Investigation of the Time Evolution of Hadronization in DIS: Semi-Exclusive Processes and Grey Track Production

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1. INTRODUCTION and MOTIVATIONS

- The investigation of hadron attenuation processes is providing(HERMES at HERA) and will provide (Jlab) precious information on the space-time evolution of hadronization.
- The relevant question (Heavy Ion Collision and Possible Quark-Gluon Plasma Formation): *Is the observed hadron attenuation due to pre-hadron and hadron absorptions in the final state or to medium induced quark energy loss?* is under intensive investigation.
- In order to build up an internally-consistent and reliable theory of hadronization, it is also useful to analyze other processes which could discriminate various hadronization models.

Present Contribution

Analysis of two processes which, unless the rare process of leading hadron production, depend upon the **bulk** of the FSI of the hadronizing quark with the nuclear medium(Collaboration with: **L. Kaptari, B. Kopeliovich**)

1. **Semi- Exclusive DIS (SEDIS) processes $A(e,e'B)X$.**
   B - detected recoiling heavy fragment (nucleus $A-1$, $A-2$, etc.) and X- the unobserved jets of hadrons resulting from hadronization;

2. **Grey Tracks (GT) production in SIDIS.**
   GT-recoiling protons created in inelastic collisions of the hadronizing quark with the spectator nucleons.

The theoretical treatment of both processes within a Glauber-like treatment of FSI requires an

effective time-dependent nucleon debris-nucleon cross section

2. The EFFECTIVE *Debris-Nucleon* CROSS SECTION

(CdA, B. Kopeliovich, EPJA, A17(2003)133)

The hadronization model:

the formation of the final hadrons occurs during and after the propagation of the created nucleon debris through the nucleus, with a sequence of soft and hard production processes.

soft production $\rightarrow Q < \lambda = 0.65 GeV$ npQCD, string model
hard production $\rightarrow Q > \lambda = 0.65 GeV$ pQCD, gluon radiation model.

This model of hadronization is inspired and close to the one of:
B. Kopeliovich, J. Nemchik, E. Predazzi, A. Hayashigaki, Nucl.Phys. A740(2004)212

String decay:

- probability $W(t)$ for a string to create no quark pairs since its origin;
- time dependent length of the string $L(t)$, with $L_{max} = \frac{m_{qq}}{\kappa}$ with m_{qq}-mass of the "diquark" and $\kappa \simeq 1\, GeV\, fm^{-1}$ - the string tension;
- first breaking of the string (**S**) (within $\Delta t \simeq 1\, fm$) into a shorter string and a baryon (**B**);
- the creation of mesons (**M**) occurs as follows

$$\mathbf{S} \Rightarrow \mathbf{B} + \mathbf{S} \Rightarrow \mathbf{B} + \mathbf{S} + \mathbf{M} \Rightarrow \mathbf{B} + \mathbf{S} + \mathbf{2}\,\mathbf{M} + ...$$

The mean multiplicity of Mesons:

$$n_M(t) = \frac{\ln(1 + t/\Delta t)}{\ln 2}.$$

Gluon radiation mechanism:

- coherence time

$$t_c = \frac{2\,E_q\,\alpha\,(1-\alpha)}{k_T^2}\ ,$$

time which elapses from the creation of the leading quark and the emission of the gluon which lost coherence with the color field of the quark. α, $k_T = |\mathbf{k}_T|$, and E_q are the fraction of the quark light-cone momentum carried by the radiated quantum, its transverse momentum, and the quark energy, respectively.

- mean number of radiated gluons

$$n_G(t) = \int_{\lambda^2}^{Q^2} dk_T^2 \int_{k_T/E_q}^{1} d\alpha\, \frac{dn_G}{dk_T^2\, d\alpha}\, \Theta(t - t_c)\ ,$$

with number of radiated gluons (Gunion, Bertsch, Phys. Rev.D25(82)746)

$$\frac{dn_G}{d\alpha\, dk_T^2} = \frac{4\alpha_s(k_T^2)}{3\,\pi}\, \frac{1}{\alpha\, k_T^2}$$

