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Analysis of High P_T HERA II Data

H1 Collaboration

Abstract

Searches for events with isolated leptons and missing transverse momentum, for multi–lepton events and a general search for new phenomena are performed on a data sample collected in $e^{\pm}p$ collisions with the H1 detector at HERA in the period 1994–2004. This data sample corresponds to an integrated luminosity of 163 pb^{-1}, which includes 45 pb^{-1} of $e^{+}p$ data recently taken in the new HERA II phase.

1 Search for Events with Isolated Electrons or Muons and Missing Transverse Momentum

The search for events containing isolated leptons and missing transverse momentum is performed in the new HERA II data using the same selection as for HERA I. Seven events in the electron channel and one event in the muon channel are found in the recent HERA II data compared to Standard Model predictions of 4.1 $\pm$ 0.6 and 1.2 $\pm$ 0.2, respectively. Events with large hadronic transverse momentum are observed in the new data, similar to the previous observation at HERA I.

1.1 Introduction

The H1 Collaboration has reported the observation of events with energetic isolated electrons or muons associated with missing transverse momentum [1]. The analysis included the full HERA I data sample corresponding to an integrated luminosity of 118 pb^{-1}. Presented here is an update of the published analysis, including the new e^+p data sample accumulated at HERA II from October 2003 to July 2004, corresponding to an integrated luminosity of 45 pb^{-1}.

Standard Model (SM) "signal" processes are defined as those events which contain a genuine high P_T isolated lepton accompanied by genuine, large missing transverse momentum. The dominant SM process that may produce events with this topology is the production of real W bosons with subsequent leptonic decay. In the SM W bosons are mainly produced in the photoproduction regime. "Background" processes also contribute to the measurement when either the isolated lepton or the missing transverse momentum is faked. Main contributions to the background are due to neutral current and charged current deep inelastic scattering and to the lepton pair production.

In the HERA I data, the H1 Collaboration observe 11 electron events and 8 muon events compared to a SM expectation of 11.5 $\pm$ 1.5 and 2.9 $\pm$ 0.5, respectively. At large hadronic transverse momentum $P_T^X > 25$ GeV, 5 electron events and 6 muon events are observed compared to a SM expectation of 1.8 $\pm$ 0.3 and 1.7 $\pm$ 0.3 respectively. The dominant contribution to the SM expectation arises from signal processes.

1.2 Analysis of HERA II Data

The event selection is identical to that used in the HERA I analysis and is detailed in table 1. The main selection requirements are as follows. The lepton should have high transverse momentum P_T^l, should have a polar angle θ_l corresponding to the central region of the detector, and should be isolated with respect to jets and other tracks in the event. The isolation of the lepton is quantified using the distances in $\eta - \phi$ space to the nearest jet D_{jet} and the nearest track D_{track}. The event should contain a large transverse momentum imbalance, both measured in the calorimeter, P_T^{calo} and over the complete event, P_T^{miss}. In order to reduce background contributions, further cuts are applied using variables sensitive to the presence of high energy undetected particles in the event: the azimuthal balance of the event $\frac{V_{ap}}{V_p}$, the difference in azimuthal angle between

Variable	Electron	Muon
θ_l	$5^\circ < \theta_l < 140^\circ$	
P_T^l	> 10 GeV	
$P_T^{\rm calo}$	> 12 GeV	
$P_T^{\rm miss}$	> 12 GeV	
P_T^X	–	> 12 GeV
D_{jet}	> 1.0	
D_{track}	> 0.5 for $\theta_e \geq 45^\circ$	> 0.5
ζ_l^2	> 5000 GeV^2 for $P_T^{\rm calo} < 25$ GeV	–
$\frac{V_{ap}}{V_p}$	< 0.5 (< 0.15 for $P_T^e < 25$ GeV)	< 0.5 (< 0.15 for $P_T^{\rm calo} < 25$ GeV)
$\Delta\phi_{l-X}$	$< 160^\circ$	$< 170^\circ$
# isolated μ	0	1
$\delta_{\rm miss}$	> 5 GeV †	–

† *if only one e candidate is detected, which has the same charge as the beam lepton.*

Table 1: Selection requirements for the electron and muon channels in the search for events with isolated leptons and missing transverse momentum.

the lepton and the hadronic system, $\Delta\phi_{l-X}$, and the longitudinal momentum imbalance δ_{miss}. Further details on these variables and the event selection can be found in [1].

The analysis of the HERA II data yields seven electron events and one muon event for an expectation of 4.1 ± 0.6 and 1.2 ± 0.2 respectively. The SM prediction is dominated by signal processes, mainly real W production. Table 2 summarises the results obtained from the analysis of the HERA II data sample. The P_T^X distribution for the electron and muon channels combined for the HERA II data is displayed in figure 1. In the electron channel a slight excess of events is observed in the data compared to the SM expectation for $P_T^X > 25$ GeV. The isolated electron charge is negative in one event and positive in the other six events, including all three candidates at large $P_T^X > 25$ GeV. The observation of one muon event in the data is in agreement with the SM predicted event yield. The muon charge is positive in this event. The signal is expected to produce similar yields for both lepton charges. The same is true for all background processes except neutral current DIS, which represents about a half of the background in the electron channel, and which produces mainly positively charged candidates.

Figure 2 displays one of the HERA II electron events. It shows a high P_T electron and large missing transverse momentum. The absence of any reconstructed hadronic system X makes this event a candidate for elastic W production. Figure 3 shows a HERA II electron event with high P_T^X. Similar features are visible to those in figure 2: a high P_T electron and large missing transverse momentum. However, also present in this event is a prominent hadronic jet, giving rise to the large P_T^X.

