Recent Results on Jet-Physics and QCD Tests by UA1 and UA2 at the CERN Proton-Antiproton Collider

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Invited talk presented at the VIII European Symposium on Nucleon-Antinucleon Interactions Thessaloniki, Greece, 1-5 September 1986

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Abstract

The jet cross-sections of the UA1 and UA2 experiments at CERN are discussed and compared with the predictions of QCD at order $\alpha_s^2$ (inclusive and two-jet cross-sections), $\alpha_s^3$ (three-jet events), $\alpha_s^4$ (four-jet events). Inclusive cross-section has been measured for production of high-$p_T$ direct photons and is compared with QCD predictions. A status report is given on the search for the decay of the intermediate vector bosons $V$ and $Z$ into a quark-antiquark pair.

1. INTRODUCTION

The study of hadron collisions in the new energy domain opened by the CERN proton-antiproton collider\(^1\) has showed the emergence of spectacular two-jet events\(^2\) which are interpreted as the result of hard collisions between the hadron constituents. The interactions of these constituents — quarks and gluons — are described by perturbative expansion in the coupling constant $\alpha_s(Q^2)$ in the frame of Quantum Chromodynamics (QCD). This paper reviews most of the recent results obtained by the UA1 and UA2 collaborations testing QCD. Fragmentation studies, heavy quark decays and non-leading QCD contributions to $V$ production are reported elsewhere\(^3\,5\). Results for inclusive jet production are shown in section 2, two-jet, three-jet and four-jet production are presented in sections 3-5. The direct photon cross section is given in section 6 and finally in section 7 a status report on the search for the decay of the intermediate vector bosons $V$ and $Z$ (IVB's) into a quark-antiquark pair.

The UA1 detector has been described in detail elsewhere\(^6\). Data have been selected with three types of trigger: minimum-bias trigger (at least two charged particles in opposite rapidity hemispheres); jet trigger based on localized energy deposition in the calorimeter (typically $E_T > 20$ GeV); and $E_T$ trigger based on total scalar transverse-energy deposition.

Jets in the UA1 central calorimeter (pseudorapidity $|\eta| < 3$) are defined using the UA1 jet algorithm\(^9\): the energy and momentum of a jet...
are obtained by forming scalar and vector sums of energies in all calorimeter cells within a cone of $\Delta R < 1$ with respect to the jets. The parameter $\Delta R$ is defined by $\Delta R^2 = \Delta \eta^2 + \Delta \phi^2$, where $\Delta \eta$ is the separation in pseudorapidity and $\Delta \phi$ is the separation in azimuthal angle (in radians) measured around the beam direction.

The UA2 detector\(^1\), in order to study hadronic jets is instrumented in the central region ($|\eta| < 1$) with a highly segmented calorimeter\(^4\) built with 240 cells ($\Delta \theta \times \Delta \phi = 10^\circ \times 15^\circ$) pointing to the center of the apparatus. At $\sqrt{s} = 630$ GeV three different triggers were used:

i) "one jet trigger": the transverse energy deposited in any azimuthal wedge ($\Delta \phi = \pm 60^\circ$) had to be larger than a given threshold, set at $\sim 30$ GeV;

ii) "two-jet trigger": the transverse energies deposited in any two opposite azimuthal wedges ($\phi_1$ and $\phi_2 = \phi_1 + \pi$, $\Delta \phi_1 = \pm 30^\circ$, $\Delta \phi_2 = \pm 60^\circ$) are both required to exceed a given threshold, set at $\sim 20$ GeV during the 1984 data-taking period (0.31 pb\(^{-1}\)), at $\sim 15$ GeV for part of the 1985 (0.27 pb\(^{-1}\)) and at $\sim 12.5$ GeV for the rest of the 1985 data (0.15 pb\(^{-1}\))

iii) total transverse energy trigger (used in multi-jet studies): the total transverse energy in the central calorimeter ($E_{Tc}$) was required to exceed a given threshold, set at $\sim 60$ GeV.

The standard UA2 jet algorithm\(^10\) generally used consists in joining of cells on the fine grained central calorimeter around local energy maxima. A vector momentum is associated to each jet, with a direction defined by the interaction point and the cluster centroid and with a magnitude given by the cluster energy (in this definition the jets are taken to be massless).

Most of the data reported here have been collected by both experiments during the high luminosity runs in 1983 at $\sqrt{s} = 546$ GeV ($\approx 100$ nb\(^{-1}\)) for each experiment, and in 1984 (\approx 300 nb\(^{-1}\)) and 1985 (\approx 400 nb\(^{-1}\)) at $\sqrt{s} = 630$ GeV. In addition, UA1 has taken data during the low luminosity (\approx 0.005 nb\(^{-1}\)) run of 1985 when the collider, operating in a pulsed mode\(^11\), explored a new energy range $200 < \sqrt{s} < 900$ GeV.

