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Publication Date
1987-08-01
Lectures presented at the 1987 SLAC Summer School, Stanford, CA, August 10–21, 1987, and to be published in the Proceedings

Physics at Hadron Colliders: Experimental View

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August 1987
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The physics of the hadron-hadron collider experiment is considered from an experimental point of view. The problems encountered in determination of how well the standard model describes collider results are discussed.
OVERVIEW

I. INTRODUCTION

In these lectures, the problems encountered by the experimentalist attempting to analyze collider data and determine the validity of the standard model will be considered in detail. Special note will be taken of differences between \( \bar{p}p \) analyses and \( e^+e^- \) analyses. An attempt will be made to distinguish between fundamental problems in \( \bar{p}p \) physics, and 'merely' difficult technical problems. This discussion will focus on the full detector system as a tool for data analysis, including the online (trigger) and offline (computing) environment. A framework for understanding the capabilities and limitations of present and planned apparatus is developed.

• Basic Facts about \( \bar{p}p \) Physics—Theory

The standard model\(^1\) has, as 'fundamental' entities, various objects, the leptons \( (e, \mu, \tau, \nu) \) and quarks \( (u, d, c, s, b) \). There are hypothesized various force mediators among these objects for the strong (gluons) and electroweak \( (\gamma, Z^0, W^\pm) \) interactions. The standard model also requires a symmetry breaking (Higgs) sector and various parameters such as quark and lepton masses and interaction coupling strengths. Extensions and alternatives to the standard model reduce to the standard model at low \( (\ll M_W) \) energy, since almost all known experimental results 'fit' the standard model.

The \( \bar{p}p \) colliders, as well as the \( e^+e^- \) colliders, allow a spectrum of possible experiments ranging from specific searches for particular particles, e.g., monopole searches, to searches for new phenomena by careful study of the production of one type of object in the standard model, e.g., very high luminosity interaction regions, encased in steel, surrounded by muon detection and measuring equipment. Only considerations relevant to detectors designed and built to detect a wide range of the final states generated by the fundamental entities in the standard model will be discussed here. This class of particle detectors, the general purpose detectors, measure leptons \( (e, \mu, \tau, \nu) \) and the quarks and gluons which manifest themselves in the detector as jets of hadrons. Such experiments, beginning with the SLAC-LBL magnetic detector,\(^2\) through the present-day CERN UA experiments,\(^3\) have been enormously successful. Other possible final states such as free quarks, monopoles, etc., are not the main focus in such experiments. An important note is that nearly all extensions to the standard model produce particles that decay into the usual fundamental entities, or particles that have a signature in their detection that mimics that of one of the usual objects.

• Basic Facts about \( \bar{p}p \) Physics—Experiment

The first thing to note about the characteristics of \( \bar{p}p \) collisions is that the
total cross section is large, ranging from 65 mb for the CERN UA experiments at \( \sqrt{s} = 630 \) GeV to of order 100 mb expected for the Superconducting Super Collider (SSC) at \( \sqrt{s} = 40 \) TeV. The soft collision processes that produce many low energy particles and that give rise to most of the total cross section [so called ln(s) physics] will not be discussed here. Rather these lectures will concentrate on the hard scattering processes among proton constituents that lead to events containing few, energetic products. The ln(s) physics provides a background of soft particles from which the hard constituent collisions must be separated. Since collision rates for the proton constituents can be more or less reliably estimated in QCD, hard collisions in \( \bar{p}p \) provide a laboratory for looking for new phenomena and testing standard model predictions at high \( Q^2 \).

In contrast with the experimental situation in the \( e^+e^- \) machine, the center-of-mass energy available to the hard collision (\( \sqrt{s} \)) is less than the \( \sqrt{s} \) of the beams. Further, the center of mass of the hard collision is not the laboratory frame of reference, and the presence of collision products from the soft interactions can complicate the analysis of the hard collision final states. However, in the near future, the highest energies will be available at hadron colliders, which usually overcompensates for the low \( \hat{s}/s \) ratio. The availability of different parton types in the incoming beam is also very favorable for some production processes (e.g. \( ud \rightarrow W \)).

For colliding beam machines, the total event rate \( R \) is given by \( R = \mathcal{L} \cdot \sigma_{TOT} \), where \( \mathcal{L} \) is the luminosity and \( \sigma_{TOT} \) is the total cross section. For the Tevatron at FNAL and the SPS at CERN,\(^4\) luminosities achieved so far are in the range \( \mathcal{L} \sim 10^{29} \) cm\(^{-2}\) sec\(^{-1}\). For the SSC,\(^5\) luminosities are expected to be in the range \( \mathcal{L} \sim 10^{33} \) cm\(^{-2}\) sec\(^{-1}\). For \( \sigma_{TOT} \) of 60 mb, this luminosity implies a total event rate of 6 kHz at FNAL and CERN, and 60 MHz for the SSC. The event size on a typical collider experiment such as the Collider Detector at Fermilab (CDF) is of order 80 kbytes of data. Present-day tape drives and electronics do not have enough data handling capability to record all this information. Even if the data could be recorded, present-day computers do not run fast enough or have enough storage capacity to fully analyze all the events.

This technical fact puts the \( \bar{p}p \) experimenter at a definite disadvantage relative to the \( e^+e^- \) experimenter, as already at this first stage of data acquisition, the \( \bar{p}p \) experimenter will be forced to think. The \( \bar{p}p \) experiment requires a 'filter' to reduce the amount of both information and events to be recorded. But on what quantities should such filtering decisions be made? The answer for the general purpose experiment is that filter decisions are made based on a search for final states containing the fundamental entities in the standard model. In addition, some fraction of the total cross section is kept with low bias through the use of prescaled event samples. This filtering process begins in the online 'trigger' system (indeed, in the design of the detector hardware) and continues through the offline data analysis.
• Physics Beyond the Z—What and Why

The main goal of collider experiments in the next few years, at FNAL, CERN, and the SSC is to check the limits of validity of the standard model, most especially in the multi-boson 'gauge' couplings. Also, extensive searches for 'new' particles decaying to known final states will be mounted. A very important ingredient in the current round of FNAL and CERN experiments is to perform the necessary 'engineering' physics to accomplish the first two goals.

In the general purpose experiment, the search for new particles requires the identification of some particular exclusive decay of the new particle. This alone is not sufficient to establish a signal. An inclusive analysis is also needed along with the exclusive analysis to determine if signals are 'unexpected'. In attempting such particle searches, final states containing jets of hadrons play a crucial role in two ways. The jets provide the main source of background to the identification of final states containing leptons. In addition, if the signature of the decaying particle into jets of hadrons can be used to aid in its identification, the discovery reach of the apparatus can be greatly extended, since leptonic branching fractions are typically of order a few percent. To date, no experiment has discovered a new particle utilizing decays into jets of hadrons, but study of jets has played a role in understanding background to leptonic signals in the UA experiments.⁶

Four general-purpose experiments are presently planned for the energy range 630 GeV to 2 TeV. They are the upgraded UA1 and UA2 experiments at CERN, and the CDF and D0 experiments at FNAL. These experiments each expect to collect 5 pb⁻¹ of data over the next few years. The main physics goals for these experiments include the search for the elusive top quark, setting limits on production of supersymmetric particles, setting limits on compositeness scales, and the search for new, heavier vector bosons W’, Z’. Also, important 'engineering' work will be done to better understand the details of the standard model in the pp collider environment. Future experiments may operate at the proposed SSC in the U.S., or possibly at the LHC at CERN. The SSC machine is expected to gather about 10⁴ pb⁻¹/year, which allows for searches for W, Z boson pair production, Higgs bosons, compositeness, heavier quarks, new W’, Z’ bosons, etc.⁷

The key question for the future of hadron-hadron colliders is how well new particles and the nature of their interactions can be found at such machines. In order to try to answer this question, we will look now in some detail at the results from the first 700 nb⁻¹ of data recorded by the CERN UA experiments. After brief historical and theoretical introductions and description of the relevant apparatus, we will discuss results from the experiments on jet production and QCD, then on lepton production and the electroweak interaction.
II. HISTORICAL INTRODUCTION—HIGH $p_t$ HADRONIC FINAL STATES IN HADRON-HADRON COLLISIONS

In order to interpret SLAC results on electron-nucleon scattering in the deeply inelastic region, Bjorken suggested in 1969 the scaling behavior of the nucleon structure functions. In the same year, Feynman proposed the parton model according to which a hadron, when described in a reference frame where its momentum is infinite, is composed of independent, point-like constituents (partons). These ideas led to the prediction of the existence of a class of hadron collisions producing high-$p_t$ particles in the final state. Furthermore, the model predicted that the invariant cross section for inclusive production of high-$p_t$ hadrons at $90^\circ$ is $E \frac{d^2\sigma}{dp_t^2} = p_t^{-n} F(X_t)$, where $F$ is a dimensionless function of the scaling variable $X_t = 2p_t/\sqrt{s}$, and $n = 4$. In fact large $p_t$ single particles were found to be produced at the CERN Intersecting Storage Rings (ISR) at a rate that exceeded a naive extrapolation from lower energy data by several orders of magnitude. The early ISR experiments were all based on high $p_t$ single particle triggers. In fitting the data to the functional form above, they found $n \approx 8$. Eventually, evidence for the production of jets of hadrons was found, but the analysis was complicated by the trigger bias. In the meantime, jets were also seen in $e^+e^-$ annihilations, but most clearly only at higher energies.

The contradiction between the success of the parton model in explaining the jet structure of the high-$p_t$ events and scaling exponents different from $p_t^{-4}$ was partially resolved in the late seventies with the advent of Quantum Chromo-Dynamics (QCD).

Following a suggestion by Bjorken, experiments were also performed using calorimeters to trigger on the whole jet, so as to avoid the single particle trigger bias. First experiments were performed at FNAL with limited solid angle detectors. The NA5 experiment was performed in 1980-81 at the CERN SPS with a large solid-angle, highly segmented detector featuring $2\pi$ azimuthal coverage. The NA5 experiment observed an exponential fall of $d\sigma/d\Sigma E_t$ vs. $\Sigma E_t$, where $\Sigma E_t$ is the summed total transverse energy observed in the calorimeter. No evidence for jet-like character of the events was found at the time.

