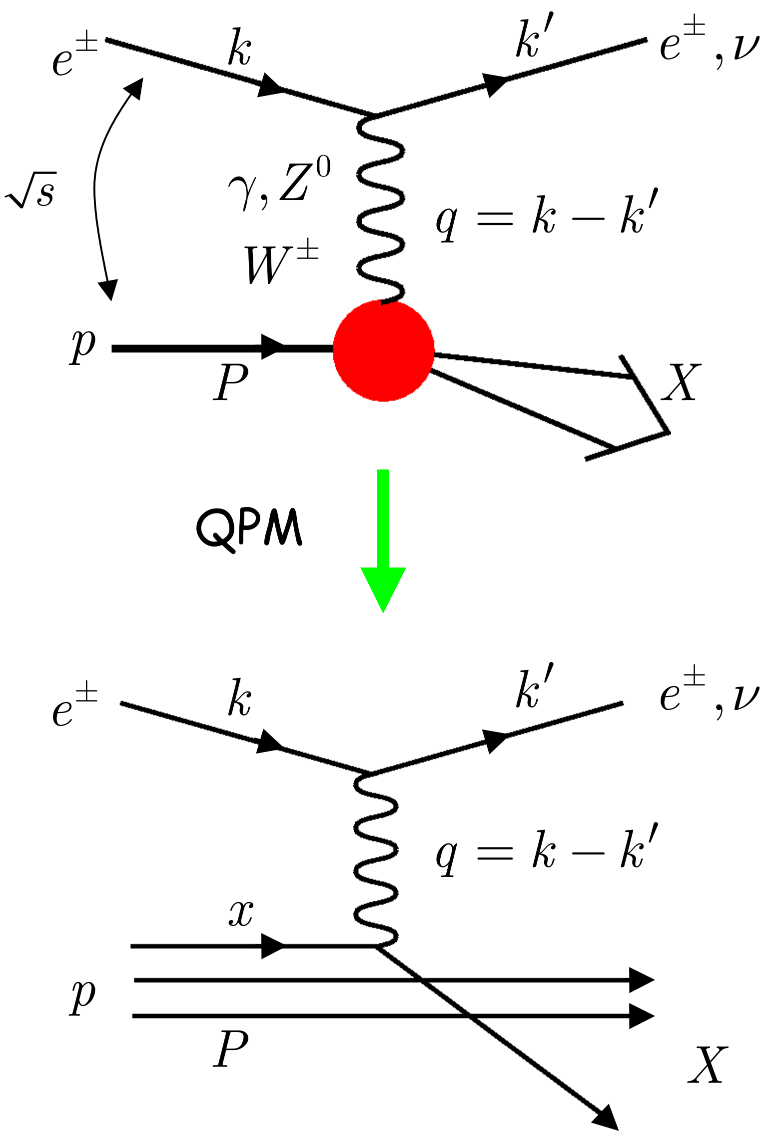
HERA Physics - Present and Future

- Introduction to Electron-Proton Deep Inelastic Scattering

  Structure Functions, Quark-Parton-Model, Quantum Chromodynamics
- Measurements of the Structure Functions
- Gluon density and the Strong Coupling Constant
- What makes the Proton spin ?
- Testing the Electroweak Model in the Space-like Region
- Physics beyond the Standard Model
- Prospects at HERA II
- Conclusions

Deep Inelastic Scattering (DIS)



$$Q^2 = -(k-k')^2 = -q^2$$

(momentum transfer)^2

virtuality of $\gamma^*, Z^0, W^\pm$

→ („size" of the probe)$^{-1}$

$$x = \frac{Q^2}{2\,P \cdot q}$$

fraction of the proton momentum carried by the charged parton

$$y = \frac{P \cdot q}{P \cdot k}$$

fraction of the electron energy carried by the virtual photon („inelasticity")

$$s = (k+P)^2$$

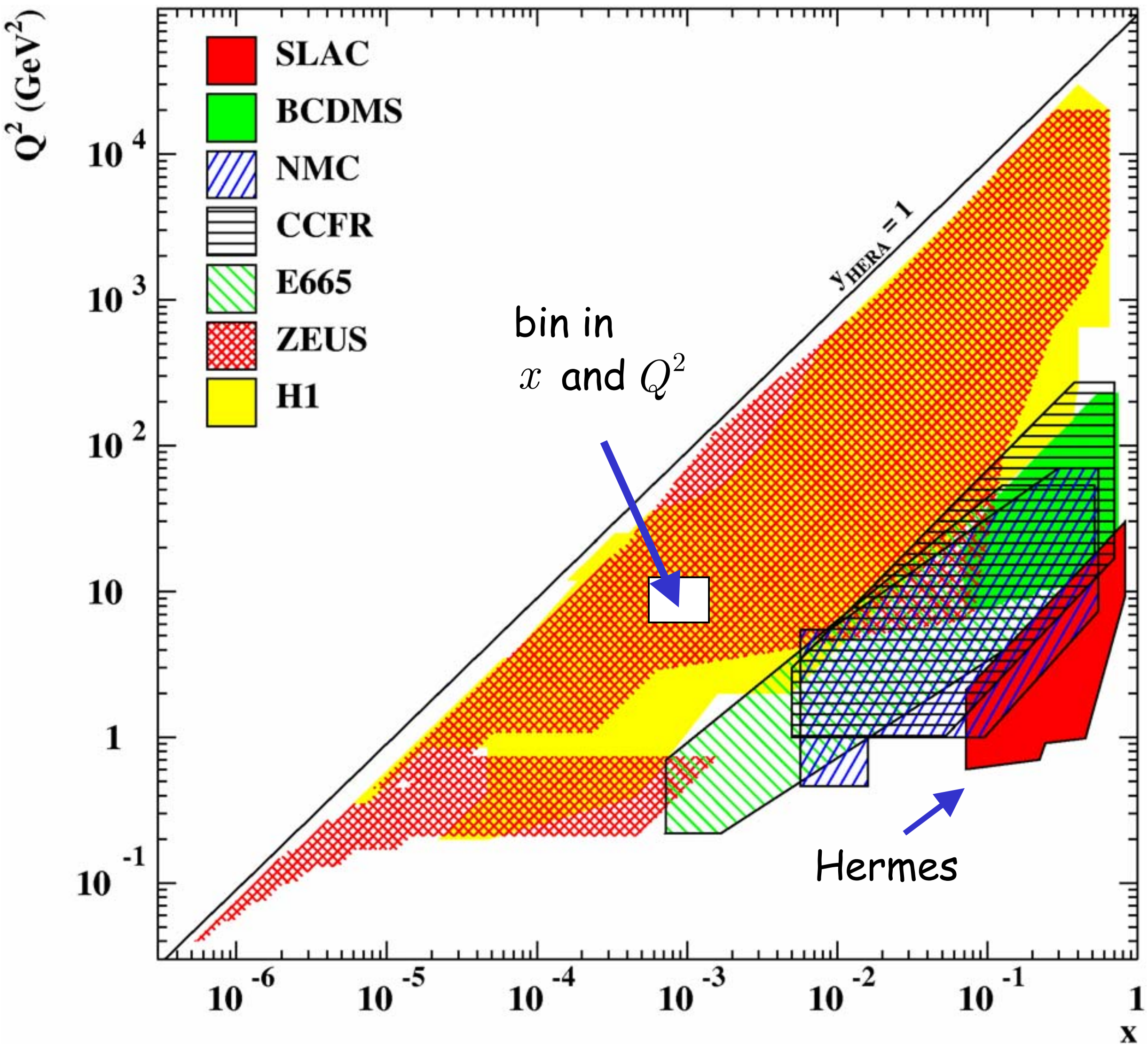
center of mass energy of ep system

$$W^2 = M_X^2 = (q+P)^2$$

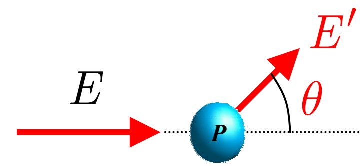
(mass)^2 of $\gamma^* p$ system

$$Q^2 = sxy$$

The Kinematic Reach of HERA



Determination of kinematics („e"-method) :



$$Q^2 = 4EE' \cos^2\left(\frac{\theta}{2}\right)$$

$$y = 1 - \frac{E'}{E}\sin^2\left(\frac{\theta}{2}\right)$$

$$x = \frac{Q^2}{sy}$$

Determination of cross sections :

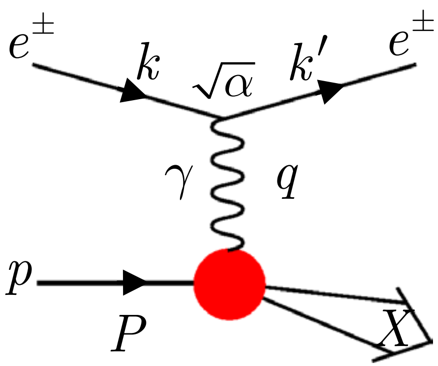
$$\frac{d^2\sigma}{dx dQ^2} \sim \frac{N - B}{\mathcal{L}\,\varepsilon}$$

backgr.

efficiency

luminosity

Cross Section and Structure Functions



(unpolarized particles)

$$\frac{d^2\sigma}{d\Omega dE'} = \frac{\alpha^2}{2MQ^4}\frac{E'}{E}L_{\mu\nu}W^{\mu\nu}$$

$L_{\mu\nu}$ lepton tensor

$W_{\mu\nu}$ hadronic tensor

$$L_{\mu\nu} = 2\left[k_\mu k'_\nu + k'_\mu k_\nu + \frac{q^2}{2}g_{\mu\nu}\right]$$

← minimal electromagnetic coupling

$$W_{\mu\nu} = \left(-g_{\mu\nu} + \frac{q_\mu q_\nu}{q^2}\right)2F_1 + \left(P_\mu - \frac{P\cdot q}{q^2}q_\mu\right)\left(P_\nu - \frac{P\cdot q}{q^2}q_\nu\right)\frac{2}{P\cdot q}F_2$$

↖ most general tensor satisfying charge conservation

NC cross section :

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

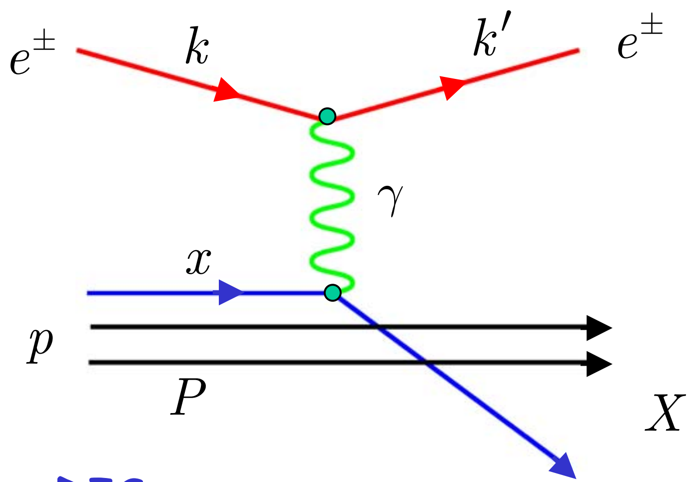
$$= \frac{2\pi\alpha^2}{xQ^4}\left[Y_+F_2 - y^2F_L\right]$$

$$F_L \equiv F_2 - 2xF_1$$

longitudinal structure function

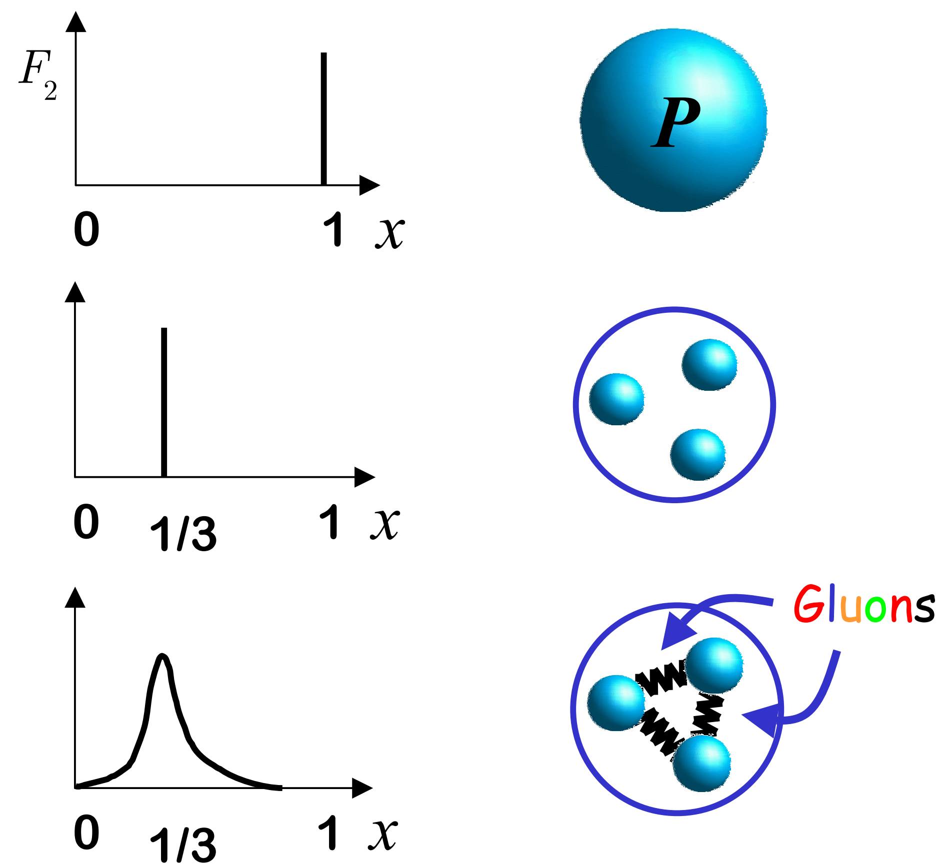
$$Y_\pm = 1 \pm (1-y)^2$$

Structure Functions within the Quark-Parton-Model



$$\frac{d^2\sigma(e^\pm p)}{dx\,dQ^2} = \frac{2\pi\alpha^2}{xQ^4}\left[Y_+ F_2 - y^2 F_L\right]$$

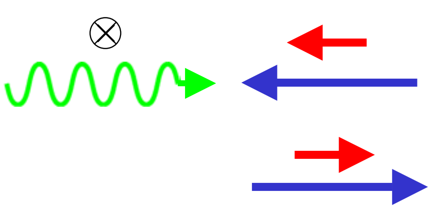
QPM: $F_2(x) = \sum_{i=u,d} e_i^2 x q_i(x)$ ← parton densities $xq_i(x)$ (pdf)



DIS =

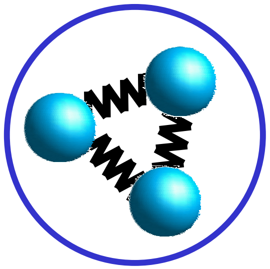
- electron scatters off a charged constituent (parton) of the proton (= elastic scattering)
- identify the charged partons with QUARKS (= spin 1/2 fermions)

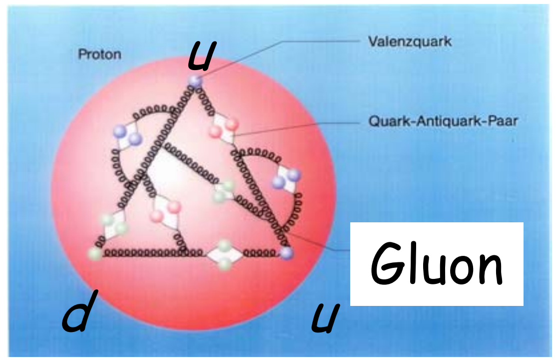
→ Quark-Parton-Model (QPM)

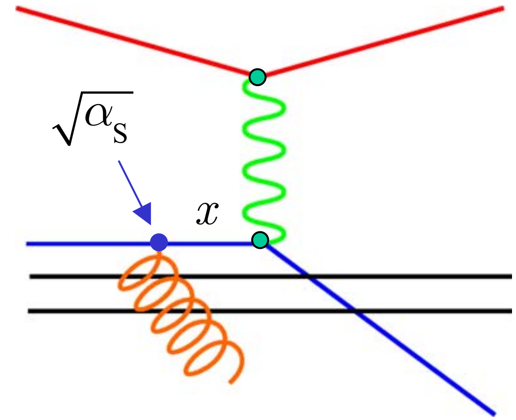


$$F_L = 0$$

Quantum Chromodynamics (QCD)







Basic ingredients of QCD:

1. Asymptotic freedom :

$\alpha_S \to 0$ at short distances

→ perturbative QCD (pQCD)

2. Factorization :

„hard" scale Q^2

$$\sigma = \sum_i \sigma_{\gamma^* i}(Q^2) \otimes pdf_i$$

non-perturbative part

3. Evolution :

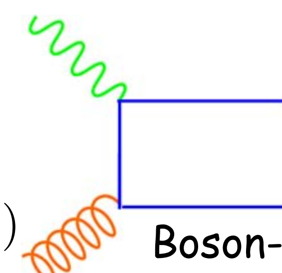
Parton densities become functions of Q^2

$xq_i(x) \to xq_i(x, Q^2)$ quarks

$x\overline{q}_i(x, Q^2)$ antiquarks

+ gluons

$g(x, Q^2)$



Boson-gluon fusion (BGF)

Quantum Chromodynamics (cont.)