2. INCLUSIVE JET CROSS-SECTION

Preliminary results for the inclusive jet cross-section $pp \rightarrow \text{jet} + X$ measured by UA1 at $\sqrt{s} = 546$ and 630 GeV and averaged over the interval $|\eta| < 0.7$ are shown in Fig. 1 as a function of the jet momentum $P_T$. The lines are leading order QCD predictions based on current parametrization of
Fig. 1 - Inclusive jet cross-section by UA1
a) $\sqrt{s} = 646$ GeV,
b) $\sqrt{s} = 630$ GeV.

Fig. 2 - Ratios of the inclusive jet cross-sections measured by UA1 at $\sqrt{s} = 200, 500, 900$ GeV.

Fig. 3 - Inclusive jet production cross-sections (see text).
the structure functions\textsuperscript{[12]} (assuming $A_{QCD} = 0.2$ GeV and $Q^2 = P_T^2$) scaled up by a factor 1.5. Minimum-bias trigger data have been used to extend this study to lower values of $P_T$ where experimental systematic errors tend to be larger (about a factor of 2) due to uncertainties related to the energy response of the calorimeter and of the jet algorithm. Perturbative QCD is expected to break down at low $Q^2$. Moreover, its predictions depend strongly upon the behaviour of the gluon density at low $x$, which is not measured directly\textsuperscript{[13]}. Nevertheless the inclusive jet cross-section, now measured over nine orders of magnitude, shows good agreement with perturbative QCD predictions within the systematic errors.

Fig. 2 shows preliminary results from the pulsed collider run where the ratio of inclusive jet cross-sections is shown for $\sqrt{s} = 200$, 500 and 900 GeV. There is a good agreement with what is expected from leading order QCD.

The inclusive jet cross-section measured by UA2 at $\sqrt{s} = 630$ GeV have been analysed\textsuperscript{[14]} in terms of deviations from QCD, including the effects of a hypothetical super-strong interaction binding quarks inside quarks, following the parametrization of Ref\textsuperscript{[15]}\textsuperscript{15}. In this model, a substructure of partons would manifest itself as a contact interaction visible at momentum transfers well below the characteristic energy scale $\Lambda_c$. Finite values of $\Lambda_c$ would produce an excess of events compared to ordinary QCD predictions ($\Lambda_c = \infty$) at large $P_T$ values. Hence the analysis is possible to the extent that the main uncertainties (systematic errors and ignorance of higher order corrections) are approximately constant over the $P_T$ range, so that the data can be normalized in the low $P_T$ region and deviations can be observed in the high $P_T$ tail. In Fig. 3 the results are plotted for the pure QCD calculation ($\Lambda_c = \infty$) and for the best fit ($\Lambda_c = 460$ GeV), together with the expected behaviour for $\Lambda_c = 300$ GeV as an illustration of the sensitivity to $\Lambda_c$. When both theoretical and experimental uncertainties are taken into account, a lower limit is obtained of $\Lambda_c = 370$ GeV at 95\% C.L.

The same analysis done by UA1\textsuperscript{[16]} gives similar results ($\Lambda_c > 400$ GeV 95\% C.L).

3. TWO-JET CROSS SECTIONS

It is by now well known that the two-jet cross-section in hadron-hadron collisions to a very good approximation may be expressed in terms of a universal\textsuperscript{[17,22]} parton-parton cross-section

$$\frac{d\sigma}{d\cos\theta} = \alpha_s^2 \hat{s} (1-\cos\theta)^{-2}$$
(θ is the c.m.s. scattering angle) multiplied by a product of effective structure functions \( F(x_1)/x_1 \cdot F(x_2)/x_2 \) where

\[ F(x) = G(x) + \frac{4}{9} [Q(x) + \bar{Q}(x)] \]

\( G(x), Q(x) \) and \( \bar{Q}(x) \) being the appropriate momentum weighted parton densities in the proton.

Both UA1\(^{118}\) and UA2\(^{119}\) have analysed two-jet data in this context, extracting the effective structure function with results which are largely consistent with each other and with QCD expectations (Fig. 4).