The increase of the data sample with respect to the published HERA I analysis is, at the present time, modest at about 40%. Nevertheless, events with $\ell + P_T^{\rm miss}$ topology have also been observed in the HERA II data sample, including events containing prominent hadronic system. Table 3 shows the combined results for the HERA I and HERA II searches for events containing isolated electrons or muons and large missing transverse momentum, corresponding to an integrated luminosity of 163 pb^{-1}. In both channels the SM expectation is dominated by signal processes, the main contribution arising from real W production. Combining the electron and muon channels, 27 events are observed in the full data sample, for an expectation from SM processes of 19.5±2.8. At large hadronic momentum $P_T^X > 25$ GeV, 14 events are observed in the data for an expectation of 5.1±1.0. The probability for the SM expectation to fluctuate to the observed number of events or more is 0.0022 for $P_T^X > 25$ GeV, compared to 0.0015 reported for the same region in the HERA I data. The P_T^X distribution in the electron and muon channels combined for the combined HERA I and HERA II data is displayed in figure 4.

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[1] V. Andreev *et al.* [H1 Collaboration], Phys. Lett. B **561** (2003) 241 [hep-ex/0301030].

H1 Preliminary, HERA II data $\mathcal{L} = 45$ pb^{-1}

Electron	H1 Data	SM expectation	SM Signal
Total	7	4.08 $\pm$ 0.58	2.69 $\pm$ 0.40
$P_T^X > 25$ GeV	3	0.74 $\pm$ 0.16	0.52 $\pm$ 0.08

Muon	H1 Data	SM expectation	SM Signal
Total	1	1.20 $\pm$ 0.16	0.94 $\pm$ 0.14
$P_T^X > 25$ GeV	0	0.76 $\pm$ 0.11	0.57 $\pm$ 0.09

Combined	H1 Data	SM expectation	SM Signal
Total	8	5.28 $\pm$ 0.68	3.63 $\pm$ 0.55
$P_T^X > 25$ GeV	3	1.50 $\pm$ 0.24	1.09 $\pm$ 0.17

Table 2: The results of the search for events with isolated electrons or muons and missing transverse momentum in the HERA II data ($\mathcal{L}$=45 pb^{-1}): observed and predicted numbers of events in the electron channel, the muon channel and the sum of electron and muon channels. The signal component of the SM expectation, dominated by real W production, is also given. The quoted errors contain statistical and systematic uncertainties added in quadrature.

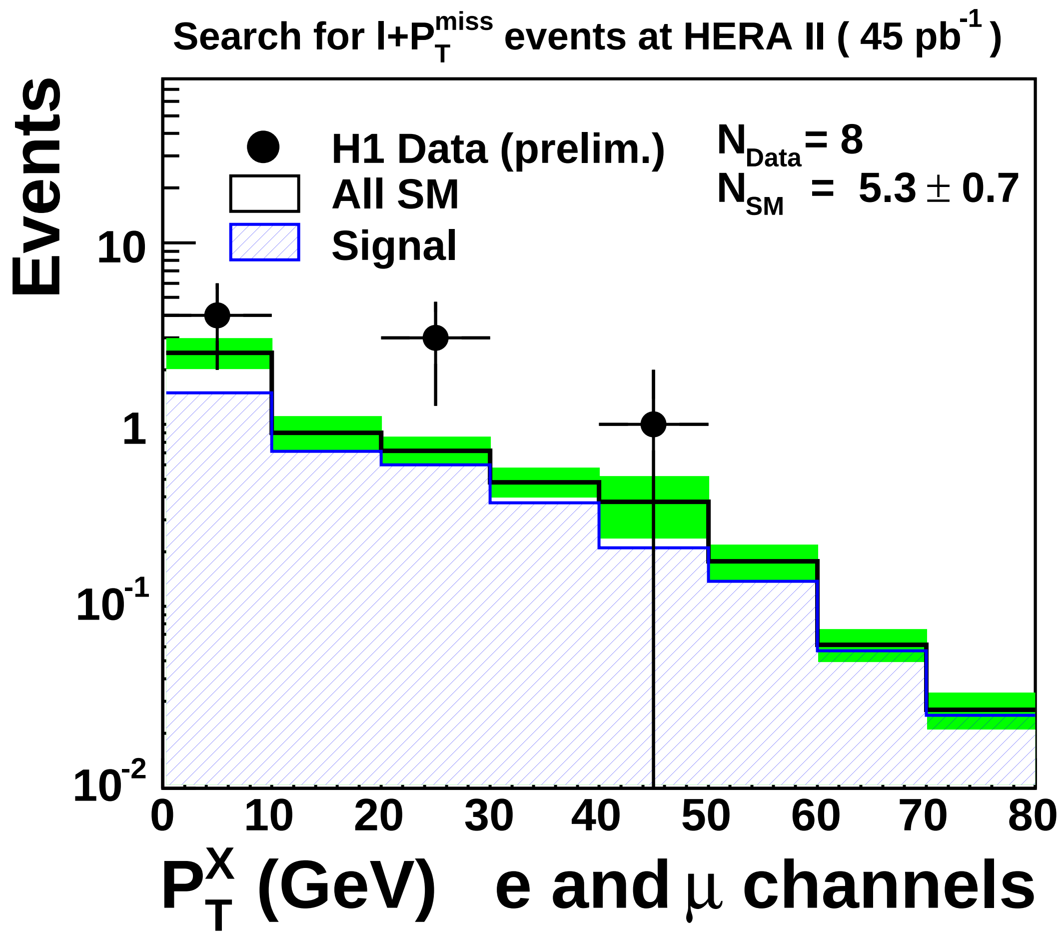

Figure 1: The hadronic transverse momentum distribution in the electron and muon channels combined: data (HERA II, $\mathcal{L} = 45$ pb^{-1}) are compared to the SM expectation (open histogram). The signal component of the SM expectation, dominated by real W production, is given by the hatched histogram. $\mathrm{N_{Data}}$ is the total number of data events observed, $\mathrm{N_{SM}}$ is the total SM expectation. The total error on the SM expectation is given by the shaded band.

