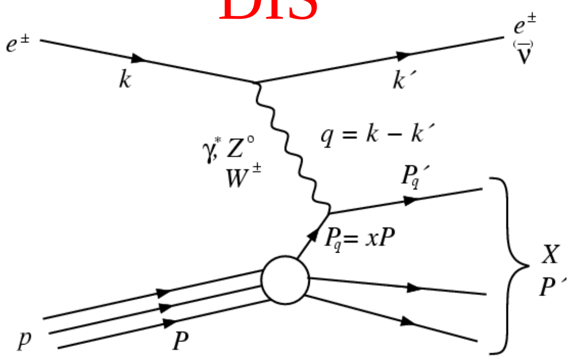
Experimental Review of Unpolarised Structure Functions

Vladimir Chekelian (MPI for Physics, Munich)

- SF and parton densities
- A few historical remarks
- Recent JLAB and NuTeV results
- HERA results:
  F_2, gluon, α_s, jets, F_2^{cc}, F_2^{bb}, F_L ,
  NC&CC at high Q^2, xF_3 ,
  pdf
- First results from HERA II
- Summary

Unpolarised SF and Parton Densities

DIS



$Q^2 = -q^2$ *virtuality of* $\gamma^*, Z^o, W^\pm$

$x = Q^2/2(pq)$ *Bjorken scaling variable*

$y = (Pq)/(pk)$ *inelasticity*

DIS cross section and SF

$$\frac{d^2\sigma_{NC}^{e^\pm p}}{dx\,dQ^2} = \frac{2\pi\alpha^2}{xQ^4} Y_+ \left[F_2 - \frac{y^2}{Y_+} F_L \mp \frac{Y_-}{Y_+} xF_3 \right], \quad Y_\pm = 1 \pm (1-y)^2$$

in QPM: $F_2(x,Q^2) = x \sum A_i (q_i + \bar{q}_i)$

$$xF_3(x,Q^2) = x \sum B_i (q_i - \bar{q}_i)$$

$$F_L = F_2 - 2xF_1 = 0$$

Factorisation

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

$\hat{\sigma}$ – perturbative QCD cross section
pdf - universal parton distribution functions

QCD evolution (NLO, NNLO)

DGLAP

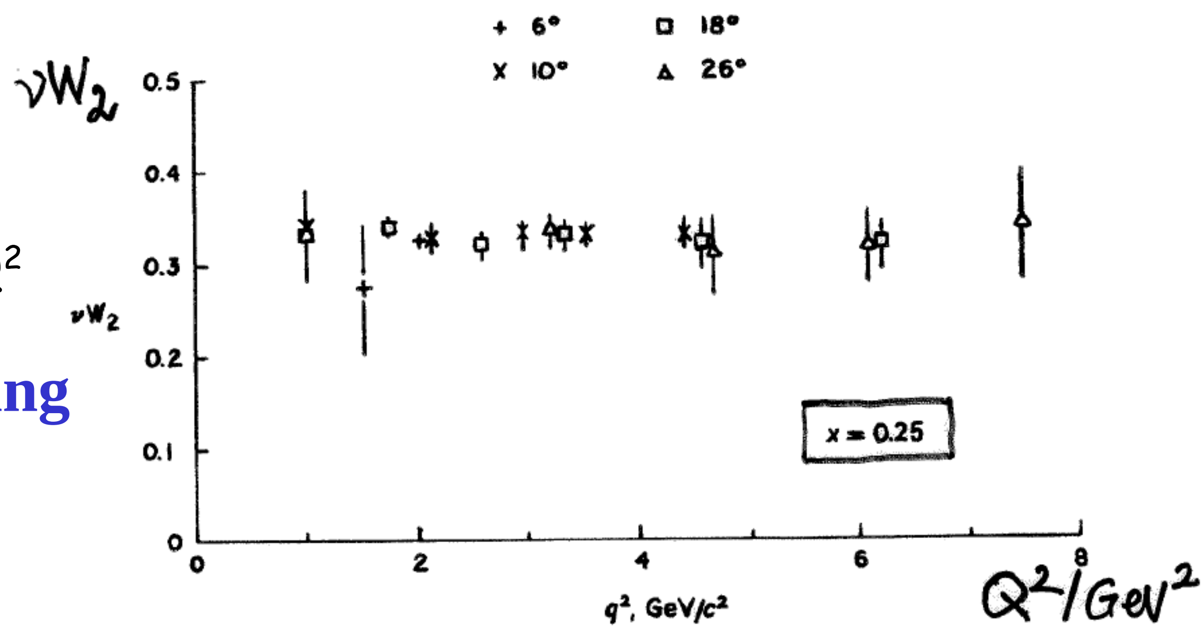
BFKL, CCFM

SF: a few Historical Remarks

1969 SLAC-MIT
observation that
the proton SF
is independent of Q^2
at fixed Bjorken x

→ **Bjorken scaling**

QPM



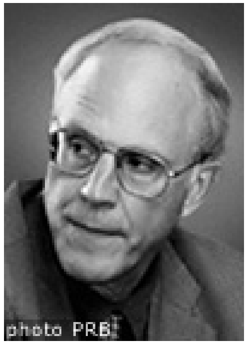
1974 - … SLAC, EMC, BCDMS, NMC, CDHS, CHARM, CCFR, …
logarithmic Q^2 dependence of $F_2(x,Q^2)$ established in e/μ/νN scattering experiments

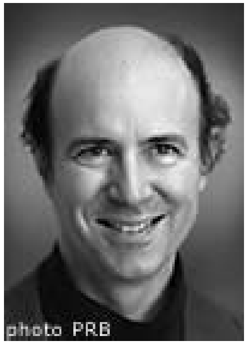
→ **scaling violations**

QCD

2004 Nobel Prize in Physics for the Discovery of Asymptotic Freedom

David Gross, David Politzer, Frank Wilczek





Selected Publications of Frank Wilczek, with Brief Commentary

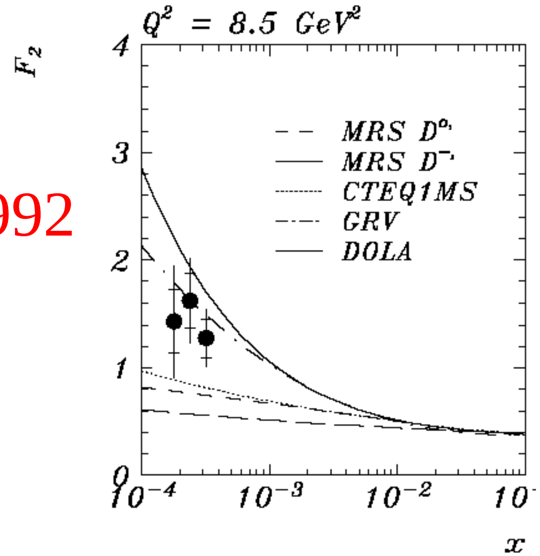
http://web.mit.edu/physics/facultyandstaff/faculty_documents/wilczek_select_pubs.pdf

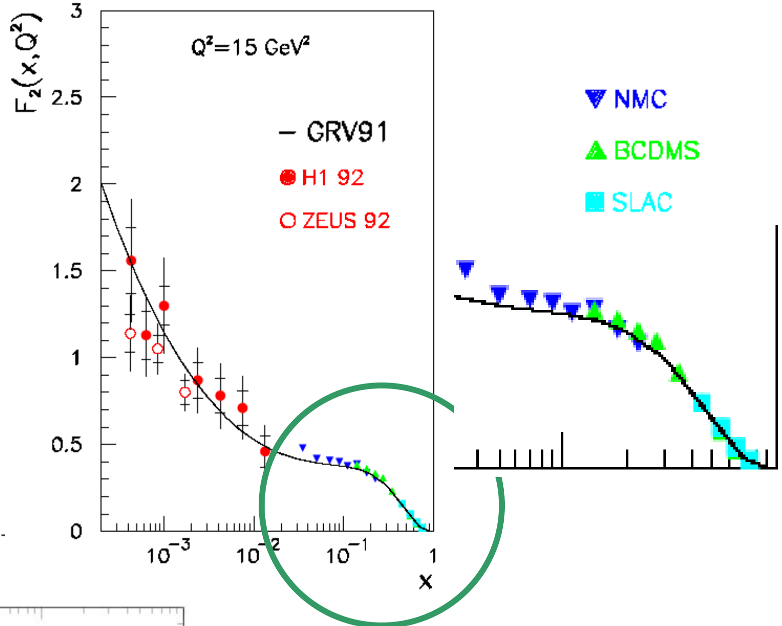
QCD: Foundational Papers

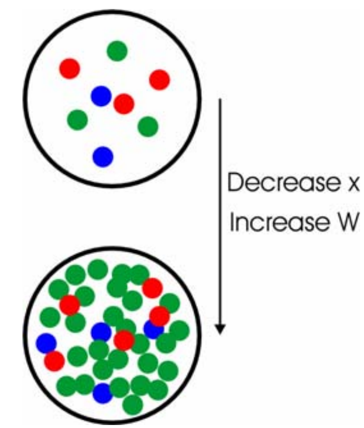
… in the fifth and sixth papers further experimental consequences, regarding the pointwise evolution of structure functions, were derived. **The most dramatic of these, that proton viewed at ever higher resolution would appear more and more as field energy (soft glue), was only clearly verified at HERA twenty years later**. …

Rise of F_2 to Low x at HERA

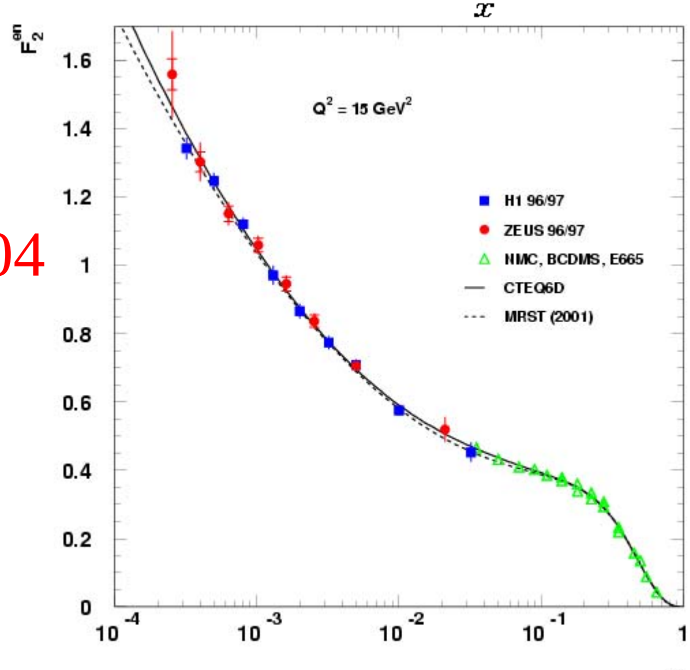
1992







2004



the first HERA data:

- discovery of the F_2 rise at low x

driven by gluon !

