Structure Functions at Low Q^2 and Very Low x

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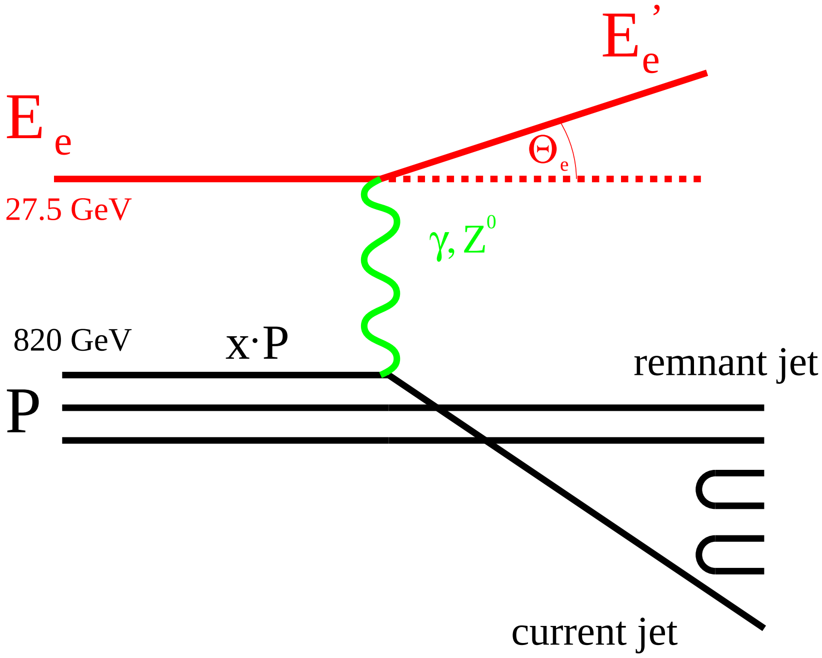
- Introduction: kinematics and cross sections;
- the proton structure function F_2 at low Q^2 and very low x;
- logarithmic derivatives of F_2;
- summary and outlook.

Kinematics of e^+P scattering



$$Q^2 = -q^2 = -(k-k')^2$$
negative squared 4-momentum transfer;

$$x = \frac{Q^2}{2p \cdot q}$$
parton momentum fraction $(0 \le x \le 1)$;

$$y = \frac{p \cdot q}{p \cdot k}$$
energy transfer fraction $(0 \le y \le 1)$;

$$W^2 = (q+p)^2 \simeq \frac{Q^2}{x}(1-x)$$
squared $\gamma^* P$ Center-of-Mass energy;

$$s = (k+p)^2 \simeq 4E_e E_P$$
squared e^+P CM energy $(\sim 300$ GeV$)$;

$\boxed{Q^2 \simeq x \cdot y \cdot s}$ $\Rightarrow$ 2 independent variables

Cross section and structure functions

Differential NC e^+P cross section (OBE):

$$\frac{d\sigma^{NC}(e^{\pm}p)}{dx\,dQ^2} = \frac{2\pi\alpha^2}{x\,Q^4} Y_+ \left[F_2 - \frac{y^2}{Y_+} F_L \right] = \Gamma \left[\sigma_T^{\gamma^* P} + \epsilon\, \sigma_L^{\gamma^* P} \right],$$

where:

