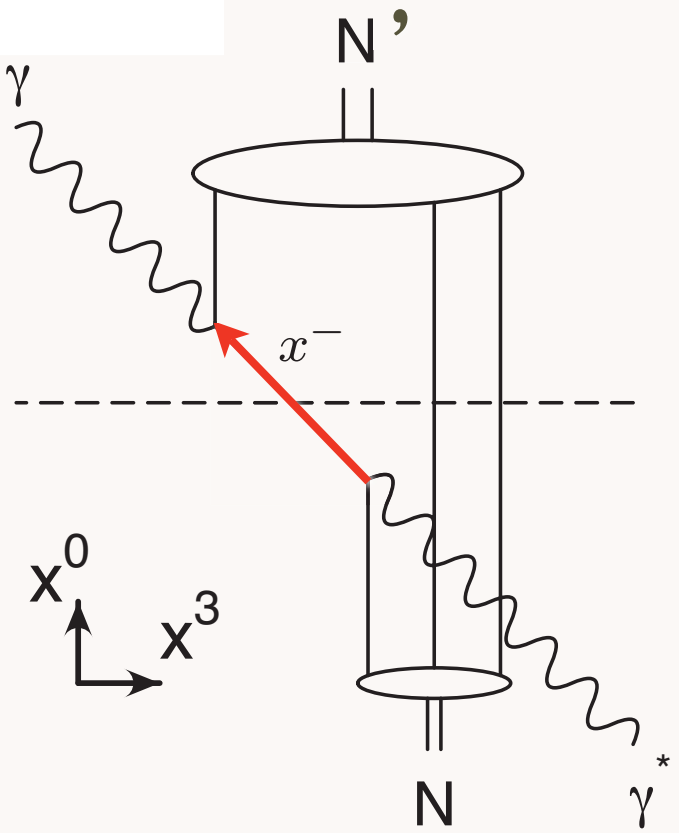
# Space-time picture of DVCS

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

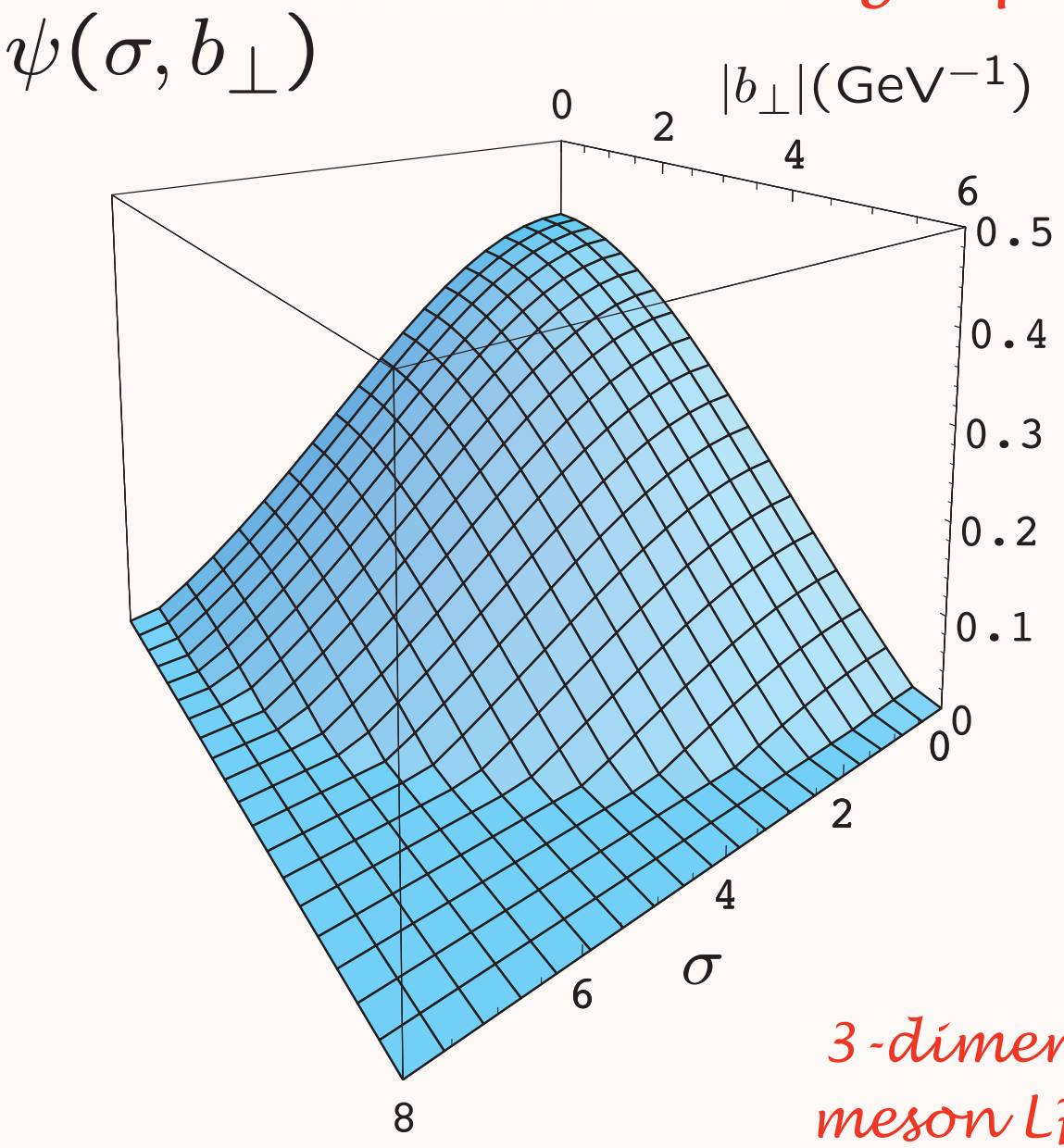
**Measure x- distribution from DVCS: Take Fourier transform of skewness, the longitudinal momentum transfer**

