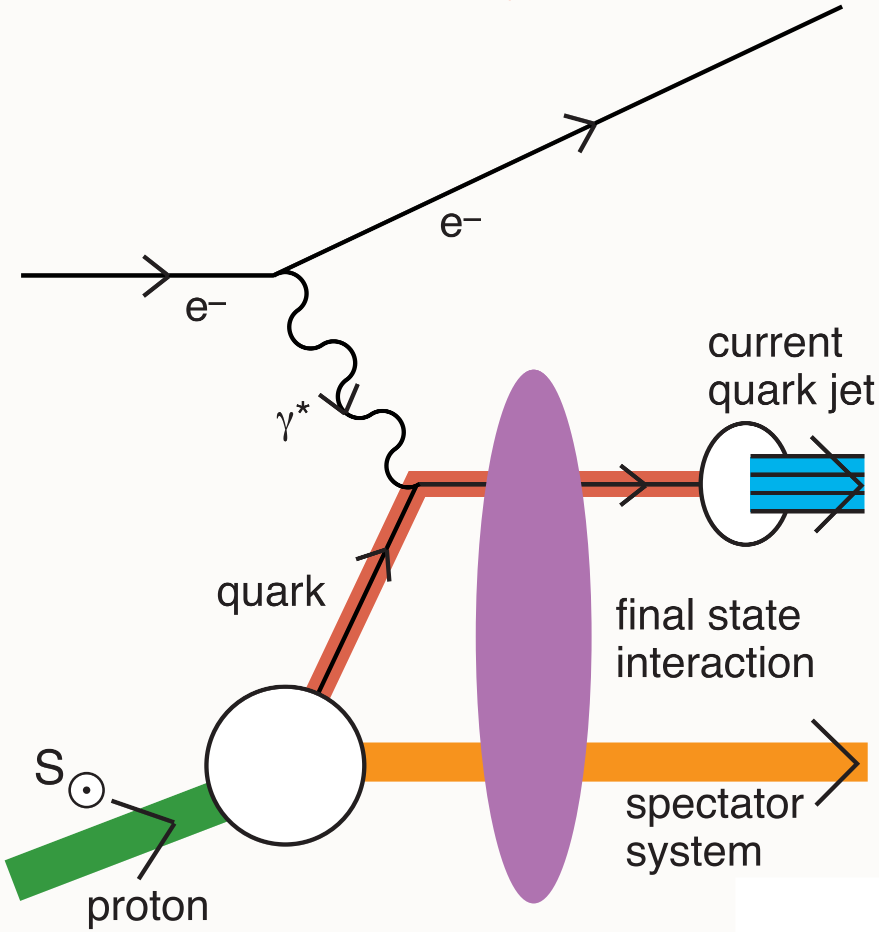
# Novel Initial-State and Final-State Interactions in QCD

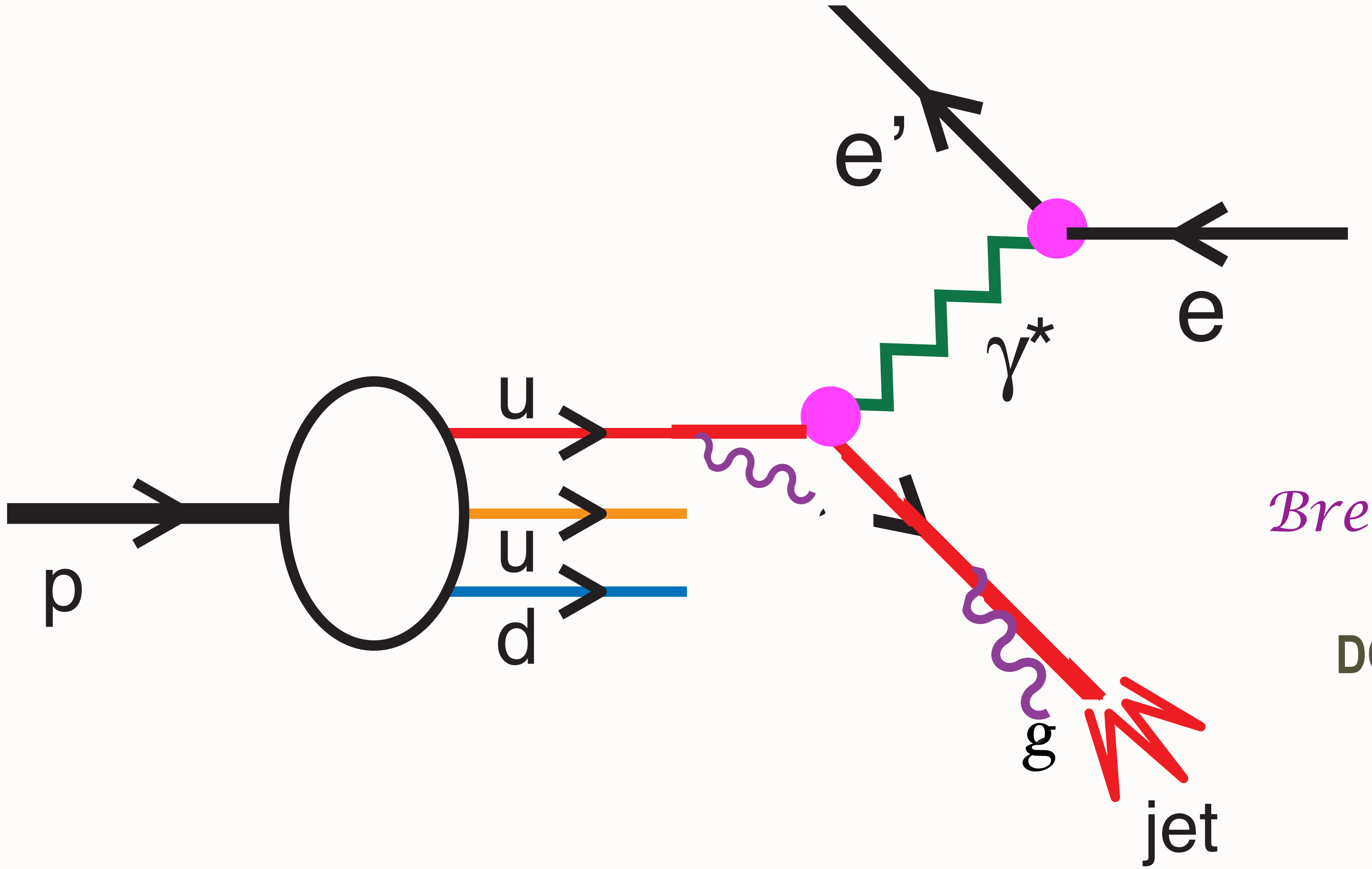



**Stan Brodsky, SLAC**

*JLab Conference on Exclusive Reactions*

**May 24, 2007**

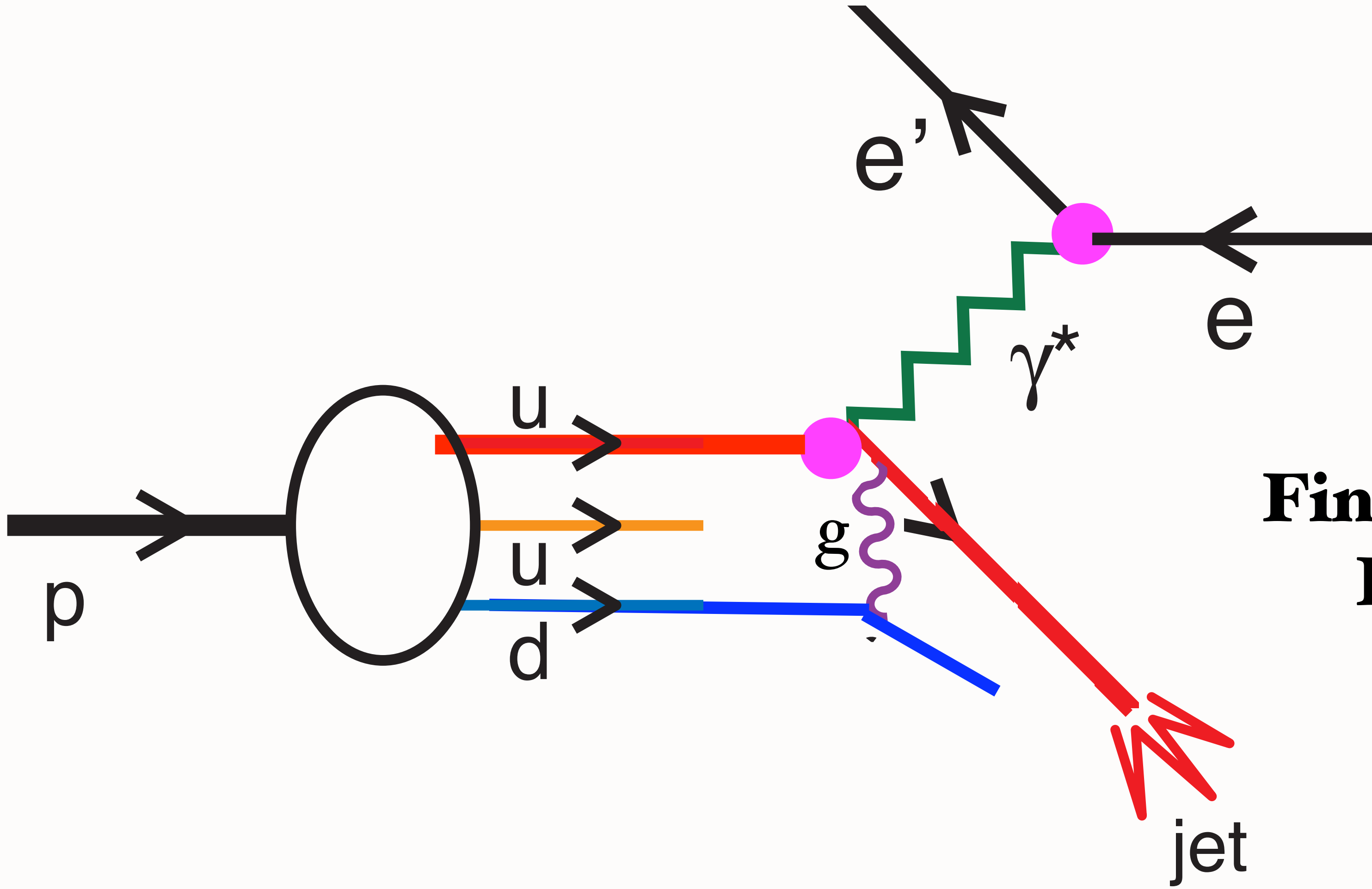
# Deep Inelastic Electron-Proton Scattering




*Gluonic Bremmstrahlung*

**DGLAP Evolution**

# Deep Inelastic Electron-Proton Scattering




**Final-State QCD Interaction**

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

# Physics of Rescattering

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

# Single-spin asymmetries

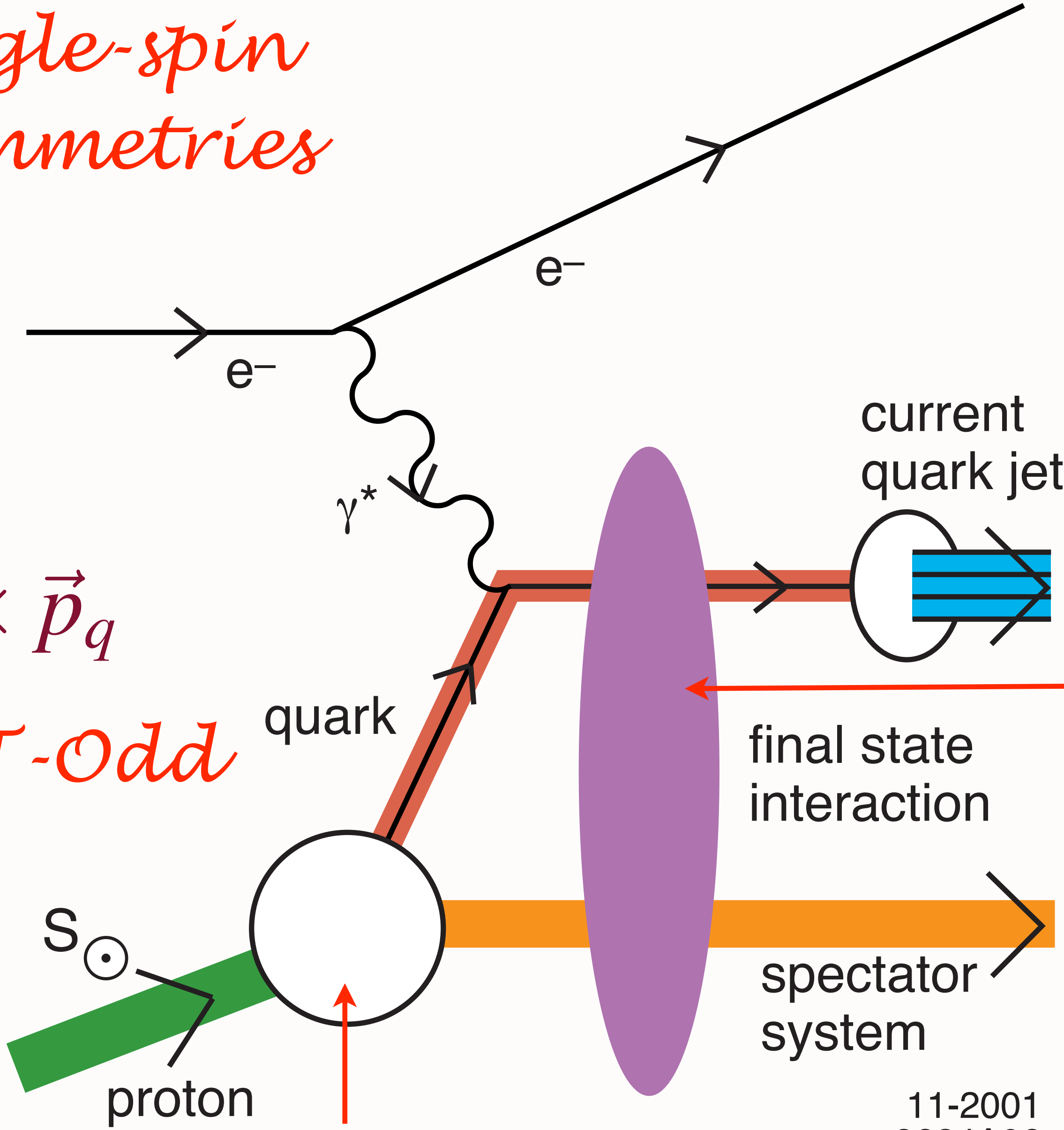
# Leading Twist Sivers Effect

Hwang, Schmidt, sjb

Collins, Burkardt Ji, Yuan

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

*Pseudo-T-Odd*



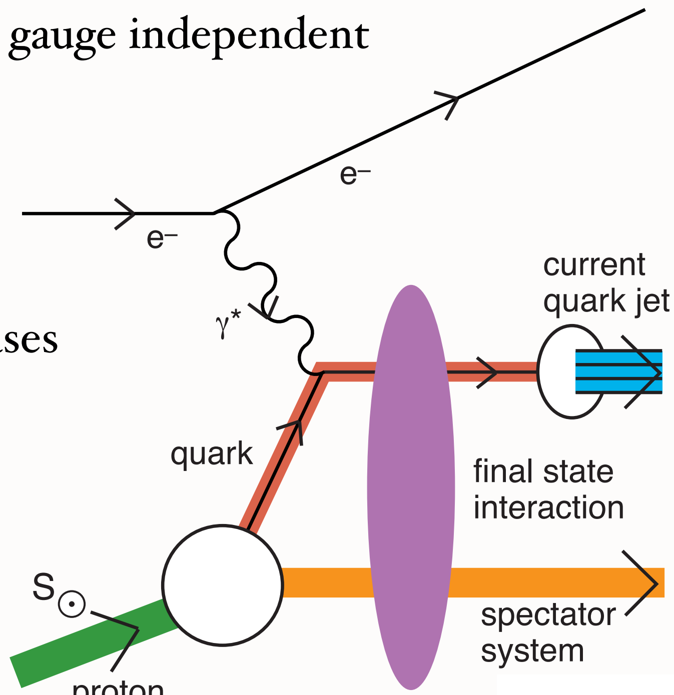

*QCD S- and P-Coulomb Phases --Wilson Line*

*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
- Unexpected QCD Effect -- thought to be zero!
- Relate to the quark contribution to the target proton anomalous magnetic moment and final-state QCD phases
- QCD Coulomb phase at soft scale
- Measure in jet trigger or leading hadron
- Sum of Sivers Functions for all quarks and gluons-- relate to (Zero gravito-anomalous magnetic moment: B(0)= 0)

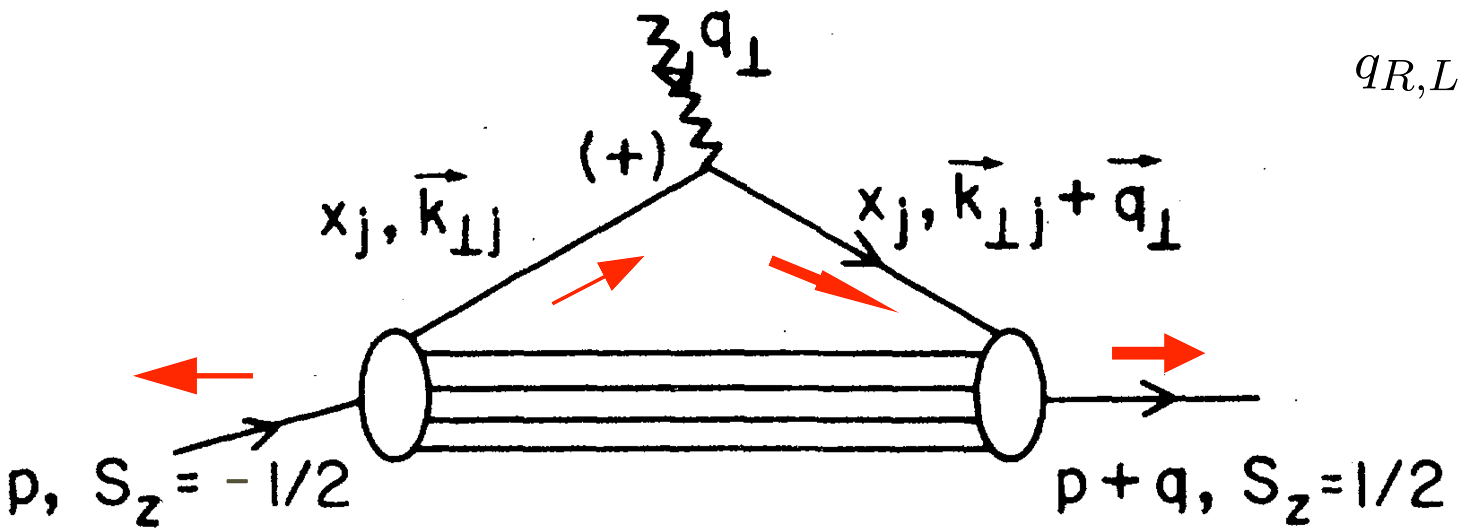


$$\frac{F_2(q^2)}{2M} = \sum_a \int [\mathrm{d}x][\mathrm{d}^2\mathbf{k}_\perp] \sum_j e_j \, \frac{1}{2} \, \times$$

Drell, sjb

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

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



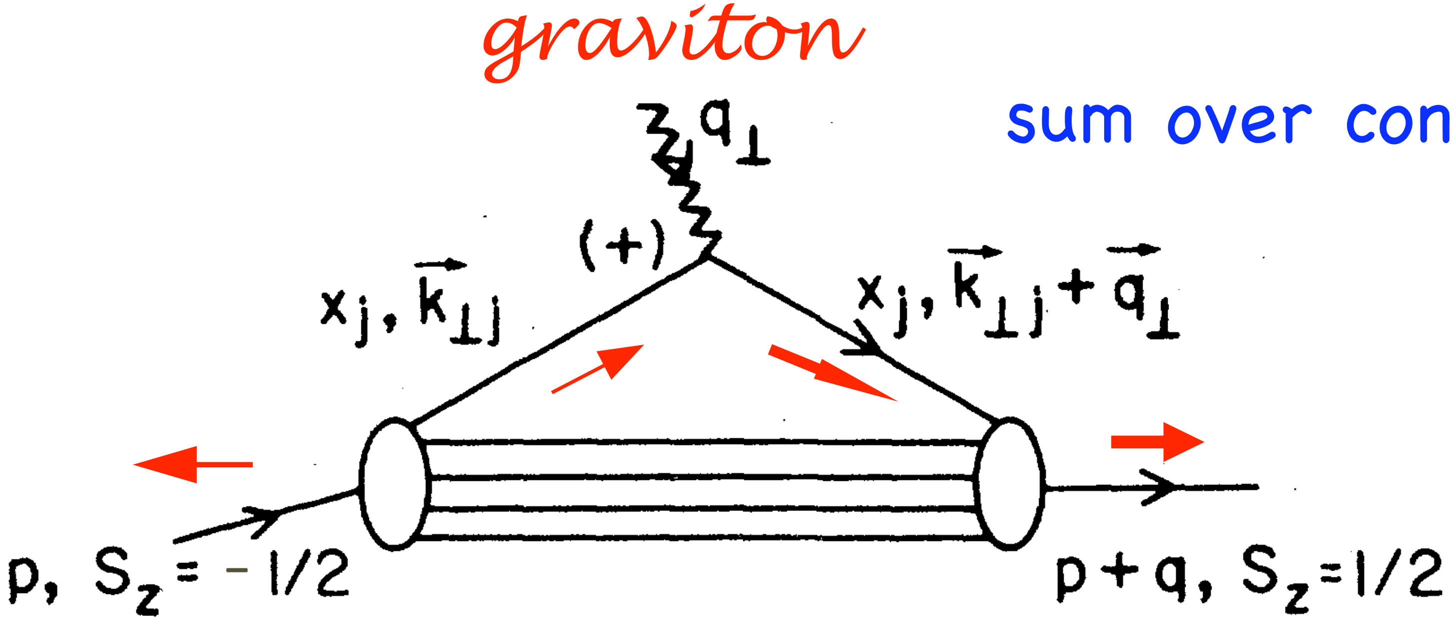

$$q_{R,L} = q^x \pm i q^y$$

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*

# Anomalous gravitomagnetic moment B(0)

Okun et al: B(0) Must vanish because of Equivalence Theorem




sum over constituents

Hwang, Schmidt, sjb; Holstein et al

$B(0) = 0$

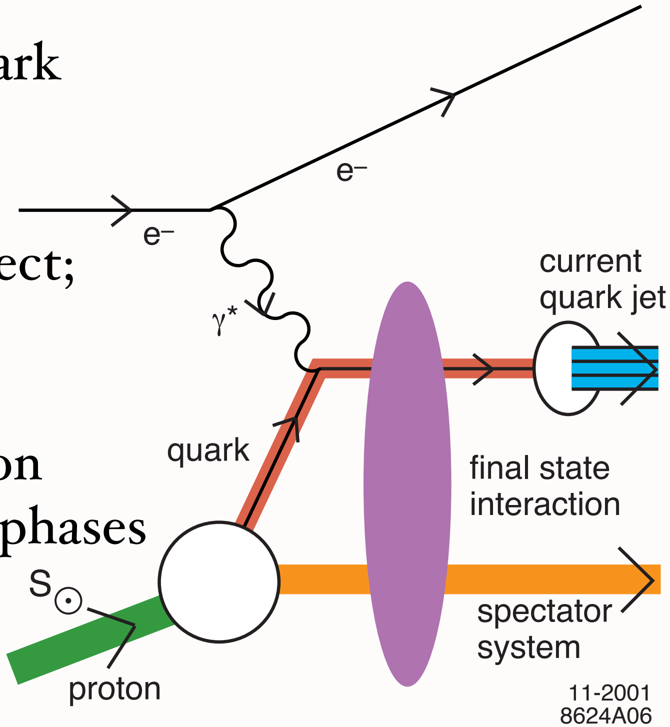
Each Fock State

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

- Leading-Twist Bjorken Scaling!

