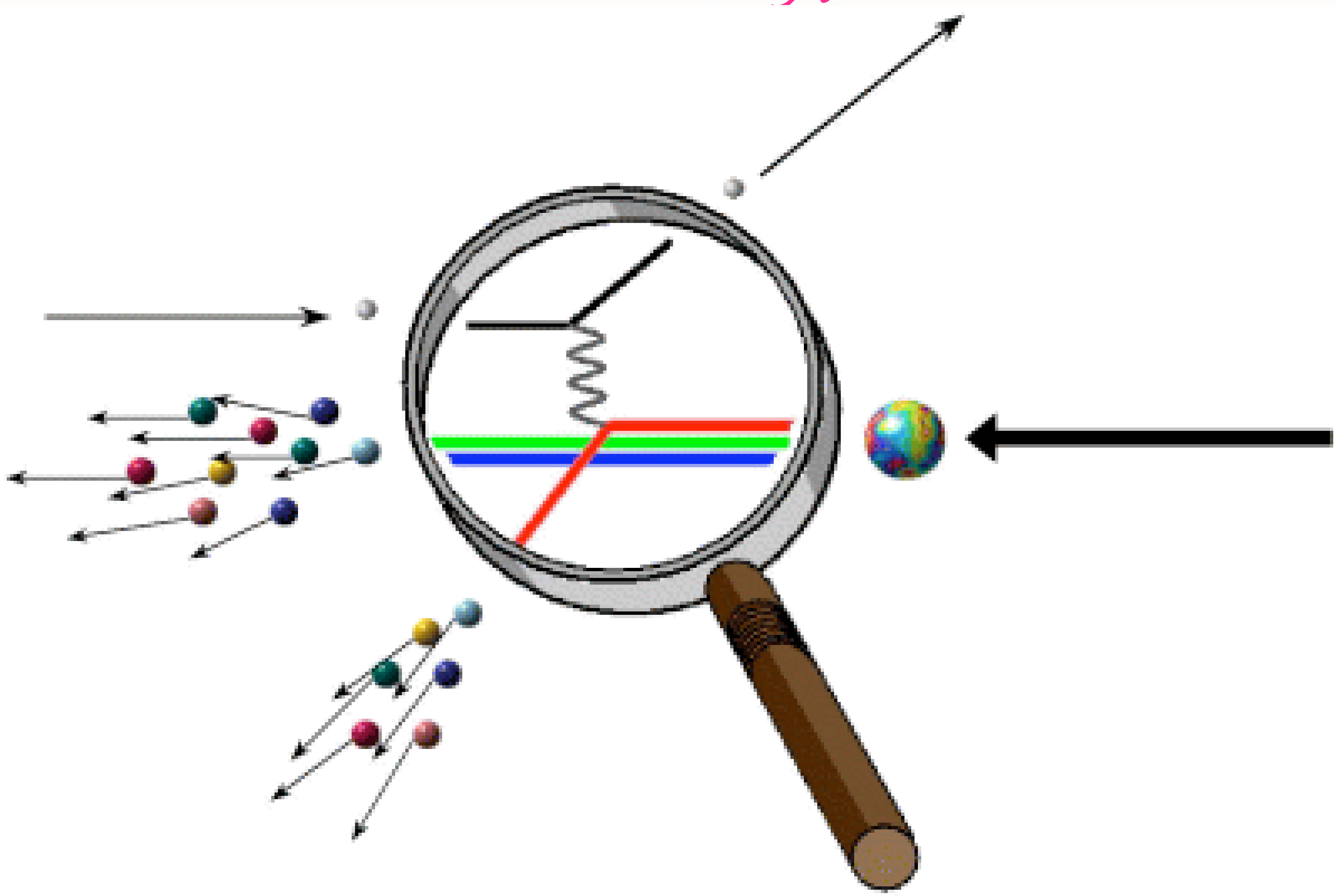
Novel QCD Phenomena at an Electron-Ion Collider

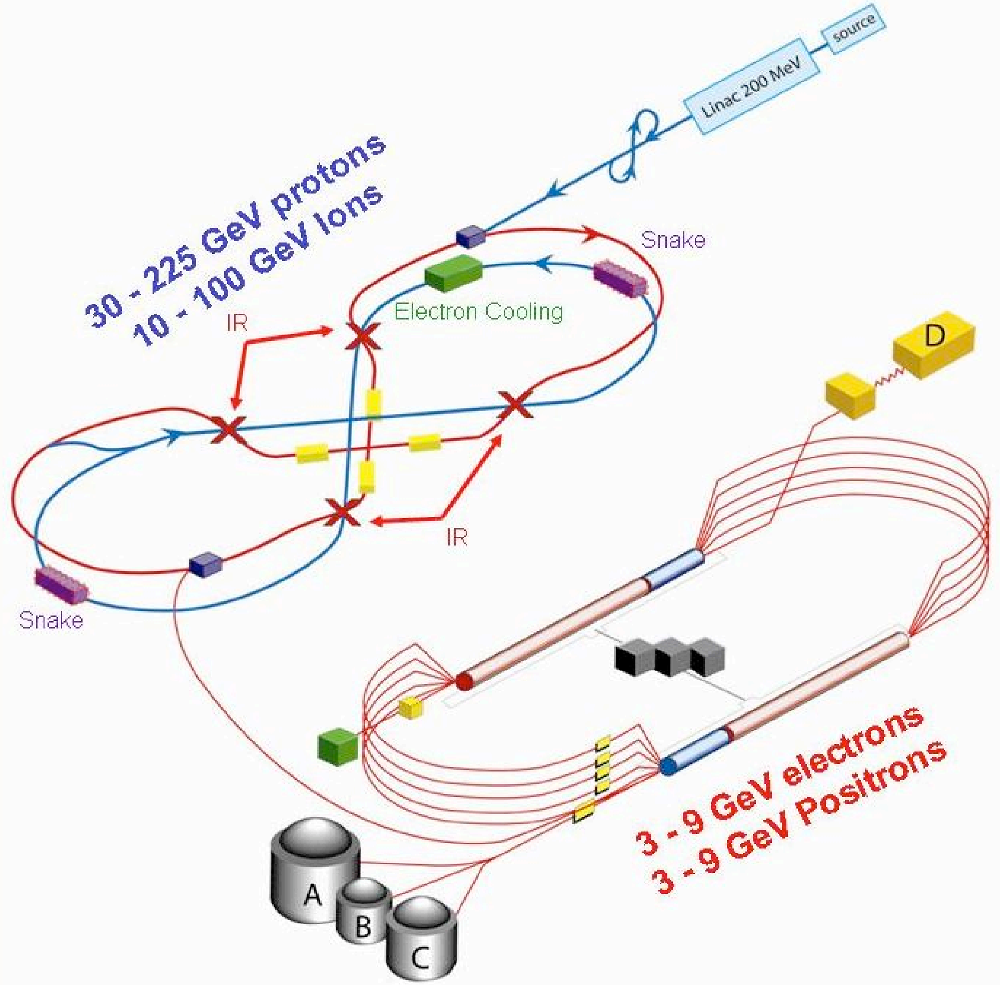
Stan Brodsky, SLAC

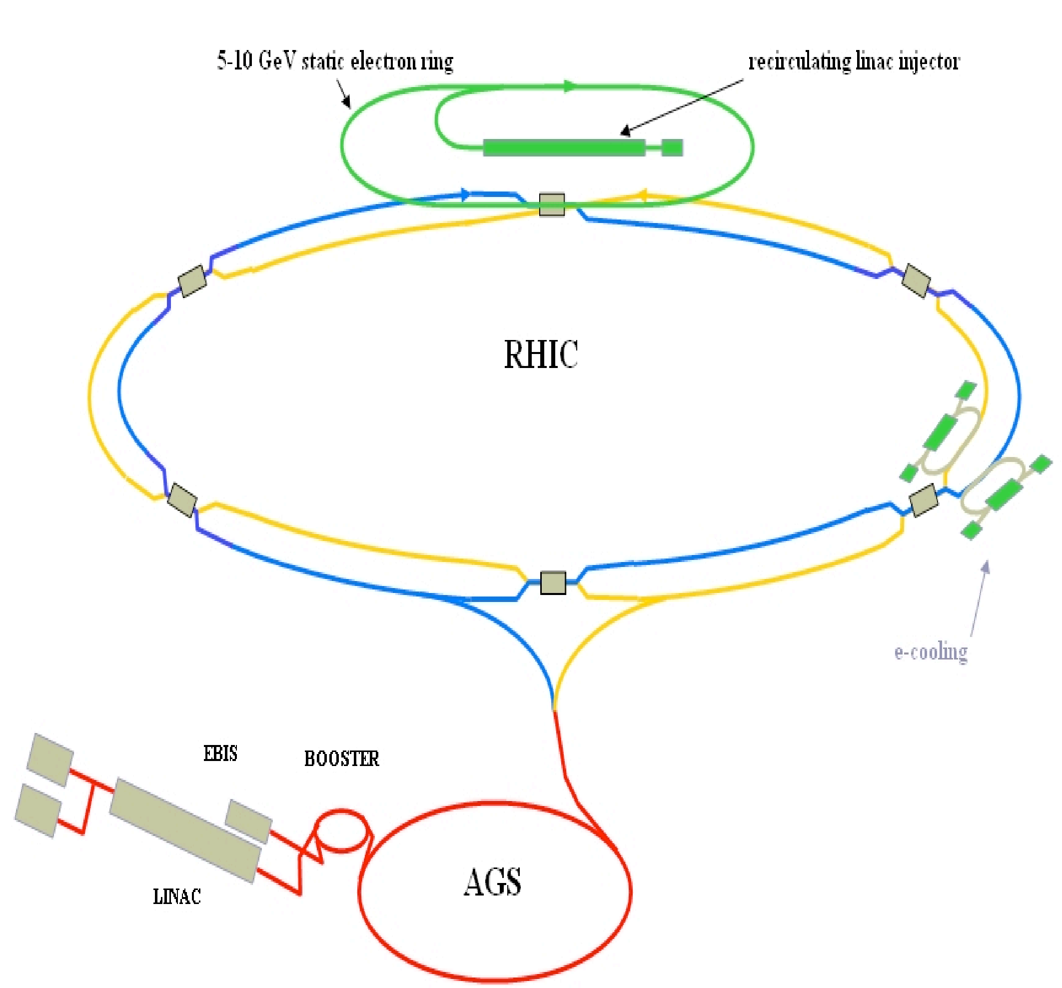


Novel QCD Phenomena at an Electron-Ion Collider

Stan Brodsky, SLAC

BNL November 29, 2007



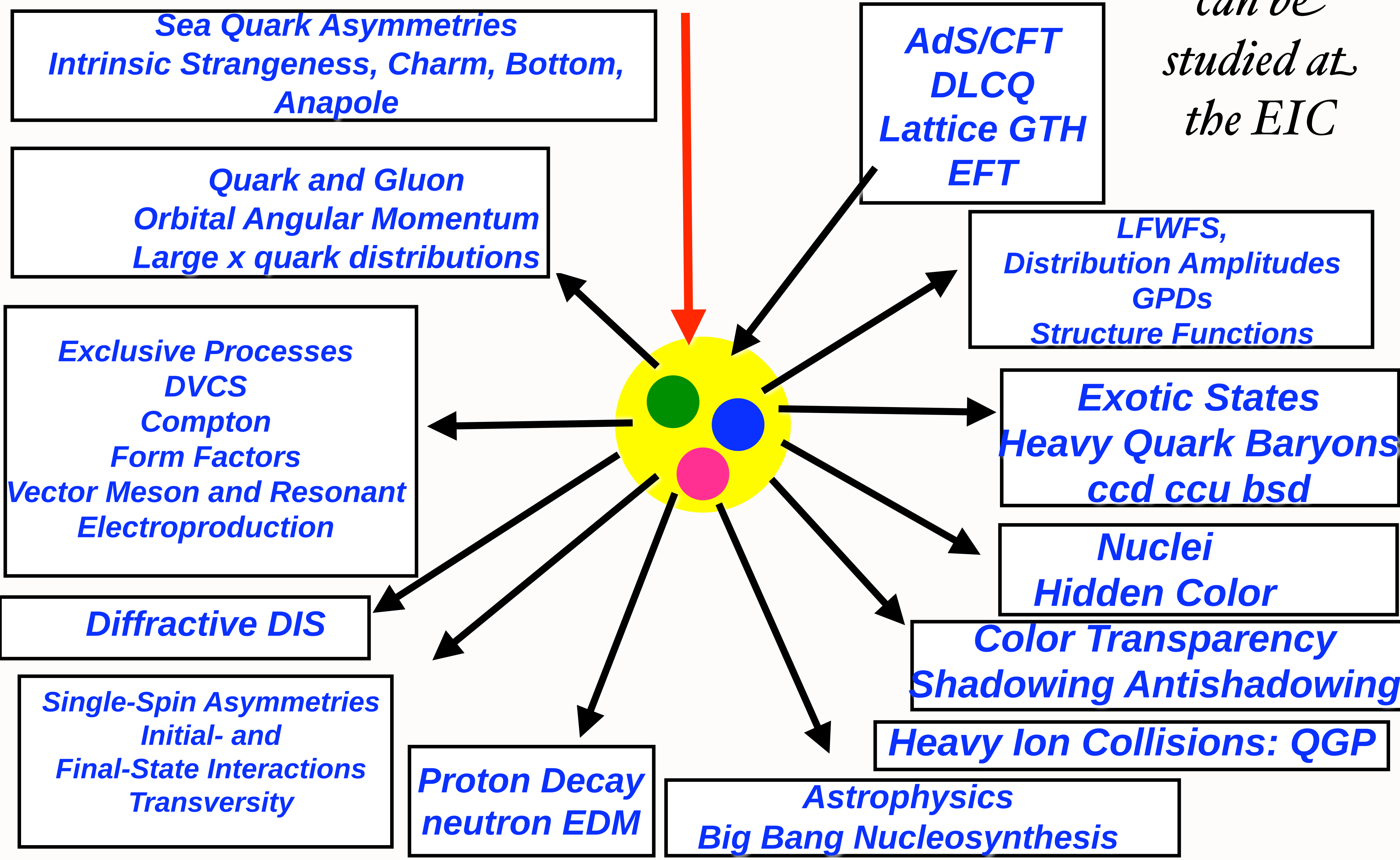


QCD: Central Topic of High Energy, Hadron, Nuclear Physics

- QCD: Fundamental Theory of Strong and Nuclear Interactions:
- Non-Abelian Yang-Mills gauge theory
- Quarks and Gluons: fundamental constituents of hadrons
- Central Probe: Lepton-Nucleon, Lepton-Nucleus Scattering
- Novel QCD phenomena
- Spin !
- Key Issue: structure of hadrons at the ***amplitude level***
- Light-Front Wavefunctions
- New theoretical methods: AdS/CFT

QCD Lagrangian

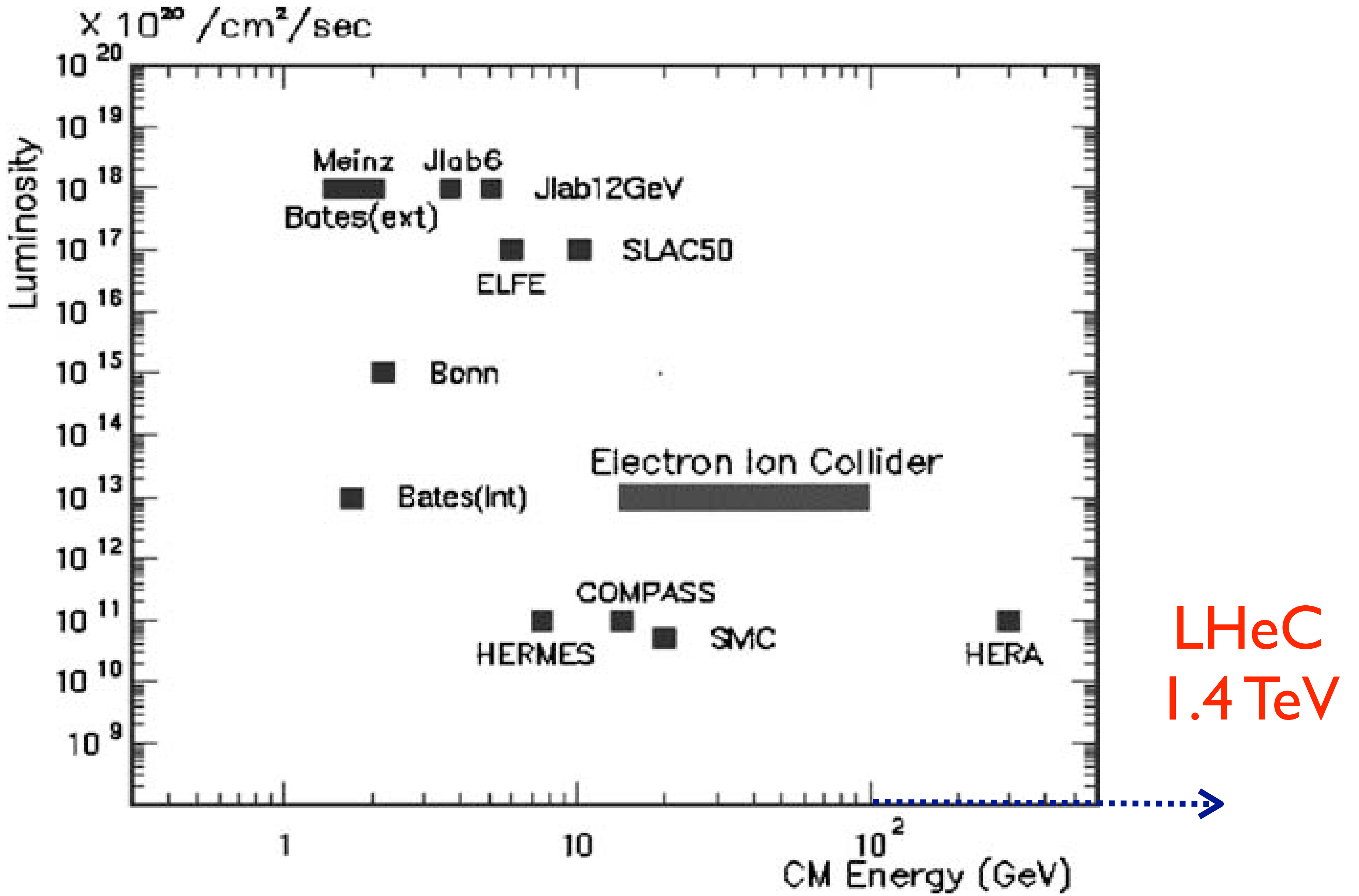
Most topics can be studied at the EIC



Annu. Rev. Nucl. Part. Sci. 2005. 55:165–228

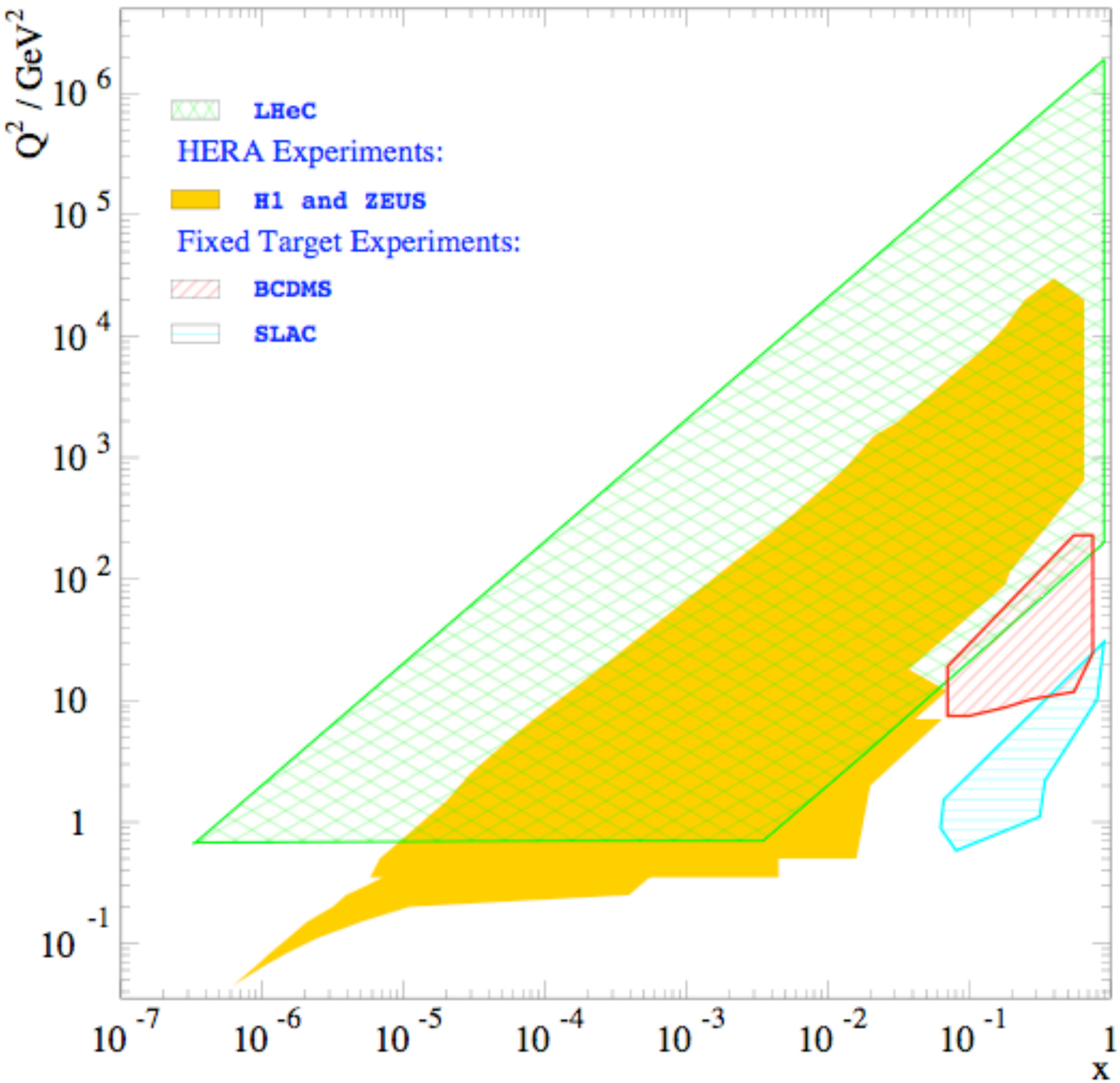
Study of the Fundamental Structure of Matter with an Electron-Ion Collider

Abhay Deshpande,[1] Richard Milner,[2] Raju Venugopalan,[3]
and Werner Vogelsang[4]



The center-of-mass energy vs. luminosity of the proposed Electron-Ion Collider eRHIC compared to other lepton scattering facilities.

Kinematic coverage of lepton proton scattering experiments



$s = 4E_eE_p$

$LHeC: 70 \cdot 7000 \rightarrow 2 \cdot 10^6 GeV^2$

$HERA: 27.6 \cdot 920 \rightarrow 10^5 GeV^2$

$s = 2M_pE_l$

$BCDMS: 280 \rightarrow 500 GeV^2$

$SLAC: 20 \rightarrow 40 GeV^2$

$Q^2 = sxy$

$x = \frac{Q^2}{sy}$

$Bjorken - x \leq 1$

$inelasticity - y \leq 1$

$Q^2 \leq s$

Asymmetric Electron-Ion Collider

- Collide High-Luminosity Low-Energy 2 GeV Electrons with 200 GeV Polarized protons and Ions at RHIC
- Highly Asymmetric Collisions
- Access high x domain: valence quarks, strong spin and quantum number correlations
- Fixed Target Kinematics: Forward Proton Fragmentation

$$s = 400 \text{ GeV}^2, \sqrt{s} = 20 \text{ GeV}$$

$$Q^2 > 2\ GeV^2 \qquad 0.005 < x = \frac{Q^2}{2p \cdot q} < 1$$

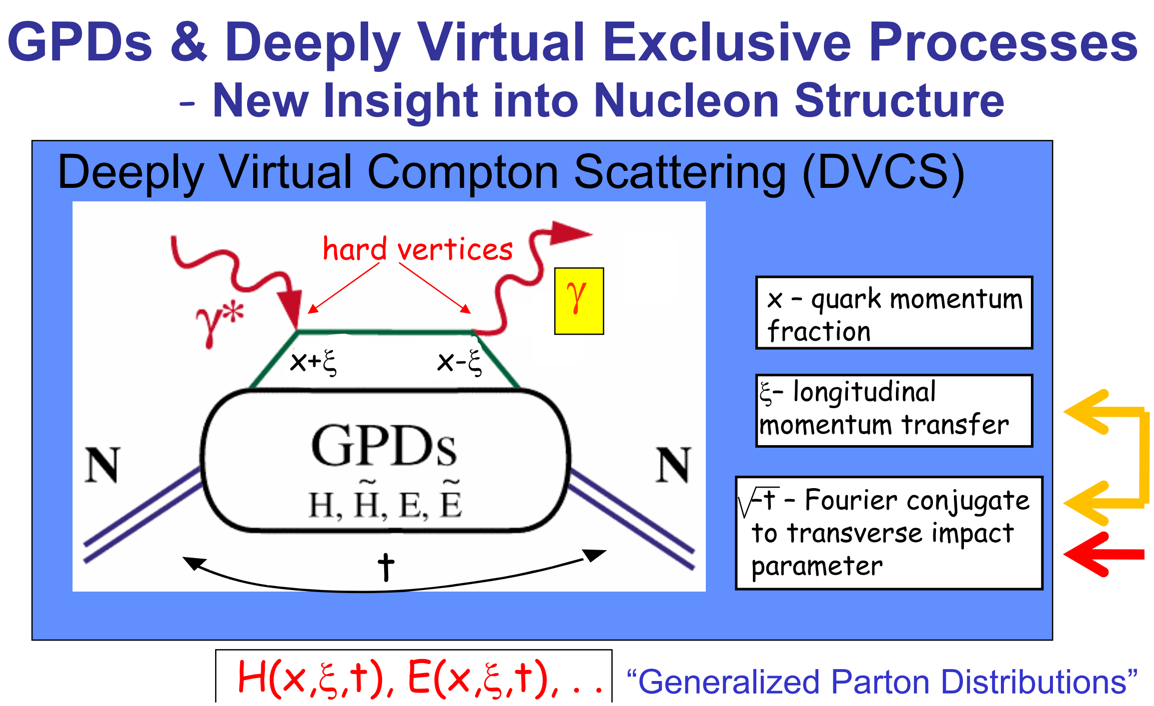
Linac-Ring Design

Based on superconducting energy recovery electron linac (ERL).
Electron beam is used for collisions just once. No beam-beam limitation for electron beam.
Multiple interaction points are possible.
Electron polarization is achievable in the whole energy range, including longitudinal polarization.
IR design has less restrictions that in ring-ring design.
Considerably higher luminosity than in the ring-ring design may be achieved.
Small storage ring can be added for positron storage.
Considerable R&D for polarized electron source is needed.

BNL High Energy Nuclear Physics PAC Report
March 23-24, 2006

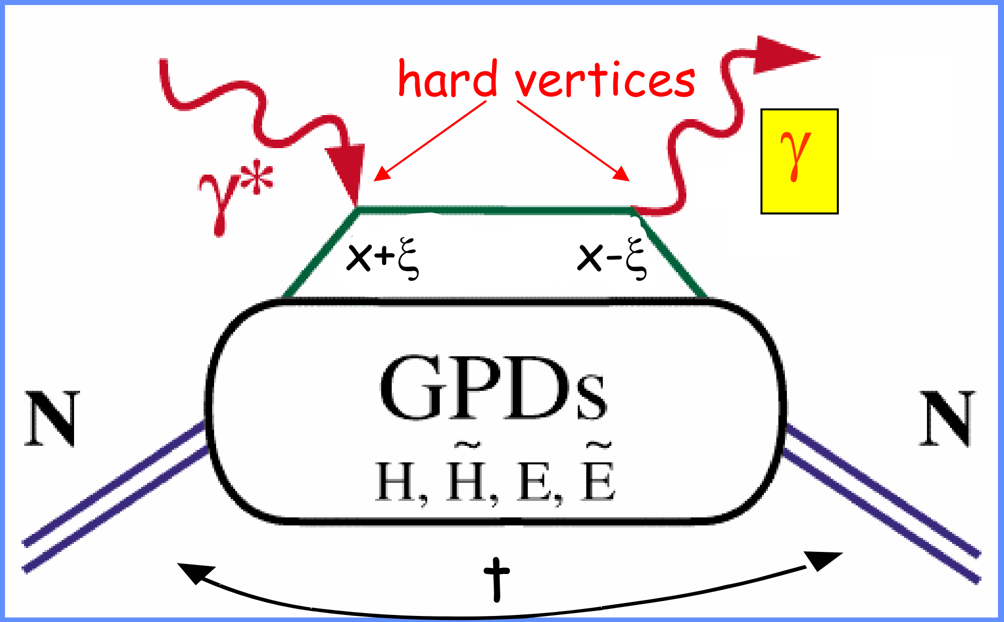
DVCS

Deeply virtual Compton scattering $\gamma^*(q)p \to \gamma(k)p'$ provides a remarkable way to study the fundamental structure of the proton at the amplitude level. When the incoming photon is highly virtual $Q^2 = -q^2 >> \Lambda^2_{QCD}$, the underlying scattering process measures Compton scattering on bound quarks, convoluted with the fundamental microscopic wavefunctions of the initial and final state proton. In addition, the photons can scatter and annihilate virtual quarks pairs in the initial state, thus probing quantum fluctuations of hadron wavefunctions predicted by relativistic quantum field theory. Thus DVCS provides direct and unique information on the proton's light-front wavefunctions.



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

Deeply Virtual Compton Scattering (DVCS)



x – quark momentum fraction

ξ– longitudinal momentum transfer

√-t – Fourier conjugate to transverse impact parameter

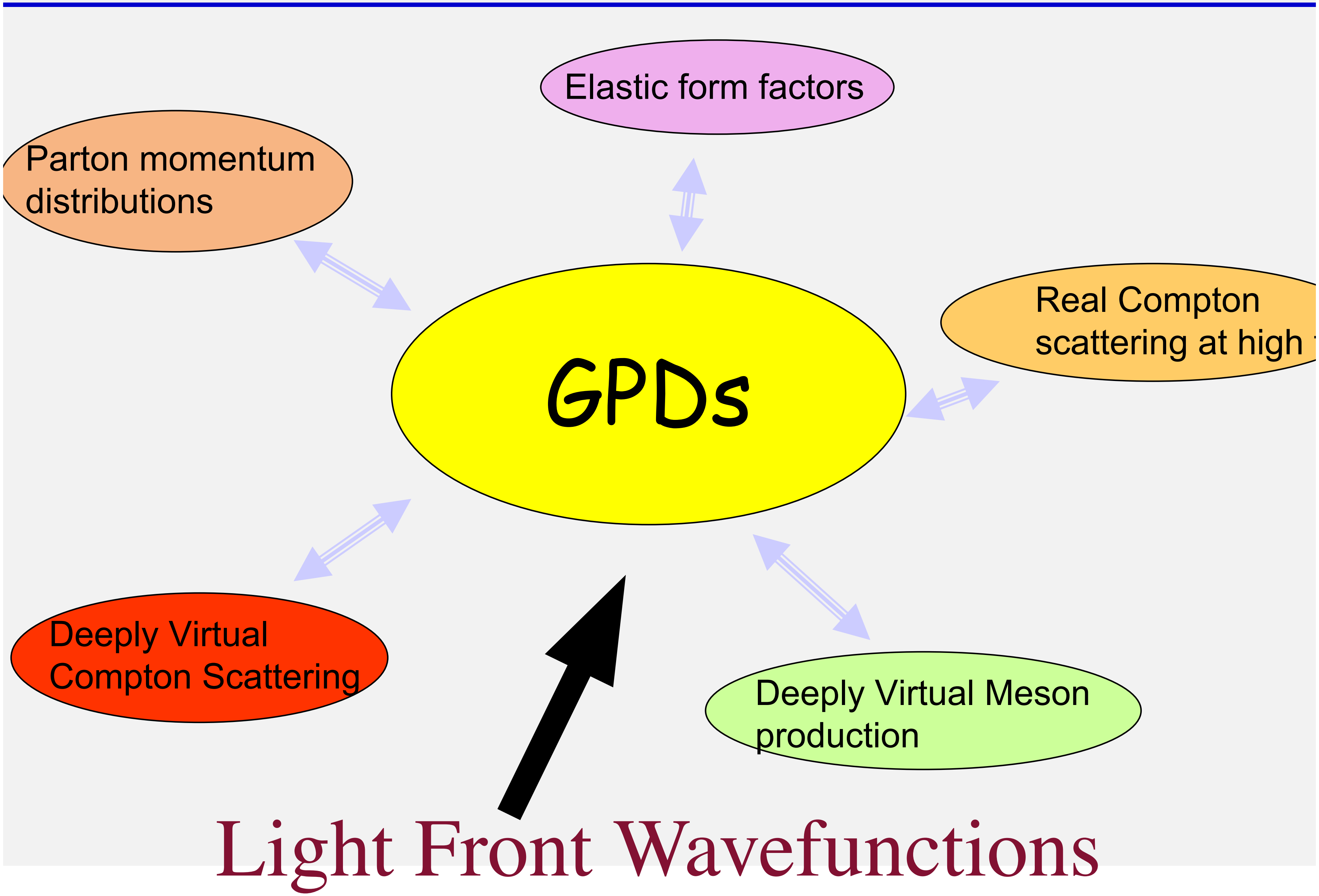
H(x,ξ,t), E(x,ξ,t), . . . "Generalized Parton Distributions"

Quark angular momentum (Ji 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)

A Unified Description of Hadron Structure

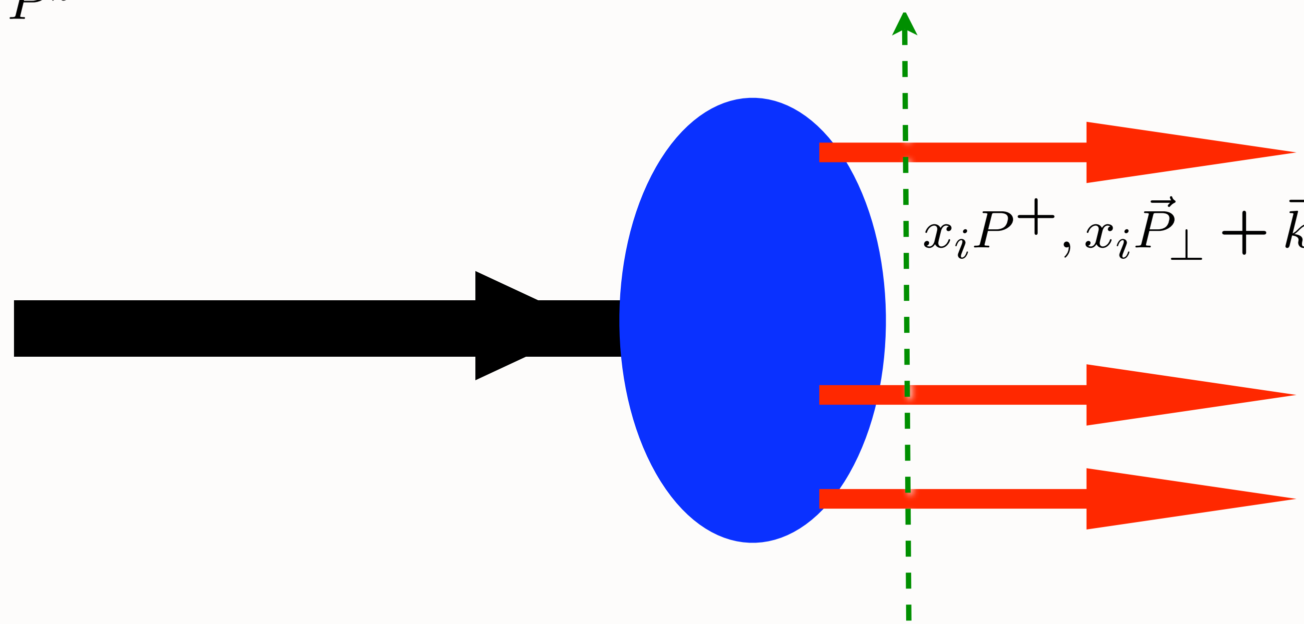


Light-Front Wavefunctions
Fundamental Representation of Hadron Dynamics

Fixed $\tau = t + z/c$

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

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



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

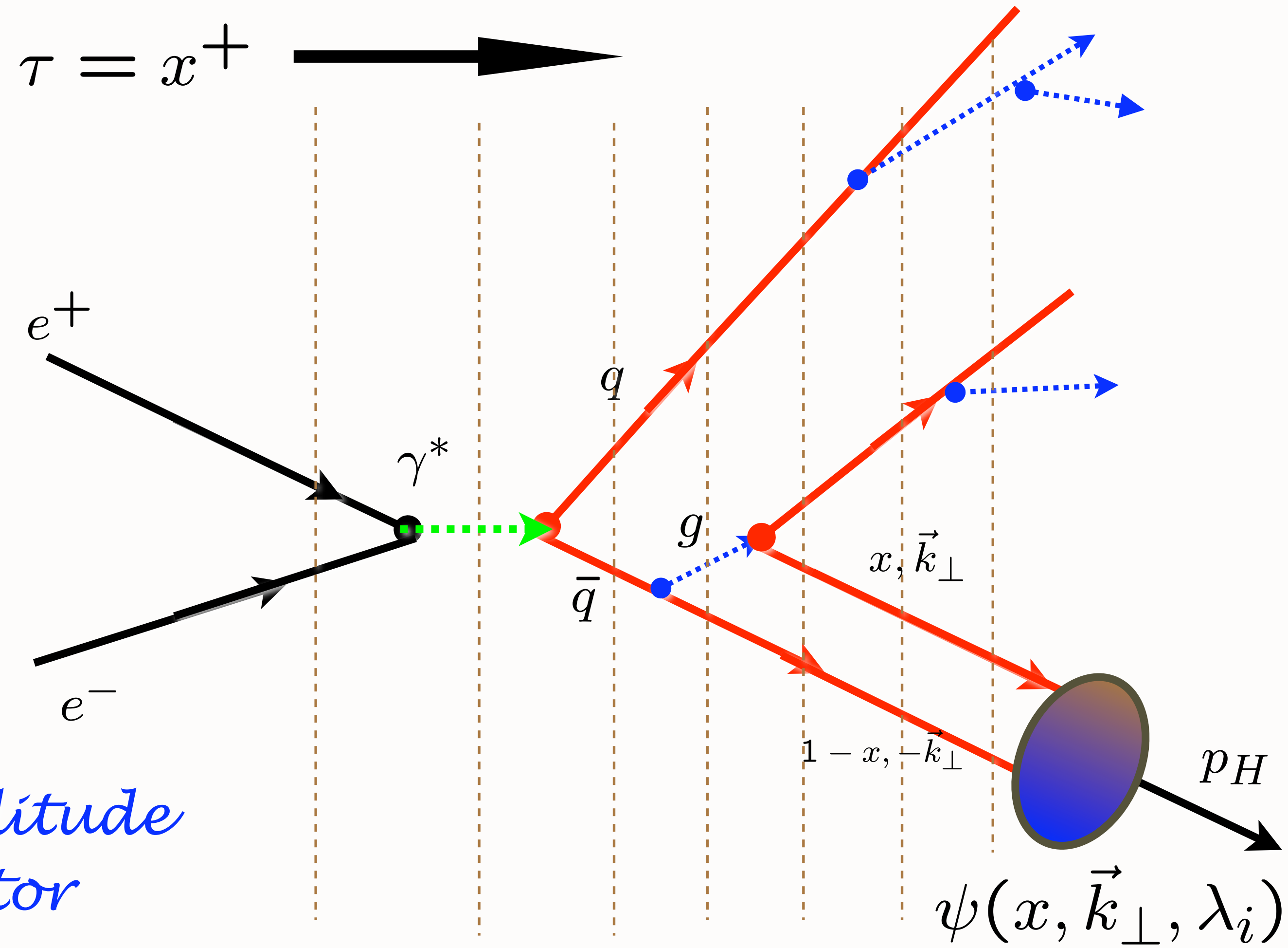
$$\Psi_n(x_i, \vec{k}_{\perp i}, \lambda_i)$$

