

String Theory

AdS/CFT

Mapping of Poincare' and Conformal  $SO(4,2)$  symmetries of 3+1 space to AdS5 space

Goal: First Approximant to QCD

AdS/QCD

Counting rules for Hard Exclusive Scattering  
Regge Trajectories  
QCD at the Amplitude Level

Conformal behavior at short distances  
+ Confinement at large distance

Semi-Classical QCD / Wave Equations

Holography

Boost Invariant 3+1 Light-Front Wave Equations

$J=0, 1, 1/2, 3/2$  plus  $L$

Integrable!

Hadron Spectra, Wavefunctions, Dynamics

# *AdS/CFT and Integrability*

- L. Infeld, “On a new treatment of some eigenvalue problems”, Phys. Rev. 59, 737 (1941).
- Generate eigenvalues and eigenfunctions using Ladder Operators
- Apply to Covariant Light-Front Radial Dirac and Schrodinger Equations

## Algebraic Structure , Integrability and Stability Conditions (HW Model)

- If  $L^2 > 0$  the LF Hamiltonian,  $H_{LF}^L$ , can be written as a bilinear form

$$H_{LF}^L(\zeta) = \Pi_L^\dagger(\zeta)\Pi_L(\zeta)$$

in terms of the operator

$$\Pi_L(\zeta) = -i \left( \frac{d}{d\zeta} - \frac{L + \frac{1}{2}}{\zeta} \right),$$

and its adjoint

$$\Pi_L^\dagger(\zeta) = -i \left( \frac{d}{d\zeta} + \frac{L + \frac{1}{2}}{\zeta} \right),$$

with commutation relations

$$\left[ \Pi_L(\zeta), \Pi_L^\dagger(\zeta) \right] = \frac{2L + 1}{\zeta^2}.$$

- For  $L^2 \geq 0$  the Hamiltonian is positive definite

$$\langle \phi | H_{LF}^L | \phi \rangle = \int d\zeta |\Pi_L \phi(z)|^2 \geq 0$$

and thus  $\mathcal{M}^2 \geq 0$ .

## Ladder Construction of Orbital States

- Orbital excitations constructed by the  $L$ -th application of the raising operator

$$a_L^\dagger = -i\Pi_L$$

on the ground state:

$$a^\dagger|L\rangle = c_L|L+1\rangle.$$

- In the light-front  $\zeta$ -representation

$$\begin{aligned}\phi_L(\zeta) &= \langle\zeta|L\rangle = C_L\sqrt{\zeta}(-\zeta)^L\left(\frac{1}{\zeta}\frac{d}{d\zeta}\right)^L J_0(\zeta\mathcal{M}) \\ &= C_L\sqrt{\zeta}J_L(\zeta\mathcal{M}).\end{aligned}$$

- The solutions  $\phi_L$  are solutions of the light-front equation ( $L = 0, \pm 1, \pm 2, \dots$ )

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

- Mode spectrum from boundary conditions :  $\phi(\zeta = 1/\Lambda_{\text{QCD}}) = 0$ .

## Non-Conformal Extension of Algebraic Integrability (SW Model)

- Soft-wall model [Karch, Katz, Son and Stephanov (2006)] retain conformal AdS metrics but introduce smooth cutoff which depends on the profile of a dilaton background field  $\varphi(z)$ .
- Consider the generator (short-distance Coulombic and long-distance linear potential)

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

and its adjoint

$$\Pi_L^\dagger(\zeta) = -i \left( \frac{d}{d\zeta} + \frac{L + \frac{1}{2}}{\zeta} + \kappa^2 \zeta \right),$$

with commutation relations

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

- The LF Hamiltonian

$$H_{LF} = \Pi_L^\dagger \Pi_L + C$$

*Integrable!*

is positive definite  $\langle \phi | H_{LF} | \phi \rangle \geq 0$  for  $L^2 \geq 0$ , and  $C \geq -4\kappa^2$ .

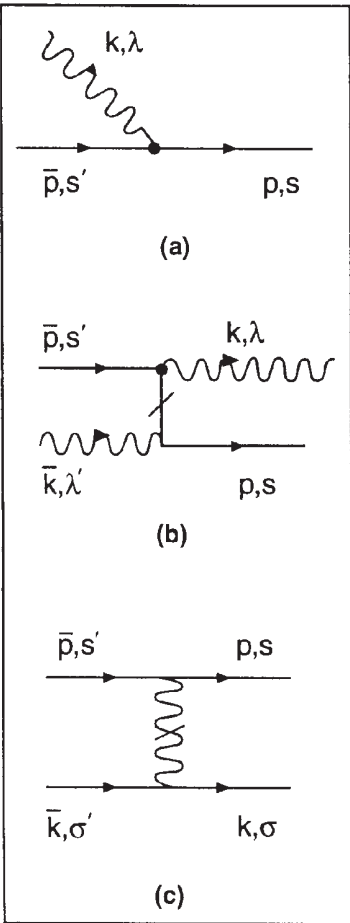
- Orbital and radial excited states are constructed from the ladder operators from the  $L = 0$  state.

*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 $\bar{q}$	.	.	.	.	.	.			.	.	.		

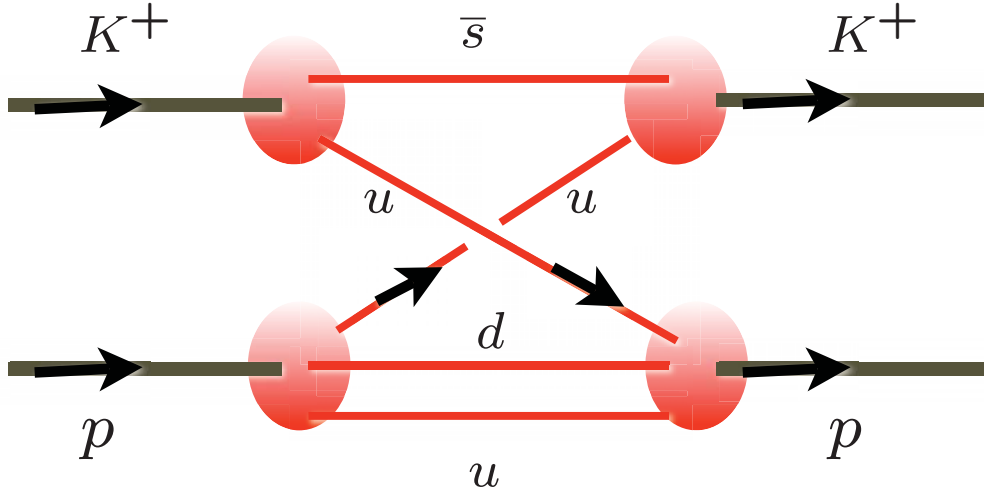
Use AdS/QCD basis functions

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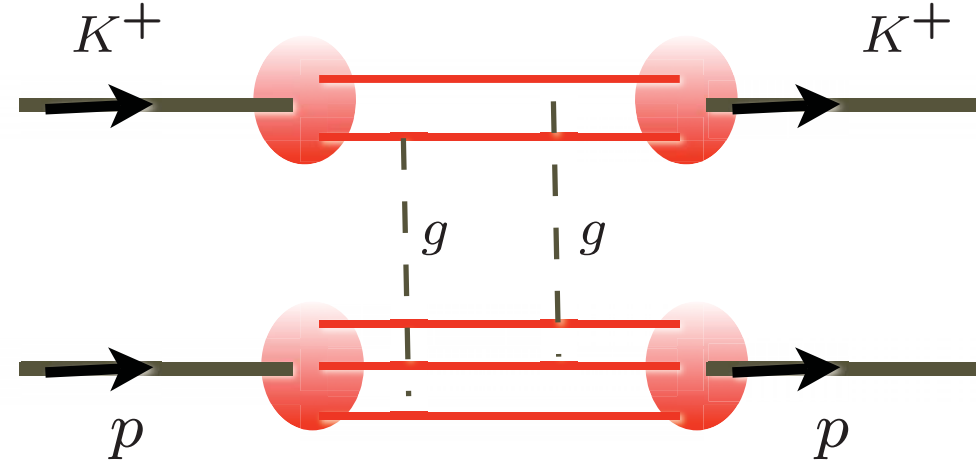
QCD on the LF

