Single Spin Asymmetry at large x_F and k_T

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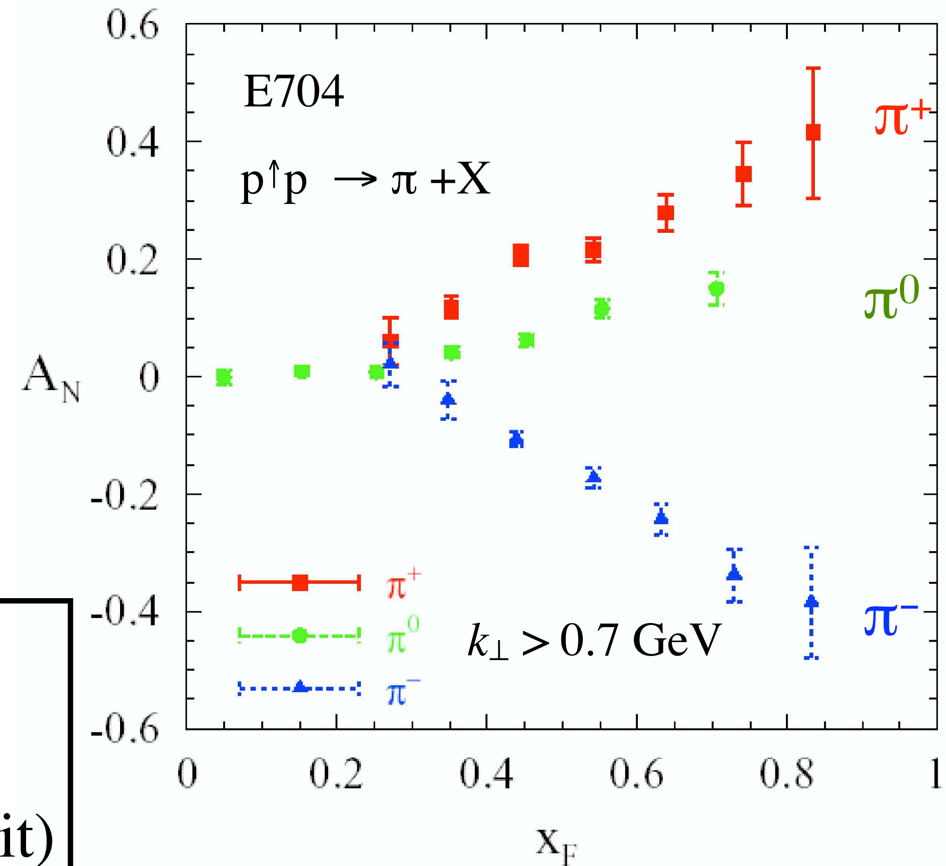
**Workshop on
Transverse momentum, spin, and position
distributions of partons in hadrons**

ECT*, 11 - 15 June 2007

PH and M. Järvinen, JHEP 02 (2007) 039

Question:

Does the large A_N measured in $p^{\uparrow}p \to \pi(x_F, k_T) + X$ at high x_F and k_T arise from multiparton coherence?



Consider two distinct asymptotic limits:

$k_T \to \infty$ with

- x_F fixed (Bj limit)
- $(1-x_F)\,k_T^2$ fixed (BB limit)

Bj limit: Leading twist dominates. Only hard partons are coherent

BB limit: All twists contribute. Coherence between soft and hard partons

Berger – Brodsky

In the BB limit, soft scattering influences the hard dynamics at leading order in k_T.

This enables an unsuppressed single spin asymmetry at high k_T.

Cf. talk by G. Bunce

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^-P^+ of order Q^2 can 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 $x \sim \Lambda^2{}_{QCD}/Q^2$

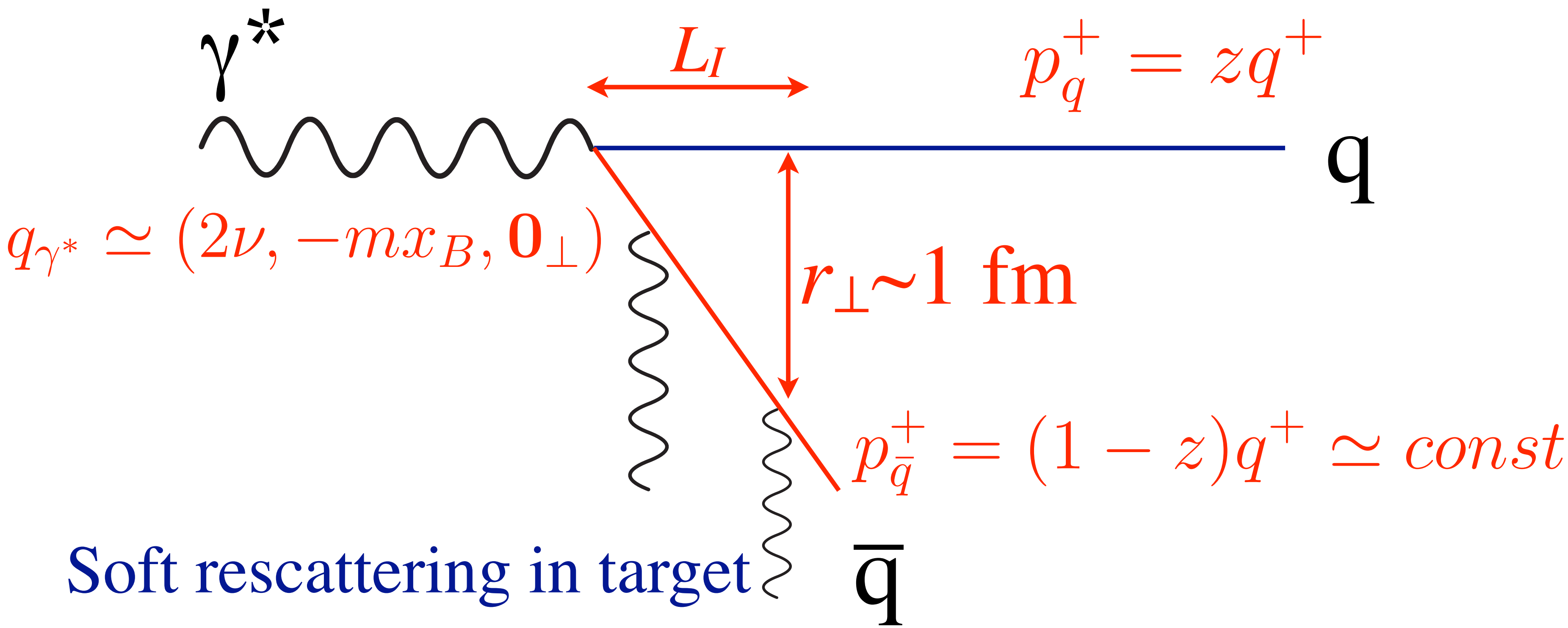
Both give commensurate, short life-times $\sim 1/P^-$

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

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

the full Fock state interacts coherently.

