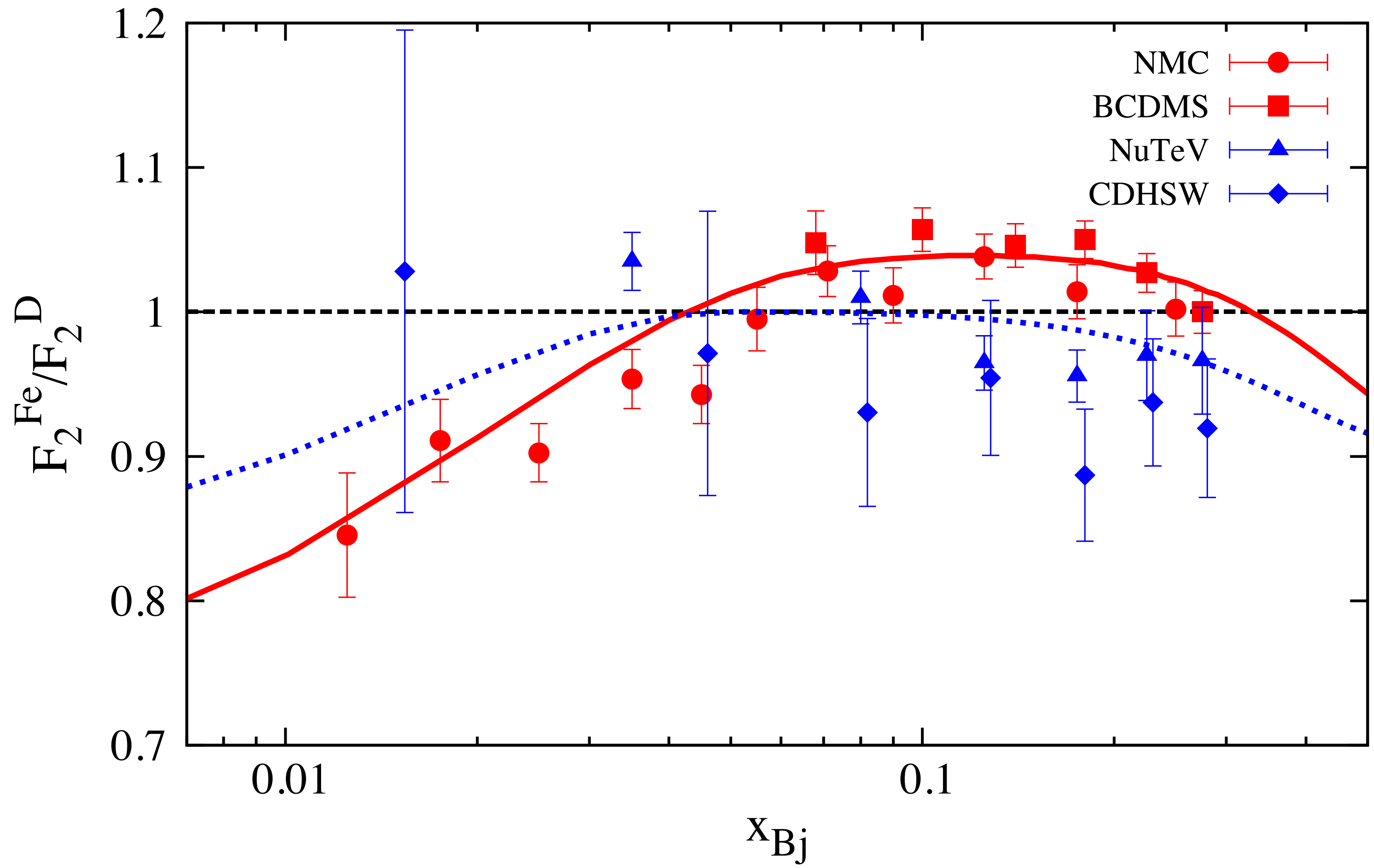
If the scattering on nucleon N_1 is via pomeron exchange, the one-step and two-step amplitudes are opposite in phase, thus diminishing the $\bar{q}$ flux reaching N_2.

$\rightarrow$ Shadowing of the DIS nuclear structure functions.

Diffraction via Pomeron gives destructive interference!

Shadowing

Shadowing depends on understanding leading-twist diffraction in DIS



Comparison of the ratio of iron to deuteron nuclear structure functions measured in deep inelastic neutrino-nucleus scattering (NuTeV [2], CDHSW [8]), and muon-nucleus scattering (BCDMS [9] and NMC [10, 11]). All data are displayed in the online Durham HepData Project Database [12]. Anti-shadowing is absent in the neutrino charged current data.

Does Diffractive DIS
Obey Momentum and other Sum Rules?

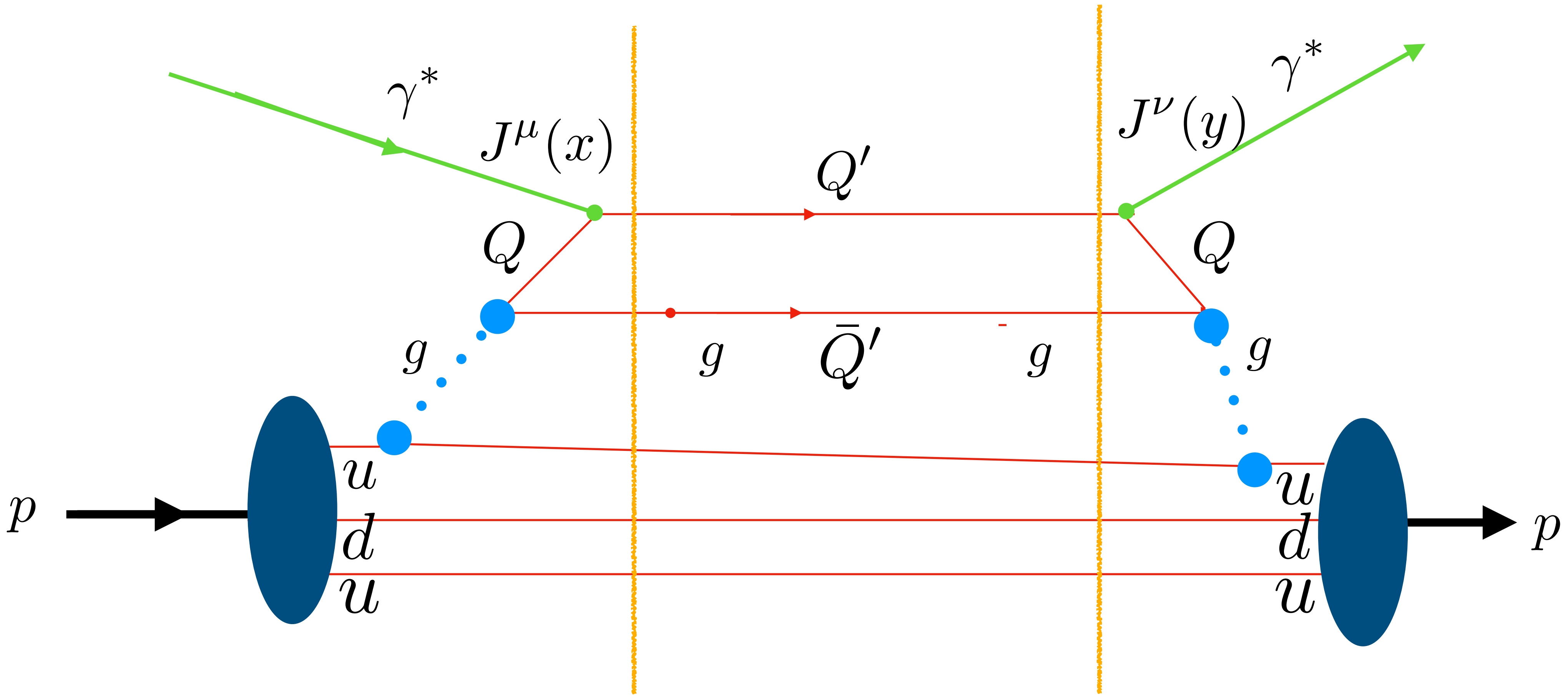
Is Antishadowing in DIS
Non-Universal, Flavor-Dependent?

Do Nuclear PDFS
Obey Momentum and other Sum Rules?

Forward Virtual Compton scattering for a usual DIS event

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

Unitarity: Imaginary part (cut) gives DIS cross-section



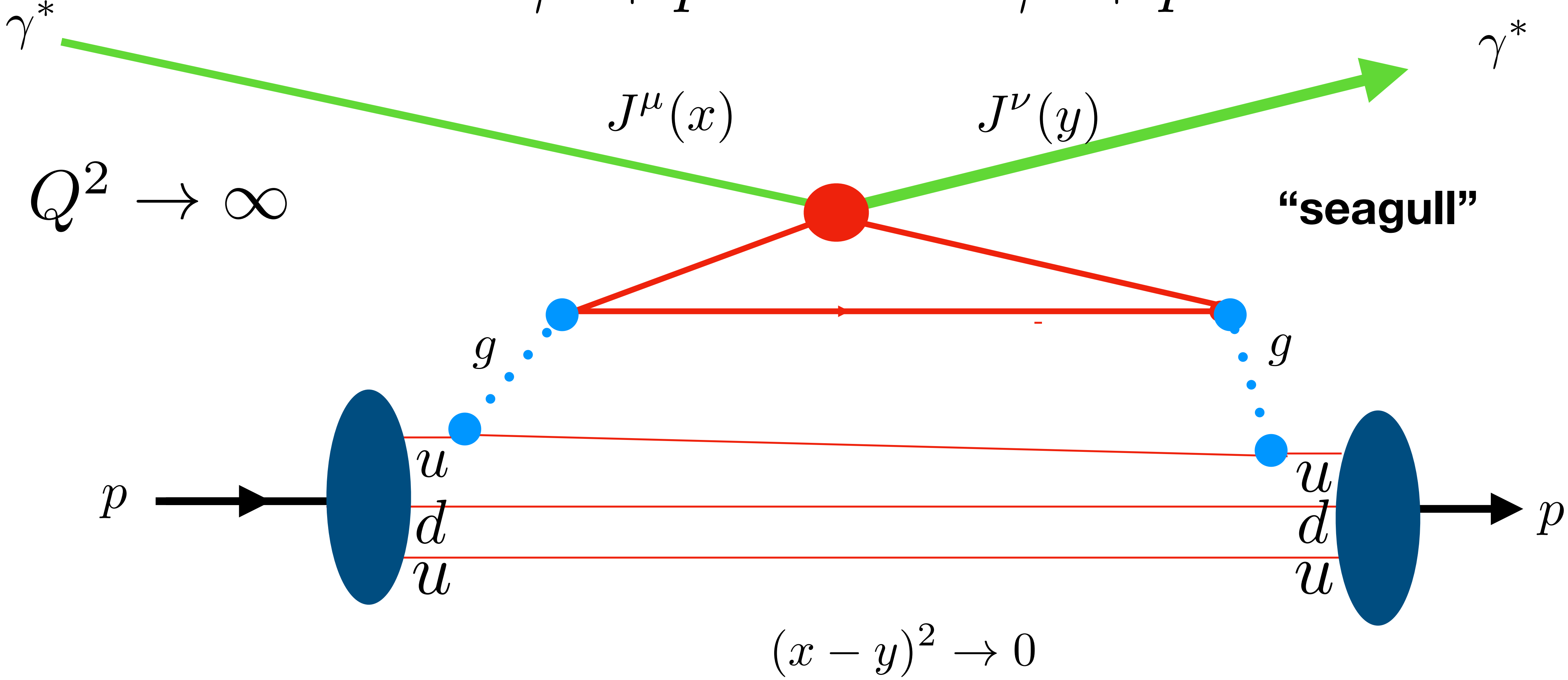
Vanishing LF time between currents of virtual photons at large q^2 : OPE!

$$(x-y)^2 \to 0$$

Forward Virtual Compton scattering for a DIS event

$$Q^2 \to \infty$$

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



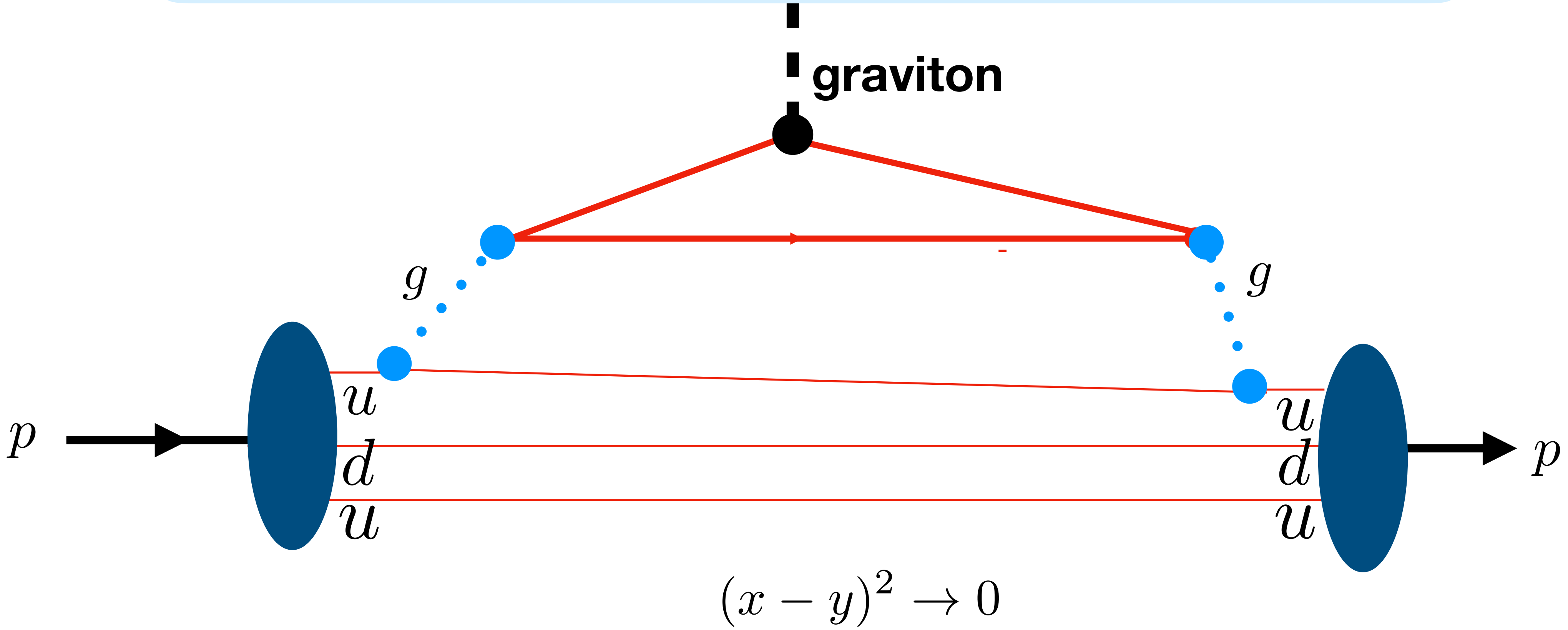
Vanishing LF time between currents of virtual photons at large q^2 : OPE!

Reduces at $Q^2 \to \infty$ to a local operator: $T^{\mu\nu}$:
the energy momentum tensor; i.e., the coupling of a graviton

Forward Virtual Compton scattering for a DIS event

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

T^{++} gives the momentum sum rule



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

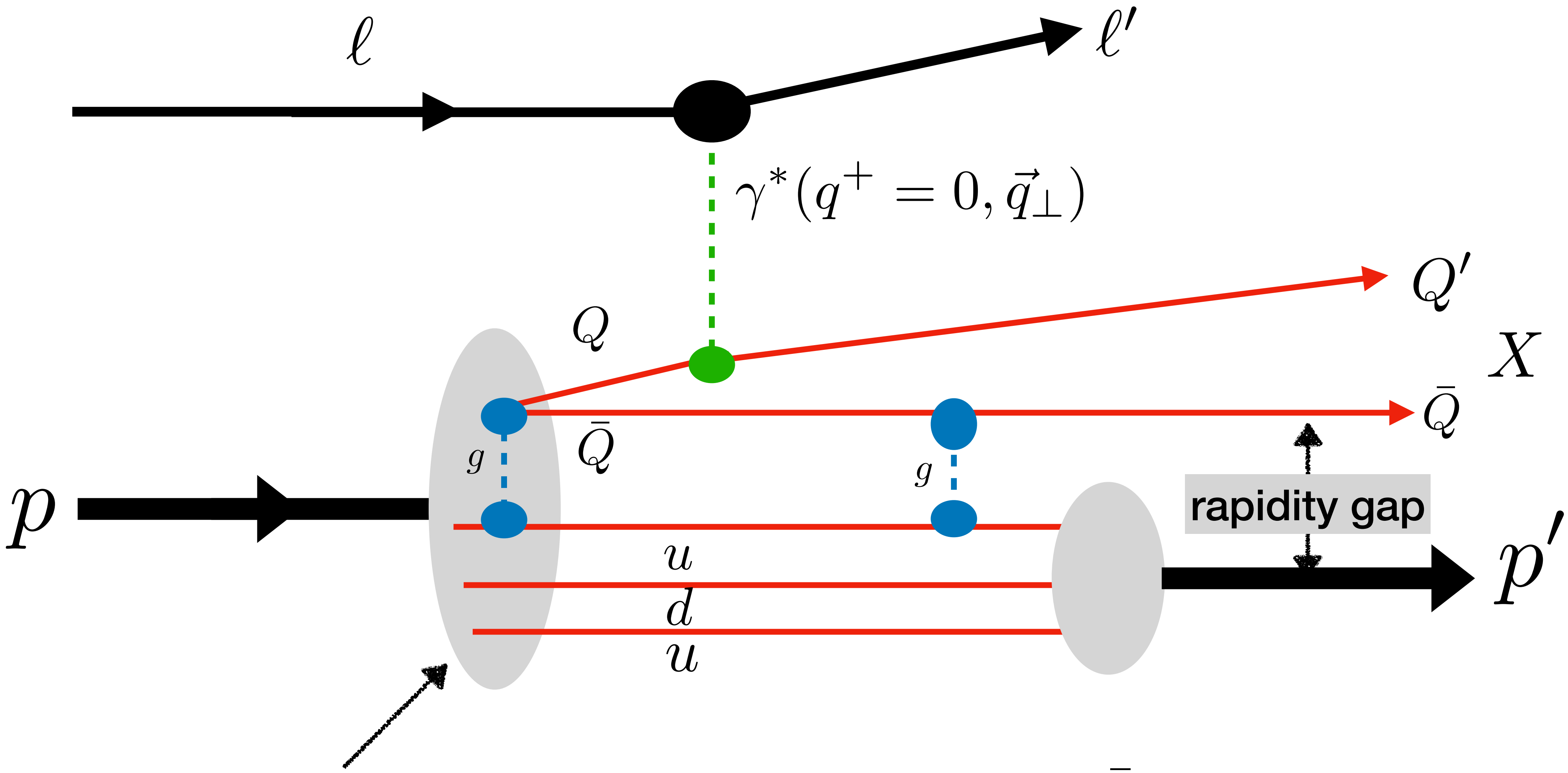
Reduces at $Q^2 \to \infty$ to a local operator: $T^{\mu\nu}$:
the energy momentum tensor; i.e., the coupling of a graviton

T^{++} gives the momentum sum rule

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

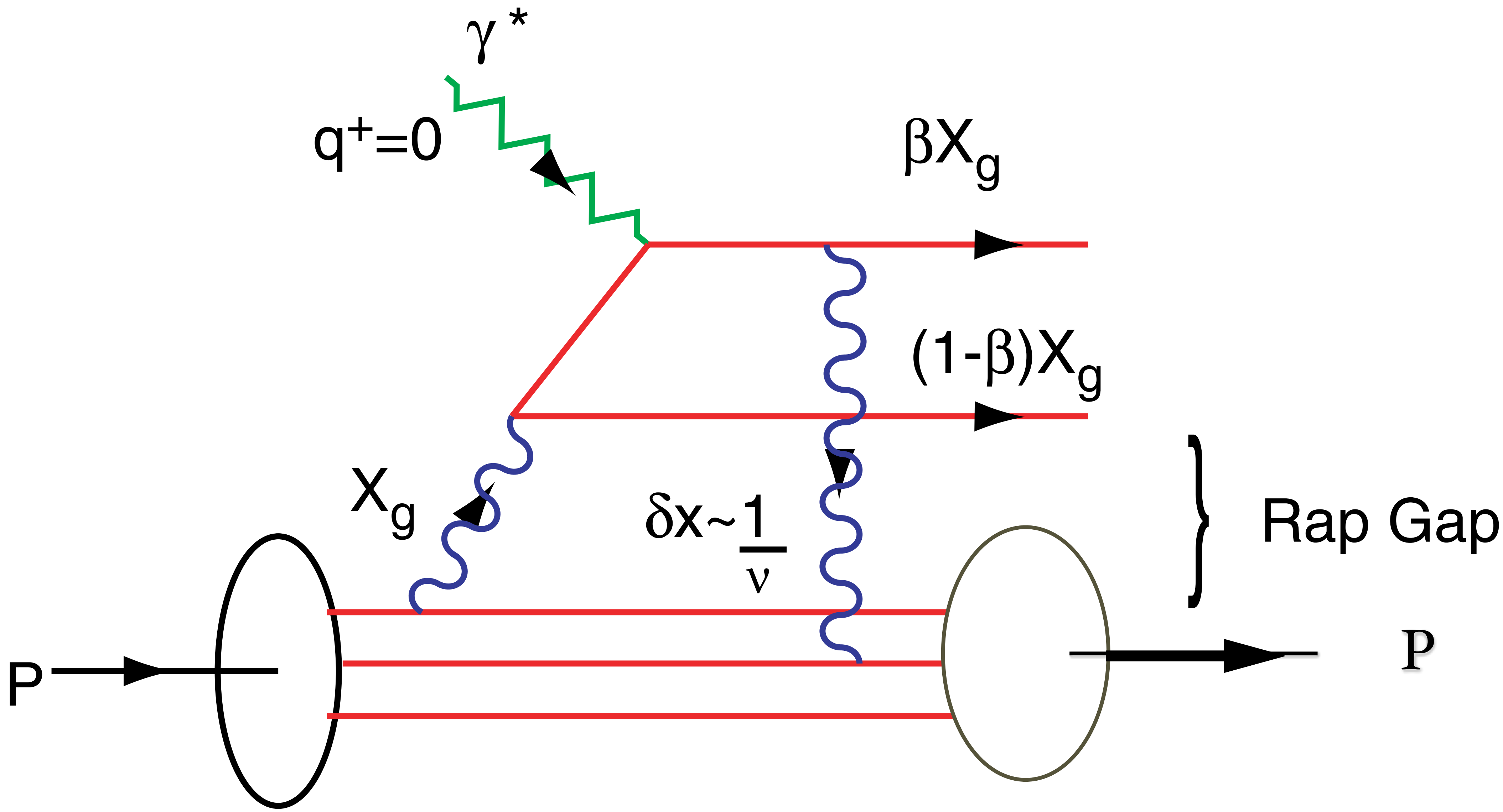


Five-quark Fock state of proton: $|\{udu\}_{8C}\{Q\bar{Q}\}_{8C} >$

Low-Nussinov Two-Gluon Model of Pomeron

Diffractive Deep Inelastic Scattering DDIS

QCD Mechanism for Rapidity Gaps

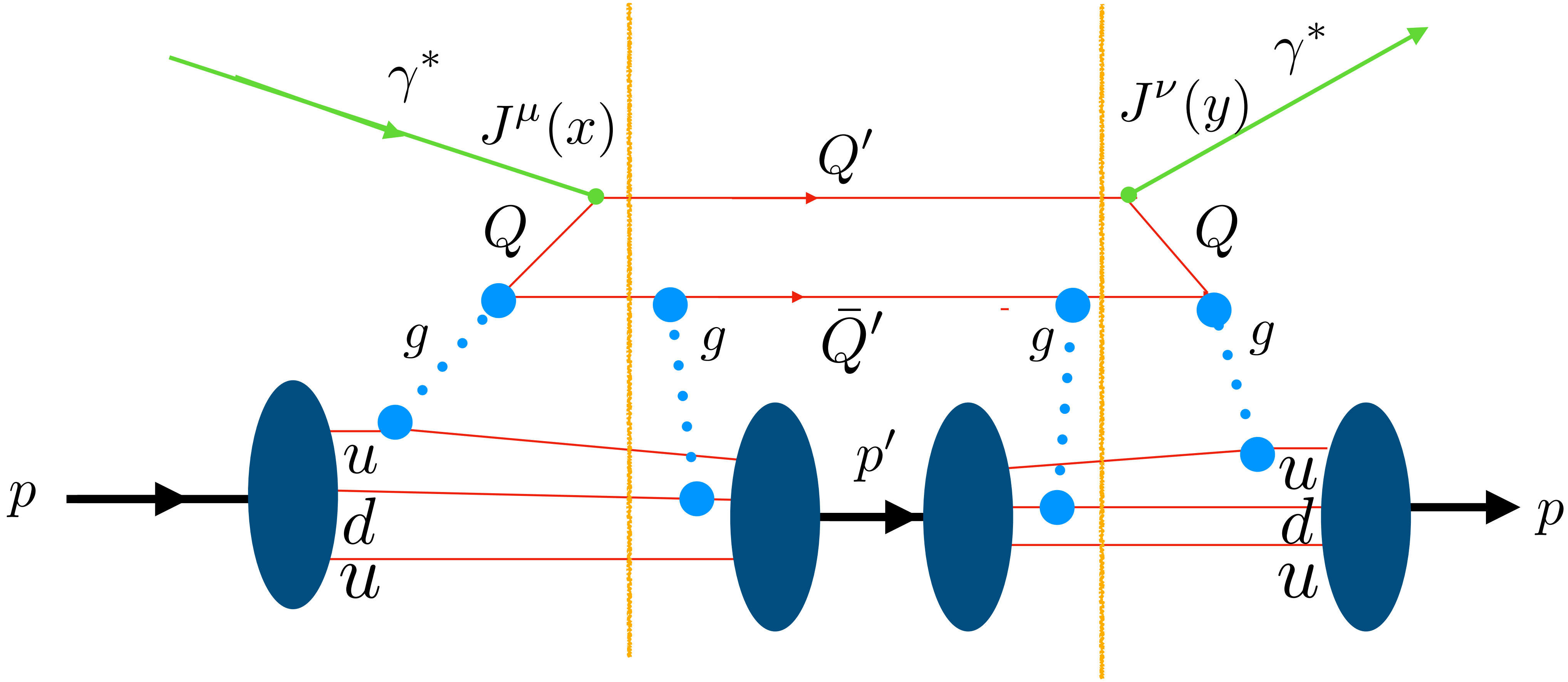


Reproduces lab-frame color dipole approach
DDIS: Input for leading twist nuclear shadowing

Forward Virtual Compton scattering for a DDIS event

Unitarity: Cut gives DDIS cross section

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

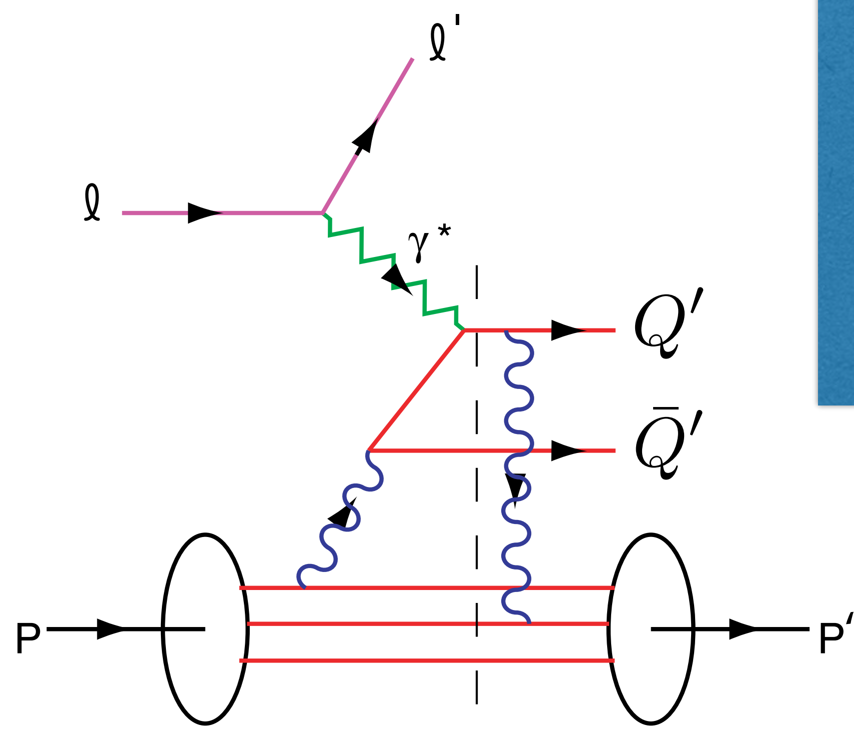


Nonzero LF propagation time between virtual photons: No OPE!

