

- Note: in the Weyl representation ( $i\alpha = \gamma_5\beta$ )

$$i\alpha = \begin{pmatrix} 0 & I \\ -I & 0 \end{pmatrix}, \quad \beta = \begin{pmatrix} 0 & I \\ I & 0 \end{pmatrix}, \quad \gamma_5 = \begin{pmatrix} I & 0 \\ 0 & -I \end{pmatrix}.$$

- Baryon: twist-dimension  $3 + L$  ( $\nu = L + 1$ )

$$\mathcal{O}_{3+L} = \psi D_{\{\ell_1 \dots D_{\ell_q} \psi D_{\ell_{q+1}} \dots D_{\ell_m}\}} \psi, \quad L = \sum_{i=1}^m \ell_i.$$

- Solution to Dirac eigenvalue equation with UV matching boundary conditions

$$\psi(\zeta) = C \sqrt{\zeta} [J_{L+1}(\zeta \mathcal{M}) u_+ + J_{L+2}(\zeta \mathcal{M}) u_-].$$

Baryonic modes propagating in AdS space have two components: orbital  $L$  and  $L + 1$ .

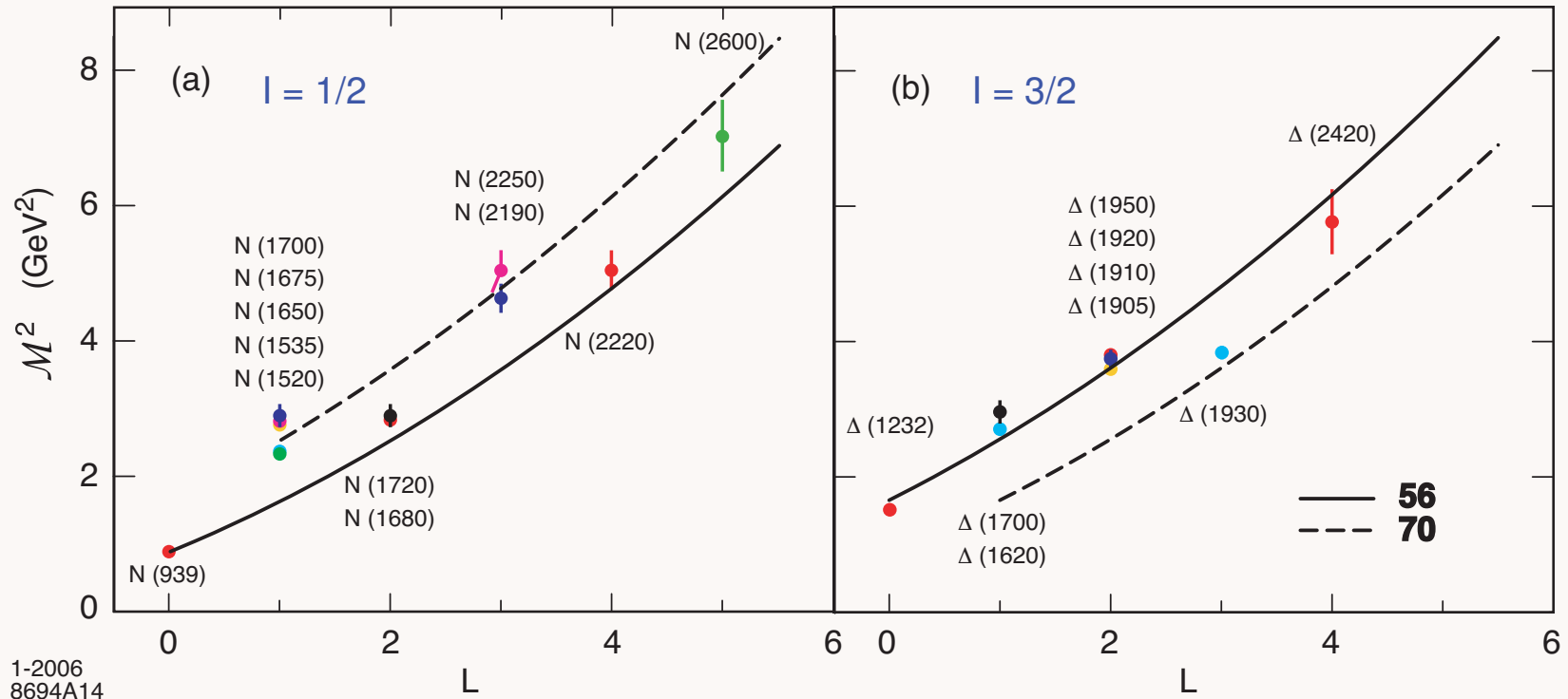
- Hadronic mass spectrum determined from IR boundary conditions

$$\psi_{\pm}(\zeta = 1/\Lambda_{\text{QCD}}) = 0,$$

given by

$$\mathcal{M}_{\nu,k}^+ = \beta_{\nu,k} \Lambda_{\text{QCD}}, \quad \mathcal{M}_{\nu,k}^- = \beta_{\nu+1,k} \Lambda_{\text{QCD}},$$

with a scale independent mass ratio.



1-2006  
8694A14

Fig: Light baryon orbital spectrum for  $\Lambda_{QCD} = 0.25$  GeV in the HW model. The **56** trajectory corresponds to  $L$  even  $P = +$  states, and the **70** to  $L$  odd  $P = -$  states.

$SU(6)$	$S$	$L$	Baryon State
<b>56</b>	$\frac{1}{2}$	0	$N_{\frac{1}{2}}^{1+}$ (939)
	$\frac{3}{2}$	0	$\Delta_{\frac{3}{2}}^{3+}$ (1232)
<b>70</b>	$\frac{1}{2}$	1	$N_{\frac{1}{2}}^{1-}$ (1535) $N_{\frac{3}{2}}^{3-}$ (1520)
	$\frac{3}{2}$	1	$N_{\frac{1}{2}}^{1-}$ (1650) $N_{\frac{3}{2}}^{3-}$ (1700) $N_{\frac{5}{2}}^{5-}$ (1675)
	$\frac{1}{2}$	1	$\Delta_{\frac{1}{2}}^{1-}$ (1620) $\Delta_{\frac{3}{2}}^{3-}$ (1700)
<b>56</b>	$\frac{1}{2}$	2	$N_{\frac{3}{2}}^{3+}$ (1720) $N_{\frac{5}{2}}^{5+}$ (1680)
	$\frac{3}{2}$	2	$\Delta_{\frac{1}{2}}^{1+}$ (1910) $\Delta_{\frac{3}{2}}^{3+}$ (1920) $\Delta_{\frac{5}{2}}^{5+}$ (1905) $\Delta_{\frac{7}{2}}^{7+}$ (1950)
<b>70</b>	$\frac{1}{2}$	3	$N_{\frac{5}{2}}^{5-}$ $N_{\frac{7}{2}}^{7-}$
	$\frac{3}{2}$	3	$N_{\frac{3}{2}}^{3-}$ $N_{\frac{5}{2}}^{5-}$ $N_{\frac{7}{2}}^{7-}$ (2190) $N_{\frac{9}{2}}^{9-}$ (2250)
	$\frac{1}{2}$	3	$\Delta_{\frac{5}{2}}^{5-}$ (1930) $\Delta_{\frac{7}{2}}^{7-}$
<b>56</b>	$\frac{1}{2}$	4	$N_{\frac{7}{2}}^{7+}$ $N_{\frac{9}{2}}^{9+}$ (2220)
	$\frac{3}{2}$	4	$\Delta_{\frac{5}{2}}^{5+}$ $\Delta_{\frac{7}{2}}^{7+}$ $\Delta_{\frac{9}{2}}^{9+}$ $\Delta_{\frac{11}{2}}^{11+}$ (2420)
<b>70</b>	$\frac{1}{2}$	5	$N_{\frac{9}{2}}^{9-}$ $N_{\frac{11}{2}}^{11-}$ (2600)
	$\frac{3}{2}$	5	$N_{\frac{7}{2}}^{7-}$ $N_{\frac{9}{2}}^{9-}$ $N_{\frac{11}{2}}^{11-}$ $N_{\frac{13}{2}}^{13-}$

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

- We write the Dirac equation

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

in terms of the matrix-valued operator  $\Pi$

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

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

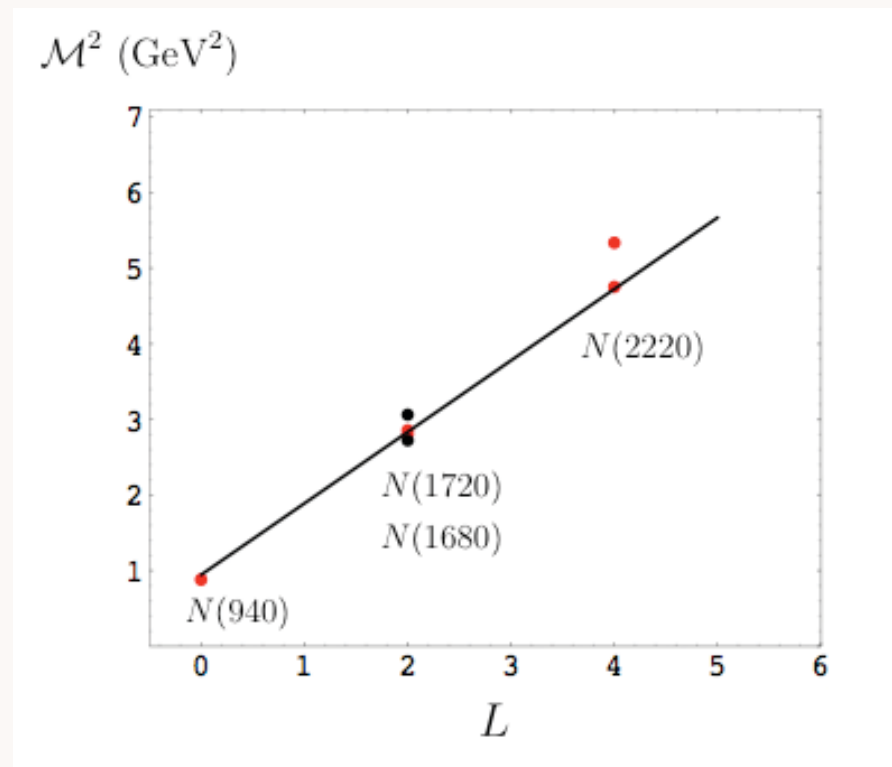
$$\mathcal{M}^2 = 4\kappa^2(n + \nu + 1).$$

- Baryon: twist-dimension  $3 + L$  ( $\nu = L + 1$ )

$$\mathcal{O}_{3+L} = \psi D_{\{\ell_1 \dots D_{\ell_q} \psi D_{\ell_{q+1}} \dots D_{\ell_m}\}} \psi, \quad L = \sum_{i=1}^m \ell_i.$$

- Define the zero point energy (identical as in the meson case)  $\mathcal{M}^2 \rightarrow \mathcal{M}^2 - 4\kappa^2$ :

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



Proton Regge Trajectory  $\kappa = 0.49\text{GeV}$

## 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.

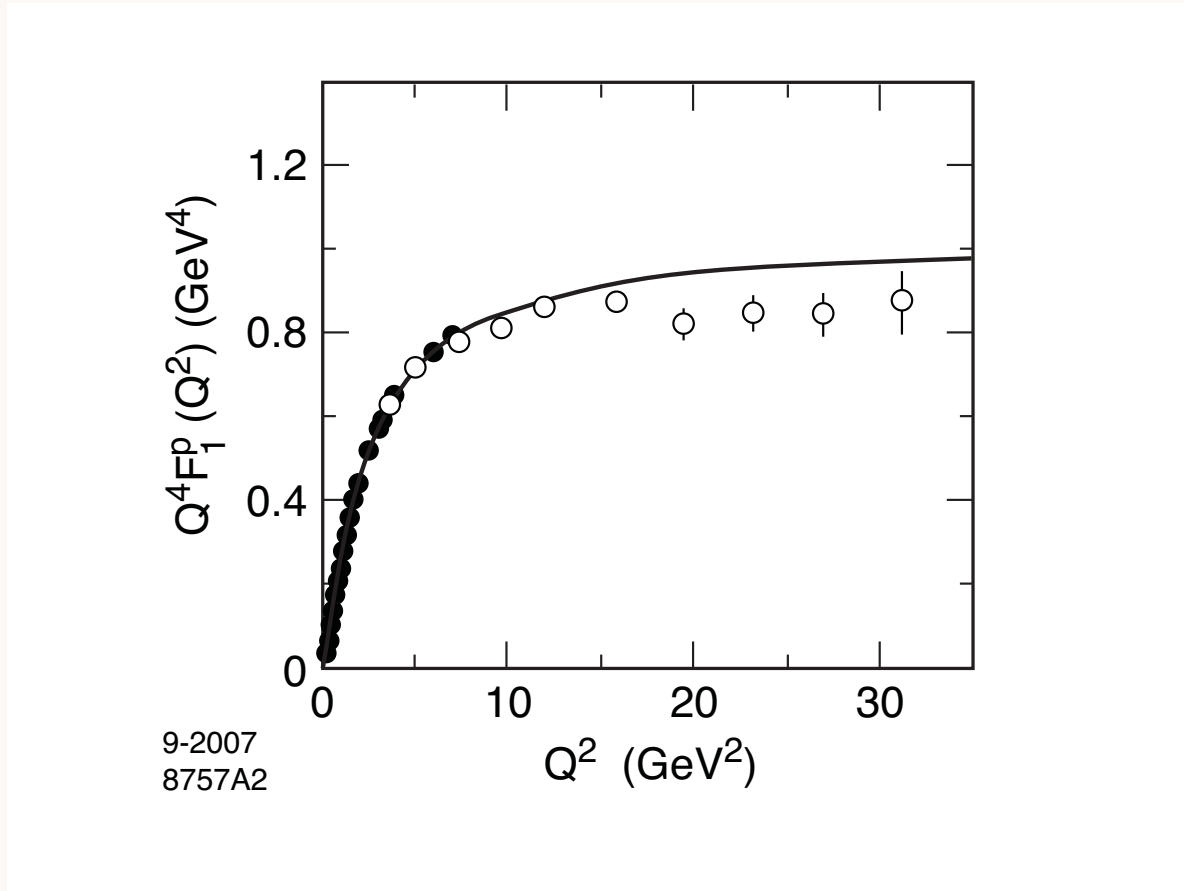
- Choose the struck quark to have  $S^z = +1/2$ . The two AdS solutions  $\psi_+(\zeta)$  and  $\psi_-(\zeta)$  correspond to nucleons with  $J^z = +1/2$  and  $-1/2$ .
- For  $SU(6)$  spin-flavor symmetry

