Parton $k_\perp$ - broadening in DIS and DY in a scalar QED model

S. Peigné

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collaboration: J. Aichelin, F. Arleo, P.B. Gossiaux
T. Gousset, M. Thomas.

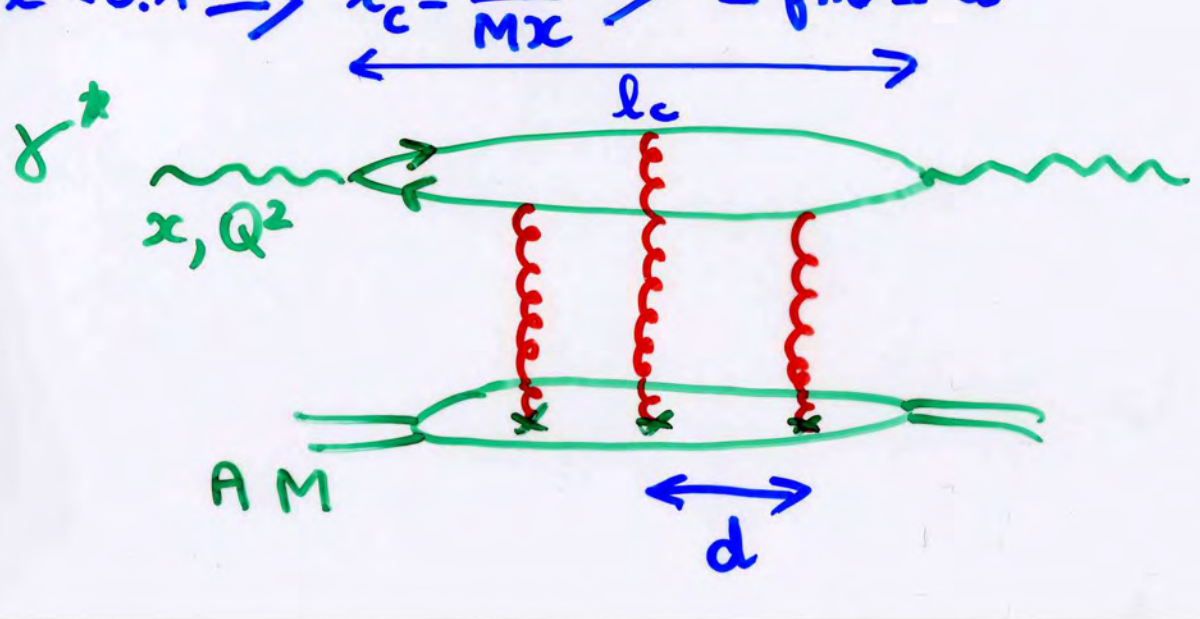
hep-ph/0505066
PRD72: 054010, 2005

- (NP) PDF's depend on target.

DIS : $F_2^A \neq A F_2^p$ □

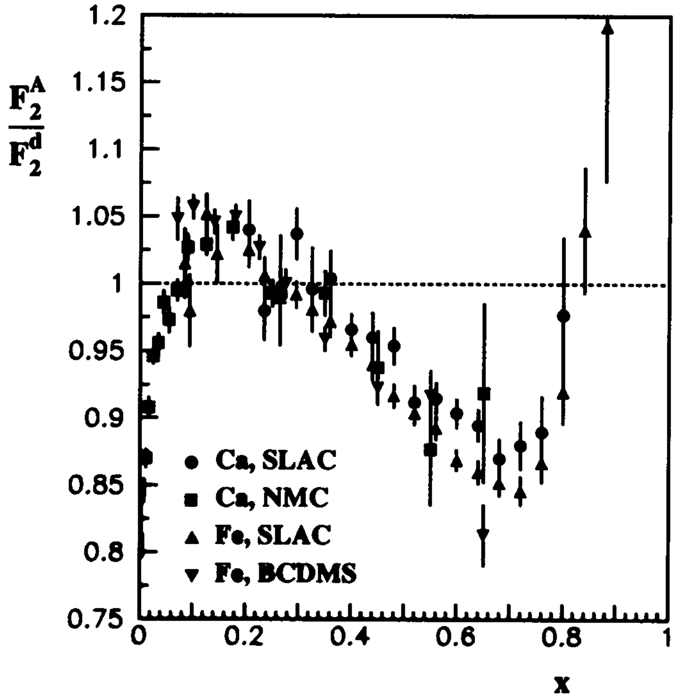
$x < 0.1 \Rightarrow F_2^A < A F_2^p$ (shadowing)

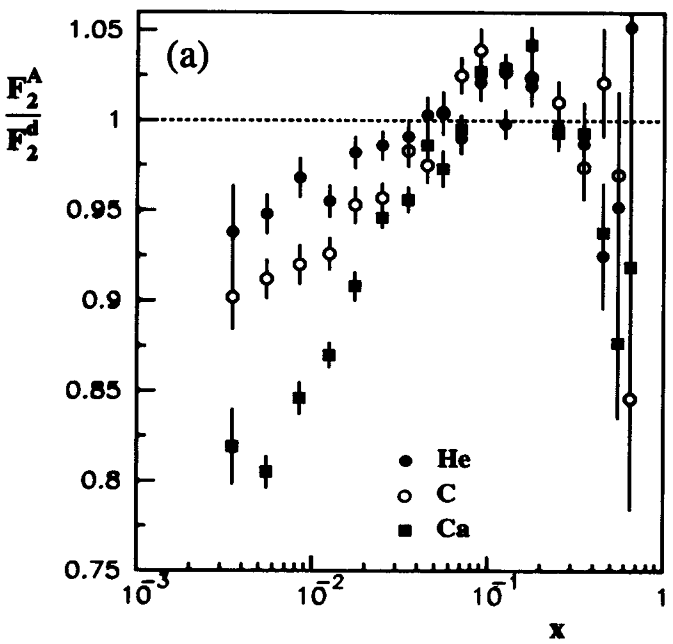
$x<0.1 \Rightarrow l_c = \frac{1}{Mx} > 2\,\text{fm} \simeq d$