- Time dependence of the gluon radiationcontrolled by the parameter $t_0 = (m_N x_{Bj})^{-1} = 0.2 fm/x_{Bj}$

$$t < t_0 \quad n_G(t) = \frac{16}{27}\left\{\ln\left(\frac{Q}{\lambda}\right) + \ln\left(\frac{t\,\Lambda_{QCD}}{2}\right)\ln\left[\frac{\ln(Q/\Lambda_{QCD})}{\ln(\lambda/\Lambda_{QCD}}\right]\right\}$$

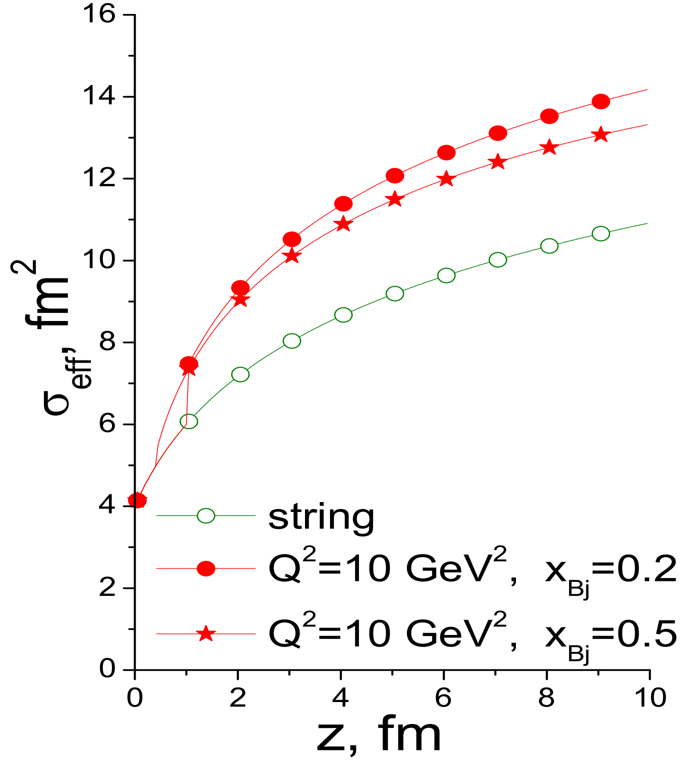
levels off at

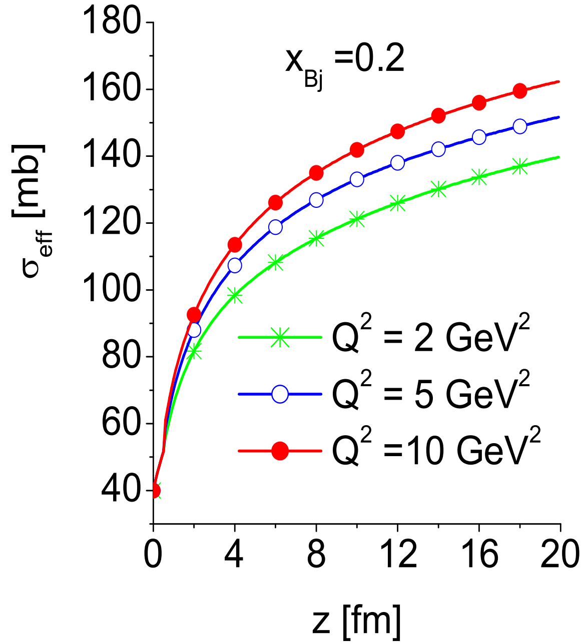
$$t > t_0 \quad n_G(t) = \frac{16}{27}\left\{\ln\left(\frac{Q}{\lambda}\frac{t_0}{t}\right) + \ln\left(\frac{t\,\Lambda_{QCD}}{2}\right)\ln\left[\frac{\ln(Q/\Lambda_{QCD}\sqrt{t_0/t})}{\ln(\lambda/\Lambda_{QCD})}\right]\right.$$
$$\left. + \ln\left(\frac{Q^2\,t_0}{2\,\Lambda_{QCD}}\right)\ln\left[\frac{\ln(Q/\Lambda_{QCD})}{\ln(Q/\Lambda_{QCD}\sqrt{t_0/t})}\right]\right\}$$

saturates at $t > t_0\,Q^2/\lambda^2 = 2\nu/\lambda^2$.

