Submitted to the
International Conference on High Energy Physics
16-22 August 2004, Beijing, China

Abstract: EW 4-0231, BSM 12-0230

Sessions: Electro Weak, Beyond the Standard Model

Study of di-muon production with the ZEUS detector at HERA

ZEUS Collaboration

Abstract

A search for events containing high-transverse-momentum isolated muons has been performed with the ZEUS detector at HERA using an integrated luminosity of 101 pb^{-1}. The number of observed events with two or more muons in the final state has been compared with the prediction from the Standard Model (SM). The largest contribution from the SM is expected from photon-photon interactions. Total and differential cross sections have been measured for the process. Possible deviations from the SM, especially for di-muon events with invariant mass greater than 100 GeV, are searched for.

1 Introduction

The high centre-of-mass energy of ep collisions at HERA allows the production of events with two or more leptons with high transverse momentum (p_T). The Standard Model (SM) cross section for the production of isolated muon pairs is dominated by the two-photon process $\gamma\gamma \to \mu^+\mu^-$, depicted in Figure 1.

The production rate of such events can be accurately predicted within the Standard Model (SM). In this analysis, events with two or more muons at high p_T were selected and compared with the predictions of the SM in order to detect possible new physics beyond the SM. Such a search complements the analysis of multi electron pair production where the H1 experiment observed possible deviations from the Standard Model at large di-electron masses [1]. It is also of interest in relation to the analysis of events with a lepton and missing transverse momentum [2–4].

The analysis is based on data collected in the years between 1996 and 2000; the corresponding integrated luminosity is 101 pb^{-1}. The uncertainty on the luminosity measurement is 2%.

In the years 1996–97, HERA collided 820 GeV protons with 27.5 GeV positrons. In the period 1998–00, the proton energy was increased to 920 GeV; during the 1998–99 running period, an electron beam rather than a positron beam was used.

2 Experimental set-up

A detailed description of the ZEUS detector can be found elsewhere [5]. A brief outline of the components that are most relevant for this analysis is given below.

Charged particles are tracked in the central tracking detector (CTD) [6], which operates in a magnetic field of 1.43 T provided by a thin superconducting solenoid. The CTD consists of 72 cylindrical drift chamber layers, organized in nine superlayers covering the polar-angle[1] region $15^\circ < \theta < 164^\circ$. The transverse-momentum resolution for full-length tracks is $\sigma(p_T)/p_T = 0.0058 p_T \oplus 0.0065 \oplus 0.0014/p_T$, with p_T in GeV.

The high-resolution uranium–scintillator calorimeter (CAL) [7] consists of three parts: the forward (FCAL), the barrel (BCAL) and the rear (RCAL) calorimeters. Each part is subdivided transversely into towers and longitudinally into one electromagnetic section (EMC) and either one (in RCAL) or two (in BCAL and FCAL) hadronic sections

[1] The ZEUS coordinate system is a right-handed Cartesian system, with the Z axis pointing in the proton beam direction, referred to as the “forward direction”, and the X axis pointing left towards the centre of HERA.

(HAC). The smallest subdivision of the calorimeter is called a cell. The CAL energy resolutions, as measured under test-beam conditions, are $\sigma(E)/E = 0.18/\sqrt{E}$ for electrons and $\sigma(E)/E = 0.35/\sqrt{E}$ for hadrons (E in GeV).

The muon system consists of rear, barrel (R/BMUON) [8] and forward (FMUON) [5] tracking detectors. The B/RMUON consists of limited-streamer (LS) tube chambers placed behind the BCAL (RCAL), inside and outside a magnetized iron yoke surrounding the CAL. The barrel and rear muon chambers cover polar angles from 34° to 135° and from 135° to 171°, respectively. The FMUON consists of six trigger planes of LS tubes and four planes of drift chambers covering the angular region from 5° to 32°. The muon system exploits the magnetic field of the iron yoke and, in the forward direction, of two iron toroids magnetized to ~ 1.6 T to provide an independent measurement of the muon momentum.

The luminosity was measured using the bremsstrahlung process $ep \rightarrow ep\gamma$. The resulting small-angle energetic photons were measured by the luminosity monitor [9], a lead-scintillator calorimeter placed in the HERA tunnel at $Z = -107$ m.