DIS Nuclear Shadowing

G. Piller, W. Weise, Phys. Rept. 330 (2000) 1-94,
hep-ph/9908230





- QCD factorization theorems (Collins, Soper, Sterman)

$\Rightarrow$ $f_{q/T}(x, Q^2)$ is "universal" $\equiv$ process-independent

shadowing also seen in DY $\square$
compatible with shadowing in DIS

Universality of <u>inclusive</u> PDFs
widely checked and successful

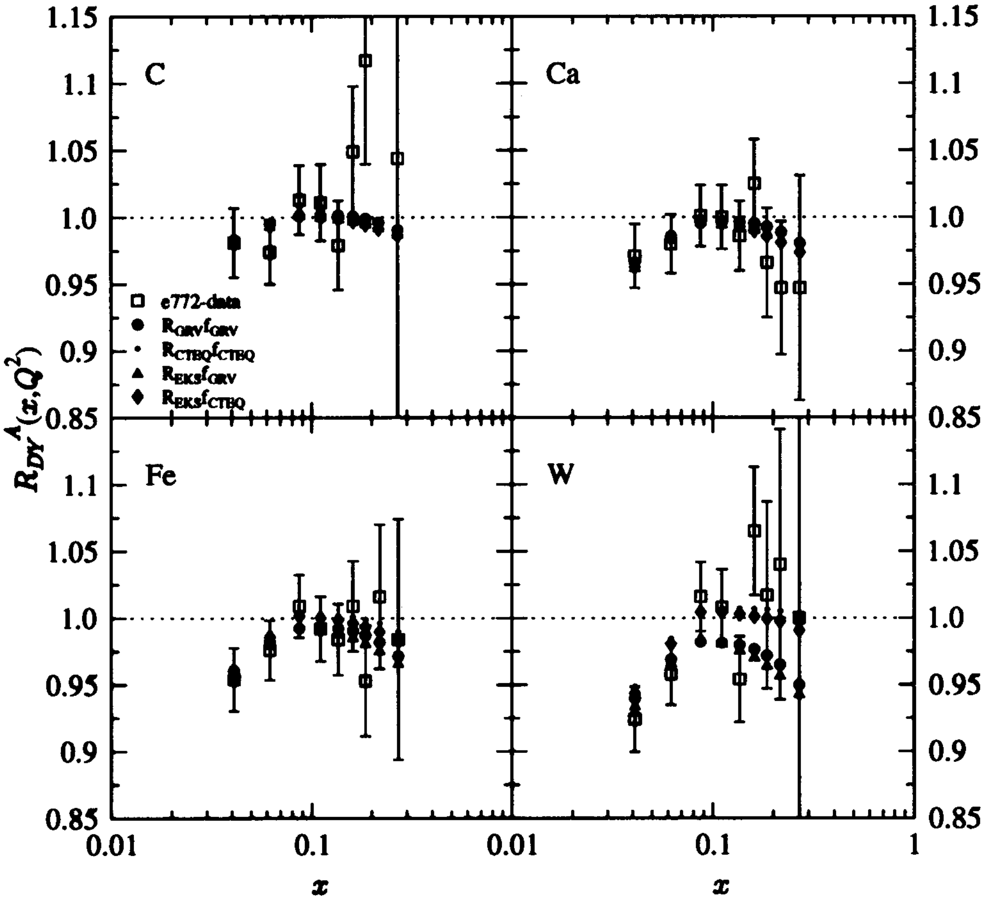
What about other NP quantities?

- nuclear $k_\perp$-broadening
- $f_{q/T}(x, \underline{\underline{\ell_\perp}})$

