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HERA experimental QCD and EW results

1. Introduction
   HERA and experiments
2. DIS at HERA
   Measurement of F_2, F_L
3. QCD analysis
   Extraction of $g(x)$, α_s
4. DIS at very high Q^2
   Comparison with SM
5. $W^{\pm}$ production at HERA

HERA

(**H**adron **E**lectron **R**ing **A**nlage)

27.5 GeV electrons on 820 GeV protons

$\Rightarrow$ γ $(Z^\circ, W^\pm)$ beam energies (in p frame) up to 48 TeV

$\Rightarrow$ Q^2 range 0 $\rightarrow \sim 10^4$ GeV^2
space resolution of $\sim 10^{-16}$ cm

Experiments:

	H1	e $\rightarrow\leftarrow$ p
	ZEUS	e $\rightarrow\leftarrow$ p
	HERMES	e $\rightarrow$ gas target
under construction	HERA-B	p $\rightarrow$ wire target

HERA ep luminosity

Delivered:	1992	0.05 pb^{-1}
	1993	1.1
	1994	6.2
	1995	12.3

Planned: up to 2000 $\sim$ 170. pb^{-1} per year

$\Rightarrow$ 1000 pb^{-1} until 2005

HERA results submitted to ICHEP'96

H1 Collaboration — 42 abstracts

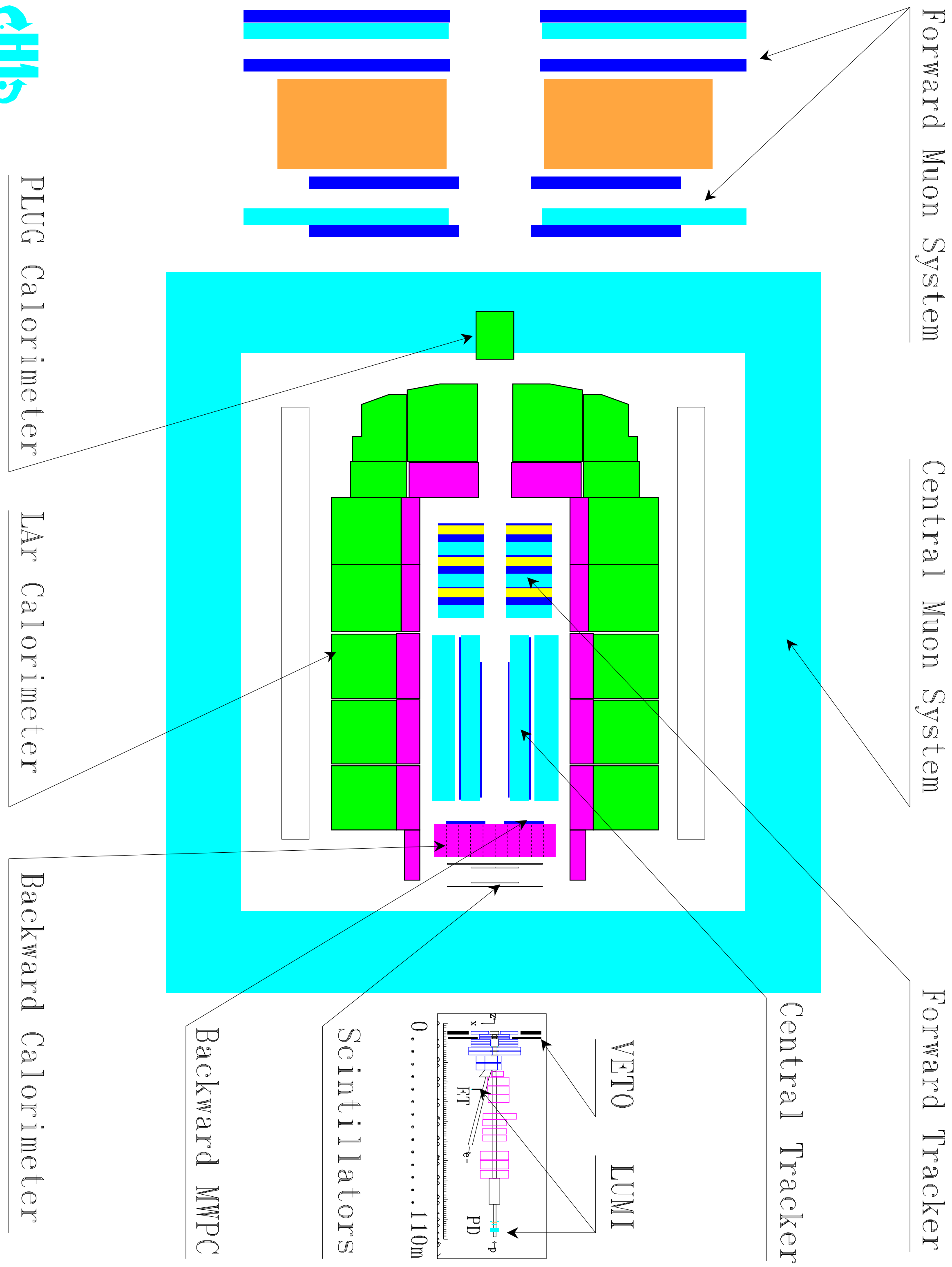
- Elastic ρ' Electroproduction at High Q^2
- Leading Neutron Production in Deep-Inelastic ep Scattering at HERA
- Thrust Jet Analysis of Deep–Inelastic Large Rapidity Gap Events at HERA
- Strangeness Production in Deep-Inelastic Positron-Proton Scattering at HERA
- Charged Particle Multiplicities in Deep-Inelastic Scattering at HERA
- The Transverse Momentum Evolution of the W^2 dependence of Inclusive Charged Particle Photoproduction at HERA
- Differential Cross Sections for the Photoproduction of Two High p_T Jets at HERA
- Comparison of Charged Particle Pseudorapidity Distributions in Photoproduction and Deeply Inelastic Scattering at HERA
- Jet Production in Real and Virtual γp Interactions at HERA
- Diffractive and Non-diffractive Photo-production of J/ψ Mesons at HERA
- Multi-jet Cross Sections in Deep-Inelastic Scattering at HERA
- A Search for Squarks of R_p-violating SUSY at HERA
- A Search for Sfermions and Light Gluinos at HERA

ZEUS Collaboration — 34 abstracts

- Measurement of the Cross Section and t Distribution in Diffractive DIS Events with Leading Protons at HERA
- High Q^2 Exclusive Vector Meson Production at HERA
- $D^{*\pm}(2010)$ Production in Deep Inelastic Scattering at HERA
- Measurement of Fragmentation Functions and Charged Multiplicity in the Breit Frame
- Dijet Angular Distributions in Direct and Resolved Photoproduction at HERA
- Dijet Cross Sections and Evidence for a Resolved-Photon Component in Diffractive Photoproduction at HERA
- High-E_T Jet Cross Sections in Photoproduction at HERA
- Prompt Photons at HERA
- Measurement of Jet Shapes in ep Collisions at HERA
- J/psi Photoproduction at HERA
- Measurement of dσ/dt in Proton Dissociative Photoproduction of rho0, phi and J/psi Mesons at HERA
- Search for Lepton Flavor Violation in ep Collisions of $\sqrt{s} = 300\,\mathrm{GeV}$
- Search for Heavy Right-Handed Neutrinos in ep Collisions of $\sqrt{s} = 300\,\mathrm{GeV}$

HERA ep experiments

H1 detector



Deep Inelastic ep Scattering

Kinematic variables:

$$\begin{aligned} Q^2 &= -q^2 \\ x &= \frac{Q^2}{2q \cdot p} \\ y &= \frac{q \cdot p}{k \cdot p} \end{aligned}$$

$$Q^2 = x \cdot y \cdot s$$

NC DIS cross section:

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

$$\text{where :} \qquad Y^\pm = 1 \pm (1-y)^2$$

Extraction of F_2 from NC DIS cross section ($Q^2 < M_{Z^\circ}^2$):

$$\frac{d^2\sigma(e^\pm p)}{dxdQ^2} = \frac{2\pi\alpha^2}{xQ^4} \cdot (1 + (1-y)^2) \cdot F_2^\gamma \cdot (1+\delta_Z)(1-\delta_L \mp \delta_3)(1+\delta_r)$$

Corrections to be applied:

