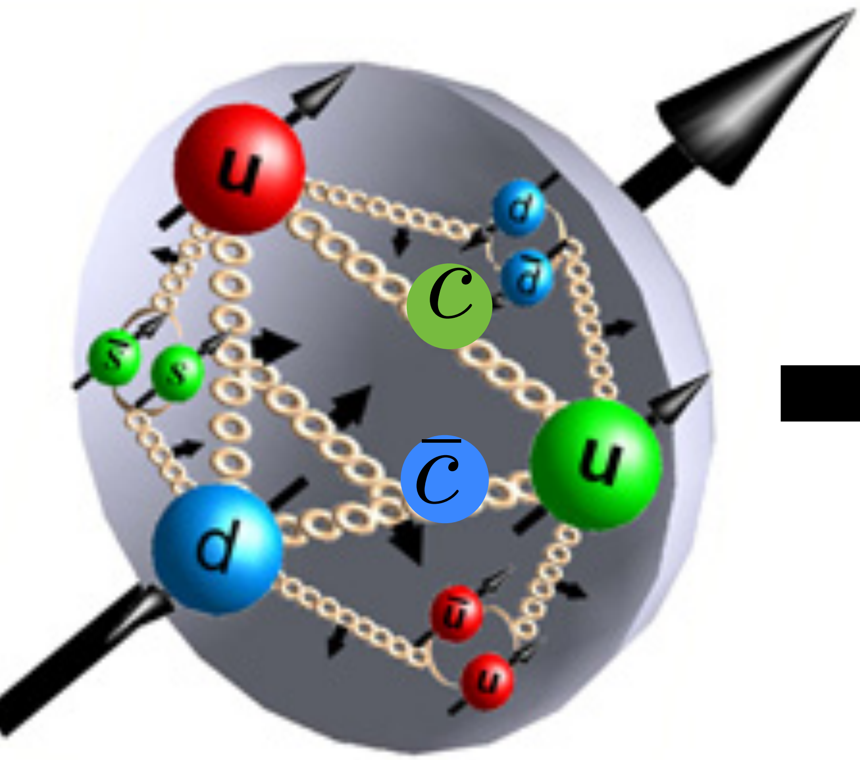
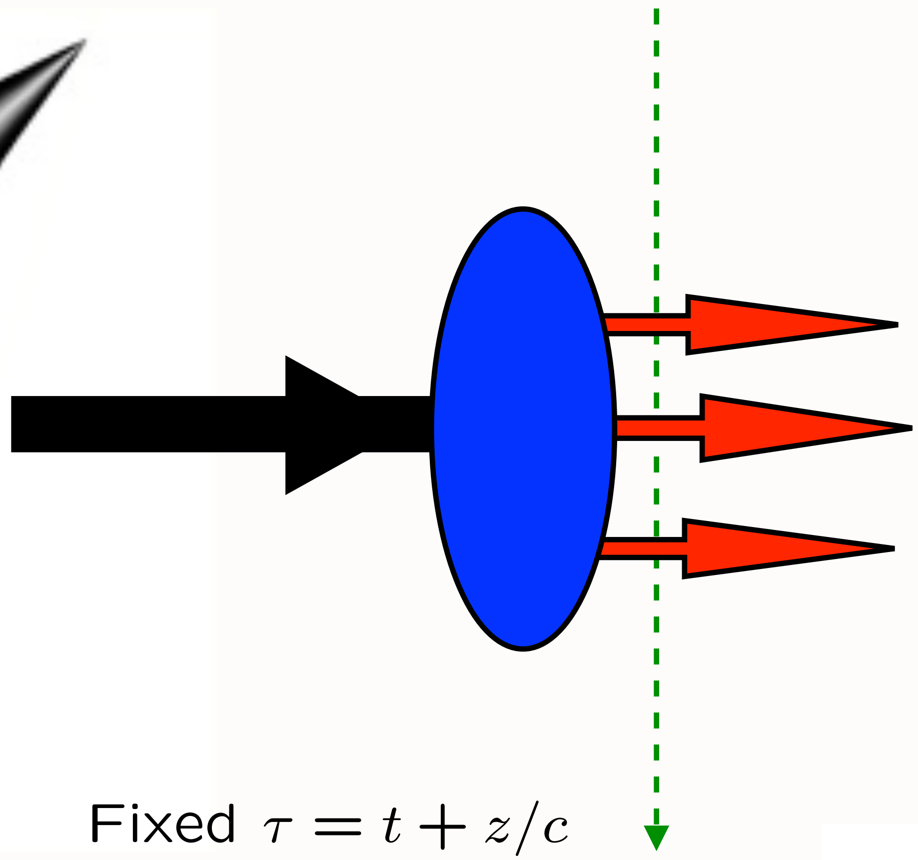
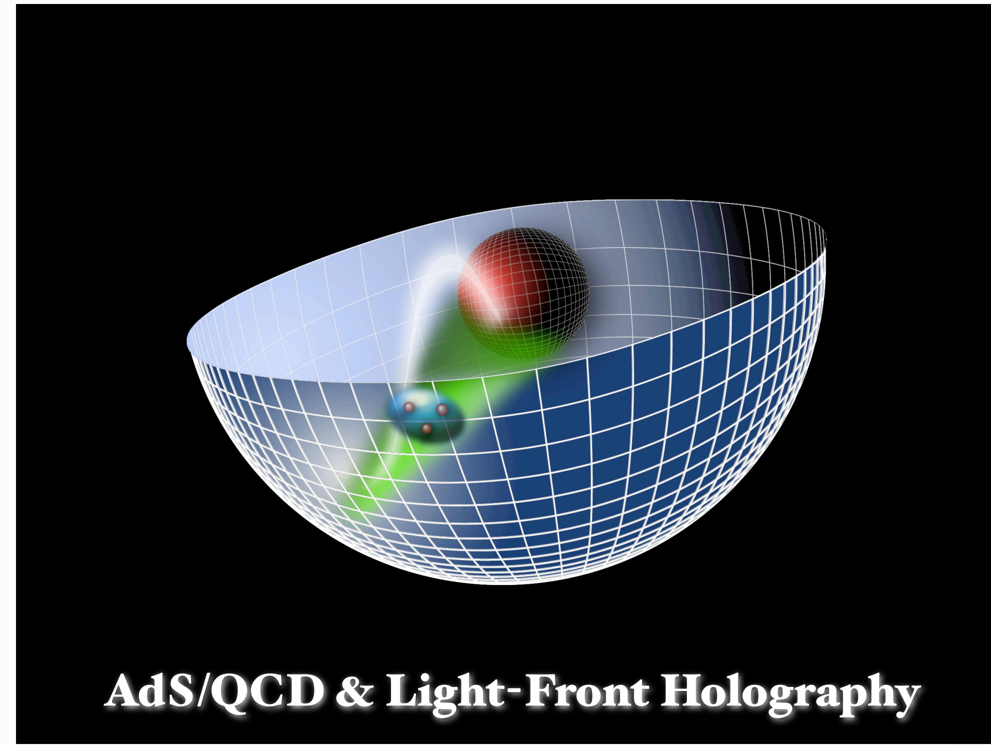
Light-Front Holography and QCD Myths







CP3 - Origins
Particle Physics & Origin of Mass

Stan Brodsky

SLAC
NATIONAL ACCELERATOR LABORATORY

QCD Myths

- Anti-Shadowing is Universal
- 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

Some Outstanding QCD Problems

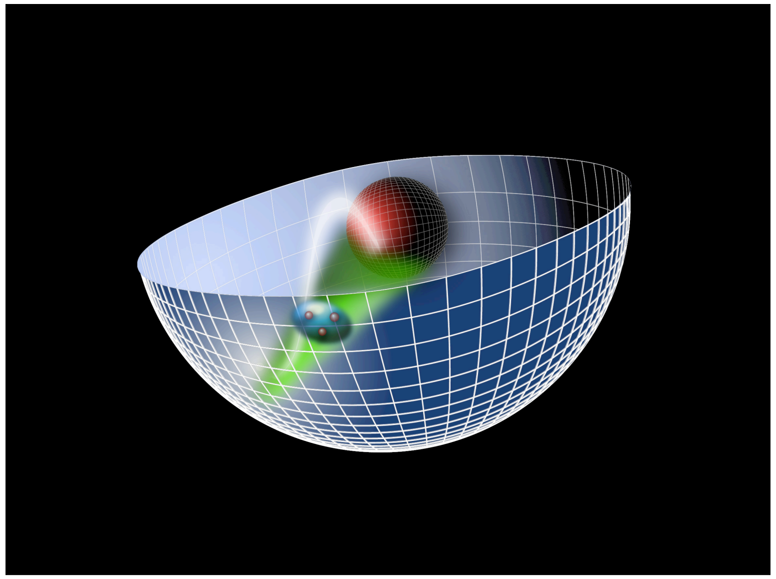
- Solving Hadron Spectroscopy and Dynamics Simultaneously
- Proton Spin
- Anti-Shadowing is Not Universal
- Breakdown of QCD Factorization Theorems
- The Baryon Anomaly at RHIC
- The DZero Anomaly: heavy quarks at large x
- Setting the Renormalization Scale
- QCD condensates and Dark Energy
- Fixing the D Term in DVCS
- $J/\psi \to \rho\pi$ puzzle
- Anomalous Physics of Sea Quarks
- Hadronization at the Amplitude Level
- QCD Running Coupling in the Infrared

More Outstanding QCD Problems

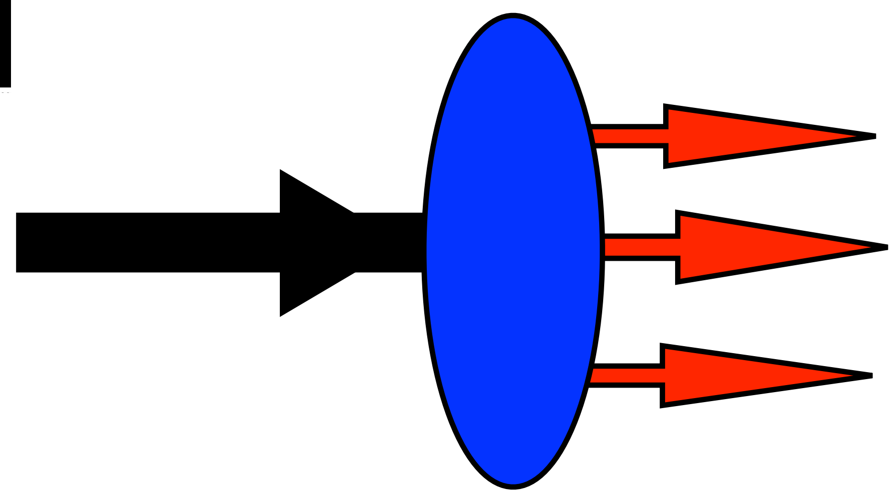
- **Single inclusive high-p_T hadrons -- wrong scaling !**
- **Quark Interchange dominance in hadron scattering reactions**
- **Quarkonium nuclear target dependence**
- **The Same-Side Ridge at CMS**
- **How to Find the Odderon?**
- **Signals of Hidden Color in the Deuteron**
- **Quark-Gluon Phase of Heavy Ion Collisions**
- **Quark-Gluon Phase in the Target Frame**
- **The Top/anti-Top Asymmetry**
- **Color Transparency and Opaqueness**
- **BaBar Photon-to-Pion Transition Form Factor**
- **...**

Studies of QCD just beginning!

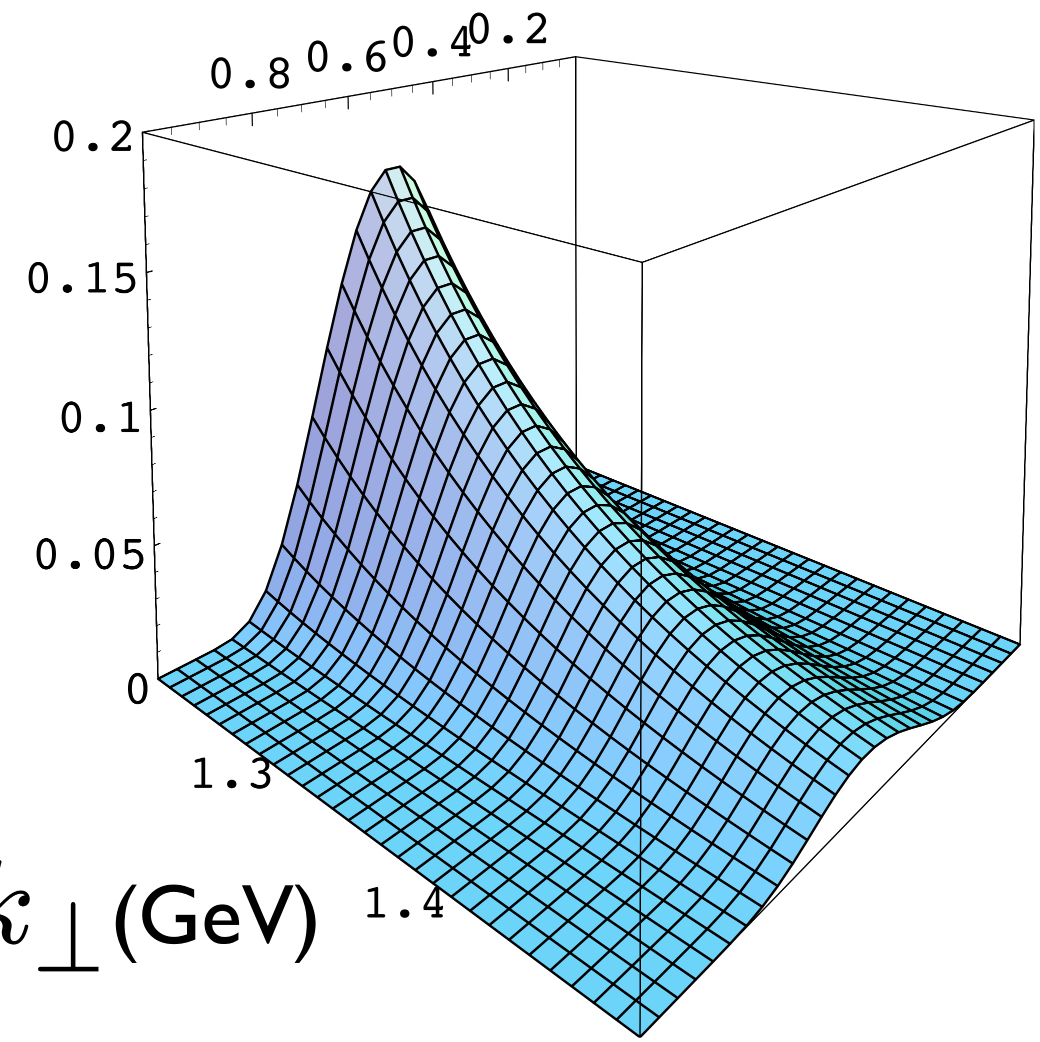
$\phi(z)$



- *Light-Front Holography*



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



- *Light Front Wavefunctions:*

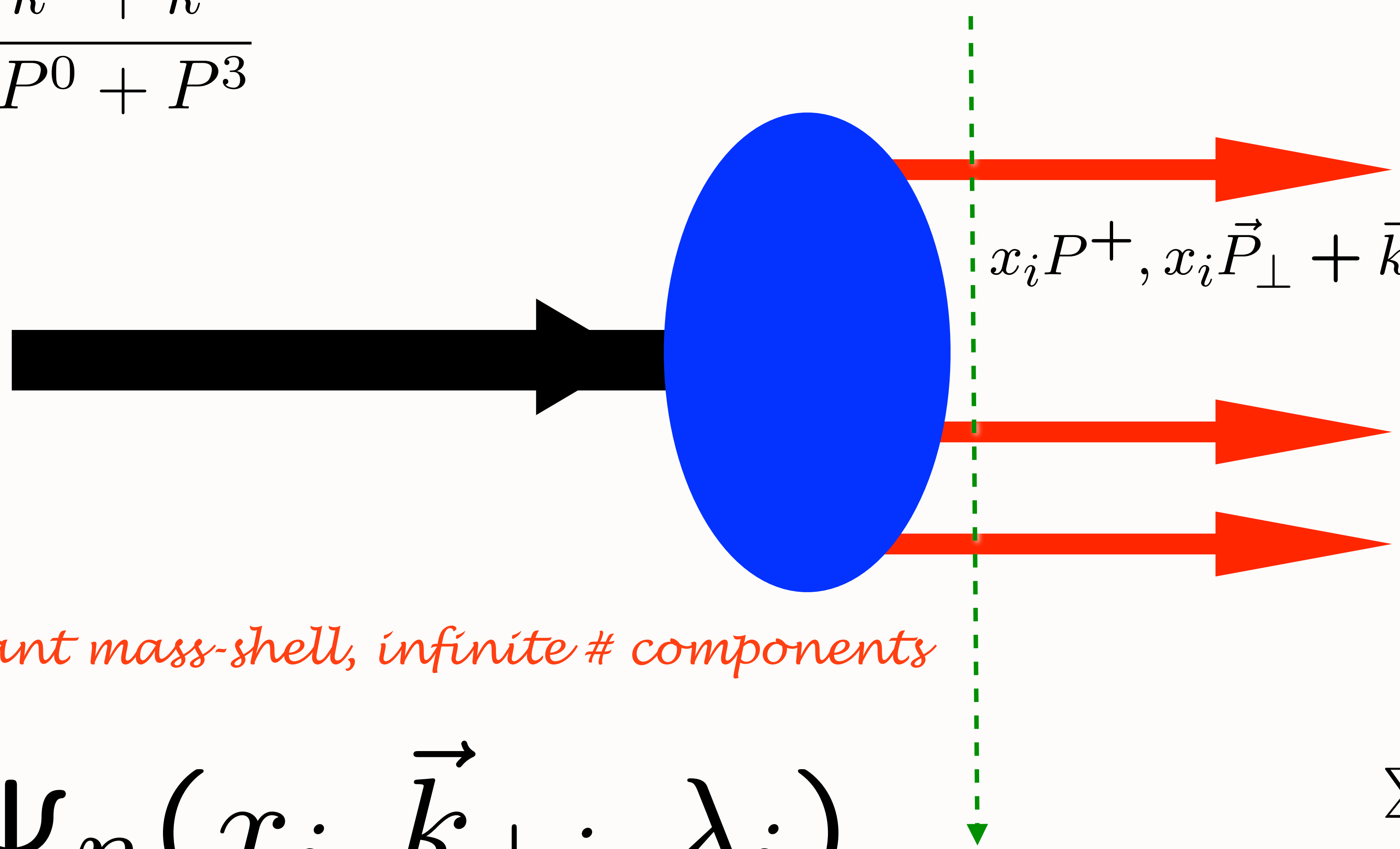
  Schrödinger Wavefunctions of Hadron Physics

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

Fixed $\tau = t + z/c$

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

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



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

LFWFs: off invariant mass-shell, infinite # components

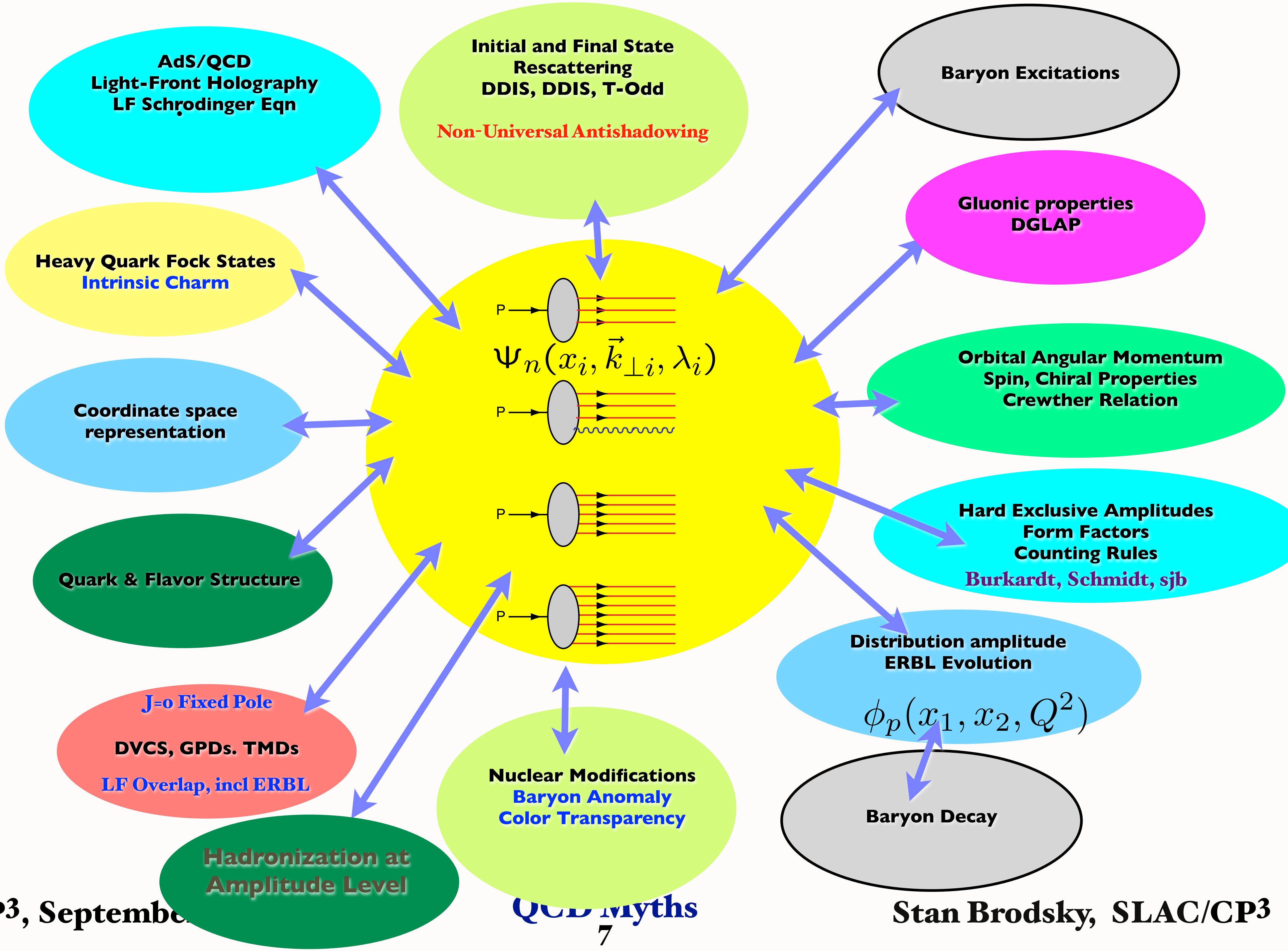
$$\Psi_n(x_i, \vec{k}_{\perp i}, \lambda_i)$$

$\sum_i^n x_i = 1$

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

Invariant under boosts! Independent of P^μ

QCD and LF Hadron Wavefunctions



Light-Front Wavefunctions

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

$$\psi(x, k_\perp)$$

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

Invariant under boosts. Independent of P^μ

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

Direct connection to QCD Lagrangian

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

Each element of flash photograph illuminated at same LF time

$$\tau = t + z/c$$

Evolve in LF time

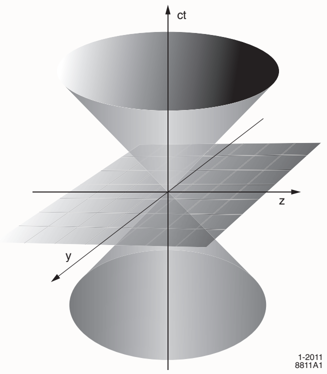
$$P^- = i\frac{d}{d\tau}$$

Eigenstate -- independent of τ

HELEN BRADLEY - PHOTOGRAPHY

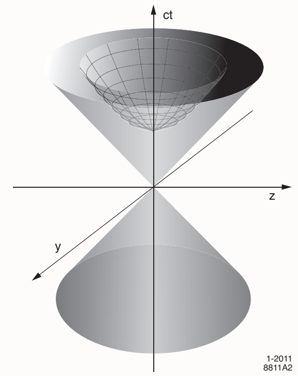
Light-Front Dynamics

- Different possibilities to parametrize space-time [Dirac (1949)]
- Parametrizations differ by the hypersurface on which the initial conditions are specified. Each evolve with different “times” and has its own Hamiltonian, but should give the same physical results
- Forms of Relativistic Dynamics: dynamical *vs.* kinematical generators [Dirac (1949)]
- *Instant form*: hypersurface defined by $t = 0$, the familiar one



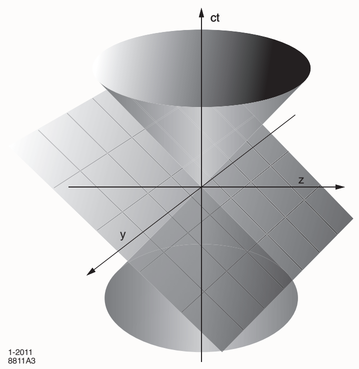
$$H, \ \mathbf{K} \ \text{ dynamical}, \qquad \mathbf{L}, \ \mathbf{P} \ \text{ kinematical}$$

- *Point form*: hypersurface is an hyperboloid



$$P^\mu \ \text{ dynamical}, \qquad M^{\mu\nu} \ \text{ kinematical}$$

- *Front form*: hypersurface is tangent to the light cone at $\tau = t + z/c = 0$



$$P^-, \ L^x, \ L^y \ \text{ dynamical}, \qquad P^+, \ \mathbf{P}_\perp, \ L^z, \ \mathbf{K} \ \text{ kinematical}$$

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

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

The Light Front Fock State Wavefunctions

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

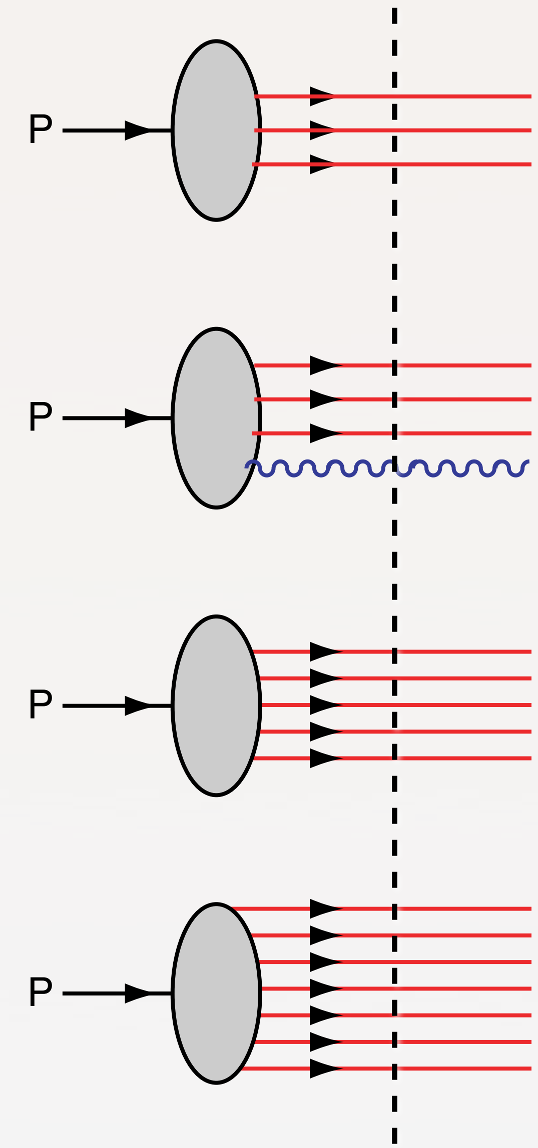
are boost invariant; they are independent of the hadron's energy and momentum P^μ.

The light-cone momentum fraction

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

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
Coupled. infinite set

Intrinsic heavy quarks
c(x), b(x) at high x !

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

Mueller: gluon Fock states **BFKL Pomeron**

Deuteron: Hidden Color

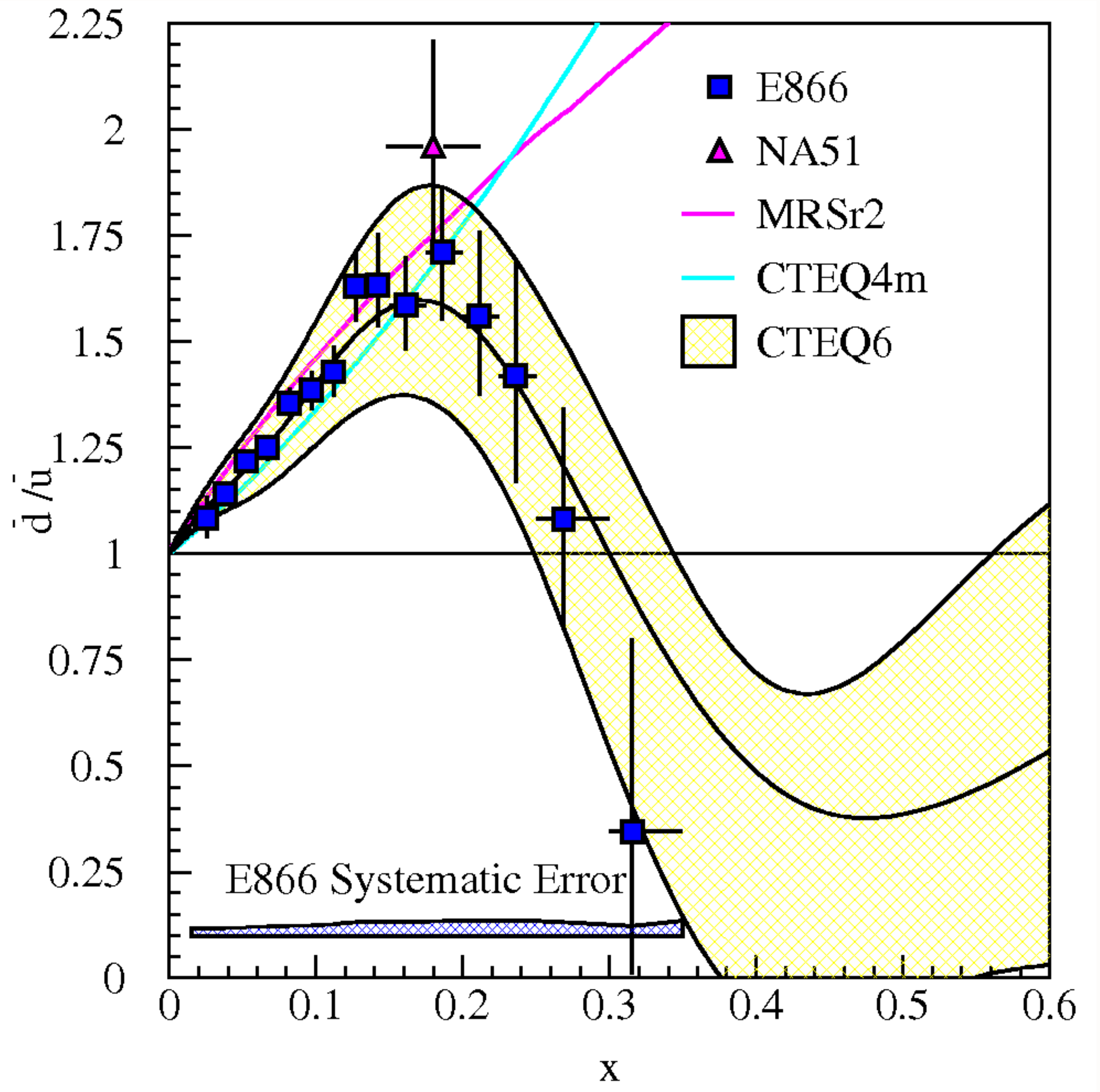
- E866/NuSea (Drell-Yan)

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

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

Intrinsic glue, sea, heavy quarks

$\bar{d}(x)/\bar{u}(x)$ for $0.015 \leq x \leq 0.35$



Angular Momentum on the Light-Front

$$J^z = \sum_{i=1}^{n} s_i^z + \sum_{j=1}^{n-1} l_j^z.$$

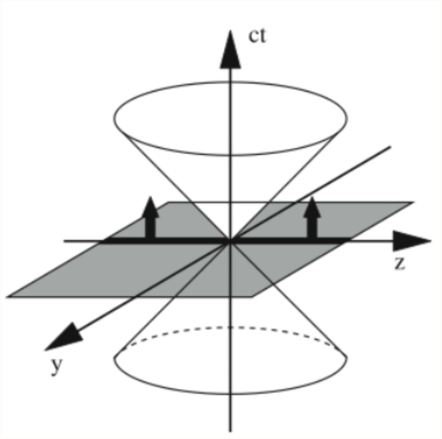
Conserved
LF Fock state by Fock State

$$l_j^z = -\mathrm{i}\left(k_j^1 \frac{\partial}{\partial k_j^2} - k_j^2 \frac{\partial}{\partial k_j^1}\right)$$

n-1 orbital angular momenta

Nonzero Anomalous Moment -->Nonzero orbital angular momentum

- Different possibilities to parametrize space-time [Dirac (1949)]
- Parametrizations differ by the hypersurface on which the initial conditions are specified. Each evolve with different "times" and has its own Hamiltonian, but should give the same physical results
- *Instant form*: hypersurface defined by $t = 0$, the familiar one



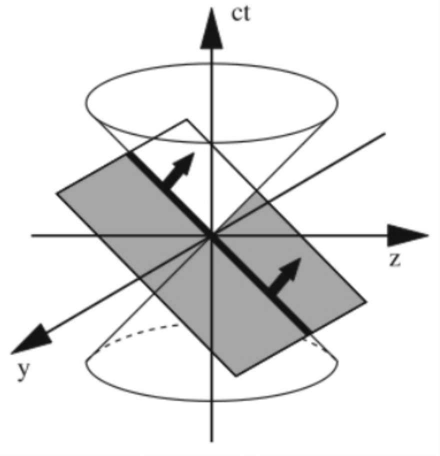
- *Front form*: hypersurface is tangent to the light cone at $\tau = t + z/c = 0$

$x^+ = x^0 + x^3$ light-front time

$x^- = x^0 - x^3$ longitudinal space variable

$k^+ = k^0 + k^3$ longitudinal momentum $(k^+ > 0)$

$k^- = k^0 - k^3$ light-front energy



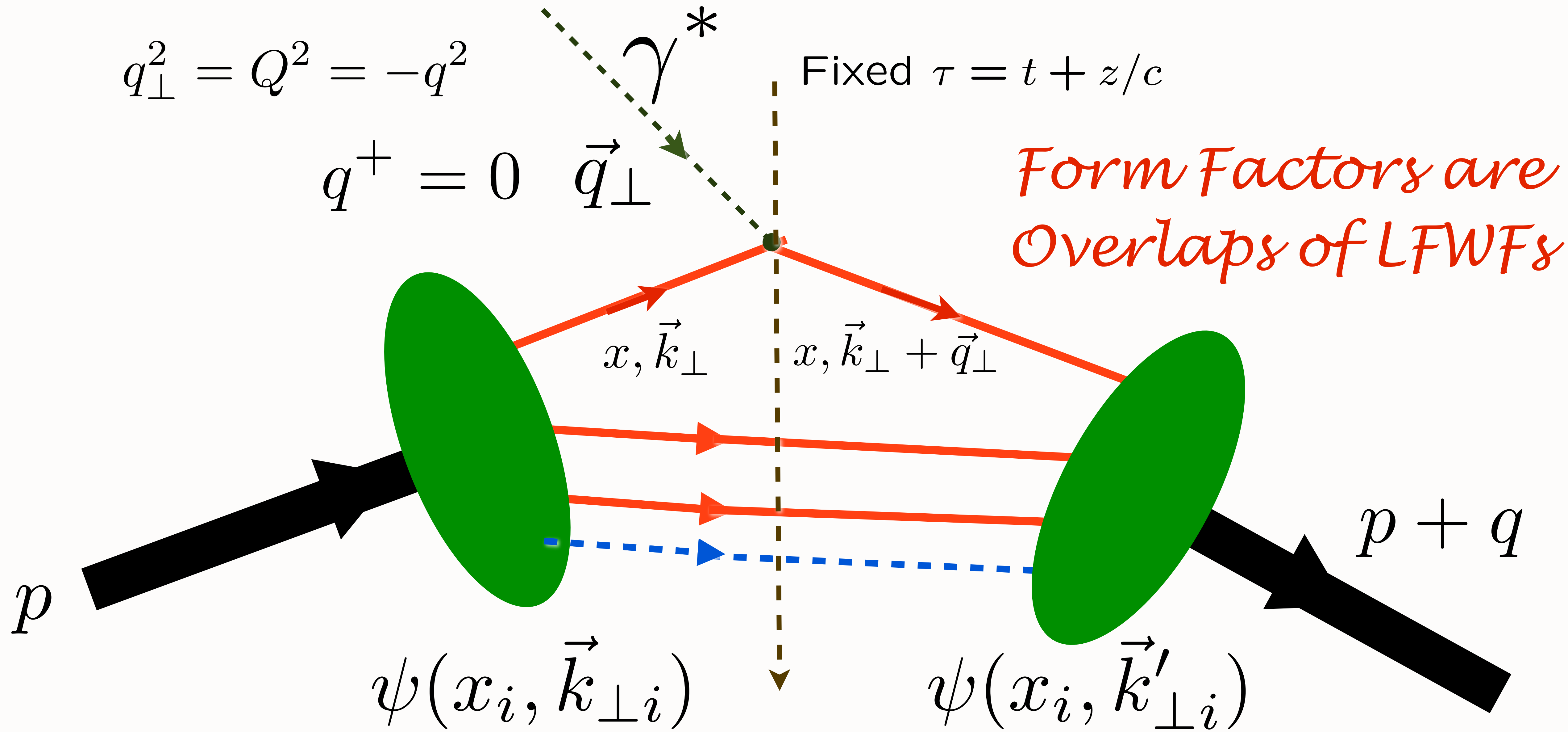
$$k \cdot x = \frac{1}{2}\left(k^+ x^- + k^- x^+\right) - \mathbf{k}_\perp \cdot \mathbf{x}_\perp$$

On shell relation $k^2 = m^2$ leads to dispersion relation $k^- = \frac{\mathbf{k}_\perp^2 + m^2}{k^+}$

Quantum chromodynamics and other field theories on the light cone.
Stanley J. Brodsky (SLAC), Hans-Christian Pauli (Heidelberg, Max Planck Inst.),
Stephen S. Pinsky (Ohio State U.). SLAC-PUB-7484, MPIH-V1-1997. Apr 1997. 203 pp.
Published in **Phys.Rept. 301 (1998) 299-486**
e-Print: **hep-ph/9705477**

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

Interaction picture



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

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

Drell &Yan, West

Exact LF Formula for Pauli Form Factor

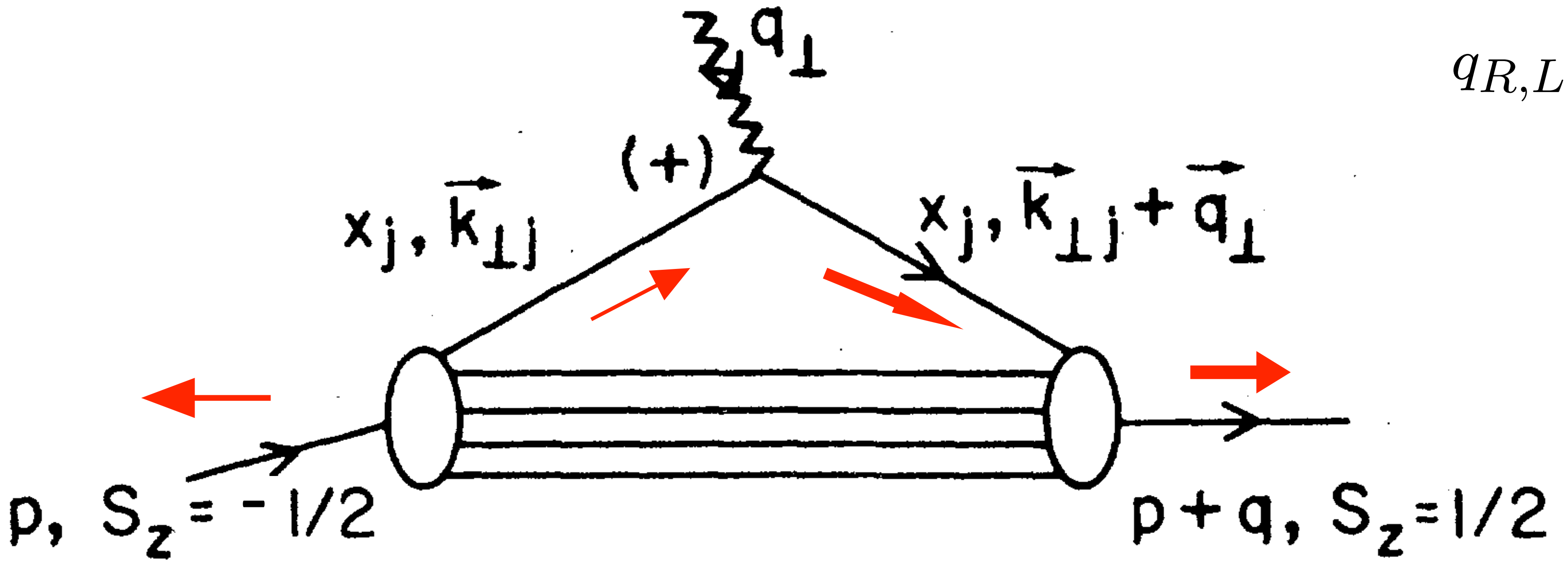
Drell, sjb

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

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

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

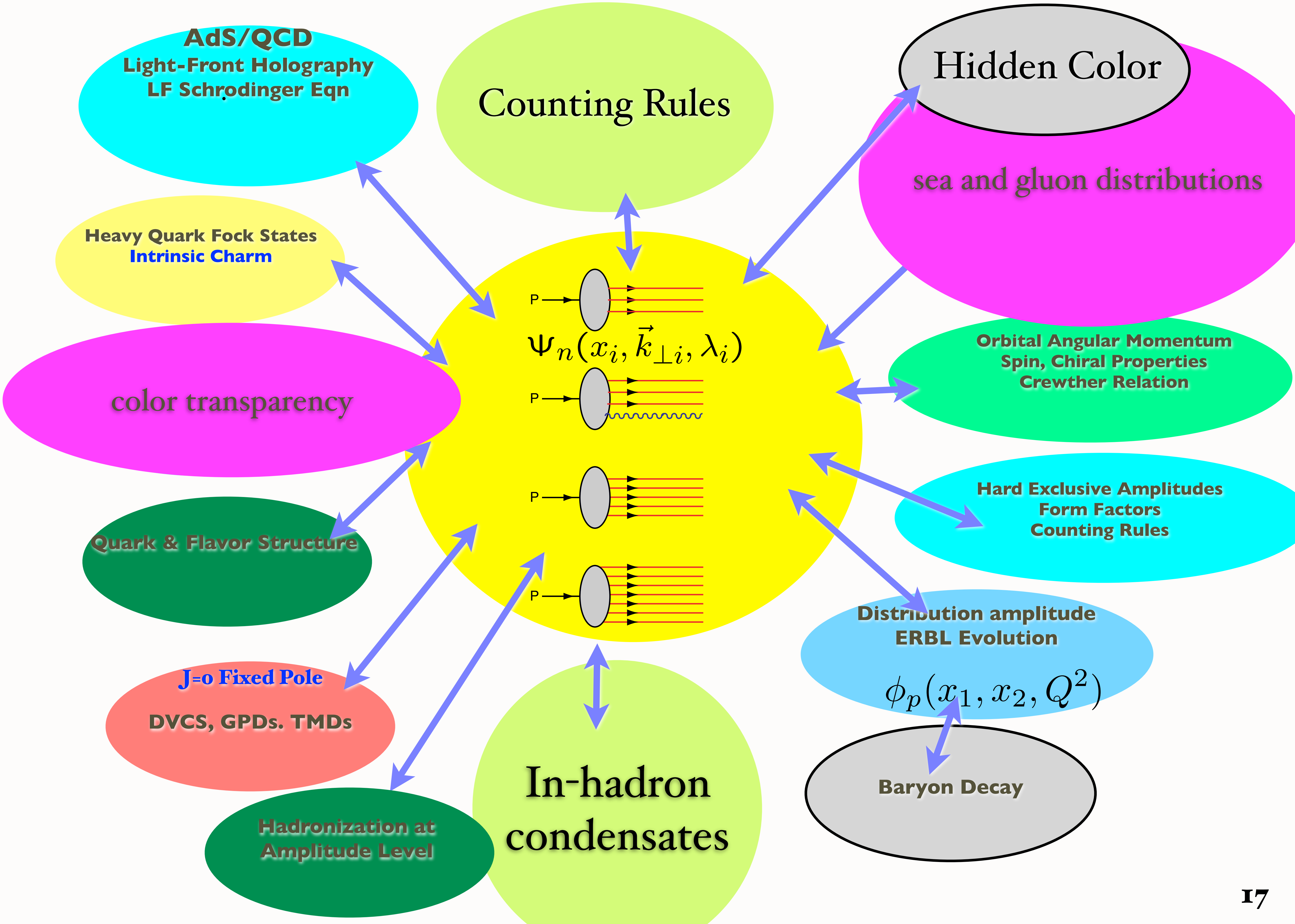
$$q_{R,L} = q^x \pm i q^y$$



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

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

QCD and the LF Hadron Wavefunctions



Light-Front QCD

Heisenberg Matrix Formulation

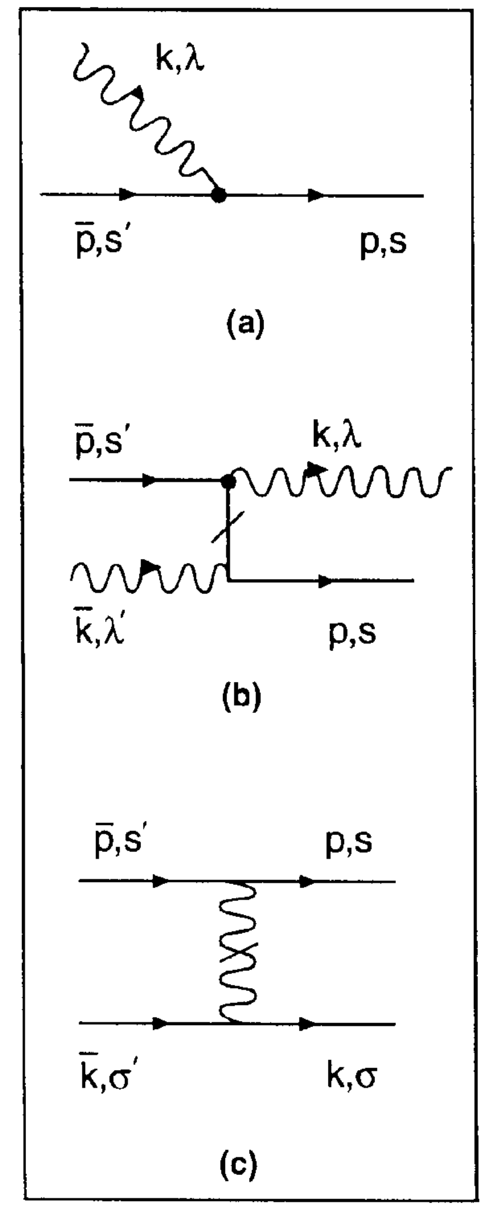
Physical gauge: $A^+ = 0$

$$L^{QCD} \rightarrow H_{LF}^{QCD}$$

$$H_{LF}^{QCD} = \sum_i [\frac{m^2 + k_\perp^2}{x}]_i + H_{LF}^{int}$$

H_{LF}^{int}: Matrix in Fock Space

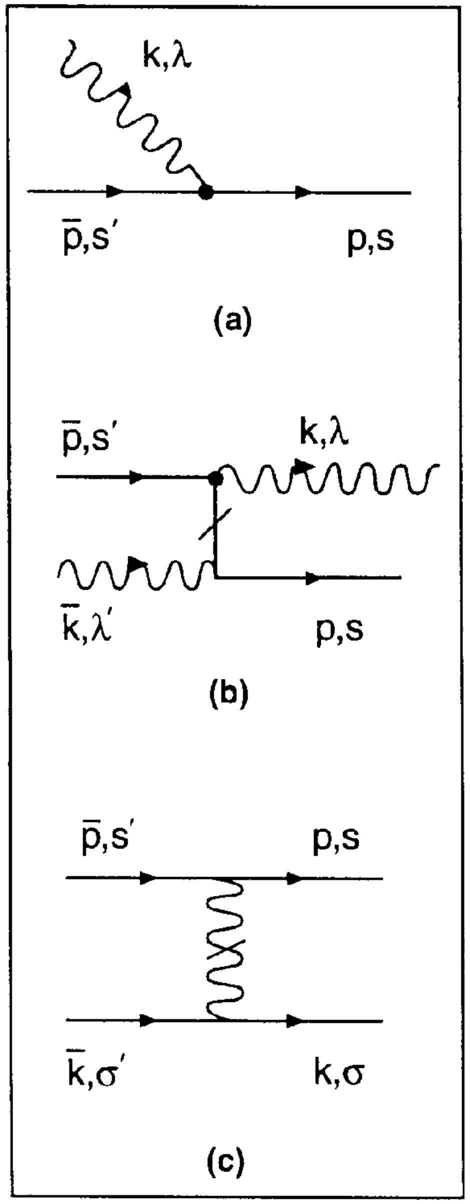
$$H_{LF}^{QCD}|\Psi_h> = \mathcal{M}_h^2|\Psi_h>$$



Eigenvalues and Eigensolutions give Hadron Spectrum and Light-Front wavefunctions

Light-Front QCD
Heisenberg Equation

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



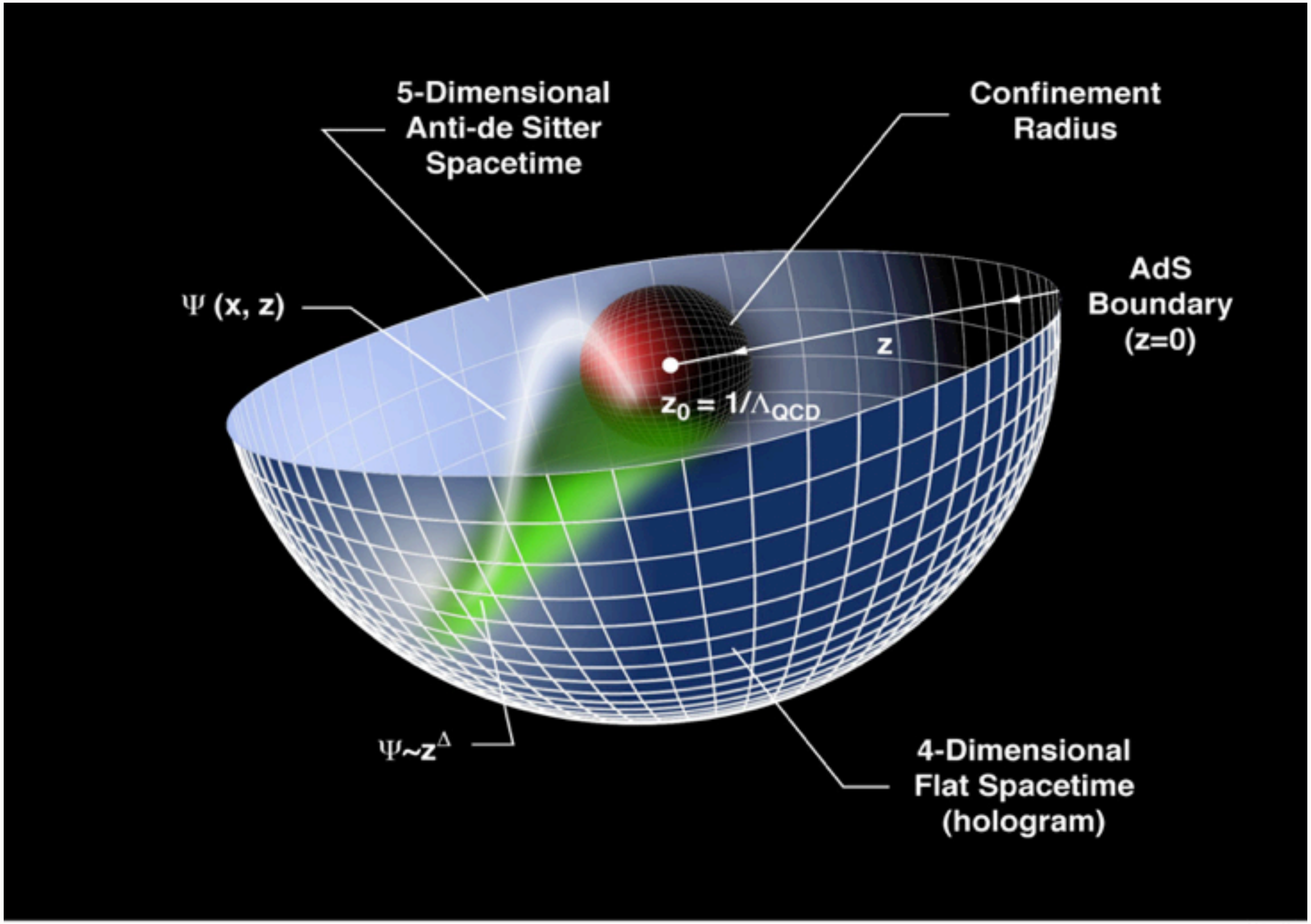
n	Sector	1 qq̄	2 gg	3 qq̄ g	4 qq̄ qq̄	5 gg g	6 qq̄ gg	7 qq̄ qq̄ g	8 qq̄ qq̄ qq̄	9 gg gg	10 qq̄ gg g	11 qq̄ qq̄ gg	12 qq̄ qq̄ qq̄ g	13 qq̄ qq̄ qq̄ qq̄
1	qq̄					•		•	•	•	•	•	•	•
2	gg				•			•	•		•	•	•	•
3	qq̄ g								•	•		•	•	•
4	qq̄ qq̄		•			•				•	•		•	•
5	gg g	•			•			•	•			•	•	•
6	qq̄ gg								•				•	•
7	qq̄ qq̄ g	•	•			•				•				•
8	qq̄ qq̄ qq̄	•	•	•		•	•			•	•			
9	gg gg	•		•	•			•	•			•	•	•
10	qq̄ gg g	•	•		•				•				•	•
11	qq̄ qq̄ gg	•	•	•		•				•				•
12	qq̄ qq̄ qq̄ g	•	•	•	•	•	•			•	•			
13	qq̄ qq̄ qq̄ qq̄	•	•	•	•	•	•	•		•	•	•		

Goal: an analytic first approximation to QCD

- **As Simple as Schrödinger Theory in Atomic Physics**
- **Relativistic, Frame-Independent, Color-Confining**
- **QCD Coupling at all scales**
- **Hadron Spectroscopy**
- **Light-Front Wavefunctions**
- **Form Factors, Hadronic Observables, Constituent Counting Rules**
- **Insight into QCD Condensates**
- **Systematically improvable**

de Teramond, sjb

Applications of AdS/CFT to QCD



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

in collaboration with Guy de Teramond and Fu Guang Cao

Scale Transformations

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

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

invariant measure

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

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

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

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

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

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

Soft-Wall Model

$$S = \int d^4x\, dz\, \sqrt{g}\, e^{\varphi(z)} \mathcal{L}, \qquad \varphi(z) = \pm \kappa^2 z^2$$

Retain conformal AdS metrics but introduce smooth cutoff which depends on the profile of a dilaton background field

Karch, Katz, Son and Stephanov (2006)]

- Equation of motion for scalar field $\mathcal{L} = \frac{1}{2}\left(g^{\ell m}\partial_\ell \Phi \partial_m \Phi - \mu^2 \Phi^2\right)$

$$\left[z^2 \partial_z^2 - \left(3 \mp 2\kappa^2 z^2\right) z\, \partial_z + z^2 \mathcal{M}^2 - (\mu R)^2\right] \Phi(z) = 0$$

with $(\mu R)^2 \geq -4$.

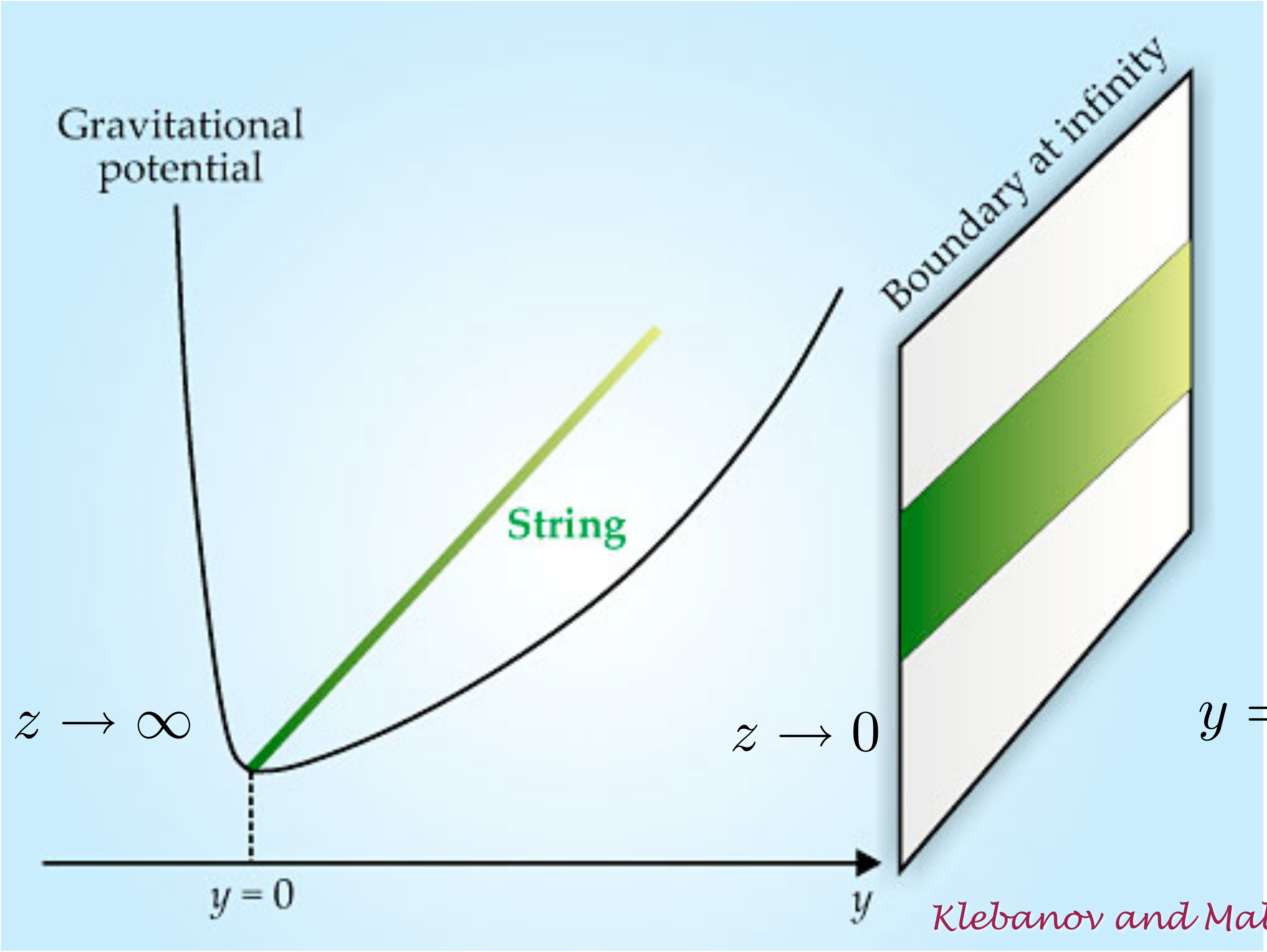
- LH holography requires 'plus dilaton' $\varphi = +\kappa^2 z^2$. Lowest possible state $(\mu R)^2 = -4$

$$\mathcal{M}^2 = 0, \quad \Phi(z) \sim z^2 e^{-\kappa^2 z^2}, \quad \langle r^2 \rangle \sim \frac{1}{\kappa^2}$$

A chiral symmetric bound state of two massless quarks with scaling dimension 2:

Massless pion

$$ds^2 = e^{\kappa^2 z^2} \frac{R^2}{z^2}(dx_0^2 - dx_1^2 - dx_3^2 - dx_3^2 - dz^2)$$



$z \to \infty$

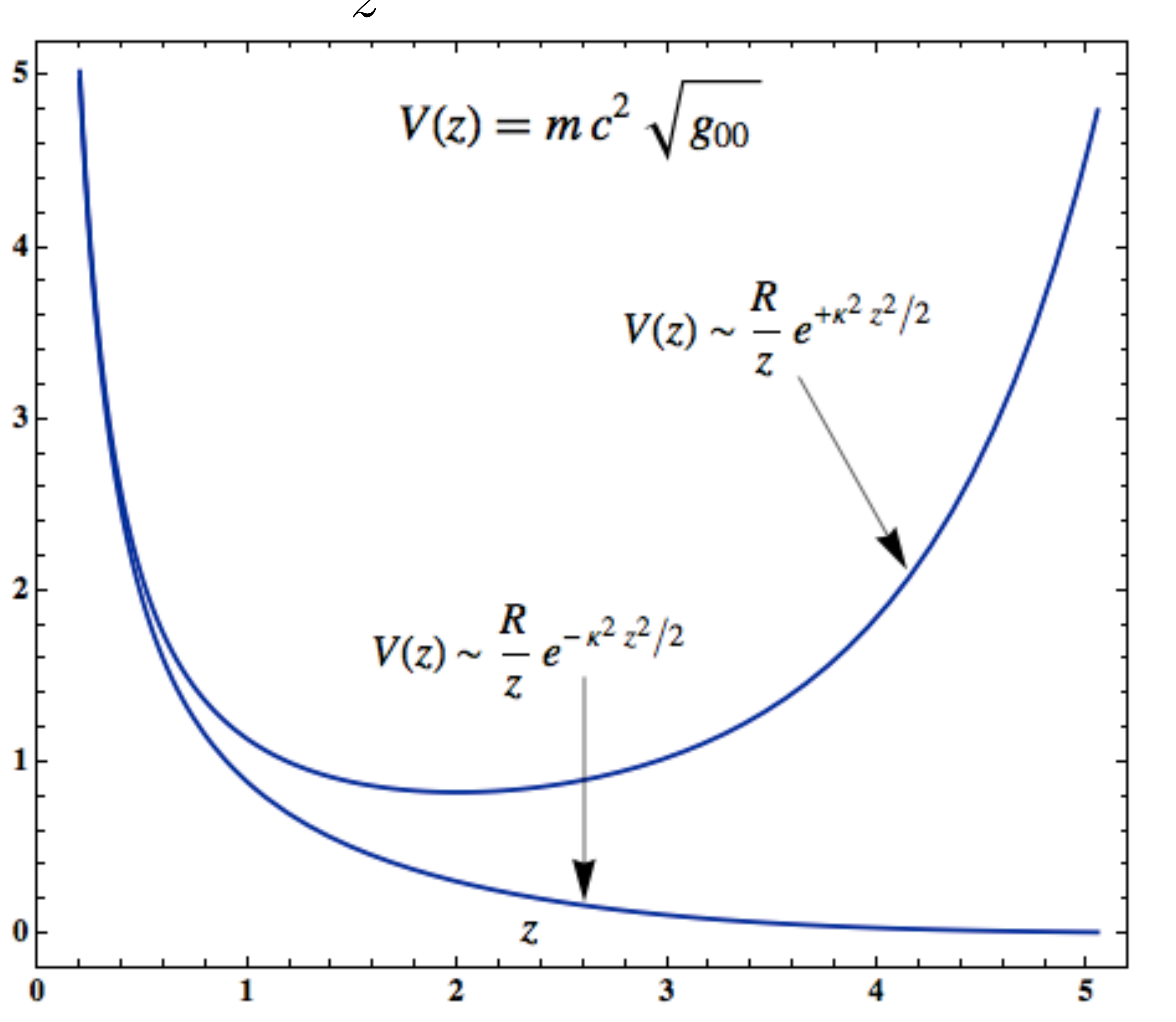
$z \to 0$

$y = R/z$

Klebanov and Maldacena

$$ds^2 = e^{A(y)}(-dx_0^2 + dx_1^2 + dx_3^2 + dx_3^2) + dy^2$$

$$ds^2 = e^{\kappa^2 z^2}\frac{R^2}{z^2}(dx_0^2 - dx_1^2 - dx_3^2 - dx_3^2 - dz^2)$$



Agrees with Klebanov and Maldacena for positive-sign exponent of dilaton

- Erlich, Karch, Katz, Son, Stephanov
- de Teramond, sjb

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

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

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

Derived from variation of Action Dilaton-Modified AdS_5

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

Positive-sign dilaton

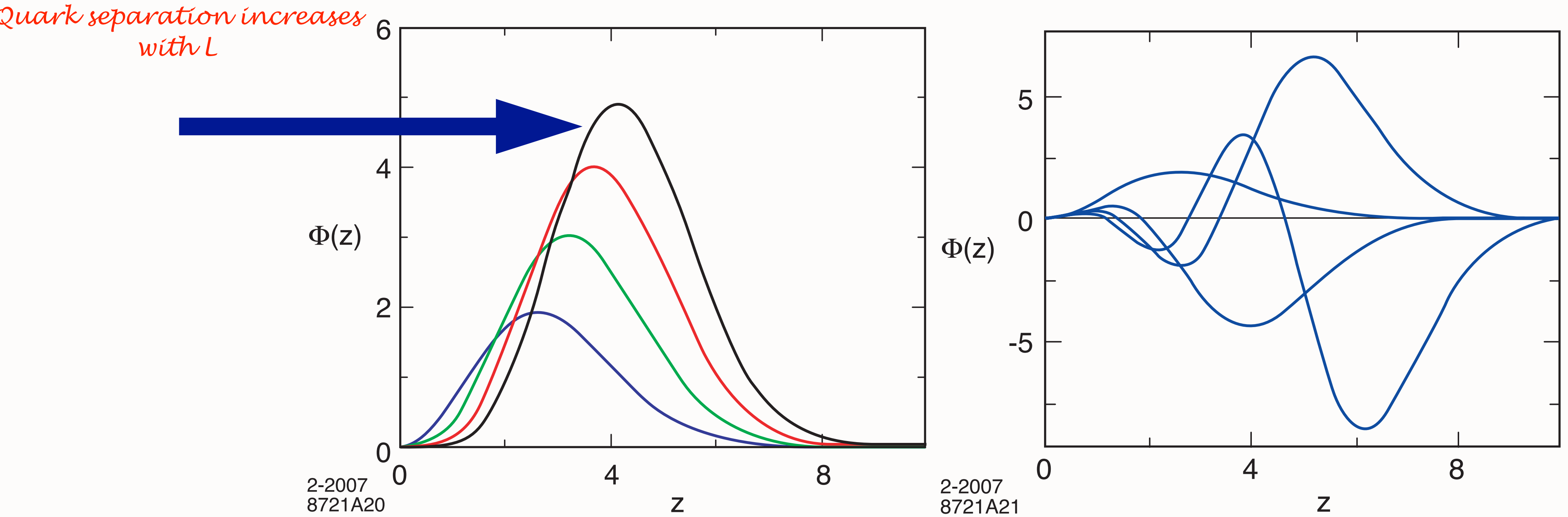
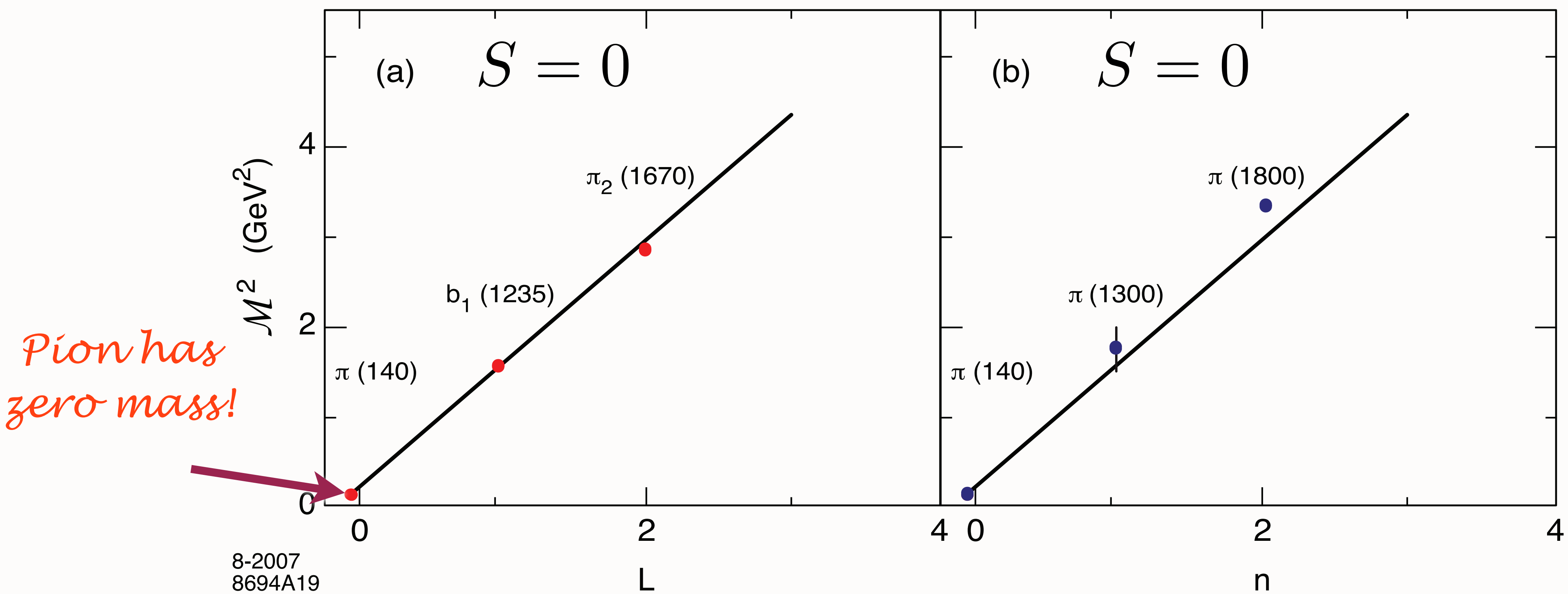


Fig: Orbital and radial AdS modes in the soft wall model for κ = 0.6 GeV .

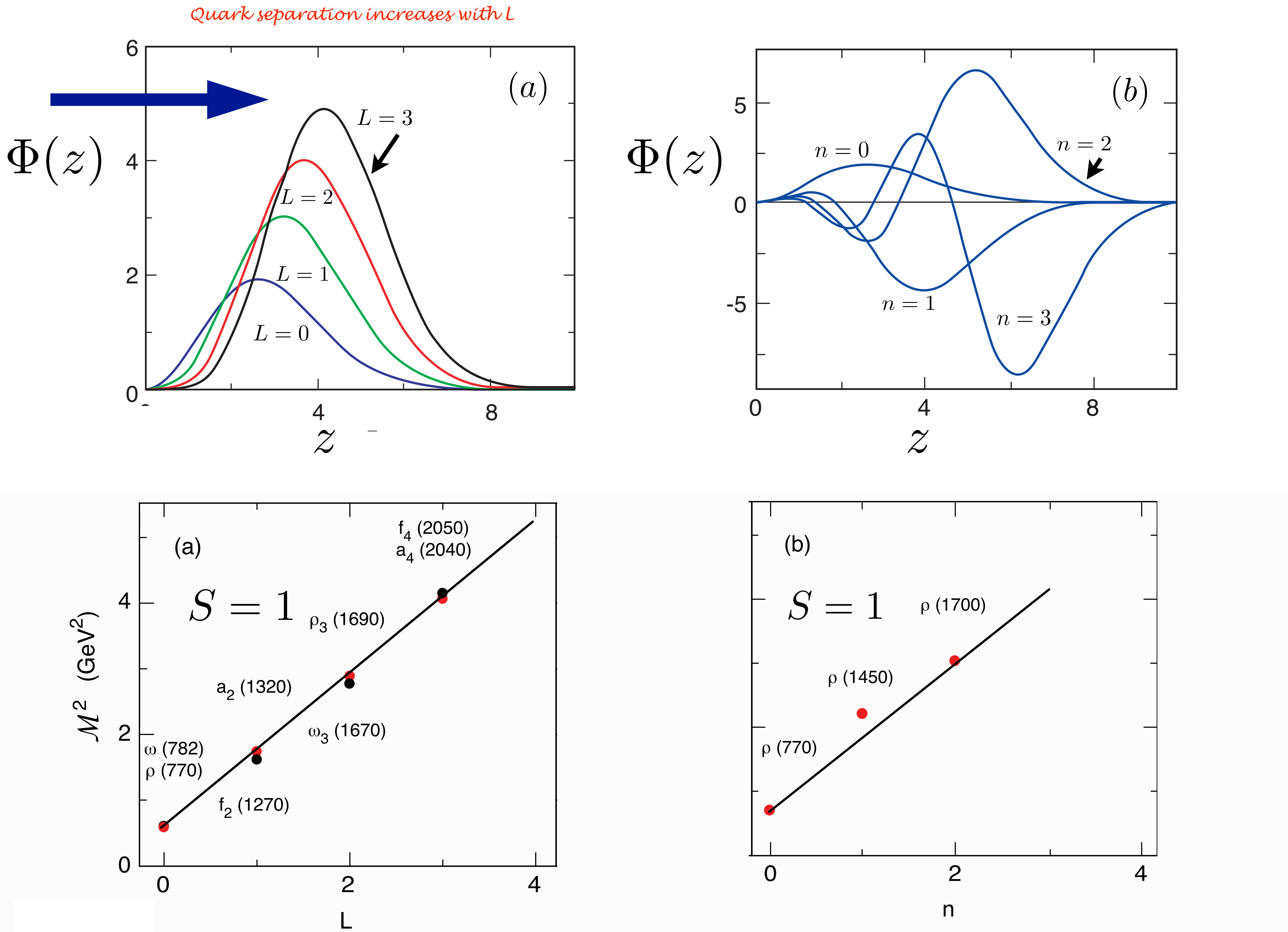
Soft Wall Model

Pion mass automatically zero!