Parton evolution according to Altarelli-Parisi (DGLAP) integro-differential equations:

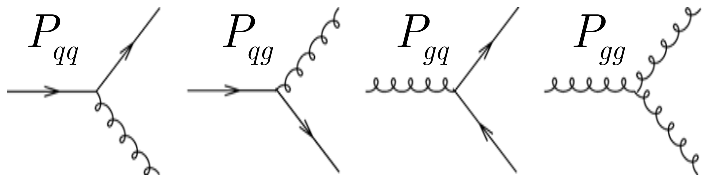
$$\frac{d}{d\ln Q^2}\begin{pmatrix} g \\ q_S \end{pmatrix} = \frac{\alpha_S(Q^2)}{2\pi}\begin{bmatrix} P_{gg} & P_{gq} \\ P_{qg} & P_{qq} \end{bmatrix} \otimes \begin{pmatrix} g \\ q_S \end{pmatrix}$$

$$\frac{d}{d\ln Q^2} q_{NS} = \frac{\alpha_S(Q^2)}{2\pi} P_{qq}^{NS} \otimes q_{NS}$$

$$q_S(x,Q^2) = \sum_i (q_i + \bar{q}_i)$$

$$q_{NS}(x,Q^2) = \sum_i (q_i - \bar{q}_i)$$

P_{ij} : splitting functions



$$\frac{1}{x}F_2(x,Q^2) = \sum_{i=1}^{n_f} e_i^2 C_i(x,Q^2) \otimes (q+\bar{q})(x,Q^2) + C_g(x,Q^2) \otimes g(x,Q^2)$$

$C_i(x,Q^2), C_g(x,Q^2), P_{ij}$ calculable in QCD ~ $O\left(\alpha_S\left(Q^2\right)\right) + \ldots$

Theoretical approach:

Test of the QCD evolution

QCD fits to F_2 using gluon and quark densities

→ input: parton densities at some (low) Q_0^2

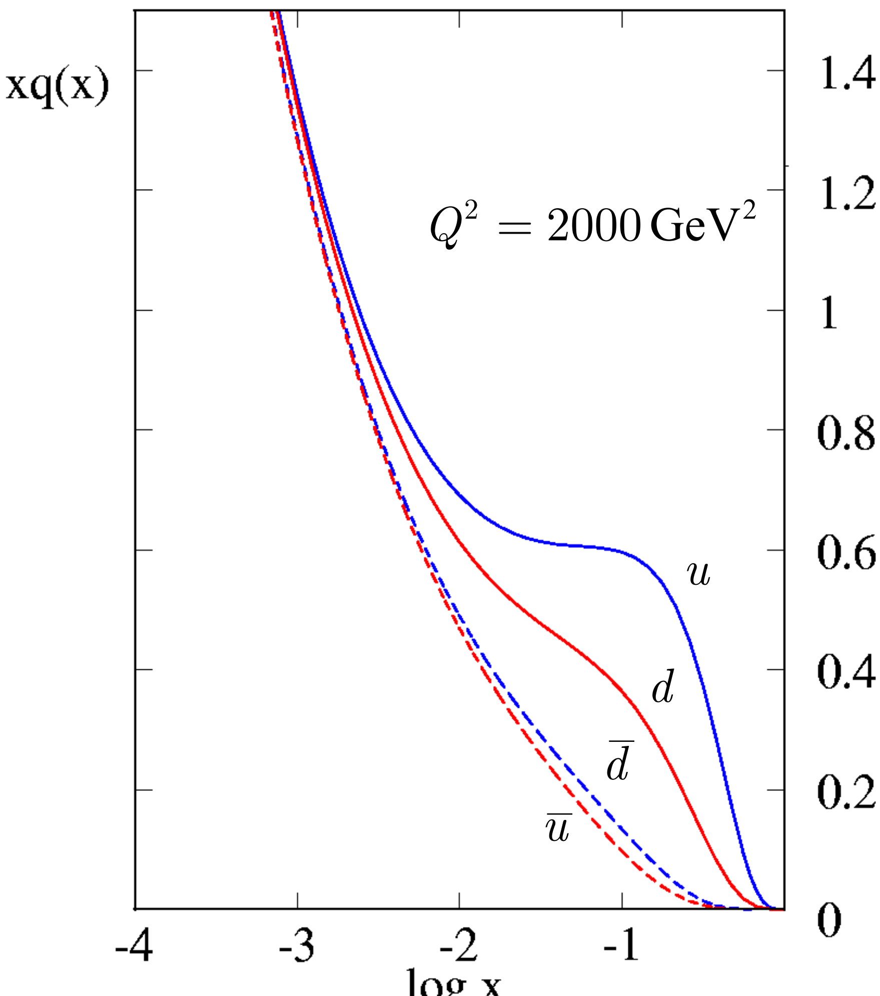
→ fit F_2 for $Q^2 > Q_0^2$

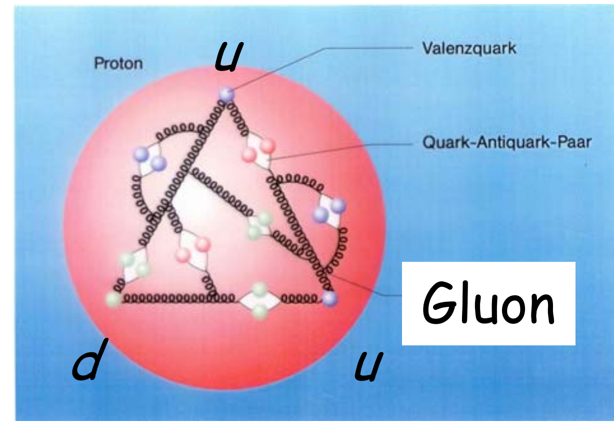
Quantitative Picture of the DGLAP Evolution

Ansatz for parton densities:

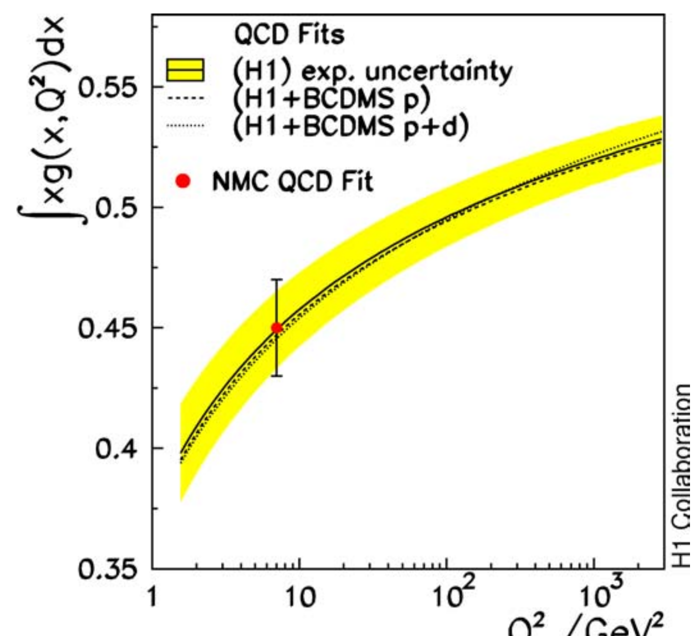
$$xq(x,Q_0) = Ax^B(1-x)^C\left[1 + D\sqrt{x} + Ex\right]$$

QCD evolution:

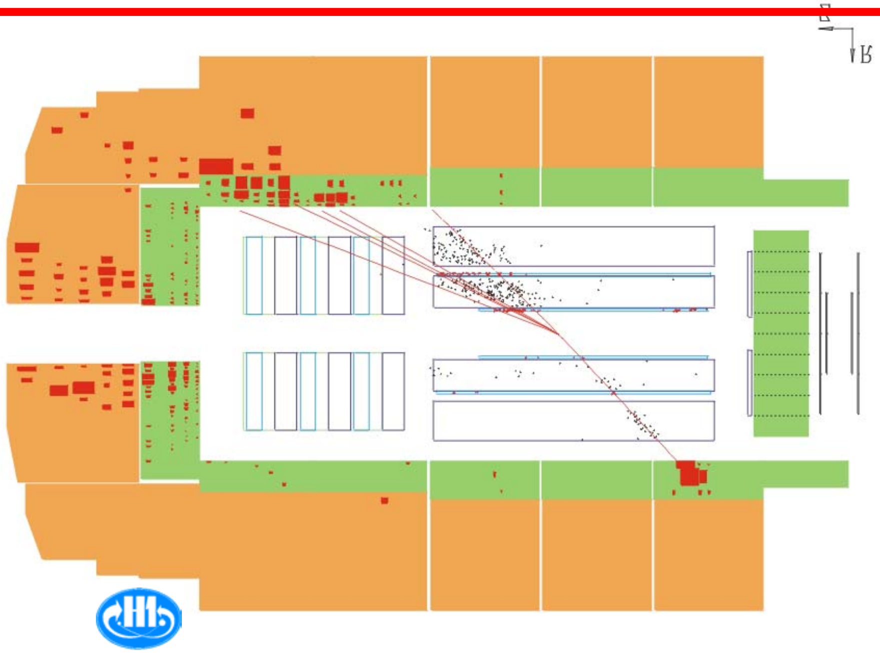


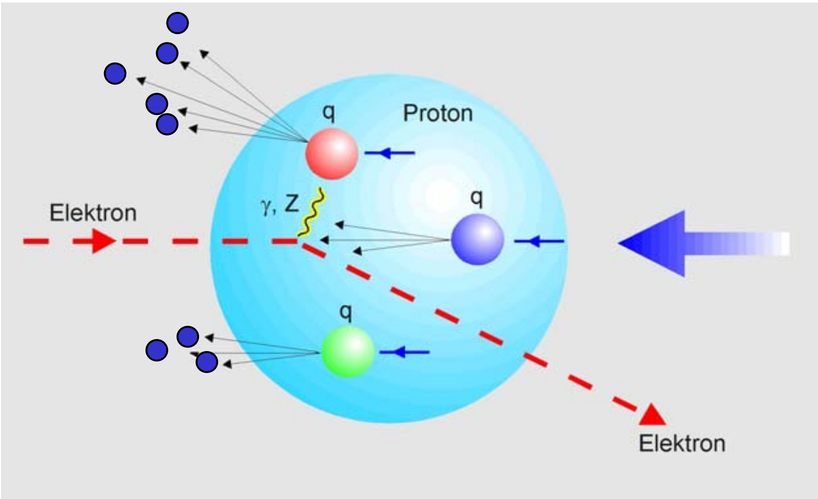


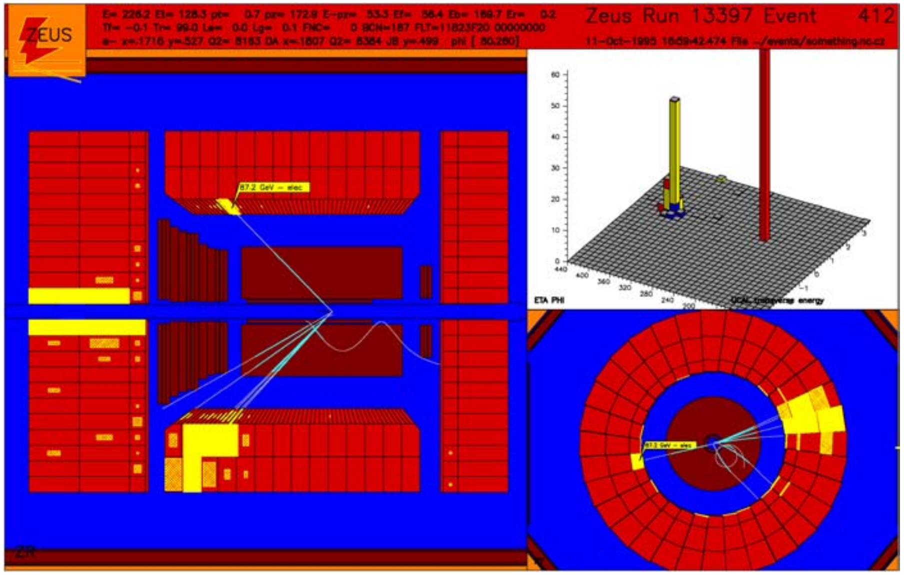
Quarks carry only about 1/2 of the nucleon momentum:



Electron Proton Scattering in Real Detectors ....







Netral current events in

H1 (medium Q^2)

ZEUS (large Q^2)

Precision Measurements of F_2

$$\frac{d^2\sigma(e^{\pm}p)}{dx\,dQ^2} = \frac{2\pi\alpha^2}{xQ^4}\left[Y_+ F_2 - y^2 F_L\right]$$

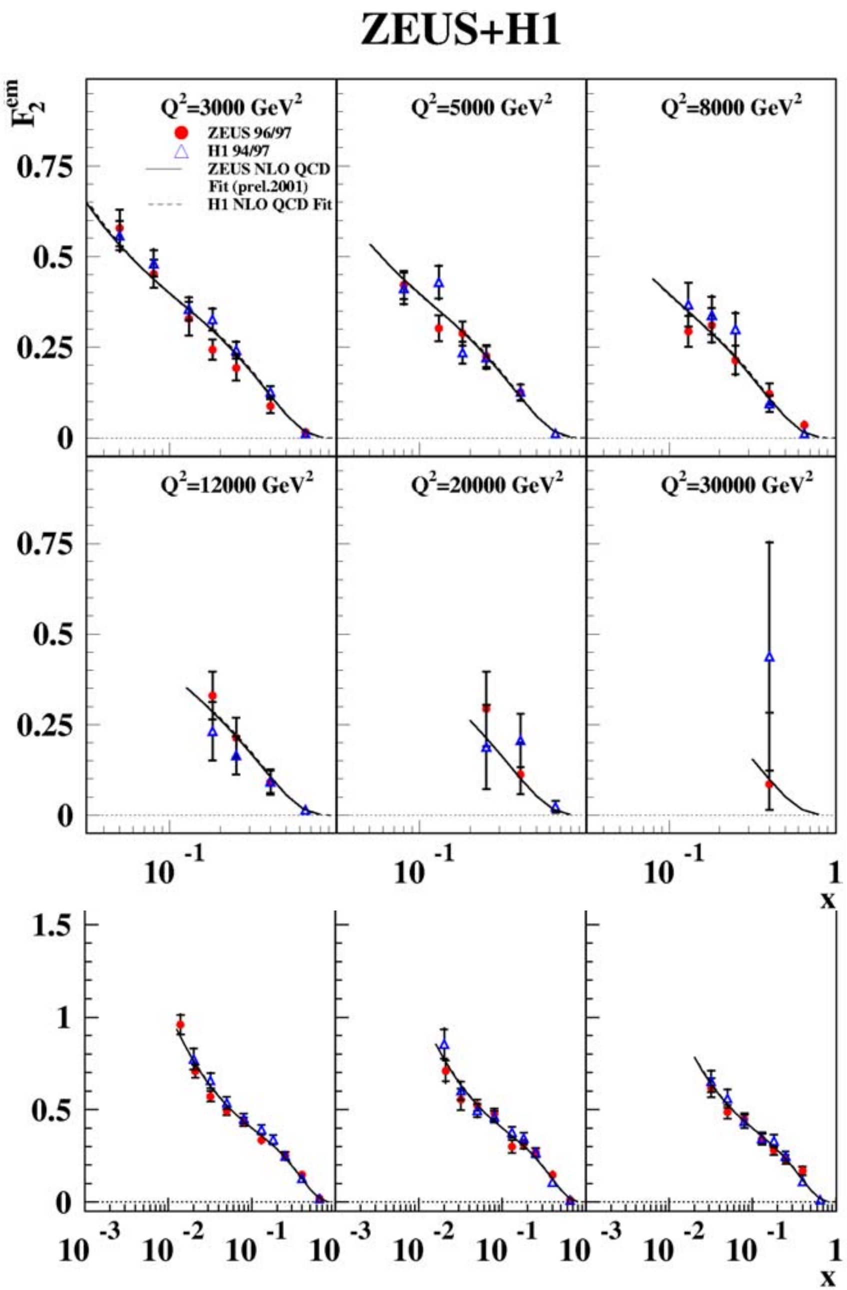
measured cross section in bins of x and Q^2

→ to measure F_2 need to get rid of F_L !

- cut: use only events with $y < y_{\text{cut}}$
  (typically $y_{\text{cut}} = 0.6$)
- Correct for remaining contribution using QCD

Big surprise in the early HERA running:

→ F_2 rising much faster with falling x than expected in Regge picture



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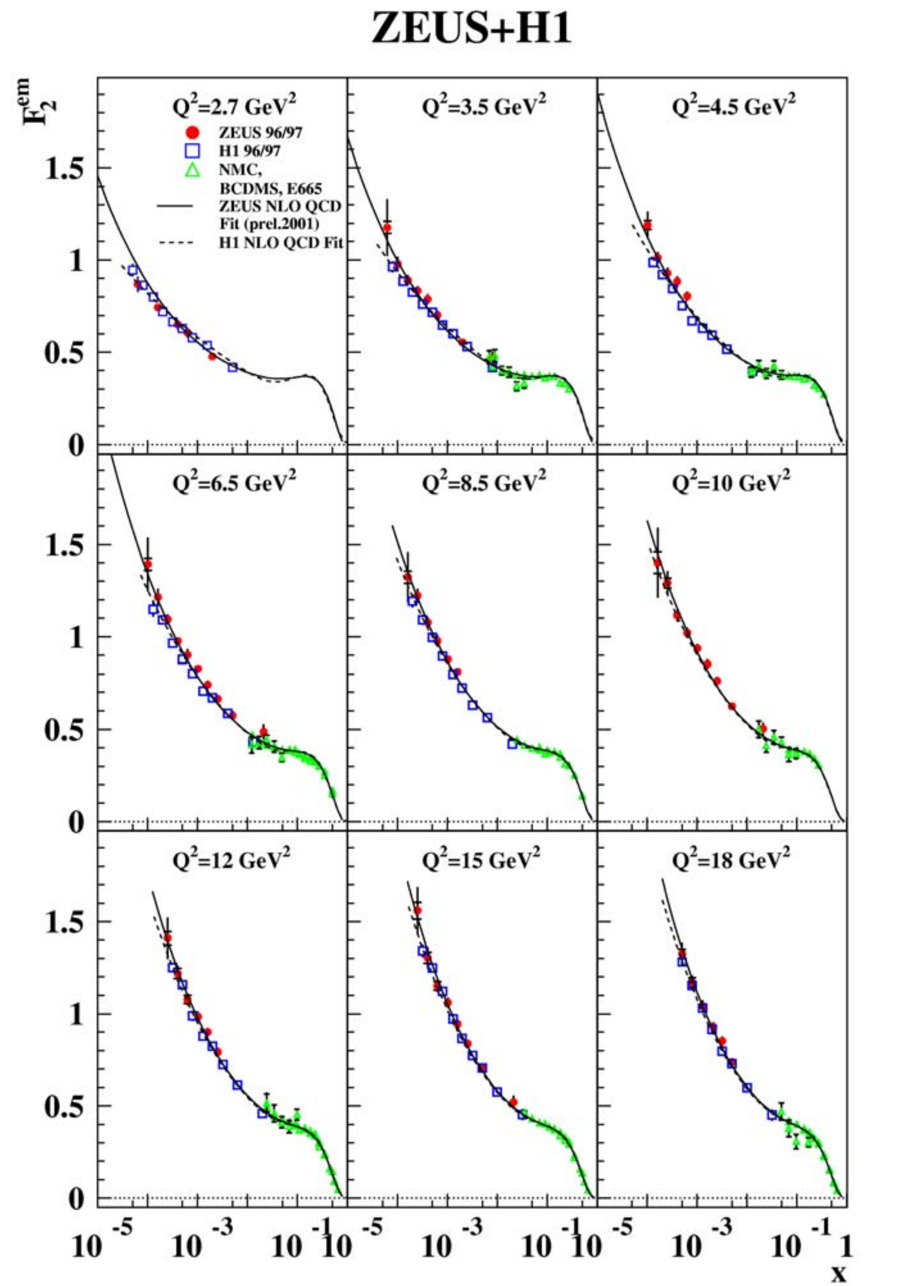
HERA data overlap and agree with fixed target data, similar in precision

