New HERA Results on Deep–Inelastic ep Scattering at Very High Q^2

Ulrich F. Katz, ZEUS
University of Bonn

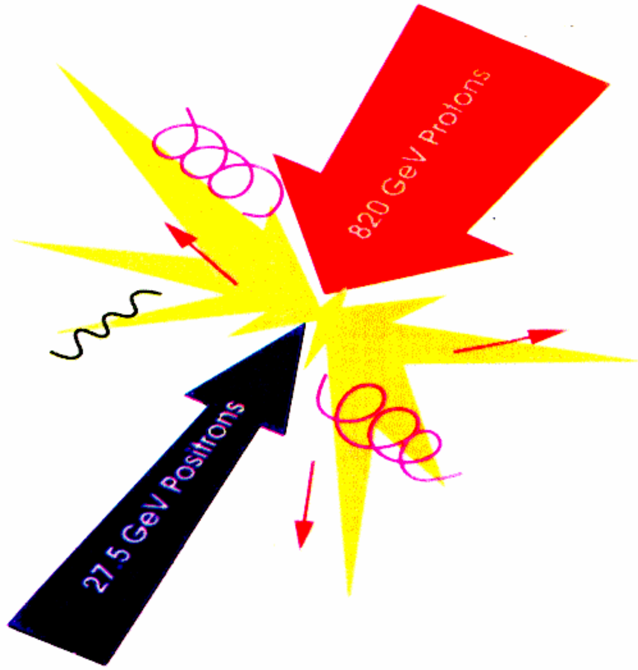
Representing the ZEUS and H1 Collaborations

SLAC Topical Conference
Stanford, 12–14 August 1998

- Introduction
- DIS in the Standard Model
- Cross–Section Measurements
- Scenarios Beyond the Standard Model
- Conclusion and Outlook

Introduction

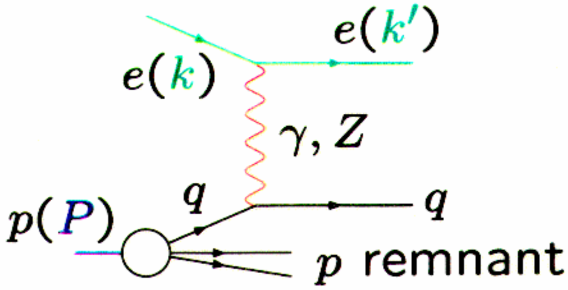
HERA= first electron–proton collider



ep centre–of–mass energy = 300 GeV
electron–quark invariant mass up to $\sim$ 200 GeV
spatial resolution down to $\sim 10^{-16}$ cm

ZEUS 1994–1997 integrated $\mathcal{L} = 46.6\,\mathrm{pb}^{-1}$
H1 1994–1997 integrated $\mathcal{L} = 37.0\,\mathrm{pb}^{-1}$
$\longrightarrow$ sensitive to $\sigma \sim 50$ fb

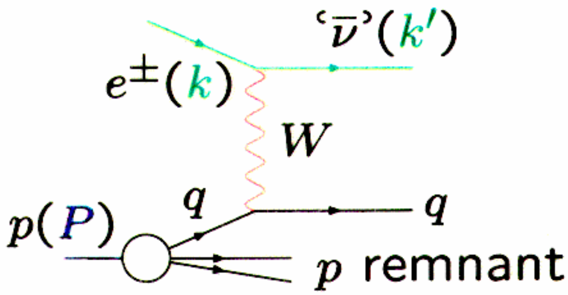
DIS Signatures and Kinematics



Neutral Current (NC)

Scattered e in main detector

e balances hadronic p_t



Charged Current (CC)

Scattered ν invisible

Only hadronic system available for measurements

Kinematic Variables:

Four–momentum transfer:

$$q = k - k'; \qquad Q^2 = -q^2 = 2E_e E'(1 + \cos\theta_e)$$

Bjorken scaling variable:

$$x = Q^2/(2\,q \cdot P) = \text{momentum fraction of quark}$$

Inelasticity:

$$y = (q \cdot P)/(k \cdot P)$$

$$y = (1 - \cos\theta_e^*)/2; \quad \theta_e^* = eq \text{ c.m.s. scattering angle}$$

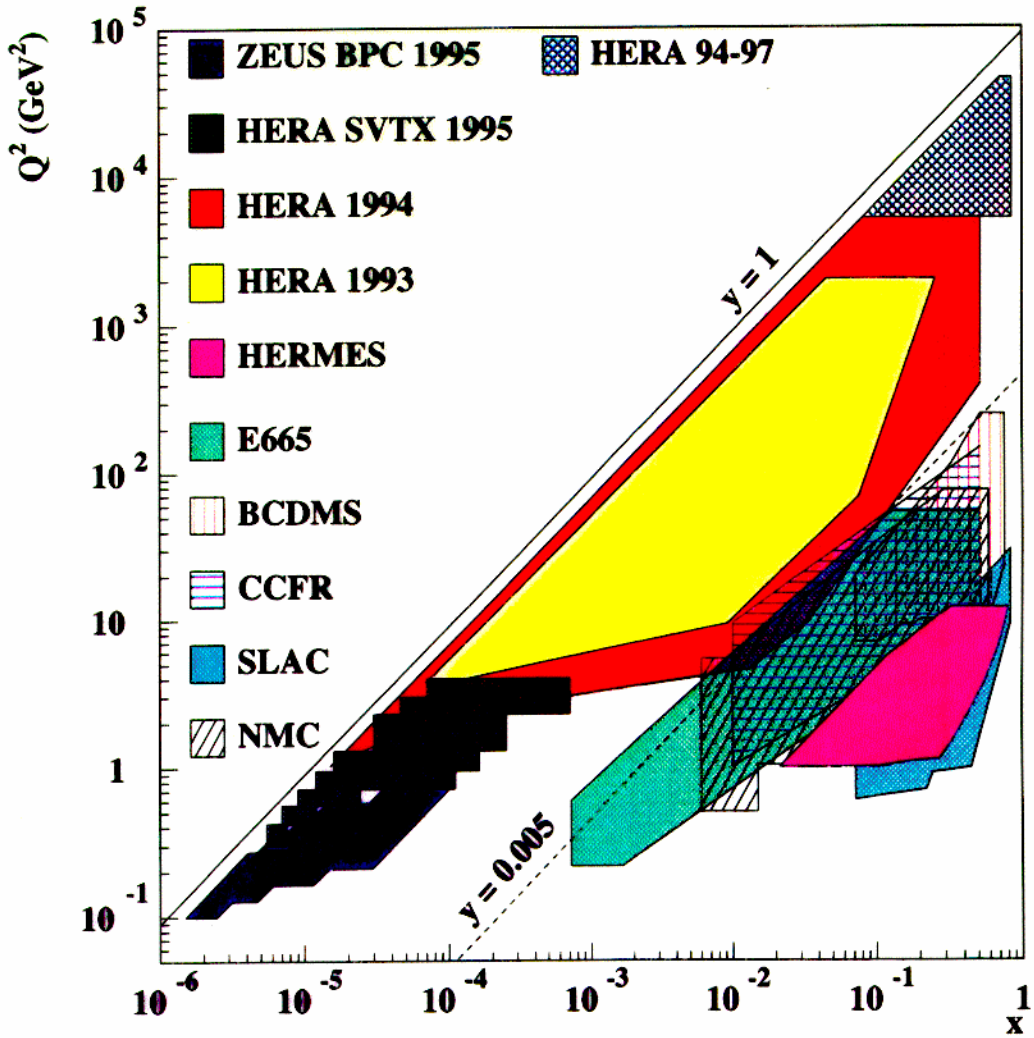
ep centre-of-mass energy:

$$s = (k + P)^2 = 4E_e E_p$$

eq invariant mass:

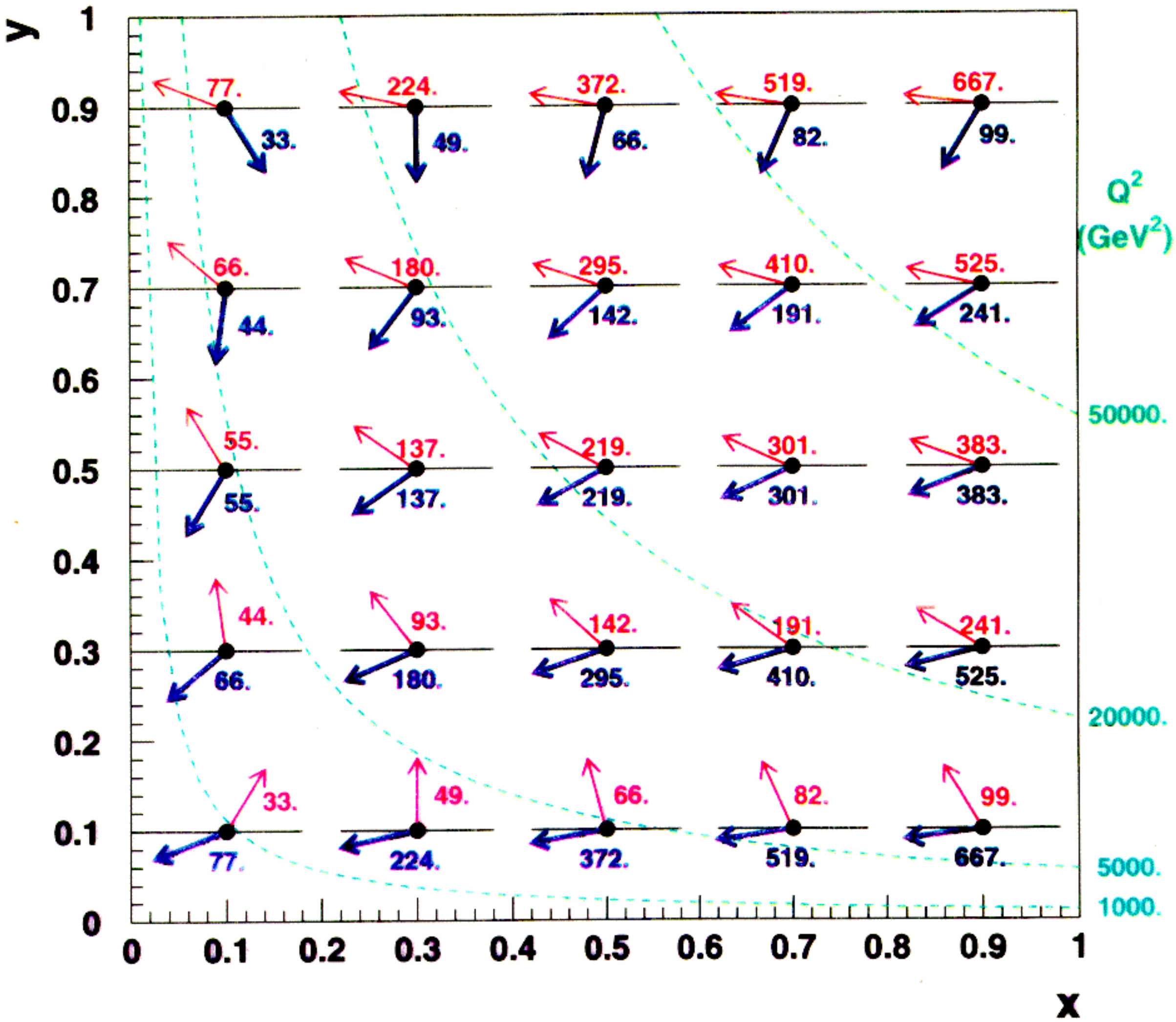
$$M = \sqrt{xs}$$

The HERA Kinematic Plane



DIS at $Q^2 \gtrsim 5000\,\mathrm{GeV}^2$ became accessible with the high–statistics 1996+1997 e^+p data

High–Q^2 Event Topologies



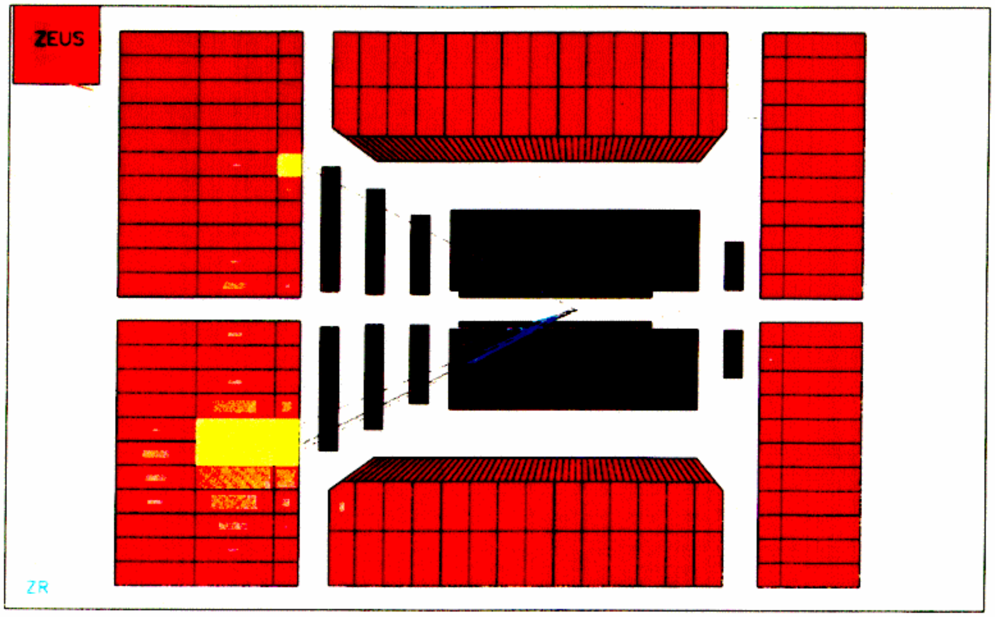
Final state topologies for elastic $eq \to eq$ scattering