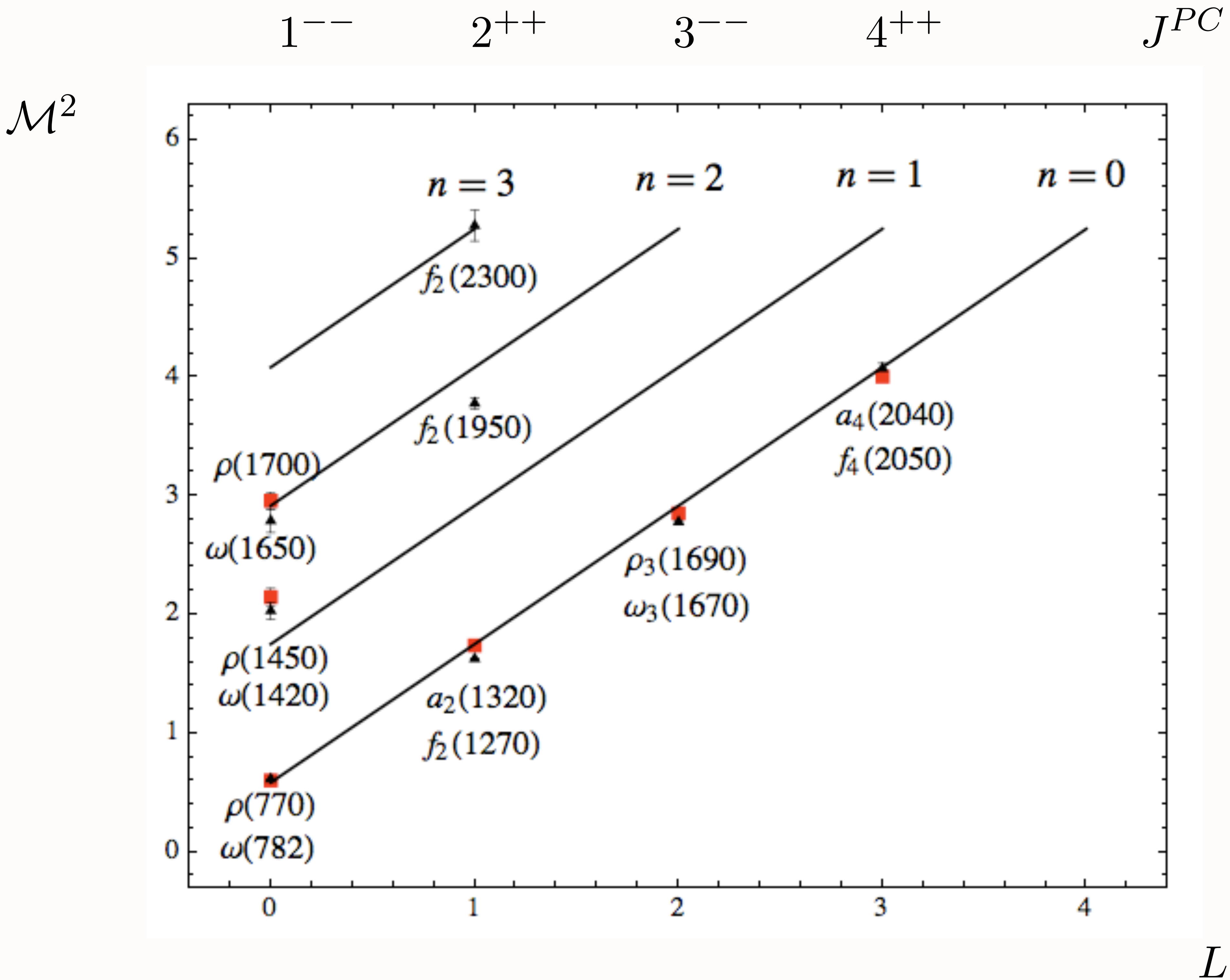
$$m_q = 0$$



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



Quark separation increases with L
$\Phi(z)$
(a)
L = 3
L = 2
L = 1
L = 0
z
(b)
n = 0
n = 1
n = 2
n = 3
(a)
S = 1
$\mathcal{M}^2$ (GeV^2)
f$_4$ (2050)
a$_4$ (2040)
ρ$_3$ (1690)
a$_2$ (1320)
ω$_3$ (1670)
ω (782)
ρ (770)
f$_2$ (1270)
L
(b)
ρ (1700)
ρ (1450)
ρ (770)
n



Parent and daughter Regge trajectories for the $I=1$ ρ-meson family (red)

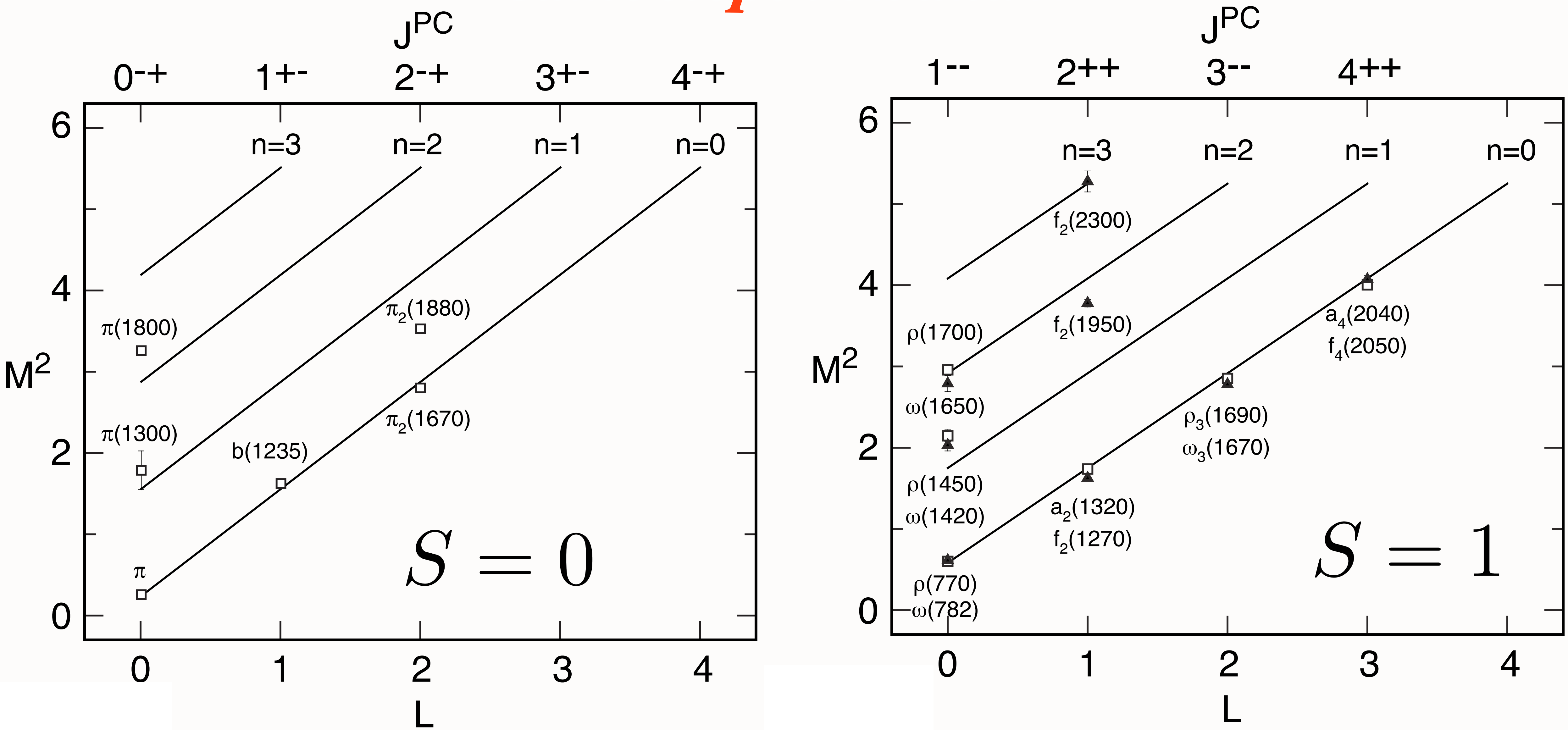
and the $I=0$ ω-meson family (black) for $\kappa=0.54$ GeV

Bosonic Modes and Meson Spectrum

$$\mathcal{M}^2 = 4\kappa^2(n + J/2 + L/2) \to 4\kappa^2(n + L + S/2)$$

$4\kappa^2$ for $\Delta n = 1$
$4\kappa^2$ for $\Delta L = 1$
$2\kappa^2$ for $\Delta S = 1$

Same slope in n and L



Regge trajectories for the π ($\kappa = 0.6$ GeV) and the $I=1$ ρ-meson and $I=0$ ω-meson families ($\kappa = 0.54$ GeV)

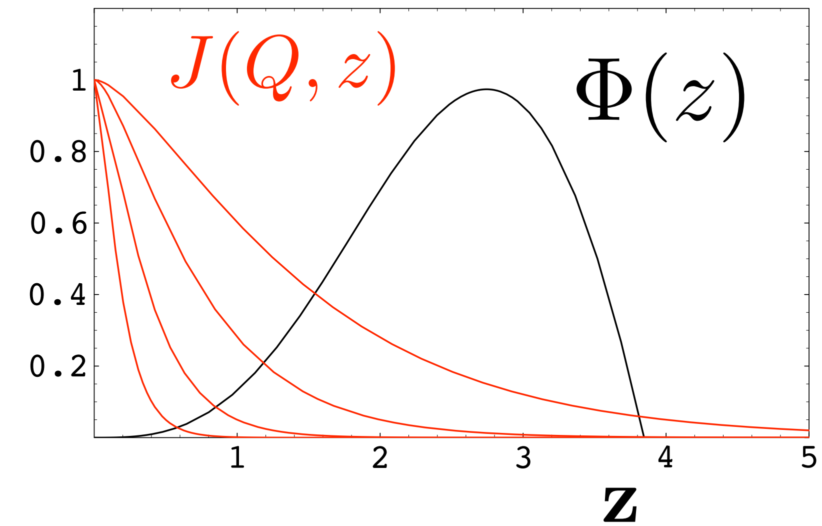
Hadron Form Factors from AdS/CFT

Propagation of external perturbation suppressed inside AdS.

$$J(Q,z) = zQK_1(zQ)$$

$$F(Q^2)_{I \to F} = \int \frac{dz}{z^3} \Phi_F(z) J(Q,z) \Phi_I(z)$$

High Q^2
from
small z ~ 1/Q



Polchinski, Strassler
de Teramond, sjb

Consider a specific AdS mode $\Phi^{(n)}$ dual to an n partonic Fock state $|n\rangle$. At small z, Φ scales as $\Phi^{(n)} \sim z^{\Delta_n}$. Thus:

$$F(Q^2) \to \left[\frac{1}{Q^2}\right]^{\tau-1},$$

Dimensional Quark Counting Rules:
General result from
AdS/CFT and Conformal Invariance

where $\tau = \Delta_n - \sigma_n$, $\sigma_n = \sum_{i=1}^{n} \sigma_i$. The twist is equal to the number of partons, $\tau = n$.

Light-Front Representation of Two-Body Meson Form Factor

- Drell-Yan-West form factor

$$\vec{q}_\perp^{\,2} = Q^2 = -q^2$$

$$F(q^2) = \sum_q e_q \int_0^1 dx \int \frac{d^2\vec{k}_\perp}{16\pi^3} \, \psi^*_{P'}(x, \vec{k}_\perp - x\vec{q}_\perp) \, \psi_P(x, \vec{k}_\perp).$$

- Fourrier transform to impact parameter space $\vec{b}_\perp$

$$\psi(x, \vec{k}_\perp) = \sqrt{4\pi} \int d^2\vec{b}_\perp \, e^{i\vec{b}_\perp \cdot \vec{k}_\perp} \widetilde{\psi}(x, \vec{b}_\perp)$$

- Find $(b = |\vec{b}_\perp|)$:

$$\begin{aligned} F(q^2) &= \int_0^1 dx \int d^2\vec{b}_\perp \, e^{ix\vec{b}_\perp \cdot \vec{q}_\perp} \left|\widetilde{\psi}(x,b)\right|^2 \\ &= 2\pi \int_0^1 dx \int_0^\infty b \, db \, J_0\left(bqx\right) \, \left|\widetilde{\psi}(x,b)\right|^2, \end{aligned}$$

Soper

Holographic Mapping of AdS Modes to QCD LFWFs

- Integrate Soper formula over angles:

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

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

- Transversality variable

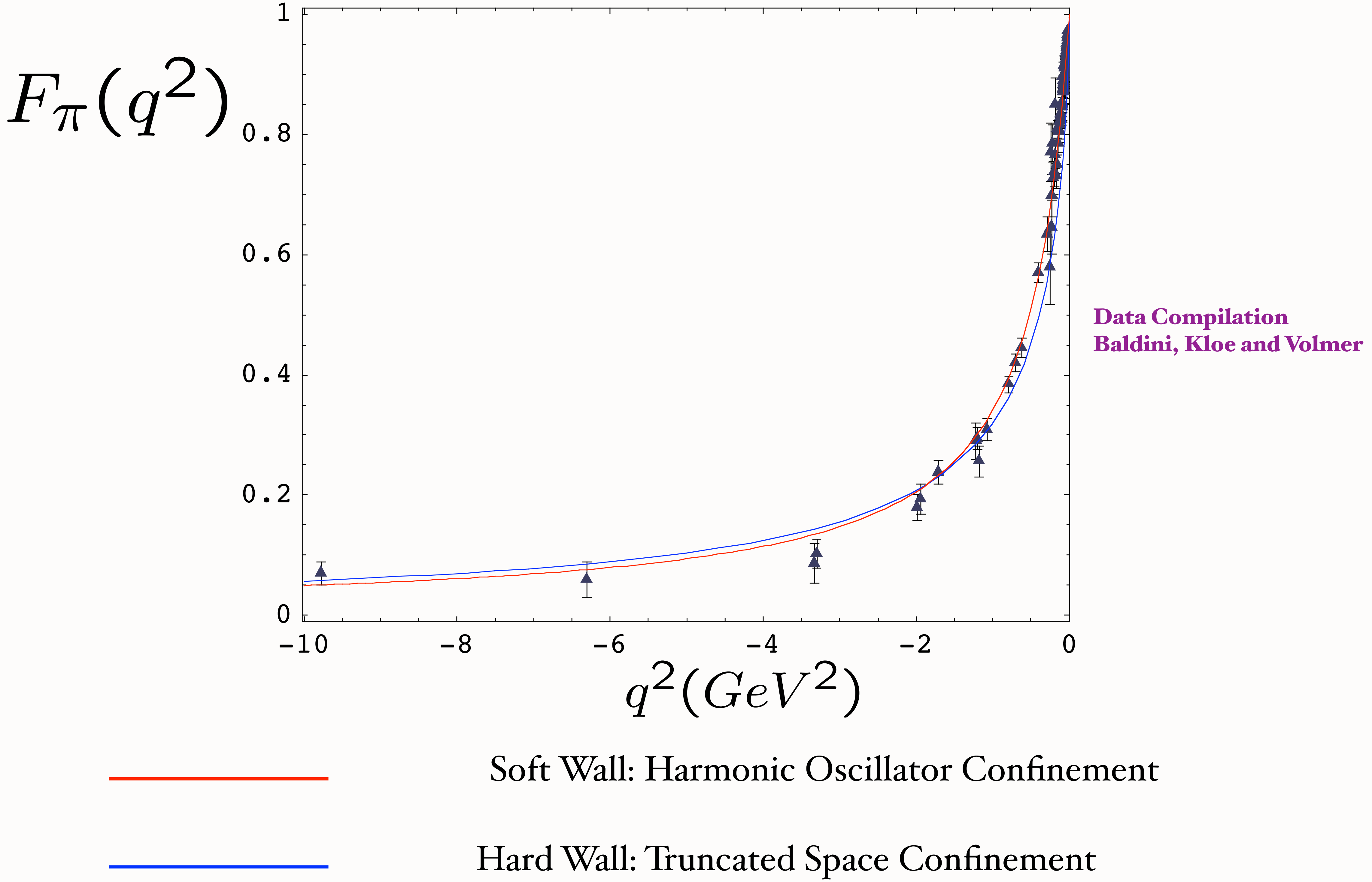
$$\zeta = \sqrt{x(1-x)\vec{b}_\perp^2}$$

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

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

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

Spacelike pion form factor from AdS/CFT



One parameter - set by pion decay constant

de Teramond, sjb
See also: Radyushkin

Gravitational Form Factor in AdS space

- Hadronic gravitational form-factor in AdS space

$$A_\pi(Q^2) = R^3 \int \frac{dz}{z^3} \, H(Q^2, z) \, |\Phi_\pi(z)|^2 \, ,$$

Abidin & Carlson

where $H(Q^2, z) = \frac{1}{2} Q^2 z^2 K_2(zQ)$

- Use integral representation for $H(Q^2, z)$

$$H(Q^2, z) = 2 \int_0^1 x \, dx \, J_0\left(zQ\sqrt{\frac{1-x}{x}}\right)$$

- Write the AdS gravitational form-factor as

$$A_\pi(Q^2) = 2R^3 \int_0^1 x \, dx \int \frac{dz}{z^3} \, J_0\left(zQ\sqrt{\frac{1-x}{x}}\right) |\Phi_\pi(z)|^2$$

- Compare with gravitational form-factor in light-front QCD for arbitrary Q

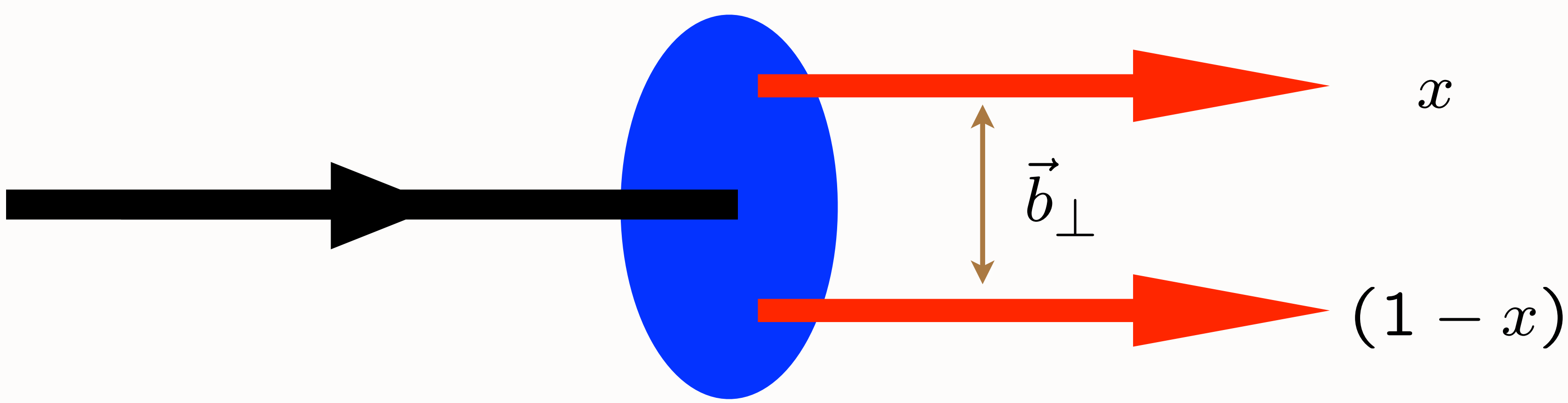
$$\left|\tilde{\psi}_{q\overline{q}/\pi}(x, \zeta)\right|^2 = \frac{R^3}{2\pi} \, x(1-x) \frac{|\Phi_\pi(\zeta)|^2}{\zeta^4},$$

Identical to LF Holography obtained from electromagnetic current de Teramond, sjb

LF(3+1) ⟷ AdS$_5$

$\psi(x, \vec{b}_\perp)$ ⟷ $\phi(z)$

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



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

Light Front Holography: Unique mapping derived from equality of LF and AdS formula for current matrix elements

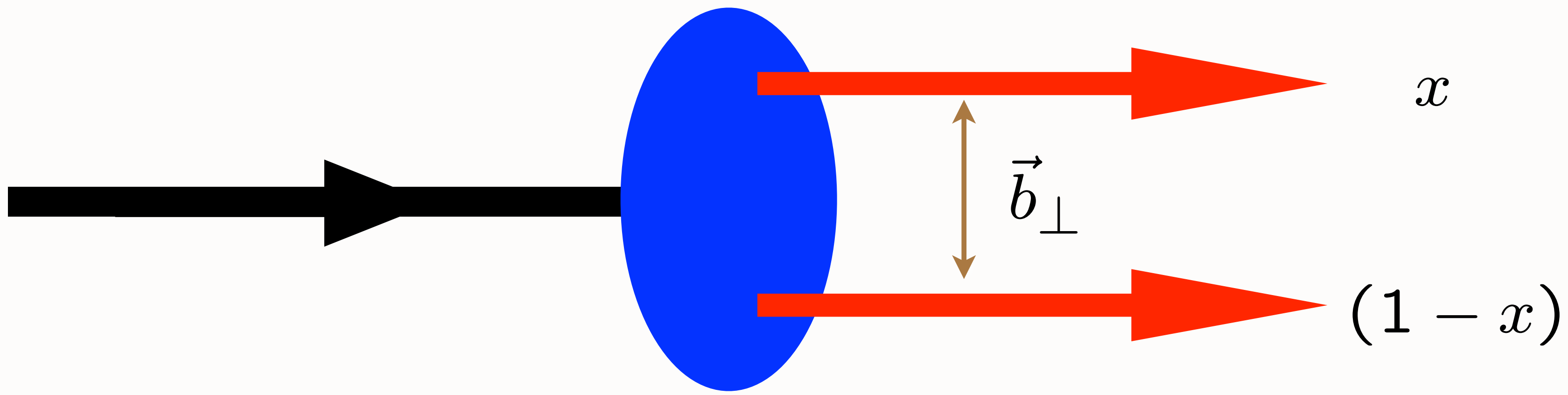
Light-Front Holography: Map AdS/CFT to 3+1 LF Theory

Relativistic LF radial equation

Frame Independent

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

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



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

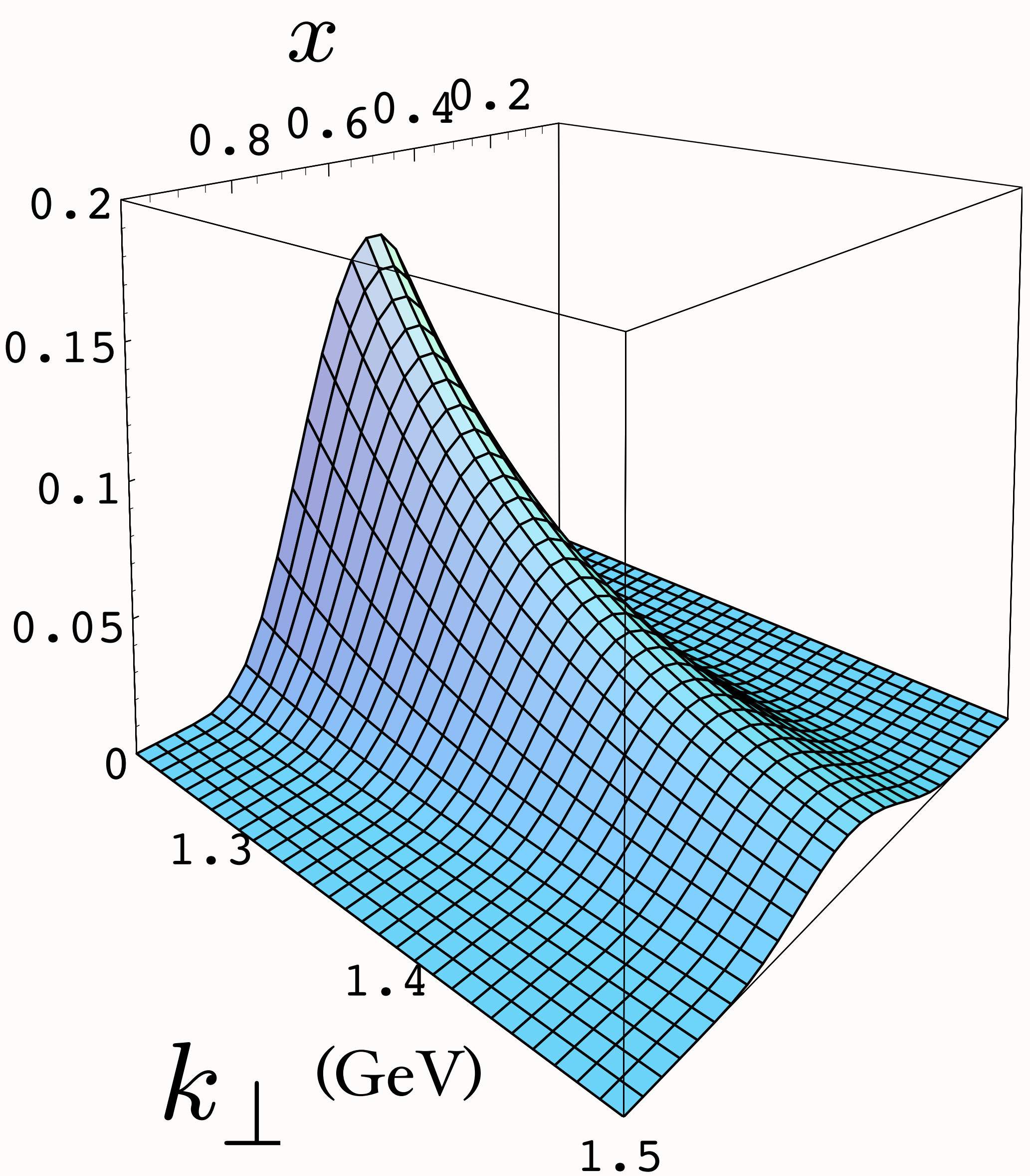
soft wall confining potential:

G. de Teramond, sjb

Prediction from AdS/CFT: Meson LFWF

de Teramond, sjb

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



"Soft Wall" model

$\kappa = 0.375$ GeV

massless quarks

Note coupling

$k_\perp^2, x$

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

$$\phi_M(x, Q_0) \propto \sqrt{x(1-x)}$$

Connection of Confinement to TMDs

$$H_{QED}$$

QED atoms: positronium and muonium

$$(H_0 + H_{int})\ |\Psi >= E\ |\Psi >$$

Coupled Fock states

$$[-\frac{\Delta^2}{2m_{\rm red}} + V_{\rm eff}(\vec{S},\vec{r})]\ \psi(\vec{r}) = E\ \psi(\vec{r})$$

Effective two-particle equation

Includes Lamb Shift, quantum corrections

$$[-\frac{1}{2m_{\rm red}}\frac{d^2}{dr^2} + \frac{1}{2m_{\rm red}}\frac{\ell(\ell+1)}{r^2} + V_{\rm eff}(r,S,\ell)]\ \psi(r) = E\ \psi(r)$$

Spherical Basis r, θ, ϕ

$$V_{eff} \to V_C(r) = -\frac{\alpha}{r}$$

Coulomb potential

Bohr Spectrum

Semiclassical first approximation to QED

$$H_{QCD}^{LF}$$

QCD Meson Spectrum

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

Coupled Fock states

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

Effective two-particle equation

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

$$[-\frac{d^2}{d\zeta^2} + \frac{-1+4L^2}{\zeta^2} + U(\zeta,S,L)]\ \psi_{LF}(\zeta) = M^2\ \psi_{LF}(\zeta)$$

Azimuthal Basis ζ, ϕ

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

Confining AdS/QCD potential

Semiclassical first approximation to QCD

de Teramond, sjb

Non-Conformal Extension of Algebraic Structure (Soft Wall Model)

- We write the Dirac equation

$$\left(\alpha\Pi(\zeta) - \mathcal{M}\right)\psi(\zeta) = 0,$$

in terms of the matrix-valued operator Π

$$\nu = L + 1$$

$$\Pi_\nu(\zeta) = -i\left(\frac{d}{d\zeta} - \frac{\nu + \frac{1}{2}}{\zeta}\gamma_5 - \kappa^2\zeta\gamma_5\right),$$

and its adjoint $\Pi^\dagger$, with commutation relations

$$\left[\Pi_\nu(\zeta), \Pi_\nu^\dagger(\zeta)\right] = \left(\frac{2\nu+1}{\zeta^2} - 2\kappa^2\right)\gamma_5.$$

- Solutions to the Dirac equation

$$\psi_+(\zeta) \sim z^{\frac{1}{2}+\nu} e^{-\kappa^2\zeta^2/2} L_n^\nu(\kappa^2\zeta^2),$$

$$\psi_-(\zeta) \sim z^{\frac{3}{2}+\nu} e^{-\kappa^2\zeta^2/2} L_n^{\nu+1}(\kappa^2\zeta^2).$$

- Eigenvalues

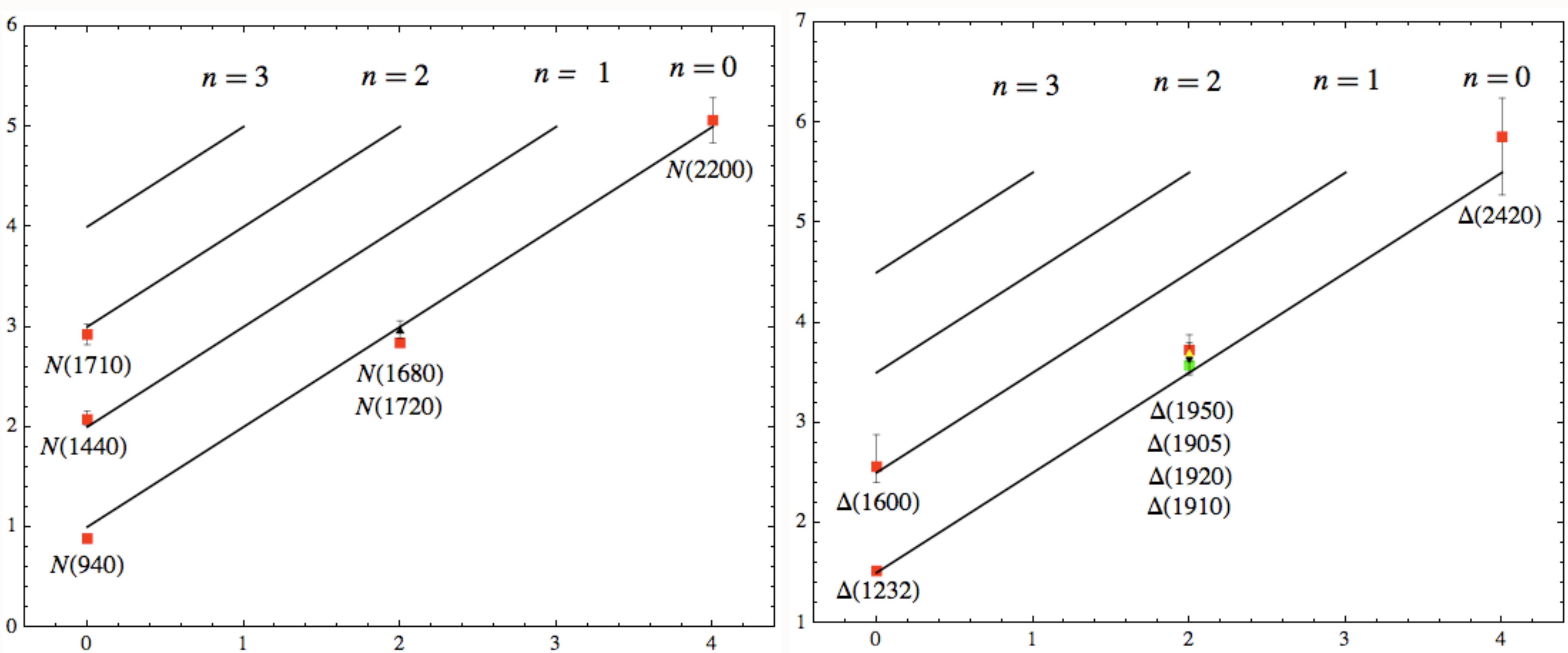
$$\mathcal{M}^2 = 4\kappa^2(n + \nu + 1).$$

- **Δ spectrum identical to Forkel and Klempt, Phys. Lett. B 679, 77 (2009)**

$4\kappa^2$ for $\Delta n = 1$
$4\kappa^2$ for $\Delta L = 1$
$2\kappa^2$ for $\Delta S = 1$

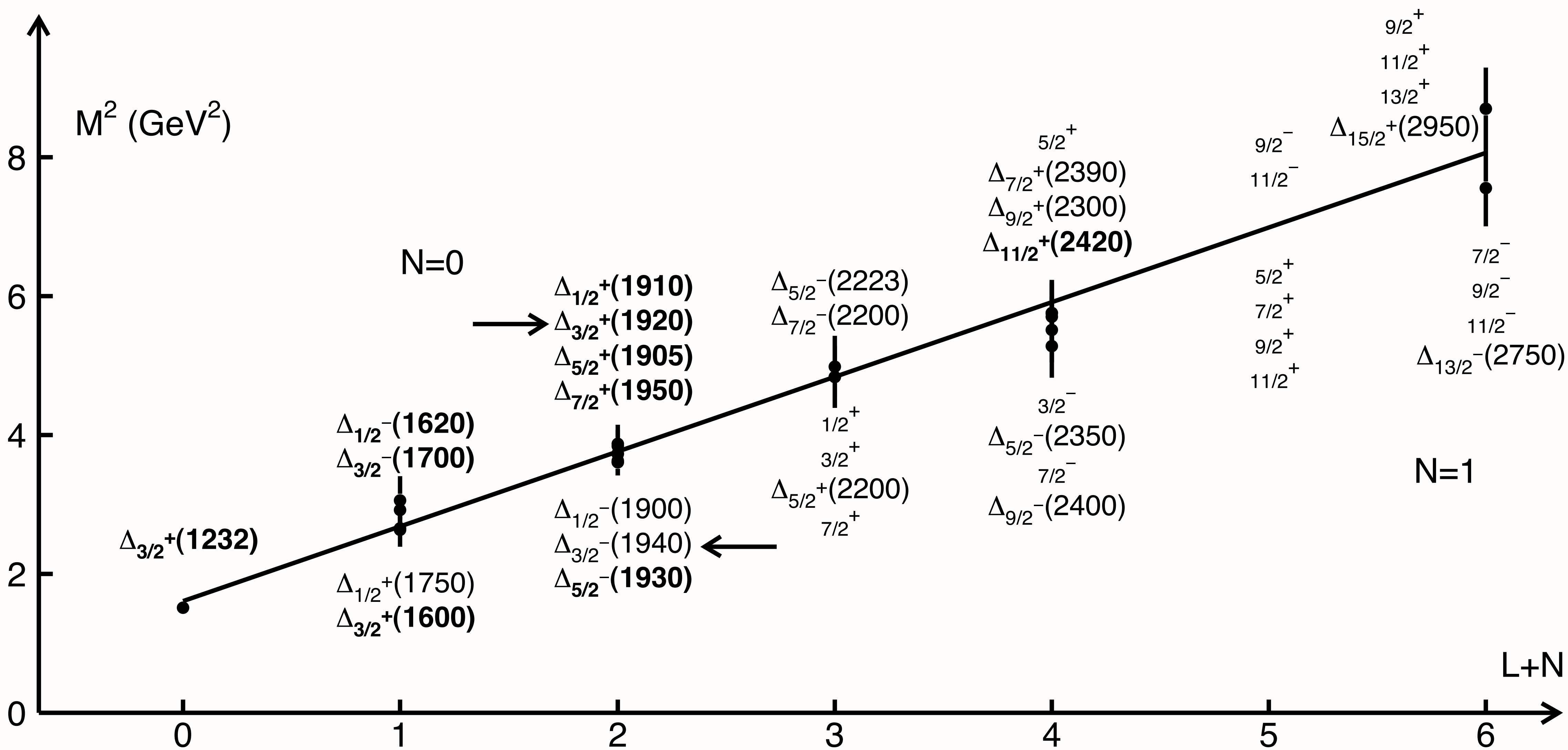
Same multiplicity of states for mesons and baryons!

$\mathcal{M}^2$



L

Parent and daughter **56** Regge trajectories for the N and Δ baryon families for $\kappa = 0.5$ GeV



E. Klempt *et al.*: Δ^* resonances, quark models, chiral symmetry and AdS/QCD

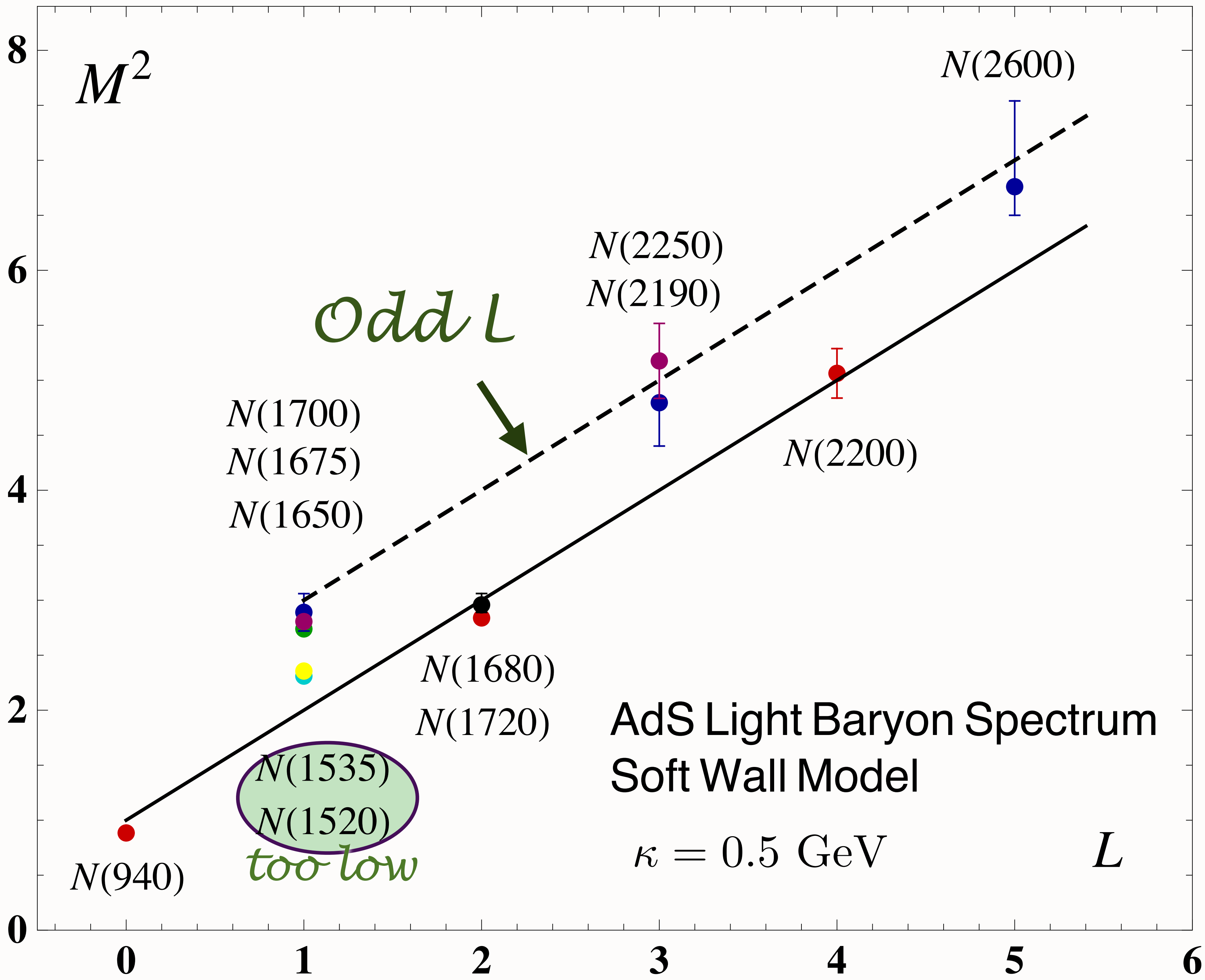
H. Forkel, M. Beyer and T. Frederico, JHEP **0707** (2007) 077.
H. Forkel, M. Beyer and T. Frederico, Int. J. Mod. Phys. E **16** (2007) 2794.

Positive Parity Nucleons

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

Negative Parity Nucleons

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



$L + 1 = \nu = \mu R - 1/2$ **(even P)**

$L + 1 = \nu = \mu R + 1/2$ **(odd P)**

- 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

$$\mathcal{M}^2_{n,L,S=1/2} = 4\kappa^2\left(n+L+1\right)$$

- "Chiral partners"

$$\frac{\mathcal{M}_{N(1535)}}{\mathcal{M}_{N(940)}} = \sqrt{2}$$

Chiral Features of Soft-Wall AdS/QCD Model

- **Boost Invariant**
- **Trivial LF vacuum.**

Proton spin
carried by quark angular momentum!

- **Massless Pion**
- **Hadron Eigenstates have LF Fock components of different L^z**
- **Proton: equal probability** $S^z = +1/2, L^z = 0; S^z = -1/2, L^z = +1$

$$J^z = +1/2 :< L^z >= 1/2, < S_q^z = 0 >$$

- **Self-Dual Massive Eigenstates: Proton is its own chiral partner.**
- **Label State by minimum L as in Atomic Physics**
- **Minimum L dominates at short distances**
- **AdS/QCD Dictionary: Match to Interpolating Operator Twist at z=0.**

Space-Like Dirac Proton Form Factor

- Consider the spin non-flip form factors

$$F_+(Q^2) = g_+ \int d\zeta \, J(Q,\zeta) |\psi_+(\zeta)|^2,$$
$$F_-(Q^2) = g_- \int d\zeta \, J(Q,\zeta) |\psi_-(\zeta)|^2,$$

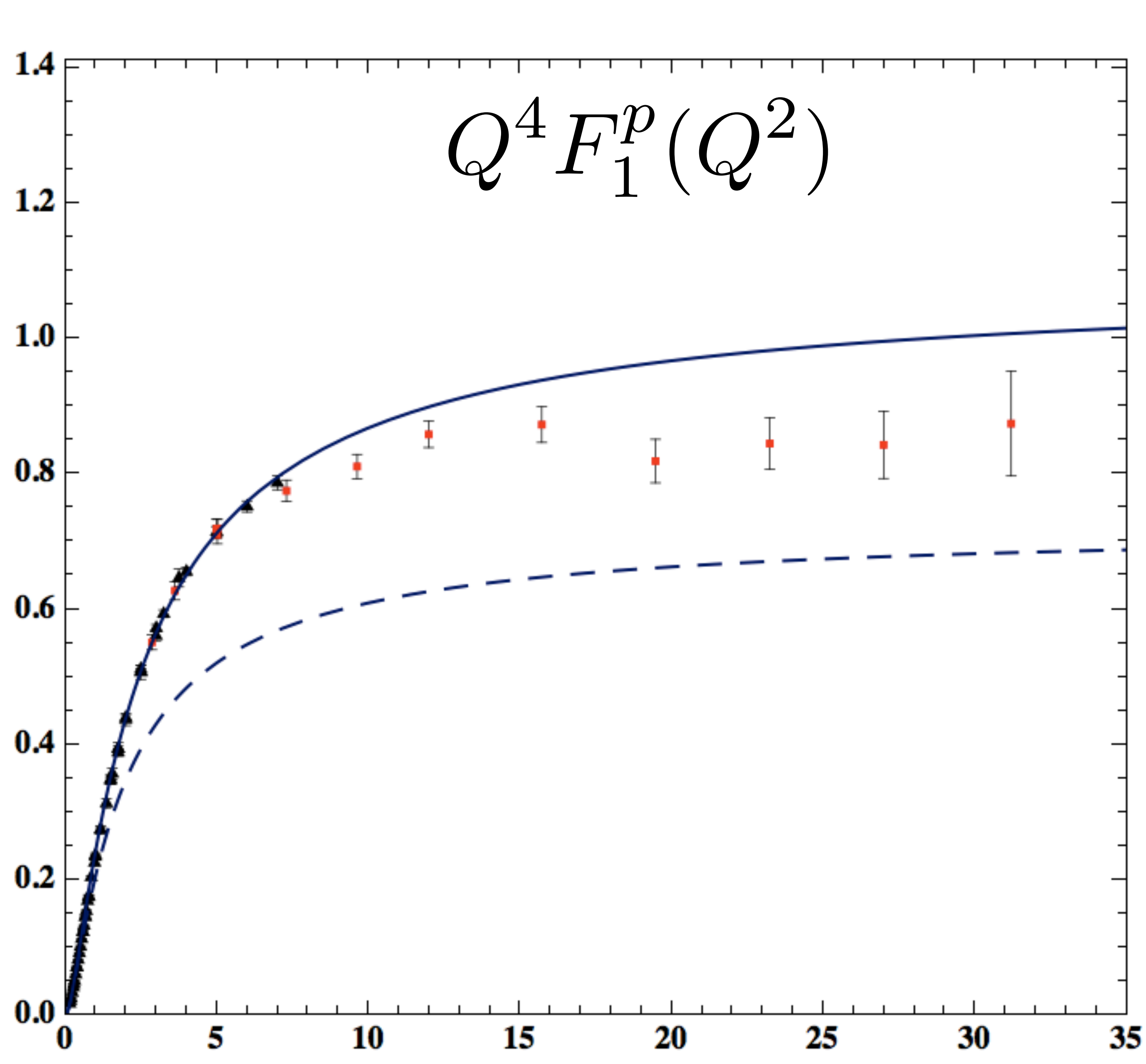
where the effective charges g_+ and g_- are determined from the spin-flavor structure of the theory.

- Choose the struck quark to have $S^z = +1/2$. The two AdS solutions $\psi_+(\zeta)$ and $\psi_-(\zeta)$ correspond to nucleons with $J^z = +1/2$ and $-1/2$.

- For $SU(6)$ spin-flavor symmetry

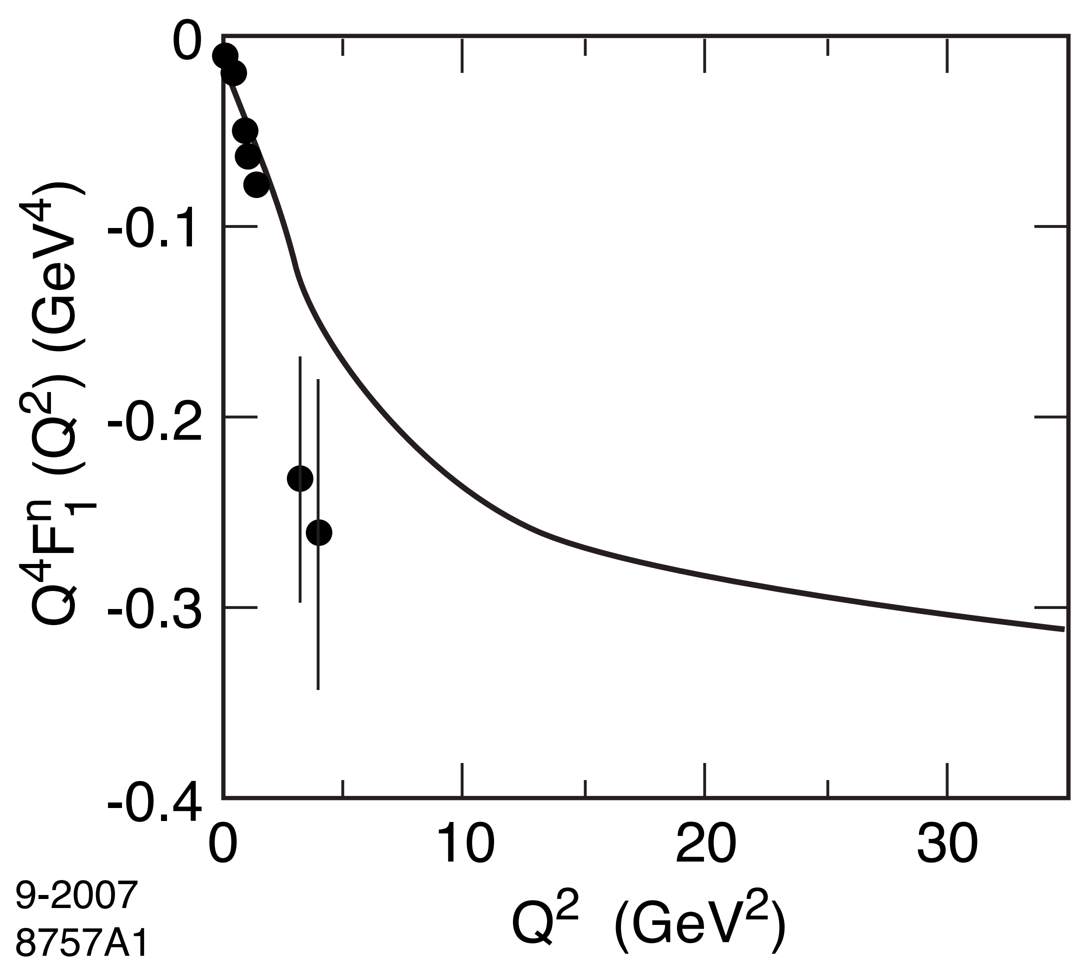
$$F_1^p(Q^2) = \int d\zeta \, J(Q,\zeta) |\psi_+(\zeta)|^2,$$
$$F_1^n(Q^2) = -\frac{1}{3} \int d\zeta \, J(Q,\zeta) \left[|\psi_+(\zeta)|^2 - |\psi_-(\zeta)|^2 \right],$$

where $F_1^p(0) = 1, \; F_1^n(0) = 0$.



$Q^4 F_p^1(Q^2)$ in a negative (dashed line, $\kappa = 0.3877$ GeV) and positive dilaton backgrounds (continuous line, $\kappa = 0.5484$ GeV). The data compilation is from Diehl.

- Scaling behavior for large Q^2: $Q^4 F_1^n(Q^2) \rightarrow \text{constant}$ $\boxed{\text{Neutron } \tau = 3}$



SW model predictions for $\kappa = 0.424$ GeV. Data analysis from M. Diehl *et al.* Eur. Phys. J. C **39**, 1 (2005).

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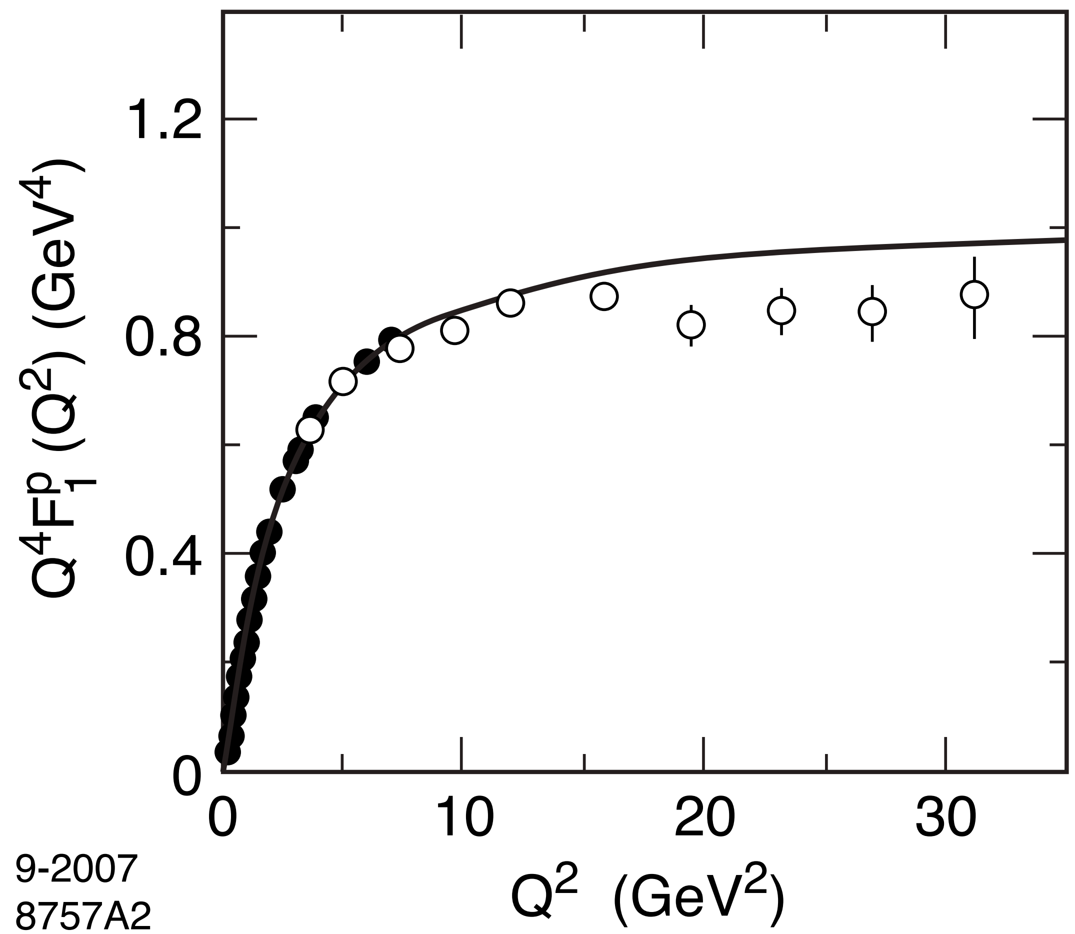

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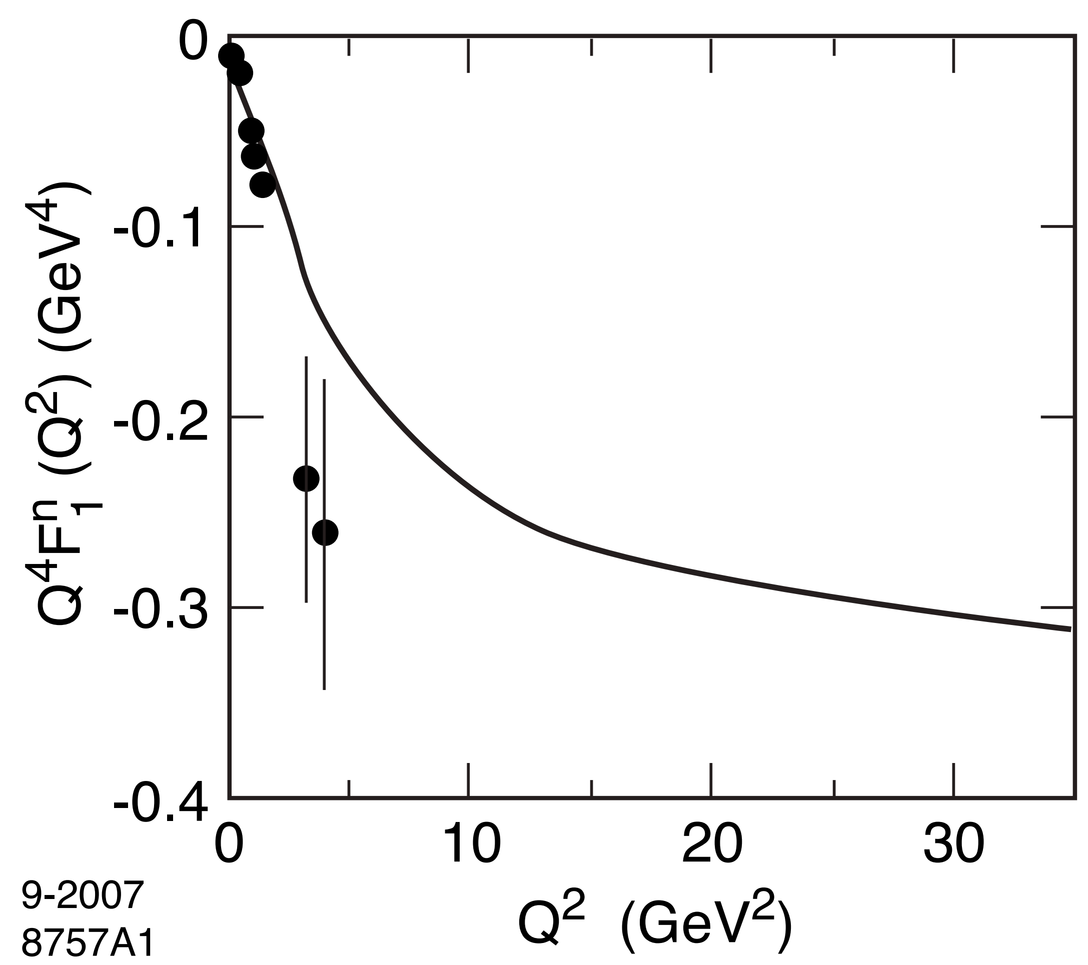
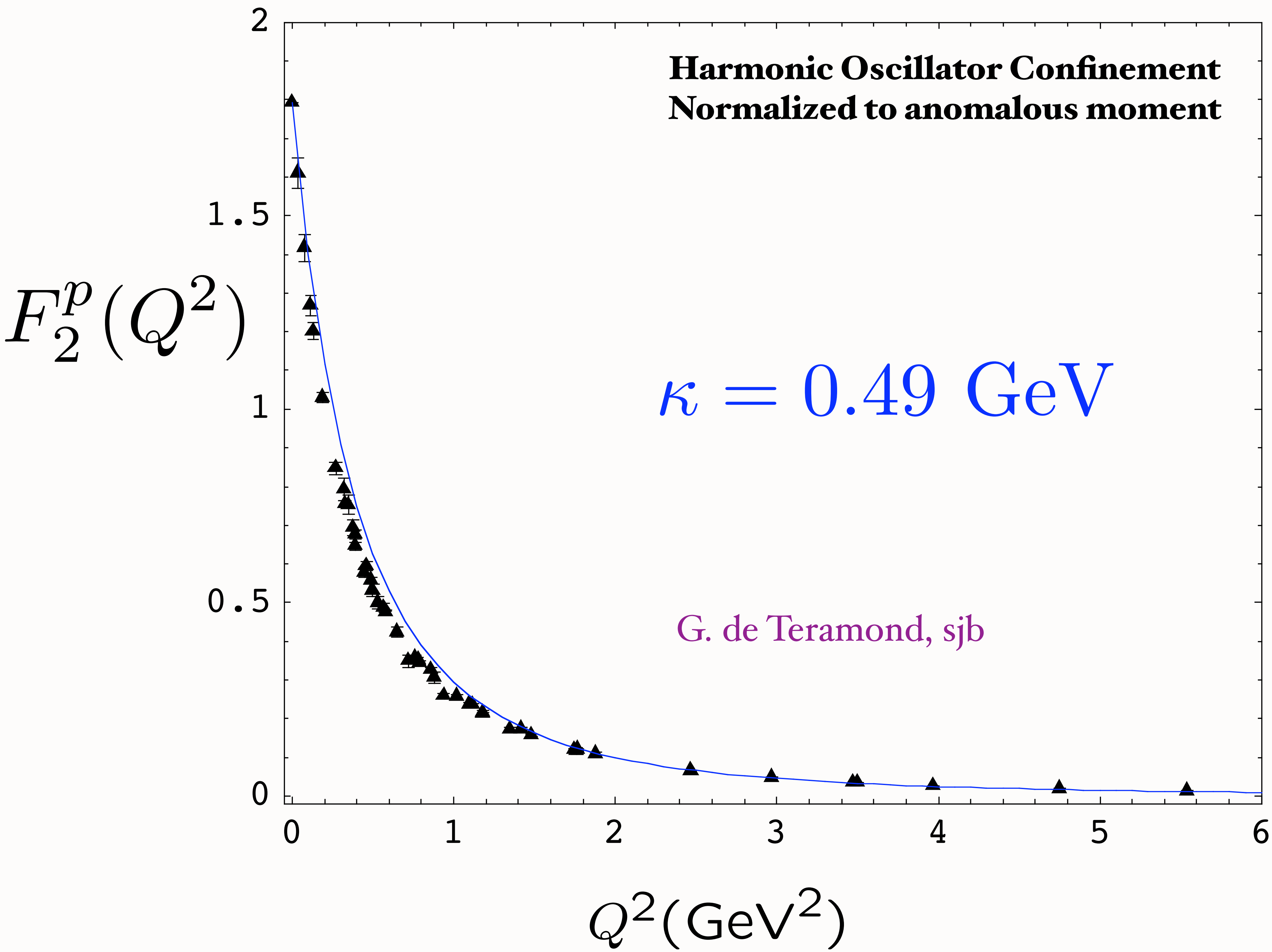


SW model predictions for $\kappa = 0.424$ GeV. Data analysis from M. Diehl *et al.* Eur. Phys. J. C **39**, 1 (2005).

Spacelike Pauli Form Factor

Preliminary

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



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- Trivial LF vacuum.
- Massless Pion
- Hadron Eigenstates have LF Fock components of different L^z
- Proton: equal probability $S^z = +1/2, L^z = 0; S^z = -1/2, L^z = +1$
- Self-Dual Massive Eigenstates: Proton is its own chiral partner.
- Label State by minimum L as in Atomic Physics
- Minimum L dominates at short distances
- AdS/QCD Dictionary: Match to Interpolating Operator Twist at z --> 0

Nucleon Transition Form Factors

- Compute spin non-flip EM transition $N(940) \to N^*(1440)$: $\Psi_+^{n=0,L=0} \to \Psi_+^{n=1,L=0}$
- Transition form factor

$$F_{1\,N\to N^*}^{\,p}(Q^2) = R^4 \int \frac{dz}{z^4}\, \Psi_+^{n=1,L=0}(z) V(Q,z) \Psi_+^{n=0,L=0}(z)$$

- Orthonormality of Laguerre functions $\left(F_{1\,N\to N^*}^{\,p}(0) = 0,\quad V(Q=0,z) = 1\right)$

$$R^4 \int \frac{dz}{z^4}\, \Psi_+^{n',L}(z) \Psi_+^{n,L}(z) = \delta_{n,n'}$$

- Find

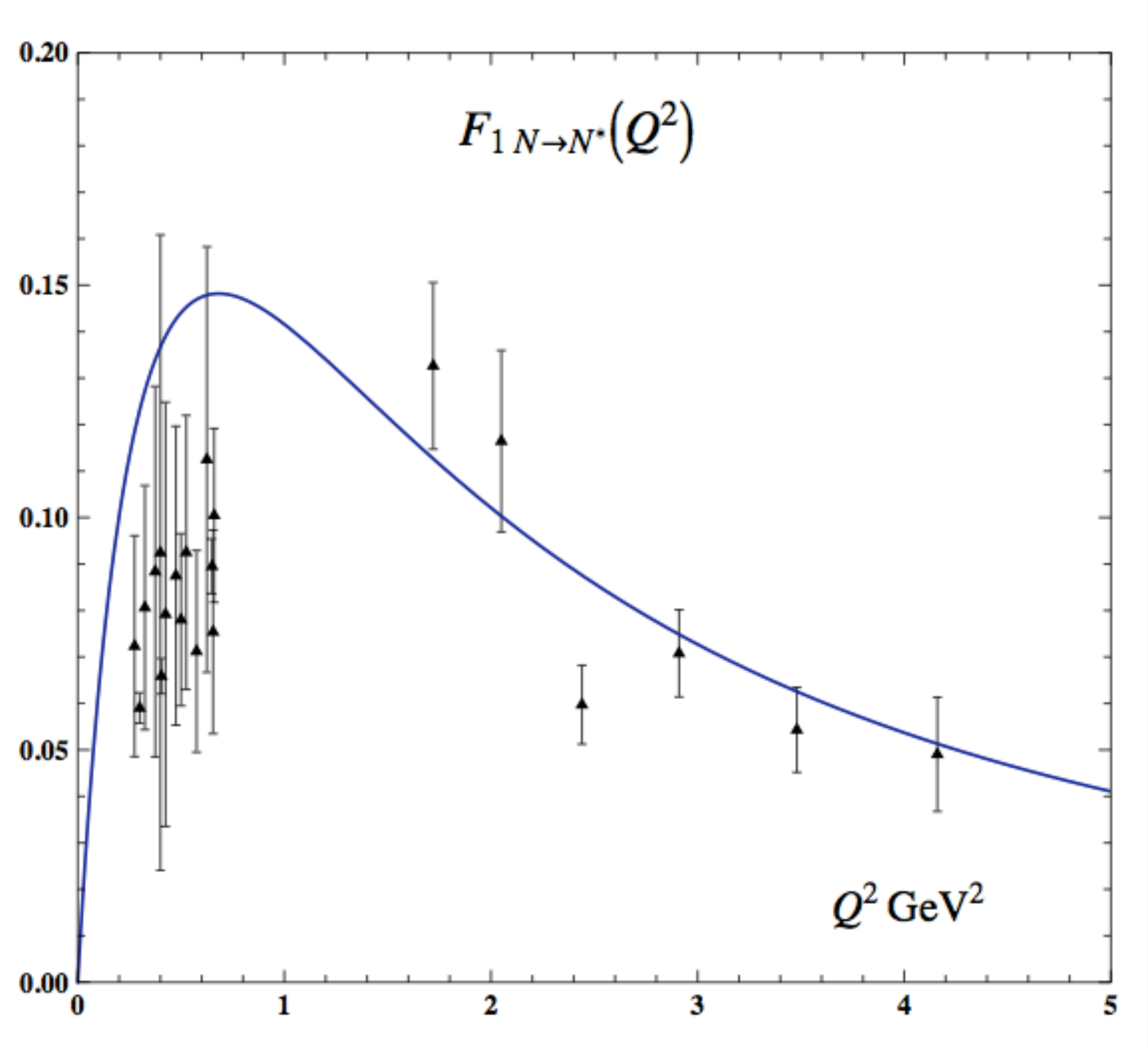
$$F_{1\,N\to N^*}^{\,p}(Q^2) = \frac{2\sqrt{2}}{3} \frac{\frac{Q^2}{M_P^2}}{\left(1+\frac{Q^2}{\mathcal{M}_\rho^2}\right)\left(1+\frac{Q^2}{\mathcal{M}_{\rho'}^2}\right)\left(1+\frac{Q^2}{\mathcal{M}_{\rho''}^2}\right)}$$

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

de Teramond, sjb

Consistent with counting rule, twist 3

$$N(940) \to N^*(1440): \quad \Psi_+^{n=0,L=0} \to \Psi_+^{n=1,L=0}$$



Data from I. Aznauryan, *et al.* CLAS (2009)

$$F_{1\,N\to N^*}^{\,p}(Q^2) = \frac{2\sqrt{2}}{3} \frac{\frac{Q^2}{M_P^2}}{\left(1+\frac{Q^2}{\mathcal{M}_\rho^2}\right)\left(1+\frac{Q^2}{\mathcal{M}_{\rho'}^2}\right)\left(1+\frac{Q^2}{\mathcal{M}_{\rho''}^2}\right)}$$

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

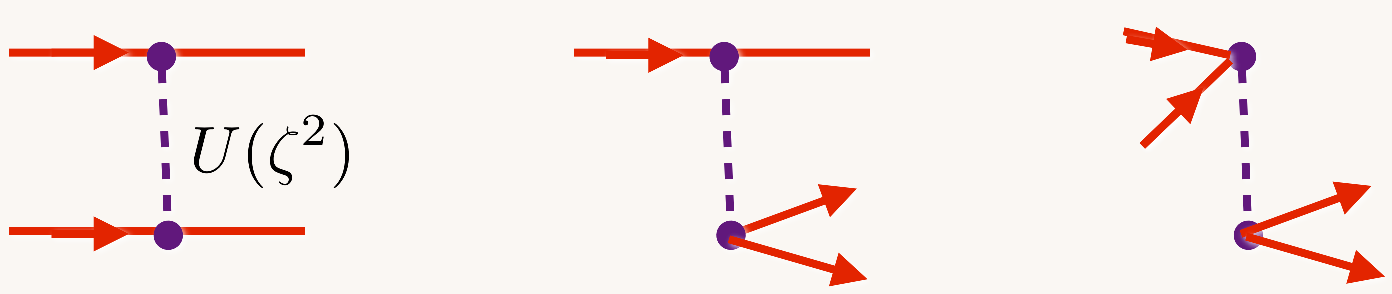
AdS/QCD predicts Higher Fock States

- Exposed by timelike form factor through dressed current.

- Created by confining interaction

$$P^-_{\text{confinement}} \simeq \kappa^4 \int dx^- d^2\vec{x}_\perp \frac{\overline{\psi}\gamma^+ T^a \psi}{P^+} \frac{1}{(\partial/\partial_\perp)^4} \frac{\overline{\psi}\gamma^+ T^a \psi}{P^+}$$

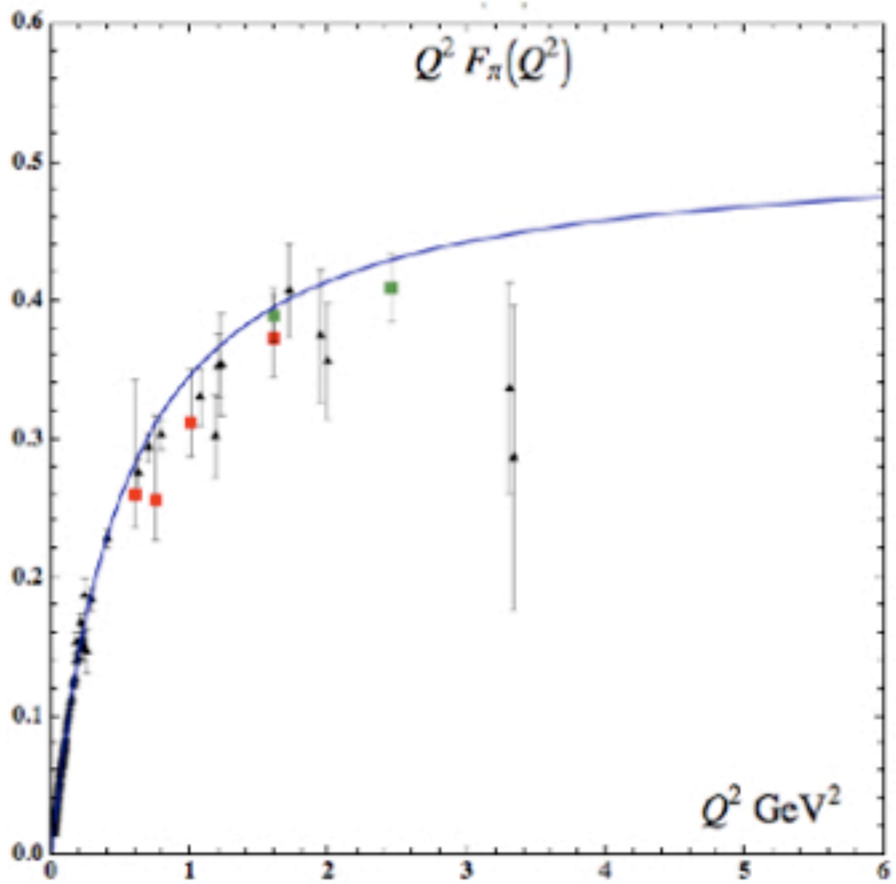
- Similar to QCD(1+1) in lcg

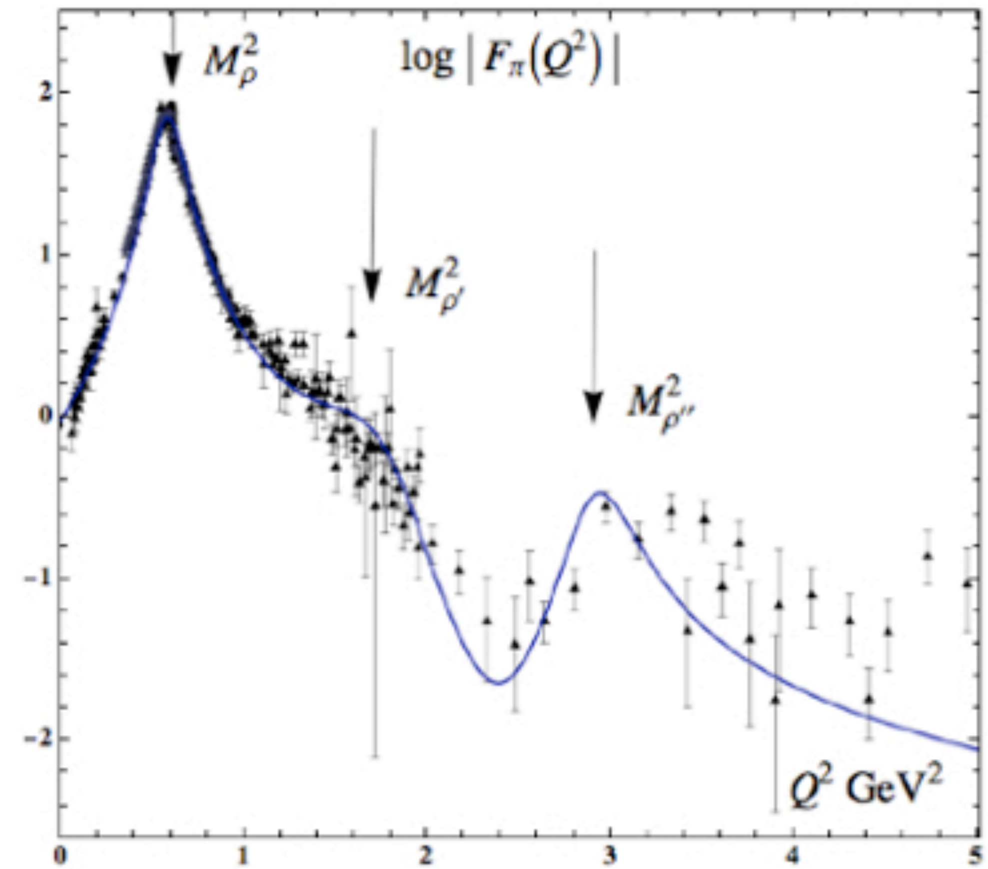


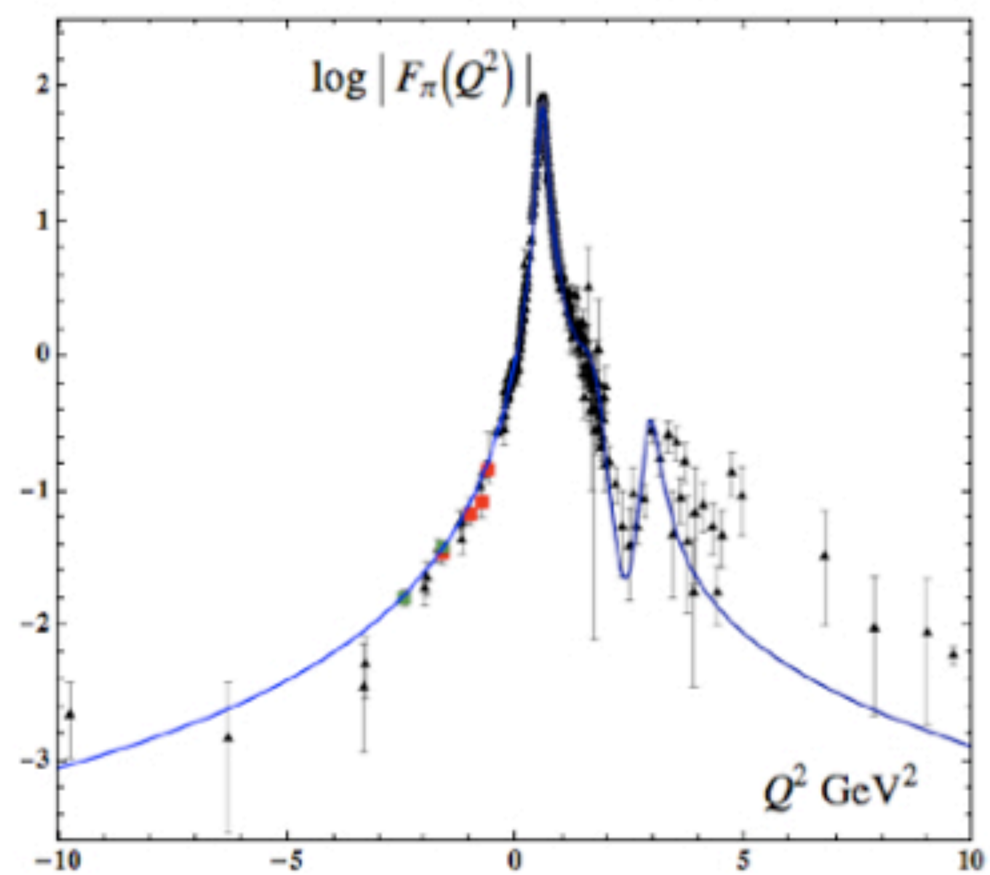
de Teramond, sjb

Space- and Time Like Pion Form-Factor (HFS)

PRELIMINARY







$$|\pi\rangle = \psi_{q\bar{q}/\pi}|q\bar{q}\rangle + \psi_{q\bar{q}q\bar{q}/\pi}|q\bar{q}q\bar{q}\rangle$$

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

$$\kappa = 0.54 \text{ GeV}$$

$$\Gamma_\rho = 130,\ \Gamma_{\rho'} = 400,\ \Gamma_{\rho''} = 300 \text{ MeV}$$

$$P_{q\bar{q}q\bar{q}} = 13\ \%$$

Note: Analytical Form of Hadronic Form Factor for Arbitrary Twist

- Form factor for a string mode with scaling dimension τ, Φ_τ in the SW model

$$F(Q^2) = \Gamma(\tau) \frac{\Gamma\left(1 + \frac{Q^2}{4\kappa^2}\right)}{\Gamma\left(\tau + \frac{Q^2}{4\kappa^2}\right)}.$$

- For $\tau = N$, $\quad \Gamma(N + z) = (N - 1 + z)(N - 2 + z) \ldots (1 + z)\Gamma(1 + z)$.