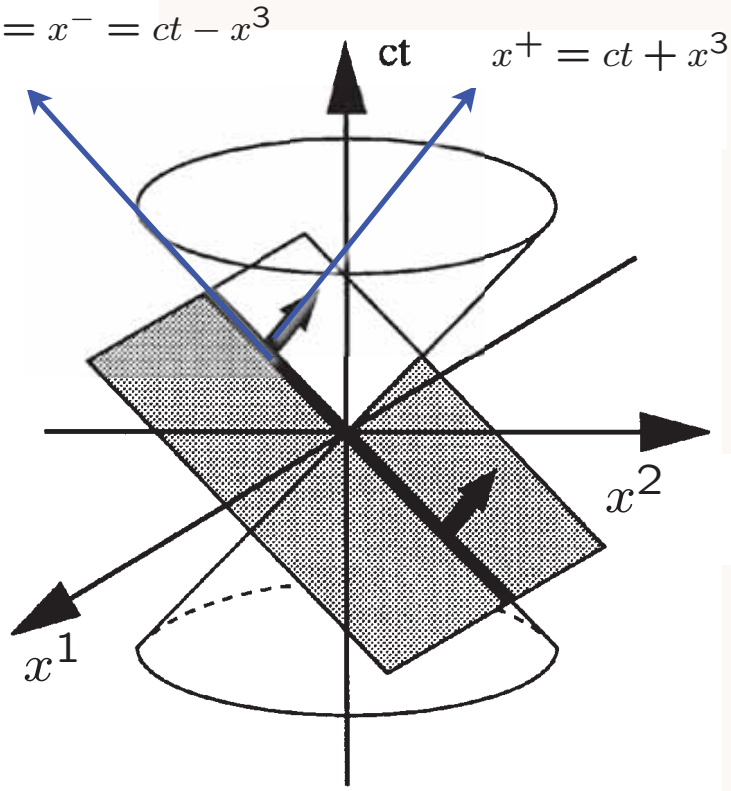
$$\zeta = \frac{Q^2}{2p\cdot q}$$

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

# AdS/CFT Holographic Model

G. de Teramond
SJB



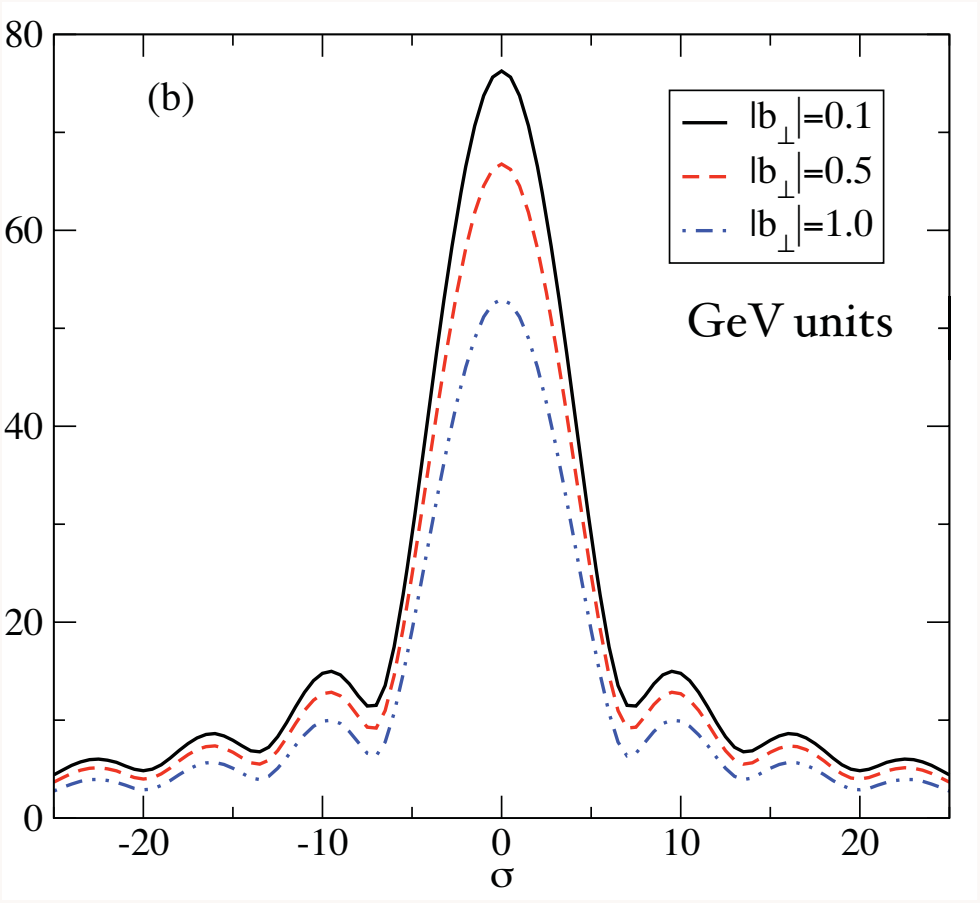

The front form

*3-dimensional photograph: meson LFWF at fixed LF Time*

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

# Hadron Optics

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

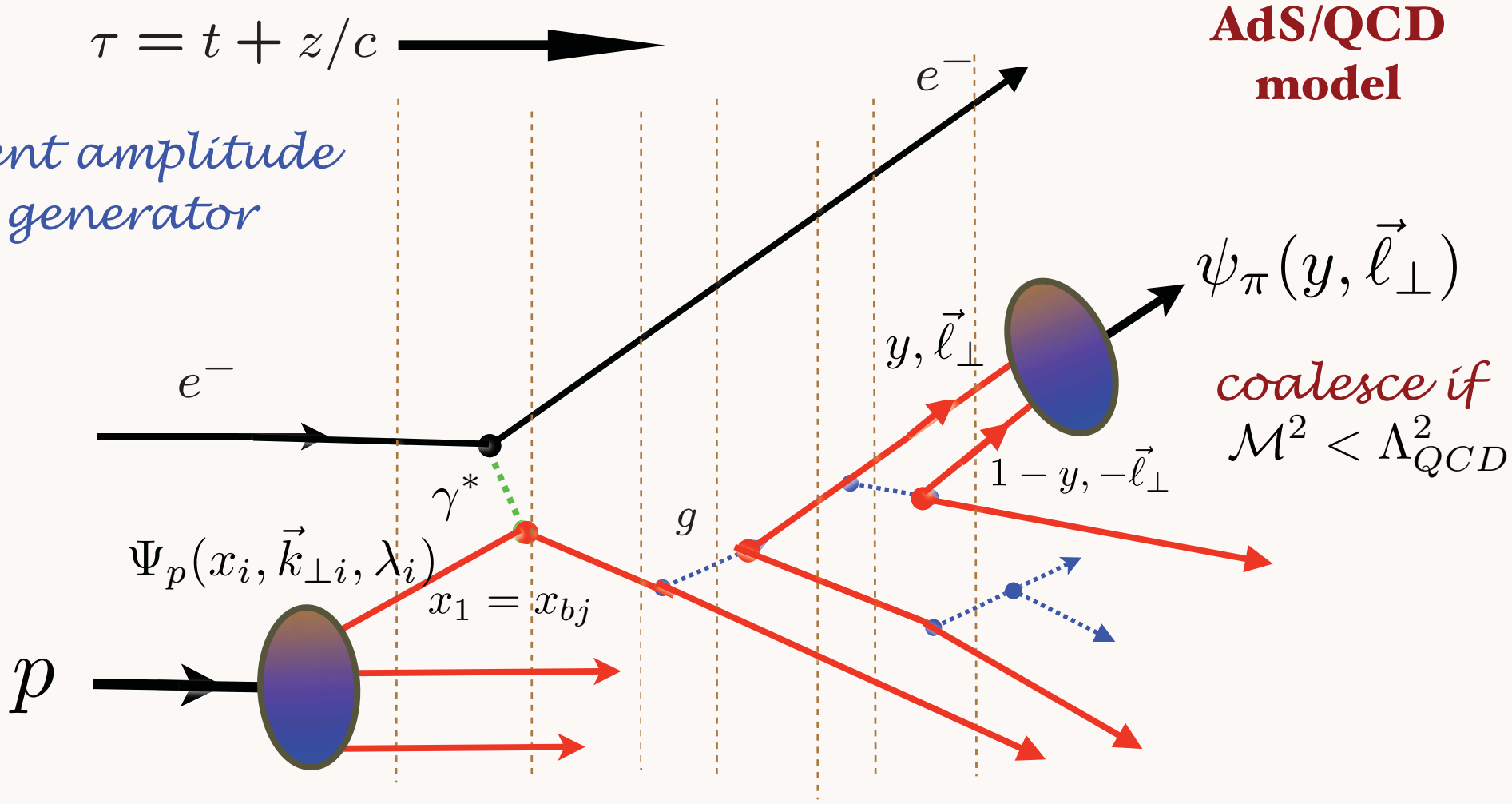



The Fourier Spectrum of the DVCS amplitude in $\sigma$ space for different fixed values of $|b_\perp|$.

DVCS Amplitude using holographic QCD meson LFWF

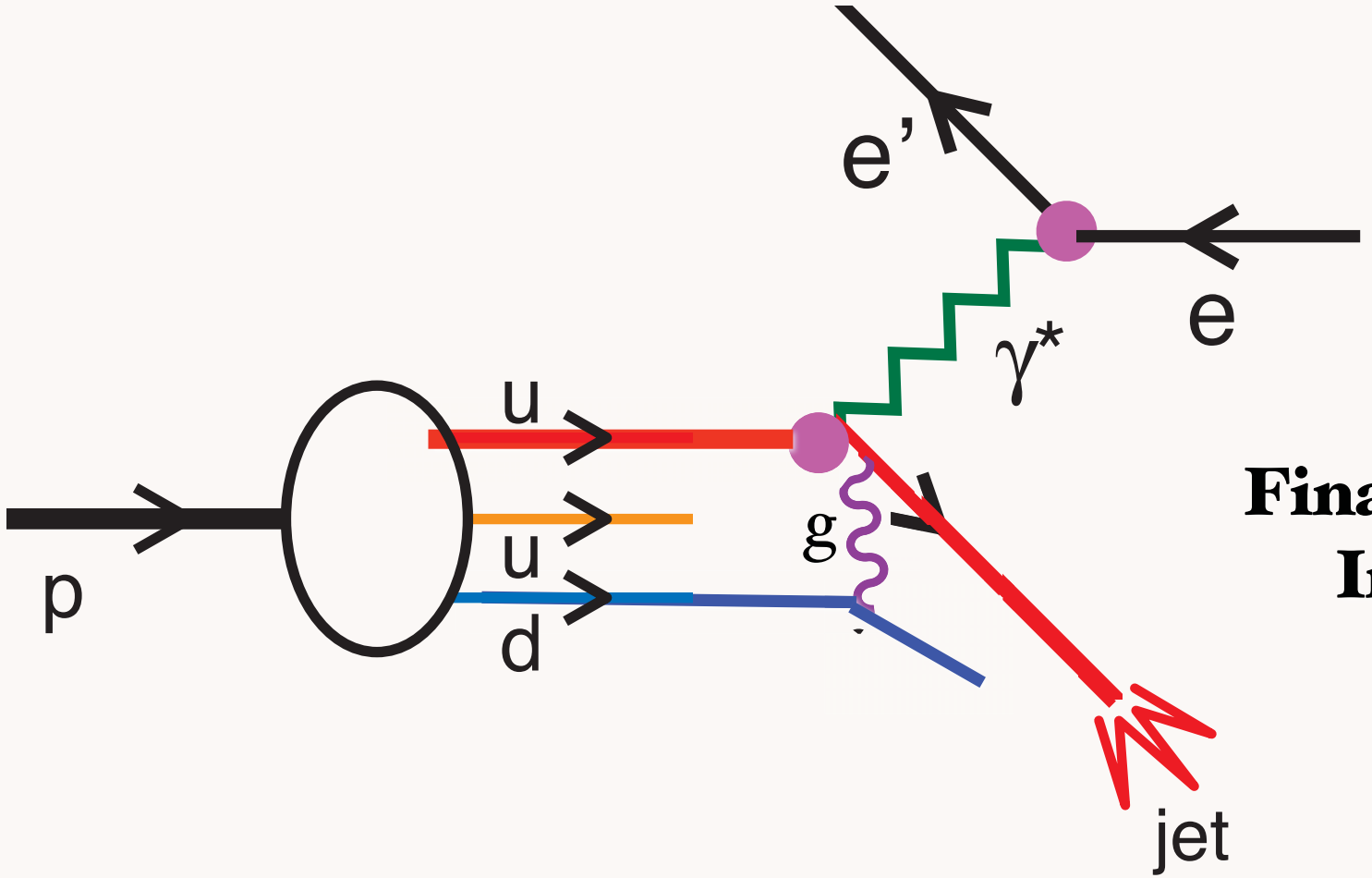
$\Lambda_{QCD} = 0.32$

# Jet Hadronization at the Amplitude Level




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

# Deep Inelastic Electron-Proton Scattering




**Final-State QCD Interaction**

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

# Leading Twist Sivers Effect

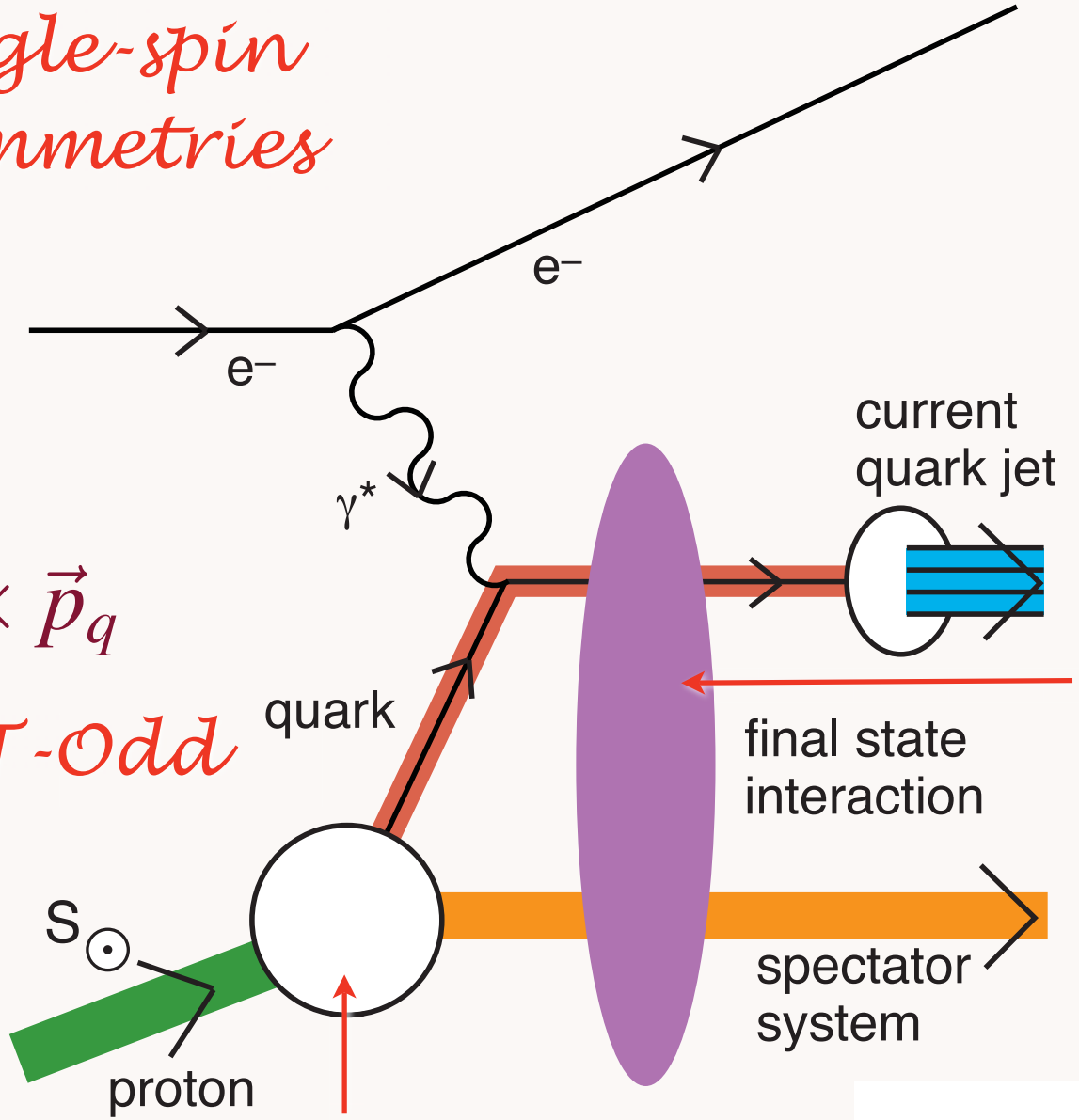
Hwang, Schmidt, sjb

Collins, Burkardt Ji, Yuan

*Single-spin asymmetries*

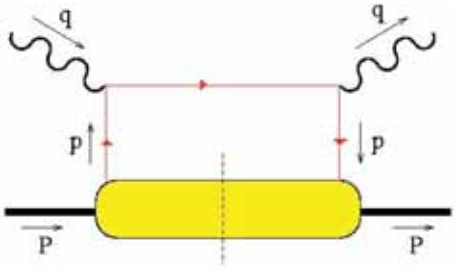
$i\,\vec{S}_p \cdot \vec{q} \times \vec{p}_q$

