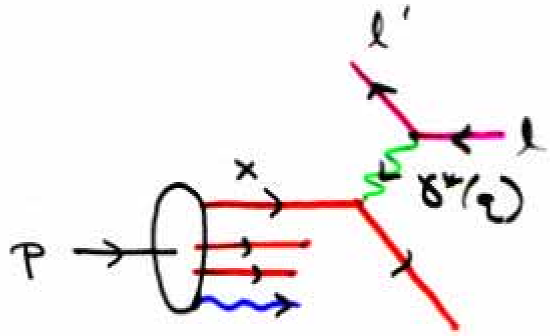
Structure Functions are not Parton Probabilities!

hep/ph/0104291



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QCD parton model: (leading twist)

$$F_2(x, Q^2) = \sum_q e_q^2 \, x_B \, P_{q/N}(x_B, Q^2)$$

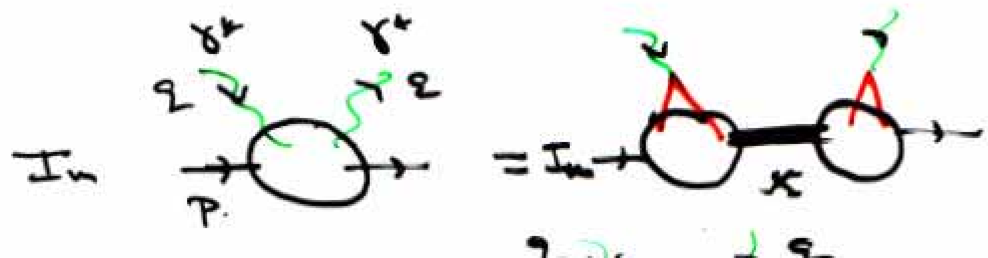
$$P_{q/N}(x_B, Q^2) = \sum_n \int^{Q^2} d^2k_\perp \prod_i' dx_i \, d^2k_{\perp i} \, |\psi_n(x_i, k_{\perp i})|^2 \sum_{j=q} \delta(x_B - x_j)$$

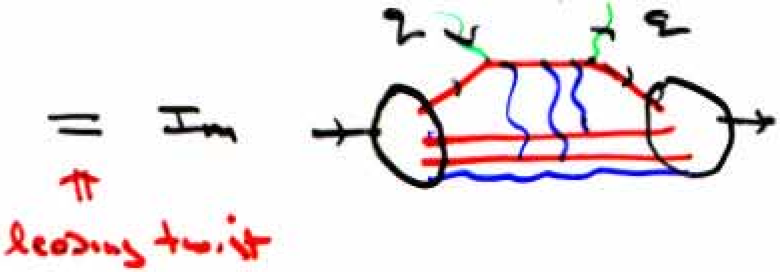
$\uparrow q(x_B, Q^2)$

$$|N\rangle = \sum_n\!\!\!\!\!\!\int \; \psi_n(x_i, k_{\perp i}) \, |n\rangle$$ l.c. Fock expansion

Usual proof:

QCD Factorization for virtual Compton amplitude

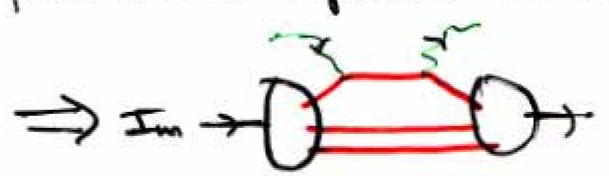




$$P_{q/N}(x_B, Q^2) = \frac{1}{8\pi}\int dy^- \, e^{-i x_B p^+ y^-}$$

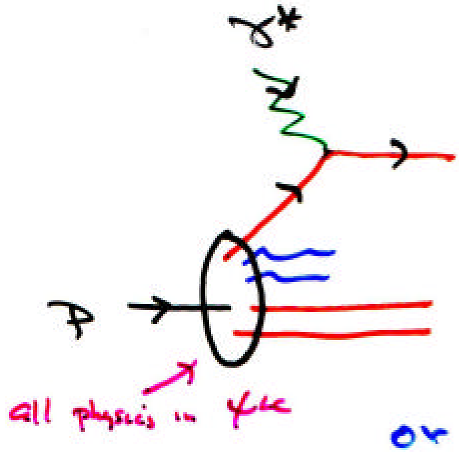
$$\langle N(p)|\, \bar{q}(y^-)\gamma^+ \, \mathcal{P}\, e^{ig\int_0^{y^-} dw^- A^+(w^-)} q(0)|N\rangle$$