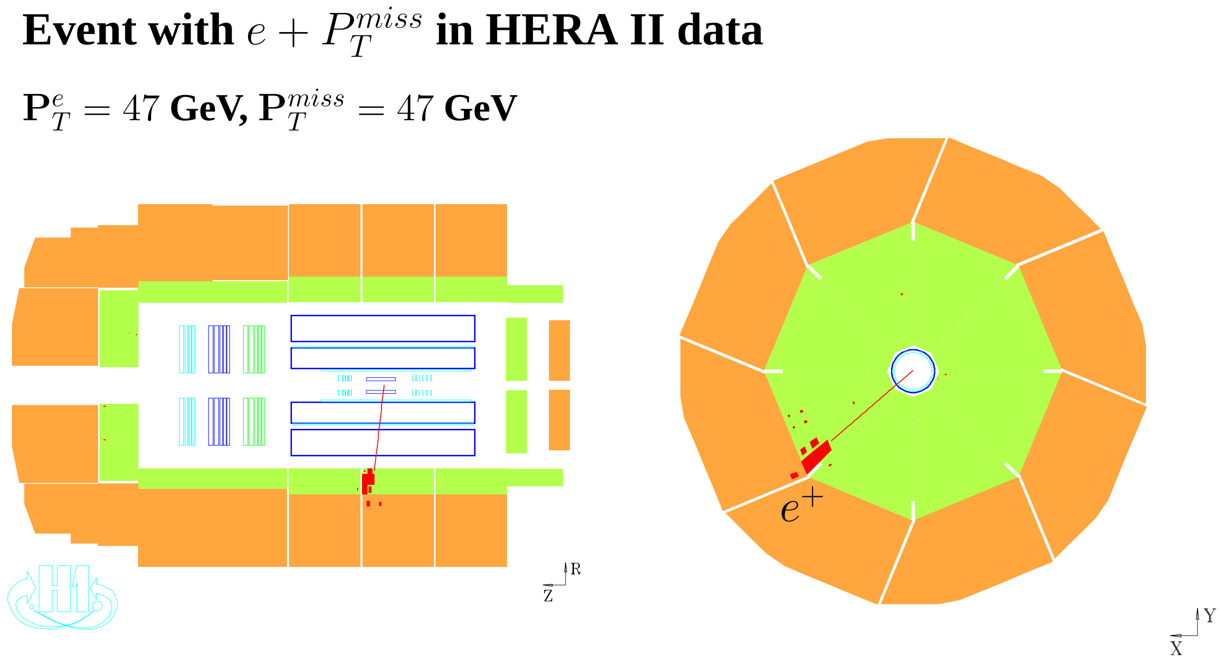

Figure 2: Display of an event with an isolated electron and missing transverse momentum: a candidate for elastic W production (HERA II data).

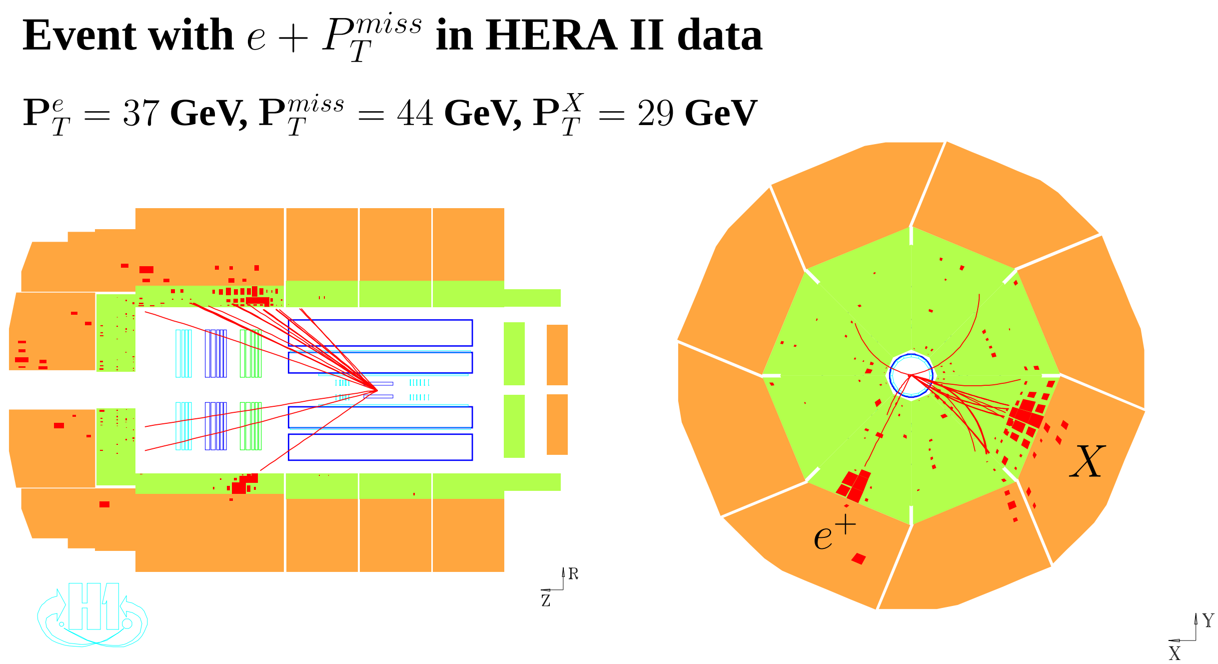

Figure 3: Display of an event with an isolated electron, missing transverse momentum and a prominent hadronic jet (HERA II data).

H1 Preliminary

1994-2004 $e^{\pm}p$ $\mathcal{L} = 163$ pb^{-1}	Electron obs./exp. (signal contribution)	Muon obs./exp. (signal contribution)	Combined obs./exp. (signal contribution)
Full sample	18 / 15.4±2.1 (71%)	9 / 4.1±0.7(86%)	27 / 19.5±2.8(74%)
$P_T^X > 25$ GeV	8 / 2.6±0.5(82%)	6 / 2.5±0.5 (88%)	14 / 5.1±1.0 (85%)

Table 3: Summary of the H1 results of searches for events with isolated electrons or muons and missing transverse momentum in the full HERA data set ($\mathcal{L}$=163 pb^{-1}). The results are shown for the full selected sample and for the subsample at large $P_T^X > 25$ GeV. The number of observed events is compared to the SM prediction. The signal component of the SM expectation, dominated by real W production, is given as a percentage in parentheses. The quoted errors contain statistical and systematic uncertainties added in quadrature.

