RECENT RESULTS FROM THE UA1 COLLABORATION AT THE CERN
PROTON-ANTIPROTON COLLIDER

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1. Introduction

This workshop takes place at a critical time for the CERN SPS Collider community. In a few days, the UA1 and UA2 collaborations will begin an intensive two month period of data-taking, with expected peak luminosities between $10^{28}$ and $10^{29}$ cm$^{-2}$ sec$^{-1}$, and strong hopes to produce exciting new results in the field of electro-weak interactions. I will indicate the high level of preparation to study new phenomena by summarising results achieved so far by the UA1 collaboration, using a data sample taken at the end of 1981 at $\sqrt{s} = 540$ GeV and corresponding to a total integrated luminosity of 22 $\mu$b$^{-1}$. I will discuss the results under three general headings which reflect the highly dynamic nature of this field.

"OLD" Collider Physics (up to summer 1982) covering basic studies of the general nature of $\bar{p}p$ interactions at $\sqrt{s} = 540$ GeV. I apologise for focusing here, and elsewhere, on UA1 results; in this case prolific contributions have been made by all collaborations, UA1, UA2, UA4 and UA5.

Presented at the DESY Workshop on Electroweak Interactions
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"NEW" Collider Physics (summer 1982) dealing with existence of jets and preliminary studies of their properties, first highlighted by new results from UA2 and UA1 at the XXI Paris conference in July and at the European Symposium at Santiago de Compostela in August.

"FUTURE" Collider Physics (from end 1982). At the time of writing, the future has already been reached, both for UA1 and UA2, and I can profitably conclude with a brief resumé of the first "electro-weak" results from UA1, derived from the 1982 data.

2. THE UA1 DETECTOR

The UA1 detector has been extensively described in existing literature\(^1\), and I recall only general features which are relevant to this presentation. The central region of the apparatus is designed to provide detection of W, Z bosons via different decay modes. The interaction area is enclosed in a transverse dipole magnet which can provide a uniform magnetic field of maximum strength 0.7 Tesla. Closest to the interaction is the central detector, a high resolution cylindrical drift chamber complex, 5.8 m long by 2.3 m diameter, which gives a detailed bubble-chamber quality image of each event, and allows momentum analysis of individual tracks with a typical accuracy of ±20% for a 1 m track at \( p = 40 \) GeV/c. The central detector is surrounded in turn by fine-grain lead-scintillator electromagnetic calorimeters and by iron-scintillator hadron calorimeters, the latter incorporated in the return yoke of the magnet. This allows localisation and energy measurement of high energy electrons, identified by their characteristic energy deposition profile, with a typical energy resolution of \( \Delta E/E = 0.15/\sqrt{E} \) GeV. High energy muons will penetrate beyond the iron of the magnet, and can be detected by 2 x 4 planes of drift tubes installed around the magnet on all 6 sides.

The calorimetry also permits measurement of global or local hadronic energy deposition, with a resolution \( \Delta E/E = 0.8/\sqrt{E} \) GeV,
and with a coverage extended down to 0.2° with respect to each beam tube by additional electromagnetic and hadron calorimeters in the forward arms. This capability is important in two respects for W, Z searches, namely the missing transverse energy can be determined per event (characteristic of a neutrino) and high energy jets can be identified and measured (hadronic decay modes, QCD "background").

For the 1981 run, 4 pairs of small precision drift chambers and trigger scintillators were installed in the forward arms at ± 23 m from the interaction vertex to allow a specific analysis of elastic scattering events.

During data-taking, various trigger processors can select events which are primarily electron, muon or jet candidates; at 10^{28} - 10^{29} luminosities the data rate can be then controlled below 1 event/sec with a consequent dead time for rare processes < 10%.

The ensemble of elements for W, Z detection provides in UA1 a universal, near 4π, detector adapted to a wide range of physics topics. In addition to those discussed here, I mention in particular the study of heavy flavour decays, another important objective of future running periods.

3. "OLD" COLLIDER RESULTS

3.1. CHARGED PARTICLE MULTIPLICITIES

The charged particle multiplicity distribution has been studied in rapidity range |η| < 3.5 with a sample of 8000 minimum bias events recorded without magnetic field. Beam gas events have been removed by timing and topological cuts, and corrections have been applied for track finding efficiency (96%) and geometrical acceptance (80%). Further corrections, estimated by Monte Carlo, have been included for γ-conversion, neutral particle decay and nuclear interaction losses.