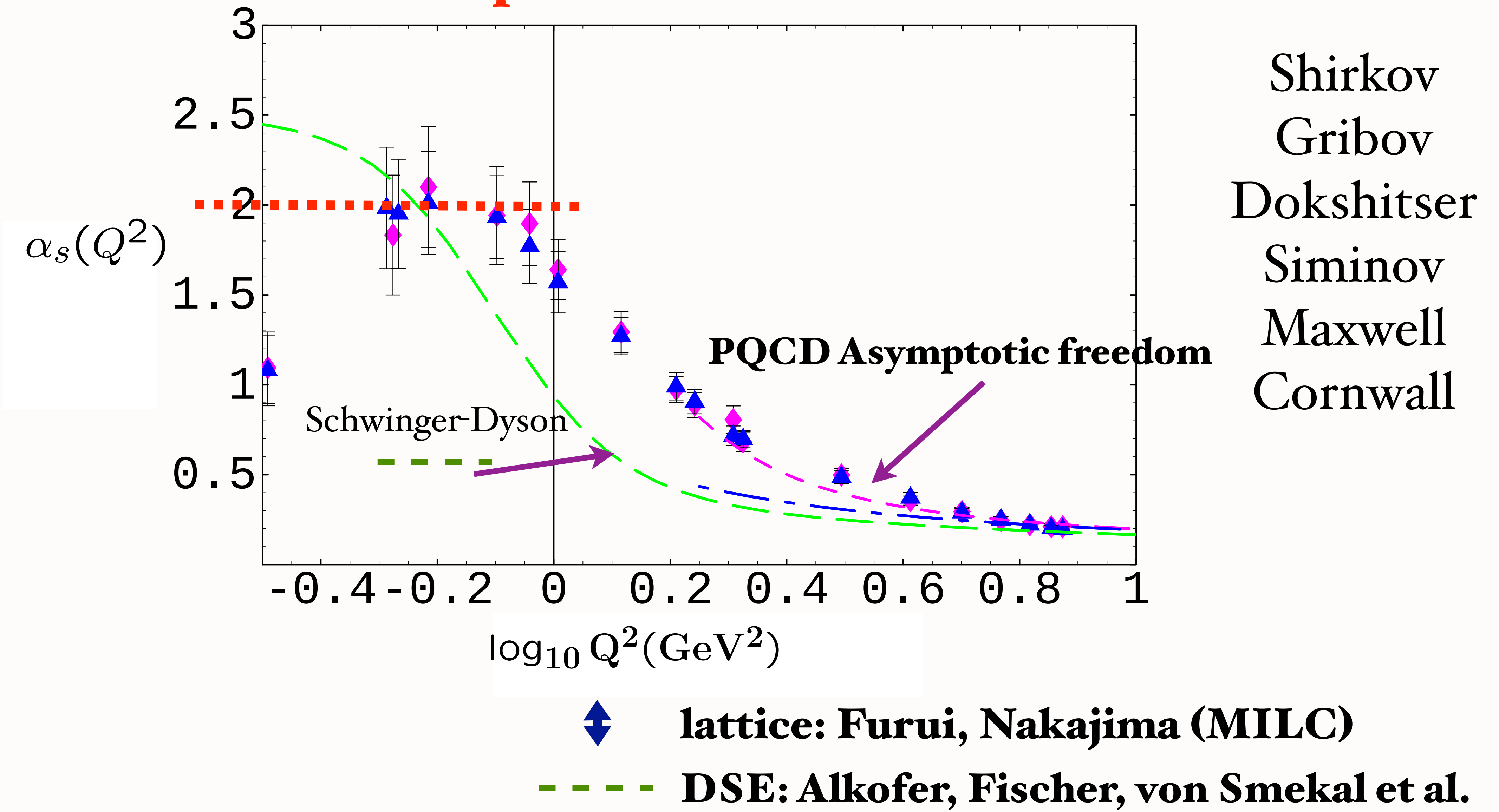
$$\mathbf{i}\ \vec{S} \cdot \vec{p}_{jet} \times \vec{q}$$

- 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



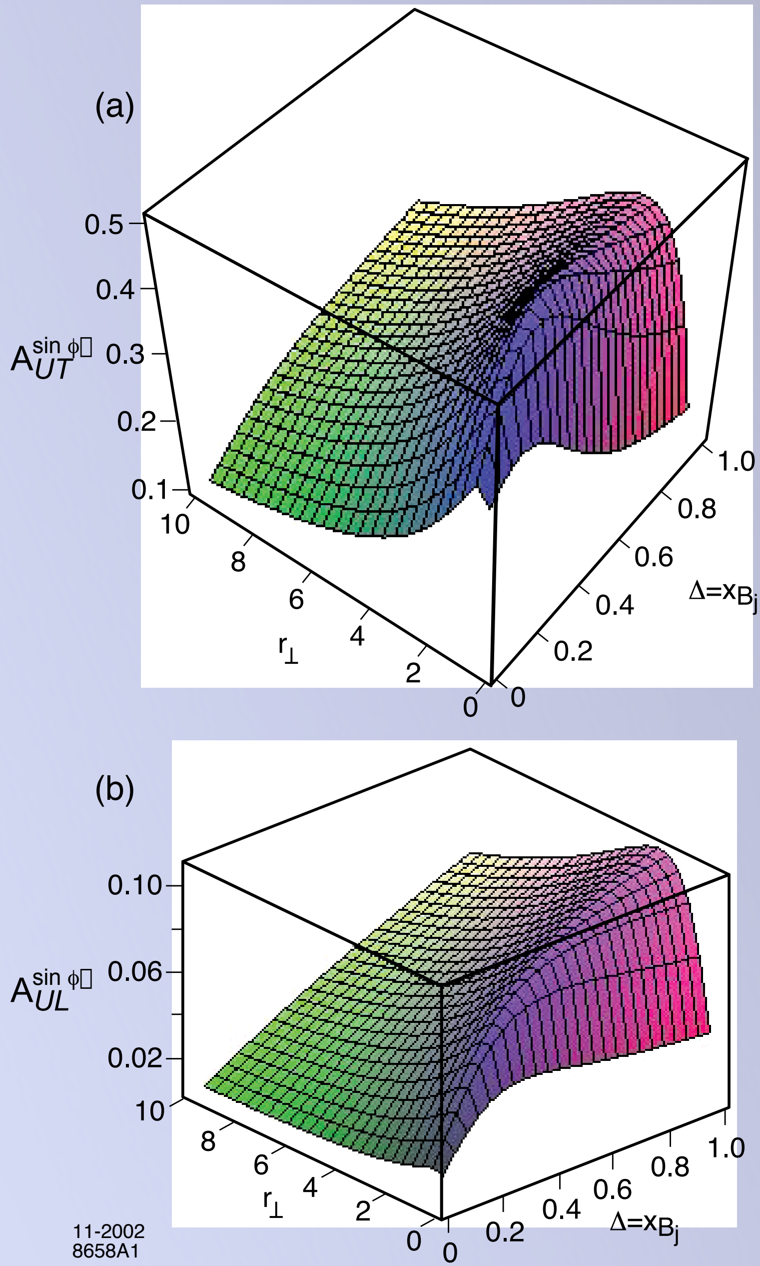
# Conformal window
# Infrared fixed-point

$$\beta(Q^2) = \frac{d\alpha_s(Q^2)}{d\log Q^2} \to 0$$

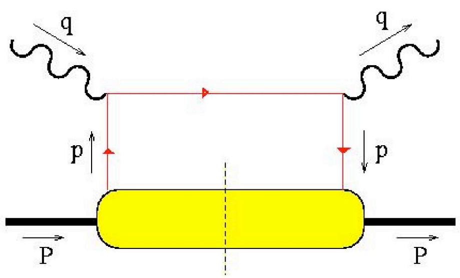



Shirkov
Gribov
Dokshitser
Siminov
Maxwell
Cornwall

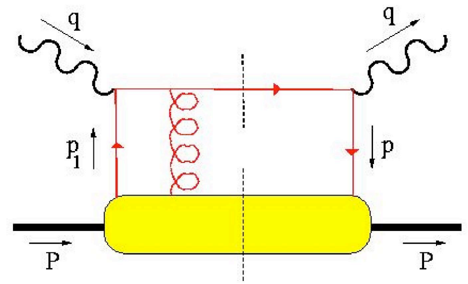
# Prediction for Single-Spin Asymmetry




Hwang, Schmidt, sjb



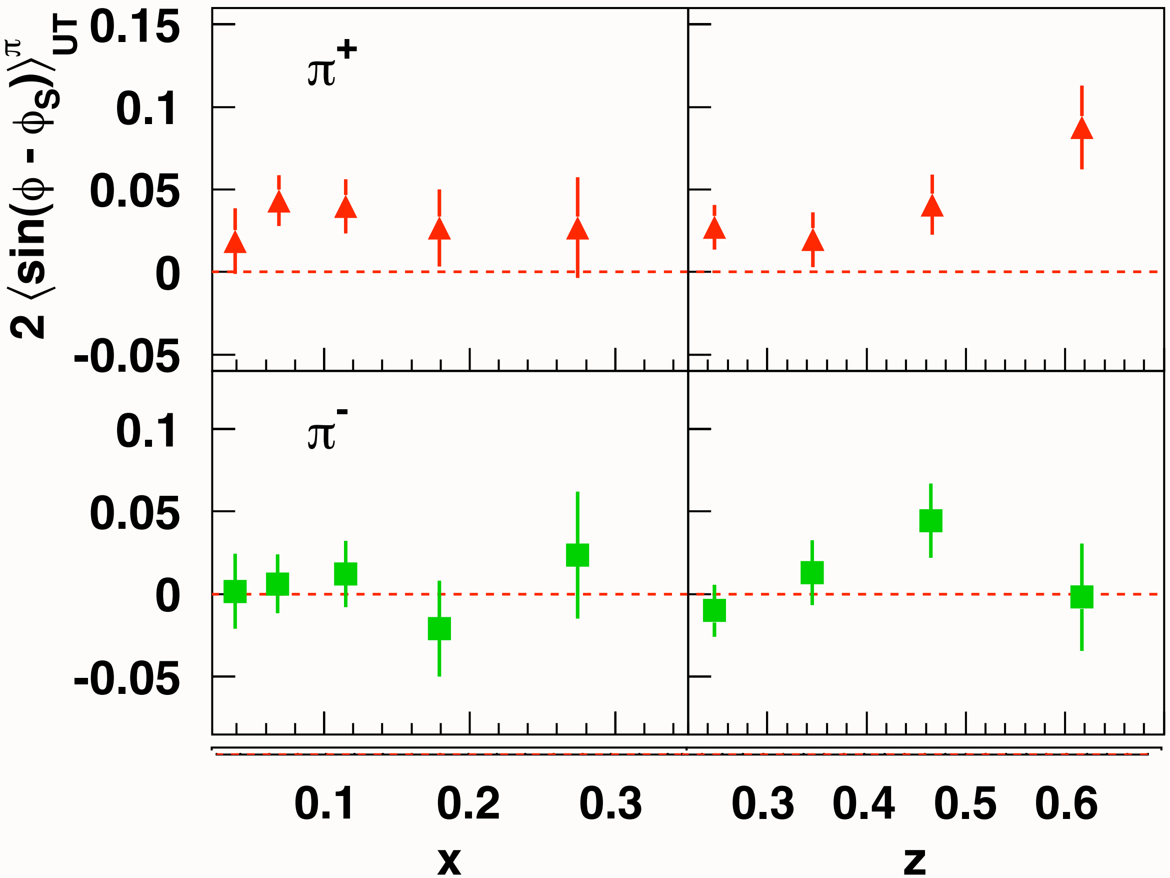

can interfere with




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 **$\pi^-$**...

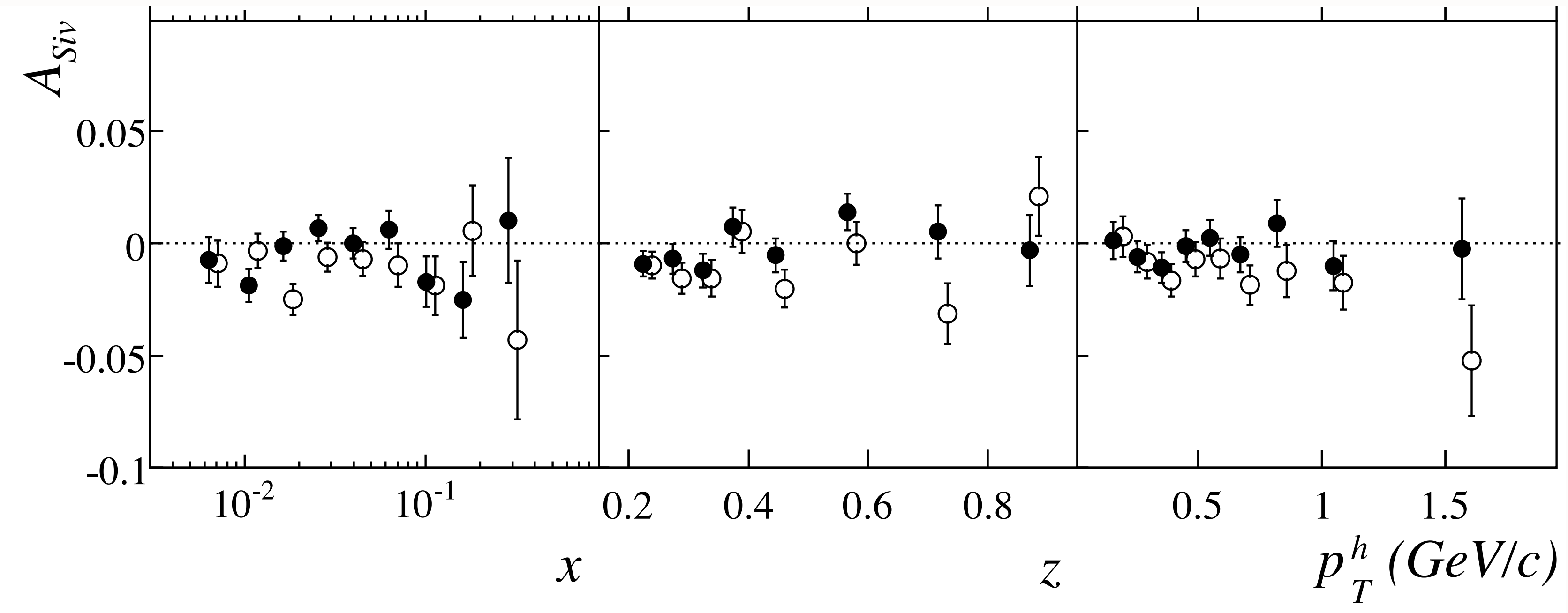
**Gamberg: Hermes data compatible with BHS model**

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

# 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**

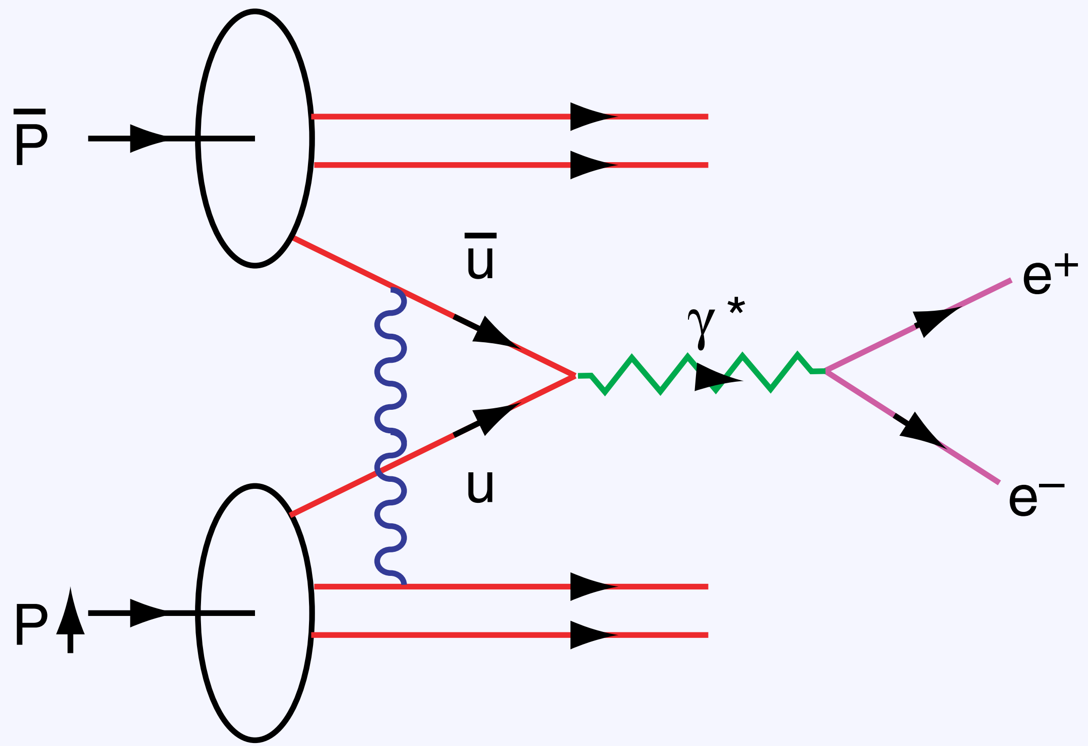
Gardner, sjb

# Recent COMPASS data on deuteron: small Sivers effect

- The anomalous magnetic moment, the Sivers function, and the generalized parton distribution $E$ can all be connected to matrix elements involving the orbital angular momentum of the nucleon's constituents.
- The SSA can be generated by either a quark or gluon mechanism, and the isospin structure of the two mechanisms is distinct. The approximate cancellation of the SSA measured on a deuterium target suggests that the gluon mechanism, and thus the orbital angular momentum carried by gluons in the nucleon, is small.
- Studies of the SSA in $\phi$ or $K^+K^-$ production, via $\gamma^* g \to s\bar{s} \to \phi + X$ or $\gamma^* g \to s\bar{s} \to K^+K^- + X$ should provide additional constraints on the gluon mechanism.

