# Inclusive Perspectives

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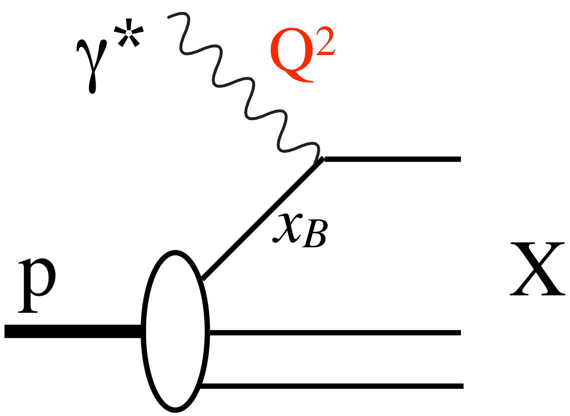
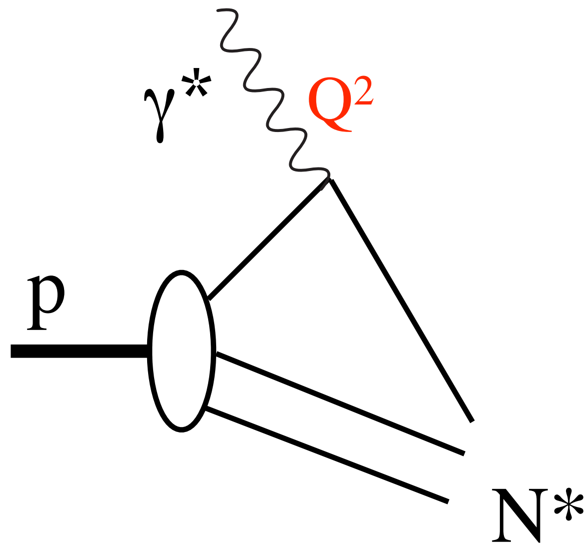
**Exclusive Reactions at High Momentum Transfer**
Jefferson Lab, 21 - 24 May 2007

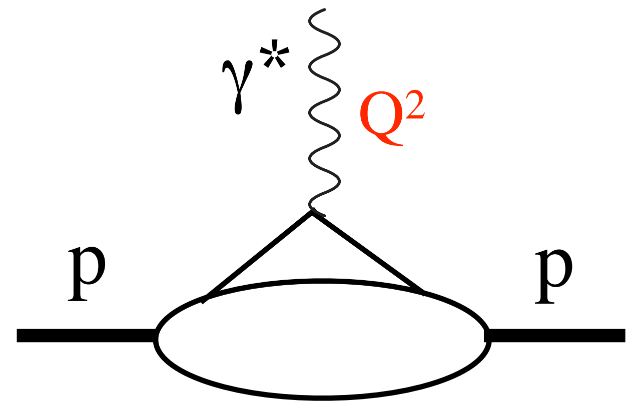
# The inclusive - exclusive connection

Use our understanding of (semi-)inclusive processes to gain insights into exclusive form factors and processes

S. D. Drell and T. M. Yan, PRL **24** (1970) 181
G. B. West, PRL **24** (1970) 1206



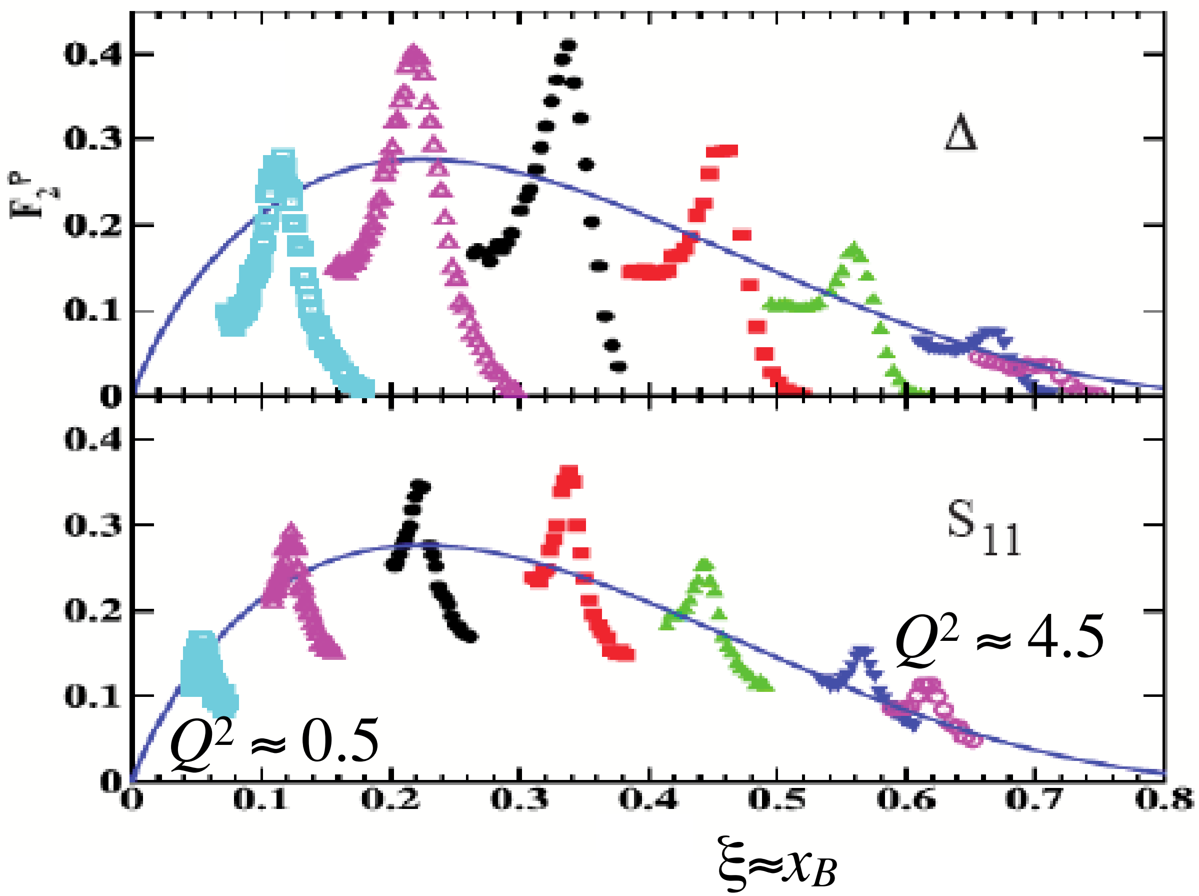




$e\,p \to e\,X$ | $e\,p \to e\,N^*$ | $e\,p \to e\,p$

DIS $\Rightarrow$ Semi-exclusive, or Transition FF $\Rightarrow$ Elastic FF

# Bloom-Gilman Duality

Jlab Hall C




Duality between $ep \to eN^*$ resonance contributions at low $Q^2$ and the scaling curve for $ep \to eX$ at high $Q^2$ works locally for each resonance

Bloom and Gilman, PRL **25** (1970) 1140

W. Melnitchouk et al, Phys. Rep. 406 (2005) 127

Workshop on Duality, Frascati 2005 http://www.lnf.infn.it/conference/duality05/

A given resonance appears, with increasing $Q^2$, at fixed $Q^2(1-x_B)$

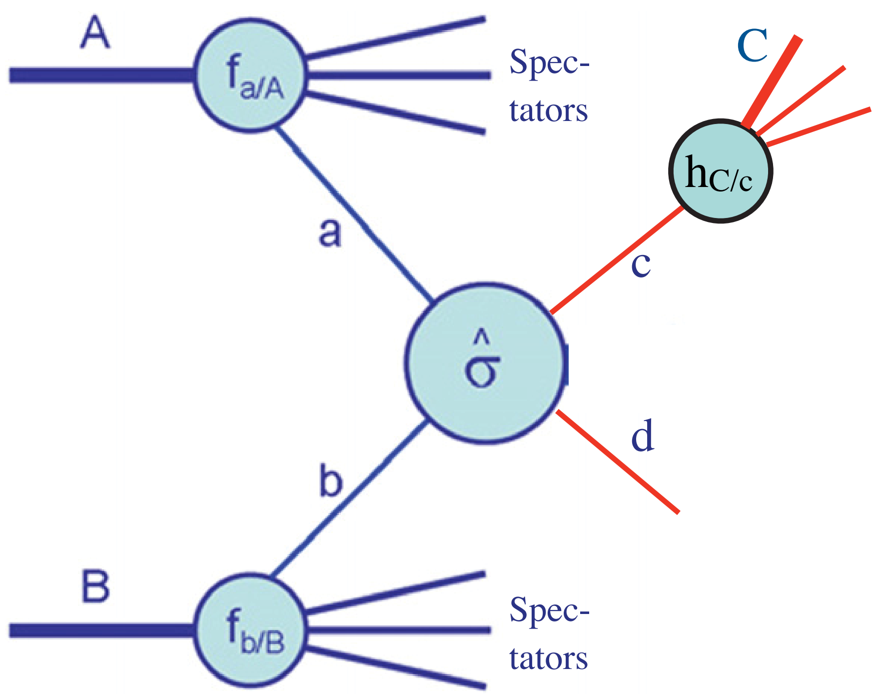
$$M_{N^*}^2 = m_N^2 + \frac{(1-x_B)Q^2}{x_B}$$

Note: The limits of $Q^2 \to \infty$ at fixed $x_B$ (Bjorken limit) and at fixed $Q^2(1-x_B)$ are distinct!

