Parton Propagation in a Gluon Field

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Quarks and gluons always move in a color field

- In hadrons and nuclear media
- In the QCD vacuum

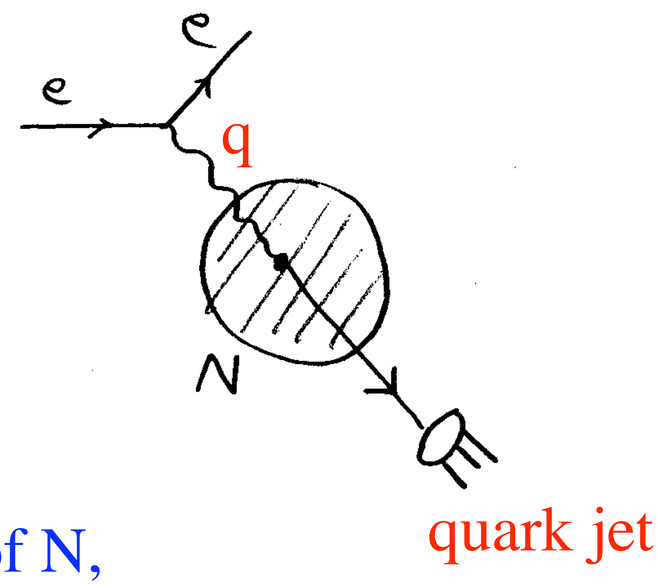
Tests of PQCD rely on eliminating unknown rescattering effects

- Short distance — $e^+e^- \to q\bar{q}$, color transparency,...
- Universality — DIS: $ep \to e\,X$,...
- Inclusiveness — σ_{tot}, jets + X,...

Measurements of medium require sensitivity to rescattering

- Quarkonia — J/ψ requires reinteraction
- Diffraction — Rapidity gaps form only between color singlets
- Confinement — Finite propagation of quarks and gluons

Example: Deep Inelastic Scattering



– Virtual photon deposits large energy ν on quark, which moves in a straight path out of the target, scattering elastically on the way.

– Large Q^2 ensures γ* scattering on single quark.

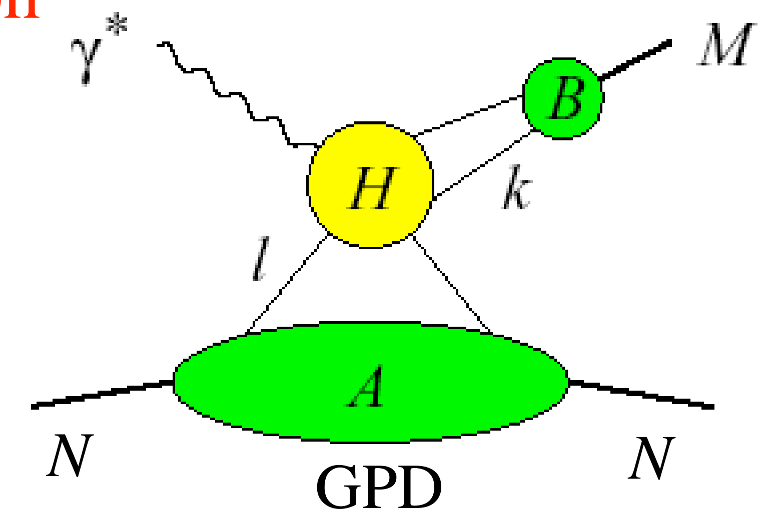
– Quark density and rescattering are characteristic of N, and independent of how the quark was kicked.

– Hadronization (outside N) is characteristic of q

Rescattering and hadronization effects are contained in universal parton density and fragmentation functions.

Inclusive DIS cross section can be used to test QCD without knowing medium effects.

Example: Deeply Virtual Meson Production



$$\gamma^* N \to M N$$

- Hard subprocess produces meson in a configuration of transverse size 1/Q.
- Meson does not rescatter in target due to color transparency.

Allows prediction of exclusive process in terms of Generalized Parton Distribution (GPD), without sensitivity to (new) rescattering effects.

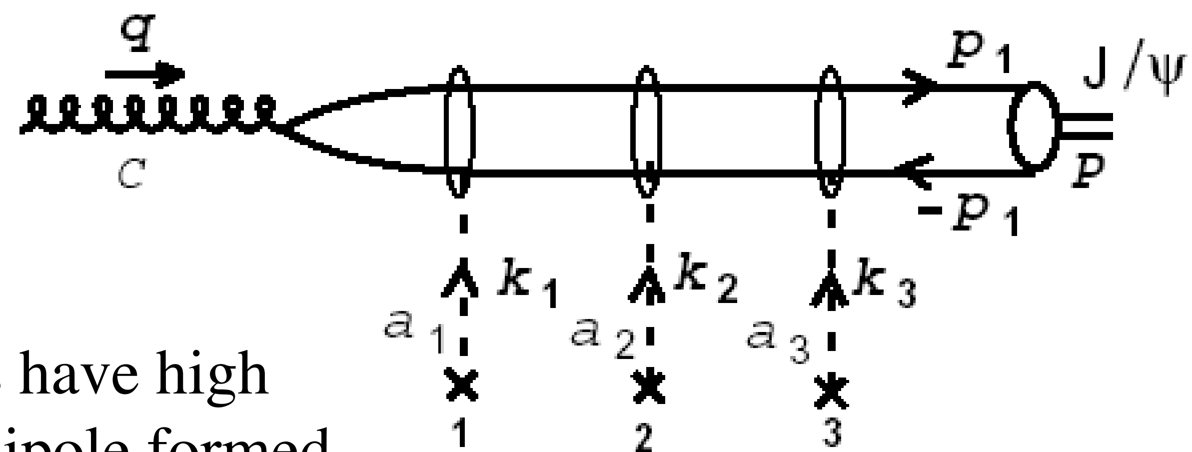
Sensitivity to surrounding medium requires measurement of processes which require rescattering, such as

- Quarkonium production: Quantum numbers may require extra gluon
- Hard diffraction: Color neutralization of diffractive system requires additional gluon exchange

Rescattering in quarkonium production

PH and S. Peigné, hep-ph/9706485

Incoming high energy gluon creates a cc pair, which via rescattering turns into a J/ψ.