$$F_1^p(Q^2) = \int d\zeta J(Q, \zeta) |\psi_+(\zeta)|^2,$$

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

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

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

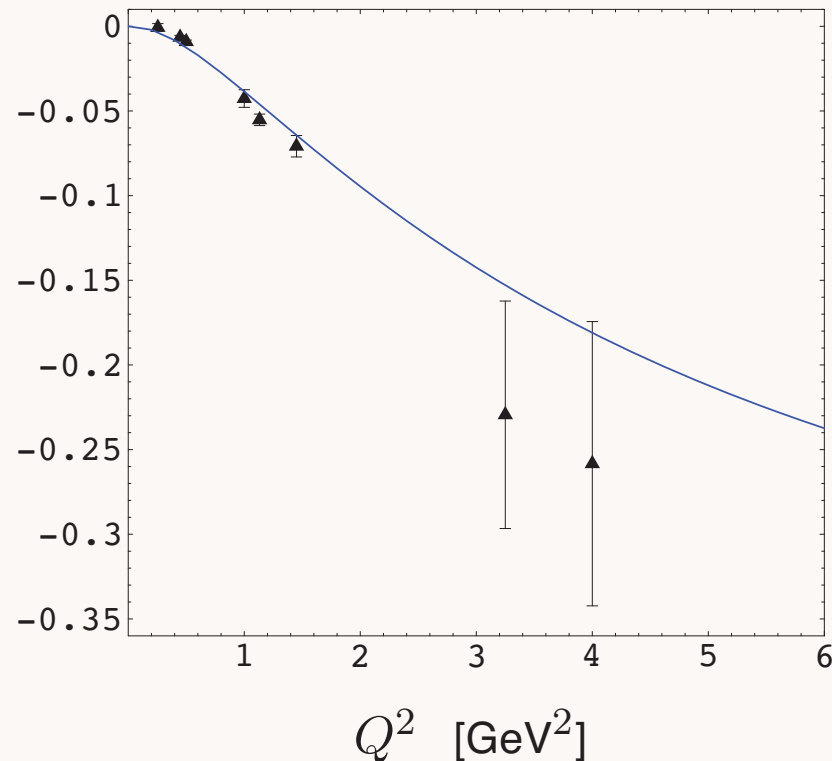


SW model predictions for  $\kappa = 0.424$  GeV. Data analysis from: M. Diehl *et al.* Eur. Phys. J. C **39**, 1 (2005).

# Dirac Neutron Form Factor (Valence Approximation)

Truncated Space Confinement

$$Q^4 F_1^n(Q^2) \text{ [GeV}^4\text{]}$$



Prediction for  $Q^4 F_1^n(Q^2)$  for  $\Lambda_{\text{QCD}} = 0.21$  GeV in the hard wall approximation. Data analysis from Diehl (2005).

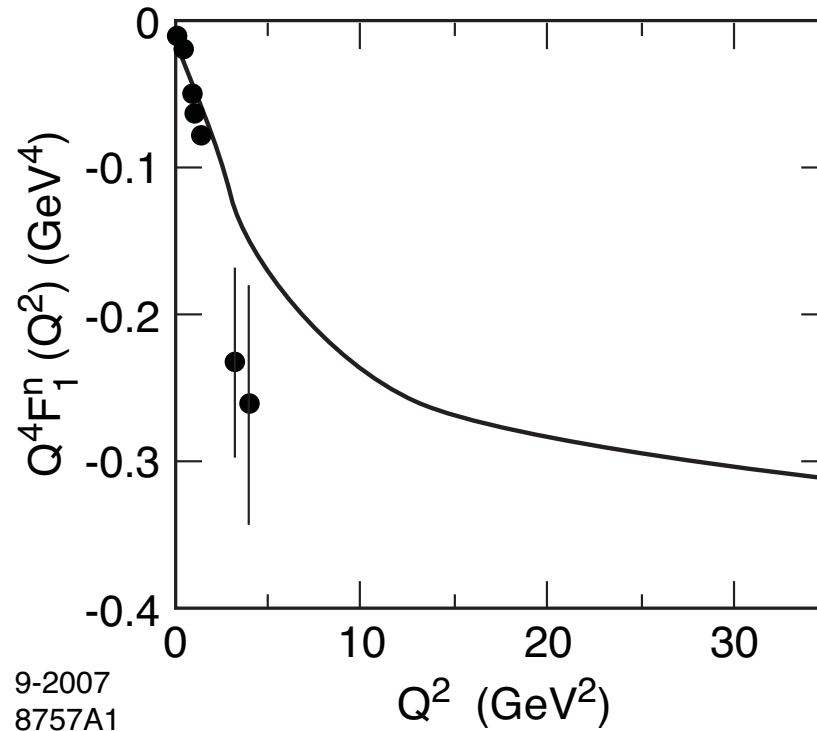
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**March 28, 2008**

**AdS/QCD**  
**107**

**Stan Brodsky, SLAC**



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

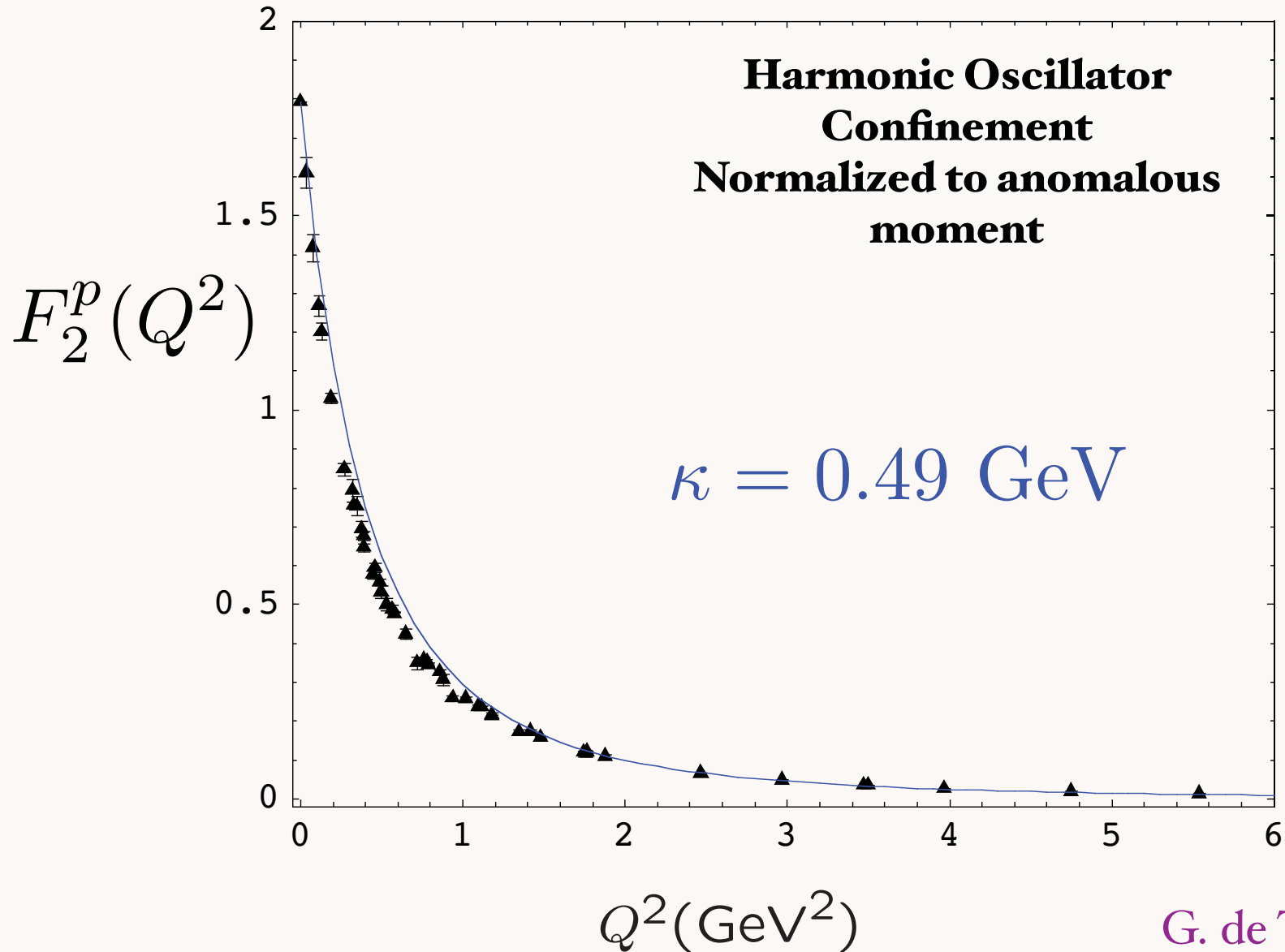


SW model predictions for  $\kappa = 0.424$  GeV. Data analysis from M. Diehl *et al.* Eur. Phys. J. C **39**, 1 (2005).

# Spacelike Pauli Form Factor

Preliminary

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



G. de Teramond, sjb

INT  
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109

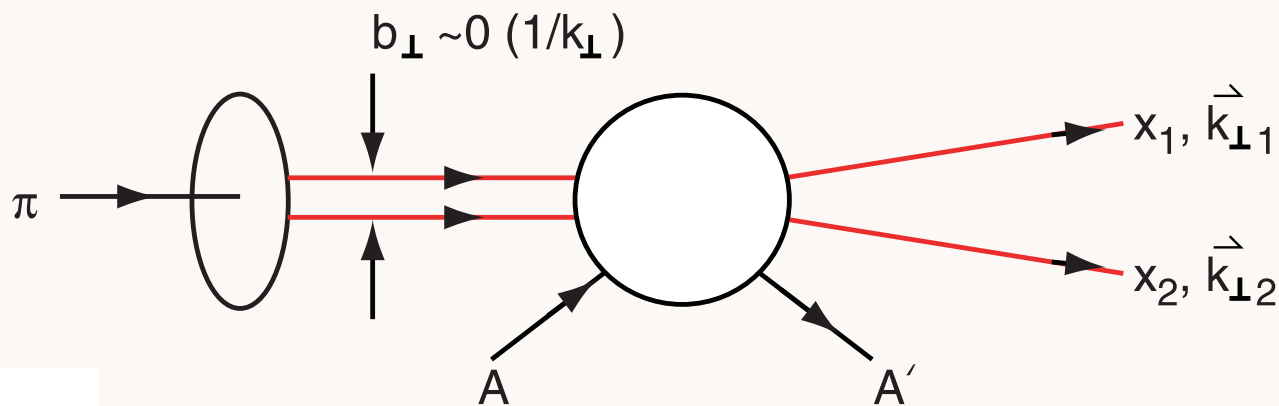
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# Holographic Connection between LF and AdS/CFT

- Predictions for hadronic spectra, light-front wavefunctions, interactions
- Deduce meson and baryon wavefunctions, distribution amplitude, structure function from holographic constraint
- Identification of Orbital Angular Momentum Casimir for  $SO(2)$ : LF Rotations
- Extension to massive quarks

# Diffractive Dissociation of Pion into Quark Jets

E791 Ashery et al.

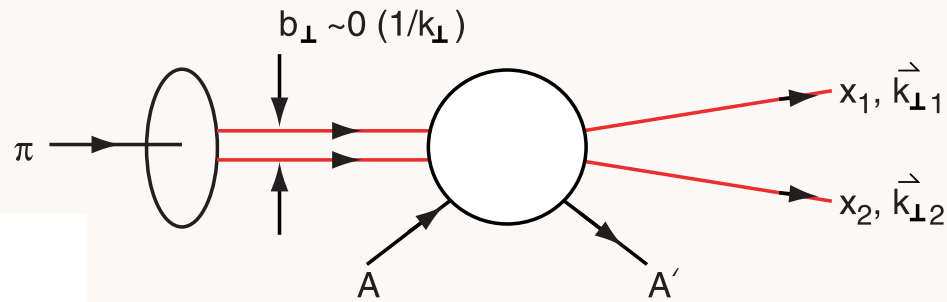


$$M \propto \frac{\partial^2}{\partial^2 k_{\perp}} \psi_{\pi}(x, k_{\perp})$$

Measure Light-Front Wavefunction of Pion

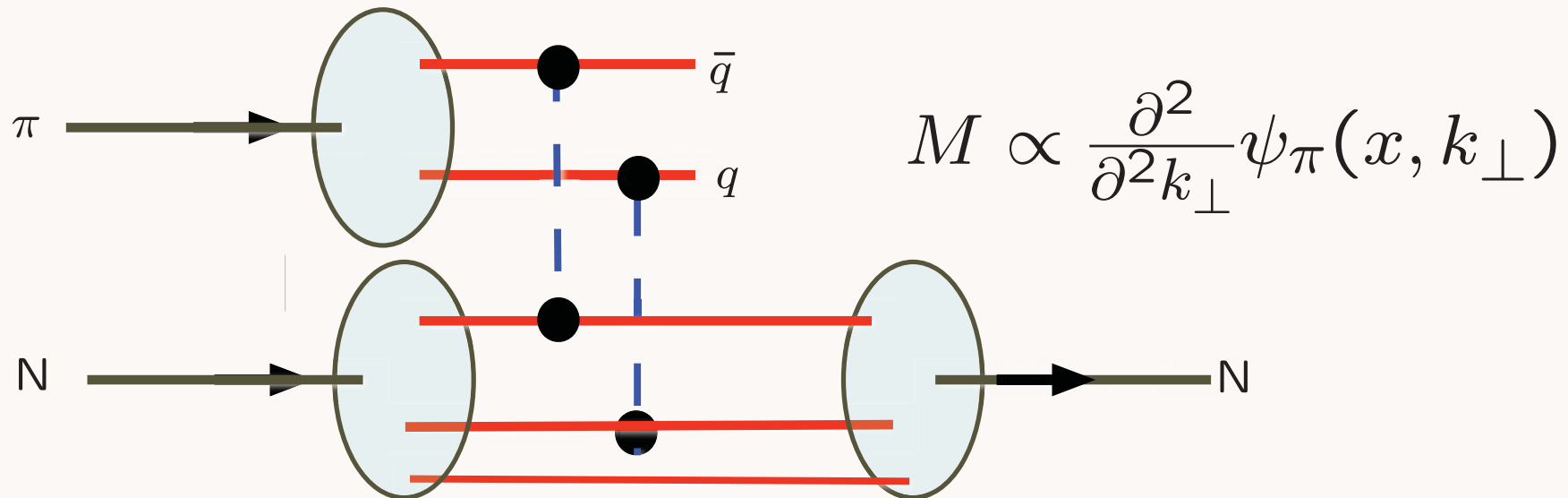
Minimal momentum transfer to nucleus  
Nucleus left Intact!