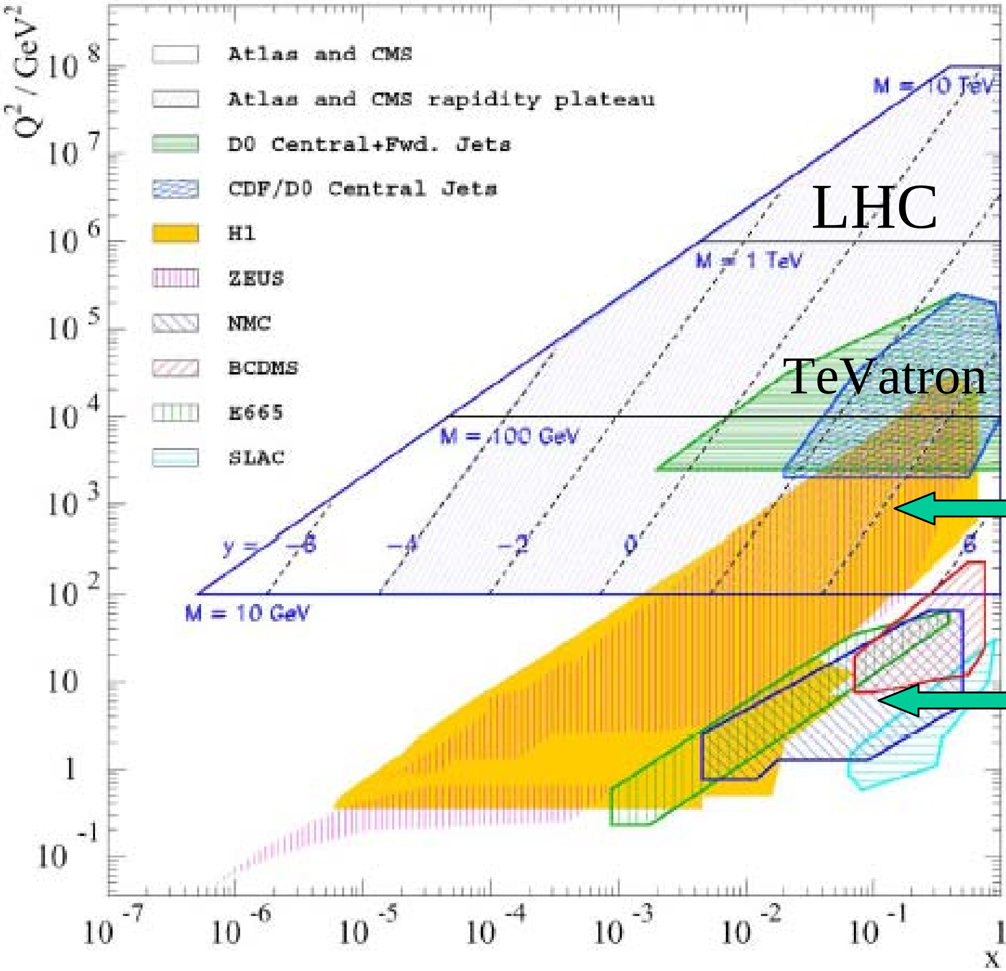
can not rise forever

search for new gluon dynamics (saturation effects, …)

after 12 years of HERA:

precise data allowing to look for smallest deviations

Kinematic Reach in Q^2 and x



full HERA x range is needed for LHC

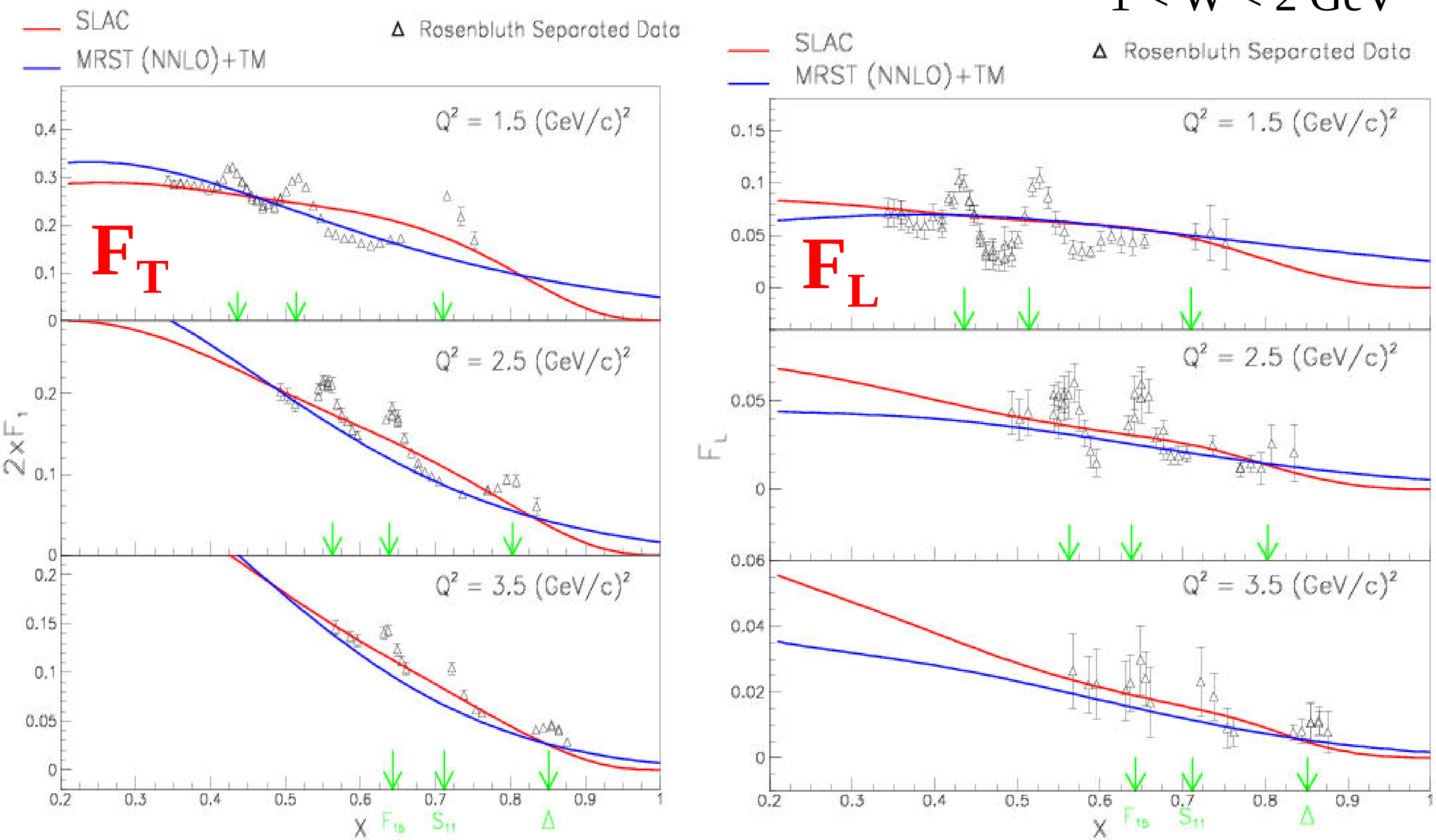
HERA

fixed target experiments

SLAC,BCDMS,NMC,E665, …

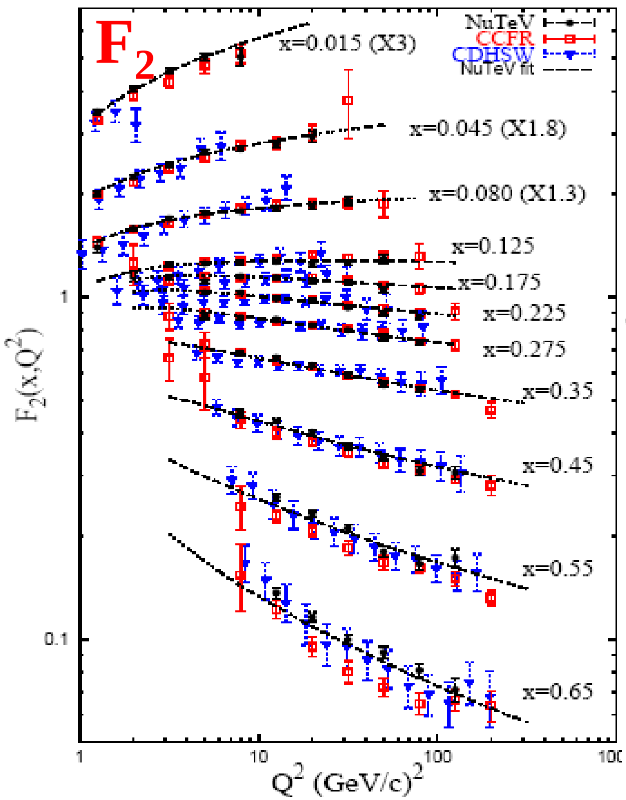
F_T and F_L in Resonance Region (JLAB E94-110)

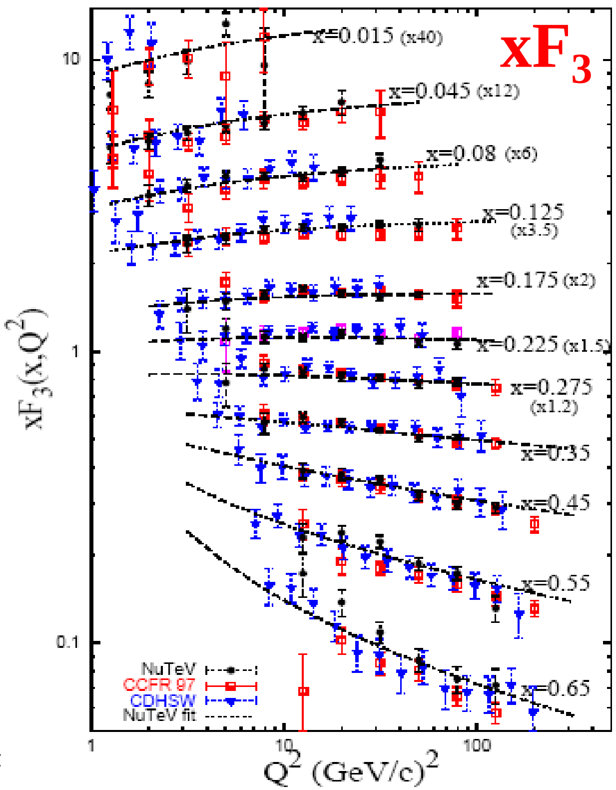
1 < W < 2 GeV



Quark-hadron duality works well for both F_T and F_L above Q^2 ~ 1.5 GeV^2

Recent NuTeV Results





ν-Fe

$$F_2(x,Q^2) = 2x\sum(q_i + \overline{q}_i)$$

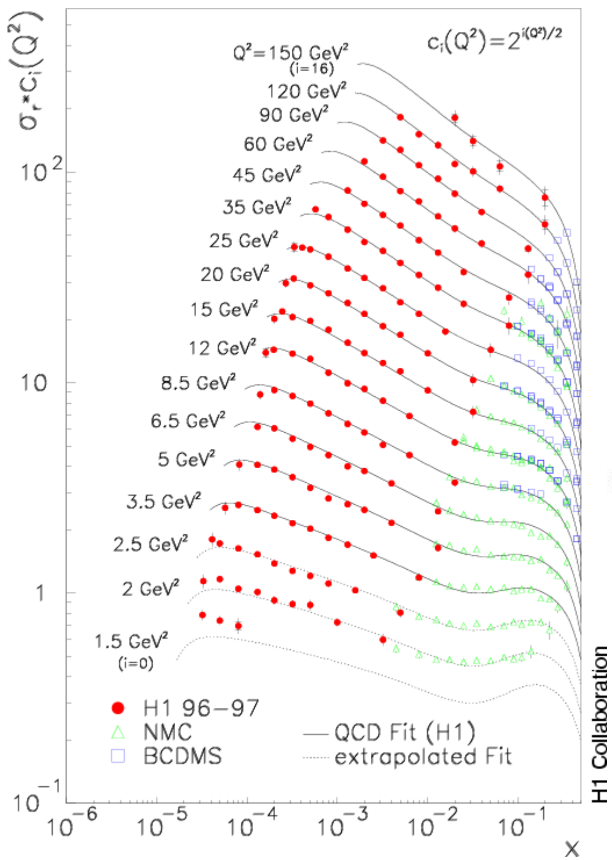
$$xF_3(x,Q^2) = 2x\sum(q_i - \overline{q}_i)$$

