Physics and Visions at HERA

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Introduction

- ep scattering is like a *cantus firmus* in Gerd Buschhorn's scientific life and HERA is the coronation
- We are both members of H1 experiment at HERA
- E.Lohrmann's talk shows that GWB on familar terms with e and p interacting via γ
- GWB had to wait for HERA to see also the weak aspects induced by Z and W
- Since 1972 director at the MPI München: –exciting moment in physics: beginning of the *Standard Model*
- GWB had all the knowledge and experience necessary to push the HERA project and then to participate actively in the program
- GWB proved vision by opting for HERA

HERA

- ep collider has a long history (CHEEP, PROPER)
  HERA is the result of a vision
  one of the proponents : Bjorn Wiik
- ECFA recommendation on May 9, 1980:
  The e-p working group of ECFA has conclusively demonstrated the unique scientific interest of ep collisions. Such investigations are complementary to the program realizable by LEP and other projects elsewhere. ECFA recommends strongly the construction of this machine at DESY and welcomes the possibility of it being used by the European Community
- Proposal : July 1981
  also signed by Gerd Buschhorn
- Various international workshops to assess physics potential
  Note: SM established at lowest order; clear jets at PETRA; W, Z not yet observed

HERA's virtues

Prominent invited speakers present their visions of physics with HERA

Unique properties :

a. colliding pointlike particle on extended object

b. the quantum numbers of the initial state

c. huge extension of (Q^2, x)-phase space

d. simultaneous study of NC and CC

Also pessimistic voices :

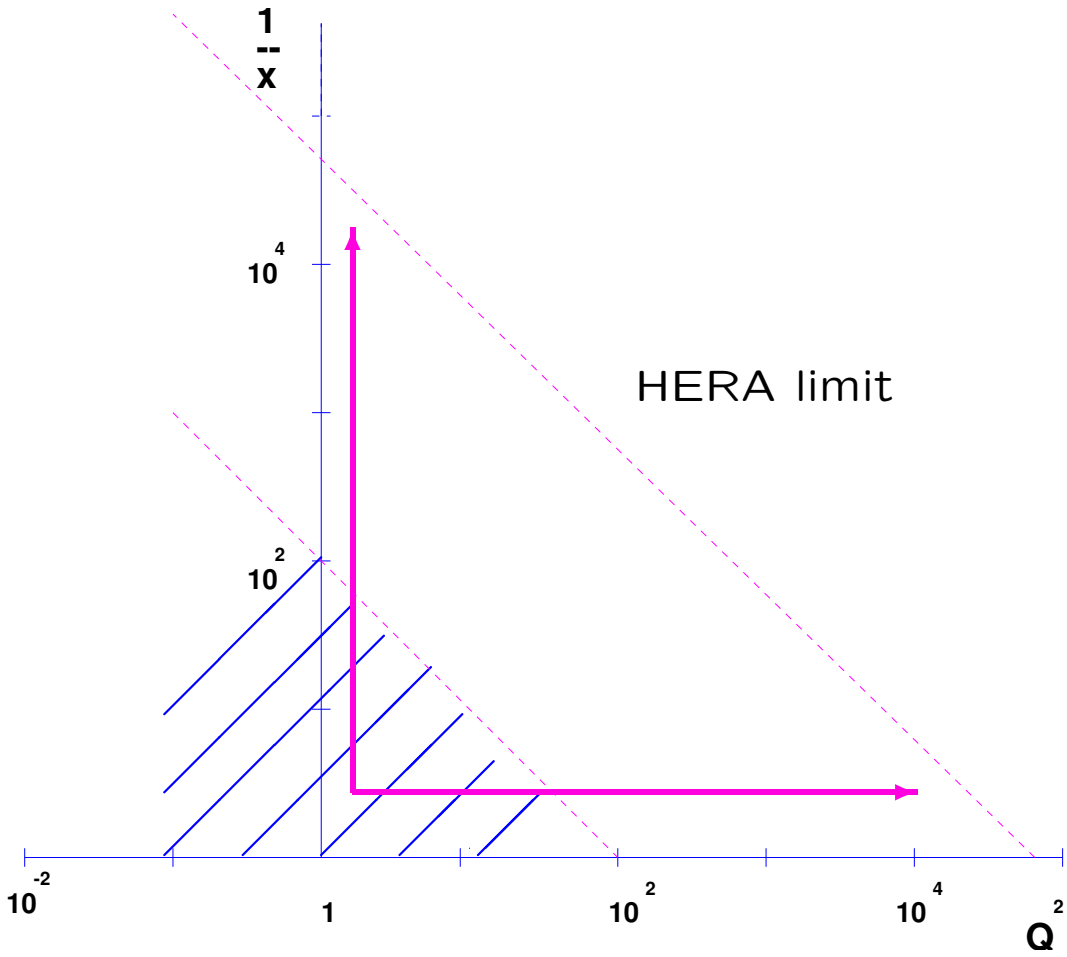
- no discoveries at HERA
- jets ?

Approval 1984 and start operation 1992

3 first-year results :

1. New weak process and W propagator
2. Rise of F_2 at low x
3. Large diffractive contribution

Phase space regions

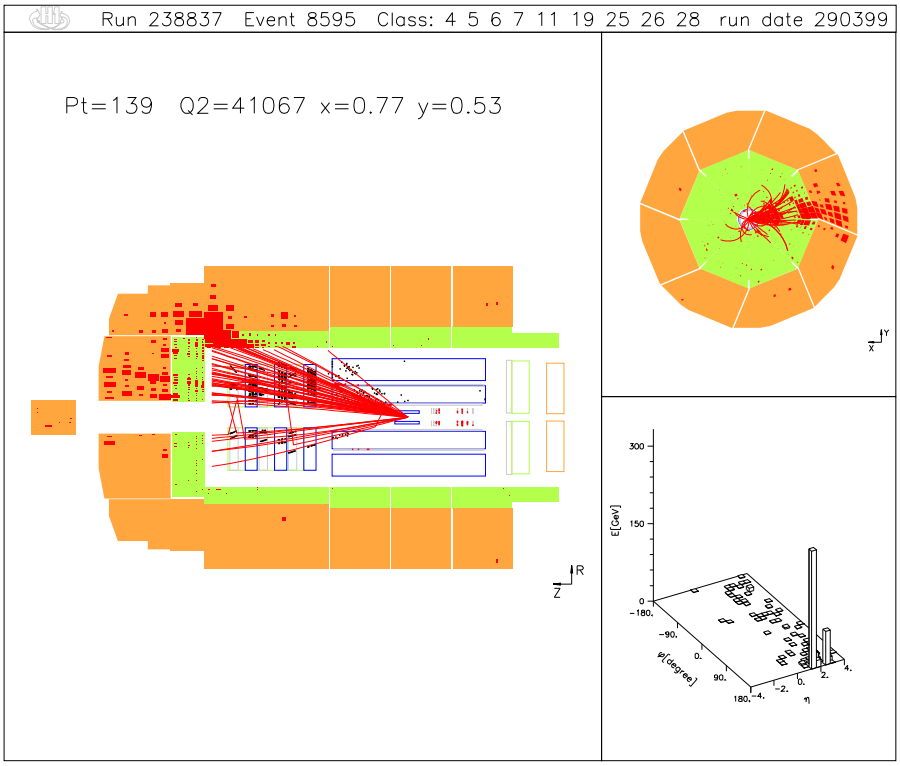


Proton size defines a scale : $Q_p^2 \approx 1$ GeV^2

- $Q^2 > Q_p^2$: QCD evolution
- Propagator effects for $Q^2 = \mathcal{O}(M_W^2)$
- Transition from perturbative to nonperturbative physics
- Limit $Q^2 \to 0$: γp physics
- access to deep sea (low x)
  also in perturbative region

