Dipole approach to DIS scattering processes

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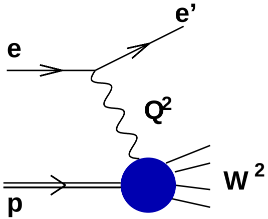
Uniwersytet Warszawski, 13 stycznia 2017

Deep inelastic scattering

- Rutherford experiments 1911 - scattering of alpha particles on atoms of gold
- Experiments at SLAC, CERN, DESY 1967 - 2007 - Lepton scattering on nucleons: eN, μN, νN.



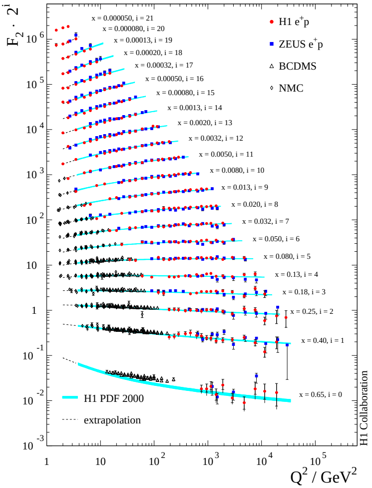
Photon virtuality: $Q^2 = -q^2$

Bjorken variable: $x = \frac{Q^2}{W^2+Q^2}$

- Cross section $\gamma^* p$ through scattered electron:

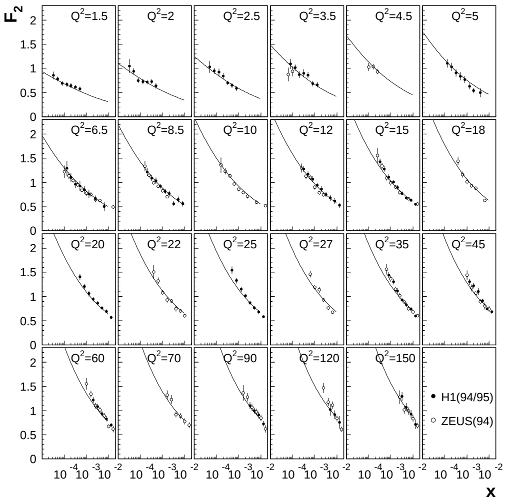
$$F_2(x, Q^2) \qquad F_L(x, Q^2) \qquad F_3(x, Q^2)$$

Various ways of showing the results



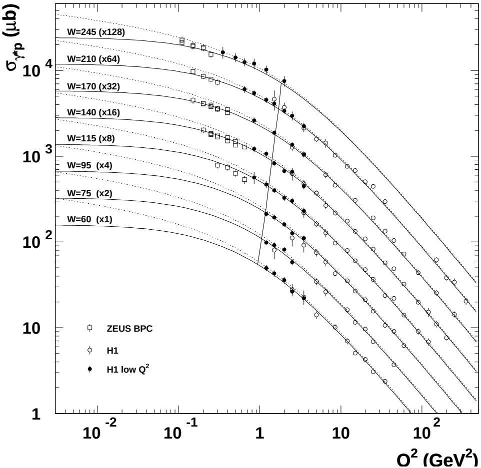
- Logarithmic dependence on Q^2 – Bjorken scaling violation

Various ways of showing the results



- Strong rise as $x \to 0$ - low x effects

Various ways of showing the results



- Transition to low Q^2 for $\sigma_{\gamma^* p} = F_2/Q^2$

Different theoretical aspect

The three ways of showing the same data concentrate of three different theoretical aspects of QCD description of DIS:

- scaling violation - DGLAP evolution (pdf determination)
- low x behaviour - BFKL evolution
- transition to low Q^2 - saturation/unitarization effects

These aspects are interconnected.

DGLAP eqvolution equations

- Parton distribution functions from structure functions

$$F_2(x, Q^2) = \sum_f e_f^2 \left\{ q_f^2(x, Q^2) + \overline{q}_f(x, Q^2) \right\}$$

- PDFs evolve logarithmically with Q^2

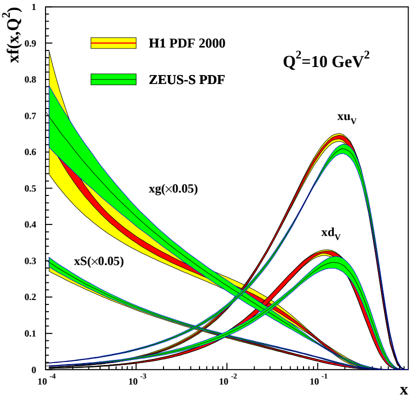
$$\frac{\partial q_f(x, Q^2)}{\partial \ln Q^2} = \frac{\alpha_s}{2\pi} \int_x^1 \frac{dz}{z} P_{ff}(x/z)\, q_f(z, Q^2) + P_{fg} \otimes g$$

$$\frac{\partial g(x, Q^2)}{\partial \ln Q^2} = P_{gg} \otimes g + \sum_f P_{gf} \otimes q_f$$