Find:

– Two of the rescattering gluons have high enough $k_\perp$ to resolve the color dipole formed by the charm quarks.

– Further gluons are soft and scatter from cc as from a pointlike gluon.

– Final gluon (k_3) is a hard one: it turns color octet cc into singlet.

– In η_c production there is only one hard gluon: the final one.

⇒ Rescattering in QCD depends on the process, and is in agreement with intuition based on the resolution required.

Quarkonia with various quantum numbers act as "thermometers" of the surrounding color field.

N. Marchal, S. Peigné and PH, hep-ph/0004234

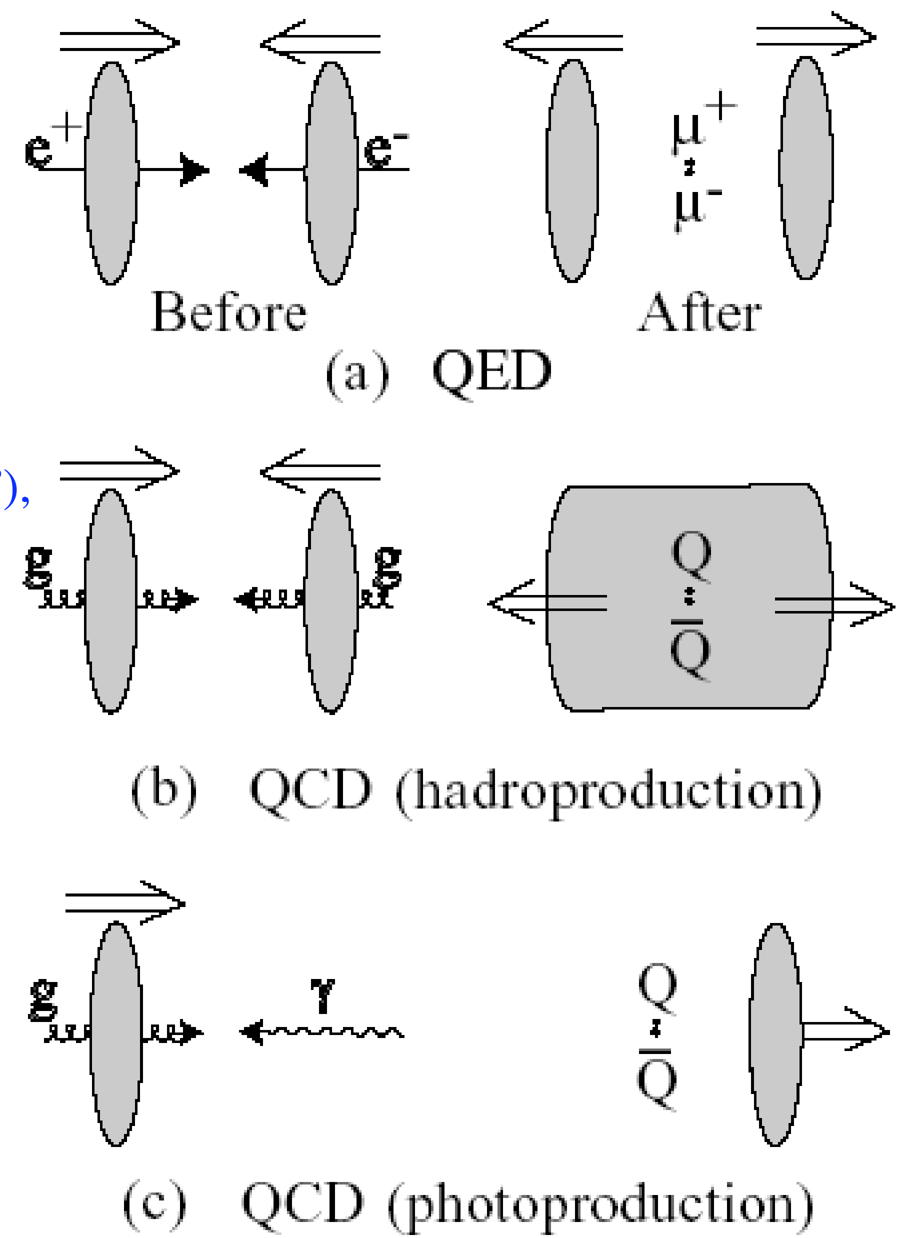
– In contrast to open charm production, for which rescattering does not affect the total cross section.

Experimental information on quarkonium production is extensive, and has striking, but poorly understood features.

– In particular, whereas photoproduction is an agreement with the simplest QCD expectation ("Color Singlet Model"), the data is more than an order of magnitude larger than CSM in hadroproduction.

Data suggests a scenario where the heavy quark pair is created in a surrounding gluon field in hadroproduction ($gg \to QQ$), but not for photoproduction ($\gamma g \to QQ$)

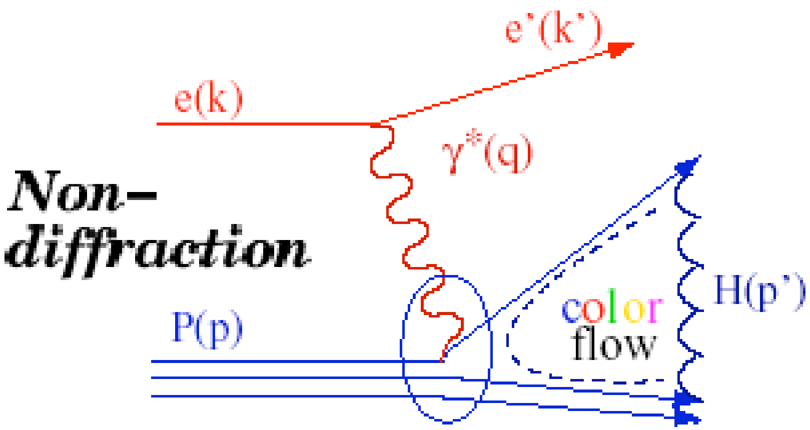
– While intuitively plausible, a precise theoretical framwork for this scenario is not available.