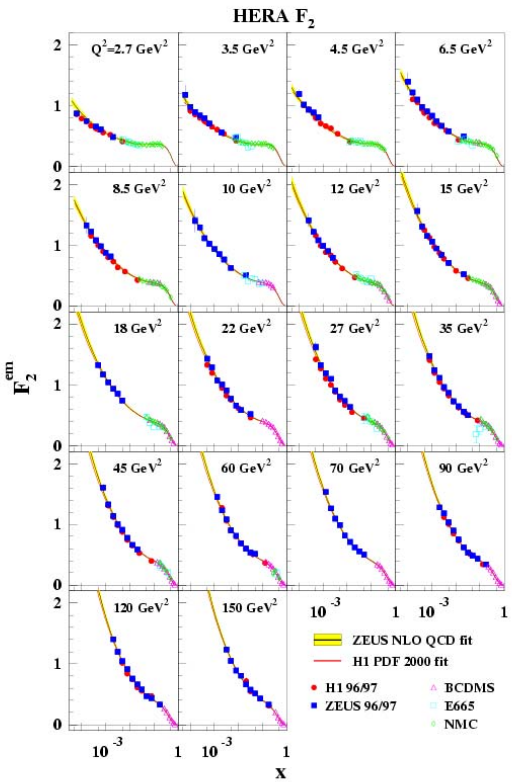
- extended to high y (low x)
- most precise measurements of this kind
- half of syst.err. of CCFR

Strange Sea Asymmetry vs. the "NuTeV Anomaly":

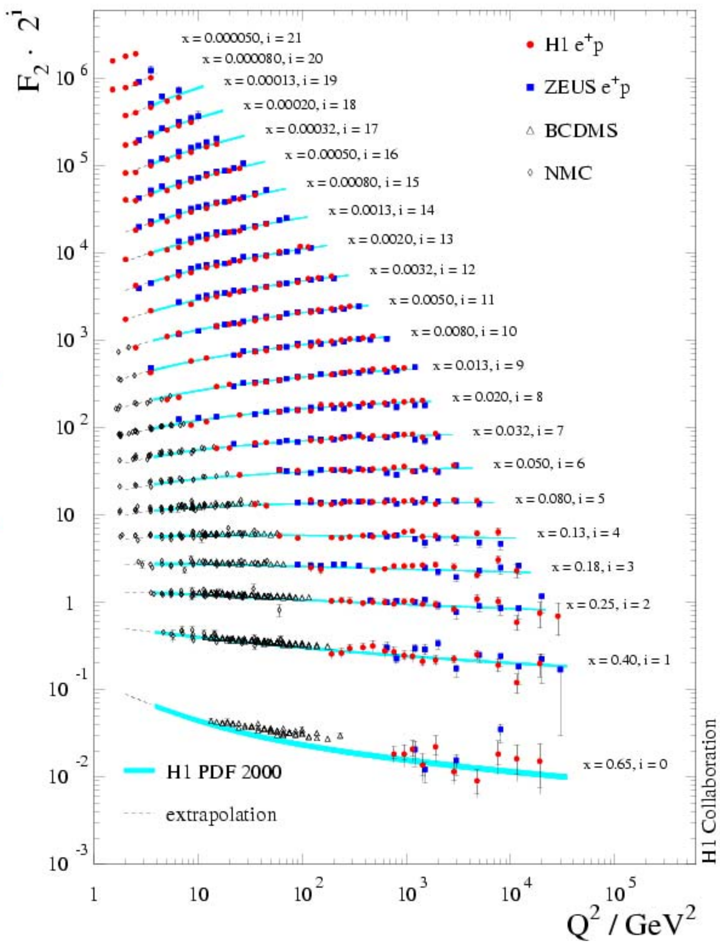
→ see talk of S. Forte

$F_2(x,Q^2)$ Measurements at HERA





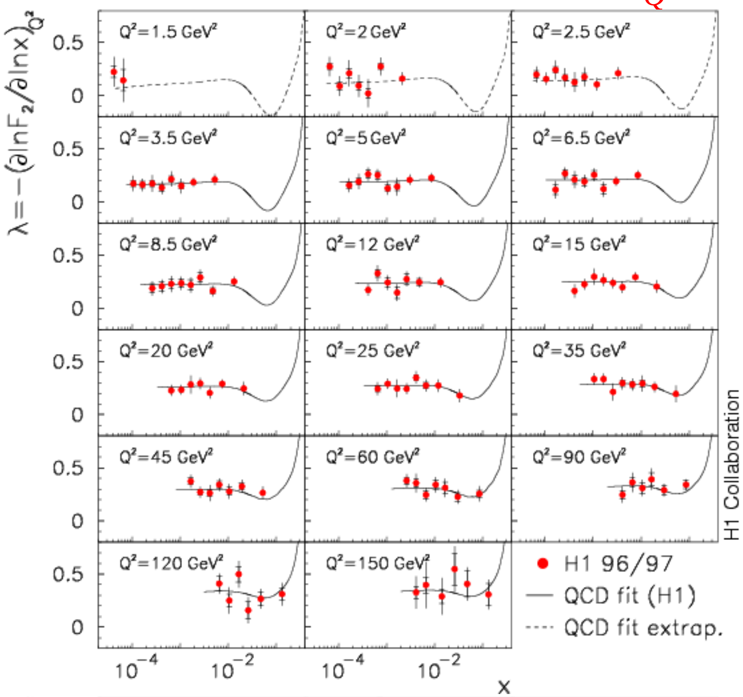
precision data ±2-3%
5 decades in x
5 decades in Q^2

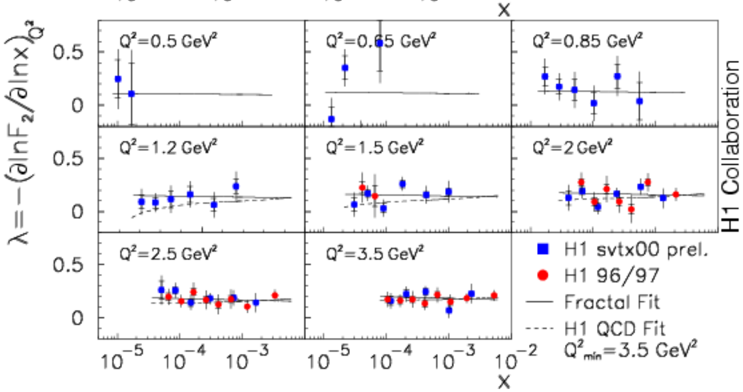


rich possibilities to determine pdfs, test QCD, transition to γp, search for saturation effects, …