More work has been done studying angular distributions, mainly by UA1\(^{120,21}\), due to their better longitudinal acceptance. Fig. 5a shows the angular distribution as a function of \( \cos \theta \) for high mass two-jet events. Note that the shape of the angular distribution can be measured almost independent of the systematic error on the jet energy scale and that remaining systematic errors, coming for example from uncertainties in the energy response as a function of angle, are believed to be at the level of a few percent only. The broken curve represents the scaling predictions for the angular distributions while the solid curves incorporate various non-scaling effects, i.e. variation of the effective structure function and \( \alpha_s \) with \( Q^2 \) (\( Q^2 \) being in general, at fixed \( \hat{s} \), a function of \( \cos \theta \)). The data show evidence for non-scaling effects in the angular distribution and we can expect that a quantitative analysis including the effects of higher order corrections could be a sensitive QCD test. It is interesting to remark that non-scaling effects which one might reasonably have assumed to be rather unimportant at these energies turn out to be large and measurable in contrast with the case of the leading order differences between the various subprocesses \( gg \rightarrow gg, q\bar{q} \rightarrow q\bar{q}, \) etc., which are almost completely unobservable. In order to look at the scale-breaking effects, it is better to plot the cross-section as a function of the variable \( X \)

\[ X = \frac{u}{t} = \frac{1+\cos \theta}{1-\cos \theta} \approx e^{\eta_1 - \eta_2} \]

where \( u \) and \( t \) are the Mandelstam variables and \( \eta_1 \) and \( \eta_2 \) the jet pseudorapidities measured in the pp c.m. system. In this variable, the event rate is expected to be approximatively uniform for \( X > 2 \).

In Fig. 6 the angular cross-section \( d\sigma/dX \) is shown for different jet-jet mass values. The data are compared with QCD predictions based on the structure functions of Ref. 23 with \( A_{QCD} = 0.2 \) GeV and scale \( Q^2 = P_T^2 \). Indeed the behaviour of scaling violation effects is in good agreement with the experimental results. Using the data of Fig. 6b, a test has been done to constrain the \( Q^2 \) scale by varying the \( Q^2 \) (taken proportional to \( P_T^2 \)) in
Fig. 4 - Measurement of the effective structure function.

Fig. 5 - High mass two-jet angular distribution from UA1.
Fig. 6 - Two-jet cross-sections as a function of $x$. 
the QCD calculation. The result of a chi 2-test shows that
\[ 0.1 \, \text{P}^2 \, \text{T}^2 < Q^2 < 67 \, \text{P}^2 \]
at 90 % C.L. The choice \( Q^2 = \hat{s} \) (no scaling violations) is excluded by the
data with chi2/DOF = 42.3/5.

Modifications of parton-parton scattering due to contact interactions
(see section 2) will modify the two-jet angular distribution and will tend
to populate more the region at large angles, \( x = 1 \) relative to QCD predic-
tions. Fig. 6c shows the modification of the cross-section corresponding
to \( \Lambda_c = 300 \text{ GeV} \) for the large mass events, \( m_{2J} > 240 \text{ GeV} \) (where we expect
more than 50 % of the jet pairs to be produced by \( q\bar{q} \) scattering). A limit
\( \Lambda_c > 415 \text{ GeV} \) at 95 % C.L. is set\textsuperscript{121}, similar to the one obtained in sec-
tion 2 using inclusive jet cross-sections.

4. THREE JET CROSS-SECTION

Both UA1\textsuperscript{120} and UA2\textsuperscript{124} have performed a study of events containing
three hard jets in the final state. The yield of three-jet events relative
to that of two-jet events provides a measure of the strong coupling con-
tant \( \alpha_s K_j/K_2 \) where \( K_j \) and \( K_2 \) represent the contributions arising from
higher order corrections in \( \alpha_s \) to the two- and three-jet cross-sections.

The UA1 analysis of the process \( 1 + 2 \rightarrow 3 + 4 + 5 \) is done in the
three-jet c.m. system in terms of the dimensionless scaling variables
\( x_j = P_j/E_j \mid P_j \mid \) ordered as \( x_j > x_4 > x_5 \), of the angles \( \theta_j \) of the jets with the
average beam direction, and of the angle \( \Psi \) between the planes (jet \( j \)-jet \( s \))
and (jet \( j \)-beam).

At fixed subprocess c.m.s. energy, the three-jet matrix element depends
on four independent variables \( x_j, x_4, \Psi \) and \( \cos \theta_j \). The angular distribu-
tions are shown on Fig. 7, where the closed circles correspond to the
published data (\( \sqrt{s} = 546 \text{ GeV}, \sqrt{s} = 150-250 \text{ GeV} \)) while the crosses represent
the preliminary 1984 data (\( \sqrt{s} = 630 \text{ GeV}, \sqrt{s} = 180-350 \text{ GeV} \)). Since, as it
has been emphasized, the variables plotted are dimensionless data sets at
different beam energies, and different subprocess c.m.s. energies may
readily be superposed. It is interesting to note that the agreement with
QCD predictions (solid curves) is only qualitative. The angular distribu-
tions have a tendency to be more strongly peaked than is predicted by the
leading order (scaling) QCD matrix element. The ratio of three-jet to
two-jet cross-sections can be calculated in leading order QCD and is then
equal to
\[
\sigma_{3J}/\sigma_{2J} = \left[ \alpha_s^2(Q_{3J}^2)/\alpha_s^2(Q_{2J}^2) \right]
\]
\[
\left< F(x_1, Q_{3J}^2)F(x_2, Q_{3J}^2)/F(x_1, Q_{2J}^2)F(x_2, Q_{2J}^2) \right> [C_3/C_2]
\]
Fig. 7 - Angular distribution of the 3 jet events.
where $C_1$ and $C_2$ are the results of the integration of the differential cross-sections over the acceptance$^{[27]}$. 

