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

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On behalf of

H1 Collaboration

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DESY

PLAN :

- Introduction:
  - High Q^2 at HERA
  - The H1 Detector
  - Basic Kinematics
- Event Selection
- The Standard DIS Model
- Results :
  - Q^2 Dependence
  - M and y Dependence
  - Events at Very High M and y
- Non-Standard Contributions at High Q^2
- Summary

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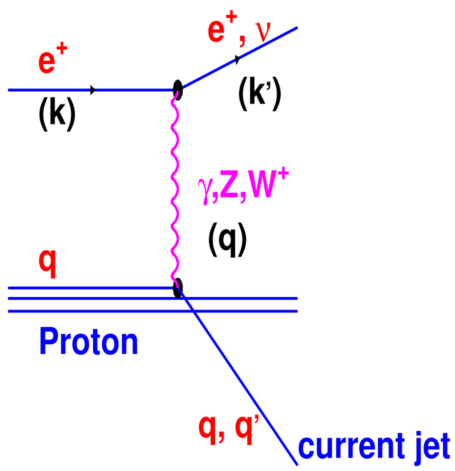
Introduction

HERA = unique colliding facility for :

• probing the proton at very small distances
($\simeq 10^{-16}$cm)
e.g. t-channel exchange of a highly virtual gauge boson



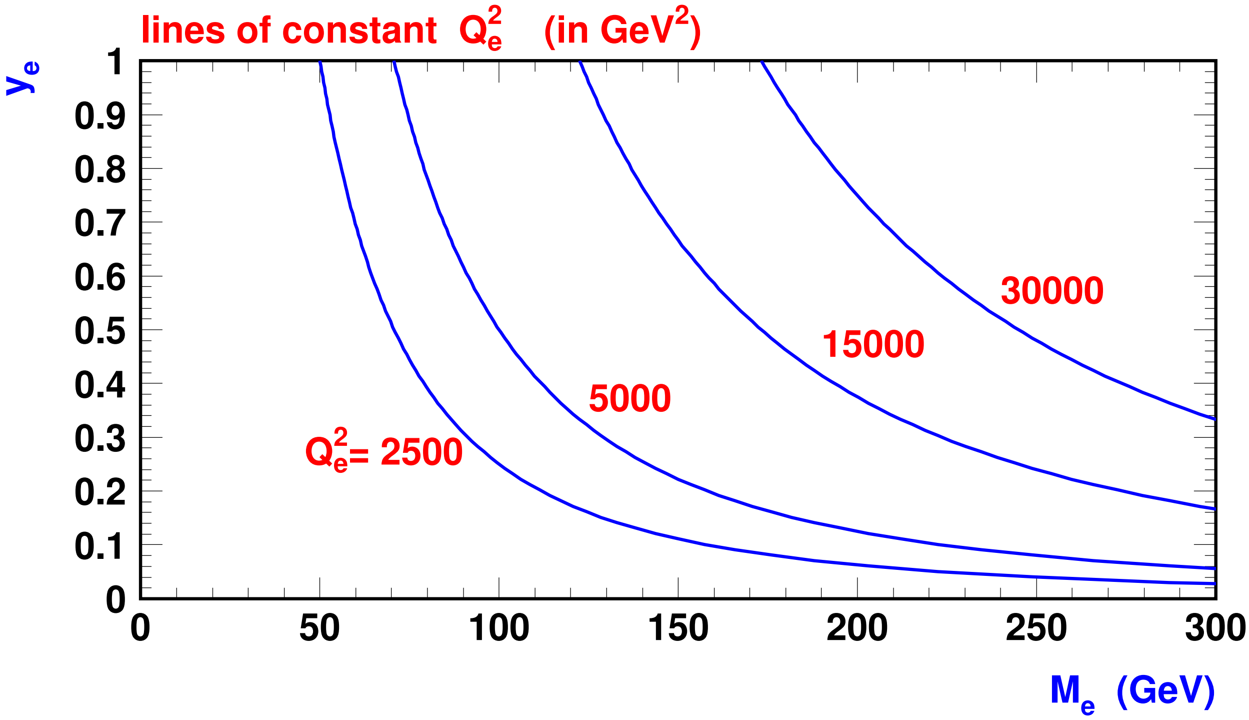
$$Q^2 = -q^2$$
$$x = \frac{Q^2}{2(P.q)}$$
$$M = \sqrt{sx} = \sqrt{Q^2/y}$$
$$y = \frac{(P.q)}{(P.k)} \qquad y = \frac{1+\cos\theta_e^*}{2}$$
(wrt proton beam)

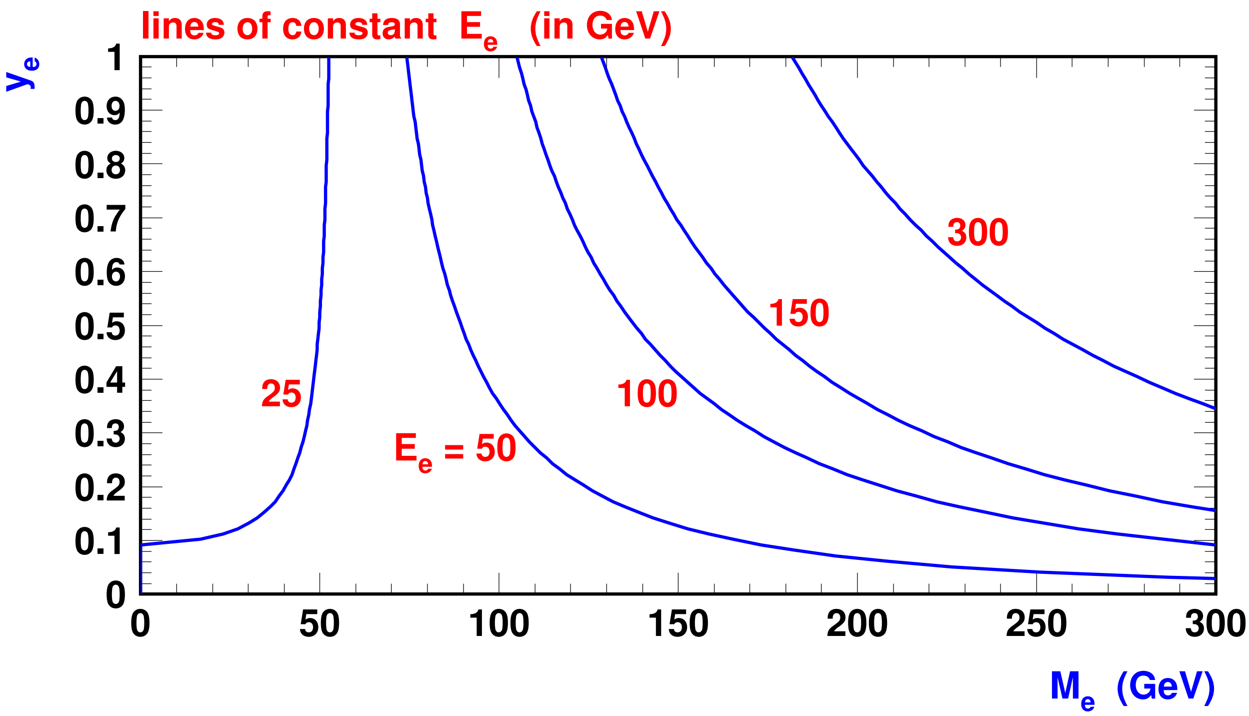
• search for s-channel resonant production of new particles possessing couplings to lepton-quark pairs
e.g. leptoquarks, squarks, ... up to
$M = \sqrt{sx} \leq 300$ GeV

$\rightarrow$ Study very hard processes at high momentum transfer squared Q^2 !

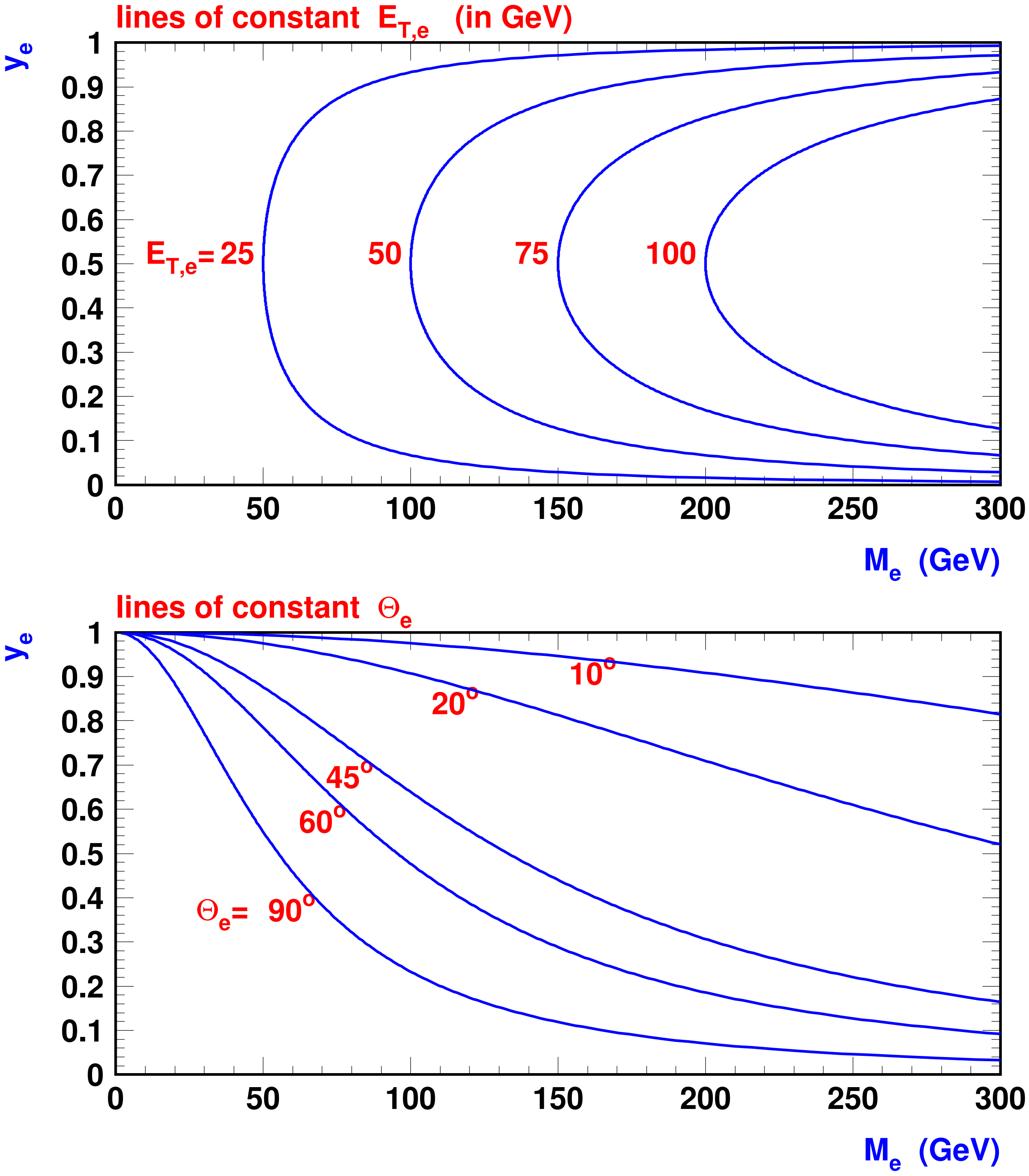
H1 published 1994 data : 2.83pb^{-1}
NEW Final results 1994-1996 : 14.19pb^{-1} $\rightarrow \mathcal{L} \times 5$