The distribution of the average pseudo rapidity density, dn/dη, is shown in Figure 1, giving a measurement at η = 0 of 3.3 ± 0.2, compatible with earlier results from UA5 and UA1. As illustrated in Figure 2, this represents a 70% rise from ISR results at √s = 63
Figure 1. Charged Particle Pseudo-Rapidity Density vs Pseudo-Rapidity.

Figure 2. Charged Particle Pseudo-Rapidity Density vs CMS Energy.
Figure 3. Moments of the Density Distribution of Charged Particles vs CMS Energy.
GeV. The shape of the distribution shows a narrowing of about 2 units with respect to a simple extrapolation from ISR energies. Analysis of the moments of the distribution allows comparison with other energies. Figure 3 shows the energy dependence of the following three moments:

\[
Y_2 = \frac{\langle (n-\langle n \rangle)^2 \rangle}{\langle n \rangle} \\
Y_3 = \frac{\langle (n-\langle n \rangle)^3 \rangle}{\langle n \rangle} \\
Y_4 = \frac{\langle (n-\langle n \rangle)^4 \rangle - 3\langle (n-\langle n \rangle)^2 \rangle^2}{\langle n \rangle}
\]

Little change has occurred between ISR and collider energies, i.e. the moments are independent of \( s \), implying that KNO scaling is approximately valid over this very large energy range.

3.2. SMALL ANGLE ELASTIC SCATTERING

\( \bar{p}p \) elastic scattering has been studied in the range \( 0.14 < |t| < 0.26 \) GeV\(^2\) using a sample of 5437 elastic trigger events obtained at a luminosity of \( \sim 10^{26} \) cm\(^2\) sec\(^{-1}\) with normal beta operation of the SPS. The detector was arranged to record elastic scattering events in the vertical plane, and approximately 20% of the triggers gave a clean coincidence of "up-down" or "down-up" single tracks in the respective forward arms. The remaining triggers contained large splashes in one arm, partly due to accidental coincidence of beam-gas secondaries and partly to inelastic beam-beam events.

The acceptance of the apparatus has been studied in detail by Monte Carlo simulation. The full acceptance regions of the up-down and down-up categories have been combined for the final \( t \) distribution shown in Figure 4 which is well described by the hypothesis \( dN/dt = e^{bt} \) with \( b = 13.3 \pm 1.5 \) GeV\(^{-2}\). The data is presented as a differential cross-section, involving scale factors with systematic uncertainties, the most important being 30% for the integrated luminosity measurement.
Figure 4. Elastic Differential Cross-Section.

Figure 5. Elastic Slope Parameter vs CMS Energy.
of $2.6 \times 10^{10}$ cm$^2$. Figure 4 also shows the UA4 data$^4$) over
the range $0.05 < |t| < 0.19$ GeV$^2$, which give a measured slope
parameter $b = 17.2 \pm 1.0$ GeV$^{-2}$. The combined results suggest
that $b$ increases with decreasing $t$, as observed in pp scattering at
the ISR$^7$).

A comparison with the compilation of Burq et al.$^8$) in Figure 5
indicates that the forward elastic $\bar{p}p$ peak is shrinking over the
ISR-Collider energy range.

3.3. SEARCH FOR CENTAURO EVENTS

The expected characteristics of Centauro events, reported from
Cosmic Ray experiments$^9$), are:
- high hadron multiplicity
- negligible fraction of electromagnetically showering particles
- high $<p_T>$ per particle (above 1 GeV/c).

It is natural to search for similar features in collider events where
the equivalent energy on a stationary target is 155 TeV, always
admitting a possible higher threshold (typical Centauro energies are
estimated at around 1500 TeV).

Interpretation of Centauro events in the collider context is
difficult due to various uncertainties. One concerns the $\gamma$ factor
i.e. the fraction of hadronic energy converting electromagnetically,
which depends on the pion/nucleon population. Another concerns the
accuracy of the vertex height determination which directly affects
measurement of $<p_T>$. The expected kinematics in the collider is
also dependent on the underlying mechanism, being very different for
the two popular hypothesis, namely collision with an air nucleon or
decay of a massive object.

With such reservation in mind, we have looked for equivalent
dramatic behaviour in a sample of 48000 minimum bias events$^{10}$),
recorded with a magnetic field of 0.56 Tesla. A reasonable measure of
the overall e.m./hadron composition is given in the central
calorimeters by the respective energy depositions in the first 4
radiations lengths (e.m.) and beyond 12 radiation lengths (hadronic).
Figure 6. "Electromagnetic" vs "Hadronic" Energy.
Figure 7. Mean Transverse Momentum vs Charged Multiplicity.
Figure 6 shows a smooth behaviour in different relevant angular regions, without any clearly anomalous events, and consistent with a Monte Carlo simulation. The same is true for the mean transverse energy of charged tracks as a function of their multiplicity, shown in Figure 7.

