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Multi–lepton events at HERA

H1 Collaboration

Abstract

A search for multi–lepton (electron or muon) events at high transverse momenta is performed on a data sample collected in $e^{\pm}p$ collisions with the H1 detector at HERA during the period 1994–2005. This data sample corresponds to an integrated luminosity of 275 pb^{-1}, which includes 52 pb^{-1} of $e^{+}p$ data taken in 2004 and 105 pb^{-1} of $e^{-}p$ data taken in 2005. With respect to the published HERA I multi-electron and multi-muon analyses, additional topologies with high P_T electrons and muons are investigated. Yields of di-lepton and tri-lepton events are measured and a general good agreement is found with the Standard Model (SM) predictions. Combining all channels, four events are observed with a scalar sum of lepton transverse momenta ($\sum P_T$) greater than 100 GeV, compared to a SM expectation of 1.1 $\pm$ 0.2. The four events with $\sum P_T > 100$ GeV are observed in $e^{+}p$ collisions only where the SM expectation is of 0.6 $\pm$ 0.1.

1 Introduction

Within the Standard Model (SM) the production of multi-lepton events in ep collisions mainly proceeds via photon-photon interactions [1]. Precise cross-section measurements of both electron (e) and muon (μ) pair production at high transverse momentum (P_T) have already been performed by the H1 collaboration [2, 3] using HERA I data taken until 2000. At large di-electron masses, an excess of events is observed in both the di-electron and tri-electron samples [2].

The present analysis extends our previous measurements to the eμ and e$\mu\mu$ topologies and to a higher luminosity, combining new HERA II data taken in 2003–2004 ($\mathcal{L} = 52$ pb^{-1}) and 2005 ($\mathcal{L} = 105$ pb^{-1}) with the previous HERA I data sample from 1994–2000 ($\mathcal{L} = 118$ pb^{-1}).

2 Standard Model Processes and their Simulation

Multi–lepton events are generated with the GRAPE [4] program, which includes all electroweak matrix elements at tree level. Multi-lepton production via $\gamma\gamma$, γZ, ZZ collisions, internal photon conversion and the decay of virtual or real Z bosons is considered. Initial and final state QED radiation is included. The complete hadronic final state is simulated via interfaces to PYTHIA and SOPHIA [5] for the inelastic and quasi-elastic regimes, respectively. Consequently, GRAPE predicts $ep \rightarrow \mu\mu X$ and $ep \rightarrow eeX$, as well as $ep \rightarrow e\mu\mu X$ and $ep \rightarrow eeeX$ if the scattered electron is detected. The $ep \rightarrow \tau\tau X$ process is also simulated with GRAPE and its contribution was found to be negligible.

The dominant background contributions arise from neutral current deep-inelastic scattering (DIS) events ($ep \rightarrow eX$) [2]. QED Compton scattering $ep \rightarrow e\gamma X$ can also contribute. The DIS and elastic Compton processes are simulated using the RAPGAP [6] (for HERA I) or DJANGO [7] (HERA II) and WABGEN [8] generators, respectively.

All generated events are passed through the full GEANT [9] based simulation of the H1 apparatus, which takes into account the running conditions of the different data taking periods.

3 Multi-lepton Event Selection

The electron identification procedure follows the criteria described in [2]. Electron candidates with energies above 5 GeV are identified in the liquid argon and backward calorimeters, in the range $5^\circ < \theta < 175^\circ$. Electron candidates are required to be isolated by demanding that they are separated from other leptons or jets by at least 0.5 units in the pseudorapidity-azimuth ($\eta - \phi$) plane. In addition, the total hadronic energy within 0.75 units in $\eta - \phi$ of the electron direction is required to be below 2.5 % of the electron energy. In the region of angular overlap between the liquid argon calorimeter and the central drift chambers ($20^\circ < \theta < 150^\circ$), the calorimetric electron identification is complemented by tracking conditions. In this region it is required that a high quality track geometrically matches the electromagnetic cluster within a distance of closest approach to the cluster centre-of-gravity of 12 cm. No other good track is allowed within 0.5