*Pseudo-T-Odd*

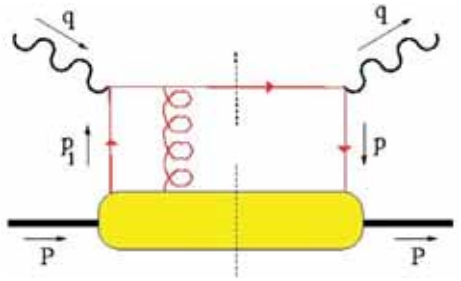



*QCD S- and P- Coulomb Phases --Wilson Line*

*Light-Front Wavefunction S and P- Waves*



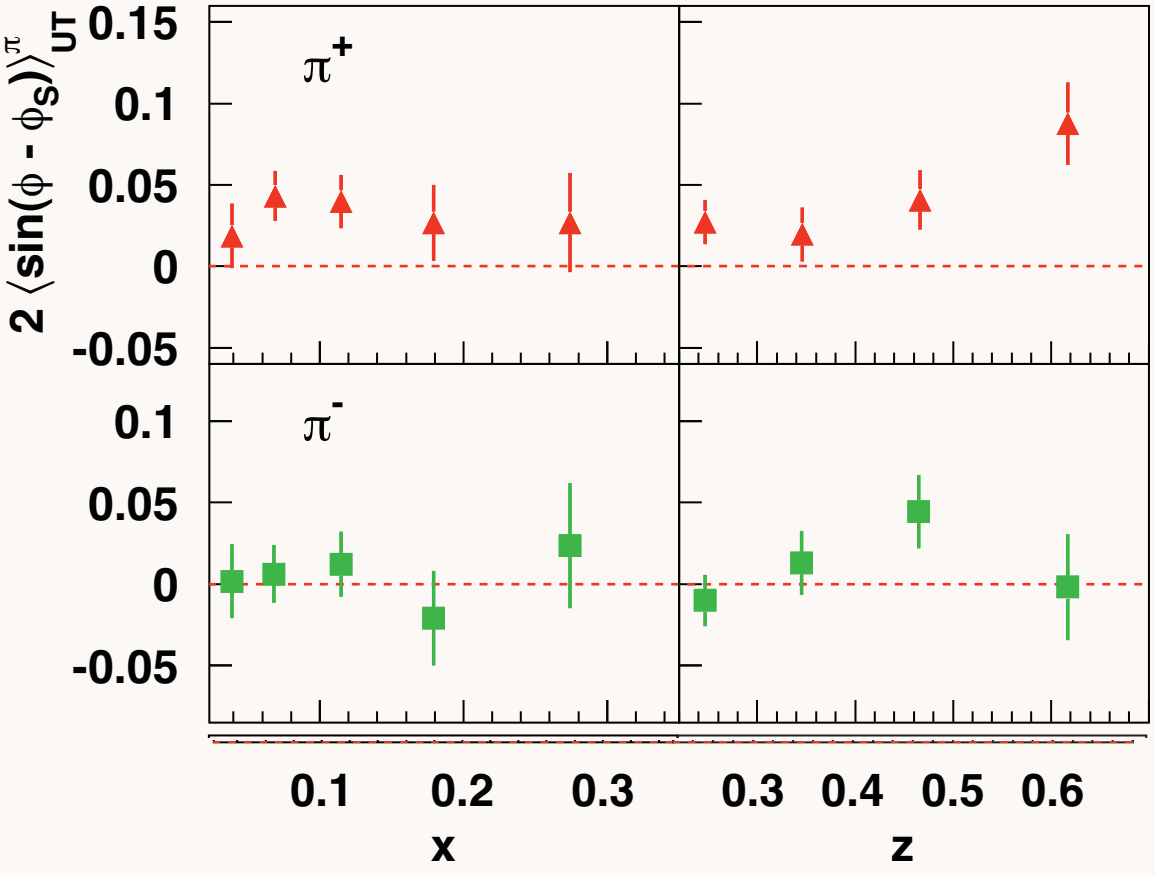
can interfere with



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 $\pi^+$...
  Consistent with zero for $\pi^-$...

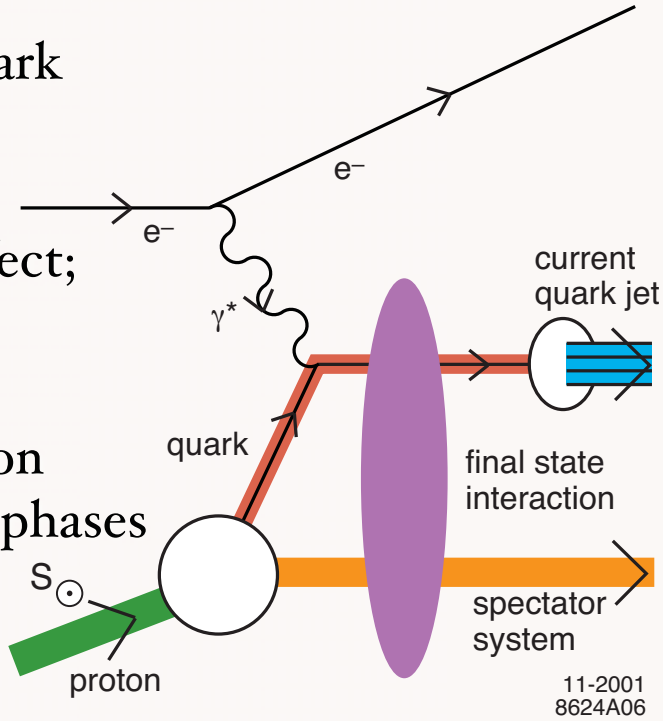
**Gamberg: Hermes data compatible with BHS model**

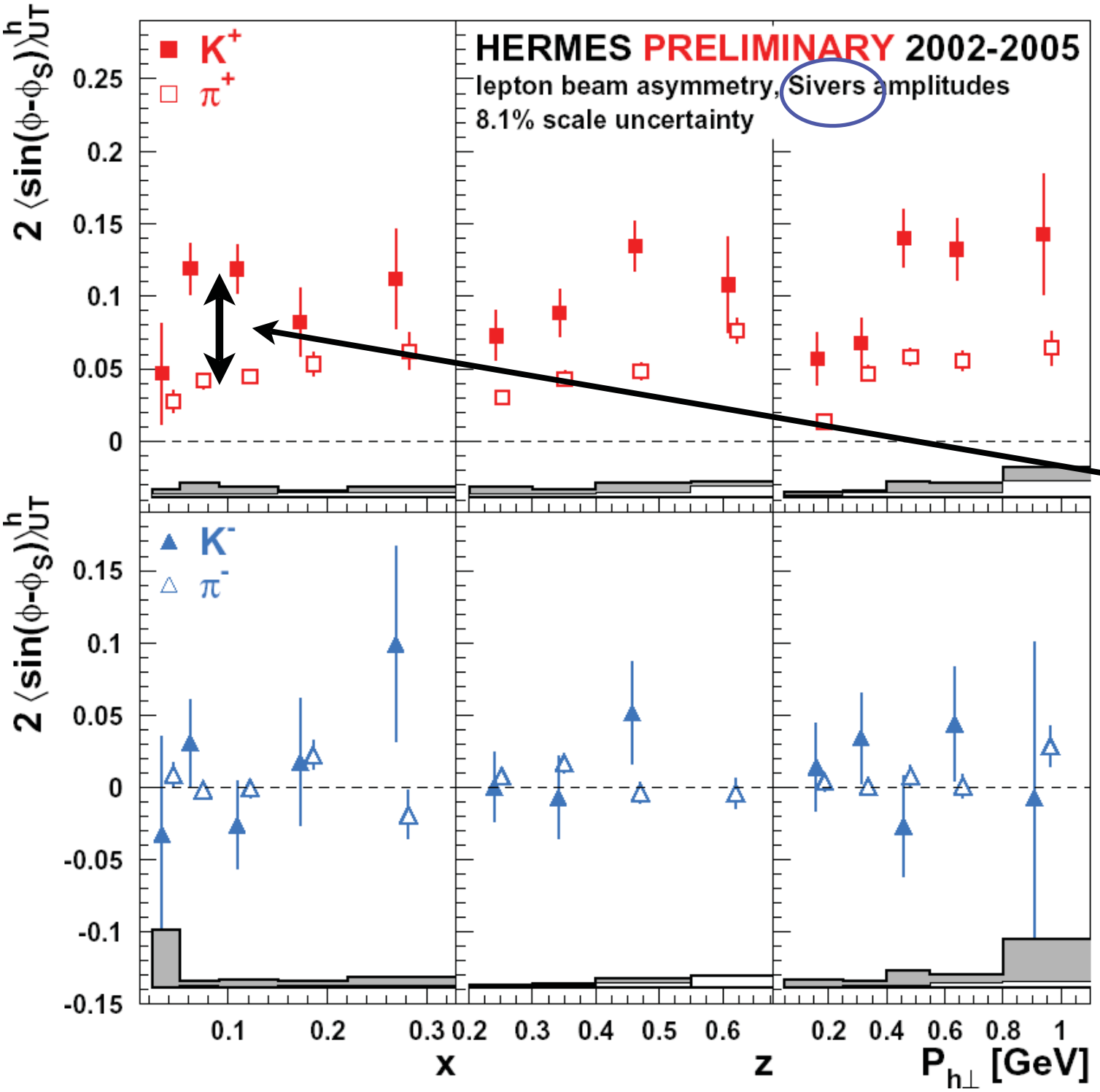
**Schmidt, Lu: Hermes charge pattern follow quark contributions to anomalous moment**

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

- Leading-Twist Bjorken Scaling!
- Requires nonzero orbital angular momentum of quark
- Arises from the interference of Final-State QCD Coulomb phases in S- and P- waves; Wilson line effect; gauge independent
- 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!

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



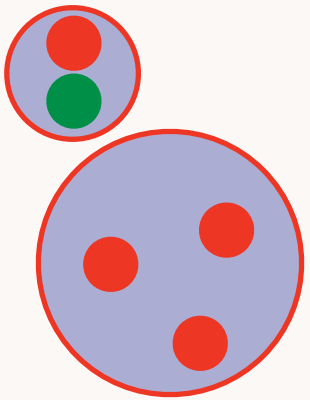


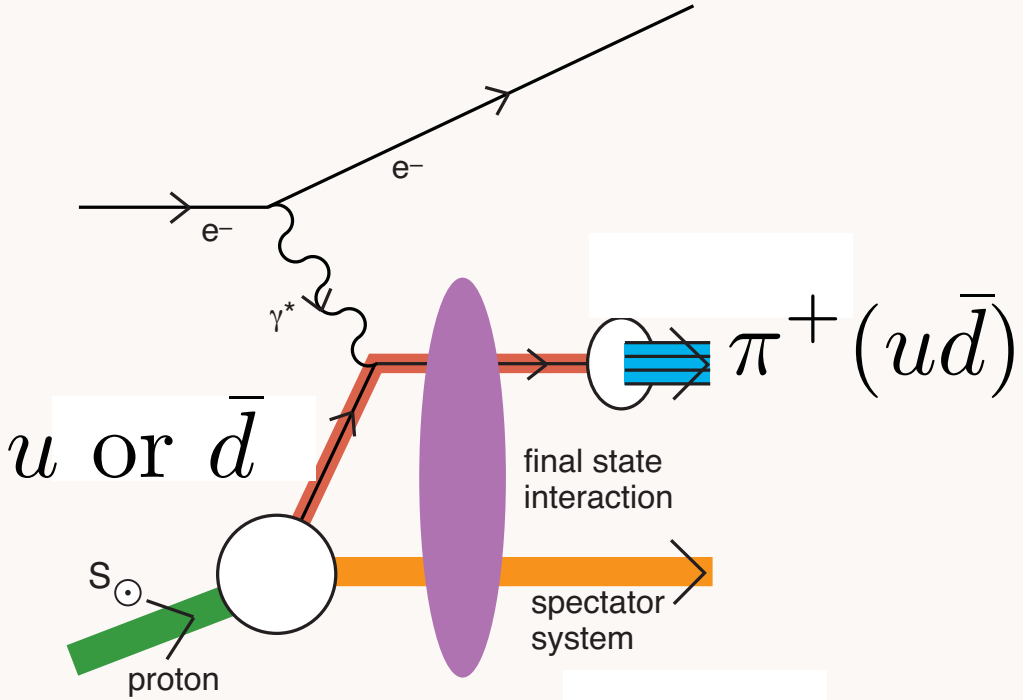

Large $K^+$ asymmetry!