The debris-nucleon effective cross section

$$\sigma_{\mathbf{eff}}(\mathbf{t}) = \sigma_{\mathbf{tot}}^{\mathbf{NN}} + \sigma_{\mathbf{tot}}^{\mathbf{MN}}[\mathbf{n_M}(\mathbf{t}) + \mathbf{n_G}(\mathbf{t})]$$

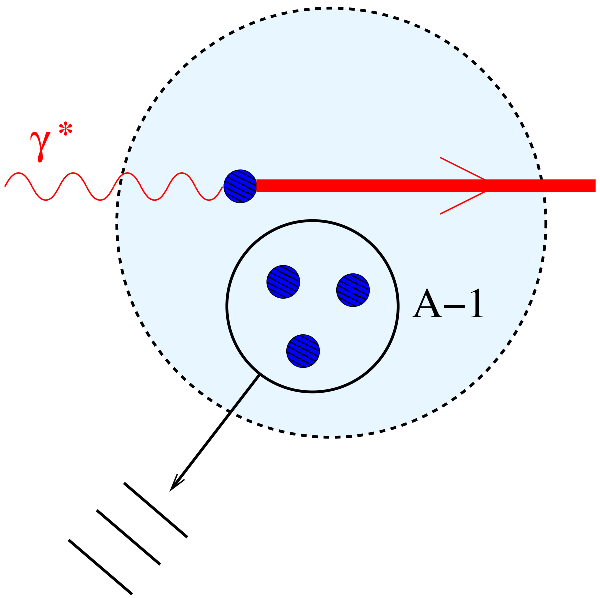




- Steep rise with time (distance).
- Q^2 and x_{Bj} dependence due to gluon radiation mechanism.

3. THE SEMI-EXCLUSIVE DIS $A(e,e'B)X$ PROCESS

PWIA : The debris propagates through the nucleus freely



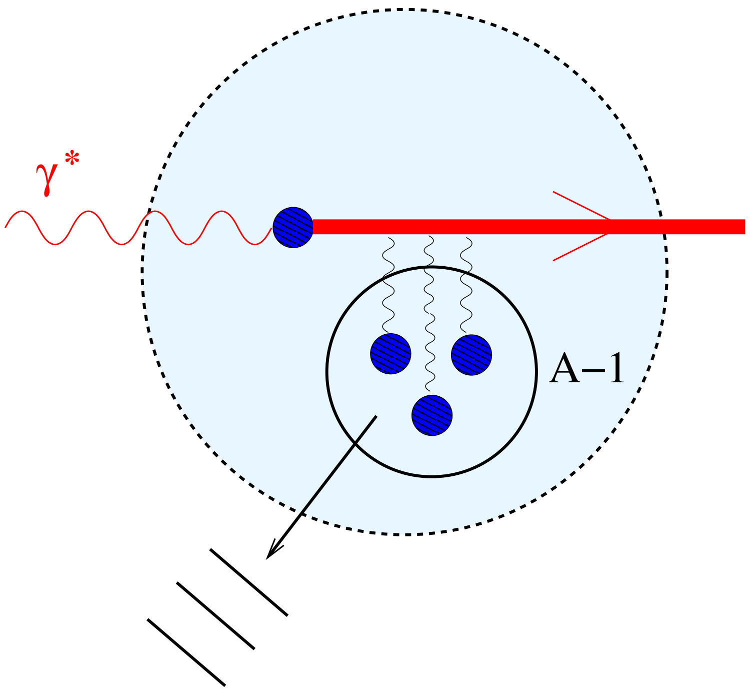
Melnitchouk, Sargsian, Strikman,
Z. Phys.A356(97)99

Simula, Phys. Lett. B387(96)245

CdA, Kaptari, Scopetta, EPJA 5(99)181

$$\frac{d\sigma^A}{dx dQ^2 d\vec{P}_{A-1}} = K^A(x, Q^2, y_A, z_1^{(A)}) z_1^{(A)} F_2^{N/A}(x_A, Q^2, p_1^2)\, P^A(E, |\vec{P}_{A-1}|)$$

FSI



- The hadronizing quark interacts with the spectator nucleons via $\sigma_{eff}(t)$
- The survival probability of (A-1) is reduced depending on the features of $\sigma_{eff}(t)$.

