PHYSICS AT HIGHEST Q^2

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XVIII Physics in Collision, Frascati, June 17–19, 1998

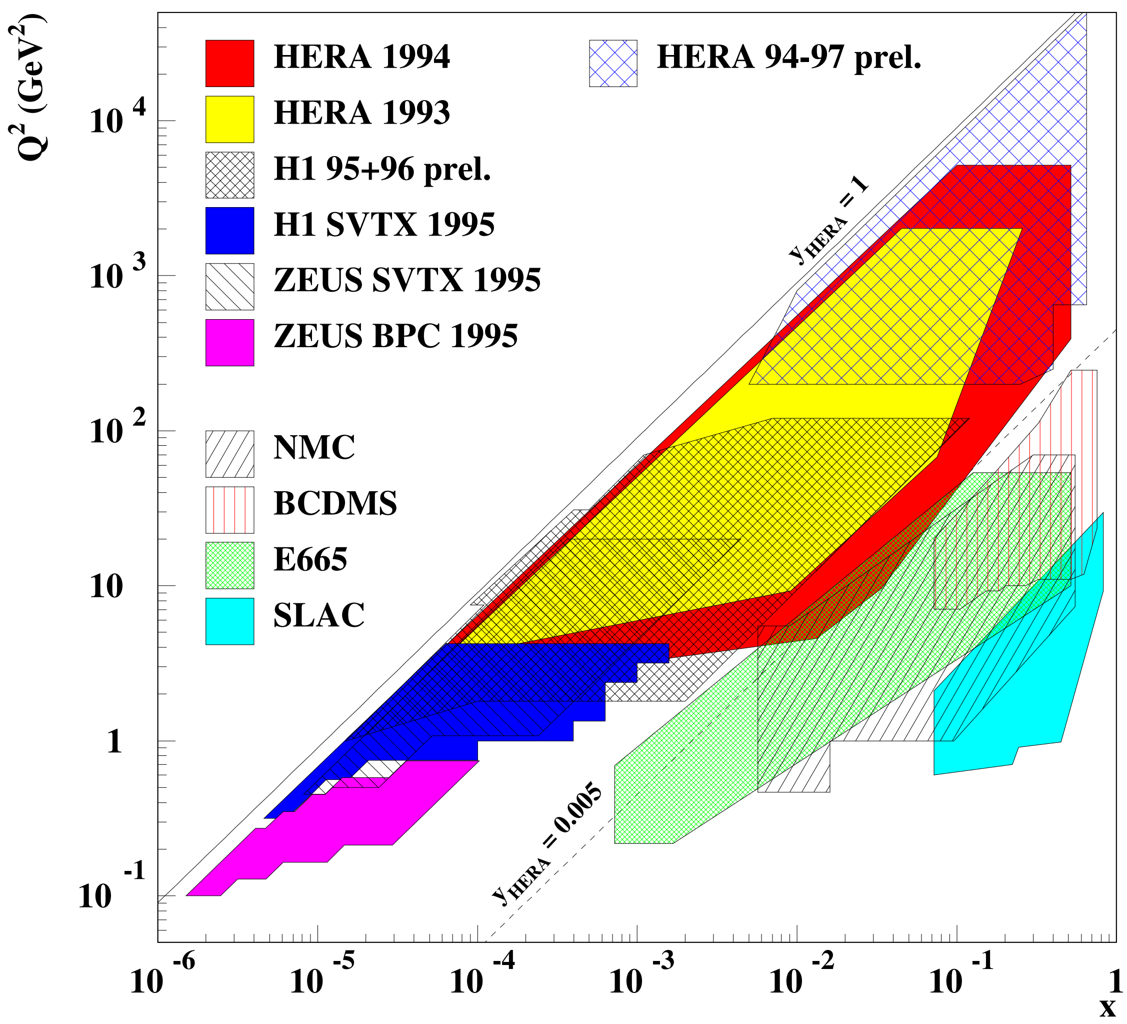
Outline

- Deep Inelastic Scattering at HERA
- Neutral Currents $ep \to eX$
- Charged Currents $ep \to \nu X$
- Others $ep \to \ell\nu(?)X$
- Conclusions

Deep Inelastic Lepton Nucleon Scattering

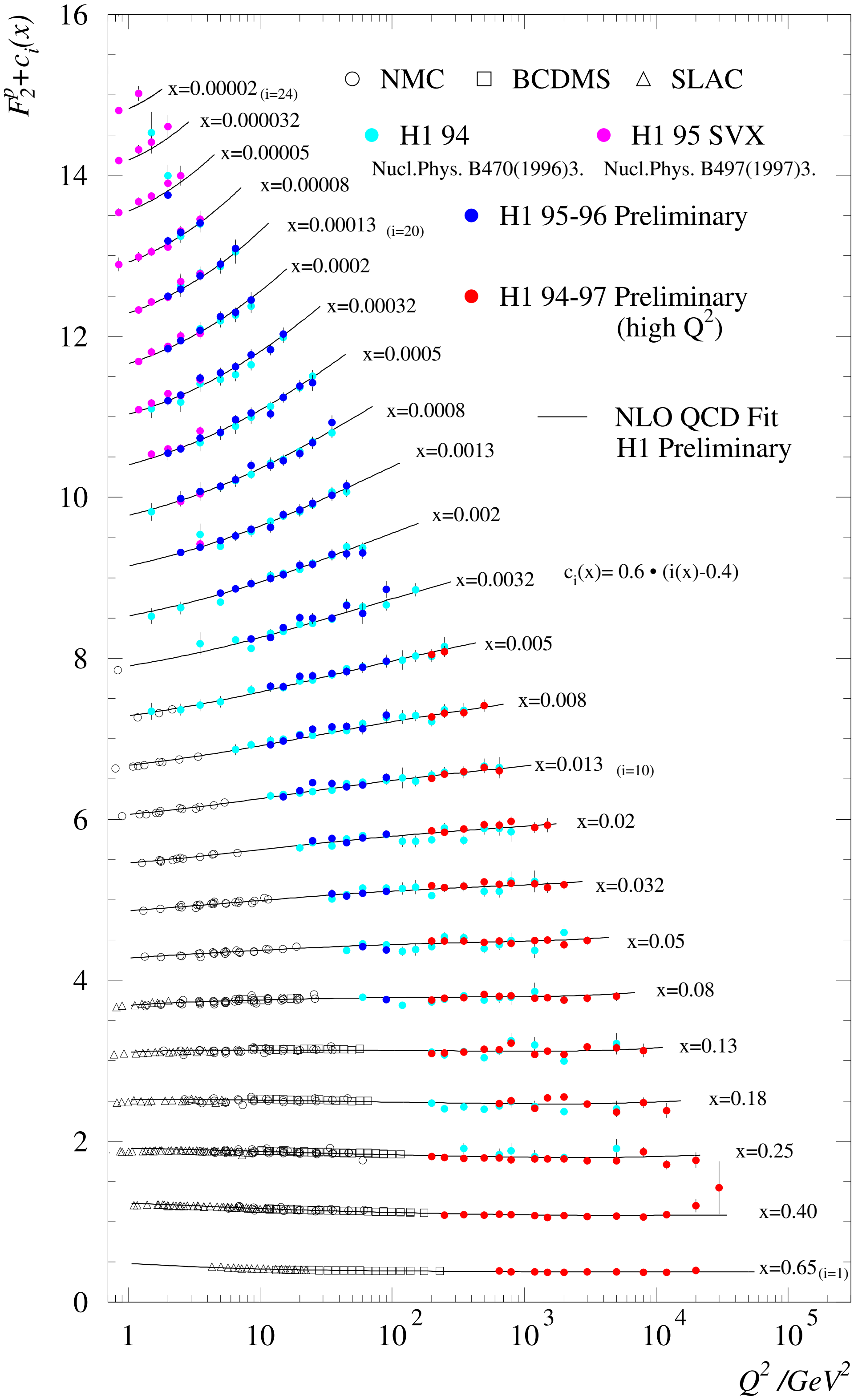
Inclusive Lepton Nucleon Scattering $\ell p \to \ell' X$
described by two kinematic parameters e.g. :

- Squared Momentum Transfer Q^2
- Fractional parton momentum x



Hera extends Q^2 range by two orders of magnitude

The Data



See talk on Structure Functions by F. Eisele

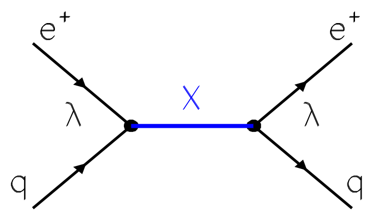
Physics Motivation

- Probe physics at a distance scale down to $d \sim 1/Q \sim 10^{-18}m$
- Probe physics in a region where electromagnetic (γ) and weak (W, Z) interactions are of comparable strength

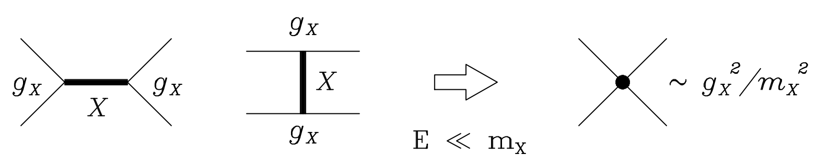
Test the Standard Model at highest Q^2

Is there more than SM at highest Q^2 ?

- s - channel resonances (Leptoquarks ?)

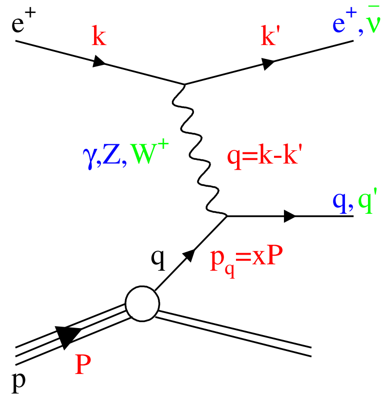


- Contact interaction



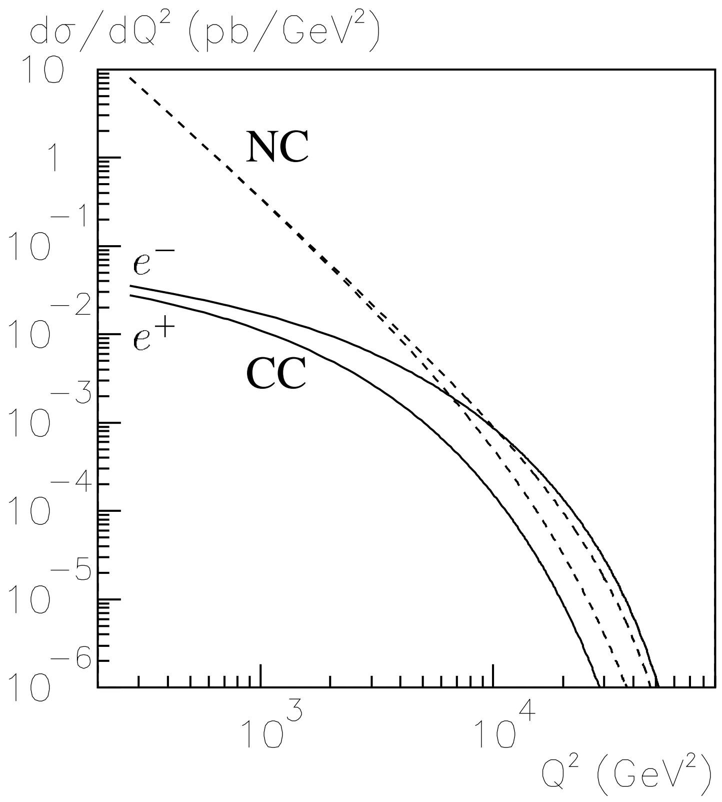
- Others ?