- Fit x-shape of initial conditions to DIS data

$$q_f(x, Q_0^2) \qquad\qquad g(x, Q_0^2)$$

PDFs from global fits



- Fast partons $x \sim 1$: valence quarks
- Wee partons $x \ll 1$: sea $q\overline{q}$ quarks and gluons

Low x - BFKL evolution

The observed strong rise of sea quark and gluon distributions is predicted by

- double logarithmic limit of DGALP equation: $x \to 0 \;\; \text{and} \;\; Q^2 \to \infty$

$$xg(x, Q^2) \sim \exp\{2\sqrt{\overline{\alpha}_s \ln(1/x) \ln(Q^2)}\}$$

- BFKL equation for transverse momentum dependent gluon distribution

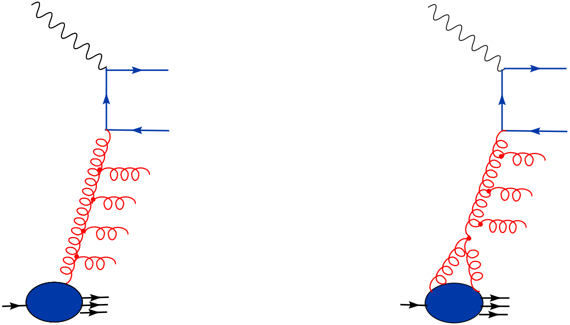
$$f(x, k_\perp) \sim x^{-4\overline{\alpha}_s \ln 2} \times \exp\left\{\frac{-\ln^2(k_\perp^2)}{\sqrt{a \ln(1/x)}}\right\} \qquad x \to 0$$

Strong increase of gluon (and sea) distributions calls for taming -

saturation/unitarization effects

Cartoon of gluon recombination

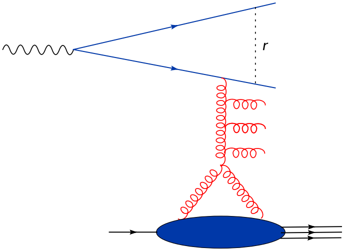
DIS on sea quarks



- gluon recombination as a mechanism of saturation effects
- multiple scattering

Dipole scattering view of DIS at low x

- in the proton rest frame photon splits into $q\overline{q}$ dipole



- dipole - proton interaction is well separated from photon splitting

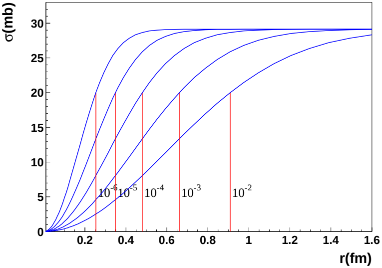
$$\sigma_{\gamma^* p} = \frac{F_2}{4\pi Q^2} = \int d^2 r \int_0^1 dz \, |\Psi(z, r, Q^2, m_f)|^2 \, \hat{\sigma}(x, r)$$

- saturation effects are contained in dipole cross section $\hat{\sigma}$

Saturation model for dipole cross section $\hat{\sigma}(x, r)$

(KGB, M.Wuesthoff, PRD 59 (1998) 014017)

- strength of the dipole interaction with the proton



- small dipoles interact weakly, large dipole interaction saturates to σ_0
- for $x \to 0$ even small dipoles start to interact strongly
- physical interpretation: proton becomes denser as $x \to 0$

Further discussion

- Dipole cross section with 3 parameters fitted to DIS data with $x \leq 10^{-2}$

$$\hat{\sigma}(x,r) = \sigma_0 \left\{ 1 - \exp\left(-r^2 / R_s^2(x) \right) \right\}$$

- Saturation scale $R_s(x) = R_0 \, x^{\lambda > 0}$ sets the scale for dipole size