Example: Coherent dynamics of DIS in "lab frame":

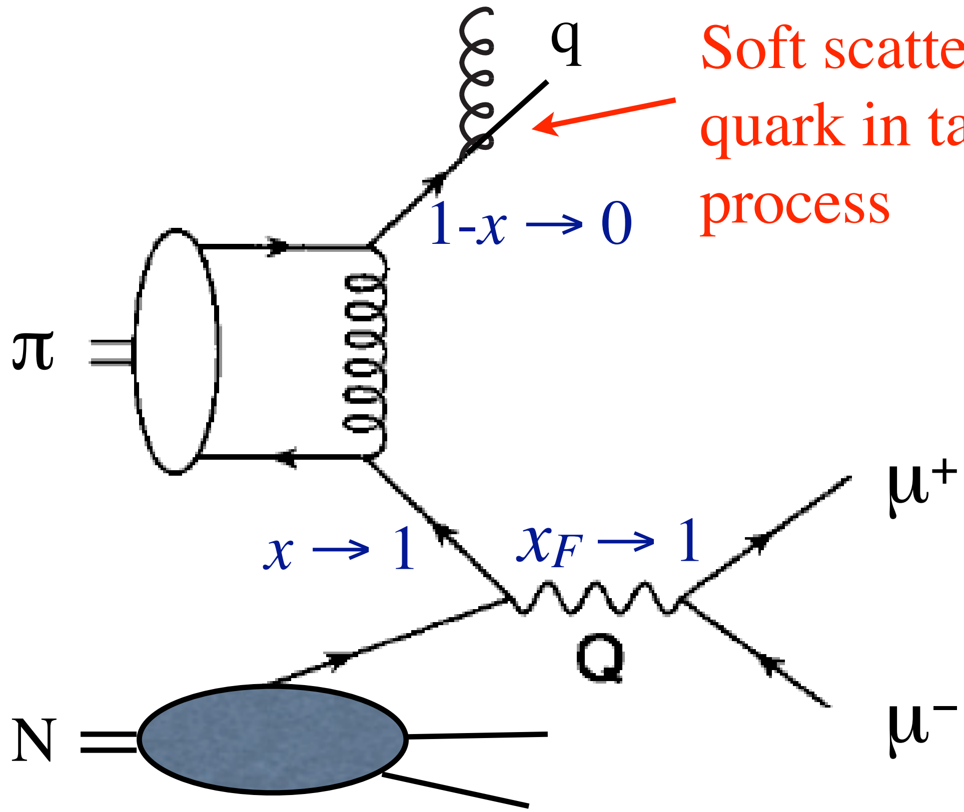


The antiquark takes a fraction $1\text{-}z \propto 1/Q^2$ of the photon energy

Soft scattering of the slow antiquark within $L_I \simeq 1/2mx_B$ is coherent with and determines the cross section of the hard γ* scattering process.

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

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



Soft scattering of stopped quark in target affects hard process

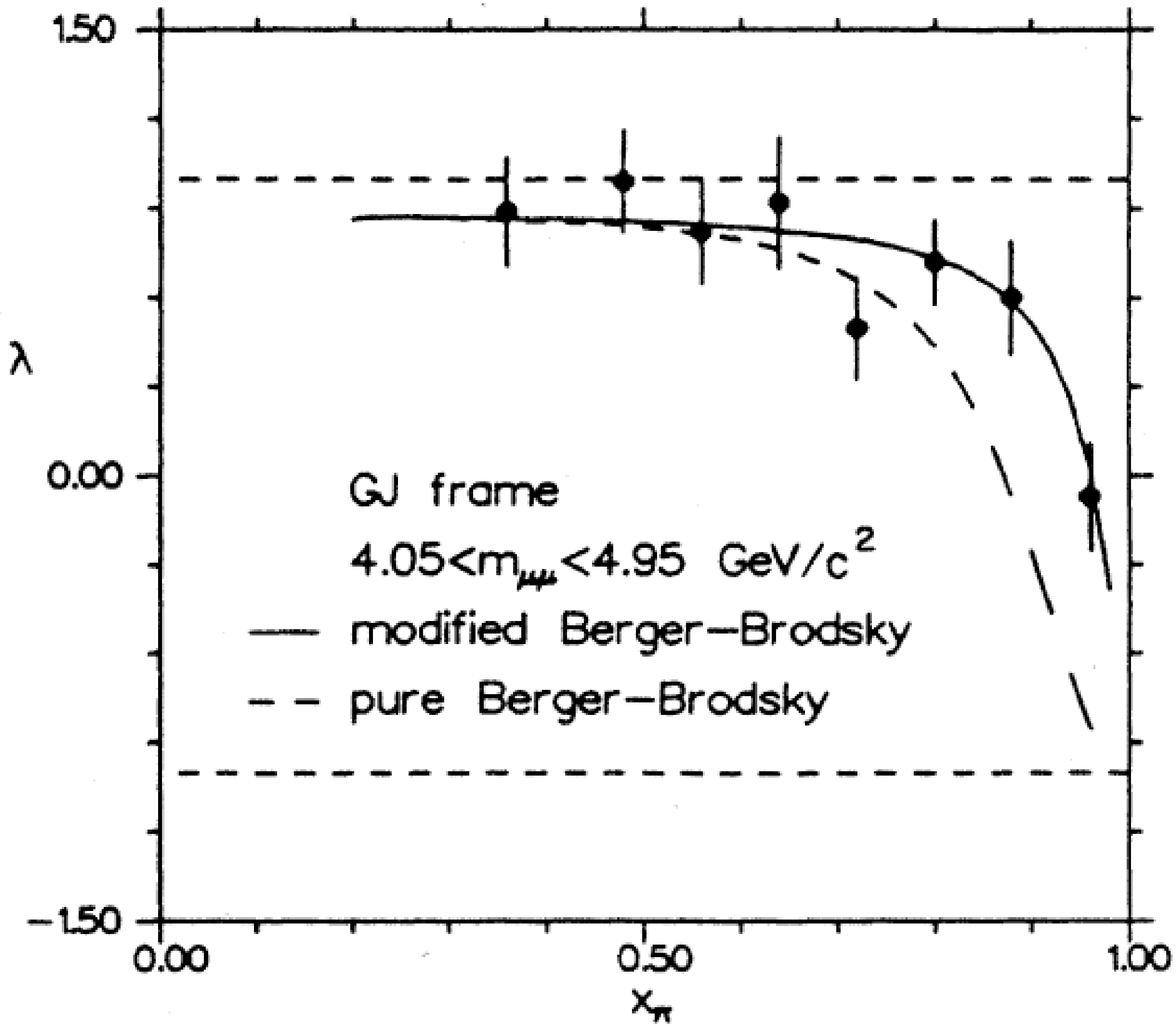
Entire pion wf contributes to hard process

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 $x_F \to 1$

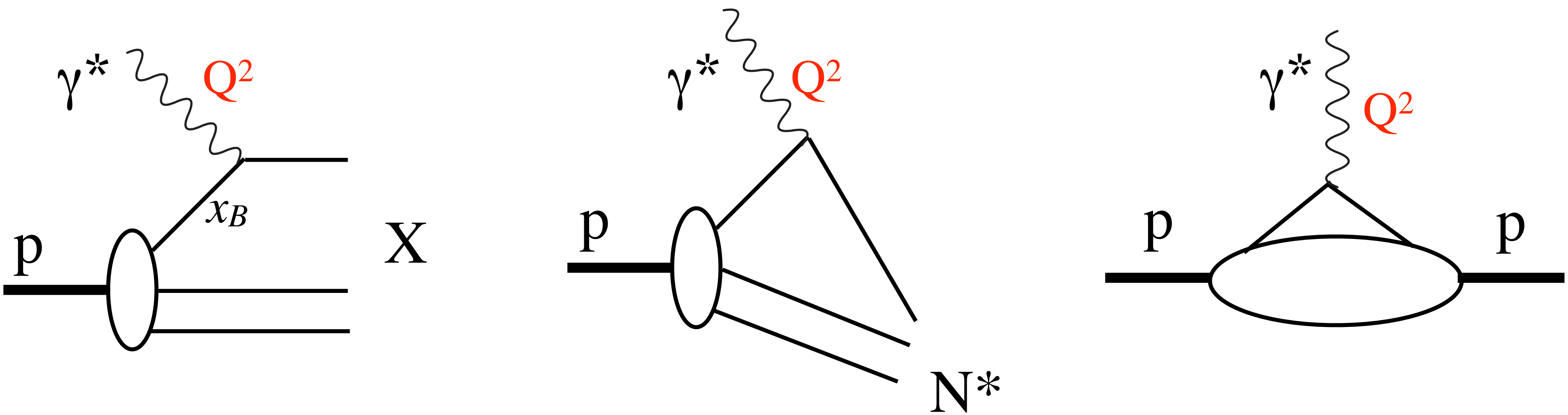
J. S. Conway et al, PRD **39** (1989) 92

The inclusive - exclusive connection

As $x_B \to 1$, inclusive DIS becomes semi-exclusive, and finally exclusive.