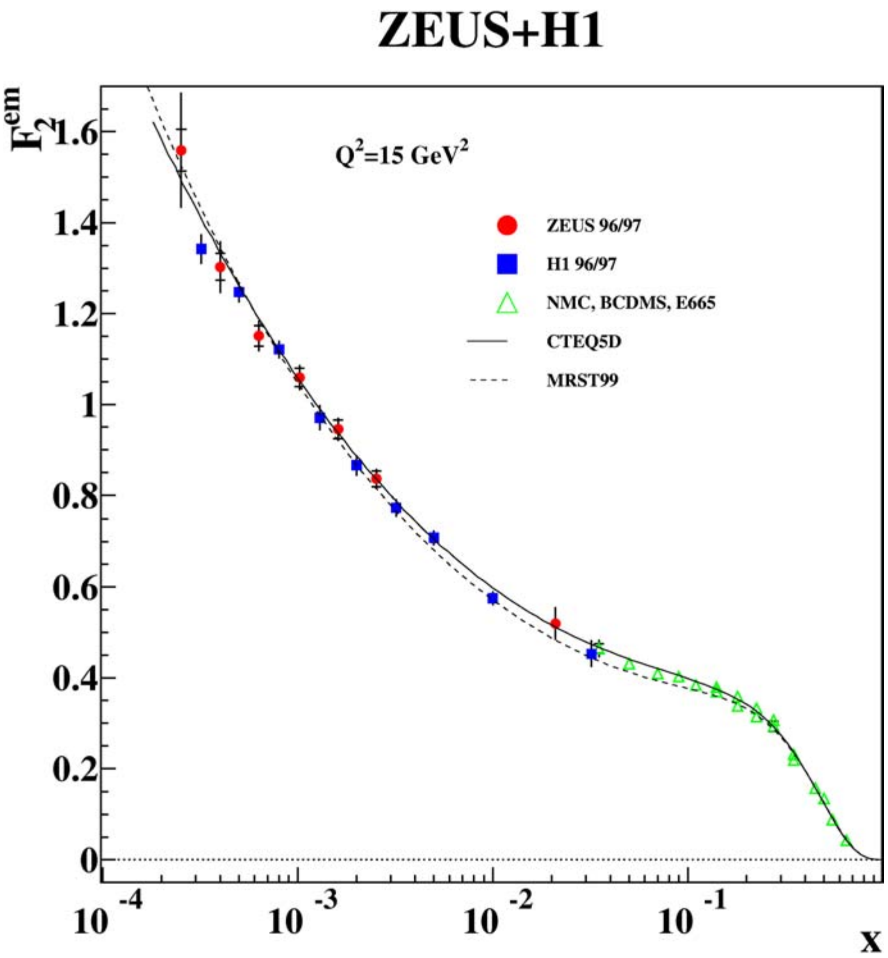
Data well described by QCD evolution

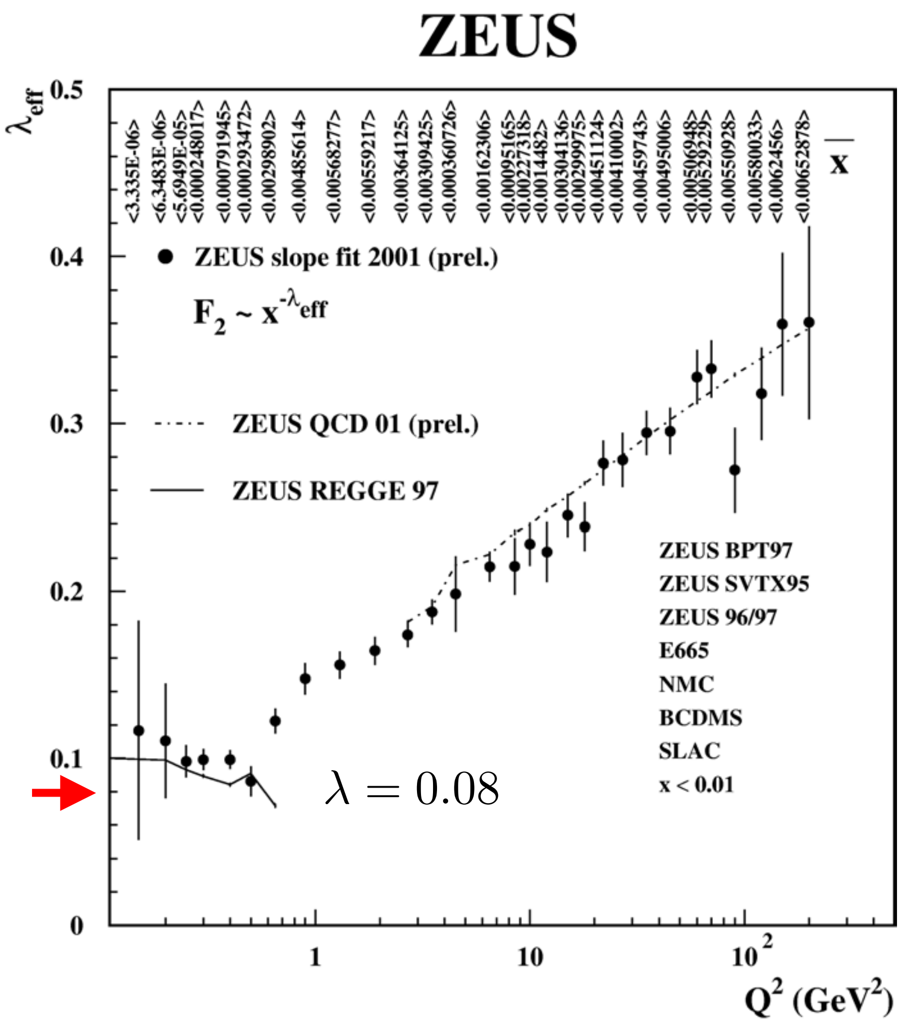


Strong Rise of F_2 Towards low x

QCD fits: rise is driven by the gluons

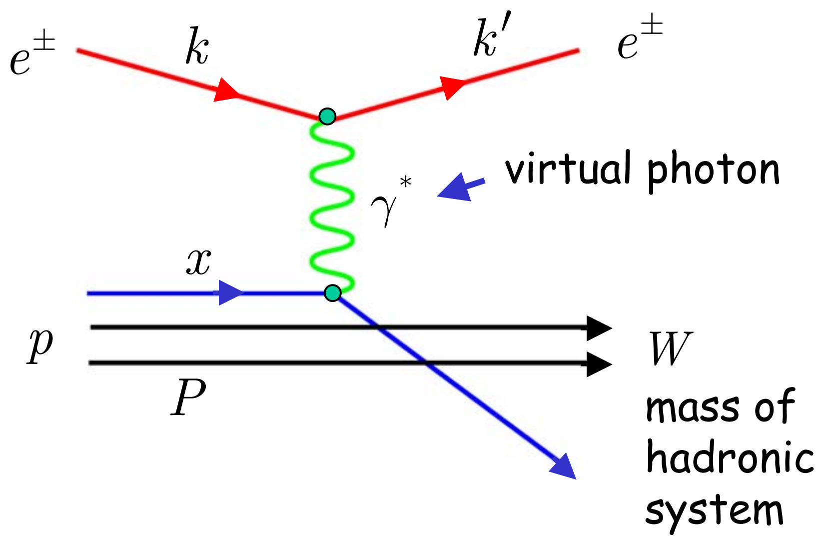
Parameterize low x part of $F_2 \sim x^{-\lambda}$





At low Q^2 the slope λ is approaching the „soft" Regge limit

Another Surprise ...



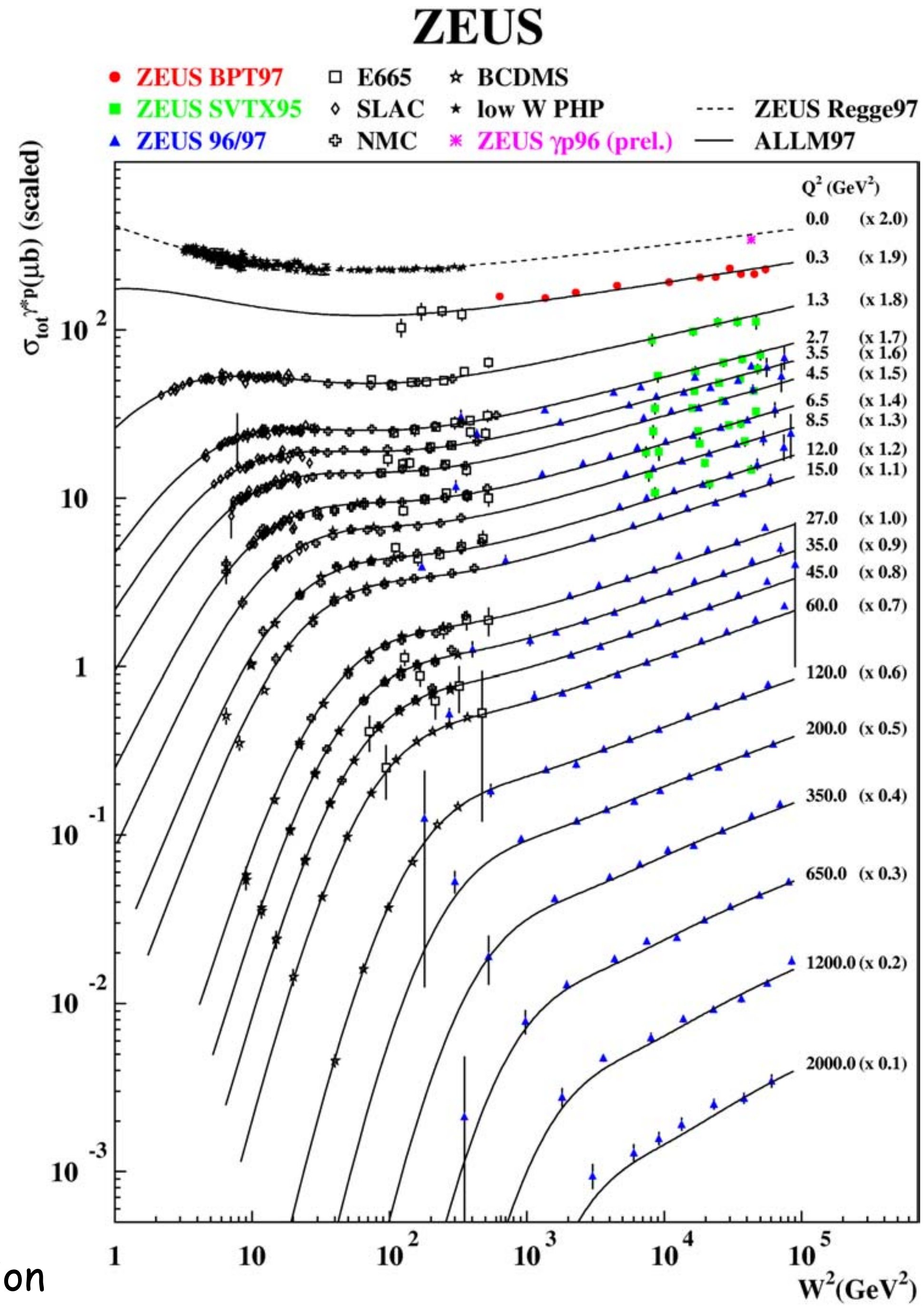
Virtual-photon proton cross section:

$$\frac{d\sigma}{dx dQ^2} \sim \sigma_{\text{tot}}^{\gamma^* p}(W^2, Q^2)$$

$\sigma_{\text{tot}}^{\gamma^* p}$ is rising faster with W^2 as Q^2 is increasing

Transition from „soft" (Regge) to „hard" (QCD) region

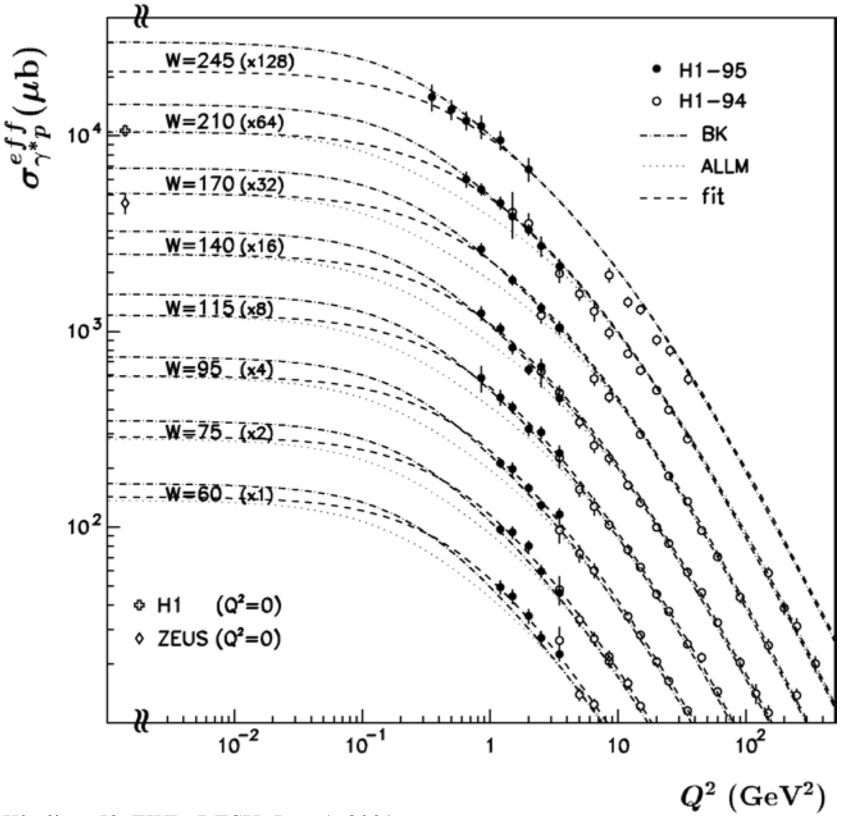
Same rise seen, e.g., in elastic J/ψ production



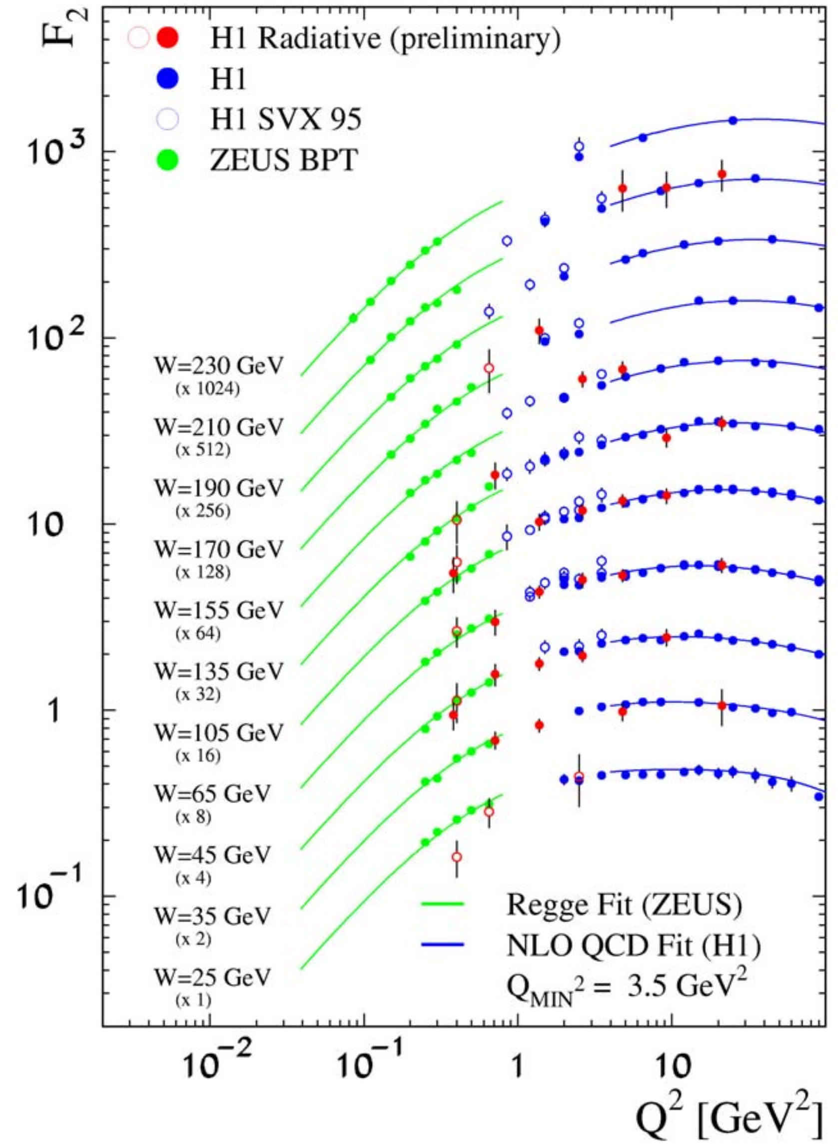
Transition to the Photoproduction Limit

$$\sigma_{\rm tot}^{\gamma^* p}(W^2,Q^2) = \sigma_T^{\gamma^* p} + \sigma_L^{\gamma^* p}$$
$$\approx \frac{4\pi\alpha^2}{Q^2} F_2(x = Q^2/W^2, Q^2)$$

(at low x : $W^2 \approx Q^2/x$)

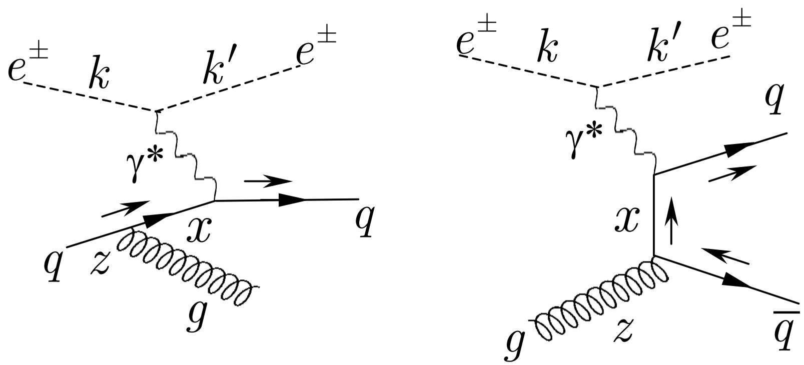


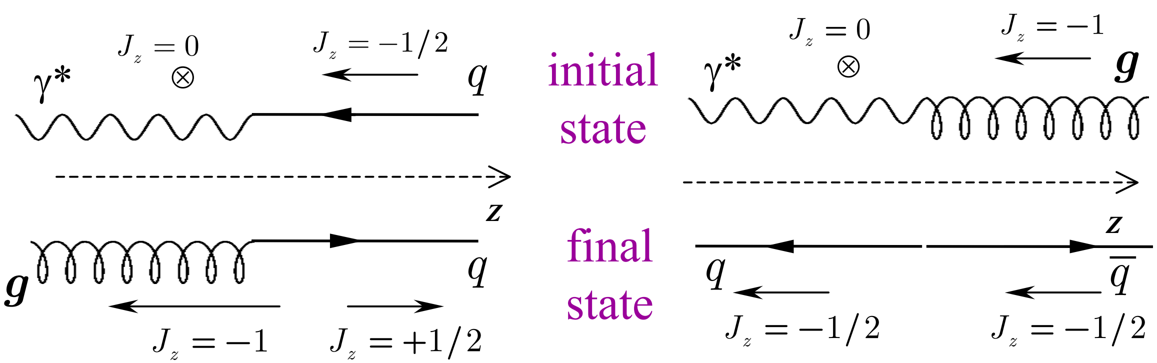
$Q^2 \to 0 \Rightarrow F_2 \to 0$ the gap is filled ....

