PHYSICS WITH JETS - RECENT RESULTS FROM UA2

The UA2 Collaboration

presented by
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Abstract

This paper presents an overview of initial results on jet physics obtained with the upgraded UA2 detector. The detector has collected data corresponding to an integrated luminosity of 7.8 pb\(^{-1}\) during the years 1988 and 1989. The single inclusive jet cross-section has been measured and compared to the absolute prediction of leading order QCD. Qualitative comparisons with leading order QCD have been performed on two jet and four jet event samples. In all cases QCD has been found to describe the data well. An exclusive sample of two jet events has been used to search for the weak decays of the intermediate vector bosons into pairs of light quarks. A significant signal (5 S.D.) has been observed on top of the strong interaction background. Special emphasis is given to a discussion on technical aspects of jet detection.

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1. INTRODUCTION

The observation of hadronic jets in the early phase of experimentation at the CERN proton-antiproton collider [1] has opened a field of research in which jets are used as experimentally observed objects for QCD tests [2], fragmentation studies [3] and an attempt to use their kinematic properties to perform spectroscopy [4].

The successful operation of the improved CERN proton-antiproton collider [5] together with the upgraded UA2 detector [6] does now provide data improved in quantity and quality to extend these studies.

In an initial study using these data results have been obtained on a measurement of the inclusive jet cross-section (chapter 3.1), two jet and four jet studies (chapters 3.2 and 3.3) and a successful attempt to perform particle spectroscopy using hadronic jets originating from the decay of W/Z bosons into jet pairs (chapter 3.4). Special emphasis is put on a detailed discussion of jet detection and triggering (chapter 2).

2. TECHNICAL ASPECTS OF JET DETECTION IN UA2

2.1 The UA2 Calorimeter

The entire UA2 apparatus has been upgraded during the years 1985 to 1987. A global overview of the different components can be found in [6]. Due to the large QCD cross-sections giving rise to high jet production rates the UA2 jet analysis is restricted to calorimetric measurements starting at the lowest trigger level up to the final analysis (see chapter 2.3 for details). The following summarizes the main features of the UA2 calorimeter relevant to the analysis presented here. A more complete description can be found in [7].

Both hadronic and electromagnetic calorimetry are provided over the full azimuthal range, $0 < \phi < 360$ and the pseudorapidity region $-3 < \eta < 3$. The calorimeter is physically divided into the central calorimeter (CC) covering pseudorapidities $-1 < \eta < 1$ and two end cap calorimeters (EC) covering the region down to $|\eta| < 3$.

The CC is segmented into 240 cells subtending $10^\circ$ in $\theta$ and $15^\circ$ in $\phi$. The electromagnetic part is a multi-layer sandwich of lead and scintillator, 17 radiation lengths deep, while the hadronic part, subdivided into two compartments, is an iron-scintillator sandwich, resulting in a total thickness of 4.5 absorption lengths including the electromagnetic compartment.

Each EC consists of 12 wedge-shaped modules transversely segmented into 16 cells. In a given module the cells closest to the beam axis ($2.5 < |\eta| < 3.0$ and $2.2 < |\eta| < 2.5$) cover $30^\circ$ in azimuth. All cells in the pseudorapidity intervall $1.0 < |\eta| < 2.5$ have one electromagnetic
and one hadronic compartment with a segmentation of $\Delta \phi = 15^\circ$, $\Delta \eta = 0.2$. The electromagnetic compartment is a multi-layer sandwich of lead (3mm thick) and acrylic scintillator (4mm thick), with a total thickness varying from 17.1 to 24.4 radiation lengths depending on the polar angle. The hadronic calorimeter is a multi-layer sandwich of iron (25mm thick) and scintillator (4mm thick) corresponding to about 6.5 absorption lengths, including the electromagnetic cells. The cells nearest to the beam axis have only a hadronic compartment. Additional cells with only hadronic calorimetry cover the pseudorapidity interval $0.9 < |\eta| < 1.0$ to measure the energy of particles escaping detection in the interface between EC and CC calorimeter modules. To minimize inefficiencies in the boundaries between two neighbouring EC modules, the modules have been rotated by 50 mr around their symmetry axis normal to the beam.

The rapidity range ($2.3 < |\eta| < 4.1$) is covered by a matrix of scintillation counters with good time resolution (300 ps). In the absence of track reconstruction (as in the case of jet events), this detector provides the measurement of the event vertex by a time-of-flight method with a precision of 25 mm.

2.2 The Determining Factors For Jet Measurements

Hadronic jets are known to originate from the fragmentation of parent quarks and gluons, which results in a continuous hadron momentum spectrum (fragmentation function) strongly peaked at small values. It is the task of a jet detector to measure the energy of the fragmentation products with well understood response and good resolution. Of equal importance is the procedure applied to group the particles together in order to form the experimental definition of a 'jet' (jet algorithms). Both these ingredients together determine the quality of an experimental jet measurement. The following three paragraphs summarize the specific performance and procedures relevant for the UA2 calorimeter.

