Probing the nuclear structure at small $x$ with $e+A$ collisions

Cyrille Marquet

Theory Division - CERN

Dominguez, CM and Wu (2009)
CM, Xiao and Yuan (2009)
Albacete and CM (2010)
Dominguez, CM, Xiao and Yuan (2011)
Outline

- Introduction to small-x physics
- DIS structure functions at small x
  - integrated parton distributions
- Semi-inclusive DIS at small x
  - $k_T$-dependent parton distribution
- Di-hadron production in DIS at small x
  - gluon (momentum) correlations
- Coherent vs incoherent diffractive VM production
  - $b$-dependent parton distributions
  - gluon (spatial) correlations
The hadron wave function in QCD

\[ |\text{hadron}\rangle = |k_T \sim \Lambda_{QCD}\rangle + |k_T \gg \Lambda_{QCD}, x \leq 1\rangle + |k_T \gg \Lambda_{QCD}, x << 1\rangle \]
The dilute regime

\[ |\text{hadron}\rangle = |k_T \sim \Lambda_{QCD}\rangle + |k_T \gg \Lambda_{QCD}, x \leq 1\rangle + |k_T \gg \Lambda_{QCD}, x << 1\rangle \]

hadron = a dilute system of partons

1/k_T \sim \text{parton transverse size}

transverse view of the hadron

leading-twist regime

Dokshitzer, Gribov, Lipatov, Altarelli, Parisi

for instance, the total cross-section in DIS

\[ \sigma_{DIS}(x_{Bj}, Q^2) = \sum_{\text{partons } a} \int dx \frac{1}{x_{Bj}} \phi_{a/p}(x, Q^2) \hat{\sigma}_a(x_{Bj}/x, Q^2) + O\left(\frac{Q_0^2}{Q^2}\right) \]

parton density \hspace{1cm} \text{partonic cross-section} \hspace{1cm} \text{higher twist}

\[ \ln(k_T^2/\Lambda_{QCD}^2) \longrightarrow \frac{(A/x)^{1/3}}{Q^2} \]

not valid if x is too small when the hadron becomes a dense system of partons
The saturation regime

\[ |\text{hadron}\rangle = |k_T \sim \Lambda_{QCD}\rangle + |k_T >> \Lambda_{QCD}, x \leq 1\rangle + |k_T >> \Lambda_{QCD}, x << 1\rangle \]

the separation between the dilute and dense regimes is characterized by a momentum scale:

the saturation scale \( Q_s(x) \)

in the saturation regime, higher-twists are important:

\[ \frac{\Lambda_{QCD}}{k_T} << 1, \frac{Q_s(x)}{k_T} \sim 1 \]

hadron = a dense system of partons

evolution: as \( x \) decreases,
the hadron gets more dense

in the saturation regime, the evolution becomes non-linear
the partons interact coherently

the saturation regime of QCD:
- non-linear yet weakly-coupled
- describes the collective behavior of partons in the nuclear wave function
Map of parton evolution in QCD

$x$: parton longitudinal momentum fraction

$k_T$: parton transverse momentum

the distribution of partons as a function of $x$ and $k_T$

QCD linear evolutions: $k_T \gg Q_s$
- DGLAP evolution to larger $k_T$ (and a more dilute hadron)
- BFKL evolution to smaller $x$ (and denser hadron)

dilute/dense separation characterized by the saturation scale $Q_s(x)$

QCD non-linear evolution: $k_T \sim Q_s$ meaning $x \ll 1$

$$\rho \sim \frac{xf(x,k_T^2)}{\pi R^2}$$

it grows with decreasing $x$

$$\sigma_{rec} \sim \frac{\alpha_s}{k^2}$$

recombinations important when $\rho \sigma_{rec} > 1$

the saturation regime: for $k^2 < Q_s^2$ with

$$Q_s^2 = \frac{\alpha_s f(x,Q_s^2)}{\pi R^2}$$

this regime is non-linear yet weakly coupled

$$\alpha_s(Q_s^2) \ll 1$$
DIS structure functions at small $x$
Kinematics, structure functions

\[ S = (k+p) \]

\[ \text{\( \gamma^* h \) center-of-mass energy} \]
\[ W = (k-k'+p) \]

\[ \text{photon virtuality} \]
\[ Q^2 = - (k-k')^2 > 0 \]

\[ x = \frac{Q^2}{2p.(k-k')} = \frac{Q^2}{W^2 - M_h^2 + Q^2} \]

\[ y = \frac{p.(k-k')}{p.k} = \frac{Q^2 / x}{S - M_h^2} \]

\[ x \sim \text{momentum fraction of the struck parton} \]
\[ y \sim W^2/S \]