CdA, Kopeliovich, EPJA17(2003)133

Spectral Function ⇒ *Distorted* (D) Spectral Function.

$$P_D^A(E, \vec{P}_{A-1}) = \sum_f |F^{f,D}_{A-1,A}(\vec{P}_{A-1})|^2 \delta(E - (E_{min} + E^f_{A-1}))$$

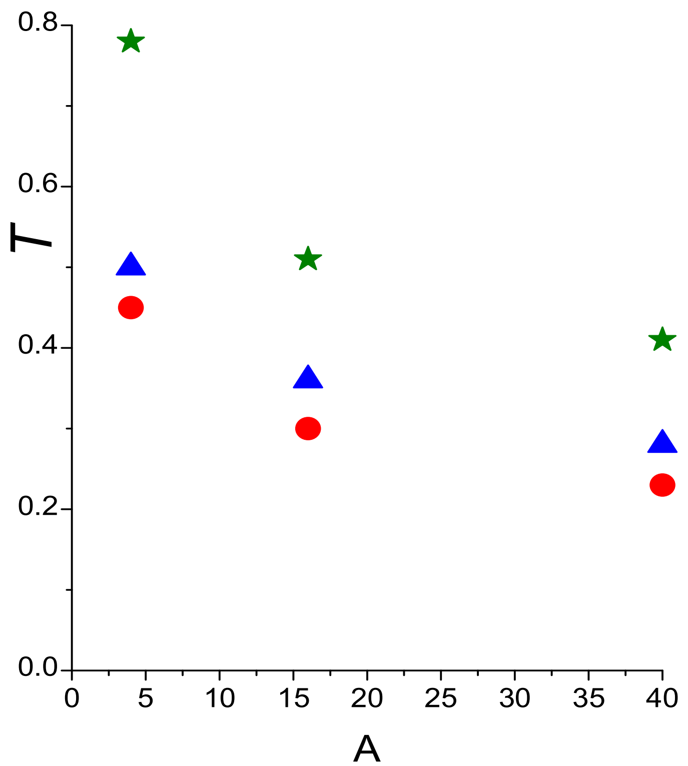
$$F^{f,D}_{A-1,A}(\vec{P}_{A-1}) =$$

$$= \int e^{i\vec{p}_{A-1}\vec{r}_1} S_G^\dagger(\vec{r}_1 \dots \vec{r}_A) \Psi^f_{A-1}{}^*(\vec{r}_2 \dots \vec{r}_A) \Psi^0_A(\vec{r}_1, \vec{r}_2 \dots \vec{r}_A)\ \delta\left(\sum_{j=1}^A \vec{r}_j\right) \prod_{i=1}^A d\vec{r}_i$$

$$S_G(\vec{r}_1 \dots \vec{r}_A) = \prod_{i=2}^A \left[1 - \Gamma^{N^*N}(\vec{b}_1 - \vec{b}_i, z_i - z_1)\Theta(z_i - z_1)\right]$$

$\Gamma^{N^*N}(\vec{b}_1 - \vec{b}_i, z_i - z_1)$-**time-dependent profile function**