2.2.2 Single particle calibration

The absolute calibration of the calorimeter has been obtained by exposing every cell to a beam of particles of known momentum. The electromagnetic compartments have been calibrated using electrons of 40 GeV. For the single hadronic compartments of end cap modules pions of 40 GeV momentum were used. For the two compartment structure of the central hadronic calorimeter a measurement of the relative response was first performed using a muon beam. The absolute hadronic scale was then defined with a 40 GeV pion beam.

To optimize the energy resolution for single pions in the non-compensating UA2 calorimeter, relative weight factors were defined for all compartments in order to compensate (on the average) for the difference in response. The calorimeter weights applied to the electromagnetic cells were 1.18 in the central calorimeter and 1.20 in the end caps. An
additional weight of 1.06 was applied to the second hadronic compartment of the central calorimeter to account for hadronic energy leaking through the back of the calorimeter. The weighting technique is relevant for the electromagnetic and hadronic shower components of a single pion as well as for a hadronic jet being composed of charged and neutral pions decaying into photons.

The relative loss of response due to aging of calorimeter components like scintillators, light guides and photomultipliers has been monitored by measuring the light output produced by a radioactive (Co$^{60}$) source placed at the front layers of electromagnetic and hadronic compartments. The precision of this relative response monitoring has been measured by re-exposing a subsample of calorimeter cells to a calibration beam. This provides another absolute calibration which is then to be compared to the initial absolute calibration corrected for the relative response loss as determined from the source measurements.

The knowledge of the absolute calibration was determined to be within ~1% for the electromagnetic energy scale and ~2% for the hadronic energy scale. Since jets consist mainly of charged pions (50%) and photons (50%), a typical jet fragment has therefore an uncertainty on its absolute energy scale of ~1.5%.

2.2.3 Single particle response and resolution

The calibration procedure described in the previous paragraph ensures a correct energy measurement for particles with momenta equal to those used in the calibration beam. A jet fragment typically carries a small fraction of the parent parton momentum. A measurement of its energy is therefore sensitive to deviations from calorimeter linearity at low momenta. This important effect has been studied for the UA2 end cap calorimeter using beams of charged pions, protons and electrons covering a momentum range from 300 MeV up to 150 GeV. The deviation from linearity has then been defined as the difference from unity of the observed calorimeter energy divided by the kinetic energy of the beam particle. The experimental results together with the corresponding measurements of the energy resolution are shown in Figs. 1a and 1b.

In particular the momentum range below 1 GeV exhibits non-linearities of about 30% in magnitude. These are due to the fact that the light produced in the scintillator at these very low momenta mainly originates directly from the energy loss of the primary particle itself. The calibration at high momenta has however been performed on hadronic showers developing from the original beam particle. Both the measurement of response and that of resolution are well reproduced by calculations done with the GEANT [8] simulation package. This fact motivates the use of the GEANT simulation to study the same effects for the central calorimeter where no such beam measurements are available.
2.2.4 Jet algorithms

The parton fragmentation process with the subsequent deposition of single particle energies into the cells of the calorimeter creates the typical jet structures observed in collisions producing high transverse energy [1,9]. This observation motivates the identification of the localized energy depositions in the calorimeter with 'jets'. The assignment of cells to a jet is not uniquely defined but needs to be adapted to the particular problem under study. Currently four different algorithms are being used in the UA2 jet analyses presented in this paper:
• Cluster Algorithm
Clusters are structures of adjacent calorimeter cells having an energy deposition in excess of a 400 MeV threshold. A momentum vector is assigned to each cluster joining the centre of the detector to the cluster centroid with magnitude equal to the cluster energy. This basic cluster method provides a good two jet resolution in space. The energy collection is however limited to the central core of the jet (depending on the threshold cell energy). For a jet with a transverse energy $E_T = 40$ GeV, typically 10% of the energy is not seen in the clustering procedure. The cluster algorithm has been used for the two- and four-jet studies presented in chapters 3.2 and 3.3.

• Cluster Merging
To improve the energy collection the basic cluster algorithm can be modified by merging clusters around a primary seed cluster within a well defined cone. The cone size used in the measurement of the inclusive jet momentum spectrum (chapter 3.1) is coso $> 0.2$ (half aperture). Apart from the improved energy collection efficiency, this algorithm provides a sharply defined cone for the inclusion of hard, final-state radiation. Such a definition is necessary to compare the jet cross-sections with next-to-leading order QCD calculations. This algorithm does not resolve close-by jets, as expected from final-state gluon radiation. The space resolution is instead sharply defined by the cone size.