Positrons enter from left, protons from right

Arrows = scattering angles of e and q

Numbers = energies of scattered e and q (in GeV)

A NC Event in the ZEUS Detector



Uranium-Scintillator Calorimeter

6000 Cells, each read out by 2 PMTs

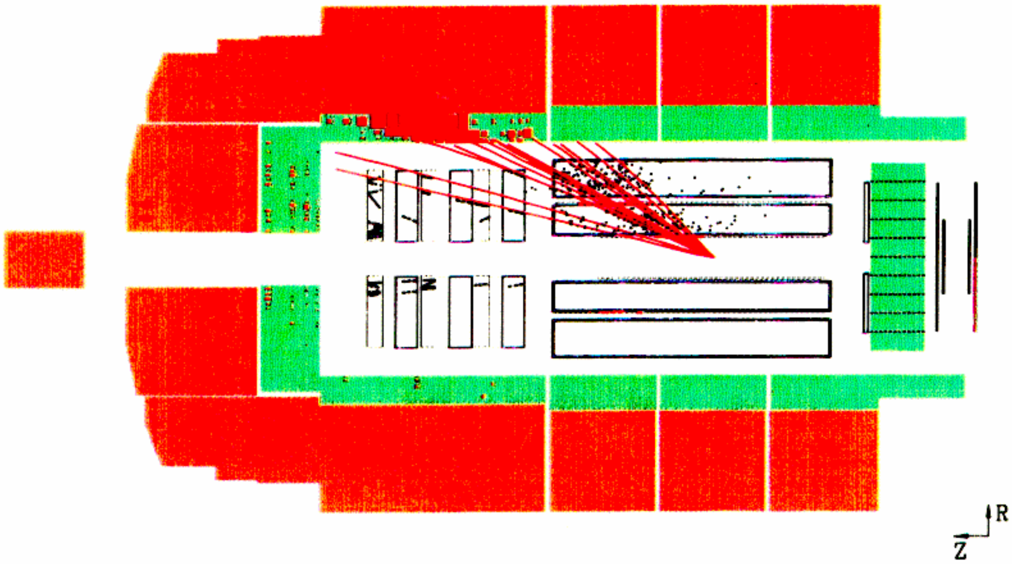
σ_{θ_e} = 3 mrad

$\sigma/\sqrt{E}$ (e) = 18 %

$\sigma/\sqrt{E}$ (had) = 35 %

$\Delta E/E$ (syst) = 1 - 3 %

A CC Event in the H1 Detector



Liquid Argon Calorimeter

44000 Cells

σ_{θ_e} = 2-5 mrad

$\sigma/\sqrt{E}$ (e) = 12 %

$\sigma/\sqrt{E}$ (had) = 50 %

$\Delta E/E$ (syst) = 1 - 4 %

in situ calibration good to $1-3\%$ (e)

DIS in the Standard Model

Deep–inelastic ep scattering =
incoherent sum of elastic eq scatterings

$$\sigma(ep) = \sum_{q,\bar{q}} f_{q|p} \cdot \sigma(eq)$$

$f_{q|p} \equiv q =$ Parton distribution function (PDF)

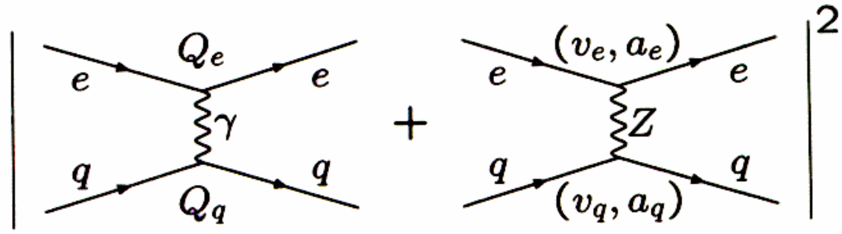
Probability density to find quark q in the proton carrying a fraction x of the proton momentum

Not predicted by theory

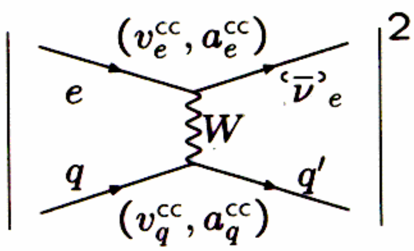
$\sigma(eq) =$ electron–quark cross–section

Leading Order:

$\sigma(eq \to eq) \propto$



$\sigma(eq \to \nu q') \propto$



Given by electroweak sector of Standard Model as functions of α, G_F, $\sin^2\theta_W$, (m_t, m_H)

DIS Cross–Section Formulae (NC)

$$\frac{d^2\sigma^{e^\pm p\to e^\pm X}}{dx\,dQ^2} = \frac{2\pi\alpha^2}{Q^4}\left[Y_+ \cdot \mathcal{F}_2^{\mathrm{NC}} \mp Y_- \cdot \mathcal{F}_3^{\mathrm{NC}}\right]$$

$$\begin{aligned}
Y_\pm &= \left(1 \pm (1-y)^2\right)\\
\mathcal{F}_2^{\mathrm{NC}} &= \sum_{q=d,u,s,c,b} A_q \cdot [q + \bar{q}]\\
\mathcal{F}_3^{\mathrm{NC}} &= \sum_{q=d,u,s,c,b} B_q \cdot [q - \bar{q}]\\
A_q &= Q_q^2 - 2Q_q v_e v_q \cdot P_Z + (v_e^2 + a_e^2)(v_q^2 + a_q^2) \cdot P_Z^2\\
B_q &= \quad - 2Q_q a_e a_q \cdot P_Z + 4 v_e a_e v_q a_q \cdot P_Z^2\\
P_Z &= \frac{Q^2}{Q^2 + M_Z^2}
\end{aligned}$$

→ Photon–exchange dominates at low Q^2

→ For $Q^2 \gtrsim M_Z^2$, γ and Z contributions are similar

Radiative corrections are substantial

DIS Cross–Section Formulae (CC)

$$\frac{d^2\sigma^{e^+p\to\nu X}}{dx\,dQ^2} = \frac{G_F^2}{2\pi} P_W^2 \left[(\bar{u}+\bar{c}) + (1-y)^2(d+s)\right]$$

$$\frac{d^2\sigma^{e^-p\to\bar{\nu} X}}{dx\,dQ^2} = \frac{G_F^2}{2\pi} P_W^2 \left[(u+c) + (1-y)^2(\bar{d}+\bar{s})\right]$$

$$P_W = \frac{M_W^2}{Q^2 + M_W^2}$$

→ e^+ and e^- couple to different quark flavors

→ e^+p cross–section dominated by d and $\bar{q}$

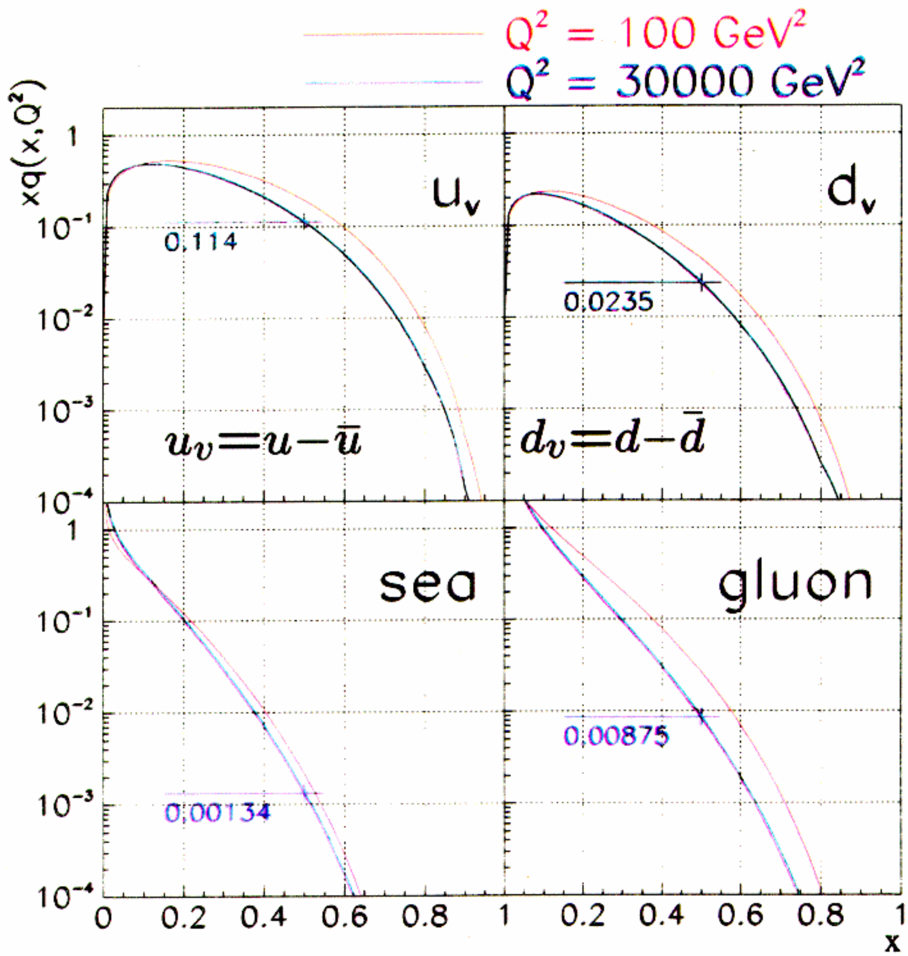
→ b, t contributions compressed by m_t and CKMM

→ At low Q^2: weak Q^2 dependence

→ At high Q^2: sensitivity to W mass

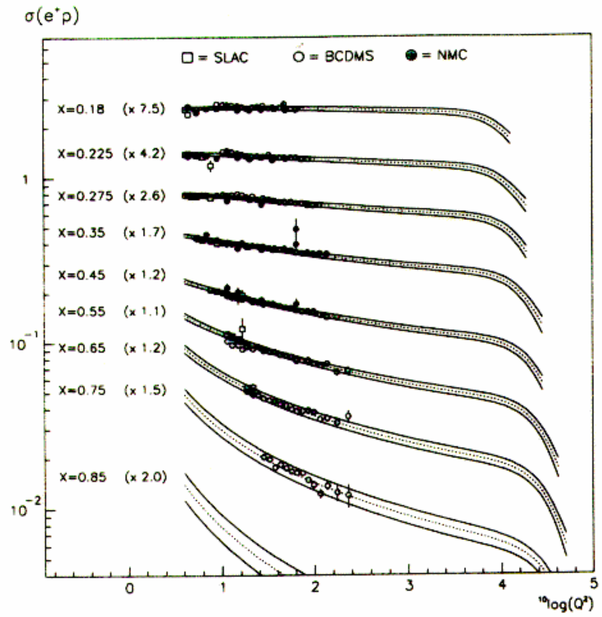
Radiative corrections are substantial

PDF's in the High-Q^2 Regime



- $\rightarrow$ For $x \gtrsim 0.2$: valence $\gg$ sea
- $\rightarrow$ $d/u \ll 0.5$ for $x \rightarrow 1$; $d/u(x \rightarrow 1) = 0$?
- $\rightarrow$ $\sigma^{e^\pm p}$(NC) is dominated by u
- $\rightarrow$ $\sigma^{e^+ p}$(CC) is dominated by d

