Events with Large Transverse Momentum in ep Collisions at HERA

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Representing the

H1 & ZEUS Collaborations

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Current status: Results as presented in Aug. 97 including some of the 97 data

L (H1) = 23.7 pb^{-1}
L (ZEUS) = 33.5 pb^{-1}

Outline

- Introduction
- Standard Model DIS
- Neutral and Charged Current Events at Very High Q^2
- Events with High p_t Isolated Leptons and Large p_t^{miss}
- Conclusions

Introduction

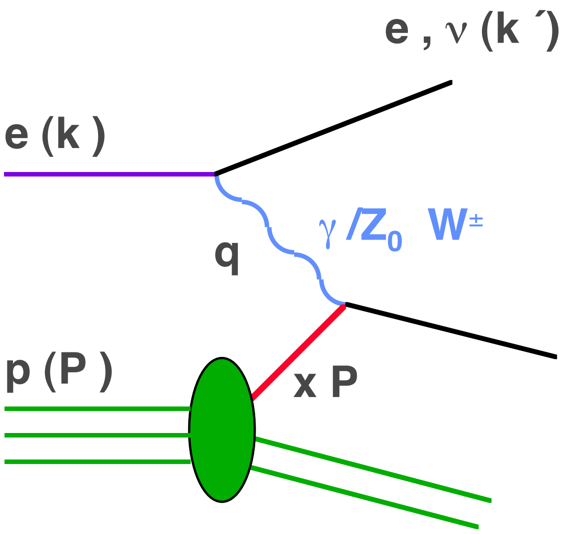
HERA: e p Collider

e^+ beam E_e = 27.6 GeV

p beam E_p = 820 GeV

probing the proton at distances down to 10^{-16} cm

e^+ - parton scattering



$$s = (k + P)^2$$

$$q^2 = (k - k')^2 = -Q^2$$

$$M = \sqrt{xs} = E_{cm}^{eq}$$

$$Q^2 = M^2 y$$

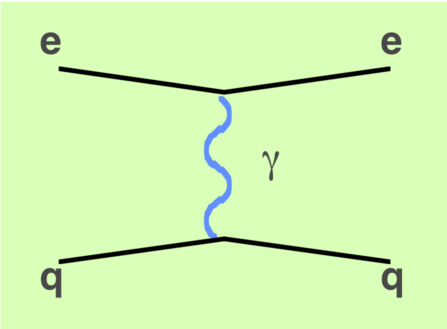
$$y = \frac{1 + \cos\theta_e^*}{2}$$

- **t-channel** exchange of a highly virtual gauge boson
- **s-channel** potential resonant production of leptoquarks, squarks,...

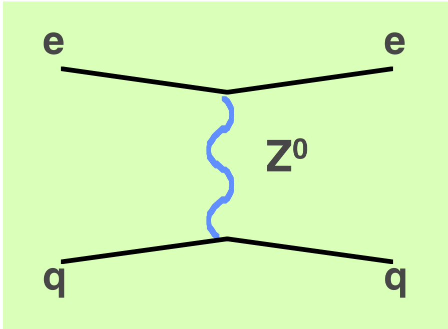
Study e^+ - parton interactions at very high Q^2.

Standard Deep-Inelastic Scattering Model

Neutral Currents (NC):



+

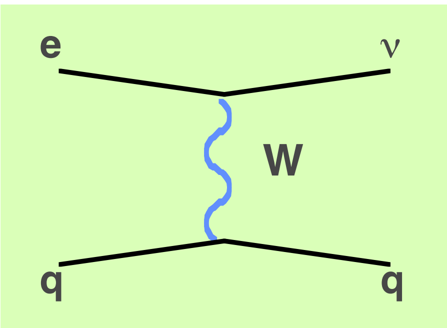


$$\frac{d^2\sigma}{dx\,dQ^2} \approx \frac{2\pi\alpha^2}{x\,Q^4}\,\{\,Y_+(y)\,F_2(x,Q^2)\; - \;Y_-(y)\,x\,F_3(x,Q^2)\,\}$$

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

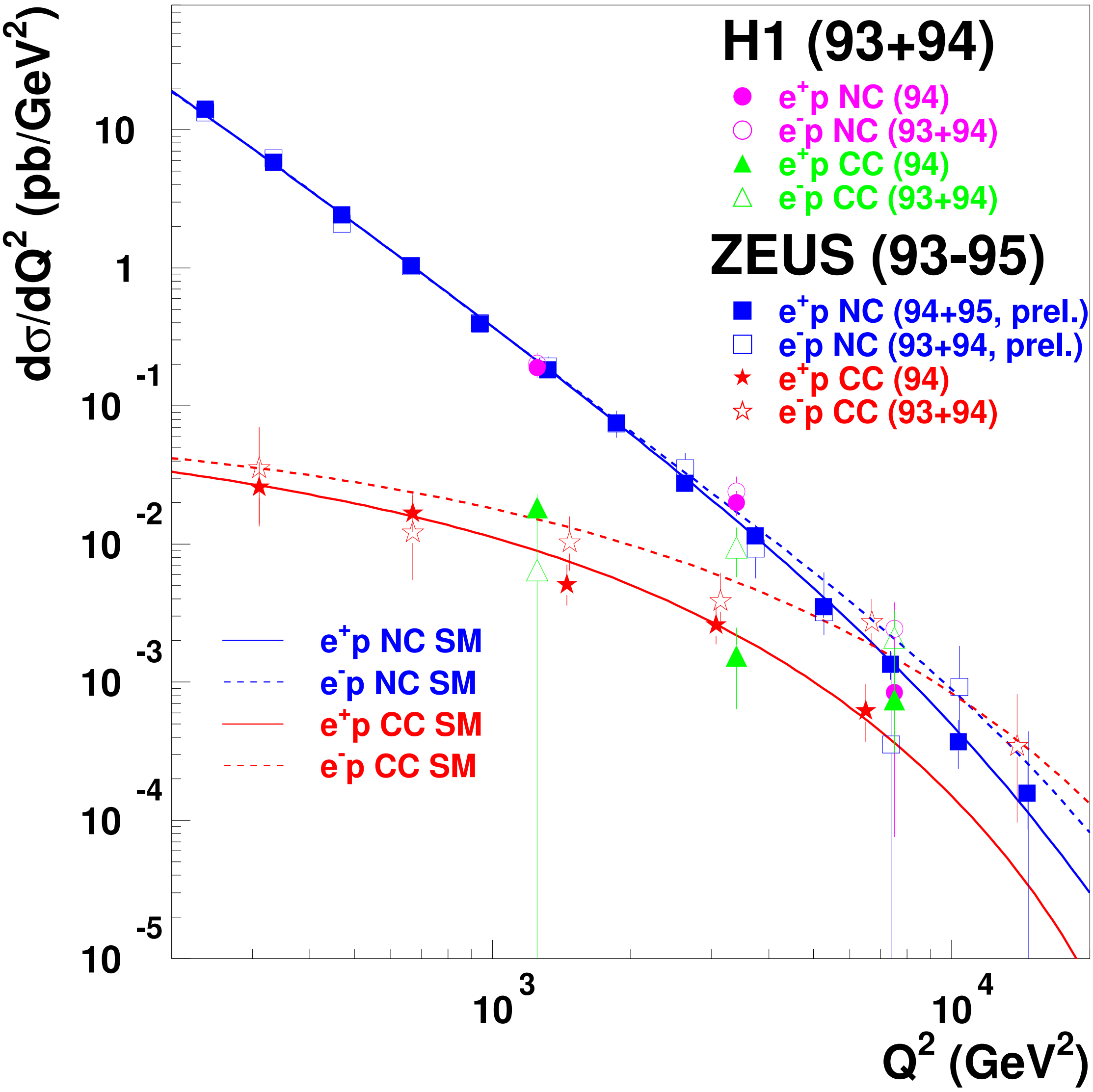
F_i contain the dependence on the quark structure of the proton, on the Z^0 propagator and on the electroweak parameters

Charged Currents (CC):



$$\frac{d^2\sigma}{dx\,dQ^2} \approx \frac{G_F^2}{2\pi}\left(\frac{M_W^2}{M_W^2 + Q^2}\right)^2 [\,(1-y)^2\, d(x,Q^2)\,]$$