A more detailed study has been performed on Centauro 1, the best determined of the family of (currently) 6 events. Centauro 1 has been transformed to the collider cms under various K\gamma and production mechanism hypotheses. There is no concentration of collider events in the predicted regions, which are nonetheless fully accessible.

With the qualifications mentioned above, we can give an upper limit for Centauro-like processes at 155 TeV equivalent energy of around 1 \mu b.

3.4. CHARGED PARTICLE p_{T} SPECTRA

The inclusive transverse momentum spectrum of charged particles in rapidity range |y| < 2.5 has been measured up to 10 GeV/c \cite{11}, using the sample of 48000 minimum bias events taken with a magnetic field of 0.56 Tesla. Track momenta were reconstructed in the central detector which has a typical resolution \sim 280 \mu in the drift plane and \sim 2.3% of wire length for the transverse coordinate given by current division. The track finding efficiency was \sim 97%.

Corrections have been applied for geometrical acceptance and for smearing due to resolution. Contamination near p_{T} = 10 GeV/c is estimated as < 17% due to bad track reconstruction and < 30% due to particle decays. At this stage only about one third of the wires were equipped with electronics.

Figure 8 compares the UA1 inclusive spectrum with ISR results \cite{12}, showing an increase of about 3 orders of magnitude in cross-section at p_{T}= 10 GeV/c. Both the ISR and collider spectra are in good agreement with QCD predictions by Odorico \cite{13}. The UA1 spectrum is also well described by a simple empirical form:

\[ E d\sigma = A p_{T}^{n} / (p_{T} + p_{T}^{0})^{N} \]
with \[ P_t \sim 1.3 \] and \[ n \sim 9.1 \]

The spectrum is clearly dependent on charged track multiplicity in the same rapidity interval. This is illustrated in Figure 9 where the mean transverse momentum is plotted as a function of the charged particle density; the \(<P_T>\) increases from about 350 to 470 MeV/c, apparently saturating beyond \(\sim 10\) particles per unit of rapidity. This saturation may be kinematic, due to exhaustion of available energy, but may also be interpreted as a thermodynamic effect, involving a change of state of hot hadronic matter, as suggested by Van Hove\(^{19}\).

3.5. CORRELATIONS BETWEEN HIGH \(P_T\) CHARGED PARTICLES

Extensive studies at the CERN ISR\(^{15}\) have demonstrated strong correlations in the production of high transverse momentum particles; these correlations are interpreted as hard scattering of partons, where the scattered partons fragment into clusters of hadrons, or jets. Similar correlations have been observed in UA1 events\(^{16}\), both in the minimum bias sample, and in a sample of 39000 events recorded with a central transverse energy trigger, \(E_T > 30\) GeV.

Selected events have been analysed which include a "software trigger" particle of transverse momentum \(P_T > 4\) GeV/c. Using the trigger direction to define two regions, respectively "towards" ie. within azimuthal angle \(|\Delta \phi| < 90^\circ\) of the trigger, and "away", Figure 10 shows the rapidity and azimuthal difference with respect to the trigger for other particles in each region. For "towards" particles, a clear trend is seen, increasing strongly with the \(P_T\) of the other particles, to cluster around the trigger in rapidity/azimuthal space. This is further demonstrated in Figure 11 where the \(P_T\) spectrum of particles near to the trigger is compared with the inclusive minimum bias distribution.

In the away region, the higher \(P_T\) particles tend to be produced at \(\Delta \phi = \pm 180^\circ\), ie. coplanar, with respect to the trigger. There is no obvious correlation with the trigger rapidity. However
Figure 10. Rapidity-Azimuth Correlations of other Particles Relative to Trigger Track of $p_T > 4$ GeV.

$p_T$ of other Particles $> 0$ GeV/c (a + c)

$> 1$ GeV/c (d + f)

$> 2$ GeV/c (g + i)
Figure 11.

Figure 12. Rapidity Correlations w.r.t. highest $p_t$ particle in the "away" region.

...all other "away" particles.

...$p_t > 0.8$ GeV/c

...$p_t > 1.5$ GeV/c
Figure 12 demonstrates a clustering of other high $p_T$ particles around the highest $p_T$ particle in the away region.