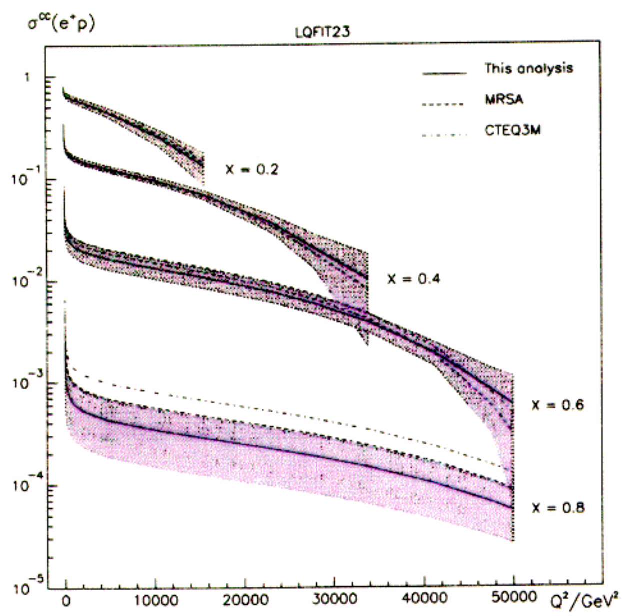
PDF Uncertainties



NC:

$$\tilde{\sigma} = \frac{xQ^4}{2\pi\alpha^2 Y_+} \frac{d^2\sigma}{dx\, dQ^2}$$

$\Delta\tilde{\sigma}/\tilde{\sigma} \lesssim 6.5\%$



CC:

$$\tilde{\sigma} = x \frac{2\pi}{G_F^2 P_W^2} \frac{d^2\sigma}{dx\, dQ^2}$$

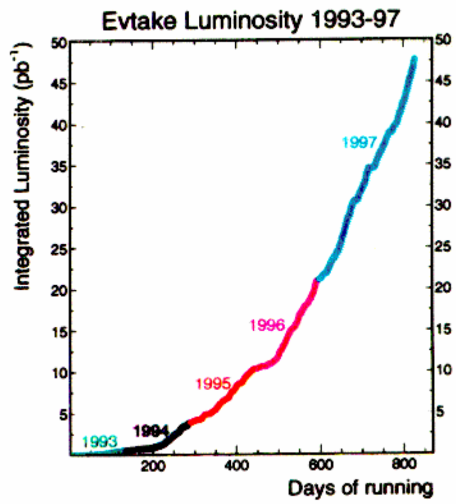
$\Delta\tilde{\sigma}/\tilde{\sigma} \gtrsim 20\%$
for $x \gtrsim 0.5$ or
$Q^2 \gtrsim 2 \cdot 10^4$ GeV^2

- $\tilde{\sigma} =$ reduced cross–section (∼PDF's)
- Experimental errors on input data and on α_s were propagated in QCD fit (M. Botje, ZEUS)

Cross–Section Measurements

- 1994–1996 data:
  Excess at high x, Q^2
- LP97: Updated results

  What we have now:
- Increased data samples
- Improved analysis methods
- Differential cross–sections



Focus on results at high x and Q^2
(mainly $d\sigma/dQ^2$ and $d\sigma/dx$)
Only few analysis details

- Available results from NC analyses:
  - → $d\sigma/dQ^2$, $d\sigma/dx$, $d\sigma/dy$ (ZEUS)
  - → $d^2\sigma/(dx\,dQ^2)$ and QCD fit (H1)

- Available results from CC analyses:
  - → $d\sigma/dQ^2$, $d\sigma/dx$ (ZEUS), $d\sigma/dy$ (ZEUS)
  - → reduced cross–section $\tilde{\sigma}(x, Q^2)$

NC Analyses

Kinematic Reconstruction:

- 4 independent measurements per event:

  θ_e, E' (e) γ_h, E_{had} (hadrons)

- Only two independent variables ($Q^2 = xys$)
- Different reconstruction methods
- ZEUS: "double–angle"; H1: $e\Sigma$ (e based)
- Resolutions: $dQ^2/Q^2, dx/x \sim \mathcal{O}$(few %)

Initial State Radiation (ISR):

→ Undetected γ radiation in e beam direction

→ Effectively reduces s

→ $\langle|\Delta_{\text{ISR}}x/x|\rangle, \langle|\Delta_{\text{ISR}}Q^2/Q^2|\rangle = \mathcal{O}(1-3\%)$

→ Shift in opposite directions for ZEUS,H1

Event Selection:

- Require identified scattered electron
- Vertex reconstructed and in fiducial region
- $E - p_z > 40$ GeV (ZEUS); 35 GeV (H1)

The $E - p_z$ cut:

$$(E - p_z)(\text{final}) = (E - p_z)(\text{initial}) = 2E_e$$

→ Cut removes photoproduction and hard ISR

NC Data Samples and Systematics

Event Samples:

ZEUS	H1
$Q^2 > 400\,\mathrm{GeV}^2$ $y_e < 0.95$	$Q^2 > 200\,\mathrm{GeV}^2$ $y_e < 0.9$
$\sim$ 38000 events	$\sim$ 75000 events

Main Systematic Effects:

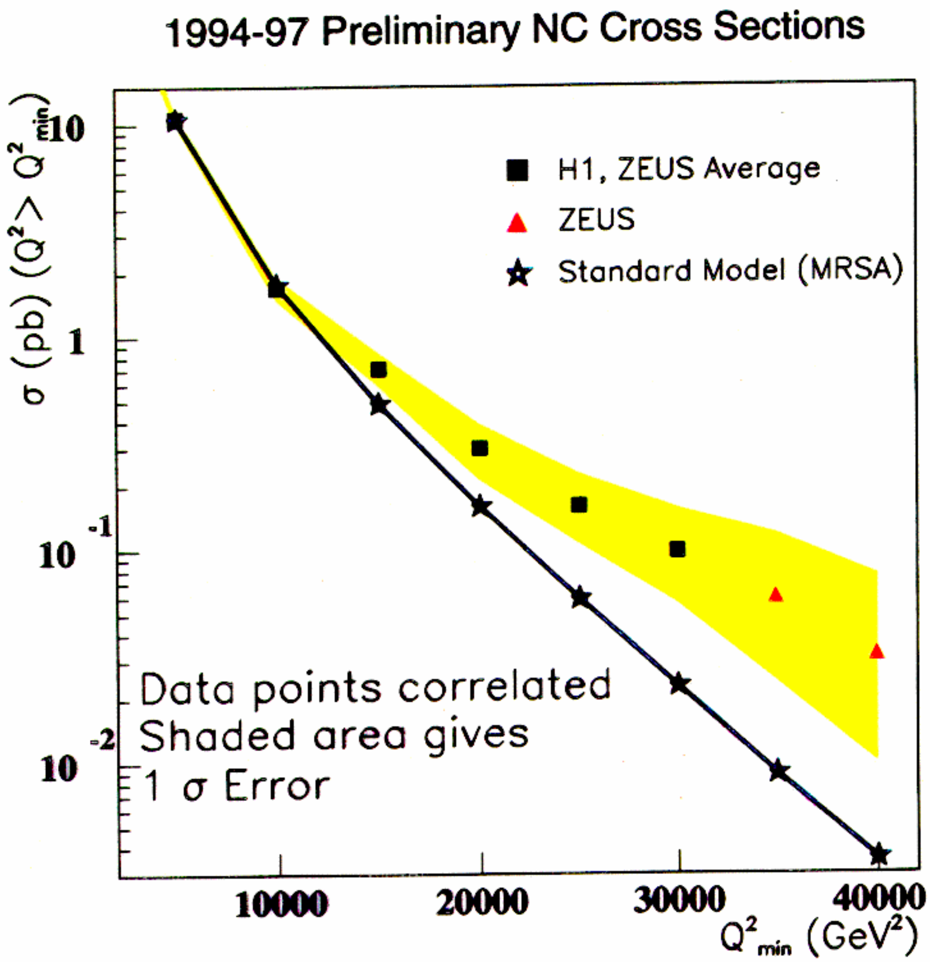
- Electron energy scale (affects mainly H1)
- Electron finding efficiency
- Accuracy of detector simulation
- Vertex reconstruction
- Trigger efficiency (small effect)
- Luminosity uncertainty ($\sim 2.5\%$)
- Photoproduction background ($< 1\%$)

→ No dominating source
→ Typical systematic errors = a few %
→ Analyses are statistics–limited
for Q^2 above a few $1000\,\mathrm{GeV}^2$

NC Cross–Section Status at LP97

ZEUS and H1 NC 1994–1997, LP97

(based on about 70% of the current data samples)



→ Indication of cross–section excess

→ Deviation data – SM increases with Q^2

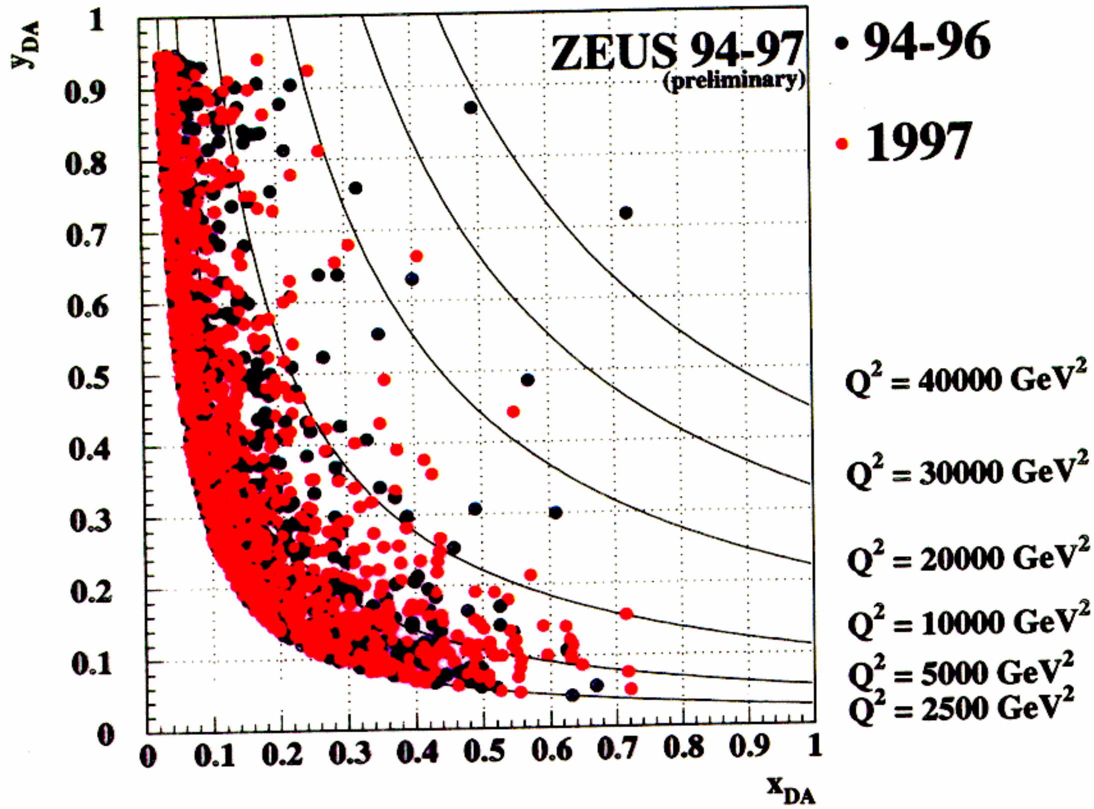
→ Let's look at $d\sigma/dQ^2$ first

ZEUS Kinematic Plane (NC)

Changes w.r.t. the 1996/LP97 analyses:

Improved analysis algorithms

Slightly modified event selection



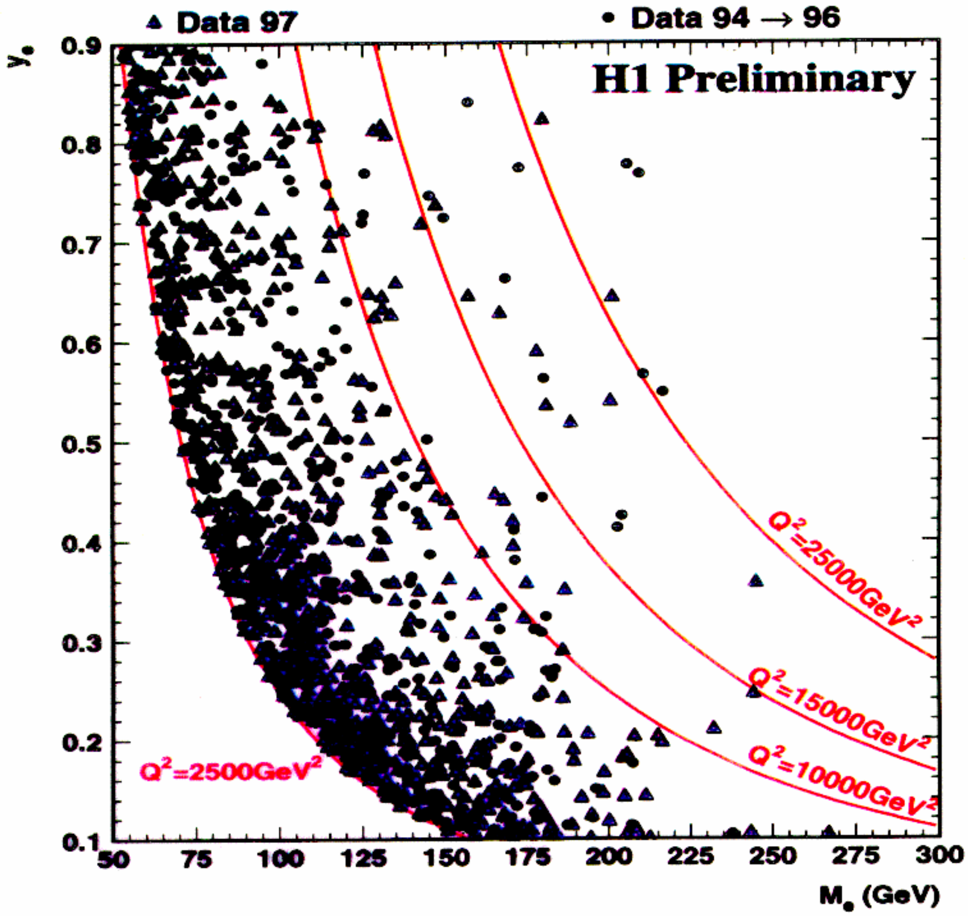
Q^2_{min} (GeV^2)	N_{obs}	N_{exp}
2500	1817	1792 ± 93
5000	440	396 ± 24
10000	66	60 ± 4
15000	20	17 ± 2
35000	2	0.29 ± 0.02