Kinematic of Deep Inelastic Scattering

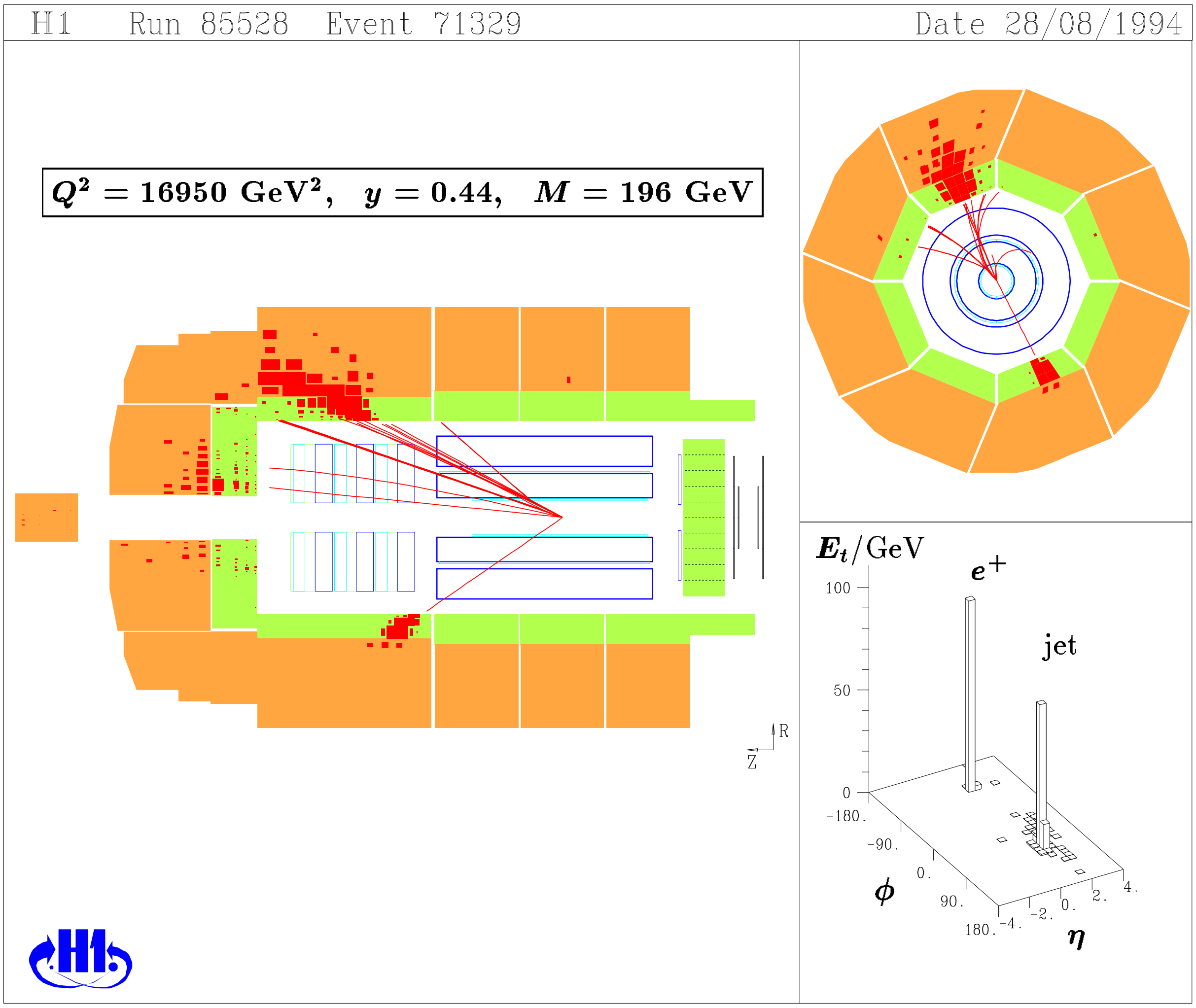




Kinematic of Deep Inelastic Scattering



NC DIS Candidate



LAr Calorimetry

- Very fine granularity $\quad \Delta\theta_e \sim 2$mrad for $10^\circ < \theta_e < 30^\circ$

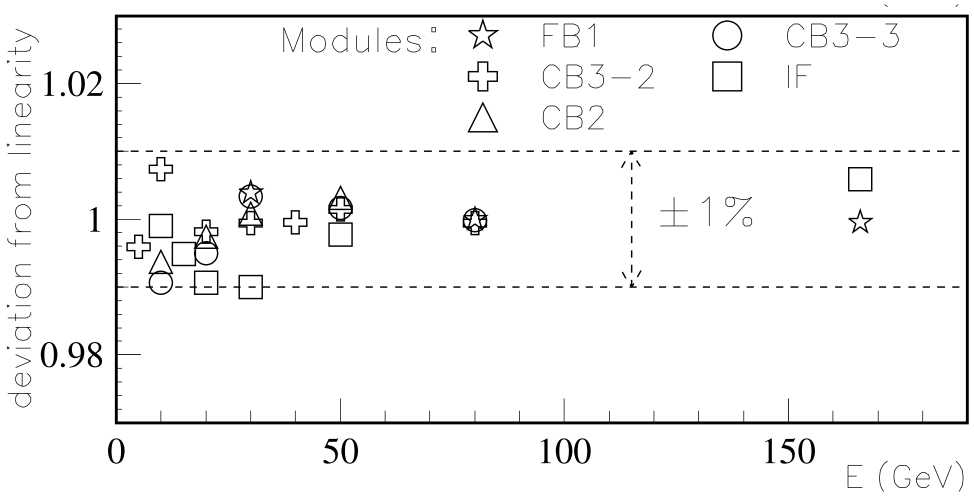
  ($\approx$ 44000 cells) $\quad \Delta\theta_e \lesssim 5$mrad for $30^\circ < \theta_e < 145^\circ$
- Optimal for e-identification $\quad \sigma(E)/E \simeq 12\%/\sqrt{E/\text{ GeV}} \oplus 1\%$
- Hadronic energy compensation $\quad \sigma(E)/E \simeq 50\%/\sqrt{E/\text{ GeV}} \oplus 2\%$

  by offline weighting

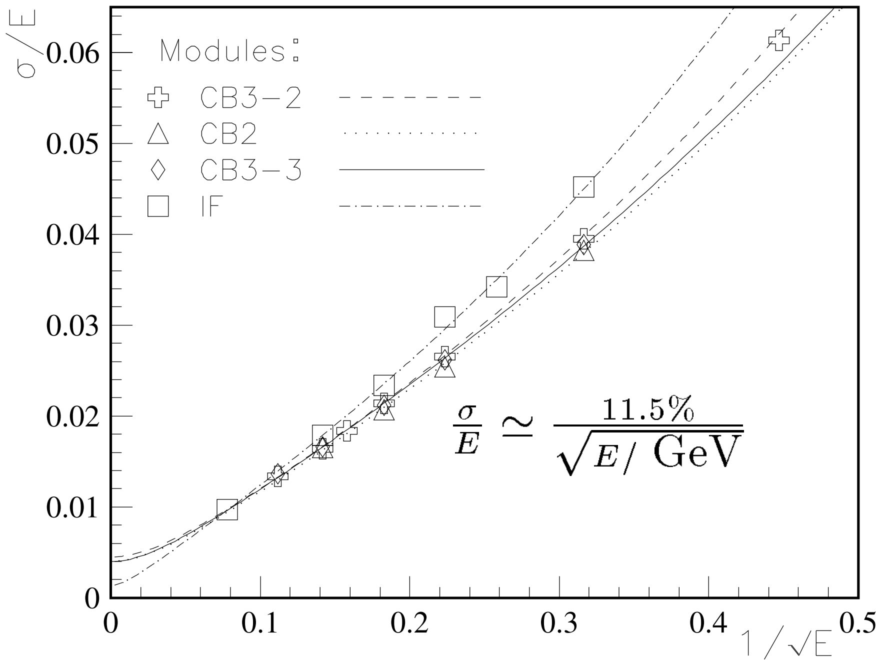
TEST BEAMS: E_e up to 166 GeV $\quad E_\pi$ up to 205 GeV

Electron test beam NIM A344 (1994)

Linearity



Resolution



Kinematic Variables
Reconstruction Methods

e-method

$$M_e = \sqrt{s x_e} = \sqrt{\frac{Q_e^2}{y_e}} \qquad \frac{\delta M_e}{M_e} \propto 1/y_e$$

$$Q_e^2 = \frac{E_{T,e}^2}{1-y_e}$$

$$y_e = 1 - \frac{E_e - E_e \cos\theta_e}{2E_e^0}$$

2α-method

$\alpha_e = \tan(\theta_e/2)$

$\alpha_h = \tan(\theta_h/2)$

$$M_{2\alpha} = \sqrt{\frac{s}{\alpha_e \alpha_h} \frac{E_e^0}{E_p}}$$

$$Q_{2\alpha}^2 = \frac{E_e^0}{E_p} \frac{s}{\alpha_e(\alpha_e + \alpha_h)}$$

$$y_{2\alpha} = \frac{\alpha_h}{\alpha_e + \alpha_h}$$

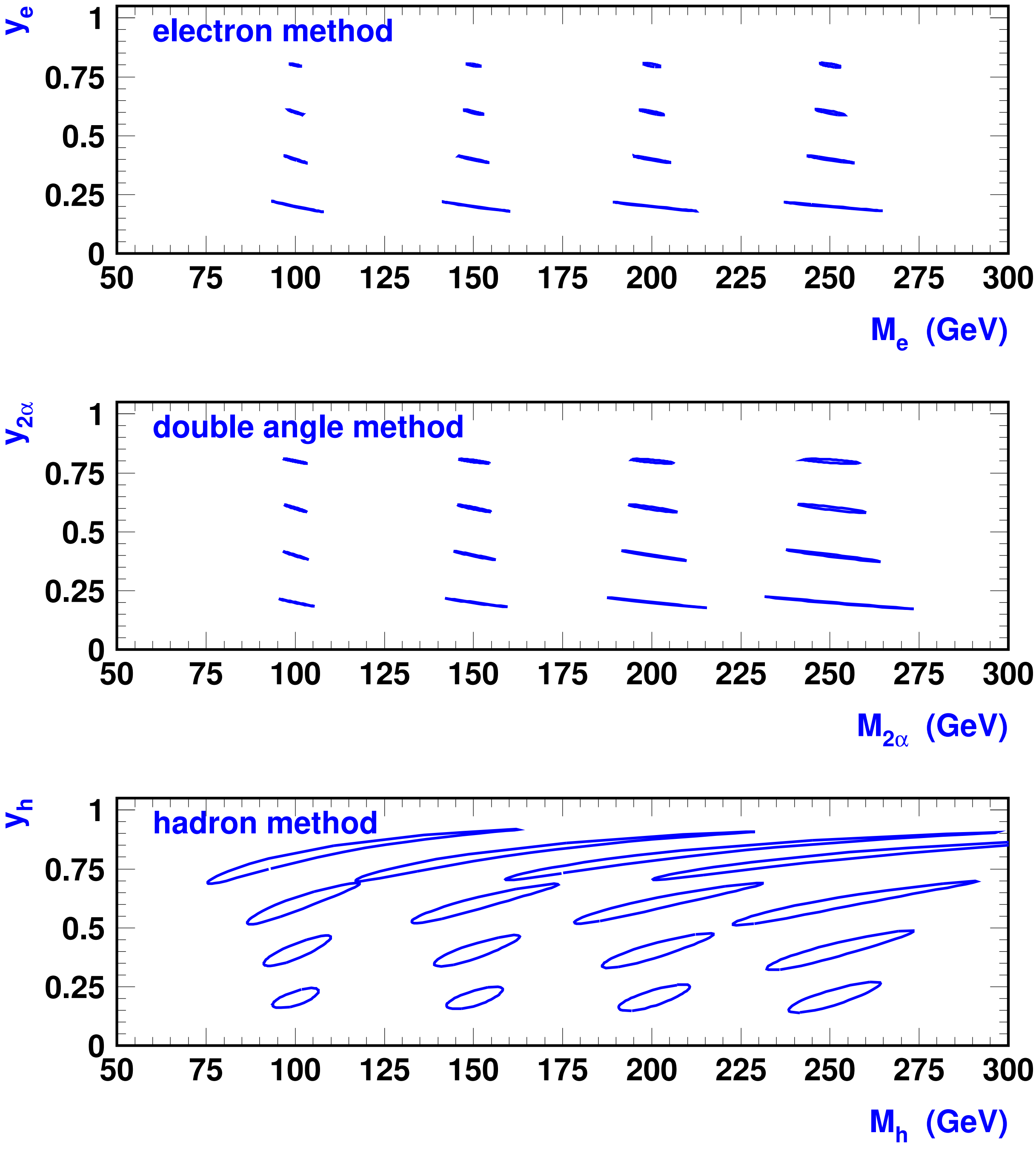
h-method

$$M_h = \sqrt{\frac{Q_h^2}{y_h}} \qquad \frac{\delta M_h}{M_h} \propto \frac{1}{1-y_h} \text{ for } y_h \sim 1$$

$$Q_h^2 = \frac{P_{T,h}^2}{1-y_h} \qquad \frac{\delta Q_h^2}{Q_h^2} \propto \frac{1}{1-y_h} \text{ for } y_h \sim 1$$

$$y_h = \frac{\sum_{had}(E - P_z)}{2E_e^0}$$

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.