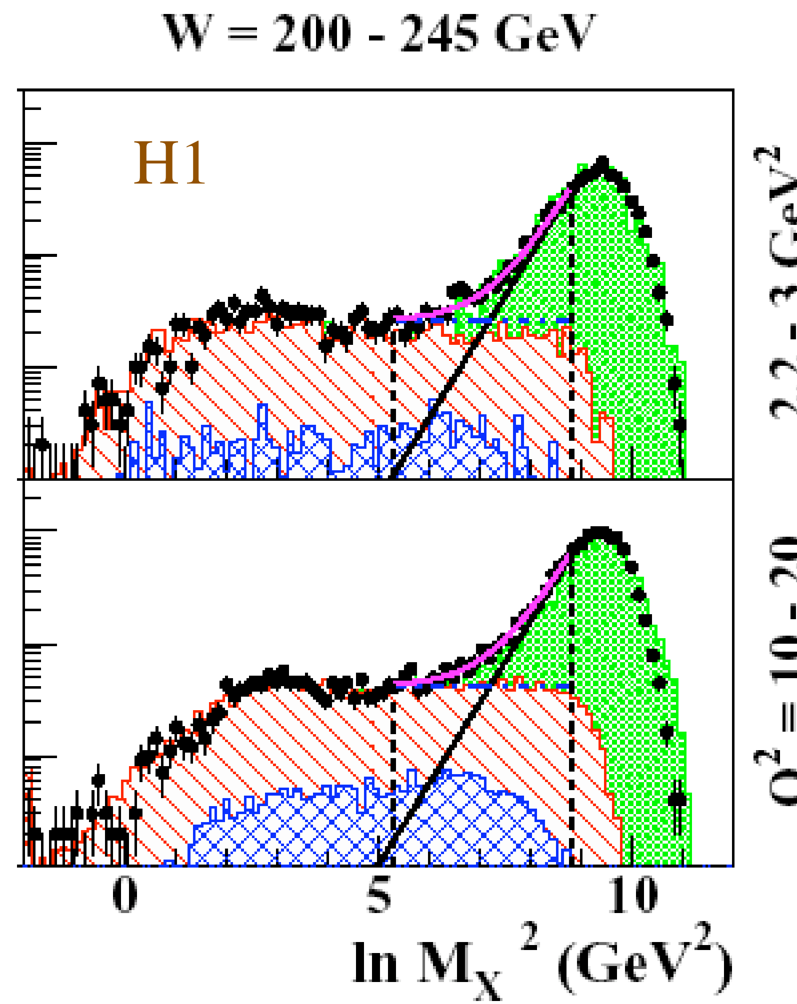


Diffractive DIS: $e + p \to e + X + p$

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

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

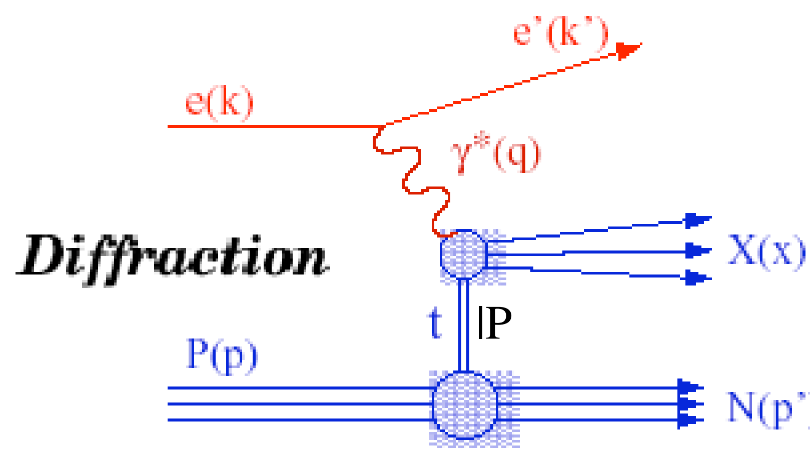




DDIS: No hadrons emerge in an extended rapidity region.

DDIS/DIS ≈ 10 %, independent of Q^2

What is the dynamics of DDIS?