- Form factor expressed as $N - 1$ product of poles

$$F(Q^2) = \frac{1}{1 + \frac{Q^2}{4\kappa^2}}, \quad N = 2,$$

$$F(Q^2) = \frac{2}{\left(1 + \frac{Q^2}{4\kappa^2}\right)\left(2 + \frac{Q^2}{4\kappa^2}\right)}, \quad N = 3,$$

$$\cdots$$

$$F(Q^2) = \frac{(N-1)!}{\left(1 + \frac{Q^2}{4\kappa^2}\right)\left(2 + \frac{Q^2}{4\kappa^2}\right)\cdots\left(N - 1 + \frac{Q^2}{4\kappa^2}\right)}, \quad N.$$

- For large Q^2:

$$F(Q^2) \to (N-1)! \left[\frac{4\kappa^2}{Q^2}\right]^{(N-1)}.$$

Meson Transition Form-Factors

[S. J. Brodsky, Fu-Guang Cao and GdT, arXiv:1005.39XX]

- Pion TFF from 5-dim Chern-Simons structure [Hill and Zachos (2005), Grigoryan and Radyushkin (2008)]

$$\int d^4x \int dz\, \epsilon^{LMNPQ} A_L \partial_M A_N \partial_P A_Q$$
$$\sim (2\pi)^4 \delta^{(4)}\left(p_\pi + q - k\right) F_{\pi\gamma}(q^2) \epsilon^{\mu\nu\rho\sigma} \epsilon_\mu(q) (p_\pi)_\nu \epsilon_\rho(k) q_\sigma$$

- Take $A_z \propto \Phi_\pi(z)/z, \quad \Phi_\pi(z) = \sqrt{2P_{q\bar{q}}}\, \kappa\, z^2 e^{-\kappa^2 z^2/2}, \quad \langle \Phi_\pi | \Phi_\pi \rangle = P_{q\bar{q}}$
- Find $\left(\phi(x) = \sqrt{3} f_\pi x(1-x), \quad f_\pi = \sqrt{P_{q\bar{q}}}\, \kappa/\sqrt{2}\pi\right)$

$$Q^2 F_{\pi\gamma}(Q^2) = \frac{4}{\sqrt{3}} \int_0^1 dx \frac{\phi(x)}{1-x} \left[1 - e^{-P_{q\bar{q}} Q^2 (1-x)/4\pi^2 f_\pi^2 x}\right]$$

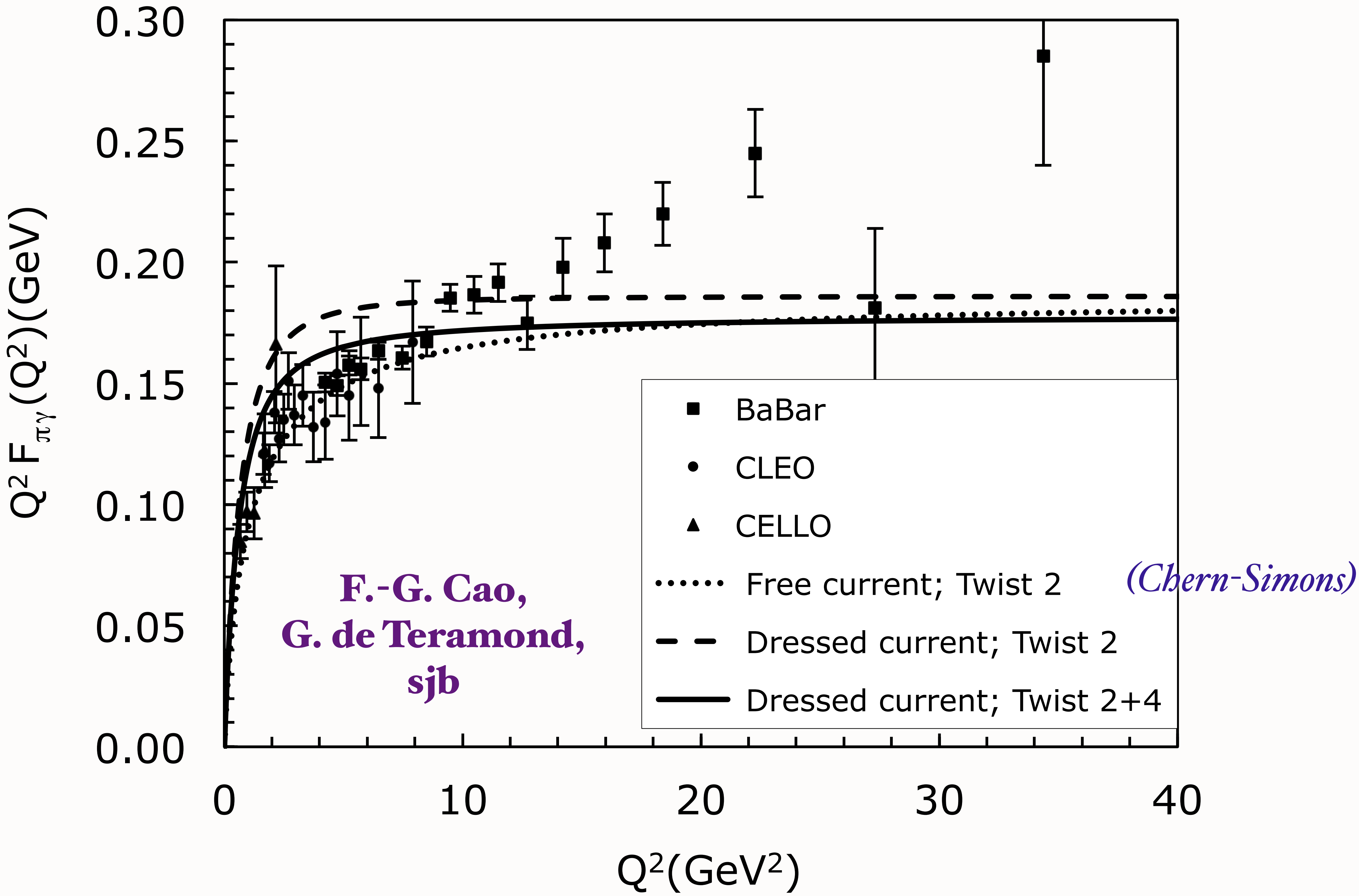
normalized to the asymptotic DA [$P_{q\bar{q}} = 1 \to$ Musatov and Radyushkin (1997)]

G.P. Lepage, sjb

- Large Q^2 TFF is identical to first principles asymptotic QCD result $Q^2 F_{\pi\gamma}(Q^2 \to \infty) = 2 f_\pi$
- The CS form is local in AdS space and projects out only the asymptotic form of the pion DA

Photon-to-pion transition form factor

$$Q^2 F_{\pi\gamma}(Q^2 \to \infty) = 2 f_\pi$$



Running Coupling from Modified AdS/QCD

Deur, de Teramond, sjb

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

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

- Flow equation

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

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

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

- Coupling measured at momentum scale Q

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

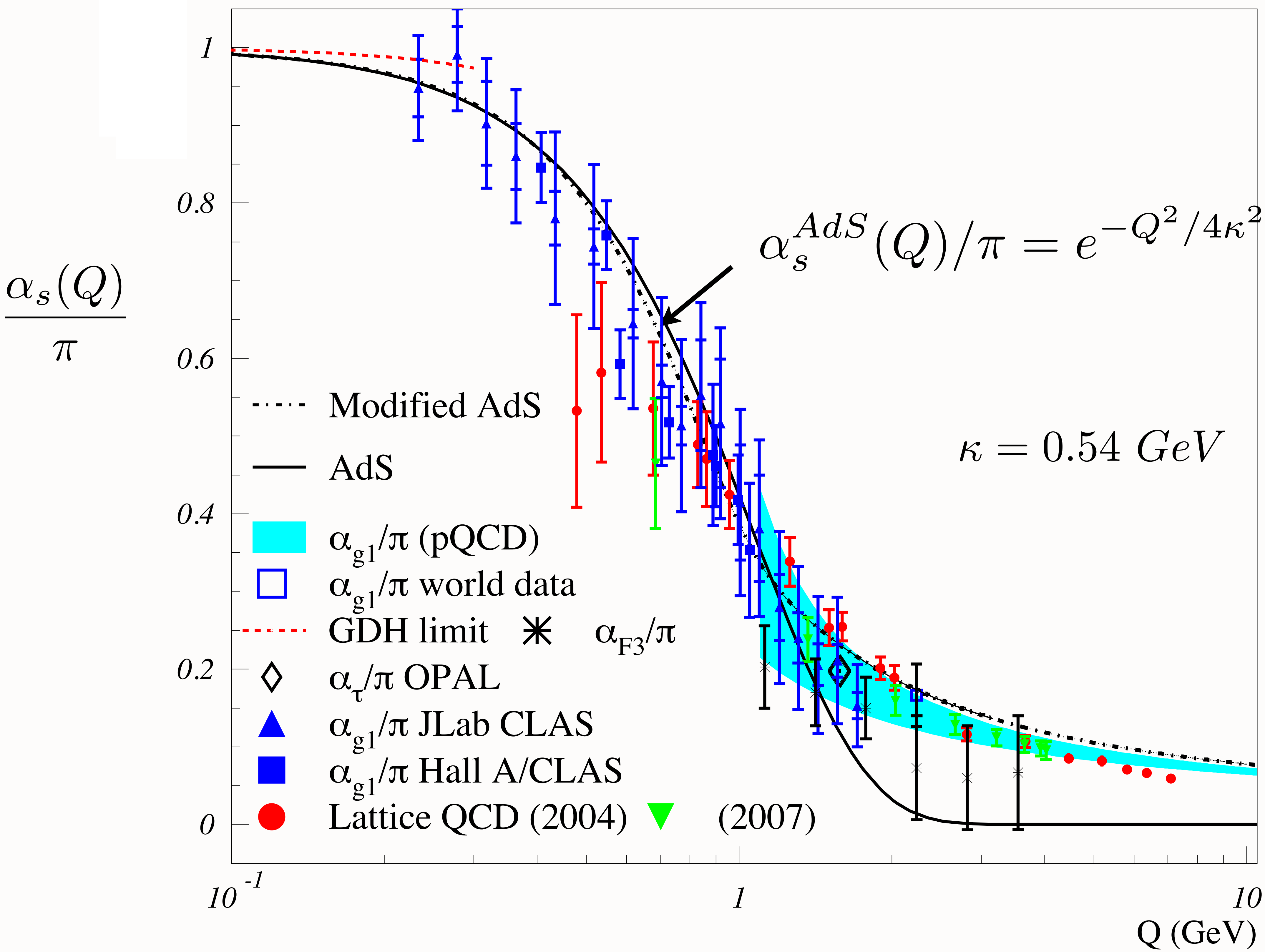
- Solution

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

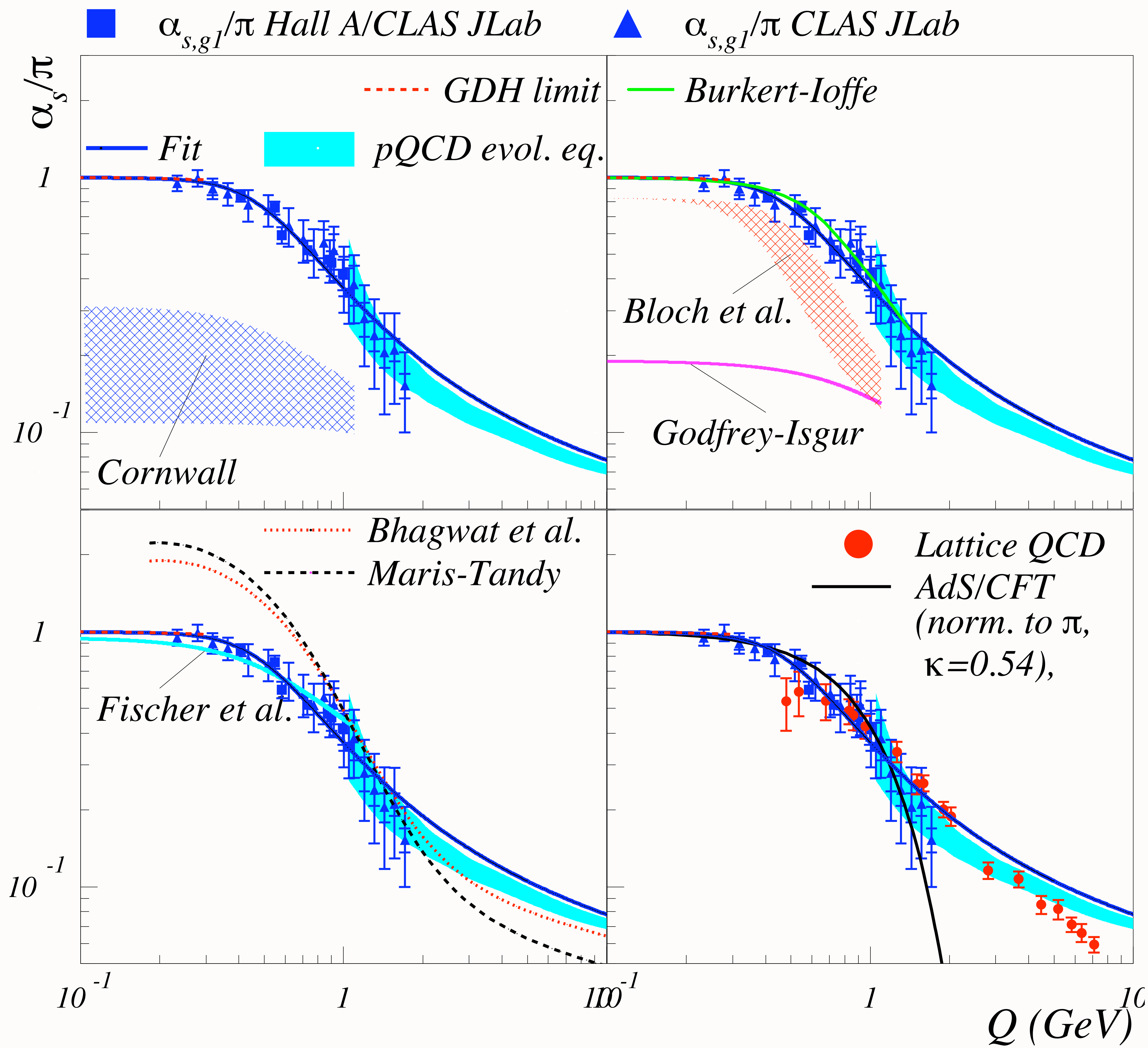
where the coupling α_s^{AdS} incorporates the non-conformal dynamics of confinement

Running Coupling from Light-Front Holography and AdS/QCD

Analytic, defined at all scales, IR Fixed Point

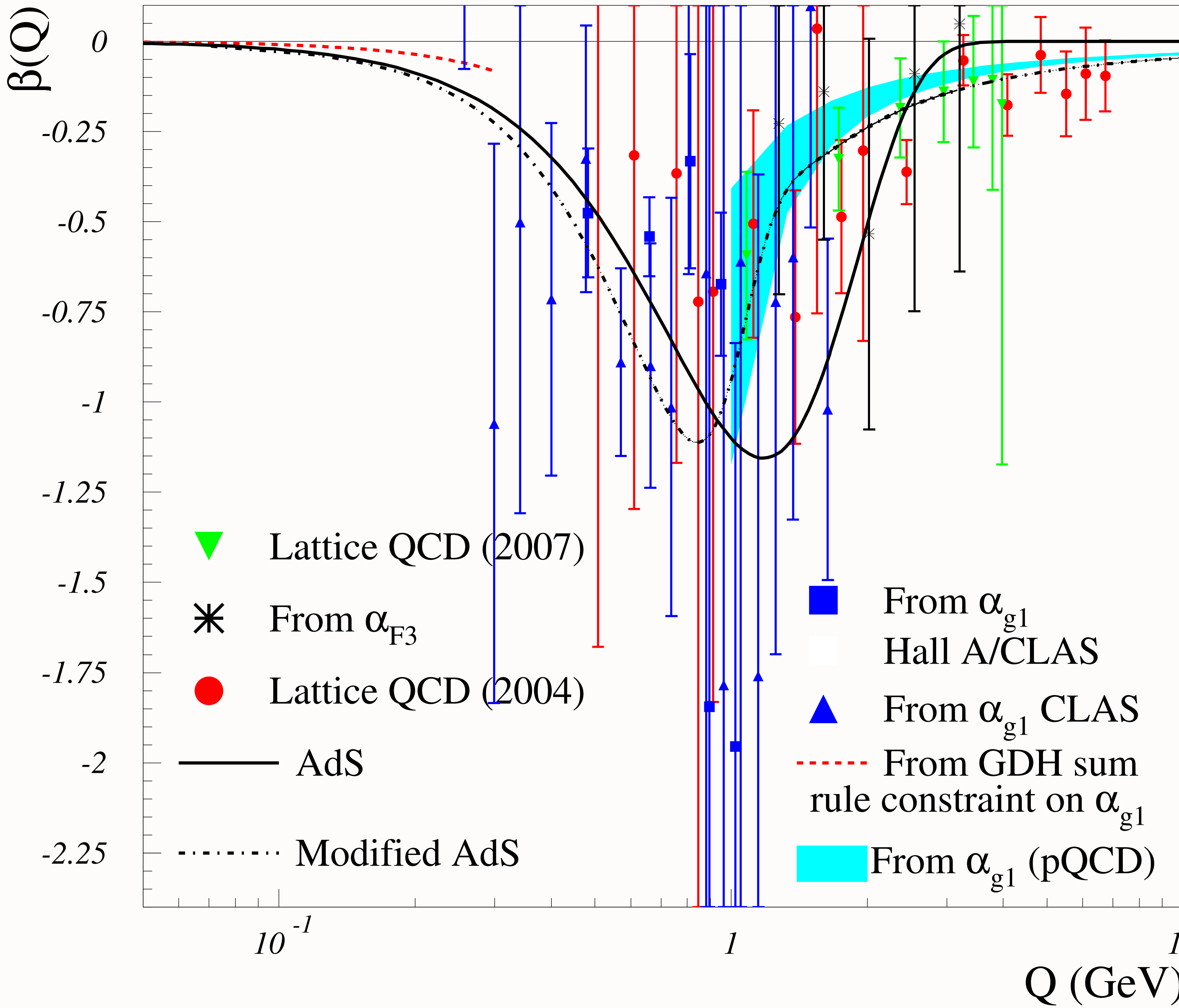


Deur, de Teramond, sjb



Deur, de Teramond, sjb, (preliminary)

$$\beta^{AdS}(Q^2) = \frac{d}{d\log Q^2}\alpha_s^{AdS}(Q^2) = \frac{\pi Q^2}{4\kappa^2} e^{-Q^2/4\kappa^2}$$



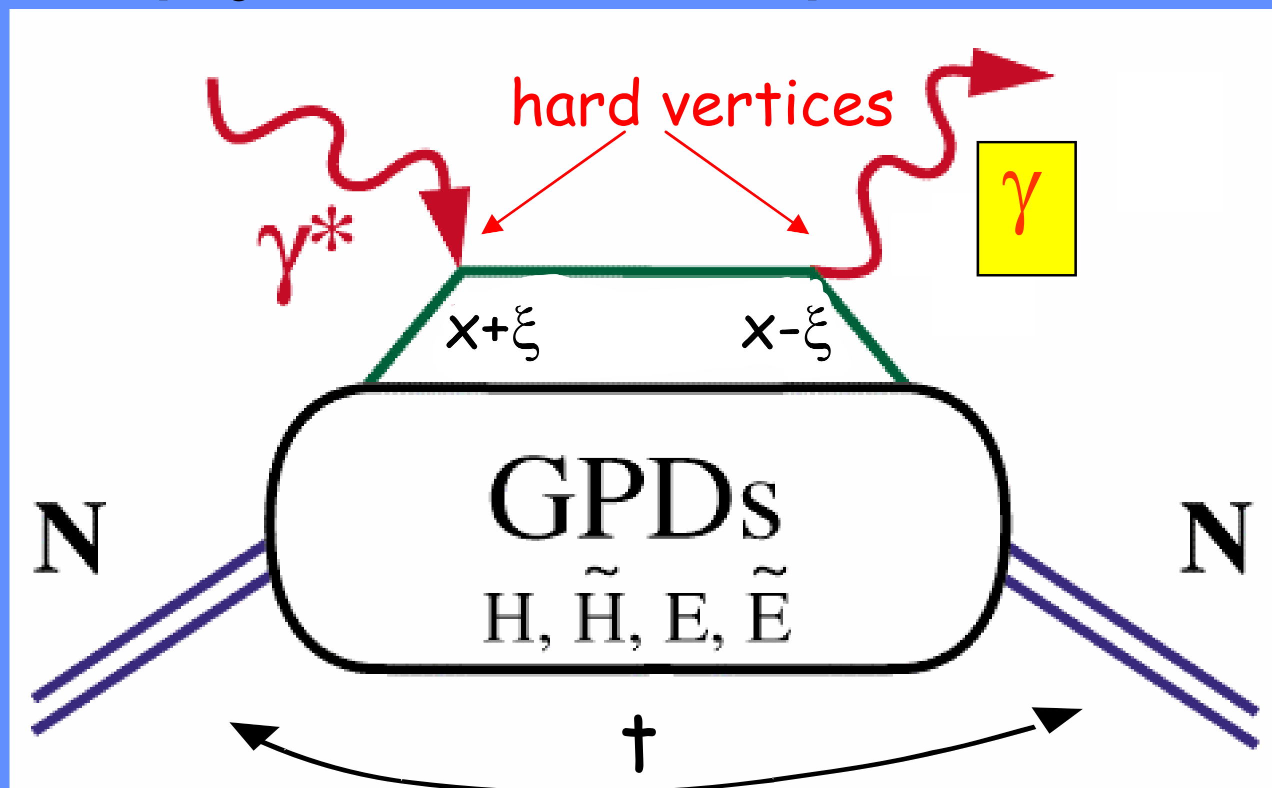
Deur, de Teramond, sjb

Features of AdS/QCD LF Holography

- **Based on Conformal Scaling of Infrared QCD Fixed Point**
- **Conformal template: Use isometries of AdS5**
- **Interpolating operator of hadrons based on twist, superfield dimensions**
- **Finite Nc = 3: Baryons built on 3 quarks -- Large Nc limit not required**
- **Break Conformal symmetry with dilaton**
- **Dilaton introduces confinement -- positive exponent**
- **Origin of Linear and HO potentials: Stochastic arguments (Glazek); General 'classical' potential for Dirac Equation (Hoyer)**
- **Effective Charge from AdS/QCD at all scales**
- **Conformal Dimensional Counting Rules for Hard Exclusive Processes**

GPDs & Deeply Virtual Exclusive Processes
- New Insight into Nucleon Structure

Deeply Virtual Compton Scattering (DVCS)



x – quark momentum fraction

ξ– longitudinal momentum transfer

$\sqrt{-t}$ – Fourier conjugate to transverse impact parameter

H(x,ξ,t), E(x,ξ,t), . . . "Generalized Parton Distributions"

- Generalized Parton Distributions in gauge/gravity duals

  [Vega, Schmidt, Gutsche and Lyubovitskij, Phys.Rev. D83 (2011) 036001]

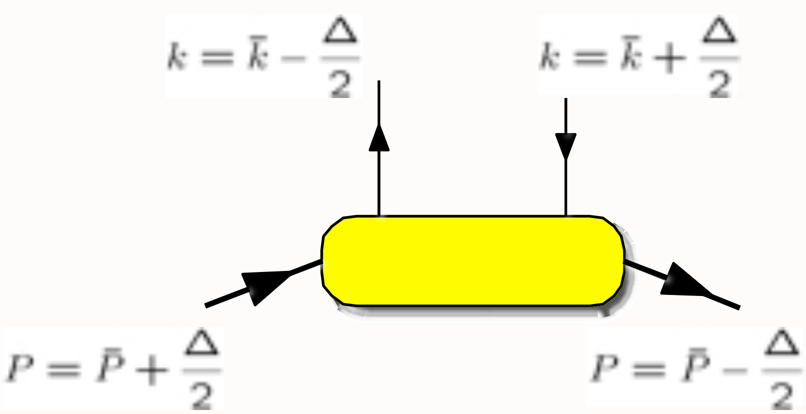
  [Nishio and Watari, arXiv:1105.290]

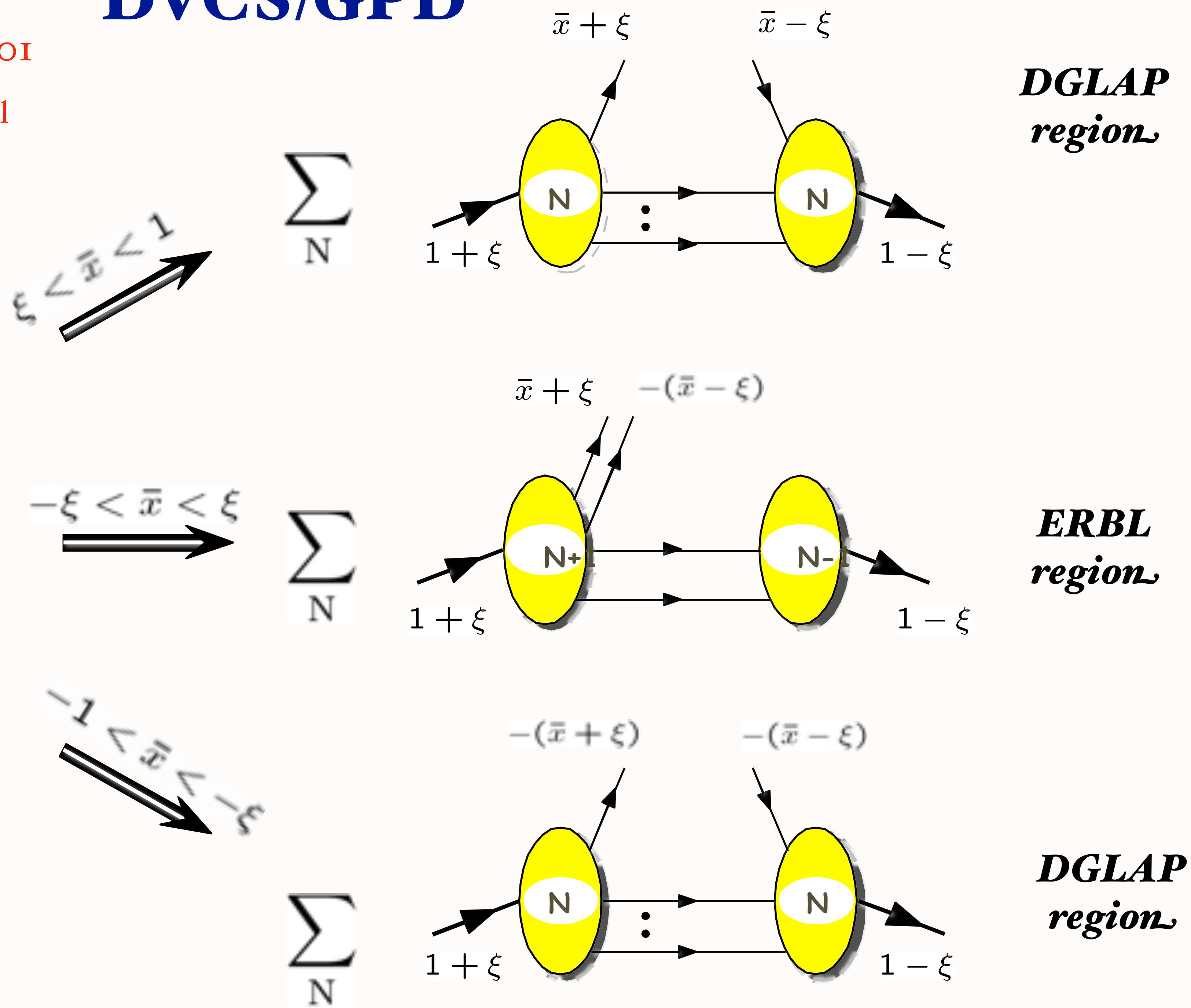
Light-Front Wave Function Overlap Representation

DVCS/GPD

Diehl, Hwang, sjb, NPB596, 2001

See also: Diehl, Feldmann, Jakob, Kroll





Bakker & JI
Lorce

Example of LFWF representation of GPDs (n => n)

Diehl, Hwang, sjb

$$\frac{1}{\sqrt{1-\zeta}} \frac{\Delta^1 - i\Delta^2}{2M} E_{(n\to n)}(x,\zeta,t)$$

$$= \left(\sqrt{1-\zeta}\right)^{2-n} \sum_{n,\lambda_i} \int \prod_{i=1}^{n} \frac{\mathrm{d}x_i\, \mathrm{d}^2\vec{k}_{\perp i}}{16\pi^3}\, 16\pi^3 \delta\left(1-\sum_{j=1}^{n} x_j\right) \delta^{(2)}\left(\sum_{j=1}^{n} \vec{k}_{\perp j}\right)$$

$$\times\, \delta(x - x_1)\, \psi^{\uparrow *}_{(n)}(x'_i, \vec{k}'_{\perp i}, \lambda_i)\, \psi^{\downarrow}_{(n)}(x_i, \vec{k}_{\perp i}, \lambda_i),$$

where the arguments of the final-state wavefunction are given by

$$x'_1 = \frac{x_1 - \zeta}{1-\zeta}, \qquad \vec{k}'_{\perp 1} = \vec{k}_{\perp 1} - \frac{1-x_1}{1-\zeta}\vec{\Delta}_\perp \quad \text{for the struck quark,}$$

$$x'_i = \frac{x_i}{1-\zeta}, \qquad \vec{k}'_{\perp i} = \vec{k}_{\perp i} + \frac{x_i}{1-\zeta}\vec{\Delta}_\perp \quad \text{for the spectators } i = 2, \ldots, n.$$

Link to DIS and Elastic Form Factors

DIS at $\xi = t = 0$

$$H^q(x,0,0) = q(x), \quad -\bar{q}(-x)$$

$$\widetilde{H}^q(x,0,0) = \Delta q(x), \quad \Delta\bar{q}(-x)$$

Form factors (sum rules)

$$\int_{-1}^{1} dx \sum_q \left[H^q(x,\xi,t)\right] = F_1(t) \quad \text{Dirac f.f.}$$

$$\int_{-1}^{1} dx \sum_q \left[E^q(x,\xi,t)\right] = F_2(t) \quad \text{Pauli f.f.}$$

$$\int_{-1}^{1} dx\, \widetilde{H}^q(x,\xi,t) = G_{A,q}(t), \quad \int_{-1}^{1} dx\, \widetilde{E}^q(x,\xi,t) = G_{P,q}(t)$$

$$H^q, E^q, \widetilde{H}^q, \widetilde{E}^q(x,\xi,t)$$

Verified using LFWFs

Diehl, Hwang, sjb

Quark angular momentum (Ji's sum rule)

$$J^q = \frac{1}{2} - J^G = \frac{1}{2}\int_{-1}^{1} x\,dx\left[H^q(x,\xi,0) + E^q(x,\xi,0)\right]$$

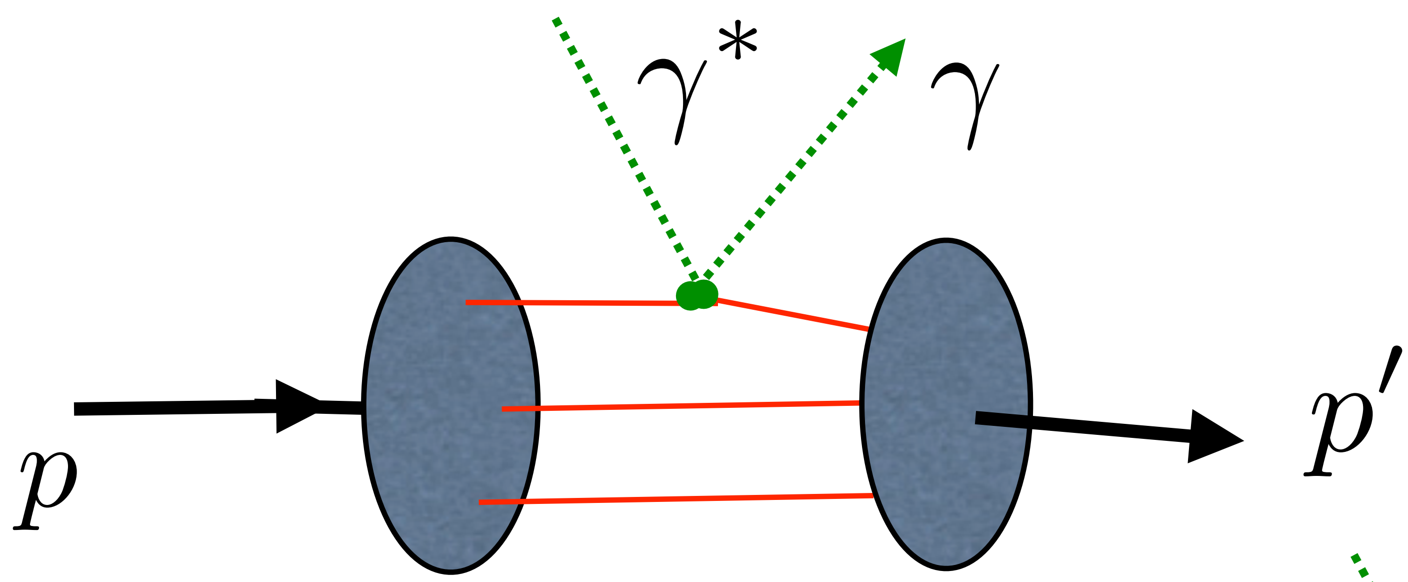
X. Ji, Phy.Rev.Lett.78,610(1997)

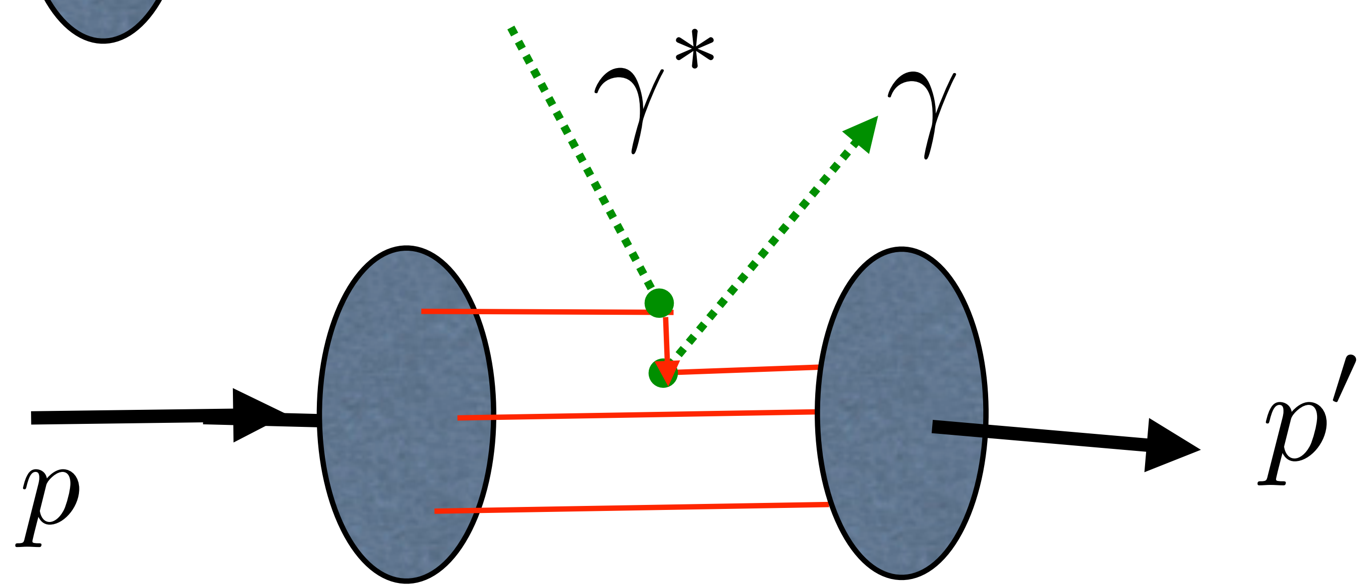
J=0 Fixed Pole Contribution to DVCS

- **J=0 fixed pole -- direct test of QCD locality -- from seagull or instantaneous contribution to Feynman propagator**

Szczepaniak, Llanes-Estrada, sjb

Close, Gunion, sjb

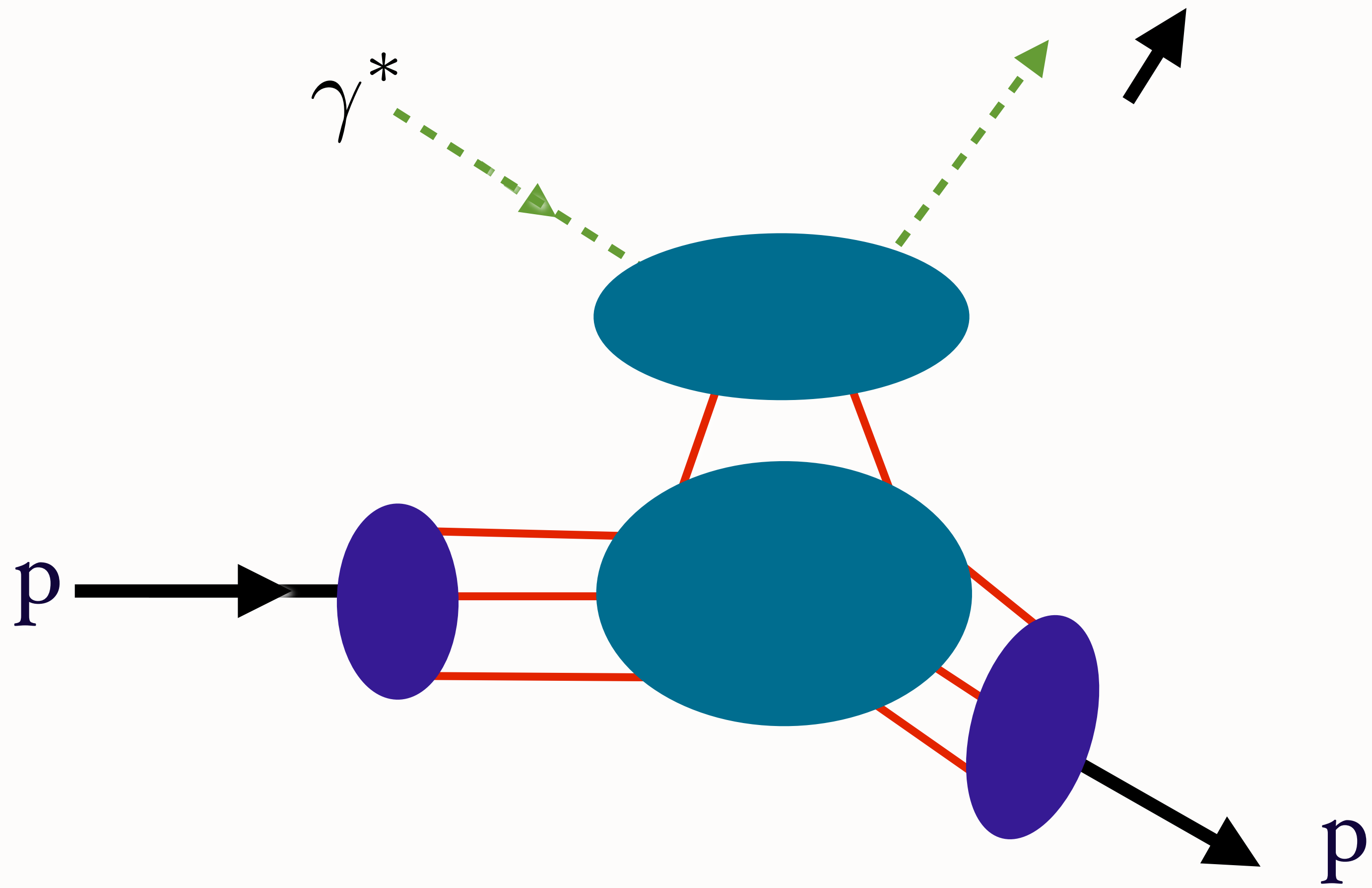




Real amplitude, independent of Q^2 at fixed t

Deeply Virtual Compton Scattering

$$\gamma^* p \to \gamma p$$



Hard Reggeon Domain

$$s >> -t, Q^2 >> \Lambda^2_{QCD}$$

$$T(\gamma^*(q)p \to \gamma(k) + p) \sim \epsilon \cdot \epsilon' \sum_R s_R^{\alpha}(t)\beta_R(t)$$

$$\alpha_R(t) \to 0$$

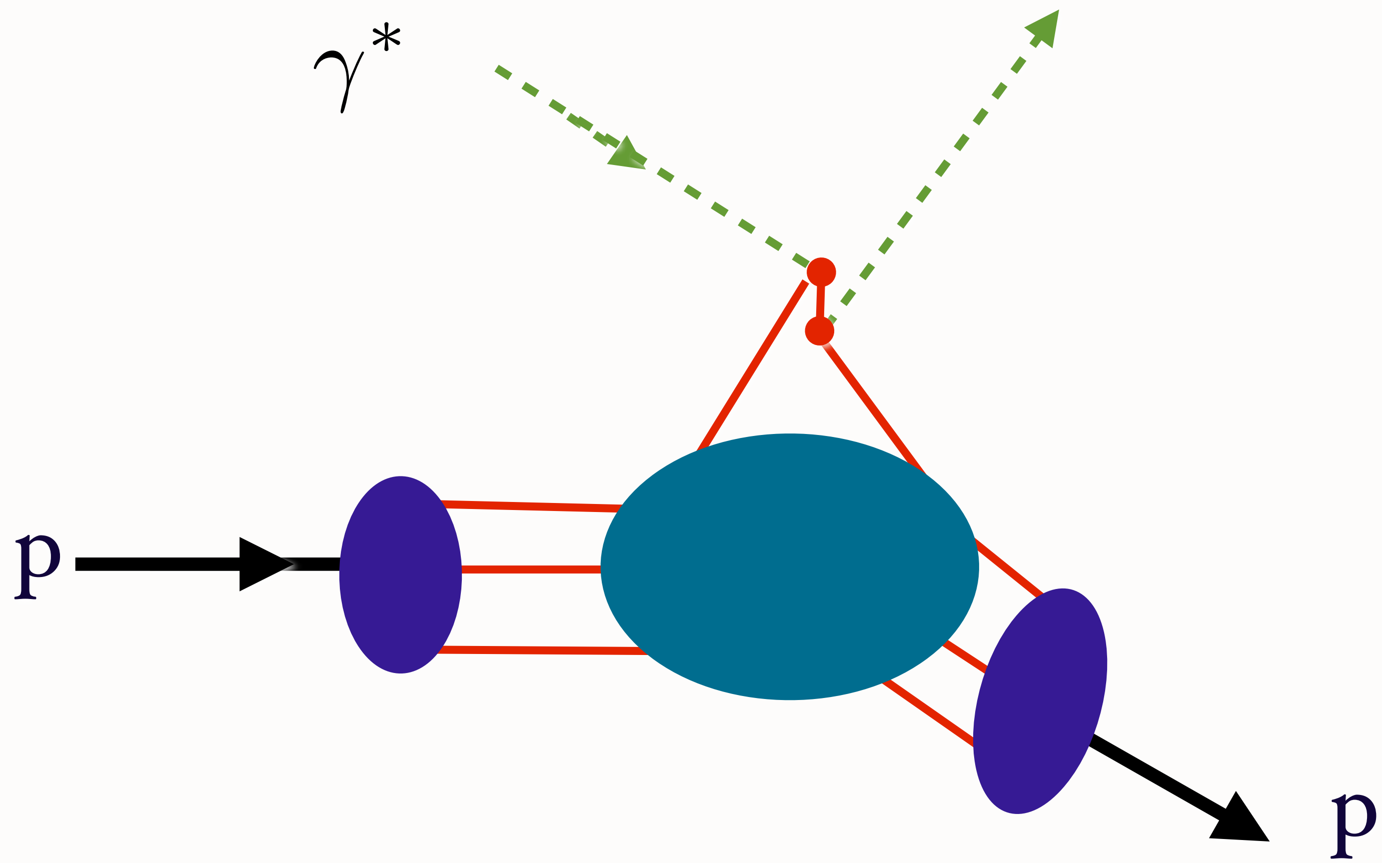
Reflects elementary coupling of two photons to quarks

$$\beta_R(t) \sim \frac{1}{t^2}$$

$$\frac{d\sigma}{dt} \sim \frac{1}{s^2}\frac{1}{t^4} \sim \frac{1}{s^6} \text{ at fixed } \frac{Q^2}{s}, \frac{t}{s}$$

Deeply Virtual Compton Scattering

$$\gamma^* p \to \gamma p$$



Seagull interaction (instantaneous quark exchange or Z-graph)

$$s >> -t, Q^2 >> \Lambda^2_{QCD}$$

Hard Reggeon Domain

$$T(\gamma^*(q)p \to \gamma(k) + p) \sim \epsilon \cdot \epsilon' \sum_R s_R^{\alpha}(t)\beta_R(t)$$

$$\alpha_R(t) \to 0$$

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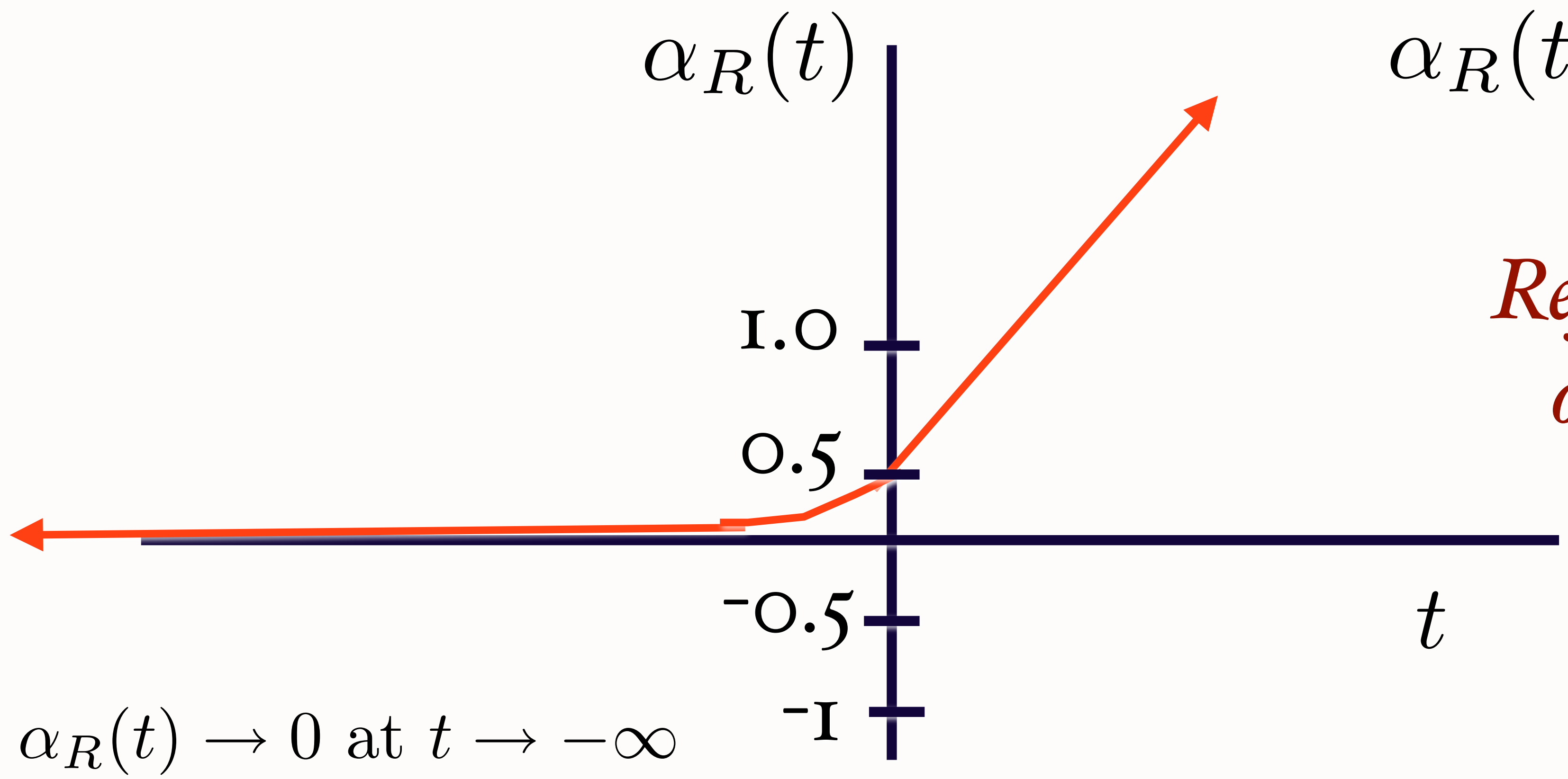
$$\frac{d\sigma}{dt} \sim \frac{1}{s^2}\frac{1}{t^4} \sim \frac{1}{s^6} \text{ at fixed } \frac{Q^2}{s}, \frac{t}{s}$$

Regge domain

$$T(\gamma^* p \to \pi^+ n) \sim \epsilon \cdot p_i \sum_R s_R^{\alpha}(t)\beta_R(t) \qquad s >> -t, Q^2$$



$\alpha_R(t) \to 0$ at $t \to -\infty$

J=0 fixed pole

Reflects elementary coupling of two photons to quarks

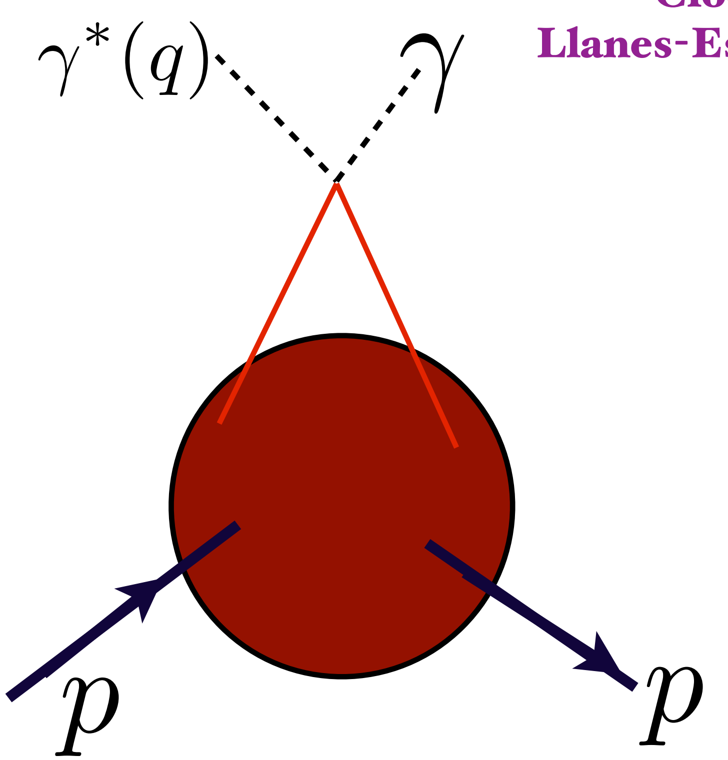
$$\beta_R(t) \sim \frac{1}{t^2}$$

$$\frac{d\sigma}{dt}(\gamma^* p \to \gamma p) \to \frac{1}{s^2}\beta_R^2(t) \sim \frac{1}{s^2 t^4} \sim \frac{1}{s^6} \text{ at fixed } \frac{t}{s}, \frac{Q^2}{s}$$

Fundamental test of QCD

J=0 Fixed pole in real and virtual Compton scattering

Damashek, Gilman;
Close, Gunion, sjb
Llanes-Estrada, Szczepaniak,
sjb



Effective two-photon contact term

Seagull for scalar quarks

Real phase

$$M = s^0 \sum e_q^2 F_q(t)$$

Independent of Q^2 at fixed t

<1/x> Moment: Related to Feynman-Hellman Theorem

Fundamental test of local gauge theory

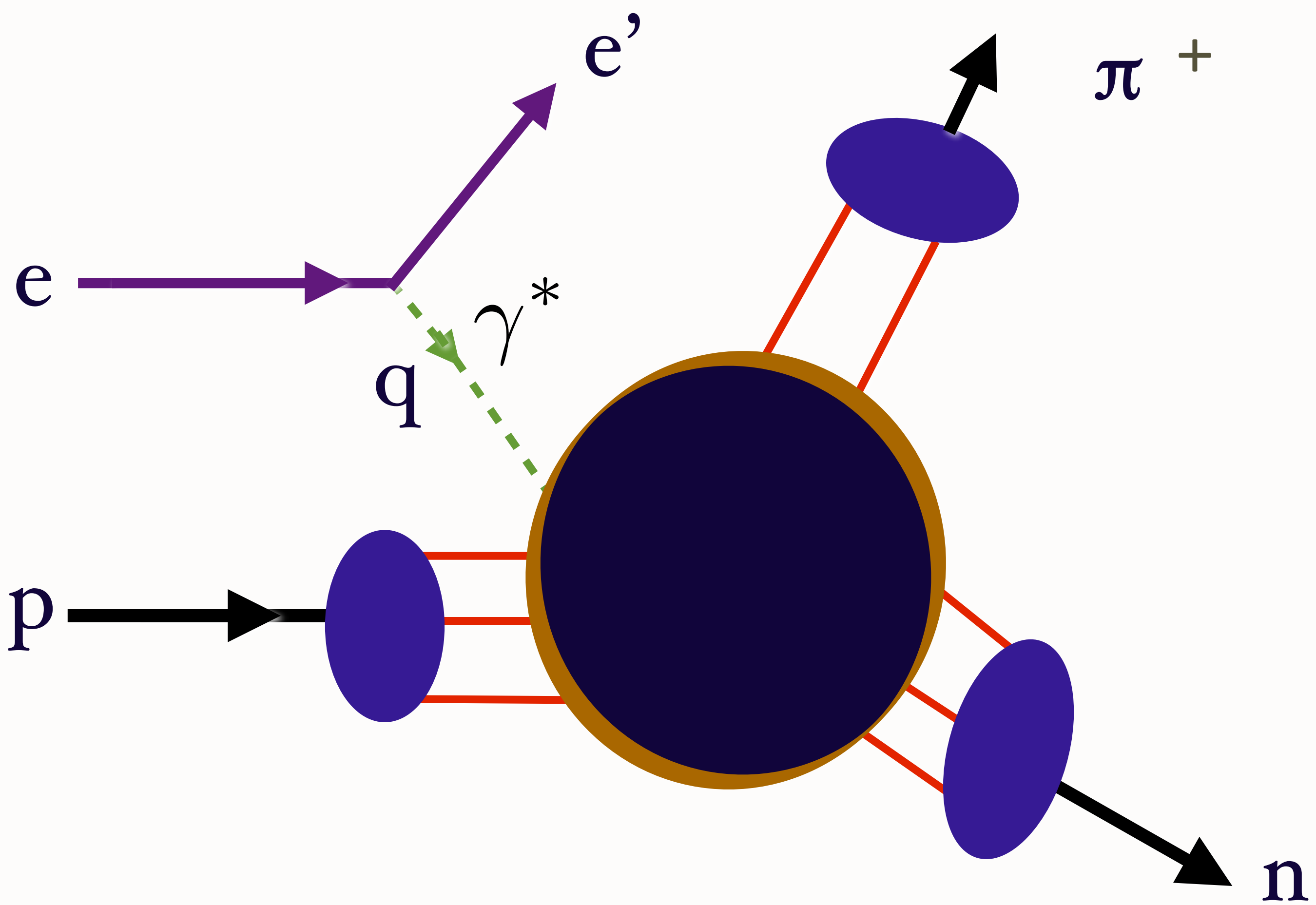
No ambiguity in D-term

Q^2-independent contribution to Real DVCS amplitude

$$s^2 \frac{d\sigma}{dt}(\gamma^* p \to \gamma p) = F^2(t)$$

Exclusive Electroproduction

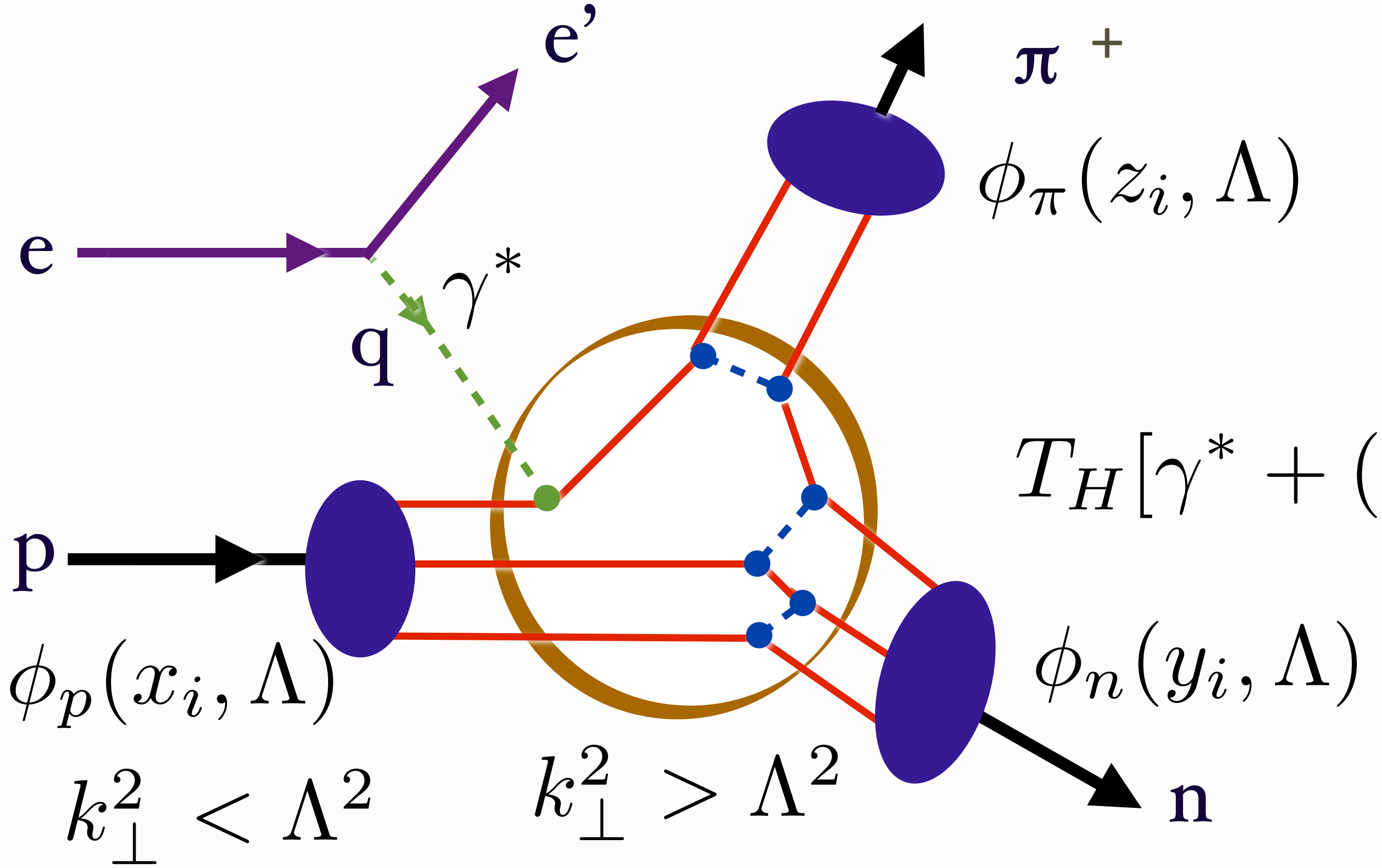
$$ep \rightarrow e'\pi^+ n$$



Iterate kernel of LFWF to expose hard-scattering amplitude

QCD Factorization
Exclusive Electroproduction

$$ep \to e'\pi^+ n$$



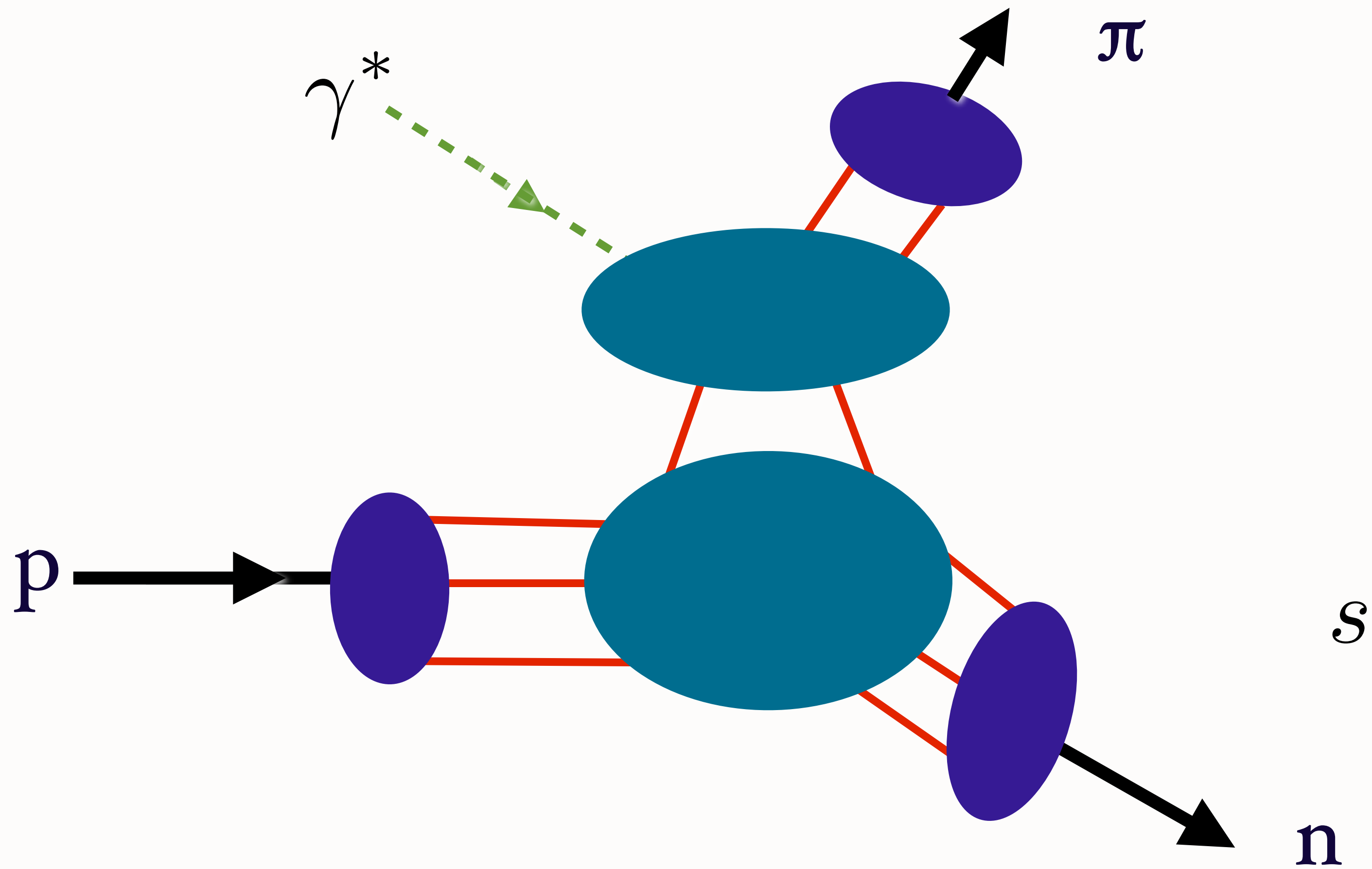
$$T = \int_0^1 dx \int_0^1 dy \int_0^1 dx\ \phi_p(x,\Lambda) T_H(x,y,z;Q^2,s,t;\Lambda)\phi_n(y,\Lambda)\phi_\pi^+(z,\Lambda)$$

$$\frac{d\sigma}{dt} \sim \frac{1}{s^7} \text{ at fixed } Q^2/s, t/s$$

Universal distribution amplitudes. Renormalization Group Invariance:
The factorization scale Λ is arbitrary. The renormalization scale is unambiguous

Exclusive Electroproduction

$$ep \to e'\pi^+ n$$



Hard Reggeon Domain

$$s >> -t, Q^2 >> \Lambda^2_{QCD}$$

$$T(\gamma^* p \to \pi^+ n) \sim \epsilon \cdot p_i \sum_R s_R^{\alpha}(t) \beta_R(t)$$

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

Reflects elementary exchange of quarks in t-channel

$$\beta_R(t) \sim \frac{1}{t^2}$$

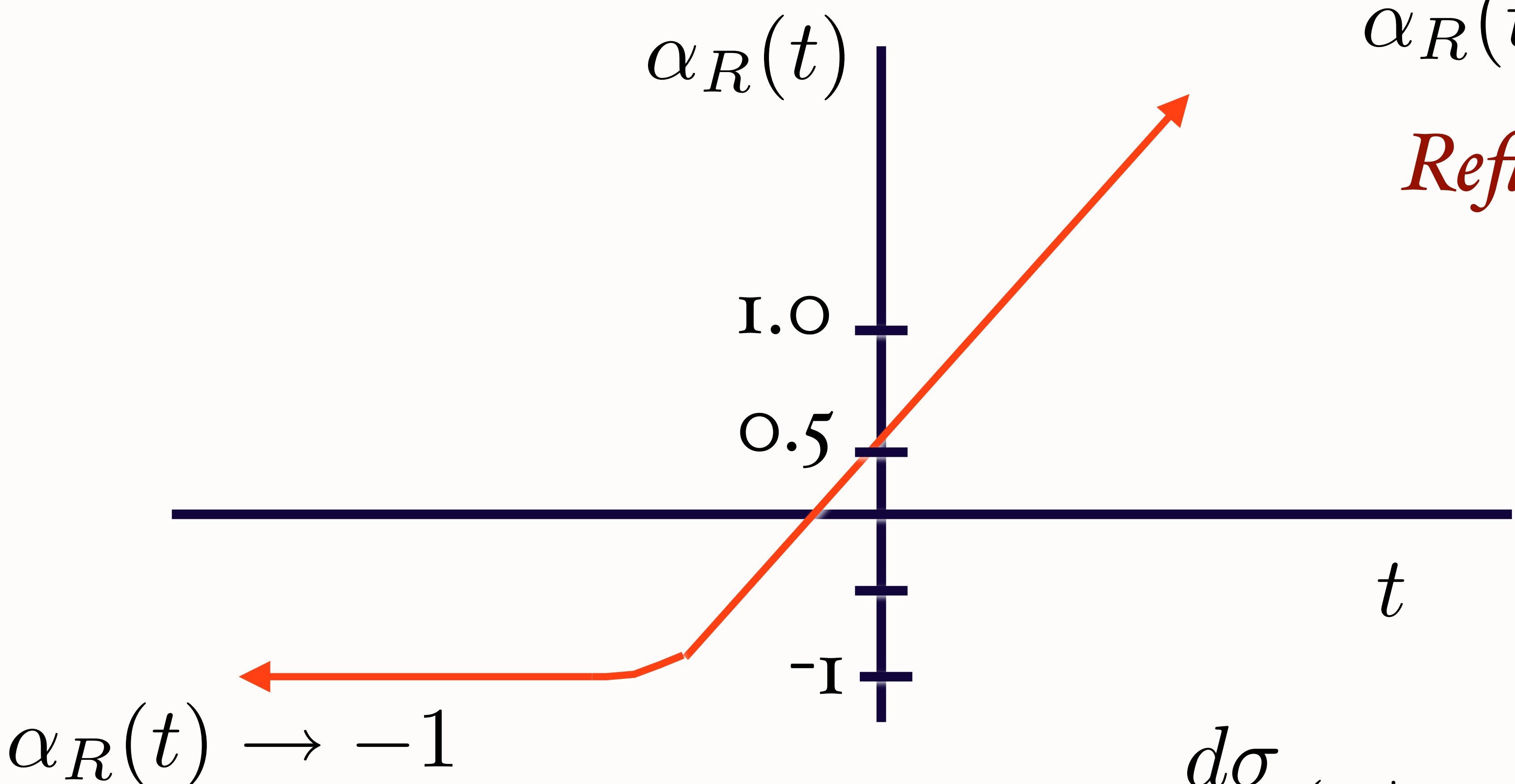
$\frac{d\sigma}{dt} \sim \frac{1}{s^7}$ at fixed $\frac{Q^2}{s}, \frac{t}{s}$

Regge domain

$$T(\gamma^* p \to \pi^+ n) \sim \epsilon \cdot p_i \sum_R s_R^{\alpha}(t) \beta_R(t) \qquad s >> -t, Q^2$$

$$\alpha_R(t) \to -1 \text{ at } t \to -\infty$$

Reflects elementary exchange of quarks in t-channel

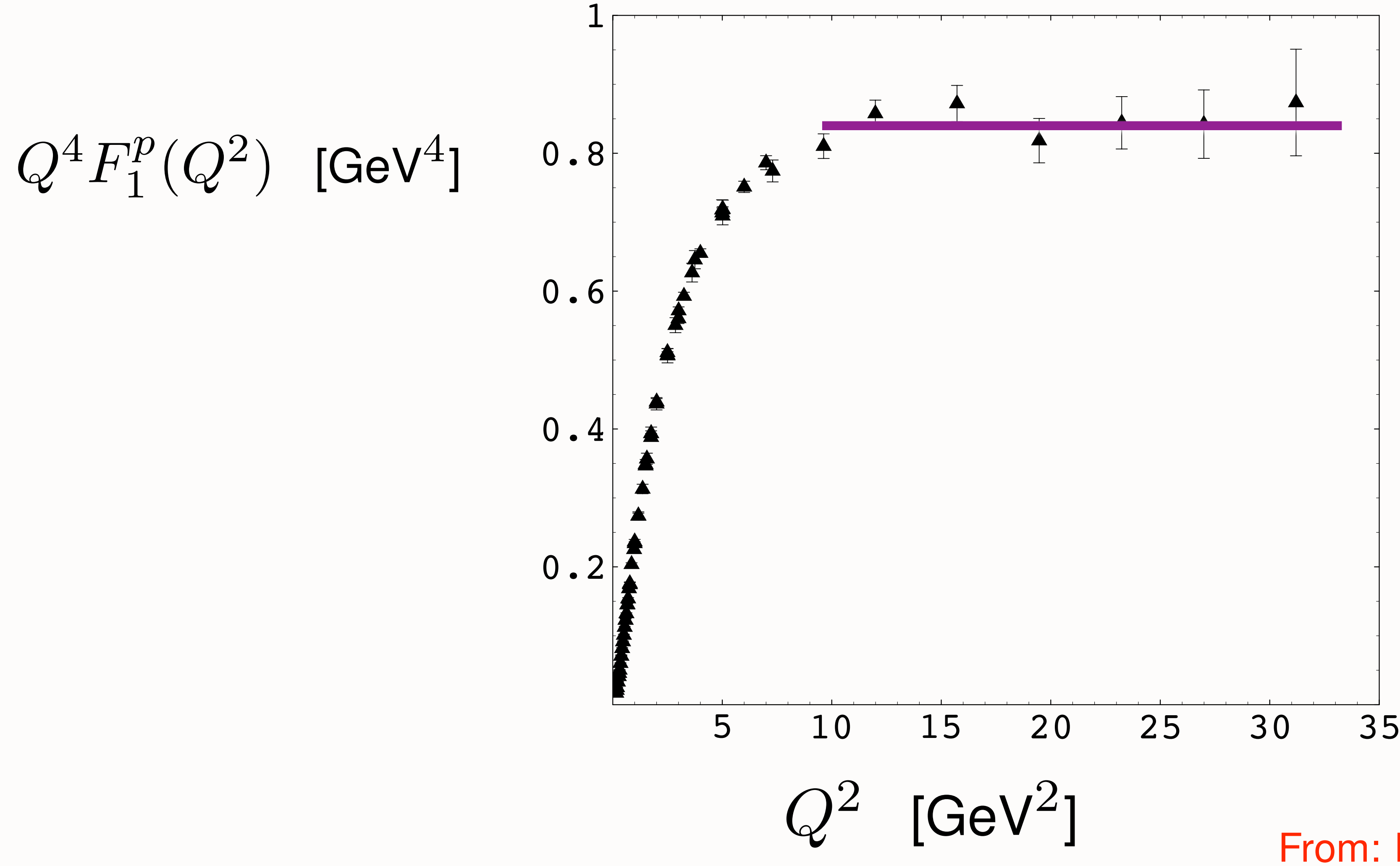


$$\beta_R(t) \sim \frac{1}{t^2}$$

$$\frac{d\sigma}{dt}(\gamma^* p \to \pi^+ n) \to \frac{1}{s^3} \beta_R^2(t)$$

$$\frac{d\sigma}{dt} \sim \frac{1}{s^3} \frac{1}{t^4} \sim \frac{1}{s^7} \text{ at fixed } \frac{Q^2}{s}, \frac{t}{s}$$

Fundamental test of QCD



$$F_1(Q^2) \sim \left[1/Q^2\right]^{n-1}, \quad n=3$$

From: M. Diehl *et al.* Eur. Phys. J. C **39**, 1 (2005).

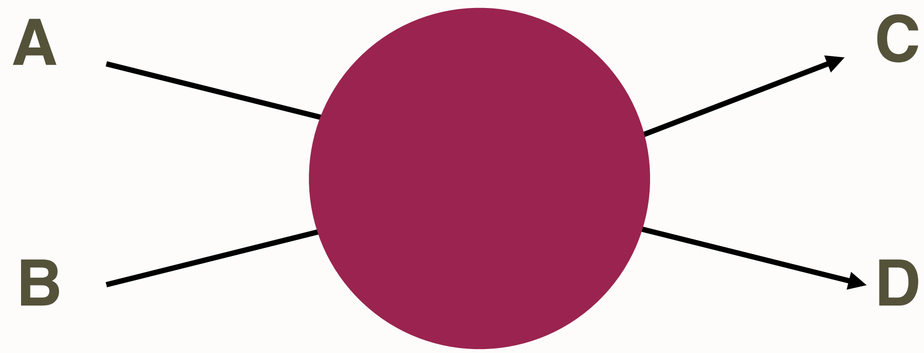
- Phenomenological success of dimensional scaling laws for exclusive processes

$$d\sigma/dt \sim 1/s^{n-2}, \quad n = n_A + n_B + n_C + n_D,$$

implies QCD is a strongly coupled conformal theory at moderate but not asymptotic energies
Farrar and sjb (1973); Matveev *et al.* (1973).

- Derivation of counting rules for gauge theories with mass gap dual to string theories in warped space (hard behavior instead of soft behavior characteristic of strings) Polchinski and Strassler (2001).

