Observation of Events at Very High Q^2 in ep Collisions at HERA

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on behalf of

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Deep Inelastic Scattering

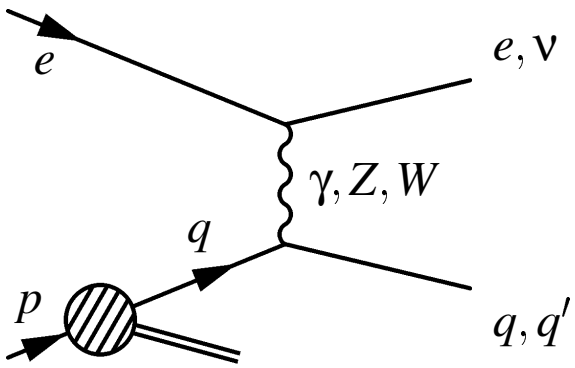
HERA: e^+ **beam 27.55** GeV, p **beam 820** GeV

$\rightarrow \sqrt{s} = 300$ GeV $\quad 1 < Q^2 < 90000$ GeV^2

probing distances below $10^{-16} cm$

fixed targed experiments: $Q^2 \sim 200$ GeV^2

lowest order parton kinematics



$e^+ + parton$ **center of mass system:**

invariant mass^2 = $\boxed{M^2 = xs}$

Θ_e^* = **angle between scattered** e^+ **and proton**

$$\boxed{y = \frac{1}{2}\left(1 + \cos\Theta_e^*\right)}$$

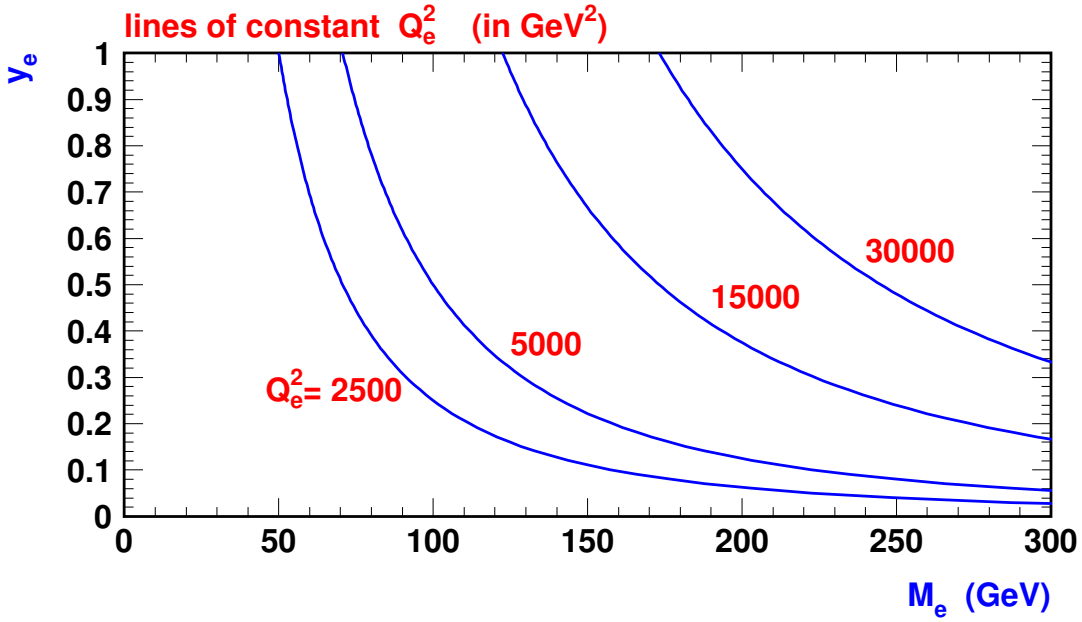
$$\boxed{Q^2 = M^2 y}$$

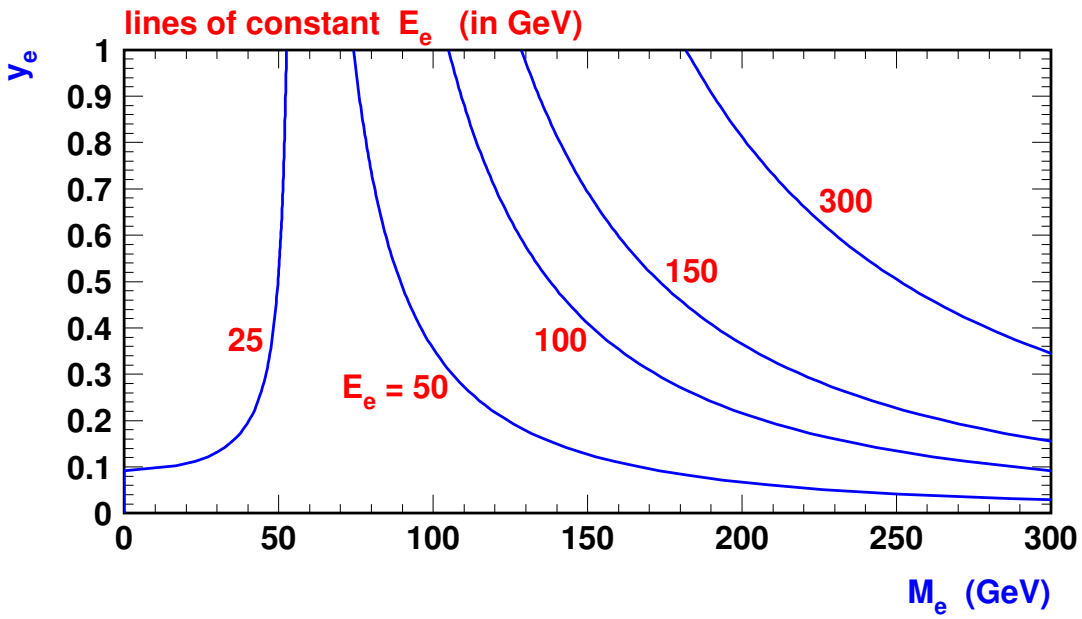
2 independent kinematic variables

4 measured variables: $E_e, \Theta_e, E_q, \Theta_q$

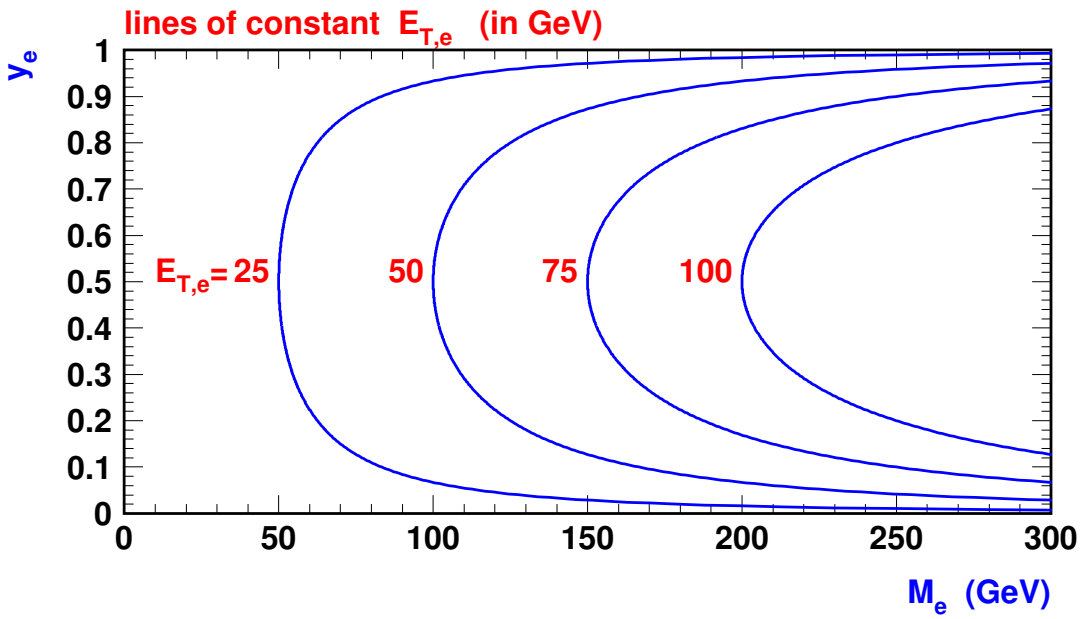
$\rightarrow$ **overconstrained system**