Gardner, sjb

# Predict Opposite Sign SSA in DY !




Collins;
Hwang, Schmidt.
sjb

Single Spin Asymmetry In the Drell Yan Process

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

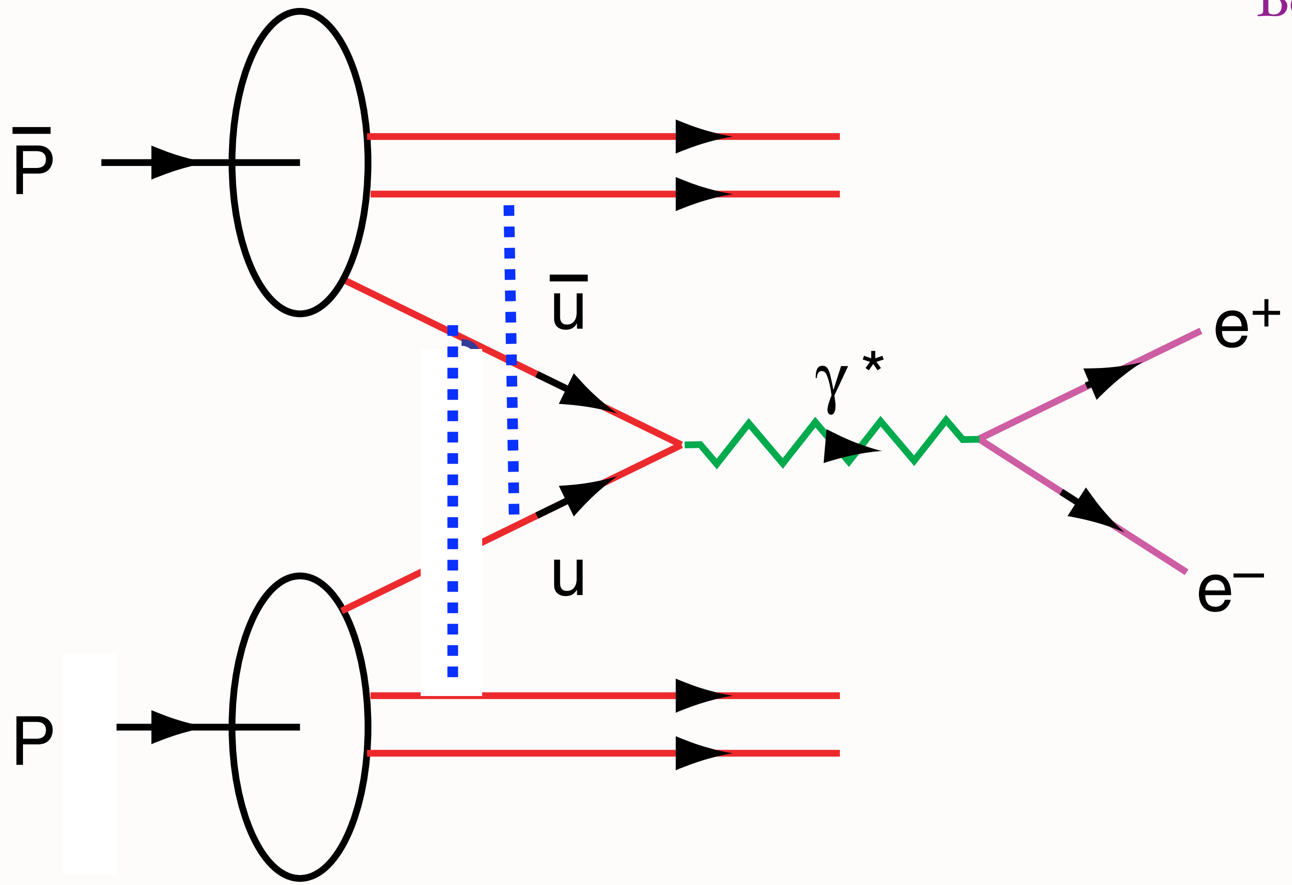
Quarks Interact in the Initial State

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

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

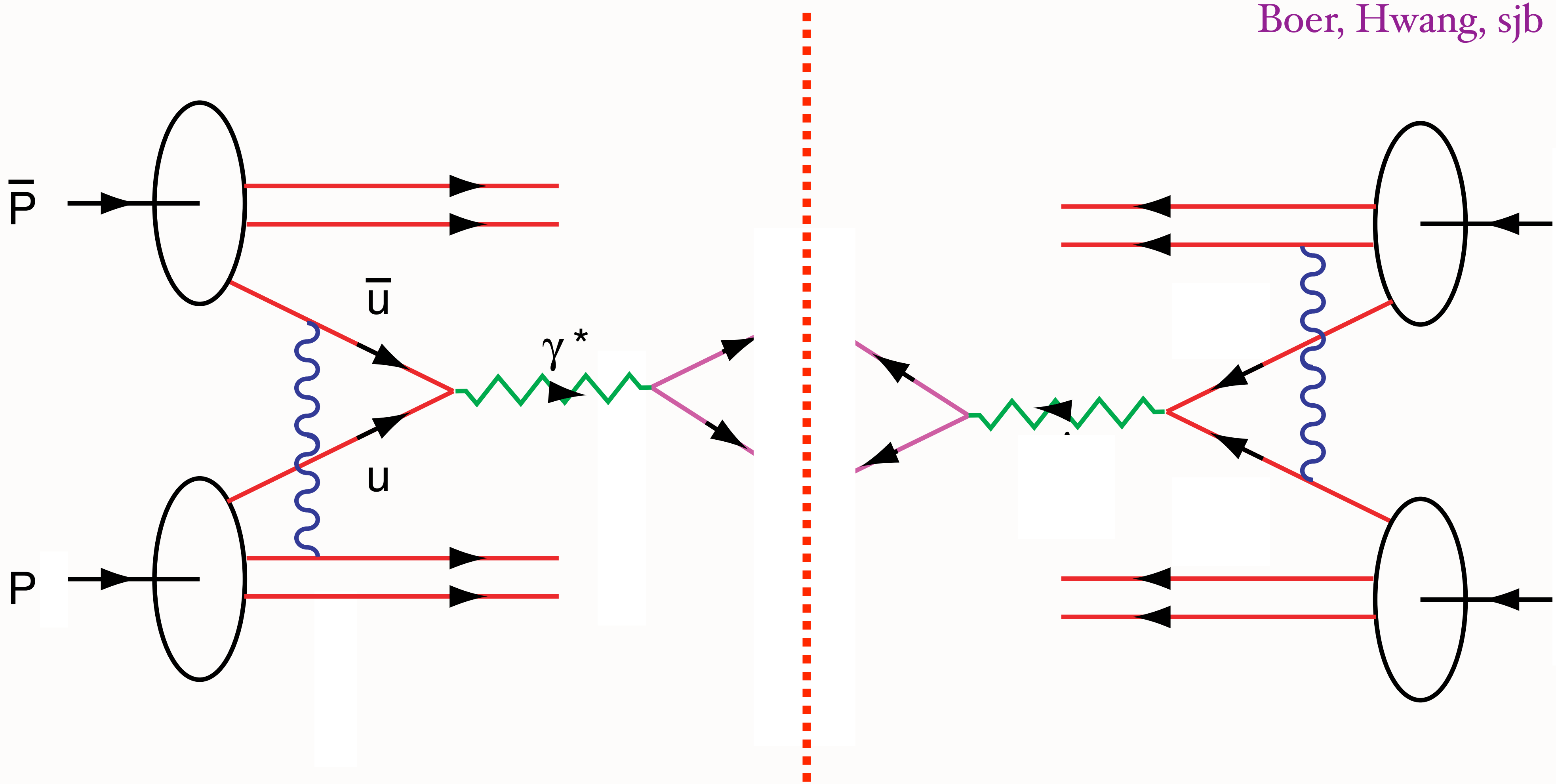
Opposite Sign to DIS! No Factorization

Boer, Hwang, sjb




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

Boer, Hwang, sjb




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

# Double Initial-State Interactions generate anomalous $\cos 2\phi$

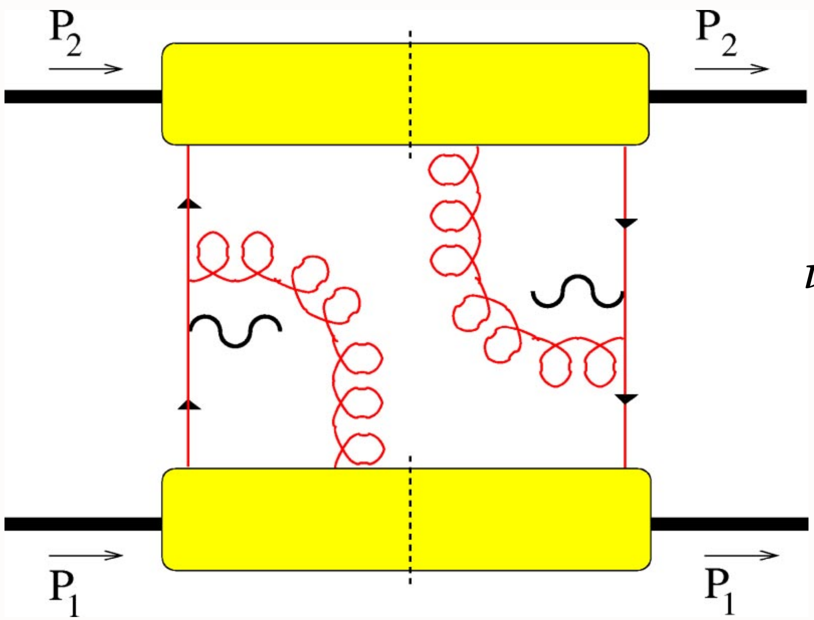
Boer, Hwang, sjb

## Drell-Yan planar correlations

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

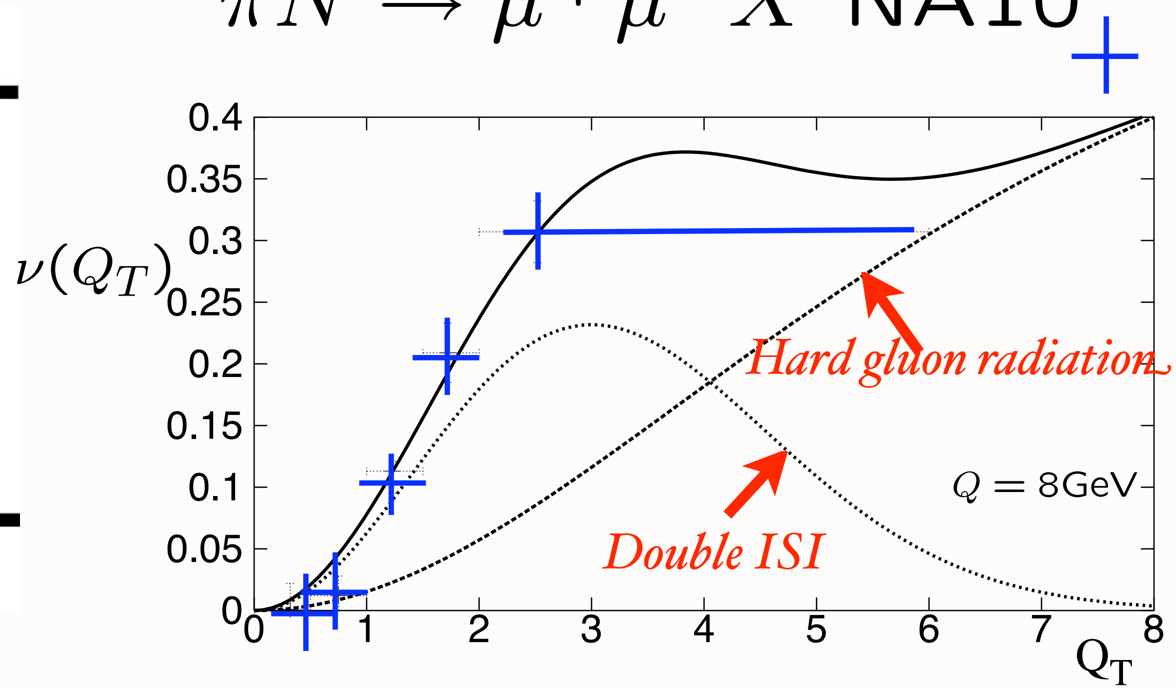
PQCD Factorization (Lam Tung): $1 - \lambda - 2\nu = 0$

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




**Violates Lam-Tung relation!**

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

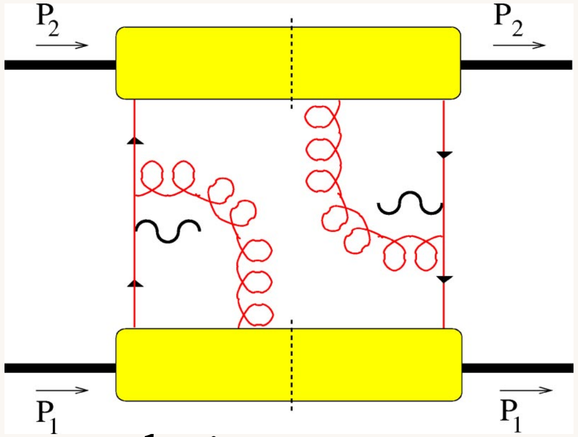



Model: Boer,

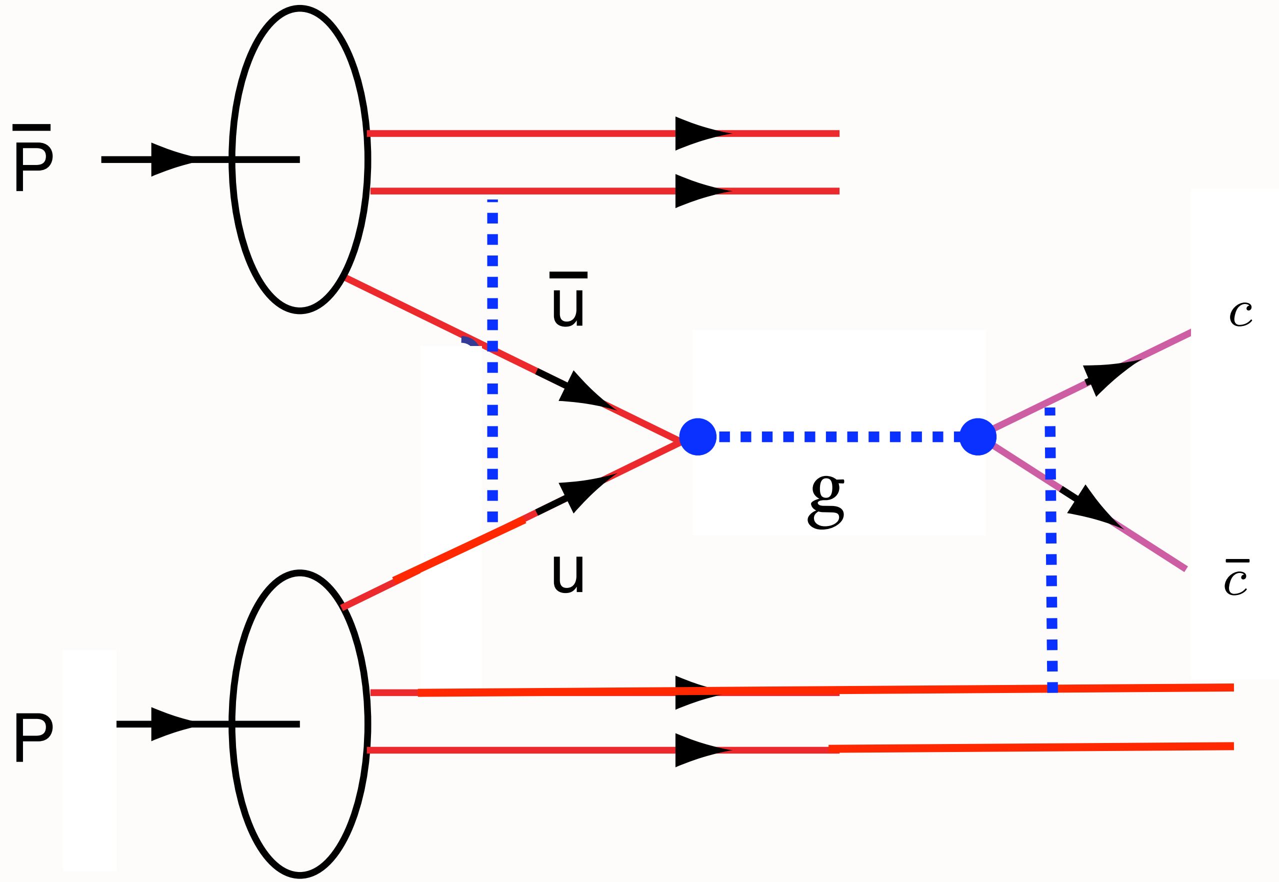
# Anomalous effect from Double ISI in Massive Lepton Production

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

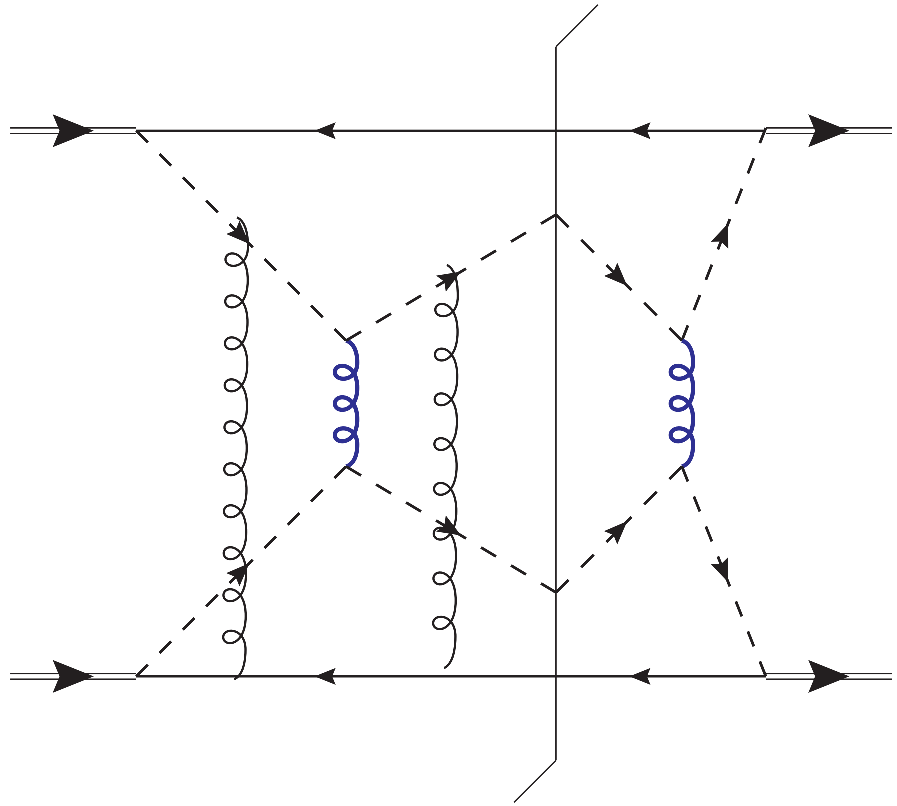



*Problem for factorization when both ISI and FSI occur*

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

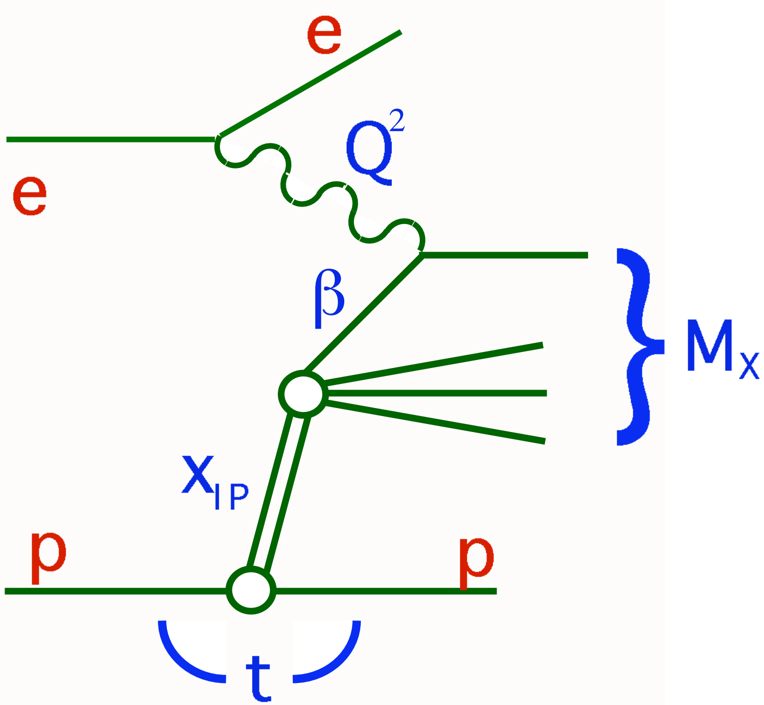
John Collins, Jian-Wei Qiu . ANL-HEP-PR-07-25, May 2007.

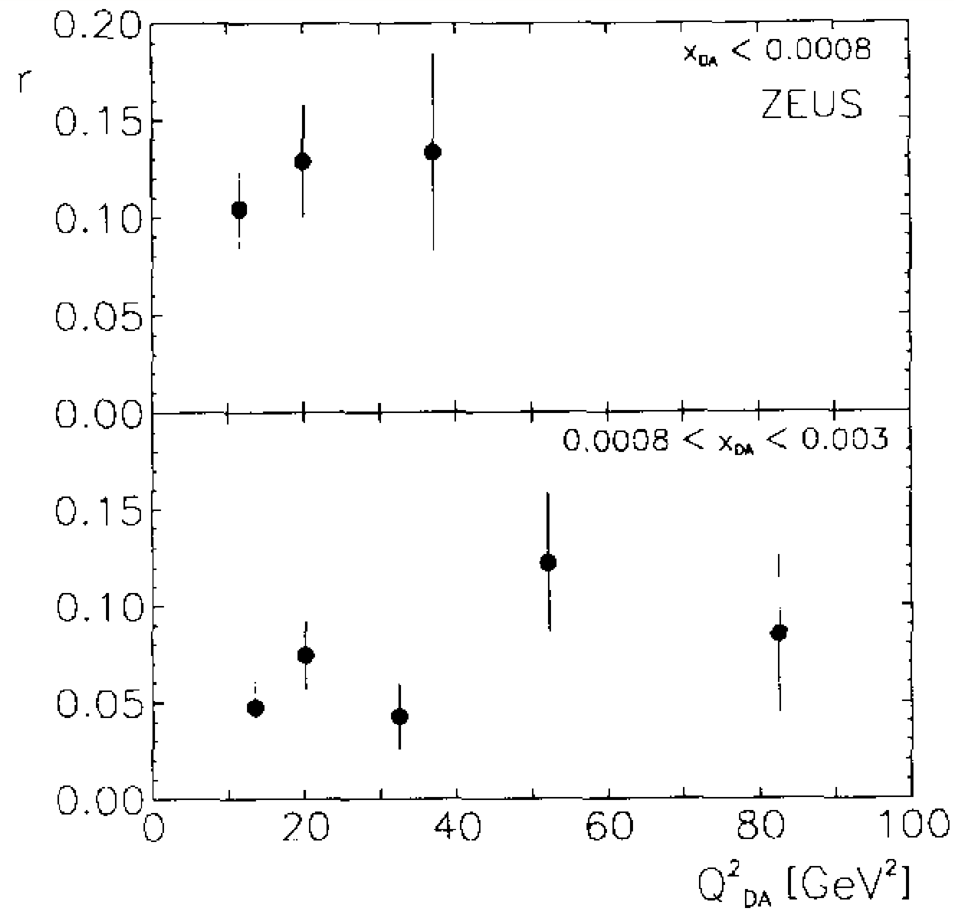
e-Print: **arXiv:0705.2141** [hep-ph]



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

# Remarkable observation at HERA



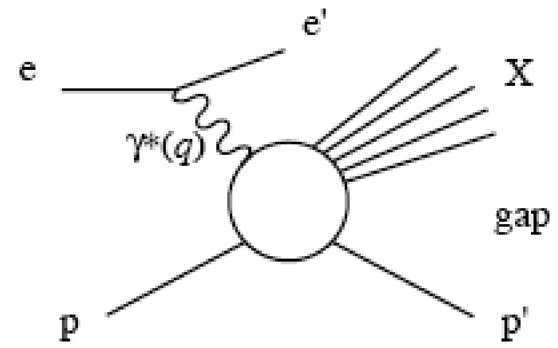




Fraction $r$ of events with a large rapidity gap, $\eta_{max} < 1.5$, as a function of $Q^2_{DA}$ for two ranges of $x_{DA}$. No acceptance corrections have been applied.

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

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

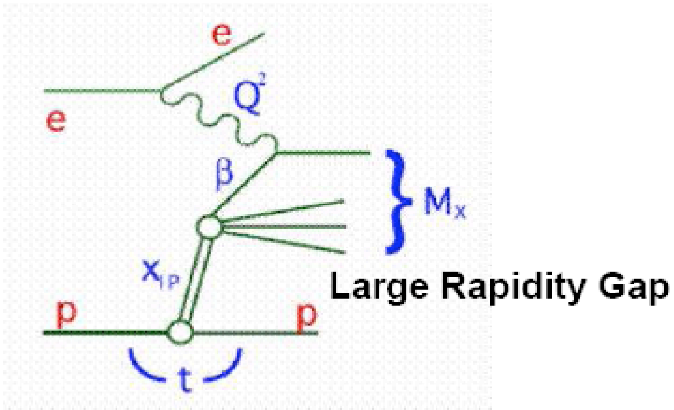
# DDIS

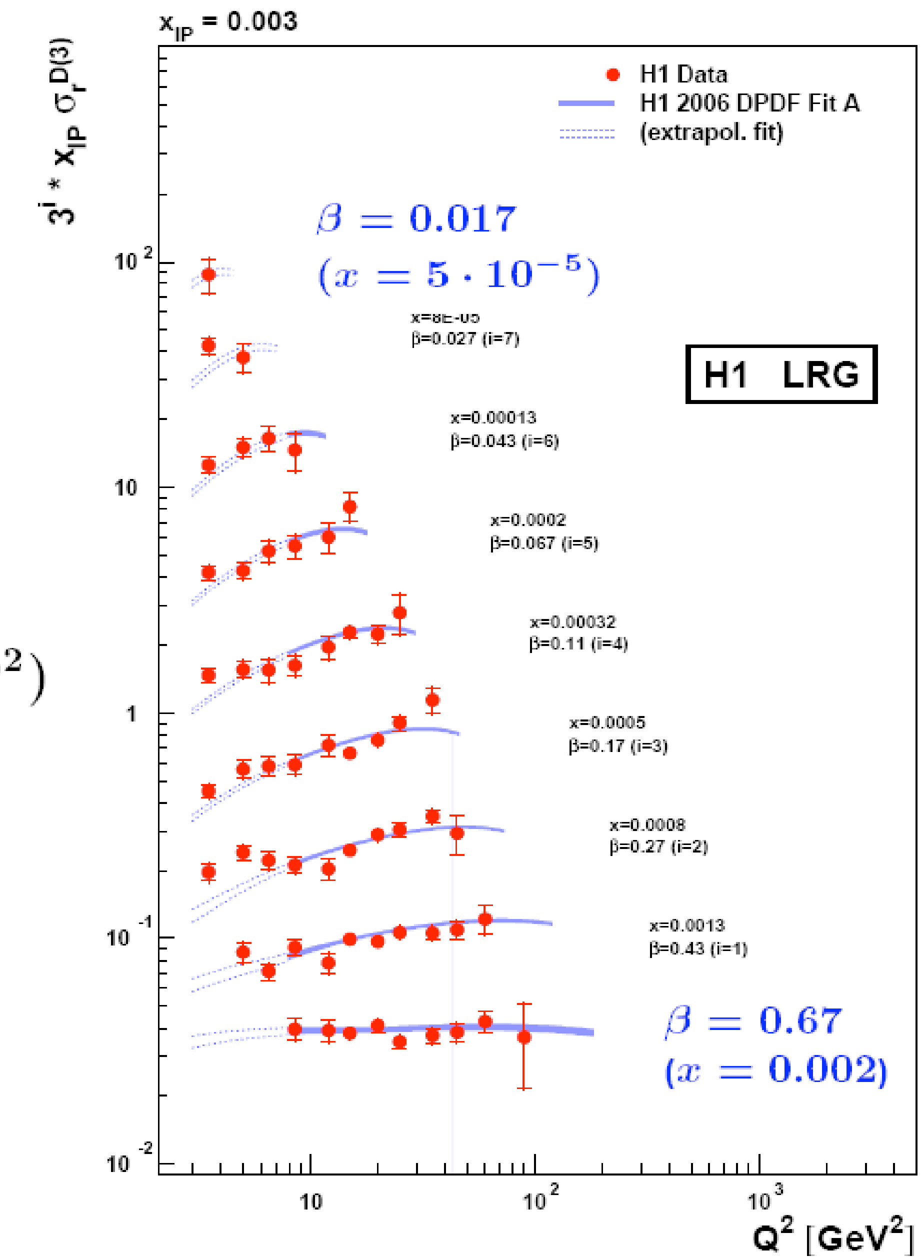



- In a large fraction ($\sim$ 10–15%) of DIS events, the proton escapes intact, keeping a large fraction of its initial momentum
- This leaves a large *rapidity gap* between the proton and the produced particles
- The $t$-channel exchange must be *color singlet* $\rightarrow$ a pomeron??

