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

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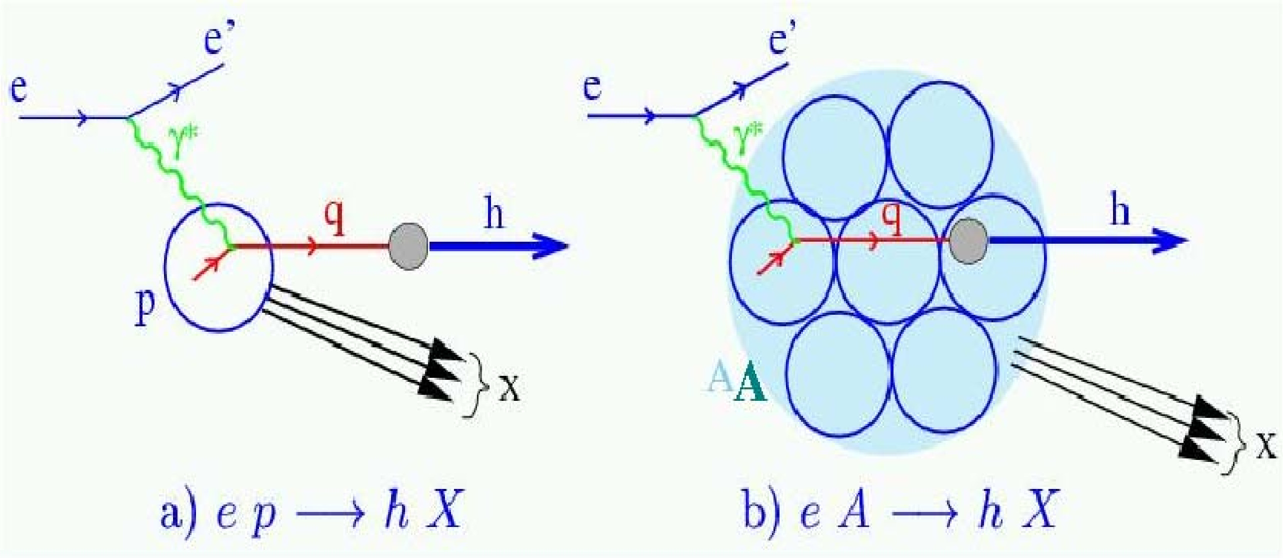
1. INTRODUCTION and MOTIVATIONS

Nuclear targets serve as a natural and unique analyzer of the space-time development of strong interactions at high energies:

Hadron Formation Length $\simeq$ *order of fermis* $\Rightarrow$ *Nuclear Target*

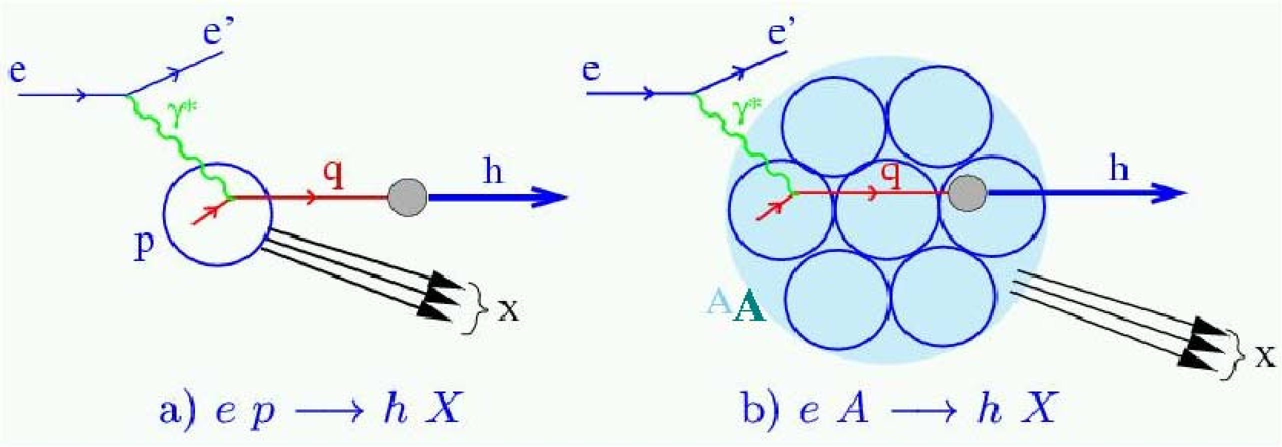


a) $e\,p \longrightarrow h\,X$ b) $e\,A \longrightarrow h\,X$

The cross section of the final state interaction (FSI) increases and the nucleus may act as a filter of hadronization mechanisms.

Most investigated process:

attenuation of leading hadrons created in Semi-Inclusive Deep Inelastic Scattering (SIDIS) off Nuclei (HERMES at HERA, Jlab at CEBAF)

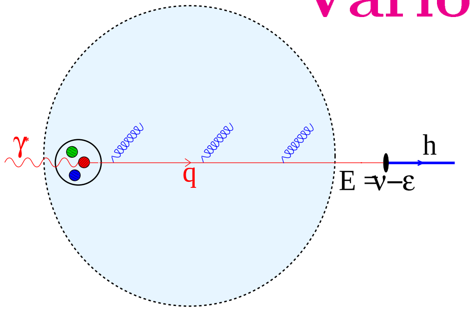


a) $e\,p \longrightarrow h\,X$ b) $e\,A \longrightarrow h\,X$

$$R^h(z) = \frac{1}{N_A^{DIS}}\frac{dN_A^h}{dz} \Big/ \frac{1}{N_D^{DIS}}\frac{dN_D^h}{dz} \qquad z = \frac{E_h}{\nu}$$

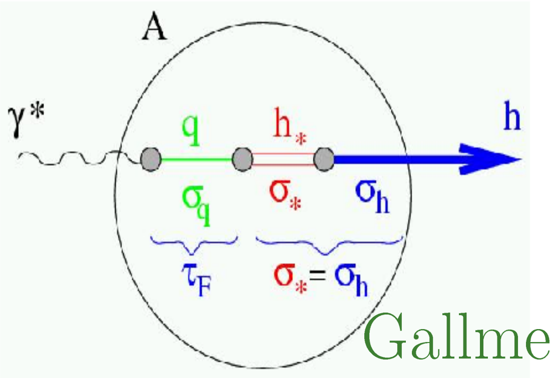
R^h depends upon $q_i(x)$ and $D_i^h(z)$