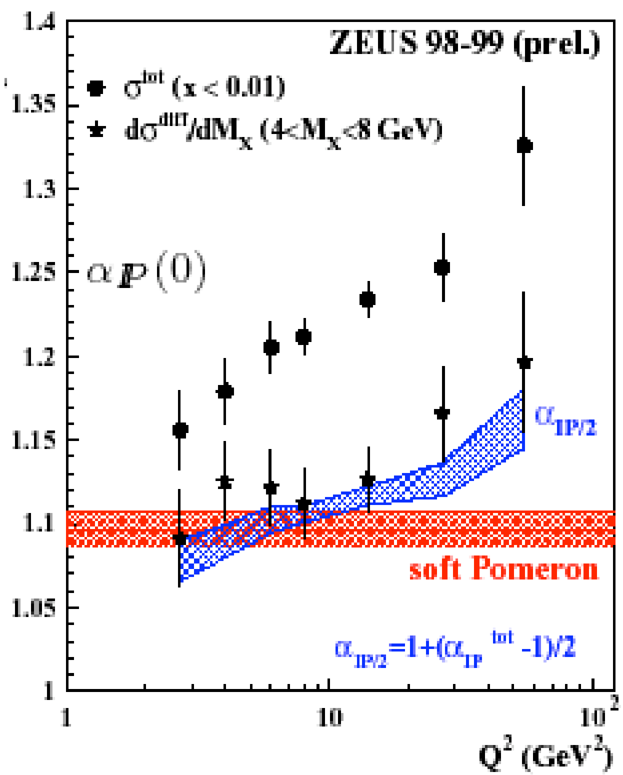


2. The DDIS/DIS ratio is independent of W

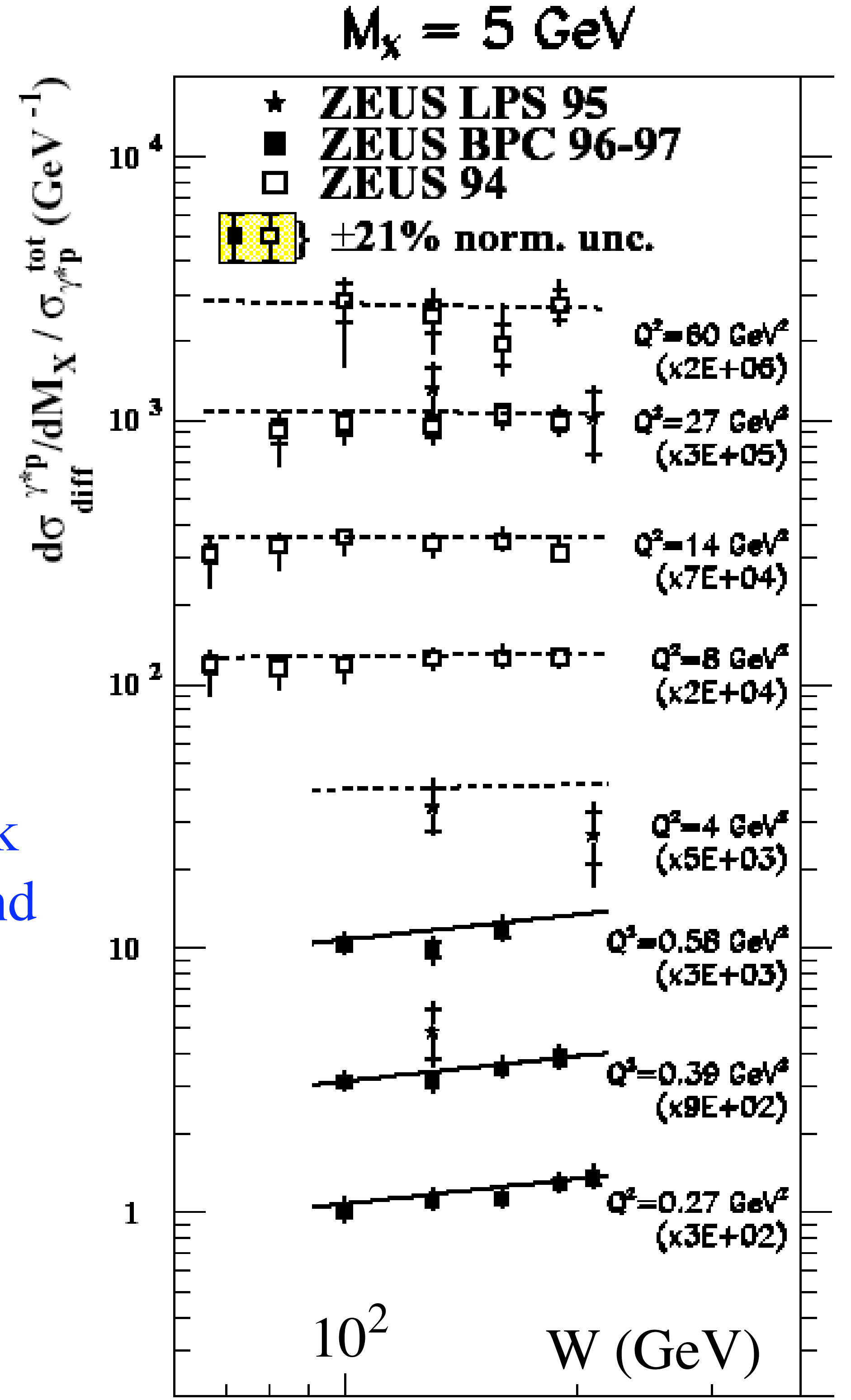
$$\frac{(d\sigma_{\rm diff}^{\gamma^* p}/dM_X)}{\sigma_{\rm tot}^{\gamma^* p}} \propto \frac{(W^2)^{2\bar{\alpha}_{I\!P}-2}}{(W^2)^{\alpha_{I\!P}(0)-1}}$$

$\propto W^{0.19}$ (Regge)

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



Need a framework in which DDIS and DIS can have the same dependence on W (ie., on x_{Bj})



Rescattering in inclusive Deep Inelastic Scattering

Brodsky
PH
Marchal
Peigné
Sannino

The DIS cross section is given by the target parton distributions. For scattering on quarks,

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

Note: The matrix element is evaluated at $x^+ = t + z = 0$ (in the Bj limit)

– The photon moves in the negative z-direction: $q^- = q^0 - q^z \approx 2\nu$
– The struck quark likewise moves through the target with $v \approx c$,

i.e., with $t \approx -z$: The struck quark exits the target in $x^+ = 0$ LF time

Matrix elements at equal LF time ($x^+ = 0$) involve arbitrarily long distances in x^- for partons moving with the velocity of light!

Note: The relevant 'Ioffe' distance for DIS is given by the Fourier transform:

$x^- \sim 2/mx_B = 4L_I$ (in the target rest frame, $p^+ = m$).

Note: The Ioffe distance is the coherence length of the virtual photon:

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

Struck quark rescattering on target spectators within the Ioffe length adds coherently to the DIS amplitudes. In the expression for the parton distribution, the rescatterings are described by the Wilson line:

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

Note: Only instantaneous A^+ exchange is allowed:
The struck quark scatters on the Coulomb field of the target.
The formation time of physical, transverse gluons is >> L_I .

Can we eliminate the rescattering effects using Light Front (LF) gauge $A^+ = 0$?

No: Rescattering affects the DIS cross section and is gauge independent.