$\sum_i^n x_i = 1$

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

Invariant under boosts! Independent of P^μ

Hadronization at the Amplitude Level



Relativistic Anti-hydrogen production

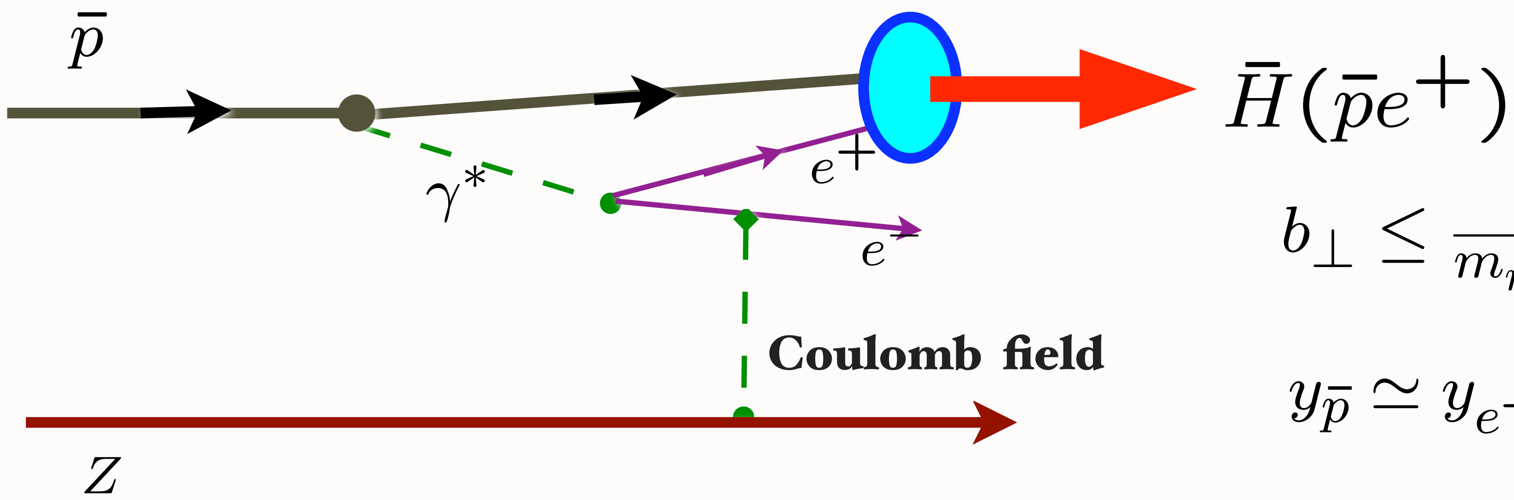
Event amplitude generator

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

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

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

Gluon orbital angular momentum defined in physical lc gauge

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

n-1 orbital angular momenta

Nonzero Anomalous Moment -->
Nonzero orbital angular momentum

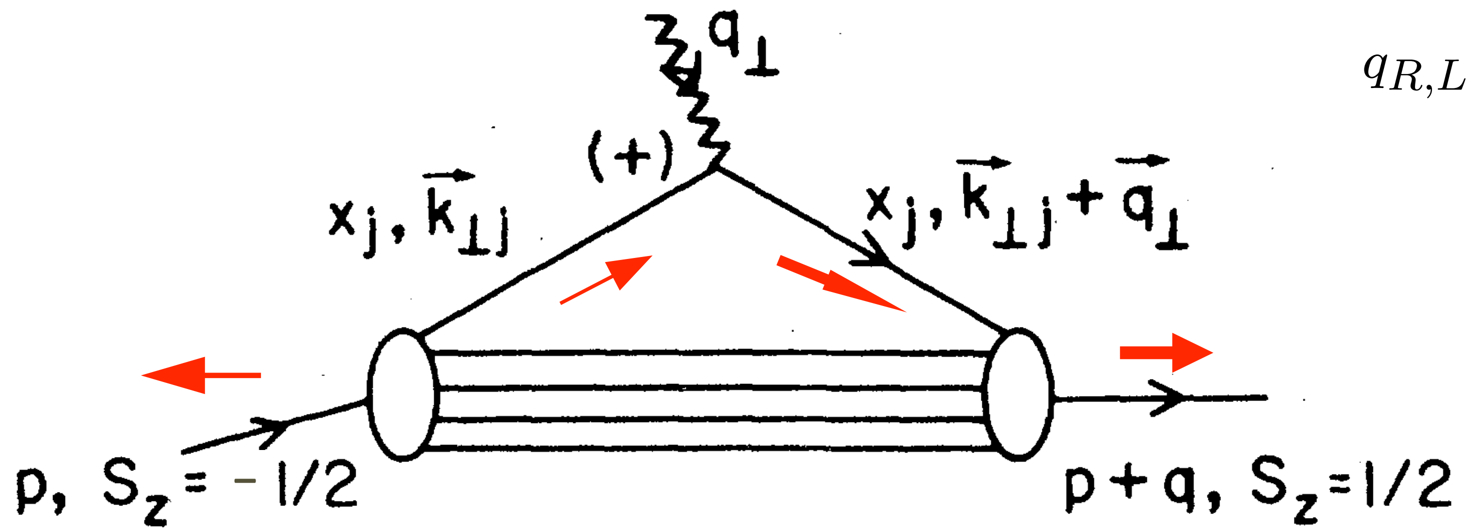
Drell, sjb

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

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

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

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



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

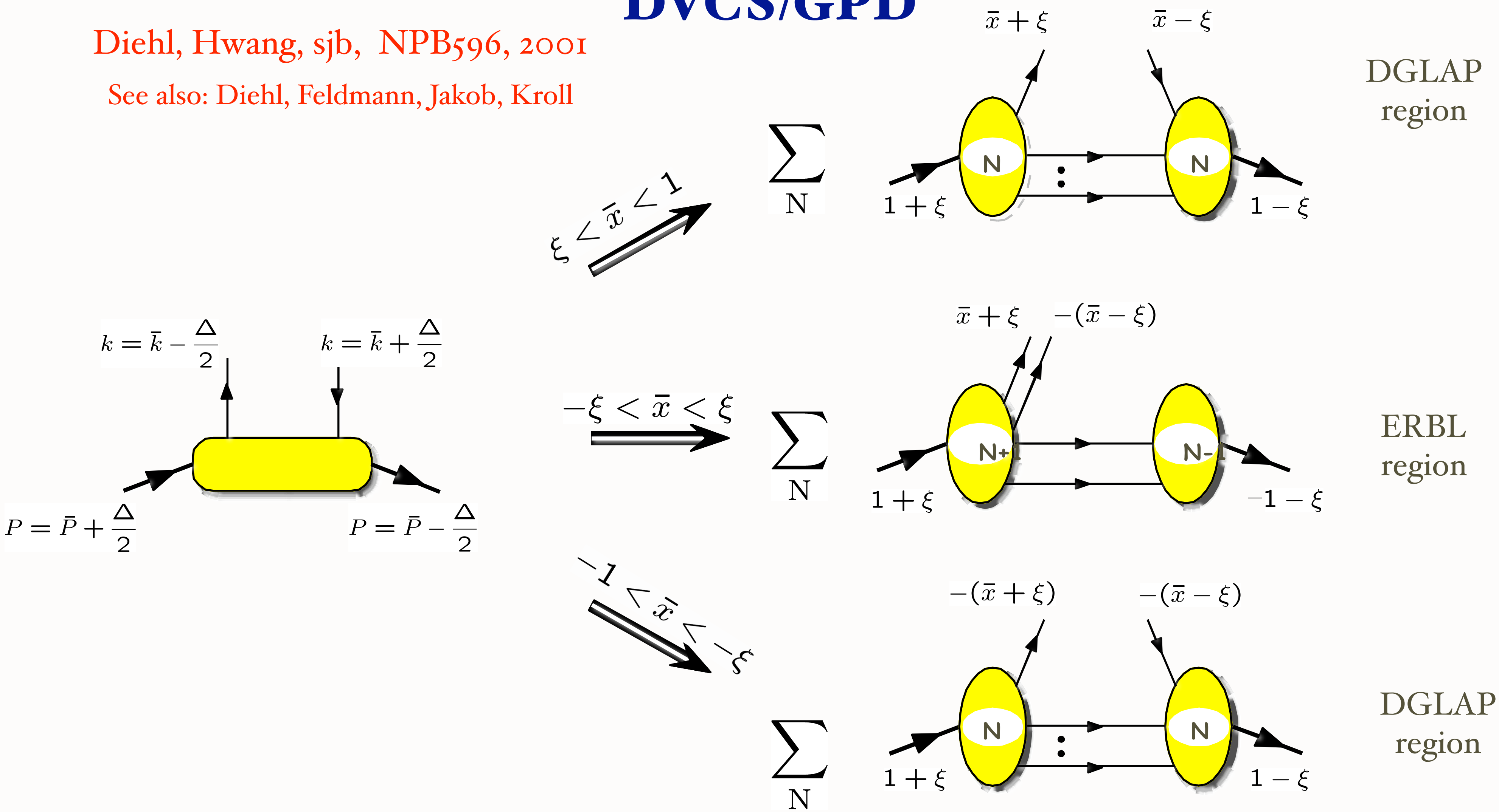
Same matrix elements appear in Sivers effect
-- connection to quark anomalous moments

Light-Front Wave Function Overlap Representation

DVCS/GPD

Diehl, Hwang, sjb, NPB596, 2001

See also: Diehl, Feldmann, Jakob, Kroll



N=3 VALENCE QUARK ⇒ Light-cone Constituent quark model

N=5 VALENCE QUARK + QUARK SEA ⇒ Meson-Cloud model

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

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

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

Example of LFWF representation of GPDs (n+1 => n-1)

Diehl,Hwang, sjb

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

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

$$\times 16\pi^3 \delta(x_{n+1}+x_1-\zeta)\delta^{(2)}(\vec{k}_{\perp n+1}+\vec{k}_{\perp 1}-\vec{\Delta}_\perp)$$

$$\times \delta(x-x_1)\psi^{\uparrow *}_{(n-1)}(x'_i,\vec{k}'_{\perp i},\lambda_i)\psi^{\downarrow}_{(n+1)}(x_i,\vec{k}_{\perp i},\lambda_i)\delta_{\lambda_1 -\lambda_{n+1}},$$

where $i = 2, \ldots, n$ label the $n-1$ spectator partons which appear in the final-state hadron wavefunction with

$$x'_i = \frac{x_i}{1-\zeta}, \qquad \vec{k}'_{\perp i} = \vec{k}_{\perp i} + \frac{x_i}{1-\zeta}\vec{\Delta}_\perp.$$

Link to DIS and Elastic Form Factors

DIS at $\xi = t = 0$

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

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

Form factors (sum rules)

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

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

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

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

Verified using LFWFs

Diehl, Hwang, sjb

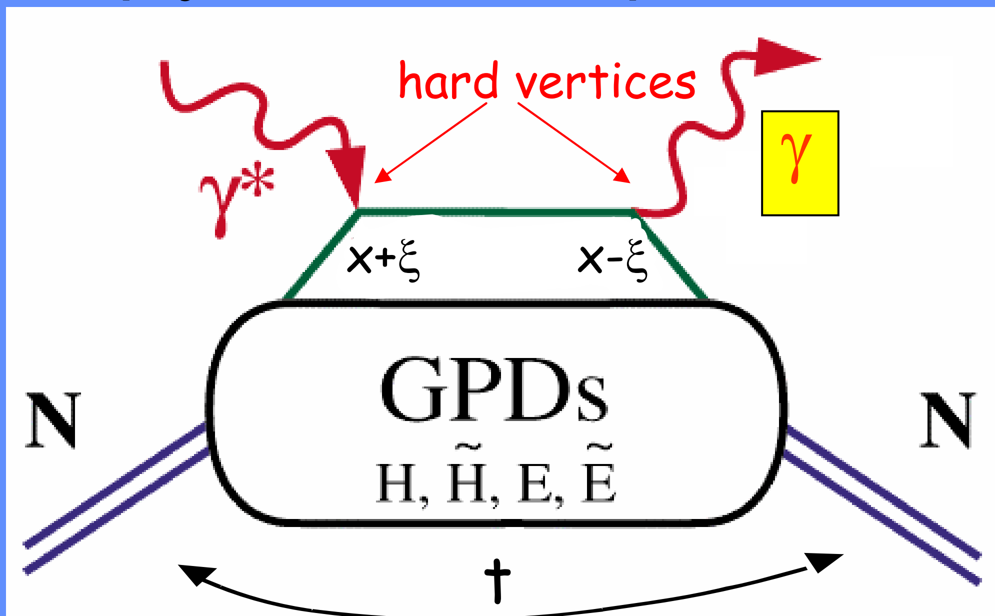
Quark angular momentum (Ji's sum rule)

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

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

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

$H(x,\xi,t), E(x,\xi,t), \ldots$ "Generalized Parton Distributions"

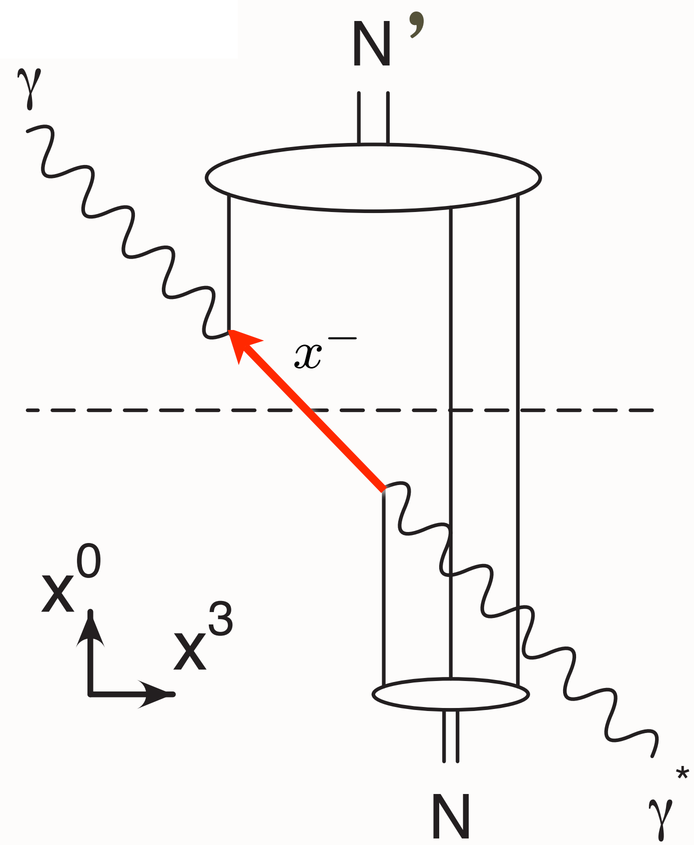
Corrections to Handbag approximation -- not gauge invariant!
Wilson line: SSA and Diffractive in DIS
Cat's ears
Real Compton: PQCD not handbag

Spatial Structure of DVCS

The Fourier transform of the DVCS amplitude with respect to the momentum transfer and the skewness parameter can provide a three-dimensional spatial picture of the proton at fixed light-front time. Measurements of the DVCS cross sections with specific proton and photon polarizations can thus provide comprehensive probes of the spin as well as spatial structure of the proton at the most fundamental level of QCD.

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:
Take Fourier transform of skewness, $\xi = \frac{Q^2}{2p.q}$
the longitudinal momentum transfer

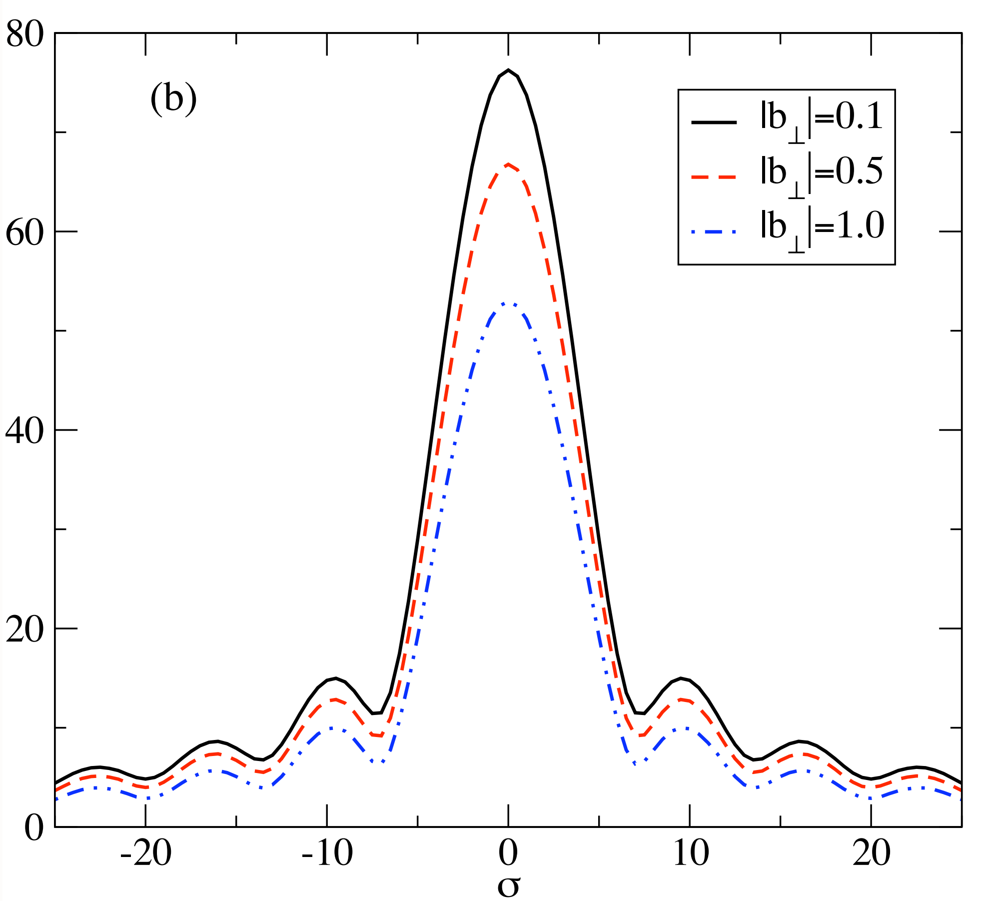
S. J. Brodsky[a], D. Chakrabarti[b], A. Harindranath[c], A. Mukherjee[d], J. P. Vary[e,a,f]

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

Hadron Optics

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

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

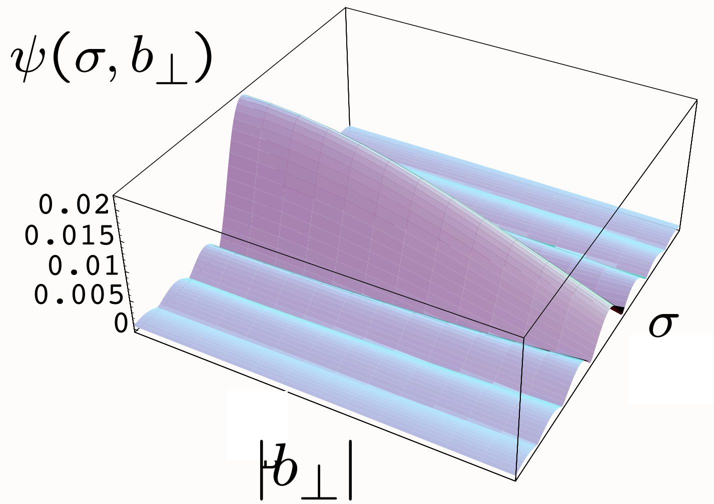


The Fourier Spectrum of the DVCS amplitude in σ space for different fixed values of $|b_\perp|$.

GeV units

DVCS Amplitude using holographic QCD meson LFWF

$$\Lambda_{QCD} = 0.32$$

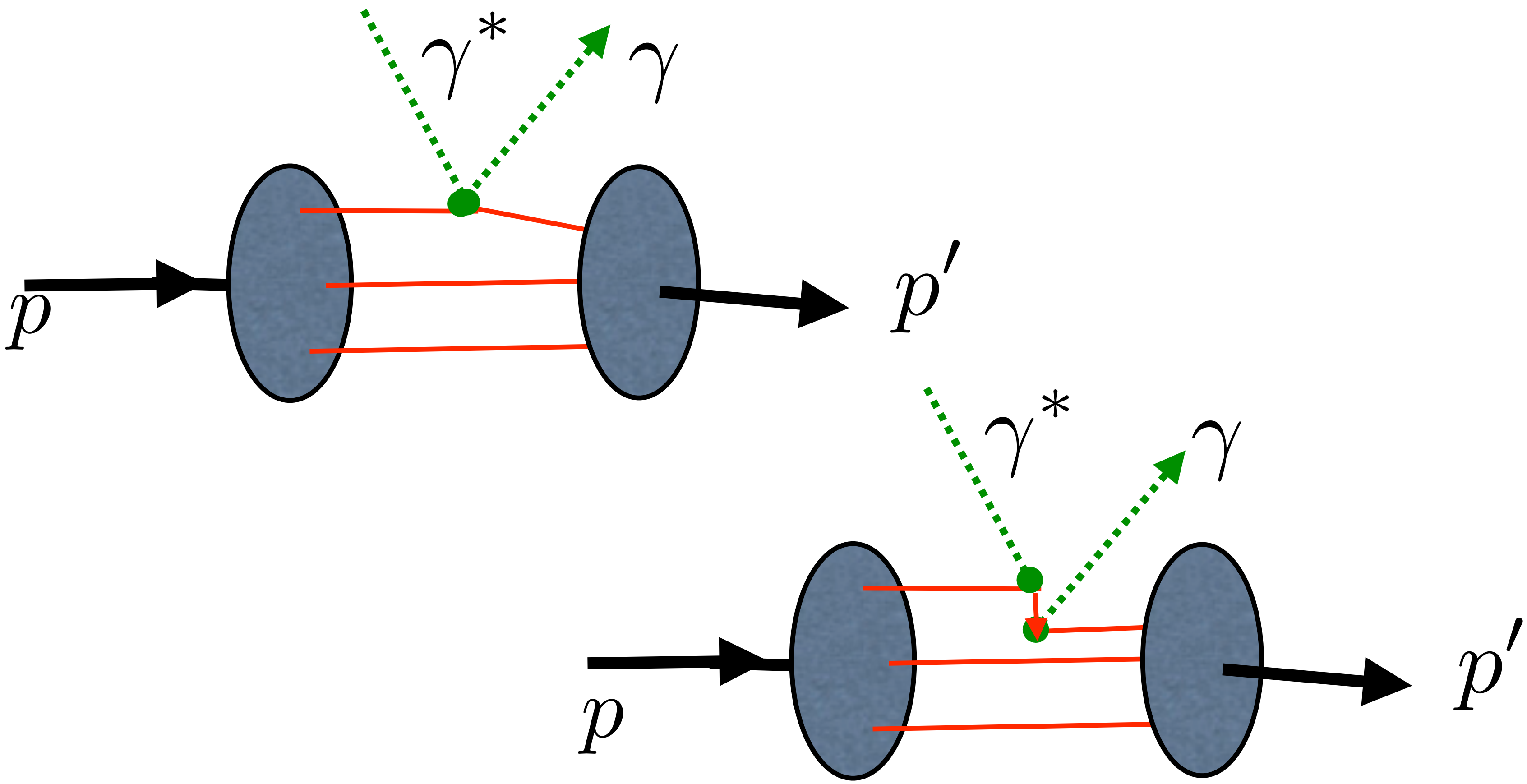


Phase Structure of DVCS

The DVCS amplitude is complex, so one must have the capability of measuring both its real and imaginary part. Measuring the electron-positron asymmetry allows the measurement of the real part of the DVCS amplitude from its interference with the Bethe-Heitler bremsstrahlung amplitude. One can thus test for the presence of a constant in energy J=0 fixed pole characteristic of quark Compton scattering. Single proton-spin asymmetries provide the interfering imaginary part related to the generalized parton distributions.

J=0 Fixed Pole Contribution to DVCS

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



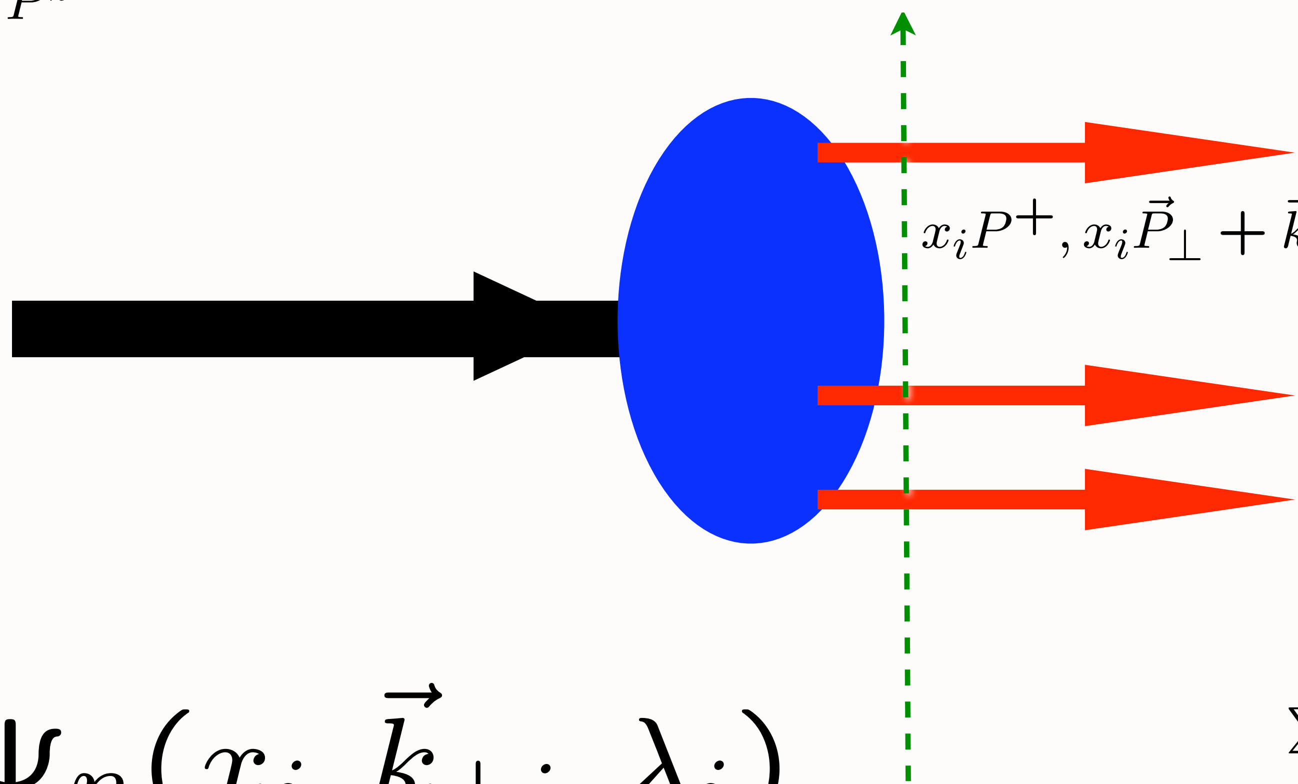
Issues for DVCS

- J=0 fixed pole -- direct test of QCD locality -- from seagull or instantaneous contribution to Feynman propagator
- <1/x> Moment
- Dominance of Handbag diagram?
- Breakdown at large t ; effects of FSI in DIS, diffractive intermediate states
- Timelike studies at BaBar/Belle and GSI FAIR
- BH/Compton interference from charge asymmetry

Light-Front Wavefunctions

Fixed $\tau = t + z/c$

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



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

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

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

$\sum_i^n x_i = 1$

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

Invariant under boosts! Independent of P^μ

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

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

The Light Front Fock State Wavefunctions

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

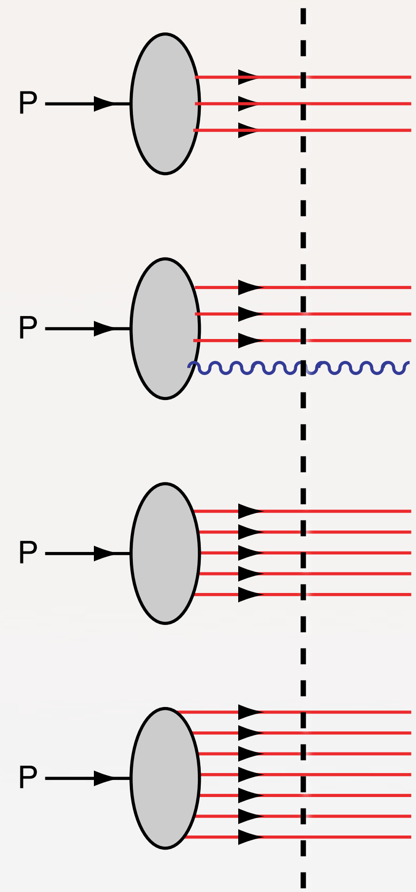
are boost invariant; they are independent of the hadron's energy and momentum P^μ.

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

Intrinsic heavy quarks $\bar{u}(x)\neq\bar{d}(x)$

Mueller: BFKL DYNAMICS $\bar{s}(x)\neq s(x)$

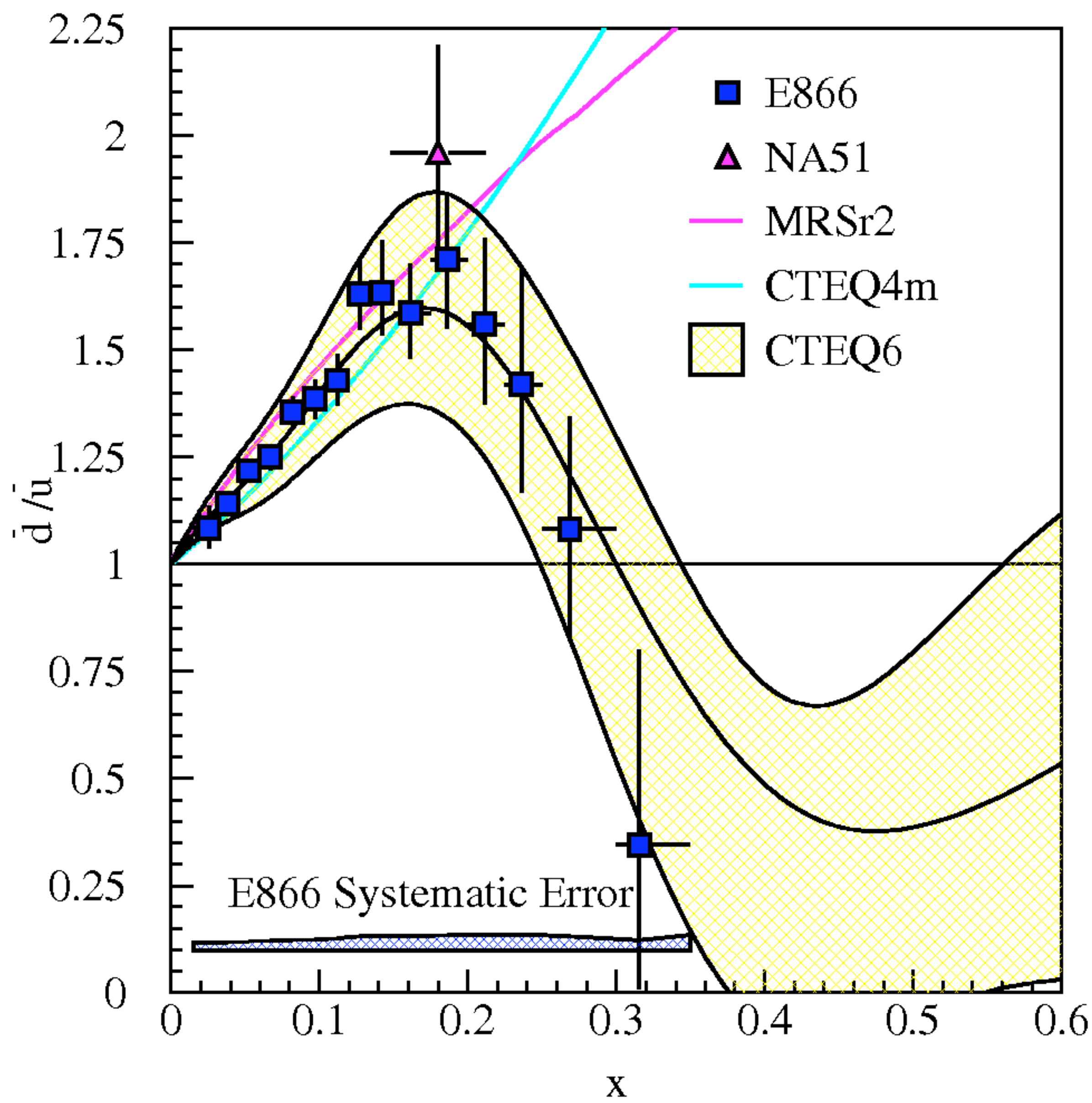
Light Antiquark Flavor Asymmetry

- Naïve Assumption from gluon splitting:

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

- E866/NuSea (Drell-Yan)

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



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

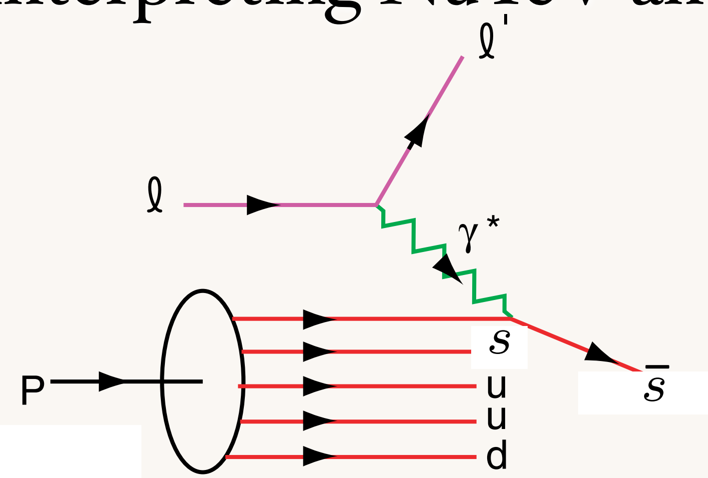
$$\Delta s(x) \neq \Delta \bar{s}(x)$$

- Non-symmetric strange and antistrange sea $\bar{s}(x) \neq s(x)$
- Intrinsic charm and bottom at high x
- Hidden-Color Fock states of the Deuteron

Measure strangeness distribution from DIS at EIC

$$\bar{s}(x) \neq s(x) \qquad ep \to e'KX$$

- 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



Strangeness Asymmetry

The strange and anti-strange distributions of the proton need not be $s(x, Q^2) \neq \bar{s}(x, Q^2)$; this asymmetry reflects fundamental nonperturbative aspects of the proton's structure.

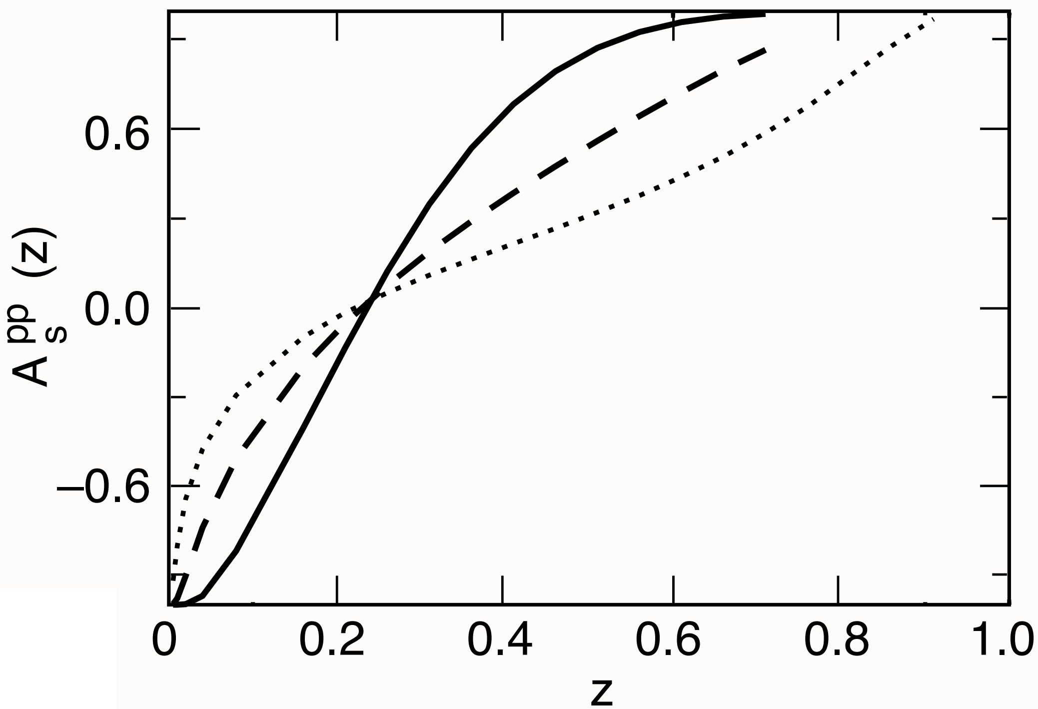
Meson-Baryon fluctuations produce asymmetry

Compare $D(s\bar{c})$ and $D(\bar{s}c)$
in proton fragmentation region at the EIC

Compare protons versus anti-proton in $\bar{s}$ current quark fragmentation

$$D_{s\to p}(z) \neq D_{s\to\bar{p}}(z)$$

Tag s quark via high x_F Λ production in proton fragmentation region.



B.Q. Ma and sjb

$$A_s^{p\bar{p}}(z) = \frac{D_{s\to p}(z) - D_{s\to\bar{p}}(z)}{D_{s\to p}(z) + D_{s\to\bar{p}}(z)}$$

Consequence of $s_p(x) \neq \bar{s}_p(x)$ $\quad |uuds\bar{s}> \simeq |K^+\Lambda>$

Intrinsic Charm and Bottom

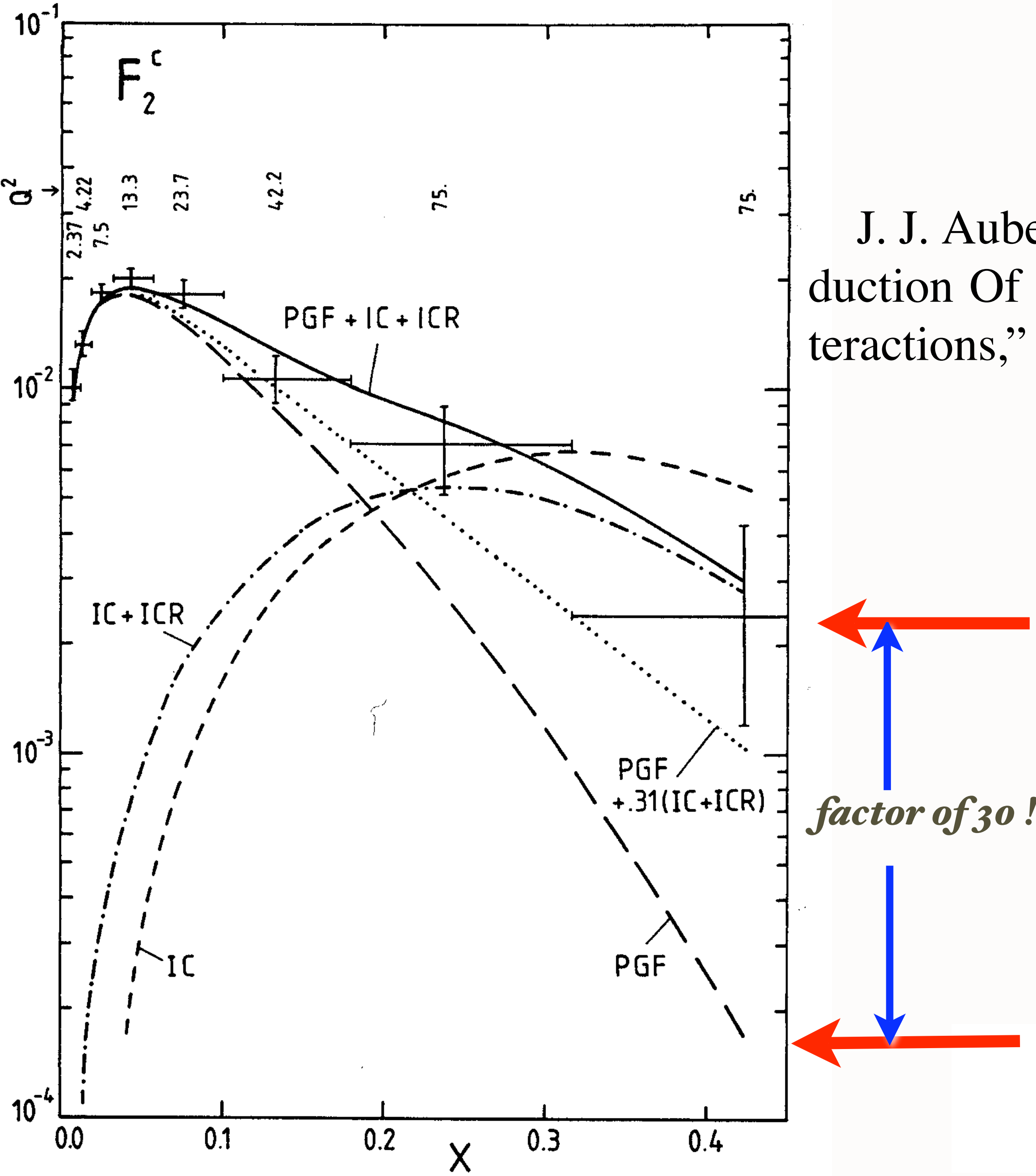
QCD predicts that the charm and bottom quark distributions $c(x, Q^2), b(x, Q^2)$ measured in DIS have support at large x; these contributions arise from diagrams in which the heavy quarks are multi-connected to the valence quarks of the proton. These intrinsic contributions are addition to those derived from gluon splitting and DGLAP evolution. The probability for intrinsic heavy quarks scales as $1/m_Q^2$ due to the non-Abelian interactions of QCD.

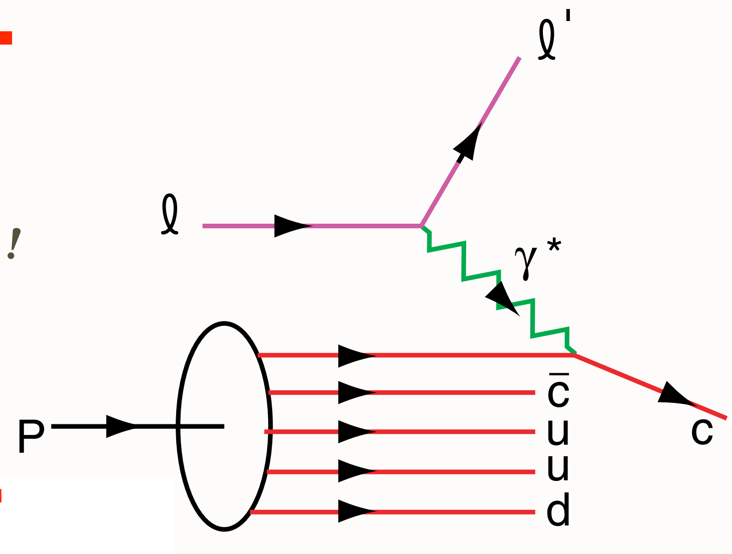
The presence of intrinsic charm and bottom fluctuations leads to the production of heavy mesons, baryons, and quarkonia at high x_F in the proton fragmentation region.

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).