• Window Algorithm
The two algorithms previously described are based on interconnected structures of calorimeter cells (clusters). Low transverse momentum jets may deposit energy into cells not connected to such structures which is therefore not included in the total jet energy. To overcome this problem an alternative algorithm has been designed. Based on measurements of the transverse energy flow in two-jet events (chapter 3.2), a fixed jet aperture can be defined. The cell structure of the UA2 calorimeter suggests a rectangular 'window' of dimension $70^\circ \times 75^\circ$ in the $\theta, \phi$ plane. All energy deposited in the window is assigned to the jet. This simple fixed-aperture jet algorithm has the advantage of easy implementation and very fast execution time. It has therefore been used in a trigger processor to obtain the second level trigger decision (chapter 2.3).

• Cone Algorithm
The rectangular shape of the windows does not reflect the expected rotational symmetry of the energy flow around the jet axis. In the final analysis of jet mass spectra (chapter 3.4), the jet energy is collected in cones. The cones have a circular cross-section in the $\eta, \phi$ plane to account for the distortion expected from the Lorentz transformation. The actual cone size used in the analysis of chapter 3.4 is

$$\eta^2 + \phi^2 < 0.64$$
2.3 Jet Triggers in UA2

The UA2 trigger system performs decisions on 3 levels, corresponding to increasing decision times and increasing quality of available data for the decisions.

The first level is based on analog sums of transverse energy measured in sections of the UA2 calorimeter. The building blocks are either global sums over the full azimuth in different rapidity intervals or wedges of the azimuthal angle again with different rapidity intervals. The wedges are a first approximation to jets. Single wedges can be combined to trigger on either inclusive one-jet or two-jet structures. Due to the strong dependence of jet cross-sections on the minimum required transverse energy, thresholds have to be carefully tuned in order to cope with the processing capabilities of the higher trigger levels. The sharpness of the first level trigger thresholds is determined by the uniformity of the analog output signals of the calorimeter with respect to the transverse energy deposited. This uniformity is achieved at a level of 5%. The 1.3 µs decision time of the first level trigger is smaller than the time between two consecutive bunch crossings and does therefore not produce any deadtime in the acquisition of data.

The second level trigger refines the crude jet definition available at the previous level. A fast digitisation of individual cell energies allows the execution of jet algorithms by a special trigger processor [10]. Cluster and window algorithms as described in the previous paragraph are available. The trigger performs a decision within 1 ms and initiates the readout of the calorimeter.

The final decision is then done on the third trigger level, which repeats the second level algorithms with improved energy measurements and floating point precision. Since the processing of events at this highest level does not interfere with the readout of events, the calculations can be performed on several processors in parallel with a processing time of typically 200 ms [11].

A complete list of jet triggers operational in the UA2 experiment is given in Table 1. The cross-sections given in the last column can be used to calculate the total number of events written out to tape as well as the rate of accepted jet triggers. At luminosities \( \mathcal{L} = 2 \times 10^{30} \) cm\(^{-2}\) s\(^{-1}\), a cross-section of 2000 nb corresponds to an output rate of 4 Hz.
| Description                | $|\eta|-$ coverage | threshold at highest level | output cross-section |
|----------------------------|----------------|---------------------------|----------------------|
| total transverse energy    | < 2            | 150 GeV                   | 60 nb                |
| total transverse energy    |                |                           |                      |
| in the central calorimeter | < 1            | 90 GeV                    | 100 nb               |
| single-jet                 | < 2            | 40 GeV                    | 150 nb               |
| two-jet                    | < 2            | 30 GeV                    | 350 nb               |
| two-jet low masses         | < 1            | 17 GeV                    | 2000 nb              |
| two-jet very low masses    |                |                           |                      |
| pre-scaled 1 : 8           | < 1            | 13 GeV                    | 600 nb               |
| three-jet                  | < 2            | 10 GeV                    | 300 nb               |
| four-jet                   | < 2            | 8 GeV                     | 60 nb                |

Table 1: List of Jet Triggers Operational in the UA2 Experiment

3. RESULTS

3.1 Single Inclusive Jet Cross-Section

The inclusive cross-section of jets defined according to the cluster merging algorithm (chapter 2.4.4) has been measured for pseudorapidities $|\eta| < 0.85$. The analysis is based on data collected with the single jet trigger. The preliminary acceptance corrected momentum spectrum of the jets corresponding to an integrated luminosity of 7.8 pb$^{-1}$ is shown in Figure 2. The errors assigned to the individual data points reflect only the statistical uncertainties.

The measurement of a steeply falling jet cross-section is affected by overall systematic uncertainties independent of the transverse momentum itself. Those mainly arise from uncertainties in the jet energy measurement and the luminosity and affect the cross-section at
Figure 2
The Single Inclusive Jet Cross Section
Full Dots : UA2 measurement
Open Dots  : Previous UA2 Measurement [12]
Full Curve : L.O. QCD calculation
Dashed Curve : L.O. QCD calculation + expected contribution from a contact interaction with $\Lambda_c = 700$ GeV [13].

this stage of the analysis by 50%. The dominating contribution is the uncertainty on the jet energy measurement estimated to be 5%. This number is a first conservative estimate and expected to improve with a more refined analysis in the near future.