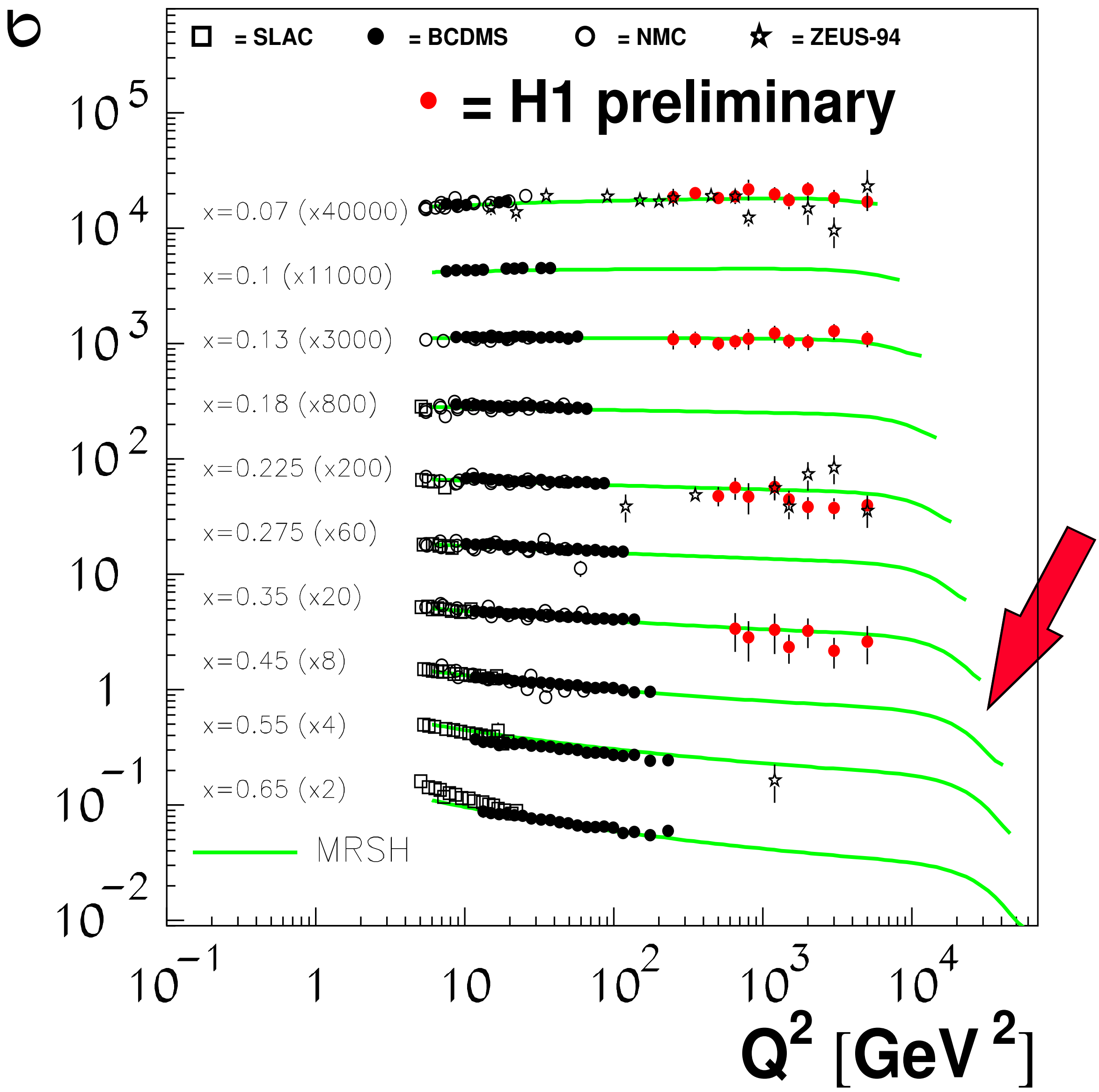
NC and CC Cross Sections: Measurements



- The cross sections are steeply falling with Q^2 .
- The cross sections are well described by the Standard Model for $Q^2 < 10000$ GeV^2 .

The Structure Function of the Proton

Reduced cross-sections: $\sigma_{NC}(e^+p) = \frac{x\,Q^4}{2\pi\alpha^2}\,\frac{1}{Y_+}\,\frac{d^2\sigma}{dx\,dQ^2}$



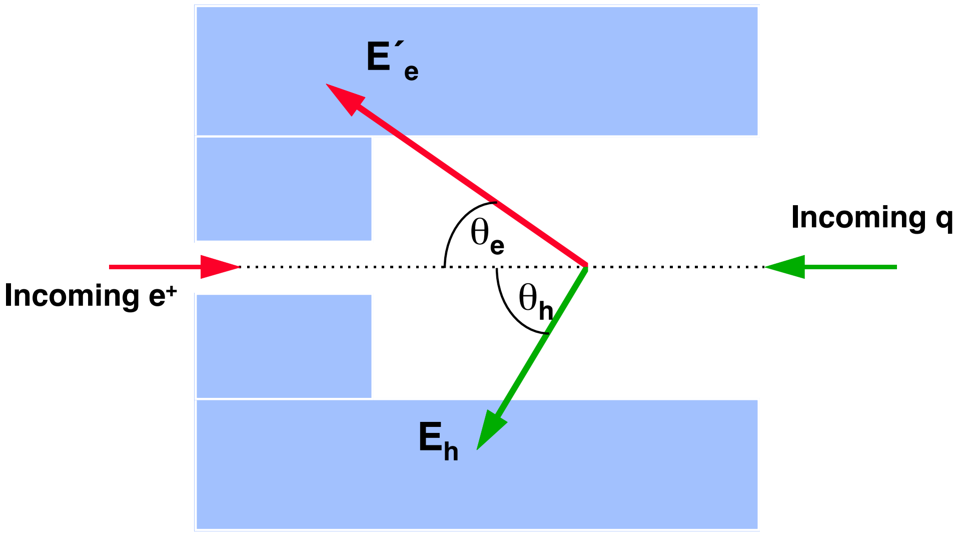
The parton densities are evolved to high Q^2, high x using NLO DGLAP equations.

Uncertainties of the Standard Model NC Expectations

Theoretical uncertainties:

• parton density distributions	5 %
- uncertainties in the input data	
- initial shapes of the distributions (Q_0^2)	
• value of α_s	4 %
- vary α_s [0.110 - 0.122] compare CTEQ (A1) to A(5)	
• higher order QED corrections	2 %
• electroweak parameters	0.25 %
total	**7 %**

Reconstruction of the Kinematic Variables



Measure 4 independent quantities E'_e , θ_e , E_h , θ_h while any combination of 2 variables is sufficient to describe the final state (kinematic variables x , y , Q^2) .

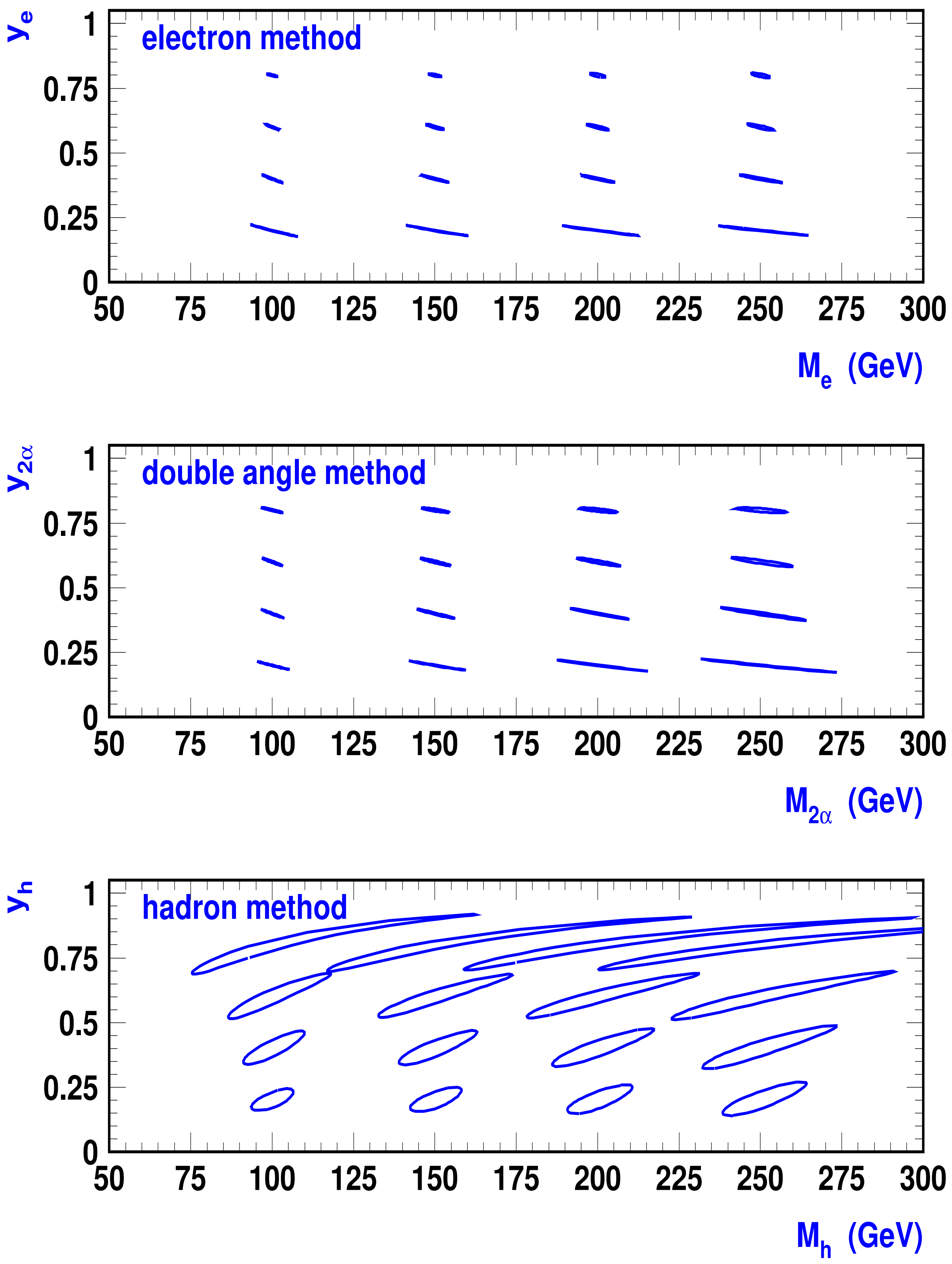
- E'_e , θ_e : electron method
  - most precise for high y / low x
  - degrades severly at low y
- E_h , θ_h : hadron method
  - less precise
  - only choice for Charged Current DIS
- θ_e , θ_h : double angle method
  - insensitive to the calorimeter energy scale
  - degrades at low Q^2 and sensitive to QED radiation