A new weak process

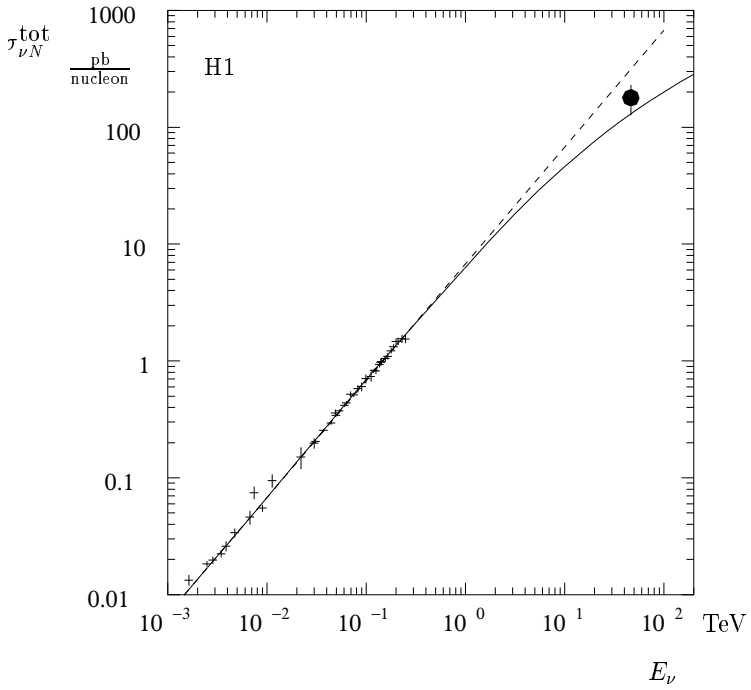
HERA reveals the process : $e^+p \rightarrow \overline{\nu}_e + anything$



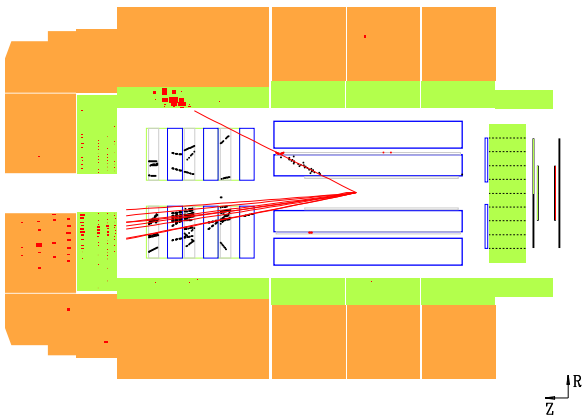
- Expected as inverse of $\nu_\mu N \rightarrow \mu + anything$
- Purely weak process; precisely predicted within SM
- 1^{st} analysis : $|\sum_i (\vec{p}_T)_i| > 25$ GeV
  14 CC almost background free $\Rightarrow \sigma_{tot}$
- Example of physics with missing momentum (need hermetic detector)

Two striking conclusions

a. Effect of W-propagator manifest in σ_{tot}



b. Discover new event type: missing p_T and high p_T charged lepton (here: e^-)



Historical note

SIENA conference 1963 : first results from CERN ν experiments

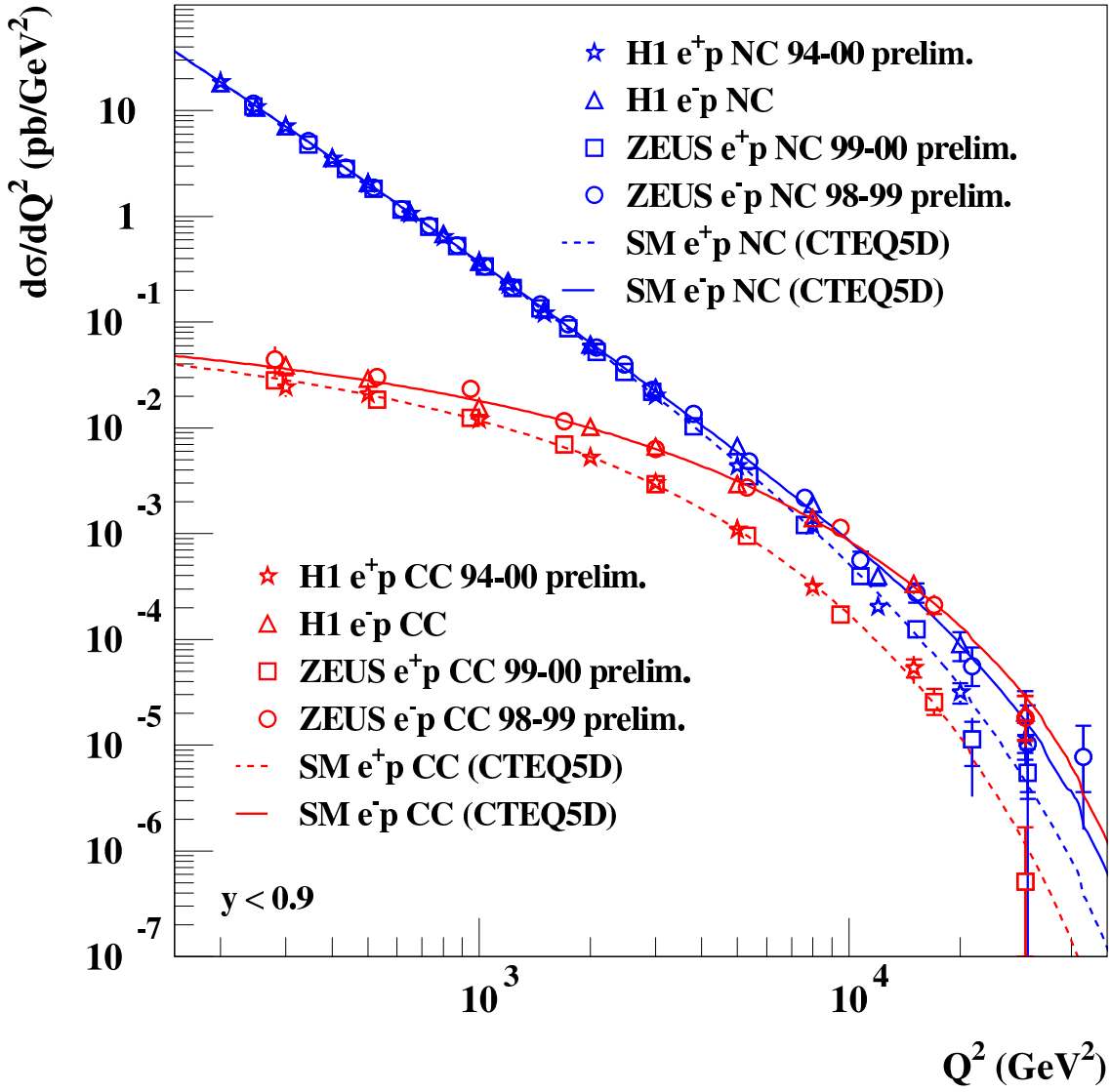
- Problem No.1 of weak interactions: where is the IVB?
- Two signatures :
  a. if W light, production and leptonic decay of $W \rightarrow$ two leptons in final state (here begin searches with two-lepton signature !).
  b. if W too heavy, detect W-propagator effect causing σ_{tot} to deviate from linearity (first hint to pointlike constituents)
- Result : observe a handfull dilepton events (BC and SC); W? no, assign to background, nobody dares thinking about new degree of freedom (charm).