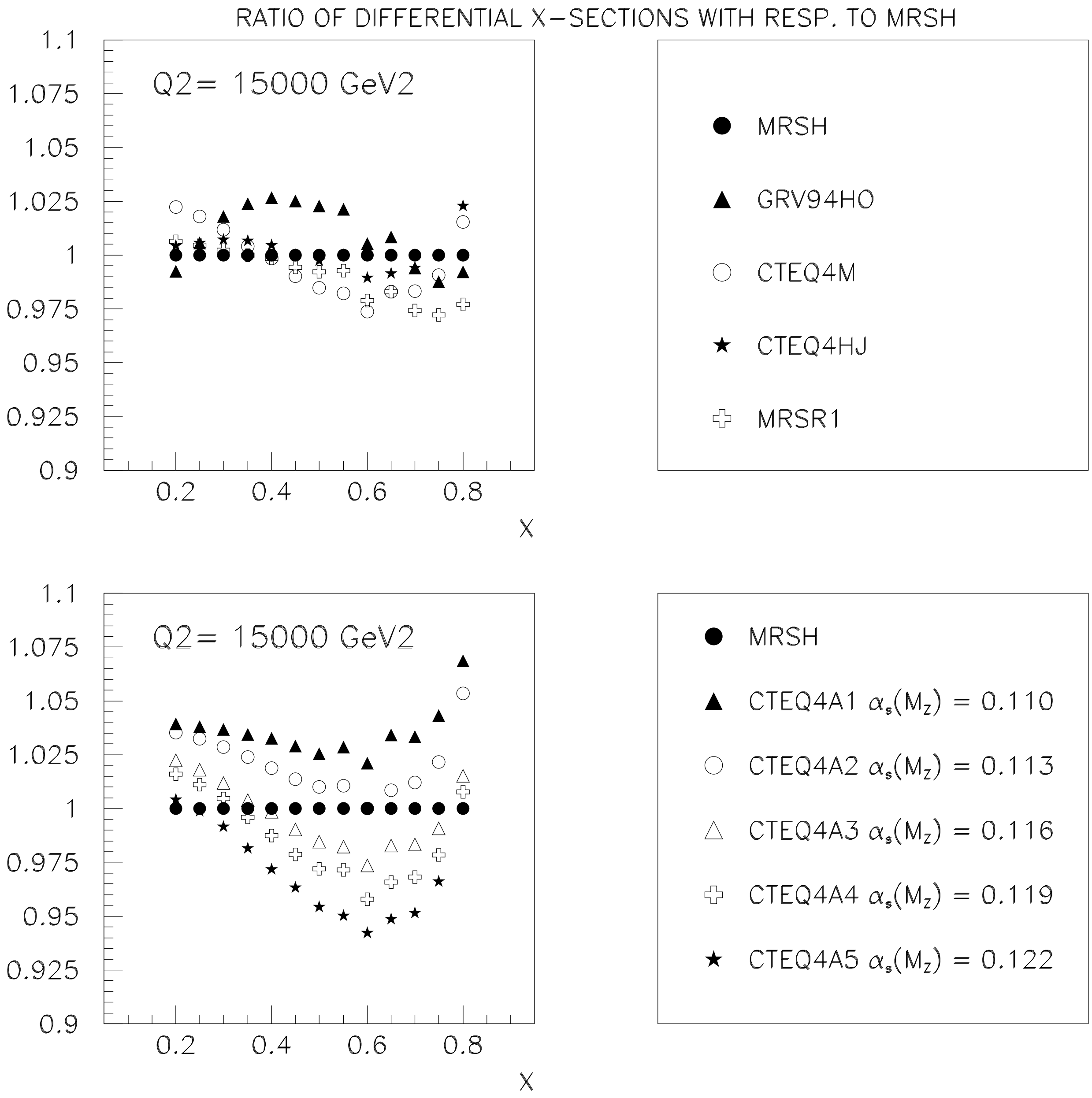
Systematic Errors

Experimental errors :

- integrated luminosity
  $\rightarrow$ $\pm 2.3\%$
- electromagnetic energy scale
  $\rightarrow$ $\pm 3\%$
- hadronic energy scale
  $\rightarrow$ $\pm 4\%$

"Theoretical" errors :

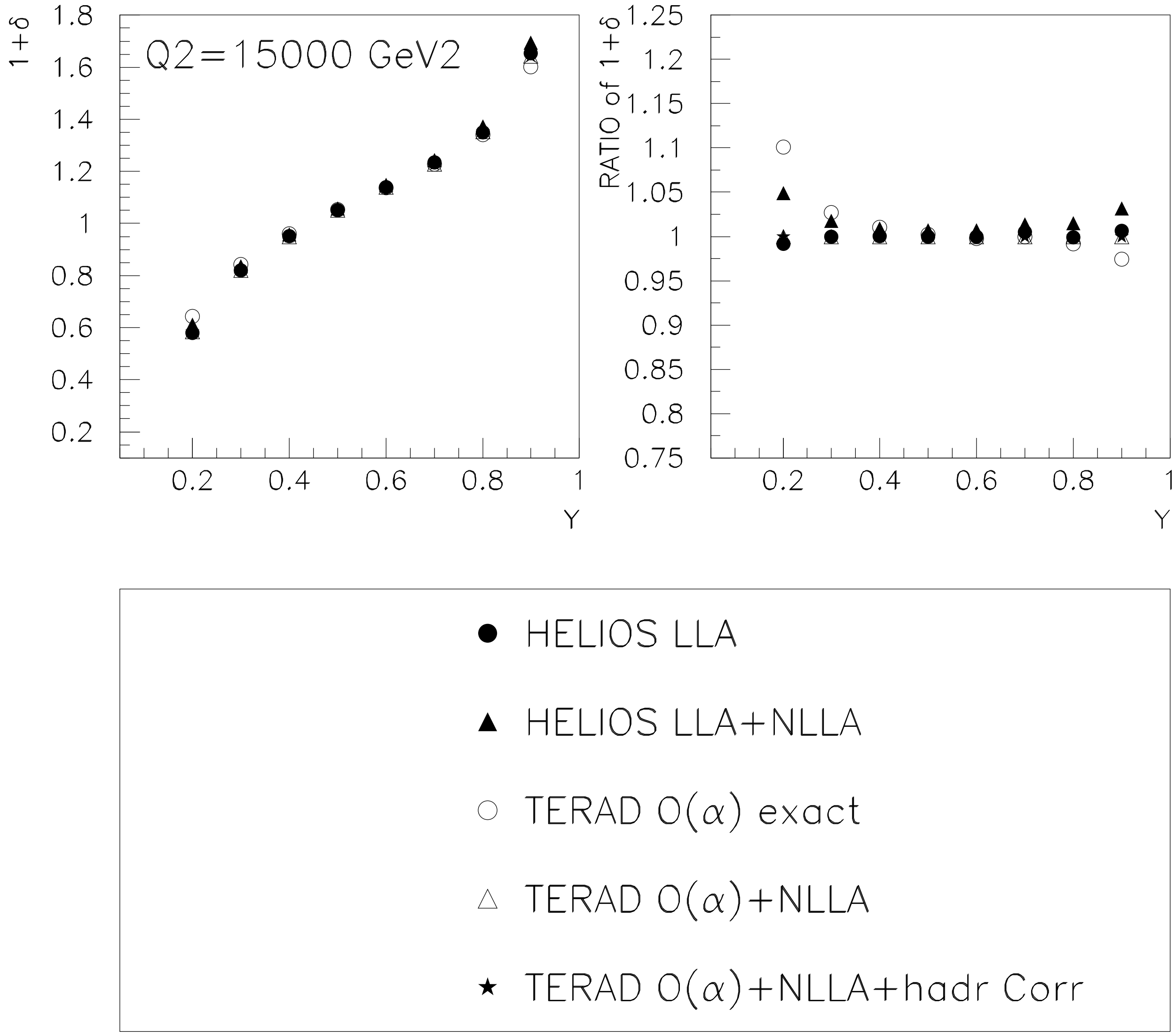
- parton density distribution
  $\rightarrow$ $\pm 5\%$
  1. input data (e.g. BCDMS at high x and low Q^2)
  2. shapes of distributions (at Q_0^2 starting point of QCD evolution)
- value of α_s
  $\rightarrow$ $\pm 4\%$
  comparison CTEQ (A1) $\rightarrow$ (A5) and
  MRS (R1) $\rightarrow$ MRS (R2)
- higher order QED corrections
  $\rightarrow$ $\pm 2\%$



* Using HECTOR

Divergences regulated in the $\overline{MS}$ scheme

$1+\delta$ for leptonic variables



Event Selection

Background Rejection

- vertex within nominal interaction region
- time measurement in Jet chamber (± 1.6 ns / event)
- filters against cosmic and halo muons (μ-system, calorimeter and tracking)

Neutral Current Selection

- electron identification:
  - shower shape test in calorimeter
  - isolation in $\eta - \phi$ cone ($R < 0.25$)
  - track matching the calorimeter cluster
- $\boxed{E_{T,e} > 25 \text{ GeV}}$ $\boxed{\Theta_e > 10^o}$
- $\boxed{0.1 < y_e < 0.9}$ $\boxed{Q_e^2 > 2500 \text{ GeV}^2}$
- 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

