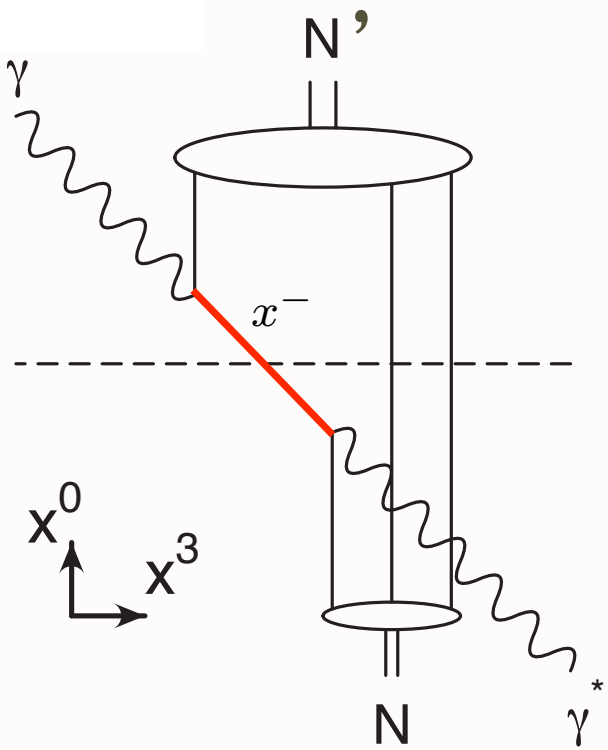
Space-time picture of DVCS

P. Hoyer

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



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

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

Measure x- distribution from DVCS:
Use Fourier transform of skewness,
the longitudinal momentum transfer

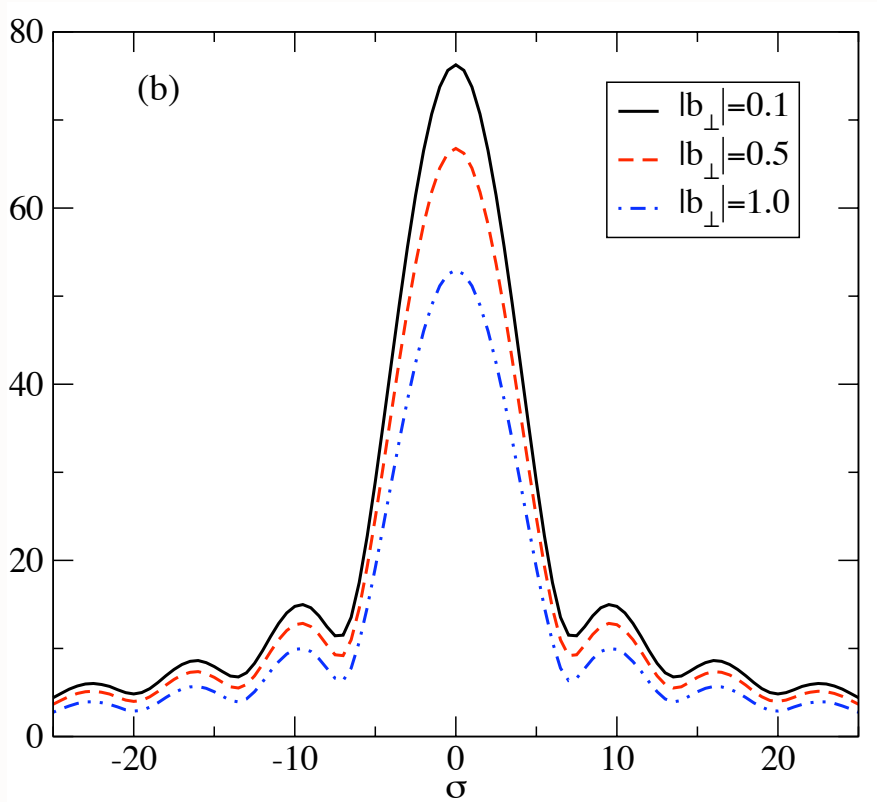
$$\zeta = \frac{Q^2}{2p \cdot q}$$

S. J. Brodsky[a], D. Chakrabarti[b], A. Harindranath[c], A. Mukherjee[d], J. P. Vary[e,a,f]

S. J. Brodsky[a], D. Chakrabarti[b], A. Harindranath[c], A. Mukherjee[d], J. P. Vary[e,a,f]

Hadron Optics

$$A(\sigma, b_\perp) = \frac{1}{2\pi}\int d\zeta e^{i\sigma\zeta}\tilde{A}(b_\perp, \zeta) \qquad \sigma = \tfrac{1}{2}x^- P^+ \qquad \zeta = \frac{Q^2}{2p\cdot q}$$

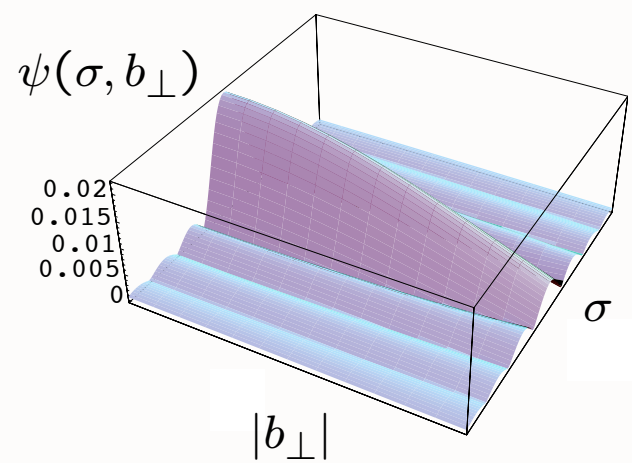


The Fourier Spectrum of the DVCS amplitude in σ space for different fixed values of $|b_\perp|$.

GeV units

DVCS Amplitude using holographic QCD meson LFWF

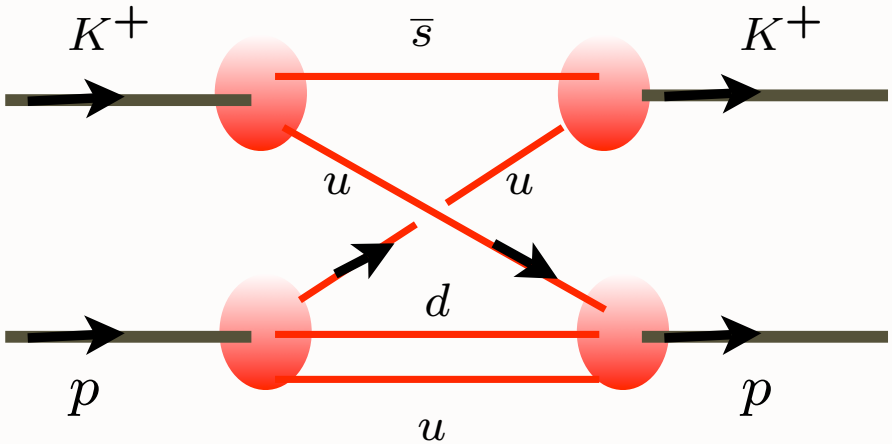
$$\Lambda_{QCD} = 0.32$$

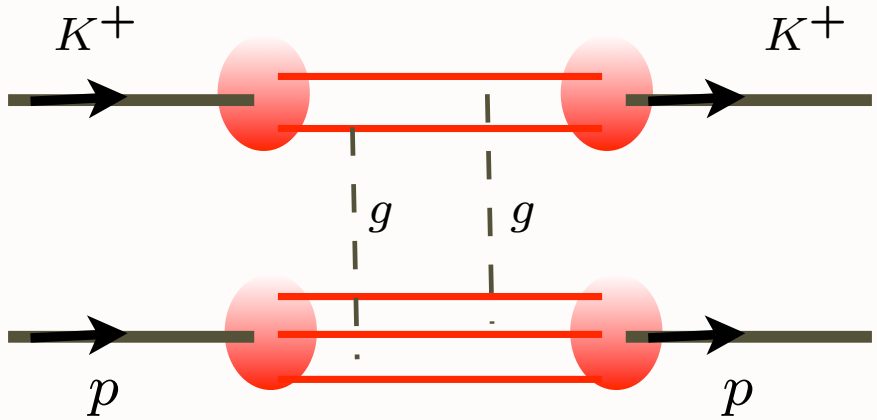


New Perspectives for QCD from AdS/CFT

- 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

CIM: Blankenbecler, Gunion, sjb





Quark Interchange
(Spin exchange in atom-atom scattering)

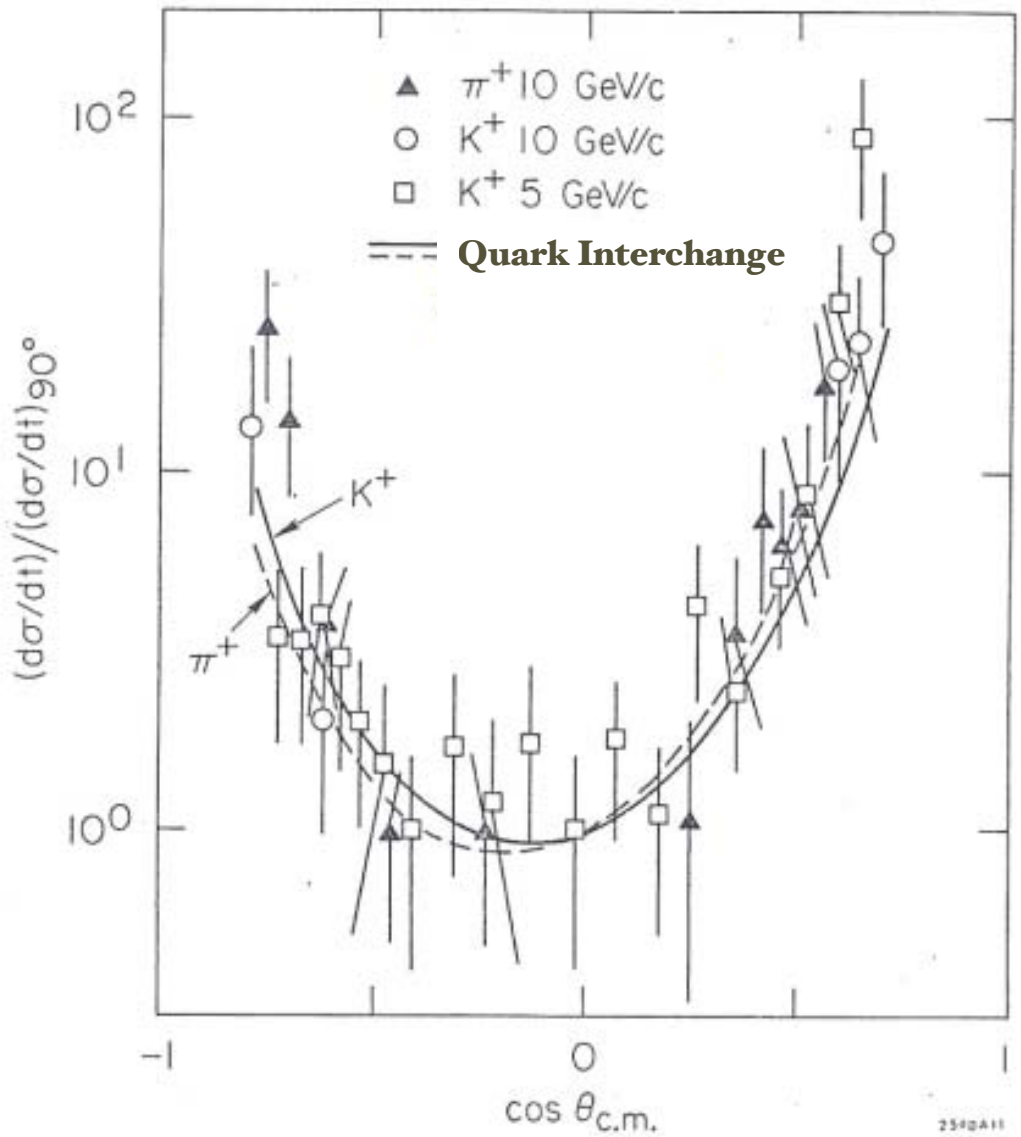
Gluon Exchange
(Van der Waal -- Landshoff)

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

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

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

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:

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

Why is quark-interchange dominant over gluon exchange?