HERA H1 plot ready in fall 1993 (H1 meeting at Rome) closing a 30-year old question.
Benefit from: $Q^2 = \mathcal{O}(M_W^2)$

γ, Z interference

Neutral current process : $e^{\pm}p \rightarrow e^{\pm} + anything$

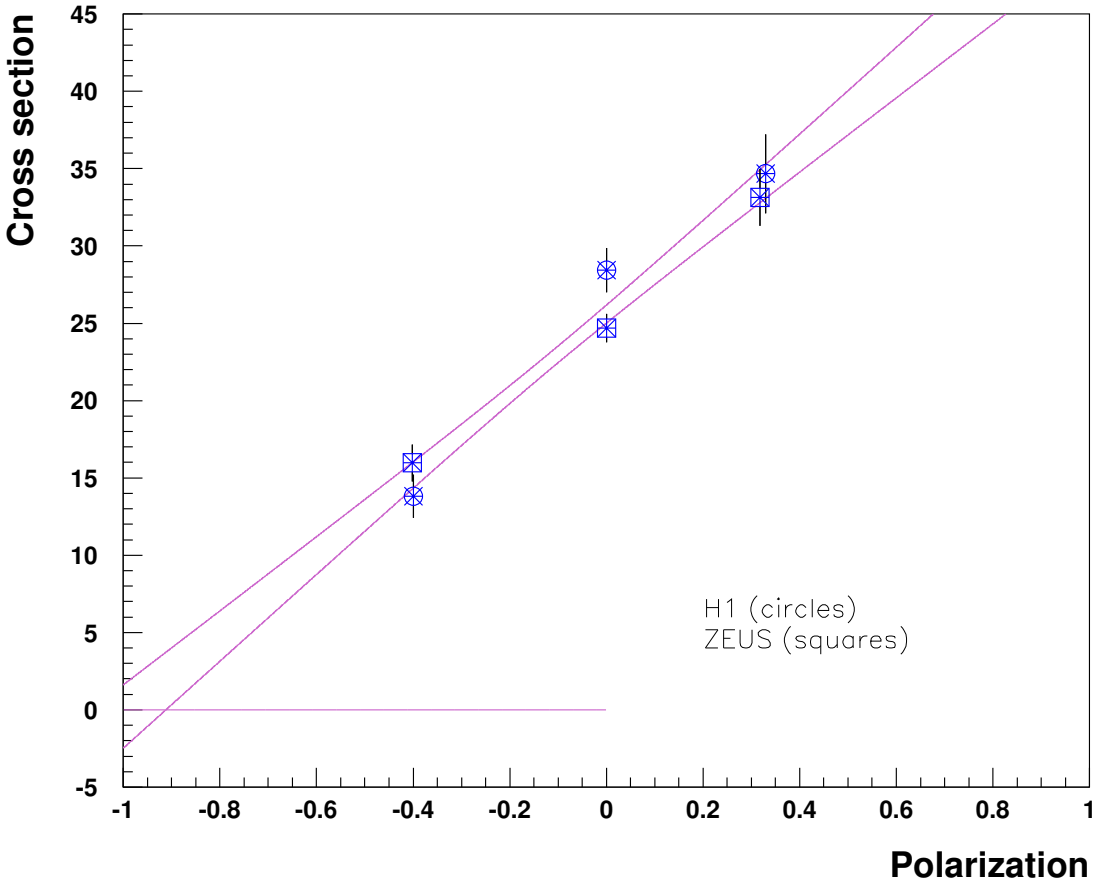
- process mediated by γ and $Z \Rightarrow$ observe interference effect at large Q^2
- compare with $ep \rightarrow \nu + anything$



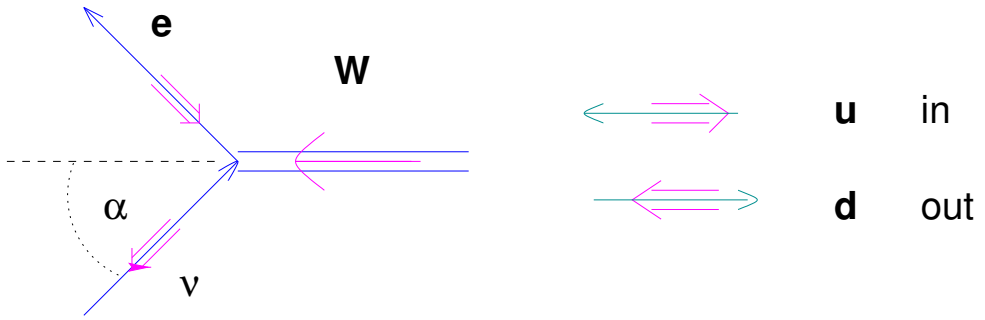
Earlier : SLAC ed, APV, PETRA, LEP

HERA: polarized positrons

- e^+ is massive $\Rightarrow$ two helicity states : $(e^+)_R$ and $(e^+)_L$
- Textbook experiment to test V-A theory
  Weak processes : only $(e^+)_R$ participates $\Rightarrow$ show $(e^+)_L + p \rightarrow \overline{\nu_e} + anything$ vanishes
- Present status (ICHEP 2004)