Jet production at hadron colliders is expected to be dominated by two jet production. This feature has earlier been verified experimentally [1,14]. Higher jet multiplicities and next to leading order contributions are expected at the 20% level and their contribution is therefore experimentally inaccessible with this type of measurement. Figure 2 shows a comparison of the measured jet momentum spectrum with the leading order QCD expectation [15] taking the parton distribution function from [16]. The calculation coincides well with the measured data points taking into account the overall normalisation uncertainty of 50%.

The spectrum at large transverse momenta is dominated by hard scattering processes between quarks and antiquarks. A hypothetical substructure of quarks would result in an
increase of the cross-section at these large transverse momenta. The increase can be expressed as a new interaction appearing at a scale given by a parameter $\Lambda_C$ [13]. The expected effect for a $\Lambda_C$ value of 700 GeV is indicated in Figure 2. An effect of this magnitude can currently not yet be excluded by the UA2 results. It does however correspond to the estimated limit of sensitivity at this center-of-mass energy.

Finally, Figure 2 presents a comparison between two sets of UA2 data separated in time by about 4 years [12]. In the period between those measurements the UA2 central calorimeter has undergone a substantial upgrade and recalibration. The good agreement between the two datasets gives confidence on the understanding of the absolute jet energy scale.

3.2 Two-Jet Studies

Motivated by the good agreement between the measured single inclusive jet cross-section and a leading order QCD calculation an exclusive selection of two jet events has been performed to study their kinematics. The data presented here are based on an integrated luminosity of 3.1 pb$^{-1}$ and have been taken with the two jet trigger. Jets are identified using the standard cluster algorithm. In each event, the jets are sorted in order of decreasing transverse energy and labeled 1, 2, 3 etc. The exclusive two jet event sample has been selected with the following selection criteria:

\[
E_T,1,2 > 35 \text{ GeV} \quad \text{(leading two jets above trigger threshold)}
\]

\[
E_T,3 < 10 \text{ GeV} \quad \text{(veto on third jet)}
\]

\[
p_T^\xi < 10 \text{ GeV}
\]

\[
p_T^\eta < 50 \text{ GeV}
\]

$p_T^\xi$ and $p_T^\eta$ are the components of the transverse momentum of the jet pair projected on the bisectors of the transverse momenta. $p_T^\xi$ describes the energy imbalance of a two jet event. This variable receives contributions from soft initial state bremsstrahlung and the energy measurement error. $p_T^\eta$ describing non back-to-back two-jet configurations is dominated by the bremsstrahlung contribution because the error in the position measurement of jets is small. The cuts on $p_T^\xi$ and $p_T^\eta$ select well balanced two jet events without large contributions from bremsstrahlung not detected as a third jet. The final event sample consists of $\sim 32000$ events.

Figure 3 shows the transverse energy flow around the jet axes of the leading two jets in the lab-system. In this figure the measured transverse energy has been integrated over the pseudorapidity range $-2 < \eta < 2$ and binned in $\Delta\phi$-bins corresponding to the cell structure of $15^\circ$ width. The jet axis of one of the two jets has been placed into the second bin of the histogram.
A two jet structure is clearly visible. It is instructive to compare the experimental data to the PYTHIA (version 4.8) [17] simulation. This simulation contains the leading order QCD matrix elements for two jet production as well as an explicit implementation of initial state radiation. Fragmentation is performed through a parton shower development with subsequent breakup of colour strings to produce the final state hadrons. The model treats in a complete way all produced partons including the "spectators" not contributing to the hard scattering process under investigation here. Therefore a complete simulation of the entire proton-antiproton interaction is performed. The full line in Figure 3 compares the data to PYTHIA 4.8 switching off the explicit implementation of initial state radiation. This approach describes well the width of the jet structures but fails to account for the transverse energy experimentally detected at large angles to the jet axes. This transverse energy is however well described by the contribution originating from initial state radiation (dashed line). This contribution is in fact expected to be uncorrelated to the jet structure, creating a $\Delta\phi$ - independent transverse energy offset.