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

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,[a] G. C. Blazey,[b] H. Courant, K. J. Heller, S. Heppelmann,[c] M. L. Marshak, E. A. Peterson, M. A. Shupe, and D. S. Wahl[d]
University of Minnesota, Minneapolis, Minnesota 55455

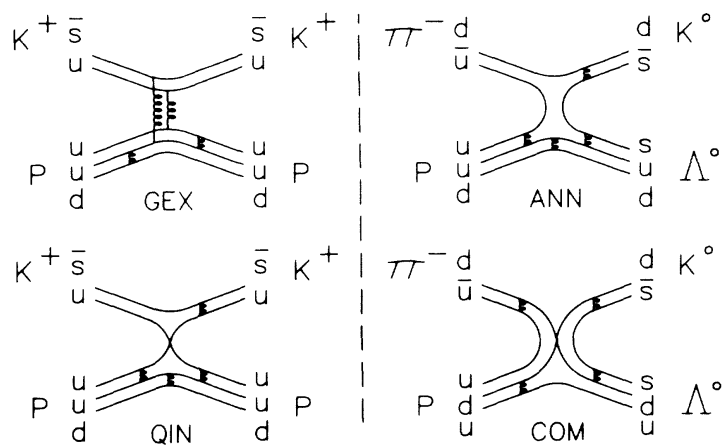
D. S. Barton, G. Bunce, A. S. Carroll, and Y. I. Makdisi
Brookhaven National Laboratory, Upton, New York 11973

and

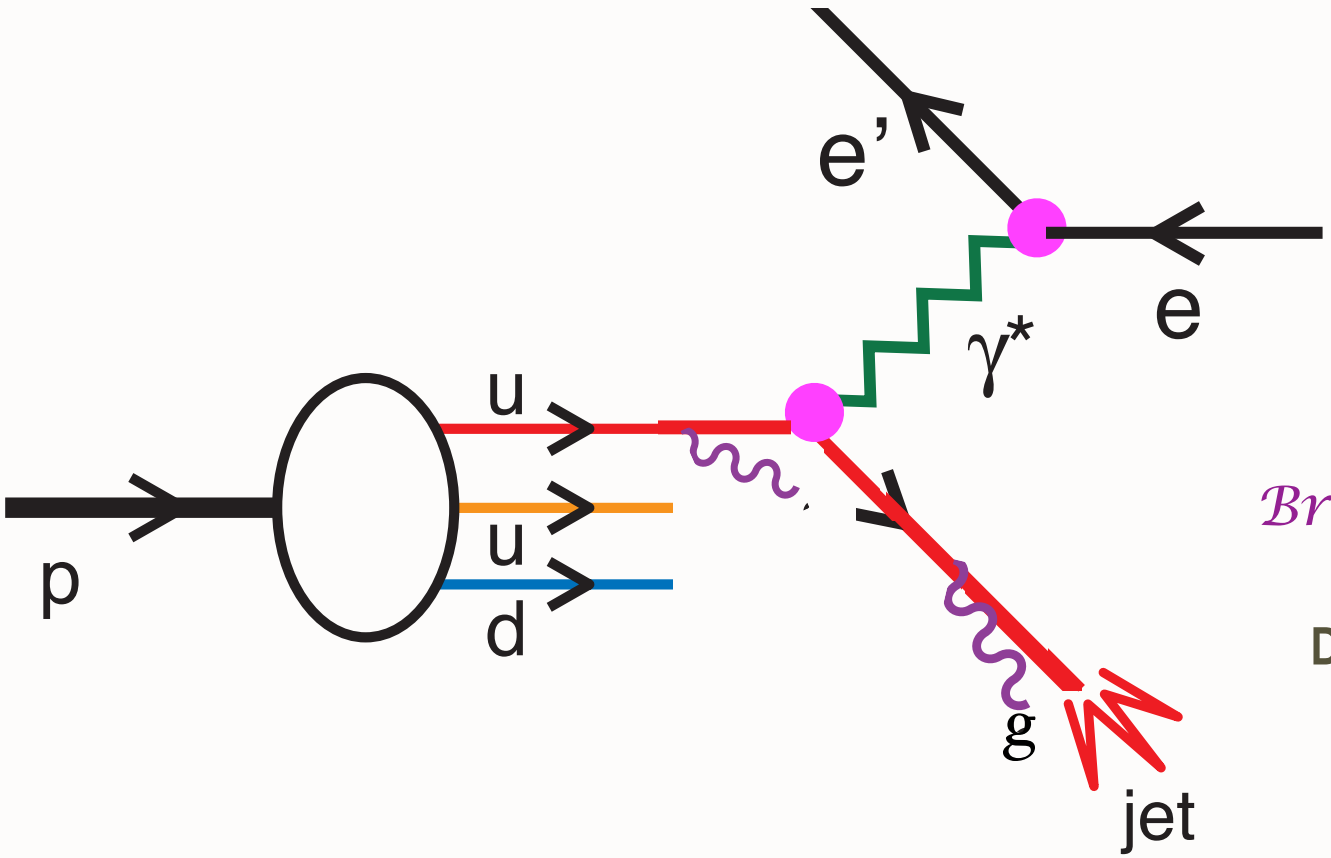
S. Gushue[e] and J. J. Russell
Southeastern Massachusetts University, North Dartmouth, Massachusetts 02747
(Received 28 October 1987; revised manuscript received 3 February 1988)

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.: $\pi^{\pm}p \to p\pi^{\pm}, p\rho^{\pm}, \pi^{+}\Delta^{\pm}, K^{+}\Sigma^{\pm}, (\Lambda^0/\Sigma^0)K^0$; $K^{\pm}p \to pK^{\pm}$; $p^{\pm}p \to pp^{\pm}$. 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.

$$\pi^{\pm}p \to p\pi^{\pm},$$
$$K^{\pm}p \to pK^{\pm},$$
$$\pi^{\pm}p \to p\rho^{\pm},$$
$$\pi^{\pm}p \to \pi^{+}\Delta^{\pm},$$
$$\pi^{\pm}p \to K^{+}\Sigma^{\pm},$$
$$\pi^{-}p \to \Lambda^0 K^0, \Sigma^0 K^0,$$
$$p^{\pm}p \to pp^{\pm}.$$



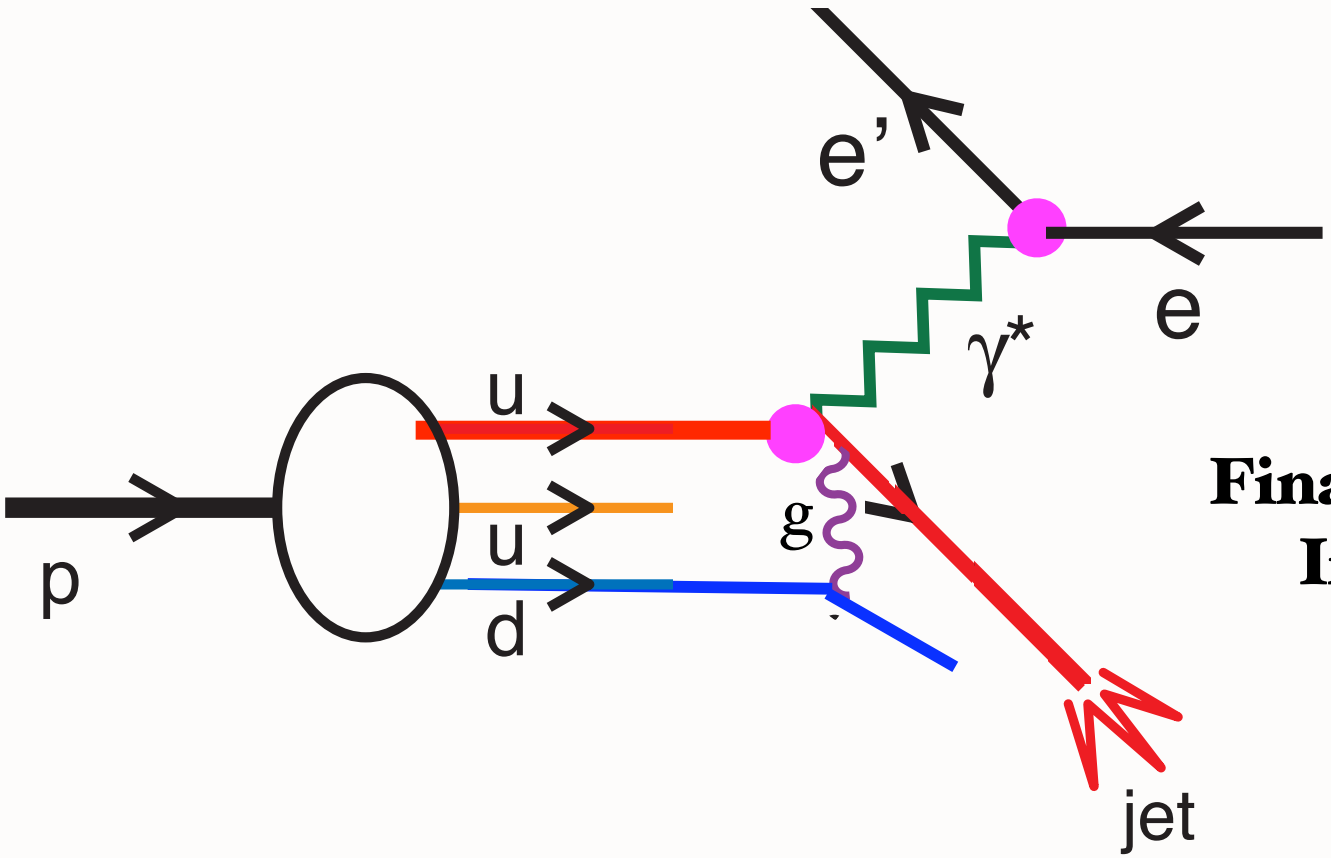
Deep Inelastic Electron-Proton Scattering



Gluonic Bremsstrahlung

DGLAP Evolution

Deep Inelastic Electron-Proton Scattering



Final-State QCD Interaction

Conventional wisdom:
Final-state interactions of struck quark can be neglected

Physics of Rescattering

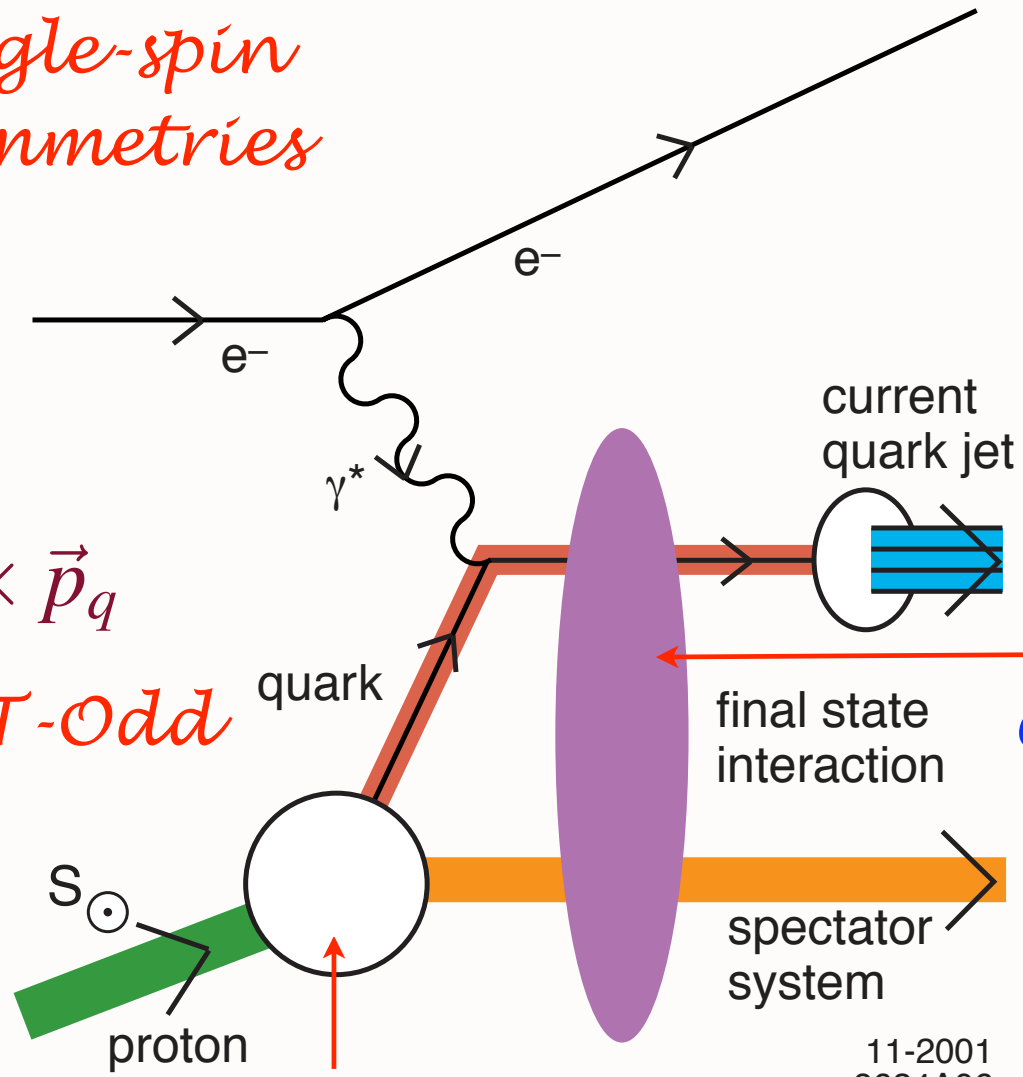
- Diffractive DIS: New Insights into Final State Interactions in QCD
- Origin of Hard Pomeron
- Structure Functions not Probability Distributions!
- T-odd SSAs, Shadowing, Antishadowing
- Diffractive dijets/ trijets, doubly diffractive Higgs
- Novel Effects: Color Transparency, Color Opaqueness, Intrinsic Charm, Odderon