Various Hadron Formation Mechanisms



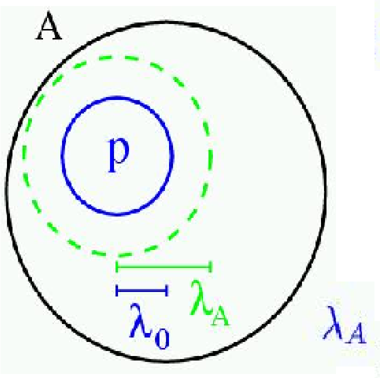
Induced Energy Loss

Wang, Phys. Rev. Lett,89(02)162301



Nuclear Absorption

Gallmeister, Cassing, Falter, Mosel et al, Nucl-th/0303011

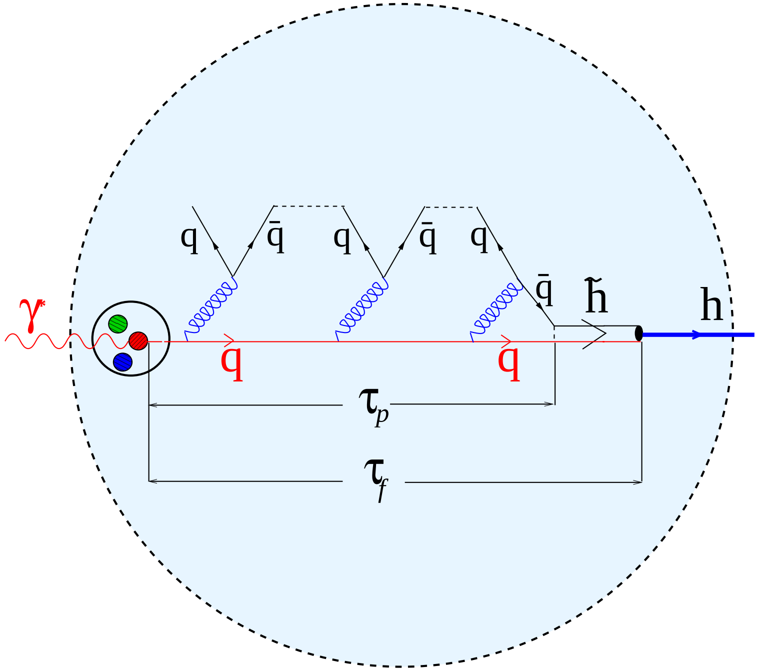


Q^2 Rescaling of fragmentation functions

Accardi, Muccifora, Pirner, Nucl. Phys.A720(03)131

Gluon Radiation Mechanism

B. Kopeliovich, J. Nemchik, E. Predazzi, A. Hayashigaki,
Nucl.Phys. A740(2004)212



Attenuation of the leading hadron(*formed at* τ_f) $\Longrightarrow$**absorption of the pre-hadron** $\tilde{h}$ **(the small** $\bar{q}q$ **configuration,** *formed at* τ_p) **produced in the color neutralization of the radiating quark created in the hard** $\gamma*$**-nucleon interaction.**

The comparison between theory and experiment seems to show that :

- Various approaches based upon different physical ideas explain the experimental data.
- Apparently not yet conclusive answer to the basic question as to whether the observed nuclear attenuation has to be ascribed to pre-hadron and hadron absorptions or to medium induced quark energy loss.

In view of the above situation :

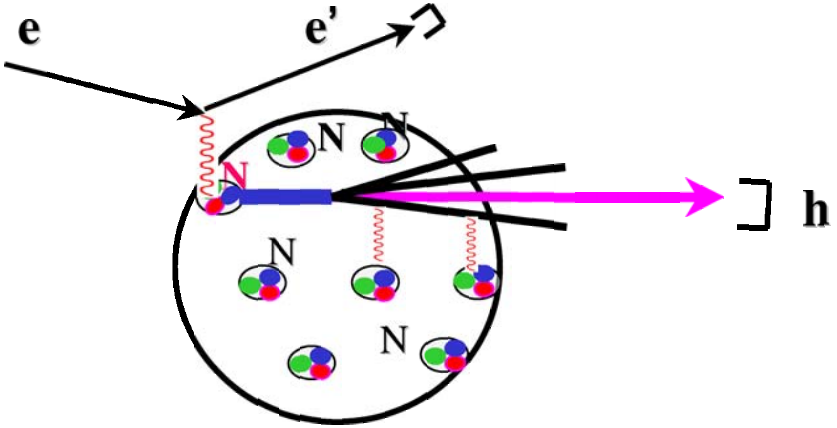
- more data on hadron attenuation would be necessary, and, at the same time, other types of experimental data should also be considered to discriminate various models of the space-time evolution of hadronization.

This is precisely the aim of our work :

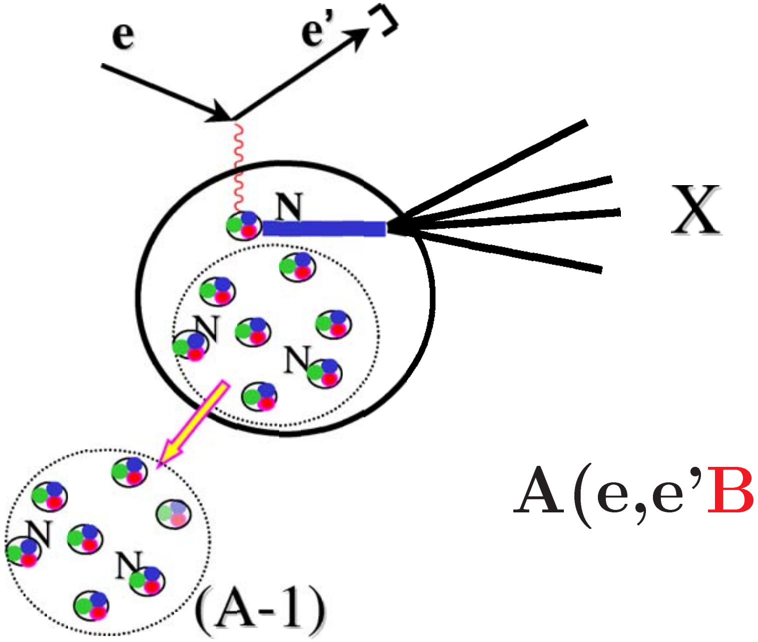
to look for other types of processes which could provide complementary information on hadronization.

To this end, unless the rare process of leading hadron production, we will analyze possible processes which depend upon the bulk of the final state interaction of the hadronizing quark (the nucleon debris).

(Collaboration with B. Kopeliovich and L. Kaptari).