units in $\eta - \phi$ around the electron direction. In the central region ($20^\circ < \theta < 150^\circ$) the distance between the first measured point in the central drift chambers and the beam axis is required to be below 30 cm in order to reject photons that convert late in the central tracker material. In addition, in this central region, the transverse momentum measured from the associated track $P_T^{e_{tk}}$ is required to match the calorimetric measurement P_T^e with $1/P_T^{e_{tk}} - 1/P_T^e < 0.02$ GeV^{-1}. This criteria is relaxed to 0.04 for the new HERA II data since a final calibration and alignment have not been performed yet. Due to the higher material density in the forward region ($5^\circ < \theta < 20^\circ$) the electrons are more likely to shower and therefore no track conditions are required. The same applies in the backward region ($150^\circ < \theta < 175^\circ$). The electron energy threshold is raised to 10 GeV in the forward region.

Muon candidates are identified with a $P_T > 2$ GeV in the range $20^\circ < \theta < 160^\circ$, with a similar procedure to that described in [3]. The muon identification is based on a track in the inner tracking systems associated with a track segment or an energy deposit in the instrumented iron [10]. The muon momentum is measured in the central region from the track curvature in the solenoidal magnetic field. A muon candidate should have no more than 5 GeV deposited in the LAr calorimeter in a cylinder of radius 25 cm and 50 cm in the electromagnetic and hadronic sections of the LAr calorimeter, respectively, centred on the muon track direction. In di-muon events, the requirement of an opening angle between the two muons smaller than 160° discards cosmic rays background. Beam halo events are rejected by requiring that the muons originate from the event vertex. Finally, misidentified hadrons are strongly suppressed by requiring that the muon candidate be separated from the closest jet and from any good quality track by 1 unit in the $\eta - \phi$ plane.

The final multi-lepton selection requires that there be at least two central ($20^\circ < \theta < 150^\circ$) lepton (electron or muon) candidates, of which one must have $P_T^l > 10$ GeV and the other $P_T^l > 5$ GeV. Additional lepton candidates are identified in the detector according to the above criteria without any additional explicit P_T or angular requirement. The lepton candidates are ordered according to decreasing P_T, $P_T^{l_i} > P_T^{l_{i+1}}$. The selected events are classified as belonging to the two lepton sample if only two central leptons are identified, and to the three lepton sample if exactly one additional lepton candidate is identified. According to the flavours of the identified leptons, these samples are further classified into ee, $\mu\mu$, eμ, eee and e$\mu\mu$.

4 Results

The event yields observed in all channels are summarised in table 1. The observed event yields are in good agreement with SM expectations, which are dominated by pair production.

The distributions of the invariant mass of the two leptons in the di-lepton event classes are presented in figure 1. The agreement with the SM prediction is good, except in the ee invariant mass distribution for $M_{12} > 100$ GeV, where the three events already described in [2] are present, compared to an expectation of 0.86 ± 0.21 (see table 2). The distribution of the invariant mass M_{12} of the two highest P_T electrons for the eee sample is shown in figure 2, as well as the invariant mass combinations of the electron with the higest P_T muon ($M_{e\mu}$) and of both muons ($M_{\mu\mu}$) in the e$\mu\mu$ sample. The event yields in the tails of invariant mass distributions ($M > 100$ GeV) of all channels are summarised in table 2. The three ee events with $M_{12} >$

100 GeV are observed in HERA I data and are discussed in [2], as well as the three eee with $M_{12} > 100$ GeV. Two e$\mu\mu$ events are observed in the new HERA II data, of which one has a high muon-muon and the other a high electron-muon invariant mass. The e$\mu\mu$ event with the high $M_{e\mu}$ invariant mass is shown in figure 3.

The distributions of the scalar sum of P_T of all identified leptons for the combination of di– and tri–lepton samples is shown in figure 4. For $\sum P_T > 100$ GeV 4 events are observed in all channels combined while 1.1 $\pm$ 0.2 are expected. These four data events correspond to the three ee events observed in HERA I data [2] and one new e$\mu\mu$ event observed in HERA II data.