Standard Model Expectation



Q^2 dependence of cross section determined by :

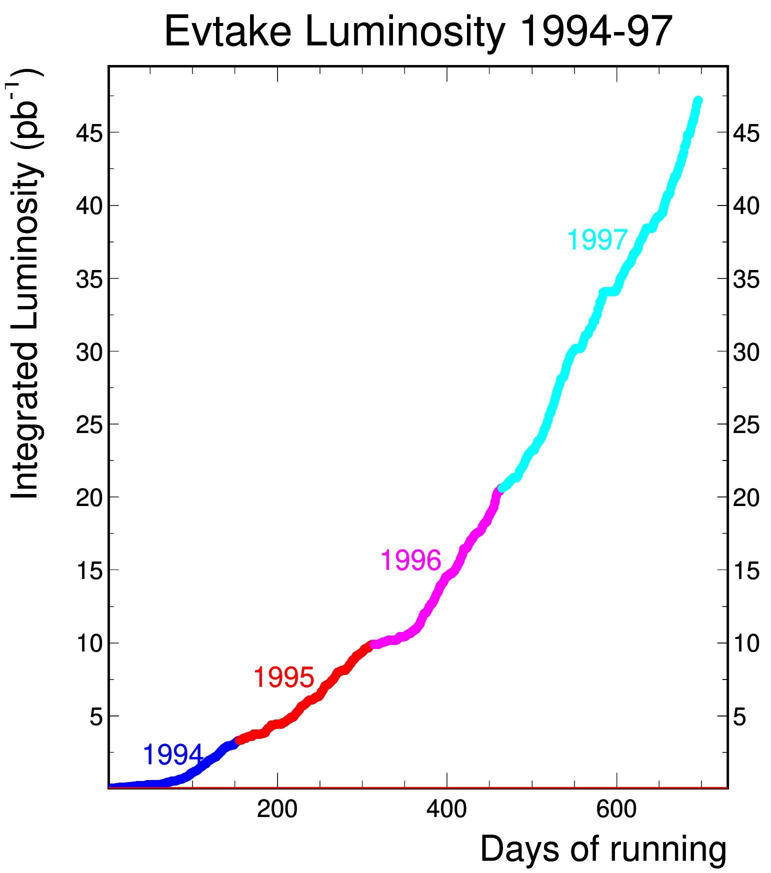
- Propagator $(\frac{M_B^2}{Q^2+M_B^2})^2$, M_B = Mass of exchanged Boson
- Q^2 - dependence of Structure functions



Energy and Luminosity

HERA : 27.5 GeV Positrons $\Longrightarrow\Longleftarrow$ 820 GeV Protons

The highest Q^2 are only accessible with high Integrated Luminosities
A big step was taken in 1997



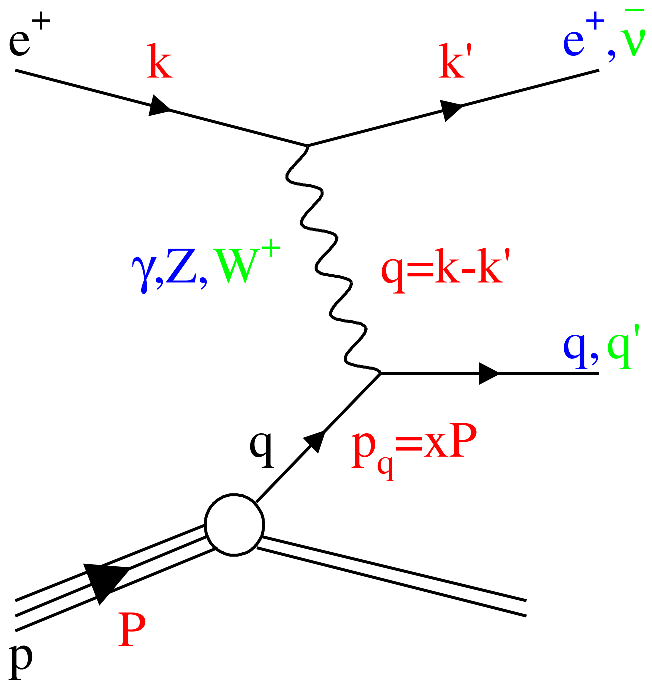
The data presented are based on Luminosities integrated in 1994 - 1997 for e^+p running at HERA with

$47\ pb^{-1}$ for the ZEUS experiment

and

$37\ pb^{-1}$ for the H1 experiment

DIS Kinematics



- $Q^2 = -(k - k')^2$ Squared Four Momentum Transfer
- $x = Q^2/2Pq$ Fractional parton momentum
- $y = \frac{Pq}{Pk}$ Inelasticity
- $s = (k + P)^2$ Squared CM Energy
- $M^2 = xs$ Squared Lepton-parton invariant mass
- $Q^2 = xys$

DIS Cross Sections and Structure Functions

Neutral Current e^+p DIS Cross Section

$$\frac{d^2\sigma}{dxdQ^2} = \frac{2\pi\alpha^2}{xQ^4}(Y_+F_2(x,Q^2) - y^2F_L(x,Q^2) - Y_-xF_3(x,Q^2))$$

$$Y_\pm = 1 \pm (1-y)^2$$

F_2 : Generalized Structure Function including electroweak coupling parameters to γ and Z_0
F_L : Longitudinal Structure Function
F_3 : Parity Violating term from Z_0 exchange

QPM :
$F_2 = \sum_f A_f(Q^2)(xq_f + x\overline{q}_f)$
$F_L = 0$
$F_3 = \sum_f B_f(Q^2)(xq_f - x\overline{q}_f)$

.

Charged Current e^+p DIS Cross Section (QPM)

$$\frac{d^2\sigma}{dxdQ^2} = \frac{G_F^2}{2\pi}\left(\frac{M_W^2}{M_W^2+Q^2}\right)^2(\overline{u} + \overline{c} + (1-y)^2(d+s))$$

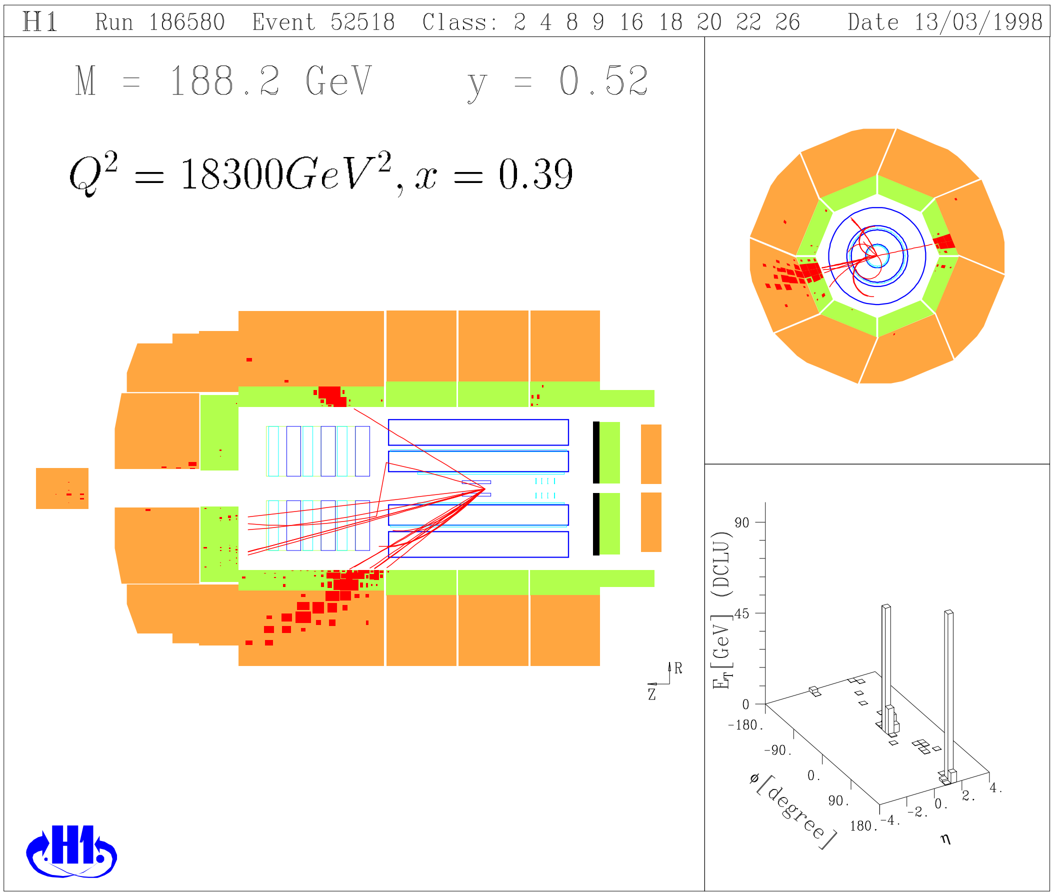
NC Events $e^+p \rightarrow e^+X$

Measurable are four kinematic parameters :

$$E_e, \theta_e, E_X, \theta_X$$

Overconstrained system (used for cross-checks)

- H1 uses Electron Method : E_e, θ_e
- ZEUS uses Double Angle Method : θ_e, θ_X

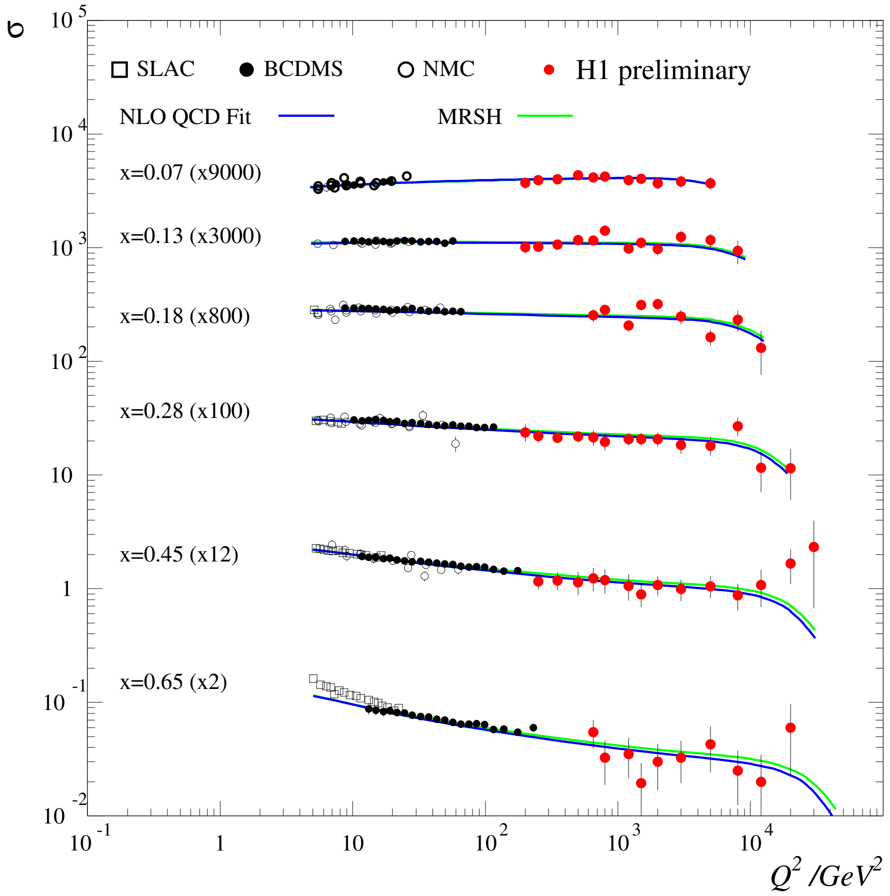


NC Cross Section

Define 'reduced cross section' :

$$\sigma = \frac{xQ^4}{2\pi\alpha^2 Y_+} \frac{d^2\sigma^{NC}}{dxdQ^2} = F_2 - \frac{y^2}{Y_+}F_L - \frac{Y_-}{Y_+}xF_3$$

$$Y_\pm = 1 \pm (1-y)^2$$

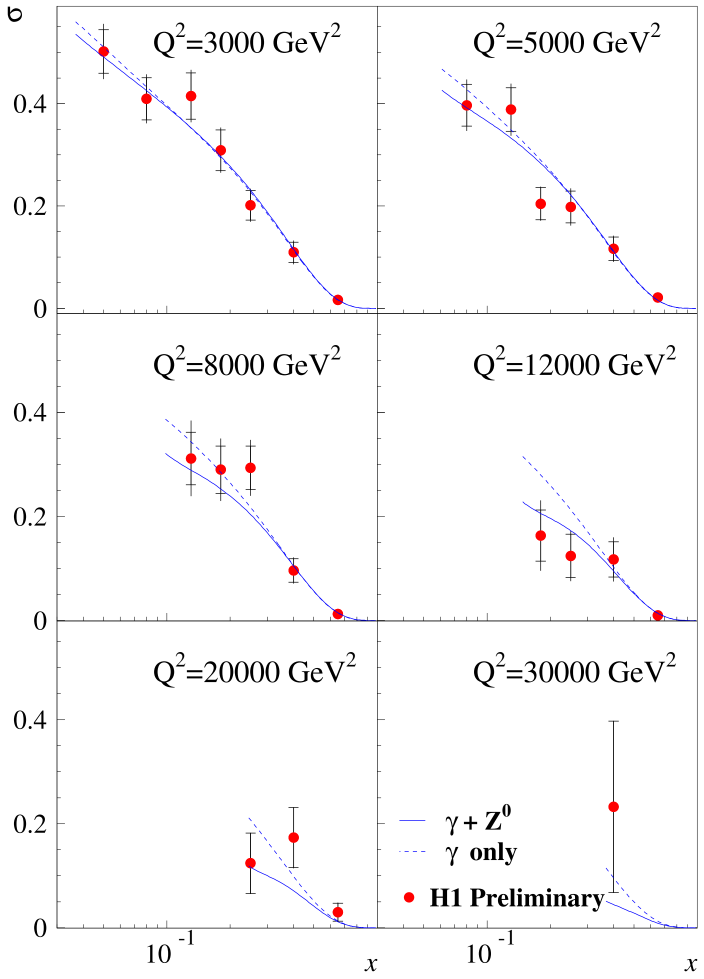


- High x , high Q^2 region explored
- Well described by NLO - QCD fit and MRSH parametrisation
- Excess of events around x = 0.45 at highest Q^2 ?