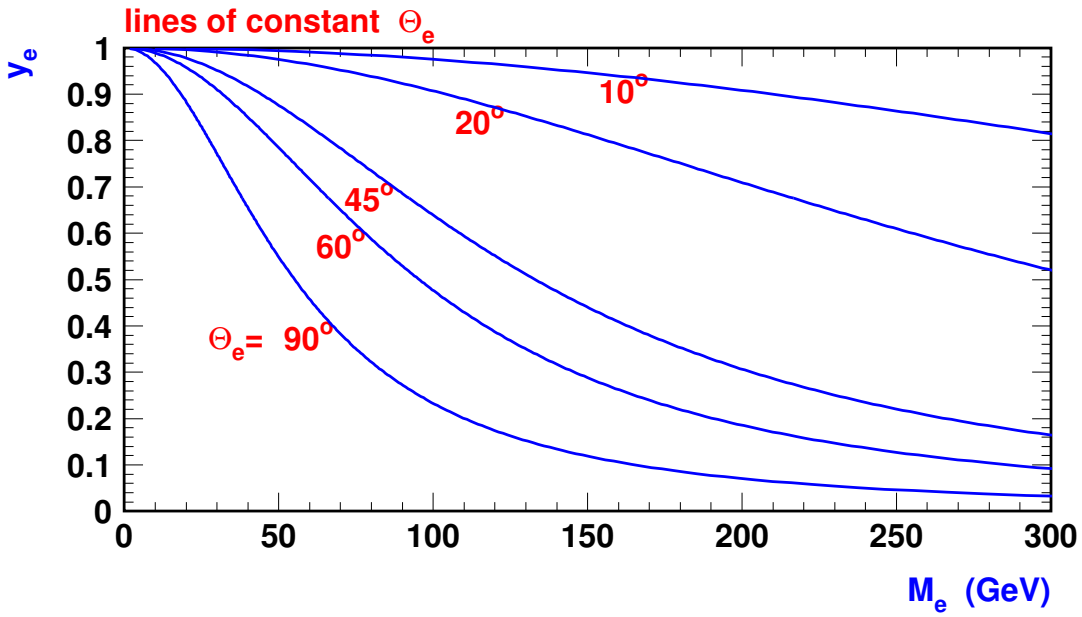
Kinematic of Deep Inelastic Scattering





Kinematic of Deep Inelastic Scattering





Reconstruction of Kinematics

electron - method: for H1 NC results

$$Q^2 = -(e_o - e)^2 = -q^2 \qquad y = qp/e_0 p$$
$$M^2 = xs = Q^2/y$$

hadron - method: for H1 CC results

similar, using hadronic energy flow

double angle (2α method): for cross checks

no dependence on energy measurement

$$E_e^0 = 27.55 \text{ GeV}$$

let $E_q^0 = 27.55$ GeV $\rightarrow M = 55.1$ GeV

$e^+ +$ quark system at rest

let $E_q^0 > 27.55$ GeV $\rightarrow M > 55.1$ GeV

$e^+ +$ quark system boosted

use pseudorapidities $\eta_{e,h} = -ln \tan \Theta_{e,h}/2$

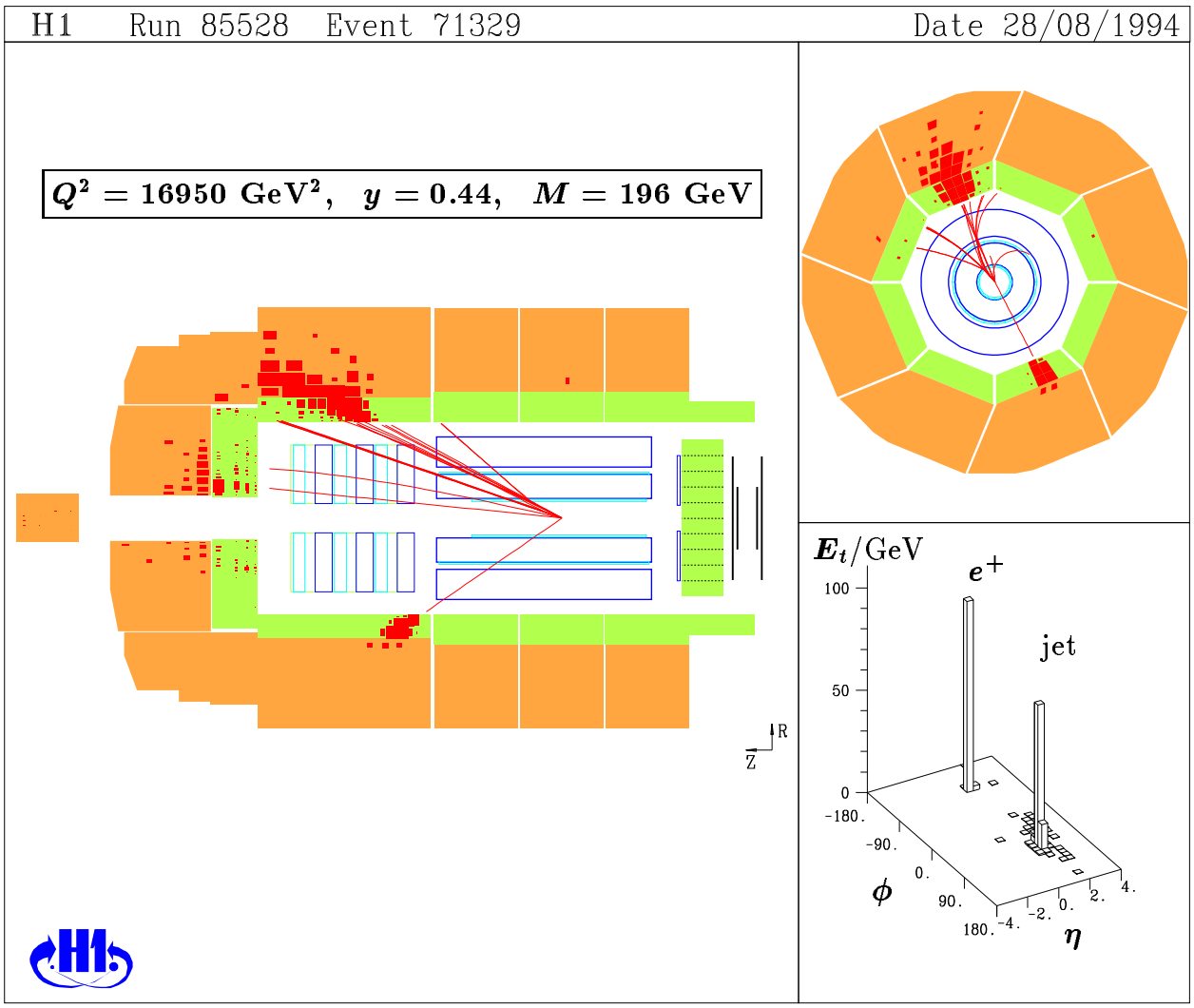
$$M = 2E_e^0 e^{(\eta_h + \eta_e)/2}$$

$$y = \frac{1}{1+e^{\eta_h - \eta_e}}$$

$\eta_e + \eta_h$ large: M large

$\eta_e - \eta_h$ large: y large

Neutral Current Candidate



LAr Calorimetry

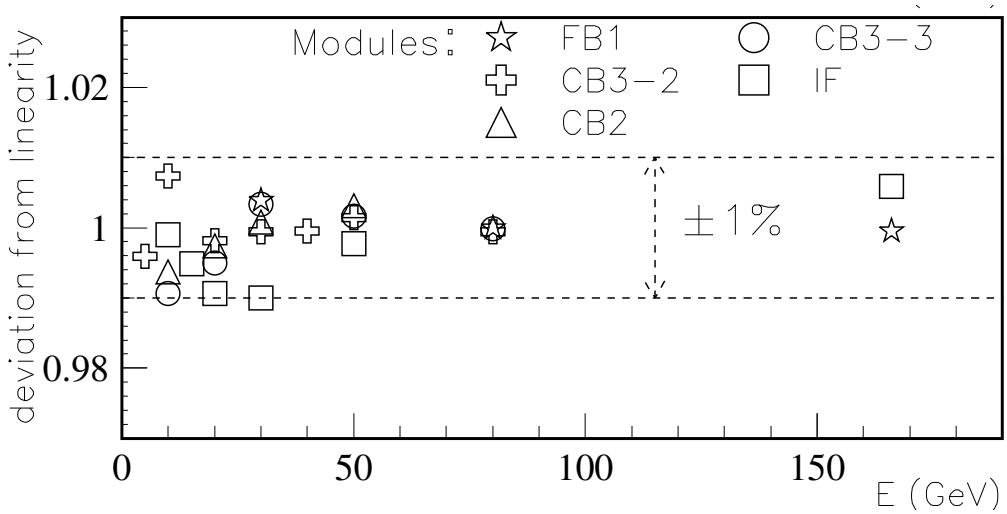
- **Very fine granularity** $\Delta\theta_e \sim 2\text{mrad for } 10^\circ < \theta_e < 30^\circ$

  (≈ 44000 cells) $\Delta\theta_e \leq 5\text{mrad for } 30^\circ < \theta_e < 145^\circ$
- **Optimized for e-identification** $\sigma(E)/E \simeq 12\%/\sqrt{E/\ \mathrm{GeV}} \oplus 1\%$
- **Hadronic energy compensation** $\sigma(E)/E \simeq 50\%/\sqrt{E/\ \mathrm{GeV}} \oplus 2\%$