- the measured cross-section

\[ \frac{d^2 \sigma^{eh\rightarrow eX}}{dx dQ^2} = \frac{4\pi \alpha_{em}^2}{xQ^4} \left[ \left( 1 - y + \frac{y^2}{2} \right) F_2(x, Q^2) - \frac{y^2}{2} F_L(x, Q^2) \right] \]

Experimental data are often shown in terms of

\[ \sigma_{tot}^{\gamma^* h\rightarrow X} = \sigma_T^{\gamma^* h\rightarrow X} + \sigma_L^{\gamma^* h\rightarrow X} = \frac{4\pi^2 \alpha_{em}}{Q^2} F_2 \]
DIS off the proton

Albacete, Armesto, Milhano and Salgado (2009)

\[
\sigma_{\gamma^* h \rightarrow X} (x, Q^2) = \sigma_{\gamma^* h \rightarrow X} (Q^2/Q_s^2(x))
\]

\(x < 10\)

Stasto, Golec-Biernat and Kwiecinski (2001)

rcBK fit (~ 850 points) \(\chi^2/dof = 1.1\)

geometric scaling seen in the data, but scaling violations are essential for a good fit
The dipole factorization in DIS

- **the cross section at small x**
  
  \[ \sigma_{T,L}^{\gamma^* p \rightarrow X} = 2 \int d^2r \, dz \left| \psi_{T,L}(z, \mathbf{r}; Q^2) \right|^2 \int d^2b \, T_{q\bar{q}}(\mathbf{r}, \mathbf{b}, x_B) \]

  overlap of \( \gamma^* \rightarrow q\bar{q} \)

  dipole-hadron cross-section computed in the CGC or with dipole models

  \[ \dipole-hadron \]

  Mueller (1990), Nikolaev and Zakharov (1991)

  \[ \text{Mueller (1990), Nikolaev and Zakharov (1991)} \]

  diehl and

  chirilli

  the existing CGC phenomenology is still based on the leading log approximation, \( F_2 \) and \( F_L \) will be the first observables where NLL will be available for practical analysis

  \[ \text{diehl and lappi} \]

- **estimating the importance of saturation**

  \[ \langle T_{q\bar{q}} \rangle_{2,L}(x, Q^2) = \frac{\int d^2r \, dz \left| \psi_{2,L}(z, \mathbf{r}; Q^2) \right| \int d^2b \, T_{q\bar{q}}^2(\mathbf{r}, \mathbf{b}; x)}{\int d^2r \, dz \left| \psi_{2,L}(z, \mathbf{r}; Q^2) \right| \int d^2b \, T_{q\bar{q}}(\mathbf{r}, \mathbf{b}; x)} \]

  average dipole scattering amplitude \( \langle T_{q\bar{q}} \rangle_{T,L} < 0.6 \to 0.7 \) and not 1 because of b int
Average strength of scattering

- off the proton
  \[ \langle T_{q\bar{q}} \rangle_{2,L} < 0.25 \text{ for } Q^2 > 2 \text{ GeV}^2 \]

- off the nucleus
  \[ \langle T_{q\bar{q}} \rangle_L \simeq 0.4 \text{ for } Q^2 = 2 \text{ GeV}^2 \]
Expectations for e+A

- using the small-x QCD evolution

extrapolating from relatively large-x data, the non-linear QCD evolution can predict the structure functions

still this need to be checked with data, it is not absolutely clear that the CGC is already applicable in the x range where one starts the evolution

the CGC initial conditions for heavy-ion collisions are based on such extrapolations too
Semi-inclusive DIS
(or single-hadron production)
The dipole factorization in SIDIS

\[ \Phi(\xi, x, y; Q^2) = \psi(\xi, x; Q^2)\psi^*(\xi, y; Q^2) \]

dipoles in amplitude / conj. amplitude

\[ \frac{d\sigma^{\gamma^*p\rightarrow hX}}{dz_h d^2P_\perp} = \frac{d\sigma_{T,L}^{\gamma^*p\rightarrow qX}}{d\xi d^2k_\perp} \left( k_\perp = \frac{\xi}{z_h} P_\perp \right) \otimes D_{h/q}(z_h/\xi) \]

\[ \frac{d\sigma_{T,L}^{\gamma^*p\rightarrow qX}}{d\xi d^2k_\perp} = \int \frac{d^2x}{2\pi} \frac{d^2y}{2\pi} e^{-ik_\perp \cdot (x-y)} \Phi_{T,L}(\xi, x, y; Q^2) \int d^2b \left[ T_{q\bar{q}}(x, x_B) + T_{q\bar{q}}(y, x_B) - T_{q\bar{q}}(x-y, x_B) \right] \]

