Experimental studies of QCD

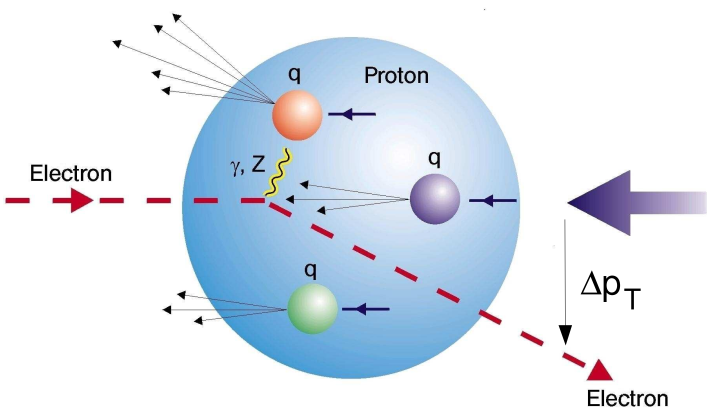
1. Elements of QCD
2. Tests of QCD in e^+e^- annihilation
3. Studies of QCD in DIS
4. QCD in $pp(p\overline{p})$ collisions

Q² – resolution power

$$\Delta p_T \Delta r \geq \hbar$$

$$Q^2 = \frac{(\Delta p_T)^2}{1-y}$$

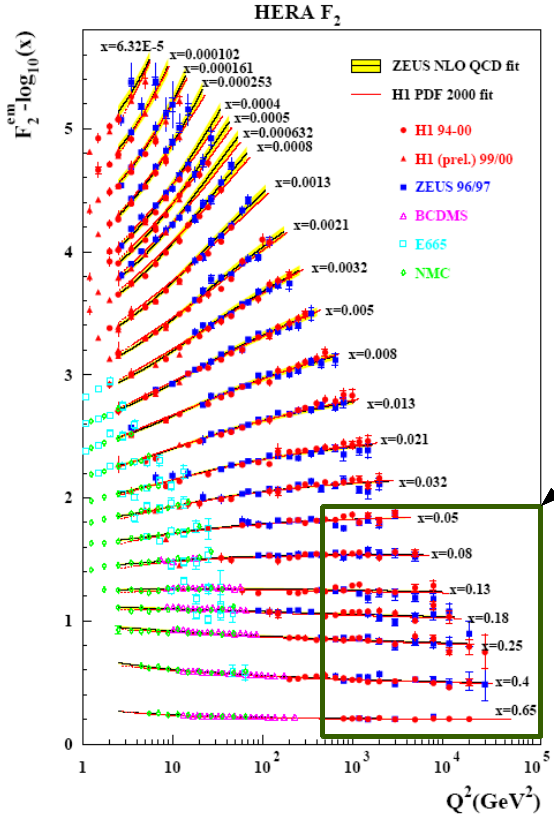
$$\Rightarrow Q \cdot r \sim \hbar$$



Large Q² = resolve small distances

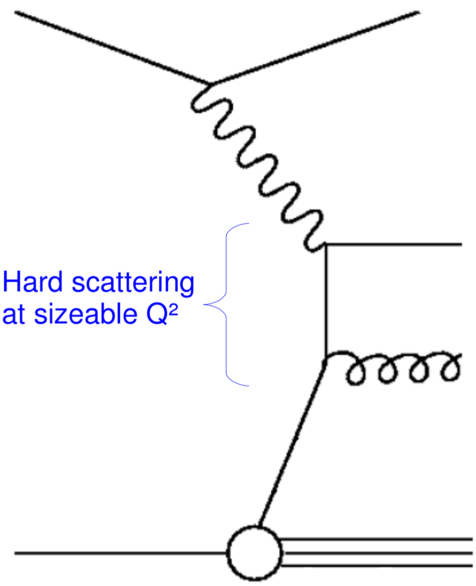
At HERA $r \sim 10^{18}\,\mathrm{m} = \frac{1}{1000} r_p$

Similarly: Large Q² = short time scales



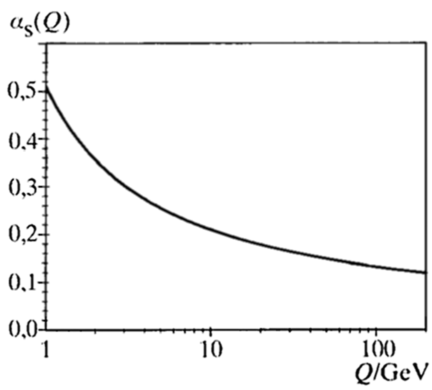
Errors are larger at high Q²

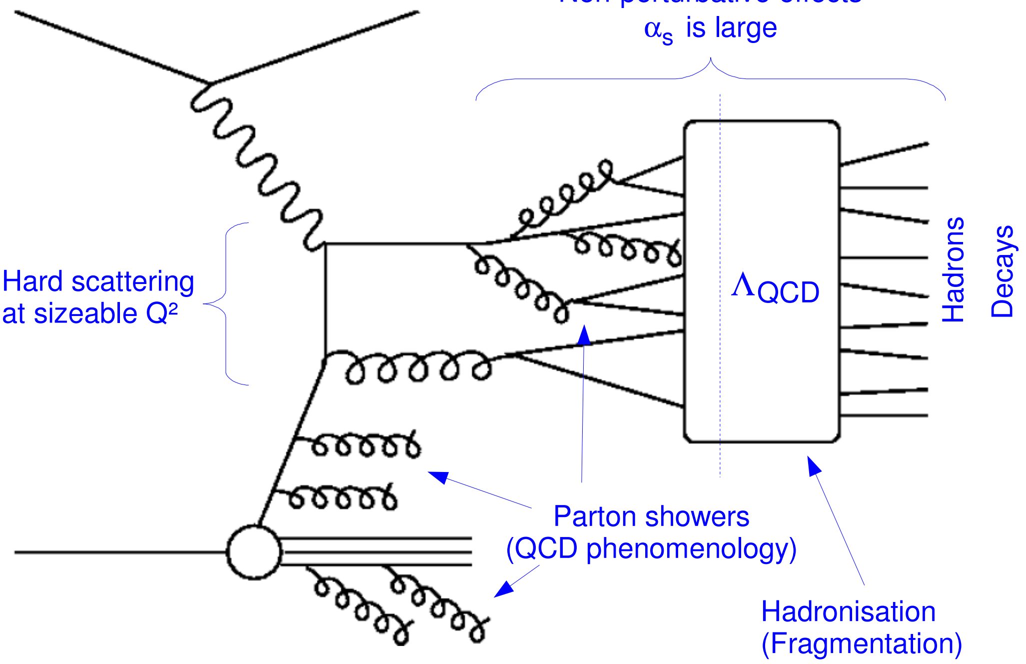
$$\frac{d^2\sigma}{dQ^2\,dx}=\left(\frac{4\pi\alpha^2}{\boldsymbol{Q^4}x}\right)\cdot\left[(1-y)F_2(x)+xy^2F_1(x)\right]$$

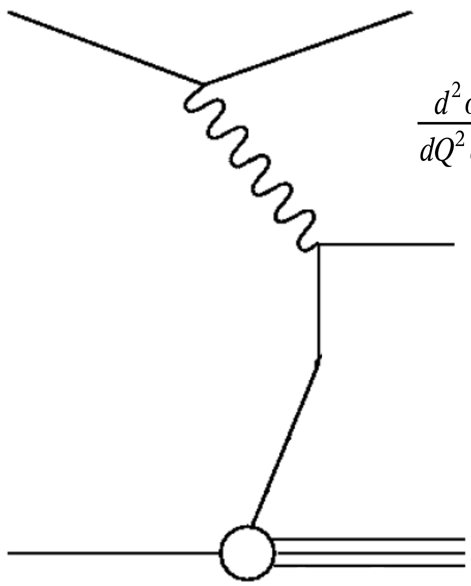


Matrix element calculable at fixed order QCD
because $\alpha_S(Q^2)$ is small

$$\alpha_s(Q^2)=\frac{1}{\beta_0\log(Q^2/\Lambda_{QCD}^2)}$$







$$\frac{d^2\sigma}{dQ^2\,dx}=\frac{4\pi\alpha^2}{Q^4 x}\cdot\left[(1-y)F_2(x,Q^2)+xy^2F_1(x,Q^2)\right]$$

