Theoretical review of parton saturation

Krzysztof Golec-Biernat

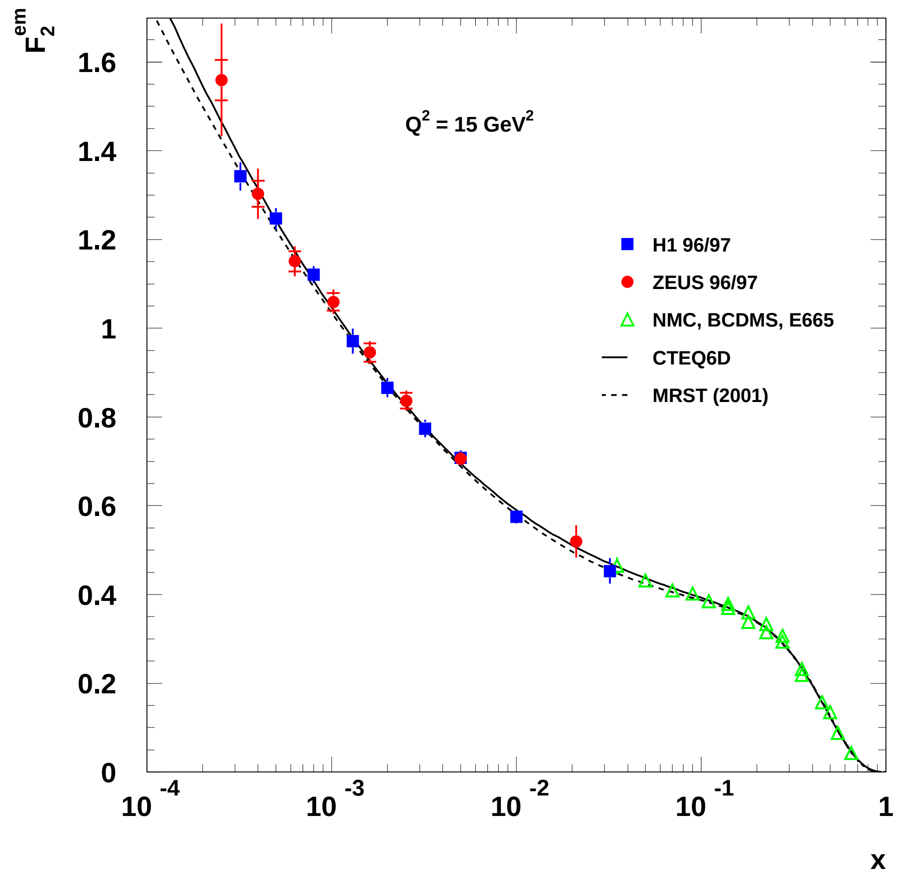
Institute of Nuclear Physics PAN, Krakow