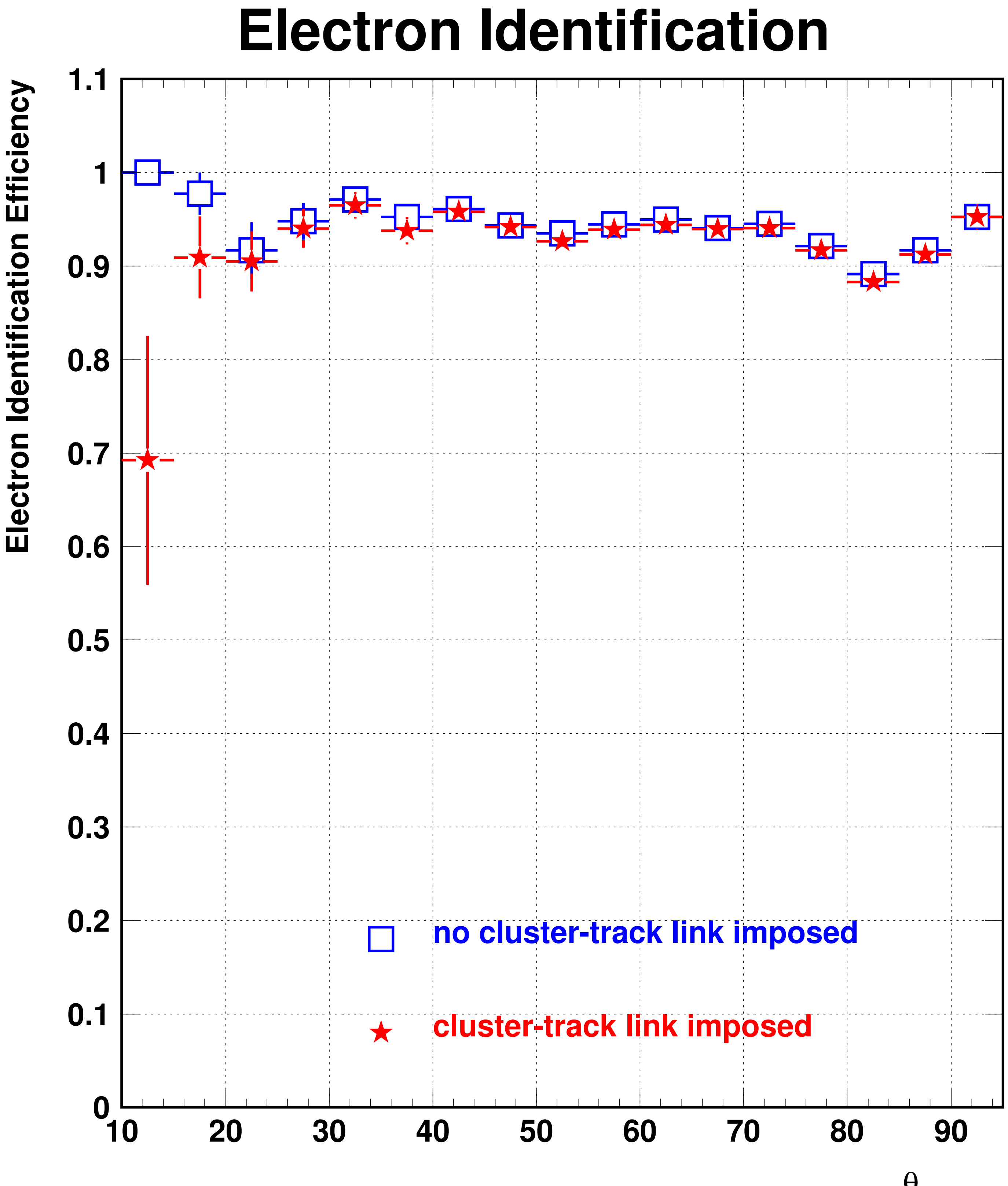
Charged Current Selection

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

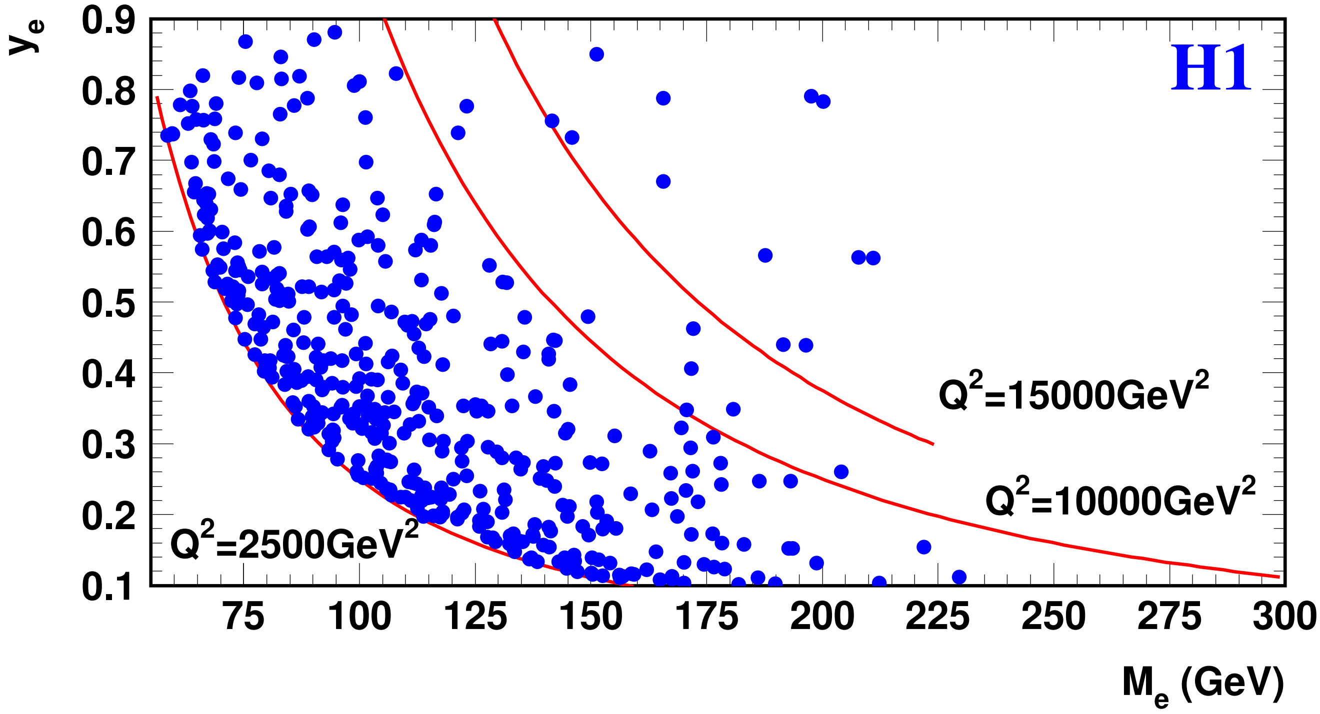
Partonic Process (example)	Generator Model [refs.]	Simulated Luminosity (pb^{-1})	Upper Limits (95% CL) on Events per 14.19 pb^{-1}
Single W and Z Boson Production			
$e+q \longrightarrow W + e+X$			
$\hookrightarrow e+\nu$	H1EPVEC	8600	0.005
$\hookrightarrow$ jet + jet		1400	0.16
$e+q \longrightarrow Z + e+X$			
$\hookrightarrow e^+ + e^-$	H1EPVEC	42000	0.003
$\hookrightarrow \tau^+ + \tau^-$		59000	0.001
$\hookrightarrow$ jet + jet		3600	0.18
High P_T jets photoproduction (direct and resolved)			
$\gamma+q \to q+g, \quad \gamma+g \to q+\bar{q}'$			
(hard jet)	PYTHIA	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)			
$\gamma+q \to q+\gamma$	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

Contamination $< 0.1\%$ ($95\% CL$ full NC sample)

less than 0.1 event ($95\% CL$ at $Q^2 > 10000$ GeV)



Electron Identification
Electron Identification Efficiency
1.1
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
10
20
30
40
50
60
70
80
90
no cluster-track link imposed
cluster-track link imposed
$\theta_{electron}$



NC DIS candidates e-method

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

Observed 443 events

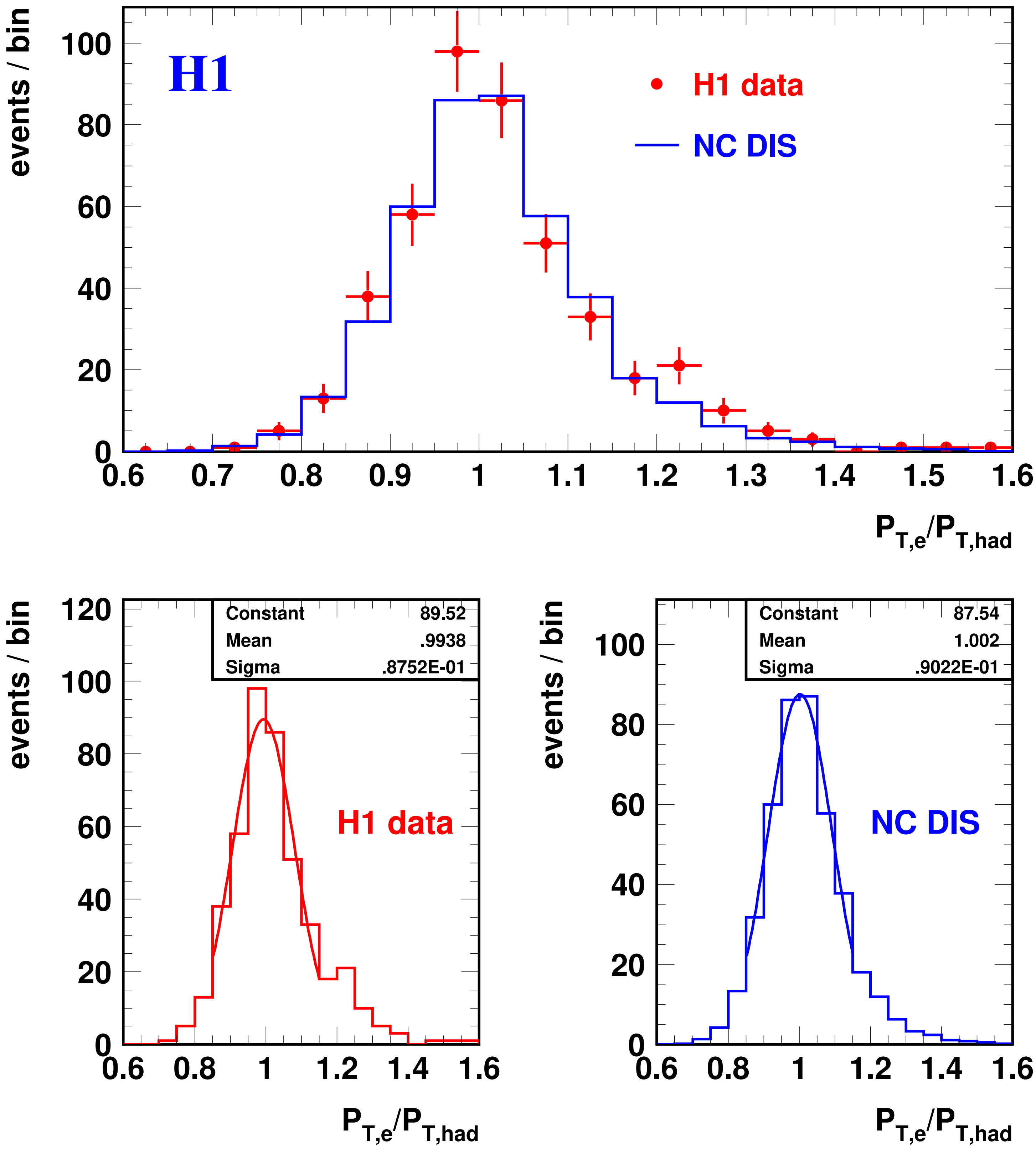
Expected 427 ± 38 events $\qquad (N_{exp}/N_{gen} \sim 80\%)$