At the Paris conference of 1982, models were presented that explained the observed total transverse energy spectrum as a sum of a soft scattering contribution from a cylindrically symmetric multiplicity and transverse mass distribution, and a hard scattering contribution predicted by a QCD parton level calculation and a fragmentation model. This model predicted a strong $\sqrt{s}$ dependence of this sum, such that at low $\Sigma E_t$ one would expect to see an exponential fall of $d\sigma/d\Sigma E_t$, but at larger $\sqrt{s}$ values, the hard scattering contribution would cause the $d\sigma/d\Sigma E_t$ spectrum to fall less steeply than exponential. At the Paris conference, data were presented by the ISR R807 experiment and the SPS UA2 experiment that showed evidence for a jet-like structure in the events at large $\Sigma E_t$. Figure 1 shows the observed $d\sigma/d\Sigma E_t$ spectrum for 1982 UA2 data. The data of Figure 1 show an exponential fall for $\Sigma E_t < 60$ GeV,
Fig. 1. Observed distribution of $d\sigma/d\Sigma E_t$ (nb GeV$^{-1}$) vs. $\Sigma E_t$ for the 1982 UA2 data. The solid line shows the exponential fall of the data below $\Sigma E_t$ of about 60 GeV.
while, for $\Sigma E_t > 60$ GeV, the data are above the exponential extrapolation. Since the electromagnetic and hadronic calorimeters of the UA experiments are highly segmented, a straightforward clustering algorithm could be applied to join adjacent towers into energy clusters. The UA2 experiment found that typical 2 GeV $E_t$ clusters contained three calorimeter cells, while 40 GeV $E_t$ clusters contained ten cells. The clusters were ordered according to transverse energy, $E_t^1 > E_t^2 > E_t^3 > \ldots$, and the distribution of the phi separation of the two highest $E_t$ clusters was made for $\Sigma E_t > 60$ GeV (Figure 2). The strong back-to-back peaking is expected if the energy clusters are produced by jets of hadrons arising from hard parton scattering. Figure 3(a) shows the ratio of the transverse energy contained in the highest (two highest) clusters to the total transverse energy deposited in the calorimeter as a function of $\Sigma E_t$. Figure 3(b) shows the ratios $E_t^2/E_t^1$ and $E_t^3/E_t^2$ as a function of $\Sigma E_t$. These Figures show that at large $\Sigma E_t$, a large fraction of the total energy in the calorimeter is deposited in two back-to-back clusters, which tend to balance each other in $E_t$, and the transverse energy in additional clusters tends to be small. This behavior would be expected in the hard scattering model of jet production. R807 at the ISR and the CERN UA experiments\(^{18}\) at the SPS collider provided the first direct observations of jet production using hadron calorimeter triggers. Figure 4 shows the early measured jet yield as a function of jet $E_t$ from the R807 and UA2 experiments along with the QCD predictions.\(^{19}\) These early predictions and measurements provided a tremendous success for QCD, as the theory predicted within errors the dramatic three order of magnitude rise in the jet production cross section between the ISR and the SPS. The investigation of how the hard scattering two-jet production processes 'blend' with the $\ln(s)$ physics at low $\Sigma E_t$ continues today.\(^{20}\) Such studies probe the limits of applicability of QCD to low $p_t$ processes and provide information on the character of the event underlying the hard scattering debris. However, since statistical fluctuations in the energy depositions may be mistaken for hard scattering products, careful modeling and interpretation of the data is required before firm conclusions may be drawn.

III. THE PARTON MODEL PICTURE OF HARD SCATTERING IN HADRON-HADRON COLLISIONS

Figure 5a shows a schematic illustration of the collisions among the $p\bar{p}$ constituents. The partons are distributed within the proton with some distribution of fractional momentum characterized by the structure function $f$. The incoming parton interaction is described by the elementary scattering cross section $\hat{\sigma}$, and the outgoing parton lines materialize into the observed hadrons according to some fragmentation function $D$. In the final state, the two high-$p_t$ partons fragment into hadrons having small transverse momentum with respect to the directions of the scattered protons (jets). The total $p_t$ of the jet-jet system is limited, and the two jets are produced back to back in azimuthal angle $\phi$.

In the parton model, the inclusive jet yield is obtained by a folding integral
Fig. 2. The distribution of difference in azimuth between the two clusters of highest transverse energy in events with $\Sigma E_t > 60$ GeV from the UA2 experiment.
Fig. 3. (a) The ratio of the transverse energy in the highest \((h_1)\) and two highest \((h_2)\) \(E_t\) clusters to the total transverse energy in the calorimeter is plotted against \(\Sigma E_t\). (b) The ratio of the transverse energy in the second highest \(E_t\) cluster to the highest \(E_t\) cluster \((r_{21})\) and third highest to second highest \((r_{32})\) is plotted against \(\Sigma E_t\). Data are from the UA2 experiment.
Fig. 4. Early measurements of the jet production cross sections \( \frac{d^2\sigma}{dE_T dy} \) vs. jet \( E_T \) from the R807 and UA2 experiments. The curves show the QCD expectations.
Fig. 5. (a) Schematic illustration of $\bar{p}p$ collisions. $F$ represents the proton structure functions, $\hat{\sigma}$ the elementary parton-parton scattering cross sections, and $D$ the fragmentation function of the outgoing parton line. (b) Coordinate system to describe collisions. The $z$ axis lies along the incoming proton beam. (c) View along the beam line of a collision event, $P_1, P_2$ are the incoming partons, $\theta_3$ and $\theta_4$ are the outgoing scattering angles. (d) Transformation to the center-of-mass system, showing the center-of-mass scattering angle $\theta^*$. 

\[ P_t = p \sin \theta \]

\[ S = (2 E_b)^2 \]

\[ P_L = \frac{\sqrt{s}}{2} (x_1 - x_2) \]
over the parton distributions, each contribution being weighted by the relevant parton-parton differential cross section

\[ E \frac{d^3\sigma}{d^3p} = \sum_{ij} \int \frac{dx_1 dx_2 f_i(x_1, Q^2) f_j(x_2, Q^2) \delta(s + \hat{t} + \hat{u})}{\pi} \frac{\hat{s}}{\hat{t}^2} \sum_k \frac{d\sigma(ij \to k)}{d\hat{t}}, \]

where \( i, j, k \) sum over parton species. The differential cross section can be written in terms of the matrix element \( M \) as

\[ \frac{d\sigma}{d\hat{t}} = \pi \alpha_s^2(Q^2) \frac{|M|^2}{\hat{s}^2}. \]

The matrix element \( |M|^2 \) can be calculated in QCD, and the structure functions, along with their scaling violations, can be measured and parameterized in deeply inelastic lepton-nucleon scattering. Figures 5b and 5c show the coordinate system for this problem. The momentum transverse to the beam direction is \( p_t = p \sin \theta \). The variables \( \hat{s}, \hat{t}, \hat{u} \) are given by:

\[
\begin{align*}
\hat{s} &= (p_1^\mu + p_2^\mu)^2 = x_1x_2s = \frac{1}{2}Xts(x_1 \tan \theta/2 + x_2 \cot \theta/2) \\
\hat{t} &= (p_1^\mu - p_\mu)^2 = -\frac{1}{2}Xtsx_1 \tan \theta/2 = -\frac{\hat{s}}{2}(1 - \cos \theta^*) \\
\hat{u} &= (p_2^\mu - p_\mu)^2 = -\frac{1}{2}Xtsx_2 \cot \theta/2 = -\frac{\hat{s}}{2}(1 + \cos \theta^*).
\end{align*}
\]

With initial parton \( p_t = 0 \), and all masses zero, \( x_1 = 2p_1/\sqrt{s} \) and \( x_2 = 2p_2/\sqrt{s} \) are the initial parton momentum fractions while \( X_t = 2p_t/\sqrt{s}, \) \( p_t = p \sin \theta \) is the scaled transverse momentum of the outgoing parton. Figure 5d shows the definition of \( \theta^* \), the parton-parton center-of-mass scattering angle; the LAB system has been boosted by an amount \( p_L = \sqrt{s}/2(x_1 - x_2) \) along the beam axis. Other useful variables are the rapidity \( y \) defined by

\[ y = \frac{1}{2} \ln \frac{E + p_L}{E - p_L} \]

with \( E \) and \( p_L \) the energy and longitudinal momentum of, e.g., the parton-parton system. The pseudorapidity \( \eta \) is defined by

\[ \eta = \frac{1}{2} \ln \frac{P + p_L}{P - p_L} = -\ln \tan \frac{\theta}{2}. \]

A change of variable and integration over azimuthal angle yields

\[ \frac{E d^3\sigma}{d^3p} = \frac{1}{2\pi p_t} \frac{d^2\sigma}{dp_t d\eta}. \]
The QCD predicted matrix elements yield similar dependences on \( d\sigma/d\cos\theta^* \), independent of parton type (see Figure 6). In the experiment, \( d^3\sigma/dx_1dx_2d\cos\theta^* \) can be measured using

\[
x_1 = \frac{P_L + [P_L^2 + m^2]^{\frac{1}{2}}}{\sqrt{s}}, \quad x_2 = \frac{-P_L + [P_L^2 + m^2]^{\frac{1}{2}}}{\sqrt{s}},
\]

where \( P_L \) is the longitudinal momentum and \( m^2 \) the mass of the jet-jet system. In the parton model,\(^2^1\) using the above,

\[
\frac{d^3\sigma}{dx_1dx_2d\cos\theta^*} = f(x_1)f(x_2)\frac{d\sigma}{d\cos\theta^*}
\]

(1)

\[
= \frac{F(x_1)}{x_1} \frac{F(x_2)}{x_2} \frac{d\sigma}{d\cos\theta^*}
\]

(2)

with \( F \) some sum over parton-parton distributions, or, less restrictively,

\[
= \frac{S(x_1,x_2)}{x_1x_2} \frac{d\sigma}{d\cos\theta^*}
\]

The 'natural' coordinates for describing particle kinematics in hadron colliders are\(^2^2\)

\[
y \equiv \frac{1}{2} LN \left( \frac{E + P_z}{E - P_z} \right), \quad \phi \equiv \tan^{-1}(P_y/P_x), \quad \epsilon_t \equiv [m^2 + P_x^2 + P_y^2]^{\frac{1}{2}},
\]

so that \( P^\mu = (E, P_x, P_y, P_z) = \epsilon_t(\cosh y, \beta_t \cos \phi, \beta_t \sin \phi, \sinh y) \), with \( \beta_t \equiv [P_x + P_y^2]^{1/2}/\epsilon_t = P_t/\epsilon_t \).