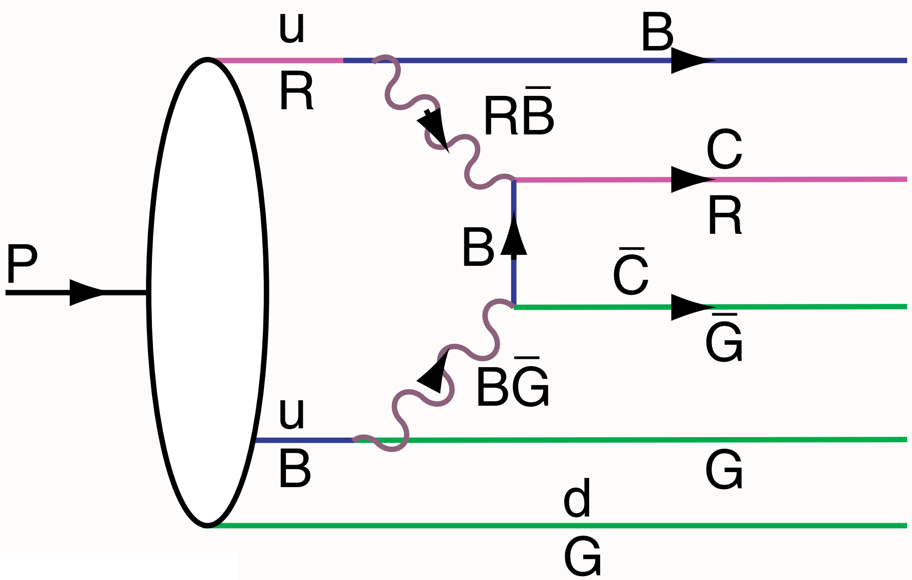
First Evidence for Intrinsic Charm





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

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

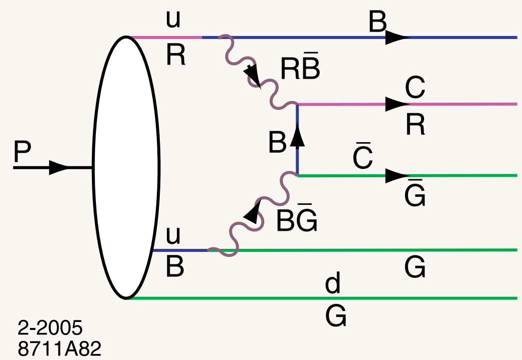
Distribution peaks at equal rapidity (velocity)
Therefore heavy particles carry the largest momentum fractions

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

High x charm! *Charm at Threshold*

Hoyer, Peterson, Sakai, sjb

Intrinsic Heavy-Quark Fock States



- Rigorous prediction of QCD, OPE
- Color-Octet Color-Octet Fock State!
- Probability $P_{Q\bar{Q}} \propto \frac{1}{M_Q^2}$ $P_{Q\bar{Q}Q\bar{Q}} \sim \alpha_s^2 P_{Q\bar{Q}}$ $P_{c\bar{c}/p} \simeq 1\%$
- Large Effect at high x
- Greatly increases kinematics of colliders such as Higgs production (Kopeliovich, Schmidt, Soffer, sjb)
- Severely underestimated in conventional parameterizations of heavy quark distributions (Pumplin, Tung)
- Many empirical tests

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

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

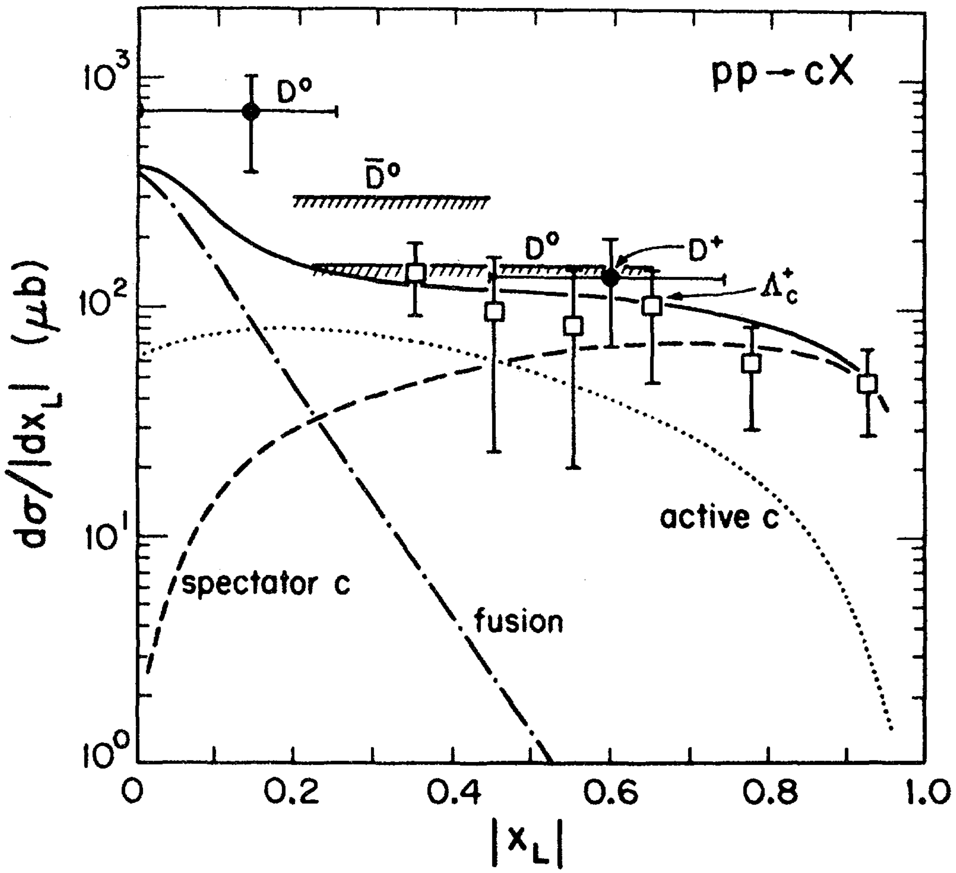
- High x_F $pp \rightarrow J/\psi J/\psi X$

- High x_F $pp \rightarrow \Lambda_c X$

- High x_F $pp \rightarrow \Lambda_b X$

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

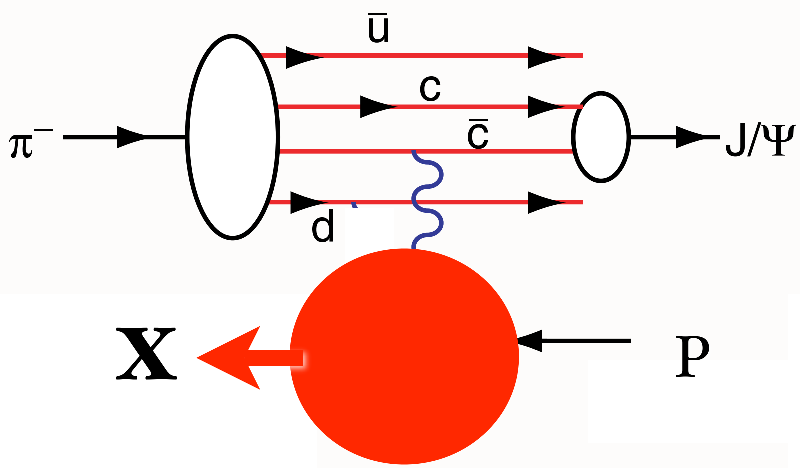
IC Structure Function: Critical Measurement for EIC

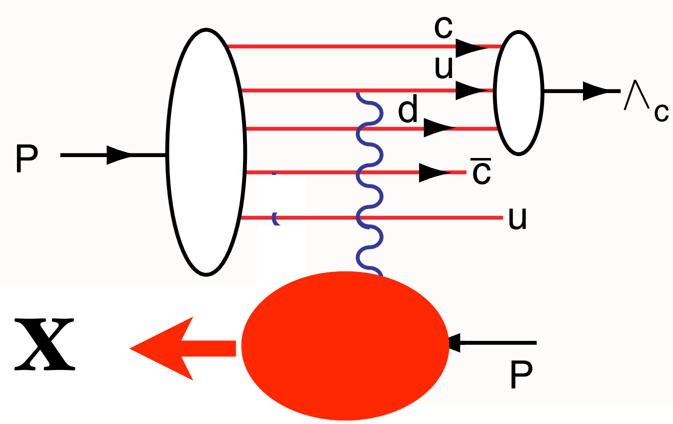


Model similar to Intrinsic Charm

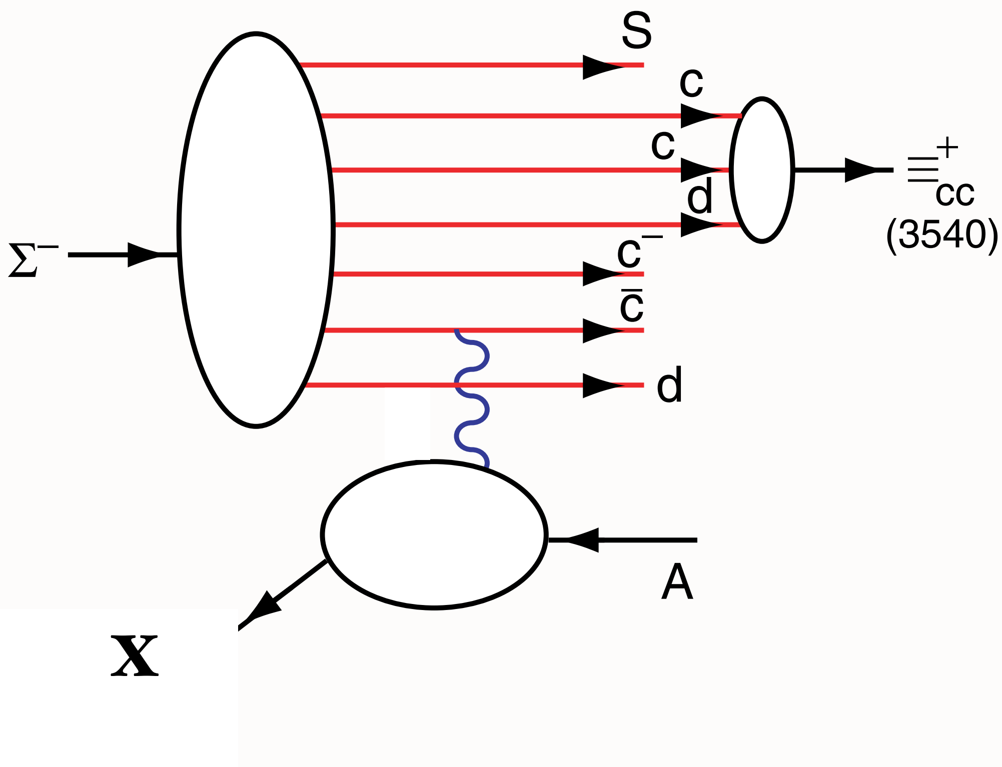
V. D. Barger, F. Halzen and W. Y. Keung,
"The Central And Diffractive Components Of Charm Production,"
Phys. Rev. D 25, 112 (1982).

Leading Hadron Production from Intrinsic Charm





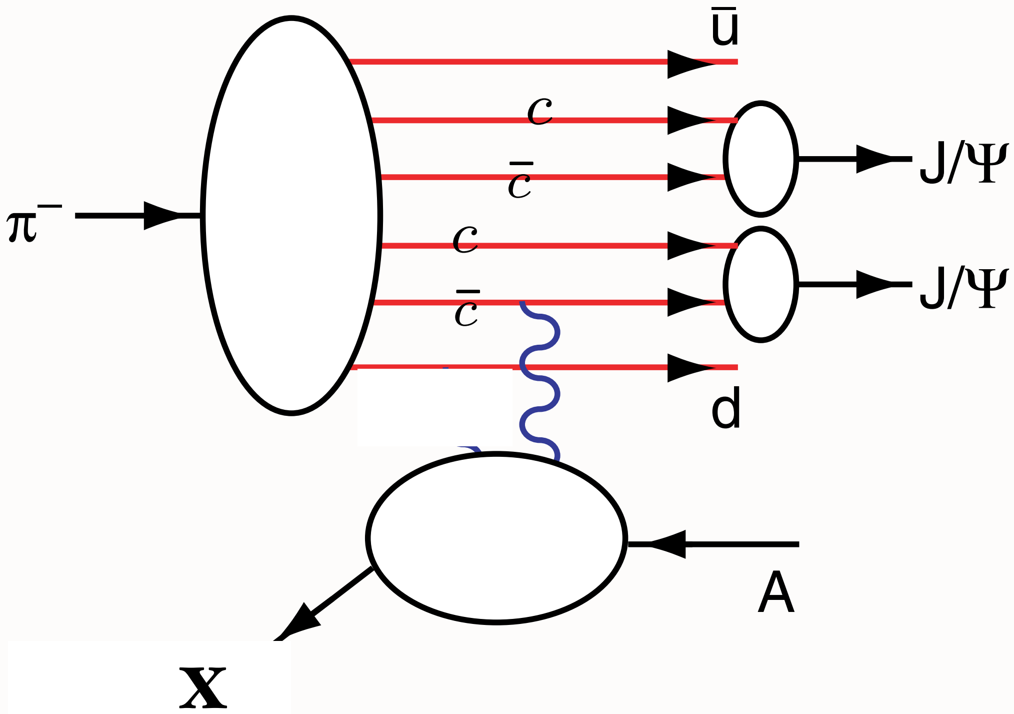
Coalescence of Comoving Charm and Valence Quarks Produce J/ψ, Λ_c and other Charm Hadrons at High x_F



Production of a Double-Charm Baryon

SELEX high x_F $\langle x_F \rangle = 0.33$

Production of Two Charmonia at High x_F



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

Excludes `color drag' model

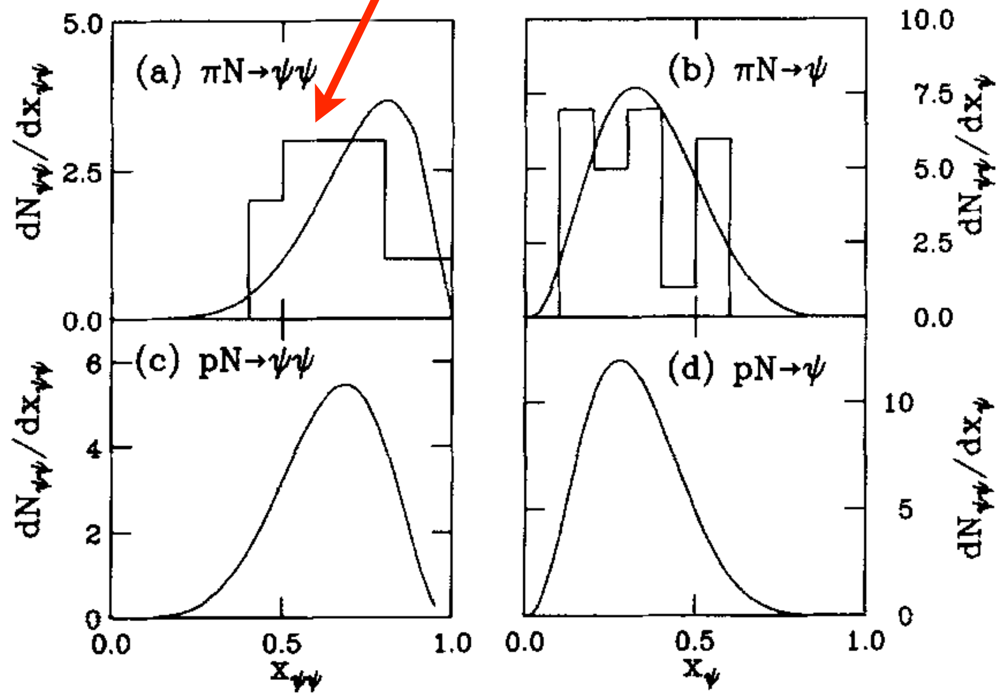


Fig. 3. The $\psi\psi$ pair distributions are shown in (a) and (c) for the pion and proton projectiles. Similarly, the distributions of J/ψ's from the pairs are shown in (b) and (d). Our calculations are compared with the $\pi^- N$ data at 150 and 280 GeV/c [1]. The $x_{\psi\psi}$ distributions are normalized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

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

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

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

- 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

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

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

Higgs production at $x_F = 0.8$

Forward Fragmentation

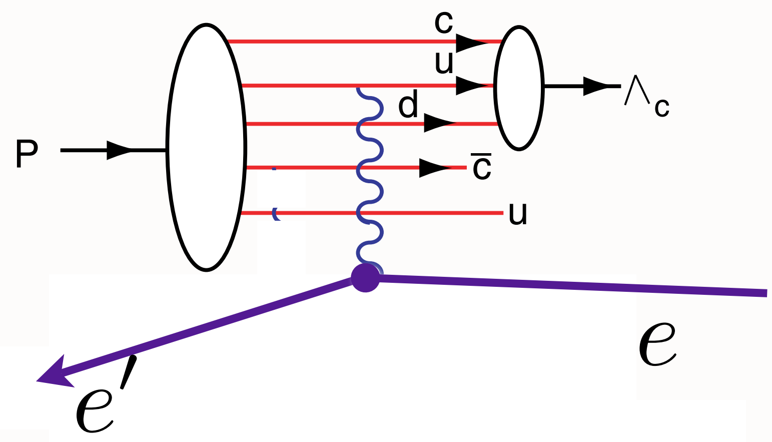
Heavy Hadron Production from IC, IB

When the electron interacts with the intrinsic charm or bottom quark, heavy hadrons such as the Λ_b and even doubly charmed baryons such as the $\Xi(ccd)$ are created with high momentum fractions and Lorenz-dilated lifetimes.

Leading charm production in proton fragmentation region at the EIC

Intrinsic charm and bottom quarks have same rapidity as valence quarks

Produce $\Xi(ccd), B(\bar{b}u), \Lambda(cbu), \Xi(bbu)$

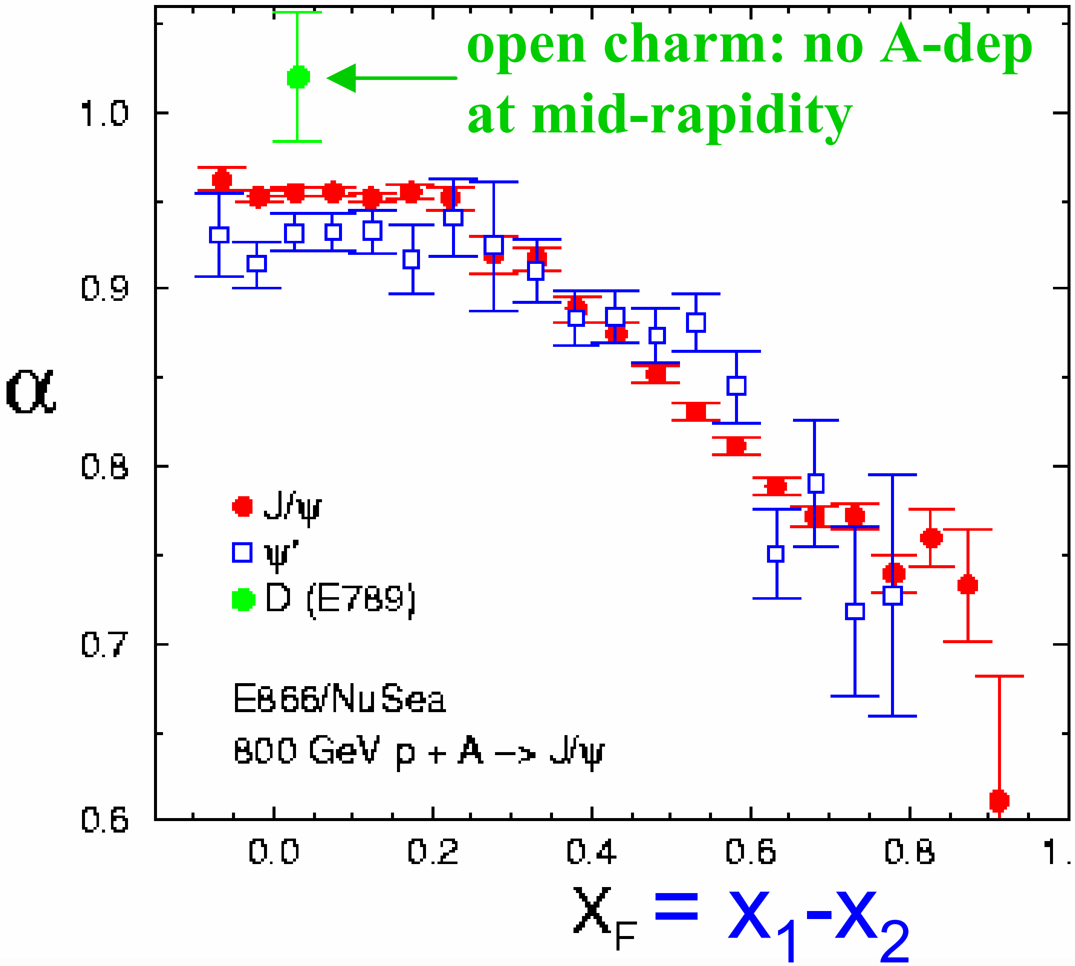


Coalescence of Comoving Charm and Valence Quarks Produce J/ψ, Λ_c and other Charm Hadrons at High x_F

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

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

M. Leitch



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

Remarkably Strong Nuclear Dependence for Fast Charmonium

Violation of PQCD Factorization

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

Heavy Quark Anomalies

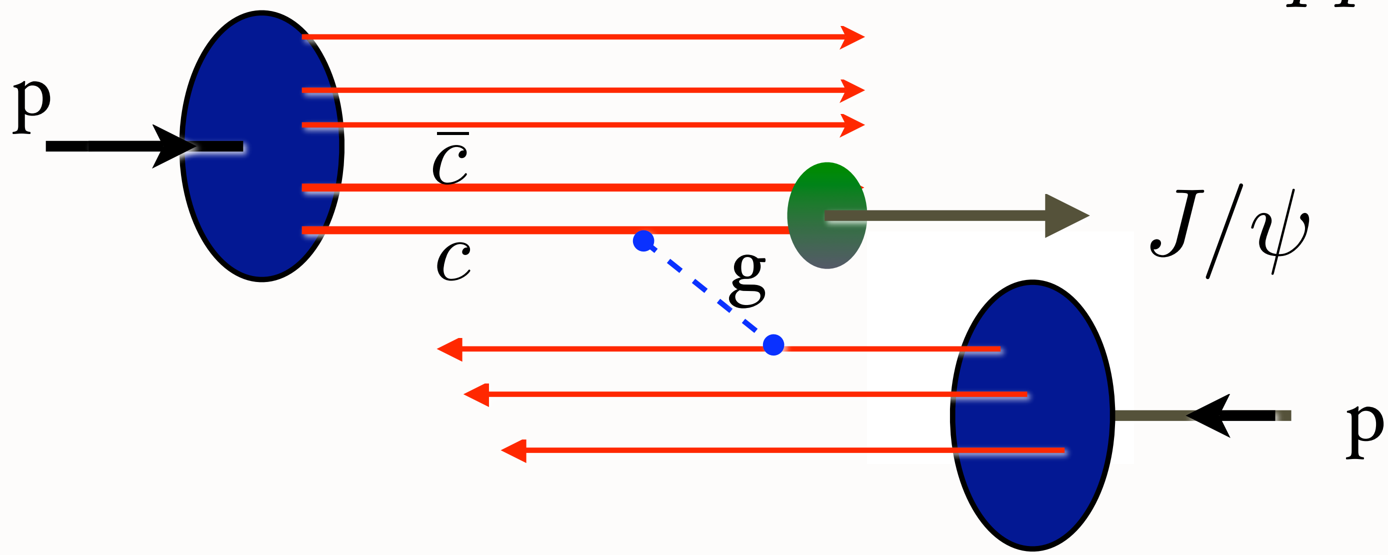
Nuclear dependence of J/ψ hadroproduction

Violates PQCD Factorization: $A^{\alpha}(x_F)$ not $A^{\alpha}(x_2)$

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

Intrinsic Charm Mechanism for Inclusive High-X_F Quarkonium Production

$$pp \to J/\psi X$$



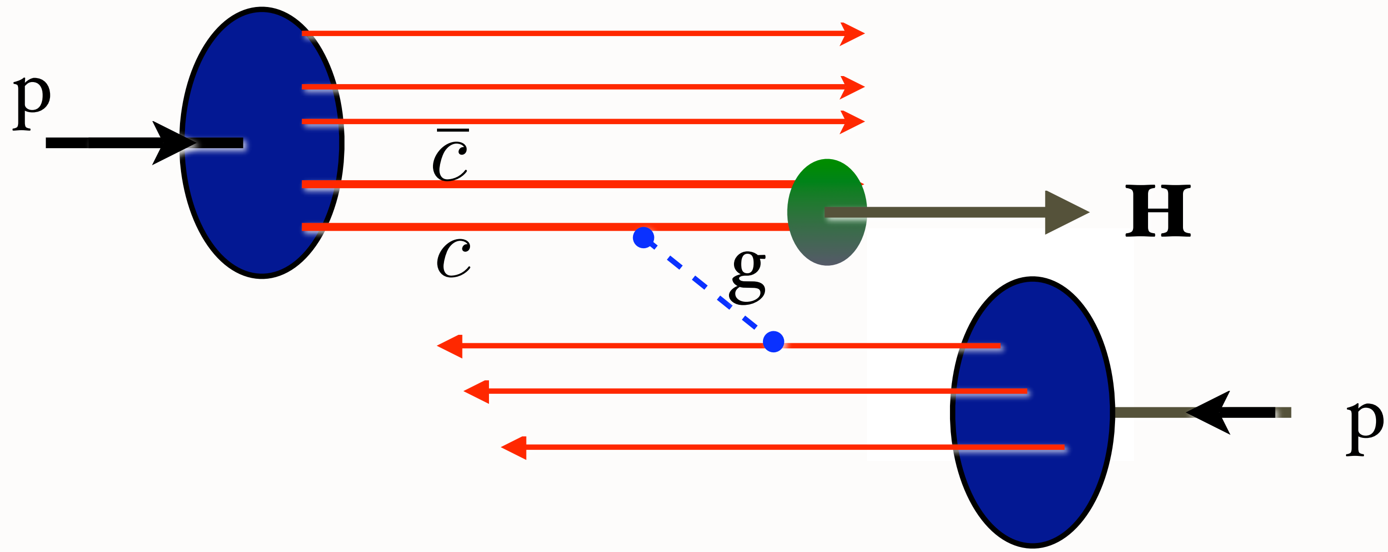
Goldhaber, Kopeliovich, Soffer, Schmidt, sjb

Quarkonia can have 80% of Proton Momentum!

Color-octet IC interacts at front surface of nucleus

IC can explains large excess of quarkonia at large x_F, A-dependence

Intrinsic Charm Mechanism for Inclusive High-X_F Higgs Production



$$pp \rightarrow HX$$

Goldhaber, Kopeliovich, Schmidt, sjb

Also: intrinsic bottom, top

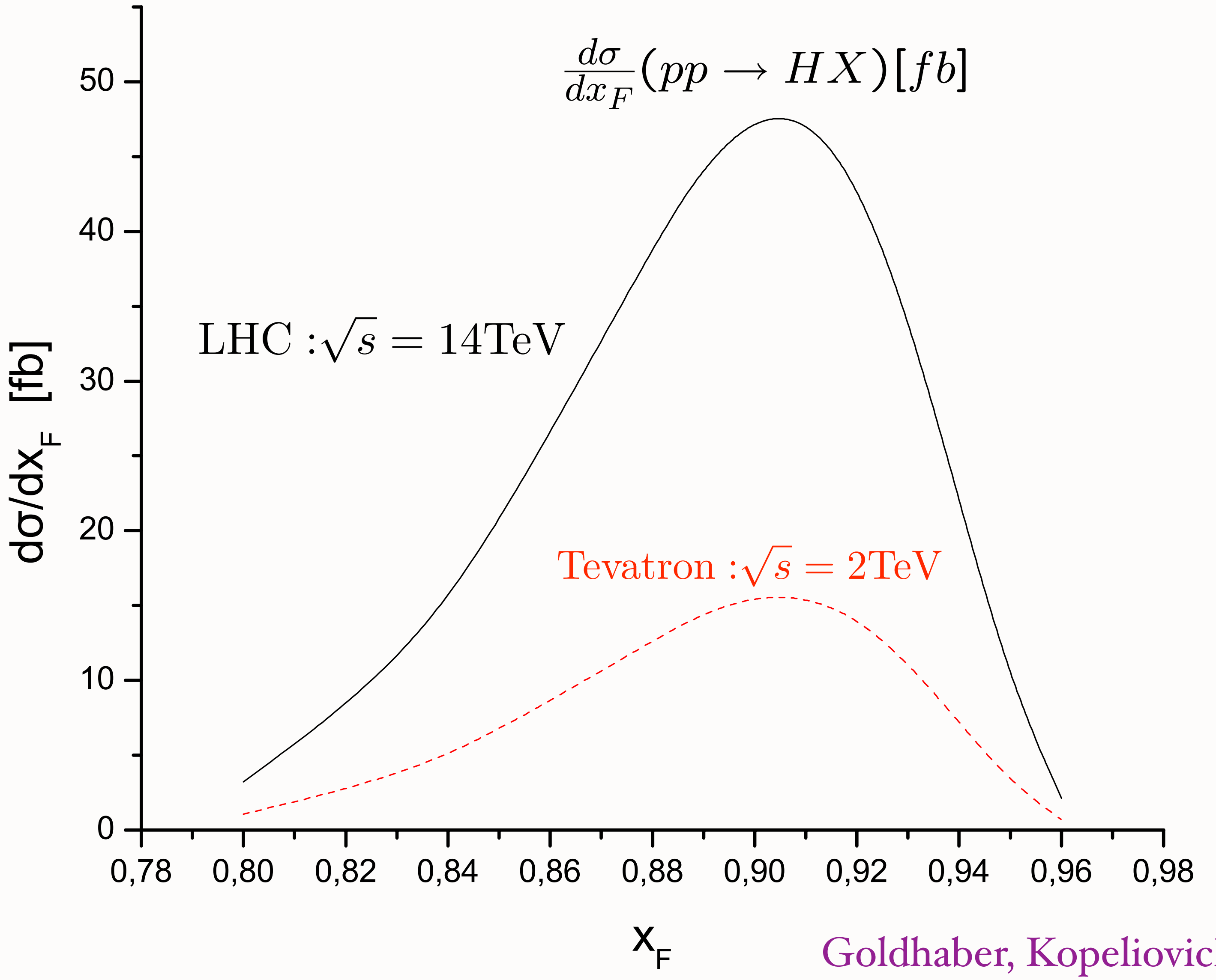
Higgs can have 80% of Proton Momentum!

New search strategy for Higgs

Heavy Quarkonium Production in e A collisions

x_F Dependence
A dependence
Polarization Dependence

Intrinsic Bottom Contribution to Inclusive Higgs Production



Goldhaber, Kopeliovich, Schmidt, sjb

Tagging Gluons with Charm

Studies of the gluon distribution utilize subprocesses such as $\gamma^* g \to c\bar{c}$. The presence of intrinsic charm complicates using the charm tag to determine the gluon distribution at high x. This effect can be reduced by requiring that c and $\bar{c}$ jets balance in transverse momenta since the associated charm quark appears in the proton fragmentation region in the case of the intrinsic contributions.

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

Forward Fragmentation

Hidden Color

When the electron strikes a quark in DIS, the remnant part of the proton emerges along the proton direction. The remnant system for DIS on nuclei such as the deuteron and ^3He targets do not always leave the spectator nucleons intact, because of QCD hidden-color degrees of freedom in the nuclear wavefunction as well as the final-state interactions of the quarks.

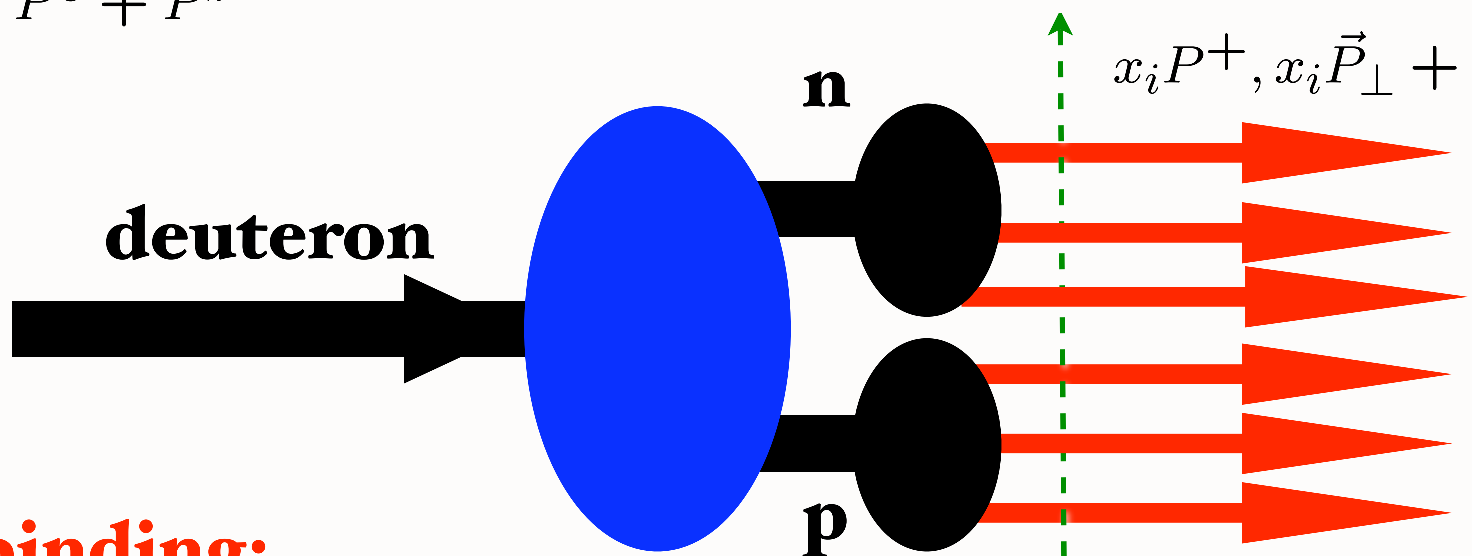
Deuteron Light-Front Wavefunction

Fixed $\tau = t + z/c$

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

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

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



Weak binding:

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

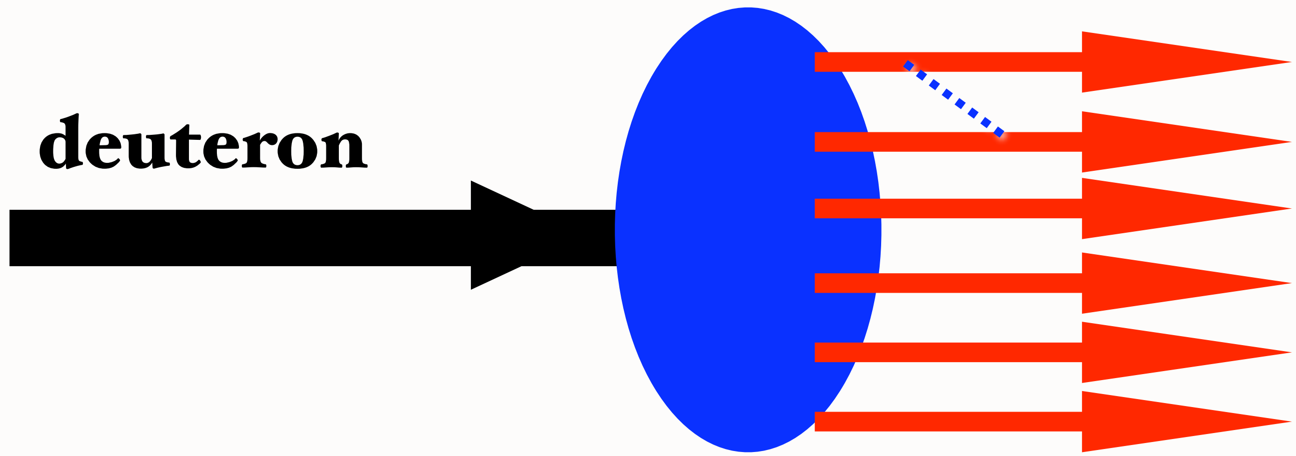
$\sum_i^n x_i = 1$

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

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 of Deuteron

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

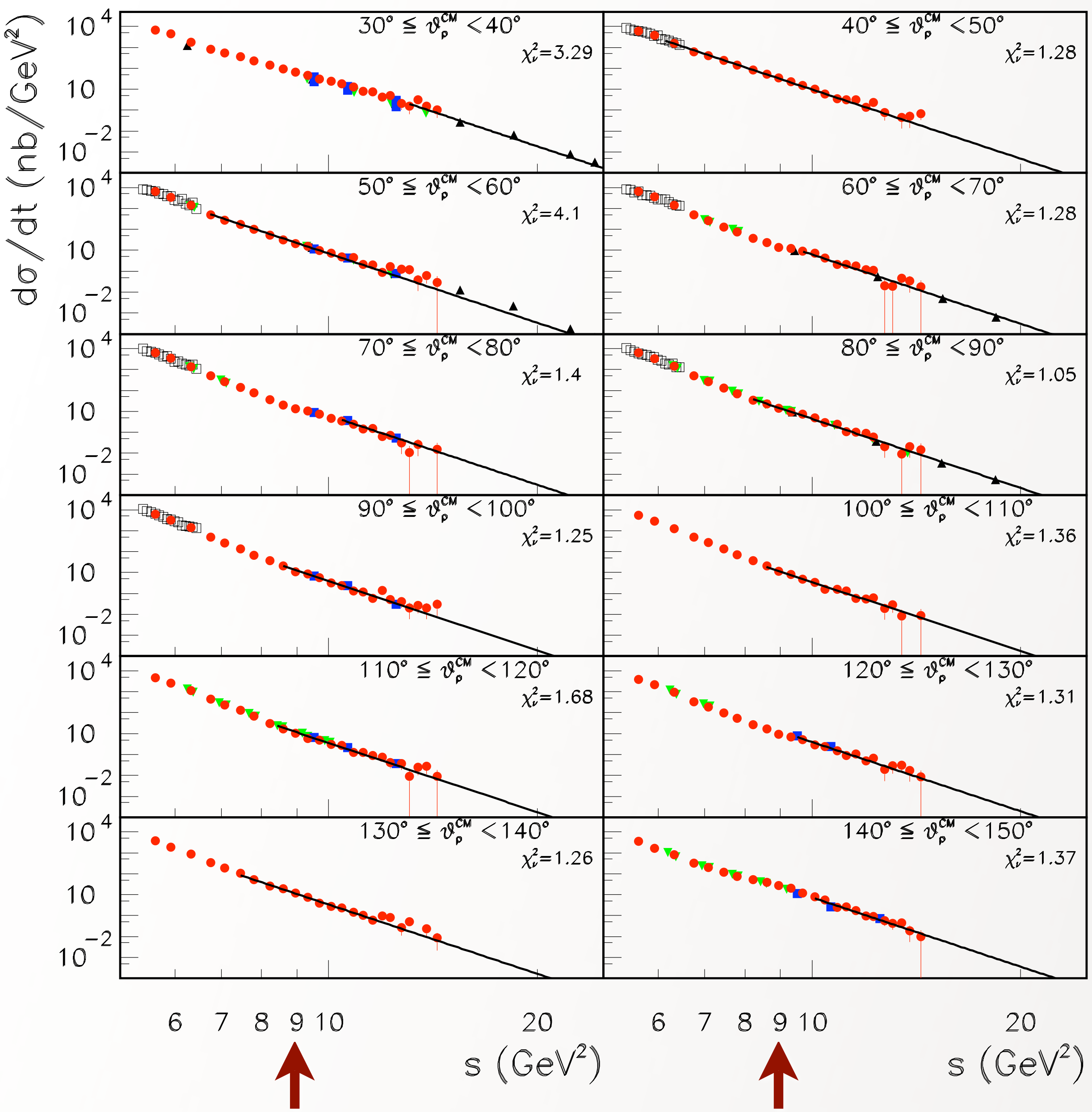
Asymptotic Solution has Expansion

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

Look for strong transition to Delta-Delta

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

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

at $s \simeq 9$ GeV^2

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

at $s \simeq 25$ GeV^2

$\gamma d \to np$

$\gamma d \to (uudddus\bar{s}) \to np$ at $s = 9$ GeV^2

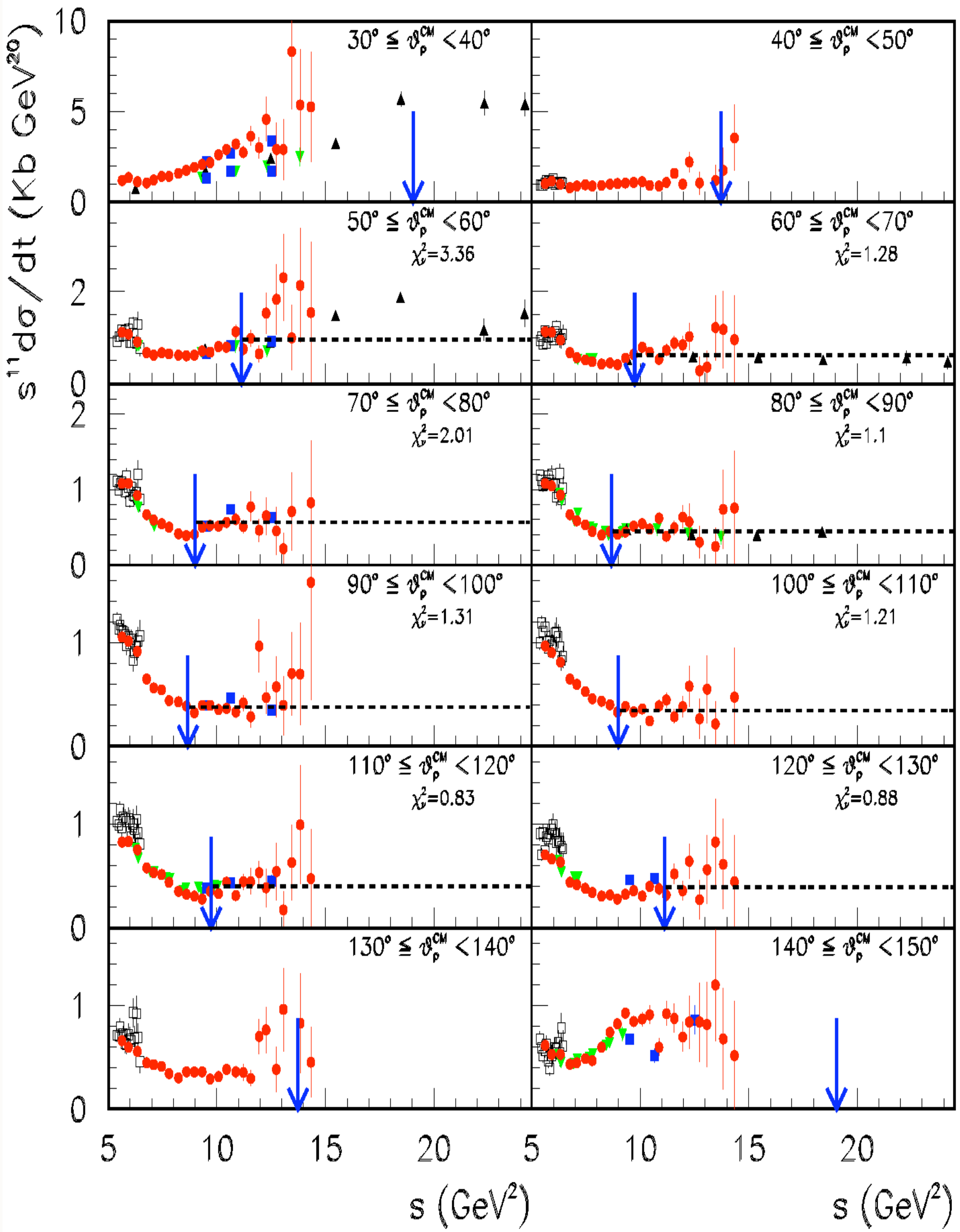
Fit of dσ/dt data for the central angles and $P_T \geq 1.1$ GeV/c with $A\, s^{-11}$

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

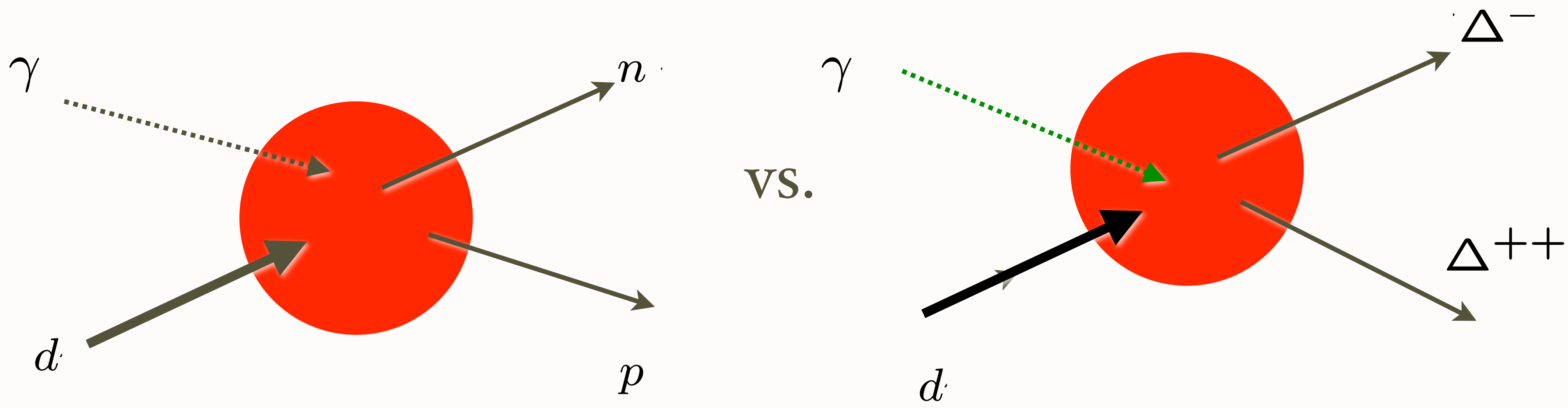
Test of Hidden Color in Deuteron Photodisintegration

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

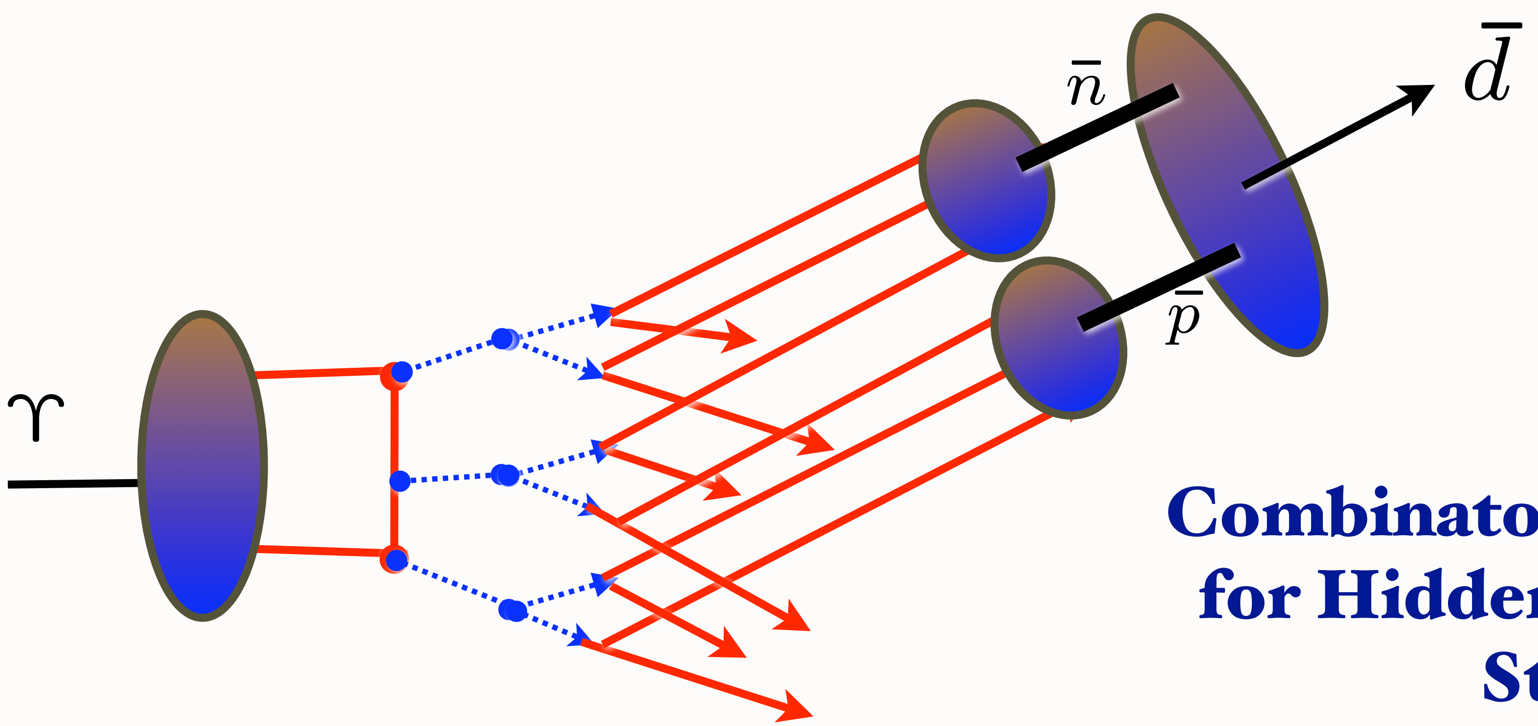
Ratio predicted to approach 2:5

Possible contribution from pion charge exchange at small t.