CC DIS candidates h-method

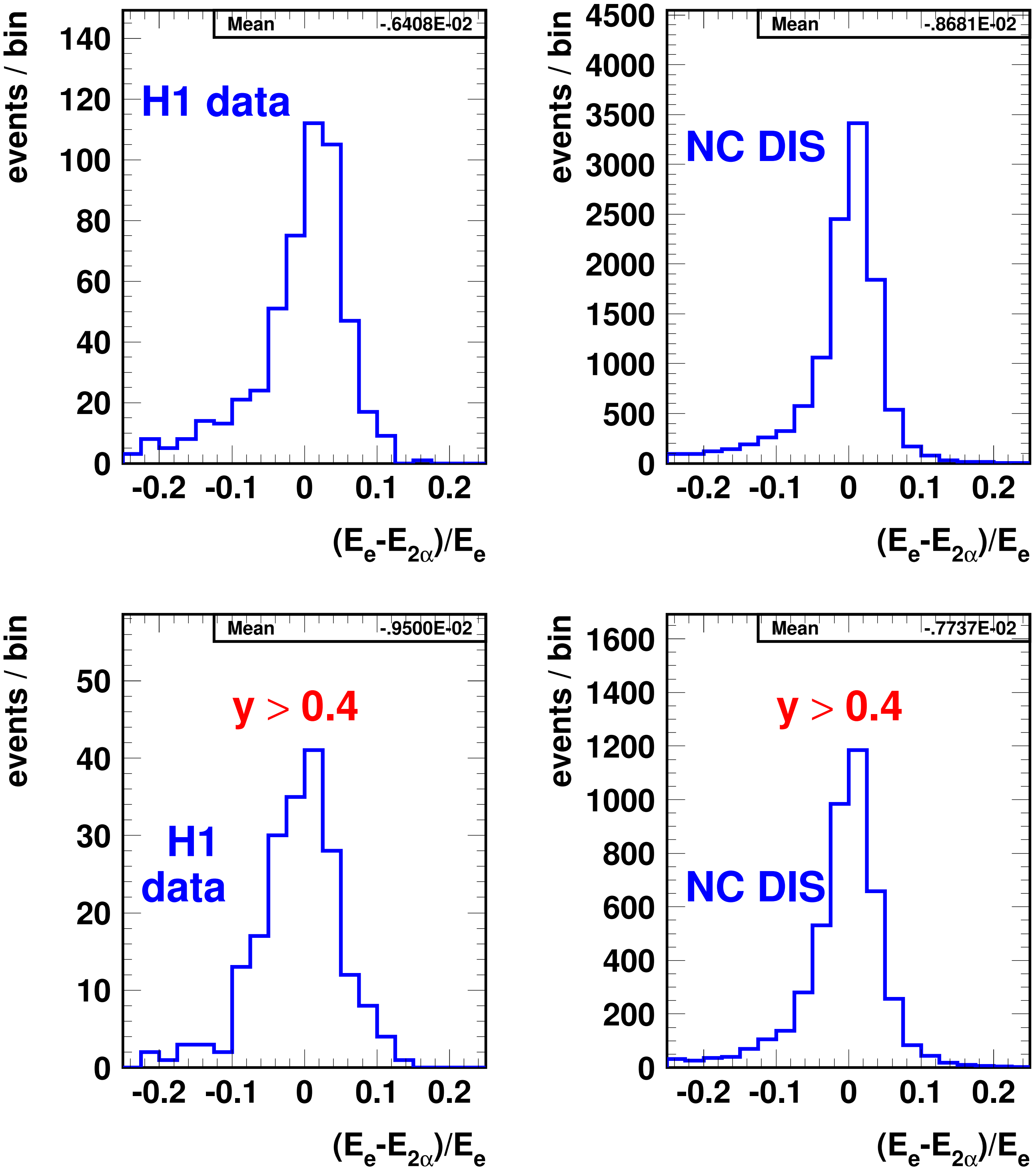
$y_h < 0.9$ $\qquad P_{T,h} > 50$ GeV

Observed 31 events

Expected 34.2 ± 5.8 events

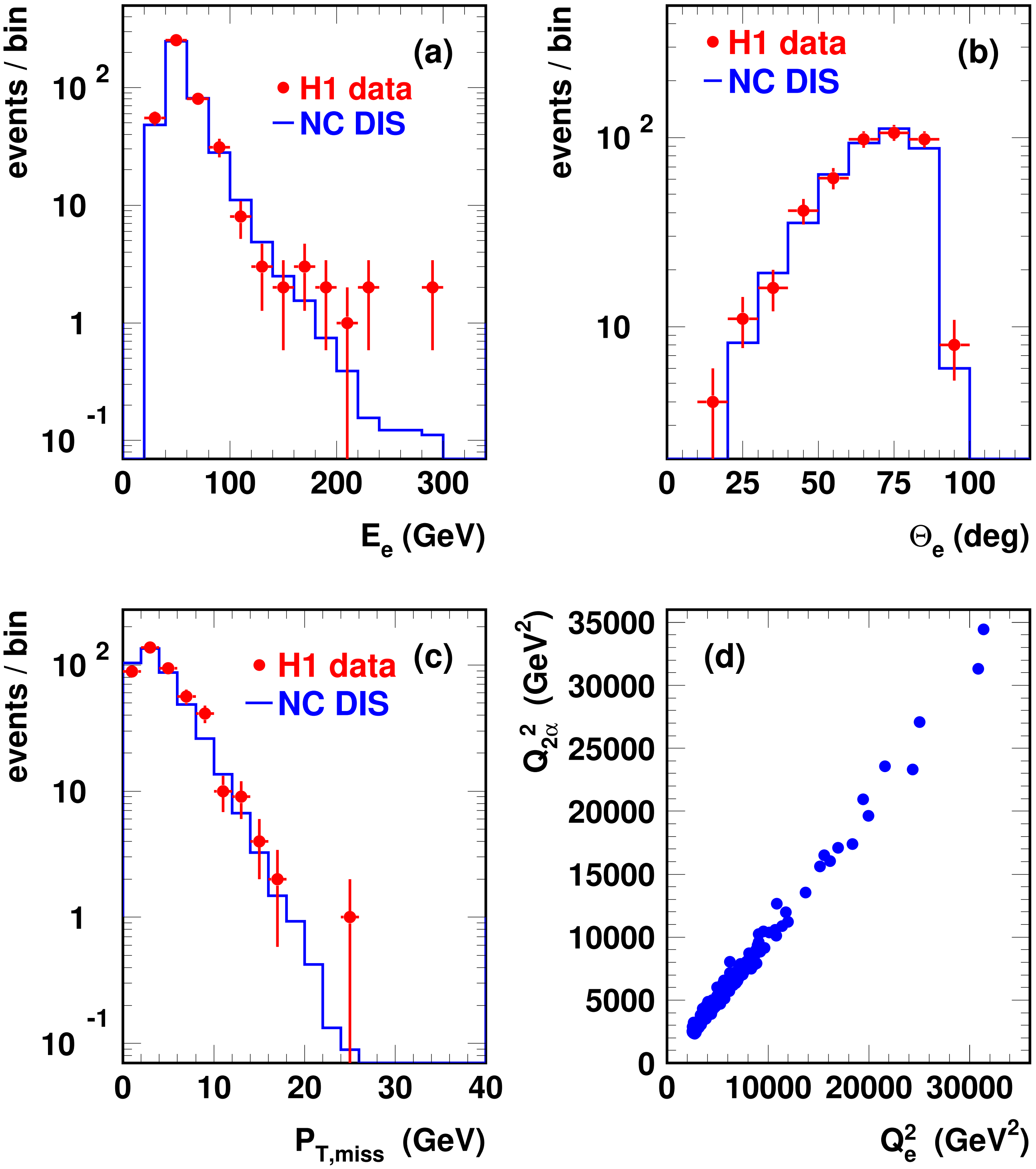

H1
H1 data
NC DIS
events / bin
$P_{T,e}/P_{T,had}$
Constant 89.52
Mean .9938
Sigma .8752E-01
H1 data
Constant 87.54
Mean 1.002
Sigma .9022E-01
NC DIS

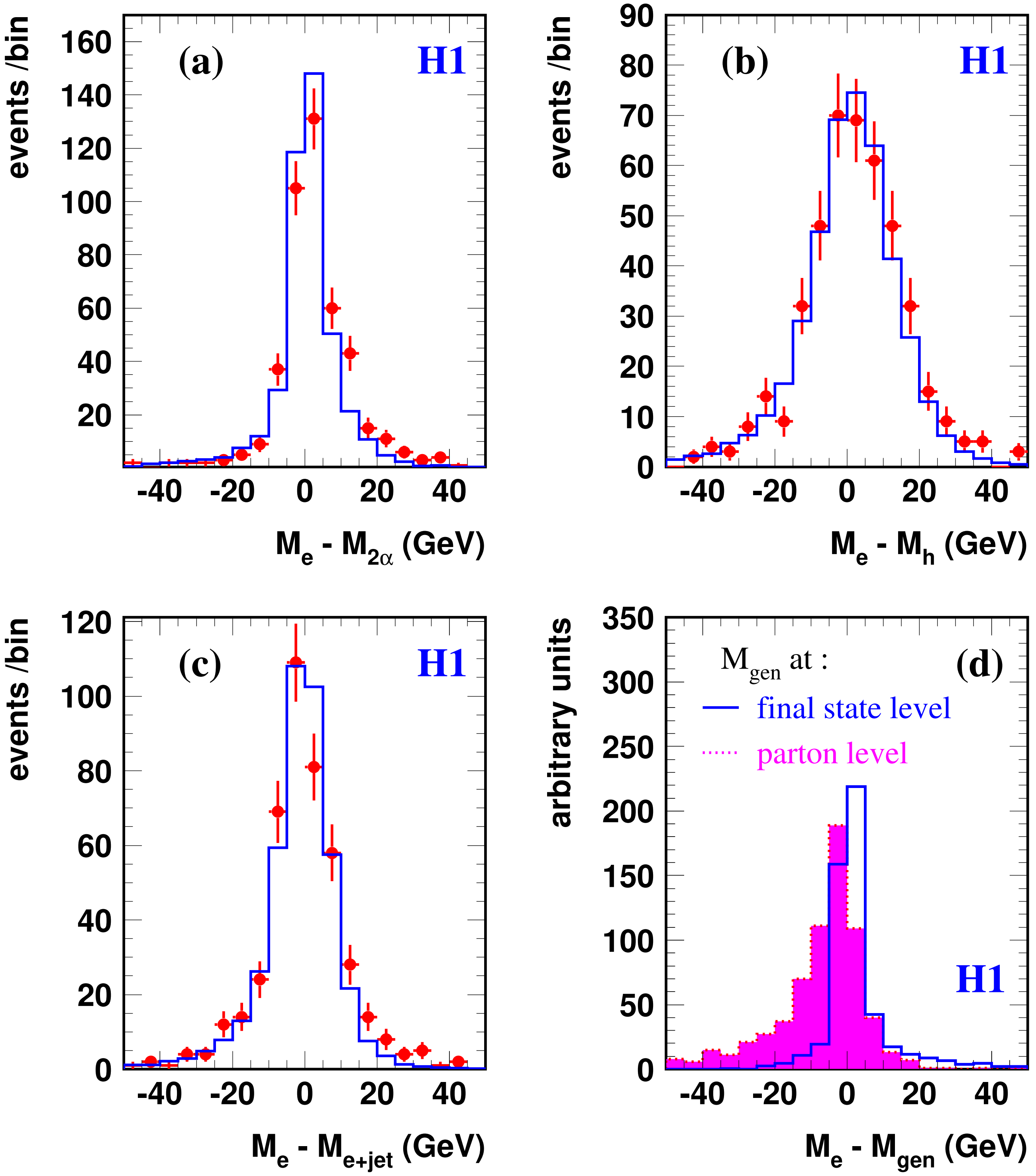
Electromagnetic calibration

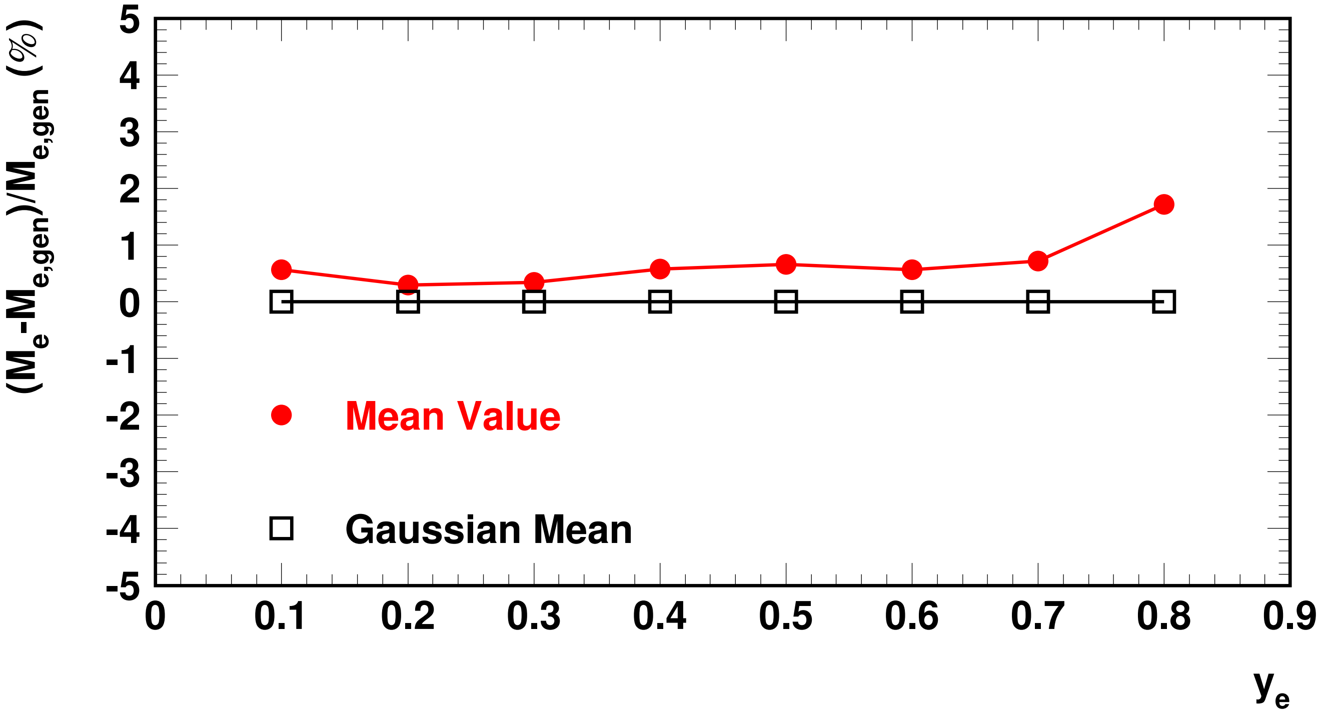


$$E_{2\alpha} = \frac{27.55 \text{ GeV} \times (1 - \alpha_h/(\alpha_h - \alpha_e))}{\sin^2\theta_e}$$