The advantage of this coordinate system is that it has simple Lorentz transformation properties, has a natural phase space element \( d^3p/E = 1/2de_t^2dyd\phi \) and \( y, \epsilon_t \) are easy to measure \( (y \sim \eta = -LN\tan\theta/2, \epsilon_t \sim p_t) \). Using these coordinates, we find for the invariant (relativistic) mass of two particles \( M_{12}^2 \sim 2E_{t1}E_{t2}(\cosh \Delta y - \cos \Delta \phi) \). This equation is very convenient for calculating invariant masses of two-jet final states from plots of the calorimeter tower energy deposition patterns ('Lego' plots). Figure 7 shows a typical two-jet event from the CDF experiment. The invariant mass of the two clusters with \( E_{t1} = 90.5 \text{ GeV} \), and \( E_{t2} = 80.1 \text{ GeV} \) is 288 GeV. To understand the energy deposition pattern we should expect to see in a calorimeter divided into towers in \( \eta-\phi \) space such as that of CDF, consider a particle with momentum \( \vec{p} \) and transverse momentum \( \vec{p}_n \) relative to an arbitrary direction \( \hat{n} \). In these coordinates, if \( \hat{n} \) has \( (y, \phi) \) coordinates \( y_0, \phi_0, \) \( \vec{p} = (E_t, y, \phi) \), and \( (\hat{s}, \hat{t}, \hat{n}) \) form a right-hand coordinate system, with \( \hat{t} \) perpendicular to the \( \hat{n} - \hat{\bar{z}} \) plane, then

\[
\vec{p}_n = E_t(\hat{t}\sin \Delta \phi + \hat{s}[\sinh \Delta y + \tanh y_0(\cosh \Delta y - \cos \Delta \phi)]),
\]

with \( \Delta y = y - y_0, \Delta \phi = \phi - \phi_0 \). For jets, \( \Delta \phi, \Delta y \lesssim 1 \), which implies that \( \vec{p}_n \sim E_t(\hat{t}\Delta \phi + \hat{s}\Delta y) \) for particles with lab energy \( E_t \). This means that particles
Fig. 6. Shapes of center-of-mass angular distributions for various parton subprocesses vs. $\cos \theta^*$, where $\theta^*$ is the center-of-mass scattering angle. The solid line is the total for all subprocesses, and subprocess normalization is set at $\cos \theta^* = 0$. (See Reference 21.)
Fig. 7. Lego plot of calorimeter energy deposition for a typical two-jet event in the CDF experiment.
with fixed $p_t$ relative to an axis and transverse momentum $E_t$ form a circle about
the axis in $y - \phi$ space and $|\vec{p}_n| = E_t[(\Delta y)^2 + (\Delta \phi)^2]^{1/2} \equiv \Delta R E_t$. The fact
that for hadron jets the $p_t$ is limited to $\sim 0.5$ GeV is the origin of the $\Delta R \lesssim 1$
clustering rule.

IV. HARDWARE DIGRESSION I—DETECTOR DESCRIPTIONS AND
DATA SAMPLES

In this section a brief description is given of the three experiments UA1, UA2, and CDF, from which data are shown in these lectures. Other present or
planned experiments such as UA4, UA5, and DΦ24 are not discussed here.

Figure 8 shows a side and end view of the UA125 experiment at the CERN
SPS. The beam crossing region is surrounded by a vacuum chamber, central
track detector immersed in a dipole magnetic field and followed by电磁
netic and hadronic calorimeters. The drift chambers of the track detector fill a
cylindrical volume 5.8 meters long and 2.3 meters in diameter for a total of 6110
sense wires. The device provides about 100 measurements/track, each point with
a resolution of $300 \mu$. The large angle calorimeter that surrounds the central track
detector covers the angular range with respect to the beam of $25^\circ$–$155^\circ$, and $2\pi$
in azimuth (Figure 9). The electromagnetic compartment of the calorimeter is
divided into "gondolas", each subtending a solid angle $\Delta \phi \times \Delta \theta$ of $180^\circ \times 5^\circ$,
and consist of 26.6 radiation lengths of lead-scintillator stack divided into four
separate compartments in depth for readout purposes. The resolution for elec-
tric showers is $\sigma_E/E \sim 0.15/\sqrt{E}$, and the calibration is performed with
a $^{60}$Co source. The hadronic compartment behind the gondolas is segmented for
readout into regions covering $\Delta \theta \times \Delta \phi$ of $15^\circ \times 8^\circ$. The scintillator-steel plate
stack serves as the flux return for the magnet and provides a resolution for pion
showers of $\sigma_E/E \sim 0.8/\sqrt{E}$. Additional angular coverage for the calorimetry is
provided by the end-cap (bouchon) calorimeters. Outside the calorimeters is the
muon detection system, which will be described in more detail later. For the lumino-
sity upgrade of the CERN $\bar{p}p$ collider, the UA1 collaboration has chosen to
replace the central and end cap electromagnetic shower counters with U/TMP
, calorimeters. The general layout is shown in Figure 10.26

Figure 11 shows a side view of the UA227 experiment at the CERN SPS.
The beam crossing region is surrounded by a vacuum chamber, the central track
detector in a region free of magnetic field and, outside that, lead-scintillator
and iron-scintillator electromagnetic and hadron calorimeters. The track de-
tector consists of a sandwich of multiwire proportional chambers, a scintillator
hodoscope, and JADE-type JET drift chambers. Outside the central track de-
tector is a tungsten converter followed by another proportional chamber. This
preshower counter system provides an accurate track position measurement on entry to the shower counter for aid in electron identification. The central
calorimeters cover $40^\circ$ to $140^\circ$ in $\theta$, and $2\pi$ in azimuth. The calorimeter is seg-
mented into towers with $\Delta \phi \times \Delta \theta$ of $15^\circ \times 10^\circ$, for a total of 240 such cells.
Fig. 8. Longitudinal and end view of the UA1 experiment at CERN.
Fig. 9. View of the UA1 large angle calorimeter showing the electromagnetic and hadronic calorimeter compartments.
Fig. 10. (a) The UA1 detector in its original form. (b) General layout of the plan for the improved UA1 detector, with the central and forward calorimeters replaced by U/TMP calorimeters.
Fig. 11. Side view of the UA2 experiment at CERN.
The electromagnetic calorimeter is 17 radiation lengths thick and achieves a resolution $\sigma_E/E = 17%/\sqrt{E}$ (GeV) for electromagnetic showers. The hadronic calorimeter is divided into two samples in depth for 4.5 absorption lengths total, and has a resolution for charged pion showers that varies from $\sigma_E/E = 32%$ at 1 GeV to $\sigma_E/E = 11%$ at 70 GeV. Readout of all compartments is by BBQ wavelength shifters for a total of seven photomultipliers per tower. In the forward regions, a system of toroids and chambers provides a track momentum measurement, and is followed by a preshower converter and electromagnetic calorimeters. For the luminosity upgrade of the CERN $\bar{p}p$ collider, the UA2 collaboration has chosen to discard the existing system of forward toroids and detectors, and to close the solid angle down to 2° with hadron calorimeters.\textsuperscript{28} The central track detector is also considerably improved for electron identification and includes transition radiation detectors, a silicon hodoscope, and a scintillation fiber preshower counter and track detector (Figure 12). With the new system, about a factor 20 improvement in electron identification capability over the old experiment is expected.

Figure 13 shows a plan view of the CDF experiment at Fermilab.\textsuperscript{29} The collision region is surrounded by the vacuum pipe, vertex TPC track detectors, and the central tracking drift chamber immersed in a 15 kg solenoidal field from the superconducting coil. The central track detectors are surrounded by electromagnetic and hadronic calorimeters. Above 30° with respect to the beam line, the calorimeters are of lead/scintillator and iron/scintillator construction, and, below 30°, they are of lead/proportional tube and iron/proportional tube construction. Outside the calorimeters are muon detectors, and, in the forward region, muon toroids.

The vertex TPC detectors have a 3.5 $\mu$s maximum drift time, and are divided into 8 modules along the beam line. They run at atmospheric pressure and achieve a resolution $\sigma_Z \sim 500\mu$. The central track drift chamber (CTC) has 84 wire layers arranged in nine superlayers, with small angle stereo in some layers to provide for $Z$ position measurement. The resolution in $r$-$\phi$ is about 200 microns, and the total number of wires is about 36 thousand. At the outside radius of the CTC, drift tubes are located to measure the $Z$ coordinate of tracks by using a charge division technique. In the forward region, below 10° with respect to the beam line, the forward tracking chambers measure particle trajectories in a system of radial drift chambers. These chambers have 20 wires/$\Delta\phi = 5°$, and a resolution of about 120$\mu$. Very small angle scattering events are measured in forward silicon detectors located inside the beam pipe. Finally, a hodoscope of beam-beam counters located in front of the forward calorimeters surrounds the beam pipe to determine the event time and monitor luminosity.