Proton structure functions



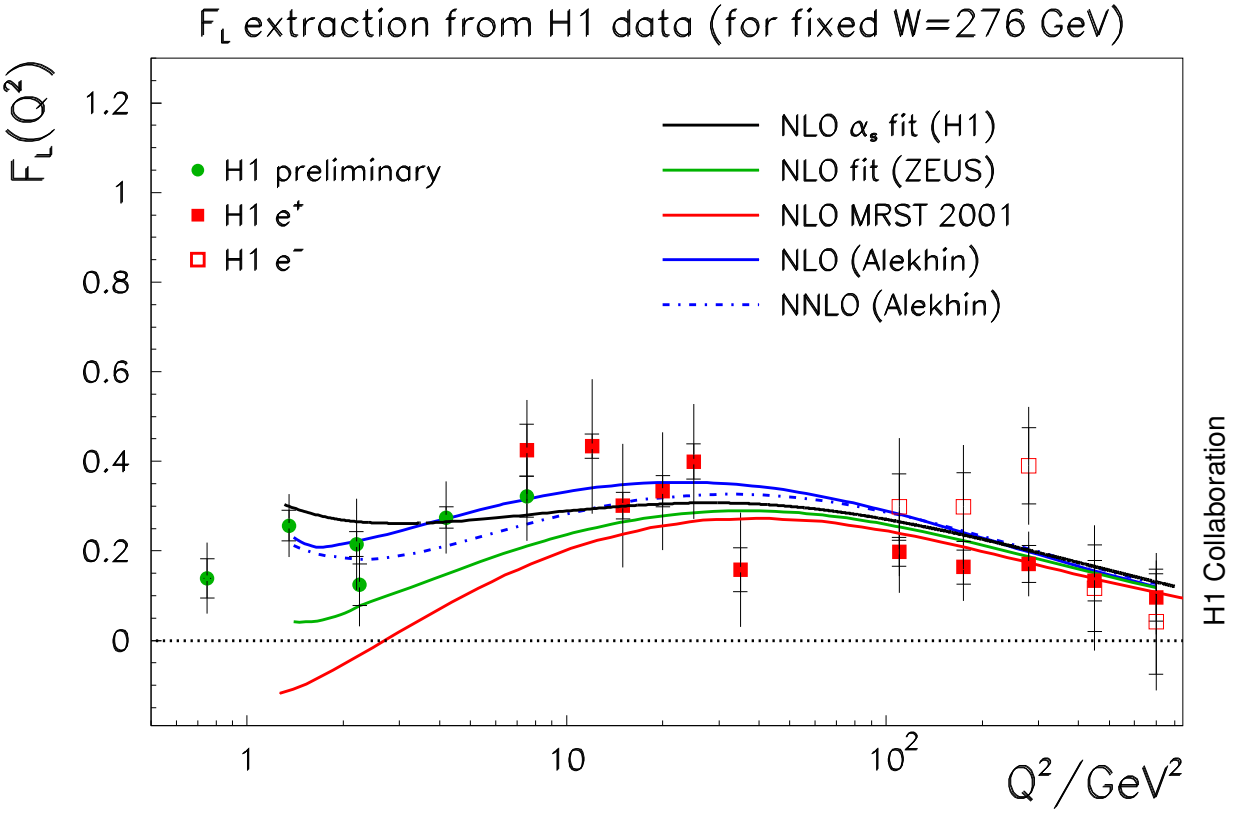
- spin(W)=1 $\Rightarrow$ three helicity states (1,0,-1)
  $\Rightarrow$ angular distribution (1,$\cos\alpha, \cos^2\alpha$)
  $\cos\alpha \leftrightarrow$ 1-y
- Cross section has the generic form :

  $$d\sigma \sim (F_+ * 1 + F_0 * \cos\alpha + F_- * \cos^2\alpha)\, dx dQ^2$$

- Structure functions: fundamental scalars depending on x and Q^2
- Usual notation: $F_\pm = xF_1 \pm \frac{1}{2}xF_3$ $\qquad$ $F_0 = F_L$
- $F_2 = F_+ + F_- + F_0$ is best measured
  Interpretation in QPM $\sum x(q+\overline{q})$

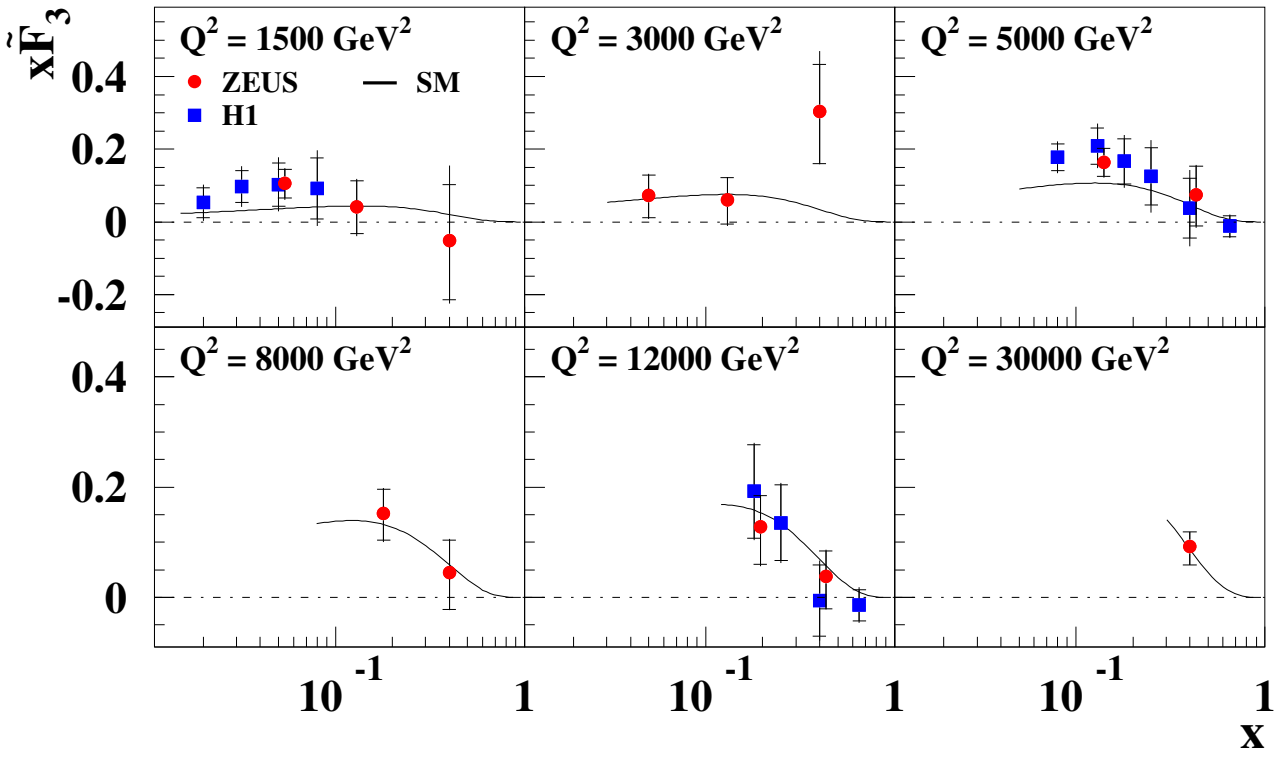
F_L

- QPM: F_L=0
- QCD-NLO: $F_L \geq 0$
- $d\sigma^{\gamma p} \sim F_2 - \frac{1}{2}y^2 F_L$
- Canonical method : vary machine energy
- But total energy fixed, thus apply trick: at large y the differential cross section sensitive to F_L, then disentangle F_2 and F_L via shape

