EXPERIMENTAL STUDY OF THE EMERGENCE
OF TWO-JET DOMINANCE
IN $\bar{p}p$ COLLISIONS AT $\sqrt{s} = 630$ GeV

The UA2 Collaboration

Bern¹ - CERN² - Copenhagen (NBI)³ - Heidelberg⁴ - Orsay (LAL)⁵ -
Pavia⁶ - Perugia⁷ - Pisa⁸ - Saclay (CEN)⁹ Collaboration

J.A. Appel^{9,a}, P. Bagnaia², M. Banner⁹, R. Battiston⁷, K. Bernlöhner⁴, K. Borer¹, M. Borghini²,
G. Carboni⁸, V. Cavasinni⁸, P. Cenci⁷, J.-C. Chollet⁵, A.G. Clark², C. Conta⁶,
P. Darriulat², B. De Lotto⁵, T. Del Prete⁸, L. Di Lella², J. Dines-Hansen³, K. Einsweiler²,
R. Engelmann^{2,b}, L. Fayard⁵, M. Fraternali⁶, D. Froidevaux⁵, J.-M. Gaillard⁵, O. Gildemeister²,
V.G. Goggi⁶, C. Gössling², B. Hahn¹, H. Hänni¹, J.R. Hansen², P. Hansen^{2,3}, N. Harnew²,
T. Himel^{2,c}, L. Iconomidou-Fayard⁵, P. Jenni², E.E. Kluge⁴, O. Kofoed-Hansen³, E. Lançon⁹,
M. Livan⁶, S. Loucatos⁹, B. Madsen³, P. Mani¹, B. Mansoulié⁹, G.C. Mantovani⁷, L. Mapelli^{2,d},
K. Meier², B. Merkel⁵, R. Møllerud³, M. Moniez⁵, R. Moninger¹, M. Morganti⁸, C. Onions²,
M.A. Parker², G. Parrou⁵, F. Pastore⁶, M. Pepe⁷, H. Plothow-Besch⁴, M. Polverel⁹,
J.-P. Repellin⁵, A. Rimoldi⁶, A.F. Rothenberg^{2,c}, A. Roussarie⁹, V. Ruhlmann⁹, G. Sauvage⁵,
J. Schacher¹, M. Schlötelburg⁴, F. Stocker¹, M. Swartz², J. Teiger⁹, S.N. Tovey^{2,e},
W.Y. Tsang^f, M. Valdata-Nappi⁸, V. Vercesi⁶, A.R. Weidberg², M. Wunsch⁴ and H. Zaccane⁹.

(Submitted to Physics Letters)

ABSTRACT

A heuristic model is used to describe data collected by the UA2 experiment at $\sqrt{s} = 630$ GeV. Distributions of the energy sharing between the leading clusters and the rest of the event are examined. The main features of these distributions can be described by a two-component model with soft, collective interactions dominating at low transverse energy and hard, constituent interactions dominating at high transverse energy. This model provides a simple picture of the emergence of two-jet dominance at SPS $\bar{p}p$ Collider energies.

1. Laboratorium für Hochenergiephysik, Universität Bern, Sidlerstrasse 5, Bern, Switzerland.

2. CERN, 1211 Geneva 23, Switzerland.

3. Niels Bohr Institute, Blegdamsvej 17, Copenhagen, Denmark.

4. Institut für Hochenergiephysik der Universität Heidelberg, Schröderstrasse 90, 6900 Heidelberg, FRG.

5. Laboratoire de l'Accélérateur Linéaire, Université de Paris-Sud, Orsay, France.

6. Dipartimento di Fisica Nucleare e Teorica, Università di Pavia and INFN, Sezione di Pavia, Via Bassi 6, Pavia, Italy.

7. Gruppo INFN del Dipartimento di Fisica dell'Università di Perugia, Italy.

8. Dipartimento di fisica dell'Università di Pisa and INFN, Sezione di Pisa, Via Livornese, S. Piero a Grado, Pisa, Italy.

9. Centre d'Etudes Nucléaires de Saclay, France.

a) On leave from FNAL, Batavia, USA.

b) On leave from New York State University, Stony Brook, NY, USA.

c) Now at SLAC, Stanford University, Stanford, USA.

d) On leave from INFN, Pavia, Italy.