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

Complex phases from Pomeron Exchange

DDIS: No OPE and No Momentum Sum Rule!!



DDIS: Diffractive Deep Inelastic Scattering

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

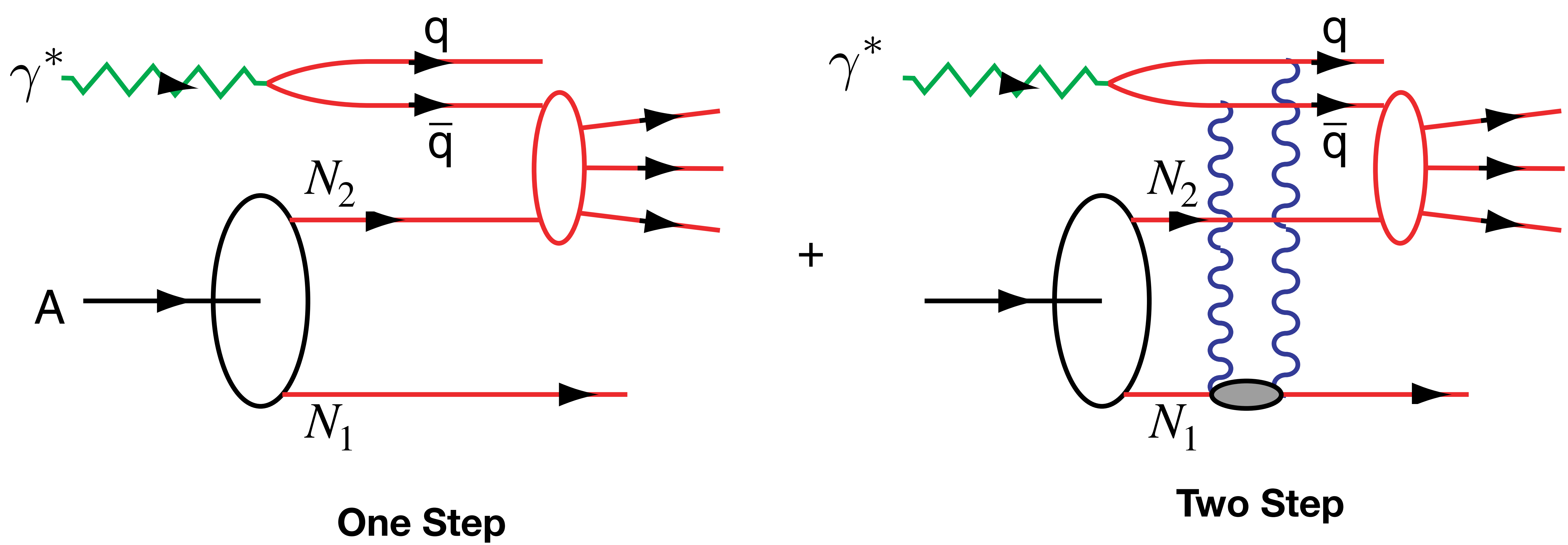
Gluon momentum fraction may be misidentified!

Violates Momentum and other Sum Rules

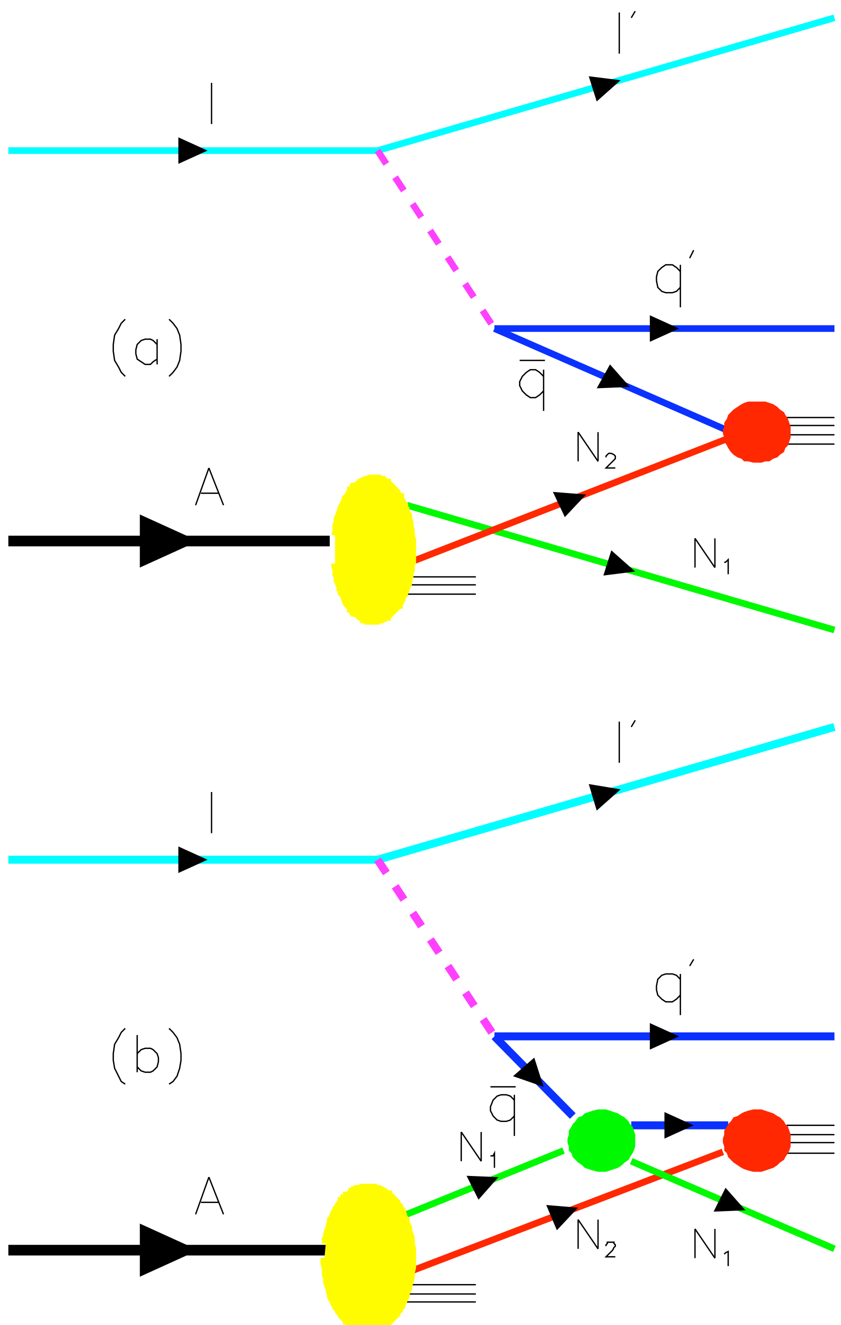
DIS on a Nuclear Target $\gamma^* \ A \to X$

Stodolsky
Gribov
Pumplin, sjb

Theory of Nuclear Shadowing in DIS



Shadowing depends on understanding leading twist-diffraction in DIS



The one-step and two-step processes in DIS on a nucleus.

Coherence at small Bjorken x_B :
$1/Mx_B = 2\nu/Q^2 \geq L_A$.

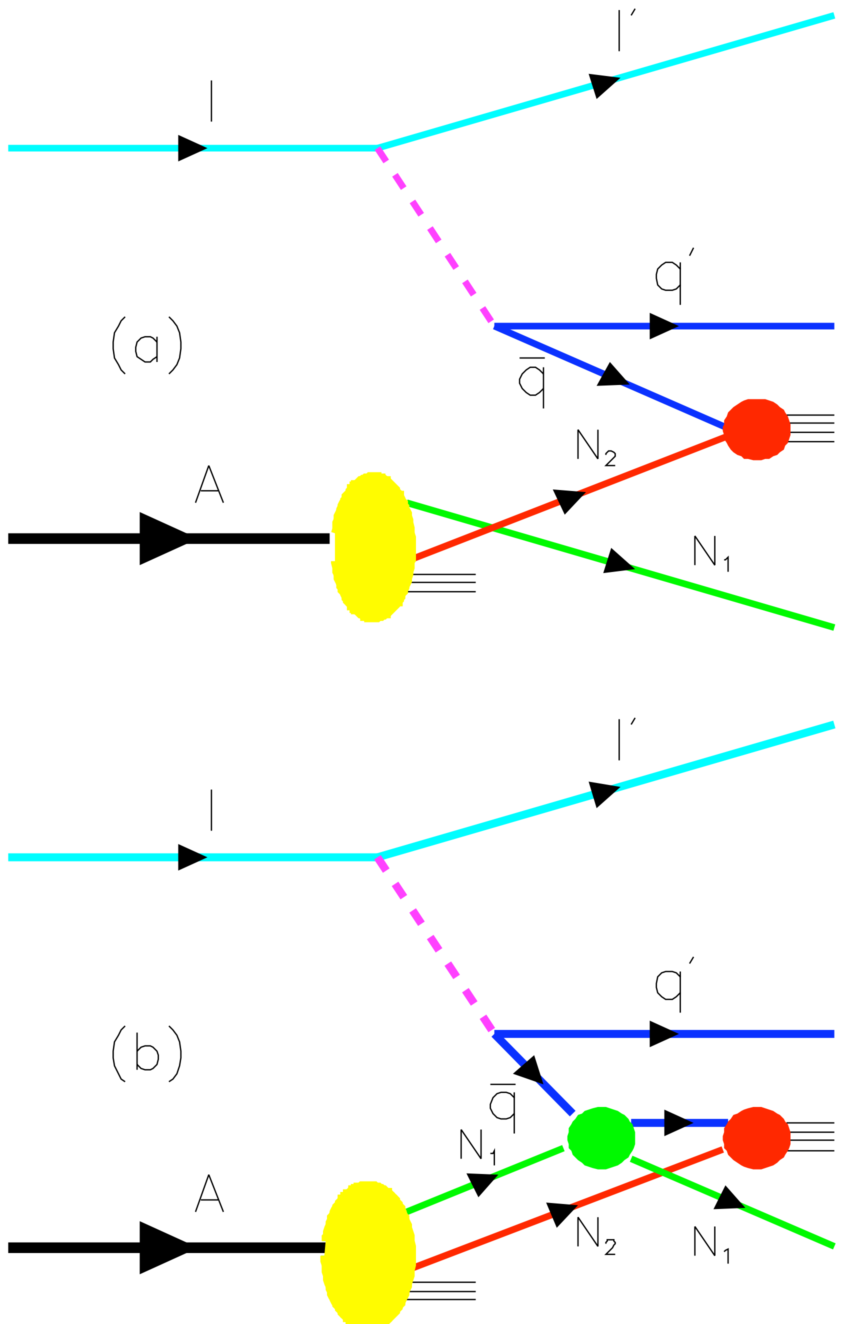
If the scattering on nucleon N_1 is via pomeron exchange, the one-step and two-step amplitudes are opposite in phase, thus diminishing the $\bar{q}$ flux reaching N_2.

$\rightarrow$ Shadowing of the DIS nuclear structure functions.

Diffraction via Pomeron gives destructive interference!

Shadowing

Shadowing depends on understanding leading-twist diffraction in DIS



The one-step and two-step processes in DIS on a nucleus.

Coherence at small Bjorken x_B : $1/Mx_B = 2\nu/Q^2 \geq L_A$.

If the scattering on nucleon N_1 is via pomeron exchange, the one-step and two-step amplitudes are opposite in phase, thus diminishing the $\overline{q}$ flux reaching N_2.

Interior nucleons shadowed

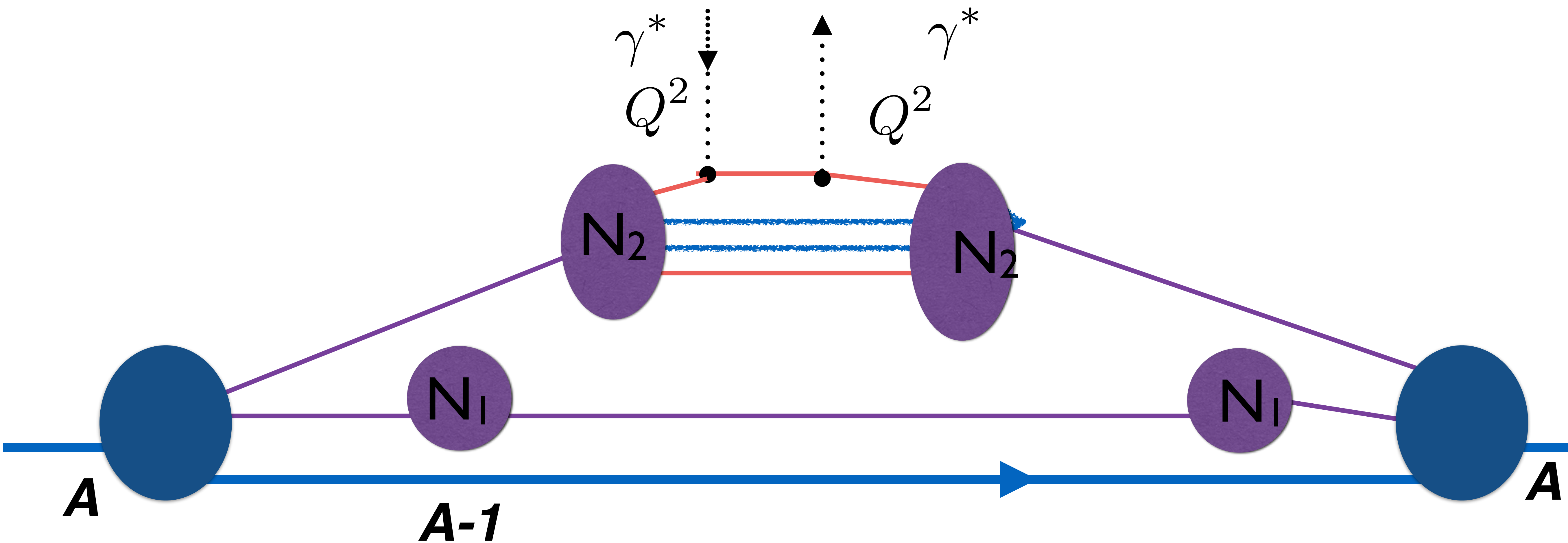
$\rightarrow$ Shadowing of the DIS nuclear structure functions.

Observed HERA DDIS produces nuclear shadowing

Study Forward Virtual Compton Scattering on Nucleus

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

Unitarity: Cut gives DIS Cross Section



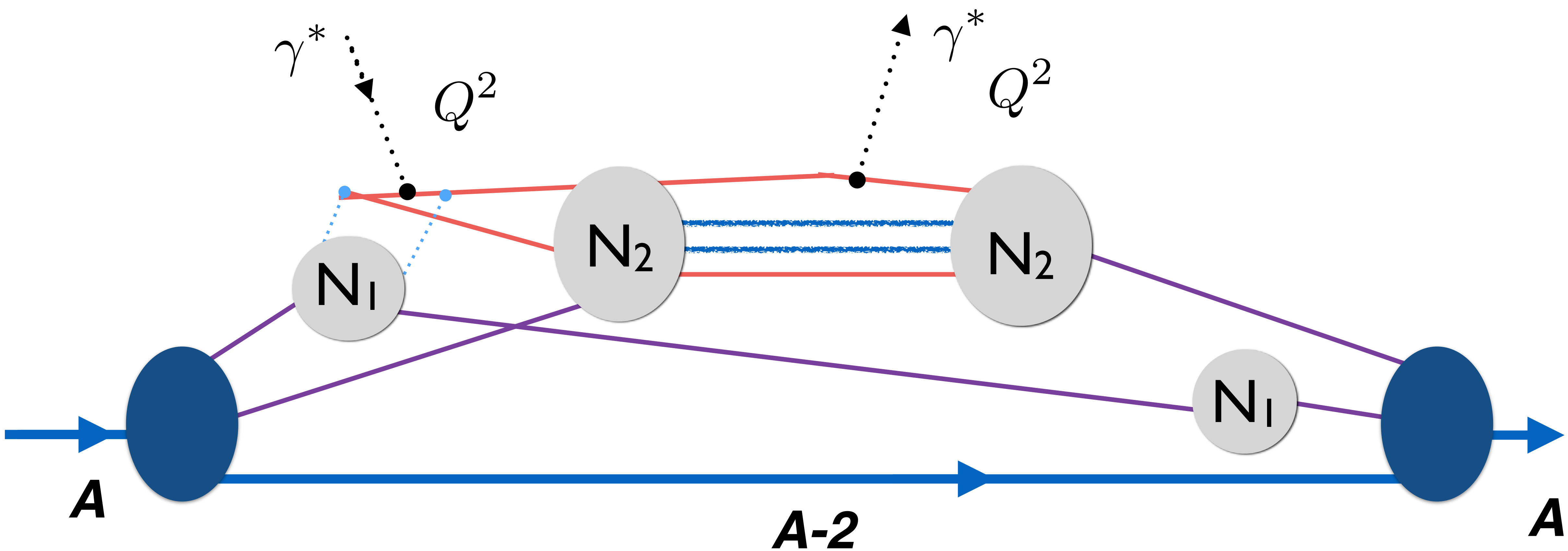
Usual "Handbag" Diagram: no DDIS

Double Virtual Compton Scattering $\gamma^* A \to \gamma^* A$

Reduces to matrix element of local operator: Sum Rules

LFWFs are real for stable hadrons, nuclei

Doubly Virtual Nuclear Compton Scattering $\gamma^*(q)A \to \gamma^*(q)A$



Front-Face Nucleon N_1 struck

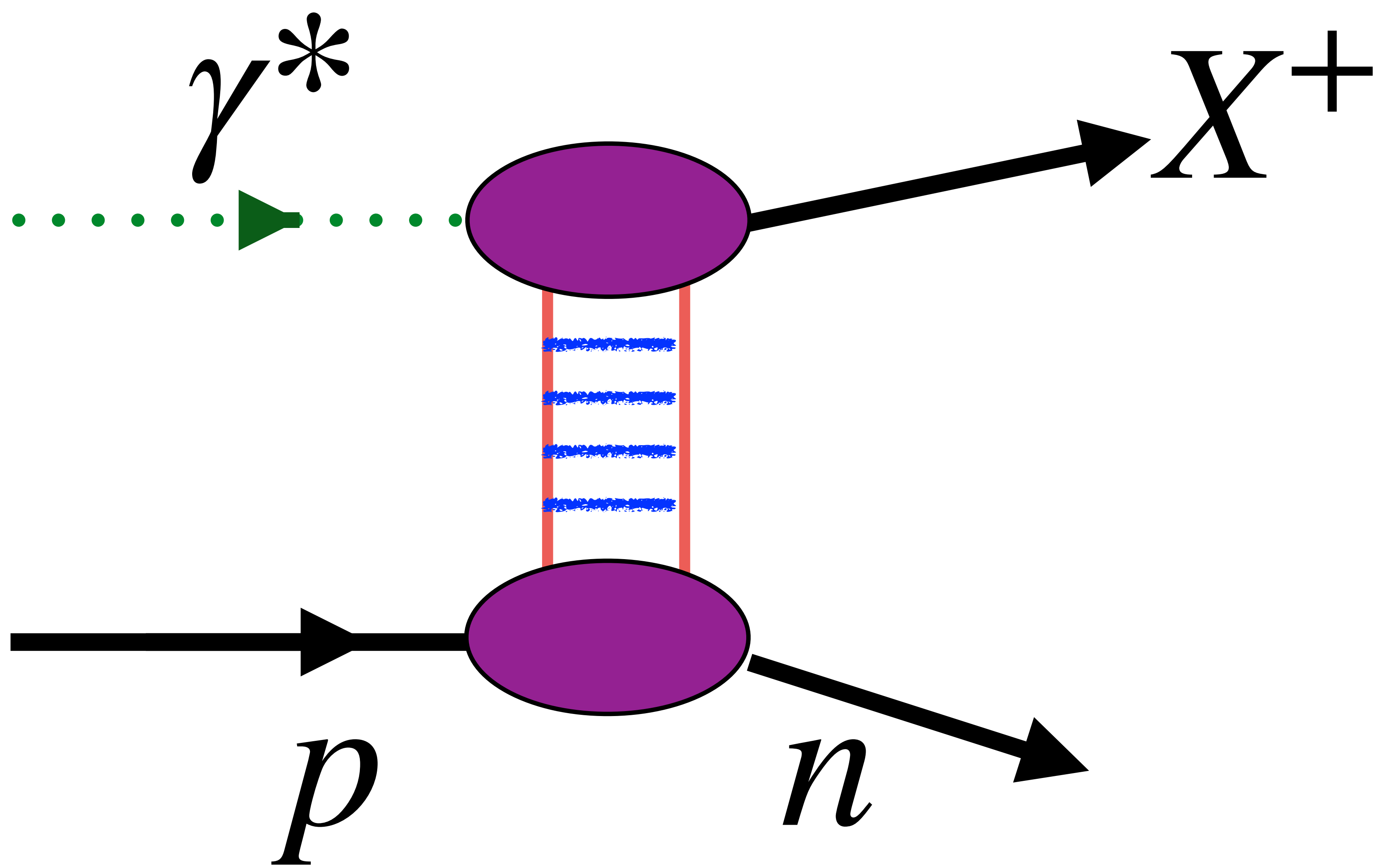
Front-Face Nucleon N_1 not struck

Contribution from One-Step / Two-Step Interference

Nonzero LF propagation time between virtual photons: No OPE!