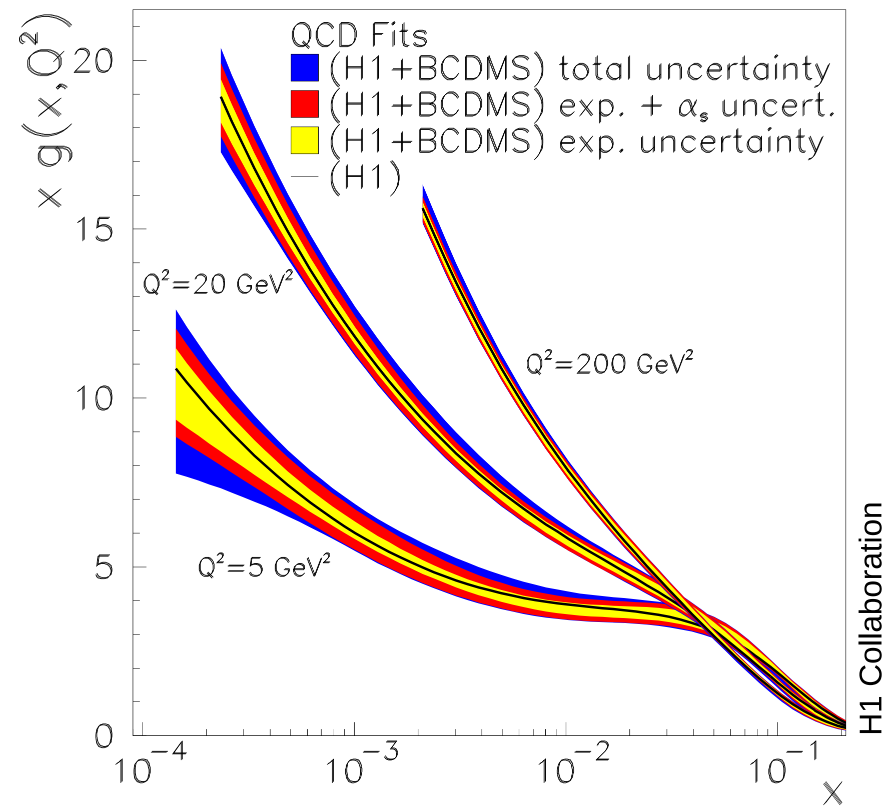
Rzeszow University

ISMD 2008 at DESY

19^{th} September 2008

DIS results from HERA





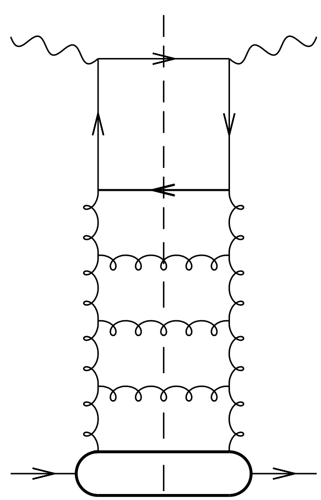
- Power-like rise: $F_2 \sim x^{-\lambda}$ when $x = Q^2/s \to 0$ and Q^2 fixed.
- Rise driven by strong growth of the gluon distribution.

Collinear factorization approach

- Convolution in longitudinal momenta

$$F_2(x,Q^2) = \underbrace{\sum_{i=q,g} C_i(x,Q^2) \otimes f_i(x,Q^2)}_{\textit{leading twist}} \quad + \quad \underbrace{\sum_{n=1} \frac{\Lambda_n(x)}{Q^{2n}}}_{\textit{higher twists}}$$

- Universal parton distribution functions $f_i = \{q, \bar{q}, G\}$ evolved in Q^2 by DGLAP evolution equations.

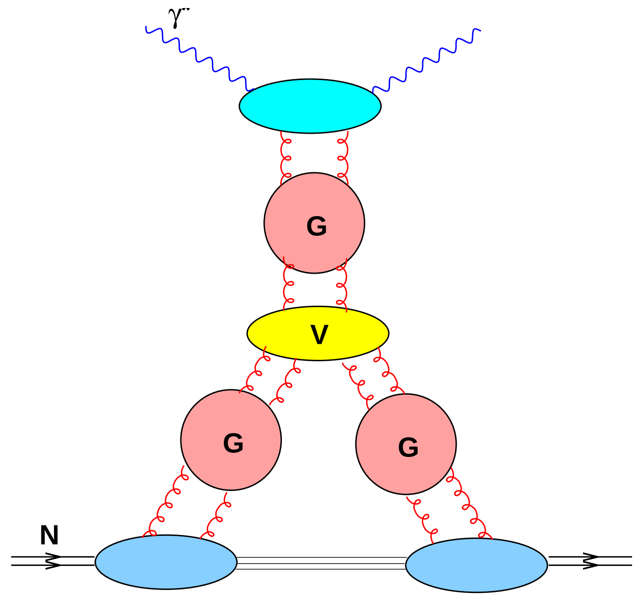


$$\frac{\partial\, G}{\partial \ln Q^2 \ln(1/x)} = \overline{\alpha}_s\, G$$

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

- Higher twist terms usually small.