# Soft Coherence in Hard Inclusive Processes

Cartoon:

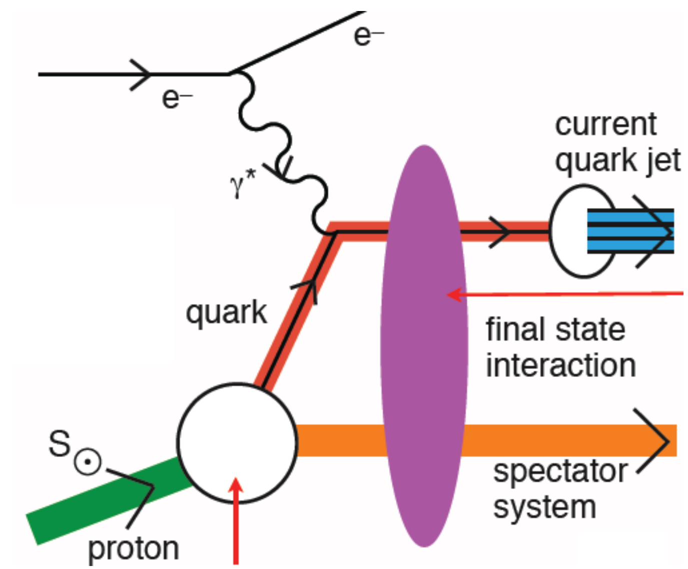
- One active parton in each hadron
- No interactions with spectators
- Hard subprocess is pointlike




$\Rightarrow$

In fact:

Soft spectator interactions influence the hard process, even as $Q^2 \to \infty$



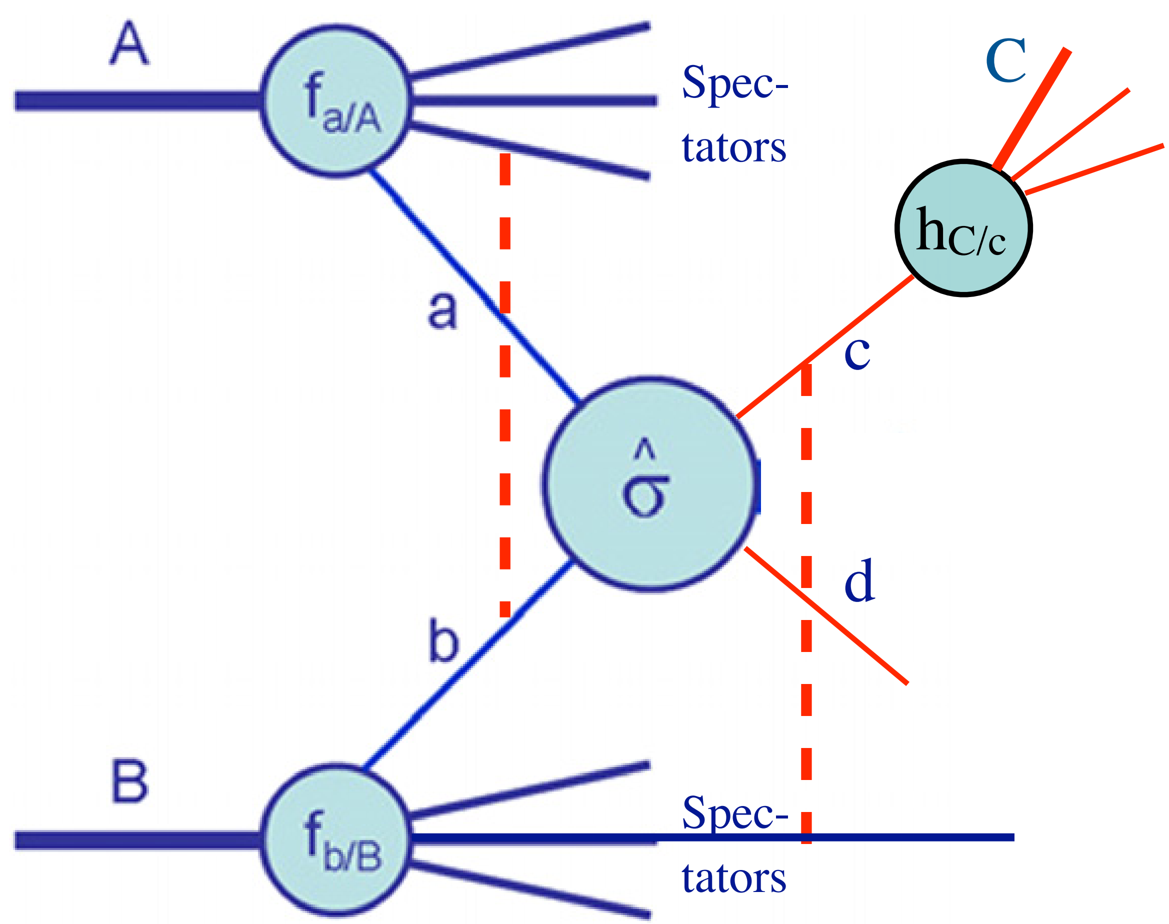

- Shadowing of parton distrib.
- Hard diffractive scattering
- SSA (SIDIS) = – SSA (DY)
- DVES?

# Breaking News: QCD factorization violated

No universality of ($k_\perp$-dependent) parton distributions in hh → h

J. Collins and J-W. Qiu, arXiv:0705.2141 [hep-ph]

Soft rescattering of active partons on spectators in both initial and final states is not consistent with universal parton distributions.



# Hard-Soft Coherence in large x Fock States

The (Light-Front) energy of a Fock state with total momentum $P$ is

$$P^- = \sum_i \frac{p_{i\perp}^2 + m_i^2}{x_i P^+} \qquad\qquad \sum_i x_i = 1$$

Hence contributions to $P^-$ of order $Q^2$ arise in two ways:

– From hard partons, with $p_\perp^2 \sim Q^2$

– From soft partons with $p_\perp^2 \sim m^2 \sim \Lambda^2_{QCD}$ but with low $x \sim 1/Q^2$

Both give commensurate, short life-times $\sim 1/P^-$

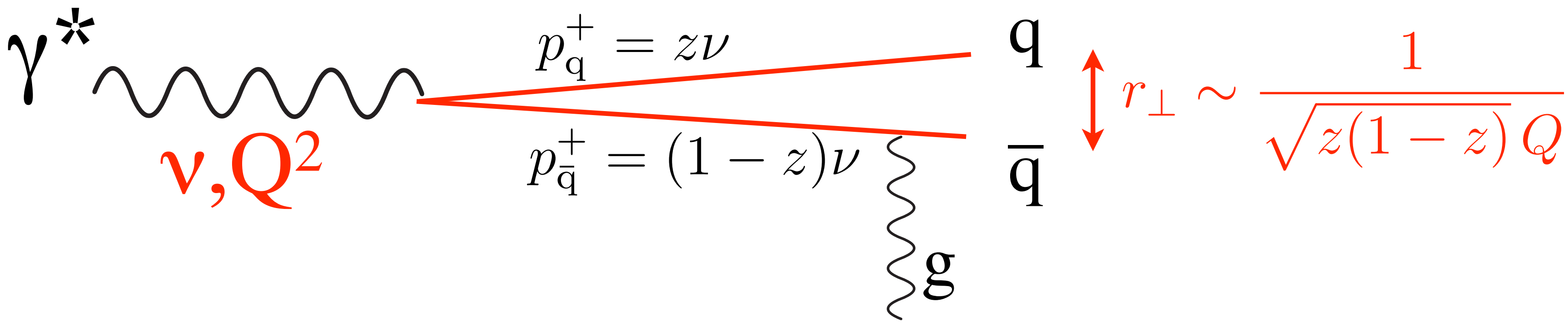
In the limit where a hard parton takes nearly all the hadron momentum:

$x \to 1$ with $(1-x)Q^2 \sim \Lambda^2_{QCD}$ fixed

the full Fock state interacts coherently.

# DIS as Dipole Dynamics

In the dipole picture of DIS dynamics the virtual photon splits into a quark pair, which scatters on a gluon in the target: $\gamma^* g \to q\bar{q}$




The typical transverse size of the (color singlet) dipole is $\propto 1/Q$, hence the DIS cross section $\sigma_{DIS}(\gamma^* g \to qq) \propto 1/Q^2$ (Color Transparency, CT)

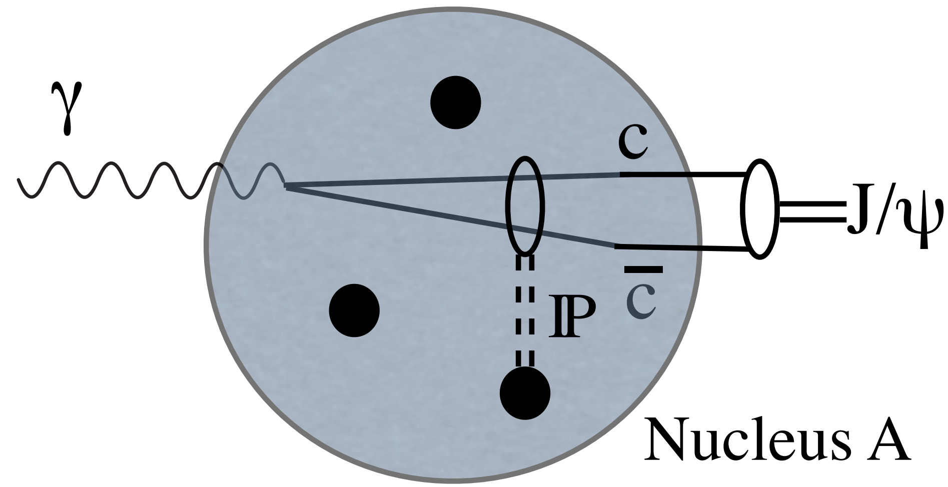
However, at the endpoint $z \to 1$ such that $(1\text{-}z)Q^2 \sim \Lambda^2_{QCD}$ the antiquark propagator becomes soft and the transverse size of the quark pair becomes $r_\perp \sim 1$ fm:

$\Rightarrow$ we enter the parton model dynamics: $\gamma^* q \to q$

# CT in Coherent J/ψ Photoproduction

In $\gamma + A \rightarrow J/\psi + A$ the charm quark pair is produced as a compact color singlet configuration,