*Difference at low x from sea-quark OAM?*

**Gardner, sjb in progress**

# Sea quarks carry orbital angular momentum






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

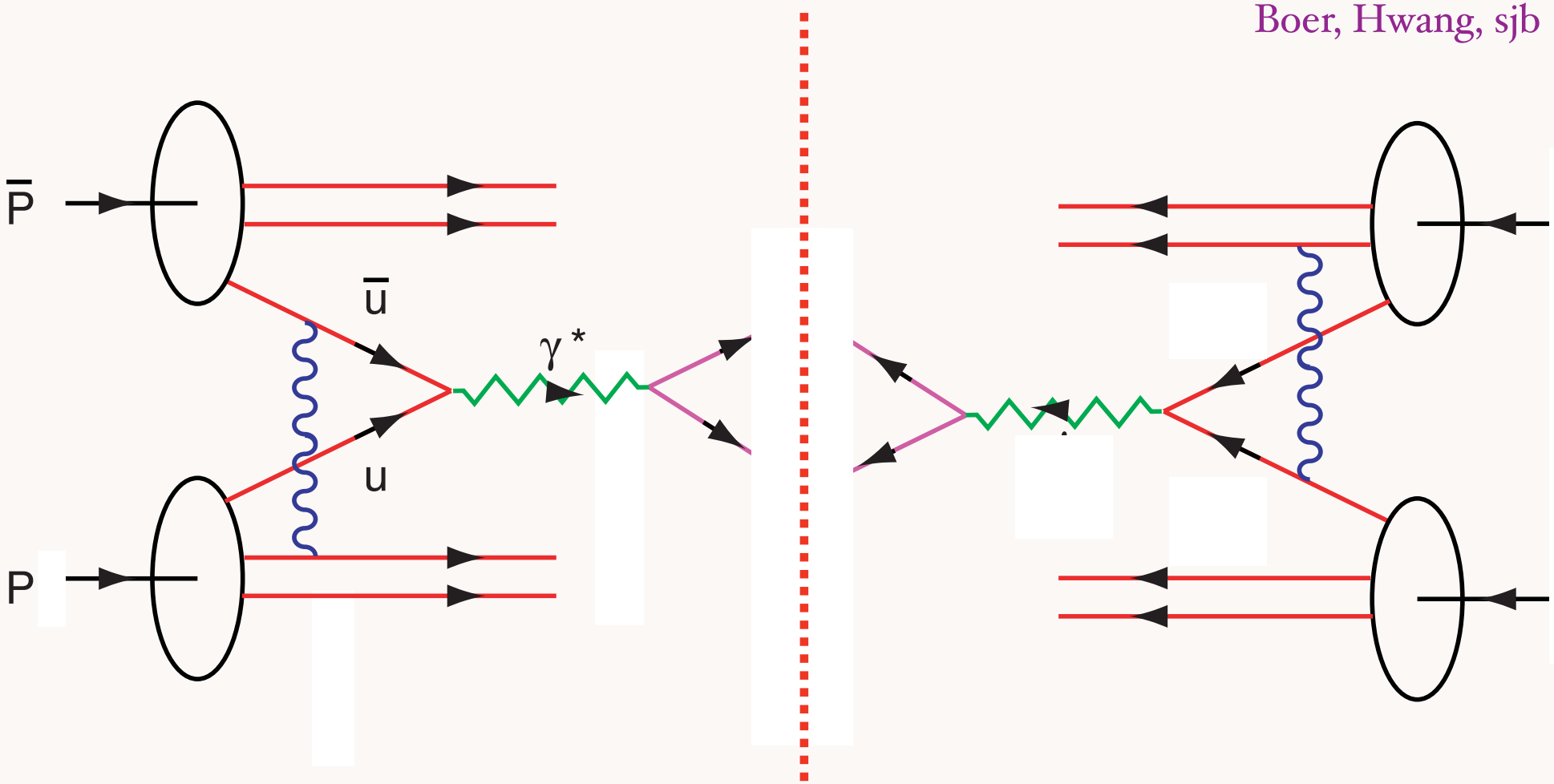
Sivers effect for $\pi^-(d\bar{u})$ reduced by $L_{\bar{u}}$ at low $x$

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

# 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

Boer, Hwang, sjb

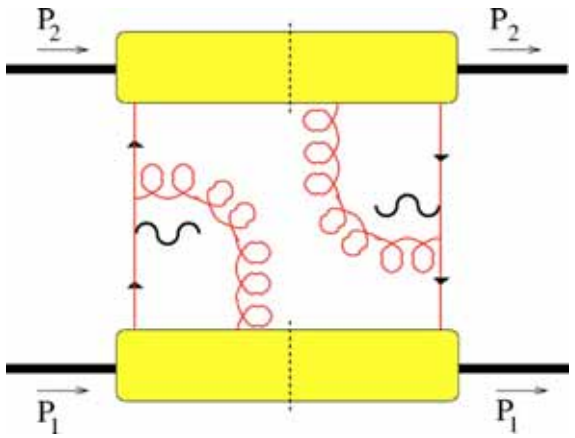



**DY $\cos 2\phi$ correlation at leading twist from double ISI**

# 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 $\cos 2\phi$

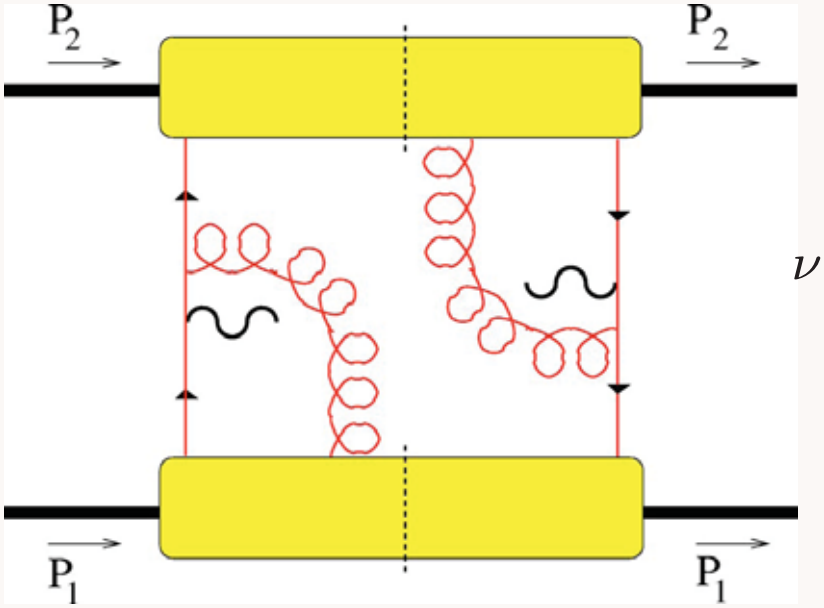
Boer, Hwang, sjb

## Drell-Yan planar correlations

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

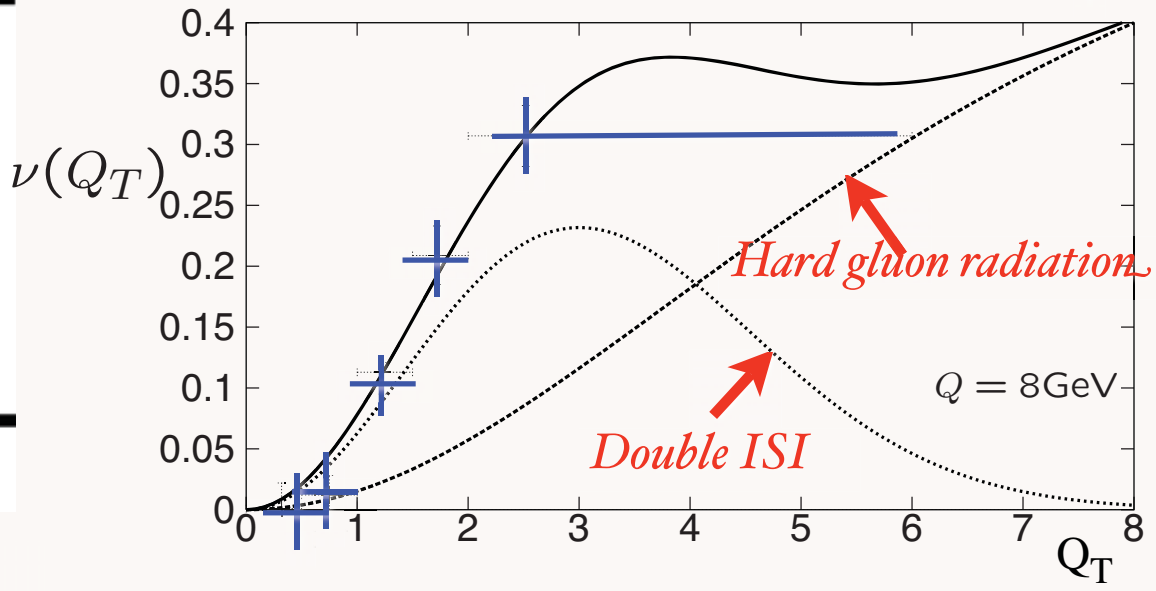
PQCD Factorization (Lam Tung): $1 - \lambda - 2\nu = 0$

