Rescattering effects in DIS

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With acknowledgements to my collaborators:

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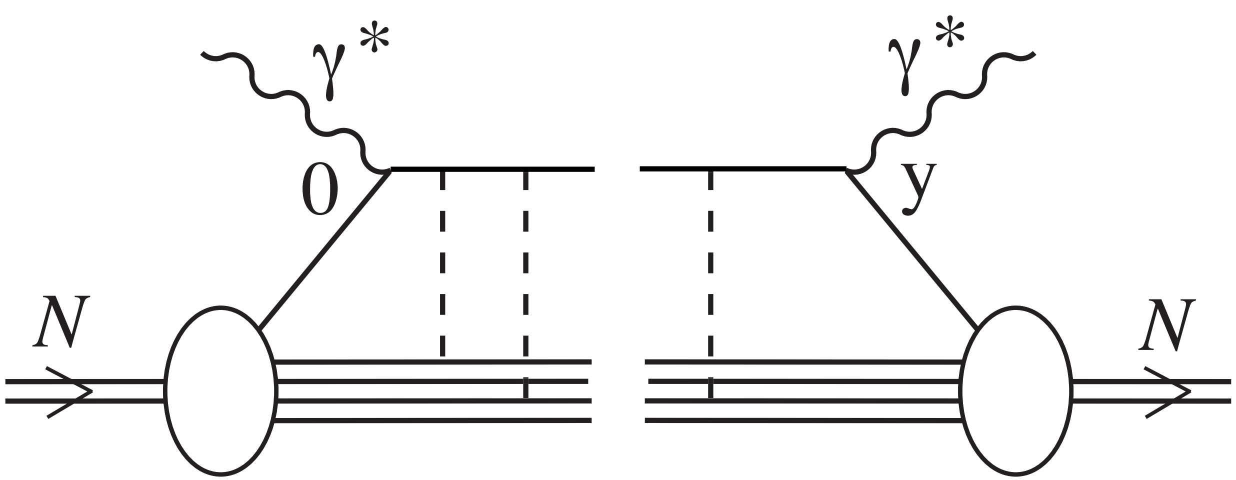
Parton distributions are non-local

Inclusive parton distributions are given by matrix elements, e.g.,

$$f_{q/N}(x_B, Q^2) = \frac{1}{8\pi}\int dx^- e^{-ix_B p^+ x^-/2} \langle N(p)|\bar{q}(x^-)\gamma^+ W[x^-,0]q(0)|N(p)\rangle_{x^+=0}$$

where the Wilson line $\quad W[x^-,0] \equiv \mathrm{P}\exp\left[\frac{ig}{2}\int_0^{x^-} dw^- A^+(w^-)\right]$

ensures gauge invariance and
arises from rescattering of the struck quark on target spectators:



The intermediate states between rescatterings can be on-shell

$\Rightarrow$ Complex phases, giving rise to observable effects in DIS:

Shadowing, Diffraction and

Single Spin Asymmetries (in SIDIS)

Brodsky, Hwang, Schmidt
Collins

How can soft rescattering be coherent with a hard process ($Q^2 \to \infty$)?

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

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

And because in gauge theories

- Coulomb (A^+) exchange is "instantaneous"
- Amplitude for scattering off target spectators is $\propto \nu$.

The struck quark senses the color field along its path out of the target.
Due to coherence, these interactions affect the DIS cross section.

Three remarks:

1. Soft rescattering 'sees' only the color charge of struck parton (q or g).

   It is independent of the hard subprocess. E.g.:

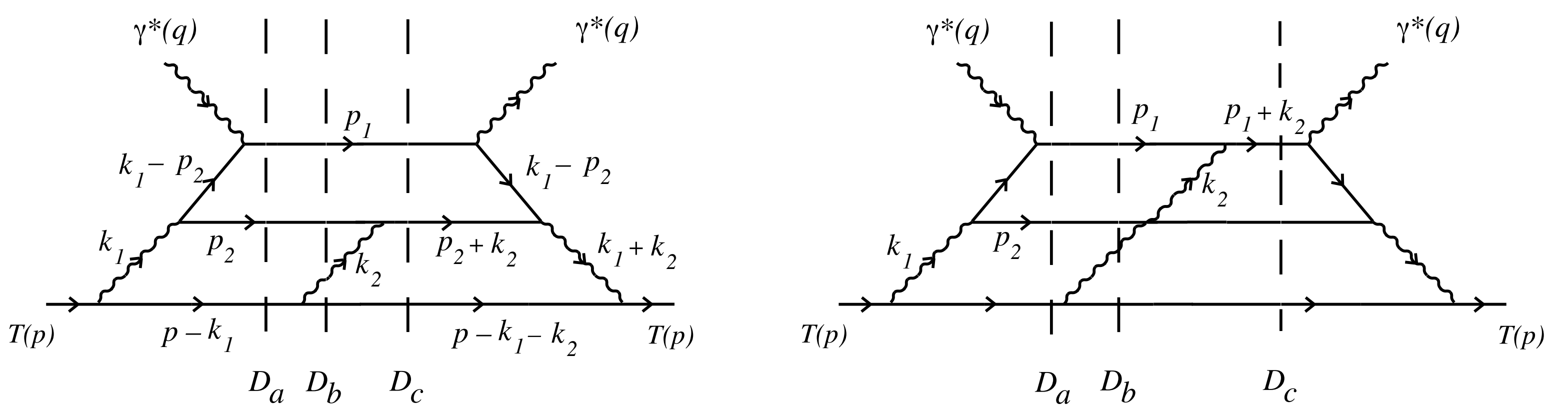
   In $\gamma^* + g \to q\bar{q}$ the rescattering is as from a gluon ($q\bar{q}$ is not resolved)

   Hence the rescattering is factorized into the target parton distribution.

2. Interactions within the spectator system do not affect σ_{DIS}

   The target spectators are "frozen" during the γ^* interaction.

   Can be demonstrated explicitly in Feynman gauge:



(a)

(b)

But does not hold in LC gauge ($A^+ = 0$)!

3. Comoving interactions (hadronization) have long time-scales

$$q(\nu) \to q[(1-z)\nu, \vec{p}_\perp] + g(z\nu, -\vec{p}_\perp)$$

Hadronization time $\Delta t \sim O(\nu)$
for finite z and $p_\perp \sim \Lambda_{QCD}$
$\Rightarrow$ No effect on σ_{DIS}

$$\frac{1}{\Delta t} \sim \Delta E \sim \frac{p_\perp^2}{z(1-z)\nu}$$

$z \sim 1/\nu \;\Rightarrow \Delta t \sim L_I$ is finite: Coherence with hard process, affects σ_{DIS}
Emission of such soft gluons is abundant
This is the “instantaneous” Coulomb exchange.

Hadronization is a Final State Interaction: No effect on σ_{DIS} at leading twist
Soft rescattering is not a final state interaction: Coherent with hard process
DIS measures a convolution of Fock state wave functions and struck quark rescattering amplitudes (cannot be resolved).

Why are rescattering effects not eliminated in LC (and hence any) gauge?

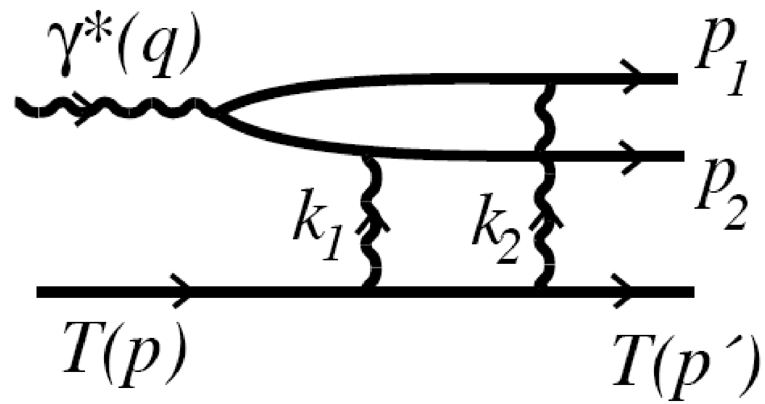
$$W[x^-,0] \equiv \mathrm{P}\exp\left[\frac{ig}{2}\int_0^{x^-} dw^- A^+(w^-)\right] = 1 \quad \text{for } A^+ = 0$$

For $k_\perp$ - dependent parton distributions there remains a finite transverse gauge link. This link is absent in the inclusive parton distribution.