NC cross section. Highest Q^2

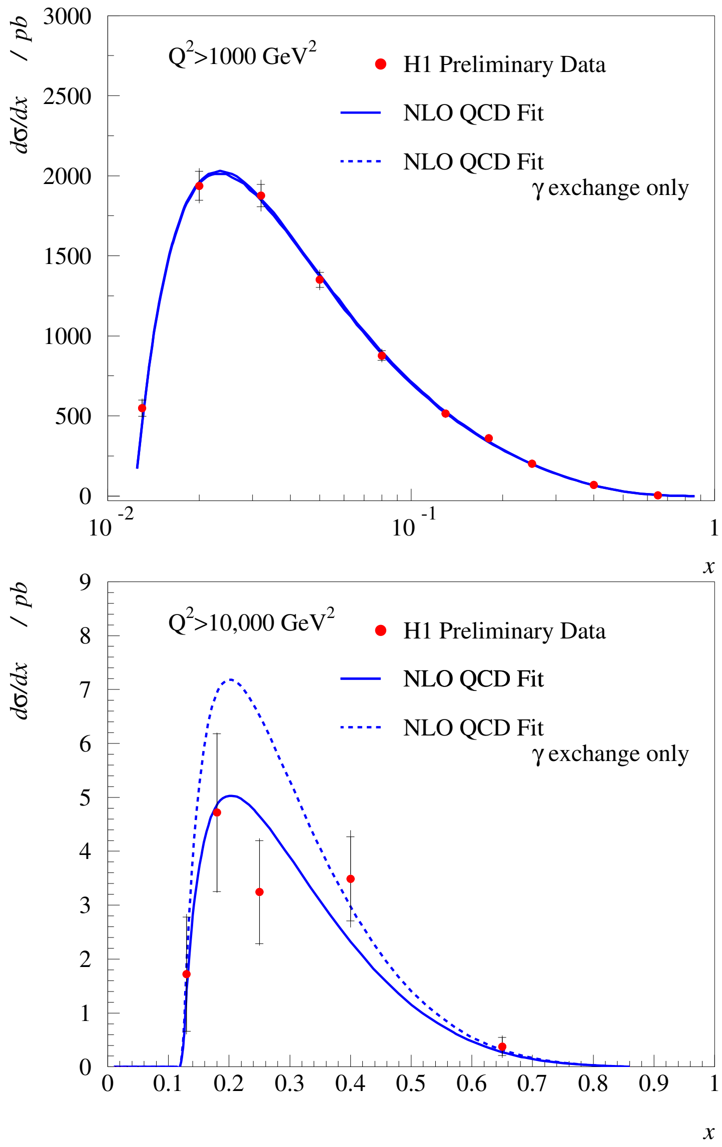
$$\sigma = \frac{xQ^4}{2\pi\alpha^2 Y_+} \frac{d^2\sigma^{NC}}{dxdQ^2}$$

$$Y_+ = 1 + (1-y)^2$$



Sensitivity to $\gamma - Z_0$ Interference in highest Q^2 bins.

NC Gamma - Z Interference



Highest Q^2 data favour destructive $\gamma - Z_0$ Interference , as predicted in SM for e^+p DIS.

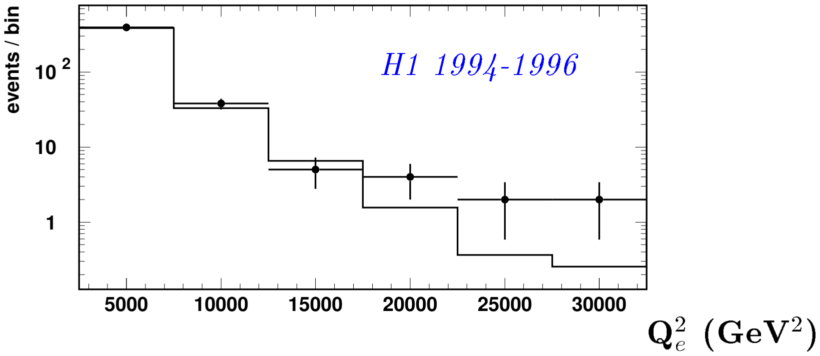
Excess of High Q^2, high x Events ?

1994 - 1996 Data

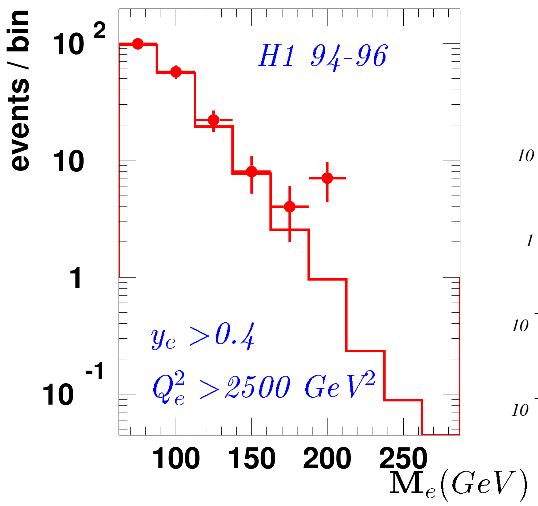
first publications:

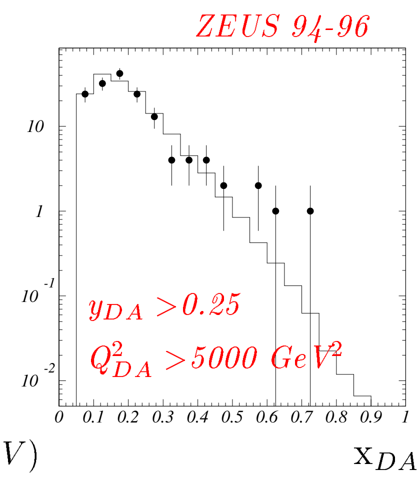
H1: 14.2 pb^{-1} Z.Phys **C74** (1997) 191

ZEUS: 20.1 pb^{-1} Z.Phys **C74** (1997) 207



$Q_e^2 > 15000$ GeV^2: N_{obs}=12 $\Leftrightarrow$ N_{exp}=4.71, $\mathcal{P} = 6 \times 10^{-3}$





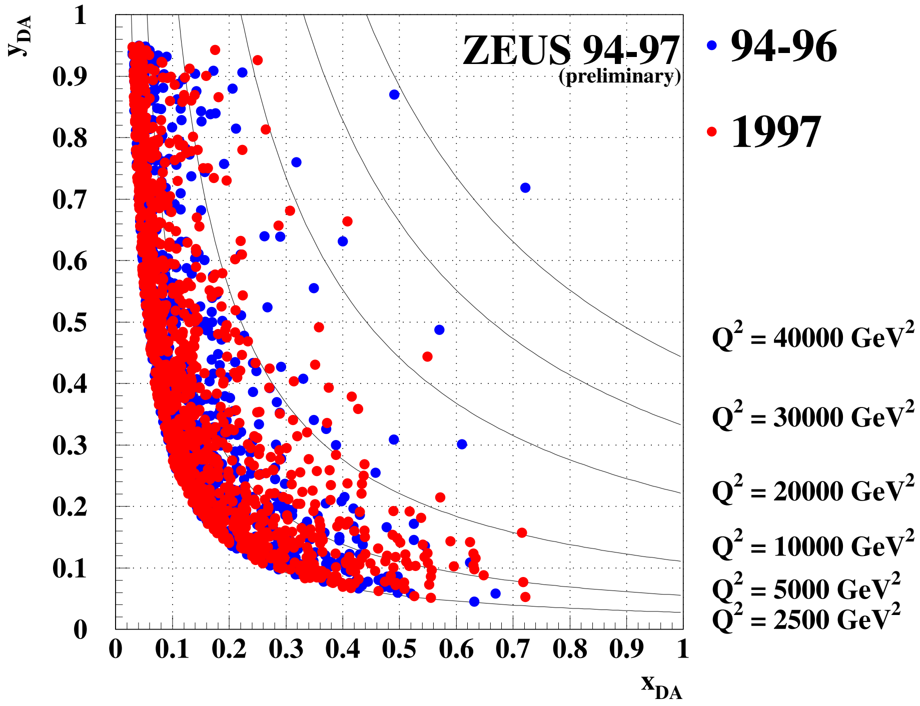
M_e=200±12.5 GeV $y_e > 0.4$: N_{obs}=7 $\Leftrightarrow$ N_{exp}=0.95

$x_{DA} > 0.55$ $y_{DA} > 0.25$: N_{obs}=4 $\Leftrightarrow$ N_{exp}=0.91

What does the 1997 Lumi add ?

Excess of High Q^2, high x Events ?

Now all 1994 - 1997 Data



New
Positron/hadron energy corrections from data

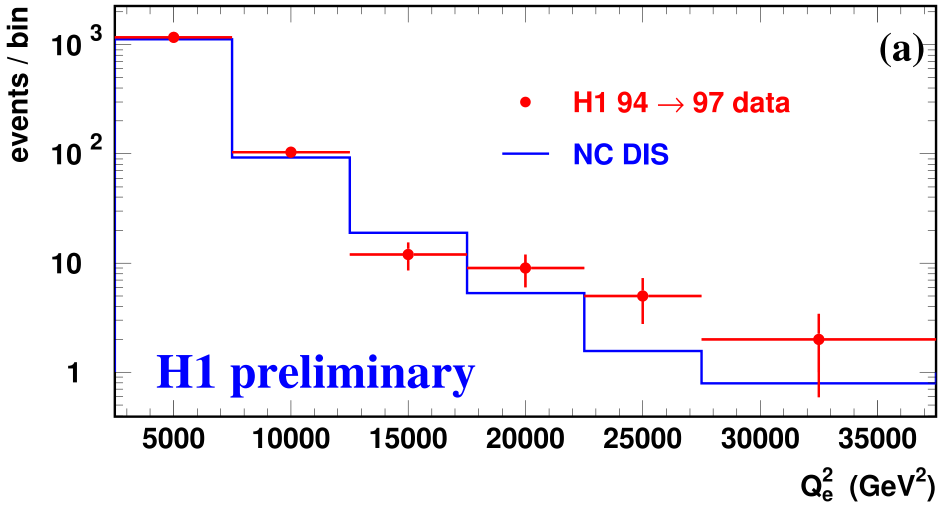
Q^2_{min}	N_{obs}	N_{exp}
2500	1817	1792 $\pm$ 93
5000	440	396 $\pm$ 24
10000	66	60 $\pm$ 4
15000	20	17 $\pm$ 2
35000	2	0.29 $\pm$ 0.02

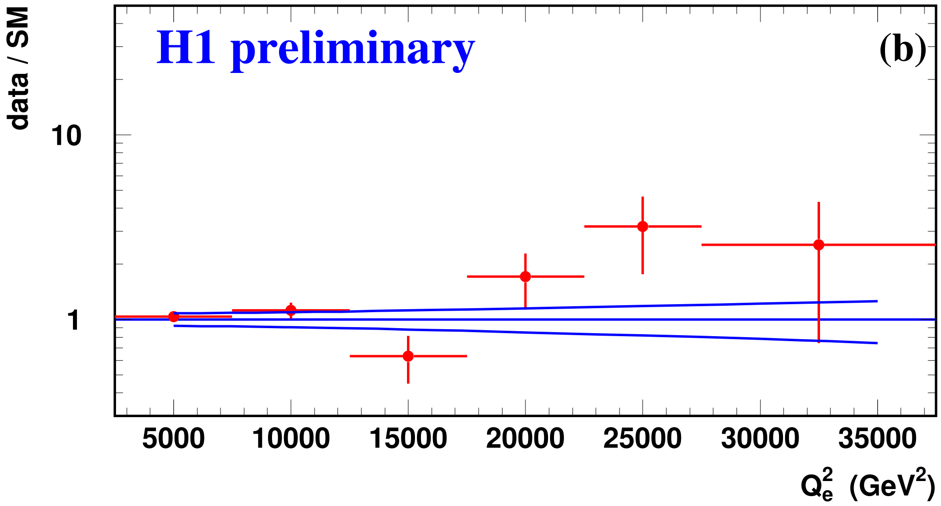
Note: Quoted errors refer to PDF uncertainty

Two outstanding events with $Q^2 > 35000 GeV^2$

Excess of High Q^2, high x Events ?