Proof from AdS/QCD: Polchinski and Strassler



$$\frac{d\sigma}{dt}(s,t) = \frac{F(\theta_{\rm cm})}{s^{[n_{\rm tot}-2]}} \qquad s = E^2_{\rm cm}$$

$$F_H(Q^2) \sim [\frac{1}{Q^2}]^{n_H - 1}$$

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

Fixed t/s or $\cos\theta_{cm}$

Farrar & sjb;
Matveev, Muradyan, Tavkhelidze

QCD predicts leading-twist scaling behavior of fixed-CM angle exclusive amplitudes

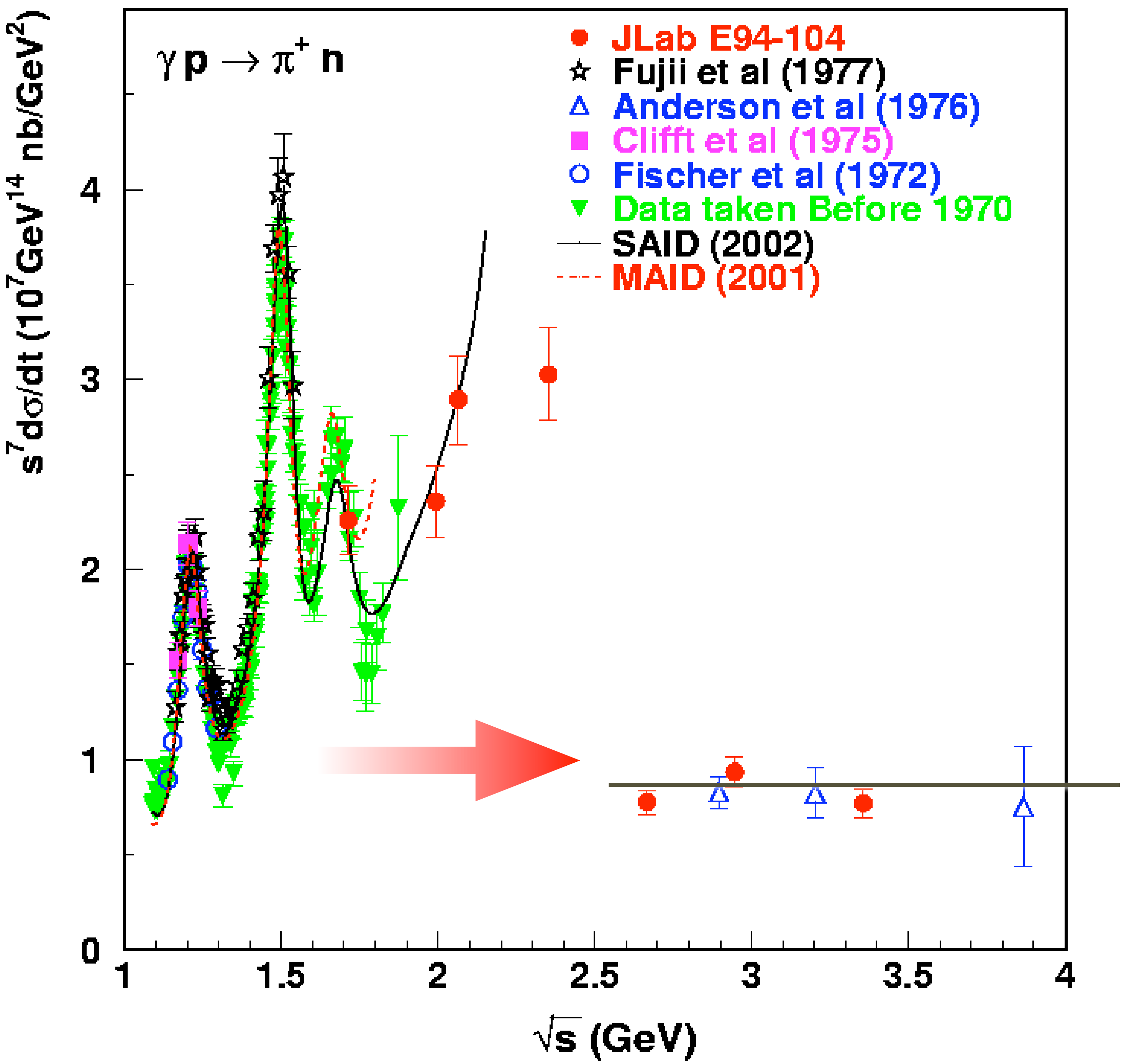
$$s, -t >> m^2_\ell$$

Extension to soft pions: Strikman, Pobylitsa, Polyakov $D : N + \pi$

Test of Scaling Laws

Constituent counting rules

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

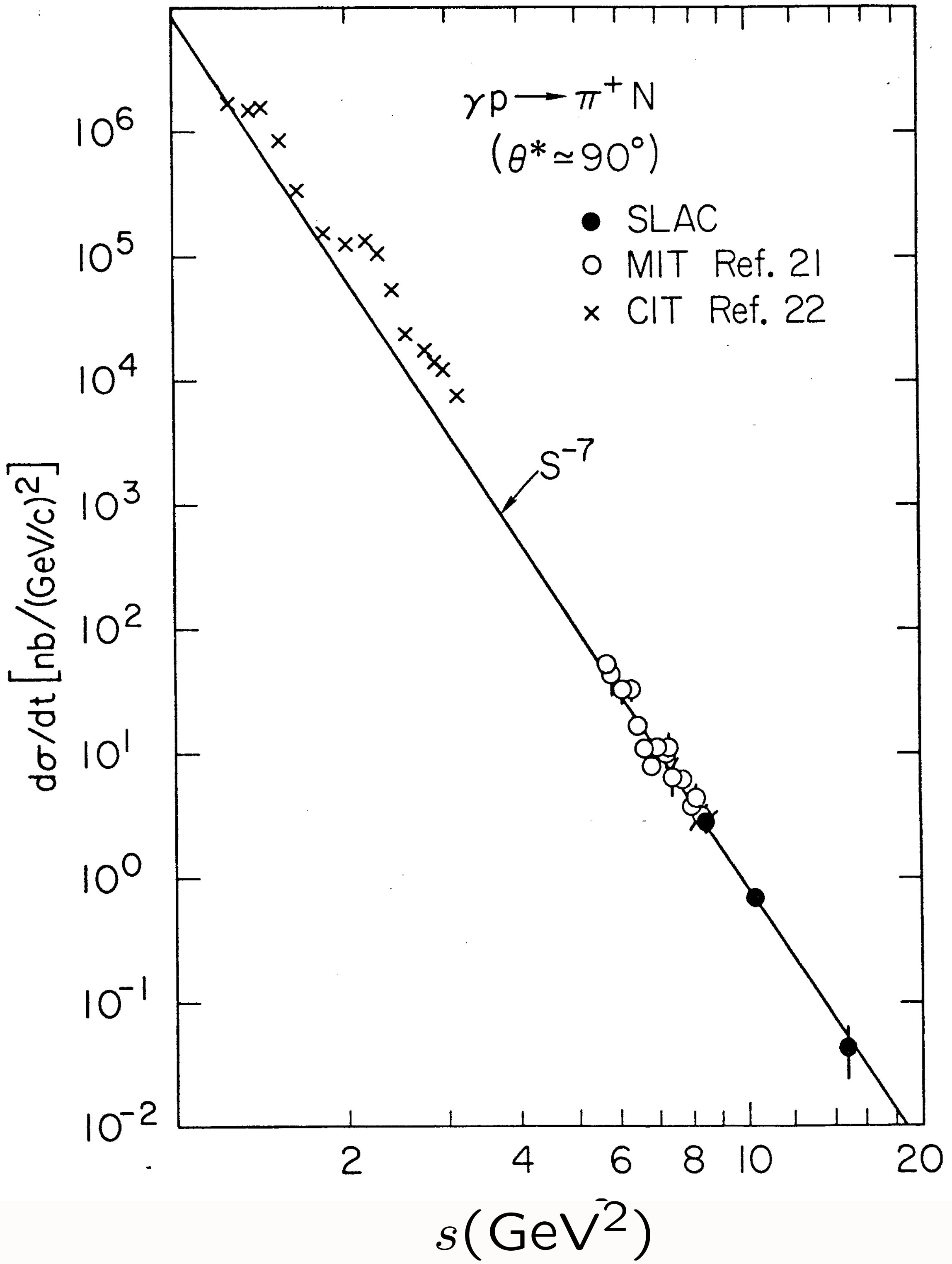


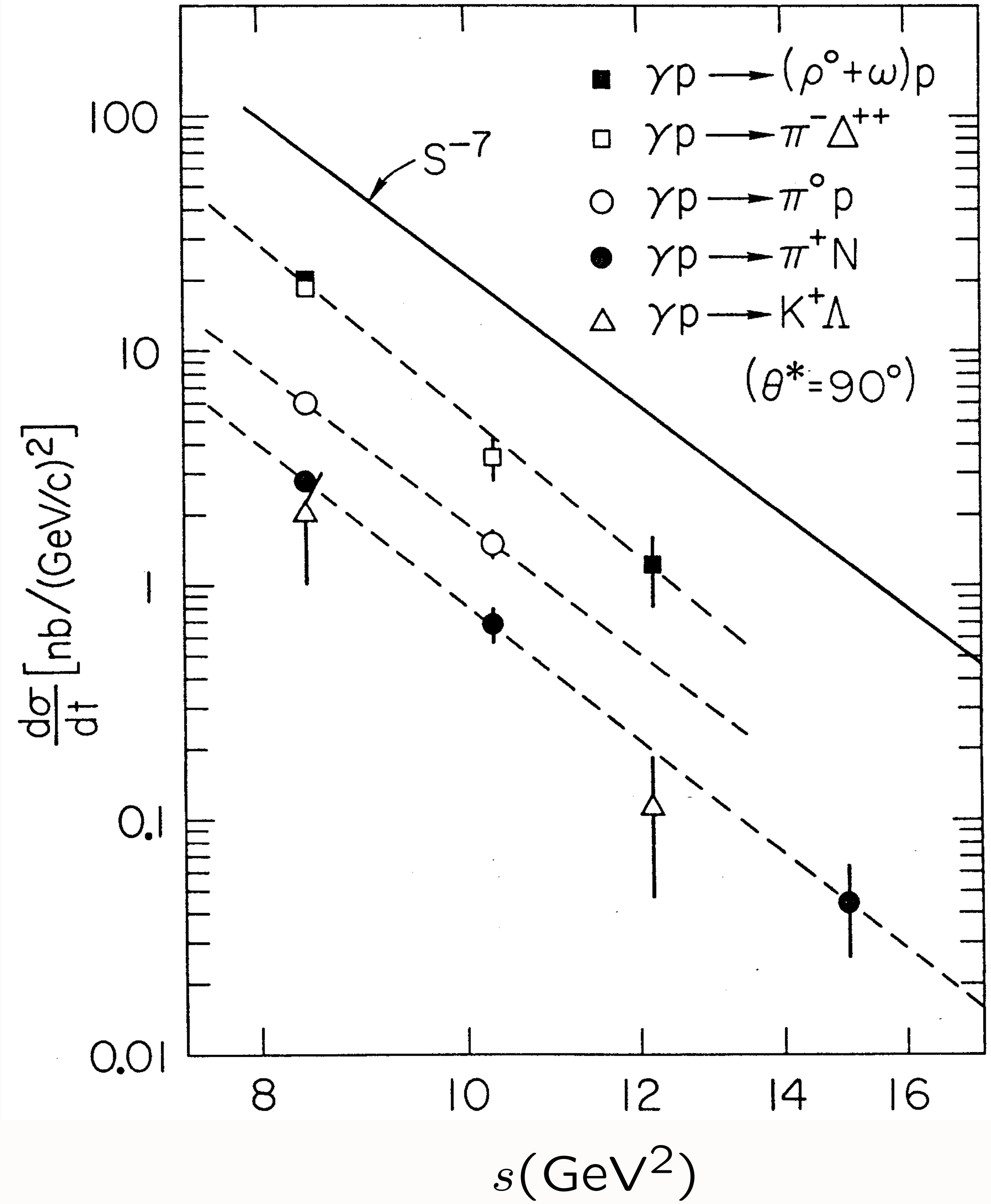
$$s^{n_{tot}-2}\frac{d\sigma}{dt}(A+B\to C+D) = F_{A+B\to C+D}(\theta_{CM})$$

$$s^7\frac{d\sigma}{dt}(\gamma p\to\pi^+ n) = F(\theta_{CM})$$
$$n_{tot} = 1+3+2+3 = 9$$

$s^7 d\sigma/dt(\gamma p\to\pi^+ n)\sim const$
$fixed\ \theta_{CM}$ scaling

Conformal invariance at high momentum transfers!





Counting Rules: n=9

$$\frac{d\sigma}{dt}(\gamma p \to MB) = \frac{F(\theta_{cm})}{s^7}$$

Compton Scattering Cross Section on the Proton at High Momentum Transfer

(The Jefferson Lab Hall A Collaboration)

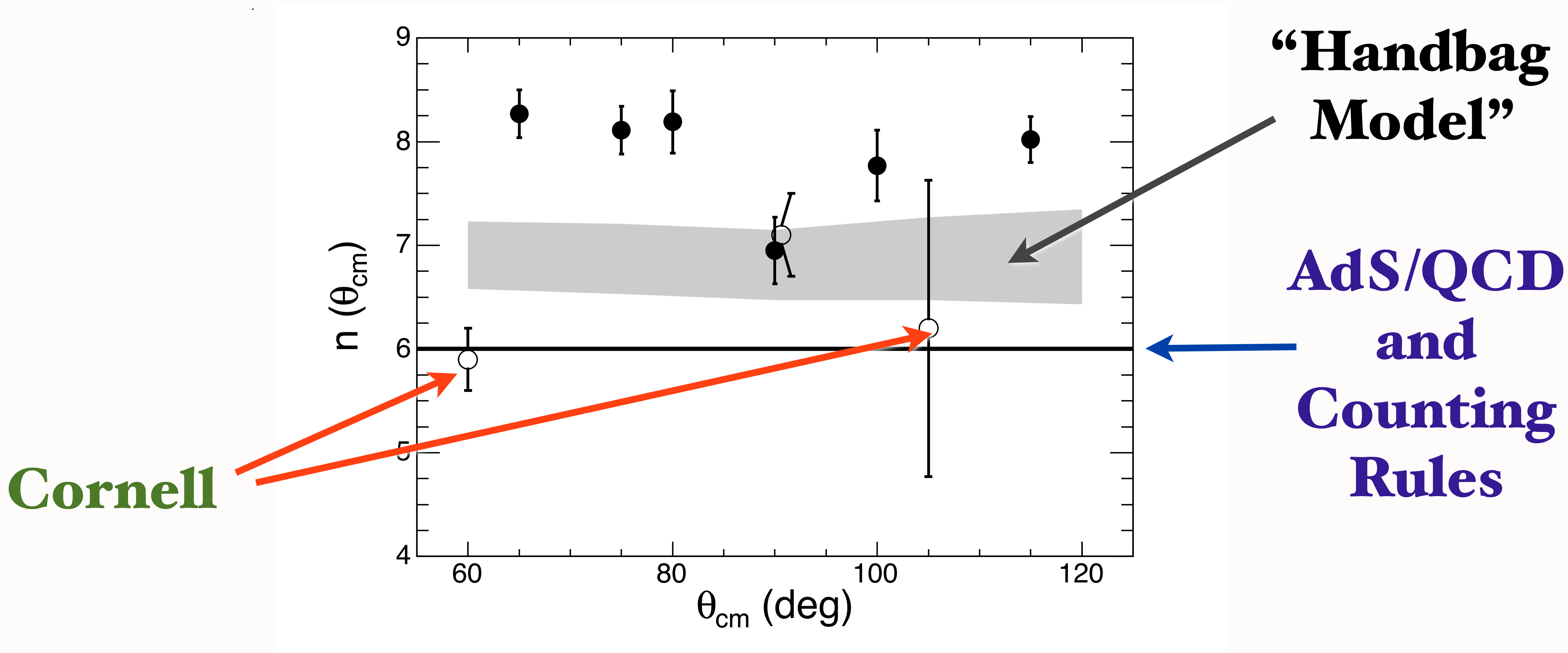
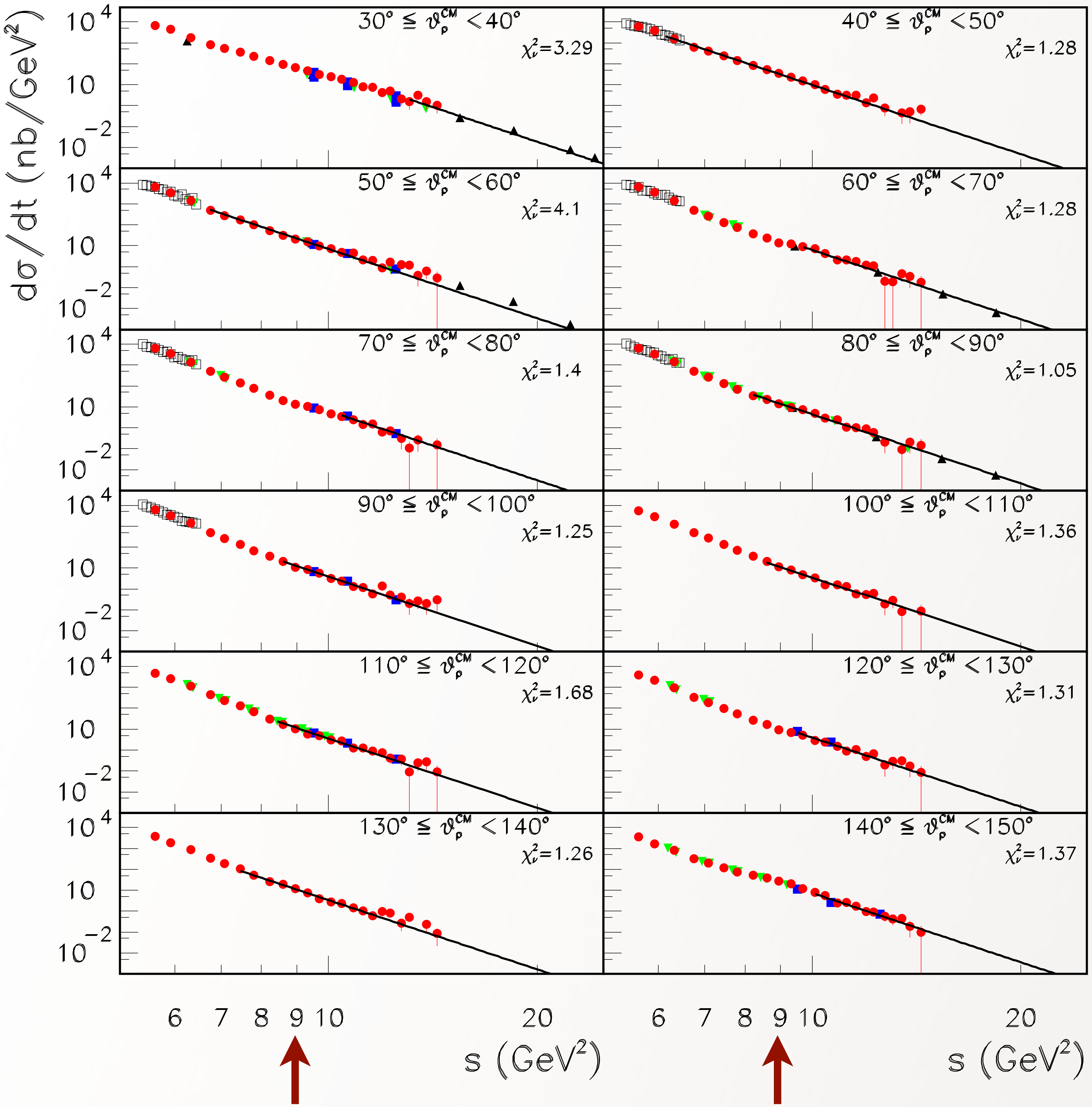


FIG. 5: Scaling of the RCS cross section at fixed θ_{cm}. Open points are results from Cornell experiment [1]. Closed points are results from the present experiment. The line at $n = 6$ is the prediction of asymptotic perturbative QCD, while the shaded area shows the fit range obtained from the cross sections of GPDs-based handbag calculation [8].

Deuteron Photodisintegration and Dimensional Counting

P.Rossi et al, P.R.L. 94, 012301 (2005)



PQCD and AdS/CFT:

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

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

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

$\gamma d\to (uuddd us\bar{s})\to np$

at $s\simeq 9$ GeV^2

$\gamma d\to (uuddd uc\bar{c})\to np$

at $s\simeq 25$ GeV^2

$\gamma d \rightarrow np$

$\gamma d \rightarrow (uuddd us\bar{s}) \rightarrow np$ at $s = 9$ GeV^2

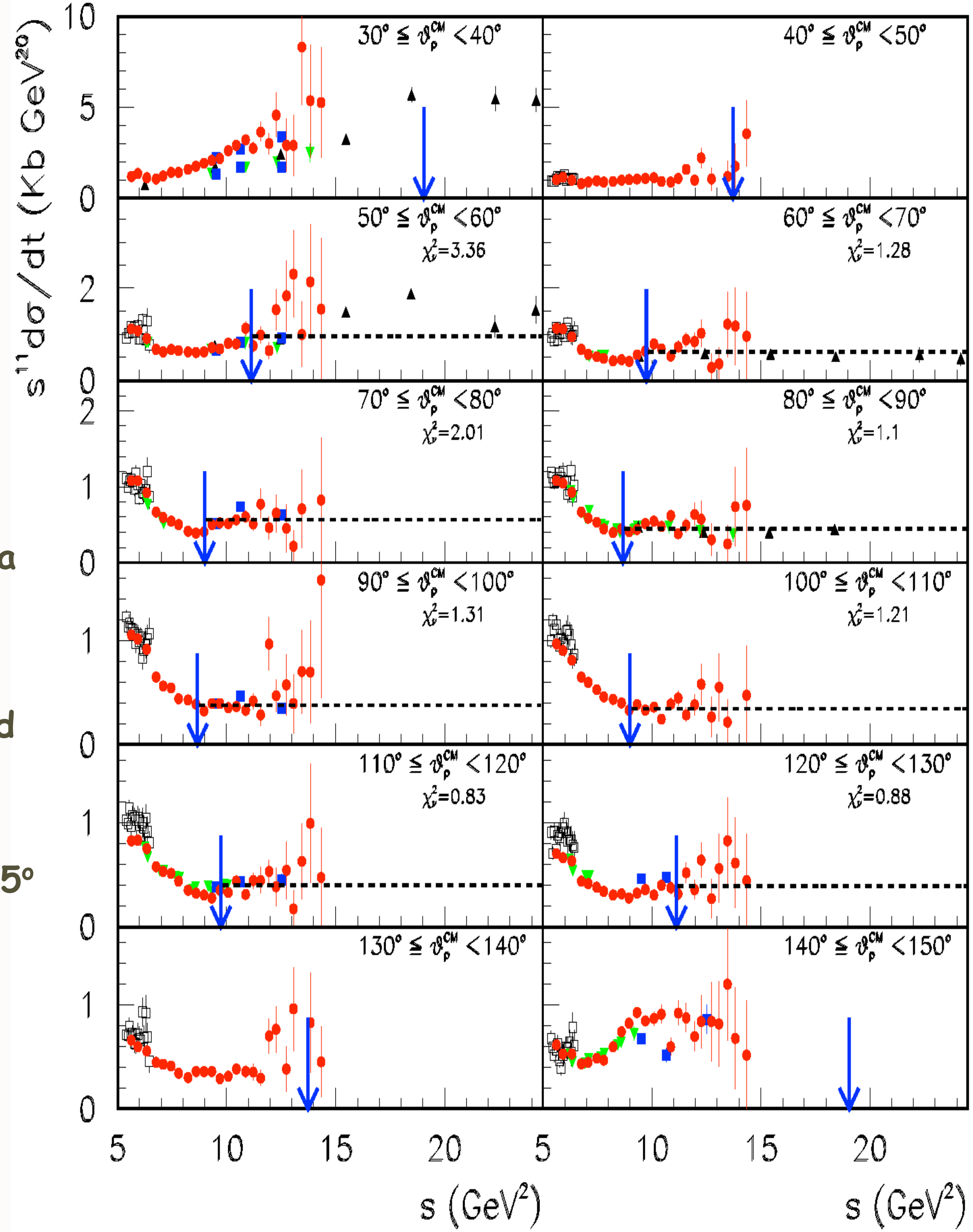
Fit of $d\sigma/dt$ data for the central angles and $P_T \geq 1.1$ GeV/c with $A\ s^{-11}$

For all but two of the fits $\chi^2 \leq 1.34$

- Better χ^2 at 55° and 75° if different data sets are renormalized to each other
- No data at $P_T \geq 1.1$ GeV/c at forward and backward angles
- Clear s^{-11} behaviour for last 3 points at 35°

Data consistent with CCR

P.Rossi et al, P.R.L. 94, 012301 (2005)



- Remarkable Test of Quark Counting Rules

- Deuteron Photo-Disintegration $\gamma d \to np$

$$\frac{d\sigma}{dt} = \frac{F(t/s)}{s^{n_{tot}-2}}$$

- $$n_{tot} = 1 + 6 + 3 + 3 = 13$$

Scaling characteristic of
scale-invariant theory at short distances

Conformal symmetry

Hidden color: $$\frac{d\sigma}{dt}(\gamma d \to \Delta^{++}\Delta^{-}) \simeq \frac{d\sigma}{dt}(\gamma d \to pn)$$

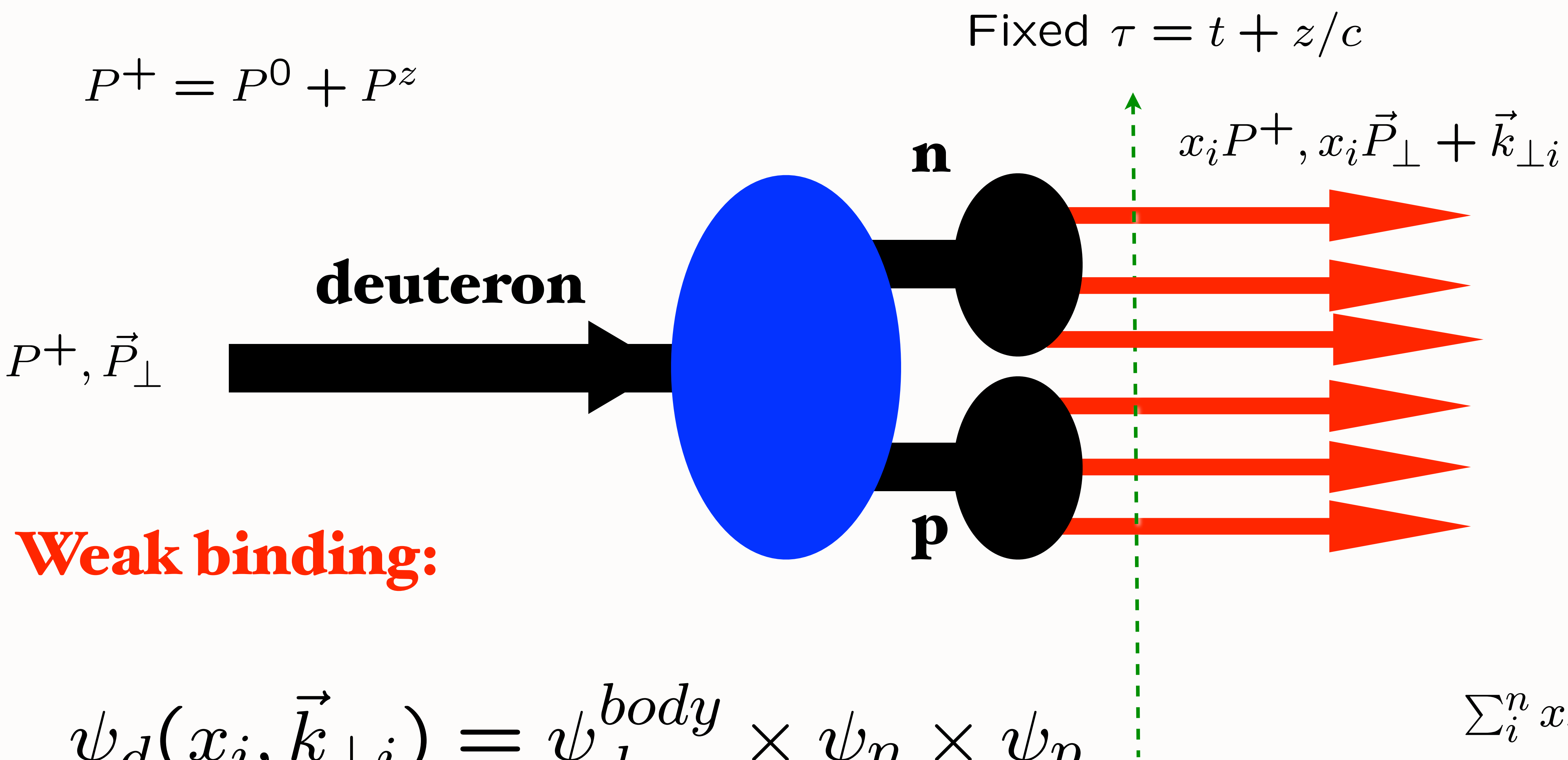
at high p_T

Ratio predicted to approach 2:5

Properties of Hard Exclusive Reactions

- Dimensional Counting Rules at fixed CM angle
- Hadron Helicity Conservation
- Color Transparency
- Hidden color
- $s \gg -t \gg \Lambda_{QCD}$: Reggeons have negative-integer intercepts at large $-t$
- J=0 Fixed pole in DVCS
- Quark interchange
- Renormalization group invariance
- No renormalization scale ambiguity
- Exclusive inclusive connection with spectator counting rules
- Diffractive reactions from pomeron, Reggeon, odderon

Deuteron Light-Front Wavefunction



Weak binding:

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

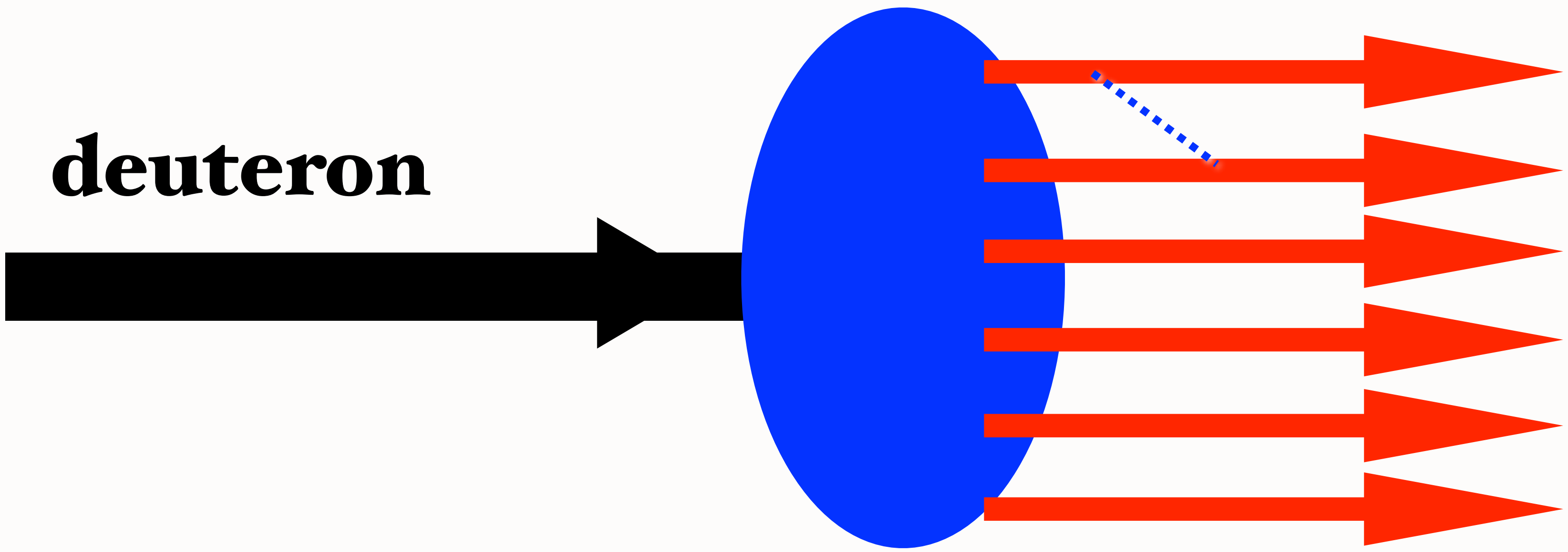
$\sum_i^n x_i = 1$

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

Two color-singlet combinations of three 3_C

Evolution of 5 color-singlet Fock states

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



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

$$\sum_i^n x_i = 1$$

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

5 X 5 Matrix Evolution Equation for deuteron distribution amplitude

Hidden Color in QCD

Lepage, Ji, sjb

- Deuteron six-quark wavefunction
- 5 color-singlet combinations of 6 color-triplets -- only one state is |n p>
- Components evolve towards equality at short distances
- Hidden color states dominate deuteron form factor and photodisintegration at high momentum transfer
- Predict

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

Hidden Color of Deuteron

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

Asymptotic Solution has Expansion

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

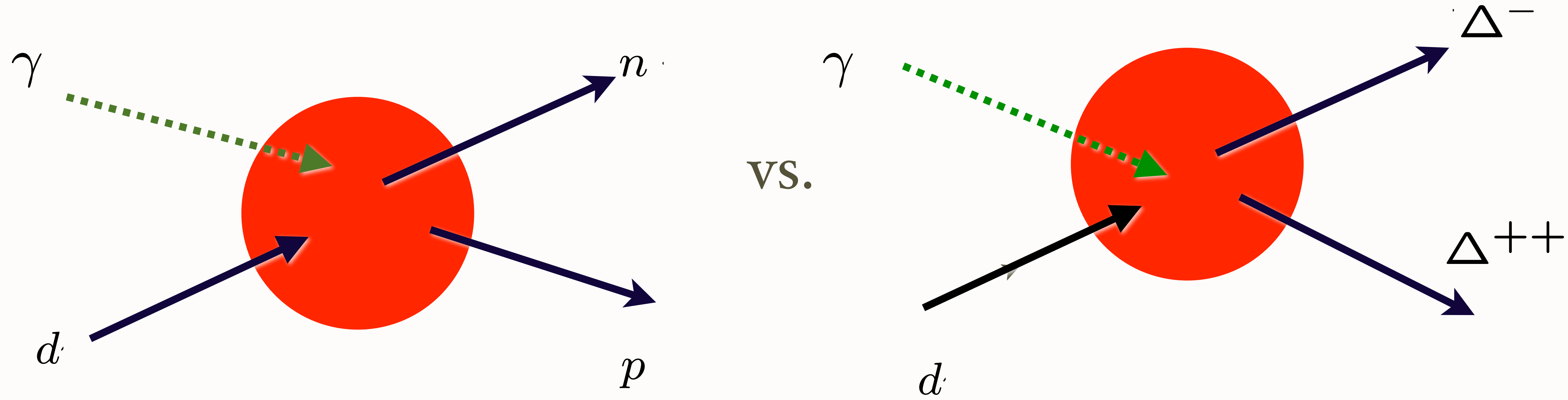
Look for strong transition to Delta-Delta

Test of Hidden Color in Deuteron Photodisintegration

$$R = \frac{\frac{d\sigma}{dt}(\gamma d \to \Delta^{++}\Delta^{--})}{\frac{d\sigma}{dt}(\gamma d \to pn)}$$

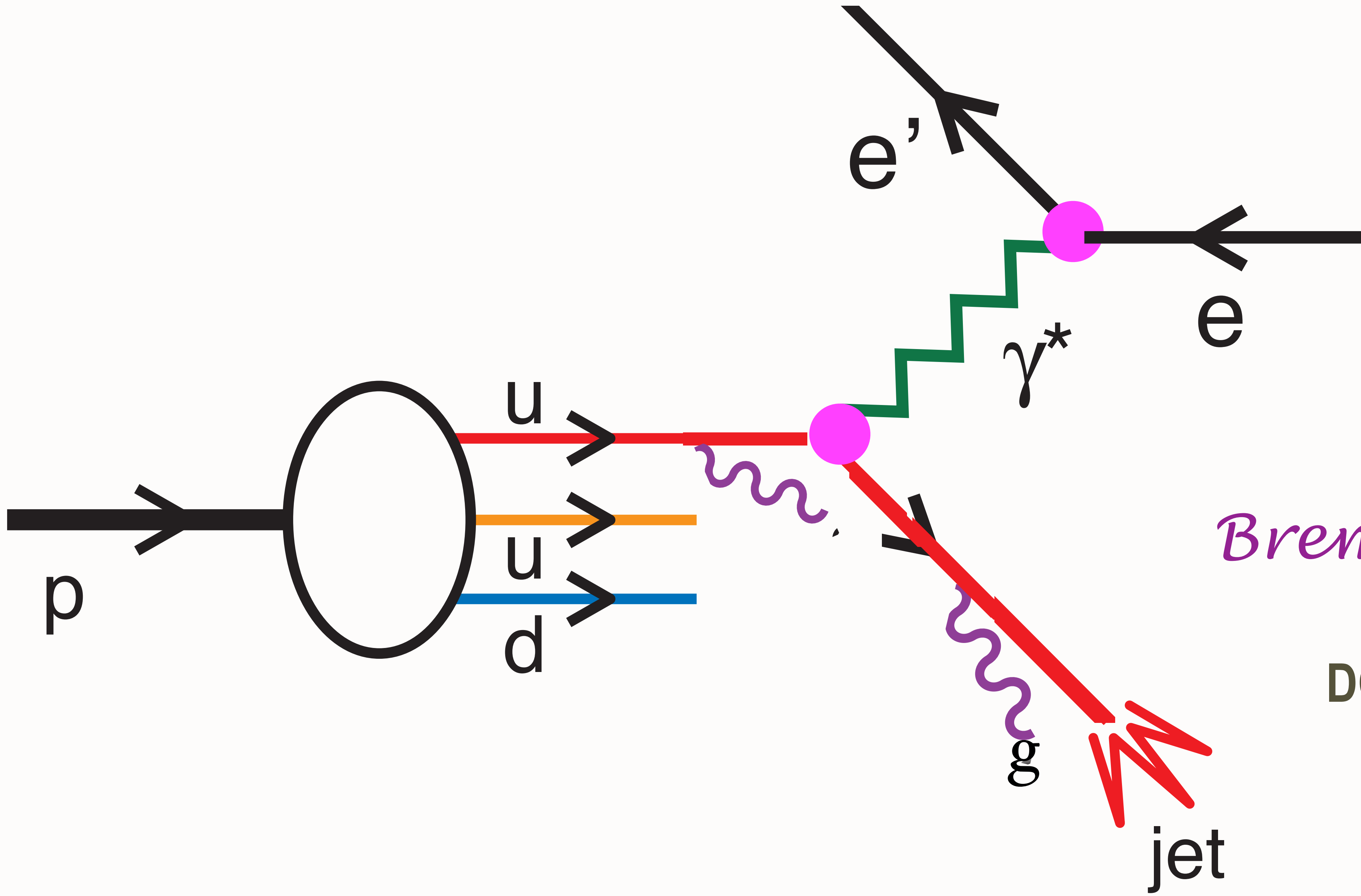
Ratio predicted to approach 2:5

Ratio should grow with transverse momentum as the hidden color component of the deuteron grows in strength.



Possible contribution from pion charge exchange at small t.

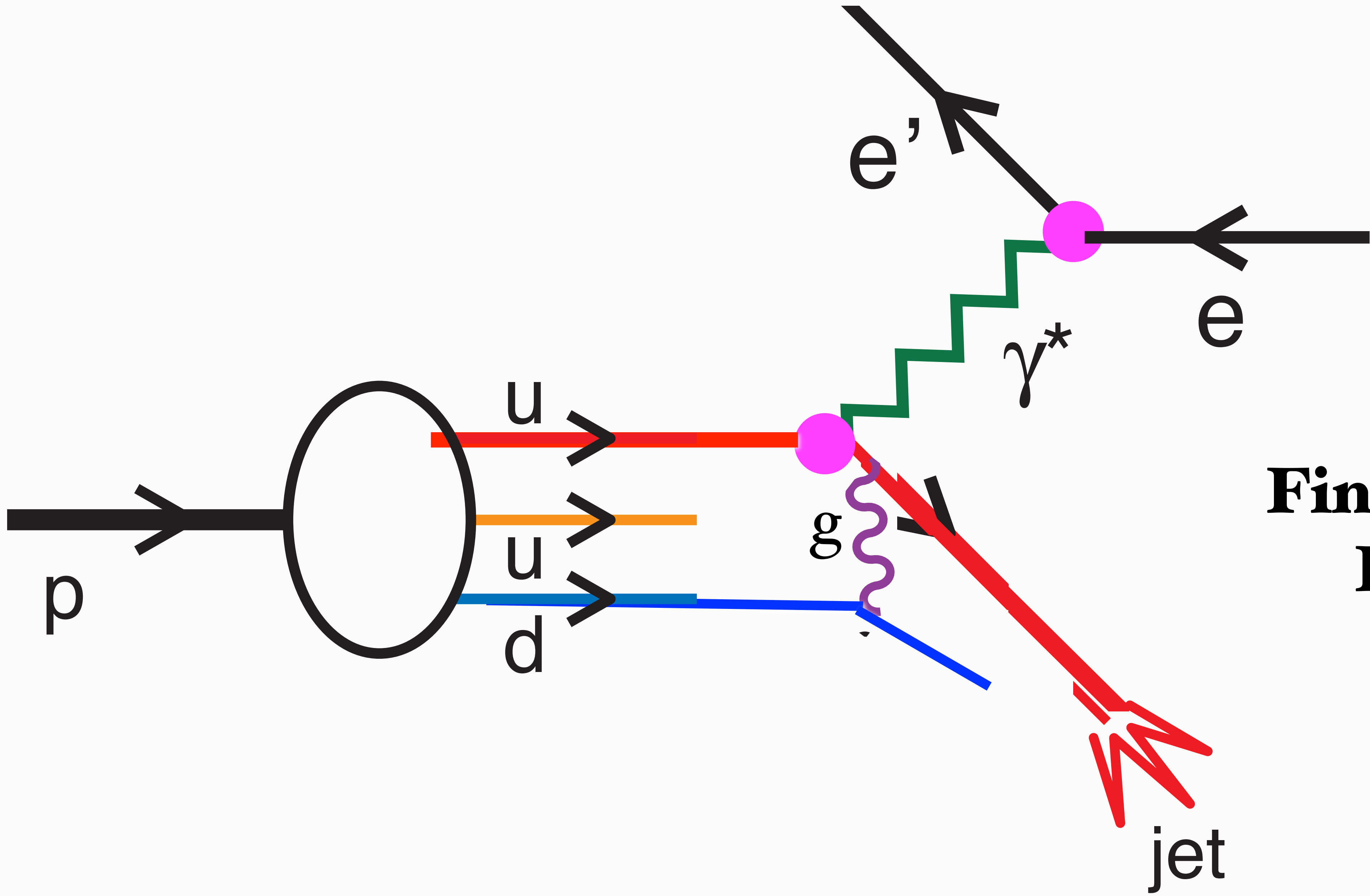
Deep Inelastic Electron-Proton Scattering



Gluonic Bremmstrahlung

DGLAP Evolution

Deep Inelastic Electron-Proton Scattering



Final-State QCD Interaction

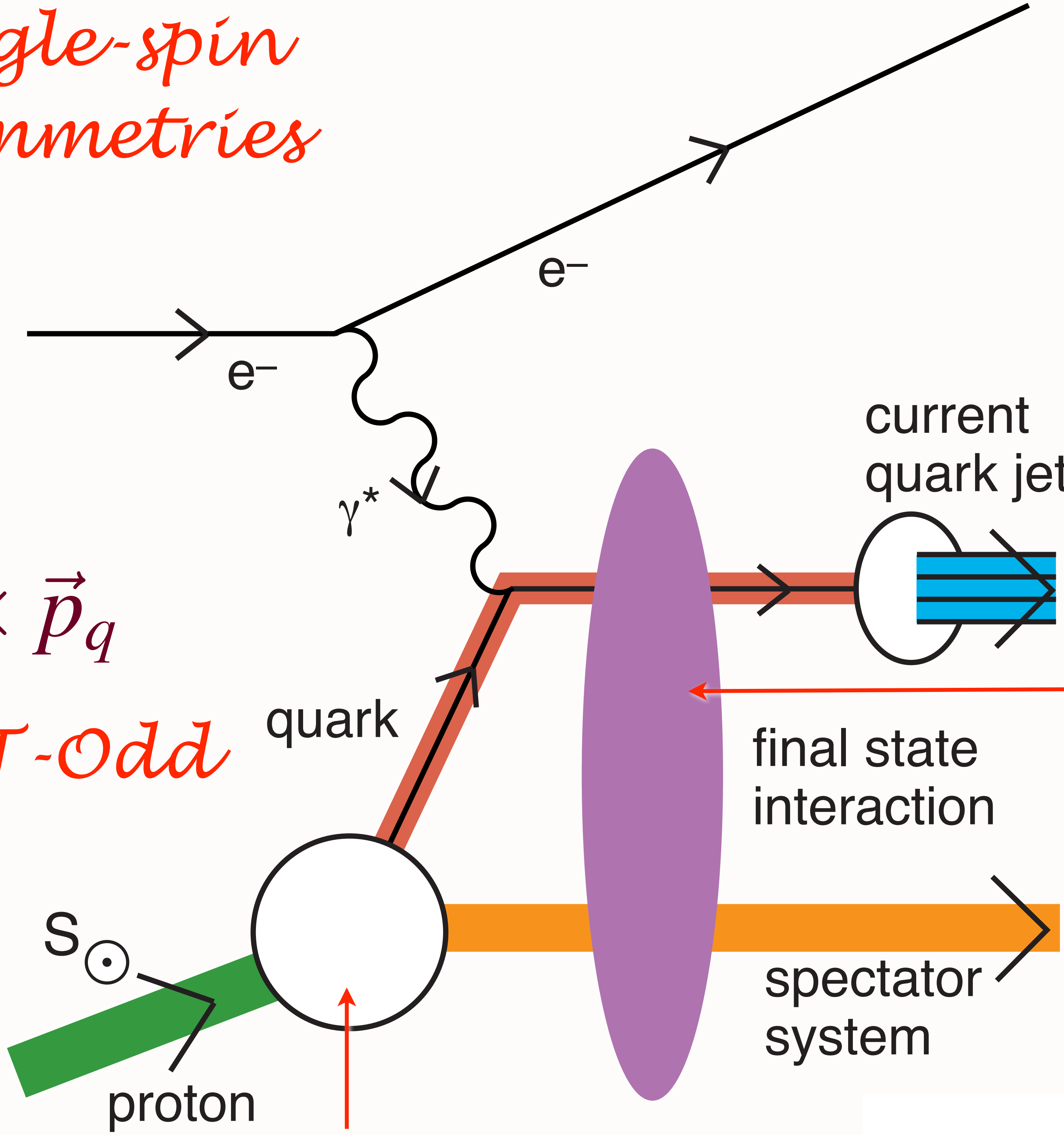
Conventional wisdom:

Final-state interactions of struck quark can be neglected

Single-spin asymmetries

Leading Twist Sivers Effect

Dae Sung Hwang, Ivan Schmidt, sjb



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

Pseudo- T-Odd

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

Light-Front Wavefunction S and P- Waves

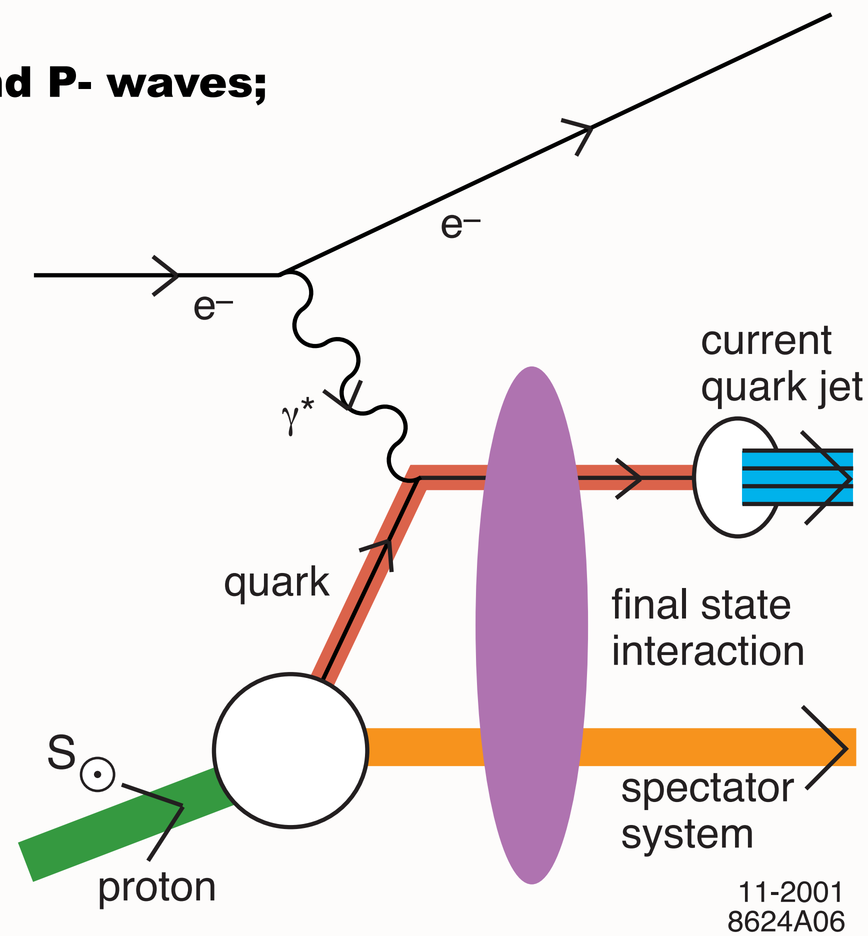
Leading-Twist Rescattering Violates pQCD Factorization!

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

Hwang, Schmidt, sjb
Collins

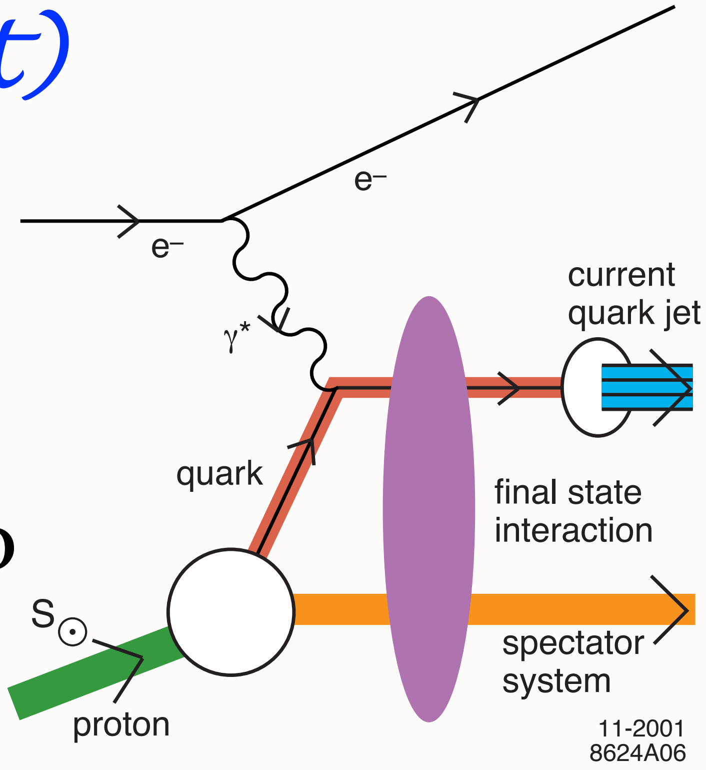
$$\mathbf{i}\ \vec{S} \cdot \vec{p}_{jet} \times \vec{q}$$

- **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 -- gauge independent**
- **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**



Pasquini, Xiao, Yuan, sjb
Mulders, Boer Qiu, Sterman

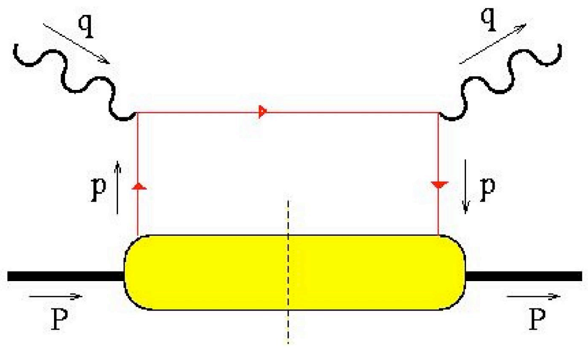
Final State Interactions Produce T-Odd (Sivers Effect)



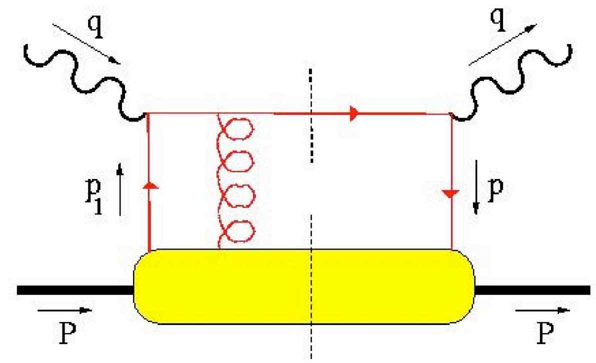
- Bjorken Scaling!
- Arises from Interference of Final-State Coulomb Phases in S and P waves
- Relate to the quark contribution to the target proton anomalous magnetic moment
- Sum of Sivers Functions for all quarks and gluons vanishes. (Zero anomalous gavitomagnetic moment)

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

Hwang, Schmidt. sjb



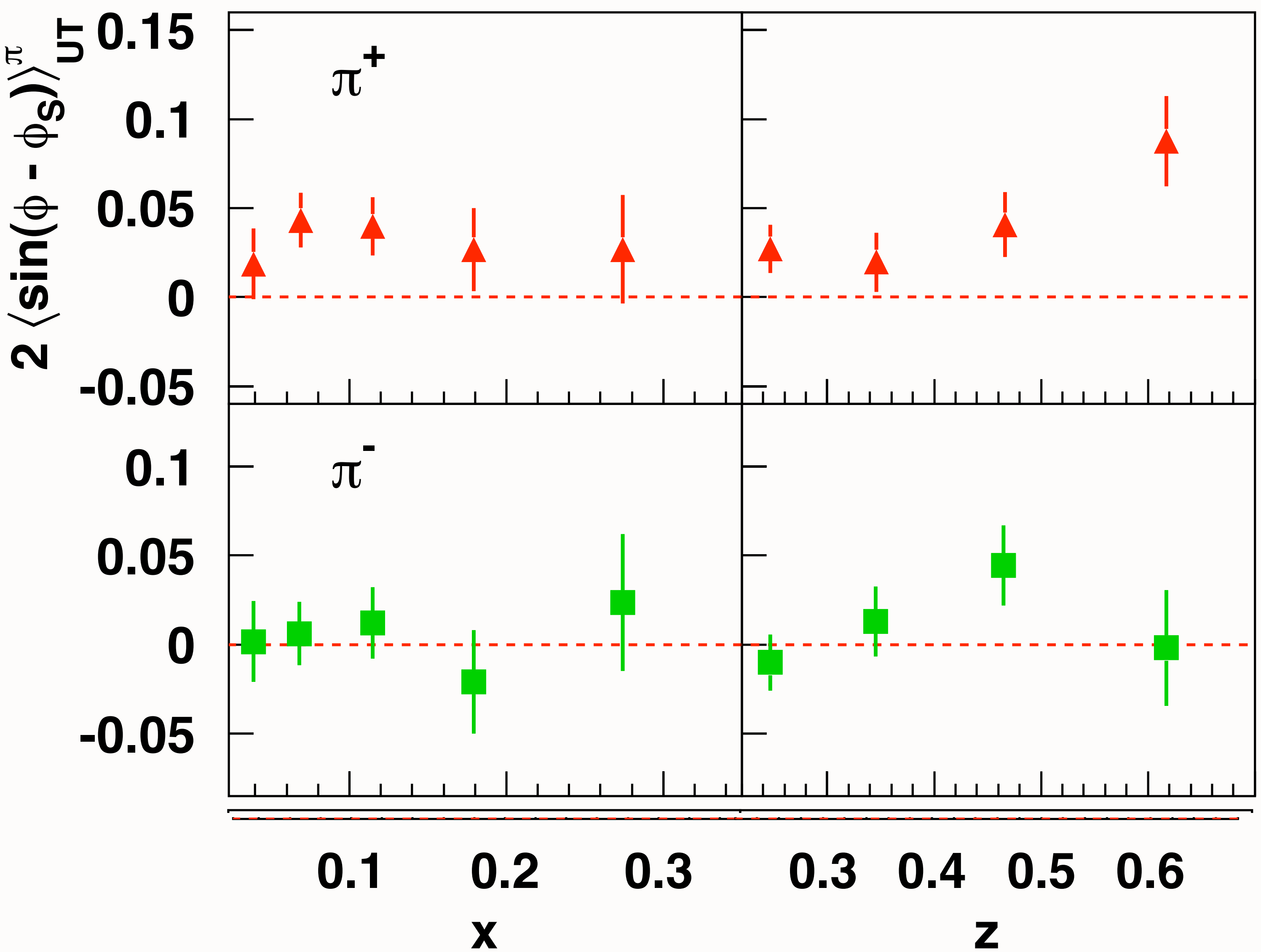
can interfere with



and produce a T-odd effect! (also need $L_z \neq 0$)

HERMES coll., A. Airapetian et al., Phys. Rev. Lett. 94 (2005) 012002.

Sivers asymmetry from HERMES



- First evidence for non-zero Sivers function!
- ⇒ presence of non-zero **quark orbital angular momentum**!
- Positive for **π⁺**...
  Consistent with zero for **π⁻**...

Gamberg: Hermes data compatible with BHS model

Schmidt, Lu:
Asymmetry ratios should follow quark contributions to anomalous moment

PHYSICAL REVIEW D **75,** 073008 (2007)

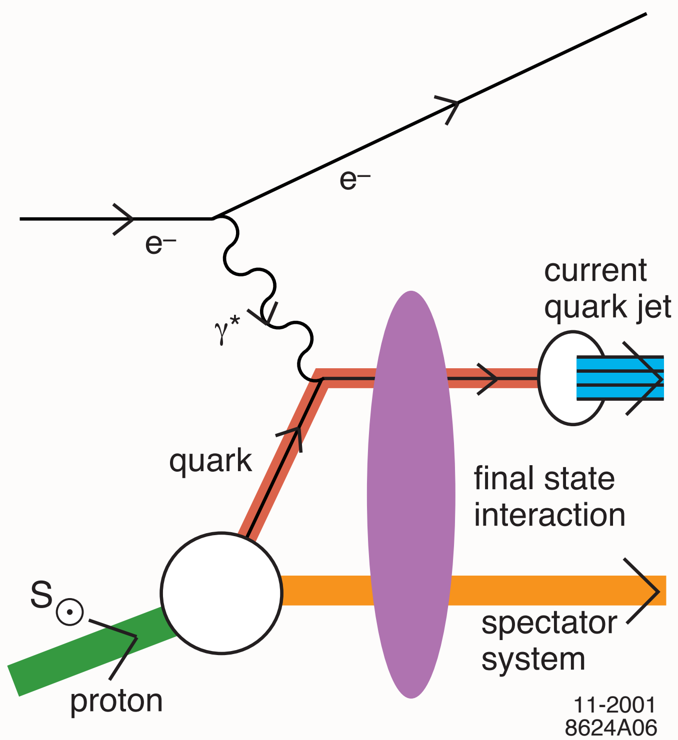
Connection between the Sivers function and the anomalous magnetic moment

Zhun Lu* and Ivan Schmidt†

Departamento de Física, Universidad Técnica Federico, Santa María, Casilla 110-V, Valparaíso, Chile
and Center of Subatomic Physics, Valparaíso, Chile

(Received 8 January 2007; revised manuscript received 14 February 2007; published 9 April 2007)

The same light-front wave functions of the proton are involved in both the anomalous magnetic moment of the nucleon and the Sivers function. Using the diquark model, we derive a simple relation between the anomalous magnetic moment and the Sivers function, which should hold in general with good approximation. This relation can be used to provide constraints on the Sivers single spin asymmetries from the data on anomalous magnetic moments. Moreover, the relation can be viewed as a direct connection between the quark orbital angular momentum and the Sivers function.



$$\kappa_p = (2)(2/3)\kappa_{u/p} + (-1/3)\kappa_{d/p},$$

$$\kappa_n = (2)(-1/3)\kappa_{u/p} + (2/3)\kappa_{d/p}.$$

$$\frac{A_{UT}^{\text{Siv}}(\pi^+)}{A_{UT}^{\text{Siv}}(\pi^-)} \approx \frac{2e_u^2 f_{1T}^{\perp u} D_1^{\pi^+/u}}{e_d^2 f_{1T}^{\perp d} D_1^{\pi^-/d}} \approx \frac{2e_u^2 \kappa_u}{e_d^2 \kappa_d} = -3.3.$$

$$\frac{A_{UT}^{\text{Siv}}(\pi^0)}{A_{UT}^{\text{Siv}}(\pi^-)} \approx \frac{2e_u^2 f_{1T}^{\perp u} D_1^{\pi^0/u} + e_d^2 f_{1T}^{\perp d} D_1^{\pi^0/d}}{e_d^2 f_{1T}^{\perp d} D_1^{\pi^-/d}} \approx \frac{2e_u^2 \kappa_u + e_d^2 \kappa_d}{2e_d^2 \kappa_d} = -1.15,$$

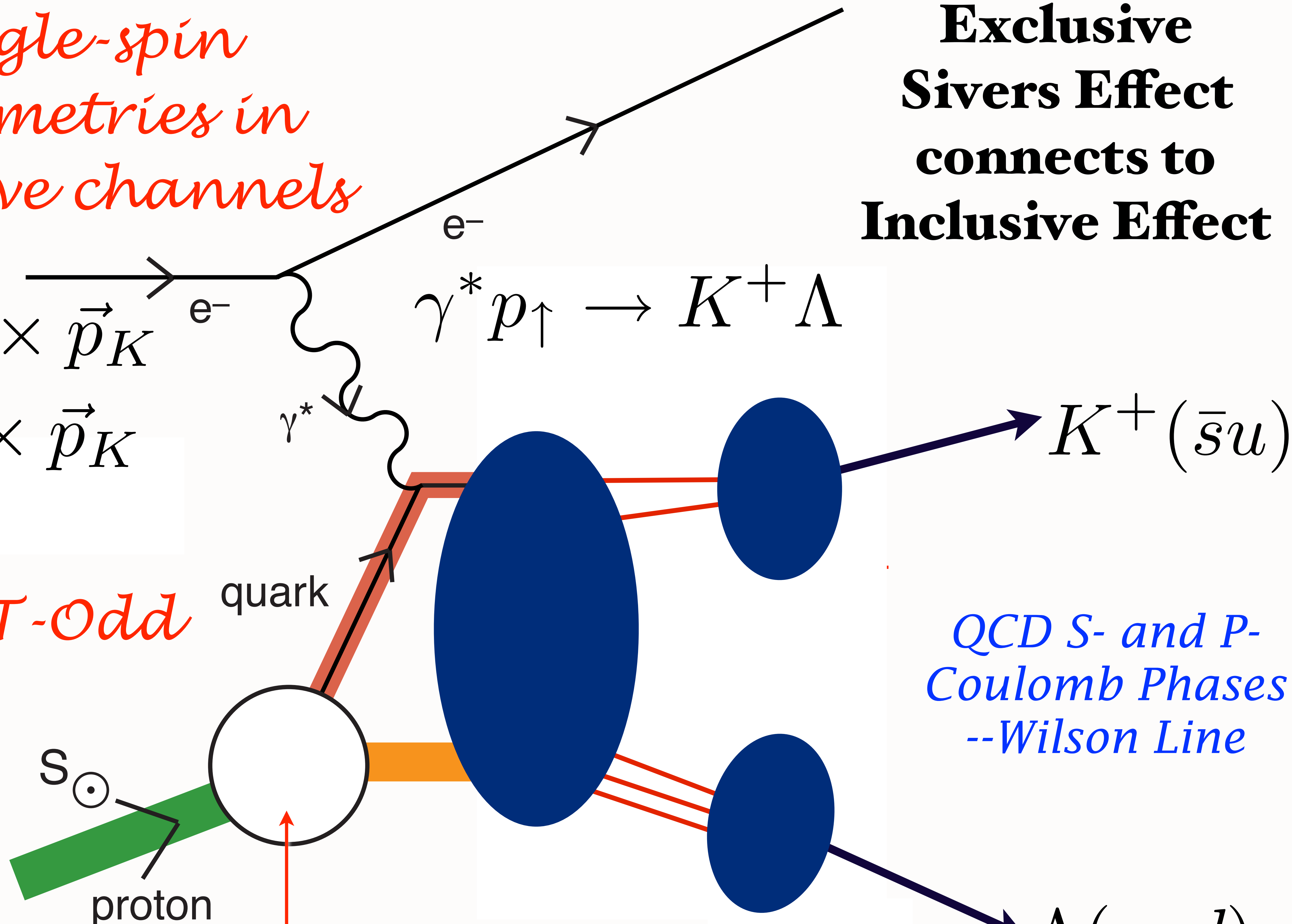
$$\frac{A_{UT}^{\text{Siv}}(K^+)}{A_{UT}^{\text{Siv}}(K^0)} \approx \frac{2e_u^2 f_{1T}^{\perp u} D_1^{K^+/u}}{e_d^2 f_{1T}^{\perp d} D_1^{K^0/d}} \approx \frac{4e_u^2 \kappa_u}{e_d^2 \kappa_d} = -6.6.$$

Single-spin asymmetries in exclusive channels

Exclusive Sivers Effect connects to Inclusive Effect

$$i\vec{S}_\Lambda \cdot \vec{q} \times \vec{p}_K$$
$$i\vec{S}_p \cdot \vec{q} \times \vec{p}_K$$

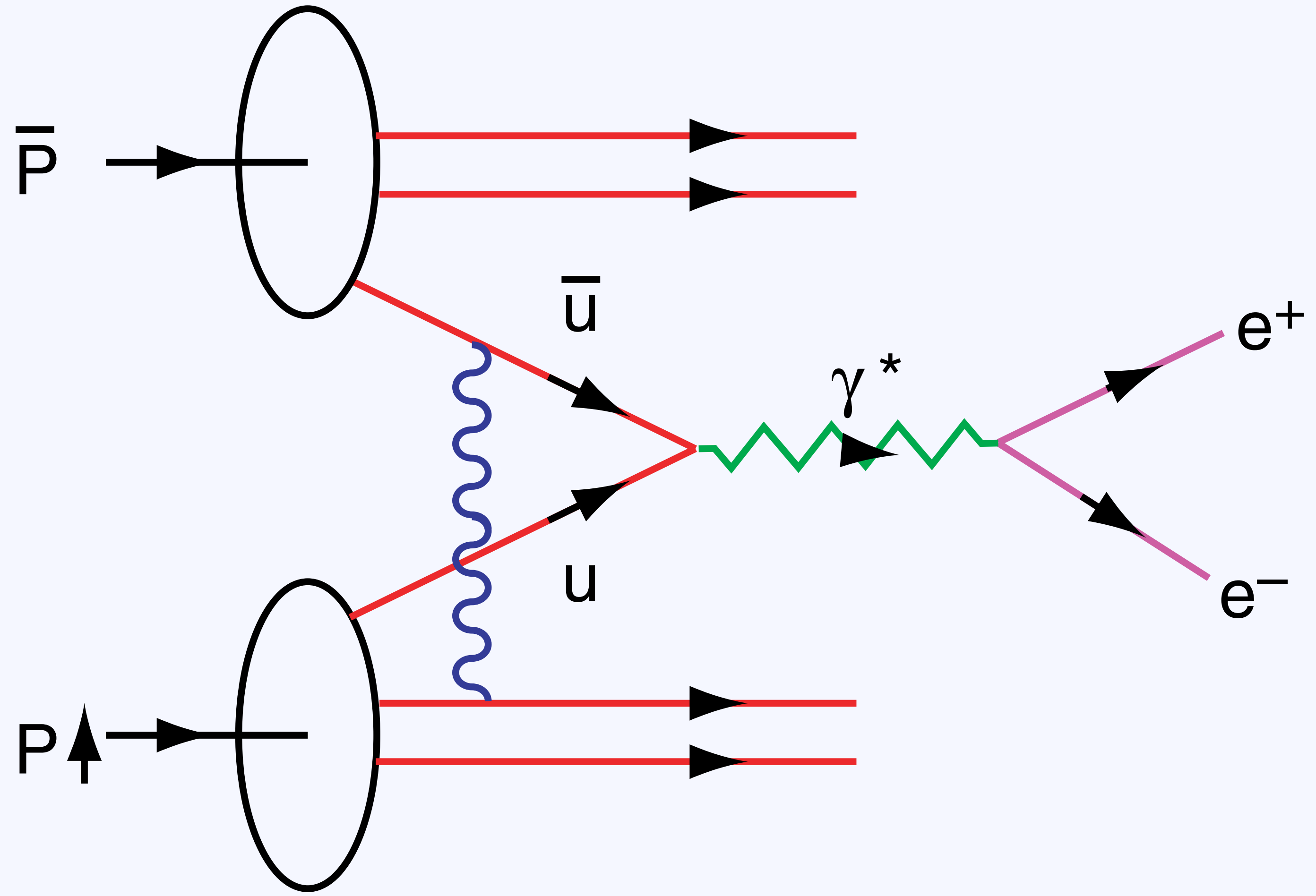
Pseudo- T-Odd



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

Light-Front Wavefunction S and P- Waves

Predict Opposite Sign SSA in DY !



Collins

Hwang
Schmidt
sjb

Single Spin Asymmetry In the Drell Yan Process

$\vec{S}_p \cdot \vec{\overline{p}} \times \vec{q}_{\gamma^*}$

Quarks Interact in the Initial State

Interference of Coulomb Phases for *S* and *P* states

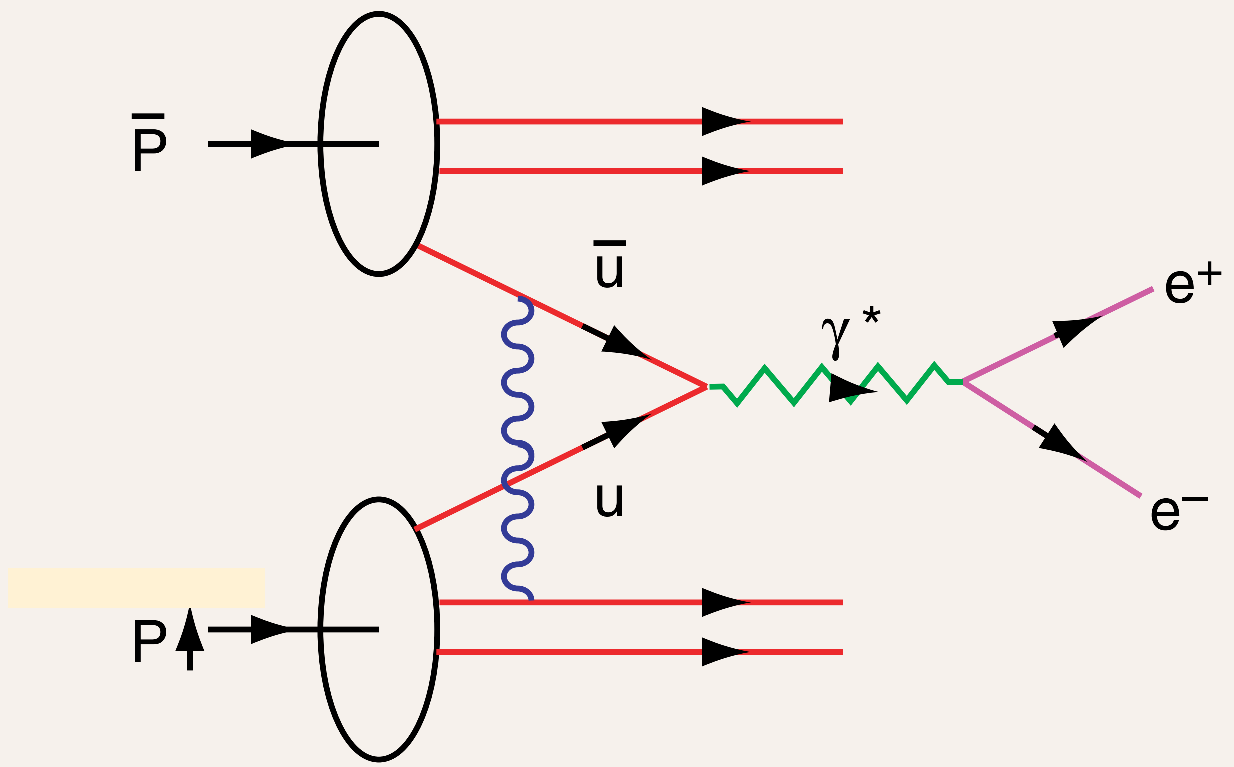
Produce Single Spin Asymmetry [Siver's Effect]Proportional to the Proton Anomalous Moment and α_s.

Opposite Sign to DIS! No Factorization

Key QCD Experiment

Collins;
Hwang, Schmidt.
sjb

Measure single-spin asymmetry A_N
in Drell-Yan reactions



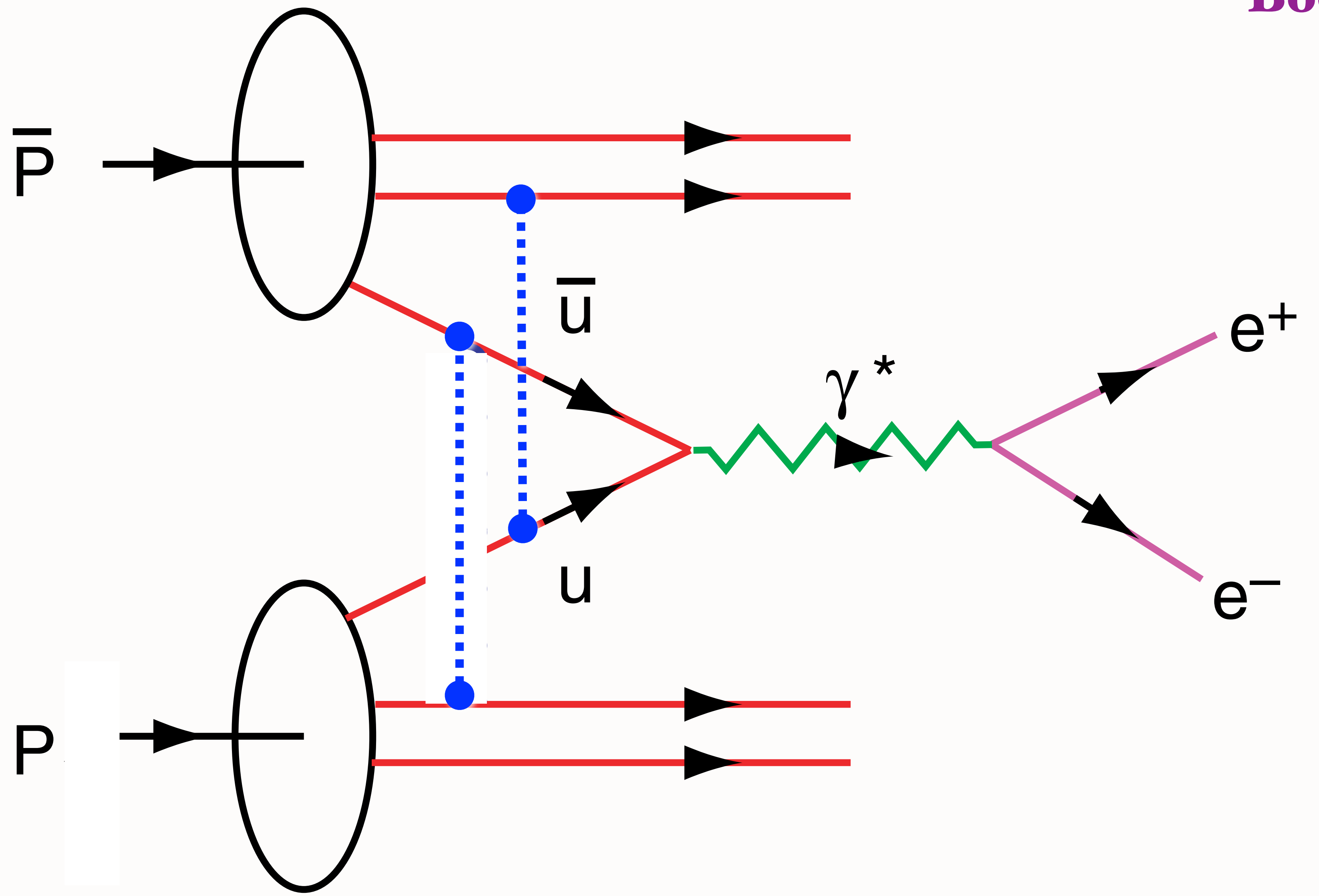
Leading-twist Bjorken-scaling A_N
from S, P-wave
initial-state gluonic interactions

$$\bar{p}p_{\uparrow} \to \ell^+\ell^- X$$

Predict: $A_N(DY) = -A_N(DIS)$
Opposite in sign!