Belitsky, Ji, Yuan

But this is not the whole story!

Couplings to struck quark (p_1) vanish in LC gauge due to a cancellation between Feynman and LC term in gluon propagator



The poles at $k^+ = 0$ contribute to interactions within the spectator system, and give the same contribution as $-g^{\mu\nu}$ for struck quark rescattering in Feynman gauge.

$$d_{LF}^{\mu\nu}(k) = \frac{i}{k^2+i\varepsilon}\left[-g^{\mu\nu} + \frac{n^\mu k^\nu + k^\mu n^\nu}{k^+}\right]$$

Spectators are not frozen in LC gauge!

A scary thought... Spin dependence in Wilson line?

Rescattering is soft and nonperturbative: How reliable a model is PQCD?

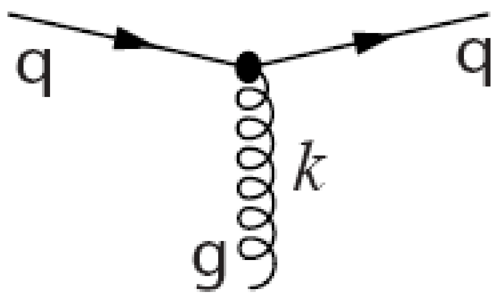
- PQCD is the basis of factorization proofs
- PQCD allows only spin-independent A^+ exchange in rescattering
- QCD vacuum fields (instantons...) might contribute?

Ellis et al (1979)
Nachtmann et al (1984)

⇒ Can we exclude a Pauli (spin-flip) contribution to quark-gluon scattering?

$$e\gamma^\mu \rightarrow e\gamma^\mu + ia(k^2)\sigma^{\mu\nu}k_\nu$$

Leading twist contribution
Flips massless quark helicity



- Momentum transfers in coherent soft rescattering are finite ($k << \nu$)
  Affect momentum distributions only via interference effects

- Spin effects could be dramatic!

The SSA in pp → π(*k*) X should decrease at large transverse momentum:

$A_N \propto 1/k_\perp$ Qiu and Sterman, Sivers

Recent Star data suggests an *increase* even for $k_\perp > 1.5$ GeV: Ogawa, hep-ex 0412035