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



Anti-Deuteron Production at the Amplitude Level



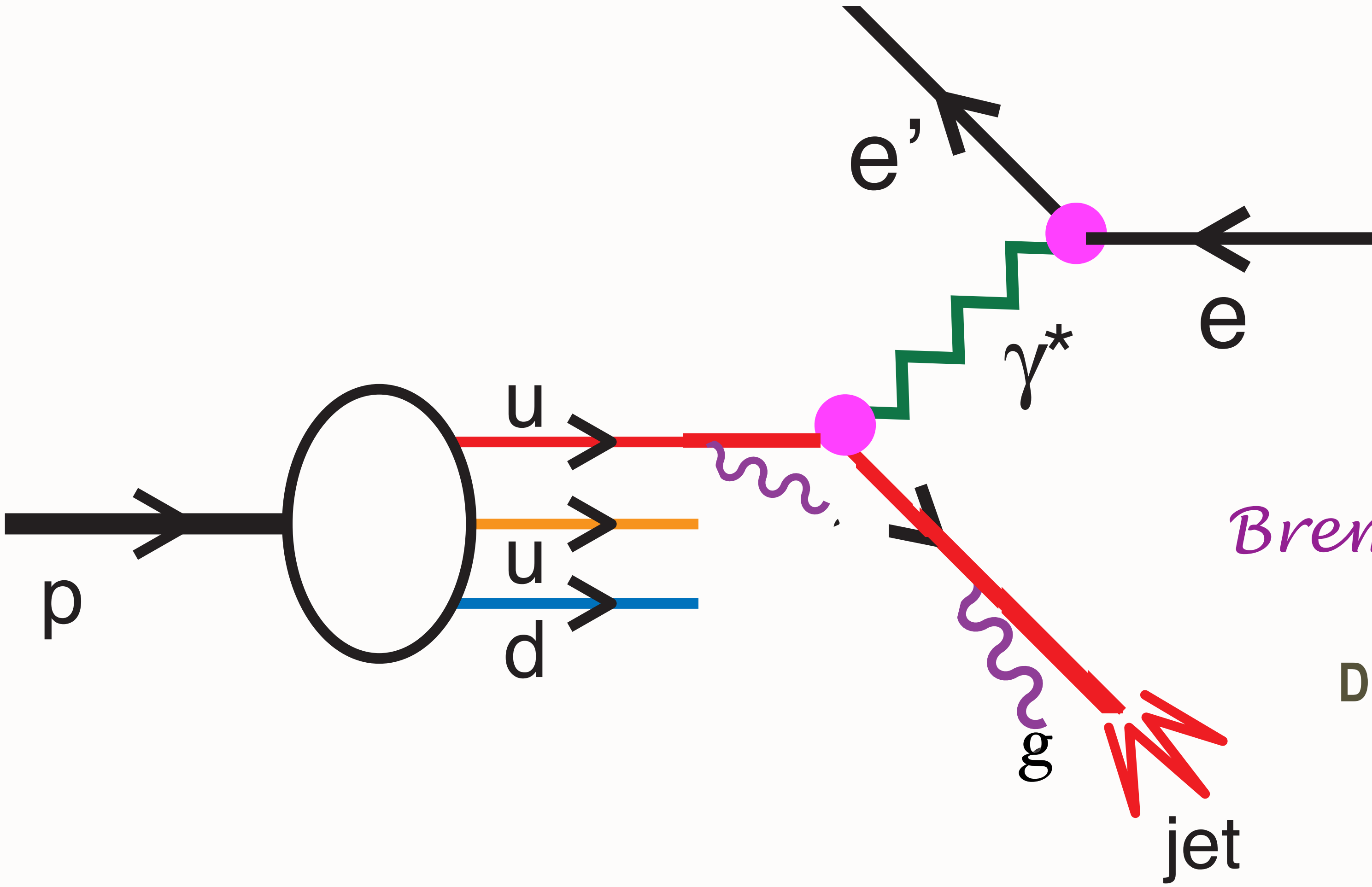
Combinatoric Advantage for Hidden-Color Fock States

$$\Upsilon \to ggg \to q\bar{q}\ q\bar{q}\ q\bar{q}\ q\bar{q}\ q\bar{q}\ q\bar{q} \to \bar{d}\ X$$

Compare Anti-Deuteron production with double anti-baryon production

$$\Upsilon \to ggg \to q\bar{q}\ q\bar{q}\ q\bar{q}\ q\bar{q}\ q\bar{q}\ q\bar{q} \to \bar{p}\ \bar{n}\ X$$

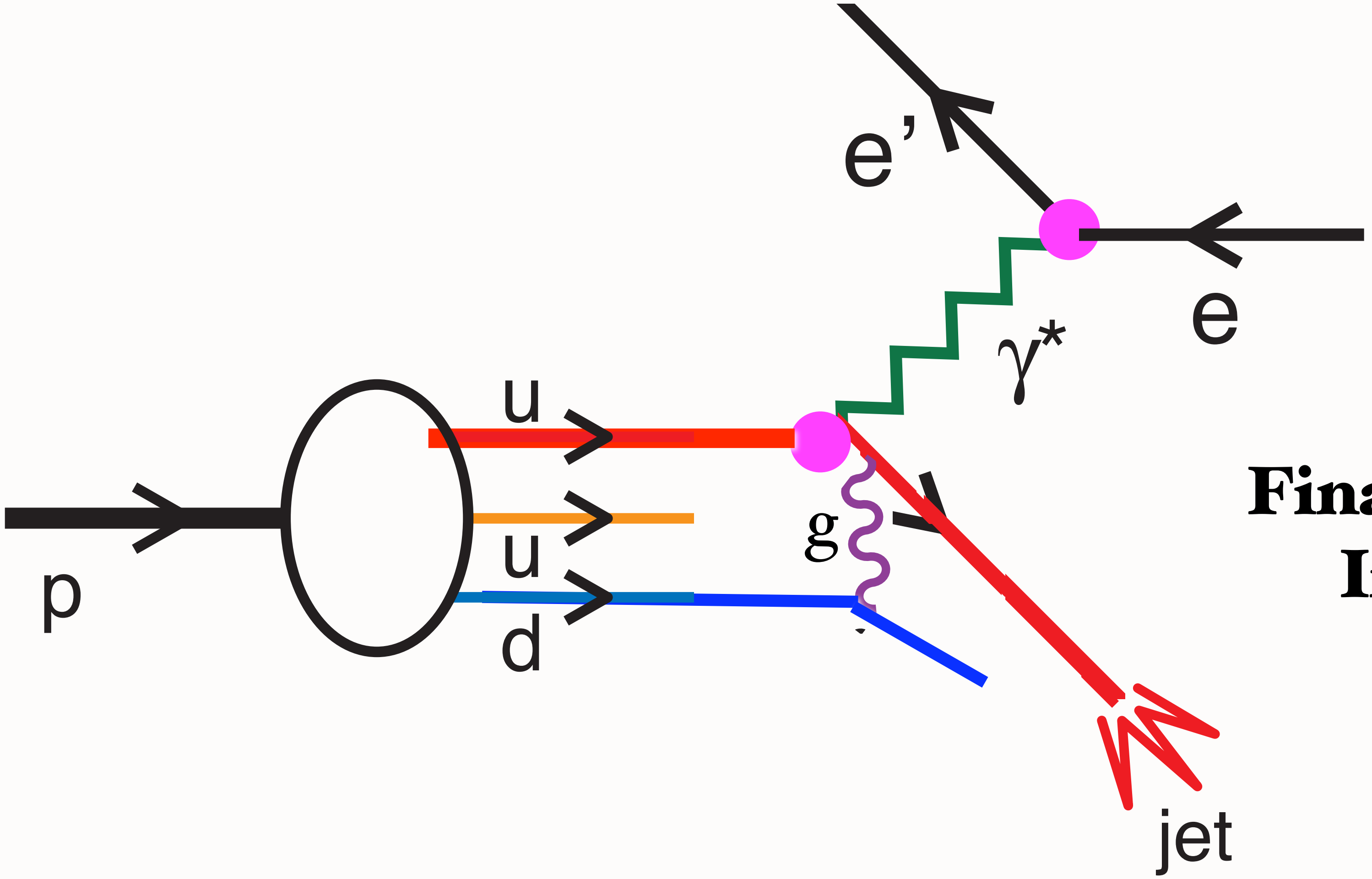
Deep Inelastic Electron-Proton Scattering



Gluonic Bremmstrahlung

DGLAP Evolution

Deep Inelastic Electron-Proton Scattering



Final-State QCD Interaction

Conventional wisdom:

Final-state interactions of struck quark can be neglected

Leading Twist Sivers Effect

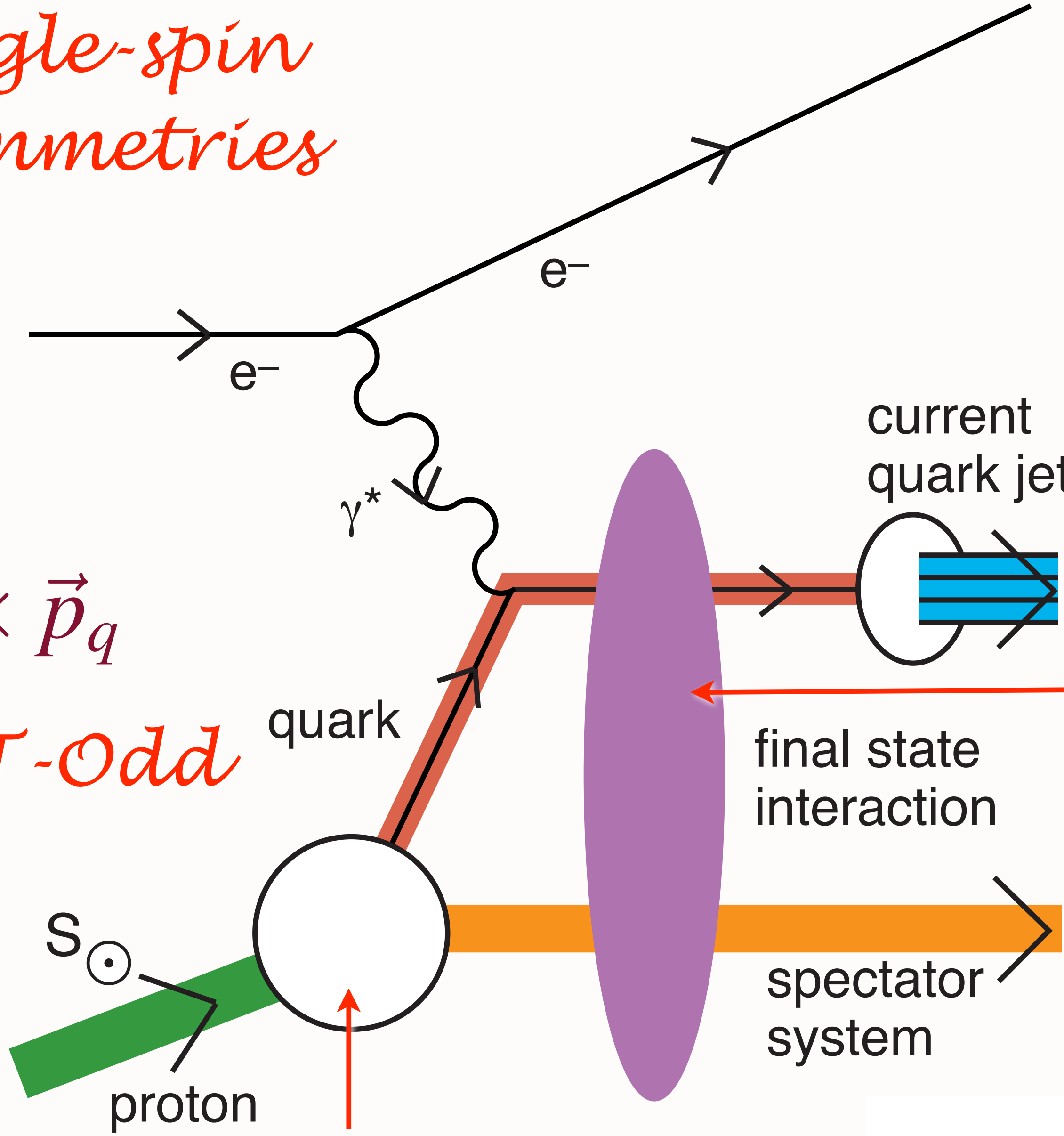
Single-spin asymmetries

Hwang, Schmidt, sjb

Collins, Burkardt Ji, Yuan

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

Pseudo-T-Odd

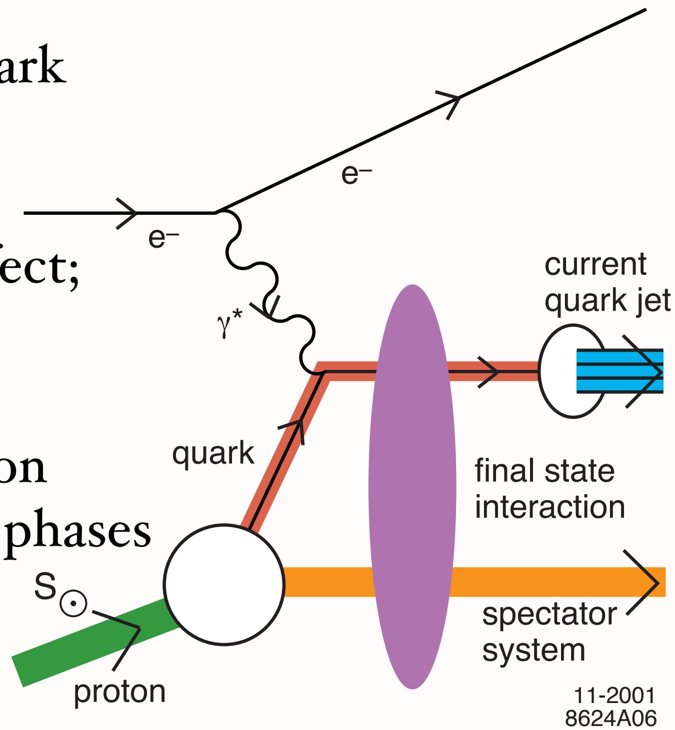


QCD S- and P-Coulomb Phases --Wilson Line

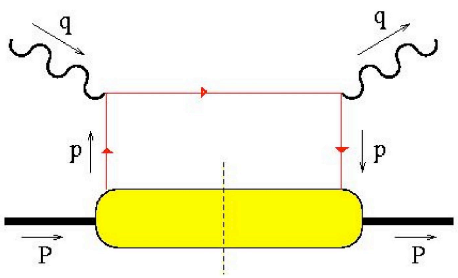
Light-Front Wavefunction S and P- Waves

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

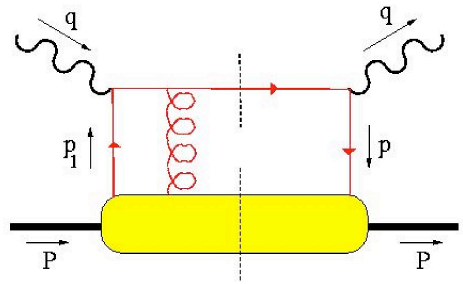
$$\mathbf{i}\ \vec{S} \cdot \vec{p}_{jet} \times \vec{q}$$



- 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!



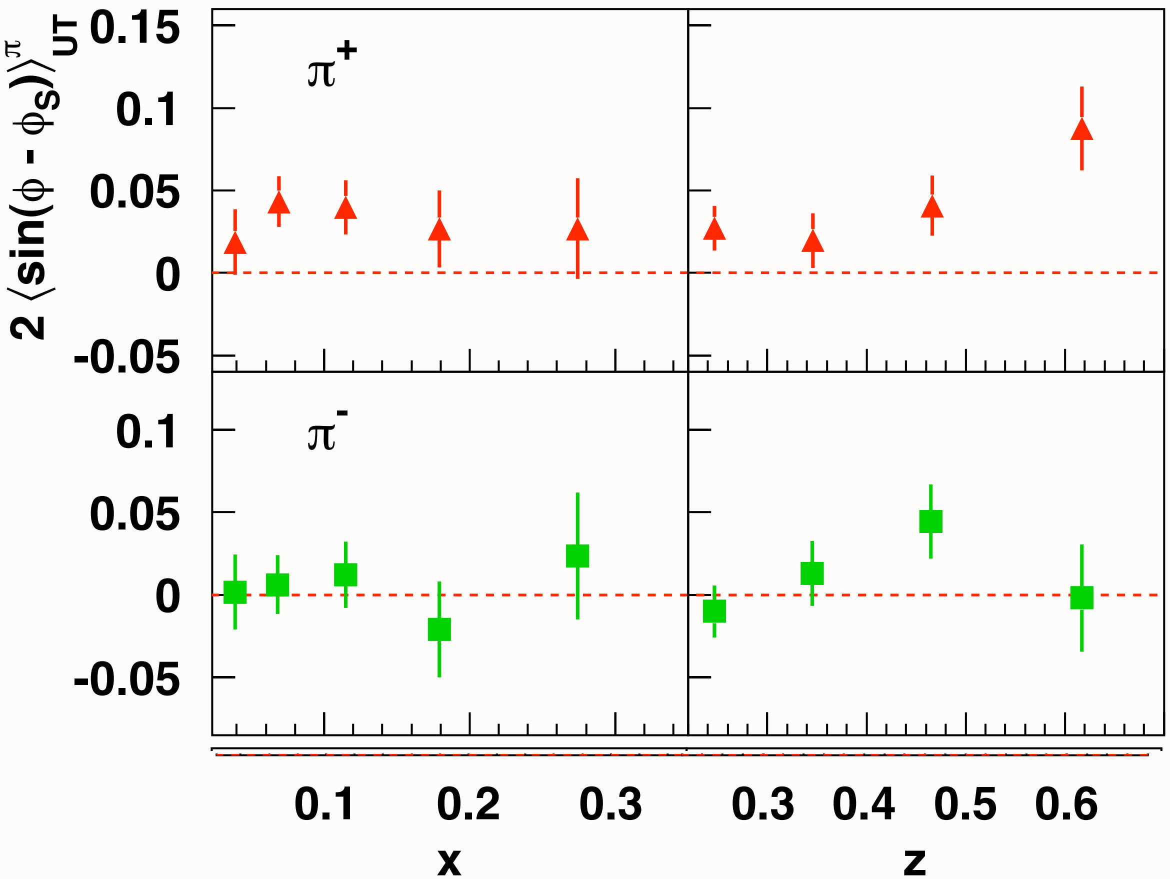
can interfere with



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



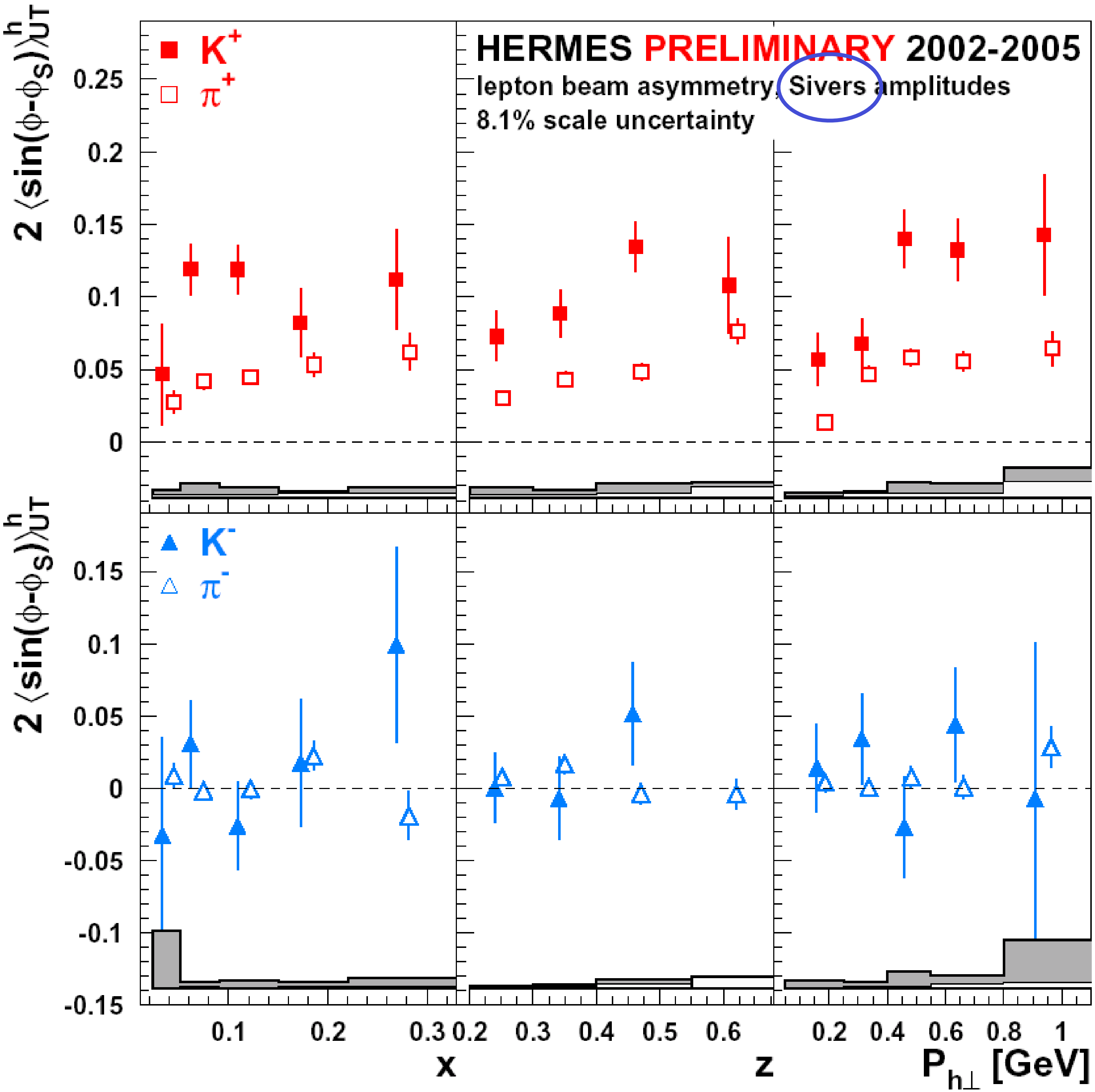
- First evidence for non-zero Sivers function!
- ⇒ presence of non-zero **quark orbital angular momentum**!
- Positive for **π⁺**... Consistent with zero for **π⁻**...

Gamberg: Hermes data compatible with BHS model

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

Physics of Rescattering

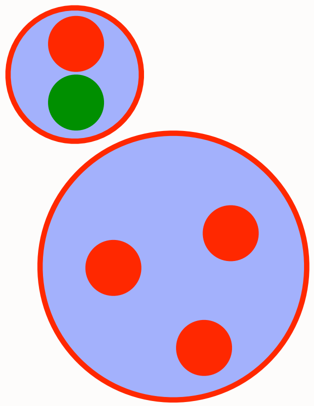
- Sivers Amplitude is Imaginary
- Phase comes from FSI
- Cannot be computed from wavefunction of proton in isolation!
- Phase requires QCD coupling in infrared
- Process dependent
- Input from hadron dynamics: Overlap of spin parallel and antiparallel LFWFS
- Same amplitudes which determine Pauli form factor

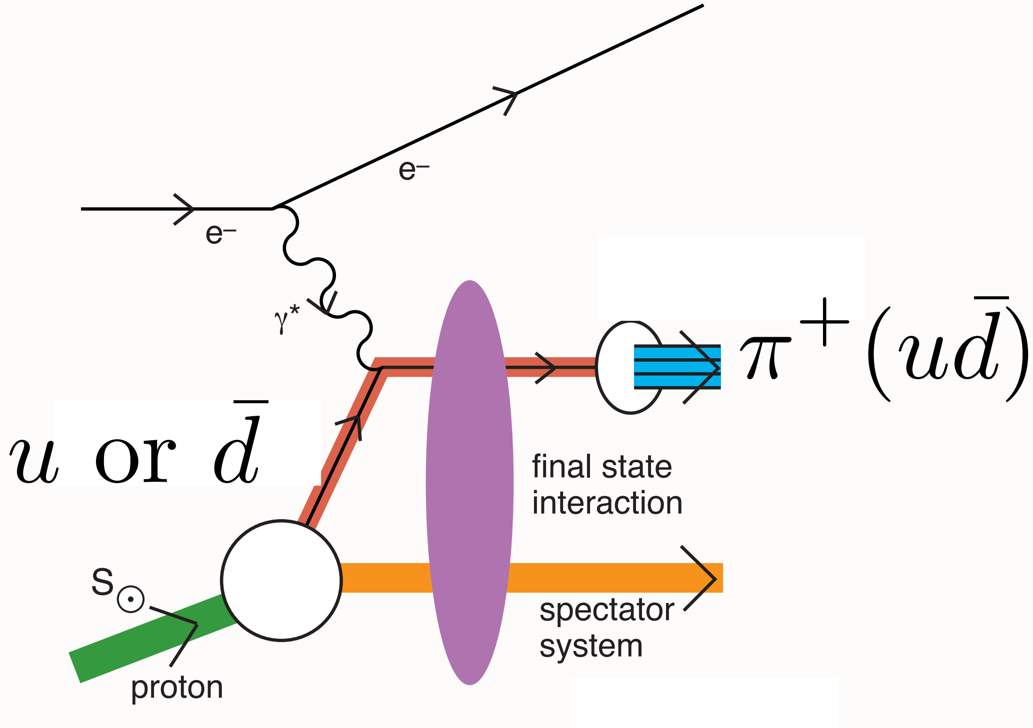


Large K+ asymmetry!

Gardner, sjb

Sea quarks carry orbital angular momentum

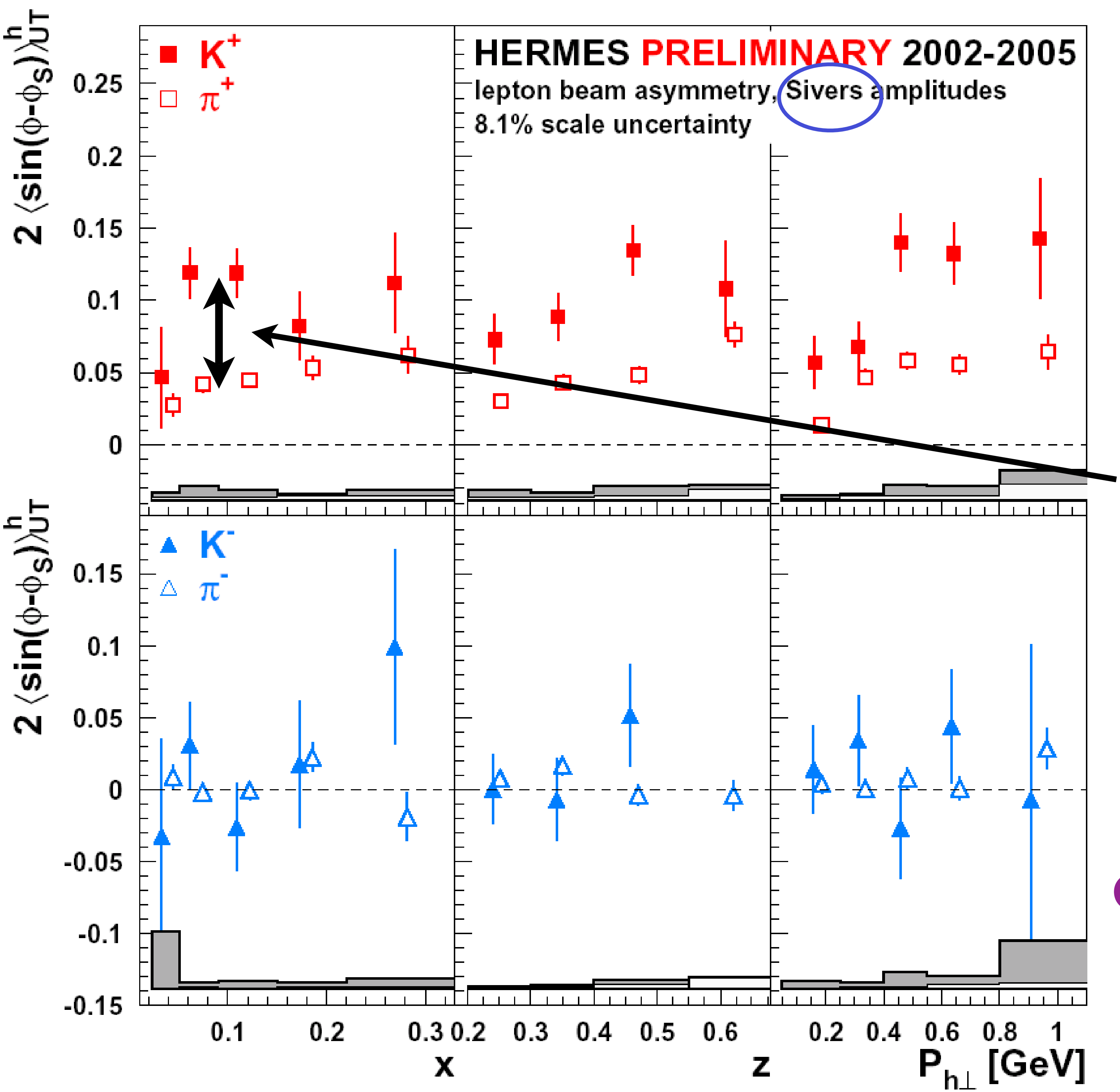




Sivers effect for $\pi^+(u\bar{d})$ reduced by $L_{\bar{d}}$ at low x

Sivers effect for $\pi^-(d\bar{u})$ reduced by $L_{\bar{u}}$ at low x

Sivers effect for $K^+(u\bar{s})$ increased by $L_{\bar{s}}$!



Large K^+ asymmetry!

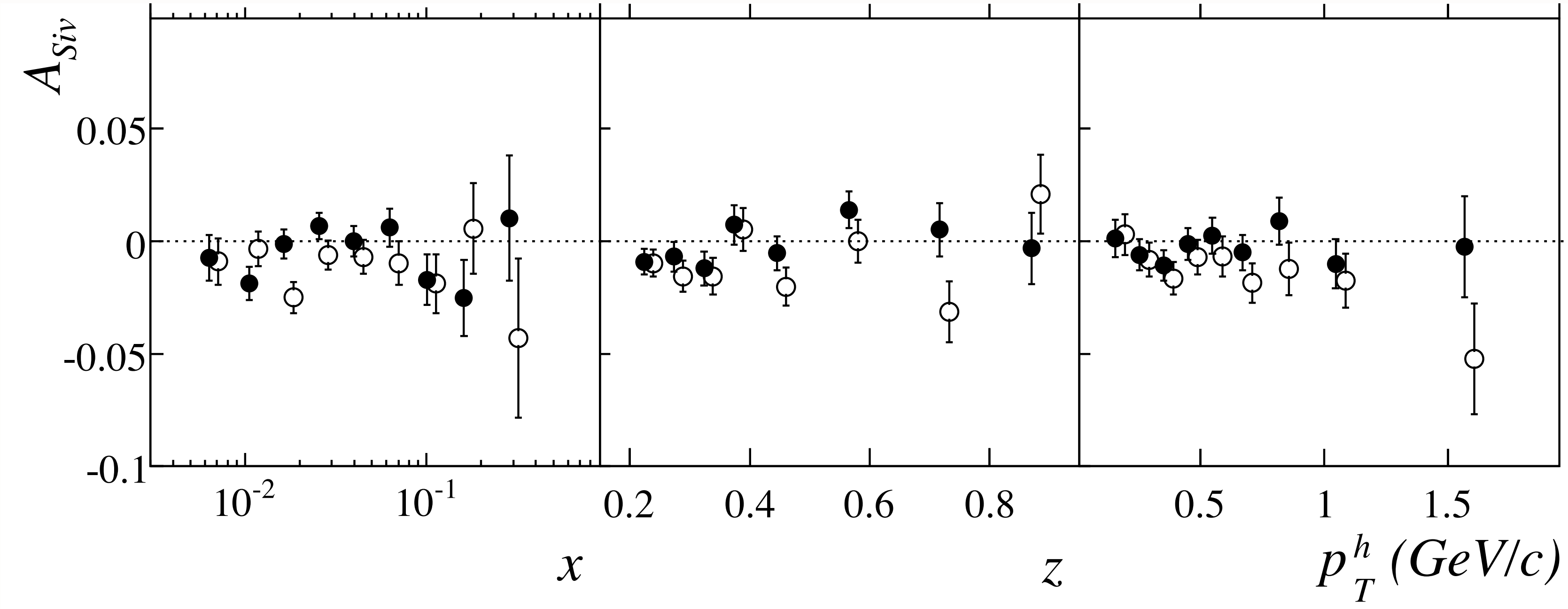
Difference at low x from sea-quark OAM?

Gardner, sjb in progress

A new measurement of the Collins and Sivers asymmetries on a transversely polarised deuteron target

The COMPASS Collaboration

hep-ex/0610068



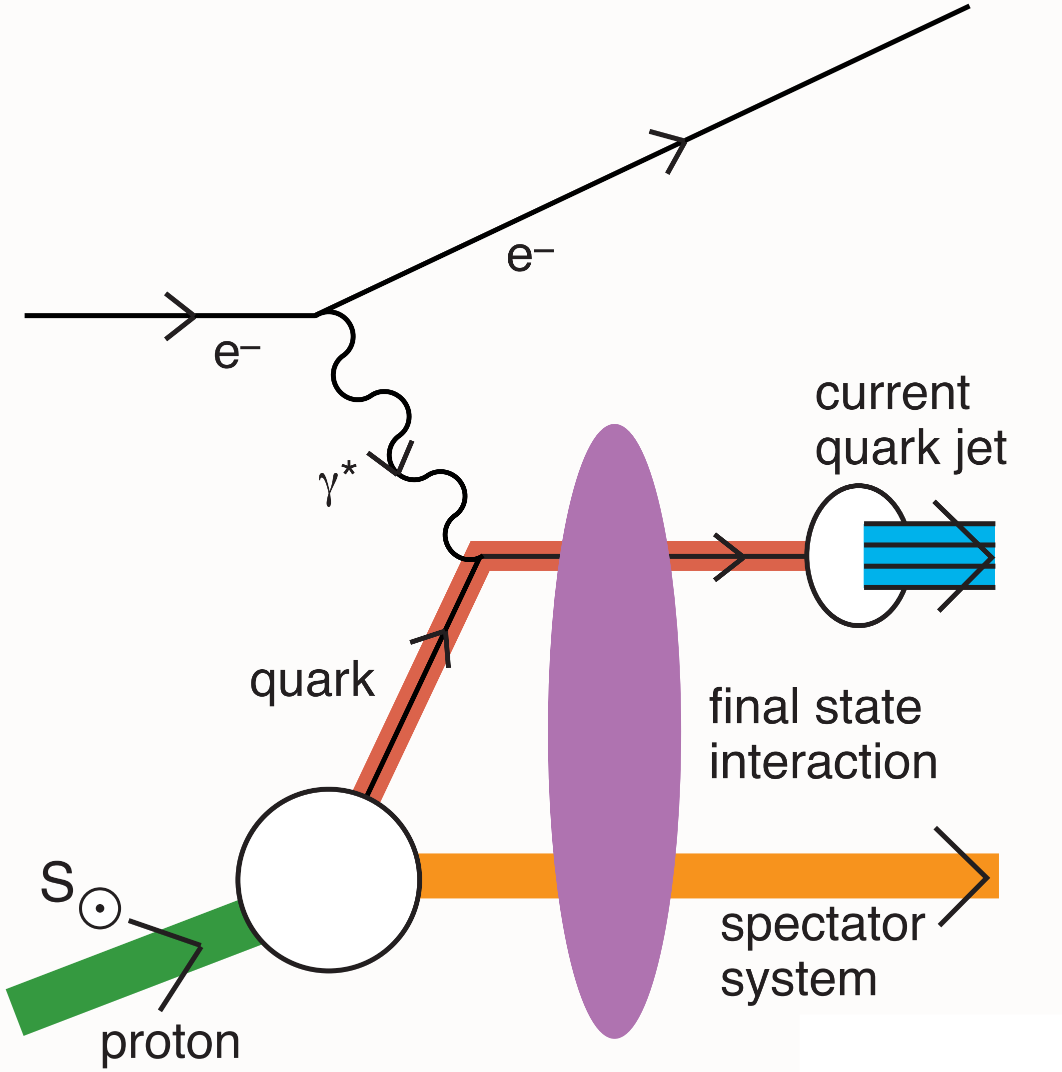
Sivers SSA cancels on an isospin zero target --
gluon contribution to the Sivers asymmetry small
small gluon contribution to orbital angular momentum of nucleon

Polarized Deuteron Target

Gardner, sjb

Sivers Single-Spin Asymmetries for Jets

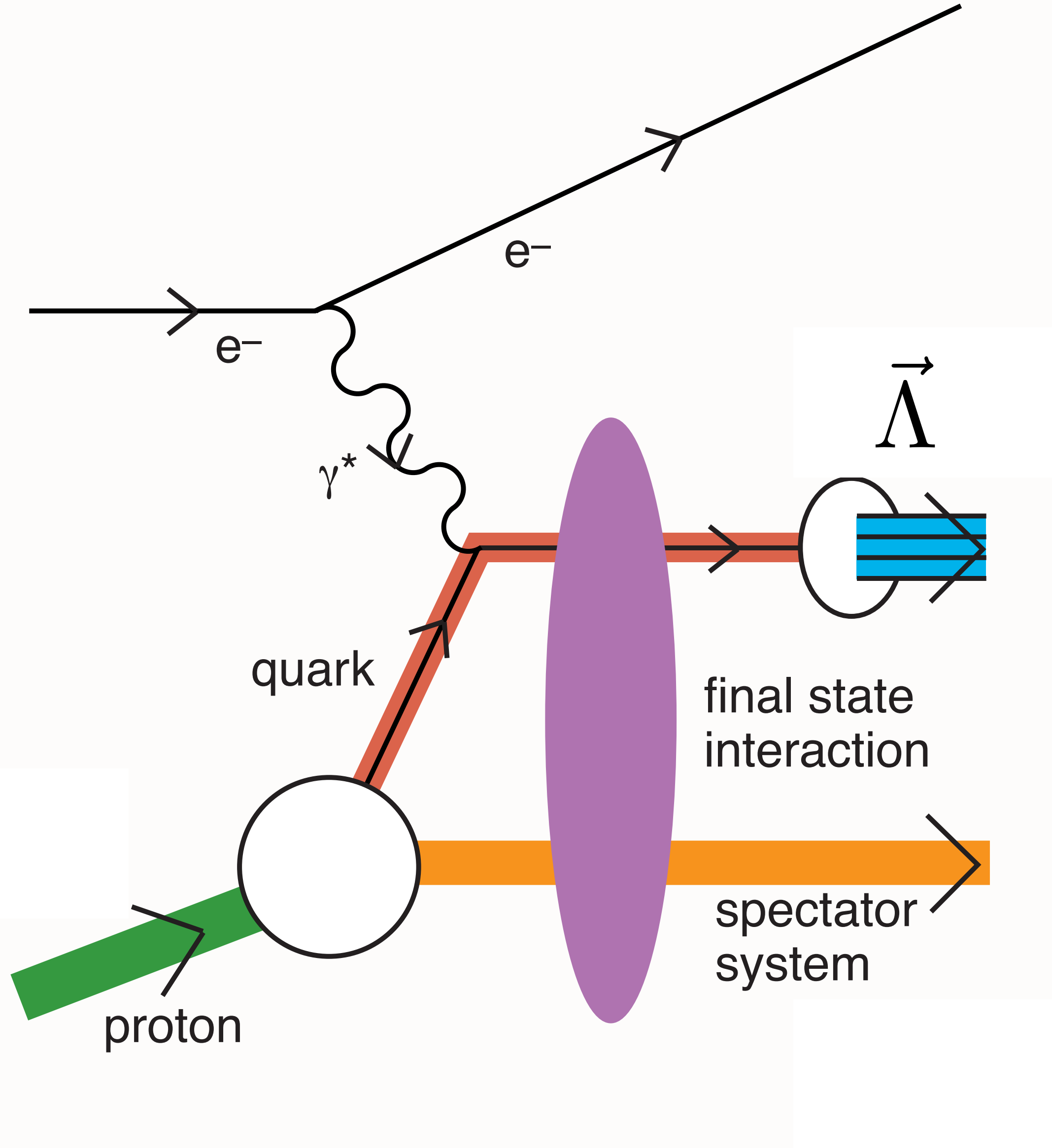
Single-spin asymmetries measuring the $\vec{S} \cdot \vec{p} \times \vec{q}$ correlation in DIS arise from the final-state interactions of the struck quark in DIS; the Wilson line of the quark propagator cannot be neglected in any gauge. Here $\vec{S}$ can be the electron or proton spin and $\vec{p}'$ is the quark momentum as determined by a jet measure such as thrust, or it can be the momentum $\vec{p}_H$ of a hadron from the jet fragmentation. The SSA for jets in DIS is free of the Collins asymmetry from jet fragmentation. It has never been measured.