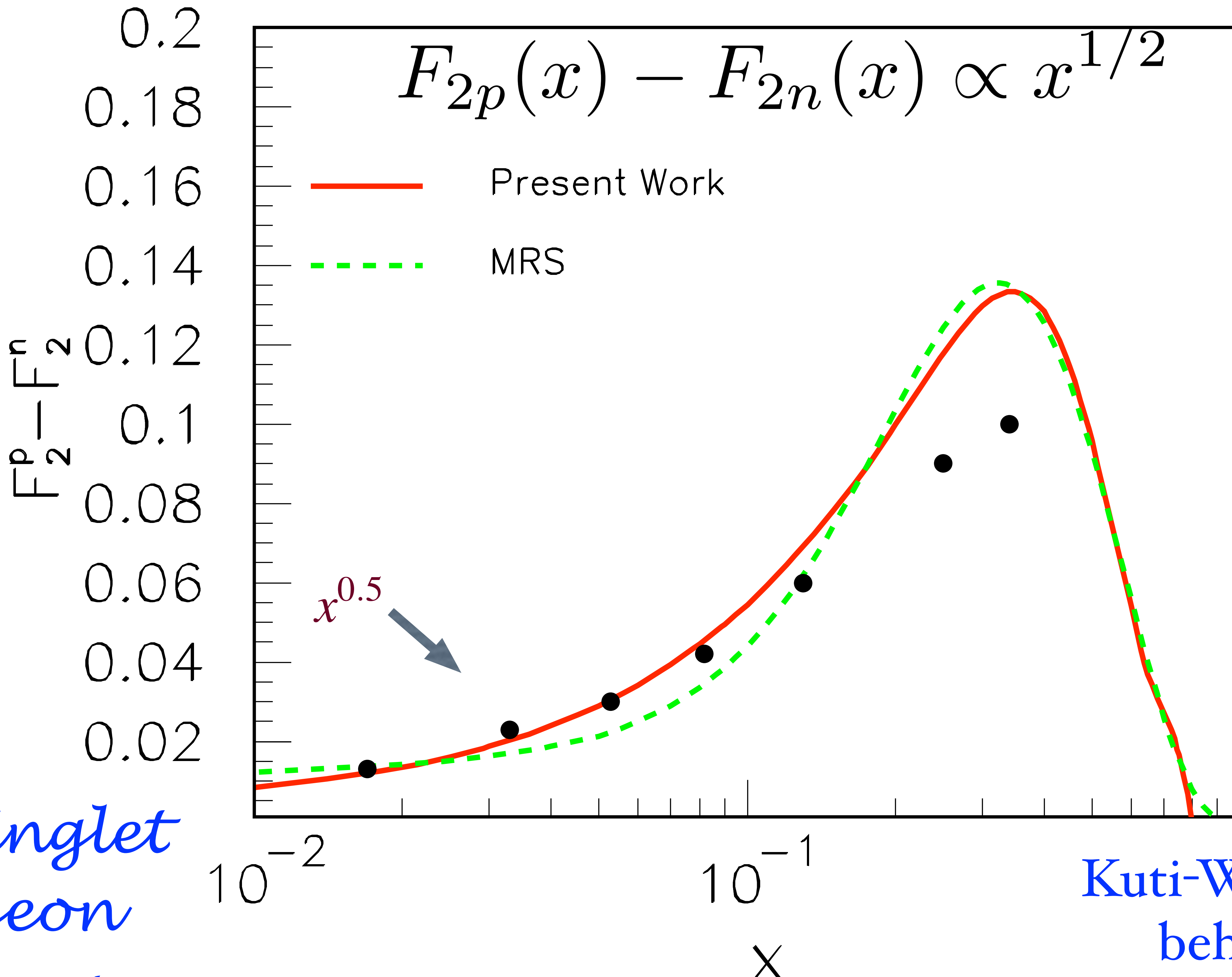
Complex phases from Pomeron Exchange

DDIS: No Momentum Sum Rule



Reggeon Exchange Contribution to Charge-Exchange DDIS

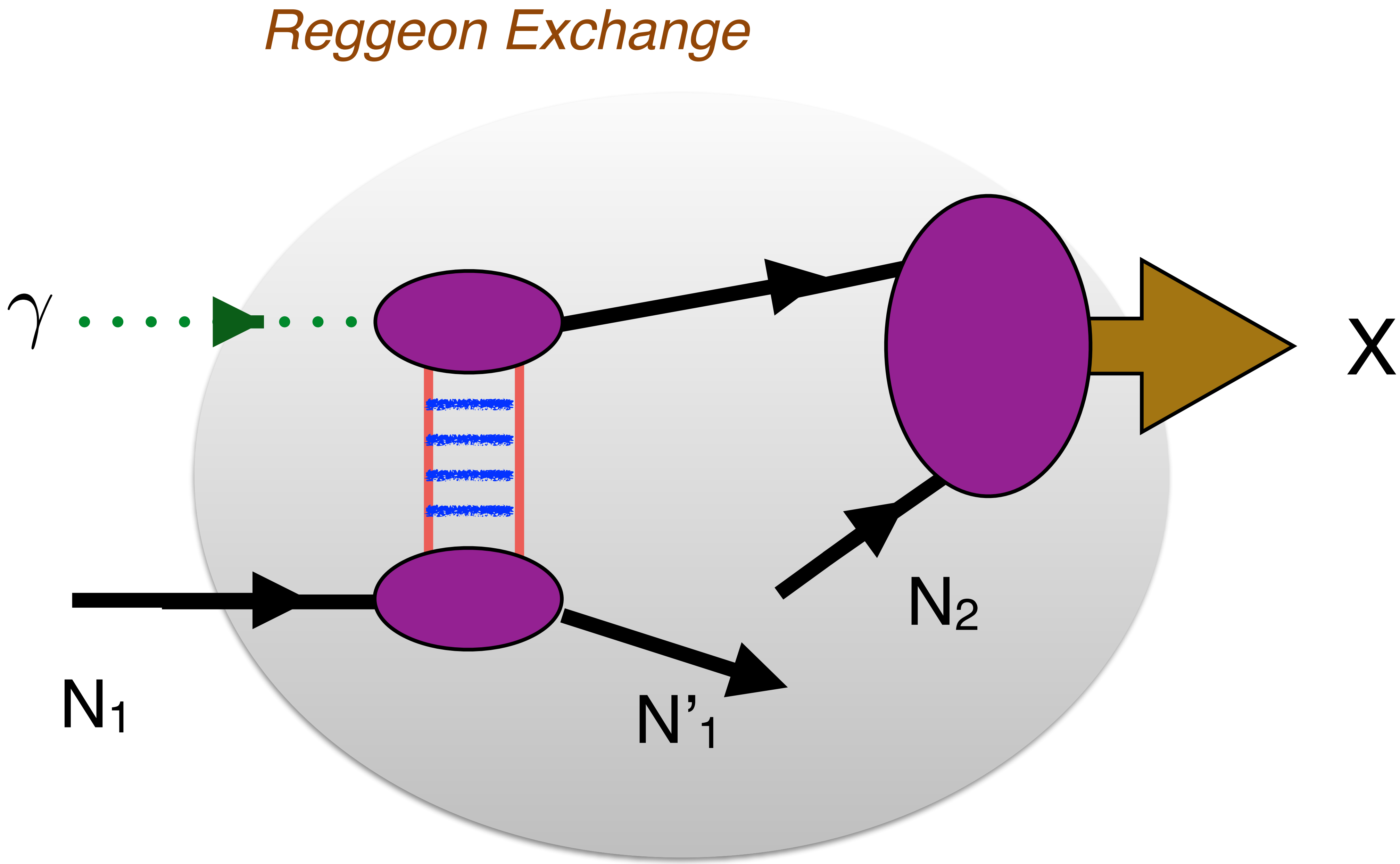
Regge contribution: $\sigma_{\bar{q}N} \sim \hat{s}^{\alpha_R - 1}$ $\alpha_R \simeq 1/2$



Non-singlet Reggeon Exchange

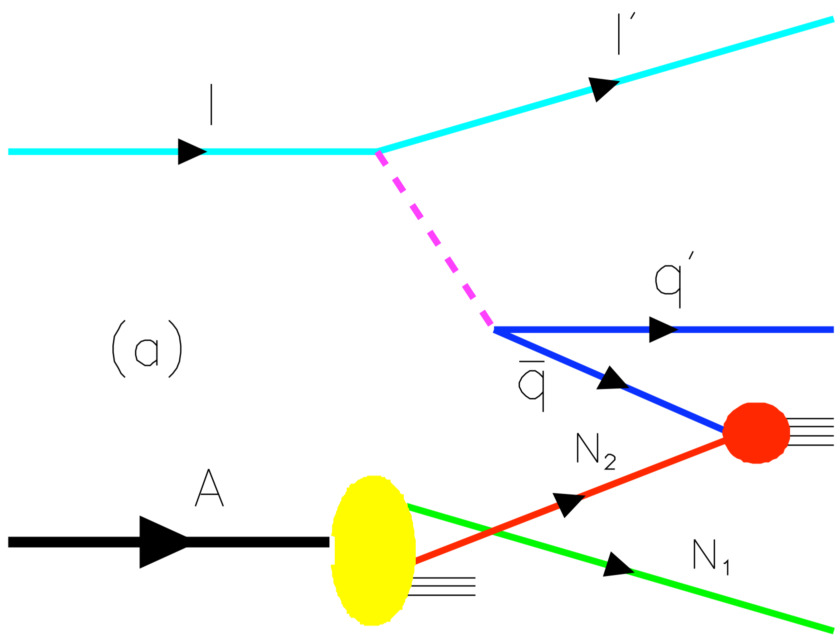
Kuti-Weisskopf behavior

Two-step Glauber process



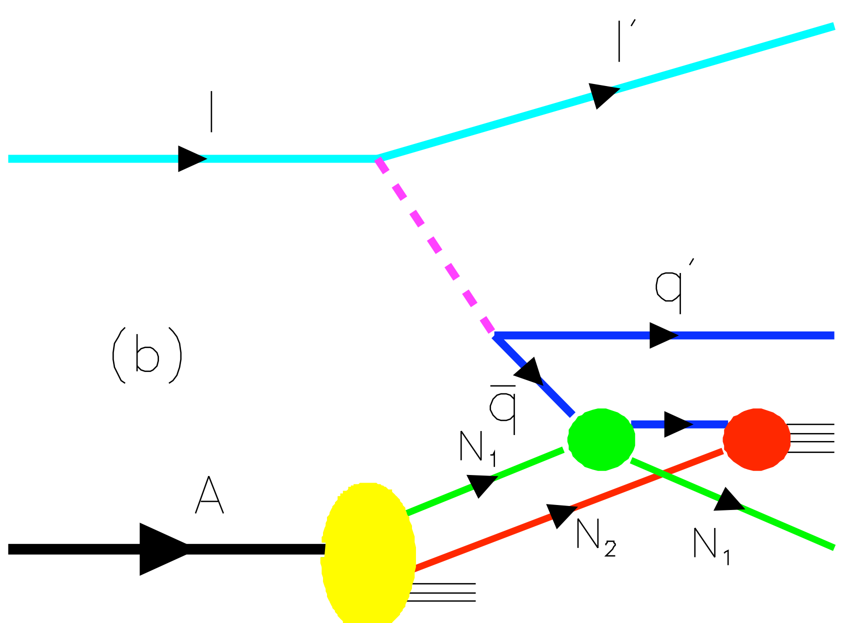
Can give constructive interference !

Schmidt, Lu, Yang, sjb



The one-step and two-step processes in DIS on a nucleus.

Coherence at small Bjorken x_B : $1/Mx_B = 2\nu/Q^2 \geq L_A$.



Regge

If the scattering on nucleon N_1 is via ~~pomeron~~ exchange, the one-step and two-step amplitudes are ~~opposite in phase, thus diminishing the $\bar{q}$ flux reaching N_2.~~

constructive in phase

thus ***increasing*** the flux reaching N_2

Interior nucleons anti-shadowed

Regge Exchange in DDIS produces nuclear anti-shadowing

Reggeon Exchange

Regge contribution: $\sigma_{\bar{q}N} \sim \hat{s}^{\alpha_R - 1}$ $\quad \alpha_R \simeq 1/2$

Phase of two-step amplitude relative to one step:

$$\frac{1}{\sqrt{2}}(1 - i) \times i = \frac{1}{\sqrt{2}}(i + 1)$$

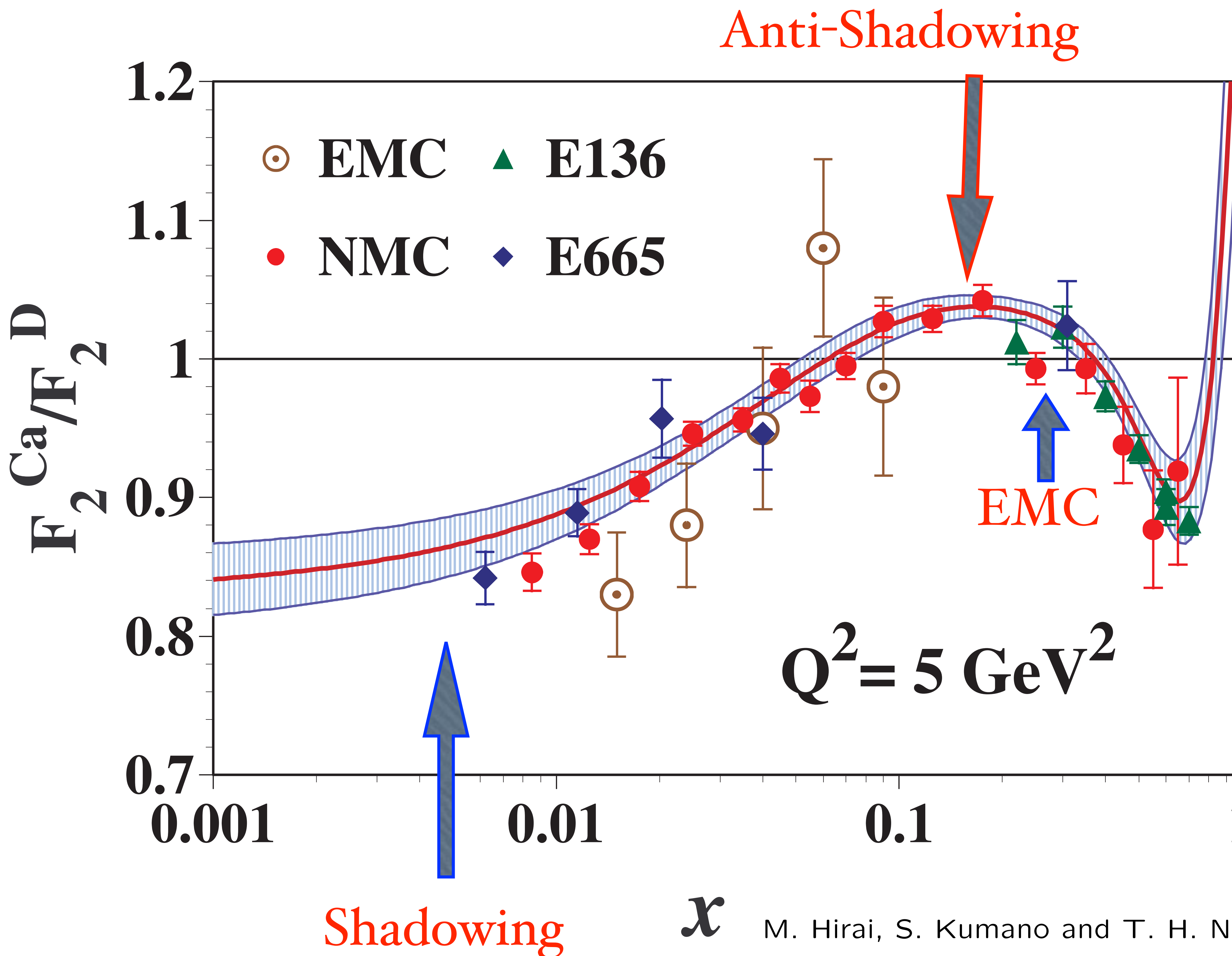
Constructive Interference

Depends on quark flavor!

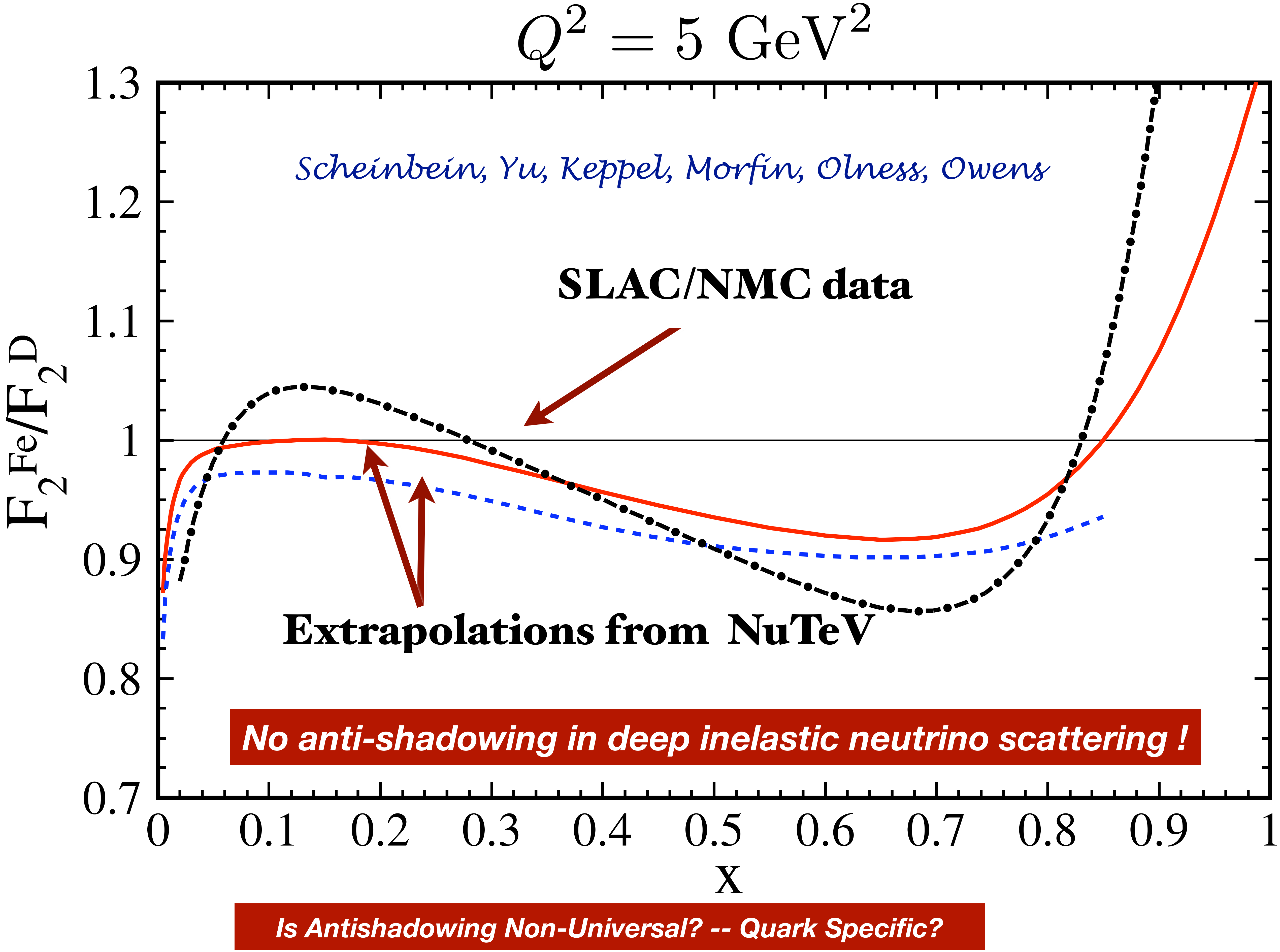
Thus antishadowing is not universal

Different for couplings of $\gamma^*, Z^0, W^\pm$

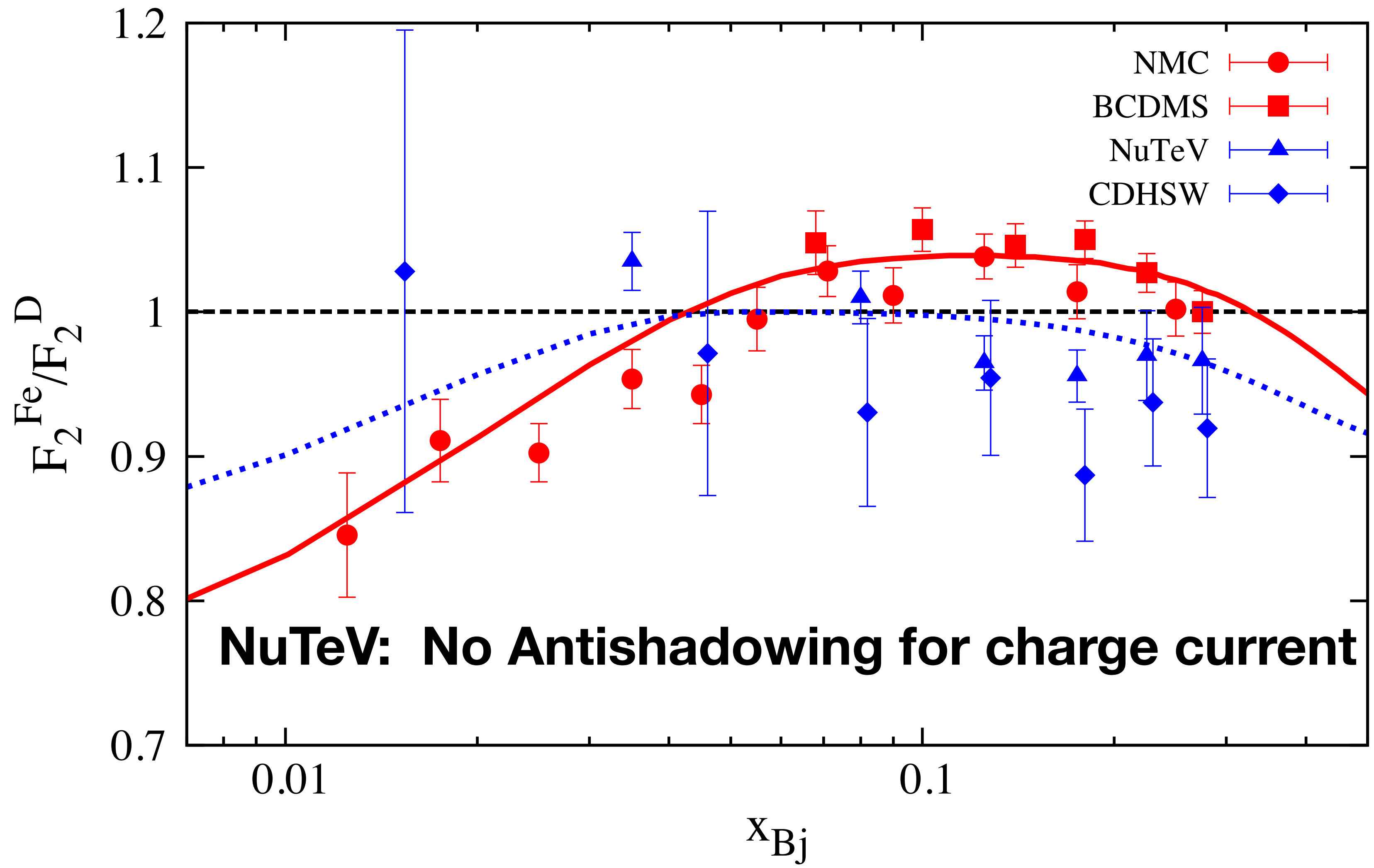
Test: Tagged Drell-Yan



M. Hirai, S. Kumano and T. H. Nagai, "Nuclear parton distribution functions and their uncertainties," Phys. Rev. C **70**, 044905 (2004) [arXiv:hep-ph/0404093].

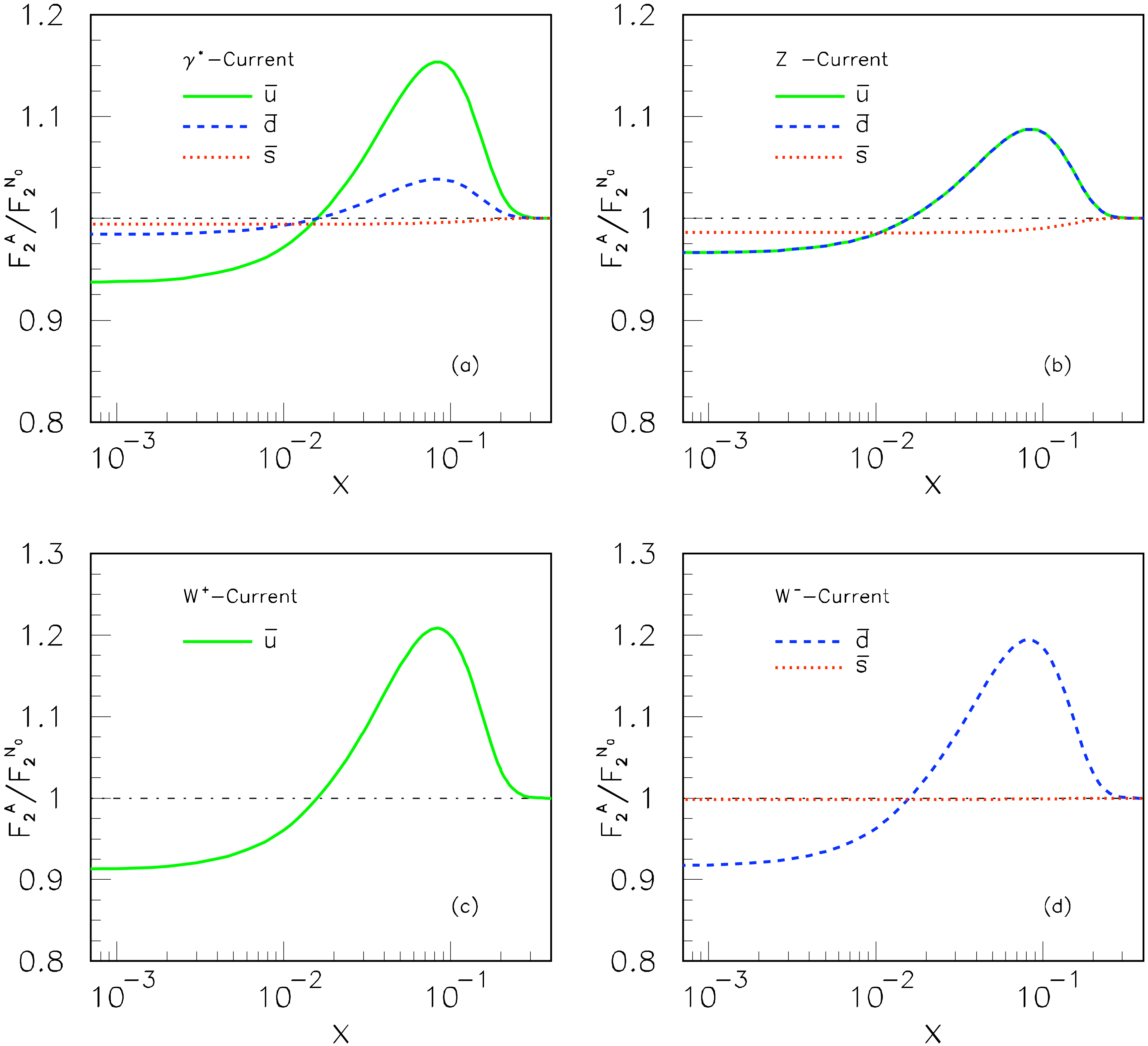


$Q^2 = 5\ \mathrm{GeV}^2$
Scheinbein, Yu, Keppel, Morfin, Olness, Owens
SLAC/NMC data
Extrapolations from NuTeV
No anti-shadowing in deep inelastic neutrino scattering !
F_2^{Fe}/F_2^{D}
x
1.3
1.2
1.1
1
0.9
0.8
0.7
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
Is Antishadowing Non-Universal? -- Quark Specific?



Is Antishadowing Non-Universal? -- Quark Specific?

Comparison of the ratio of iron to deuteron nuclear structure functions measured in deep inelastic neutrino-nucleus scattering (NuTeV [2], CDHSW [8]), and muon-nucleus scattering (BCDMS [9] and NMC [10, 11]). All data are displayed in the online Durham HepData Project Database [12]. Anti-shadowing is absent in the neutrino charged current data.



Lu, Schmidt, Yang; sjb

Modifies NuTeV extraction of

$\sin^2 \theta_W$

Test in flavor-tagged DIS at the EIC

Nuclear Antishadowing is flavor dependent not universal !