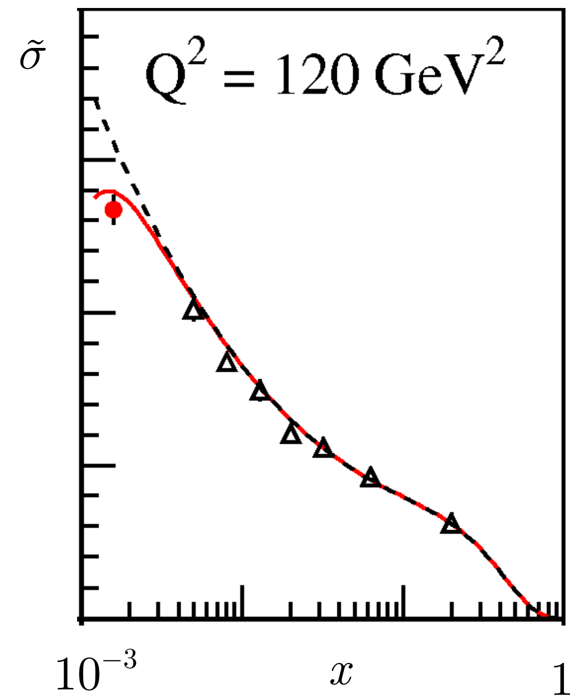


The Longitudinal Structure Function F_L

LO QCD :







$$F_L = \frac{Y_+}{y^2}\left(F_2^{\mathrm{QCD}} - \tilde{\sigma}\right)$$

$$\frac{d^2\sigma(e^{\pm}p)}{dx\,dQ^2} = \frac{2\pi\alpha^2}{xQ^4}\left[Y_+ F_2 - y^2 F_L\right]$$

in principle need 2 measurements at different $\sqrt{s}$

extrapolated in Q^2 using DGLAP

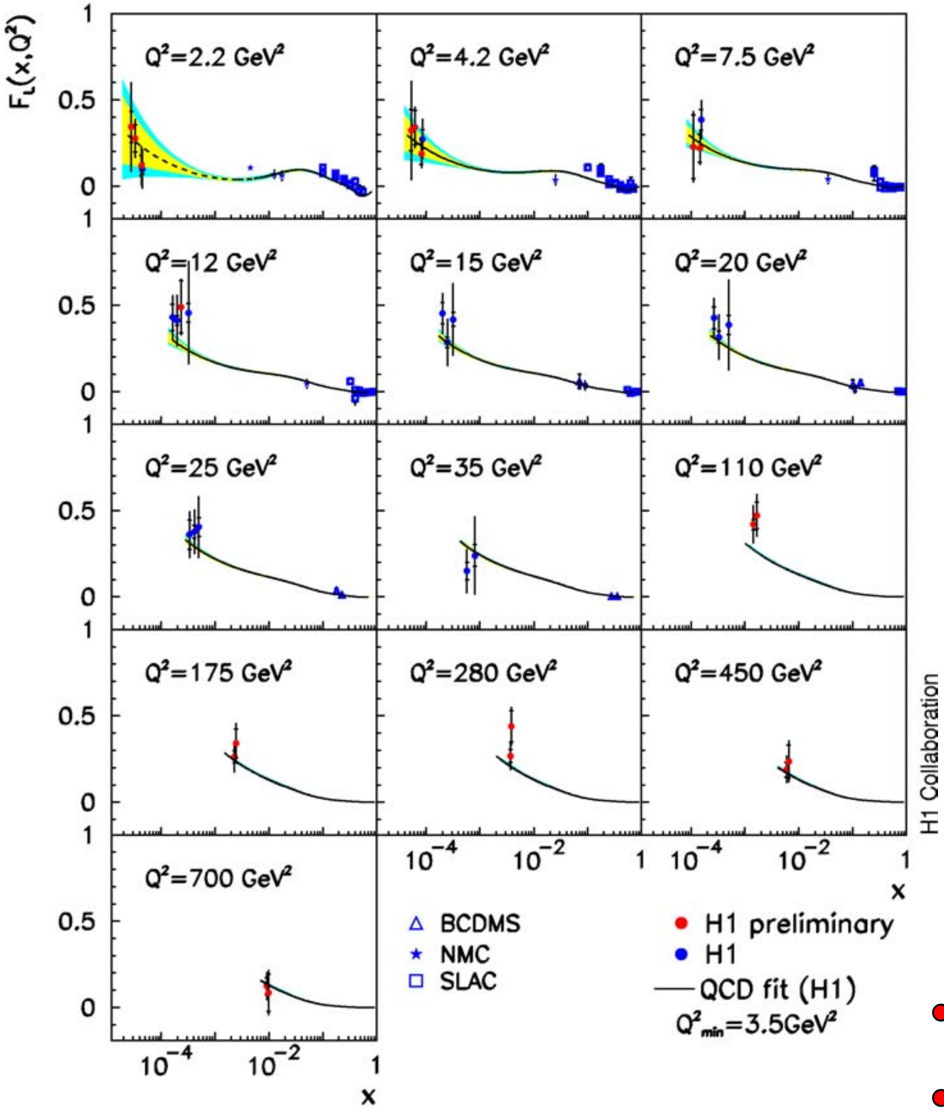
F_L important at high $y\ (= \mathrm{low}\ x)$

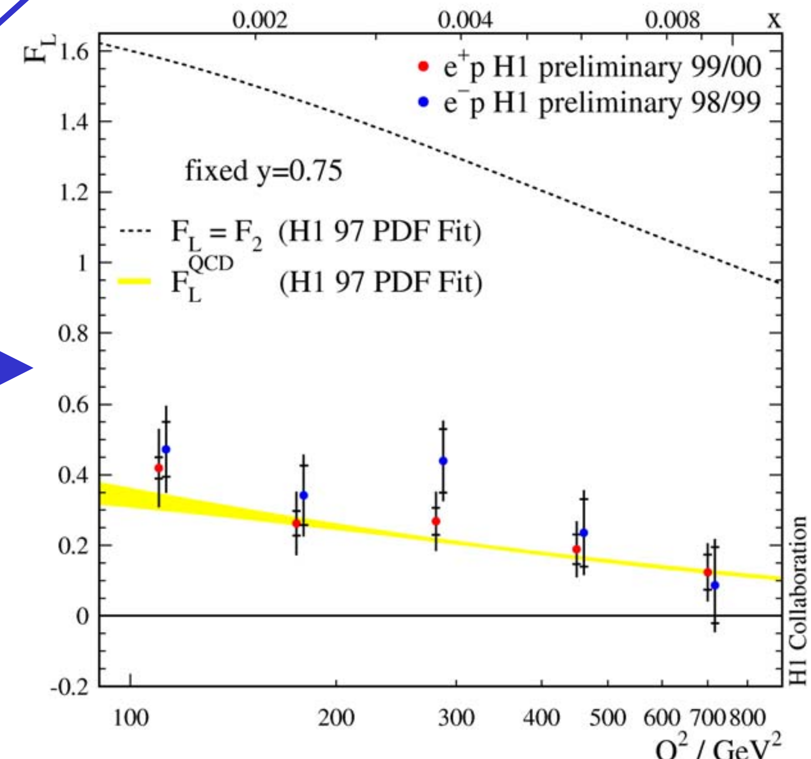
„Subtraction method"

Longitudinal Structure Function (cont.)

„derivative method“ $\left(\frac{\partial\tilde{\sigma}}{\partial \ln y}\right)_{Q^2}$

„subtraction method“





- extension of F_L to much lower x
- consistent with QCD

QCD Analyses

Very precise measurements of F_2 provided by ZEUS and H1

Clear scaling violation observed, violation is driven by gluon emission

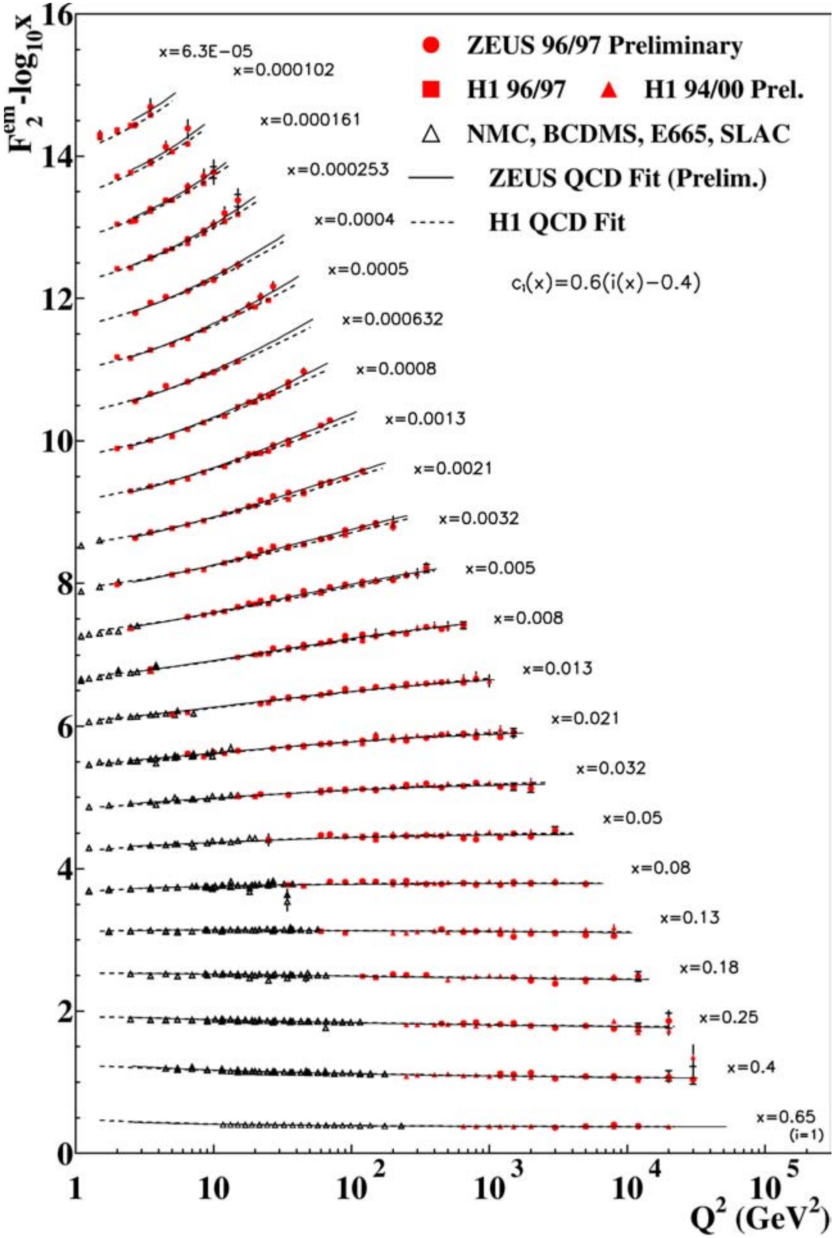
Describing this data in a QCD fit will give access to the gluon density within the proton

- Parameterize parton densities

$$xq(x,Q_0) = Ax^B(1-x)^C\left[1 + D\sqrt{x} + Ex\right]$$

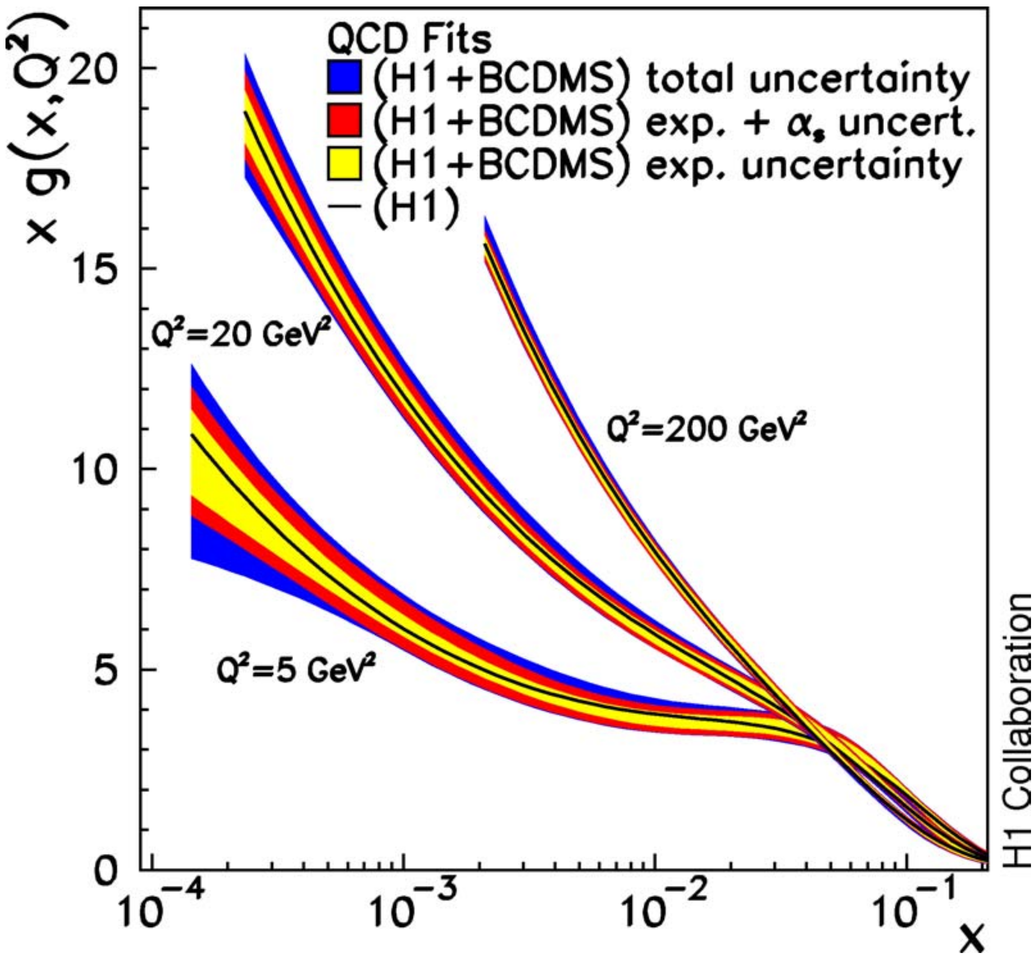
- Fit data to obtain the various parameters (e.g. H1 uses 16 including α_S)

Data are very well described by QCD



Gluon density and the strong coupling constant

Example: NLO QCD fit by H1



- Gluon density is rising at low x
- Resulting value for α_s

$$\alpha_s(M_Z) = 0.1150$$

$$\pm 0.0017(\text{exp}) \pm^{0.0009}_{0.0005} (\text{"model"})$$

- Theoretical uncertainties (renormalization and factorization scales) are rather large:

$$0.005$$

Need NNLO !

Strong Coupling Constant from Jets

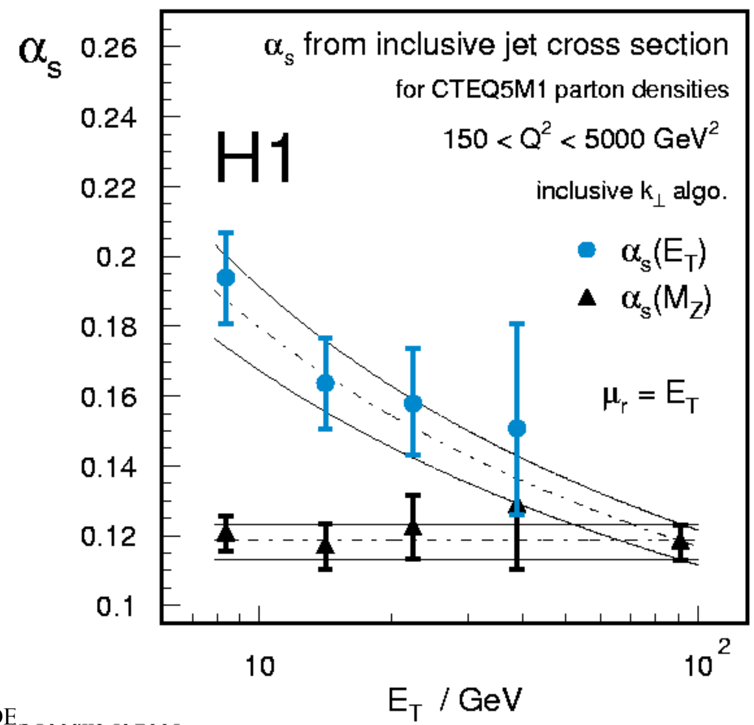
- In QCD, the strong coupling constant is „running“
- unique possibility to test this feature in a single experiment (large Q^2 range)

Theoretical errors similar to exp.

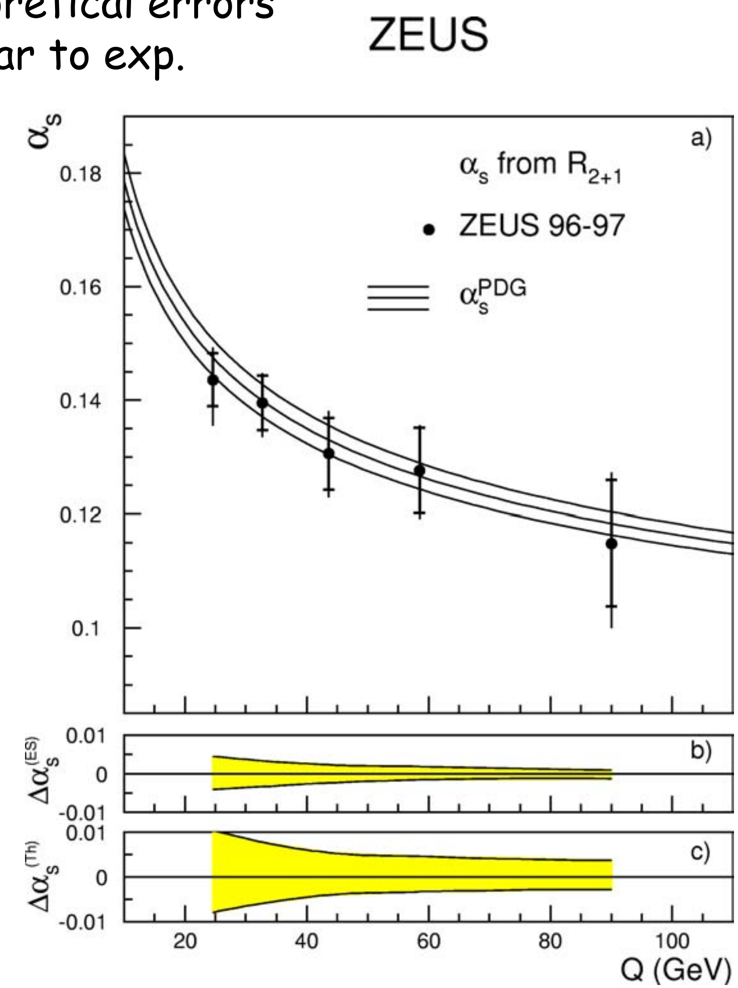
H1: $\alpha_s(M_Z) = 0.1186 \pm 0.0030(\mathrm{exp})$

ZEUS: $\alpha_s(M_Z) = 0.1166 \pm 0.0019(\mathrm{stat}) \pm^{0.0024}_{0.0033}(\mathrm{exp.})$

From jet cross sections

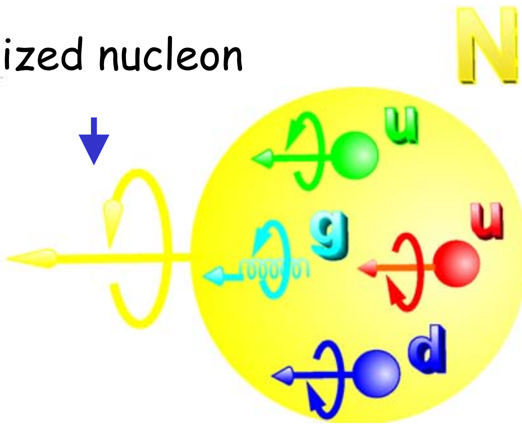


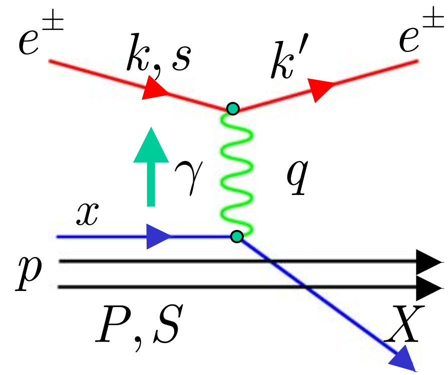
From jet rates



What makes the Proton spin ?