δ_Z – correction for contribution from Z° exchange and γZ° interference term

δ_L – correction for contribution from longitudinal structure function F_L

δ_3 – correction for F_3 contribution

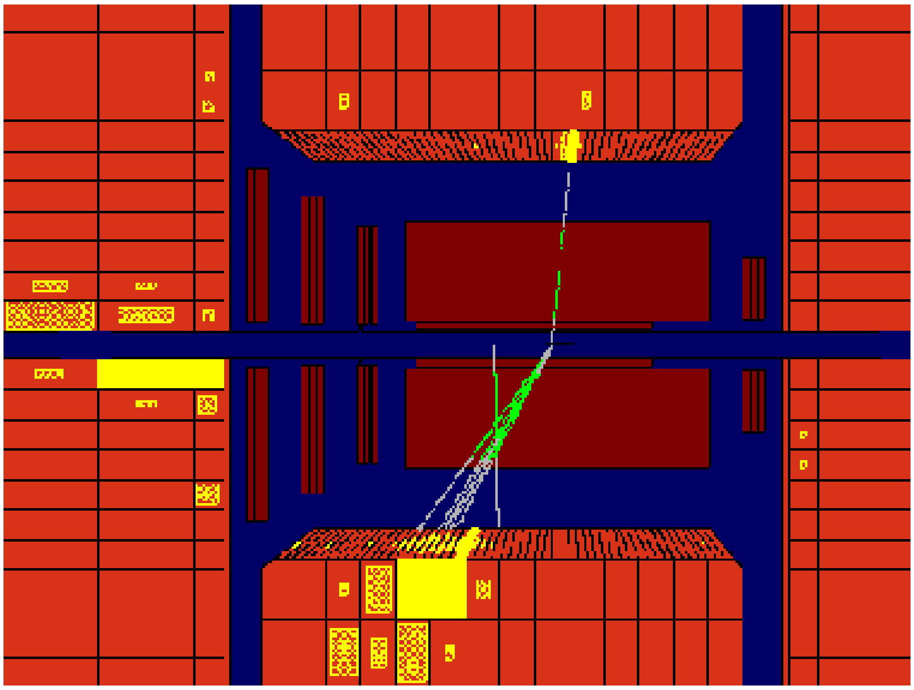
δ_r – radiative correction

ep DIS at HERA

NC DIS event measured in ZEUS detector

$x \approx 0.05 \quad Q^2 \approx 1600 GeV^2$

$e^{\pm}$ $\longrightarrow$



p $\longleftarrow$

Kinematics reconstruction:

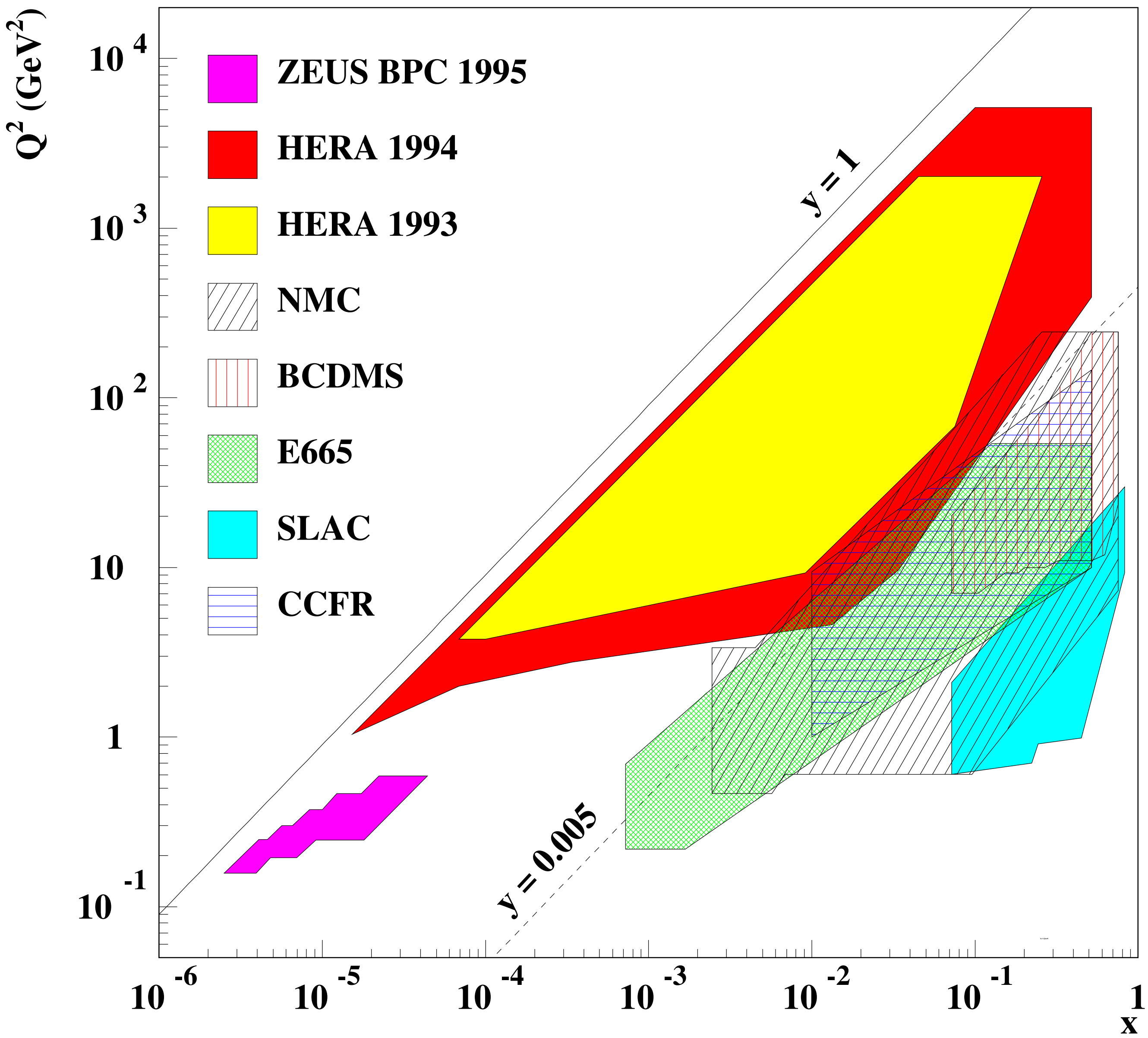
- electron energy and scattering angle measurement in calorimeter
- electron momentum and scattering angle measurement in tracking detectors
- hadronic final state measurement in calorimeter
- transverse momentum conservation
- $E - p_z$ conservation [1]
  assuming that only proton remnant escapes from detector

[1] z axis along proton beam direction

NC DIS measurement at HERA

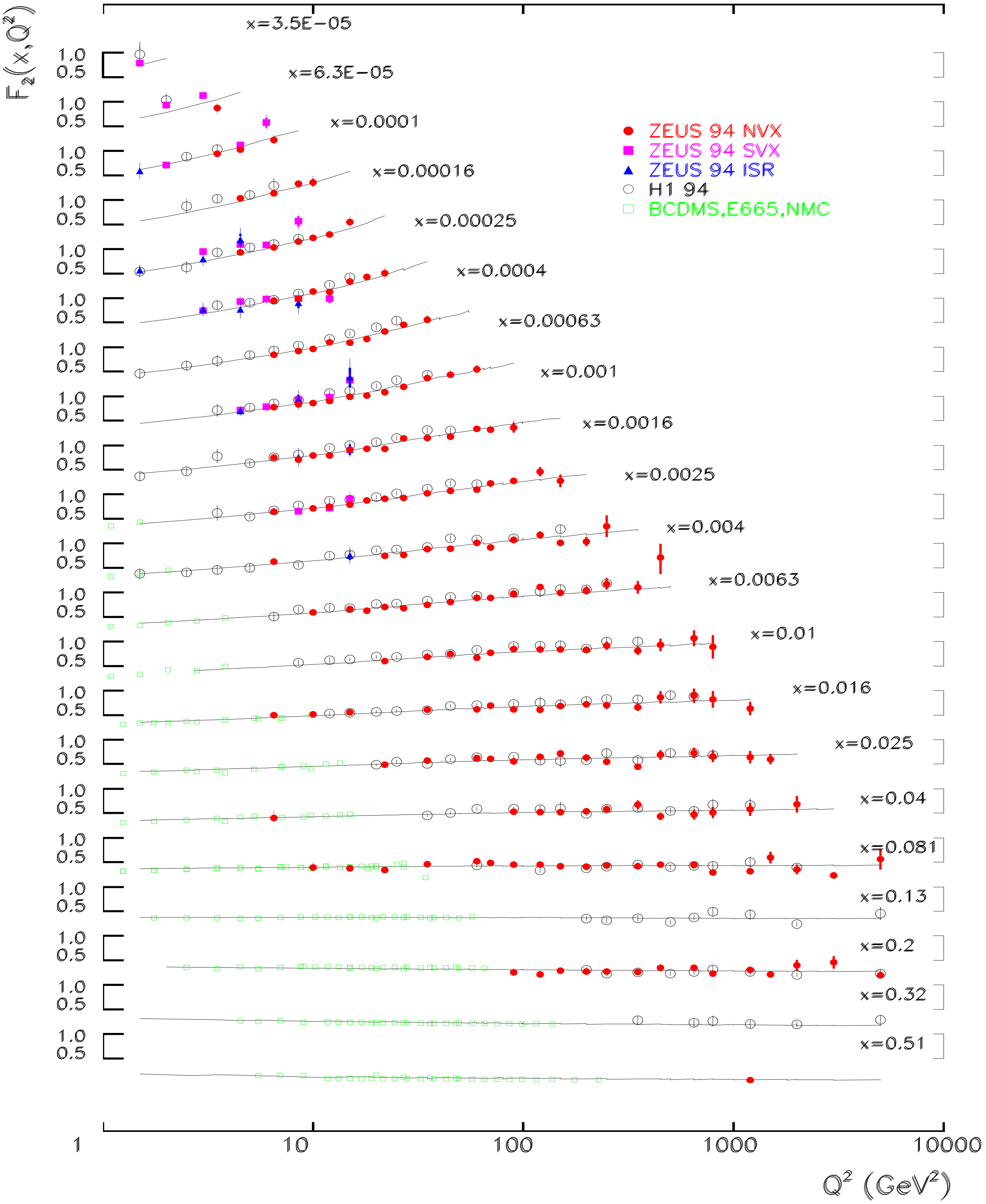
Kinematic range accessible for of F_2 measurement