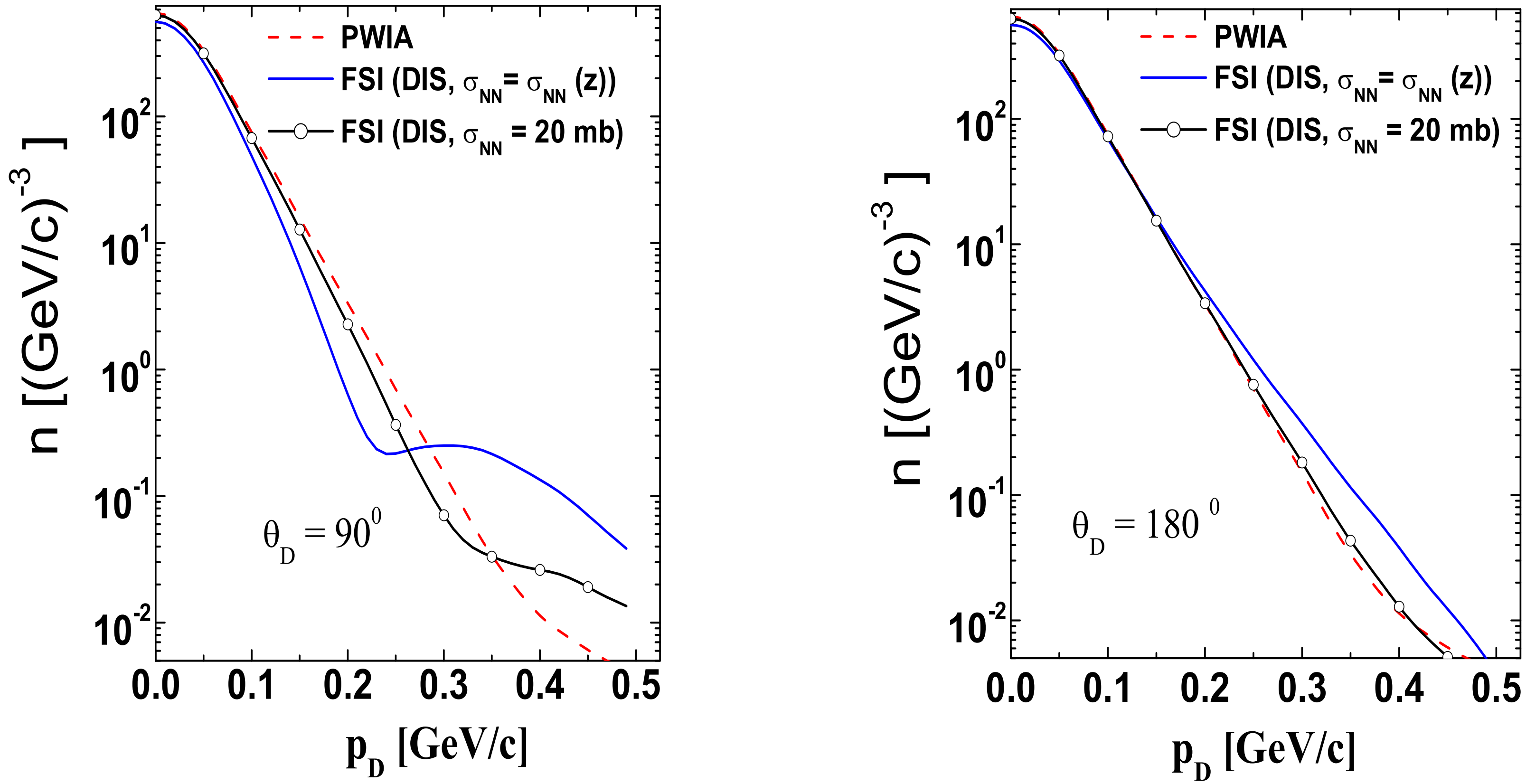
Survival probability of A-1



$$T = \int_{-\infty}^{\infty} dz\, \rho(\vec{b}, z) \exp\left[- S(\vec{b}, z)\right] \qquad S(\vec{b}, z) = \int_{z}^{\infty} dz'\, \rho_A(\vec{b}, z')\, \sigma_{eff}(z' - z)$$

(After CdA, Kopeliovich, EPJA17(2002)133)

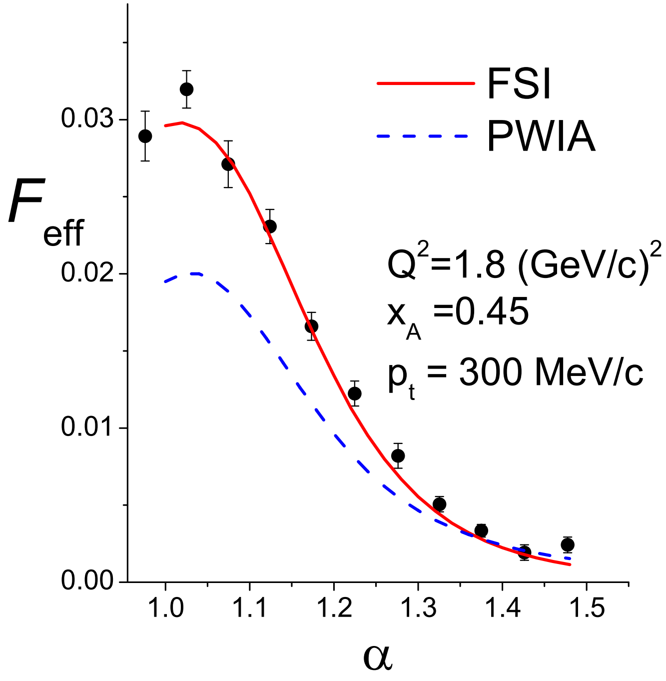
$^3He(e, e'D)X$



$$\theta_D = \widehat{\mathbf{q}\mathbf{p}}_D$$

(After CdA, Kaptari unpublished)