# E791 FNAL Diffractive DiJet



Gunion, Frankfurt, Mueller, Strikman, sjb  
Frankfurt, Miller, Strikman

*Two-gluon exchange measures the second derivative of the pion light-front wavefunction*

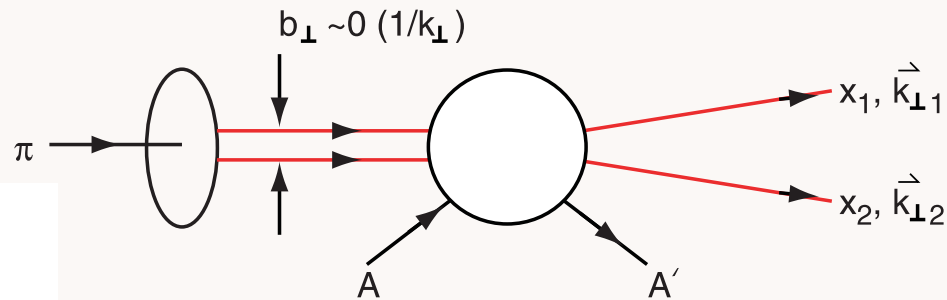


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Stan Brodsky, SLAC

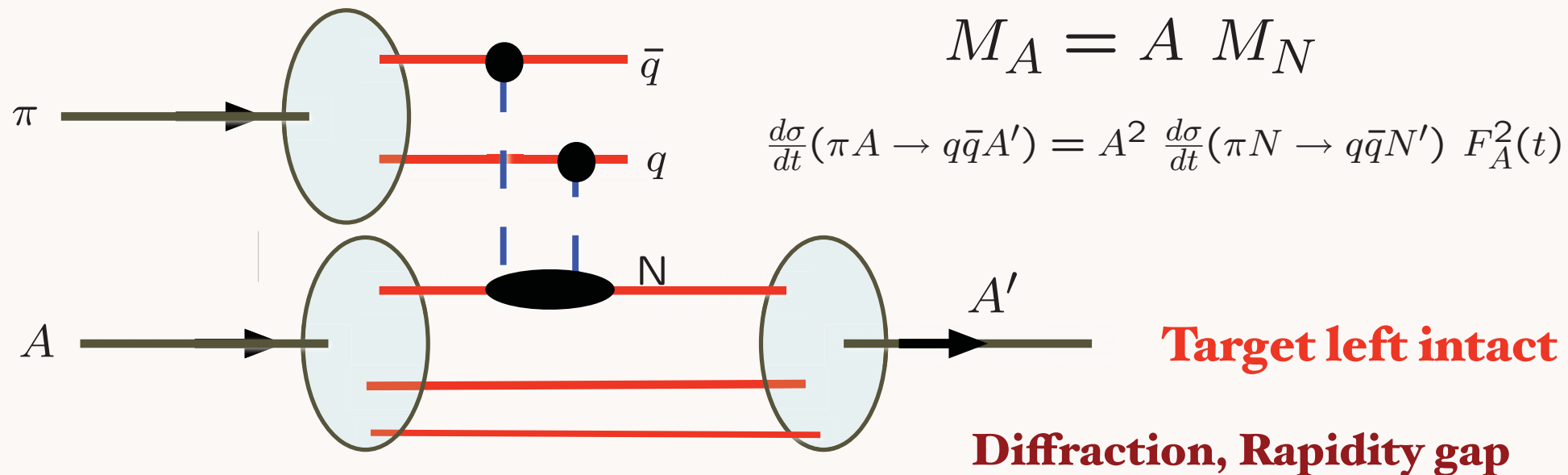
# Key Ingredients in E791 Experiment



Brodsky Mueller  
Frankfurt Miller Strikman

*Small color-dipole moment pion not absorbed;  
interacts with each nucleon coherently*

## QCD COLOR Transparency



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AdS/QCD  
II3

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# Color Transparency

Bertsch, Gunion, Goldhaber, sjb  
A. H. Mueller, sjb

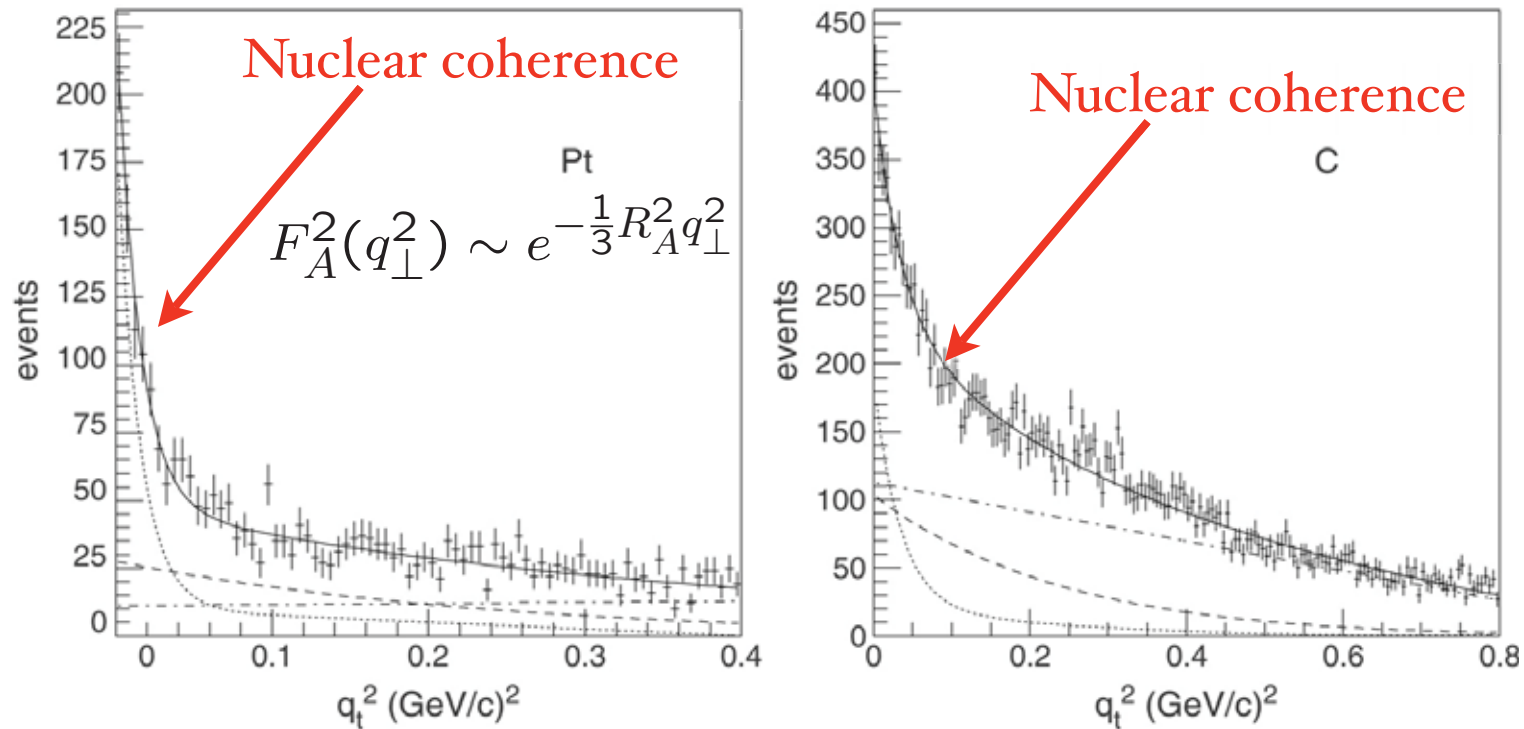
- Fundamental test of gauge theory in hadron physics
- Small color dipole moments interact weakly in nuclei
- Complete coherence at high energies
- Clear Demonstration of CT from Diffractive Di-Jets

- Fully coherent interactions between pion and nucleons.
- Emerging Di-Jets do not interact with nucleus.

$$M(A) = A \cdot M(N)$$

$$\frac{d\sigma}{dq_t^2} \propto A^2 \quad q_t^2 \sim 0$$

$$\sigma \propto A^{4/3}$$





# Measure pion LFWF in diffractive dijet production

## Confirmation of color transparency

A-Dependence results:  $\sigma \propto A^\alpha$

<u><math>k_t</math> range (GeV/c)</u>	<u><math>\alpha</math></u>	<u><math>\alpha</math> (CT)</u>
$1.25 < k_t < 1.5$	$1.64 +0.06 -0.12$	1.25
$1.5 < k_t < 2.0$	$1.52 \pm 0.12$	1.45
$2.0 < k_t < 2.5$	$1.55 \pm 0.16$	1.60

Ashery E791

$\alpha$  (Incoh.) =  $0.70 \pm 0.1$

*Conventional Glauber Theory Ruled  
Out!*

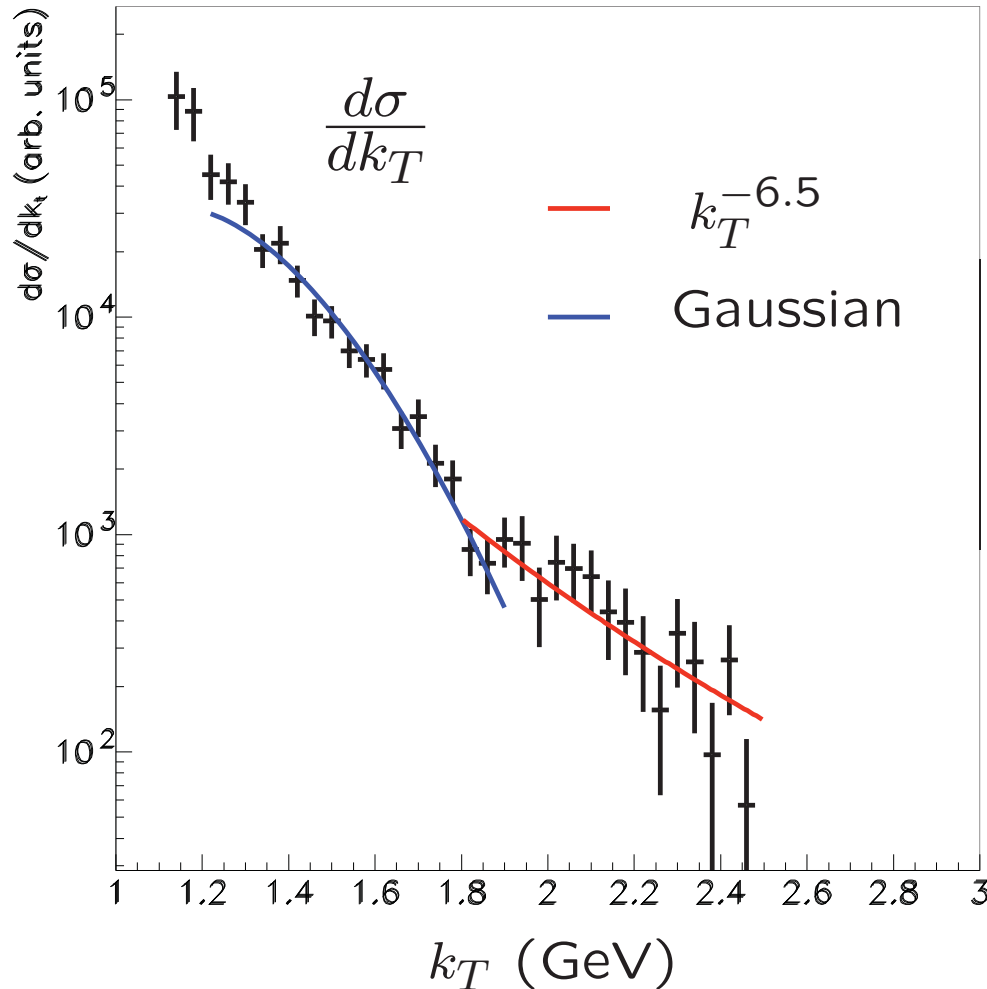
**Factor of 7**

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# E791 Diffractive Di-Jet transverse momentum distribution



## Two Components

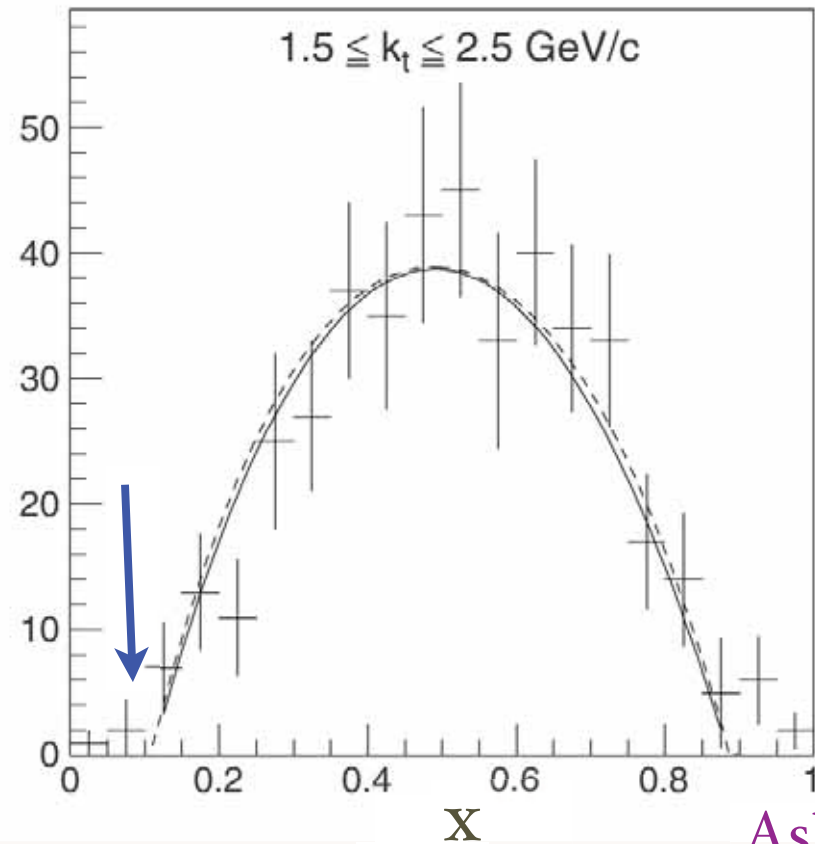
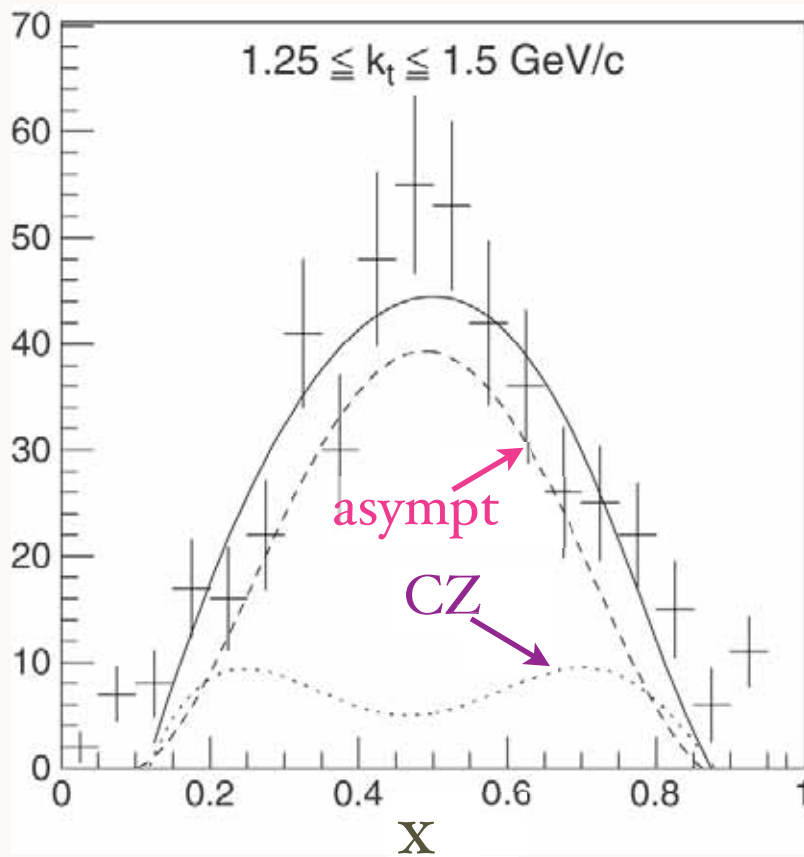
*High Transverse momentum dependence  $k_T^{-6.5}$  consistent with PQCD, ERBL Evolution*

*Gaussian component similar to AdS/CFT HO LFWF*

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Ashery E791

*Narrowing of  $x$  distribution at higher jet transverse momentum*

$x$  distribution of diffractive dijets from the platinum target for  $1.25 \leq k_t \leq 1.5$  GeV/c (left) and for  $1.5 \leq k_t \leq 2.5$  GeV/c (right). The solid line is a fit to a combination of the asymptotic and CZ distribution amplitudes. The dashed line shows the contribution from the asymptotic function and the dotted line that of the CZ function.