3 Monte Carlo simulation

The Grape Monte Carlo event generator [10] was used to simulate di-muon events. It is based on the exact electroweak matrix elements at tree level for photon-photon (and also photon-Z^0 and Z^0-Z^0) collisions and internal photon/Z^0 conversions.

For the proton vertex, three contributions are considered: elastic, where the proton stays intact; quasi-elastic, where a resonant state is formed; and inelastic, where the proton interacts via its quark constituents.

Various Standard Model processes may constitute a background to the $ep \rightarrow \mu\mu X$ process. The sources considered in this search were:

- the decay of a Υ meson into a muon pair; this process was simulated with the Diffvm Monte Carlo program [11].

- $b\bar{b}$ and $c\bar{c}$ production, where a heavy quark decays into a lighter quark and a virtual W which subsequently decays semi-leptonically in $\mu\nu_\mu$. This processes were simulated with the Pythia Monte Carlo program [12].

4 Search for multi-muon events

Muons were selected by looking for CTD tracks matching with tracks reconstructed in the muon detectors. If only one muon in the event was reconstructed by the muon chambers, a CTD track pointing towards an energy deposit in the calorimeter, compatible with that of a minimum ionizing particle, was selected as the other muon. In cases when a muon candidate was found in the barrel or rear part of the detector, the muon momentum was taken to be the one measured by the CTD, while for muons in the forward muon chambers the momentum measured by the forward muon detector was used in the fit to match the CTD track with the FMUON track. This allowed the extention of the acceptance in the forward part of the detector beyond the normal CTD acceptance.

Events were selected if:

- a vertex was reconstructed having $|Z| < 50$ cm and $\sqrt{X^2 + Y^2} < 0.5$ cm;
- two muons were found as described above, both with $p_T^\mu > 5$ GeV;
- no tracks were found in the CTD in a cone of radius $R = 1$ in the η-ϕ plane around the muon;
- the acollinearity angle, Ω, between the two highest-p_T muons was such that $\cos\Omega > -0.995$ to eliminate cosmic ray muon background.

After this selection, the background from $c\bar{c}$ and $b\bar{b}$ was found to be negligible, and only a small contribution remained from Υ. No events were found in data with more than two muons satisfying the cuts. The comparison between the number of selected events in the data and the prediction from the SM is reported in Table 1. Reasonable agreement is found between the data and SM predictions, especially in the high-mass region. Two events with di-muon mass greater than 100 GeV were found, to be compared with an expectation of 2.16 from $\gamma\gamma$ process.

In Fig. 2 the data and SM Monte Carlo predictions are compared for transverse momentum (p_T) and polar angle (θ) of the highest- and second-highest-p_T muon, the cosine of the acollinearity angle between the two and the invariant mass ($M_{\mu\mu}$) distribution. The Υ contribution is also displayed. No excess in the high-invariant-mass region is observed. In Fig. 3 one of the di-muon events is shown.

5 Cross section measurement

Total and differential cross sections for di-muon production have been determined for events with two muons in the kinematic region defined by: $p_T^{\mu 1,2} > 5$ GeV, $12^\circ < \theta^{\mu 1,2} < 164^\circ$,

$M_{\mu\mu} > 5$ GeV. The total cross section is shown in Table 2, compared with the predictions from the GRAPE Monte Carlo. The main systematic uncertainty arises from the uncertainty with which the muon chamber efficiencies are determined [13]. Given the statistical and the systematic uncertainties, reasonable agreement is observed between the data and the SM predictions.

Differential cross sections as a function of the invariant mass, $M_{\mu\mu}$, muon transverse momentum, p_T^μ, and polar angle, θ^μ, have been measured and are shown in Figure 4. For the latter two plots, there is an entry per muon and not per event. Reasonable agreement is found between data and SM predictions.

6 Conclusions

Events with two or more muons with high transverse momentum have been selected and compared with the predictions of the Standard Model. No events with three or more muons have been found in the data. The total and differential cross sections have been measured and found to be in agreement with the Standard Model prediction, especially at high transverse momentum of the muons and at high invariant mass of the di-muon pair.

References

[1] H1 Coll., Eur. Phys. J. **C 31**, 17 (2003).

[2] H1 Coll., V. Andreev et al., Phys. Lett. **b561**, 241 (2003).