## Diffractive Deep Inelastic Lepton-Proton Scattering

# Diffractive Structure Function $F_2^D$




**Diffractive inclusive cross section**

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

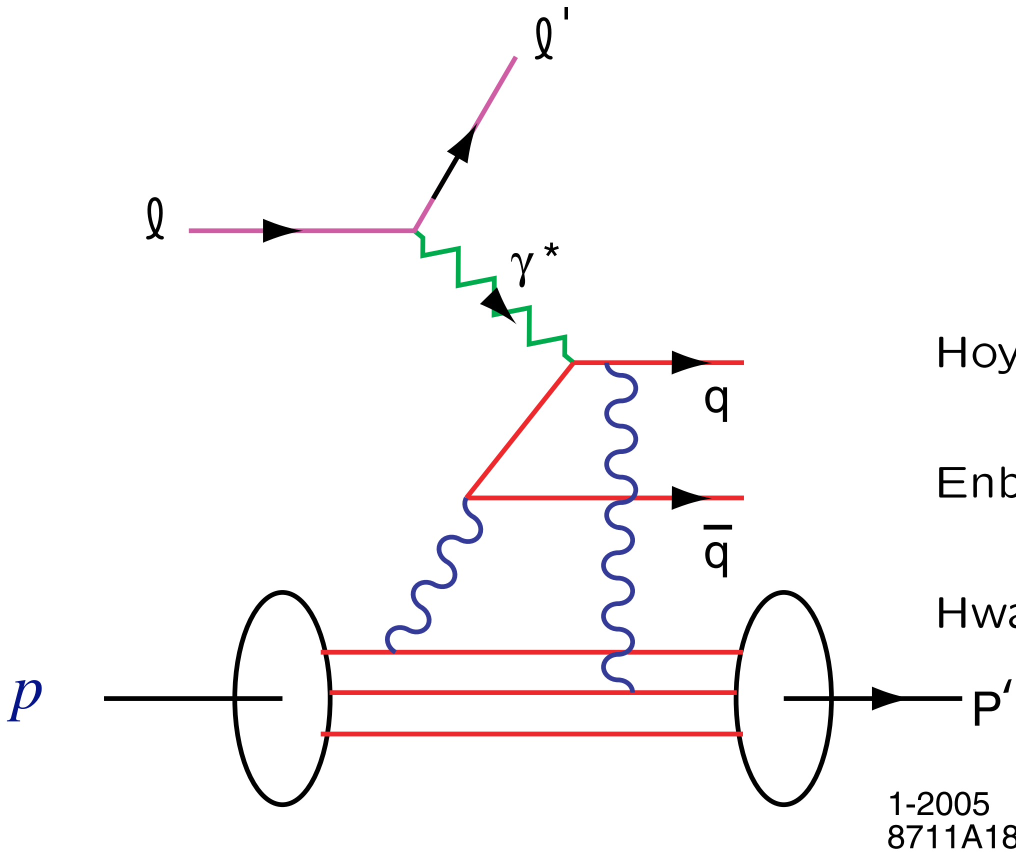
$$F_2^D(x_{I\!P}, \beta, Q^2) = f(x_{I\!P}) \cdot F_2^{I\!P}(\beta, Q^2)$$

**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

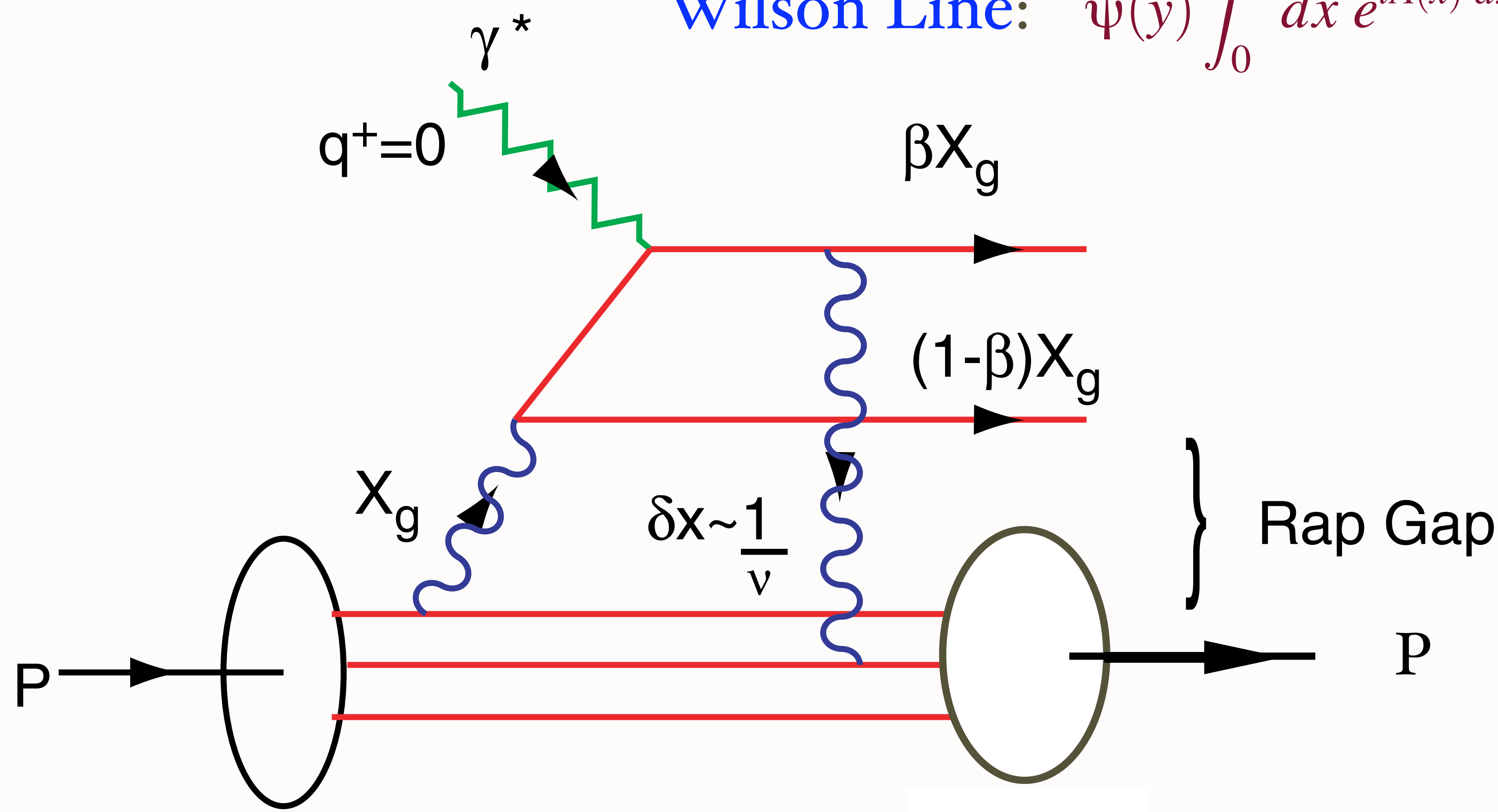
Hwang, Schmidt, SJB

**Low-Nussinov model of Pomeron**

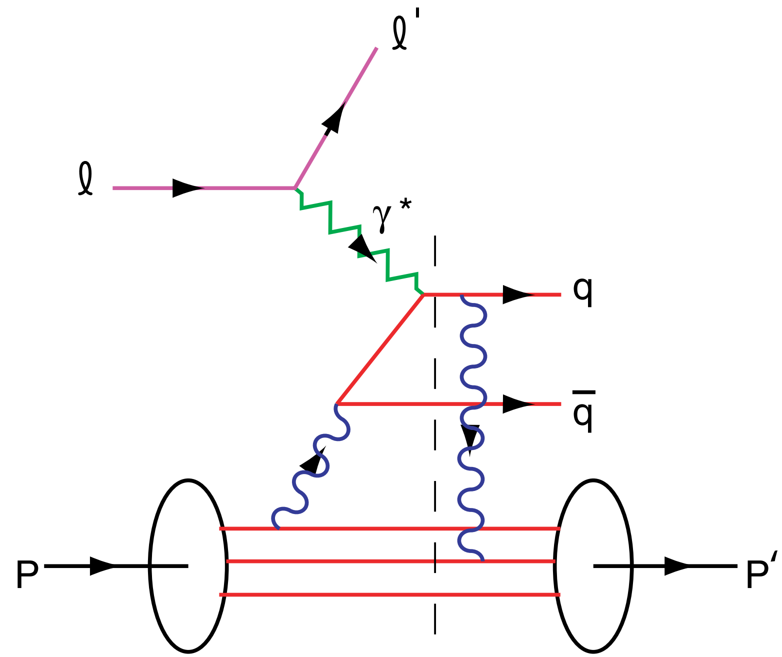
Hoyer, Marchal, Peigne, Sannino, sjb

# 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**



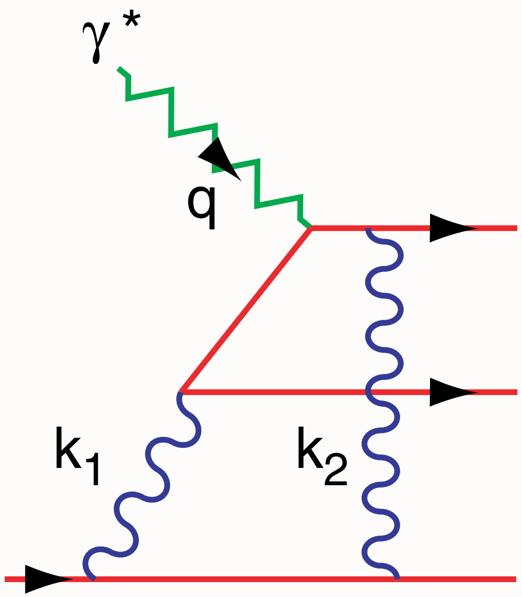

Integration over on-shell domain produces phase i

Need Imaginary Phase to Generate Pomeron

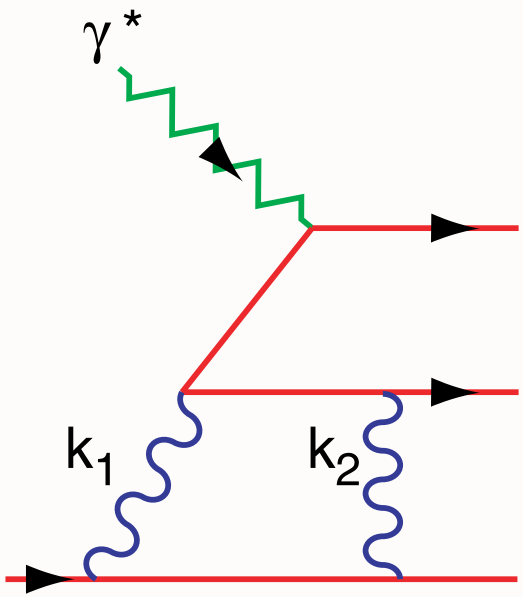
Need Imaginary Phase to Generate
T-Odd Single-Spin Asymmetry

*Physics of FSI not in Wavefunction of Target*

# *Final State Interactions in QCD*



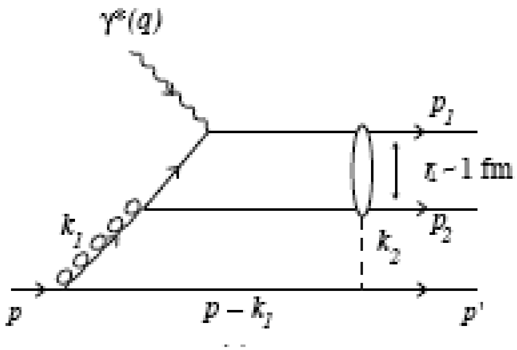

Feynman Gauge




Light-Cone Gauge

*Result is Gauge Independent*

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




- *Effective* $I\!P$ distribution and quark structure function:

$$f_{I\!P/p}(x_{I\!P}) \quad \propto \quad g(x_{I\!P}, Q_0^2)$$

$$f_{q/I\!P}(\beta, Q_0^2) \quad \propto \quad \beta^2 + (1-\beta)^2$$

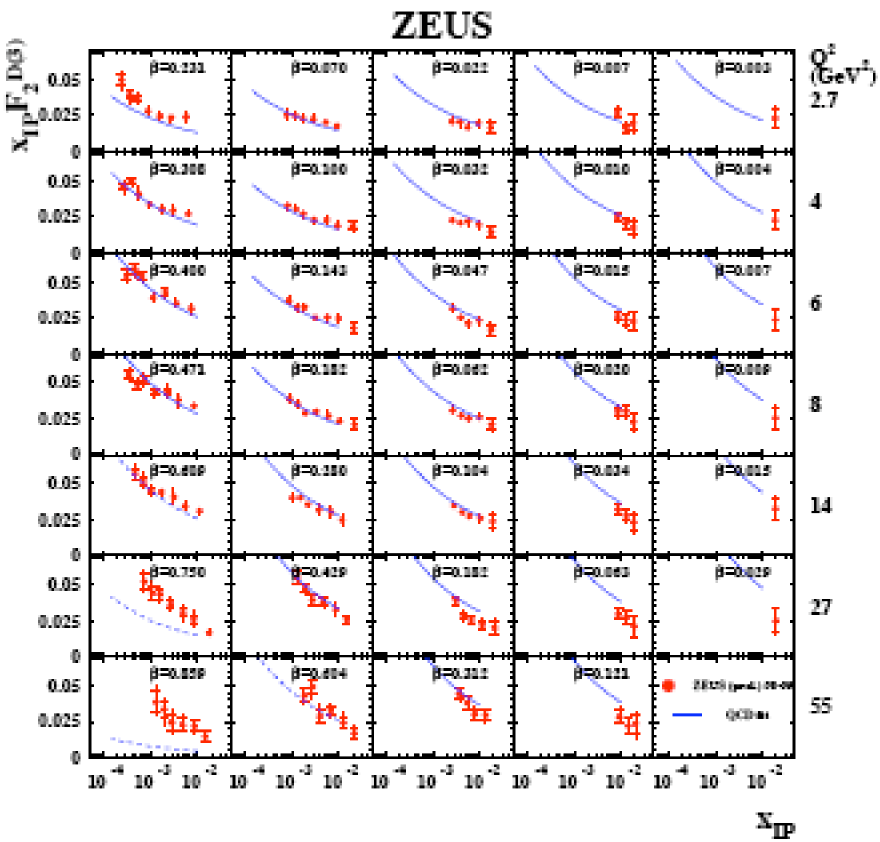
- Diffractive amplitudes from rescattering are dominantly *imaginary* — as expected for diffraction (Ingelman–Schlein $I\!P$ model has real amplitudes)

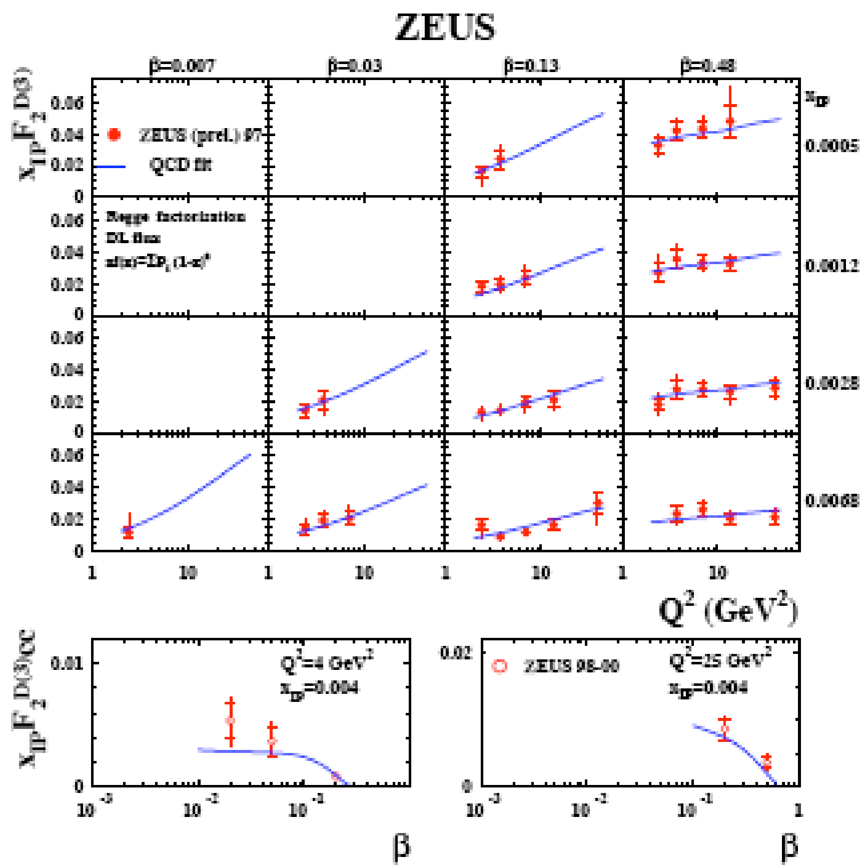
S. J. Brodsky, P. Hoyer, N. Marchal, S. Peigne and F. Sannino, Phys. Rev. D 65, 114025 (2002) [arXiv:hep-ph/0104291].
S. J. Brodsky, R. Enberg, P. Hoyer and G. Ingelman, arXiv:hep-ph/0409119.

Enberg, Hoyer, Ingelman, sjb

# The Pomeron formalism

$F_2^D$ is fitted to HERA data $\longrightarrow$ good description




Lines given by fit with NLO QCD evolution

# Consequences for DDIS

- Underlying hard scattering sub-process is the same in diffractive and non-diffractive events
- Same $Q^2$ dependence of diffractive and inclusive PDFs
- and same energy ($W$ or $x_B$) dependence

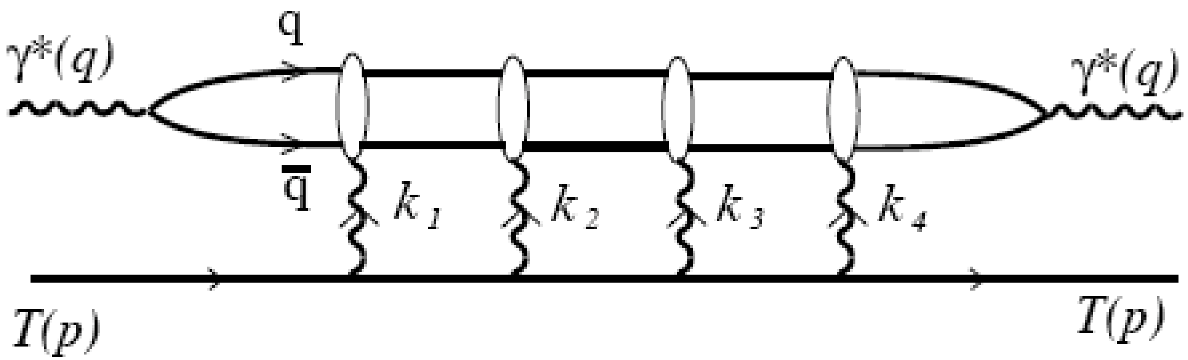
$\Rightarrow \frac{\sigma_{\text{diff}}}{\sigma_{\text{tot}}}$ independent of $x_B$ and $Q^2$ (as in data)

Also describes: vector meson leptoproduction BGMFS

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

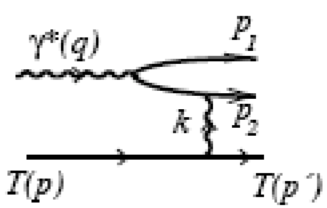
# Rescattering toy model

BHMPS: Toy model — scalar abelian gauge theory:



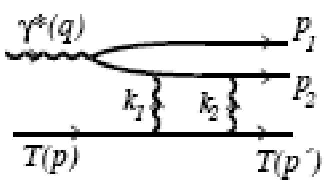

$x_B \to 0$: on-shell intermediate states $\to$ imag. 2-gluon ampl.