**Possibly two components:**

**Nonperturbative (AdS/CFT) and  
Perturbative (ERBL)**

$$\phi(x) \propto \sqrt{x(1-x)}$$

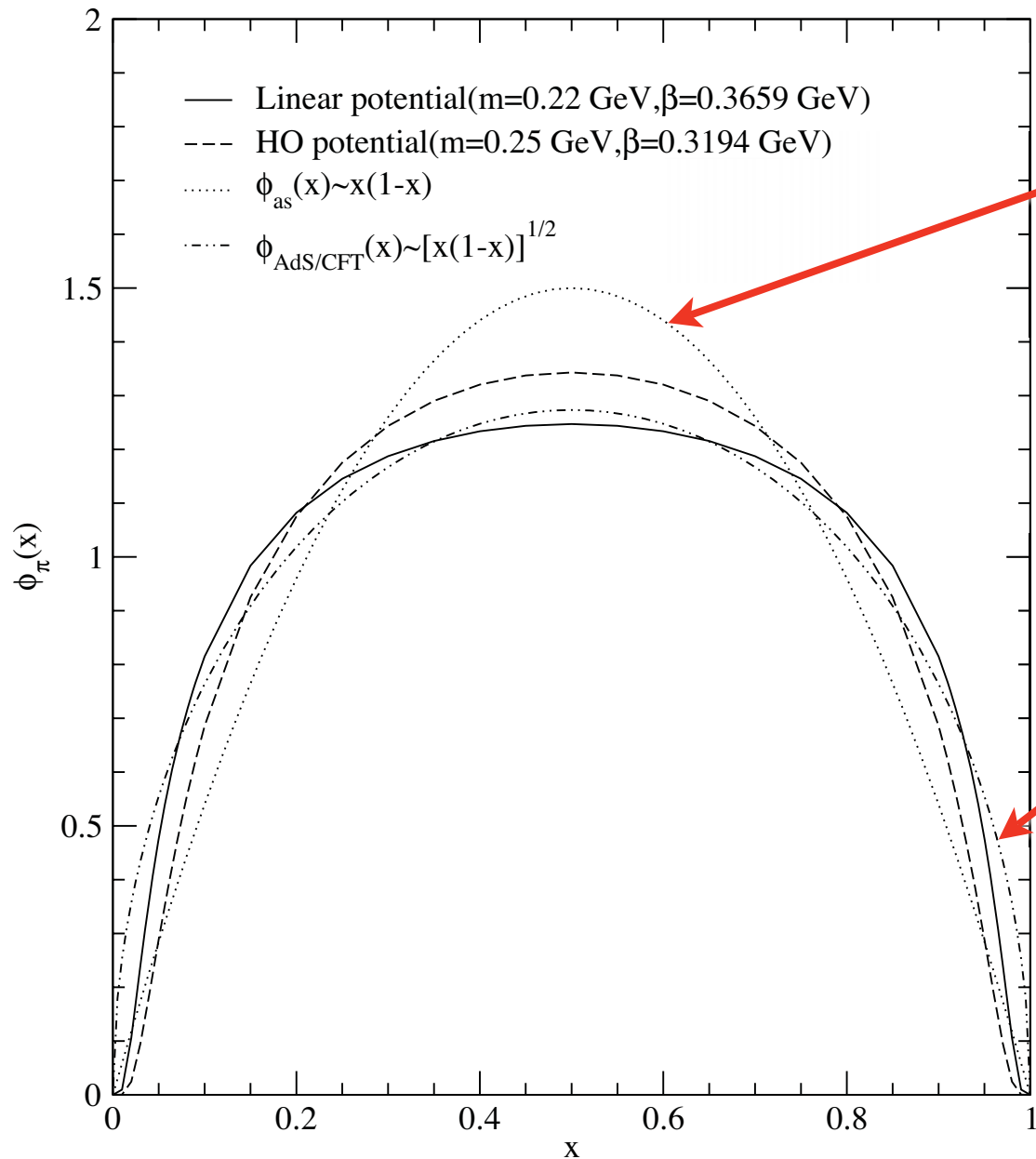
**Evolution to asymptotic distribution**

**AdS/QCD**

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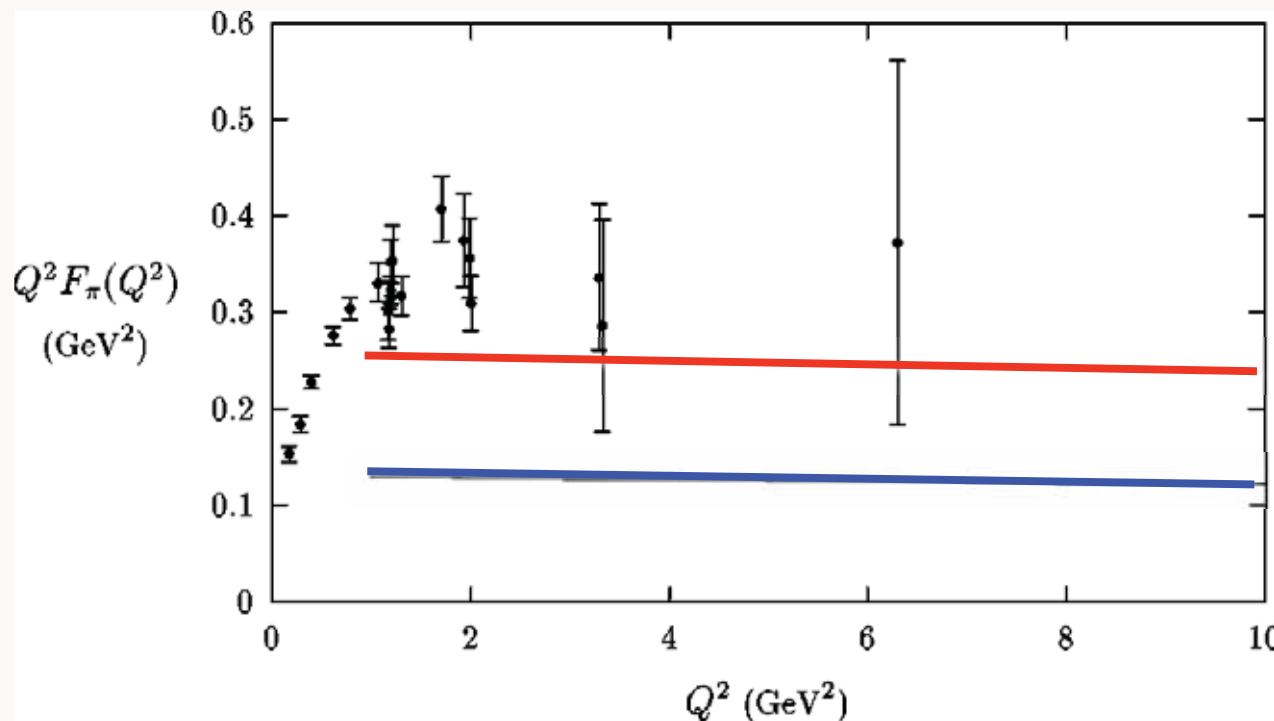
$$\phi_{asympt} \sim x(1-x)$$

***AdS/CFT:***

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

Increases PQCD leading twist prediction  
 $F_\pi(Q^2)$  by factor 16/9

$$F_{\pi}(Q^2) = \int_0^1 dx \phi_{\pi}(x) \int_0^1 dy \phi_{\pi}(y) \frac{16\pi C_F \alpha_V(Q_V)}{(1-x)(1-y)Q^2}$$



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

$$\phi_{asymptotic} \propto x(1-x)$$

Normalized to  $f_{\pi}$

***AdS/CFT:***

Increases PQCD leading twist prediction for  $F_{\pi}(Q^2)$  by factor 16/9

INT  
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**AdS/QCD**  
120

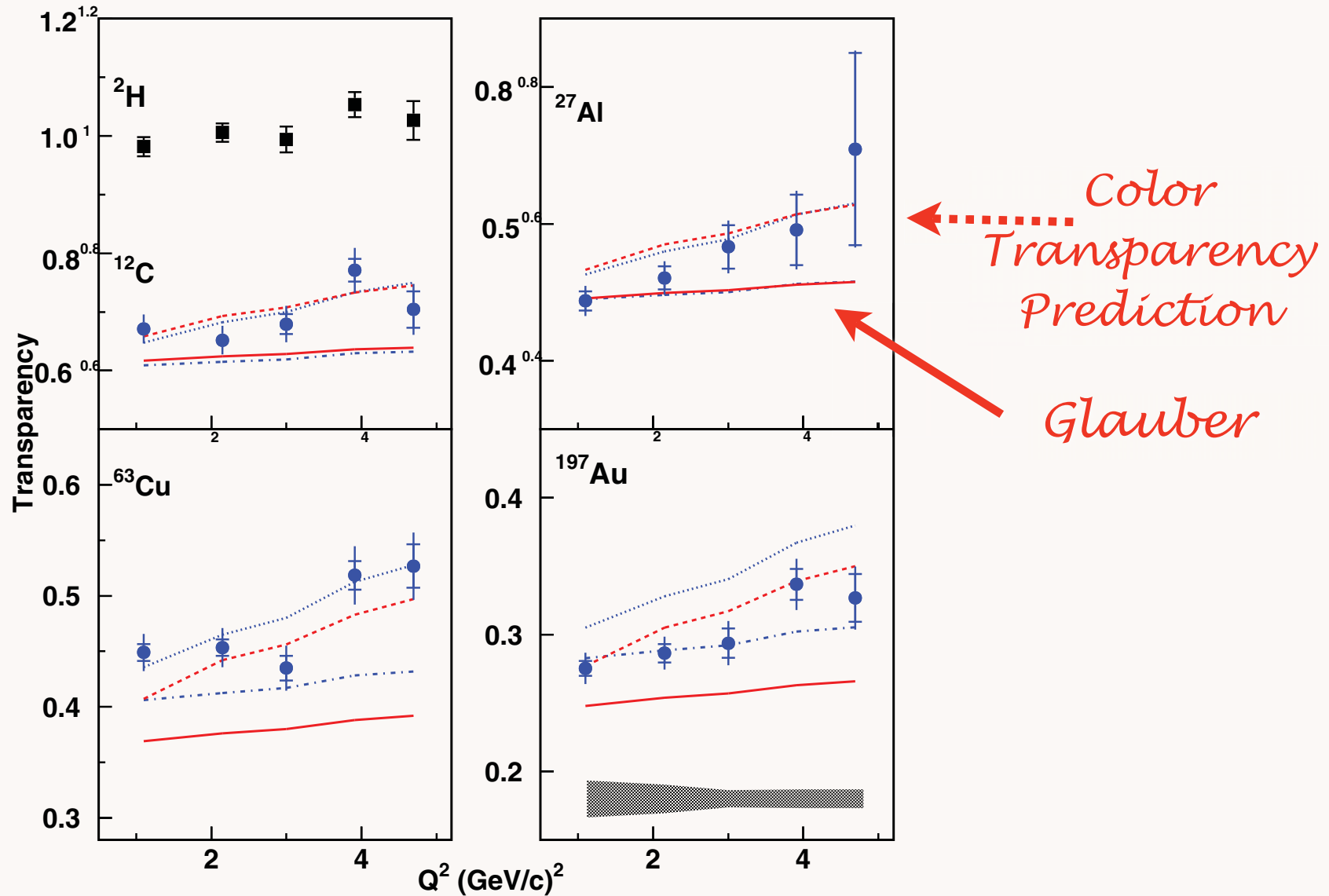
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# Measurement of Nuclear Transparency for the $A(e, e' \pi^+)$ Reaction

$$eA \rightarrow e' \pi^+ X$$

B. Clasie, et al, Jlab

PRL 99, 242502 (2007)