In LO (QPM): $2x F_1 = F_2$

$$\frac{d^2\sigma}{dQ^2\,dx}=\frac{2\pi\alpha^2}{Q^4 x}\cdot\left[1+(1-y)^2\right]F_2(x,Q^2)$$

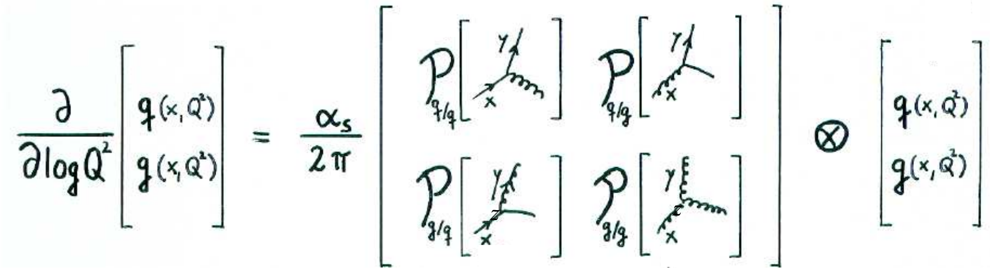
In LO: $F_2(x,Q^2)=x\sum e_i^2 q_i(x,Q^2)$

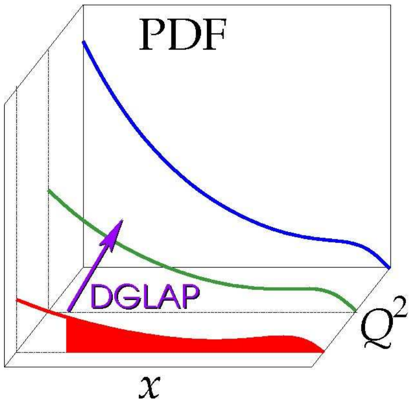
$$\frac{d^2\sigma}{dQ^2\,dx}=\frac{2\pi\alpha^2}{Q^4}\cdot\left[1+(1-y)^2\right]\sum e_i^2 q_i(x,Q^2)$$

Hard scattering — PDFs

Perturbative DGLAP Evolution:

reminder



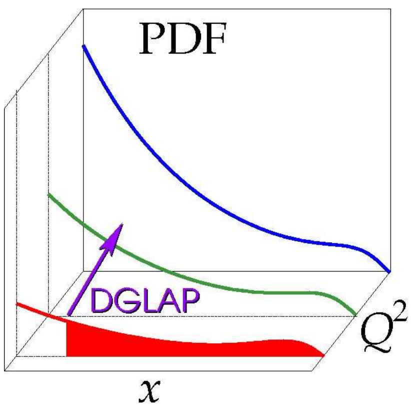


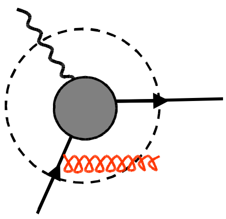
$$P \otimes f(x,Q^2) = \int_x^1 \frac{dz}{z} P\left(\frac{x}{z}\right) f(z,Q^2)$$

Start at low scale Q_0^2
and evolve perturbatively to higher Q^2

Are PDFs perturbative? - No, they are not!

The starting scale cannot be at $Q^2 = 0$, as it is non-perturbative region.
PDFs $q(x)$ at Q_0^2 encode non-perturbative input to perturbative evolution.

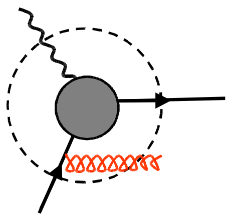


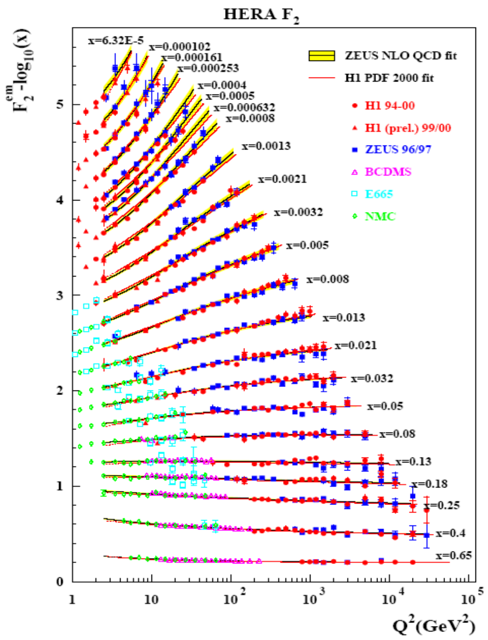


Cross section = hard scattering × PDFs
Factorization: (short range) (long range)

Prerequisite for Factorization

Quarks are quasi-free (asymptotic freedom)
only perturbative radiation may occur at the time of hard interaction



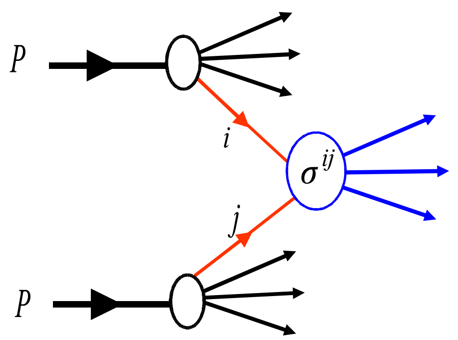


Prerequisite for QCD evolution:

Quarks are point-like

Since HERA data are described by QCD fits, quark substructure is ruled out down to 10^{-18} m

4. Factorization – QCD at LHC



Generalized cross section for n parton production can be **factorized**:

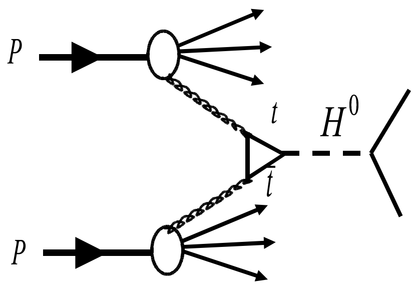
- PDFs $f_i(x,\mu^2)$ and $f_j(x,\mu^2)$
- "short distance" cross section, $\sigma^{ij\to k1\ldots k2}$, pertubatively calculable

$$\sigma^n = \sum_{i,j,k_1,\ldots k_n = q,\bar{q},g} \int dx_1 dx_2\, f_i(x_1,\mu^2)\, f_j(x_2,\mu^2)\, \hat{\sigma}^{ij\to k_1,\ldots k_n}$$

Factorization scale is the value μ at which the structure functions are defined and at which the distinction between short//long range parts is done.