$z \sim 1/2, \quad r_\perp \sim 1/m_c$

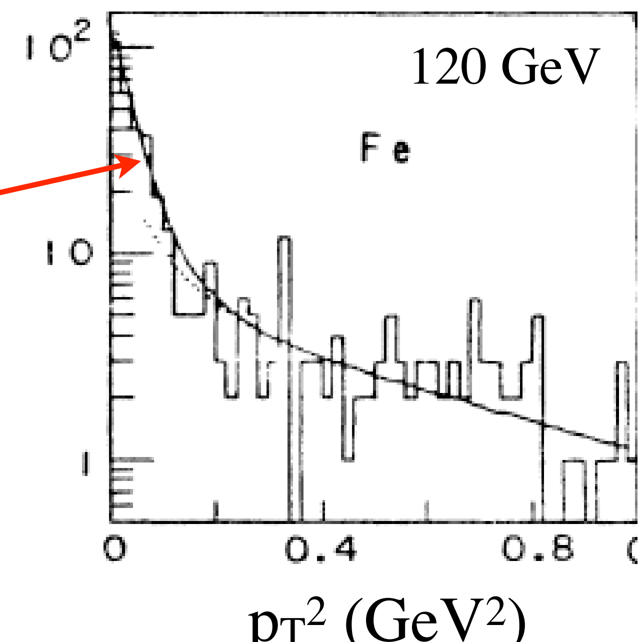



The compact quark pair has a small cross section and scatters coherently on all A nucleons, giving an enhanced production on nuclei:

$\sigma_{coh} \sim A^{\alpha}$ , $\alpha = 1.40 \pm 0.04$

Coherent peak

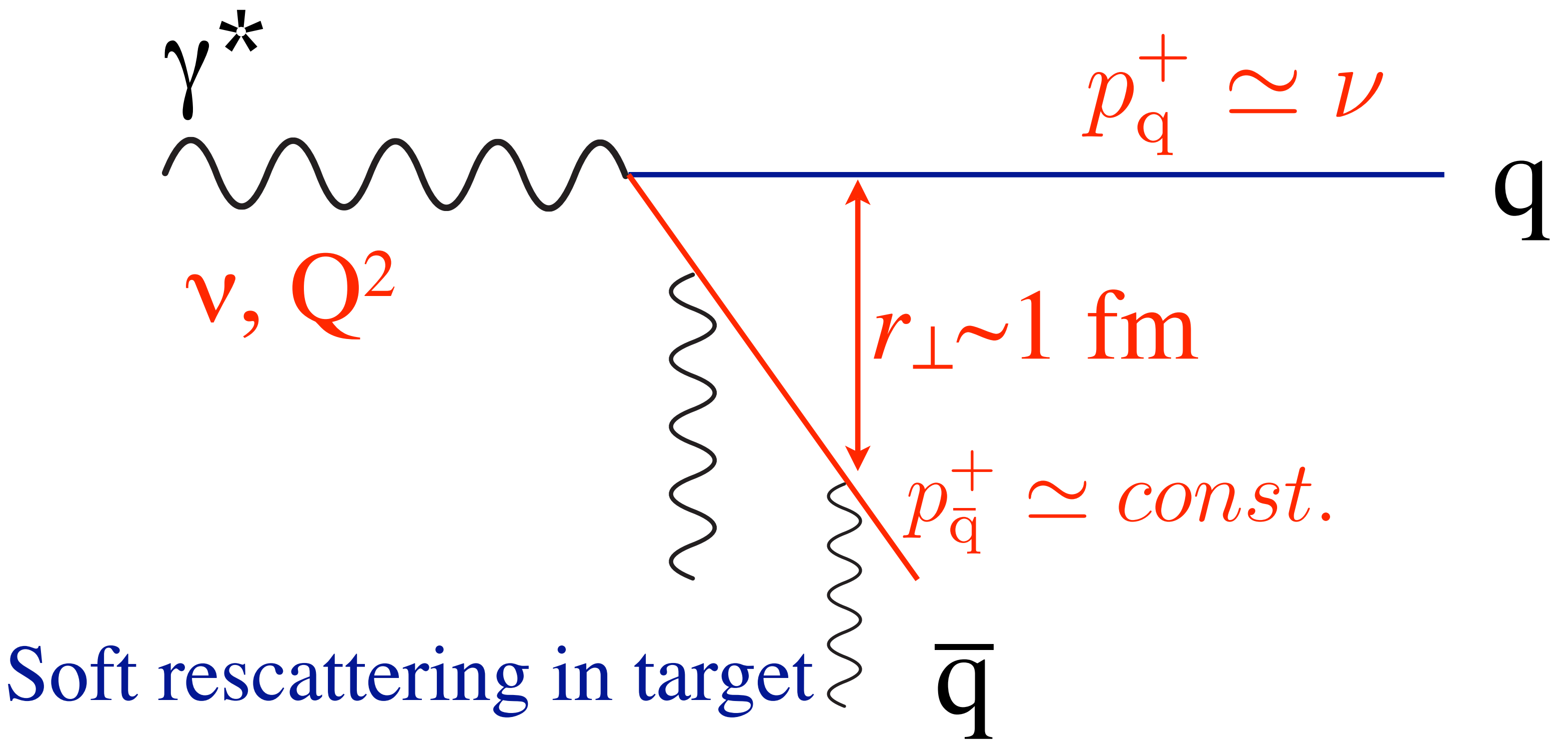
$\gamma + Fe \rightarrow J/\psi + Fe$




**Sokoloff et al, PRL 57 (1986) 3003**

# The Mother of all End-points: DIS

Parton model dynamics of DIS in "lab frame":



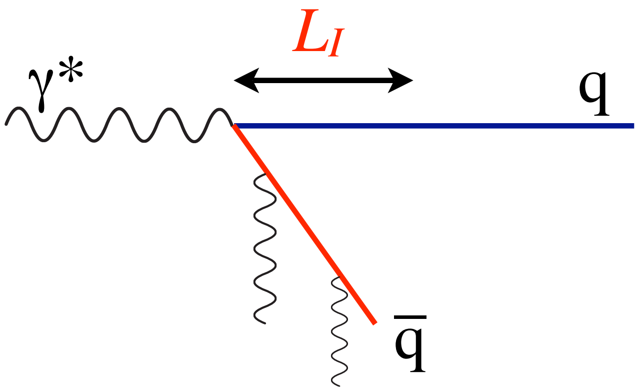

The antiquark takes a fraction $1\text{-}z \propto 1/Q^2$ of the photon energy

Soft scattering of slow antiquark is coherent with and determines the cross section of the hard scattering process.

# The Ioffe Coherence Length

Because the longitudinal momentum of the virtual photon $\nu \propto Q^2$, the virtual photon coherence ('Ioffe') length in target rest frame is finite:

$$L_I = \frac{1}{Q} \cdot \frac{\nu}{Q} = \frac{\nu}{Q^2} = \frac{1}{2mx_B}$$




The antiquark has finite longitudinal and transverse momentum in the target rest frame.

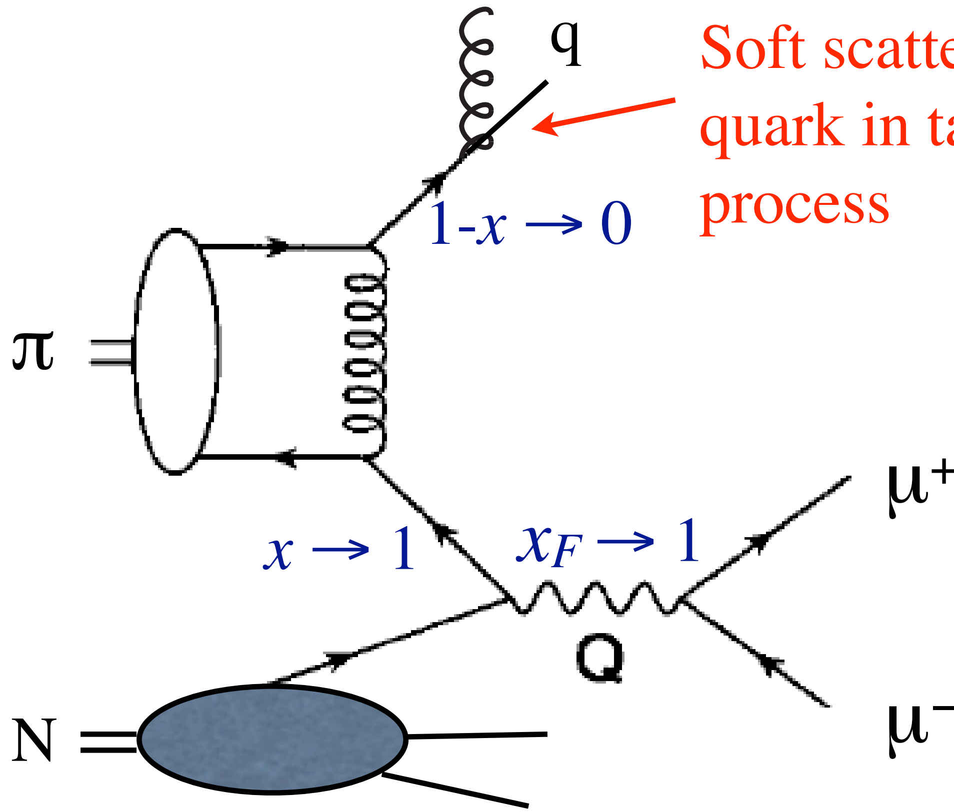
Within $L_I$ its (re)interactions liberate the fast quark.