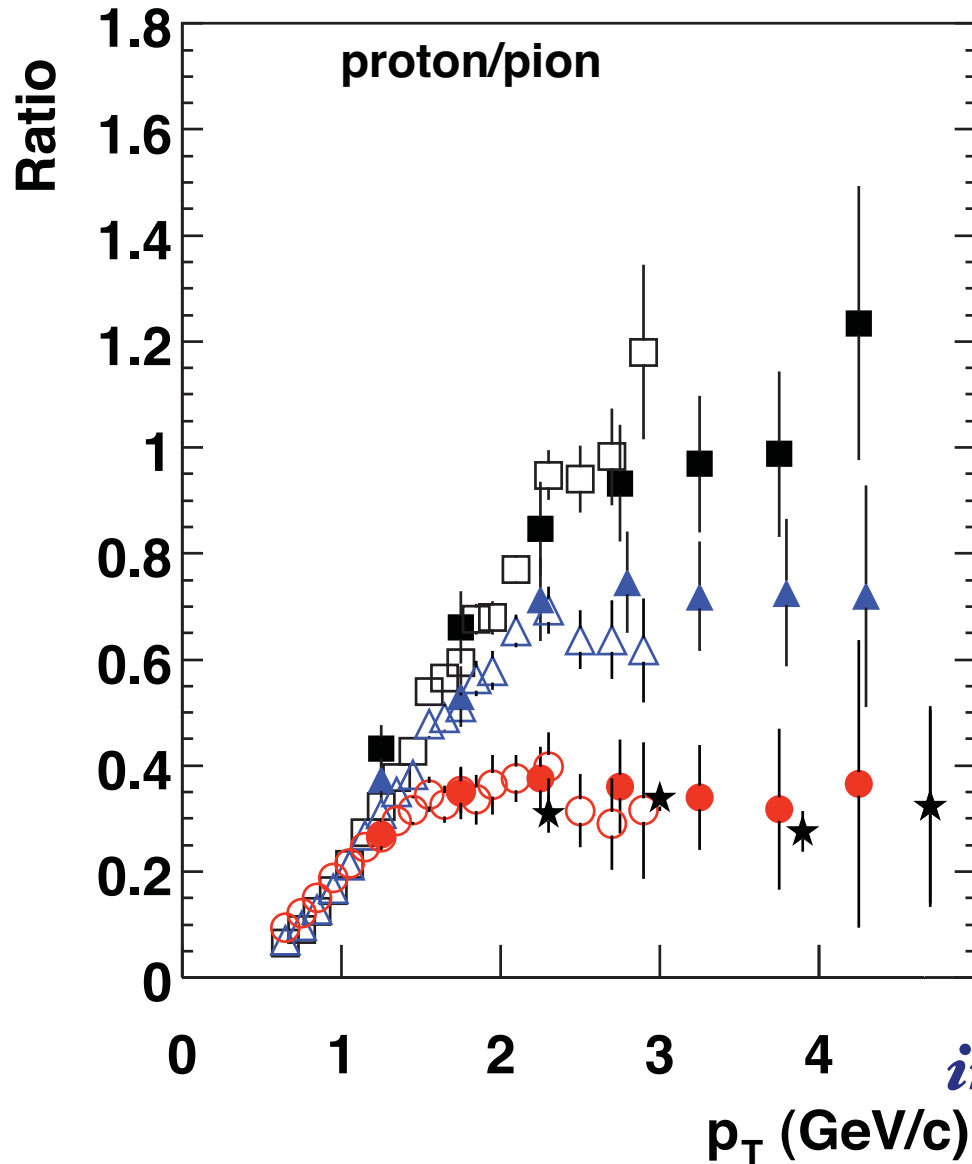


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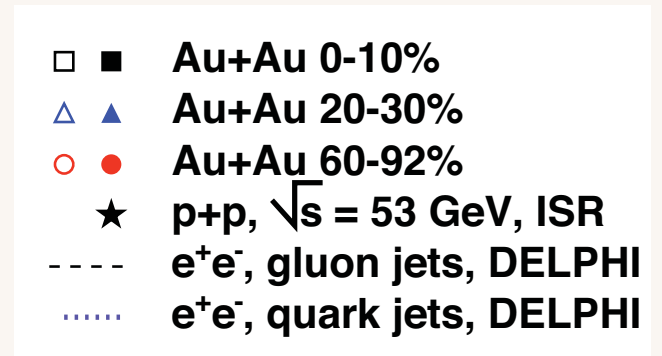
AdS/QCD  
I2I

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*Particle ratio changes with centrality!*



← **Central**



← **Peripheral**

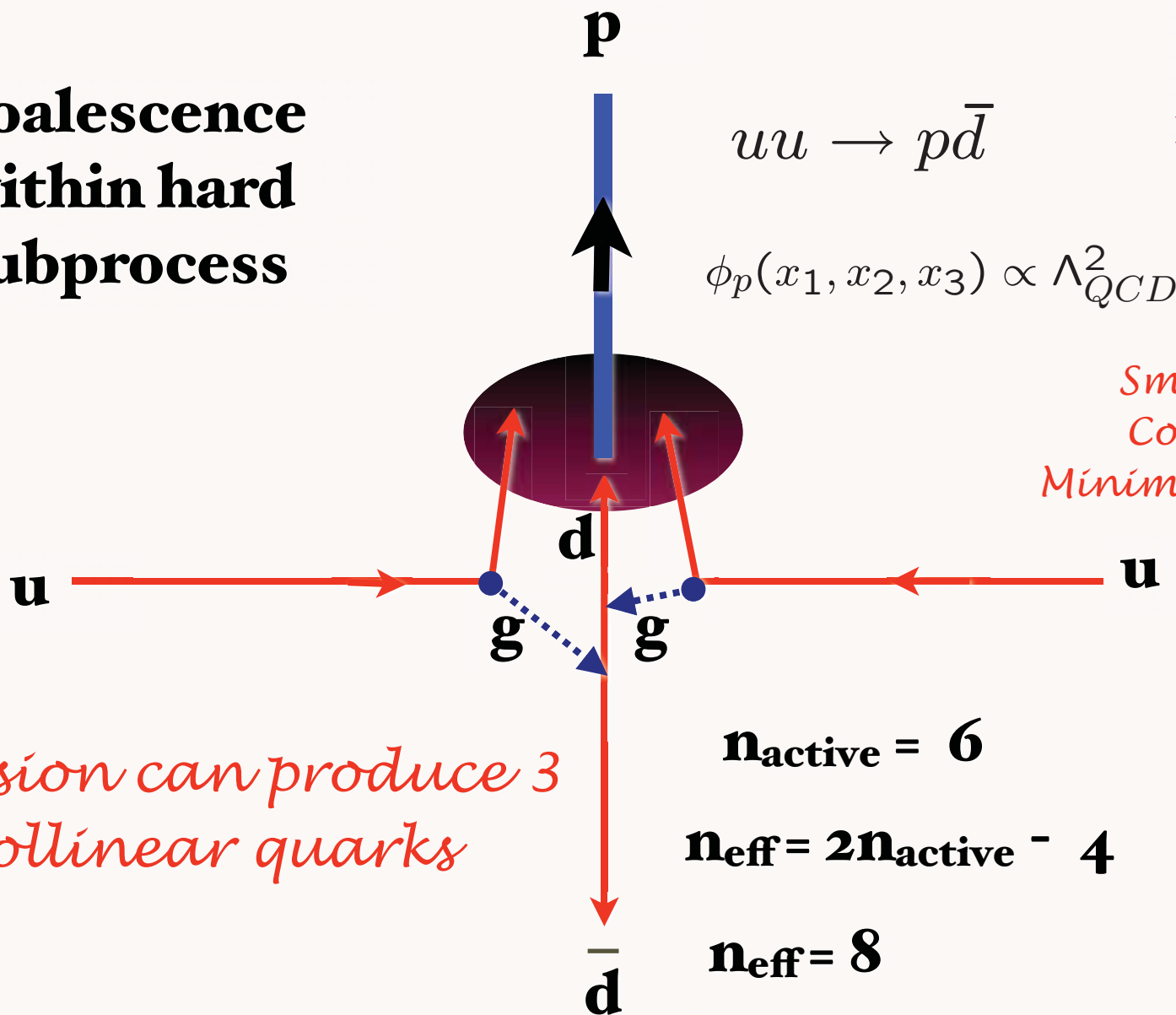
*Protons less absorbed  
in nuclear collisions than pions!*

Open (filled) points are for  $\pi^\pm$  ( $\pi^0$ ), respectively.

# Baryon can be made directly within hard subprocess

**Coalescence  
within hard  
subprocess**

Bjorken  
Blankenbecler, Gunion, sjb  
Berger, sjb  
Hoyer, et al: Semi-Exclusive



*Small color-singlet  
Color Transparent  
Minimal same-side energy*

$qq \rightarrow B\bar{q}$

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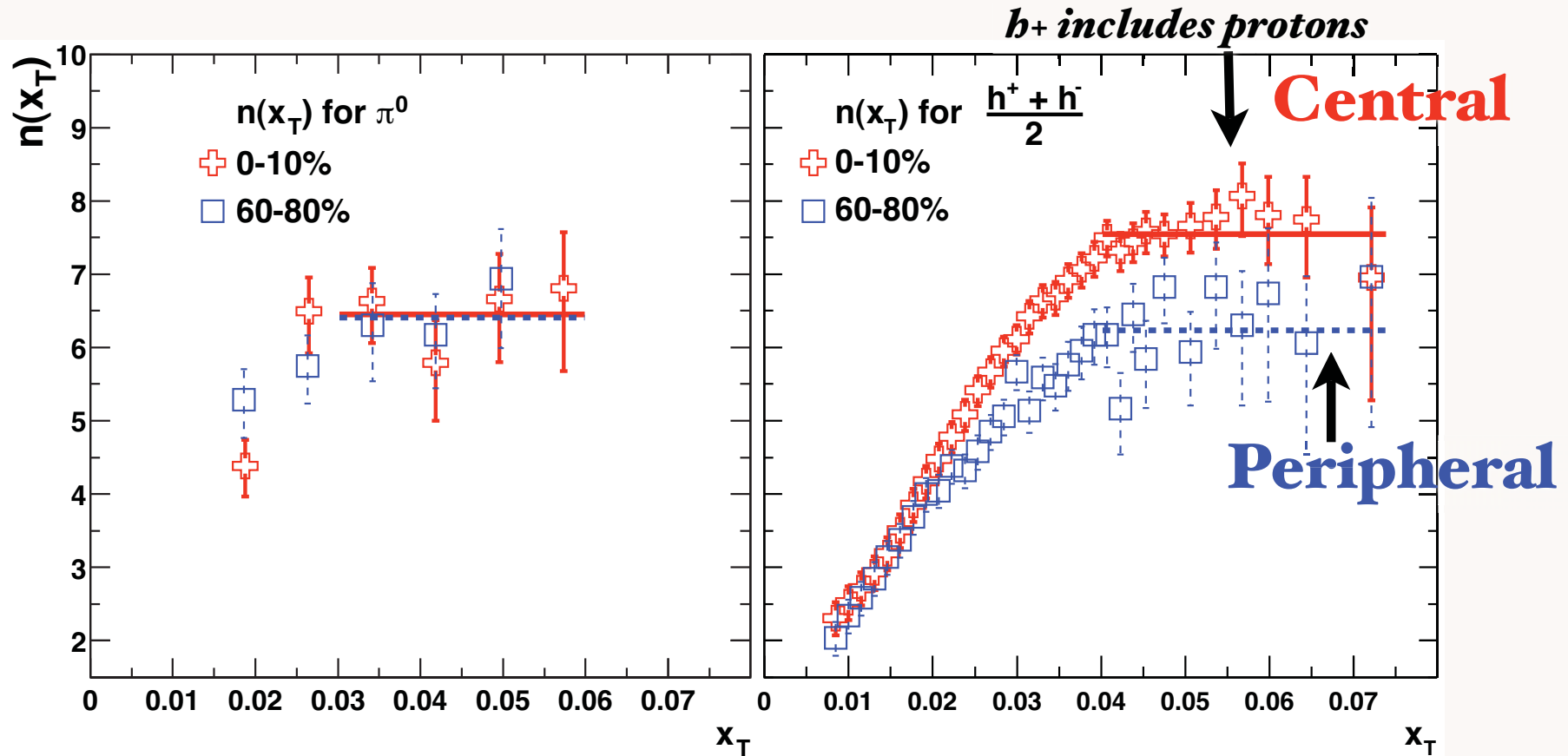
AdS/QCD  
123

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Power-law exponent  $n(x_T)$  for  $\pi^0$  and  $h$  spectra in central and peripheral Au+Au collisions at  $\sqrt{s_{NN}} = 130$  and 200 GeV

S. S. Adler, *et al.*, PHENIX Collaboration, *Phys. Rev. C* **69**, 034910 (2004) [nucl-ex/0308006].



*Proton production dominated by color-transparent direct high  $n_{eff}$  subprocesses*

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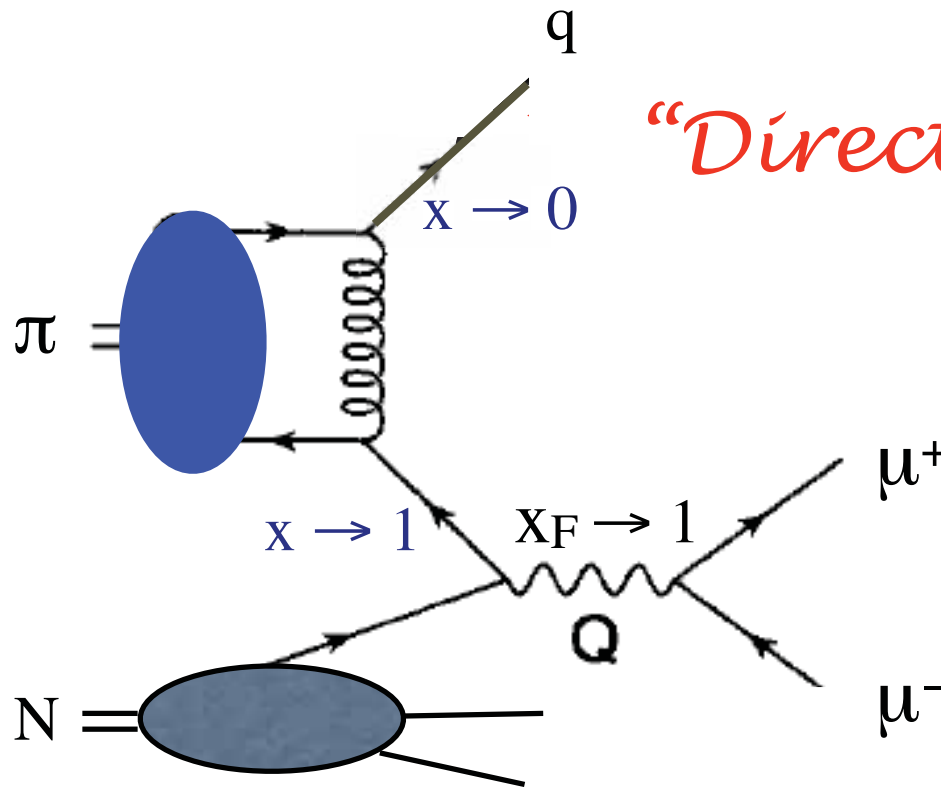
AdS/QCD  
I24

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$$\pi N \rightarrow \mu^+ \mu^- X \text{ at high } x_F$$