S. Liuti, I. Schmidt, sjb

- Unlike shadowing, anti-shadowing from Reggeon exchange is flavor specific;
- Each quark and anti-quark will have distinctly different constructive interference patterns.
- The flavor dependence of antishadowing explains why anti- shadowing is different for electron (neutral electro- magnetic current) vs. neutrino (charged weak current) DIS reactions.
- Test of the explanation of antishadowing: Bjorken-scaling leading-twist charge exchange DDIS reaction $\gamma^* p \to n X^+$ with a rapidity gap due to I=1 Reggeon exchange
- The finite path length due to the on-shell propagation of V^0 between N_1 and N_2 contributes a finite distance $(\Delta z)^2$ between the two virtual photons in the DVCS amplitude.

The usual "handbag" diagram where the two $J^\mu(x)$ and $J^\nu(0)$ currents acting on an uninterrupted quark propagator are replaced by a local operator $T^{\mu\nu}(0)$ as $Q^2 \to \infty$, is inapplicable in deeply virtual Compton scattering from a nucleus since the currents act on different nucleons.

$$\Delta z^2 \text{ does not vanish as } \frac{1}{Q^2}.$$

OPE and Sum Rules invalid for nuclear pdfs

One of the most interesting aspects of neutrino-nucleus DIS measurements is the apparent absence of antishadowing of the nuclear parton distributions, in direct contradiction to electron-nucleus and muon-nucleus measurements.

Implications:

(1) **anti-shadowing is flavor specific.**

(2) **This can be tested in flavor-tagged semi-inclusive deep inelastic lepton scattering.**

(3) **antishadowing cannot compensate for shadowing in the momentum sum rule**

(5) **the momentum sum rule is inapplicable for the nuclear pdf,**

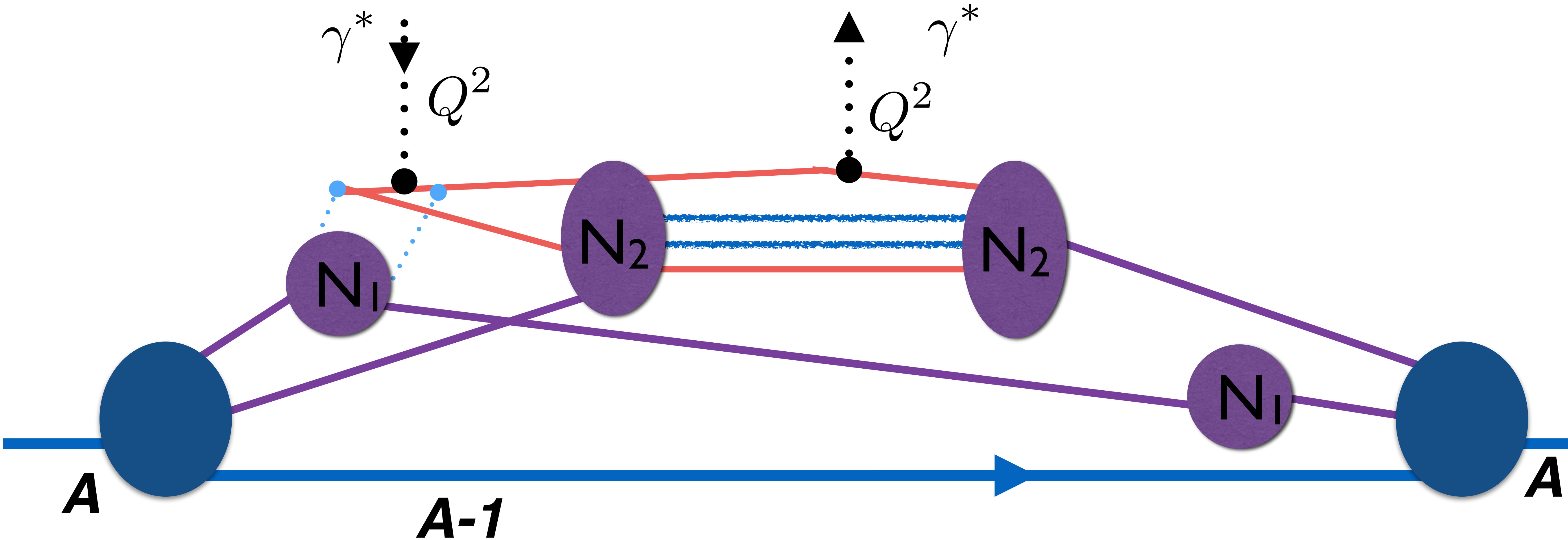
(6) **the standard operator product analysis fails for nuclei because of shadowing and antishadowing.**

(7) **Implications of these issues for nuclear pdfs in QCD based on Glauber-Gribov theory**

(9) **Important connections to leading-twist diffractive DIS.**

Illustrates the LF time sequence

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



Front-Face Nucleon N_1 struck — *Front-Face Nucleon N_1 not struck*

One-Step / Two-Step Interference

Study Double Virtual Compton Scattering $\gamma^* A \to \gamma^* A$

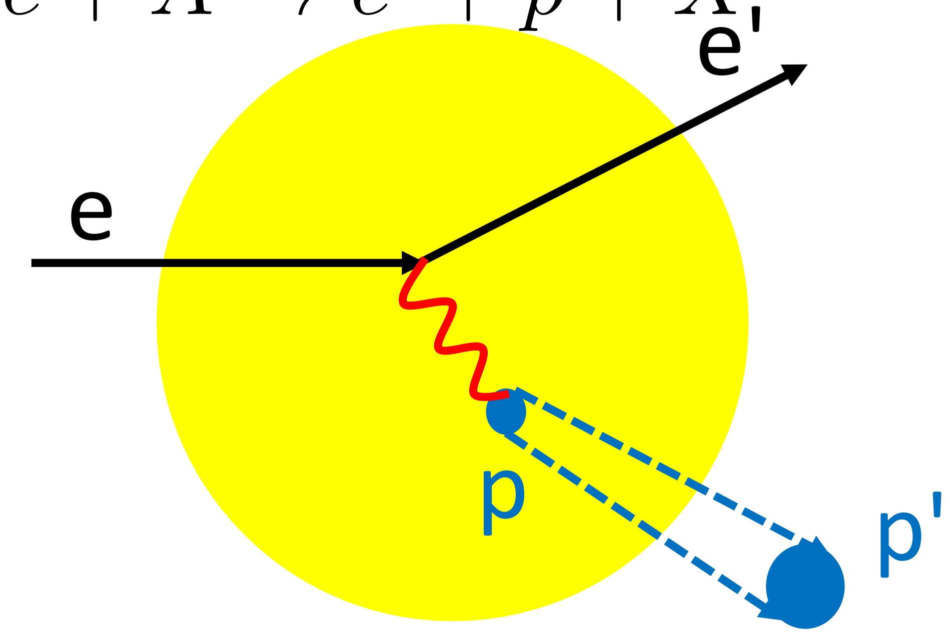
Cannot reduce to matrix element of local operator! No Sum Rules!

Liuti, Schmidt sjb

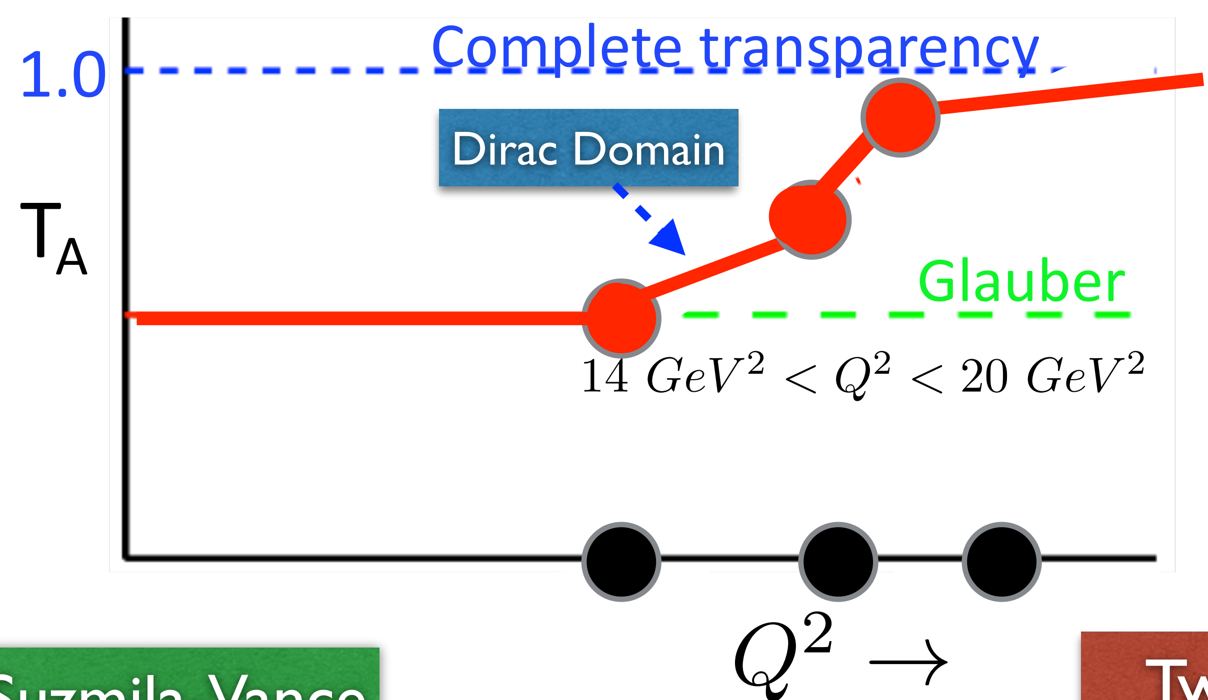
A.H. Mueller, sjb

Color transparency fundamental prediction of QCD

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



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



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

σ_A (nuclear cross section)

σ_N (free nucleon cross section)

Holly Suzmila-Vance

Two-Stage Color Transparency for Proton

Static	Dynamic
Square of Target LFWFs	Modified by Rescattering: ISI & FSI
No Wilson Line	Contains Wilson Line, Phases
Probability Distributions	No Probabilistic Interpretation
Process-Independent	Process-Dependent - From Collision
T-even Observables	T-Odd (Sivers, Boer-Mulders, etc.)
No Shadowing, Anti-Shadowing	Shadowing, Anti-Shadowing, Saturation
Sum Rules: Momentum and J^z	**Momentum and Other Sum Rules Invalid**
DGLAP Evolution; mod. at large x	
No Diffractive DIS	Hard Pomeron and Odderon Diffractive DIS

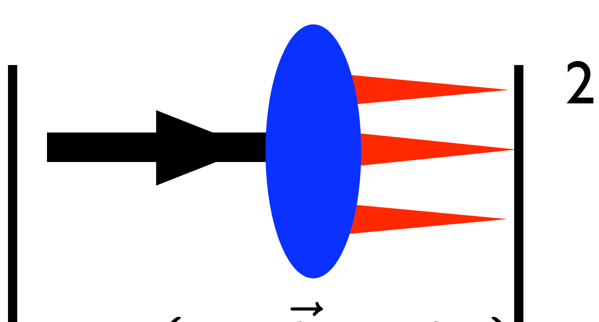
Mulders, Boer

Qiu, Sterman

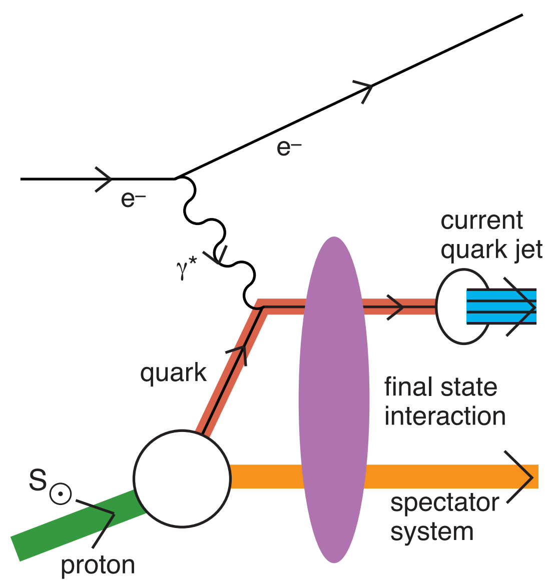
Collins, Qiu

Pasquini, Xiao, Yuan, sjb

Hwang, Schmidt, Lyubovitskij, Luiti, sjb,



$$\left| \Psi_n(x_i, \vec{k}_{\perp i}, \lambda_i) \right|^2$$



Leading Twist Sivers Effect

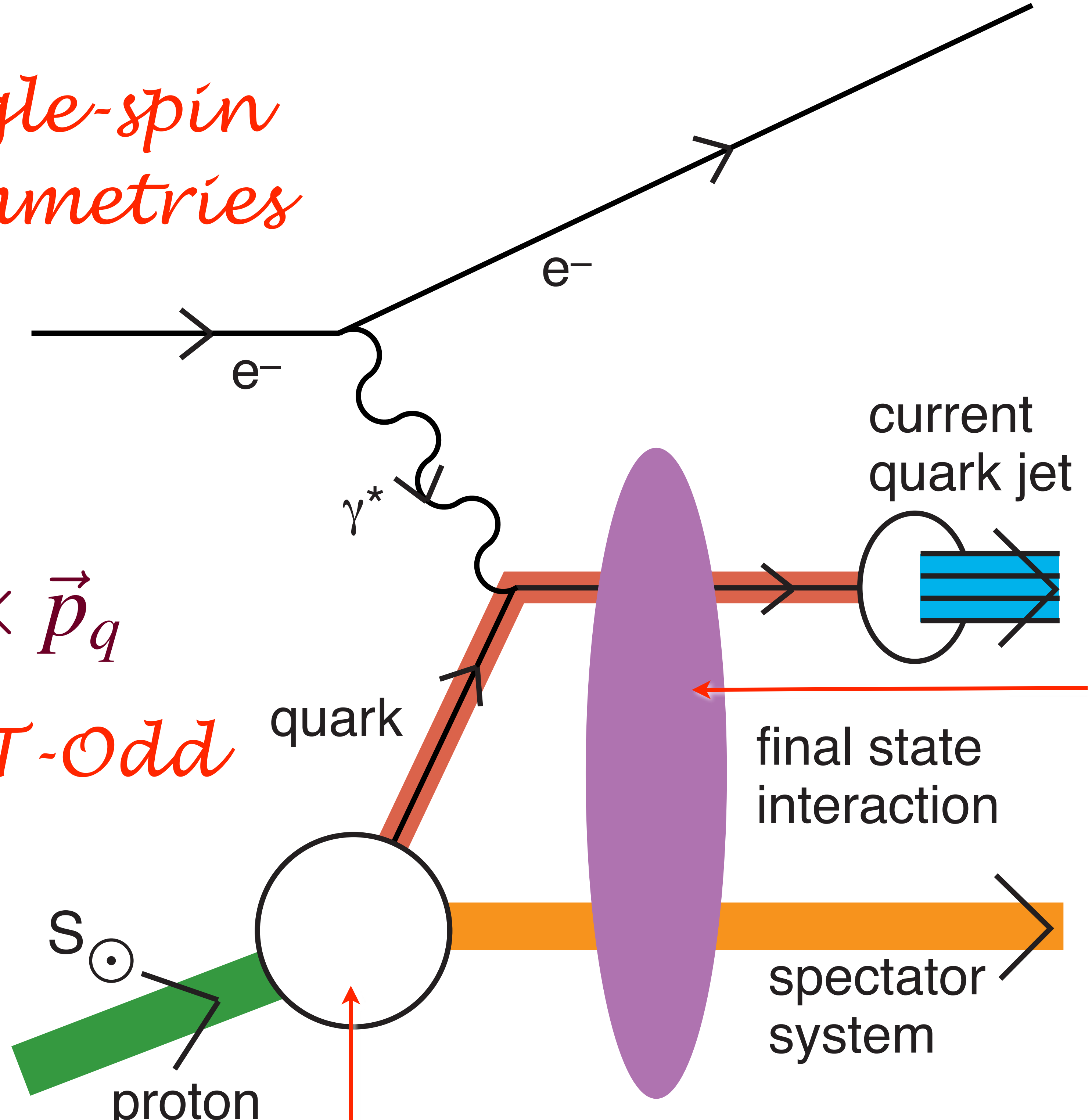
Single-spin asymmetries

Hwang, Schmidt, sjb

Collins, Burkardt, Ji, Yuan. Pasquini, ...

$$i \; \vec{S}_p \cdot \vec{q} \times \vec{p}_q$$

Pseudo- T-Odd



QCD S- and P- Coulomb Phases --Wilson Line

“Lensing Effect”

“Lensing” involves soft scales

Light-Front Wavefunction S and P- Waves!

Sign reversal in DY!

Leading-Twist Rescattering Violates pQCD Factorization!

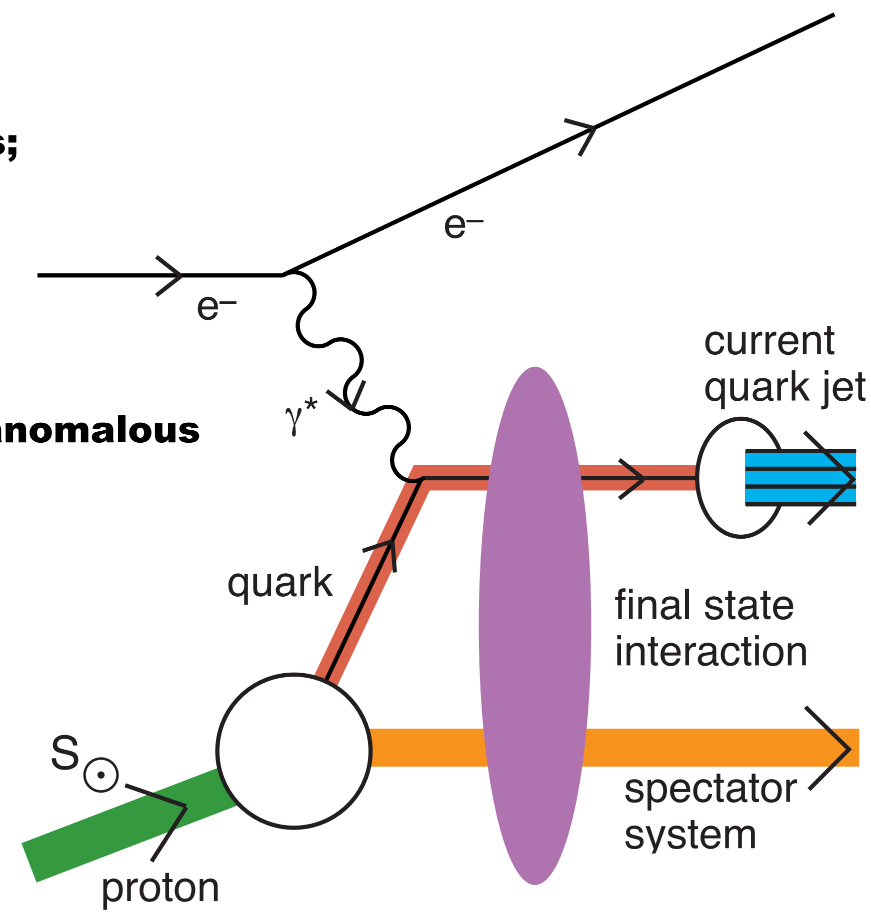
Final-State Interactions Produce Pseudo T-Odd (Sivers Effect)

Hwang, Schmidt, sjb
Collins

- **Leading-Twist Bjorken Scaling!**
- **Requires nonzero orbital angular momentum of quark**
- **Arises from the interference of Final-State QCD Coulomb phases in S- and P- waves;**
- **Wilson line effect -- lc gauge prescription**
- **Relate to the quark contribution to the target proton anomalous magnetic moment and final-state QCD phases**
- **QCD phase at soft scale!**
- **New window to QCD coupling and running gluon mass in the IR**
- **QED S and P Coulomb phases infinite -- difference of phases finite!**
- **Alternate: Retarded and Advanced Gauge: Augmented LFWFs**

Dae Sung Hwang, Yuri V. Kovchegov,
Ivan Schmidt, Matthew D. Sievert, sjb

$$\mathbf{i}\ \vec{S} \cdot \vec{p}_{jet} \times \vec{q}$$



Pasquini, Xiao, Yuan, sjb

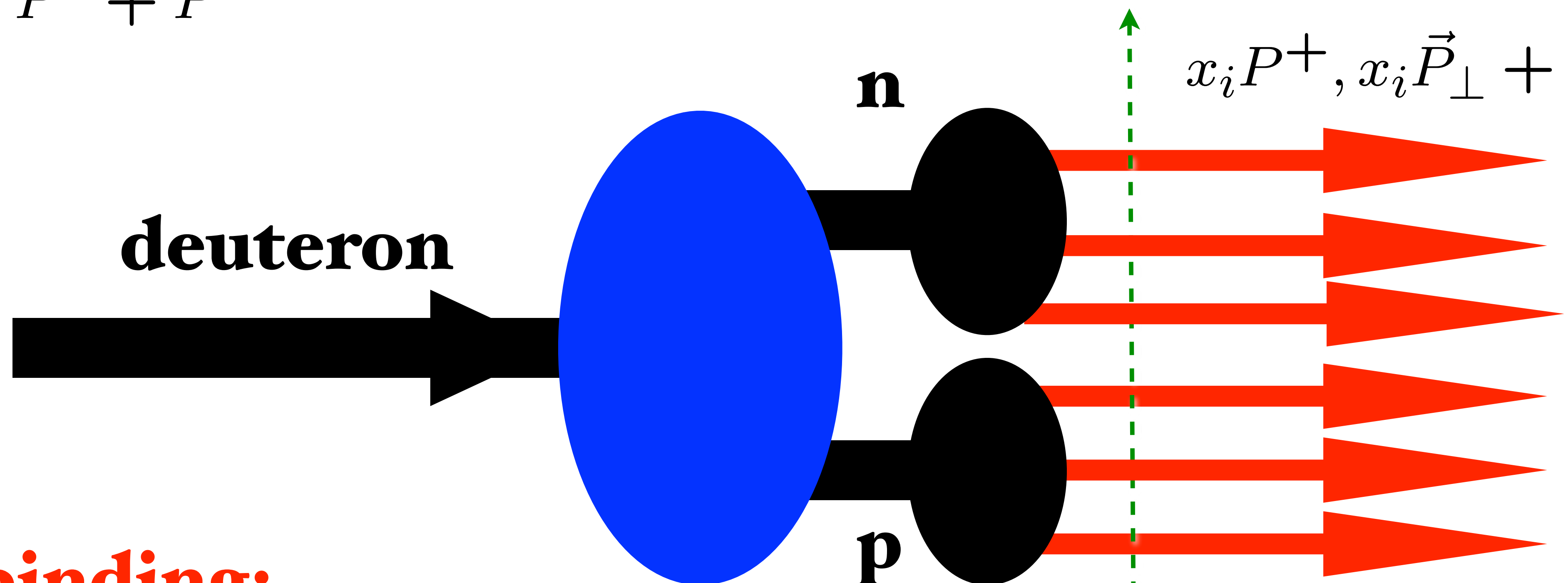
Mulders, Boer **Qiu, Sterman**

Fixed $\tau = t + z/c$

$P^+ = P^0 + P^z$

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

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



Weak binding:

$$\psi_d(x_i, \vec{k}_{\perp i}) = \psi_d^{body} \times \psi_n \times \psi_p$$

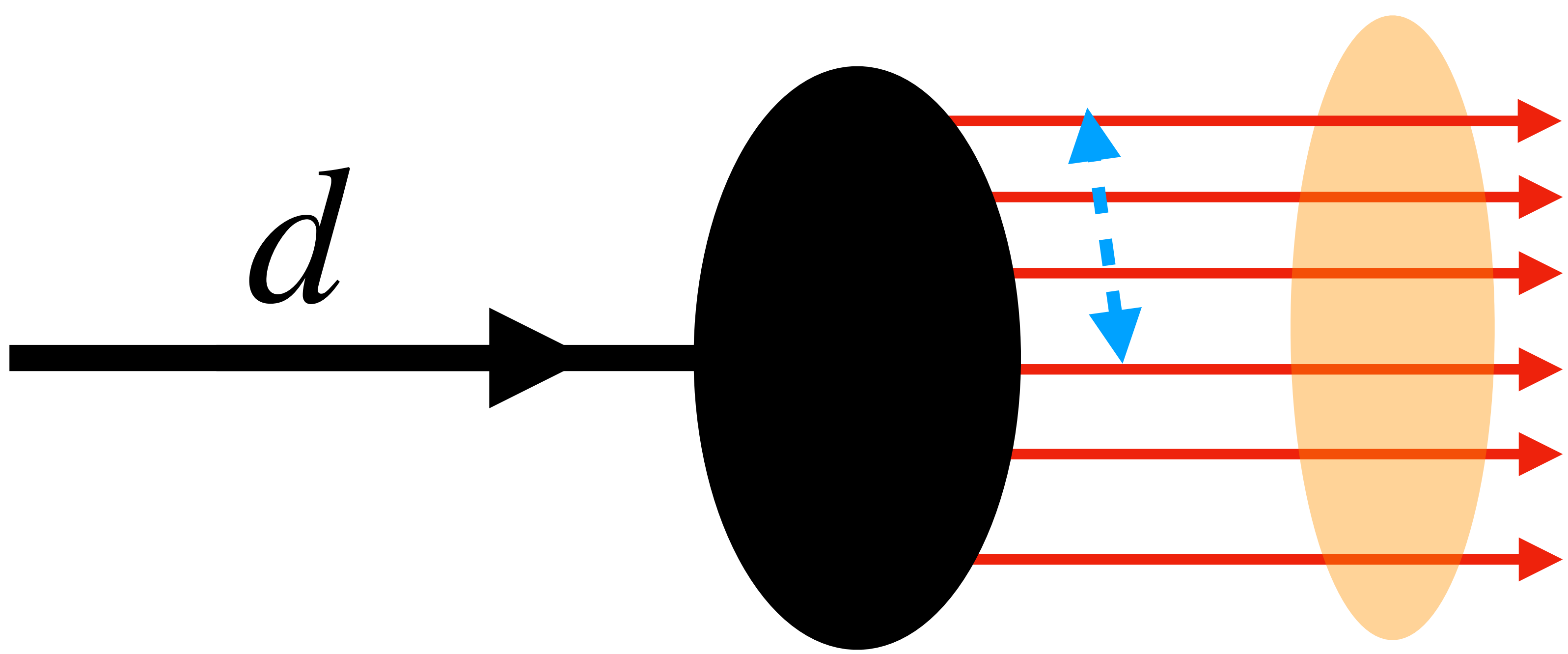
$\sum_i^n x_i = 1$

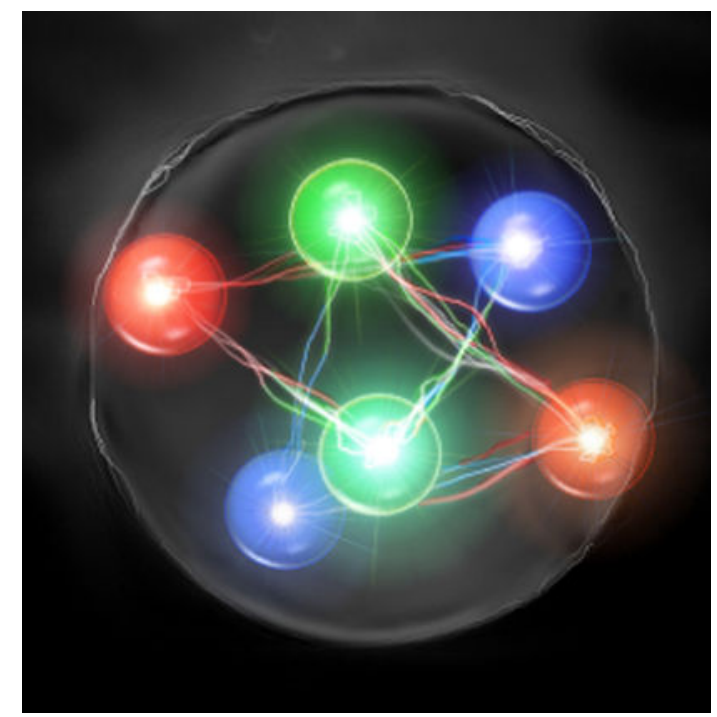
$\sum_i^n \vec{k}_{\perp i} = \vec{0}_\perp$

Standard Nuclear Physics:
Two color-singlet combinations of three 3_C

Hidden Color in QCD

- Deuteron: Five color-singlet combinations of 6 color-triplets
- One Fock state is n p nucleon clusters, one state is Δ Δ





Hidden Color 6-Quark Fock State

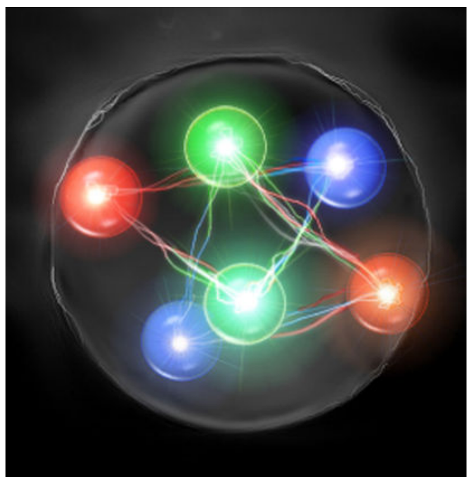
Rigorous Feature of QCD!