Comparison of published H1 and ZEUS results with fixed target experiments



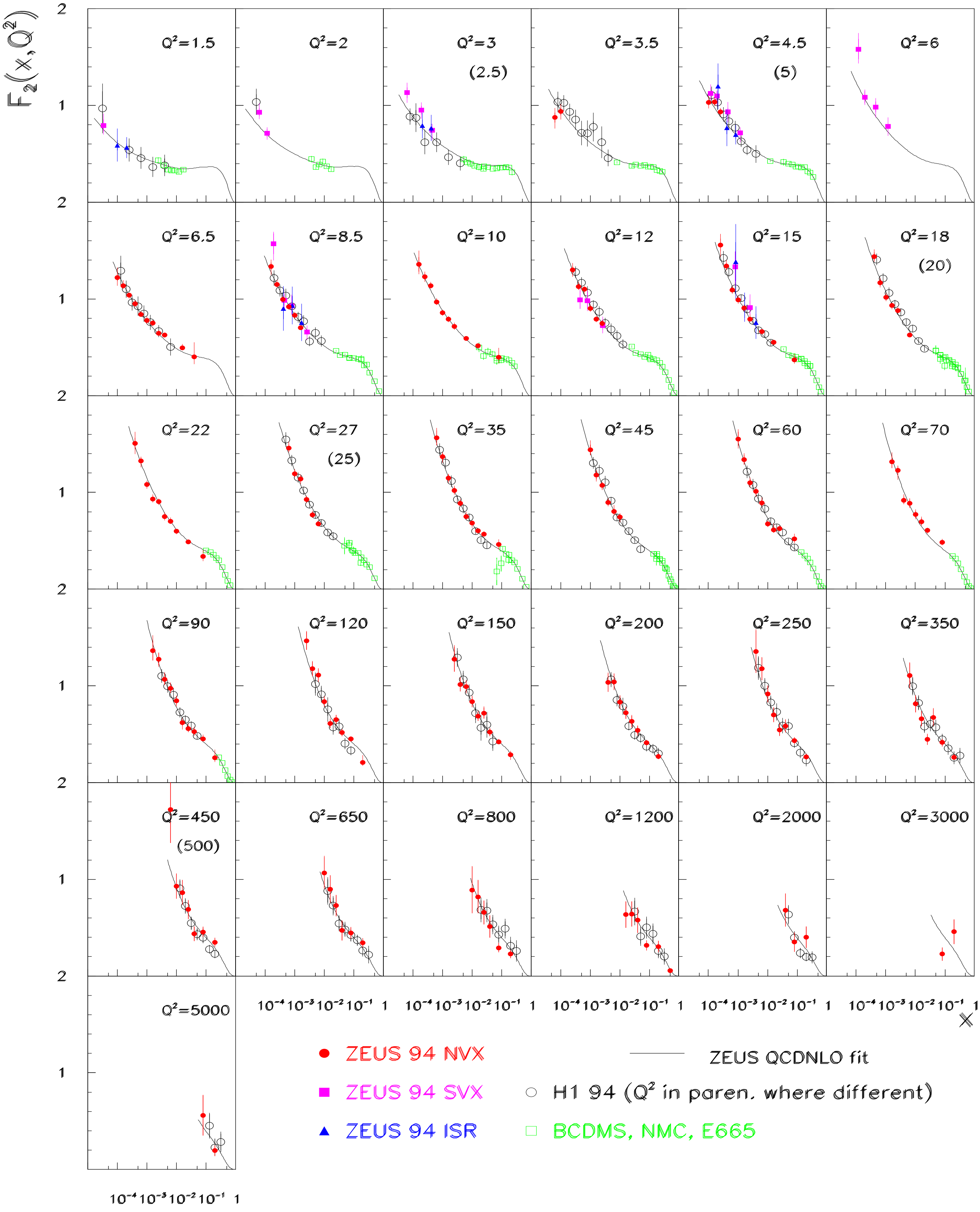
accessible 1995

F_2 measurement at HERA



F_2 scaling violation as predicted by QCD

F_2 measurement at HERA



F_2 rise at low x persists down to lowest Q^2 values

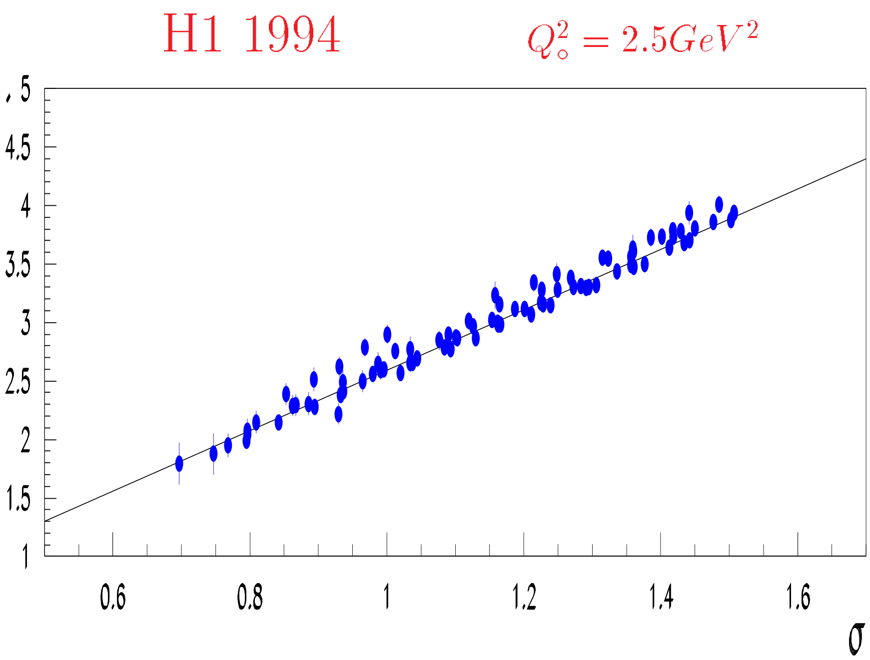
Double Asymptotic Scaling

F_2 measurement at large Q^2 and small x values at HERA
can be compared with QCD prediction of asymptotic scaling

If the gluon distribution is not singular at some low $Q^2_\circ$ scale
F_2 should scale in variables:

$$\sigma = \sqrt{\log\frac{x_\circ}{x}\cdot\log\frac{\alpha_s(Q^2_\circ)}{\alpha_s(Q^2)}}$$

$$\rho = \sqrt{\frac{\log(x_\circ/x)}{\log(\alpha_s(Q^2_\circ)/\alpha_s(Q^2))}}$$