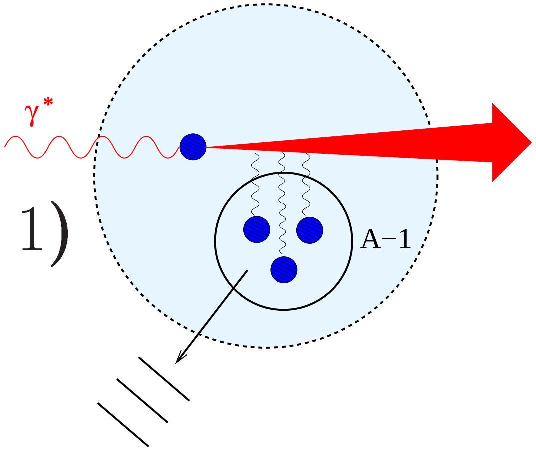
A(e,e'h)X



A(e,e'B)X

Instead of detecting, in coincidence with the scattered lepton, the leading hadron, we will consider the detection of nuclear fragments. We will show that these processes is sensitive to the hadronization mechanism. Data of this kind already exist (FERMILAB) and are being produced (Jlab).

The following processes will be considered:

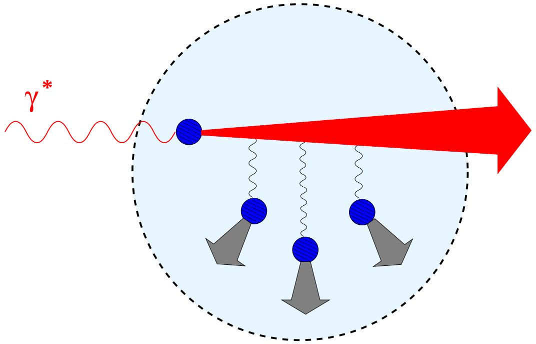


- **Semi- Exclusive DIS (SEDIS) processes**

  $A(e,e'B)X$.

  B - detected recoiling heavy fragment (e.g $A-1$)

  X - unobserved jets from hadronization;



- **Grey Tracks (GT) production in SIDIS.**

  GT -recoiling protons created in the inelastic collisions of the hadronizing quark with the spectator nucleons.

Both processes depend upon the bulk of the FSI generated by the hadronizing quark (the Nucleon Debris) in the final state and therefore upon the hadronization mechanism.

OUTLINE of the WORK

- derive an effective cross section of the debris with the A-1 nucleons of the nucleus;

- use such a cross section in a Glauber like calculation of the FSI;

- extract information on hadronization from such FSI.

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**

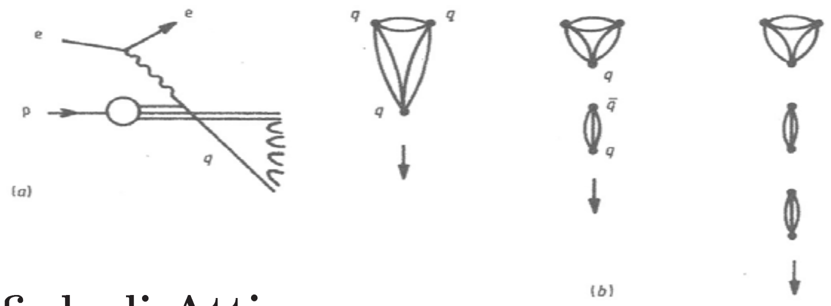
This model of hadronization is inspired and close to the one of: B. Kopeliovich, J. Nemchik, E. Predazzi, A. Hayashigaki, Nucl.Phys. A740(2004)212

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**

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

The mean multiplicity of Mesons:



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

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 (Gunion, Bertsch, Phys. Rev.D25(82)746)

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

with

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

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

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

levels off at

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

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

The total multiplicity of the produced pre-hadrons (colorless dipoles)

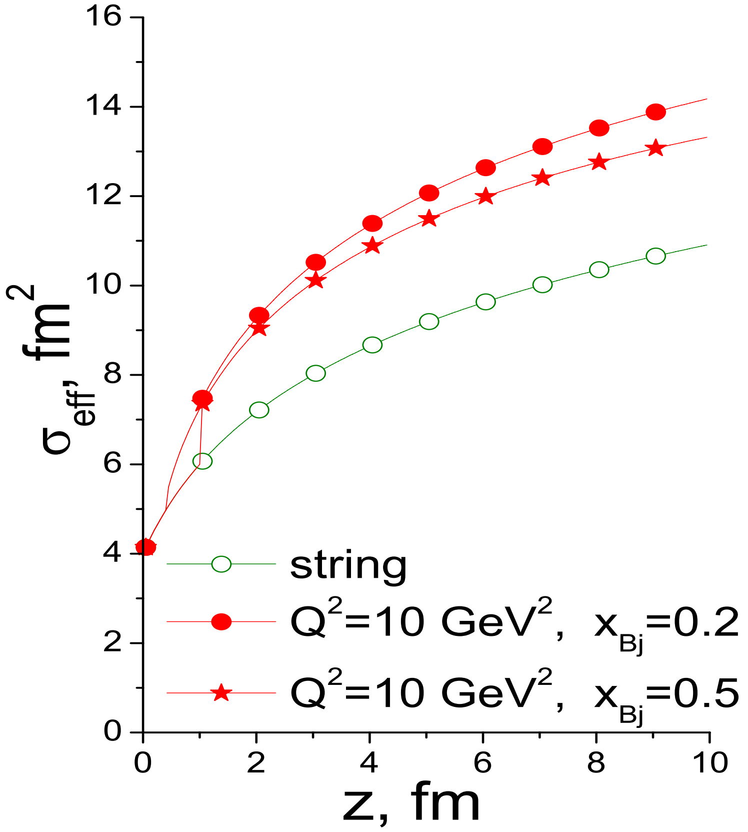
$$\langle\, n_h(t)\,\rangle = n_M(t) + n_G(t)$$