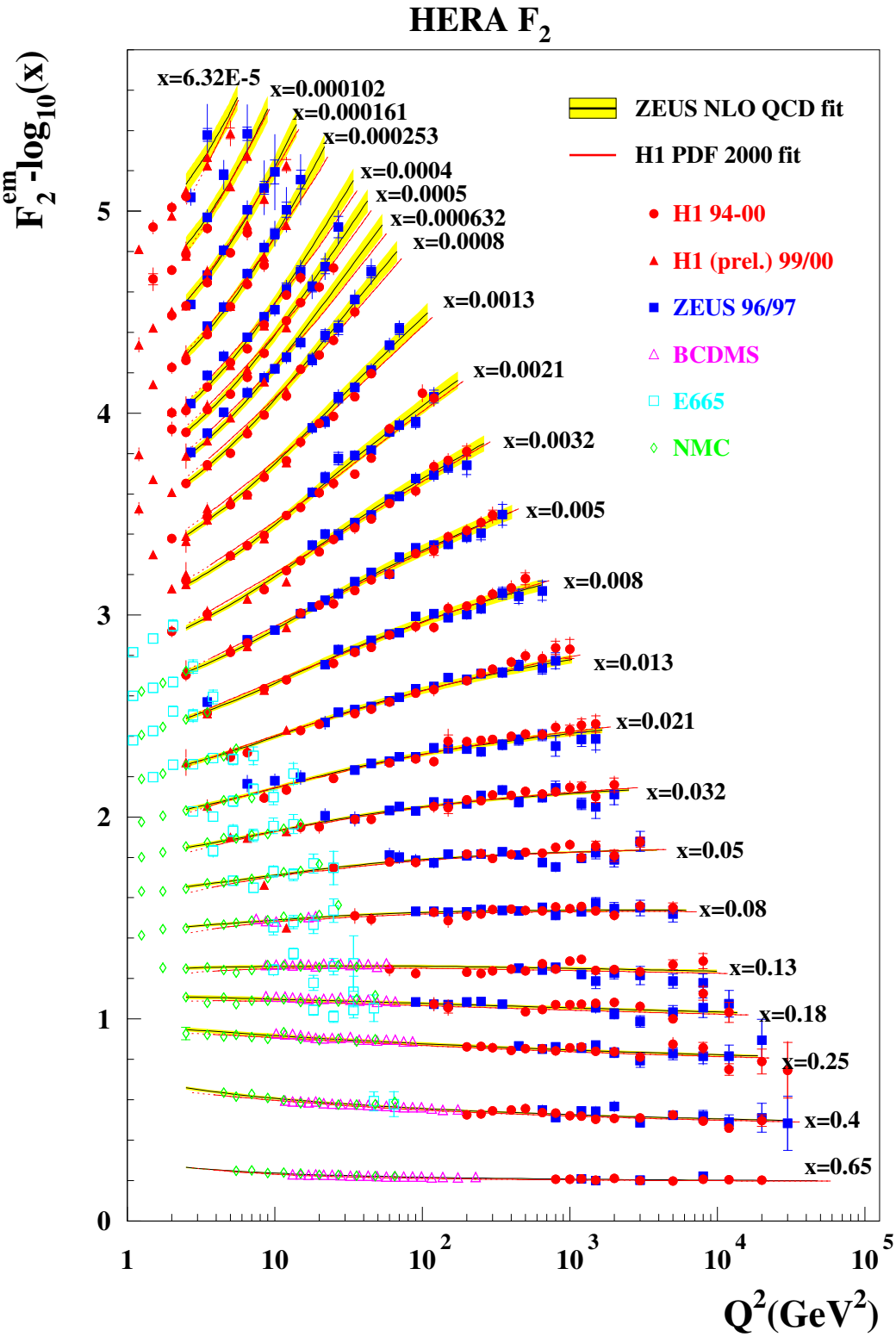


F_{weak}

- $ep \to e + anything$ proceeds via γ and Z exchange
- Measure weak effects for $Q^2 =$ order M_Z^2:
  1. $\gamma - Z$ interference
  2. xF_3



