High energy DIS and the dipole picture

Outline

- Electron Proton DIS (eP) and Diffraction
  - "Standard" perturbative QCD theory:
    collinear factorization
    $\rightarrow$ Universal parton distribution functions
  - The dipole model $\rightarrow$ Universal Interaction Cross section
    Discuss some of the models on the market
    Successes, problems and implications

- Electron Nucleus DIS (eA)
  - HERA III ? $\sqrt{s} = 300$ GeV
    M.Arneodo et al., Proc. Future Physics at HERA, hep-ph/9610423.
  - THERA $\sqrt{s} = 1$ TeV
    L. Frankfurt, V.Guzey, M.M, and M. Strikman, THERA book, hep-ph/0104252
  - eRHIC/EIC $\sqrt{s} \sim 60 - 100$ GeV
    R.Venugopalan, hep-ph/0102087
  - Diffraction and Nuclear shadowing
  - A = Amplifier of small-x partons
  - Predictions in Gribov's black limit
    FGMS, Phys. Rev. Lett. 87 (2001) 192301

Standard pQCD: examples

Inclusive: e.g. DIS structure functions F_L, F_T

$$F_L(x,Q^2) = \Sigma_{q,\bar{q}}\ e_q^2\ \int_x^1\ \frac{dx'}{x'}$$

$$[C^{\gamma^* q}(\frac{x'}{x}, \alpha_s(Q^2), \frac{Q^2}{\mu^2})\ xq(x',\mu^2) +$$

$$C^{\gamma^* g}(\frac{x'}{x}, \alpha_s(Q^2), \frac{Q^2}{\mu^2})\ xg(x',\mu^2)]$$

Factorization theorem: A convolution of long distance non-perturbative *Universal* PDFs, $xq(x,Q^2)$, $xg(x,Q^2)$ with short distance pQCD calculable coefficients functions, $C^{\gamma^* g}, C^{\gamma^* q}$.

e.g. R. K. Ellis, W. J. Stirling, B. Webber "QCD and Collider Physics" (1996, CUP)

$F_2 = F_T + F_L$ is now a mature analysis: approaching NNLO

Inclusive diffraction: e.g. Diffractive structure function $F_2^D(4)(x_{I\!P}, Q^2, \beta, t)$ is factorized into a convolution of coefficient functions with diffractive parton distributions Universal DPDs, $f^{i,D}(x_{I\!P}, Q^2, \beta', t)$

A. Berera and D. E. Soper, Phys. Rev. D50 (1994) 4328, D53 (1996) 6162;

J. C. Collins, Phys.Rev. D57 (1998) 3051; Erratum-ibid. D61 (2000) 019902

Standard pQCD: examples

Inclusive diffraction: Currently models for DPDs at NLO: (these often assume Regge factorization too)

A. Hebecker, Nucl. Phys. B505 (1997) 349;

W. Buchmüller, T. Gehrmann, A. Hebecker, Nucl. Phys. B537 (1999) 477;

L. Alvero, J. C. Collins, J. Terron and J. Whitmore, Phys. Rev. D59 (1999) 074022;

F. Hautmann, Z. Kunszt and D. E. Soper, Phys. Rev. Lett. 81 (1998) 3333

Exclusive: e.g. Deeply virtual Compton scattering
Factorization of $A^{DVCS}(\gamma^* p \to \gamma p)$: convolution of perturbatively calculable coefficient functions with Generalized Parton Distributions Universal GPDs: $\mathcal{F}^i(X', Q^2, \zeta, t)$

A. V. Radyushkin Phys. Rev. D56 (1997) 5524; X. Ji and J. Osborne, Phys. Rev. D58 (1998) 094018; J. C. Collins and A. Freund, Phys. Rev. D (1999) 074009; B. White, hep-ph/0102121; Blümlein, B. Geyer, D. Robaschik, Nucl. Phys. B560 (1999) 283