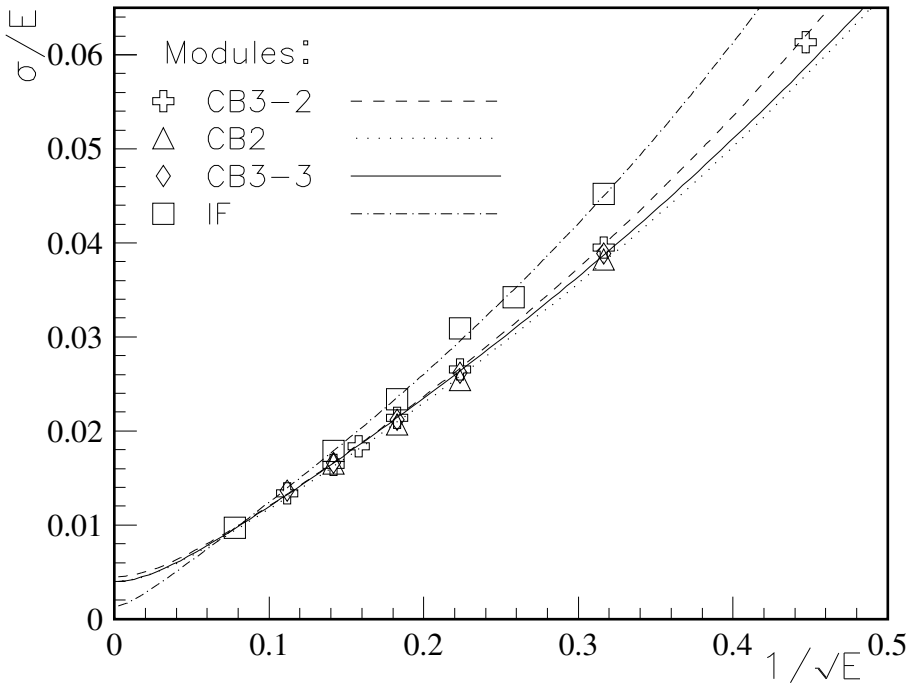
  by offline weighting

Electron Test Beam Results

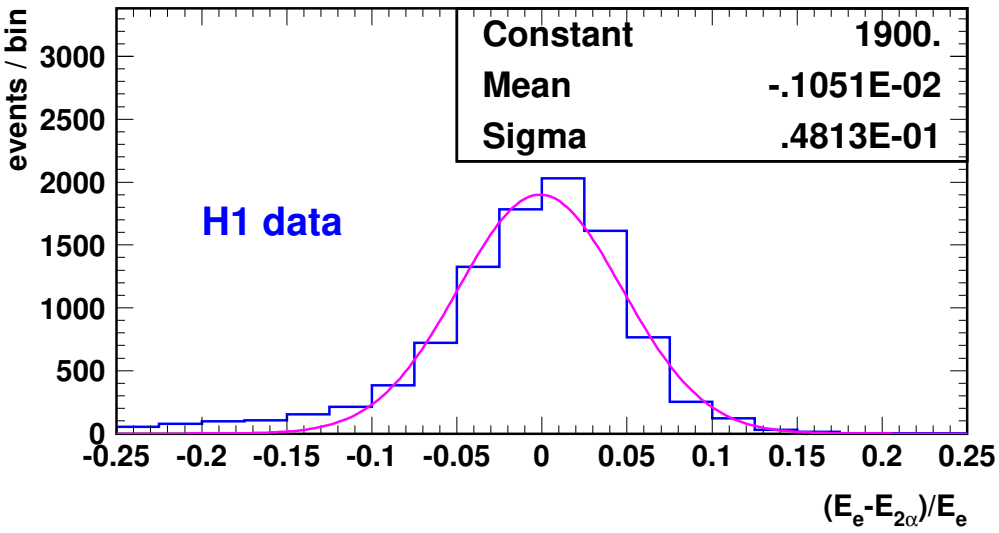
Linearity: $\pm 1\%$ **up to 166 GeV**

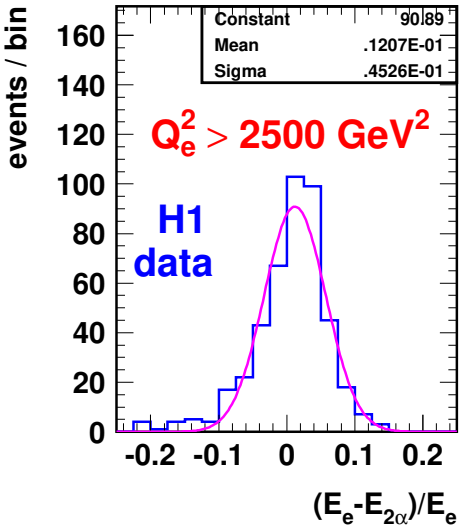


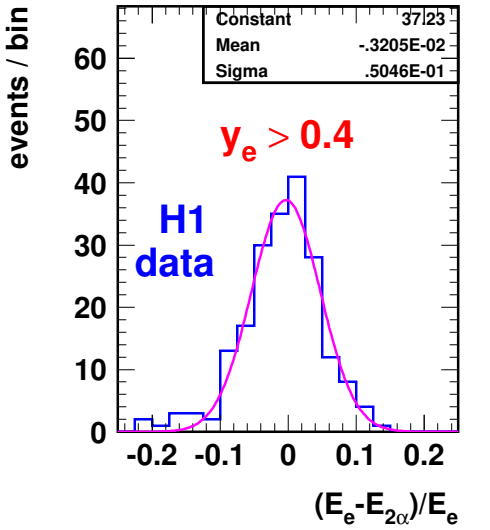
Resolution: $dE_e/E_e = 12\%/\sqrt{E_e(\mathrm{GeV})} \oplus 1\%$



Electromagnetic calibration





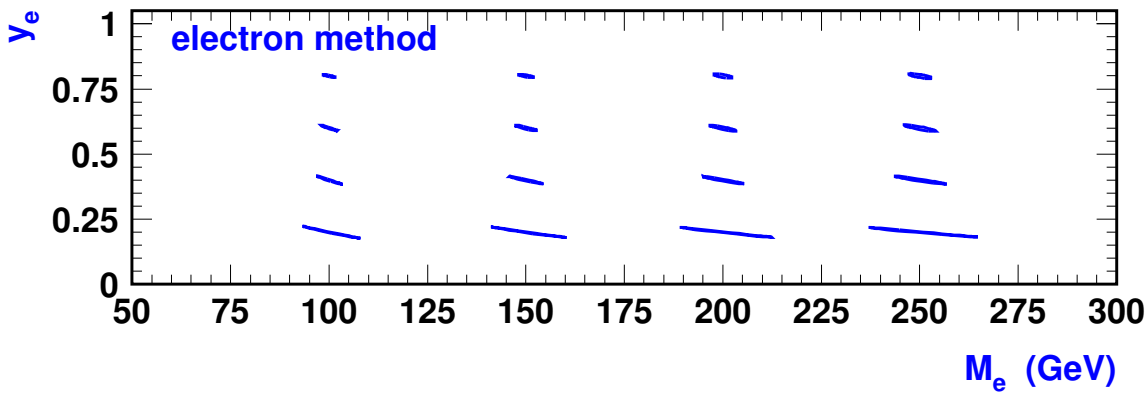


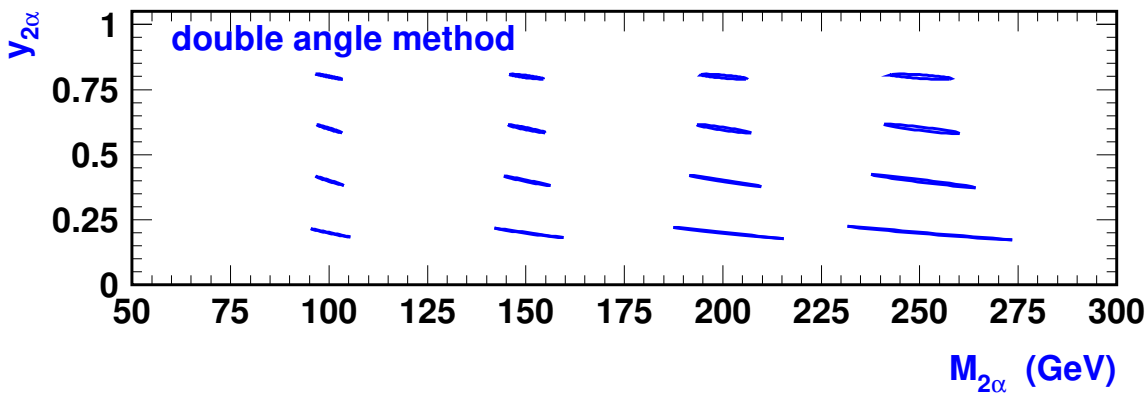
Systematic Uncertainty on Calorimeter Energy Scale:

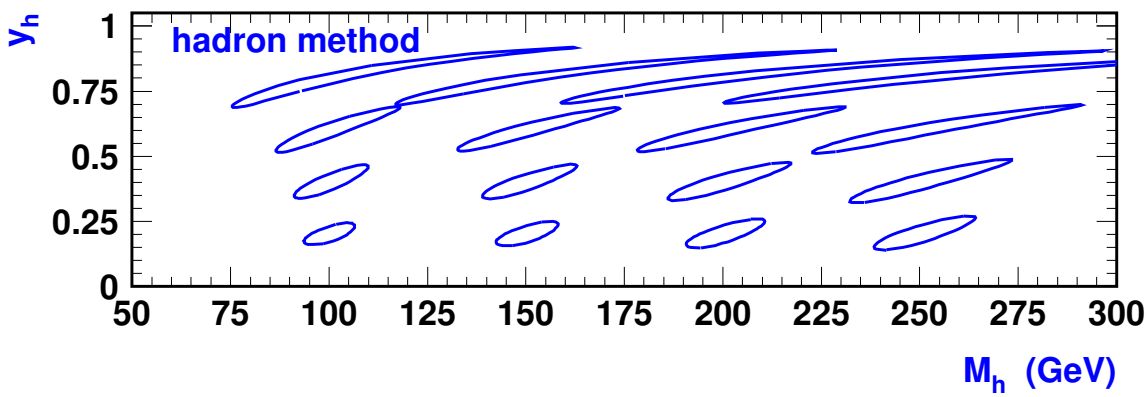
electrons: $\pm 3\%$

hadrons: $\pm 4\%$

Measurement errors for Mass and y





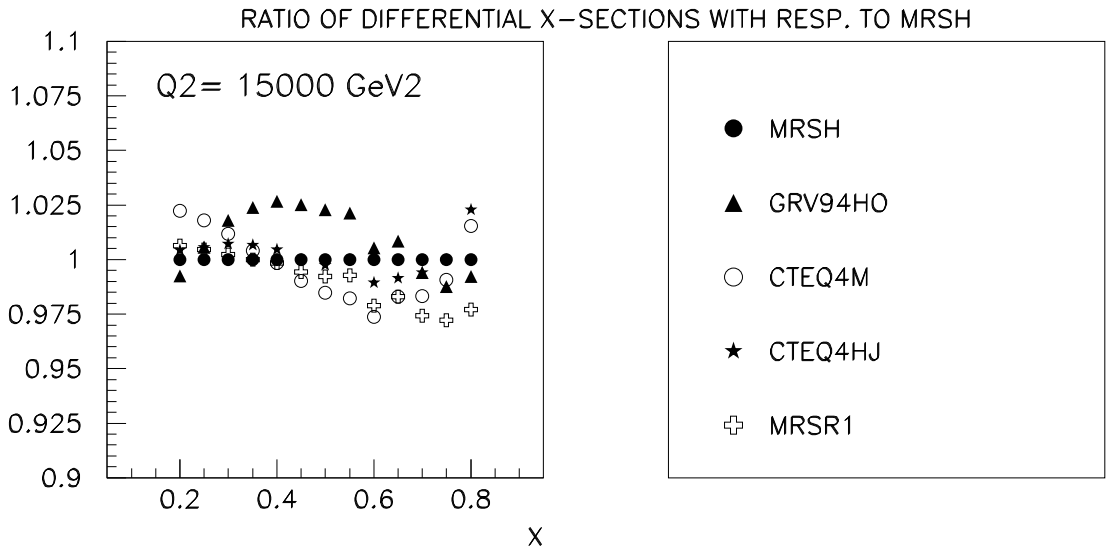


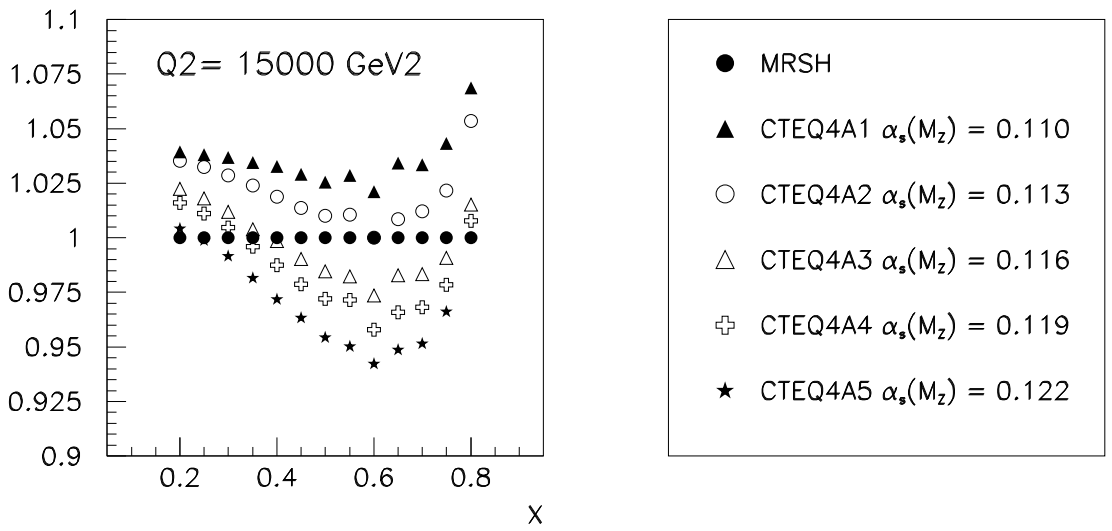
The Standard DIS Model

Expectation from NC and CC DIS $\rightarrow$

- **Parton Model (single γ/Z and W exchange)**
  - **Description of the proton in terms of scale dependent structure functions (SF);**
  - **F_L set to $\simeq 0$;**
  - **parton density parametrizations extracted from global fits of**
    Martin-Stirling-Roberts MRS (H)
    SF Measurements at fixed target
    BCDMS, NMC, CCFR, EMC, ...
    $+$ inclusive lepton + direct photon
    WA70, E605, CDF, UA68, ...
    $+$ low Q^2 SF Measurements at HERA
    H1, ZEUS;
- **Standard Strong-Electroweak Model**
  Gauge Groups $SU(3)_c \times SU(2)_L \times U(1)_Y$
  - **Parton densities evolved to high Q^2 using next-to-leading order DGLAP equations**
    - **Divergencies regulated in DIS renormalization scheme;**
    - **Higher twist contributions neglected.**