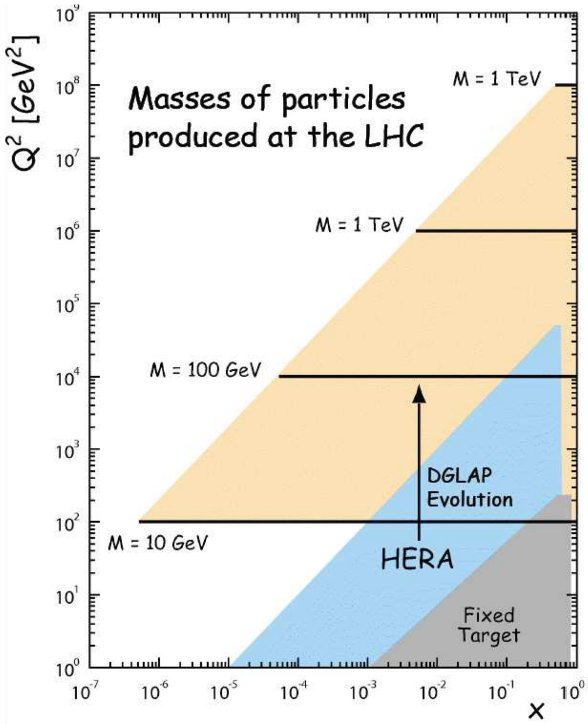
Parton densities are important to predict signals and backgrounds at the LHC

Higgs-production at LHC



(main production process)

PDFs are extrapolated from HERA using DGLAP



Some definitions

Rapidity: $y = \frac{1}{2} \ln \frac{E + P_z}{E - P_z}$

For two particles, differences in rapidity is invariant vs. boosts along beam axis:

$$y_1 - y_2 = \text{const}$$

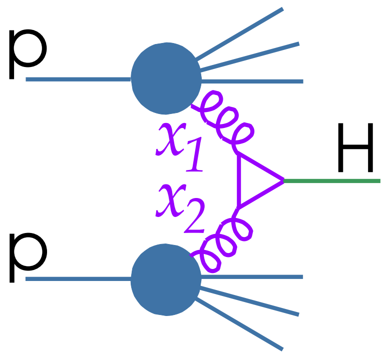
For $\theta = 90°$: $P_z = 0$ $\Rightarrow$ $y = 0$ – central production

Neglecting masses: $P_z = E \cos\theta$

Pseudo-rapidity: $\eta = \frac{1}{2} \ln \frac{1 + \cos\theta}{1 - \cos\theta} = -\frac{1}{2} \ln \tan \frac{\theta}{2}$

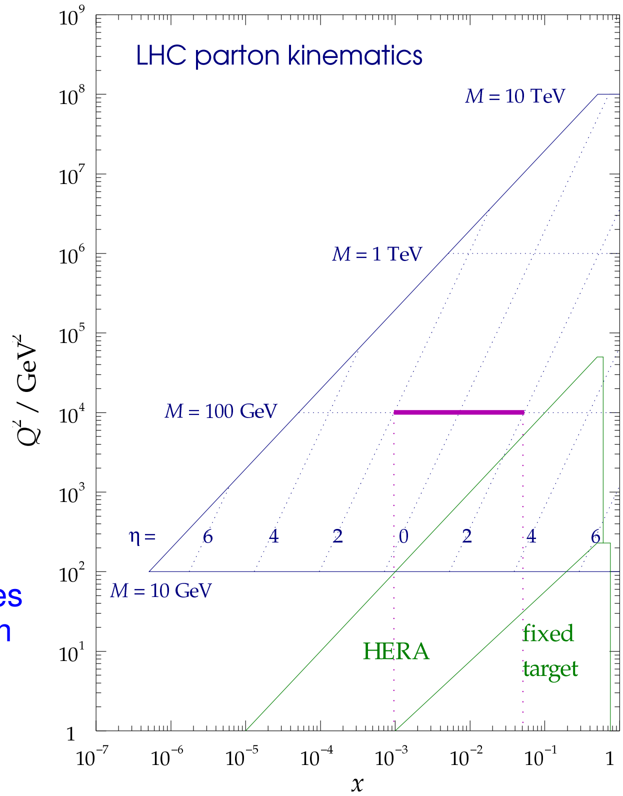
For $\theta = 0$: $\eta = -\infty$ For $\theta = 180°$: $\eta = \infty$

while rapidity remains finite



$$x_{1,2} = \frac{M}{\sqrt{s}} \exp(\pm\eta)$$

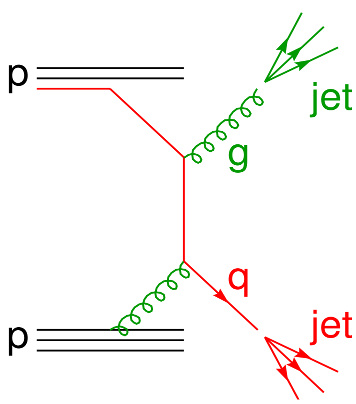
Precise quark and gluon densities are required in the whole Bjorken x range to predict signals and backgrounds at the LHC

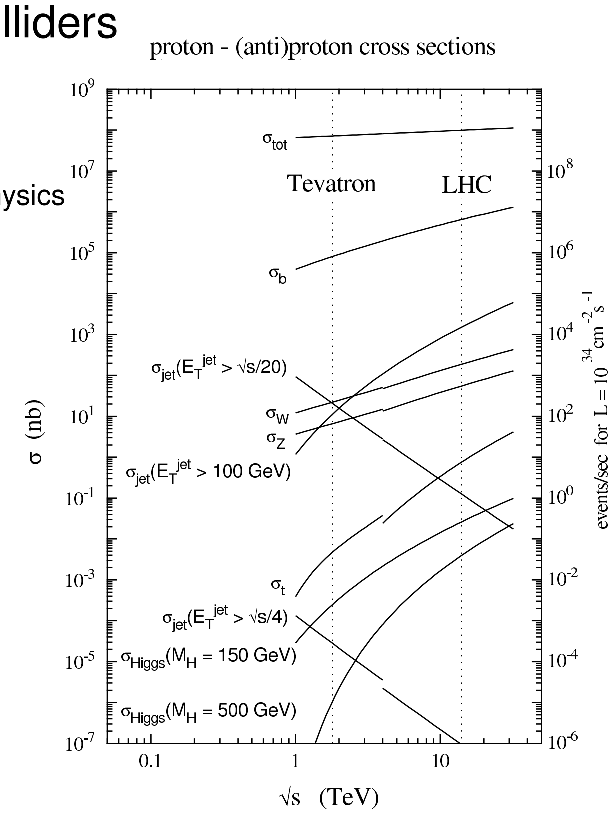


Jet Production at *pp* Colliders

Dijet production — dominant process at hadron colliders

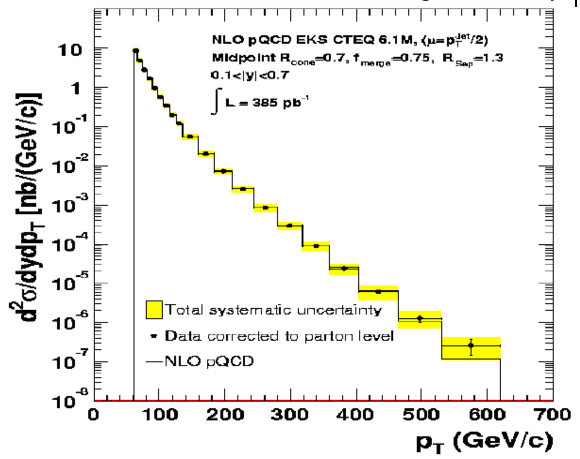
- Background for searches for new physics
- Crucial test of QCD