In the limit where  $(1-x_F)Q^2$  is fixed as  $Q^2 \rightarrow \infty$

Entire pion wf  
contributes to  
hard process



*“Direct” Subprocess*

Virtual photon is  
longitudinally  
polarized

Berger and Brodsky, PRL 42 (1979) 940

$$\pi^- N \rightarrow \mu^+ \mu^- X \text{ at } 80 \text{ GeV}/c$$

$$\frac{d\sigma}{d\Omega} \propto 1 + \lambda \cos^2\theta + \rho \sin 2\theta \cos\phi + \omega \sin^2\theta \cos 2\phi.$$

$$\frac{d^2\sigma}{dx_\pi d\cos\theta} \propto x_\pi \left[ (1 - x_\pi)^2 (1 + \cos^2\theta) + \frac{4}{9} \frac{\langle k_T^2 \rangle}{M^2} \sin^2\theta \right]$$

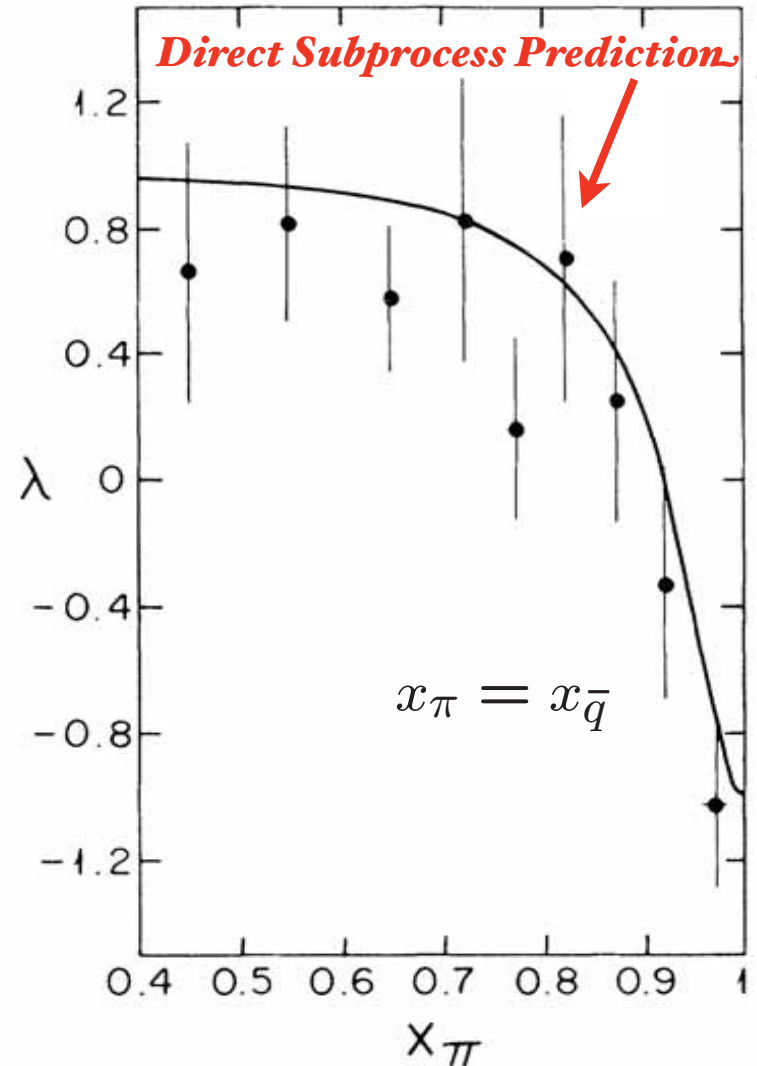
$$\langle k_T^2 \rangle = 0.62 \pm 0.16 \text{ GeV}^2/c^2$$

*Dramatic change in  
angular distribution at  
large  $x_F$*

**Example of a higher-twist  
direct subprocess**

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126



Chicago-Princeton  
Collaboration

Phys.Rev.Lett.55:2649,1985

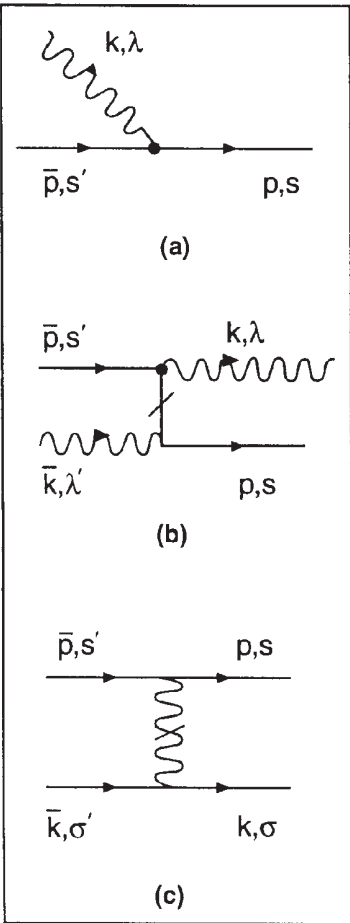
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*Use AdS/CFT orthonormal LFWFs  
as a basis for diagonalizing  
the QCD LF Hamiltonian*

- Good initial approximant
- Better than plane wave basis Pauli, Hornbostel, Hiller,  
McCartor, sjb
- DLCQ discretization -- highly successful 1+1
- Use independent HO LFWFs, remove CM motion Vary, Harinandrath, Maris, sjb
- Similar to Shell Model calculations

# Light-Front QCD Heisenberg Equation

$$H_{LC}^{QCD} |\Psi_h\rangle = M_h^2 |\Psi_h\rangle$$



n	Sector	1 q $\bar{q}$	2 gg	3 q $\bar{q}$ g	4 q $\bar{q}$ q $\bar{q}$	5 gg g	6 q $\bar{q}$ gg	7 q $\bar{q}$ q $\bar{q}$ g	8 q $\bar{q}$ q $\bar{q}$ q $\bar{q}$	9 gg gg	10 q $\bar{q}$ gg g	11 q $\bar{q}$ q $\bar{q}$ gg	12 q $\bar{q}$ q $\bar{q}$ q $\bar{q}$ g	13 q $\bar{q}$ q $\bar{q}$ q $\bar{q}$ q $\bar{q}$
1	q $\bar{q}$					.		.	.	.	.	.	.	.
2	gg				.			.	.		.	.	.	.
3	q $\bar{q}$ g								.	.		.	.	.
4	q $\bar{q}$ q $\bar{q}$		.			.			.	.	.		.	.
5	gg g	.			.			.	.			.	.	.
6	q $\bar{q}$ gg							.	.				.	.
7	q $\bar{q}$ q $\bar{q}$ g	.	.			.				.				.
8	q $\bar{q}$ q $\bar{q}$ q $\bar{q}$	.	.	.		.			.	.	.			
9	gg gg	.		.	.			.	.			.	.	.
10	q $\bar{q}$ gg g	.	.		.			.	.				.	.
11	q $\bar{q}$ q $\bar{q}$ gg	.	.	.		.			.	.				.
12	q $\bar{q}$ q $\bar{q}$ q $\bar{q}$ g	.	.	.	.	.			.	.				
13	q $\bar{q}$ q $\bar{q}$ q $\bar{q}$ q $\bar{q}$	.	.	.	.	.	.		.	.	.			

Use AdS/QCD basis functions

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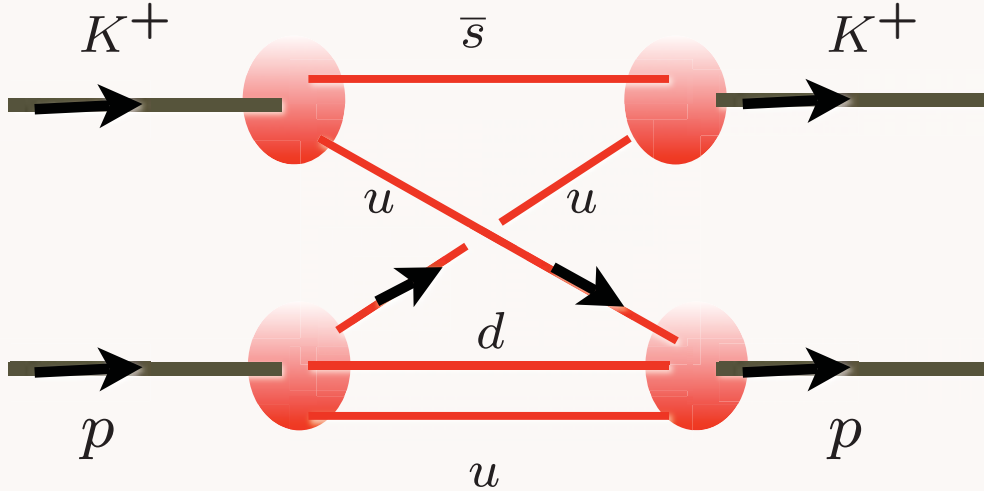
AdS/QCD

128

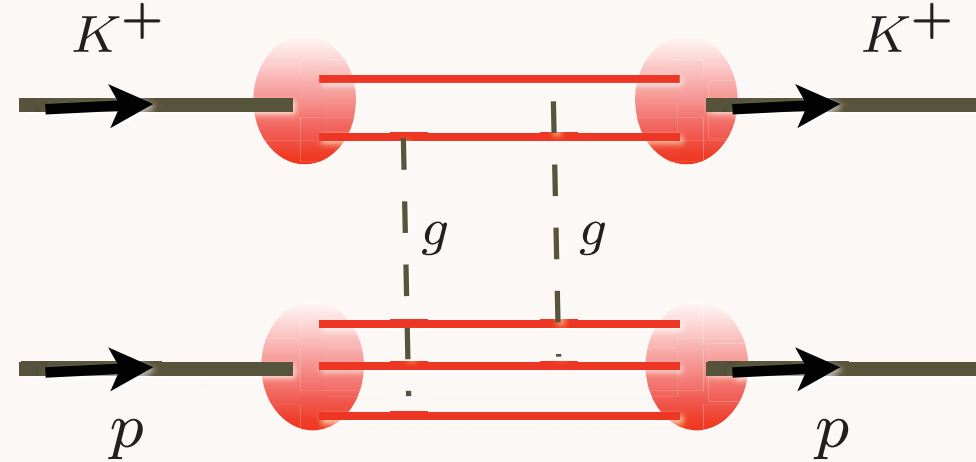
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# *New Perspectives for QCD from AdS/CFT*

- LFWFs: Fundamental frame-independent description of hadrons at amplitude level
- Holographic Model from AdS/CFT : Confinement at large distances and conformal behavior at short distances
- Model for LFWFs, meson and baryon spectra: many applications!
- New basis for diagonalizing Light-Front Hamiltonian
- Physics similar to MIT bag model, but covariant. No problem with support  $0 < x < 1$ .
- Quark Interchange dominant force at short distances



*Quark Interchange  
(Spin exchange in atom-atom scattering)*



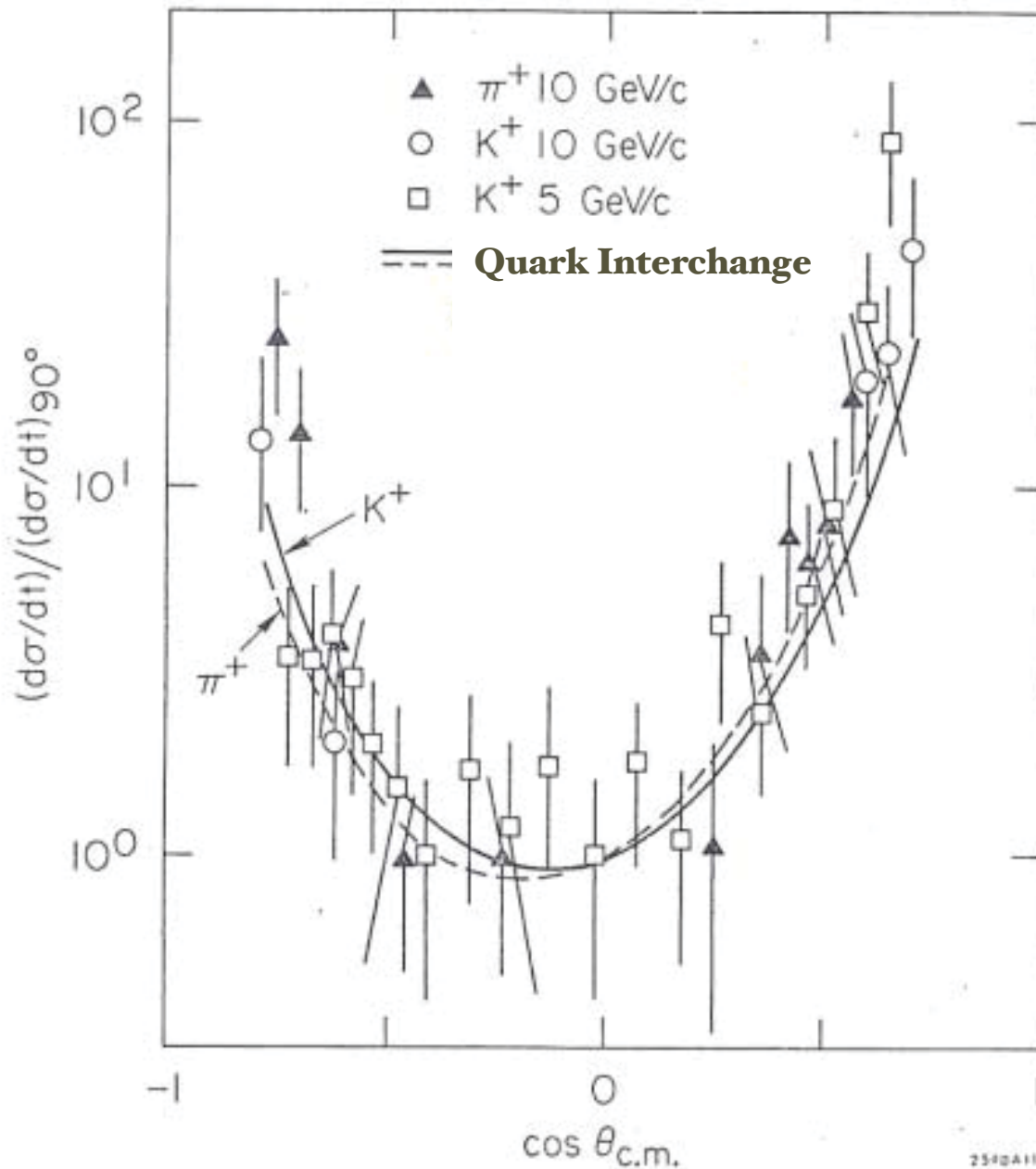
*Gluon Exchange  
(Van der Waal -- Landshoff)*

$$\frac{d\sigma}{dt} = \frac{|M(s,t)|^2}{s^2}$$

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

$$M(s, t)_{\text{gluonexchange}} \propto sF(t)$$

*MIT Bag Model (de Tar), large  $N_c$ , ('t Hooft), AdS/CFT  
all predict dominance of quark interchange:*



*AdS/CFT explains why quark interchange is dominant interaction at high momentum transfer in exclusive reactions*

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

***Non-linear Regge behavior:***

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



# Why is quark-interchange dominant over gluon exchange?

Example:  $M(K^+p \rightarrow K^+p) \propto \frac{1}{ut^2}$

Exchange of common  $u$  quark

$$M_{QIM} = \int d^2k_{\perp} dx \psi_C^{\dagger} \psi_D^{\dagger} \Delta \psi_A \psi_B$$

Holographic model (Classical level):

Hadrons enter 5th dimension of  $AdS_5$

Quarks travel freely within cavity as long as separation  $z < z_0 = \frac{1}{\Lambda_{QCD}}$

LFWFs obey conformal symmetry producing quark counting rules.