If the two $Q^2$ scales $Q^2_{1J}$ and $Q^2_{1J}$ are identical at fixed $\hat{s}$ the leading order formula becomes $\sigma_{1J}/\sigma_{2J} = \alpha_s C_2/C_1$. The result quoted for this hypothesis is $\alpha_s[K_3/K_2] = 0.23 \pm 0.01 \pm 0.04$ at $<Q^2> = 4000$ GeV$^2$ where the unknown factor $K_3/K_2$ accounts for the higher order corrections to the three-jet and two-jet cross-sections. If the two $Q^2$ scales are not identical at fixed $\hat{s}$ (it would be the case if $Q^2 < \langle p_T^2 \rangle$; see section 3) then $\alpha_s$ cannot be trivially computed from the ratio of three-jet to two-jet cross-sections at fixed $\hat{s}$, owing to the non cancellation on formula (1) of the factor $\alpha_s^2$ and to scaling-violation effects in the structure functions. Selecting from the data a sample of two-jet events with smaller scattering angles (i.e. more comparable values for $Q^2_{1J}$ and $Q^2_{1J}$) a smaller result is then obtained: $\alpha_s [K_3/K_2] = 0.16 \pm 0.02 \pm 0.03$. 

The UA2 analysis$^{[24,25]}$, quotes $\alpha_s K_3/K_2 = 0.236 \pm 0.004 \pm 0.040$, with the assumption that the definition of the $Q^2$-scale using the transverse momentum of the leading jet is appropriate for both the two-jet and the three-jet samples. Like in UA1 conceptual rather than instrumental limitations preclude a more accurate and more reliable measurement of $\alpha_s$ using the present method: a first order calculation of $K_3/K_2^{[26]}$ and a deeper understanding of the relevant $Q^2$-scales are the next questions to be addressed.

5. FOUR-JET EVENTS

UA2 has done a preliminary analysis$^{[28]}$ of four-jet events using the total luminosity ($\sim 750$ nb$^{-1}$) at $\sqrt{s} = 630$ GeV. The following four conditions are applied:

1) $E_T^1 + \ldots + E_T^4 > 70$ GeV,
2) $E_T^i > 10$ GeV $i=1,\ldots,4$ $E_T^5 < 10$ GeV,
3) $|\eta_i| < 0.8$ $i=1,\ldots,4$,
4) $|p_T^1 + \ldots + p_T^4| < 20$ GeV where $E_T^1 > E_T^2 > \ldots$.

Furthermore secondary clusters with an opening angle smaller than $30^\circ$ are merged into a single cluster. This reduces the sensitivity to fragmentation effects while still retaining good angular resolution, and results in a sample of $\sim 2200$ events.

The four jet system can be described in terms of nine variables: three describing the orientation of the jet system and six describing the
internal configuration of the jets. This large number of variables make the
description of this final state rather complex. The jets do not lie in a
plane, nor can they be described by simple Dalitz plots. A natural set of
variables are six $x_{ij} \ (x_{ij}^2 = m_{ij}^2/\hat{s})$, or equivalently the space angles be­tween the jets in the center of mass, $\cos \theta_{ij}$. Only five of these variables
are independent - the sixth degree of freedom corresponds to the total mass
of the jet system.

Comparisons are made between the data, a parton level QCD model based
on recent $O(a_s^4)$ calculations$^{199}$ and a phase space model. At this stage of
the analysis, only the shapes of the distributions are studied - questions
of normalization are avoided by setting the area of the distributions to
one. To examine the qualitative features of the events, we first look at
the sphericity calculated from the jet momenta in the center of mass. The
distribution is shown in Fig. 8a, and it is apparent that the observed
event shape agrees well with the QCD model, and is significantly less
spherical than phase space. A more detailed understanding of the features
of four-jet events can be obtained by examining the space angles defined
previously. Fig. 8b shows the distribution of $\cos \theta_{21}$. The data shows a
significant enhancement above the phase space model in the region of small
angular separation, indicating the presence of bremsstrahlung. This enhance­
cement agrees very well with the QCD model.

