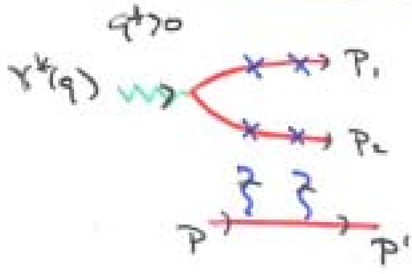
Effect of Rescatterings on the DIS Cross Section



$+\cdots$

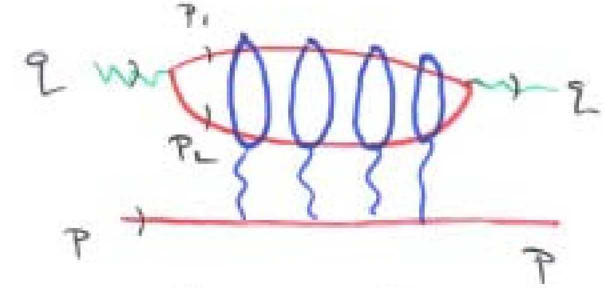
p_1: aligned jet
p_2: spectator jet

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

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

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

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



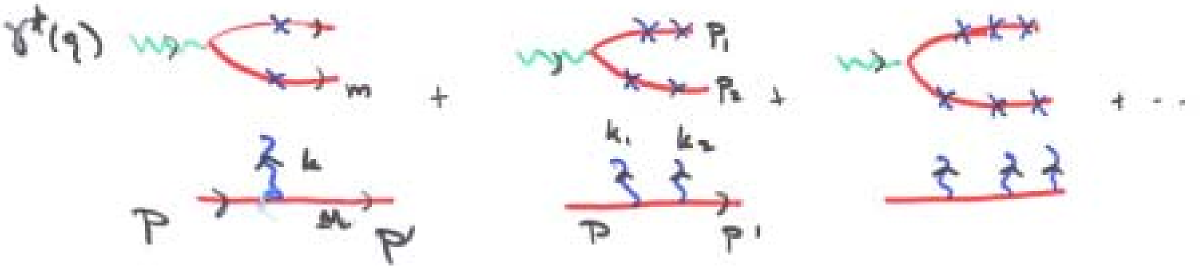
Find shadowing only arises from diagrams involving attachments to p_1 in F.G.!

cuts give Glauber-Gribov shadowing

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

↑ from $\frac{2\vec{p}_{\perp 1}-\vec{k}_\perp}{k^+}$ term

Model Calculation



Scalar quarks, crossed + uncrossed graphs, large
+ seagulls

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

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

$$\mathcal{M}_{Born} = -2ieMQ\,P_2^- \, V(m_{\|}, r_\perp)$$

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

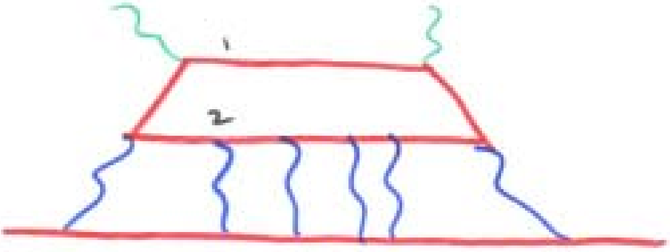
$$m_{\|}^2 = P_2^- M x_B + m^2$$

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

$$Q^4 \frac{d\sigma}{dQ^2 dx_B} = \frac{\alpha}{16\pi^2} \frac{1-y}{y^2} \frac{1}{2M\nu} \int \frac{dP_2^-}{P_2^-} d^2r_\perp \, d^2R_\perp \, |\mathcal{M}|^2$$

In Light-Cone gauge (Kovchegov prescription)

must keep



Final state rescattering

↑ P_2 line

These graphs are suppressed in Feynman gauge

but in l.c.g

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

and $n\cdot k = k^+ = O\left(\frac{1}{\nu}\right)$ for on-shell states!

* Result: identical answer as Feynman gauge
* Not included in l.c.g wavefunctions!