Now all 1994 - 1997 Data





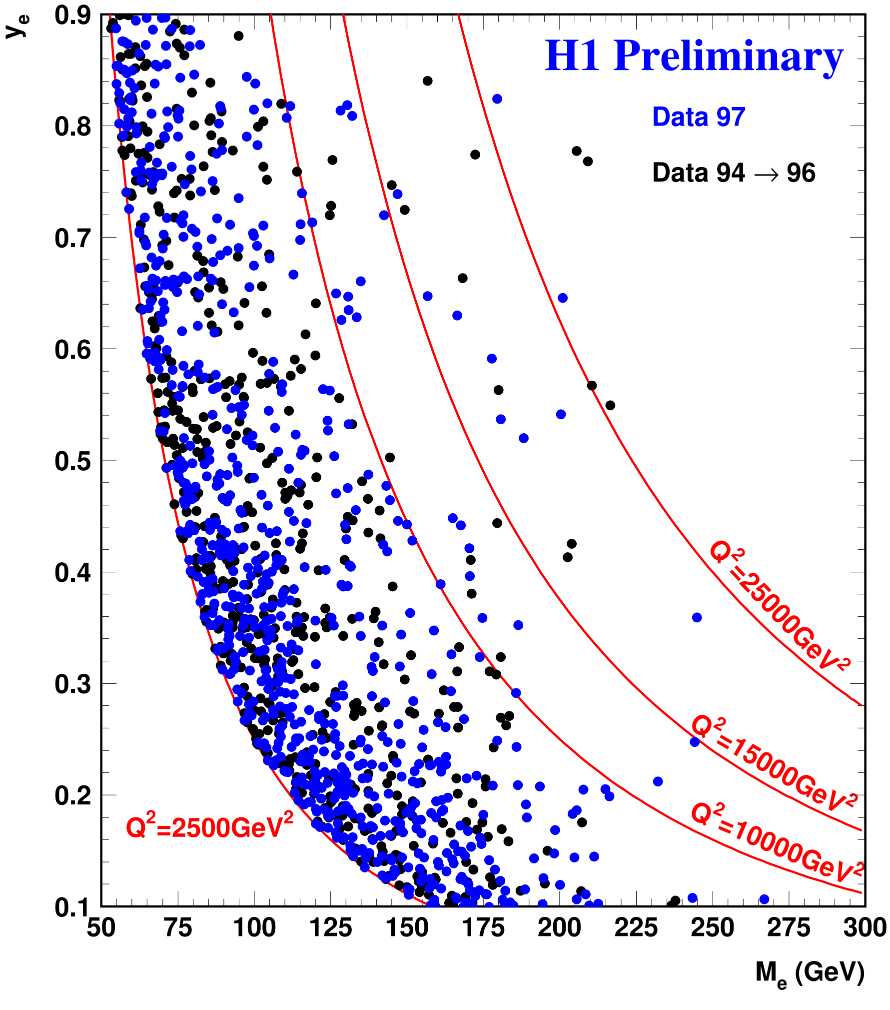
For $Q^2 > 15000 GeV^2$

Period	Data	SM Expectation
94 - 96	12	4.7 ± 0.8
94 - 97	22	14.8 ± 2.1

Still some excess of events at high Q^2
But less significant than in 1994 - 1996 Data sample

NC Events in y - M_e Plane

Do the excess events cluster in M_e ?



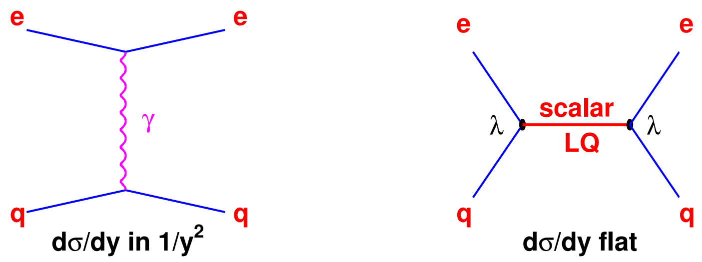
For $M_e = 200 \pm 12.5 GeV$ and $0.4 < y < 0.9$:

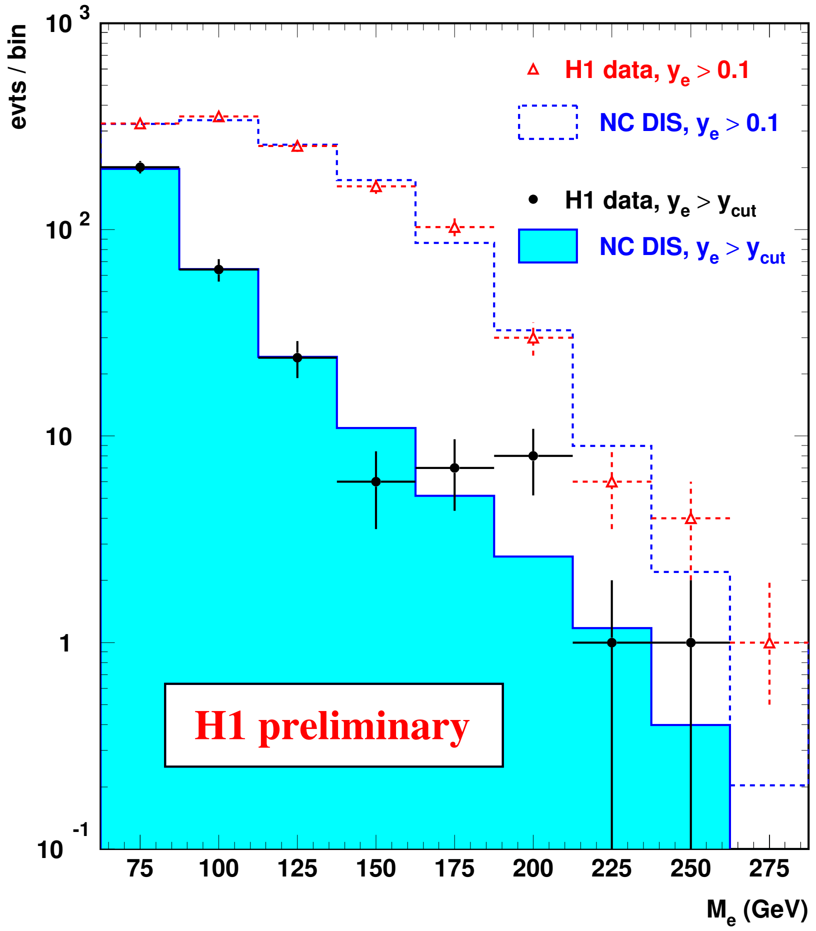
Period	Data	SM Expectation
94 - 96	7	1.0 ± 0.2
94 - 97	8	3.0 ± 0.5

Mass clustering not supported by 1997 data

$\frac{dN}{dM_e}$: Search for s- channel Resonances

Search for Leptoquarks as s-channel resonance
Optimise y-cut to reduce DIS





In absence of significant signal derive
$\Longrightarrow$ Limits on LQ Production

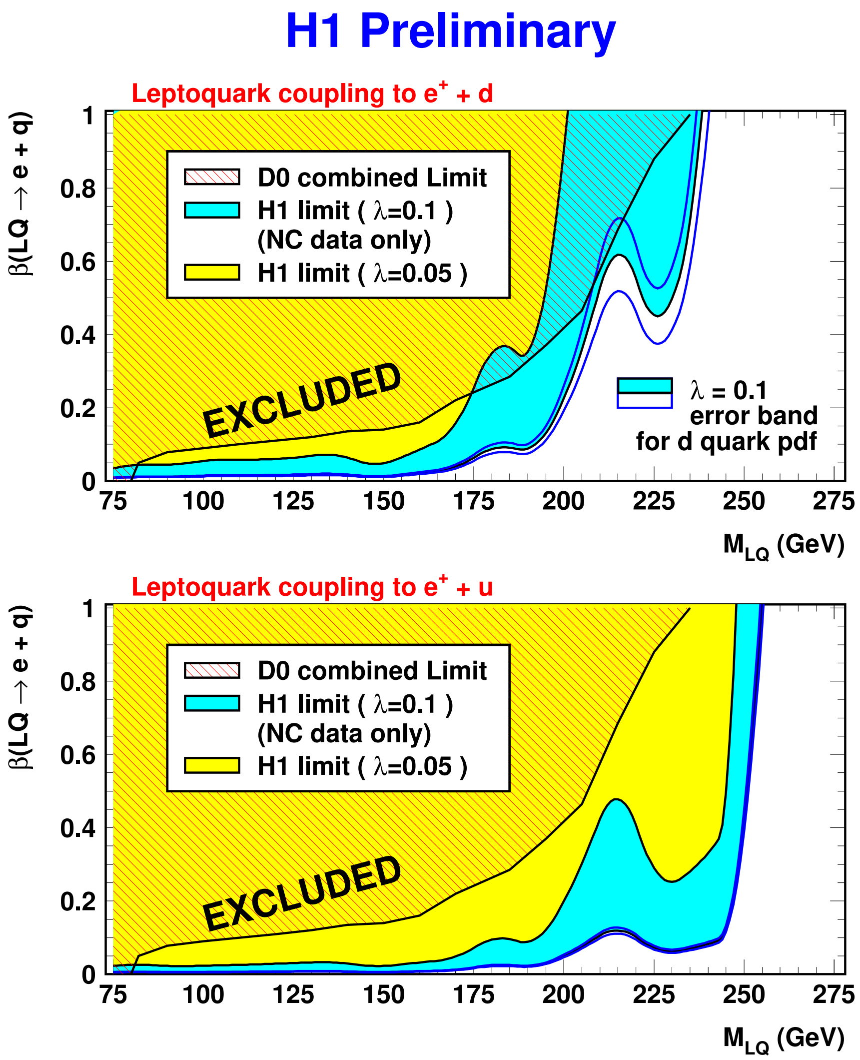
Leptoquark Limits

LQ - Production and Decay Parameters :

Yukawa coupling λ , Mass M_{LQ} and decay BR β $(LQ \rightarrow e^+q)$

Assume fixed λ and derive limits in $\beta - M_{LQ}$ plane

($\lambda = 0.3$ corresponds to electromagnetic coupling strength).

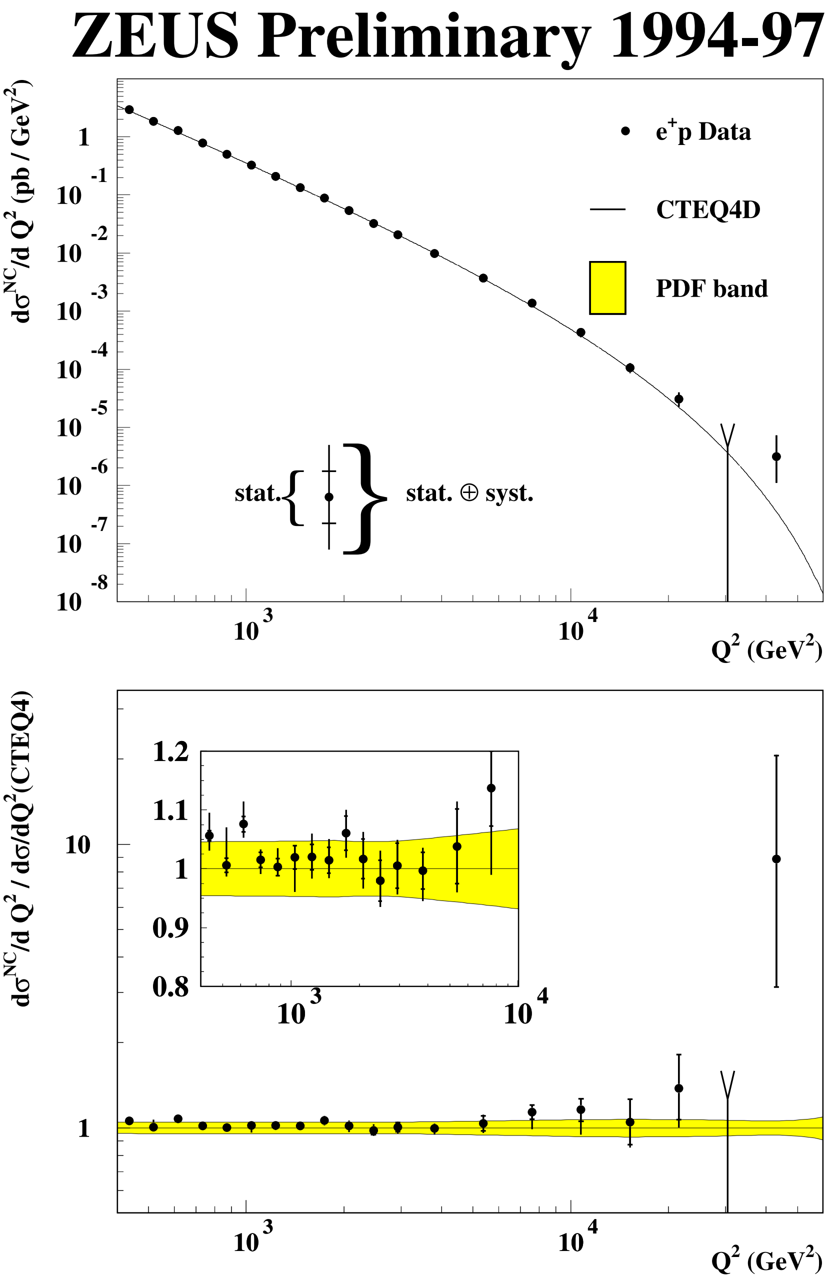


Stronger limits than Tevatron (for $\lambda = 0.1$)

Especially at low decay branching ratios β

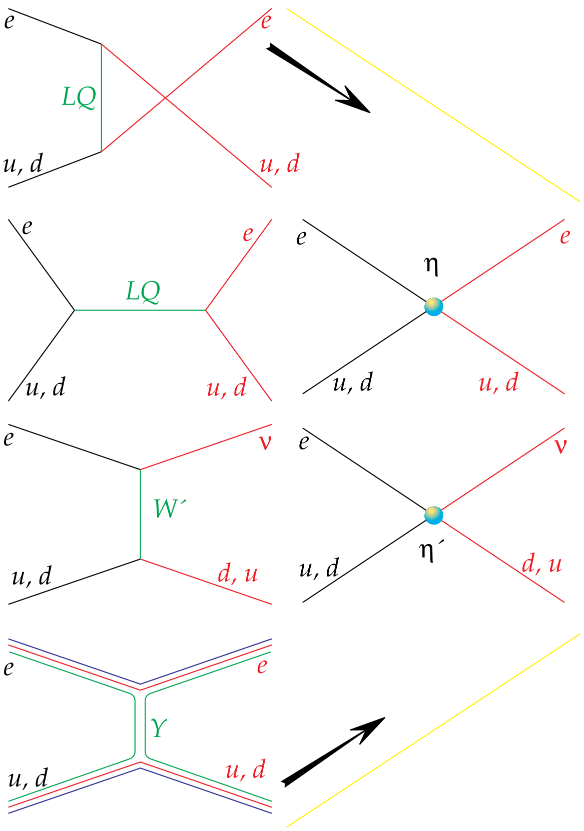
NC Cross Section $d\sigma/dQ^2$

$Q^2 > 400 GeV^2$: 38000 events



Cross section well described over 7 orders of magnitude in Q^2.