Leading Twist Sivers Effect

Single-spin asymmetries

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

Pseudo-T-Odd



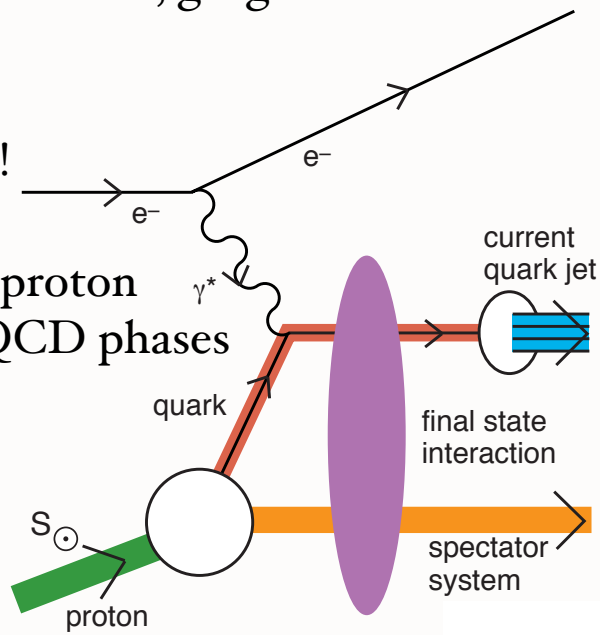
QCD S- and P- Coulomb Phases

Light-Front Wavefunction S and P- Waves

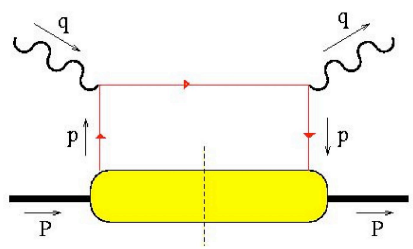
D. S. Hwang, I. A. Schmidt, sjb

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

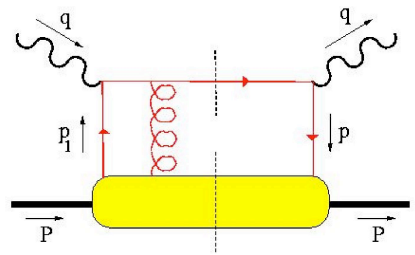
- Leading-Twist Bjorken Scaling!
- Requires nonzero orbital angular momentum of quark! $i\,\vec{S}\cdot\vec{p}_{jet}\times\vec{q}$
- Arises from the interference of Final-State QCD Coulomb phases in S- and P- waves; Wilson line effect; gauge independent
- Unexpected QCD Effect -- thought to be zero!
- 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



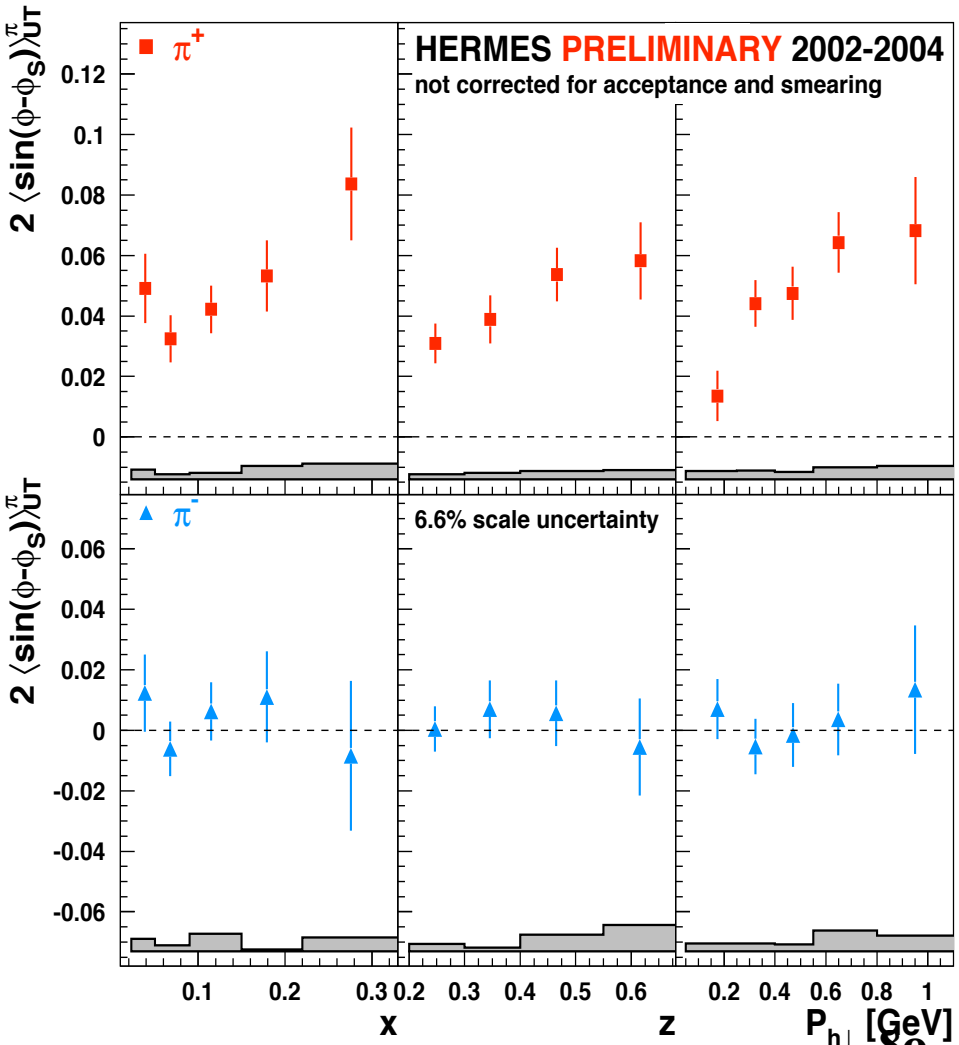
- Sum of Sivers Functions for all quarks and gluons vanishes. (Zero gravito-anomalous magnetic moment: B(0)= 0)



can interfere with



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

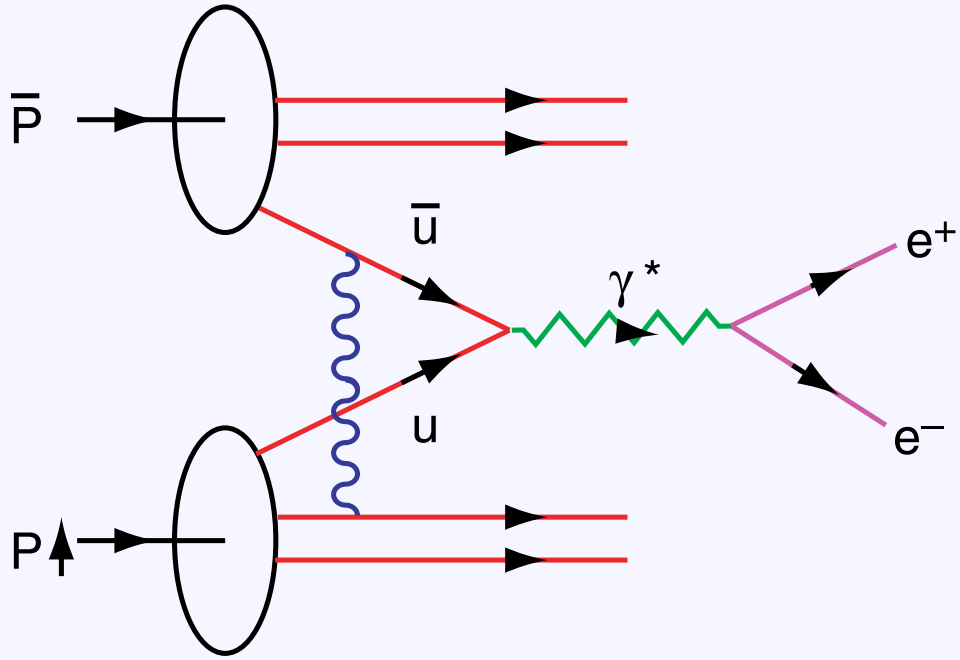


- First evidence for non-zero Sivers function!
- ⇒ presence of non-zero **quark orbital angular momentum**!
- Positive for π^+...
  Consistent with zero for π^-...

Gamberg: Hermes data compatible with BHS model

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

Predict Opposite Sign SSA in DY !