Taming the growth for $x \to 0$



- Gribov-Levin-Ryskin evolution equation for the gluon distribution

$$\frac{\partial G}{\partial \ln Q^2 \ln(1/x)} = \overline{\alpha}_s G - \frac{\overline{\alpha}_s^2}{Q^2 R_H^2} G^2$$

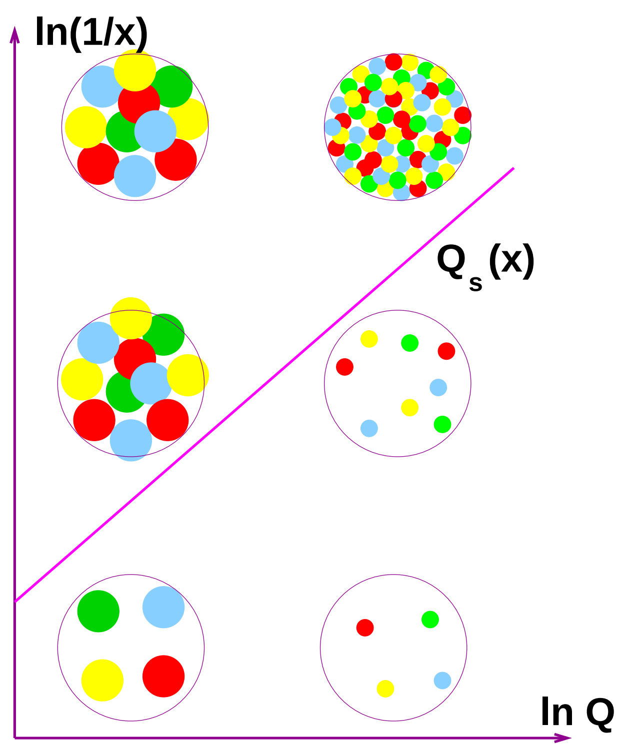
- Still leading twist description.

Saturation scale

- Saturation of gluon density when nonlinear term $\approx$ linear term

$$\frac{\alpha_s(Q_s^2)}{Q_s^2} G(x, Q_s^2) \approx \pi R_H^2$$

- x-dependent saturation scale $Q_s(x)$ emerges



$k_\perp$-factorization

- At small x higher twists become very important (large $\ln(1/x)$ terms).
- Partial resummation by exact treatment of quark transverse momentum $p_\perp$ in the quark box (in DGLAP: $Q \gg p_\perp \gg k_\perp$)

$$F_2(x, Q^2) = \int d^2k_\perp \, \phi_{q\bar{q}}(k_\perp/Q) \, f(x, k_\perp)$$

- Unintergrated gluon density $f(x, k_\perp)$ obeys BFKL equation which gives power-like growth:

$$f(x, k_\perp) \sim x^{-4\ln 2\, \alpha_s}$$

- Still a problem! F_2 rises too fast.

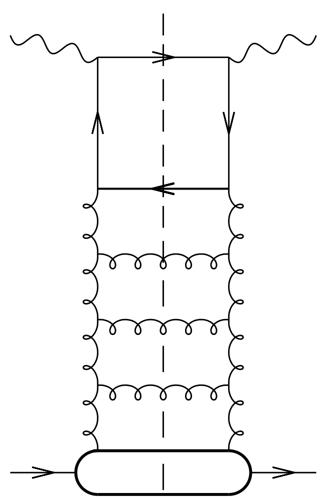
Dipole models

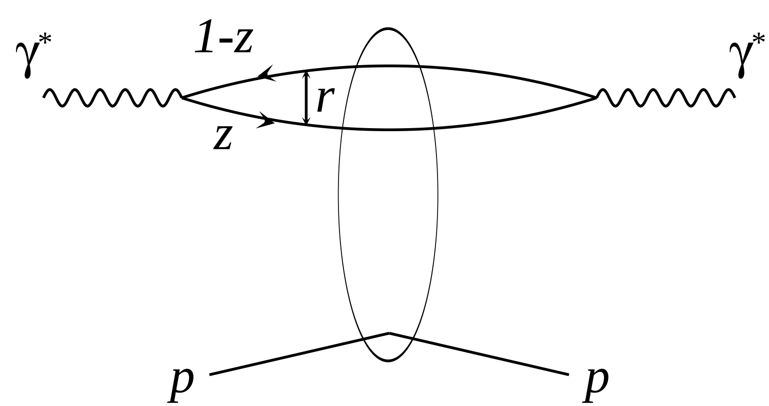
- Fourier transform quark transverse momentum: $p_\perp \leftrightarrow r$

$$\sigma_{T,L}(x,Q^2) = \int d^2r \int_0^1 dz\, |\Psi_{T,L}(z,r,Q^2)|^2\, \sigma_{q\bar{q}}(x,r)$$