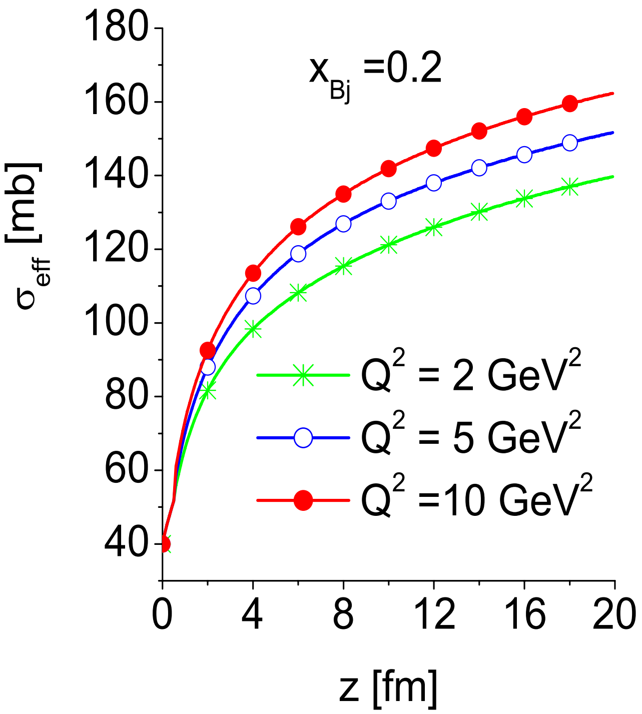
- transverse size of the decaying pre-hadrons from the string $\simeq$ hadronic transverse size; the same cross section;
- transverse size of pre-hadrons produced from perturbative gluons. The mean transverse momenta of the gluons follow the photon virtuality Q^2 $\Rightarrow$initial size of the produced pre-hadrons of the order of $1/Q$ $\Rightarrow$ color transparency effects ;
- $\bar{q}q$ colorless dipoles treated as mesons (M).

The *debris-nucleon* cross section is then

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

The debris-nucleon effective cross section

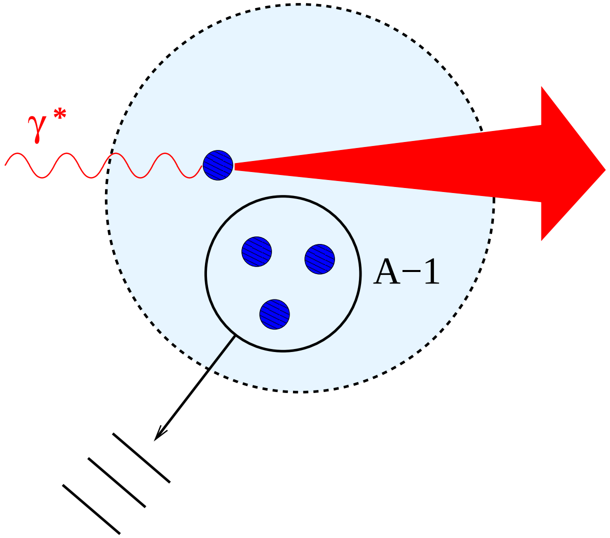




- **Steep rise with time (distance).**
- Q^2**and** x_{Bj} **dependence due to gluon radiation mechanism.**

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

PWIA : **The debris propagates through the nucleus freely**



Melnitchouk, Sargsian, Strikman, Z. Phys A359(1997)99

Simula, Phys. Lett. B387(1996)245

CdA, Kaptari, Scopetta, EPJA 5(1999)181

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

$$p_1 \equiv (p_{10}, \vec{p_1}), \qquad \vec{p_1} \equiv -\vec{P}_{A-1}$$

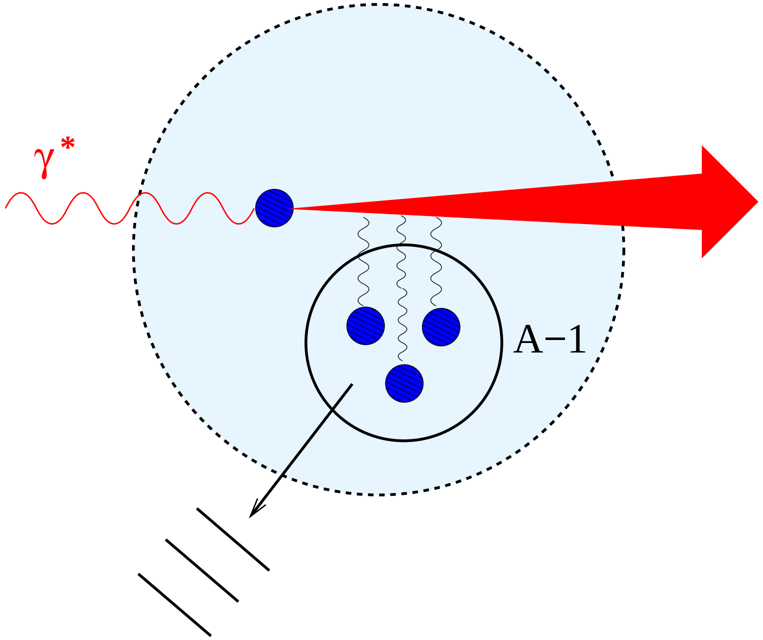
$$K^A(x, Q^2, y_A, z_1^{(A)}) = \frac{4\alpha^2}{Q^4}\frac{\pi}{x} \cdot \left(\frac{y}{y_A}\right)^2 \left[\frac{y_A^2}{2} + (1 - y_A) - \frac{p_1^2 x_{Bj}^2 y_A^2}{z_1^{(A)2} Q^2}\right]$$

$$y = \nu/E_e\ , \quad y_A = (p_1 \cdot q)/(p_1 \cdot k_e), \quad x_A = \frac{x_{Bj}}{z_1^{(A)}}, \qquad z_1^{(A)} = \frac{p_1 \cdot q}{M\nu}$$

$F_2^{N/A}(x_A, Q^2, p_1^2)$ **Bound Nucleon Structure Function**

$P_A(E, |\vec{P}_{A-1}|)$ **Nucleon Spectral Function**

FSI: the debris multiple scatters in the medium



- **The Debris interacts with the spectator nucleons via $\boldsymbol{\sigma}_{eff}(t)$**
- **The survival probability of (A-1) is reduced depending on the features of $\boldsymbol{\sigma}_{eff}(t)$.**

CdA, Kopeliovich, EPJA17(2003)133

$$P_A(E,|\vec{P}_{A-1}|) \Longrightarrow P_A^{FSI}(E,\vec{P}_{A-1})$$

$$P_A^{FSI}(E,\vec{P}_{A-1}) = \sum_f |F_{A-1,A}^{f,FSI}(\vec{P}_{A-1})|^2 \delta(E-(E_{min}+E_{A-1}^f))$$

