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Observation of an $e^+p \rightarrow \mu^+X$ Event with High Transverse Momenta at HERA

H1 Collaboration

Abstract

At the HERA electron-proton collider an event has been observed in the H1 detector which shows an isolated muon recoiling against a hadronic system, both of high transverse momentum. The event was registered in a total integrated luminosity of $4\,\mathrm{pb}^{-1}$.

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1 Introduction

An event of unusual topology and signature has been observed in the H1 detector [1] at the HERA electron-proton storage ring. The event was recorded when HERA was colliding positrons with protons. The total data sample analysed corresponds to an accumulated luminosity of $3.2\,\mathrm{pb}^{-1}$ in positron ($27.5\,\mathrm{GeV}$) - proton ($820\,\mathrm{GeV}$) collisions and of $0.8\,\mathrm{pb}^{-1}$ in electron-proton collisions. Figs. 1a) and 1b) show the event as seen in views perpendicular ($R-\phi$) to and along ($R-z$) the direction of the beams. It exhibits an isolated penetrating track recoiling against a hadronic system. There is no scattered positron visible in the event.

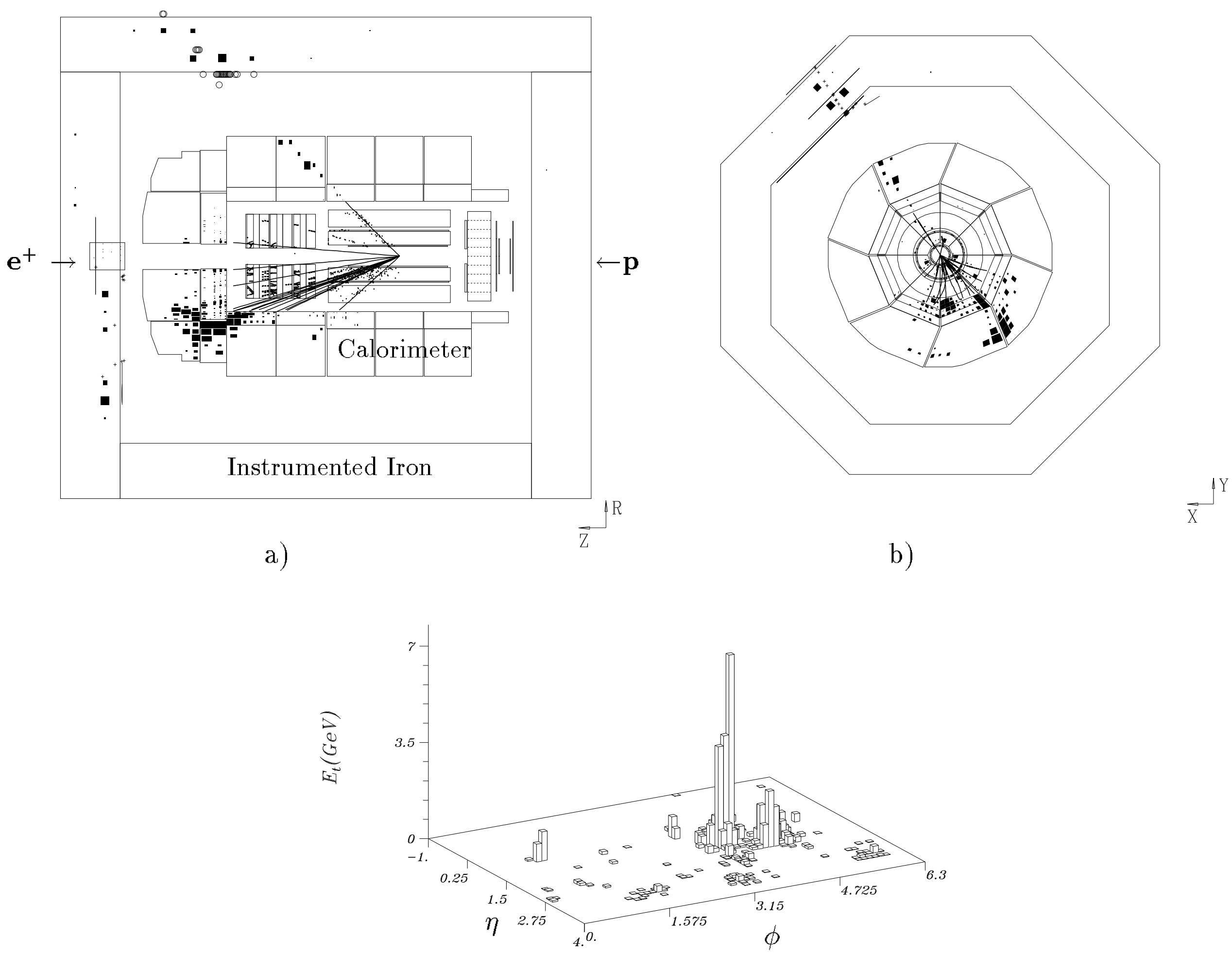

Figure 1: Event display : a) $R-z$ view b) $R-\phi$ view and c) transverse calorimetric energy

2 Data Selection

The event was found in a selection using criteria similar to those applied in the determination of the charged current cross section at HERA [2]. The main condition is the requirement that the event shows an imbalance of $P_t^{calo} \geq 25\,\mathrm{GeV}$ in the transverse (with respect to the beam directions) momentum measured by the calorimeters.

Apart from the event under consideration none of the other events fulfilling the selection criteria contain an isolated penetrating track.

3 Event Properties

The isolated track

The isolated track is measured in the central track detector, the barrel liquid argon (LAr) calorimeter and in the muon chambers of the instrumented iron return yoke. Details on the detector components are given in ref. [1].