The contribution of the Wilson line in Feynman gauge

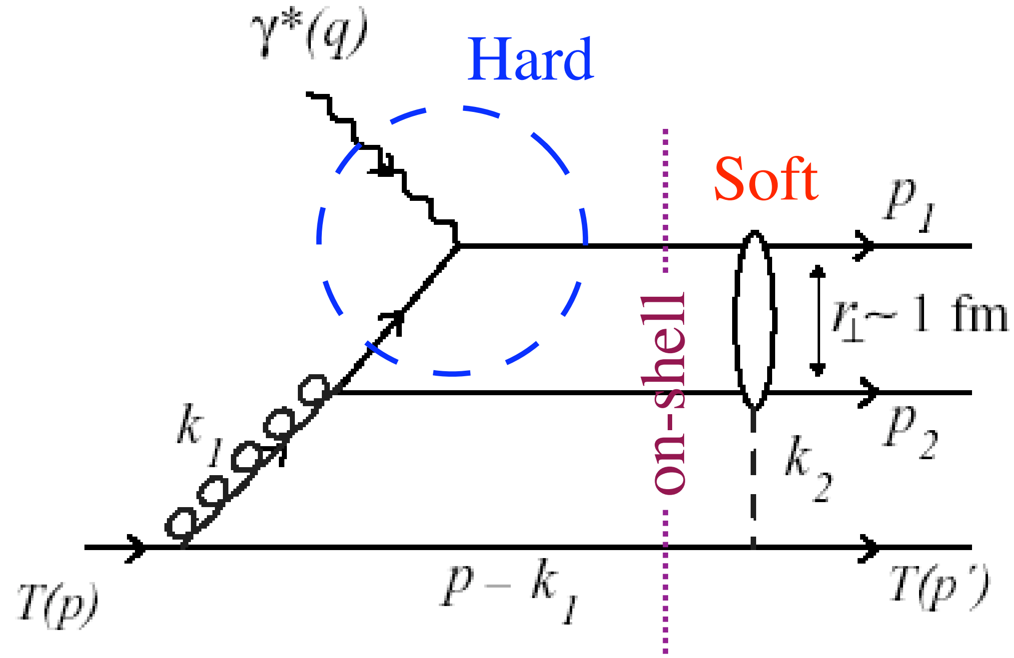
shifts to the spectator system in LF gauge (where $W[x^-, 0] = 1$):

The “frozen target” approximation is not valid in LF gauge ($A^+ = 0$).

Rescattering amplitudes have dynamical phases

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

Intermediate state is on-shell



DIS shadowing arises from interference of complex rescattering amplitudes BHMPS

Rescattering phase gives rise to single transverse spin asymmetry

Brodsky
Hwang
Schmidt

Rescattering can neutralize the color exchange from target

Within the Ioffe coherence length (at $x^+ = 0$)
Before hadronization and color string formation

⇒ Mechanism for diffraction

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

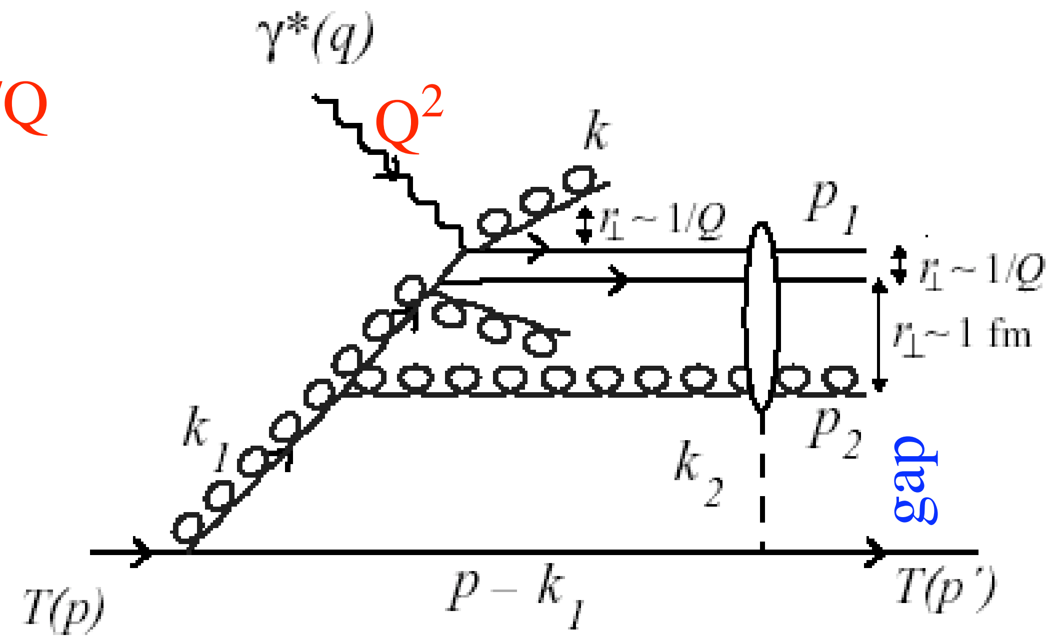
Soft rescattering sees only the color charge of struck parton:

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.

Note: 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.

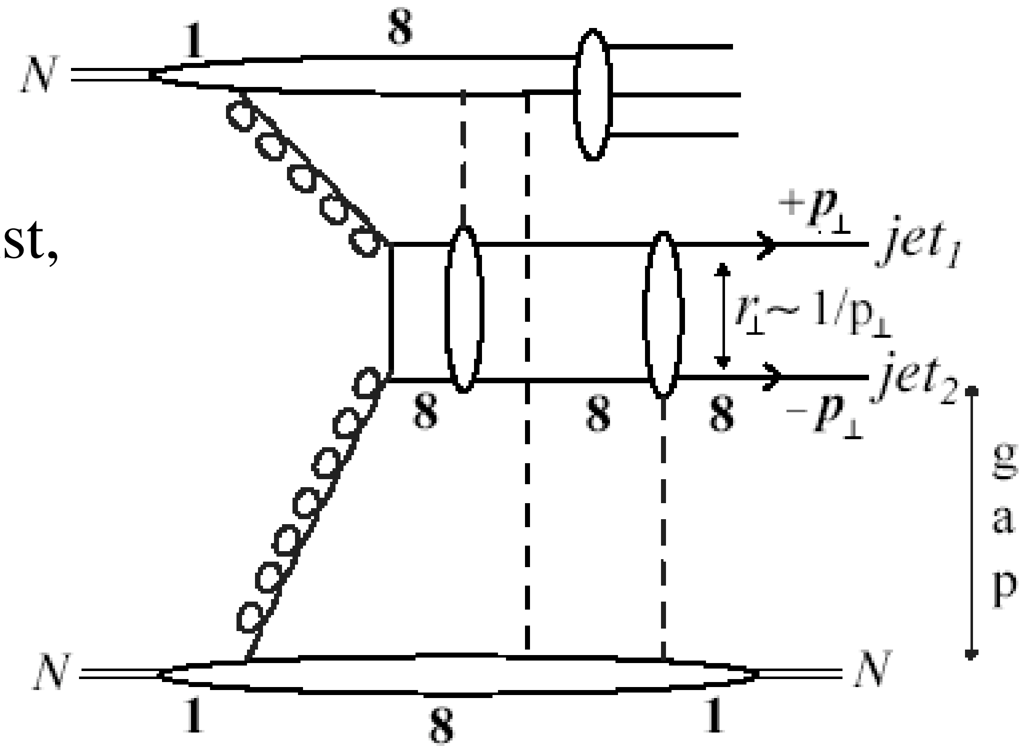
Data shows that $f^D_{g/N}(x_B, Q^2)$ $f_{g/N}(x_B, Q^2)$ have the same dependence also on x_B (or W)

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

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

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.