Several authors have predicted an additional source of four-jet
events$^{130}$ the multi-parton mechanism, in which multiple hard parton colli­
sions take place in a single hadron collision. This mechanism, which is
suppressed by extra powers of $\hat{s}$, becomes important for small values of the
parton momentum fraction, where the density of partons in the nucleon be­
comes very large. The simplest form of this process, in which two indepen­
dent pairs of partons interact, can be described as follows:

$$\sigma_{mp} \sim \int G(x_1, x_2) G(x_3, x_4) \, d\hat{\sigma}_{12} \, d\hat{\sigma}_{34}$$

where the $G$ are double structure functions and the $d\hat{\sigma}$ are the cross­
sections for the two parton sub-processes. In order to search for evidence
of multi-parton interactions, a simple model has been constructed, in which
the double structure functions factorize in terms of single parton den­sities
$\{G(x_1, x_2) \sim F(x_1) \, F(x_2)\}$ and the effects of soft gluon radiation
from the initial state partons are simulated by giving each jet-jet system
a Gaussian $\tau$ kick, whose magnitude has been adjusted to agree with the
measured two-jet data$^{199}$. The most characteristic feature of multi parton
events should be the appearance of pair-wise correlations among the jets.
Fig. 8 - a) Sphericity of the four-jet system,
b) Angle in the c.m.s. between the
second and the third jet.

Fig. 9 - a) azimuthal difference between the leading and the
other jets.
b) \( i_t \) (unb) – see equation (2) in the text.
To search for these correlations, transverse variables in the lab frame are chosen, since they are relatively insensitive to center of mass motion. A simple variable of this kind is the difference between the azimuthal angle of the leading jet, and the azimuthal angles of the other jets in the event. This variable, called \( \Delta \phi_{\text{lead}} \), is sensitive to the presence of a second jet opposite to the leading jet. The distribution of this variable with three entries per event, is shown in Fig. 9a. The data agree well with the QCD model, and show no sign of the narrow peak that is expected for the multi-parton process. An alternate variable is the \( P_T \) unbalance in the event, defined by the expression:

\[
P_T(\text{unb})^2 = 2 \min \left( P_T^1 + P_T^2 \right) \tag{2}
\]

where \( i \) is chosen to minimize the unbalanced \( P_T \). This variable should take on small values for the multi-parton process since there will be a second jet balancing the \( P_T \) of the leading jet. The observed distribution is shown in Fig. 9b, and agrees well with QCD model. Again, there is no sign of the enhancement expected at small \( P_T \) unbalance from the multi-parton mechanism.

Two preliminary conclusions emerge from this discussion. The first is that the observed four-jet distributions agree well with a leading order QCD calculation, and differ significantly from four-body phase space. The second is that there is no evidence for the additional contribution from the multi-parton processes.

6. DIRECT PHOTON PRODUCTION

The measurement of direct photon production cross-sections offers an alternative test of QCD with the advantages that the photon energy measurement is not affected by fragmentation effects and that QCD calculations have been carried out to the next to leading order in the strong coupling constant \( \alpha_s \). However, the production cross-section for direct photons is nearly four orders of magnitude smaller than the production cross-section for hadronic jets. This is a consequence of the low average parton charge, of the small size of the electromagnetic coupling constant as compared with the strong coupling constant, and of the fact that subprocesses such as gluon-gluon collisions are important for jet production but do not contribute to photon production.

The relatively copious production of high-\( P_T \) hadronic jets is responsible for the dominant background to the measurement of direct photons. Hadronic jets often contain high-\( P_T \) \( \pi^0 \) and \( \eta \) mesons which decay into photon
pairs. Since it is usually not possible to resolve both decay photons, the \( \pi^0 \)'s and \( \eta \)'s behave as single photons in the detectors. The analysis done by the UA2 experiment\(^\text{(33)}\) exploits the fact that such "photons" are generally accompanied by other jet fragments whereas direct photons are expected to be more isolated. A sample of well isolated direct photon candidates is defined. The residual background from isolated \( \pi^0 \)'s and \( \eta \)'s is estimated by considering the fraction of the sample for which the photon has begun showering. Independant measurements are made in the central region (\( |\eta| < 1.0 \)) and in the forward regions (\( 1.0 < |\eta| < 1.8 \)).