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

Measure Sivers Asymmetry in DIS Jet Production

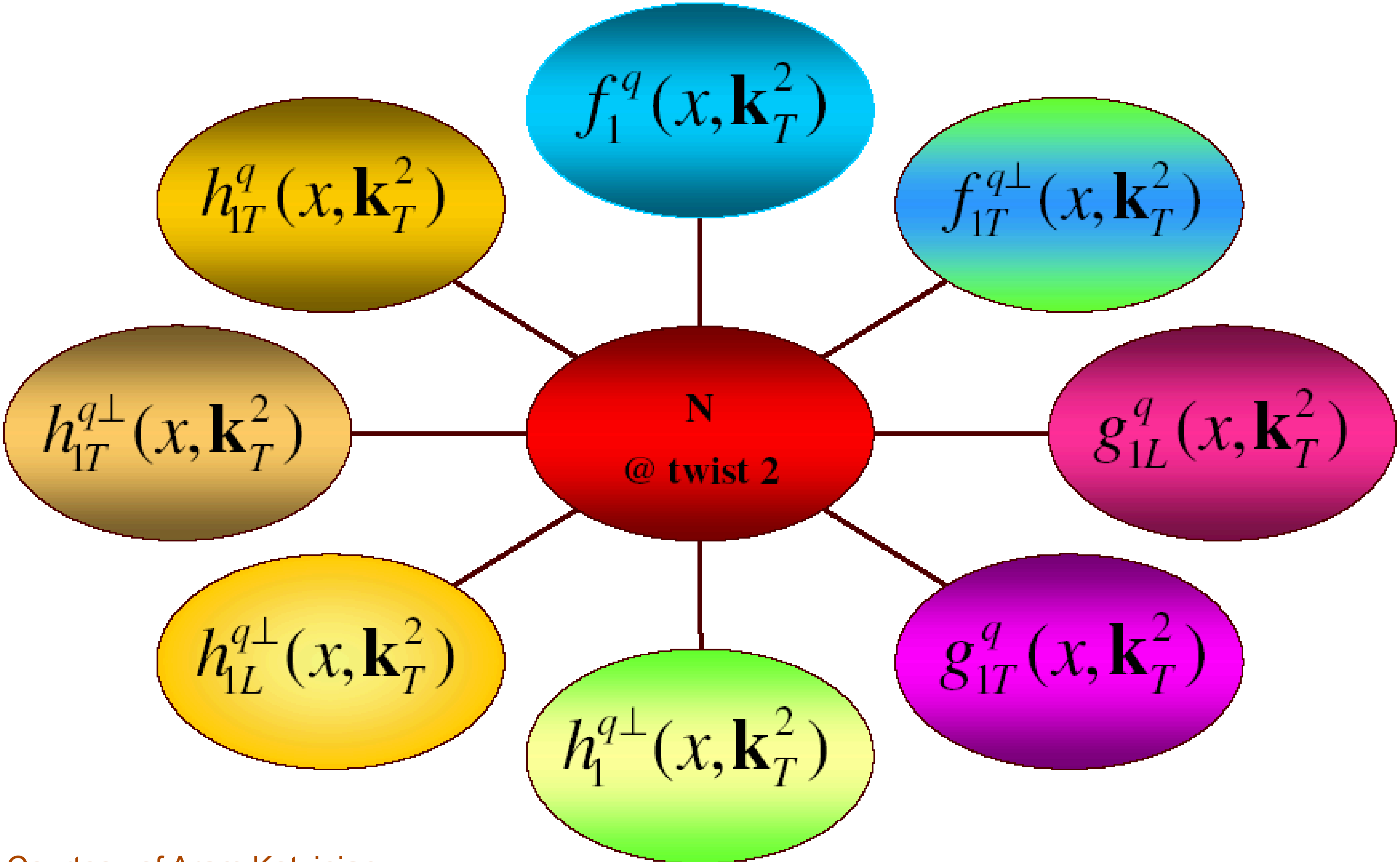
No Collins Effect



$$\vec{S}_\Lambda \cdot \vec{q} \times \vec{p}_q$$

Measure Single-Spin Asymmetry in Polarized Hyperon Production

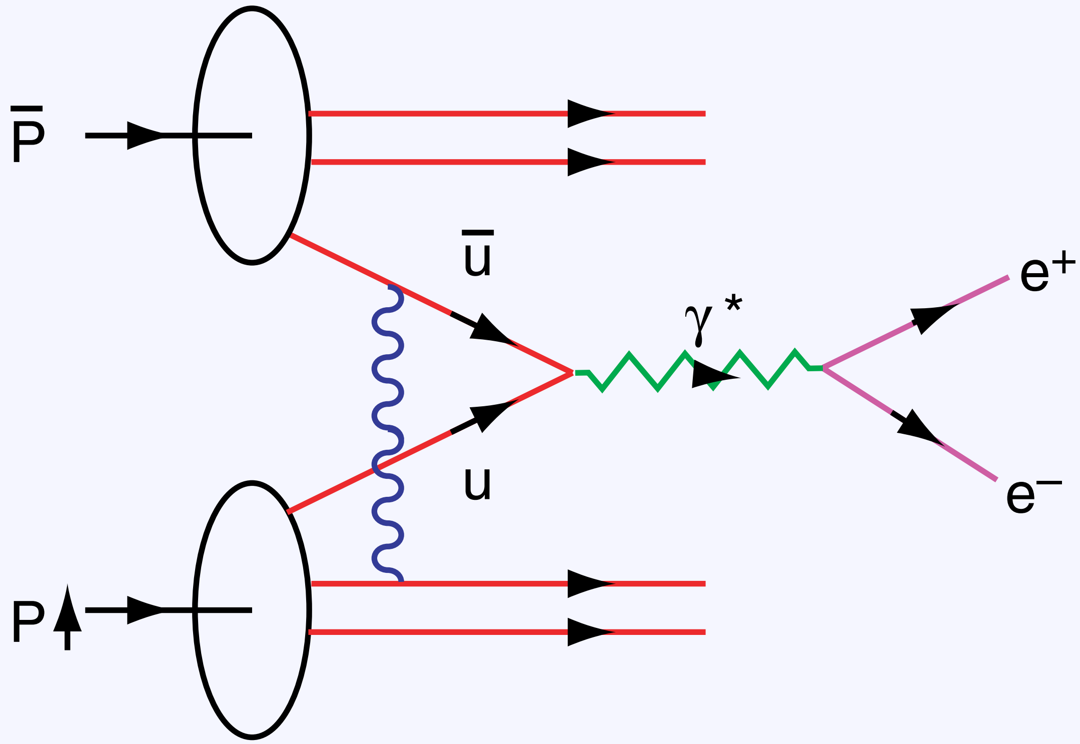
8 leading-twist spin-$k_\perp$ dependent distribution functions



Courtesy of Aram Kotzinian

Predict Opposite Sign SSA in DY !

Collins;
Hwang, Schmidt.
sjb



Single Spin Asymmetry In the Drell Yan Process

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

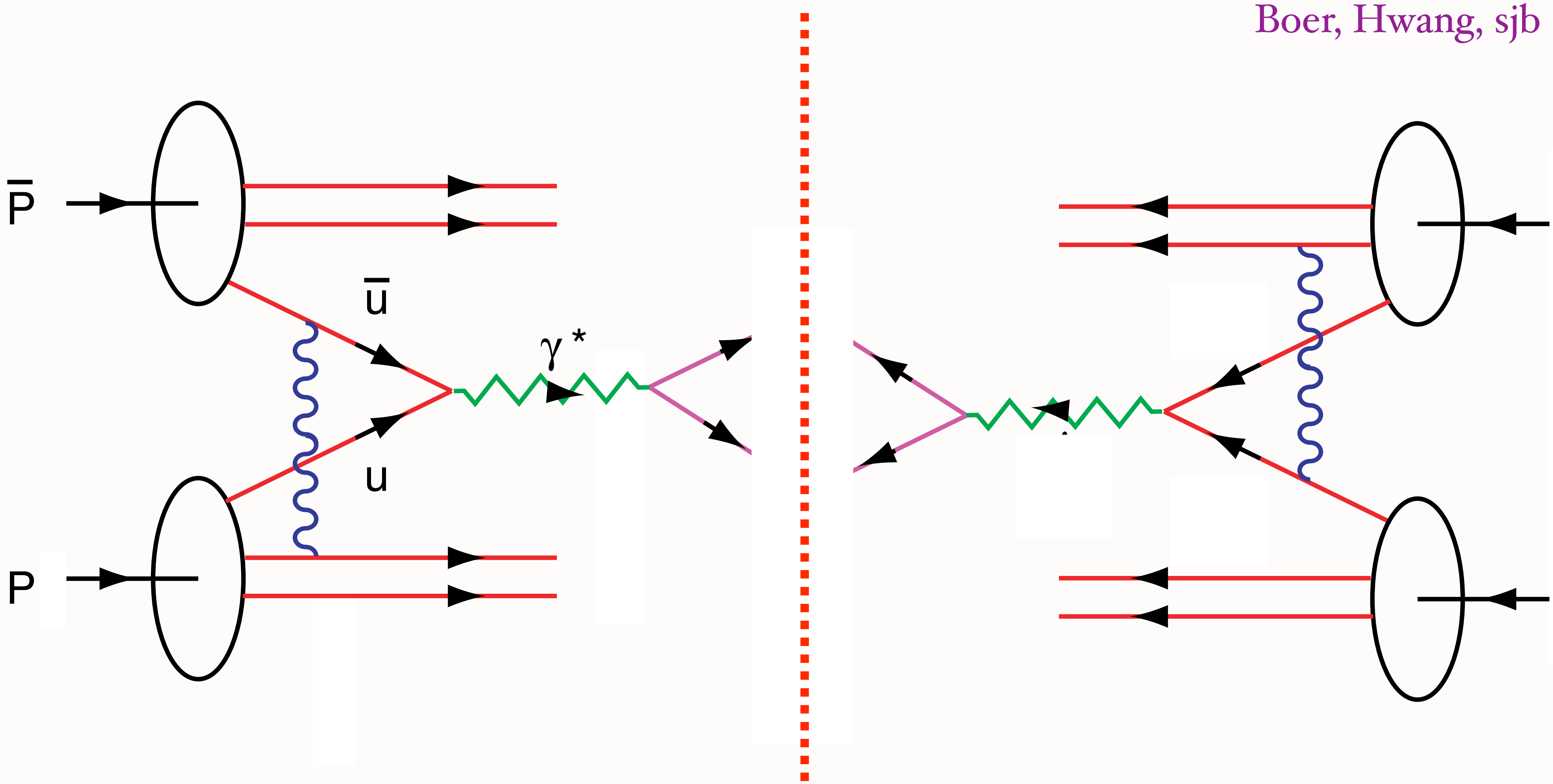
Quarks Interact in the Initial State

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

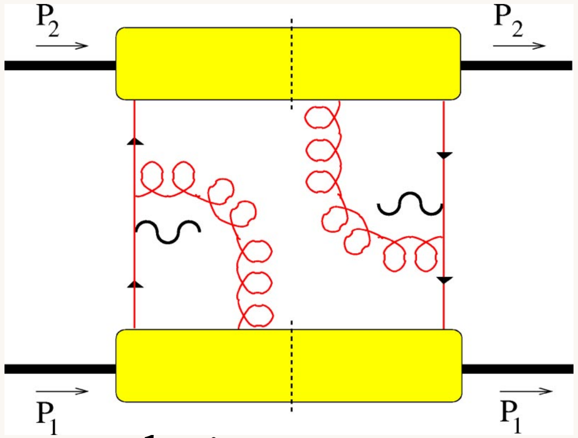


DY $\cos 2\phi$ correlation at leading twist from double ISI

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 $\cos 2\phi$

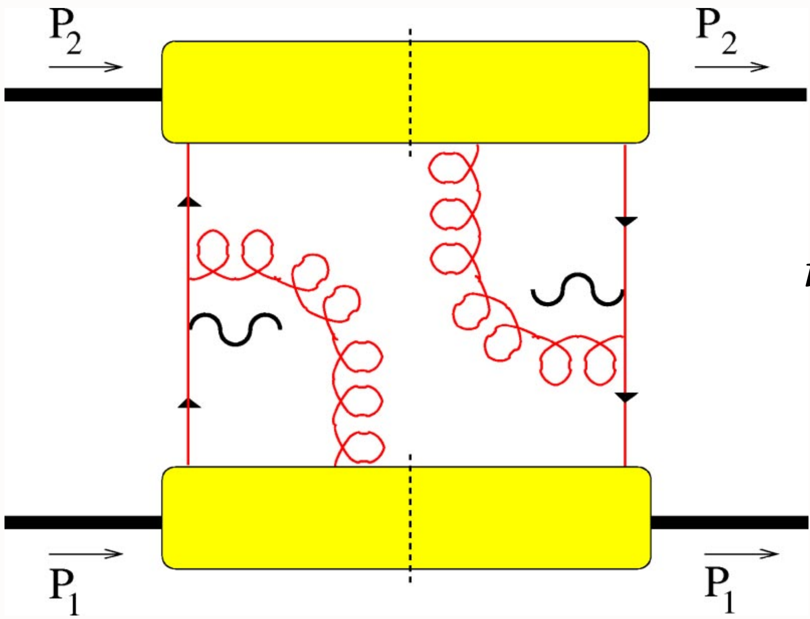
Boer, Hwang, sjb

Drell-Yan planar correlations

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

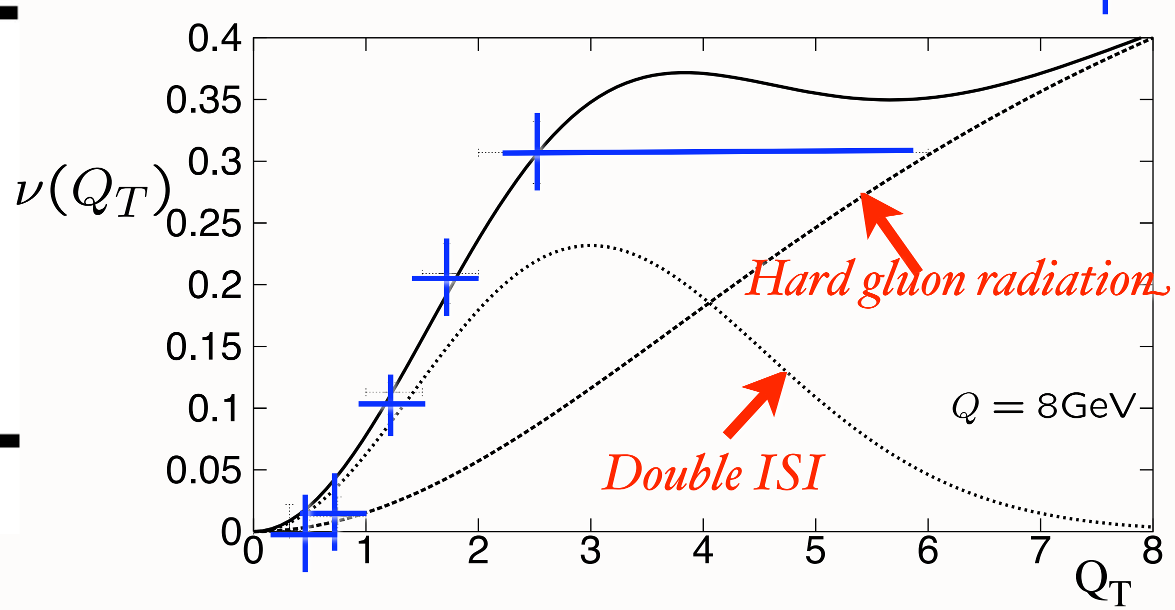
PQCD Factorization (Lam Tung): $1 - \lambda - 2\nu = 0$

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

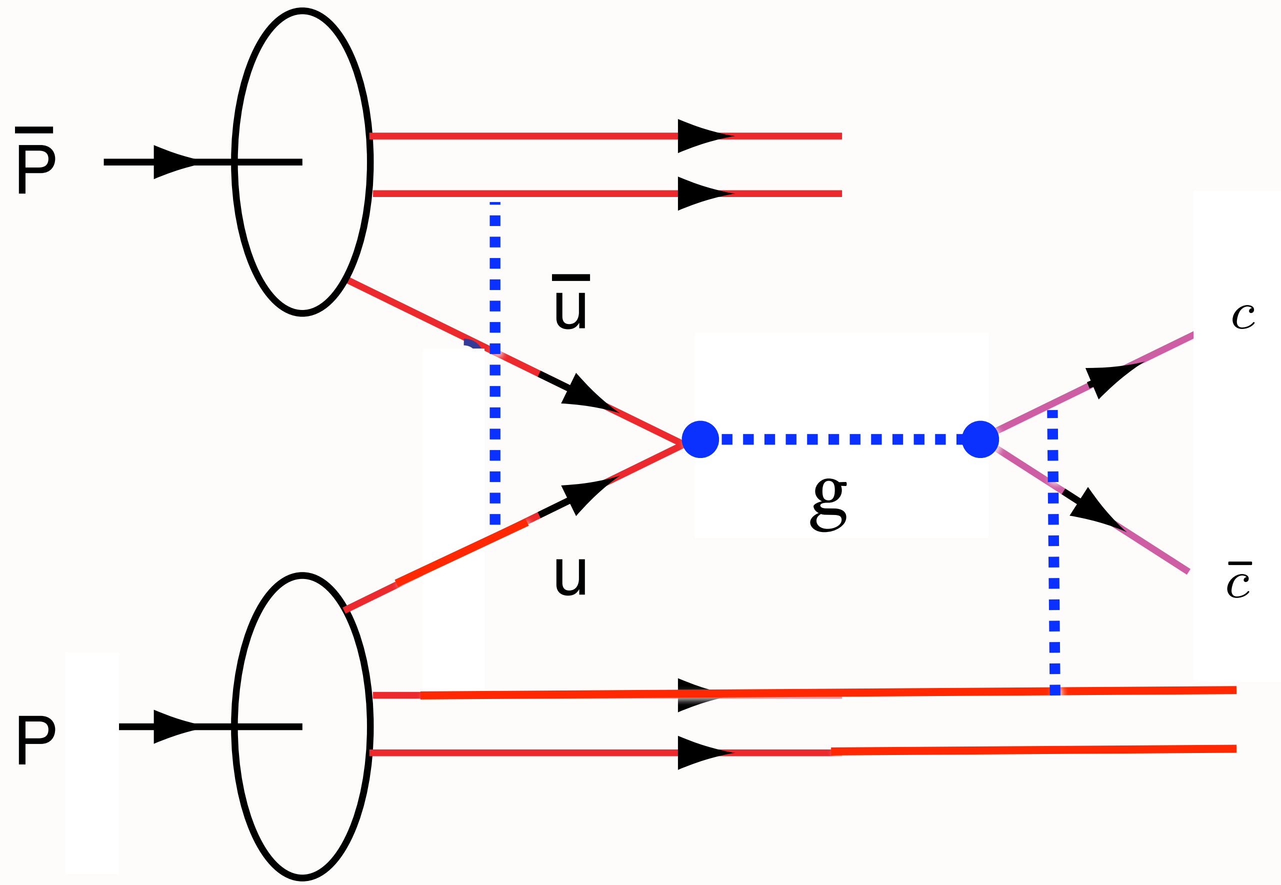


Violates Lam-Tung relation!

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



Model: Boer,

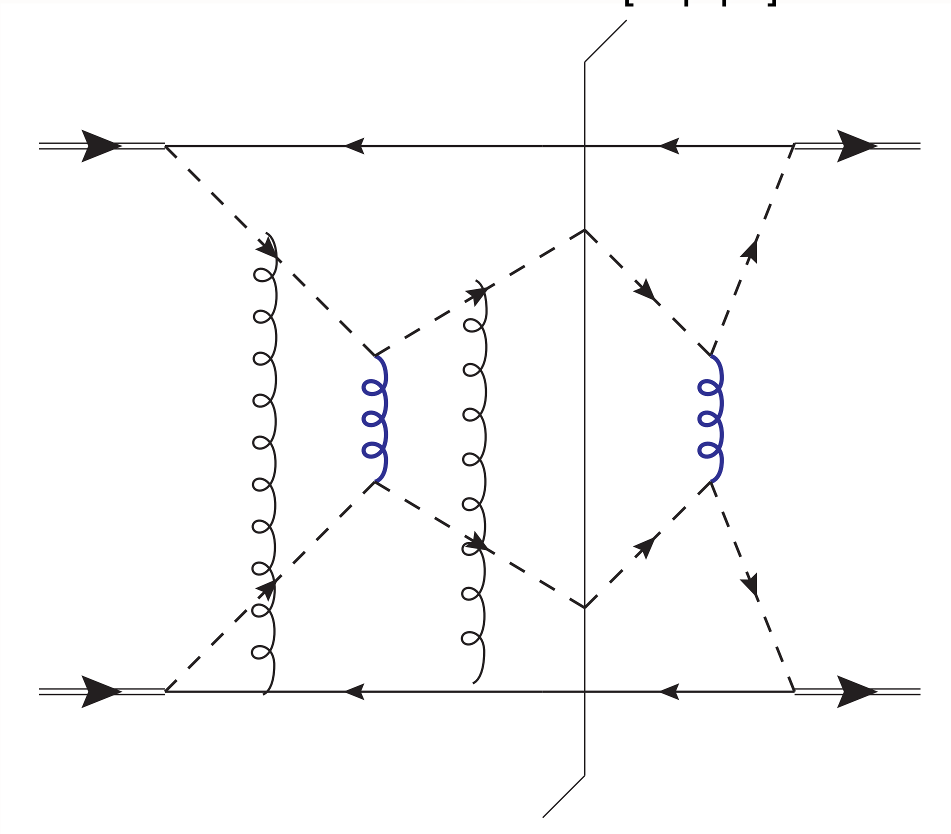


Problem for factorization when both ISI and FSI occur

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.

"Dangling Gluons"

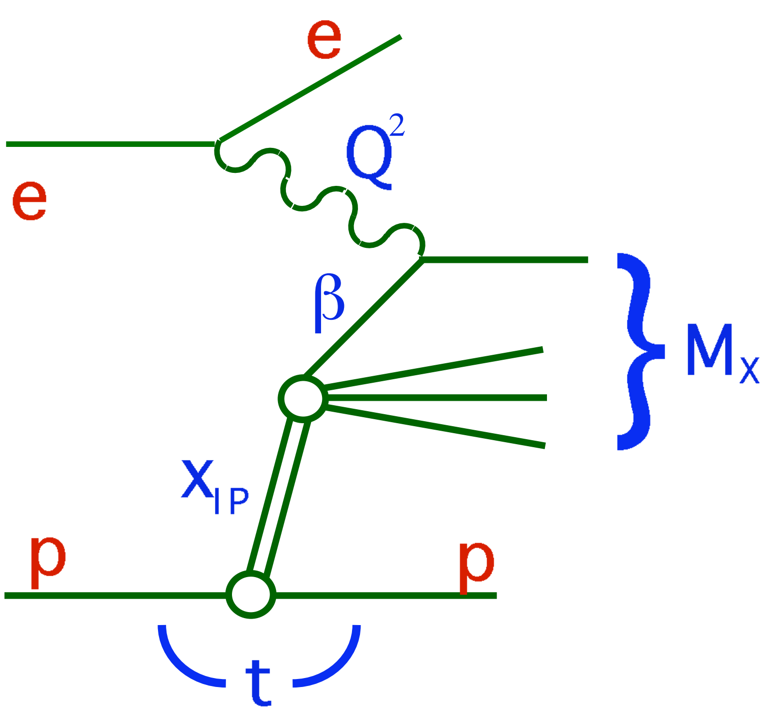
- Diffractive DIS
- Non-Unitary Correction to DIS: Structure functions are not probability distributions
- Nuclear Shadowing, Antishadowing- Not in Target WF
- Single Spin Asymmetries -- opposite sign in DY and DIS
- DY $\cos 2\phi$ distribution at leading twist from double ISI-- not given by PQCD factorization -- 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!

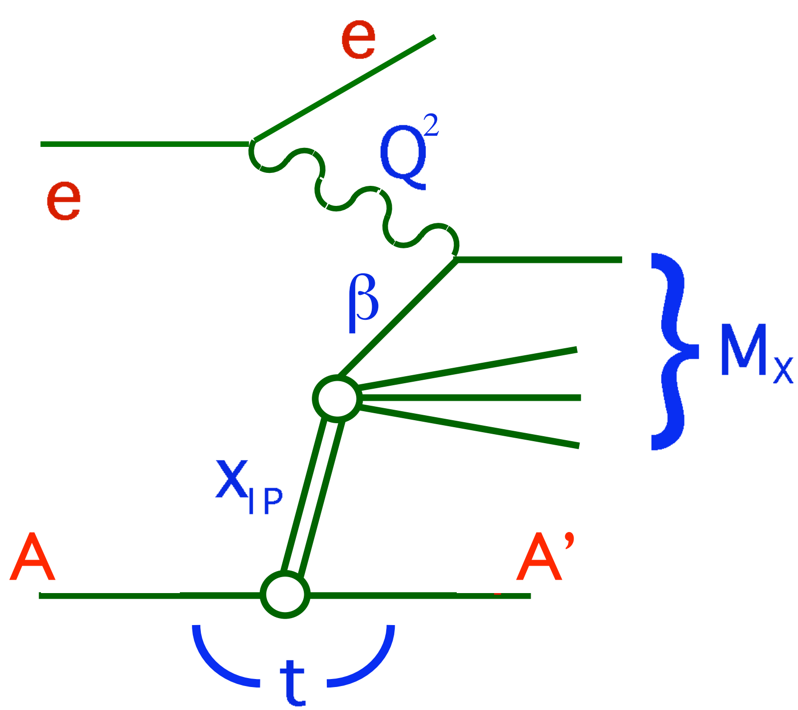
Hoyer, Marchal, Peigne, Sannino, sjb

Diffractive Deep Inelastic Scattering

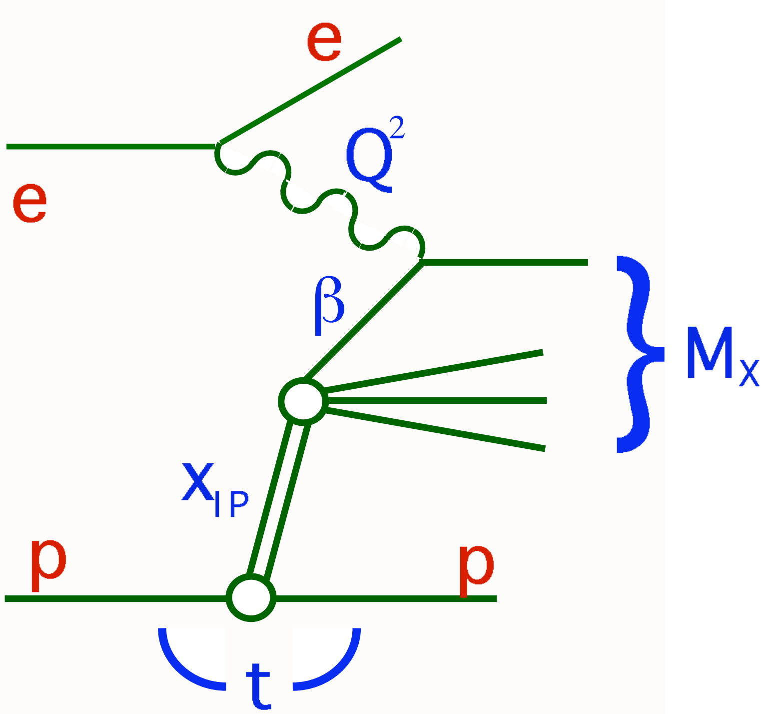
Diffractive DIS $ep \to epX$ where there is a large rapidity gap and the target nucleon remains intact probes the final state interaction of the scattered quark with the spectator system via gluon exchange.

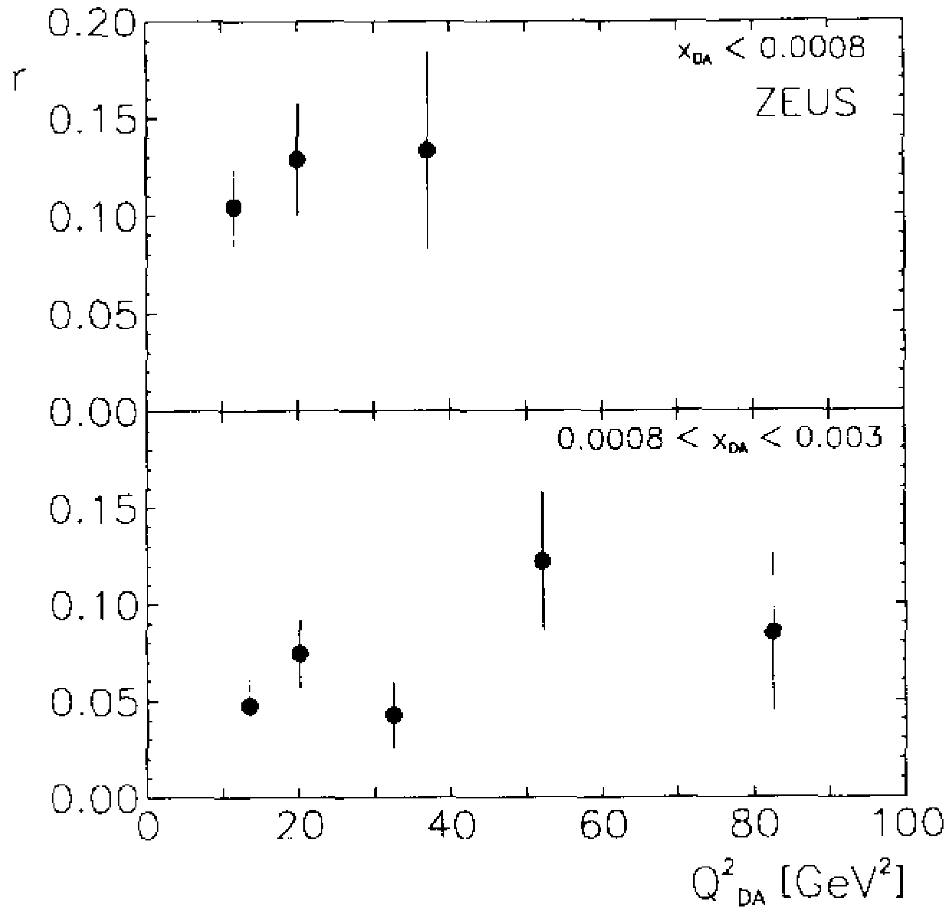
Diffractive DIS on nuclei $eA \to e'AX$ and hard diffractive reactions such as $\gamma^* A \to VA$ can occur coherently leaving the nucleus intact.





Remarkable observation at HERA



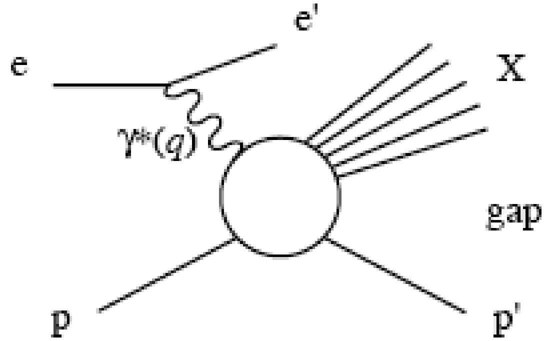


Fraction r of events with a large rapidity gap, $\eta_{max} < 1.5$, as a function of Q^2_{DA} for two ranges of x_{DA}. No acceptance corrections have been applied.

10% to 15% of DIS events are diffractive !

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

DDIS

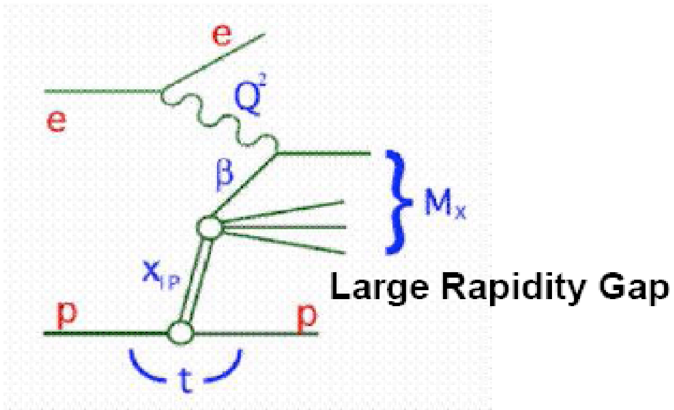


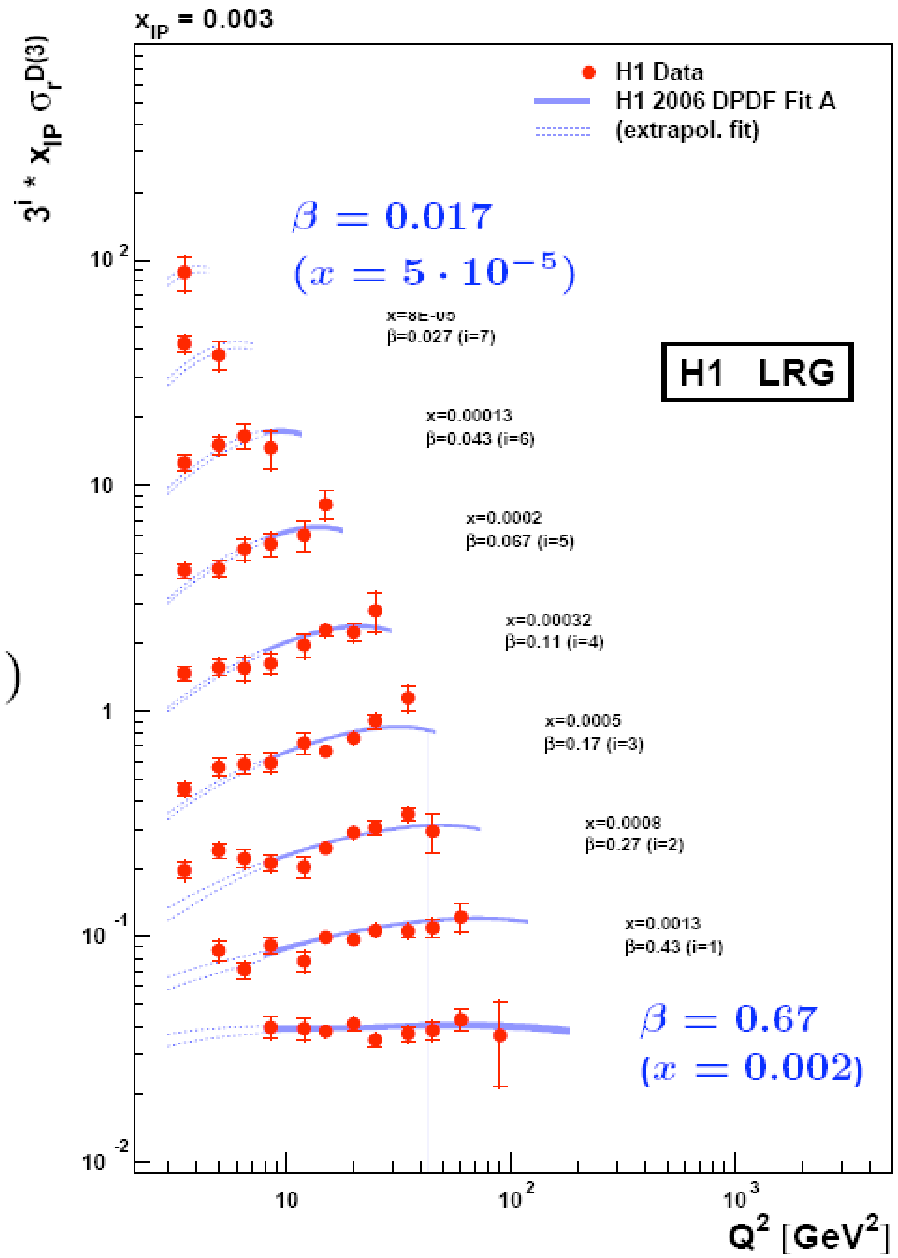
- In a large fraction ($\sim$ 10–15%) of DIS events, the proton escapes intact, keeping a large fraction of its initial momentum
- This leaves a large *rapidity gap* between the proton and the produced particles
- The t-channel exchange must be *color singlet* $\rightarrow$ a pomeron??

Diffractive Deep Inelastic Lepton-Proton Scattering

de Roeck

Diffractive Structure Function F_2^D





Diffractive inclusive cross section

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

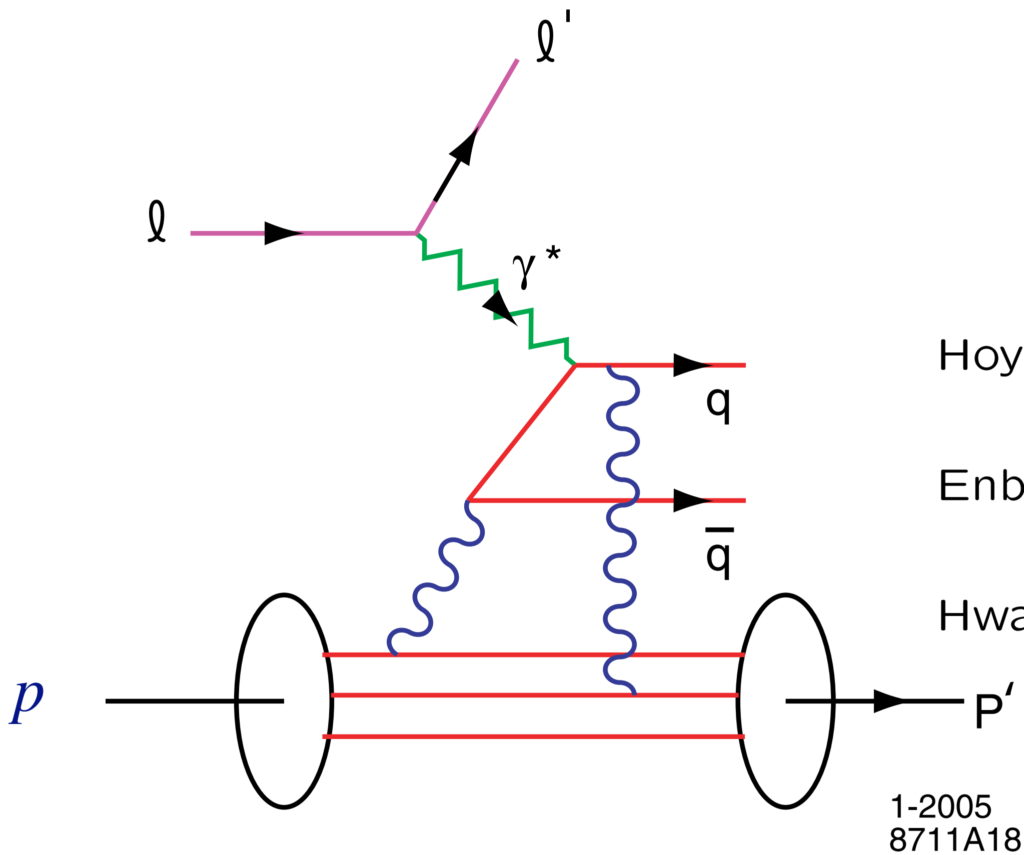
$$F_2^D(x_{I\!P}, \beta, Q^2) = f(x_{I\!P}) \cdot F_2^{I\!P}(\beta, Q^2)$$

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

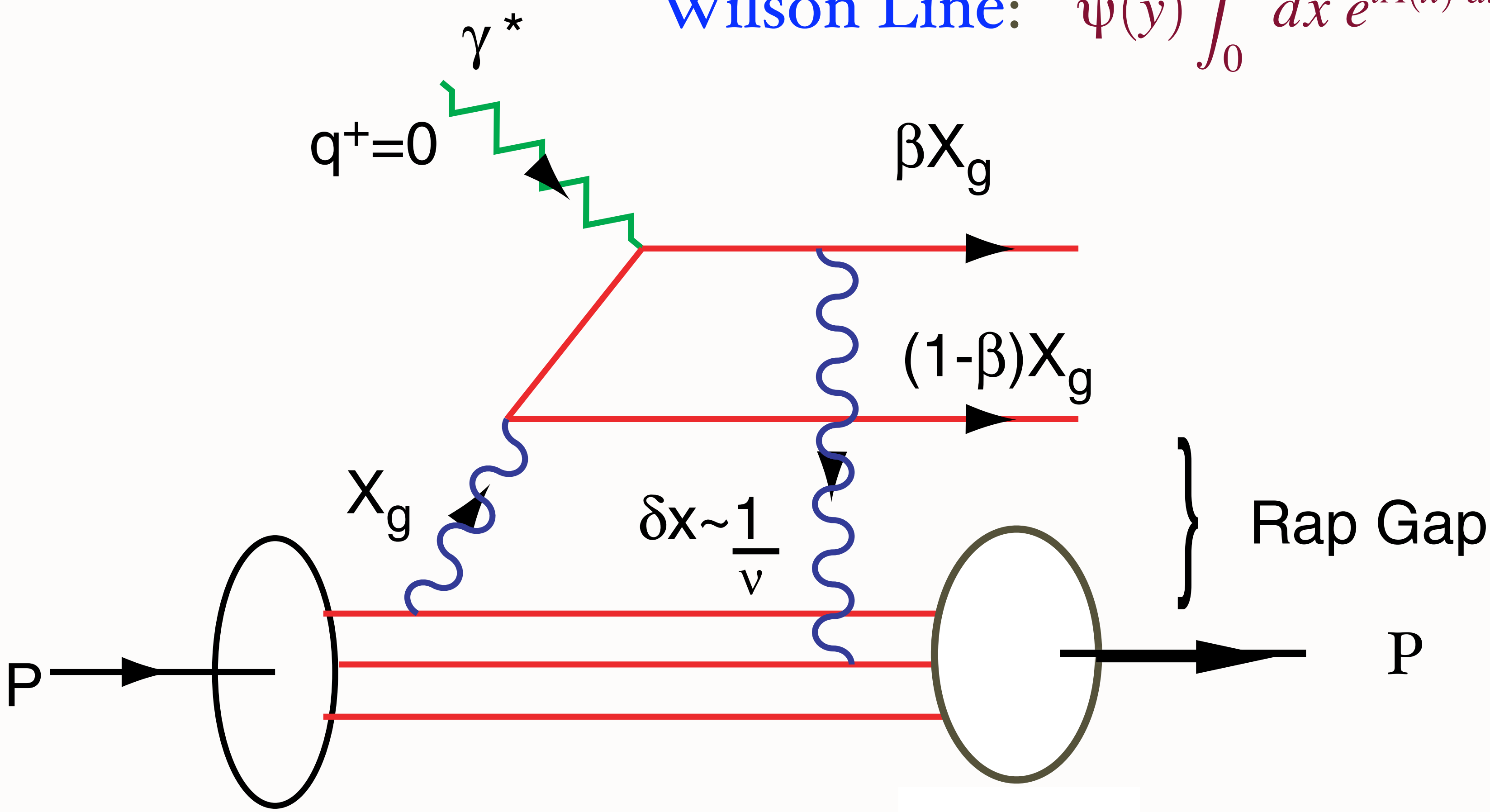
Hwang, Schmidt, SJB

Low-Nussinov model of Pomeron

Hoyer, Marchal, Peigne, Sannino, sjb

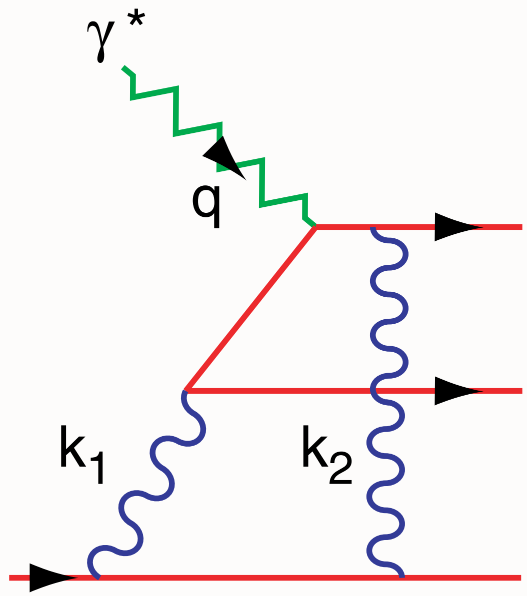
QCD Mechanism for Rapidity Gaps

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

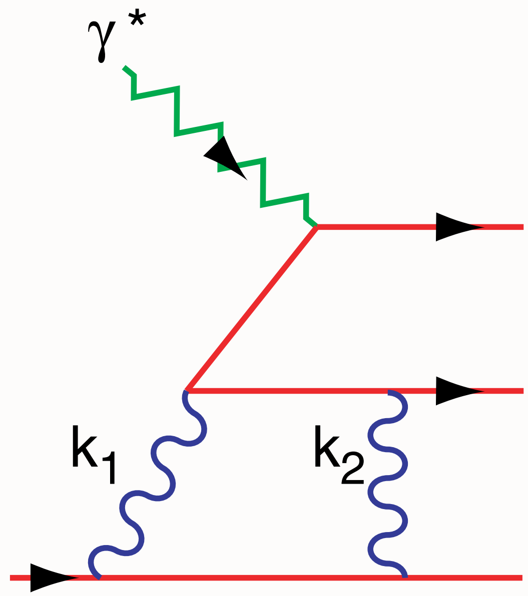


Reproduces lab-frame color dipole approach

Final State Interactions in QCD

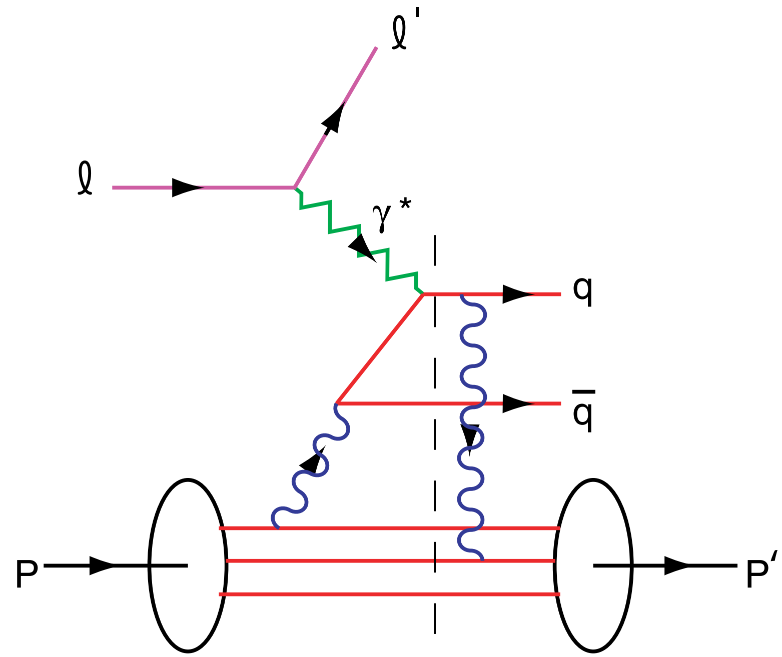


Feynman Gauge



Light-Cone Gauge

Result is Gauge Independent



Integration over on-shell domain produces phase i

Need Imaginary Phase to Generate Pomeron

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

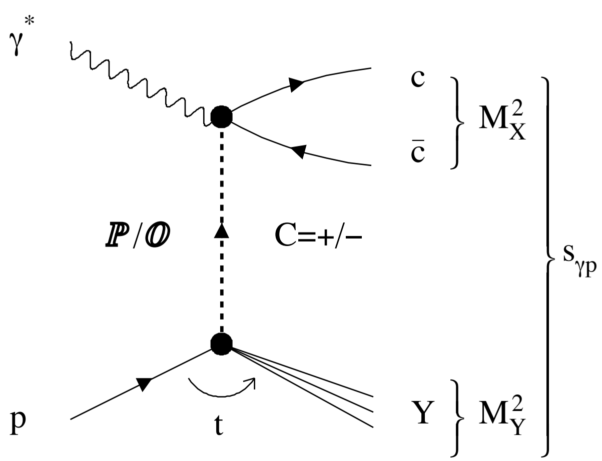
Physics of FSI not in Wavefunction of Target