Comparison of Parton Density Parameterizations



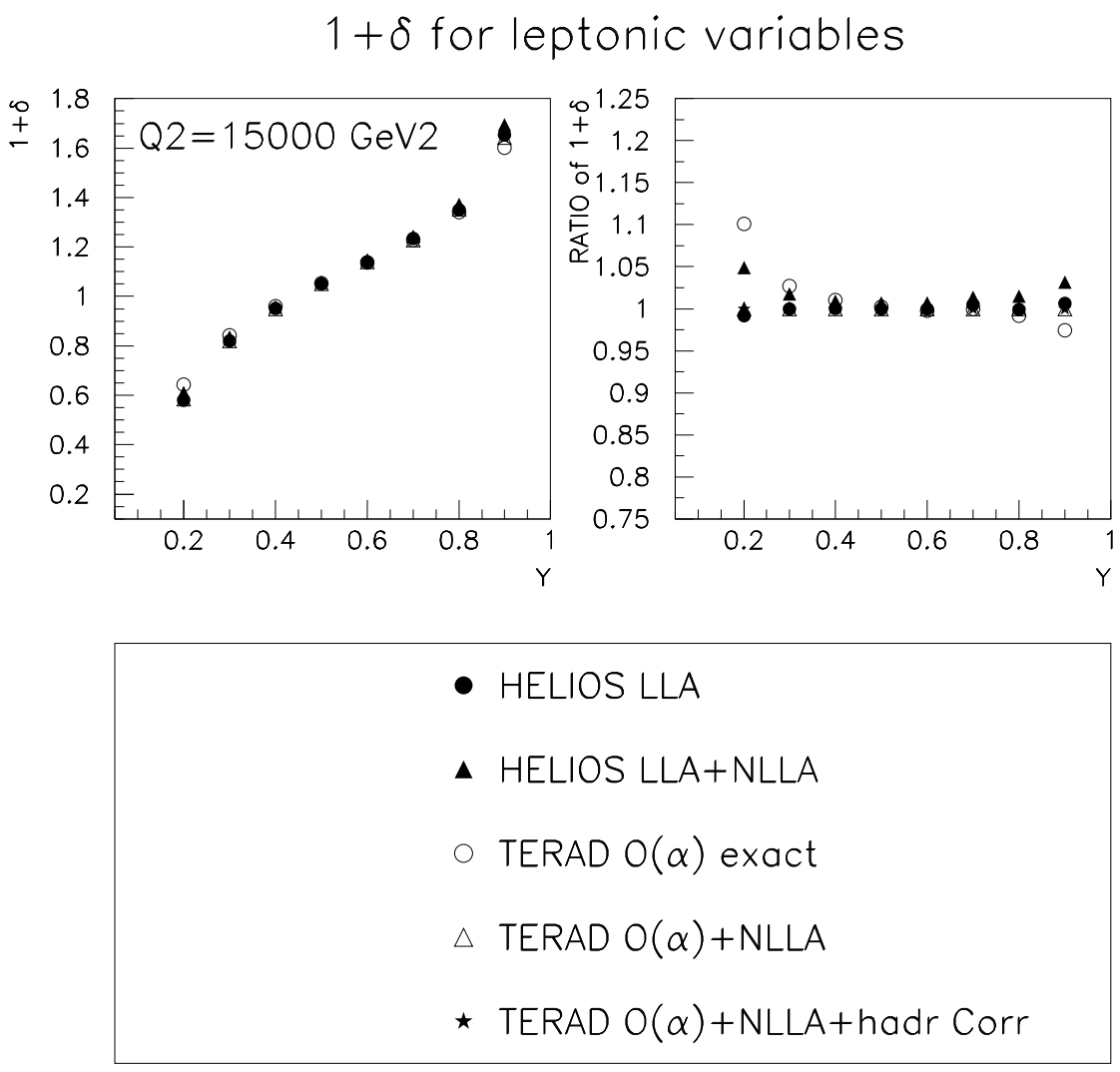


$\overline{MS}$ **scheme**

parton densities: $\pm 5\%$

$0.11 \leq \alpha_s \leq 0.122$**:** $\pm 4\%$

Higher Order QED Corrections



systematic error: $\pm 2\%$

Neutral Current Event Selection

e^+p data from 94' + 95' + 96': $14.19 \pm 0.32\, pb^{-1}$

Background Rejection

- vertex within nominal interaction region
- timing in Jet chamber (± 1.6 ns / event)
- filters against cosmic and halo muons

Selection based on e^+

- electron identification:
  - shower shape test in calorimeter
  - isolation in $\eta - \phi$ cone ($R < 0.25$)
  - track matching the calorimeter cluster
- $E_{T,e} > 25$ GeV $\Theta_e > 10^o$
- $Q_e^2 > 2500$ GeV^2 $0.1 < y_e < 0.9$
- momentum balance
  - transverse: $P_{T,miss}/\sqrt{E_T} < 3\sqrt{GeV}$
  - longitudinal: $43 < \sum E - P_z < 63$ GeV

    $2E_e^o = 55$ GeV expected

    cuts events with initial state radiation

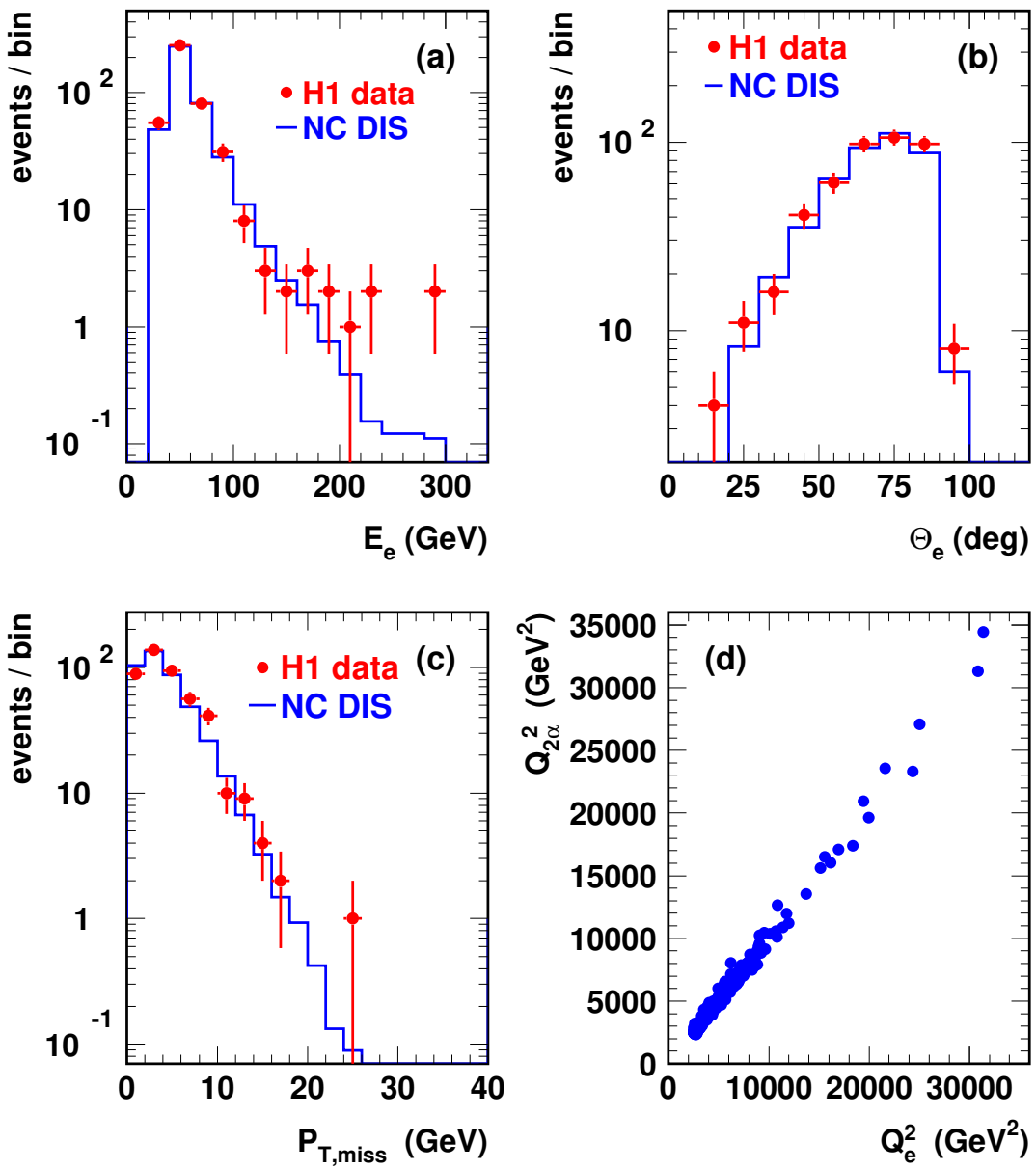
Background Processes

Partonic Process (example)	Generator Model	Simulated Luminosity (pb^{-1})	Upper Limits (95% CL) on Events per 14.19 pb^{-1}
Single W and Z Boson Production			
$e + q \longrightarrow W + e + X$	H1EPVEC		
$\hookrightarrow e + \nu$		8600	0.005
$\hookrightarrow$ jet + jet		1400	0.16
$e + q \longrightarrow Z + e + X$	H1EPVEC		
$\hookrightarrow e^+ + e^-$		42000	0.003
$\hookrightarrow \tau^+ + \tau^-$		59000	0.001
$\hookrightarrow$ jet + jet		3600	0.18
Photoproduction of high P_T jets (direct and resolved)			
$\gamma + q(g) \rightarrow q + g(\bar{q})$	PYTHIA		
(hard jet)		500	0.38
(hard fragmentation)		500	0.31
Heavy Flavour Production (direct and resolved)			
$\gamma + g \longrightarrow c + \bar{c}$	PYTHIA	600	0.07
$\gamma + g \longrightarrow b + \bar{b}$		600	0.07
Prompt Photon Production (direct and resolved)			
$\gamma + q \rightarrow q + \gamma$	PYTHIA	500	0.09
Two-photon processes			
$\gamma + \gamma \longrightarrow e^+ + e^-$	LPAIR	4500	0.04
$\gamma + \gamma \longrightarrow q + \bar{q}$		17000	0.002