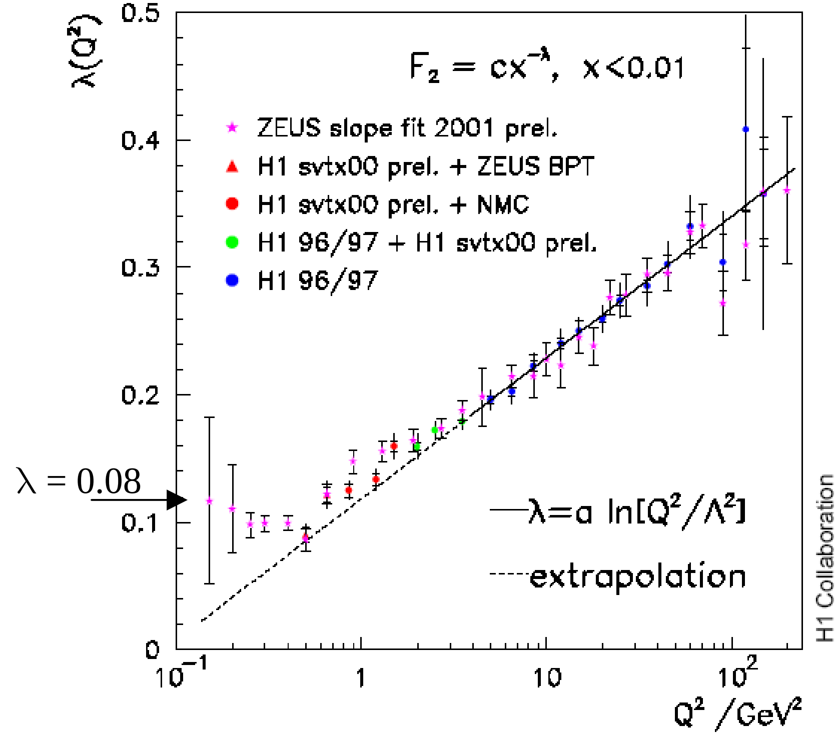
Low x at HERA

locally $\lambda = -(\partial F_2 / \partial \ln x)_{Q^2}$





$\lambda(Q^2)$ from fit $F_2(x,Q^2) = c(Q^2)x^{-\lambda(Q^2)}$

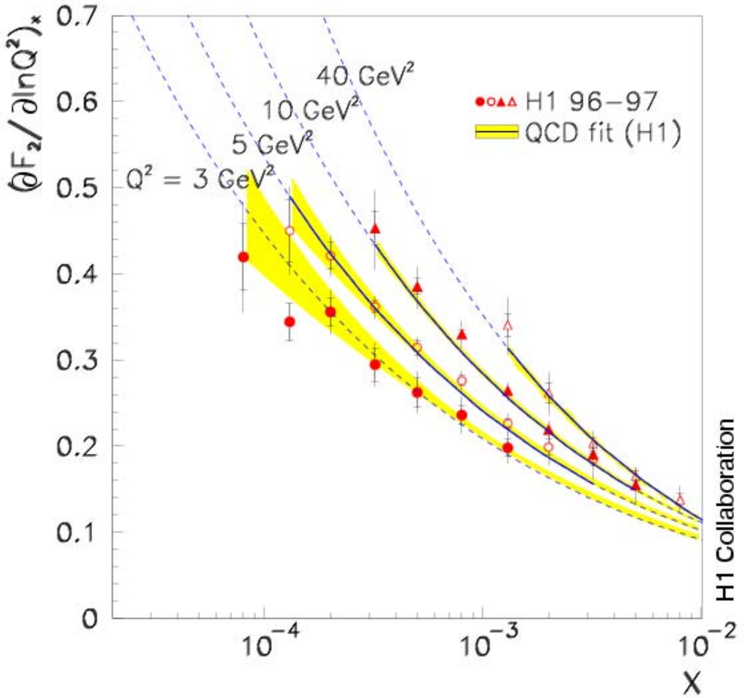


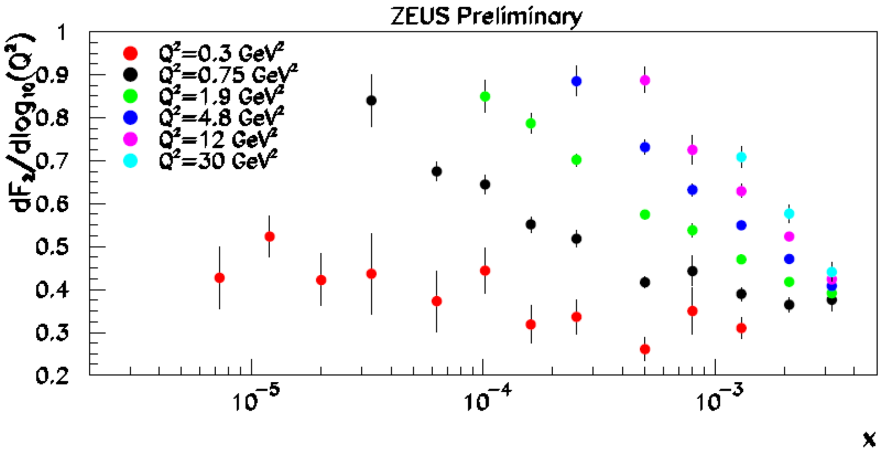
- $\lambda \approx$ constant at fixed Q^2 ($x < 0.01$)
- $\lambda(Q^2)$ depends linearly on $\ln(Q^2)$
- agrees with QCD for $Q^2 \geq 2$ GeV^2
- change of behavior at $Q^2 \approx 1$ GeV^2
- soft pomeron limit $\lambda = 0.08$ (DL)

no taming of the rise of F_2 towards low x for $Q^2 \geq 0.5$ GeV^2

Scaling Violations at Low x

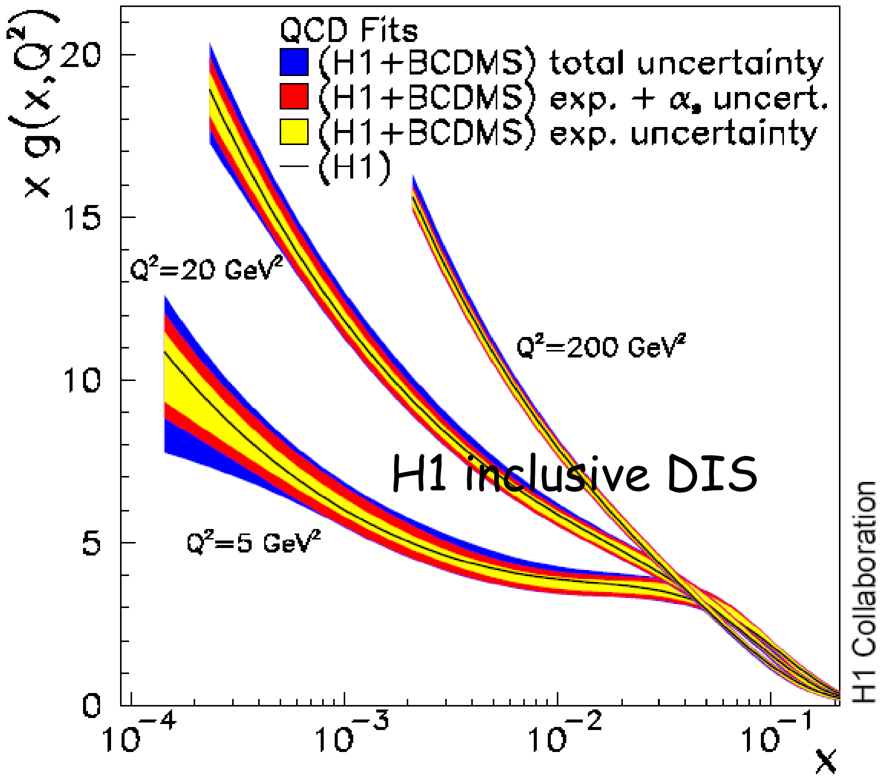
driven by gluon $(\partial F_2/\partial \ln Q^2)_x \propto \alpha_s(Q^2) x g(2x, Q^2)$ (LO)

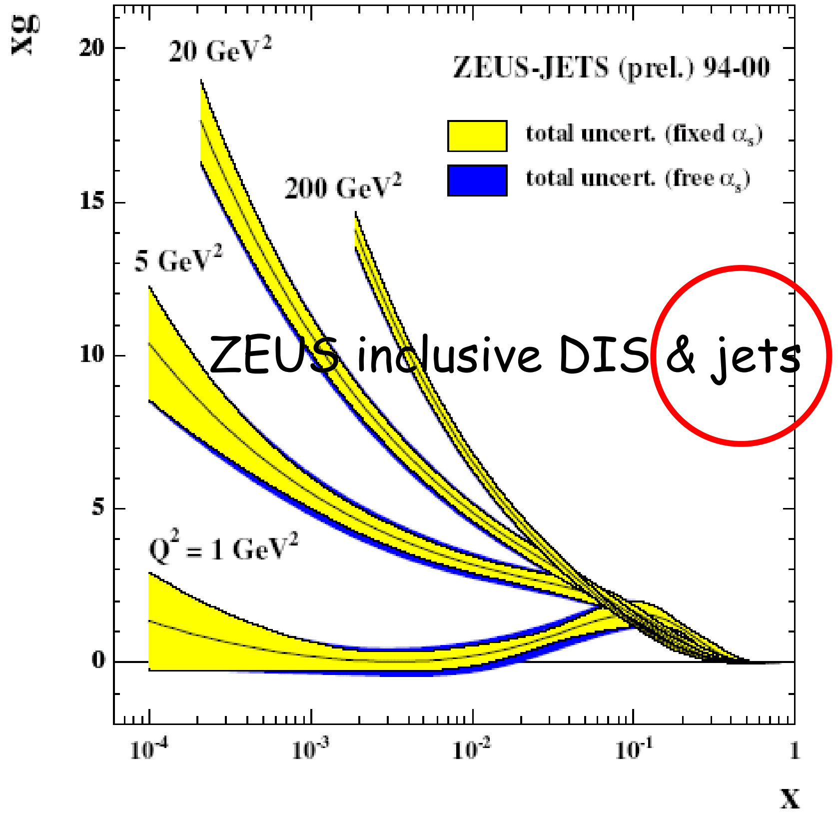




- continuous rise towards low x
- consistent with QCD fit ($Q^2 \geq 3$ GeV²)
- no evidence for new gluon dynamics

Gluon Density from HERA NLO QCD Fits





Gluon → scaling violations

pin down the gluon alows to resolve correlation of $xg \leftrightarrow \alpha_s$
charm treatment important
at $Q^2 \sim 1\ GeV^2$ the gluon distribution becomes very small → xg is NOT an observable

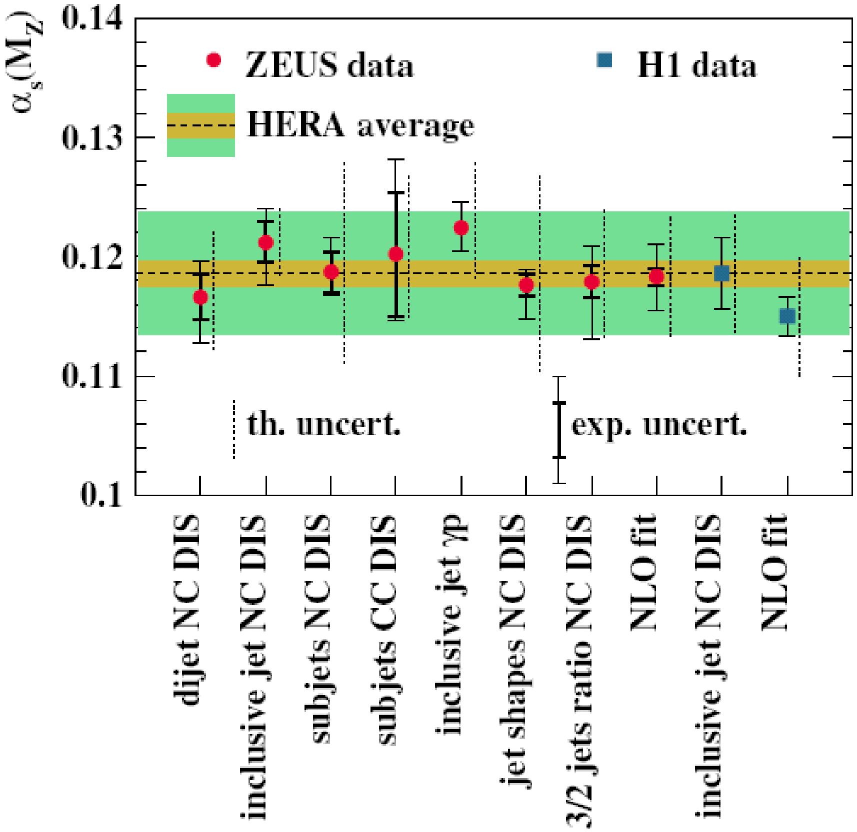
Gluon → jets, heavy flavours, $F_L(x,Q^2)$ directly sensitive to xg

Strong Coupling from HERA NLO QCD Fits and Jets

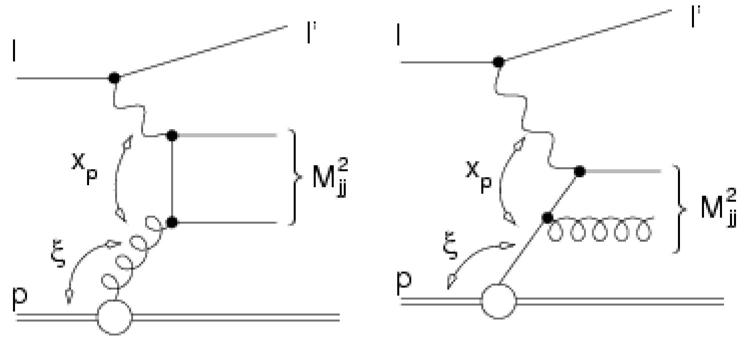
From scaling violations:

$$\alpha_s(M_Z^2) = 0.1209 \pm 0.0015(\exp) \pm^{0.0048}_{0.0049} (thy) - ZEUS$$

$$\alpha_s(M_Z^2) = 0.1160 \pm 0.0016(\exp) \pm^{0.0058}_{0.0046} (thy) - H1$$



Jets



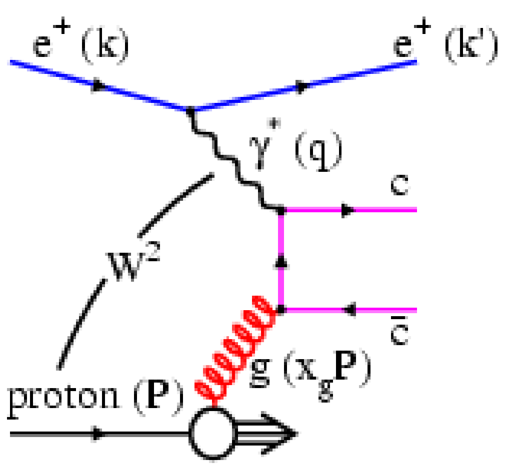
HERA(prel.)