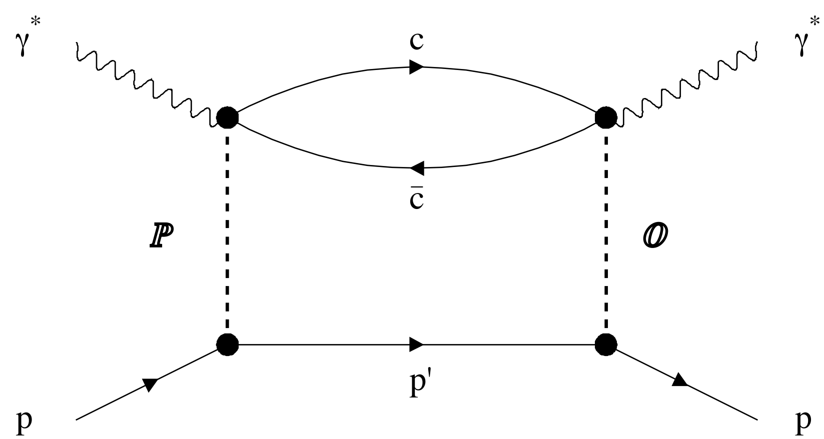
Physics of Rescattering

- 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

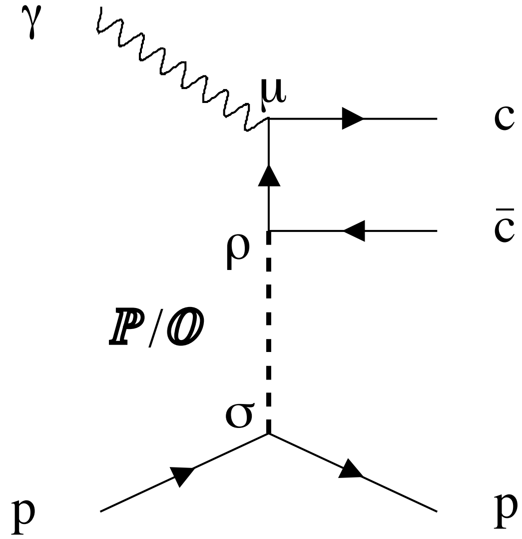
The Odderon

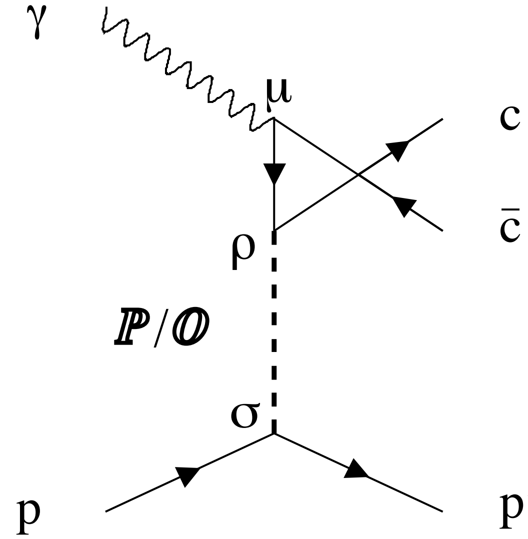
A fundamental prediction of QCD is the existence of the Odderon exchange with odd charge conjugation in the t-channel reflecting three-gluon exchange. The measurement of the asymmetry in the fractional energy distribution of charm versus anti-charm jets produced in high energy diffractive photoproduction $\gamma p \to c\bar{c} + p$ at eRHIC would provide a sensitive test of the interference of the Odderon and Pomeron exchange amplitudes in QCD. Another possible test is to measure the energy dependence of exclusive process such as $\gamma p \to \pi^0 p$.

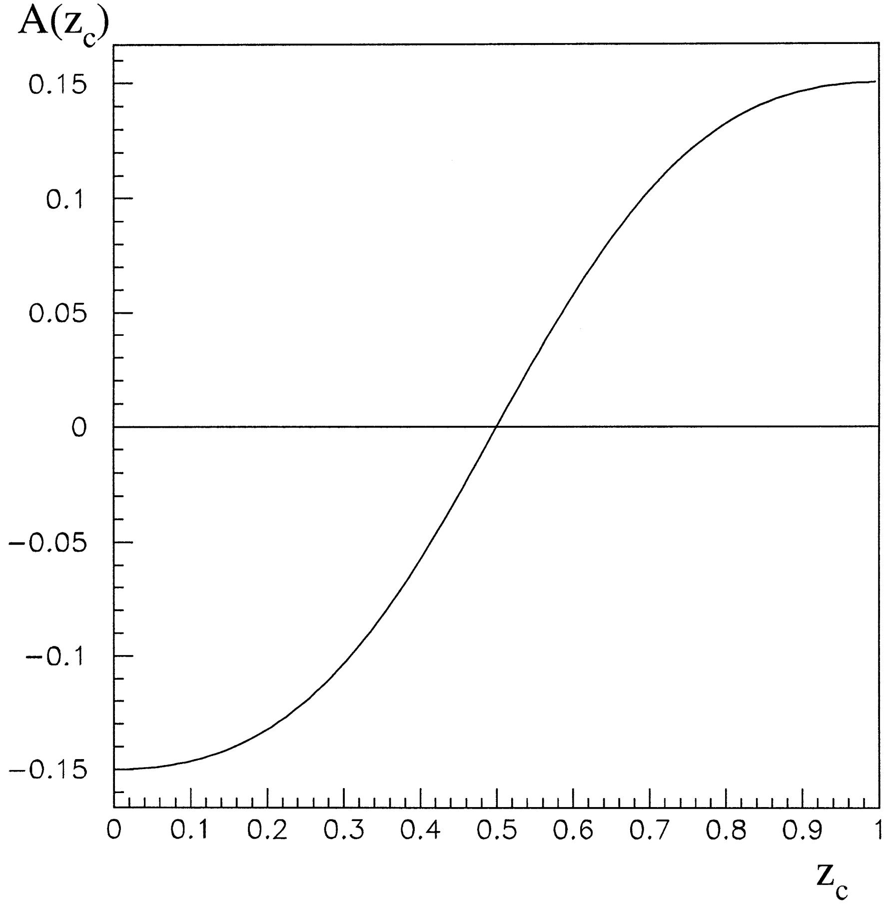




Merino, Rathsman, sjb hep-ph/9904280



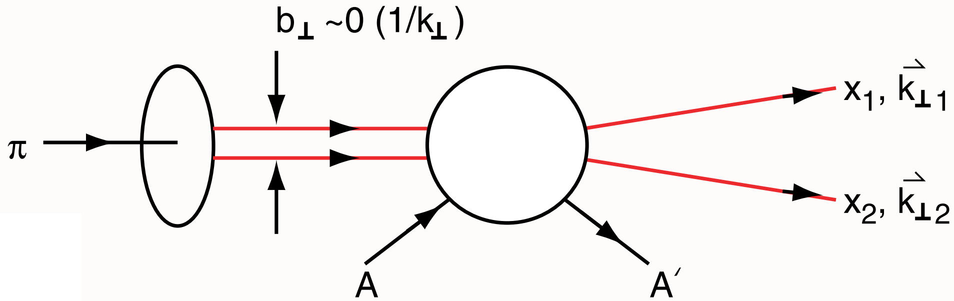




$$\mathscr{A}\left(t \simeq 0, M_X^2, z_c\right) \simeq 0.45 \left(\frac{s_{\gamma p}}{M_X^2}\right)^{-0.25} \frac{2\,z_c - 1}{z_c^2 + (1 - z_c)^2}$$

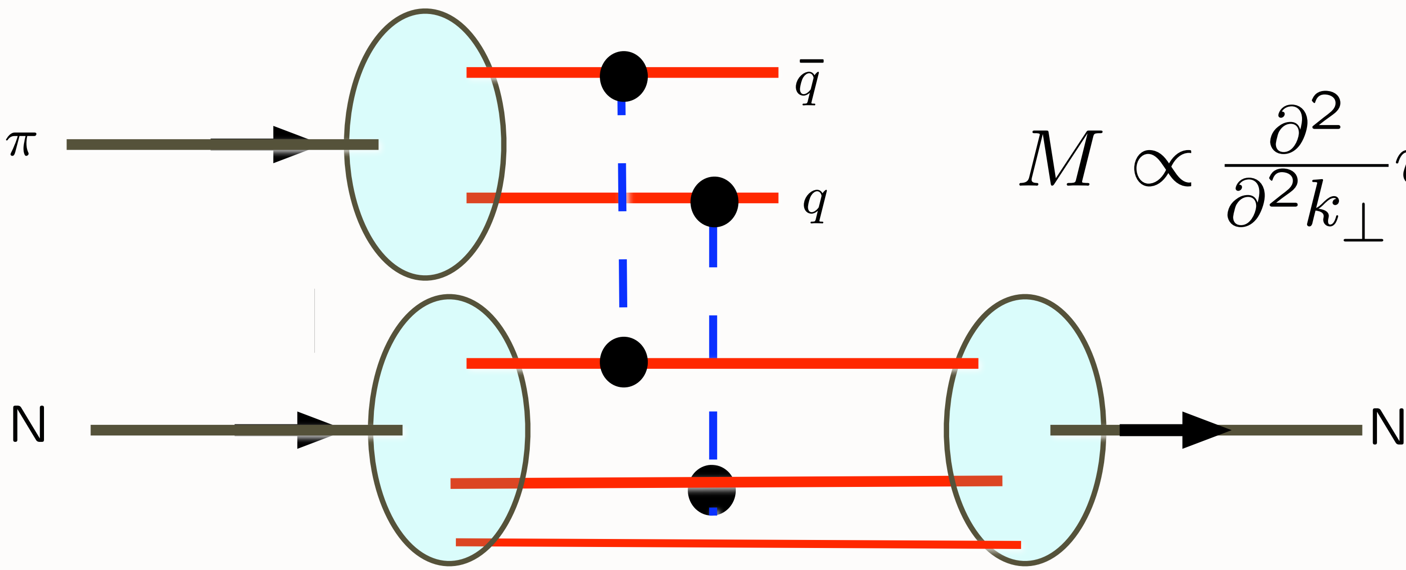
Measure charm asymmetry
in photon fragmentation region

E791 FNAL Diffractive DiJet



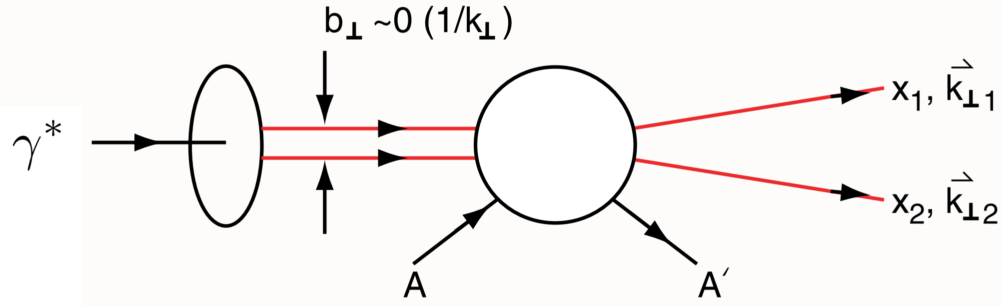
Gunion, Frankfurt, Mueller, Strikman, sjb
Frankfurt, Miller, Strikman

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

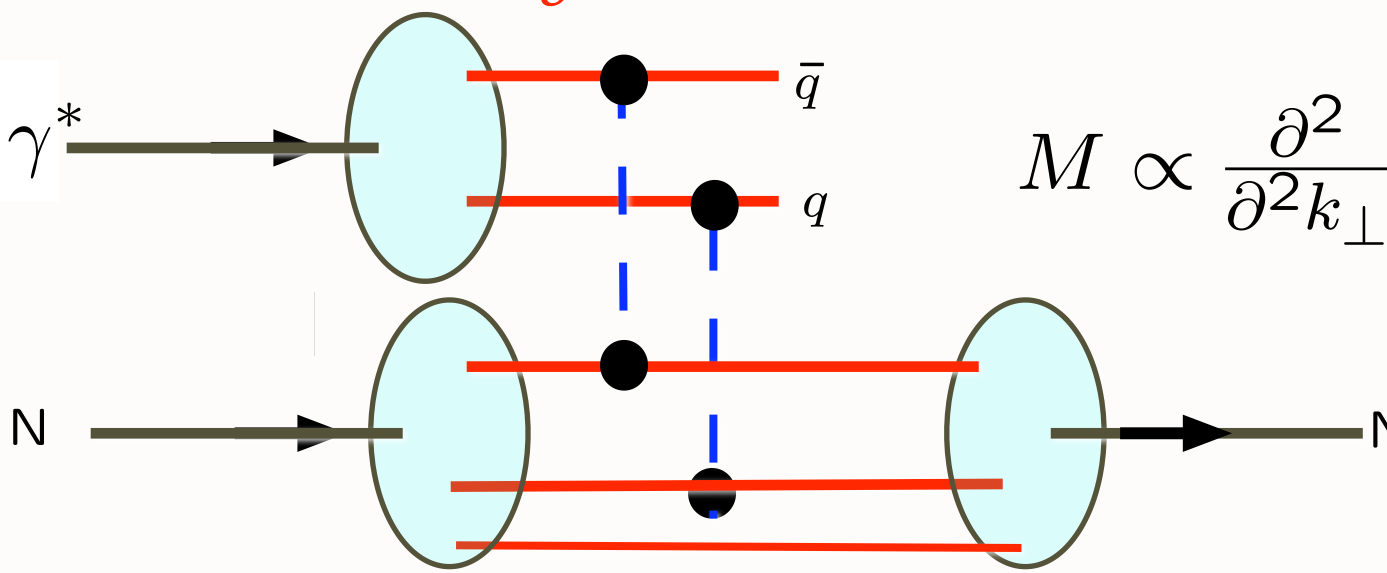


$$M \propto \frac{\partial^2}{\partial^2 k_\perp} \psi_\pi(x, k_\perp)$$

Diffractive Dissociation of the Photon to Jets



Two-gluon exchange measures the second derivative of the photon's
light-front wavefunction



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

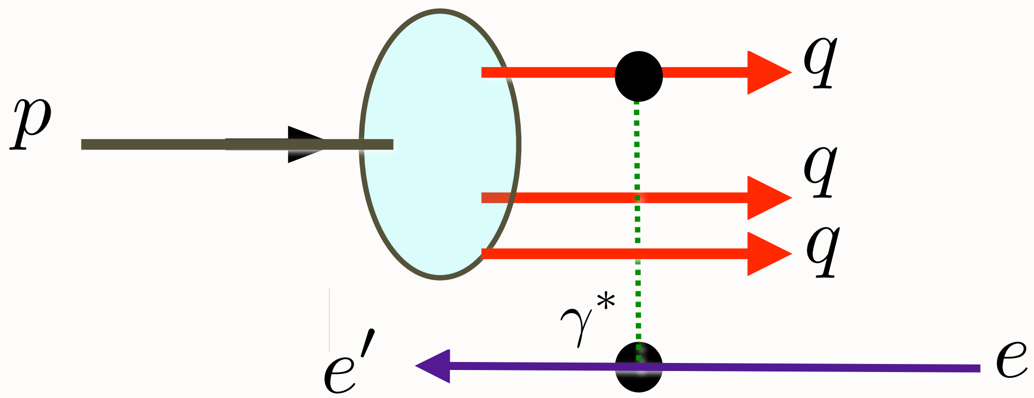
Coulomb Dissociation of the Proton to Jets

The diffractive dissociation of the pion into di-jets was measured by E791 at Fermilab, thus determining the pion light-front $q\bar{q}$ wavefunction. An analogous measurement of the proton's wavefunction via diffractive dissociation of the proton into three jets can be carried out using Coulomb excitation $ep \to e'qqq$.

Coulomb Dissociation of the Proton to Jets

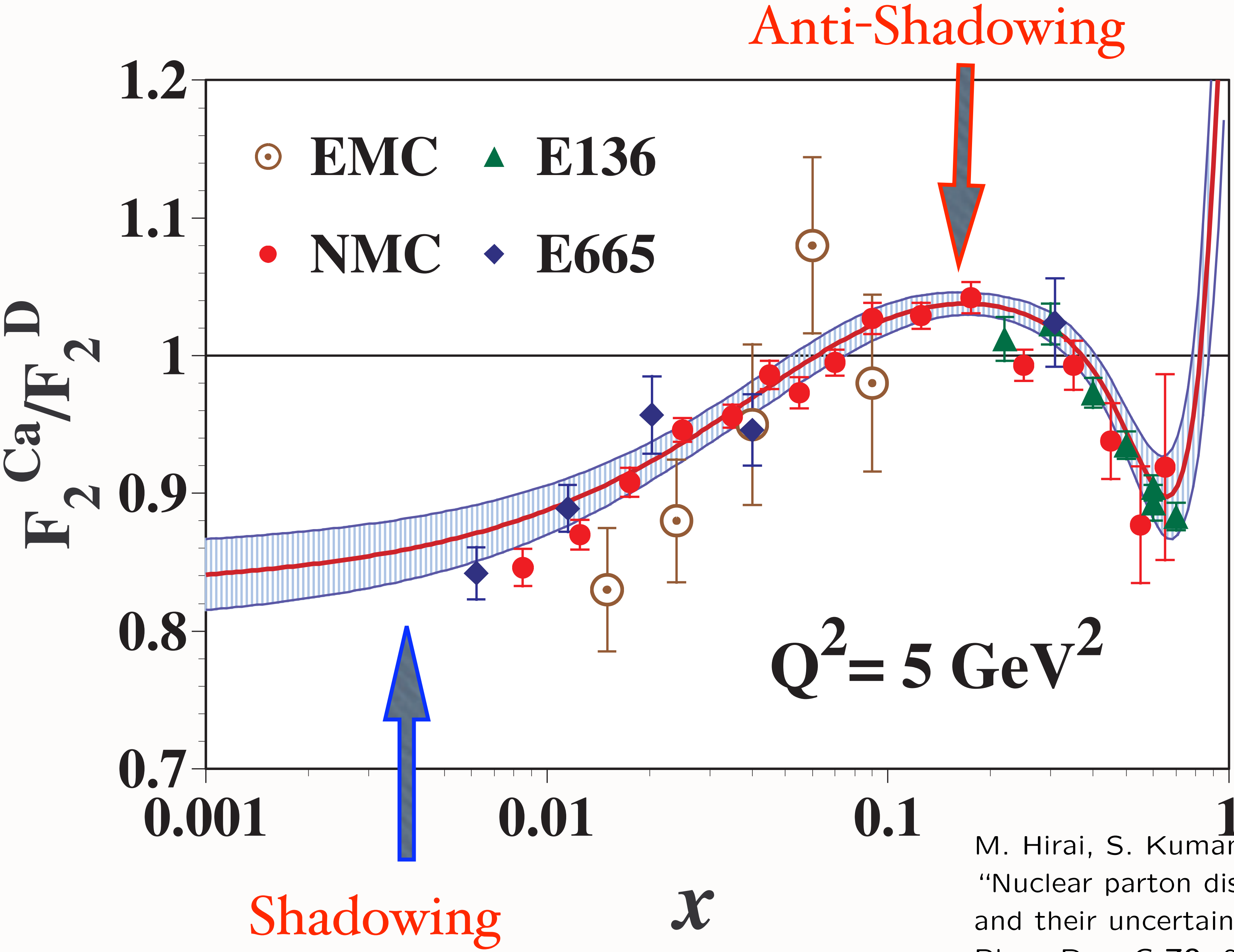
$$p\ e \rightarrow jet\ jet\ jet\ e'$$

Coulomb exchange measures the first derivative of the proton light-front wavefunction



Anti-Shadowing: Flavor Specific?

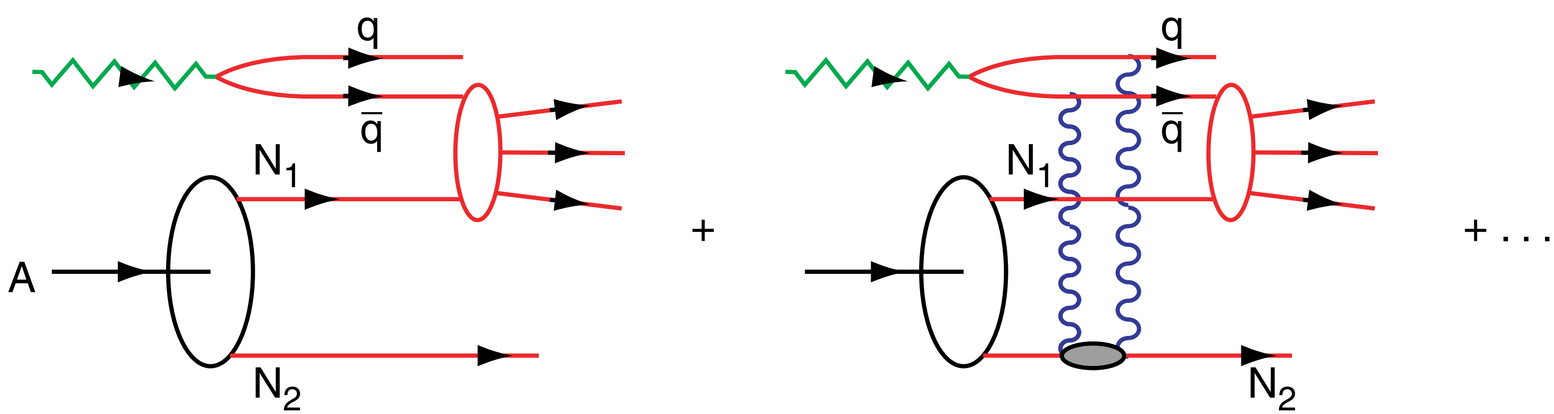
It has been predicted that the anti-shadowing of nuclear structure functions is not universal, but rather is quark- flavor specific. This phenomenon may be related to the NuTeV anomaly. It can be tested in semi-inclusive DIS in nuclei where the quark flavor can be tagged.



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

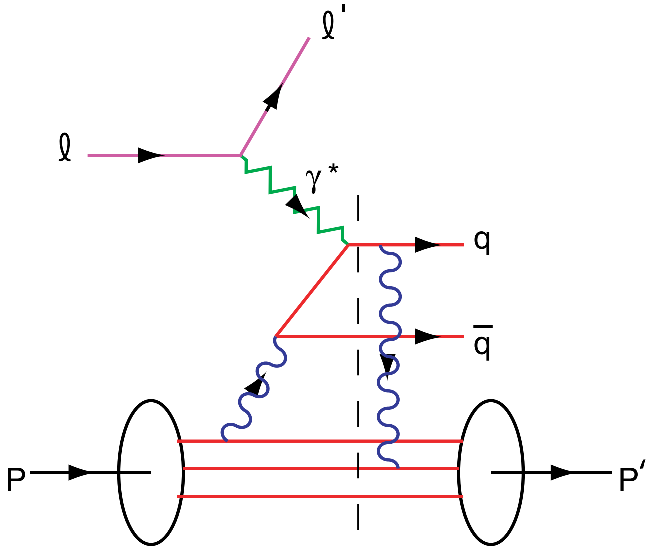
Nuclear Shadowing in QCD



Shadowing depends on understanding leading twist-diffraction in DIS

Nuclear Shadowing not included in nuclear LFWF !

Dynamical effect due to virtual photon interacting in nucleus



Shadowing depends on understanding leading-twist-diffraction in DIS

Integration over on-shell domain produces phase i

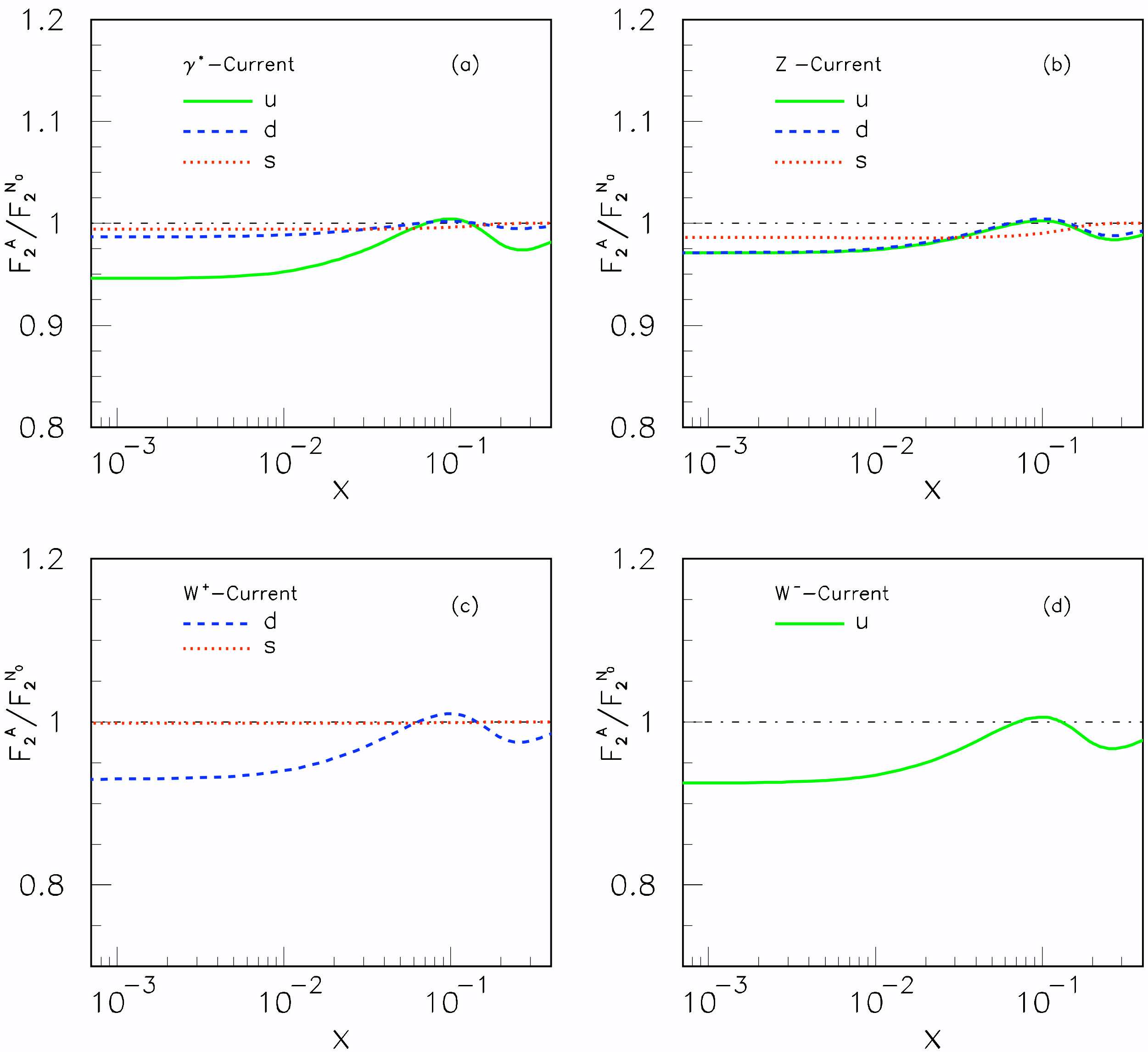
Need Imaginary Phase to Generate Pomeron

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

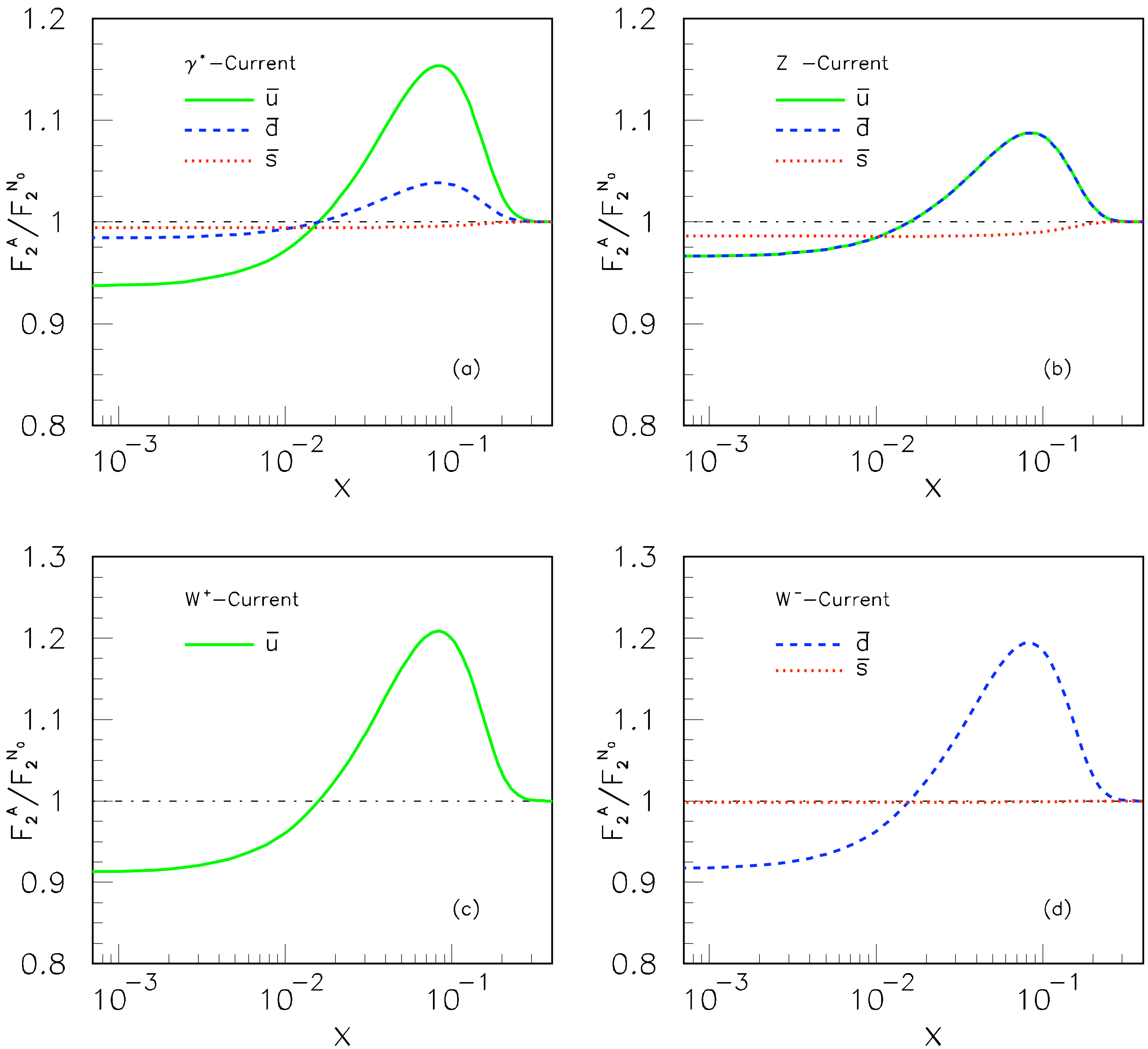
Physics of FSI not in Wavefunction of Target

Antishadowing (Reggeon exchange) is 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].



Nuclear Effect not Universal !

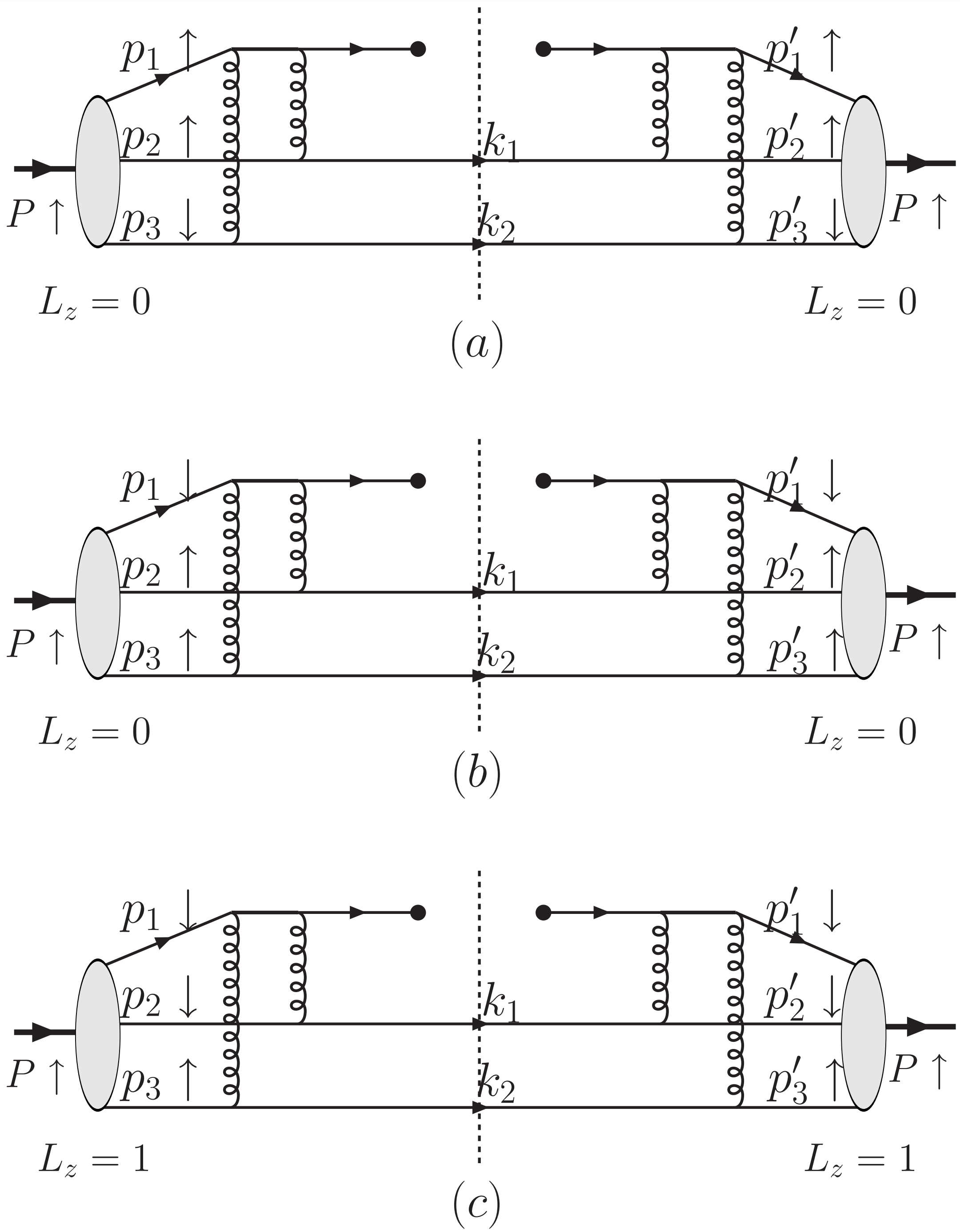
Breakdown of DGLAP at Large x

DGLAP evolution of the proton structure breaks down as one enters the large x fixed W^2 domain since the struck quark is far off shell at $x \to 1$. This phenomena is essential in order to preserve exclusive-inclusive duality even at large Q^2. The structure functions of nuclei at $x > 1$ reflect fundamental features of the nuclear wavefunction in QCD, including hidden color dynamics.