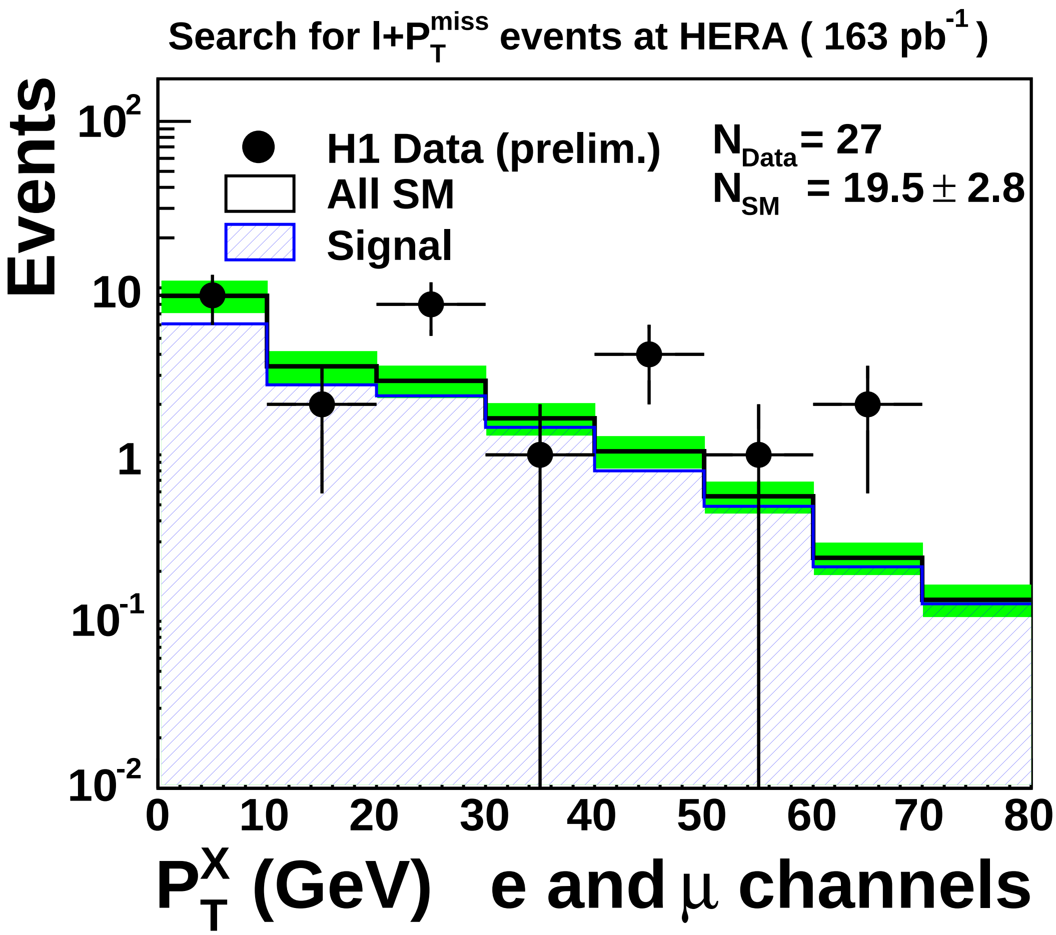

Figure 4: The hadronic transverse momentum distribution in the electron and muon channels combined: data (full HERA data set, $\mathcal{L} = 163$ pb^{-1}) arecompared to the SM expectation (open histogram). The signal component of the SM expectation, dominated by real W production, is given by the hatched histogram. $\mathrm{N_{Data}}$ is the total number of data events observed, $\mathrm{N_{SM}}$ is the total SM expectation. The total error on the SM expectation is given by the shaded band.

2 Multi-lepton Analysis

Multi-lepton (electron or muon) production is measured at high transverse momentum using the full HERA data sample. In addition to an update of the published HERA I multi-electron and multi-muon analyses, new topologies with high P_T electrons and muons are investigated here for the first time. Yields of di-lepton and tri-lepton events are measured and a general good agreement is found with the Standard Model predictions. However, combining all channels, four events are observed with a scalar sum of lepton transverse momenta greater than 100 GeV, compared to a Standard Model expectation of 0.61 ± 0.11.

2.1 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]. 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 ($\mathcal{L} = 45$ pb^{-1}) with the previous HERA I data sample from 1994–2000 ($\mathcal{L} = 118$ pb^{-1}).

2.2 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.

2.3 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. 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 forward muon system or the inner tracking systems associated with a track segment or an energy deposit in the instrumented iron [10]. The momentum of the muons detected in the forward muon detector is measured from the curvature in a toroidal magnetic field. 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 is separated from the closest jet and from any good quality track by 1 unit in the $\eta - \phi$ plane. Muon canditates are also required to be isolated from other leptons by at least 0.5 units 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 requirements. 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$\mu\mu$.

2.4 Results

The event yields observed in all channels are summarised in table 4. The observed event yields are in good agreement with SM expectations, which are dominated by pair production. In addition to the events in the classes listed, one event is classified as $ee\mu$. Upon closer inspection, this event is consistent with an $e\mu$ topology with an additional radiated low P_T photon. 0.92 $\pm$ 0.56 such events are expected. One event is identified as a four lepton event, compared to a SM expectation of 0.56 $\pm$ 0.14, which is domintated by three lepton events containing a radiated photon. The data event is consistent with this explanation. Such events enter the sample because no tracks are required to be associated with the electron cluster at the most backward angles ($\theta > 150°$). No event with three muons is observed.

The distributions of the invariant mass of the two leptons in the di-lepton event classes are presented in figure 5. 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 0.44 $\pm$ 0.10 (see table 5). The distribution of the invariant mass M_{12} of the two highest P_T electrons for the eee sample is shown in figure 6, 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 5. 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 7.