This observation of two coplanar cluster, uncorrelated in rapidity, and present in < 1% of minimum bias events, is the first indication that parton jets are present in collisions at the SPS collider.

4. "NEW" COLLIDER PHYSICS

At the time of this workshop, the most recent collider results concern the production of jets, and in particular the dominance of jet production at high transverse energies $^{17,18}$. From the jet physics viewpoint, particle tracking and calorimetry are complementary; however, for analysis of the initial low statistics data samples, separate analysis have been carried out, concentrating on different $p_T$ regions and stressing different measurable characteristics.

4.1. LOW ENERGY JETS

Low energy jets, containing dominantly soft fragments which are spread by the magnetic field, are most accurately measured in the central detector (at least for charged tracks!). For the present analysis $^{13}$, a jet-finding algorithm has been developed to isolate clusters which have low relative internal transverse momenta. Initially considering each track as a cluster, the two clusters with the lowest relative $p_T$ are merged and this procedure monotonously repeated until the relative $p_T$ increases too steeply or crosses a threshold. Various fiducial cuts are then applied, and events are retained with at least one "central" cluster $(25^\circ < \theta < 155^\circ)$ with $p_T > 5$ GeV/$c$. The following table gives the percentage yields from different data samples recorded at 0.56 Tesla. The numbers are approximate due to uncorrected acceptance effects and inefficiencies, but show clearly the increased fraction of "jetty" events at higher global transverse energies, both for single and multi-cluster production.
Figure 13. Properties of Charged Particle Jets 
$(25^0 < \theta < 155^0)$. 
TABLE I

<table>
<thead>
<tr>
<th>Data sample</th>
<th>Number of Events</th>
<th>&gt; 1 cluster</th>
<th>3 clusters</th>
<th>&gt; 4 cluster</th>
</tr>
</thead>
<tbody>
<tr>
<td>Min. Bias</td>
<td>44887</td>
<td>2.1(± 0.1)</td>
<td>0.96(± 0.05)</td>
<td>0.83(± 0.04)</td>
</tr>
<tr>
<td>High $E_T$ (&gt; 30,40 GeV)</td>
<td>37062</td>
<td>12.4(± 0.2)</td>
<td>4.9(± 0.2)</td>
<td>6.1(± 0.2)</td>
</tr>
<tr>
<td>$E_T &gt; 60$ GeV in $\Delta y = \pm 1.5$</td>
<td>436</td>
<td>51(± 4)</td>
<td>12(± 2)</td>
<td>34(± 3)</td>
</tr>
</tbody>
</table>

Events mixing and Monte Carlo techniques have been used to demonstrate that the measured jet signals are not due to chance fluctuations. In addition there is only a weak dependence on the parameters of the algorithm.

A first indication of internal jet properties is given in Figures 13 (a), (b) and (c), although it is stressed that these results are preliminary and much more sensitive to acceptance corrections and to algorithm parameters. The normalised fragmentation function $D^2(z) = 1/N dN/dz$ is compared with the functions $(1-z)/z$ and $(1-z)^2/z$, and shows a preference for the softer form. The mean multiplicity of charged particles within a cluster is $\approx 8$, and the mean internal $p_T^2$ is $\approx 0.2$ GeV².

4.2. HIGH ENERGY JETS

High energy jets have been studied by detection of large local deposition of transverse energy in the central calorimeters. The present analysis is restricted to the barrel calorimeters, covering pseudo rapidity range $|\eta| < 1.5$, but will be extended later to include the end-cap calorimeters $1.5 < |\eta| < 2.6$. The data samples were obtained by triggering on local transverse energy in the
central calorimeters in excess of various thresholds ($E_T > 20, 30, 40 \text{ GeV}$), representing a total integrated luminosity of $22 \text{ pb}^{-1}$. The combined samples contain 6051 events with $E_T > 40 \text{ GeV}$, 279 with $E_T > 20 \text{ GeV}$ and 5 with $E_T > 100 \text{ GeV}$.

Any jet study depends on initial definition of a jet, leading to a choice of algorithm and associated parameters which may influence quantitative results, especially concerning jet properties. A simple algorithm is however sufficient to demonstrate the presence of high energy jets at the collider. In the UA1 "window" algorithm, a jet is declared present in one half-shell of the barrel calorimeters if at least two-thirds of the transverse energy in that half shell is contained within 8 (out of 24) adjacent electromagnetic cells plus the matching hadronic ones. This allows events to be clearly categorised as 0-jet, 1-jet or 2-jet.