The track parameters as determined by the central jet chamber (CJC) are given in Table 1. The track has a positive charge and a transverse momentum of $23.4 \pm 2.4^{+7}_{-5}$ GeV, where the first error quoted is of statistical nature and the second errors are conservative estimates of boundaries allowed by systematic effects. The relatively large systematic uncertainty arises because a contiguous group of CJC hits associated with the track is affected by cross talk in the readout electronics.
The track as reconstructed in the CJC was extrapolated through the calorimeter and the coil up to the instrumented iron system. Taking into account the magnetic field traversed and the expected multiple scattering and energy loss in the material along the path, the track could be successfully linked to a track reconstructed in the muon chambers. This confirms the momentum and charge measurement in the CJC and provides first evidence that the track is a muon.
The specific ionization dE/dx is measured in the CJC as 1.14 times that of a minimum ionizing particle. This is, given the dE/dx resolution of 10%, consistent with the interpretation that a single minimum ionizing track penetrates the chamber. The energy deposition in the liquid argon calorimeter (7.5 absorption lengths (λ_{abs})) is compatible with that expected from a minimum ionizing particle, although an extra energy deposition of up to 1 GeV cannot be excluded. The signal in the instrumented iron (6.3 λ_{abs}) is as expected for a single penetrating particle.
In conclusion, the signals seen in the central track detector, the calorimeter and the instrumented iron system strongly support the interpretation that the isolated track is a muon.
A primary muon signature can however be simulated by a pion. In order to produce the signature of a muon in the LAr calorimeter and in the instrumented iron system, the pion has either to decay undetected in the CJC before reaching the calorimeter or pass through the calorimeter and the iron system without obvious showering. The probability for a decay before reaching the calorimeter is $5 \cdot 10^{-4}$. This figure assumes a pion of 60 GeV momentum, which balances the transverse momentum of the hadronic system. The probability that a pion traverses the 14 λ_{abs} and leaves signals compatible with those of a muon (energy deposition, track extrapolation match, hit multiplicity) is smaller than 10^{-4} [3]. The probability to observe an isolated high momentum particle is discussed below.

