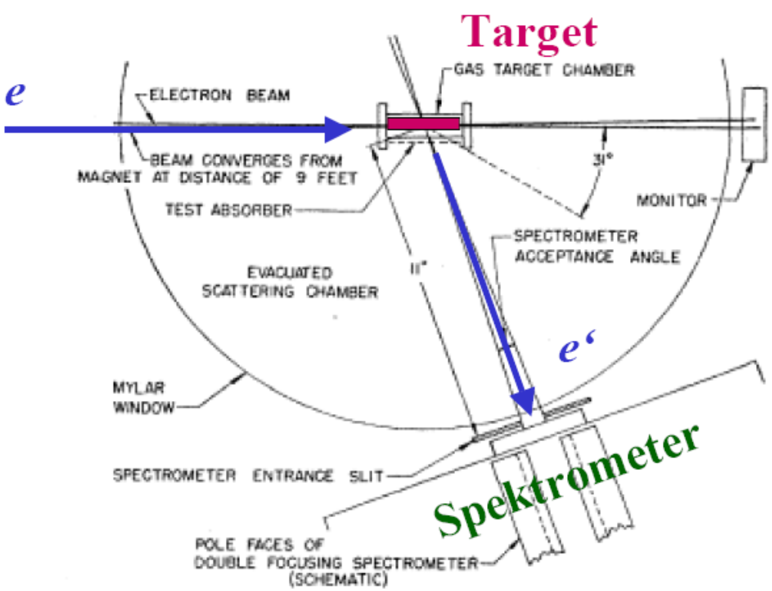
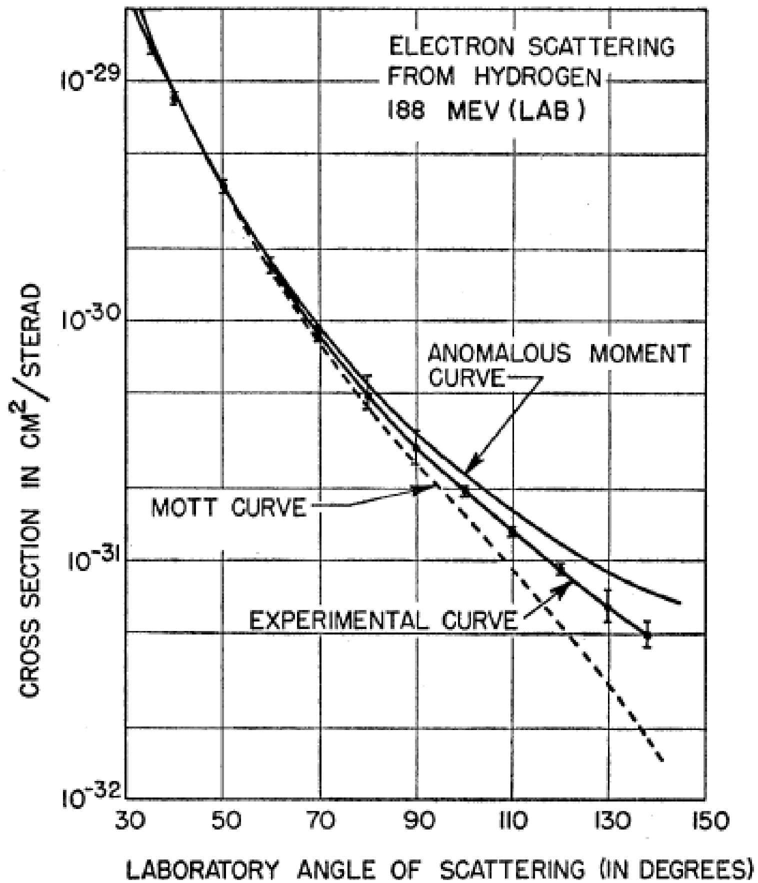
Neutral Current Measurements at High Q^2 in the H1 Experiment at HERA

S.Shushkevich, MPIM

ep scattering @ 200 MeV

- Hofstadter and McAllister, LINAC Stanford, 1955
- 100 - 250 MeV e^- beams, protons at rest
- Elastic scattering
- Magnetic spectrometer
- Measurement of scattering angle and energy of electron



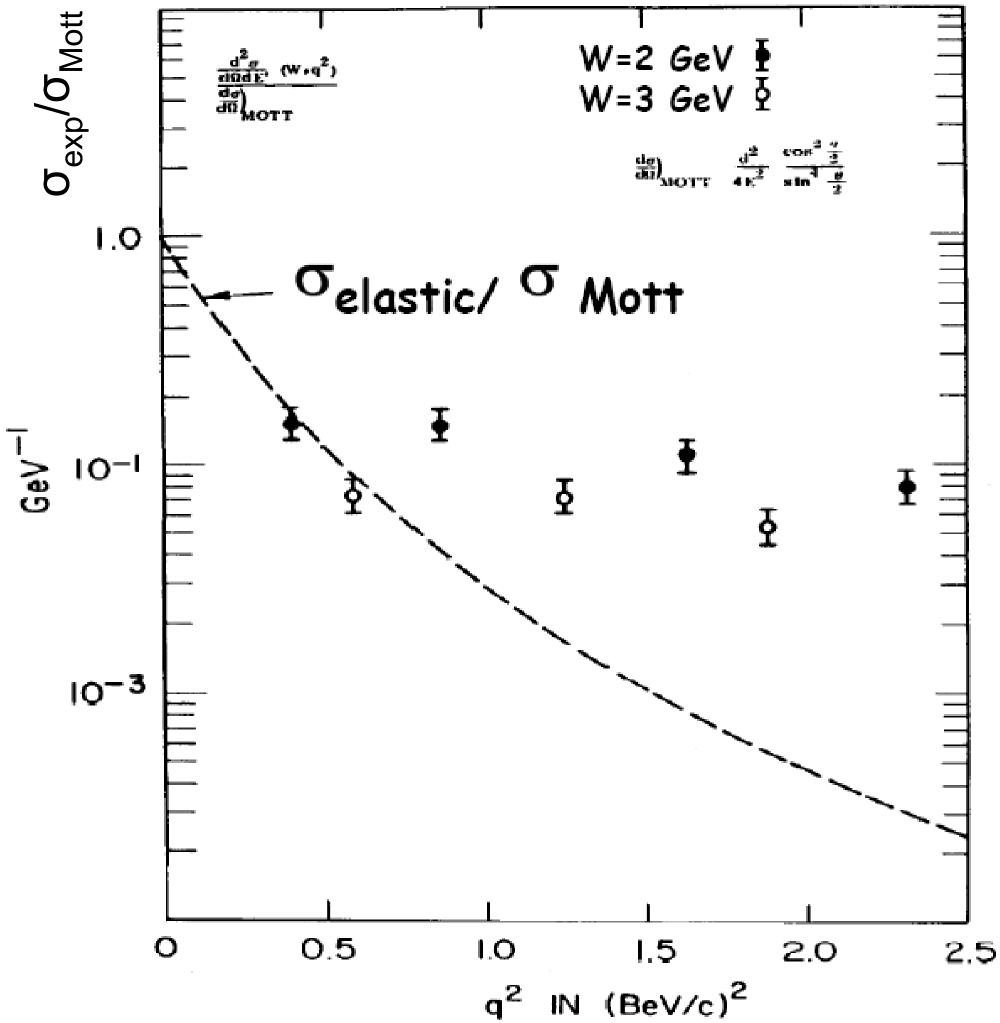


Mott curve (point-like particles) doesn't describe the measurements

Proton has structure !