– In LF gauge $A^+ = 0$, the fast (current) quark does not even interact

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



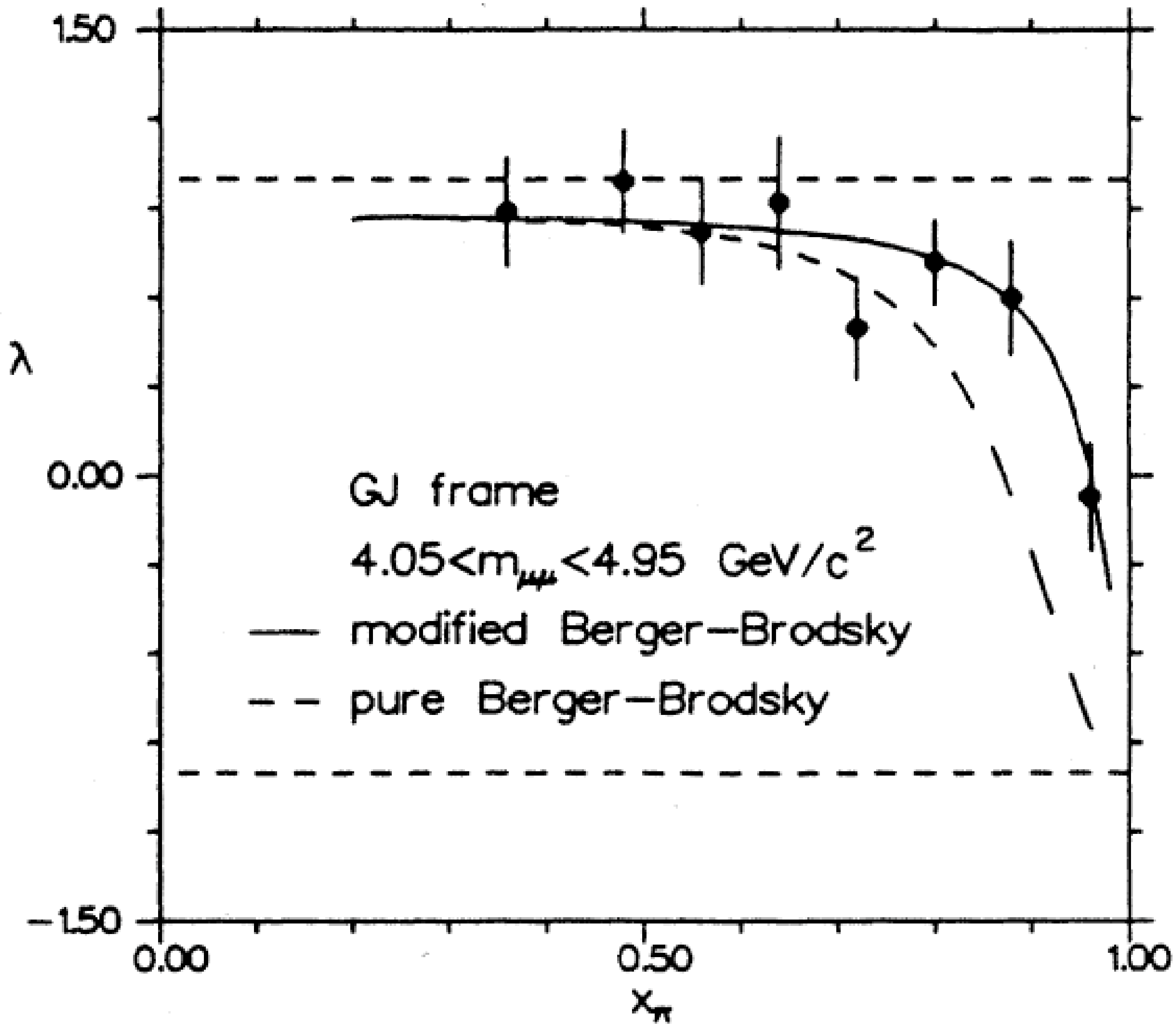

Soft scattering of stopped quark in target affects hard process

Virtual photon is longitudinally polarized

Berger and Brodsky, PRL 42 (1979) 940

The polarization of the virtual photon is revealed by the angular distribution of the muon pair:

$d\sigma/d\Omega_{\mu\mu} \propto 1 + \lambda \cos^2\theta$




$\pi N \to \mu^+ \mu^- X$
$p_{lab} = 252$ GeV

Evidence for virtual photon becoming longitudinally polarized ($\lambda \to -1$) as $x_F \to 1$

J. S. Conway et al, PRD **39** (1989) 92

# Single Spin Asymmetry

$$A_N = \frac{d\sigma^{\uparrow} - d\sigma^{\downarrow}}{d\sigma^{\uparrow} + d\sigma^{\downarrow}} = \frac{2\Sigma_{\{\sigma\}}\mathrm{Im}\left[\mathcal{M}^*_{\leftarrow,\{\sigma\}}\mathcal{M}_{\rightarrow,\{\sigma\}}\right]}{\Sigma_{\{\sigma\}}\left[\left|\mathcal{M}_{\rightarrow,\{\sigma\}}\right|^2 + \left|\mathcal{M}_{\leftarrow,\{\sigma\}}\right|^2\right]}$$

An SSA ($A_N \neq 0$) requires:

- A dynamical phase (absorptive part)
- Helicity flip

In hard perturbative diagrams both features are suppressed

Kane, Pumpkin and Repko, PRL **41** (1978) 1689

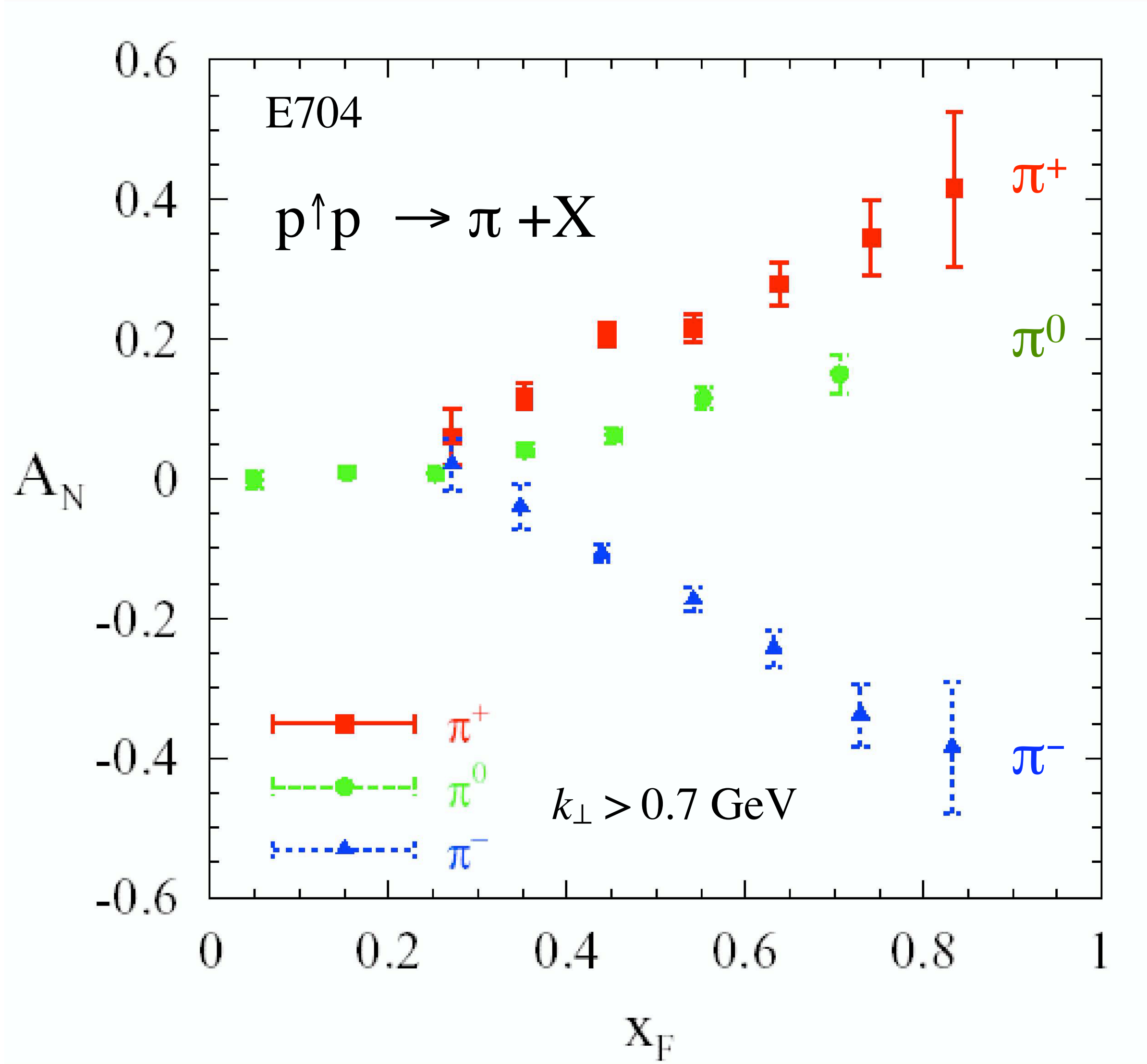
Hence the observed $A_N$ reveals important aspects of the dynamics of scattering at large transverse momentum

# $p^{\uparrow}p \rightarrow \pi(x_F, k_\perp) + X$

Single spin asymmetry is twist-3: $A_N \propto 1/k_\perp$ for $k_\perp \rightarrow \infty$ at fixed $x_F$

To produce a pion with $x_F = 0.8$:
At leading twist, a single quark would have to carry $x \geq 0.9$ of the proton momentum, and then pass on $z \geq 0.9$ of its momentum to the pion.