# *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)



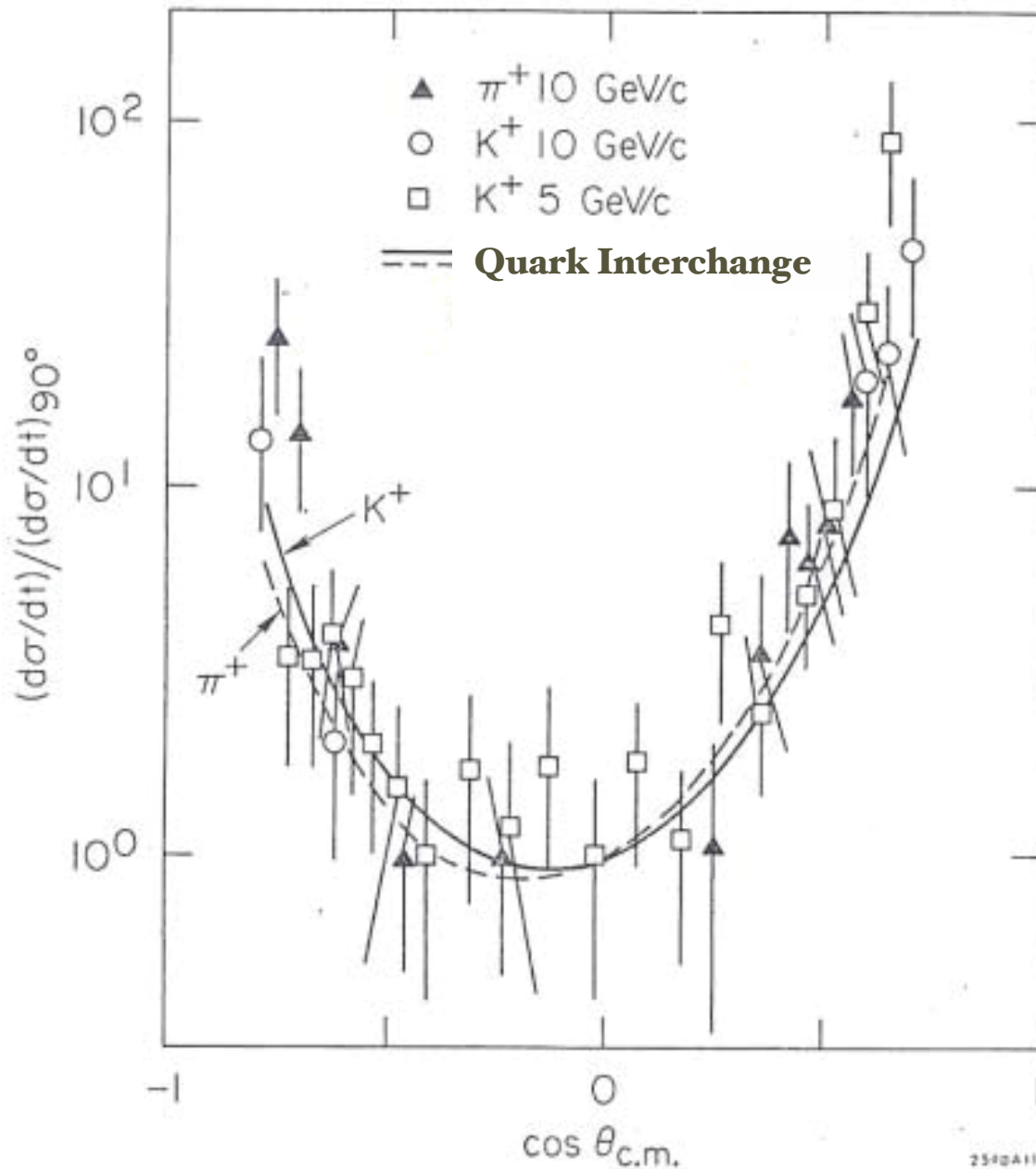
Gluon Exchange  
(Van der Waal -- Landshoff)

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

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

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

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*

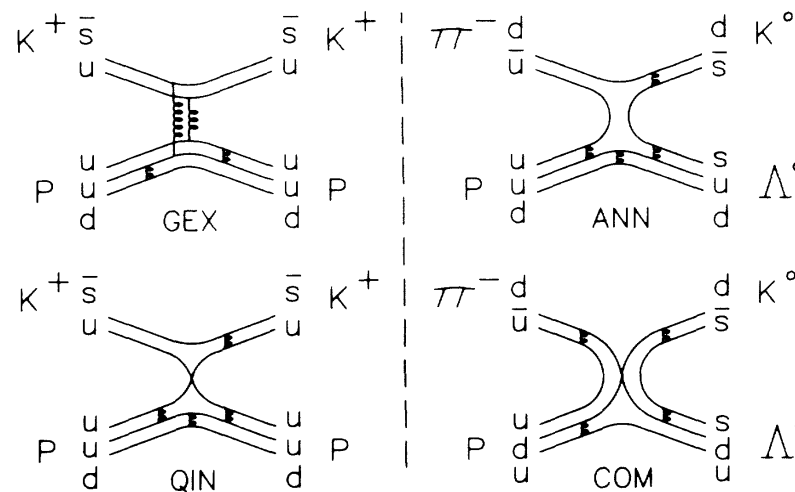
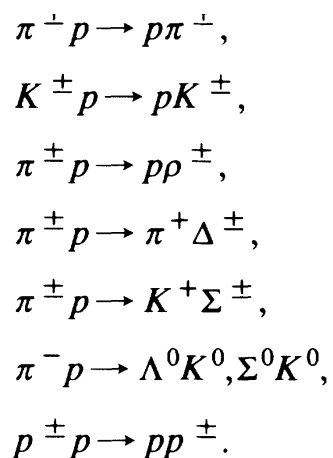
and

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  $\tau = t + z/c$

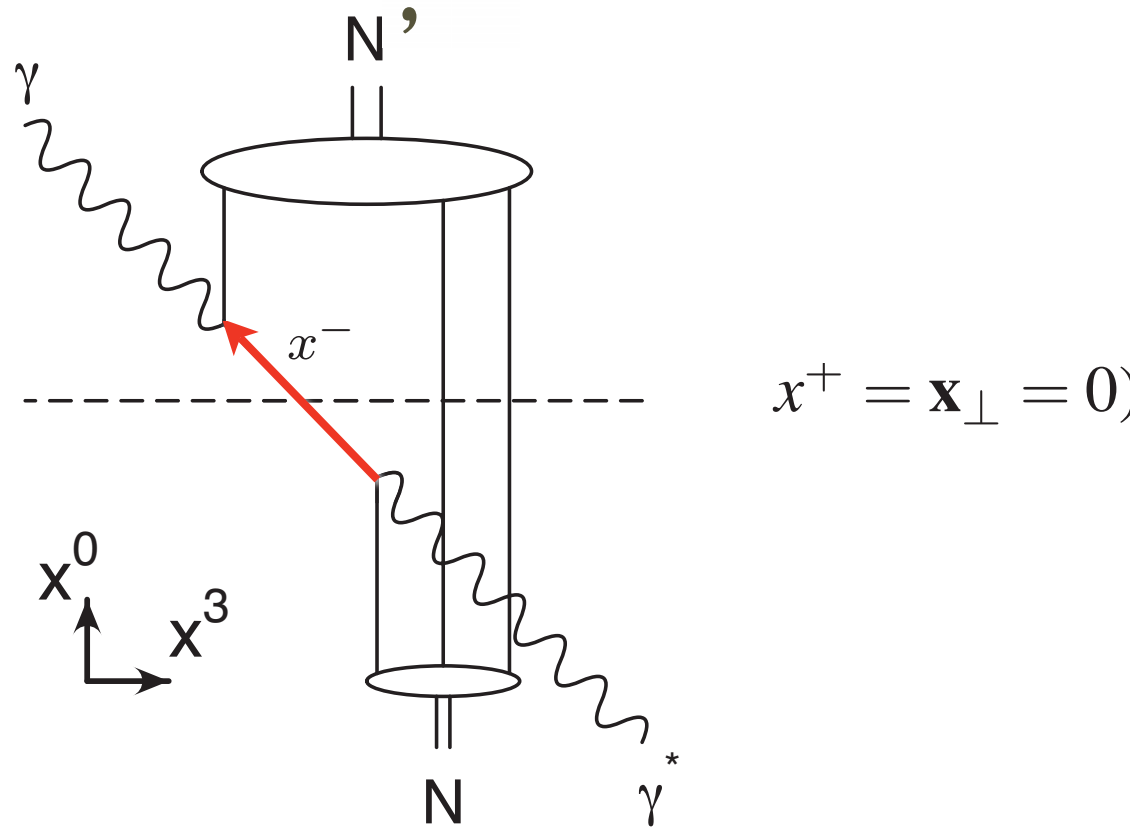
$$\Psi(x, k_{\perp}) \quad x_i = \frac{k_i^+}{P^+}$$

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

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



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>

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**QCD on the LF**

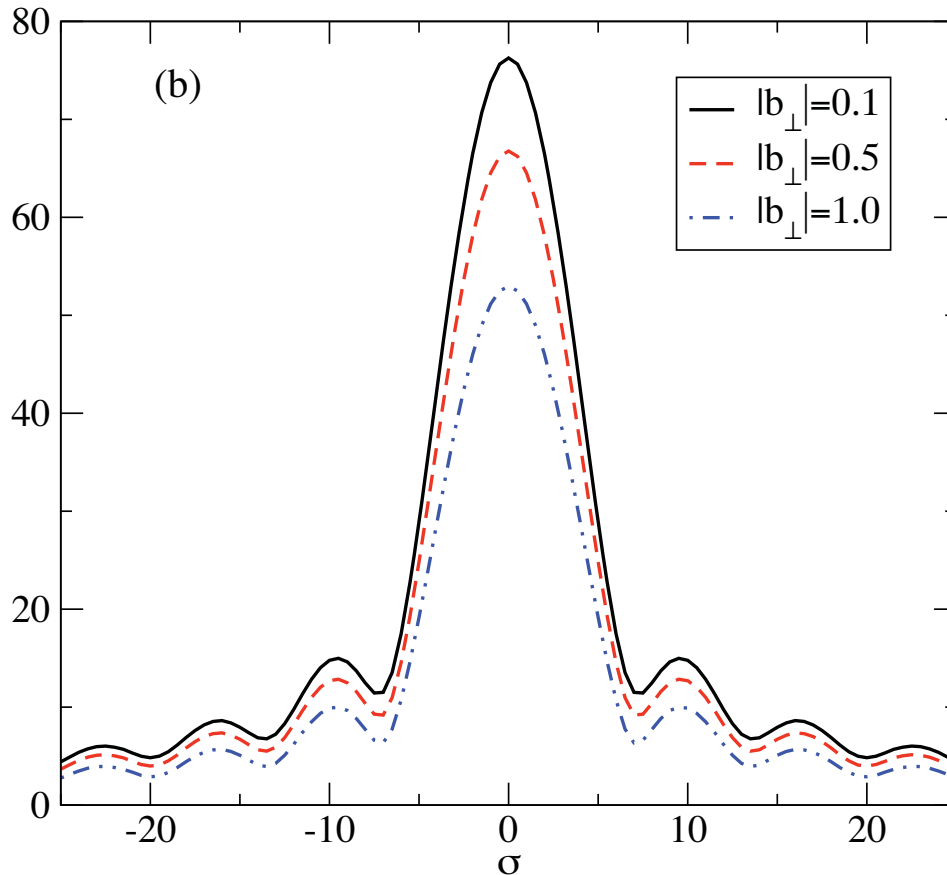
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# Hadron Optics