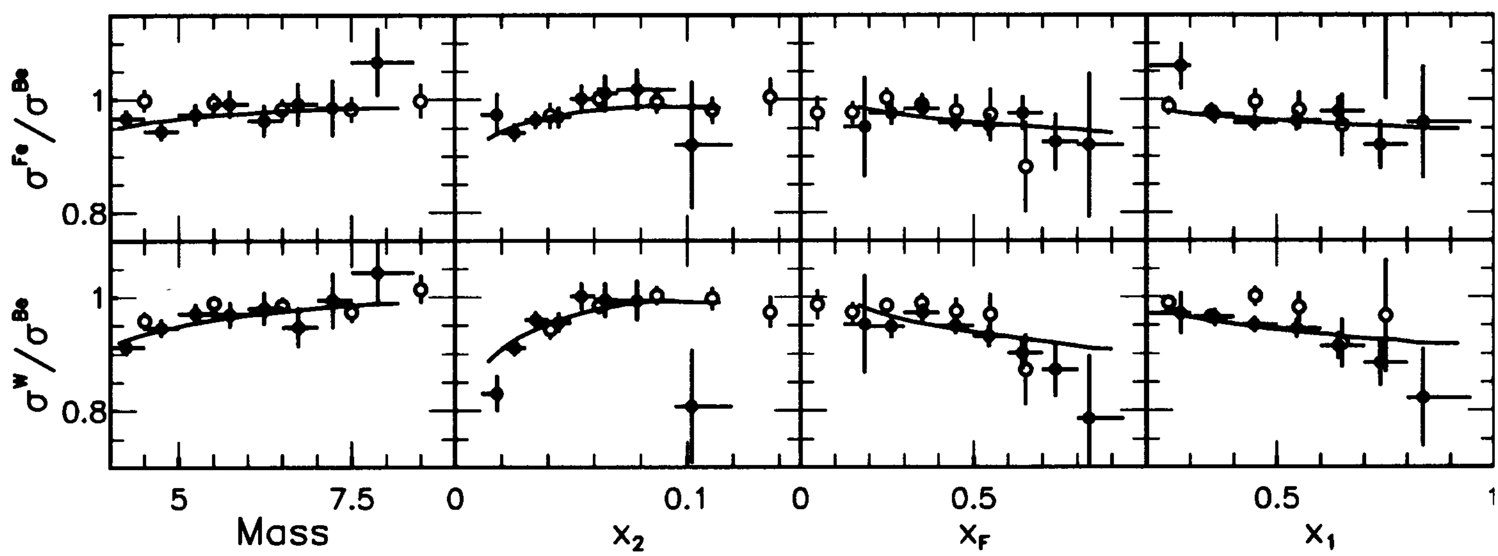
Nuclear Shadowing in Drell-Yan Production

(Figure from Eskola, Kolhinen, Salgado, Eur.Phys.J.C9:61-68,1999)

E772 Collab., Phys. Rev. Lett. 64 (1990) 2479



E866/NuSea Collab., Phys. Rev. Lett. 83 (1999) 2304



large $x > 0.1$ $\Rightarrow$ rescatterings and hard production process are incoherent

$\to \langle p_T^2 \rangle_A \propto \Lambda_i^2 \; A^{1/3} \quad (i = q, g)$

(random walk in $\vec{p}_\perp$ - space
Chiappetta, Pirner (1987))

Λ_i^2 NP universal scale

Data on nuclear $p_\perp$ - broadening ?

- dijet γA production [E683]
- dijet hA " [E609]
- quarkonium hA p^o [NA3, E772]
- DY (hA) [NA3, E772]
- nuclear DIS [HERMES, CLAS]

gross feature :

$$\Lambda^2_{DY} < \Lambda^2_{J/\psi,\Upsilon} < \Lambda^2_{dijet}$$

(GeV²) 0.02 0.05 – 0.1 0.2 – 0.6

difficult to understand :

- Luo, Qiu, Sterman (1994)
- Guo (1998)

- Johnson, Kopeliovich, Tarasov (2001)
- Raufeisen (2003)

breaking of universality ?

maybe not

most of the data involves $x \sim 0.1$
at the frontier between coherent and incoherent regimes

no universality of $\langle p_T^2 \rangle_A$ expected at $x \ll 1$ $\Longrightarrow$ differences in Λ^2 could be due to coherent effects

$x \ll 1$ regime studied in

- Kopeliovich, Schäfer, Tarasov (1999)
- Kopeliovich, Raufeisen, Tarasov, Johnson (2003)

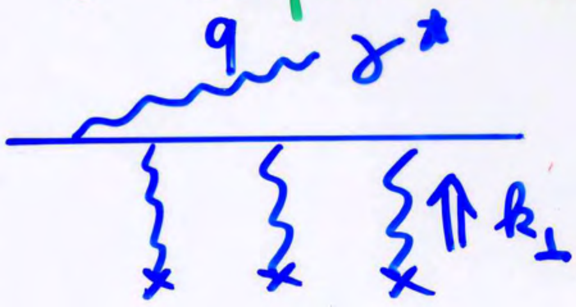
for $\langle q_\perp^2 \rangle_{\underline{\underline{DY}}}$ and nuclear modification

in "color dipole formulation"

- connection with standard QCD fact^o ?
- $\langle q_\perp^2 \rangle_{DY}$ compared to $\langle q_\perp^2 \rangle_{dijet}$?
- Consistent with universality of $f(x, \ell_\perp)$?

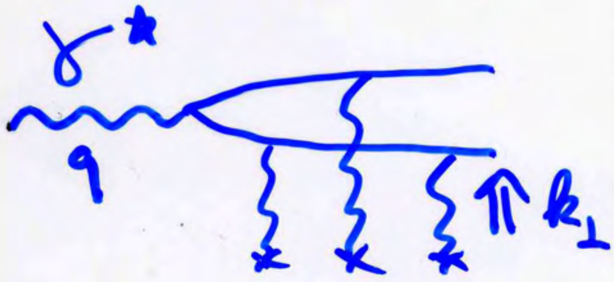
To study those questions :

- "full" coherence $x = \dfrac{Q^2}{2M\nu} \ll 1$
- Explicit model (SQED) to compare



DY

AND



DIS

($\sim$ dijet $\gamma \rho^o$)

Pedagogical model illustrating several features :

probed quark

- universality of $f_{q/T}(x \ll 1, \ell_\perp)$ checked for T = "p" and T = "A"

(agrees with factorization :

Collins, Soper (1981)
Ji, Ma, Yuan (2005))

- universality in other "$\perp$" variables can be broken

$k_\perp \equiv$ Coulomb rescattering $\neq \ell_\perp$

$$\langle k_\perp^2 \rangle_{DY} \overset{(x \ll 1)}{\neq} \langle k_\perp^2 \rangle_{DIS}$$