Collins;
Hwang, Schmidt.
sjb

Single Spin Asymmetry In the Drell Yan Process

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

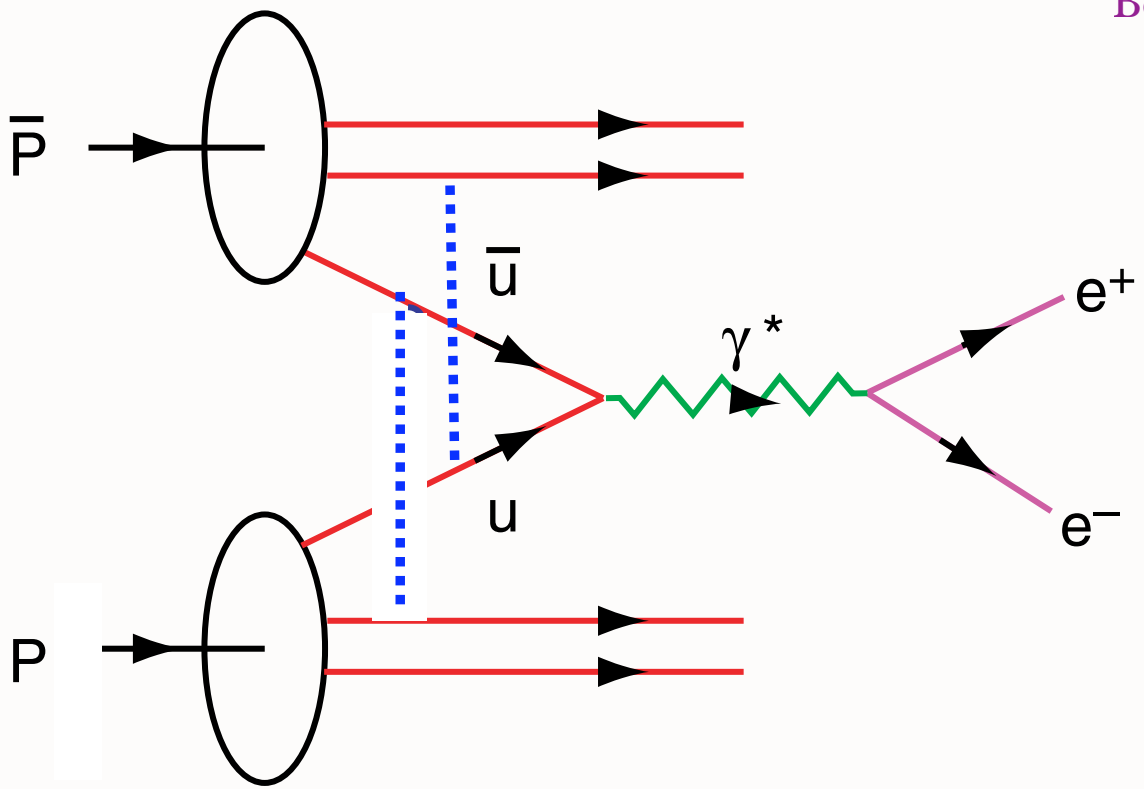
Quarks Interact in the Initial State

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

Boer, Hwang, sjb

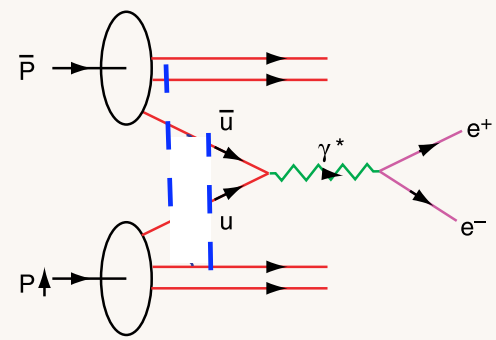


DY $\cos 2\phi$ correlation at leading twist from double ISI

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 $\cos 2\phi$

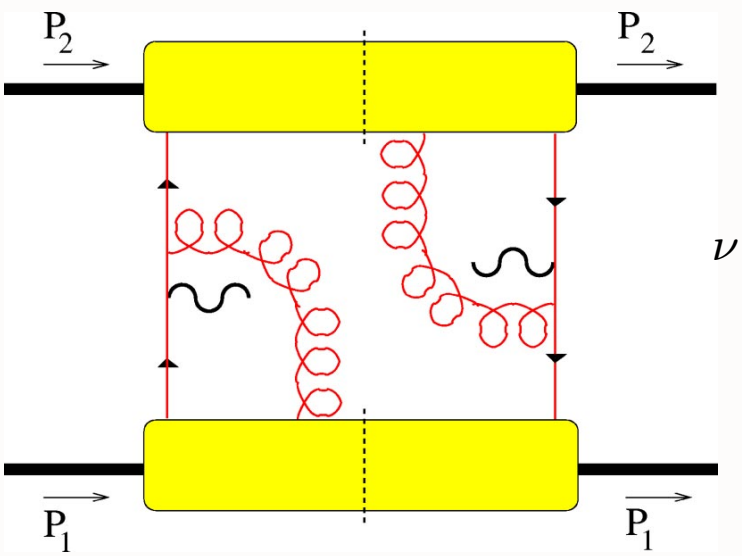
Boer, Hwang, sjb

Drell-Yan planar correlations

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

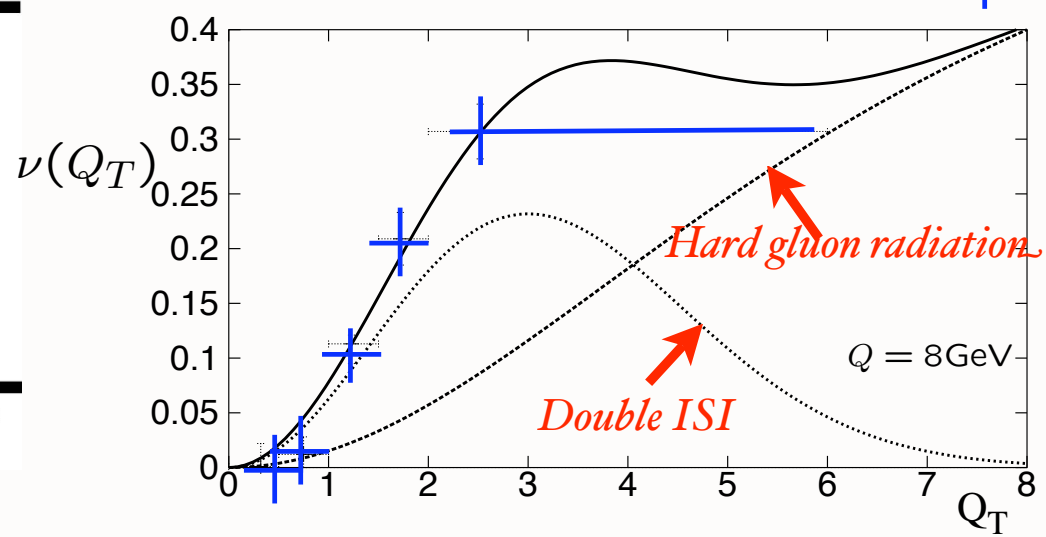
PQCD Factorization (Lam Tung): $1 - \lambda - 2\nu = 0$

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



Violates Lam-Tung relation!

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



Model: Boer,

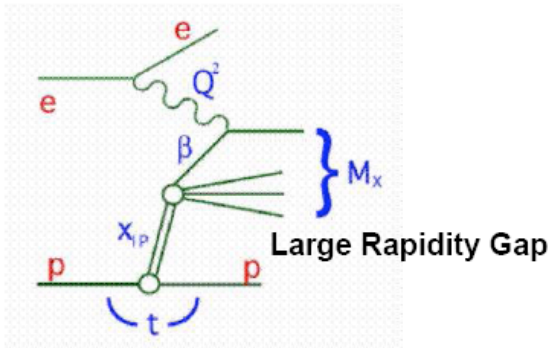
Dangling Gluons

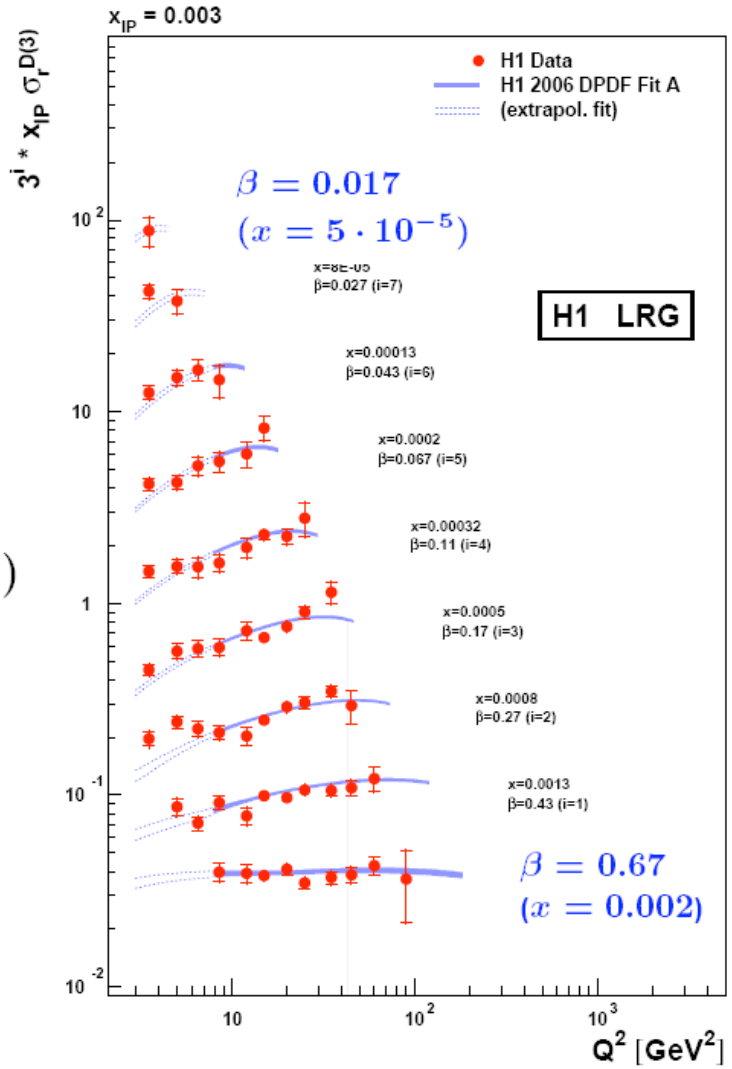
- Diffractive DIS
- Non-Unitary Correction to DIS: Structure functions are not probability distributions
- Nuclear Shadowing, Antishadowing
- Single Spin Asymmetries -- opposite sign in DY and DIS
- DY $\cos 2\phi$ correlation at leading twist from double ISI-- not given by standard PQCD factorization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

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

de Roeck

Diffractive Structure Function F_2^D





Diffractive inclusive cross section

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

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

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

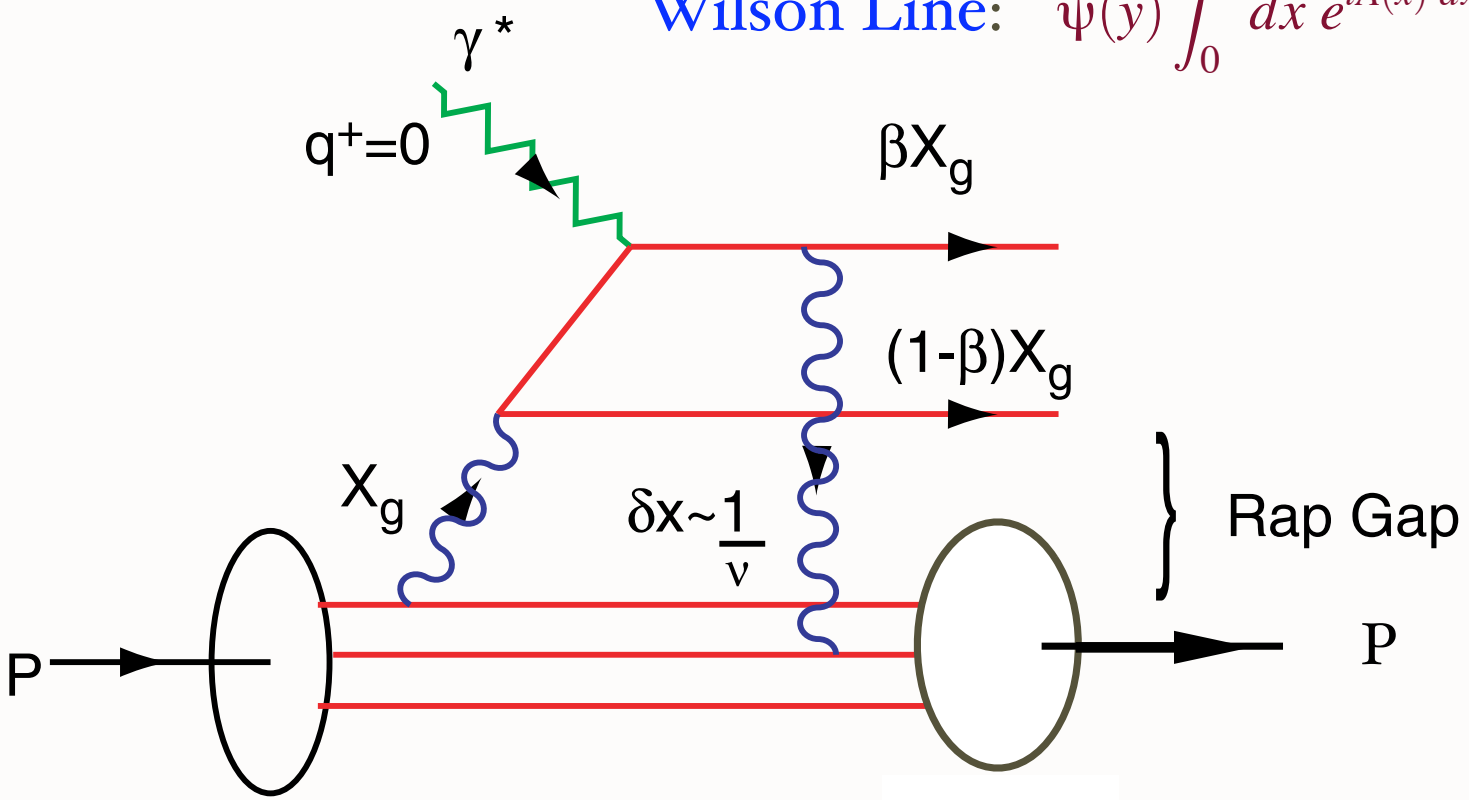
Large kinematic domain $3 < Q^2 < 1600\ \mathrm{GeV}^2$