1. INTRODUCTION

The emergence of two-jet dominance was one of the most important early observations [1] made at the SPS $\bar{p}p$ collider. With increasing ΣE_T (the total transverse energy of all final state particles observed in a given central rapidity interval) more and more events are found to consist mostly of two hadron jets having approximately opposite transverse momenta. Detailed studies of such events have been performed since [2] and have given full support to an interpretation in terms of QCD parton models [3]. Such models picture a large ΣE_T interaction as a short distance "hard" collision between two of the incident partons which subsequently fragment into hadron jets, with the remnants of the incident nucleons (spectators) independently producing a number of "soft" secondaries.

In contrast with this large ΣE_T regime, the overwhelming majority of $\bar{p}p$ interactions produce final states in which ΣE_T is more uniformly distributed among the collision products. The main features of such "soft" collisions have been the subject of extensive experimental studies [4] and empirical parametrizations of various characteristic distributions (multiplicity, rapidity, transverse momentum, etc...) are available [5]. However, a reliable theoretical model of the collective constituent interactions at play is still lacking.

As a function of total cms energy, $\sqrt{s}$, hard and soft collisions behave differently. The former obey approximate Bjorken scaling [6] while the latter evolve very slowly, typically like $\ln s$. As a consequence the transition between the two regimes takes place in a region of ΣE_T which depends upon $\sqrt{s}$ [7]. The purpose of the present letter is to investigate this transition in some detail, to assess the validity of the above naive picture, and to estimate the contamination of soft events in samples of jet events selected to study the mechanism of hard collisions.

2. THE DATA

The data of the present study have been obtained using the UA2 central calorimeter [8] which covers the pseudo-rapidity region, $-1 \leq \eta \leq +1$, over the whole azimuthal range. Its high granularity (240 cells, each covering 15° in azimuth and 10° in polar angle) is well suited for the efficient reconstruction of energy clusters [1,8]. We shall label 1 and 2 the clusters with the highest and next to highest transverse energies in each event and define the sum of their transverse energies

$$\hat{E}_T = E_T^1 + E_T^2.$$

The quantity

$$\tilde{E}_T = \Sigma E_T - \hat{E}_T$$

includes the transverse energies of all other clusters as well as that of cells containing too little energy to be part of a cluster.

The energy response of the UA2 calorimeter is approximately linear [8]. Distortions taking place at low energies have not been corrected for, as the conclusions of the present study are not sensitive to small systematic changes in the energy scale.

The trigger is obtained from a coincidence between a minimum bias signal [9], ensuring the occurrence of a non-diffractive $\bar{p}p$ collision, and the requirement that ΣE_T exceeds a given threshold (usually set at 60 GeV). Lower threshold data (including "minimum bias" data at zero threshold) have been collected for a small fraction of the running time. Most of the data used here were obtained at $\sqrt{s} = 630$ GeV for a total integrated luminosity of 310 nb^{-1} (60 GeV threshold) or $12 \text{ } \mu\text{b}^{-1}$ (minimum bias). Data collected with a 30 GeV threshold at $\sqrt{s} = 546$ GeV are also used after suitable transformation [10] to $\sqrt{s} = 630$ GeV (the corresponding correction never exceeds 5%).

A small background contamination resulting from the interactions of beam halo particles in the UA2 calorimeter is reduced to a negligible level ($< 2\%$ independent of ΣE_T) after application of sharp timing cuts and rejection of events with characteristic background configurations in the pattern of energy deposition [10].

3. SOFT AND HARD COLLISIONS

We use low ΣE_T data ($\Sigma E_T < 35$ GeV) and high $\hat{E}_T$ data ($\hat{E}_T > 65$ GeV) to determine the main features of soft and hard collisions in the regions where they are respectively dominant. From these data we deduce very simple parametrizations of the transverse energy sharing between the two leading clusters and the rest of the event for each of the two collision mechanisms.

The soft collision cross-section is a steeply falling function of ΣE_T . The distribution of $\hat{E}_T/\Sigma E_T$ is observed to depend only slightly upon ΣE_T (Figure 1a) in the region $\Sigma E_T > 10$ GeV. At lower values of ΣE_T serious distortions take place as a result of biases introduced by the cluster algorithm. We make no attempt to reproduce faithfully the event configuration in this region. The distribution of E_T^2/E_T^1 at fixed ΣE_T is almost independent of ΣE_T (Figure 1b). These observations suggest a parametrization in which the dependences upon ΣE_T , upon $\hat{E}_T/\Sigma E_T$ and upon E_T^2/E_T^1 factorize and are universal functions obtained from the data themselves :

$$d\sigma_{\text{soft}}/d(\Sigma E_T)d(\hat{E}_T/\Sigma E_T)d(E_T^2/E_T^1) = F_{\text{soft}}(\Sigma E_T)G_{\text{soft}}(\hat{E}_T/\Sigma E_T)H_{\text{soft}}(E_T^2/E_T^1) \quad (1)$$

The ΣE_T dependence, $F_{\text{soft}}(\Sigma E_T)$, is taken to be exponential, $F_{\text{soft}}(\Sigma E_T) \propto \exp(-\Sigma E_T / 5.7 \text{ GeV})$, a form giving a good fit to the data in the region $\Sigma E_T < 35$ GeV.