- $F_2 = Q^2(\sigma_T + \sigma_L)$

- $q\bar{q}$ dipole probes the proton structure (in the frame where photon q^+ momentum is large)

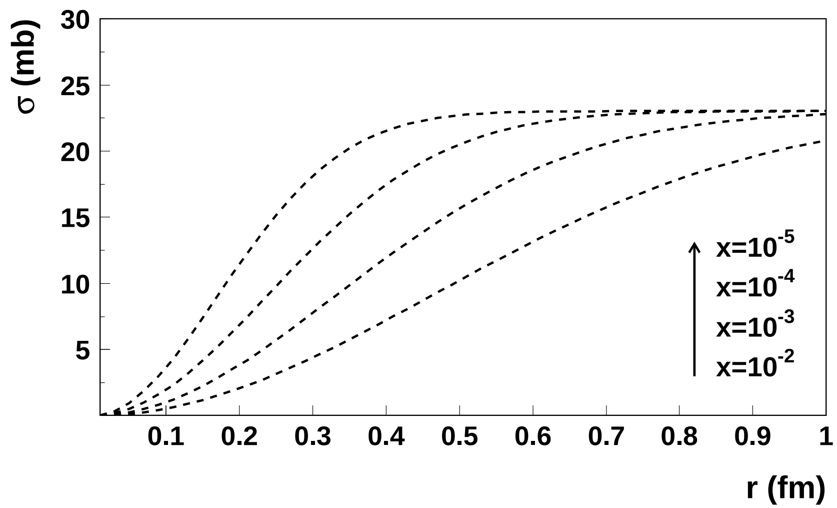




Dipole cross section

- Gluonic interactions contained in the dipole cross section

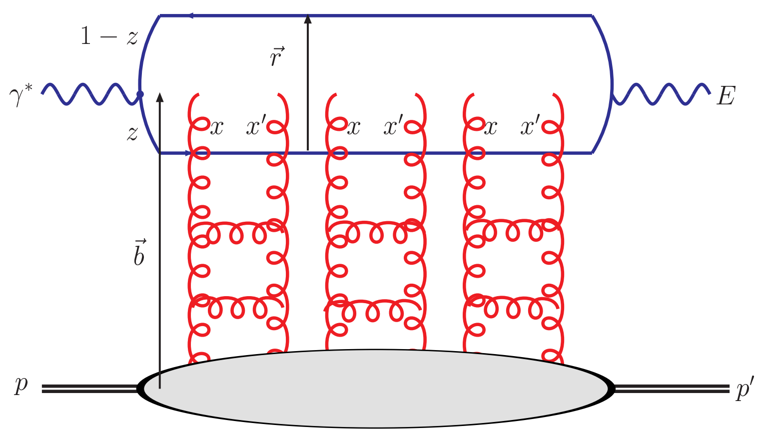
$$\sigma_{q\bar{q}}(x,r) = 2 \int d^2b\, N(x,r,b)$$



- Dipole scattering amplitude N obeys:
  - color transparency: $N \sim r^2$ for $r \to 0$
  - unitarity constraint: $N \leq 1$ always

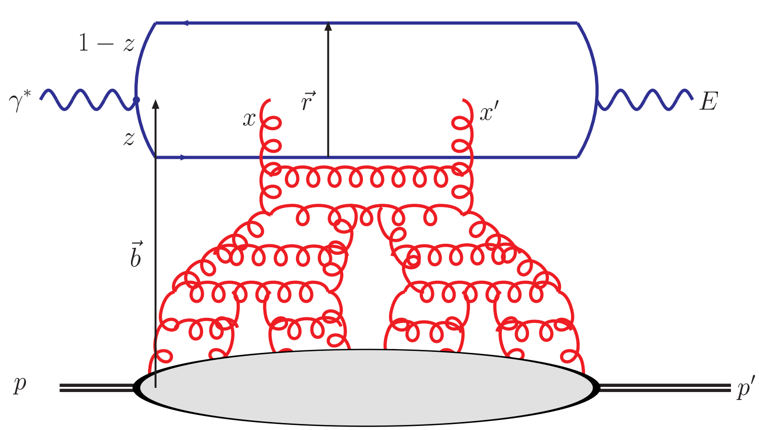
QCD models of dipole scattering amplitude