Contact Interactions



Contact terms represented by adding terms to Standard Model Lagrangian

$$
\begin{aligned}
\mathcal{L}_{\mathcal{NC}} &= \mathcal{L}_{\mathcal{SM}} \\
&+ \eta_s(\bar{e}_L e_R)(\bar{q}_L q_R) + \eta_s'(\bar{e}_L e_R)(\bar{q}_R q_L) + h.c. \\
&+ \eta_{LL}(\bar{e}_L \gamma^\mu e_L)(\bar{q}_L \gamma_\mu q_L) + \eta_{LR}(\bar{e}_L \gamma^\mu e_L)(\bar{q}_R \gamma_\mu q_R) \\
&+ \eta_{RL}(\bar{e}_R \gamma^\mu e_R)(\bar{q}_L \gamma_\mu q_L) + \eta_{RR}(\bar{e}_R \gamma^\mu e_R)(\bar{q}_R \gamma_\mu q_R) \\
&+ \eta_T(\bar{e}_L \sigma^{\mu\nu} e_R)(\bar{q}_L \sigma_{\mu\nu} q_R) + h.c.
\end{aligned}
$$

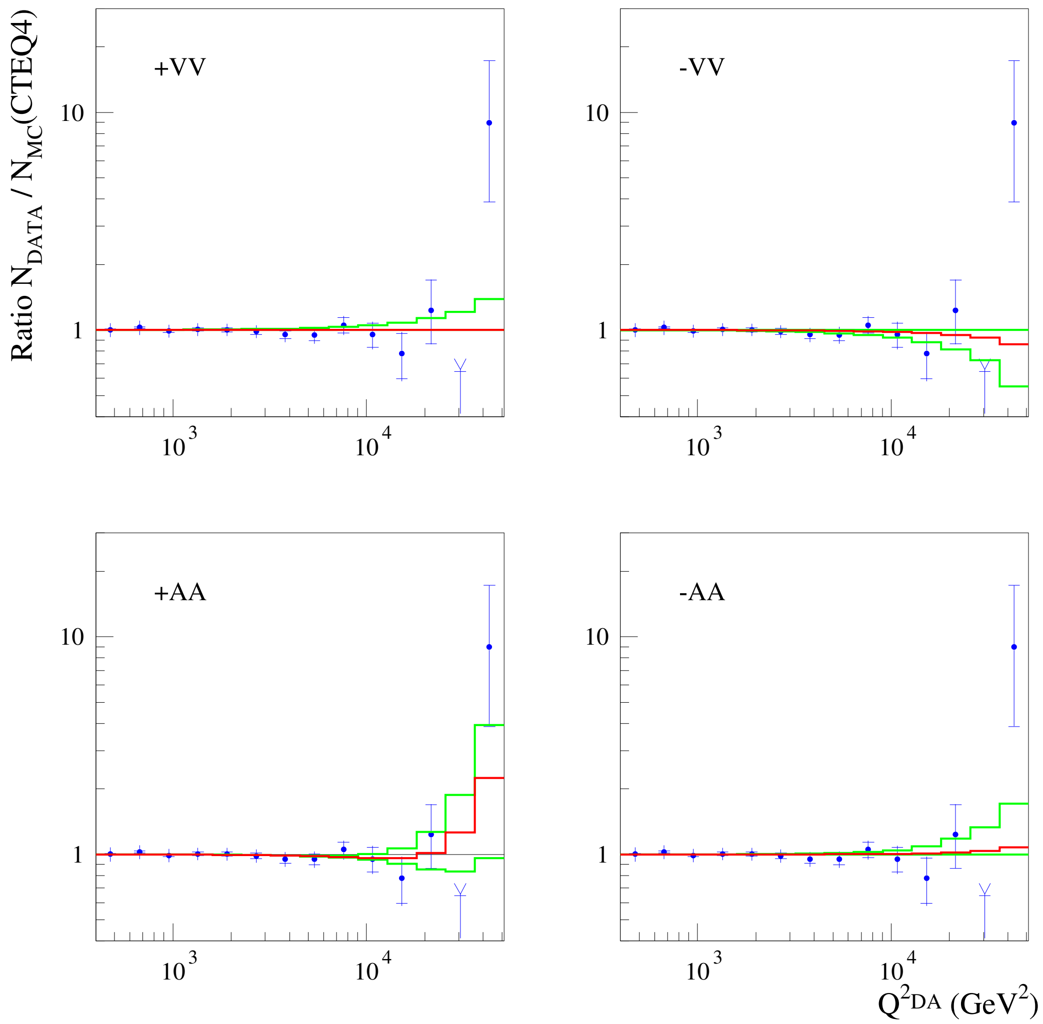
$$
\eta = a\frac{g^2}{\Lambda^2} = a\frac{4\pi}{\Lambda^2}
$$

$\frac{d\sigma}{dQ^2}$ and Contact Interactions

Fit $\frac{d\sigma}{dQ^2}$ to SM + Contact Interactions

Results for some specific coupling types ($\pm VV or \pm AA$)

: best fit , : $\pm 1\sigma$



Within 1σ bounds agreement with SM

Limits (95% CL) on Contact Interaction Scale $\Lambda >$ 2 to 4 TeV

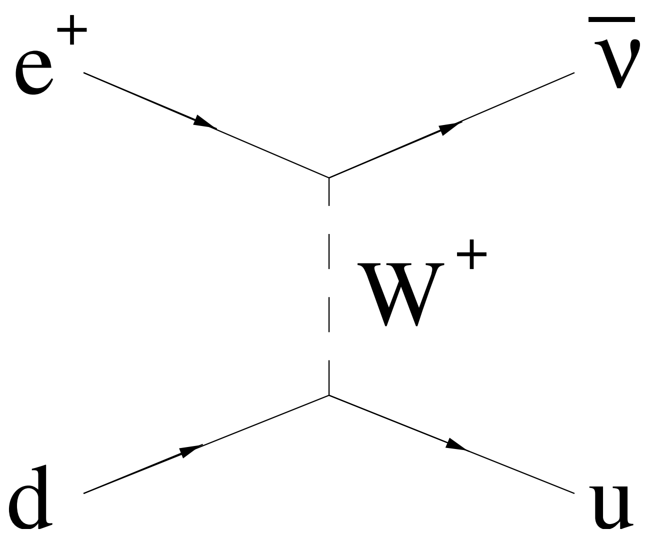
Contact Interactions

Comparison to other Experiments

Type	a	**Fit** from ZEUS Λ (TeV)	**Limit** from ZEUS Λ (TeV)	Limit from CDF Λ (TeV)	Limit from Opal Λ (TeV)	Limit from Aleph Λ (TeV)
VV	$+1$	∞	4.9	3.5	5.8	3.6
VV	-1	> 10	4.6	5.2	5.8	4.6
AA	$+1$	2.5	2.0	3.8	5.6	5.0
AA	-1	> 10	4.0	4.8	2.5	3.3
$X3$	$+1$	∞	2.8	-	4.3	3.7
$X3$	-1	> 10	1.5	-	3.4	3.2
$X4$	$+1$	∞	4.5	-	4.3	2.7
$X4$	-1	> 10	4.1	-	5.4	4.3
$U4$	$+1$	∞	4.6	-	-	2.1
$U4$	-1	> 10	4.4	-	-	2.6

- A comprehensive analysis of vector terms has been performed.
- Central values typically consistent with Standard Model.
- Typical limits of a few TeV are comparable to LEP and Tevatron limits.

CC Interactions

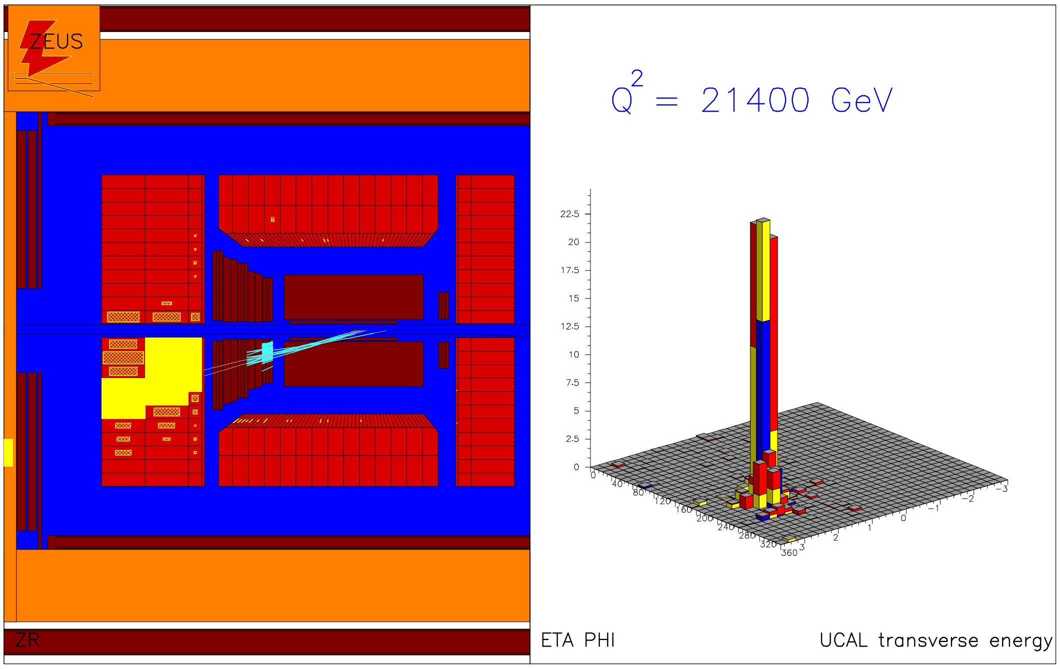


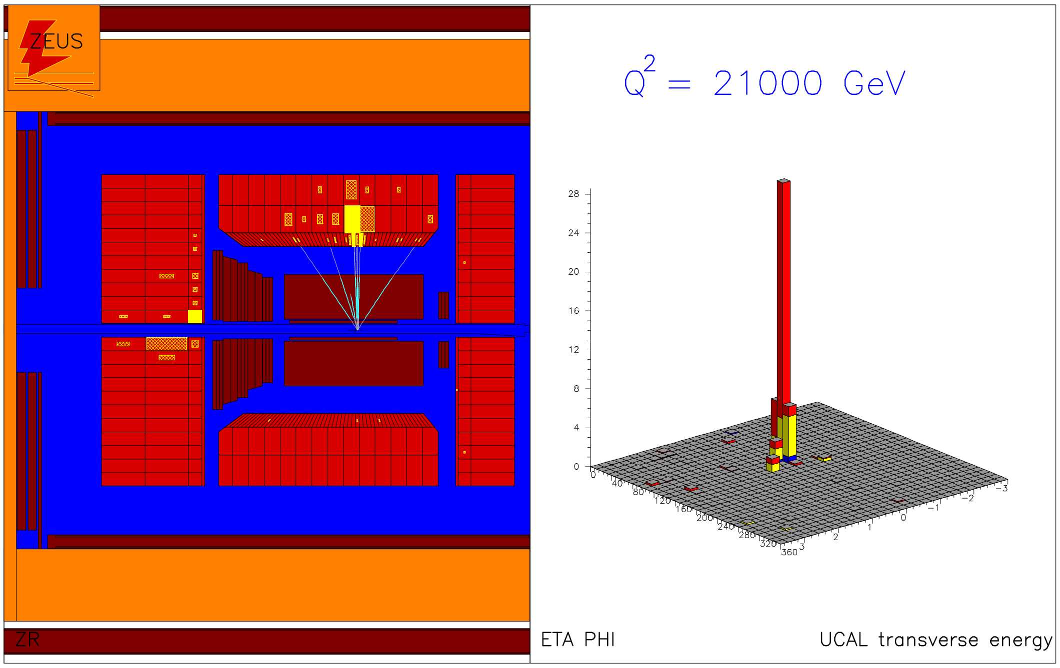
$$\frac{d^2\sigma}{dxdQ^2} = \frac{G_F^2}{2\pi}\left(\frac{M_W^2}{M_W^2+Q^2}\right)^2(\overline{u}+\overline{c}+(1-y)^2(d+s))$$

- Explore Propagator Mass
- Explore Helicity Structure (V - A) of CC Interactions
- Explore Quark - Antiquark Composition