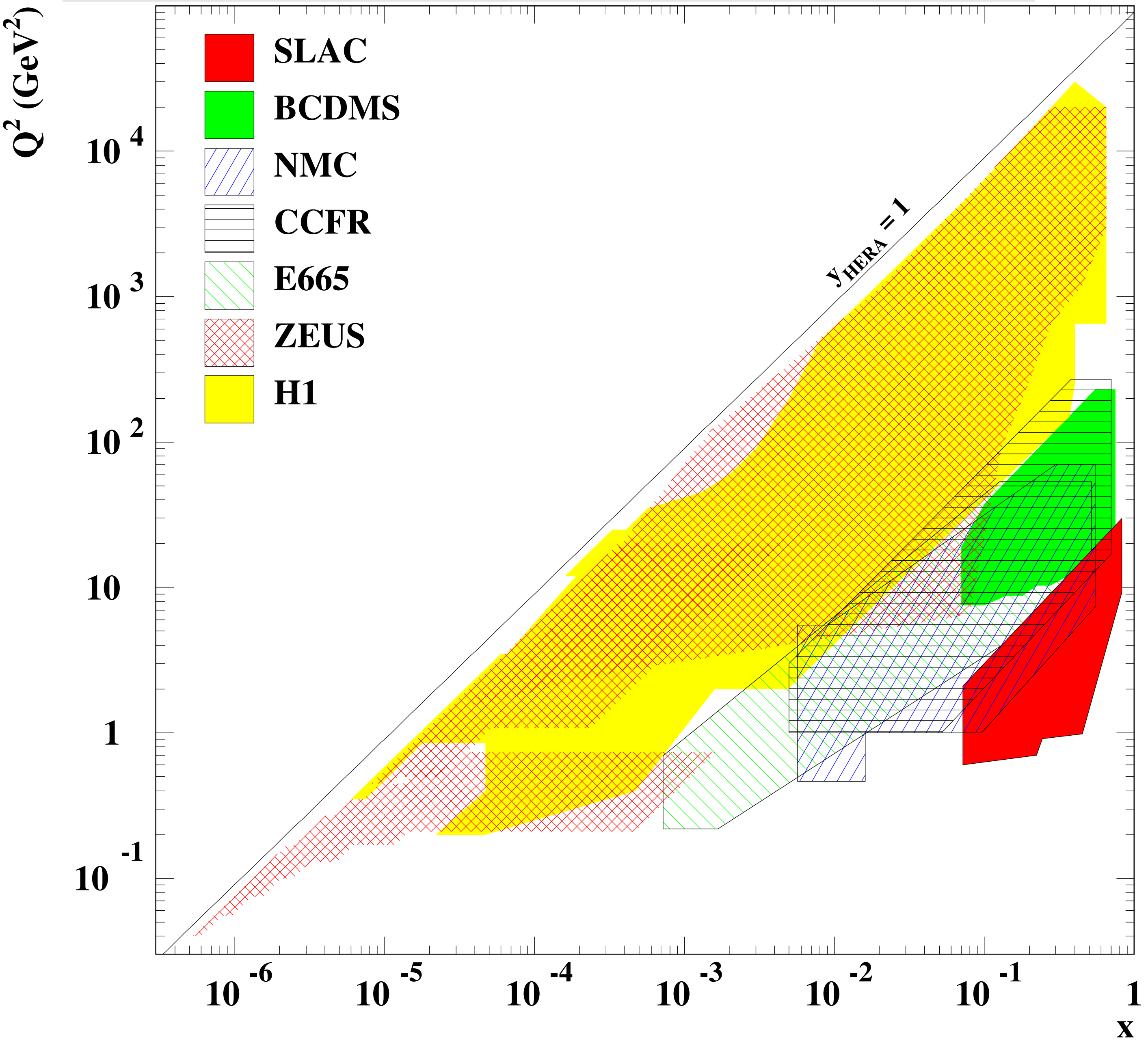
$$\begin{aligned} Y_{\pm} &= 1 \pm (1-y)^2, \\ \Gamma &= \alpha Y_+ / (2\pi Q^2 y), \\ \epsilon &= 2(1-y)/Y_+. \end{aligned}$$

Total $\gamma^* P$ cross-section:

$$\begin{aligned} \sigma_{tot}^{\gamma^* P} &\equiv \sigma_T^{\gamma^* P} + \sigma_L^{\gamma^* P} \\ &= \frac{4\pi^2\alpha}{Q^4} \frac{4M^2x^2 + Q^2}{1-x} F_2 \\ &\simeq \frac{4\pi^2\alpha}{Q^2} F_2. \end{aligned}$$

$$\begin{aligned} F_L &= \text{longitudinal structure function (0 in QPM);} \\ F_2 &= F_2^{em} + \frac{Q^2}{Q^2 + M_z^2} F_2^{int} + \frac{Q^4}{(Q^2+M_z^2)^2} F_2^{wk}; \\ &= F_2^{em}(1+\delta_Z); \\ F_2^{em} &= \sum_f e_f^2 \cdot x\, q_f(x) \text{ in QPM.} \end{aligned}$$

Experimental Range



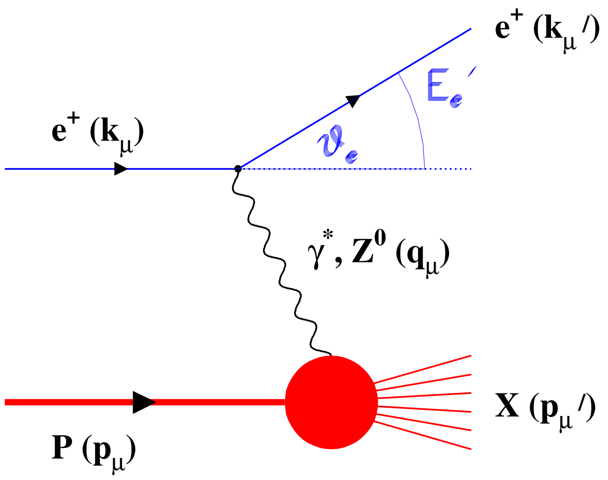
- large coverage: 6 decade both in x and Q^2;
- very large Q^2 (electroweak unification and new physics) and very low Q^2 (transition to non-perturbative regime);
- medium Q^2 (precision tests of pQCD), but small overlap with fixed-target experiments
- HERA covers a much lower x domain (sensitivity to F_L and parton saturation effects), usually kinematically coupled to low Q^2.