- trivially : $p_\perp$ nuclear broadening differs (at $x \ll 1$) if $\neq$ transverse mom. variables are compared :

$$\langle \ell_\perp^2 \rangle = \langle q_\perp^2 \rangle_{DY} \neq \langle k_\perp^2 \rangle_{DIS}$$

- equivalence between "PDF" and "color dipole" formulations is explicit

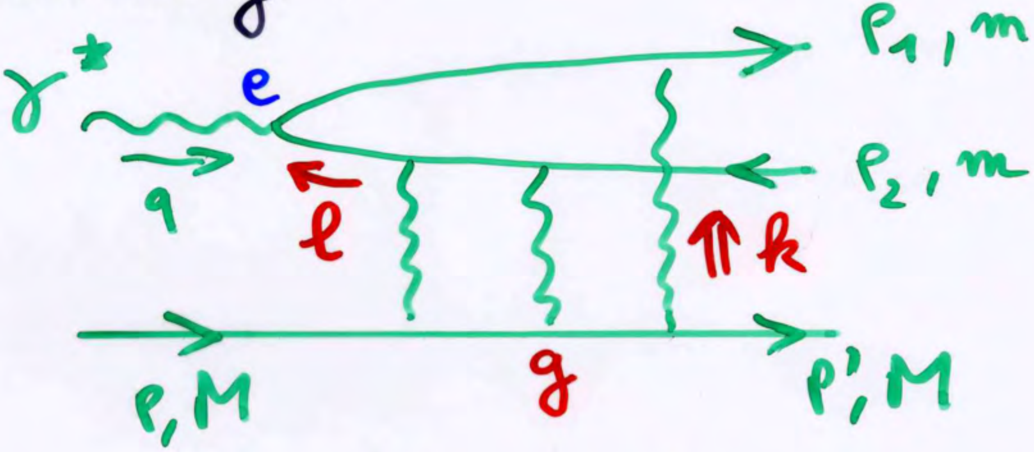
(1) Model in aligned_jet kinematics and interpretation

DIS off a proton

use model of Brodsky et al (2002)

for DIS shadowing :

$\mathcal{M}_{DIS} =$



- SQED ; $k^\pm \equiv k^0 \pm k^z$
- Bjorken limit : $q^- = 2\nu$, $Q^2 \to \infty$

  at fixed $x_B = \dfrac{Q^2}{2M\nu}$

$$q = (q^+, q^-, \vec{0}_\perp) = (-Mx_B, q^-, \vec{0}_\perp)$$

- full coherence : $x_B \ll 1$
- Study Coulomb soft rescatterings

at leading_twist $\Rightarrow$ "ALIGNED_JET"

$$\begin{cases} p_1^- \simeq q^- \to \infty \\ p_2^- \text{ fixed} \end{cases} \Rightarrow y = \frac{p_2^-}{2\nu} \to 0$$

$(Q^2, \nu \to \infty \gg p_2^- \gg k_{i\perp}, p_{i\perp} \gg k_i^+, p_2^+ \sim M x_B \gg p_1^+)$

interpretation:

hard scale ν does not flow in lower part

$\Rightarrow$ • hard vertex: $\gamma^* q \to q \sim \mathcal{O}(g^0)$

(∞ mom. frame)

• $|\mathcal{M}_{DIS}|^2 \Leftrightarrow$ soft dynamics

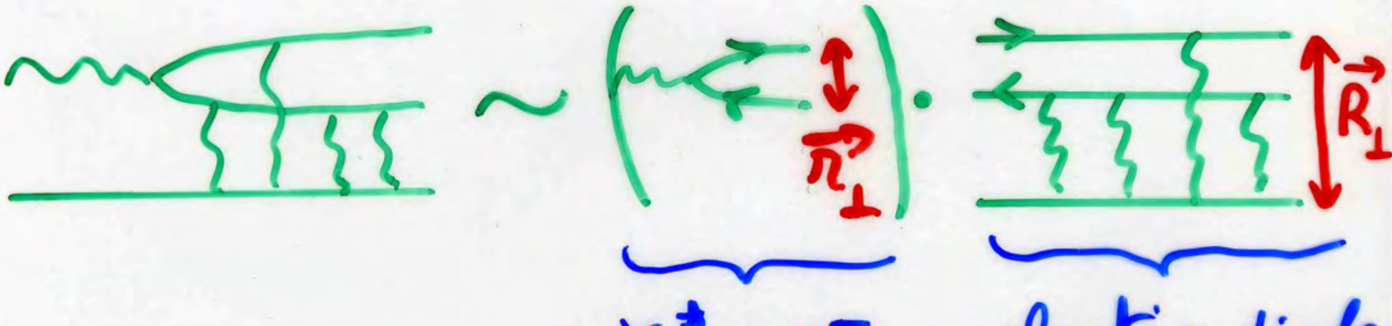
contribution to $f_{q/T}^{DIS}(x, \ell_\perp)$

probed quark momentum:

$$\begin{cases} x = \dfrac{\ell^+}{p^+} = \dfrac{p_1^+ - q^+}{p^+} = x_B \\ \ell_\perp = k_\perp - p_{2\perp} \neq k_\perp \end{cases}$$

exact calculation resumming Coulomb rescatterings

$$\mathcal{M}_{DIS}(\vec{r}_\perp, \vec{R}_\perp) \sim \psi(r_\perp) \cdot T_{q\bar{q}}(\vec{r}_\perp, \vec{R}_\perp)$$



$\gamma^* \to q\bar{q}$ elastic dipole scatt. amp.