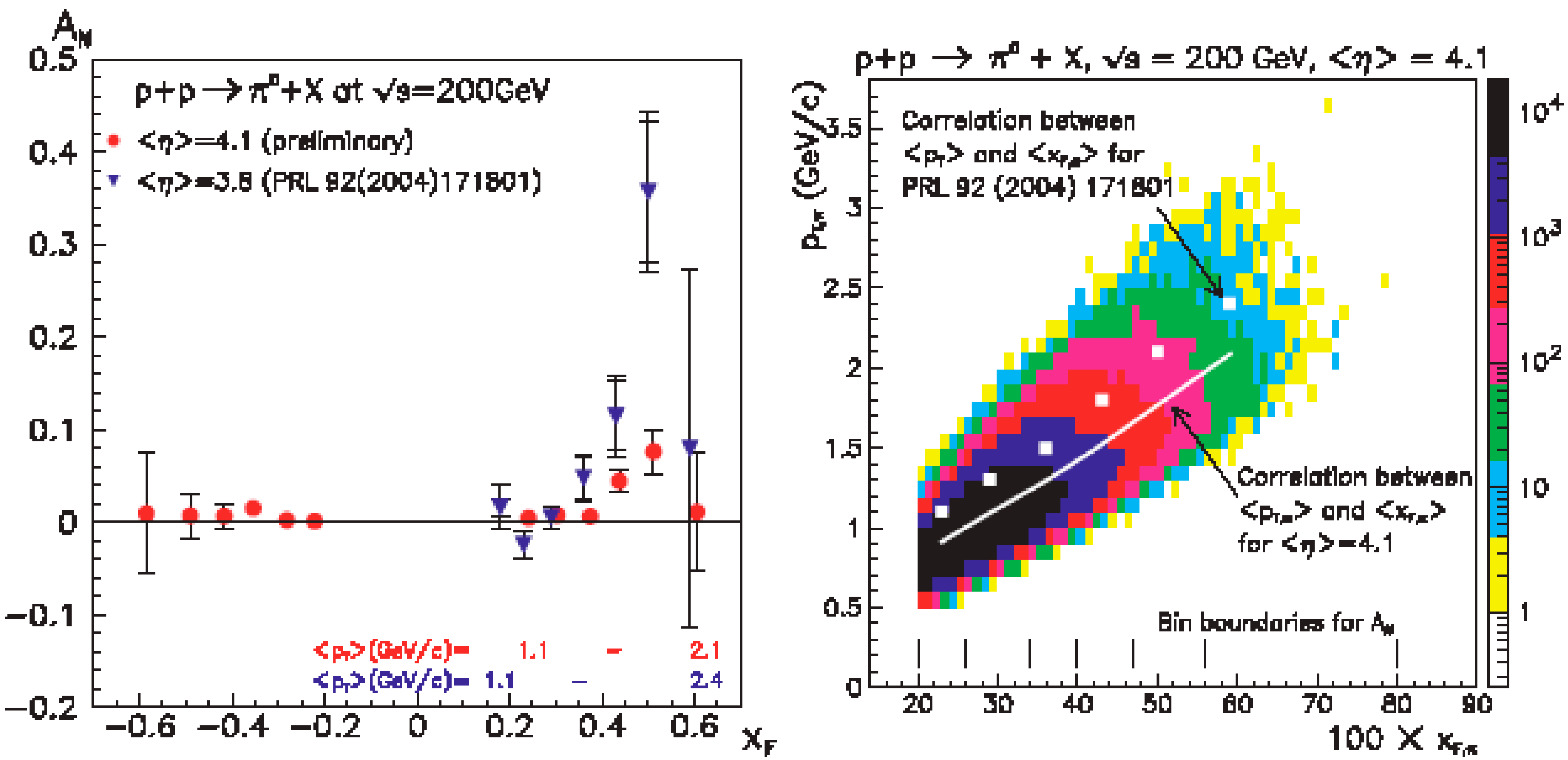
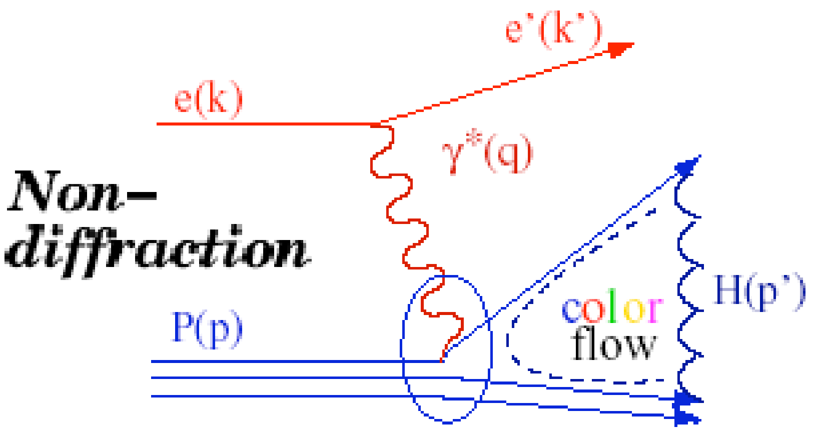
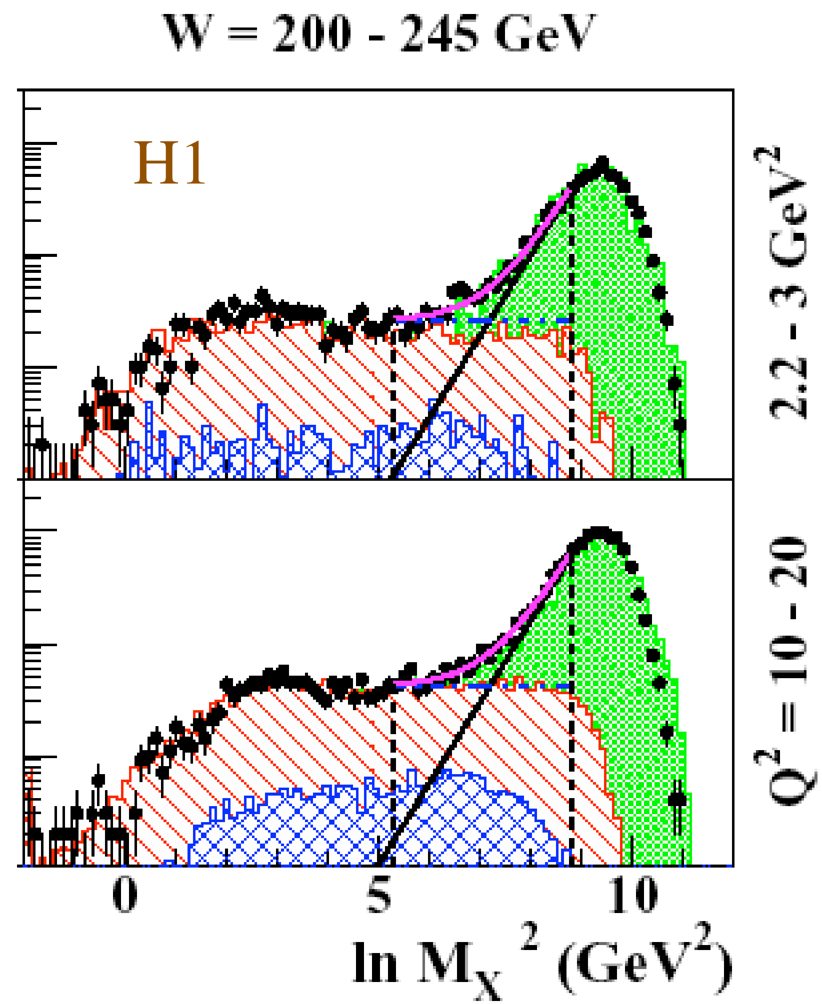