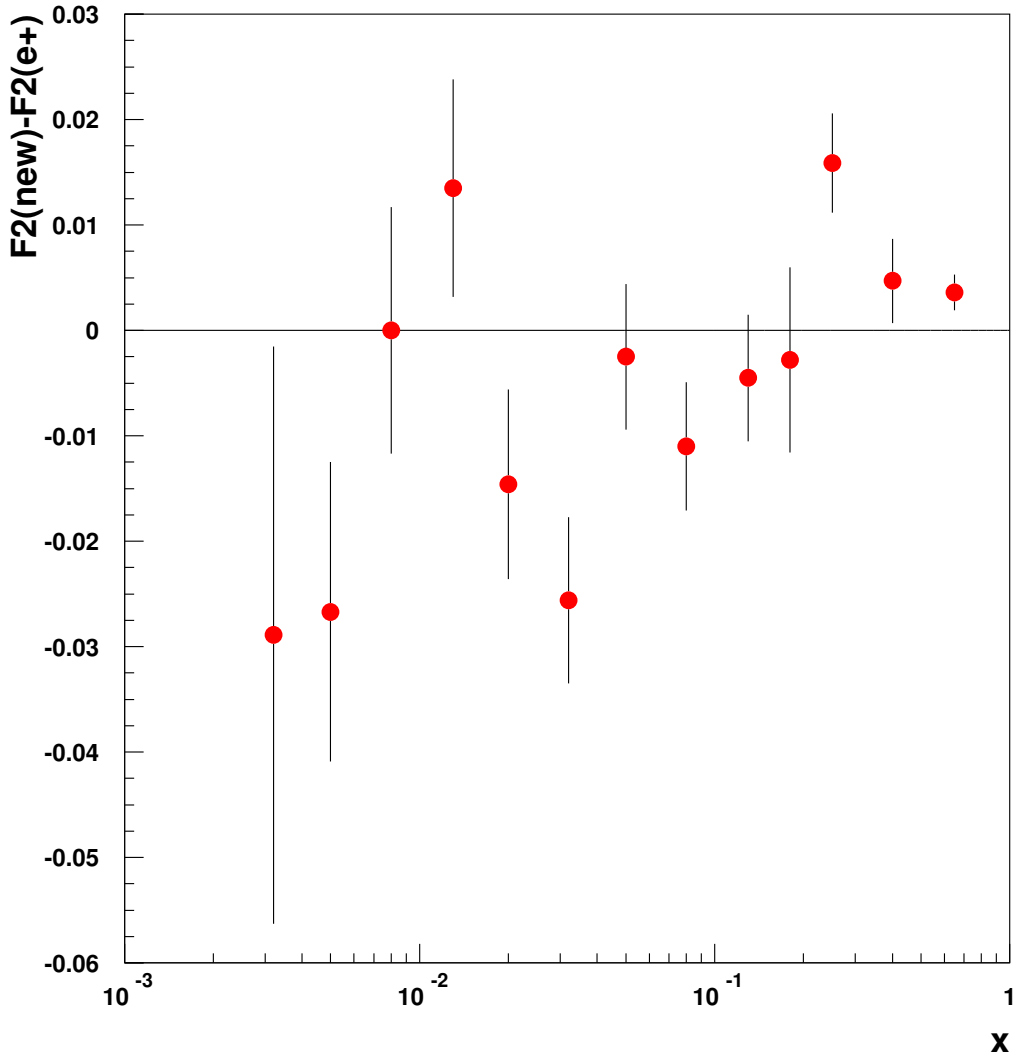
The HERA F_2-plot



A critical look

Test importance of systematic uncertainties :

- H1 measured $F_2(x_i, Q_j^2)$ independently from data 1996/7 and 1999/2000
- $F_2(x, Q^2)_a$-$F_2(x, Q^2)_b = 0$ within statistics, provided there is no bias



Discussion of F_2

Strong aspects

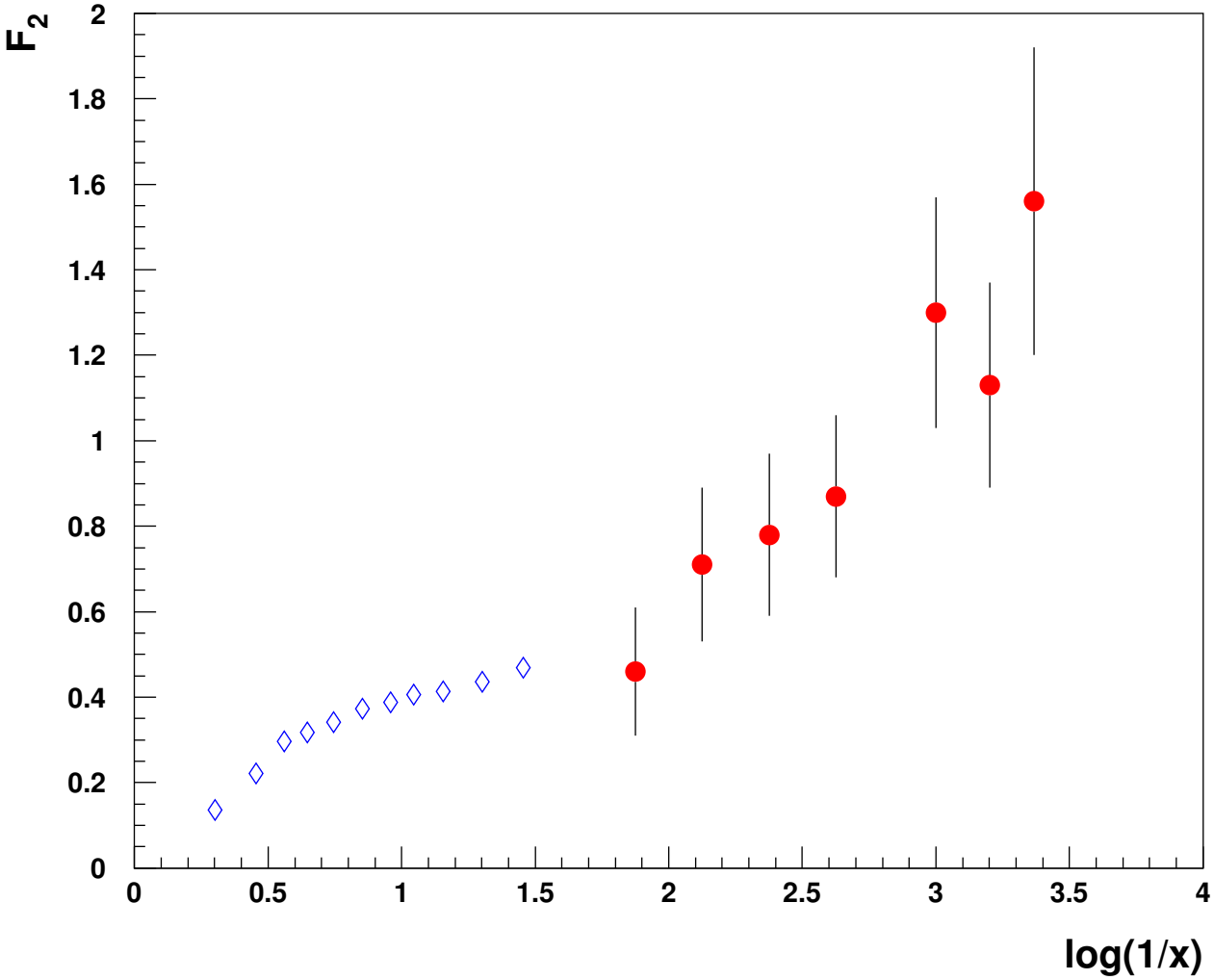
- The HERA experiments H1 and ZEUS have done a good job
- Test pQCD through DGLAP evolution at large x over 4 decades in Q^2
- Open a new regime at low x (high gluon density)
- Smooth transition in Q^2 from perturbative into nonperturbative physics

Weak aspects

- It is time to establish region of validity for DGLAP in (x, Q^2)-phase space
- QCD fit depends on all pdf (too many free parameters); only consistency is tested
- Crucial rôle of gluon
- $\int dx(s - \overline{s})(x, Q^2)$=0 does not imply $s = \overline{s}$ (NUTEV and discrepancy in $\sin^2\theta$)