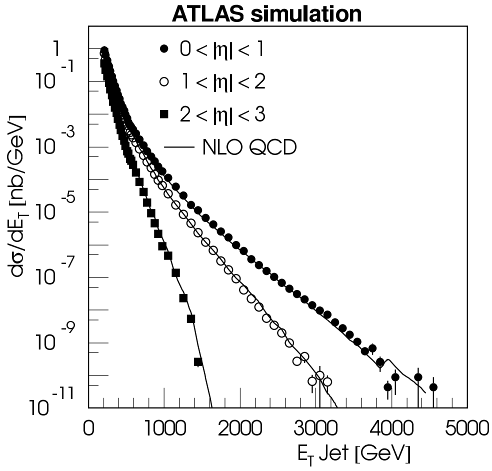


Inclusive Jet Spectrum

NLO QCD describes jet spectrum at Tevatron over 8 orders of magnitude in p_T

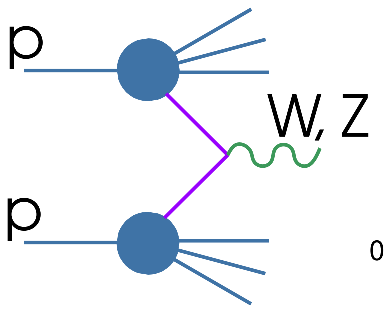


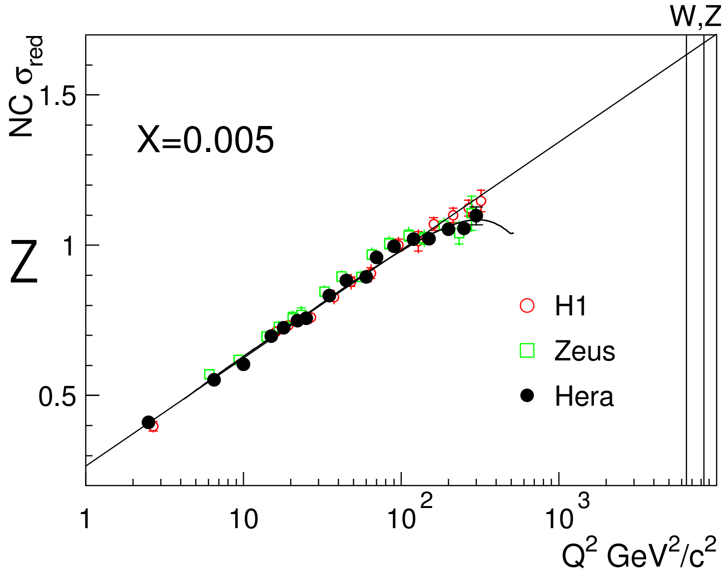
The same will be tested at the LHC
"First plot to do"



- Sensitive to detector effects – jet energy scale
- Sensitive to PDFs – provides additional info on PDFs

W and *Z* Production at the LHC

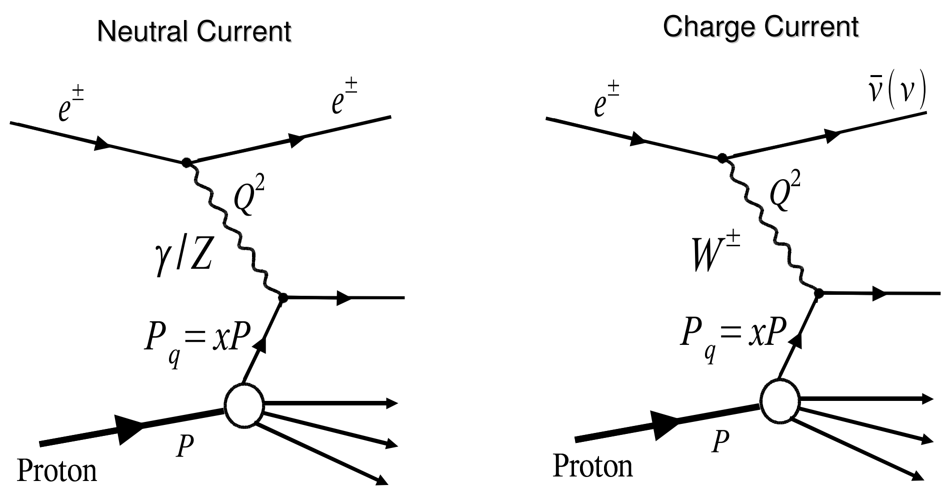




Good candidate for luminosity measurement

Electroweak effects at high Q²

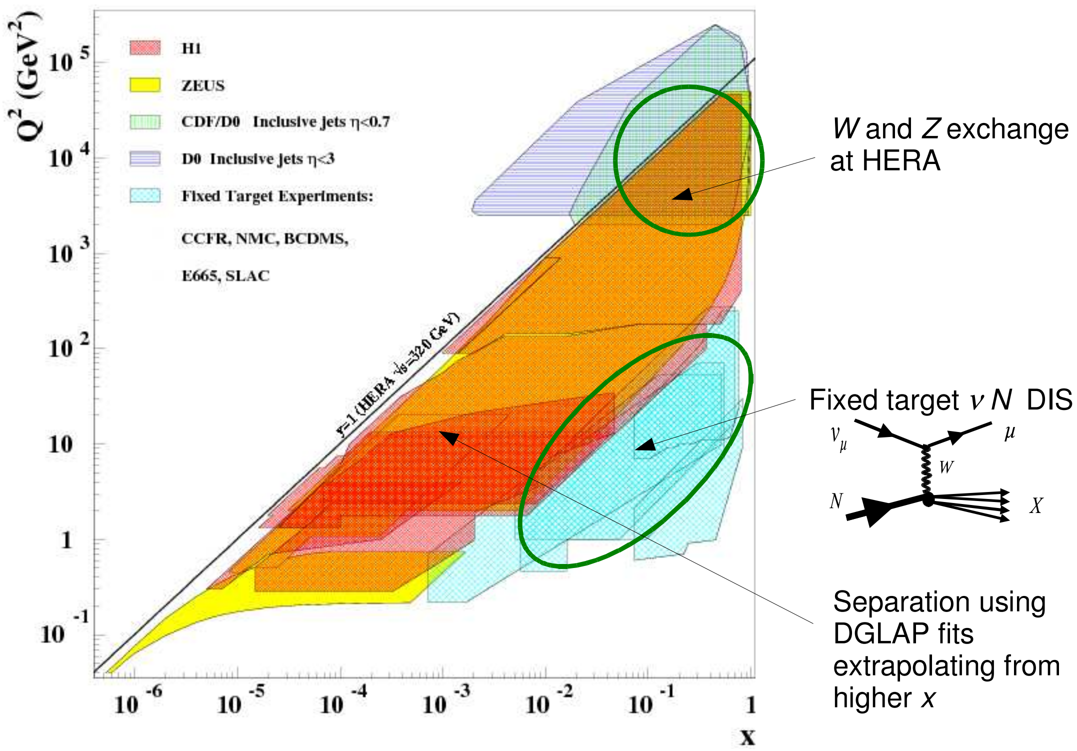
reminder



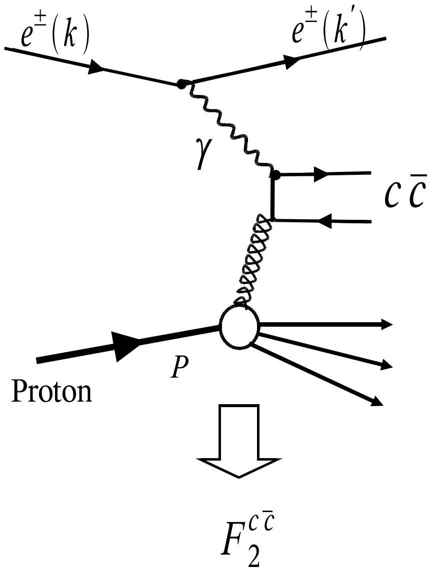
4 cross sections: NC e^+p, e^-p and CC e^+p, e^-p

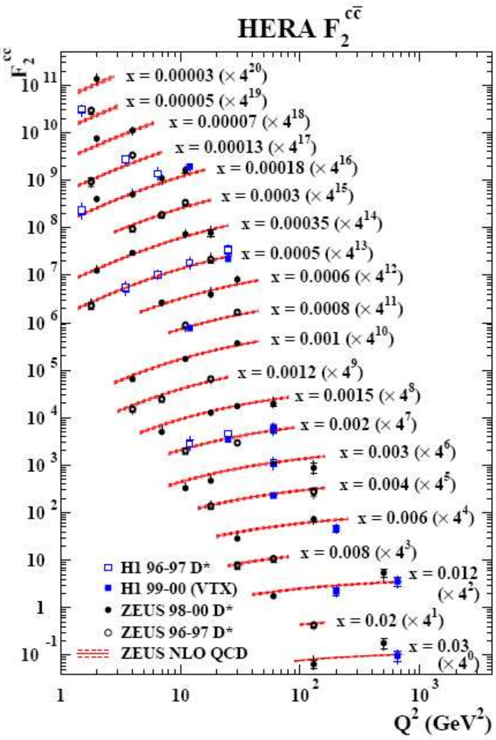
Different sensitivy to quarks and anti-quarks ; to *u* and *d* quarks