The hadronic final state

The event shows a large energy deposition in the forward calorimeter ($+z$ denotes the incident proton beam direction) which can be associated with 14 charged tracks reconstructed in the tracking system. The spatial distribution of the energy is in accord with the expectation for a shower of hadronic origin. The transverse energy is distributed mainly between two clusters as seen in Fig. 1c) where the transverse energy measured in the calorimeter is shown as a function of azimuthal angle ϕ and pseudo-rapidity $\eta = -\ln(\tan(\theta/2))$, θ being the polar angle with respect to the incident proton direction. Applying a jet algorithm the two clusters would be combined into a single cone with radius less than 1 (in the $\eta - \phi$ plane). An energy deposition of 22 GeV is visible at very small angles ('proton-remnant region', $\eta > 3$) contributing only 0.4 GeV to the total transverse momentum of the hadronic final state. No energy was detected in the small angle calorimeters (the forward plug calorimeter, the backward electron tagger and the backward photon tagger [1]). The kinematic parameters of the hadronic system are given in Table 1.

The kinematic event balance

The momentum balance has been calculated from the muon momentum and the total hadronic energy deposition.

The total missing transverse momentum amounts to $P_t^{miss} = |\vec{P}_t^{\mu} + \vec{P}_t^{had}| = 18.7 \pm 4.8^{+5}_{-7}\,\mathrm{GeV}$. This suggests that particles carrying transverse momentum have escaped detection. There is also a deficit seen in the value of $\delta = \sum E(1 - \cos\theta)$, where E and θ denote the energy and angle of any detected particle. For an event where only longitudinal momentum along the proton direction ('proton-remnant region') is undetected one would expect $\delta = 2E_e$, with E_e being the energy of the incident positron. The event shows a value of $\delta = 19.2 \pm 1.6^{+3.0}_{-2.1}\,\mathrm{GeV}$.

The detector resolutions in P_t^{miss} and δ have been determined from a sample of candidates fulfilling a neutral current preselection where the transverse momentum of the scattered positron exceeds 25 GeV. In this case the positron and the recoiling hadronic shower are measured in the detector. These events are intrinsically balanced in P_t^{miss} and δ assumes a value of $2E_e$ for non-radiative events. In Fig. 2 a) the P_t^{miss} spectrum is shown while Fig. 2 b) gives the δ spectrum for these candidates.

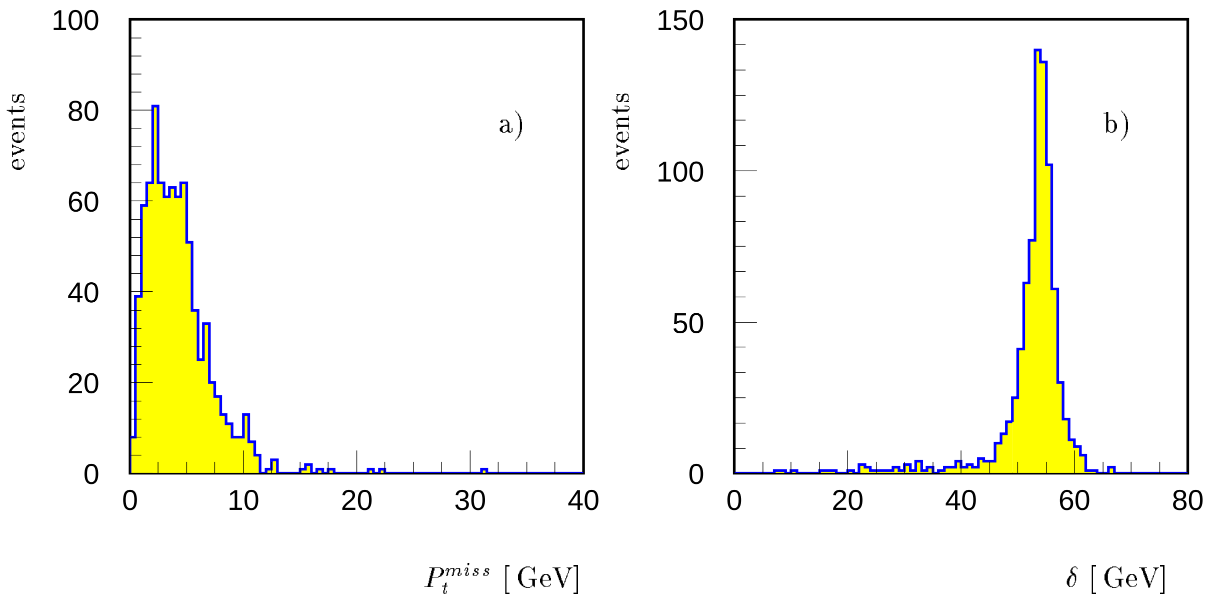

Figure 2: Candidates from a neutral current preselection a) missing transverse momentum b) $\delta = \sum E(1 - \cos\theta)$