- Glauber-Mueller eikonal rescattering



$$N = 1 - \exp\{-\kappa\, r^2\, G(x, 1/r^2)\, T(b)\}$$

- BFKL pomeron fan diagram resummation



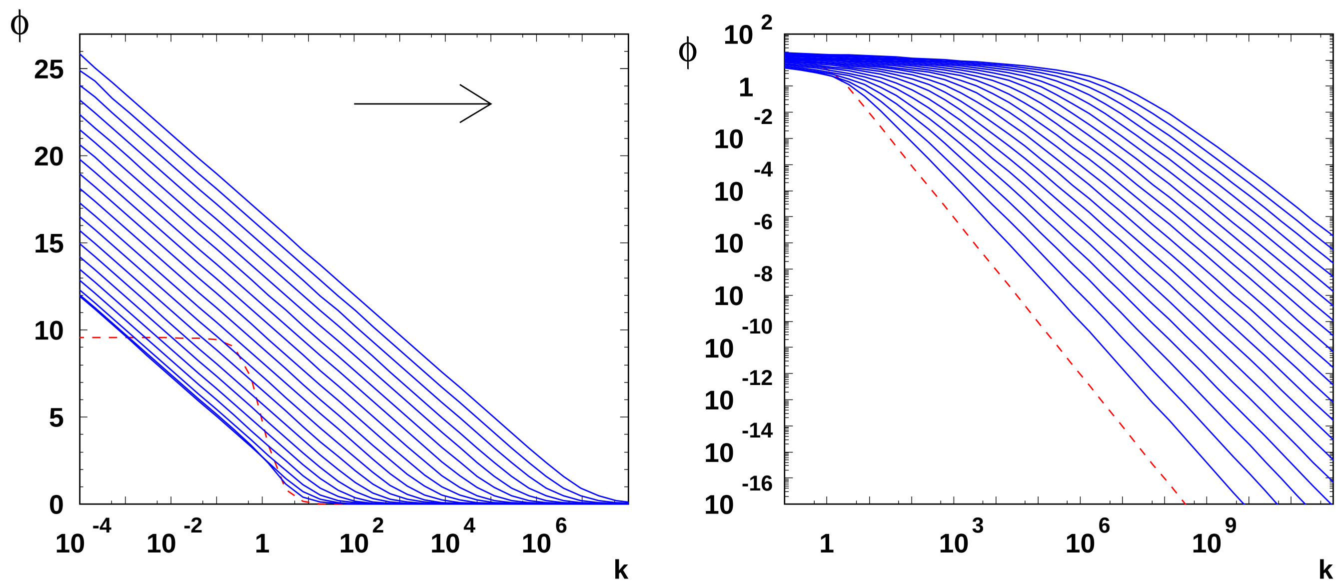
Balitsky-Kovchegov equation

$$\partial_Y N = K_{BFKL} \otimes (N - N^2)$$

Saturation scale and geometric scaling

- Gluon density saturation from the BK equation solution:

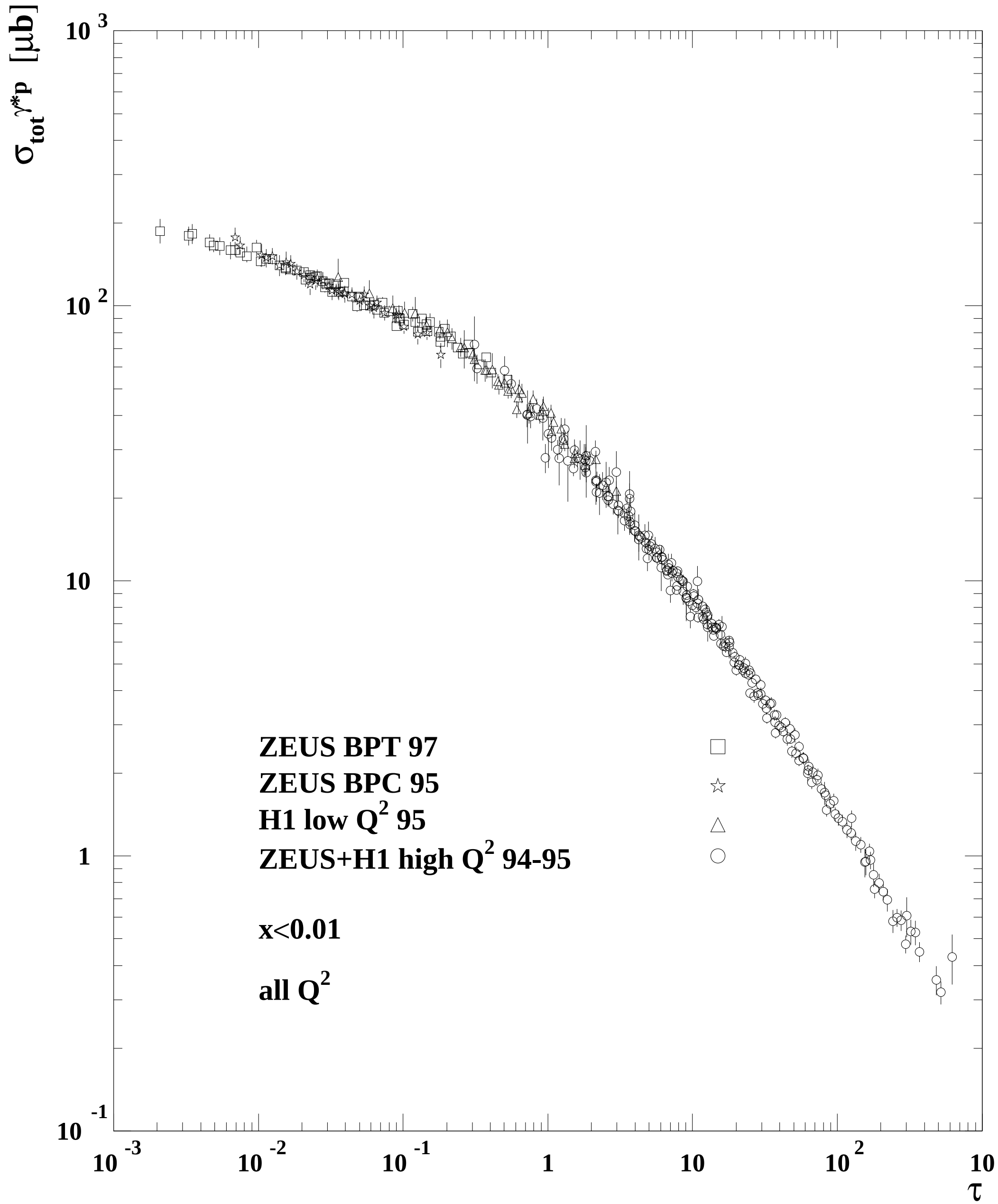
$$\phi(x,k_\perp) = \frac{dN_g}{dY\,dk_\perp^2} = \int d^2r\,\frac{\sigma(x,r)}{r^2}\,\mathrm{e}^{ik_\perp\cdot r}$$



- Geometric scaling in gluon density: $\phi(x,k_\perp) = \phi(k_\perp/Q_s(x))$
- Geometric scaling in observable:

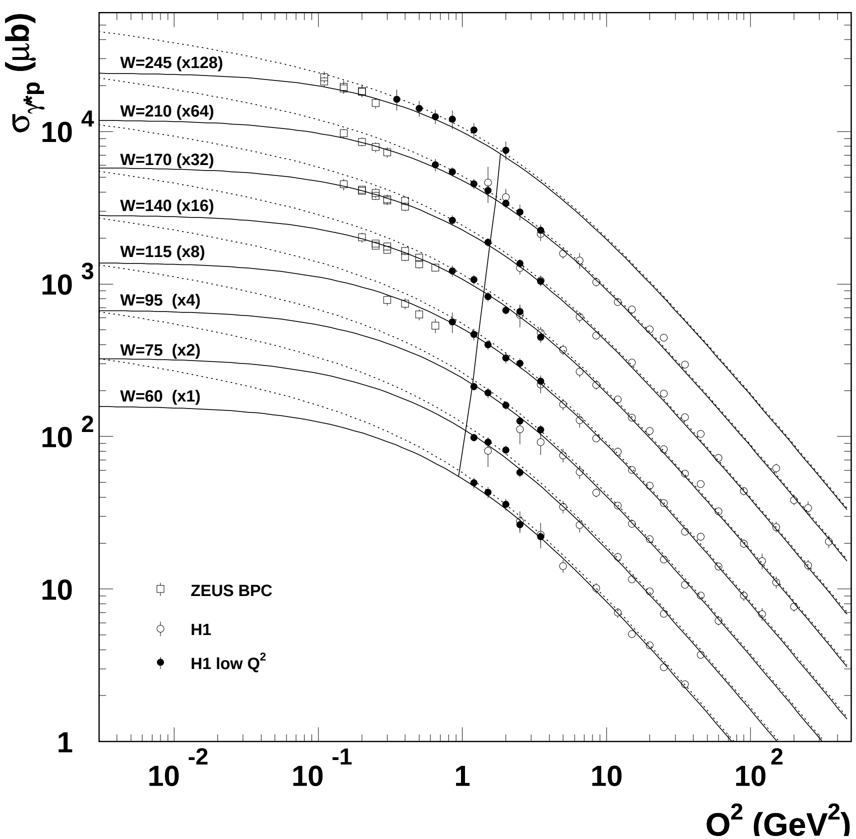
$$\sigma^{\gamma^* p}(x,Q^2) = F_2/Q^2 = \sigma\Big(\underbrace{Q^2/Q_s^2(x)}_{\tau}\Big)$$