Empiric dipole form-factor fits well

QPM @ 20 GeV



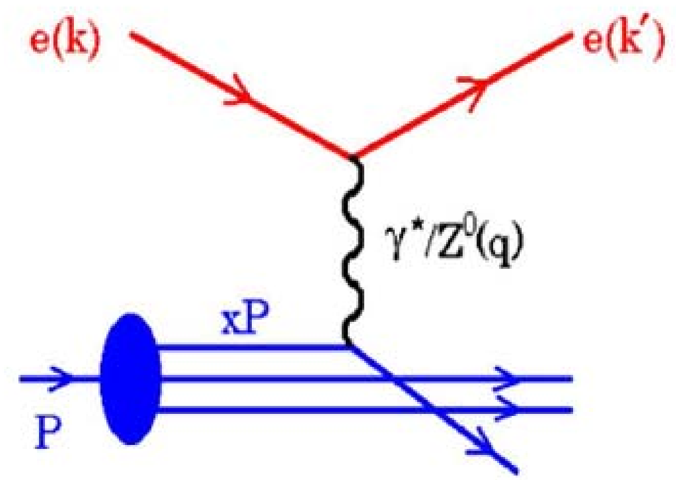
- Taylor, Kendall, Friedman, SLAC Stanford, 1967
- 20 GeV e$^-$ beams, protons at rest
- Inclusive measurement

First evidence for the scattering on the point-like partons inside a proton

Inclusive Deep Inelastic Scattering

E′ and θ fully determine kinematics (at proton rest frame)

$$e + p \rightarrow e' + X$$



Convenient variables:

$s = (k+P)^2$ center-of-mass energy

$Q^2 = -q^2 = -(k-k')^2$ virtuality of γ^* / Z

$x = \dfrac{Q^2}{2(q,P)}$ Bjorken x - parton momentum fraction

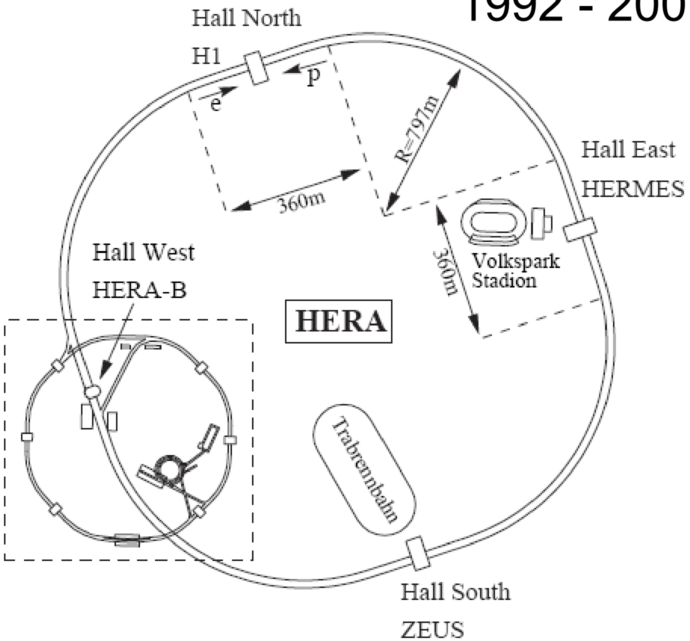
$y = \dfrac{(q,P)}{(k,P)} \rightarrow \left.\dfrac{E_\gamma}{E_{ele}}\right|_{\vec{P}=0}$ inelasticity

Related by $sxy = Q^2$

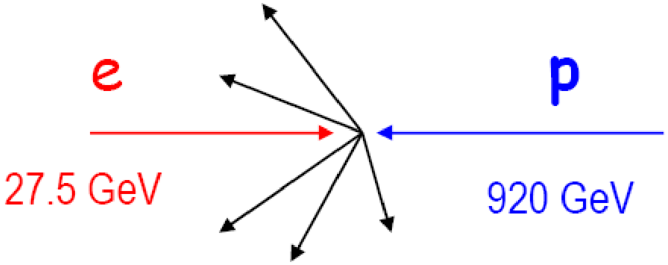
Include hadronic measurements to improve the result

The HERA ep collider at DESY (Hamburg)