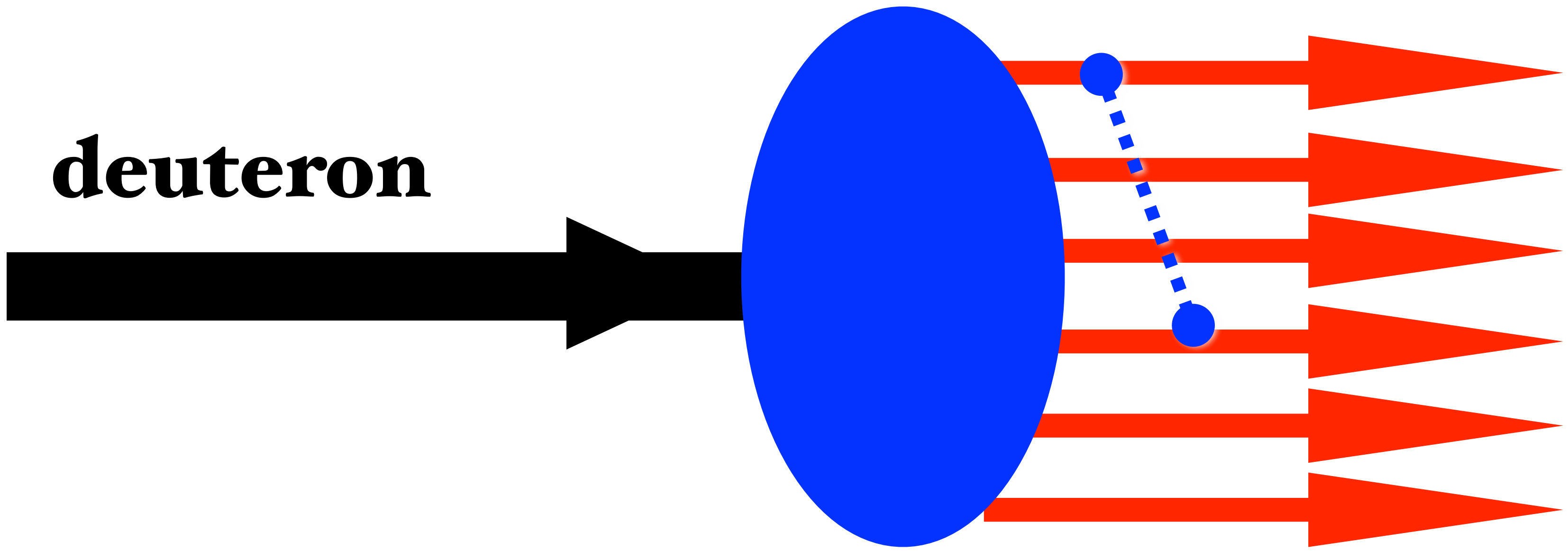
Lepage, Ji, sjb

pQCD Evolution of 5 color-singlet Fock states

Lepage, Ji, sjb

$$\Psi^{\mathbf{d}}_n(x_i, \vec{k}_{\perp i}, \lambda_i)$$





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

$\sum_i^n x_i = 1$

$$\Phi_n(x_i, Q) = \int^{k^2_{\perp i} < Q^2} \Pi' d^2 k_{\perp j} \psi_n(x_i, \vec{k}_{\perp j})$$

5 X 5 Matrix Evolution Equation for deuteron distribution amplitude

Hidden Color of Deuteron

Deuteron six-quark state has five color-singlet configurations, only one of which is n-p.

Asymptotic Solution has Expansion

$$\psi_{[6]\{33\}} = \left(\frac{1}{9}\right)^{1/2} \psi_{NN} + \left(\frac{4}{45}\right)^{1/2} \psi_{\Delta\Delta} + \left(\frac{4}{5}\right)^{1/2} \psi_{CC}$$

ERBL Evolution: Transition to Delta-Delta

Lepage, Ji, sjb

Hidden Color in QCD

Lepage, Ji, sjb

- Deuteron: six-quark wavefunction
- ERBL Evolution of deuteron distribution amplitude $\phi_D(x_i, Q^2)$
- 5 color-singlet combinations of 6 color-triplets -- one state is |n p>
- Components of deuteron distribution amplitude evolve towards equality at short distances:

$$\phi_D(x_i, Q^2) \to C x_1 x_2 x_3 x_4 x_5 x_6$$

- Hidden color states dominate deuteron form factor and photo-disintegration at high momentum transfer

$$\frac{d\sigma}{dt}(\gamma d \to \Delta^{++}\Delta^{-}) \simeq \frac{d\sigma}{dt}(\gamma d \to pn) \text{ at high } Q^2$$

QCD Hidden-Color Hexadiquark in the Core of Nuclei

Jennifer Rittenhouse West[a,b,c], Stanley J. Brodsky[c], Guy F. de Téramond[d], Alfred S. Goldhaber[e], Iván Schmidt[f]

- *Nucl.Phys.A* 1007 (2021) 122134

$$
\begin{aligned}
|\alpha\rangle = & \; C_{pnpn} \left|(u[ud])_{\mathbf{1}_C}(d[ud])_{\mathbf{1}_C}(u[ud])_{\mathbf{1}_C}(d[ud])_{\mathbf{1}_C}\right\rangle \\
+ & \; C_{\mathrm{HdQ}} \left|([ud][ud])_{\bar{\mathbf{6}}_C}([ud][ud])_{\bar{\mathbf{6}}_C}([ud][ud])_{\bar{\mathbf{6}}_C}\right\rangle .
\end{aligned}
$$

Explain strong nuclear binding of ^4He, EMC effect

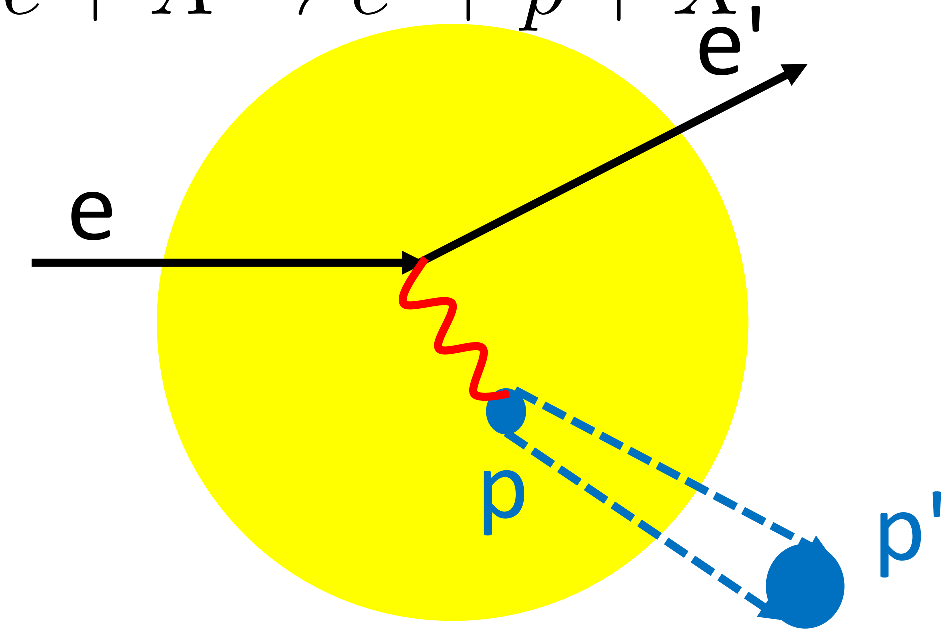
Abstract

Hidden-color configurations are a key prediction of QCD with important physical consequences. In this work we examine a QCD color-singlet configuration in nuclei formed by combining six scalar $[ud]$ diquarks in a strongly bound $SU(3)_C$ channel. The resulting hexadiquark state is a charge-2, spin-0, baryon number-4, isospin-0, color-singlet state. It contributes to alpha clustering in light nuclei and to the additional binding energy not saturated by ordinary nuclear forces in ^{4}He as well as the alpha-nuclei sequence of interest for nuclear astrophysics. We show that the strongly bound combination of six scalar isospin-0 $[ud]$ diquarks within the nuclear wave function - relative to free nucleons - provides a natural explanation of the EMC effect measured by the CLAS collaboration's comparison of nuclear parton distribution function ratios for a large range of nuclei. These experiments confirmed that the EMC effect; i.e., the distortion of quark distributions within nuclei, is dominantly identified with the dynamics of neutron-proton ("isophobic") short-range correlations within the nuclear wave function rather than proton-proton or neutron-neutron correlations.

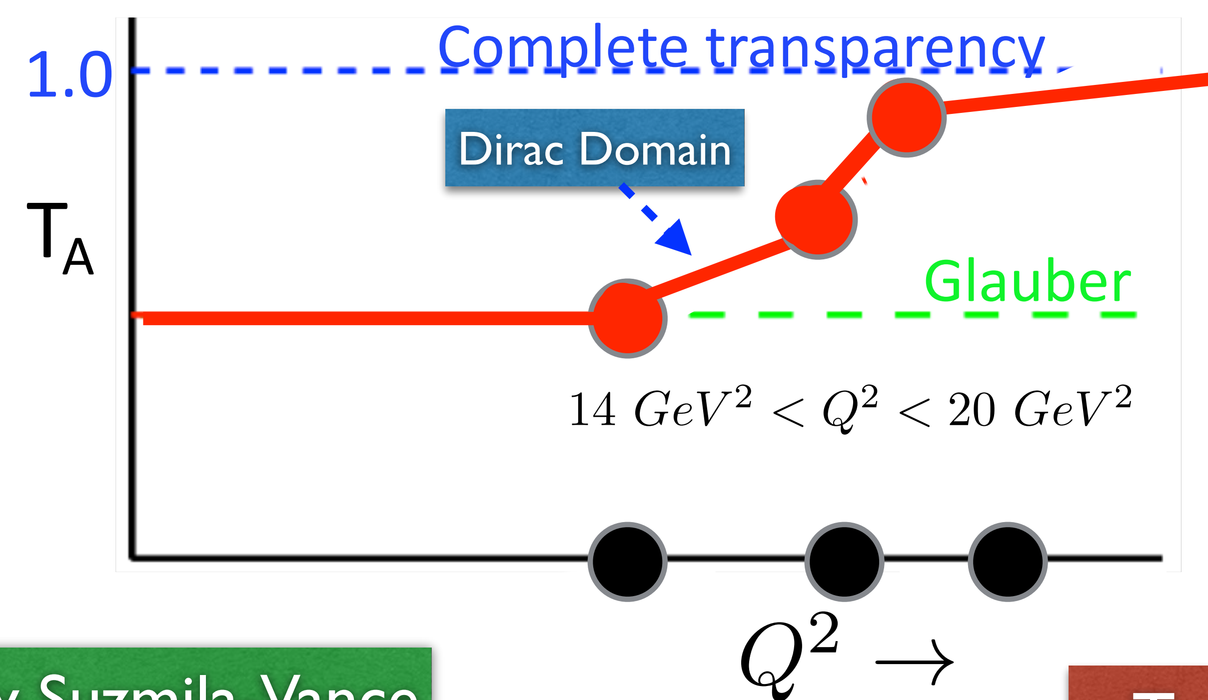
Color transparency: fundamental prediction of QCD

A.H. Mueller, sjb

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



- 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)

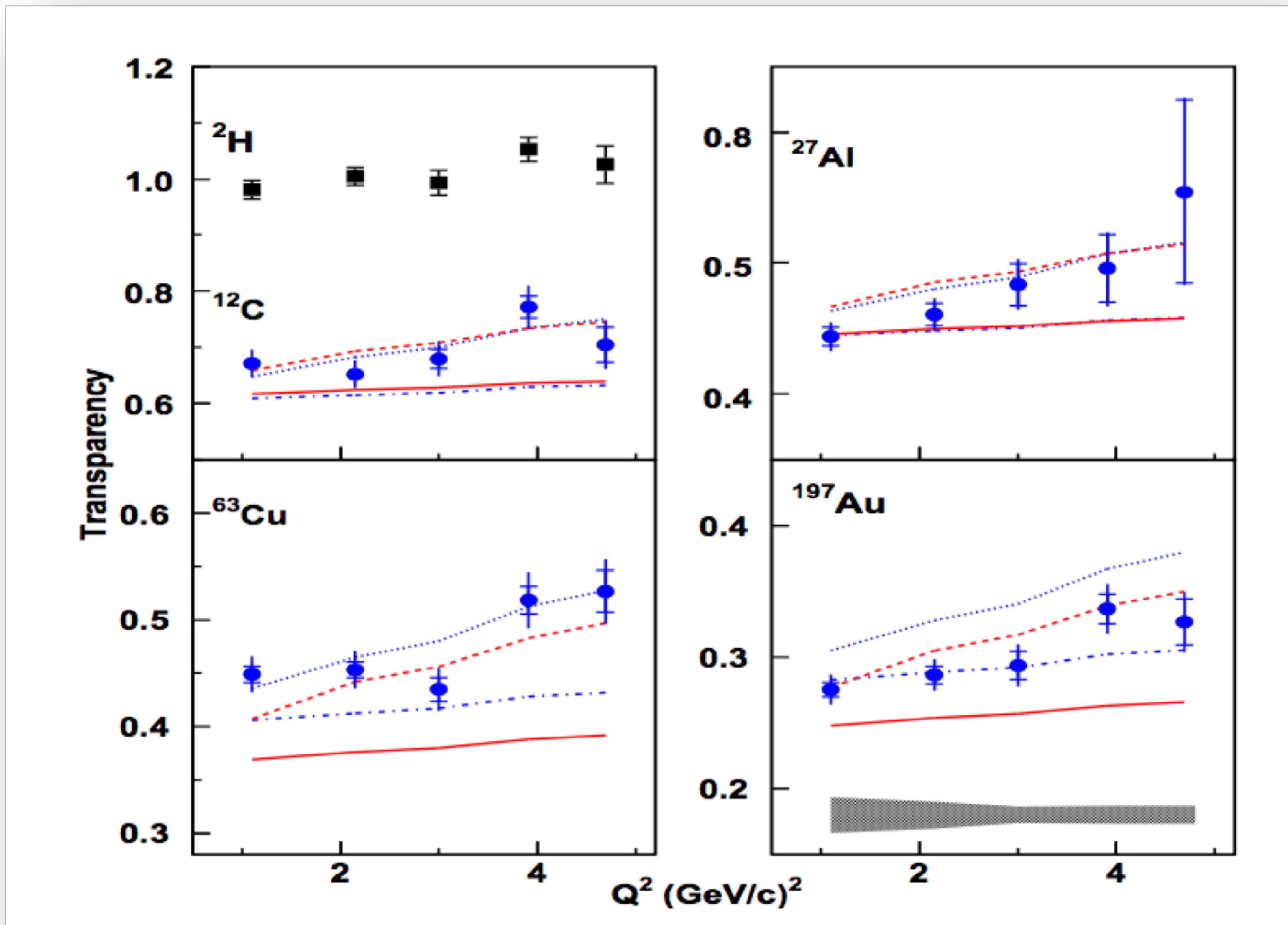
Holly Suzmila-Vance

Two-Stage Color Transparency for Proton

Color Transparency verified for π^+ and ρ electroproduction

Hall C E01-107 pion electro-production

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

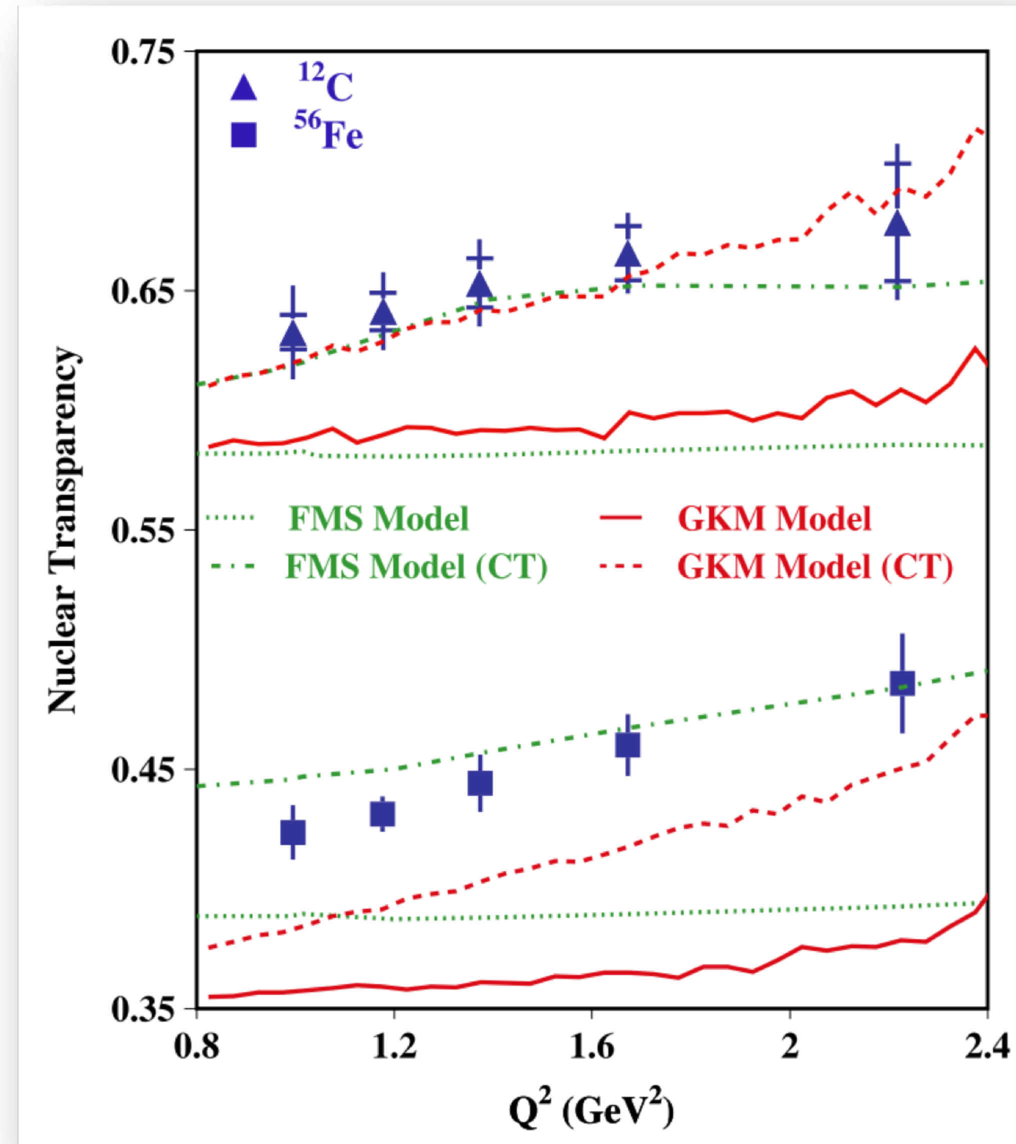


B.Clasie *et al.* PRL 99:242502 (2007)

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

CLAS E02-110 rho electro-production

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



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

$$F(q^2) =$$

G. de Teramond, sjb

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

$$\sum_i x_i = 1$$

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

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

Proton radius squared at $Q^2 = 0$

Color Transparency is controlled by the transverse-spatial size $\vec{a}_\perp^2$ and its dependence on the momentum transfer $Q^2 = -t$:
The scale Q^2_τ required for Color Transparency grows with twist τ

Light-Front Holography:

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

For large Q2 :

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

Drell-Yan-West Formula in Impact Space

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

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

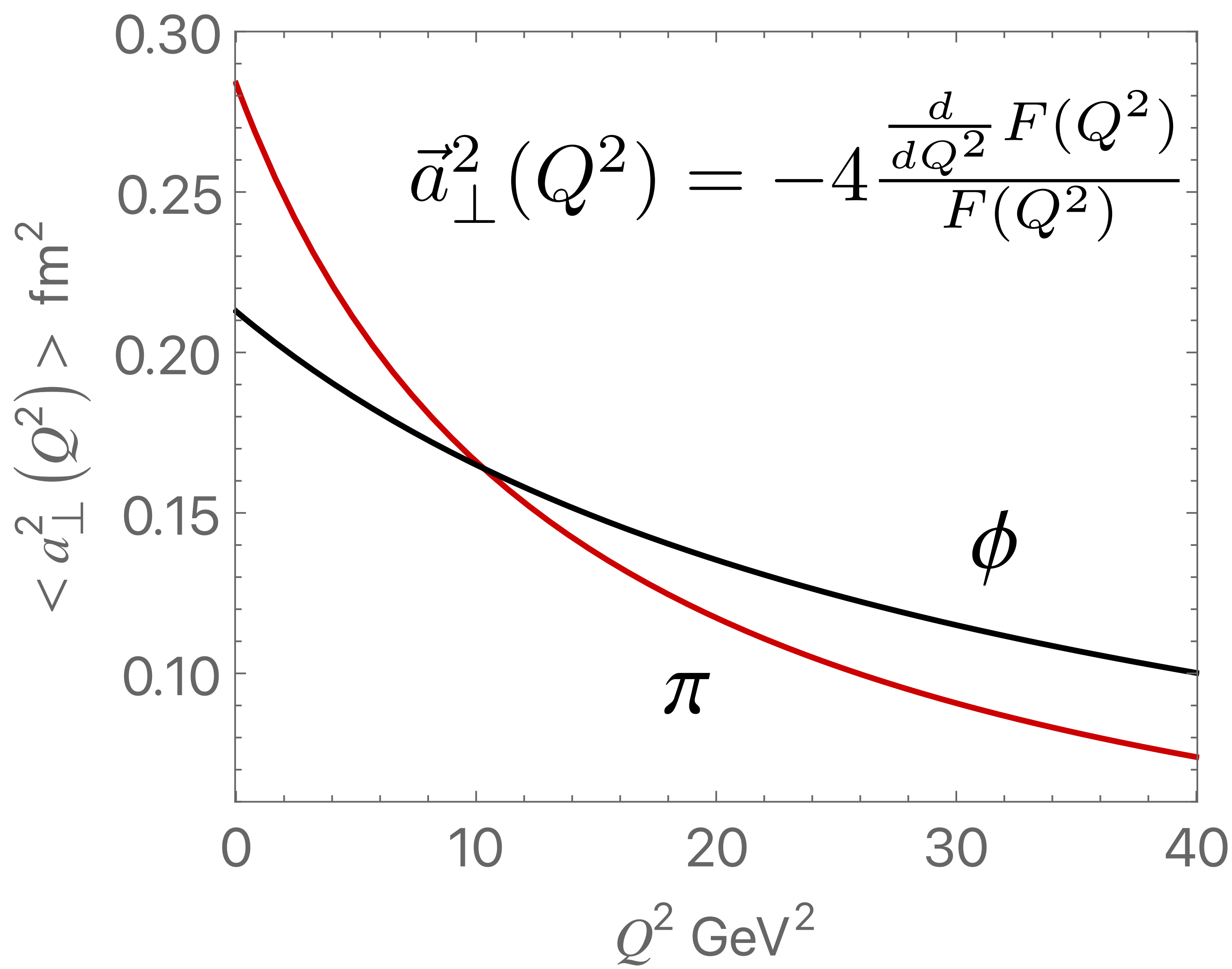
$$= \sum_n \prod_{j=1}^{n-1} \int dx_j \int d^2\mathbf{b}_{\perp j} \exp\Big(i\mathbf{q}_\perp \cdot \sum_{j=1}^{n-1} x_j \mathbf{b}_{\perp j}\Big) \left|\psi_n(x_j, \mathbf{b}_{\perp j})\right|^2$$