This gives insights into the dynamics of inclusive and exclusive processes

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

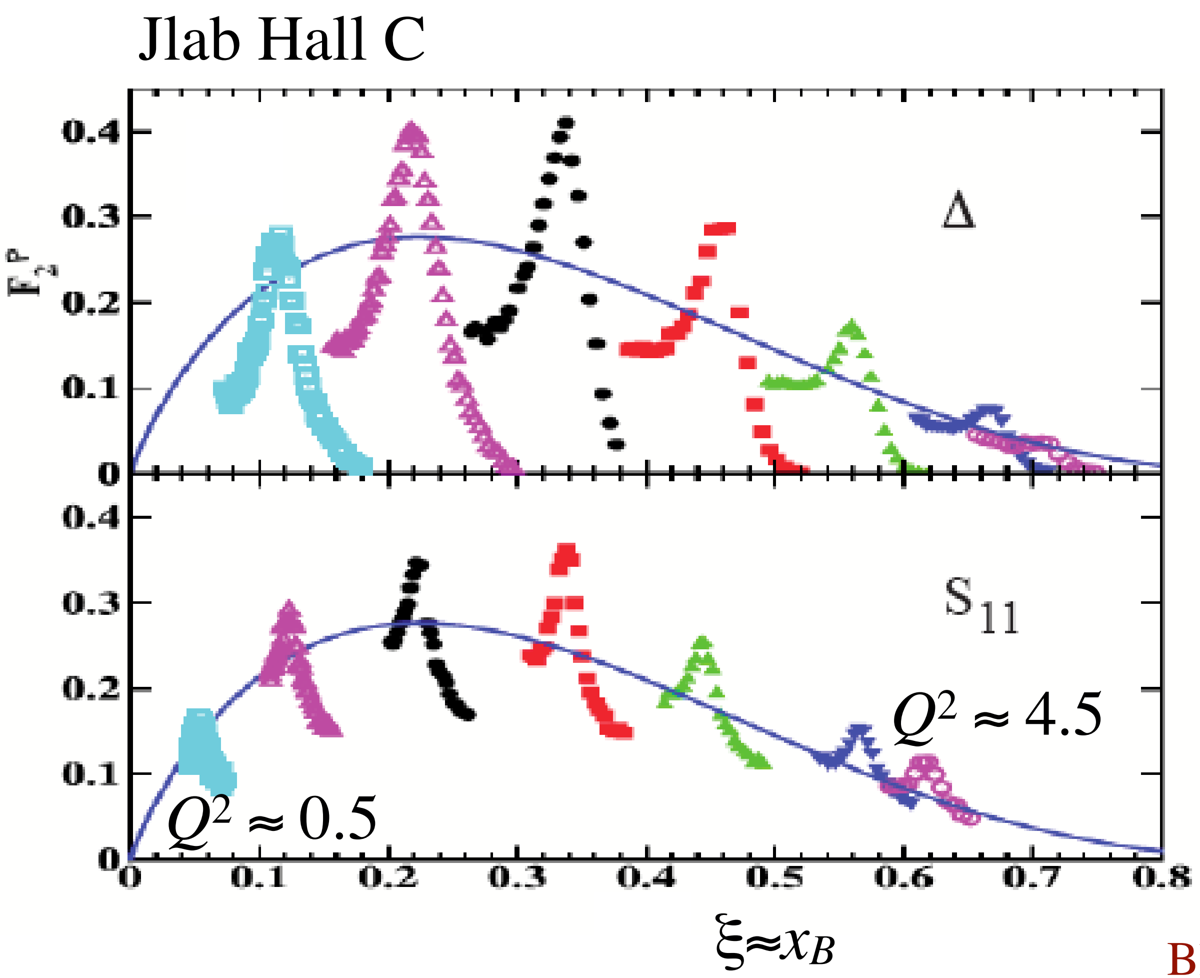


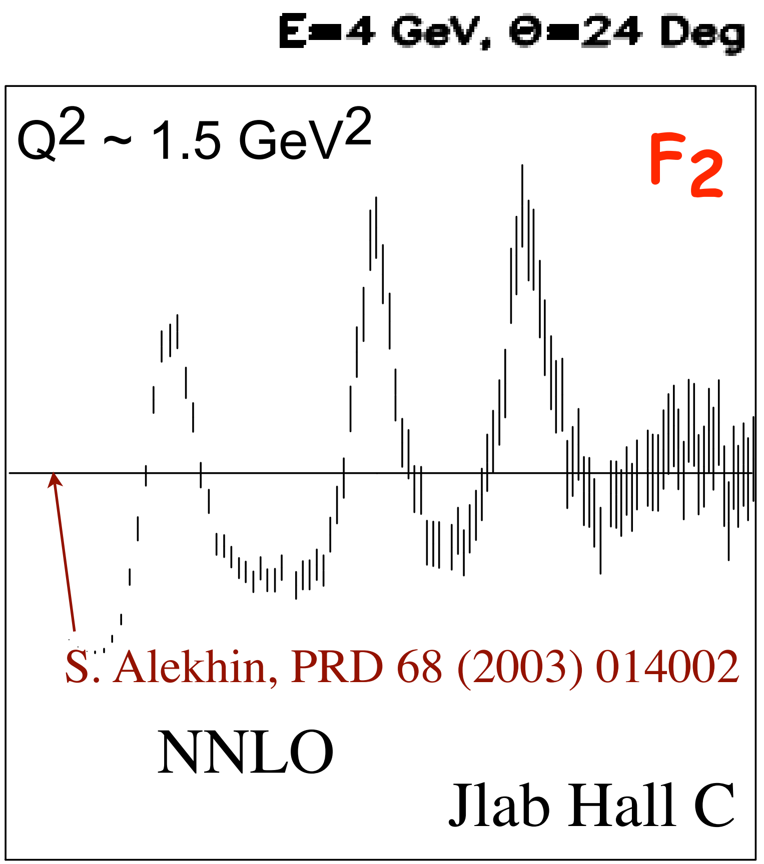
$e\,p \to e\,X$		$e\,p \to e\,N^*$		$e\,p \to e\,p$
DIS	$x_B \to 1$ $\Rightarrow$	Semi-exclusive, or Transition FF	$x_B = 1$ $\Rightarrow$	Elastic FF