The distributions of the scalar sum of P_T of all identified leptons for the di and tri–lepton samples and the combination of both is shown in figure 8. For $\sum P_T >$ 100 GeV 4 events are observed in all channels combined while 0.61 $\pm$ 0.11 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.

2.5 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 new HERA II data corresponding to a luminosity of 45 pb$^{-}1$. 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 and 0.61 $\pm$ 0.11 are expected.

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H1 Preliminary 163 pb^{-1} (HERA I+II)

Selection	Data	SM	Pair Production (GRAPE)	NC-DIS + Compton
ee	147	149.8 ± 24.8	125.5 ± 13.0	24.3 ± 18.7
$\mu\mu$	66	63.7 ± 12.7	63.7 ± 12.3	—
eμ	86	78.4 ± 12.0	46.4 ± 3.8	31.9 ± 9.9
eee	24	30.4 ± 3.9	30.41 ± 3.9	0.04 ± 0.06
e$\mu\mu$	41	39.5 ± 6.5	39.5 ± 6.5	—

Table 4: Observed and predicted event yields for the ee, $\mu\mu$, eμ, eee and e$\mu\mu$ event classes. The analysed data sample corresponds to an integrated luminosity of 163 pb^{-1} of HERA I and II data. The errors on the prediction include model uncertainties and experimental systematic errors added in quadrature.

H1 Preliminary 163 pb^{-1} (HERA I+II)

Selection	Data	SM	Pair Production (GRAPE)	NC-DIS + Compton
ee M_{12} >100 GeV	3	0.44 ± 0.10	0.32 ± 0.10	0.12 ± 0.03
$\mu\mu$ $M_{\mu\mu}$ >100 GeV	0	0.04 ± 0.02	0.04 ± 0.02	—
eμ $M_{e\mu}$ >100 GeV	0	0.31 ± 0.03	0.31 ± 0.03	—
eee M_{12} >100 GeV	3	0.31 ± 0.08	0.31 ± 0.08	—
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	0.02 ± 0.01	0.02 ± 0.01	—

Table 5: 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 analysed data sample corresponds to an integrated luminosity of 163 pb^{-1} of HERA I and II data. The errors on the prediction include model uncertainties and experimental systematic errors added in quadrature.

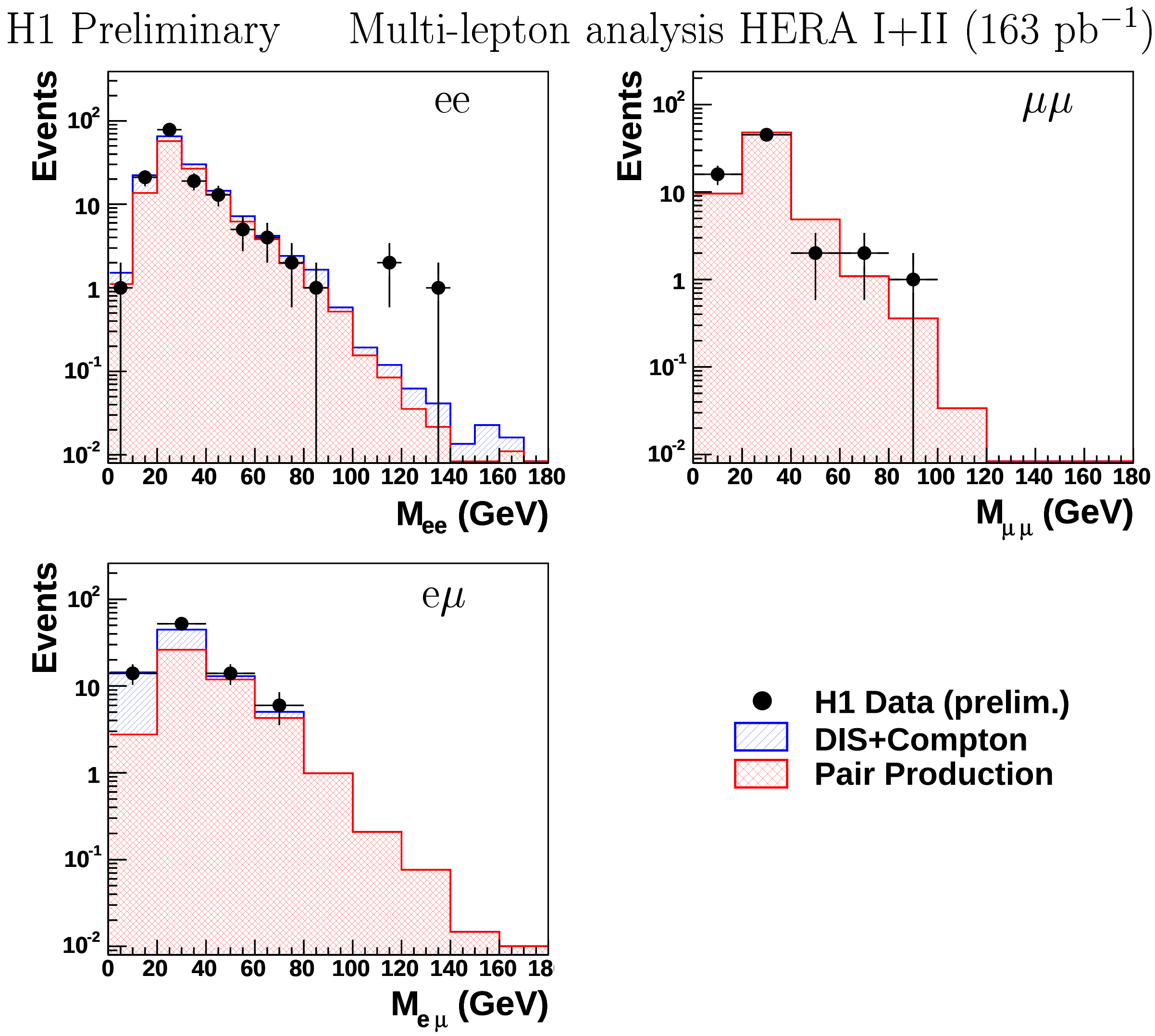

Figure 5: Distibution of the invariant mass M of the two leptons compared to expectations for events classified as ee, $\mu\mu$ and eμ. The analysed data sample corresponds to an integrated luminosity of 163 pb^{-1} of HERA I and II data.