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

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

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

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



Transverse size depends on internal dynamics

Transparency controlled by transverse size

Universality of Generalized Parton Distributions in Light-Front Holographic QCD

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

(HLFHS Collaboration)

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

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

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

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

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

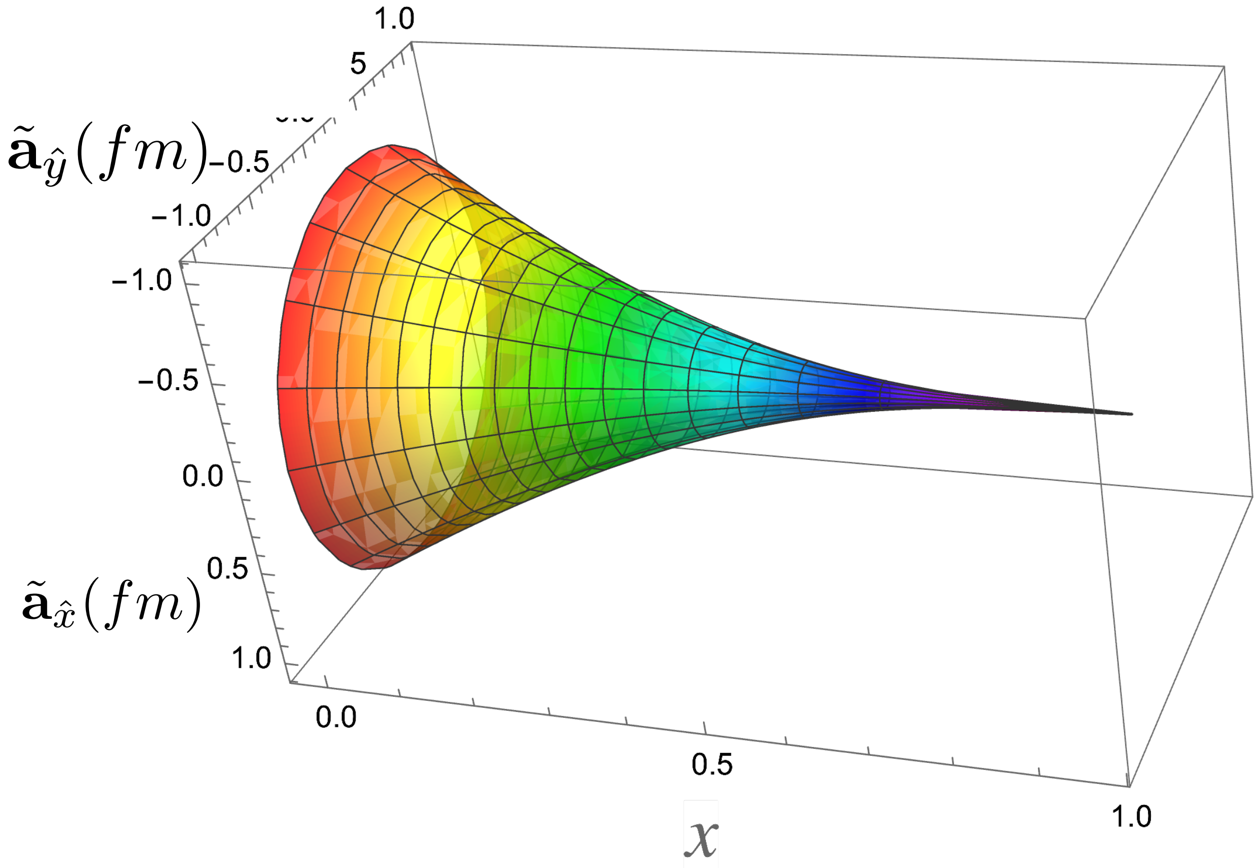
$$M_n^2 = 4\lambda(n + \tfrac{1}{2}), n = 0, 1, 2, \ldots, \tau - 2,$$

$$M_0 = m_\rho$$

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

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

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



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

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

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

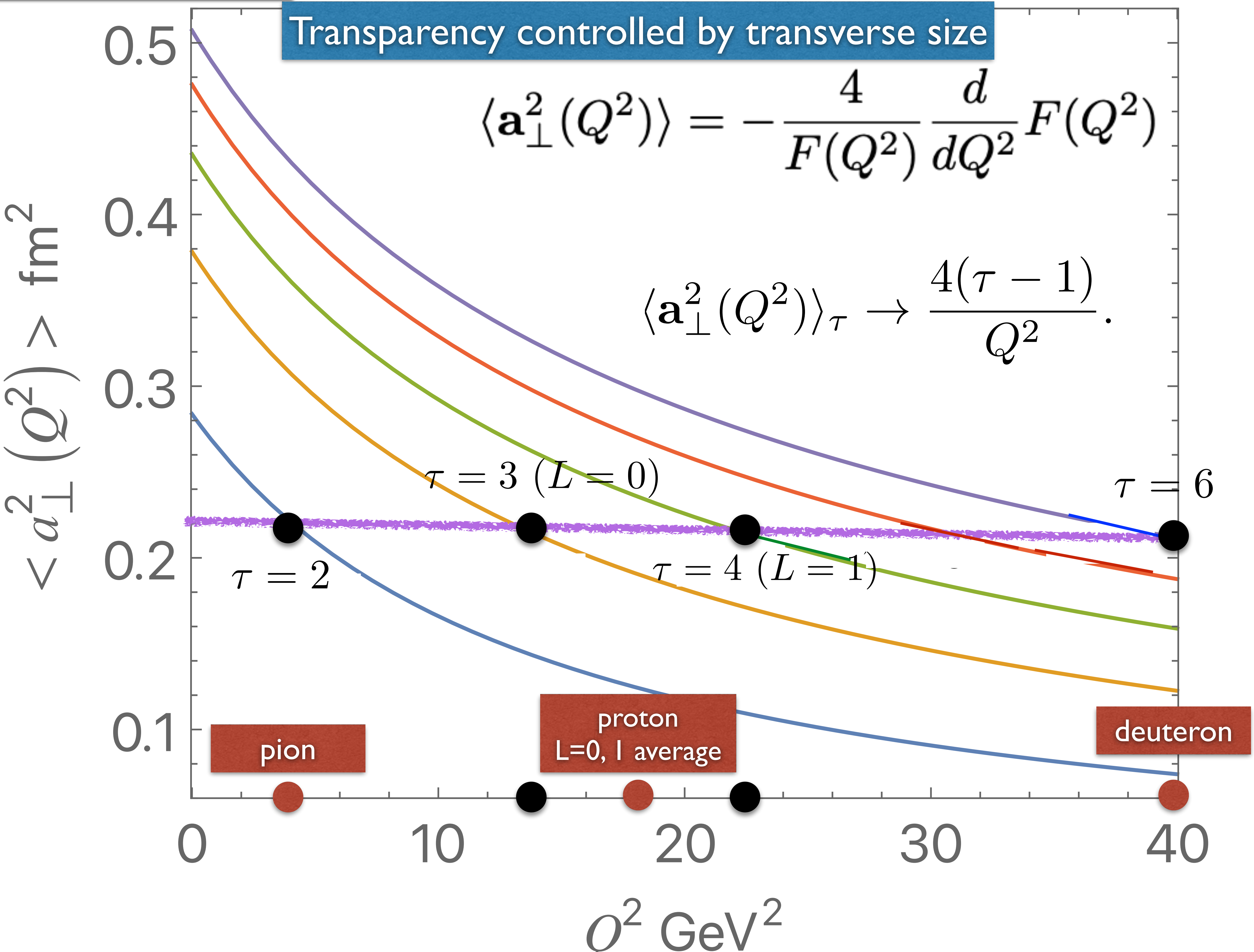
$$\langle \mathbf{a}_\perp^2(Q^2)\rangle_\tau \to \frac{4(\tau-1)}{Q^2}.$$

Mean transverse size as a function of Q and Twist

Transparency scale Q increases with twist

Light-Front Holography

Transparency controlled by transverse size



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

Two-Stage Color Transparency

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

Two-Stage Color Transparency

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

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

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

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

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

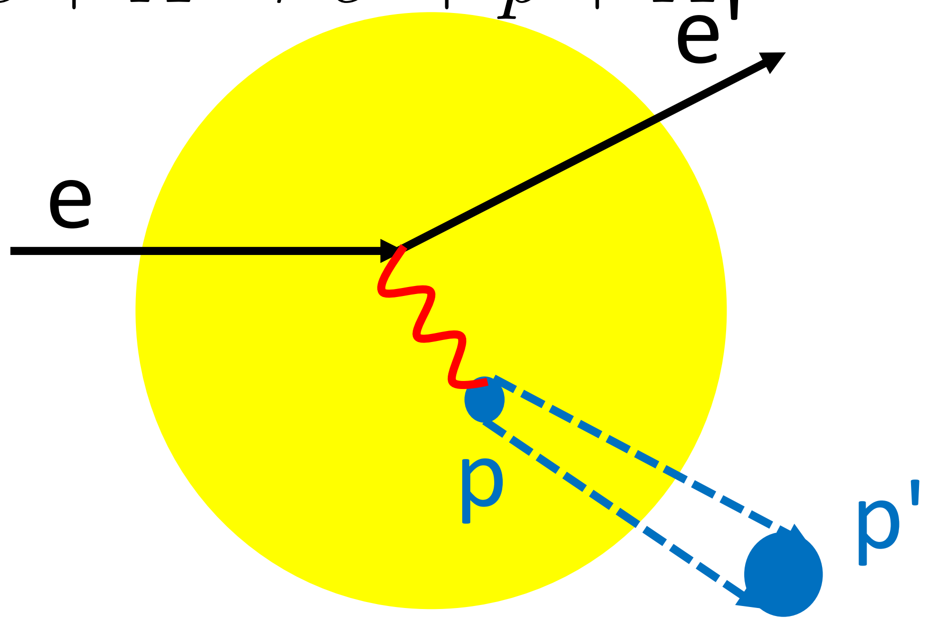
$$Q^2 > 20\ GeV^2$$

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

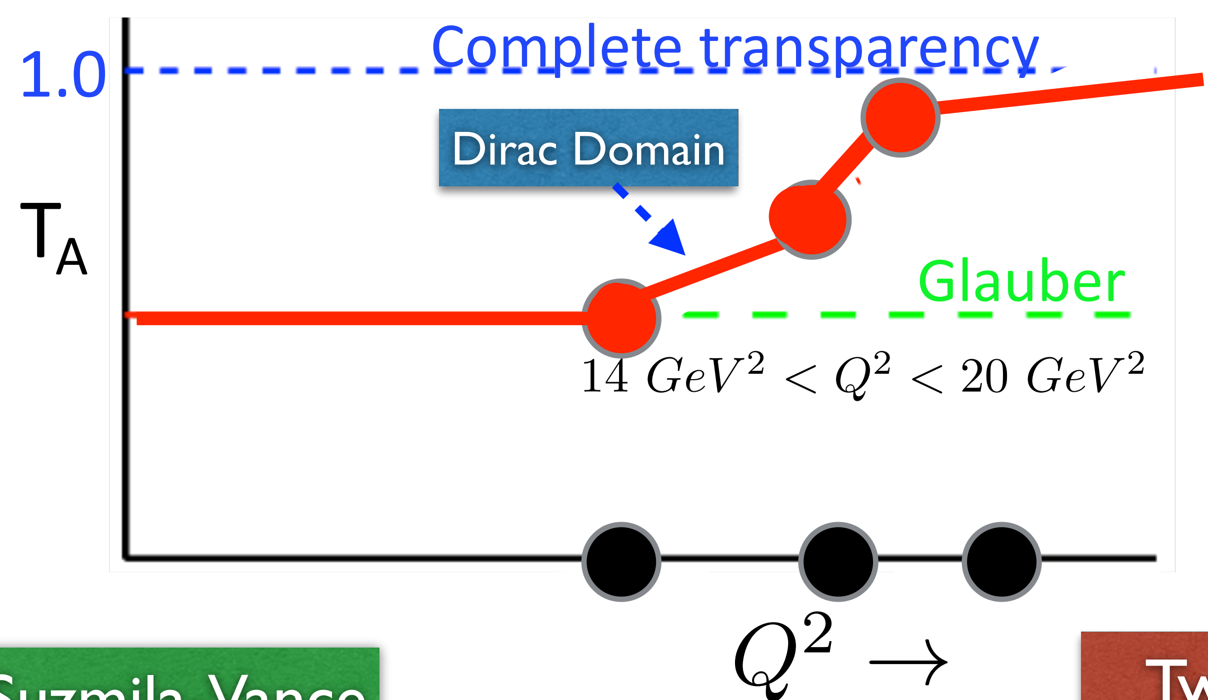
A.H. Mueller, sjb

Color transparency fundamental prediction of QCD

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



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



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

σ_A (nuclear cross section)

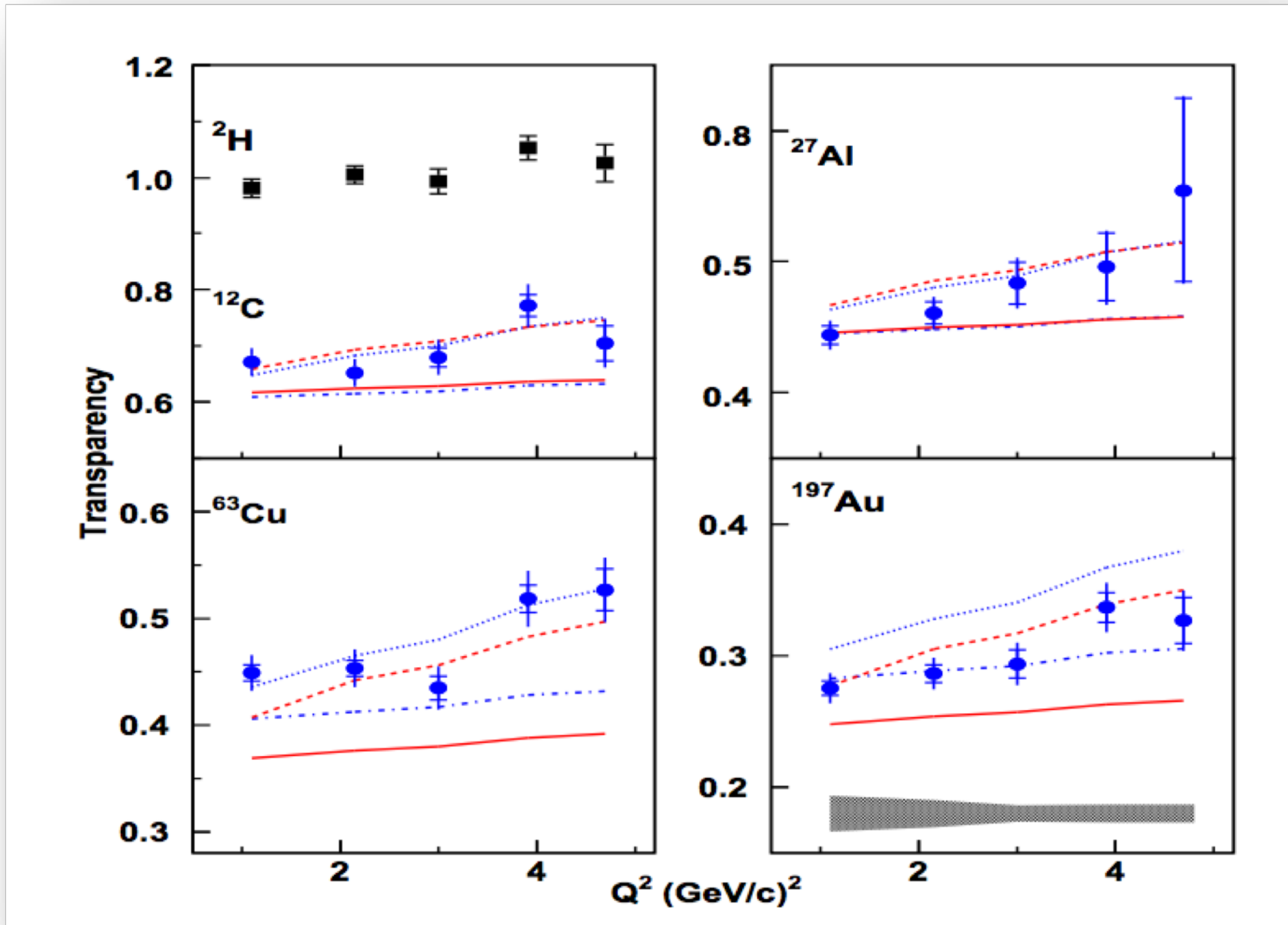
σ_N (free nucleon cross section)

Holly Suzmila-Vance

Two-Stage Color Transparency for Proton

Hall C E01-107 pion electro-production

A(e,e'π^+)

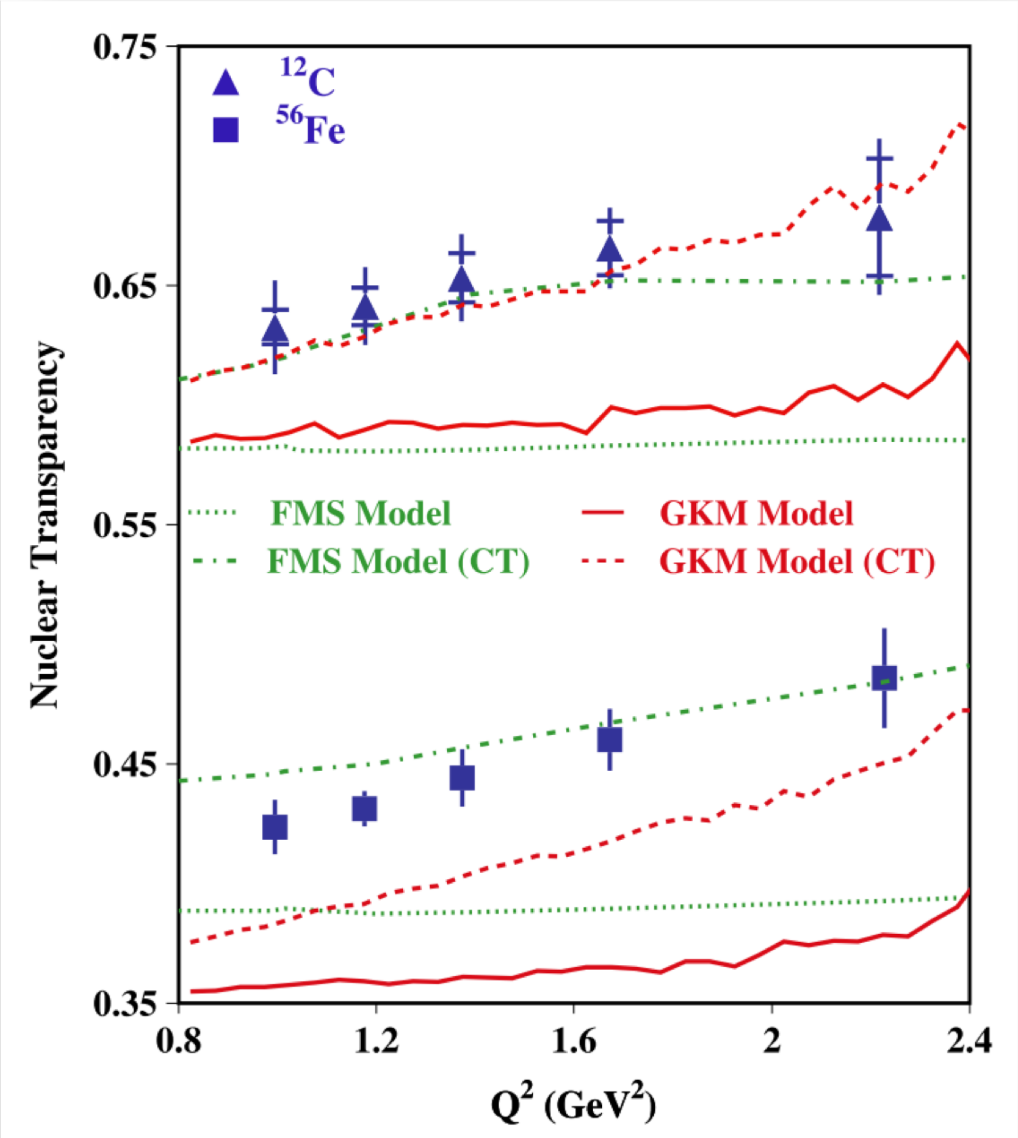


B.Clasie *et al.* PRL 99:242502 (2007)

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

CLAS E02-110 rho electro-production

A(e,e'ρ^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 $Q^2 = 18\ GeV^2$

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

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

Novel Effects Derived from Light-Front Wavefunctions

- Color Transparency
- Intrinsic heavy quarks at high x $c(x), b(x)$
- Asymmetries $s(x) \neq \bar{s}(x), \ \bar{u}(x) \neq \bar{d}(x)$
- Spin correlations, counting rules at x to 1
- Diffractive deep inelastic scattering $ep \rightarrow epX$
- Nuclear Effects: Hidden Color

Light-Front Holography

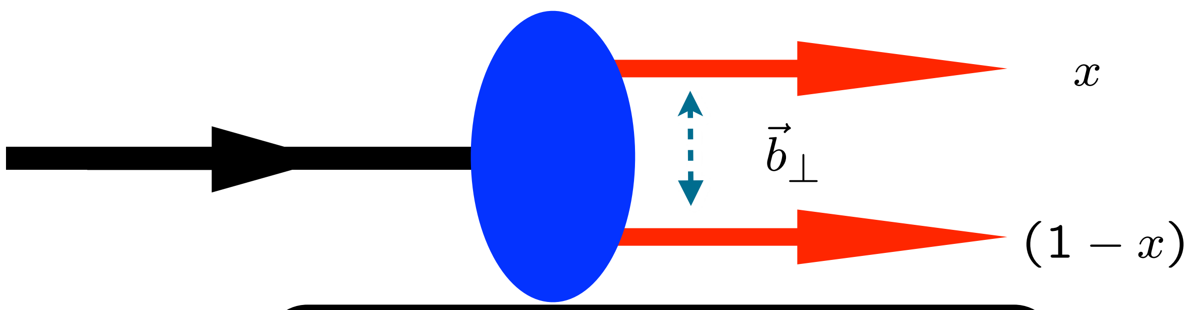
- *Color Confinement*
- *Origin of the QCD Mass Scale*
- *Meson and Baryon Spectroscopy*
- *Exotic States: Tetraquarks, Pentaquarks, Gluonium,*
- *Universal Regge Slopes: n, L, Mesons and Baryons*
- *Almost Massless Pion: GMOR Chiral Symmetry Breaking*

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

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

Light-Front QCD

Fixed $\tau = t + z/c$



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

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

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

Coupled Fock states

Eliminate higher Fock states and retarded interactions

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

Effective two-particle equation

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

Azimuthal Basis ζ, ϕ

Single variable Equation

$m_q = 0$

AdS/QCD:

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

Confining AdS/QCD potential!

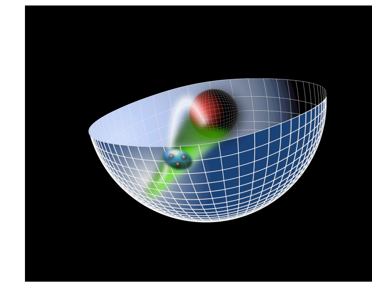
Semiclassical first approximation to QCD

Sums an infinite # diagrams

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***

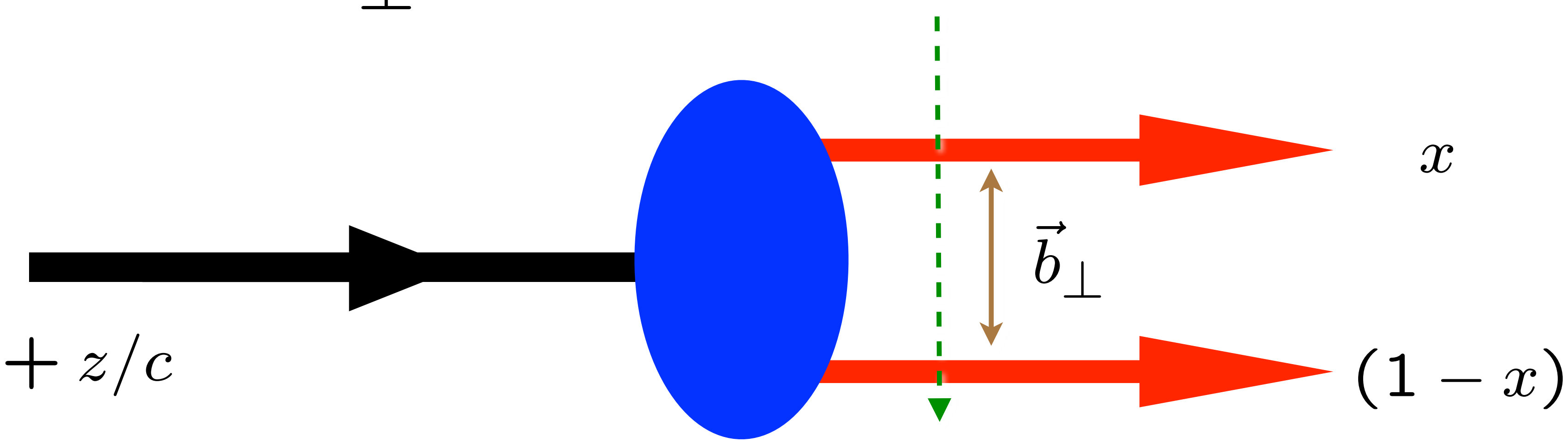
de Tèramond, Dosch, sjb

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 $\tau = t + z/c$

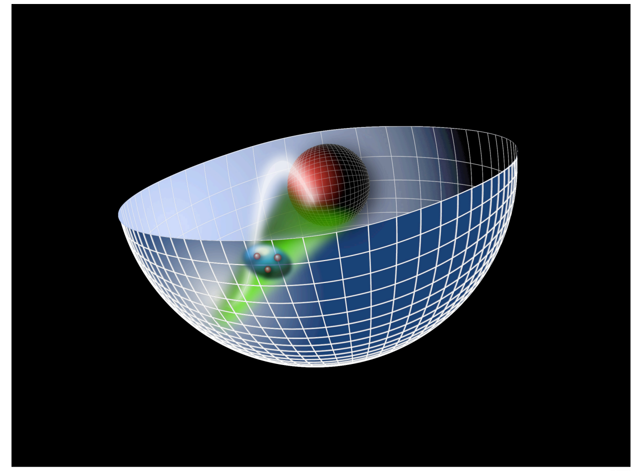
$$\psi(x,\zeta) = \sqrt{x(1-x)}\,\zeta^{-1/2}\phi(\zeta)$$

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

Light-Front Holography: *Unique mapping derived from equality of LF and AdS f* **Is Antishadowing Non-Universal? -- Quark Specific?** *atrix elements and identical equations of motion* de Tèramond, Dosch, sjb

AdS/QCD Soft-Wall Model

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



Light-Front Holography

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

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

Light-Front Schrödinger Equation

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

Single variable ζ

Unique Confinement Potential!