Perturbative QCD Analysis of Structure Functions at x ~ 1

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

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



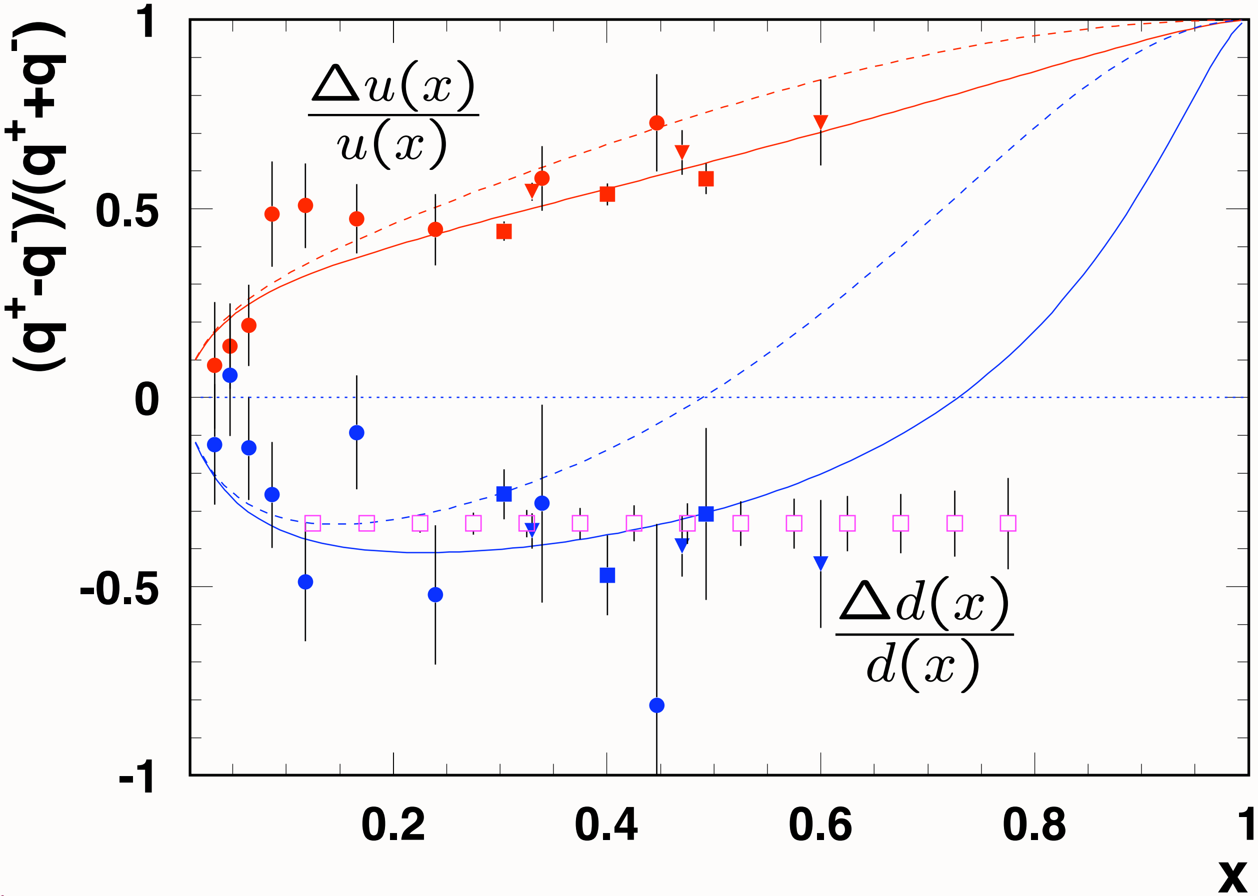
$q^-(x) \propto (1-x)^5 \log^2(1-x)$

From nonzero orbital angular momentum

Avakian, sjb, Deur, Yuan

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

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



Avakian, sjb, Deur, Yuan

Similar to Ji, Balitsky, Yuan's PQCD analysis of $F_2(Q^2)/F_1(Q^2)$

Perturbative QCD Analysis of Structure Functions at x ~ 1

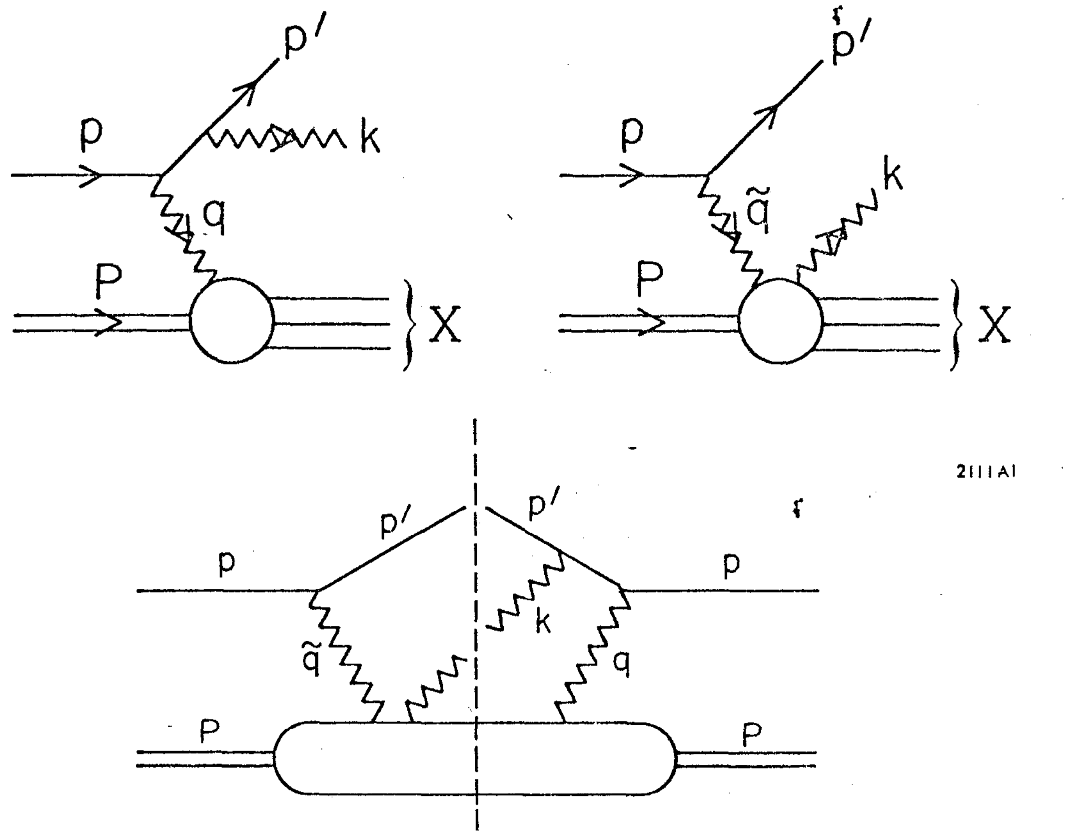
- Struck quark far off-shell at large x $\quad k_F^2 \propto \frac{-k_\perp^2}{1-x}$
- DGLAP evolution quenched due to off-shell struck quark

$$(1-x)^{P+\xi} \qquad \xi(Q^2, Q_0^2) = \frac{1}{4\pi}\int_{Q_0^2}^{Q^2} d\ell^2 \, \frac{\alpha_s(\ell^2)}{\ell^2 + \frac{k_\perp^2}{1-x}}$$

- Duality/ Exclusive-Inclusive connection at fixed W

Fractional Quark Charge Test

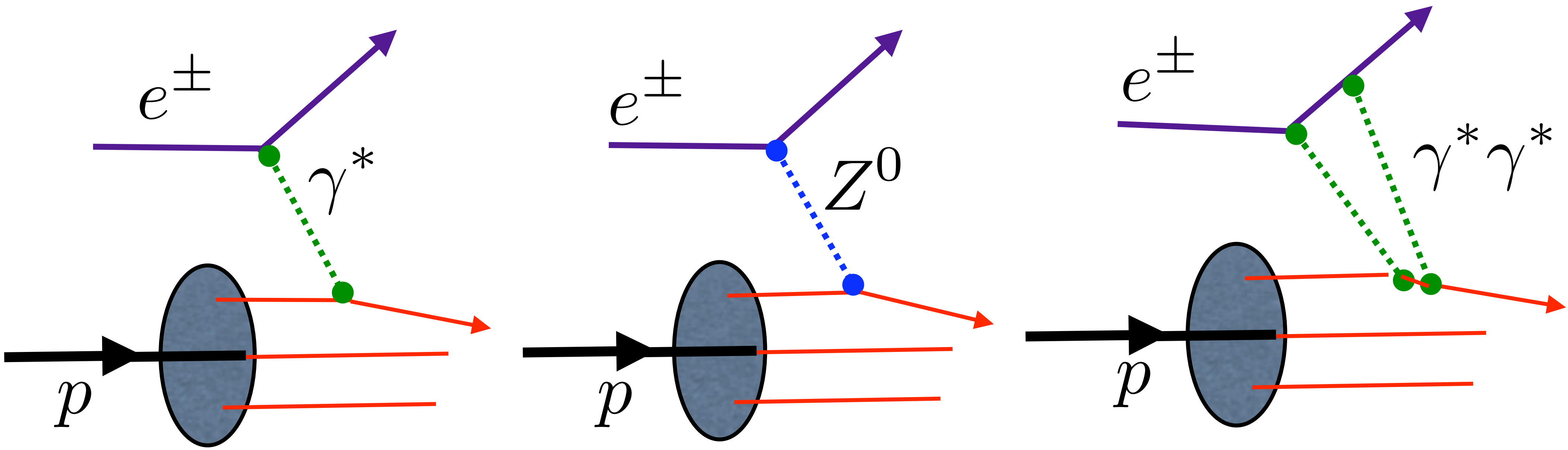
The inclusive reaction $e^{\pm}p \to e^{\pm\prime} + \gamma + X$ at high photon transverse momentum measures Compton scattering on quarks. The electron-positron asymmetry from the interference with Bethe-Heitler bremsstrahlung measures the cube of the quark charges.



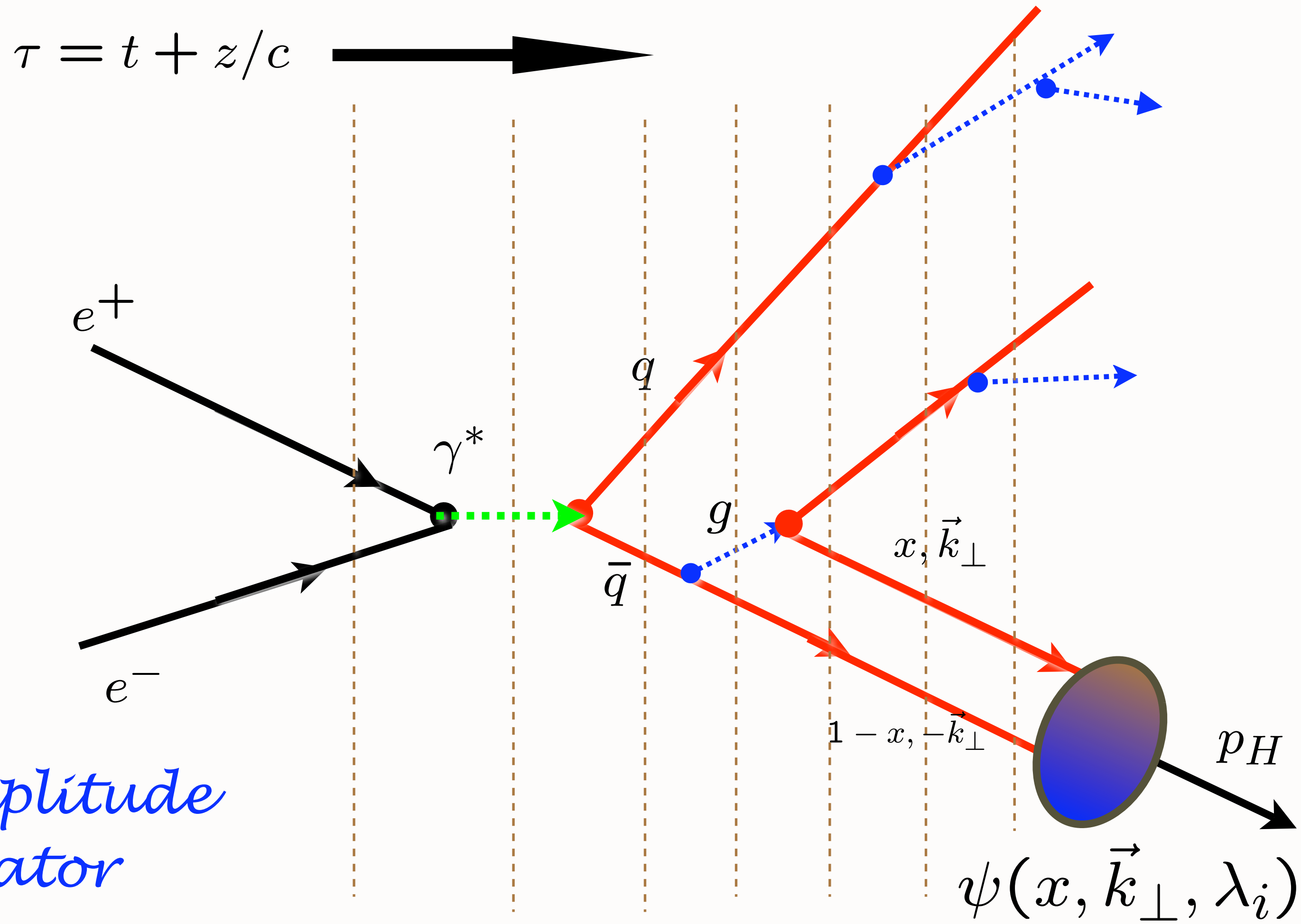
A Test For Fractionally Charged Partons From Deep Inelastic Bremsstrahlung In The Scaling Region.
Stanley J. Brodsky, J.F. Gunion, Robert L. Jaffe (SLAC) . SLAC-PUB-1064, Jul 1972. 24pp.
Published in **Phys.Rev.D6:2487,1972**.

Electron-Positron Asymmetry

The electron-positron asymmetry in DIS tests the electroweak neutral current as well the presence of two-photon exchange contributions, which in the case of exclusive amplitudes, are believed to cause a breakdown of the Rosenbluth separation method.



Hadronization at the Amplitude Level

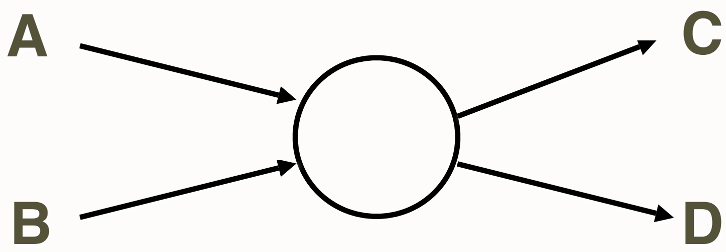


Event amplitude generator

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

Hard Exclusive Reactions

The hard exclusive reactions $\gamma^* p \to M p$ and $\gamma^* A \to V A$ which keep the nucleon or nucleus intact provide important tests of hadron structure and QCD color transparency, The connection of these processes with exclusive reactions at fixed angle could be explored at eRHIC.



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

$$s = E^2_{\rm cm}$$

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

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

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

Farrar & sjb; Matveev, Muradyan, Tavkhelidze

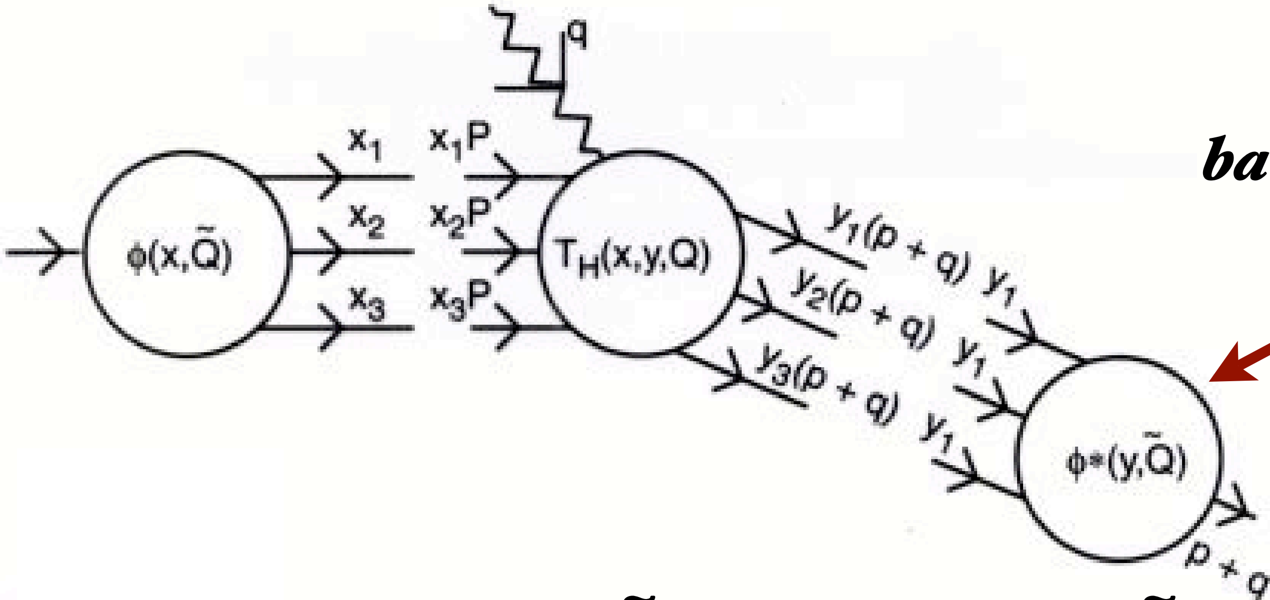
Conformal symmetry and PQCD predict leading-twist scaling behavior of fixed-CM angle exclusive amplitudes

Characteristic scale of QCD: 300 MeV

Many new J-PARC, GSI, J-Lab, Belle, Babar tests

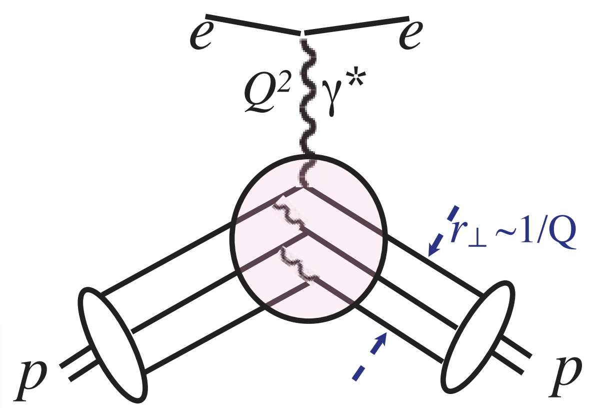
Leading-Twist PQCD Factorization for form factors, exclusive amplitudes

Lepage, sjb



baryon distribution amplitude

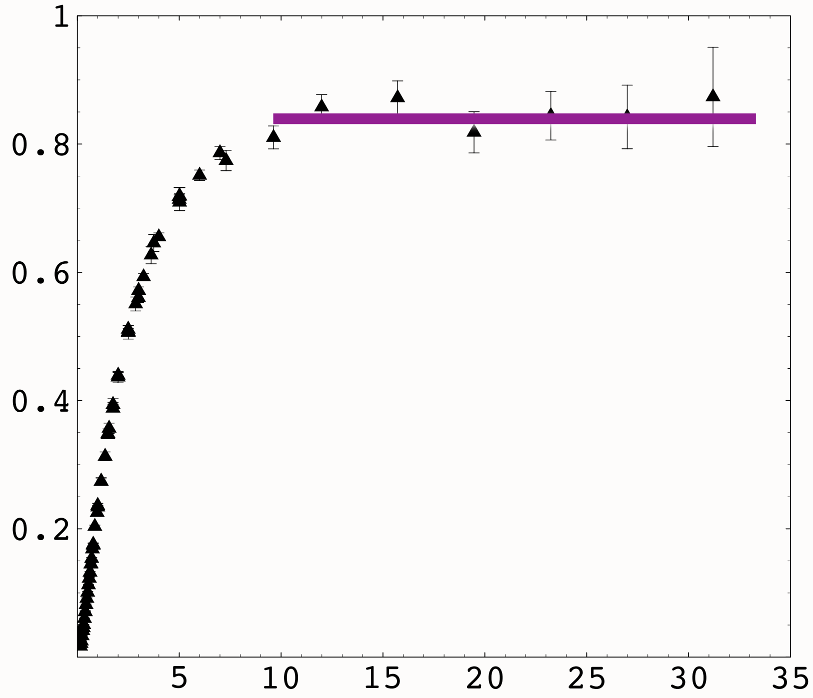
$$M = \int \Pi dx_i dy_i \phi_F(x_i, \tilde{Q}) \times T_H(x_i, y_i, \tilde{Q}) \times \phi_I(y_i, \tilde{Q})$$



If $\alpha_s(\tilde{Q}^2) \simeq$ constant

$Q^4 F_1(Q^2) \simeq$ constant

$Q^4 F_1^p(Q^2)$ [GeV^4]



Q^2 [GeV^2]

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

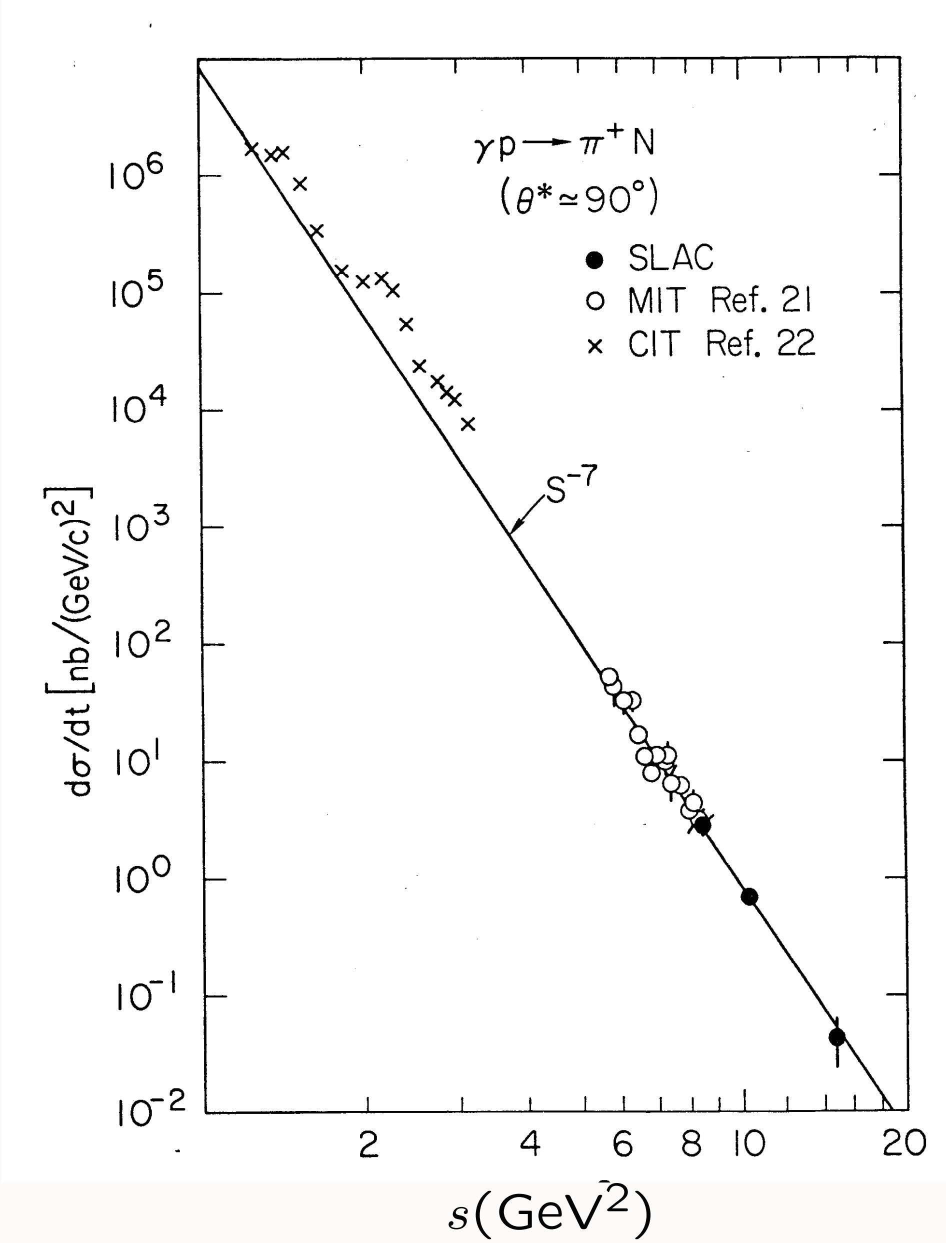
From: M. Diehl *et al.* Eur. Phys. J. C **39**, 1 (2005).

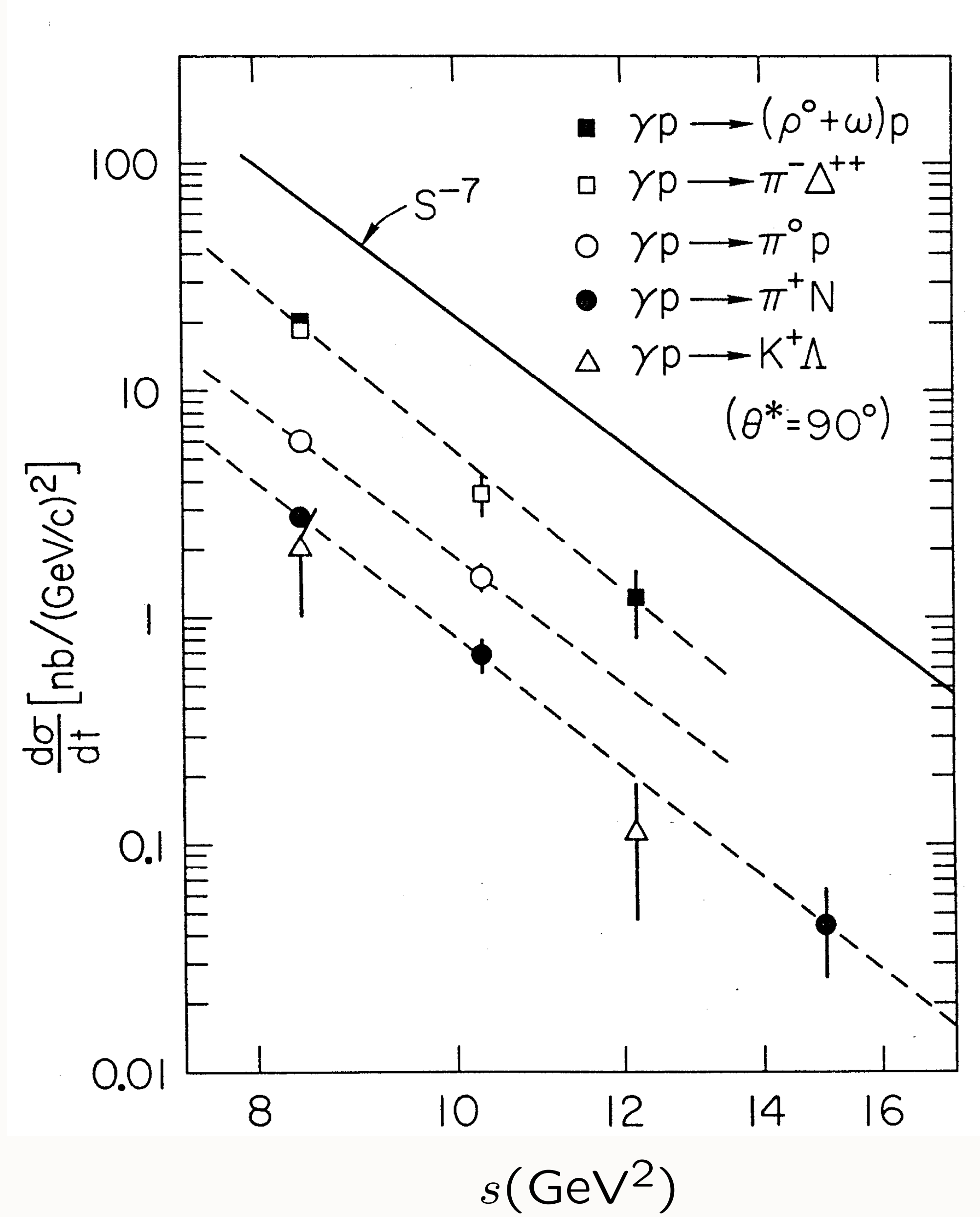
- Phenomenological success of dimensional scaling laws for exclusive processes

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

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).





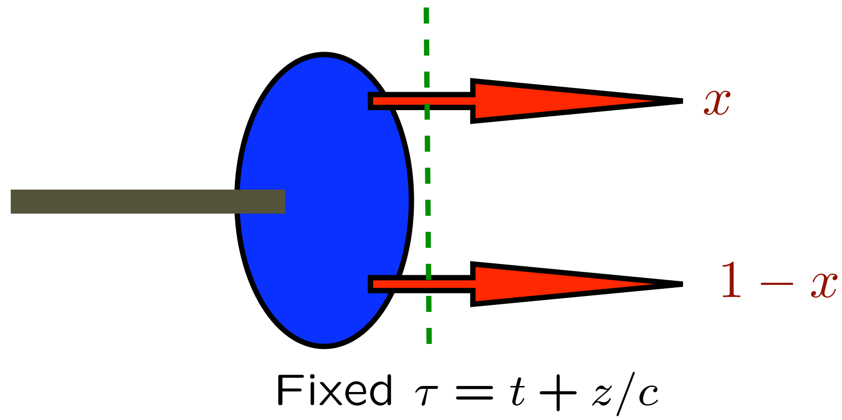
Conformal Invariance: $$\frac{d\sigma}{dt}(\gamma p \to MB) = \frac{F(\theta_{cm})}{s^7}$$

Hadron Distribution Amplitudes

Lepage, sjb

$$\phi_H(x_i, Q)$$

$$\sum_i x_i = 1$$



$k_\perp^2 < Q^2$

- Fundamental gauge invariant non-perturbative input to hard exclusive processes, heavy hadron decays. Defined for Mesons, Baryons

- Evolution Equations from PQCD, OPE, Conformal Invariance

Lepage, sjb
Frishman, Lepage, Sachrajda, sjb
Peskin Braun
Efremov, Radyushkin Chernyak etal

- Compute from valence light-front wavefunction in light-cone gauge

$$\phi_M(x, Q) = \int^Q d^2\vec{k}\ \psi_{q\bar{q}}(x, \vec{k}_\perp)$$

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

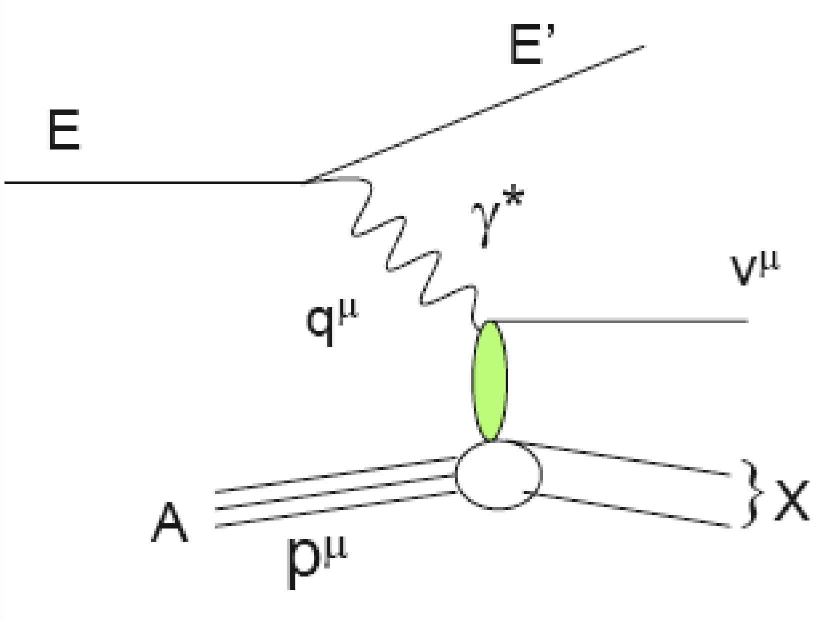
Color

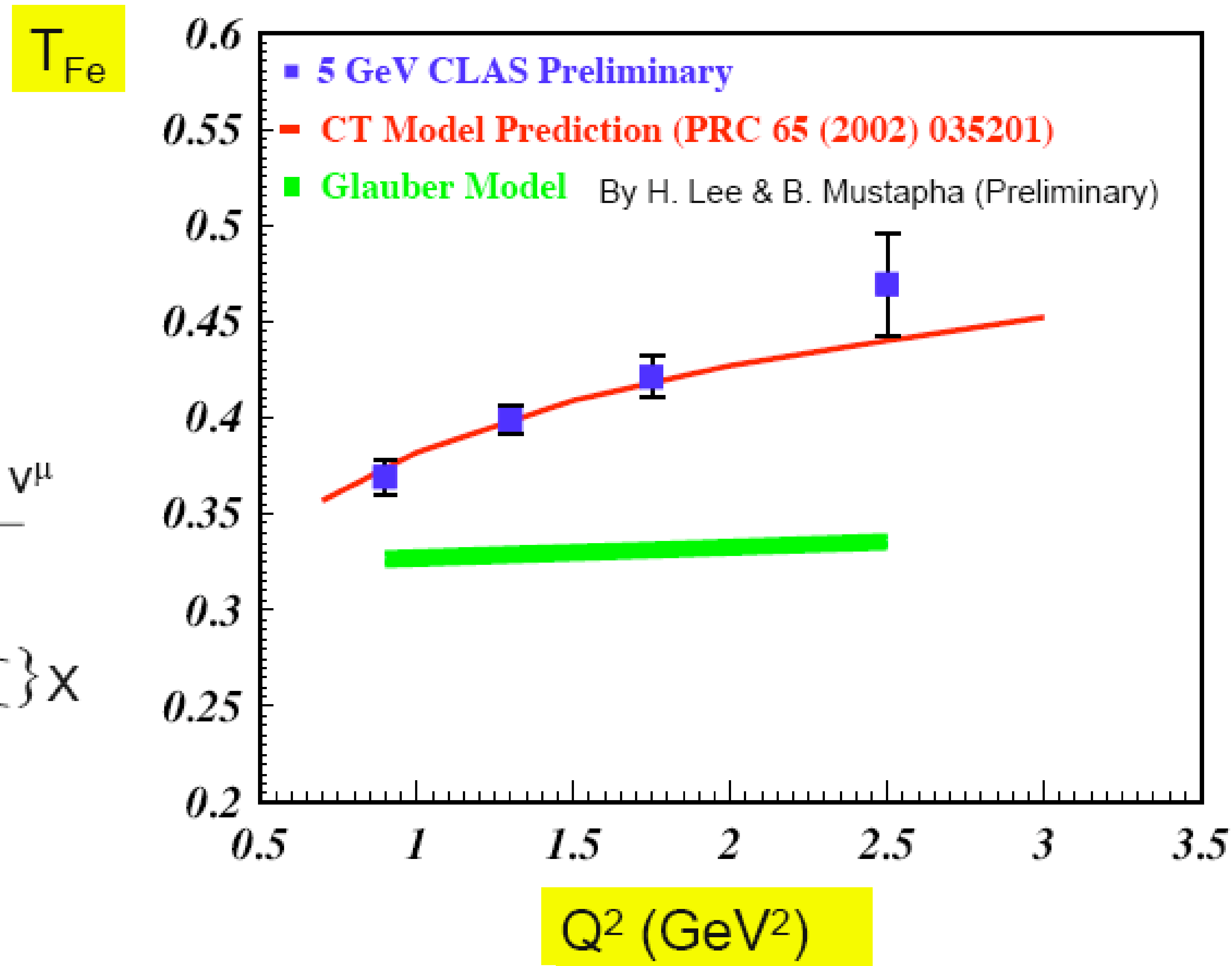
Bertsch, Gunion, Goldhaber, sjb

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

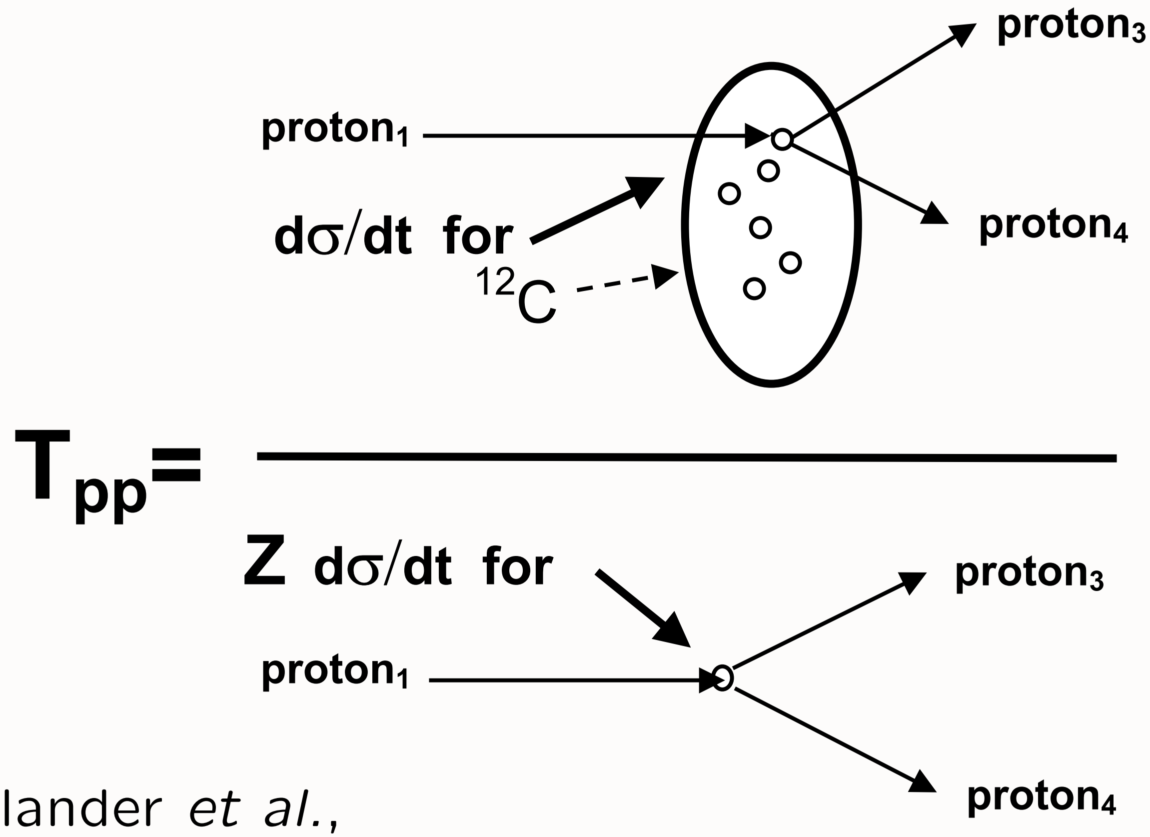




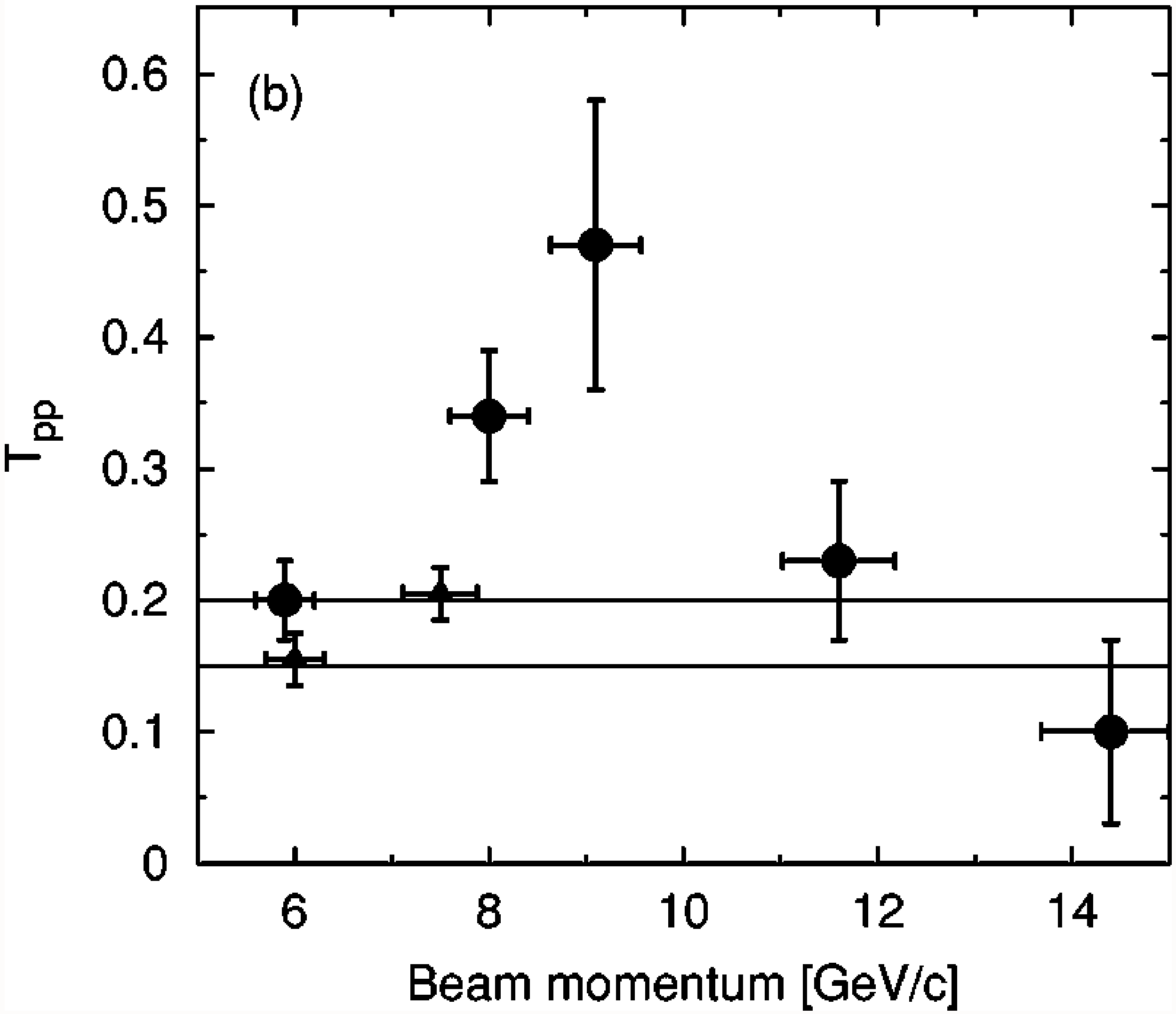
Theory:

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].

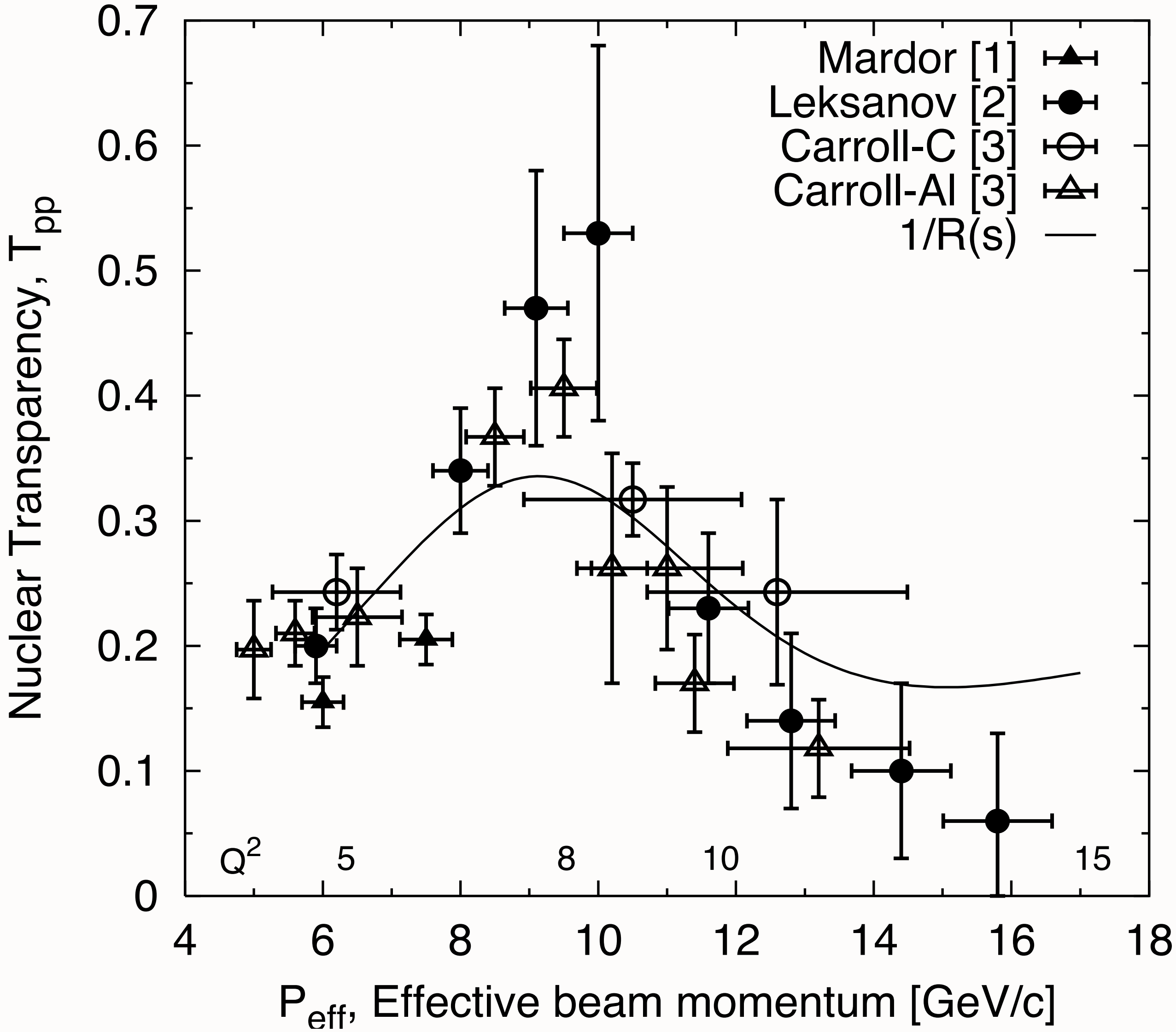


PHYSICAL REVIEW C **70**, 015208 (2004)

Nuclear transparency in $90^\circ_{c.m.}$ quasielastic $A(p,2p)$ reactions

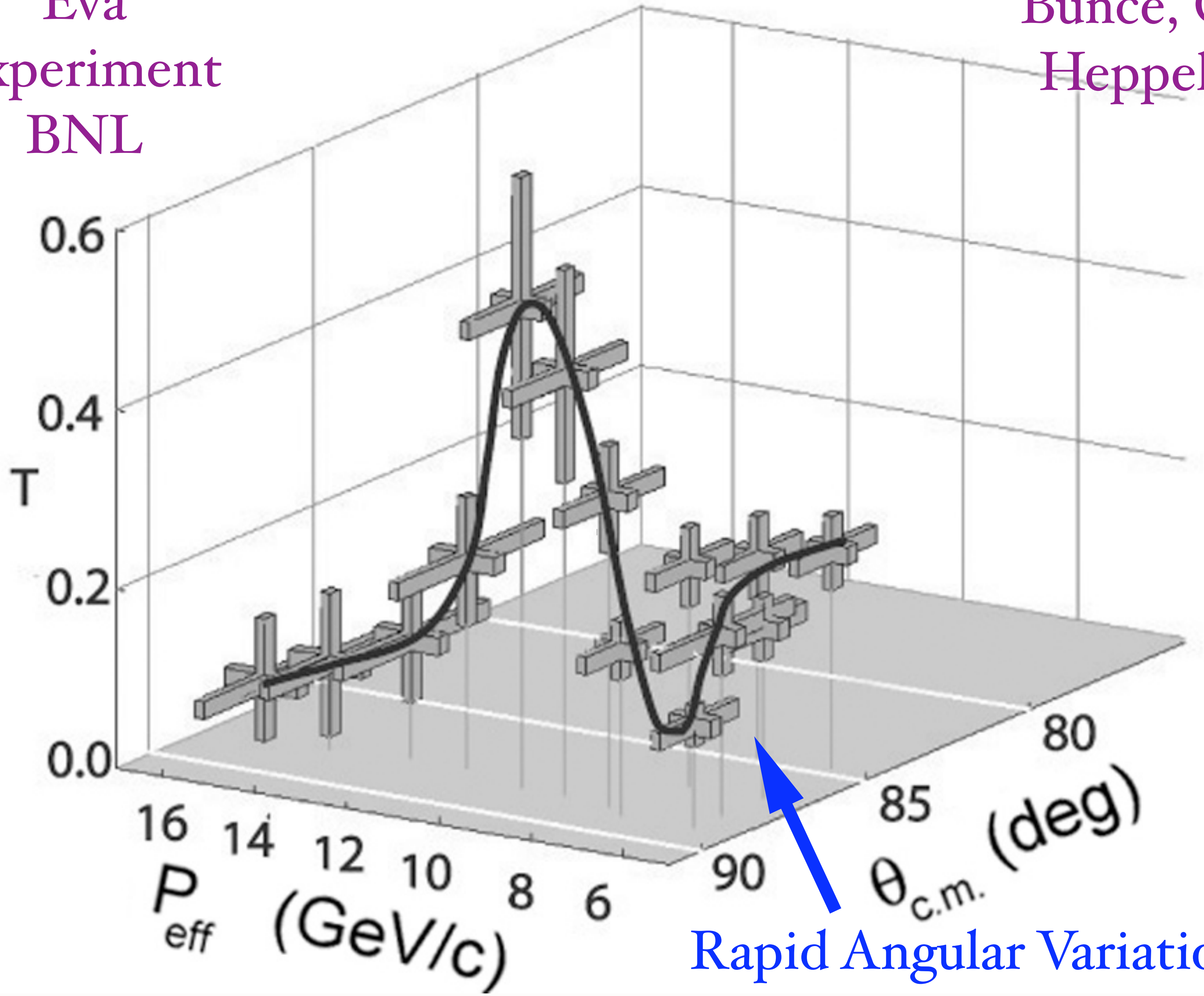
J. Aclander,[7] J. Alster,[7] G. Asryan,[1,*] Y. Averiche,[5] D. S. Barton,[1] V. Baturin,[2,†] N. Buktoyarova,[1,†] G. Bunce,[1]
A. S. Carroll,[1,‡] N. Christensen,[3,§] H. Courant,[3] S. Durrant,[2] G. Fang,[3] K. Gabriel,[2] S. Gushue,[1] K. J. Heller,[3] S. Heppelmann,[2]
I. Kosonovsky,[7] A. Leksanov,[2] Y. I. Makdisi,[1] A. Malki,[7] I. Mardor,[7] Y. Mardor,[7] M. L. Marshak,[3] D. Martel,[4]
E. Minina,[2] E. Minor,[2] I. Navon,[7] H. Nicholson,[8] A. Ogawa,[2] Y. Panebratsev,[5] E. Piasetzky,[7] T. Roser,[1] J. J. Russell,[4]
A. Schetkovsky,[2,†] S. Shimanskiy,[5] M. A. Shupe,[3,||] S. Sutton,[8] M. Tanaka,[1,¶] A. Tang,[6] I. Tsetkov,[5] J. Watson,[6] C. White,[3]
J-Y. Wu,[2] and D. Zhalov[2]

Color Transparency fails when A_{nn} is large



Eva
Experiment
BNL

Bunce, Carroll,
Heppelman...