1992 - 2007



15 years of data taking

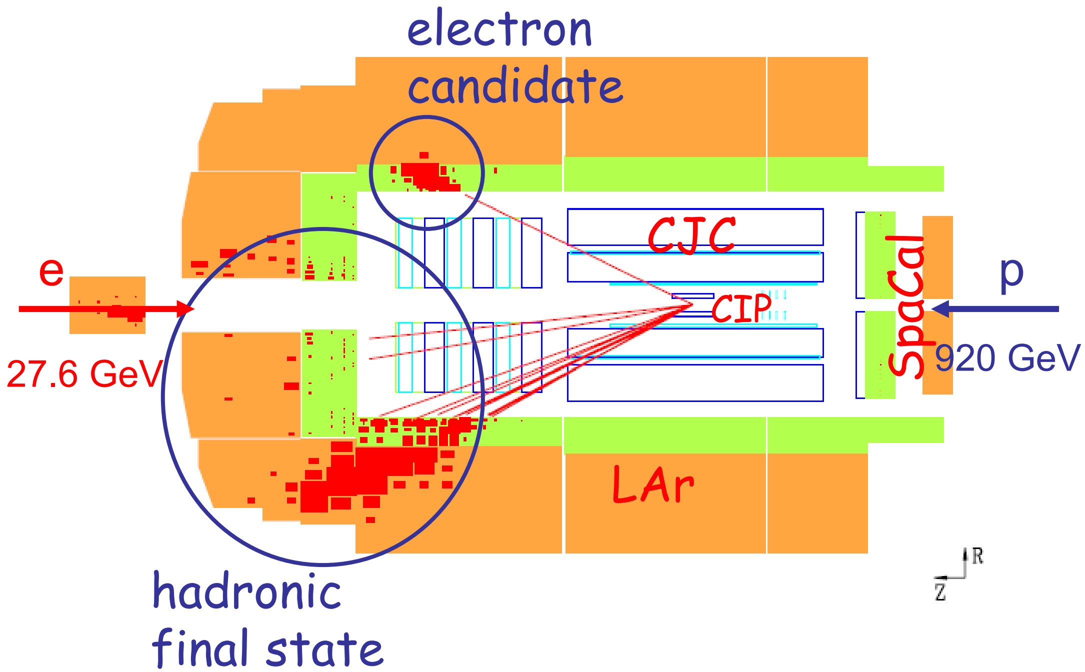


$\sqrt{s} \approx 320$ GeV

Q^2 up to 10^5 GeV^2/c^2

$\lambda_{min} \sim R_p/1000$

Main components of the H1 detector



LAr

Liquid Argon calorimeter

CJC

Central Jet Camber

CIP

Central Inner Proportional chamber

SpaCal

SPAghetti CALorimeter

ep scattering in general form

Cross section for the ep scattering is $d\sigma \propto L^{e}_{\mu\nu} W^{\mu\nu}_{had}$

where (the most general form)

$$W^{\mu\nu} = -g^{\mu\nu} W_1 + \frac{1}{m^2} W_2 - i e^{\mu\nu\alpha\beta} p_\alpha q_\beta \frac{1}{2m^2} W_3$$

$$+ q^\mu q^\nu \frac{1}{m^2} W_4 + (p^\mu q^\nu + q^\mu p^\nu) \frac{1}{m^2} W_5 + i(p^\mu q^\nu - p^\mu q^\nu) \frac{1}{2m^2} W_6$$

and $W_i = W_i(x, Q^2)$

ep scattering in general form

Cross section for the ep scattering is $d\sigma \propto L^e_{\mu\nu} W^{\mu\nu}_{had}$

where

violates parity => 0 for γ* exchange, antisymmetric, appears with Z exchange

$$W^{\mu\nu} = -g^{\mu\nu} W_1 + \frac{1}{m^2} W_2 - i e^{\mu\nu\alpha\beta} p_\alpha q_\beta \frac{1}{2m^2} W_3$$

$$+ q^\mu q^\nu \frac{1}{m^2} W_4 + (p^\mu q^\nu + q^\mu p^\nu) \frac{1}{m^2} W_5 + i(p^\mu q^\nu - p^\mu q^\nu) \frac{1}{2m^2} W_6$$

current conservation

$$q_\mu W^{\mu\nu} = q_\nu W^{\mu\nu} = 0$$

0 after convolution with symmetric lepton tensor (in case of unpolarized scattering)

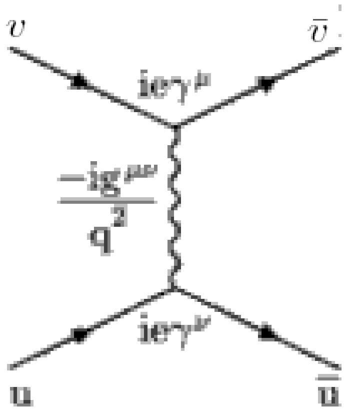
$$W^{\mu\nu} = A^{\mu\nu}(q,p,g) W_1(x,Q^2) + B^{\mu\nu}(q,p,g) W_2(x,Q^2)$$

after substitution and reordering

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

(for Z exchange term xF_3 see later)

eμ scattering (a reminder)



Start from the matrix element

$$\mathrm{M} = i\frac{ee'}{q^2}[\bar{u}\gamma_\mu u][\bar{v}\gamma^\mu v]$$

Average initial spin states, sum final states

$$\frac{1}{4}\sum_{spins}|M|^2 = \frac{e^2e'^2}{q^4}(L_e^{\mu\nu}L_{\mu\nu}^{muon}) = \frac{e^2e'^2}{q^4}\cdot 2(s^2+u^2)$$

Substitute $\frac{u}{s} = y - 1$

$$\frac{1}{4}\sum_{spins}|M|^2 = \frac{e^2e'^2}{Q^4}2s^2[1+(1-y)^2]$$

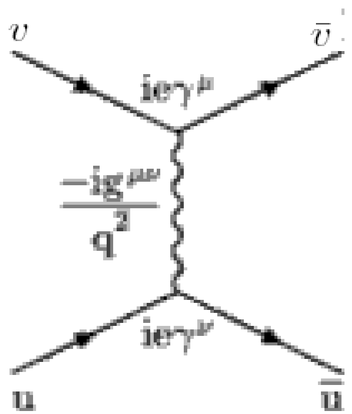
Finally (with phase space and flux factors)

$$\frac{d\sigma}{dy} = \frac{e^2e'^2}{8\pi Q^4}[1+(1-y)^2]s$$

ep scattering in QPM

QPM

- incoherent scattering of the lepton on the partons of the proton
- parton momentum: p' = xp



Parton changes

charge $e' = \{2/3,\ 1/3,\ \text{-}2/3,\ \text{-}1/3,\ 0\}$ for u, d, $\bar{u}$, $\bar{d}$, g

center-of-mass energy $s \rightarrow xs$

scaling is assumed

flux of incoming particles $1 \rightarrow q_i(x)$ *"density"*

Sum over all partons

$$\frac{d^2\sigma}{dx dQ^2} = \frac{2\pi\alpha^2}{xQ^4}[1 + (1-y)^2] \sum_i e_i^2 x q_i(x)$$

ep scattering in QPM

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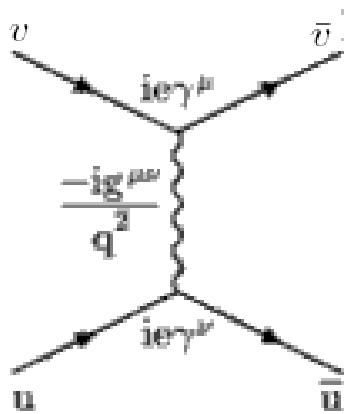


Parton changes

charge $e' = \{2/3, 1/3, -2/3, -1/3, 0\}$ (u, d, $\bar{u}$, $\bar{d}$, g)

center-of-mass energy $s \rightarrow xs$

flux of incoming particles $1 \rightarrow q_i(x)$

Sum over all partons

$$\frac{d^2\sigma}{dx dQ^2} = \frac{2\pi\alpha^2}{xQ^4}[1 + (1-y)^2] \sum_i e_i^2 x q_i(x)$$