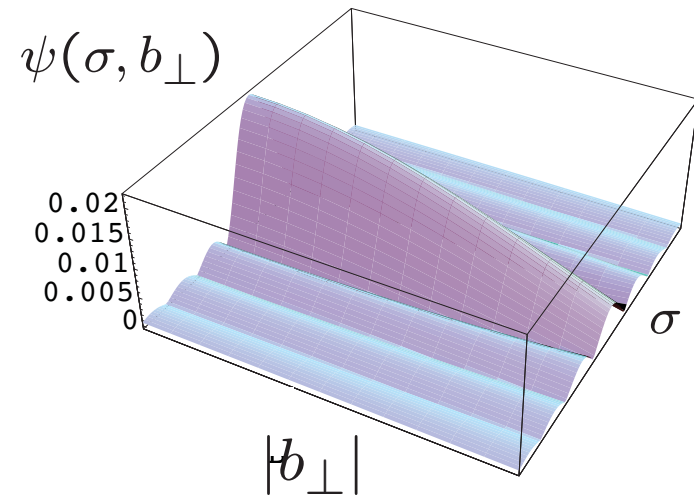
$$A(\sigma, \vec{b}_\perp) = \frac{1}{2\pi} \int d\xi e^{i\frac{1}{2}\xi\sigma} \tilde{A}(\xi, \vec{b}_\perp)$$

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



## 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*

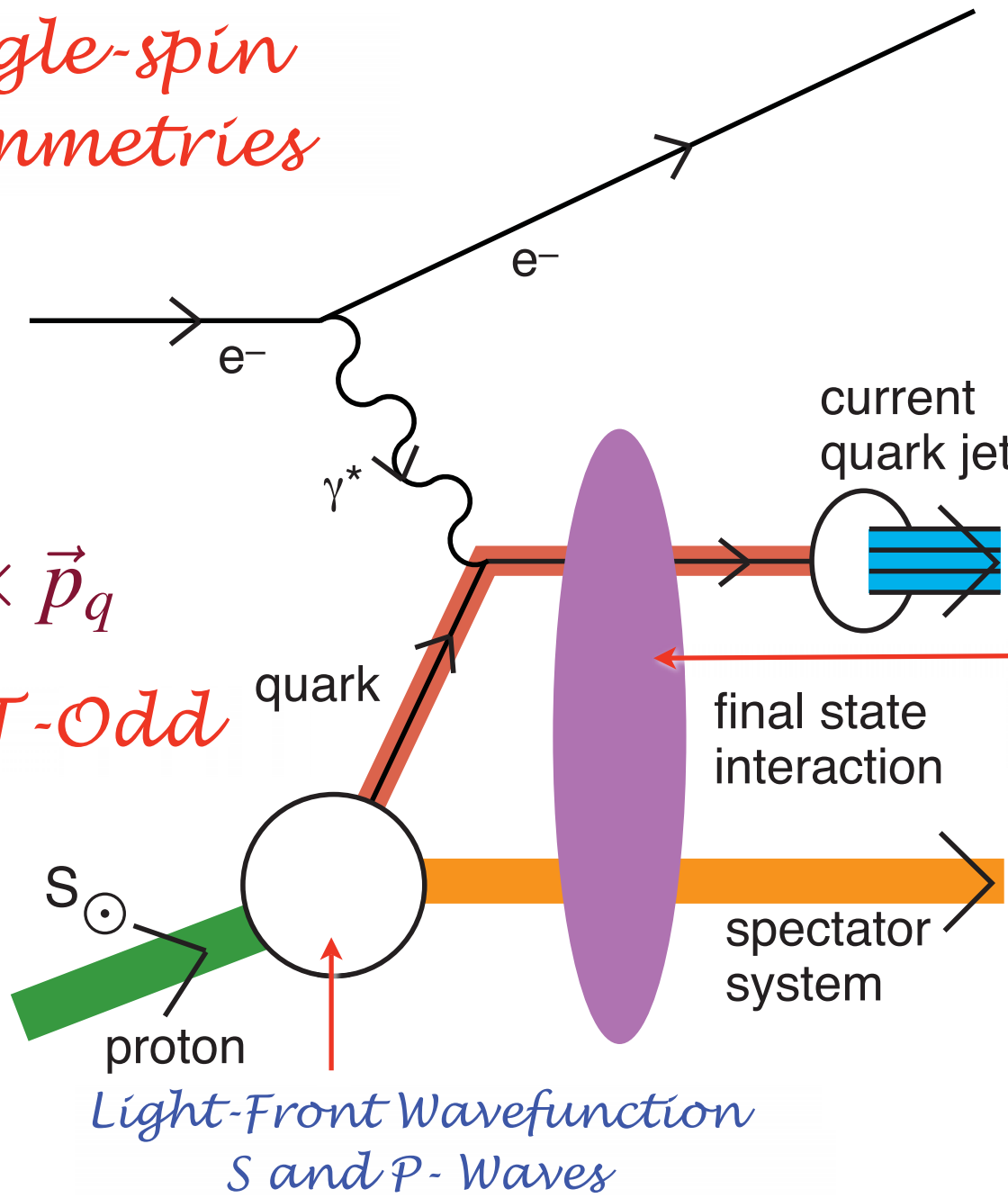
- Exact formulae for form factors, quark and gluon distributions; vanishing anomalous gravitational moment; edm connection to anm
- Deeply Virtual Compton Scattering, generalized parton distributions, angular momentum sum rules
- Exclusive weak decay amplitudes
- Single spin asymmetries: Role of ISI 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

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# Final-State Interactions Produce

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

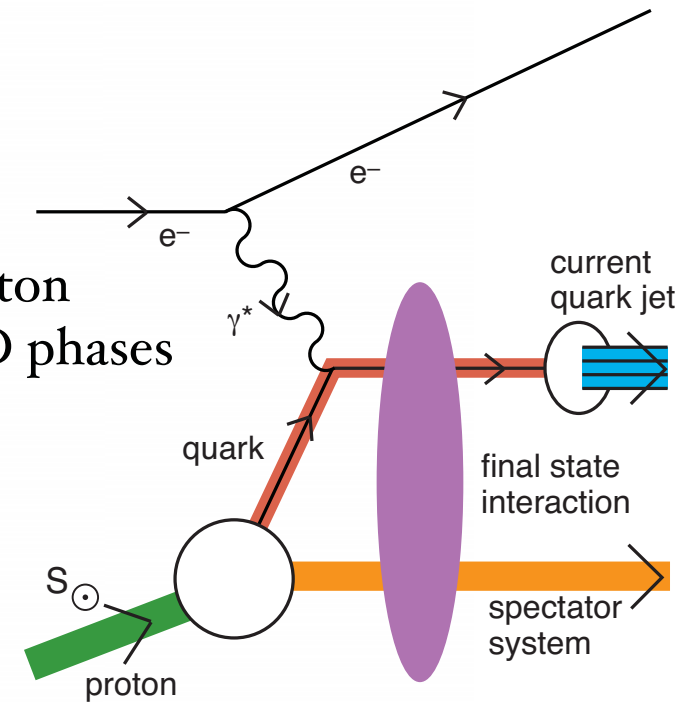
- Bjorken Scaling!
- Arises from Interference of Final-State Coulomb Phases in S and P waves
- Relate to the quark contribution to the target proton anomalous magnetic moment

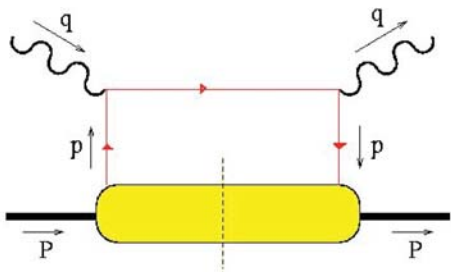
Hwang, Schmidt. sjb;  
Burkardt

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

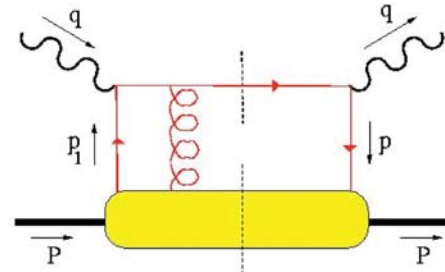
- Leading-Twist Bjorken Scaling!
- Requires nonzero orbital angular momentum of quark!
- Arises from the interference of Final-State QCD Coulomb phases in S- and P- waves; Wilson line effect; gauge independent
- Unexpected QCD Effect -- thought to be zero!
- Relate to the quark contribution to the target 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:  $B(0) = 0$ )