$A_N(k_\perp > 0.7\ \text{GeV}) >> A_N(k_\perp < 0.7\ \text{GeV})$

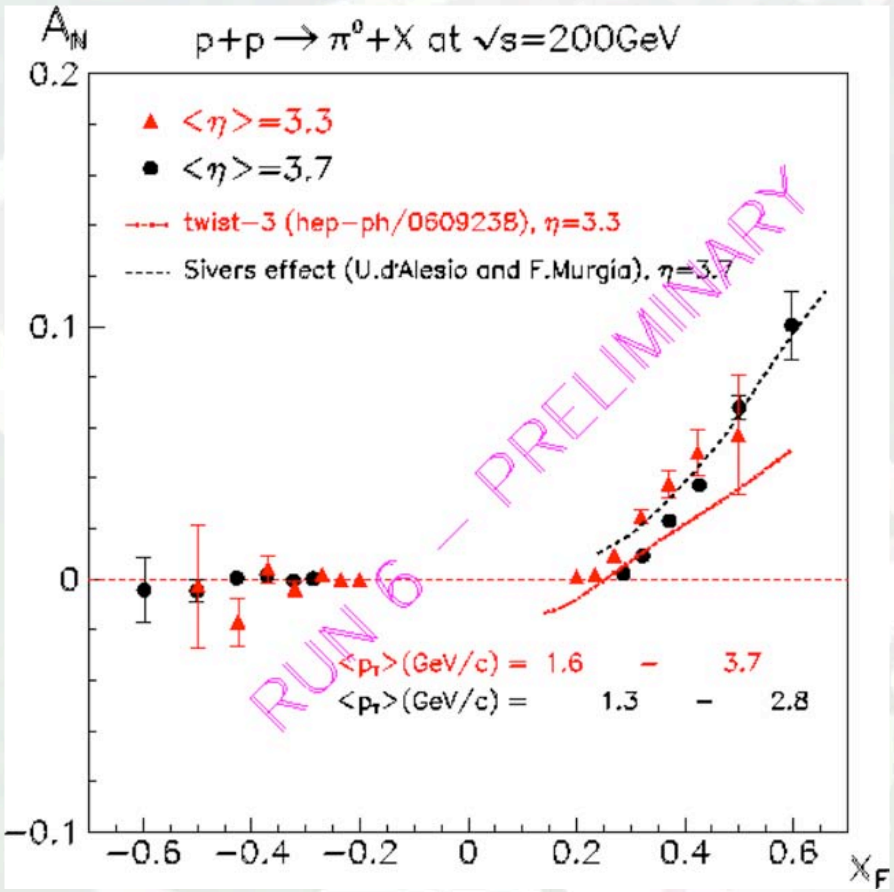


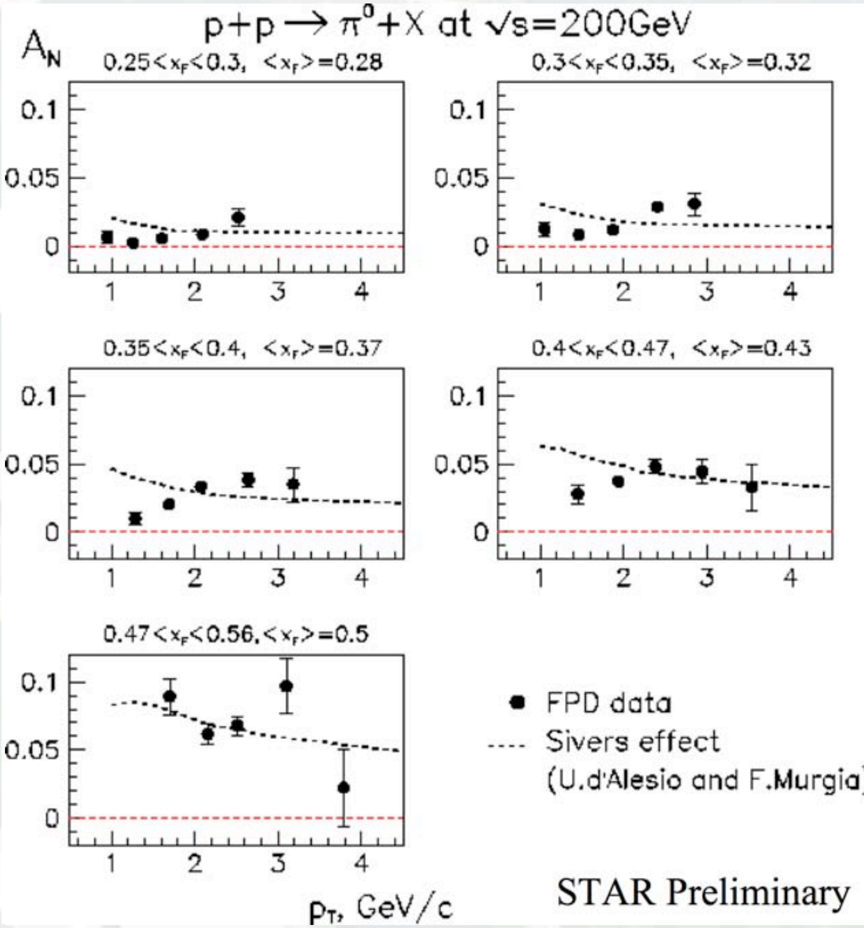

The large $A_N \sim 0.4$ at $x_F \sim 0.8$ suggests soft rescattering which is coherent with the large $k_\perp$ dynamics. This allows the full projectile wave function to contribute, with unsuppressed phases and helicity flip.

# STAR transverse spin program - Recent results

L. Nogach (IHEP-Protvino)

- $A_N$ measurement as a function of $x_F$ and $p_T$

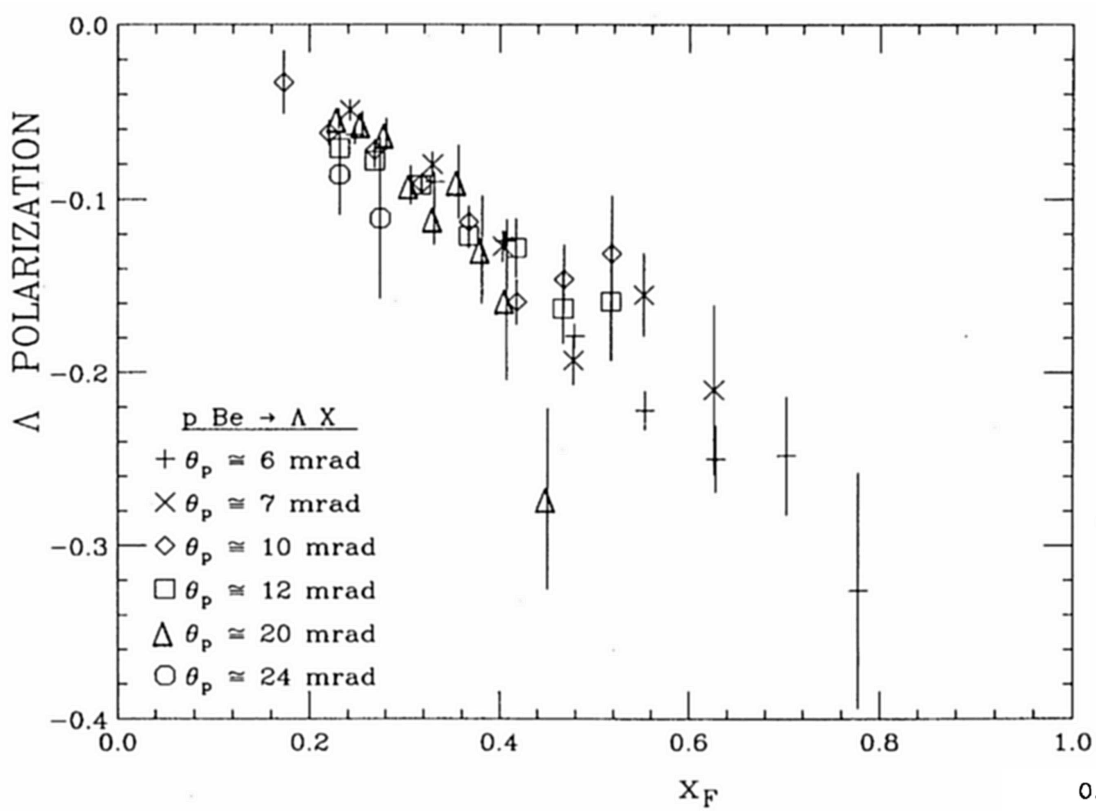


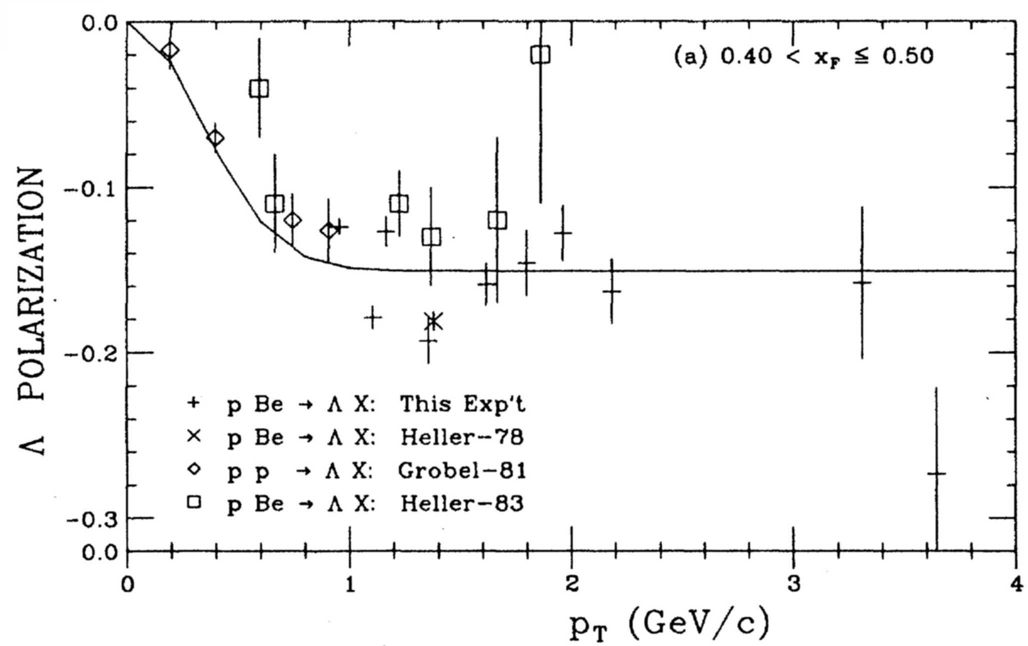

- Run 6 results consistent with previous results
- $A_N$ calculations (Sivers / Twist-3) inconsistent with precise $x_F$ dependence of measured $A_N$

- Measured $A_N$ is not found to decrease in $p_T$ in all $x_F$ bins
- In contrast: Theoretical models predict $A_N$ to decrease with $p_T$