QCD Green Functions in a Gluon field

PH and S. Peigné, hep-ph/0410235

Quarks and gluons are not asymptotic states in QCD

– likely due to the non-trivial "condensate" vacuum:

The ultimate medium

- How does analyticity and unitarity of quark and gluon Green functions work out in a confining theory?
- Could we perturbatively expand in the presence of a 'vacuum' field?
  – Confinement may not imply large α_s, only long distance propagation in the condensate medium

Find:
- Quark and gluon propagators with a novel analytic structure
- Partons removed from in- and out-states (no pole at $p^2 = 0$)
- Infrared singularities regularized
- Chiral symmetry breaking solution for quark propagator

Method

Consider the shift $A_\mu(x) \to A_\mu(x) + \Phi_\mu$ of the gluon field in L_{QCD}

- Green functions unchanged, since

$$\int \mathcal{D}[A_\mu] = \int \mathcal{D}[A_\mu + \Phi_\mu]$$

- Perturbative expansion is modified.

- Quark term in L_{QCD} generates $\bar{q} i \not{D} q \to \bar{q} i \not{D} q - g\, \bar{q} \not{\Phi}\, q$

- New term is gauge invariant under $q \to Uq$ provided

$$\Phi_\mu \to U \Phi_\mu U^\dagger$$

The Φ_μ – gluon coupling

The shift $A_\mu(x) \longrightarrow A_\mu(x) + \Phi_\mu$ generates $\mathcal{L}_g \longrightarrow \mathcal{L}_g + \mathcal{L}_\Phi$, where $\mathcal{L}_\Phi$ has several, separately gauge invariant terms.

We have studied the simplest one: $\mathcal{L}_\Phi^{(1)} = -\mathrm{Tr}\left(F_{\mu\nu}F_\Phi^{\mu\nu}\right)$, where

$$F_\Phi^{\mu\nu} = \partial_\mu\Phi_\nu - \partial_\nu\Phi_\mu + ig\left(\left[\Phi_\mu, A_\nu\right] - \left[\Phi_\nu, A_\mu\right]\right)$$

transforms into $UF_\Phi^{\mu\nu}U^\dagger$ under a gauge transformation U.

We take Φ_μ to be independent of x, and average over its values with a gaussian weight with a mass parameter Λ.

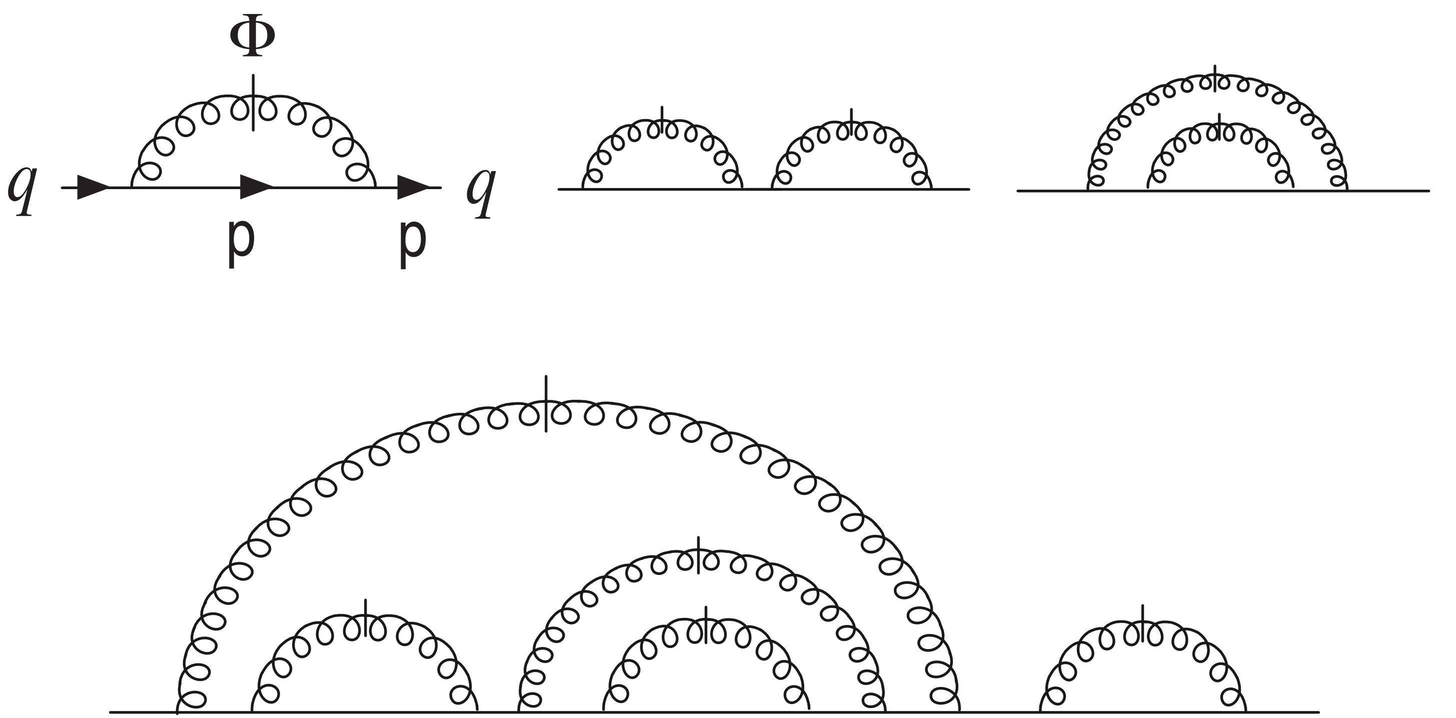
$$\int_{-\infty}^{\infty}\prod_\mu d\Phi_\mu \exp\left[\frac{1}{\Lambda^2}\,\mathrm{Tr}(\Phi_\mu\Phi^\mu)\right]$$

Poincaré and gauge invariance is thus ensured.