In general, small values of δ suggest a particle leaving undetected in the direction of the incident positron beam without affecting the P_t balance. This particle could be a photon radiated from the incident positron (initial state radiation) generating the tail towards smaller values of δ as seen for the neutral current events in Fig 2 b). It could on the other hand also be the primary positron in the case of the event having a low Q^2 photoproduction origin. It has been verified that events in Fig. 2 with $\delta < 40\,\mathrm{GeV}$ can be attributed to photoproduction background or to neutral current events with large initial state radiation.

In the transverse plane the muon and the direction of the hadronic system, as derived from the calorimeter measurement, are back-to-back; the difference in azimuthal angle is $\Delta\phi = 183 \pm 1°$, where the error does not account for particles lost in the beam pipe. The imbalance in the transverse momenta shows an apparent significance of more than two standard deviations, which is, however, dominated by systematic effects.

The isolated track :	
Charge	Positive
Transverse momentum	$23.4 \pm 2.4^{+7}_{-5}$ GeV
Polar angle	$46.2 \pm 1.3°$
Azimuthal angle	$57.4 \pm 0.1°$
The total hadronic system :	
Transverse momentum	42.1 ± 4.2 GeV
Average azimuthal angle	$240 \pm 1°$
Hadronic cluster 1:	
Transverse momentum	25.3 ± 3.0 GeV
Polar angle	$22.3 \pm 0.5°$
Azimuthal angle	$227 \pm 1°$
Hadronic cluster 2 :	
Transverse momentum	15.2 ± 1.9 GeV
Polar angle	$16.5 \pm 0.5°$
Azimuthal angle	$270 \pm 1°$
Global event properties :	
Missing transverse momentum	$18.7 \pm 4.8^{+5}_{-7}$ GeV
$\delta = \sum E(1 - \cos\theta)$	$19.2 \pm 1.6^{+3.0}_{-2.1}$ GeV
$\Delta\phi$ muon-hadronic system	$183 \pm 1°$

Table 1: Event kinematics

4 Interpretation of the Event

In the following we discuss some hypotheses concerning the origin of the event:

- Production of two high P_t jets, where one jet consists of only a single particle (pion) which fakes the signature of a primary muon. This category includes heavy quark pair (charm or bottom) production with the subsequent semileptonic decay of one of the quarks.
- Production of a W-boson which decays leptonically.
- A flavour changing neutral current process $e^+ + p \rightarrow \mu^+ + X$. This process is topologically identical to the production of a leptoquark decaying into a muon and a quark.
- A background event produced by a halo muon accompanying the proton beam.

Production of high P_t jets

To evaluate the probability that the event is a high P_t^{jet} event, where one jet appears as a single muon, we use data measured by H1.

We consider the following aspects :

- **Cross section for $e + p \rightarrow jet + X$ for $P_t^{jet} \geq 40\,\mathrm{GeV}$**
  The cross section for jet production in tagged photoproduction processes has been measured by H1 [4]. The data taken in 1994 extend the measured region to $P_t^{jet} = 35\,\mathrm{GeV}$. Using the slope determined for $d\sigma/dP_t^{jet}$ in the region $20 < P_t^{jet} < 35\,\mathrm{GeV}$ for extrapolation one obtains a total (untagged) inclusive jet cross section $\sigma(P_t^{jet} \geq 40\,\mathrm{GeV}) < 10\,\mathrm{pb}$.

- **Probability that one jet fluctuates into a single charged particle**
  We use a sample of events where at least one jet has $P_t^{jet} \geq 20\,\mathrm{GeV}$. Jets with $P_t^{jet} \geq 20\,\mathrm{GeV}$ show a mean charged particle multiplicity of 8.7, the actual distribution of the multiplicity being well described by a Poisson distribution. This leads to a probability of 0.15 % that a jet consists of only a single charged particle. This probability value is an upper limit for the actual event since there is another suppression factor due to the fact that along the track no electromagnetic energy deposition (photons from π^0 decays) has been seen, which is not taken into consideration here.