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





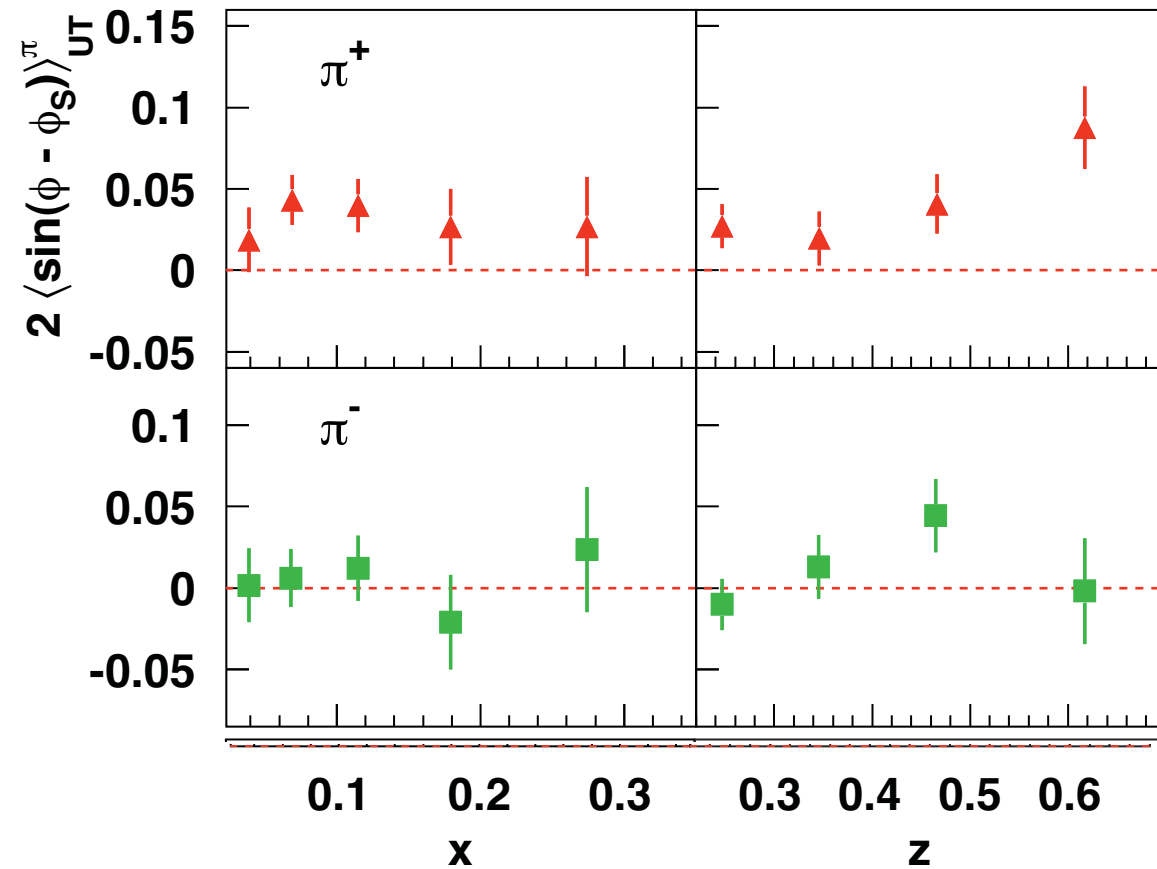
can interfere with



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**

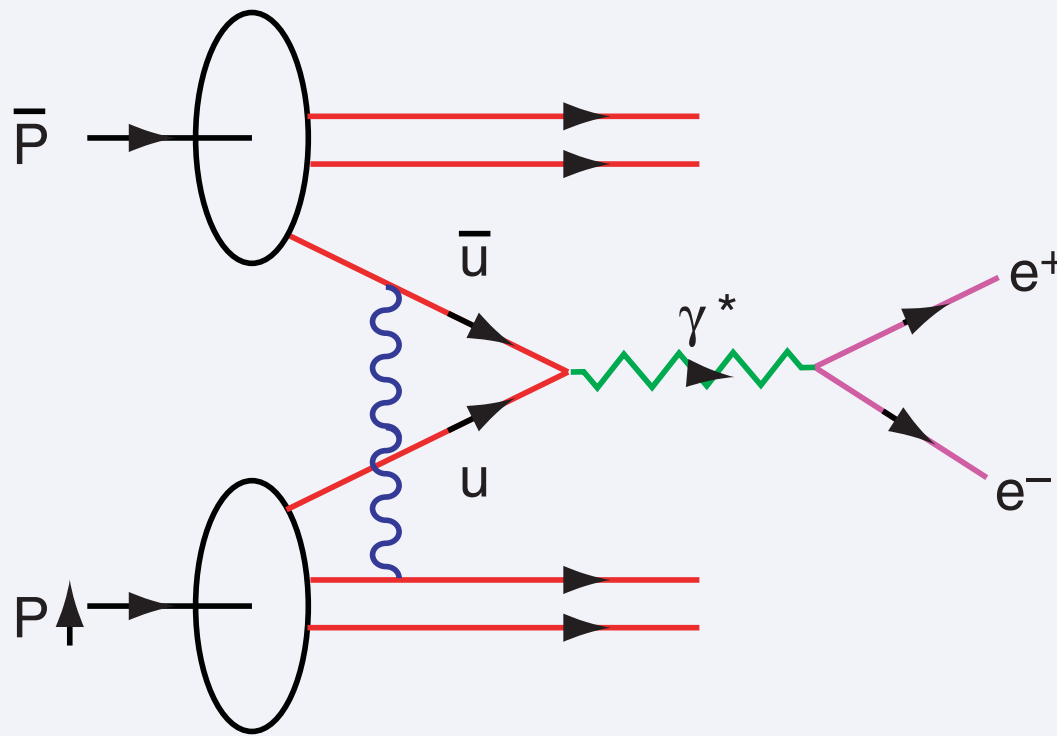
**Schmidt, Lu: Hermes charge pattern follow quark contributions to anomalous moment**

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# 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

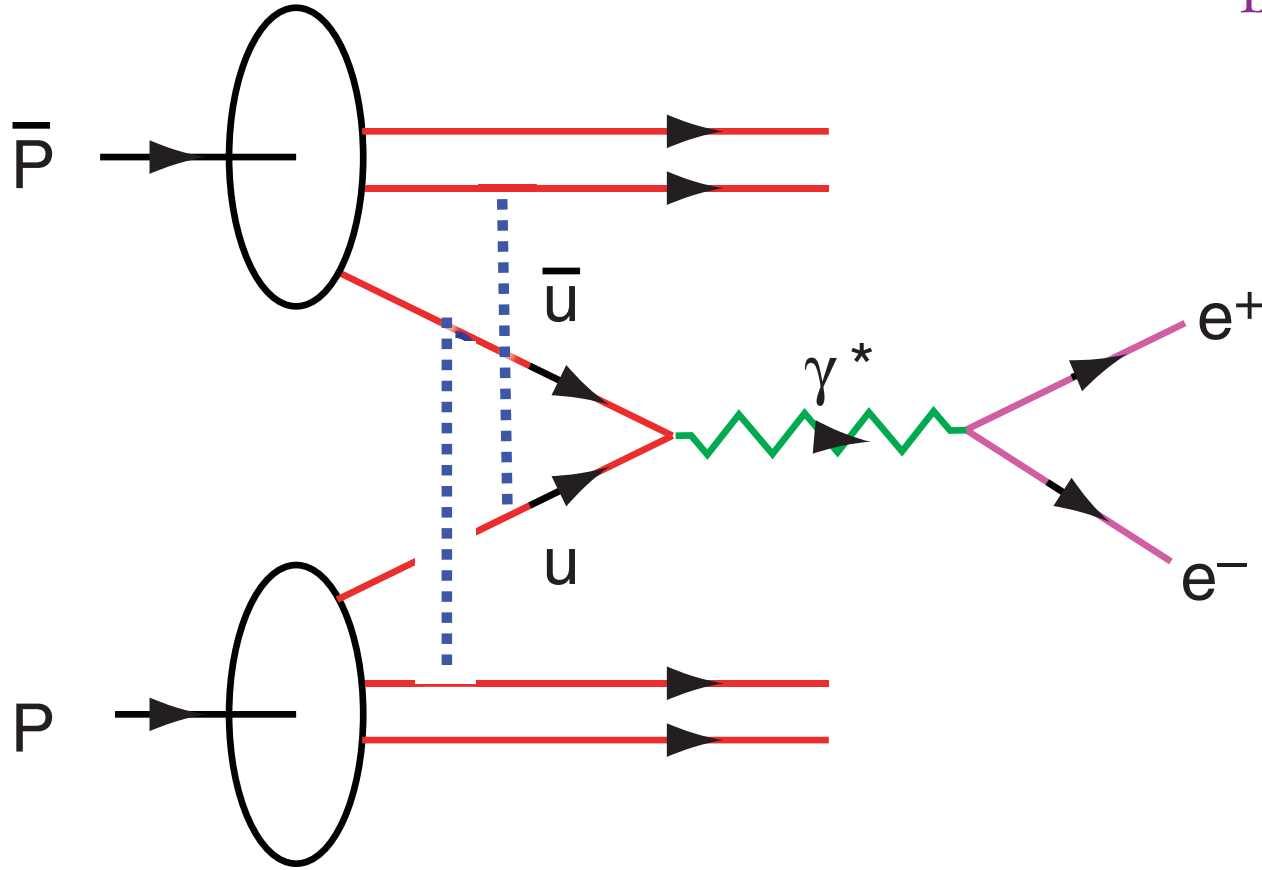
Produce Single Spin Asymmetry [Siver's Effect] Proportional to the Proton Anomalous Moment and  $\alpha_s$ .