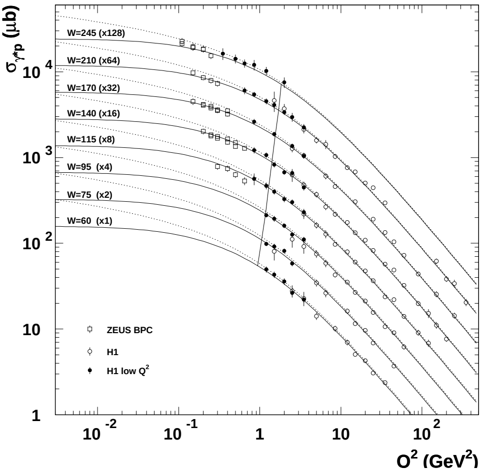
- Transition to saturation, $\hat{\sigma} \to \sigma_0$, can be achieved in two different ways

$$x \to 0 \qquad \text{or} \qquad r \to \infty$$

- the first is parton saturation, the second describe transition to low Q^2

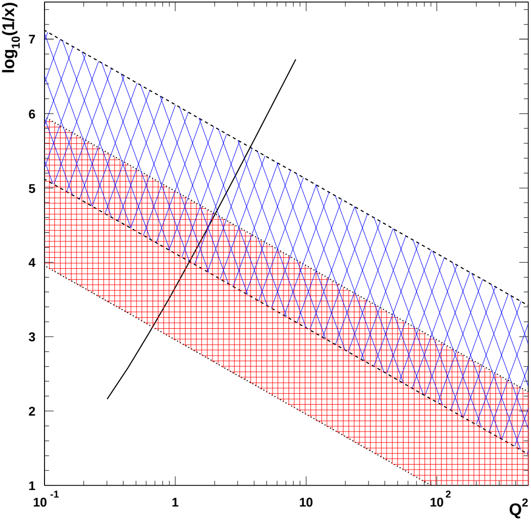
$$r_{charact} = \frac{1}{Q}$$

Transition of $\sigma_{\gamma^* p} = F_2/Q^2$ to low Q^2



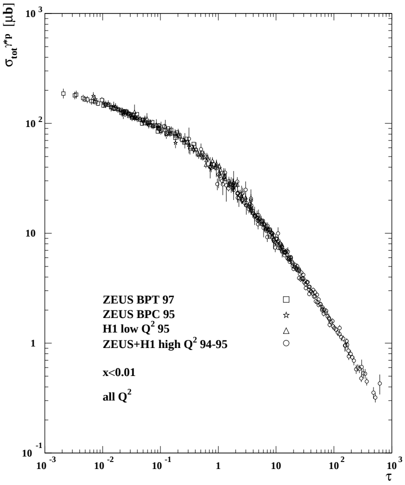
- saturation line: $\frac{1}{Q} = R_s(x)$

Saturation line on (Q^2, x) plane



Geometric scaling

$$\hat{\sigma}(r/R_s(x)) \quad => \quad \sigma_{\gamma^* p}(\tau = Q^2 R_s^2(x))$$

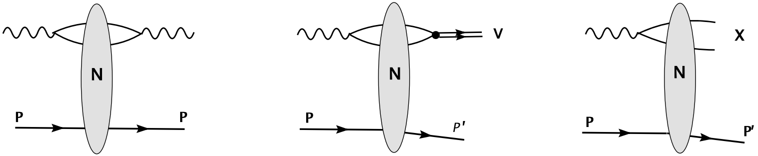


(A. Staśto, KGB, J. Kwieciński, PRL 86 (2001) 596)

Application to diffractive processes

- Universality of dipole scattering amplitude $N(x, r, b)$ in diffractive processes

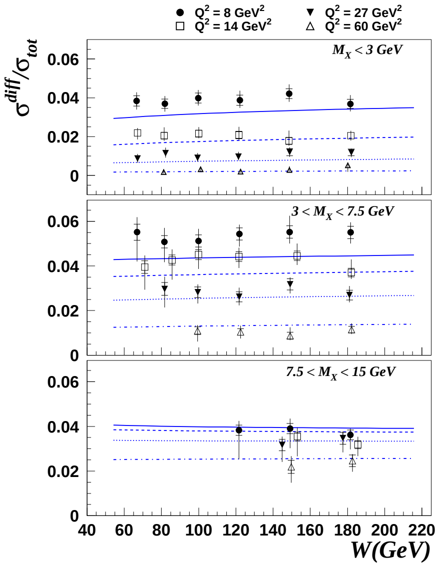
$$\hat{\sigma}(x, r) = 2 \int d^2b\, N(x, r, b)$$