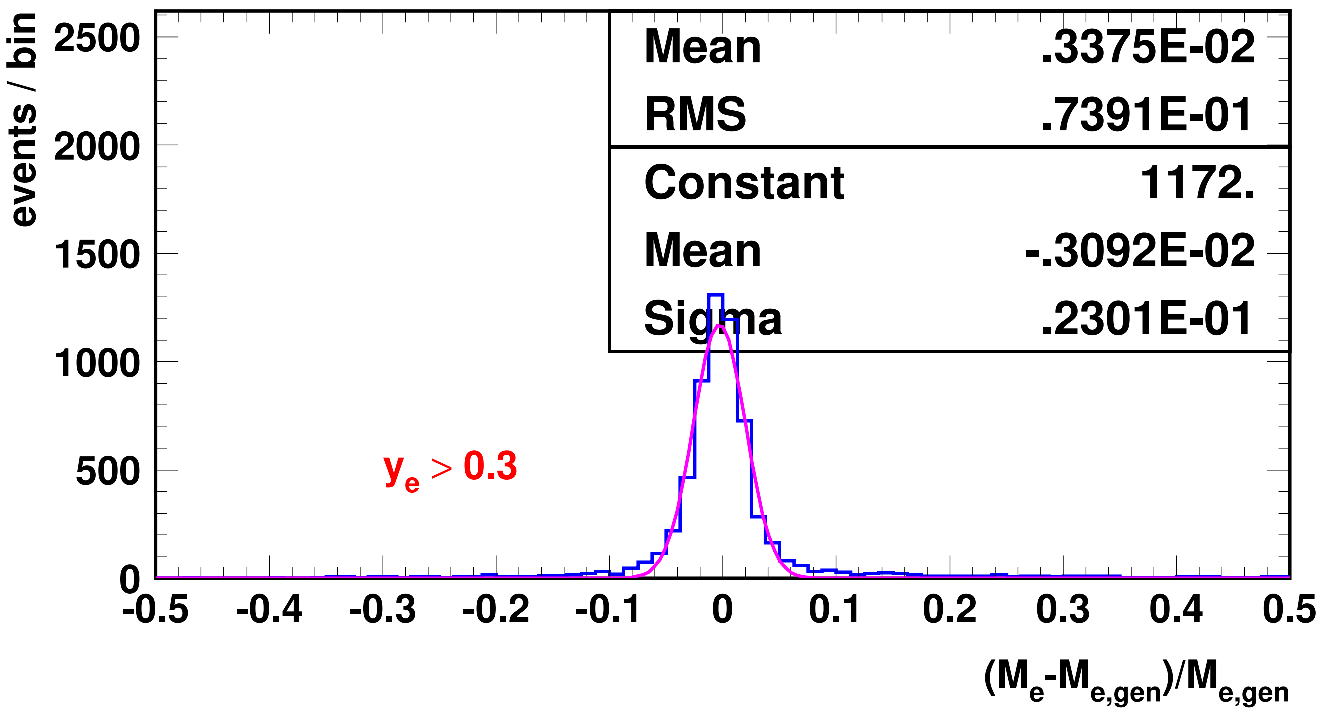
$$\alpha_h = \sum_{had} (E - P_z)/P_{T,h} \qquad \alpha_e = (E_e - P_{z,e})/E_{T,e}$$


events / bin
(a)
H1 data
NC DIS
10^{2}
10
1
10^{-1}
0
100
200
300
E_e (GeV)
events / bin
H1 data
NC DIS
(b)
10^{2}
10
0
25
50
75
100
Θ_e (deg)
events / bin
H1 data
NC DIS
(c)
10^{2}
10
1
10^{-1}
0
10
20
30
40
$P_{T,miss}$ (GeV)
$Q^2_{2\alpha}$ (GeV^2)
(d)
35000
30000
25000
20000
15000
10000
5000
0
0
10000
20000
30000
Q^2_e (GeV^2)


events /bin
(a)
H1
$M_e - M_{2\alpha}$ (GeV)
events /bin
(b)
H1
$M_e - M_h$ (GeV)
events /bin
(c)
H1
$M_e - M_{e+jet}$ (GeV)
arbitrary units
M_{gen} at :
(d)
final state level
parton level
H1
$M_e - M_{gen}$ (GeV)

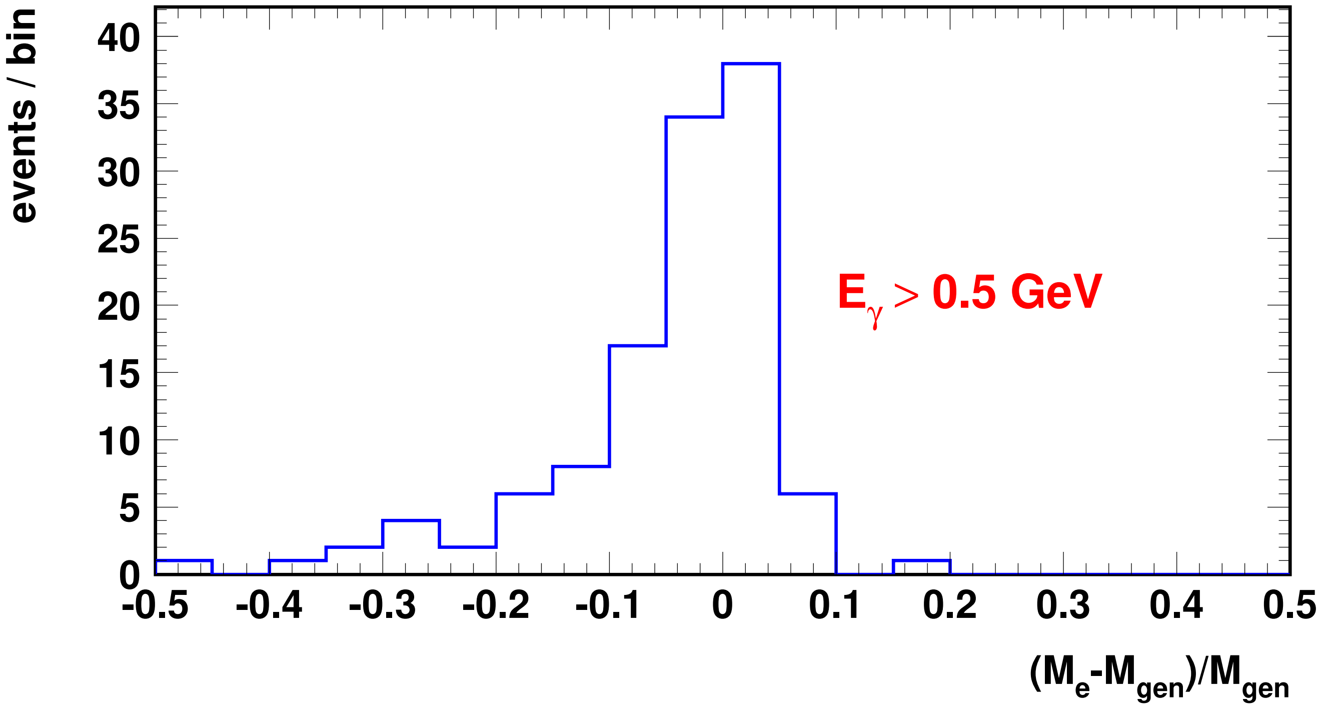


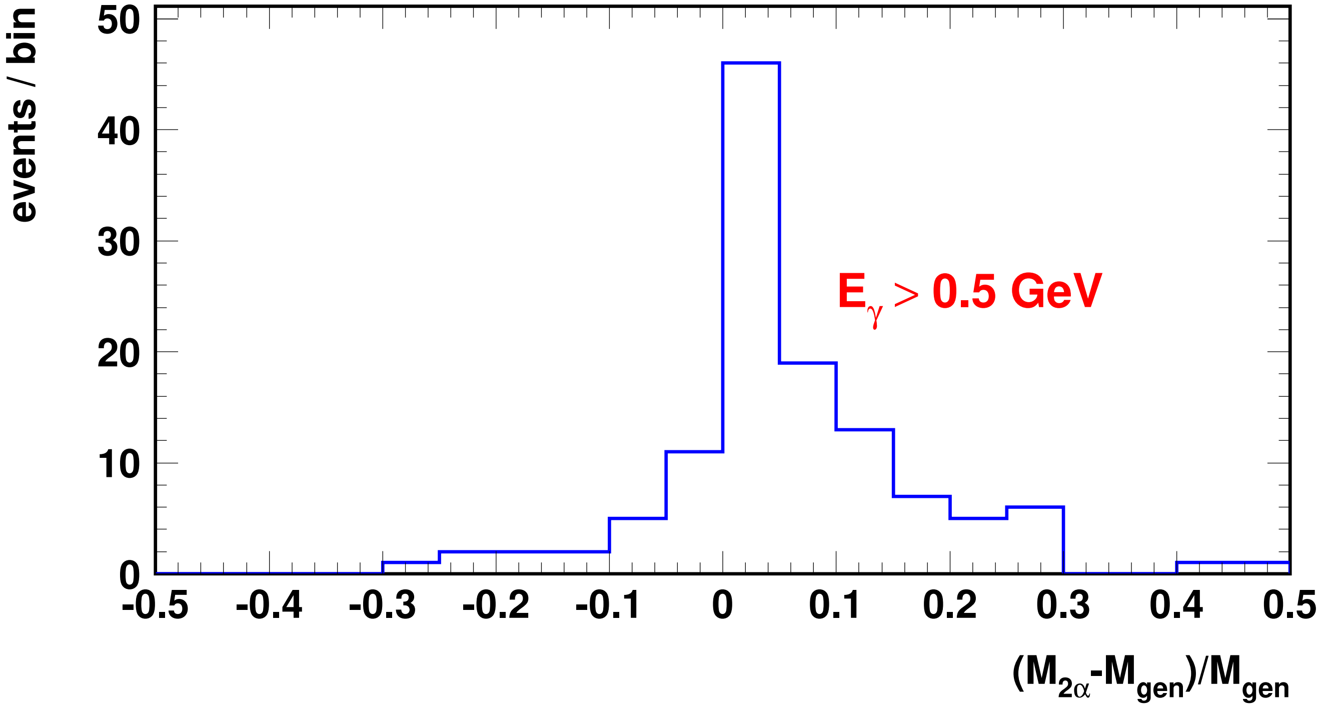
(M_e-M_e,gen)/M_e,gen (%)
Mean Value
Gaussian Mean
y_e

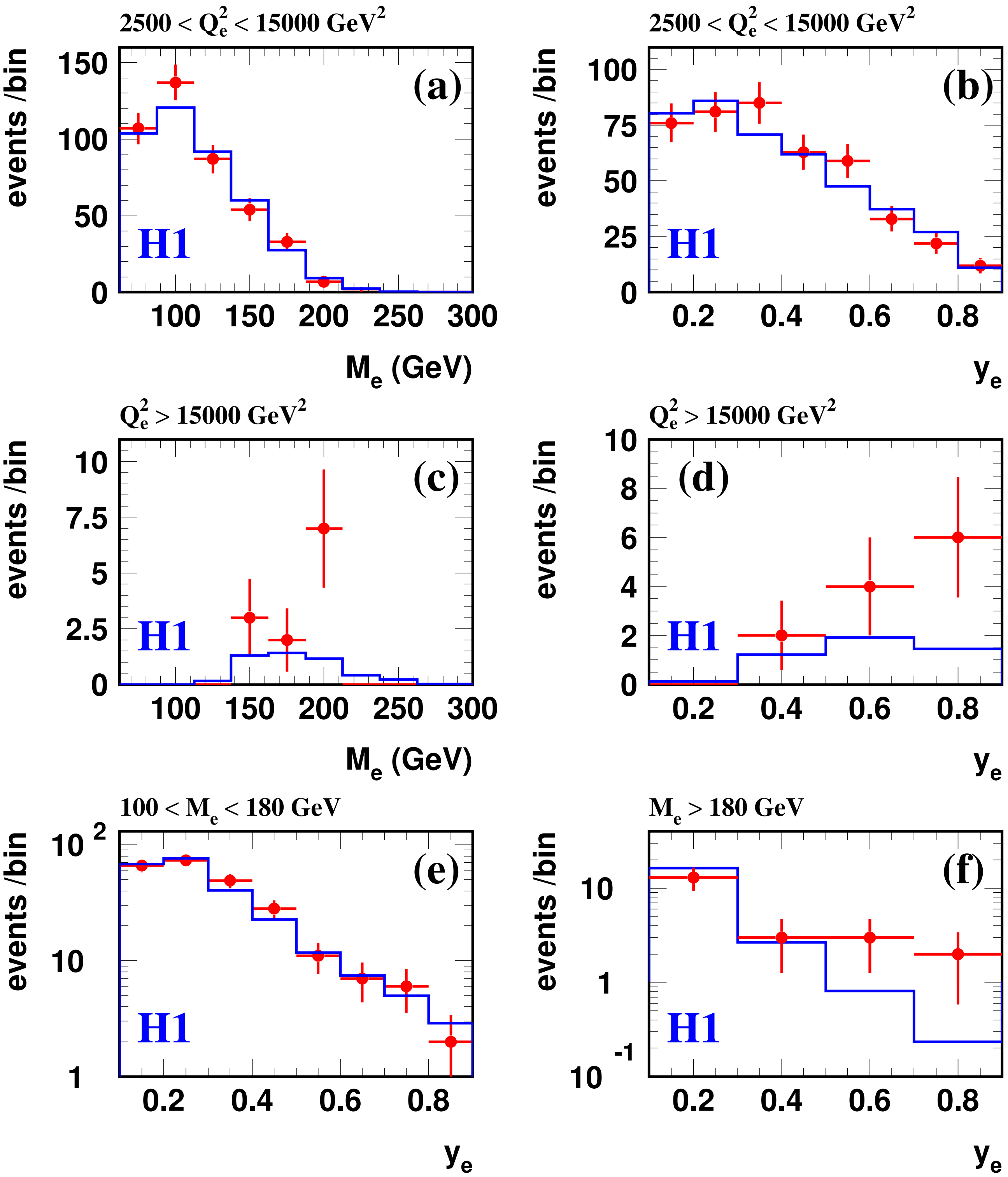


events / bin
Mean .3375E-02
RMS .7391E-01
Constant 1172.
Mean -.3092E-02
Sigma .2301E-01
y_e > 0.3
(M_e-M_e,gen)/M_e,gen