The data were recorded with the same trigger as that which was used in the study of the process \( p\bar{p} \rightarrow W + e^- \nu \)\(^\text{(34)}\) : at least 10 GeV of transverse energy into a 2 x 2 cell matrix of the electromagnetic calorimeter. The analysis correspond to the 1981-1984 periods at \( \sqrt{s} = 546 \text{ GeV} \) (\( \sim 140 \text{ nb}^{-1} \)) and \( \sqrt{s} = 630 \text{ GeV} \) (\( \sim 300 \text{ nb}^{-1} \)). Due to different characteristics of the central and forward detectors, we use two different sets of criteria to select single photon candidates.

**Central candidates satisfy the criteria:**

a) the associated cluster must have small longitudinal and lateral size as expected for electron candidates\(^\text{(34)}\)

b) no charged track and at most one preshower signal may be found in a cone of \( (\Delta \phi^2 + \Delta \eta^2)^{1/2} < 0.35 \) about the direction defined by the event vertex and the cluster centroid,

c) the associated cluster must be well isolated in the calorimeter. The pattern of photomultiplier signals is required to be consistent with that expected for a single isolated electron or photon.

**Forward candidates satisfy the criteria:**

a) the associated cluster must have small lateral and longitudinal extent (as for electron candidates\(^\text{(34)}\))

b) no charged track is permitted to point to the cluster,

b) the total energy of all charged and neutral particles impinging on the cells adjacent to the cluster must not exceed 0.3 GeV.

There are \( \sim 1300 \) events in the central region with \( P_T > 15 \text{ GeV} \) and \( \sim 2600 \) events in the forward regions with \( P_T > 12 \text{ GeV} \) which satisfy the selection criteria.

The conversion probability \( \alpha \) is shown in Fig. 10 for both regions. The dots represent the conversion probability for the selected photon candidates and the triangles represent the conversion probability for
candidates that fail certain isolation criteria. The curves labelled \( \epsilon_Y \) (resp \( \epsilon_n \)) is an EGS simulation of the conversion probability for single photons (single \( \pi^0 \)'s and \( \eta \)'s). Since the measured values of \( \alpha \) are between \( \epsilon_Y \) and \( \epsilon_n \), it is clear that both data samples have a substantial content of single (direct) photon events. But there is a residual contamination of unresolved \( \pi^0 \) and \( \eta \) decays. If this contamination was only due to single \( \pi^0 \)'s, and \( \eta \)'s the fractional contamination of the sample, \( b(P_T) \), would be given by the relation: \( b(P_T) = (\alpha - \epsilon_Y)/(\epsilon_n - \epsilon_Y) \). In addition, a correction (less than 10\%) due to the contribution of unresolved multi-(\( \pi^0 \)/\( \eta \)) states is evaluated using the ISAJET Monte-Carlo program\(^{135}\) and is applied to \( b(P_T) \).

The invariant direct photon production cross-section is evaluated from

\[
\frac{d\sigma}{d^3 p} = N_Y(P_T) \left[ 1 - b(P_T) \right] / |P_T \cdot dP_T \cdot L \cdot \epsilon_{c} \cdot A
\]

where \( N_Y(P_T) \) is the number of photon candidates in a \( P_T \) bin of width \( \Delta P_T \), \( L \) is the integrated luminosity that corresponds to the data sample, \( \epsilon_c \) is the efficiency of the experimental selection criteria for retaining direct photon events (\( \epsilon_c = 0.55 \pm 0.06 \) in the central region; \( \epsilon_c = 0.79 \pm 0.07 \) in the forward regions), and \( A \) is the geometrical acceptance in the (\( \eta, \phi \)) plane. The results at \( \sqrt{s} = 630 \) GeV are shown in Fig. 11. Only the \( P_T \)-dependent errors are presented and they are dominantly statistical. The total systematic uncertainty on the normalisation cross-section is 20\%.

In Fig. 11b is also listed the inclusive \( \pi^0 \) spectrum in the forward regions\(^{133,134}\). The cross-sections are compared with an \( O(g^2) \) QCD calculation\(^{137}\) (labelled I in Fig. 11) which includes contributions from the bremsstrahlung of the final state quarks.

The isolation criteria partly suppress such processes in the data. This effect has been studied by excluding from the calculation all bremsstrahlung photons with quark-photon angles smaller than 20\° and 45\°. The results are shown by the curves labelled II and III in Fig. 11. The difference between the two curves indicate the range of the uncertainty in the calculation caused by the isolation cuts. Reasonable agreement is observed between the measurements and the calculations. We can note that the ratio of the direct photon cross-sections

\[
\frac{\sigma_Y(\sqrt{s} = 630 \text{ GeV, } P_T > 15 \text{ GeV})}{\sigma_Y(\sqrt{s} = 546 \text{ GeV, } P_T > 15 \text{ GeV})}
\]

is measured in the central region equal to \( 1.14 \pm 0.07 \), which agrees with the expected ratio of 1.14 from a lowest order QCD calculation\(^{112}\). The corresponding ratio for the \( \pi^0 \) cross-sections at \( \langle \eta \rangle = 1.4 \) is measured equal to \( 1.47 \pm 0.05 \), where an expected ratio of 1.41 is calculated\(^{138}\).
Fig. 10 - The probability for conversion in the preshower detectors (and for recognition of the signal) as a function of energy (see text).