Figure 14 shows the angular segmentation of one quadrant of the CDF calorimeters. Physical tower sizes range from $35 \times 70$ cm$^2$ down to $5.8 \times 5$ cm$^2$. Table I shows the thicknesses, resolutions, and $\eta$ coverage of each of the calorimeter subsystems. The total system requires about 22 thousand channels of electronics for readout of towers alone.
Fig. 12. (a) General layout of the upgraded UA2 experiment at CERN. (b) Longitudinal view of the upgraded UA2 central track detector.
Fig. 13. Plan view of the CDF experiment at FNAL.
Fig. 14. One quadrant of the CDF calorimeters, showing their segmentation in $\eta$-$\phi$ and regions of coverage.
TABLE I
CDF Calorimeter Systems

Electromagnetic Calorimeters

<table>
<thead>
<tr>
<th>Absorber thickness</th>
<th>CEM</th>
<th>PEM</th>
<th>FEM</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>18.0X₀</td>
<td>19.4X₀</td>
<td>25.7X₀</td>
</tr>
<tr>
<td>Resolution at 50 GeV</td>
<td>2%</td>
<td>4%</td>
<td>4%</td>
</tr>
<tr>
<td>η coverage</td>
<td>0-1.1</td>
<td>1.1-2.4</td>
<td>2.2-4.2</td>
</tr>
</tbody>
</table>

Hadronic Calorimeters

<table>
<thead>
<tr>
<th>Absorber thickness</th>
<th>CHA</th>
<th>WHA</th>
<th>PHA</th>
<th>FHA</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>5.3λ₀</td>
<td>6.0λ₀</td>
<td>6.3λ₀</td>
<td>8.1λ₀</td>
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<tr>
<td>Resolution at 50 GeV</td>
<td>11%</td>
<td>14%</td>
<td>20%</td>
<td>20%</td>
</tr>
<tr>
<td>η coverage</td>
<td>0.9</td>
<td>0.7-1.3</td>
<td>1.3-2.4</td>
<td>2.3-4.2</td>
</tr>
</tbody>
</table>

CEM — central electromagnetic
PEM — plug electromagnetic
FEM — forward electromagnetic
CHA — central hadronic
WHA — wall hadronic
PHA — plug hadronic
FHA — forward hadronic
All three experiments select $\bar{p}p$ interactions by the use of the beam-beam counter hodoscope (BBC) arrayed along the beam line. Signals from the BBC hodoscope are put in coincidence with trigger signals from the calorimeters to reduce non-$\bar{p}p$ background. Usually some runs are taken without the BBC in coincidence to check trigger bias, but the BBC are sensitive to almost all the nondiffractive cross section, so their influence on the efficiency for hard-scattering events is usually found to be small. So far, the UA1 and UA2 experiments have each collected about 770 nb$^{-1}$ of data, mostly at $\sqrt{s} = 630$ GeV. The CDF experiment has collected about 30 nb$^{-1}$ of data, at $\sqrt{s} = 1800$ GeV. All three experiments have specialized hardware triggers designed to provide data samples suited for the study of jet production phenomena, or leptons. Jet phenomena are usually studied in data samples coming from triggers requiring that either the $\Sigma E_T$ deposited in the whole calorimeter, or that within a limited region of solid angle, exceed a certain threshold. The threshold chosen varies with luminosity to hold the event rate constant, and, for the central calorimeter, it may be in the region of 50-60 GeV of $\Sigma E_T$. ‘Electron’ triggers require that the transverse energy in a few towers of the shower counter exceed a threshold of, typically, 10 GeV. Triggers requiring two such clusters of energy can be run at lower thresholds, perhaps 3 GeV. Muon triggers require a stiff track match with hits in the outer muon chambers. The useful data sample (not overwhelmed by background) extends down to $p_T$ of 6 GeV for the UA1 and CDF experiments; UA2 has no muon system. Triggers designed to detect the missing transverse energy carried away by energetic neutrinos are also employed by all three experiments.

JETS AND QCD

V. TWO-JET PRODUCTION PROPERTIES

Figure 2 shows that the clusters deposited in the calorimeter in high $\Sigma E_T$ events are back-to-back in azimuth as expected for elastic scattering of two incoming partons. Figure 15a shows the coordinate system used by the UA2 experiment to study the $k_T$ of the dijet system. The $k_T$ of the dijet system is decomposed along the axis formed by the bisector of the $p_T$ vectors of the two outgoing jets, and along the perpendicular to this axis. The resulting $k_T$ components have very different physical and instrumental origins. The $\xi$ component, along the bisector, contributes $k_T$ dominated by the energy resolution of the apparatus, while the $\eta$ component is dominated by angular resolution. Figures 15b,c show that the observed dijet $k_T$ is described by a simple model taking into account the detector energy and angular resolution and a distribution of the form $dN/dk_T^2 \propto e^{-k_T^2}$ with a mean $k_T$ of 5 ± 2 GeV. The $k_T$ of the dijet system is indeed limited, as expected in the standard model.

Equation 1 showed that $d\sigma/dx_1 dx_2 d\cos \theta^*$ can be factored into a product of some sum over initial parton structure functions and $d\sigma/d\cos \theta^*$. Apart from overall weighting factors, the individual parton-parton scattering cross sections
Fig. 15. (a) Coordinate system used for $k_t$ of the two-jet system (see text). (b) Components $p_\xi$, $p_\eta$ of the dijet $k_t$ measured by UA2. The curves are from a simple model with mean dijet $k_t$ of 5 GeV.
calculated in QCD can be treated as a signal effective subprocess, with angular distribution given by

\[ \frac{d\sigma}{d\cos \theta^*} |_{ij} \approx \lambda_{ij} \left[ \frac{\pi \alpha_s^2(Q^2)}{\hat{s}} \right] (1 - \cos^2 \theta^*)^{-2}, \]

with the weighting factors \( \lambda_{ij} \) given by \( \lambda_{gg} : \lambda_{gq} : \lambda_{qq} = 1 : 4/9 : (4/9)^2 \).

Figure 16 shows the results from the UA1 experiment for the \( \cos \theta^* \) distribution for dijets in the mass range 150-250 GeV along with the QCD prediction. Instead of plotting the data in terms of \( \cos \theta^* \), another angular variable, \( \chi \), is useful. The \( \chi \) distribution

\[ \frac{d\sigma}{d\chi} \sim \frac{\pi \alpha_s^2(Q^2)}{\hat{s}} \left( \frac{\chi^{-2} + 1 + \chi + \chi^2}{(1 + \chi)^2} \right) \]

is approximately constant for \( \chi > 2 \). Figure 17 shows the \( \chi \) distribution from the UA1 experiment along with the QCD prediction. The figures show that the parton model description, along with scaling violations from the \( Q^2 \) dependence of \( \alpha_s \), provide a good description of the data. The effective structure function in the single effective subprocess approximation can be extracted from the data by weighting the events in the observed \( d\sigma/d\chi \) distribution by

\[ W^{-1} = \int_0^{C_{\max}(x_1,x_2)} K \left[ d\sigma/d\cos \theta^* \right]_{QCD} d\cos \theta^* \]

to determine \( S(x_1,x_2) \) from Equation 2, where \( K \) is a phenomenological factor to account for higher-order QCD terms. Evidence for factorization into the form of Equation 1 can be found by comparing the observed \( d\sigma/d\cos \theta^* \) distributions for different mass \( (x_1,x_2) \) ranges. Figure 18 shows the ratio of \( d\sigma/d\cos \theta^* \) in two different mass ranges vs. \( \cos \theta^* \) from the UA2 experiment. Since the ratio stays constant, this provides some evidence that \( d\sigma/d\cos \theta^* \) is independent of \( x_1,x_2 \). Likewise, one can see if \( S(x_1,x_2) \) is independent of \( x_2 \) for fixed \( x_1 \) to check the factorization of \( S \) into the form

\[ S(x_1,x_2) = F(x_1)F(x_2) \]

where \( F \) is the effective structure function. Figure 19 from the UA2 experiment shows the ratio \( S(x_1,x_2)/S(x_1,x_2 + \Delta x) \), which is expected and shown to be independent of \( x_1 \). Finally, \( F(x) \), given by \( F(x) = G(x) + \frac{1}{3}[Q(x) + \bar{Q}(x)] \), where \( G(x) \) and \( Q(x) \) are the quark and gluon structure functions, can be extracted from the data. Figure 20 shows the result from the UA1 experiment, along with
Fig. 16. Angular distribution for two-jet events with mass of the two jets in the range 150-250 GeV from the UA1 experiment.
Fig. 17. $\chi$ distribution for two-jet events with dijet masses in the range 150-250 GeV from the UA1 experiment.
Fig. 18. The ratio of $d\sigma/d\cos\theta^{*}$ in two different dijet mass ranges vs. $\cos\theta^{*}$ from the UA2 experiment.
Fig. 19. Test for factorization of \( S(x_1, x_2) \) into \( F(x_1)F(x_2) \) from the UA2 experiment (see text).
Fig. 20 Effective structure function $F(x) = G(x) + \frac{2}{3}[Q(x) + \bar{Q}(x)]$ measured by the UA1 experiment. The curves are the extrapolated expectation from Reference 33.
the curves of the appropriate mixture of quark and gluon structure functions extrapolated to the relevant $Q^2$ range from Reference 33. The data show that single effective subprocess approximations with input structure functions from the neutrino experiments provide a reasonable overall description of the parton-parton scattering process details.

VI. HARDWARE DIGRESSION II: HADRON CALORIMETRY AT HIGH $Q^2$

The energy scale for jets is determined from the calorimeter calibration, test beam studies of the response to single pions and electrons, and model simulation of jet fragmentation. The results can be checked against artificial ‘jets’ generated by pions hitting a thin target placed in front of the calorimeter. Hadron calorimetry forms the heart of the measurements on jet-jet systems. This section outlines some of the experimental detail that goes into the connection between the pulse heights observed in the calorimeter and the partons that precipitate the hadronic shower.

In order to utilize a hadron calorimeter for jet energy measurement, one first has to understand how the calorimeter responds to single pions, muons, and electrons. For this purpose, studies are made in calibration beams set up in the style of a small fix target experiment. First, the calorimeter ‘calibration’ is set by choosing some standard beam condition. Typically, for calorimeters built in the style of the CERN UA and CDF experiments, electrons of one beam energy directed to the center of a tower are used to set the electromagnetic compartment energy scale. Then, muons at tower center are used to set the relative scales of the hadronic compartments, or, if there is only one readout in depth in the hadronic compartment (CDF), pions of one beam energy, minimum ionizing in the electromagnetic compartment, can be used for this purpose. Having thus set the calibration of each tower of the calorimeter, any other variation is termed the ‘response’ of the calorimeter. In particular, measurements are made with pions and electrons of various energies as a function of impact point across the calorimeter face, and as a function of incidence angle. Such measurements provide the single pion and electron response of the calorimeters. Since the measurements must be performed with some precision, dedicated calibration beam facilities are of crucial importance for this work.