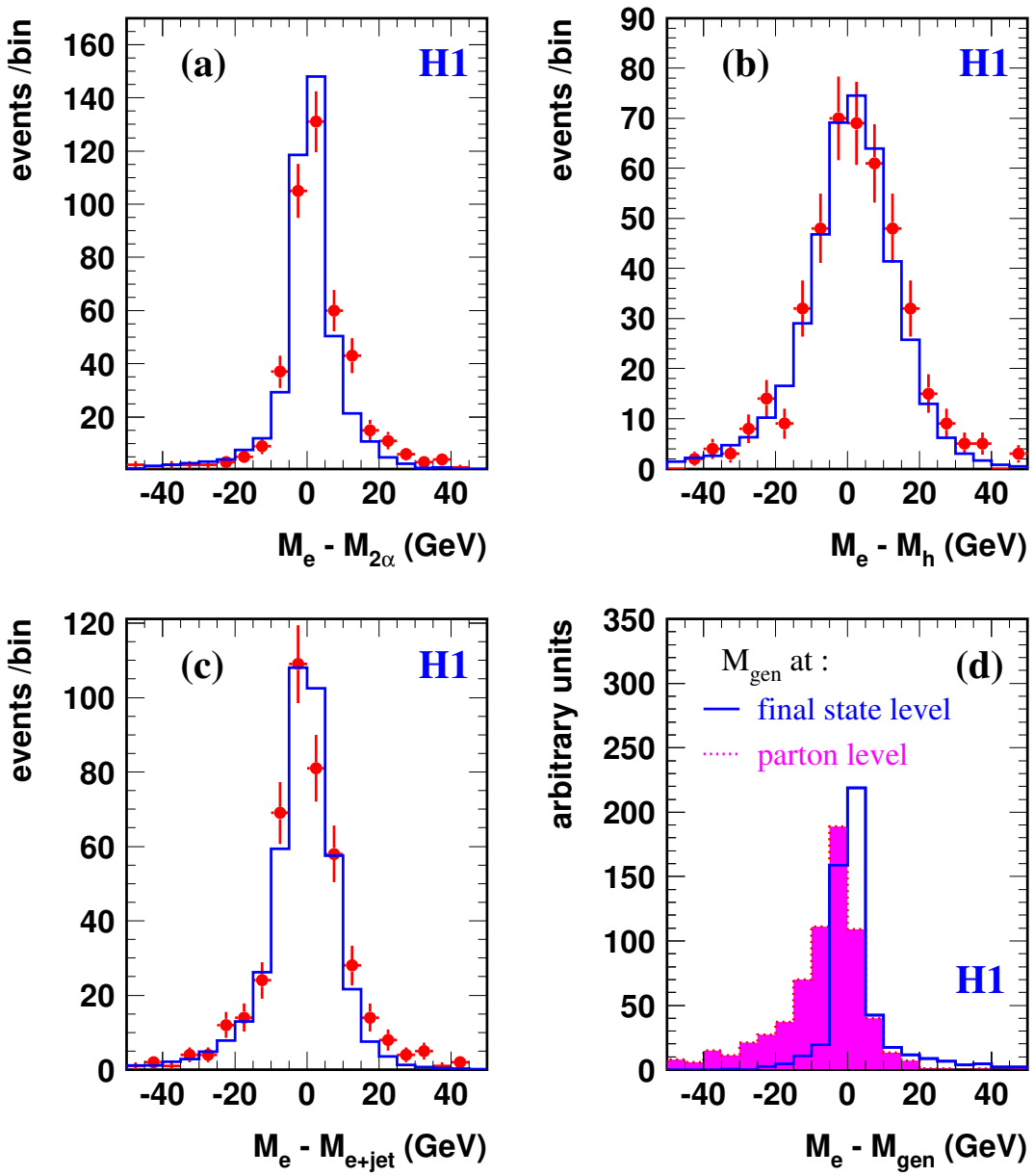
full data sample: **Contamination $< 0.1\%$**

$Q^2 > 10000$ GeV^2: **Contamination < 0.1 event**

Neutral Current Data

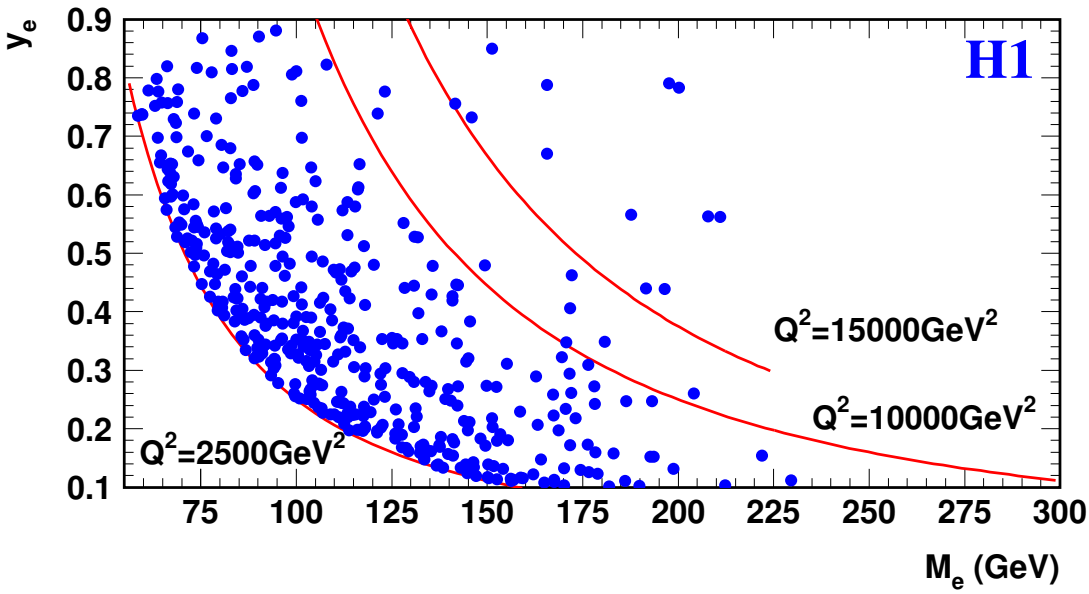


Mass Reconstruction



Events are kinematically well constrained.