Experimental access to low Q^2

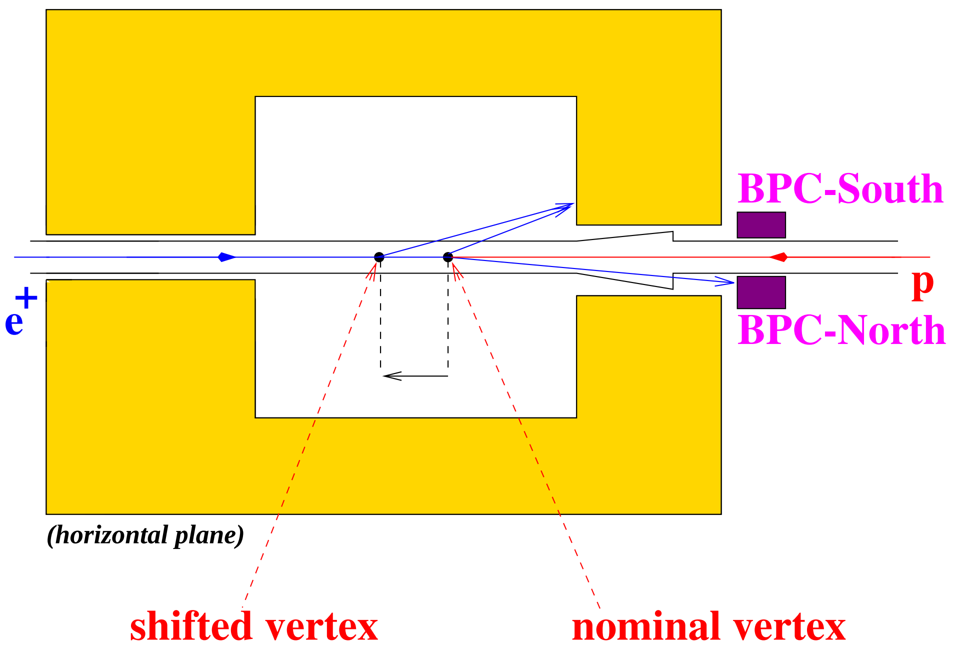
Experimental approach to explore the low Q^2-region:

$$\boxed{Q^2 = 4E_e E_e^{'} \cdot \sin^2 \frac{\vartheta_e^{'}}{2}}$$

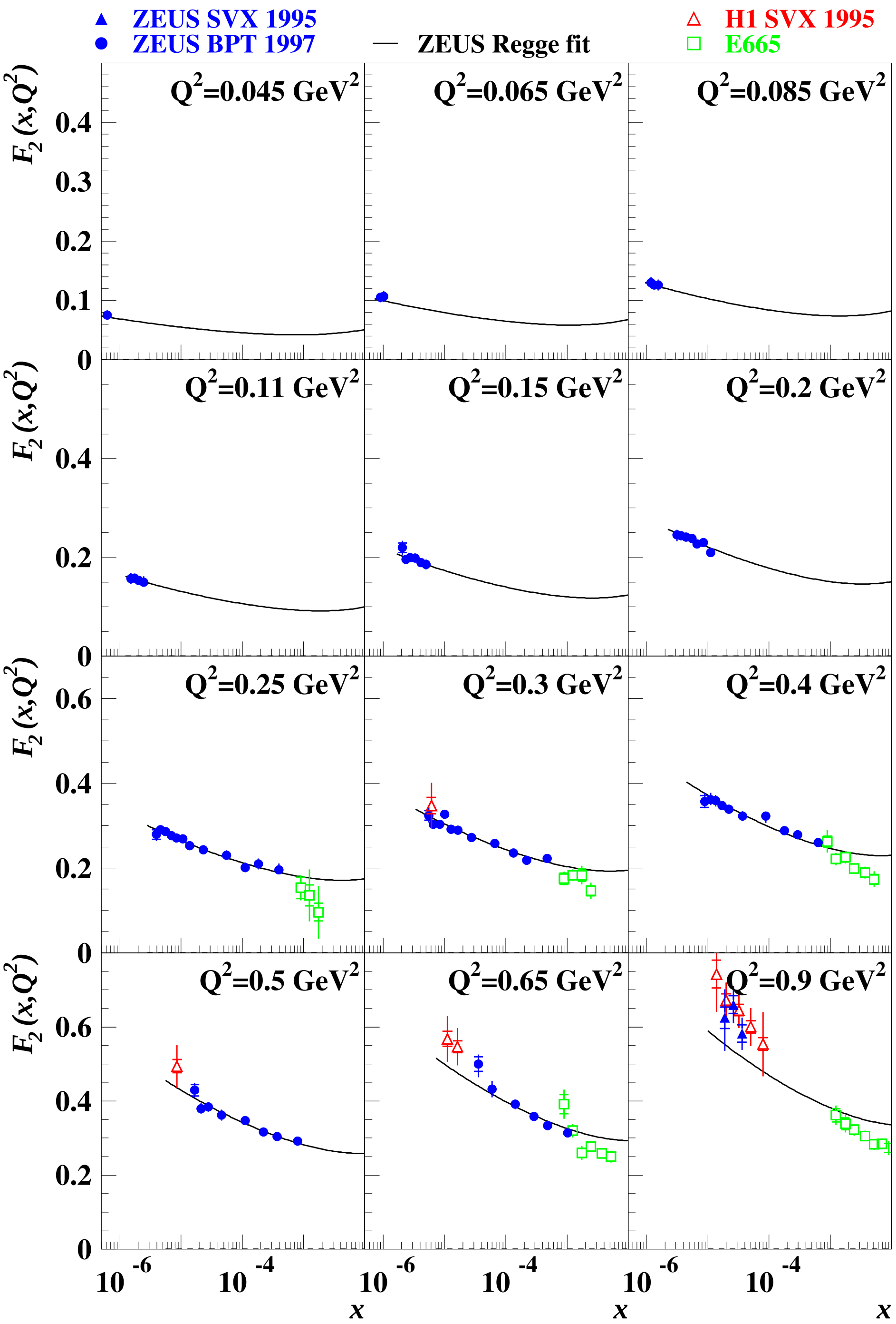
⇒ Tag **positron** scattered under very small angles
⇒ Measure **energy** $E_e^{'}$ and **angle** $\vartheta_e^{'}$ of the scattered **positron**