Observed scaling indicates that at low x F_2 is dominated by QCD evolution

QCD fits to F_2 measurements

Parametrisation

Parton distributions in the proton:

$$\begin{aligned} xg(x) &= A_g \cdot x^{B_g} \cdot (1-x)^{C_g} \cdot (1 + D_g x) \quad \text{ZEUS} \\ xS(x) &= A_s \cdot x^{B_s} \cdot (1-x)^{C_s} \cdot (1 + D_s x + E_s \sqrt{x}) \end{aligned}$$

Similar description for $xu_v(x)$ and $xd_v(x)$ (H1) or $x\Delta^{ud}(x)$ (ZEUS)

Fit

Based on NLO QCD evolution with 3 light flavours
and dynamically generated heavy flavours contribution

Data

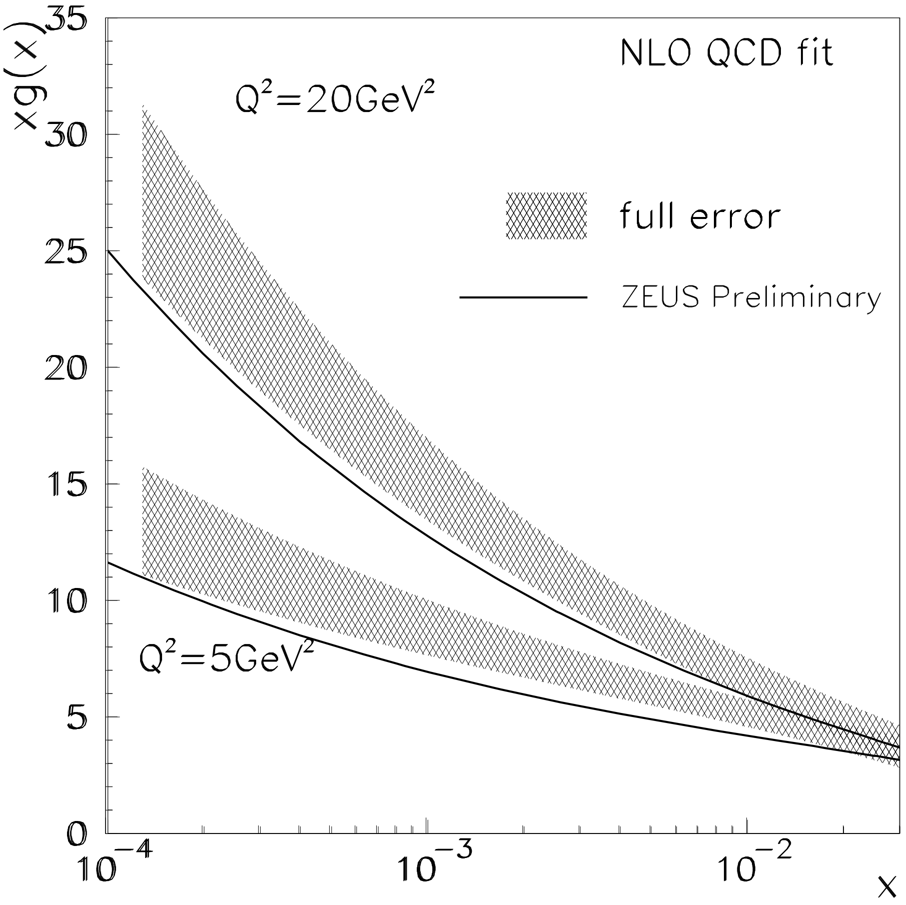
Fixed target experiments data inluded to constraint distributions at high x
(NMC data for ZEUS, NMC and BCDMS data for H1)

Results

$$\begin{array}{llr} B_g = -0.20 & B_s = -0.19 & \text{H1 at } Q^2 = 5GeV^2 \\ B_g = -0.24 & B_s = -0.23 & \text{ZEUS at } Q^2 = 7GeV^2 \end{array}$$

QCD fit results on gluon density

H1 1994



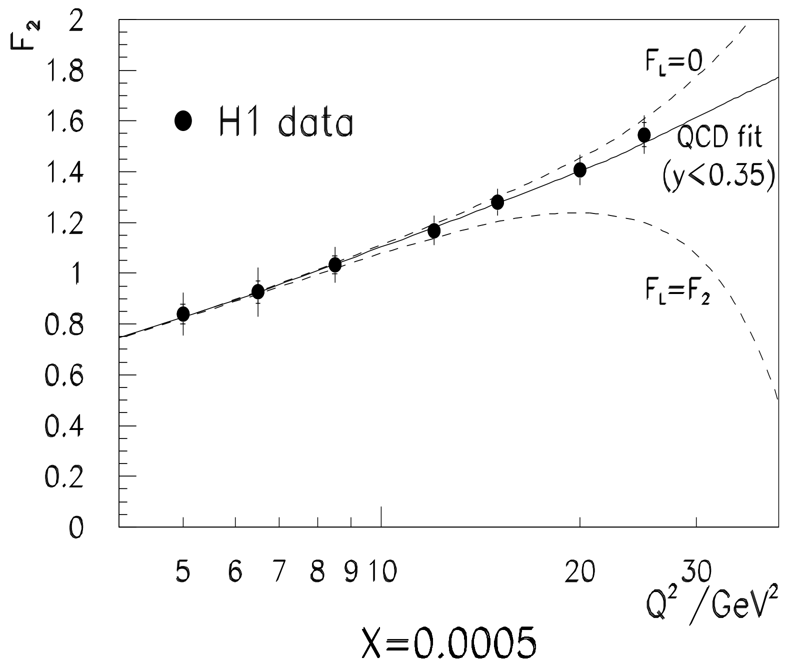
9% systematic error coming from uncertainty on $\Lambda_{\bar{M}S}$ not included

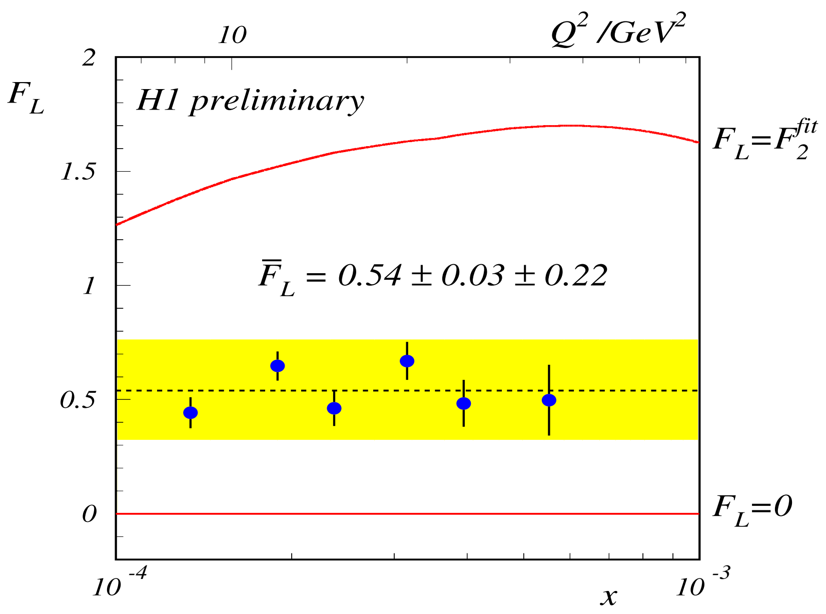
F_L at HERA

F_L contribution to the NC DIS cross section:

$$\frac{d^2\sigma(e^{\pm}p)}{dxdQ^2} \propto (1+(1-y)^2)\cdot F_2(x,Q^2) - y^2 \cdot F_L(x,Q^2)$$

Assuming that F_2 is correctly described by QCD evolution, F_L can be extracted from measured NC DIS cross section by subtracting F_2 extrapolated from small y region.