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

Hoyer, Marchal, Peigne, Sannino, sjb

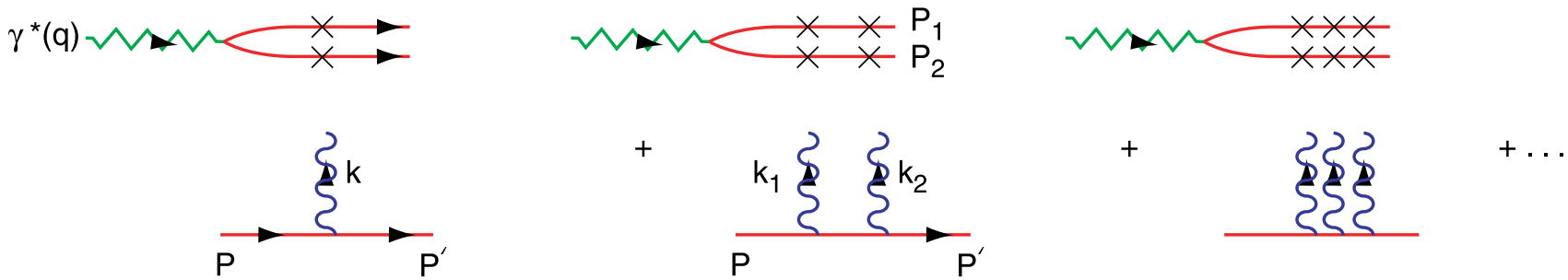
QCD Mechanism for Rapidity Gaps

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



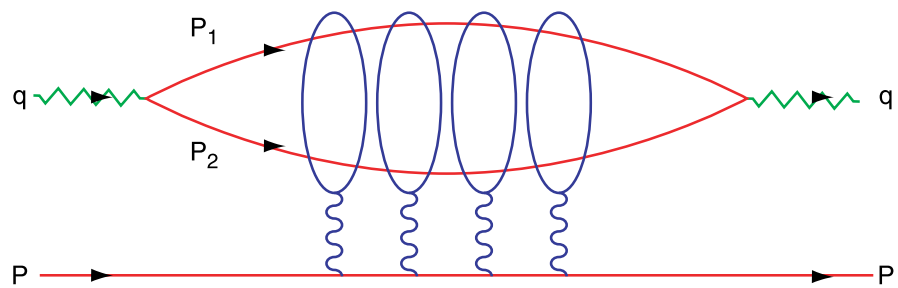
Reproduces lab-frame color dipole approach

Same result obtained in Lab or Parton $q^+=0$ Frame



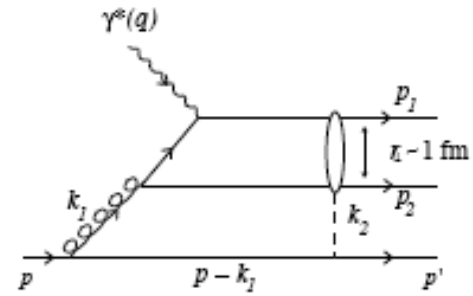
Sum Eikonal Interactions

Similar to Color-Dipole Model



Final-state interactions included

- Rescattering gluons have small momenta
  $\Rightarrow \beta$ dependence of diffractive PDFs arises from underlying (non-perturbative) $g \to q\bar{q}$ and $g \to gg$



- *Effective* $\mathbb{P}$ distribution and quark structure function:

$$f_{\mathbb{P}/p}(x_{\mathbb{P}}) \propto g(x_{\mathbb{P}}, Q_0^2)$$
$$f_{q/\mathbb{P}}(\beta, Q_0^2) \propto \beta^2 + (1-\beta)^2$$

- Diffractive amplitudes from rescattering are dominantly *imaginary* — as expected for diffraction (Ingelman–Schlein $\mathbb{P}$ model has real amplitudes)

S. J. Brodsky, P. Hoyer, N. Marchal, S. Peigne and F. Sannino, Phys. Rev. D 65, 114025 (2002) [arXiv:hep-ph/0104291].
S. J. Brodsky, R. Enberg, P. Hoyer and G. Ingelman, arXiv:hep-ph/0409119.

Consequences for DDIS

- Underlying hard scattering sub-process is the same in diffractive and non-diffractive events
- Same Q^2 dependence of diffractive and inclusive PDFs (remember: hard radiation not resolved)
- and same energy (W or x_B) dependence

$\Rightarrow \frac{\sigma_{\text{diff}}}{\sigma_{\text{tot}}}$ independent of x_B and Q^2 (as in data)

Also describes: vector meson leptoproduction BGMFS

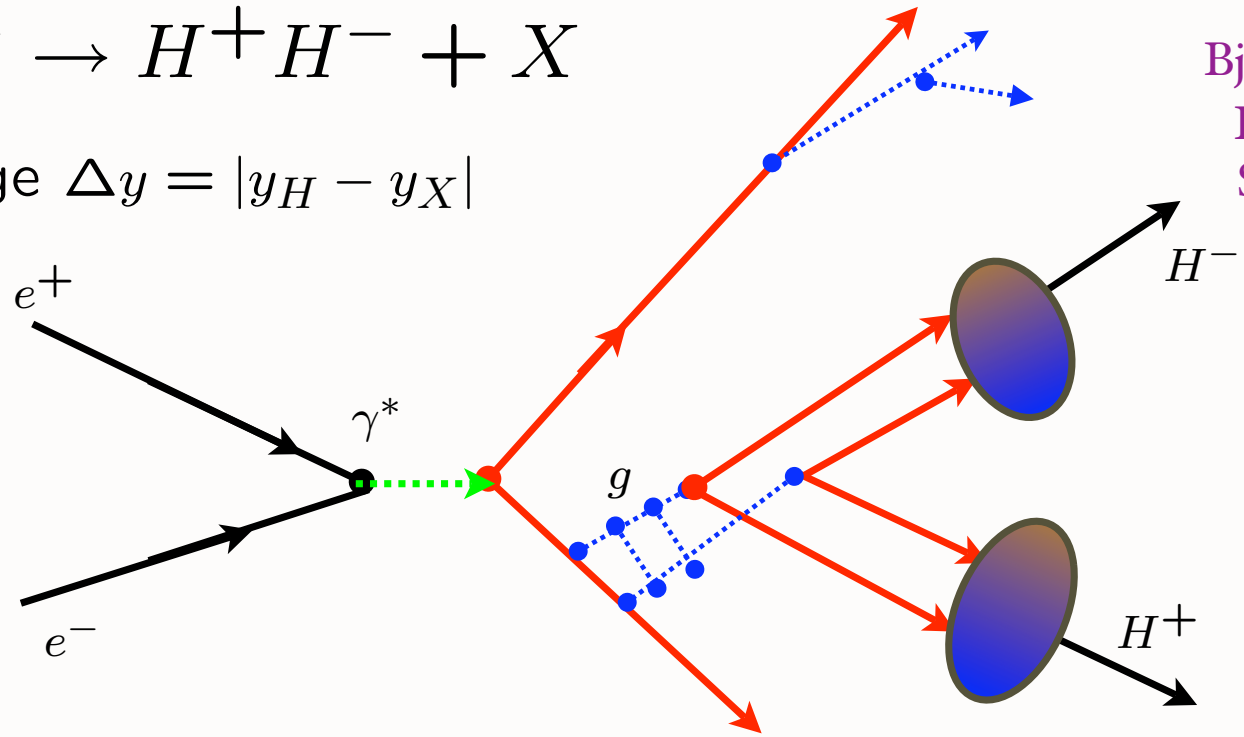
- Note:
  - In pomeron models the ratio depends on $x_B^{1-\alpha_{I\!P}}$ *which is ruled out*
  - In a two-gluon model with two hard gluons, the diffractive cross section depends on $[f_{g/p}(x_B, Q^2)]^2$

Hadronization at the Amplitude Level

$$e^+e^- \to H^+H^- + X$$

Bjorken, Lu, sjb
Kopeliovich, Schmidt, sjb

Large $\Delta y = |y_H - y_X|$



Timelike Pomeron ***C= +*** ***Gluonium Trajectory***

Large Rapidity Gap Events

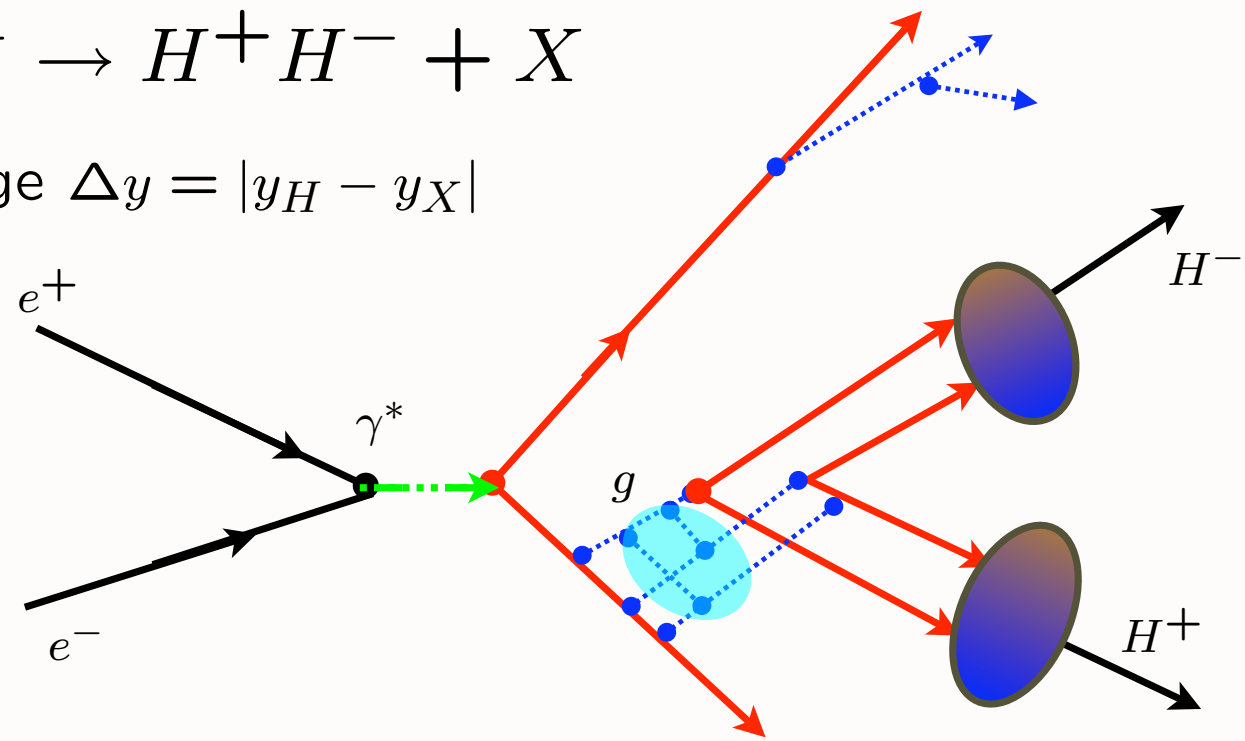
Crossing analog of Diffractive DIS $eH \to eH + X$