$\vec{S} \cdot \vec{q} \times \vec{p}$ correlation

Boer, Hwang, sjb

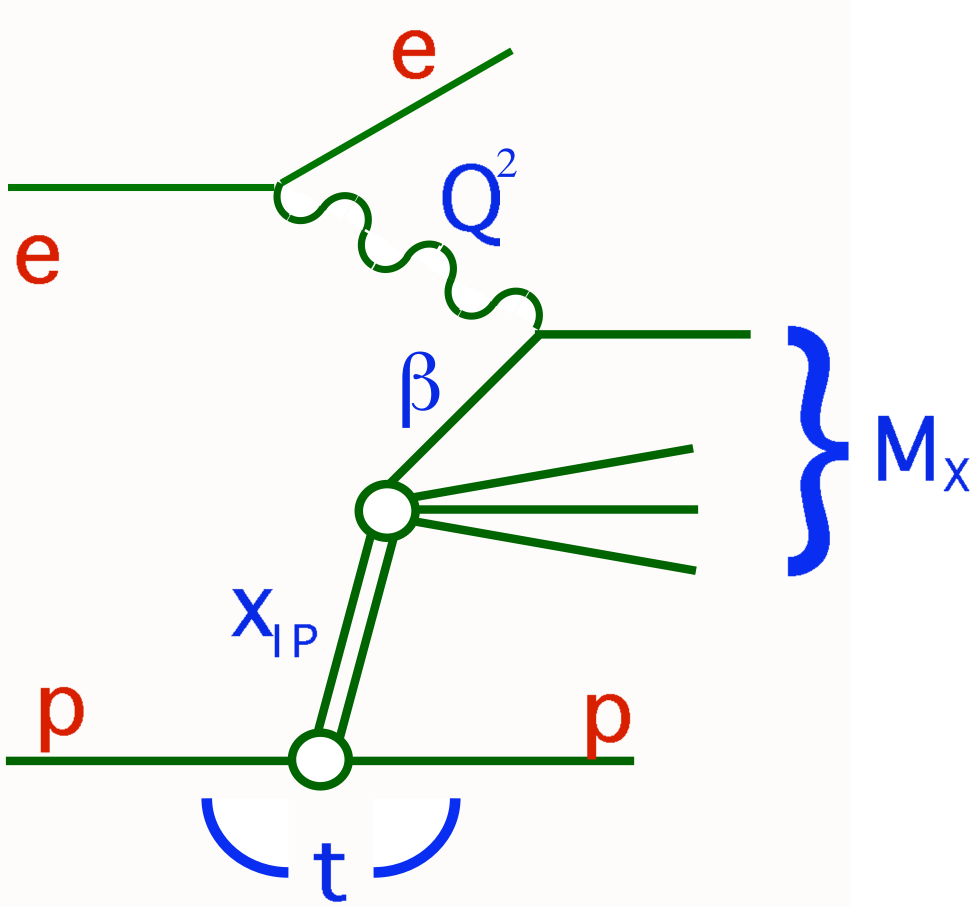


DY $\cos 2\phi$ correlation at leading twist from double ISI

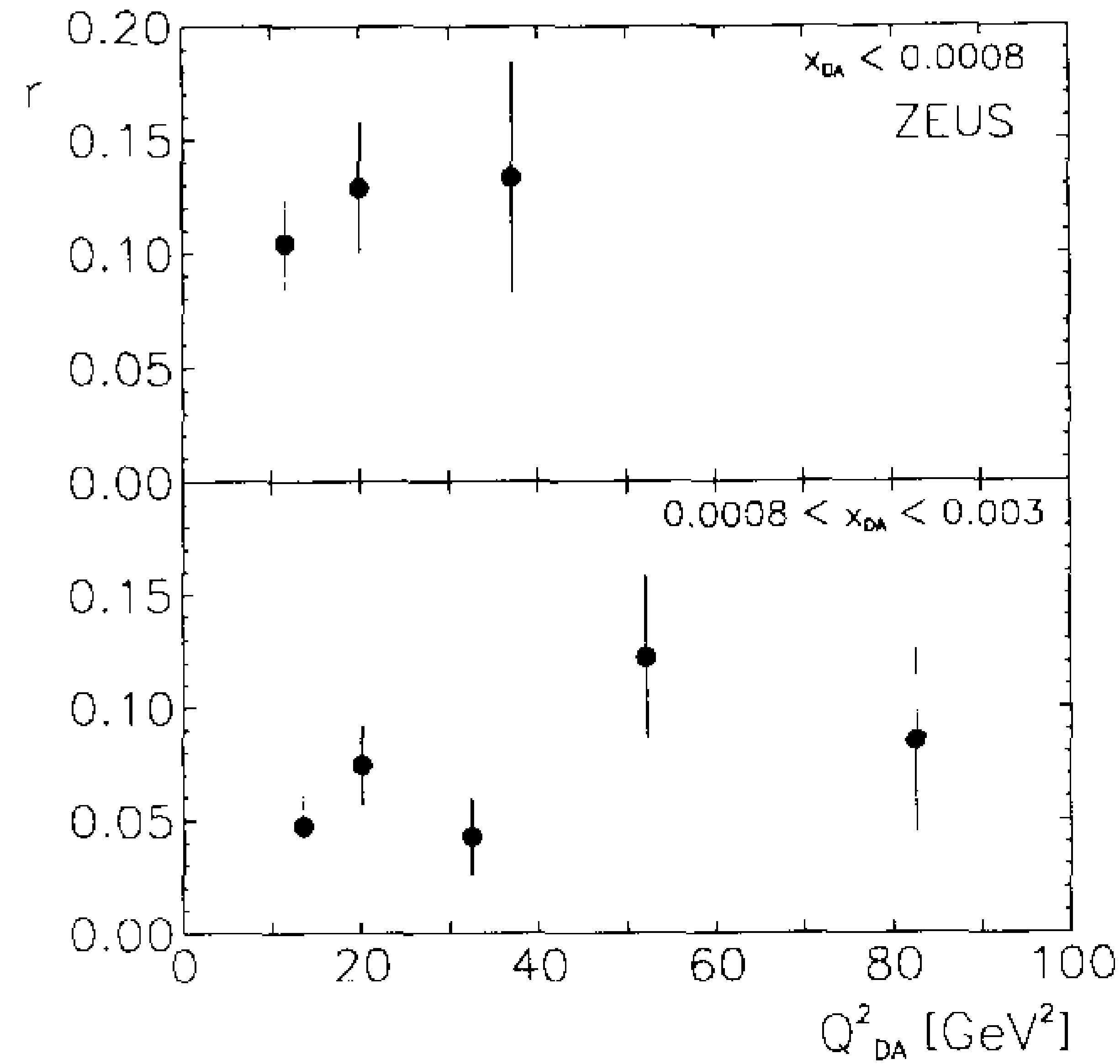
Product of Boer - Mulders Functions

$$h_1^{\perp}(x_1, \boldsymbol{p}_\perp^2) \times \bar{h}_1^{\perp}(x_2, \boldsymbol{k}_\perp^2)$$

Remarkable observation at HERA



10% to 15% of DIS events are diffractive !

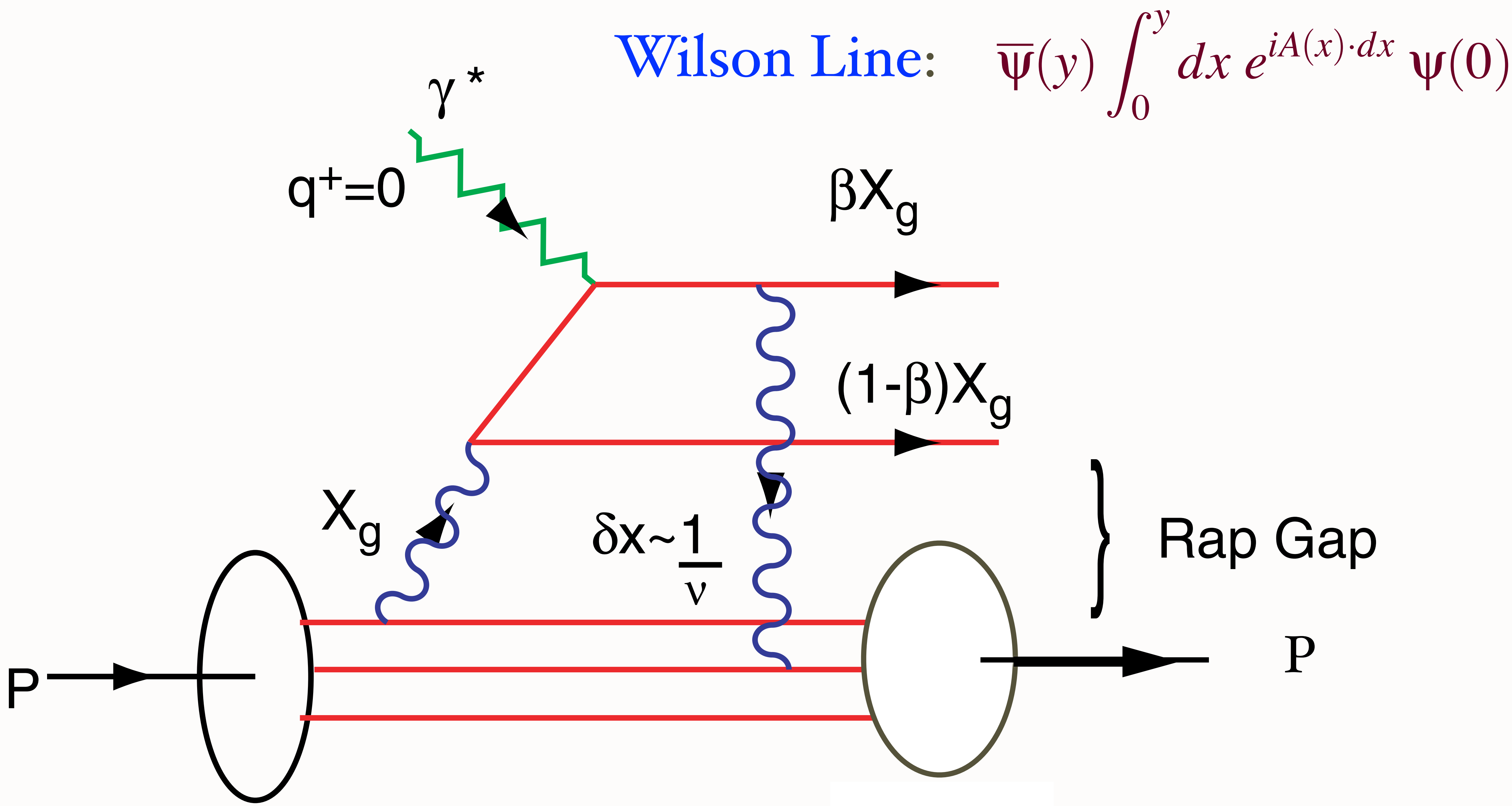


Fraction r of events with a large rapidity gap, $\eta_{max} < 1.5$, as a function of Q^2_{DA} for two ranges of x_{DA}. No acceptance corrections have been applied.

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

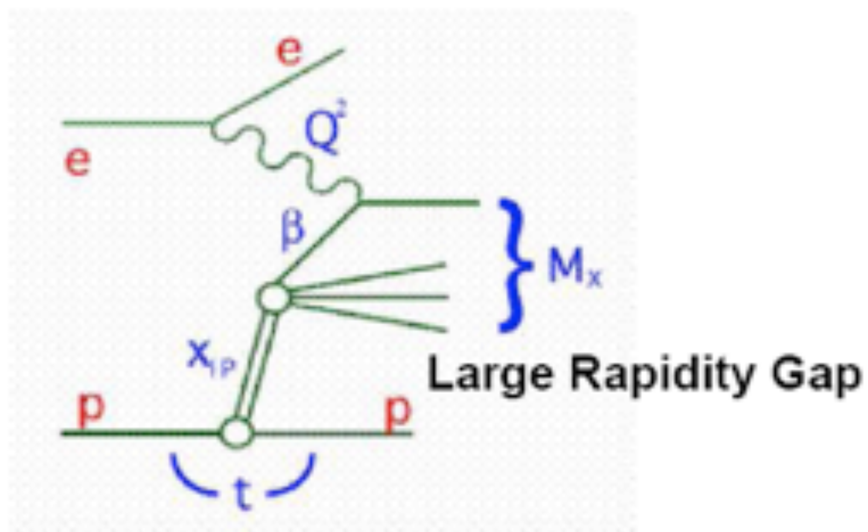
Hoyer, Marchal, Peigne, Sannino, sjb

QCD Mechanism for Rapidity Gaps



Reproduces lab-frame color dipole approach

Diffractive Structure Function F_2^D



Diffractive inclusive cross section

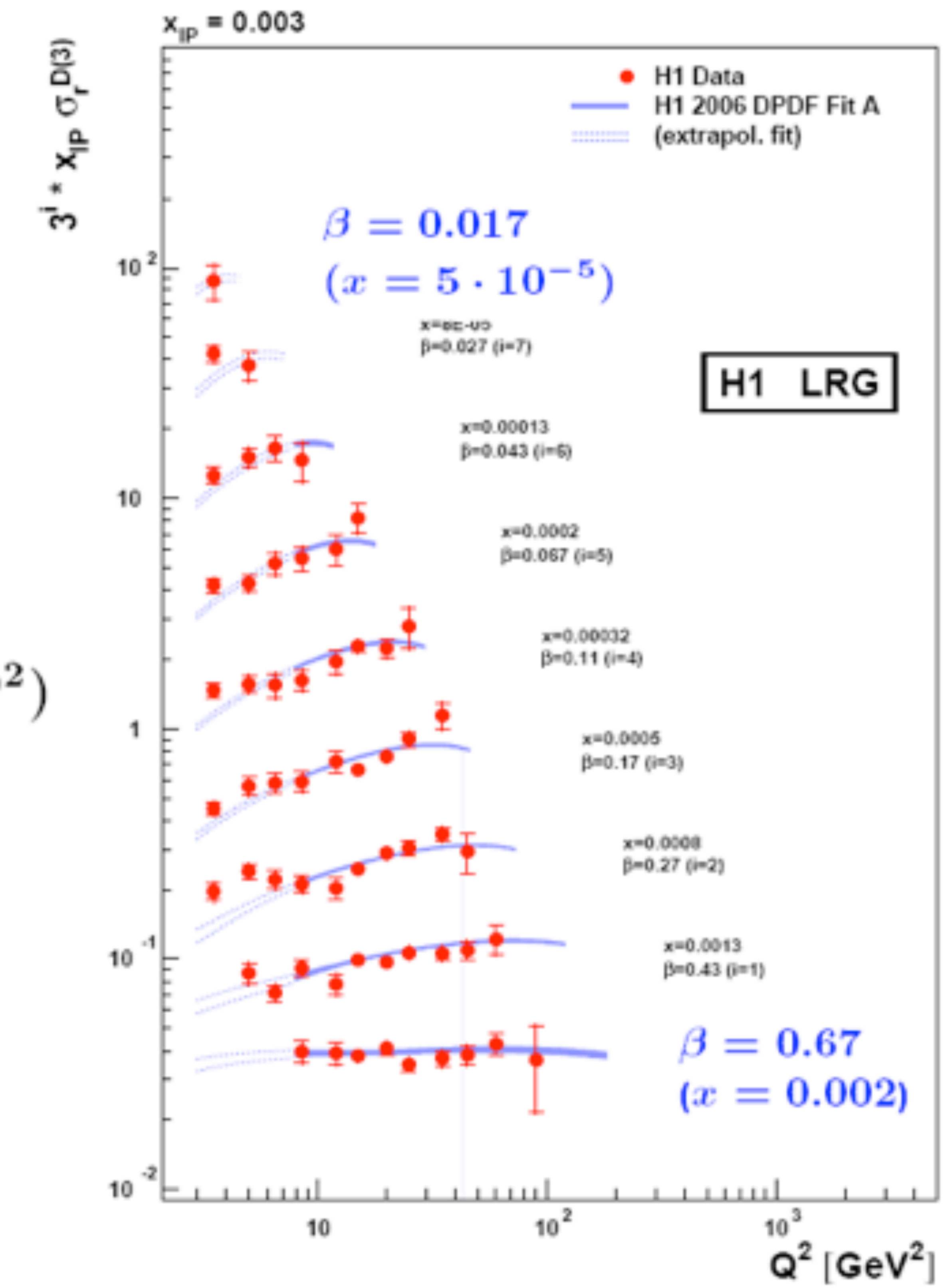
$$\frac{d^3\sigma_{NC}^{diff}}{dx_{I\!P}\, d\beta\, dQ^2} \propto \frac{2\pi\alpha^2}{xQ^4} F_2^{D(3)}(x_{I\!P}, \beta, Q^2)$$

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

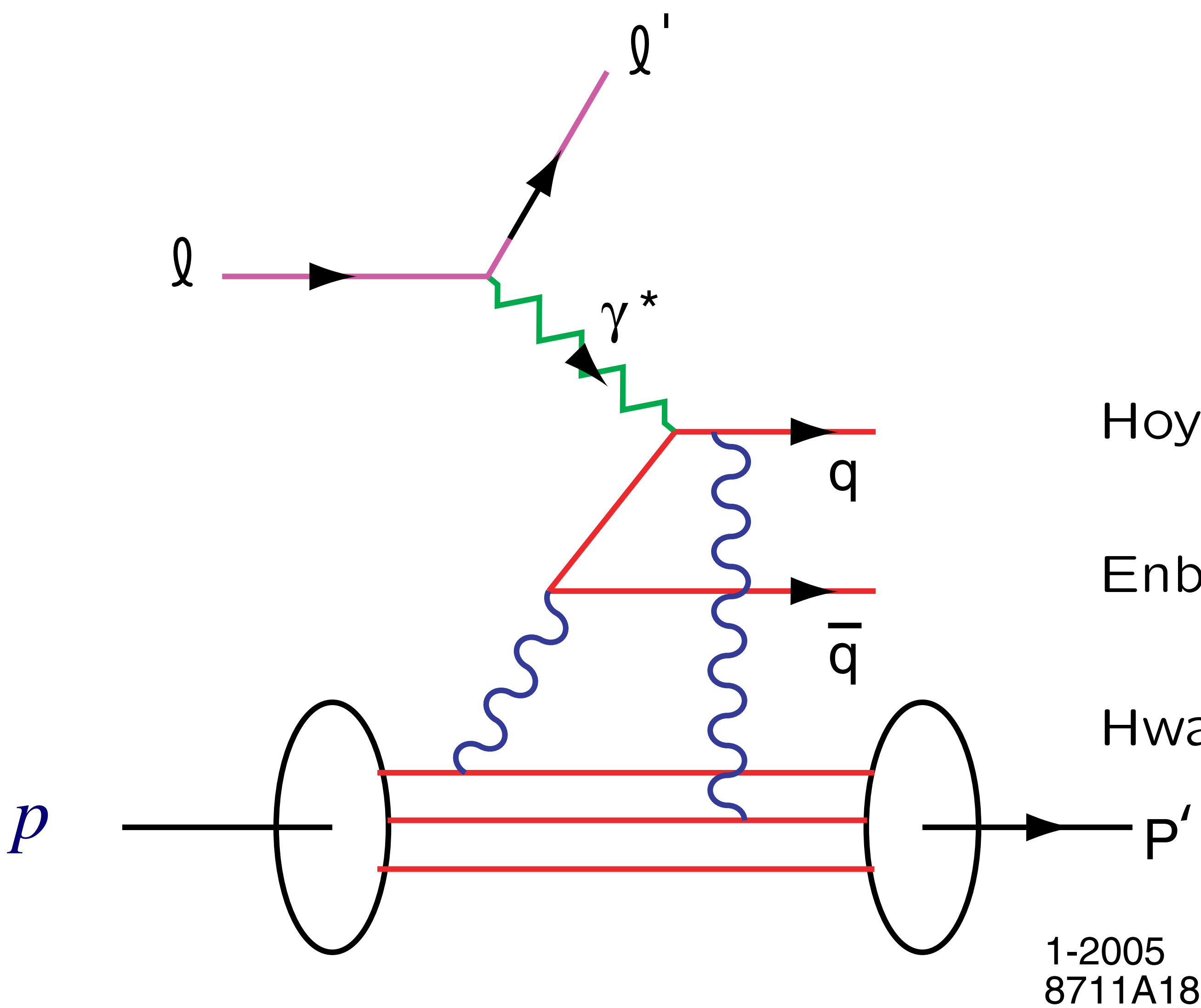
extract DPDF and $xg(x)$ from scaling violation

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

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



Final-State Interaction Produces Diffractive DIS



Quark Rescattering

Hoyer, Marchal, Peigne, Sannino, SJB (BHM

Enberg, Hoyer, Ingelman, SJB

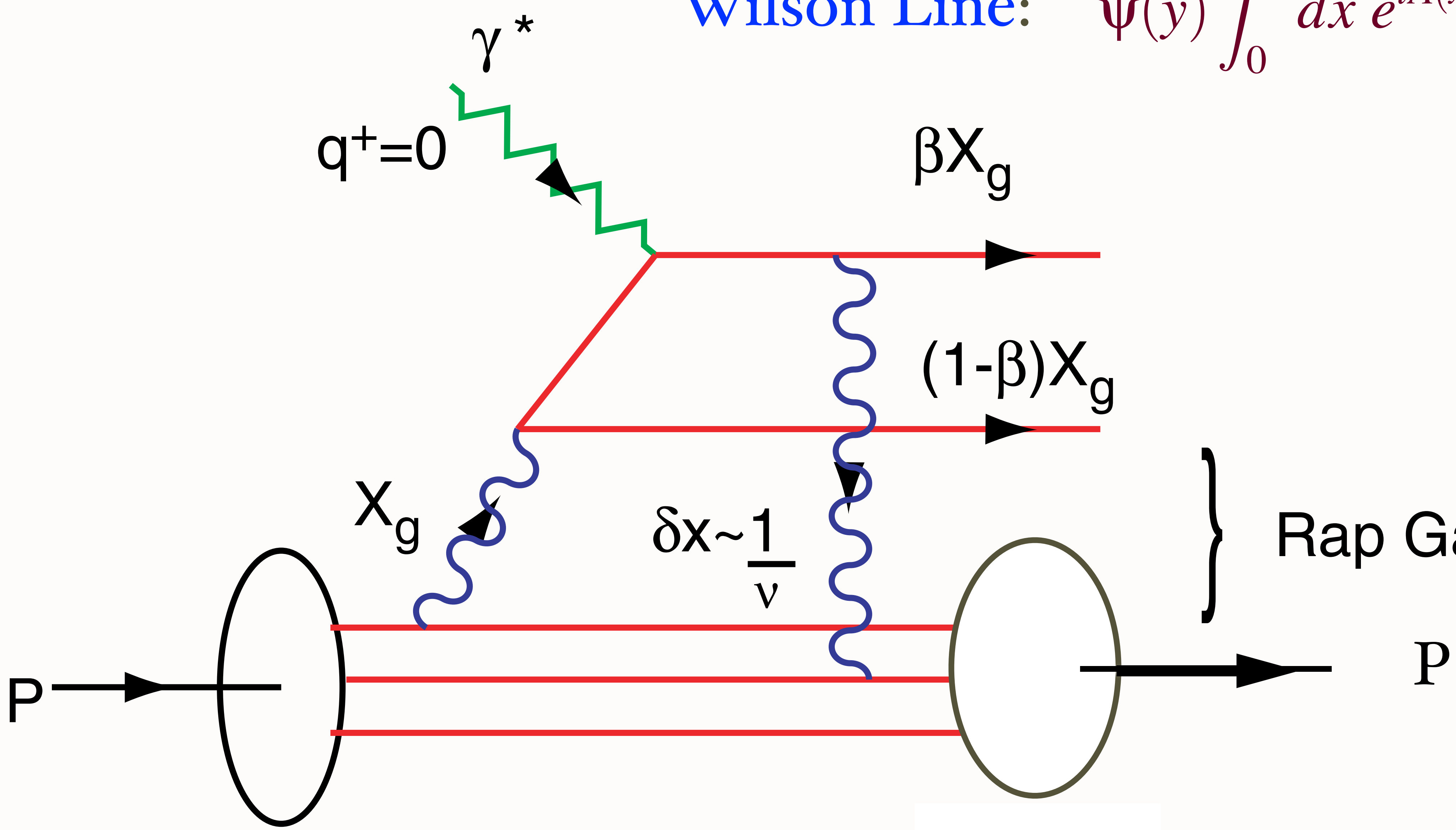
Hwang, Schmidt, SJB

Low-Nussinov model of Pomeron

Hoyer, Marchal, Peigne, Sannino, sjb

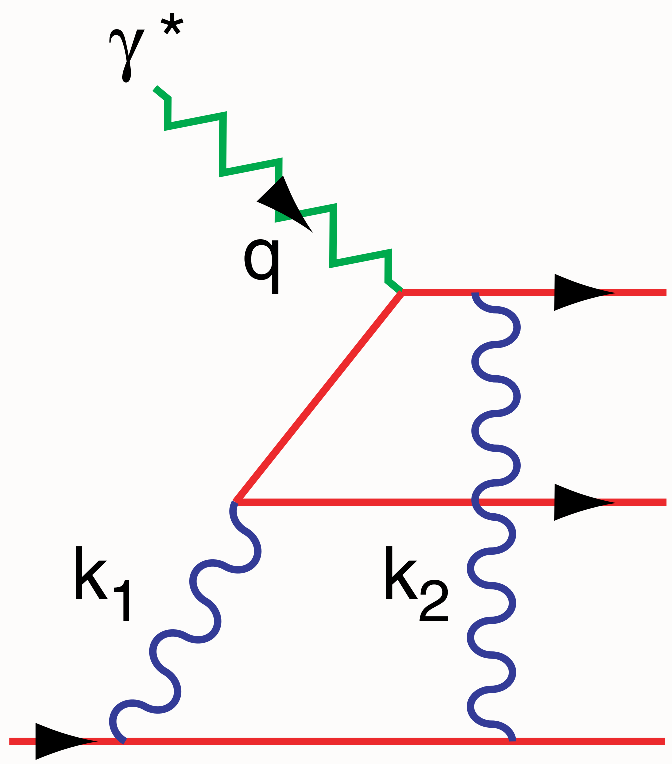
QCD Mechanism for Rapidity Gaps

Wilson Line: $\overline{\psi}(y) \int_0^y dx\, e^{iA(x)\cdot dx}\, \psi(0)$

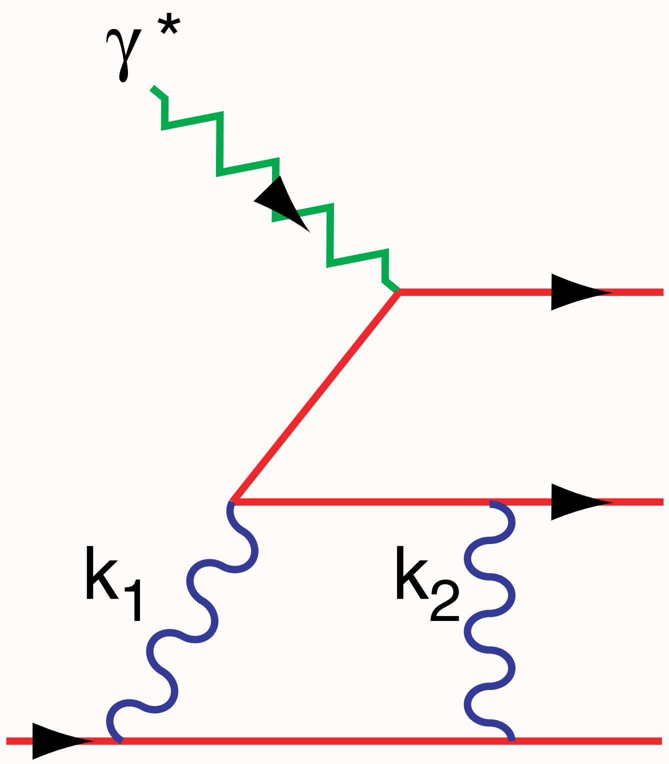


Reproduces lab-frame color dipole approach

Final State Interactions in QCD



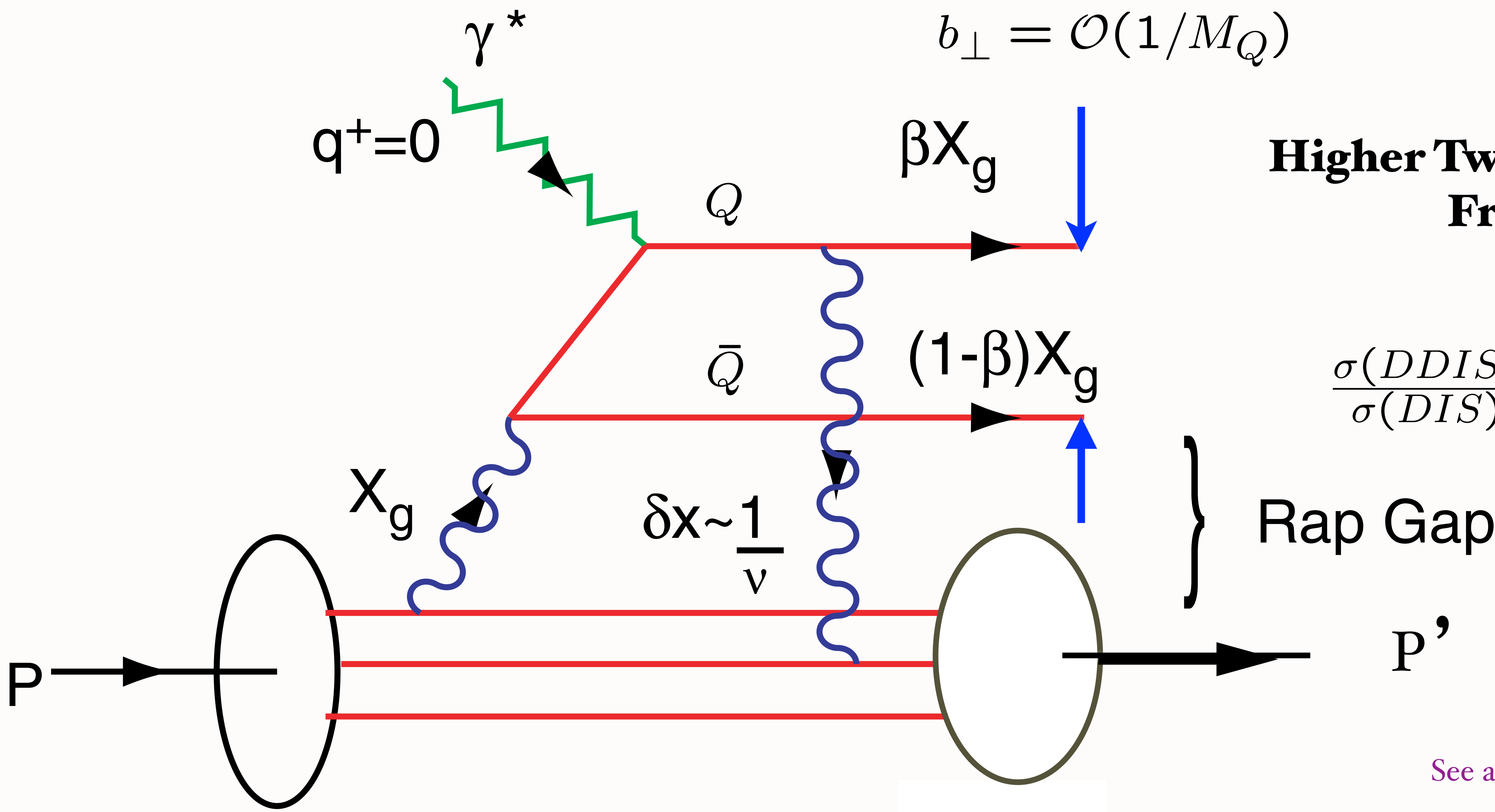
Feynman Gauge



Light-Cone Gauge

Result is Gauge Independent

Predict: Reduced DDIS/DIS for Heavy Quarks



Higher Twist Diffraction Fraction

$$\frac{\sigma(DDIS)}{\sigma(DIS)} \simeq \frac{\Lambda^2_{QCD}}{M_Q^2}$$

See also: Bartels et al

Kopeliovitch, Schmidt, sjb

Reproduces lab-frame color dipole approach

Physics of Rescattering

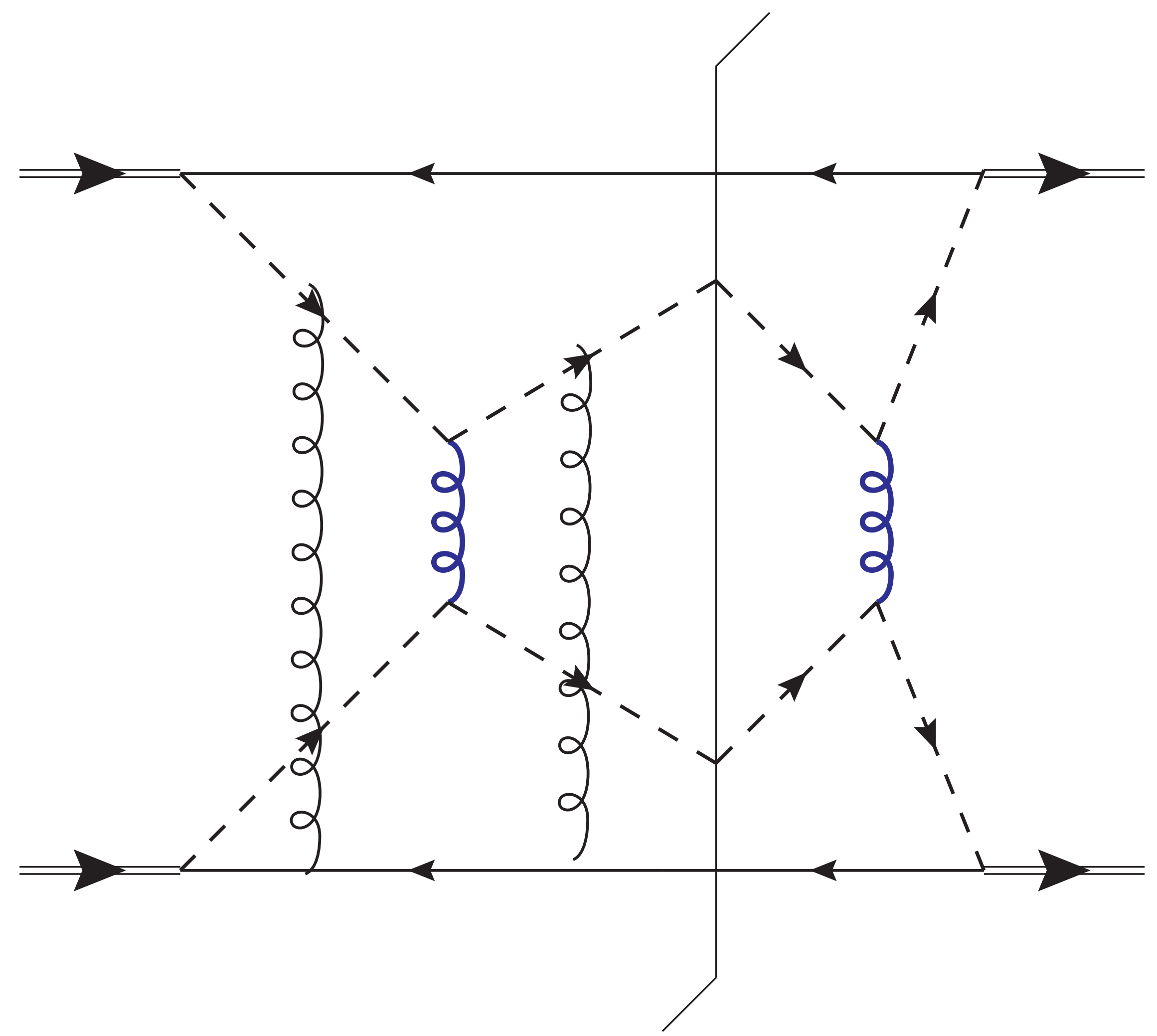
- Sivers Asymmetry and Diffractive DIS: New Insights into Final State Interactions in QCD
- Origin of Hard Pomeron
- Structure Functions not Probability Distributions!

  Not square of LFWFs
- T-odd SSAs, Shadowing, Antishadowing
- Diffractive dijets/ trijets, doubly diffractive Higgs
- Novel Effects: Color Transparency, Color Opaqueness, Intrinsic Charm, Odderon

Factorization is violated in production of high-transverse-momentum particles in hadron-hadron collisions

John Collins, Jian-Wei Qiu . ANL-HEP-PR-07-25, May 2007.

e-Print: **arXiv:0705.2141** [hep-ph]



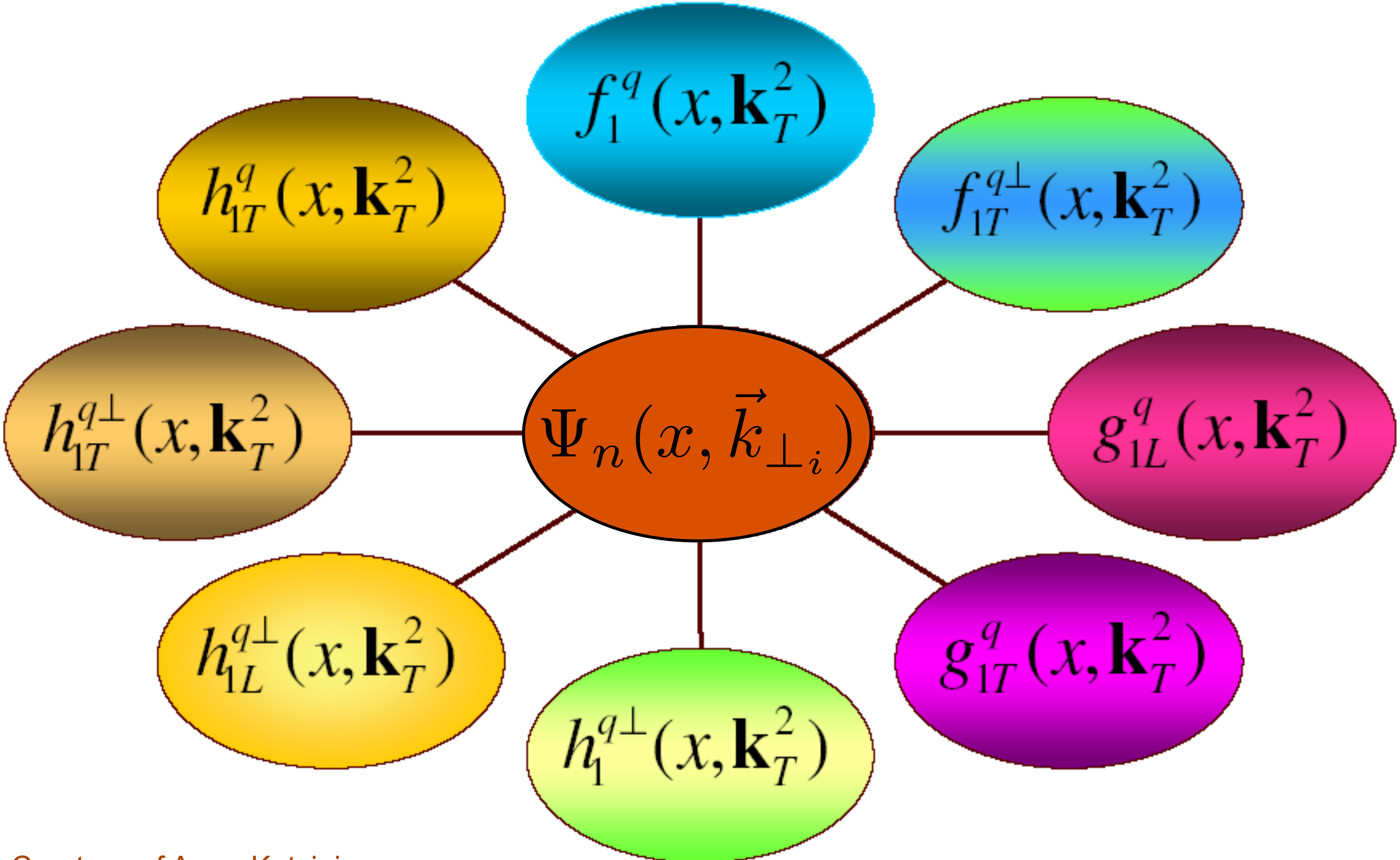
The exchange of two extra gluons, as in this graph, will tend to give non-factorization in unpolarized cross sections.

Recent COMPASS data on deuteron: small Sivers effect

- The anomalous magnetic moment, the Sivers function, and the generalized parton distribution E can all be connected to matrix elements involving the orbital angular momentum of the nucleon's constituents.
- The SSA can be generated by either a quark or gluon mechanism, and the isospin structure of the two mechanisms is distinct. The approximate cancellation of the SSA measured on a deuterium target suggests that the gluon mechanism, and thus the orbital angular momentum carried by gluons in the nucleon, is small.
- Studies of the SSA in ϕ or K^+K^- production, via $\gamma^* g \to s\bar{s} \to \phi + X$ or $\gamma^* g \to s\bar{s} \to K^+K^- + X$ should provide additional constraints on the gluon mechanism.

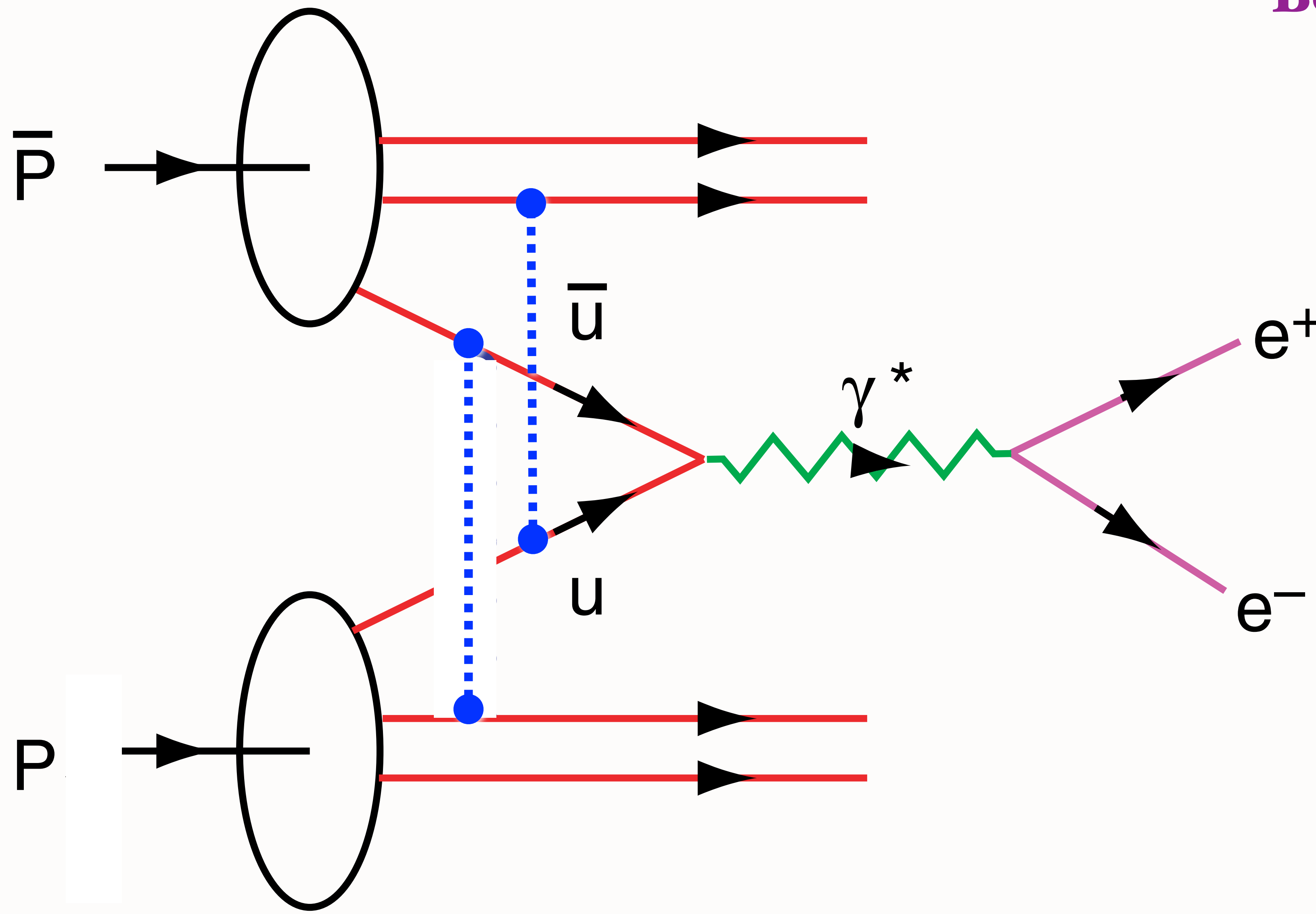
Gardner, sjb

8 leading-twist spin-$k_\perp$ dependent distribution functions



Courtesy of Aram Kotzinian

Boer, Hwang, sjb



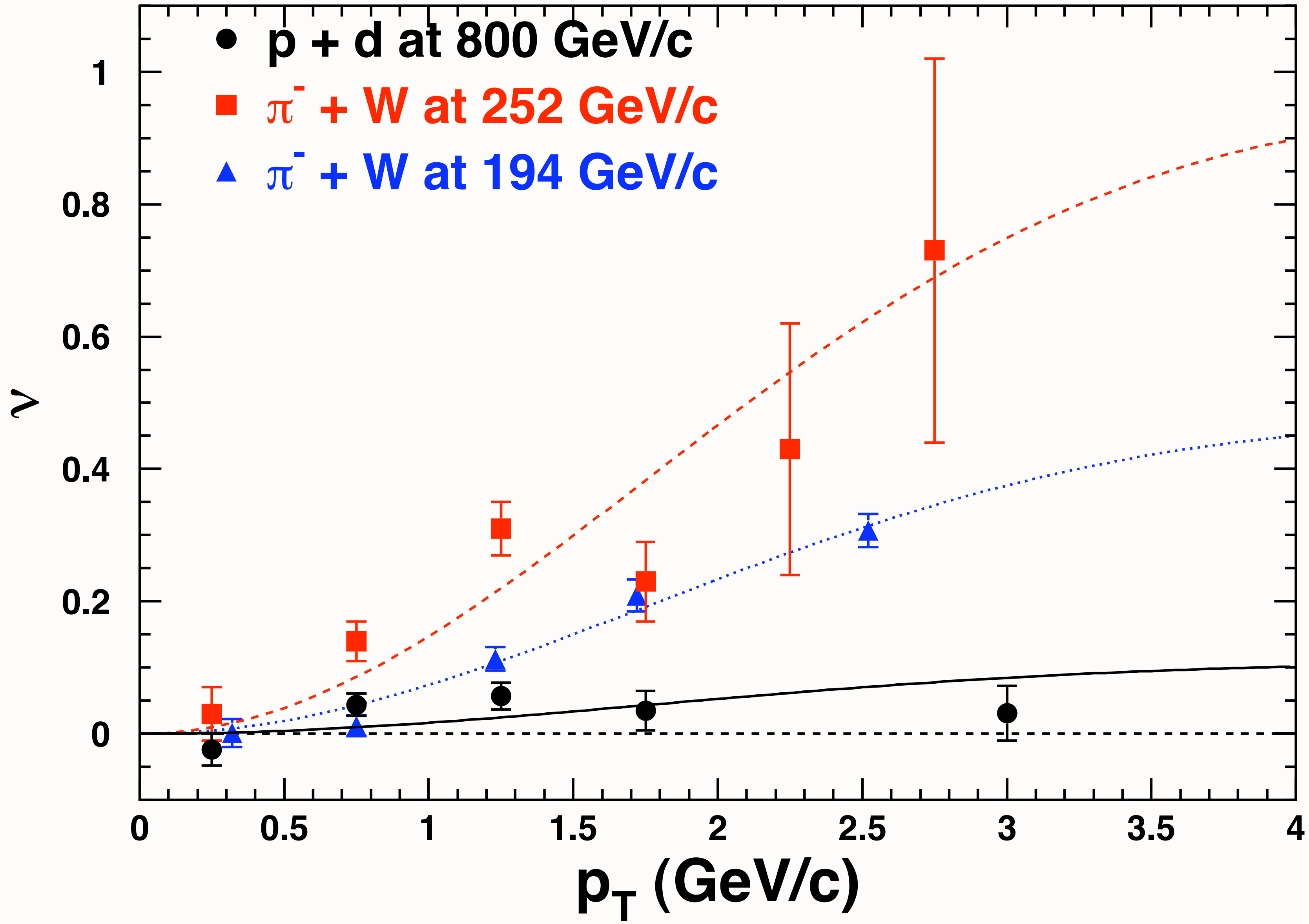
DY $\cos 2\phi$ correlation at leading twist from double ISI

Product of Boer - Mulders Functions

$$h_1^{\perp}(x_1, \boldsymbol{p}_{\perp}^2) \times \bar{h}_1^{\perp}(x_2, \boldsymbol{k}_{\perp}^2)$$

Measurement of Angular Distributions of Drell-Yan Dimuons in $p + d$ Interaction at 800 GeV/c

(FNAL E866/NuSea Collaboration)



Parameter ν vs. p_T in the Collins-Soper frame for three Drell-Yan measurements. Fits to the data using Eq. 3 and $M_C = 2.4$ GeV/c^2 are also shown.

Huge Effect in $\pi W \to \mu^+ \mu^- X$

Negligible Effect $pd \to \mu^+ \mu^- X$

Double Initial-State Interactions generate anomalous $\cos 2\phi$

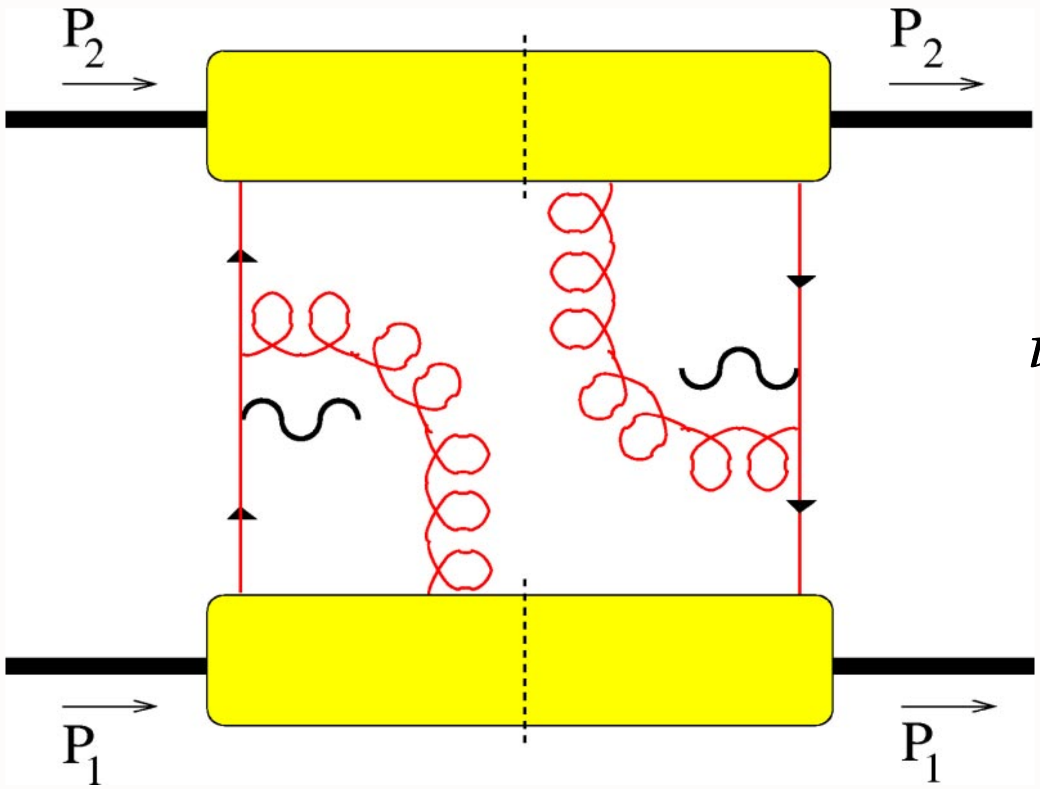
Boer, Hwang, sjb

Drell-Yan planar correlations

$$\frac{1}{\sigma}\frac{d\sigma}{d\Omega} \propto \left(1 + \lambda \cos^2\theta + \mu \sin 2\theta \, \cos\phi + \frac{\nu}{2} \sin^2\theta \cos 2\phi\right)$$

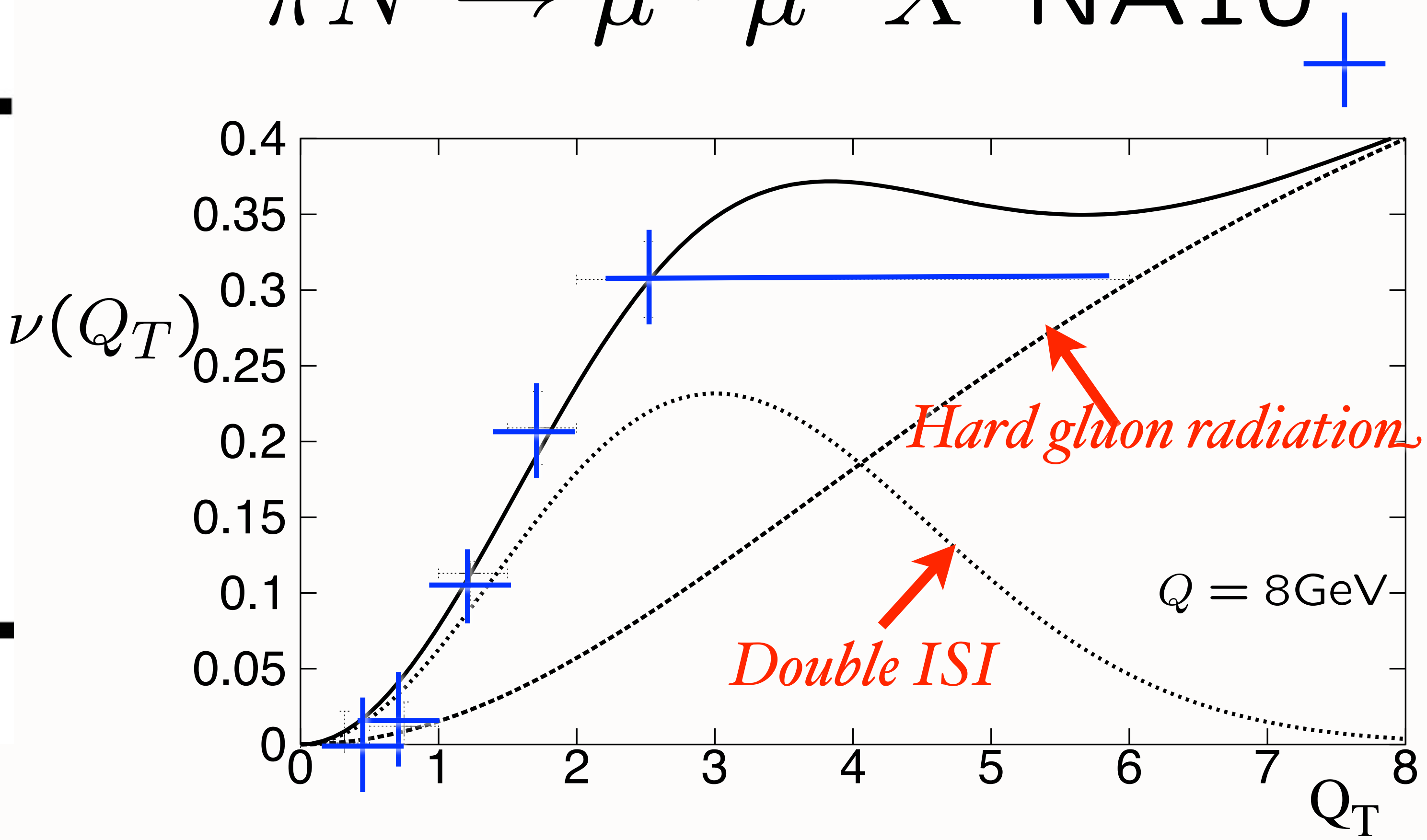
PQCD Factorization (Lam Tung): $1 - \lambda - 2\nu = 0$

$$\frac{\nu}{2} \propto h_1^{\perp}(\pi)\, h_1^{\perp}(N)$$

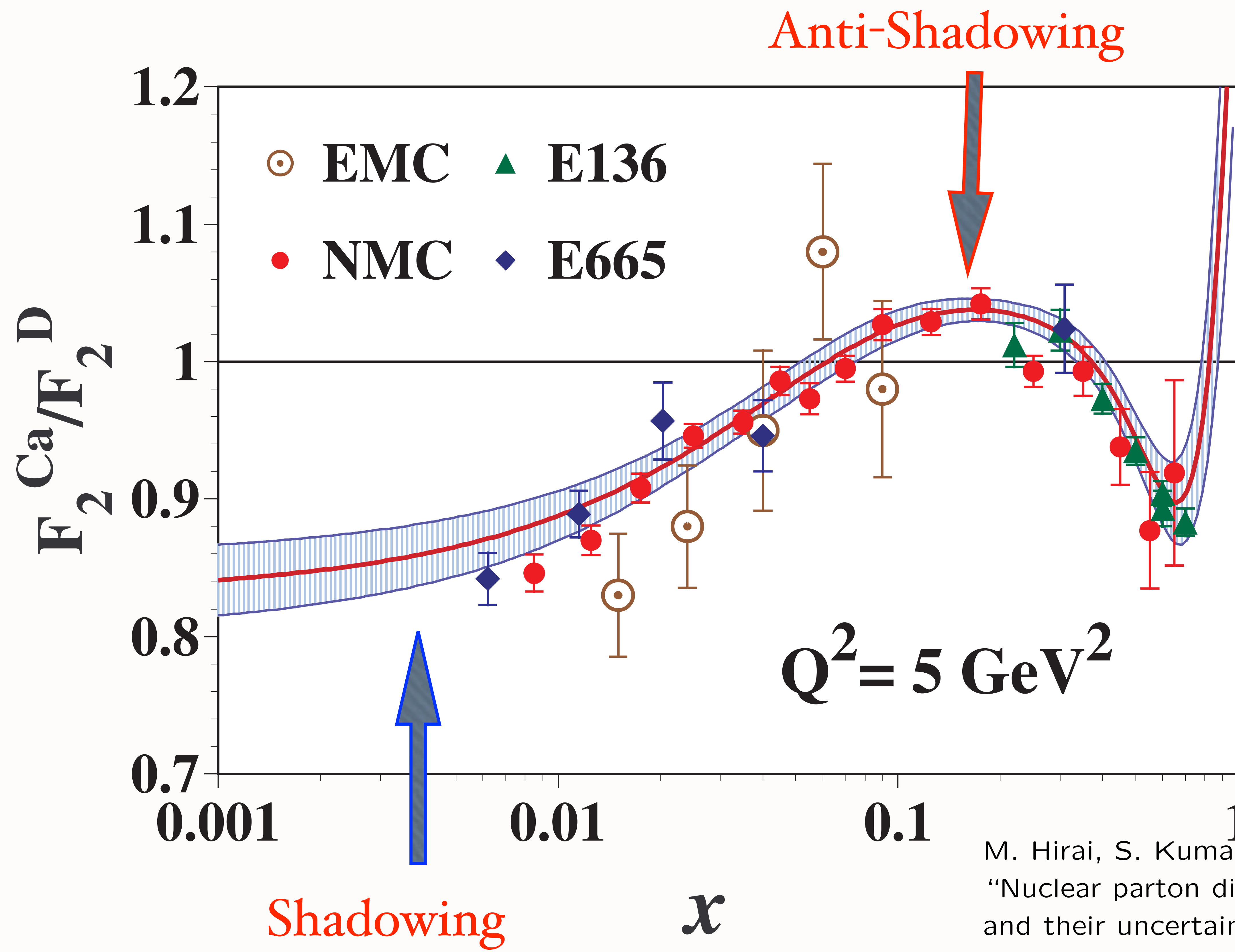


Violates Lam-Tung relation!

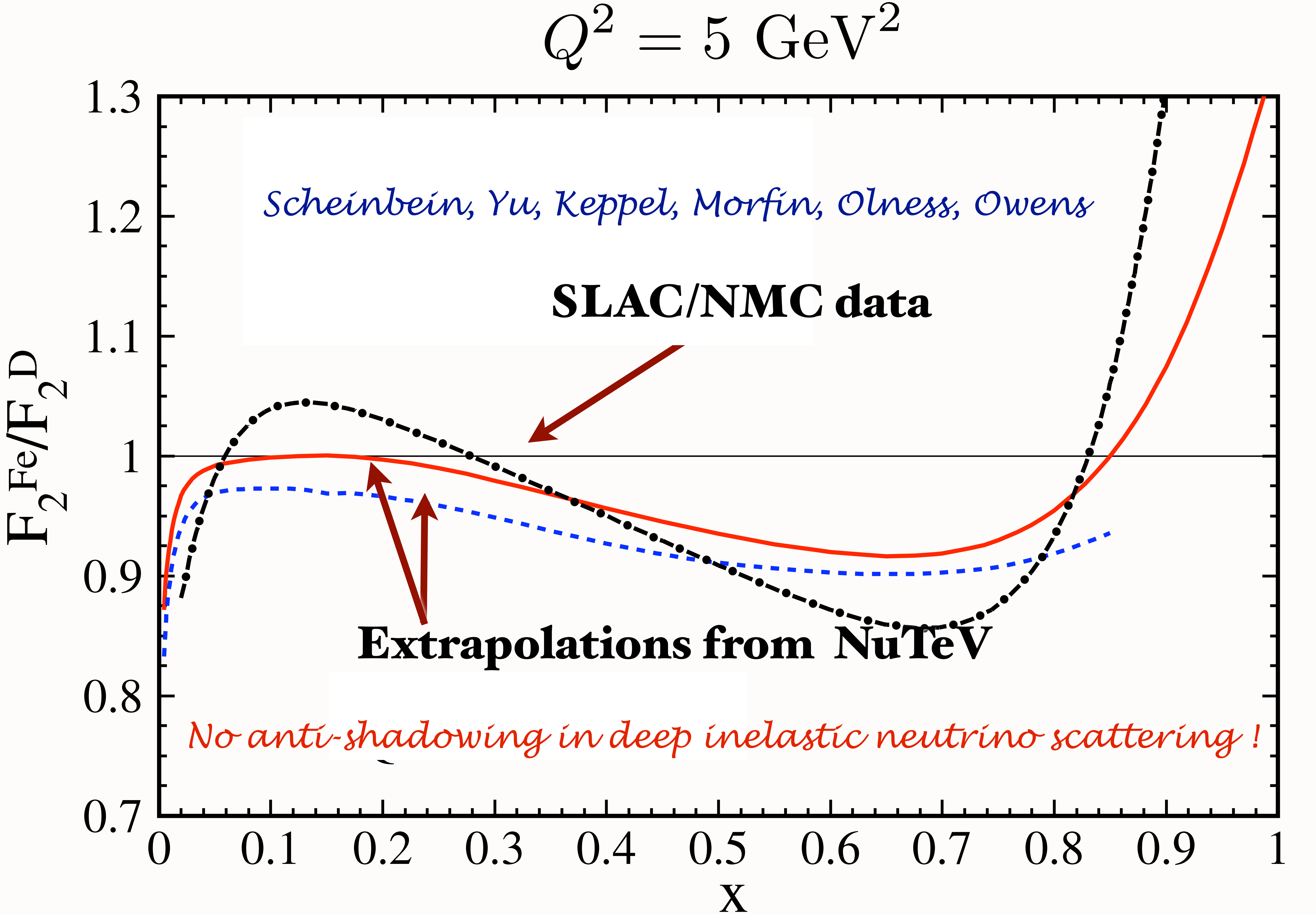
$\pi N \to \mu^+\mu^- X$ NA10



Model: Boer,



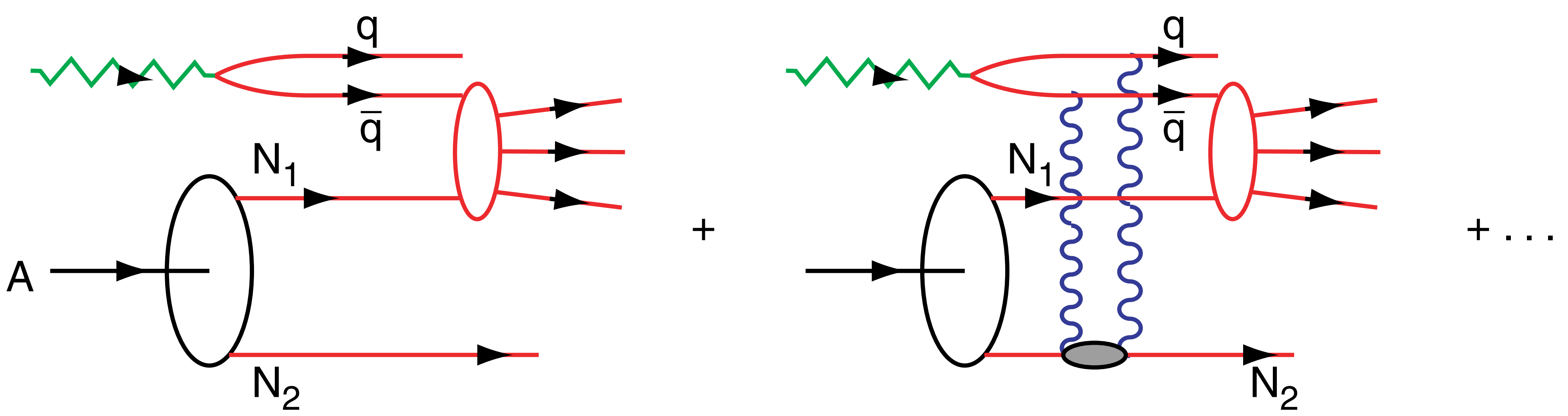
M. Hirai, S. Kumano and T. H. Nagai, "Nuclear parton distribution functions and their uncertainties," Phys. Rev. C **70**, 044905 (2004) [arXiv:hep-ph/0404093].



$Q^2 = 5\ \mathrm{GeV}^2$
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

Stodolsky
Pumplin, sjb
Gribov

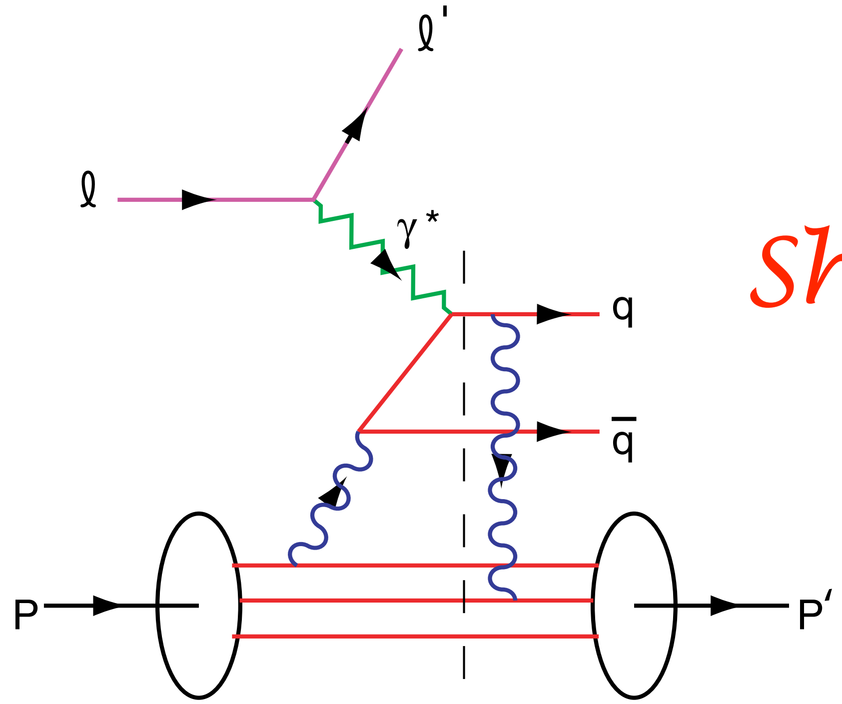
Nuclear Shadowing in QCD



Shadowing depends on understanding leading twist-diffraction in DIS

Nuclear Shadowing not included in nuclear LFWF !

Dynamical effect due to virtual photon interacting in nucleus



Shadowing depends on leading-twist DDIS

Integration over on-shell domain produces phase i

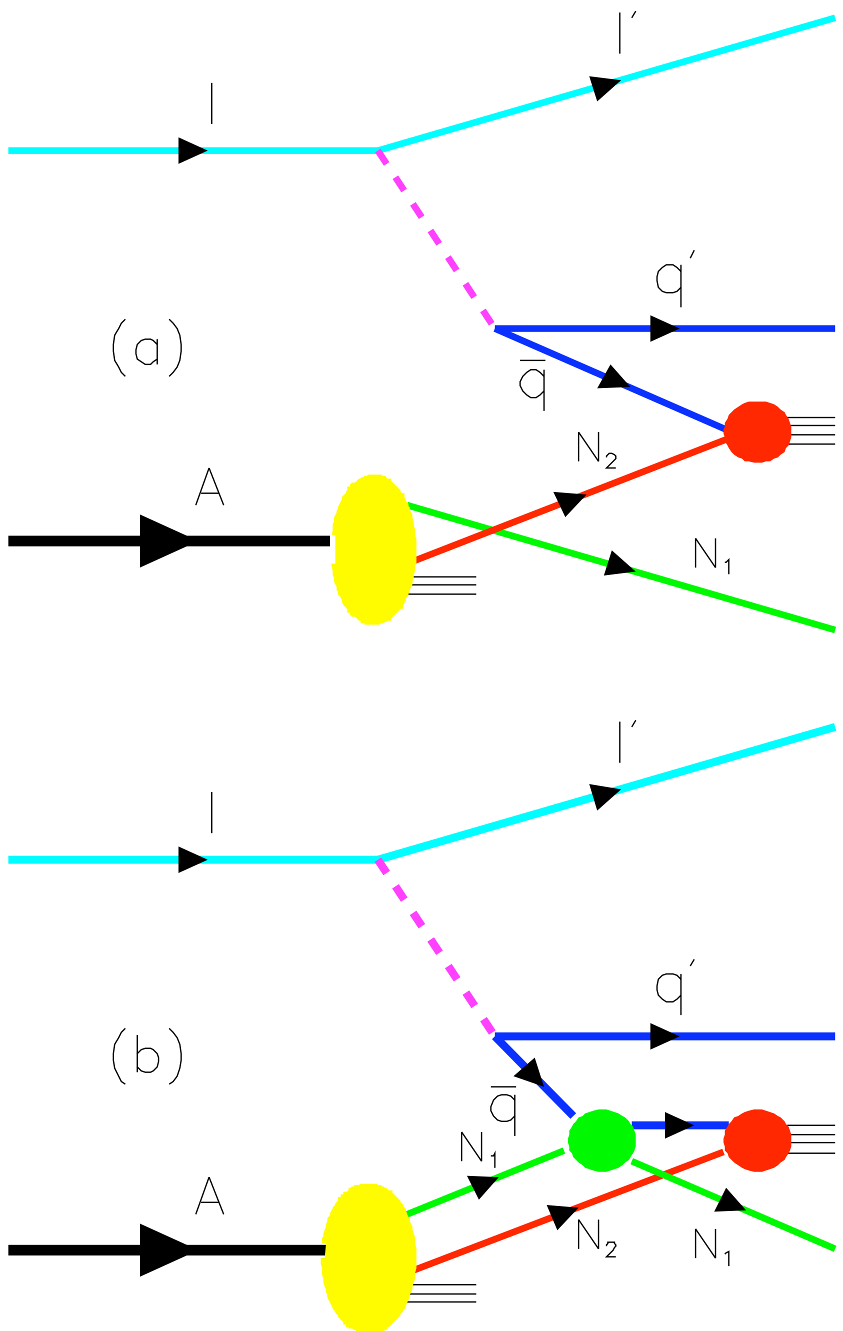
Need Imaginary Phase to Generate Pomeron

Need Imaginary Phase to Generate T-Odd Single-Spin Asymmetry

Physics of FSI not in Wavefunction of Target

Antishadowing (Reggeon exchange) is not universal!

Schmidt, Yang, sjb



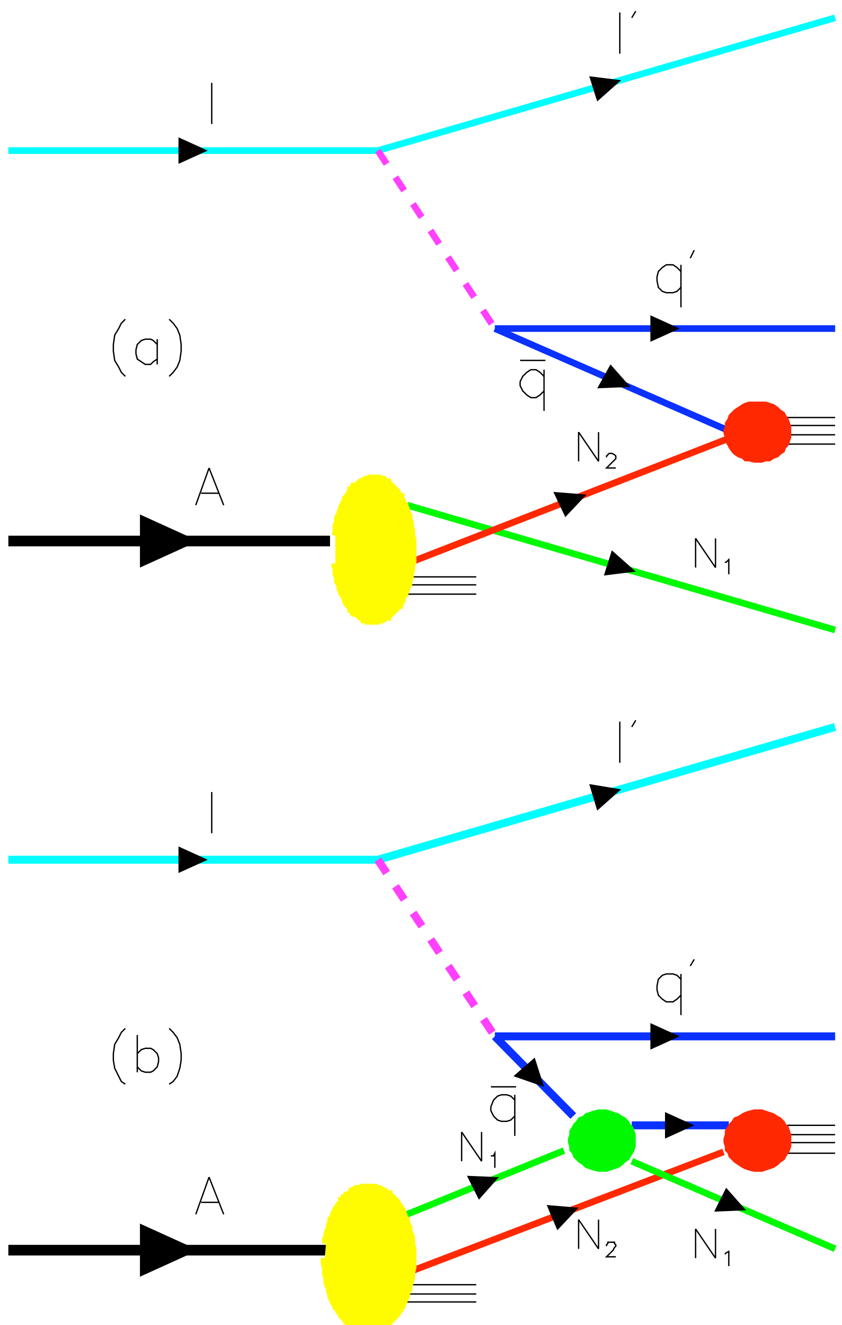
The one-step and two-step processes in DIS on a nucleus.

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

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.

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

Observed HERA DDIS produces nuclear shadowing



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~~ *Reggeon* exchange, the one-step and two-step amplitudes are ~~opposite~~ in phase, thus ~~diminishing~~ *increasing* the $\bar{q}$ flux reaching N_2.

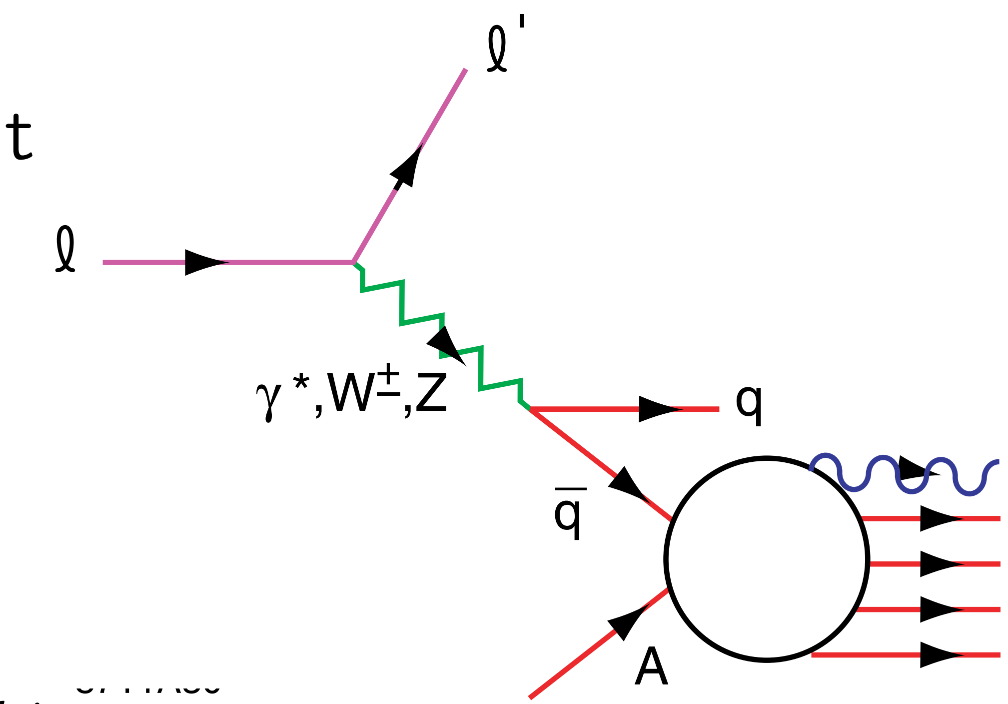
→ *Anti-* Shadowing of the DIS nuclear structure functions.