## Comparison of Exclusive Reactions at Large $t$

B. R. Baller,<sup>(a)</sup> G. C. Blazey,<sup>(b)</sup> H. Courant, K. J. Heller, S. Heppelmann,<sup>(c)</sup> M. L. Marshak,  
E. A. Peterson, M. A. Shupe, and D. S. Wahl<sup>(d)</sup>  
*University of Minnesota, Minneapolis, Minnesota 55455*

D. S. Barton, G. Bunce, A. S. Carroll, and Y. I. Makdisi  
*Brookhaven National Laboratory, Upton, New York 11973*

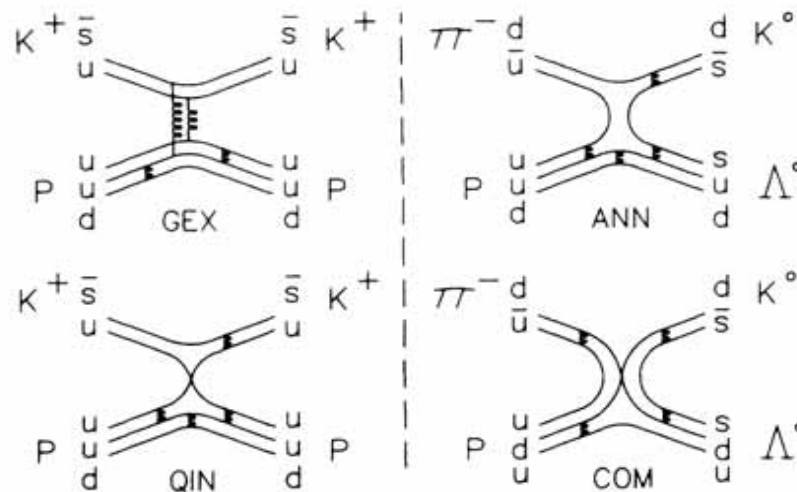
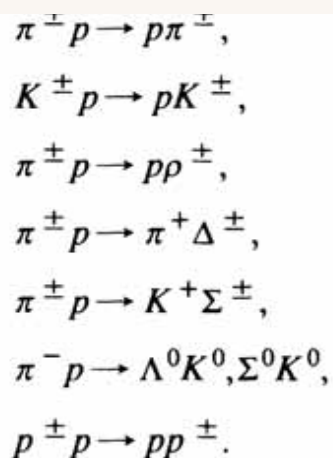
and

S. Gushue<sup>(e)</sup> and J. J. Russell

*Southeastern Massachusetts University, North Dartmouth, Massachusetts 02747*

(Received 28 October 1987; revised manuscript received 3 February 1988)

Cross sections or upper limits are reported for twelve meson-baryon and two baryon-baryon reactions for an incident momentum of 9.9 GeV/c, near 90° c.m.:  $\pi^\pm p \rightarrow p\pi^\pm, p\rho^\pm, \pi^+\Delta^\pm, K^+\Sigma^\pm, (\Lambda^0/\Sigma^0)K^0, K^\pm p \rightarrow pK^\pm; p^\pm p \rightarrow pp^\pm$ . By studying the flavor dependence of the different reactions, we have been able to isolate the quark-interchange mechanism as dominant over gluon exchange and quark-antiquark annihilation.



# Light-Front Wavefunctions

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

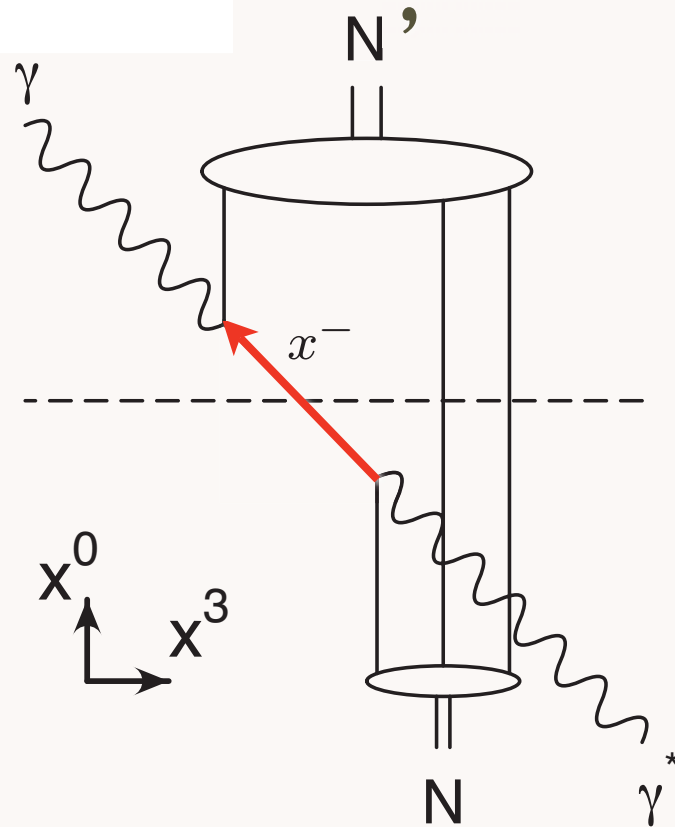
$$\Psi(x, k_{\perp}) \quad x_i = \frac{k_i^+}{P^+}$$

Invariant under boosts. Independent of  $P^{\mu}$

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

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

$$\sigma = \frac{1}{2}x^- P^+$$



$$x^+ = \mathbf{x}_\perp = 0$$

The position of the struck quark differs by  $x^-$  in the two wave functions

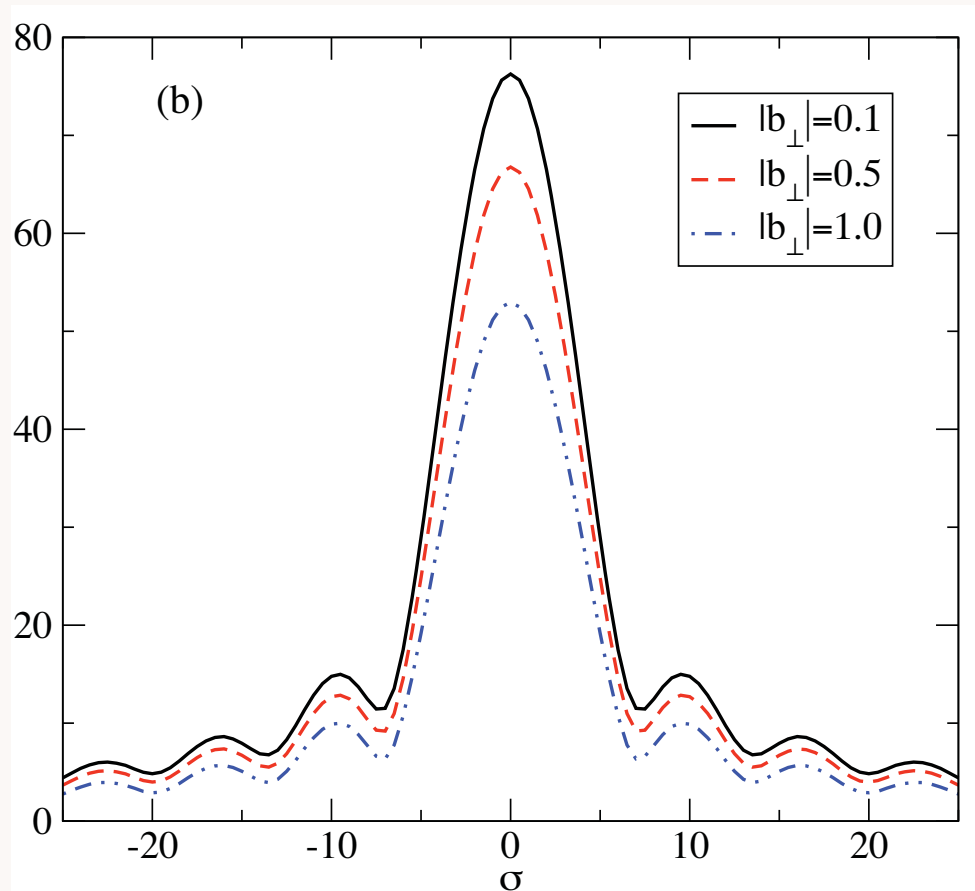
**Measure  $x^-$  distribution from DVCS:  
Take Fourier transform of skewness,  $\xi = \frac{Q^2}{2p \cdot q}$   
the longitudinal momentum transfer**

S. J. Brodsky<sup>a</sup>, D. Chakrabarti<sup>b</sup>, A. Harindranath<sup>c</sup>, A. Mukherjee<sup>d</sup>, J. P. Vary<sup>e,a,f</sup>

# Hadron Optics

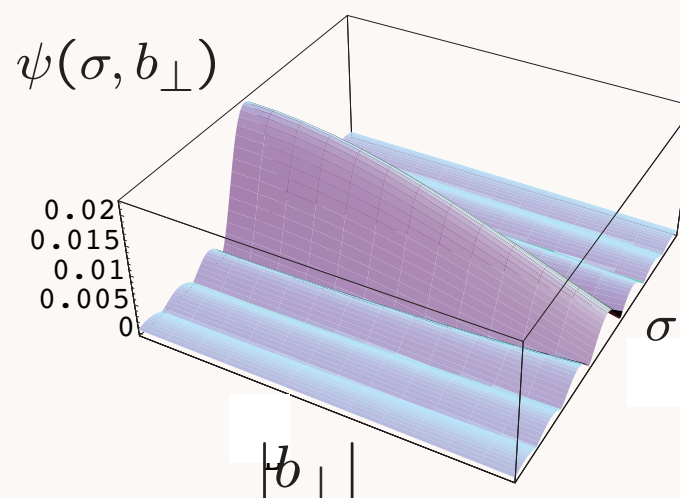
$$A(\sigma, \vec{b}_\perp) = \frac{1}{2\pi} \int d\xi e^{i\frac{1}{2}\xi\sigma} \tilde{A}(\xi, \vec{b}_\perp)$$

$$\sigma = \frac{1}{2}x^-P^+ \quad \xi = \frac{Q^2}{2p \cdot q}$$



## DVCS Amplitude using holographic QCD meson LFWF

$$\Lambda_{QCD} = 0.32$$



The Fourier Spectrum of the DVCS amplitude in  $\sigma$  space for different fixed values of  $|b_\perp|$ .  
GeV units

# *Hadron Dynamics at the Amplitude Level*

- LFWFS are the universal hadronic amplitudes which underlie structure functions, GPDs, exclusive processes, distribution amplitudes, direct subprocesses, hadronization.
- Relation of spin, momentum, and other distributions to physics of the hadron itself.
- Connections between observables, orbital angular momentum
- Role of FSI and ISIs--Sivers effect

# *Some Applications of Light-Front Wavefunctions*

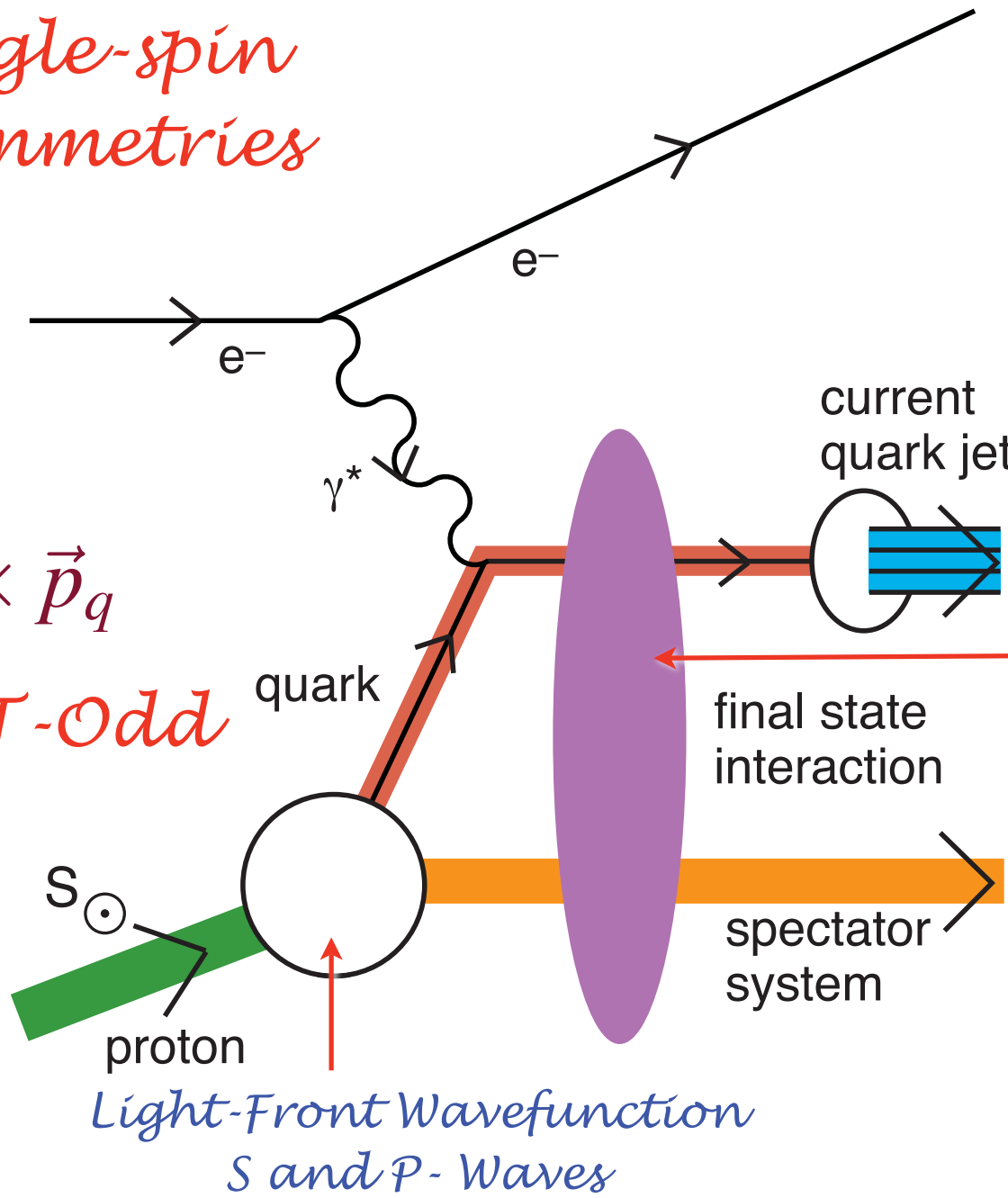
- Exact formulae for form factors, quark and gluon distributions; vanishing anomalous gravitational moment; edm connection to anm
- Deeply Virtual Compton Scattering, generalized parton distributions, angular momentum sum rules
- Exclusive weak decay amplitudes
- Single spin asymmetries: Role of ISI and FSI
- Factorization theorems, DGLAP, BFKL, ERBL Evolution
- Quark interchange amplitude
- Relation of spin, momentum, and other distributions to physics of the hadron itself.