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

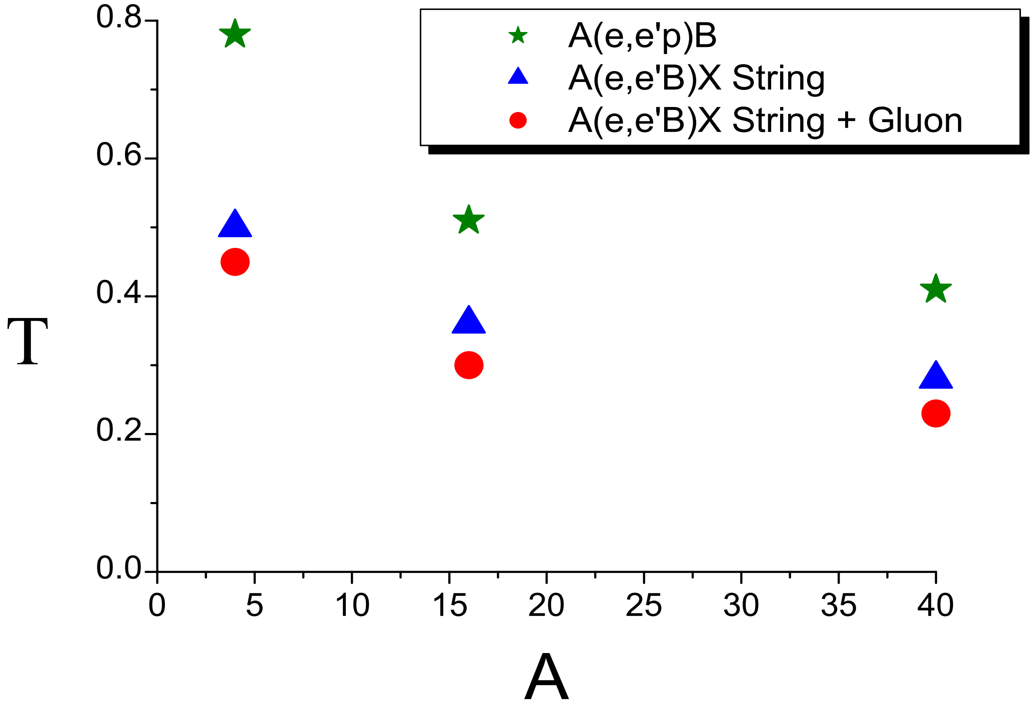
$$= \int e^{i\vec{p}_{A-1}\vec{r}_1} S_{FSI}^{\dagger}(\vec{r}_1\ldots\vec{r}_A)\Psi_{A-1}^{f}{}^{*}(\vec{r}_2\ldots\vec{r}_A)\Psi_A^0(\vec{r}_1,\vec{r}_2\ldots\vec{r}_A)\ \delta\left(\sum_{j=1}^{A}\vec{r}_j\right)\prod_{i=1}^{A} d\vec{r}_i$$

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

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

$$N^* \equiv Debris$$

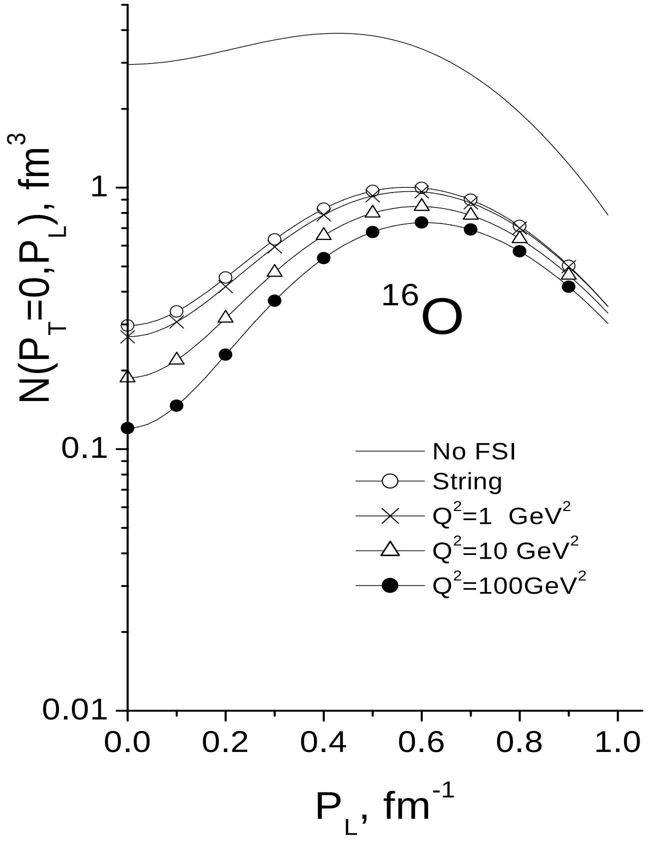
Survival probability of A-1

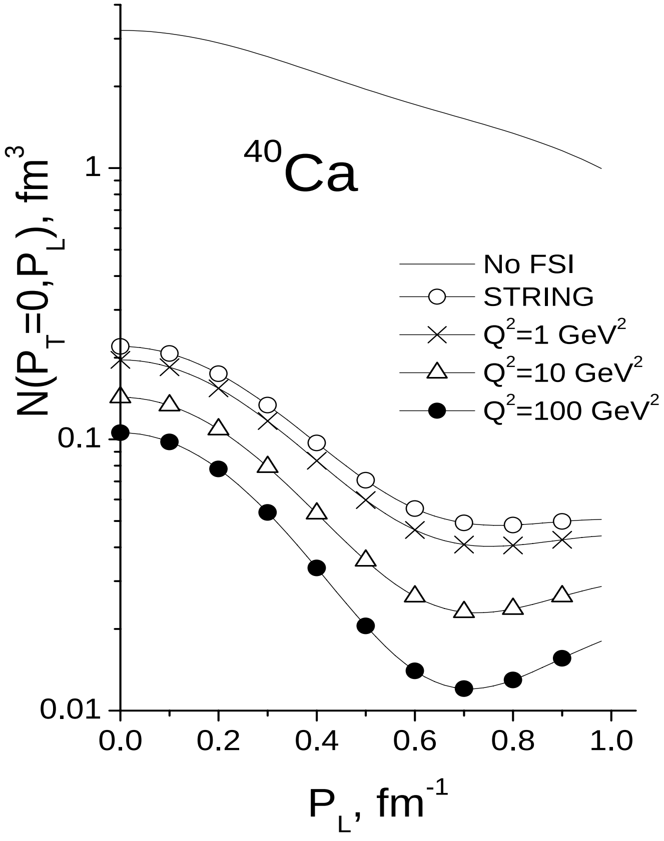


$$T = \int_{-\infty}^{\infty} dz\, \rho(\vec{b}, z) \exp\left[-S(\vec{b}, z)\right] \qquad S(\vec{b}, z) = \int_{z}^{\infty} dz'\, \rho_A(\vec{b}, z')\, \sigma_{eff}(z' - z)$$