Schmidt, Yang, sjb

Origin of Regge Behavior of Deep Inelastic Structure Functions

$$F_{2p}(x) - F_{2n}(x) \propto x^{1/2}$$

Antiquark interacts with target nucleus at energy $\widehat{s} \propto \frac{1}{x_{bj}}$



Regge contribution: $\sigma_{\bar{q}N} \sim \widehat{s}^{\alpha_R - 1}$

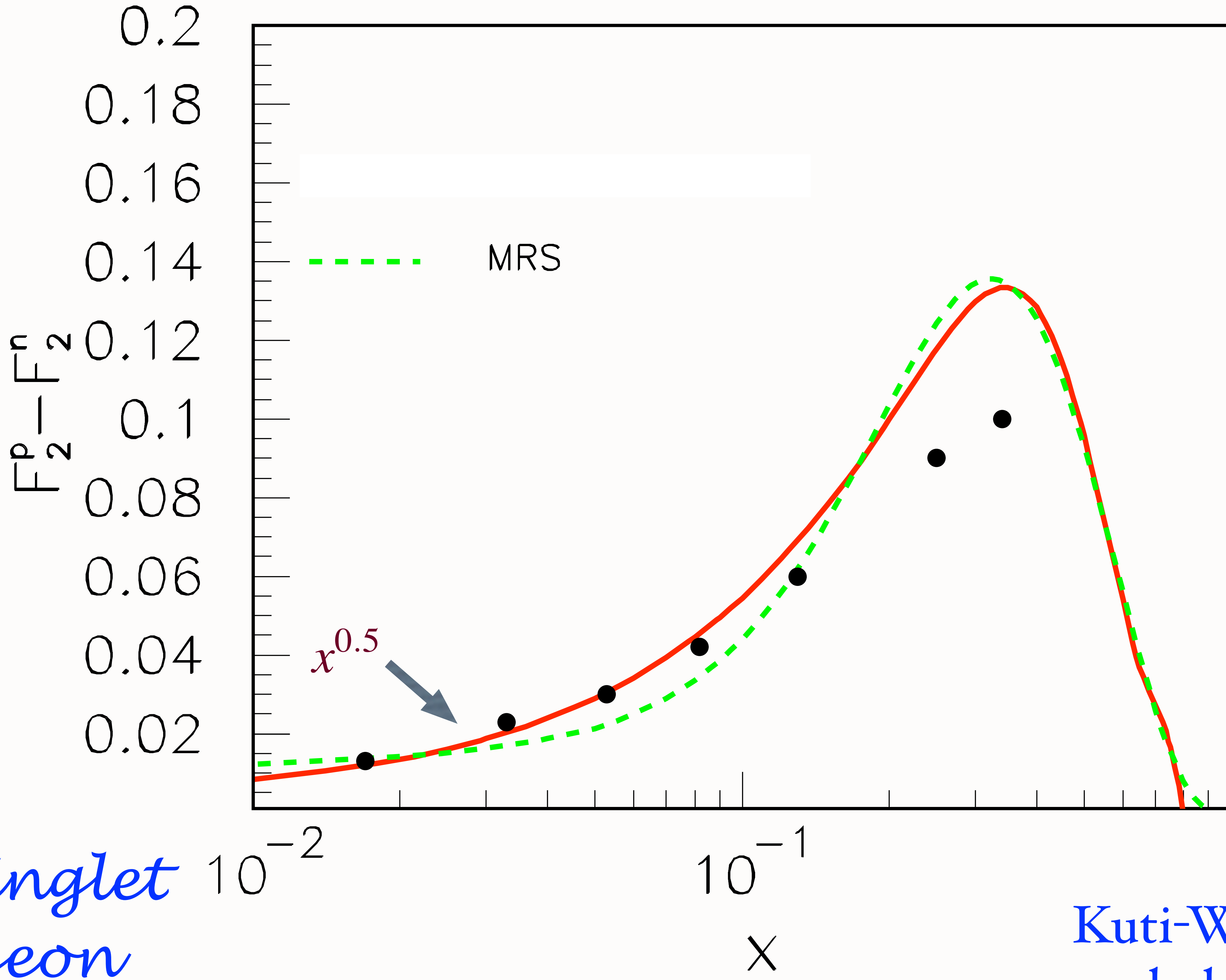
Nonsinglet Kuti-Weisskoff $F_{2p} - F_{2n} \propto \sqrt{x_{bj}}$ at small x_{bj}.

Shadowing of $\sigma_{\bar{q}M}$ produces shadowing of nuclear structure function.

Landshoff, Polkinghorne, Short

Close, Gunion, sjb

Schmidt, Yang, Lu, sjb



Non-singlet Reggeon Exchange

Kuti-Weisskopf behavior

Reggeon Exchange

Phase of two-step amplitude relative to one step:

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

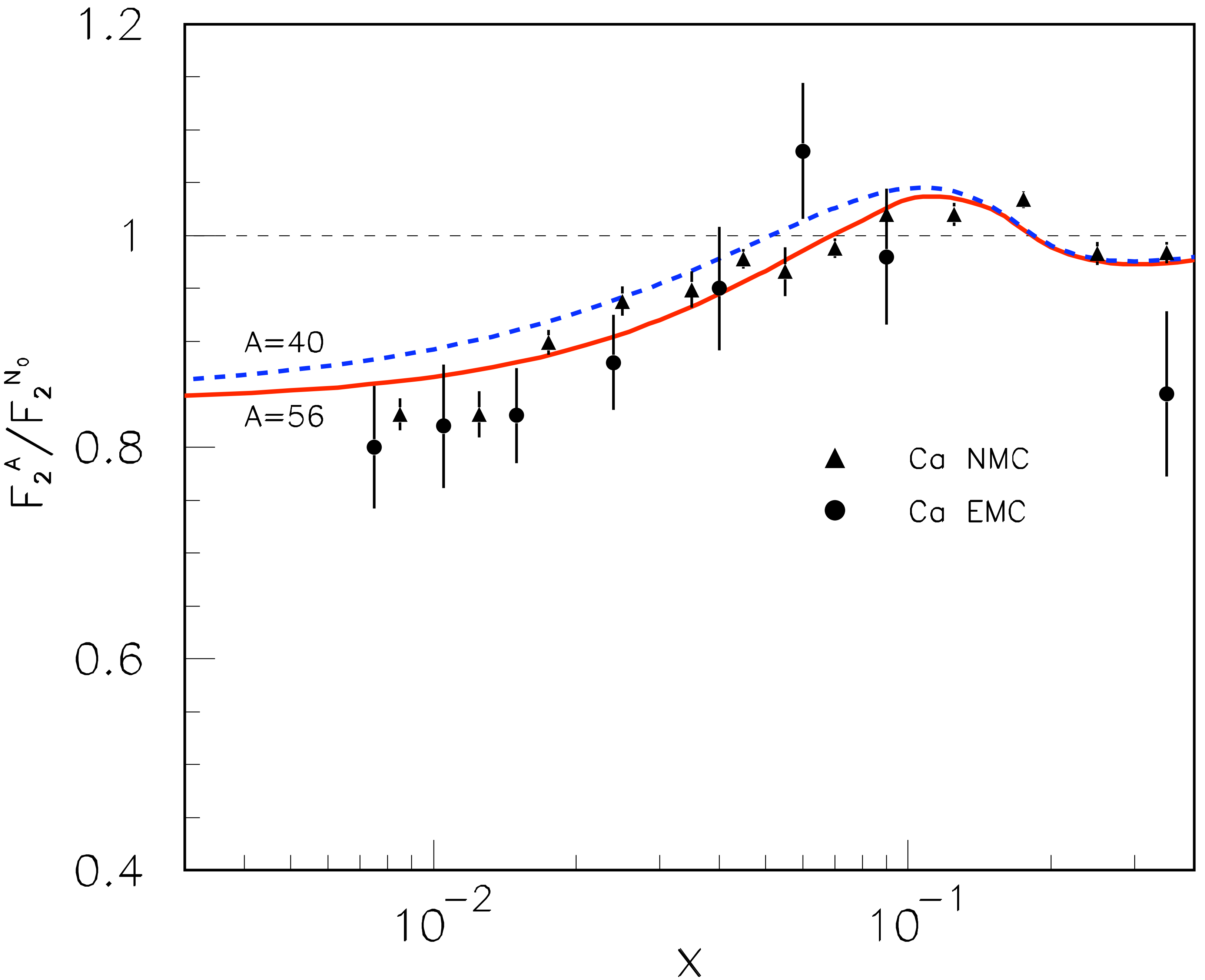
Constructive Interference

Depends on quark flavor!

Thus antishadowing is not universal

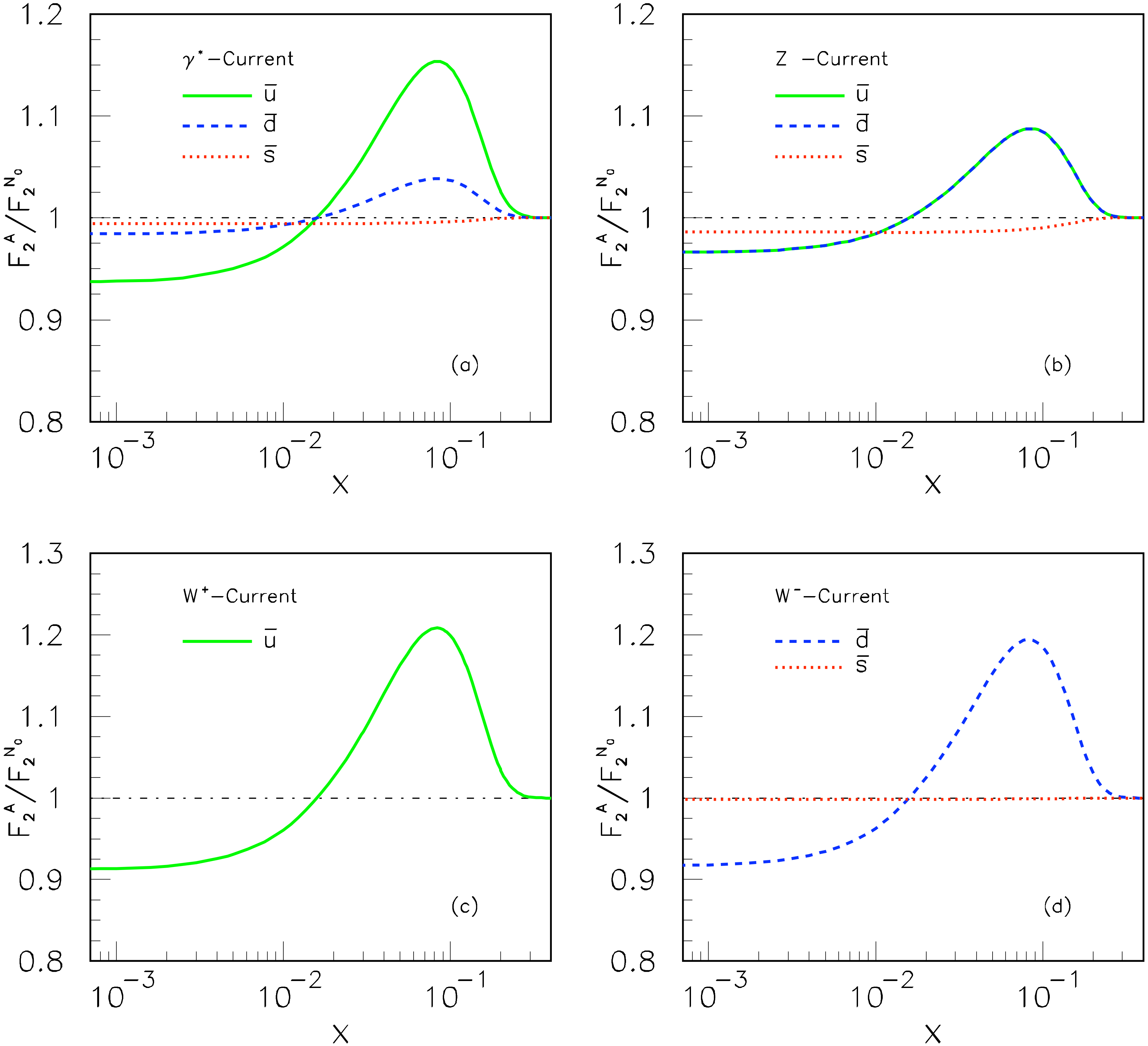
Different for couplings of $\gamma^*, Z^0, W^\pm$

Critical test: Tagged Drell-Yan



Predicted nuclear shadowing and and antishadowing at $Q^2 = 1\ \text{GeV}^2$

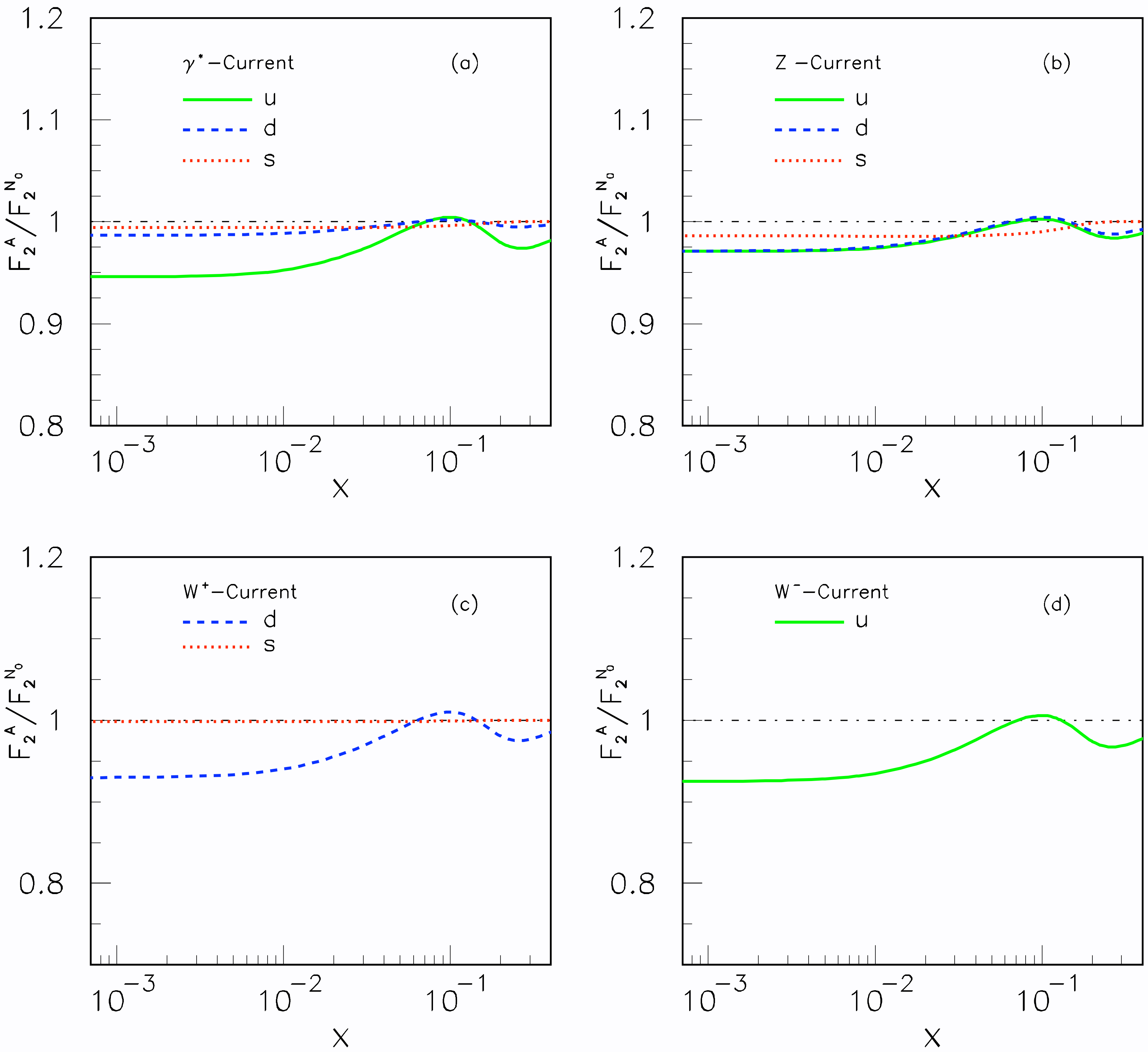
S. J. Brodsky, I. Schmidt and J. J. Yang,
"Nuclear Antishadowing in
Neutrino Deep Inelastic Scattering,"
Phys. Rev. D 70, 116003 (2004)
[arXiv:hep-ph/0409279].



Schmidt, Yang; sjb

Nuclear Antishadowing not universal !

Shadowing and Antishadowing of DIS Structure Functions



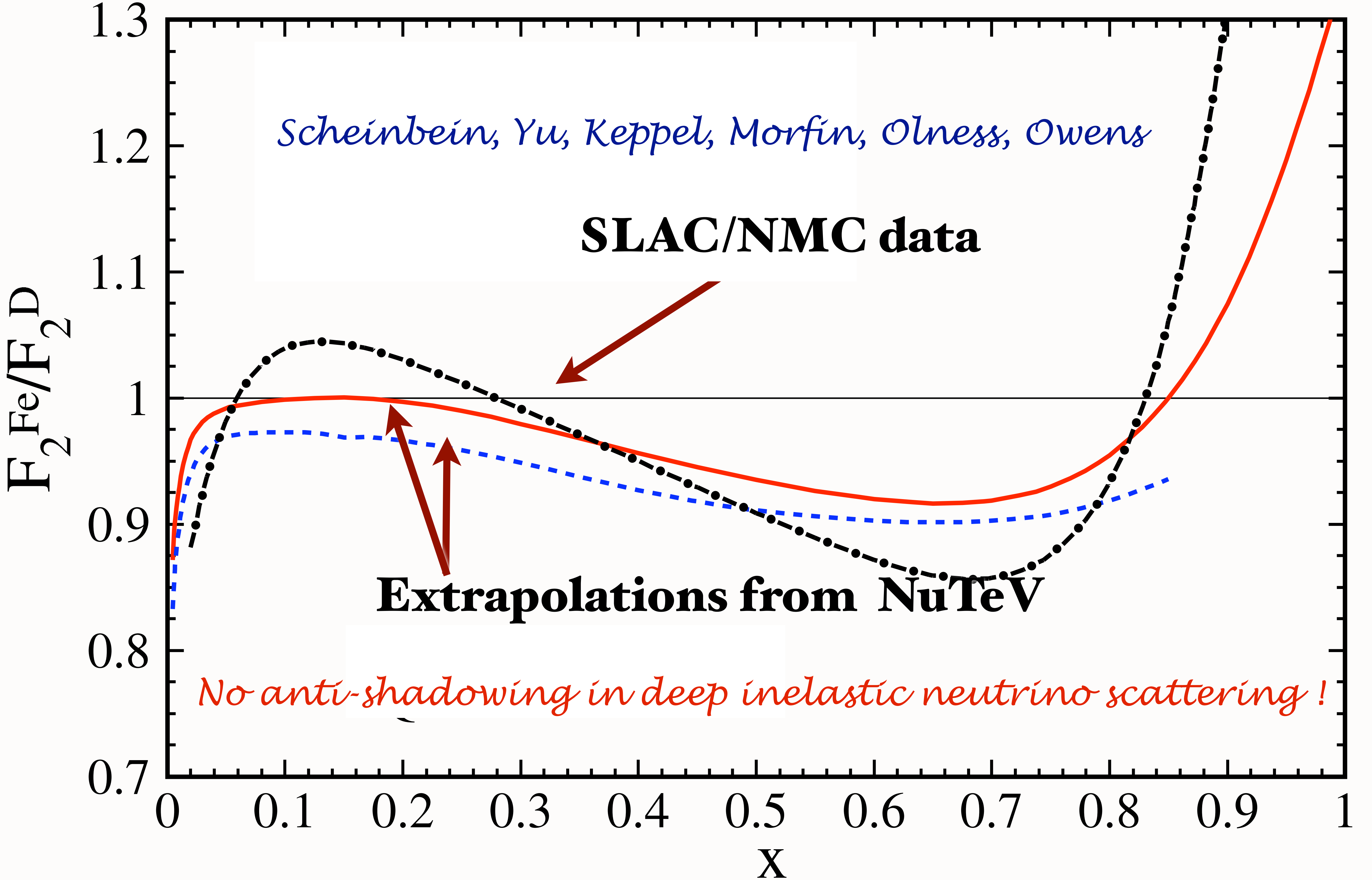
S. J. Brodsky, I. Schmidt and J. J. Yang, "Nuclear Antishadowing in Neutrino Deep Inelastic Scattering," Phys. Rev. D 70, 116003 (2004) [arXiv:hep-ph/0409279].

Modifies NuTeV extraction of

$$\sin^2 \theta_W$$

Test in flavor-tagged lepton-nucleus collisions

$Q^2 = 5\ \text{GeV}^2$



Shadowing and Antishadowing in Lepton-Nucleus Scattering

- Shadowing: Destructive Interference of Two-Step and One-Step Processes *Pomeron Exchange*

- Antishadowing: Constructive Interference of Two-Step and One-Step Processes! *Reggeon and Odderon Exchange*

- Antishadowing is Not Universal! Electromagnetic and weak currents: different nuclear effects !

Jian-Jun Yang

Ivan Schmidt

Hung Jung Lu

sjb

Can explain NuTeV result!

Physics of Rescattering

- Sivers Asymmetry and Diffractive DIS: New Insights into Final State Interactions in QCD
- Origin of Hard Pomeron
- Structure Functions not Probability Distributions!

  Not square of LFWFs
- T-odd SSAs, Shadowing, Antishadowing
- Diffractive dijets/ trijets, doubly diffractive Higgs
- Novel Effects: Color Transparency, Color Opaqueness, Intrinsic Charm, Odderon

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	Sum Rules Not Proven
DGLAP Evolution; mod. at large x	DGLAP Evolution
No Diffractive DIS	Hard Pomeron and Odderon Diffractive DIS

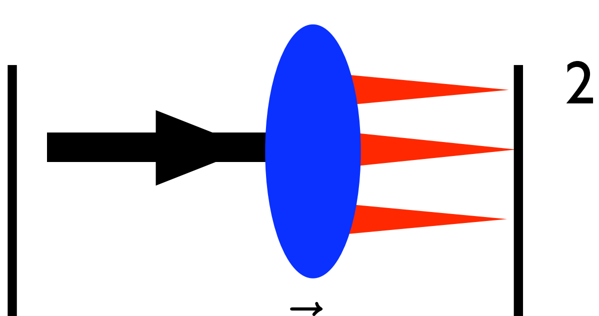
Hwang, Schmidt, sjb,

Mulders, Boer

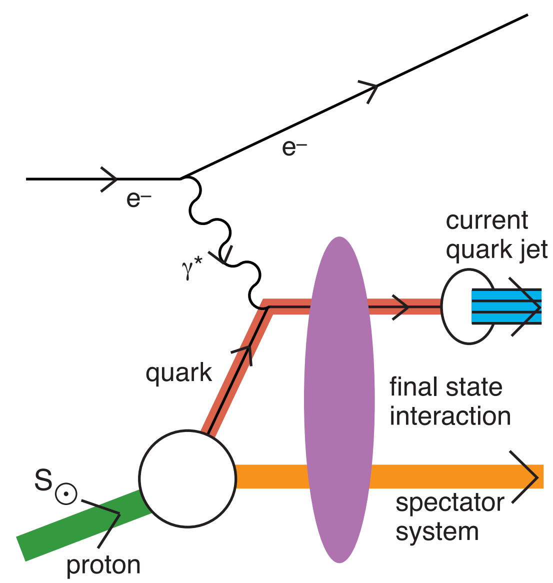
Qiu, Sterman

Collins, Qiu

Pasquini, Xiao, Yuan, sjb



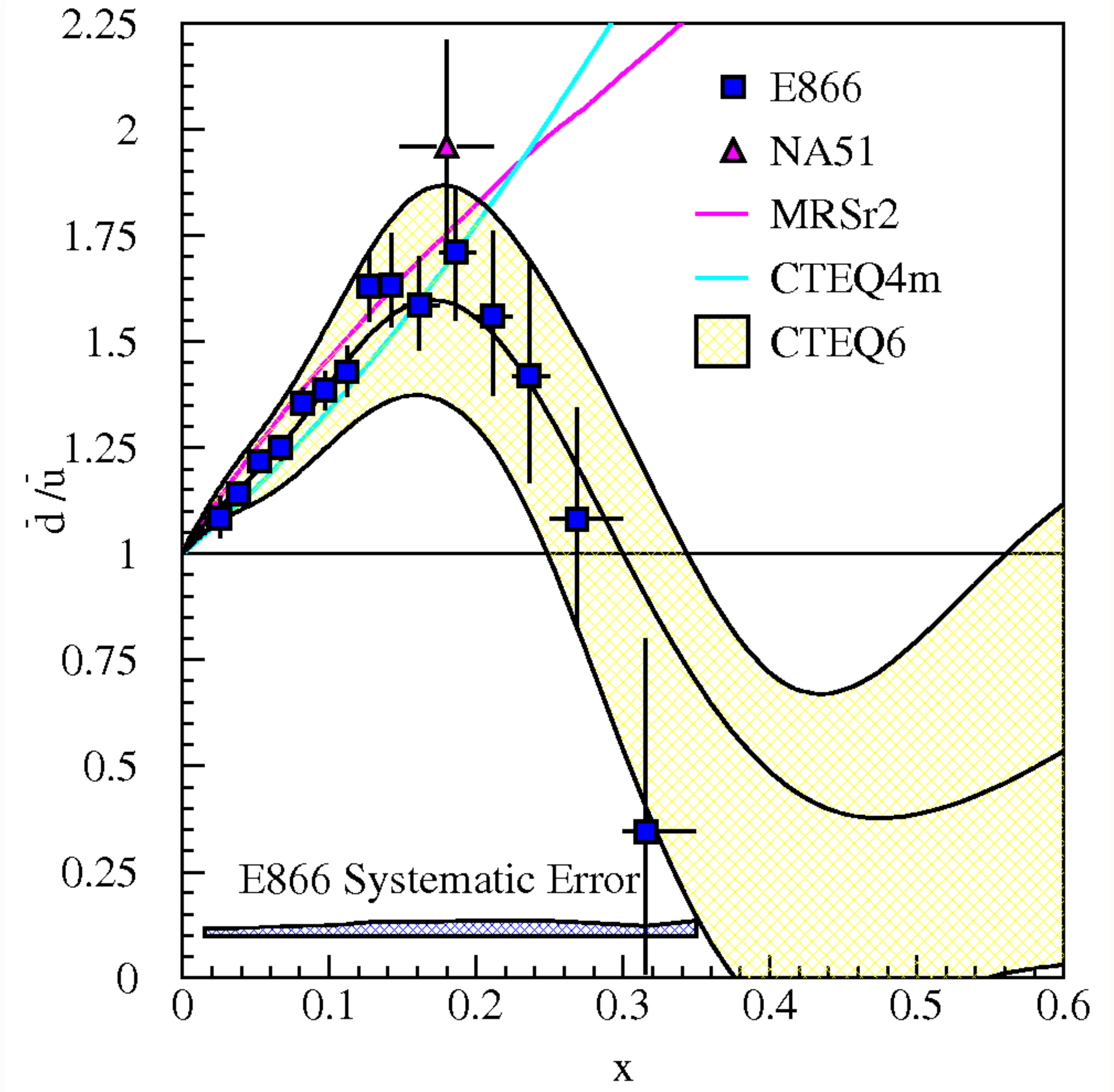
$$\Psi_n(x_i, \vec{k}_{\perp i}, \lambda_i)$$



Remarkable Features of Hadron Structure

- Valence quark helicity represents less than half of the proton's spin and momentum
- Non-zero quark orbital angular momentum!
- Asymmetric sea: $\bar{u}(x) \neq \bar{d}(x)$ relation to meson cloud
- Non-symmetric strange and anti-strange sea $\bar{s}(x) \neq s(x)$
- Intrinsic charm and bottom at high x $\Delta s(x) \neq \Delta \bar{s}(x)$
- Hidden-Color Fock states of the Deuteron

$\bar{d}(x)/\bar{u}(x)$ for $0.015 \leq x \leq 0.35$



- E866/NuSea (Drell-Yan)

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

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

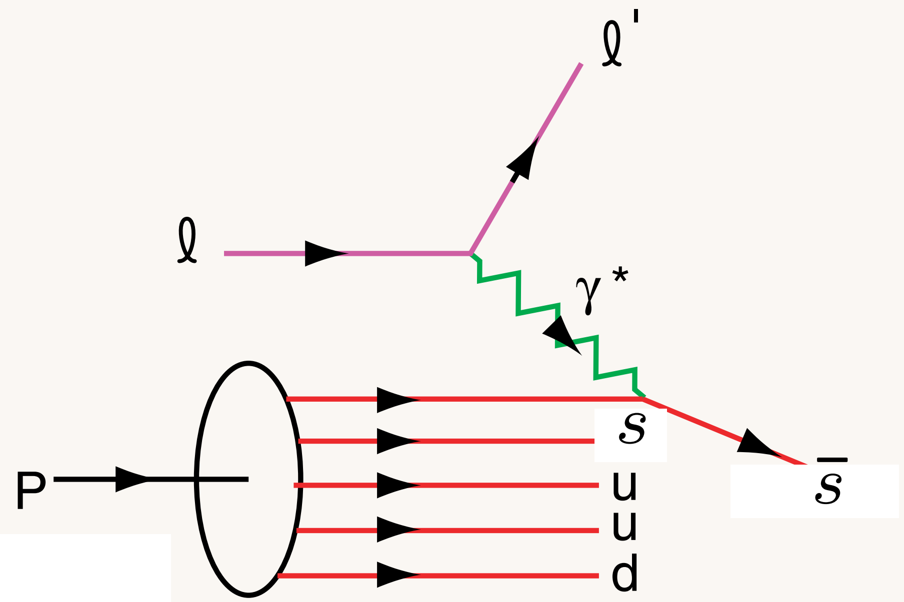
Intrinsic glue, sea, heavy quarks

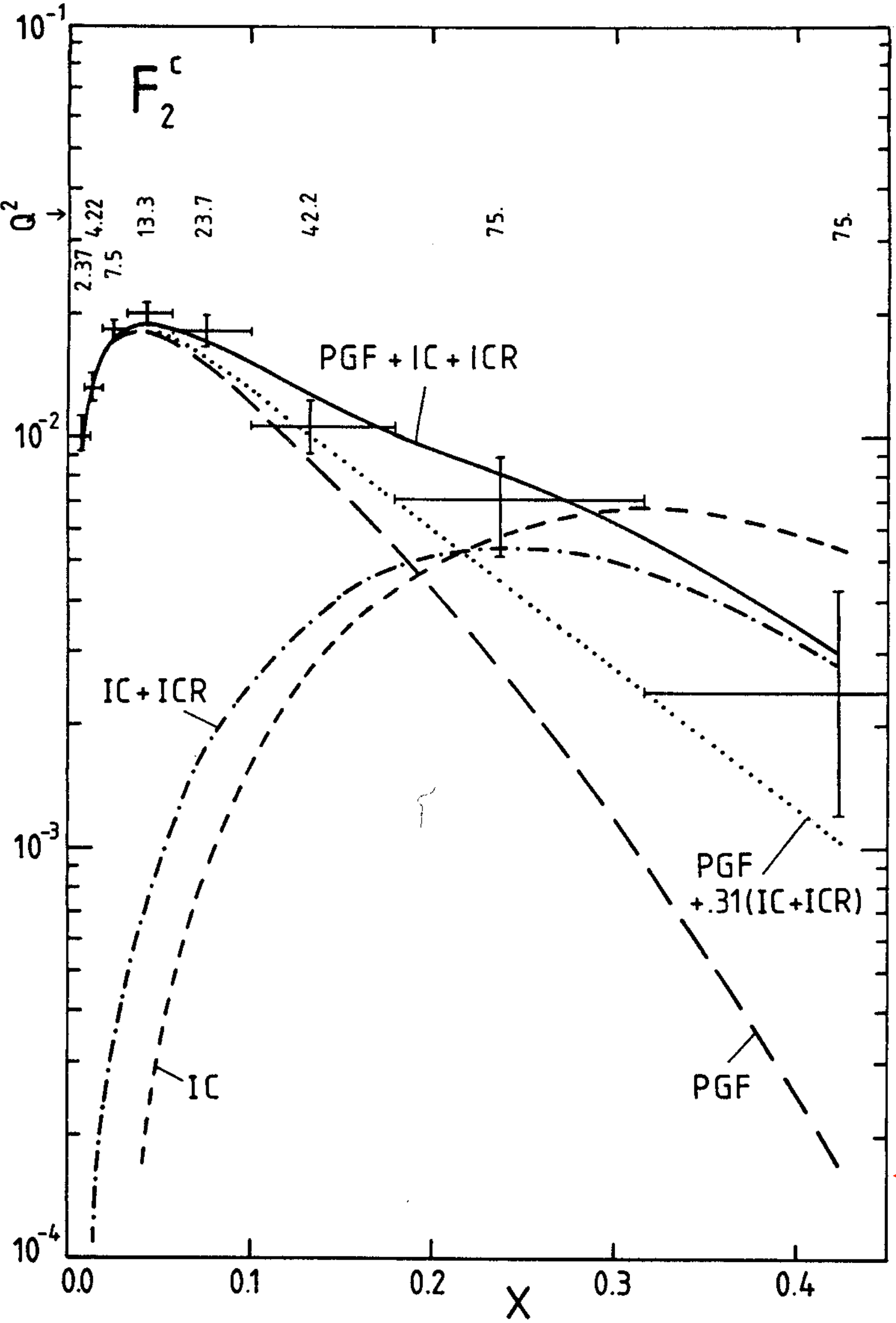
Measure strangeness distribution from DIS at EIC

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

- Non-symmetric strange and antistrange sea
- Non-perturbative input; e.g $|uuds\bar{s}> \simeq |\Lambda(uds)K^+(\bar{s}u)>$
- Crucial for interpreting NuTeV anomaly

Ma, sjb



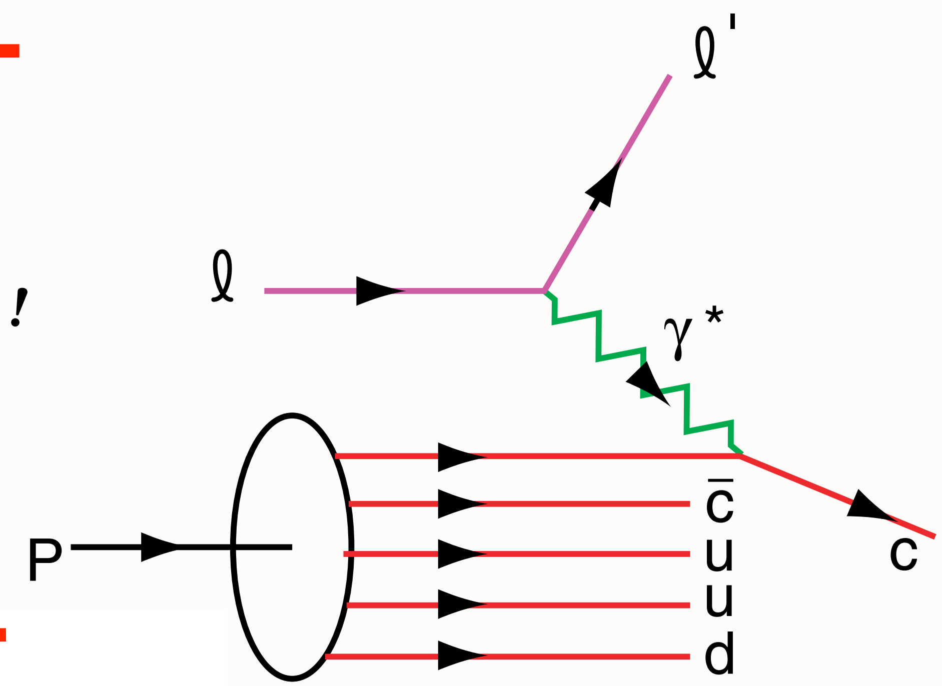


Measurement of Charm Structure Function

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

First Evidence for Intrinsic Charm

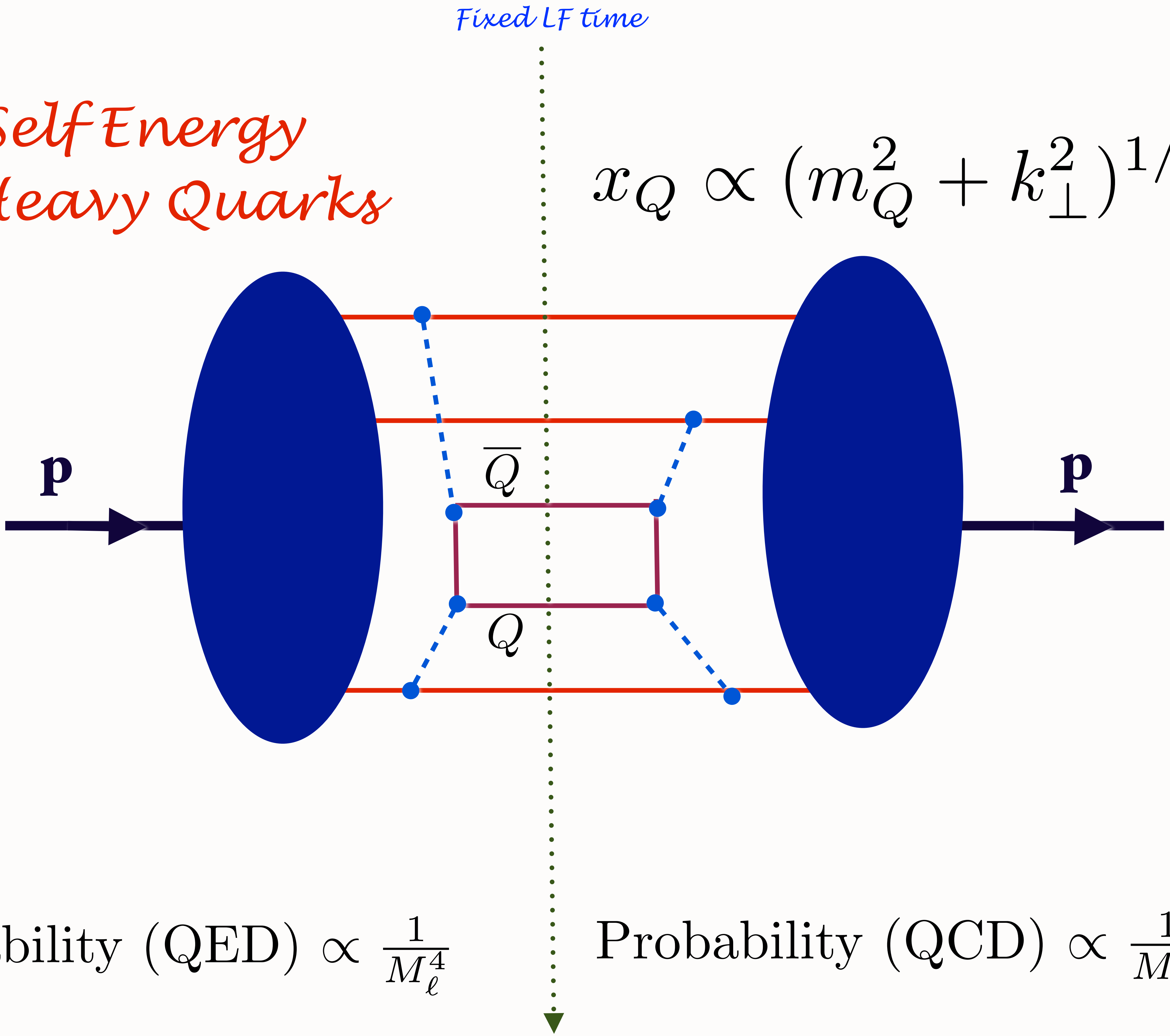
factor of 30 !



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

Proton Self Energy
Intrinsic Heavy Quarks

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

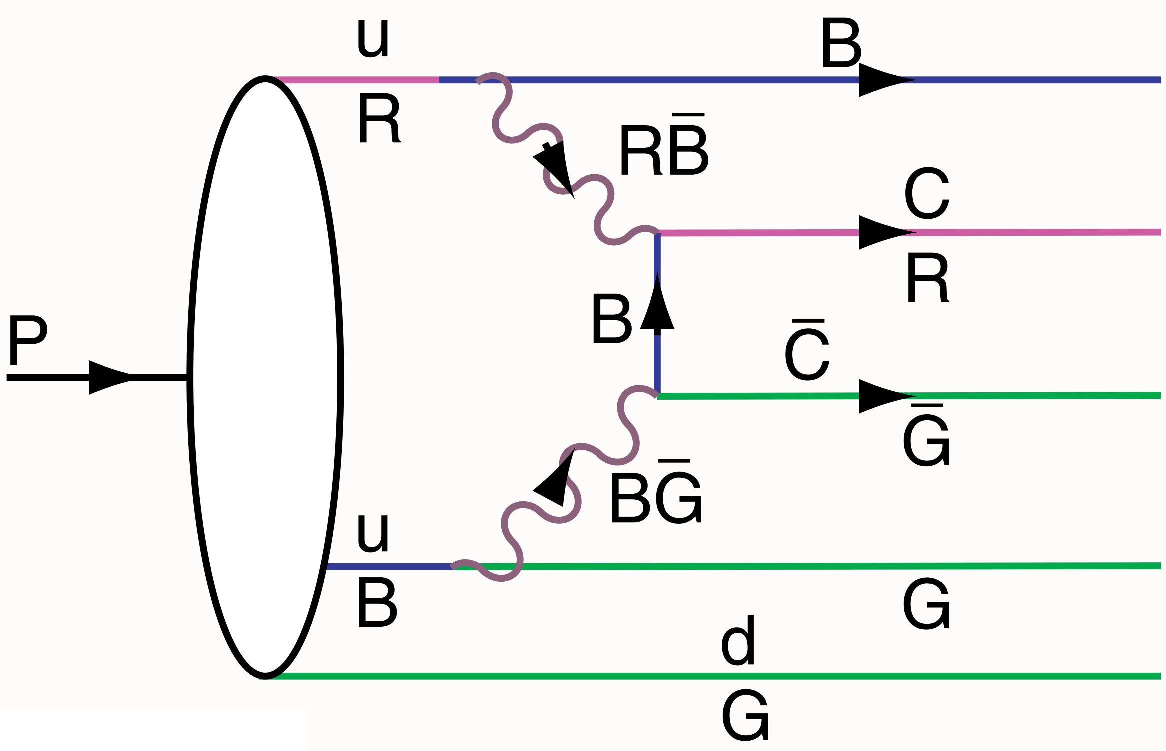


Probability (QED) $\propto \frac{1}{M_\ell^4}$

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

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

Hoyer, Peterson, Sakai, sjb



$|uudc\bar{c} >$ Fluctuation in Proton

QCD: Probability $\frac{\sim\Lambda^2_{QCD}}{M^2_Q}$

$|e^+e^-\ell^+\ell^- >$ Fluctuation in Positronium

QED: Probability $\frac{\sim(m_e\alpha)^4}{M^4_\ell}$

OPE derivation - M.Polyakov et al.

$< p|\frac{G^3_{\mu\nu}}{m^2_Q}|p >$ vs. $< p|\frac{F^4_{\mu\nu}}{m^4_\ell}|p >$

$c\bar{c}$ in Color Octet

Distribution peaks at equal rapidity (velocity)
Therefore heavy particles carry the largest momentum fractions

$$\hat{x}_i = \frac{m_{\perp i}}{\sum_j^n m_{\perp j}}$$

High x charm! *Charm at Threshold*

Action Principle: Minimum KE, maximal potential

- EMC data: $c(x,Q^2) > 30 \times$ DGLAP
  $Q^2 = 75$ GeV^2, $x = 0.42$

- High x_F $pp \to J/\psi X$

- High x_F $pp \to J/\psi J/\psi X$

- High x_F $pp \to \Lambda_c X$

- High x_F $pp \to \Lambda_b X$

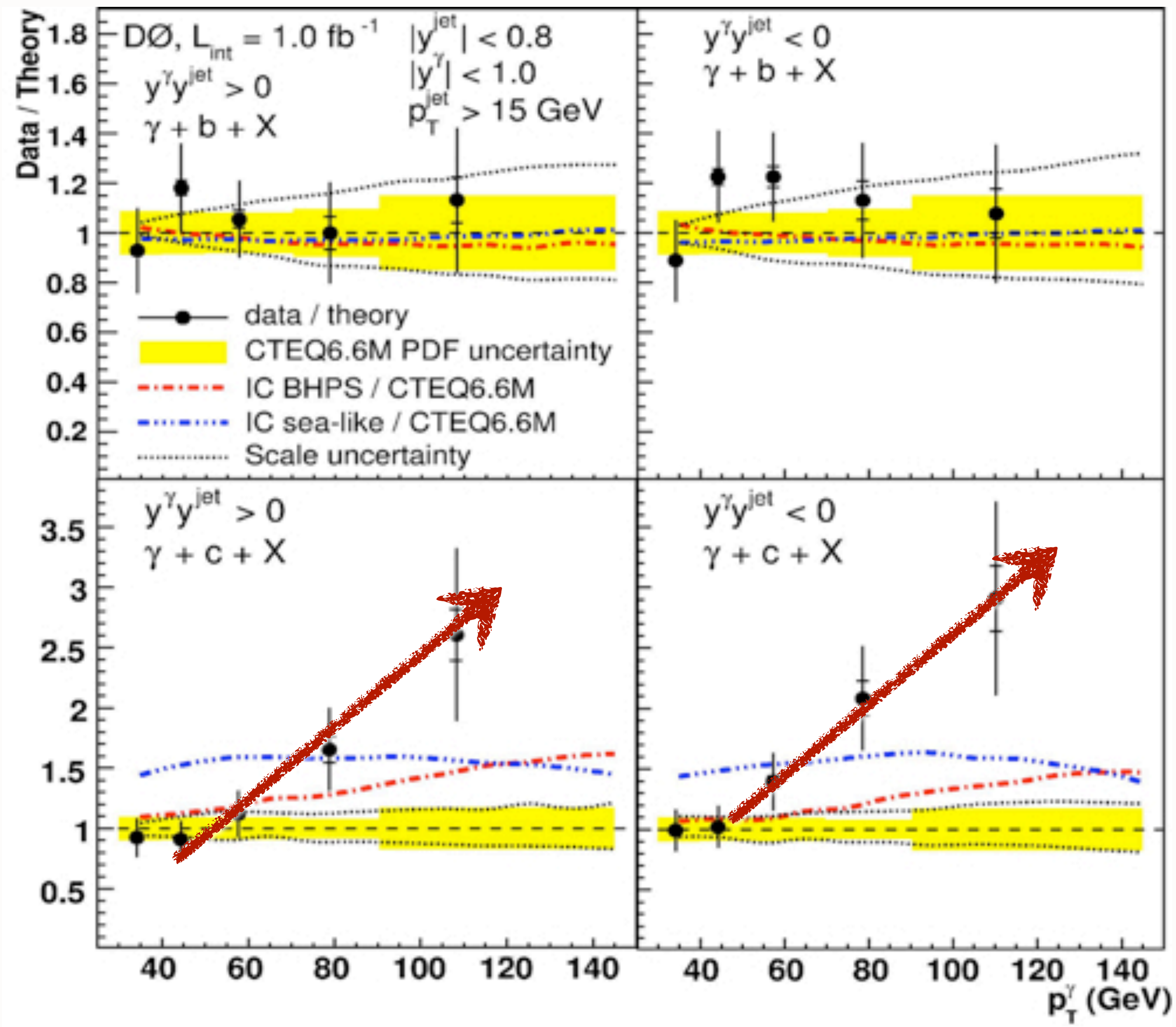
- High x_F $pp \to \Xi(ccd)X$ (SELEX)

IC Structure Function: Critical Measurement for EIC

Many interesting spin, charge asymmetry, spectator effects

PRL 102, 192002 (2009) PHYSICAL REVIEW LETTERS week ending 15 MAY 2009

Measurement of $\gamma + b + X$ and $\gamma + c + X$ Production Cross Sections in $p\bar{p}$ Collisions at $\sqrt{s} = 1.96$ TeV



$$\frac{\Delta\sigma(\bar{p}p \to \gamma c X)}{\Delta\sigma(\bar{p}p \to \gamma b X)}$$

Ratio insensitive to gluon PDF, scales

Signal for significant IC at x > 0.1 ?

Extraction of Various Five-Quark Components of the Nucleons

Wen-Chen Chang[a], Jen-Chieh Peng[a,b]

[a]*Institute of Physics, Academia Sinica, Taipei 11529, Taiwan*
[b]*Department of Physics, University of Illinois at Urbana-Champaign, Urbana, Illinois 61801, USA*

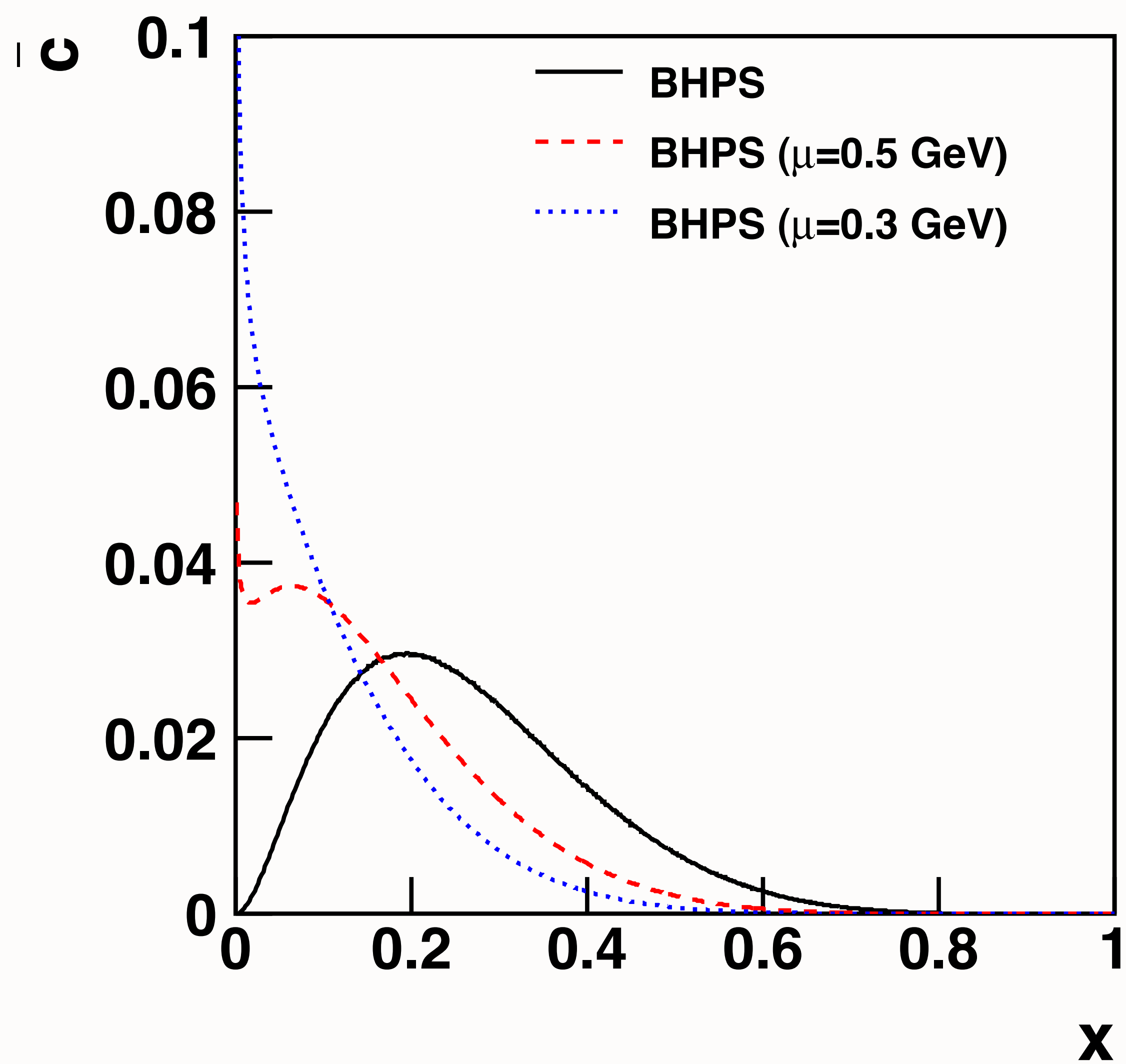


Figure 4: Calculations of the $\bar{c}(x)$ distributions based on the BHPS model. The solid curve corresponds to the calculation using Eq. 1 and the dashed and dotted curves are obtained by evolving the BHPS result to $Q^2 = 10$ GeV^2 using $\mu = 0.5$ GeV and $\mu = 0.3$ GeV, respectively. The normalization is set at $\mathcal{P}_5^{c\bar{c}} = 0.01$.

Extraction of Various Five-Quark Components of the Nucleons

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[a] *Institute of Physics, Academia Sinica, Taipei 11529, Taiwan*
[b] *Department of Physics, University of Illinois at Urbana-Champaign, Urbana, Illinois 61801, USA*

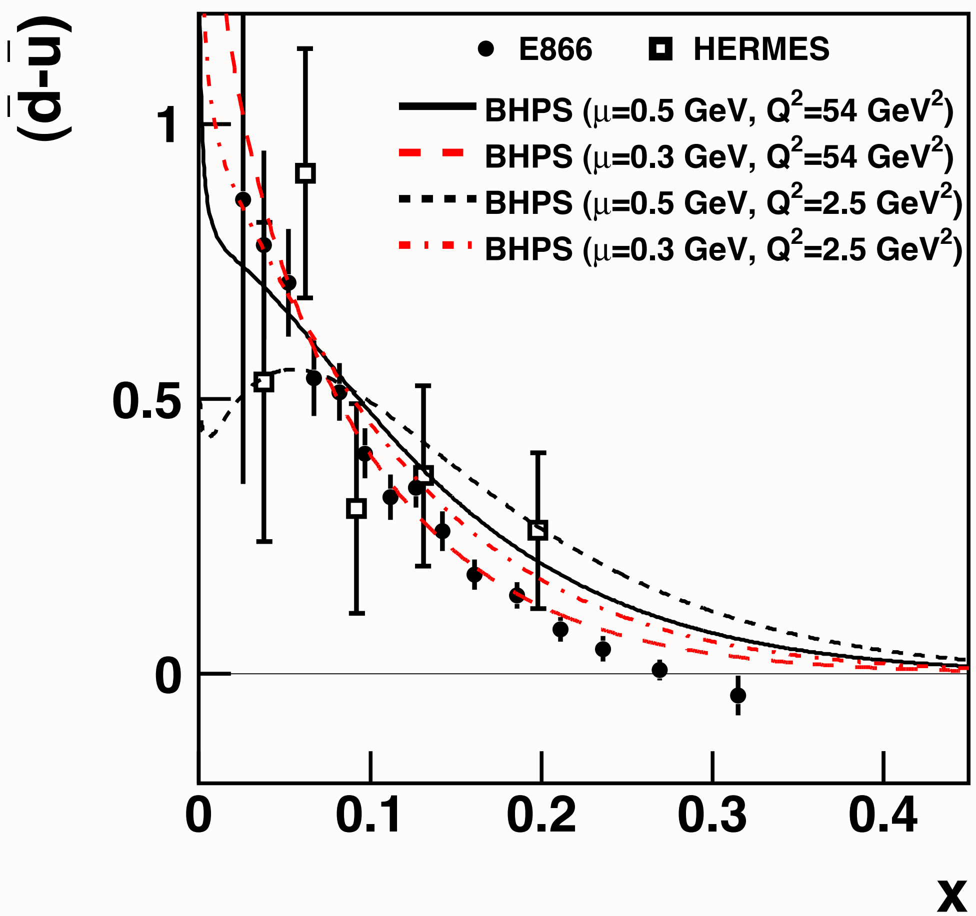


Figure 1: Comparison of the $\bar{d}(x)-\bar{u}(x)$ data from Fermilab E866 and HERMES with the calculations based on the BHPS model. Eq. 1 and Eq. 3 were used to calculate the $\bar{d}(x)-\bar{u}(x)$ distribution at the initial scale. The distribution was then evolved to the Q^2 of the experiments and shown as various curves. Two different initial scales, $\mu = 0.5$ and 0.3 GeV, were used for the E866 calculations in order to illustrate the dependence on the choice of the initial scale.

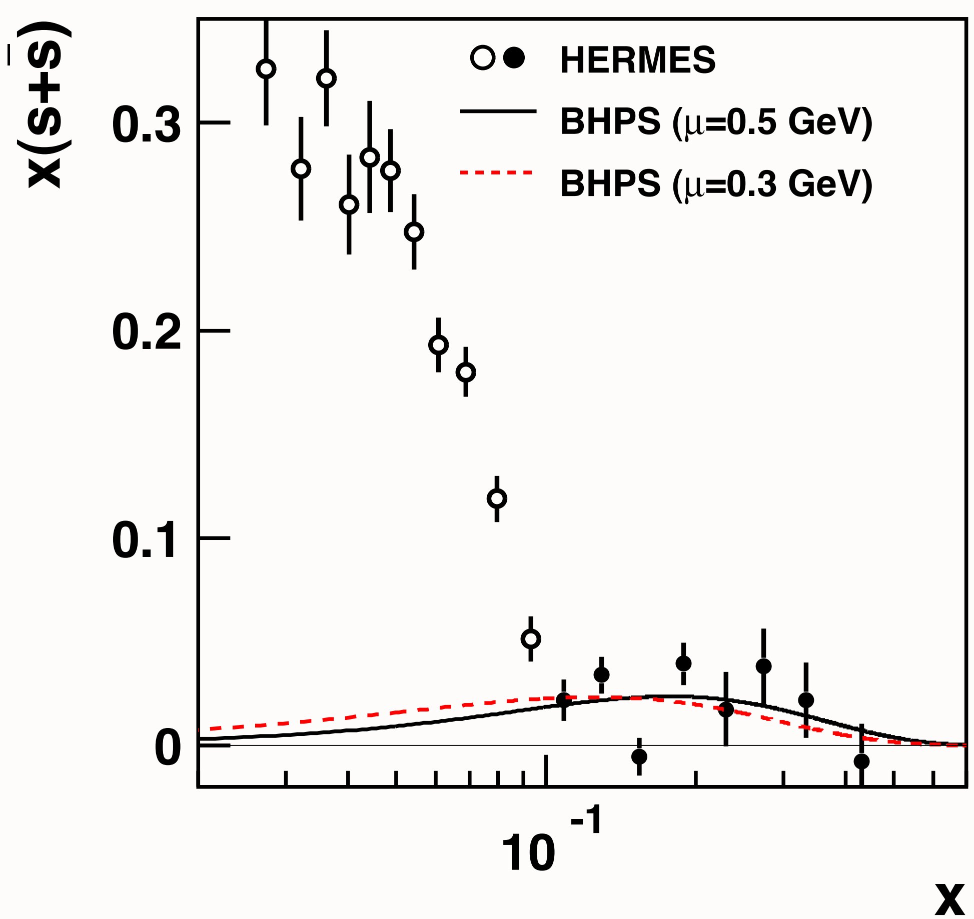


Figure 2: Comparison of the HERMES $x(s(x)-\bar{s}(x))$ data with the calculations based on the BHPS model. The solid and dashed curves are obtained by evolving the BHPS result to $Q^2 = 2.5$ GeV^2 using $\mu = 0.5$ GeV and $\mu = 0.3$ GeV, respectively. The normalizations of the calculations are adjusted to fit the data at $x > 0.1$ with statistical errors only, denoted by solid circles.

- IC Explains Anomalous $\alpha(x_F)$ not $\alpha(x_2)$ dependence of $pA \to J/\psi X$ (Mueller, Gunion, Tang, SJB)

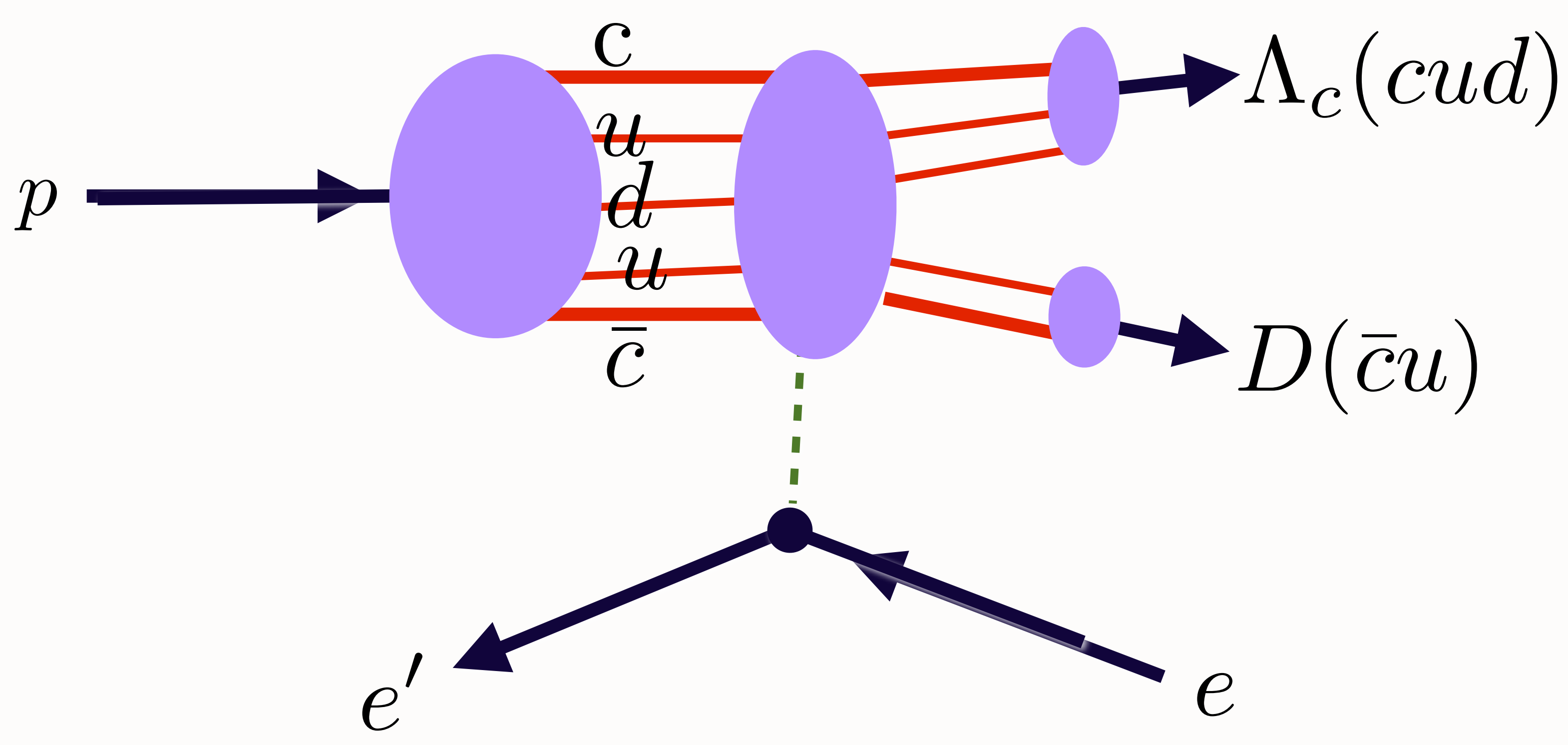
- Color Octet IC Explains $A^{2/3}$ behavior at high x_F (NA3, Fermilab) (Kopeliovitch, Schmidt, Soffer, SJB)

Color Opaqueness

- IC Explains $J/\psi \to \rho\pi$ puzzle (Karliner, SJB)

- IC leads to new effects in B decay (Gardner, SJB)

Higgs production at x_F = 0.8

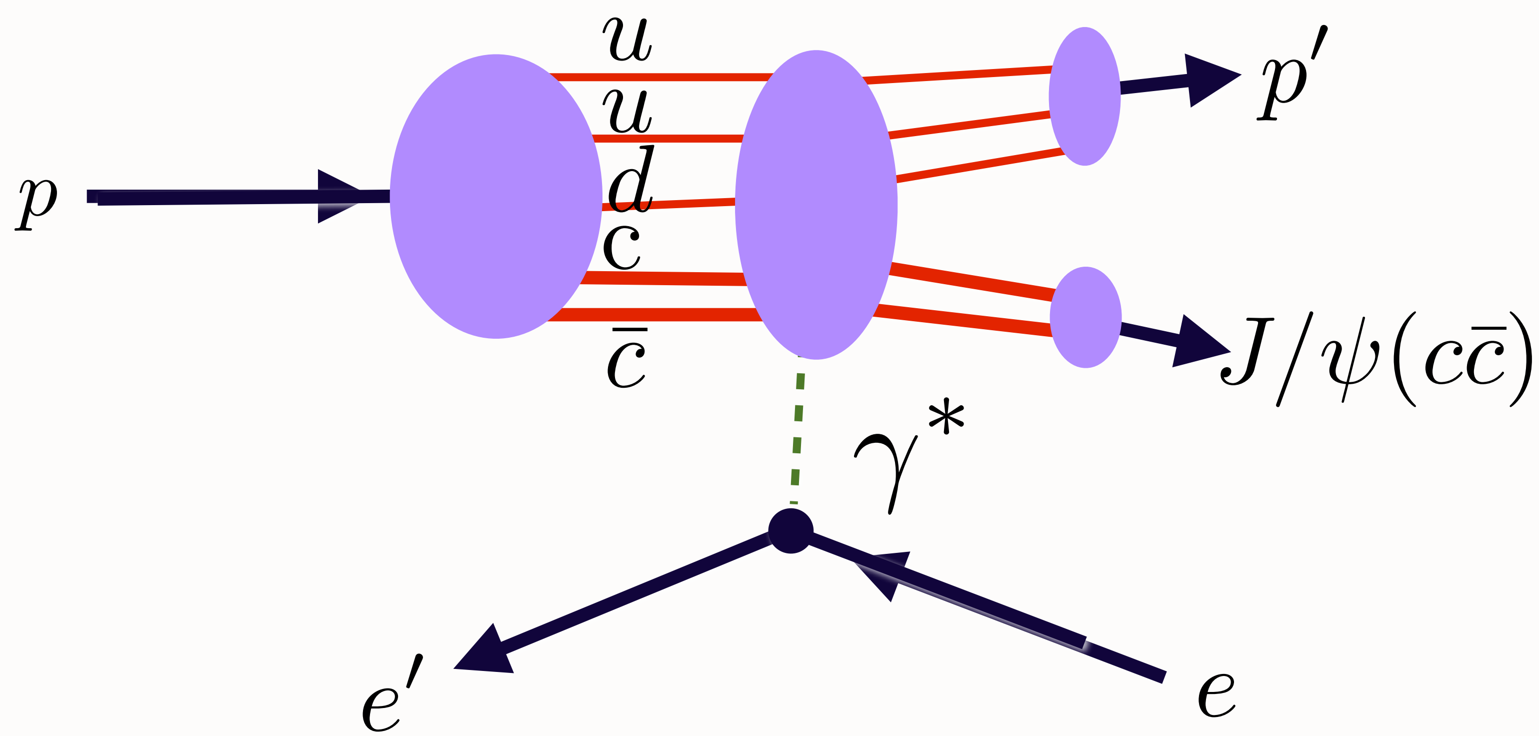


JLAb 12 Experiment

Dissociate proton to high x_F heavy-quark pair

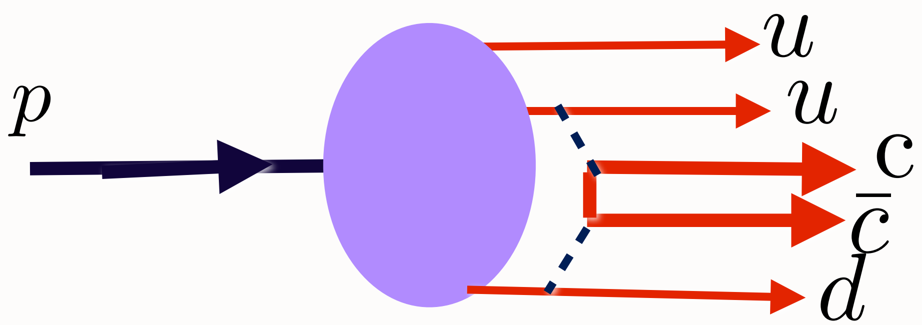
$$\gamma^* p \to \Lambda_c(cdd) + D(\bar{c}u)$$

Test intrinsic charm



Lansberg, sjb

Dissociate proton to high x_F Quarkonium:



$$\gamma^* p \to J/\psi + p'$$

$$\gamma^* p \to \Upsilon + p'$$

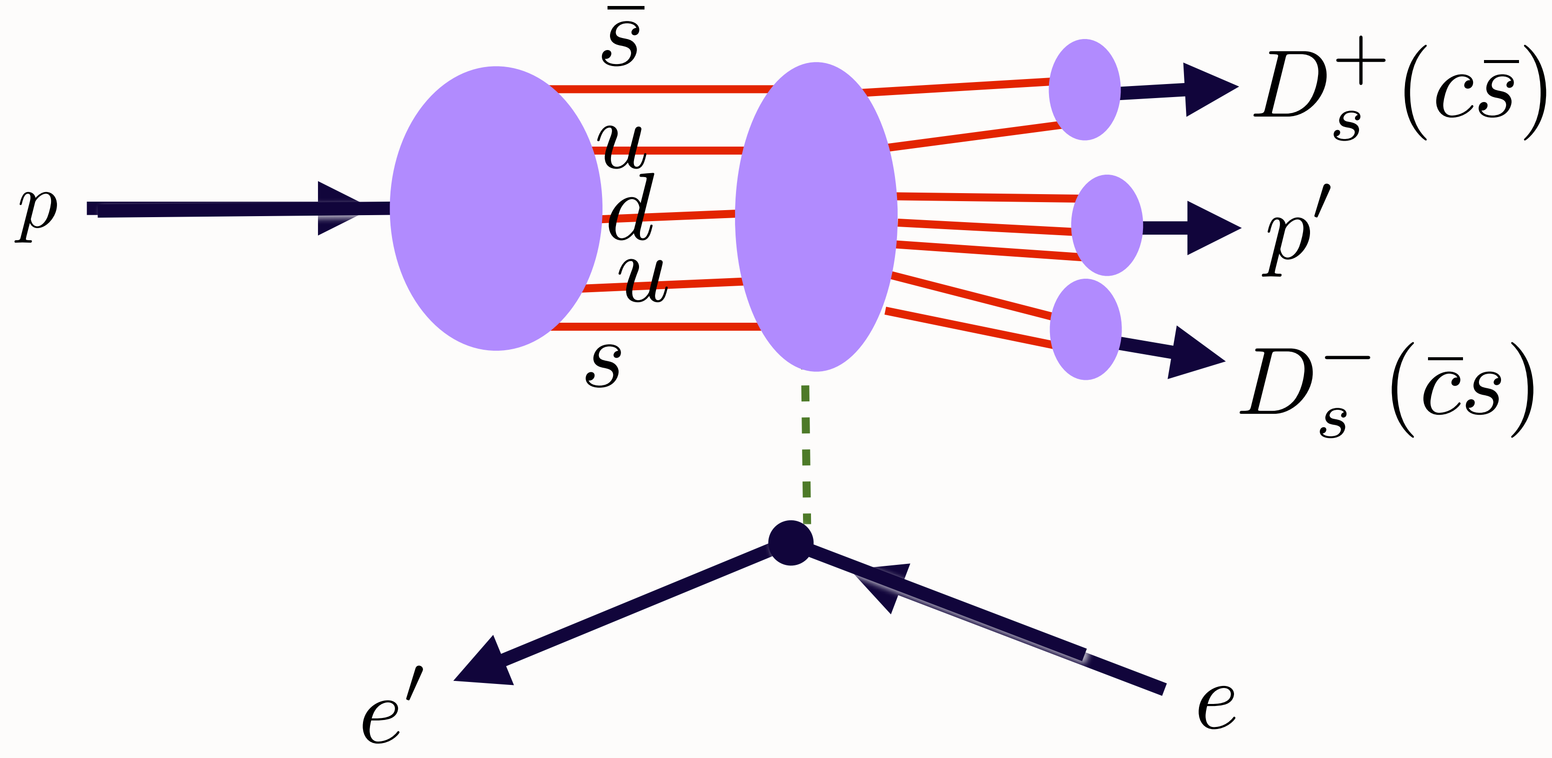
But disfavored since

$$|p> \simeq |(uud)_{8_C}(c\bar{c})_{8C}>$$

Test intrinsic charm, bottom

Collins, Ellis, Haber, Mueller, sjb

M. Polyakov et al.



Look for $D_s^-(\bar{c}s)$ vs. $D_s^+(c\bar{s})$ asymmetry

Reflects s vs. $\bar{s}$ asymmetry in proton $|uuds\bar{s}>$ Fock LF state.

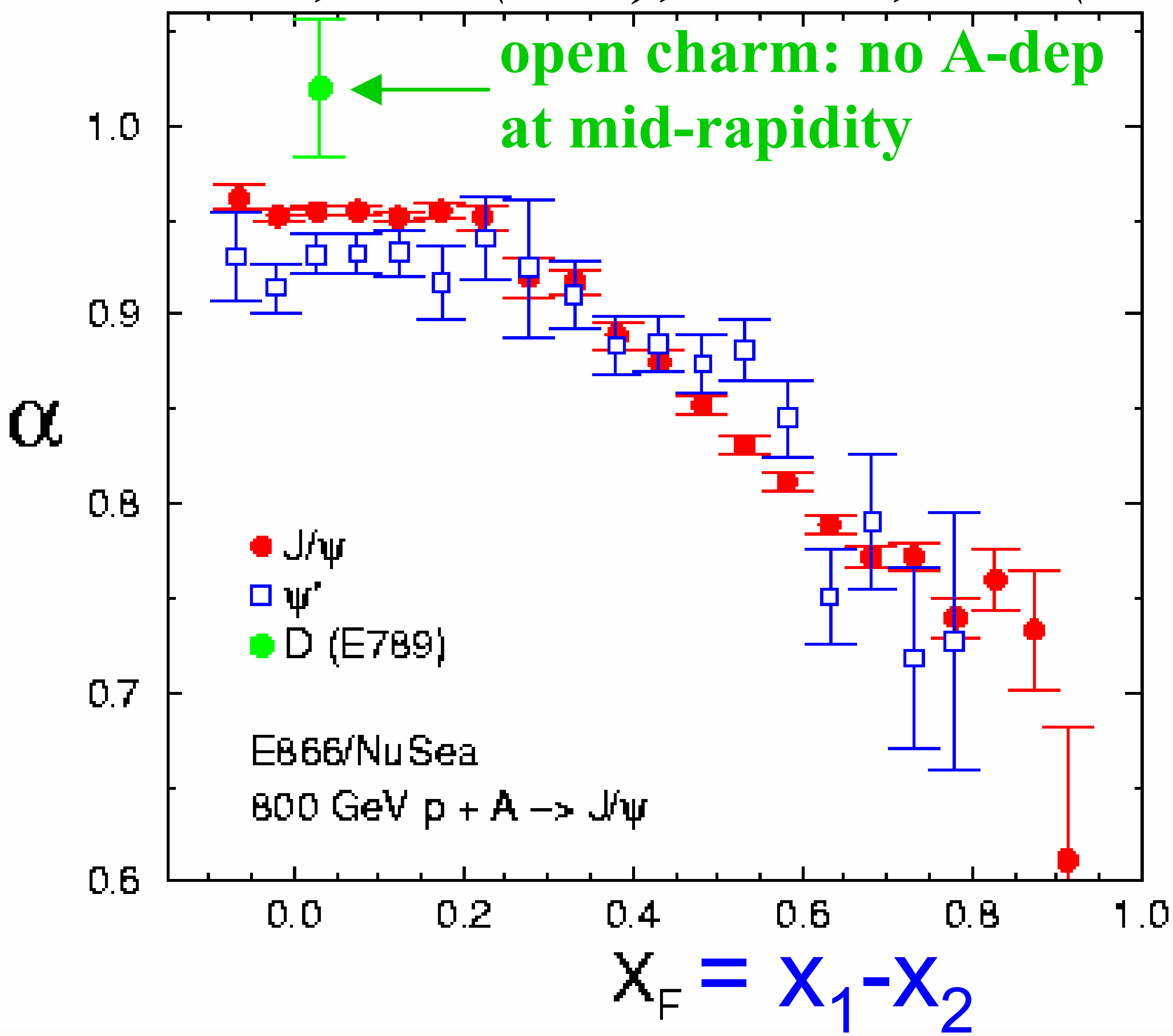
Asymmetry natural from $|K^+\Lambda>$ excitation **Ma, sjb**

Assumes symmetric charm and anti-charm distributions

M. Leitch

800 GeV p-A (FNAL) $\sigma_A = \sigma_p * A^\alpha$

PRL 84, 3256 (2000); PRL 72, 2542 (1994)



$$\frac{d\sigma}{dx_F}(pA \to J/\psi X)$$

Remarkably Strong Nuclear Dependence for Fast Charmonium

Violation of PQCD Factorization!