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

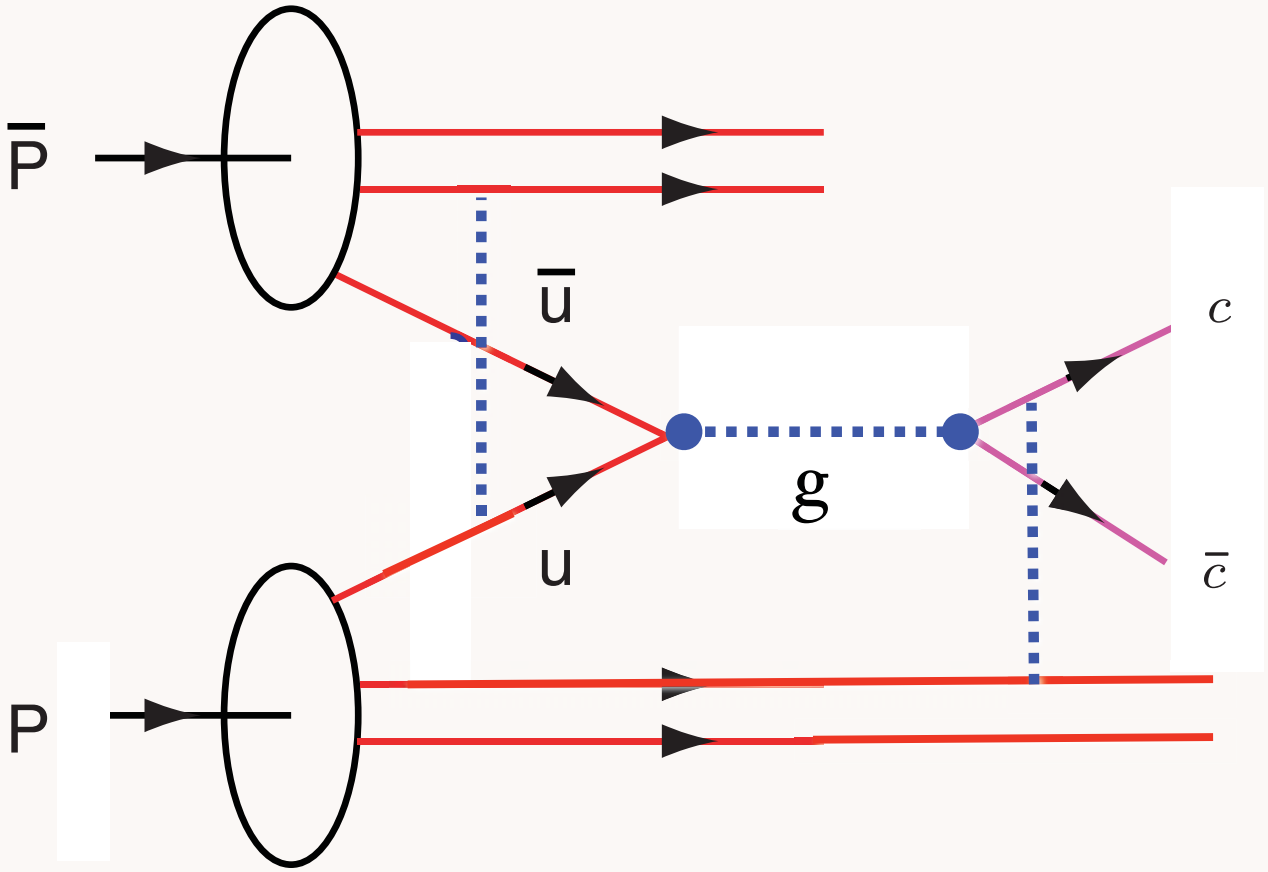



**Violates Lam-Tung relation!**

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




Model: Boer,

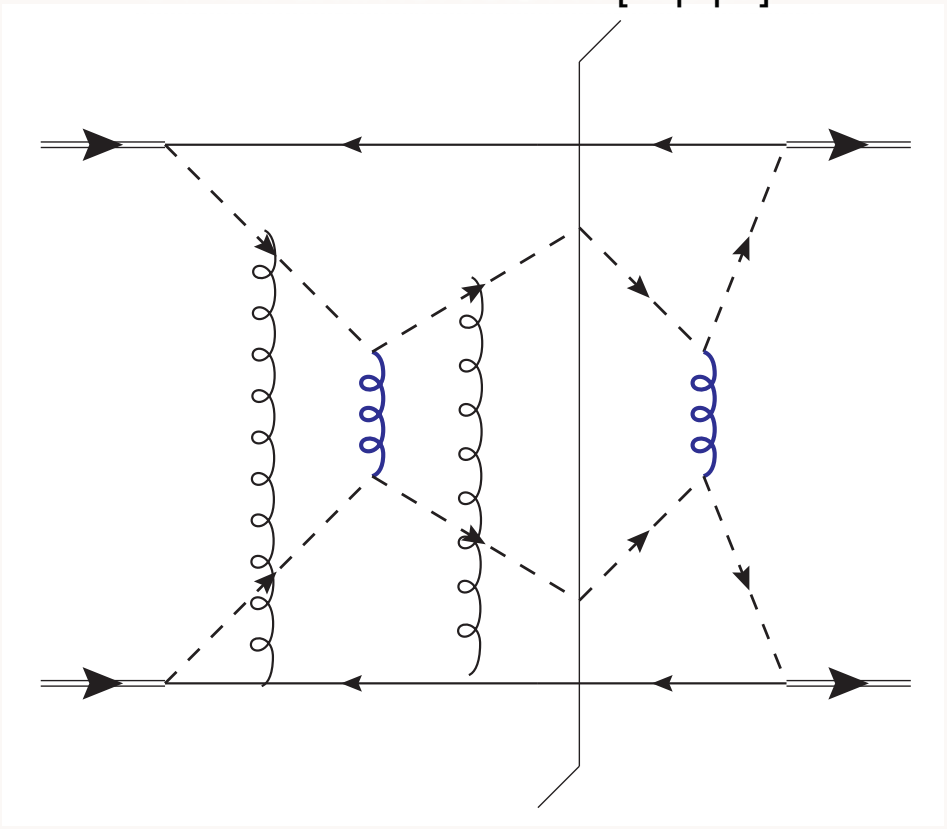



*Problem for factorization when both ISI and FSI occur*

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

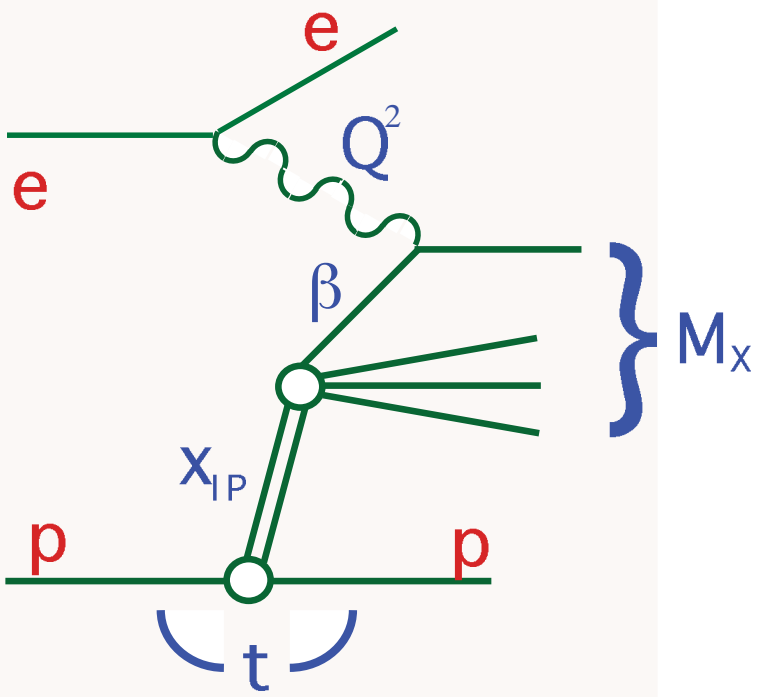
John Collins, Jian-Wei Qiu . ANL-HEP-PR-07-25, May 2007.

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

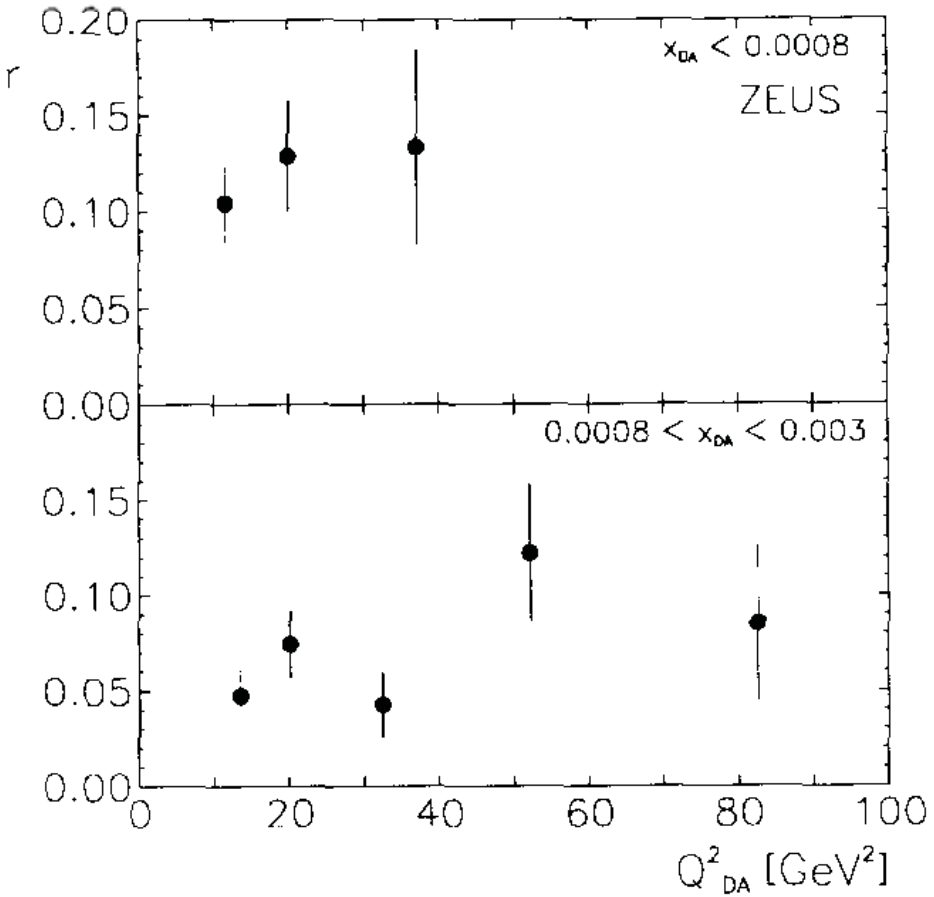


The exchange of two extra gluons, as in this graph, will tend to give non-factorization in unpolarized cross sections.

# Remarkable observation at HERA




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



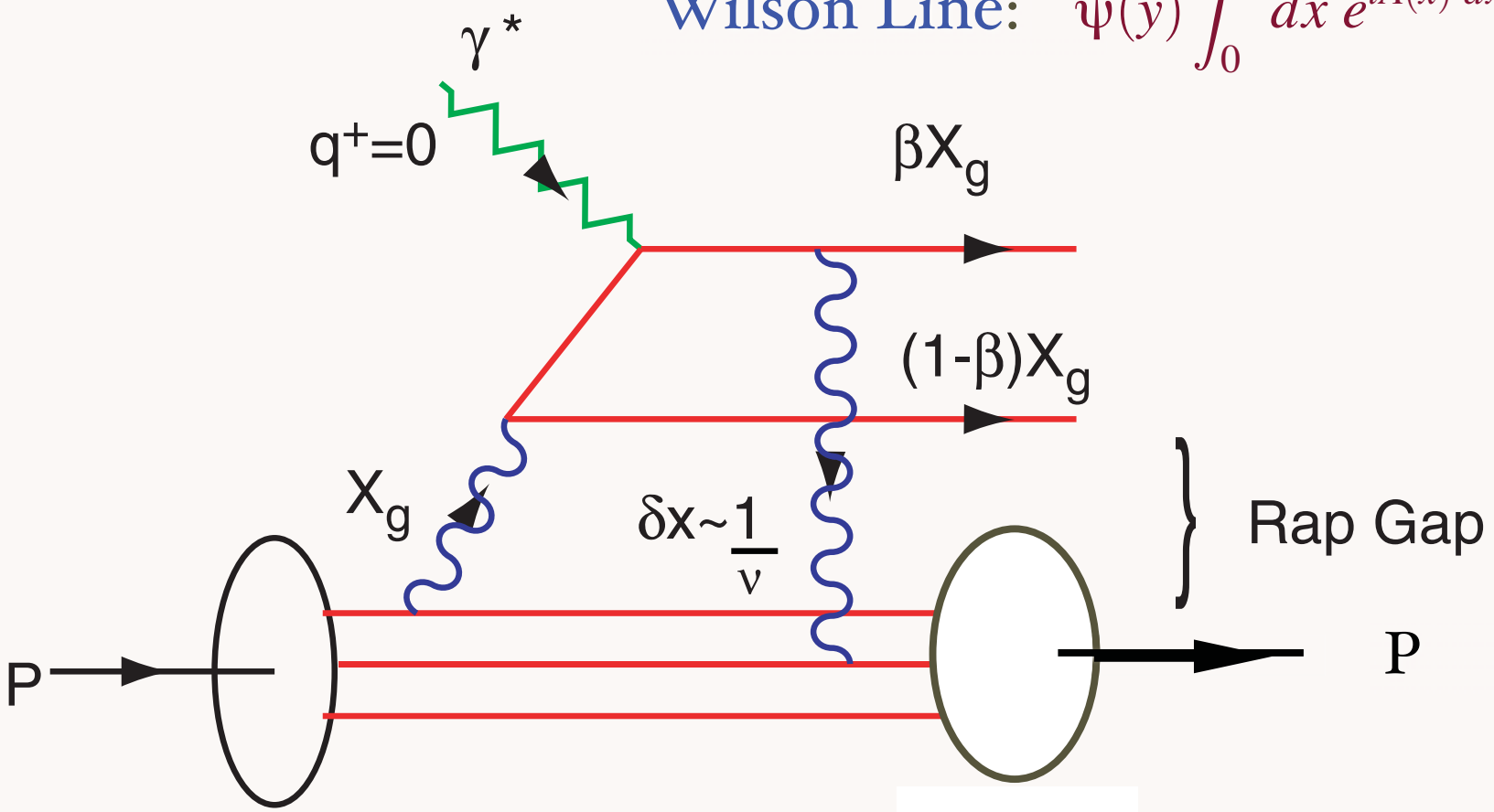

Fraction $r$ of events with a large rapidity gap, $\eta_{max} < 1.5$, as a function of $Q^2_{DA}$ for two ranges of $x_{DA}$. No acceptance corrections have been applied.