Choose light-cone gauge: $A^+ = 0$,
path-ordered exponential $= 1$



$= \sum_n |\psi_n|^2$

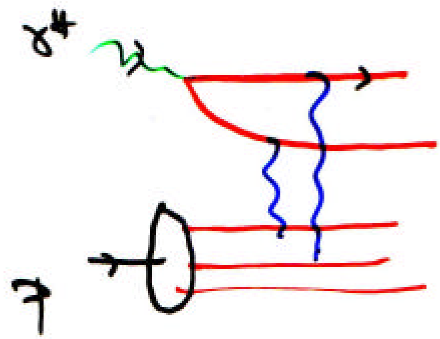
DIS at Small x_{Bj}



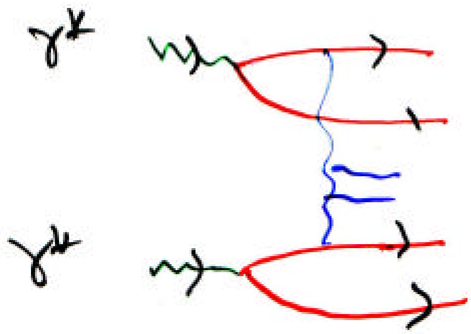
quark-parton model

No FSI at leading twist!

or

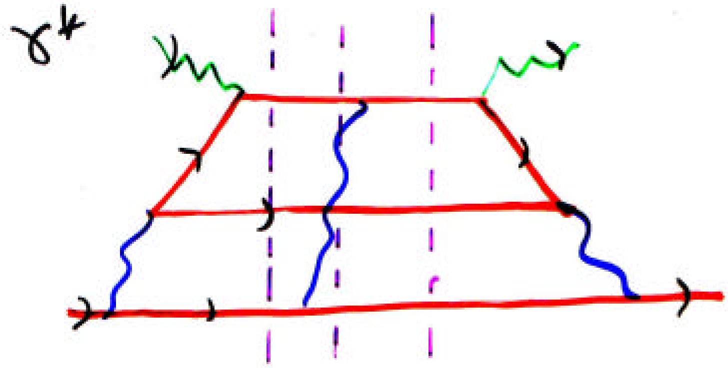


Color-dipole interactions



$\gamma^* \gamma^* \to X$
Color dipole
BFKL hard pom.

Hautmann, Soper, MB
Bartels, et al.



Usual argument: no time for f.s.i.

- three denominators of order ν
- numerator coupling finite in l.c.g.

$\therefore$ f.s.i. suppressed by power of $\frac{1}{\nu}$

Equivalent to setting P.O.E. = 1.

$$\int_0^{b^-} d\omega^- \, A^+(\omega^-) = 0.$$

in $A^+=0$ gauge.

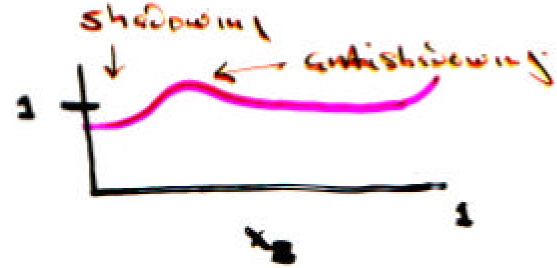
But argument is wrong!

Paradox:

Nuclear structure functions cannot

be interpreted as probability distributions

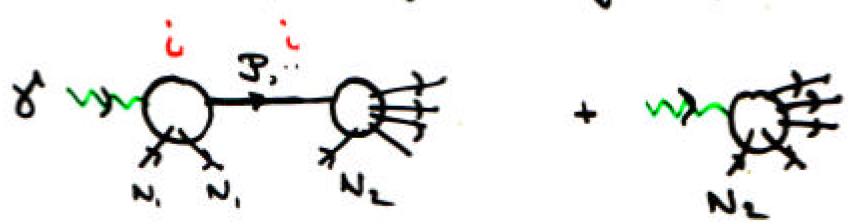
$$\frac{F_{2A}(x_B, Q^2)}{A\, F_{2N}(x_B, Q^2)}$$