polarized nucleon





In DIS: determine number densities of quarks and anti-quarks

the players:
- spin 1/2 quarks and antiquarks
- spin 1 gluons

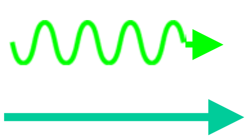
$$\Delta\Sigma = \Delta u + \Delta\bar{u} + \Delta d + \Delta\bar{d} + \Delta s + \Delta\bar{s}$$

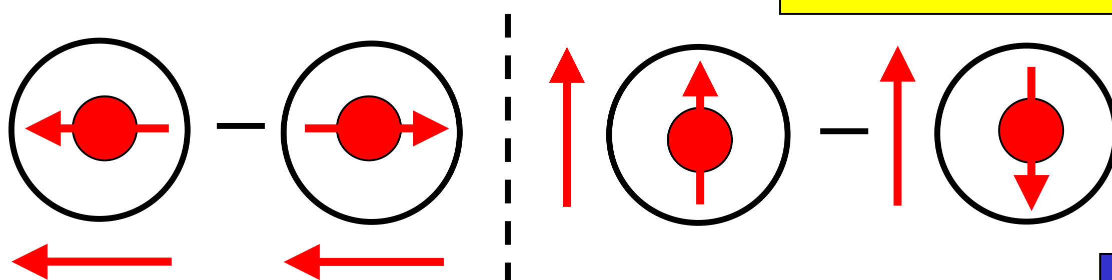
Sum rule

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L_q + L_G$$

How to probe the spin direction of quarks:

polarized photon





$q_i^+(x)$ $q_i^-(x)$ $q_i^\uparrow(x)$ $q_i^\downarrow(x)$

quark helicity

$$\Delta q_i(x) = q_i^+(x) - q_i^-(x)$$

quark transversity

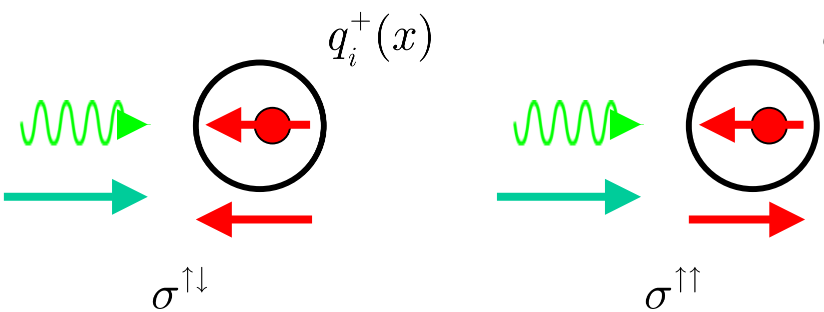
$$\delta q_i(x) = q_i^\uparrow(x) - q_i^\downarrow(x)$$

DIS as a Probe of the Nucleon Spin Structure

In analogy to the structure function F_1
define $g_1(x)$

$$g_1(x) = \frac{1}{2}\sum_i e_i^2(\Delta q_i(x) + \Delta \bar{q}_i(x))$$

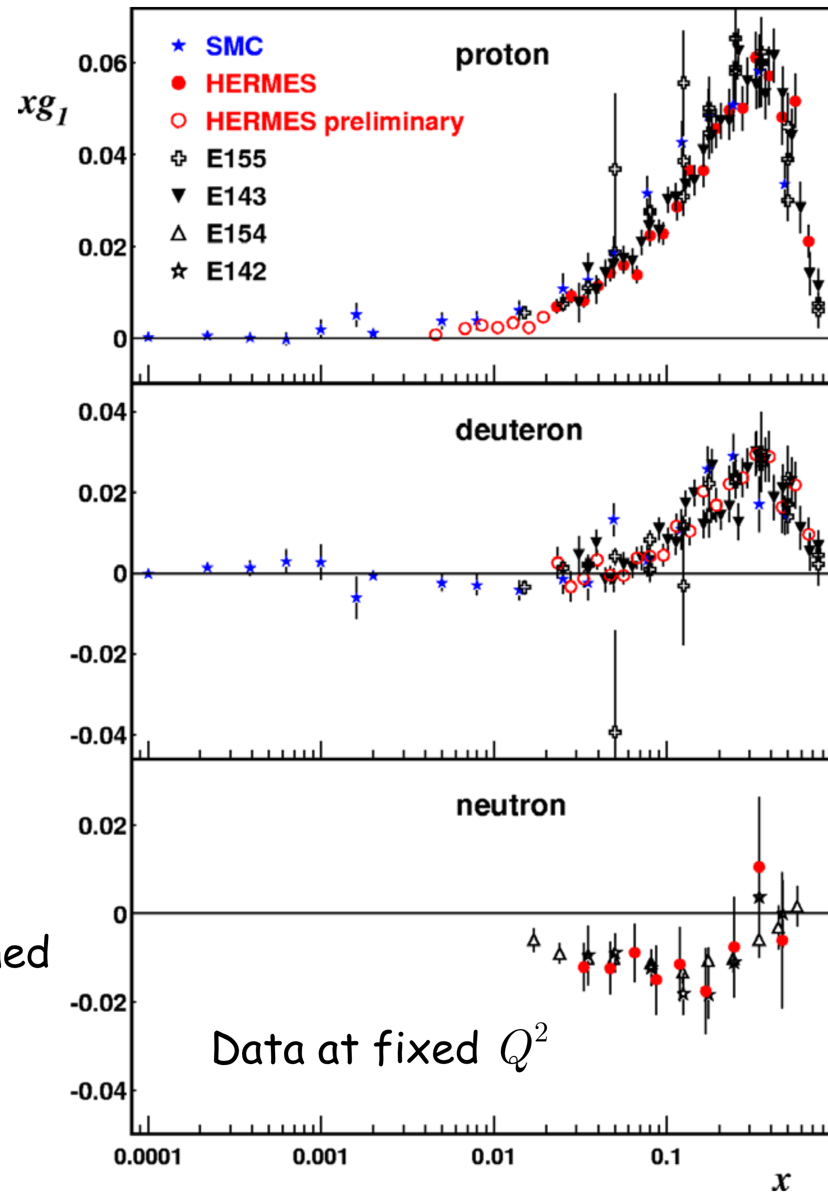
Inclusive Spin Asymmetries:



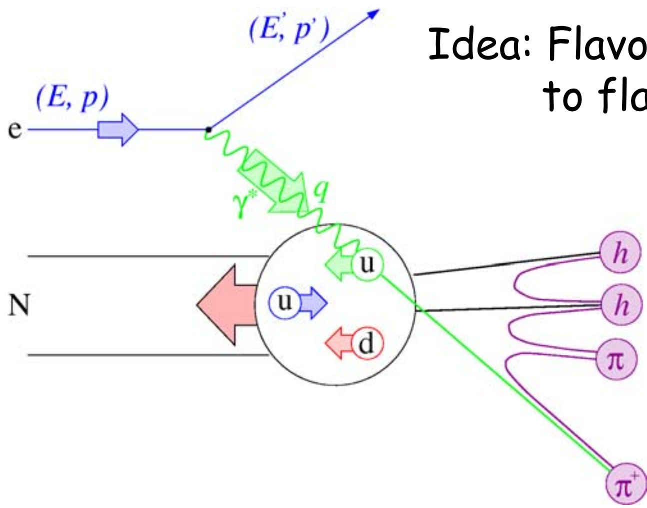
$$A_{\|}(x,Q^2) = \frac{\sigma^{\uparrow\downarrow} - \sigma^{\uparrow\uparrow}}{\sigma^{\uparrow\downarrow} - \sigma^{\uparrow\uparrow}} \approx \frac{g_1(x,Q^2)}{F_1(x,Q^2)}$$

Via Q^2 evolution $\Delta\Sigma\,(\Delta G)$ could be determined in principle.

But: no full flavor decomposition in incl. DIS



Individual Quark Flavors: Semi-Inclusive DIS



Idea: Flavor of leading hadron related to flavor of struck quark

Fragmentation function D_i^h

Caveat:

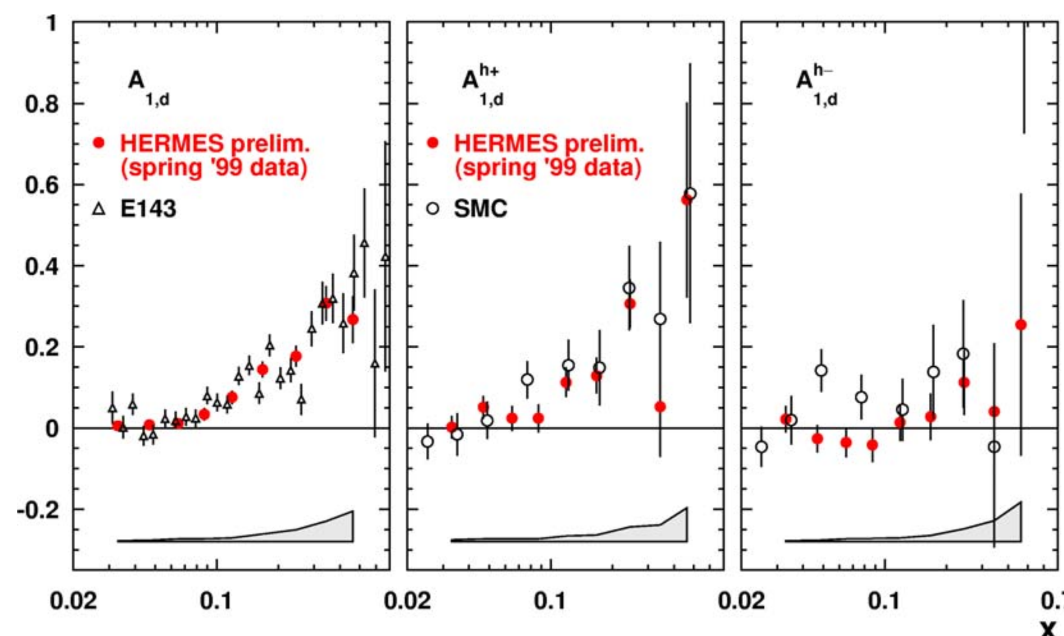
Since leading hadron is taken, there is no sensitivity to sea: Need symmetry assumptions on the sea:

$$\Delta q_s \equiv \Delta u_s = \Delta \bar{u} = \ldots = \Delta \bar{s}$$

$$A_{\parallel}^h(x,Q^2) = \frac{N^{\uparrow\downarrow} - N^{\uparrow\uparrow}}{N^{\uparrow\downarrow} - N^{\uparrow\uparrow}}$$

$$\approx \sum_i \left(\frac{e_i^2 q_i(x) \int D_i^h(z)dz}{\sum_j e_j^2 q_j(x) \int D_j^h(z)dz} \right) \frac{\Delta q_i(x)}{q_i(x)}$$

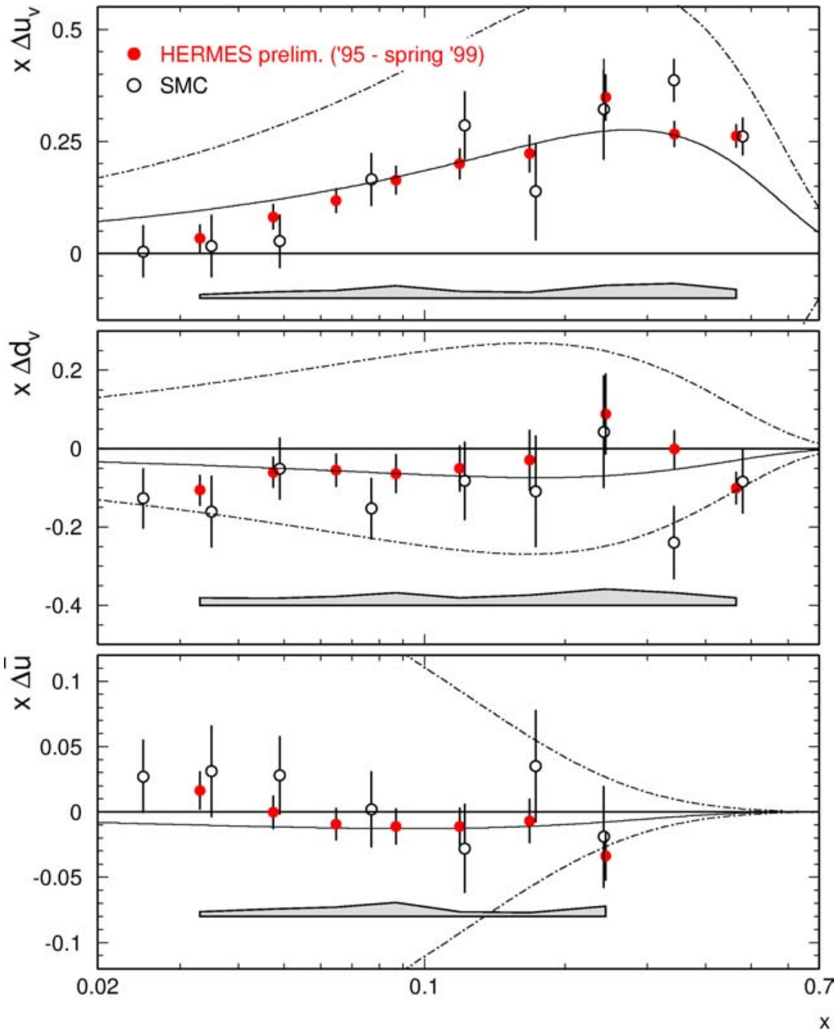
„purity" : probability that hadron h orignates from quark i



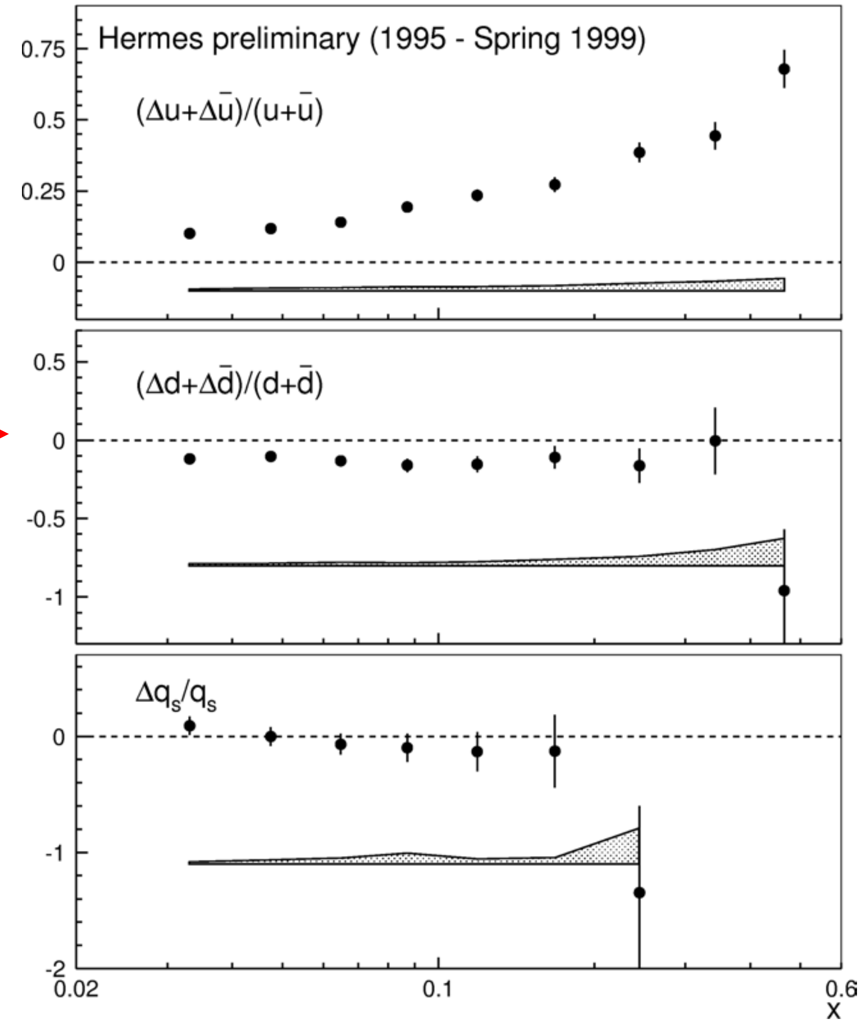
Example of recent measurements (on deuterium)

Semi-Inclusive DIS (cont.)

Results on valence quarks and sea (using p, He, D)

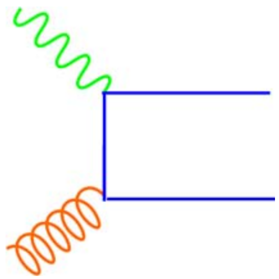


Resulting flavor decomposition



What about the Gluon ?