Parton Distribution Function

F_2 & F_L (and something else)

QPM

$$\frac{d^2\sigma}{dx dQ^2} = \frac{2\pi\alpha^2}{xQ^4}[1 + (1-y)^2] \sum_i e_i^2 x q_i(x)$$

Proton structure functions

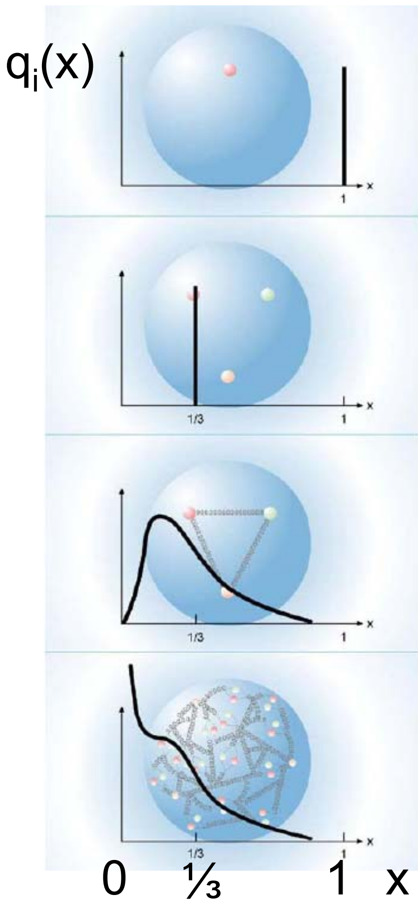
$$\frac{d^2\sigma}{dx dQ^2} = \frac{2\pi\alpha^2}{xQ^4}[(1 + (1-y)^2)F_2(x,Q^2) - y^2 F_L(x,Q^2)]$$

- Meaning of $F_2(x,Q^2) = \sum_i e_i^2 x q_i(x)$
- Bjorken scaling $F_2(x,Q^2) = F_2(x)$
- Callan-Gross relationship $F_L(x,Q^2) = 0$

$\rightarrow$ scattering on spin-$\frac{1}{2}$ partons

How F_2 could look like

$$F_2(x, Q^2) = \sum_i e_i^2 x q_i(x)$$

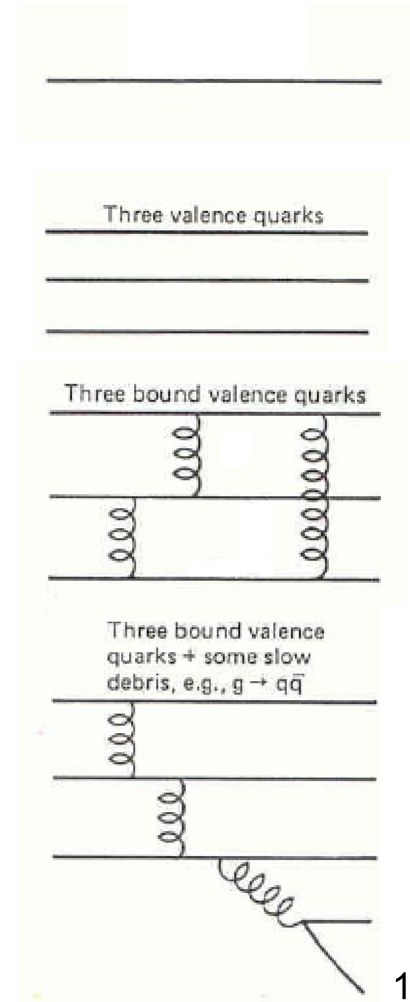


Point-like proton

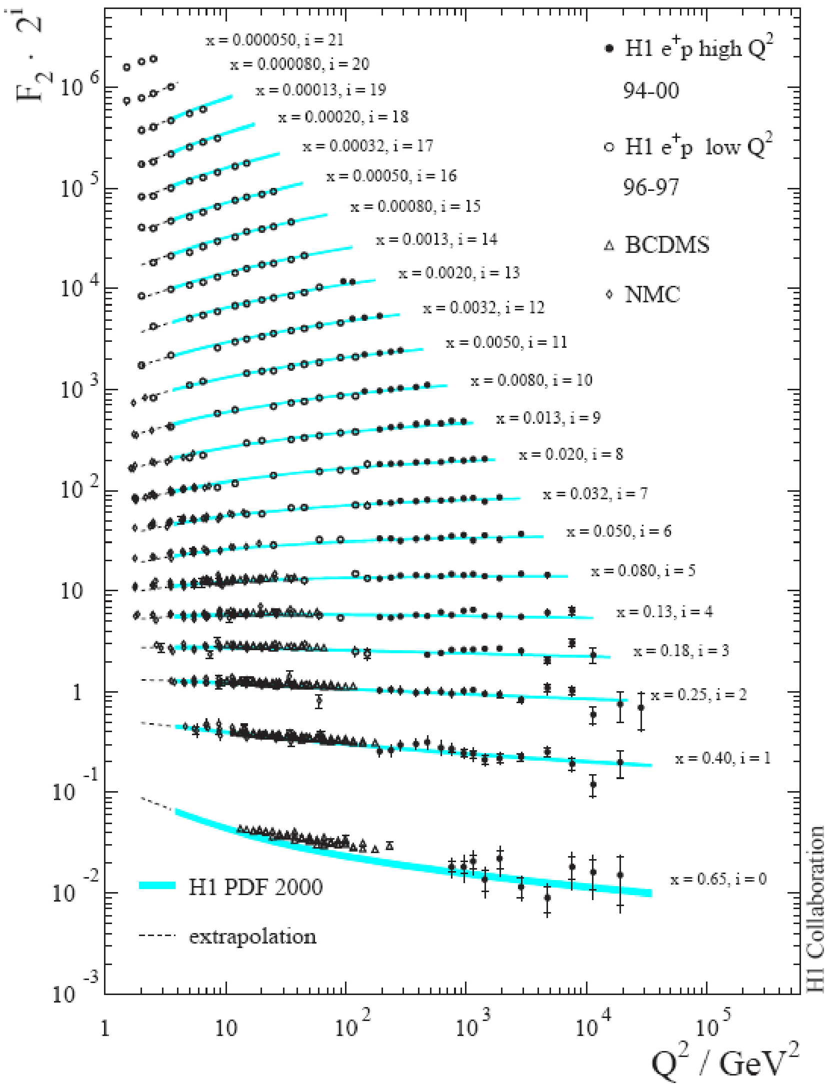
Just 3 static valence quarks

3 valence quarks and gluons

Real quark-gluon structure
(valence + sea + gluons)