Opposite Sign to DIS! No Factorization

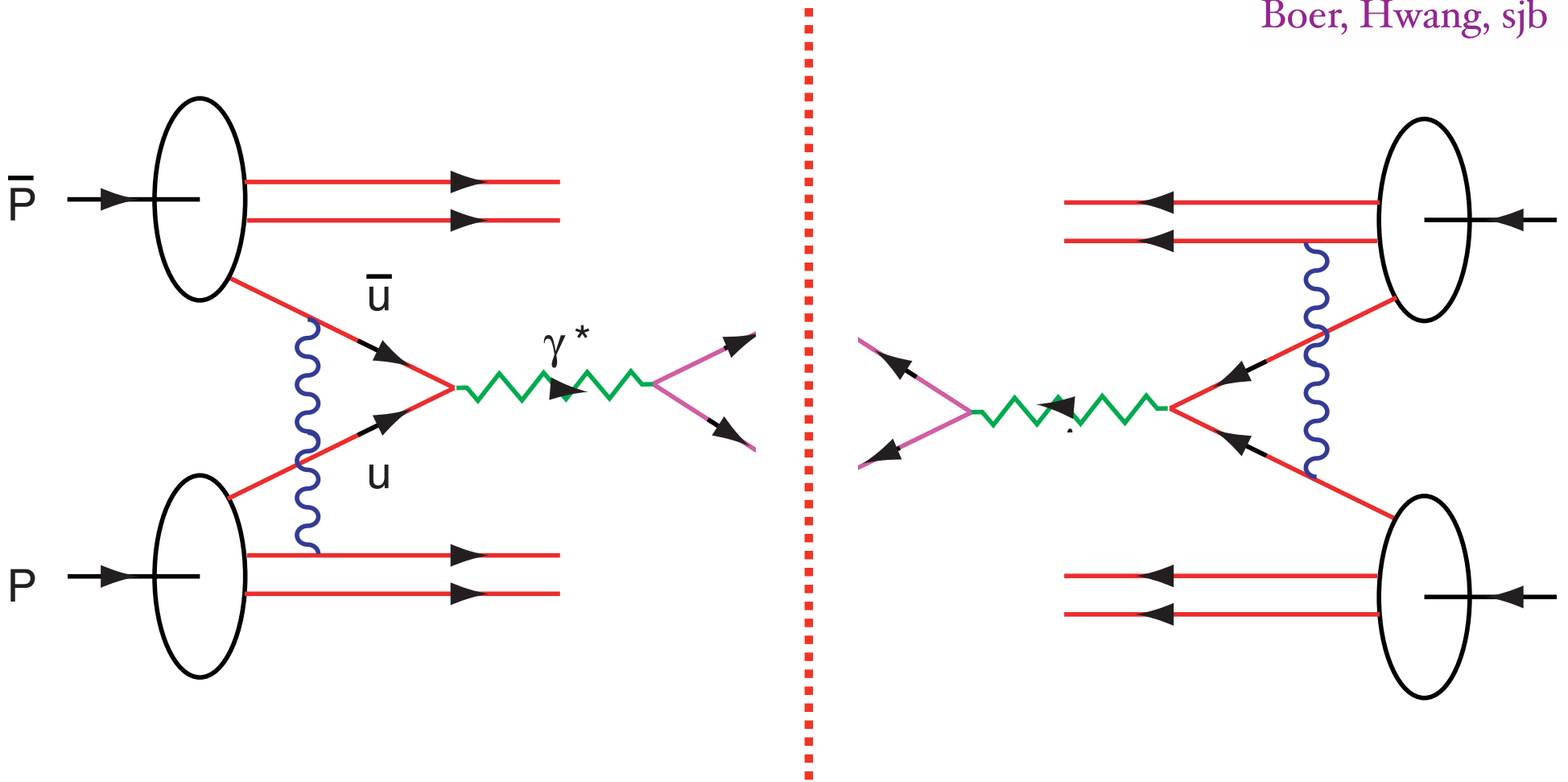
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**$DY \cos 2\phi$  correlation at leading twist from double ISI**



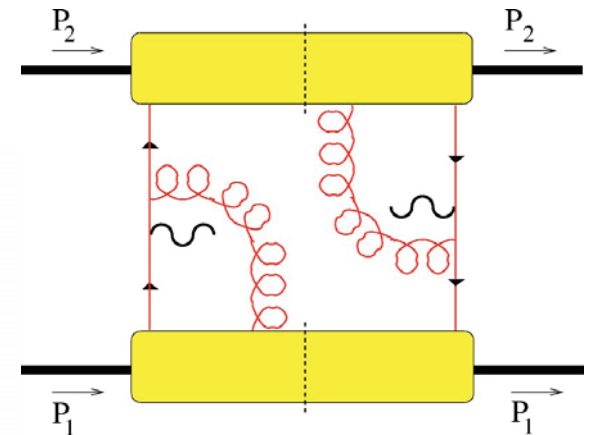
**$DY \cos 2\phi$  correlation at leading twist from double ISI**

# Anomalous effect from Double ISI in Massive Lepton Production

Boer, Hwang, sjb

$\cos 2\phi$  correlation

- Leading Twist, valence quark dominated
- Violates Lam-Tung Relation!
- Not obtained from standard PQCD subprocess analysis
- Normalized to the square of the single spin asymmetry in semi-inclusive DIS
- No polarization required
- Challenge to standard picture of PQCD Factorization



# Double Initial-State Interactions

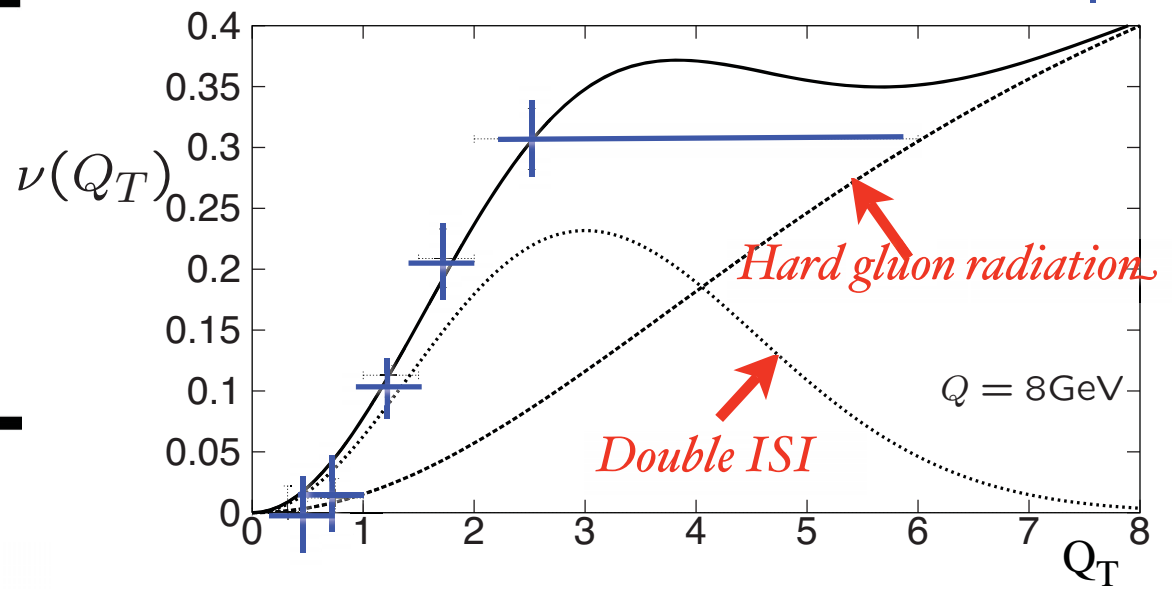
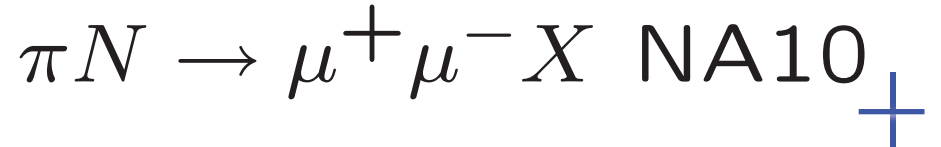
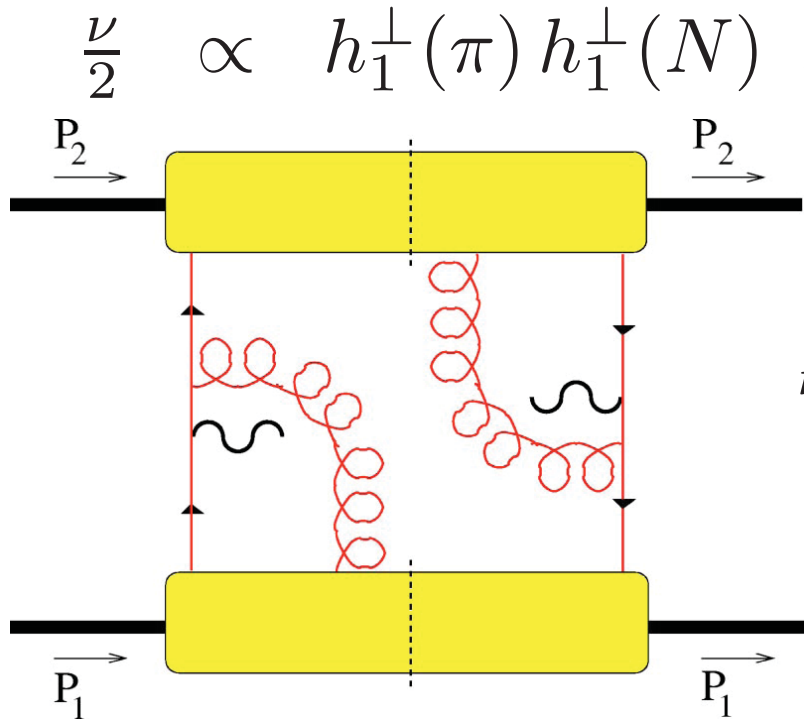
generate anomalous  $\cos 2\phi$

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):  $1 - \lambda - 2\nu = 0$