M-L, PV prescriptions differ by resid. g. trans

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

$$n \cdot n = 0$$

Light-Cone Gauge Prescriptions

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

The pole at $n\cdot k = k^+ = 0$ requires an analytic presc:

$$\frac{1}{k^+} = \begin{cases} \dfrac{k^+}{(k^+-i\eta)(k^++i\eta)} & \text{Principal value} \\[2ex] \dfrac{1}{k^+-i\eta} & \text{Kovchegov} \\[2ex] \dfrac{1}{k^+-i\eta\,\epsilon(k^-)} & \text{Mandelstam-Leibbrandt} \end{cases}$$

$$\epsilon(x) = \theta(x) - \theta(-x)$$

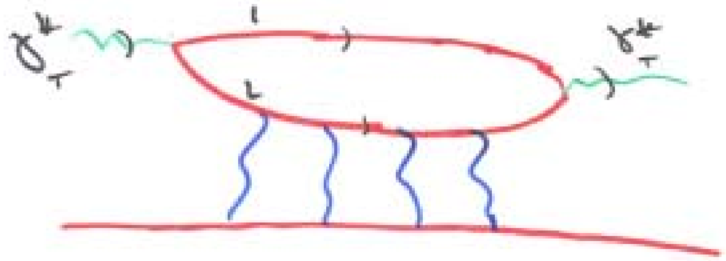
M-L : $\dfrac{k^-}{k^-k^+ - i\eta} = \dfrac{k^-}{k^2 - k_\perp^2 - i\eta}$ causal simila to Feynman-prop.

Kovchegov : non-causal !

- * Find FSI of current get vanishes in k pres!
- * But corresponds to solving LC w.f. in external field!

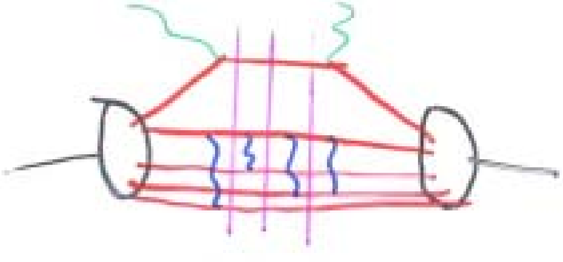
McLerran et al

In lab frame, l.c. gauge calc. looks like:



aligned jet config

- On-shell rescattering of line p_2
- Shadowing of structure functions
- leading twist
- large color dipole moment $r_\perp \sim O(\frac{1}{M})$
- leading twist diffractive dissociation
- Not part of l.c. wavefunctions



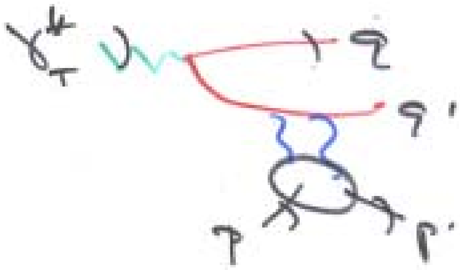
leading twist
not in
$\psi_n(x, k_\perp)$

Diffractive Dissociation $\gamma^* p \to q\bar{q}\, p'$

is leading twist contrib to

DIS structure function $F_T(x, Q^2)$

Hoyer, Magnea, SJB



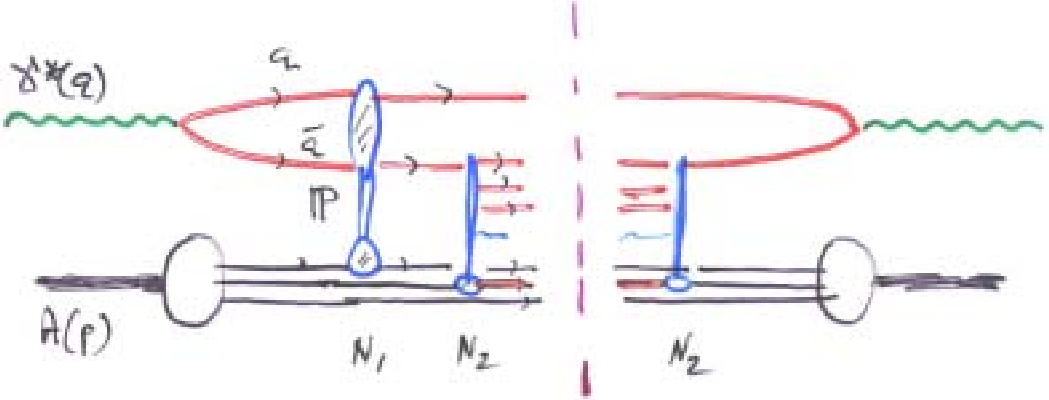
* Not given by $|\psi^p_n(x, k_\perp, \lambda)|^2$!

⇒ Nuclear shadowing from destructive interference of diffractive dissociation channels

* Not given by $|\psi^A_n(x, k_\perp, \lambda)|^2$!

∘∘ Structure functions not Prob. Dists!