Neutral Current Events

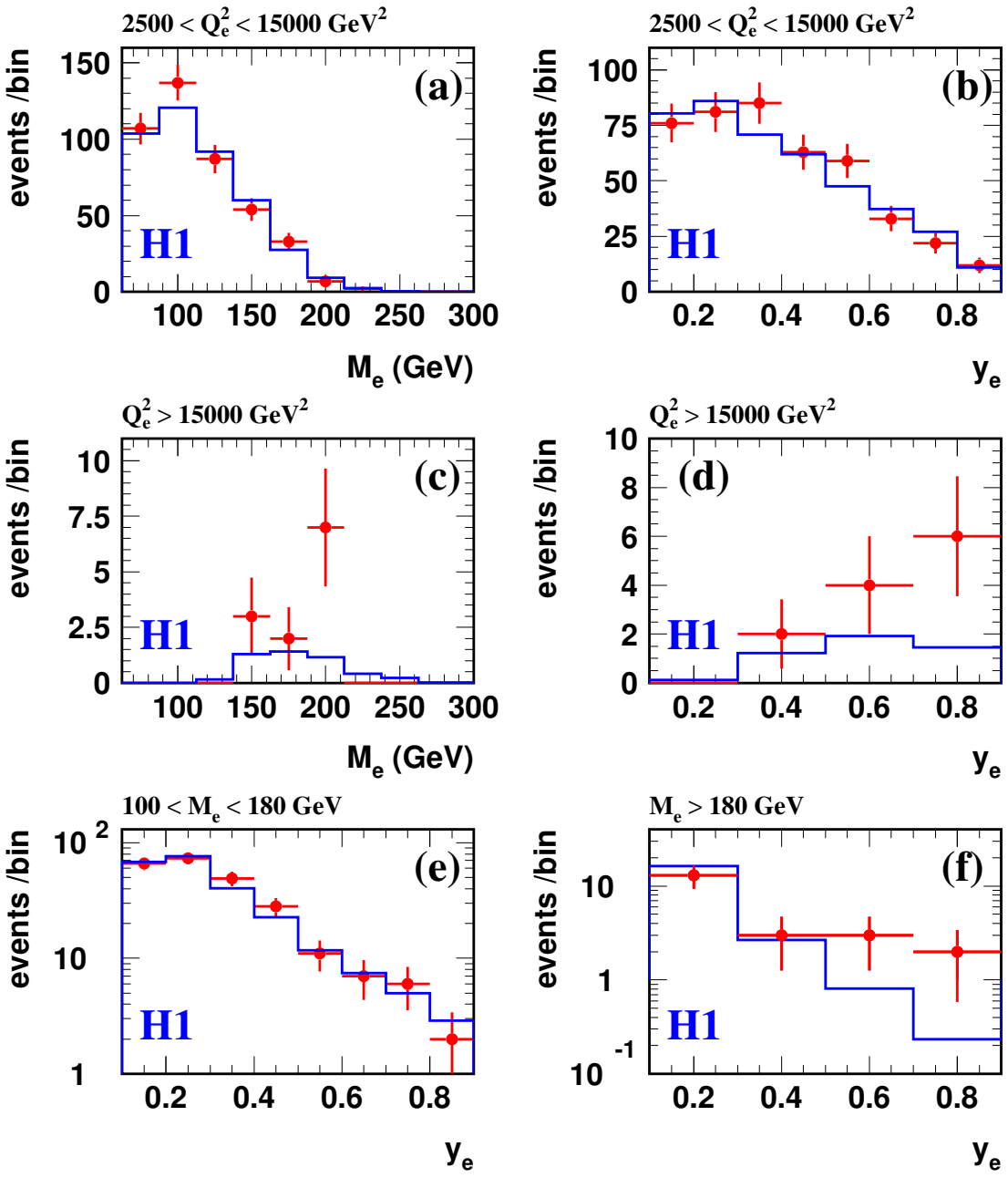


electron - method

$Q^2 > 2500$ GeV^2 $\qquad 0.1 < y_e < 0.9$

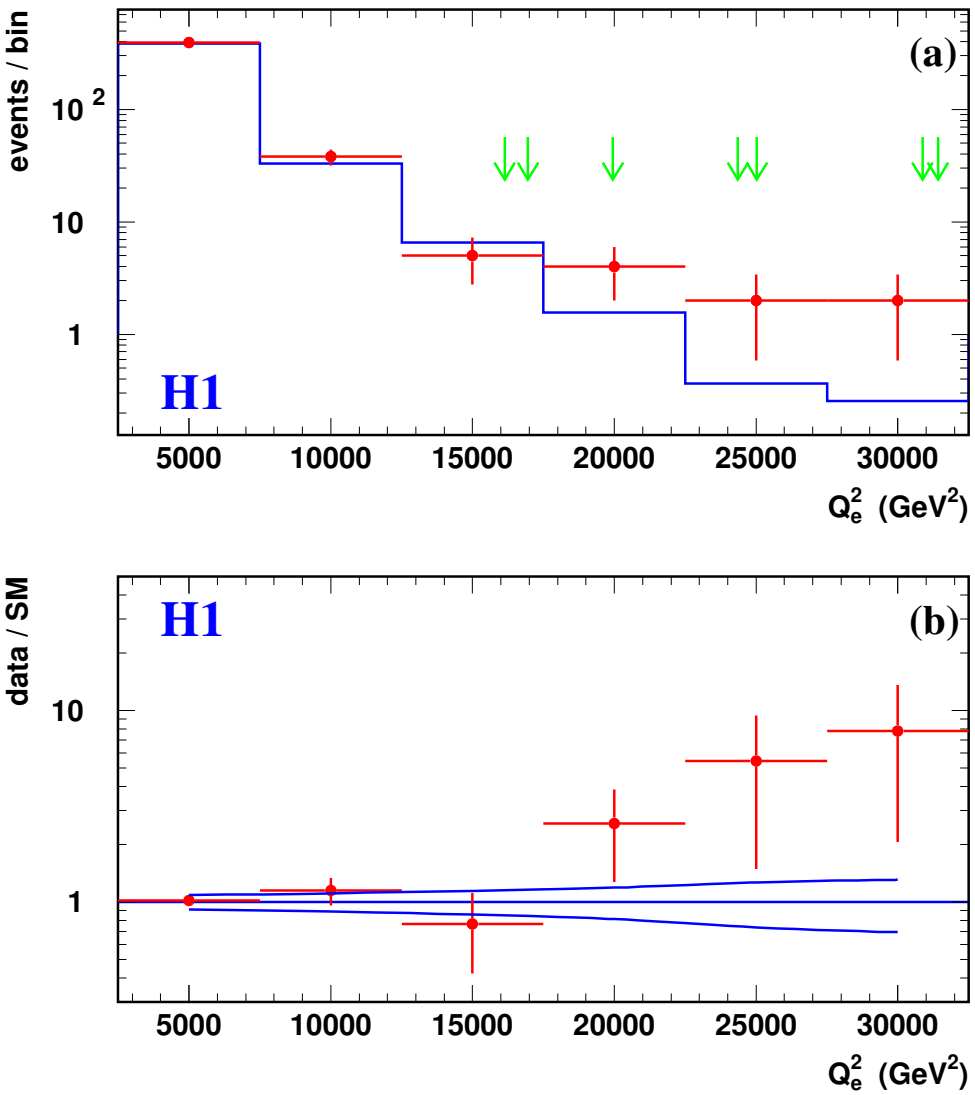
- **observed events:** 443
- **expected events:** 427 ± 38

overall efficiency: $N_{exp}/N_{gen} \sim 80\%$



- data exceeds NC DIS expectation at high Q^2 (especially at $M_e \sim 200$ GeV).
- at high $M_e \Rightarrow$ difference apparent at large y_e.

Q^2 Distribution



Errors dominated by uncertainty on e.m. energy scale

$\sim 8.5\%$ **at low** Q_e^2 $\sim 30\%$ **at highest** Q_e^2

Neutral Current Events with $Q^2 > Q^2_{min}$

Q^2_{min} (GeV^2)	2500	10000	15000	20000	30000
N_{obs}	443	20	12	5	2
N_{DIS}	426.7 $\pm$ 38.4	18.3 $\pm$ 2.4	4.71 $\pm$ 0.76	1.32 $\pm$ 0.27	0.23 $\pm$ 0.05
$\mathcal{P}(N \geq N_{obs})$	0.35	0.39	6×10^{-3}	1.4×10^{-2}	2.3×10^{-2}

Poisson probability that

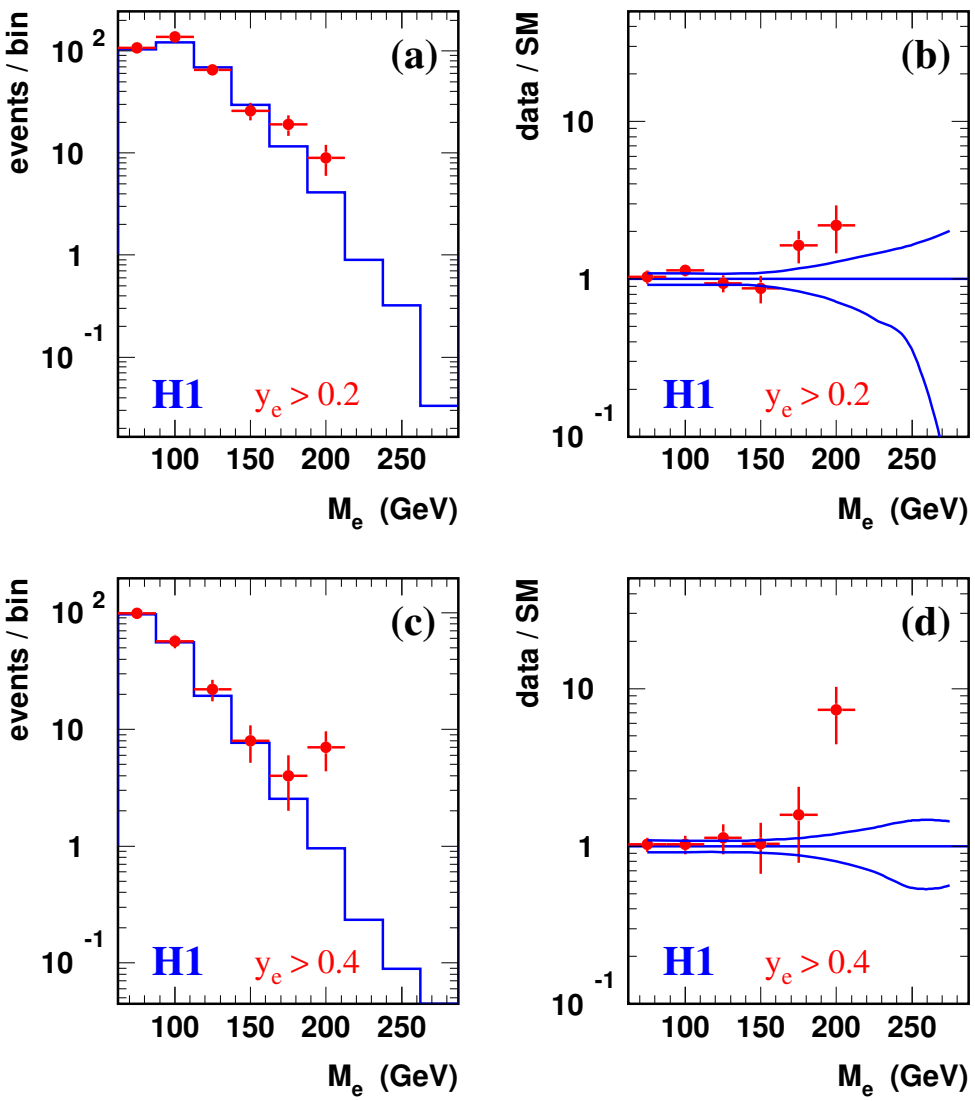
number of expected events $\geq$ number of observed events:

$$\mathcal{P}(N \geq N_{obs}) = \int_0^{+\infty} dx G(x; b, \delta b) \sum_{k=N_{obs}}^{\infty} p(k; x)$$

where:

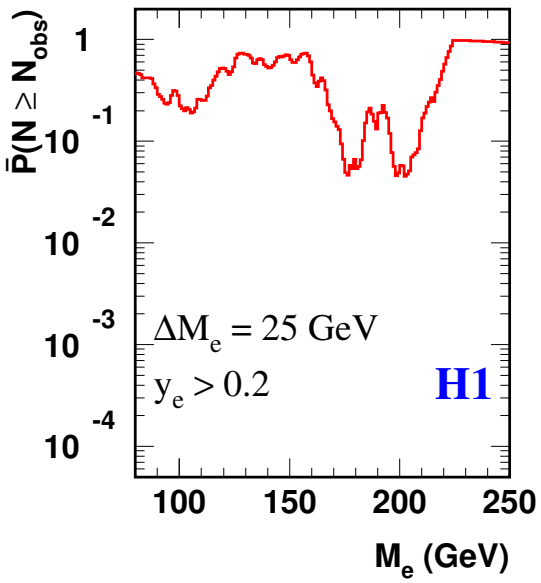
- $p(k; x)$ = Poisson probability to observe k events for x expected events.
- $G(x; b, \delta b)$: Gaussian smearing of mean expected number of events with systematic error on expectation.

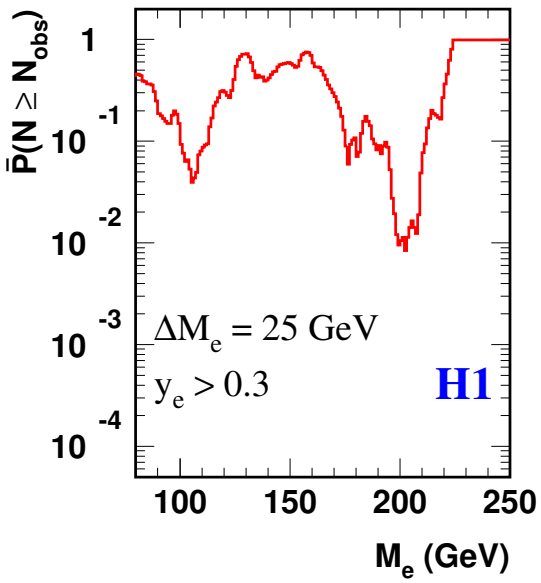
Mass Distributions

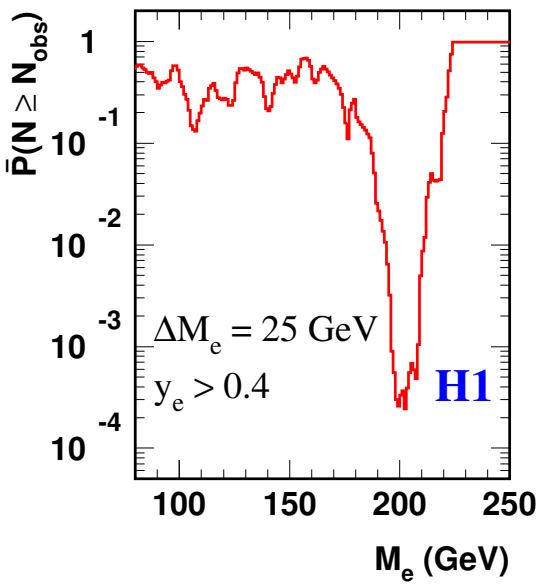


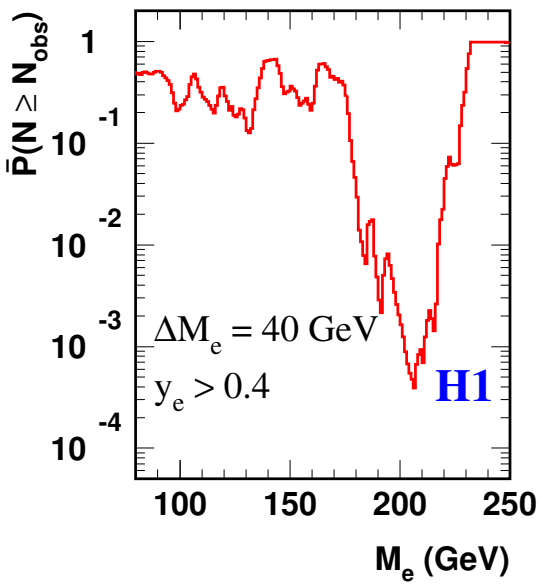
- Excess seen at highest mass
- More visible at large y_e