McLerran and Venugopalan, Mueller, Kovchegov and McLerran (1999)
Cross section in momentum space

- the lepto-production cross section

\[
\frac{d\sigma(ep \rightarrow e' h X)}{dP} = \frac{\alpha_{em}^2 N_c}{2\pi^3 x_B Q^2} \sum_f e_f^2 \int_{z_h}^{1} \frac{dz}{z^2} D(z) \int d^2 b d^2 q_\perp F(q_\perp, x_B) \mathcal{H}\left(\xi = \frac{b}{z}, k_\perp = \frac{P_\perp}{z}\right)
\]

phase space \( dP = dx_B dQ^2 dz_h dP_\perp^2 \)

the unintegrated gluon distribution

\[
F(q_\perp, x_B) = \int \frac{d^2 r}{(2\pi)^2} e^{-i q_\perp \cdot r} \left[1 - T_{qq}(r, x_B)\right]
\]

F.T. of photon wave function \( \epsilon_f^2 = \xi(1 - \xi) Q^2 \)

massless quarks

\[
\mathcal{H}(\xi, k_\perp) = \left(1 - y + \frac{y^2}{2}\right) (\xi^2 + (1 - \xi)^2) \left| \frac{k_\perp}{k_\perp^2 + \epsilon_f^2} - \frac{k_\perp - q_\perp}{(k_\perp - q_\perp)^2 + \epsilon_f^2} \right|^2
\]

\[+(1 - y) 4\xi^2 (1 - \xi)^2 Q^2 \left(\frac{1}{k_\perp^2 + \epsilon_f^2} - \frac{1}{(k_\perp - q_\perp)^2 + \epsilon_f^2}\right)^2\]

\(\text{photon T}\)

\(\text{photon L}\)
The x evolution of the u-pdf

- the Balitsky-Kovchegov (BK) evolution

\[ \frac{d}{dY} f_Y(k) = \bar{\alpha} \int \frac{dk'^2}{k'^2} \left[ \frac{k'^2 f_Y(k') - k^2 f_Y(k)}{k^2 - k'^2} \right] + \frac{k^2 f_Y(k)}{\sqrt{4k'^4 + k^4}} \]  

Here, \( f_Y(k) \) is not exactly the u-pdf, but a slightly modified F.T. of \( T_{q\bar{q}} \)

\[ f_Y(k) = \int \frac{d^2r}{2\pi r^2} e^{ikr} T_{q\bar{q}}(r, Y) \]

\( Y = \ln \left( \frac{1}{x} \right) \)

\( \bar{\alpha} = \frac{\alpha_s N_c}{\pi} \)

- in the saturation regime

  the evolution of the u-pdf becomes non-linear

  in general cross sections become non-linear functions of the gluon distribution

  however, SIDIS is a special case in which the \( k_T \)-factorization formula written previously still holds

  BK evolution at NLO has been recently calculated

  Balitsky-Chirilli (2008)


non-linearity important when the gluon density becomes large

\( \ln(1/x) \)

\( Q_s(x) \)

\( \ln(k_T^2/\Lambda_{QCD}^2) \)

the distribution of partons as a function of \( x \) and \( k_T \)
Large-$Q^2$ limit of small-$x$ result

- keeping the leading $1/Q$ term:

$$\frac{d\sigma(ep \to e'hX)}{dP} \bigg|_{P_\perp \ll Q^2} = \frac{\alpha_{em}^2 N_c}{2\pi^3 Q^4 x_B} \sum_f e_f^2 \left( 1 - y + \frac{y^2}{2} \right) \frac{D(z_h)}{z_h^2} \int d^2 b d^2 q_\perp F(q_\perp, x_B) A(q_\perp, k_\perp = P_\perp/z_h)$$

only transverse photons

simple function

$$A(q_\perp, k_\perp) = \int d\xi \left| \frac{k_\perp |k_\perp - q_\perp|}{(1 - \xi)k_\perp^2 + \xi(k_\perp - q_\perp)^2} - \frac{k_\perp - q_\perp}{k_\perp - q_\perp} \right|^2$$