H1 and ZEUS Detectors

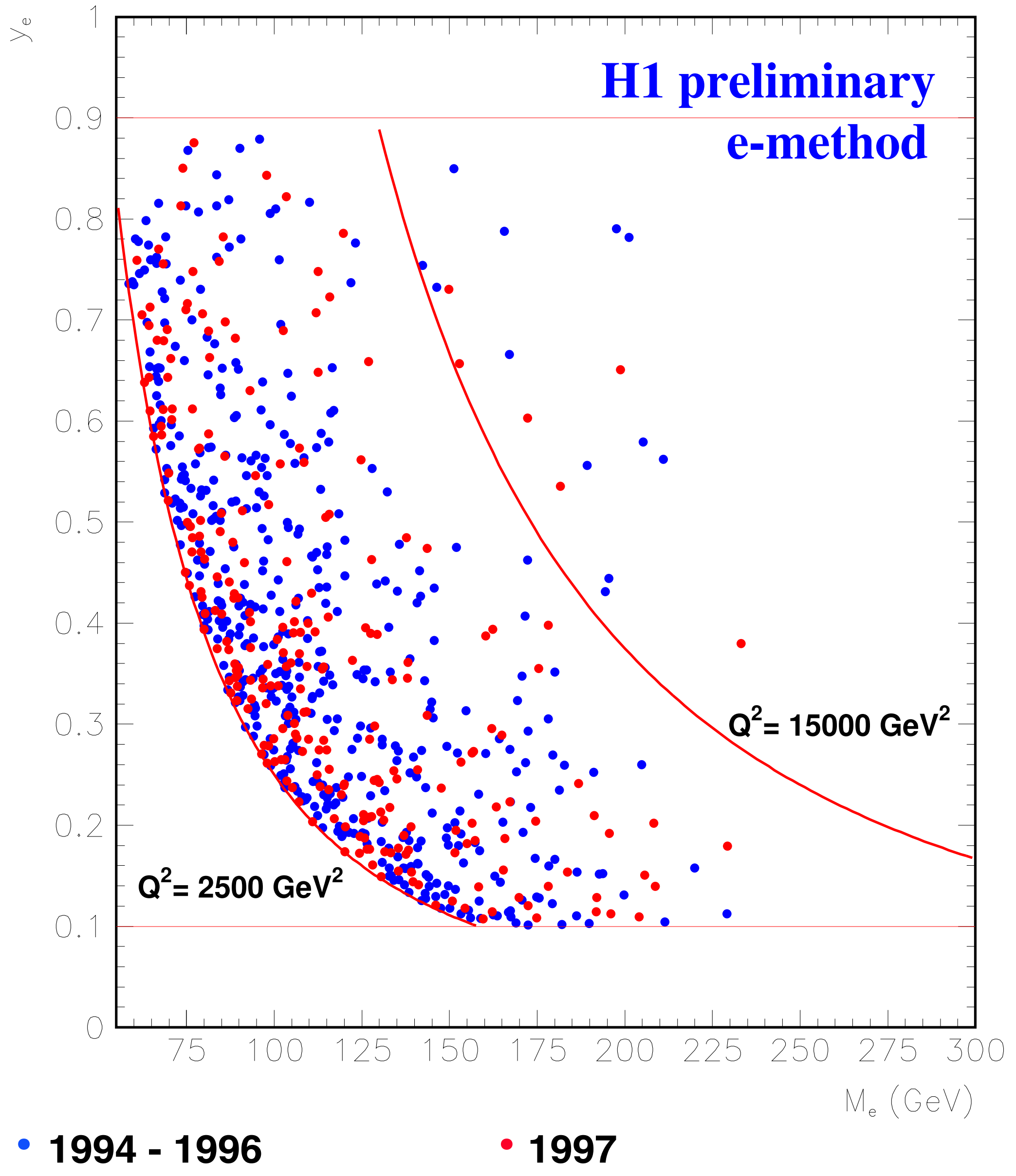
	H1	ZEUS
Calorimeter	**Liquid Argon 44000 cells**	**Uranium Scintillator 6000 cells**
$\sigma(\theta_e)$	**~ 2 mrad**	**5 mrad**
$\sigma/\sqrt{E}$ **(e)**	**12 %**	**18 %**
$\sigma/\sqrt{E}$ **(hadrons)**	**50 %**	**35 %**
$\Delta E/E$ **(sys.)**	**3 % / 4 %**	**3 %**
Reconstruction Method	**Electron (e)**	**Double Angle (DA)**
	excellent resolution	**better systematics**
	small migration	**larger migration due to radiative corrections**

The Standard Model expectations contains theoretical and experimental uncertainties.

Measurement errors for Mass and y



H1 Neutral Current Data 1994 - 97
(L = 23.7 pb^{-1})



Region	Observed Events	Expectation
$Q^2 > 2500$ GeV^2	724	714 ± 69
$Q^2 > 15000$ GeV^2	18	8.0 ± 1.2
M_e [200 ± 12.5 GeV], $y_e > 0.4$	8	1.53 ± 0.29

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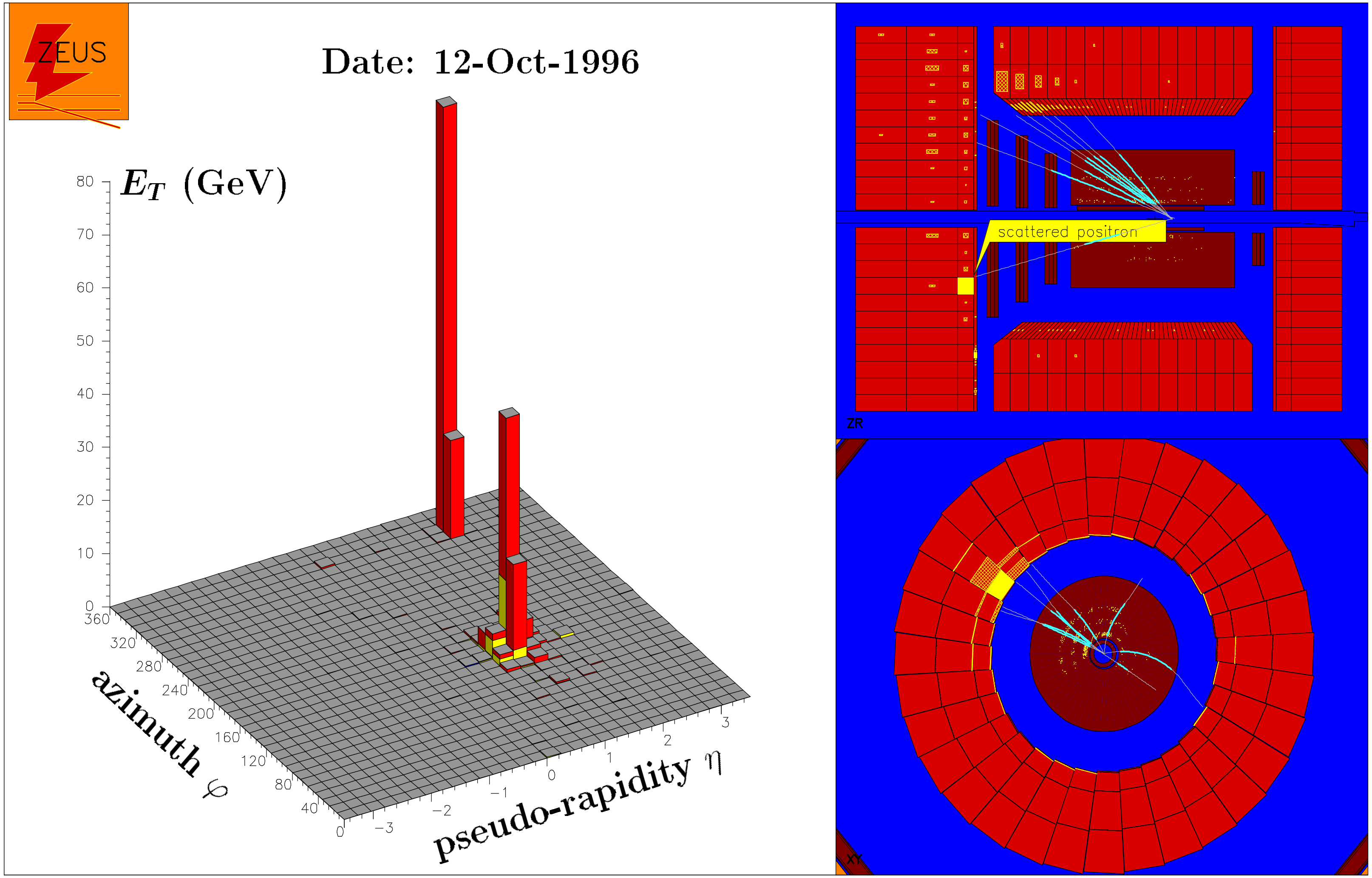
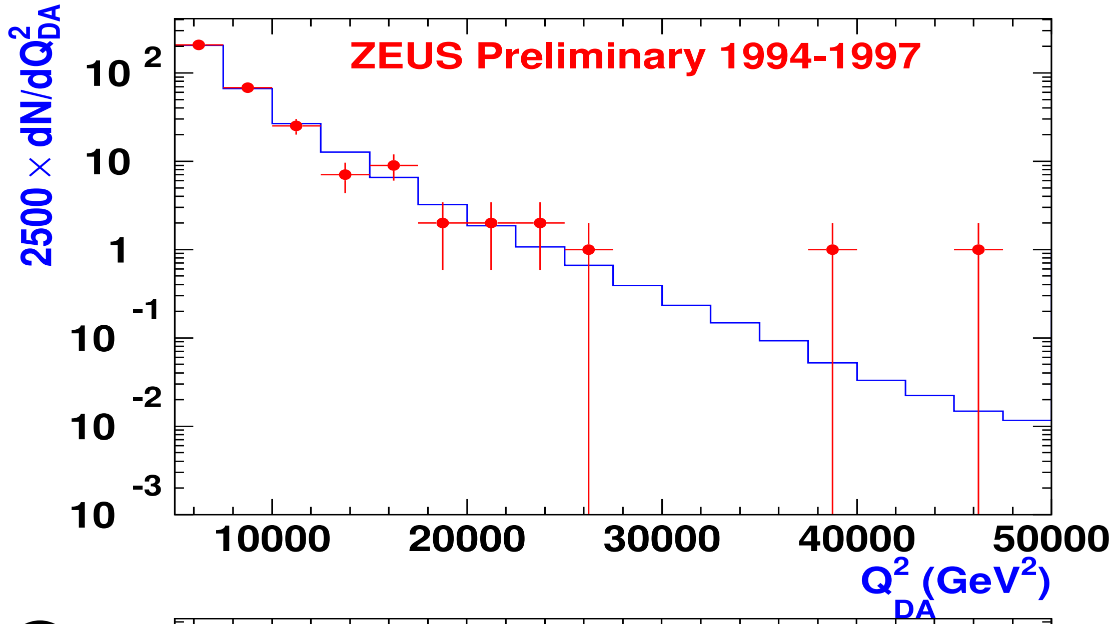
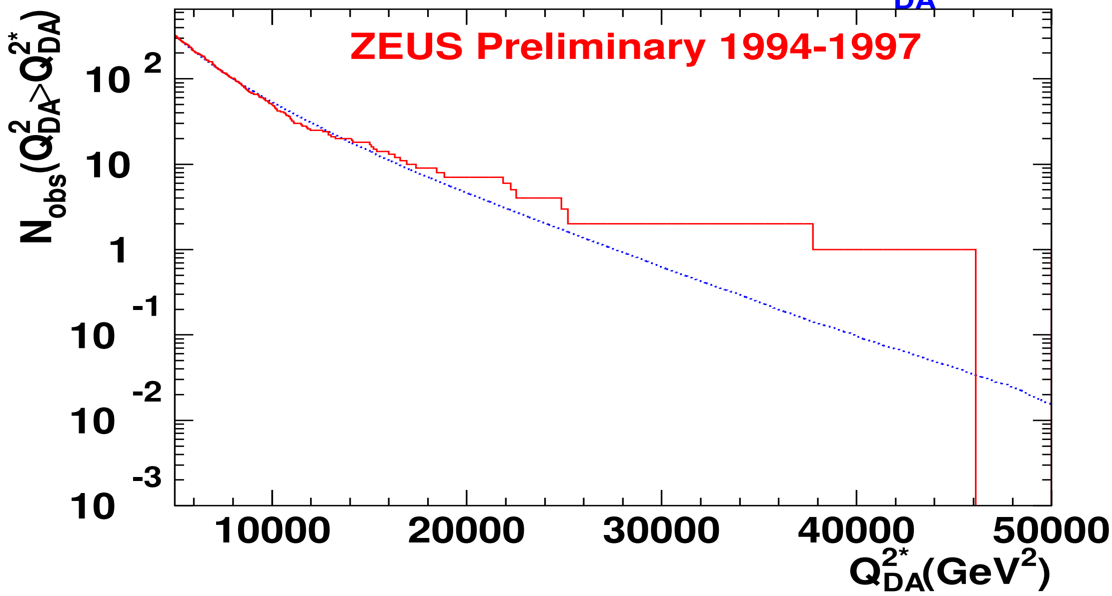
$$E_t = 204\ GeV \qquad E - p_Z = 50.2\ GeV \qquad \gamma = 38.6^\circ$$
$$p_t = 2.2\ GeV \qquad E'_e = 380\ GeV \qquad \theta_e = 15.4^\circ$$