Relation (1) implies that $\hat{E}_T$ and $\tilde{E}_T$ have average values proportional to ΣE_T

$$\langle \hat{E}_T \rangle \simeq 0.29 \Sigma E_T,$$

$$\langle \tilde{E}_T \rangle \simeq 0.71 \Sigma E_T.$$

In particular the quantities

$$h_1 = E_T^1 / \Sigma E_T, \text{ and}$$

$$h_2 = \hat{E}_T / \Sigma E_T$$

have average values independent of ΣE_T

$$\langle h_1 \rangle \simeq 0.18, \quad \langle h_2 \rangle \simeq 0.29.$$

For hard collisions the parton model suggests a parametrization in which the $\hat{E}_T$ (jets) and $\tilde{E}_T$ (spectators) dependences factorize. This is supported by the observation (Figure 1c) that $\tilde{E}_T$ distributions have shapes nearly independent of $\hat{E}_T$. However, some dependence is expected from QCD parton models in which gluon bremsstrahlung contributes a fraction of $\tilde{E}_T$ increasing with $\hat{E}_T$. This effect is indeed observed in the data and is the subject of another publication [11]. For the purpose of the present study it can be ignored. We write

$$d\sigma_{\text{hard}} / d\hat{E}_T d\tilde{E}_T d(E_T^2 / E_T^1) = F_{\text{hard}}(\hat{E}_T) G_{\text{hard}}(\tilde{E}_T) H_{\text{hard}}(E_T^2 / E_T^1) \quad (2)$$

where F_{hard} , G_{hard} and H_{hard} are universal functions taken from the data themselves (Figure 1c,d). The extrapolation of $F_{\text{hard}}(\hat{E}_T)$ to the region $\hat{E}_T < 65$ GeV uses an exponential form joining smoothly with the large $\hat{E}_T$ data.

Relation (2) implies that $\tilde{E}_T$ has an average value independent of $\hat{E}_T$

$$\langle \tilde{E}_T \rangle \simeq 17.5 \text{ GeV}.$$

4. RESULTS

Within the approximation implied by their factorized forms, relations (1) and (2) provide descriptions of the soft and hard collision regimes well suited to an extrapolation away from the regions where they are respectively dominant. If there were no other mechanism than soft and hard, and no correlation between them, the $\bar{p}p$ cross-section would simply read:

$$\sigma = \sigma_{\text{soft}} + \sigma_{\text{hard}}$$

and any event would be of one or the other type according to the probabilities implied by relations (1) and (2). In what follows we compare the predictions of this naive model with the data and study the dependences of $\langle \tilde{E}_T \rangle$, $\langle h_1 \rangle$ and $\langle h_2 \rangle$ upon $\tilde{E}_T$ and upon ΣE_T .

The results are displayed in Figure 2 where, by construction, σ_{soft} is seen to describe well the low energy region and σ_{hard} the high energy region. At intermediate energies each parameter evolves from the soft to the hard regime, following the increase of $\sigma_{\text{hard}}/\sigma_{\text{soft}}$ with energy :

$$\langle \tilde{E}_T \rangle = f_{\text{soft}} \langle E_T \rangle_{\text{soft}} + f_{\text{hard}} \langle E_T \rangle_{\text{hard}}, \text{ with}$$

$$f_{\text{soft}} = \sigma_{\text{soft}} / (\sigma_{\text{soft}} + \sigma_{\text{hard}})$$

$$f_{\text{hard}} = \sigma_{\text{hard}} / (\sigma_{\text{soft}} + \sigma_{\text{hard}}).$$

Given the simplicity of the model, the agreement between the data and its predictions over the whole transverse energy range is remarkable. In particular the dominance of large $\langle \tilde{E}_T \rangle$ events in the region $50 \text{ GeV} < \Sigma E_T < 100 \text{ GeV}$ is well reproduced.