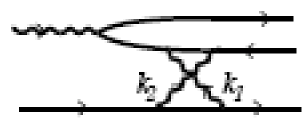
*as required for pomeron from crossing symmetry*





$$\propto g^2 K_0(mr_\perp) \log\left(\frac{|\boldsymbol{R}_\perp + \boldsymbol{r}_\perp|}{|\boldsymbol{R}_\perp|}\right)$$




$$\propto i g^4 K_0(mr_\perp) \left[\log\left(\frac{|\boldsymbol{R}_\perp + \boldsymbol{r}_\perp|}{|\boldsymbol{R}_\perp|}\right)\right]^2$$

Rescattering factorizes in coordinate space!

$$Q^4 \frac{d\sigma}{dQ^2\, dx_B} = \frac{\alpha_{\rm em}}{16\pi^2} \frac{1-y}{y^2} \frac{1}{2M\nu} \int \frac{dp_2^-}{p_2^-} d^2\vec{r}_T\, d^2\vec{R}_T\, |\tilde{M}|^2$$

where

$$|\tilde{M}(p_2^-, \vec{r}_T, \vec{R}_T)| = \left| \frac{\sin\left[g^2 W(\vec{r}_T, \vec{R}_T)/2\right]}{g^2 W(\vec{r}_T, \vec{R}_T)/2} \tilde{A}(p_2^-, \vec{r}_T, \vec{R}_T) \right|$$

is the resummed result. The Born amplitude is

$$\tilde{A}(p_2^-, \vec{r}_T, \vec{R}_T) = 2eg^2 MQp_2^- V(m_{||} r_T) W(\vec{r}_T, \vec{R}_T)$$

where $m_{||}^2 = p_2^- M x_B + m^2$ and

FSI not Unitary Phase!

$$V(m\, r_T) \equiv \int \frac{d^2\vec{p}_T}{(2\pi)^2} \frac{e^{i\vec{r}_T\cdot\vec{p}_T}}{p_T^2 + m^2} = \frac{1}{2\pi} K_0(m\, r_T).$$

The rescattering effect of the dipole of the $q\overline{q}$ is controlled by

$$W(\vec{r}_T, \vec{R}_T) \equiv \int \frac{d^2\vec{k}_T}{(2\pi)^2} \frac{1 - e^{i\vec{r}_T\cdot\vec{k}_T}}{k_T^2} e^{i\vec{R}_T\cdot\vec{k}_T} = \frac{1}{2\pi} \log\left(\frac{|\vec{R}_T + \vec{r}_T|}{R_T}\right).$$

Precursor of Nuclear Shadowing

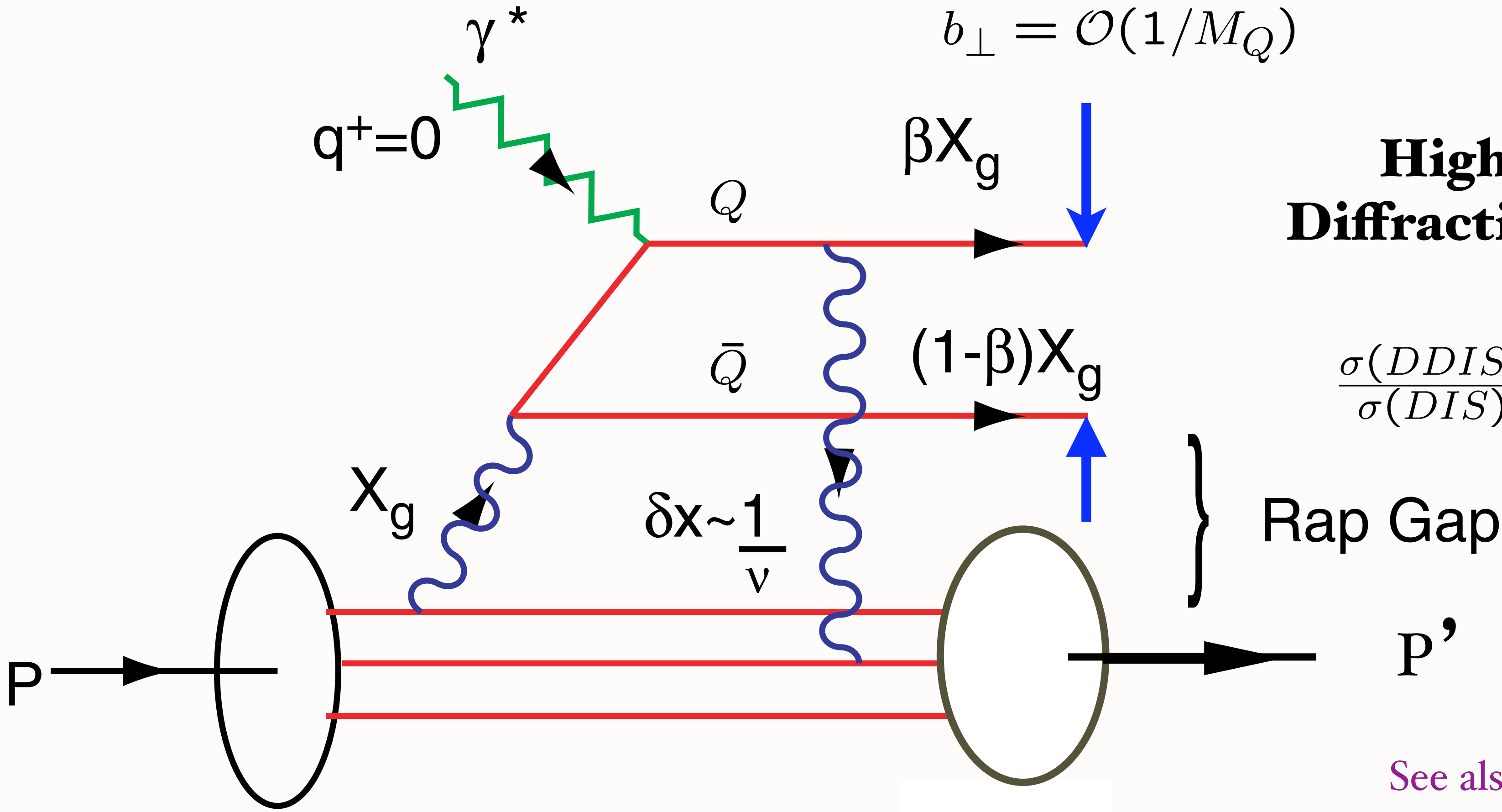
BHMPS

# Hard Diffractive Hadron-Hadron Collisions

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

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

# Predict: Reduced DDIS/DIS for Heavy Quarks




**Higher Twist Diffraction Fraction**

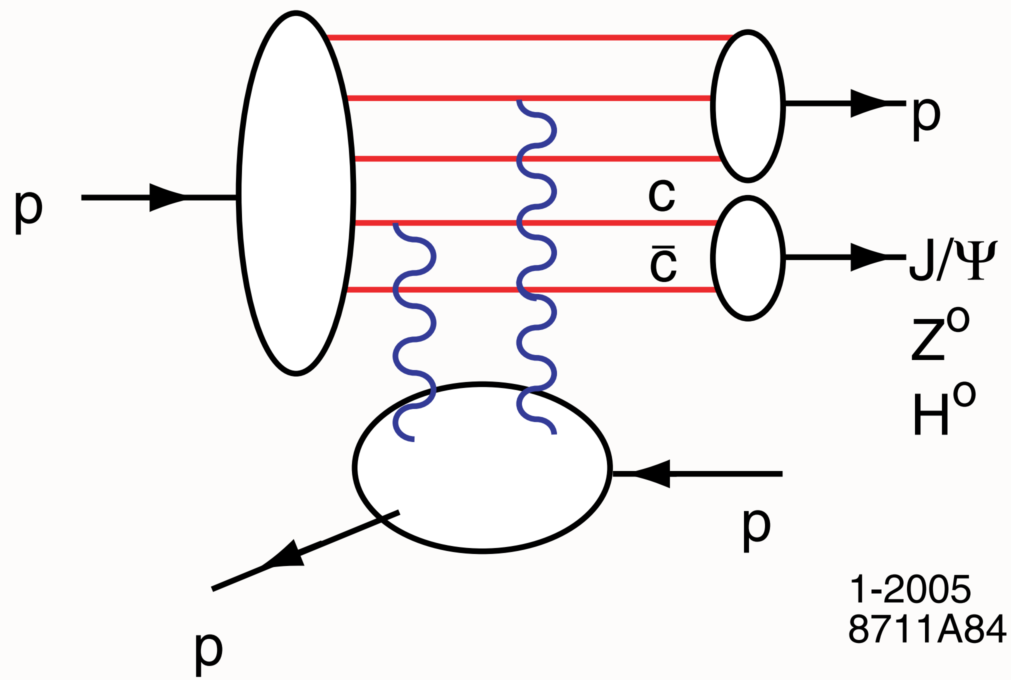
$$\frac{\sigma(DDIS)}{\sigma(DIS)} \simeq \frac{\Lambda^2_{QCD}}{M^2_Q}$$

See also: Bartels et al

Kopeliovitch, Schmidt, sjb

**Reproduces lab-frame color dipole approach**

# Intrinsic Charm Mechanism for Exclusive Diffraction Production




$$\mathrm{p\,p} \rightarrow J/\psi\; p\; p$$

$$x_{J/\psi} = x_c + x_{\bar{c}}$$

Exclusive Diffractive
High-$X_F$ Higgs Production

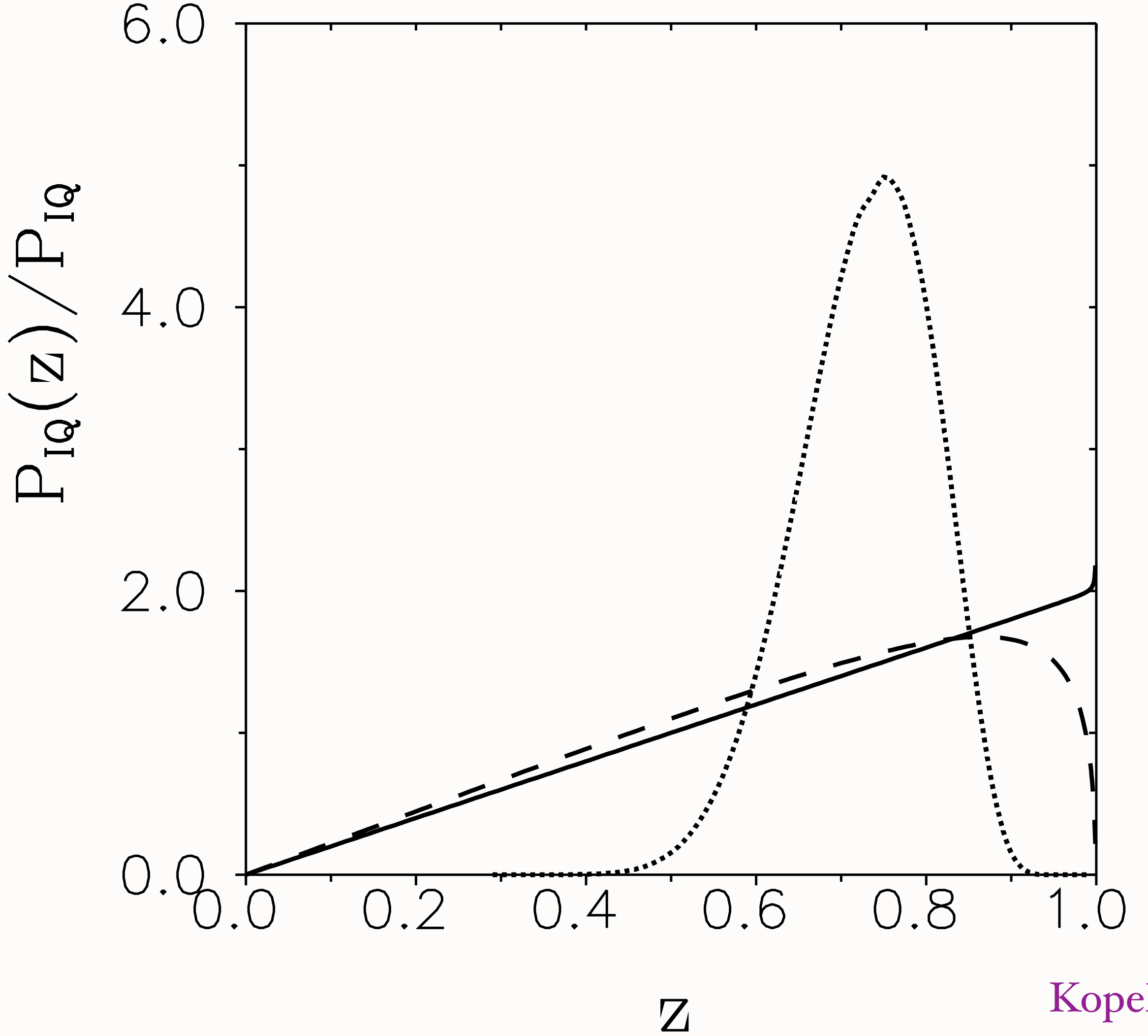
Kopeliovitch, Schmidt, Soffer, sjb

Intrinsic $c\bar{c}$ pair formed in color octet $8_C$ in proton wavefunction Large Color Dipole

Collision produces color-singlet $J/\psi$ through color exchange

RHIC Experiment

# Intrinsic Charm Mechanism for Exclusive Diffraction Production

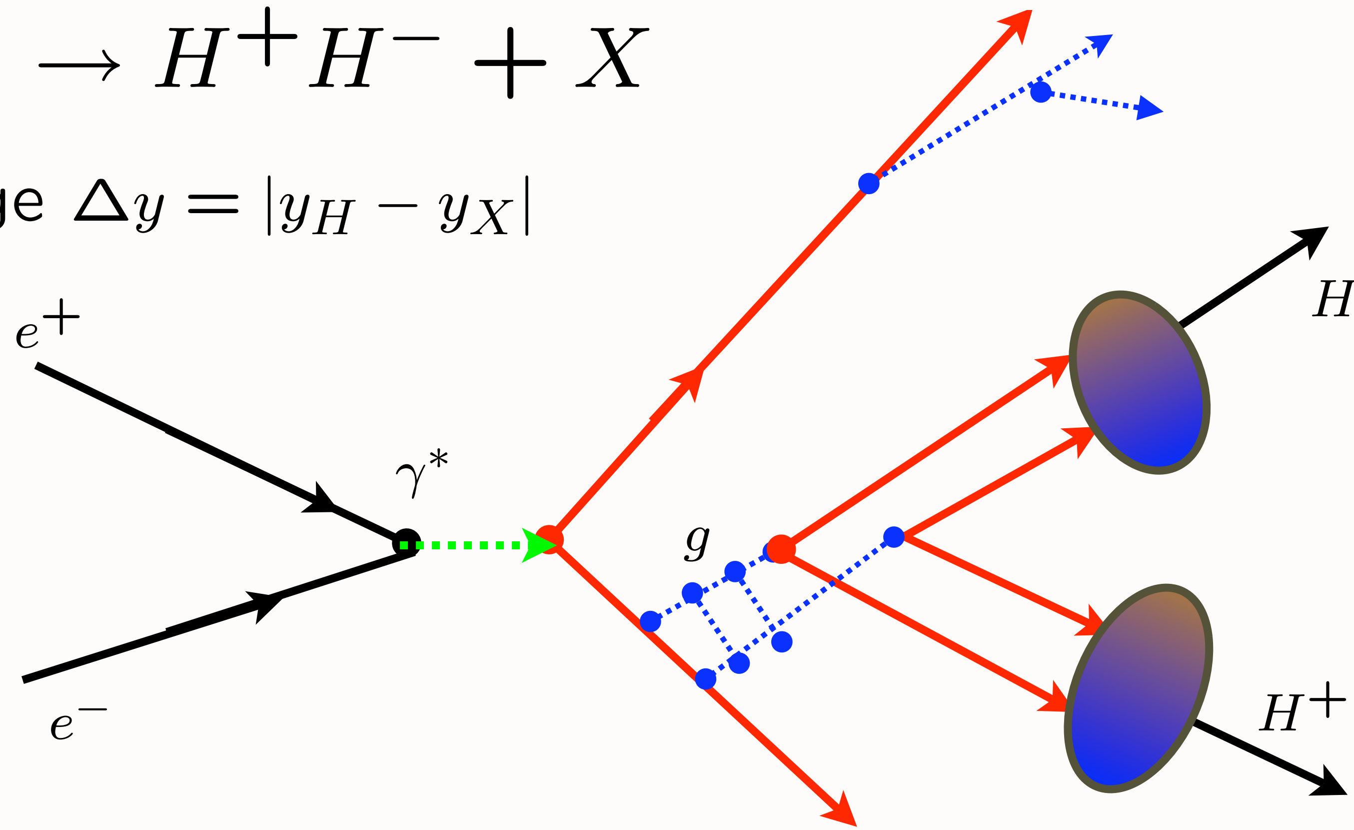



Kopeliovitch, Schmidt, Soffer, sjb

# Hadronization at the Amplitude Level

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

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




Bjorken, Lu, sjb
Kopeliovich, Schmidt, sjb

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

**Large Rapidity Gap Events**

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

# Hadronization at the Amplitude Level

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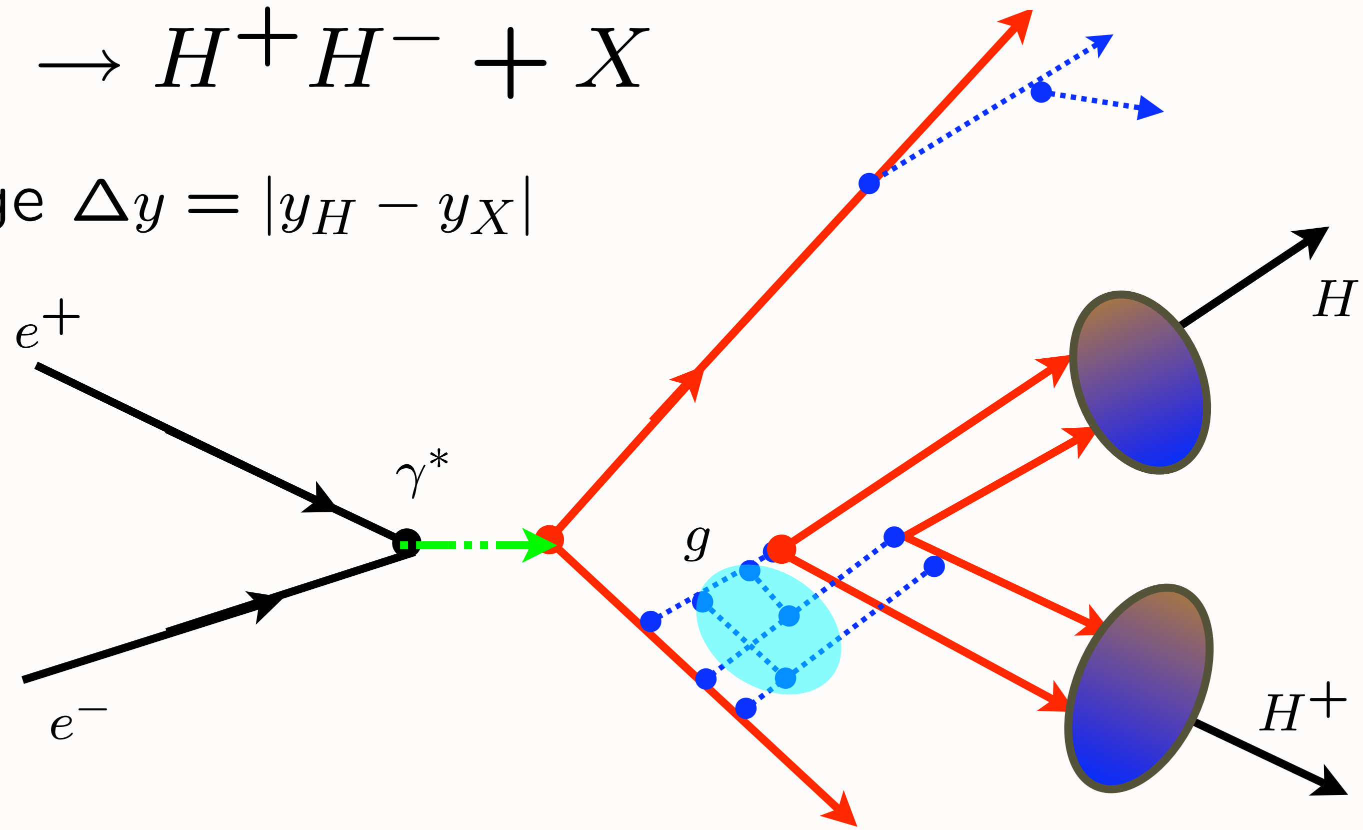
Large $\Delta y = |y_H - y_X|$

Kopeliovich, Schmidt, sjb

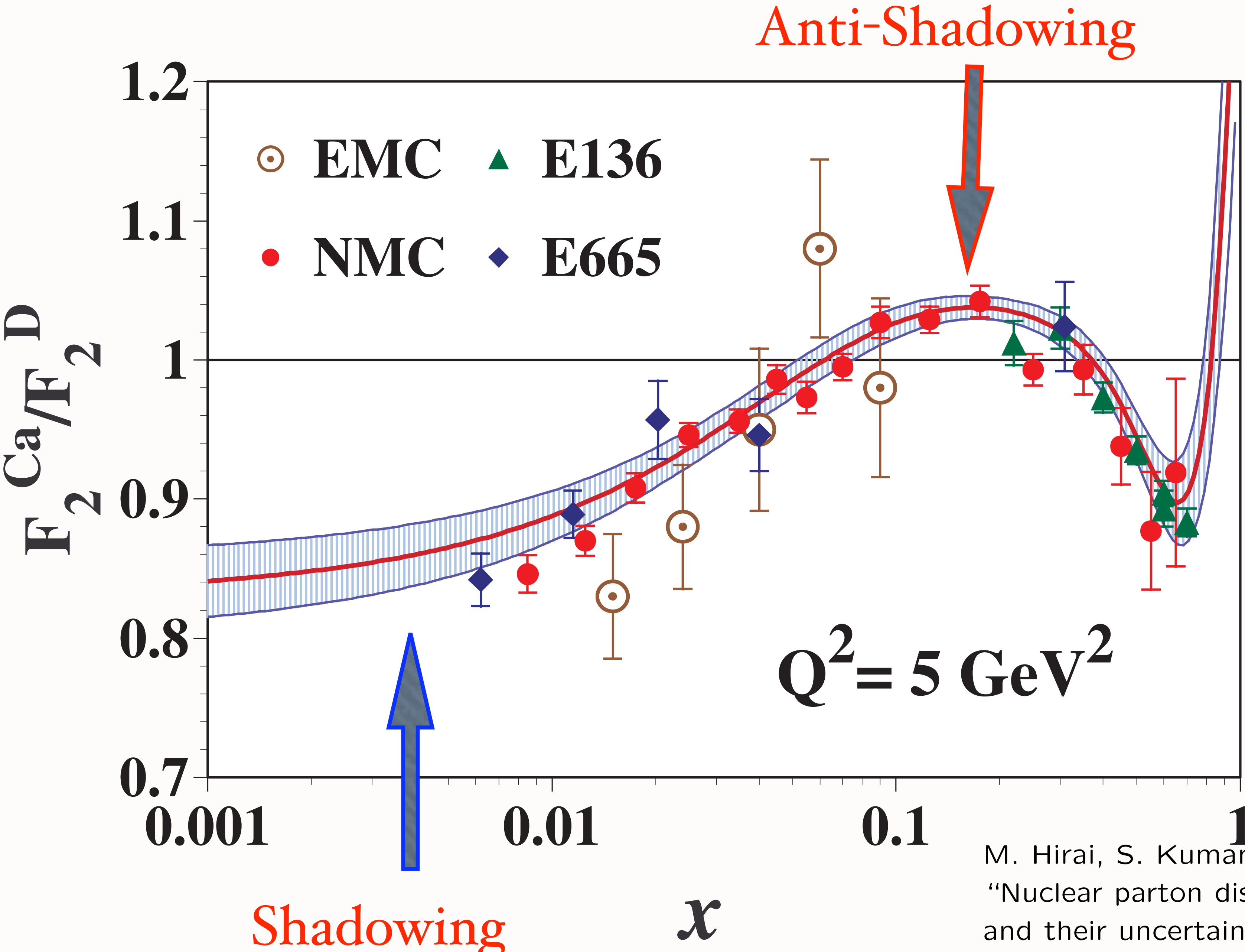



**Timelike Odderon**

**Large Rapidity Gap Events**

**C= - Gluonium Trajectory**

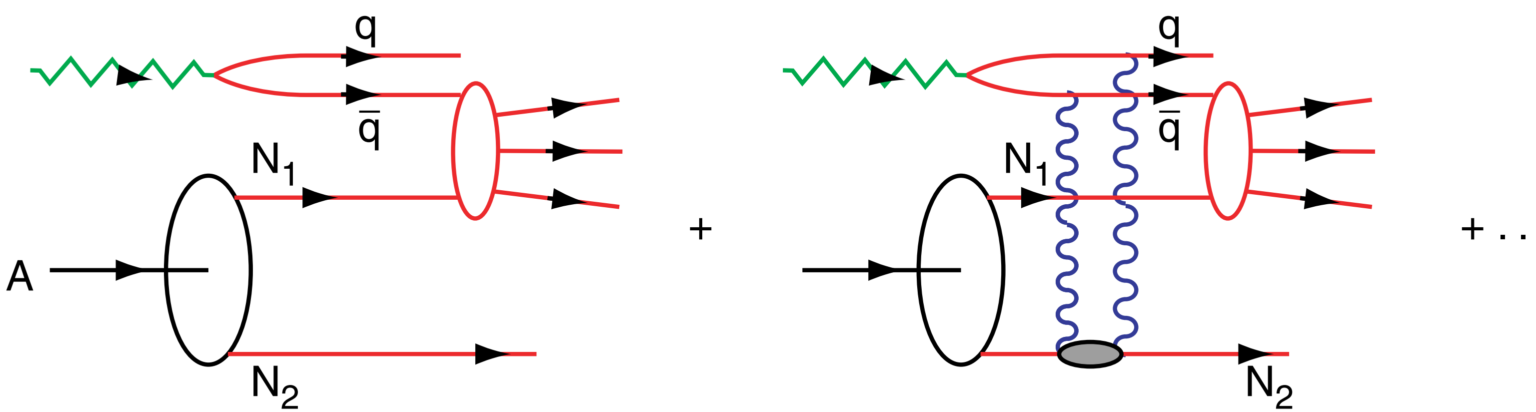
$H^+H^-$ asymmetry from Odderon-Pomeron interference