Finally, the angular distribution of the two jets in their center-of-mass system has been measured. A two jet system having zero transverse momentum has a well defined center-of-mass scattering angle with respect to the beam axis. However, for systems with non-zero transverse momentum the boost to the center-of-mass frame results in the beam axes becoming non-collinear, resulting in an ambiguity in the definition of the scattering angle with respect to them. Thus, the scattering angle has been defined according to the Collins&Soper [18] convention whereby it is the angle between the dijet axis and the bisector of the beam directions in the centre of mass frame. The measured $\cos \theta^*$ distribution for events with a two jet mass exceeding 120 GeV is shown in Figure 4. No corrections for acceptance have been applied. The PYTHIA 4.8 simulation has been normalised to the number of observed events and exhibits good agreement with the data.
3.3 Four-Jet Studies

Four jet events are the subject of the following study. Their yield and phase space density provide additional tests of perturbative QCD. Here (at least in principle) a new production mechanism could play a role: the production of two jets from two independent pairs of incoming partons [19]. This process is a major motivation for four jet physics but the current study concentrates on a comparison with leading order QCD (order $\alpha_s^4$) [20].

The UA2 trigger system (chapter 2.3) provides a variety of triggers for multijet physics, including those specially designed to serve this purpose. The combination of these triggers requires a careful understanding of various biases possibly introduced on the three trigger levels. In order to perform a first survey with the newly collected data a restricted data sample originating from the two jet trigger has been used. This trigger requires the observation of two high transverse energy jets on all trigger levels. The selection criteria for the analysis are listed below (the jets are sorted in order of decreasing transverse energy).

\[
\begin{align*}
E_{T,1,2} &> 30 \text{ GeV} \\
E_{T,3,4} &> 15 \text{ GeV} \\
|\eta| &< 2 \text{ for all four jets} \\
\text{opening angle (jet1,jet2)} &> 143^\circ \text{ (trigger condition)}
\end{align*}
\]

The selected data sample corresponding to an integrated luminosity of 3.1 pb$^{-1}$ consists of 857 such events. Figure 5 presents the observed mass distribution of the four jet final states together with the normalised prediction from the leading order QCD calculation. The spectrum is well understood in terms of this QCD calculation and in particular does not exhibit any structure or deviation from smooth behaviour.
The overall event topology can be described by the sphericity [21]. This variable designed to measure event shapes using individual reconstructed particles can also be applied to experimentally observed jets representing the parent partons. Small sphericities represent 'cigar-shape' narrow event structures expected e.g. from two hard final state partons both radiating gluons which are in turn reconstructed as additional jets in the event. Large sphericities can be expected from hard initial state radiations and also from possible new sources (e.g. multiparton scattering). Figure 6 shows the experimental data together with the QCD calculation. Again good agreement is observed and the data show no indication for additional production mechanisms at this level of the analysis.

![Figure 5](image_url)  
**Figure 5**  
The Mass Distribution of Four Jet Events  
Points : Experimental Data  
Histogram : Leading order QCD [20]  
(normalised to the data)

![Figure 6](image_url)  
**Figure 6**  
The Sphericity Distribution of Four Jet Events  
Points : Experimental Data  
Histogram : Leading order QCD [20]  
(normalised to the data)

### 3.4 Mass Spectroscopy with Jets

The intermediate vector bosons $W$ and $Z$ are expected to decay into quark-antiquark pairs with well defined branching ratios [22].

$$\Gamma(Z^0 \to q\bar{q}) / (Z^0 \to ee) = 20$$

$$\Gamma(W \to q\bar{q}) / (W \to ev) = 6$$  
(excluding modes with a top quark)
The motivations to experimentally search for these decays are manifold.

An observation of these signals in the two jet mass spectrum provides a qualitative and quantitative test of Standard Model predictions.

Of fundamental importance for the physics at hadron colliders is an experimental verification of the parton/jet assignment. Many studies at hadron collider experiments have assumed that jets do directly represent the kinematics of their parent partons (see e.g. chapters 3.1 - 3.3). This assumption, although supported by fragmentation models [17], can be experimentally verified by observing the mass peak of known particles (like the intermediate vector bosons) from jets reconstructed in the calorimeter. Once this verification is done the method can in principle be applied to search for new particles using the measured parameters of the W/Z bosons as a calibration [23].

The direct use of jets as 'fundamental particles' (i.e. representing their parent parton) has also been proposed for planned particle searches at future hadron colliders [24].

The two jet final state produced by the weak process of the W/Z decays is experimentally very similar to two jet events originating from QCD parton parton interactions (e.g. to order $\alpha_s^2$). The search for the W/Z resonances can therefore not be performed on an event-by-event basis but has to statistically measure a localized peak structure on the smooth two jet mass spectrum originating from QCD processes. The QCD background is expected to dominate over the weak production and decay of W/Z bosons by about two orders of magnitude. The mass resolution for two jet final states in UA2 is of the same order as the mass difference between the W and the Z (i.e. about 10 GeV) so that the two peaks will not be resolved but instead appear as a broad enhancement in the W/Z mass region.