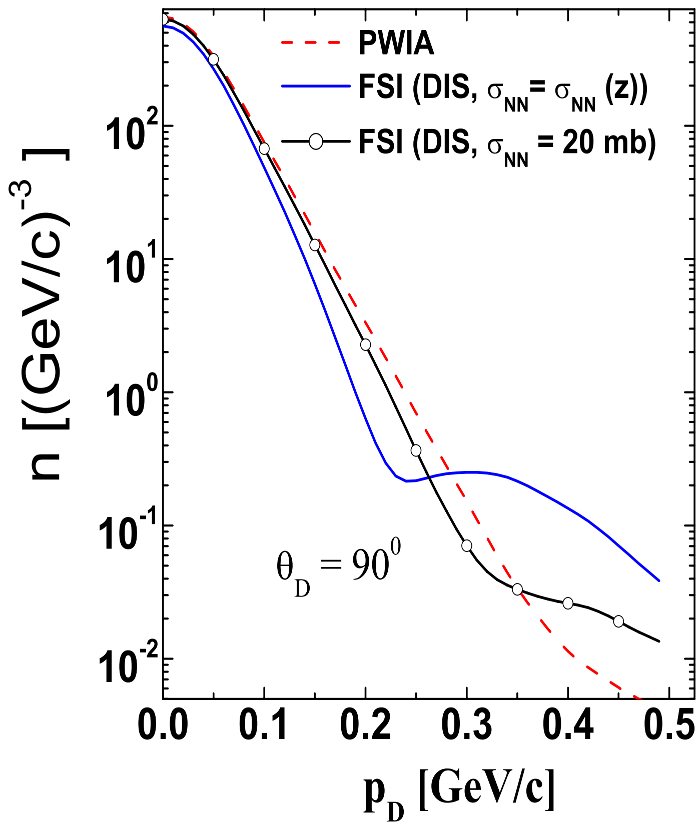
(**CdA, Kopeliovich, EPJA17(2002)133**)