$^2H(e,e'p)X$ theory *vs.* experiment



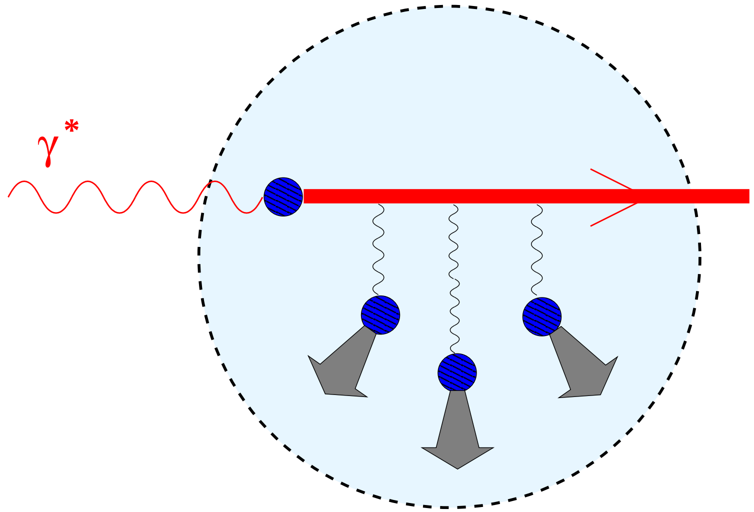
$$F_{eff} \equiv P_A^D(\alpha, \mathbf{p}_T) F_2^{(N/A)}\left(\frac{x_{Bj}}{2-\alpha}, Q^2\right) \quad \alpha = \frac{E - p_{\|}}{m_N}$$

Experiment(PRELIMINARY):

Jlab 94-102 S. E. Kuhn, K. A. Griffioen , co-spokespersons, *Inelastic electron scattering off a moving nucleon in deuterium*

Theory (After CdA, Kaptari, unpublished)

4. HADRONIZATION MECHANISM AND GREY TRACKS



- **The whole jet inelastically interacts with spectators nucleons, which recoil and form Grey Tracks (GT). GT production covers the main bulk of inelastic events.**

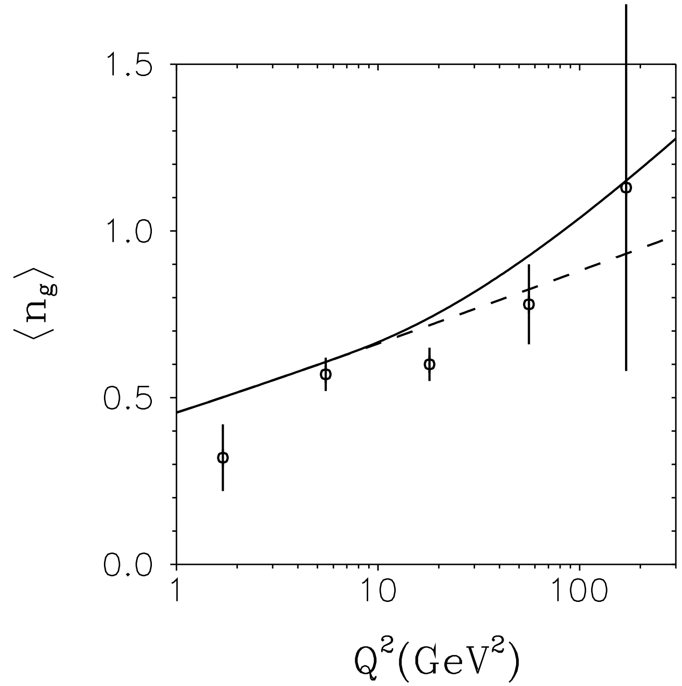
Calculation of GT production (CdA, Kopeliovich, hep-ph/0409077)