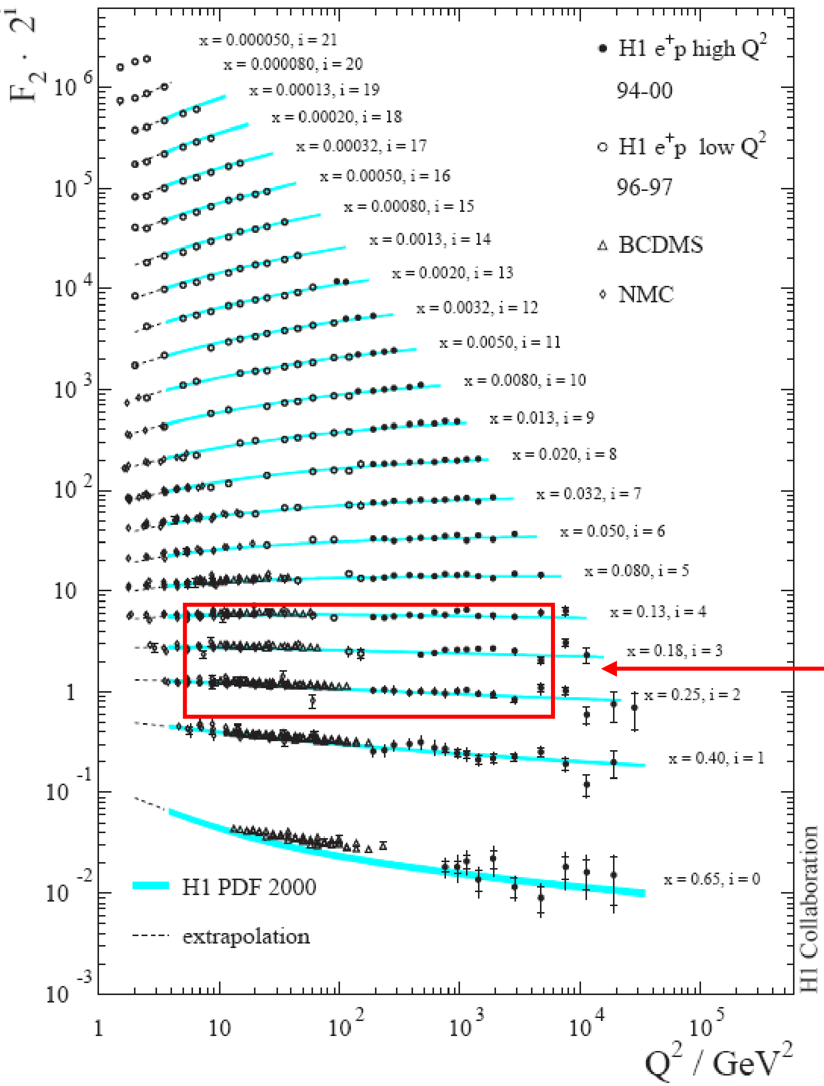


F_2 results

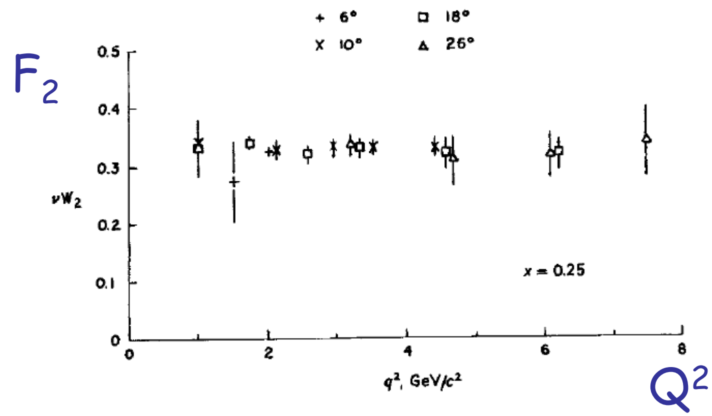


$F_2 \cdot 2^i$
x = 0.000050, i = 21
x = 0.000080, i = 20
x = 0.00013, i = 19
x = 0.00020, i = 18
x = 0.00032, i = 17
x = 0.00050, i = 16
x = 0.00080, i = 15
x = 0.0013, i = 14
x = 0.0020, i = 13
x = 0.0032, i = 12
x = 0.0050, i = 11
x = 0.0080, i = 10
x = 0.013, i = 9
x = 0.020, i = 8
x = 0.032, i = 7
x = 0.050, i = 6
x = 0.080, i = 5
x = 0.13, i = 4
x = 0.18, i = 3
x = 0.25, i = 2
x = 0.40, i = 1
x = 0.65, i = 0
H1 e^+p high Q^2
94-00
H1 e^+p low Q^2
96-97
BCDMS
NMC
H1 PDF 2000
extrapolation
H1 Collaboration
Q^2 / GeV^2

F_2 results



SLAC results, 1968



scaling at x ~ 0.15

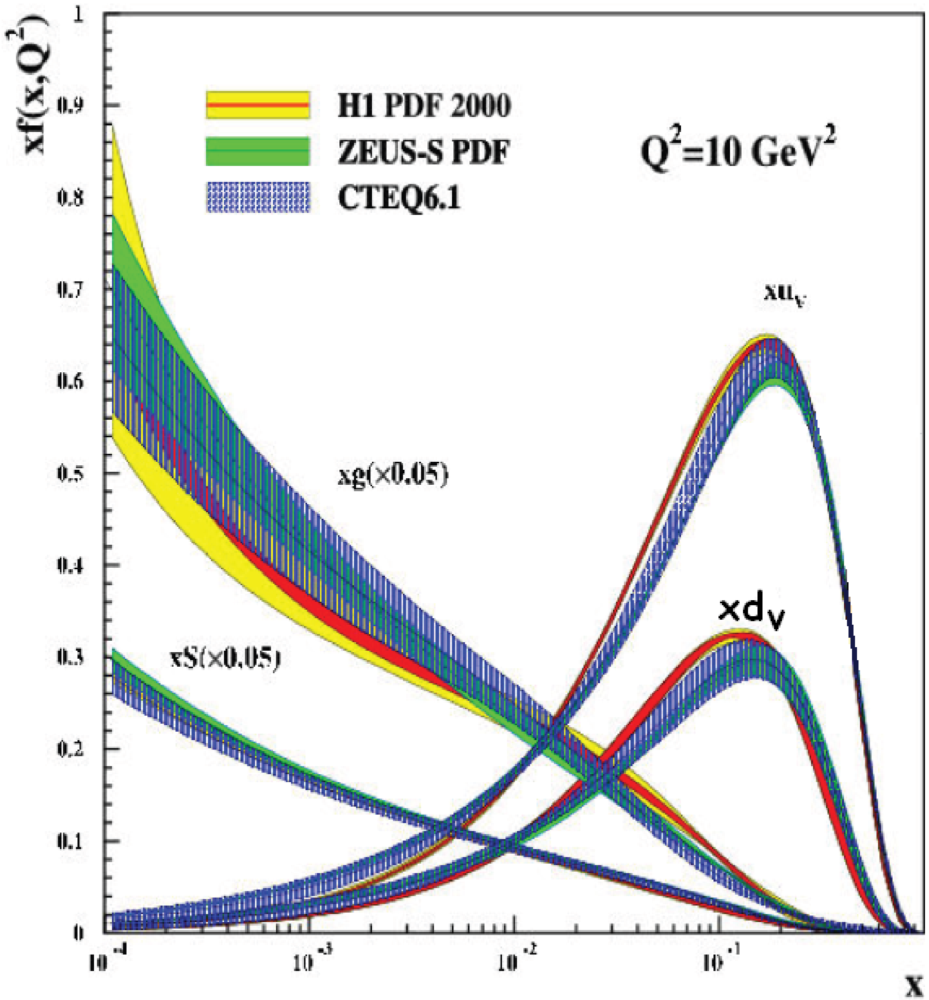
$$x_{min} > \frac{Q^2}{s} = \frac{Q^2}{4E_eE_p}$$