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

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

Bloom - Gilman duality





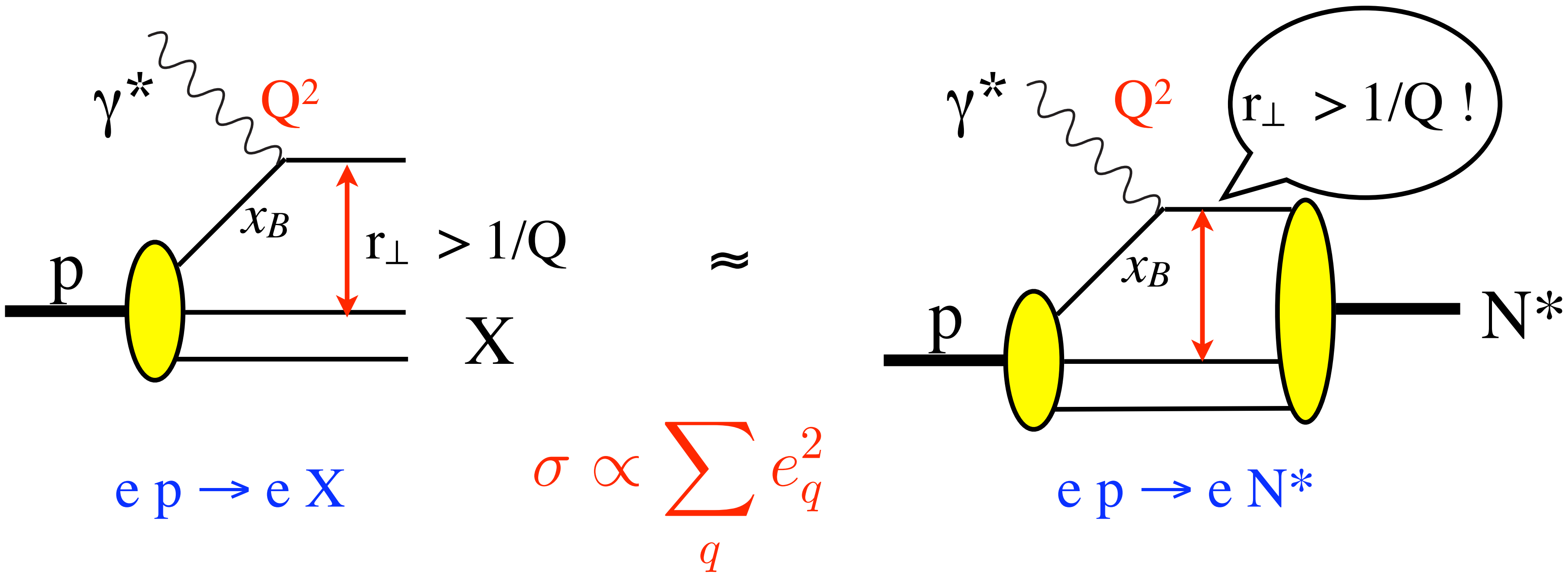
Bloom and Gilman, PRL **25** (1970) 1140

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

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



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

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 for ep → ep in nuclear targets

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, helicity-dependent phase
- Helicity flip

In hard perturbative diagrams both features are suppressed

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

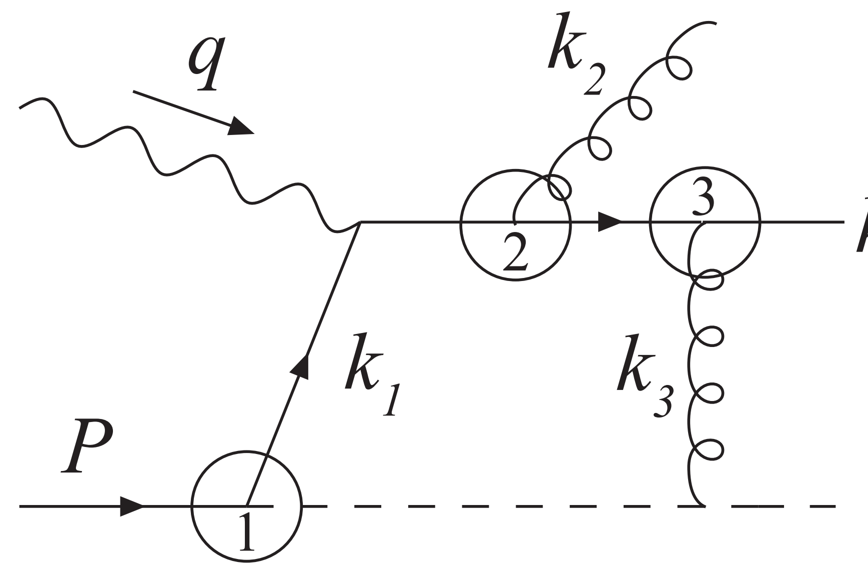
Hence the observed A_N reveals important aspects of the dynamics of scattering at large transverse momentum

SSA suppression at high k_T: The BHS model

The helicity may flip at either of the vertices 1, 2 or 3.

– If the large k_T is generated at the flip vertex, $A_N \propto m_q/k_T$, where m_q is the current quark mass

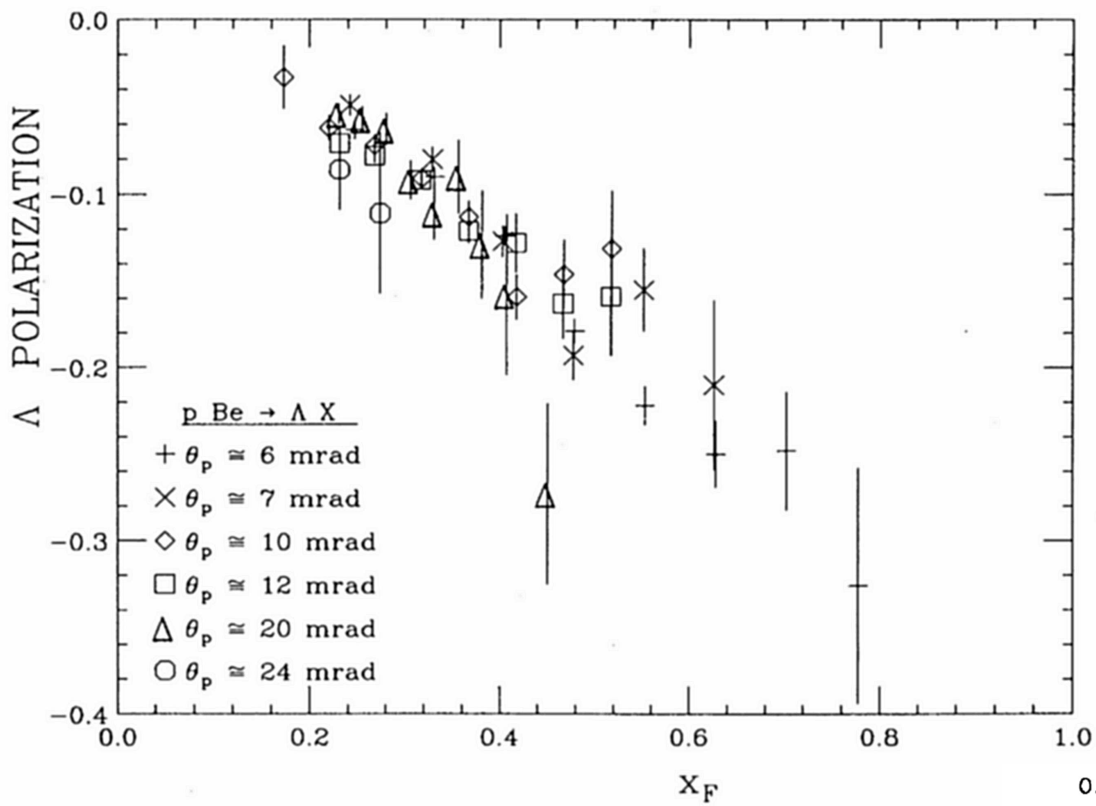
– Flip at 1, large k_T at 2: Due to incoherence, $A_N \propto \Lambda_{QCD}/k_T$, from trigger bias (Sivers effect)