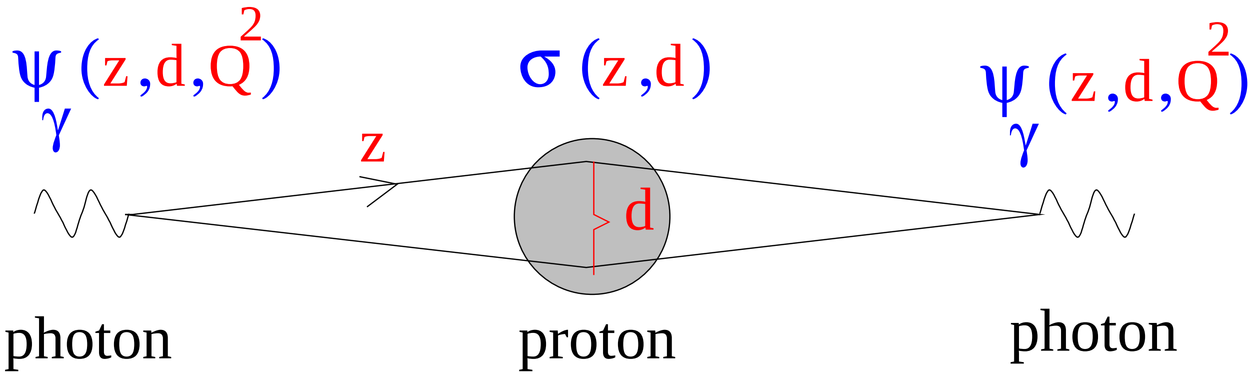
Full NLO QCD analysis of A^{DVCS} now available:

see e.g. A.V. Belitsky *et al.*, Phys. Lett. B474 (2000) 163;

A. Freund and M.M. hep-ph/0106115, hep-ph/0106319

The Dipole Picture

High energy (small $x = Q^2/2P \cdot q$) limit $\rightarrow$
factorization of timescales in process: $\tau_f \gg \tau_I$
"New" factorization of all small x processes
e.g. DIS structure functions at small x



Light-cone wavefunctions of the photon (or vector meson) weight *Universal* dipole cross section, $\sigma(x$ or $W^2, d^2, z)$, in the integral over transverse (dipole) size, d, according to x, Q^2 and the process concerned.

Integrand in d determines mixture of short/long distances
Phenomenology seems to work very well !
A good model looking for a theory !

Example: Total γ^*-P Cross section in d-space

Total cross sections for long. and trans. polarised photon:

$$\sigma^{\text{tot}}_{L,T}(x,Q^2) = \int dz \int d^2d \; \sigma(d^2,x) |\psi_{L,T}(z,d^2,Q^2)|^2$$

$$|\psi_L|^2 = \frac{6\alpha_{em}}{\pi^2} \Sigma_{q=1}^{nf} z^2(1-z)^2 Q^2 K_0^2(\epsilon d)$$

$$|\psi_T|^2 = \frac{3\alpha_{em}}{2\pi^2} \Sigma_{q=1}^{nf} \epsilon^2 K_1^2(\epsilon d) + m_q^2 K_0^2(\epsilon d)$$

$$\epsilon^2 = z(1-z)Q^2 + m_f^2$$

Generally use QED wavefunctions for the photon

For exclusive processes, e.g. diffractive vector meson production σ appears on the amplitude level

For inclusive diffraction σ^2 appears at the cross section level

Models for $\sigma(d^2, x)$: 1

Saturation model of:

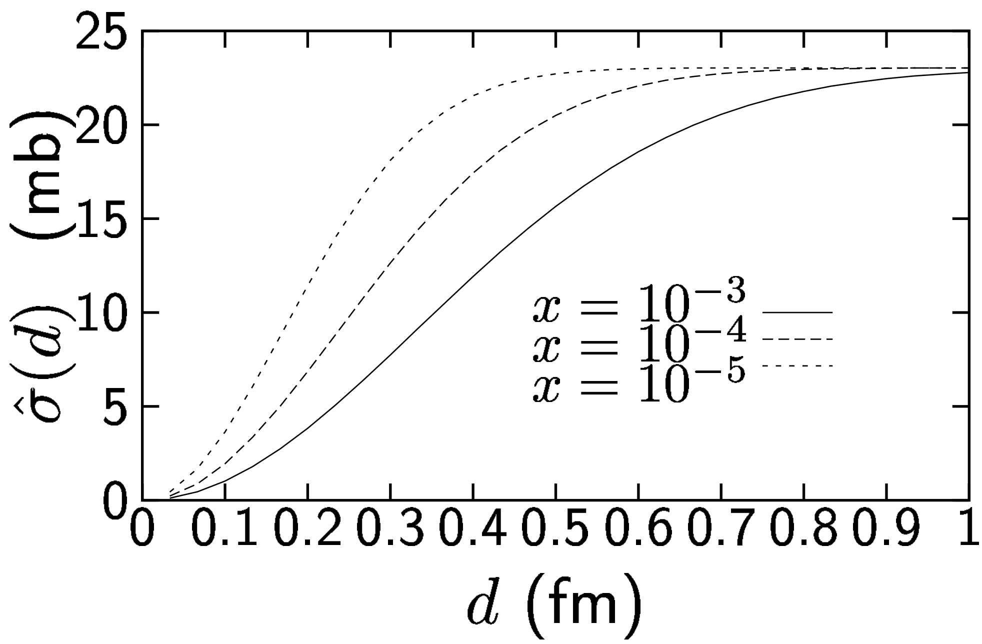
K. Golec-Biernat and M. Wusthoff, Phys.Rev. D59 (1999) 014017;

E. Gotsman, E. Levin and U. Maor, Phys. Lett. B425 (1998) 369.

$$\sigma(x, d^2) = \sigma_0(1 - \exp[-d^2 Q_0^2/4(x/x_0)^\lambda])$$

Successful Fit to HERA DIS, $x < 0.01$, $Q_0 = 1.0$ GeV:
$\sigma_0 = 23.03$ mb, $x_0 = 0.0003$, $\lambda = 0.288$.
Diffraction also described well.
(including $q\bar{q}g$ component with the same σ...)

K. Golec-Biernat and M. Wusthoff, Phys.Rev. D60 (1999) 114023



Models for $\sigma(d^2, x)$: 2

Forshaw, Kerley, Shaw (FKS) adopted a two-power fit strategy:
Phys. Rev. **D60** (1999) 074012, Nucl. Phys. A675 (2000) 80c:

$$\sigma(W^2, d) = a_0^S \frac{P_s^2(d)}{1+P_s^2(d)} (d^2W^2)^{\lambda_s} + a_2^H\ d^2\ (1 + P_h^2(d))\ \exp(-\nu_h^2 d)\ (d^2W^2)^{\lambda_h}$$

$P_s(d)$, $P_h(d)$ are polynomials in d.

Good fit to $F_2, \gamma P$, $x < 0.01, Q^2 < 60$ GeV^2
$\lambda_s = 0.06, \lambda_h = 0.44$ cf "Two Pomerons" model:
A. Donnachie and P. V. Landshoff, Phys. Lett. B437 (1998) 408
Good predictions $F_2^A, F_2^{c\bar{c}}, F_2^{D(3)}$, DVCS
σ function of d^2W^2 rather than x

Different modelling of photon wf at large d (Gaussian factor) reflects the uncertainty of the dipole model in this region

pQCD Model for $\sigma(d^2, x)$: 1

QCD-improved ansatz for $\sigma(d^2, x)$ (MFGS)

MM, Frankfurt, Guzey, Strikman, Eur Phys J. C16 (2000) 641

$$\sigma_{\mathrm{pQCD}}(x, d^2) \quad = \quad \frac{\pi^2}{3} d^2 \alpha_s(\bar{Q}^2) x^{'} g(x^{'}, \bar{Q}^2)$$

$\bar{Q}^2 = \lambda/d^2, \lambda = 4 - 10$, model for $x'(d) > x$.

Based on known LLA (Q^2) pQCD formula for small dipoles: sum of two-gluon exchange graphs: colour transparency $\sigma \propto d^2$

F. E. Low, Phys. Rev. D12 (1975) 163; S. Nussinov, Phys. Rev. Lett. 34 (1975) 1286;

N. N. Nikolaev and B.G.Zakharov, Z. Phys C49 (1990) 607; M. Ryskin, Z. Phys. C 57 (1991) 89;

S. Brodsky *et al.*, Phys. Rev. D50 (1994) 3134; L. Frankfurt, W. Kopf and M. Strikman, Phys. Rev. D54 (1996) 3194; D57 (1998) 512;

Durham Group: A. Martin, R. Roberts. T. Teubner, E. Levin

Hamburg Group: J. Bartels, H. Lotter, C. Ewerz, M Wüsthoff *et al.*

Tel Aviv Group: E. Gotsman, E. Levin and U. Maor *et al.*, eikonal, i.e. multiple exchange !