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

Hoyer, Marchal, Peigne, Sannino, sjb

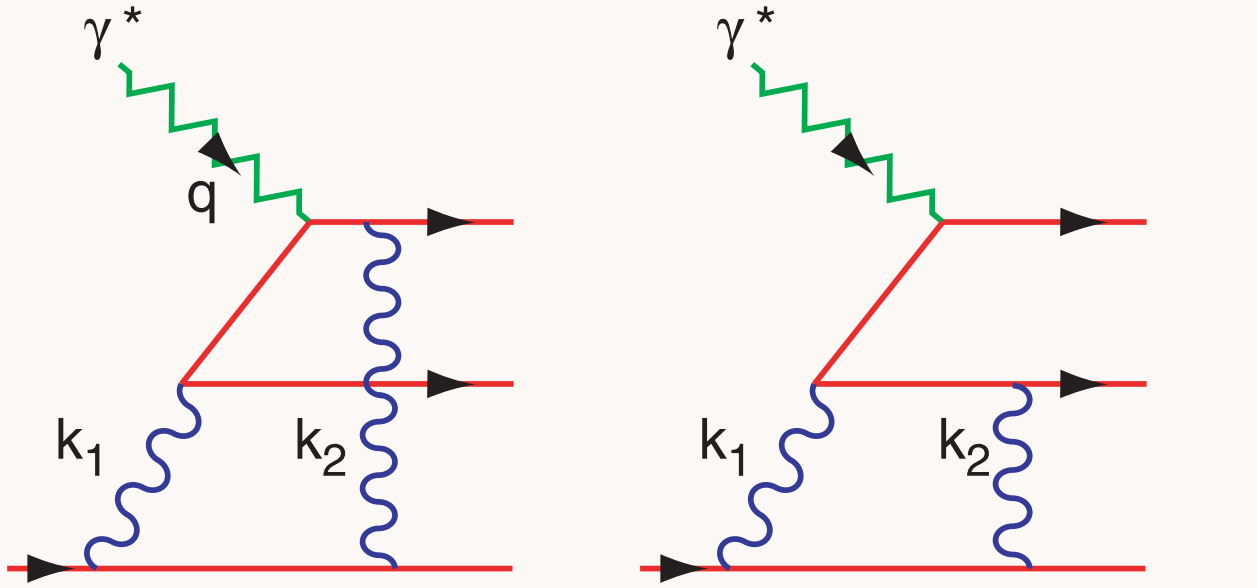
# QCD Mechanism for Rapidity Gaps

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



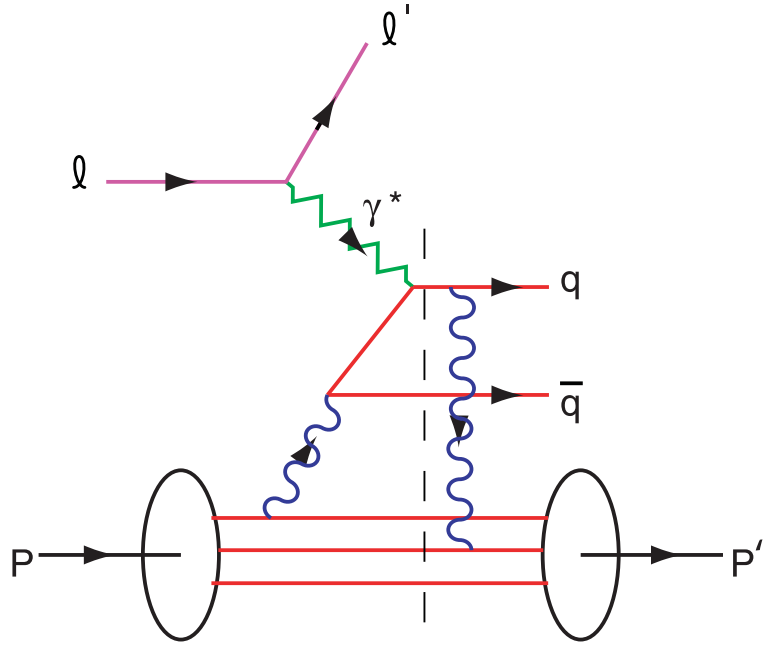

**Reproduces lab-frame color dipole approach**

# Final State Interactions in QCD




Feynman Gauge  Light-Cone Gauge

Result is Gauge Independent

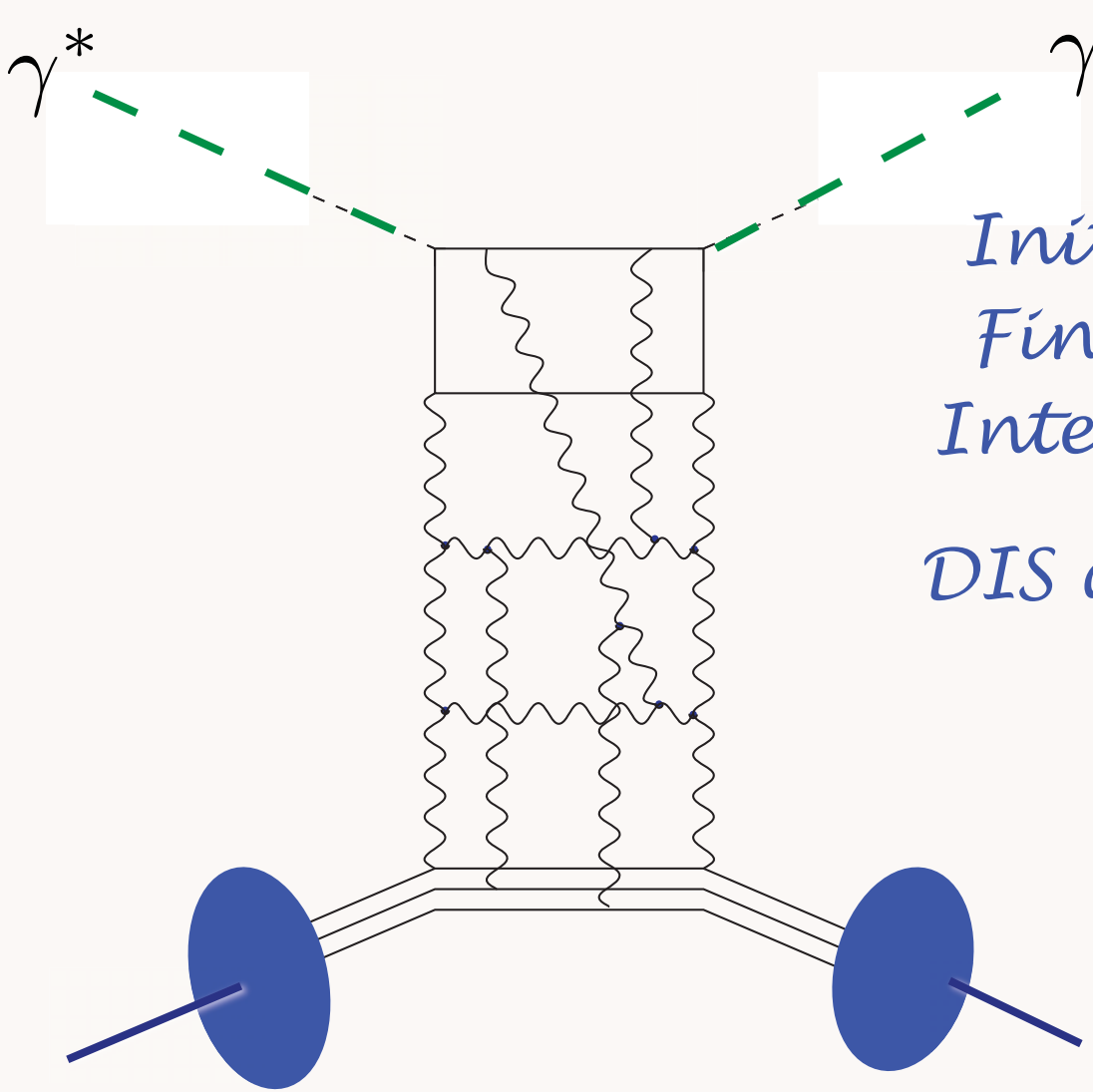



Integration over on-shell domain produces phase i

Need Imaginary Phase to Generate Pomeron

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

*Physics of FSI not in Wavefunction of Target*