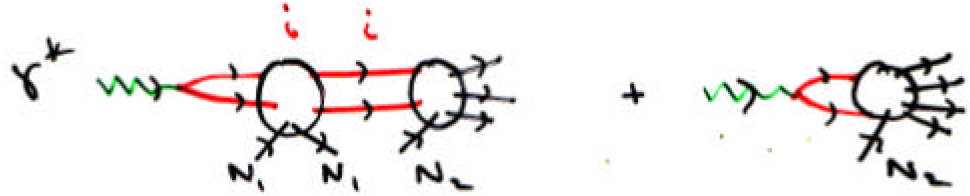


Physical origin of shadowing same as

$\sigma_{\gamma A}$, $\sigma_{\pi A}$: Glauber Gribov

Destructive interference of Diffractive Channels





$\therefore$ Nucleon N_2 sees less flux!

$$\sigma_A < A\, \sigma_N$$

* Nuclear shadowing due to destructive interference of diffractive channels.

Pomeron exchange $\Rightarrow i$ $\left(-e^{i\pi\alpha_P(0)}\right)$

Cut contribution $\Rightarrow i$

* But $\psi_{n/N}(x_i, \vec{k}_{\perp i}, \lambda_i)$

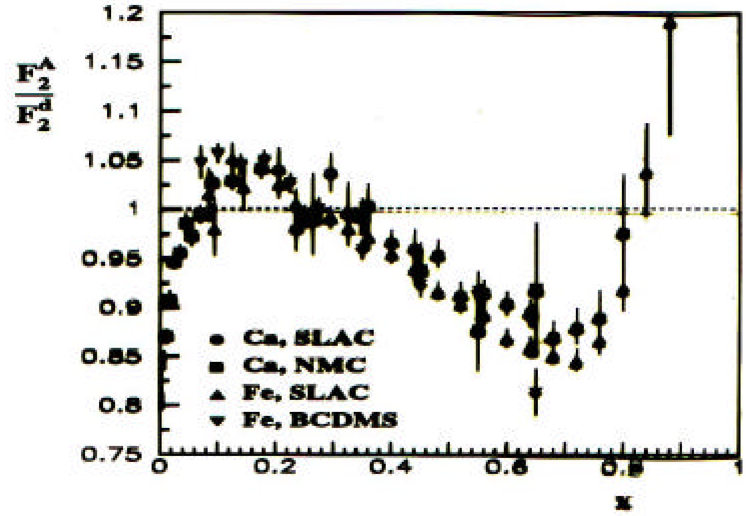
$\psi_{n/A}(x_i, \vec{k}_{\perp i}, \lambda_i)$

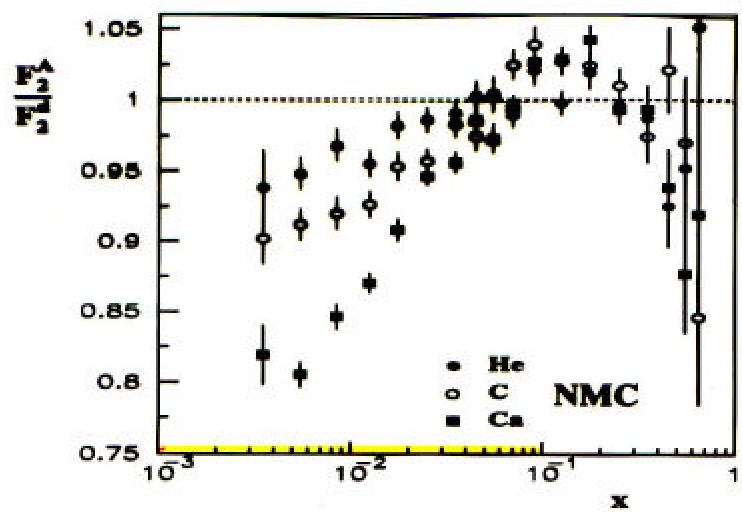
are real! No phase info from intermediate on shell states for stable targets.

– Anti-shadowing from non-singlet Reggeon exchange.

H.J. Lu + S.J.B.

Nuclear structure functions



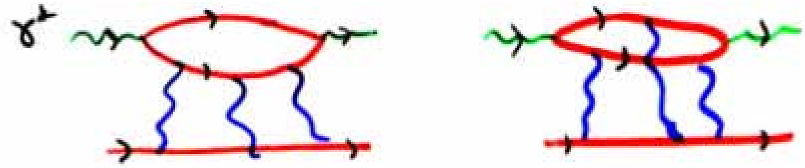


coherence length of hadronic configurations

$$\lambda \simeq \frac{1}{Mx} > 2\,\mathrm{fm} \leftrightarrow x < 0.1$$

Where is the error?