Low-x

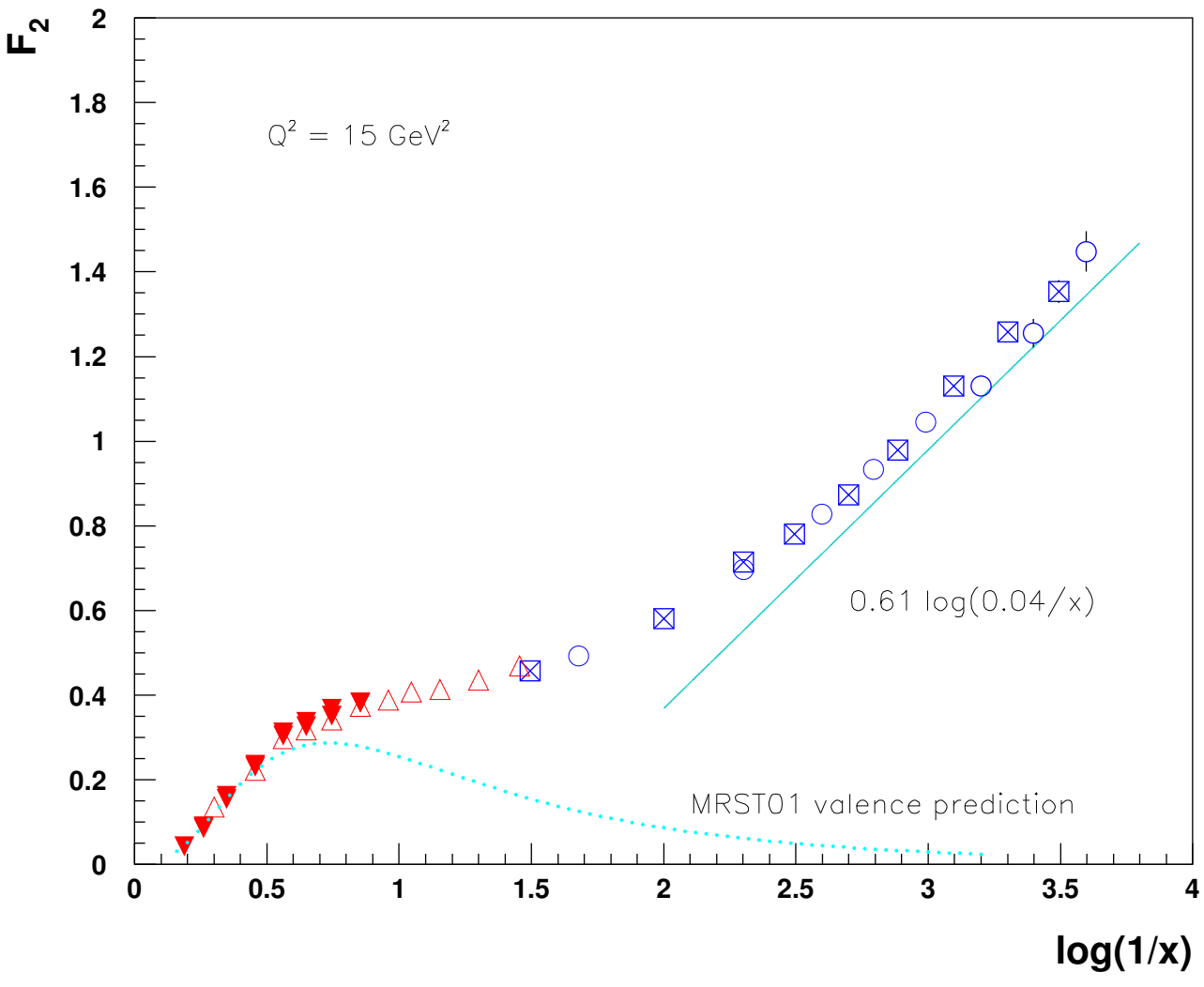
Earliest H1 data (1992/3) reveal a surprise:
F_2 increases as x decreases (fixed Q^2=15 GeV^2)



- Rise not foreseen (exception pub 1975)
- New field for QCD — high gluon density

Low-x update

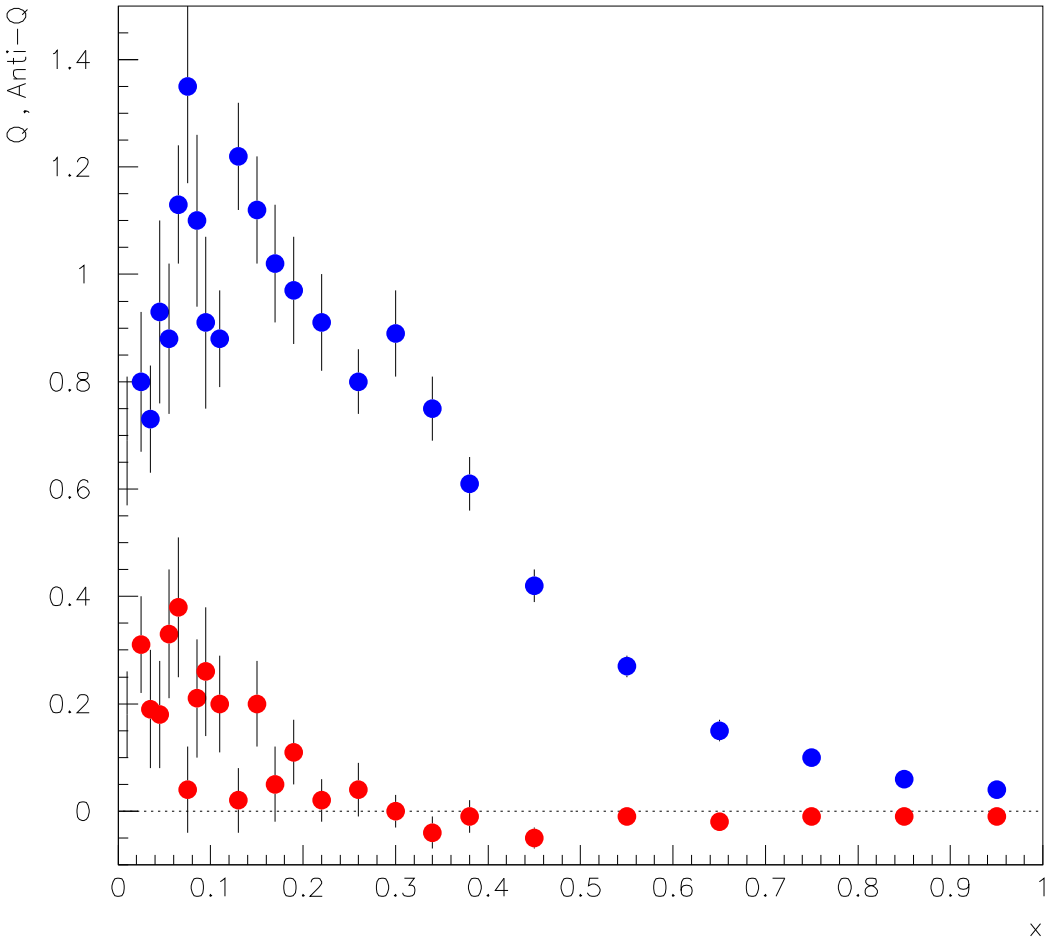
- $F_2 \sim \sum x(q + \overline{q})$
  q and $\overline{q}$ on same footing
- But: shape of F_2 distinctly different at large x (valence) and at low x (sea)
- power law or logarithmic ?