H1 Kinematic Plane (NC)

Changes w.r.t. the 1996/LP97 analyses:

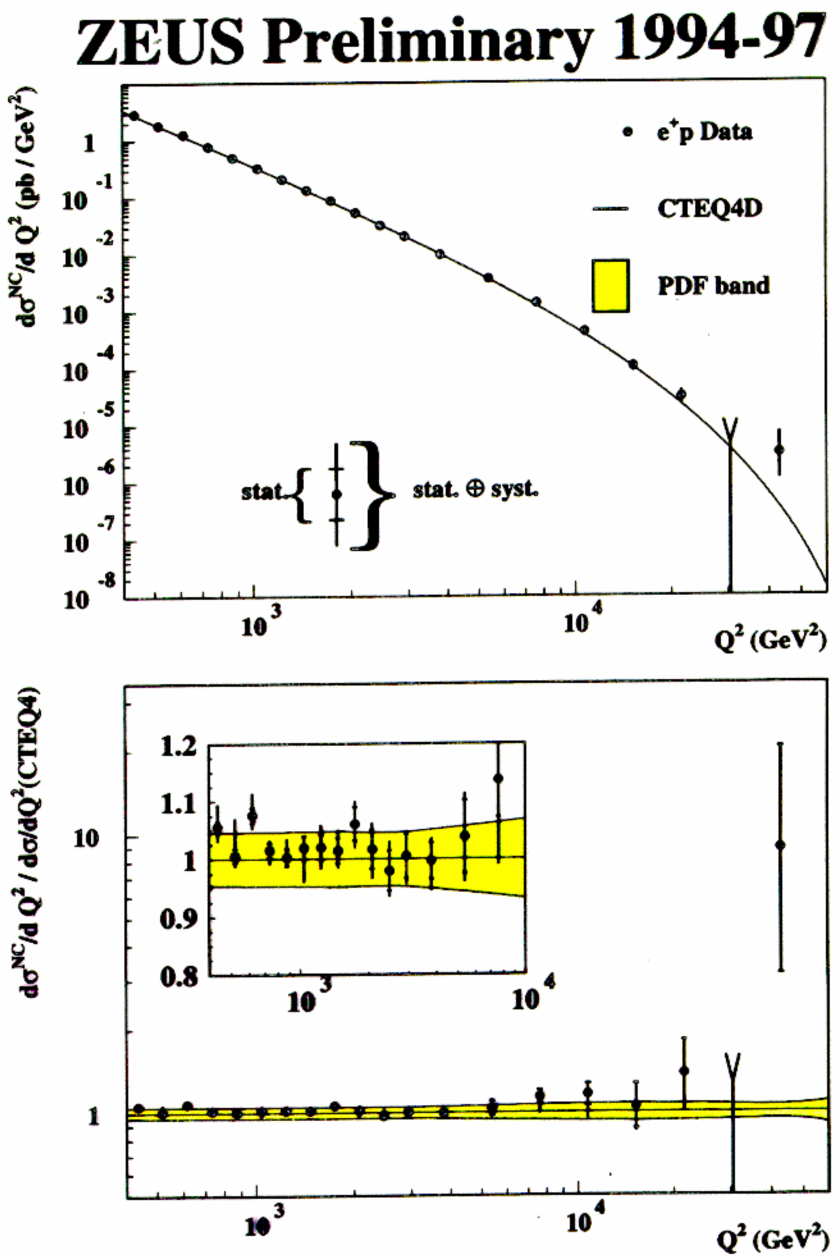
New E' calibration

Slightly modified event selection



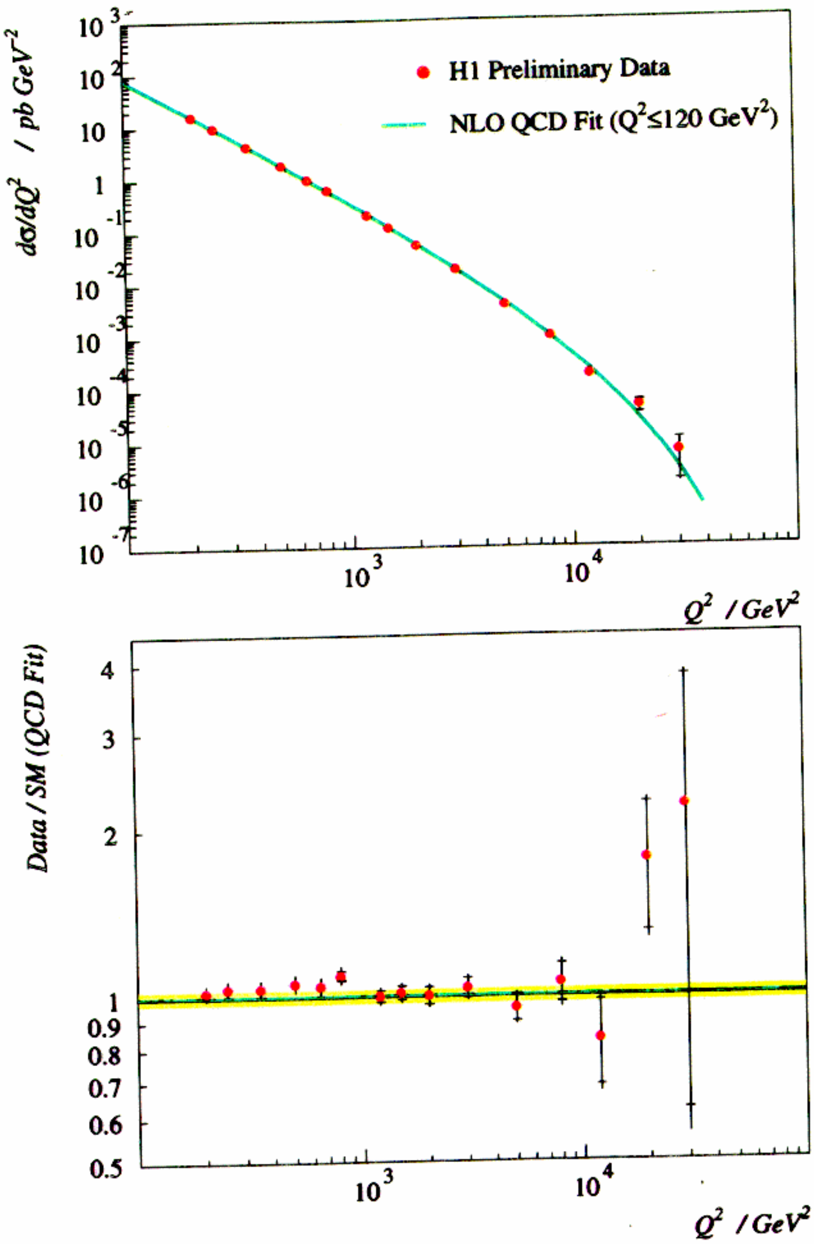
kinematic region	N_{obs}	N_{exp}
$Q^2 > 15000$ GeV^2	22	14.7 ± 2.1
$M_e = (200 \pm 12.5)$ GeV	8	3.01 ± 0.54
(94–96)	7	0.95 ± 0.18

NC Cross–Section $d\sigma/dQ^2$ (ZEUS)



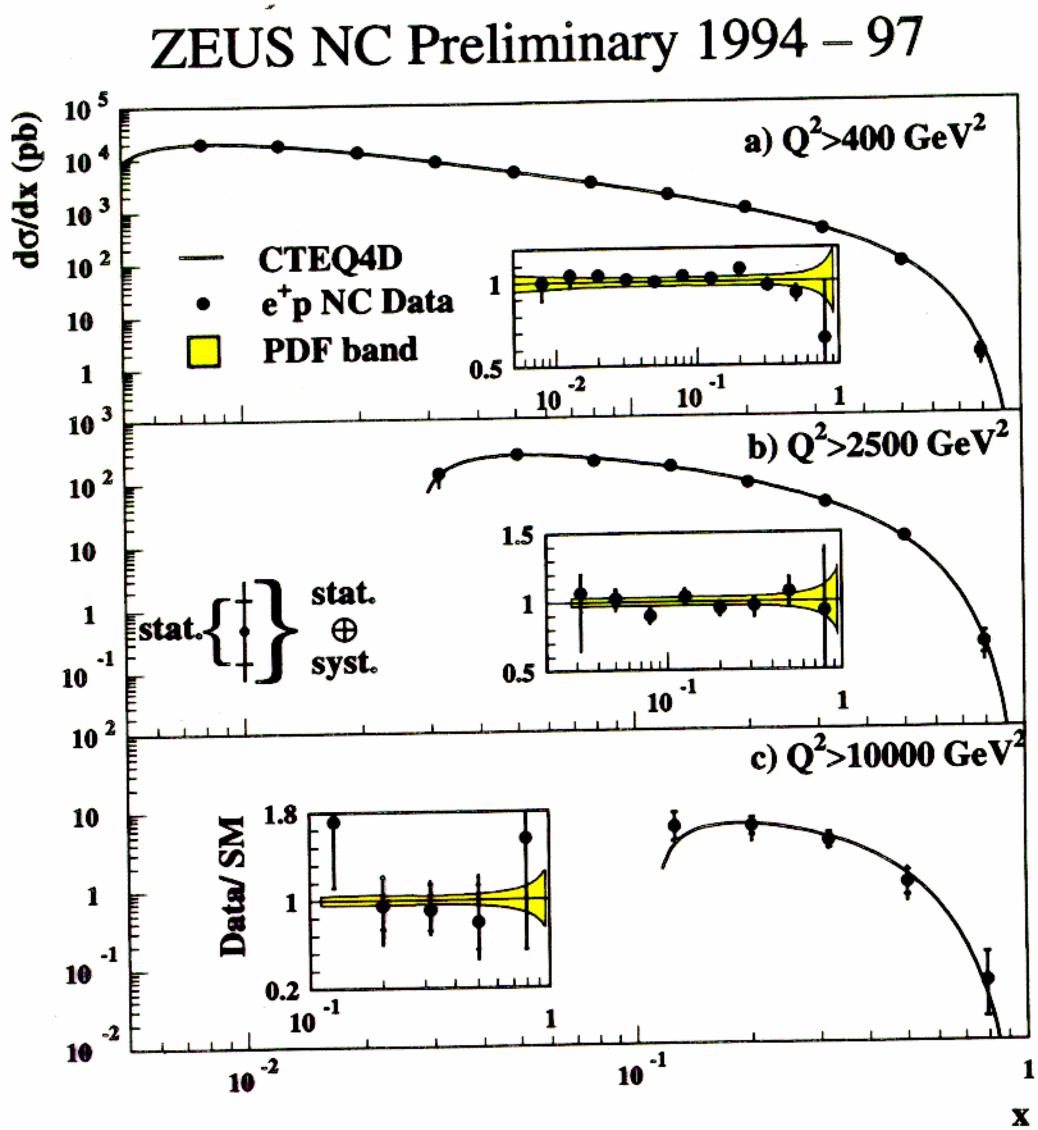
- Error band = PDF uncertainty
- Very good agreement with SM prediction
- Slight excess at highest Q^2

NC Cross–Section $d\sigma/dQ^2$ (H1)



- Error band = luminosity uncertainty
- Very good agreement with SM prediction
- Slight excess at highest Q^2