- Calorimeter Calibration

The central calorimeters of the UA2$^{27}$ and CDF$^{29}$ experiments have a tower by tower initial calibration from the calibration beams. In the shower counter, the UA2 uses 10 GeV electrons, while CDF relies on 50 GeV electrons in the scintillator calorimeters, and 100 GeV electrons in the gas calorimeters. For the hadron compartment calibration, UA2 uses 10 GeV pion and muon beams, while CDF uses 50 GeV pions in the scintillator calorimeters, and 200 GeV pions in the gas calorimeters. The UA1 experiment and the CDF gas calorimeters both measure some modules in the beam, and rely upon construction similarity and
source measurements to obtain the calibration of the other towers.

Since the response of the calorimeter to even the fixed calibration beam condition varies with time, systems must be used to track the short and long term stability of the energy scale. The scintillator calorimeters use Co$^{60}$ or Cs$^{137}$ sources to track the long term stability of the energy scale, and light flashers (Xenon, LED, or Laser systems) with optical fiber couplings to the phototubes to track the short term stability. Gas calorimeter systems use the peak positions of Fe$^{55}$ source spectra to track both the short and long term stability of the calibration. Frequent checks of these systems in the calibration beam with spare calorimeter modules are required. Figure 21 shows the result for the CDF central electromagnetic calorimeter of several such recalibrations. The spread in the data can be used to estimate the overall systematic uncertainty on the energy scale setting. The UA2 finds scale errors of ±1.5% (±6.5%) with a spread over modules of ±2.5% (±8%) in the electromagnetic (hadronic) compartment, while CDF finds scale errors of ±6% (±2%) with a spread over modules of ±8% (±2.5%) in the electromagnetic (hadronic) compartments. Such tracking of the time variation of the energy scale seems simple, but can be complicated by the large number of precision steps needed to carry the calibration from the calibration beam to the collider environment.

• Calorimeter Response to Hadrons

After the calorimeter calibration and its time dependence are understood and controlled, detailed studies can be made of the calorimeter response. Figure 22 shows a typical response map as a function of position for single pions in the UA2 experiment. With tower calibrations set as outlined above, the figure shows the ratio of the measured response to the beam energy ($\bar{r}$) from a scan in the $\theta$ direction (along the beam line) for two different azimuthal positions. The effects of tower mechanical boundaries in the calorimeter are visible. Figure 23 shows the response to 50 GeV electrons relative to tower center for a single tower of the CDF central electromagnetic calorimeter. For showers contained within the tower, the total rms error on the energy scale is ±1.5% from the map, ±2% from the resolution, and ±6% from the absolute calibration. In addition to spatial variation of the calorimeter response to both electrons and pions, the energy dependence of the response must be measured. Figure 24 shows the energy (non) linearity for the UA2 experiment measured with single pions in the range 1–70 GeV. The response drops by 15% for energies less than 2 GeV. Such effects are folded with the jet $dN/dZ$ distribution to modify the observed jet energy scale.

To determine the corrections needed to convert observed cluster energies into incident parton energies, a detector simulation program is used that reproduces the details of the test beam measurements. The inputs to the simulation are the test beam measurements of single pion and electron response, and jet production and fragmentation models. The resulting predicted distributions are
Fig. 21. Differences in calibration constants taken at various times for the CDF central electromagnetic calorimeter.
Fig. 22. Single pion response as a function of position in the UA2 experiment. (See text.)
Fig. 23. Response to 50 GeV electrons relative to tower center for a single tower of the CDF central electromagnetic calorimeter. The $x$ direction shown is the azimuthal coordinate and the $z$ direction shown is the coordinate along the beam line in the collider hall.
Fig. 24. (a) Energy dependence of the average calorimeter response (\( \bar{r} \)) to single pions vs. energy for the UA2 experiment. (b) Single pion resolution vs. energy for UA2.
compared with collider data to check the details of the simulation, and the performance of the detector. The azimuthal symmetry of the detector is a powerful tool that aids in finding problems at this stage. Such comparisons reveal deficiencies in the systems that track the calibration stability, the calibration beam data, the detector simulation, and the event generation models. This process of cross checking is repeated again and again until the systematic errors become small enough (or until the experimenters become exhausted). Since many of the uncertainties in this process are systematic in nature, care must be taken to identify the important errors early on, and thus determine when further parameter variation is fruitless. The results of such work are corrections that can be applied to the observed data to set the cluster energy scale such that hypothetical objects, decaying into jets of hadrons, would, when reconstructed, have mass values corresponding to the produced particles. Another invaluable side product of this work is the expected resolution as a function of jet energy. The resolution is very important in providing the expected width of any signals in searches for new phenomena.

- Recent Advances in Understanding of Calorimeter Operation

Recently, new progress has been made in understanding how calorimeters operate. The energy deposition in sampling hadronic calorimeters occurs in the following forms:

- Electromagnetic component \((\gamma, e)\)
- Ionizing charged hadrons \((\pi, P, ...)\)
- Nuclear binding energy
- Low energy neutrons
- Low energy \(\gamma\)'s from nuclear de-excitation.

The resolution of the calorimeter \((\sigma/E)\) has contributions from sampling fluctuations \((\propto 1/\sqrt{E})\) between the absorber and active medium, and in how the energy is divided into the above categories, folded with the detector sensitivity for each category. This second contribution to the resolution typically varies more slowly than \(1/\sqrt{E}\) and therefore dominates at a high enough energy, and can be minimized if the intrinsic response of the calorimeter to electrons is the same as for pions \((e/\pi = 1)\). The \(e/\pi\) ratio depends upon the thicknesses of the sampling medium and the absorber. However, since the low energy neutron detection efficiency depends only on the density of free protons in the sampling medium, and nuclear binding losses are strongly correlated with low energy neutrons in the shower, for a sampling medium containing free protons, the relative thickness of the sampling medium and absorber can be adjusted until \(e/\pi = 1\) to minimize the resolution. By using this technique, a lead-scintillator calorimeter with 2.5 mm/10 mm scintillator/lead plates has been constructed that achieves \(44%/\sqrt{E}\) resolution for pions, a significant improvement over existing iron/scintillator devices. Figure 25 shows measurements of resolution
Fig. 25. The resolution and $e/\pi$ ratio vs. energy for various uranium-scintillator test calorimeters. Scintillator/uranium plate thicknesses were: WA78: 5 mm/10 mm, T60B: 3 mm/3.2 mm, T35: 2.5 mm/3 mm, T60A: 5 mm/3.2 mm.
and $e/\pi$ in various uranium-scintillator test calorimeters as a function of energy. The scintillator/uranium plate thicknesses used were: WA78: 5 mm/10 mm, T60B: 3 mm/3.2 mm, T35: 2.5 mm/3 mm, T60A: 5 mm/3.2 mm. The data show that the best resolution is indeed achieved over the widest energy range for calorimeters that obtain $e/\pi = 1$.

With this new understanding, it seems no longer necessary to construct poorly behaving calorimeters, but what should be the expected impact of these advances on future experiments (e.g., SSC, LHC)? If $e/\pi = 1$, systematic errors will dominate the resolution at high energy. If detectors are constructed no better than now, $\sigma/E \sim .35/\sqrt{E} + .02$, and systematic errors will be as important as sampling fluctuations in the measurement at around 300 GeV. Since signal lines and power to the electronics must be passed through the calorimeters to the inner (tracking) detectors, there is some non-uniform response somewhere in any large calorimeter experiment. To take full advantage of small intrinsic systematic error afforded by $e/\pi = 1$, systematic errors introduced by the construction and operation of the apparatus must be controlled to a corresponding level. The improvements in resolution provided by constructing calorimeters with $e/\pi = 1$ ('compensating' calorimeters), probably help the most in obtaining a detailed understanding of the detector performance in calibration beams—there are no clear physics motivations at this time for achieving any particular value of $\sigma/E$, other than as low a value as possible. Additional techniques to check the calorimeter performance should be available at machines like the SSC—for example $Z^0 \rightarrow e^+e^-$ has a rate at full luminosity of 1/2 Hz and may be used to check the calibration of the electromagnetic calorimeter. Even with the recent advances in understanding of calorimeter performance, a heavy reliance on calibration beam work can still be expected, and high quality calibration beam areas will be an integral part of all future hadron calorimeter-based experiments. Note also that the physics problem of making the best possible jet energy measurement has many variables so that even though existing experiments (e.g., CDF, UA1, UA2) do not use 'preferred' technology, a great deal can be learned from these experiments about the other aspects of the problem.

VII. JET PRODUCTION CROSS SECTIONS

Data in Section V show that the details of the angular distributions and structure functions from the dijet events are in agreement with QCD expectations. The digression on hadron calorimetry discussed some of the details required to convert the observed cluster $p_t$ spectra into jet $p_t$ spectra. The results on the total production rate for $\bar{p}p \rightarrow \text{jet} + x$ as a function of jet $p_t$ are shown in Figure 26 from the UA experiments at $\sqrt{s} = 546$ GeV, 630 GeV.

These measurements are made from events selected by total $\Sigma E_t$ triggers in the calorimeters. The requirement that there be one or more clusters with $E_t > 30$ GeV in the pseudorapidity interval $-0.85(-0.7) < \eta < 0.85(0.7)$ for the UA2 (UA1) is made, and, in the UA2, additional clusters with $E_t > 3$ GeV within an
opening angle of 78° from the main cluster axis are vectorially added to the main cluster. To calculate the jet cross section from the observed cluster $p_t$ spectrum, the luminosity from the BBC system is needed, and the acceptance is obtained from a Monte Carlo calculation. The Monte Carlo simulation is adjusted to reproduce the details of the event configurations, and the details of the detector response. Systematic uncertainties on the cross section arise from several sources including the luminosity measurement ($\pm 8\%$), calorimeter calibration uncertainty ($\pm 30\%$) sensitivity of the results to various analysis parameters ($\eta$-range, clustering cuts, etc., $\pm 15\%$), and sensitivity to the fragmentation model parameters and the jet production model ($\pm 35\%$). Overall errors quoted by the UA2 experiment are in the range $\pm 45\%$, and $\pm 70\%$ for the UA1, with the larger UA1 uncertainty mainly due to larger calorimeter calibration uncertainty.$^{36}$ The curves in Figure 26 are the QCD expectations. Since many of the experimental uncertainties are cancelled by taking the ratio of the cross sections at the two energies, Figure 27 compares this ratio vs. $p_t$ with the QCD expectation. In all cases, the data show support for the QCD model of jet production.