The separation of the total HERA data sample between events taken in collisions with a positron or electron beam is also presented in figure 4 and in table 2. All high invariant masses and $\sum P_T$ events have been recorded in e^+p collisions and none is observed in e^-p data. In e^+p collisions and for $\sum P_T > 100$ GeV 4 events are observed in all channels combined while 0.6 $\pm$ 0.1 are expected (see table 3).

5 Summary

The production of multi-leptons (electrons and muons) at high transverse momenta in ep scattering has been studied. The measurement extends previous analyses [2, 3] by including the HERA II data recorded in e^+p and e^-p collisions and corresponding to integrated luminosities of 52 pb^{-1} and 105 pb^{-1}, respectively. The event yields in the di-lepton (ee, $\mu\mu$ and eμ) and tri-lepton (eee and e$\mu\mu$) sub-samples are in good agreement with the SM predictions. The distribution of the scalar sum of transverse momenta of the leptons is studied for the combination of all di- and tri-lepton sub-samples. For $\sum P_T > 100$ GeV 4 events are observed while 1.1 $\pm$ 0.2 are expected.

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H1 Preliminary 275 pb^{-1} (1994–2005)

Selection	Data	SM	Pair Production	NC-DIS + Compton
ee	266	261 ± 37	217 ± 23	44 ± 22
$\mu\mu$	113	112 ± 21	112 ± 21	—
eμ	137	136 ± 21	83 ± 6.5	53 ± 16
eee	52	52 ± 6	52 ± 6	—
e$\mu\mu$	63	67 ± 10.5	67 ± 10.5	—

Table 1: Observed and predicted event yields for the ee, $\mu\mu$, eμ, eee and e$\mu\mu$ event classes. The errors on the prediction include model uncertainties and experimental systematic errors added in quadrature.

H1 Preliminary 275 pb^{-1} (1994–2005)

Selection	Data	SM	Pair Production	NC-DIS + Compton
e^+p collisions (156 pb^{-1})				
ee M_{12} >100 GeV	3	0.44 ± 0.10	0.29 ± 0.09	0.15 ± 0.04
$\mu\mu$ $M_{\mu\mu}$ >100 GeV	0	0.03 ± 0.02	0.03 ± 0.02	—
eμ $M_{e\mu}$ >100 GeV	0	0.29 ± 0.03	0.29 ± 0.03	—
eee M_{12} >100 GeV	3	0.29 ± 0.06	0.29 ± 0.06	—
e$\mu\mu$ $M_{e\mu}$ >100 GeV	1	0.04 ± 0.01	0.04 ± 0.01	—
e$\mu\mu$ $M_{\mu\mu}$ >100 GeV	1	0.015 ± 0.007	0.015 ± 0.007	—
e^-p collisions (119 pb^{-1})				
ee M_{12} >100 GeV	0	0.42 ± 0.11	0.23 ± 0.06	0.19 ± 0.06
$\mu\mu$ $M_{\mu\mu}$ >100 GeV	0	0.02 ± 0.02	0.02 ± 0.02	—
eμ $M_{e\mu}$ >100 GeV	0	0.24 ± 0.04	0.24 ± 0.04	—
eee M_{12} >100 GeV	0	0.18 ± 0.05	0.18 ± 0.05	—
e$\mu\mu$ $M_{e\mu}$ >100 GeV	0	0.03 ± 0.01	0.03 ± 0.01	—
e$\mu\mu$ $M_{\mu\mu}$ >100 GeV	0	0.004 ± 0.003	0.004 ± 0.003	—

Table 2: Yields for high di-lepton masses, $M > 100$ GeV in all analysed samples. For the eee sample, the mass of the two highest P_T electrons is shown. The errors on the prediction include model uncertainties and experimental systematic errors added in quadrature.

H1 Preliminary 275 pb^{-1} (1994–2005)

Selection	Data	SM	Pair Production	NC-DIS + Compton
e^+p $\sum P_T$ >100 GeV	4	0.6 ± 0.1	0.49 ± 0.09	0.11 ± 0.04
e^-p $\sum P_T$ >100 GeV	0	0.5 ± 0.1	0.37 ± 0.10	0.13 ± 0.04
All $\sum P_T$ >100 GeV	4	1.1 ± 0.2	0.86 ± 0.18	0.24 ± 0.06

Table 3: Yields of events with $\sum P_T > 100$ GeV for the combination of di- and tri-leptons. The errors on the prediction include model uncertainties and experimental systematic errors added in quadrature.