Direct way to measure the gluon contribution:
Photon-gluon fusion

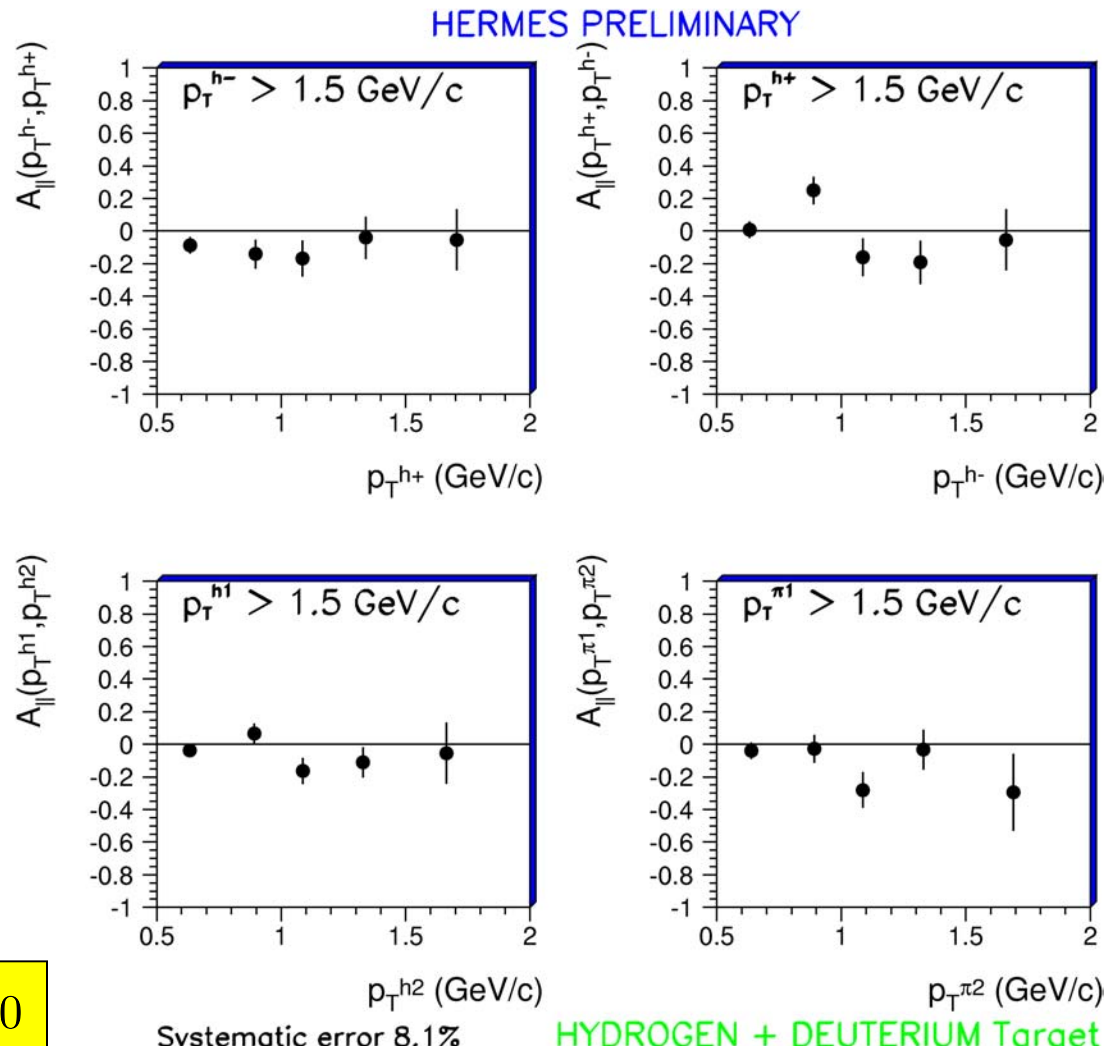


Identification of PGF:
pairs of oppositely charged particles with high p_T
(enrich sample with charm events)

$$A_{\parallel}^{h}(x,Q^2) = \frac{N_{P_T}^{\uparrow\downarrow} - N_{P_T}^{\uparrow\uparrow}}{N_{P_T}^{\uparrow\downarrow} + N_{P_T}^{\uparrow\uparrow}}$$

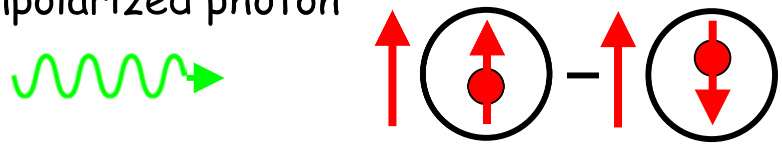
$$\sim -\frac{\Delta G(x,Q^2)}{G(x,Q^2)}$$

First indications that $\Delta G > 0$



Transversity

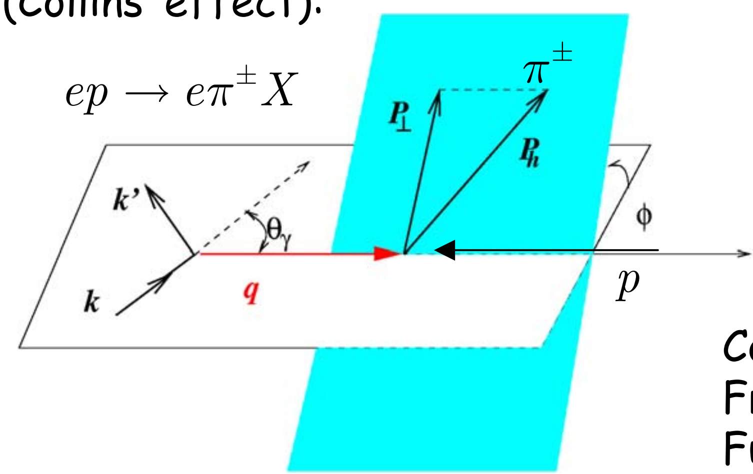
unpolarized photon



$$\delta q_i(x) = q_i^{\uparrow}(x) - q_i^{\downarrow}(x) \qquad q_i^{\uparrow}(x) \qquad q_i^{\downarrow}(x)$$

accessible via spin dependence of the azimuthal distribution of the leading pion (Collins' effect):

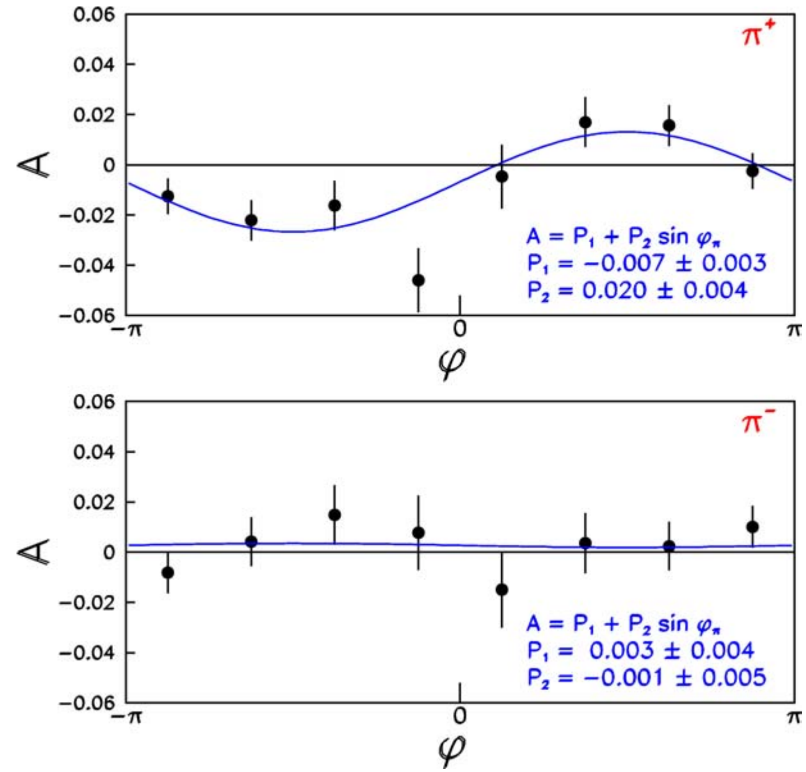
$$ep \rightarrow e\pi^{\pm} X$$



Collins Fragmentation Function

$$A_\perp^h \sim \frac{\langle \sin\phi_C (N^{\uparrow} - N^{\downarrow}) \rangle}{(N^{\uparrow} + N^{\downarrow})} \propto \frac{\sum_i e_i^2 \delta q_i(x) H_1^{\perp(1),i}(z)}{\sum_i e_i^2 q_i(x) D_i^h(z)}$$

Hermes measurement with long. pol. Target (also sensitive to Collins effect):



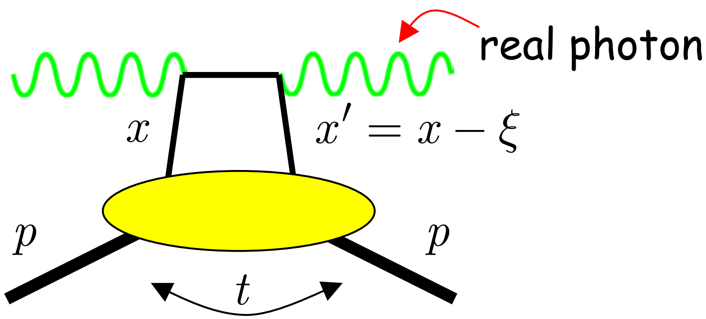
Measured asymmetries in agreement with Collins' prediction:
u-quark dominance in valence region

Last not Least: Orbital Angular Momentum

Recent theoretical development:

Skewed Parton Distributions offer unique way to access orbital momentum of the quarks

Cleanest reaction to test:
Deeply virtual Compton scattering (DVCS)



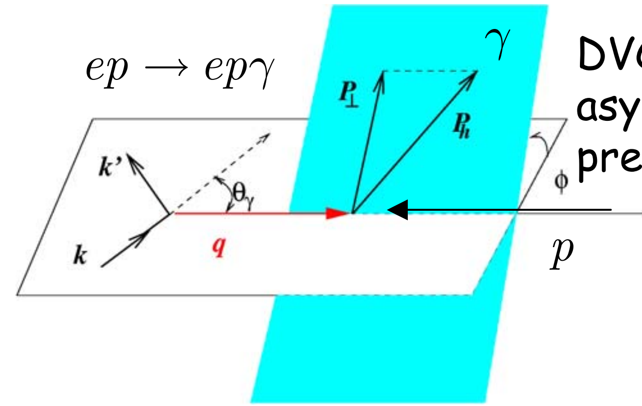
4 SPDF's per quark: $H(x,\xi,t), \tilde{H}, E, \tilde{E}$

In the limit $t, \xi \to 0$ („forward")

$$H_i(x,0,0) = q_i(x),\ \tilde{H}_i(x,0,0) = \Delta q_i(x)$$

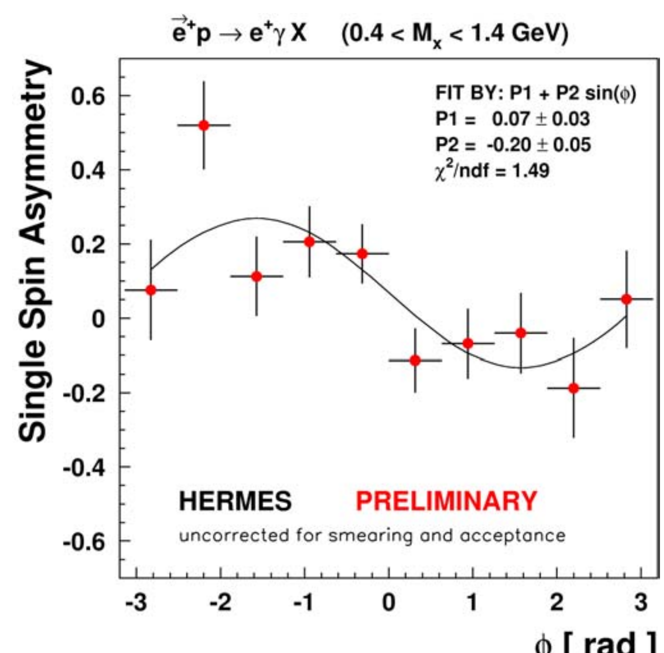
ang. mom. dens.

$$J_i(x) = \frac{x}{2}\left(H_i(x,0,0) + E_i(x,0,0)\right)$$



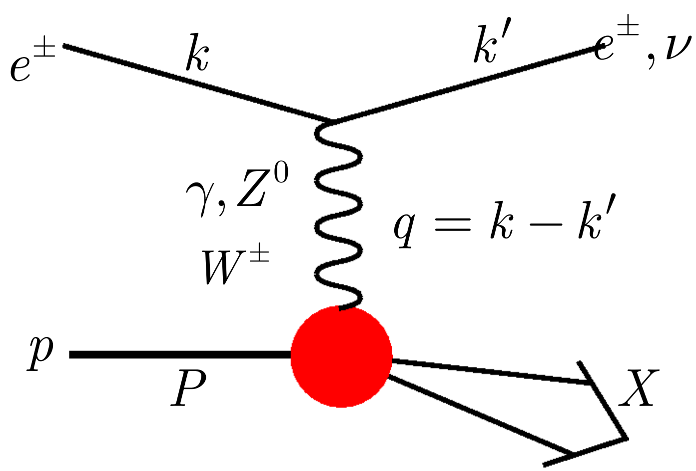
DVCS: asymmertry predicted

Polarized e on unpolarized p



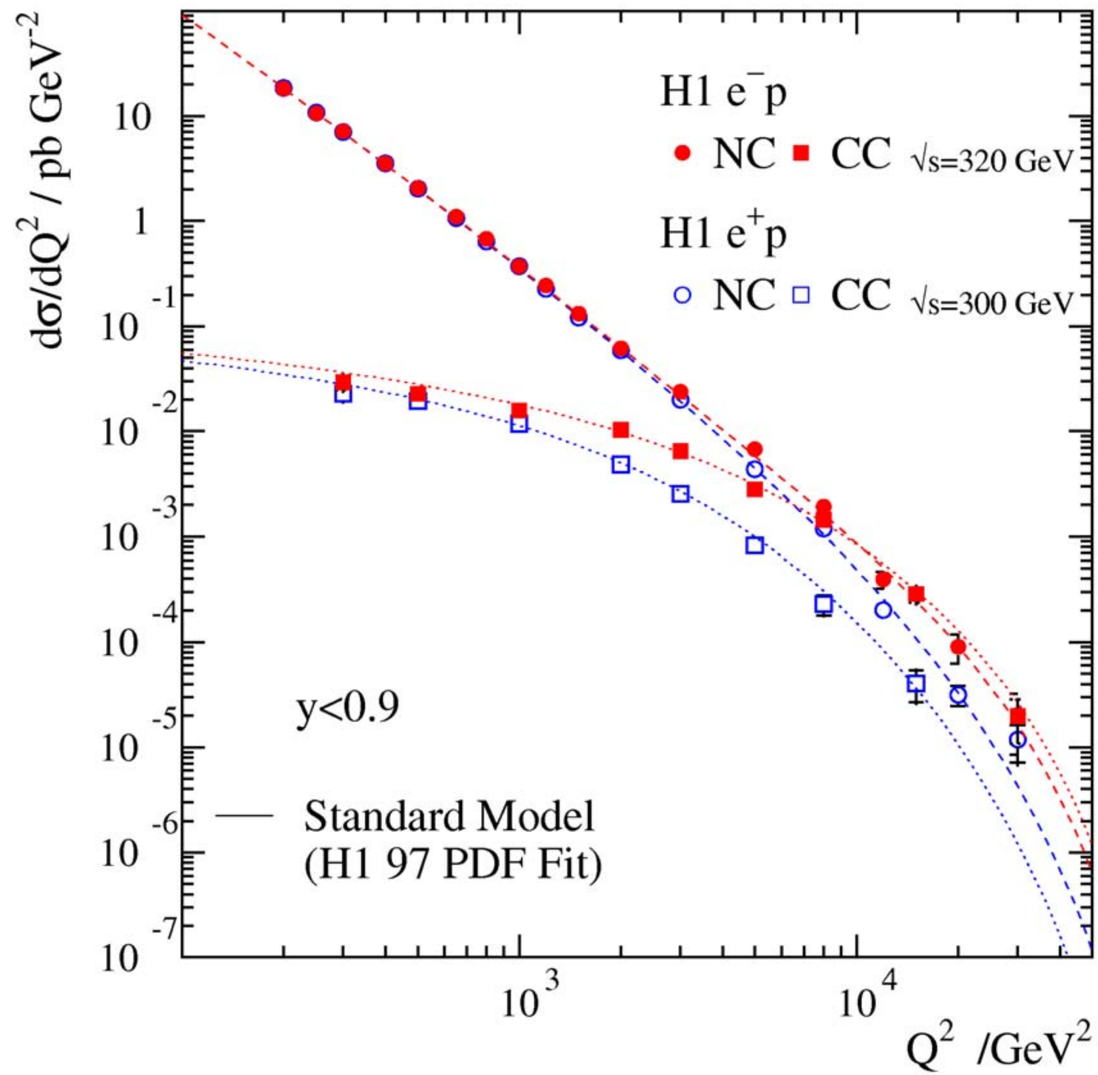
Electroweak Sector: Scattering at high Q^2

High $Q^2 \approx M_Z^2, M_W^2$

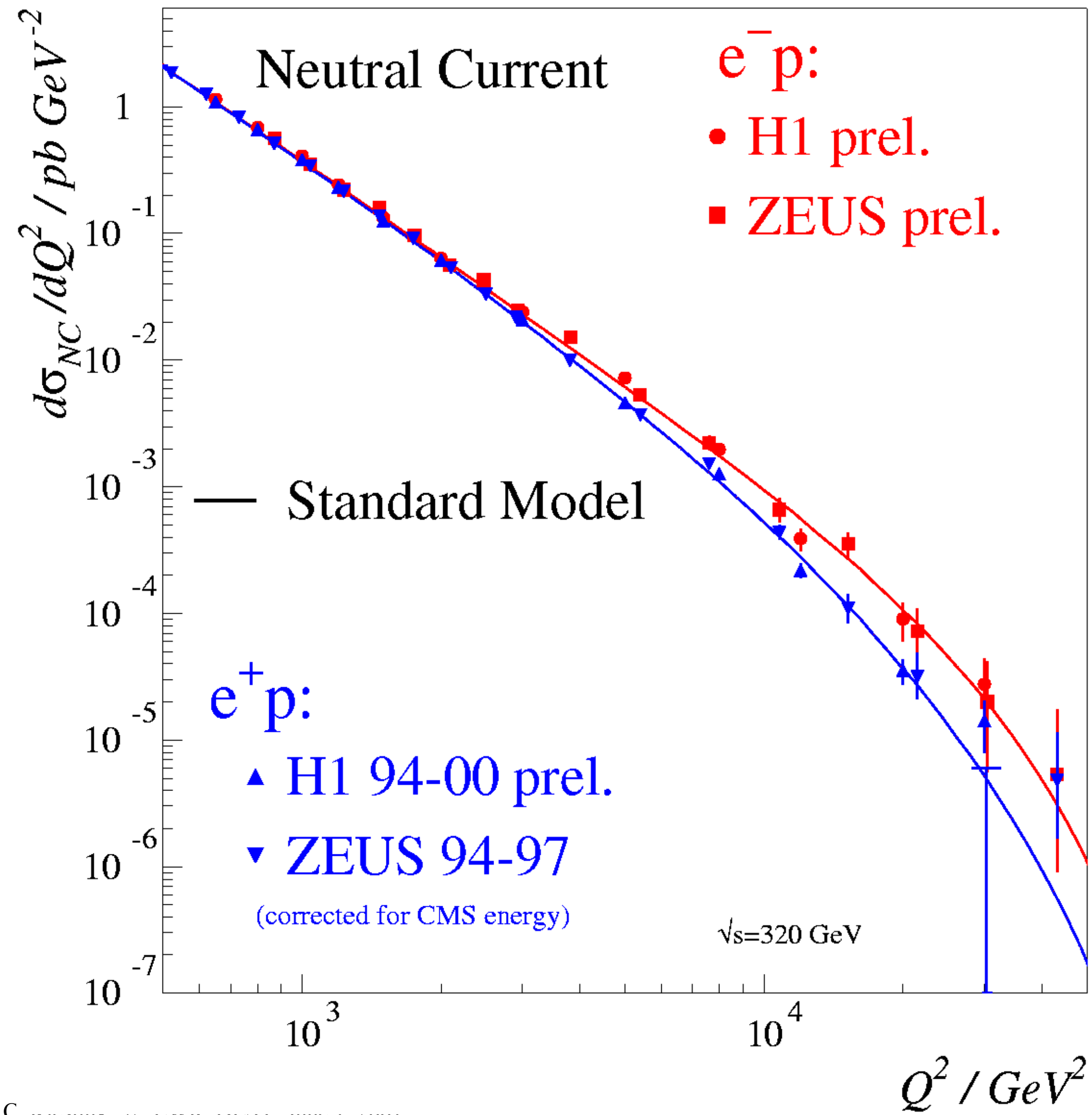


e^+ and e^- cross sections are different !