$$x_{min}^{SLAC} \approx 0.1$$

$$x_{min}^{HERA} \approx 0.00005$$

@ $Q^2 = 10\,GeV$

PDFs



Universality: factorization theorem

$$\sigma_{DIS} \propto \hat{\sigma} \otimes \mathrm{pdf}(x)$$

$\hat{\sigma}$ - perturbative QCD cross-section

$\mathrm{pdf}(x)$ - universal parton distribution functions

Measure in ep collisions (HERA)
use in pp collisions (LHC)

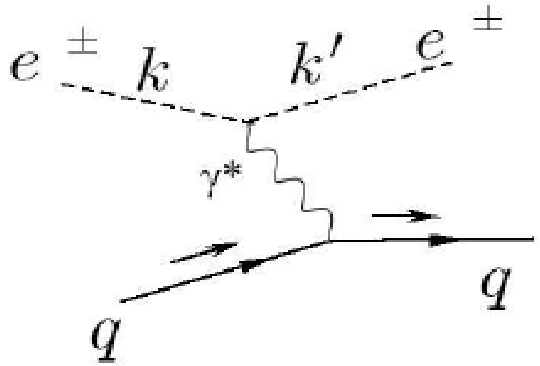
F_L is beyond QPM

$F_2 \sim \sigma_L^{\gamma p} + \sigma_T^{\gamma p}$, $F_L \sim \sigma_L^{\gamma p}$

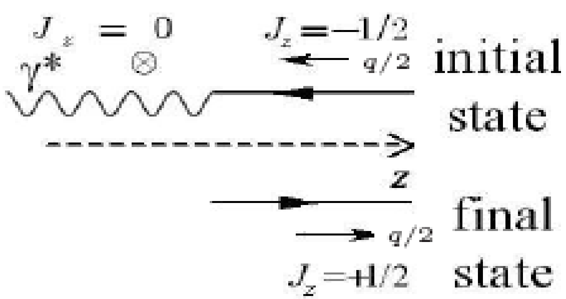
$0 < F_L < F_2$

longitudinal photon polarization

QPM



Conservation of helicity and angular momentum

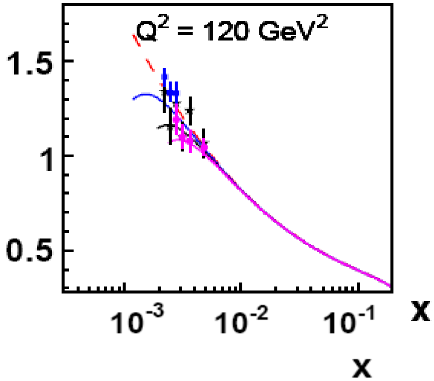


pure QCD effect

$$F_L(x,Q^2) = \frac{\alpha_s}{2\pi}\int_x^1 \frac{d\xi}{\xi}\left[\frac{8}{3}\left(\frac{x}{\xi}\right)^2 F_2(x,Q^2) + 4\left(\sum e_i^2\right)\left(\frac{x}{\xi}\right)^2\left(1-\frac{x}{\xi}\right)\xi g(\xi,Q^2)\right]$$

F_L probes the gluon distribution

F_L extraction

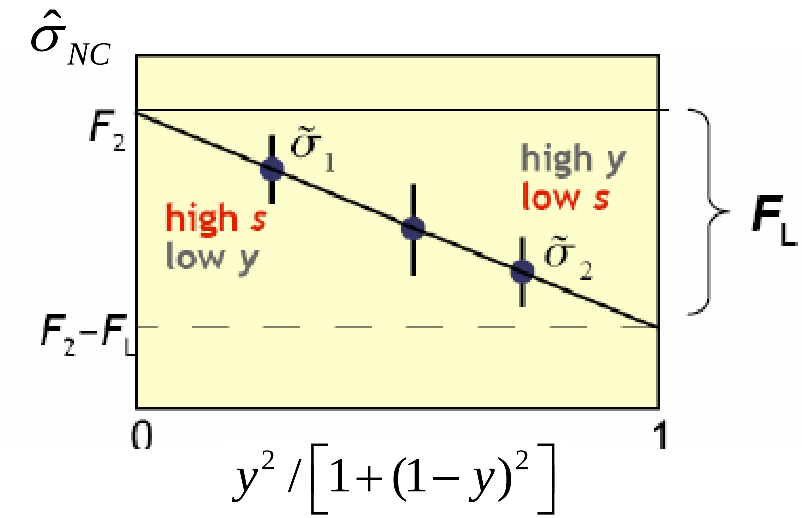


$$\tilde{\sigma}_{NC} = \frac{d^2\sigma^{ep}_{NC}}{dxdQ^2} \Bigg/ \left(\frac{2\pi\alpha^2}{xQ^4} Y_+\right) = F_2 - \boxed{\frac{y^2}{1-(1-y)^2}} F_L$$