Fig. 11 - Invariant inclusive cross-section for direct photon production
a) in the central region of UA2,
b) in the forward regions of UA2.
7. SEARCH FOR HADRONIC DECAYS OF THE W AND Z BOSONS

This search has been done by the UA2 experiment\textsuperscript{[23]} at $\sqrt{s} = 630$ GeV. Selection criteria have been refined in order to achieve the best mass resolution compatible with retaining a large data sample. Events showing a large departure from the average behaviour are populating the tails of the mass resolution curve (particularly dangerous in the present case since the sought signal is superimposed on a steeply falling distribution). The jet algorithm (see section 2) is slightly modified: the jet directions are the same than the standard ones but the energy is taken as the sum of the energies of all calorimeter cells having their centre within a cone of angle $\omega$ around the jet axis. The value of $\omega$ is adjusted in order to minimize energy measurement errors, using as monitor the difference between the average values of $P_T^\xi$ and $P_T^\eta$, the components of the transverse momentum of the jet pair projected on the bisectors of the jet transverse momenta. While the component $P_T^\xi$, parallel to the jet axis, is mostly affected by energy measurement errors, $P_T^\eta$ is only influenced by angular measurement errors, which results in a much smaller effect\textsuperscript{[19]}. As a result, the value $\cos \omega = 0.6$ is chosen.

In order to ensure sufficient containment, only jets having their axes within a fiducial volume, $|\cos \Theta| < 0.6$, are considered. Corrections to the energy and polar angle of each jet, accounting for the lack of calorimeter coverage outside the interval $40^\circ < \Theta < 140^\circ$, are applied. They are evaluated from a study performed on a sample of well contained jets and amount to

$$\Delta \Theta \text{ (radians)} = -0.05 \cos \Theta$$
$$\Delta E = 0.06 E (\cos^2 \Theta + |\cos \Theta|).$$

The following selection criteria are adopted:

i) criteria applied to each jet:

. The energy $\Delta E$ measured between the two cones having $\cos \omega = 0.5$ and $\cos \omega = 0.7$ must not exceed 4 GeV;

. the fraction $f_{\text{em}}$ of jet energy measured in the calorimeter electromagnetic compartment must exceed $0.235 - 0.094 \ln(E/40 \text{ GeV})$;

. the fraction $f_{H_2}$ of jet energy measured in the second hadronic compartment must not exceed $0.410 + 0.087 \ln(E/40 \text{ GeV})$;
ii) **Criteria applied to each jet pair:**

- the mass $m_{cl}$ of the pair, calculated using cluster energies, must not differ from the two-jet invariant mass $m$ by more than 17 GeV;
- the transverse momentum $P_T$, expressed in GeV, must not exceed $24 + 11.5 \ln (m/80 \text{ GeV})$.

The cuts were tuned to reject a small fraction — typically 5 to 10% each — of the event sample, uniformly across the explored range of jet-pair masses. They reduce the event sample to a fraction $\varepsilon_{\text{cut}} = 0.66$ of its original population. Their efficiency to retain IVB decays may be slightly larger, to the extent that quark jets may be expected to obey slightly tighter cuts than gluon jets, which dominate the event sample from which $\varepsilon_{\text{cut}}$ has been evaluated.

An additional cut may be applied:

$$\tilde{E}_T^F < 6 \text{ GeV}, \quad \tilde{E}_T^C < 10 \text{ GeV}$$

where $\tilde{E}_T^C$ (resp. $\tilde{E}_T^F$) is the transverse energy in the central calorimeter (resp. electromagnetic forward calorimeters) outside the jet definition cone.

The $\tilde{E}_T^F,\tilde{E}_T^C$ distribution of events passing the selection criteria defined above and having a jet-pair mass in the IVB region ($70 < m < 100 \text{ GeV}$) are shown in Fig. 12.

![Fig. 12 - Distribution of $\tilde{E}_T^F$ and $\tilde{E}_T^C$ (see text).](image_url)
The cuts $E_T^C < 10$ GeV, $E_T^F < 6$ GeV retain $\approx 60\%$ of the jet pairs in the IVB region.