$\Psi(r_\perp) \sim K_0(m_\parallel r_\perp)$ $\qquad m_\parallel^2 = p_2^- M x_B + m^2$

dipole size $r_\perp \lesssim m_\parallel^{-1}$ $\qquad = y\,Q^2 + m^2$

(soft)

$$i\,T_{q\bar{q}}(\vec{r}_\perp, \vec{R}_\perp) = 1 - \exp\left[-ig^2\,W(\vec{r}_\perp, \vec{R}_\perp)\right]$$

W = dipole single scatt. amp.

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

$\lambda^2 \leftarrow$ photon mass

$$= \frac{1}{2\pi}\Big[\underbrace{K_0(\lambda R_\perp)}_{\substack{\text{quark}\\ \text{rescatt.}}} - \underbrace{K_0(\lambda|\vec{R}_\perp + \vec{r}_\perp|)}_{\substack{\text{antiquark}\\ \text{rescatt.}}}\Big]$$

unitarity relation:

$$|T_{q\bar{q}}|^2 = -2\,\mathrm{Im}\,(T_{q\bar{q}})$$

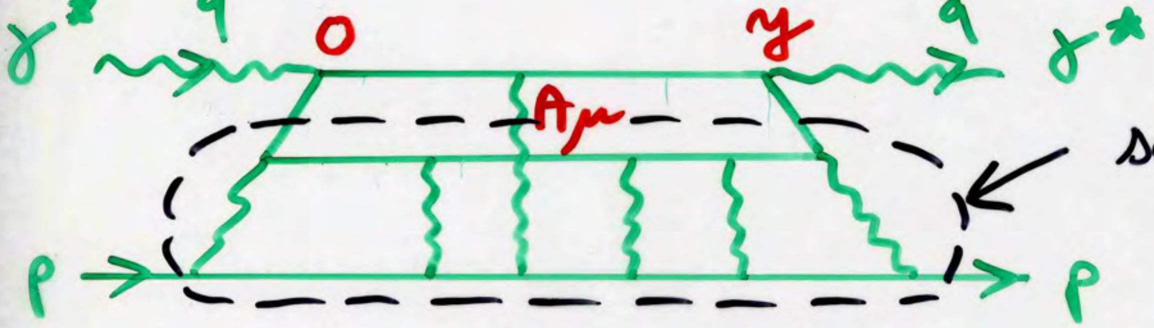
dipole scattering cross section:

$$\sigma_{q\bar{q}}(r_\perp) = \int d^2\vec{R}_\perp\, |T_{q\bar{q}}(\vec{r}_\perp, \vec{R}_\perp)|^2$$

Recall QFT expression of $f_{q/T}$:

$$f_{q/T}(x_B, Q^2) = \int \frac{dy^-}{8\pi} e^{-i x_B p^+ y^-} \langle T(p) | \bar{q}(y^-) \gamma^+ P\exp\left[ig \int_0^{y^-} A^+ \right] q(0) | T \rangle$$

(Collins , Soper 1982)



soft target dynamics

- in general gauge, struck quark rescatt. do modify $\sigma_{DIS}^{L.T.}$ Brodsky et al 2002
- they build $P\exp\left[\int_0^{y^-} ig A^+\right]$ to ensure gauge invariance.

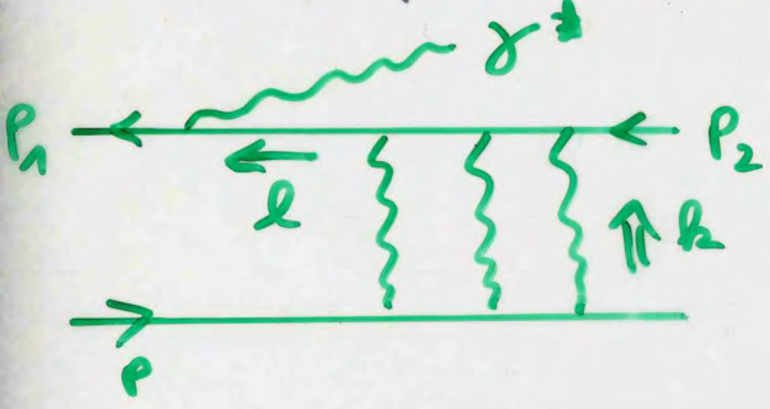
(• rescatterings in intermediate state $\langle y^- \rangle \sim \frac{1}{M x}$ are NOT a gauge artefact:
$A^+ = 0 \Rightarrow$ rescatt. within target spectators)

- in our perturbative model :

– soft target dynamics
– gauge link
are treated on same footing
(expansion in g^2)

DY off a proton

DY model obtained from DIS by crossing and $q^2 < 0 \rightarrow q^2 > 0$ (S.P. 2002)



- hard process: $\bar{q}q \rightarrow \gamma^*$
- soft dynamics

$\Longleftrightarrow f^{DY}_{q/T}(x, l_\perp)$

$$\otimes \quad \boxed{\mathcal{M}_{DY}(\vec{r}_\perp, \vec{R}_\perp) = -e^{ig^2 G(R_\perp)} \mathcal{M}_{DIS}(\vec{r}_\perp, \vec{R}_\perp)}$$

$G(R_\perp) =$ Coulomb phase (IR sensitive)

$$= \int \frac{d^2\vec{k}_\perp}{(2\pi)^2} \frac{e^{i\vec{R}_\perp \cdot \vec{k}_\perp}}{k_\perp^2 + \lambda^2} = \frac{1}{2\pi} K_0(\lambda R_\perp)$$