Flavour separation



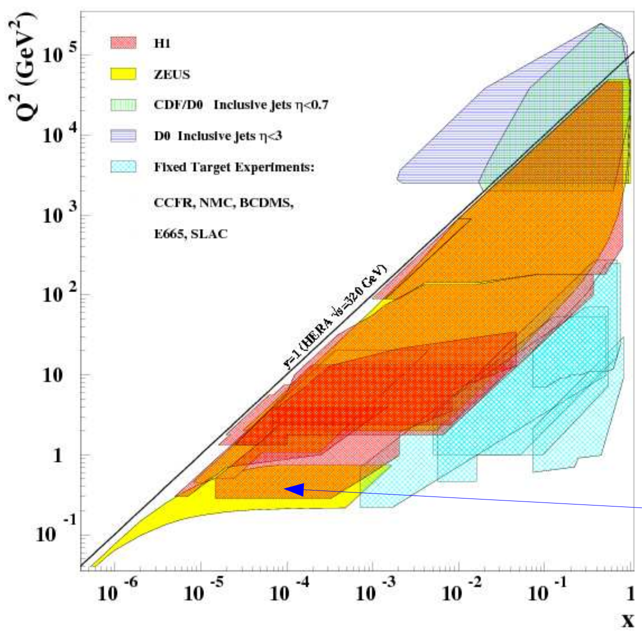
Heavy quark density



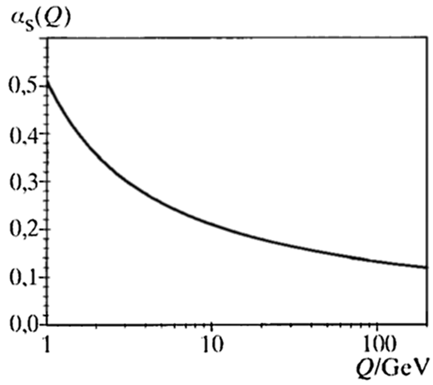


measured using jets containing *D** mesons

DIS at Low Q²



$$\alpha_s(Q^2)=\frac{1}{\beta_0\log(Q^2/\Lambda_{QCD}^2)}$$

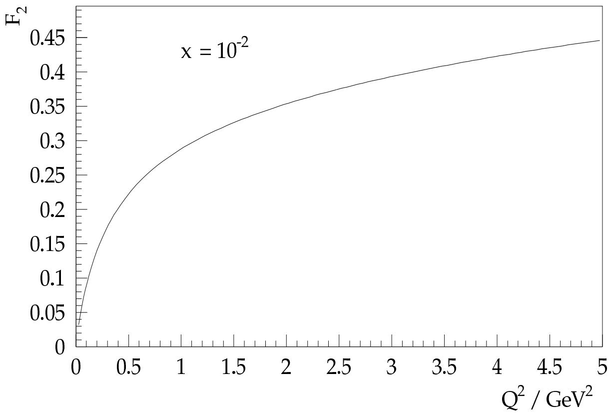


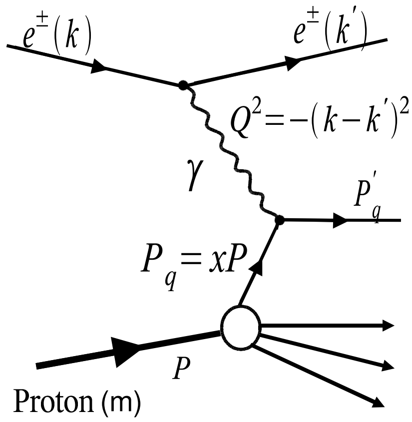
At low Q^2 factorization is not valid, as $\alpha_s(Q^2)$ gets large

$$F_2(x,Q^2)\neq x\sum e_i^2 q_i(x,Q^2)$$

Quarks are not free

At $Q^2 \to 0$ no substructure can be resolved : $F_2 \to 0$



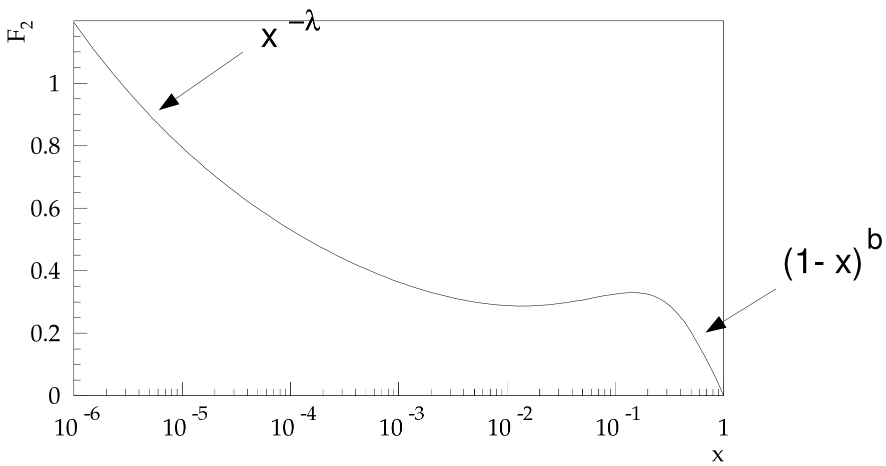


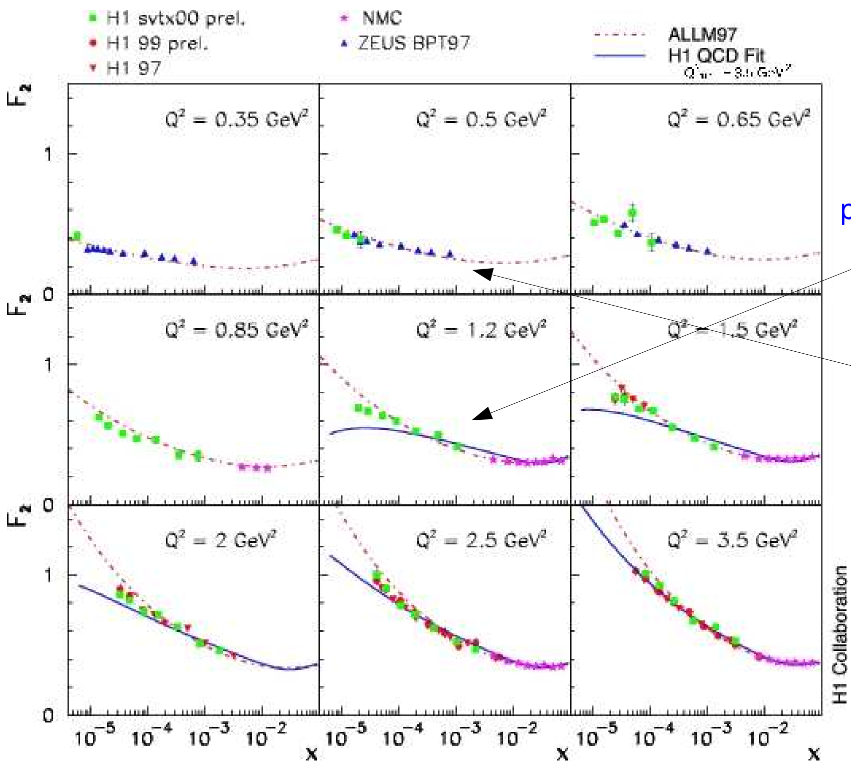
This is exactly obtained in the theory.