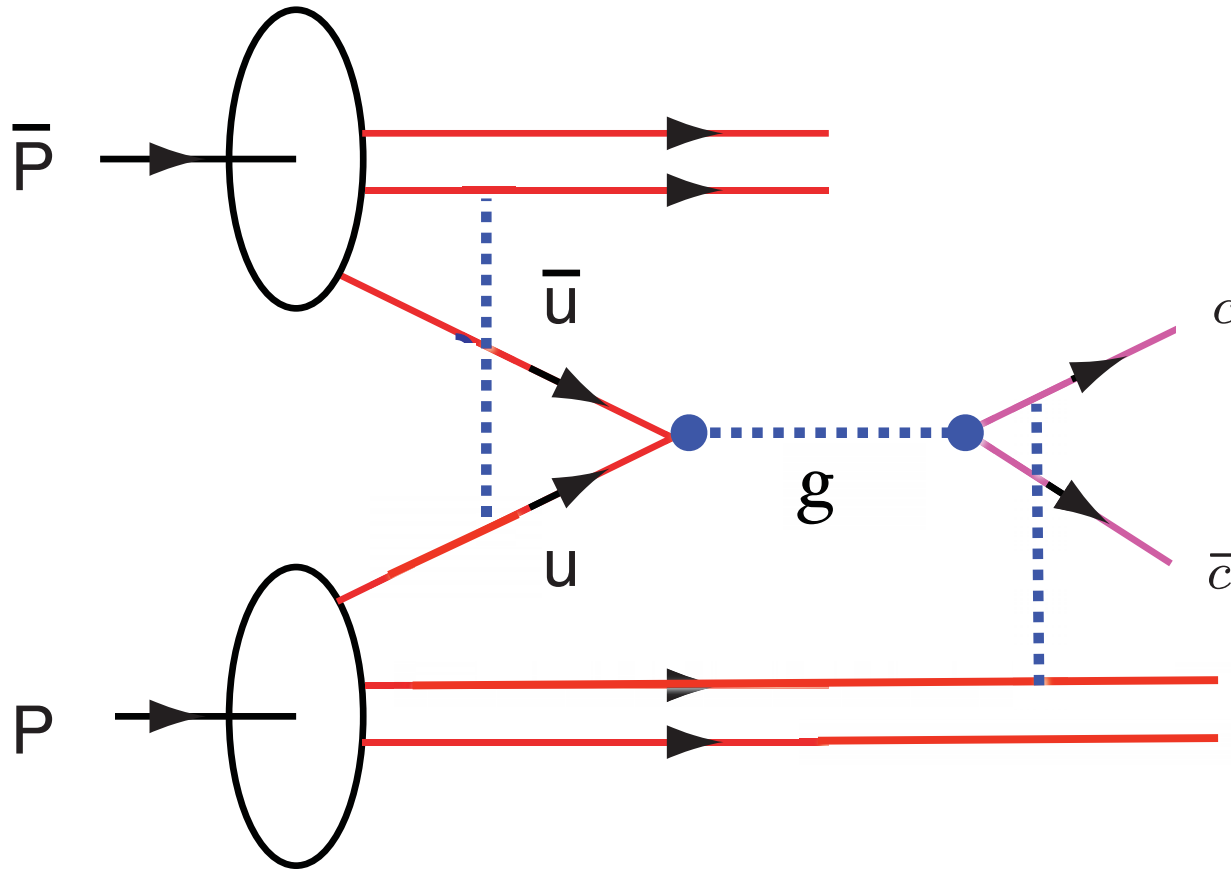
**Violates Lam-Tung relation!**

Model: Boer,

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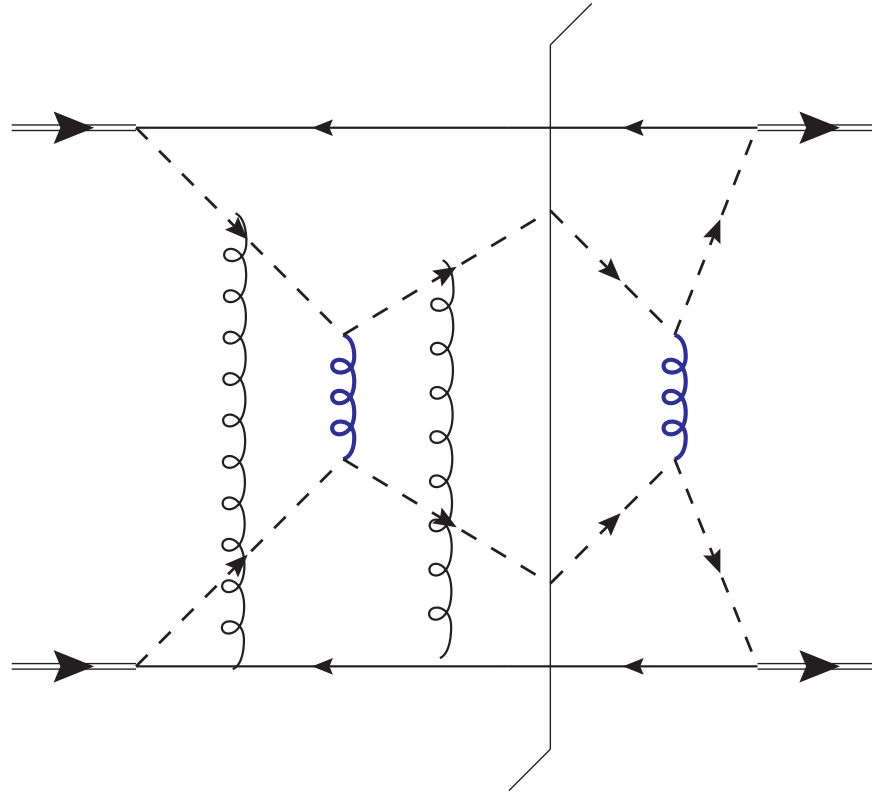


*Problem for factorization when both ISI and FSI occur*

# 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]



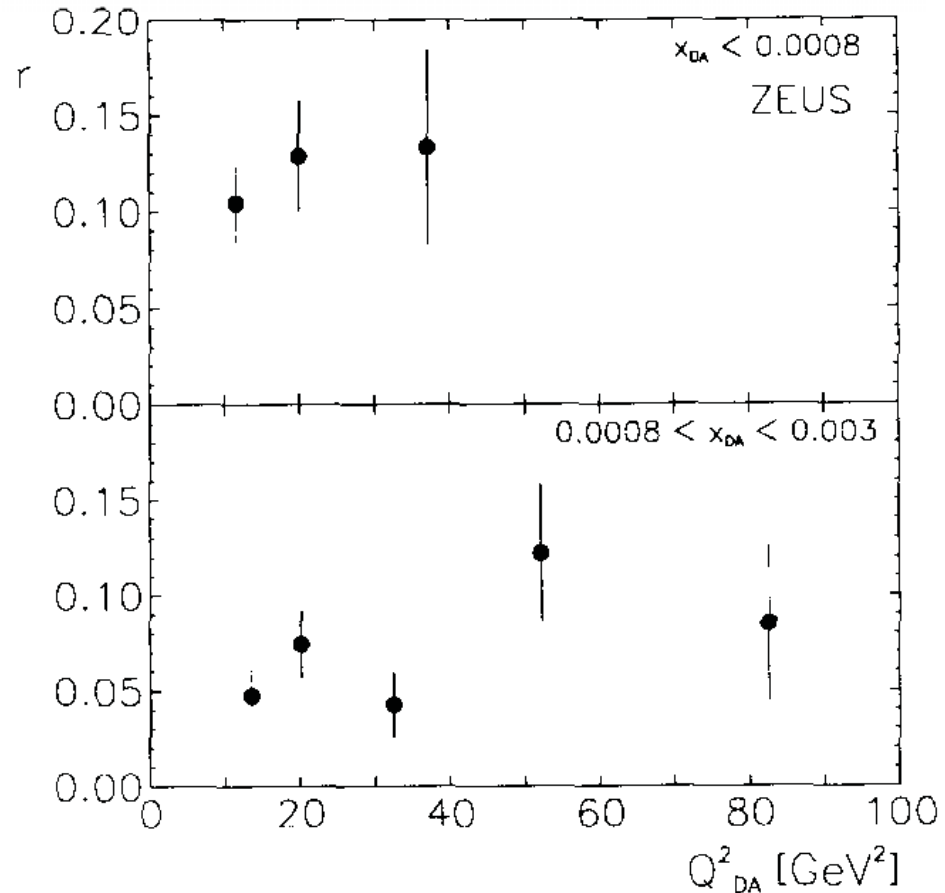
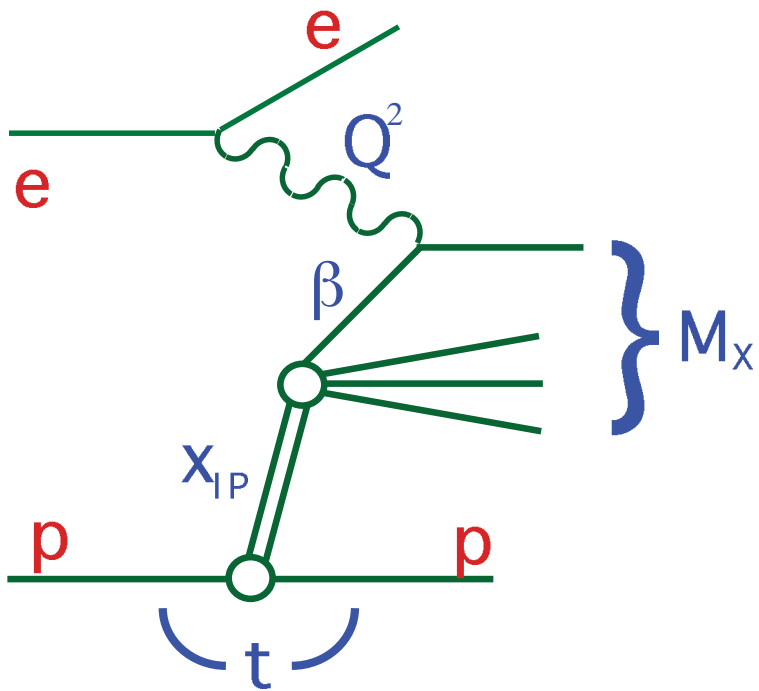
The exchange of two extra gluons, as in this graph, will tend to give non-factorization in unpolarized cross sections.

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# Remarkable observation at HERA

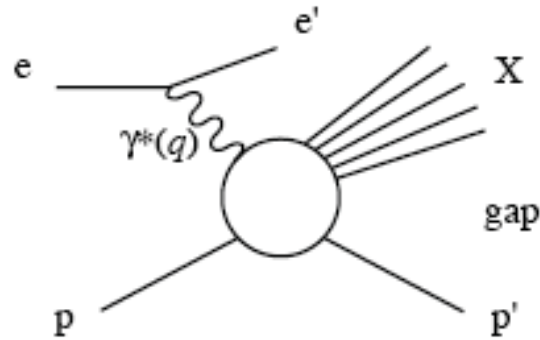


*10% to 15% of DIS events are diffractive!*

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).