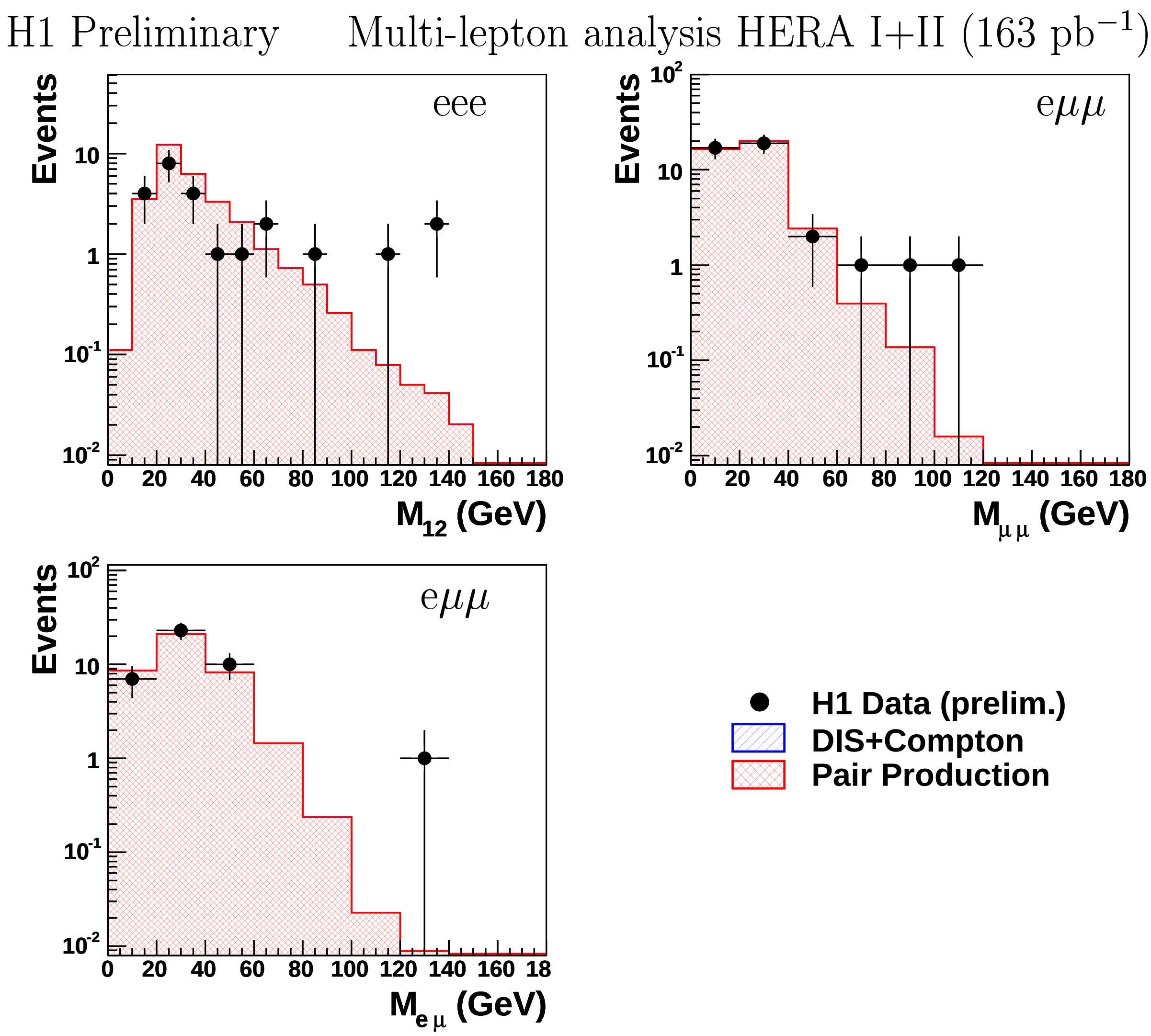

Figure 6: Distribution of the invariant mass M_{12} of the two highest P_T electrons for the eee sample (top left). For the e$\mu\mu$ sample, invariant mass combinations of the electron with the higest P_T muon ($M_{e\mu}$, bottom left) and of both muons ($M_{\mu\mu}$, top right) are presented. The analysed data sample corresponds to an integrated luminosity of 163 pb^{-1} of HERA I and II data.