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

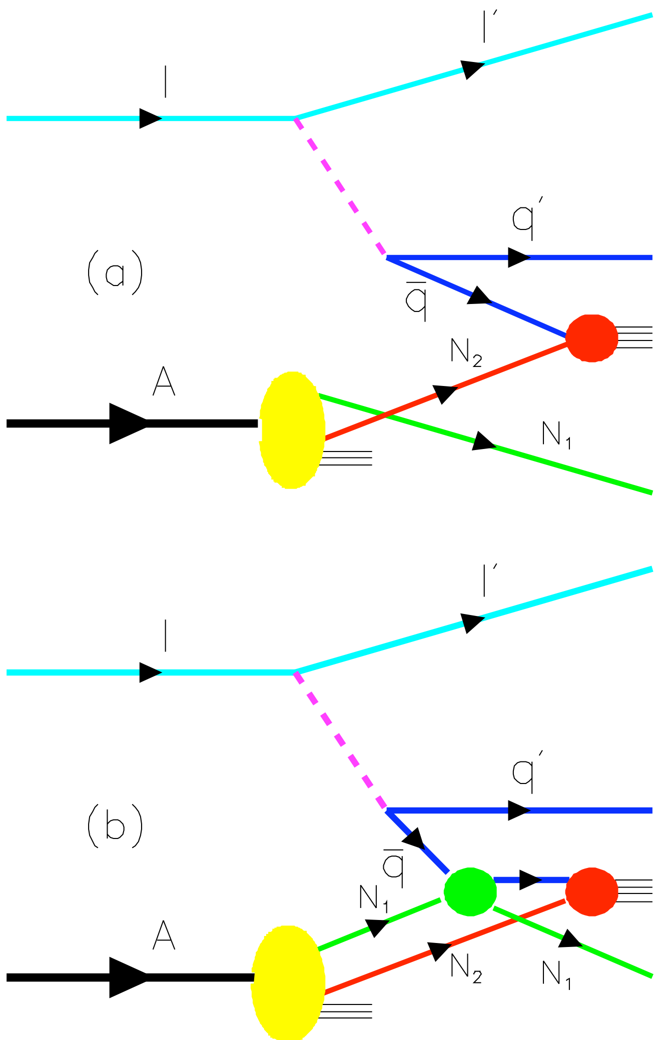
# Nuclear Shadowing in QCD




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**



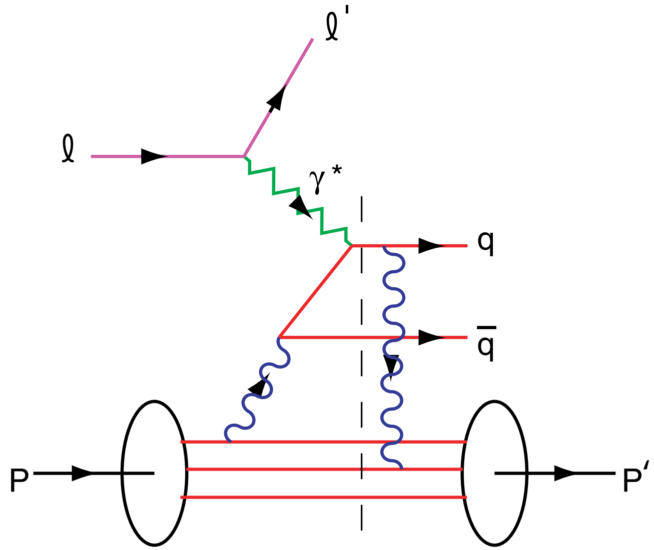

The one-step and two-step processes in DIS on a nucleus.

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

If the scattering on nucleon $N_1$ is via pomeron exchange, the one-step and two-step amplitudes are opposite in phase, thus diminishing the $\overline{q}$ flux reaching $N_2$.

$\rightarrow$ Shadowing of the DIS nuclear structure functions.

## Observed HERA DDIS produces nuclear shadowing




Shadowing depends on understanding 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

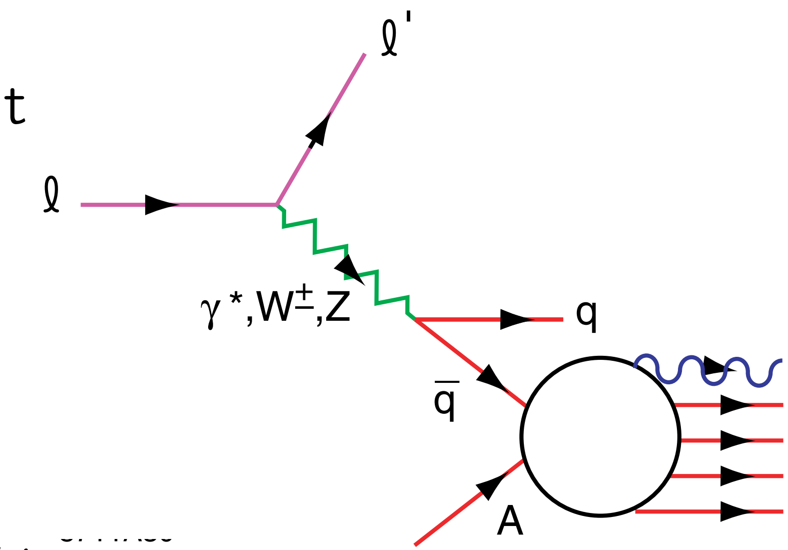
# Origin of Regge Behavior of Deep Inelastic Structure Functions

Antiquark interacts with target nucleus at energy $\widehat{s} \propto \frac{1}{x_{bj}}$

Regge contribution: $\sigma_{\bar{q}N} \sim \widehat{s}^{\alpha_R - 1}$

Nonsinglet Kuti-Weisskoff $F_{2p} - F_{2n} \propto \sqrt{x_{bj}}$ at small $x_{bj}$.

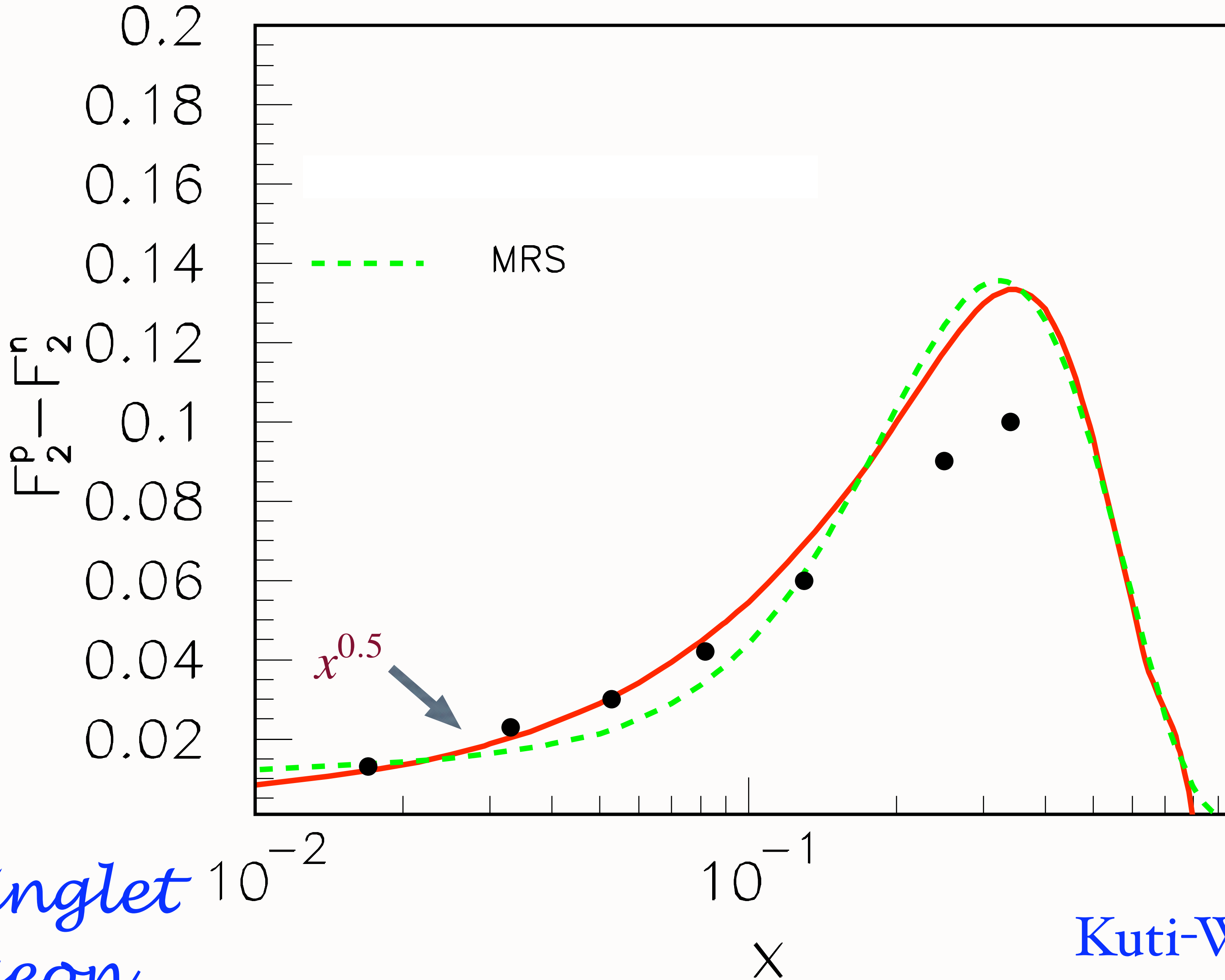
Shadowing of $\sigma_{\bar{q}M}$ produces shadowing of nuclear structure function.




Landshoff, Polkinghorne, Short

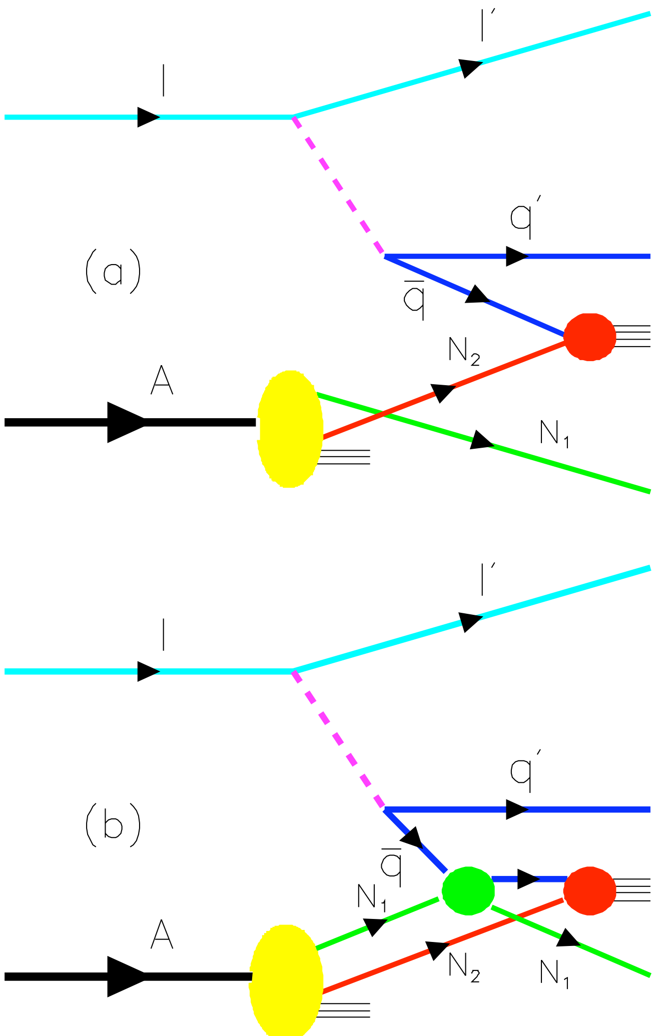
Close, Gunion, sjb

Schmidt, Yang, Lu, sjb




Non-singlet Reggeon Exchange

Kuti-Weisskopf behavior




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

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

$\rightarrow$ Antishadowing of the DIS nuclear structure functions

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

# Reggeon Exchange

Phase of two-step amplitude relative to one step:

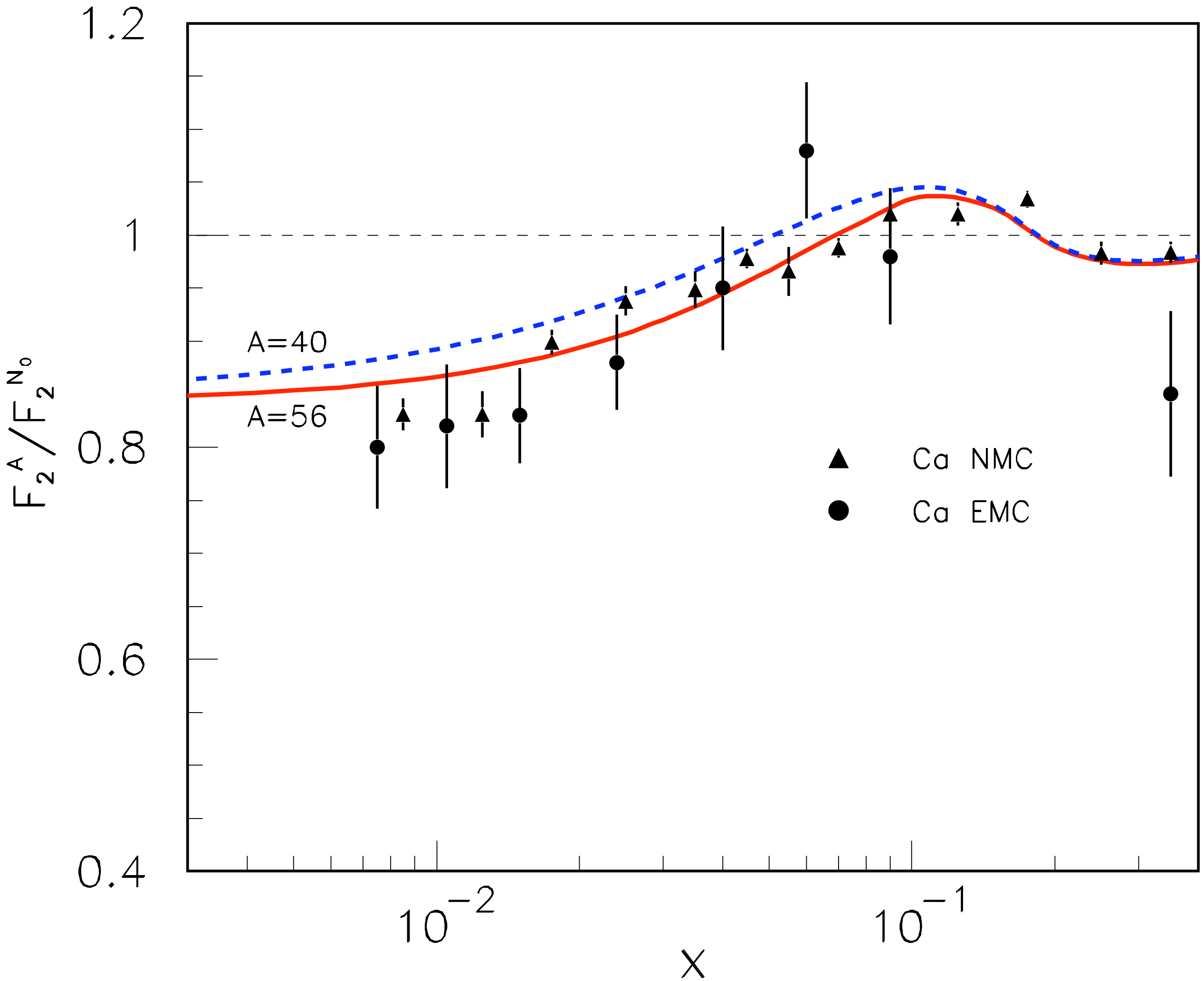
$$\frac{1}{\sqrt{2}}(1-i) \times i = \frac{1}{\sqrt{2}}(i+1)$$

Constructive Interference

Depends on quark flavor!

Thus antishadowing is not universal

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




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

S. J. Brodsky, I. Schmidt and J. J. Yang, "Nuclear Antishadowing in Neutrino Deep Inelastic Scattering," Phys. Rev. D 70, 116003 (2004) [arXiv:hep-ph/0409279].

# Shadowing and Antishadowing in Lepton-Nucleus Scattering

- Shadowing: Destructive Interference

of Two-Step and One-Step Processes

*Pomeron Exchange*

- Antishadowing: Constructive Interference

of Two-Step and One-Step Processes!

*Reggeon and Odderon Exchange*

- Antishadowing is Not Universal!

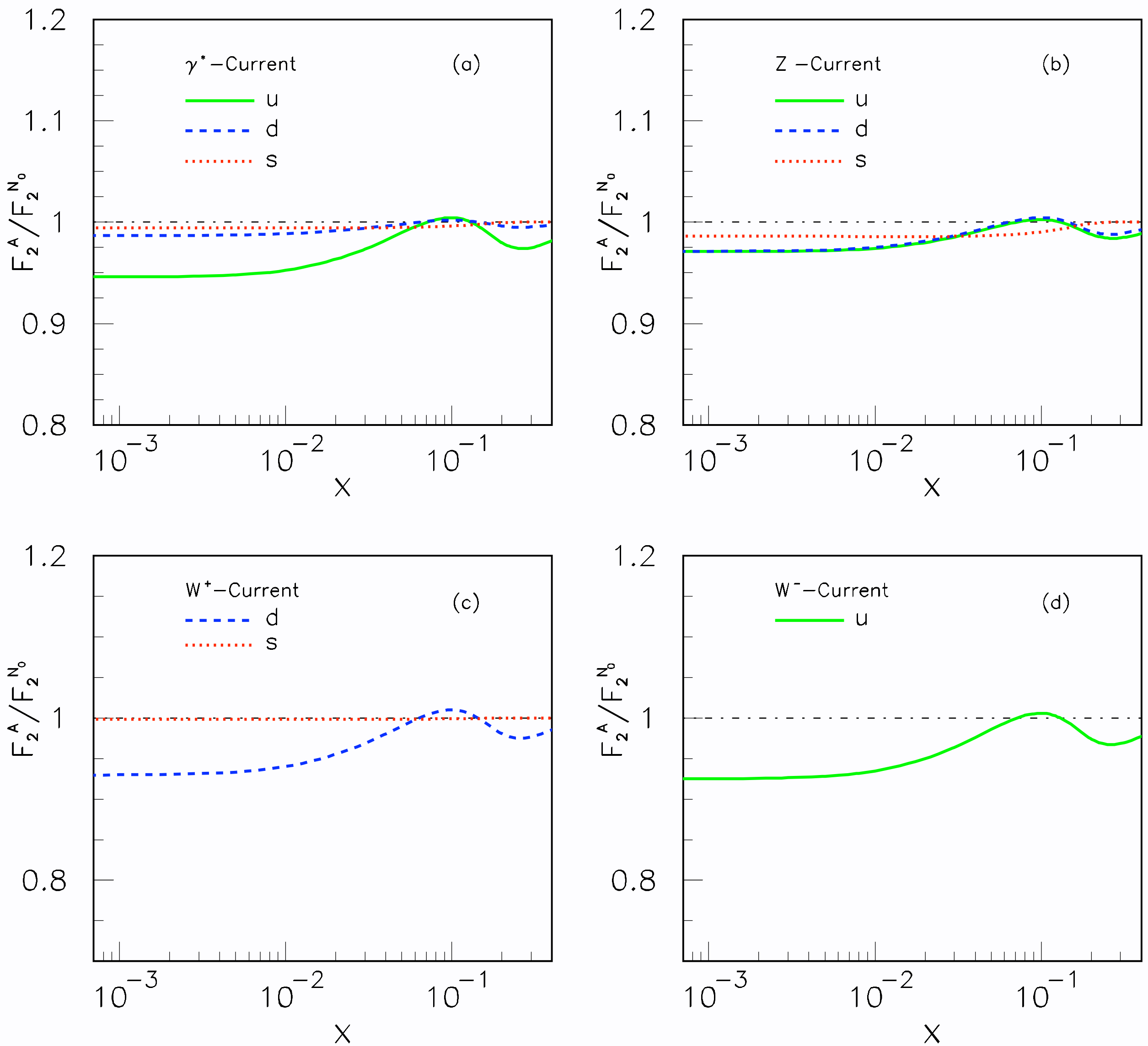
Electromagnetic and weak currents:

different nuclear effects !