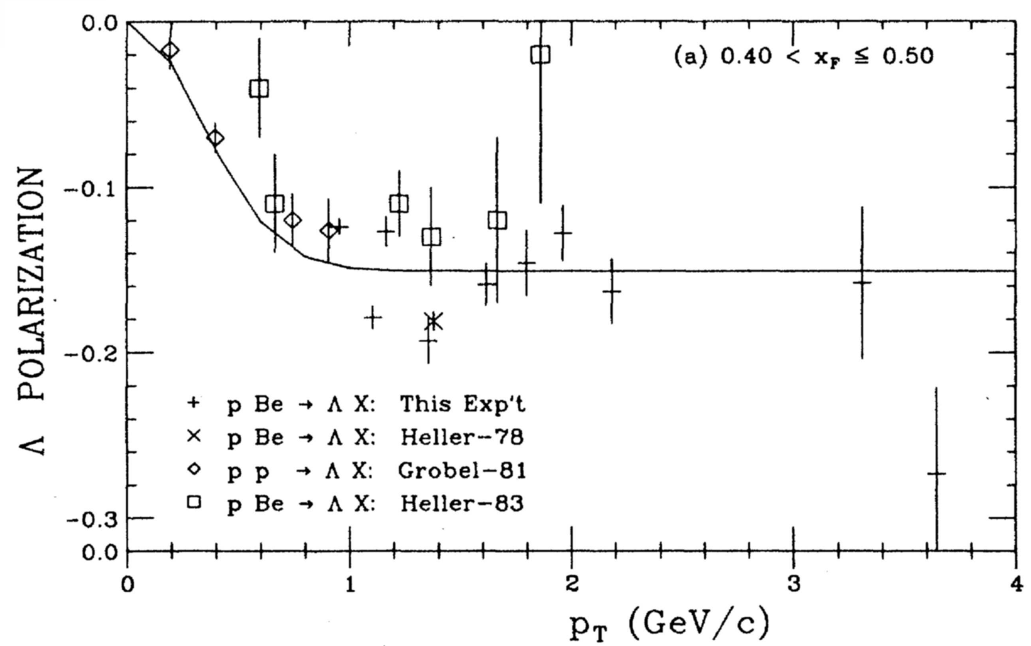
– Flip at 3, large k_T at 2: $A_N \propto m_q/\nu$, anomalous moment of bare quark is not formed (perturbatively) within coherence time. (This might possibly be upset due to QCD vacuum effects, see PH and M. Järvinen, JHEP 10 (2005) 080)

Similar arguments for $p^\uparrow p \to \pi(x_F, k_T) + X$ give $A_N \propto \Lambda_{QCD}/k_T$ for $k_T \to \infty$ at fixed x_F (twist-3 in the Bj limit).