Method:
⇒ A: ZEUS **B**eam **P**ipe **C**alorimeter (**BPC**) & Tracker (**BPT**)
⇒ B: Events with shifted event vertex



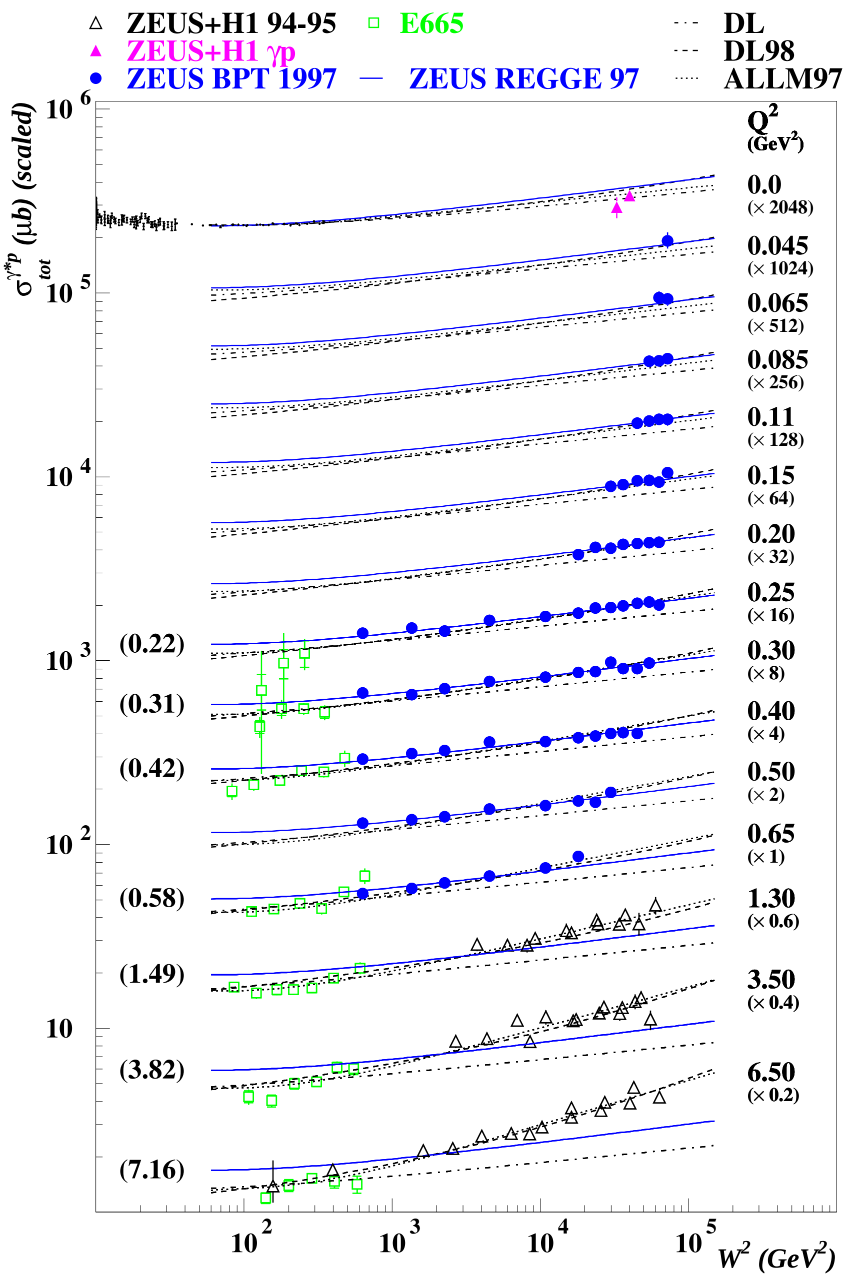
Recent Low-Q^2 Data (BPT97)



- analysis reaches **very low** $Q^2 < 1\,\mathrm{GeV}^2$, **very low** $x \sim 10^{-6}$ and some minimal overlap with fixed target (E665) data at $x \sim 10^{-3}$.
- average error: $\pm 2.6\%$ (stat), $\pm 3.3\%$ (syst);
- F_2 rises at low x even at the lowest Q^2, but it's a "soft" rise compared to what observed at higher Q^2.