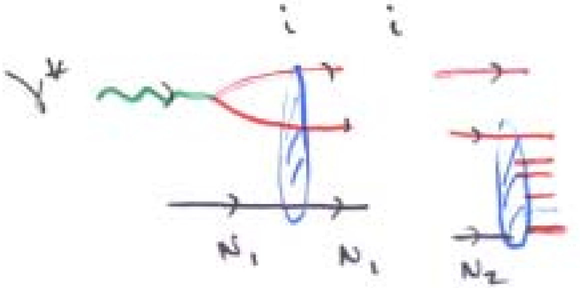
Hoyer, Peigne, Marchal, Sannino, SJB



- Nuclear shadowing due to destructive interference of diffraction amplitude (2-step + 1-step)

Glauber, Gribov

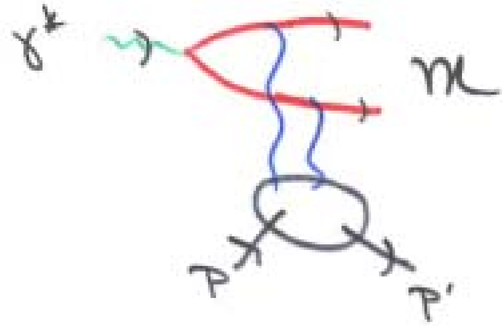
* Phase structure critical



- Diffraction $\gamma^* N_1 \to \bar{q} q N_1'$ $\left\{ \begin{array}{l} \text{leading twist} \\ \text{finite fraction of DIS} \end{array} \right.$

* None of this in l.c. w/fs! – $\psi_n(x, k_\perp)$ real! FSI!

Diffractive Dissociation (large rapidity gaps) is leading twist in QCD



$$\frac{d\sigma}{dM^2}(\gamma^* p \to M p')$$

Review by Hebecker

Kopeliovich, Nicolaev

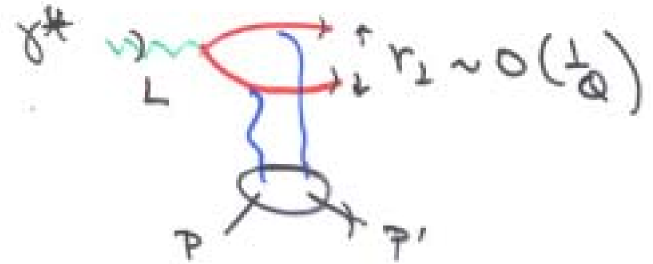
$$\frac{d\sigma_T}{dM^2} \sim \left(\frac{1}{M^2+Q^2}\right)^2 , \quad \sigma_T \sim \frac{1}{Q^2}$$

aligned jet regime   Bj + Kogut

large color dipole   Hoyer, Magnea, SJB

- Coherence for $L_{\text{Ioffe}} = \frac{2\nu}{Q^2} > R_N$
- Shadowing in nuclei for $L_{\text{Ioffe}} = \frac{2\nu}{Q^2} > R_A$