$$x_{DA} = 0.709 \pm 0.034 \qquad x_e = 0.605 \pm 0.060$$
$$y_{DA} = 0.721 \pm 0.008 \qquad y_e = 0.752 \pm 0.021$$
$$Q^2_{DA} = 46100 \pm 1600\ GeV^2 \qquad Q^2_e = 41000 \pm 3000\ GeV^2$$



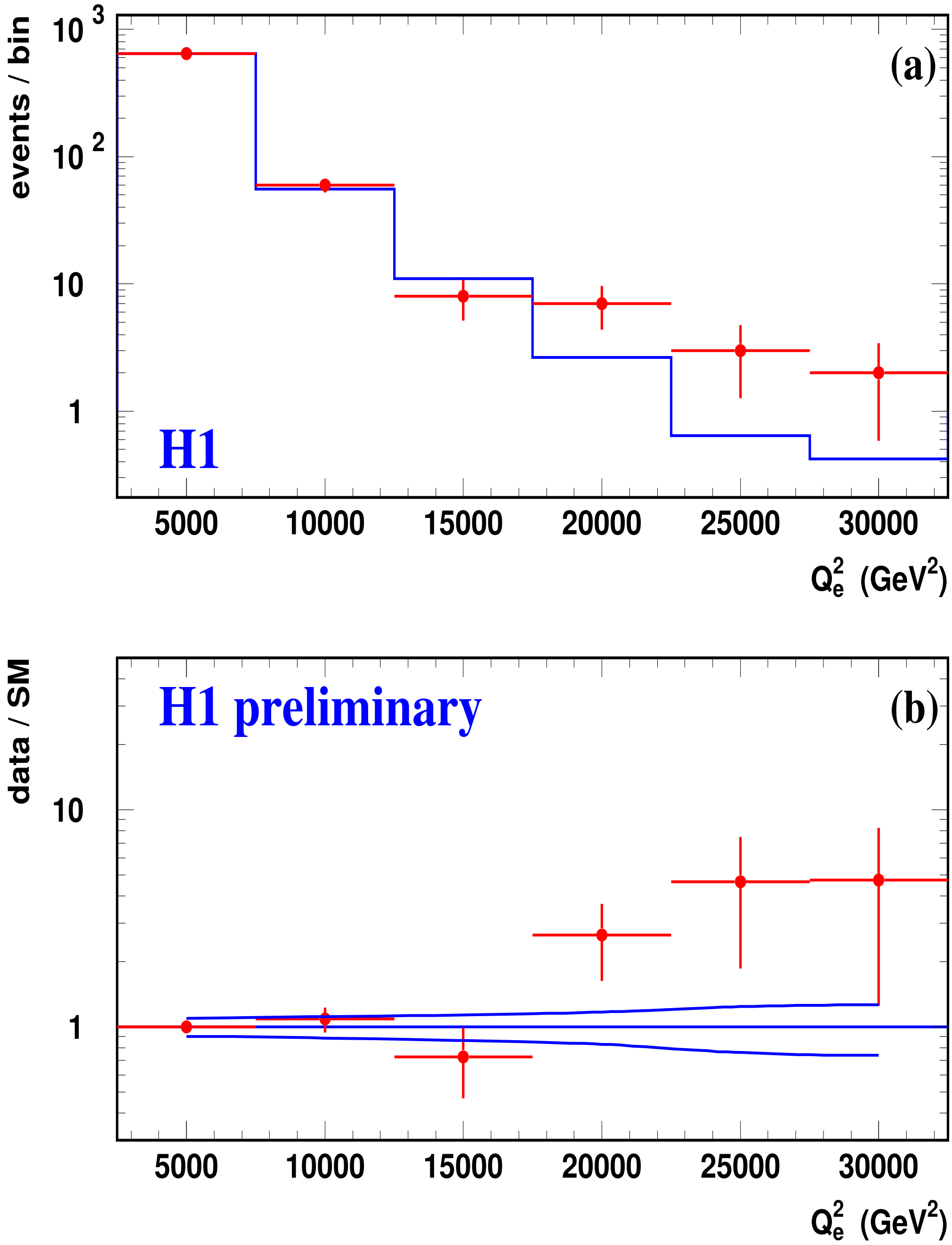
ZEUS Neutral Current Data 1994 - 97
Q^2 Dependence (L = 33.5 pb^{-1})





Region	Observed Events	Expectation
$Q^2 > 5000$ GeV^2	326	328 ± 15
$Q^2 > 35000$ GeV^2	2	0.242 ± 0.017
$x_{DA} > 0.55$, $y_{DA} > 0.25$	5	1.51 ± 0.13

H1 NC: Q^2 Dependence

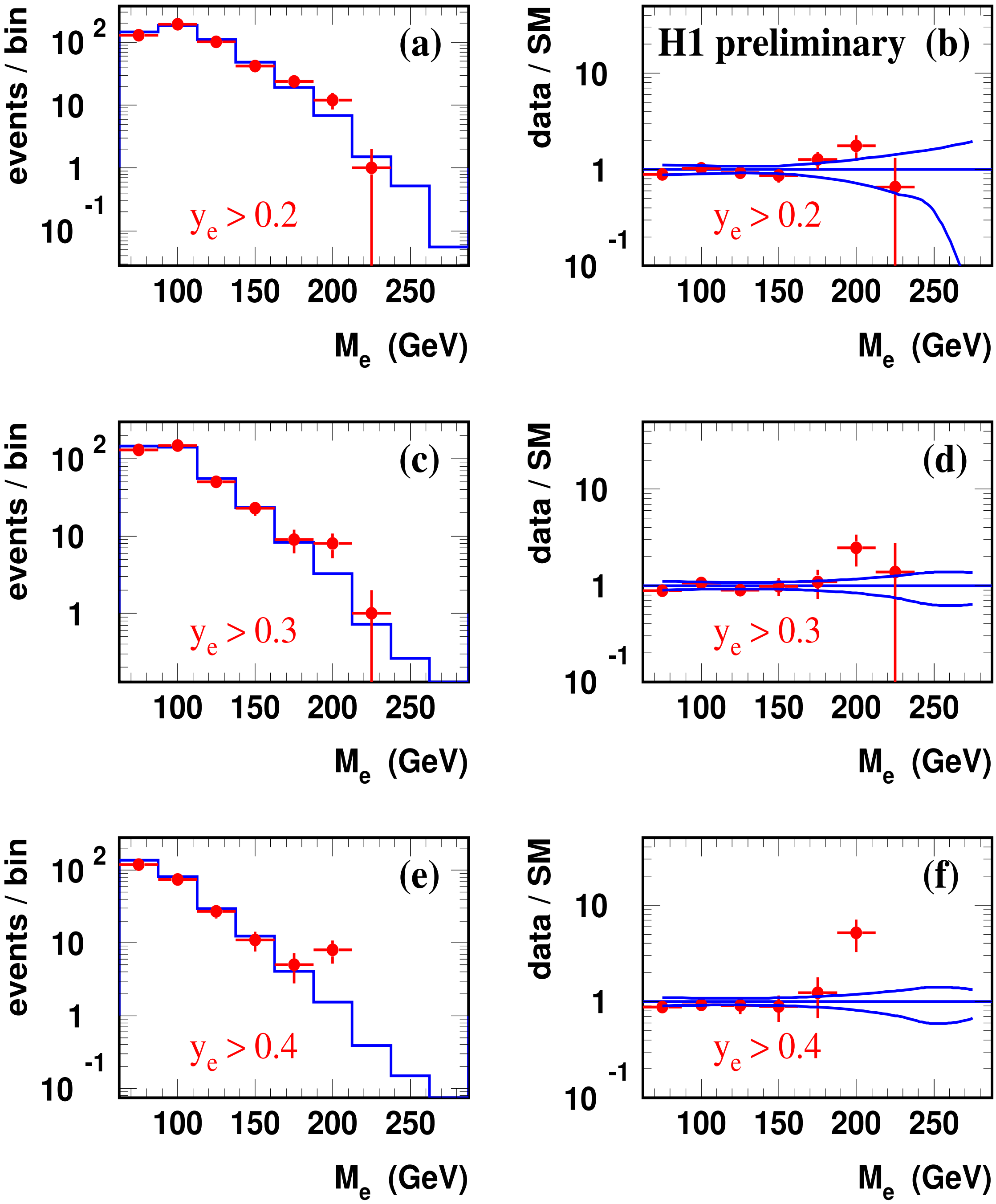


For $Q^2_e > 15000$ GeV^2:

Observed Events 18 **P = 3.4×10^{-3}**

Expected Events 8.00 ± 1.16

H1 NC: M_e for large y



- Excess of events with respect to the SM expectation at highest mass M_e.
- Effect is more pronounced at large y_e.