The experimental requirements for the search of W/Z decays in the two jet mass spectrum are summarized in the following list:

- Optimisation and knowledge of the mass resolution.
- Knowledge of the absolute mass scale taking into account the calorimeter response to single particles as well as the jet identification algorithm.
- Control of the QCD background down to masses well below the expected peak position. The lowest mass value reliably measured by the experiment is determined by the capability of the trigger and data acquisition system to cope with very high event rates. As an example the cross section for two jet systems with a mass exceeding 50 GeV and both jets reconstructed in the UA2 central calorimeter is as large as 50 µb. The typical luminosity
achieved by the upgraded CERN proton-antiproton collider is $2 \cdot 10^{30}$ cm$^{-2}$ s$^{-1}$, thus corresponding to an event rate of 1 kHz.

A previous search [4] for the W/Z bosons in the two jet mass spectrum revealed a signal of $632 \pm 190$ events (3 S.D.) with shape and position consistent with expectations. The signal size expected from the standard model was $340 \pm 80$ events. The analysis was based on a data sample corresponding to an integrated luminosity of 0.73 pb$^{-1}$.

The present analysis uses the data collected in the 1989 run corresponding to a 6 times larger sample of 4.7 pb$^{-1}$. The following paragraph describes the data reduction from the first trigger level up to the event selection for the analysis.

The large QCD two jet cross-section has imposed a trigger strategy based on two different transverse energy thresholds. A "low mass trigger" was used to collect data with the full available integrated luminosity of 4.7 pb$^{-1}$. A special trigger with a lower transverse energy threshold ("very low mass trigger") had to be pre-scaled by a factor 8, thus corresponding to an effective integrated luminosity of 0.59 pb$^{-1}$ collected with this threshold.

On the first trigger level jets have been defined as $90^\circ$ wide $\phi$-wedges covering the pseudorapidity range of the central calorimeter, i.e. $-1 < \eta < 1$. Two of these wedges back-to-back in the transverse plane, each with a transverse energy in excess of 17 (13) GeV, are required at the first level. This trigger accepted a total of 55,000,000 events corresponding to an effective cross-section of 12500 nb.

At the second trigger level (chapter 2.3), a window jet algorithm (chapter 2.2.4) was used to search for two jets within the central calorimeter acceptance each with transverse energies greater than 13 (10) GeV. The two leading jets found by this procedure had to be back-to-back in the transverse plane within $\pm 15^\circ$. This trigger accepted a total of 10,000,000 events, corresponding to an effective cross-section of 2300 nb which was recorded on tape for analysis. The factor 5 reduction provided by the second trigger level is one of the key elements of this analysis.

The recorded events were then reprocessed with the cone jet algorithm as described in chapter 2.2.4. The event vertex position along the beam as measured by the time-of-flight detector was used to correct the transverse energy measurements of individual cells. Events with a vertex offset from the center of the calorimeter by more then 20 cm were rejected. The reconstructed jet directions of the two highest transverse energy jets were required to be within $|\cos \theta| < 0.6$ corresponding to $|\eta| < 0.7$. This condition retains only events with two jets well contained in the central calorimeter acceptance. A set of additional cuts rejected $Z \rightarrow e^+ e^-$ decays, jets with insufficient longitudinal containment and events with a third jet in excess of 20 GeV transverse energy. This set of selection cuts reduces the data sample to
4,500,000 events corresponding to an effective cross-section of 1000 nb. The reduction of almost a factor 2 as compared to the output of the second trigger level is almost entirely caused by the fiducial volume requirement of $|\cos \theta| < 0.6$.

This data sample consists of an exclusive set of well measured two jet events. From this stage no further data reduction is possible. The remaining sample is then used to search for the hadronic decays of W/Z bosons by means of statistical methods.

Figure 7 shows the ratio of the two mass spectra obtained from the two triggers. It can be seen that the "low mass trigger" recording the full statistics without pre-scaling is fully efficient down to two jet masses of 66 GeV.

![Figure 7](image)

Figure 7
Efficiency of the "low mass trigger" as a function of the two jet mass. The right arrow indicates the lowest mass value of full efficiency. The left arrow indicates a cut-off mass below which no data are available.

The two sets of data originating from the two triggers are merged such that above masses of 66 GeV the "low mass trigger" is used. Below that value down to masses of 48 GeV the data are provided by the "very low mass trigger" corresponding to a sample reduced by a factor 8 in statistics.

The two jet mass spectrum was then fitted to a set of smooth background functions using the mass range from 48 GeV up to 200 GeV. The results are summarized in Table 2.

The best fit gave a $\chi^2$ of 136 for 74 degrees of freedom corresponding to a probability as small as $2 \cdot 10^{-5}$. In order to investigate whether the bad fit qualities originate from a localized region in the two jet mass spectrum a window of width $\Delta m$ with a central mass value $<m>$ has been excluded from the fit. Figure 8 summarizes the fit results for three values of $\Delta m$ as a function of $<m>$. 