Geometric scaling in HERA data



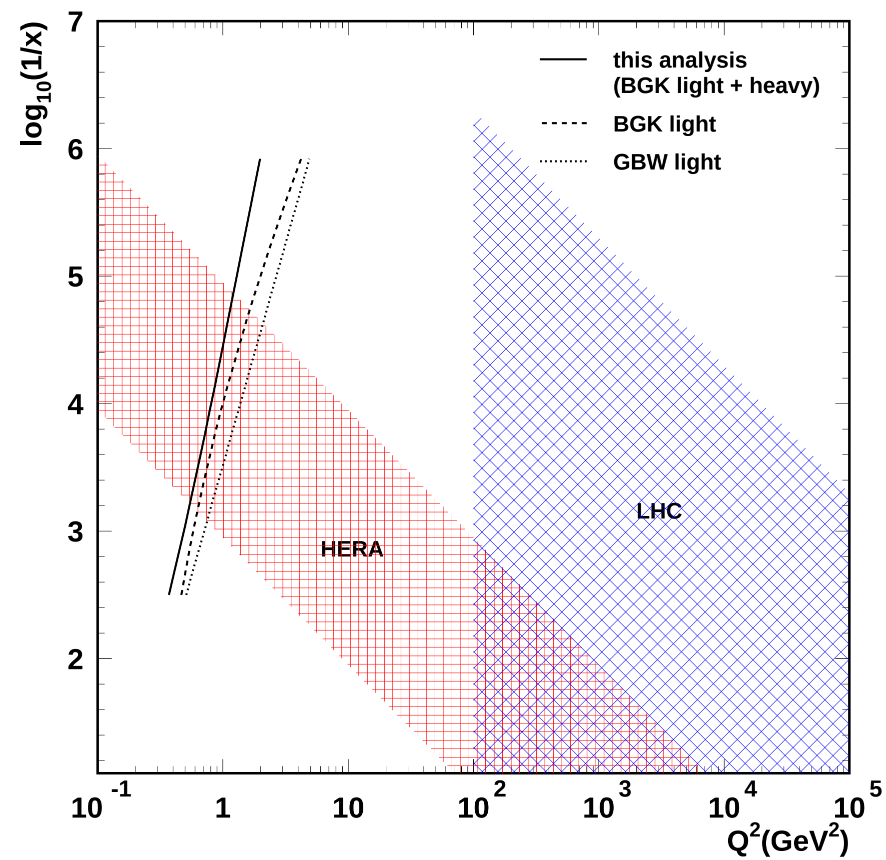
Saturation at HERA

Transition to low Q^2



$$\ln(Q_s^2(x)/Q^2) \;\to\; Q_s^2(x)/Q^2$$

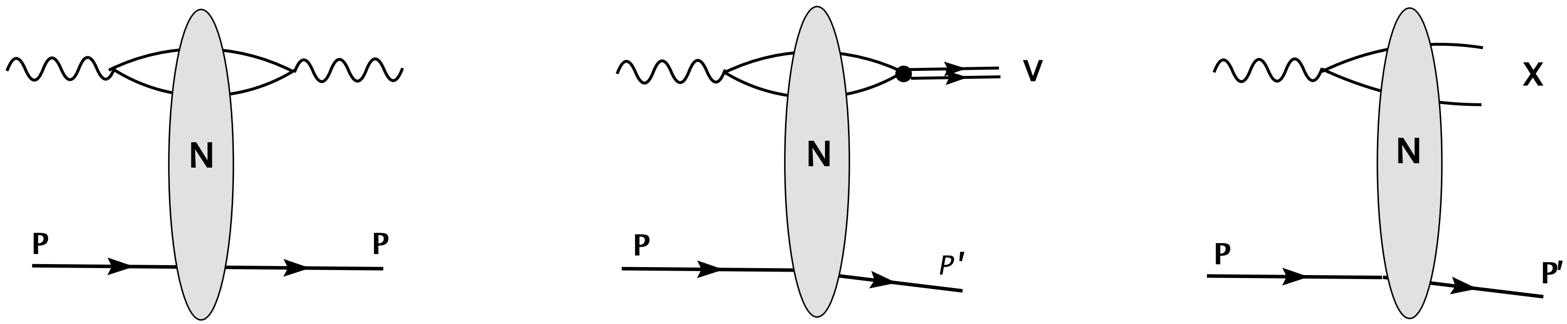
Saturation line



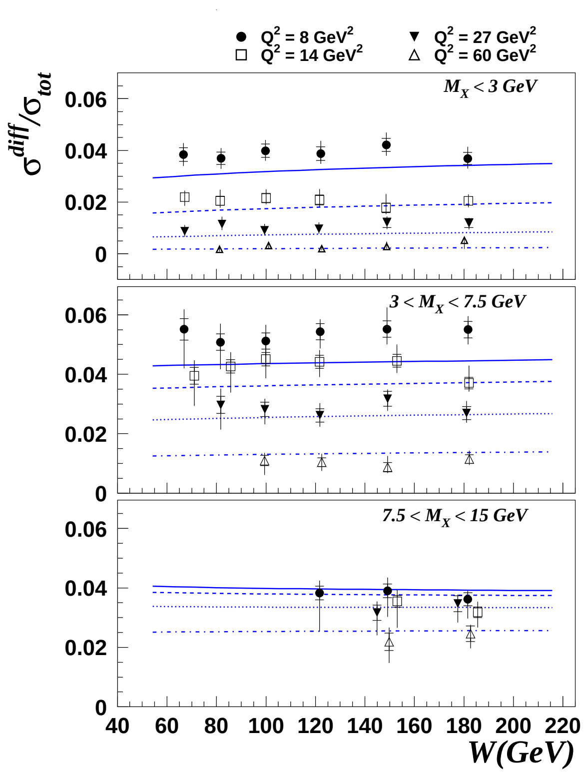
$$Q_s^2(x) \sim x^{-\lambda} \sim s^{\lambda}$$

Saturation at diffraction at HERA

- Universal description



- Constant ratio for open diffraction in DIS



$$\frac{\sigma_{diff}}{\sigma_{tot}} \sim \frac{1}{\ln(Q^2/Q_s^2(x))}$$

More on experimental verification of saturation

- ep collision at HERA
  - transition of F_2 to small Q^2
  - inclusive structure functions: F_2, $F_2^{c\bar{c}}$, F_L
  - inclusive DIS diffraction: F_2^D
  - diffractive vector meson production
  - DVCS
- pp and AA collisions
  - Drell-Yan process
  - central diffractive production
  - particle multiplicities
  - peripheral collisions
  - limiting fragmentation
  - nuclear modification factor (Cronin effect)

Conclusions

- Parton saturation models are robust in the description of ep processes in high energy limit.
- $q\bar{q}$ dipole probe reveals the small-x structure the proton which can be used in the description of pp and AA high energy collisions.
- Geometric scaling and saturation scale are key elements for parton saturation.
- LHC results will provide enough motivation for more studies in this direction.