Color-dipole picture of Diffractive Events



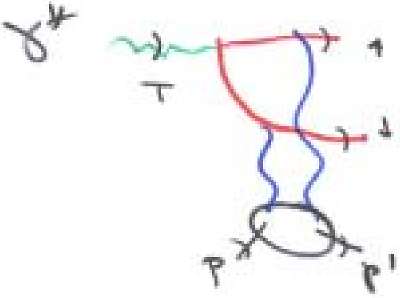
$r_\perp \sim O(\frac{1}{Q})$

$\gamma^*_T p \to m\, p'$

hard BFKL Pomeron

$\sigma^*_L \sim \frac{1}{Q^4} s^{\alpha_P - 1}$

higher twist, rapid rise in s



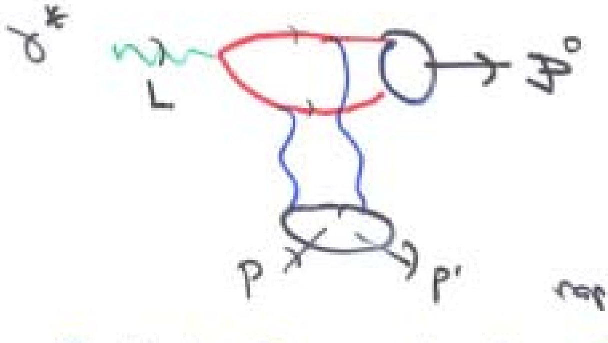
$r_\perp \sim O(\frac{1}{M})$

$\gamma^*_L p \to m\, p'$

Soft Pomeron

$\sigma^*_T \sim \frac{1}{Q^2} s^{\alpha_P - 1}$

leading twist !
moderate rise



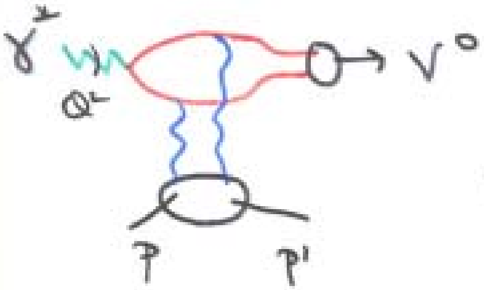
$r_\perp \sim O(\frac{1}{Q})$

$\sigma^L_{\gamma^* p \to \rho^0 p} \sim \frac{f_\rho^2}{Q^6} s^{\alpha_P - 1}$

rapid rise: hard BFKL pom.

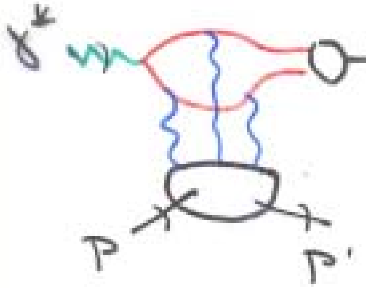
Frankfurt, Gunion, Mueller, Strikman, SJB

Hard Diffraction $\gamma^* p \to V^0 p$



Frankfurt, Gunion
Strikman, Mueller, SJB

$$V^0 = \rho^0, \omega, \phi, \underbrace{J/\psi, \Upsilon}_{\text{Ryskin, et al}} \ldots$$



$\to \pi^0, \eta^0 \ldots$

odderon, γ exchange.

σ_L dominates: small $b_\perp^{q\bar{q}}$: $\gamma_L \to \rho_L$

sensitive to $\phi_H(x,Q)$

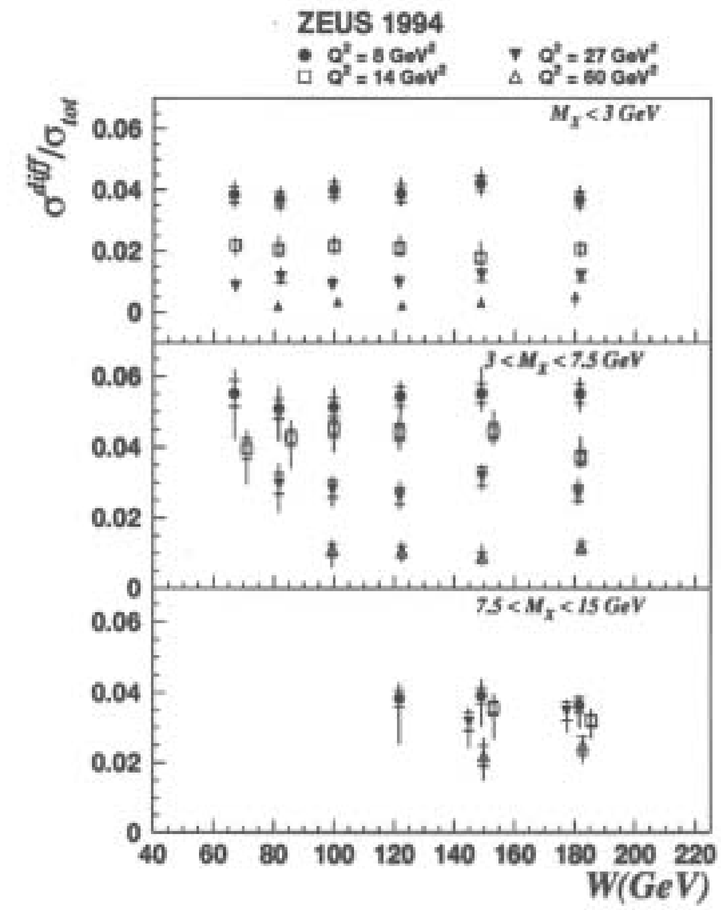
color transparency

s-dep corresponding to $g(x,Q^2)$

$$\mathcal{M} \sim s^{\alpha_P(t)} F(t)$$

↑ BFKL Pom.