For $Q^2 \to 0$: cross section $\sigma_{\gamma^* p} \to \sigma_{\gamma p}$ for real photons

$$\sigma_{\gamma^* p} = \frac{4\pi^2\alpha}{Q^2(1-x)} F_2(x, Q^2)$$

reminder: For PDF fits: $x\,p(x, Q^2) = A_p x^{a_p} (1-x)^{b_p} P(x, c_p, \ldots)$

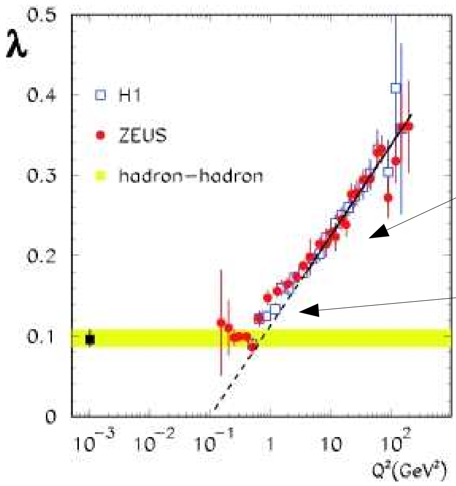


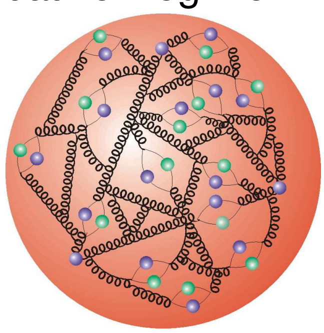


pQCD breaks down

phenomenological models with $F_2 \sim x^{-\lambda}$

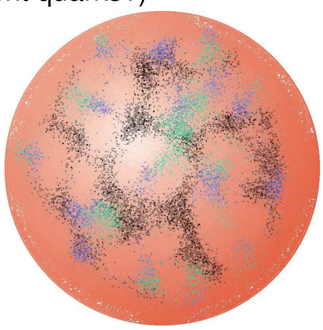
Transition from Perturbative to non-Perturbative Regime



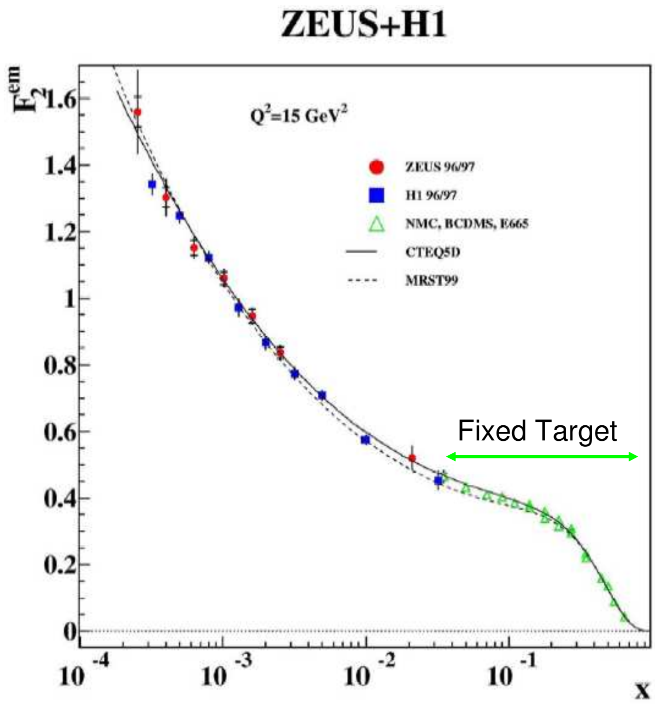


Perturbative region (free quarks)

Transition to hadronic degrees of freedom (constituent quarks?)



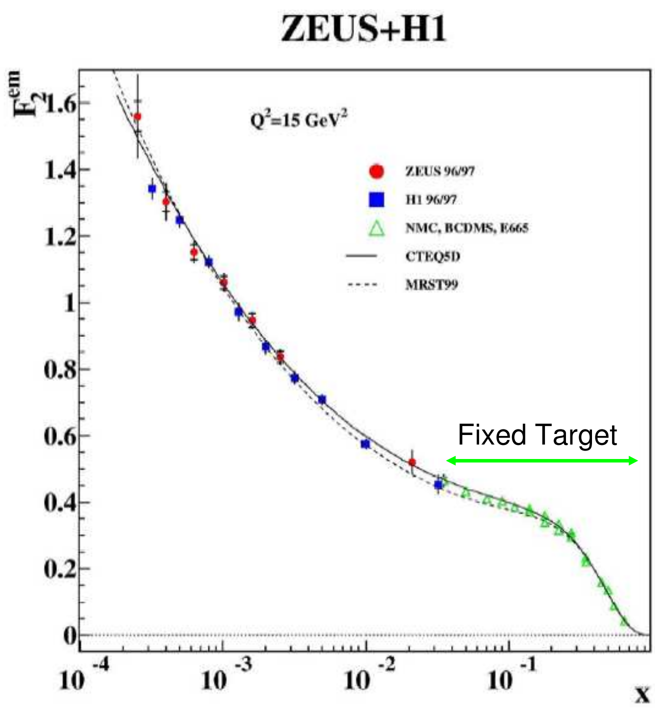
How to describe it?



Large increase of $F_2(x)$ for very small x

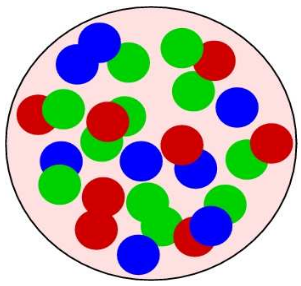
When does the rise stop? will be discussed later

Promised last time



Infinite rise will violate unitarity limit

At low x gluons should start to "overlap"



Expect to see slowing rise – deviation from $x^{-\lambda}$ dependence

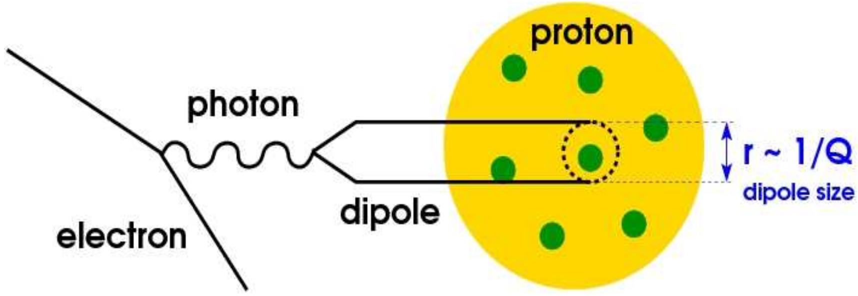
Look at very low x

No deviations observed so far

Dipole saturation model

Use colour $q\bar{q}$ dipoles as degrees of freedom

Change factorization, as photon distance is large:
Photon fluctuates in $q\bar{q}$ pair which interacts with proton



$$\sigma_{\gamma^* p} = \int d^2 r \ldots |\psi(r, \ldots)|^2 \hat{\sigma}(r, \ldots)$$