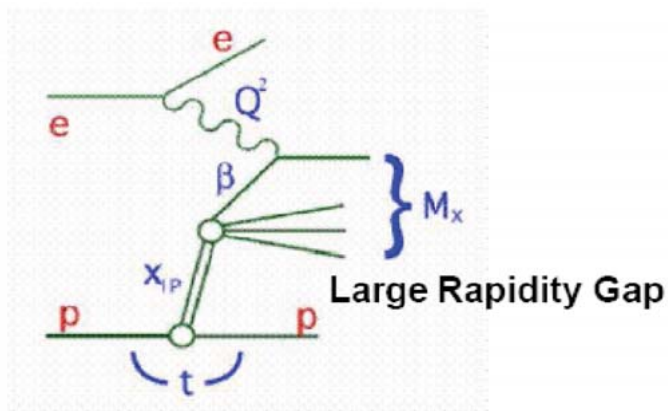
# DDIS



- In a large fraction ( $\sim 10\text{--}15\%$ ) of DIS events, the proton escapes intact, keeping a large fraction of its initial momentum
- This leaves a large *rapidity gap* between the proton and the produced particles
- The  $t$ -channel exchange must be *color singlet*  $\rightarrow$  a pomeron??

## Diffractive Deep Inelastic Lepton-Proton Scattering

# Diffractive Structure Function $F_2^D$



Diffractive inclusive cross section

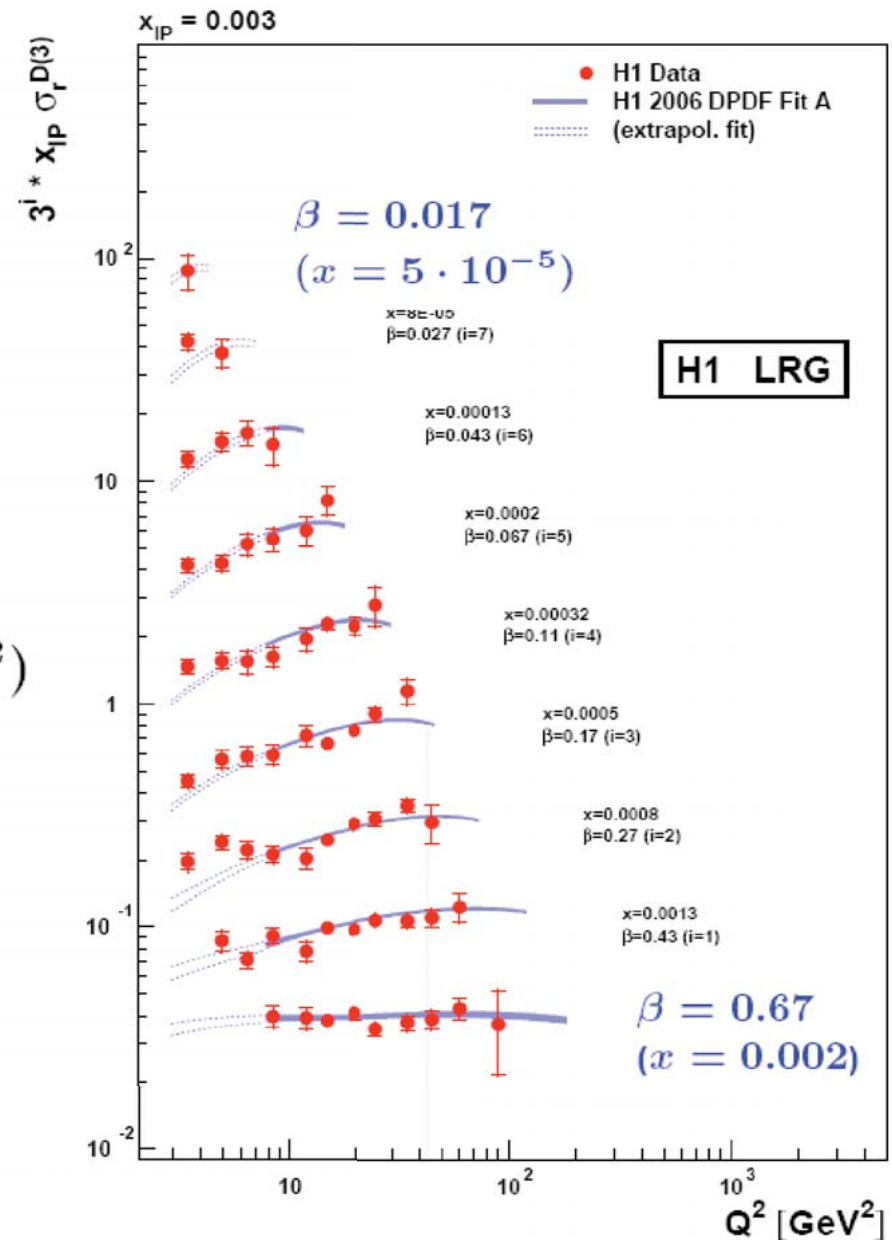
$$\frac{d^3 \sigma_{NC}^{diff}}{dx_{IP} d\beta dQ^2} \propto \frac{2\pi\alpha^2}{xQ^4} F_2^{D(3)}(x_{IP}, \beta, Q^2)$$

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

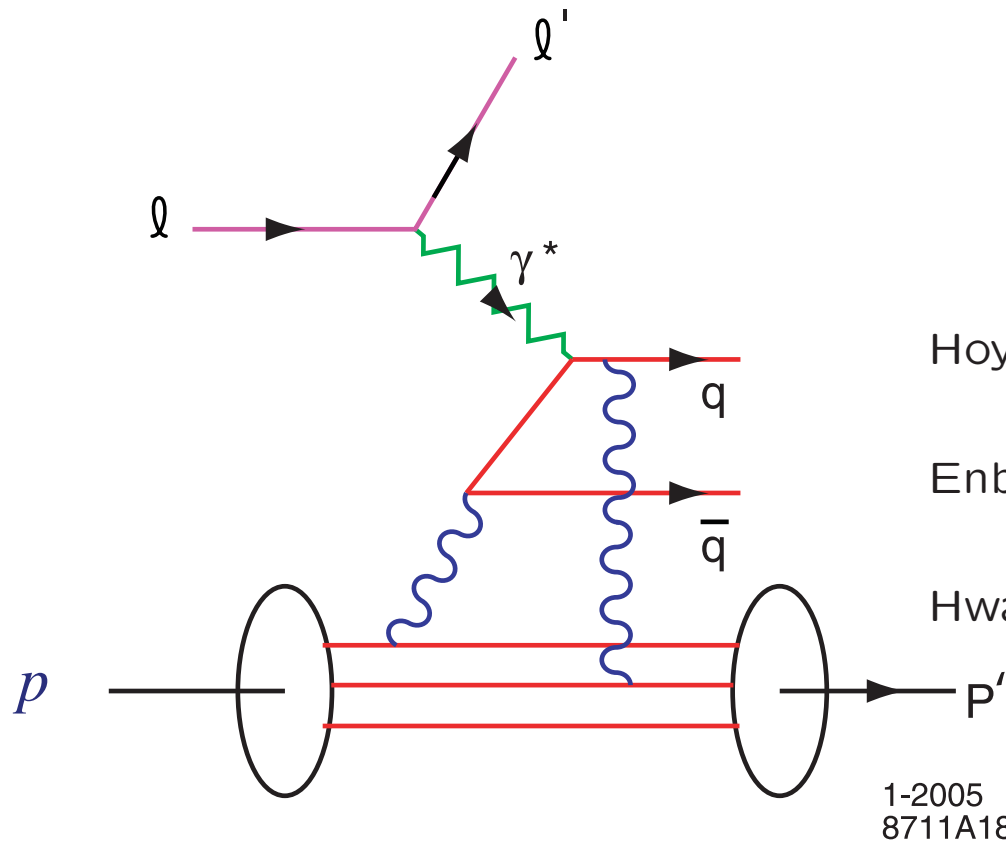
extract DPDF and  $xg(x)$  from scaling violation