The dependences of σ and of $\alpha = f_{\text{hard}} - f_{\text{soft}}$ upon $\hat{E}_T$ and ΣE_T are shown in Figure 3. The transition between the soft and hard regimes is visible as a change of slope in the σ distributions. It takes place in the regions

$$20 \leq \hat{E}_T \leq 30 \text{ GeV}$$

and $50 \leq \Sigma E_T \leq 90 \text{ GeV}.$

For $\hat{E}_T > 50 \text{ GeV}$ the contamination of soft events, f_{soft} , does not exceed 1%, while it is still about 4% for $\Sigma E_T > 100 \text{ GeV}$. This observation justifies studies of the hard collision mechanism performed on event samples selected according to an $\hat{E}_T$ cut of 50 GeV or more [1,2,10]. We have studied the dependence of these results on the form of the extrapolation of $F_{\text{hard}}(\hat{E}_T)$ below $\hat{E}_T = 65 \text{ GeV}$. For changes compatible with the data of Figure 2 we find that the α cross-over may vary by $\pm 1.5 \text{ GeV}$ in $\hat{E}_T$ or $\pm 3 \text{ GeV}$ in ΣE_T .

As an illustration of the above model, we calculate for each event the sphericity of the energy distribution in the central calorimeter, treating each cell energy as if it were associated with a single particle, thereby making the analysis independent of the clustering algorithm. We exclude events having a total transverse momentum in excess of 20 GeV and perform the calculation in the event rest frame. Typical sphericity distributions are shown in Figures 4a and 4b for ranges of ΣE_T and $\hat{E}_T$ corresponding to the soft and hard regions. The dependences of the mean sphericity over ΣE_T and $\hat{E}_T$ are shown in Figures 4c and 4d. While soft collision final states have large sphericities, increasing with ΣE_T , the opposite is true for hard collision final states. The transitions between the two regimes are observed to occur at the places expected from the α distributions of Figure 3.

Our conclusions apply to the actual experimental configuration of the UA2 experiment, namely a pseudo-rapidity acceptance of ± 1 unit over the whole azimuthal range and a total c.m.s. energy $\sqrt{s} = 630 \text{ GeV}$. We expect similar effects, resulting from the competition between soft and hard

processes, to be also present in other experimental conditions. In particular the dominance of large $\langle \tilde{E}_T \rangle$ configurations near the ΣE_T cross-over is commonly believed [7] to have precluded the observation of hadron jets in calorimeter experiments performed at low values of $\sqrt{s}$ and using ΣE_T triggers [12]. On the contrary, several early ISR experiments [13] using $\hat{E}_T$ or E_T^1 triggers were able to provide major contributions to our understanding of hard collisions. Quantitatively, however, our results are expected to depend on experimental conditions: for example, as discussed in Ref 7, the cross-over transverse energies should increase with acceptance, approximately in proportion with the azimuthal and rapidity intervals covered by the detector.

5. CONCLUSIONS

Using very simple models of the mechanisms of soft and hard collisions we have shown that the emergence of two-jet dominance in large transverse energy events observed at the CERN $\bar{p}p$ collider over two rapidity units can be simply interpreted as the result of the different dependences on transverse energy of the soft and hard interactions. The transition region between the soft regime (dominating at small transverse energies) and the hard regime (dominating at large transverse energies) occurs at very different values of $\hat{E}_T$ and ΣE_T , $\simeq 30$ GeV and $\simeq 70$ GeV respectively. Experiments dedicated to studies of the hard collision mechanism are justified in using event samples selected according to a relatively low $\hat{E}_T$ threshold. For $\hat{E}_T > 50$ GeV the contamination of soft events should not exceed 1%. On the contrary, calorimeter experiments using a ΣE_T trigger need a much higher ΣE_T threshold, typically in excess of 100 GeV, to reach the same level of purity.

While we have shown that our data are consistent with this very simple picture, we must stress the qualitative nature of our conclusions. It would, of course, be possible to devise more sophisticated models which could include correlations between the two collision mechanisms and give good fits to the data.

ACKNOWLEDGEMENTS

This experiment would have been impossible without the very successful operation of the CERN $\bar{p}p$ Collider whose staffs and coordinators we gratefully acknowledge for their collective effort.

We deeply thank the technical staffs of the institutes collaborating in UA2 for their important contributions to maintain and improve the performance of the detector.

We are grateful to the UA4 Collaboration for providing the signals from their small-angle scintillator arrays and to the UA5 Collaboration for the loan of scintillator hodoscopes.

Financial supports from the Schweizerischer Nationalfonds zur Förderung der Wissenschaftlichen Forschung to the Bern group, from the Danish Natural Science Research Council to the Niels Bohr Institute group, from the Bundesministerium für Forschung und Technologie to the Heidelberg group, from the Institut National de Physique Nucléaire et de Physique des Particules to the Orsay group, from the Istituto Nazionale di Fisica Nucleare to the Pavia, Perugia and Pisa groups and from the Institut de Recherche Fondamentale (CEA) to the Saclay group are acknowledged.