Several factors can affect the mass scale and the mass resolution. Taking into account the energy leakage of particles of a jet outside the definition cone, the spectator contribution inside the cone, the calorimeter response and the energy calibration, the mass shift is estimated to be $-2.2 \pm 4.8$ GeV. The mass resolution is estimated to be about 9 GeV.

The $Z$-$W$ mass difference is too small, compared with the experimental resolution, to allow for a separation between the signals. Therefore an excess of events should be observed in a wide mass region, typically $65 < m < 105$ GeV. A quantitative measurement of the signal yield above the level of the strong interaction background requires an interpolation from the two control regions on either side of the signal. Therefore, the mass distribution can be used only in the range not affected by distortions, such as threshold biases due to the trigger or contaminations by soft collisions. As discussed in Section 2, the two-jet data have been taken with different thresholds. The range which is free from trigger biases is found studying the mass dependence of the ratio between high- and low-threshold data. The observed values are $m = 45, 49,$ and 57 GeV for the events taken with threshold set at $E_T = 12.5, 15$ and 20 GeV respectively. The three data samples are then combined with relative normalizations evaluated using the region $m > 57$ GeV.

In Fig. 13 the mass distribution of the events which pass all the cuts (including those on $E_T^C, F$) is shown. Each event is given a weight $(m/100$ GeV)$^5$. A structure is visible in qualitative agreement with expectations from $W$ and $Z$ decays. A quantitative evaluation of the number of events in the signal and a measurement of its significance is obtained by fitting the data, distributed in 1 GeV wide mass bins, to a form...
\[ \frac{dN}{dm} = A \left( m^{-\alpha} \exp(-\beta m) + \xi S(m, m_0) \right) \]

where \( S(m, m_0) \) is the sum of two gaussian distributions, representing W and Z signals respectively. The W (Z) distribution is taken to have a mean value \( m_0 \) (1.14 \( m_0 \)) and R.H.S. 8 GeV (9 GeV). The relative normalization between the two gaussians is assumed equal to the expected ratio (\( = 3 \)) between the numbers of observed W and Z decays. The parameters \( \alpha, \beta \) and \( \xi \) are adjusted to maximize the likelihood function, the constant \( A \) being calculated each time to provide the appropriate normalization. The mass parameter \( m_0 \) is either set to the expected value, \( m_0 = 78.5 \) GeV, or treated as an additional free parameter. In the latter case, \( m_0 \) comes out to be 82 \( \pm 3 \) GeV, the significance of the signal is 3.3 standard deviations, and its content amounts to 632 \( \pm 190 \) events.

The number of events found using the fit can be compared with the results of a simulation taking into account the Standard Model predictions and the efficiency of the cuts. This calculation results in an expected number of events approximately one standard deviation below the observed signal. This result does not vary if the \( E_T \) cut is relaxed, both in the data and in the Monte-Carlo.

Other fits, using either a different parametrization of the strong interaction background or different data subsamples, obtained by altering the selection criteria, have been performed. Fits to data samples, which do not satisfy two or more selection criteria, give no evidence for a signal. Subsamples of data, which pass the selection criteria, always present a signal with a statistical significance between 2 and 3.5 standard deviations. No known systematic effect seems capable to fake the signal.

In conclusion it may be noted that the hadronic decay of the IVB's is one of the simplest test-cases of the ability of future Collider experiments to analyse multiparticle final states in terms of hadron jets identified with their parent partons. The observed signal, at the level of \( \sim 3 \) standard deviations above the copious and steeply falling strong interaction background is in agreement with Standard Model expectations. However, more data are needed to put it on firmer grounds. It will be a challenge for ACOL\(^{139}\) to show a stronger evidence for the signal and to measure the W,Z + \( q\bar{q} \) branching fractions.

8. CONCLUSIONS

The inclusive jet-cross sections have been measured and are in agreement with QCD. Two-jet angular distributions show evidence for scaling
violations. Both studies give similar limits for the characteristic compositeness energy scale: \( A_c > 400 \text{ GeV} \) (95\% C.L.). The yield of three-jet events relative to two-jet events provides a measure of \( \alpha_s^3 K_3/K_2^3 \). The observed four-jet distributions are in agreement with the leading order \( O(\alpha_s^3) \) calculation. There is no evidence for additional contribution from the multi-parton processes. The direct photon yield agrees also with QCD. A signal of hadronic decays of the IVB'S is observed at the level of \( \sim 3 \) standard deviations in agreement with the Standard Model. More data at ACOL should put it on firmer grounds.

I thank all my colleagues from UA2, in particular P. Bagnaia and K. Einsweiler (the excellent reviews they have written have helped me very much in the preparation of this one). I thank F. Ceradini and W. Scott from UA1 for useful discussions on this subject.

Finally I thank the organisers, in particular P. Pavlopoulos for this interesting conference.

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