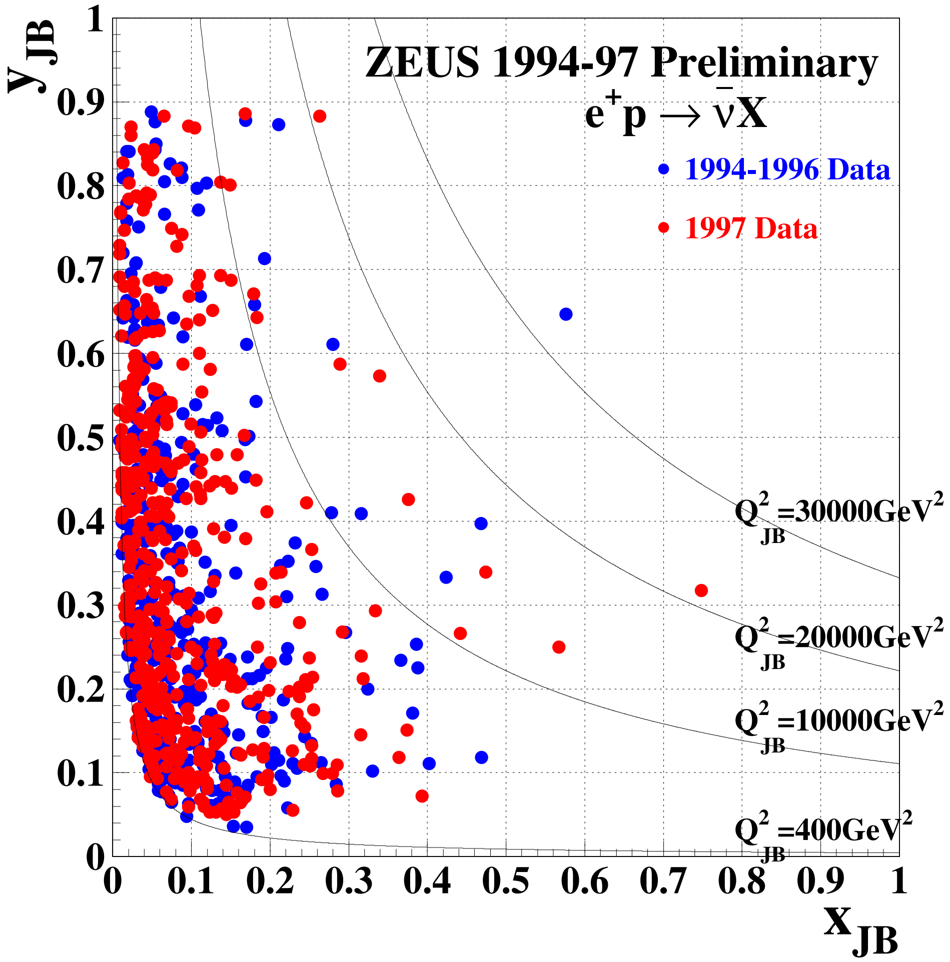
CC Events

ZEUS 1997 : 2 new events at very high Q^2





CC Rates

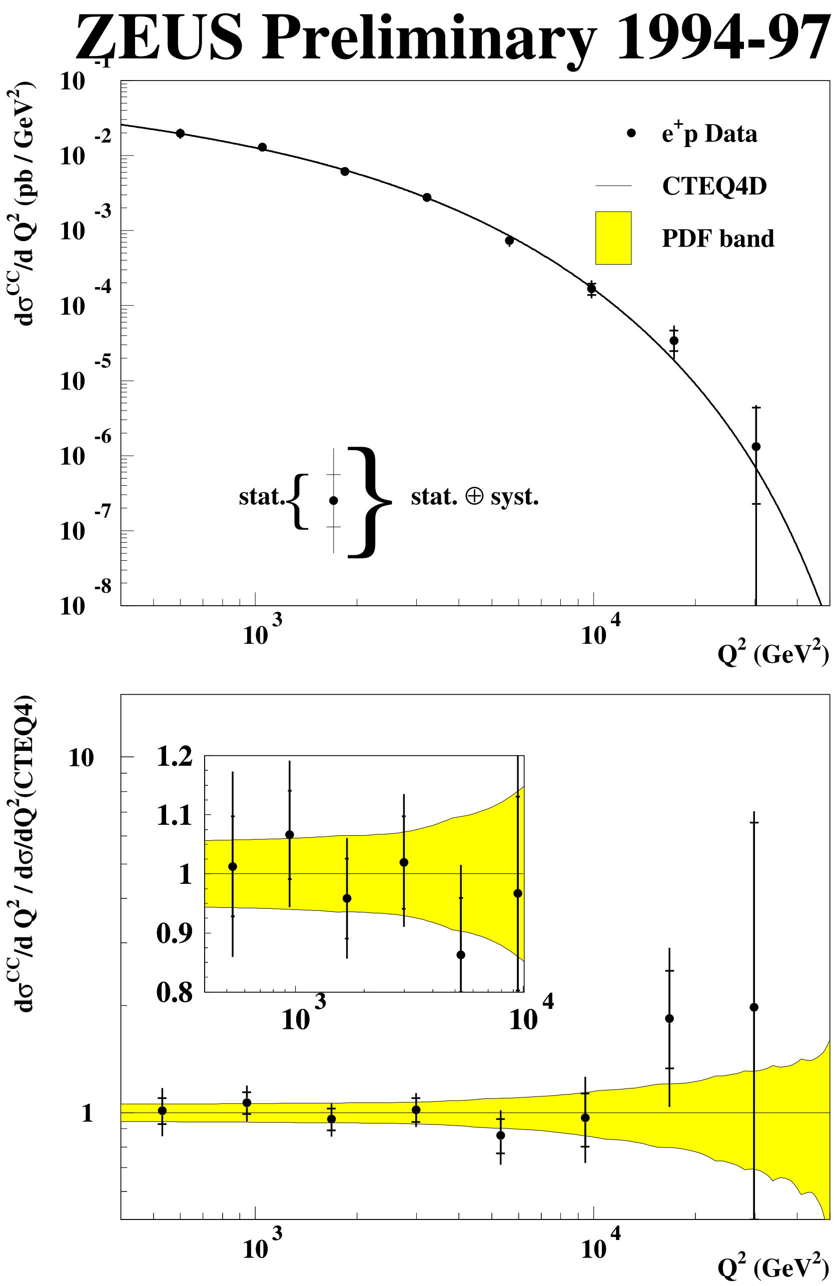


Q^2_{min}	N_{obs}	N_{exp} and errors		
1000	586	600	+52	-52
10000	22	17	+5.7	-5.2
15000	8	3.9	+1.9	-1.6
20000	3	0.97	+0.65	-0.47
30000	1	0.06	+0.08	-0.04

Slight excess above $Q^2 = 15000 GeV^2$ seen by ZEUS.

H1 Above $Q^2 = 15000 GeV^2$: 9 events seen, with 5.1 ± 2.8 expected

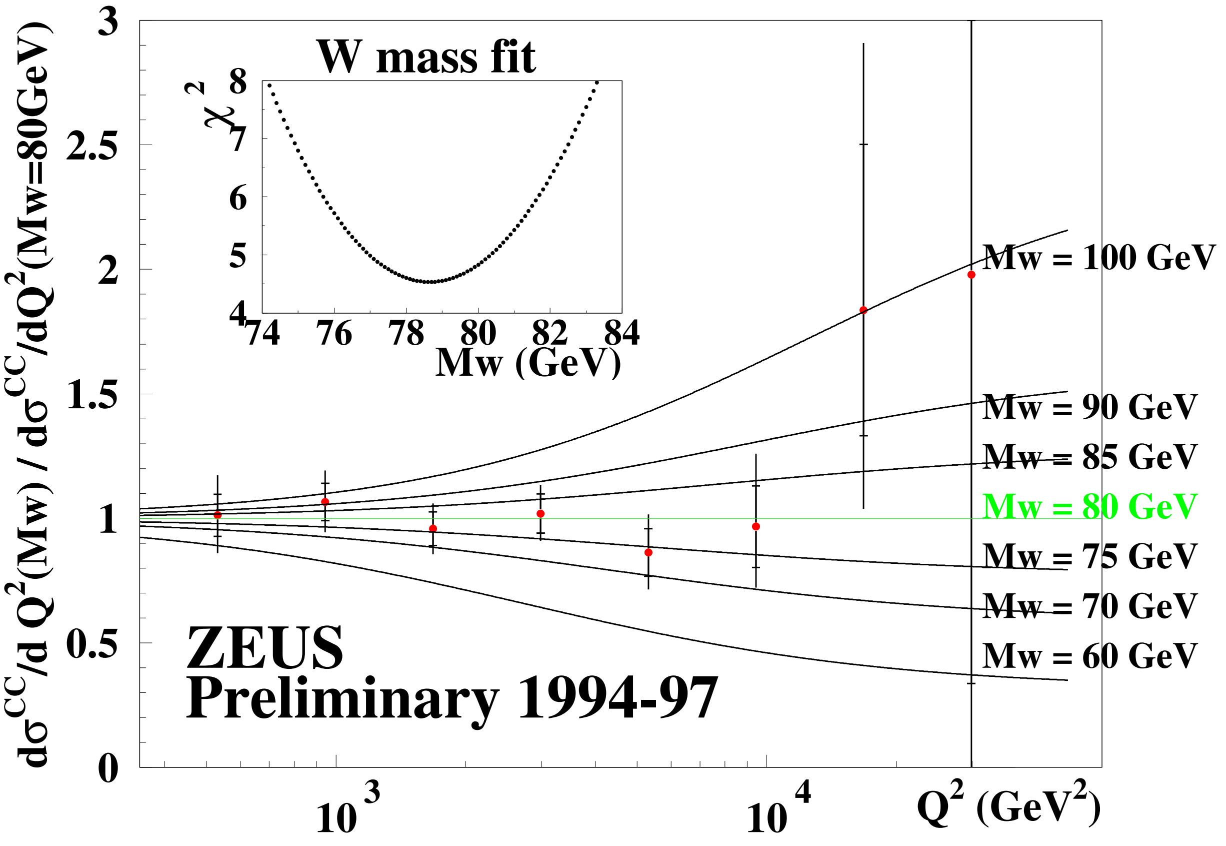
CC Cross Section $d\sigma/dQ^2$



Cross section measured up to $Q^2 = 30000 GeV^2$

CC Propagator Mass

$$\frac{d^2\sigma}{dxdQ^2} \propto \left(\frac{M_W^2}{Q^2+M_W^2}\right)^2$$



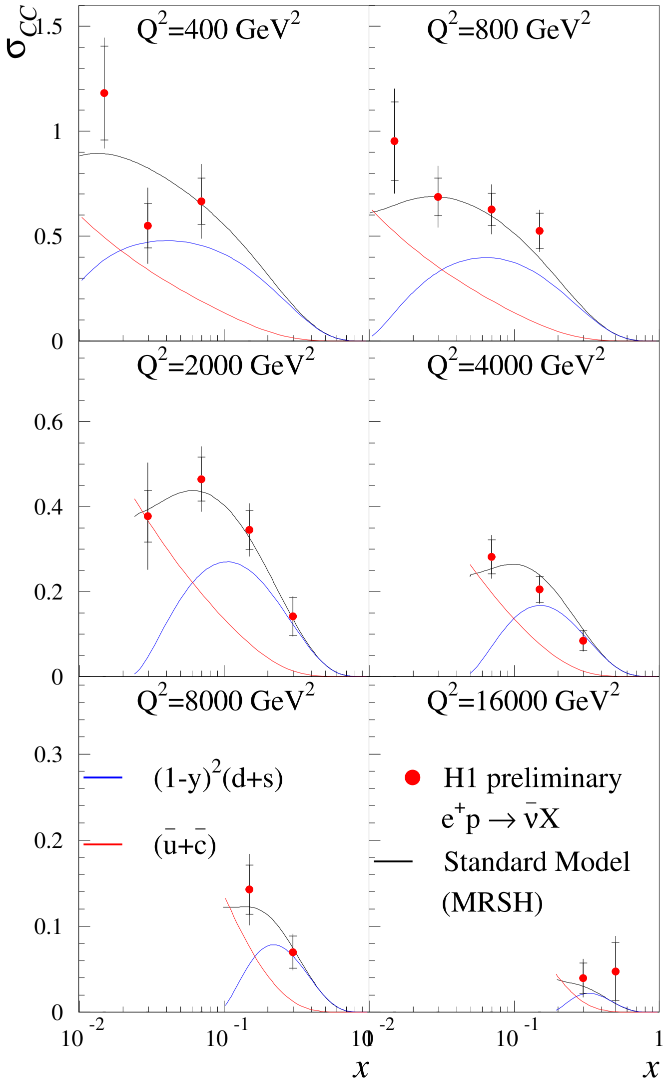
$$M_W = 78^{+2.5+3.3}_{-2.4-2.0} GeV$$

CC Cross Section $d\sigma/dxdQ^2$

First Measurement of DIS - CC double differential cross section at high x and Q^2

Define 'reduced cross section' in analogy to NC:

$$\sigma = x\frac{2\pi}{G_F^2}(1+\frac{Q^2}{M_W^2})^2\frac{d^2\sigma}{dxdQ^2}$$



Sensitivity to Quark and Antiquark Contributions

NC - CC - Other

- **NC :** $e^+p \Longrightarrow e^+X$

  Search for events with high P_T e^+ balanced by Hadrons

- **CC :** $e^+p \Longrightarrow \nu X$

  Search for events unbalanced in transverse momentum

- **Other :** $e^+p \Longrightarrow Lepton + P_T^{miss} X$

  Search for events with high P_T Leptons and transverse momentum imbalance

Isolated Leptons and P_T^{miss}

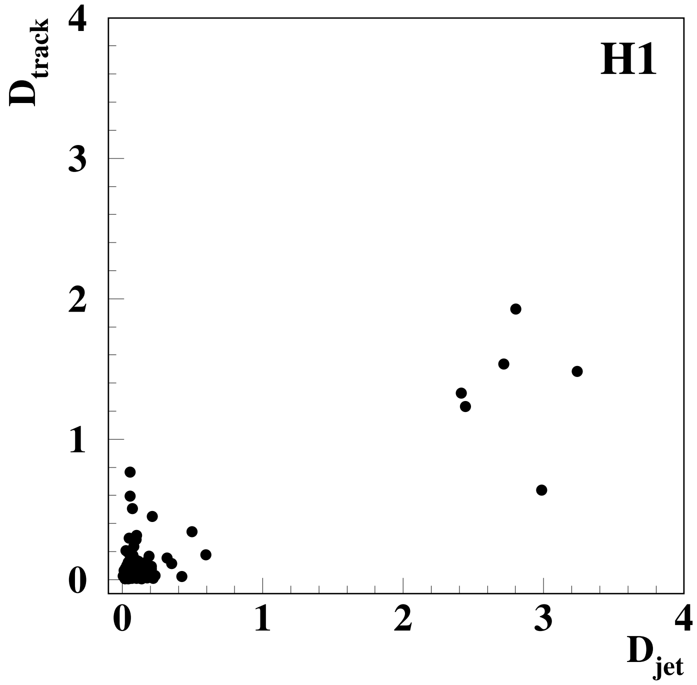
H1 (see DESY 98 - 063 and hep-ex-9806009)

Selection :

Search within CC sample ($P_T^{calo} > 25 GeV$) for high transverse momentum ($P_T > 10 GeV$) tracks.