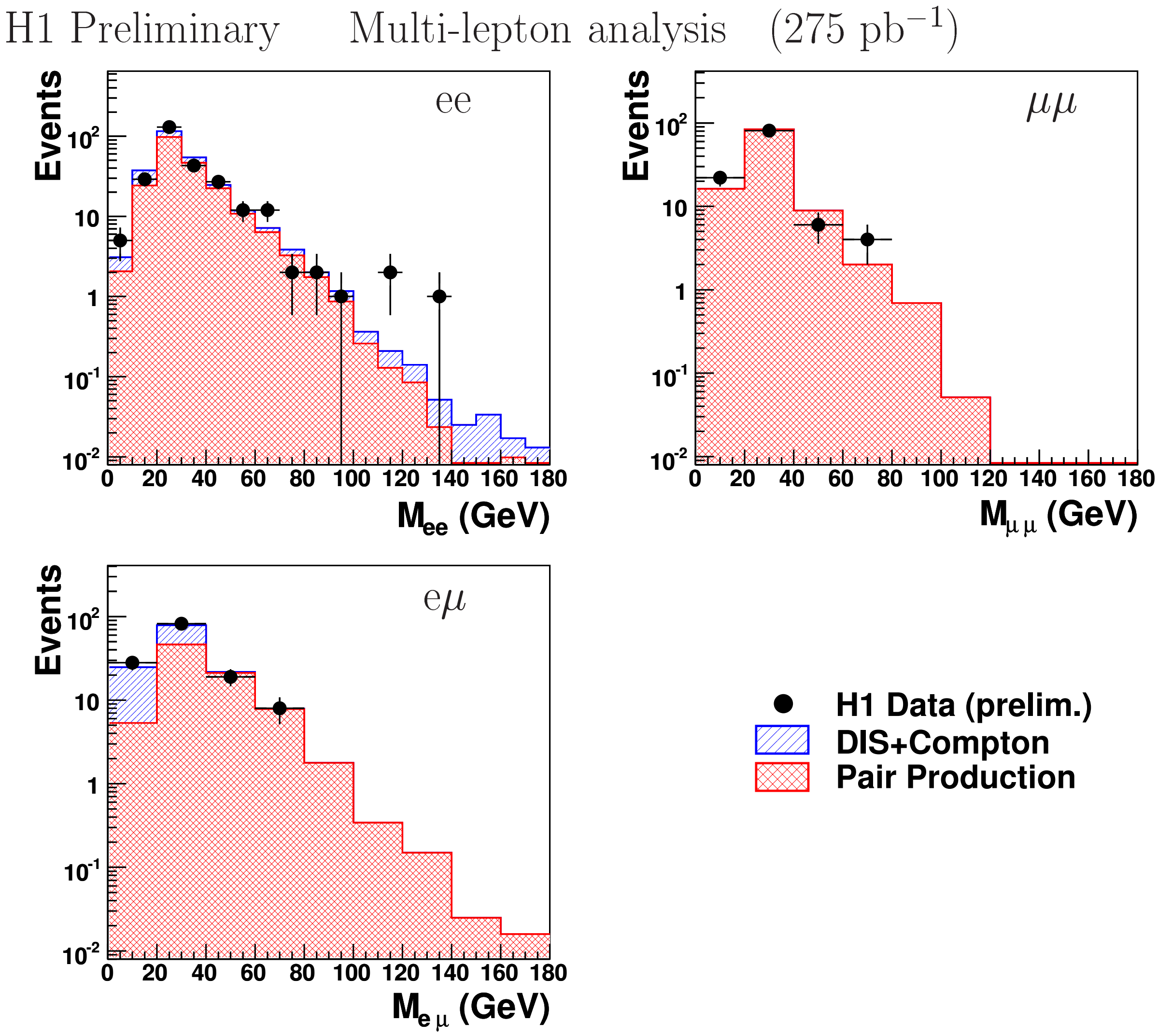

Figure 1: Distribution of the invariant mass M of the two leptons compared to expectations for events classified as ee, $\mu\mu$ and eμ.