Mass Window

Region of most significant excess over the NC expectation:

- **Slide mass windows ΔM_e within [80, 250] GeV for different ΔM_e and y_{min} and find the mass range with the lowest Poisson Probability P (N > N_{obs}).**

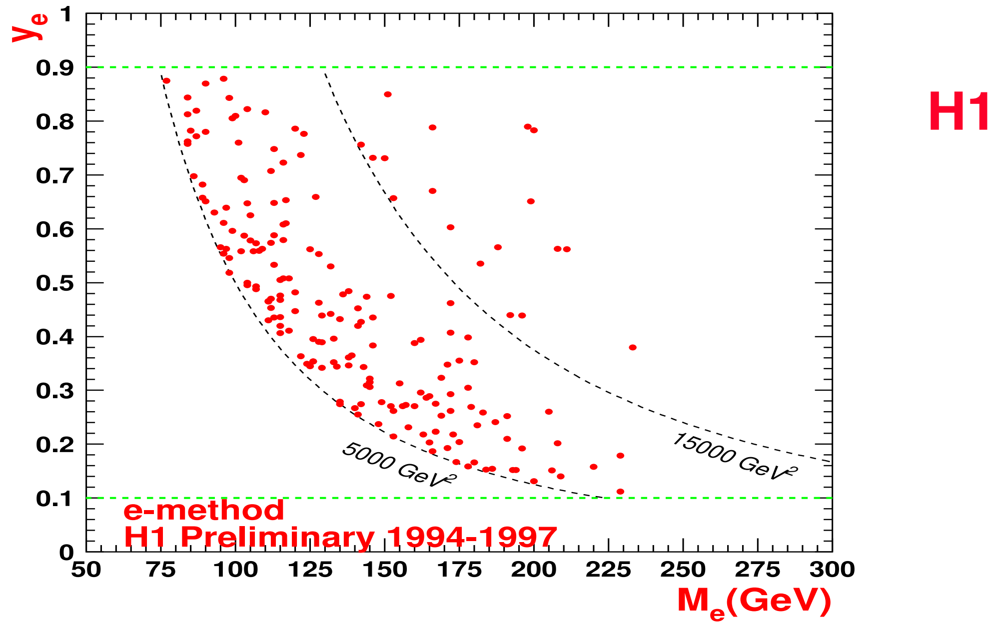
—> $M_e \approx 200$ GeV with $\Delta M_e = 25$ GeV

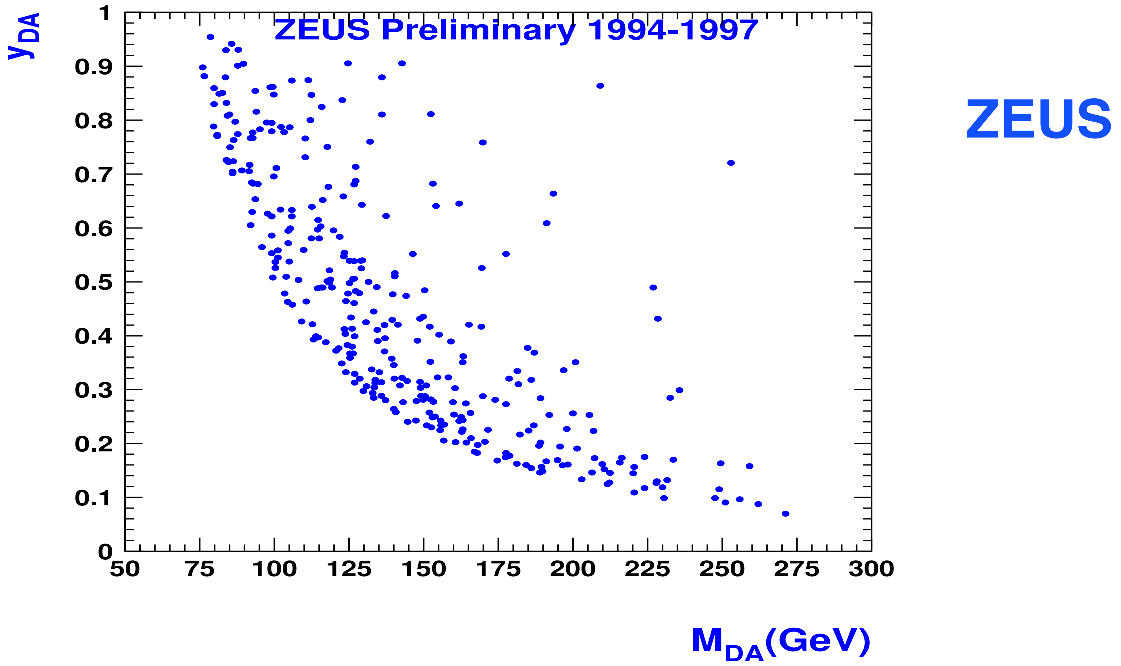
Dependence on the width of the mass window.

ΔM_e	20 GeV	25 GeV	30 GeV	40 GeV
N_{obs}	6	8	8	8
N_{exp}	1.01 ± 0.21	1.53 ± 0.29	1.75 ± 0.32	2.54 ± 0.49
P	$9.1 \cdot 10^{-4}$	$3.3 \cdot 10^{-4}$	$7.3 \cdot 10^{-4}$	$2.2 \cdot 10^{-3}$

Probability to find a fluctuation as large as observed in the mass range considered is $\approx$ 1%.

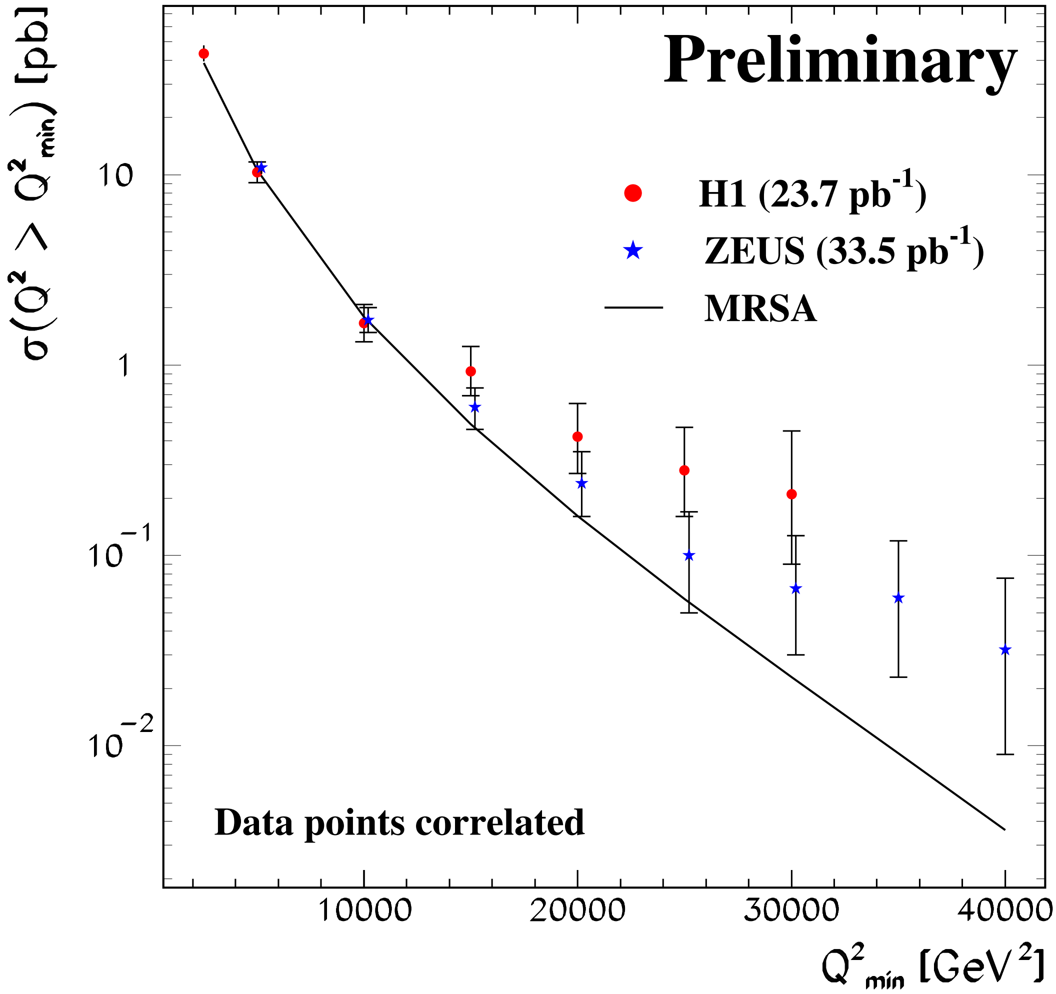
N C M-y Plane for $Q^2 > 5000\ GeV^2$





Region	ZEUS (DA)	H1 (e)
M [200 ± 12.5 GeV] and y > 0.4	$N_{obs} = 3$ $N_{exp} = 2.92 \pm 0.24$	$N_{obs} = 8$ $N_{exp} = 1.53 \pm 0.29$
x > 0.55 and y > 0.25	$N_{obs} = 5$ $N_{exp} = 1.51 \pm 0.13$	$N_{obs} = 1$ $N_{exp} = 0.752 \pm 0.305$

H1 and ZEUS Cross Sections for $Q^2 > Q^2_{min}$



Data is not corrected to the Born level.

- **Measurements of H1 and ZEUS are consistent.**
- **Good description by the SM at low Q^2.**
- **Data exceeds the SM at high Q^2.**

Neutral Currents - Summary 1994 - 1997

- High statistics cross section measurements were presented.