Huge $A^{2/3}$ effect at large x_F

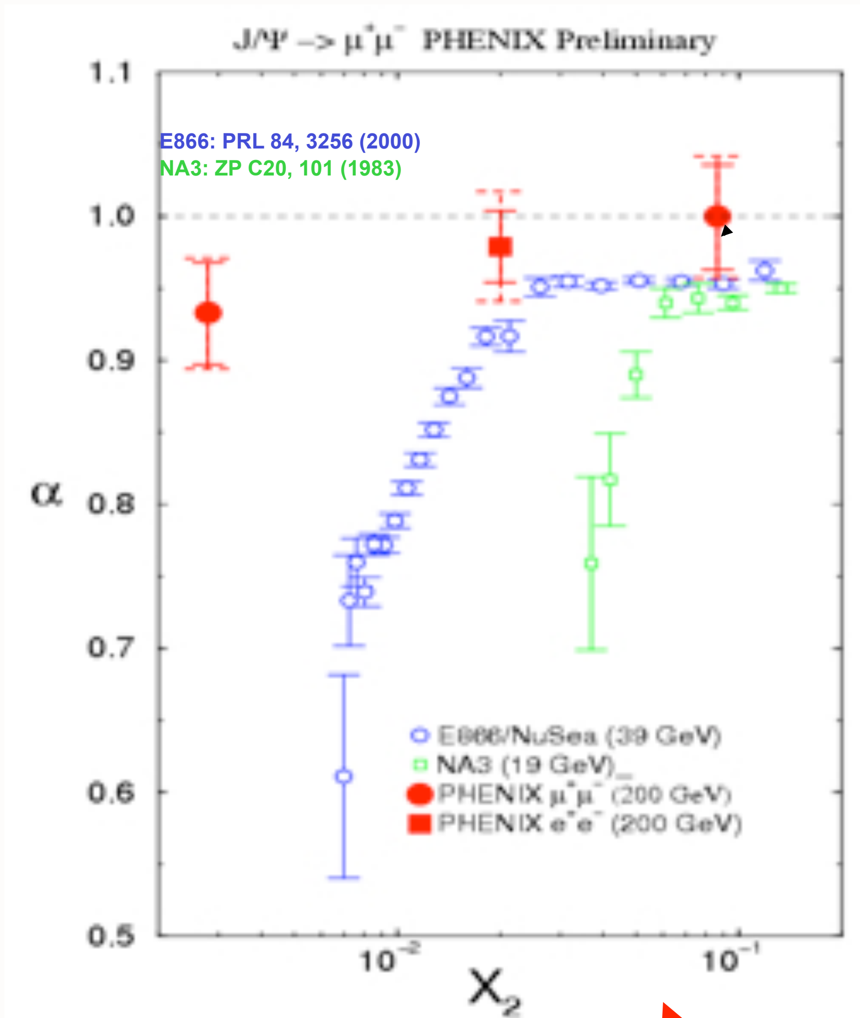
Violation of factorization in charm hadroproduction.
P. Hoyer, M. Vanttinen (Helsinki U.) , U. Sukhatme (Illinois U., Chicago) . HU-TFT-90-14, May 1990. 7pp.
Published in Phys.Lett.B246:217-220,1990

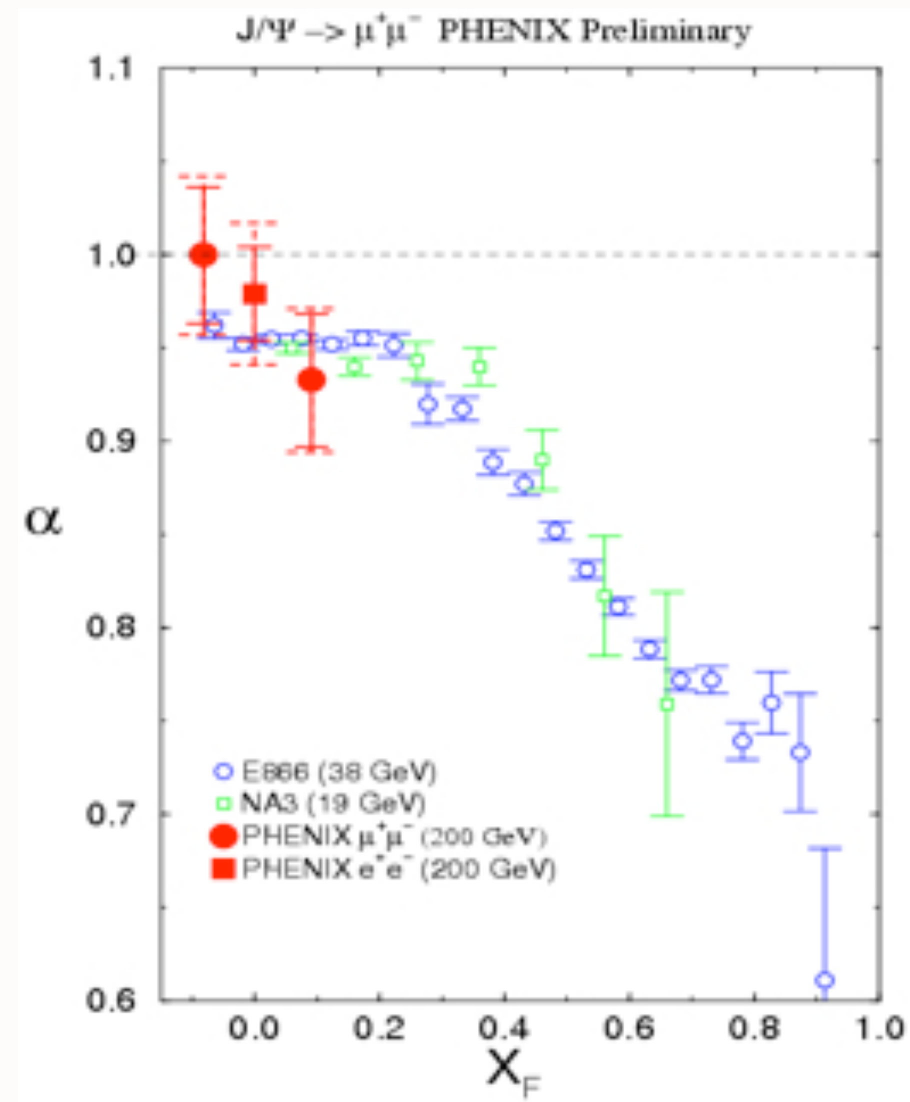
IC Explains large excess of quarkonia at large x_F, A-dependence

J/ψ nuclear dependence vrs rapidity, x_{Au}, x_F

M.Leitch

PHENIX compared to lower energy measurements





Klein,Vogt, PRL 91:142301,2003
Kopeliovich, NP A696:669,2001

Huge "absorption" effect

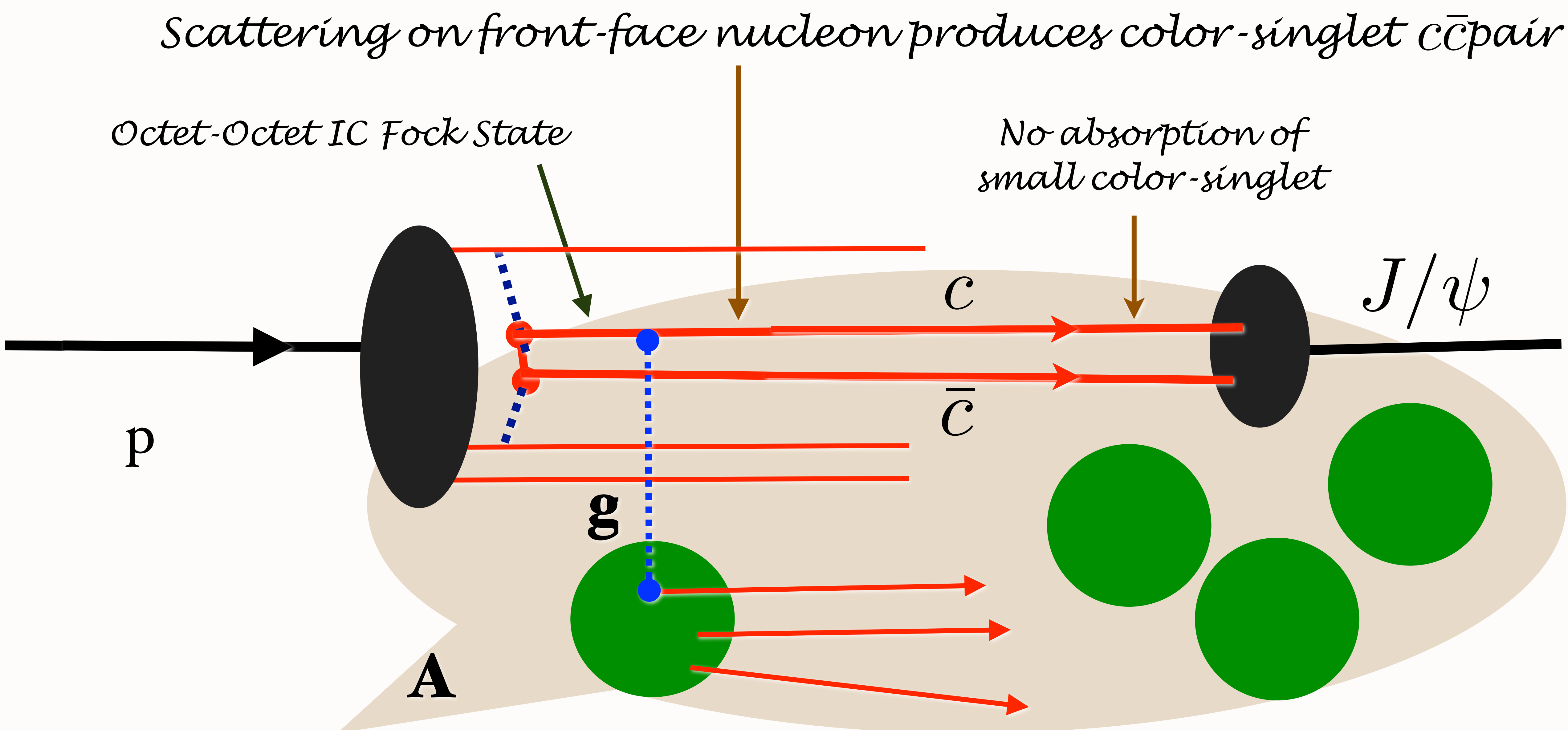
Violates PQCD factorization!

$$\frac{d\sigma}{dx_F}(pA \to J/\psi X)$$

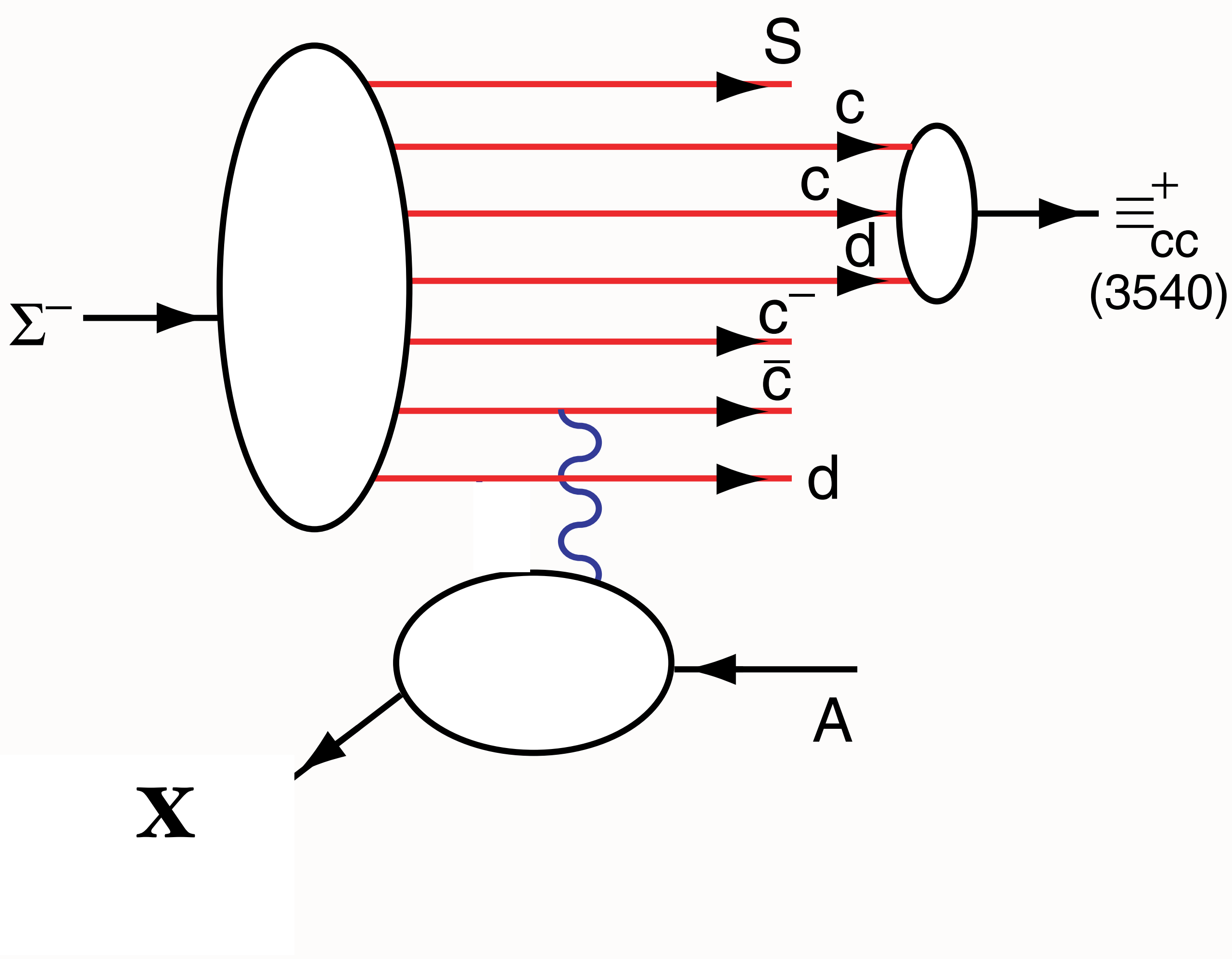
Hoyer, Sukhatme, Vanttinen

Color-Opaque IC Fock state interacts on nuclear front surface

Kopeliovich, Schmidt, Soffer, sjb



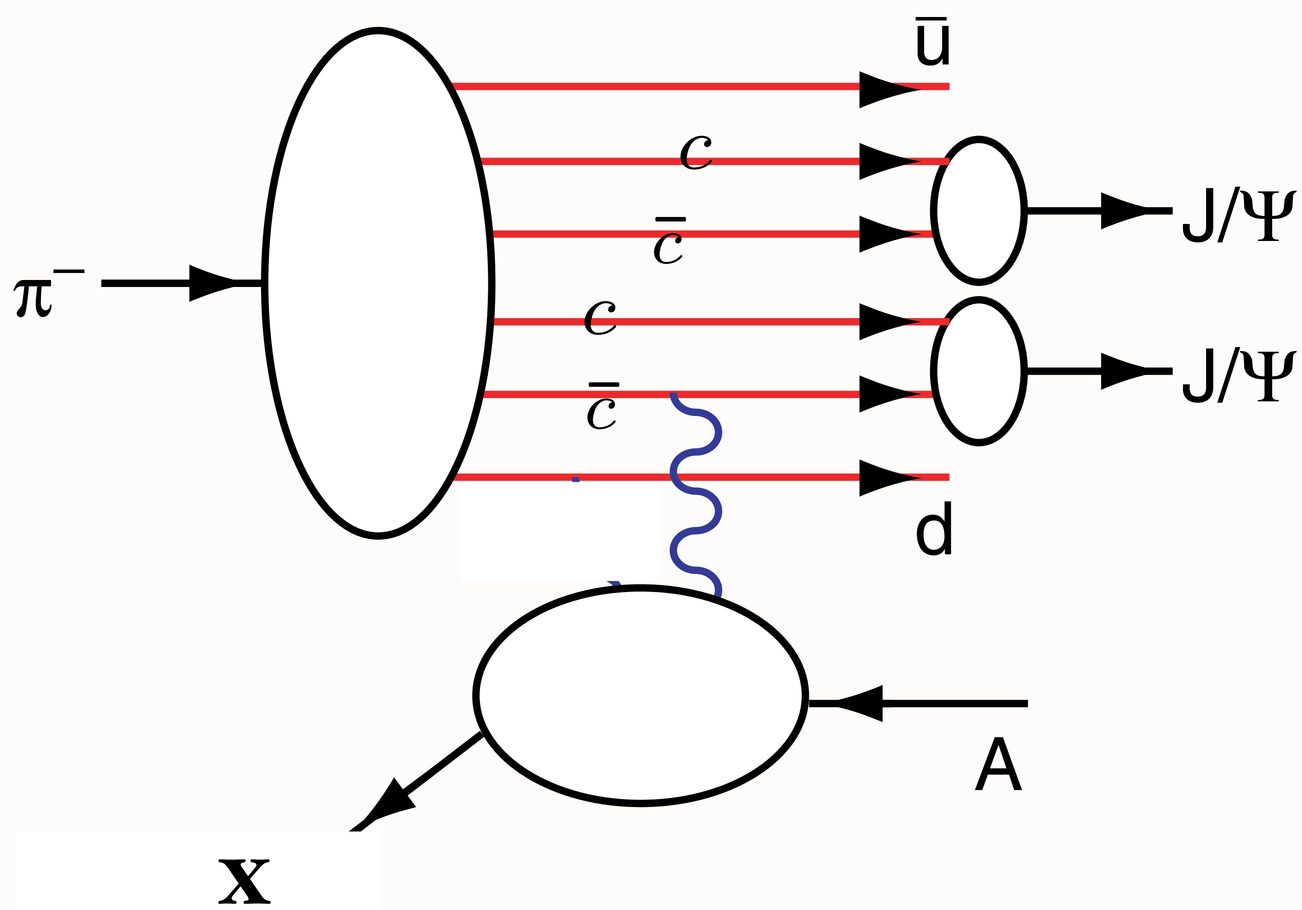
$$\frac{d\sigma}{dx_F}(pA \to J/\psi X) = A^{2/3} \times \frac{d\sigma}{dx_F}(pN \to J/\psi X)$$



Production of a Double-Charm Baryon

SELEX high x_F $< x_F >= 0.33$

Production of Two Charmonia at High x_F



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

Excludes `color drag' model

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

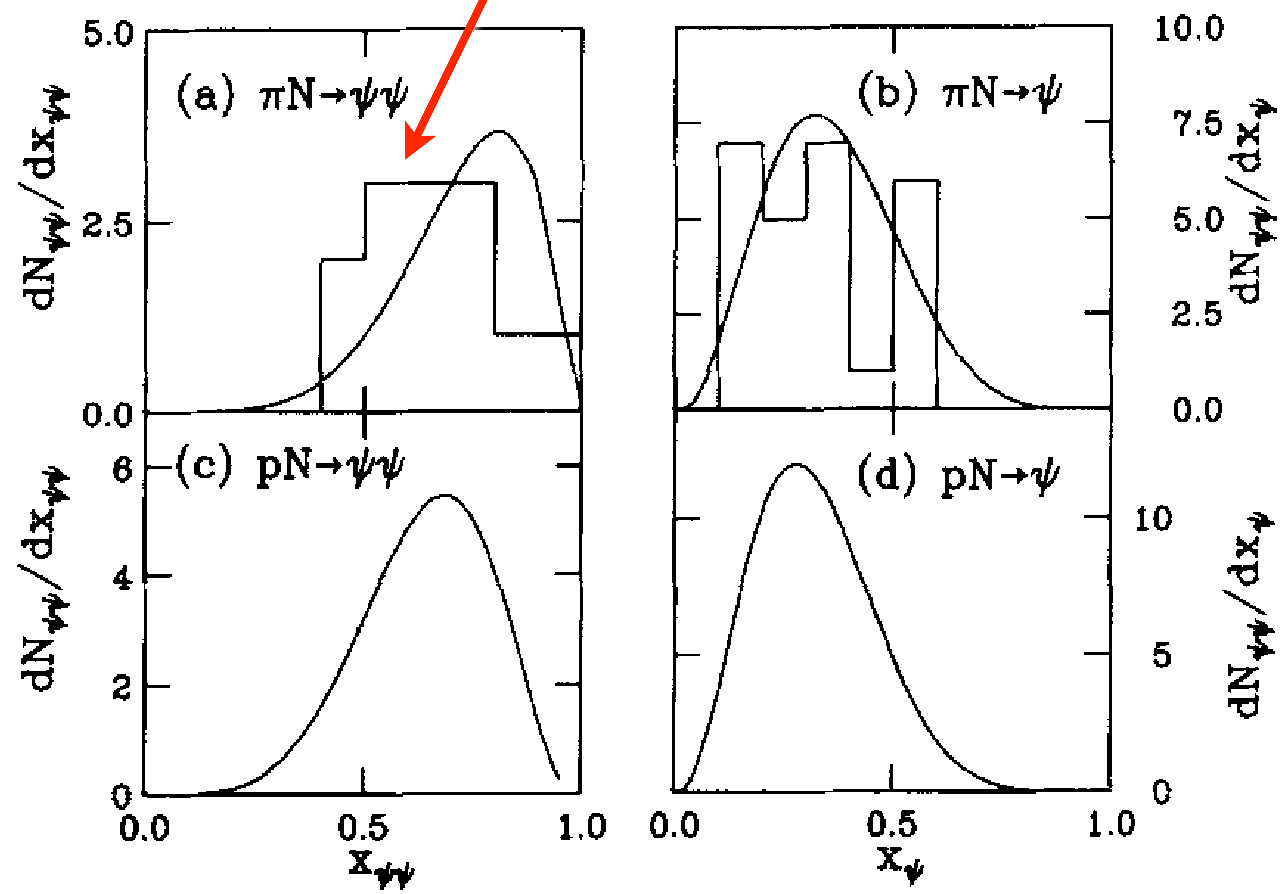


Fig. 3. The $\psi\psi$ pair distributions are shown in (a) and (c) for the pion and proton projectiles. Similarly, the distributions of J/ψ's from the pairs are shown in (b) and (d). Our calculations are compared with the $\pi^- N$ data at 150 and 280 GeV/c [1]. The $x_{\psi\psi}$ distributions are normalized to the number of pairs from both pion beams (a) and the number of pairs from the 400 GeV proton measurement (c). The number of single J/ψ's is twice the number of pairs.

NA3 Data

Intrinsic charm contribution to double quarkonium hadroproduction ★

R. Vogt[a], S.J. Brodsky[b]

The probability distribution for a general n-parti intrinsic $c\bar{c}$ Fock state as a function of x and k_T written as

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

- IC Explains Anomalous $\alpha(x_F)$ not $\alpha(x_2)$ dependence of $pA \to J/\psi X$ (Mueller, Gunion, Tang, SJB)

- Color Octet IC Explains $A^{2/3}$ behavior at high x_F (NA3, Fermilab) (Kopeliovitch, Schmidt, Soffer, SJB)

Color Opaqueness

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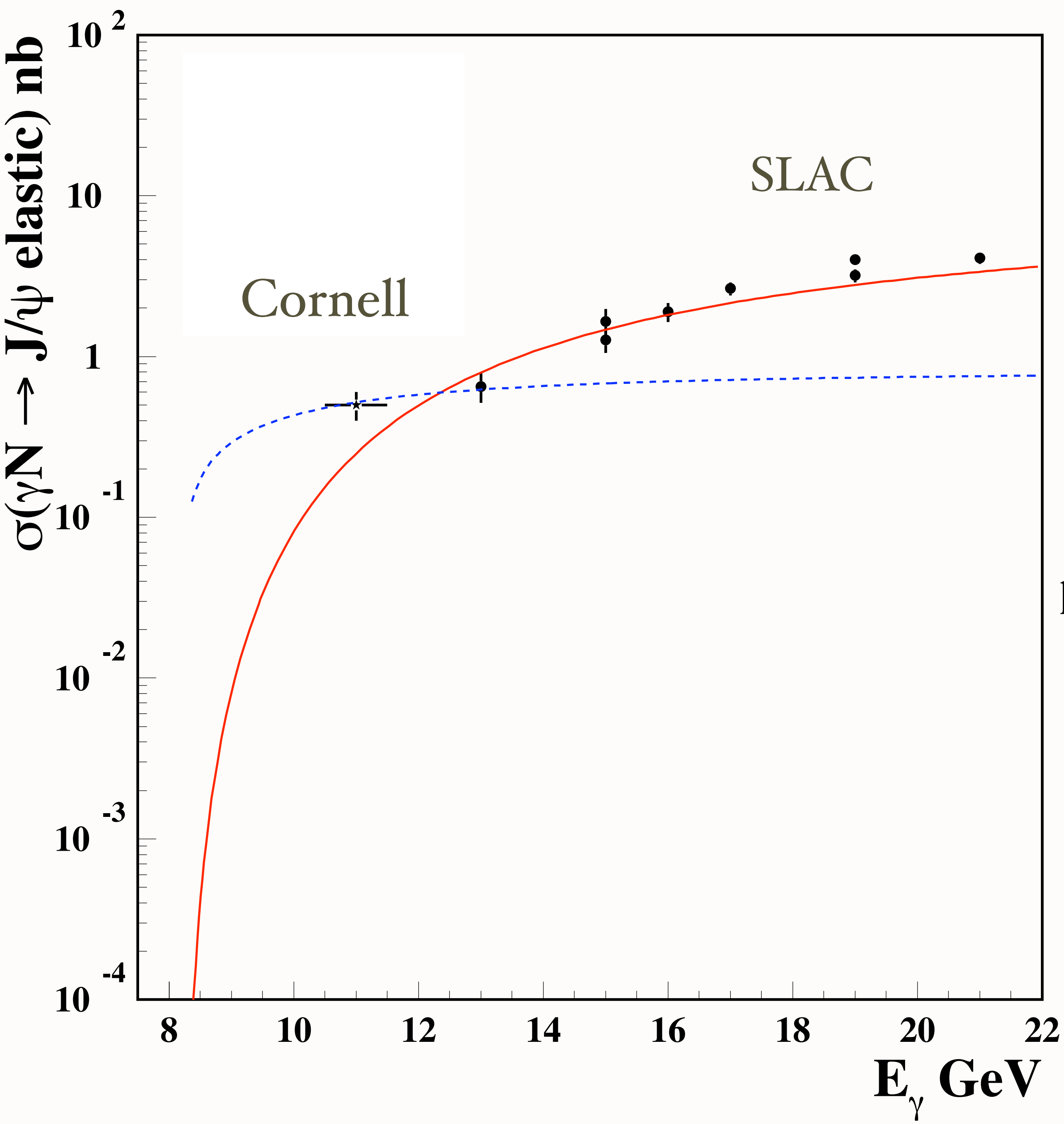
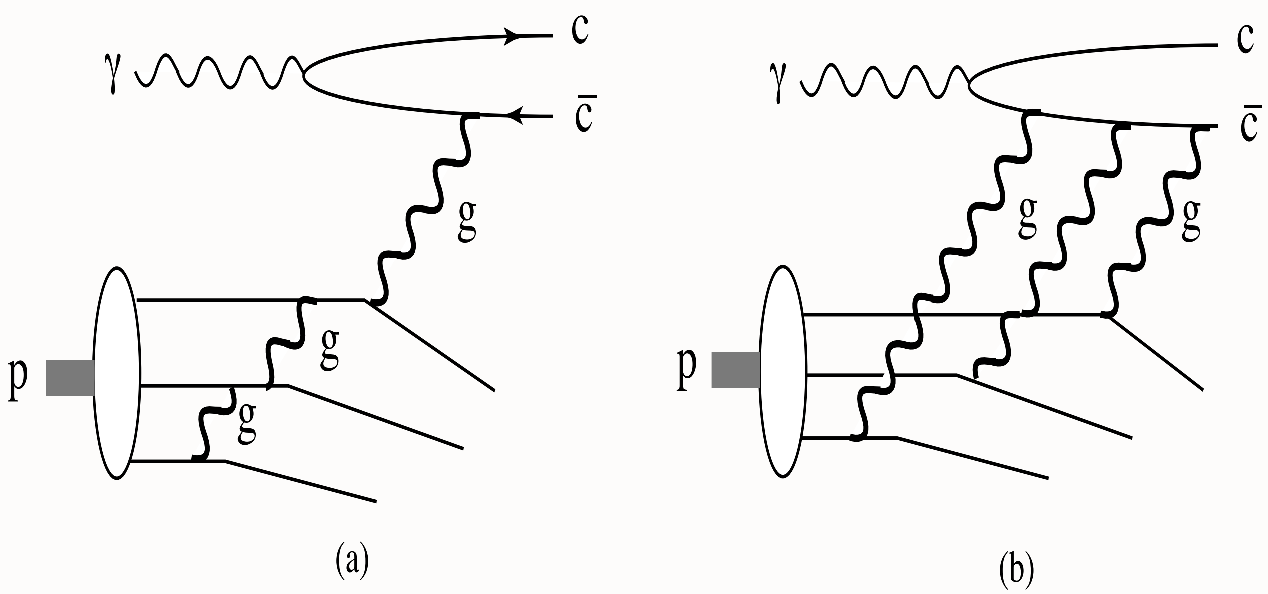
- IC leads to new effects in B decay (Gardner, SJB)

Higgs production at x_F = 0.8

$$\gamma p \to J/\psi p$$

Chudakov, Hoyer, Laget, sjb





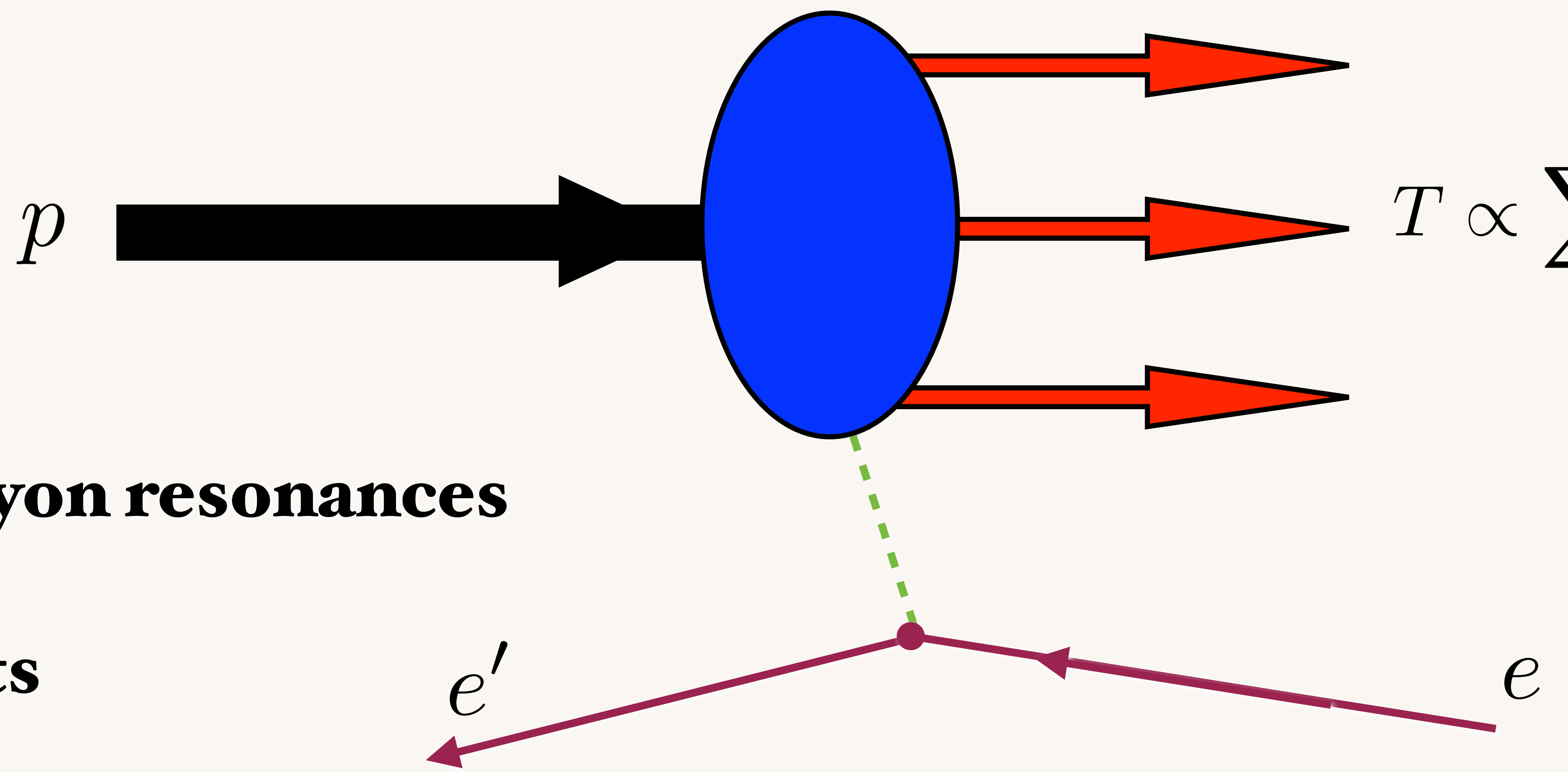
Leading twist contribution

Dominant near threshold

Use extreme caution when using $\gamma g \to c\bar{c}$ or $gg \to \bar{c}c$ to tag gluon dynamics

Interpret Electroproduction as Coulombic Excitation

Many possible B= 1 final states can reveal electric-dipole structure of proton LFWF



$$T \propto \sum_j e_j \frac{d}{d\vec{k}_{\perp j}} \psi_n(x_i, \vec{k}_{\perp i}, \lambda$$

- **baryon resonances**
- **3 jets**
- **exclusive meson-baryon; baryon-meson-meson**
- **exclusive charm and bottom pairs; charmed and bottom baryons; heavy quarkonium from heavy quark intrinsic sea**
- **"hidden-color states from deuteron such as Δ Δ**

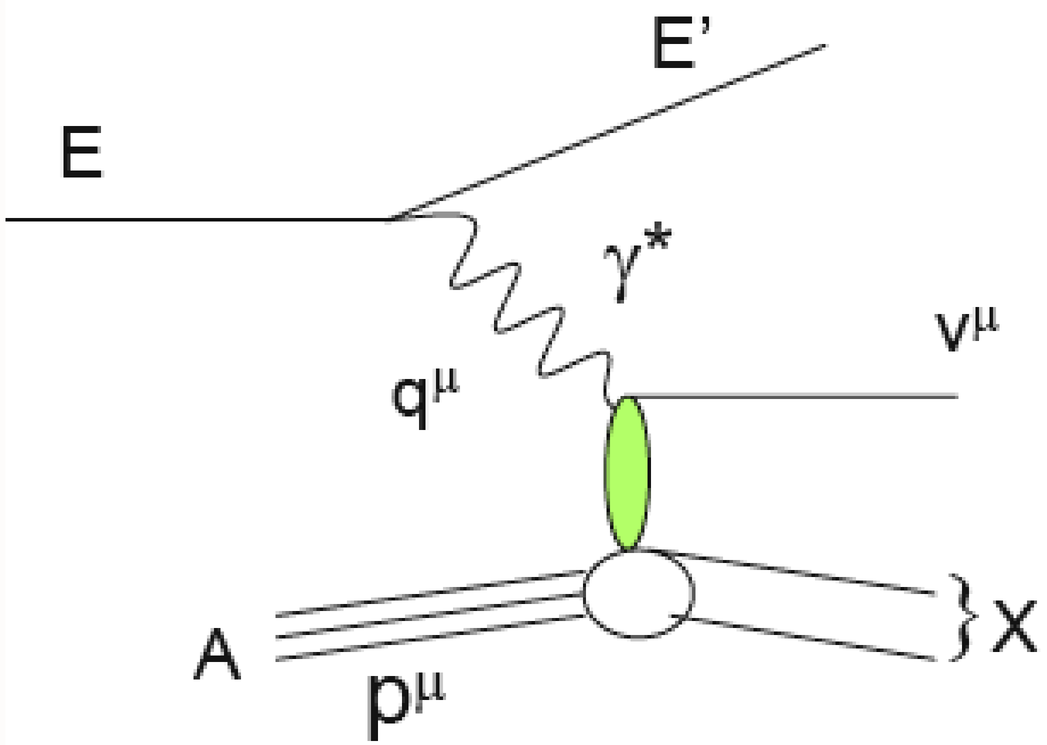
Color Transparency

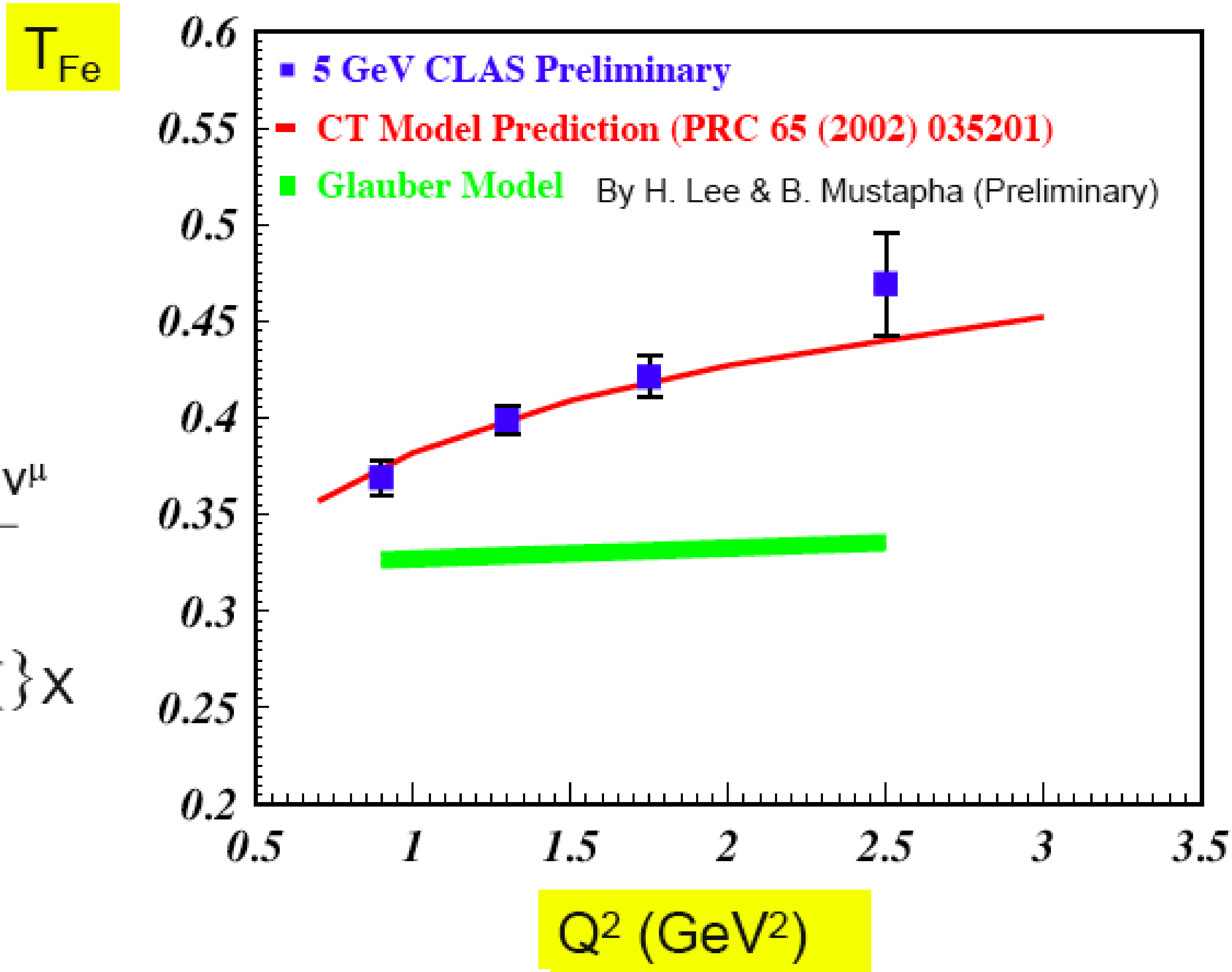
Bertsch, Gunion, Goldhaber, sjb

A. H. Mueller, sjb

- Fundamental test of gauge theory in hadron physics
- Small color dipole moments interact weakly in nuclei
- Complete coherence at high energies
- Clear Demonstration of CT from Diffractive Di-Jets

Kawtar Hafidi

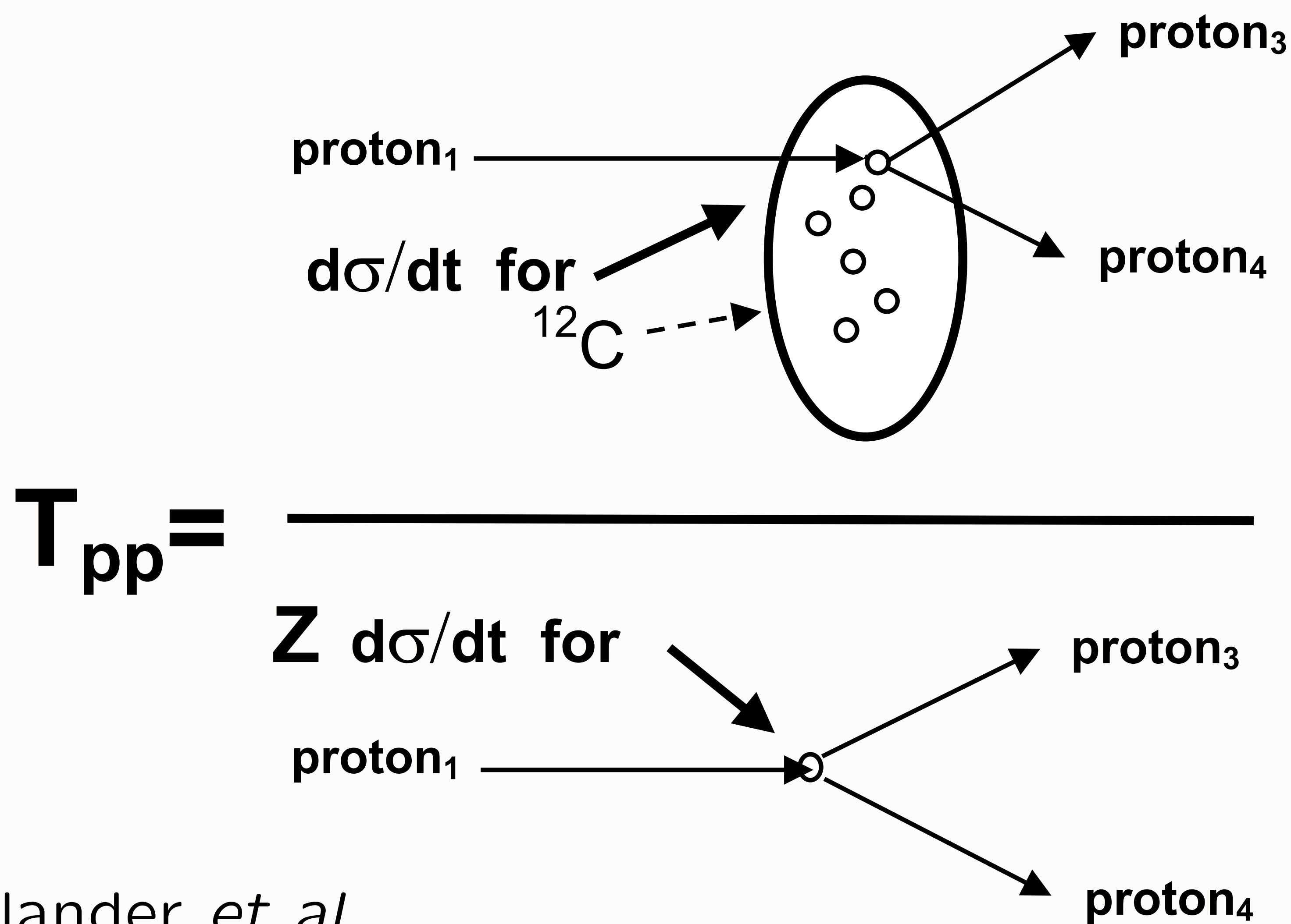




Theory:

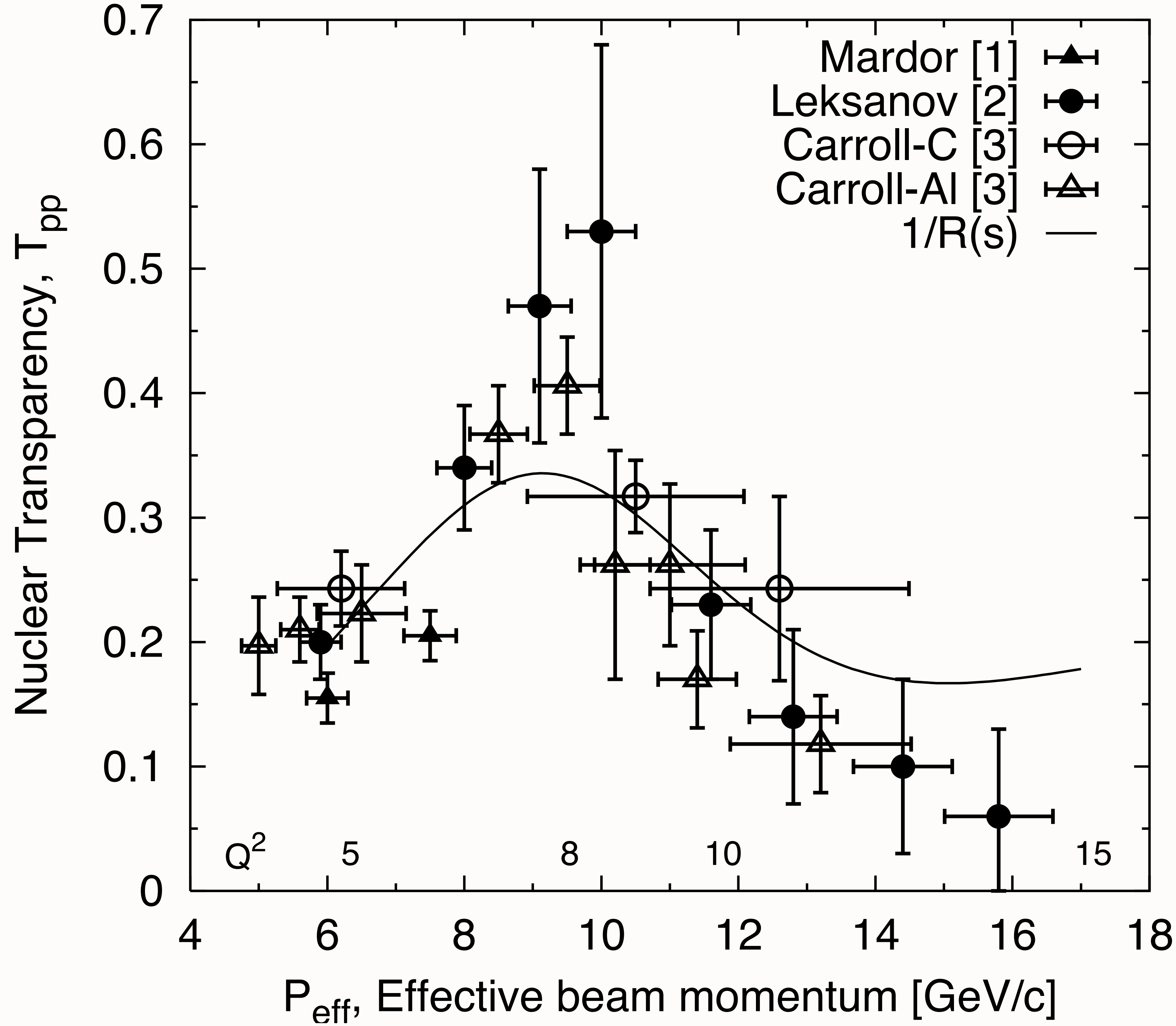
Kopeliovich et al., PRC 65 (2002) 035201

Color Transparency Ratio



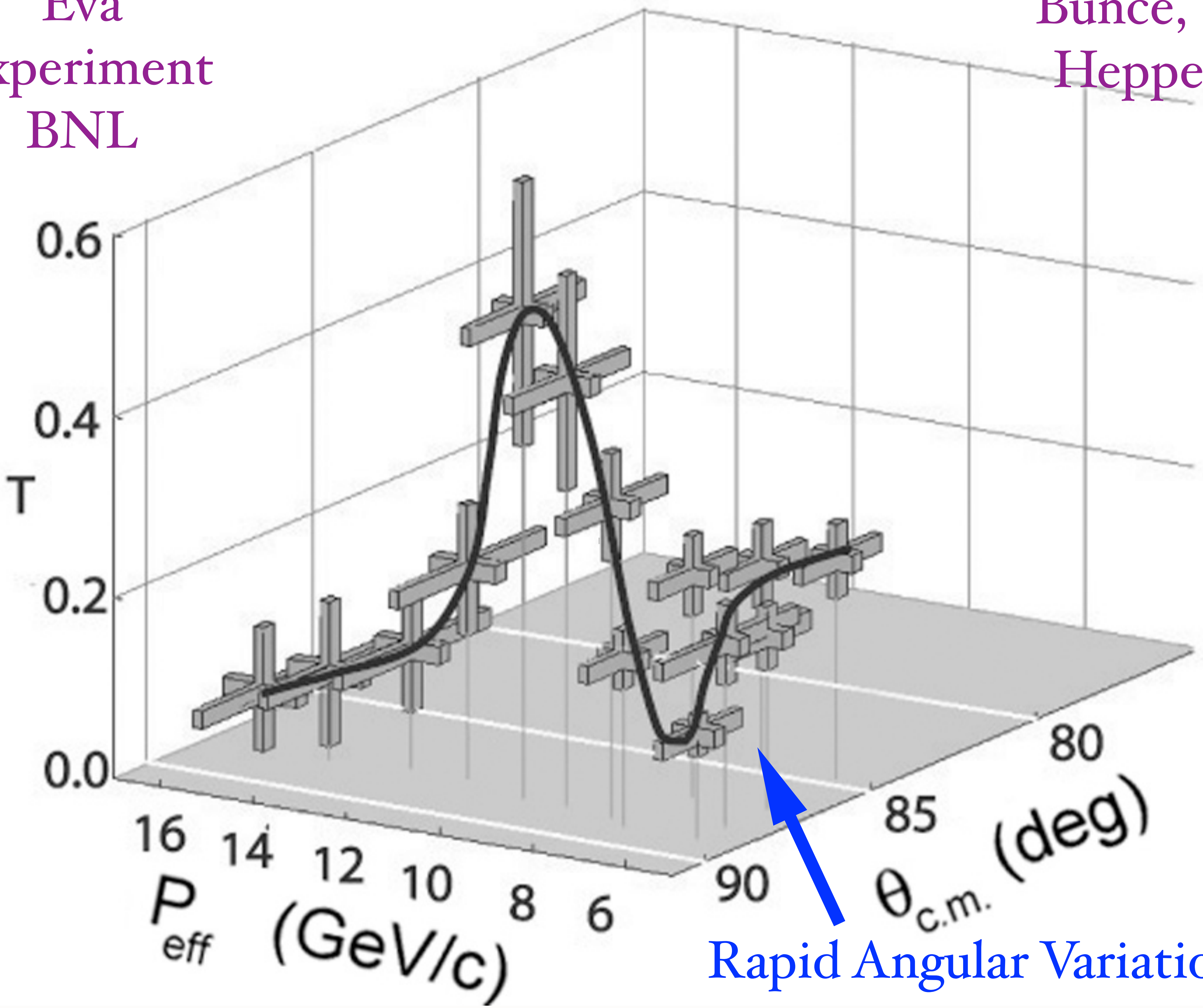
J. L. S. Aclander *et al.*,
"Nuclear transparency in $\theta_{CM} = 90^0$ quasielastic $A(p, 2p)$ reactions,"
Phys. Rev. C **70**, 015208 (2004), [arXiv:nucl-ex/0405025].

Color Transparency fails when A_{nn} is large

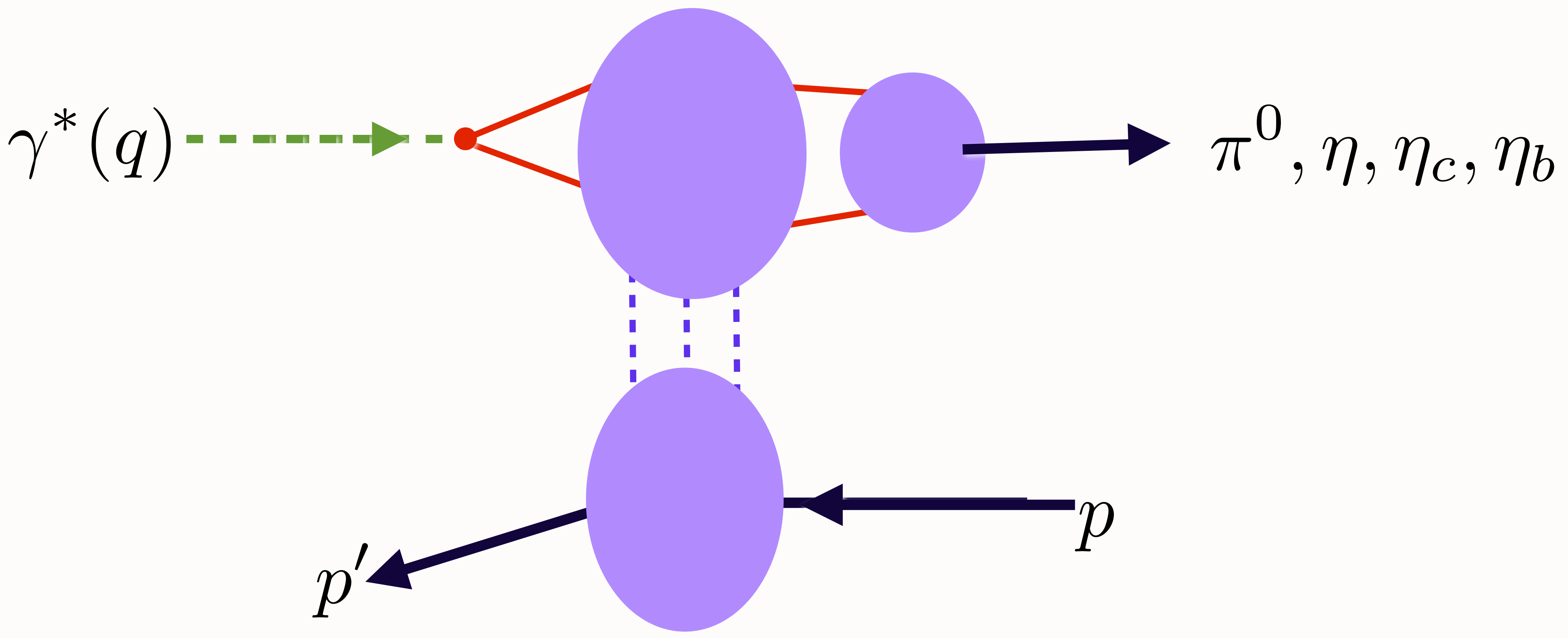


Eva Experiment BNL

Bunce, Carroll, Heppelman...



Rapid Angular Variation!



Odderon has never been observed!

Perturbative QCD Analysis of Structure Functions at x ~ 1

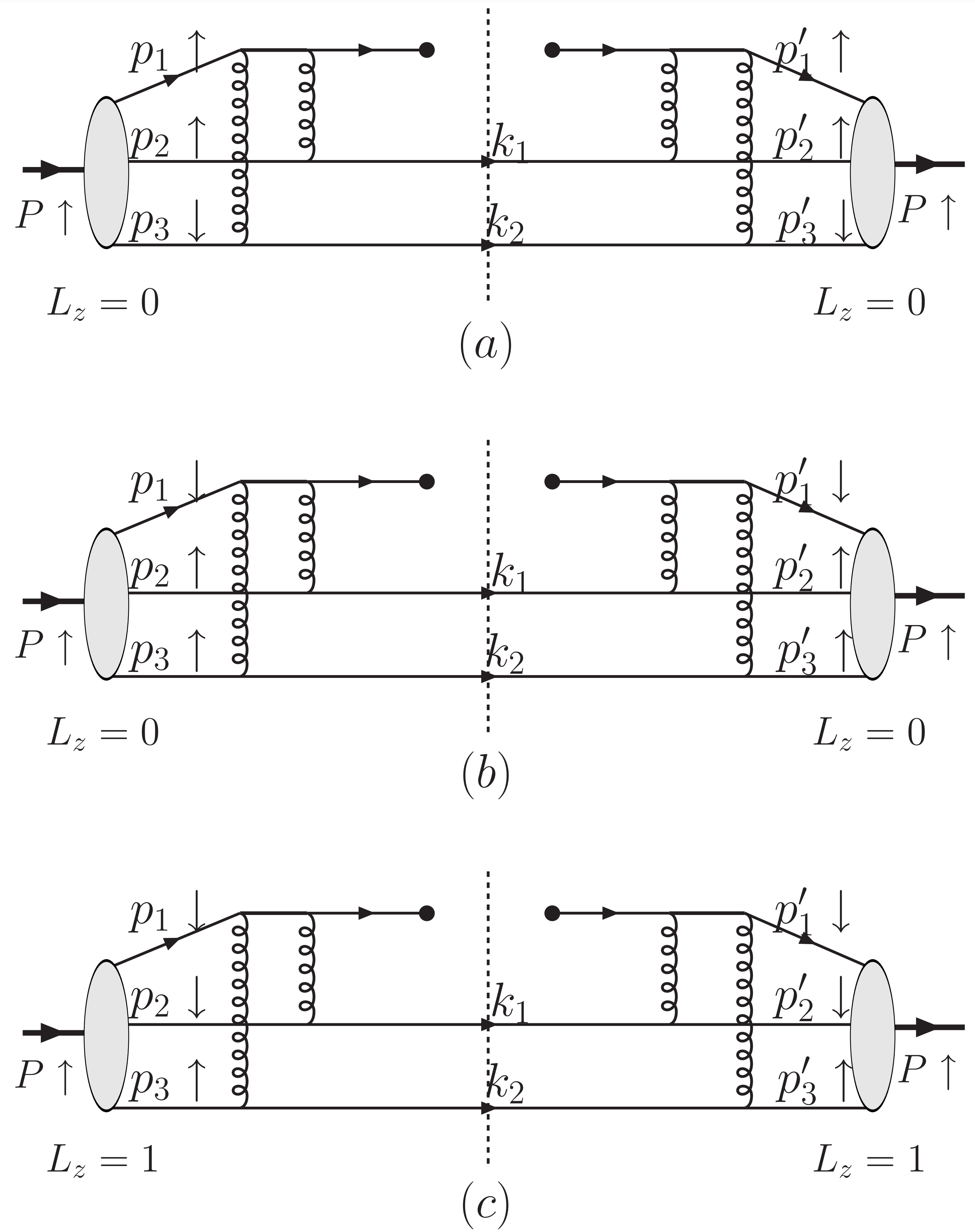
- Struck quark far off-shell at large x $\quad k_F^2 \simeq -\frac{k_\perp^2}{1-x}$
- Lowest-order connected PQCD diagrams dominate
- Spectator counting rules $\quad (1-x)^{2n_s-1+2\Delta S_z}$
- Helicity retention at large x
- Exclusive-Inclusive Connection

$$q^{+}(x) \propto (1-x)^{3}$$

$$q^{-}(x) \propto (1-x)^{5} \log^{2}(1-x)$$

From nonzero orbital angular momentum

Avakian, sjb, Deur, Yuan



Features of Hard Exclusive Processes in PQCD

Lepage, sjb; Duncan, Mueller

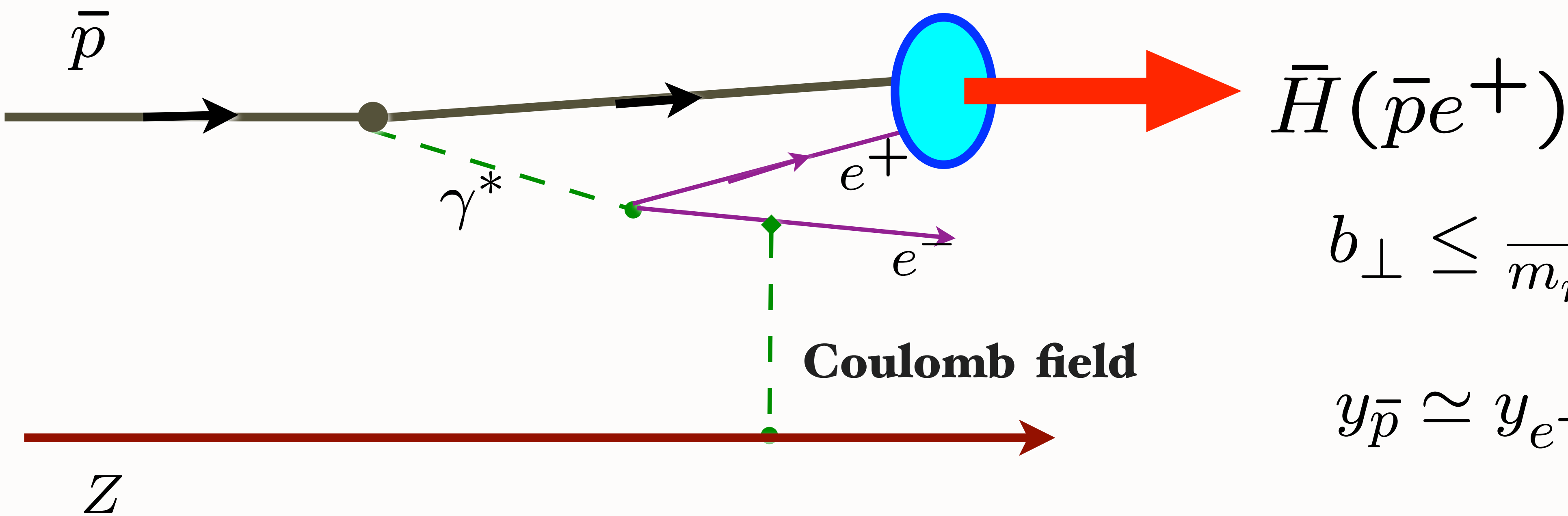
- Factorization of perturbative hard scattering subprocess amplitude and nonperturbative distribution amplitudes $M = \int T_H \times \Pi \phi_i$
- Dimensional counting rules reflect conformal invariance: $M \sim \frac{f(\theta_{CM})}{Q^{N_{tot}-4}}$
- Hadron helicity conservation: $\sum_{initial} \lambda_i^H = \sum_{final} \lambda_j^H$
- Color transparency Mueller, sjb;
- Hidden color Ji, Lepage, sjb;
- Evolution of Distribution Amplitudes

Lepage, sjb; Efremov, Radyushkin

Formation of Relativistic Anti-Hydrogen

Measured at CERN-LEAR and FermiLab

Munger, Schmidt, sjb



$$b_\perp \leq \frac{1}{m_{red}\alpha}$$

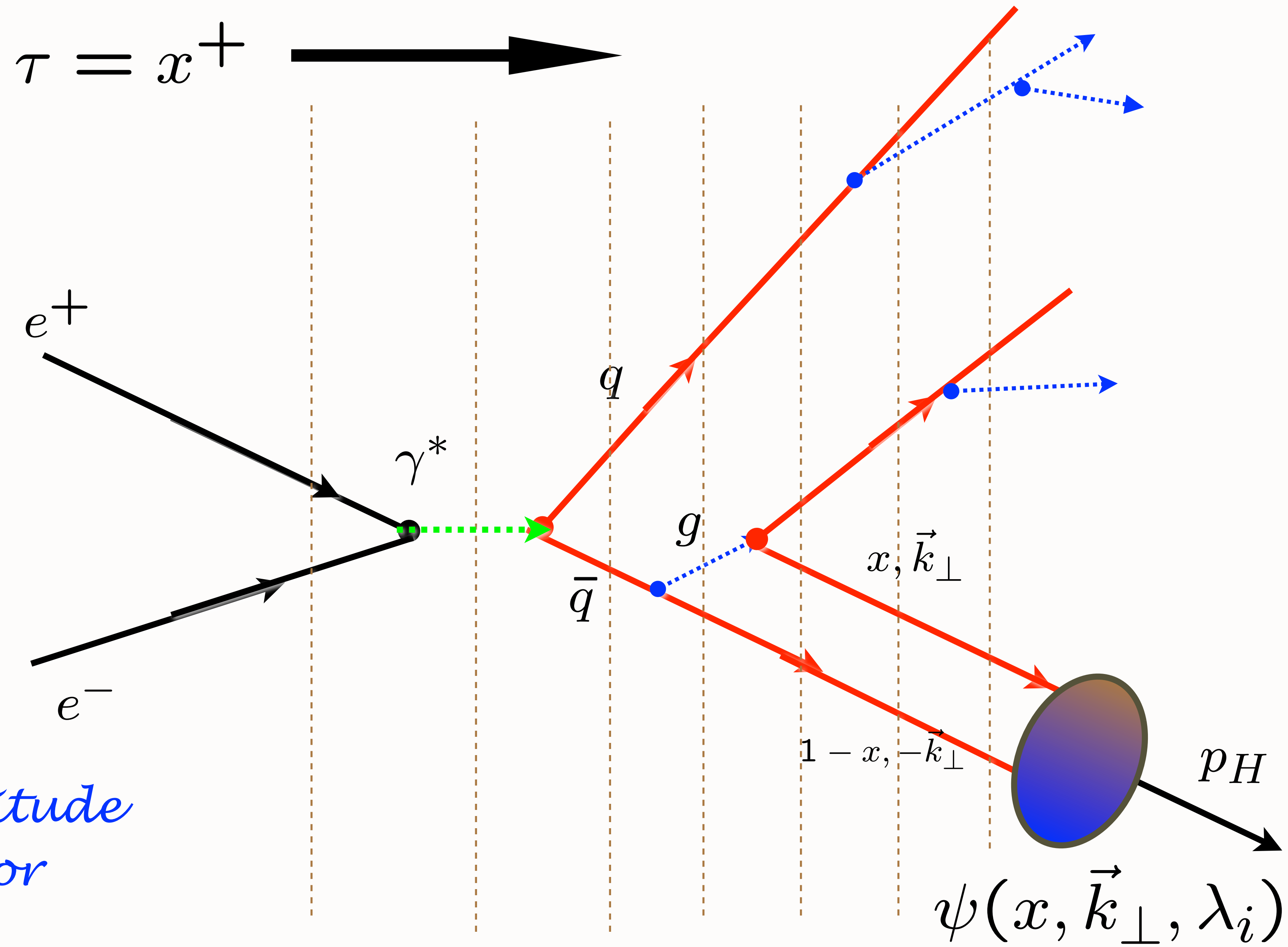
$$y_{\bar{p}} \simeq y_{e^+}$$

Coalescence of off-shell co-moving positron and antiproton

Wavefunction maximal at small impact separation and equal rapidity

"Hadronization" at the Amplitude Level

Hadronization at the Amplitude Level

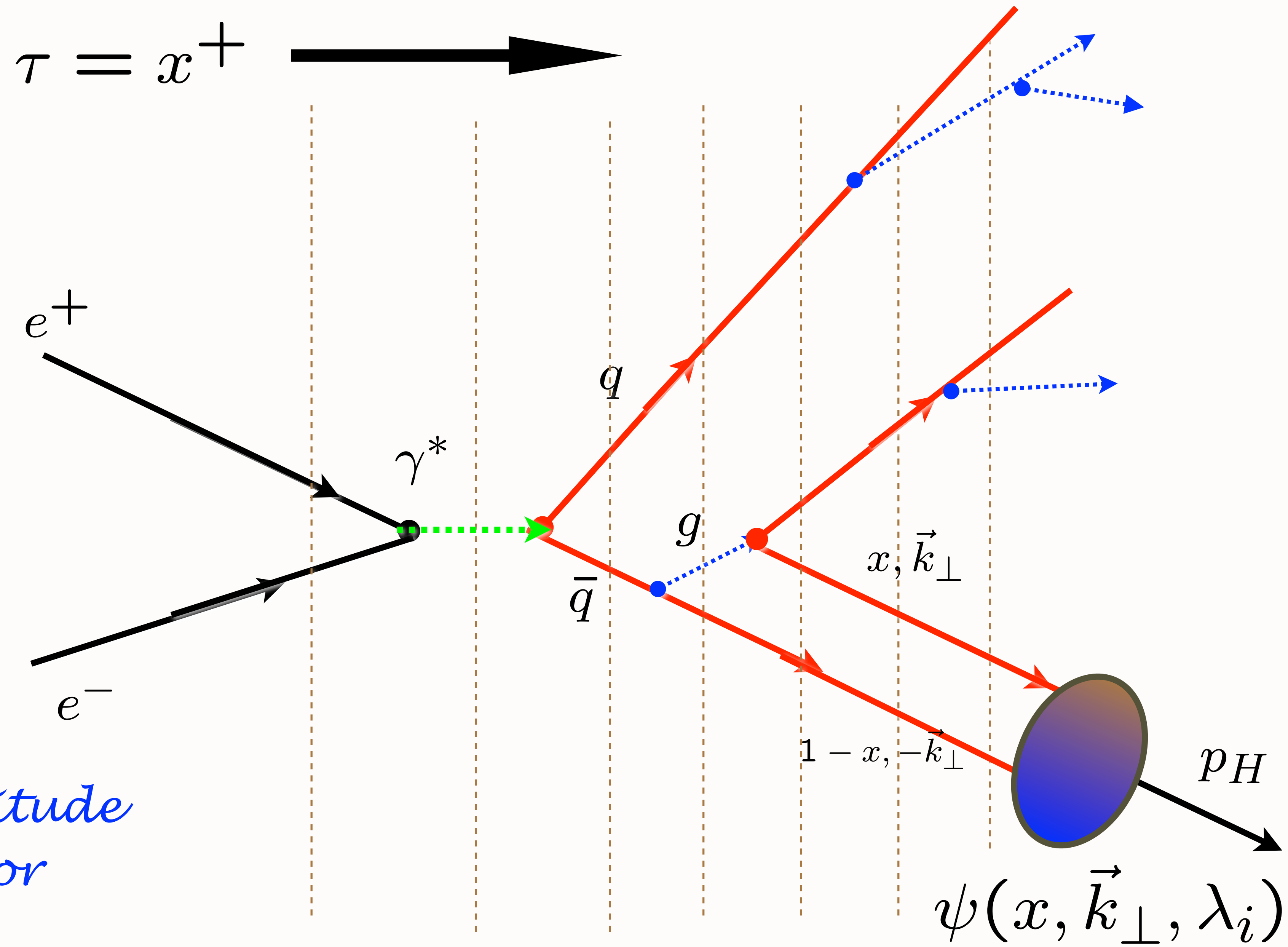


Event amplitude generator

Construct helicity amplitude using Light-Front Perturbation theory; coalesce quarks via LFWFs

Similar method for hadronization in DIS

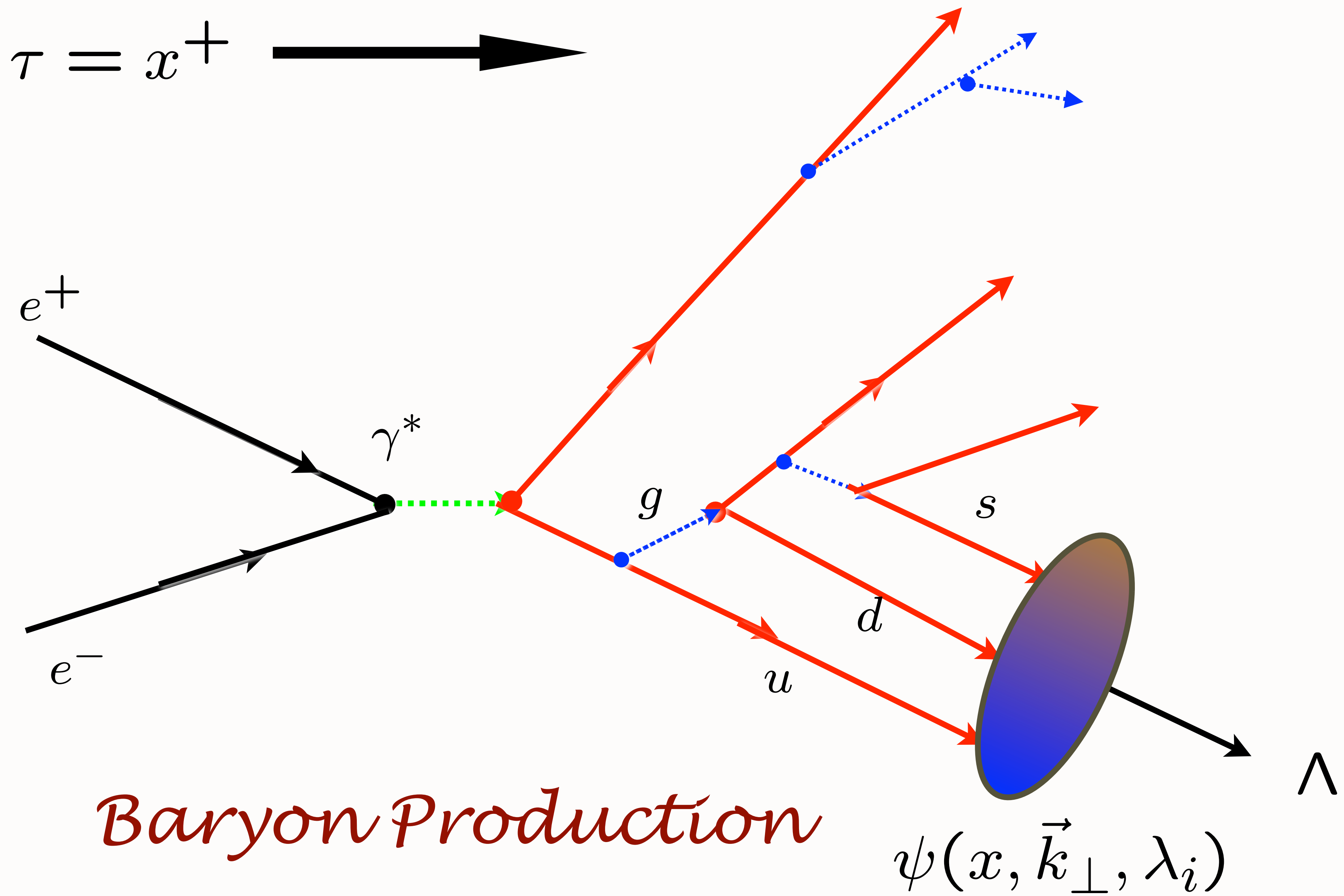
Hadronization at the Amplitude Level



Event amplitude generator

Construct helicity amplitude using Light-Front Perturbation theory; coalesce quarks via LFWFs

Hadronization at the Amplitude Level



Baryon Production

Construct helicity amplitude using Light-Front Perturbation theory; coalesce quarks via LFWFs

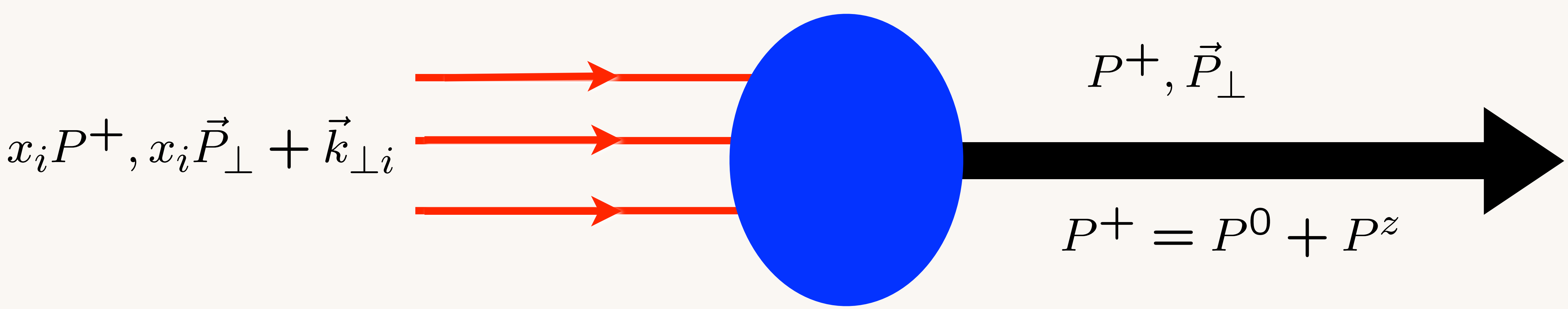
Features of LF T-Matrix Formalism
"Event Amplitude Generator"

- Coalesce color-singlet cluster to hadronic state if

$$\mathcal{M}_n^2 = \sum_{i=1}^{n} \frac{k_{\perp i}^2 + m_i^2}{x_i} < \Lambda_{QCD}^2$$

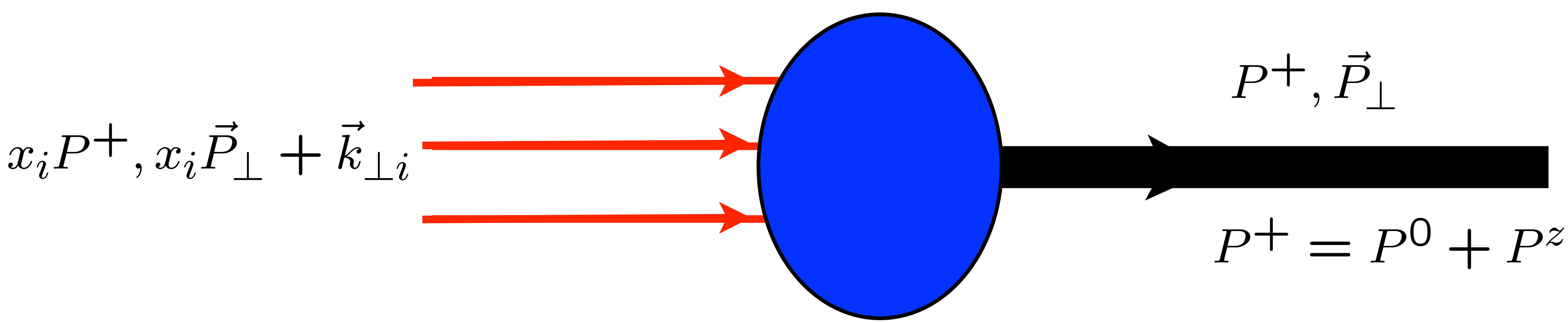
- The coalescence probability amplitude is the LF wavefunction $\Psi_n(x_i, \vec{k}_{\perp i}, \lambda_i)$

- No IR divergences: Maximal gluon and quark wavelength from confinement



Features of LF T-Matrix Formalism
"Event Amplitude Generator"

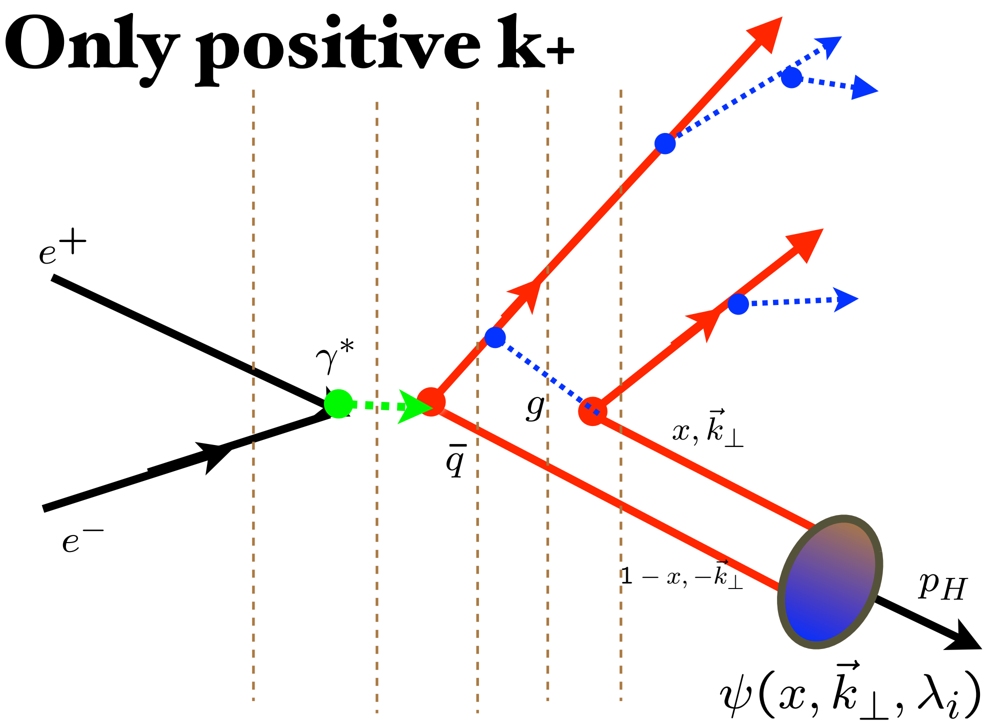
- **Same principle as antihydrogen production: off-shell coalescence**
- **coalescence to hadron favored at equal rapidity, small transverse momenta**
- **leading heavy hadron production: D and B mesons produced at large z**
- **hadron helicity conservation if hadron LFWF has $L^z = 0$**
- **Baryon AdS/QCD LFWF has aligned and anti-aligned quark spin**



Off -Shell T-Matrix

Event amplitude generator

- **Quarks and Gluons Off-Shell**
- **LFPth: Minimal Time-Ordering Diagrams-Only positive k+**
- **J^z Conservation at every vertex**
- **Frame-Independent**
- **Cluster Decomposition** Chueng Ji, sjb
- **"History"-Numerator structure universal**
- **Renormalization- alternate denominators**
- **LFWF takes Off-shell to On-shell**
- **Tested in QED: g-2 to three loops**



Roskies, Suaya, sjb

"One of the gravest puzzles of theoretical physics"

DARK ENERGY AND THE COSMOLOGICAL CONSTANT PARADOX

A. ZEE

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zee@kitp.ucsb.edu

$$(\Omega_\Lambda)_{QCD} \sim 10^{45}$$

$$(\Omega_\Lambda)_{EW} \sim 10^{56}$$

$$\Omega_\Lambda = 0.76(expt)$$

$$(\Omega_\Lambda)_{QCD} \propto < 0|q\bar{q}|0 >^4$$

QCD Problem Solved if quark and gluon condensates reside within hadrons, not vacuum!