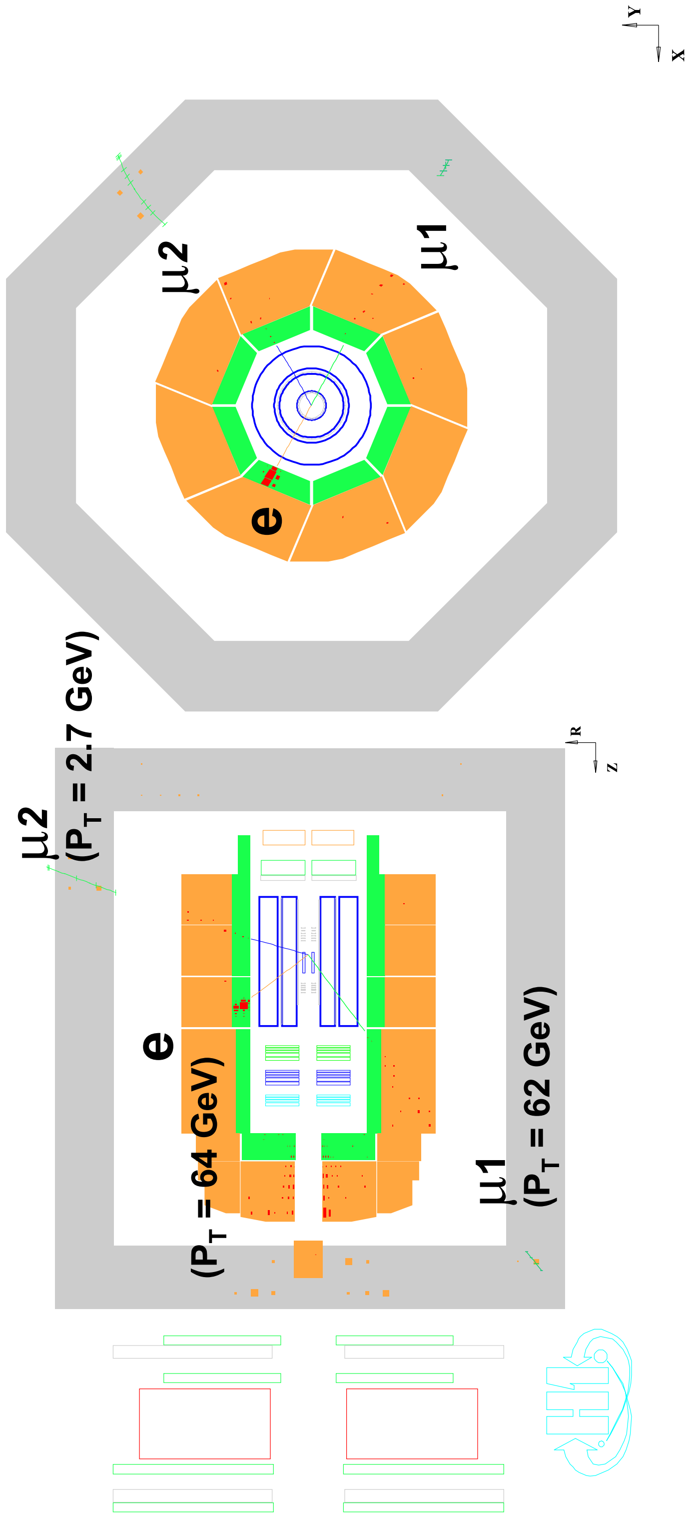

Figure 7: Display of the e$\mu\mu$ event with a scalar sum of transverse momenta of the leptons $\sum P_T > 100$ GeV, observed in the new HERA II data.

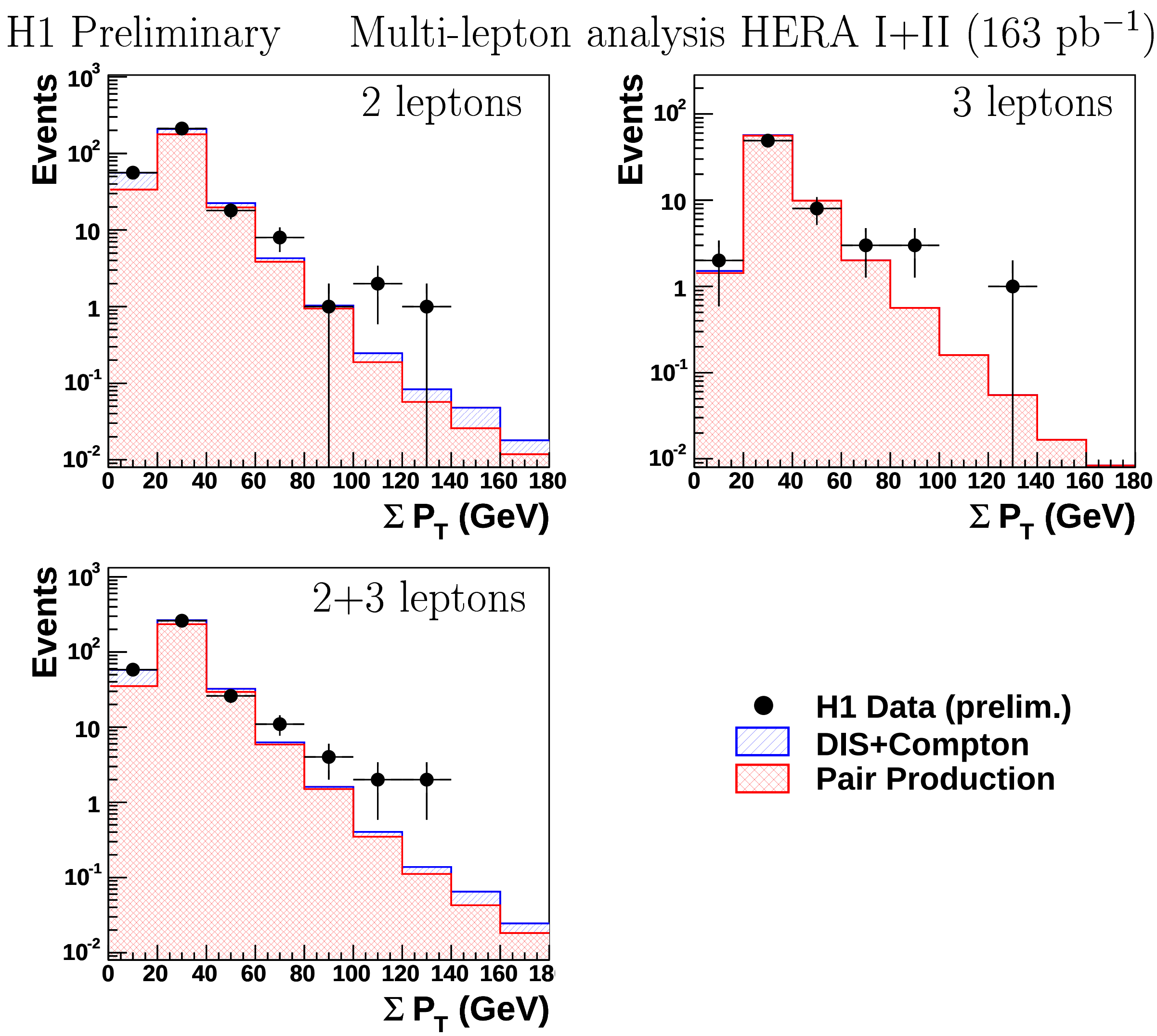

Figure 8: Distributions of the scalar sum of the transverse momenta of leptons compared to expectations in all two-lepton and three-lepton event classes and for the combination of both samples. The analysed data sample corresponds to an integrated luminosity of 163 pb^{-1} of HERA I and II data.