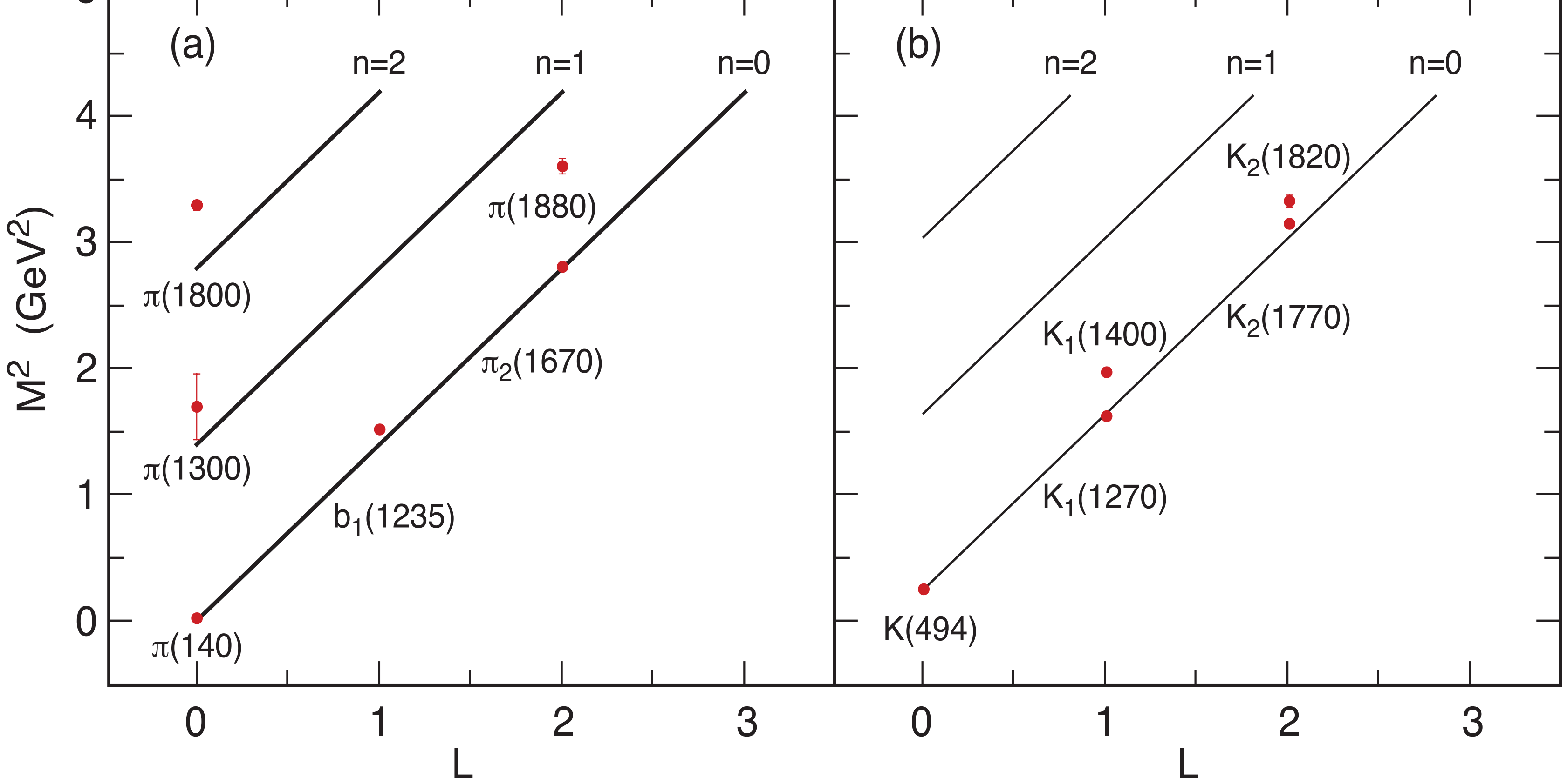
Conformal Symmetry of the action

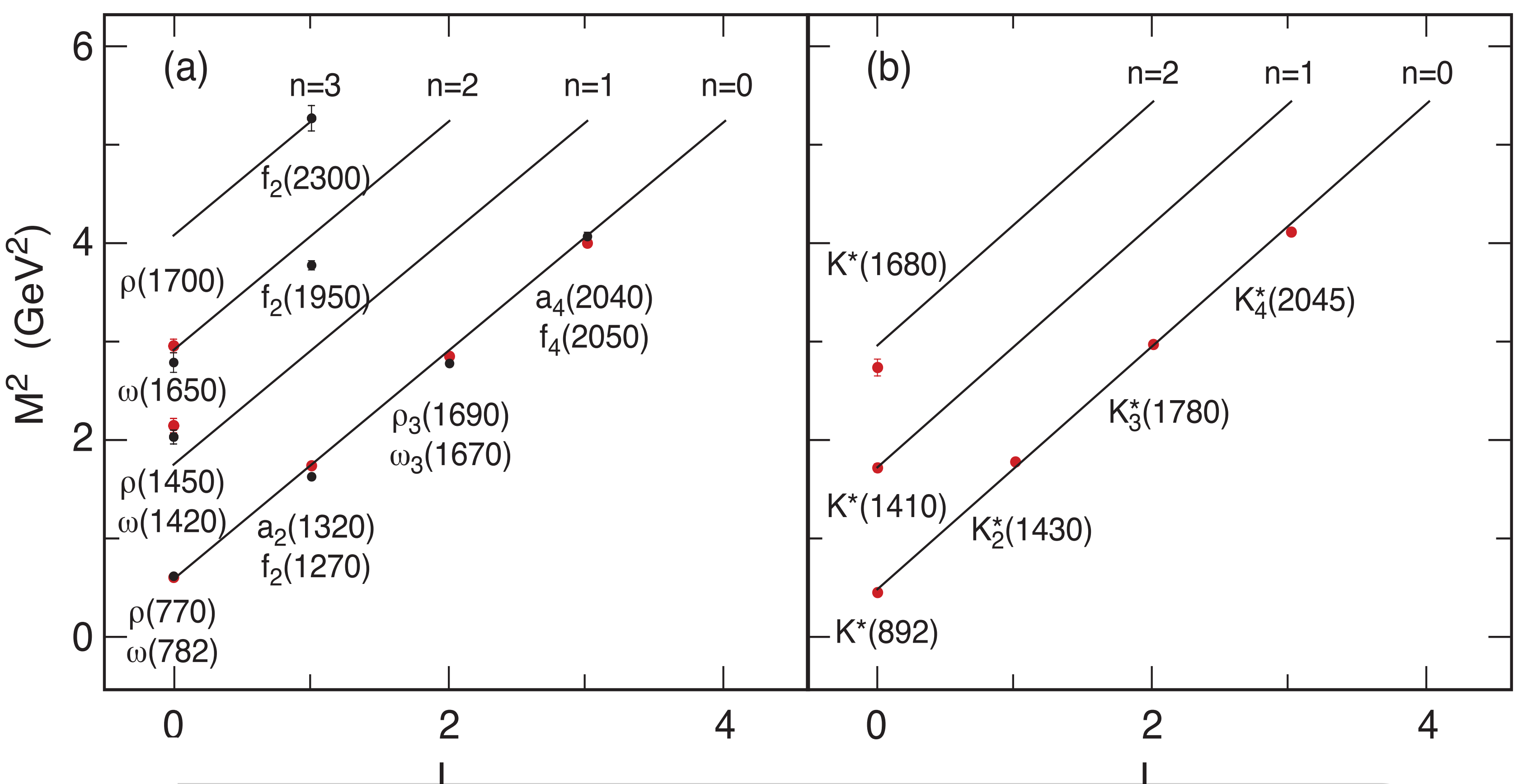
Confinement scale: $\kappa \simeq 0.5\ GeV$

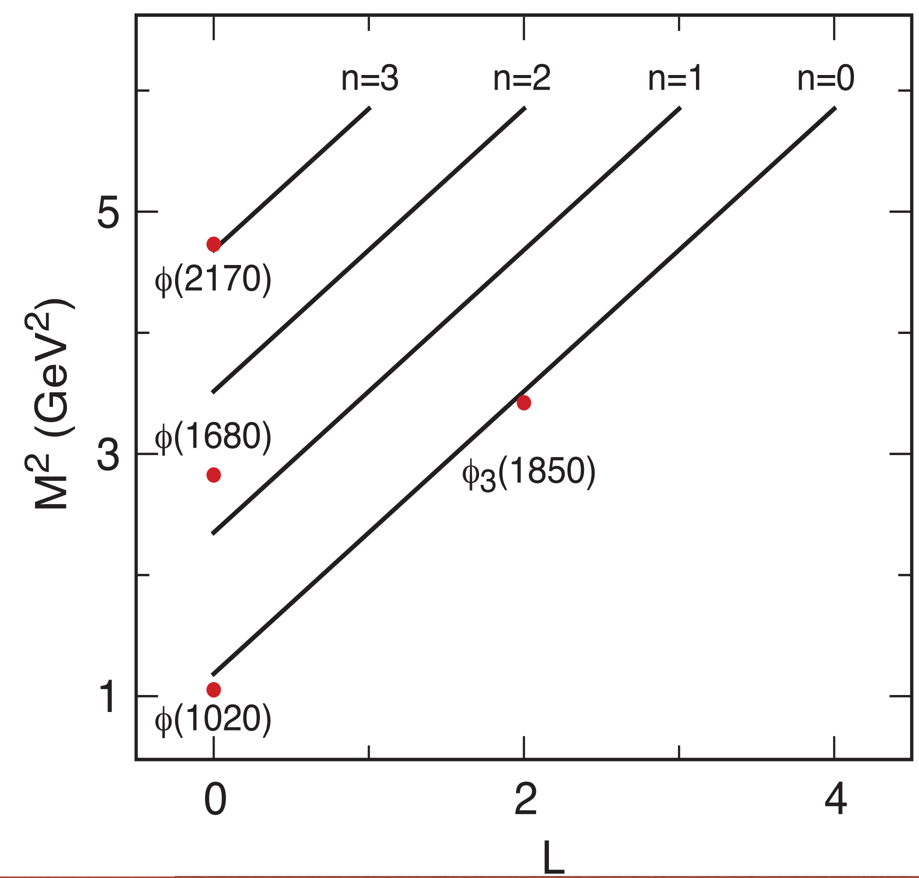
- **de Alfaro, Fubini, Furlan:**
- **Fubini, Rabinovici:**

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

GeV units external to QCD: Only Ratios of Masses Determined







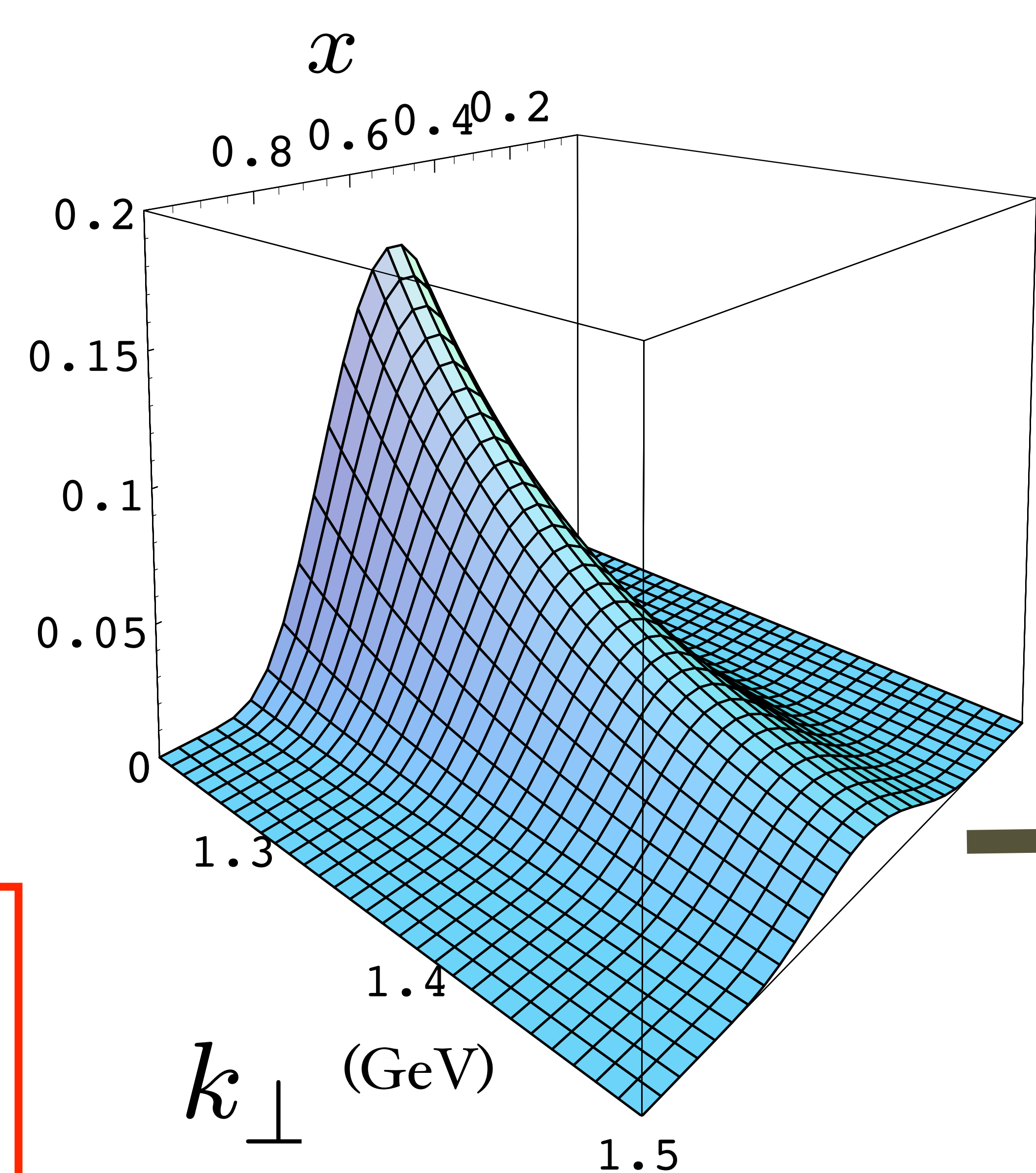
$$M^2(n, L, S) = 4\kappa^2(n + L + S/2)$$

Equal Slope in n and L

Prediction from AdS/QCD: Meson LFWF

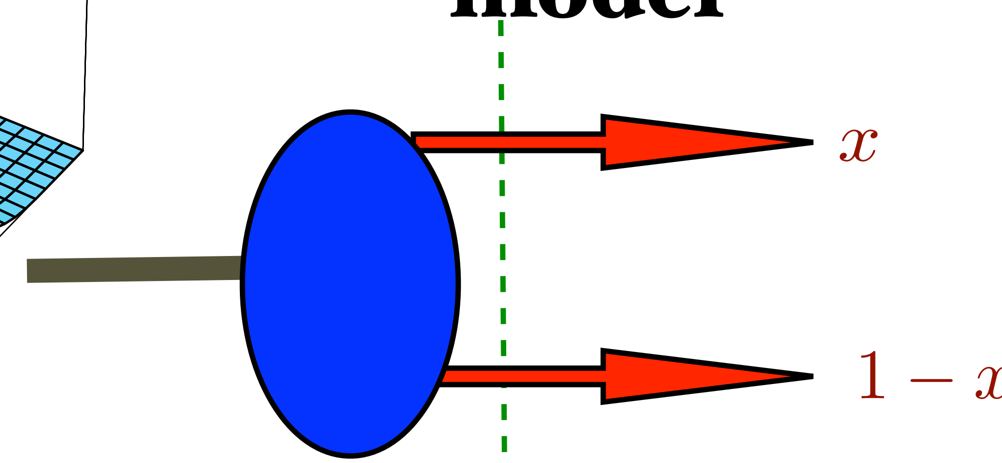
$$e^{\varphi(z)} = e^{+\kappa^2 z}$$

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



de T`eramond, Cao, sjb

"Soft Wall" model



massless quarks

Note coupling

$k_\perp^2, x$

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

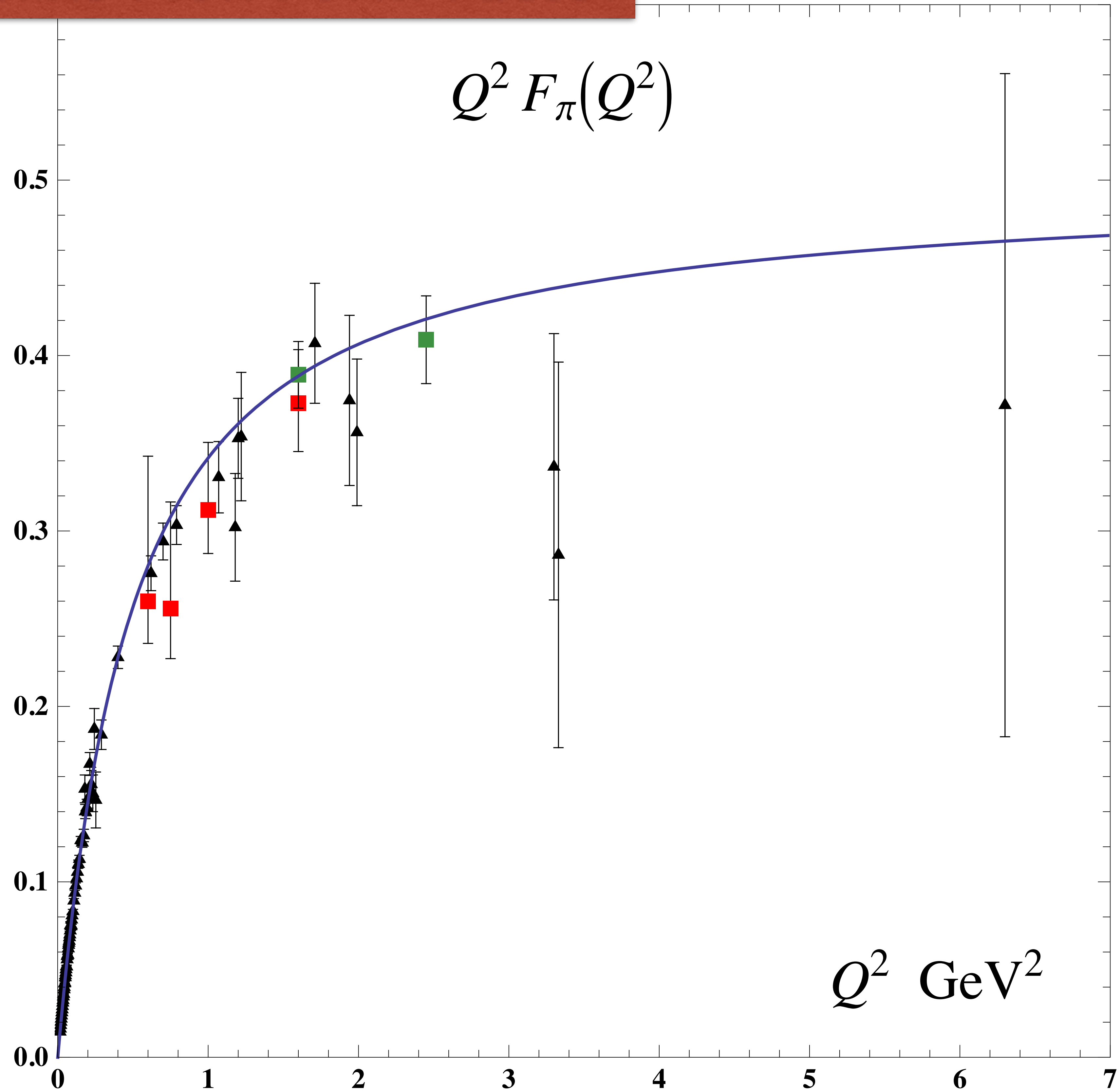
$$\phi_\pi(x) = \frac{4}{\sqrt{3}\pi} f_\pi \sqrt{x(1-x)}$$

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

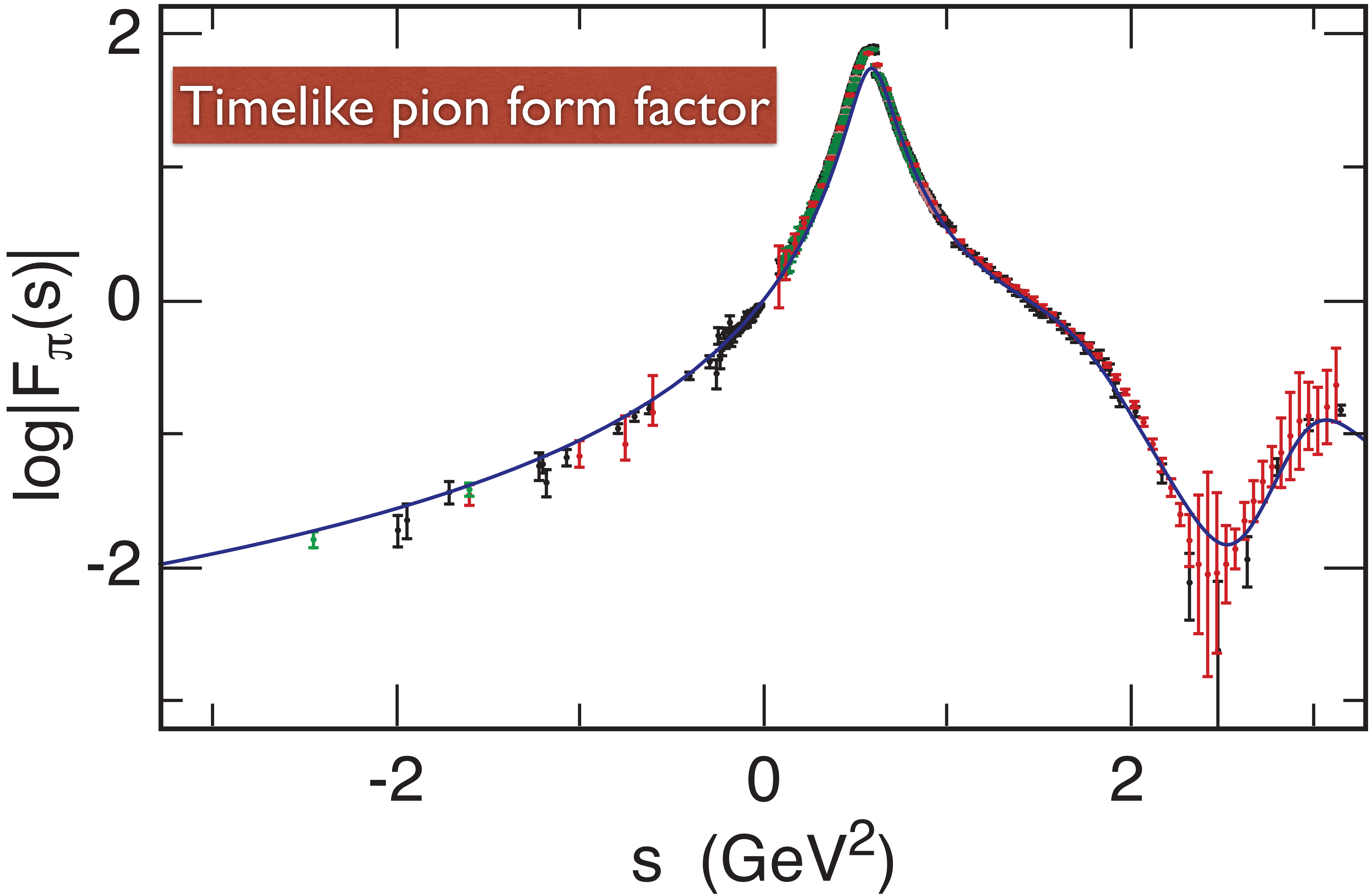
Same as DSE! **C. D. Roberts et al.**

Provides Connection of Confinement to Hadron Structure

Spacelike Pion Form Factor

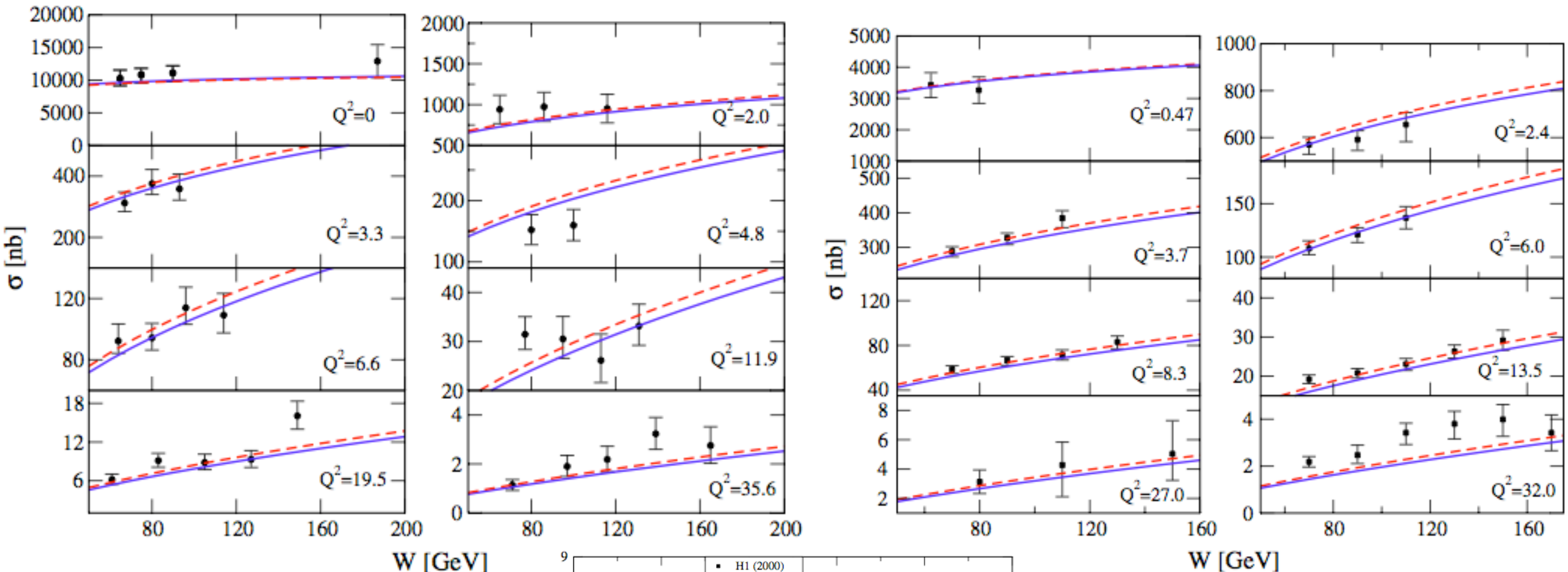


de Téramond, Dosch, sjb



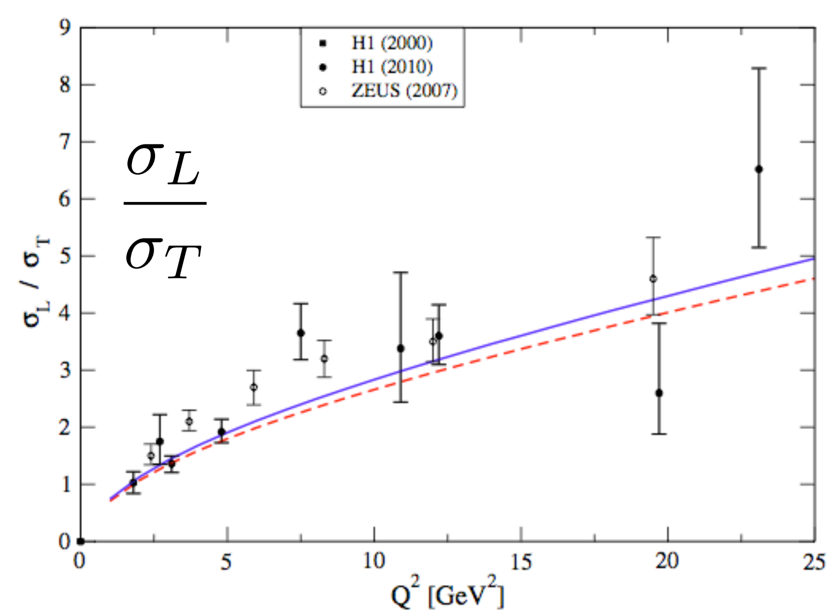
Timelike pion form factor
2
0
-2
log|F_π(s)|
-2
0
2
s (GeV²)