Hadronization at the Amplitude Level

Kopeliovich, Schmidt, sjb

$$e^+e^- \to H^+H^- + X$$

Large $\Delta y = |y_H - y_X|$

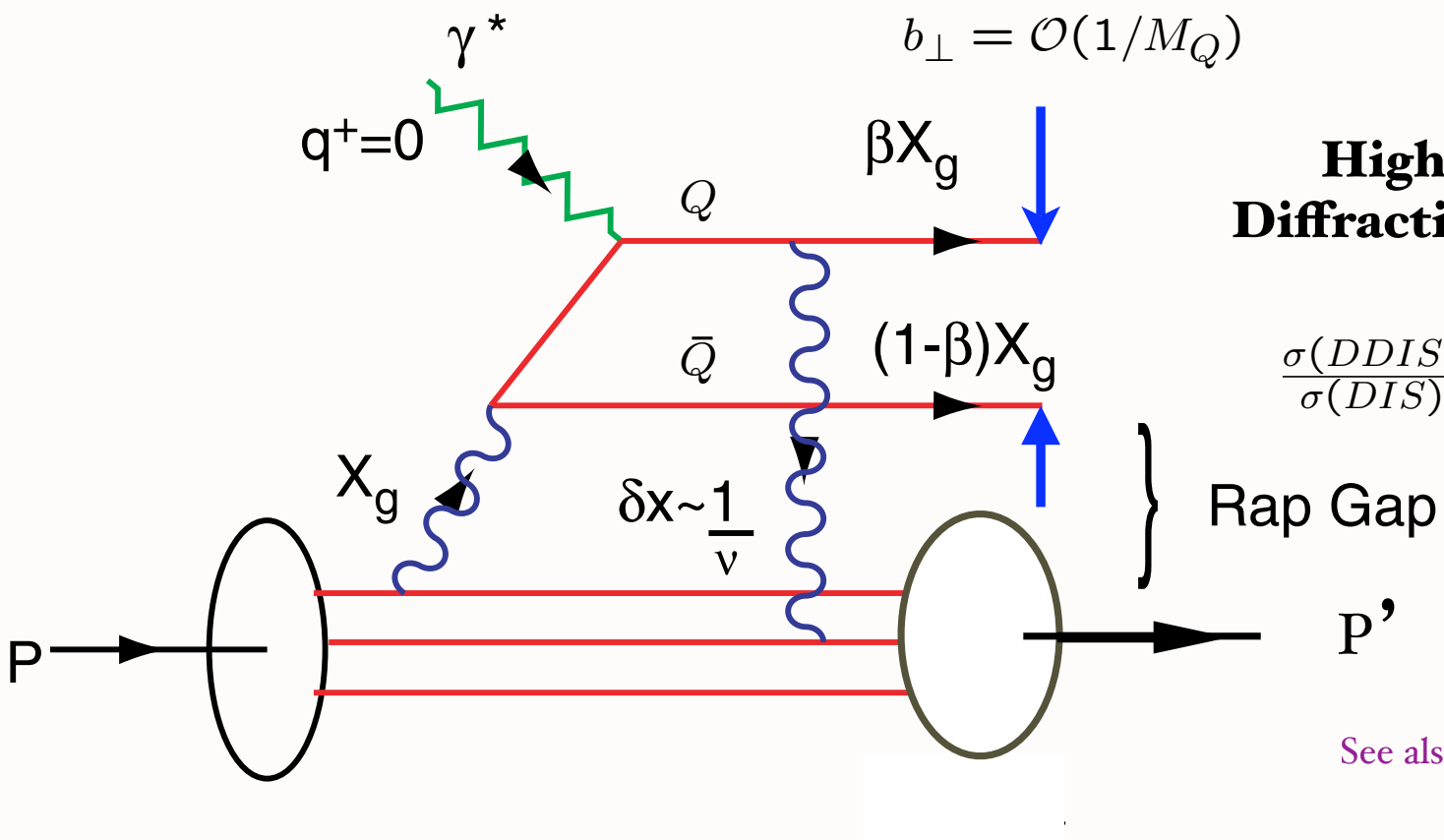


Timelike Odderon

Large Rapidity Gap Events ***$C = -$ Gluonium Trajectory***

H^+H^- asymmetry from Odderon-Pomeron interference

Predict: Reduced DDIS/DIS for Heavy Quarks



$b_\perp = \mathcal{O}(1/M_Q)$

Higher Twist Diffraction Fraction

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

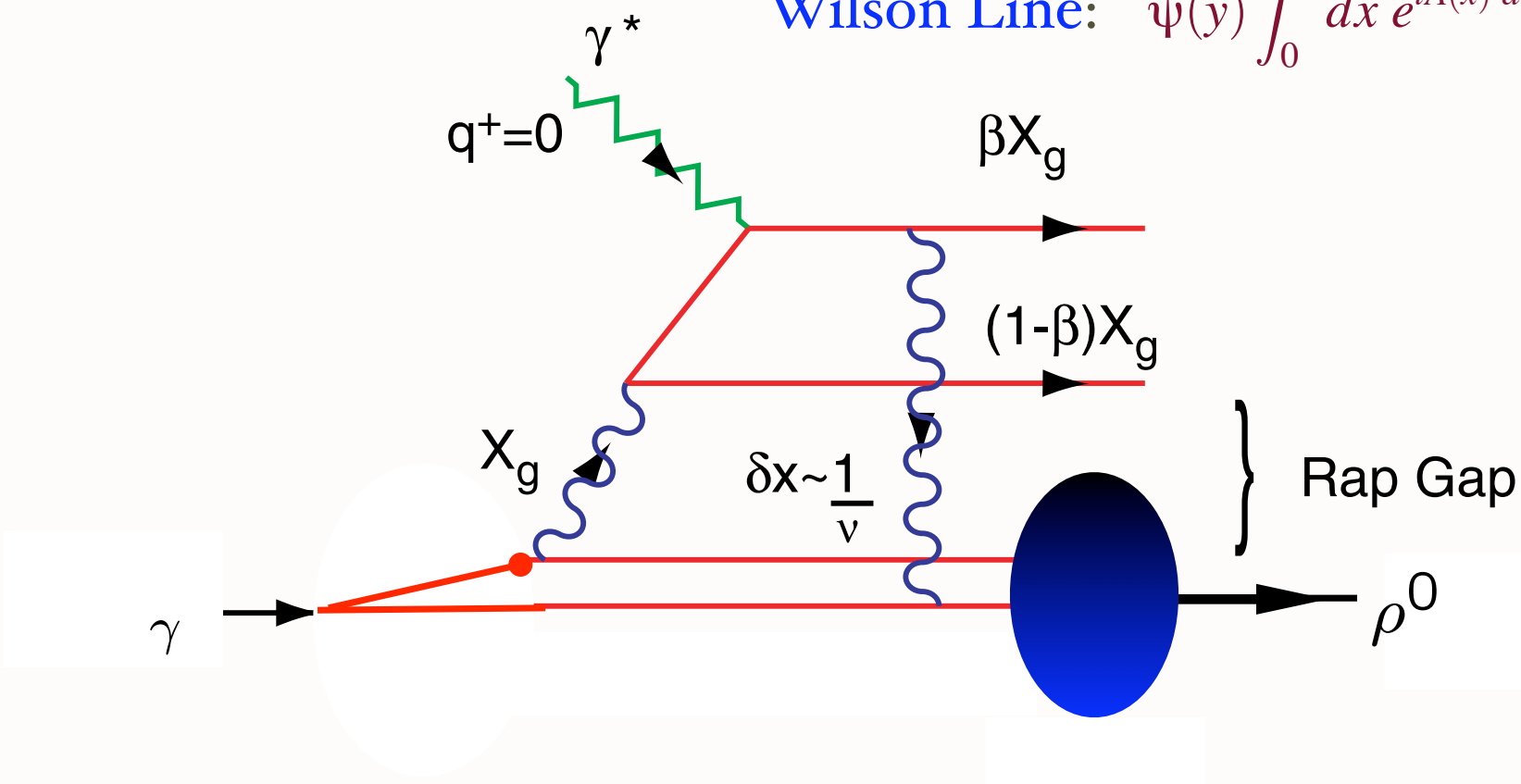
See also: Bartels et al

Kopeliovitch, Schmidt, sjb

Reproduces lab-frame color dipole approach

QCD Mechanism for Rapidity Gaps

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



Measure in $e\gamma \longrightarrow eX + \rho$

Diffractive Hadron-Hadron Hard Collisions

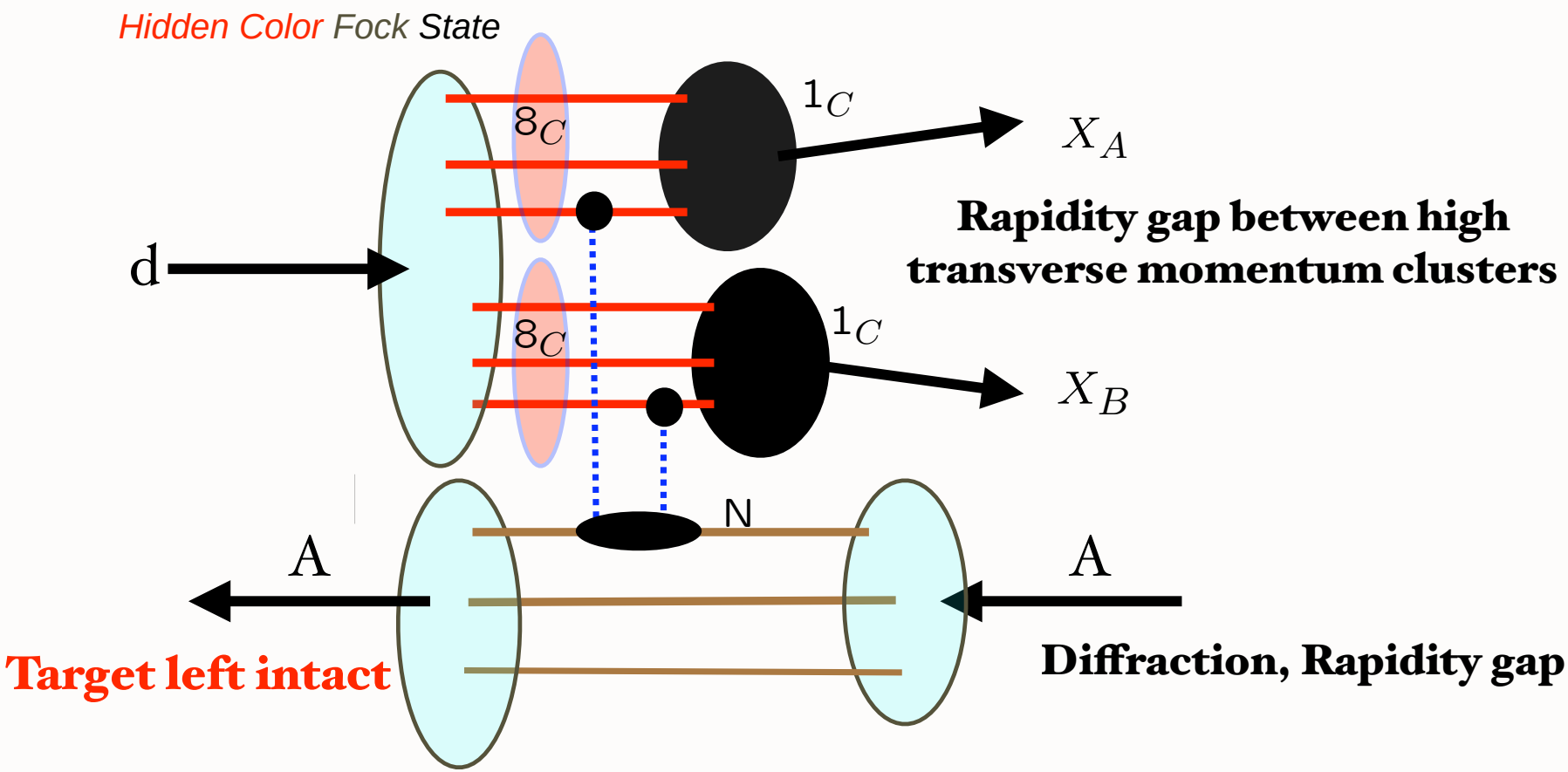
Bartels, Goulianis, Mueller, BFKL, Kovchegov, Maor, Khoze, Peigne, Gay Ducati Kopeliovitch, Schmidt, sjb