(DY: scattering of a monopole $\Longrightarrow$ IR sensitive amplitude)

Simple consequences of $\otimes$:

- $|\mathcal{M}_{DIS}|^2 = |\mathcal{M}_{DY}|^2 \Longrightarrow f^{DIS}_{q/T}(x) = f^{DY}_{q/T}(x)$ (inclusive)

- $\mathrm{Im}(\mathcal{M}_{DY}) \neq \mathrm{Im}(\mathcal{M}_{DIS})$

$\Rightarrow$ Pomeron / diffraction is not universal

Collins, Frankfurt, Strikman 1993

Berera, Soper 1994

- $\mathcal{M}_{DIS}$ and $\mathcal{M}_{DY}$ <u>not</u> related by simple phase shift in conjugate $k_\perp$ - space :

$$\frac{d\sigma_{DY}}{dk_\perp^2} \neq \frac{d\sigma_{DIS}}{dk_\perp^2}$$

$\boxed{\text{non\_univ. of Coulomb rescatt. at } x \ll 1}$

- not in contradiction with factorization : $k_\perp$ internal to target structure, integrated out in $f_{q/T}(x, \underline{\underline{\ell_\perp}})$

easy check: $\dfrac{d\sigma}{d\ell_\perp^2}$ is universal

$$\Rightarrow \quad f_{q/T}^{DY}(x, \ell_\perp) = f_{q/T}^{DIS}(x, \ell_\perp)$$

probed quark

$$\frac{d\sigma^{DIS,DY}}{d\ell_\perp^2} \sim \int d^2 r_\perp \, d^2 r'_\perp \; e^{-i(\vec{r}_\perp - \vec{r}'_\perp)\cdot\vec{\ell}_\perp} \cdot$$

$$\cdot \, \Psi(r_\perp)\Psi(r'_\perp)\left[\frac{1}{2}\sigma_{q\bar{q}}(r_\perp) + \frac{1}{2}\sigma_{q\bar{q}}(r'_\perp) - \frac{1}{2}\sigma_{q\bar{q}}(|r_\perp - r'_\perp|)\right]$$

(Kopeliovich, Tarasov, Schäfer 1999)

universality $\Rightarrow$ in DY (as in DIS),

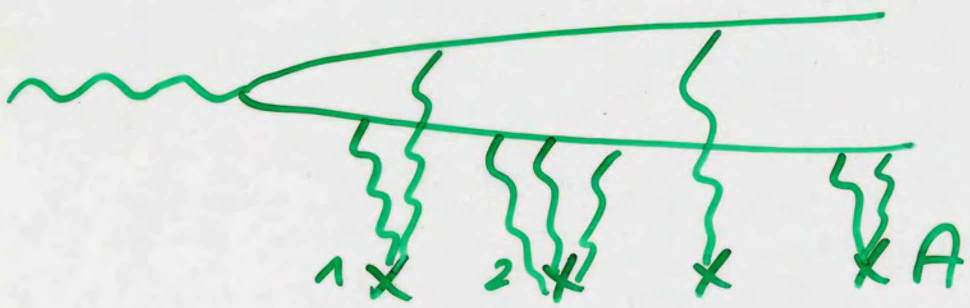
$\frac{d\sigma}{d\ell_\perp^2}$ in terms of $\underline{\underline{\sigma_{q\bar{q}}}}(r_\perp)$

(Kopeliovich 1996 (Born level)
Brodsky, Hebecker, Quack 1996
Raufeisen, Peng, Nayak 2002)

<u>Remark:</u>

$$\begin{cases} \dfrac{d\sigma}{d\ell_\perp^2} = \dfrac{d\sigma}{dq_\perp^2} & \text{(DY) DY pair} \\[2ex] \dfrac{d\sigma}{d\ell_\perp^2} = \dfrac{d\sigma}{dp_{1\perp}^2} & \text{(DIS) leading jet} \end{cases}$$

Model for nuclear target



(DIS)

1 centre $\longrightarrow$ A centres

$$R_A << l_c = \frac{1}{Mx}$$

$$G(R_\perp) \longrightarrow G_A(\vec{R}_\perp) = \sum_{i=1}^{A} G(|\vec{R}_\perp - \vec{x}_{i\perp}|)$$

$$\boxed{\begin{aligned} \mathcal{M}^A_{DIS} &\sim \Psi(r_\perp)\, T^A_{q\bar{q}}(\vec{r}_\perp, \vec{R}_\perp) \\ \mathcal{M}^A_{DY} &= -e^{ig^2 G_A(R_\perp)}\, \mathcal{M}^A_{DIS} \end{aligned}}$$

$$iT^A_{q\bar{q}} = 1 - e^{-ig^2 W_A}$$

$$W_A = G_A(\vec{R}_\perp) - G_A(\vec{R}_\perp + \vec{r}_\perp)$$

$$\Rightarrow \quad \frac{d\sigma^A}{d\vec{l}_\perp} \text{ is universal} \quad \Longrightarrow$$

$$f^{DY}_{q/A}(x, \vec{l}_\perp) = f^{DIS}_{q/A}(x, \vec{l}_\perp)$$

Average over $\vec{x}_{i_\perp}$:

$$\langle \ \rangle_A \equiv \int \prod_{i=1}^{A} \left(\frac{d^2 \vec{x}_{i_\perp}}{S} \right)$$

$$\langle e^{-ig^2 W_A} \rangle_A = \dots = \exp\left[-T \frac{\sigma_{q\bar{q}}(r_\perp)}{2} \right]$$