Rapid Angular Variation!

Light-Front Wavefunctions

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

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

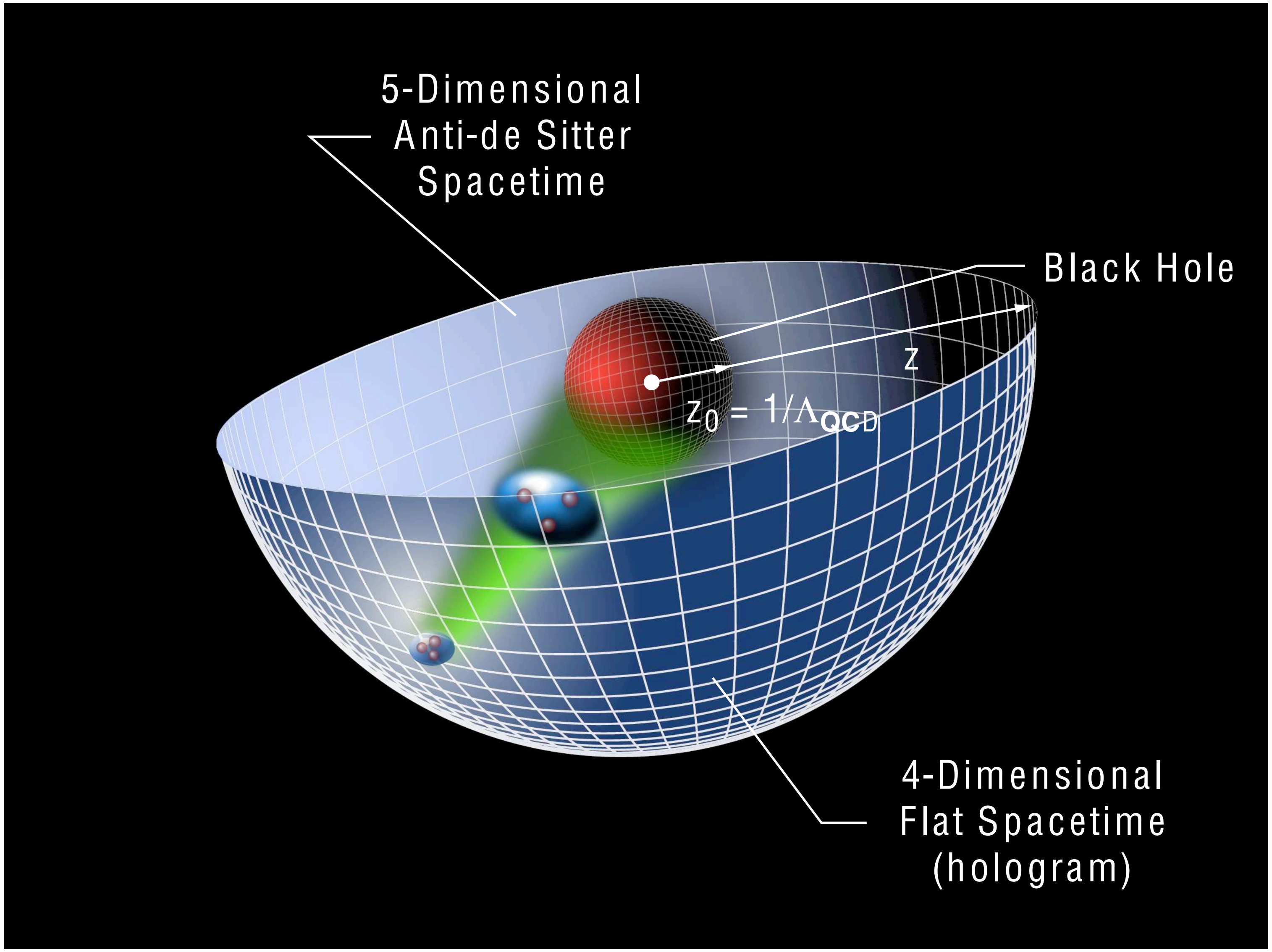
$$x_i = \frac{k_i^+}{P^+}$$

Invariant under boosts. Independent of P^μ

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

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

Applications of AdS/CFT to QCD



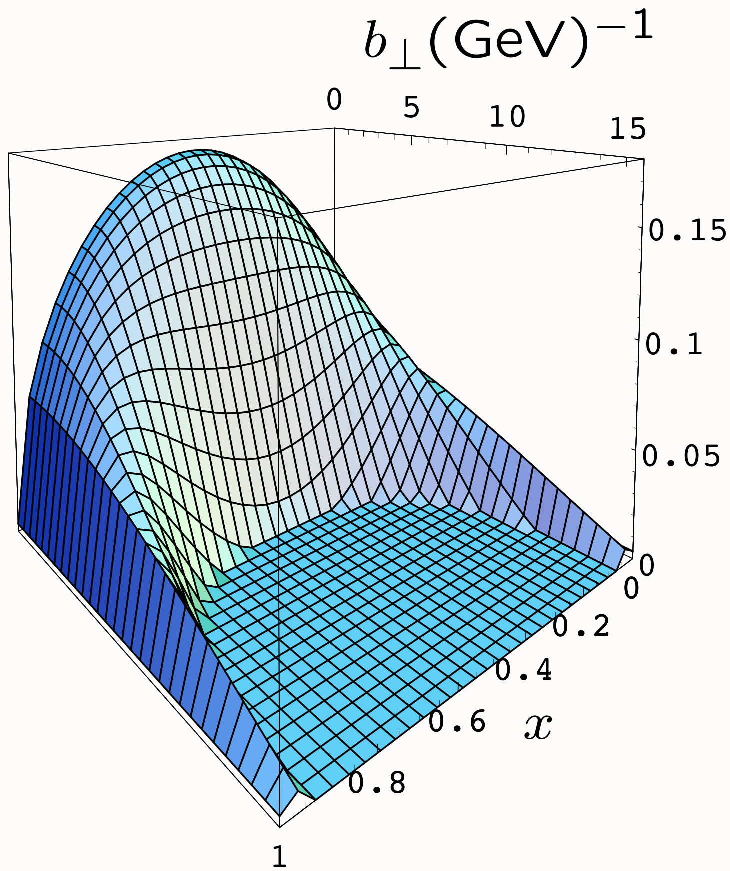
Changes in physical length scale mapped to evolution in the 5th dimension z

in collaboration with Guy de Teramond

Goal:

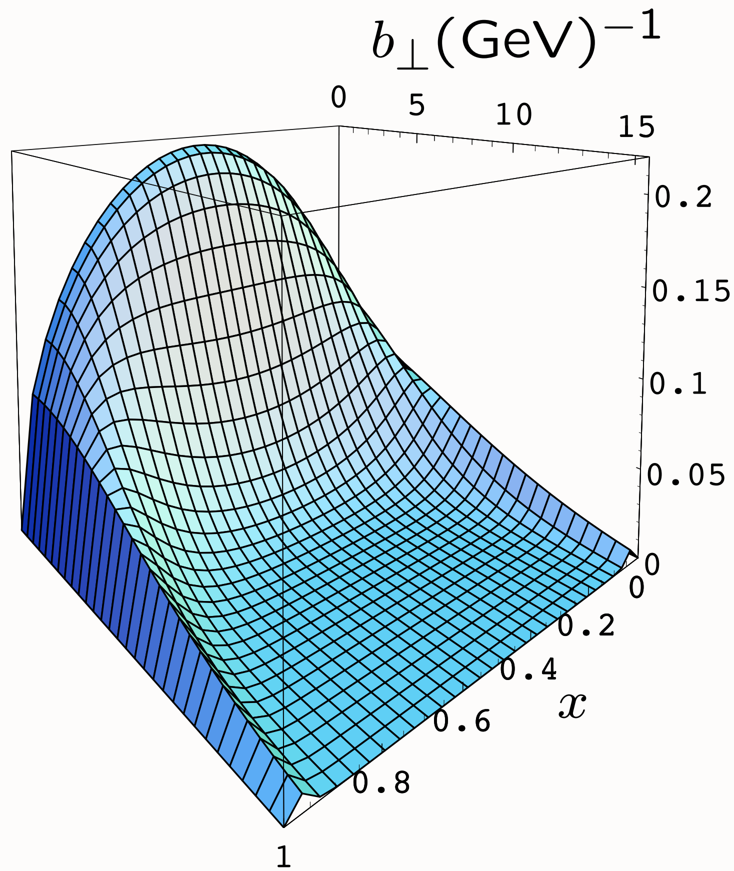
- **Use AdS/CFT to provide an approximate, covariant, and analytic model of hadron structure with confinement at large distances, conformal behavior at short distances**
- **Analogous to the Schrodinger Equation for Atomic Physics**
- *AdS/QCD Holographic Model*

AdS/CFT Predictions for Meson LFWF $\psi(x, b_\perp)$



$\Lambda_{\text{QCD}} = 0.32 \text{ GeV}$

Truncated Space



$\kappa = 0.76 \text{ GeV}$

Harmonic Oscillator

AdS/CFT: Anti-de Sitter Space / Conformal Field Theory

Maldacena:

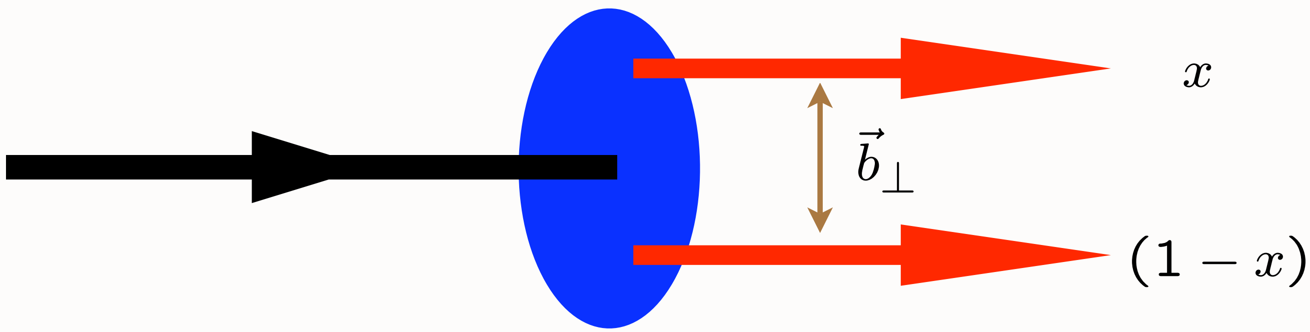
Map AdS5 X S5 to conformal N=4 SUSY

- **QCD is not conformal**; however, it has manifestations of a scale-invariant theory: Bjorken scaling, dimensional counting for hard exclusive processes
- **Conformal window:** $\alpha_s(Q^2) \simeq \text{const at small } Q^2$
- **Use mathematical mapping of the conformal group SO(4,2) to AdS5 space**

LF(3+1) ↔ *AdS₅*

$$\psi(x, \vec{b}_\perp) \longleftrightarrow \phi(z)$$

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



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

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

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

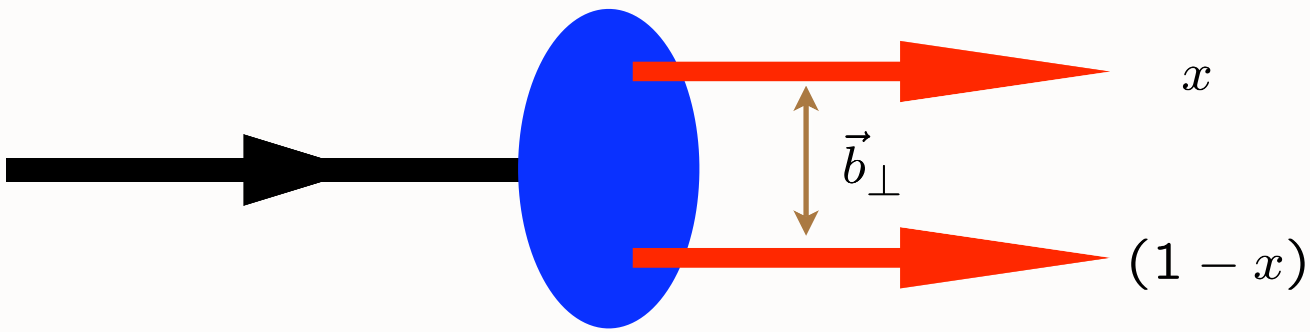
Relativistic LF radial equation

Frame Independent

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

G. de Teramond, sjb

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



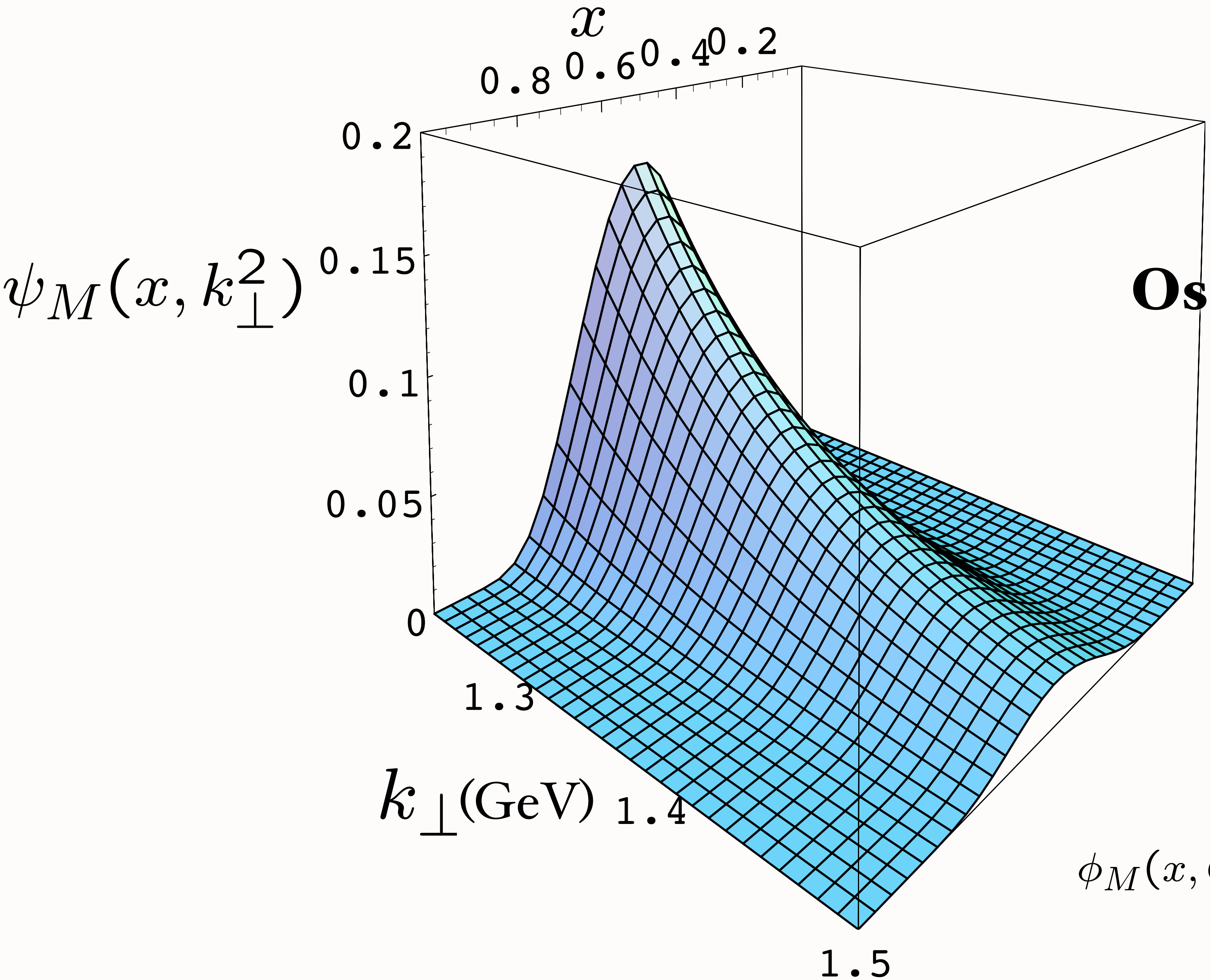
Effective conformal potential:

$$V(\zeta) = -\frac{1-4L^2}{4\zeta^2}.$$

$$+\kappa^4\zeta^2$$

Soft wall harmonic oscillator potential:

Prediction from AdS/CFT: Meson LFWF



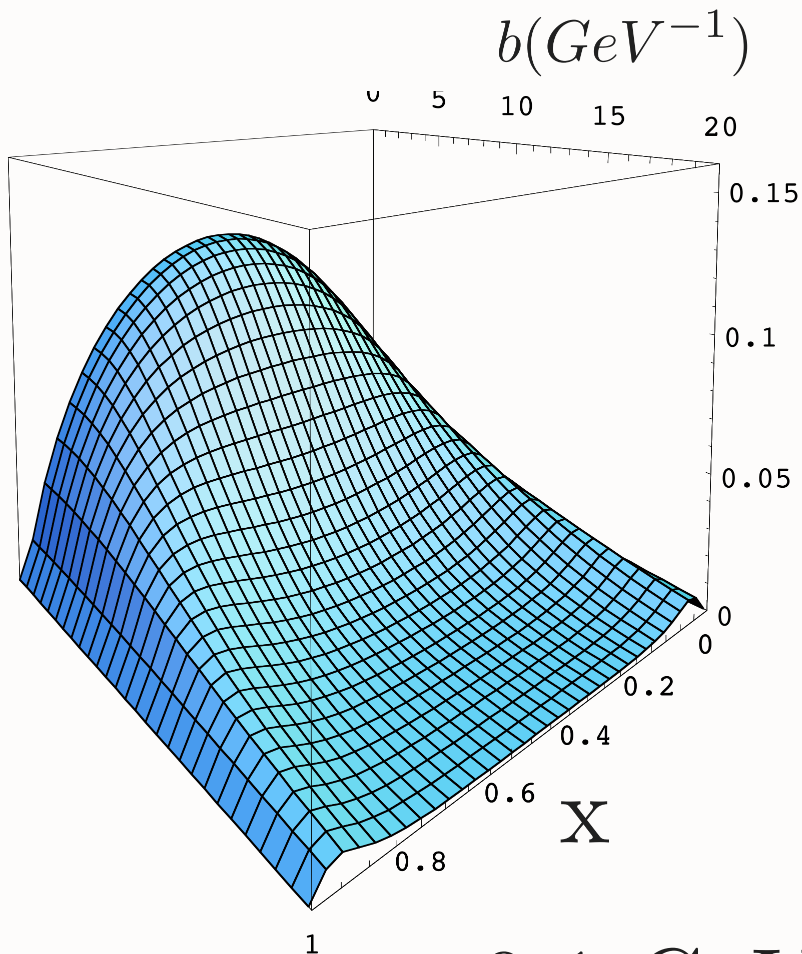
Harmonic Oscillator model

de Teramond, sjb

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

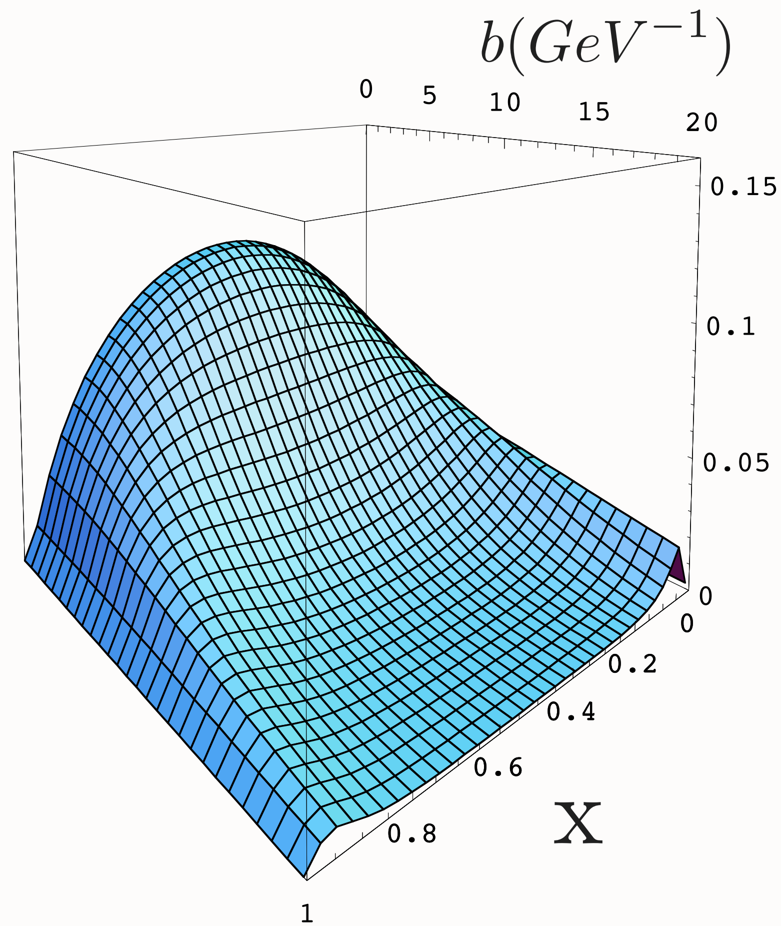
Increases PQCD prediction for $F_\pi(Q^2)$ by 16/9

$\psi_\phi(x, b_\perp)$



$m_1 = m_2 = 0.1$ GeV

$\psi_K(x, b_\perp)$



$m_1 = 0, m_2 = 0.1$ GeV

$\kappa = 0.375$ GeV

J/ψ

LFWF peaks at

$$x_i = \frac{m_{\perp i}}{\sum_j^n m_{\perp j}}$$

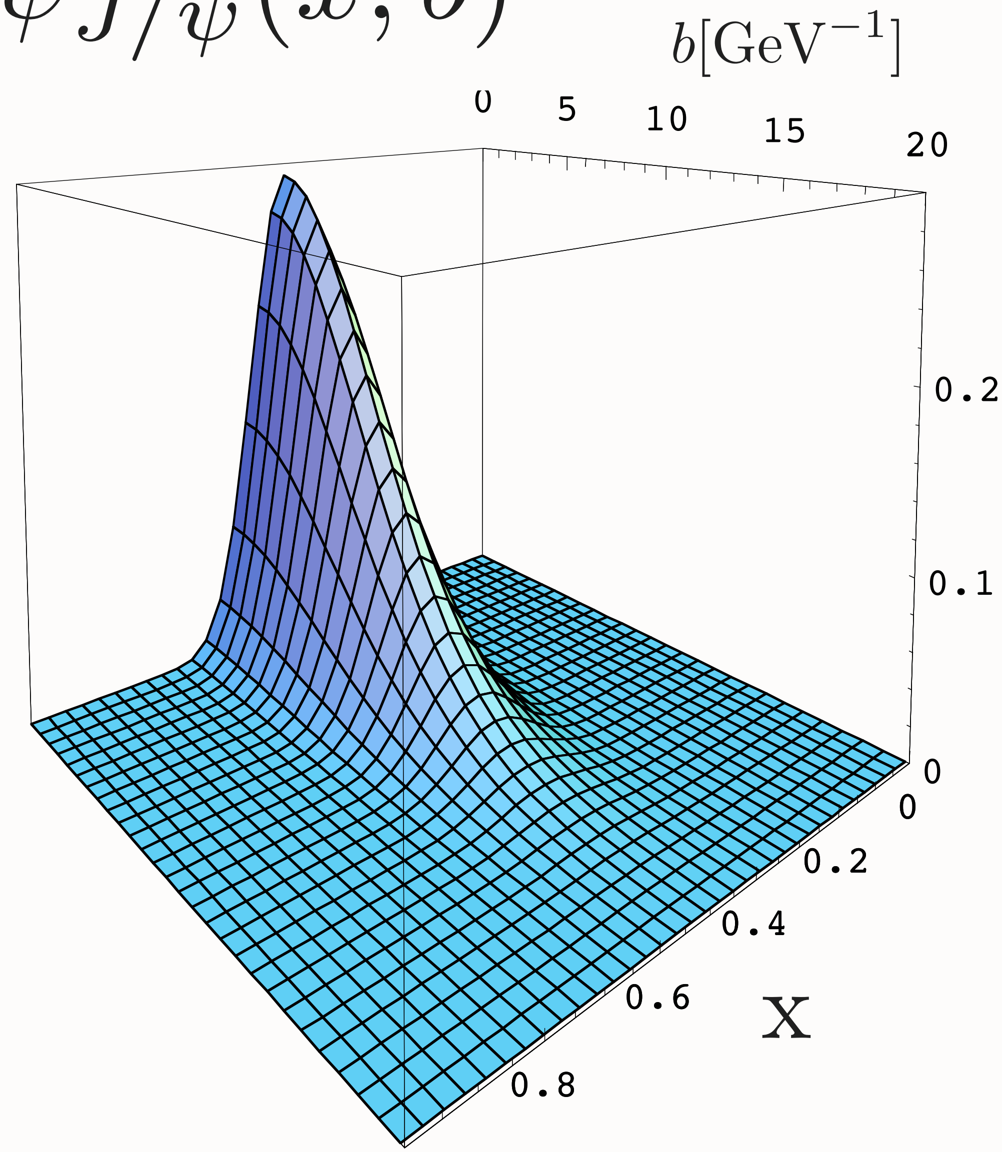
where

$$m_{\perp i} = \sqrt{m^2 + k_\perp^2}$$

minimum of LF energy denominator

$$\kappa = 0.375 \text{ GeV}$$

$\psi_{J/\psi}(x, b)$



$$m_a = m_b = 1.25 \text{ GeV}$$

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

New physics at high x_F

Direct subprocesses

Dominance of higher-twist subprocesses in some domains

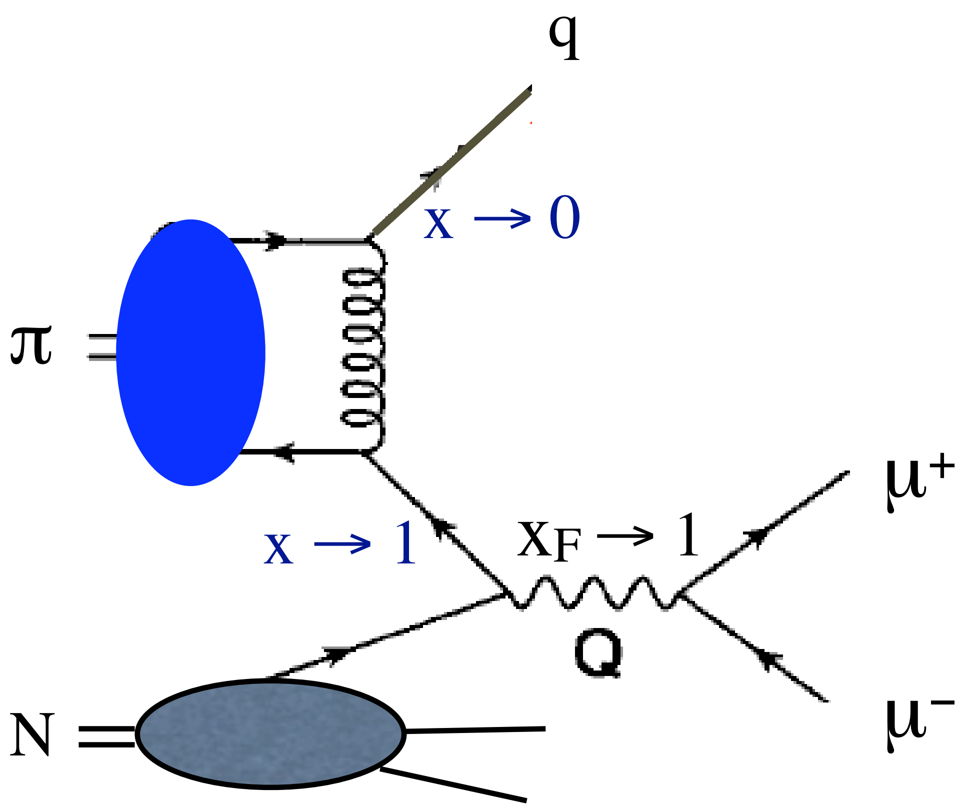
Reggeon (multiquark) exchange in both exclusive and inclusive reactions

Intrinsic Heavy Quarks

$\pi N \to \mu^+ \mu^- X$ at high x_F

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

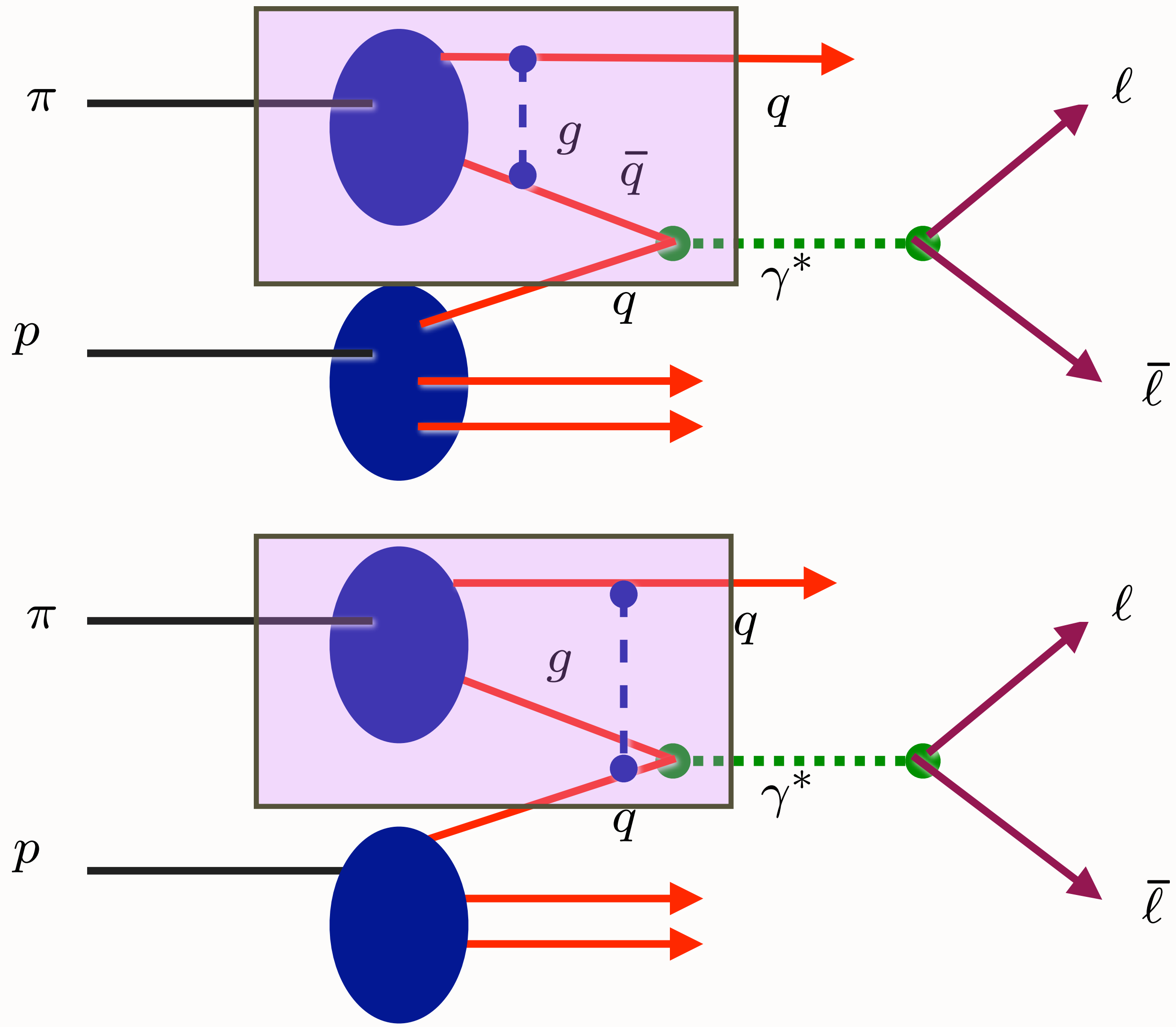
Entire pion wf contributes to hard process



Virtual photon is longitudinally polarized

Berger and Brodsky, PRL 42 (1979) 940

Berger, Lepage, sjb



$$\pi q \to \gamma^* q$$

Pion appears directly in subprocess at large x_F

All of the pion's momentum is transferred to the lepton pair

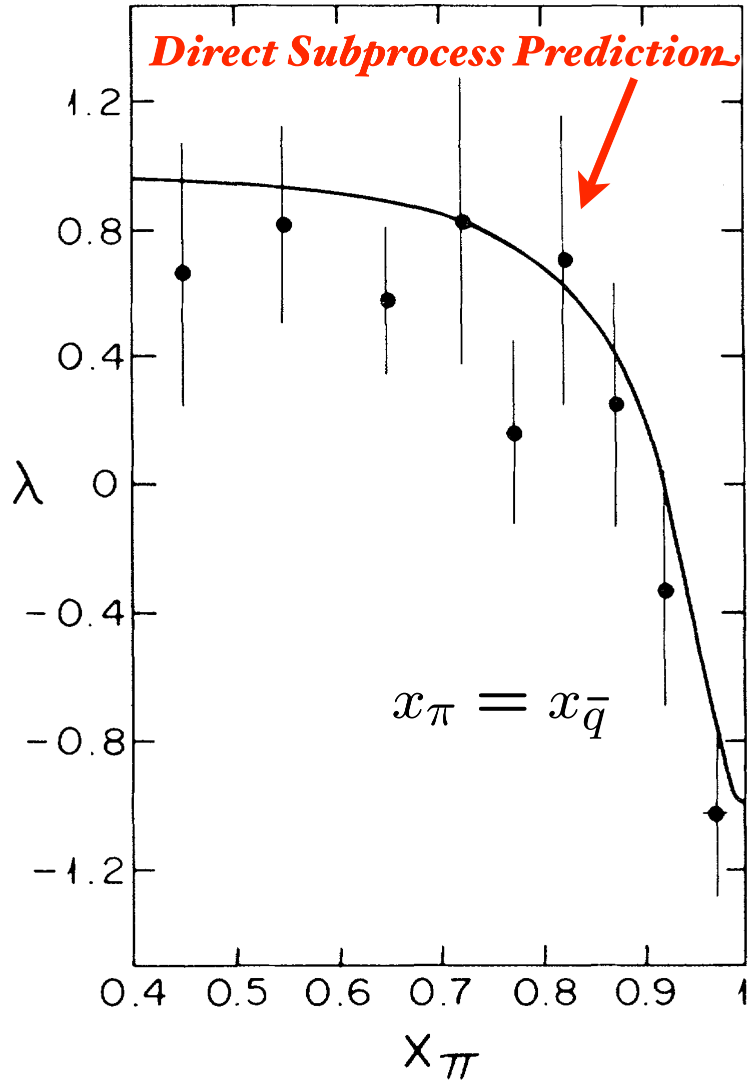
Lepton Pair is produced longitudinally polarized

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

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

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

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



Dramatic change in angular distribution at large x_F

Chicago-Princeton Collaboration

Phys.Rev.Lett.55:2649,1985

Example of a higher-twist direct subprocess

Higher Twist Subprocesses at $z \to 1$
$ep \to e\pi X$

Single-hadron in jet fragmentation Region

$$\frac{\sigma_T(1-z)^2+\sigma_L(1-z)^0}{Q^2}$$

Exclusive-Inclusive Connection

Deeply virtual meson scattering

Generalized Crewther Relation

The Generalized Crewther Relation of QCD makes the remarkable prediction that the leading-twist radiative corrections to the product of the Bjorken sum rule and $R_{e^+e^-\to X}(s)$ at commensurate values of s and Q^2 cancel to all orders in perturbation theory, thus providing a fundamental test of QCD devoid of theoretical ambiguities.

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)

Analytic matching at quark thresholds

No renormalization scale ambiguity!

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

$$R(Q)\equiv 3\sum_f Q_f^2\left[1+\frac{\alpha_R(Q)}{\pi}\right].$$

$$\begin{aligned}
\frac{\alpha_{g_1}(Q)}{\pi} &= \frac{\alpha_R(Q^*)}{\pi}-\frac{3}{4}C_F\left(\frac{\alpha_R(Q^{**})}{\pi}\right)^2 \\
&\quad+\left[\frac{9}{16}C_F^2-\left(\frac{11}{144}-\frac{1}{6}\zeta_3\right)\frac{d^{abc}d^{abc}}{C_F N}\frac{\left(\sum_f Q_f\right)^2}{\sum_f Q_f^2}\right]\left(\frac{\alpha_R(Q^{***})}{\pi}\right)^3, \\
Q^* &= Q\exp\left[\frac{7}{4}-2\zeta_3+\left(\frac{11}{96}+\frac{7}{3}\zeta_3-2\zeta_3^2-\frac{\pi^2}{24}\right)\left(\frac{11}{3}C_A-\frac{2}{3}f\right)\frac{\alpha_R(Q)}{\pi}\right], \\
Q^{**} &= Q\exp\left[\frac{523}{216}+\frac{28}{9}\zeta_3-\frac{20}{3}\zeta_5+\left(-\frac{13}{54}+\frac{2}{9}\zeta_3\right)\frac{C_A}{C_F}\right].
\end{aligned}$$

Novel EIC Topics

- DVCS, DVMS, Hard Exclusive Processes at the Amplitude Level
- Diffractive DIS
- Hidden Color in Deuteron
- $x > 1$ in Nuclei
- Shadowing, antishadowing, EMC
- Jet Energy Loss
- Proton, Nucleus Fragmentation

Novel EIC Topics

- Color Transparency in Hard Exclusive Processes
- Intrinsic Charm, Bottom and high x
- Heavy Hadron Studies; Nuclear Dependence
- Structure functions at high x; Quenching of DGLAP
- Pion, Kaon Structure Function
- Coulomb Dissociation of Proton to Jets

Novel EIC Topics

- Hard Photon Inclusive production
- Bjorken Sum Rule, Generalized Crewther Relation
- Exclusive-Inclusive Connection
- Higher Twist
- Single Spin Asymmetries; Jet correlations
- Neutral and Charge Current Studies; NuTeV anomaly

Forward Fragmentation

Hidden Color

When the electron strikes a quark in DIS, the remnant part of the proton emerges along the proton direction. The remnant system for DIS on nuclei such as the deuteron and ^3He targets do not always leave the spectator nucleons intact, because of QCD hidden-color degrees of freedom in the nuclear wavefunction as well as the final-state interactions of the quarks.

Heavy Hadron Production from IC, IB

When the electron interacts with the intrinsic charm or bottom quark, heavy hadrons such as the Λ_b and even doubly charmed baryons such as the $\xi(ccd)$ are created with high momentum fractions and Lorenz-dilated lifetimes.

One of the novel aspects of eRHIC is its capability for studying the forward fragmentation products of the struck proton in DIS. The proponents should discuss how a detector with forward hadron capability can illuminate this fundamental proton physics.

Features of Light-Front Formalism

- *Hidden Color* Nuclear Wavefunction
- *Color Transparency, Opaqueness*
- *Intrinsic glue, sea quarks, intrinsic charm*
- Simple proof of Factorization theorems for hard processes (Lepage, sjb)
- *Direct mapping to AdS/CFT* (de Teramond, sjb)
- New Effective LF Equations (de Teramond, sjb)
- Light-Front Amplitude Generator

- Although we know the QCD Lagrangian, we have only begun to understand its remarkable properties and features.

- Novel QCD Phenomena: hidden color, color transparency, strangeness asymmetry, intrinsic charm, anomalous heavy quark phenomena, anomalous spin effects, single-spin asymmetries, odderon, diffractive deep inelastic scattering, dangling gluons, shadowing, antishadowing ...

Truth is stranger than fiction, but it is because Fiction is obliged to stick to possibilities.

—Mark Twain