Influence of ISR radiation



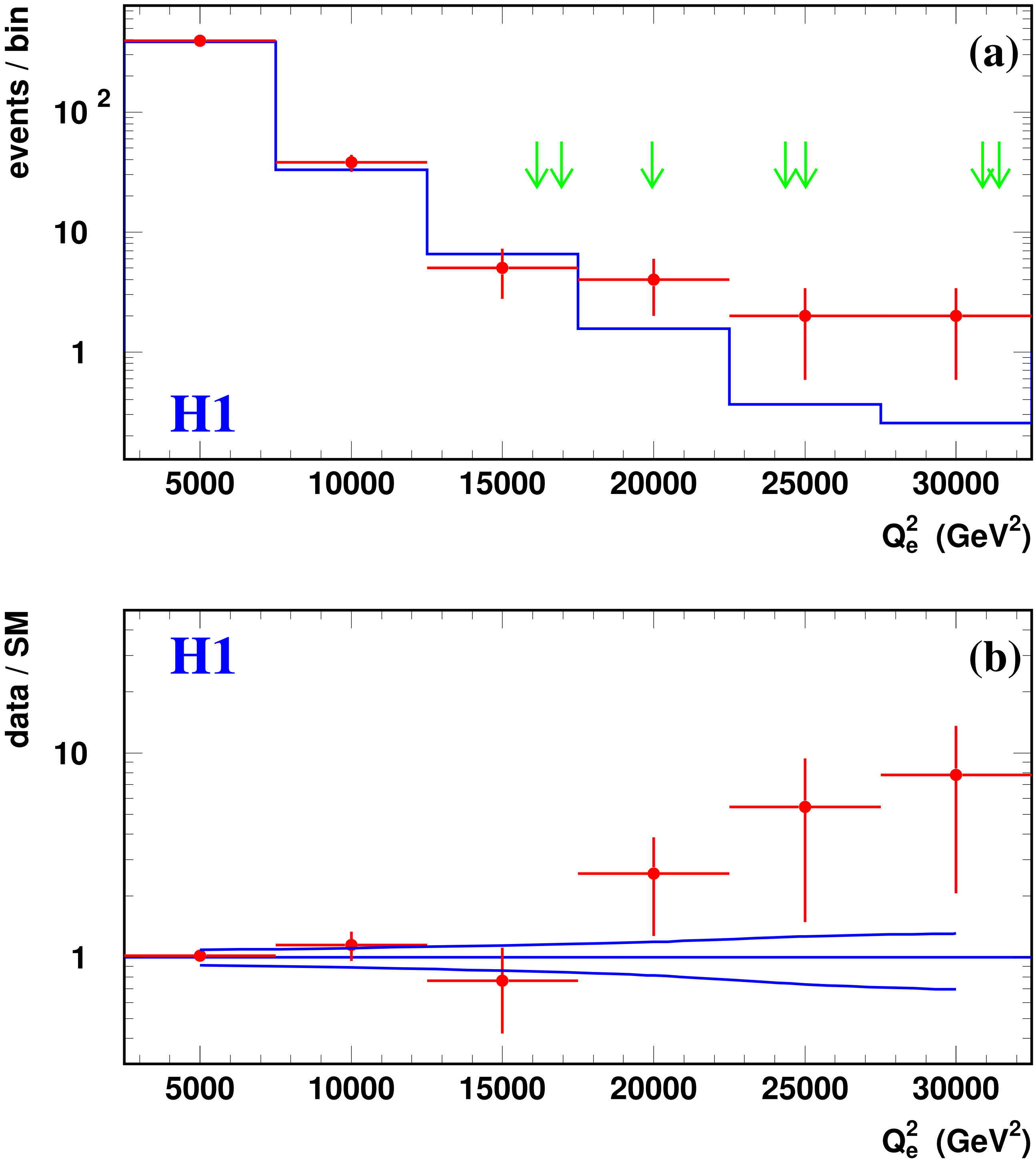




- data exceeds NC DIS expectation at high Q^2

(especially at $M_e \sim 200$ GeV).

- at high $M_e \Rightarrow$ difference apparent at large y_e.



Errors dominated by uncertainty on e.m. energy scale

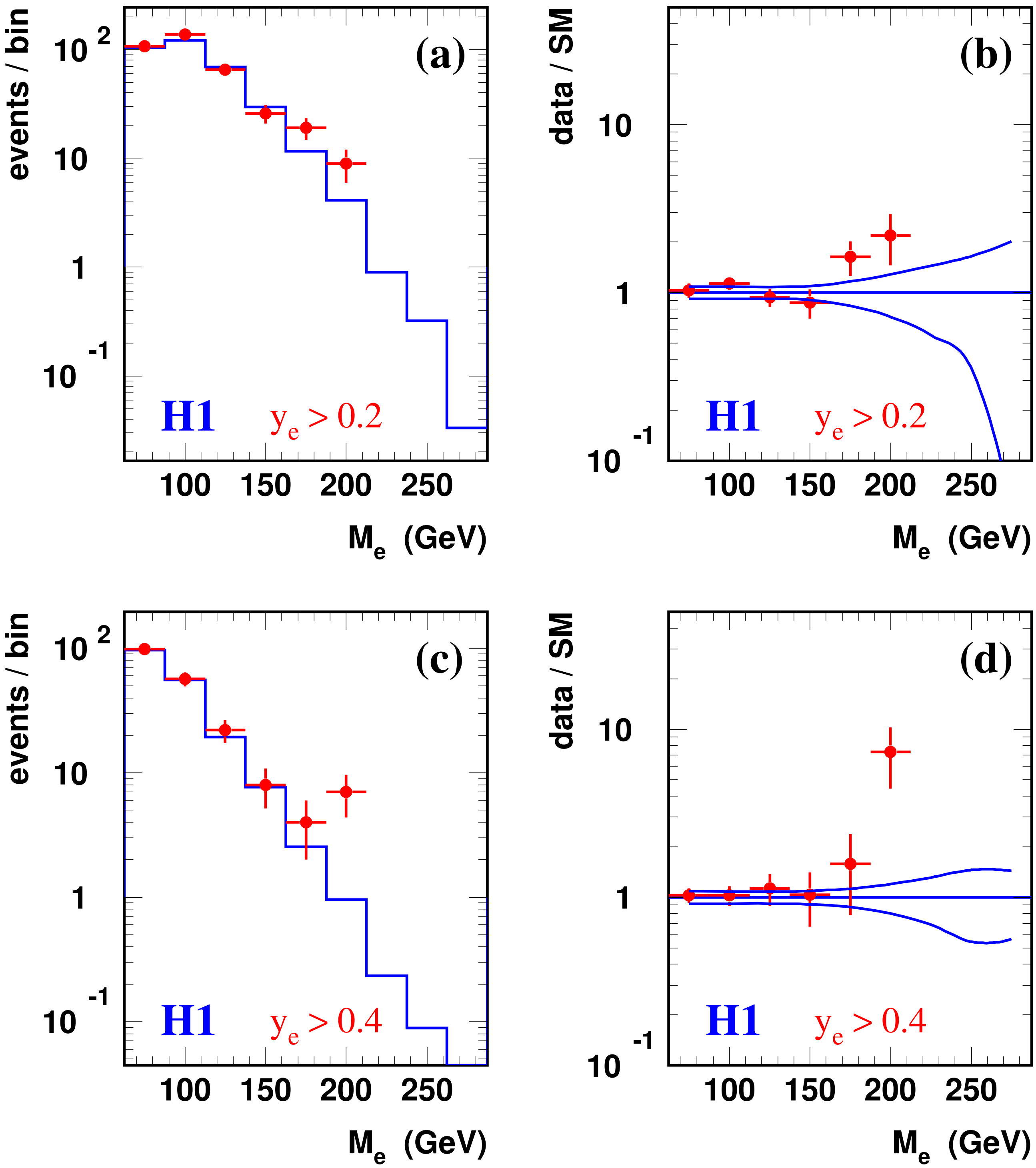
$\sim 8.5\%$ at low Q_e^2 $\qquad$ $\sim 30\%$ at highest Q_e^2

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

where:

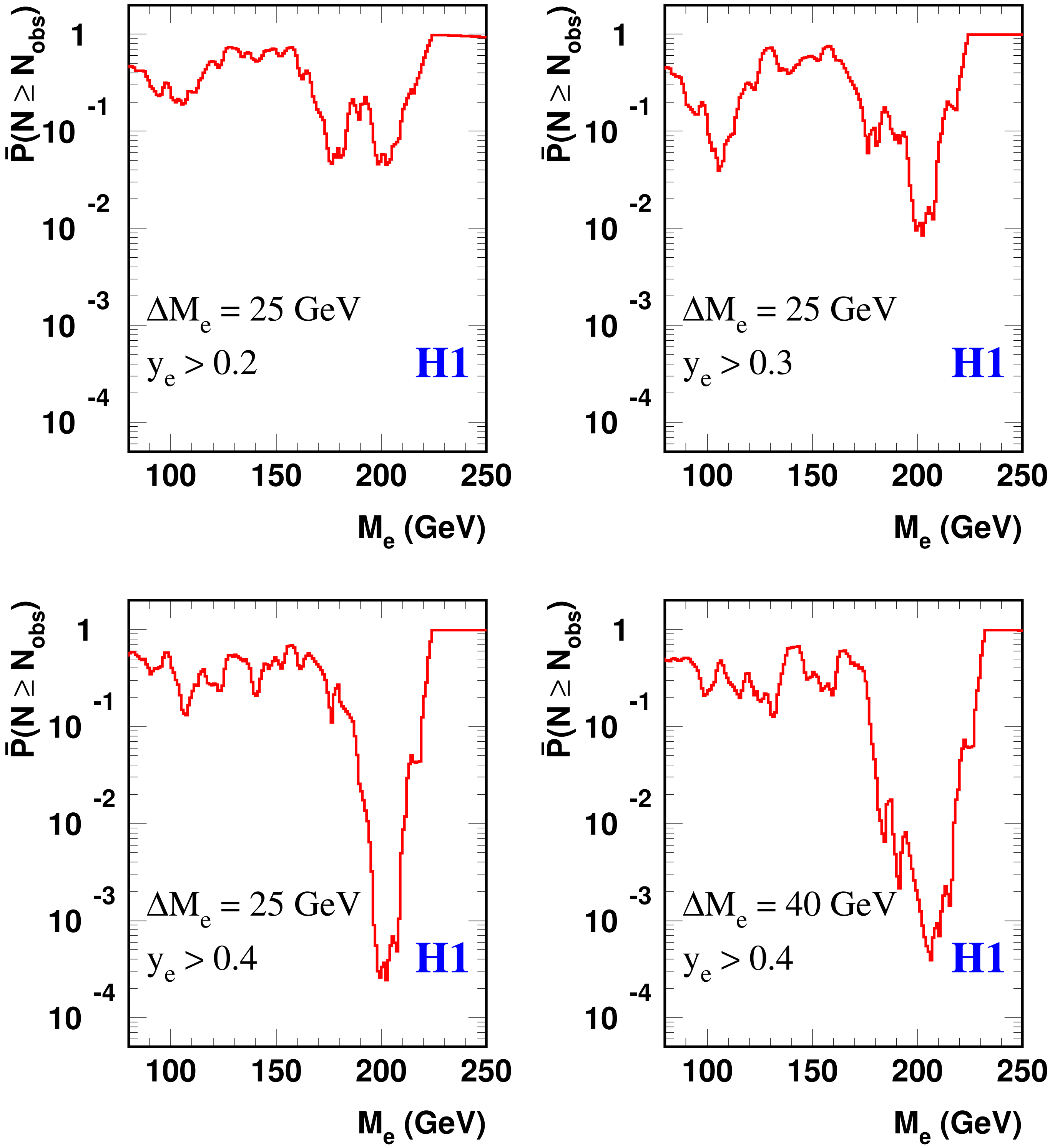
- $p(k; x) = e^{-x} x^k / k!$ to observe k events for x expected events;
- $G(x; b, \delta b) =$ Gaussian of mean value b and width δb.