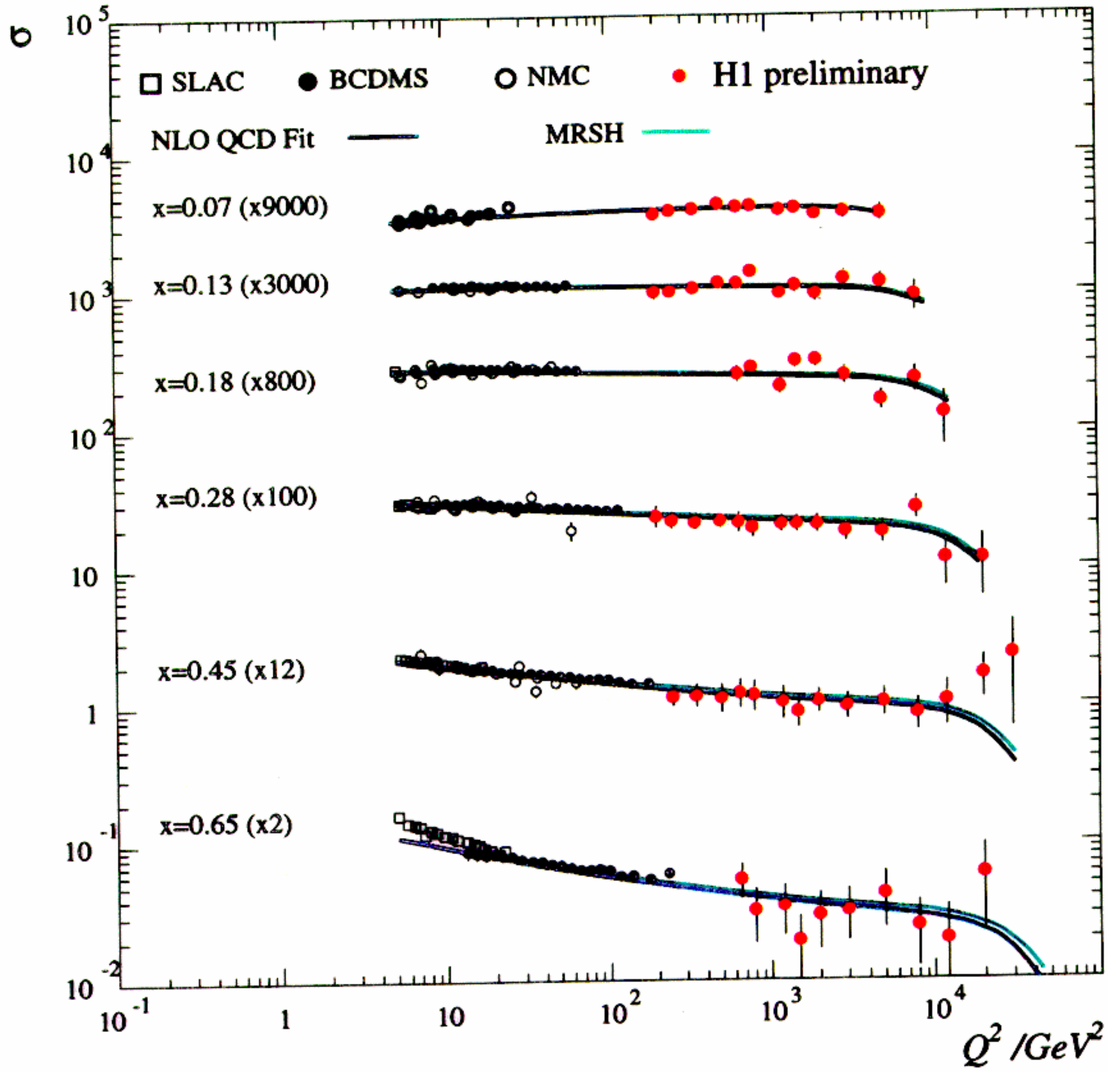
NC Cross–Section $d\sigma/dx$ (ZEUS)



- Error band = PDF uncertainty
- Very good agreement with SM prediction
- No significant "anomalies" at high x

  ... however, effects may level out in wide x–bins

Reduced NC Cross–Section (H1)



- → Gap to fixed–target experiments almost filled
- → No discrepancies HERA/fixed–target obvious
- → Statistical precision still limited
- → Excess at $x \approx 0.45$ remains visible

CC Analyses

Kinematic Reconstruction

- Scattered neutrino invisible
- Kinematic variables from hadronic system
- Resolutions: $dQ^2/Q^2, dx/x \sim \mathcal{O}(15-30\%)$

Event Selection:

- Main signature: missing p_t
  $p_t > 10\,\mathrm{GeV}$ (ZEUS); $p_t > 12\,\mathrm{GeV}$ (H1)
- Vertex reconstructed and in fiducial region
- Anti–background event topology cuts

Event Samples:

ZEUS	H1
$Q^2 > 400\,\mathrm{GeV}^2$ $y < 0.9$	$x > 0.01$ $0.03 < y < 0.9$
869 events	656 events

Systematic Effects:

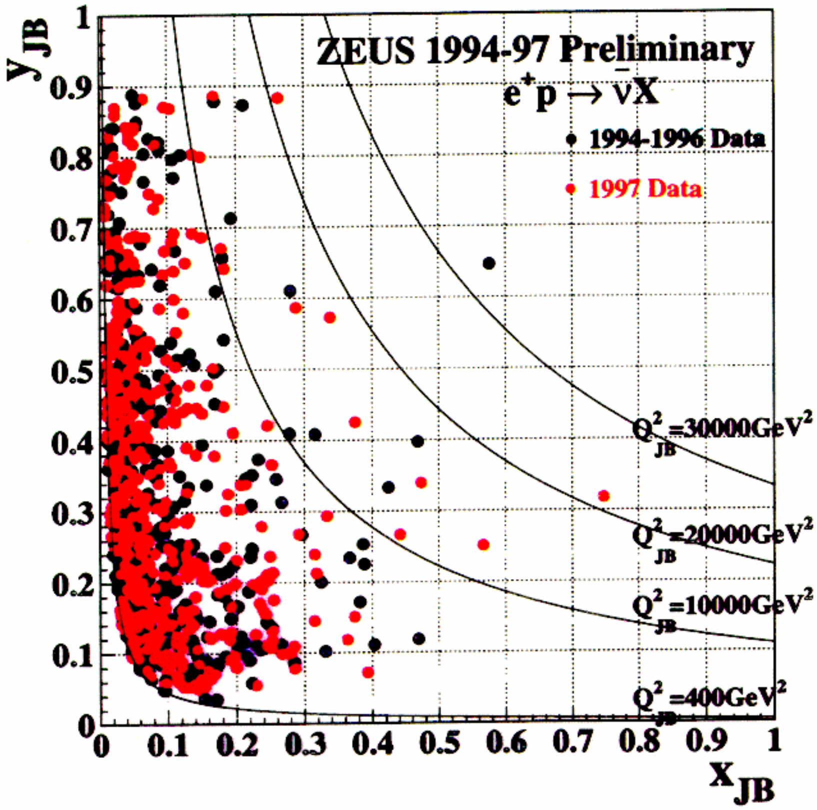
- Dominated by hadronic energy scale

ZEUS Kinematic Plane (CC)

Changes w.r.t. the 1996/LP97 analyses:

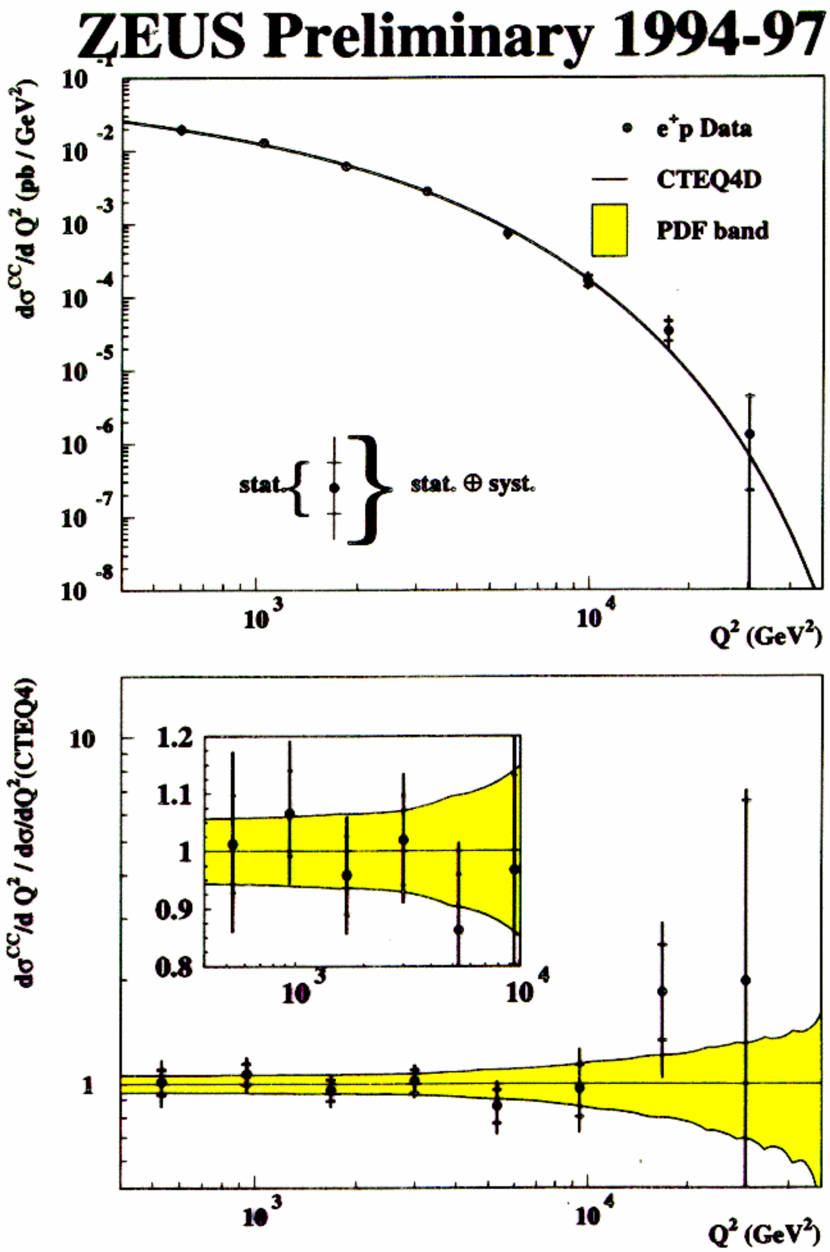
Improved analysis algorithms

Modified event selection



Q^2_{min} (GeV^2)	N_{obs}	N_{exp} and errors		
1000	586	600	+52	-52
10000	22	17	+5.7	-5.2
15000	8	3.9	+1.9	-1.6
20000	3	0.97	+0.65	-0.47
30000	1	0.06	+0.08	-0.04

CC Cross–Section $d\sigma/dQ^2$ (ZEUS)