Figure 2. Left: Preliminary results on analyzing power of $p + p \to \pi^0 + X$ as function of x_F at $< \eta >= 4.1$ (circle), compared to published results at $< \eta >= 3.8$ (triangle). Right: x_F and p_T range of the data. The line shows the correlation between $< x_F >$ and $< p_T >$ for $< \eta >= 4.1$. The square dots shows the $< x_F >$ and $< p_T >$ for $< \eta >= 3.8$.

Diffractive DIS: e + p → e + X + p

Intuitive picture of DIS: A color string extending from the struck quark to the target fills the rapidity interval with hadrons:

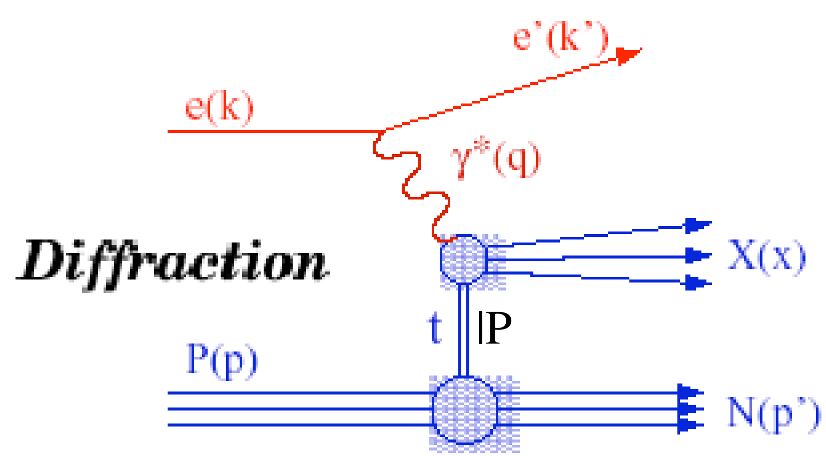




DDIS: No hadrons emerge in an extended rapidity region.