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

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

1-2005  
8711A18

## Low-Nussinov model of Pomeron

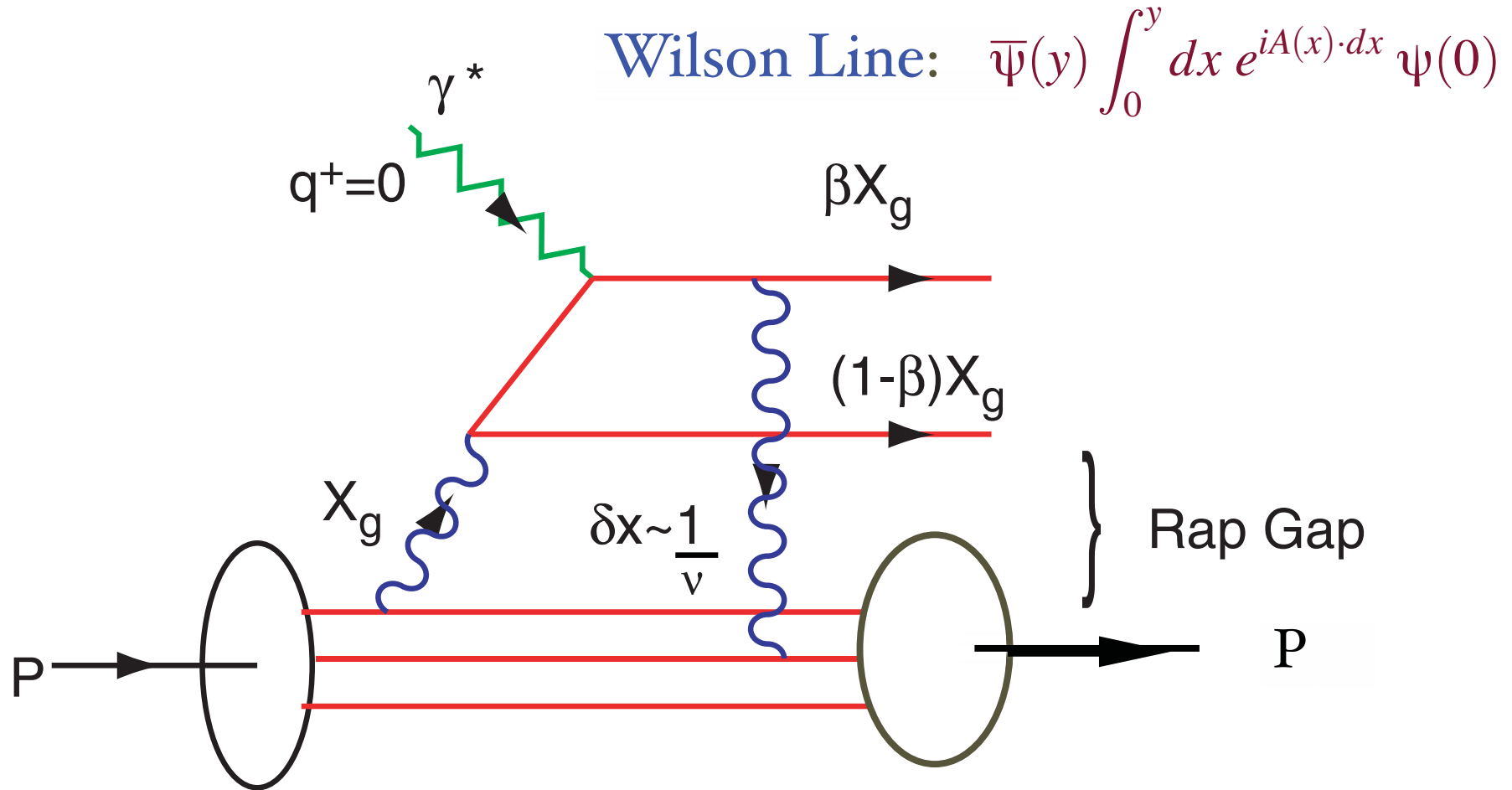
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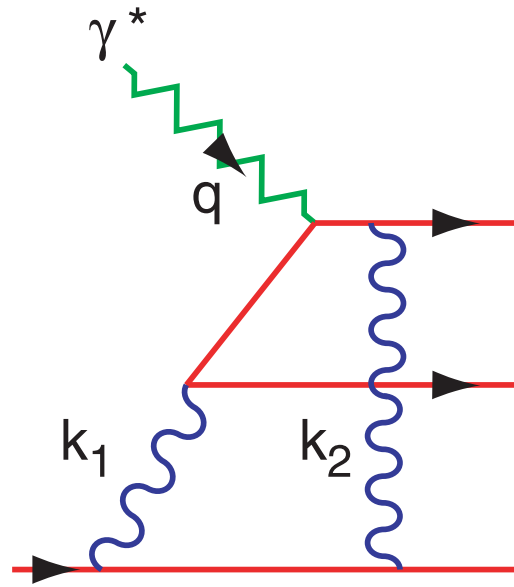
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# QCD Mechanism for Rapidity Gaps

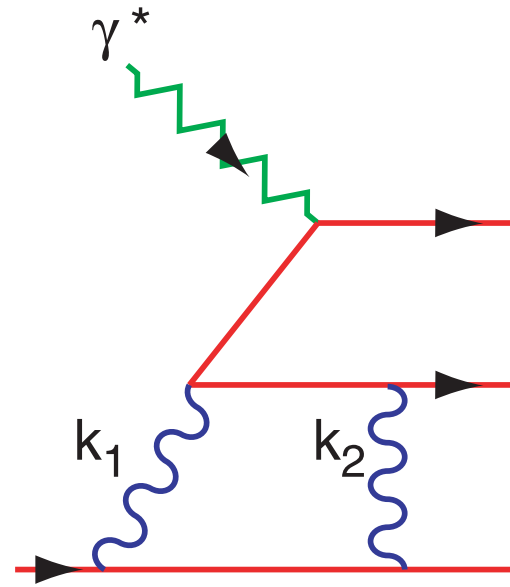


**Reproduces lab-frame color dipole approach**

# *Final State Interactions in QCD*

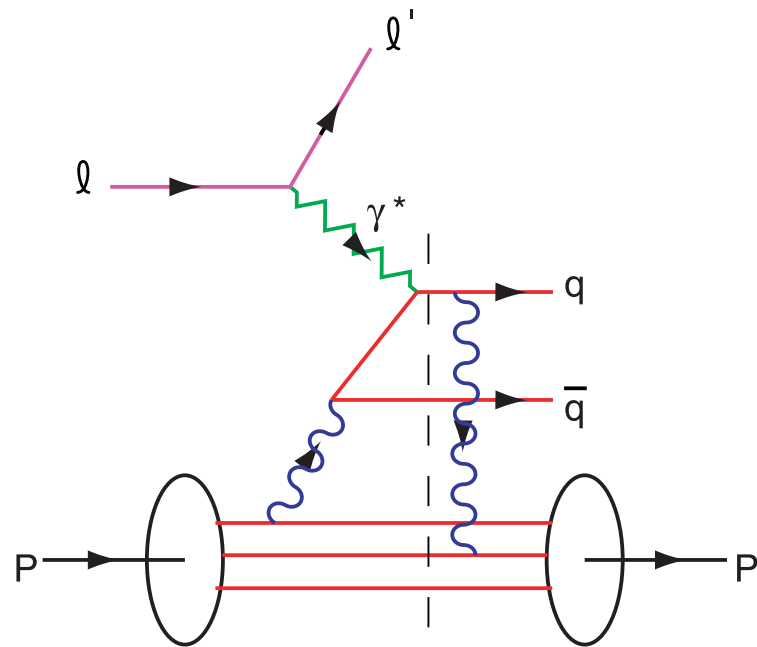


Feynman Gauge



Light-Cone Gauge

*Result is Gauge Independent*



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*

# 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!
- T-odd SSAs, Shadowing, Antishadowing
- Diffractive dijets/ trijets, doubly diffractive Higgs
- Novel Effects: Color Transparency, Color Opaqueness, Intrinsic Charm, Odderon

# Physics of Rescattering

- Diffractive DIS
- Non-Unitary Correction to DIS: Structure functions are not probability distributions
- Nuclear Shadowing, Antishadowing- Not in Target WF
- Single Spin Asymmetries -- opposite sign in DY and DIS
- $DY \cos 2\phi$  distribution at leading twist from double ISI-- not given by PQCD factorization -- breakdown of factorization!
- Wilson Line Effects not 1 even in LCG
- Must correct hard subprocesses for initial and final-state soft gluon attachments
- Corrections to Handbag Approximation in DVCS!

Hoyer, Marchal, Peigne, Sannino, sjb

# “Dangling Gluons”

- Diffractive DIS
- Non-Unitary Correction to DIS: Structure functions are not probability distributions
- Nuclear Shadowing, Antishadowing
- Single Spin Asymmetries -- opposite sign in DY and DIS
- $DY \cos 2\phi$  correlation at leading twist from double ISI-- not given by standard PQCD factorization
- Wilson Line Effects persist even in LCG
- Must correct hard subprocesses for initial and final-state soft gluon attachments -- Ji gauge link, Kovchegov gauge

Bodwin, Lepage, sjb  
Hoyer, Marchal, Peigne, Sannino, sjb

# Light-Front QCD Phenomenology

- Hidden color, Intrinsic glue, sea, Color Transparency
- Near Conformal Behavior of LFWFs at Short Distances; PQCD constraints
- Vanishing anomalous gravitomagnetic moment
- Relation between edm and anomalous magnetic moment
- Cluster Decomposition Theorem for relativistic systems
- OPE: DGLAP, ERBL evolution; invariant mass scheme

# New Perspectives on QCD Phenomena from AdS/CFT

- **AdS/CFT**: Duality between string theory in Anti-de Sitter Space and Conformal Field Theory
- New Way to Implement Conformal Symmetry
- Holographic Model: Conformal Symmetry at Short Distances, Confinement at large distances
- Remarkable predictions for hadronic spectra, wavefunctions, interactions
- AdS/CFT provides novel insights into the quark structure of hadrons

String Theory

AdS/CFT

Mapping of Poincare' and Conformal  $SO(4,2)$  symmetries of 3+1 space to AdS5 space

Goal: First Approximant to QCD

AdS/QCD

Counting rules for Hard Exclusive Scattering  
Regge Trajectories  
QCD at the Amplitude Level

Conformal behavior at short distances  
+ Confinement at large distance

Semi-Classical QCD / Wave Equations

Holography

Boost Invariant 3+1 Light-Front Wave Equations

$J=0, 1, 1/2, 3/2$  plus  $L$

Integrable!

Hadron Spectra, Wavefunctions, Dynamics

# Outlook

- Only one scale  $\Lambda_{QCD}$  determines hadronic spectrum (slightly different for mesons and baryons).
- Ratio of Nucleon to Delta trajectories determined by zeroes of Bessel functions.
- String modes dual to baryons extrapolate to three fermion fields at zero separation in the AdS boundary.
- Only dimension 3,  $\frac{9}{2}$  and 4 states  $\bar{q}q$ ,  $qqq$ , and  $gg$  appear in the duality at the classical level!
- Non-zero orbital angular momentum and higher Fock-states require introduction of quantum fluctuations.
- Simple description of space and time-like structure of hadronic form factors.
- Dominance of quark-interchange in hard exclusive processes emerges naturally from the classical duality of the holographic model. Modified by gluonic quantum fluctuations.
- Covariant version of the bag model with confinement and conformal symmetry.

## A Few References: Bottom-up-Approach

- Derivation of dimensional counting rules of hard exclusive glueball scattering in AdS/CFT:  
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- Hadron couplings and form factors in AdS/CFT:  
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- Strongly coupled quark-gluon plasma ( $\eta/s = 1/4\pi$ ):  
Policastro, Son and Starinets, hep-th/0104066; Kang and Nastase, hep-th/0410173 ...

- Counting rules, low lying meson and baryon spectra and form factors in AdS/CFT, holographic light front representation and mapping of string amplitudes to light-front wavefunctions, integrability and stability of AdS/CFT equations (Emphasis on hadronic quark constituents)

Brodsky and GdT, hep-th/0310227, hep-th/0409074, hep-th/0501022, hep-ph/0602252, 0707.3859 [hep-ph], 0709.2072 [hep-ph].

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