$Q^2 < 15000$ GeV^2 :

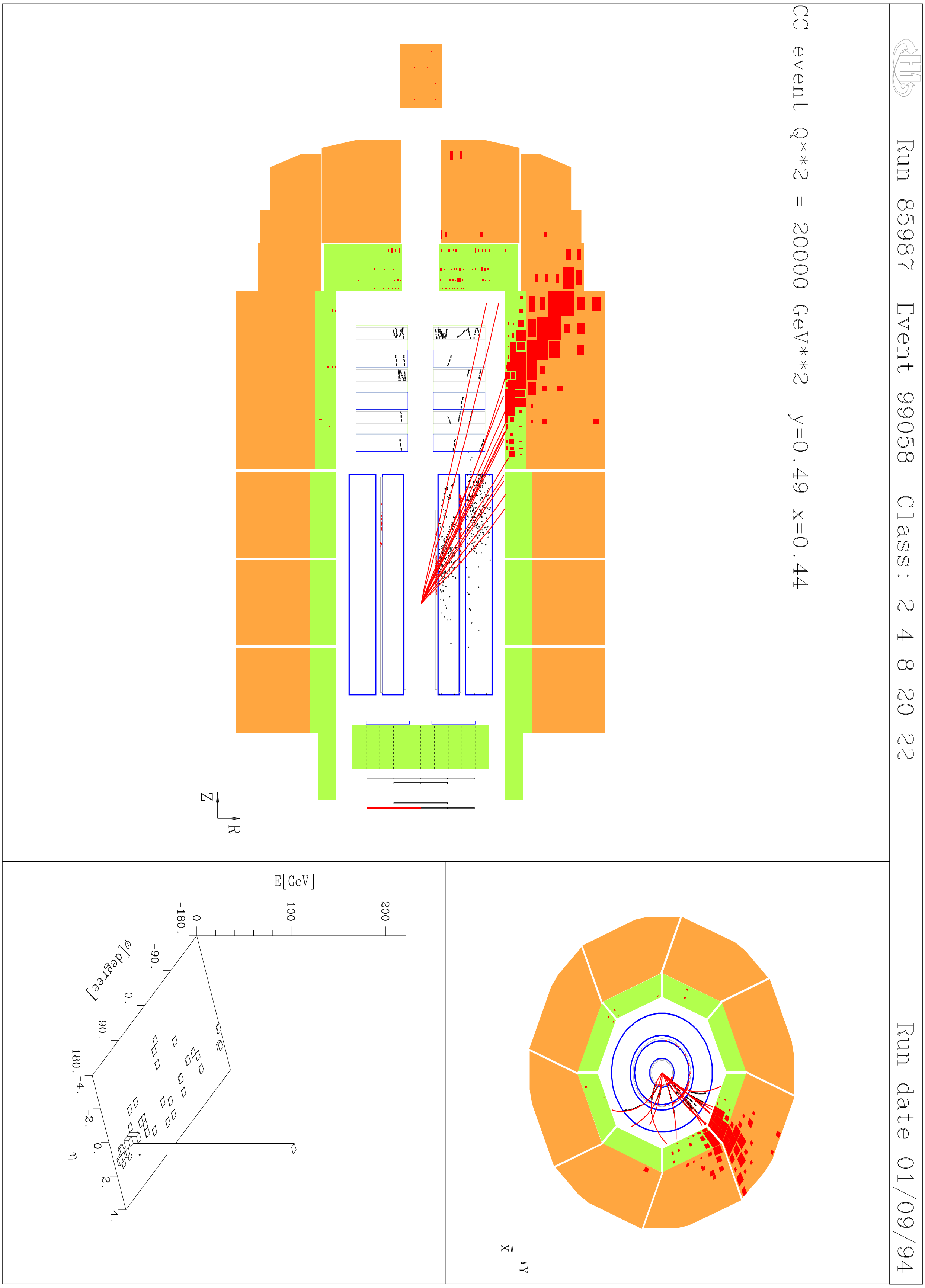
- The data confirms the Standard Model expectation in the distribution of M, x and Q^2.

$Q^2 > 15000$ GeV^2 :

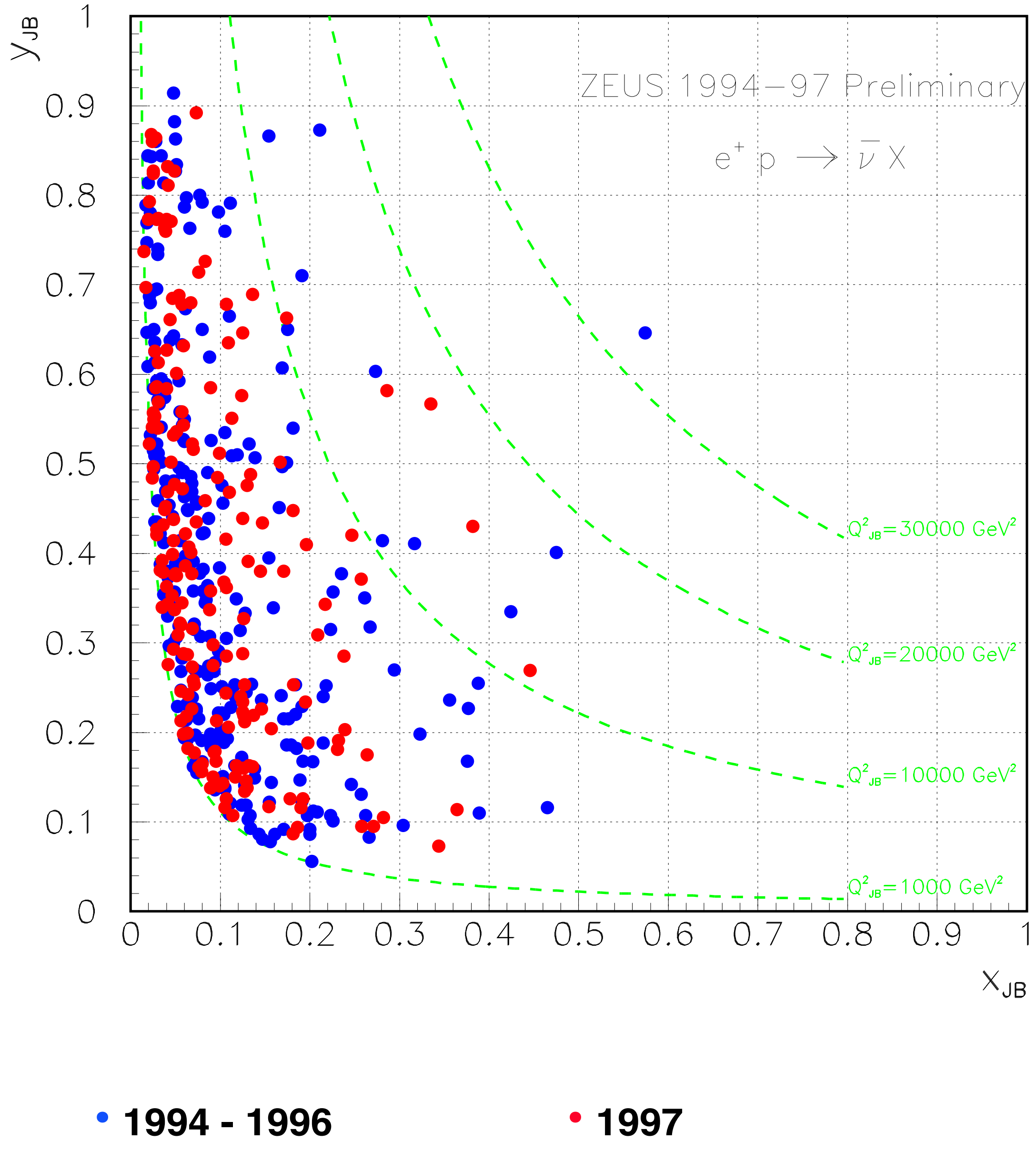
- H1 observes 8 events for $y > 0.4$ and a mass window of [200 ± 12.5 GeV], where 1.53 ± 0.29 events are expected.

- ZEUS observes 5 events for $x > 0.55$ and $y > 0.25$, where 1.51 ± 0.13 events are expected.

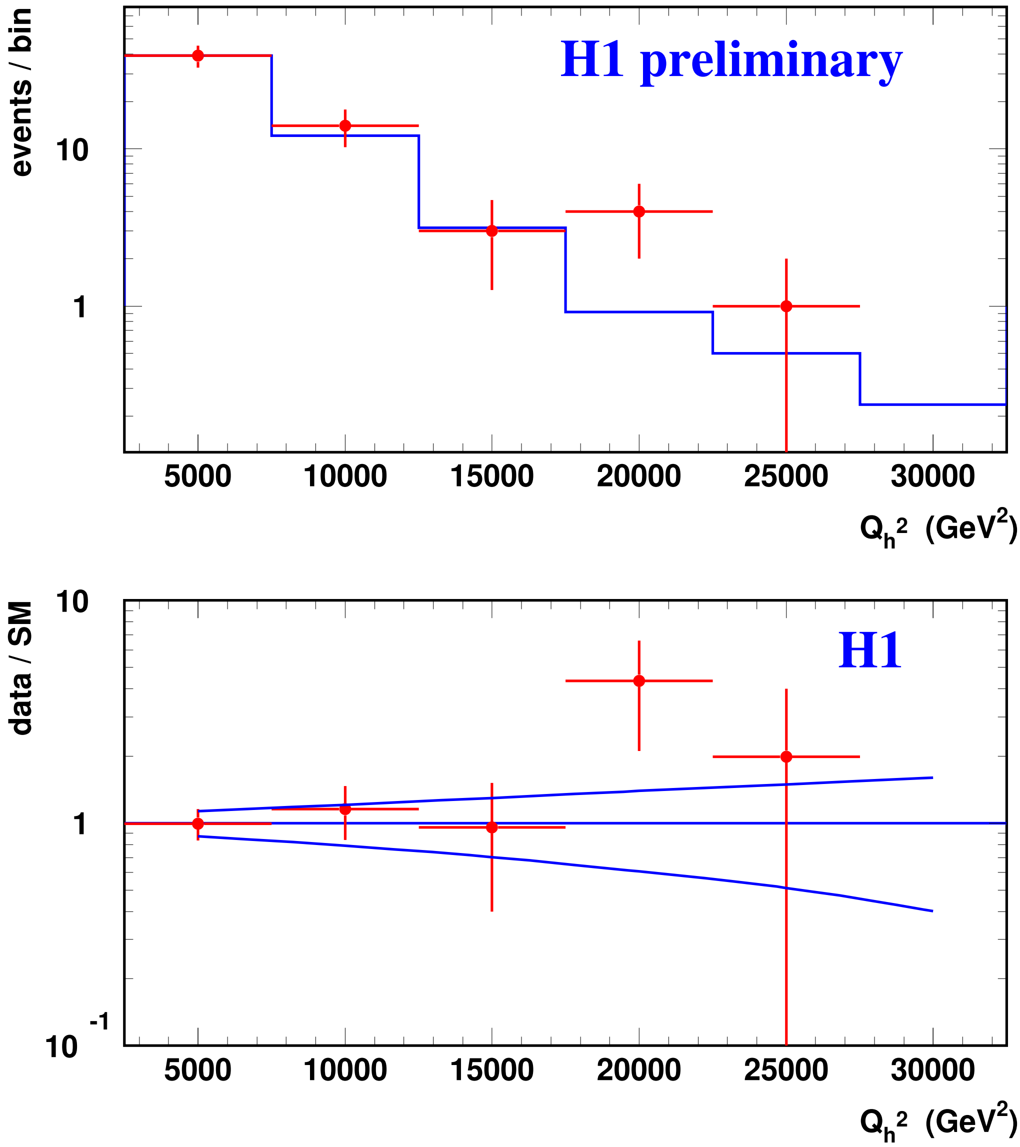
- The excess events observed at large M / x are unlikely to be due to a single narrow resonance.