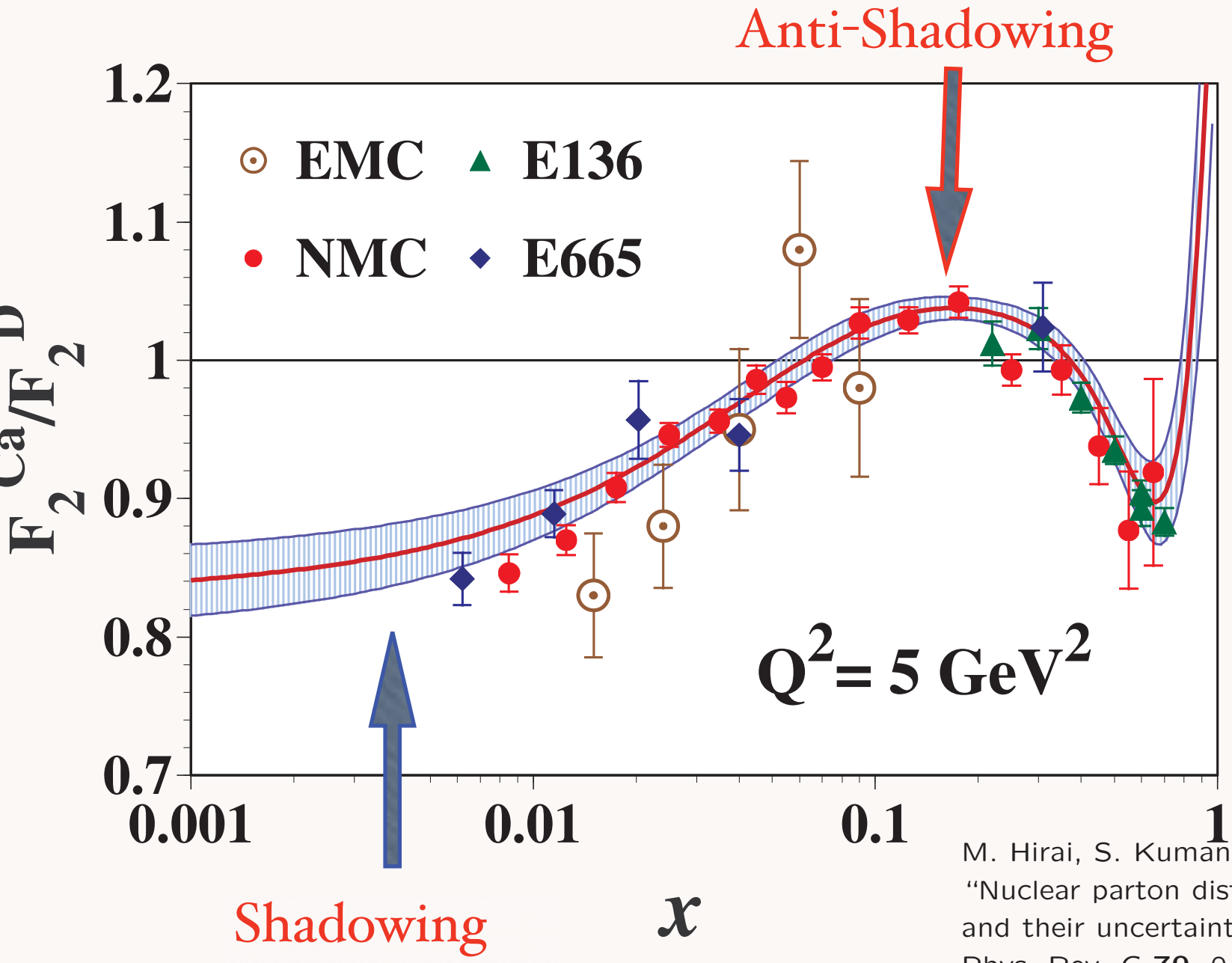



*Initial and Final-State Interactions!*

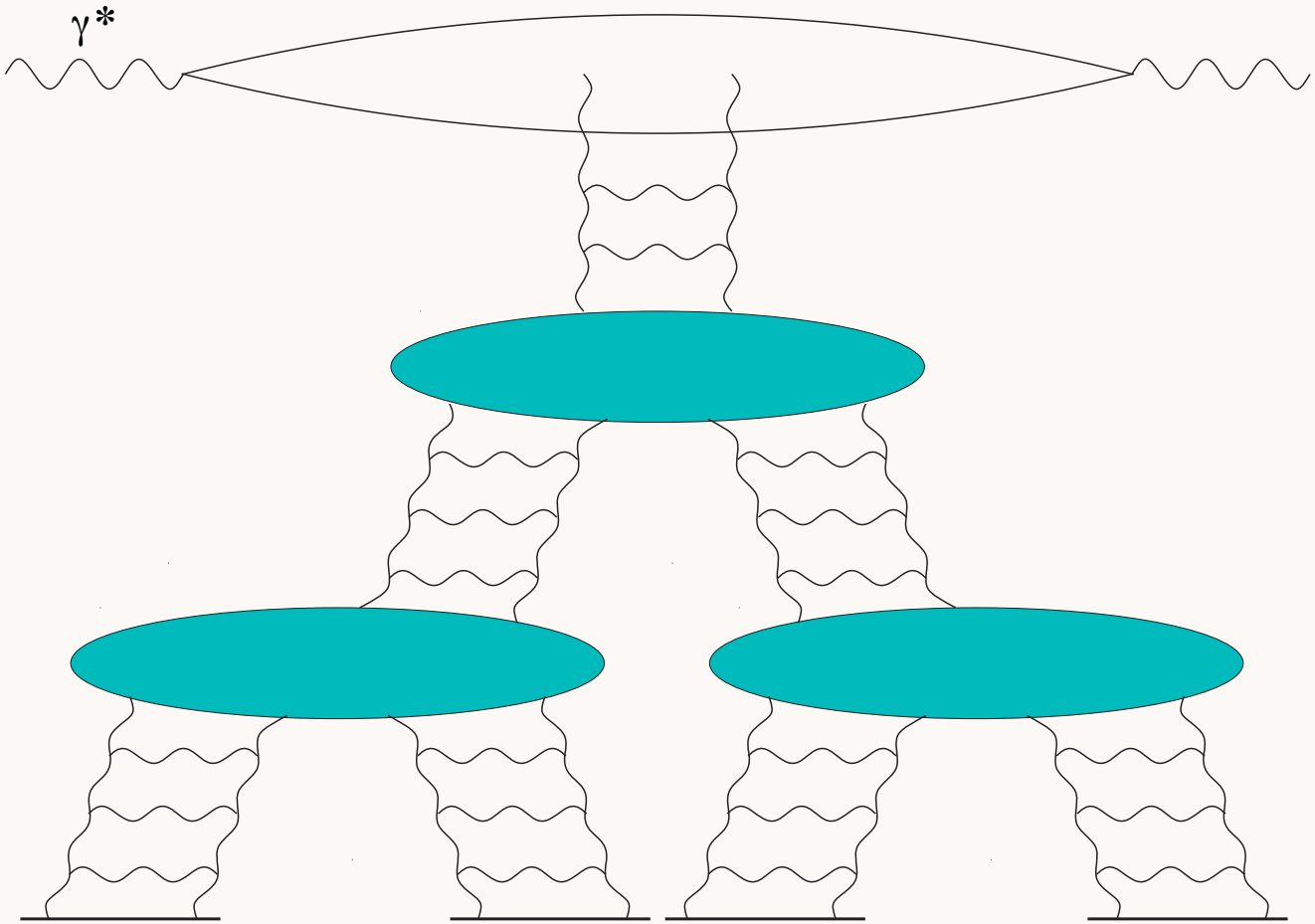
*DIS and DVCS*

# 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



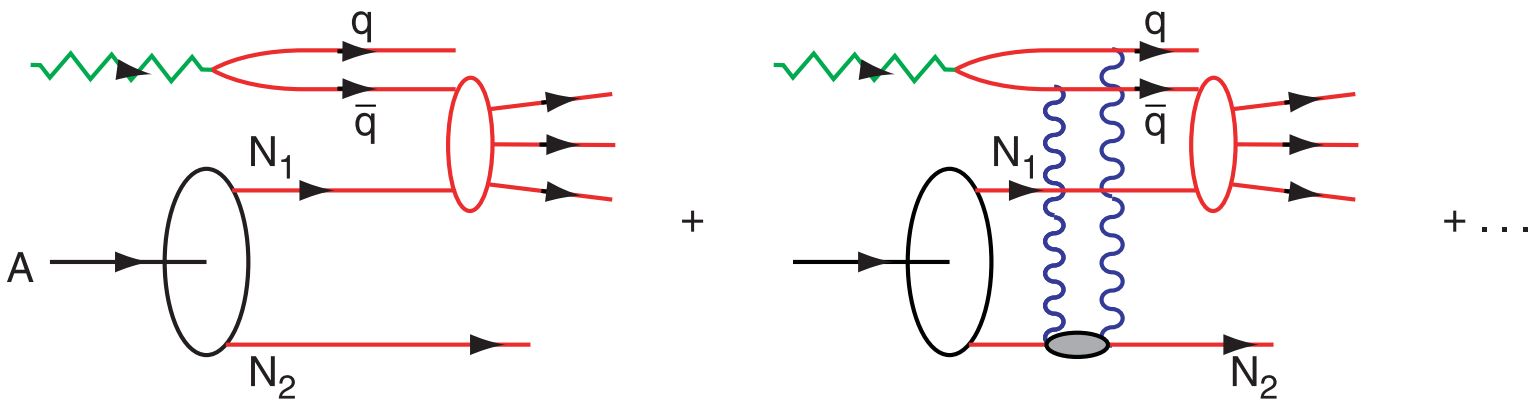

M. Hirai, S. Kumano and T. H. Nagai, "Nuclear parton distribution functions and their uncertainties," Phys. Rev. C **70**, 044905 (2004) [arXiv:hep-ph/0404093].




# Multi-scattering in Target

Stodolsky
Pumplin, sjb
Gribov

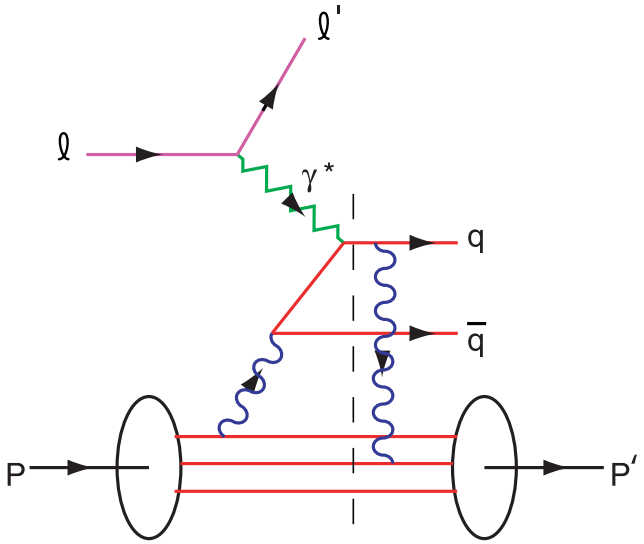
# Nuclear Shadowing in QCD




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***

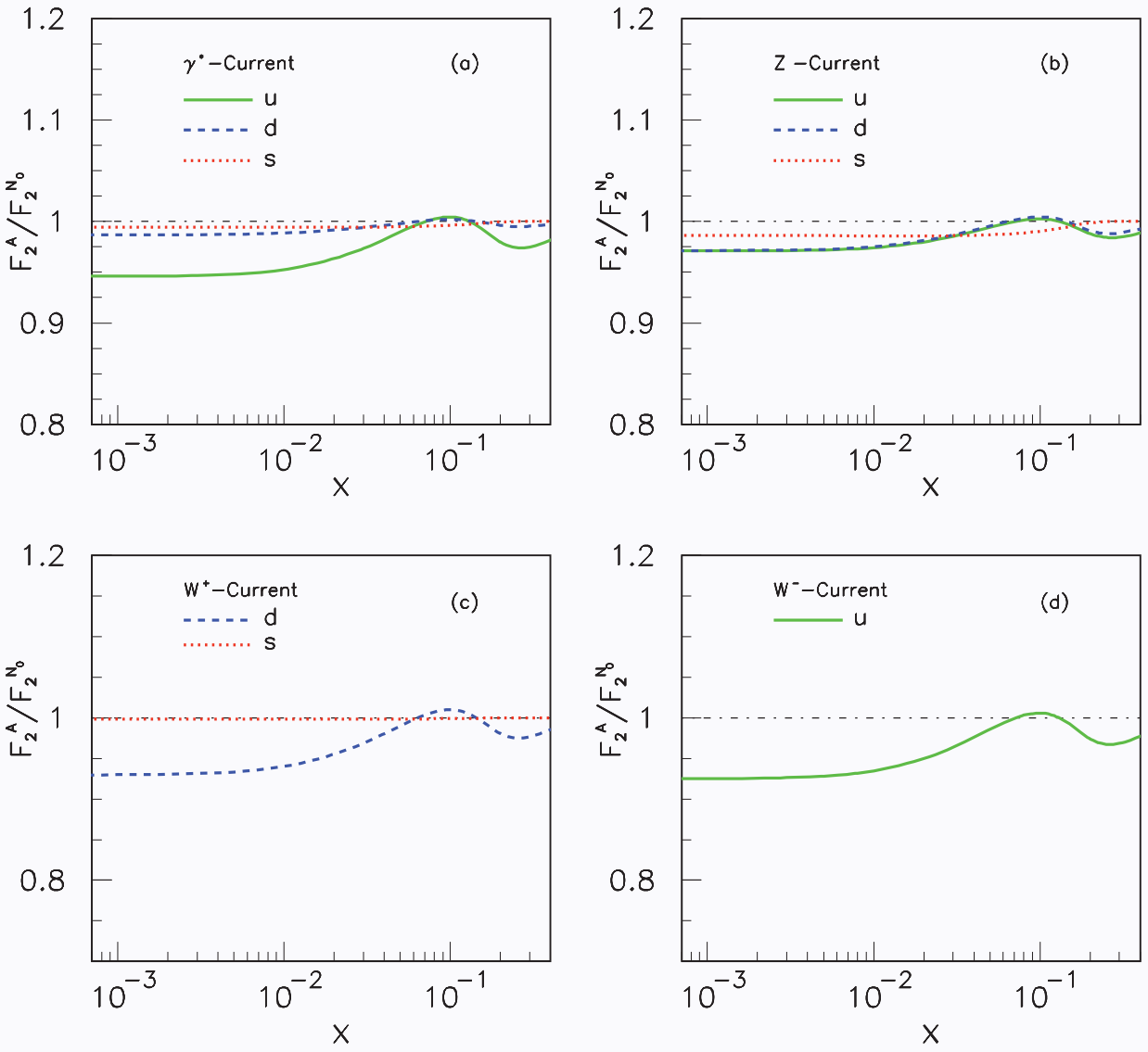
***Need Imaginary Phase to Generate Pomeron***