DDIS/DIS ≈ 10 %, independent of Q^2

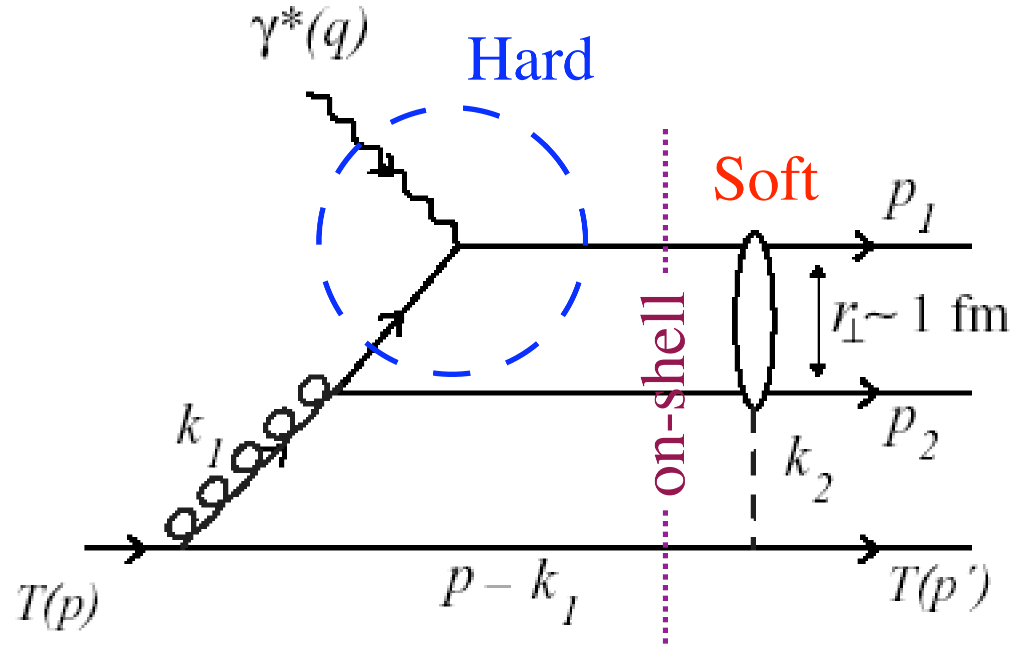
DDIS requires color singlet exchange



Rescattering amplitudes have dynamical phases

E.g., two-gluon exchange amplitude is purely imaginary for $x_B \to 0$:

Intermediate state is on-shell



Rescattering can neutralize the color exchange from target

Within the Ioffe coherence length (at $x^+ = 0$)

Before hadronization and color string formation

$\Rightarrow$ Mechanism for diffraction

Brodsky, Enberg, PH, Ingelman
hep-ph/0409119

Rapidity gap requirement imposes (color singlet) constraint on soft rescattering

$$f^D_{q/N}(x_B, Q^2) \neq f_{q/N}(x_B, Q^2)$$

Diffractive DIS parton distributions sensitive to rescattering in target

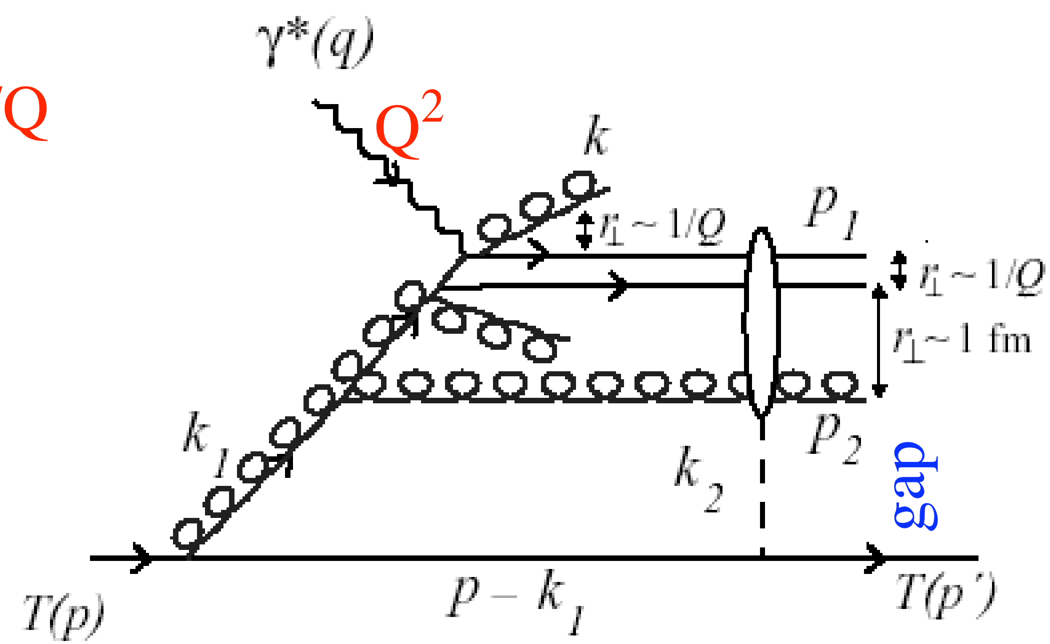
Soft rescattering sees only the color charge of struck parton:

In $\gamma^* g \to q\bar{q}$, the quark pair is produced in a compact state: $r_\perp \sim 1/Q$

and has no time to expand in target

$v_\perp \sim p_\perp/E \sim Q/\nu \to 0$ in Bj limit

Hence the quark pair interacts like a pointlike gluon in soft rescattering.



Similarly, perturbative radiation (k) at the hard vertex is not resolved in rescattering.

⇒ Hard scattering always occurs on a single parton and is the same whether a color singlet constraint is imposed on rescattering or not.

We thus understand the QCD Factorization theorem for Diffractive DIS:

$$F_2^{(D)} = \sum_{i=q,G} f_{i/p}^D \otimes \widehat{\sigma}_i$$

Collins

– The DDIS cross section is a convolution of diffractive parton distributions and the standard hard PQCD subprocesses.

– The diffractive parton distributions have the same (DGLAP) Q^2 - dependence as the inclusive distributions.

Data shows that $f^D_{g/N}(x_B, Q^2)$ $f_{g/N}(x_B, Q^2)$ have the same dependence also on x_B (or W)

DDIS / DIS $\propto W^{0.00 \pm .03}$ (ZEUS)

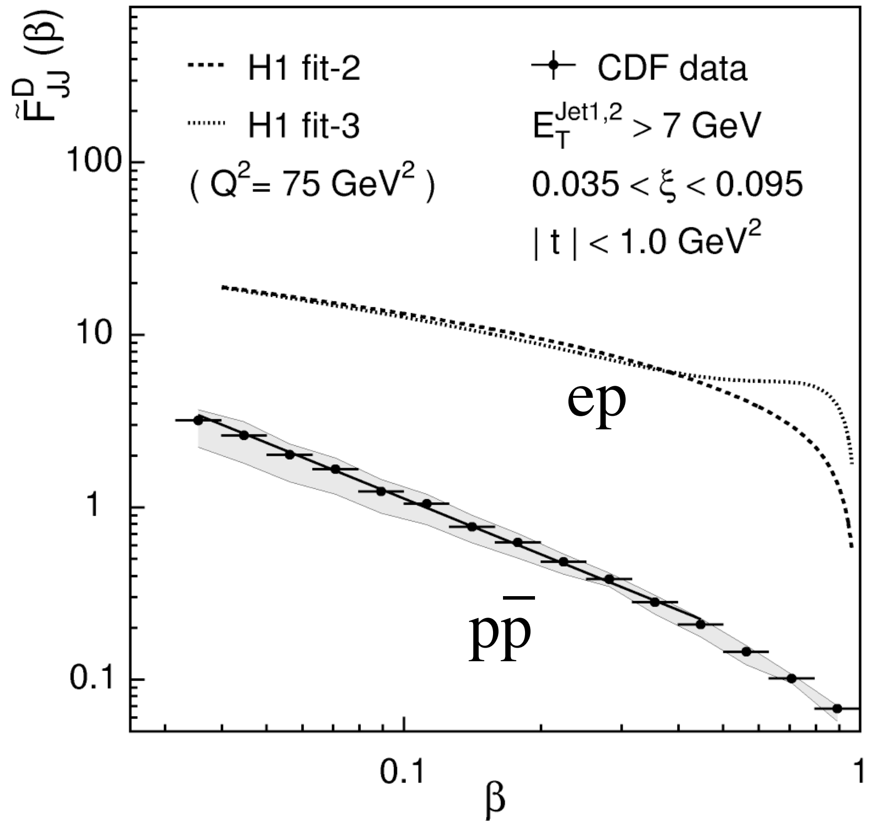
Thus the total longitudinal momentum transferred in the soft rescattering appears not to be affected by the color singlet constraint.