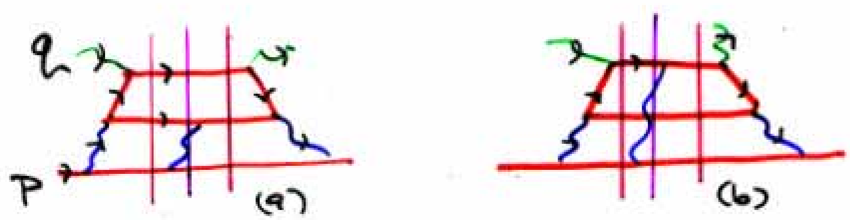
Consider



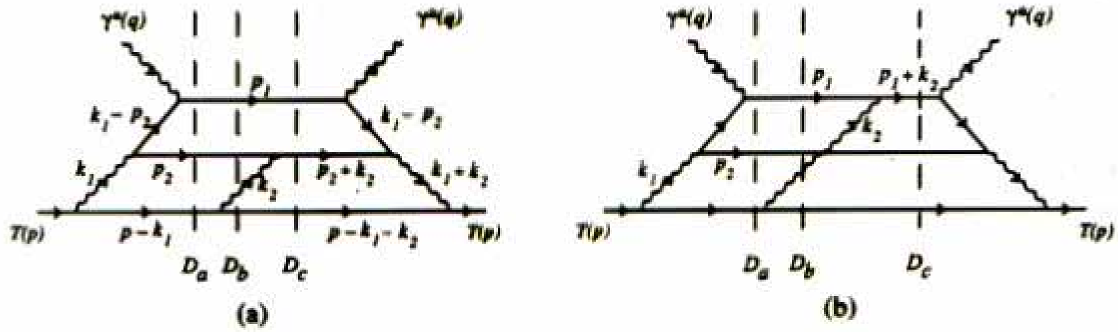
↑ contributes to P.D.F.

- Assume scalar quarks, abelian theory.
- Light-cone gauge: $d^{\mu\nu}_{LC}(k) = \dfrac{\left[-g^{\mu\nu} + \dfrac{n^\mu k^\nu + k^\mu n^\nu}{n\cdot k}\right]}{k^2+i\epsilon}$
- Mandelstam - Liebbrandt causal pres.

Use LCPTh, $q^+ < 0$ frame, aligned jet config.



These are final state interactions, not included in $|\psi_n|^2$. Find $\begin{cases} M_a = \text{higher twist} \\ M_b = \text{leading twist !} \end{cases}$

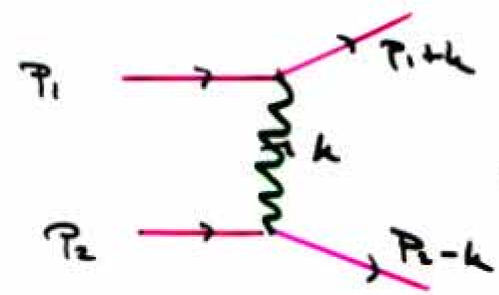


$\gamma^*(q)$
$\gamma^*(q)$
p_1
$k_1 - p_2$
$k_1 - p_2$
k_1
p_2
$p_2 + k_2$
$k_1 + k_2$
k_2
$T(p)$
$p - k_1$
$p - k_1 - k_2$
$T(p)$
D_a D_b D_c
(a)
$\gamma^*(q)$
$\gamma^*(q)$
p_1
$p_1 + k_2$
k_2
k_1
p_2
$T(p)$
$T(p)$
D_a D_b D_c
(b)

Subtlety of Light-Cone Gauge

Elastic lepton scattering in QED $\quad s \gg (-t)$

$$n^\mu = (0, 2, \vec{0}_\perp), \quad n^2 = 0$$



$$\mathcal{M} = e^2 (2p_1+k)^\mu d_{\mu\nu} (2p_2-k)^\nu$$

$$d_k^{\mu\nu}(k) = \frac{\left[-g^{\mu\nu} + \frac{n^\mu k^\nu + k^\mu n^\nu}{n \cdot k}\right]}{k^2 + i\epsilon}$$

$$\mathcal{M} = -e^2 \frac{(2p_1+k)\cdot(2p_2-k)}{k^2} \overset{s \gg -t}{=} -2e^2 \frac{s}{t}$$

Eikonal approx: $\quad (2p_1+k)^\mu \Rightarrow p_1 \cdot n^* \, n^\mu = (0, 2p_1^-, \vec{0}_\perp)$

$$n^* = (2, 0, \vec{0}_\perp), \quad (n^*)^2 = 0.$$

* Reproduces $\quad s = 2 p_1 \cdot p_2 = p_1^- p_2^+$

in Feynman gauge: $\mathcal{M} = -\frac{2e^2 s}{t}$

* But gives $\mathcal{M} = 0$ in lcg!