Comparison of diffractive and DIS cross sections



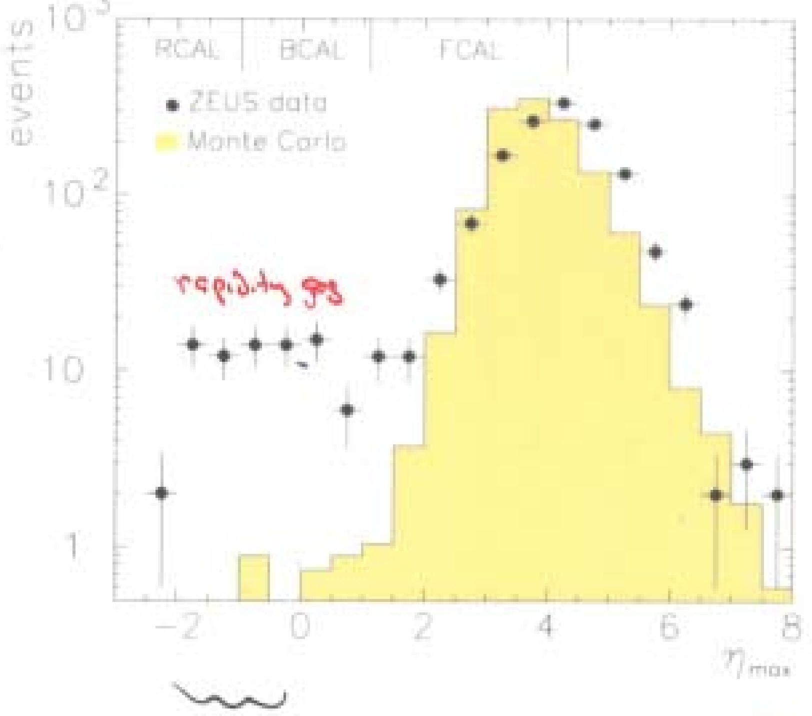
Diffractive cross section has same energy dependence as inclusive cross section !

pQCD

$$\frac{\sigma^{diff}}{\sigma^{tot}} \sim \frac{(xg)^2}{(xg)} \sim (W^2)^{\lambda_{e}}$$

optical theorem $\frac{d\sigma^{diff}}{dt}\Big|_{t=0} \sim \sigma^{diff} \sim (\sigma^{tot})^2 \sim (W^2)^{\lambda}$

Regge $\sigma^{diff} \simeq$ [illegible] $(W^2)^{\alpha_{IP}}$



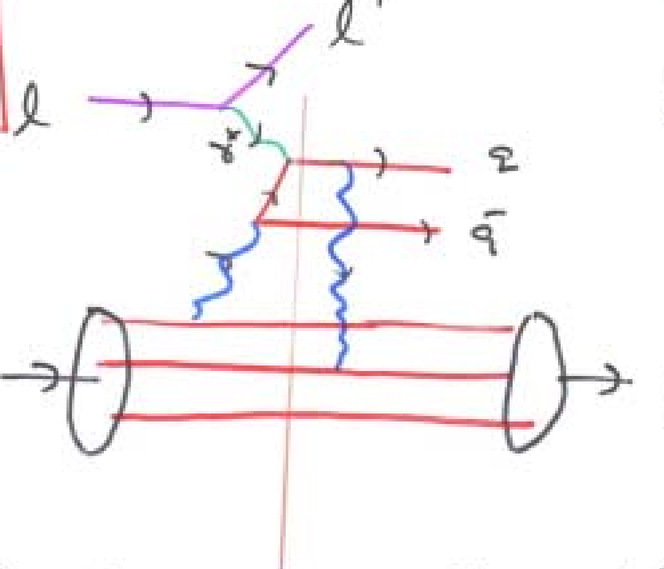
minimal excitation
of proton

Ref: Hebecker
hep-ph/9909504

Non-universal Pomeron Coupling

Hoyer, Peigne, Marchal, Sannino, SJB

DIS Diffraction



$\ell p \to \ell' p' X$

(rap gap)

- 2nd gluon occurs after γ^* interaction exchange
- Cut gives imaginary phase !
- Coupling depends on color dipole moment of $q\bar{q}$

Hebecker, Quack, SJB

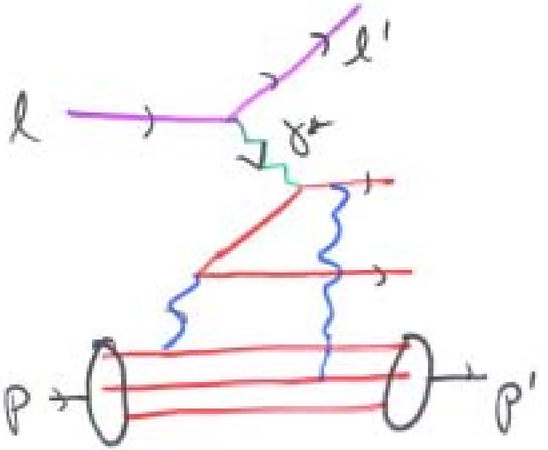
∴ Pomeron not part of proton w.f.