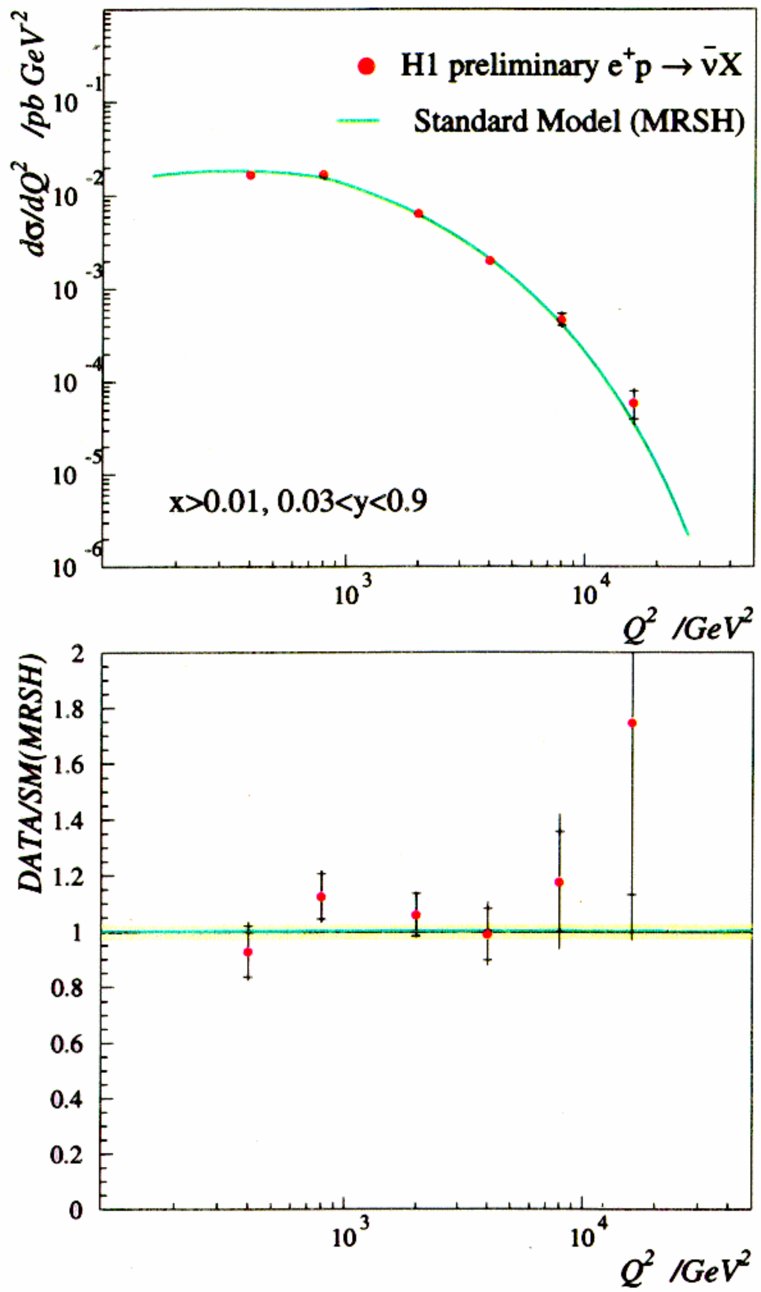


→ Error band = PDF uncertainty

→ Good agreement with SM prediction

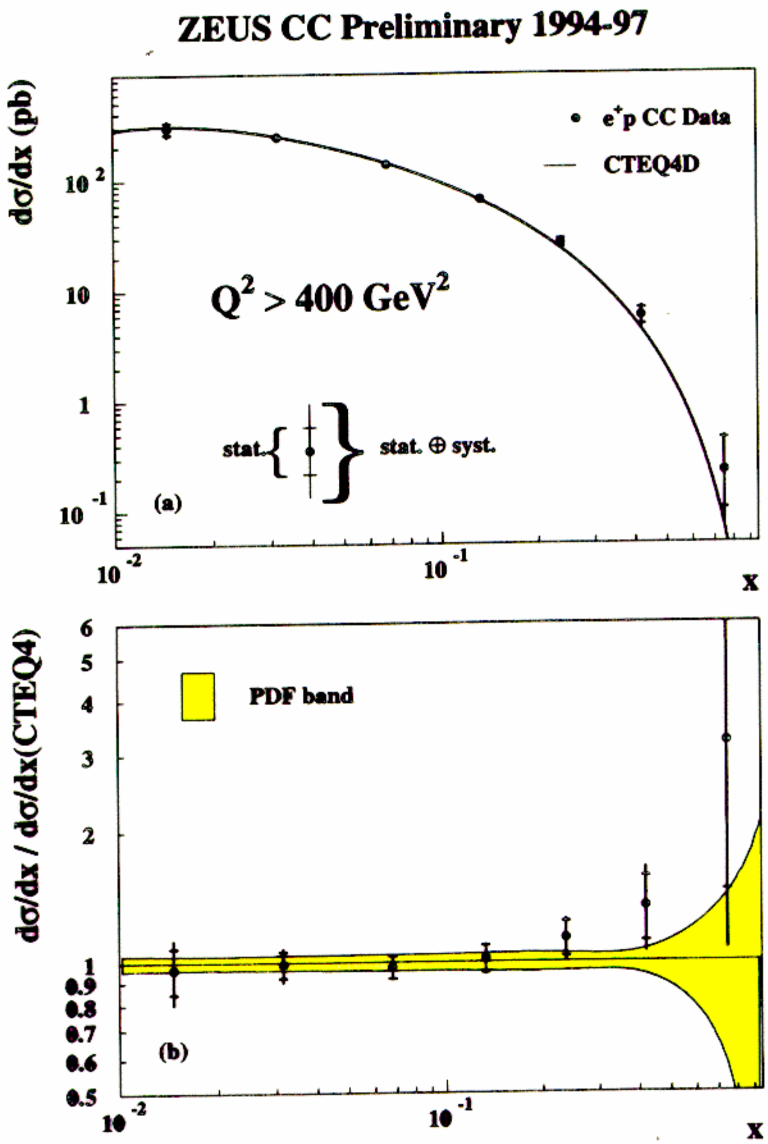
→ Slight excess at highest Q^2

CC Cross–Section $d\sigma/dQ^2$ (H1)



- → Error band = luminosity uncertainty
- → Good agreement with SM prediction
- → Slight excess at highest Q^2

CC Cross–Section $d\sigma/dx$ (ZEUS)



→ Error band = PDF uncertainty

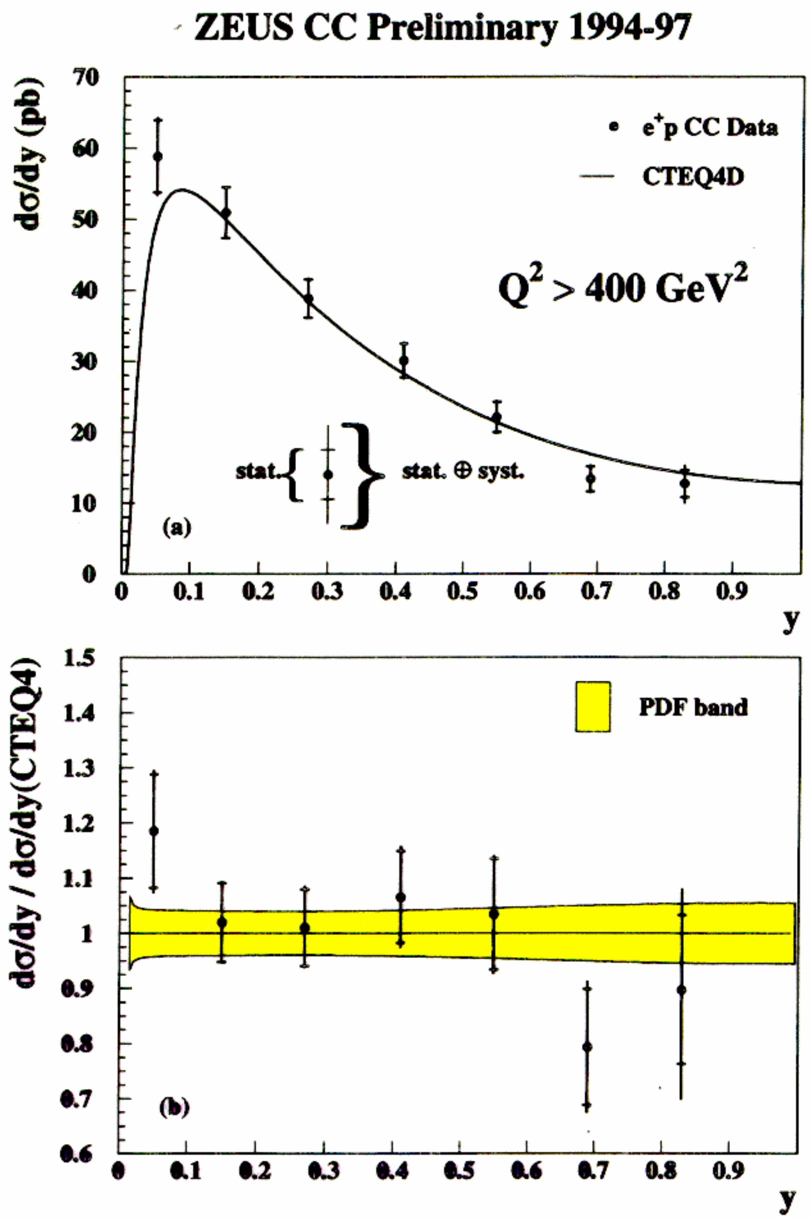
does not include the possibility $d/u(x \to 1) > 0$

→ Good agreement with SM prediction

→ Slight excess at highest x

high–x excess is Q^2–independent (not shown)

CC Cross–Section $d\sigma/dy$ (ZEUS)

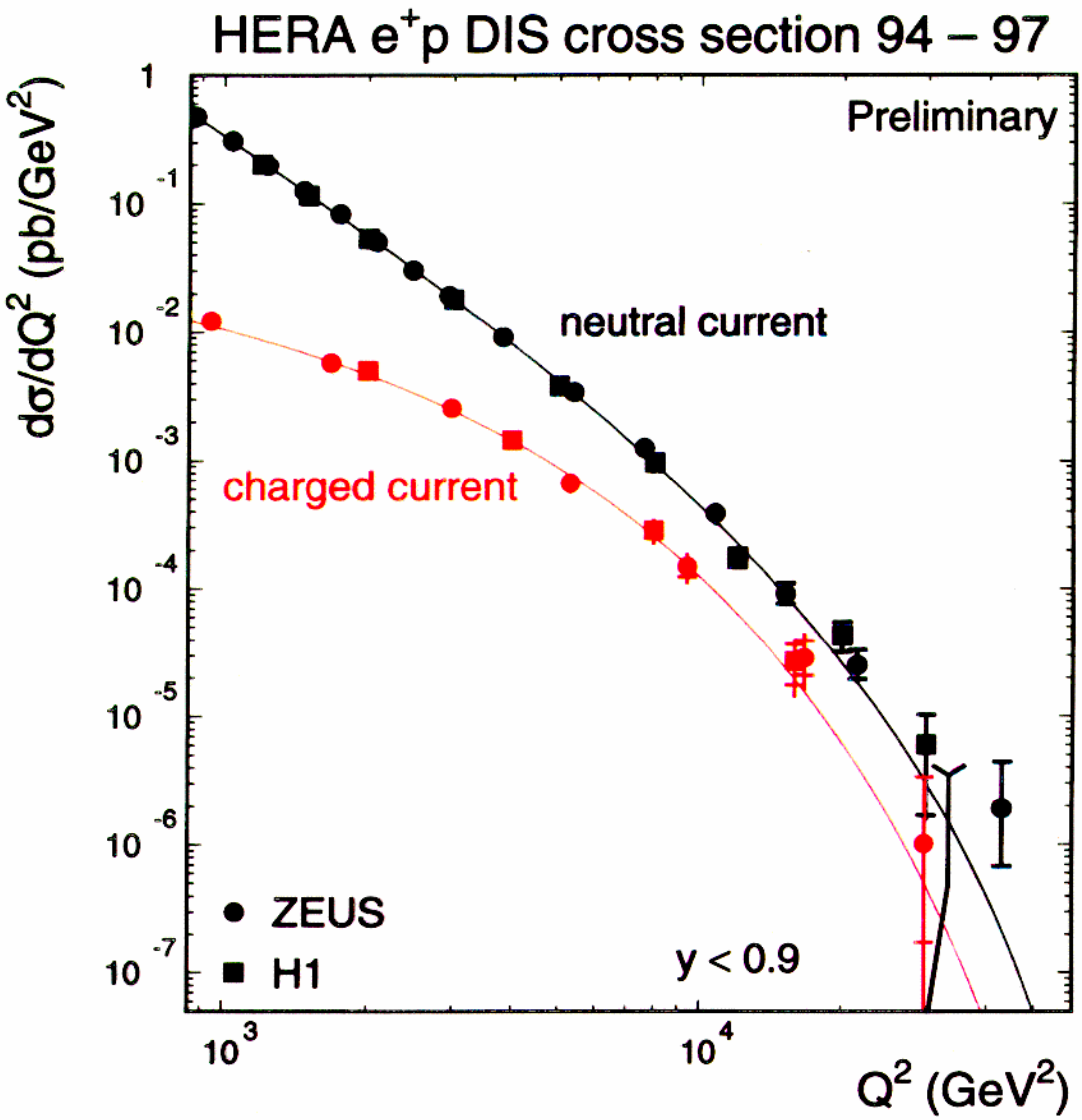


→ Error band = PDF uncertainty

→ Data slightly "softer" than expected

may indicate excess of d_v ($\sigma \propto (1-y)^2$)

NC/CC Comparison of $d\sigma/dQ^2$



- → Good agreement between ZEUS and H1
- → $\sigma(\mathrm{NC})$ and $\sigma(\mathrm{CC})$ of same order at $Q^2 \gtrsim M^2_{W,Z}$
- → Region $Q^2 \gtrsim 10^4\,\mathrm{GeV}^2$ still statistics–limited

Scenarios Beyond the Standard Model

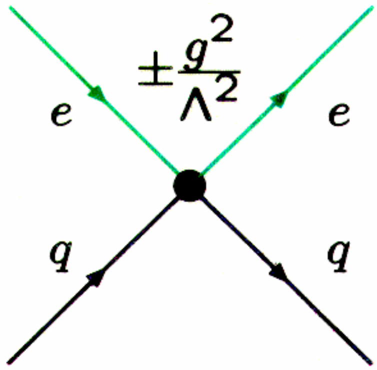
What if the high–Q^2 excess is not a statistical fluctuation?

- Which phenomenological scenarios explain the excess?
- Are they compatible with other measurements?
- How can we test them?

Two scenarios are discussed:

- **Contact Interactions**
  - → "Low–energy" manifestations of processes at mass scales far beyond the HERA regime
  - → Cover wide class of different processes
  - → Related to e^+e^- and $p\bar{p}$ scattering and to low–energy phenomena
- **Positron–quark resonances**
  - → New particles coupling to e and q can be directly produced in ep collisions
  - → Signature: resonance in $M = \sqrt{xs}$
  - → Such particles can be pair–produced in $p\bar{p}$ ⇒ detection at Fermilab possible

Contact Interactions (CI)



Can represent:

- Heavy boson exchange
- Leptoquark (s or t channel)
- Interaction of composite electron and quark
- ...