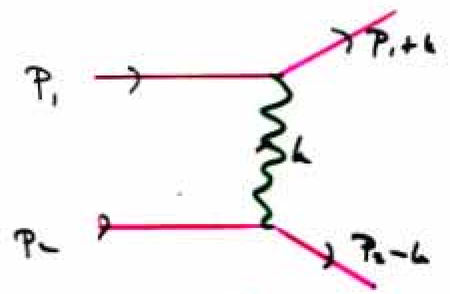
since $n^\mu d_{\mu\nu} = 0$

* Eikonal limit and l.c.g do not commute

Light-cone gauge evaluation

$n^\mu = (0, 2, 0_\perp)$

$n^2 = 0$



$2p_1 \cdot k + k^2 = 0$

$$\mathcal{M} = e^2 (2p_1 + k)_\mu \frac{\left[-g^{\mu\nu} + \frac{n^\mu k^\nu + k^\mu n^\nu}{n \cdot k} \right]}{k^2 + i\epsilon} (2p_2 - k)_\nu$$

where: $n \cdot k = k^+ = \frac{-k^2}{p_1^-} \to 0$ for $s \gg -t$

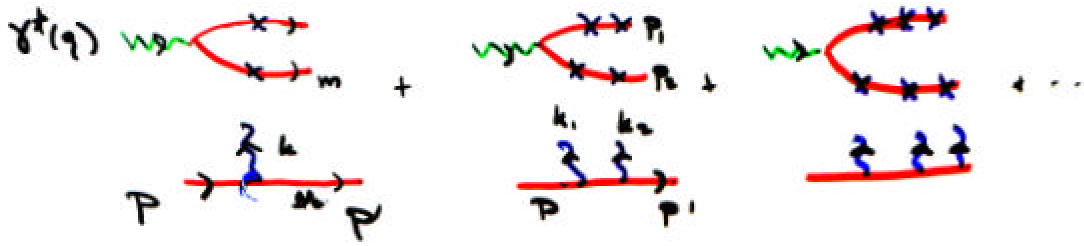
Dominant term in l.c.g. from non-eikonal current

$$\mathcal{M} = e^2 \frac{-k_\perp^2 \frac{2p_2^+}{k^+}}{k^2 + i\epsilon} \Rightarrow -2e^2 \frac{s}{t}$$

$\vec{A}_\perp$ plays crucial role in lcg: $k^+ = O\left(\frac{1}{p_1^-}\right)$

Similarly: $\int dw^\mu A_\mu \neq \int dw^- A^+$ in l.c.g.

Model Calculation



Scalar quarks , crossed + uncrossed graphs , large ν
+ seagulls

Eikonal factorization in $\vec{r}_\perp$, $\vec{R}_\perp$
Verified to 3-loops in Feynman , l.c.g.

$$\mathcal{M} = \mathcal{M}_{Born}\left[1 - e^{-ig^2 W}\right]$$

$$\mathcal{M}_{Born} = -2ieMQ\,p_2^-\,V(m_{\parallel}, r_\perp)$$

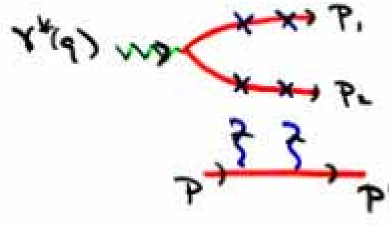
$$V(m_{\parallel}, r_\perp) = \int \frac{d^2p_\perp}{(2\pi)^2}\,\frac{e^{i\vec{r}_\perp\cdot\vec{p}_\perp}}{p_\perp^2 + m_{\parallel}^2} = \frac{1}{2\pi}K_0(m_{\parallel} r_\perp)$$

$$m_{\parallel}^2 = p_2^- M x_B + m^2$$

$$W(\vec{r}_\perp, \vec{R}_\perp) = \int \frac{d^2k_\perp}{(2\pi)^2}\,\frac{1 - e^{i\vec{r}_\perp\cdot\vec{k}_\perp}}{k_\perp^2}\,e^{i\vec{R}_\perp\cdot\vec{k}_\perp} = \frac{1}{2\pi}\ln\frac{|\vec{R}_\perp + \ldots}{R_\perp}$$

$$Q^4\frac{d\sigma}{dQ^2\,dx_B} = \frac{\alpha}{16\pi^2}\,\frac{1-y}{y^2}\,\frac{1}{2M\nu}\int\frac{dp_2^-}{p_2^-}\,d^2r_\perp\,d^2R_\perp\,|\mathcal{M}|^2$$