p p → $\Lambda(x_F, k_\perp)$ +X



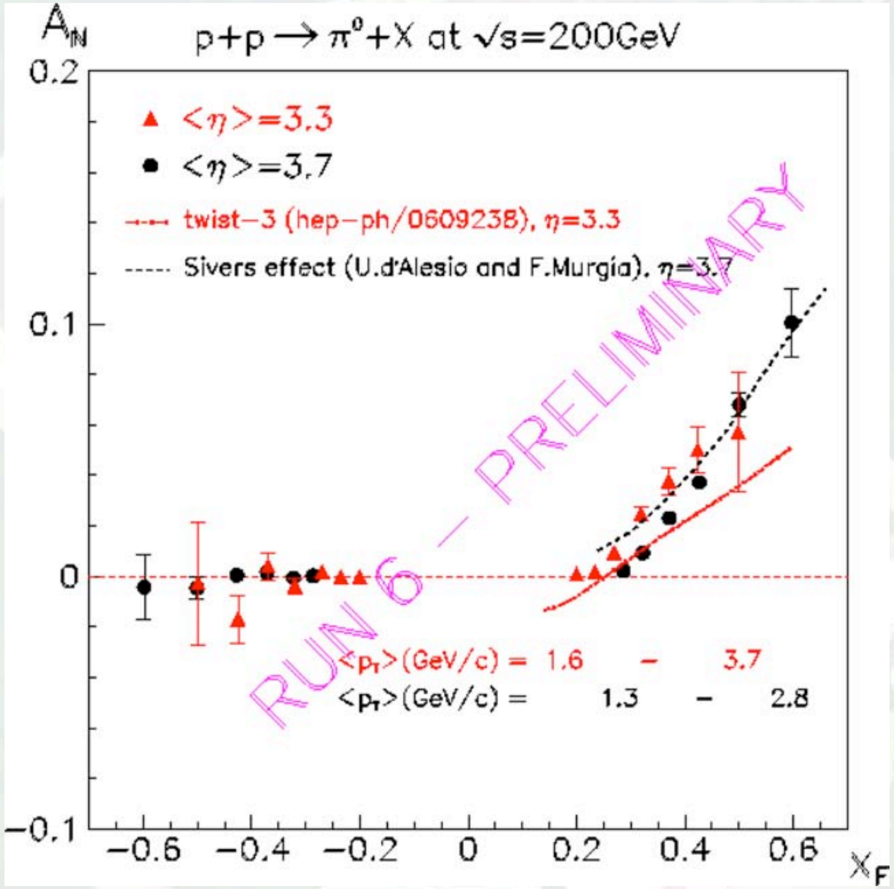
Lundberg et al., PRD **40** (1989) 3557

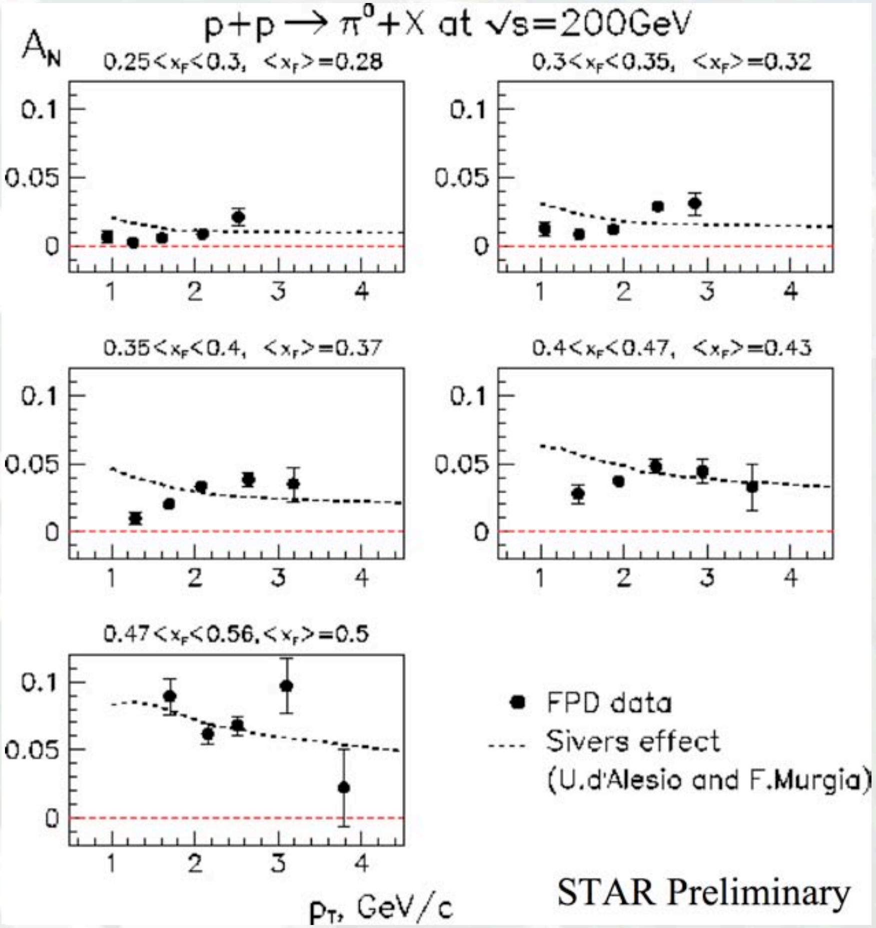


STAR transverse spin program - Recent results

- A_N measurement as a function of x_F and p_T

L. Nogach (IHEP-Protvino)



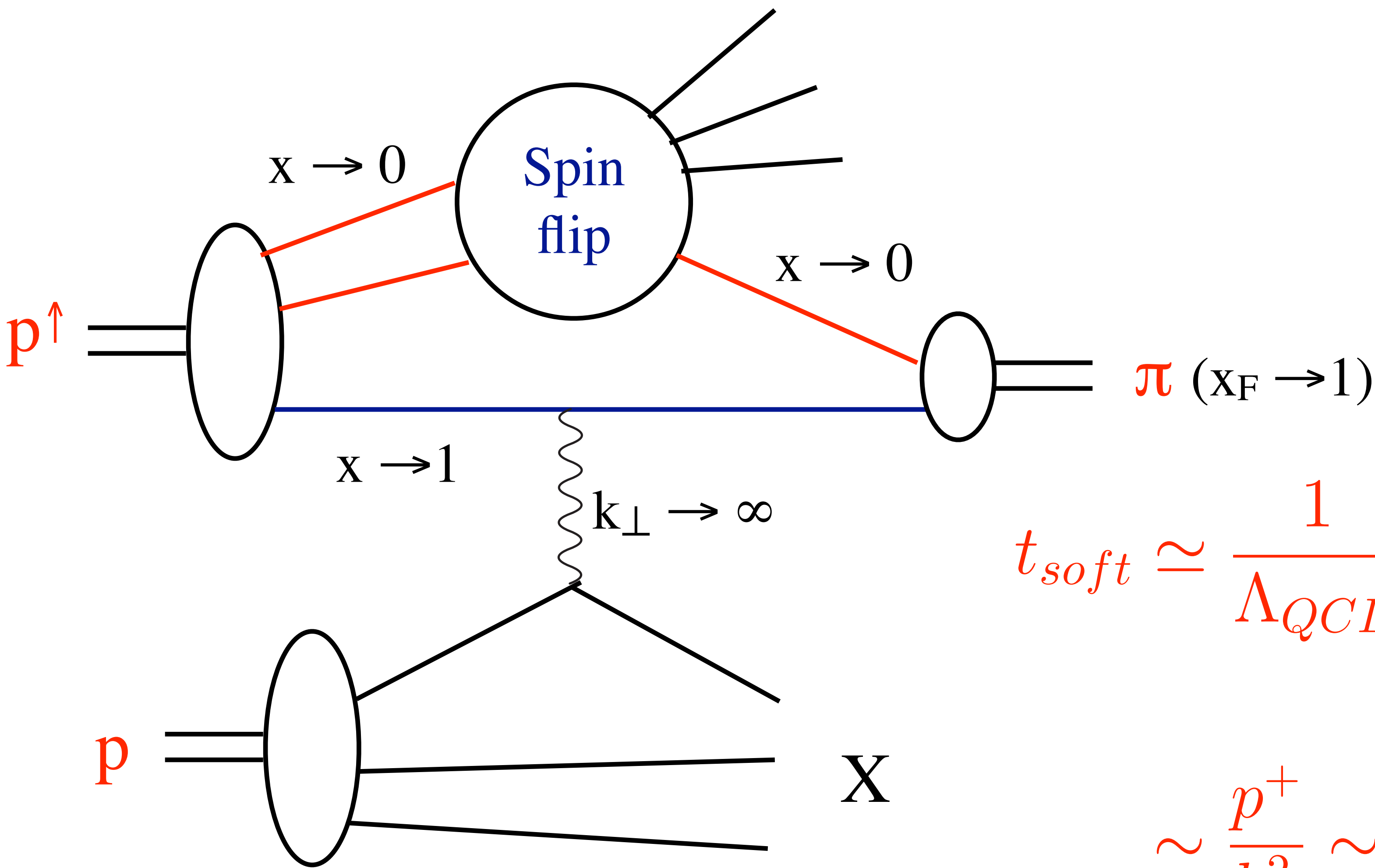


- Run 6 results consistent with previous results
- A_N calculations (Sivers / Twist-3) inconsistent with precise x_F dependence of measured A_N

- 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

SSA analysis at fixed $k_\perp^2(1\text{-}xF)$

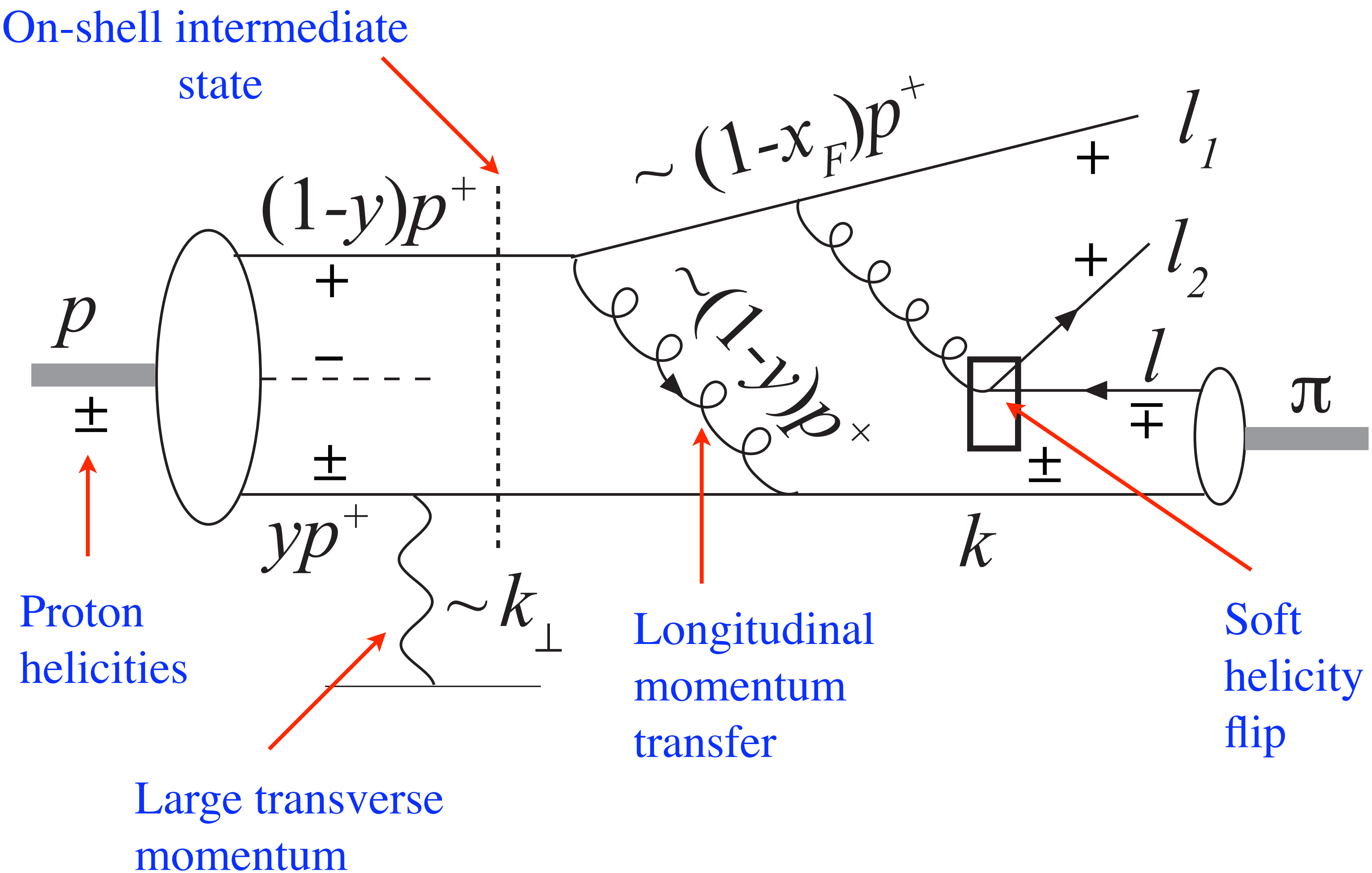
For $k_\perp \to \infty$ at fixed $k_\perp{}^2(1\text{-}x_F)$: soft "spectator" interactions remain coherent with the hard process, enabling unsuppressed spin flip contributions and a helicity dependent phase, as required for $A_N \neq 0$.