Run 85987 Event 99058 Class: 2 4 8 20 22
CC event Q**2 = 20000 GeV**2 y=0.49 x=0.44
Run date 01/09/94
E[GeV]
200
100
0
-180.
-90.
0.
90.
180.
φ[degree]
-4.
-2.
0.
2.
4.
η
Z
R
X
Y

ZEUS Charged Current Data 1994 - 97
(L = 33.5 pb^{-1})

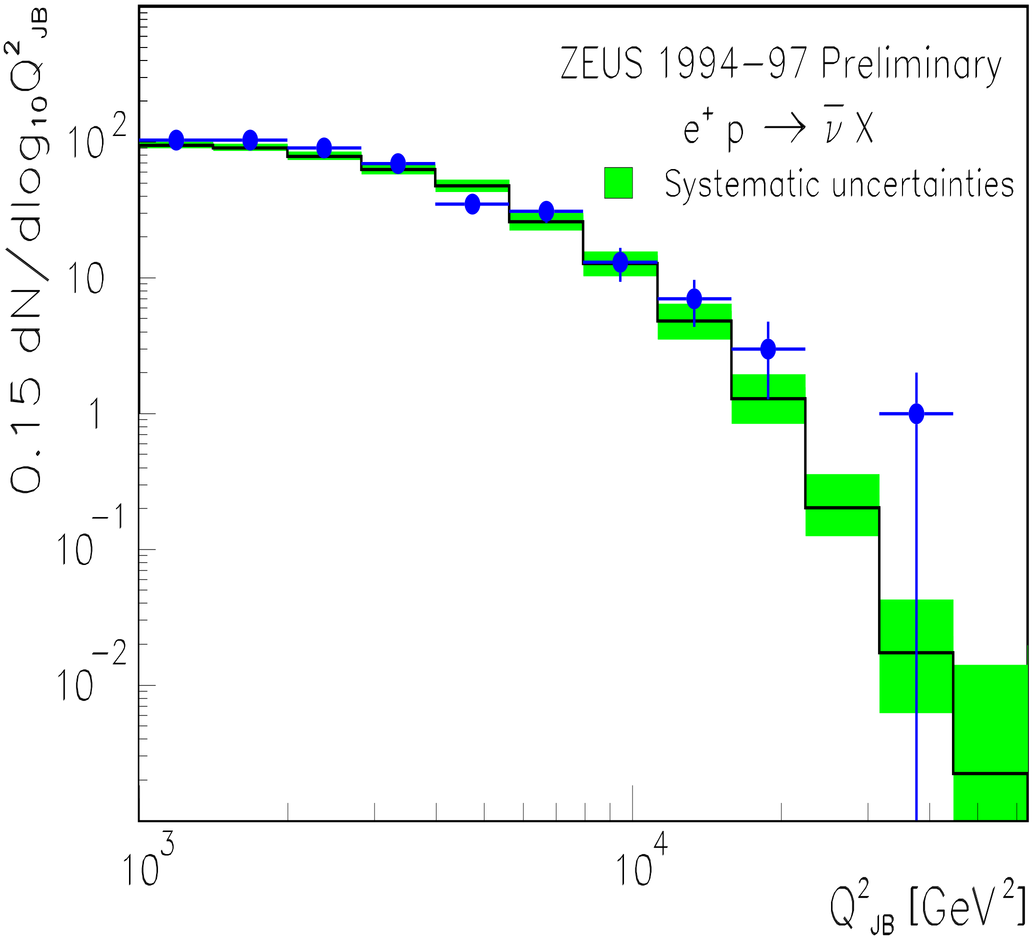


H1 Charged Current Data 1994 - 97
Q^2 Dependence (L = 23.7 pb^{-1})



Q^2_{min} (GeV^2)	N_{obs}	N_{exp}
2500	61	56.30 ± 9.40
5000	42	34.70 ± 6.90
10000	14	8.33 ± 3.10
15000	6	2.92 ± 1.44
20000	3	1.21 ± 0.64

ZEUS CC: Q^2 Dependence



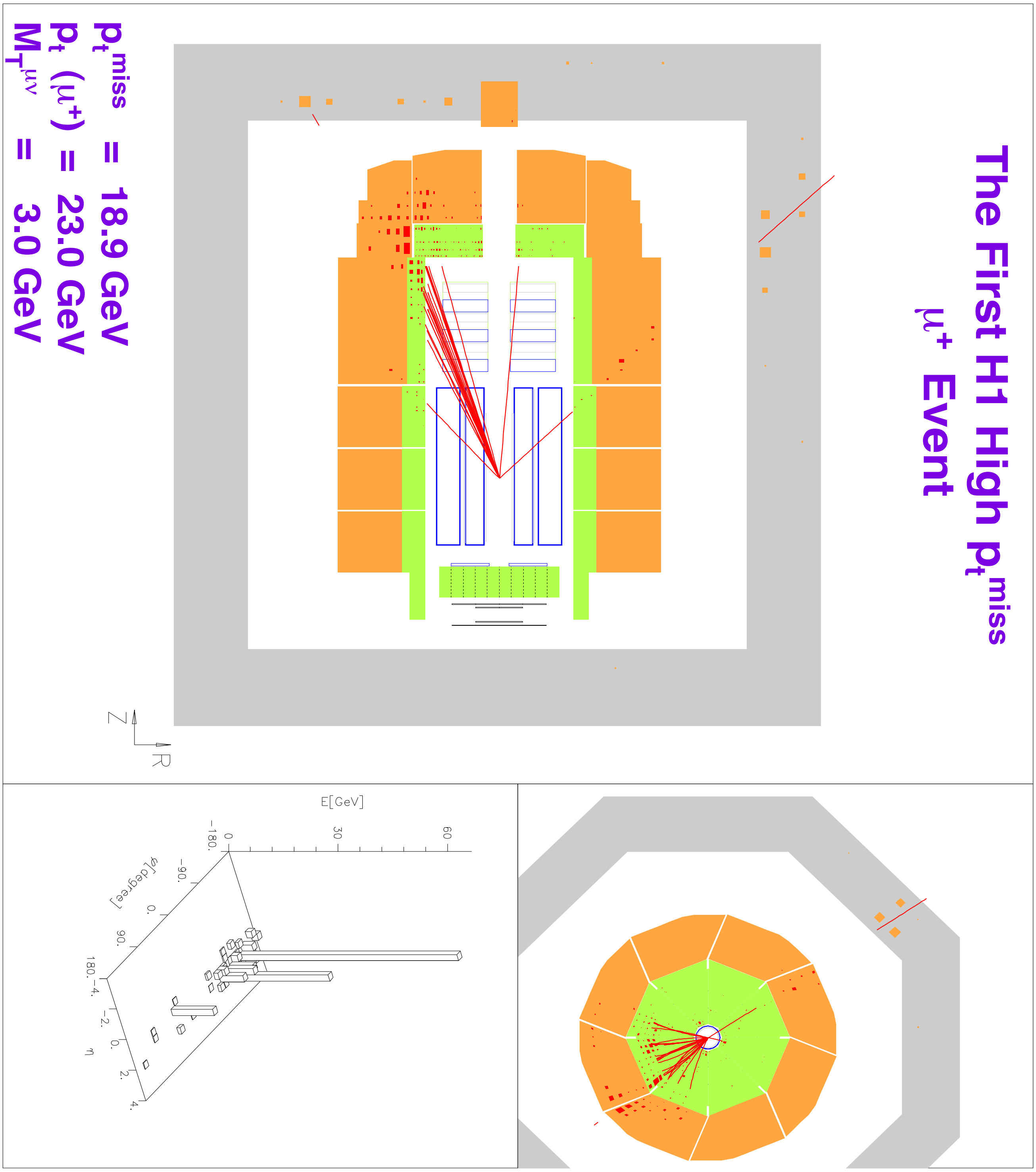
Q^2_{min} (GeV^2)	N obs	N exp	Uncertainty E scale	Uncertainty PDF
1000	455	419	±13	±33
10000	15	9.4	± 2.5	± 1.6
15000	5	2.0	+ 0.81 - 0.54	± 0.4
20000	1	0.46	+ 0.28 - 0.16	± 0.10
30000	1	0.034	+ 0.037 - 0.016	± 0.008

Charged Currents - Summary 1994 - 1997

- CC selection efficiency is about 80 %.
- Almost no background contribution.
- Data is slightly above the Standard Model expectation for high Q^2.