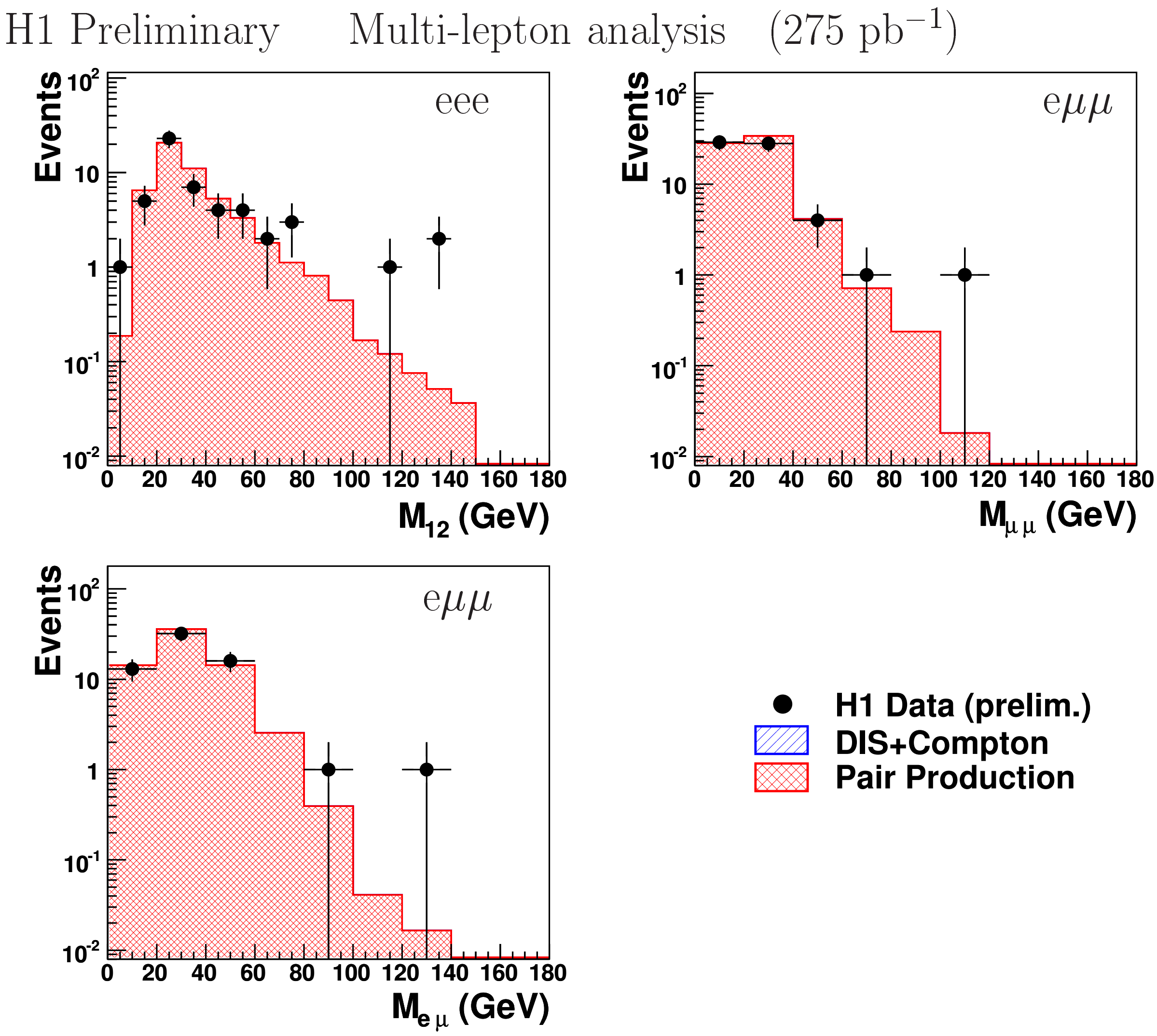

Figure 2: Distribution of the invariant mass M_{12} of the two highest P_T electrons for the eee sample (top left). For the e$\mu\mu$ sample, invariant mass combinations of the electron with the higest P_T muon ($M_{e\mu}$, bottom left) and of both muons ($M_{\mu\mu}$, top right) are presented. In the tri–lepton channels the background contribution from NC-DIS or Compton events is negligible.