Effect of Rescatterings on the DIS Cross Section



$+ \cdots$

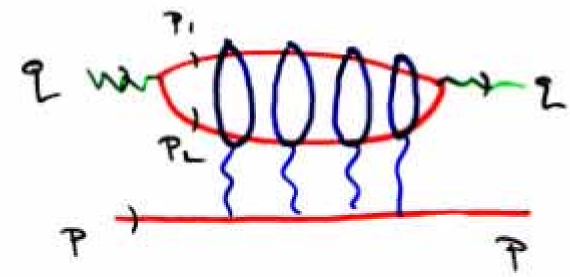
p_1: aligned jet
p_2: spectator jet

$$Q^4 \frac{d\sigma}{dQ^2\, dx_B} = \frac{\alpha}{16\pi^2}\,\frac{1-y}{y^2}\,\frac{1}{2M\nu}\int \frac{dp_2^-}{p_2^-}\, d^2r_\perp\, d^2R_\perp\, |M|^2$$

$$|M| = \left| \frac{\sin[g^2 W(\vec{r}_\perp,\vec{R}_\perp)/2]}{g^2 W(\vec{r}_\perp,\vec{R}_\perp)/2}\, M_{Born}(p_2^-,\vec{r}_\perp,\vec{R}_\perp)\right|$$

< 1 for all $\vec{r}_\perp, \vec{R}_\perp$

Equiv. to sum of cuts of forward virt. Compt. ampl.



Find shadowing only arises from diagrams involving attachments to p_1 !

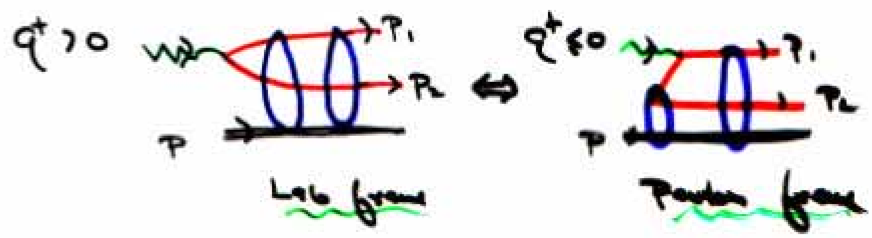
· cuts give Glauber-Gribov shadowing

Same result in Feynman, l.c.g. (ML)

↑ from $\frac{2p_{\perp 1}-k_\perp}{k^+}$ term

Conclusions

Shadowing of DIS cross section due to



Interference of Diff channels — Involves FSI of struck jet!

* Shadowing from rescattering of struck (current) quark in the target within the coherence length

$$\boxed{l_{Ioffe} = \frac{2\nu}{Q^2} = \frac{1}{M x_B}}$$

∴ Structure functions not totally specified by l.c. wavefunctions!

$$F_2(x_B, Q^2) \neq \sum_n \int |\psi_n(x_i, k_\perp)|^2 \, \delta(x_q - x_B)$$

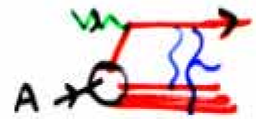
Also DVCS

* New generalized P.O.E. — $P\exp[ig\int_{-\infty}^{\infty} dw_\mu A^\mu(w)]$

* Factorization theorems, sum rules which follow from O.P.E. unchanged.

* Measurable physical effects from rescattering
  of current quark jet

– $\langle k_\perp^2 \rangle_A$



– Energy loss, but finite ΔE preserves x-scaling

– LPM effect : bremsstrahlung suppressed.

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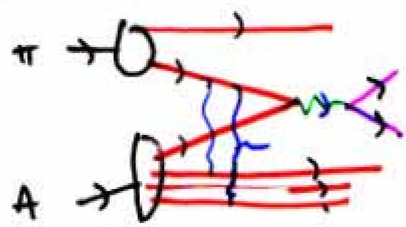
* 

Similar A-dep effects in Drell-Yan

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* Consequences for spin constraints ?

* Deeply virtual Compton scattering ?