Probability within Sliding Mass Window







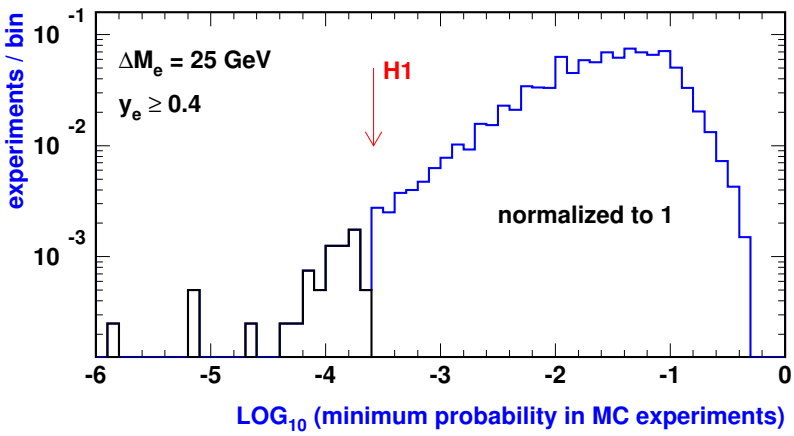


Dependence on Width of Mass Window

ΔM_e	20	25	30	40
N_{obs}	5	7	7	7
N_{DIS}	0.63 $\pm$ 0.13	0.95 $\pm$ 0.18	1.10 $\pm$ 0.19	1.57 $\pm$ 0.28
$\bar{\mathcal{P}}$ (10^{-4})	5.0	2.6	2.5	16

Probability to find a fluctuation as large as observed anywhere in the mass range considered

Lowest Probability in Monte Carlo Experiments



Probability = 0.9%

Neutral Current Events with $M > 180$ GeV, $y > 0.4$

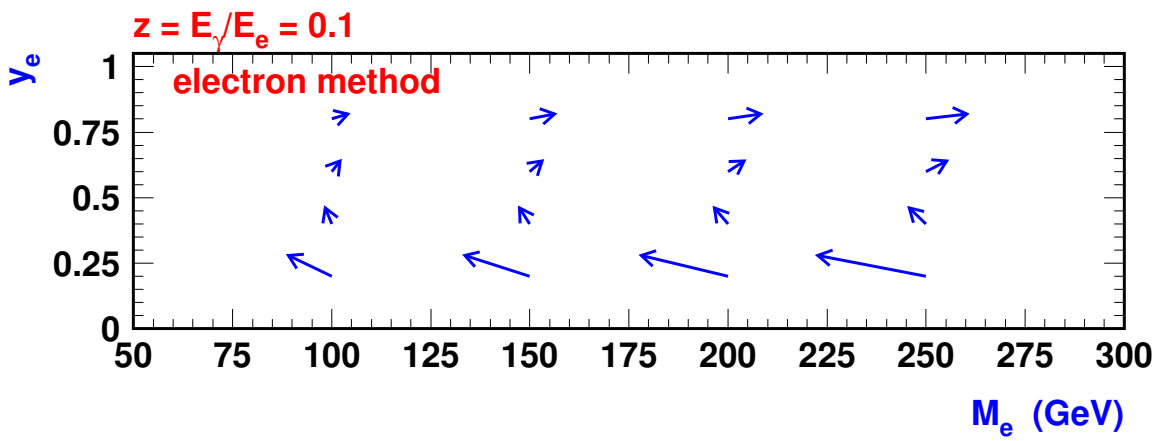
	Run # Event #	M_e (GeV)	$M_{2\alpha}$ (GeV)	M_{e+jet} (GeV)	y_e	$y_{2\alpha}$	Q^2_e (GeV^2)	$Q^2_{2\alpha}$ (GeV^2)
1	85528	196	198	195	.439	.434	16950	17100
	71329	$\pm$5			$\pm$.014		$\pm$360	
2	87050	208	200	213	.563	.582	24350	23320
	8062	$\pm$4			$\pm$.012		$\pm$430	
3	88999	188	185	184	.566	.573	19950	19640
	106218	$\pm$12			$\pm$.032		$\pm$1400	
4	119314	198	199	197	.790	.787	30870	31320
	18272	$\pm$2			$\pm$.008		$\pm$530	
5	122145	211	227	211	.562	.526	25030	27100
	69506	$\pm$4			$\pm$.012		$\pm$440	
6	155768	192	190	215	.440	.443	16130	16050
	67216	$\pm$6			$\pm$.016		$\pm$400	
7	158577	200	213	210	.783	.762	31420	34450
	100110	$\pm$2			$\pm$.008		$\pm$540	

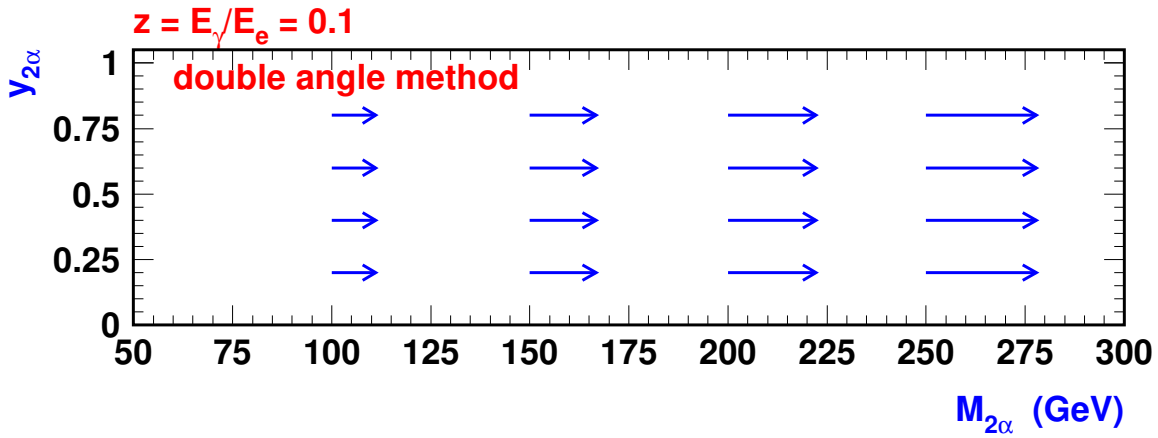
Average $M_e = 200.8 \pm 2.2$ GeV

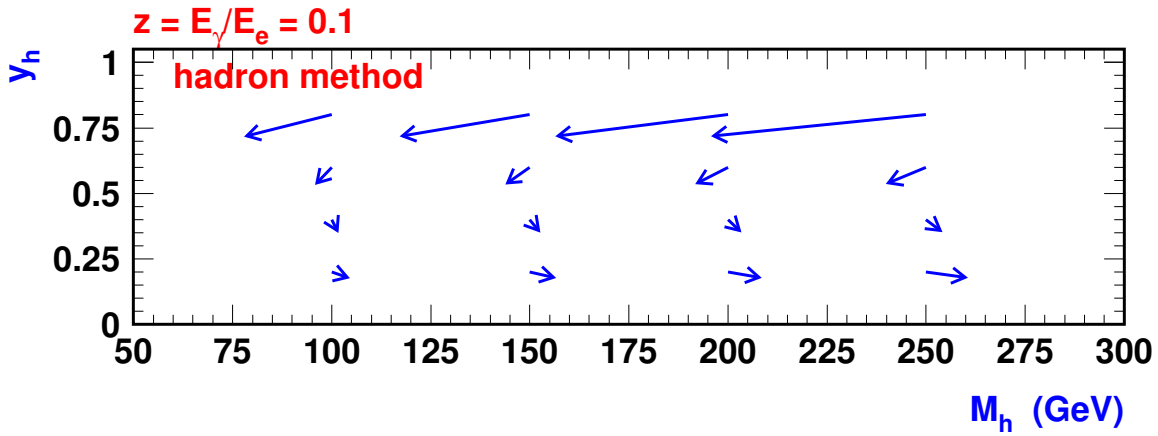
Systematic error on energy scale

$\frac{\delta E_e}{E_e} = 3\% \Rightarrow \frac{\delta M_e}{M_e} \sim \frac{0.03}{2y_e} \Rightarrow$ **shift of ± 5 GeV**