$$T = \frac{A}{S} \quad \text{thickness}$$

$$\left. \begin{array}{l} \text{total coherence} \\ + \text{ simple averaging} \end{array} \right\} \Longrightarrow$$

$$\frac{d\sigma^A}{d\vec{l}_\perp} \sim S \int d^2\vec{r}_\perp \, d^2\vec{r}\,'_\perp \, e^{-i(\vec{r}_\perp - \vec{r}\,'_\perp)\cdot \vec{l}_\perp} \Psi(r_\perp) \Psi(r'_\perp)$$

$$\cdot \left[1 - e^{-T\sigma_{q\bar{q}}(r_\perp)/2} - e^{-T\sigma_{q\bar{q}}(r'_\perp)/2} + e^{-T\sigma_{q\bar{q}}(|\vec{r}_\perp - \vec{r}\,'_\perp|)/2} \right]$$

Kopeliovich, Tarasov, Schäfer (1999)

- $\frac{d\sigma^A}{d\vec{l}_\perp}$ expressed in terms of $\sigma_{q\bar{q}}(r_\perp)$

- same target size dependence in DIS and DY

$\Rightarrow$ same $\underline{\underline{l_\perp}}$ - broadening

Compare DY (NA10, E772)

to nuclear DIS data :

HERMES (talk: V. Muccifora)

CLAS (talk: W. Brooks)

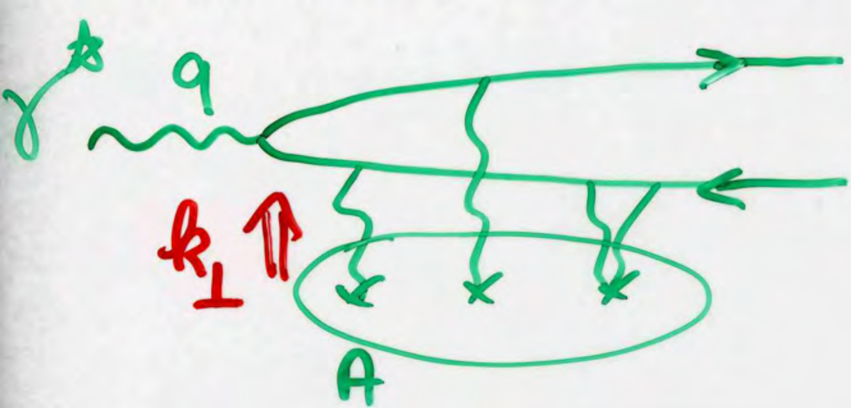
$\rightarrow$ direct test of universality of

$$f_{q/A}(x, \underline{\underline{\vec{l}_\perp}})$$

② $\boxed{\text{Symmetric kinematics and } \langle k_\perp^2 \rangle}$

Model for dijet production ?

$\rightarrow$ new kinematics :



p_2^- scales as $\nu \Rightarrow p_2$ part of hard subprocess :

- $\gamma^* g \longrightarrow q\bar{q}$ (DIS ~ dijet leptoprod.)
- $\bar{q}\, g \longrightarrow \bar{q}\, \gamma^*$ (DY + jet)

transverse mom. transfer to hard system :

$k_\perp$ = Coulomb exchange =

$\left\{ \begin{array}{ll} \bullet \text{ dijet mom. imbalance} & \text{(DIS)} \\ \bullet\ \gamma^* / \text{jet mom. imbalance} & \text{(DY)} \end{array} \right.$

$$\frac{d\sigma_{DIS}}{d\vec{k}_\perp} \neq \frac{d\sigma_{DY}}{d\vec{k}_\perp}$$

$k_\perp \neq \ell_\perp$ (probed in aligned-jet kinematics)

$\Rightarrow$ no contradiction with factorization

<u>Single center</u>: a curious property

$$\frac{d\sigma_{DIS}}{d\vec{k}_\perp} \sim \int d^2\vec{r}_\perp |\psi(r_\perp)|^2 \cdot \frac{d\sigma_{q\bar{q}}(\vec{r}_\perp, \vec{k}_\perp)}{d\vec{k}_\perp}$$

$$\frac{d\sigma_{DY}}{d\vec{k}_\perp} \underset{k_\perp \gg \lambda}{\sim} \int (\ldots) \cdot \left[\frac{d\sigma_{q\bar{q}}(\vec{r}_\perp, \vec{k}_\perp)}{d\vec{k}_\perp}\right]_{BORN}$$

(similar to e^+e^- vs bremsstrahlung
Bethe, Mascimon (1954))

$$\langle k_\perp^2 \rangle_{DIS} = \langle k_\perp^2 \rangle_{Born} + O(g^8 m_\parallel^2)$$

$$\langle k_\perp^2 \rangle_{DY} = \langle k_\perp^2 \rangle_{Born} + O(g^8 \lambda^2)$$

" Nucleus "

$$\frac{d\sigma^A_{DIS}}{d^2\vec{k}_\perp} \sim \int d^2\vec{r}_\perp \, |\Psi(r_\perp)|^2 \cdot \frac{d\sigma^A_{q\bar{q}}(\vec{r}_\perp, \vec{k}_\perp)}{d^2\vec{k}_\perp}$$

$$\frac{d\sigma^A_{DY}}{d^2\vec{k}_\perp} \sim \frac{d\sigma^A_q}{d^2\vec{k}_\perp} \cdot \int d^2\vec{r}_\perp \, |\Psi(r_\perp)|^2 \left(2 - 2\cos \vec{k}_\perp \cdot \vec{r}_\perp\right)$$