# p p → Λ($x_F$, $k_\perp$) +X

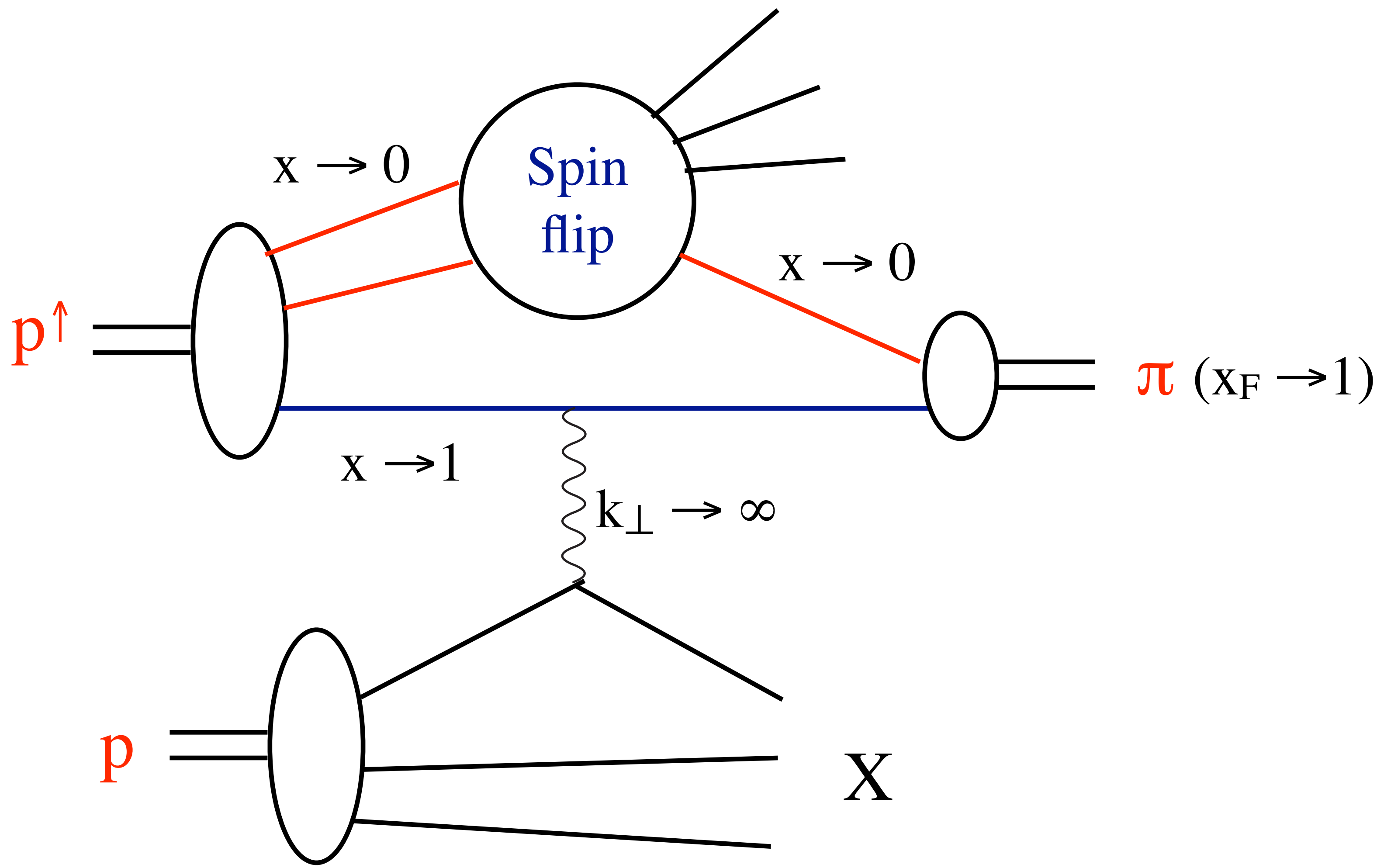



Lundberg et al., PRD **40** (1989) 3557

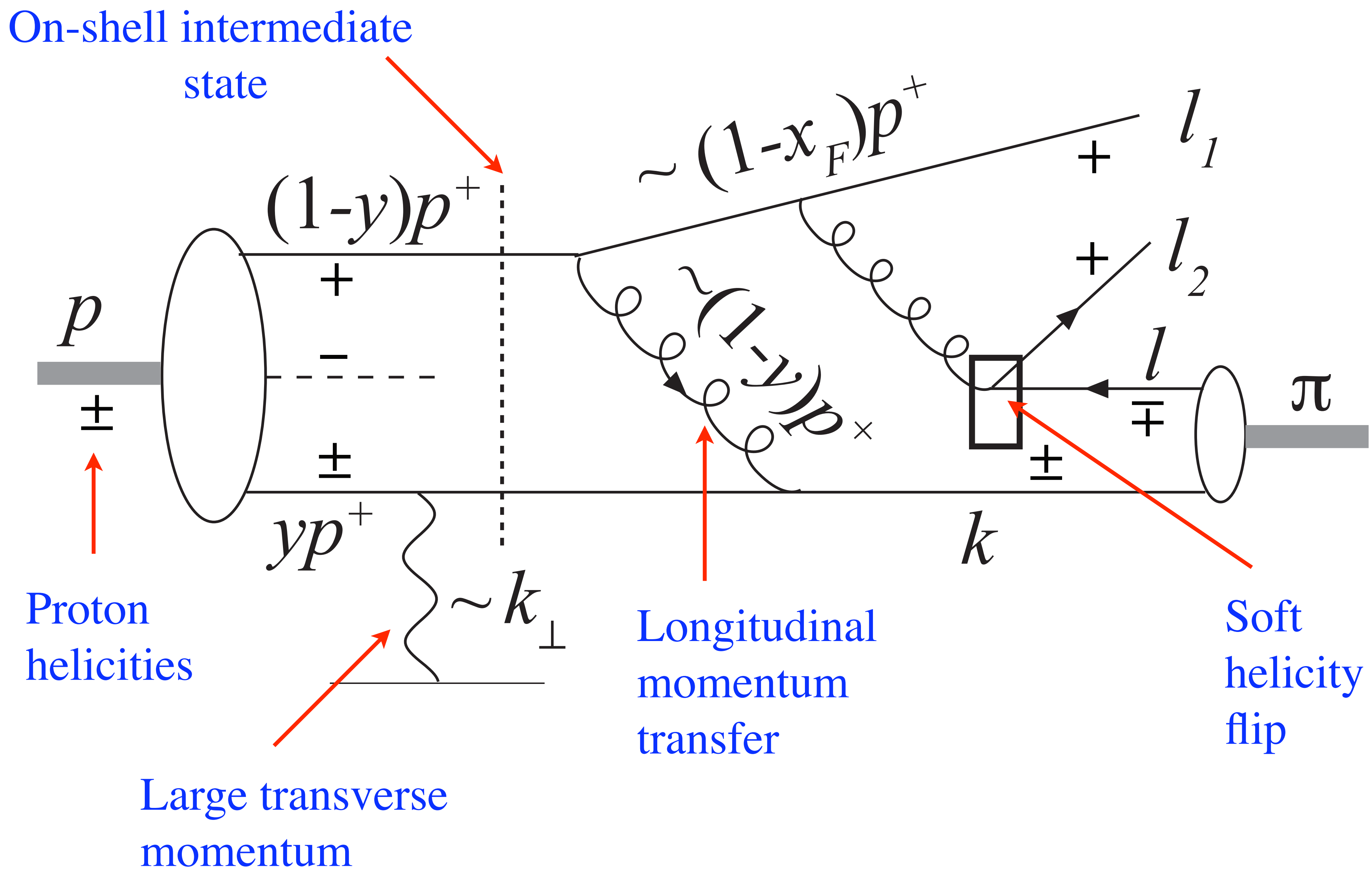


# SSA analysis at fixed $k_\perp^2(1-xF)$

For $k_\perp \to \infty$ at fixed $k_\perp{}^2(1\text{-}x_F)$: soft "spectator" interactions remain coherent with the hard process, enabling unsuppressed spin flip contributions and a helicity dependent phase, as required for $A_N \neq 0$ .