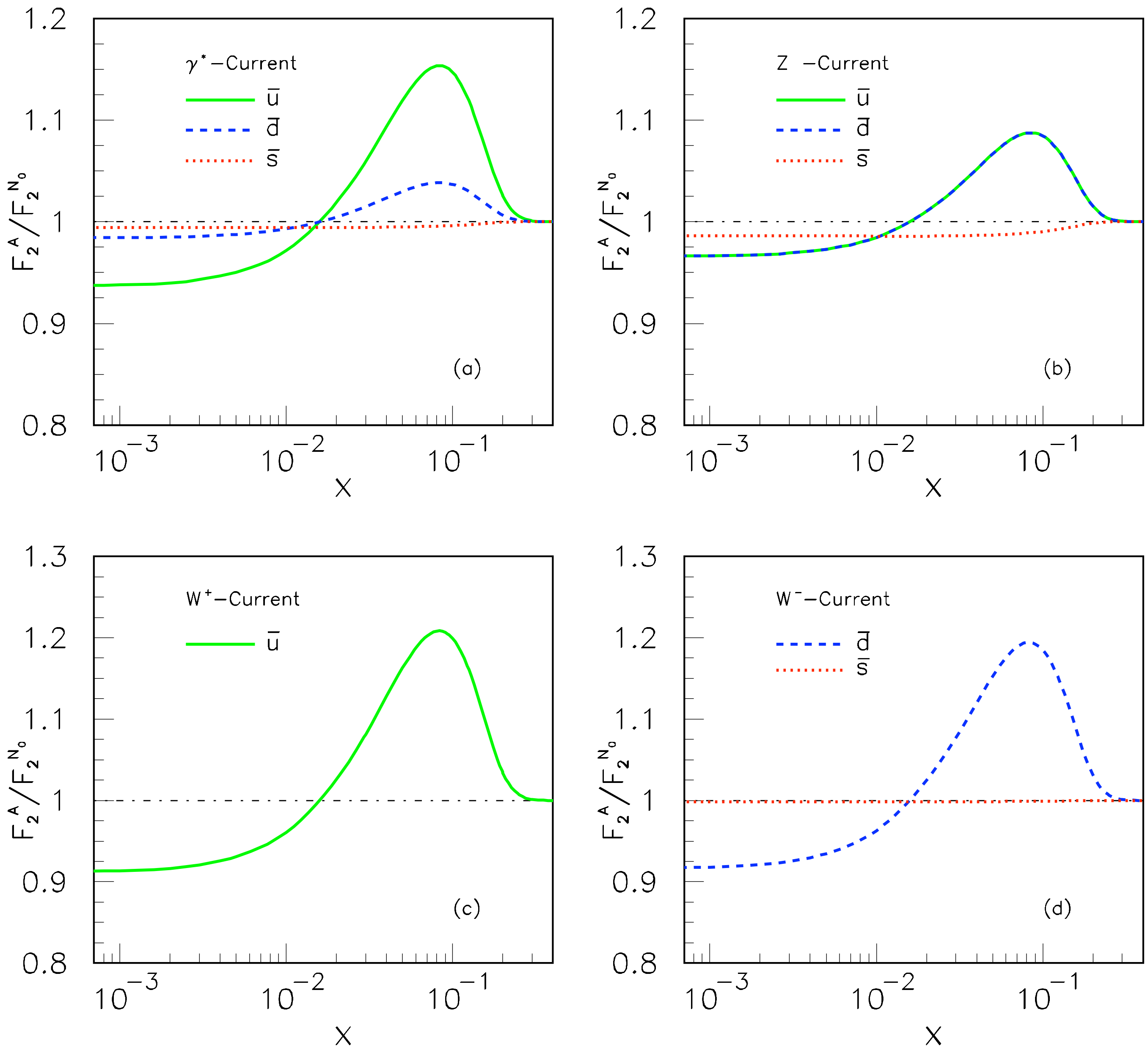
Potentially significant for NuTeV Anomaly}

Jian-Jun Yang
Ivan Schmidt
Hung Jung Lu
sjb

# 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].

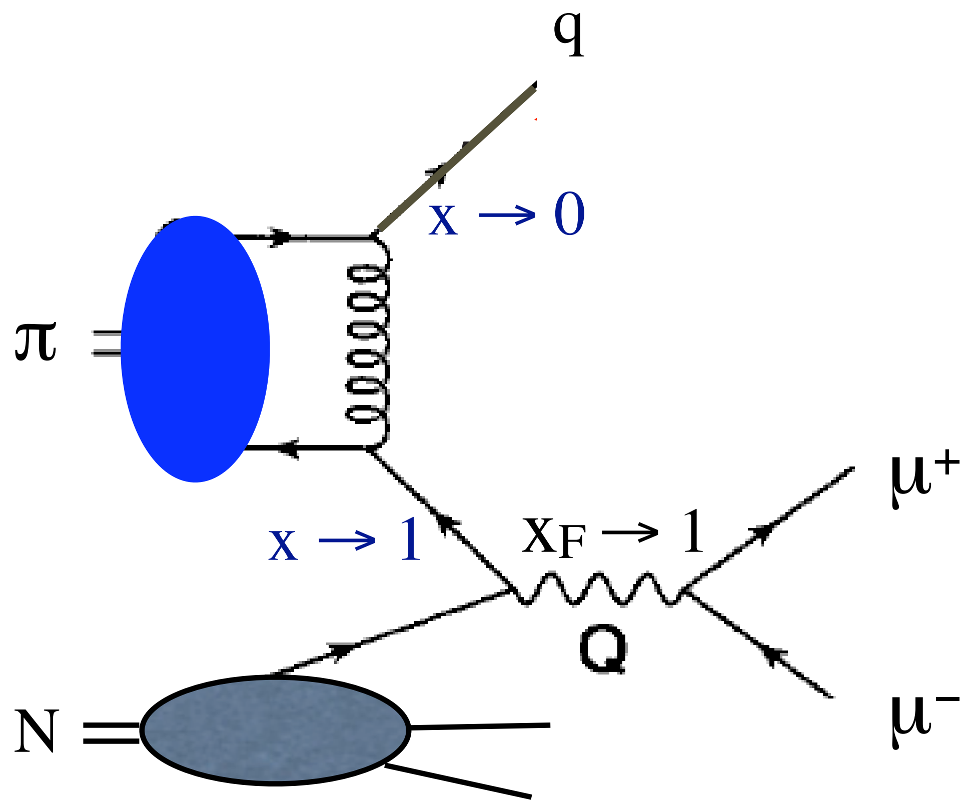



# Nuclear Effect not Universal !

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

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

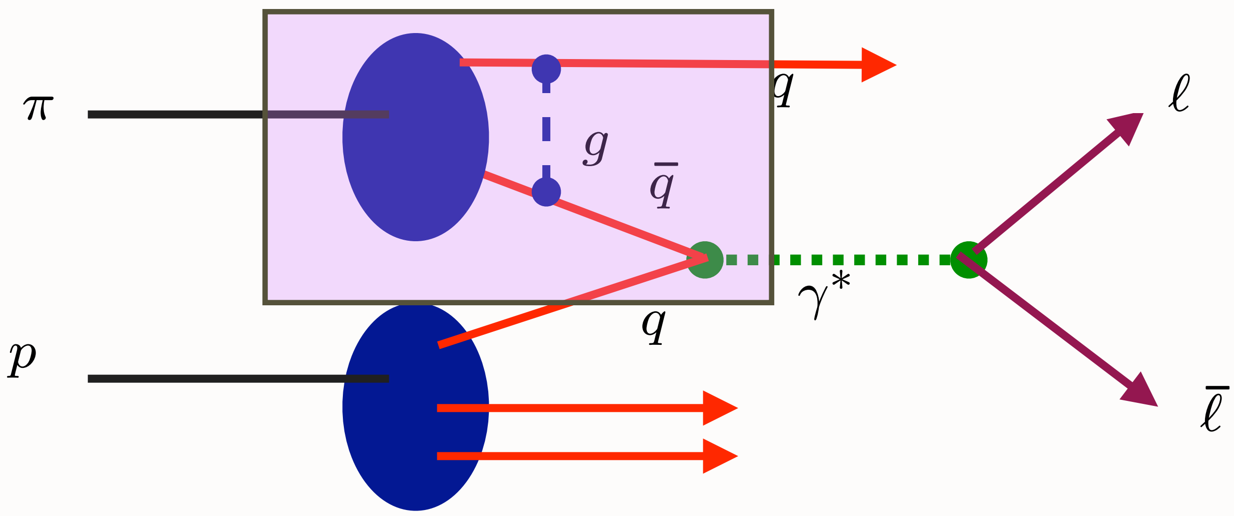
Entire pion wf contributes to hard process



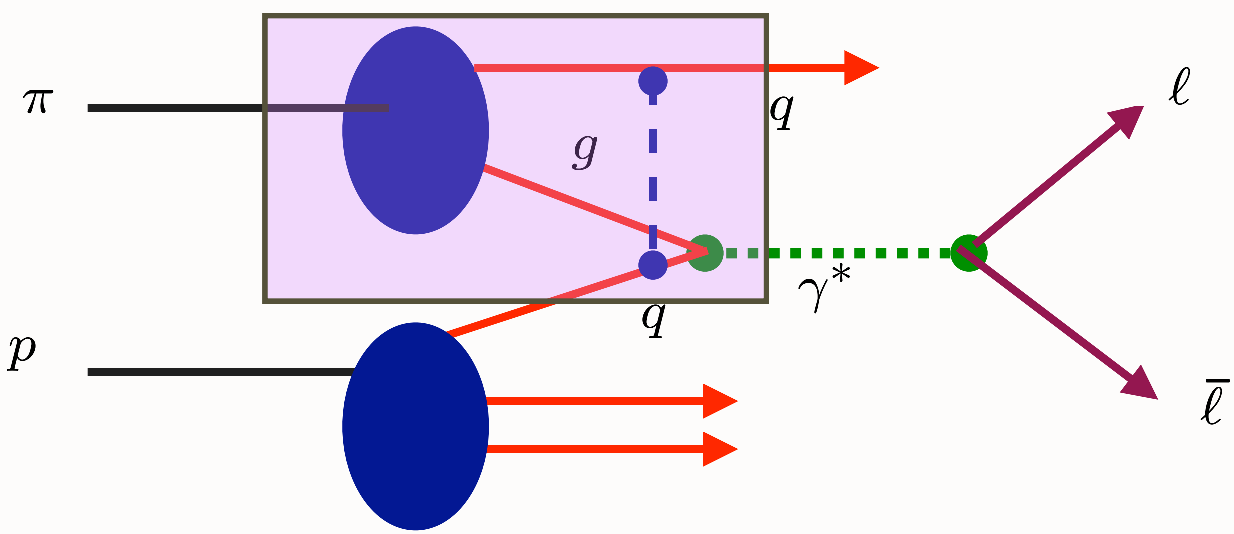

Virtual photon is longitudinally polarized

Berger and Brodsky, PRL 42 (1979) 940

Berger, Lepage, sjb




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




**Initial State Interaction**

***Pion appears directly in subprocess at large $x_F$***

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

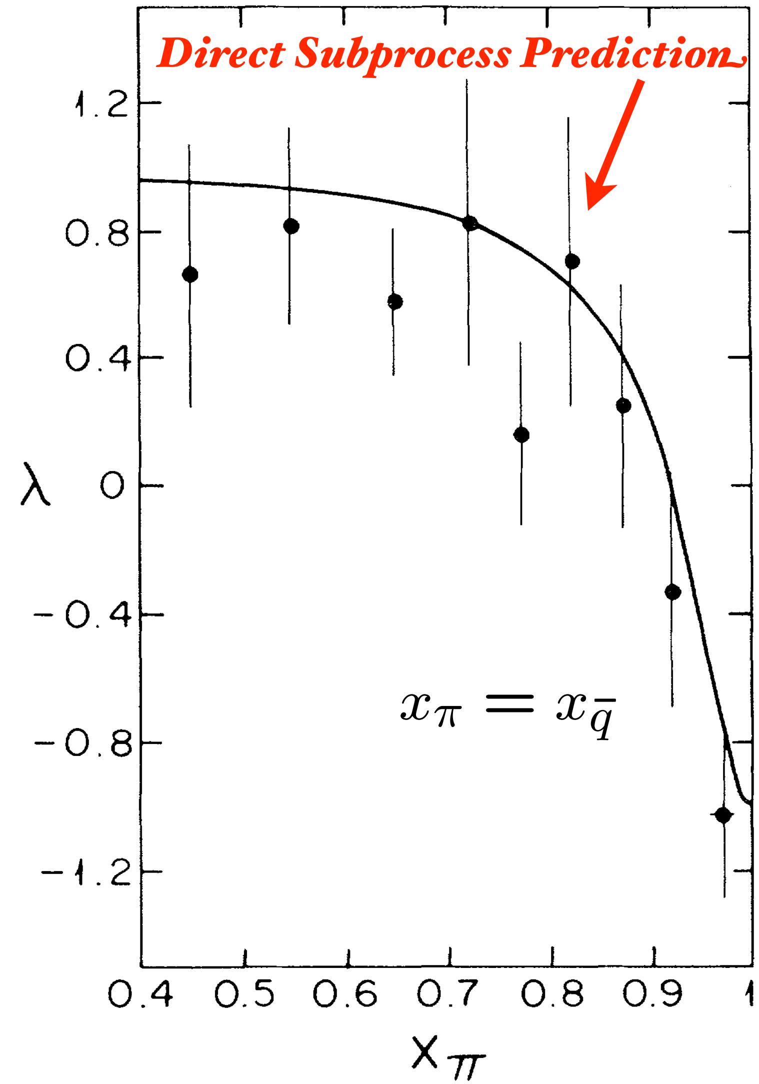
*Lepton Pair is produced longitudinally polarized*

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

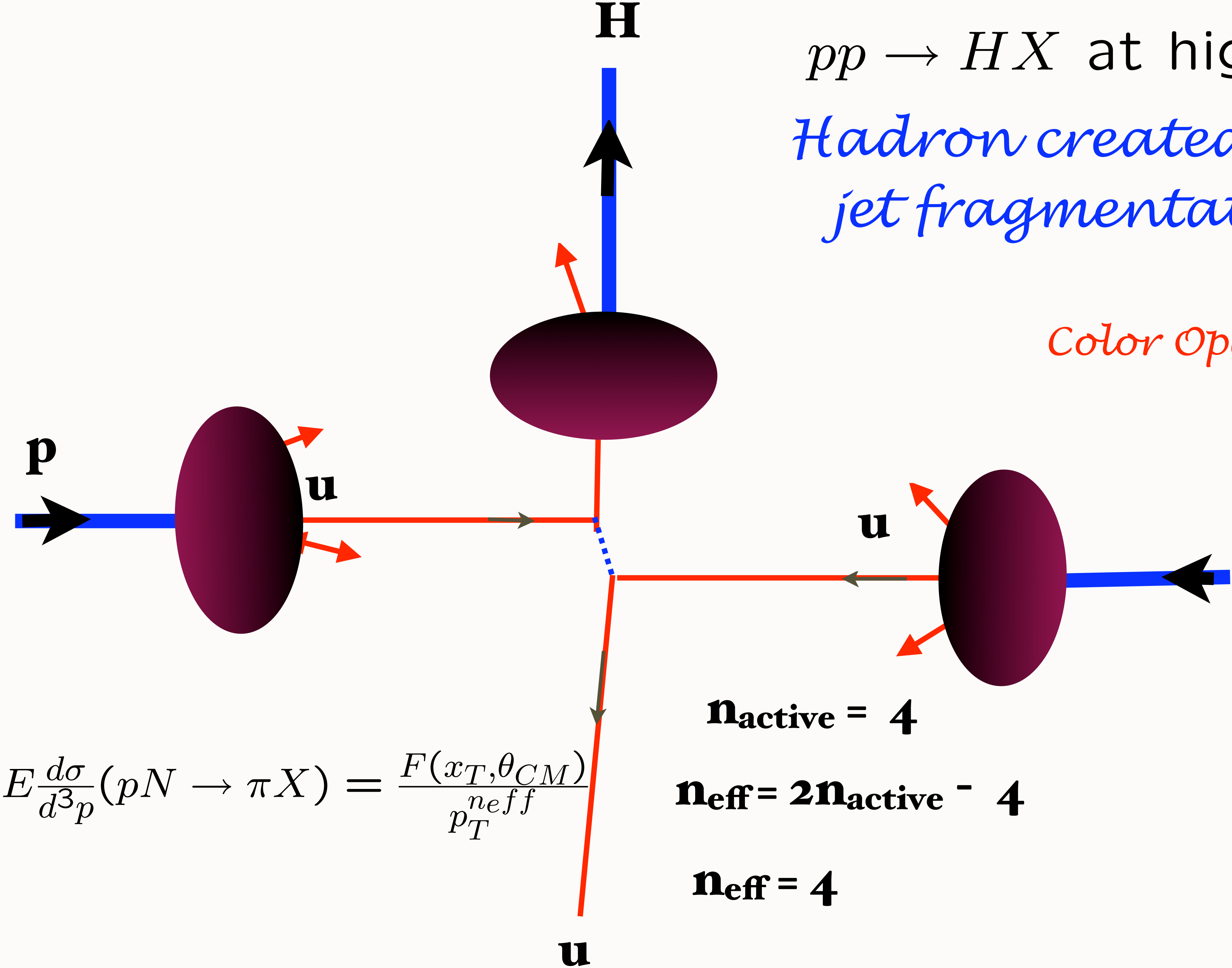
Phys.Rev.Lett.55:2649,1985

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

$pp \to HX$ at high $p_T$

*Hadron created from jet fragmentation*

*Color Opaque*




$n_{active} = 4$

$n_{eff} = 2n_{active} - 4$

$n_{eff} = 4$

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

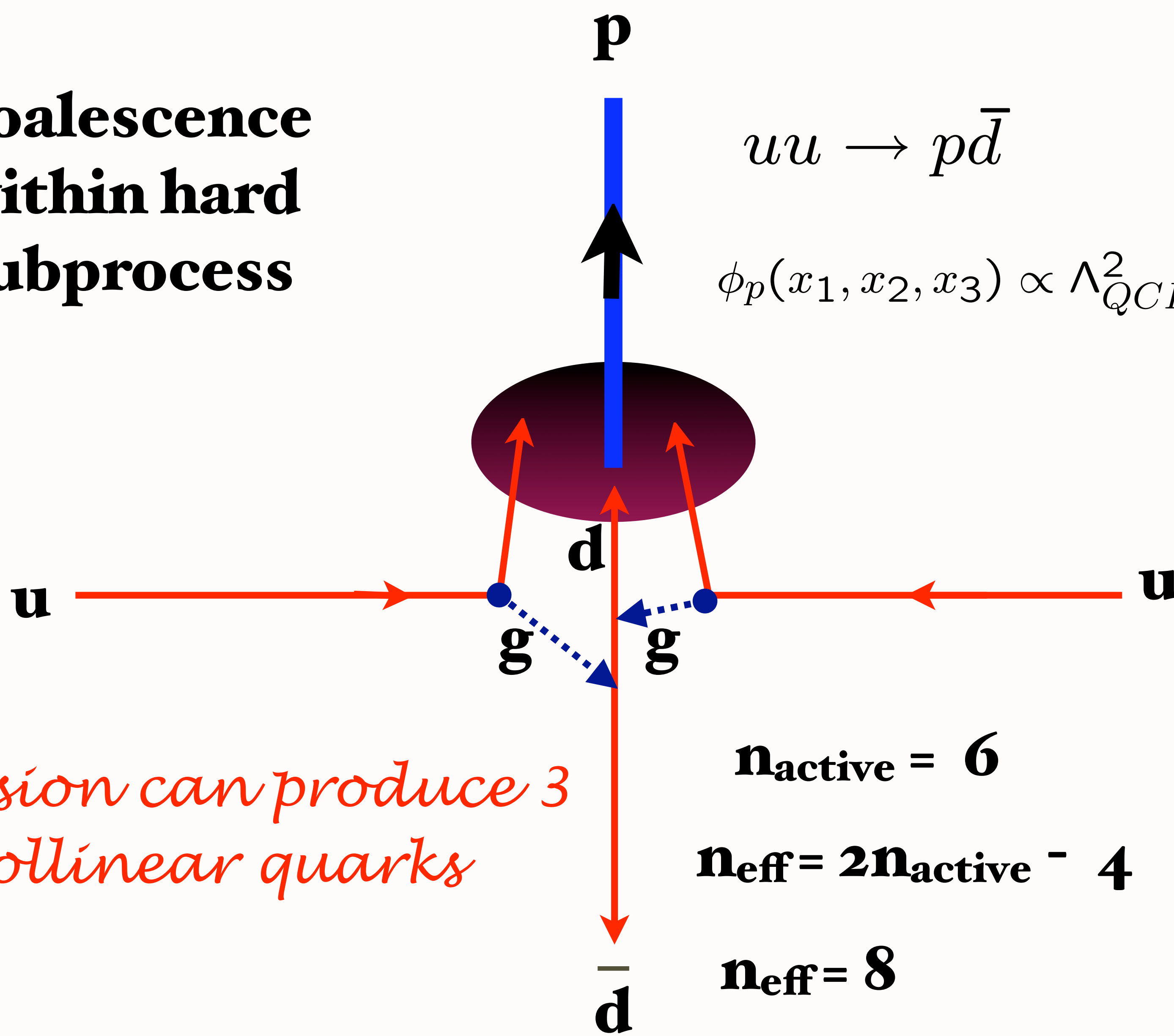
# Baryon can be made directly within hard subprocess

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

**Coalescence within hard subprocess**

$$uu \to p\bar{d}$$

$$\phi_p(x_1, x_2, x_3) \propto \Lambda^2_{QCD}$$




Collision can produce 3 collinear quarks

$n_{active} = 6$

$$qq \to B\bar{q}$$

$n_{eff} = 2n_{active} - 4$

$n_{eff} = 8$

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

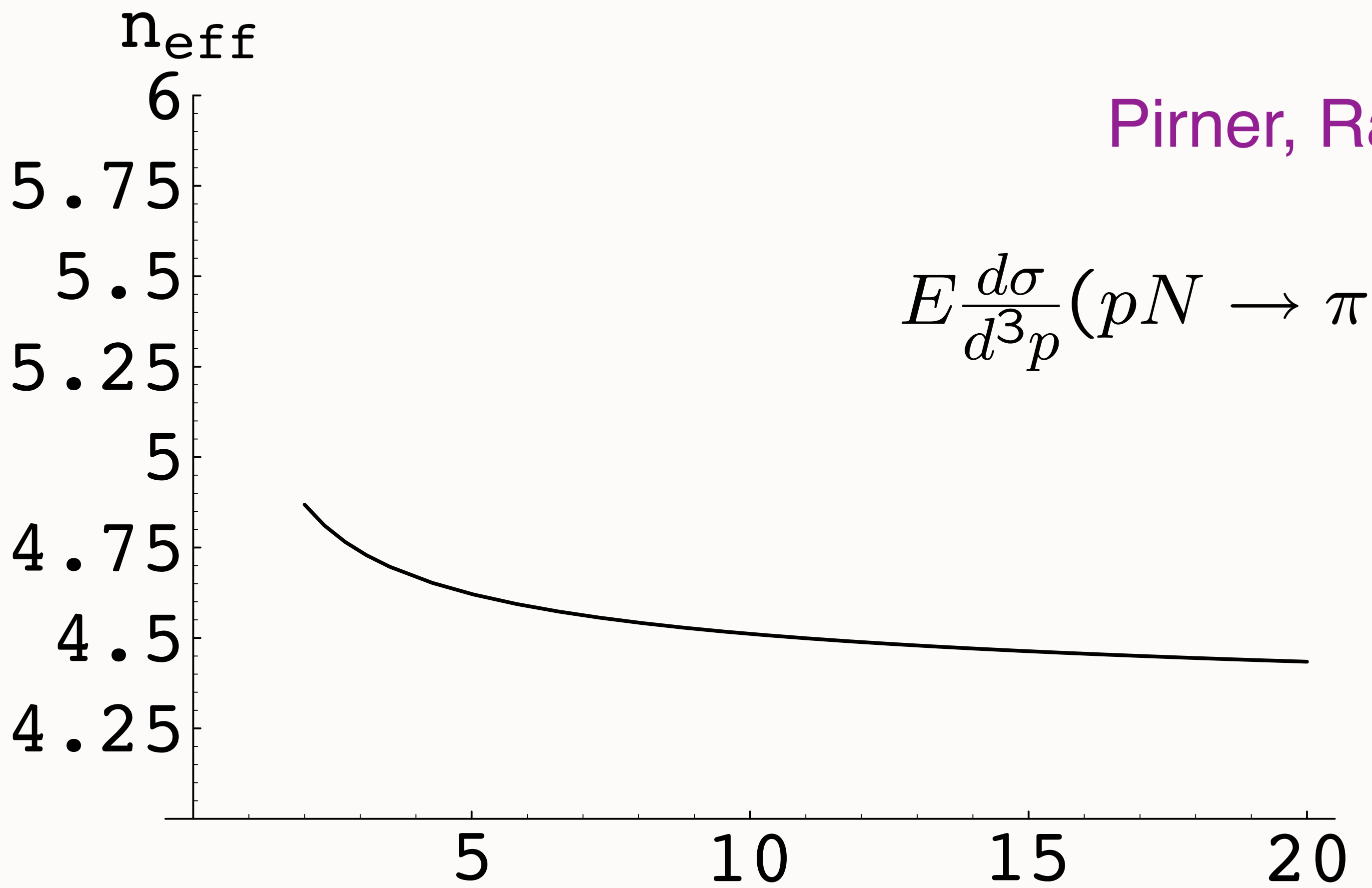
$$E\frac{d\sigma}{d^3p}(pN \to \pi X) = \frac{F(x_T,\theta_{CM})}{p_T^{n_{eff}}}$$