3 General Search Analysis

3.1 Introduction

The general search for new physics involving high P_T particle production consists of a comprehensive and generic search for deviations from the SM prediction using all high P_T final state configurations involving electrons (e), muons (μ), jets (j), photons (γ) or neutrinos (ν). The analysis covers phase space regions where the SM prediction is sufficiently precise to detect anomalies and does not rely on assumptions concerning the characteristics of any SM extension. Such a model-independent approach may discover unexpected manifestations of new physics.

Results obtained with HERA I data ($\mathcal{L} = 115$ pb^{-1}) have previously been published [1]. The results from the HERA II data sample ($\mathcal{L} = 45$ pb^{-1}) are presented here.

3.2 Analysis of HERA II Data

As in the HERA I analysis, all final states containing at least two objects (e, μ, j, γ, ν) with $P_T > 20$ GeV in the polar angle range $10^\circ < \theta < 140^\circ$ are investigated. All selected events are classified into exclusive event classes according to the number and types of objects detected in the final state, for example ej, $\mu j\nu$, $jjjj$.

Figure 9 shows the yields obtained in the various event classes. Good agreement with the SM expectation is observed in all event classes, indicating the good understanding of the SM predictions for HERA and of the H1 detector in the HERA II configuration. The majority of the events observed in the dedicated multi–lepton and isolated lepton analyses are also selected in this general analysis.

References

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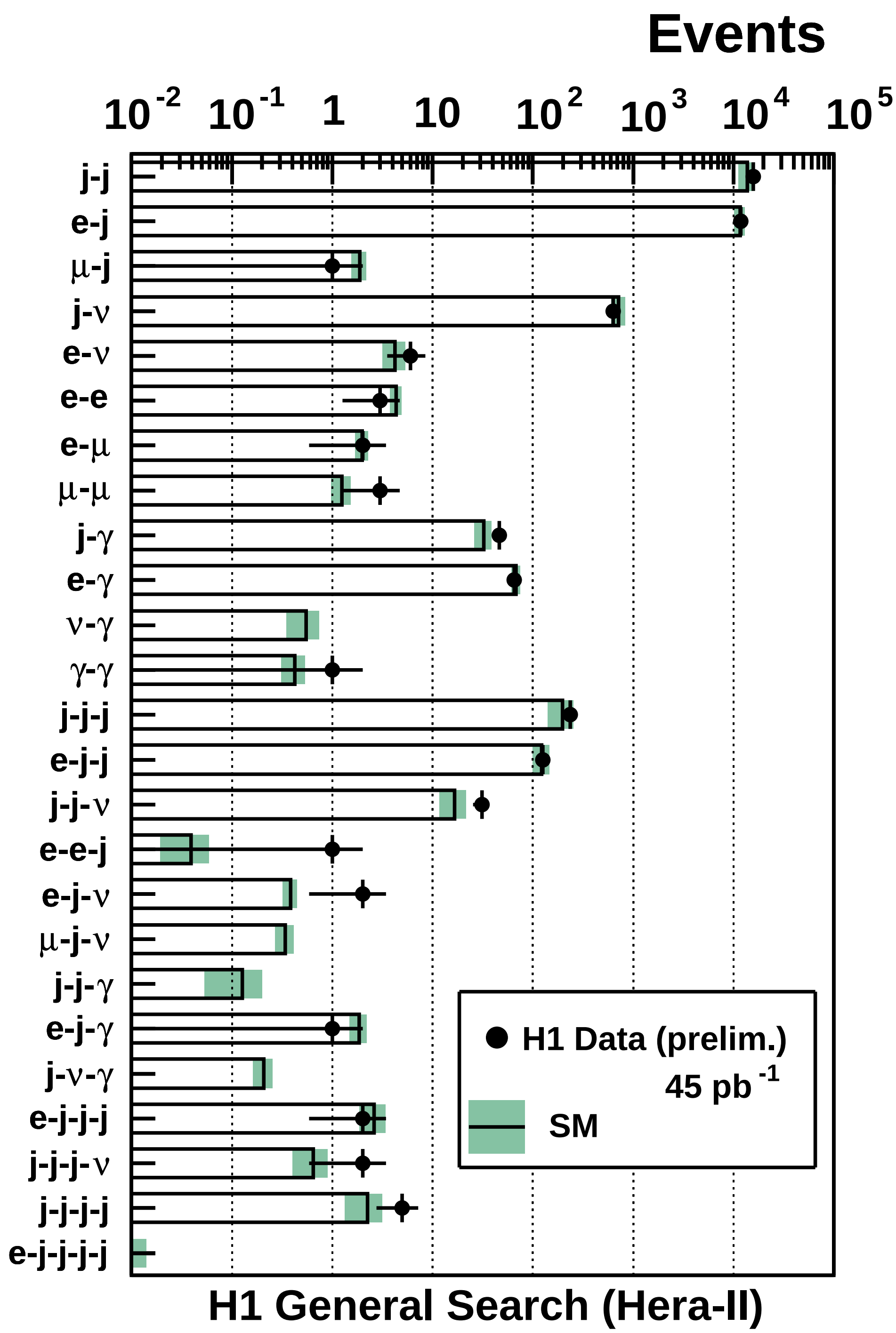

Figure 9: Results of the H1 general search using the new HERA II data (2003-2004). The analysed data sample corresponds to an integrated luminosity of 45 pb^{-1}. The errors on the prediction include model uncertainties and experimental errors added in quadrature.