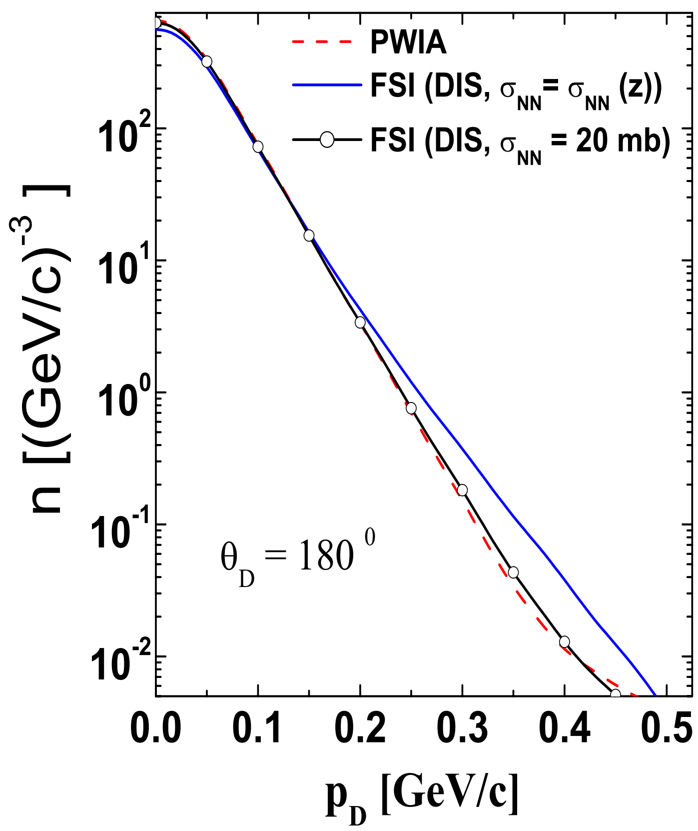
$\mathbf{A(e, e'(A-1))X}$





$^3\mathrm{He}(e,e'D)X$

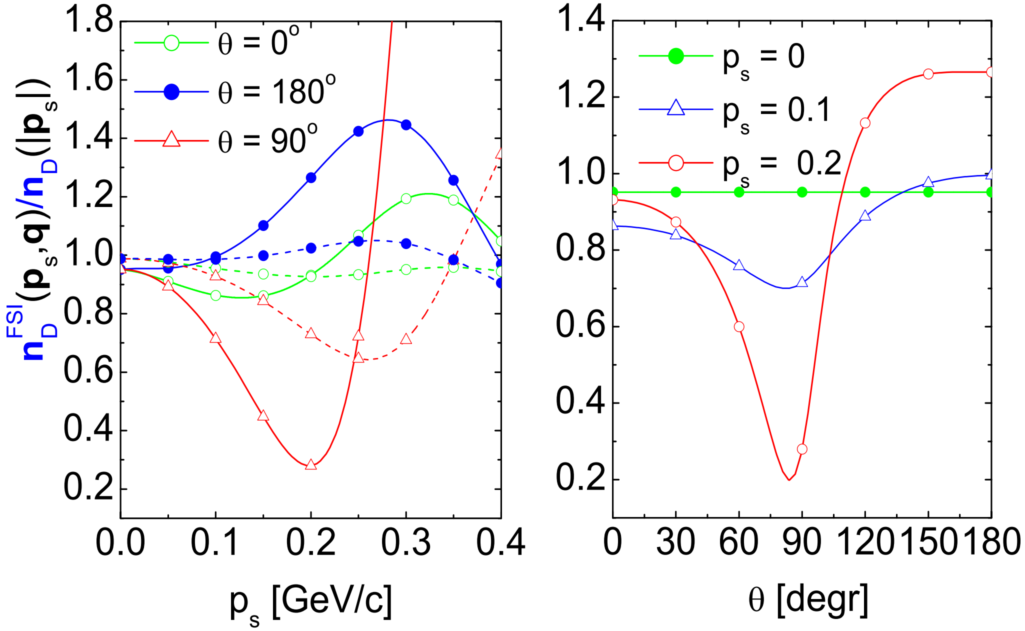




$$\theta_D = \widehat{\mathbf{q}\mathbf{p}}_D$$

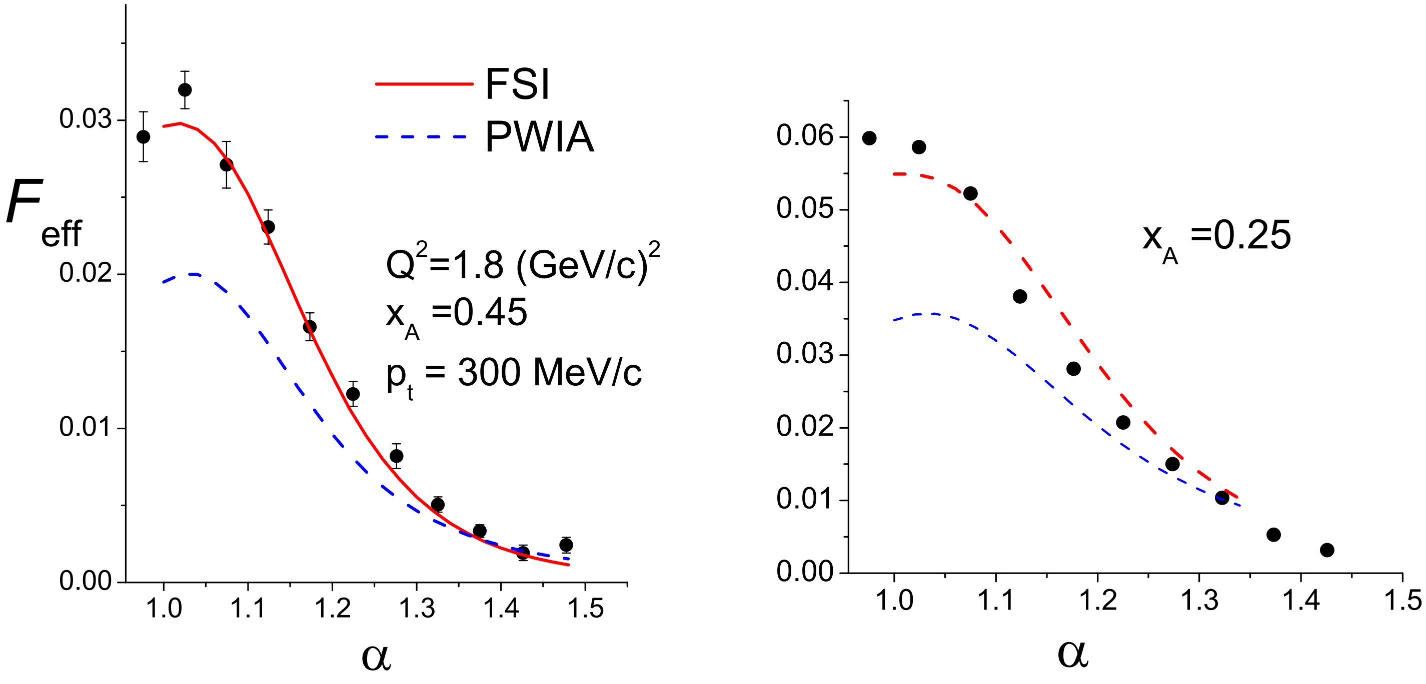
(CdA, Kaptari, Kopelioich to appear)

$^2\mathrm{H}(\mathrm{e},\mathrm{e}'\mathrm{p})\mathrm{X}$



The SIDIS ratio n_D^{FSI}/n_D with n_D^{FSI}, calculated *vs.* the momentum $p_s \equiv |\mathbf{p}_s|$ of the spectator nucleon emitted at different angles θ_s. The full lines correspond to the Q^2- and z-dependent debris-nucleon effective cross section σ_{eff}, whereas the dashed lines correspond to a constant cross section $\sigma_{eff} = 20\ mb\ Q^2 = 5\ (GeV/c)^2$, $x = 0.2$.

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



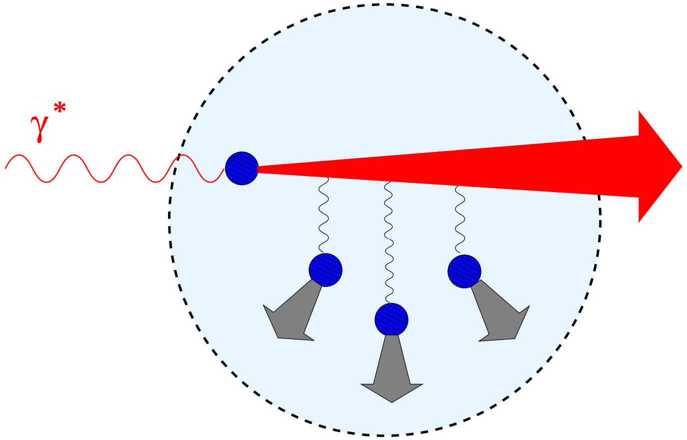
$$F_{eff} \equiv P_A^D(\alpha, \mathbf{p}_T) F_2^{(N/A)}\left(\frac{x_{Bj}}{2-\alpha}, Q^2\right) \qquad \alpha = \frac{E-p_\parallel}{m_N}$$

Experiment(PRELIMINARY):

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

Jlab 03-012 (data: one year from now)

5. HADRONIZATION MECHANISM AND GREY TRACKS



- Dominant channels of DIS $\Longrightarrow$ the recoiling nucleus B breaks apart to fragments.
- The whole jet inelastically interacts with spectators nucleons, which recoil and form Grey Tracks (GT). GT production covers the main bulk of inelastic events, and its Q^2 dependence appears to be a very sensitive tool to discriminate between different models of hadronization.

A recent calculation of GT production

(**CdA, Kopeliovich,** hep-ph/0409077)