Energy Dependence of $\sigma^{\gamma^* P}$

$$\sigma_{tot}^{\gamma^* P} = \frac{M_0^2}{M_0^2 + Q^2} \left\{ A_{\mathbb{R}} \left(W^2\right)^{\alpha_{\mathbb{R}}-1} + A_{\mathbb{P}} \left(W^2\right)^{\alpha_{\mathbb{P}}-1} \right\} \qquad (1)$$



$\sigma_{tot}^{\gamma^* P} \simeq \frac{4\pi^2\alpha}{Q^2} F_2$,

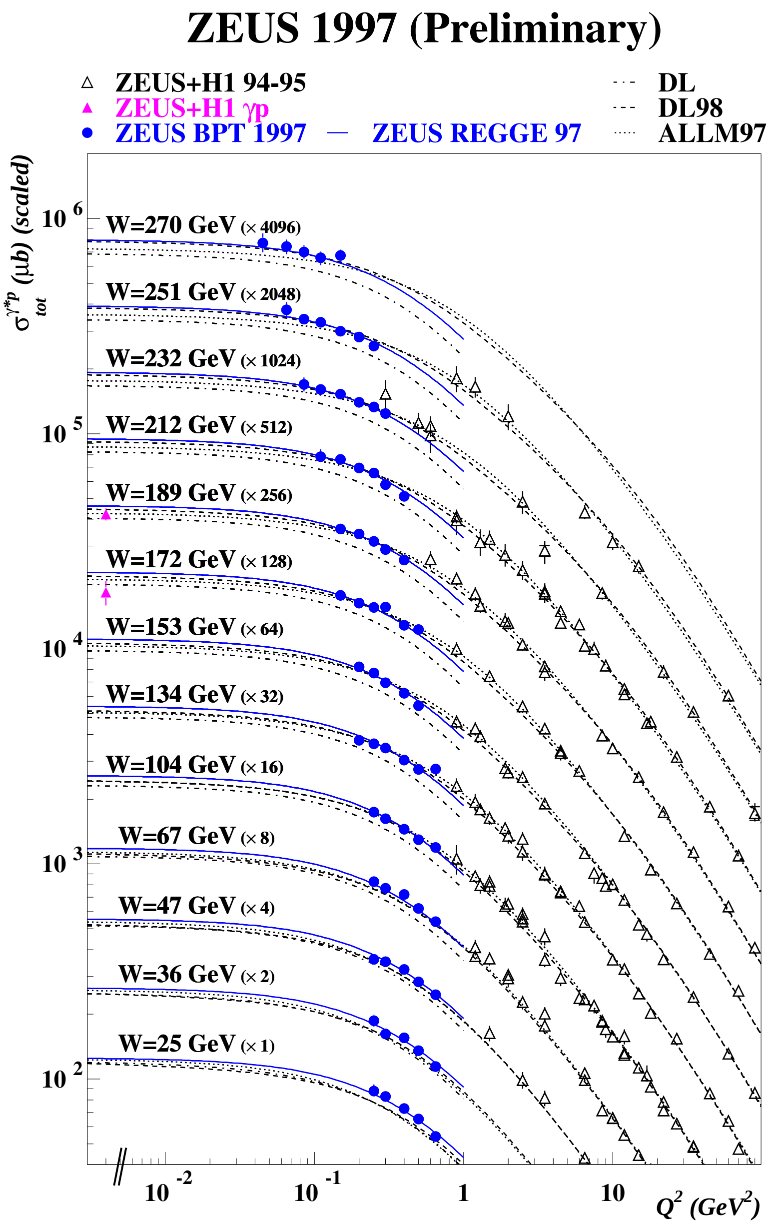
$W^2 \simeq Q^2/x$;

F_2 at low x $\Leftrightarrow$ $\sigma_{tot}^{\gamma^* P}$ at high energy

$\sigma^{\gamma^* P}$ rises with energy even at the lowest Q^2, but it's rise is **less steep ("soft")**:
low Q^2: $\sigma^{\gamma^* P} \propto (W^2)^{0.08}$; high Q^2: $\sigma^{\gamma^* P} \propto (W^2)^{0.2 \div 0.4}$

smooth "transition" around **$\mathbf{Q^2 \sim 1}$ GeV^2**

Q^2 Dependence of $\sigma^{\gamma^* P}$



conservation of e.m. current ($q_\mu W^{\mu\nu} = 0$) implies that the singularities of $W^{\mu\nu}$ for $q^2 \to 0$ cannot be real:

scaling cannot be valid at low Q^2: $F_2 = \mathcal{O}(q^2)$

Experimentally

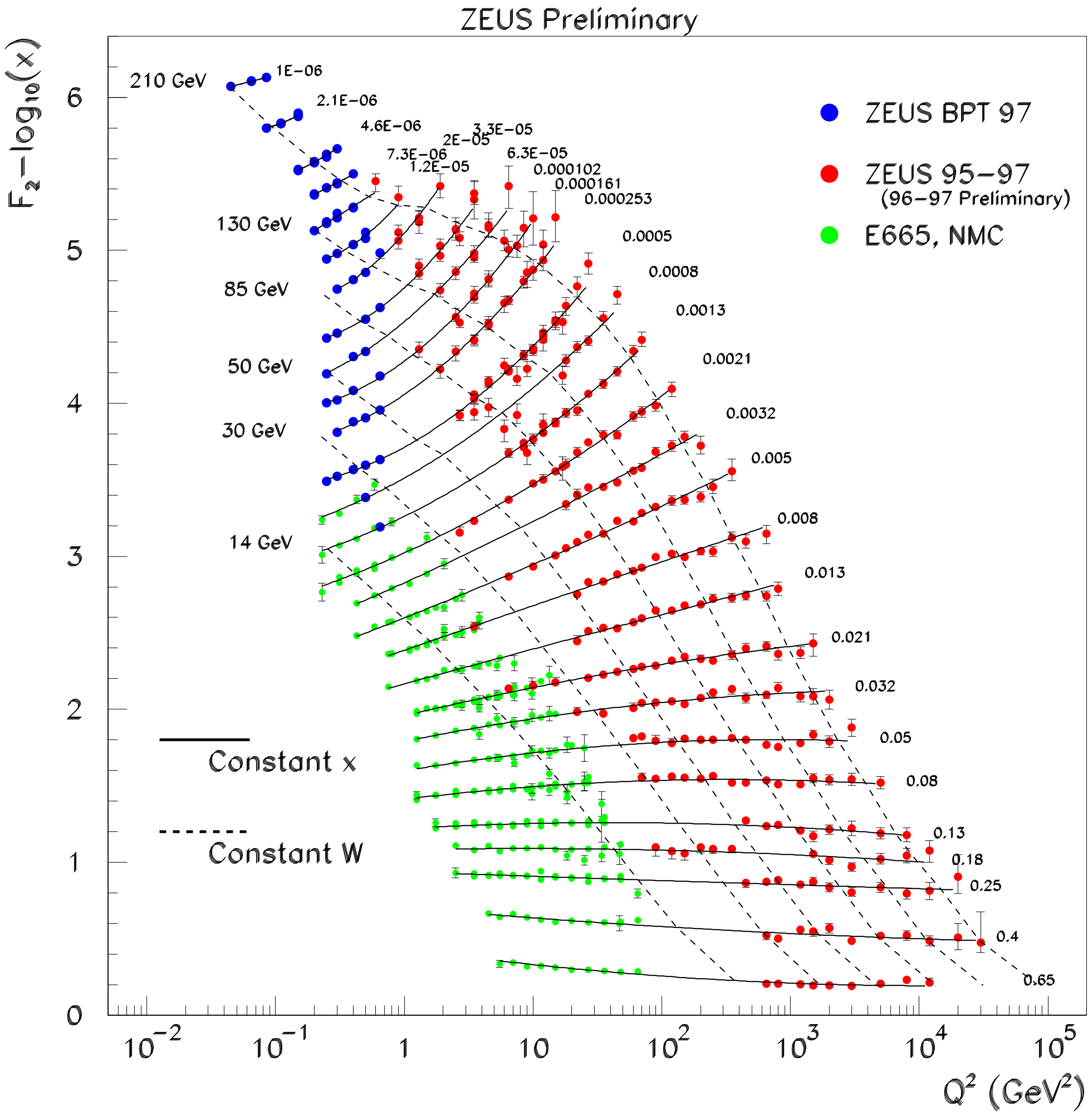
$$\sigma^{\gamma P}_{tot} = \lim_{Q^2 \to 0} \frac{4\pi^2 \alpha}{Q^2} F_2$$

is known to be finite

However, the scale for this "transition" is NOT theoretically or experimentally specified!

HERA data show that $\sigma^{\gamma^* P}$ falls approximately like $1/Q^2$ at high Q^2, but starts smoothly flattening off at lower $Q^2 \sim 1\,\mathrm{GeV}^2$.

Overview of F_2 Q^2 Evolution



Fit the form $\alpha(x) + \beta(x)\, t + \gamma(x)\, t^2$ ($t \equiv \log_{10} Q^2$) to the F_2 data at each value of x (solid lines)

[$\partial \ln F_2 / \partial \ln(Q^2)$ can be determined as $\beta(x) + \gamma(x)\, t$]

Fixed $W = Q^2\,(1/x - 1)$ points on the parameterization denoted by the dashed lines:
note the distortion in the fixed W lines that occurs around $x = 10^{-4}$ at relatively high $Q^2 \sim 5\,\mathrm{GeV}^2$ and at W above $85\,\mathrm{GeV}$.