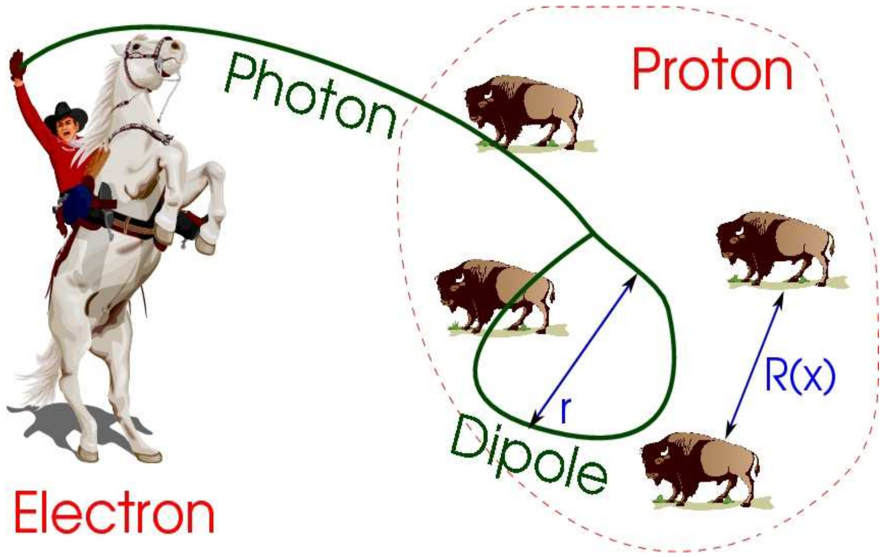
photon wave function (exactly calculable)

dipole-proton scattering cross section (phenomenological)

Dipole-Proton Cross Section

depends on transverse gluon distribution

Example model:
Golec-Biernat, Wüsthoff

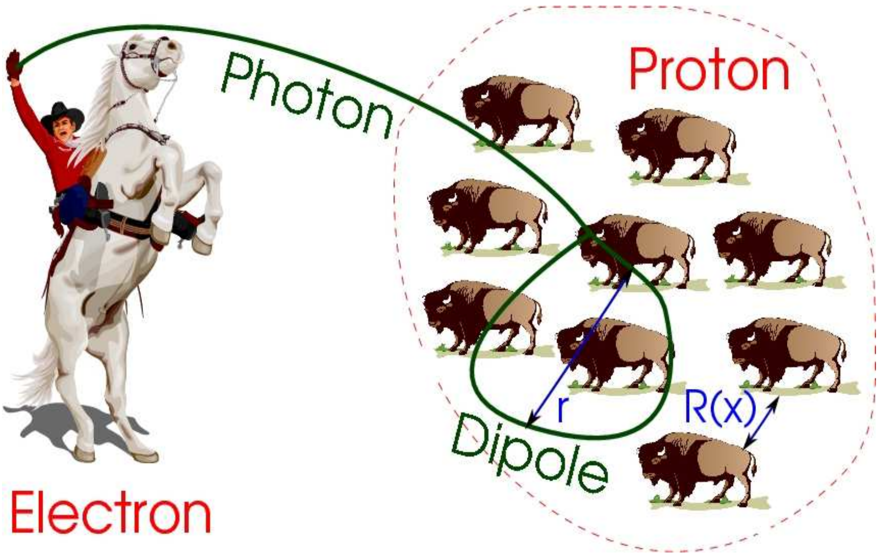


At small r: $\sigma \propto \frac{r^2}{R^2}$

Dipole-Proton Cross Section

depends on transverse gluon distribution

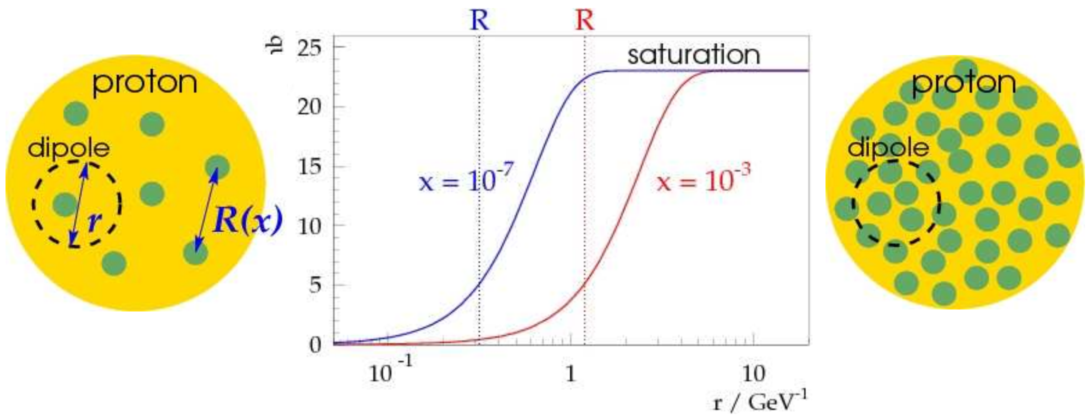
Example model:
Golec-Biernat, Wüsthoff



At large r: non-linear gluon interactions → saturation

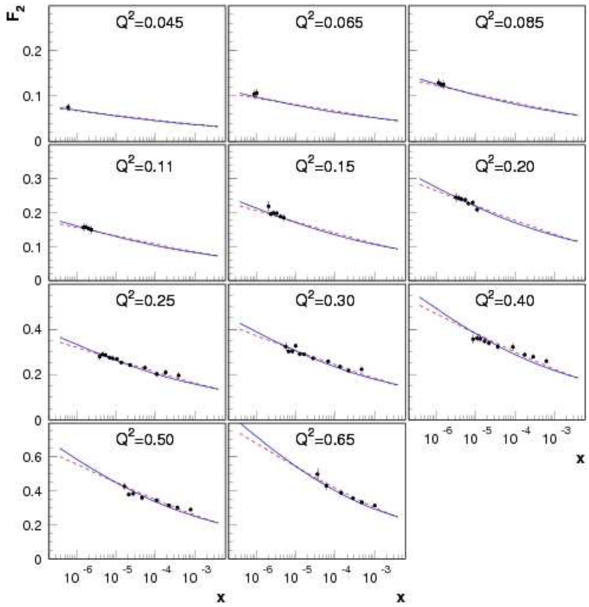
Dipole-Proton Cross Section

Example model:
Golec-Biernat, Wüsthoff



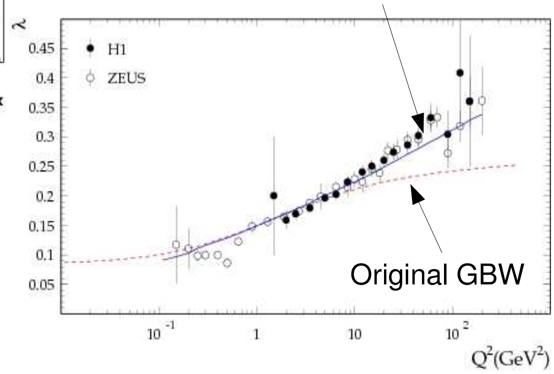
Only 3 free parameters

GBW Model – Description of Data

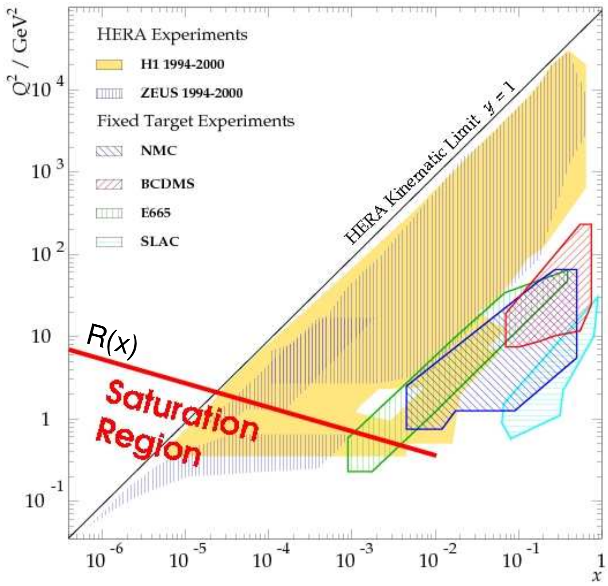


Transition region is well described

Although we don't observe deviations from $x^{-\lambda}$ dependence, the behaviour can be described employing saturation