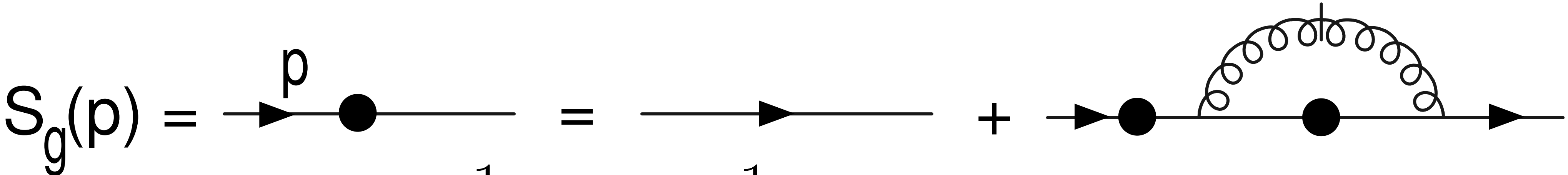
Quark propagator dressing

Since the field Φ_μ carries no momentum, it is possible to dress the tree-level quark and gluon propagtors to all orders in this field, at leading order in the $N \to \infty$ limit of a large number of colors.

Typical (planar) diagrams which contribute to the quark dressing:



The diagrams can be directly summed, or one may note that it satisfies a Dyson-Schwinger type equation for quark propagator



$$S_g(p) = \frac{1}{\not{p}} - \tfrac{1}{2}\mu^2 \frac{1}{\not{p}} \gamma^\mu S_g(p) \gamma_\mu S_g(p)$$

where $\mu^2 = g^2 N \Lambda^2$. This equation is algebraic and can be solved exactly. With the general ansatz

$$S_g(p) = a(p^2)\,\not{p} + b(p^2)$$

we find two solutions.

Dressed quark propagator (1):

$$S_{g1}(p) = \frac{2\not{p}}{p^2 + \sqrt{p^2(p^2 - 4\mu^2)}}$$

which reduces to the standard perturbative one for $p^2 \to \infty$.

At $p^2 = 0$ it has a branch point singularity, rather than a pole.

Hence the quark does not propagate to asymptotic times:

$$|S_{g1}(t, \vec{p})| \underset{|t|\to\infty}{\sim} \mathcal{O}\left(1/\sqrt{|t|}\right)$$

Thus the interactions with the zero-momentum gluons in the perturbative vacuum effectively prevent the quark from propagating very far.

NOTE: The novel analytic structure is only seen when the vacuum interactions are summed to all orders!

Dressed quark propagator (2):

$$S_{g2}(p) = -\frac{1}{\mu^2}\left(\not{p} \pm \sqrt{p^2 + \tfrac{1}{2}\mu^2}\right)$$

Breaks chiral invariance! (Diverges for $\mu \to 0$)

Does not reduce to the standard perturbative propagator for $p^2 \to \infty$.

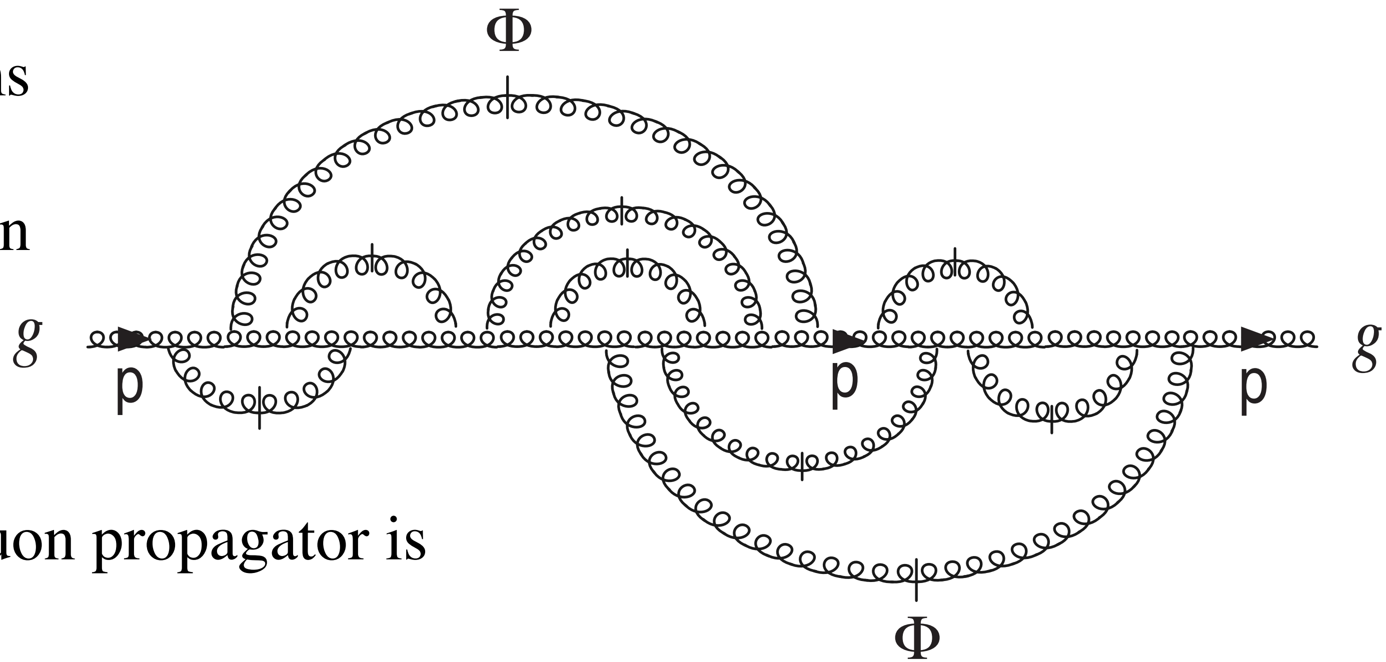
However, $S_{g2}(p) = S_{g1}(p)$ for $p^2 = -\mu^2/2$. Hence in a loop integral we

may use $S_{g2}(p)$ at low p^2.