$n_{eff} = 4$

**Bjorken scaling**

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

# PQCD prediction: Modification of power fall-off due to DGLAP evolution and the Running Coupling




Pirner, Raufeisen, sjb

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

***$n_{eff}$ ~ 4.5***

Key test of PQCD: power fall-off at fixed $x_T$

$$d\sigma(h_a h_b \to hX) = \sum_{abc} G_{a/h_a}(x_a) G_{b/h_b}(x_b) dx_a dx_b \frac{1}{2\hat{s}} \left|A_{fi}\right|^2 dX_f D_{h/c}(z_c) dz_c.$$

$$E\frac{d^3\sigma(h_a h_b \to hX)}{d^3p} = \frac{F(y, x_R)}{p_T^{n(y,x_R)}}.$$

$$n = 2n_{active} - 4,$$

Pirner, Raufeisen, sjb

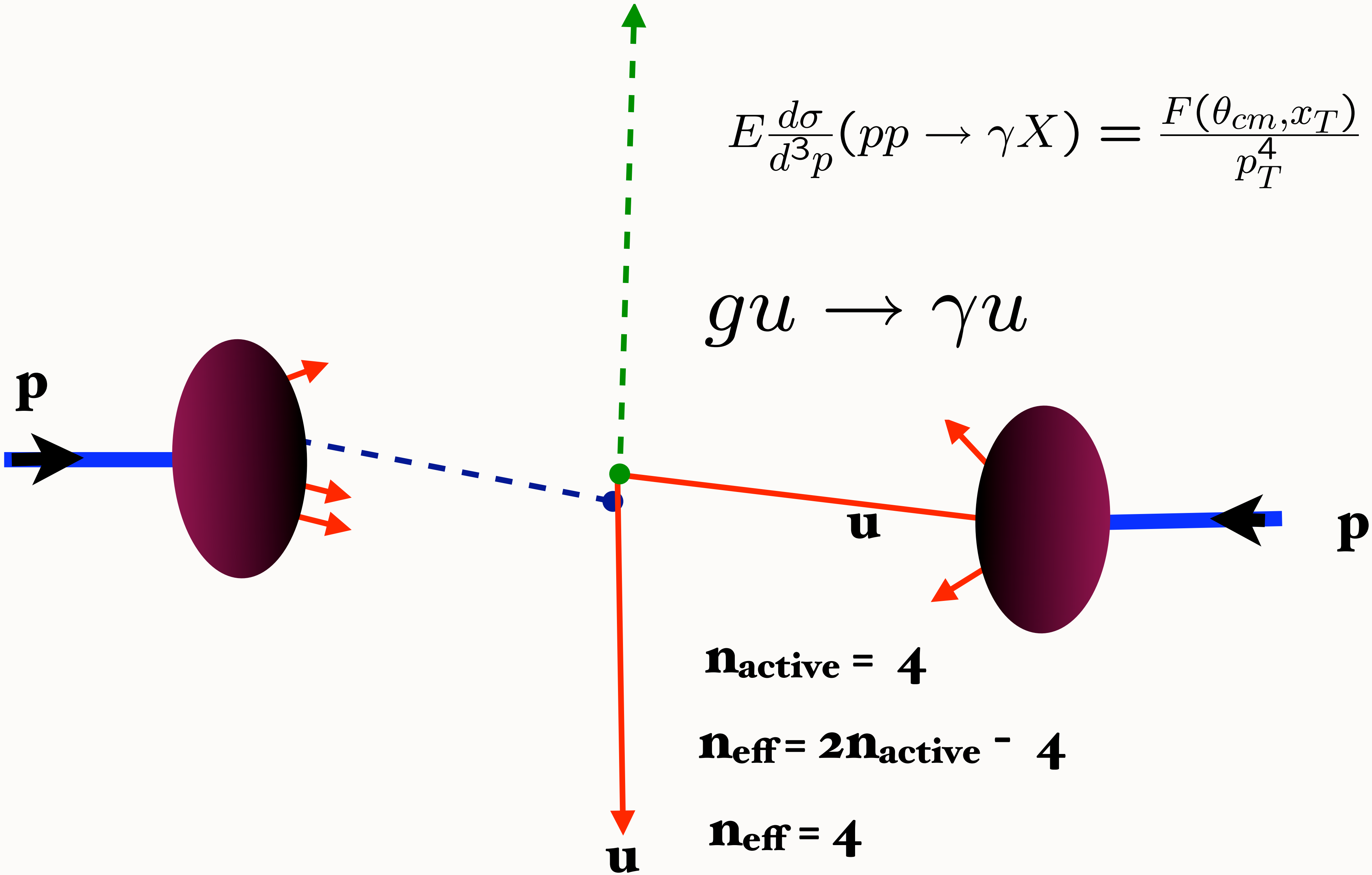
$$n_{eff}(p_T) = -\frac{d\ln E\frac{d^3\sigma(h_a h_b \to hX)}{d^3p}}{d\ln(p_T)}$$

$n_{eff} \sim 4.5$

$$E\frac{d^3\sigma(h_a h_b \to hX)}{d^3p} = \left[\frac{\alpha_s(p_T^2)}{p_T^2}\right]^{n_{active}-2} \frac{(1-x_R)^{2n_s-1+3\xi(p_T)}}{x_R^{\lambda(p_T)}} \alpha_s^{2n_s}(k_{x_R}^2) f(y).$$

$$\xi(p_T) = \frac{C_R}{\pi}\int_{k_{x_R}^2}^{p_T^2} \frac{dk_\perp^2}{k_\perp^2}\alpha_s(k_\perp^2) = \frac{4C_R}{\beta_0}\ln\frac{\ln(p_T^2/\Lambda_{QCD}^2)}{\ln(k_{x_R}^2/\Lambda_{QCD}^2)}.$$

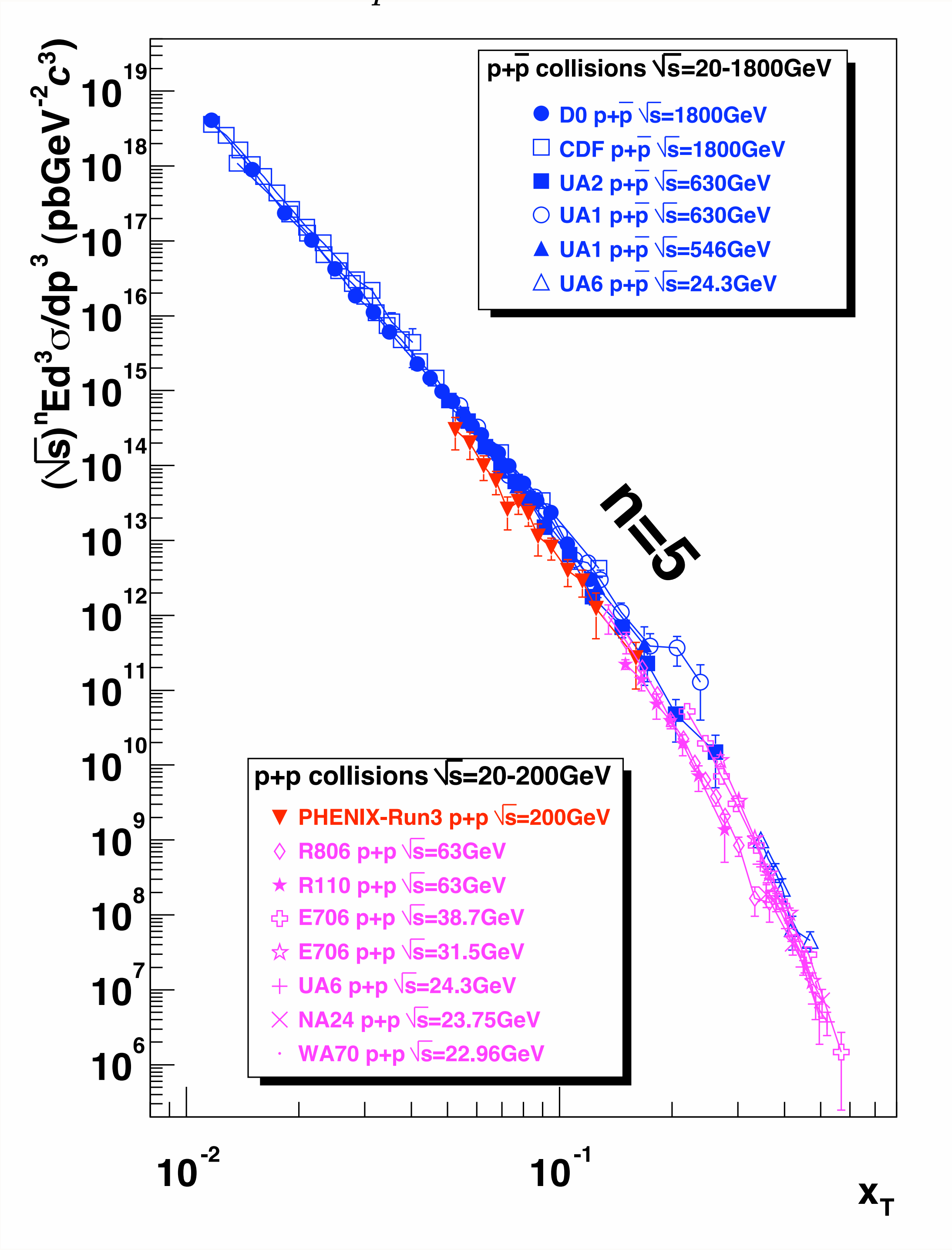
# $pp \to \gamma X$



$E\frac{d\sigma}{d^3p}(pp \to \gamma X) = \frac{F(\theta_{cm}, x_T)}{p_T^4}$
$gu \to \gamma u$
p
u
p
$n_{active} = 4$
$n_{eff} = 2n_{active} - 4$
u
$n_{eff} = 4$

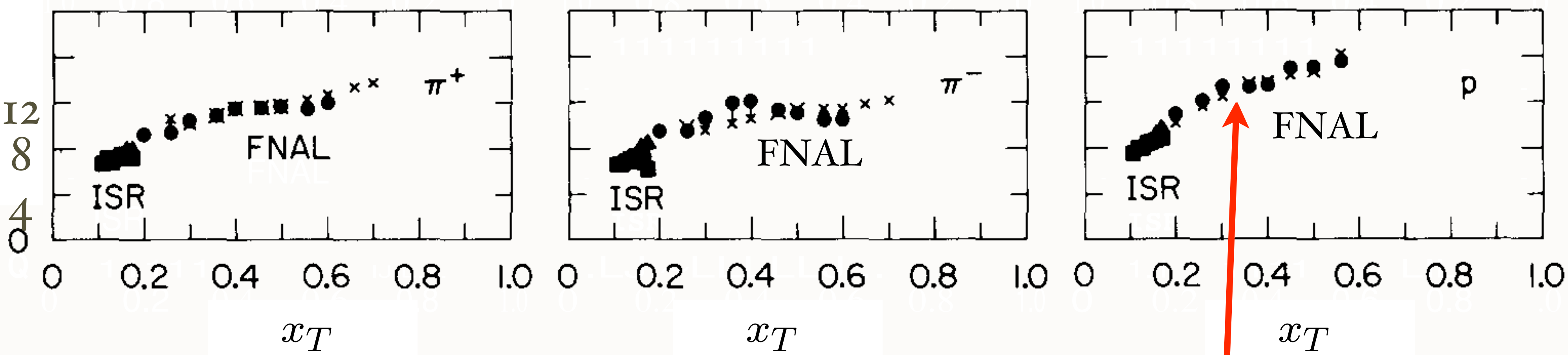
$\sqrt{s}^n E\frac{d\sigma}{d^3p}(pp \to \gamma X)$ at fixed $x_T$

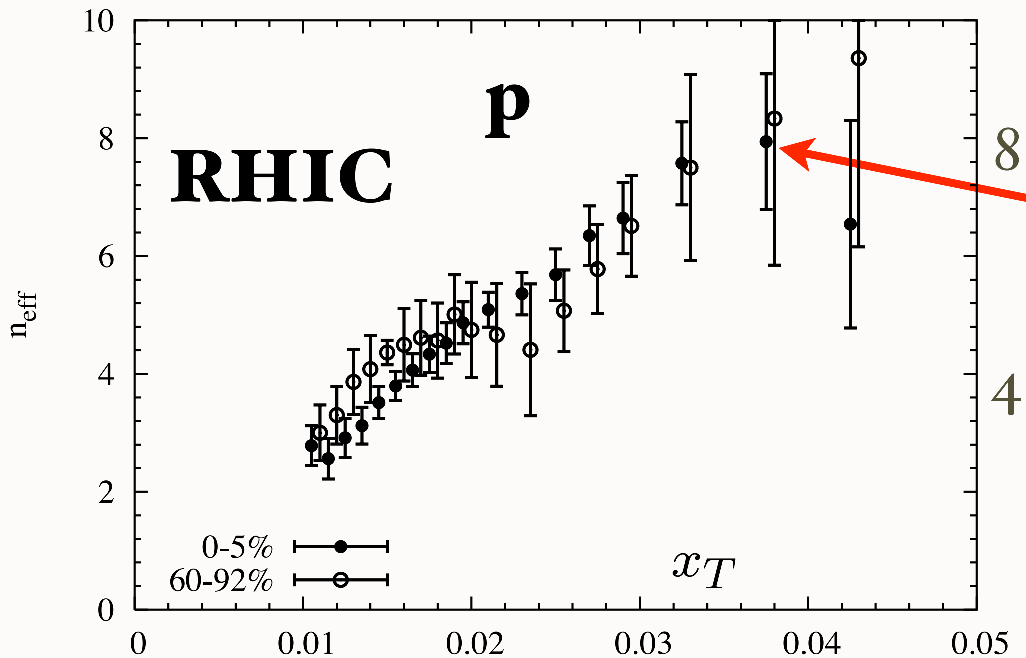
Tannenbaum




**$x_T$-scaling of direct photon production is consistent with PQCD**

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



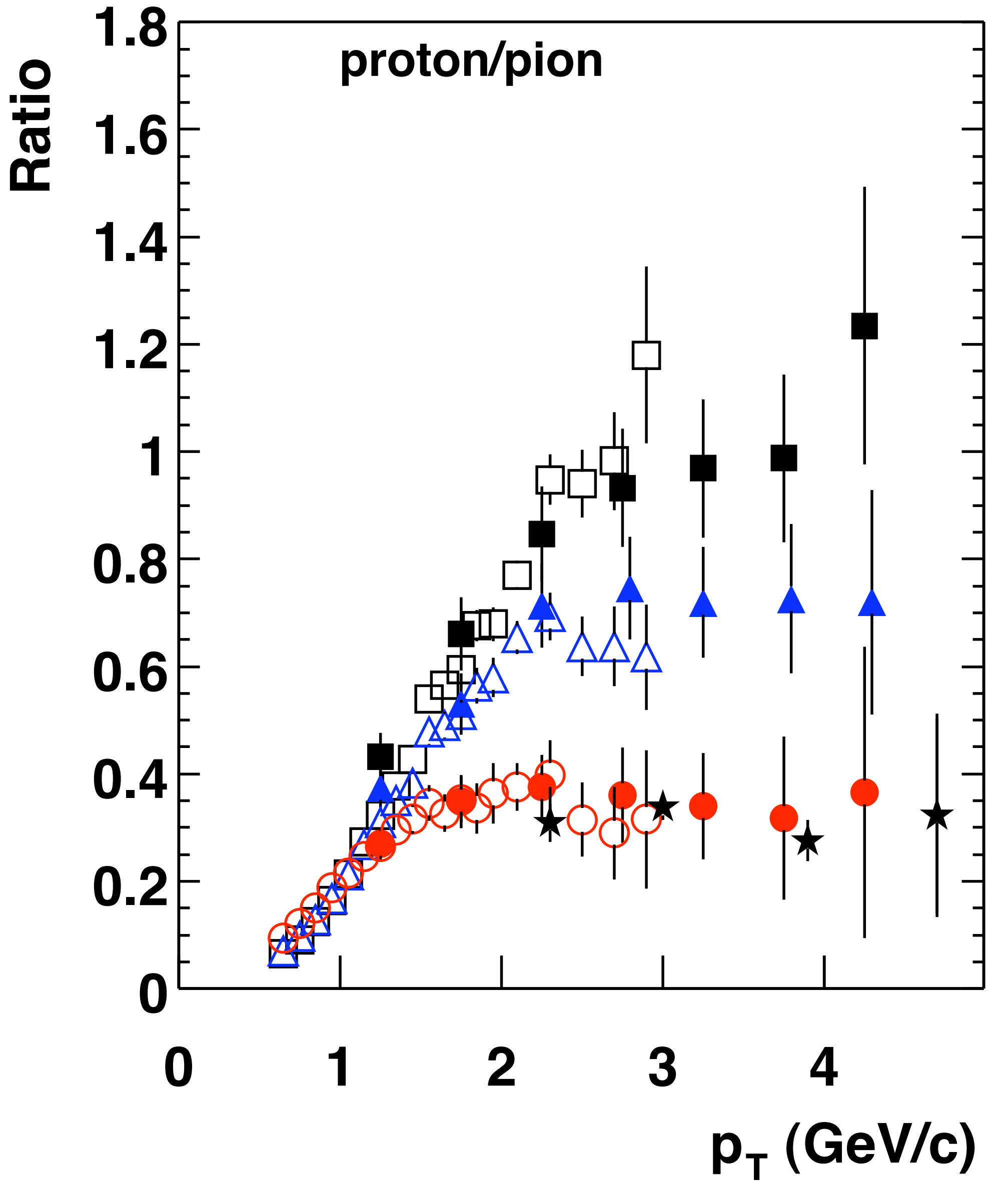

$$E\frac{d\sigma}{d^3p}(pp \to pX) = \frac{F(x_T,\theta_{CM})}{p_T^{12}}$$

$$E\frac{d\sigma}{d^3p}(pp \to pX) = \frac{F(x_T,\theta_{CM})}{p_T^{8}}$$

*Trend consistent with RHIC at small $x_T$*

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

*Particle ratio changes with centrality!*




**Central**

**Peripheral**

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

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

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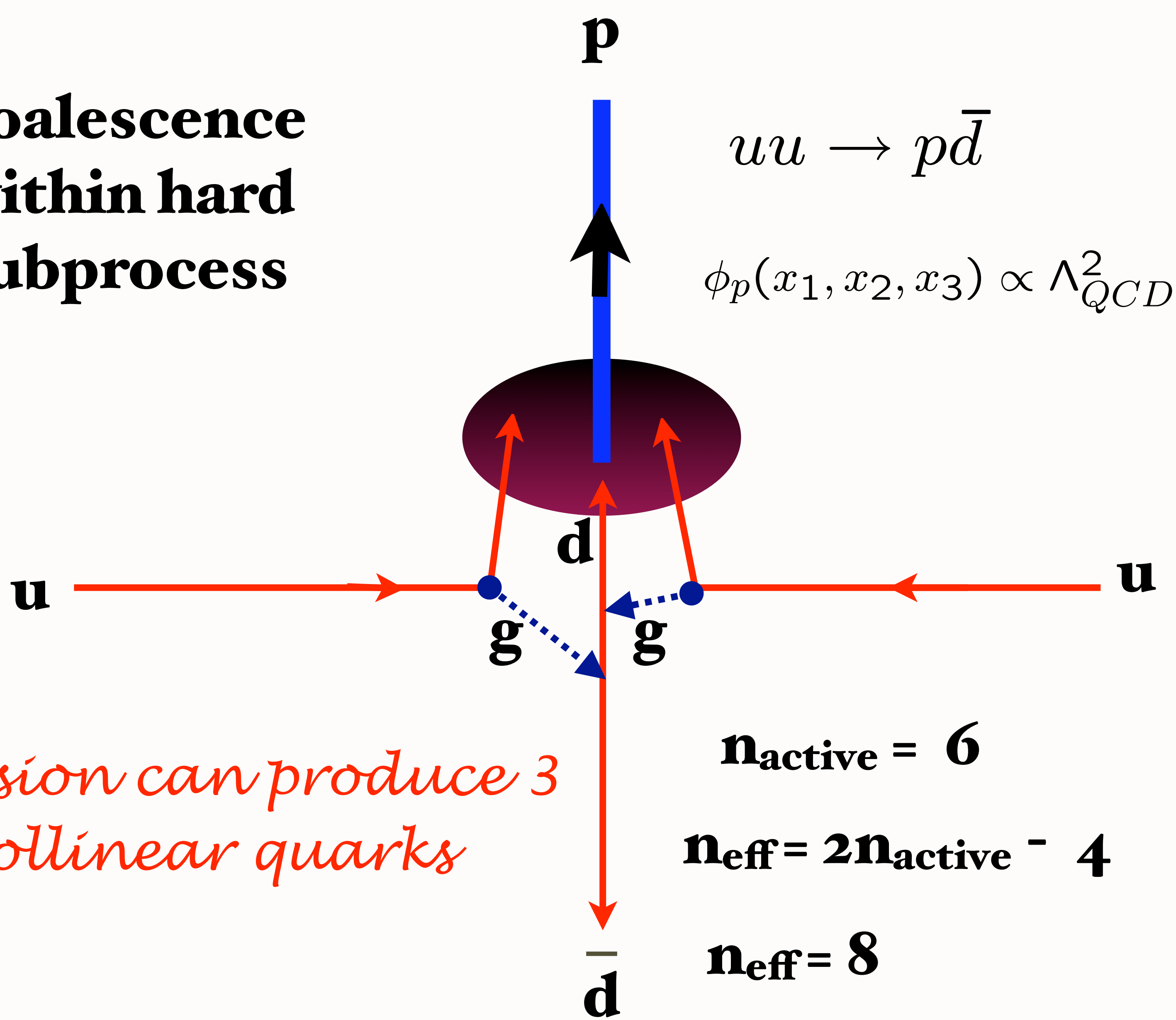


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$n_{active} = 6$

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$qq \to B\bar{q}$

# Evidence for Direct, Higher-Twist Subprocesses

- Anomalous power behavior at fixed $x_T$
- Protons more likely to come from direct subprocess than pions
- Protons less absorbed than pions in central nuclear collisions because of **color transparency**
- Predicts increasing proton to pion ratio in central collisions
- Exclusive-inclusive connection at $x_T = 1$

# "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