- Theory: debris-nucleon cross section;
- Experiment: Fermilab E665($\mu - Xe$ and $\mu - D$ processes at 490 GeV beam energy; GT- protons with momentum $200 - 600\ MeV/c$).
- Empirical relation: between the mean number of collisions, $\langle \nu_c \rangle$, and the mean number of GT $< n_g >$

$$< n_g >= \frac{\langle \nu_c \rangle - (2.08 \pm 0.13)}{(3.72 \pm 0.14)}$$

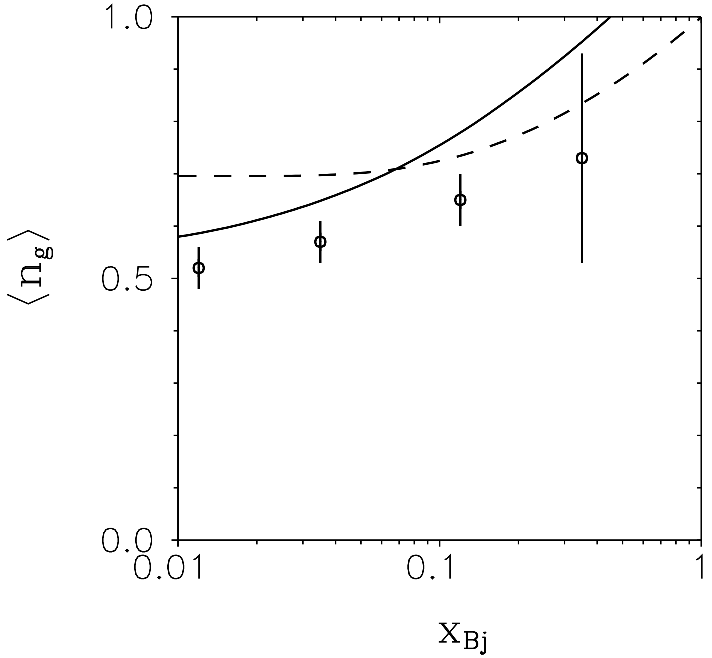
- The Model: DIS on a bound nucleon at coordinate $(\vec{b}, z)$. The hadronizing quark (The debris) propagates through the nucleus interacting with spectator nucleons via $\sigma_{eff}(z - z')$. The number of collisions, (plus the recoiling nucleon formed in the hard $\gamma * - N$ act) is

$$\langle \nu_c \rangle = \int d^2b \int_{-\infty}^{\infty} dz\, \rho_A(b, z) \int_{z}^{\infty} dz'\, \rho_A(b, z')\, \sigma_{eff}(z - z') + 1\ .$$



The mean number of grey tracks $\langle n_g \rangle$ produced in the μXe DIS *vs* Q^2 in the non-shadowing region ($x_{Bj} = 0.07$) (full). The solid curve includes the $Q^2 - x_{Bj}$ correlation.

- The Debris-Nucleon cross section,**with no readjustment of the parameters** correctly predicts the Q^2 dependence, thanks to the Q^2 and x_{Bj}-dependent gluon radiation mechanism;



The mean number of grey tracks $\langle n_g \rangle$ produced in the μXe DIS *vs* x_{Bj}. The dashed and solid curves show the results of calculations with fixed $Q^2 = 14.3 GeV^2$ and corrected for the $Q^2 - x_{Bj}$ correlation respectively.

5. CONCLUSIONS

- a time-dependent debris-nucleon cross section has been obtained; it incorporates both non perturbative (string) and Q^2-dependent perturbative (gluon radiation) effects; it accounts for the bulk of the FSI interaction of the debris created by the hard interaction of a bound nucleon with $\gamma*$; it should be used in all kinds of DIS off nuclei to describe the FSI of the hadronizing quark with the spectator nucleons;
- the (parameter-free) calculation of the Q^2 and x_{Bj} dependence of the average number of the Grey Tracks produced in Deep Inelastic $\mu - Xe$ scattering exhibits a very satisfactory agreement with the experimental data, thanks to the gluon radiation mechanism for hadron production;
- the (parameter-free) calculation of the Semi Exclusive DIS off the deuteron exhibits good agreement with preliminary data from Jlab; a systematic investigation of the x_{Bj} and Q^2 dependence of these processes at Jlab and HERA energies would shed further light on the hadronization mechanism.