A-dependence is driven by :

DIPOLE rescattering (DIS)

MONOPOLE " (DY)

$\Rightarrow$ $k_\perp$ (Coulomb)-broadening is non-universal ($x \ll 1$)

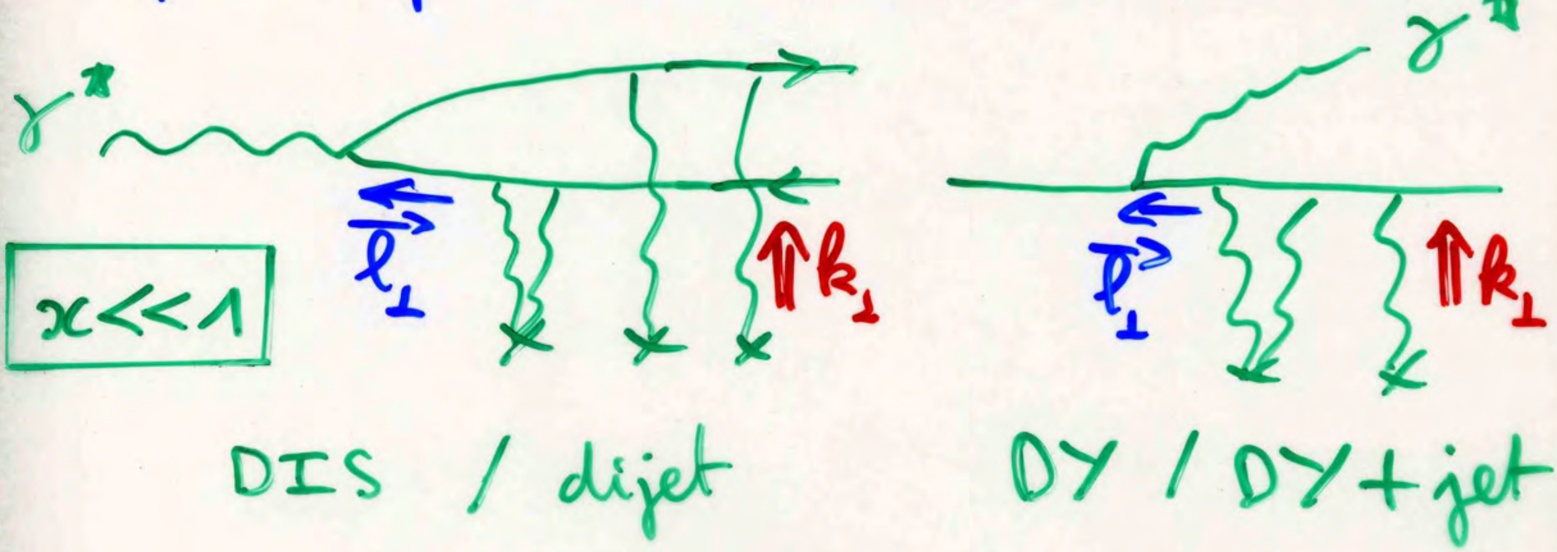
explicitly : $\Delta\langle k_\perp^2\rangle = \langle k_\perp^2\rangle_A - \langle k_\perp^2\rangle_p$

$$= \begin{cases} \left(\dfrac{g^4 T}{m_{/\!/}^2}\right) \times m_{/\!/}^2 = O(g^4 T) & \text{(DIS)} \\[2ex] \left(\dfrac{g^4 T}{k_\perp^2}\right) \times k_\perp^2 = O(g^4 T) & \text{(DY)} \end{cases}$$

(Dolejši , Hüfner, Kopeliovich , 1993)

Summary

Explicit perturbative SQED model



- universality of $\frac{d\sigma}{d\vec{l}_\perp} \Longrightarrow$

$$f_{q/T}^{DIS}(x, l_\perp) = f_{q/T}^{DY}(x, l_\perp) \quad \text{(aligned\_jet)}$$

dipole formulation $\Longleftrightarrow$ factorization approach

- non_universality of $\frac{d\sigma}{d\vec{k}_\perp}$

does not violate factorization

($k_\perp$ integrated out in $f_{q/T}(x, l_\perp)$)

– single centre : $\frac{d\sigma^{DY}}{d\vec{k}_\perp} = \left[\frac{d\sigma^{DY}}{d\vec{k}_\perp}\right]_{BORN}$

– nucleus : DIS → DIPOLE

DY → MONOPOLE

$$\boxed{\mathcal{M}_{DY}(\vec{r}_\perp, \vec{R}_\perp) \sim e^{i\varphi(R_\perp)} \mathcal{M}_{DIS}(\vec{r}_\perp, \vec{R}_\perp)}$$

- trivially : $\left.\frac{d\sigma}{d\vec{l}_\perp}\right)_{DY} \neq \left.\frac{d\sigma}{d\vec{k}_\perp}\right)_{dijet}$

not the same variable

$$R_{DY}(l_\perp) = 1 + \frac{2g^4 T}{\pi m_{//}^2} \ln^2\left(\frac{m_{//}}{\lambda}\right)$$

$(\lambda \ll l_\perp \ll m_{//})$

$$R_{dijet}(k_\perp) = 1 - \frac{4g^4 T}{5\pi m_{//}^2} \ln\left(\frac{m_{//}}{\lambda}\right)$$

- smallness of $\Delta\langle k_\perp^2\rangle_{DY}$ could be simply due to onset of coherent effects.