  N_{obs} (H1 + ZEUS) = 29 for $Q^2 > 10000\ GeV^2$

  $N_{exp} = 17.7 \pm 4.3$


The First H1 High p_t^{miss} μ^+ Event
p_t^{miss} = 18.9 GeV
p_t (μ^+) = 23.0 GeV
$M_T^{\mu\nu}$ = 3.0 GeV
Z
R
E[GeV]
0
30
60
-180.
-90.
0.
90.
180.
φ[degrees]
-4.
-2.
0.
2.
4.
η

Events with High Energy Isolated Leptons and Large P_t^{miss}

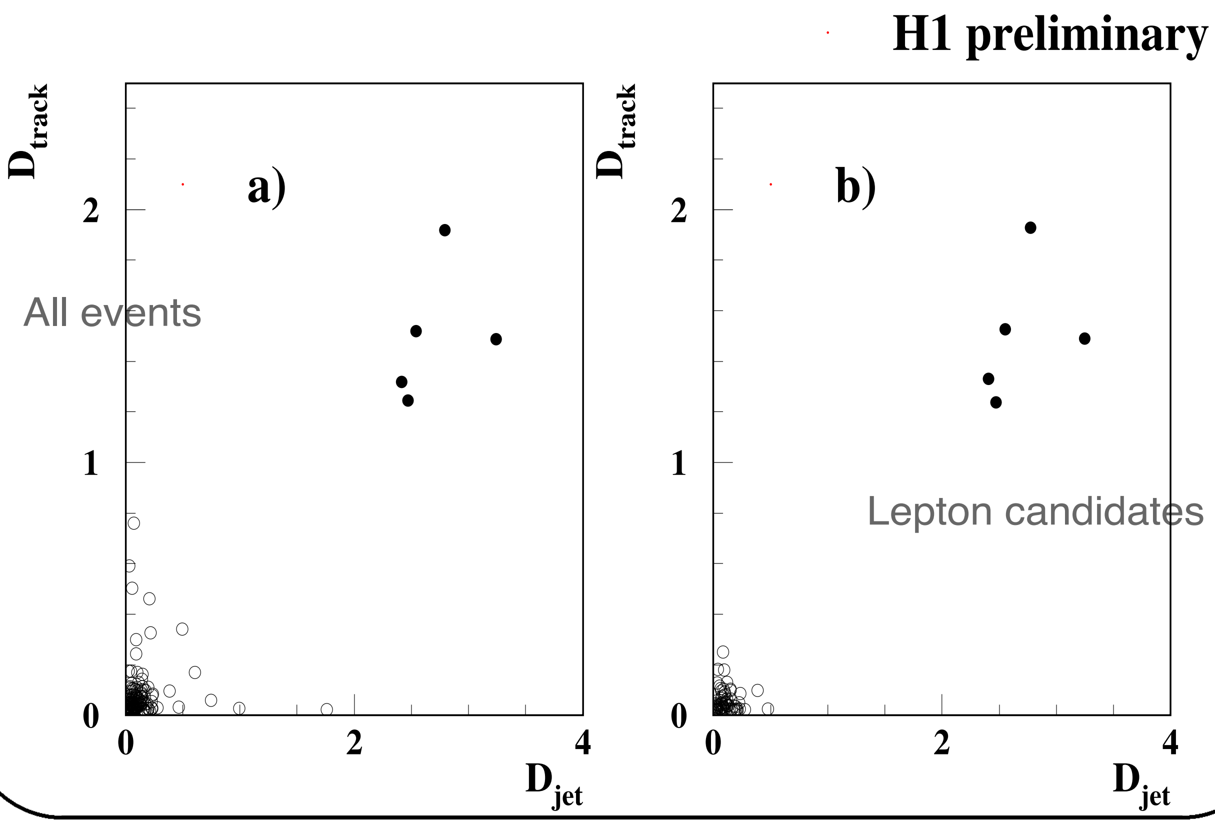
- **H1 selection requirements**
  - P_t^{mis} (calorimeter) > 25 GeV
  - background filters
  - acoplanarity (e - hadronic system) > 5^0

336 events

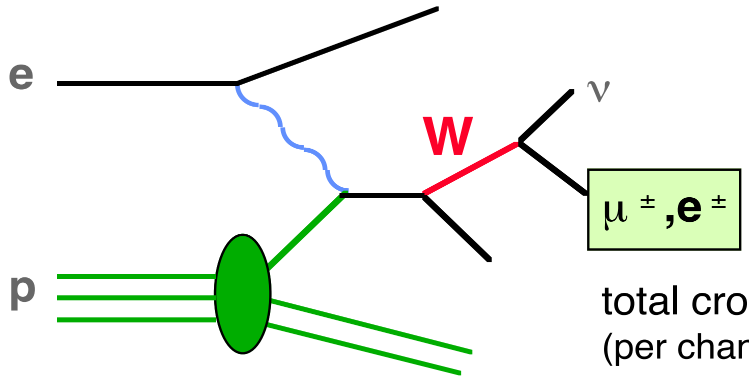
  - isolated track with $\theta_{track} > 10^0$ and $P_t > 10$ GeV
- **Select**

candidates:

μ^-	μ^+	e^-	e^+
2	2	0	1



W - Production and Leptonic Decay

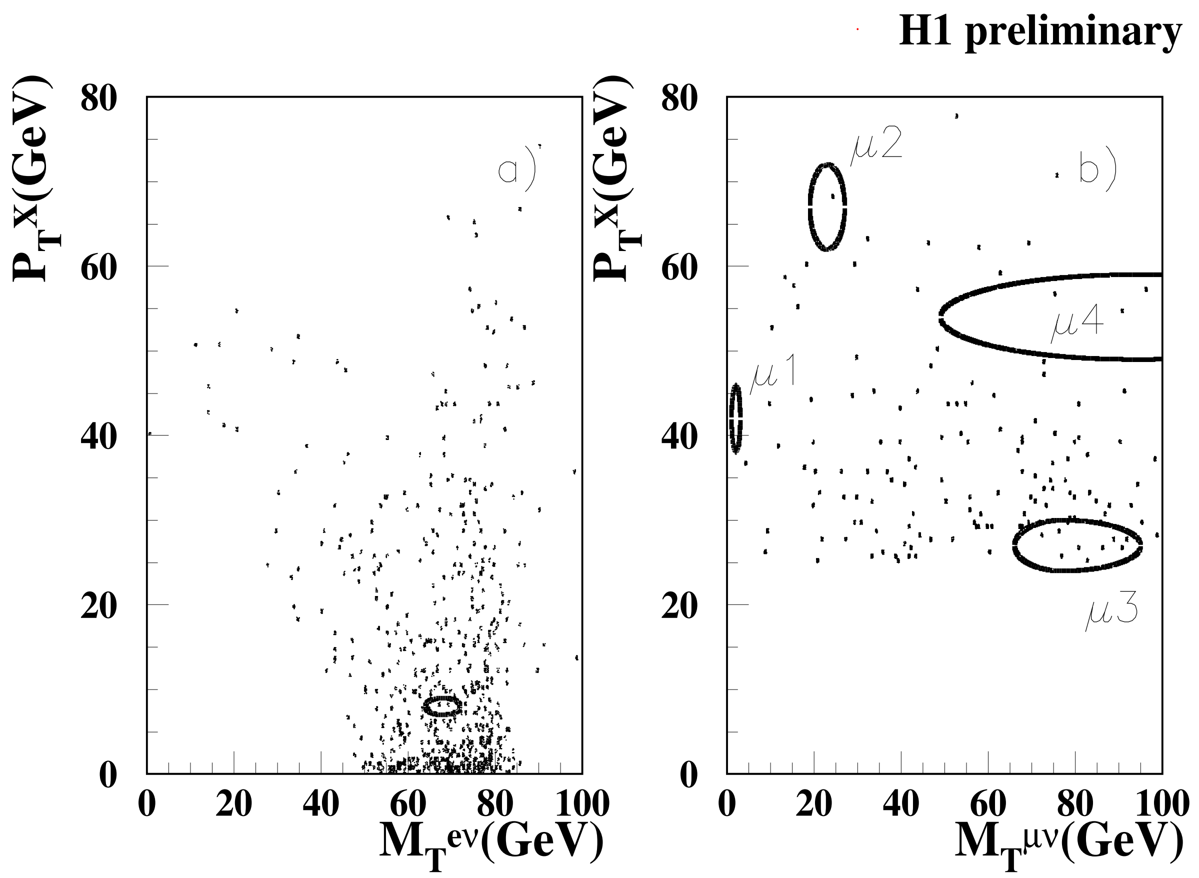


total cross section ≈ 70 fb
(per channel and charge)

- **Kinematics**
  - **Small p_t of the recoil hadron system.**
  - **Jacobian peak at W mass in p_T and $M_{T\,(l\nu)}$.**
  - **W^+ and W^- are produced at similar rates.**
  - **The scattered e^+ is observed in 25 % of the cases.**

MC study with L (MC) = 500 •L (H1)

electrons **muons**



	Observed events	Expectation for W production
e	1	1.34 ± 0.20
μ	4	0.41 ± 0.07
	(2)	0.02 ± 0.003 pt > 40 GeV, $M_{T(l\nu)}$ < 30 GeV
		< 0.05 backgrounds, γ p, HQ, $\tau^+\tau^-$, ...

ZEUS - Search for High Energy Isolated Leptons with Large P_t^{miss}

- Selection requirements

  - p_t^{mis} (calorimeter) > 25 GeV
  - p_t^{track} > 10 GeV

  - μ selection
    match with isolated mip cluster in the calorimeter
    0 Events

  - e selection
    match with isolated e of E_t > 10 GeV
    acoplanarity (e - hadronic system) > 5^0
    2 Events
    (1 high Q^2 di-μ , 1 acoplanar e + jet)

- Expected number of Events (MC)

Process	μ	e
ep -> eWX	0.28	1.4
NC	-	~ 1.5
CC	~ 0.2	~ 0.1
$\gamma\gamma \to \mu\,\mu, \tau\,\tau$	~ 0	~ 1
γp	~ 0	~ 0

Conclusions

Neutral Currents:

- H1 and ZEUS: data exceed DIS Standard Model expectation for $Q^2 > 15000$ GeV^2.

  H1: most pronounced at M = [200 ± 12.5 GeV]

  ZEUS: most pronounced for x > 0.55 , y > 0.25

Cross Sections:

- H1 and ZEUS cross sections for Q^2 cuts between 5000 and 30000 GeV^2 have been presented.

  Combined cross sections for

  $Q^2_{min} = 15000$ GeV^2: $\sigma_{comb} = 0.71^{+0.14}_{-0.12}$ pb
  $\sigma_{SM} = 0.49$ pb

  $Q^2_{min} = 30000$ GeV^2: $\sigma_{comb} = 0.098^{+0.059}_{-0.042}$ pb
  $\sigma_{SM} = 0.023$ pb

Charged Currents:

- H1 and ZEUS: data are slightly above the Standard Model expectation for high Q^2.

  N_{obs} (H1 + ZEUS) = 29 for $Q^2 > 15000$ GeV^2
  $N_{exp} = 17.7 \pm 4.3$

Events with Large p_t^{miss} and High p_t Leptons :

- H1 observes 5 candidates for W production with subsequent leptonic decay, while 2 events are expected.
- ZEUS observes 1 candidate for W production in the electron channel, while 1 event is expected.