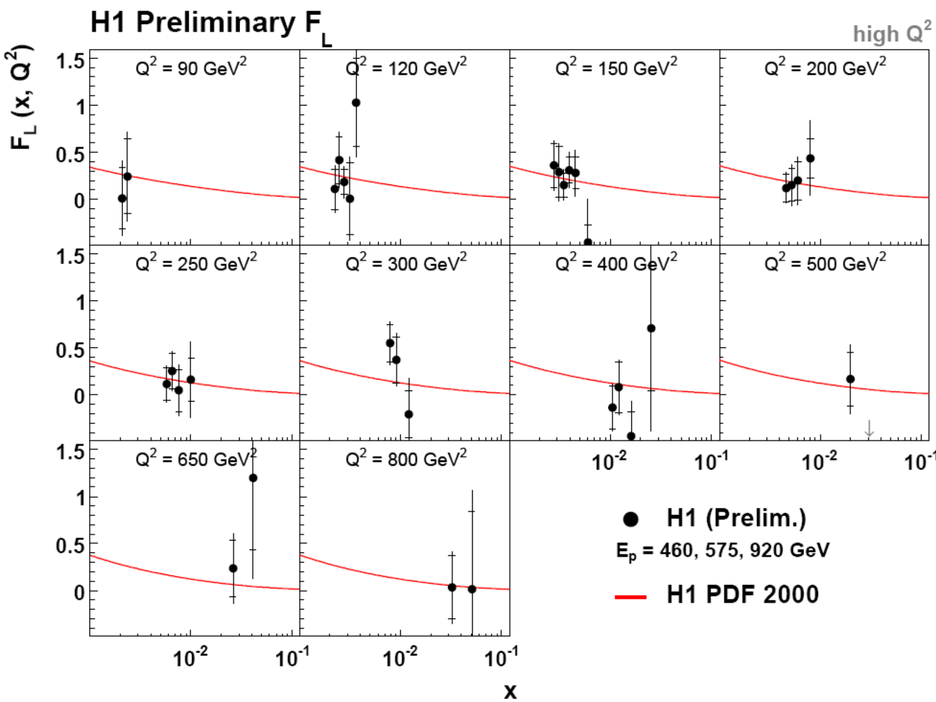
$$Q^2 = sxy,\ s = 4E_{el}E_p \Rightarrow y = y(\boxed{E_p})\Big|_{(x_0, Q_0^2)}$$

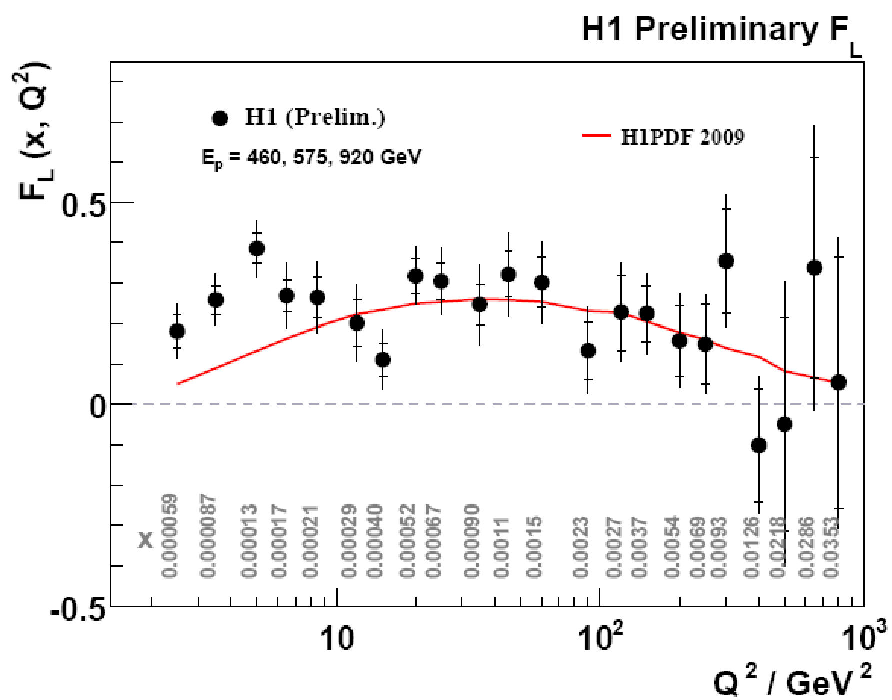
Measure σ at 3 different proton energies

E_p = 460, 575, 920 GeV



F_L results





QCD predictions are in a good agreement with the measurement @ $Q^2 > 10$ GeV^2

xF_3 appears at high Q^2

Z boson exchange accounts at $Q^2 \approx M_Z^2$ (modification of the lepton tensor)

$$\frac{d^2\sigma(l^\pm p)}{dxdQ^2} = \frac{2\pi\alpha^2}{xQ^4}[(1+(1-y)^2)F_2(x,Q^2) - y^2F_L(x,Q^2) \mp (1-(1-y)^2)xF_3(x,Q^2)]$$

LO QCD: F_L small at high Q^2

from parity violating term W_3

Again from QPM

$$xF_3(x,Q^2) = \sum_i B_i^0(Q^2)\cdot(xq_i(x,Q^2) - x\bar{q}_i(x,Q^2))$$

measures valence quarks !

where $B_i^0(Q^2) = -2e_ia_ia_eP_Z + 4a_iv_iv_ea_eP_Z^2,\ P_Z = \dfrac{Q^2}{Q^2+M_Z^2}\dfrac{1}{\sin^2\theta_W}$