[3] ZEUS Coll., J. Breitweg et al., Phys. Lett. **B 471**, 411 (2000).

[4] ZEUS Coll., Phys. Lett. **B 583**, 41 (2003).

[5] ZEUS Coll., U. Holm (ed.), *The ZEUS Detector*. Status Report (unpublished), DESY (1993), available on `http://www-zeus.desy.de/bluebook/bluebook.html`.

[6] N. Harnew et al., Nucl. Inst. Meth. **A 279**, 290 (1989);
B. Foster et al., Nucl. Phys. Proc. Suppl. **B 32**, 181 (1993);
B. Foster et al., Nucl. Inst. Meth. **A 338**, 254 (1994).

[7] M. Derrick et al., Nucl. Inst. Meth. **A 309**, 77 (1991);
A. Andresen et al., Nucl. Inst. Meth. **A 309**, 101 (1991);
A. Caldwell et al., Nucl. Inst. Meth. **A 321**, 356 (1992);
A. Bernstein et al., Nucl. Inst. Meth. **A 336**, 23 (1993).

[8] G. Abbiendi et al., Nucl. Inst. Meth. **A 333**, 342 (1993).

[9] J. Andruszków et al., Preprint DESY-92-066, DESY, 1992;
ZEUS Coll., M. Derrick et al., Z. Phys. **C 63**, 391 (1994);
J. Andruszków et al., Acta Phys. Pol. **B 32**, 2025 (2001).

[10] T. Abe, Comp. Phys. Comm. **136**, 126 (2001).

[11] B. List and A. Mastroberardino, *Proc. Workshop on Monte Carlo Generators for HERA Physics*, p. 396. DESY, Hamburg, Germany (1999). Also in preprint DESY-PROC-1999-02, available on `http://www.desy.de/~heramc/`.

[12] T. Sjöstrand et al., Comp. Phys. Comm. **135**, 238 (2001).

[13] M. Turcato, *Open beauty photoproduction at HERA*. Ph.D. Thesis, Università di Padova, Report DESY-THESIS-03-039, 2002, available on `http://www-library.desy.de/preparch/desy/thesis/desy-thesis-03-039.ps.gz`.

Mass cut	ZEUS (prel.) 1996–00	Total SM	GRAPE	Υ
All $M_{\mu\mu}$ values	255 Events	294.9	294.7 ± 2.7	0.2
$M_{\mu\mu} > 50$ GeV	11 Events	9.12	9.11 ± 0.66	0.01
$M_{\mu\mu} > 100$ GeV	2 Events	2.16	2.16 ± 0.54	0.00

Table 1: *Comparison between the number of events selected as described in the text and the predictions from the SM Monte Carlo. The comparison is done for different values of the invariant mass of the muon pair.*

Lumi (pb^{-1})	$\sigma_{\mathrm{DATA}}^{96-00}$ (pb)	σ_{MC} (pb)
100.68	6.17 ± 0.39 (*stat.*) $^{+0.49}_{-0.43}$ (*syst.*) ± 0.12 (*lumi.*)	7.13

Table 2: *Total cross section, for di-muon events in the kinematic region defined in the text, compared with the predictions from the* GRAPE *Monte Carlo.*

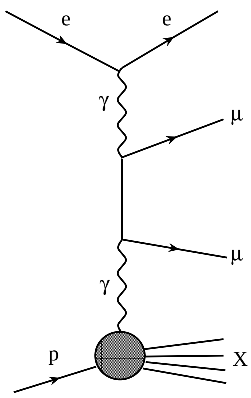

Figure 1: *Muon pair production in the two-photon process (here for the deep inelastic case).*