Diffraction in hard hadron collisions

The typical gap probability is ~ 1 %,
an order of magnitude smaller than in DIS.

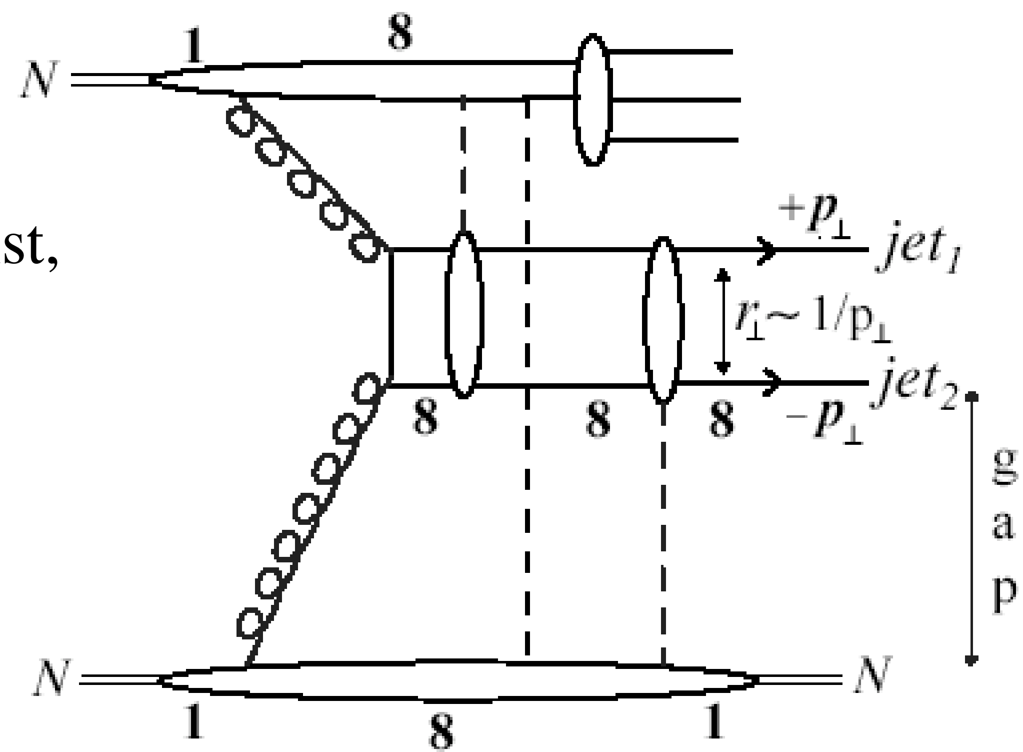
The QCD factorization theorem does not apply to diffraction in hadron collisions.

CDF Phys. Rev. Lett. **84**, 5043 2000



Soft rescattering in hard hadron collisions

Example: NN → 2 jets + X (gap) N



For this process to proceed at leading twist, the subprocesses must be the usual ones, e.g., $g + g \to q + \bar{q}$

The produced compact quark pair may rescatter with either projetile or target spectators, which may also rescatter directly with each other.

The requirement of a rapidity gap between the target and jet system imposes the constraint that the target emerge as a color singlet after all rescattering.

The rescattering is insensitive to higher order corrections at the hard vertex ⇒
The diffractive parton distributions have the standard (DGLAP) Q^2 dependence

If (as in DDIS) the color singlet constraint does not affect the momentum transfer in the soft rescattering, also

The x-dependence of the diffractive gluon distribution will be as for the inclusive one.

Since the structure of rescattering depends on the rapidity gap topology, the diffractive distributions extracted from various event topologies will have a different size.

A systematic comparison of diffractive and inclusive parton distributions will provide information on rescattering in hard processes.

Summary

- DIS and other hard QCD processes have a finite coherence length
- Soft reinteractions can thus affect the hard scattering
- Shadowing, diffraction and single spin asymmetries result
- Diffractive parton distributions are sensitive to color field environment
- The soft scattering may be affected by QCD vacuum fields
- In particular, quark helicity might not be conserved
- Spin dependence will provide qualitatively new information on QCD