"Derivation": L. Frankfurt, A. Radyushkin and M. Strikman, Phys. Rev. D55 (1997) 1280

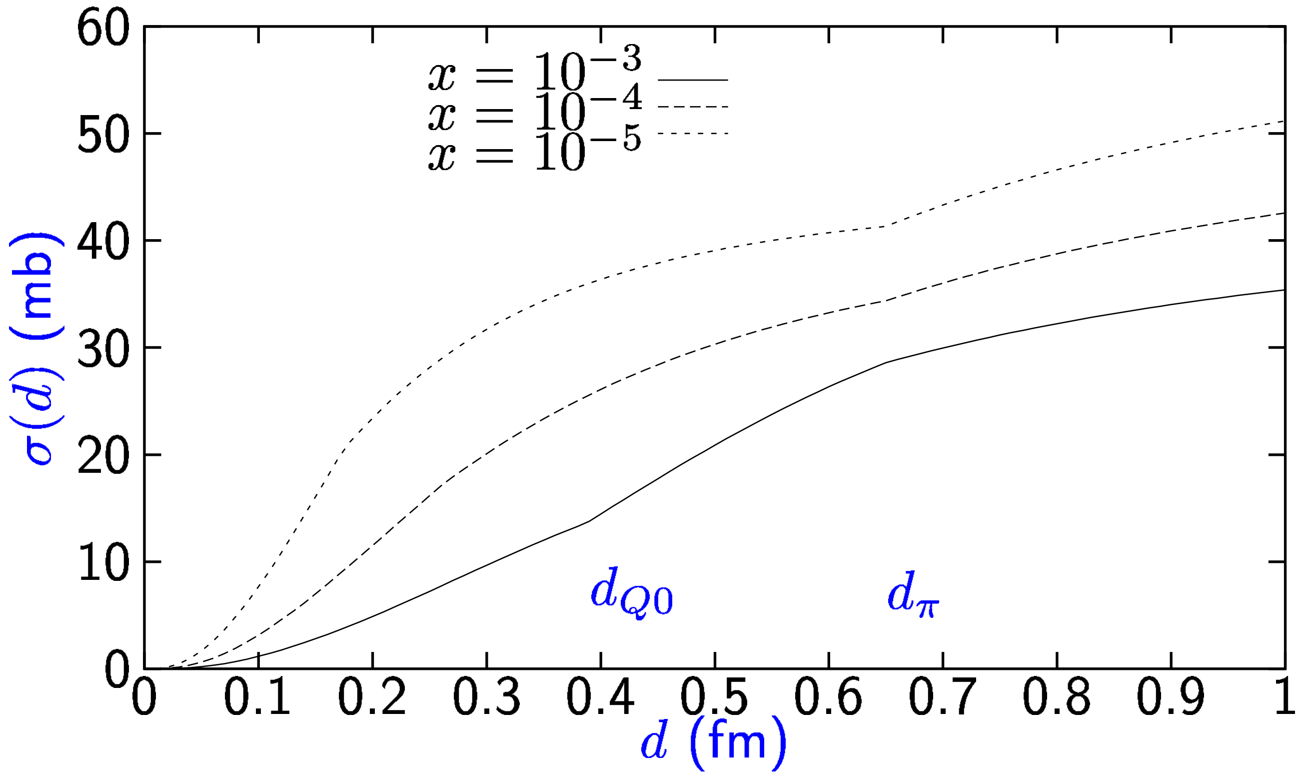
pQCD Model for $\sigma(d^2, x)$: 2

Large dipoles: match to soft dynamics via pion-proton cross section at large $d_\pi = 0.65$ fm, with its generic soft rise with energy: $\sigma_{\pi,N}(d_\pi, x) = 24\left(\frac{0.01}{x}\right)^{0.08}$ mb

Problem: LO gluon densities from DGLAP fits imply
$\sigma_{\text{pQCD}} \approx \sigma_{\pi p} \approx 20 - 40$ mb at very small x.