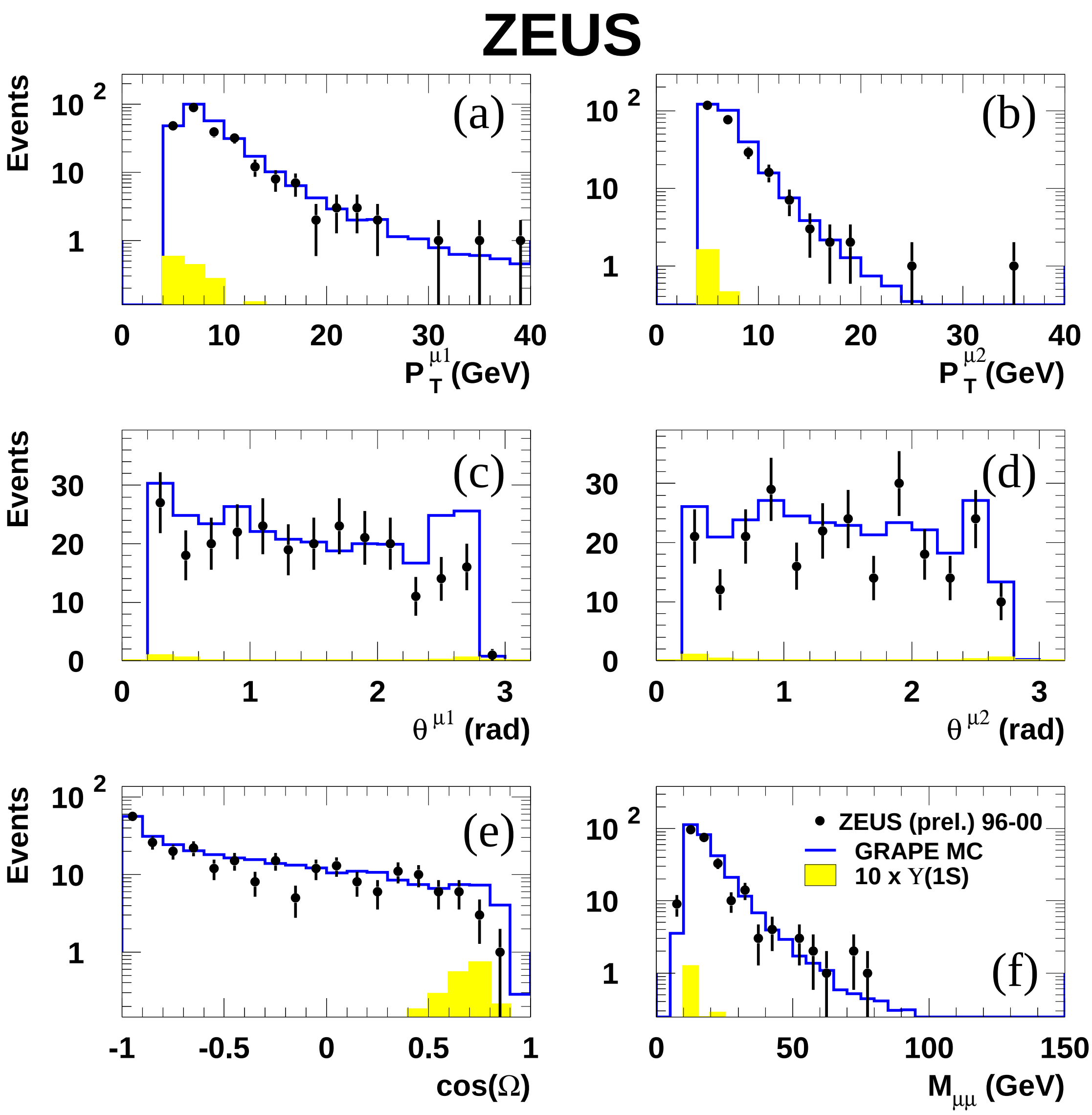

Figure 2: *Distributions of the di-muon sample compared with the predictions from the Standard Model. The data (dots) are compared with the* GRAPE *Monte Carlo predictions (solid line), normalised to the luminosity of the data. The Υ contribution, magnified by a factor 10, is shown as the shaded histogram. The plots shown: the transverse momentum p_T^μ for (a) the highest- and (b) second-highest-p_T muon, the polar angle θ^μ for (c) the highest- and (d) second-highest-p_T muon, (e) the cosine of the acollinearity angle between the two muons and (f) the invariant mass distribution.*