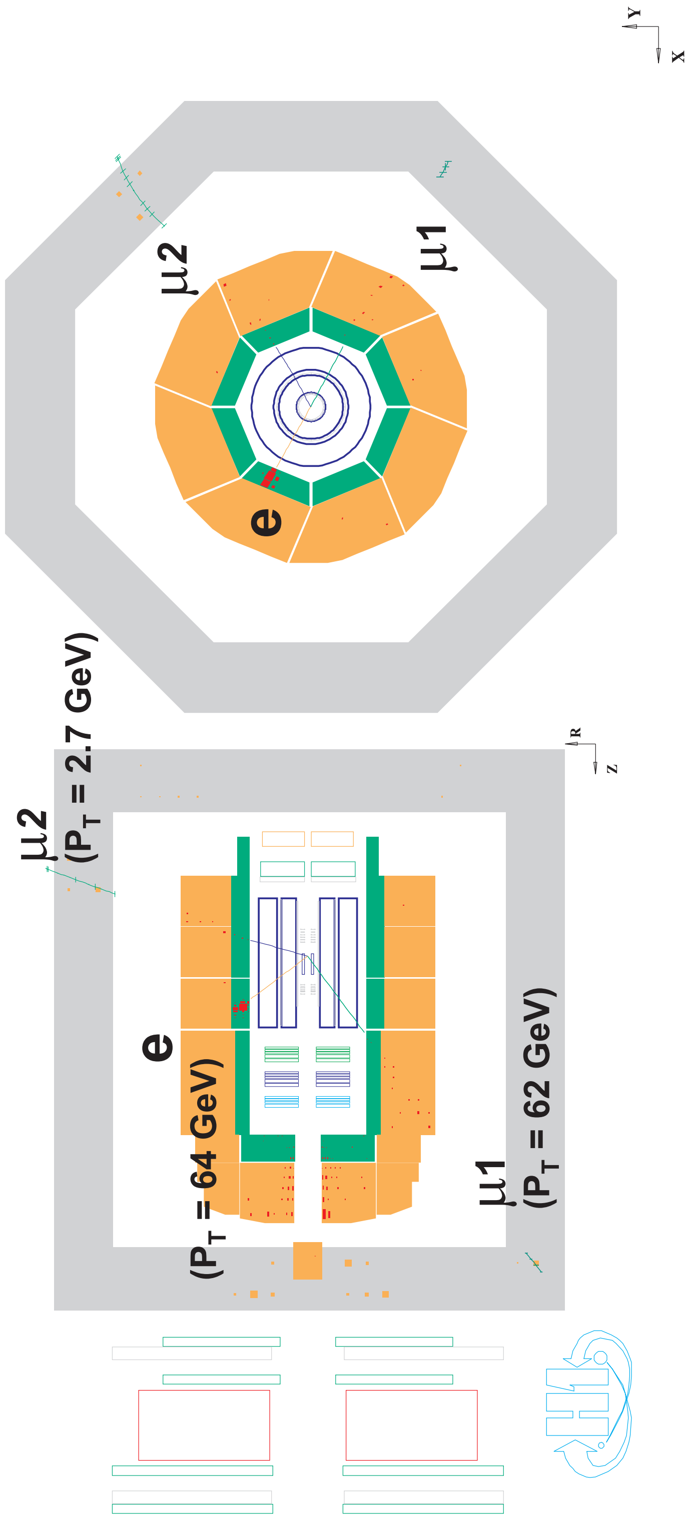

Figure 3: Display of the $e\mu\mu$ event with a scalar sum of transverse momenta of the leptons $\sum P_T > 100$ GeV, observed in the new HERA II data.