Quantify their Isolation w.r.t. hadronic jets or other tracks by distances D_{jet} or D_{track} in $\eta - \phi$ space.

Within 500 'CC Candidates' :



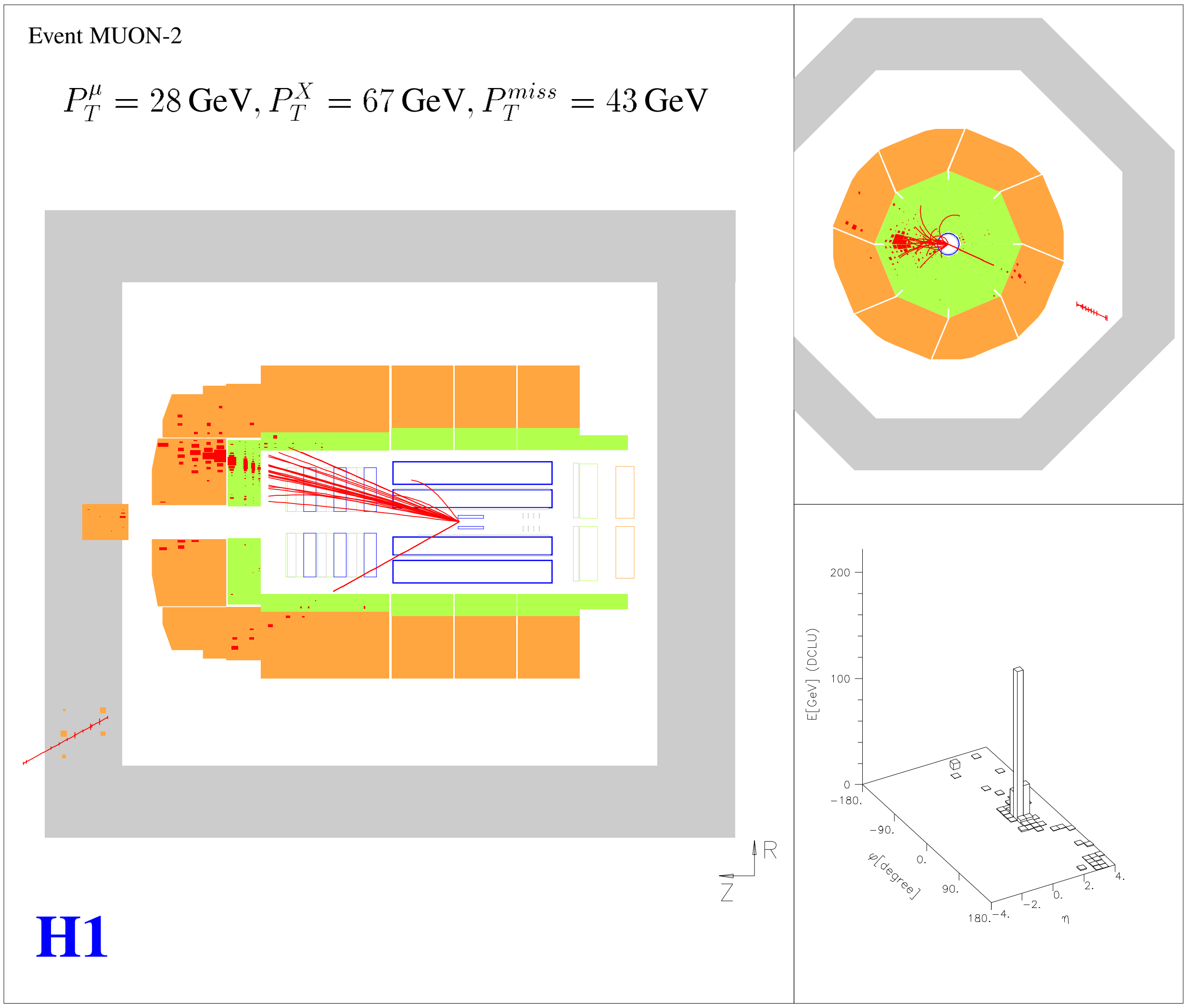
Six events with one very isolated high P_T track

All six tracks are LEPTONS

$0e^+, 1e^-, 2\mu^+, 2\mu^-, 1\mu^?$

Lepton and P_T^{miss} *Event*

$$e^+ p \rightarrow \mu^+ X$$



All 6 events show :

- High P_T Lepton
- High P_T Hadronic system
- Imbalance in Event P_T

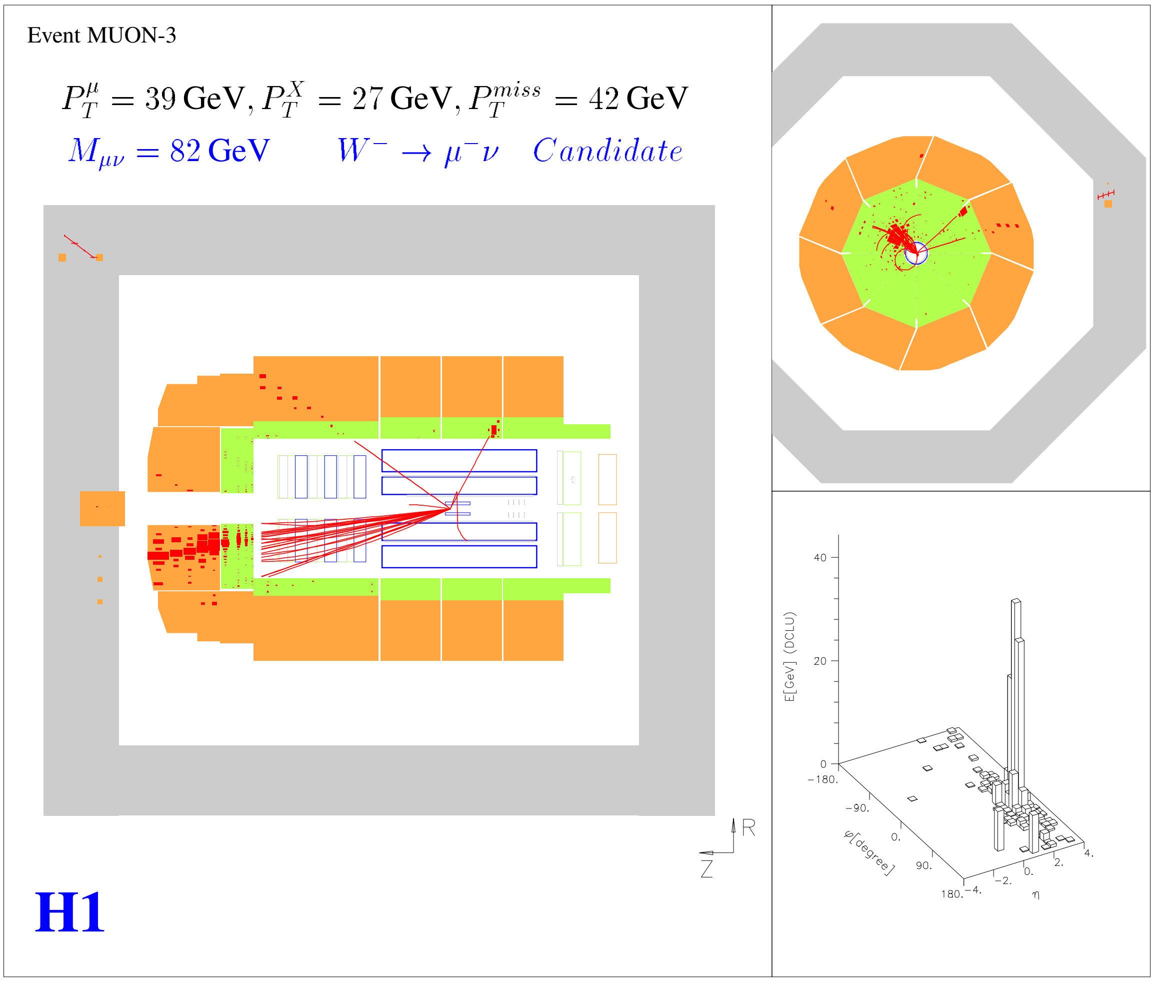
W Production ?

Main SM contribution to this event topology is expected to be

$$e^+p \Longrightarrow (e^+)W^\pm X \qquad W^\pm \Longrightarrow \ell^\pm \nu$$

In one of the μ events the scattered e^+ is detected, allowing the invaraint $\mu - \nu$ mass to be determined to $M = 82^{+19}_{-12} GeV$