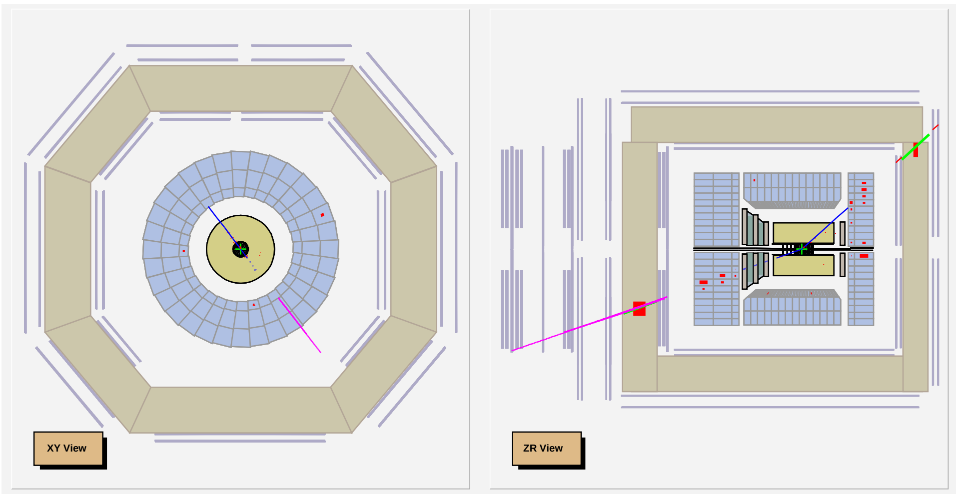

Figure 3: *An event with two muons in the ZEUS detector. The energy deposited in the CAL is proportional to the size and density of shading in the CAL cells. The invariant mass of the di-muon is* 51.4 ± 8.2 *GeV. The first muon has a transverse momentum of* $p_T^\mu = 13.8$ *GeV and a polar angle* $\theta^\mu = 0.304$*, the second muon has* $p_T^\mu = 9.29$ *GeV and* $\theta^\mu = 2.467$*.*

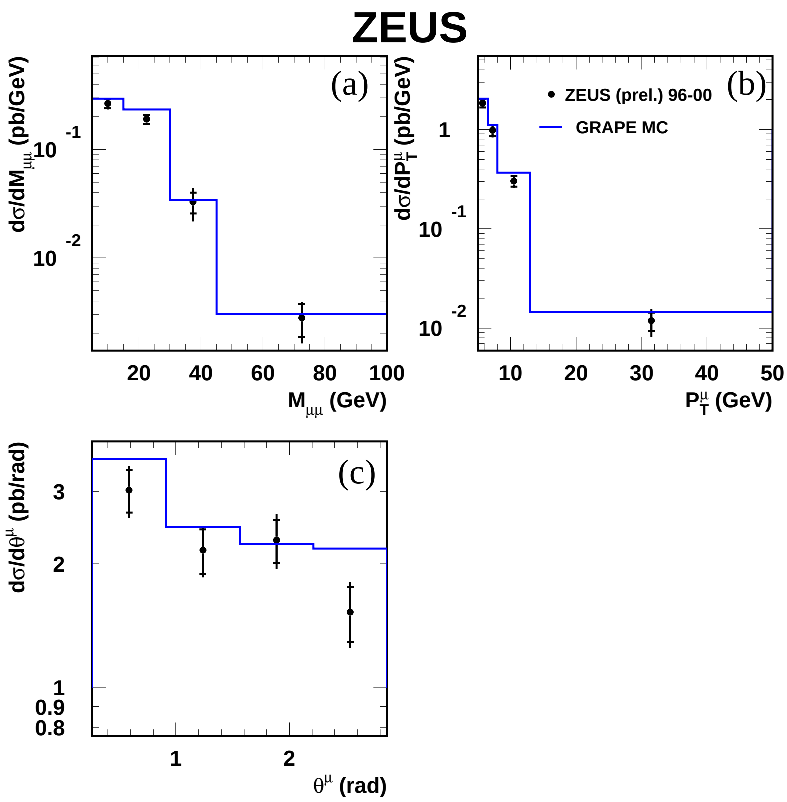

Figure 4: *Differential cross sections as a function of (a) the invariant mass of the muon pair $M_{\mu\mu}$, (b) transverse momentum p_T^{μ} and (c) polar angle θ^{μ} of the muons. The data (dots) are compared with the predictions of the* GRAPE *Monte Carlo. The full error bars are the quadratic sum of the statistical (inner part) and systematic uncertainties; the 2% systematic uncertainty on the luminosity measurement is not included in these error bars.*