Old low-x data

Compare with Gargamelle 1973

- Study of νN and $\overline{\nu} N$
- First observation of nucleon sea
  $\Rightarrow$ existence of anti-quarks



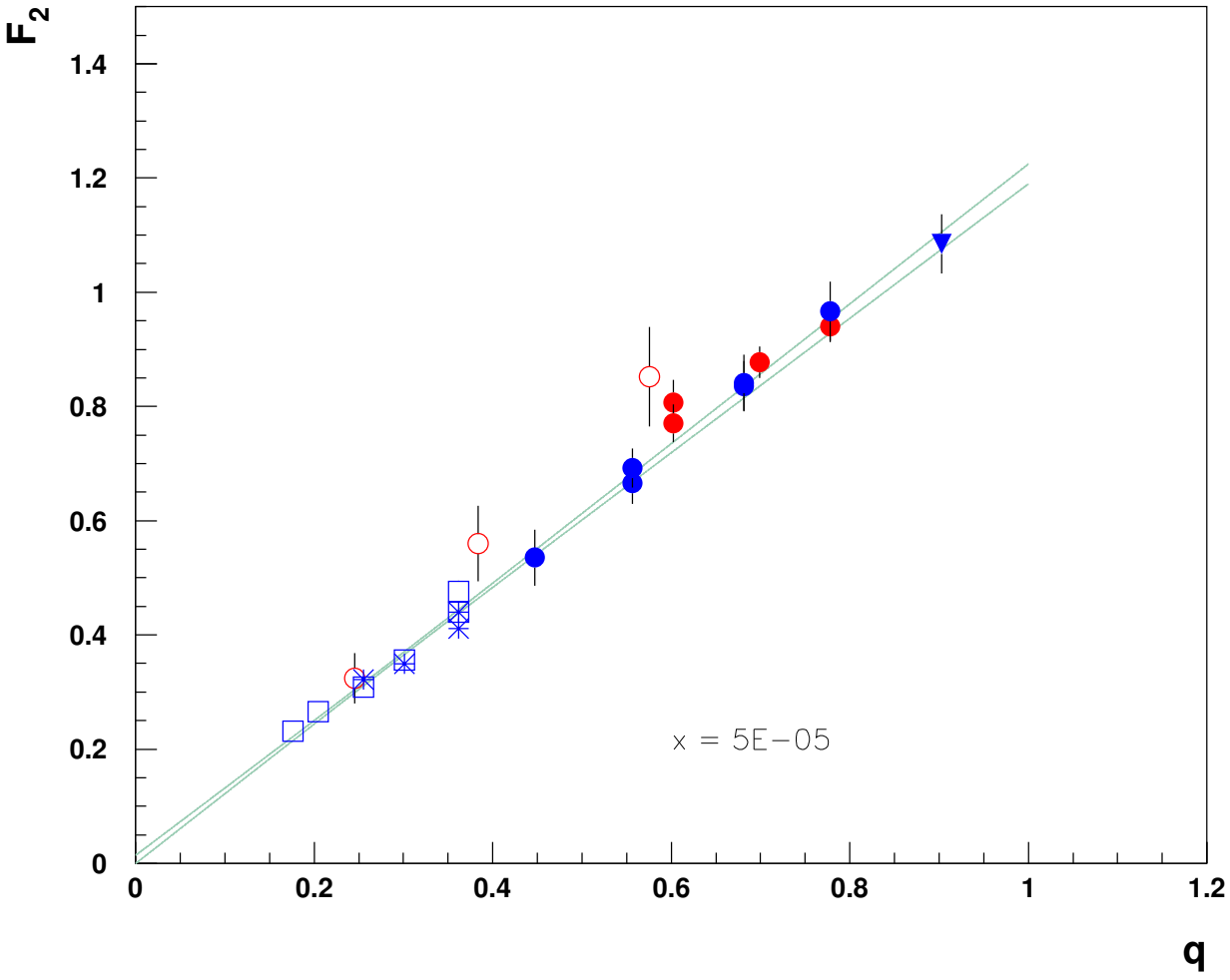
Note: Plot linear in x

Behaviour at low x ?

Low x and low Q^2

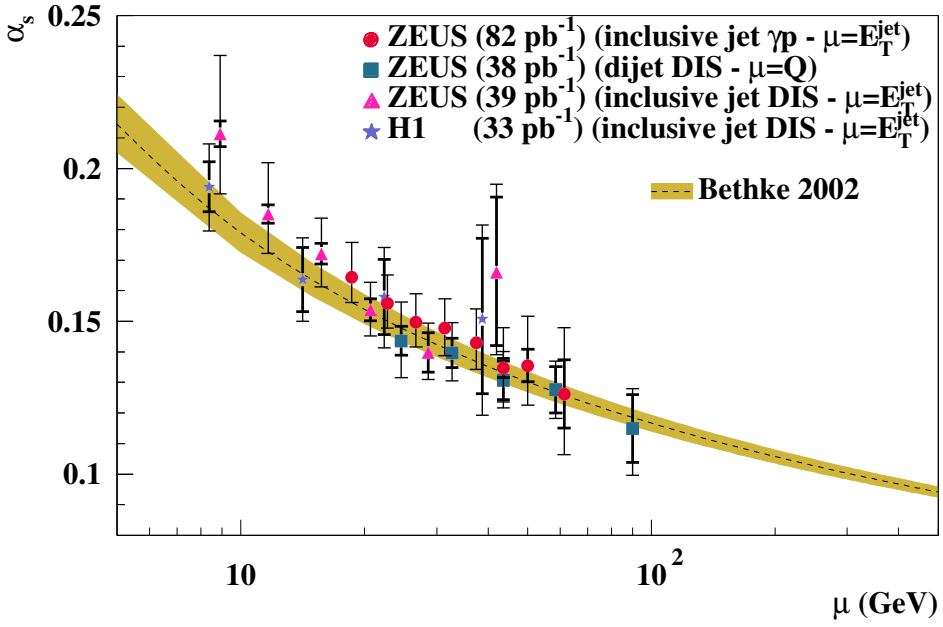
Investigate transition $Q^2 \to 0$

- Variable log Q^2 inconvenient for Q^2 near 0
- Introduce variable q=log(1+Q^2/Q_0^2)
  1. $Q^2 \to 0$ implies $q \sim Q^2$
  2. $Q^2 \gg Q_0^2 \approx$0.5 GeV^2 implies $q \sim$ log Q^2



QCD coupling $\alpha_s(Q^2)$

- QCD 1972 : explain DIS and predict nonscaling
- First QCD tests in fixed target experiments during the 70's: LO analyses without conclusive results (F_2 and gluon vs. xF_3) Perkins : *it is not even walking*
- Importance of radiative effects
- Advantage of HERA : very large phase space decrease with Q^2 seen by a single experiment



Outlook

Backward :

1. HERA is the synthesis of previous low-energy lepton-nucleon fixed target experiments
2. Major developments in the past 4 decades
   a. Genesis of the Standard Model
   b. special purpose $\rightarrow$ omnipurpose detector
   c. small $\rightarrow$ huge collaborations
   d. punched cards $\rightarrow$ personal computers
   e. particle physics and astroparticle physics

Forward :

- SM on solid base $\rightarrow$ what is the origin of its success ?
- High statistics with HERA II

Upward : Plato and Aristoteles
res divinae - res humanae
intelligibilia - sensibilia