Saturation Region in GBW Dipole Model



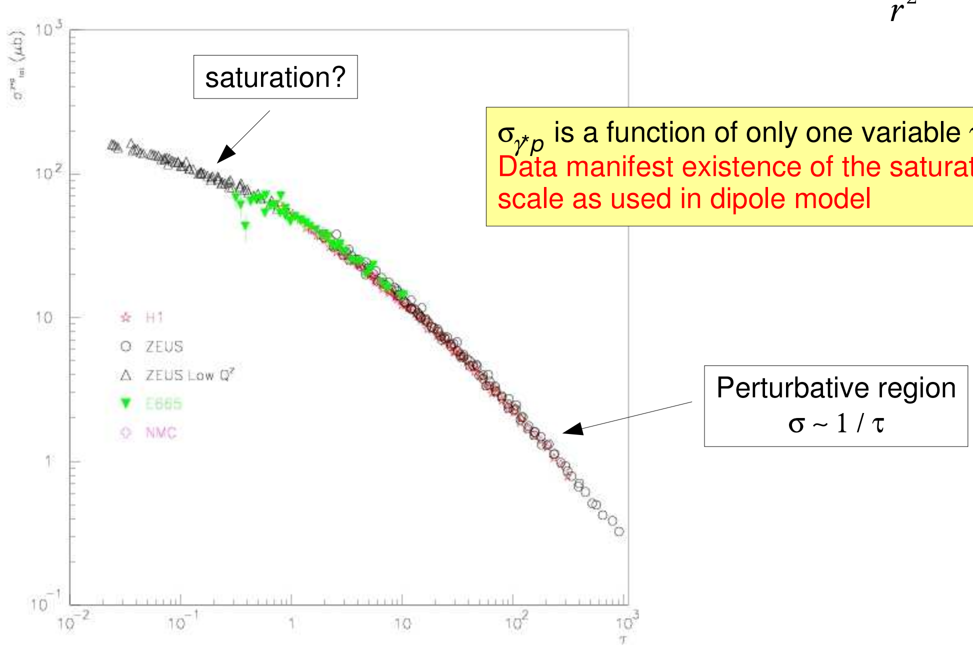
For $Q^2 < 1\text{-}2\ GeV^2$ saturation model describes transition to soft interactions with only 3 parameters

For pQCD Q^2 scales saturation region is beyond HERA reach

Still, non-linear effects can affect pQCD evolution at low x and Q^2

Geometric Scaling

$$\tau = Q^2 R^2(x) \sim \frac{R^2}{r^2}$$

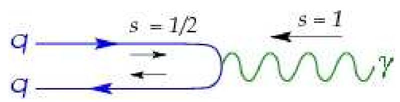


$\sigma_{\gamma^* p}$ is a function of only one variable τ
Data manifest existence of the saturation scale as used in dipole model

Longitudinal Structure Function F_L

Callan-Gross relation $2xF_1 = F_2$ is not valid in pQCD

Introduce $F_L = F_2 - 2xF_1$



$$F_L \propto \alpha_s x g$$

Only transversely polarized photons couple to quarks in QPM

Due to additional gluon radiation longitudinally polarized photons may also couple to quarks in QCD

Measurement of F_L provides additional information on the gluon density

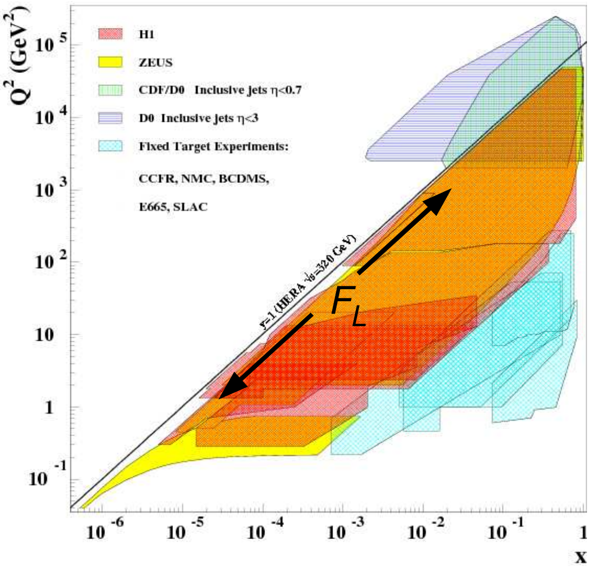
$$\frac{d^2\sigma}{dQ^2 dx} = \frac{4\pi\alpha^2}{Q^4 x}\left[(1-y)F_2(x,Q^2) + xy^2 F_1(x,Q^2)\right]$$

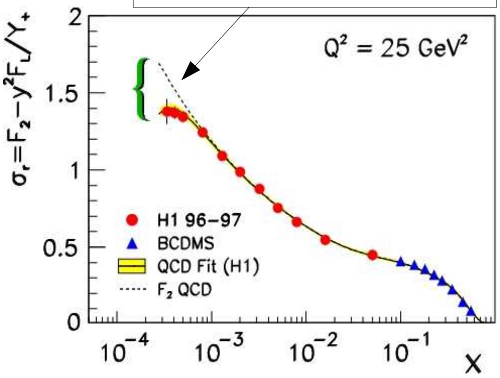
⇩

$$\frac{d^2\sigma}{dQ^2 dx} = \frac{2\pi\alpha^2}{Q^4 x}\left[(1+(1-y)^2)F_2(x,Q^2) - y^2 F_L(x,Q^2)\right]$$

Only significant at high y

$$\frac{d^2\sigma}{dQ^2\,dx}=\frac{2\pi\alpha^2}{Q^4 x}\left[\underbrace{(1+(1-y)^2)}_{Y_+}F_2(x,Q^2)-y^2F_L(x,Q^2)\right]$$

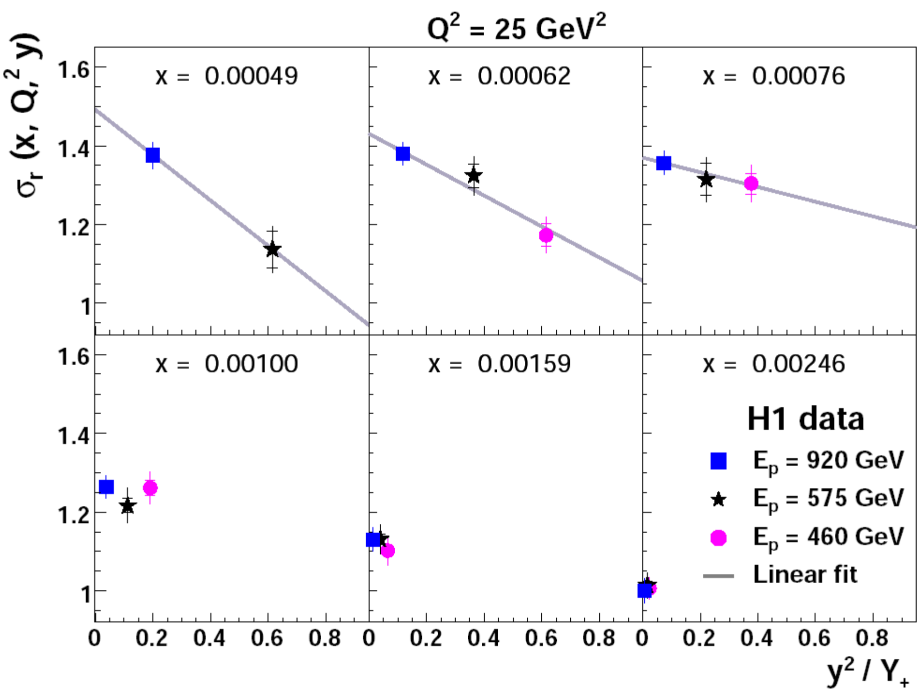




Direct measurement requires
requires data at different y
i.e. at different cms energies s

$Q^2 = x\,y\,s$ ⇨ Low energy runs

Rosenbluth Method of F_L Extraction



First Direct F_L Measurement at HERA

Submitted in May 2008, arXiv:0805.2809