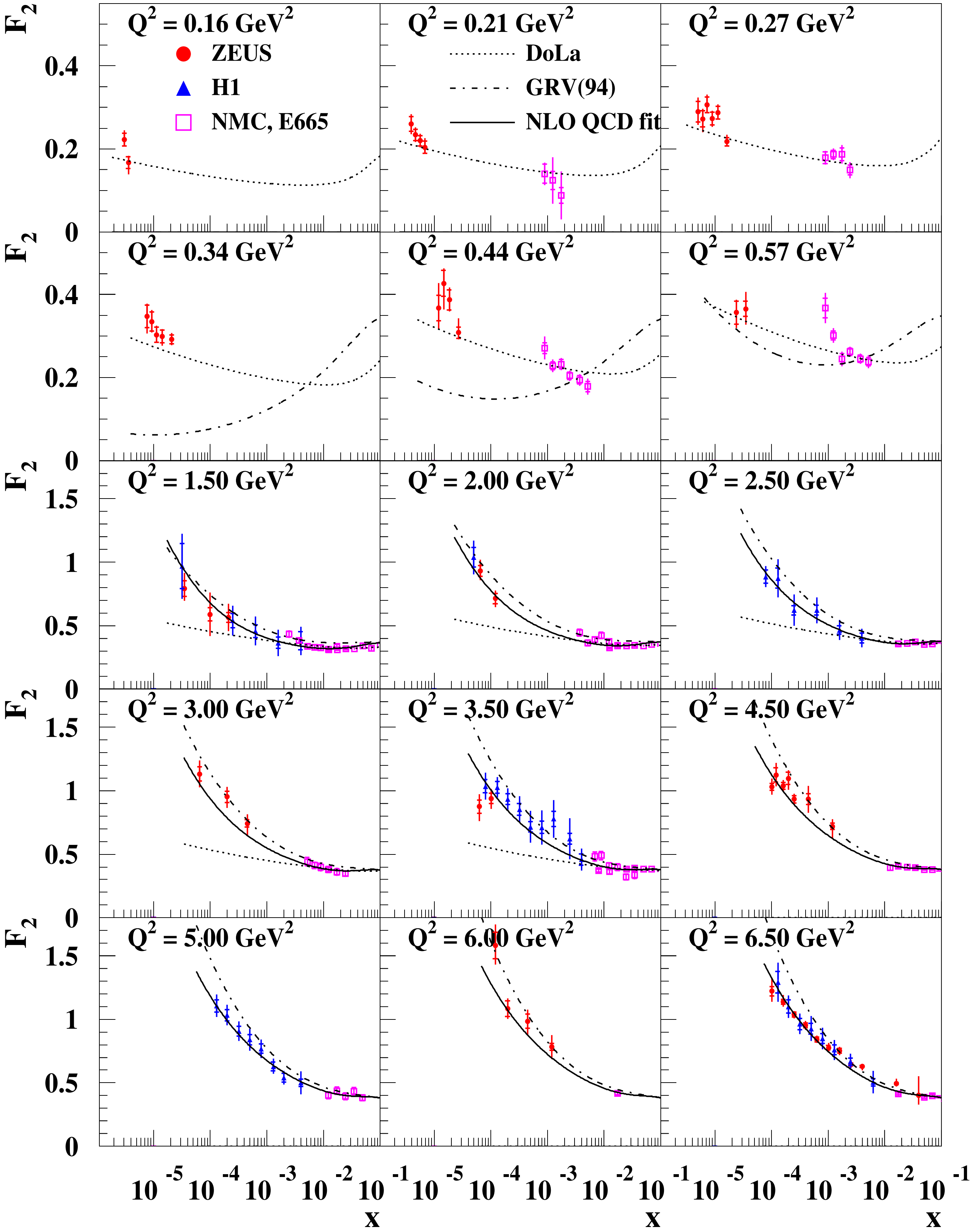




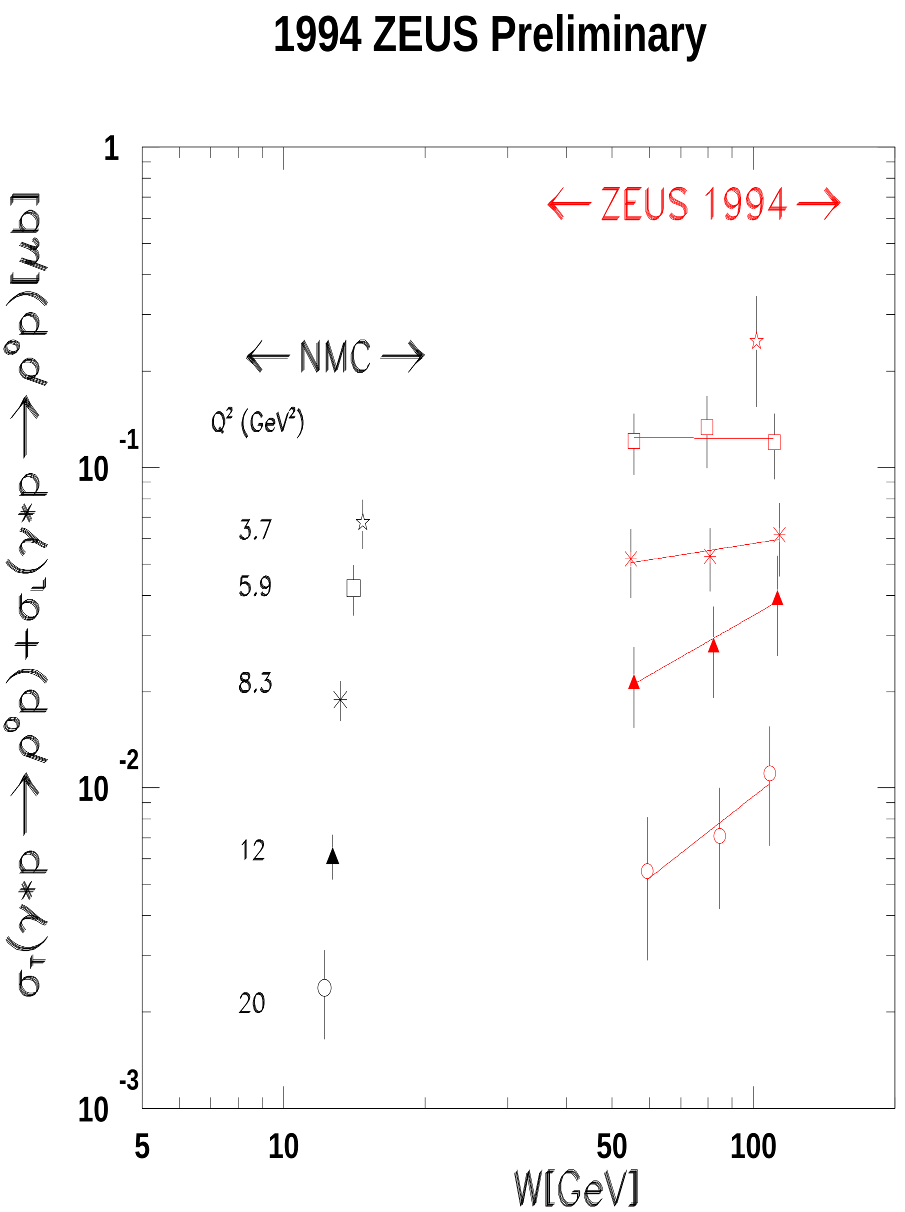
In agreement with QCD prediction from scaling violation of F_2

Transition from QCD to soft physics

HERA 1994 (for $Q^2 < 1\text{GeV}^2$ ZEUS 1995 preliminary)



Transition from QCD to soft physics



Cross section rise in W corresponds to increase of $g(x)$ towards small x.

$$W^2 \; = \; Q^2(\tfrac{1}{x} - 1) \; + \; M_p^2$$

Jet rates in DIS at HERA

- Two jet events at low x

Provide information about gluon distribution in proton

ZEUS 1994 Preliminary:

$$\lambda_g(Q^2 = 4GeV^2) = 0.43 \pm 0.05(stat.) \pm 0.20(syst.)$$

assuming $g(x) \sim x^{-\lambda_g}$ at small x

- Two jet events at high x

Provide information about value of α_s

1 jet 2 jet

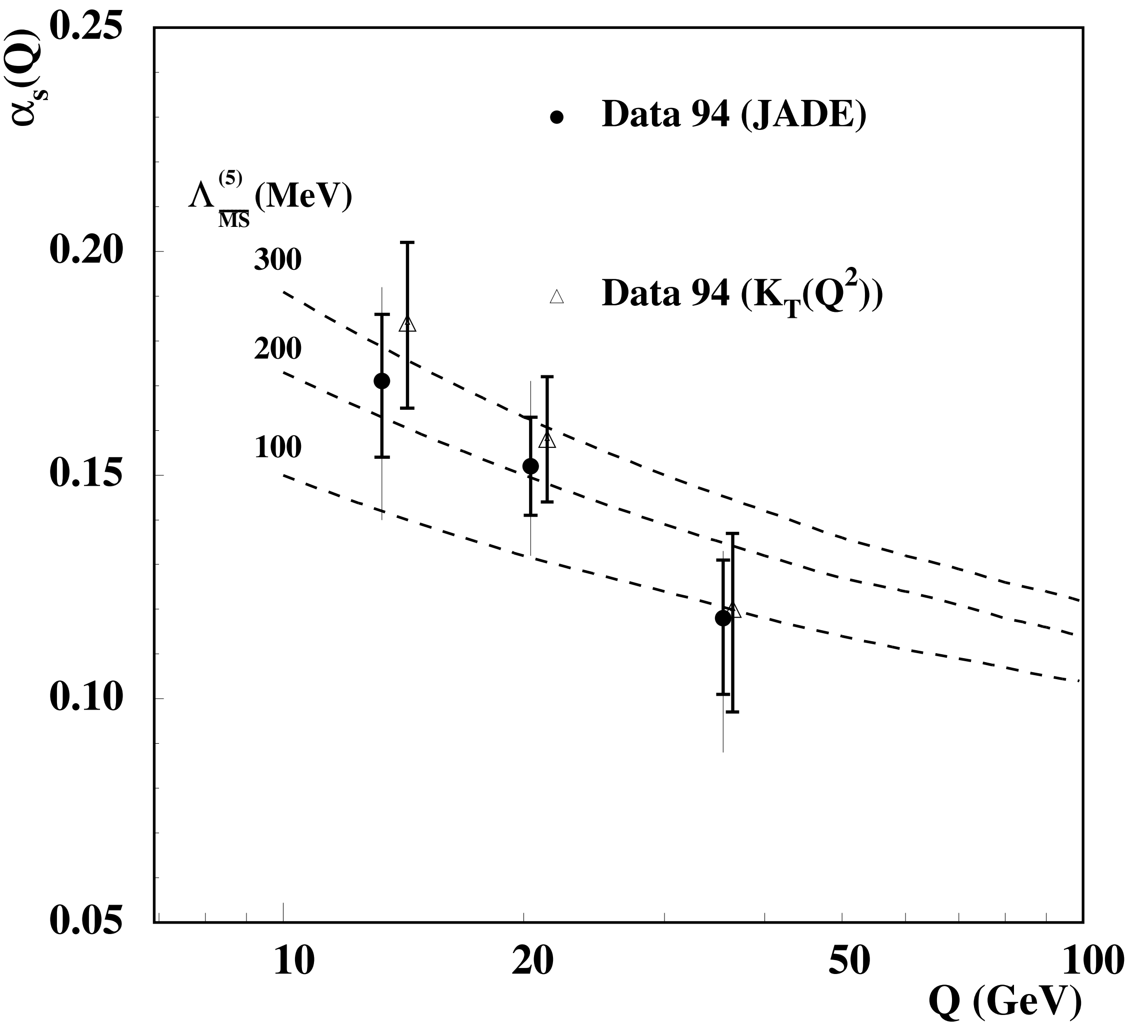
$$R_2(Q^2) \ = \ C_1(Q^2) \cdot \alpha_s(Q^2) + C_2(Q^2) \cdot \alpha_s^2(Q^2)$$

$$R_2 \ \equiv \ \frac{N(2jet)}{N_{Tot}}$$

α_s measurement from jet rates in DIS

H1 1993: $\alpha_s(M_{Z^\circ}^2) = 0.123 \pm 0.018$

ZEUS 1994 preliminary



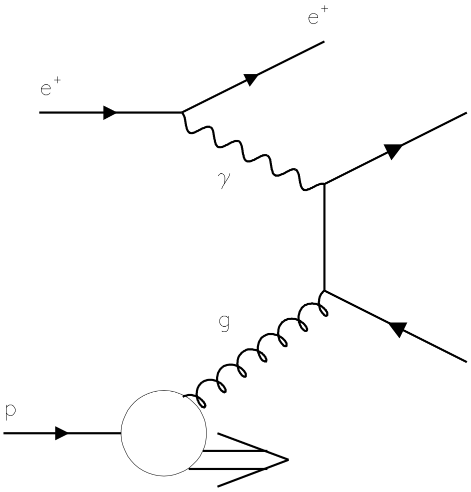
$$\alpha_s(M_{Z^\circ}^2) = 0.117 \pm 0.005 \; (JADE)$$
$$\alpha_s(M_{Z^\circ}^2) = 0.118 \pm 0.005 \; (K_T)$$

statistical errors only

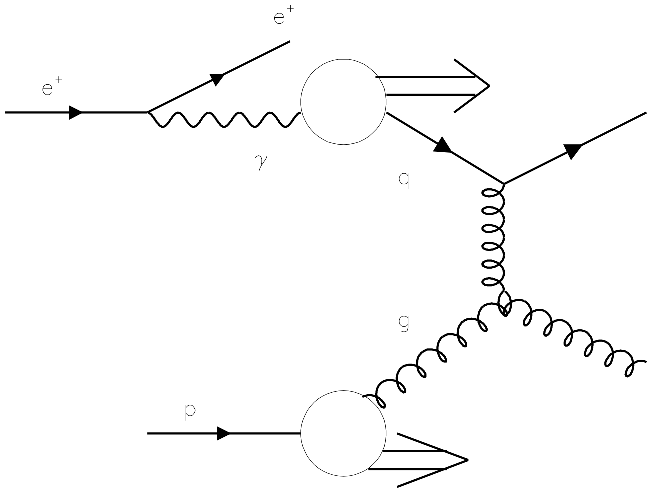
World average: $\alpha_s(M_{Z^\circ}^2) = 0.117 \pm 0.005$ (PDG 1994)

Dijet angular distribution in photoproduction

direct photoproduction



resolved photoproduction



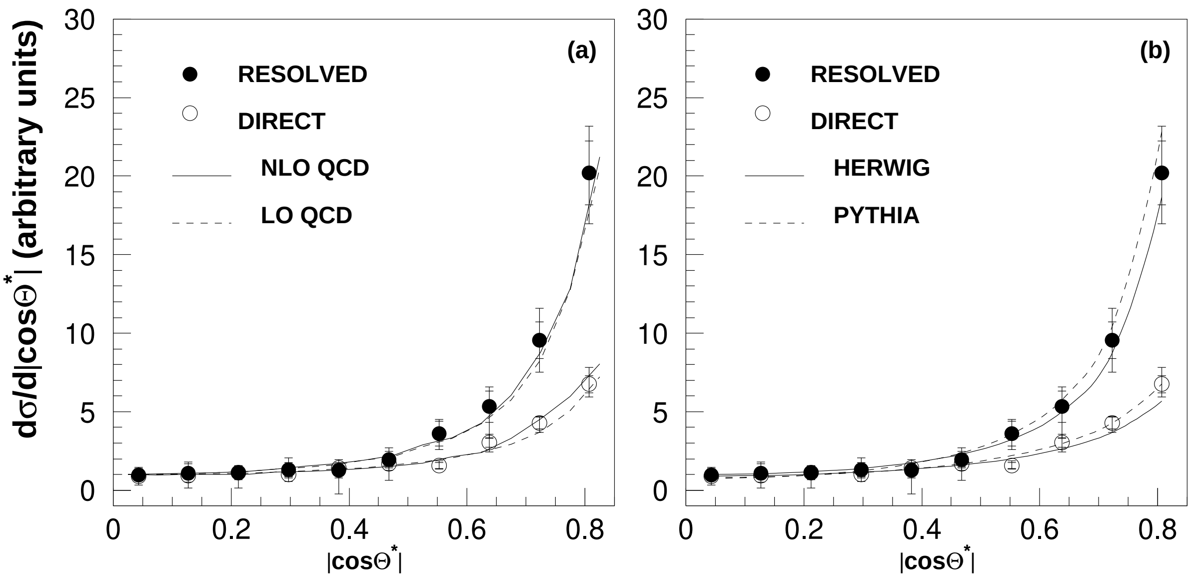
dominated by fermion exchange

$$\frac{d\sigma}{d|\cos\theta^\star|} \propto \frac{1}{1-|\cos\theta^\star|}$$

dominated by boson exchange

$$\frac{d\sigma}{d|\cos\theta^\star|} \propto \frac{1}{(1-|\cos\theta^\star|)^2}$$