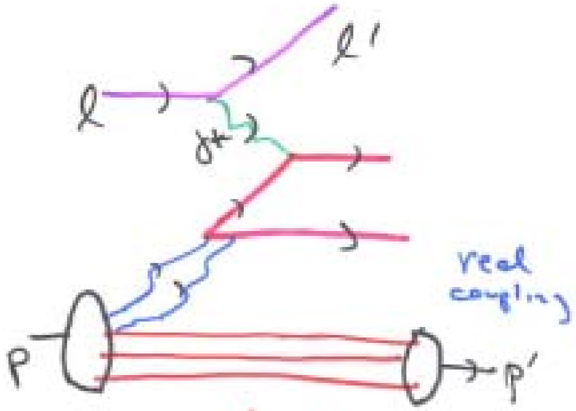
Not universal !

No!

$P_{\gamma/p}(x)$, $P_{q/p}(x)$, $P_{g/p}(x)$, $\cancel{P_{pom/p}(x)}$

Diffraction at HERA





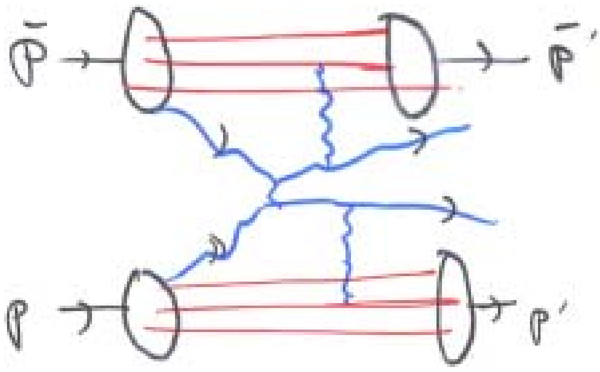
Non-universal pomeron coupling

BHMPS

~~factorized picture~~

Ingelman Schle..

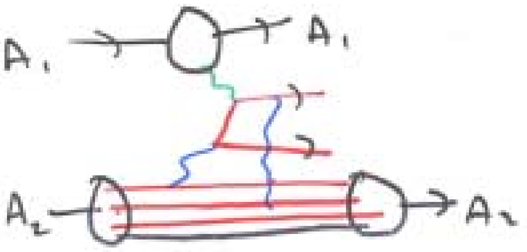
Double Diffraction at Tevatron



$\bar{p} p \to \bar{p}' p'$ Jet Jet

two rap. gaps.

UPC at RHIC



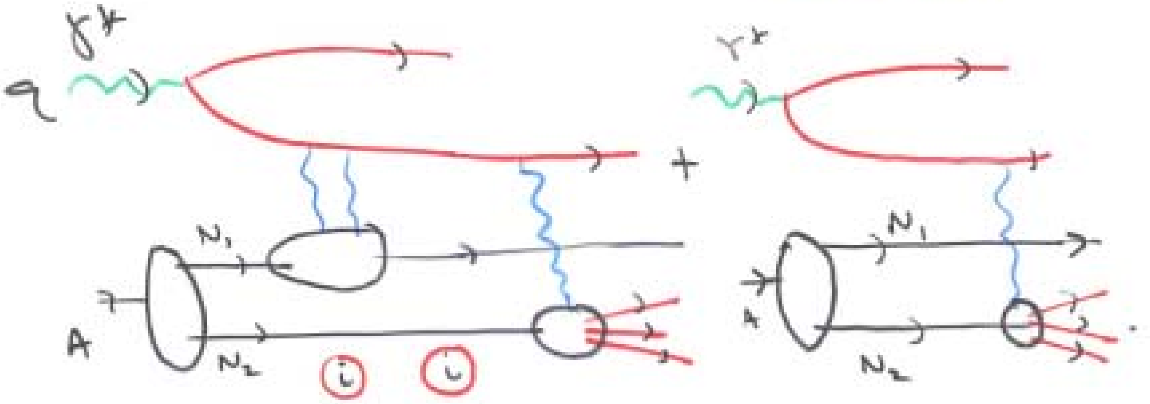
$A_1 A_2 \to A_1' A_2'$ Jet Jet

UPC two gaps

$\sigma \sim Z_1^2 A_2^{4/3}$

Diffraction leads to nuclear shadowing:

Gribov, Glauber
Pumplin, SJB



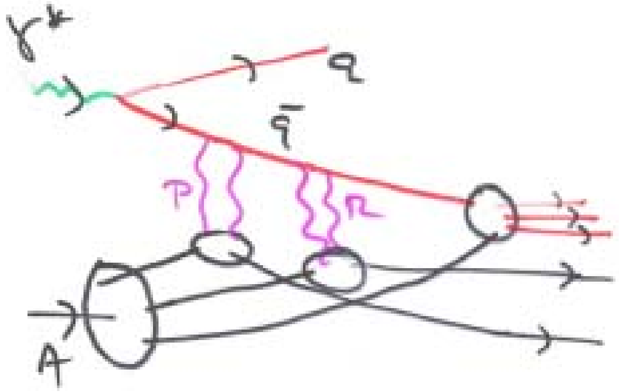
- Destructive interference leads to shadowing at low x.
  Frankfurt, Strikman
- Shadowing ↓ quark, gluon distributions
- Reggeon exchange leads to antishadowing
  Lu, SJB

H. Lu + SJB

Now apply Glauber theory to $T_{\bar{q}A}$

$$T_{\bar{q}A}(s,\mu^2) = T_{qN}(s,\mu^2)$$

$$\cdot \sum_{J=1}^{A} \frac{1}{J} \begin{bmatrix} A \\ J \end{bmatrix} \left[\frac{i\, T_{\bar{q}N}(s,\mu^2)}{4\pi\, p_{cm}\, s^{1/2} (R^2+2b)} \right]^{J-1}$$



$$\frac{F_{2A}(x)}{A\, F_{2N}(x)} = \frac{\int ds\, d^2k_\perp \,\mathrm{Im}\, T_{\bar{q}A}}{A \int ds\, d^2k_\perp \,\mathrm{Im}\, T_{\bar{q}N}}$$

produces shadowing from Pomeron $x < 0.1$

anti shadowing from Reggeon !

$x \sim 0.15$

- Nuclear shadowing due to destructive interference of diffractive channels.

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

Cut contribution ⇒ i

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

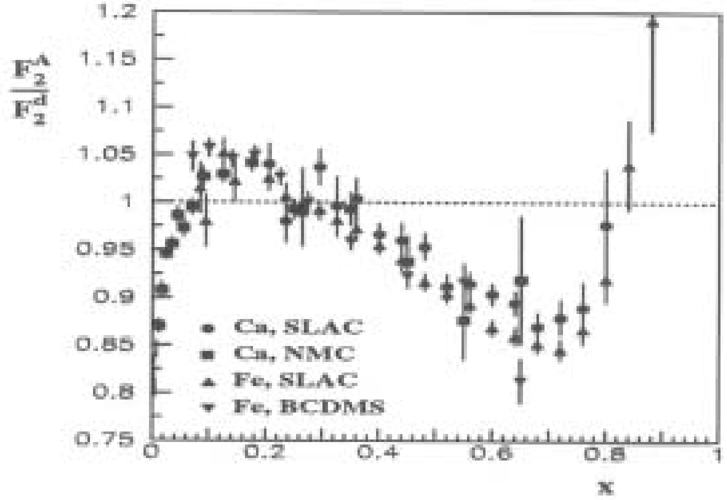
$\psi_{n/A}(x_i, \vec{k}_{\perp i}, \lambda_i)$

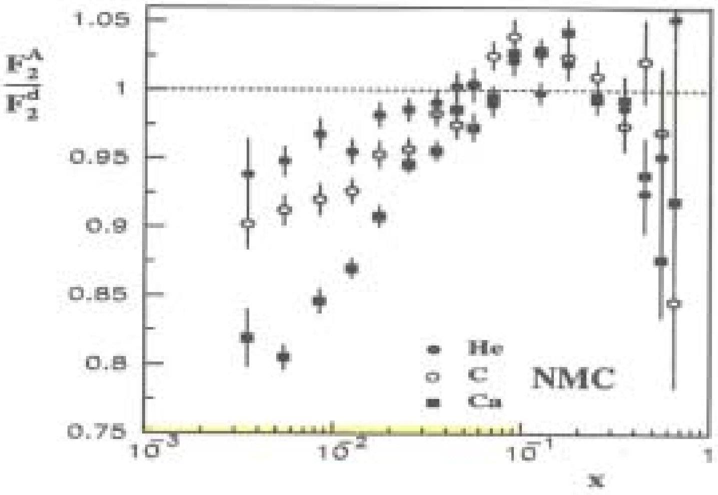
are real! No phase info from intermediate on shell states for stable targets.