*Single-spin asymmetries*

# Leading-Twist Sivers Effect

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

*Pseudo-T-Odd*



*QCD S- and P-Coulomb Phases*

*Light-Front Wavefunction  
S and P-Waves*

D. S. Hwang,  
I. A. Schmidt,  
sjb



# Final-State Interactions Produce

*T-Odd (Sivers Effect)*  $\mathbf{i} \vec{S} \cdot \vec{p}_{jet} \times \vec{q}$

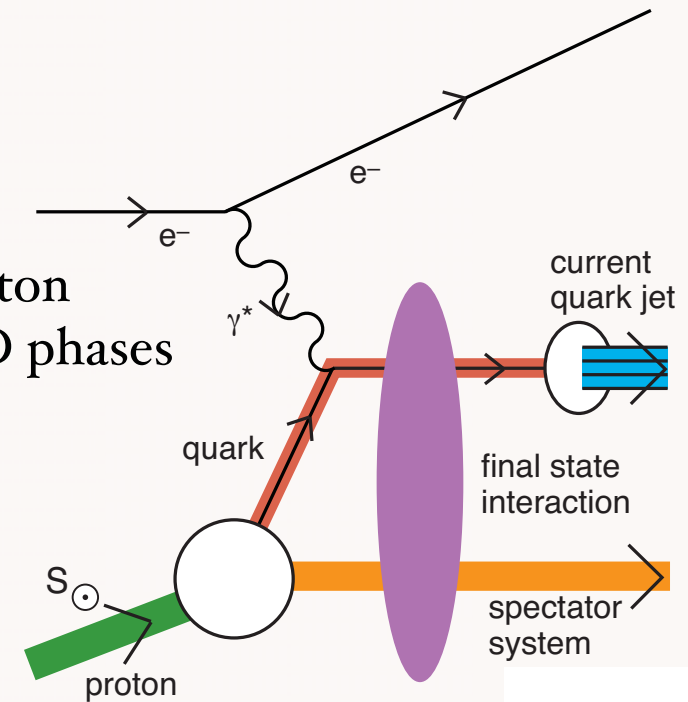
- Bjorken Scaling!
- Arises from Interference of Final-State Coulomb Phases in S and P waves
- Relate to the quark contribution to the target proton anomalous magnetic moment

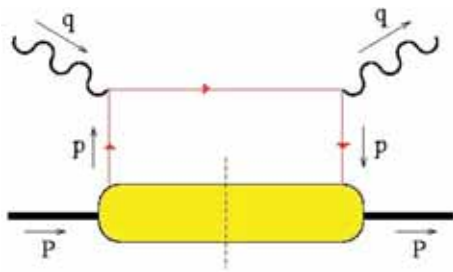
Hwang, Schmidt. sjb;  
Burkardt

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

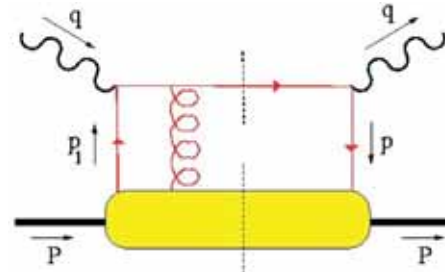
- Leading-Twist Bjorken Scaling!
- Requires nonzero orbital angular momentum of quark!
- Arises from the interference of Final-State QCD Coulomb phases in S- and P- waves; Wilson line effect; gauge independent
- Unexpected QCD Effect -- thought to be zero!
- Relate to the quark contribution to the target proton anomalous magnetic moment and final-state QCD phases
- QCD Coulomb phase at soft scale
- Measure in jet trigger or leading hadron
- Sum of Sivers Functions for all quarks and gluons vanishes. (Zero gravito-anomalous magnetic moment:  $B(0) = 0$ )

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





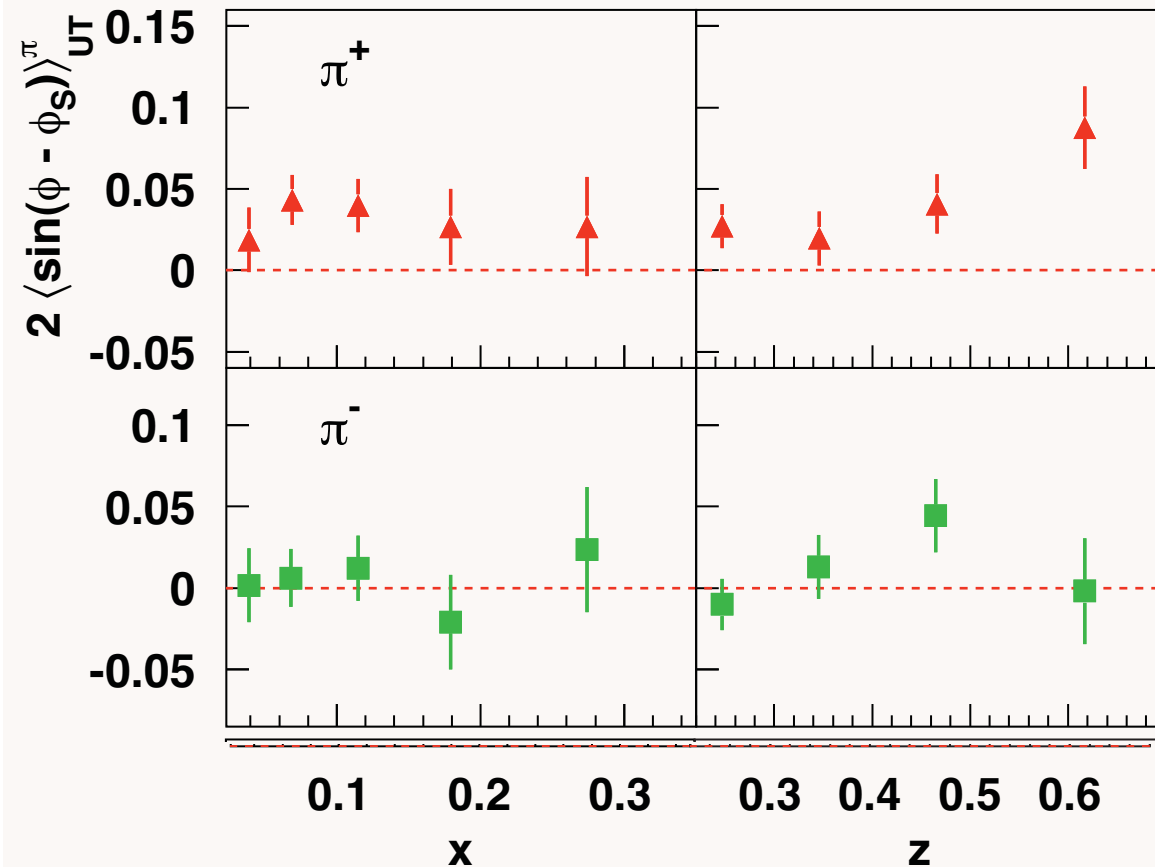
can interfere with



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!
- $\Rightarrow$  presence of non-zero quark orbital angular momentum!
- **Positive** for  $\pi^+$  ...  
Consistent with zero for  $\pi^-$  ...

**Gamberg: Hermes data compatible with BHS model**

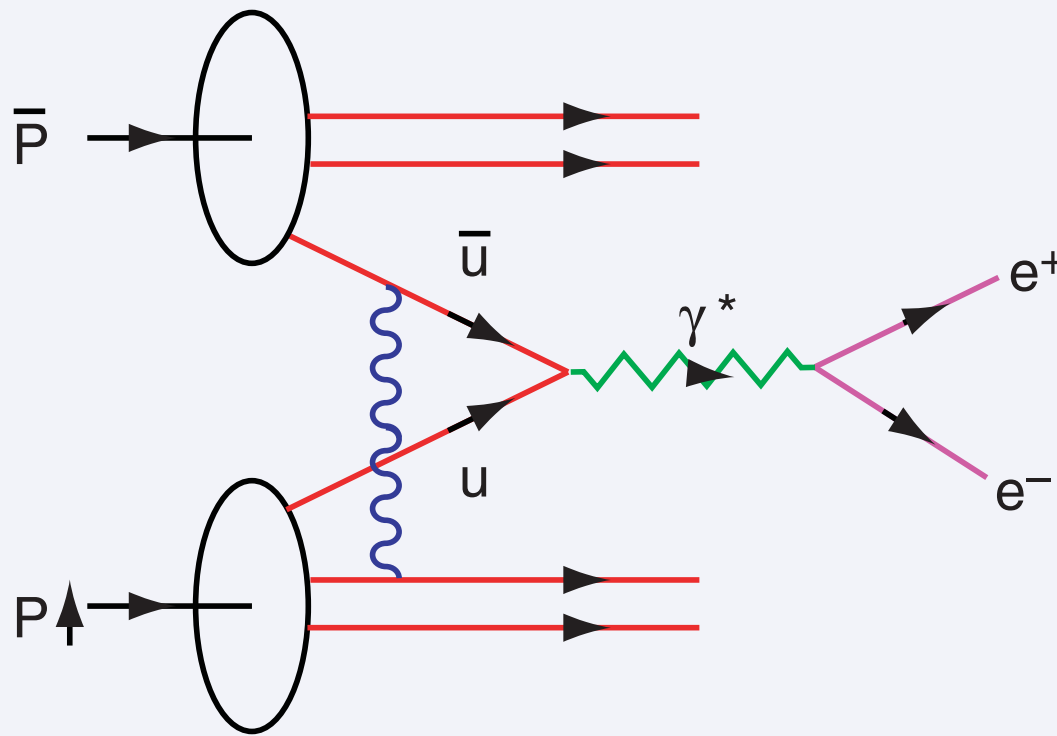
**Schmidt, Lu: Hermes charge pattern follow quark contributions to anomalous moment**

INT  
March 28, 2008

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142

Stan Brodsky, SLAC

# Predict Opposite Sign SSA in DY !



Collins;  
Hwang, Schmidt.  
sjb

Single Spin Asymmetry In the Drell Yan Process

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

Quarks Interact in the Initial State

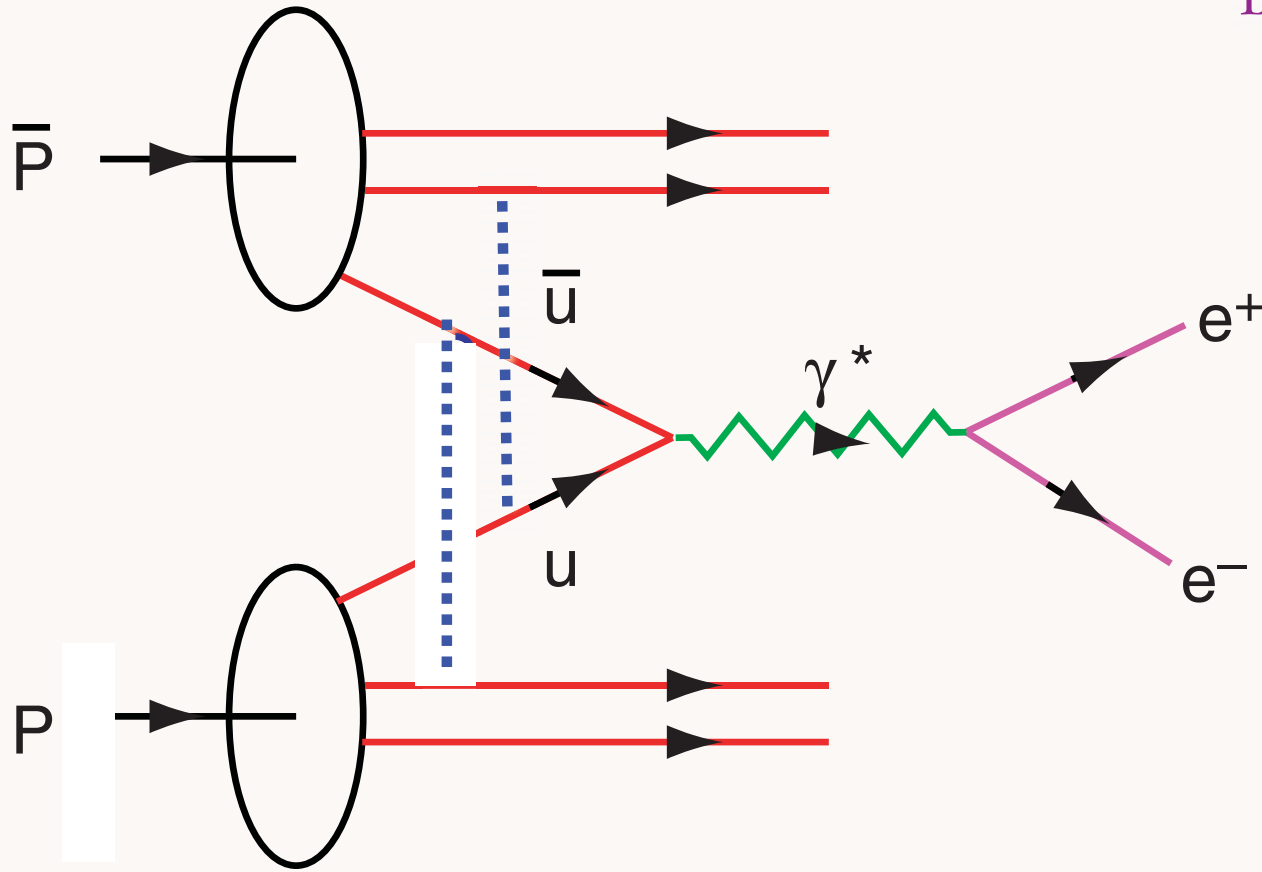
Interference of Coulomb Phases for  $S$  and  $P$  states

Produce Single Spin Asymmetry [Siver's Effect] Proportional  
to the Proton Anomalous Moment and  $\alpha_s$ .  
Opposite Sign to DIS! No Factorization

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