$$t_{soft} \simeq \frac{1}{\Lambda_{QCD}} \frac{(1-x_F)p^+}{\Lambda_{QCD}}$$

$$\sim \frac{p^+}{k_\perp^2} \sim \frac{1}{k_\perp}\frac{p^+}{k_\perp} \simeq t_{hard}$$

A Model Demonstration



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

Phase difference between flip and non-flip amplitudes

A non-vanishing SSA requires a phase difference $\exp(i\theta)$ between the helicity flip and non-flip amplitudes. In the above Feynman diagram, after some simplifying assumptions,

$$\tan\theta = \frac{\sqrt{AB}}{A+2B}$$, which vanishes if either A/B or B/A → 0 and where

$$A = \frac{\ell_{2\perp}^2 + M^2}{(1-w)(1-x)} + \frac{\ell_\perp^2 + M^2}{1-z}$$

$$B = k_\perp^2$$

This verifies that $A_N \neq 0$ only in the BB limit: $k_\perp^2(1-x) \sim fixed$

Conclusions on SSA

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

These features suggest a limit where $k_\perp^2(1-x_F)$ is fixed as $k_\perp \to \infty$

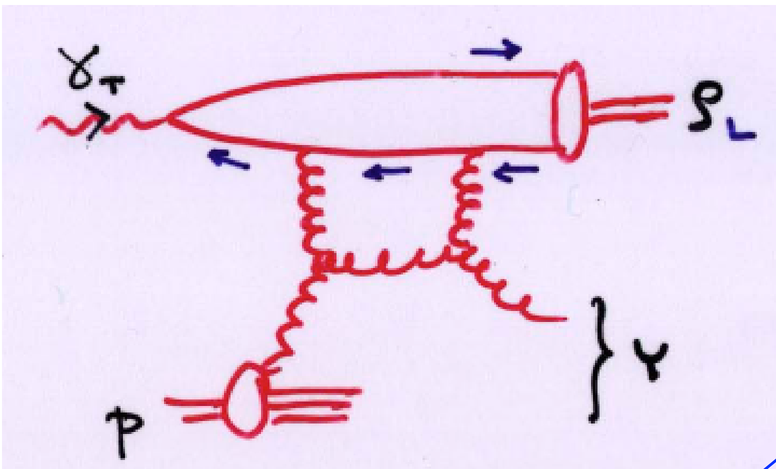
The SSA in $p^{\uparrow}p$ is an edge-of-phase-space effect

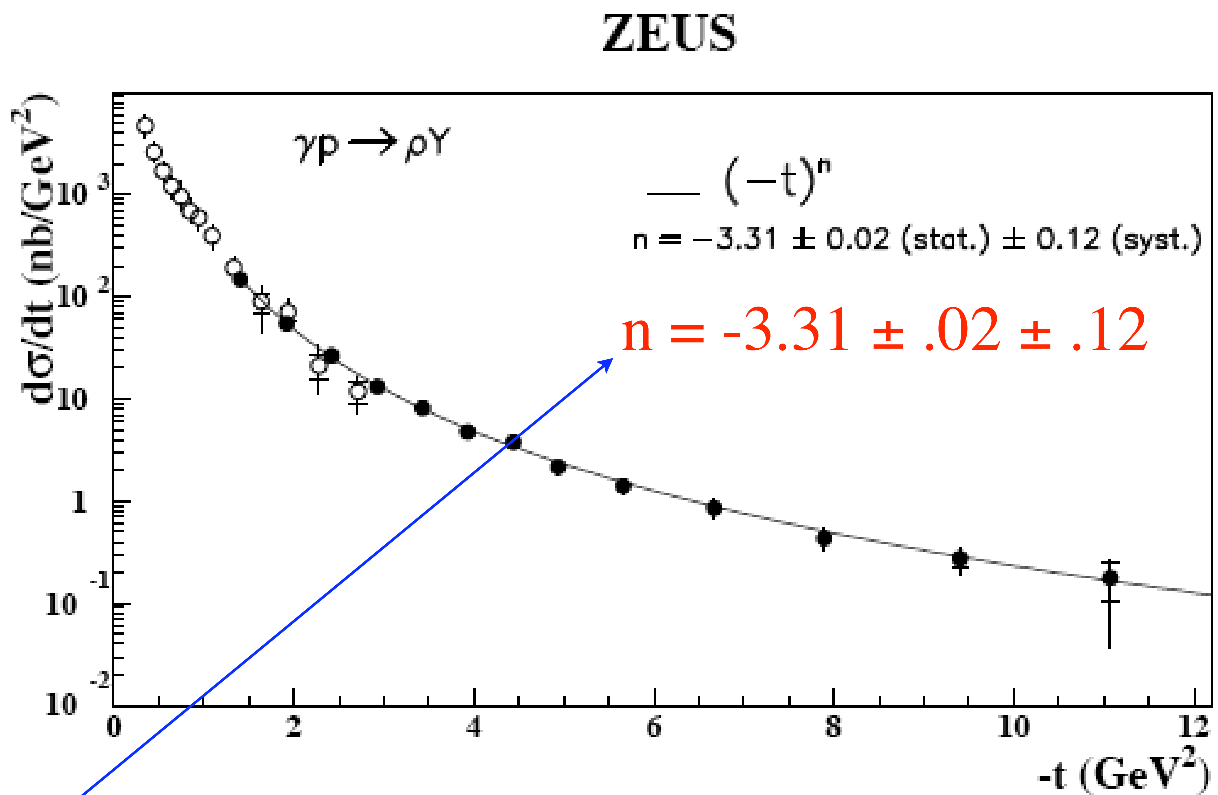
Cf. talk by G. Bunce

Via Bloom-Gilman duality, this dynamics is relevant also for hard exclusive processes

Quark helicity flip in γp → ρ Y

Partonic subprocess in perturbative QCD:





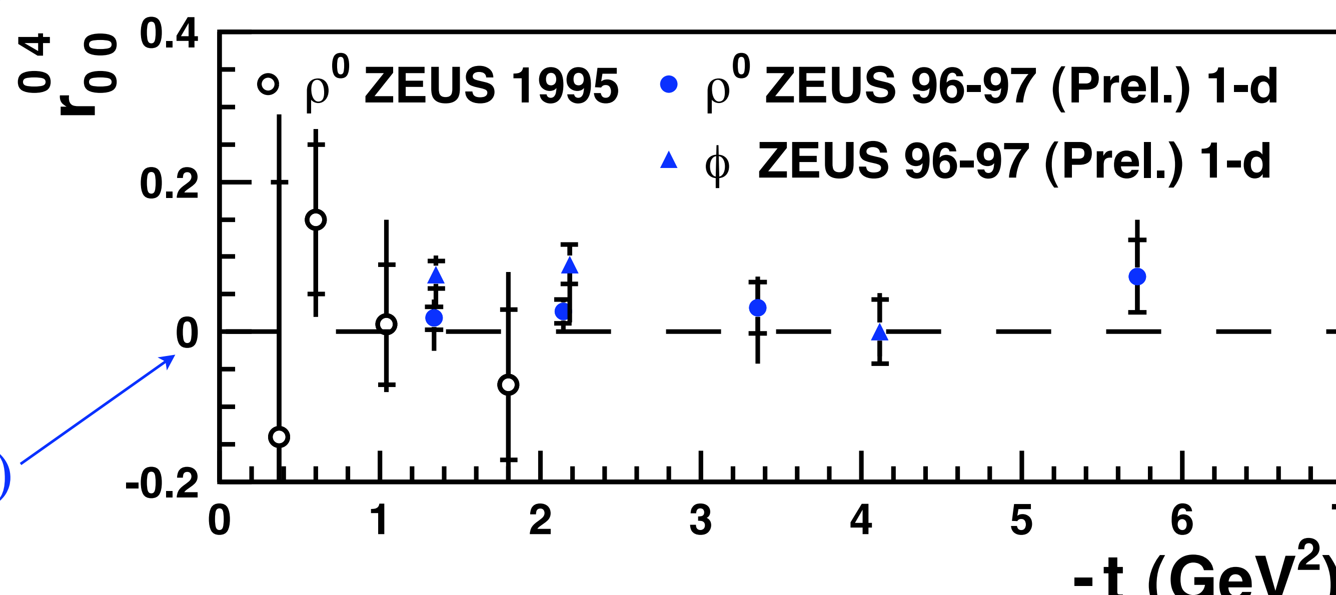
n = -3.31 ± .02 ± .12

Expect: $\frac{d\sigma}{dt} \propto \frac{1}{t^3}$

and $\lambda_\rho = 0$

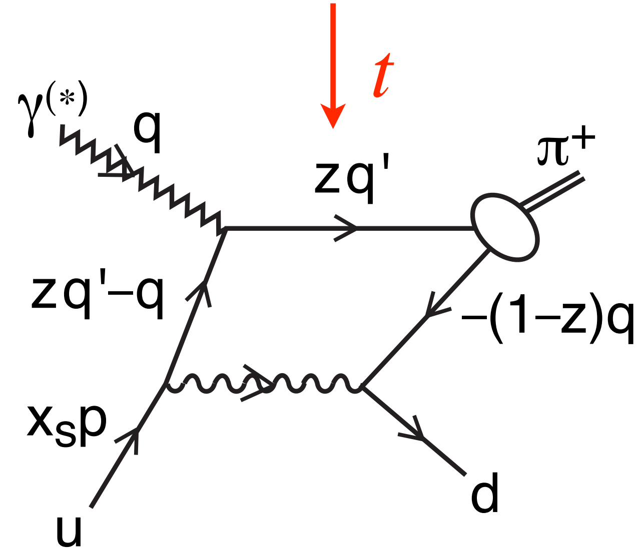
but find $\lambda_\rho = \pm 1$ (SCHC)

γp –> ρY ZEUS $r^{04}_{00} \propto |T(\lambda_\rho = 0)|^2$

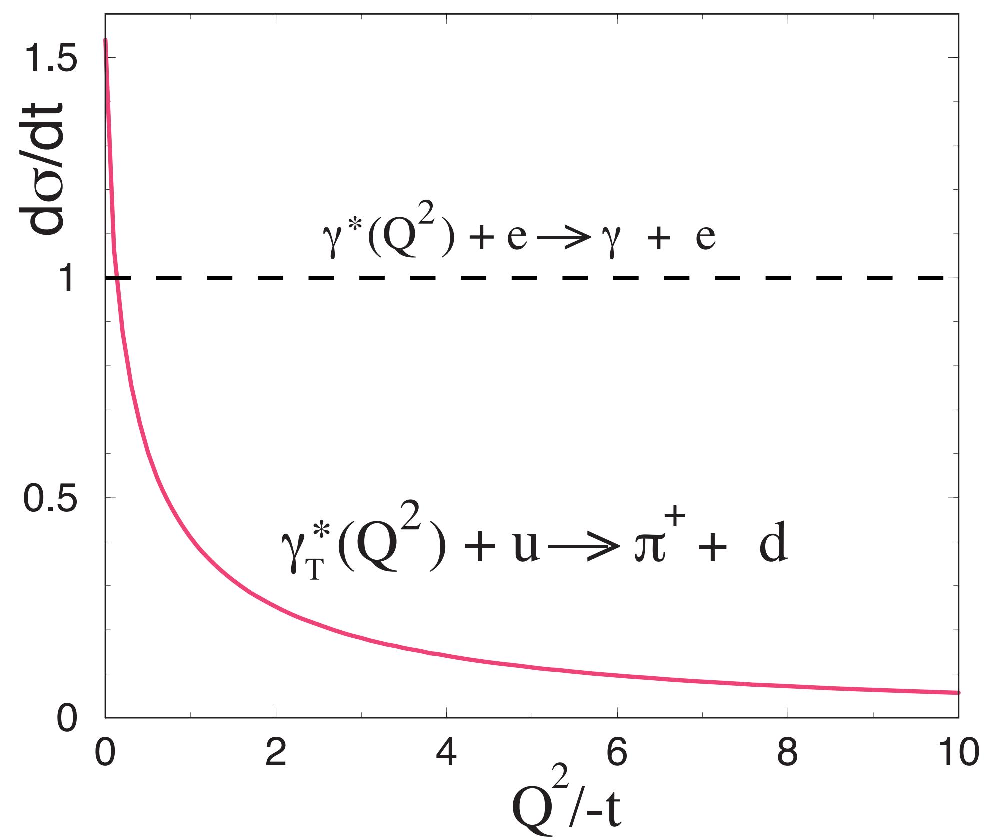


Size of Perturbative Subprocesses at large t

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

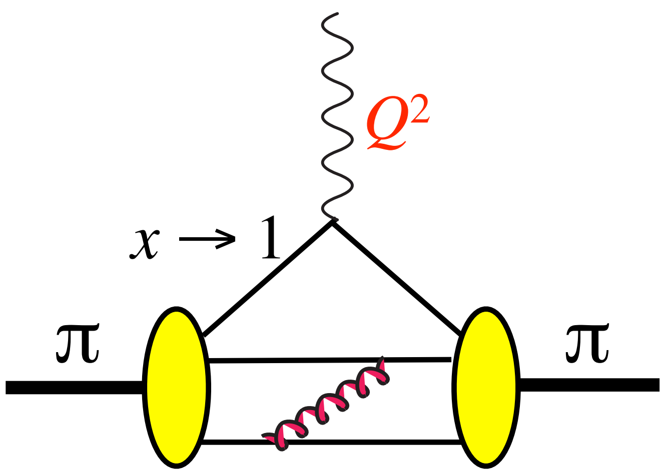
PH, J. T. Lenaghan, K. Tuominen and C. Vogt, PRD **70** (2004) 014001

Perspective: $Q^2(1-x)$ fixed?

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

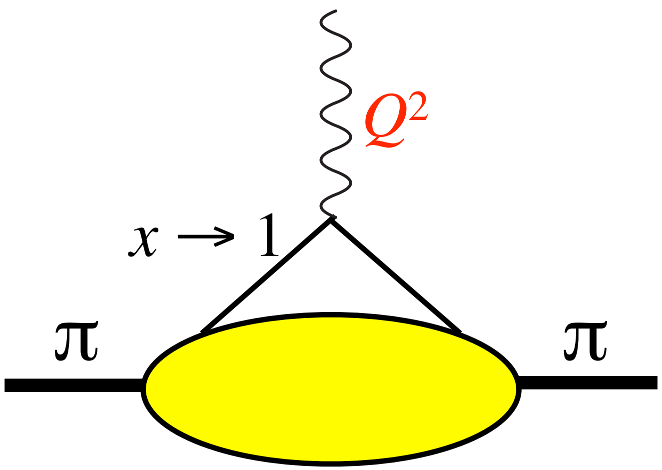
Suggest that endpoints ($x \rightarrow 0,1$) may be relevant for physical observables

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



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

$\Rightarrow$



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