Combining the jet production cross section, the probabilities for a fluctuation into a single pion and for the pion to fake a primary muon signature results in an expected cross section for this event topology of $\sigma < 2 \cdot 10^{-2}\,\mathrm{fb}$, thus rendering this interpretation unlikely.

- **Heavy quark production and semileptonic decay**
  The inclusive muon cross section measured by H1 [5] up to a $P_t^{\mu} = 10\,\mathrm{GeV}$ is in agreement with the yield expected from a simulation of heavy quark (charm and bottom) production. The cross sections for these processes decrease strongly with increasing P_t^{μ} and missing transverse momentum P_t^{miss}. From a semileptonic heavy quark decay one would expect hadronic energy around the muon. In the event no hadrons are visible in a cone of radius one around the muon.

  To estimate the probability that the event is due to a semileptonic heavy quark decay a simulation of heavy quark production with the program PYTHIA [6] has been performed. Demanding $P_t^{\mu} > 15\,\mathrm{GeV}$, $P_t^{miss} > 10\,\mathrm{GeV}$ and a muon isolation criterion (no charged particle with $P_t > 0.5\,\mathrm{GeV}$ within a cone radius $\sqrt{\Delta\phi^2 + \Delta\eta^2}$ =0.7 around the muon) the accepted cross section for charm and bottom production is found to be less than 0.1 fb.

In summary we conclude that the probability for the event being due to the production of two high P_t jets, where one jet shows the signature of a muon, is smaller than 10^{-3}.

W Production and leptonic decay

This process was investigated using a Monte Carlo calculation based on the standard model cross section of reference [7]. Since the process is dominated by low Q^2 photoproduction the e^+ is in general not detected in the apparatus, thus resulting small values of δ for the event. The undetected neutrino causes the P_t^{miss}. The total cross section for the process $e^+p \rightarrow e^+W^+X \rightarrow e^+\mu^+\nu X$ is expected to be $\approx 40\,\mathrm{fb}$.
The cross section is dominated by low transverse momenta of the W and thus also of the recoiling hadronic system. In the event, however, the hadronic system has a $P_t = 42\,\mathrm{GeV}$. The Monte Carlo calculation shows that for $P_t > 40\,\mathrm{GeV}$ the cross section is reduced to 7 fb. With one event seen in $4\,\mathrm{pb}^{-1}$ we are left with a 3% probability for this interpretation of the event. Note that this figure assumes full acceptance.
In general the muon from the W decay has no strong correlation in azimuth with the recoiling hadronic system. However, for a W of high P_t the decay muon is expected to be oriented predominantly opposite to the jet in ϕ due to the transverse Lorentz boost (in the event it is back-to-back).
If this hypothesis is applied to the event the final state is completely determined. A scattered positron of 17.8 GeV escapes detection in the small angle electron tagger, for which the corresponding acceptance amounts to 55%. The decay neutrino of several hundred GeV is emitted under very small angles in the proton direction.

Flavour changing processes

Events of this origin (FCNC or leptoquark production) would show topologies like neutral current deep inelastic events, but with the final state positron replaced by a muon. Kinematically the events would thus be within the resolutions (see Fig. 2), balanced in P_t and a value of $\delta = 2E_e$ would be expected. The fact that less than 1% of neutral current events show a value of $\delta < 20$ GeV disfavours this interpretation.

Background processes

The event cannot be explained by the interaction of a halo muon (originating from proton interactions far downstream from the interaction point) on a residual gas nucleon since the transverse energy of the event exceeds by more than a factor of 2 the center of mass energy available in such a process. Other backgrounds not associated with the colliding beams are negligible.

5 Conclusion

In positron-proton collisions an event has been observed consisting of a muon recoiling with high transverse momentum against a hadronic system back-to-back in azimuth. The event kinematics is compatible with W production. The cross section estimate within the standard model yields an expectation of 0.03 events of this type in the data sample available. This small probability leaves room for further speculations on the origin of the event.

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