$$e^+p \rightarrow e^+\mu^- X$$



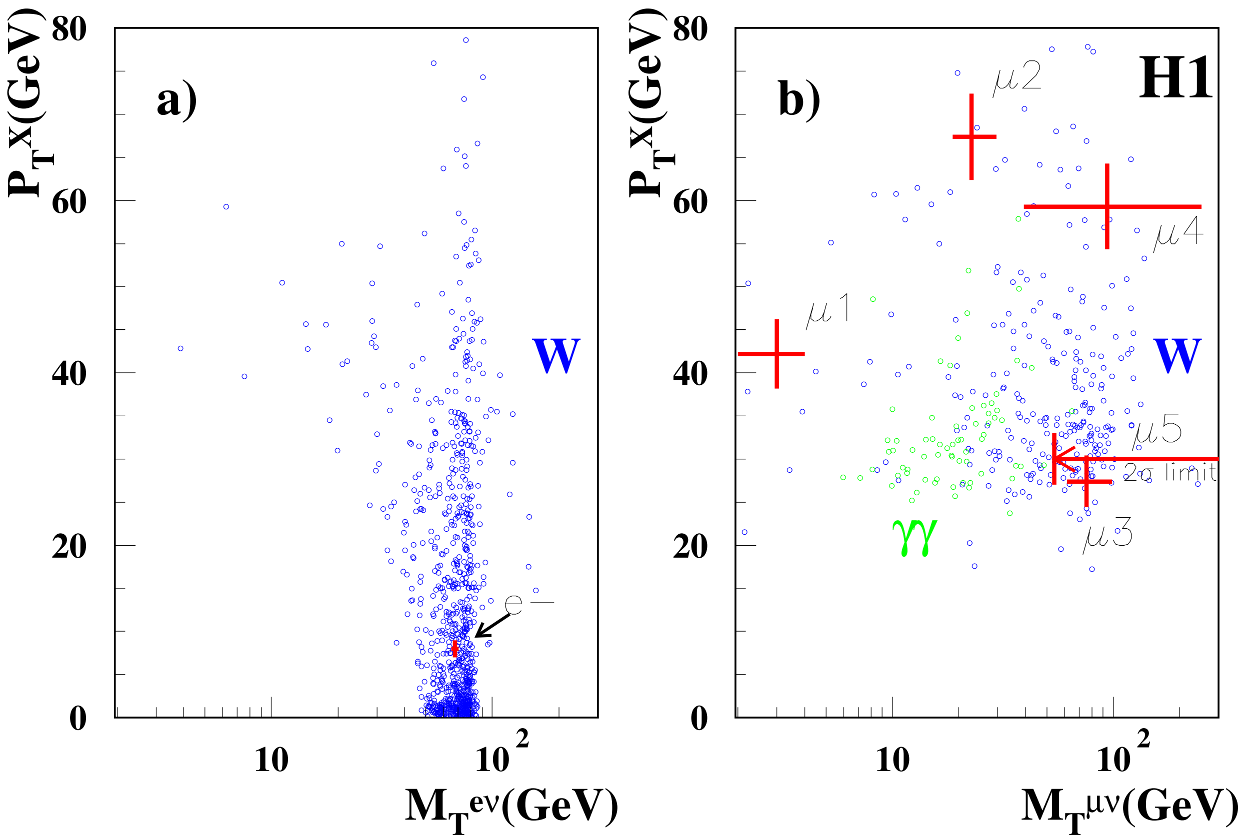
	ELECTRON	MUON-1	MUON-2	MUON-3 *)	MUON-4	MUON-5
The isolated high-P_T lepton						
Charge	Neg.(5σ)	Pos.(4σ)	Pos.(4σ)	Neg.(4σ)	Neg.(2σ)	unmeasured
P_T^l	$37.6^{+1.3}_{-1.3}$	$23.4^{+7.5}_{-5.5}$	$28.0^{+8.7}_{-5.4}$	$38.6^{+12.0}_{-7.4}$	$81.5^{+75.2}_{-26.4}$	> 44
θ^l	27.3 ± 0.2	46.2 ± 0.1	28.9 ± 0.1	35.5 ± 0.1	28.5 ± 0.1	31.0 ± 0.1
The hadronic system						
P_T^X	8.0 ± 0.8	42.2 ± 3.8	67.4 ± 5.4	27.4 ± 2.7	59.3 ± 5.9	30.0 ± 3.0
$P_{\parallel}^X$	-7.2 ± 0.8	-42.1 ± 3.8	-61.9 ± 4.9	-12.5 ± 2.1	-57.0 ± 5.5	-28.6 ± 3.1
$P_{\perp}^X$	-3.4 ± 0.9	-2.7 ± 1.8	26.8 ± 2.7	-24.3 ± 2.5	-16.3 ± 3.2	-9.1 ± 2.3
P_z^X	79.9 ± 4.4	153.1 ± 9.1	247.0 ± 18.9	183.7 ± 13.6	118.9 ± 12.1	145.4 ± 8.2
E^X	81.1 ± 4.5	162.0 ± 10.0	256.9 ± 19.5	186.8 ± 14.0	141.7 ± 13.7	154.8 ± 9.1
Global properties						
P_T^{miss}	30.6 ± 1.5	$18.9^{+6.6}_{-8.3}$	$43.2^{+6.1}_{-7.7}$	$42.1^{+10.1}_{-5.9}$	$29.4^{+71.8}_{-13.9}$	> 18
δ	10.4 ± 0.7	$18.9^{+3.9}_{-3.2}$	$17.1^{+2.5}_{-1.7}$	$26.9^{+4.2}_{-2.9}$	$43.5^{+19.3}_{-7.2}$	> 22
$M_T^{l\nu}$	67.7 ± 2.7	$3.0^{+1.5}_{-0.9}$	$22.8^{+6.7}_{-4.2}$	$75.8^{+23.0}_{-14.0}$	94^{+157}_{-54}	> 54
*) Positron in MUON-3 : $P_T^e = 6.7 \pm 0.4$, $P_{\parallel}^e = 6.1 \pm 0.4$, $P_{\perp}^e = -2.8 \pm 0.2$, $P_z^e = -3.7 \pm 0.2$						

Isolated Leptons and P_T^{miss}

For W production one expects :

- Small transverse momenta of W and thus small hadronic P_T^X
- 'Jacobian Peak' in transverse Lepton-Neutrino-Mass $M_T^{\ell\nu}$

W production has been calculated in leading order
(Luminosity in this plot is 500 times higher than in data)



e-channel : 1 event seen, 2.4 ± 0.5 expected (1.7 ± 0.1 from W)
μ-channel : 5 events seen, 0.8 ± 0.2 expected (0.5 ± 0.1 from W)

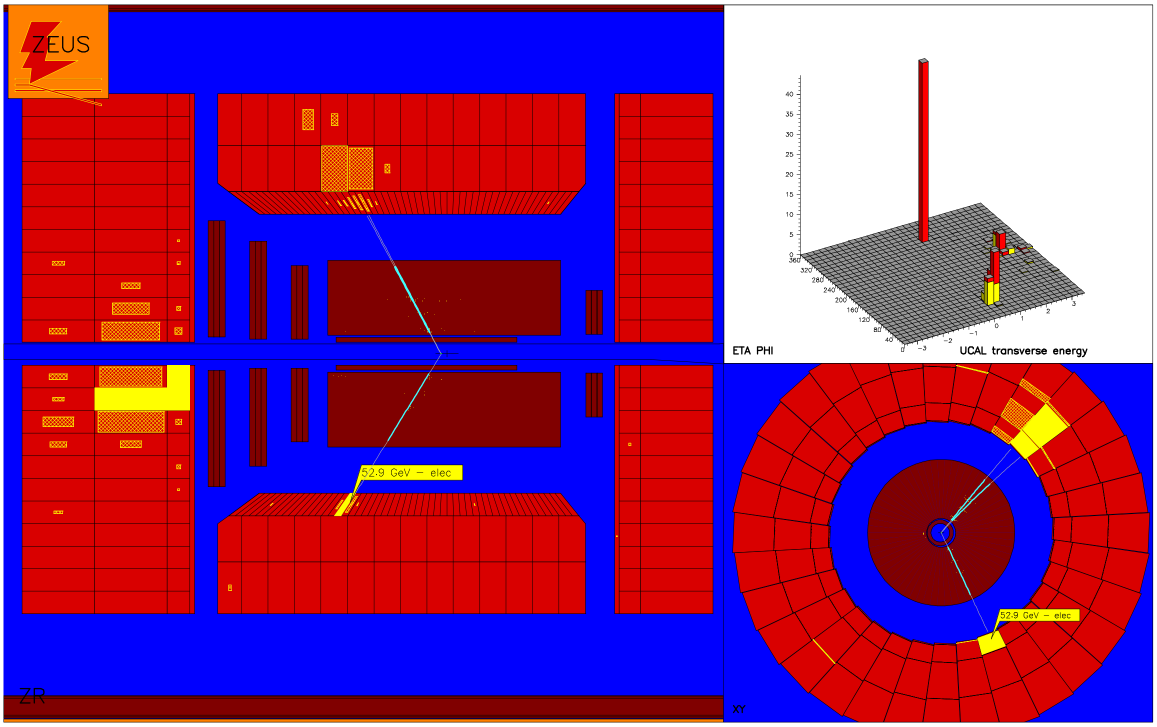
Three Muon Events not likely to be W Candidates

Isolated Leptons and P_T^{miss}

ZEUS applies similar (but not identical) selection cuts and observes

$4e^+, 0e^-, 0\mu$ Events

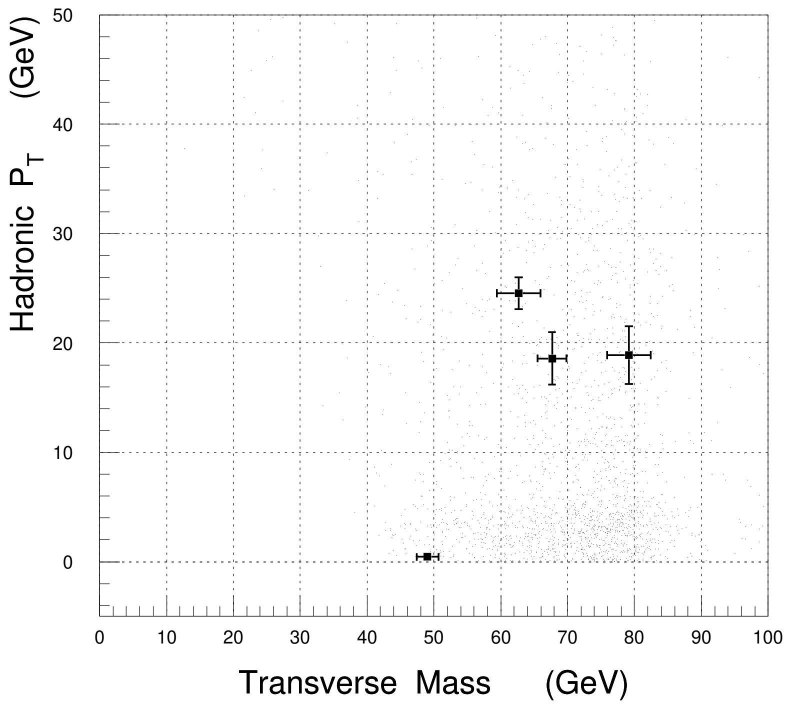
Acoplanar e^+ + jet(s) event



$$P_t(e^+) = 52.7\,\text{GeV} \qquad P_t(\text{had}) = 20.4\,\text{GeV}$$
$$\theta_e = 58.1^\circ \qquad \text{Acoplanarity} = 39.0^\circ$$
$$\not{P}_T = 39.1\,\text{GeV} \qquad E - P_z = 51.0\,\text{GeV}$$
$$M_t(l\nu) = 89.5\,\text{GeV}$$

Isolated Leptons and P_T^{miss}

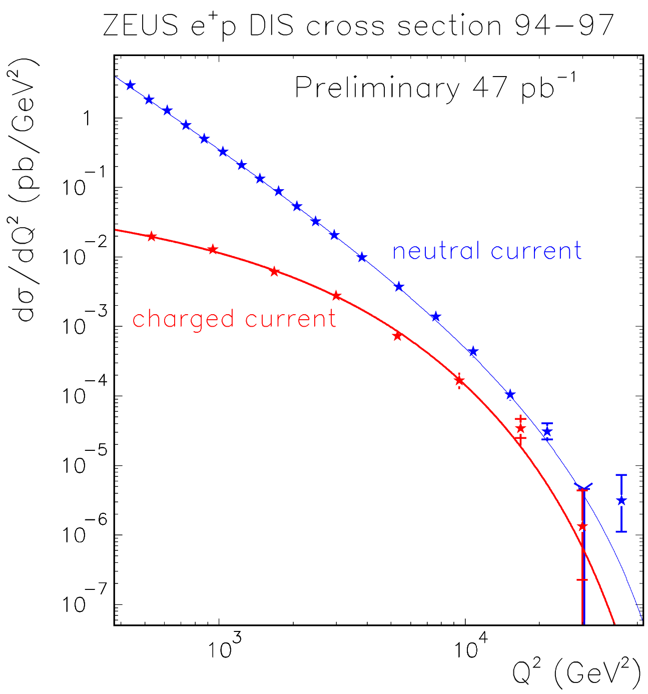
Are the 4 ZEUS e^+ events W - Candidates ?

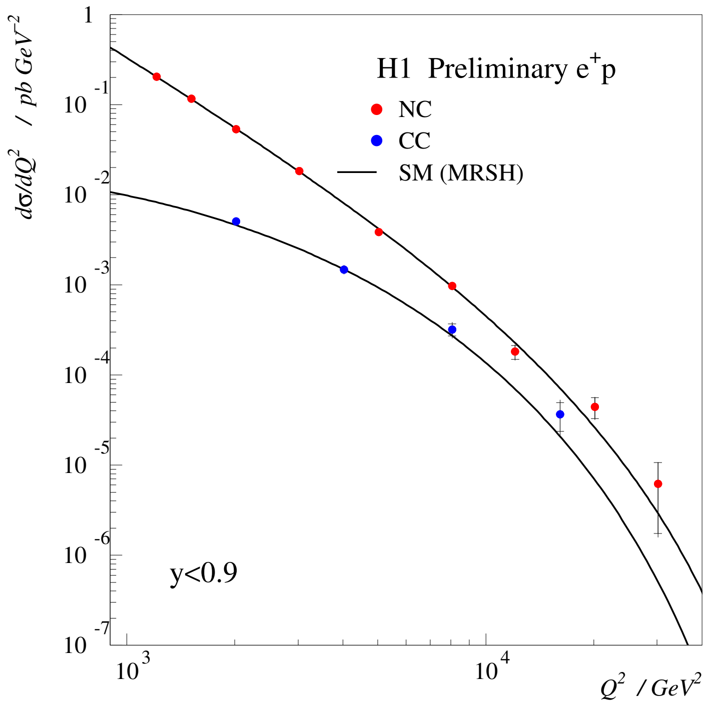


e -channel: 4 events seen, 3.4 expected (2.2 from W)
μ-channel : 0 event seen, 1.3 expected (0.5 from W)

Summary

At HERA Deep Inelastic Scattering has been explored up to values of the squared four momentum transfer $Q^2 = 30000 GeV^2$





Summary

The high luminosity now available at HERA made a big impact for

Physics at Highest Q^2

- NC and CC differential cross section have been measured at high x and Q^2. The data are well described by Standard Model expectations extrapolated from lower Q^2.
- In NC the destructive $\gamma - Z$ interference has been seen
- The rate excess seen before in the highest Q^2 region did become less significant including the 1997 data.
- Limits on Leptoquark Production and Contact term interactions have been improved
- First measurement of double differential CC cross section. Determination of propagator mass.
- Search for events with Isolated High P_T Lepton and P_T^{miss} : W - Candidates found. H1 finds excess of μ events. ZEUS finds only e^+ events with a rate in agreement with SM.

Outlook

- Hera operates in 98/99 with e^- ($\sim 50pb^{-1}$ expected)
- Lumi upgrade program 2000 ($\sim 150pb^{-1}$ / year expected)
- Longitudinal $e^{\pm}$ polarisation

Highest Q^2 Physics is there............

.... and much more will come