- the saturation regime can still be probed

the cross section above has contributions to all orders in $Q_s^2/P_\perp^2$

even if $Q^2$ is much bigger than $Q_s^2$, the saturation regime will be important when $P_\perp \sim Q_s^2$ in fact, thanks to the existence of $Q_s$, the limit $|P_\perp| \to 0$ is finite, and computable with weak-coupling techniques ($Q_s \gg \Lambda_{QCD}$)

eventually true at small $x$
TMD-pdf / u-pdf relation

- at small $x$ and large $Q^2$

one recovers the TMD factorization formula, with

$$xq(x, k_\perp) = \frac{N_c}{4\pi^4} \int d^2bd^2q_\perp F(q_\perp, x) \left[ 1 - \frac{k_\perp \cdot (k_\perp - q_\perp)}{k_\perp^2 - (k_\perp - q_\perp)^2} \ln \left( \frac{k_\perp^2}{(k_\perp - q_\perp)^2} \right) \right]$$

in the overlapping domain of validity, TMD & $k_T$ factorization are consistent

- the saturation regime

the TMD factorization can be used in the saturation regime, when $k_\perp^2 \sim Q_s^2$

there $xq(x, k_\perp) \to \text{const.}$
x evolution of the TMD-pdf

- from small $x$ to smaller $x$

\[
\frac{xq(x, k_{\perp})}{x_0 q(x_0, k_{\perp})} = \frac{1}{x_0} = 10^{-2}
\]

\[xq(x, 0) = c\]

at small $x$

not full BK evolution here, but GBW parametrization

\[F(q_{\perp}, x) = e^{-q_{\perp}^2/Q_s^2(x)}/Q_s^2(x)\]

\[Q_s^2(x) = (3.10^{-4}/x)^{0.28}\ \text{GeV}^2\]

Golec-Biernat and Wusthoff (1998)
HERA data probe saturation

- ratio of SIDIS cross sections at two different values of $x$

\[ \frac{d\sigma(ep \rightarrow e'hX)}{dP} \bigg|_{x_B \ll 1} \quad Q^2 \gg P^2 \sim q(x_B, P_\perp) \]

our (crude) calculation

one can do much better with actual BK evolution and quark fragmentation

the data show the expected trend

- at future EIC’s

the SIDIS measurement provides direct access to the transverse momentum distribution of partons in the proton/nucleus, and the saturation regime can be easily investigated
Di-hadron production in DIS
TMD factorization at large $Q^2$?

- non-universality of the TMD-pdf

  the TMD distributions involved in di-jet production and SIDIS are different

  Bacchetta, Bomhof, Mulders and Pijlman (2005)
  Collins and Qiu, Vogelsang and Yuan (2007)
  Rogers and Mulders, Xiao and Yuan (2010)

breaking of TMD factorization:

  one cannot use information extracted
  from one process to predict the other

  in this approach the breaking of TMD factorization is a problem

- is there a better approach? at small-$x$, yes

  in the Color Glass Condensate (CGC)/dipole picture, we also
  notice that $k_T$ factorization is broken, but this is not an obstacle
  we can consistently bypass the problem,
  and define improved pdfs to recover universality
No $k_T$ factorization at small-$x$

- the di-jet cross section in the dipole picture

$$\frac{d\sigma_{T,L}^{\gamma^* p \rightarrow q\bar{q}X}}{d^2 k_T d^2 k_T'} = \int \frac{d^2 x}{2\pi} \frac{d^2 y}{2\pi} \frac{d^2 x'}{2\pi} \frac{d^2 y'}{2\pi} e^{-i k_T \cdot (x-y)} e^{-i k_T' \cdot (x'-y')} \int d\xi \Phi_{T,L}(\xi, x-x', y-y'; Q^2) \times [T_{q\bar{q}}(x-x', x_B) + T_{q\bar{q}}(y-y', x_B) - T_{q\bar{q}qq}(x, x', y', y, x_B)]$$

because of the 4-point function $T_{q\bar{q}qq}$, there is no $k_T$ factorization (unless saturation and multiple scatterings can be safely neglected)

- SIDIS was a special case in SIDIS, the $k_T'$ integration sets $x'=y'$, and then

$$T_{q\bar{q}qq}(x, x', x', y, x_B) = T_{q\bar{q}}(x - y, x_B)$$

this cancellation of the interactions involving the spectator antiquark in SIDIS is what led to $k_T$ factorization with dijets, this does not happen, and as expected, the cross section is a non-linear function of the u-pdf
Constraining the 4-point function?