Unification of weak and electromagnetic forces



NC Cross Section at high Q^2 and xF_3



$$\tilde{\sigma}_{NC}(e^\pm p) \sim \tilde{F}_2 \mp \frac{Y_-}{Y_+} x\tilde{F}_3$$

$$Y_\pm = 1 \pm (1-y)^2$$

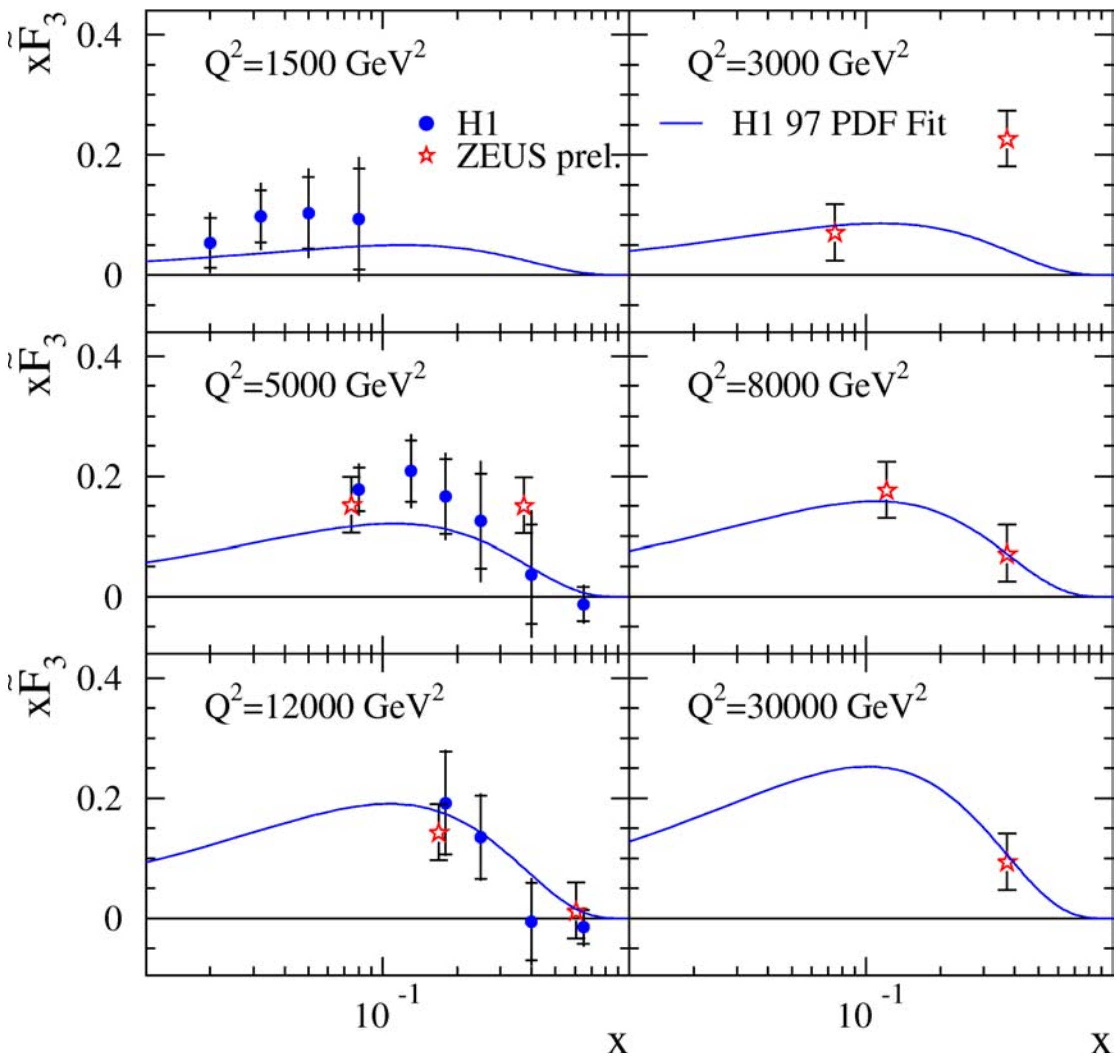
New structure function xF_3

$$xF_3(x,Q^2) = \sum_i e_i^2 \left(xq(x,Q^2) - x\bar{q}(x,Q^2)\right)$$

F_L can be safely neglected at high Q^2

Difference between $e^\pm p$ is due to γZ interference

Extraction of xF_3



First measurements of xF_3 on protons

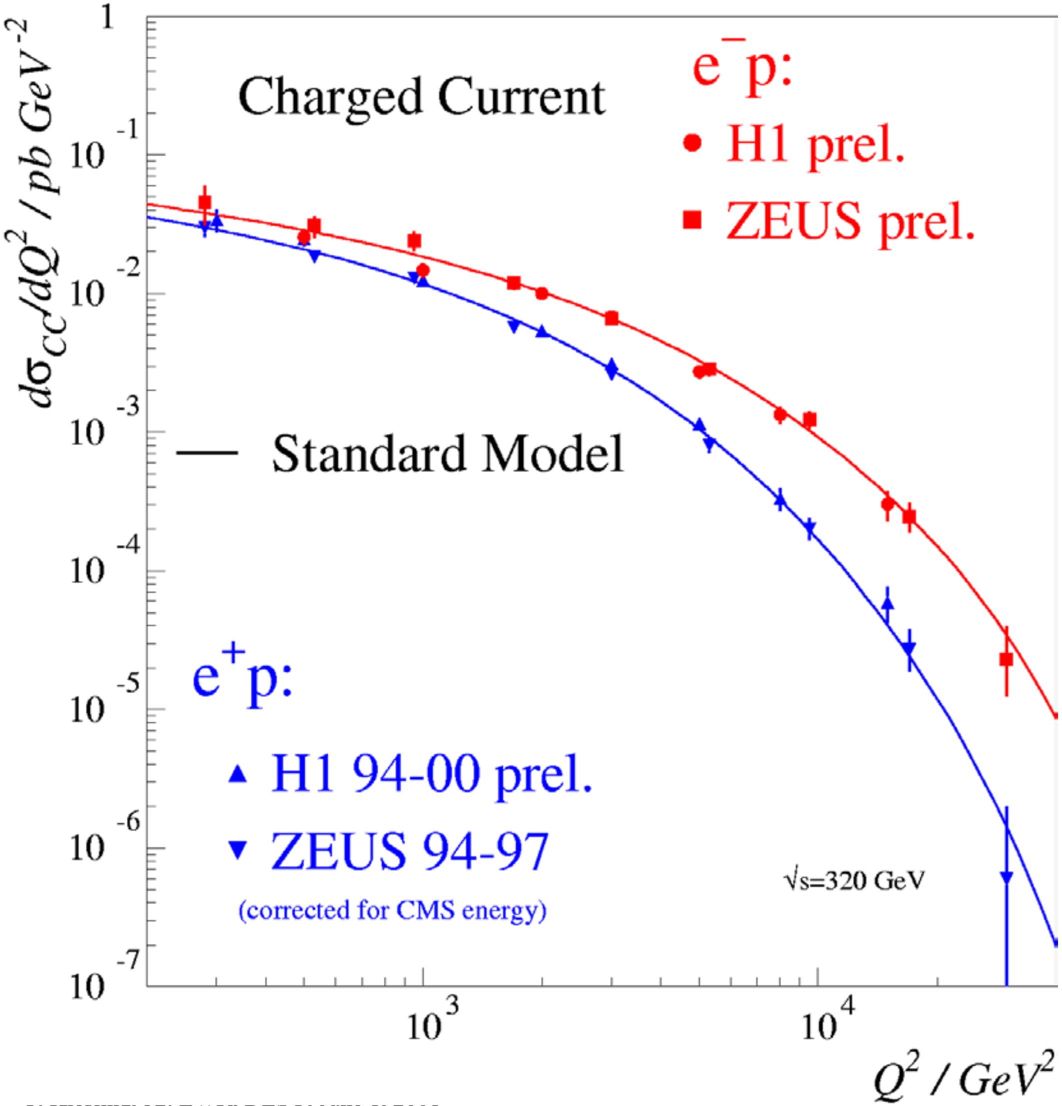
Agrees with PDF's evolved from lower Q^2

Still statistics limited

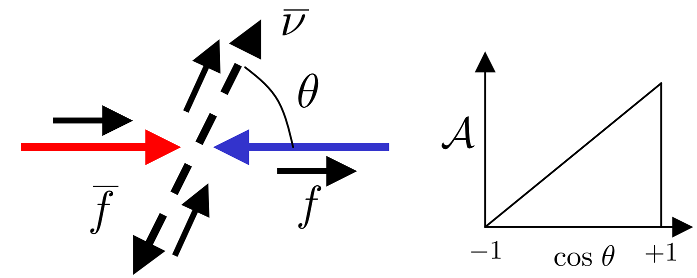
→ HERA II

CC Cross Section at high Q^2 and the valence quarks

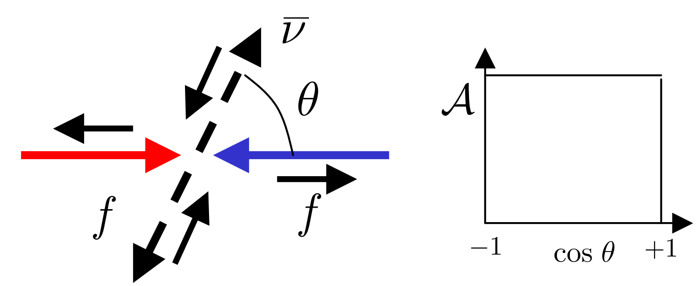
$$ep \rightarrow \nu X$$



$$\sigma_{CC}(e^+p) \sim \left(\frac{M_W^2}{M_W^2 + Q^2}\right)^2 \left[(1-y)^2 (d+s) + (\bar{u}+\bar{c})\right]$$



$$\sigma_{CC}(e^-p) \sim \left(\frac{M_W^2}{M_W^2 + Q^2}\right)^2 \left[(1-y)^2 (\bar{d}+\bar{s}) + (u+c)\right]$$



Valence Quark Densities from HERA

At low x the sea is dominating

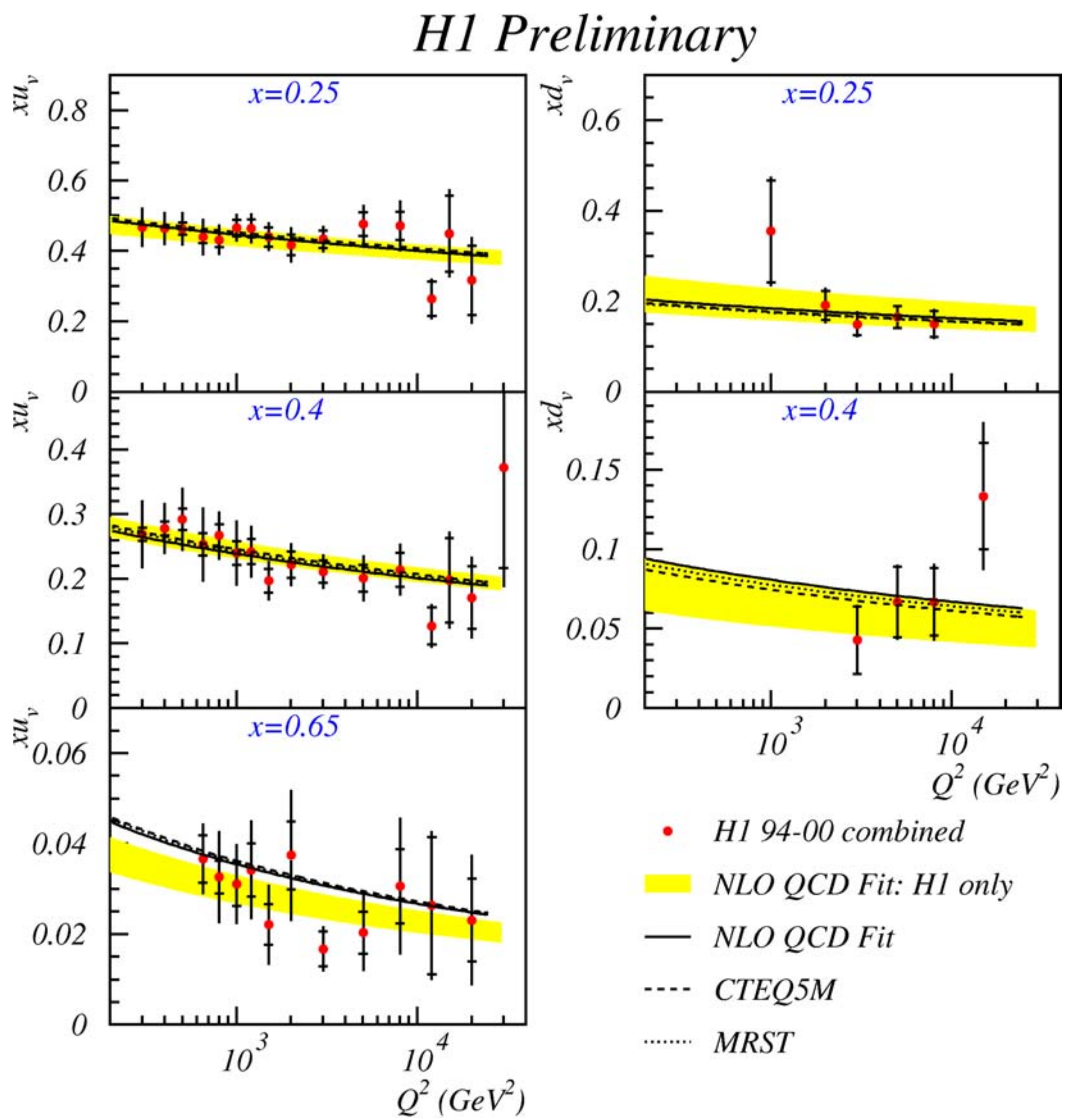
→ $\sigma_{CC}(e^+p) \approx \sigma_{CC}(e^-p)$

At high x mostly d in $\sigma_{CC}(e^+p)$

mostly u in $\sigma_{CC}(e^-p)$

→ Valence quark distributions can be extracted with minimal corrections from QCD fits

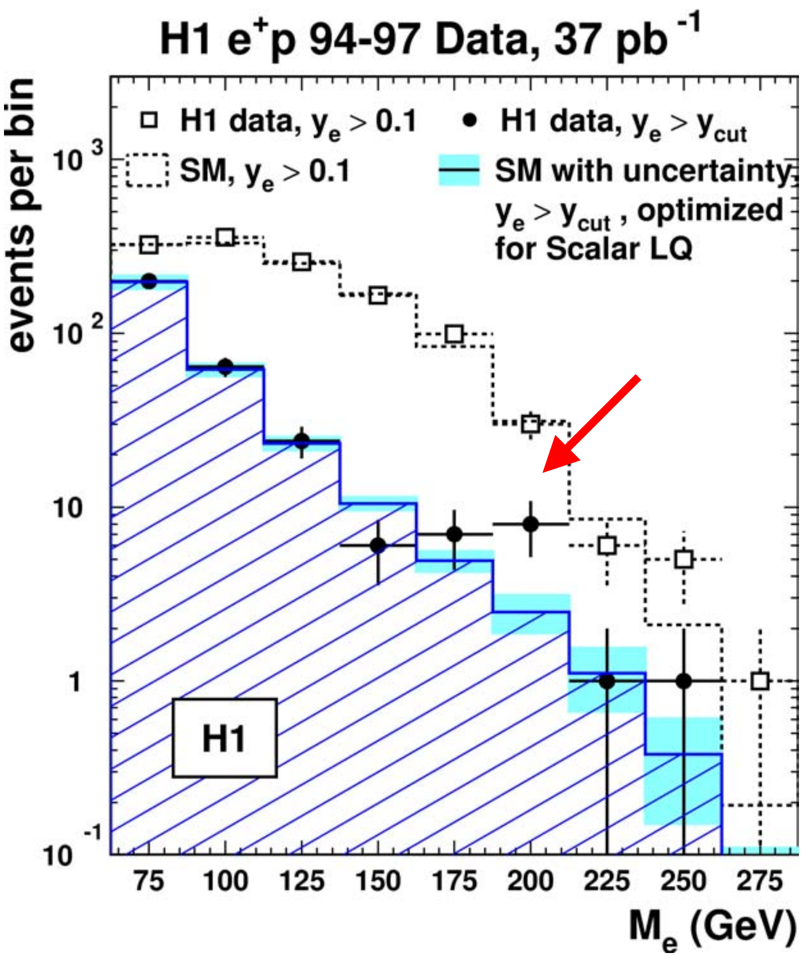
→ Measurements agree well with PDF's evolved from lower Q^2

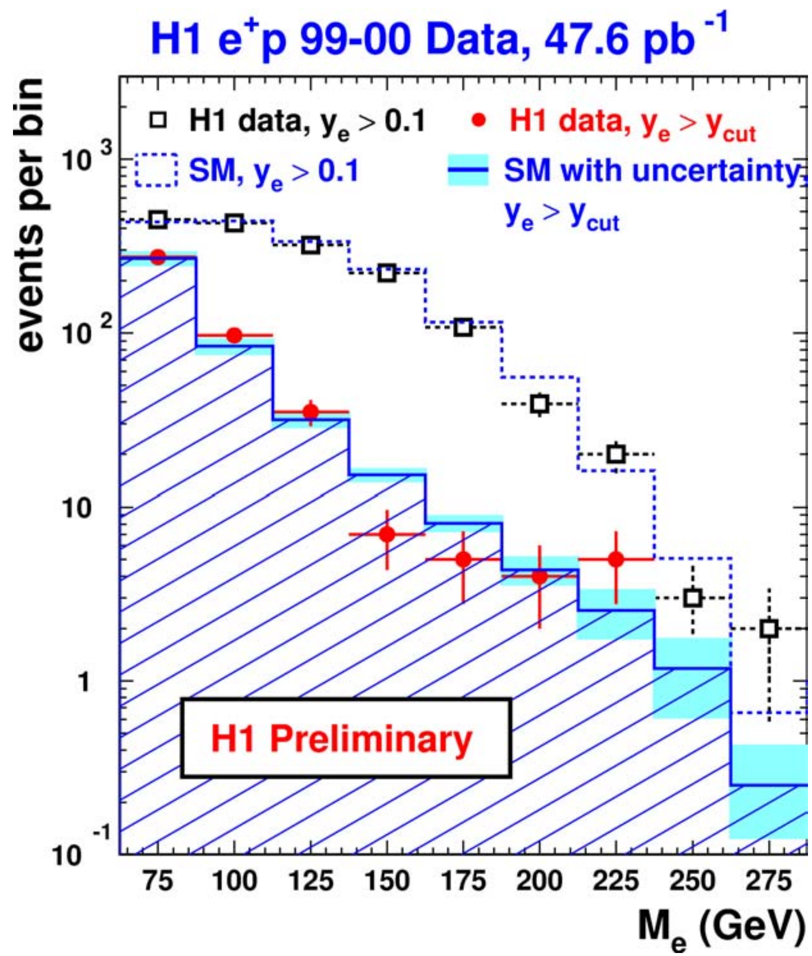


Beyond the Standard Model

High mass excess in the old H1 data
(invariant mass of electron-quark system)

New data do not confirm the effect



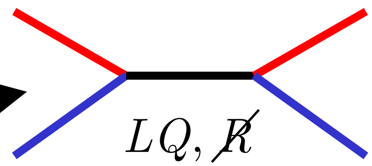


Searches for New Physics

General strategy:

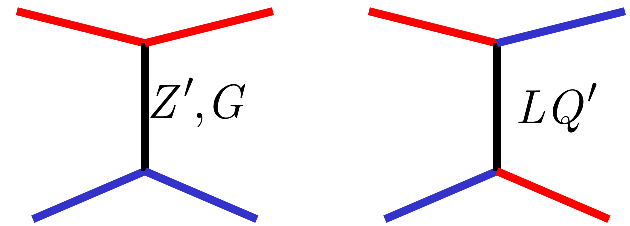
Direct searches

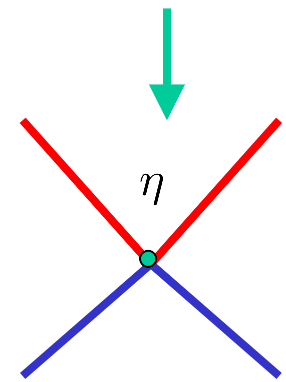
Look for „bumps" in mass spectra



$$M \leq \sqrt{s}$$

Indirect searches





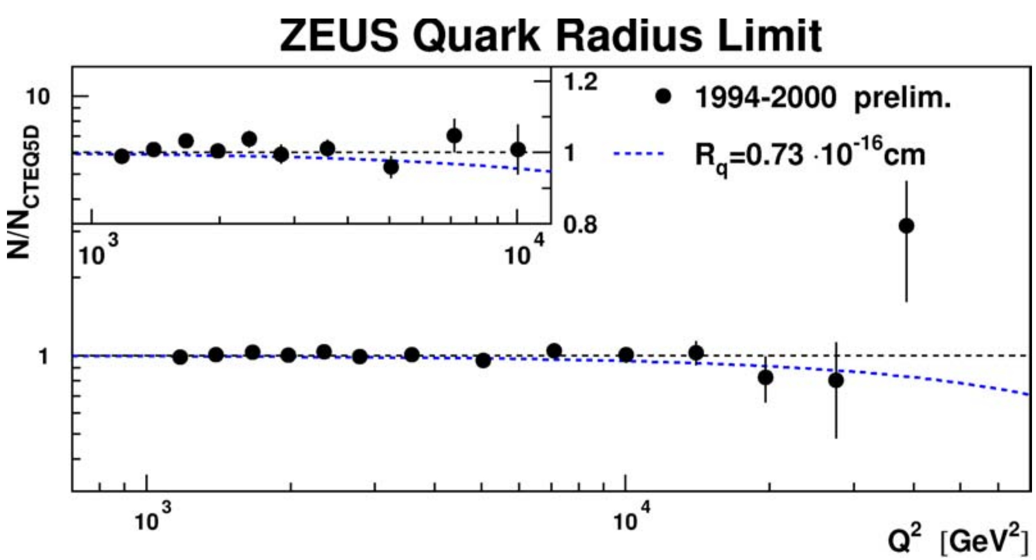
„Contact interactions"

$$\eta \approx \frac{4\pi}{M^2}$$

Look for deviations in the differential cross sections from Standard Model

Quark form factor:

$$\frac{d\sigma}{dQ^2} = \frac{d\sigma^{SM}}{dQ^2}\left(1 - \frac{R_q^2}{6} Q^2\right)^2$$



No signal found , yet

Future Physics at HERA II

The Standard Model (electroweak, QCD) seems firmly established and supported by the data, why do we want to continue?

The Standard Model is certainly incomplete:

- too many free parameters (e.g. particle masses)
- no clue how to solve the non-perturbative sector
- and many other reasons .....

HERA is the world's leading QCD machine and will strongly improve:

- Instantaneous luminosity will increase by a factor of 5
- Expect 1000 pb^{-1} until 2005
- Polarization of the electron/positron beams (> 50 % after 1 hour)
- Precision measurements of the polarization (bunch per bunch)

Future Physics at HERA II (cont.)

Some physics topics (and experimental implications) to address:

- Gluon density:

  Very little information from direct determinations, such as boson-gluon fusion (heavy quarks), exclusive final states $(J/\psi, \Upsilon)$

- QCD evolution:

  Forward jets, DGLAP vs BFKL

- Diffraction:

  Separation of diffractive systems from intact proton

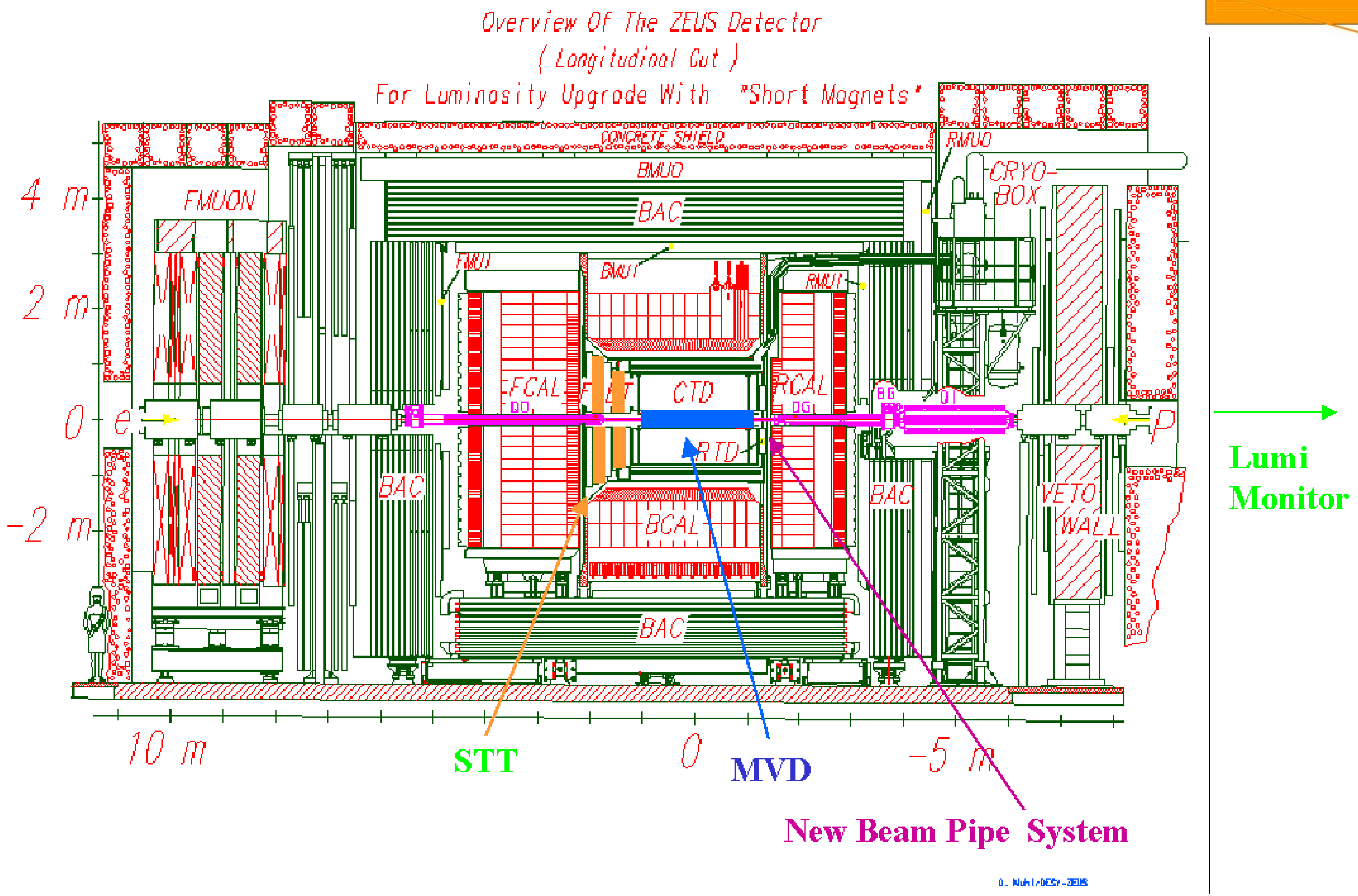
- High Q^2

  Particles will populate the forward region of detectors

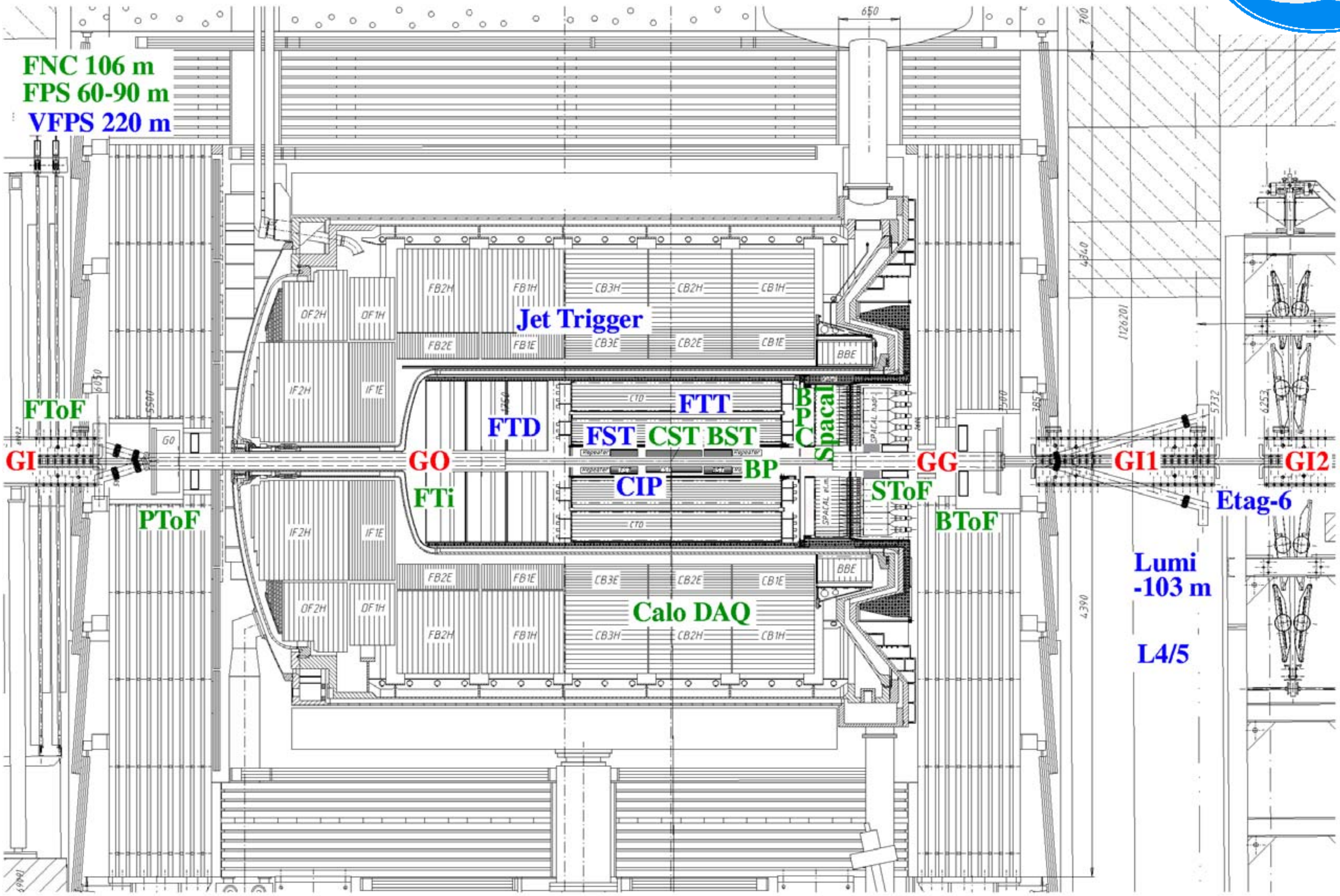
Adequate Upgrade of the detectors needed

Bending magnets close to IR !

Detector Upgrades for HERA II



Detector Upgrades for HERA II



Polarization at HERA II

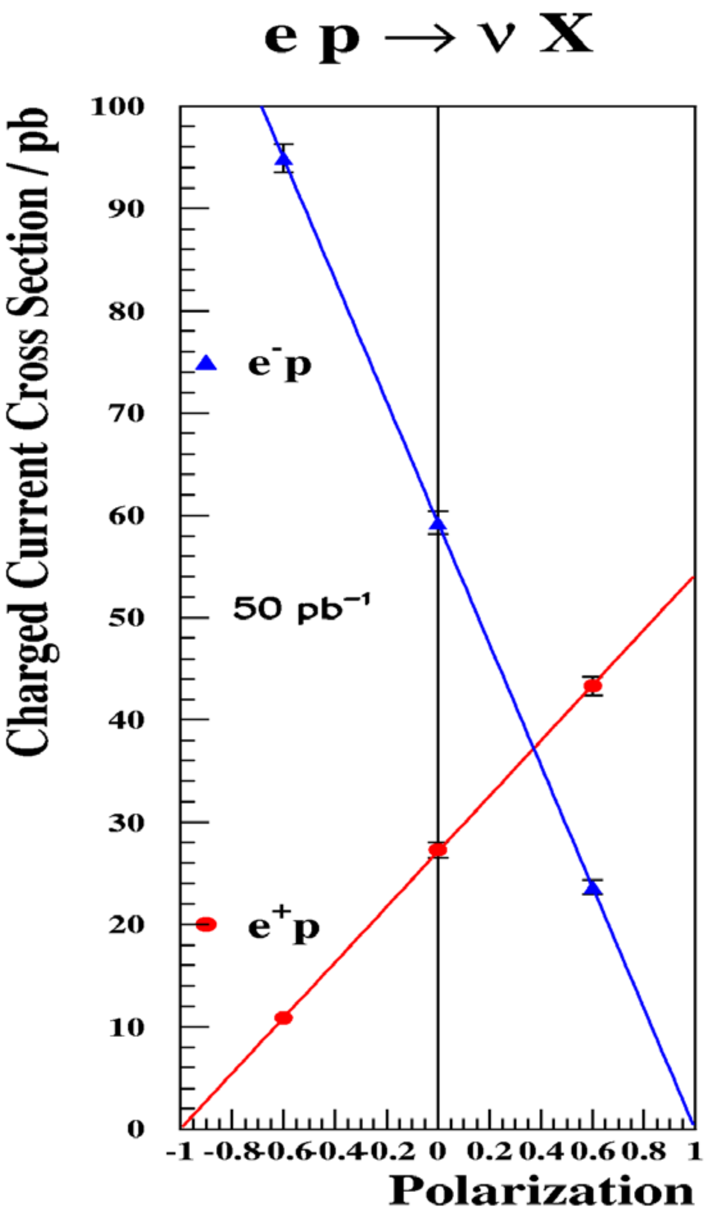
Accurate measurement of polarization,
shared by the two collider experiments:

TPOL by ZEUS, LPOL by H1

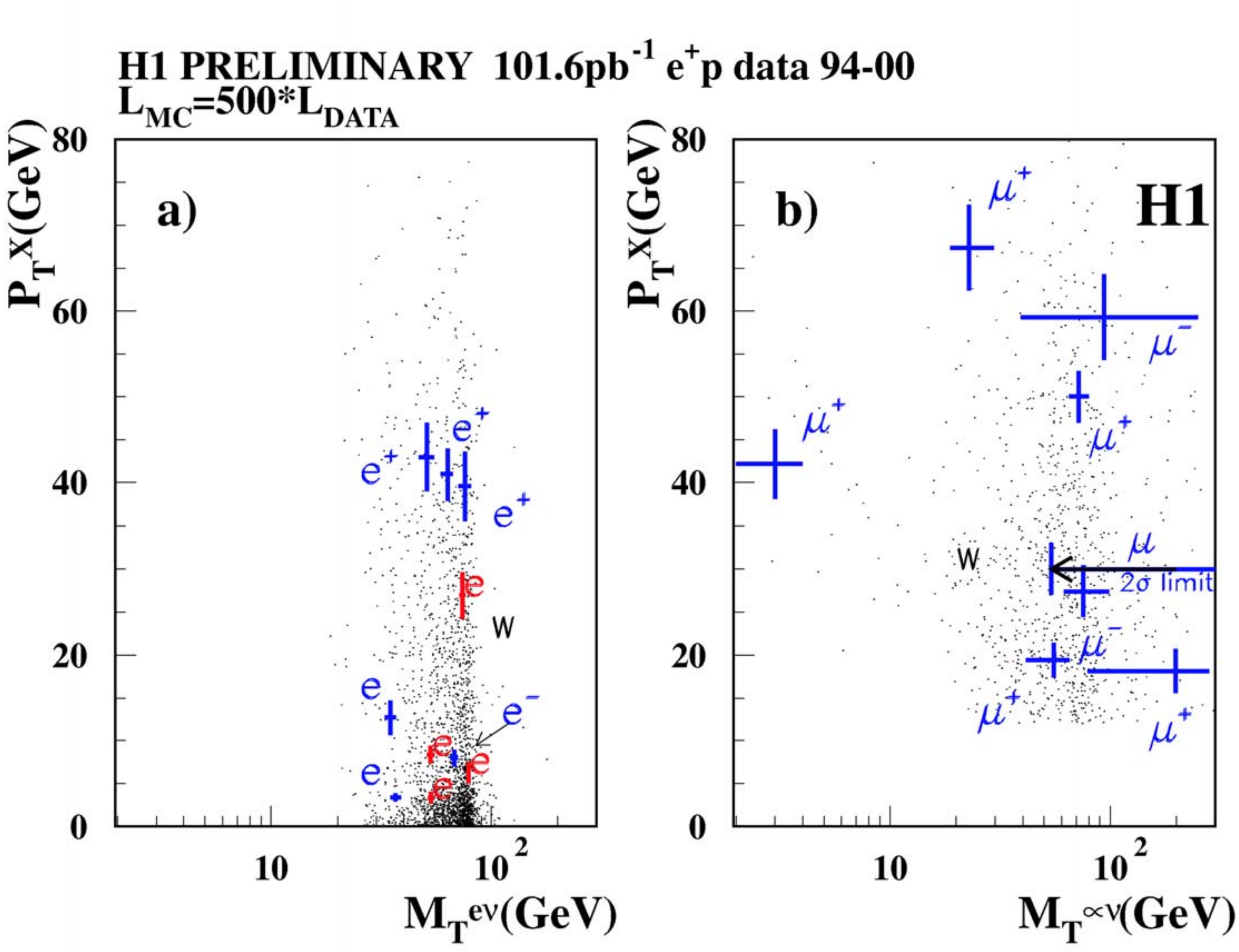
Exciting prospect of a vanishing
CC Cross Section

If New Physics is found, polarisation strongly helps to disentangle and discriminate the source

Typical limits > 400 GeV (right-handed currents)



Watch out for the Unexpected ...



Conclusions

HERA I has produced a wealth of exciting physics, e.g.

- Proton Structure: Strong rise of F_2 , central role of the gluon
- Partonic content of the (virtual) photon
- Deepened insight into diffractive processes (colorless exchange)
- Manifest Electroweak Unification

HERA II offers exciting prospects

- 1000 pb^{-1} (instantaneous luminosity increase by factor 5)
- Polarized electrons and positrons

Experiments are completing major upgrades of their detectors

- Improved hadronic final state detection (heavy quarks, forward jets etc.)
- Improved triggers for better selectivity (rare / exclusive reactions)

H1 ZEUS hermes are looking forward ...