- vector meson and open diffractive production amplitudes
- explanation of constant ratio (KGB, M. Wuesthoff, PRD 60 (1999) 114023)

$$\frac{\sigma^{diff}}{\sigma_{\gamma^* p}} \sim \frac{1}{\ln(Q^2 R_s^2(x))}$$

Constant ratio - comparison with data



Additional remarks

By the same token one can discuss

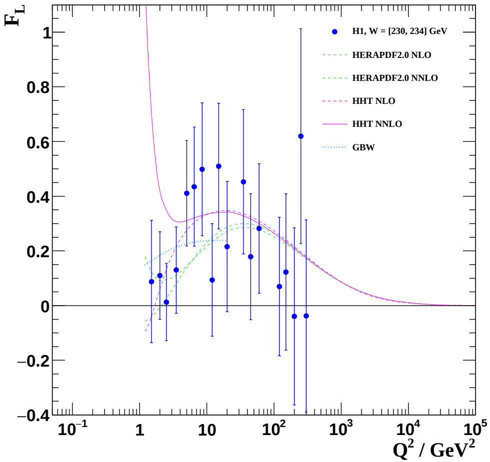
- photoproduction limit - logarithmically sensitive to dipole quark mass

$$\sigma_{\gamma p} \sim \sigma_0 \, \ln\left(\frac{1}{m_f^2 R_s^2(x)}\right) \qquad\qquad x = \frac{4m_f^2}{W^2}$$

- heavy quark contribution to structure functions: $1/m_c < R_s$ at HERA

- longitudinal structure function

Logitudinal structure function F_L



(I. Abt, A.M. Cooper-Sarkar, B.Foster, V. Myronenko, K. Wichmann, M. Wing, PRD 94 (2016) 034032)

Important improvements

- Small dipole corrections to match pQCD results

$$N(x,r) \sim r^2 \alpha_s G(x, 1/r^2)$$

(J. Bartels, KGB, H. Kowalski, PRD 66 (2002) 014001)

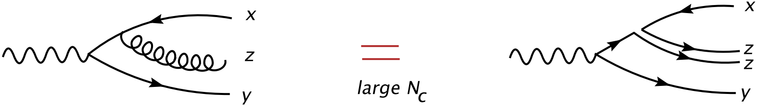
- Impact parameter dependence - to match t-dependence of VM production

$$T(b) = \frac{1}{2\pi B} \exp(-b^2/2B) \qquad\qquad Q_s(x,b) = Q_0\, x^{-\lambda}\, T(b)$$

(Kowalski, Motyka, Watt, PRD74 (2006) 074016)

QCD justification of dipole models

- Soft gluon emissions with $z_g \ll z_q$ (A. H. Mueller, Nucl.Phys. B415 (1994) 373)



- Dipole splitting probablity $(xy) \to (xz) + (zy)$:

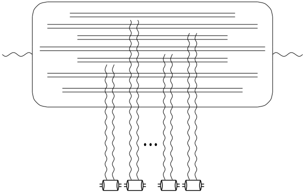
$$\frac{dP}{dY d^2 z} = \frac{N_c \alpha_s}{2\pi^2} \frac{(\vec{x}-\vec{y})^2}{(\vec{x}-\vec{z})^2(\vec{z}-\vec{y})^2} \equiv K(x,y,z)$$

- Classical branching process with generating functional $Z(x, y, Y; u)$

- Multi-dipole distributions in onium

$$n_k(r_1, b_1, \ldots, r_k, b_k; Y) = \frac{1}{k!} \frac{\delta^k Z(x,y,Y,u)}{\delta u(r_1,b_1)\ldots\delta u(r_k,b_k)}$$

- BFKL growth in a number of color dipoles: $n_1 \sim \mathrm{e}^{4 \ln 2\, \overline{\alpha}_s Y}$
- Large nucleus: multiple rescattering of each dipole on different nucleons



- Dipole scattering amplitude

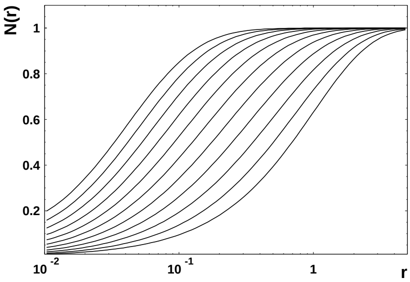
$$-N(x, y; Y) = n_1 \cdot \gamma + n_2 \cdot (\gamma)^2 + n_3 \cdot (\gamma)^3 + \ldots$$

- Nonlinear evolution equation (Y. Kovchegov, PRD 60 (1999) 034008)

$$\frac{\partial N(x,y)}{\partial Y} = \int d^2 z\, K(x,y,z) \left\{ N(x,y) + N(y,z) - N(x,y) - N(x,y)N(y,z) \right\}$$