ZEUS 1994



Measurement of high Q^2 NC+CC DIS

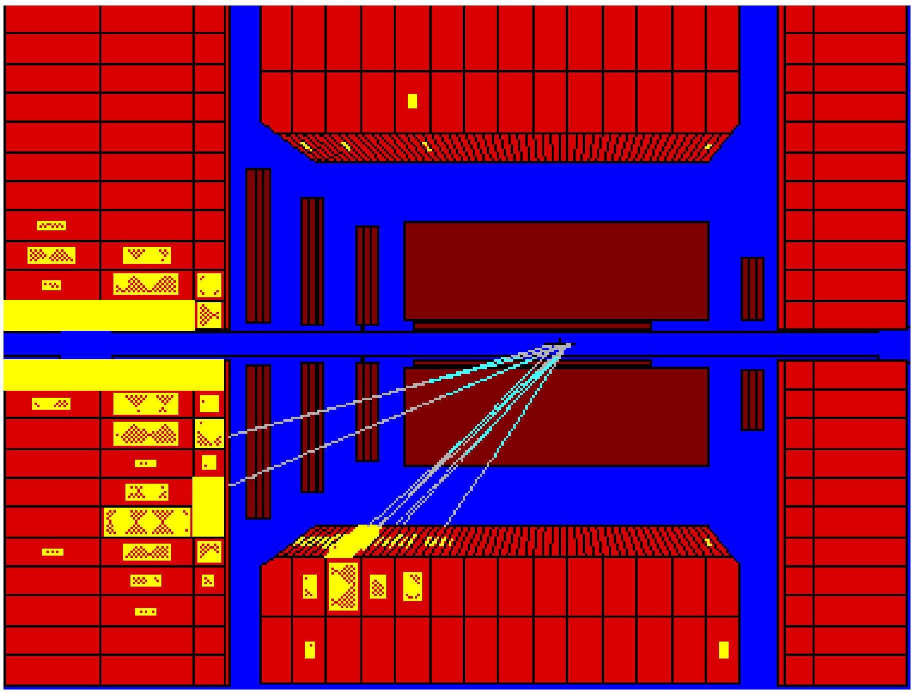
- High Q^2 NC DIS

$$\gamma \approx \frac{1}{Q^4} \qquad Z^\circ \approx \frac{1}{(M_Z^2+Q^2)^2} \qquad + \text{ interference}$$

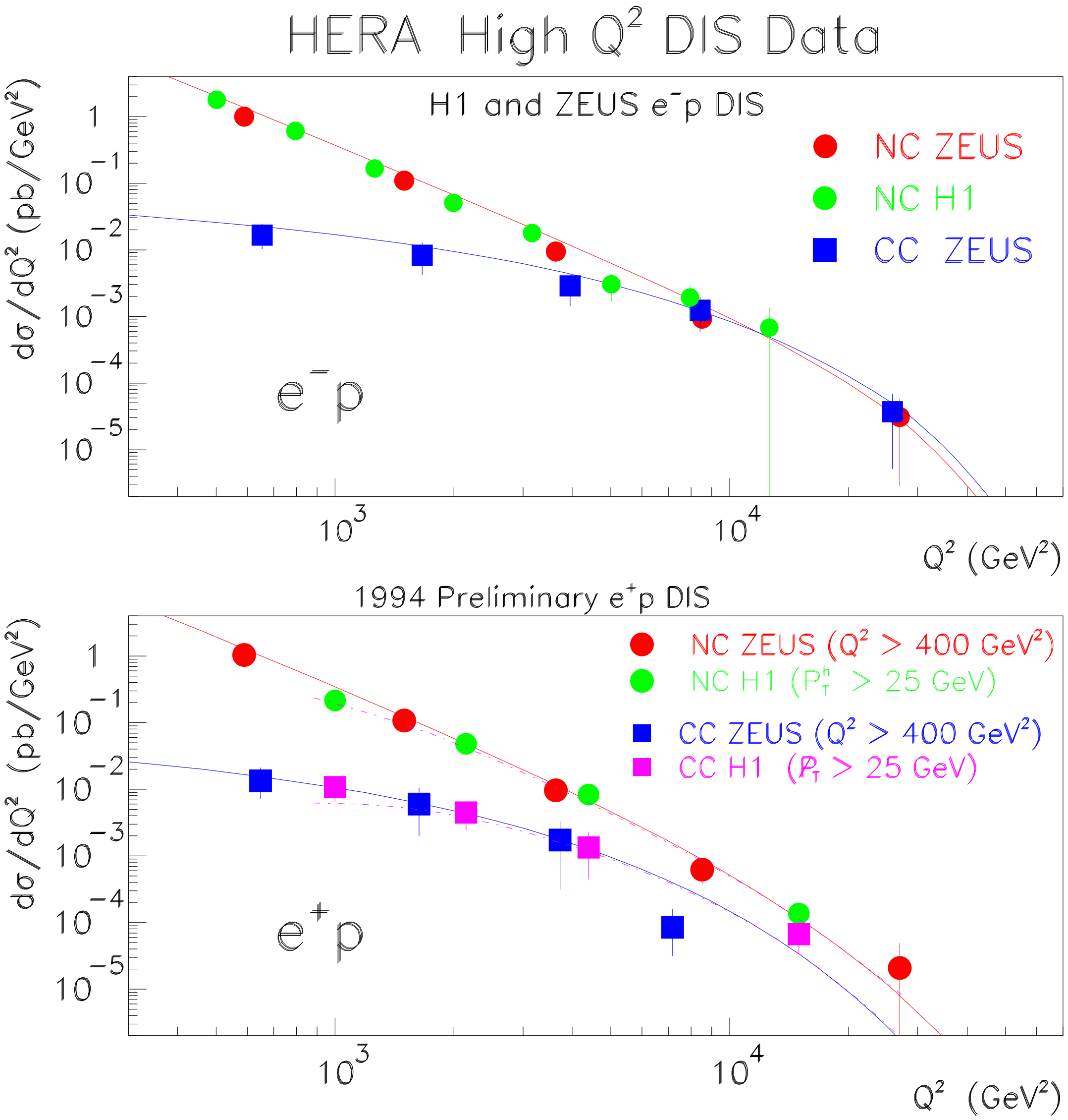
- CC DIS

$$W^\pm \approx \frac{1}{(M_W^2+Q^2)^2}$$

ZEUS $x \approx 0.05$ $Q^2 \approx 960 GeV^2$



Measurement of high Q^2 **CC** DIS



Very good agreement with SM predictions

Extraction of CC propagator mass:

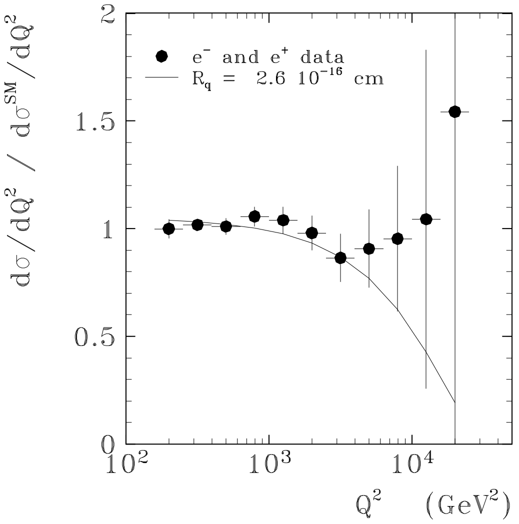
$$\begin{array}{lll} \text{H1} & M_W = & 84^{+9+4}_{-6-6}\ \text{GeV (preliminary)} \\ \text{ZEUS} & M_W = & 79^{+8+6}_{-7-3}\ \text{GeV} \end{array}$$

$$\text{Combined } M_W = 81.5^{+6+4}_{-5-3}\ \text{GeV (preliminary)}$$

"New Physics" limits from high Q^2 NC DIS

- Formfactor:

H1 1994

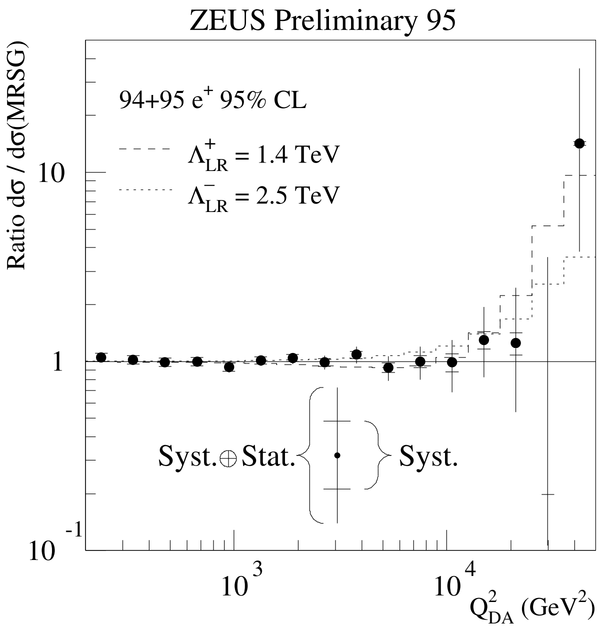


$$\frac{d\sigma}{dQ^2} = \frac{d\sigma^{SM}}{dQ^2} \cdot (1 - \frac{1}{6} R_q^2 Q^2)^2$$

$$R_q < 2.6 \cdot 10^{-16} cm \quad \text{(H1 95\% CL)}$$
$$R_q < 1.6 \cdot 10^{-16} cm \quad \text{(ZEUS 95\% CL)}$$