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

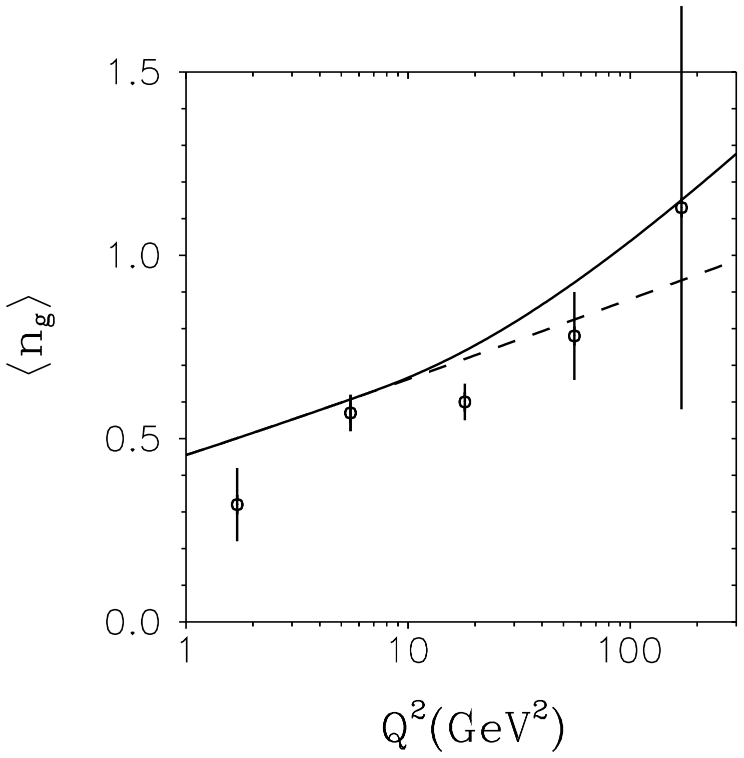
$$\langle \boldsymbol{\nu}_{\mathbf{c}} \rangle = \int \mathbf{d^2b} \int_{-\infty}^{\infty} \mathbf{dz}\, \boldsymbol{\rho}_{\mathbf{A}}(\vec{\mathbf{b}}, \mathbf{z}) \int_{\mathbf{z}}^{\infty} \mathbf{dz'}\, \boldsymbol{\rho}_{\mathbf{A}}(\vec{\mathbf{b}}, \mathbf{z'})\, \boldsymbol{\sigma}_{\mathbf{eff}}(\mathbf{z} - \mathbf{z'}) + \mathbf{1}\ .$$

- **The Experiment:**
  Fermilab E665 M. Adams et al., Z. Phys. C65(1995)
  ($\mu - Xe$ and $\mu - D$ processes at $490\ GeV$ beam energy; GT-protons with momentum $200 - 600\ MeV/c$).

- **Empirical relation from E665** between the **mean number of collisions** , $\langle \nu_c \rangle$, and the mean number of GT $< \mathbf{n_g} >$

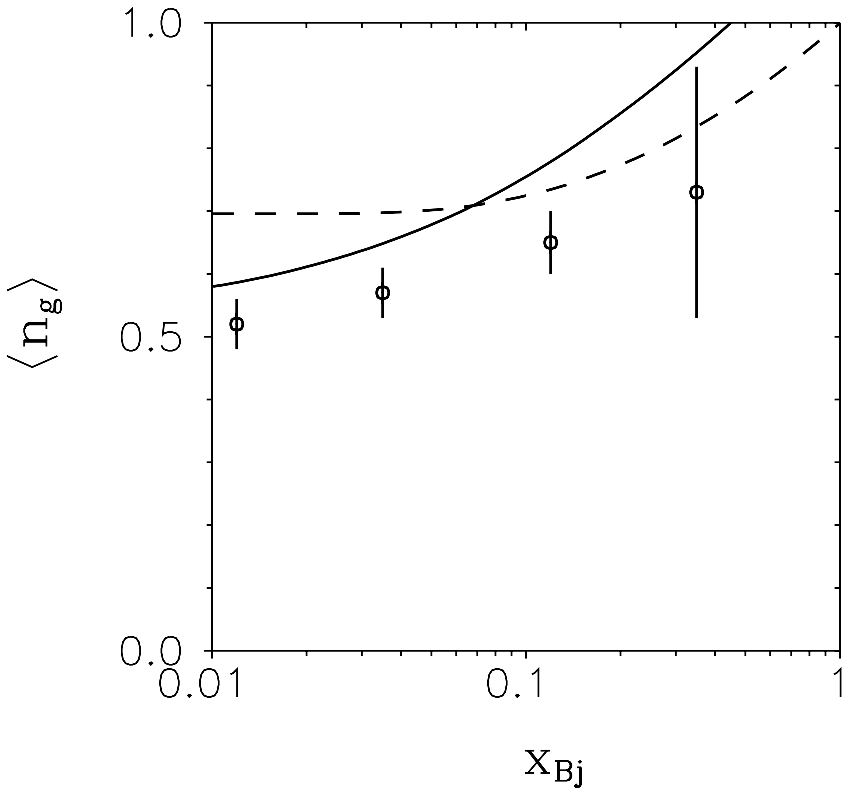
$$< \mathbf{n_g} >= \frac{\langle \boldsymbol{\nu}_\mathbf{c} \rangle - (\mathbf{2.08 \pm 0.13})}{(\mathbf{3.72 \pm 0.14})}$$

- $\langle \boldsymbol{\nu}_c \rangle$ calculated and $< \mathbf{n_g} >$ obtained from the empirical relation.
- calculations performed in the non shadowing region ($x_{Bj} \geq 0.07$).
- experimental correlation between Q^2 and x_{Bj} taken into account.
- no free parameters in the calculation: $\boldsymbol{\sigma}_{eff}$ fixed by the hadronization model and $\boldsymbol{\rho}(\mathbf{b}, z)$ fixed from *Nuclear Data Tables*.



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

The Debris-Nucleon cross section,with no readjustment of the parameterscorrectly 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 SIDIS *vs* **x_{Bj}. The dashed curve shows the results corresponding to a fixed value of $Q^2 = 14.3\, GeV^2$, whereas the solid curve includes the $Q^2 - x_{Bj}$ correlation .**

Comments:

- the Debris-Nucleon cross section, **with no readjustment of the parameters**, successfully passed the Grey Tracks test;
- The amount of grey tracks doubles within the range of Q^2 covered by the kinematics of the E665 experiment; the Debris-Nucleon cross section, **correctly predicts such a trend thanks to the Q^2-dependent gluon radiation mechanism**;
- the results of calculations may be further improved (**resonance decays** $\Longrightarrow$formation time of hadronic wave function is much shorter than the resonance life time and is rather short for pre-hadrons produced within the nucleus. **Color transparency** is disregarded for the same reason);
- we assumed that x_{Bj} is sufficiently large to neglect the sea and, accordingly, compared our results with the E665 data at large values of x_{Bj}.

5. CONCLUSIONS

- two processes, which (besides the leading hadron attenuation) appear to be sensitive to the space-time evolution of hadronization, have been identified, and a theoretical framework to describe them in terms of a time-dependent debris-nucleon cross section $\boldsymbol{\sigma}_{eff}$ has been worked out.
- the (parameter-free) description, in terms of $\boldsymbol{\sigma}_{eff}$, of the Fermilab Grey Tracks production in SIDIS off Xe, as well as of the semi-exclusive preliminary Jlab data on the $^2H(e,e'p)X$ process, exhibits a very satisfactory agreement between theoretical predictions and experimental data.
- the prediction of the above quantities by other hadronization models would be highly desirable and a systematic investigation of both processes on different nuclei at Jlab and HERMES energies would shed further light on hadronization.