The logarithmic Q^2 derivative $\partial \ln F_2 / \partial \ln(Q^2)$

The obvious way to investigate the detailed behavior of F_2 in the transition region of low x and low Q^2 is to study the logarithmic derivative

$$\frac{\partial \ln F_2}{\partial \ln(Q^2)}(x, Q^2)$$

pQCD predicts that (Prytz 93), in the limit of low x and LO:

$$(A) \quad \frac{\partial \ln F_2}{\partial \ln(Q^2)}(x/2, Q^2) \propto xg(x, Q^2)$$

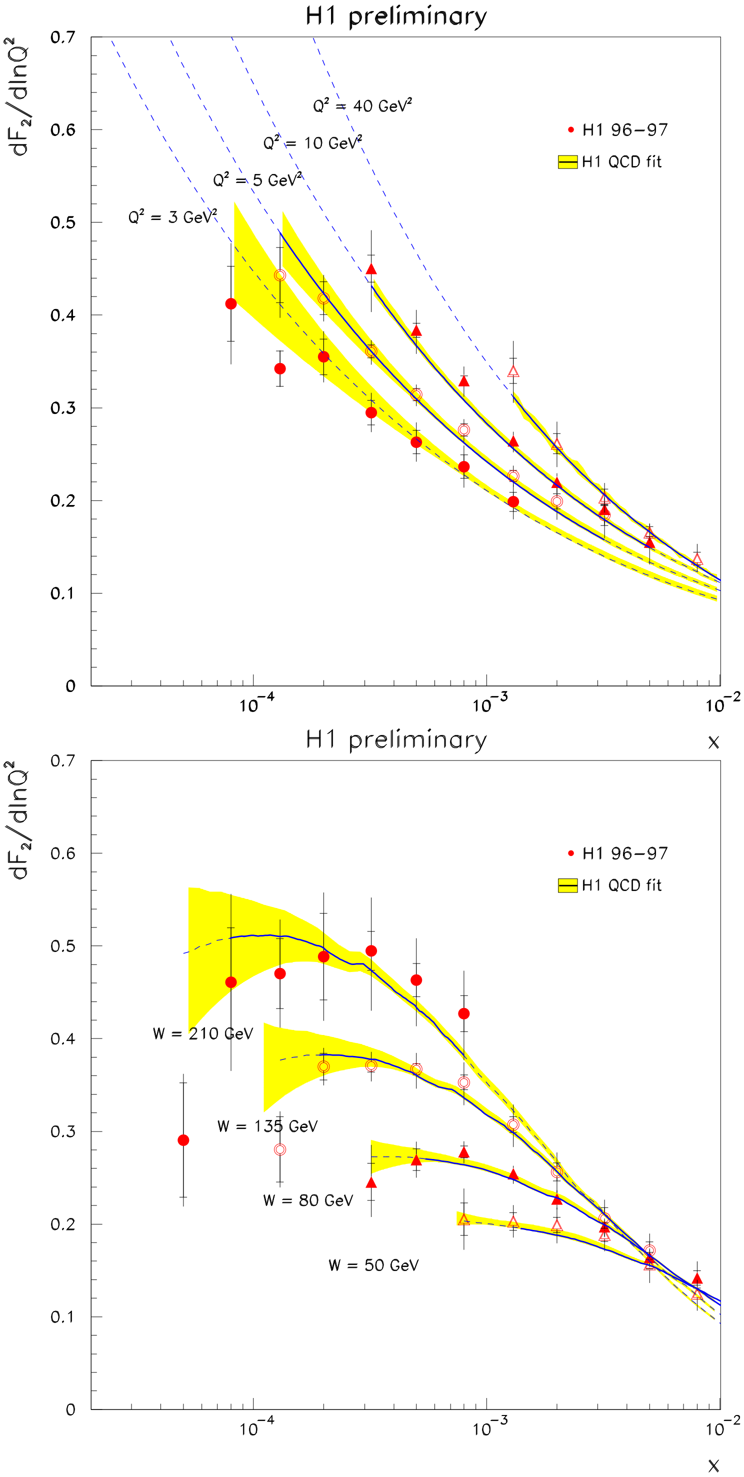
i.e. the quark contribution can be neglected and the low x behavior of $\partial \ln F_2 / \partial \ln(Q^2)$ is directly related to the low x behavior of the gluon density.

On the other hand, as discussed before F_2 must vanish like Q^2 for $Q^2 \to 0$, and thus at sufficiently low Q^2:

$$(B) \quad \frac{\partial \ln F_2}{\partial \ln(Q^2)}(x/2, Q^2) \propto Q^2 \sigma_0$$

Provided that $g(x, Q^2)$ has a weak Q^2 dependence and σ_0 a weak energy dependence, the x, Q^2 behavior of $\partial \ln F_2 / \partial \ln(Q^2)$ for constant W should clarify the transition $(A) \to (B)$