To prevent this we imposed taming (unitarity) when σ got "too large".Preserves monotonic increase of σ with dipole size
For small enough x, $d^2_{crit} < d^2_{Q0}$ is perturbative:
e.g. $x = 10^{-4}$, $d_{crit} = 0.26$ fm; $x = 10^{-5}$, $d_{crit} = 0.18$ fm.

pQCD Model for $\sigma(d^2, x)$: 3



Good qualitative description of F_2, J/ψ photoproduction and DVCS (for $\lambda = 4$)

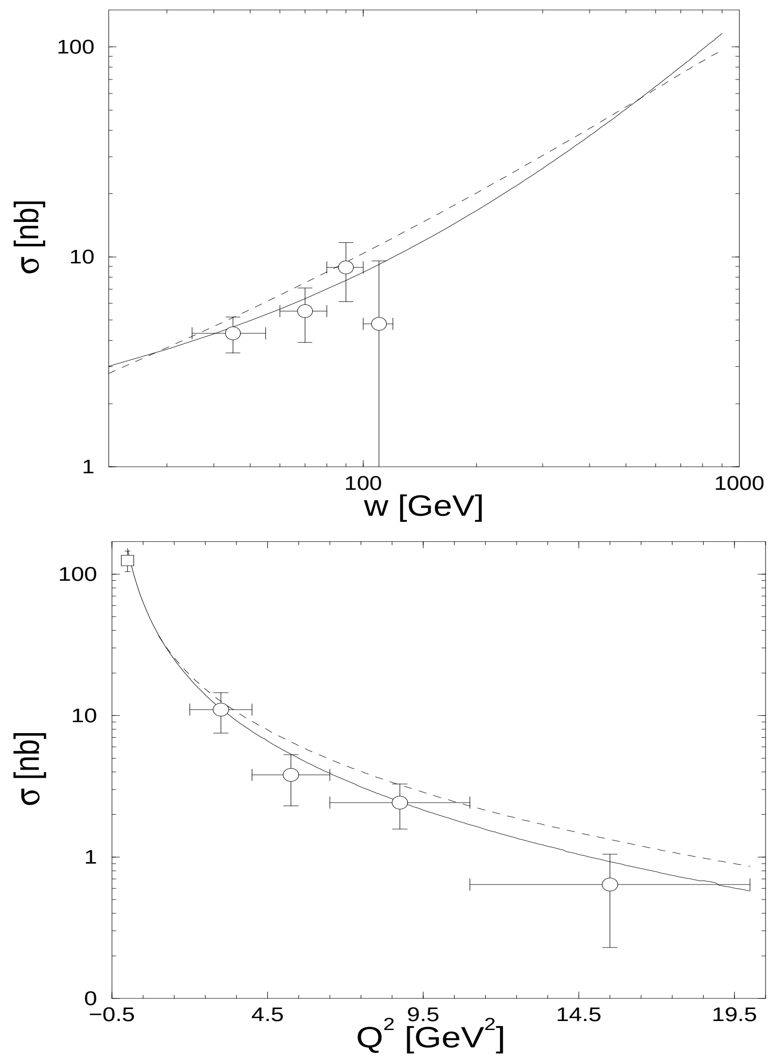
L. Frankfurt, MM, M. Strikman JHEP 0103 (2001) 045

MM, R. Sandapen and G. Shaw, hep-ph/0107224

Complete analysis of all VM data underway

Choose processes where $q\bar{q}g$ less significant !

Dipole Model for DVCS



The energy (fixed $Q^2 = 4.5$ GeV^2) and Q^2 (fixed $W = 75$ GeV) dependence of the photon level DVCS cross section compared with H1 data: FKS (solid line); MFGS (dashed line).

Problems with the Dipole Model

Factorization is not of collinear (DGLAP) QCD type !
Claimed to be "similar" to k_t-factorization (proof ?)