Unlike most observables considered in DIS, di-hadrons probe more than the dipole scattering amplitude, it probes the 4-point function:

\[ T_{q\bar{q}q\bar{q}}(x, x', y, y, x_B) \]

Only in special limits it can be simplified, such as:

\[ |k_\perp + k'_\perp| \ll |k_\perp| , |k'_\perp| \]

Dominguez, Xiao and Yuan (2010)

We expect to see the same effect in e+A vs e+p than the one discovered in d+Au vs p+p collisions at RHIC.

The same 4-point function is involved in the d+Au case but the e+A measurement could help constrain it better. The background will be much smaller than in d+Au for instance.
Forward di-hadron production

in p+A type collisions

\[ x_A = \frac{k_1 e^{-\gamma_1} + k_2 e^{-\gamma_2}}{\sqrt{s}} \ll 1 \]

the CGC cannot be described by a single gluon distribution

the saturation regime is better probed compared to single particle production

\[ d\sigma^{dAu\rightarrow h_1h_2X} \]

\[ \frac{d\sigma^{dAu\rightarrow h_1h_2X}}{d^2k_1dy_1d^2k_2dy_2} \]

is sensitive to multi-parton distributions, and not only to the gluon distribution

no kT factorization

involves 2-, 4- and 6- point functions

CM (2007)
The two-particle spectrum

Collinear factorization of quark density in deuteron

\[ \frac{d\sigma}{d^2k_\perp dy_k d^2q_\perp dy_q} = \alpha_S C_F N_c x_d q(x_d, \mu^2) \int \frac{d^2x}{(2\pi)^2} \frac{d^2x'}{(2\pi)^2} \frac{d^2b}{(2\pi)^2} \frac{d^2b'}{(2\pi)^2} e^{ik_\perp \cdot (x' - x)} e^{i q_\perp \cdot (b' - b)} \]

\[ |\Phi^{q\rightarrow qg}(z, x - b, x' - b')|^2 \left\{ S_{qqg}^{(4)}[b, x, b', x'; x_A] - S_{qqg}^{(3)}[b, x, b' + z(x' - b'); x_A] \right\} \]

\[ -S_{qqg}^{(3)}[b + z(x - b), x', b'; x_A] + S_{qqg}^{(2)}[b + z(x - b), b' + z(x' - b'); x_A] \]

PQCD \( q \rightarrow qg \) wavefunction

\[ z = \frac{|k_\perp e^{y_k}|}{|k_\perp e^{y_k}| + |q_\perp e^{y_q}|} \]

Fourier transform \( k_\perp \) and \( q_\perp \) into transverse coordinates

Interaction with hadron 2 / CGC

n-point functions that resums the powers of \( g_s A \) and the powers of \( \alpha_s \ln(1/xA) \)

Computed with JIMWLK evolution at NLO (in the large-Nc limit), and MV initial conditions, no parameters

\( b \): quark in the amplitude
\( x \): gluon in the amplitude
\( b' \): quark in the conj. amplitude
\( x' \): gluon in the conj. amplitude
Di-hadron $p_T$ imbalance in $d+Au$

- comparison of CGC calculations with RHIC data

$\Delta\phi = 0$ (near side)
$\Delta\phi = \pi$ (away side)

$p+p \sim \pi$
this happens at forward rapidities,
but at central rapidities, the $p+p$ and $d+Au$ signal are almost identical

Albacete and CM (2010)
Di-hadron $p_T$ imbalance in e+A

- the di-hadron cross section in the small momentum imbalance limit

$$|k_\perp + k'_\perp| \ll |k_\perp|, |k'_\perp|$$

not e+A vs e+p but rather e+A at two different energies
About the CGC calculation

• in the large-$N_c$ limit, the cross section is obtained from

\[ S^{(4)} = \frac{1}{N_c} \langle \text{Tr}(W_x W_y^\dagger W_u W_v^\dagger) \rangle_{x_A} \quad \text{and} \quad S^{(2)} = \frac{1}{N_c} \langle \text{Tr}(W_x W_y^\dagger) \rangle_{x_A} \]

the 2-point function is fully constrained by e+A DIS and d+Au single hadron data

• in principle the 4-point function should be obtained from an evolution equation (equivalent to JIMWLK + large $N_c$)

Jalilian-Marian and Kovchegov (2005)