# A Model Demonstration




PH and M. Järvinen, JHEP 0702 (2007) 039

# Remarks

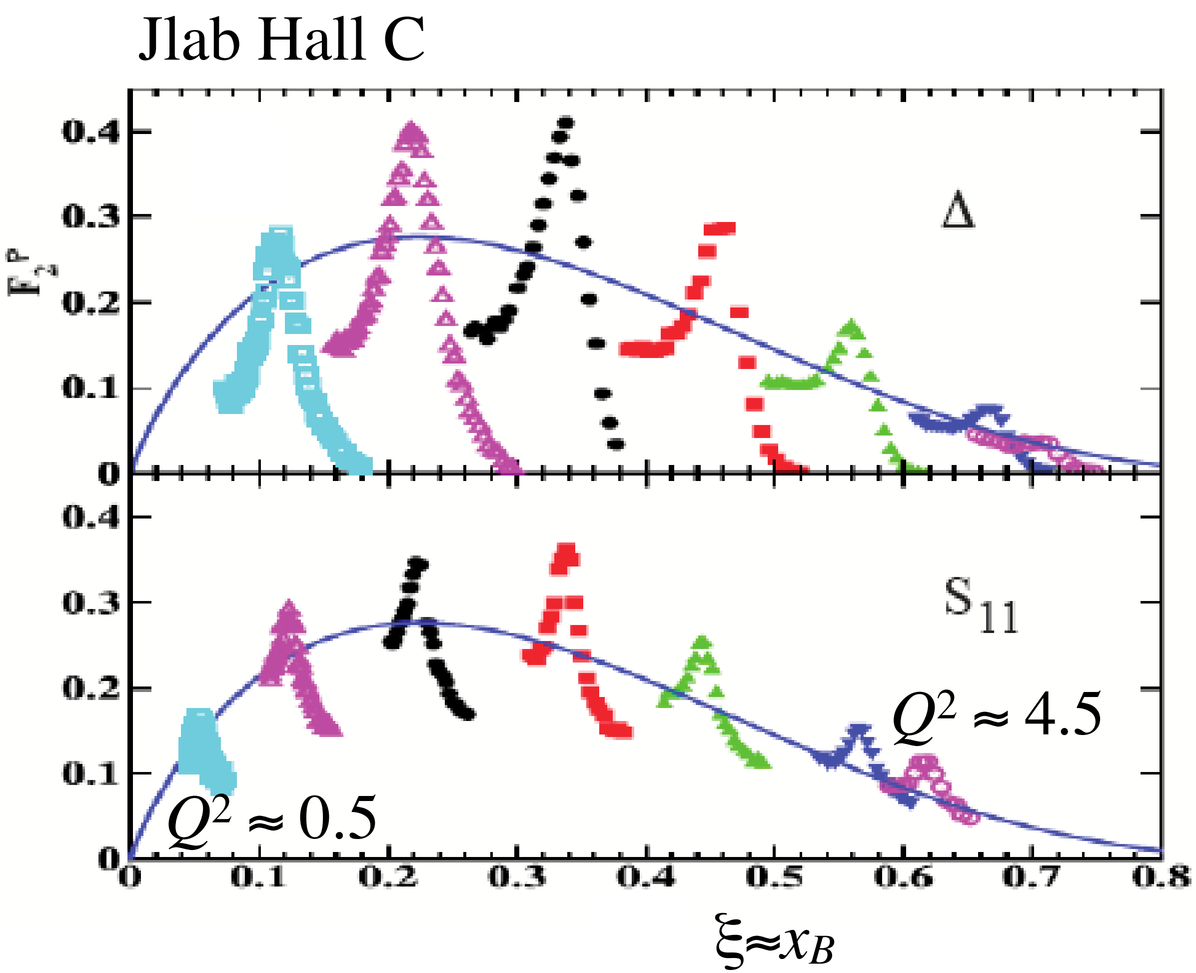
The data suggest that the SSA dynamics of $p^{\uparrow}p \to \pi + X$ and $pp \to \Lambda^{\uparrow} + X$ is distinct from that of $ep^{\uparrow} \to \pi + X$ (SIDIS):

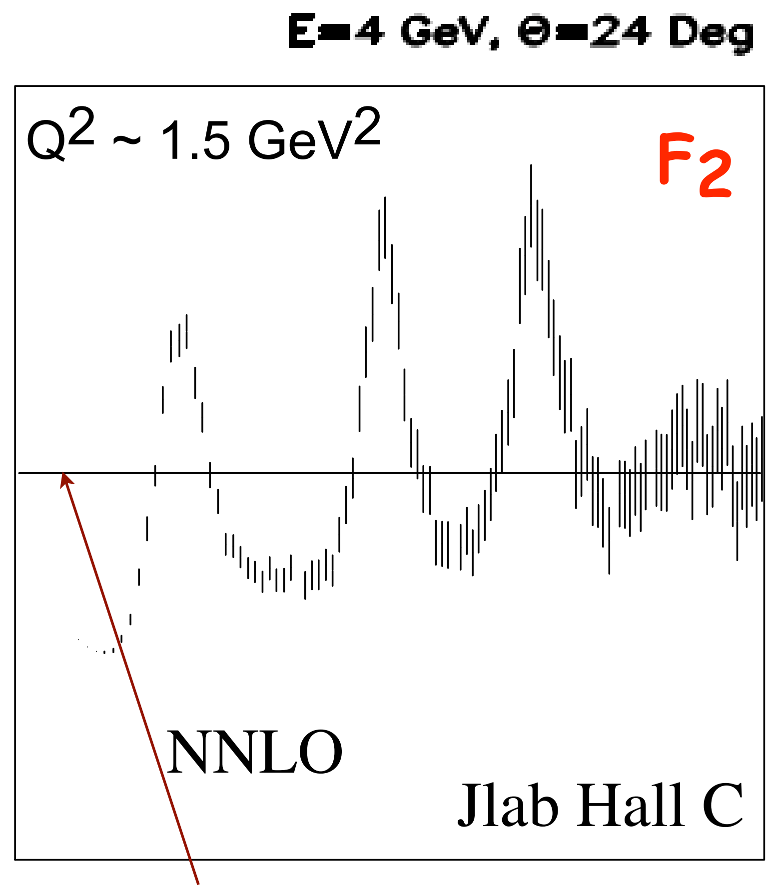
- A leading twist effect requires $A_N \propto 1/k_\perp$
- $A_N$ in $p^{\uparrow}p$ at high $x_F$ is ~ 10 times larger than $A_N$ in SIDIS

Factorization in the limit where $k_\perp^2(1\text{-}x_F)$ is held fixed is not as well studied as at leading twist (fixed $x_F$)

The limit of fixed $k_\perp^2(1\text{-}x_F)$ is (via Bloom-Gilman duality) linked to exclusive processes

# Bloom - Gilman duality



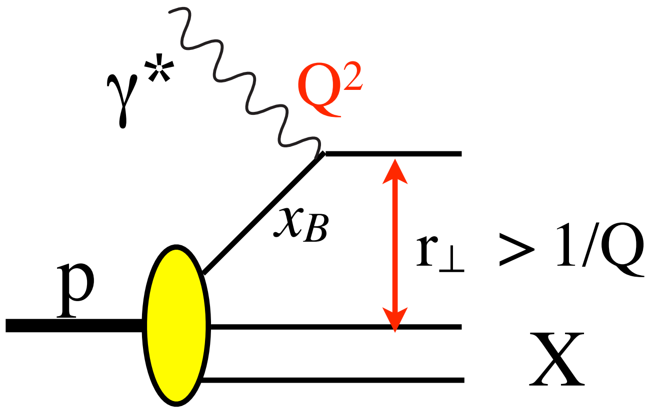




S. Alekhin, PRD 68 (2003) 014002

Duality suggests that the photon scatters from the same target Fock states in ep → eX (DIS) and ep → eN* (FF)

The formation time of resonances in the final state is long and is incoherent with the hard scattering: Unitarity preserves the cross section

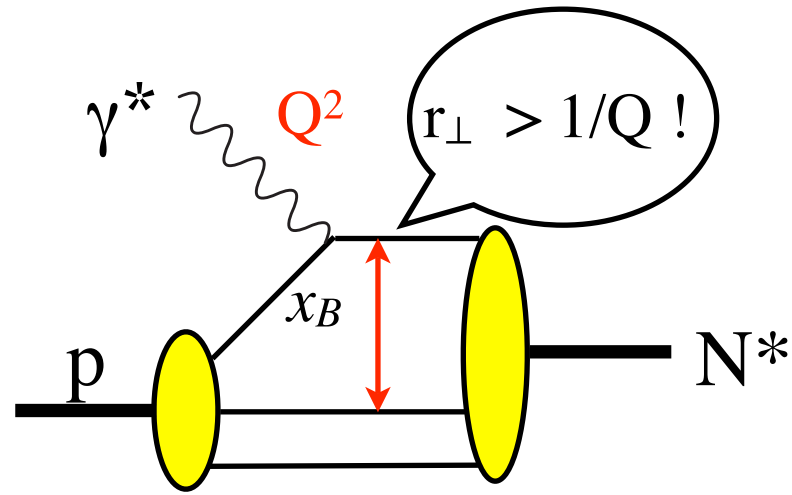
# Consequences of Duality




$e\ p \rightarrow e\ X$

$\approx$

$$\sigma \propto \sum_q e_q^2$$



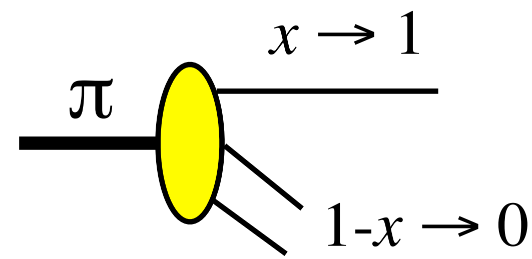

$e\ p \rightarrow e\ N^*$

In the above interpretation of duality, the virtual photon couples incoherently to single quarks in DIS as well as in exclusive form factors

- Endpoint contribution: $1\text{-}x_B \propto 1/Q^2$
- Protons remain noncompact in wide angle scattering
- No color transparency in these processes

# Endpoint behavior of wave functions

Predictions for meson distribution amplitudes:




– Perturbative: $\varphi(x) \sim x(1-x)$

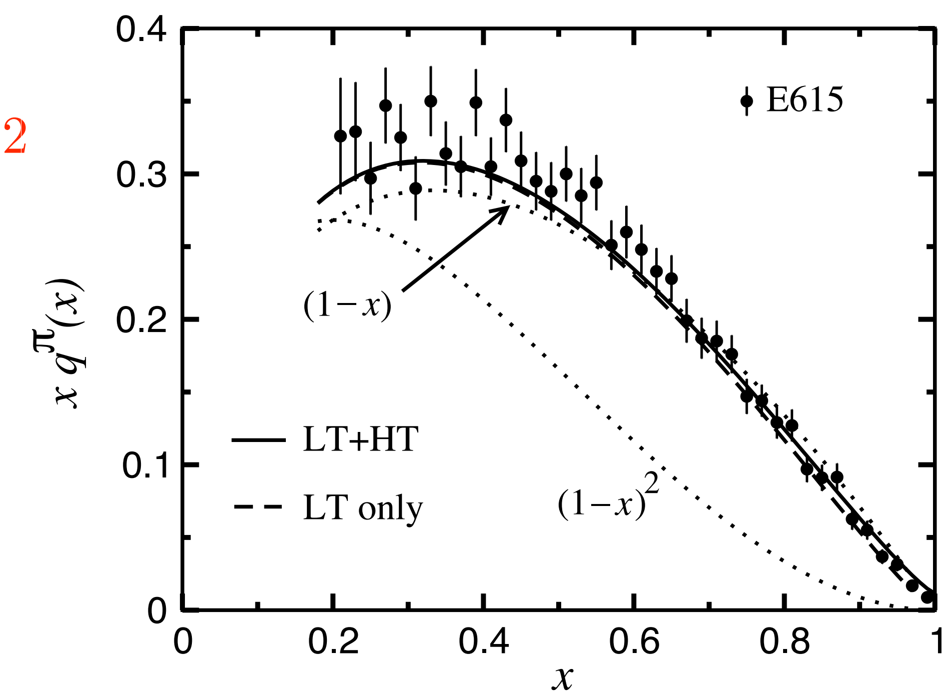
– AdS/CFT: $\varphi(x) \sim \sqrt{x(1-x)}$