S. Catani, M. Ciafaloni and F.Hautmann, Phys. Lett. B242 (1990) 97;
S. Catani, F. Fiorani and G. Marchesini, Phys. Lett. B336 (1990) 18; S. Catani and F. Hautmann, Nucl. Phys. B427 (1994) 475; J. C. Collins and K. Ellis, Nucl. Phys. B360 (1991) 3; E. M. Levin *et al.*, Sov. J. Nucl. Phys. 54 (1001) 867.

Standard techniques for analysing a particular process ?
Corrections to the dipole picture $\mathcal{O}(\log S), \mathcal{O}(1/S)$?
Relation to BFKL ? NLO $(\log 1/x)$ BFKL impact factor:

J. Bartels, S. Gieseke and C.F. Qiao, Phys.Rev. D63 (2001) 056014;
J. Bartels, S. Gieseke and A. Kyrieleis, hep-ph/0107152

Connection with DGLAP and collinear factorization ?
Problem of double counting when $q\bar{q}g$, ... included ?
This illustrates the fundamental problem: leading log Q^2 sums all logs in Q^2 to infinity implying an infinite number of partons in the photon !
Need to correctly implement the RG in d-space.
Some progress in this direction by "BNL group"

A. Kovner, L. McLerran, H. Weigert, R. Venugopalan, Yu. Kovchegov

More theoretical progress certainly required !

Advantages of eA for HERA: 1

Moderate A, Start with benchmark Deuterium, (also required for high x flavour decomposition !) shadowing corrections $F_2^A/AF_2^N < 1$ are now well understood:

Exploit the deep connection between nuclear shadowing and diffraction to make predictions:
This aspect well under control using leading twist diffractive parton densities from HERA.

L. Frankfurt and M. Strikman, Eur. Phys. J. A5 (1999) 427;

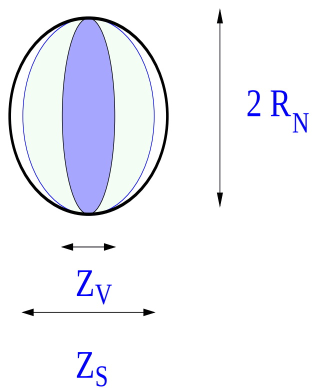
L. Frankfurt, V. Guzey, MM, and M. Strikman "Electron Nucleus Collisions at THERA" in The THERA Book, eds. U. Katz, M. Klein and A. Levy, hep-ph/0104252;

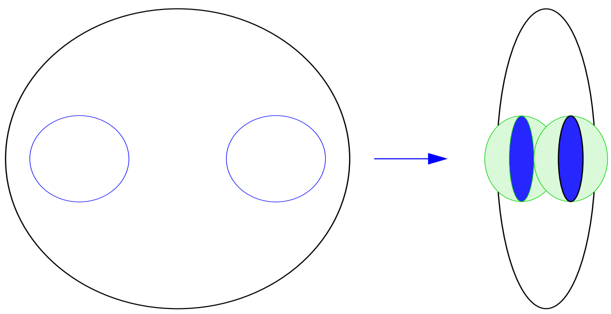
and FGMS, preprint in preparation

The "leading twist approach" and eikonal approach of Levin *et al.* leads to very different predictions for nuclear parton densities !
Reasonable quantity of data (a few bins in Q^2) would settle the issue and allows feedback: distinguish between competing models of diffraction !
NPDs are required for accurate predictions for ion-ion collisions
HERA-III could do for ion-ion what HERA did for pp !

Advantages of eA for HERA: 2

Large A: At HERA energies, $\sqrt{s} \sim 300$ GeV,
probe nucleus in the high parton density regime.
Russian dolls picture





Valence partons in nucleons contracted to Pancake of longitudinal size $Z_V = 2R_N m_N / p_N$.
But small x partons form thicker pancakes $Z_S \sim \langle x_v \rangle Z_V / x$!
Small x partons $x \ll \langle x_v \rangle R_N / R_A$ in individual nucleons overlap in fast moving (contracted) nucleus !

ep/eA and the black body limit (BBL)

DIS on large nucleus: dipoles pass through many nucleons
HERA-III: enhancement factor of small x PDFs: $A^{1/3} \approx 6$.
THERA enhancement factor of ≈ 10.
Conclusion: we can reach high density regime at much higher x than in DIS on the proton !
Can also use "centrality" triggers where nucleon density is higher (gain a factor of about 5 in x)
Common feature of all dipole models as energy increases $\sigma_{q\bar{q}}$ gets "big" $(20 - 40$ mb), $\sigma_{q\bar{q}g}$ factor of 9/4 bigger ! Are we approaching new regime of QCD, high density weakly interacting partons ?