— Anti-shadowing from non-singlet Reggeon exchange.

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

Nuclear structure functions





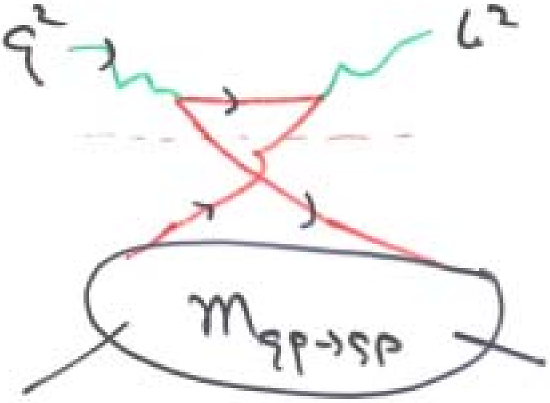
coherence length of hadronic configurations

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

BCG

Given $\mathcal{M}_{qp\to qp}(\hat{s}, t)$

predict $T_{\mu\nu}(q^2, p\cdot q, t)$



gauge-invariant
crossing symmetric

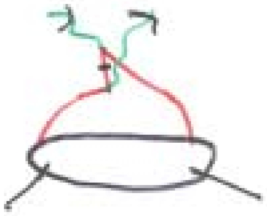
+ crossed
graph

Measure Real part from interference with B.H.

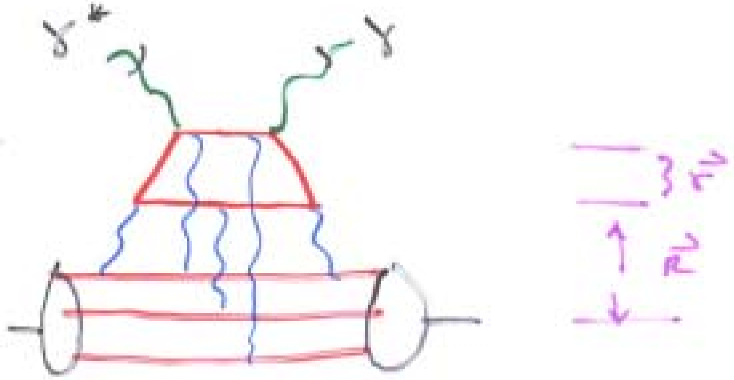
Im $T_{\mu\nu}(q^2, p\cdot q, t=0) = W_{\mu\nu}(q^2, p\cdot q)$

Bj-scaling structure functions

Extra $J=0$ pieces from
"fixed pole"
instantaneous quark exchange



Is the handbag approximation for DVCS accurate?



Dipole-dipole interaction

Khrapovitch
Hebecker, Quack
/SJB

In DIS, FSI cause shadowing, diffraction

$$W = \frac{1}{2\pi} \log \frac{|\vec R + \vec r|}{|\vec R|}$$

Correction factor $\frac{\sin^2 W g^2/2}{W^2 g^2/2} < 1$

Hoyer
Peigne
Marchal
Sannino
SJB

Expect phases, $\vec S_p \cdot \vec k \times \vec k'$ SSA.
in DVCS

Hwang
Schmidt
SJB

Hwang, Vanderhaeghen (in progress)
SJB

Alternate: Regge form gives phase for $\gamma^* p \to \gamma p'$

Close, Gunion, SJB

LPS Model

Summary:

* Diffractive Dissociation of $\gamma^*_T \to q \bar{q}$

leading twist contrib to $F_2(x, Q^2)$!

$\gamma^* p \to$ Jet Jet p'

* Leads to leading twist nuclear shadowing !

* Rescattering effect coherent if

$$\frac{2\nu}{Q^2} = \frac{1}{M x_{Bj}} > R_{Target}$$

** Not included in Ψ_{LC} ! (PV presc

$$F_2(x, Q^2) \neq \sum_q e_q^2 \, x \, q(x, Q^2) \quad |$$

$$q(x, Q^2) = \sum_n \int |\Psi_n(x, k_\perp, \lambda)|^2 \delta(x_q - x)$$

* Light-cone gauge can be misleading

* Many consequences for sum rules, low x extrap
Interpretation of DIS.