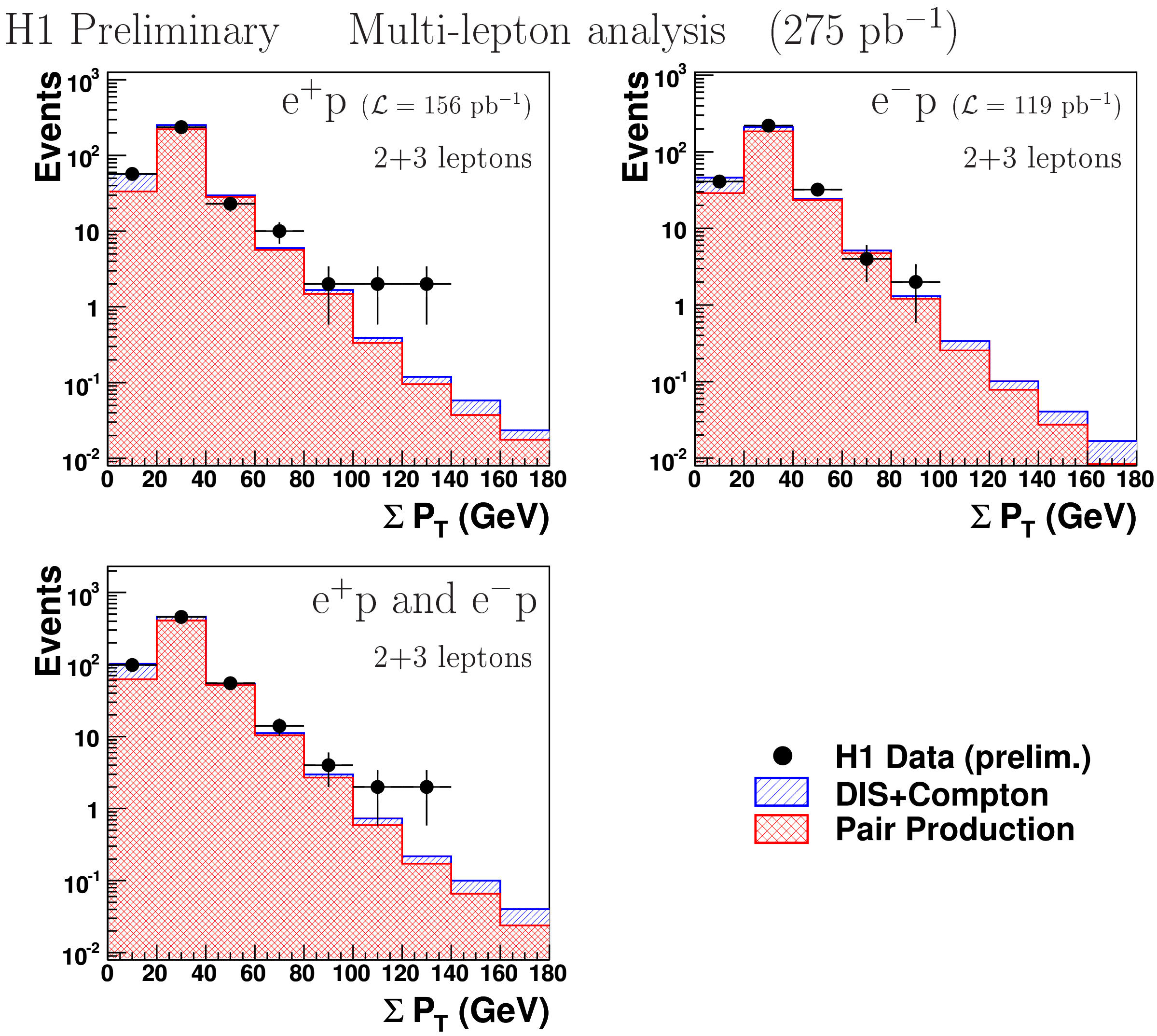

Figure 4: Distributions of the scalar sum of the transverse momenta of the combination of 2 and 3 leptons events compared to expectations for data taken in e^+p (upper left) and e^-p (upper right) collisions. The combination of all HERA data is shown in the bottom figure.