$$\alpha_s(M_Z^2) = 0.1186 \pm 0.0011(\exp) \pm 0.005(thy)$$

- small exper. error ~1%
- theory error in NNLO expected to be 3 times smaller

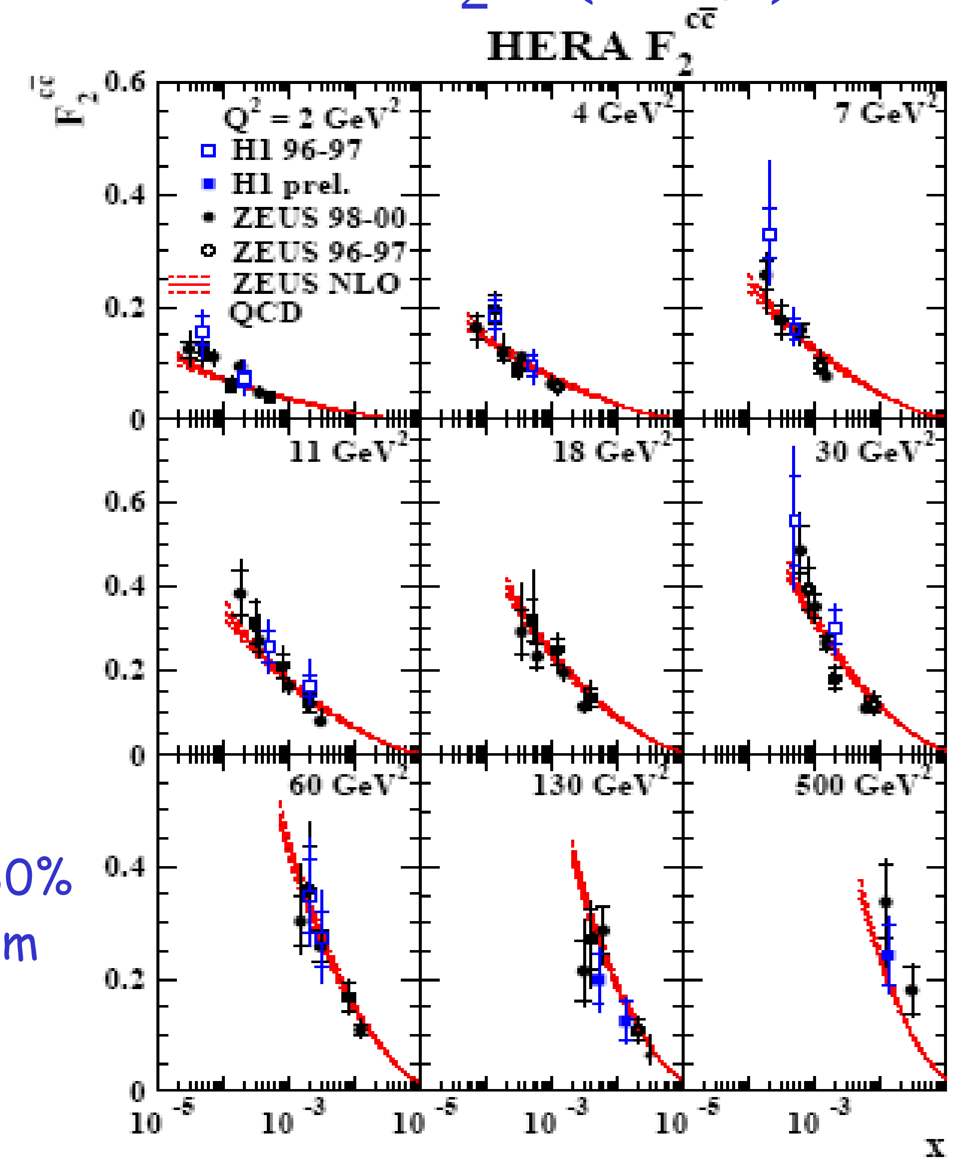
Charm Structure Function $F_2^{cc}(x,Q^2)$

Boson Gluon Fusion (BGF)



$D^* \rightarrow D^0 \pi_{slow} \rightarrow K\pi\pi_{slow}$

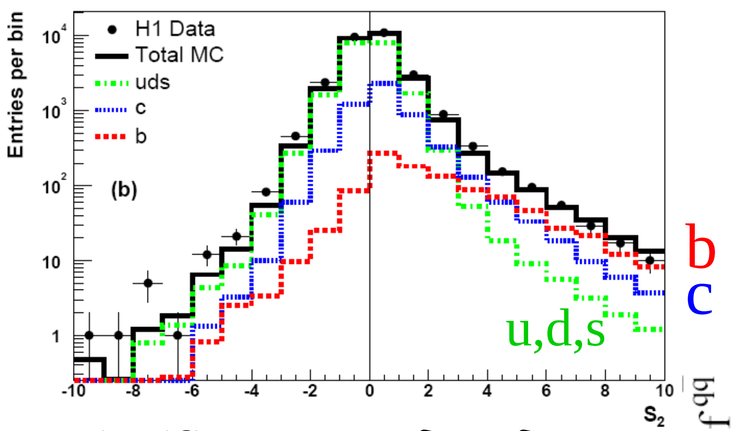
- charm contribution up to 25-30%
- consistent with with gluon from scaling violations



Beauty Structure Function $F_2^{bb}(x,Q^2)$

long lifetimes of b,c hadrons

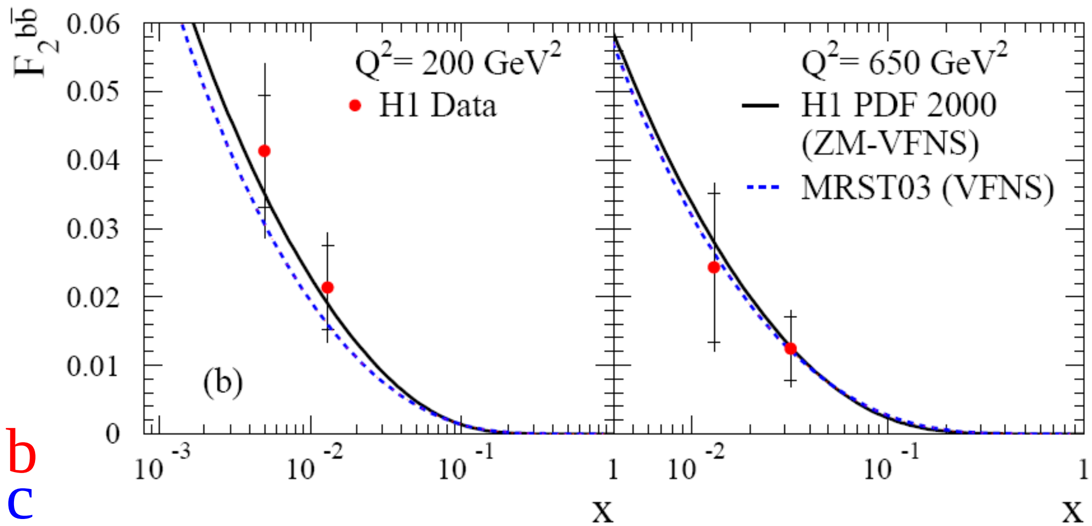
- use all tracks with p_t>500 MeV and hits in the H1 silicon tracker
- jet gives b-direction



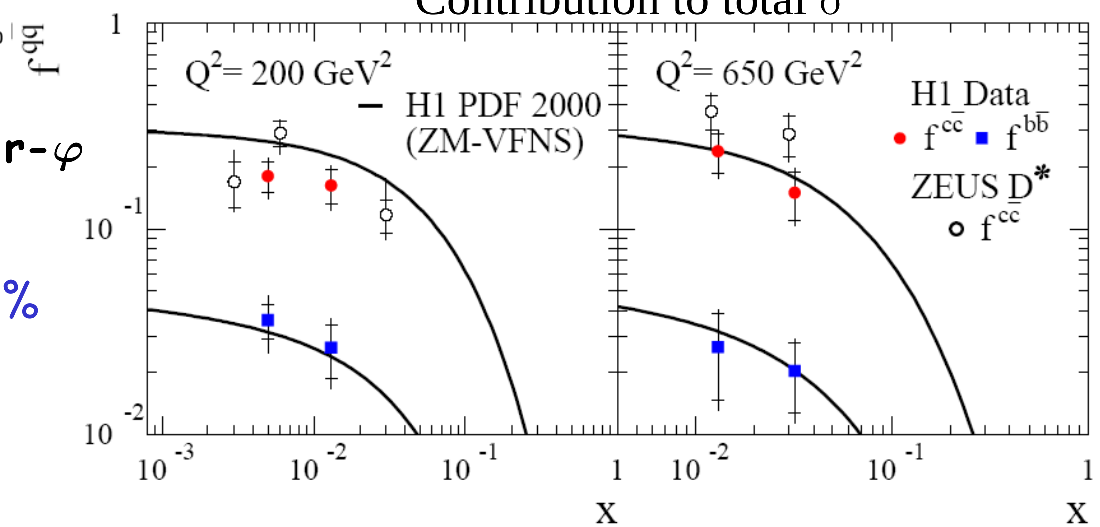
significance S= $\delta/\sigma(\delta)$

δ - track impact parameter in r-φ

- F_2^{bb} - for the first time
- beauty contribution is ~ 3%
- consistent with with QCD calculations