Alternatively strategy to full QCD calculation for eA:
assume all configs go "black"

$$\sigma(x, d^2) = \pi R_A^2$$

and make predictions !

FGMS, Phys. Rev. Lett. 87 (2001) 192301

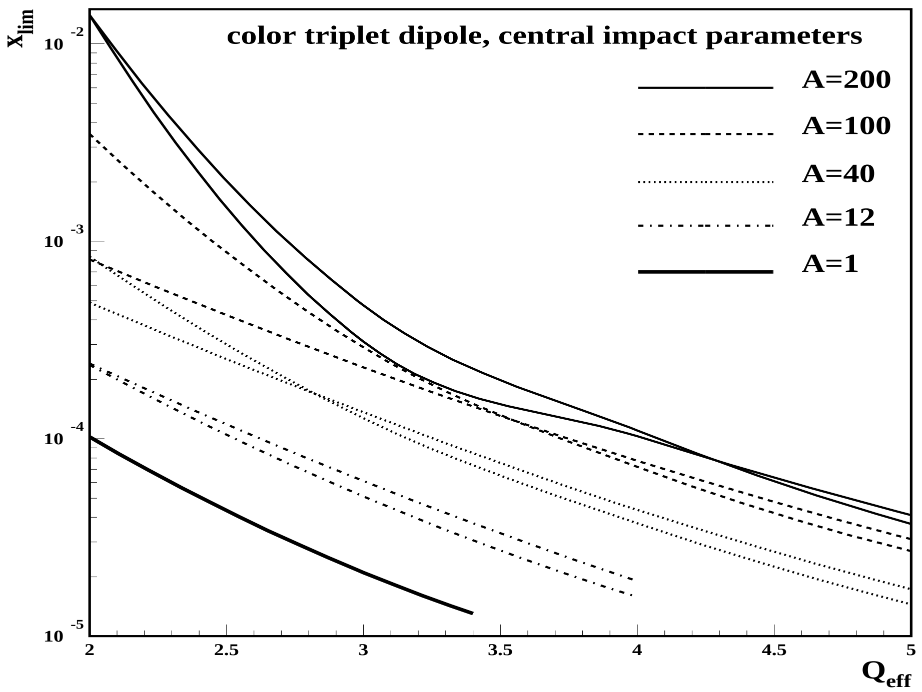
ep/eA and the black body limit (BBL)

In practice for pQCD: pointlike coupling to quarks implies some very small configs in the ensemble are not black. This makes finding BBL unambiguous signals in eP difficult !
The nuclear environment screens the expansion of the nucleon radius with energy, leading to softer x dependence of nuclear SFs compared to nucleon case.

Black limit should be easier to find in DIS on a large nucleus !

Unitarity Boundaries

$$\sigma_A^{q\bar{q}}(d_\perp^2, x) = \frac{\pi^2}{3} d_\perp^2 \alpha_s(\bar{Q}^2) \left[xG^A(x, \bar{Q}^2) \right] \lesssim \pi R_A^2$$



Unitarity boundaries for colour triplet dipole on nuclei. Regions to the left prohibited by the unitarity bound. Two sets: two extremes of nuclear shadowing

Even stronger bounds for gluon induced processes (9/4 colour factor). BBL realistic at HERA for large nucleus ($A = 200$) !

Approach to Gribov's BBL ?