S. J. Brodsky and G. F. de Teramond, PRL **96** (2006) 201601

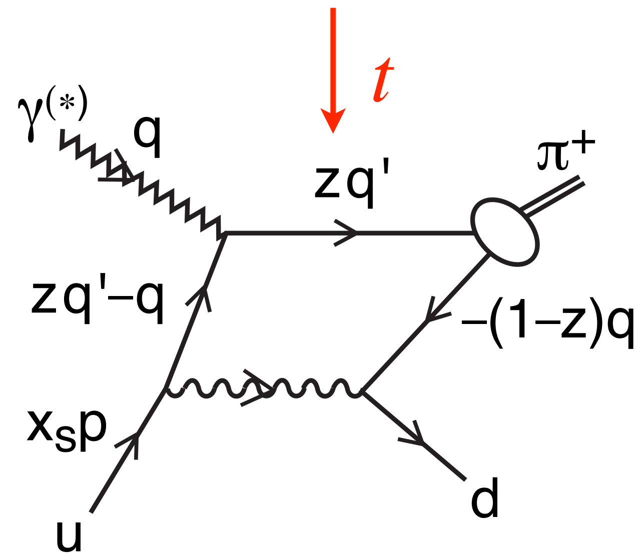
For the quark distribution in the pion:

– Perturbative: $f_{q/\pi}(x) \propto (1-x)^2$

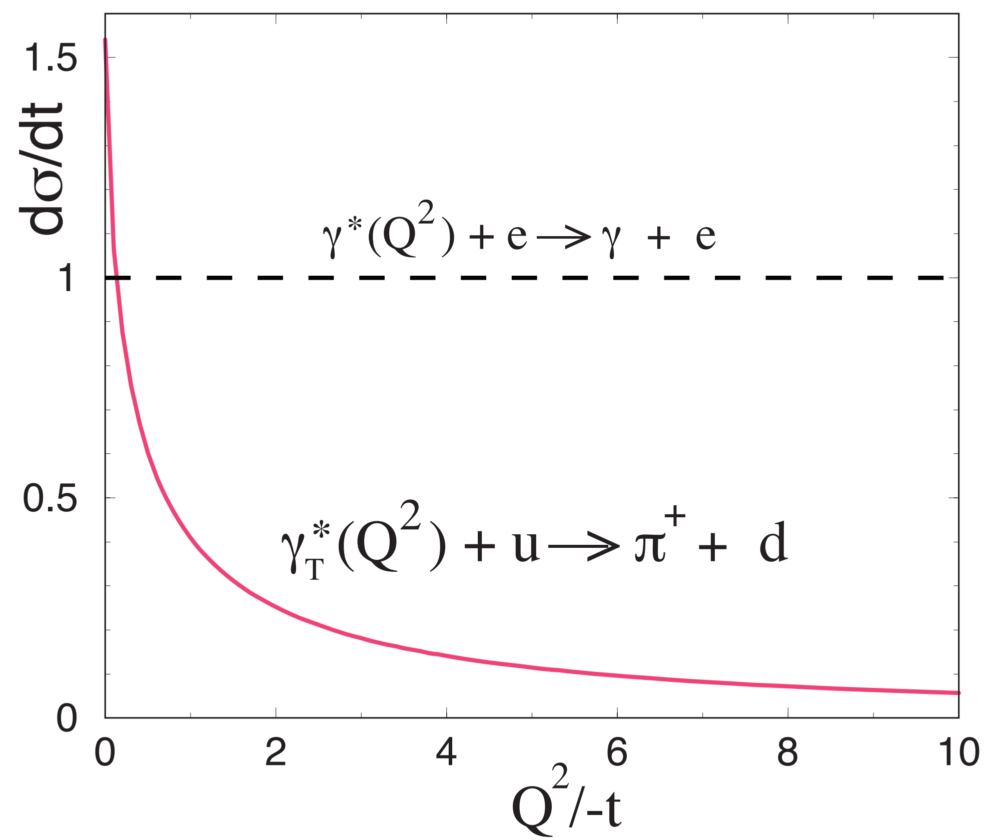
– E615: $f_{q/\pi}(x) \propto (1-x)^{1.2}$



# Size of Perturbative Subprocesses at large t




The effective size of the perturbative photoproduction amplitude for $\gamma + u \to \pi + d$ at large momentum transfer $-t$ is measured by giving the photon a small virtuality $Q^2$



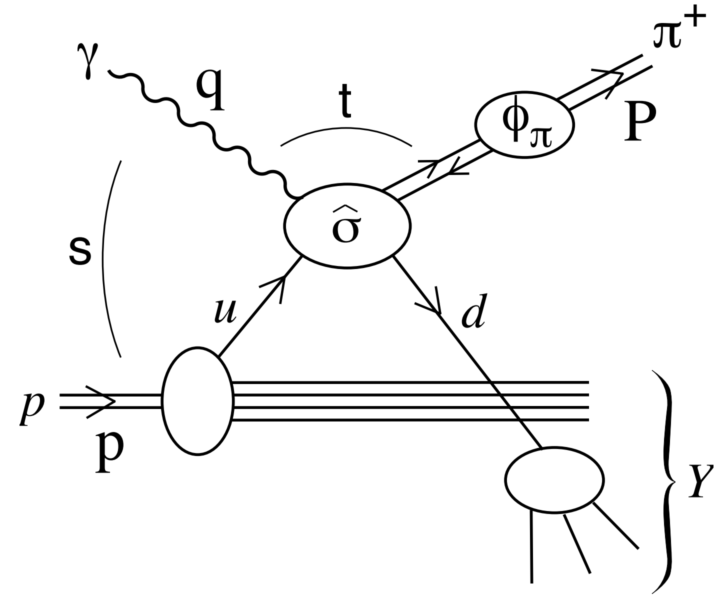

The amplitude is very sensitive to $Q^2$, even for $\varphi_\pi(x) = x(1-x)$

The singular behavior is due to the endpoints. More generally, quark helicity flip and rescattering enhance endpoint contributions

PH, J. T. Lenaghan, K. Tuominen and C. Vogt, PRD **70** (2004) 014001

# Semi-Exclusive Processes

Assuming that the $\gamma + u \to \pi + d$ subprocess is compact at large t, one may predict the semi-exclusive process $\gamma + p \to \pi + Y$ in terms of PQCD and standard parton distributions




C. Carlson, et al
S. J. Brodsky et al

While no data is available on $\gamma + p \to \pi + Y$, one may estimate $\gamma + p \to \pi^+ + n$ with the help of Bloom-Gilman duality. The prediction underestimates the data (also on $\gamma + p \to \gamma + p$) by more than an order of magnitude.

It is likely that the subprocess of semi-exclusive DVES, $\gamma^*(Q^2) + p \to \gamma + Y$ or $\gamma^*(Q^2) + p \to \pi + Y$, is more compact. It would be valuable to obtain such data and compare with the factorized PQCD prediction.

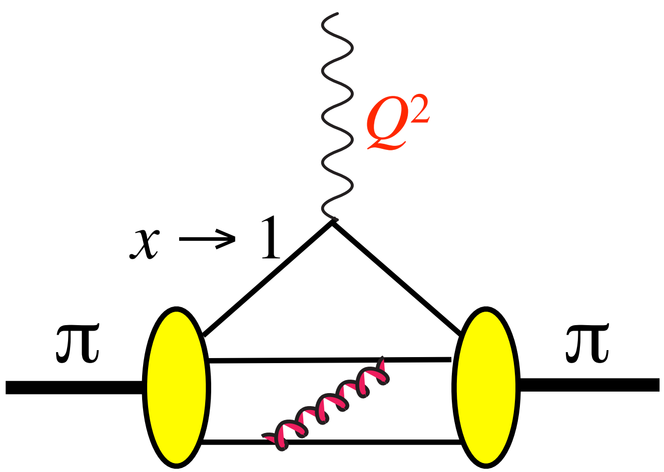
PH and H. Virtanen, PRD **75** (2007) 077502

# Perspective: $Q^2(1\text{-}x)$ fixed?

Bloom-Gilman duality,
FF Phenomenology,
SSA in $p^{\uparrow}p \to \pi + X$,...

Suggest that endpoints ($x \to 0,1$) may be relevant for physical observables

The limit where $Q^2(1\text{-}x)$ is held fixed as $Q^2 \to \infty$ needs more attention:
What can be said about soft/hard factorization in this limit?

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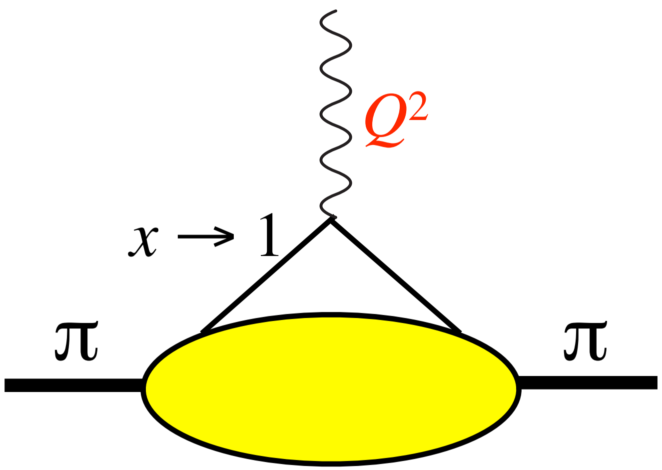


"Spectators" and struck quark have similar $p^-$. Soft spectator interactions cannot be ignored

Form factors cannot be factorized into a product of hadron wave functions