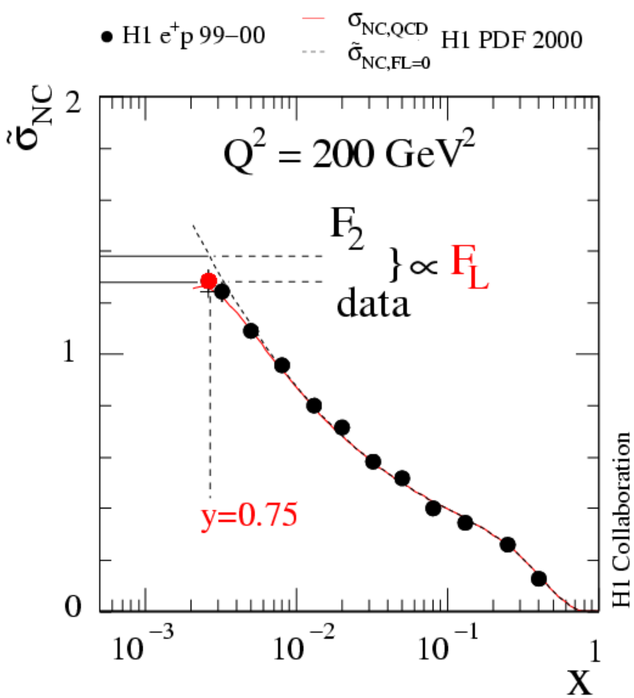


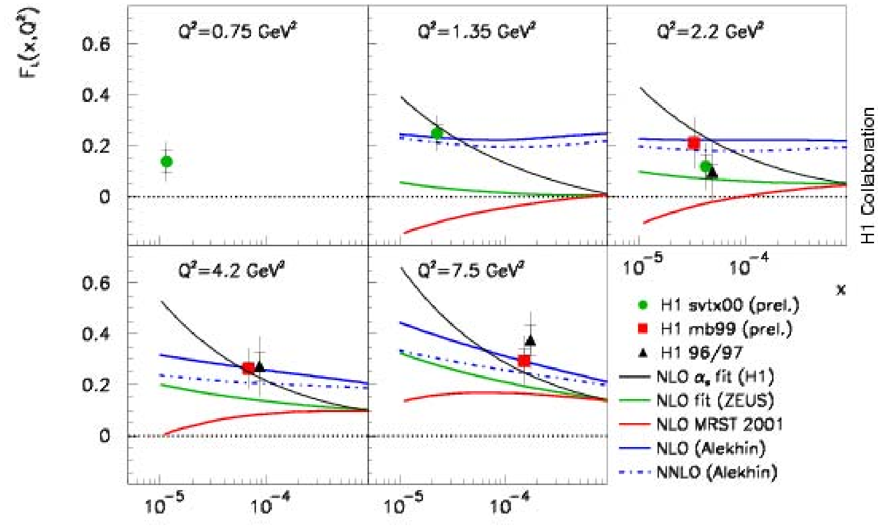
Contribution to total σ



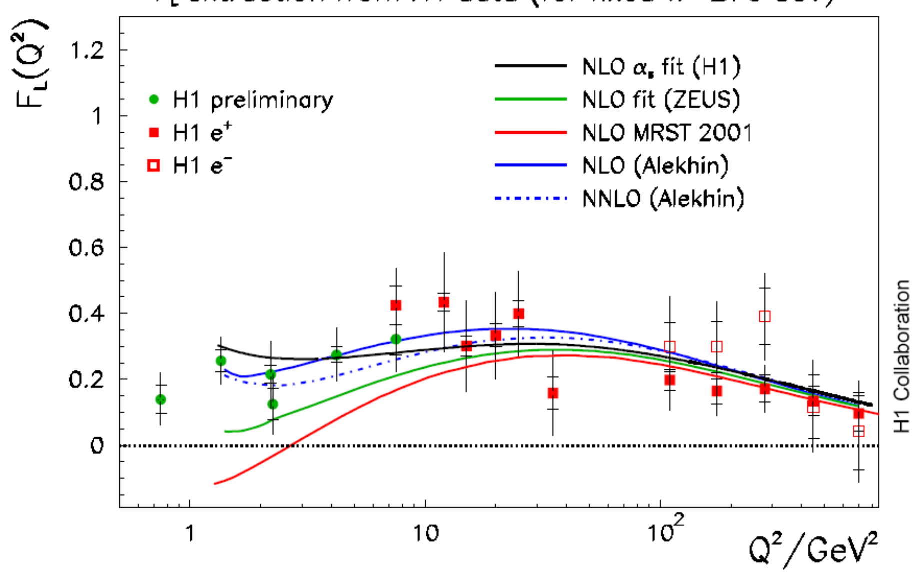
Determination of $F_L(x,Q^2)$ by H1

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





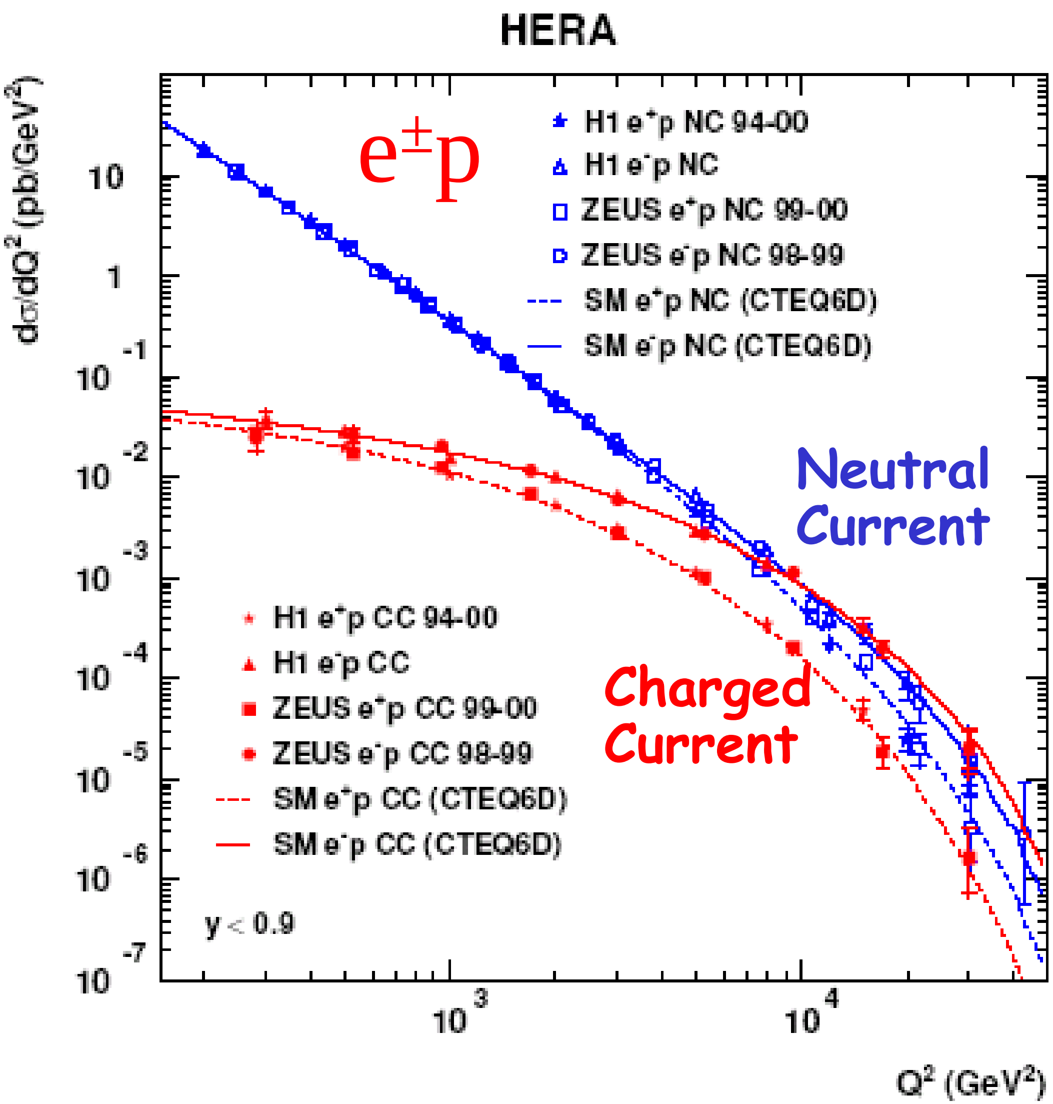
F_L extraction from H1 data (for fixed W=276 GeV)



direct F_L measurements still to be done at HERA

→ low beam energy running

NC and CC at High Q^2



quarks are pointlike
down to proton radius/1000
$r < 10^{-18}$ m

$\sigma_{NC} \approx \sigma_{CC}$ at $Q^2 \approx M_Z^2, M_W^2$
unification of electromagnetic
weak interactions

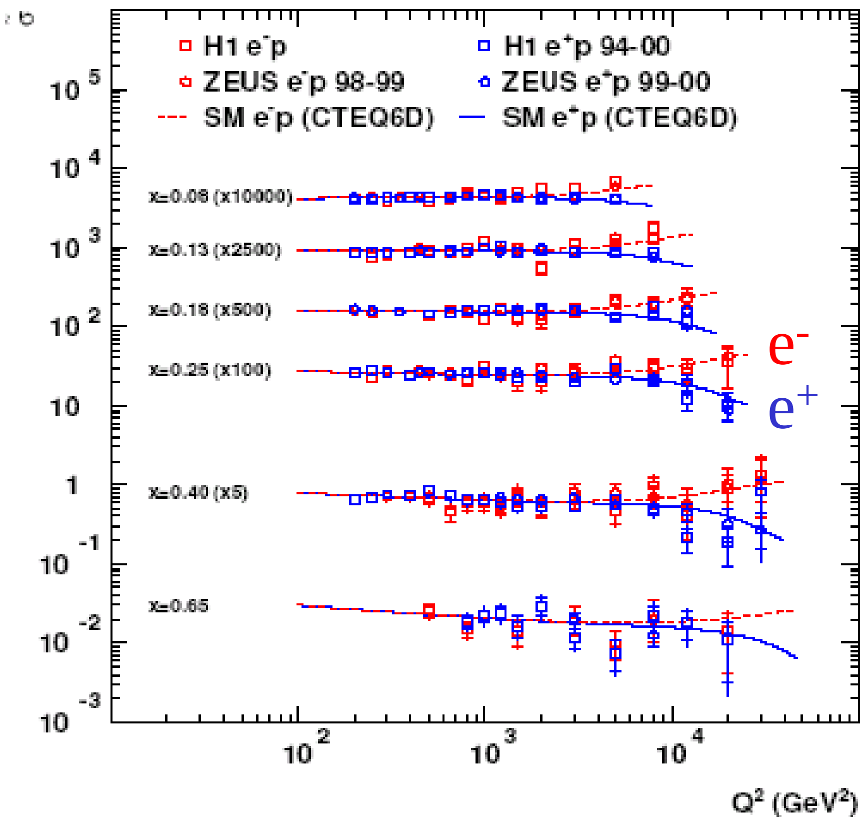
high Q^2 -> high x
provide possibility to unfold
different quark flavours

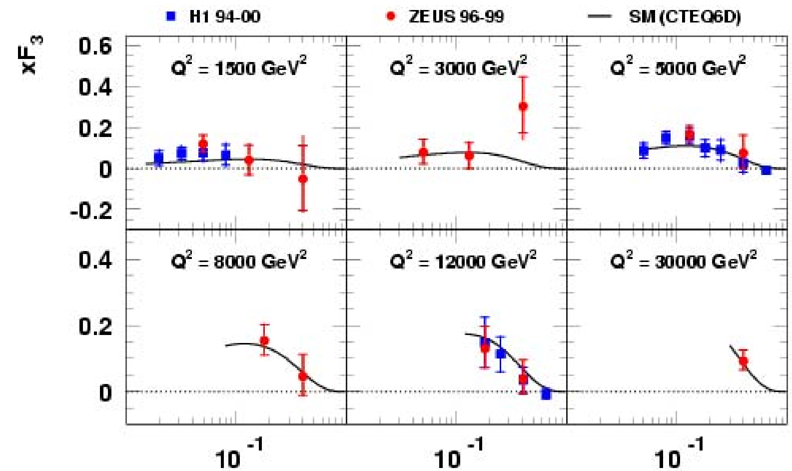
Structure Function xF_3 at HERA

reduced NC cross section:

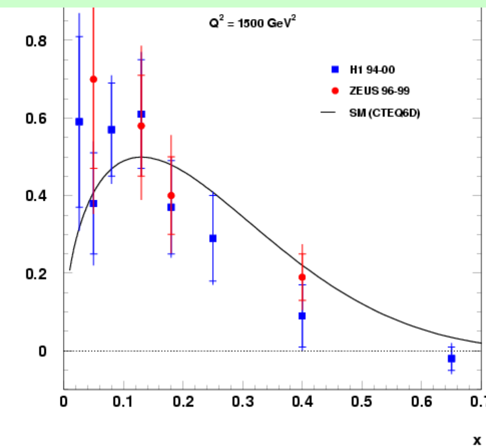
$$\tilde{\sigma}^{\pm}_{NC} = F_2 - \frac{y^2}{Y_+} F_L \mp \frac{Y_-}{Y_+} xF_3$$

HERA Neutral Current at high x





$$xF_3^{\gamma Z} = \frac{xF_3}{-a_e k_w / (Q^2 + M_Z^2)} \sim 2u_v + d_v$$

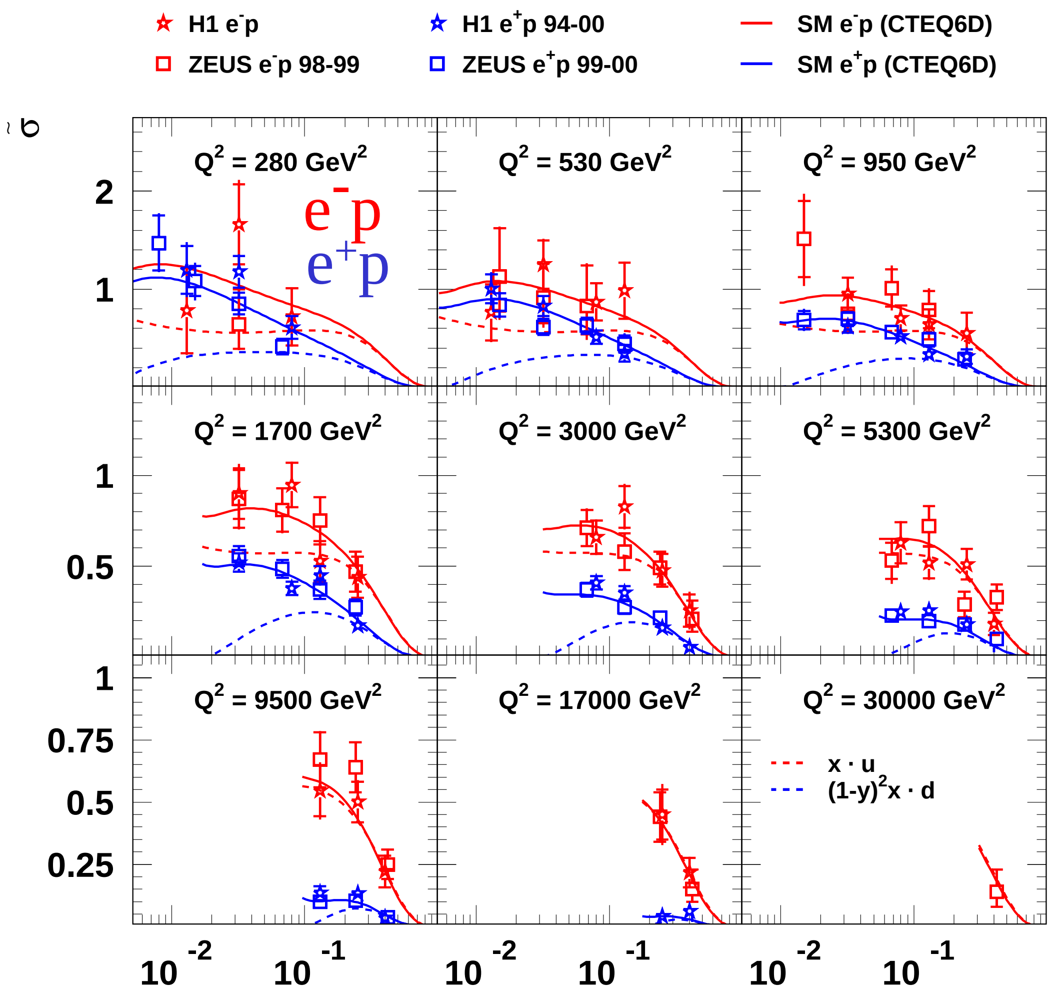


xF_3 constrains u_v,d_v at high x

Charged Currents

$$\frac{d^2\sigma_{CC}(e^{\pm}p)}{dxdQ^2} = \frac{G_F^2 M_W^4}{2\pi x}\frac{1}{(Q^2+M_W^2)^2}\underbrace{\frac{1}{2}\left[Y_+W_2 - y^2 W_L \mp Y_- xW_3\right]}_{\tilde{\sigma}_{CC}(x,Q^2)}$$

$\tilde{\sigma}_{CC}(x,Q^2)$ - reduced CC cross section



The CC e^+p cross section
- dominated by d quark

$$\tilde{\sigma}_{CC}^{e^+p}(x,Q^2) \sim (\bar{u}+\bar{c}) + (1-y)^2(d+s)$$

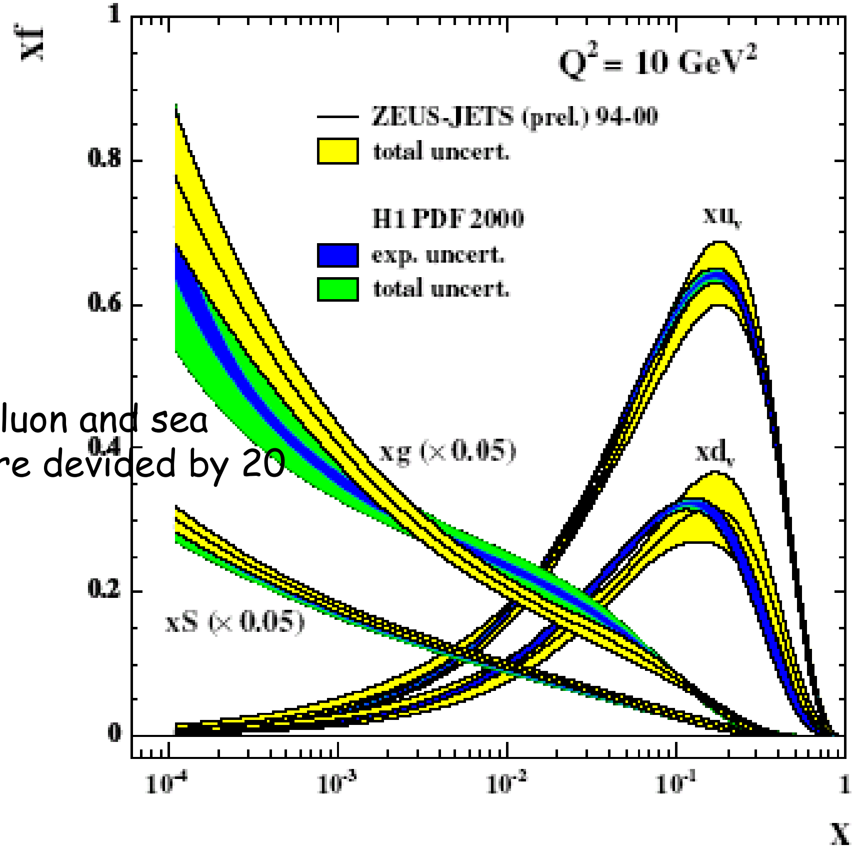
The CC e^-p cross section
- dominated by u quark

$$\tilde{\sigma}_{CC}^{e^-p}(x,Q^2) \sim (u+c) + (1-y)^2(\bar{d}+\bar{s})$$

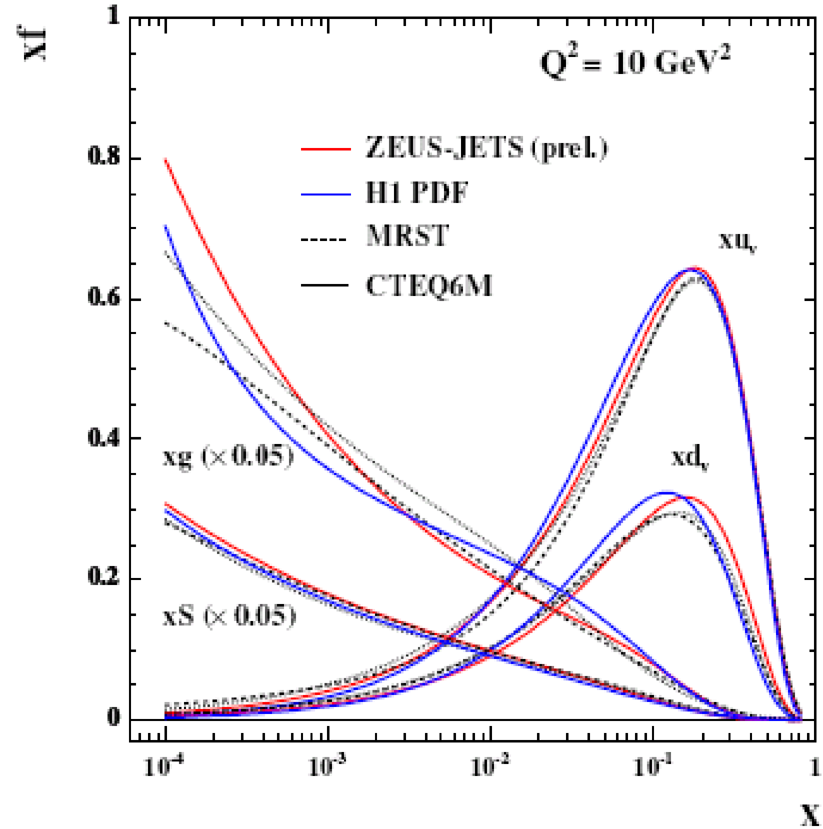
CC e^+p (e^-p) cross sections are suited for constraining d (u) quark density

PDFs from HERA

Parton distributions unfolded using HERA NC and CC data only



Gluon and sea
are devided by 20



- H1 and ZEUS parton distributions are in agreement

-Treatment of systematics, parameterisations forms and other details are subject to conventions