One method to search for new phenomena, beyond those expected in the standard model, is to search for the decays of massive particles into jet-jet or multijet final states. All the details above on dijet production make it seem plausible that such searches should be feasible, but a test case is needed in order to show that the technique can work. The UA2 experiment has attempted to see the expected signal from $W,Z$ particles decaying hadronically into two jets on top of the large QCD jet production background.$^{37}$ In order to perform this study the detector resolution on dijet mass must be well understood. The UA2 resolution has been studied by seeing the effect of various selection criteria on the distribution of dijet $k_t$. Cuts were made beyond those used in the usual jet analysis on containment, $k_t$ balance, and sharpness of the jet profile to select a well-measured event sample. Further, the mass resolution was optimized by varying the aperture size of the cone used to define the jet energy. The results for a combined fit of a smooth background and a Gaussian with width as expected for the $W,Z$ system and detector resolution are shown in Figure 28. The results show a $3\sigma$ fluctuation in the mass region where the signal from $W,Z$ hadronic decays would be expected. The expected mass resolution in the $W$ region is about 8 GeV. This result is encouraging for future searches, but suffers from poor statistics. Future colliders runs should provide more statistics to confirm this result.

VIII. JET FRAGMENTATION

Recall that in the standard model, jets of hadrons come in three basic types: gluon jets, light quark jets ($u,d,s$), and heavy quark jets ($c,b$). Can we distinguish among these three types of jets by their fragmentation properties? If possible, even on a statistical basis, this would be a valuable tool as it could help reduce background to various physics processes of interest. In any case,
Fig. 26. Jet production cross sections for $\sqrt{s} = 630, 546$ GeV for the UA1 and UA2 experiments as a function of jet $p_T$. The curves are the QCD expectations.
Fig. 27. Ratio of jet production cross sections at 630,546 GeV vs. $p_T$ for the UA1 and UA2 experiments. The curves are the QCD expectations.
Fig. 28. Combined fit to UA2 dijet mass spectrum using a smooth background and a Gaussian of width as expected from the resolution. The data show a 3σ fluctuation in the mass region expected for the W, Z.
study of the jet fragmentation is an invaluable tool for constraint of models of the calorimeter response, and for determination of background to lepton signals, contributions to tails of distributions, etc.

To measure charged particle multiplicities inside jets, the UA2 experiment uses a selection of events that have two jets in the central calorimeter with $E_T^1, E_T^2 > 15$ GeV and $\Delta \phi_{12} > 150^\circ$. Only the track density in the transverse plane is considered, since the tracking efficiency is then quite high. Also, the tracking chamber acceptance ($20^\circ < \theta < 160^\circ$, full $\phi$) is much larger than the central calorimeter acceptance, so corrections for losses in the $\eta$ direction are minimized. The two track resolution of the detector is $\sim 5$ mm. Losses are evaluated from the distribution of nearest neighbor tracks and vary from 12% far from the jet ($\Delta \phi = \pi/2$) to 25% within the jet, increasing with $E_T^{jet}$, with a systematic uncertainty estimated to be $\pm 10\%$. To check the technique, the charged particle multiplicity in minimum bias events for $|\eta| < 2$ has been measured to be $15.3 \pm 0.7$ compared with results from the UA5 experiment$^{39}$ of $13.5 \pm 0.15$, where the UA5 data have been corrected for strange particle decays and the UA2 data have not. The number of tracks per unit $\Delta \phi$ around $90^\circ$ away from the jet axis is found to be about twice the number in the minimum bias study. To determine the total charged multiplicity within the jet, an estimate must be made of how many of the tracks at $\Delta \phi \sim \pi/2$ belong to the jets, and how many are uncorrelated 'underlying event' background. In order to compare results with those from $e^+e^-$ experiments, only the charged particles in the region of the jet core are counted and a corresponding cut applied to TASSO data (Figure 29). Unfortunately, the strong $Q^2$ dependence of jet fragmentation and differing $Q^2$ ranges preclude any direct comparison of the data.

The UA1 experiment$^{40}$ measures a similar value for the jet charged multiplicity as UA2. Since they have a magnetic field, they can measure single particle momenta and thus $dN/dZ$ distributions, where

$$Z \equiv P_L/E_{\text{jet}}.$$ 

and $P_L$ is the momentum component of the charged track along the cluster direction. Figure 30 shows the $dN/dZ$ distribution for charged particles from the UA1, R807 and TASSO experiments. Since the collider data should be dominated by gluon jets, a $Z$ distribution peaking at lower $Z$ is expected when compared to $e^+e^-$ data, which is dominated by quark jets. Unfortunately, the effect of the higher $Q^2$ in the collider data relative to the $e^+e^-$ data is in the same direction, so no definitive comparison is possible.

In order to attempt to obtain a direct comparison of quark and gluon jets at the same $Q^2$ in the same experiment, the collider data can be weighted event by event using the QCD probability that each event arises from quark-quark or glue-glue scattering. With a definition of

$$Q^2 \equiv \frac{2s \hat{t} \hat{u}}{(\hat{s}^2 + \hat{t}^2 + \hat{u}^2)},$$
Fig. 29. Charged particle multiplicity in the jet core plotted against $\sqrt{s}$ for the TASSO data, and dijet mass for UA2 data. (See text.) The solid curve is the quark jet prediction and the hatched area is the gluon jet prediction in the model of Reference 38.
Fig. 30. (a) $dN/dz$ distributions from UA1 $\bar{p}p$ data, TASSO $e^+e^-$ data, and R807 $pp$ data. (b) Mean $p_T$ of tracks relative to the jet axis plotted against the $Z$ of the tracks for UA1, TASSO, and R807.
event samples can be found that are statistically gluon enriched or quark enriched, within the same $Q^2$ range. The $Z$ distribution for quark and gluon enriched samples are shown in Figure 31, along with the ratio of gluon to quark charged particle $Z$ distributions versus $Z$. Figure 32 shows the charged particle $Z$ distribution vs. $Q^2$ in various $Z$ bins for the TASSO and UA1 experiments.

Thus far, no dramatic differences in fragmentation are seen between jets from hadron-hadron collisions dominated by gluons, and $e^+e^-$ jets, dominated by quarks. The comparison is complicated by the strong $Q^2$ dependence of jet fragmentation, and the uncertainty in the proper $Q^2$ scale definition for the fragmentation comparison. The ideal case to aid in the search for new phenomena would be to provide an event by event selection criteria to choose between quark or gluon jets, but, as yet, no clear statistical separation is seen.

Since such efforts have so far yielded no positive results, the question arises why charged particle tracking is necessary at all in future (SSC or LHC) detectors, much less inside jets. The most important reason to perform charged particle tracking at any general purpose experiment in a new energy range is to provide complete event visualization. Full charged and neutral event reconstruction is important, as well as determination of the event vertex position along the beam line. The tracking detectors in the SSC can help correlate calorimeter energy with a particular event $Z$ vertex position for the transverse energy determination (in the case of such high luminosity that multiple events per crossing are found). Also, the calorimeter energy can be compared with the track energy to cross-check the data (but good tracking cannot compensate for bad calorimetry). Charged-particle track based triggers are possible, and tracking aids in lepton identification. Measurement of the sign of the particle charge for the lepton allows asymmetry measurements to be made. Finally, secondary vertices may be found that may aid in the identification of long lived particles.

IX. JET PRODUCTION AND COMPOSITENESS LIMITS

An immediate benefit of a detailed analysis of dijet events is the ability to set limits on phenomena not expected in the standard model. If the quarks are composed of other, more fundamental, constituents, deviations in dijet production from the QCD predictions can be expected. To set a limit on such behavior, some model for quark compositeness must be assumed. For example, point-like contact terms may be hypothesized of the form

\[ (g^2/2\alpha_s^2) (q\gamma^\mu\bar{q}) (q\gamma^\nu\bar{q}). \]

With $g^2/4\pi = 1$, $\Lambda_c$ is the compositeness scale. Such additional terms also effect the angular distribution:

\[ \frac{d\sigma}{d\chi}_{QCD} = \frac{\pi\alpha_s^2}{s} [\chi^{-2} + \chi^{-1} + 1 + \chi + \chi^2] /(1+\chi)^2 \]
Fig. 31. (a) Quark and gluon enriched $Z$ distributions for charged particles from the UA1 experiment. (b) Ratio of gluon enriched to quark enriched charged particle $Z$ distributions from the UA1 experiment.
Fig. 32. Charged particle $Z$ distribution as a function of $Q^2$ for various $Z$ bins in the TASSO and UA1 experiments.
becomes

$$8 \frac{\pi \alpha_s^2}{9 \hat{s}} \left\{ 1 \pm \frac{\hat{s}}{\alpha_s \Lambda_c^2} \frac{\chi^3}{(1 + \chi)^4} + \left[ \frac{\hat{s}}{\alpha_s \Lambda_c^2} \right]^2 \frac{3 \chi^2}{(1 + \chi)^4} \right\}$$

which yields a more isotropic distribution. Figure 33 shows the UA2 data for the dijet mass spectrum from which a 95% confidence limit on $\Lambda_c$ of 400 GeV is derived. Figure 34 shows UA1 data for $d\sigma/d\chi$ in various mass ranges, from which a 95% confidence limit is set at 415 GeV. The limit from the $\chi$ distribution provides an additional check, as the limit from the $p_t$ spectrum can have uncertainties arising from non-gaussian tails of the $p_t$ resolution. Figure 35 shows the expectations for modification of the jet $p_t$ spectrum at the Tevatron ($\sqrt{s} = 2$ TeV) for various values of the compositeness scale. One can expect limits from the Tevatron in the next few years of the order of 1 TeV on $\Lambda_c$.

X. MULTIJET PRODUCTION

The data show that many aspects of dijet production are well described by QCD. Production of events with more than two jets detected can also be studied in the data, and compared with QCD predictions. UA2 has looked for events with three jets in the final state by selecting events with $\Sigma E_T$ in the calorimeter $> 60$ GeV, finding three clusters separated by $30^\circ$, with $E_T^1 + E_T^2 + E_T^3 > 70$ GeV, and by requiring $E_T^3 > 10$ GeV, with $E_T^4 < 10$ GeV. All clusters are required to have $|\eta| < .8$, and the data sample contains about 6200 events in 310 nb$^{-1}$ of luminosity. Figure 36 shows the $k_t$ spectra for the three jet system of this event sample, along with the dijet $k_t$ spectrum from events with no third jet $> 10$ GeV.