Figure 14 shows the fraction of such 2-jet events as a function of total transverse energy. The decreasing fraction up to 40 GeV is expected from multiplicity fluctuations, coupled with the dependence of $E_T$ on multiplicity, and has been reproduced by Monte Carlo simulation (solid curve). Above 40 GeV, the fraction increases due to onset of jet production which becomes dominant at the highest $E_T$ values. This conclusion has been confirmed by scanning of individual events on a graphical display system. For the five events with $E_T > 100 \text{ GeV}$, four of them are clear 2-jet events while the fifth contains a multi-jet structure of three (or four) jets. The 2-jet events are dominantly coplanar, as expected in a hard-scattering process, and are roughly balanced in $p_T$. Examples of different jet topologies are given in Figures 15 (a), (b) and (c) which show the struck calorimeter cells and the central detector track vectors above modest thresholds of order 1 to 2 GeV.

The inclusive cross-section for jet production around $\eta = 0$ has been studied with both the window algorithm and with a more sophisticated "cluster" algorithm, to reveal possible sensitivity to jet definition. The cluster algorithm associates a vector to each struck calorimetric cell, and combines these vectors into clusters on the basis of their separation in $\eta \phi$ space. The inclusive cross-section
Figure 14. Fraction of 2-Jet Events vs Total Transverse Energy.
Figure 15 b)  2-JET  Back-to-antiback
Figure 16.

Figure 17.
for both algorithms is shown in Figure 6. The results agree reasonably well, with somewhat higher estimates from the cluster algorithm which tends to include more "soft" cells from the fringe area around a jet.

The results are also in good agreement with the predictions of two QCD-motivated models\textsuperscript{24).} This is again true for the 2-jet mass spectrum, shown in Figure 17, which already extends to the region of W, Z decays. There is therefore a good prospect to detect these particles via their hadronic decay into two (or more) jets from later high statistics runs at the collider.

Addendum: At the time of writing this article, the jet cross-section has been measured with 1982 data for a total integrated luminosity of about 18 nb\textsuperscript{-1} and has been presented at the January workshop in Rome on proton-antiproton collisions\textsuperscript{21).} The new spectrum is fully consistent with our previous one but remains high with respect to the published UA2 result\textsuperscript{16).}

5. "FUTURE" COLLIDER PHYSICS

(...with the benefit of hindsight!)

Future collider physics became present-day reality during November -December 1982, when UA1 collected data with a fully operational detector for a total integrated luminosity of 18 nb\textsuperscript{-1}, with peak rates of $5 \times 10^3$ cm\textsuperscript{2} sec\textsuperscript{-1}. High energy electron candidates were isolated and studied during the run, leading to a presentation by Prof. C. Rubbia in January at the Rome workshop on proton-antiproton collisions and to the first publication\textsuperscript{23) of events which are entirely consistent with the W\textsuperscript{\pm}-decay hypothesis. Independent evidence from the UA2 collaboration\textsuperscript{24) was also presented at Rome. The UA1 results are based on 5 events, plus one with an alternative interpretation, in which a high energy track in the central detector matches in position and energy with local energy deposition in the calorimeters with an electromagnetic profile. A parallel search, based on large missing transverse energy, yielded the same 5 events. To avoid background contamination from 2-jet events with precocious jet fragmentation, all events where the electron forms part of a jet, or is
Figure 18. Correlation Between Missing Transverse Energy and Electron Transverse Energy for Selected Events (1982 data).
accompanied by a coplanar jet, have been scrupulously eliminated. Under these conditions no significant background source has been found.

The analysis also reveals a sample of 11 events with a high energy electron and an opposite jet. In Figure 18, we show the correlation of the missing transverse energy and the electron transverse energy for the electron-neutrino candidates and for the electron-plus-jet events.

The simultaneous presence of an electron and a neutrino which approximately balance in $p_T$ suggests presence of the two-body decay $W^\pm \rightarrow e^\pm + \nu$. Assuming $W$-decay kinematics and $V-A$ coupling, and correcting for the transverse motion of the $W$, the $W$-mass has then been calculated as:

$$m_W = 81^{+5}_{-3} \text{ GeV/c}^2$$

in excellent agreement with the Weinberg-Salam model\textsuperscript{25}. The number of events observed, after correction for inefficiencies, is also consistent with predicted cross-sections.

6. Acknowledgements

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