Historical equivalent:
4–fermion interaction

Effective Lagrangian:

$$\mathcal{L} = \frac{g^2}{\Lambda^2} \cdot \sum_{\substack{a,b=L,R \\ q=u,d}} \eta^q_{ab} (\bar{e}_a \gamma^\mu e_a)(\bar{q}_b \gamma_\mu q_b)$$

→ $\eta^q_{ab} = \pm 1, 0$ and $g^2 = 4\pi$ by convention

→ Only chiral vector couplings considered
(avoids e.g. severe constraints from π decays)

→ Interference with SM constructive or destructive

All CI's also modify $\sigma(e^+e^-)$ and $\sigma(p\bar{p})$

→ Interference sign is different

→ LEP/Tevatron and HERA have different sensitivity

Contact Interaction Scenarios

CI scenarios = linear combinations of η^q_{ab}

CI	η^u_{LL}	η^u_{LR}	η^u_{RL}	η^u_{RR}	η^d_{LL}	η^d_{LR}	η^d_{RL}	η^d_{RR}	studied by
VV	+	+	+	+	+	+	+	+	ZEUS,H1
AA	+	−	−	+	+	−	−	+	
VA	+	−	+	−	+	−	+	−	
X1	+	−	0	0	+	−	0	0	ZEUS
X2	+	0	+	0	+	0	+	0	
X3	+	0	0	+	+	0	0	+	
X4	0	+	+	0	0	+	+	0	
X5	0	+	0	+	0	+	0	+	
X6	0	0	+	−	0	0	+	−	
U5	0	+	0	+	0	0	0	0	ZEUS
U1	+	−	0	0	0	0	0	0	
U4	0	+	+	0	0	0	0	0	
LL	+	0	0	0	+	0	0	0	H1
LR	0	+	0	0	0	+	0	0	
RL	0	0	+	0	0	0	+	0	
RR	0	0	0	+	0	0	0	+	

→ Marginal effect if including s, c, b, t

Restrictions:

- Severe limits from Atomic Parity Violation for all scenarios having

$$\eta_{LL} + \eta_{LR} - \eta_{RL} - \eta_{RR} \neq 0$$

... refers in particular to LL,LR,RL,LL

- $SU(2)_L \times U(1)_R \Rightarrow \eta^u_{ab} = \eta^d_{ab}$ (not U1–U5)

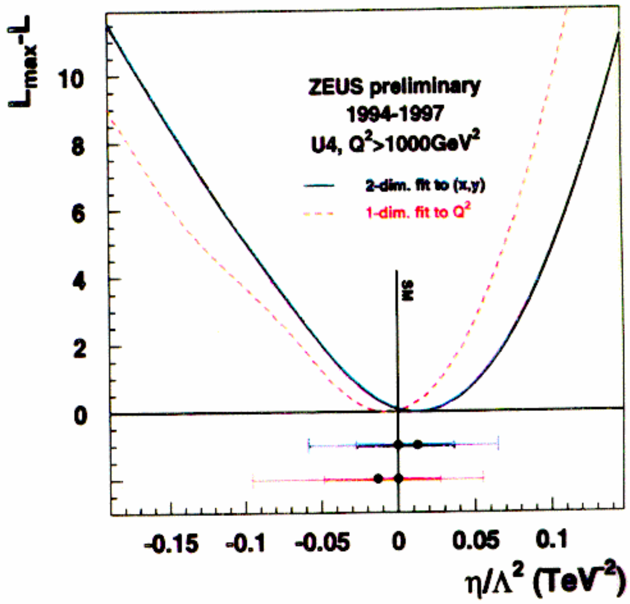
Contact Interaction Analyses

ZEUS analysis:

- Input: raw distributions without acceptance or migration corrections
- Simulate CI's by reweighting MC events
- Determine log–likelihood: $LL(\pm 1/\Lambda^2)$

Two approaches:

- Binned LL in Q^2
- Unbinned LL in (x,y)
- Very similar results

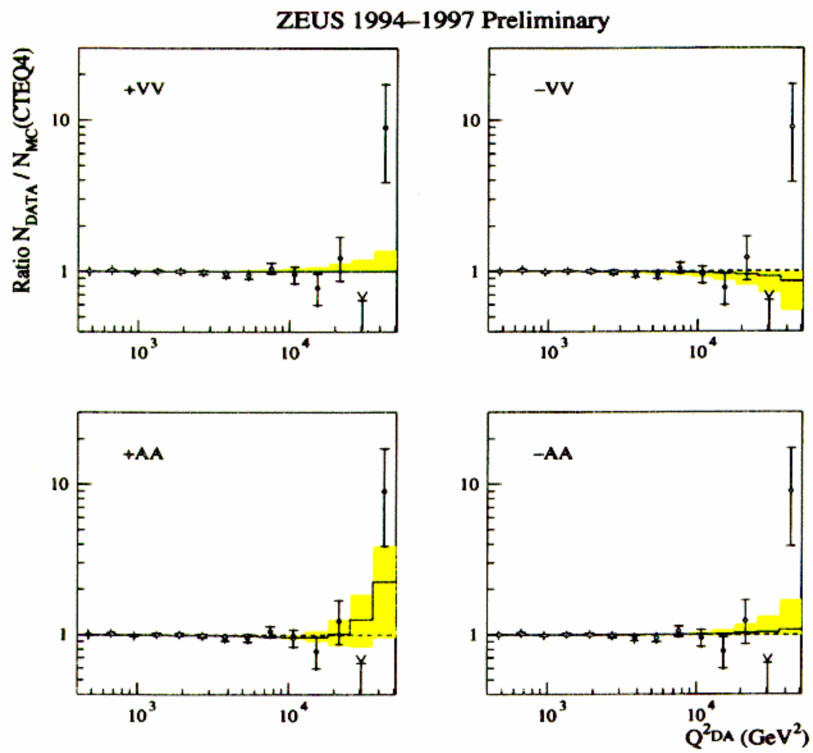


- Limit setting:
  Log–likelihood $\Rightarrow$ best fit, 1σ–intervals
  One–sided 95% C.L. limits from MC experiments

H1 analysis:

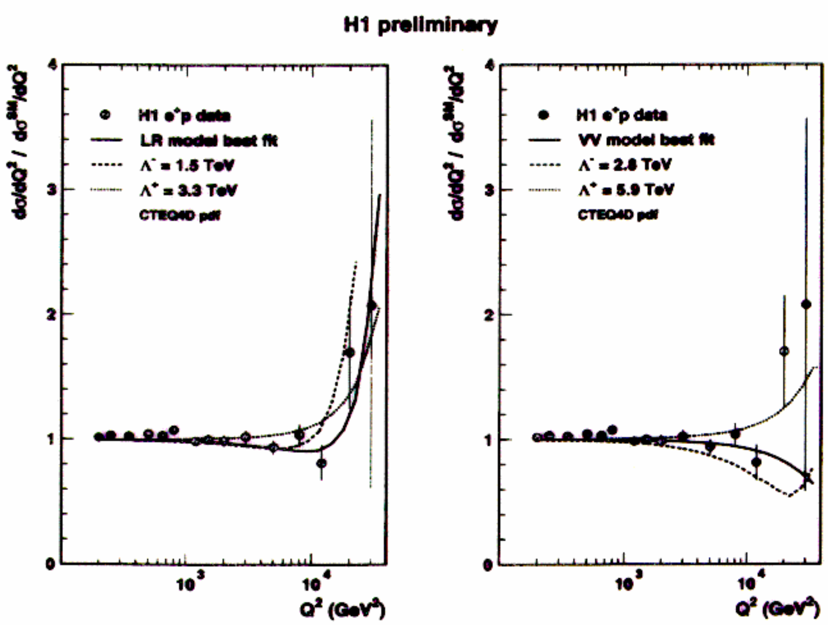
- χ^2–fit to $d\sigma/dQ^2$
- Two–sided 68% and 95% C.L. intervals from χ^2–contour

CI Example Fits $\left(\frac{d\sigma/dQ^2(\mathbf{SM+CI})}{d\sigma/dQ^2(\mathbf{SM})}\right)$



ZEUS

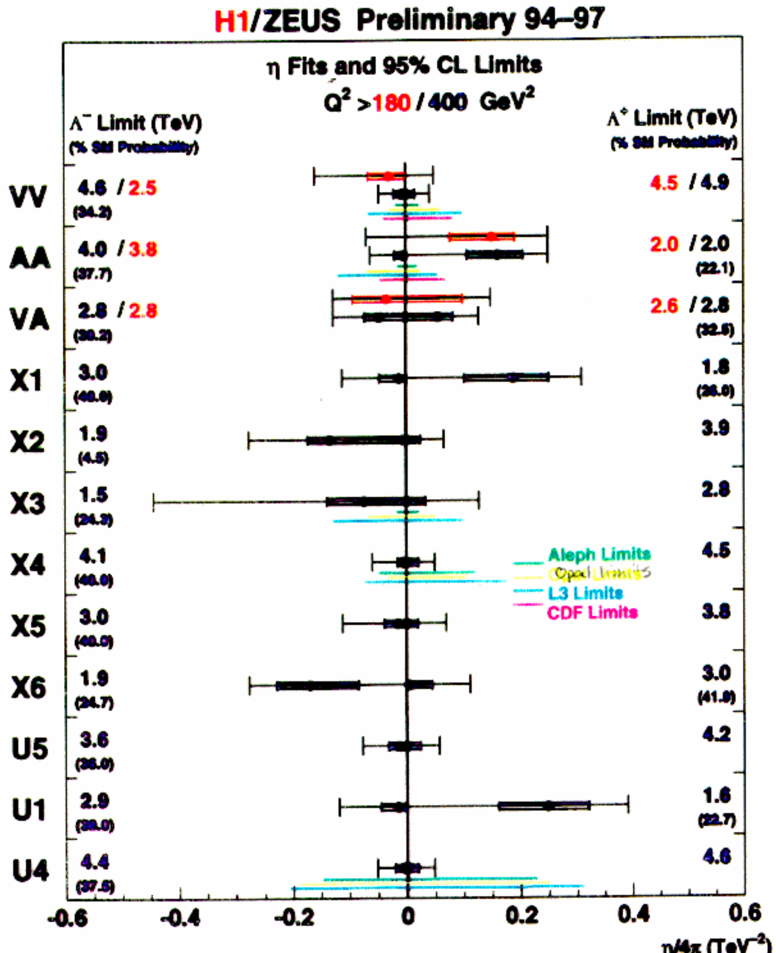
- solid line: best fit
- yellow band: 1σ contour

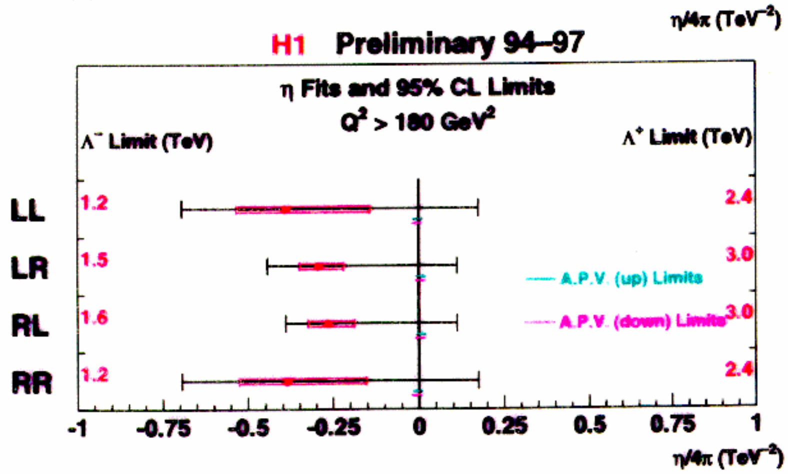


H1

- solid line: best fit
- dashed lines: 95% C.L.