- HERA QCD fits agree with the global fits

H1 $U,\bar{U},D,\bar{D},xg \leftrightarrow V,A,xg - \alpha_s$

ZEUS $u_v,d_v,\bar{u}\pm\bar{d},xg-\alpha_s$

First Results from HERA II

detector and luminosity upgrade
- efficient data taking since 2003
- $O(1fb^{-1})$ till 2007

longitudinally polarised e beam

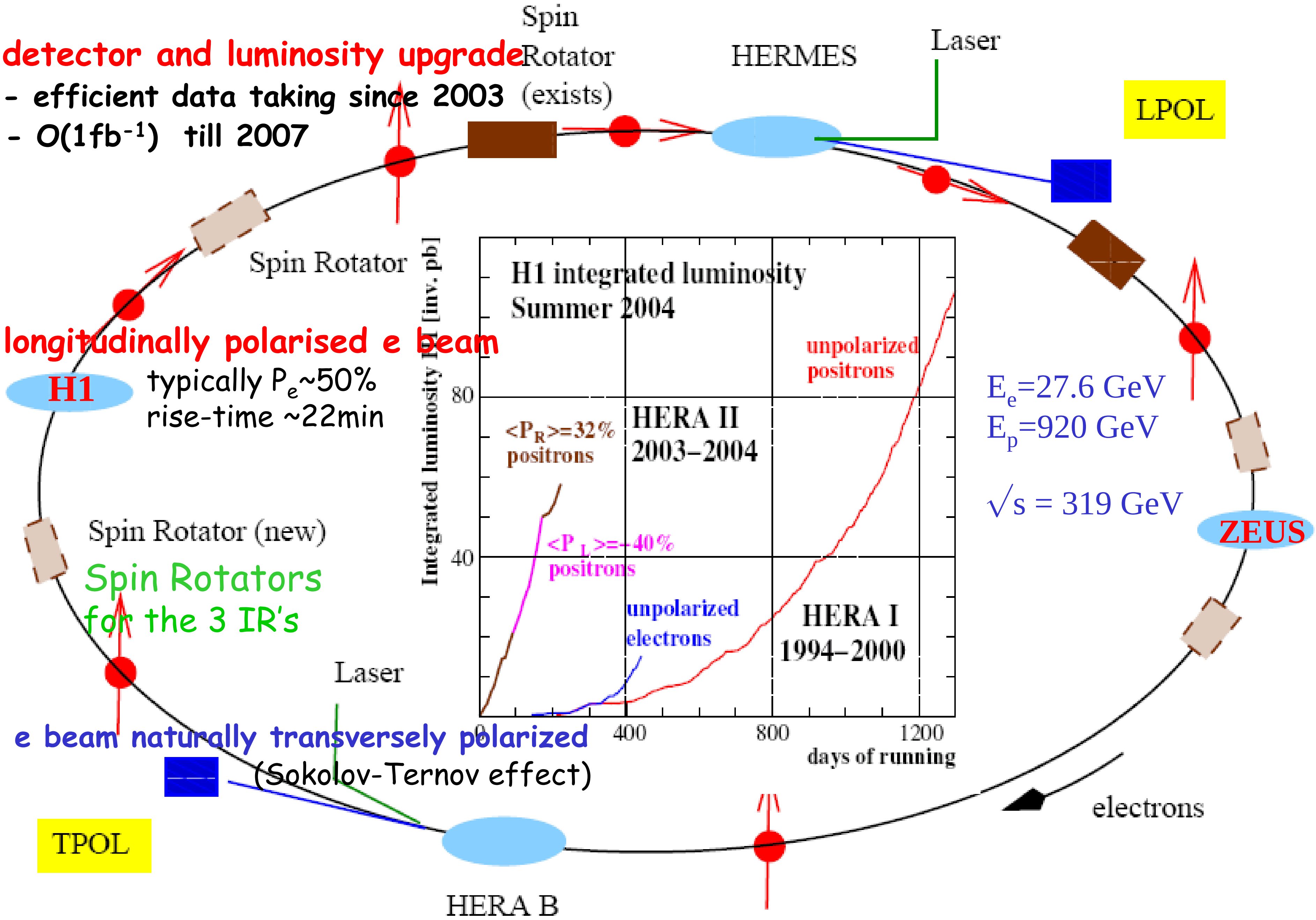
typically P_e~50%
rise-time ~22min

Spin Rotators
for the 3 IR's

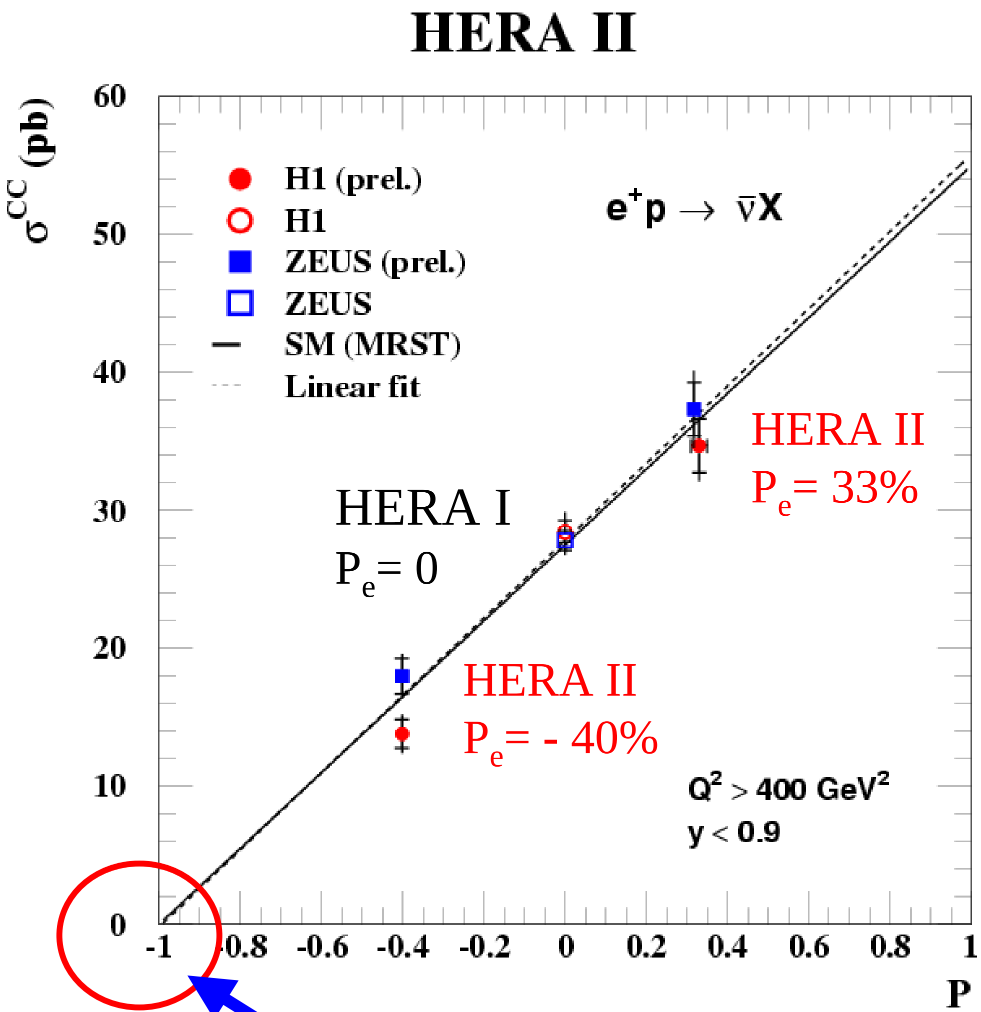
e beam naturally transversely polarized
(Sokolov-Ternov effect)

E_e=27.6 GeV
E_p=920 GeV

$\sqrt{s}$ = 319 GeV



σ_{CC} using Longitudinally Polarised e^+



$$\sigma_{CC}^{e^{\pm}p}(P_e) = (1 \pm P_e)\sigma_{CC}^{e^{\pm}p}(P_e = 0)$$

Polarisation dependence is firmly established

Linear fit $\sigma_{CC} = \alpha + \beta(1+P_e)$

$$\sigma_{CC}^{tot}(P_e = -1) = -0.2 \pm 1.8(sta) \pm 1.6(sys)\,pb$$

consistent with
- linear $(1+P_e)$ dependence
- intercept of 0

after shutdown fall 2004
$\rightarrow$ e^- running

extrapolation to P_e=-1 tests the absence of right-handed current

Summary

for more than 30 years SF provide a crucial experimental input to establish QPM, QCD and to determine pdfs

still very active area: NuTeV, JLAB, …
HERA II ~ O(1fb^{-1}) till 2007, low energy running for F_L

new level of precision (exp. ~1%, theory NNLO) allows
- to investigate applicability domains for different QCD evolutions
- to understand high density (low x) QCD
- to provide information essential for future LHC collider
  see HERA-LHC workshop: http://www.desy.de/~heralhc/

large potential for the long term future
- HERA III (ed, …), eRHIC, e(ILC)×p(HERA,TeVatron)

Strange Sea Asymmetry Results from NuTeV

the "NuTeV Anomaly" $R^- = \frac{\sigma_\nu{}^{NC} - \sigma_{\bar\nu}{}^{NC}}{\sigma_\nu{}^{CC} - \sigma_{\bar\nu}{}^{CC}} \simeq \frac{1}{2} - \sin^2\Theta_W$

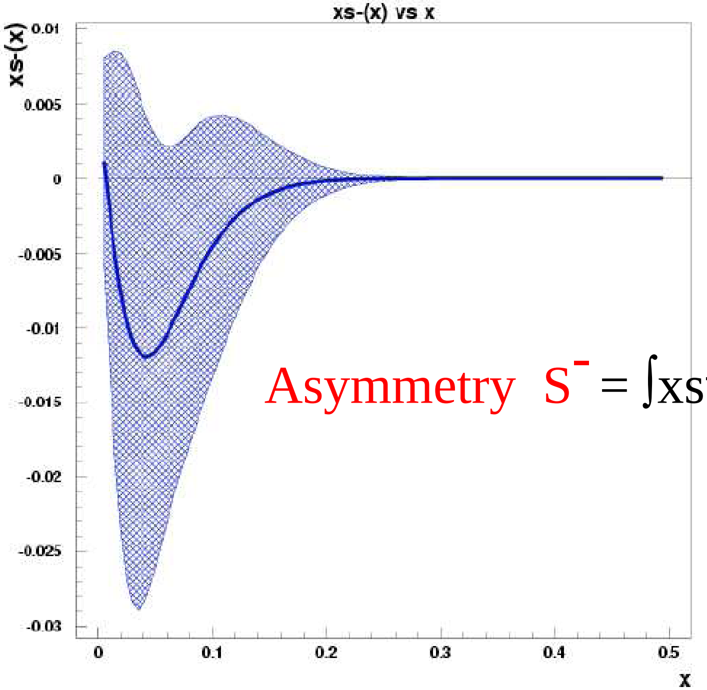
a 3.1 σ discrepancy:

NuTeV $\sin^2\Theta_W = 0.2277 \pm 0.0016$

LEP EWWG $\sin^2\Theta_W = 0.2227 \pm 0.0037$

Test one of the interpretations (from many):

- strange/anti-strange sea quark asymmetry



dimuon production:

$\nu_\mu s \rightarrow \mu^- c \rightarrow \mu^- \mu^+ X$ (CCFR, NuTeV)

NLO fits to ν and $\bar\nu$ dimuon data

Asymmetry $S^- = \int xs^- dx = \int x[s(x) - \mathrm{sbar}(x)]dx = -0.0009 \pm 0.0014$

To explain "NuTeV Anomaly" would require $S^- = +\mathbf{0.0060}$