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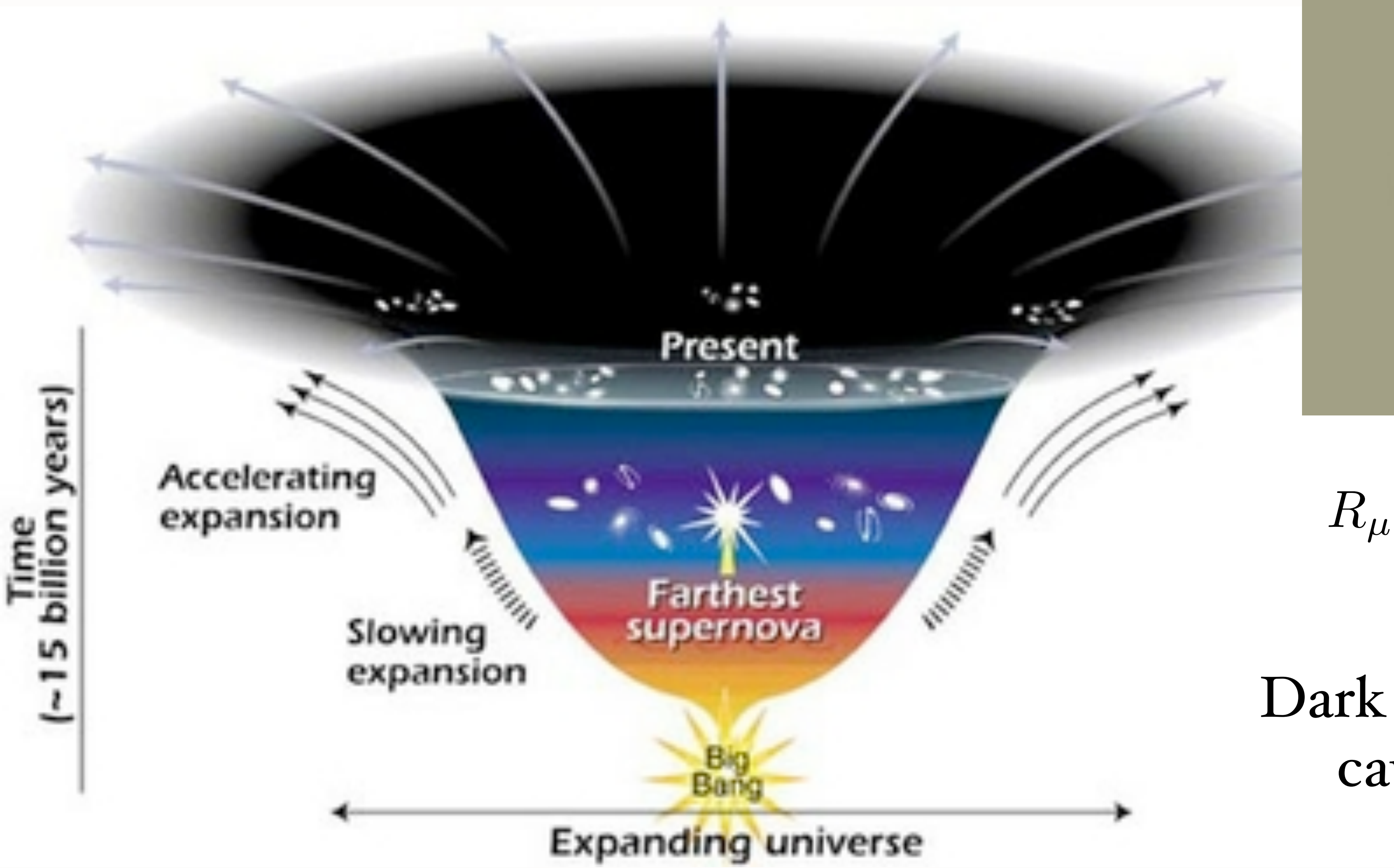
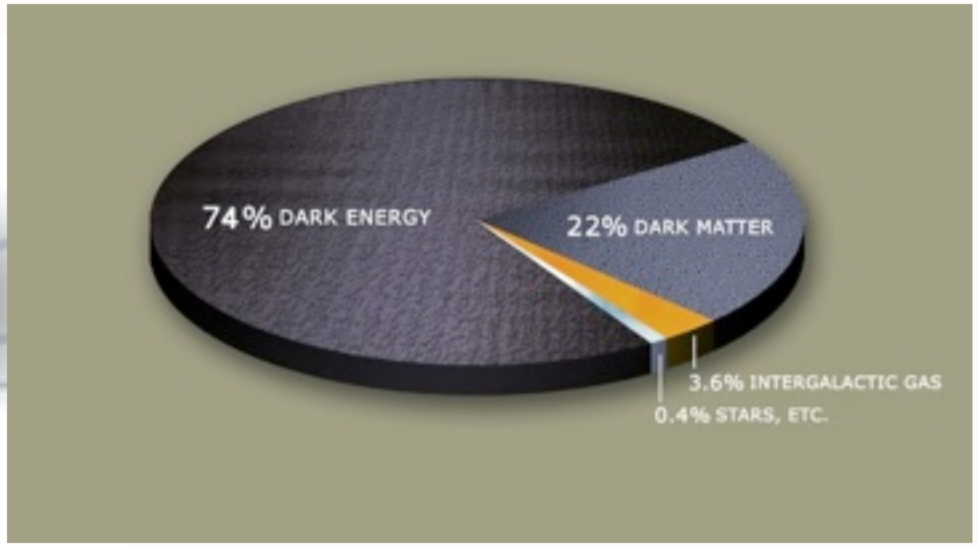




$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R - \Lambda g_{\mu\nu} = (8\pi G_N) T_{\mu\nu}$$

↑

Dark energy/cosmological constant causes accelerating expansion

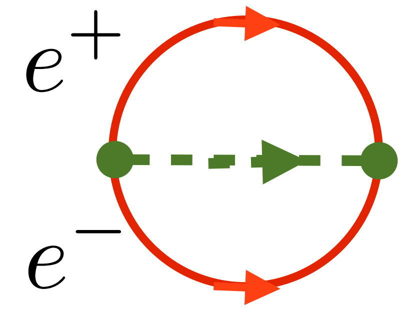
$$\frac{1}{a}\frac{d^2}{dt^2} a = \Lambda/3 = (8\pi) G_N \rho_\Lambda / 3$$

If the vacuum energy ρ is due to QCD condensates

$$\rho_\Lambda^{\mathrm{QCD}} \simeq M_{\mathrm{QCD}}^4 \simeq 10^{45} \rho_\Lambda^{\mathrm{obs}} \,!$$

$$\Omega_\Lambda = \frac{\rho_\Lambda^{\mathrm{obs}}}{\rho_c} \simeq 0.76 \qquad \rho_c = \frac{3H_0^2}{8\pi G_N}$$

Instant Form Vacuum in QED



- Loop diagrams of all orders contribute

$$\Omega_\Lambda \sim 10^{120}$$

- Huge vacuum energy
- $\frac{E}{V} = \int \frac{d^3k}{2(2\pi)^3}\sqrt{\vec{k}^2 + m^2}$ Cutoff quad div at M_{Planck}
- :Normal order: prescription
- Divide S-matrix by disconnected vacuum diagrams
- Contrast: Light-Front Vacuum empty since plus momenta are positi and conserved:

$$k^+ = k^0 + k^3 > 0$$

Gell-Mann Oakes Renner Formula in QCD

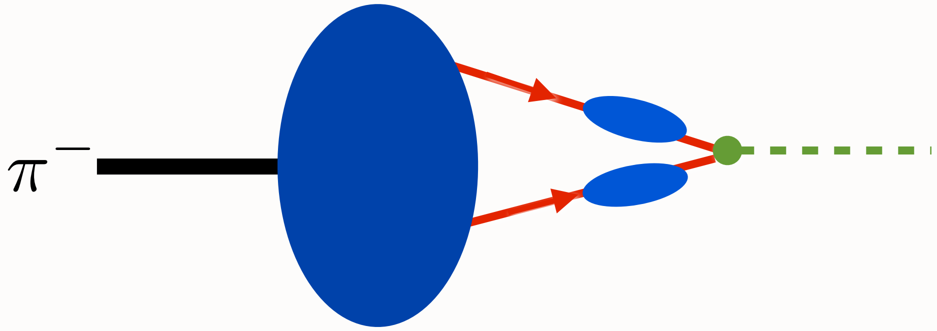
$$m_\pi^2 = -\frac{(m_u + m_d)}{f_\pi^2} < 0|\bar{q}q|0 >$$

current algebra:
effective pion field

$$m_\pi^2 = -\frac{(m_u + m_d)}{f_\pi} < 0|i\bar{q}\gamma_5 q|\pi >$$

QCD: composite pion
Bethe-Salpeter Eq.

vacuum condensate actually is an "in-hadron condensate"



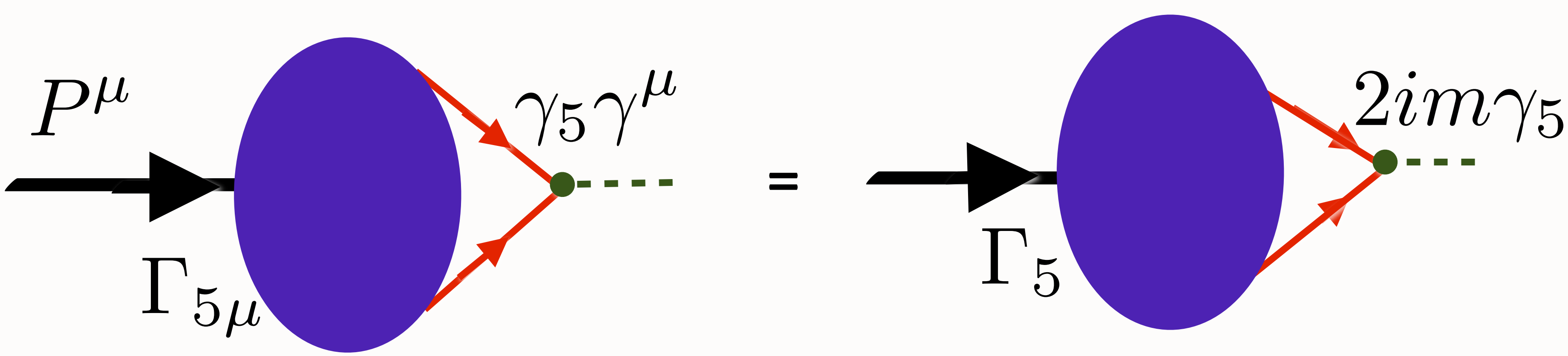
$$< 0|\bar{q}\gamma_5 q|\pi >$$

Maris, Roberts, Tandy

Ward-Takahashi Identity for axial current

$$P^{\mu}\Gamma_{5\mu}(k,P) + 2im\Gamma_5(k,P) = S^{-1}(k+P/2)i\gamma_5 + i\gamma_5 S^{-1}(k-P/2)$$

$$S^{-1}(\ell) = i\gamma\cdot\ell A(\ell^2) + B(\ell^2) \qquad m(\ell^2) = \frac{B(\ell^2)}{A(\ell^2)}$$



plus non-pole

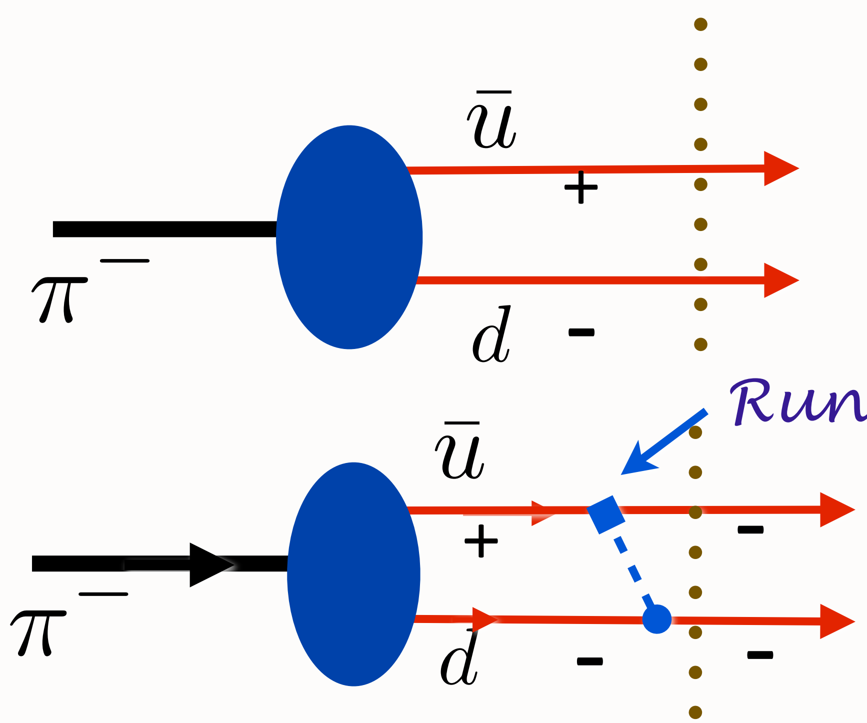
Identify pion pole at $P^2 = m_{\pi}^2$

$$P^{\mu} < 0|\bar{q}\gamma_5\gamma^{\mu}q|\pi >= 2m < 0|\bar{q}i\gamma_5 q|\pi >$$

$$f_{\pi}m_{\pi}^2 = -(m_u + m_d)\rho_{\pi}$$

Light-Front Pion Valence Wavefunctions

$S^z_{\bar{u}} + S^z_d = +1/2 - 1/2 = 0$



Couples to

$$L^z = 0, S^z = 0 \quad < \pi|\bar{\gamma}^\mu q \gamma_5 q|0 > \sim f_\pi$$

Running constituent mass at vertex

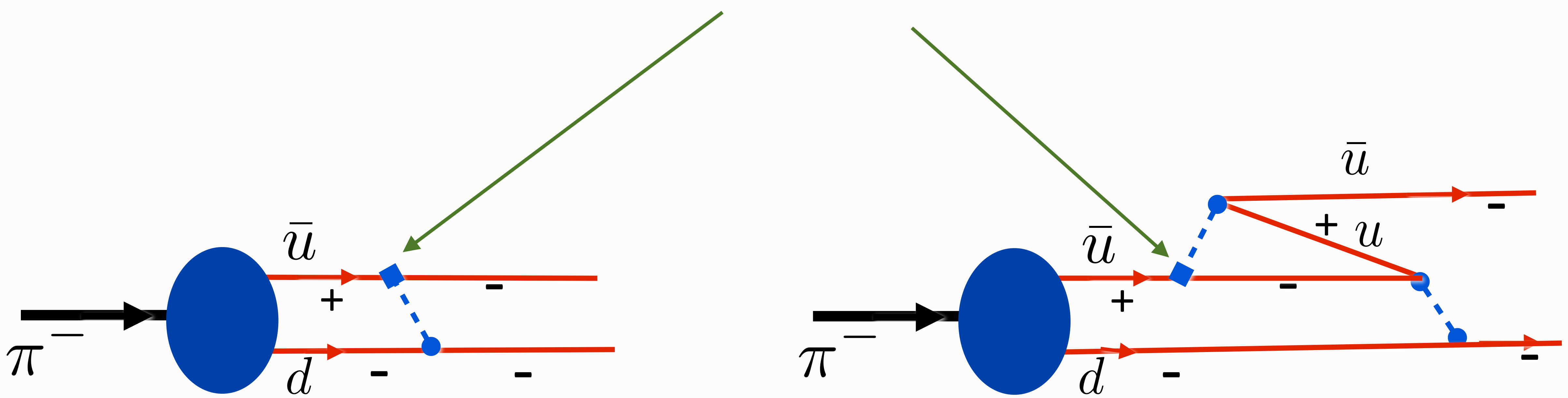
$$L^z = +1, S^z = -1 \quad < \pi|\bar{q}\gamma_5 q|0 > \sim \rho_\pi$$

$S^z_{\bar{u}} + S^z_d = -1/2 - 1/2 = -1$

Angular Momentum Conservation

$$J^z = \sum_i^n S_i^z + \sum_i^{n-1} L_i^z$$

Running constituent mass at vertex



$L^z = +1, S^z = -1$

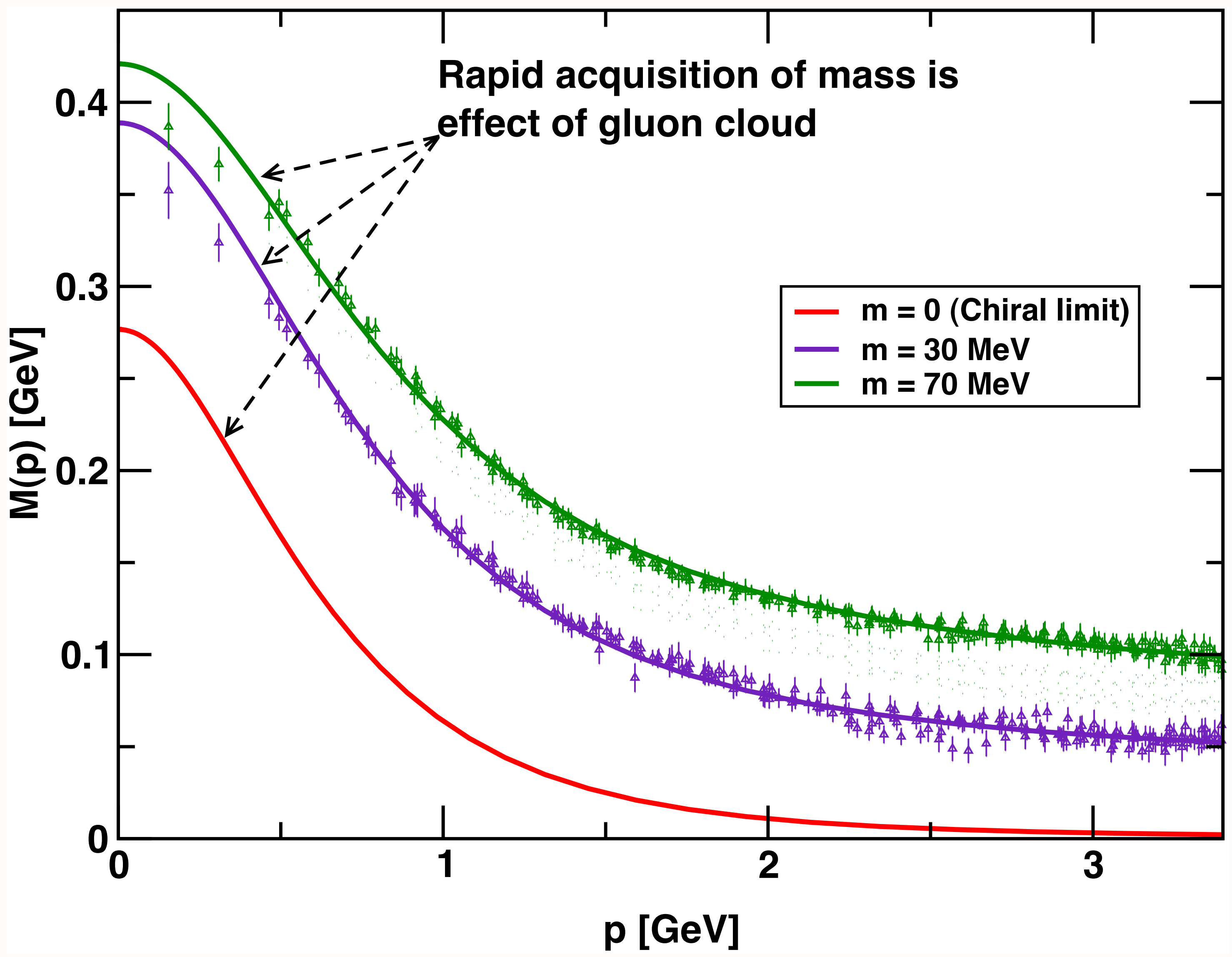
$L^z = 0, S^z = 0$ LF wavefunction couples to $< \pi|\bar{\gamma}^\mu q \gamma_5 q|0 >$

$L^z = +1, S^z = -1$ LF wavefunction couples to $< \pi|\bar{q}\gamma_5 q|0 >$

$m(\ell^2;\zeta) = B(\ell^2;\zeta)/A(\ell^2;\zeta)$ *running quark mass*

Running quark mass in QCD

$$S^{-1}(p) = i\gamma \cdot p\ A(p^2) + B(p^2) \qquad m(p^2) = \frac{B(p^2)}{A(p^2)}$$



Dyson-Schwinger

Chang, Cloet, El-Bennich Klahn, Roberts

Consistent with EW input at high p^2

Survives even at m=0!

Spontaneous Chiral Symmetry Breaking!

PHYSICAL REVIEW C **82**, 022201(R) (2010)

New perspectives on the quark condensate

Stanley J. Brodsky,[1,2] Craig D. Roberts,[3,4] Robert Shrock,[5] and Peter C. Tandy[6]
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[2] *Centre for Particle Physics Phenomenology: CP^3-Origins, University of Southern Denmark, Odense 5230 M, Denmark*
[3] *Physics Division, Argonne National Laboratory, Argonne, Illinois 60439, USA*
[4] *Department of Physics, Peking University, Beijing 100871, China*
[5] *C.N. Yang Institute for Theoretical Physics, Stony Brook University, Stony Brook, New York 11794, USA*
[6] *Center for Nuclear Research, Department of Physics, Kent State University, Kent, Ohio 44242, USA*
(Received 25 May 2010; published 18 August 2010)

We show that the chiral-limit vacuum quark condensate is qualitatively equivalent to the pseudoscalar meson leptonic decay constant in the sense that they are both obtained as the chiral-limit value of well-defined gauge-invariant hadron-to-vacuum transition amplitudes that possess a spectral representation in terms of the current-quark mass. Thus, whereas it might sometimes be convenient to imagine otherwise, neither is essentially a constant mass-scale that fills all spacetime. This means, in particular, that the quark condensate can be understood as a property of hadrons themselves, which is expressed, for example, in their Bethe-Salpeter or light-front wave functions.

QCD: Zero Contribution to Dark Energy, Cosmological Constant!

“One of the gravest puzzles of theoretical physics”

DARK ENERGY AND
THE COSMOLOGICAL CONSTANT PARADOX

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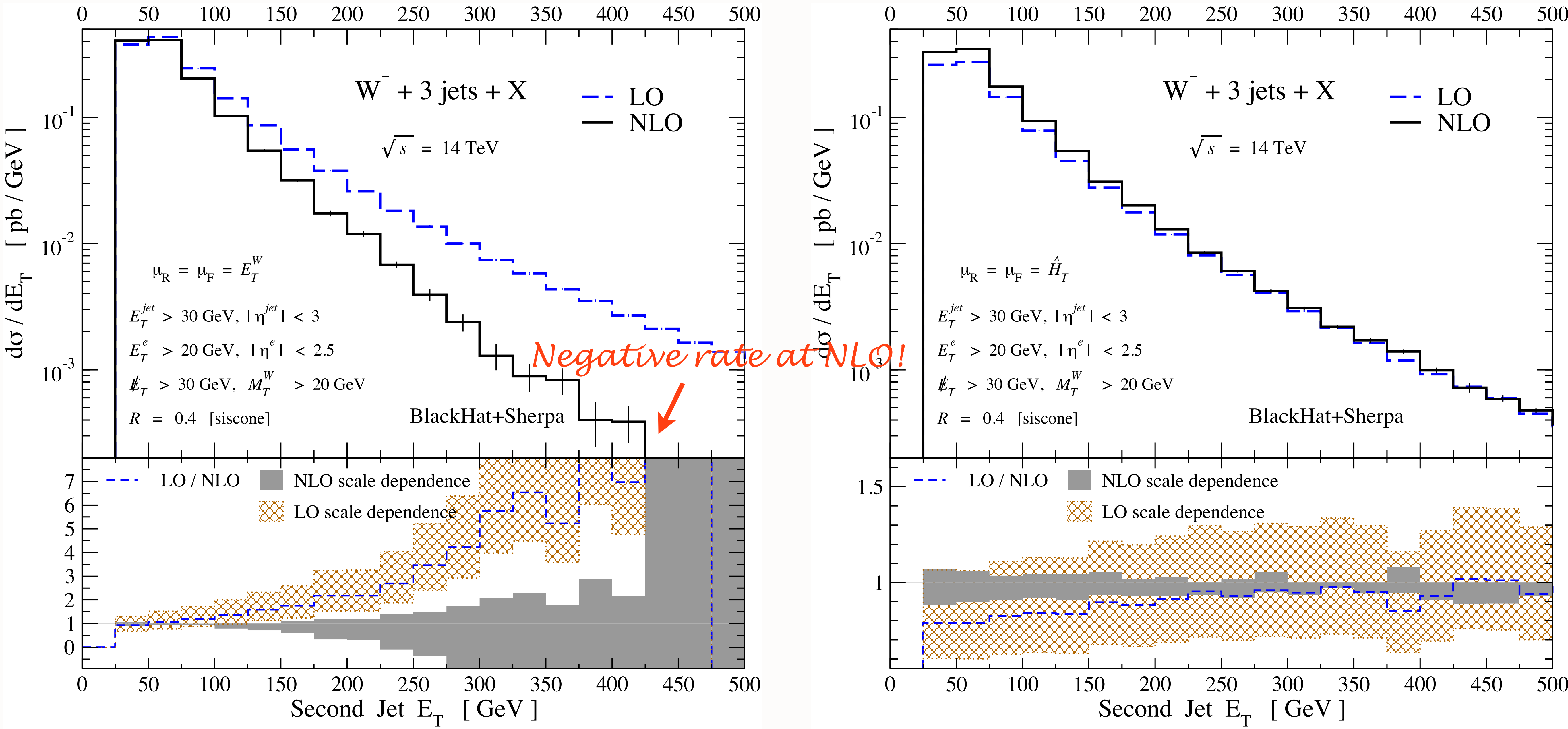
Goals

- Test QCD to maximum precision
- High precision determination of $\alpha_s(Q^2)$ at all scales
- Relate observable to observable --no scheme or scale ambiguity
- Eliminate renormalization scale ambiguity in a scheme-independent manner
- Relate renormalization schemes without ambiguity
- Maximize sensitivity to new physics at the colliders

Next-to-Leading Order QCD Predictions for W + 3-Jet Distributions at Hadron Colliders

Black Hat

$\mu_R = \mu_F = E_T^W$ $\qquad$ $\mu_R = \mu_F = \hat{H}_T$



F. Berger, Z. Bern, L. J. Dixon, F. Febres Cordero, D. Forde, T. Gleisberg, H. Ita, D. A. Kosower, and D. Maître

Electron-Electron Scattering in QED

$$\mathcal{M}_{ee\to ee}(++;++) = \frac{8\pi s}{t}\,\alpha(t) + \frac{8\pi s}{u}\,\alpha(u)$$

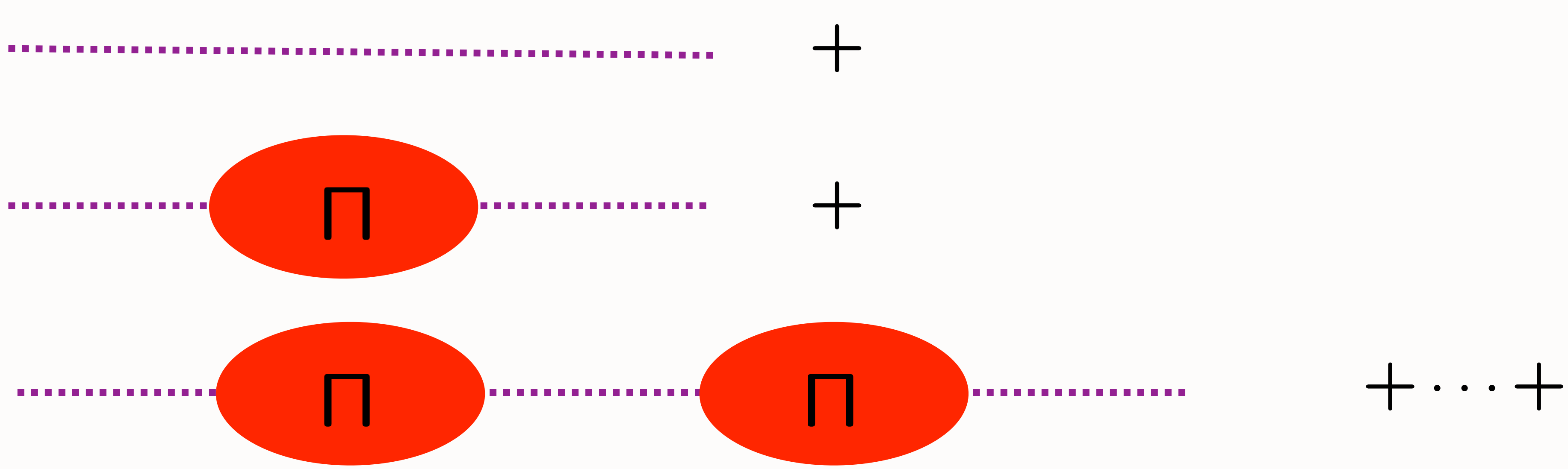
$$\alpha(t) = \frac{\alpha(0)}{1-\Pi(t)}$$

Gell-Mann--Low Effective Charge

QED Effective Charge

$$\alpha(t) = \frac{\alpha(0)}{1 - \Pi(t)}$$

All-orders lepton-loop corrections to dressed photon propagator

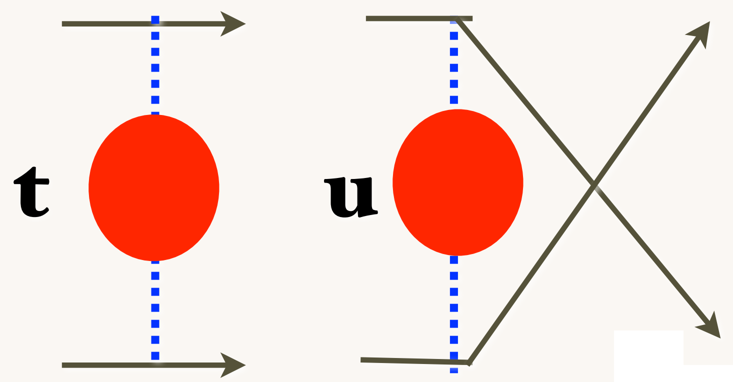


$$\alpha(t) = \frac{\alpha(t_0)}{1 - \Pi(t, t_0)} \qquad \Pi(t, t_0) = \frac{\Pi(t) - \Pi(t_0)}{1 - \Pi(t_0)}$$

***Initial* scale t_o is arbitrary -- Variation gives RGE Equations**
Physical renormalization scale t not arbitrary!

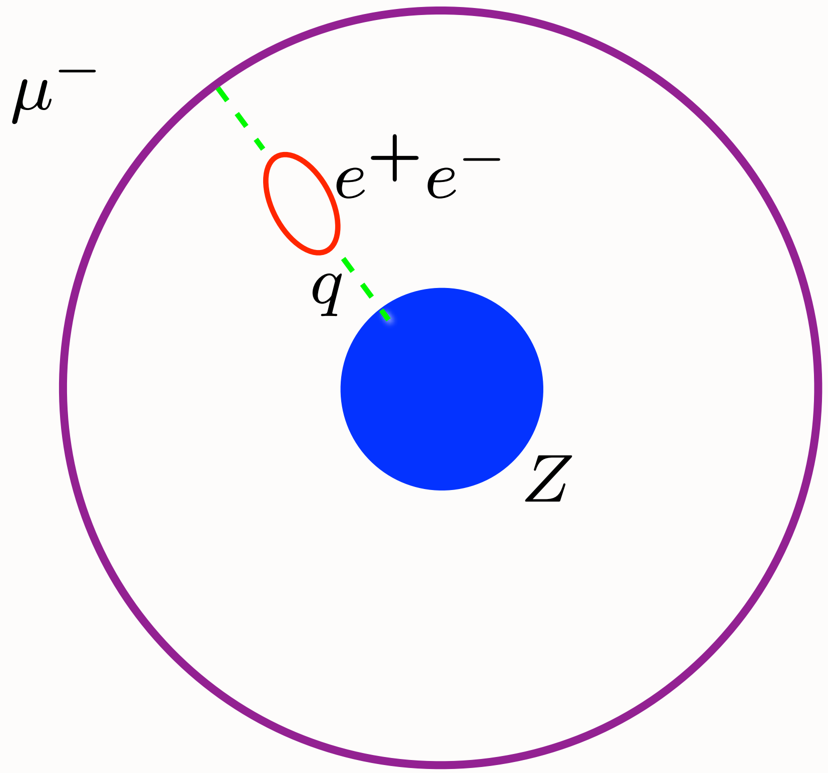
Electron-Electron Scattering in QED

$$\mathcal{M}_{ee\to ee}(++;++) = \frac{8\pi s}{t}\,\alpha(t) + \frac{8\pi s}{u}\,\alpha(u)$$



- **Two separate physical scales: t, u = photon virtuality**
- **Gauge Invariant. Dressed photon propagator**
- **Sums all vacuum polarization, non-zero beta terms into running coupling. This is the purpose of the running coupling!**
- **If one chooses a different initial scale, one must sum an infinite number of graphs -- but always recover same result!**
- **Number of active leptons correctly set**
- **Analytic: reproduces correct behavior at lepton mass thresholds**
- **No renormalization scale ambiguity!**

Another Example in QED: Muonic Atoms



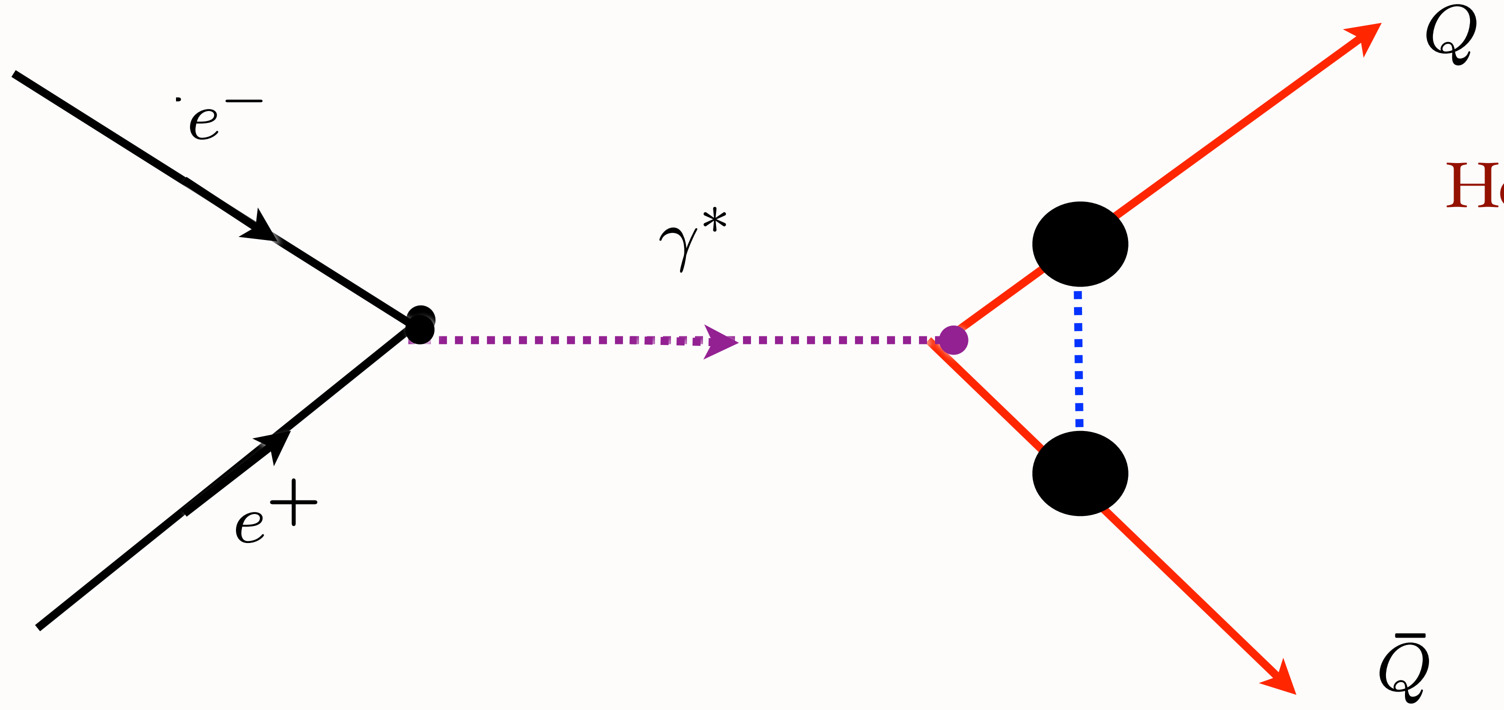
$$V(q^2) = -\frac{Z\alpha_{QED}(q^2)}{q^2}$$

$$\mu_R^2 \equiv q^2$$

$$\alpha_{QED}(q^2) = \frac{\alpha_{QED}(0)}{1-\Pi(q^2)}$$

Scale is unique: Tested to ppm

Gyulassy: Higher Order VP verified to 0.1% precision in μ Pb



Hoang, Kuhn, Teubner, sjb

$$F_1 + F_2 = [1 - 2\frac{\alpha_s(se^{3/4}/4)}{\pi}] \times [1 + \frac{\pi\alpha_s(sv^2)}{4v}]$$

Angular distributions of massive quarks close to threshold.

Example of Multiple BLM Scales

Need QCD coupling at small scales at low relative velocity v

Relation between scales of the Gell-Mann--Low and $\overline{\mathrm{MS}}$ schemes

$$\log \frac{\mu_0^2}{m_\ell^2} = 6 \int_0^1 x(1-x) \log \frac{m_\ell^2 + Q_0^2 x(1-x)}{m_\ell^2}$$

$$\log \frac{\mu_0^2}{m_\ell^2} = \log \frac{Q_0^2}{m_\ell^2} - 5/3$$

$$\boxed{\mu_0^2 = Q_0^2 \; e^{-5/3}} \quad \text{when } Q_0^2 >> m_\ell^2$$

D. S. Hwang, sjb

M. Binger

Can use $\overline{\mathrm{MS}}$ scheme in QED; answers are scheme independent
Analytic extension: coupling is complex for timelike argument

QCD Observables

$$\mathcal{O} = C(\alpha_s(\mu_0^2)) + B(\beta \log \frac{Q^2}{\mu_0^2}) + D(\frac{m_q^2}{Q^2}) + E(\frac{\Lambda_{QCD}^2}{Q^2}) + F(\frac{\Lambda_{QCD}^2}{m_Q^2}) + G(\frac{m_q^2}{m_Q^2})$$

Scale-Free Conformal Series

Running Coupling Effects

Higher Twist from Hadron Dynamics

Intrinsic Heavy Quarks

Light by Light Loops

BLM: Absorb β terms into running coupling

$$\mathcal{O} = C(\alpha_s(Q^{*2})) + D(\frac{m_q^2}{Q^2}) + E(\frac{\Lambda_{QCD}^2}{Q^2}) + F(\frac{\Lambda_{QCD}^2}{m_Q^2}) + G(\frac{m_q^2}{m_Q^2})$$

The Renormalization Scale Problem

- No renormalization scale ambiguity in QED
- Gell Mann-Low QED Coupling defined from physical observable
- Sums all Vacuum Polarization Contributions
- Recover conformal series
- Renormalization Scale in QED scheme: Identical to Photon Virtuality
- Analytic: Reproduces lepton-pair thresholds -- number of active leptons set
- Examples: muonic atoms, g-2, Lamb Shift
- Time-like and Space-like QED Coupling related by analyticity
- Uses Dressed Skeleton Expansion
- Results are scheme independent!
- *Predictions for physical observables cannot be scheme dependent*

Features of BLM Scale Setting

On The Elimination Of Scale Ambiguities In Perturbative Quantum Chromodynamics.

Lepage, Mackenzie, sjb

Phys.Rev.D28:228,1983

- "Principle of Maximum Conformality" — Di Giustino, sjb
- All terms associated with nonzero beta function summed into running coupling
- Standard procedure in QED
- Resulting series identical to conformal series
- Renormalon n! growth of PQCD coefficients from beta function eliminated!
- Scheme Independent!!!
- In general, BLM/PMC scales depend on all invariants
- Single Effective PMC scale at NLO

Relate Observables to Each Other

- Eliminate intermediate scheme
- No scale ambiguity
- Transitive!
- Commensurate Scale Relations
- Conformal Template
- Example: Generalized Crewther Relation

$$R_{e^+e^-}(Q^2) \equiv 3 \sum_{\text{flavors}} e_q{}^2 \left[1 + \frac{\alpha_R(Q)}{\pi} \right] .$$

$$\int_0^1 dx \left[g_1^{ep}(x, Q^2) - g_1^{en}(x, Q^2) \right] \equiv \frac{1}{3} \left| \frac{g_A}{g_V} \right| \left[1 - \frac{\alpha_{g_1}(Q)}{\pi} \right]$$

Define QCD Coupling from Observables

Grunberg

Effective Charges: analytic at quark mass thresholds, finite at small momenta

$$R_{e^+e^-\to X}(s) \equiv 3\Sigma_q e_q^2 \; [1 + \frac{\alpha_R(s)}{\pi}]$$

$$\Gamma(\tau \to Xe\nu)(m_\tau^2) \equiv \Gamma_0(\tau \to u\bar{d}e\nu) \times [1 + \frac{\alpha_\tau(m_\tau^2)}{\pi}]$$

Commensurate scale relations:
Relate observable to observable at commensurate scales

H.Lu, Rathsman, sjb

$$\frac{\alpha_R(Q)}{\pi} = \frac{\alpha_{\overline{MS}}(Q)}{\pi} + \left(\frac{\alpha_{\overline{MS}}(Q)}{\pi}\right)^2 \left[\left(\frac{41}{8} - \frac{11}{3}\zeta_3\right) C_A - \frac{1}{8}C_F + \left(-\frac{11}{12} + \frac{2}{3}\zeta_3\right) f\right]$$
$$+ \left(\frac{\alpha_{\overline{MS}}(Q)}{\pi}\right)^3 \left\{\left(\frac{90445}{2592} - \frac{2737}{108}\zeta_3 - \frac{55}{18}\zeta_5 - \frac{121}{432}\pi^2\right) C_A^2 + \left(-\frac{127}{48} - \frac{143}{12}\zeta_3 + \frac{55}{3}\zeta_5\right) C_A C_F - \frac{23}{32}C_F^2\right.$$
$$+ \left[\left(-\frac{970}{81} + \frac{224}{27}\zeta_3 + \frac{5}{9}\zeta_5 + \frac{11}{108}\pi^2\right) C_A + \left(-\frac{29}{96} + \frac{19}{6}\zeta_3 - \frac{10}{3}\zeta_5\right) C_F\right] f$$
$$\left. + \left(\frac{151}{162} - \frac{19}{27}\zeta_3 - \frac{1}{108}\pi^2\right) f^2 + \left(\frac{11}{144} - \frac{1}{6}\zeta_3\right) \frac{d^{abc}d^{abc}}{C_F d(R)} \frac{\left(\sum_f Q_f\right)^2}{\sum_f Q_f^2}\right\}.$$

$$\frac{\alpha_{g_1}(Q)}{\pi} = \frac{\alpha_{\overline{MS}}(Q)}{\pi} + \left(\frac{\alpha_{\overline{MS}}(Q)}{\pi}\right)^2 \left[\frac{23}{12}C_A - \frac{7}{8}C_F - \frac{1}{3}f\right]$$
$$+ \left(\frac{\alpha_{\overline{MS}}(Q)}{\pi}\right)^3 \left\{\left(\frac{5437}{648} - \frac{55}{18}\zeta_5\right) C_A^2 + \left(-\frac{1241}{432} + \frac{11}{9}\zeta_3\right) C_A C_F + \frac{1}{32}C_F^2\right.$$
$$\left. + \left[\left(-\frac{3535}{1296} - \frac{1}{2}\zeta_3 + \frac{5}{9}\zeta_5\right) C_A + \left(\frac{133}{864} + \frac{5}{18}\zeta_3\right) C_F\right] f + \frac{115}{648} f^2\right\}.$$

Eliminate MSbar,
Find Amazing Simplification

Lu, Kataev, Gabadadze, Sjb

Generalized Crewther Relation

$$[1 + \frac{\alpha_R(s^*)}{\pi}][1 - \frac{\alpha_{g_1}(q^2)}{\pi}] = 1$$

$$\sqrt{s^*} \simeq 0.52Q$$

Conformal relation true to all orders in perturbation theory

No radiative corrections to axial anomaly

Nonconformal terms set relative scales (BLM)
Analytic matching at quark thresholds
No renormalization scale ambiguity!

Relate Observables to Each Other

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- No scale ambiguity
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$$\frac{\alpha_R(Q)}{\pi} = \frac{\alpha_{\overline{MS}}(Q)}{\pi} + \left(\frac{\alpha_{\overline{MS}}(Q)}{\pi}\right)^2 \left[\left(\frac{41}{8} - \frac{11}{3}\zeta_3\right) C_A - \frac{1}{8}C_F + \left(-\frac{11}{12} + \frac{2}{3}\zeta_3\right) f\right]$$
$$+ \left(\frac{\alpha_{\overline{MS}}(Q)}{\pi}\right)^3 \left\{\left(\frac{90445}{2592} - \frac{2737}{108}\zeta_3 - \frac{55}{18}\zeta_5 - \frac{121}{432}\pi^2\right) C_A^2 + \left(-\frac{127}{48} - \frac{143}{12}\zeta_3 + \frac{55}{3}\zeta_5\right) C_A C_F - \frac{23}{32}C_F^2\right.$$
$$+ \left[\left(-\frac{970}{81} + \frac{224}{27}\zeta_3 + \frac{5}{9}\zeta_5 + \frac{11}{108}\pi^2\right) C_A + \left(-\frac{29}{96} + \frac{19}{6}\zeta_3 - \frac{10}{3}\zeta_5\right) C_F\right] f$$
$$\left. + \left(\frac{151}{162} - \frac{19}{27}\zeta_3 - \frac{1}{108}\pi^2\right) f^2 + \left(\frac{11}{144} - \frac{1}{6}\zeta_3\right) \frac{d^{abc}d^{abc}}{C_F d(R)} \frac{\left(\sum_f Q_f\right)^2}{\sum_f Q_f^2}\right\}.$$

$$\frac{\alpha_{g_1}(Q)}{\pi} = \frac{\alpha_{\overline{MS}}(Q)}{\pi} + \left(\frac{\alpha_{\overline{MS}}(Q)}{\pi}\right)^2 \left[\frac{23}{12}C_A - \frac{7}{8}C_F - \frac{1}{3}f\right]$$
$$+ \left(\frac{\alpha_{\overline{MS}}(Q)}{\pi}\right)^3 \left\{\left(\frac{5437}{648} - \frac{55}{18}\zeta_5\right) C_A^2 + \left(-\frac{1241}{432} + \frac{11}{9}\zeta_3\right) C_A C_F + \frac{1}{32}C_F^2\right.$$
$$\left. + \left[\left(-\frac{3535}{1296} - \frac{1}{2}\zeta_3 + \frac{5}{9}\zeta_5\right) C_A + \left(\frac{133}{864} + \frac{5}{18}\zeta_3\right) C_F\right] f + \frac{115}{648} f^2\right\}.$$

Eliminate MS
Find Amazing Simplification

$$R_{e^+e^-}(Q^2) \equiv 3 \sum_{\text{flavors}} e_q{}^2 \left[1 + \frac{\alpha_R(Q)}{\pi} \right].$$

$$\int_0^1 dx \left[g_1^{ep}(x, Q^2) - g_1^{en}(x, Q^2) \right] \equiv \frac{1}{3} \left| \frac{g_A}{g_V} \right| \left[1 - \frac{\alpha_{g_1}(Q)}{\pi} \right]$$

$$\frac{\alpha_{g_1}(Q)}{\pi} = \frac{\alpha_R(Q^*)}{\pi} - \left(\frac{\alpha_R(Q^{**})}{\pi} \right)^2 + \left(\frac{\alpha_R(Q^{***})}{\pi} \right)^3$$

Geometric Series in Conformal QCD

Generalized Crewther Relation

Lu, Kataev, Gabadadze, Sjb

Lu, Kataev, Gabadadze, Sjb

Generalized Crewther Relation

$$[1 + \frac{\alpha_R(s^*)}{\pi}][1 - \frac{\alpha_{g_1}(q^2)}{\pi}] = 1$$

$$\sqrt{s^*} \simeq 0.52 Q$$

Conformal relation true to all orders in perturbation theory

No radiative corrections to axial anomaly

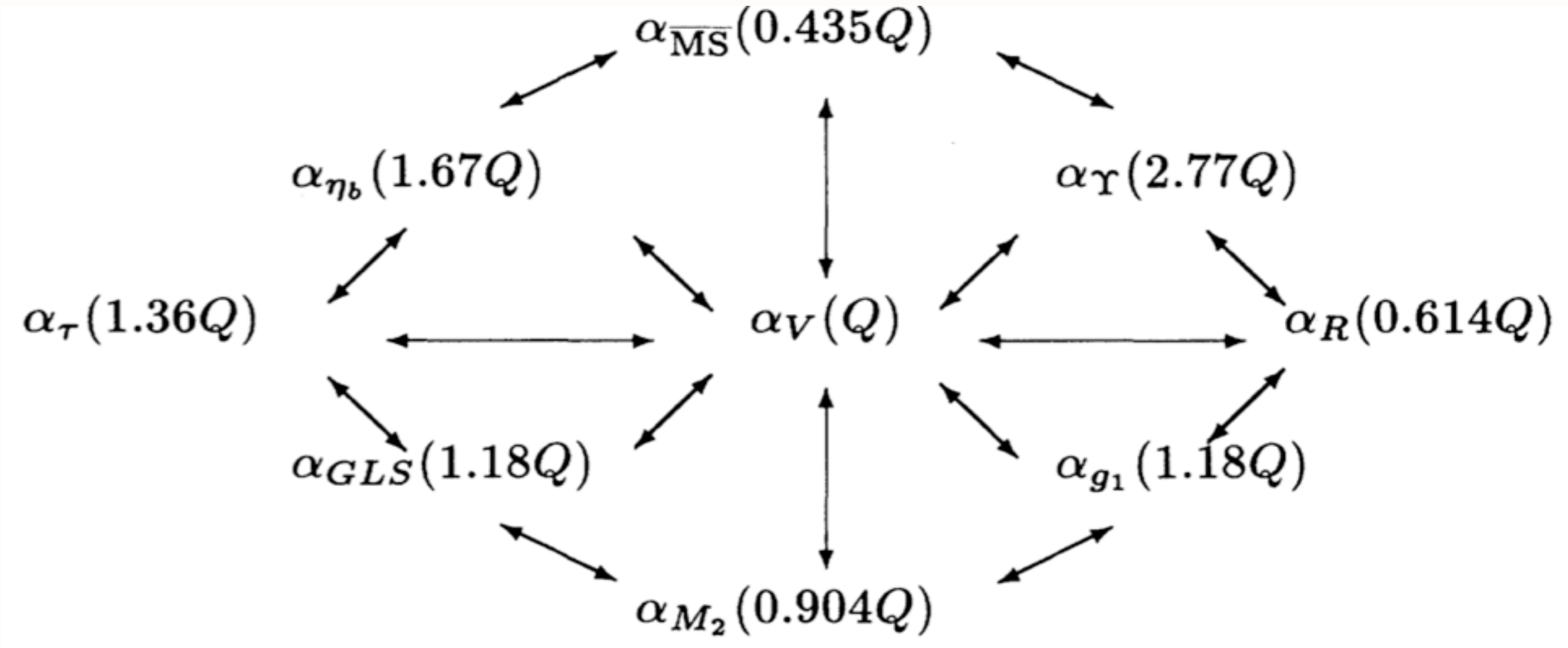
Nonconformal terms set relative scales (BLM)

No renormalization scale ambiguity!

Both observables go through new quark thresholds at commensurate scales!

$$\frac{\alpha_\tau(M_\tau)}{\pi} = \frac{\alpha_R(Q^*)}{\pi},$$

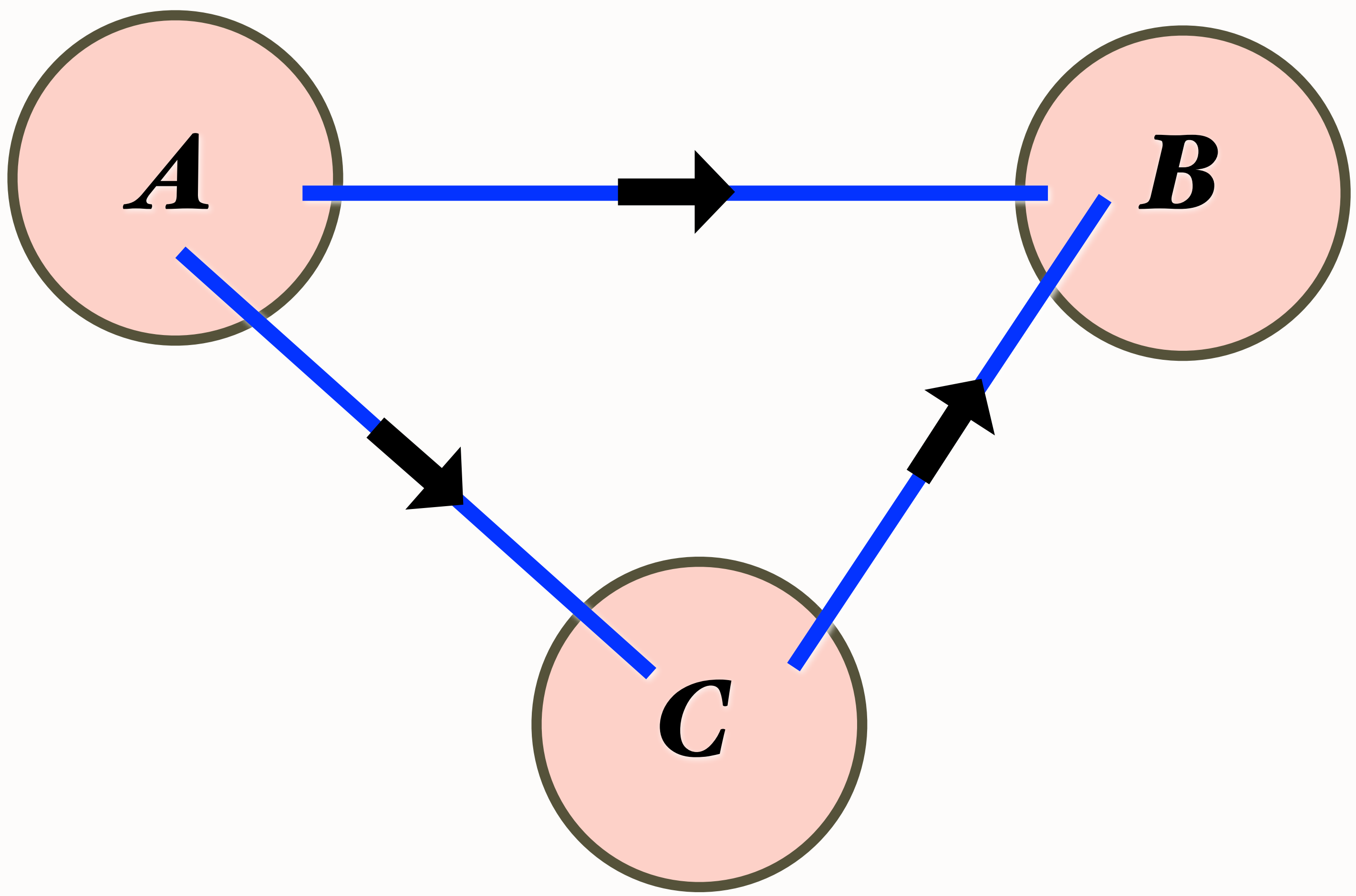
$$Q^* = M_\tau \exp\left[-\frac{19}{24} - \frac{169}{128}\frac{\alpha_R(M_\tau)}{\pi}\right]$$



$\alpha_{\overline{\rm MS}}(0.435Q)$
$\alpha_{\eta_b}(1.67Q)$
$\alpha_{\Upsilon}(2.77Q)$
$\alpha_{\tau}(1.36Q)$
$\alpha_V(Q)$
$\alpha_R(0.614Q)$
$\alpha_{GLS}(1.18Q)$
$\alpha_{g_1}(1.18Q)$
$\alpha_{M_2}(0.904Q)$

Transitivity Property of Renormalization Group

Relation of observables must be independent of intermediate scheme



A → C   C → B   identical to   A → B

Violated by PMS!

Myths concerning scale setting

- Renormalization scale "unphysical": No optimal physical scale
- Can ignore possibility of multiple physical scales
- Accuracy of PQCD prediction can be judged by taking arbitrary guess $\mu_R = Q$ with an arbitrary range $Q/2 < \mu_R < 2Q$
- Factorization scale should be taken equal to renormalization scale $\mu_F = \mu_R$

These assumptions are untrue in QED and thus they cannot be true for QCD

Clearly heuristic. Wrong in QED. Scheme dependent!

Novel JLab-12 Topics

- DVCS, DVMS, Hard Exclusive Processes at the Amplitude Level
- J=0 Fixed Pole
- Diffractive DIS
- Hidden Color in Deuteron
- x > 1 in Nuclei
- Nuclear Form Factors, Exclusive Amplitudes at large Q^2
- Shadowing, antishadowing, EMC
- Jet Energy Loss, LPM Non-Abelian Effect

Key Experiments at JLab 12 GeV

- Non-Universal Antishadowing
- Charm at High x
- J=0 Fixed Pole in DVCS
- Neutron Form Factors
- Compton Scaling at fixed t/s
- Quarkonium nuclear target dependence
- Color Transparency in high Q Electroproduction, Quasielastic Processes
- Direct Production of Hadrons at High p_T
- Signals of Hidden Color in the Deuteron: $x > 1$
- Sivers Effect
- Generalized Crewther Relation
- True Muonium Production

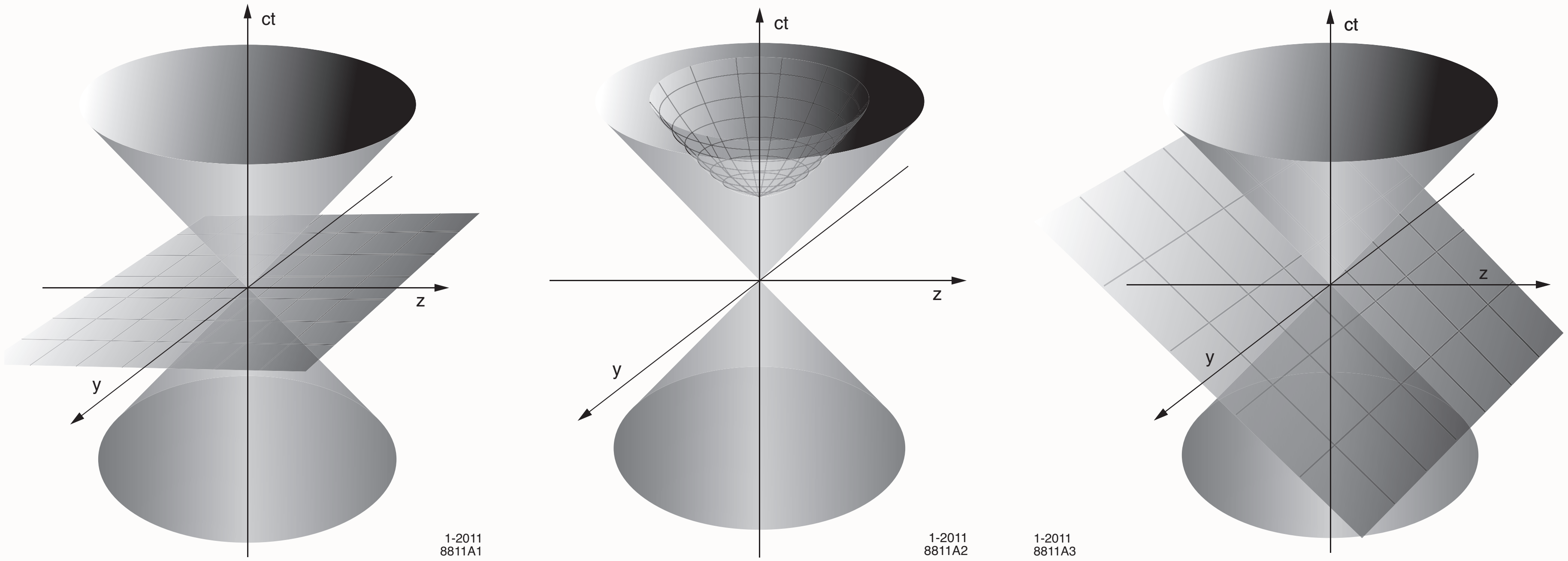
Studies of QCD just beginning!

Outstanding QCD Problems

- Solving Hadron Spectroscopy and Dynamics Simultaneously
- Proton Spin
- Anti-Shadowing is Not Universal
- Breakdown of QCD Factorization Theorems
- The Baryon Anomaly at RHIC
- The DZero Anomaly: heavy quarks at large x
- Setting the Renormalization Scale
- QCD condensates and Dark Energy
- Fixing the D Term in DVCS
- $J/\psi \to \rho\pi$ puzzle
- Anomalous Physics of Sea Quarks
- Hadronization at the Amplitude Level
- QCD Running Coupling in the Infrared

More Outstanding QCD Problems

- Single inclusive high-p_T hadrons -- wrong scaling !
- Quark Interchange dominance in hadron scattering reactions
- Quarkonium nuclear target dependence
- The Same-Side Ridge at CMS
- How to Find the Odderon?
- Signals of Hidden Color in the Deuteron
- Quark-Gluon Phase of Heavy Ion Collisions
- Quark-Gluon Phase in the Target Frame
- The Top/anti-Top Asymmetry
- Color Transparency and Opaqueness
- Krisch A_{NN}
- ...



" Working with a front is a process that is unfamiliar to physicists.
But still I feel that the mathematical simplification that it introduces
is all-important. I consider the method to be promising and have recently
been making an extensive study of it. It offers new opportunities,
while the familiar instant form seems to be played out "

P.A.M. Dirac (1977)

Future Directions

Vary
Honkanen
et al.

- **BLFQ -- use AdS/QCD basis to diagonalize H_{LF}**
- **Lippmann-Schwinger -- perturbatively generate higher Fock States and systematically approach QCD** *Hiller and Chabysheva*
- **Transverse Lattice**

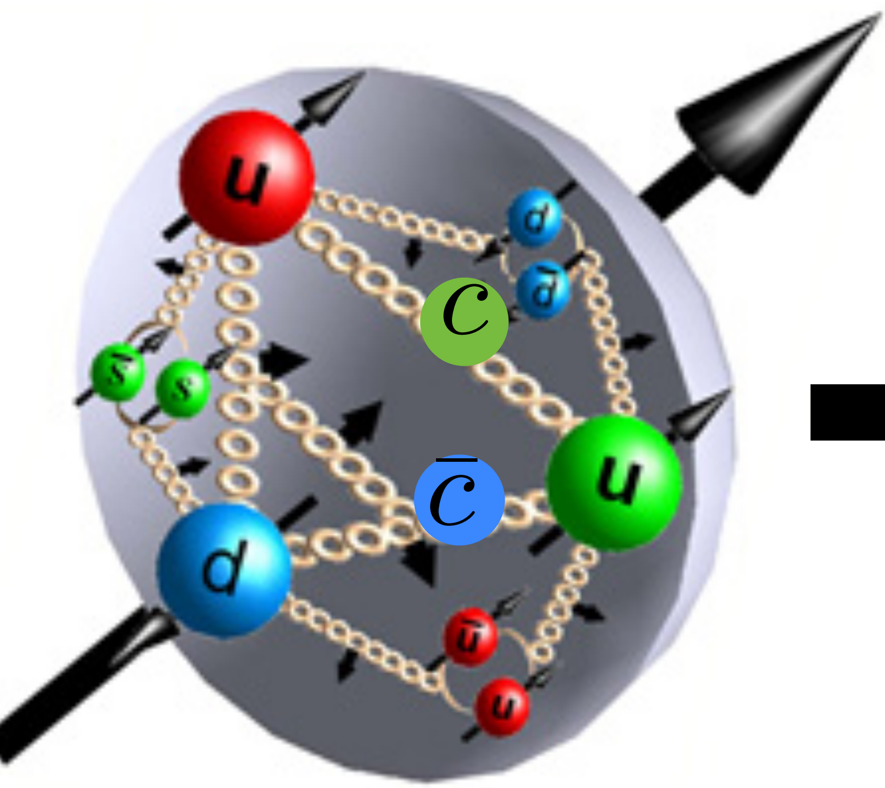
Burkardt
Dalley
Hiller

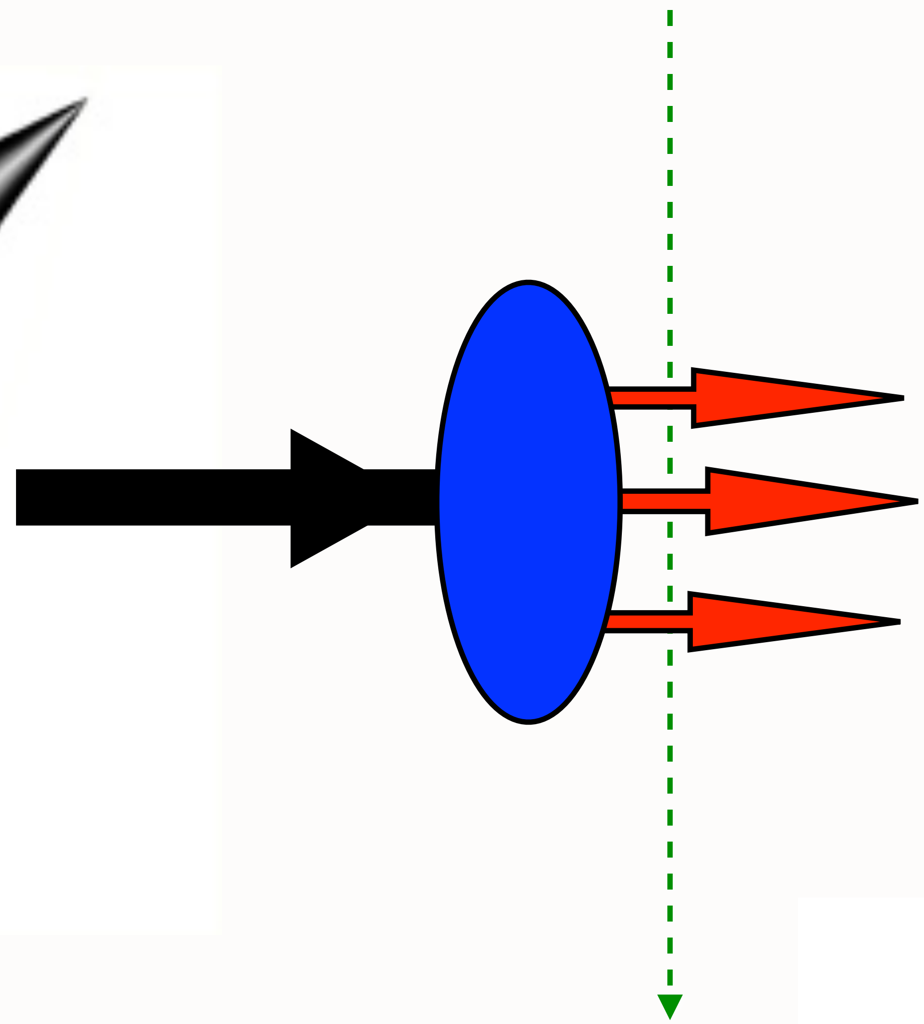
- **Hadronization at the Amplitude Level -- Off-Shell T-matrix convoluted with AdS/QCD LFWFs**
- **Hidden Color** *C. Ji , Lepage, sjb*
- **Intrinsic Heavy Quarks from confinement interaction**
- **BLM/PMC -- Automatic Scale Setting -- pinch scheme**

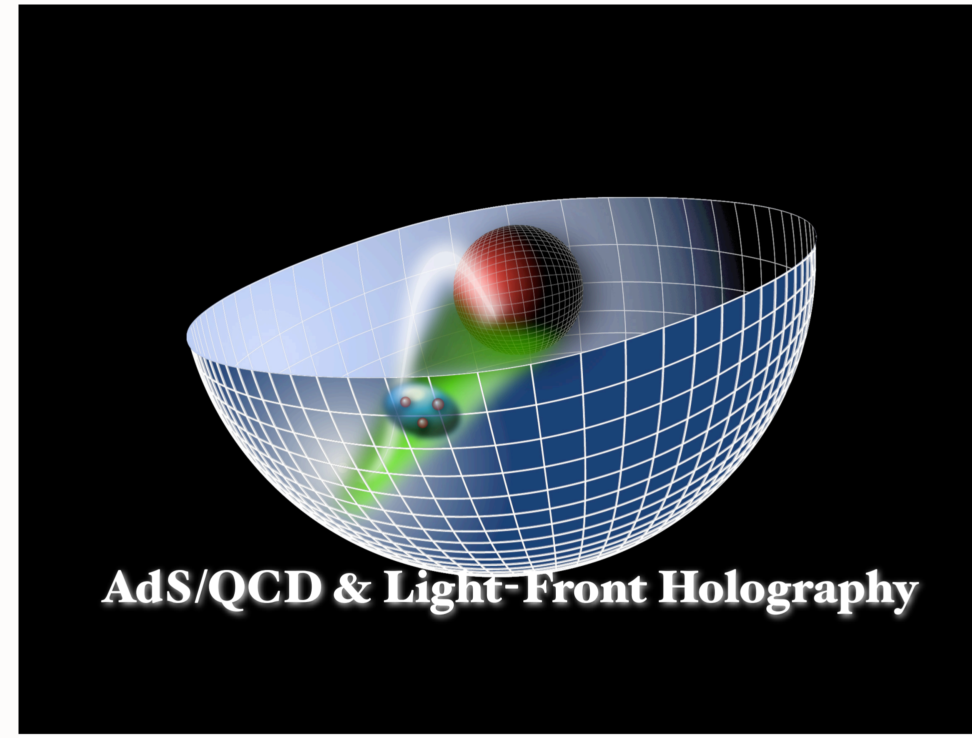
Binosi,
Cornwall,
Popavassiliu
Binger
di Giustino
sjb

- **Direct Processes at the LHC**
- **Dynamic vs. Static Structure Functions**
- **AdS/QCD for DVCS, Hadrons with Heavy Quarks**
- **LF Vacuum, In-Hadron Condensates, Zero-Modes, and the Cosmological Constant**

QCD Myths







CP3 - Origins
Particle Physics & Origin of Mass

Stan Brodsky

SLAC
NATIONAL ACCELERATOR LABORATORY