To compare the ratio of two to three jet production, a simple QCD model is used. The $n$-jet cross section is assumed to be of the form

$$\sigma_n^{LO} = \frac{[\alpha_s]^n}{\hat{s}} \int \sum_{ij} F_i(x_i) F_j(x_j) Q_n^{ij} \Phi_n \frac{dx_i}{x_i} \frac{dx_j}{x_j}$$

where $\Phi_n$ is $n$-body phase space, $Q_n^{ij}$ are the QCD matrix elements, and $F(x) = G(x) + \frac{\delta}{\hat{s}}[Q(x) + \bar{Q}(x)]$ is the effective structure function. Since there exist divergences in the QCD matrix elements $Q_n^{ij}$, cut-offs must be placed to avoid such points. This means that the observed cross section

$$\sigma_{\text{obs}}(\bar{p}p \rightarrow n \text{ jets}) = K_n \sigma_n^{LO}$$

where $K_n$ is calculable in principle, but depends upon the experimental cut-off. The ratio of the observed two to three jet cross sections should be given by $\alpha_s \times K_3/K_2$, where some $Q^2$ scale must be arbitrarily chosen to make the comparison. By setting the $Q_n^{ij} = 1$ in the equation for $\sigma_n^{LO}$, a phase space model can be made for comparison with the data to see the effect of the QCD
Fig. 33. Compositeness contributions to the dijet mass spectrum expected from the UA2 experiment. A 95% confidence limit of 400 GeV is found.
Fig. 34. $\chi$ distribution for various mass ranges from the UA1 experiment. A compositeness limit of 415 GeV at 95% confidence is set from fits to the highest mass range $\chi$ distribution.
Fig. 35. Expectations for modification of the jet $p_T$ spectrum for various values of the compositeness scale for the Tevatron at FNAL, $\sqrt{s} = 2$ TeV, from Reference 41.
Fig. 36. $k_t$ spectra for events containing two jets with no third jet > 10 GeV, and three jets with no fourth jet > 10 GeV from the UA2 experiment.
matrix elements more clearly. To see if the QCD model describes the data, the jets are boosted to the center of mass system, after a cut discarding events with $k_t > 20$ GeV. In the center of mass system, three variables describe the orientation of the plane of the three-jet system, and three more describe the configuration of the jets within that plane. Figure 37 shows the distribution of the angle of the scattering plane relative to the beam direction for two and three jet events, along with the QCD prediction for $gg \rightarrow ggg$ scattering.

To look in more detail at the structure of the events, the momenta of the three jets in the c.m. system are ordered $P_1^* > P_2^* > P_3^*$. The angle between the two lowest momentum jets, $\omega_{23}^*$ can be expected to peak at small angles on account of gluon bremsstrahlung. Figure 38a shows the distribution of $dN/d \cos \omega_{23}^*$ with comparisons to the phase space and QCD models. Another distribution of interest is the Ellis Karliner angle distribution, defined by

$$\cos \xi = (P_2^* - P_3^*)/P_1^*$$

The distribution in $\cos \xi$ normalized to 1 at $\cos \xi = 0$ is shown along with the QCD model prediction for $gg \rightarrow ggg$ in Figure 38b. In all cases, good agreement is seen in the details of the event characteristics as compared with QCD model expectations.

If the production ratios for two to three jets are taken, $\alpha_s$ times the ratios of $K$-factors can be determined. Figure 39 shows the result from UA2 as a function of the mass of the multijet system. UA2 quotes a value of $.23 \pm .01 \pm .04$ for $\alpha_s \cdot K_3/K_2$, compared with $.23 \pm .02 \pm .04$ quoted by UA1 in a similar measurement, where the first error is statistical, and the second error is systematic. The systematic errors in the UA2 measurement come from uncertainties in the jet fragmentation, in the structure of the underlying event, in the structure functions, in the energy response of the calorimeters, in the contribution to the sample of four-jet events, and in the $k_t$ dependence of the result.

The problem with both the UA2 and UA1 $\alpha_s$ determination by this method is that the $K$ factors are not calculated, and depend upon the experimental cuts. Comparison with other methods for $\alpha_s$ determination requires the assumption that $K_3/K_2$ is approximately one. One can look upon these measurements more as a test of the approximation techniques in the calculation that gives us the multijet cross sections, rather than a rigorous $\alpha_s$ determination. The importance of even approximate QCD multijet calculations is that they allow us to estimate cross sections for multijet backgrounds to new particles decaying into multijet final states. As an example, Figure 40 shows estimates for mass distributions for up to six jet final states for the LHC collider, $\sqrt{s} = 17$ TeV. Such estimates for six jet cross sections are uncertain by at least of order the uncertainty in $\alpha_s$ to the sixth power (e.g., a factor of 4), but they still provide some estimate of background to interesting possible new signals. Such work is very important 'engineering' work to help gain the full potential of $\bar{p}p$ collisions to test the standard model and search for new phenomena.
Fig. 37. Distribution of the angle of the scattering plane relative to the beam for 2 and 3 jet events from the UA2 experiment. The curve is the QCD expectation for $gg \rightarrow ggg$ scattering.
Fig. 38. (a) Distribution of the cosine of the opening angle ($\omega_{23}$) between the lowest two momentum jets in the center mass system of three jet events from the UA2 experiment. The curves are from a phase space and QCD model. (b) Ellis-Karliner angle distribution from UA2 three jet events along with a QCD model prediction for $gg \rightarrow ggg$. (See text.)
Fig. 39. Strong coupling constant times ratio of $K$ factors from the UA2 experiment, vs. dijet mass.
Fig. 40. Estimates for various multijet jet mass distributions for the proposed $\sqrt{s} = 17$ TeV LHC collider.
XI. THEORETICAL INTRODUCTION—THE DRELL-YAN PROCESS

• Electromagnetic

The lepton cross section for production by electromagnetic $qq$ annihilation (Drell-Yan process) in $\bar{p}p$ colliders is given by

$$\frac{d^2\sigma}{dx_1 dx_2} = \frac{1}{3} \sum_i e_i^2 [q_i(x_1)\bar{q}_i(x_2) + q_i(x_2)\bar{q}_i(x_1)] \frac{4\pi\alpha^2}{3sx_1 x_2}$$

where the factor $1/3$ is the average over colors, $e_i^2 = 4/9$ or $1/9$ for charge $2/3$ or $1/3$ quarks, and $\frac{4\pi\alpha^2}{3sx_1 x_2}$ is the muon pair production cross section evaluated at the mass of the outgoing lepton pair ($m^2 = sx_1 x_2 \equiv s\tau$). We define $p_L = (x_1 - x_2) \frac{\sqrt{s}}{2} \equiv x \frac{\sqrt{s}}{2}$ where $p_L$ is the momentum along the beam line. Then,

$$\frac{d^2\sigma}{dmdx} = \left(\frac{8\pi\alpha^2}{9m^3}\right) \left(\frac{\tau}{\sqrt{x^2 + 4\tau}}\right) \sum_i e_i^2 R_i(x_1, x_2)$$

with

$$R_i(x_1, x_2) = q_i(x_1)\bar{q}_i(x_2) + q_i(x_2)\bar{q}_i(x_1)$$

and

$$x_1, x_2 = \frac{1}{2}(\sqrt{x^2 + 4\tau} \pm x).$$

The lepton production cross section via this Drell-Yan process is calculated in QCD to be sensitive to non-leading graphs, which implies some uncertainty ($K$-factor) in the overall normalization. Note that $m^3 \frac{d^2\sigma}{dmdx}$ is a function of $x, \tau$ alone whereas $m^3 \frac{d^2\sigma}{dmdy}$ is $\sqrt{x^2 + 4\tau}$ times the same function of $x, \tau$.

• Weak

Since the $W$ boson mediates charged current interactions it is also produced by the (weak) Drell-Yan process, and

$$\frac{G_F}{\sqrt{2}} = \frac{g^2}{8m_W^2}$$

(3)

where $G_F$ is the Fermi constant $= 1.02 \times 10^{-5}/m_{proton}^2$ and $g = e/\sin\theta_W$ in the standard model. Radiative corrections$^{45}$ give

$$m_W = \frac{38.7 \text{ GeV}}{\sin\theta_W}.$$
If $\sin^2 \theta_W = .22$, $m_W = 83$ GeV. Since the $W$ couples equally to all fermion doublets, the branching ratio for $W$ decays into electrons is $1/4N_g$, where $N_g$ is the total number of generations of quarks and leptons. If we choose $N_g = 3$, and neglect the top mass, then $B(W \to e\nu) \sim 8\%$. In the standard model with one physical Higgs particle,

$$m_Z^2 = \frac{m_W^2}{\rho \cos^2 \theta_W} \text{ with } \rho = 1.$$ 

Again, $\sin^2 \theta_W = .22$ gives $m_{Z^0} \sim 94$ GeV. The coupling to fermions is given by an effective Lagrangian

$$\mathcal{L}_{\text{eff}} = -\frac{m_Z}{\sqrt{2}} \left( \frac{G_F}{\sqrt{2}} \right)^{1/2} \bar{f} \gamma_\mu (V_f - A_f \gamma_5) f Z^\mu$$

where

- $V_\nu = A_\nu = 1$ for neutrinos
- $A_f = \pm 1$, $V_f = \pm (1 - 4|Q_f| \sin^2 \theta_W)$

for fermions with $\pm$ charge. Note that for charged leptons, $V_f$ is small because $|Q_f| = 1$ and $\sin^2 \theta_W \sim .25$. The branching ratio for the $Z$ is 3% per lepton, and 6% per neutrino, with the rest going to hadrons.