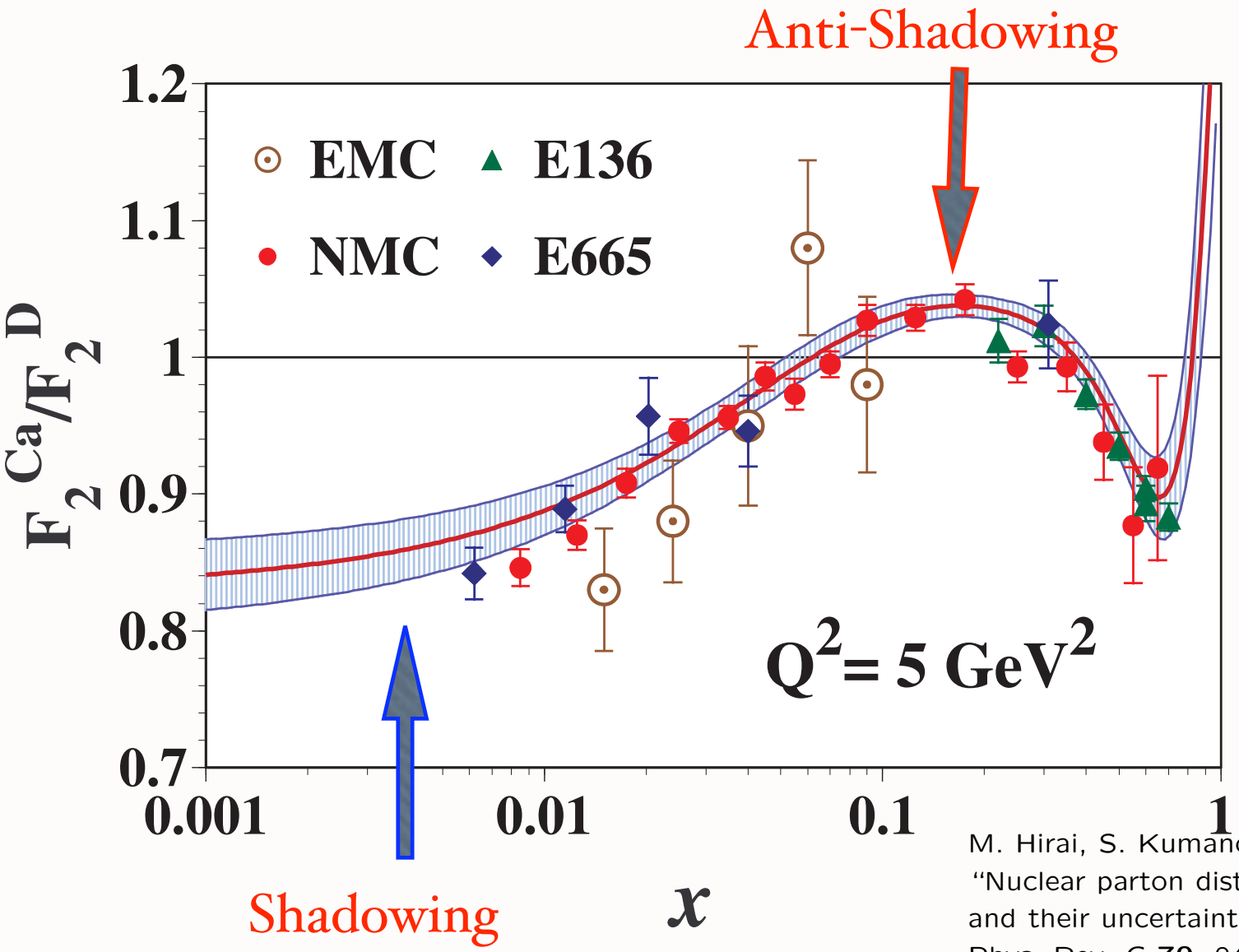
- Single diffractive + high P_T
- Double diffractive + high P_T
- Heavy quarks diffractive
- Lepton pair diffractive (Berman, Levy, Yan 1969)
- Nuclear dependence $\sigma(pA \to J/\psi X) \propto A^{2/3}$ at high x_F

Use Diffraction to Resolve Hadron Substructure

- Measure Light-Front Wavefunctions
- Test AdS/CFT predictions
- Novel Aspects of Hadron Wavefunctions: Intrinsic Charm, Hidden Color, Color Transparency/Opaqueness
- Diffractive Di-Jet, Tri-Jet Production
- Nuclear Shadowing and Antishadowing
- Novel QCD Mechanism for Higgs Production

Diffractive dissociation of color-octet deuteron to two high tranverse momentum clusters

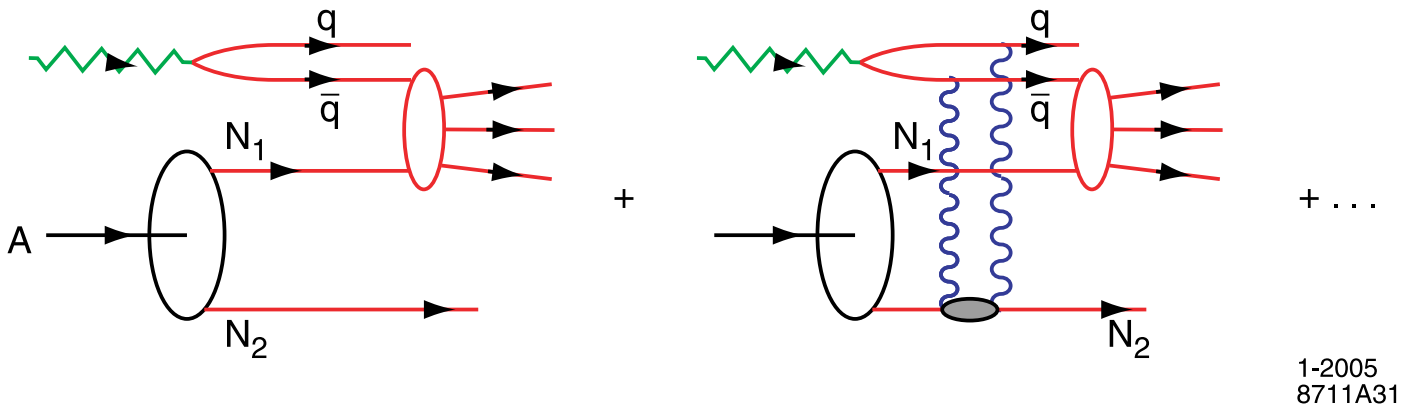




M. Hirai, S. Kumano and T. H. Nagai, "Nuclear parton distribution functions and their uncertainties," Phys. Rev. C **70**, 044905 (2004) [arXiv:hep-ph/0404093].

Stodolsky
Pumplin, sjb
Gribov

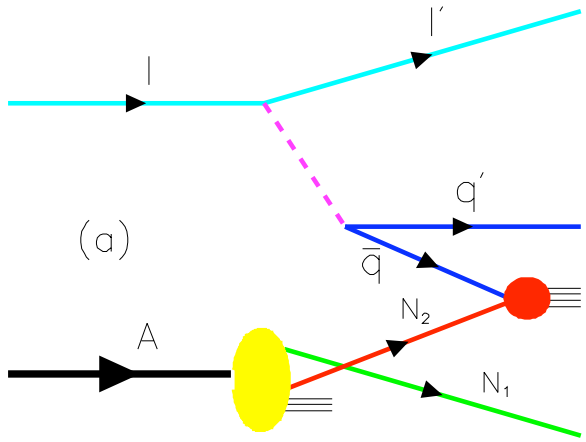
Nuclear Shadowing in QCD



Shadowing depends on understanding diffraction in DIS

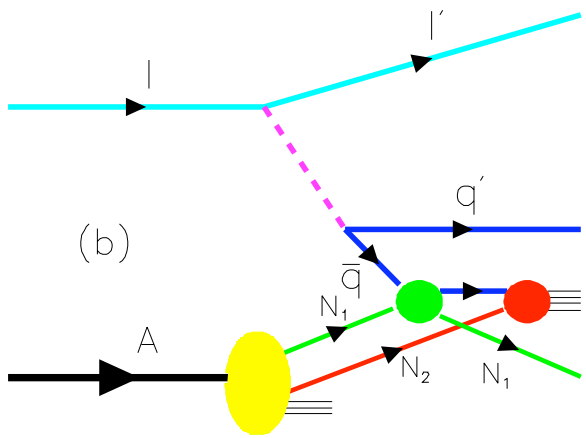
Nuclear Shadowing not included in nuclear LFWF !

Dynamical effect due to virtual photon interacting in nucleus



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

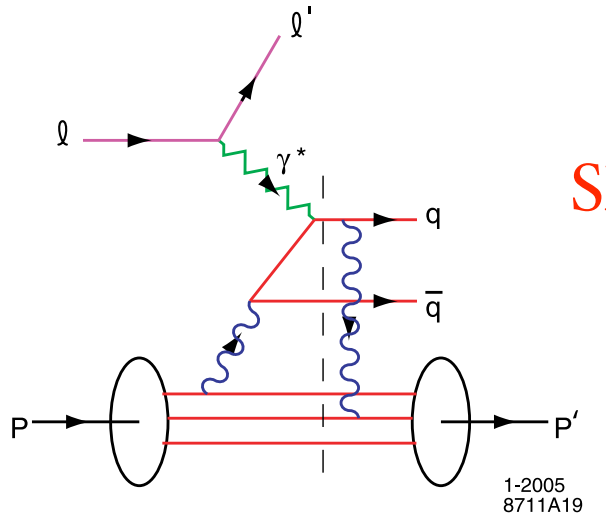
Coherence at small Bjorken x_B : $1/Mx_B = 2\nu/Q^2 \geq L_A$.



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



Shadowing depends on understanding diffraction in DIS

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

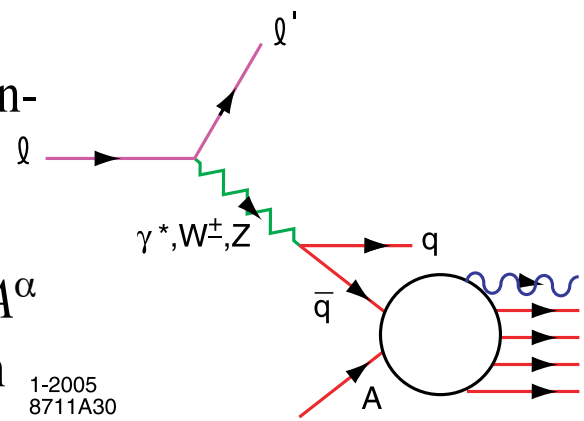
Origin of Nuclear Shadowing and Regge Behavior of Deep Inelastic Structure Functions

in light-cone gauge

Antiquark Interacts with Target Nucleus at Effective Energy $\hat{s} \propto 1/x_{Bj}$

$\sigma_{\bar{q}N} \sim \hat{s}^{\alpha_R - 1} \rightarrow F_{2N}(x_{bj}) \sim x^{1-\alpha_R}$ at small x_{bj}

Shadowing of antiquark-nucleus cross section $\sigma_{\bar{q}A} \sim A^{\alpha}$ produces same A dependence of nuclear structure function



Reggeon Exchange

Phase of two-step amplitude relative to one step:

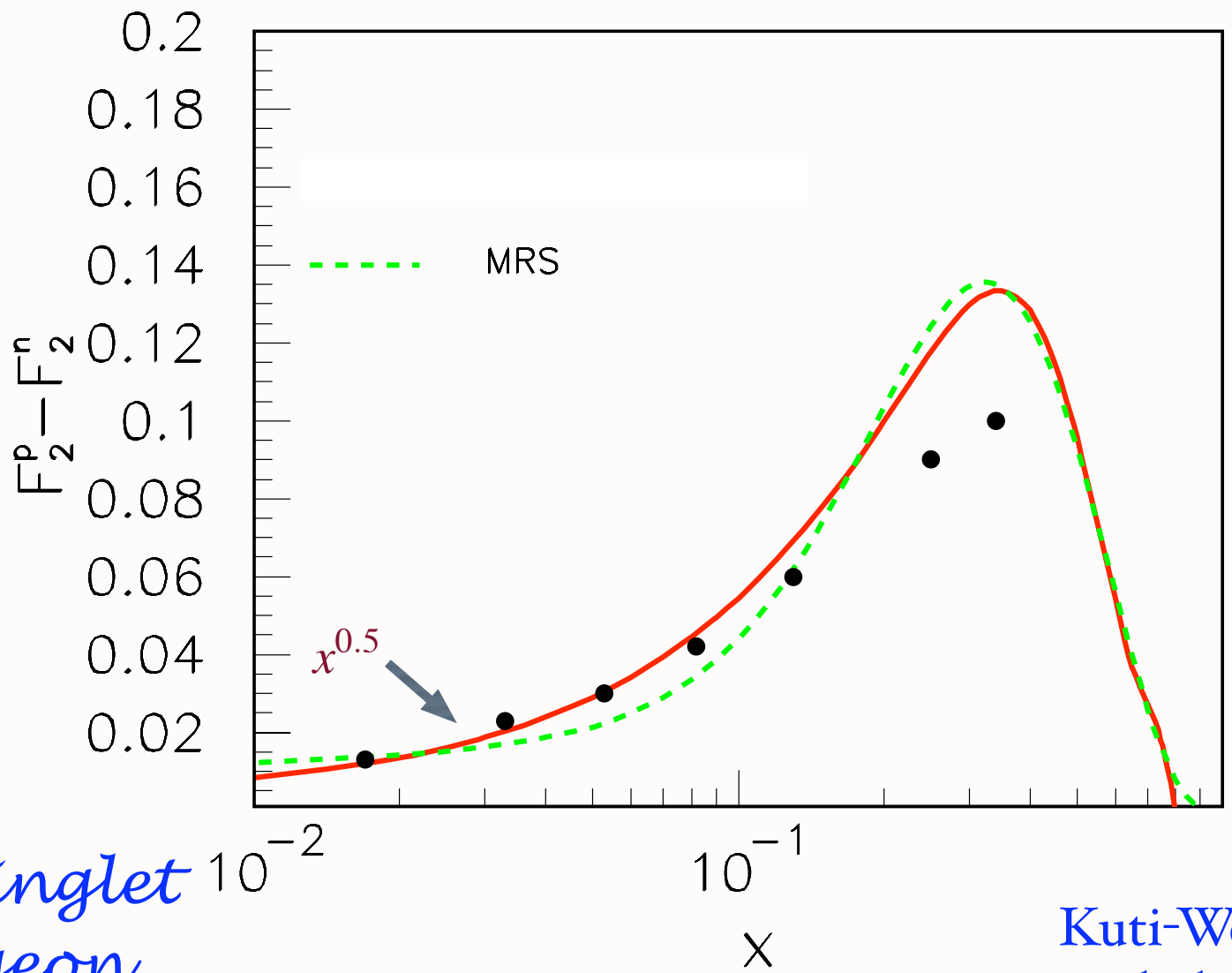
$$\frac{1}{\sqrt{2}}(1-i)\times i = \frac{1}{\sqrt{2}}(i+1)$$

Constructive Interference

Depends on quark flavor!

Thus antishadowing is not universal

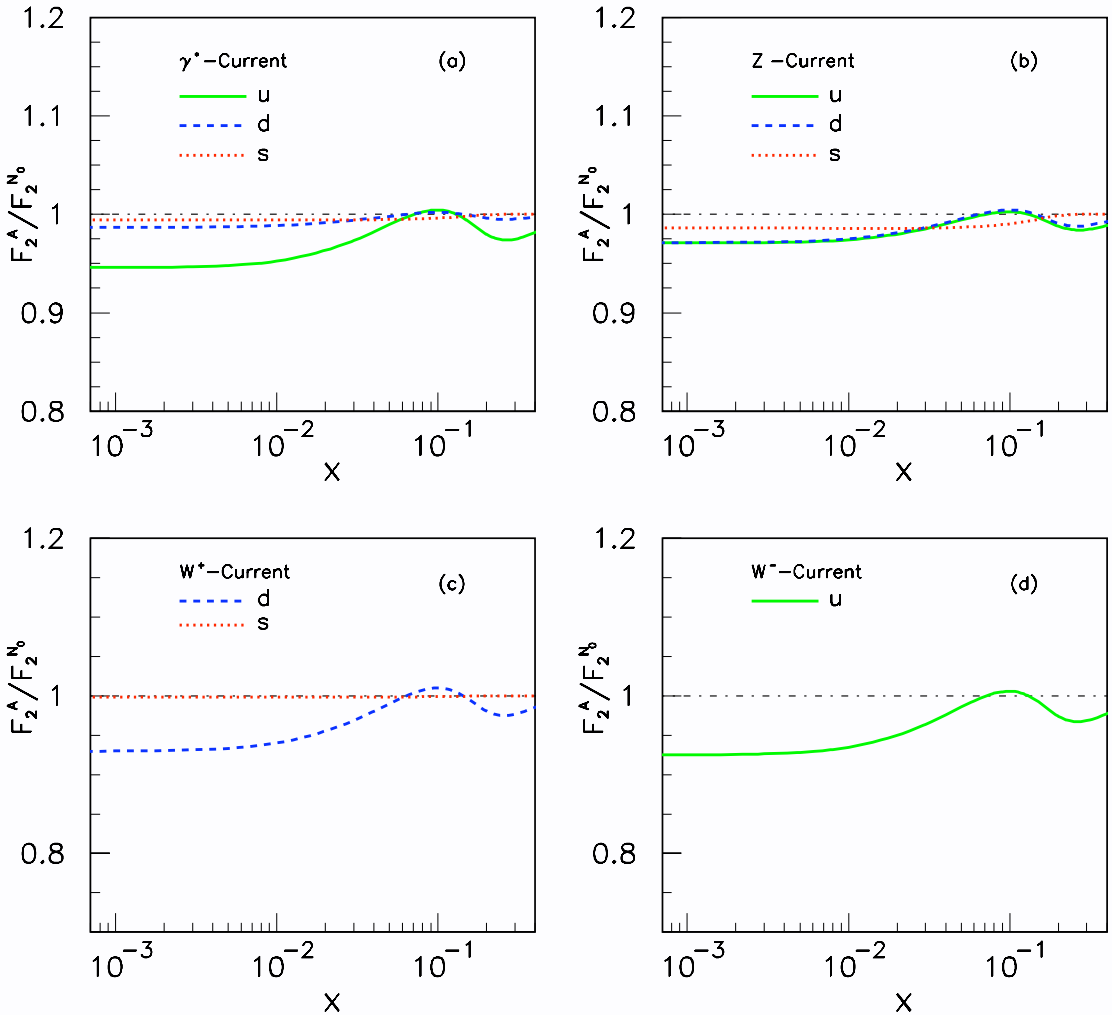
Different for couplings of $\gamma^*, Z^0, W^\pm$



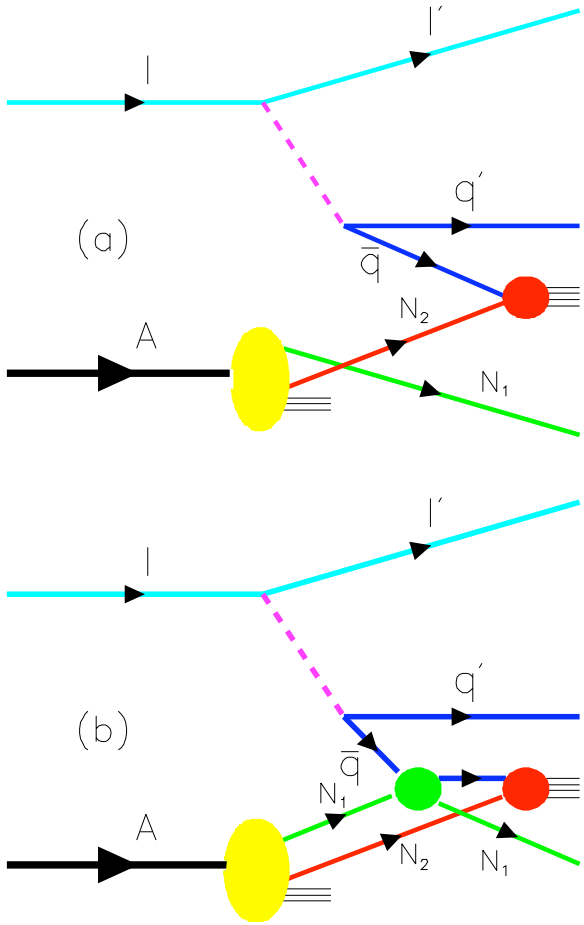
Non-singlet Reggeon Exchange

Kuti-Weisskopf behavior

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].

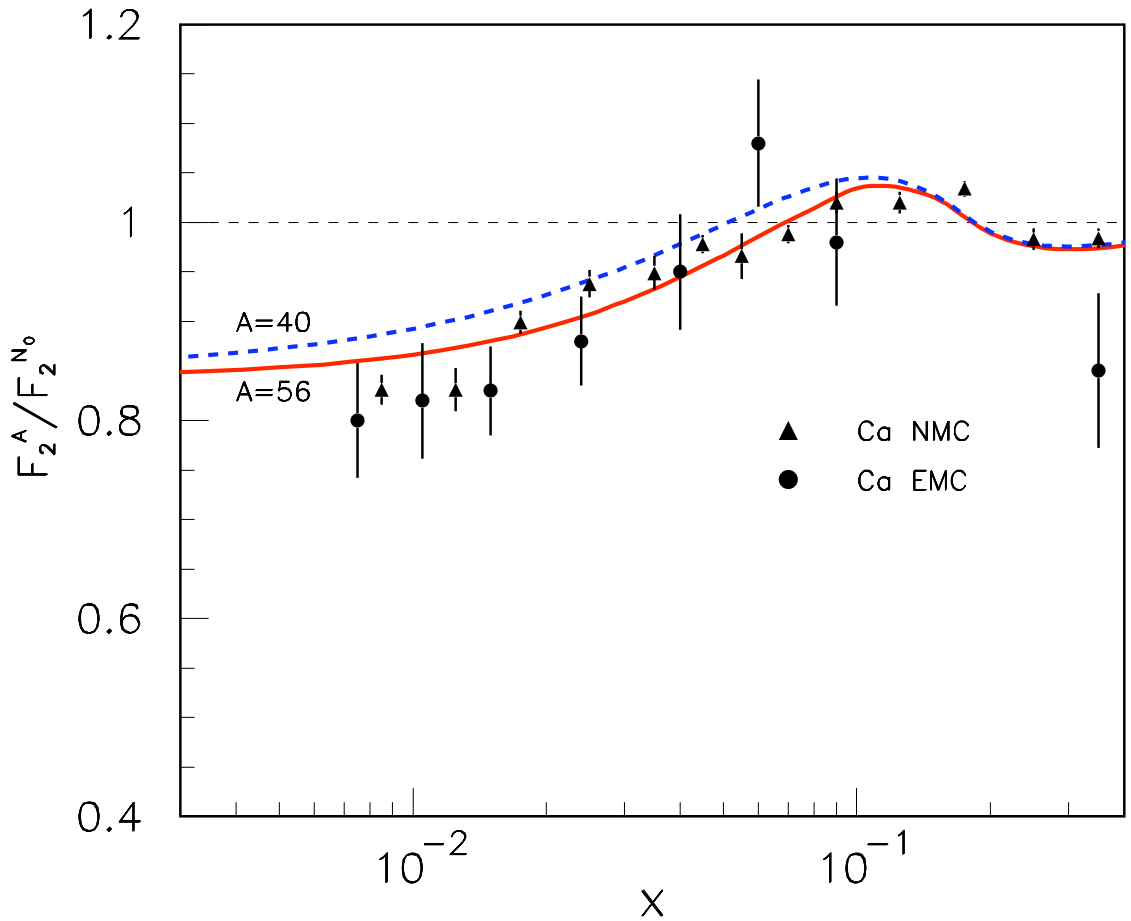


The one-step and two-step processes in DIS on a nucleus.

If the scattering on nucleon N_1 is via $C = -$ Reggeon or Odderon exchange, the one-step and two-step amplitudes are constructive in phase, enhancing the $\overline{q}$ flux reaching N_2

$\rightarrow$ Antishadowing of the DIS nuclear structure functions

H. J. Lu, sjb
Schmidt, Yang, sjb



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

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].