• in practice one uses an approximation that allows to express $S^{(4)}$ as a (non-linear) function of $S^{(2)}$

CM (2007)

even though the knowledge of $S^{(2)}$ is enough to predict the forward dihadron spectrum, there is no $k_T$ factorization:

this approximation misses some leading-$N_c$ terms

Dumitru and Jalilian-Marian (2010)
Coherent vs incoherent diffraction in DIS (or diffraction without/with target dissociation)
VM production at small $x$

- The diffractive cross section

$$\frac{d\sigma_{\gamma^* p \rightarrow VY}}{dt} = \frac{1}{4\pi} \int d^2r d^2r' \varphi(r, Q^2, M_V^2) \varphi^*(r', Q^2, M_V^2) \int d^2b d^2b' e^{iq_\perp \cdot (b-b')} \left\langle T_{q\bar{q}}(r, b) T_{q\bar{q}}(r', b') \right\rangle_x$$

Overlap functions

$\varphi$ : amplitude

$\varphi^*$ : conjugate amplitude

$r$ : dipole size in the amplitude

$r'$ : dipole size in the conjugate amplitude

Target average at the cross-section level:

Contains both broken-up and intact events

One needs to compute a 4-point function, that gives access to gluon correlations

- The exclusive part

Target average obtained by averaging at the level of the amplitude:

$$\left\langle T_{q\bar{q}}(r, b) T_{q\bar{q}}(r', b') \right\rangle_x \rightarrow \left\langle T_{q\bar{q}}(r, b) \right\rangle_x \left\langle T_{q\bar{q}}(r', b') \right\rangle_x$$

Probes $b$ dependence:

$$\frac{d\sigma_{\gamma^* p \rightarrow Vp}}{dt} = \frac{1}{\xi \pi} \left| \int d^2r \varphi(r, Q^2, M_V^2) \int d^2b e^{iq_\perp \cdot b} \left\langle T_{q\bar{q}}(r, b) \right\rangle_x \right|^2$$
Coherent diffraction

- the dipole-nucleus cross-section

Kowalski and Teaney (2003)

\[ T_{qar{q}}^p(r, b, x) = 1 - e^{-f(r, x, b)} \]
\[ T_{qar{q}}^A(r, b, x) = 1 - e^{-\sum_i f(r, x, b-b_i)} \]

\[ T_A\{b_i\} \] position of the nucleons averaged with the Wood-Saxon distribution

assumption of independent nucleons not compatible with QCD non-linear evolution

compared with CGC-inspired gluon distribution (KLN): differences are seen and are big enough to be tested (need 50 MeV resolution on momentum transfer)
Incoherent diffraction (proton case)

Dominguez, CM and Wu (2009)

• as a function of $t$

exclusive production:
  the proton undergoes elastic scattering
  dominates at small $|t|$

diffractive production:
  the proton undergoes inelastic scattering
  dominates at large $|t|$

• two distinct regimes

  exclusive
  → exp. fall at $-t < 0.7$ GeV

  diffractive
  → power-law tail at large $|t|$

the transition point is where the
data on exclusive production stop
From protons to nuclei

• qualitatively, one expects three contributions
  exclusive production is called coherent diffraction
    the nucleus undergoes elastic scattering, dominates at small $|t|$.
  intermediate regime (absent with protons)
    the nucleus breaks up into its constituents nucleons, intermediate $|t|$.
    then there is fully incoherent diffraction
      the nucleons undergo inelastic scattering, dominates at large $|t|$.

• three regimes as a function of $t$:
  coherent diffraction
    → steep exp. fall at small $|t|$
  breakup into nucleons
    → slower exp. fall at $0.02 < -t < 0.7$ GeV
  incoherent diffraction
    → power-law tail at large $|t|$.

Lappi and Mantysaari (2010)
Conclusions

• very little is known about the structure of heavy nuclei at small-x
  - only for inclusive structure functions we have data at moderate x
  - SIDIS and exclusive VM production data are at high x or for light nuclei
  - diffractive structure functions have never been measured

• e+A collisions are ideal to learn about this
  - so far we have expectations using small-x QCD evolution
  - the CGC initial conditions for HIC are based on these expectations
  - but this needs to be checked with data

• what are crucial measurements ?

  - SIDIS & di-hadrons: the \( k_T \) dependence of the gluon distribution
  - coherent diffraction: the impact-parameter dependence
  - incoherent diffraction: correlations between small-x gluons