This will give Green functions that break chiral symmetry.

Gluon propagator dressing

The sum of planar diagrams is two-sided. No algebraic D-S equation can be written down for the gluon propagator, but the diagrams can be summed "by hand": The dressed gluon propagator is



$$iD^{ab}_{g,\mu\nu}(p) = \frac{i}{p^2}\left(-g_{\mu\nu} + \frac{p_\mu p_\nu}{p^2}\right) d(-2\mu^2/p^2)$$

where

$$d(-2\mu^2/p^2) = \frac{p^2}{4\mu^2}\left[{}_2F_1(-\tfrac{1}{2},\tfrac{1}{2};2;-32\mu^2/p^2) - 1\right]$$

and ${}_2F_1$ is a hypergeometric function.

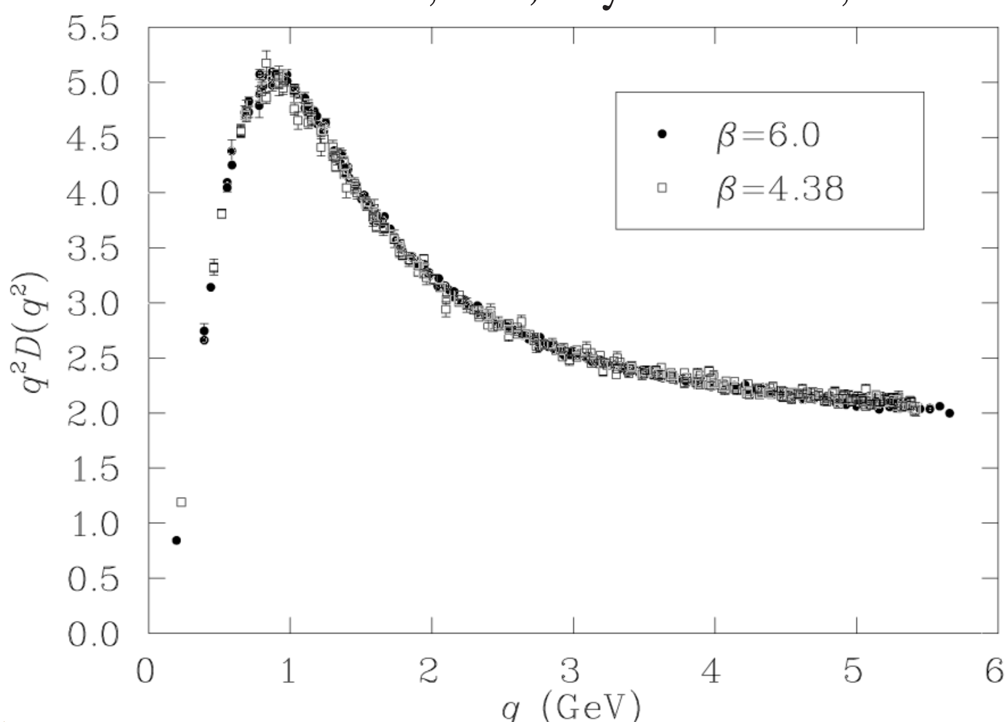
The dressed propagator thus has a cut for -32 $\mu^2 \leq p^2 \leq 0$, and has the asymptotic limits

$$d(-2\mu^2/p^2) \;\rightarrow\; 1 \;\; \text{for } p^2 \rightarrow \infty$$

$$d(-2\mu^2/p^2) \;\rightarrow\; \frac{4}{3\pi}\frac{\sqrt{p^2}}{\mu} \;\; \text{for } p^2 \rightarrow 0$$

Interestingly, the general shape of the dressed gluon propagator resembles lattice results:

F.D.R. Bonnet, *et al*, Phys. Rev. **D64**, 034501



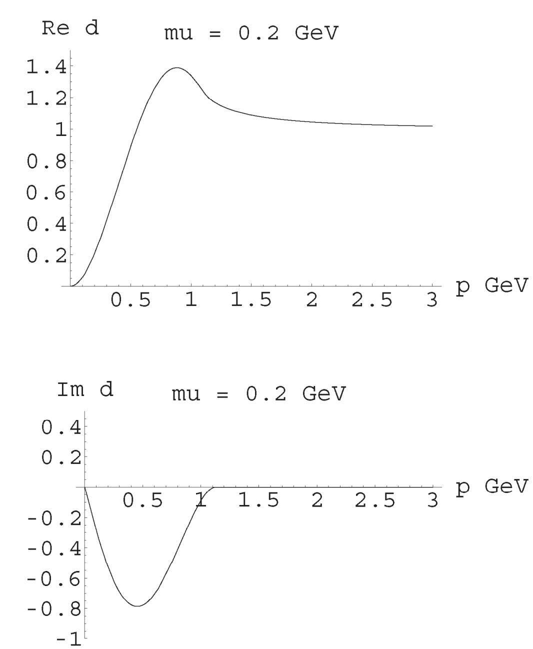


Figure 4: Our result for the gluon propagator.

Conclusions

- Parton rescattering causes prominent effects such as shadowing, diffraction and single spin asymmetries.
- The rescattering is part of the non-perturbative, universal parton distributions, and thus difficult to quantify in inclusive processes.
- Processes such as diffractive hard scattering and quarkonium production require rescattering, and thus measure the medium effect.
- It may be worthwhile to investigate the features perturbative QCD processes in the presence of a color (vacuum) field.
  – Poincaré and gauge invariant analysis is possible
  – Confinement-like behavior of quarks and gluons observed
  – Infrared singularities are tamed
- Analyticity and unitarity in case of confined fields merits study.