15
<table>
<thead>
<tr>
<th>fit function</th>
<th>N.D.F.</th>
<th>$\chi^2$</th>
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</thead>
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<tr>
<td>$m^{-\alpha}$</td>
<td>76</td>
<td>296</td>
</tr>
<tr>
<td>$m^{-\alpha} \cdot e^{-\beta m}$</td>
<td>75</td>
<td>275</td>
</tr>
<tr>
<td>$m^{-\alpha} \cdot e^{-\beta m} \cdot e^{-\gamma m^2}$</td>
<td>74</td>
<td>136</td>
</tr>
</tbody>
</table>

Table 2: $\chi^2$ of fits with a smooth background function for three different parametrisations.

Figure 8
Fit-$\chi^2$ as a function of $<m>$ (the central mass value of the excluded mass range):
- a) width of excluded window 10 GeV
- b) width of excluded window 20 GeV
- c) width of excluded window 30 GeV

The best fit is obtained for a mass window of width $\Delta m = 30$ GeV, centered at $<m> = 85$ GeV corresponding to a $\chi^2$ of 70.8 for 59 degrees of freedom. This fit together with the measured mass spectrum is shown in Figure 9.
Figure 9a presents the data using a logarithmic scale on the vertical axis. The statistical error bars are too small to be visible in this type of presentation. To overcome this problem Figure 9b shows the data with a vertical scale weighted by \((m/100)^6\). This procedure removes largely the steep slope from the background and presents the data points with visible error bars. From this presentation it is evident why the mass region \(70 < m < 100\) GeV causes the bad fit quality for a smooth background function. The data show clear evidence for an excess of two jet events in the mass region where the hadronic decays of the W/Z bosons are expected to appear.

**Figure 9**

Best fit to the measured mass spectrum excluding the mass range \(70 < m < 100\) GeV (indicated by dashed lines)

a) logarithmic scale on vertical axis

b) vertical scale weighted by \((m/100)^6\)
The procedure so far has not made any assumptions on the position and the line shape of the signal. In order to quantitatively investigate the excess of events observed in the two jet mass spectrum the following assumptions have been made:

- Double Gaussian resolution function
- \( m_Z/m_W = 1.14 \) \[25\]
- \( \sigma \cdot B(Z^0 \rightarrow q\bar{q})/\sigma \cdot B(W \rightarrow q\bar{q}) = 0.43 \) \[26\]

The total spectrum (not excluding the signal region) has then been fitted to the following function:

\[ f \cdot [\text{Background} + \text{Signal (size, } m_W, \sigma_{mW/m}] \]

This fit has 6 free parameters. The background is parametrized using 3 parameters as in the studies described in the previous paragraphs. The absolute position of the signal in the two jet mass spectrum (given by the reconstructed W boson mass) and the mass resolution have been left free in order to avoid assumptions on the performance of the calorimeter and the jet identification algorithm. These parameters will instead be determined by the fit and then compared with the expectations. The parameter \( f \) ensures the absolute normalisation of the fit function to be equal to the number of observed two jet events.

The fitted signal parameters are summarized in the following table.

| number of reconstructed events | 5620 ± 1130 |
| signficance | 5 standard deviations |
| reconstructed W boson mass | 78.9 ± 1.5 GeV |
| reconstructed mass resolution | 9.3 ± 2.0 % |

Table 3: Summary of fitted signal parameters

The fit results are displayed in Figures 10a - 10d.

The signal/background ratio (Figure 10c) displays directly the size of the signal as compared to the QCD background. The figure demonstrates that a ratio of ~ 5% at the peak is being observed.
Figure 10
Fits to the mass spectrum of two jet events.

a) Result of the fit for the full fit range (48 < m < 200 GeV)
b) Result of the fit in the mass range (56 < m < 126 GeV)
Full line : background parametrization + W/Z signal
Dashed line : background parametrization only
c) Signal/background ratio
Full line : W/Z fit result
Dashed line : W contribution only
d) Background subtracted signal
Full line : ± 1 σ bounds from W/Z fit result
Dashed line : central value of W/Z fit result
Dotted line : W contribution only
The reconstructed signal parameters have been compared to the expectations obtained using the PYTHIA (version 4.8) [17] event generator combined with a calorimeter simulation. Uncertainties on these expectations are expected to result in particular from the simulation of the energy not originating directly from the fragmentation of the quarks coming from the W/Z decays (underlying event) and from the simulation of the calorimeter response (chapter 2.2.3). The comparison of the reconstructed peak position (W boson) and the two jet mass resolution with the expectations are summarized in Table 4.