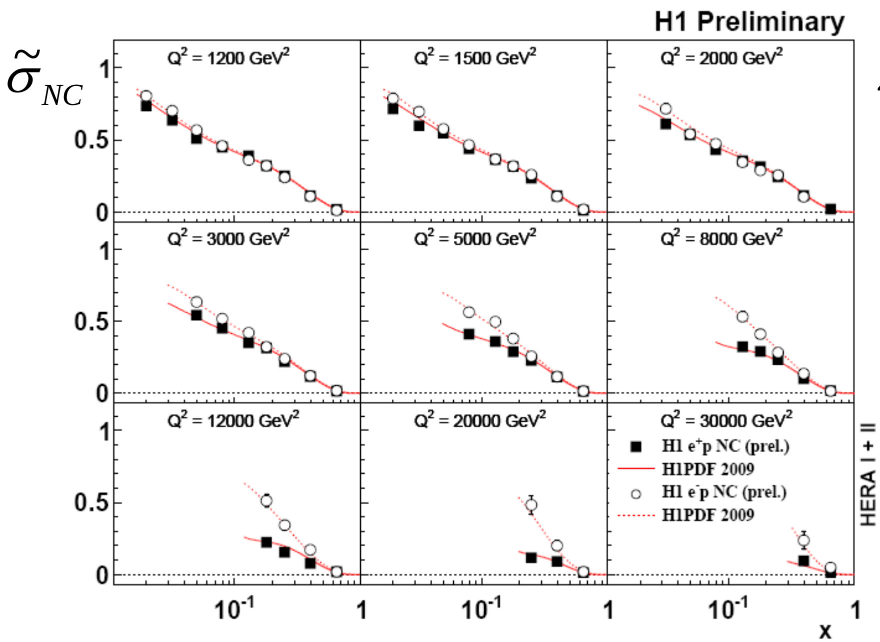
γZ interference

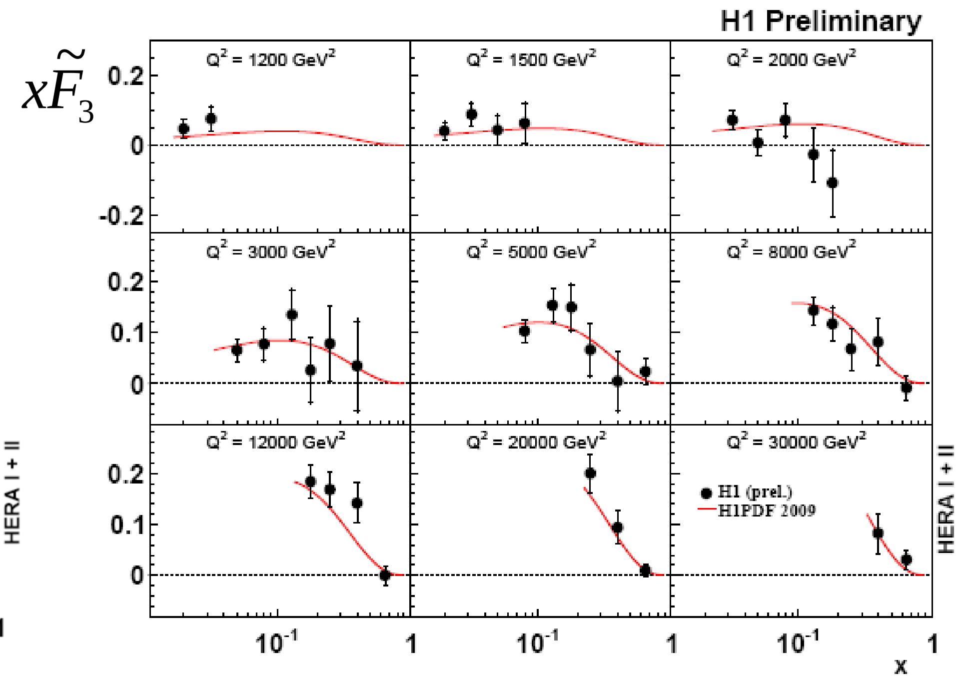
purely Z exchange

Modify F2 also

$$F_2(x,Q^2) = \sum_i A_i^0(Q^2)\cdot(xq_i(x,Q^2) + x\bar{q}_i(x,Q^2))$$

xF_3 results

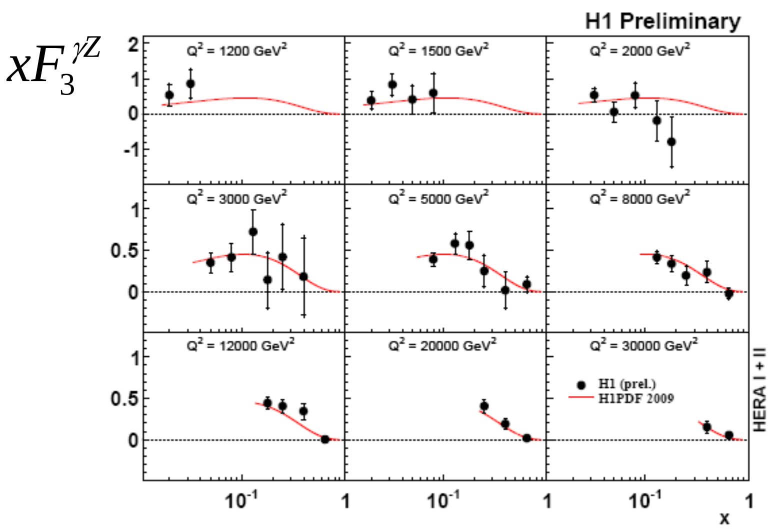


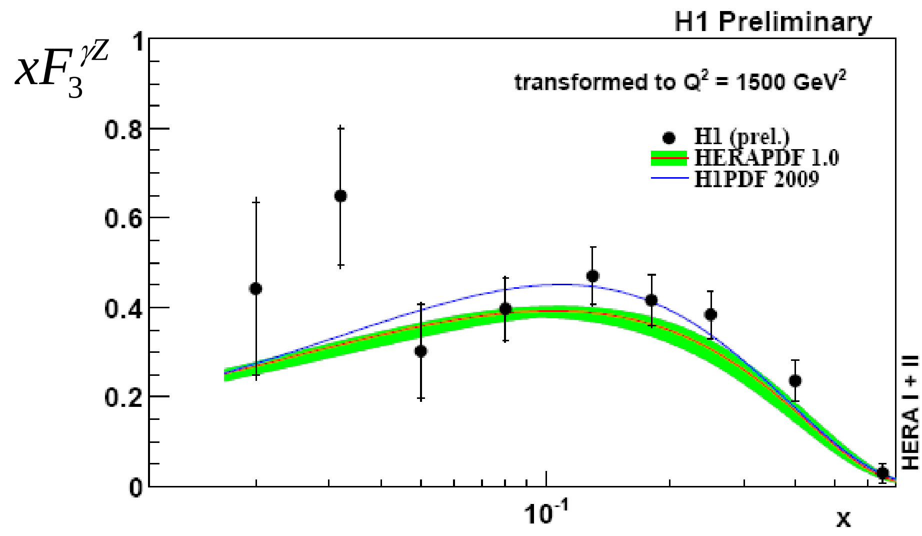


$$\tilde{\sigma}_{NC}(e^{\pm}p) = F_2 \mp \frac{Y_-}{Y_+} xF_3$$

$$x\tilde{F}_3 = \frac{Y_+}{2Y_-}[\tilde{\sigma}^-_{NC}(x,Q^2) - \tilde{\sigma}^+_{NC}(x,Q^2)]$$

xF_3 results





Dominant contribution is from γZ interference term

$$xF_3^{\gamma Z} \approx x\tilde{F}_3 \cdot \frac{Q^2 + M_Z^2}{Q^2} \cdot \frac{4\sin^2\Theta_W \cos^2\Theta_W}{a_e}$$

Log Q^2 dependence (small) => different Q^2 points could be transported to the same Q^2 to increase statistics

Conclusions

- F_2, F_L, xF_3 - the most general description of the proton structure
- All three are measured in H1
- This allows to investigate proton and verify QCD predictions and determine PDFs with QCD