- Contact interactions:

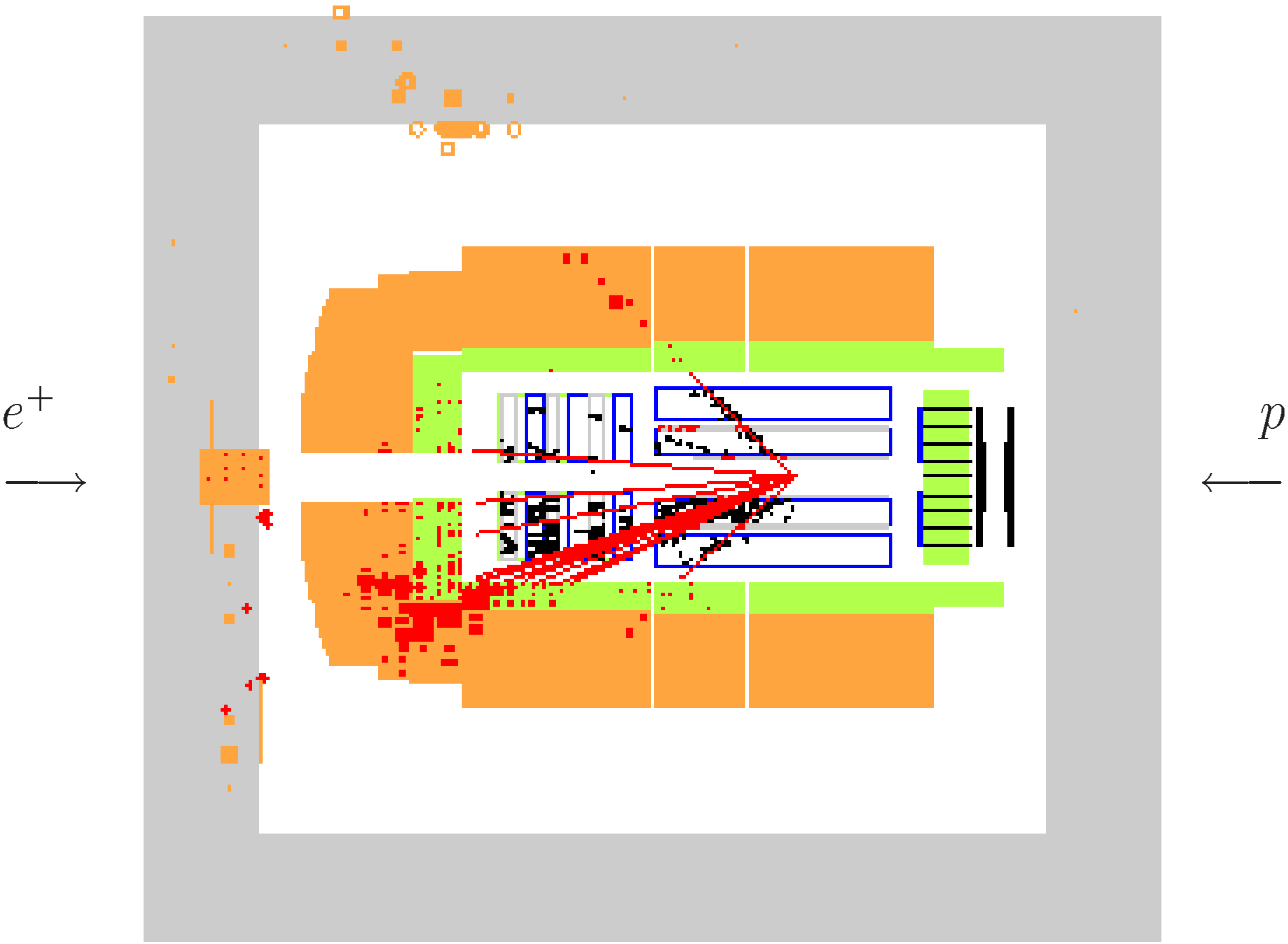
second generation Bosons, lepto-quarks, compositeness



$$\Lambda > 1 \sim 2.5 \text{ TeV}$$

Search for W production at HERA

H1 1994 candidate:
$e^+p \rightarrow \mu^+X$



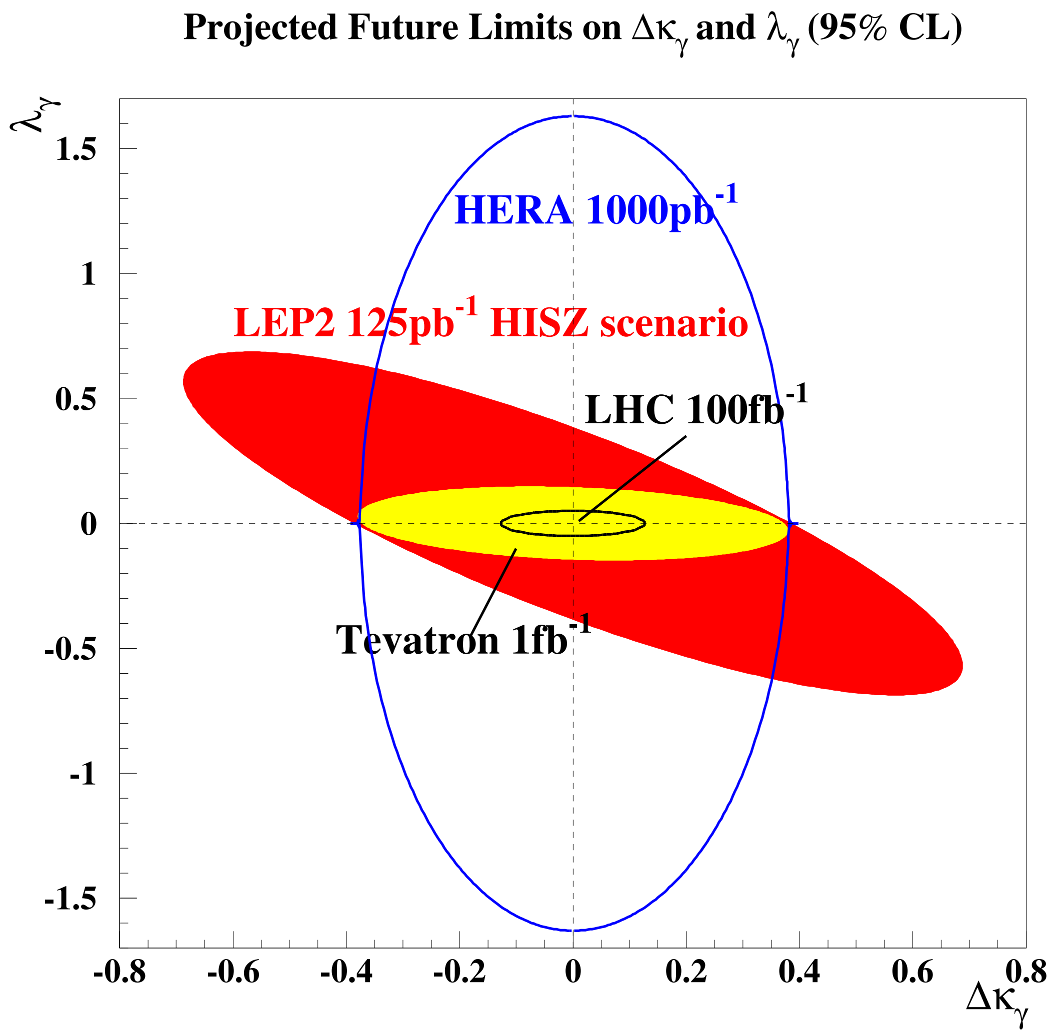
The event kinematics is compatible with W^+ production, and subsequent $W^+ \rightarrow \mu^+\nu_\mu$ decay.

Search for anomalous W production at HERA

$WW\gamma$ vertex

Two effective couplings:
κ and Λ

SM prediction:
$\kappa = 1$
$\Lambda = 0$



Conclusions

- HERA has opened a new "window" for QCD and EW studies
- Perturbative QCD describes very well HERA results on NC DIS, down to the Q^2 values of about 1 GeV^2
- HERA starts to probe the description of EW interactions
- With about 1000 pb^{-1} of integrated luminosity (forseen until 2005) very precise QCD and EW tests should be possible.