<table>
<thead>
<tr>
<th></th>
<th>rec. W mass (GeV)</th>
<th>mass resolution (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>data</td>
<td>78.9 ± 1.5</td>
<td>9.3 ± 2.0</td>
</tr>
<tr>
<td>PYTHIA</td>
<td>76.4 ± 1.0</td>
<td>11.0 ± 0.8</td>
</tr>
<tr>
<td>underlying event</td>
<td>± 2.0</td>
<td>± 1.5</td>
</tr>
<tr>
<td>uncertainty</td>
<td></td>
<td></td>
</tr>
<tr>
<td>calorimeter response</td>
<td>± 2.5</td>
<td>± 1.0</td>
</tr>
<tr>
<td>uncertainty</td>
<td></td>
<td></td>
</tr>
<tr>
<td>single particle</td>
<td>± 1.2</td>
<td>-</td>
</tr>
<tr>
<td>calibration uncertainty</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 4: Measured values of reconstructed W mass and mass resolution compared to the PYTHIA expectation with a list of systematic uncertainties (generated W mass 81 GeV).

To calculate the expected number of observed W/Z decays in the two jet mass spectrum the total number of produced events as well as their detection efficiency including all trigger and selection criteria has to be known. The total number of produced events has been calculated using a recent measurement [27] of the W and Z cross-sections in their electron decay channels:

\[ \sigma \cdot B(Z^0 \rightarrow e^+e^-) = 70 \pm 6(\text{stat.}) \pm 4(\text{syst.}) \text{ pb} \]
\[ \sigma \cdot B(W^\pm \rightarrow e) = 660 \pm 15(\text{stat.}) \pm 37(\text{syst.}) \text{ pb} \]

These values are based on a data taking period overlapping with the sample discussed here. The systematic uncertainty on the luminosity measurement accounting for 5% of the systematic error has therefore not been taken into account for the calculation of the expected number of hadronic W/Z decays. Using the standard model values for the hadronic branching ratios compared to the leptonic ones results in a total number of $25000 \pm 860$ events expected to be produced.
The overall detection efficiency has been evaluated using again the PYTHIA event generator and amounts to \((17 \pm 2)\%\). The error includes the systematic uncertainties of the simulation as discussed for the measurement of the peak position and the mass resolution. From the total number of expected events and the efficiency the number of events expected to be observed in this analysis is \(4250 \pm 150\) events. This is about 1.2 standard deviations below the \(5620 \pm 1130\) events actually observed.

Apart from a measurement of the total cross-section a study of differential distributions might be of interest to validate further the observed signal. The accuracy of such measurements will obviously be limited by the size of the observed signal. Nevertheless an attempt has been made to measure the angular distribution of the decay jets in the W/Z centre of mass system. This distribution is (at least in principle) expected to differentiate between vector boson decays and Rutherford type angular distributions as expected e.g. for gluon-gluon scattering.

\[
\begin{align*}
\text{W decays} & : & \frac{d\sigma}{d\cos\theta^*} & \sim (1 + \cos\theta^*)^2 \\
\text{gg scattering} & : & \frac{d\sigma}{d\cos\theta^*} & \sim \sin^{-4} \left( \frac{\theta^*}{2} \right) \quad \text{(Rutherford scattering)}
\end{align*}
\]

The scattering angle distribution of the observed signal has been measured in three bins. Peak position and mass resolution for the fit procedure have been fixed to the values obtained from the integrated sample in order to improve the significance of the differential measurement. These numbers are not expected to depend on the scattering angle. The uncorrected scattering angle distribution is shown in Figure 11.

The histograms in Figure 11 represent the expectation for W/Z decays and the distribution from QCD obtained by taking all measured two jet events in the mass region \(60\) GeV < \(m\) < \(100\) GeV. Although the experimental data points cannot distinguish between the two distributions, the \(\cos\theta^*\) dependence of the observed signal is in good agreement with the expectation.

In conclusion the size of the observed signal in the two jet mass spectrum as well as its position, width and scattering angle distribution are in agreement with the expectations for hadronic decays of the W/Z bosons.

The results presented here depend on specific assumptions on the observed signal line shape. Deviations from the simple double Gaussian shape are in principle expected from detector and fragmentation effects as well as from possible interference between the weak interaction signal with the QCD background [28]. This effect deserves further studies.
4. SUMMARY

The upgraded UA2 detector has collected an integrated luminosity of 7.8 pb$^{-1}$ with a variety of jet triggers. Tools for jet analysis have been developed and applied to an initial analysis of jet events.

The single inclusive jet cross section has been measured in the pseudorapidity interval $|\eta| < 0.85$. The absolute cross section agrees well with a leading order QCD calculation as well as with previous data.

Exclusive samples of two and four jet events have been compared to leading order QCD calculations and show good qualitative agreement.

An attempt to search for the hadronic decays of the W/Z bosons has succeeded in an observed signal of $5620 \pm 1130$ events, in agreement with the standard model expectation of $4250 \pm 150$ events. The position of the signal in the two jet mass spectrum as well as its width and dependence on the scattering angle are in good agreement with the expectations for the hadronic decays of W/Z bosons.
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