In pre-QCD days Gribov (1969) considered the proton looking black for all hadronic fluctuations of the photon. This implies a break down of Bjorken scaling and a new regime of QCD.

$$F_T^{\mathsf{bbl}} = \frac{2\pi R_A^2}{12\pi^3} \int_0^{\delta s} \frac{dM^2 \rho(M^2) M^2 Q^2}{(M^2+Q^2)^2}$$

$$F_L^{\mathsf{bbl}} = \frac{2\pi R_A^2}{12\pi^3} \int_0^{\delta s} \frac{dM^2 Q^4 \rho(M^2)}{(M^2+Q^2)^2}$$

$$F_2^{\mathsf{bbl}} = \frac{2\pi R_A^2 Q^2 \rho}{12\pi^3} \ln(\delta/x)$$

$Q^2 = 1$ GeV^2, $x = 10^{-5}$, $F_2^{\mathsf{bbl}} \approx 1.5 - 3$, $F_2^{\mathsf{HERA}} \approx 0.7$
Black Limit is nearby !

Investigate in eP at Tesla-HERA, up to $W^2 = 10^6$ GeV^2 and HERA/THERA eA

Predictions of BBL for eA: 1

All configurations have same strength: small symmetric configs ($z \approx 1/2, k_T^2 \sim Q^2$) in the virtual photon are no longer suppressed by colour transparency.

Many striking predictions !

Inclusive Structure functions: violate Bjorken scaling and DGLAP

$$F_2^A(x,Q^2) = \frac{2\pi R_A^2}{12\pi^3} Q^2 \rho \ln x_0/x$$

$$F_2^N\,(xG^N) = \frac{2\pi R_N^2}{12\pi^3} Q^2 \rho \ln x_0/x\ (1 + C(x) \ln^2 x_0/x)$$

Diffraction 50% of total. Spectrum of diffractive masses is very hard:

$$\frac{dF_T^{D(3)}(x,Q^2,M^2)}{dM^2} = \frac{\pi R_A^2}{12\pi^3} \frac{Q^2 M^2 \rho(M^2)}{(M^2+Q^2)^2}\ ,$$

$$\frac{dF_L^{D(3)}(x,Q^2,M^2)}{dM^2} = \frac{\pi R_A^2}{12\pi^3} \frac{Q^4 \rho(M^2)}{(M^2+Q^2)^2}$$

Predictions of BBL for eA: 2

Enhanced hard diffractive dijet production:

$$\langle p_t^2(jet)\rangle_T = 3M^2/20\ ,$$
$$\langle p_t^2(jet)\rangle_L = M^2/5$$

Leading spectrum of hadrons (fixed M^2) much reduced ('standard' are from asymmetric $z \approx 1$)

$$\frac{d(\sigma_T + \epsilon\sigma_L)}{dz} \propto \frac{M^2}{8Q^2}(1 + (2z-1)^2) + \epsilon z(1-z)$$

Factor of 5 suppression at largest z.

Parameter free predictions of exclusive electroproduction of VMs, DVCS. Much weaker Q^2-dependence (cf. for colour transparency in pQCD $\propto xG^2/Q^6 \approx 1/Q^5$)

$$\frac{d\sigma^{\gamma_L^* + A \rightarrow V + A}}{dt} = \frac{(2\pi R_A^2)^2}{16\pi}\frac{3\Gamma_V Q^2 M_V}{\alpha(M_V^2 + Q^2)^2}\frac{4\ \left|J_1(\sqrt{-t}R_A)\right|^2}{-tR_A^2}$$

Conclusions

- ♣ Phenomenological Dipole models seem to work very well for wide range of small-x processes in eP
  At present they lack theoretical support
- ♣ At very small $x \lesssim 10^{-4}$ in eP, HERA has found large and steeply rising gluon densities which imply "unitarity corrections" are required at smaller x
  Probe new saturation regime of pQCD at much higher x in eA: large A magnifies small-x pdfs: factor $A^{1/3}$
  Further enhancement for central collisions.
- ♣ Assume universal BBL $\sigma(x,d) = 2\pi R^2$
  Clear predictions for inclusive F_2^A, F_L^A
  Exclusive Vector Meson, DVCS, F_2^D...
  Finals states: leading hadrons spectrum depleted: high pt enhanced
  Very different from HERA eP !
- ♣ If there *really is* a new pQCD regime very good prospects to find it in eA at HERA or THERA
  "Standard" DGLAP predictions break down
  Investigate QCD in new (probably non-linear) regime