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

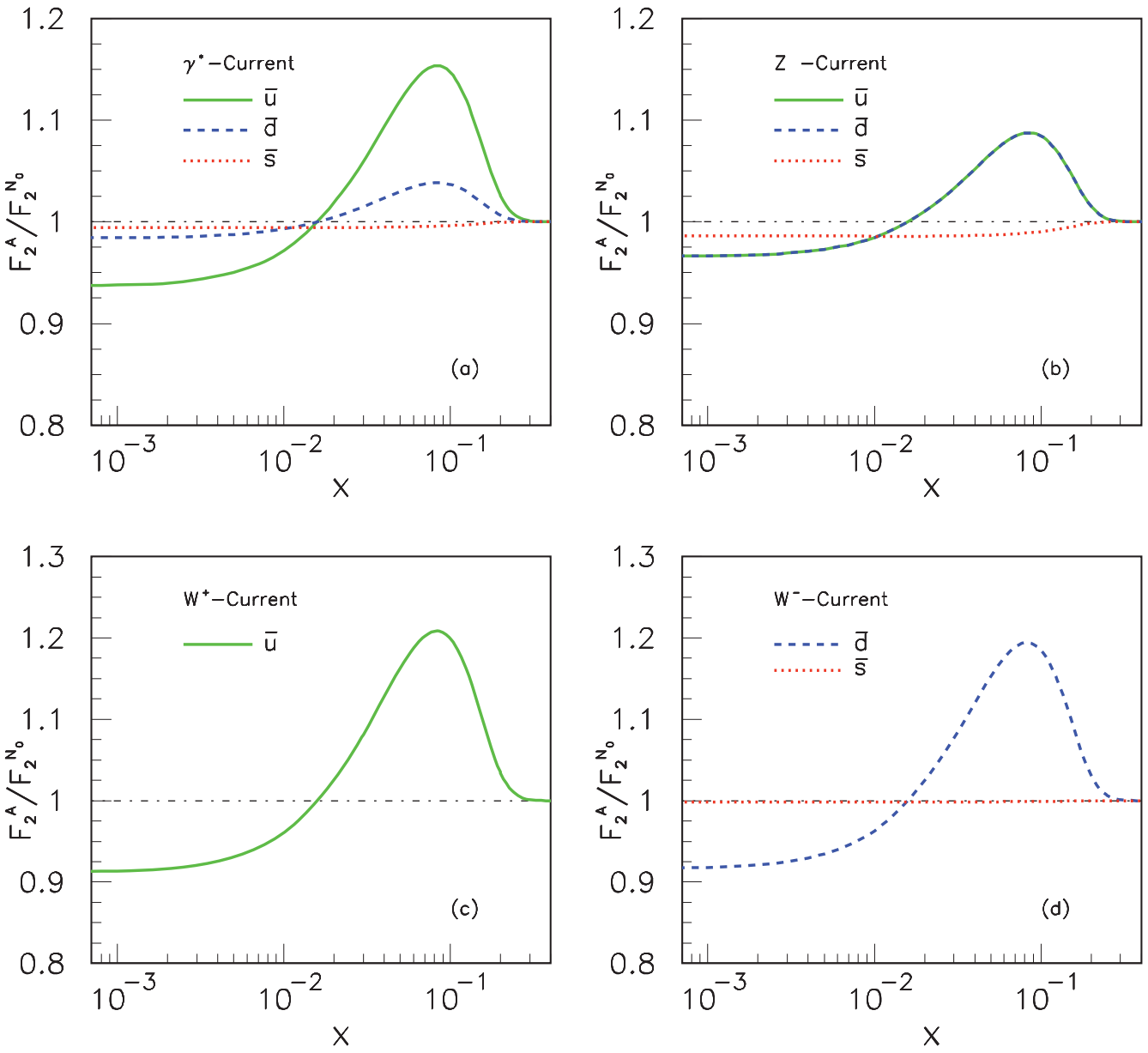
*Physics of FSI not in Wavefunction of Target*

*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 !

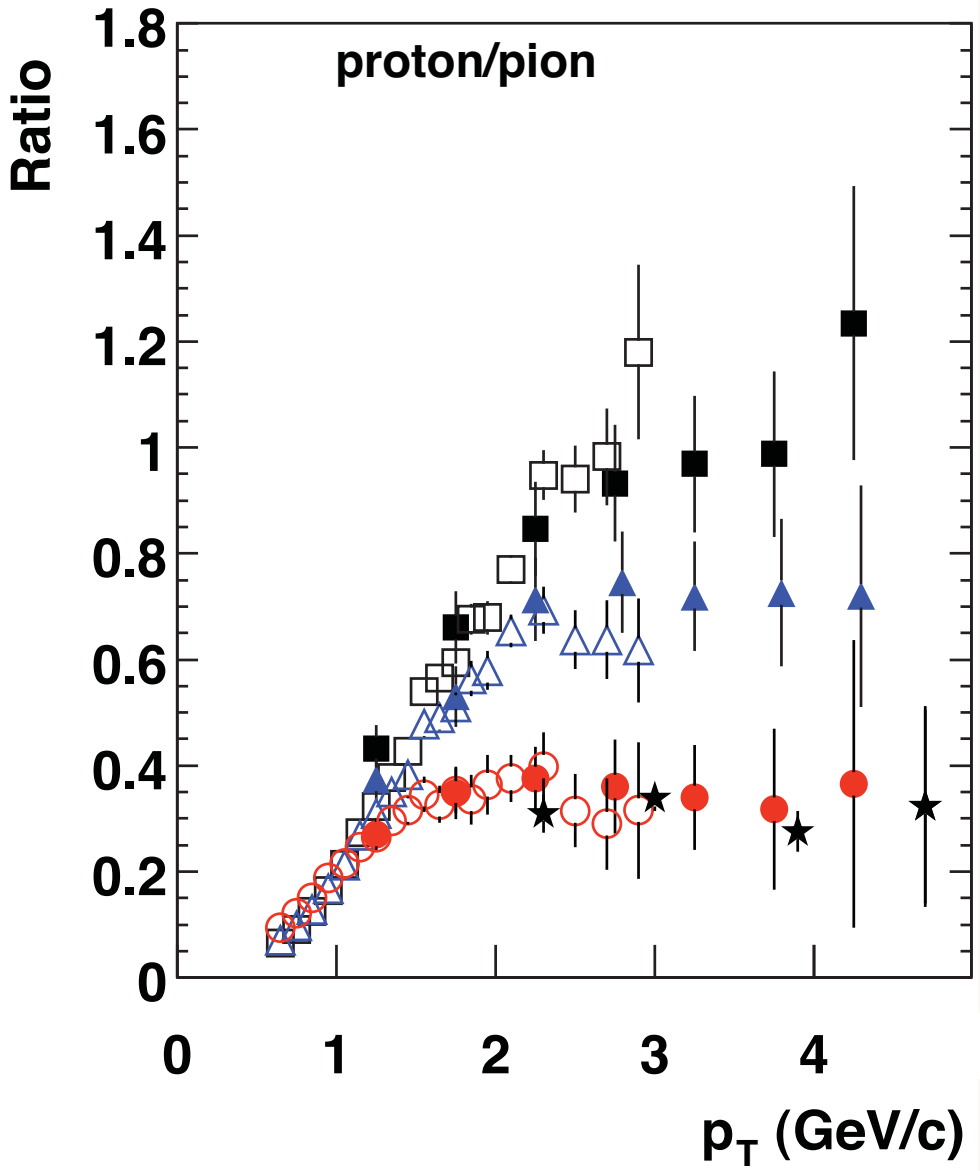
# Physics of Rescattering

- Diffractive DIS
- Non-Unitary Correction to DIS: Structure functions are not probability distributions
- Nuclear Shadowing, Antishadowing- Not in Target WF
- Single Spin Asymmetries -- opposite sign in DY and DIS
- DY angular 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

S. S. Adler *et al*. PHENIX Collaboration *Phys. Rev. Lett.* **91**, 172301 (2003).

*Particle ratio changes with centrality!*

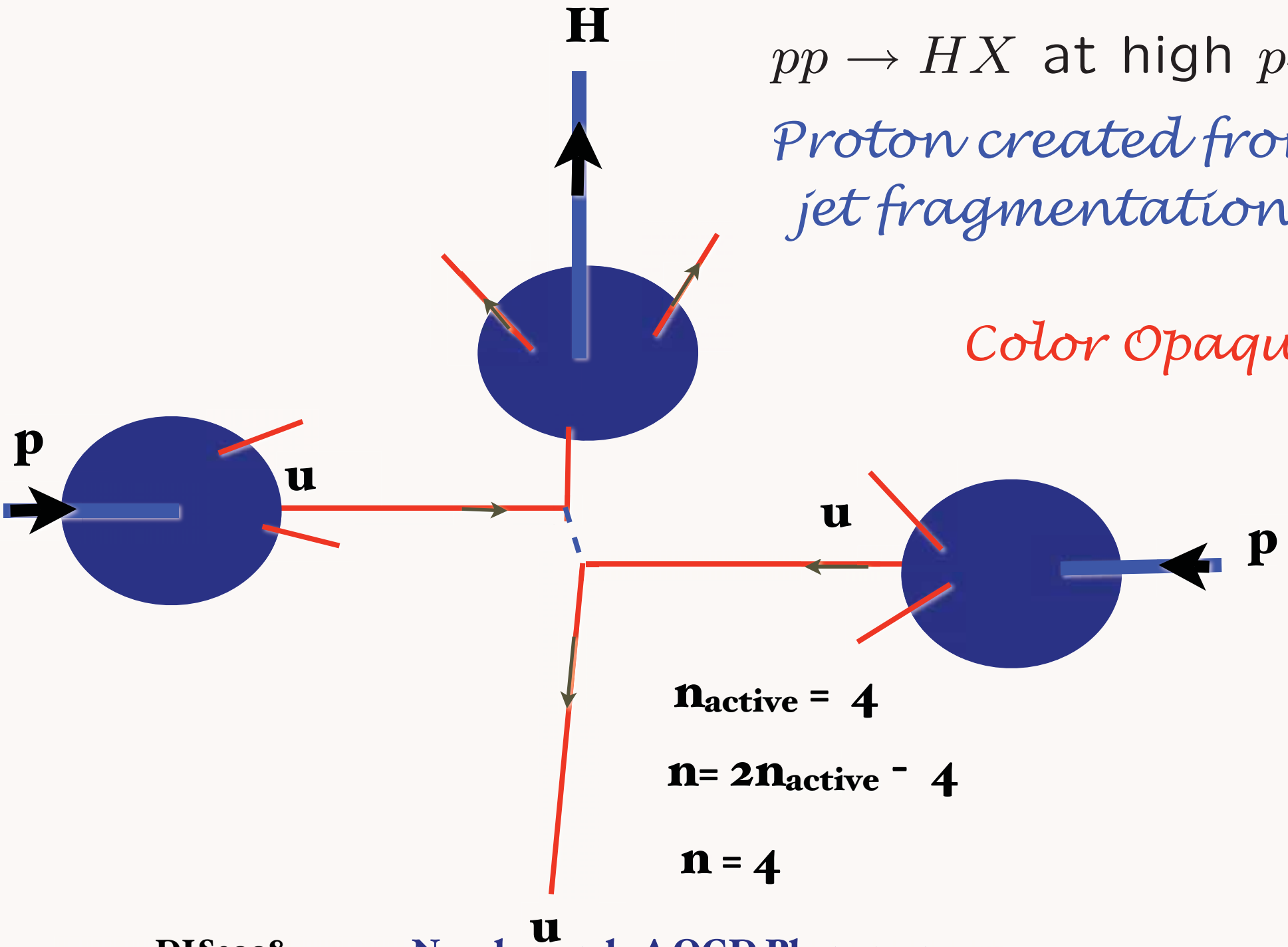



***Protons less absorbed in nuclear collisions than pions***

← **Central**

Au+Au 0-10%
Au+Au 20-30%
Au+Au 60-92%
p+p, $\sqrt{s}$ = 53 GeV, ISR
$e^+e^-$, gluon jets, DELPHI
$e^+e^-$, quark jets, DELPHI

← **Peripheral**




$pp \to HX$ at high $p_T$

*Proton created from jet fragmentation*

*Color Opaque*

$n_{active} = 4$

$n = 2n_{active} - 4$

$n = 4$

# Crucial Test of Leading -Twist QCD: Scaling at fixed $x_T$

$$x_T = \frac{2p_T}{\sqrt{s}}$$

$$E\frac{d\sigma}{d^3p}(pN \to \pi X) = \frac{F(x_T,\theta_{CM})}{p_T^{n_{eff}}}$$

***Parton model: $n_{eff} = 4$***

***As fundamental as Bjorken scaling in DIS***

**Conformal scaling: $n_{eff} = 2\, n_{active} - 4$**