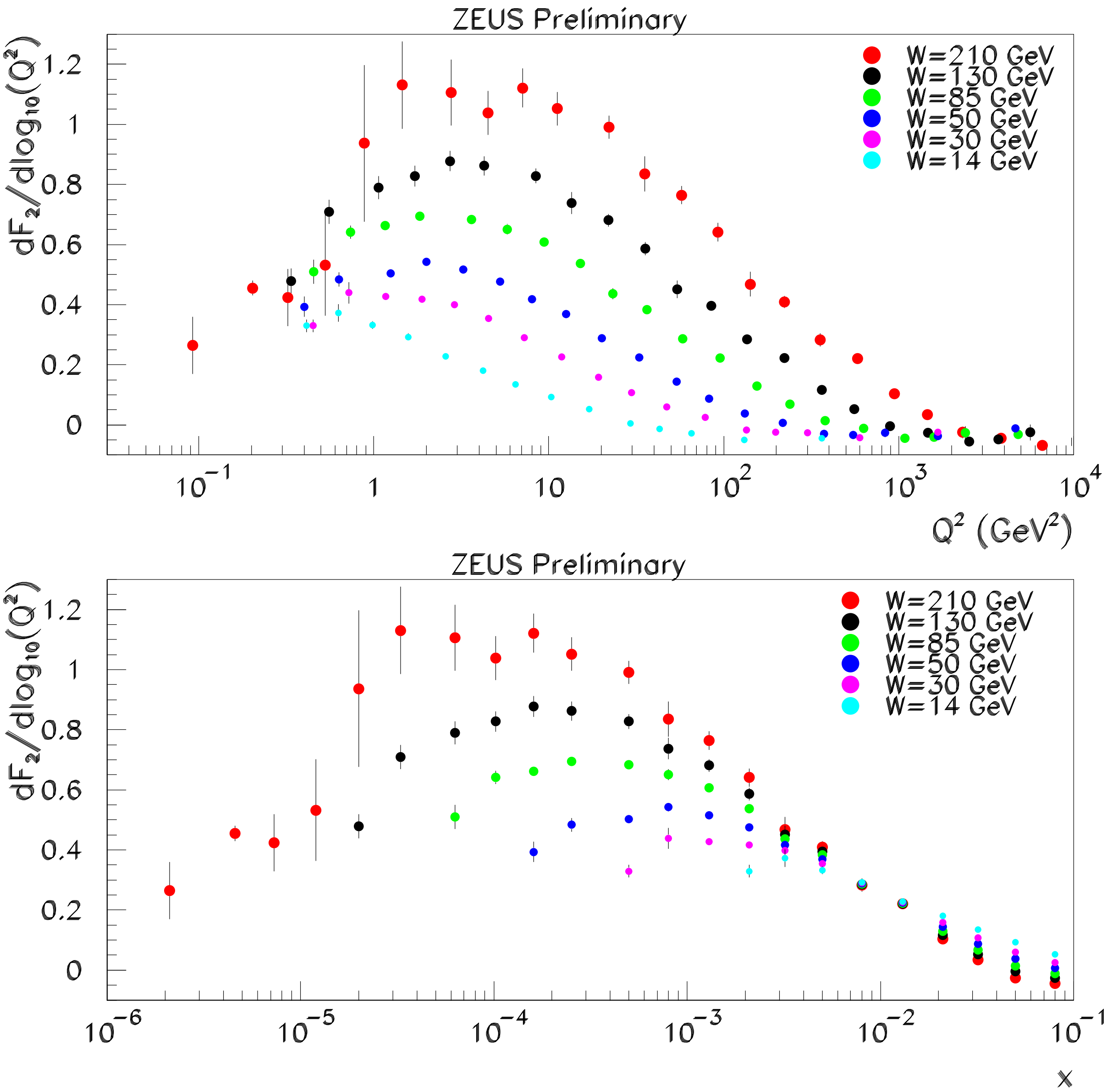
$\partial\,\ln F_2/\partial\,\ln(Q^2)$



at high Q^2, $\partial\,\ln F_2/\partial\,\ln(Q^2)$ falls with x (power-like behavior of $g(x,Q^2)$) and tends to become independent of W at high x, according to (A);

pQCD (yellow band) provides a **good description** of the $\partial\,\ln F_2/\partial\,\ln(Q^2)$ data down to $Q^2 \simeq 3\,\mathrm{GeV}^2$

$\partial \ln F_2/\partial \ln(Q^2)$ **(cont'd)**



at low Q^2, $\partial \ln F_2/\partial \ln(Q^2)$ falls with Q^2 and tends to become independent of W, according to (B);

the constant-W curves exhibit a **characteristic maximum** at **relatively high** Q^2 of 2-6 GeV^2 for $W > 85$ GeV $(0.0005 < x < 0.003)$.

Summary and Outlook

- HERA F_2 data down to $Q^2 = 0.045$ GeV^2 with statistical precision and systematic accuracy;

- soft (hadron-like) energy dependence of $\sigma_{tot}^{\gamma^* p}$ observed at low Q^2;

- flattening of the Q^2 dependence of $\sigma_{tot}^{\gamma^* p}$ (expected by current conservation toward the photoproduction limit) observed at low Q^2;

- the logarithmic Q^2 derivative of F_2 $\partial \ln F_2 / \partial \ln(Q^2)$ illustrates well the transition in the x and Q^2 dependence of F_2 around a Q^2 of $2 - 6$ GeV^2;

- HERA data, spanning six orders of magnitude both in x and Q^2, illustrate in a continuous way the transition from the perturbative to the non-perturbative regime, and thus provide the ideal input for the understanding of the dynamical mechanisms underlying this transition.