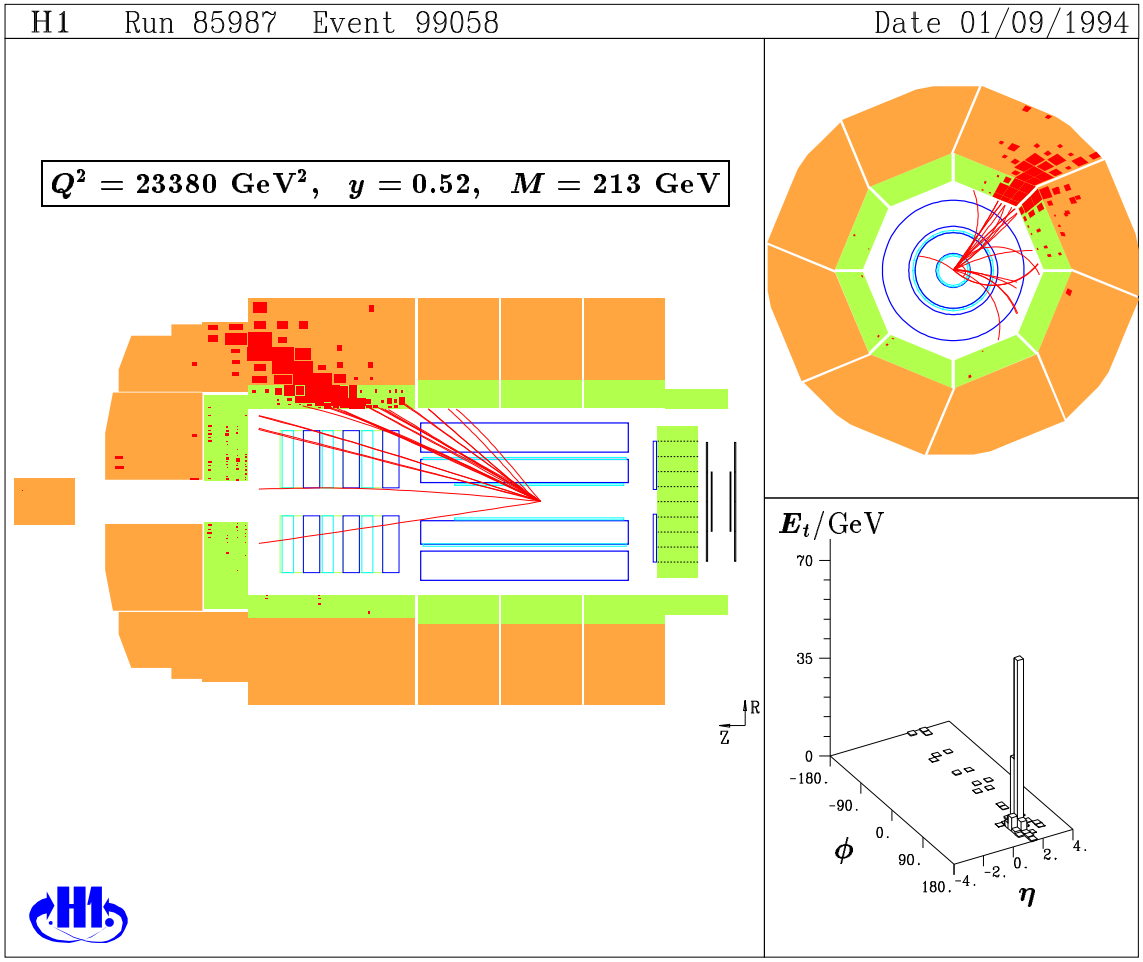
Influence of initial state radiation







CC candidate ($P_T = 106$ GeV)

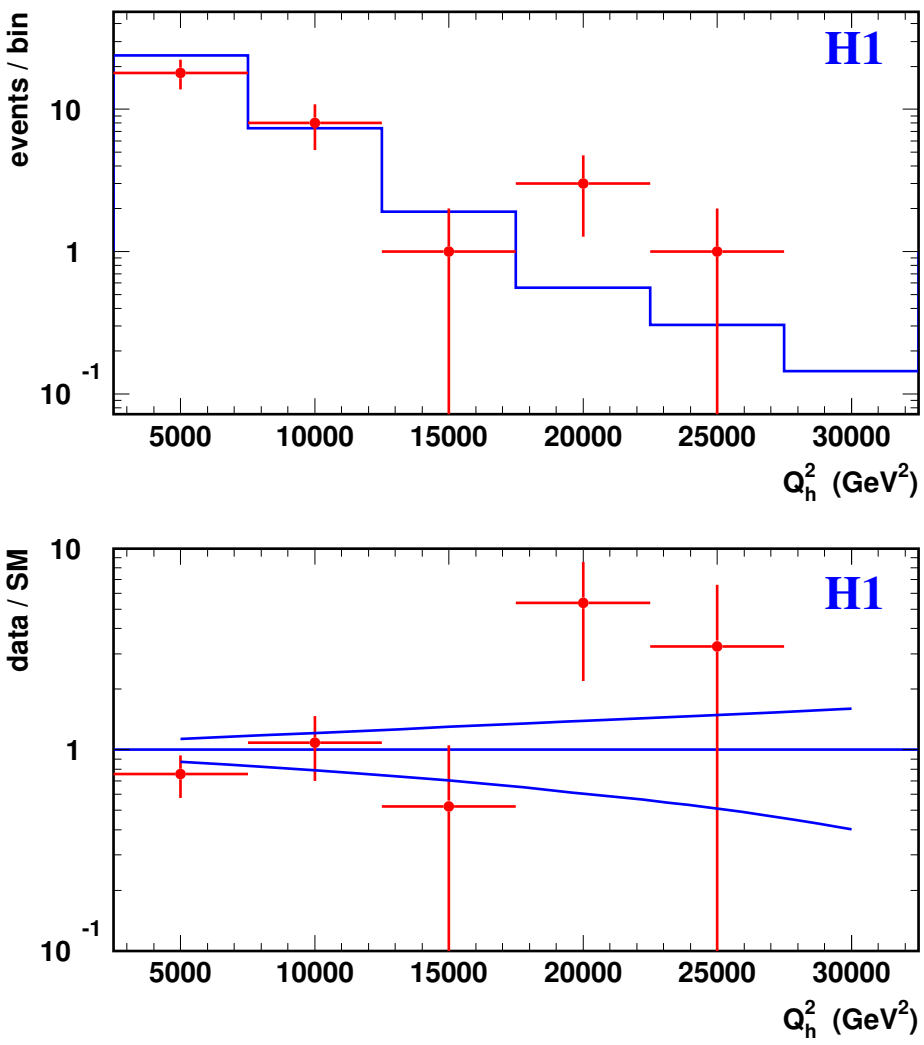


Charged Current Processes: $e^+p \to \bar{\nu}X$

Event Selection

- $P_{T,miss} > 50$ GeV
- $\frac{E_T - P_{T,h}}{E_T} < 0.5$

Q^2 distribution



Charged Current

Q^2_{min}(GeV^2)	2500	5000	10000	15000	20000
N_{obs}	31	24	10	4	3
N_{DIS}	34.2 ± 5.8	21.1 ± 4.2	5.07 ± 1.88	1.77 ± 0.87	0.74 ± 0.39
$\mathcal{P}(N \geq N_{obs})$	0.64	0.31	7×10^{-2}	0.14	5.4×10^{-2}

CC Event list at $Q^2 > 15000$ GeV^2

	Run # / Event #	M_h	y_h	Q^2_h
1	85987/ 99058	213	.52	23380
2	153720/199055	187	.58	20170
3	163852/20613	157	.75	18650
4	169851/206239	192	.56	20800

$$\delta M_h / M_h \sim 10\%$$
$$\delta y_h / y_h \sim 10\%$$
$$\delta Q^2_h / Q^2_h \sim 28\%$$

Possible Explanations within Standard DIS

Parton Distributions $0.1 \leq x \leq 0.6$

- several exp.: $Q^2 \lesssim 200$ GeV^2: expectation
  this data: $Q^2 \lesssim 15000$ GeV^2: confirms expectation
  $Q^2 \gtrsim 15000$ GeV^2: excess seen
- Tevatron jet data:
  - CTEQ (4HJ): large gluon density: $\delta\sigma_{DIS} < 5\%$.
  - MRS (R2): large α_s value (0.12): $\delta\sigma_{DIS} < 4\%$.
  - MRS (J'): contradicts low Q^2 data: $\delta\sigma_{DIS} \sim +20\%$.
- $F_L > 0$: reduces σ_{DIS}

→ Within standard predictions of DIS, no mechanism to enhance σ_{DIS} considerably at high Q^2.
The only explanation is a statistical fluctuation.

Beyond the Standard Model

leptoquarks, leptogluons, squarks in case of R_P violation.

- s-channel resonance: fixed e^+-parton mass M.
- virtual exchange: enhanced cross section at high Q^2.

→ signature of events identical to DIS, therefore more luminosity needed to study kinematic distributions.

Summary

$Q^2 \leq 15000$ GeV^2:

data confirms expectation for Neutral and Charged Current in Q^2, M and y distributions, also for large M.

$Q^2 > 15000$ GeV^2:

12 NC events observed where 4.71 ± 0.76 are expected

$$\mathcal{P}(N \geq N_{obs}) = 6 \times 10^{-3}$$

- Excess most prominent for $M \sim 200$ GeV and large y
  (7 events observed where 0.95 ± 0.18 are expected)
  Probability for comparable or larger excess anywhere in the M and y region considered $= \mathcal{O}(1\%)$
- The excess cannot be accounted for by:
  - detector effects
  - parton densities compatible with existing data
  - variation of α_s, higher order corrections

Explanation:

either a statistical fluctuation or new physics

$\longrightarrow$ more statistics needed

New data taking starts early March

$\longrightarrow$ aim to duplicate statistics in 1997

Combined results from H1 and ZEUS

	H1		ZEUS		H1 + ZEUS		
	e method $y < 0.9$ $\Theta_e > 10^\circ$		2α method $E_e > 20$ GeV ($P_{T,e} > 30$ GeV for $\Theta_e < 17^\circ$)				
Q^2 cut	data	NC exp.	data	NC exp.	data	NC exp.	P($N \geq N_{obs}$)
$Q^2 > 10000$ GeV^2	20	18.3 $\pm$ 2.4	33	32.2 $\pm$ 2.0	53	50.5 $\pm$ 3.1	0.37
$Q^2 > 15000$ GeV^2	12	4.71 $\pm$ 0.76	12	8.66 $\pm$ 0.66	24	13.4 $\pm$ 1.0	0.0074
$Q^2 > 20000$ GeV^2	5	1.32 $\pm$ 0.27	5	2.76 $\pm$0.24	10	4.08 $\pm$ 0.36	0.010
$Q^2 > 25000$ GeV^2	3	0.51 $\pm$ 0.16	3	1.01 $\pm$0.09	6	1.52 $\pm$ 0.18	0.0053
$Q^2 > 30000$ GeV^2	2	0.23 $\pm$ 0.05	2	0.37 $\pm$0.04	4	0.60 $\pm$ 0.06	0.0035
$Q^2 > 35000$ GeV^2	0	0.08 $\pm$ 0.04	2	0.15 $\pm$0.01	2	0.23 $\pm$ 0.04	0.023

Table 1: Number of observed and expected events from H1 and ZEUS. For the combination, the number of observed and expected events are added and the errors are added in quadrature. The difference for the DIS expectation between H1 and ZEUS reflects the difference in integrated luminosities, the kinematic reconstruction methods, the resolution on Q^2 and the detection efficiency within the kinematic cuts. The last column gives the probability that the expected NC DIS signal fluctuates to values equal to or larger than the number of observed events, where the error on the mean expected number of events is taken into account by gaussian smearing.