CI Limits from HERA





- dots: best fit
- double bars: 1σ limits
- single bars: 95% C.L. limits
- numbers: Λ limits

All CI fits compatible with SM within 2σ

Comparison to Other CI Results

Type	95% C.L. Limits on Λ [TeV]						
	ZEUS	H1	CDF	OPAL	ALEPH	L3	APV (u/d)
$VV+$	4.9	4.5	3.5	4.1	6.7	3.2	-
$VV-$	4.6	2.5	5.2	5.7	7.4	3.9	-
$AA+$	2.0	2.0	3.8	6.3	7.4	4.3	-
$AA-$	4.0	3.8	4.8	3.8	8.2	2.9	-
$VA+$	2.8	2.6	-	-	-	-	-
$VA-$	2.8	2.8	-	-	-	-	-
$X3+$	2.8	-	-	4.4	6.9	3.2	-
$X3-$	1.5	-	-	3.8	7.7	2.8	-
$X4+$	4.5	-	-	3.1	2.9	2.4	-
$X4-$	4.1	-	-	5.5	4.5	3.7	-
$LL+$	-	2.4	2.5	4.4	5.6	3.0	7.4/7.9
$LL-$	-	1.2	3.7	2.8	6.4	2.1	11.7/12.3
$LR+$	-	3.0	2.8	3.3	3.0	2.4	7.4/7.9
$LR-$	-	1.5	3.3	3.6	3.2	2.6	11.7/12.3
$RL+$	-	3.0	2.9	2.5	2.3	2.0	11.7/12.3
$RL-$	-	1.6	3.2	4.9	4.0	3.2	7.4/7.9
$RR+$	-	2.4	2.6	3.0	4.1	2.3	11.7/12.3
$RR-$	-	1.2	3.6	3.9	4.5	2.7	7.9/7.4

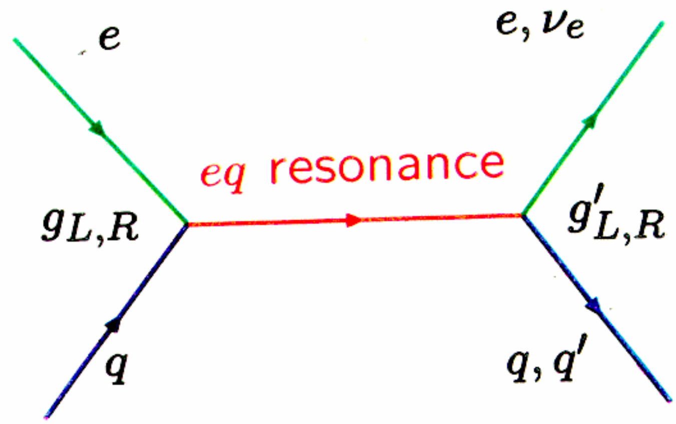
CDF Coll., F.Abe et al., Phys.Rev.Lett 79(1997)2198
OPAL Coll., G.Abbiendi et al., CERN-EP/98-108 (ICHEP98, Abs. 264)
ALEPH Coll., ALEPH 98-060(1998) (ICHEP98, Abs. 906)
L3 Coll., M.Acciarri et al., CERN-EP/98-31(1998)
APV: A.Deandrea, Phys.Lett. B409(1997)277 and references therein

→ Similar sensitivity at HERA, LEP, Tevatron

→ No obvious indication for existence of a CI

→ APV dominates P–violating CI limits

Positron–Quark Resonances



Leptoquarks (LQ's), "classical" scheme:

- LQ's only couple to e, q, γ, Z, W, g
- LQ's conserve $SU(2)_L \times U(1)_R$
- LQ's are identified by S, F, I_w, Q
- $BR(LQ \to eq) = 1 - BR(LQ \to \nu q') = 0$, 1/2 or 1

> Only few possibilities are left by low–eneregy and HERA $e^- p$ data:
> All have $BR(LQ \to eq) = 1$

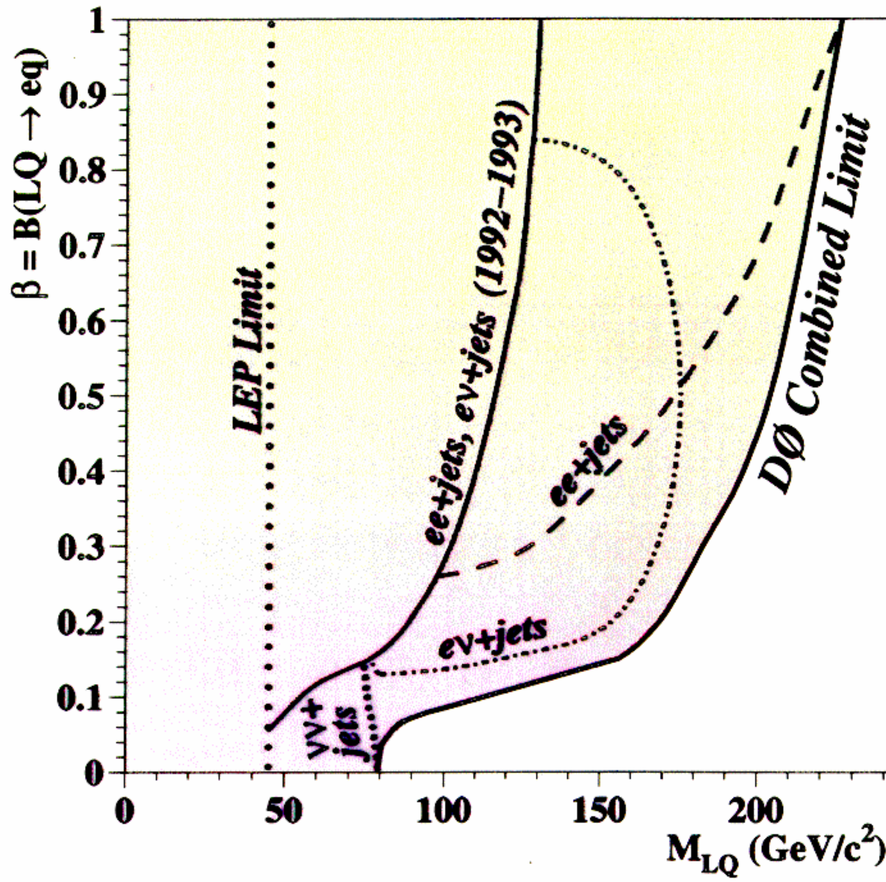
R_p–violating squarks ($\tilde{q}$):

- R_p–violation: SUSY particles can be singly produced
- Squarks can have LQ–like couplings
- Alternative, R_p–conserving decay modes $\Rightarrow BR(\tilde{q} \to eq)$ can be $\ll 1$
- No CC–type decay modes

Tevatron Leptoquark Limits

LQ's can be pair–produced in $p\bar{p}$ collisions

- Cross–section does not depend on LQ coupling
- Sensitivity decreases with BR(LQ $\rightarrow eq$)
- Stringent restiction for LQ at HERA



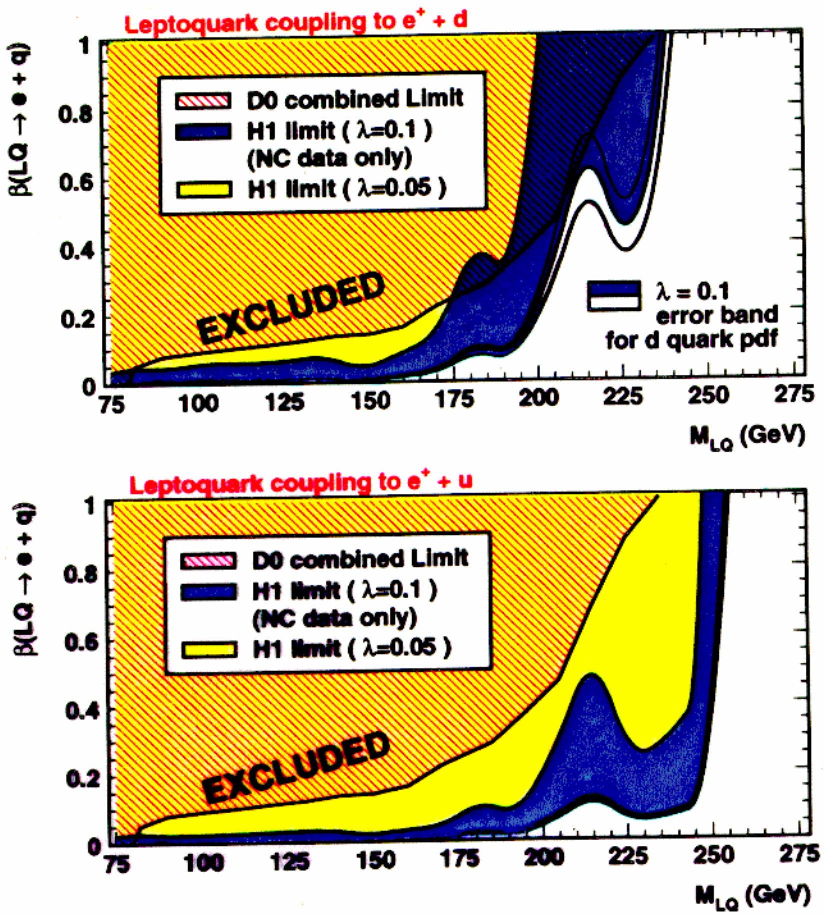
DØ 95% lower LQ mass limts (GeV)		
LQ type	BR($LQ \rightarrow eq$) = 1	BR($LQ \rightarrow eq$) = 0.5
$S = 0$ (scalar)	225	204
$S = 1$ (vector)	298	270

New LQ Limits from H1

$\sigma(ep \to \text{LQ} + X)$ depends on
M_{LQ}, coupling λ, and BR$(\text{LQ} \to eq)$

- Use Poissonian statistics in "sliding mass window"
- Fix λ; derive M_{LQ} limit as function of BR$(\text{LQ} \to eq)$

H1 Preliminary

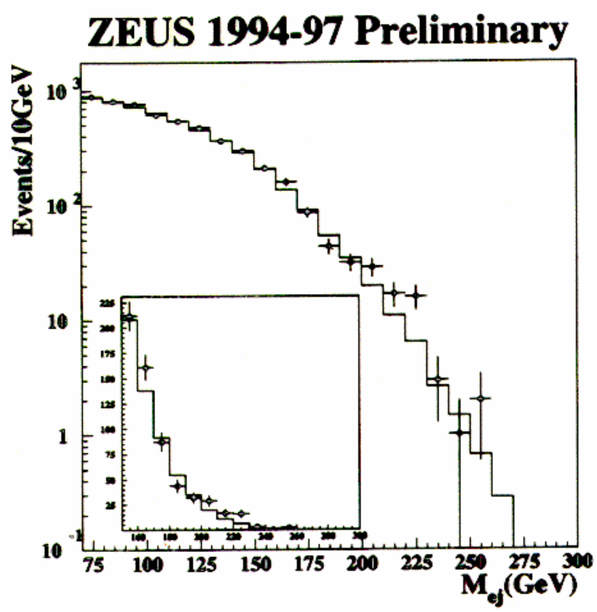


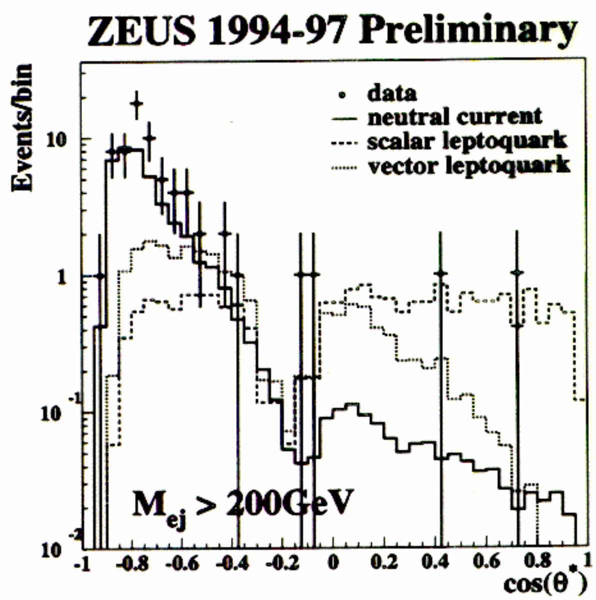
→ $M_{\text{LQ}} > \sqrt{xs}$ by ~ 4 GeV due to QCD effects

→ Open window at small BR$(\text{LQ} \to eq)$

New LQ Limits from ZEUS

Study M_{ej} and $\cos\theta^*$ of e^++jet in NC events:

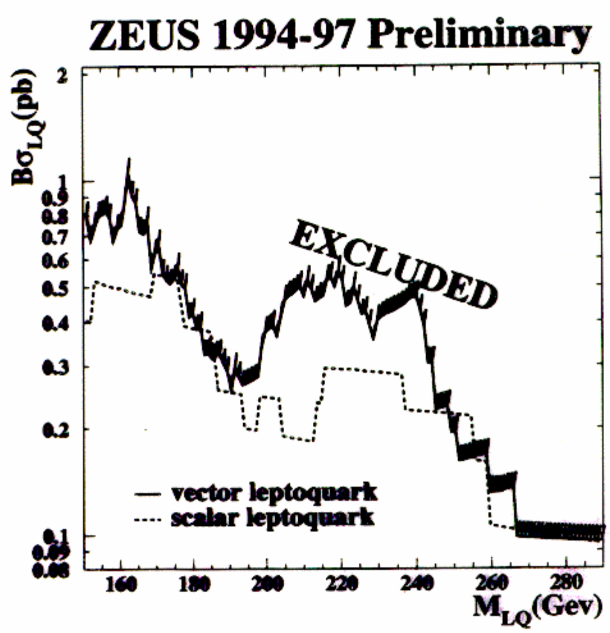




LQ limits:

- Use MC to define $\theta^*_{\text{cut}}(M_{ej})$
- Compare observed and expected event numbers with $\cos\theta^* > \cos\theta^*_{\text{cut}}$ in mass bin around M_{ej}

→ Upper limit on $\sigma(\text{LQ})\cdot\text{BR}(\text{LQ}\to e^+q)$



Conclusions and Outlook

Conclusions

- First precision NC and CC cross–section measurements for Q^2 up to several 10^4 GeV^2
- Up to $Q^2 \approx 10000$ GeV^2, the data are in perfect agreement with the Standard Model
- Excess at $Q^2 \gtrsim 20000$ GeV^2 not confirmed in the 1997 data but still present
- ZEUS and H1 report new limits on Contact Interactions and eq resonance production:

  No significant evidence for contact interactions

  HERA has discovery window for eq resonances

Outlook

- 1998–1999: e^-p data at $E_p = 920$ GeV.
- After 2000: HERA upgrade: $\sim 170\,\mathrm{pb}^{-1}$ / year
  Longitudinal e polarisation

We envisage an exciting future
for high–Q^2 physics at HERA