Q^2_{min}(GeV^2)	2500	5000	10000	15000	20000	30000
N_{obs}	443	122	20	12	5	2
N_{DIS}	426.7 $\pm$38.4	116.2 $\pm$11.6	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	0.35	0.39	6×10^{-3}	1.4×10^{-2}	2.3×10^{-2}



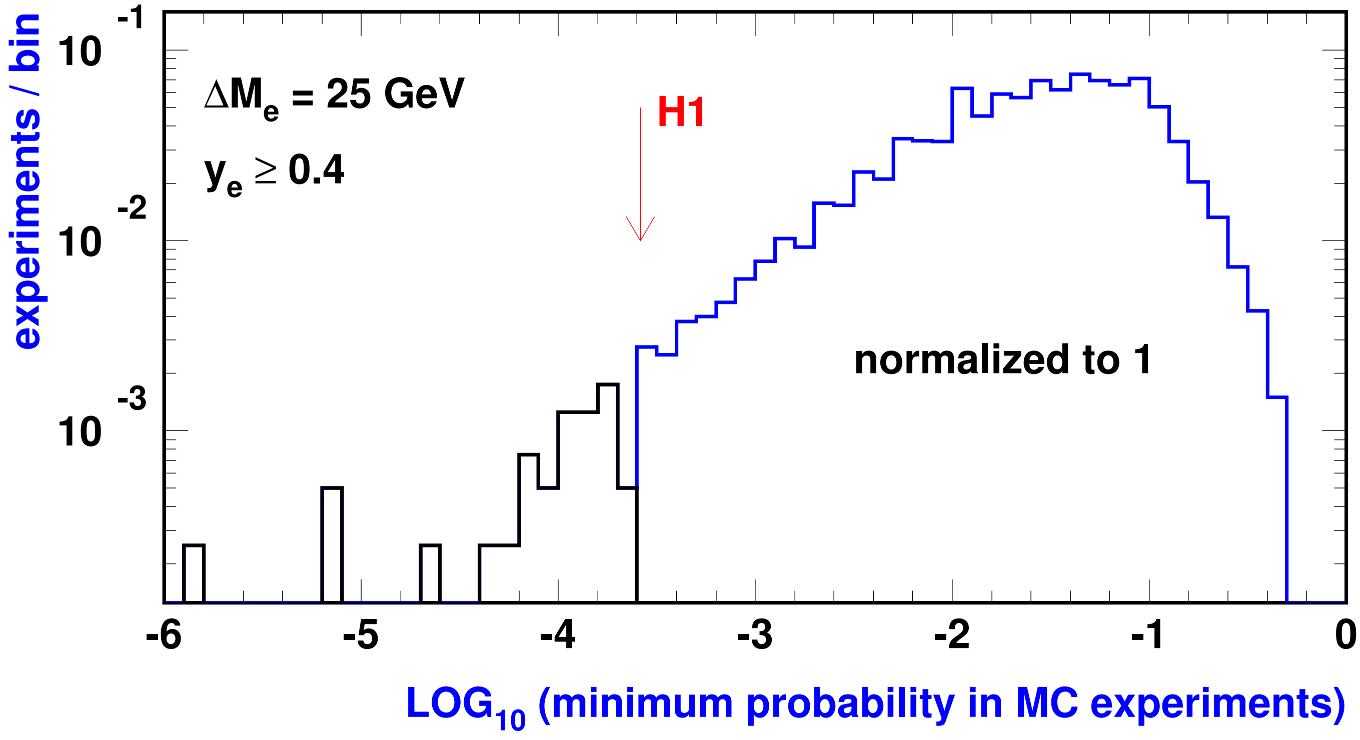
- Excess seen at highest mass
- More visible at large y_e

M_{min} (GeV) \ y_{min}		0.2	0.3	0.4	0.5
75	N_{obs}	313	232	147	84
	N_{DIS}	294.1 ± 26.2	208.1 ± 16.9	136.9 ± 11.2	77.1 ± 5.9
	$\mathcal{P}$	0.27	0.14	0.26	0.25
150	N_{obs}	34	17	12	8
	N_{DIS}	28.0 ± 4.6	12.9 ± 1.6	6.83 ± 0.80	3.51 ± 0.40
	$\mathcal{P}$	0.19	0.18	5.3×10^{-2}	3.0×10^{-2}
175	N_{obs}	14	9	7	5
	N_{DIS}	9.82 ± 2.62	4.65 ± 0.77	2.35 ± 0.38	1.31 ± 0.21
	$\mathcal{P}$	0.18	5.8×10^{-2}	1.3×10^{-2}	1.2×10^{-2}
180	N_{obs}	11	8	7	5
	N_{DIS}	7.85 ± 2.35	3.73 ± 0.70	1.83 ± 0.33	1.04 ± 0.17
	$\mathcal{P}$	0.22	4.6×10^{-2}	3.8×10^{-3}	5.0×10^{-3}
185	N_{obs}	10	7	7	5
	N_{DIS}	6.10 ± 2.06	2.89 ± 0.57	1.41 ± 0.26	0.83 ± 0.15
	$\mathcal{P}$	0.14	3.6×10^{-2}	9.4×10^{-4}	2.0×10^{-3}
190	N_{obs}	8	6	6	4
	N_{DIS}	4.65 ± 1.68	2.19 ± 0.48	1.07 ± 0.23	0.68 ± 0.13
	$\mathcal{P}$	0.15	3.1×10^{-2}	1.2×10^{-3}	5.9×10^{-3}
195	N_{obs}	6	5	5	4
	N_{DIS}	3.58 ± 1.43	1.73 ± 0.40	0.85 ± 0.19	0.53 ± 0.11
	$\mathcal{P}$	0.19	3.8×10^{-2}	2.4×10^{-3}	2.5×10^{-3}
200	N_{obs}	4	3	3	3
	N_{DIS}	2.72 ± 1.10	1.32 ± 0.33	0.63 ± 0.15	0.39 ± 0.09
	$\mathcal{P}$	0.30	0.15	2.8×10^{-2}	8.2×10^{-3}


$\bar{P}(N \geq N_{obs})$
M_e (GeV)
ΔM_e = 25 GeV
$y_e > 0.2$
ΔM_e = 25 GeV
$y_e > 0.3$
ΔM_e = 25 GeV
$y_e > 0.4$
ΔM_e = 40 GeV
$y_e > 0.4$
H1

ΔM_e (GeV)	20	25	30	40
N_{obs}	5	7	7	7
N_{DIS}	0.63 ±0.13	0.95 ±0.18	1.10 ±0.19	1.57 ±0.28
$\bar{\mathcal{P}}(N \geq N_{obs})$	5.0×10^{-4}	2.6×10^{-4}	2.5×10^{-4}	1.6×10^{-3}

Lowest Probability in Monte Carlo Experiments



0.9% probability to find a fluctuation as large as observed anywhere in the mass range considered.

	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	± 5			$\pm .014$		± 360	
2	87050	208	200	213	.563	.582	24350	23320
	8062	± 4			$\pm .012$		± 430	
3	88999	188	185	184	.566	.573	19950	19640
	106218	± 12			$\pm .032$		± 1400	
4	119314	198	199	197	.790	.787	30870	31320
	18272	± 2			$\pm .008$		± 530	
5	122145	211	227	211	.562	.526	25030	27100
	69506	± 4			$\pm .012$		± 440	
6	155768	192	190	215	.440	.443	16130	16050
	67216	± 6			$\pm .016$		± 400	
7	158577	200	213	210	.783	.762	31420	34450
	100110	± 2			$\pm .008$		± 540	

Average $M_e = 200.8 \pm 2.2$ GeV

Systematic error on energy scale $\frac{\delta E_e}{E_e} = 3\% \Rightarrow \frac{\delta M_e}{M_e} \sim \frac{0.03}{2y_e}$

Non Standard Contributions

Parton Distributions tuned to Tevatron jet data:

- CTEQ (4HJ): large gluon density at large x:
  σ_{DIS} unchanged within 5%.
- MRS (R2): large α_s value (0.12):
  drop of σ_{DIS} at large Q^2.
- MRS (J'): ignore DIS data (BCDMS) at low Q^2:
  increase of σ_{DIS} by 20%.

QCD Models

- Colour Dipol Model $\leftrightarrow$ Matrix elements + PS:
  small change.

$F_L > 0$: reduces σ_{DIS}

$\rightarrow$ 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.

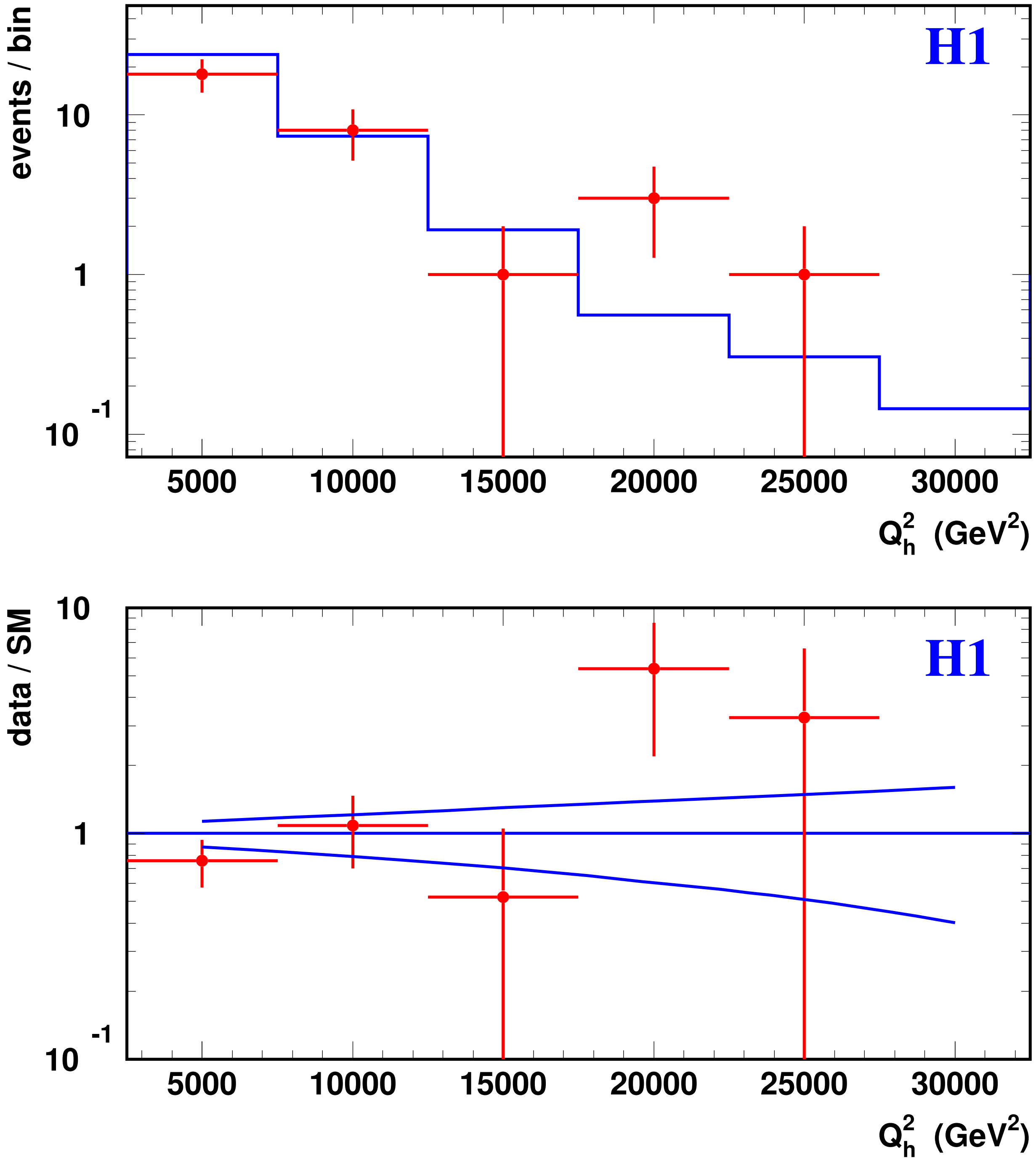
- s-channel resonance: fixed e^+-parton mass M.
- virtual exchange: enhanced cross section at high Q^2.

$\rightarrow$ signature of events identical to DIS, therefore more luminosity needed to study kinematic distributions.

Summary

- For $Q^2 \leq 15000\ \mathrm{GeV}^2$, the Q^2 or M and y distributions are well reproduced by the expectations from standard Neutral Current and Charged Current processes;
- For $Q^2 > 15000\ \mathrm{GeV}^2$, 12 Neutral Current events where 4.71 ± 0.76 are expected $\mathcal{P}(N \geq N_{obs}) = 6 \times 10^{-3}$;
- The excess of observed events in the M and y plane is most prominent for large y at $M \sim 200$ GeV ($N_{obs} = 7$ events for 0.95 ± 0.18 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 $\rightarrow$ more statistics needed !

Charged Current



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

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

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