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



(a) H1

(b) ZEUS



J. R. Forshaw, R. Sandapen

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

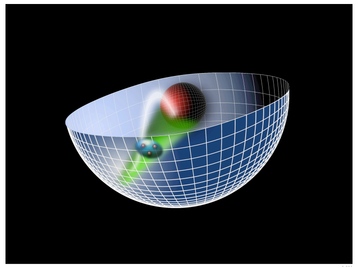
$$\psi_M(x, k_\perp) = \frac{4\pi}{\kappa\sqrt{x(1-x)}} e^{-\frac{k_\perp^2}{2\kappa^2 x(1-x)}}$$

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:***

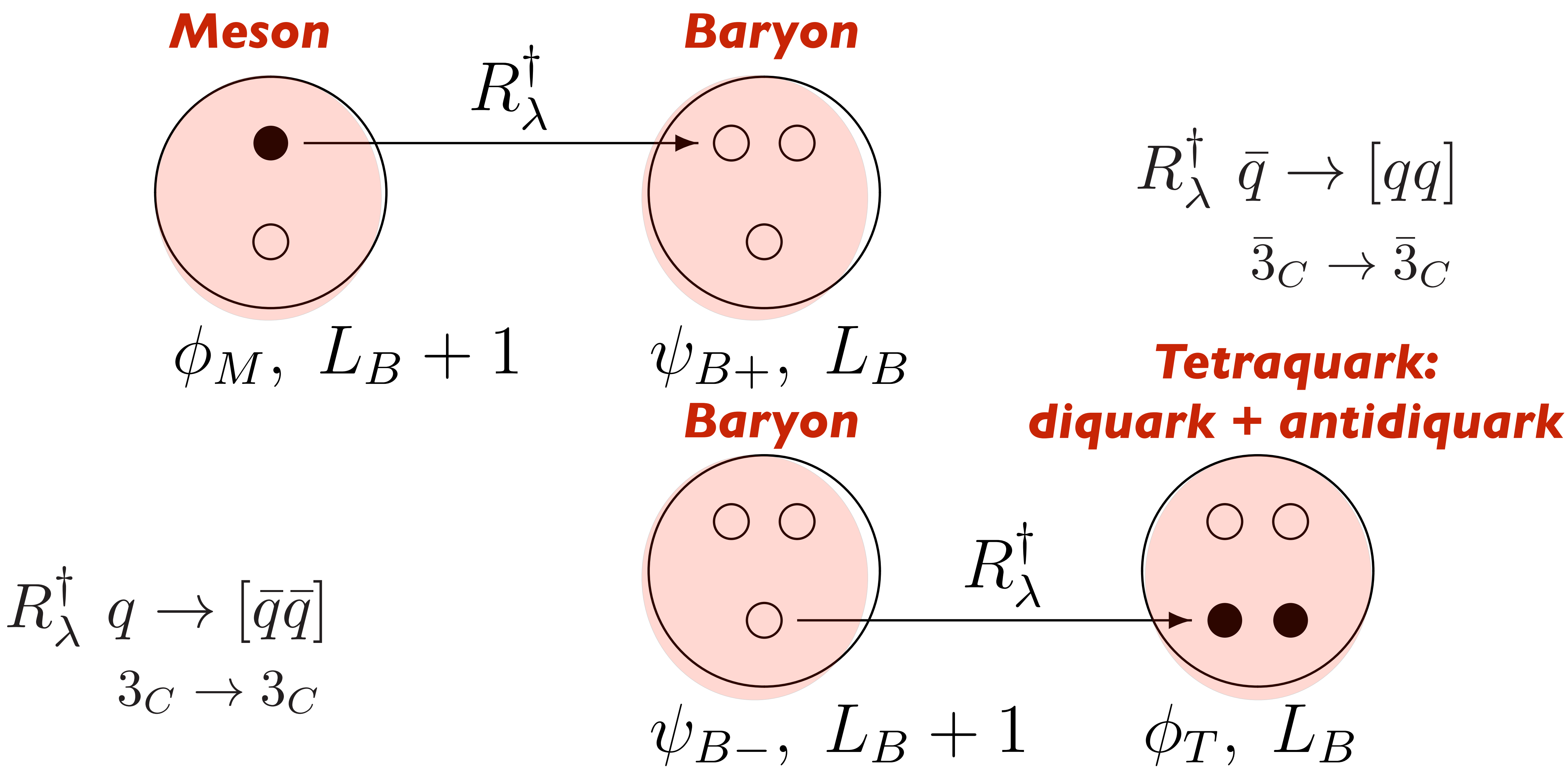
$$\text{Meson } q\bar{q} \leftrightarrow \text{Baryon } q[qq] \leftrightarrow \text{Tetraquark } [qq][\bar{q}\bar{q}]$$

Superconformal Algebra

de Téramond, Dosch, sjb

2X2 Hadronic Multiplets

Bosons, Fermions with Equal Mass!



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

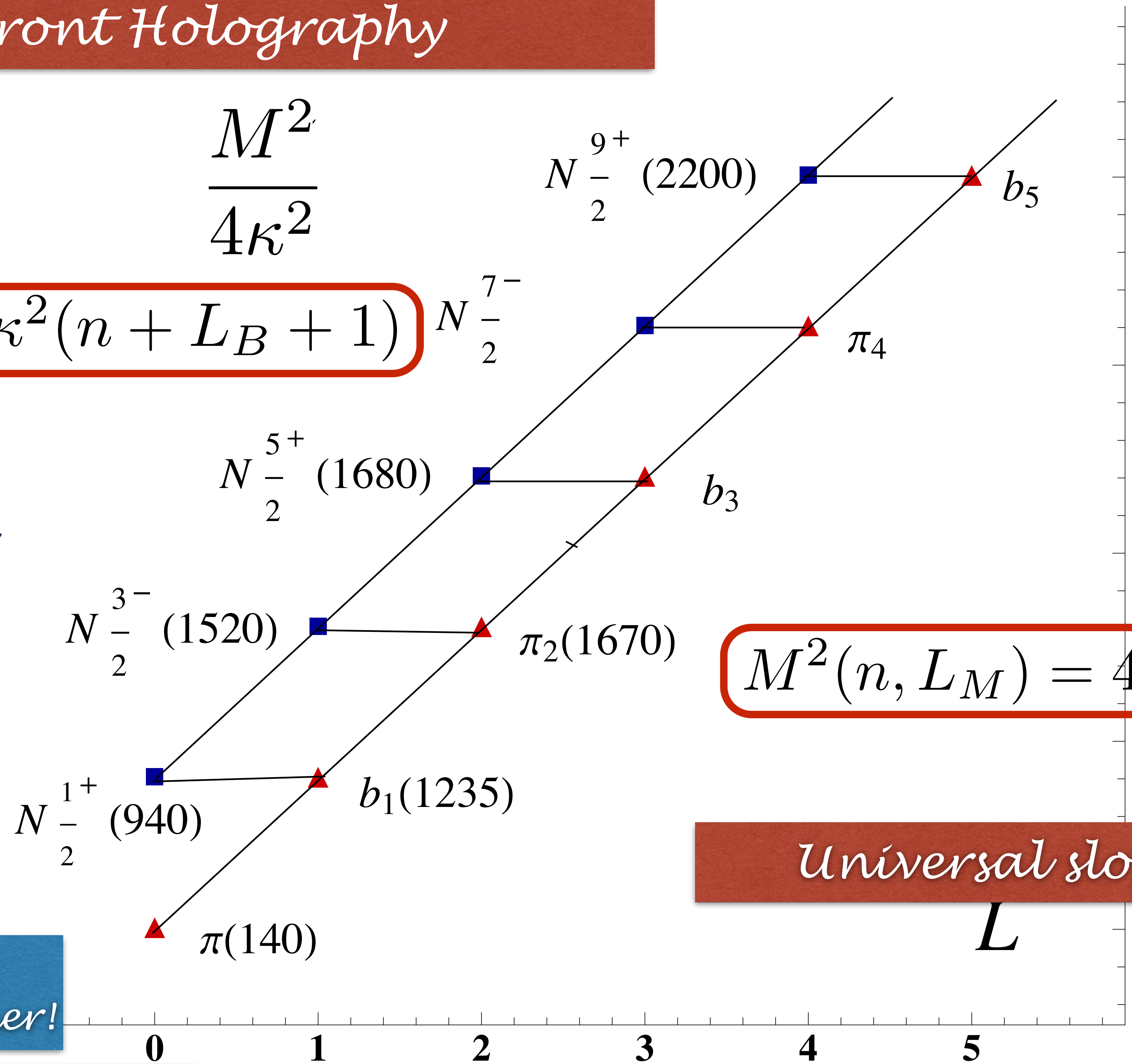
Superconformal Quantum Mechanics
Light-Front Holography

de Téramond, Dosch, Lorcé, sjb

$$\frac{M^2}{4\kappa^2}$$

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

Same slope



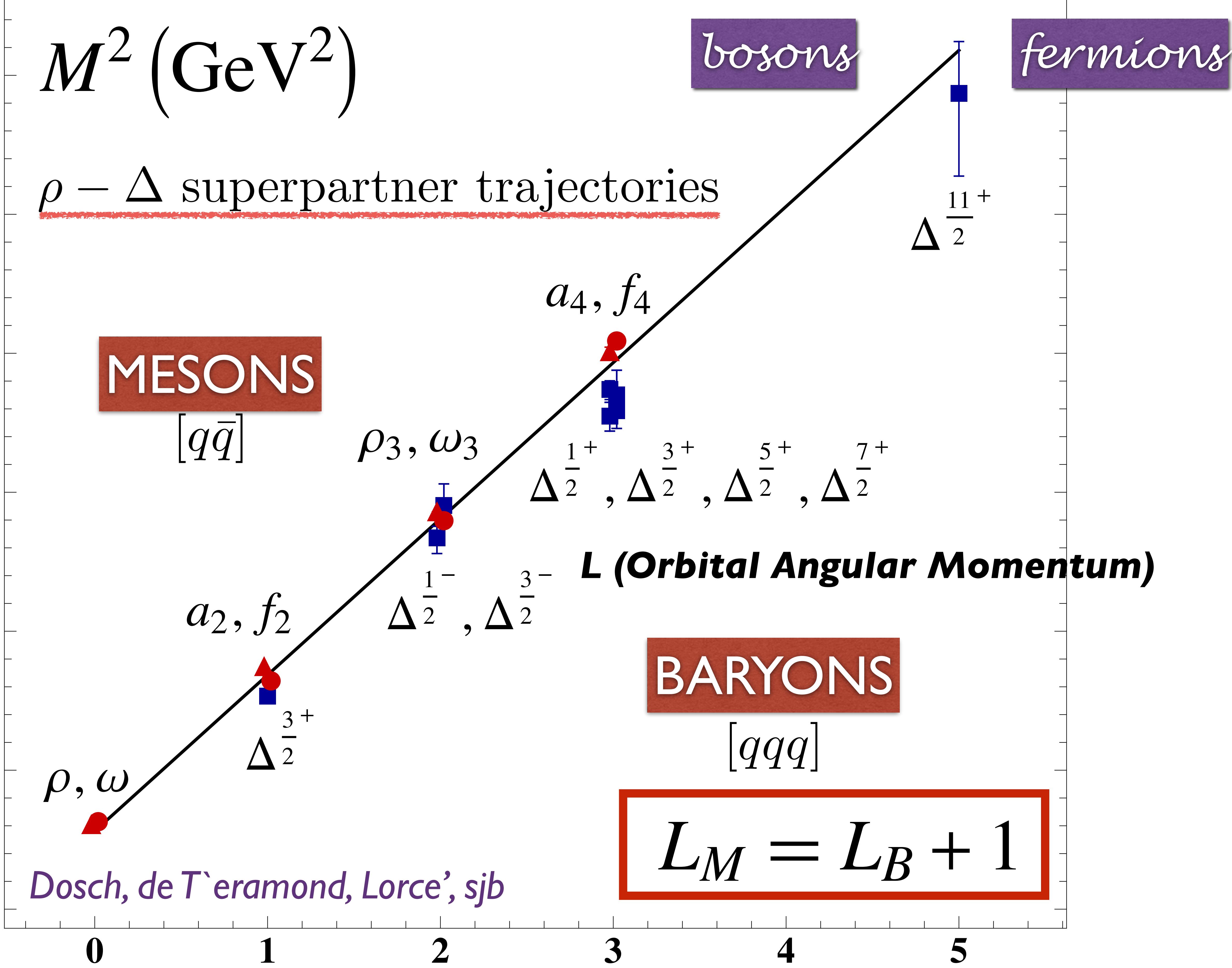
$$M^2(n, L_M) = 4\kappa^2(n + L_M)$$

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

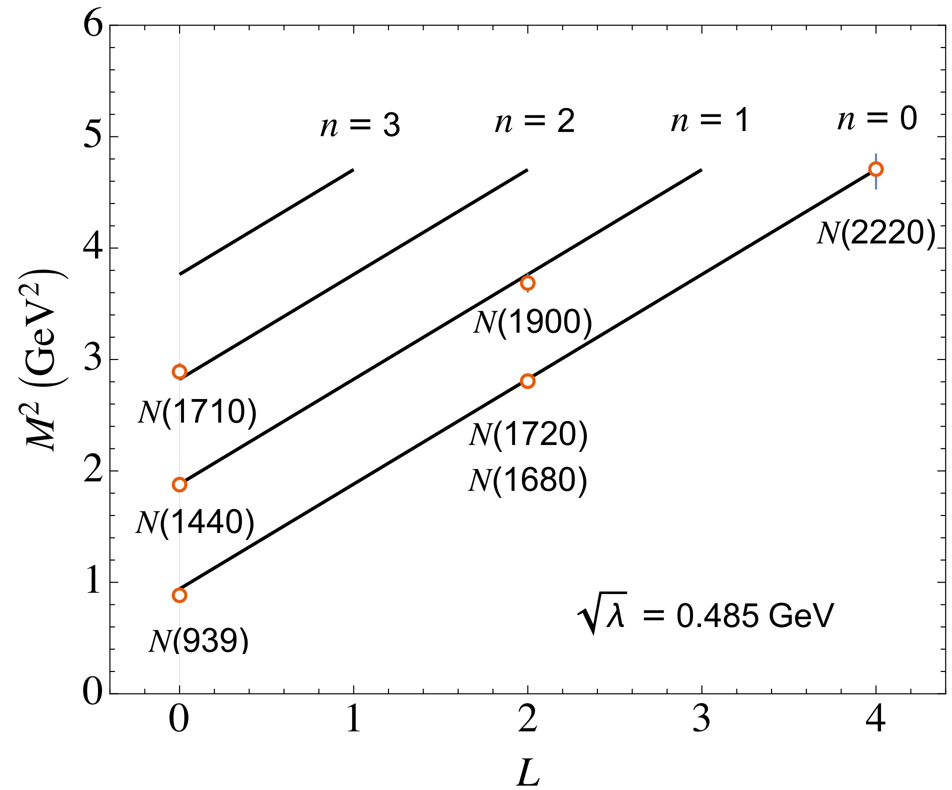


$M^2\,(\mathrm{GeV}^2)$
bosons
fermions
$\rho - \Delta$ superpartner trajectories
MESONS
$[q\bar{q}]$
BARYONS
$[qqq]$
ρ, ω
a_2, f_2
ρ_3, ω_3
a_4, f_4
$\Delta \frac{3}{2}^+$
$\Delta \frac{1}{2}^-, \Delta \frac{3}{2}^-$
$\Delta \frac{1}{2}^+, \Delta \frac{3}{2}^+, \Delta \frac{5}{2}^+, \Delta \frac{7}{2}^+$
$\Delta \frac{11}{2}^+$
L (Orbital Angular Momentum)
$L_M = L_B + 1$
Dosch, de T`eramond, Lorce', sjb
0
1
2
3
4
5
6

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!

quark-diquark structure of baryons

Rittenhouse West: Consequences for nuclear physics

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**

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

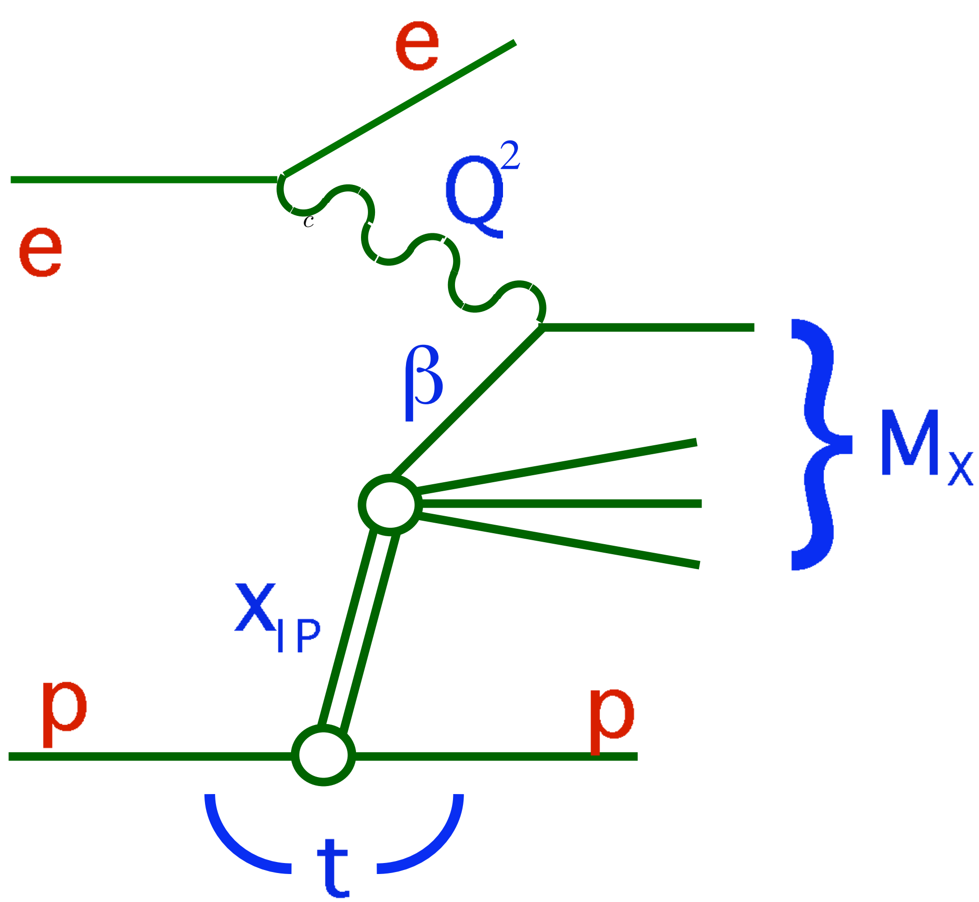
hyperfine spin-spin

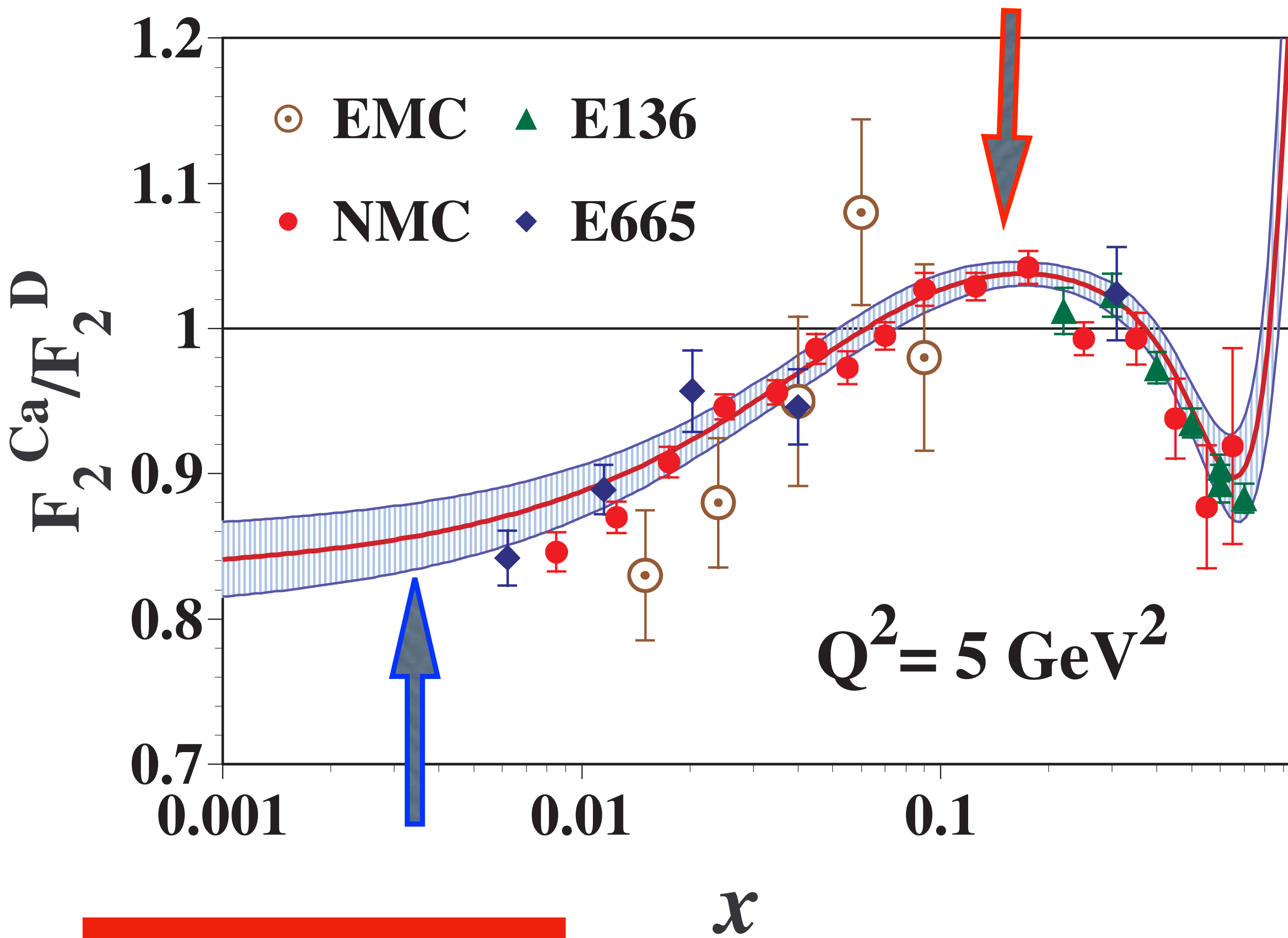
QCD Myths

- Anti-Shadowing is Universal: Nuclear PDF Sum Rules!
- ISI and FSI are higher twist effects and universal
- High transverse momentum hadrons arise only from jet fragmentation -- baryon anomaly!
- heavy quarks only from gluon splitting
- renormalization scale cannot be fixed
- QCD condensates are vacuum effects
- Infrared Slavery
- Nuclei are composites of nucleons only
- Real part of DVCS arbitrary

Diffractive Contribution to Deep Inelastic Scattering: Implications for QCD Sum Rules and Nuclear Parton Distributions

Anti-Shadowing





Diffractive DIS (DDIS)

Shadowing

Stan Brodsky

SLAC NATIONAL ACCELERATOR LABORATORY

Low-x 2021

Elba, September 27, 2021