Properties of the solution at fixed b

- Introducing $r = x - y$ and $b = (x + y)/2$



- local unitarity: $N \leq 1$
- saturation scale: $Q_s(x) = 1/R_s \sim x^{-4 \ln 2 \, \overline{\alpha}_s}$
- (approximate) geometric scaling: $N = N(r\, Q_s(x))$

Problems with BK equation

- Important problem: b-dependence - long nonpert. tail to be suppressed
- Color quadrupols and higher multipoles are neglected. In BK equation

$$N(x_\perp, y_\perp, Y) = 1 - \frac{1}{N_c}\left\langle \mathrm{Tr}(V^\dagger(x_\perp)V(x_\perp))\right\rangle_Y$$

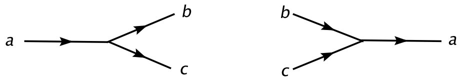
where

$$V(x_\perp) \;=\; P\exp\left(ig\int_{-\infty}^{\infty} dx^+\, A_a^-(x^+, x_\perp)\, t^a\right)$$

- Balitsky hierarchy for higher order correlators.

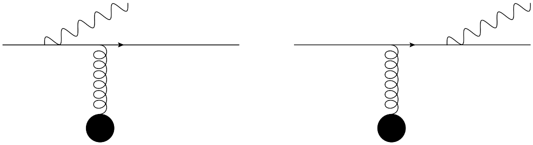
(R. Boussarie, L. Szymanowski, S. Wallon- recent works)

- No saturation in dipole number density. Missing dipole merging: $2 \to 1$



Application to hadronic collisions

- Drell-Yan productions with $q/\overline{q}$ momentum fractions $x_1 \sim 1$ and $x_2 \ll 1$
- Fast quark scatters off the proton color field

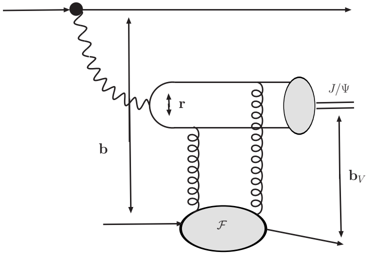


$$\sigma_{T,L}(qp \to \gamma^* X) = \int d^2r \, W_{T,L}(z, r, M^2) \, \hat{\sigma}(x_2, zr)$$

(KGB, E. Lewandowska, A. Staśto, PRD 82 (2010) 094010)

Application to hadronic collisions

- Exclusive vector meson production in pp and pA collsions



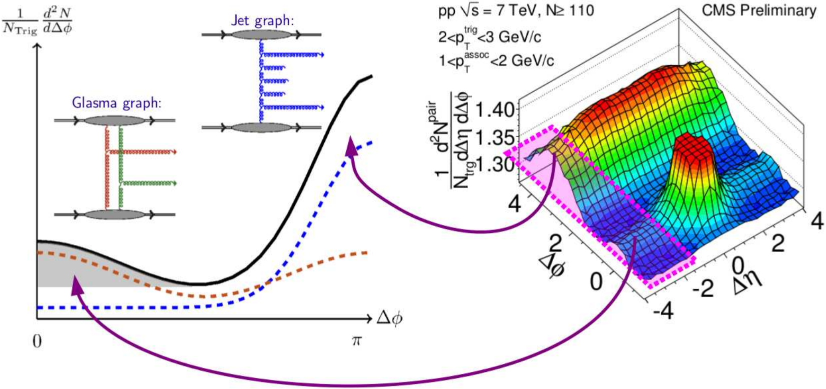
- Predictions done also in term of the unintegrated gluon distribution
- Forward production (jet, particles) in hybrid factorization

Heavy ion collisions

- Gluon density enhanced by large number of nucleons $A \gg 1$

- Collision of two dense gluon condensate. Theory behind
  - Color Glass Condensate
    (F. Gelis, E. Iancu, J. Jalilian-Marian, R. Venugopalan, arXiv:1002.0333)
  - Glasma
    (L. McLerran, T. Lappi, Nucl. Phys. A772 (2006) 200)

Ridge in pp and pA collisions



Summary

- Dipole model approach with saturation to DIS turned out to be very fruitful in understanding processes at low x.
- It triggered a lot of theoretical efforts based on QCD - CGC, glasma, Wilson lines, dipole operators, shock waves and many more.
- In *pp* and heavy ion collisions is not so much fruitful due to complexity of the initial and final state interactions.
- However - in selected kinematic configurations seems to be important: forward production in *pA*, ultraperipherial collisions, initial state for hydro evolution of *AA* or *pA*.