REFERENCES

1. UA2, M. Banner et al., Phys. Lett. **118B** (1982) 203.
2. UA2, P. Bagnaia et al., Z. Phys. **C20** (1983) 117 ;
UA2, P. Bagnaia et al., Phys. Lett. **138B** (1984) 430 ;
UA2, P. Bagnaia et al., Phys. Lett. **144B** (1984) 283 ;
UA2, P. Bagnaia et al., Phys. Lett. **144B** (1984) 291 ;
UA1, G. Arnison et al., Phys. Lett. **123B** (1983) 115 ;
UA1, G. Arnison et al., Phys. Lett. **132B** (1983) 214 ;
UA1, G. Arnison et al., Phys. Lett. **132B** (1983) 223 ;
UA1, G. Arnison et al., Phys. Lett. **136B** (1984) 294 ;
UA1, G. Arnison et al., Phys. Lett. **147B** (1984) 222.
3. For a recent review see
M. Jacob, Proceedings of the 22nd Int. Conf. on High Energy Physics, Vol. 2, p. 150, ed. by
A. Meyer and E. Wieczorek.
4. UA5, K. Alpgard et al., Phys. Lett. **115B** (1982) 65 and 71 and **121B** (1983) 209;
UA2, M. Banner et al., Phys. Lett. **122B** (1983) 322 ;
UA1, G. Arnison et al., Phys. Lett. **118b** (1982) 167.
5. G. Matthiae, Proc. Int. Europhysics Conf. on High Energy Ph., Brighton, July 1983, p. 714.
6. S.M. Berman, J.D. Bjorken, J.D. Kogut, Phys. Rev. **4D** (1971) 3388 ;
J.D. Bjorken, Phys. Rev. **D8** (1973) 4098.
7. T. Åkesson and H. Bengtsson, Phys. Lett. **120B** (1983) 233.
8. A. Beer et al., Nucl. Instr. Meth. **224** (1984) 360.

9. UA4, M. Bozzo et al., Phys. Lett. **147B** (1984) 392.
10. UA2, Measurement of the $\sqrt{s}$ dependence of the jet production at the CERN $\bar{p}p$ Collider, CERN-EP/85-111, to be published in Phys. Lett.
11. UA2, A study of three-jet events at the CERN SPS $\bar{p}p$ collider, in preparation.
12. C. de Marzo et al., Phys. Lett. **112B** (1982) 173.
13. C. Kourkounelis et al., Phys. Lett. **86B** (1979) 391 ;
M.G. Albrow et al., Nucl. Phys. **B160** (1979) 1 ;
A. Angelis et al., Phys. Scr. **19** (1979) 116 ;
A.G. Clark et al., Nucl. Phys. **B160** (1979) 397 ;
For recent ISR work see:
T. Akesson et al., Phys. Lett. **118B** (1982) 185,193, **123B** (1983) 133 and **128B** (1983) 354 ;
A. Angelis et al., Phys. Lett. **126B** (1983) 132.

FIGURE CAPTIONS

1. Energy sharing distributions for soft collision events having $\Sigma E_T < 35$ GeV (a,b), and for hard collision events having $\hat{E}_T > 65$ GeV (c,d). Full circles indicate distributions corresponding to the whole samples of each category and open symbols apply to subsamples: a,b) circles, triangles and squares respectively correspond to ΣE_T intervals of 5 to 10, 10 to 30 and 30 to 35 GeV, c,d) circles, triangles and squares respectively correspond to $\hat{E}_T$ intervals of 65 to 75, 75 to 90 and > 90 GeV.
The lines indicate the parametrization used in the model.
2. The dependences of $\langle \tilde{E}_T \rangle$, $\langle h_1 \rangle$ and $\langle h_2 \rangle$ upon $\hat{E}_T$ and ΣE_T . Full lines indicate the predictions of the model. Dashed lines indicate the individual contributions of the soft and hard mechanisms.
3. The event yields and the hard-soft asymmetry parameter α as functions of a) ΣE_T and b) $\hat{E}_T$. The data (full circles) are compared to the predictions of the model (full line). Dashed lines indicate the individual contributions of the soft and hard mechanisms.
4. Sphericity distributions in two ranges of a) ΣE_T and b) $\hat{E}_T$ corresponding to soft and hard regimes, and the dependences of the mean sphericity over c) ΣE_T and d) $\hat{E}_T$.

Figure 1

Figure 2

Figure 3

Figure 4