- $W, Z^0$ Production

If only valence quarks are considered, $u + \bar{d} \to W^+, d + \bar{u} \to W^-, u + \bar{u} \to Z^0$, $d + \bar{d} \to Z^0$. For $u + \bar{d} \to W^+$, neglecting the $W$ width,

$$\hat{\sigma}(x_1, x_2) = \sqrt{2} \pi G_F m_W^2 \cos^2 \theta_C \delta(x_1 x_2 s - m_W^2)$$

where $\theta_C$ is the Cabbibo angle. This gives

$$\sigma(\bar{p}p \to W^+ + \ldots) = \int_0^1 dx_1 \int_0^1 dx_2 \hat{\sigma}(x_1, x_2) W^+(x_1, x_2) = \sqrt{2} \pi G_F \tau \cos^2 \theta_C \int_{\tau/x}^1 \frac{dx}{x} W^+(x, \tau/x)$$

where $\tau = m_W^2/s$ and $W^+(x_1, x_2) = \frac{1}{3} [u(x_1)d(x_2) + d(x_1)u(x_2)]$. Similar results may be written down for the $Z$ production case. To get an idea of the cross section sizes the expected event rate for $W \to e\nu$ into the UA2 acceptance is about 1 event per 5 nb$^{-1}$. 
XII. ELECTRON SIGNATURE

As an example of high $p_t$ electron identification in $\bar{p}p$ experiments, the identification of electrons in the UA2 apparatus is considered. In the UA2, the electron analysis begins with a search for a localized cluster of electromagnetic energy deposition, with a small hadronic leakage, and a transverse profile that agrees with the electron hypothesis. Next, a search is made for a charged track pointing to the cluster, with good agreement between the track direction and the energy deposition pattern. Then a hit in the preshower counter, with a pulse height larger than minimum ionizing, and with distance to the track consistent with the resolution is made. This cut requires an early shower be developed in the tungsten pre-shower counter. In the UA1 experiment, a depth profile in the four depth segments of the shower counter that is consistent with that expected for electrons is required. Finally, the measured track momentum is required to match the calorimeter energy, within errors.

In the search for high $p_t$ electrons, a balance must be made between the electron detection efficiency and the background rejection power, that depends upon the electron $p_t$. Table II shows the details of the 1983 UA2 analysis, with some efficiency numbers. The overall detection efficiency is about 75%. At the last step of the analysis, the parameters of all the measurements of the electron (track parameters, calorimeter energies, etc.) are varied within errors to determine the final corrections for the electron energy. Such corrections are typically of order a few percent.

- High $p_t$ electrons from $W$ Decay

For $\bar{p}p \rightarrow W + x$, $W \rightarrow e\nu$, with the $k_t$ of the $W$ expected to be small, a large missing transverse momentum will be carried by the neutrino. For most $W$ events, the $p_t^e = -p_t^\nu \sim 0$, that is, there is almost no other energy imbalance in the event beyond that of the electron. The missing $p_t$ is calculated from a vector sum over the calorimeter towers, and the scatter plot of missing $p_t$ vs electron $p_t$ is made. Figure 41 shows this scatter plot from the UA2 electron analysis outlined above, along with the projections on the missing $p_t$ and electron $p_t$ axes.

On the scatter plot of Figure 41, a clear clustering of events with $p_t^e \sim p_t^\nu$ can be seen for $p_t^e \gtrsim 25$ GeV. Below 25 GeV, background events are visible in the plot. The sources of these background events include Dalitz decays and conversions from isolated high $p_t\pi^0$, or single $\gamma$ conversions, single high $p_t$ hadrons that interact early in the calorimeter, and ‘overlap’ background occurring when one or more high $p_t\gamma$'s have a charged track pointing to them. The overlap and conversion backgrounds coming from dijet events forms the most important high-$p_t$ background. Such background may be estimated directly from the data with good reliability by varying the electron identification cuts and finding the effect on the remaining data samples. In order to estimate the $W$ mass from the
### TABLE II

Electron Analysis Parameters, Cuts and Efficiencies

UA2, 1983

<table>
<thead>
<tr>
<th>Item</th>
<th>Fraction of Event Sample Remaining</th>
<th>Electron Efficiency Estimate</th>
</tr>
</thead>
<tbody>
<tr>
<td>0) Trigger (2 × 2 cell matrix, $E_t &gt; 8$ GeV)</td>
<td>1.0</td>
<td>~ 1.0</td>
</tr>
<tr>
<td>1) Small leakage into hadron calorimeter</td>
<td>$4.0 \times 10^{-2}$</td>
<td>~ .98</td>
</tr>
<tr>
<td>$E_{HAD}/E_{EM} + E_{HAD}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$&lt; 10% @ 10$ GeV</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$&lt; 15% @ 40$ GeV</td>
<td></td>
<td></td>
</tr>
<tr>
<td>calibration beam measurements have 4–5% leakage</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2) Small cluster size</td>
<td>$1.2 \times 10^{-2}$</td>
<td>~ 1.0</td>
</tr>
<tr>
<td>rms cluster size &lt; $\frac{1}{2}$ calorimeter tower ($\theta$ radius &lt; 5°, $\phi$ radius &lt; 7.5°)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3) Require a track</td>
<td>$0.8 \times 10^{-2}$</td>
<td>~ .9</td>
</tr>
<tr>
<td>One track within ±1 cell efficiency depends upon ‘underlying event’</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4) Track-preshower counter match</td>
<td>$5.2 \times 10^{-4}$</td>
<td>~ .9</td>
</tr>
<tr>
<td>Track-shower separation &lt; 7 mm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>no extra cluster in preshower counter within 60 mm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5) ‘Probability’ cut</td>
<td>$1.5 \times 10^{-4}$</td>
<td>~ .95</td>
</tr>
<tr>
<td>consistency of all the above, within errors</td>
<td></td>
<td></td>
</tr>
<tr>
<td>— Lateral and longitudinal particle</td>
<td></td>
<td></td>
</tr>
<tr>
<td>— BBQ ratio</td>
<td></td>
<td></td>
</tr>
<tr>
<td>— Edge effects</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Fig. 41. (a) UA2 results for missing transverse momentum versus electron transverse momentum. Standard model $W$ production occurs along the line shown. (b) Projection of (a) onto the $p_t$ of the electron. (c) Projection of (a) onto missing transverse momentum axis.
background—subtracted $p_t$ spectrum, the production properties of the $W$ are simulated by Monte Carlo to create a two-dimensional $\frac{d^2N}{dp_t^2d\phi}$ distribution which is compared with the data via a likelihood fit. Another method that reduces the model dependence coming from the uncertainties in the $W$ $p_t$ spectrum uses the transverse mass distribution defined by

$$m_T^\nu = [2p_T^e p_T^\nu(1 - \cos \Delta\phi)]^{1/2}.$$  

Figures 42 and 43 show the transverse mass distributions with background estimates from the UA1 and UA2 experiments along with the model expectation. The next section will return to the $W$ mass determination from these results.

• **$W$ Production Properties**

A charge asymmetry is expected in the $W \rightarrow e\nu$ decay because of the V-A interaction; the $W$ is produced polarized along the $\bar{p}$ direction, and, in the decay, the positrons follow the $\bar{p}$ direction, and electrons follow the proton direction. This effect is washed out at higher $\sqrt{s}$, since valence quarks become less important. Since UA1 measures the electron charge, and $\cos \theta^* = \pm[1 - 4(p^e_T)^2/m_W^2]^{1/2}$, they can find the distribution in center of mass scattering angle shown in Figure 44. In about 70% of the events the sign ambiguity in $\cos \theta^*$ can be resolved by requirement of a physical longitudinal momentum for the $W$ boson. Also, since $(u\bar{d}) \rightarrow W^+$, and $(\bar{u}d) \rightarrow W^-$; $x_W = x_p - x_\bar{p}$ and $x_p \cdot x_\bar{p} = m_W^2/s$ means that the $W$ sample can be split by charge to obtain the $u$ and $d$ structure functions separately. Figure 45 shows early UA1 results from such an analysis along with the QCD expectations. These figures taken together show that the $W$ production is well described in detail by the standard model expectations.

• **High $p_t$ Electrons from $Z^0$ Decay**

Electrons from the decay $Z^0 \rightarrow e^+e^-$ can be found using the same technique outlined above for the $W$ analysis. Since the background rejection is squared over that of the single electron case, the electron identification cuts may be loosened to obtain a high identification efficiency. Figure 46 shows the mass spectrum from electron pairs in the UA2 experiment. The electron identification criteria are less stringent than for the $W$ analysis—the hadron leakage requirement and the track-preshower match requirement are both relaxed. The curves are background estimates derived from the data.
Fig. 42. UA2 results for the transverse mass of the $W$, and the electron $p_T$ spectrum in the region dominated by $W$ decays.
Fig. 43. UA1 results for the transverse mass distribution from electron events in the $W$ region.
Fig. 44. UA1 distribution of center of mass scattering angle for electrons from \( W \) decay along with the expected curve.
Fig. 45. $u$ and $d$ quark structure functions measured by the UA1 experiment from $W$ decay events. The curves are the QCD expectation.
Fig. 46. (a) Di-electron mass distribution observed by the UA2 experiment with only calorimeter electron identification criteria used. (b) Same as (a) but with final selection criteria used. The curves are a background estimate derived from the data.
• Standard Model Electroweak Parameters and $Z^0$ Production

From the standard model for electroweak interactions (Equation 3)

$$m^2_W = \frac{A^2}{1 - \Delta r \sin^2 \theta_W} \frac{1}{\rho \sin^2 \theta_W \cos \theta_W}$$

$$m^2_Z = \frac{A^2}{1 - \Delta r} \frac{1}{\rho \sin^2 \theta_W \cos \theta_W}$$

where $\Delta r$ is the radiative correction. The radiative correction is calculated to be $\Delta r = 0.0711 \pm 0.0013$ assuming a top mass value of 35 GeV, Higgs mass of 100 GeV ($\Delta r \rightarrow 0$ at $m_{top} = 270$ GeV). Assuming the 'minimal' ($\rho = 1$) model,

$$\sin^2 \theta_W = 1 - \frac{m_W^2}{m_Z^2}. $$

Alternatively, using $A$ and $\Delta r$ from other experiments,

$$[\sin^2 \theta_W]_W = \frac{A^2}{1 - \Delta r} \frac{1}{m_W^2}$$

$$[\sin^2 \theta_W]_Z = \frac{1}{2} \left\{ 1 - \left[ 1 - \frac{4A^2}{(1 - \Delta r)m_Z^2} \right]^{1/2} \right\}. $$

Or, one can determine $\sin^2 \theta_W$ from the best fit to the above two reactions. Conversely, $\sin^2 \theta_W$ from the low energy neutrino data can be used, or one can invert the above to determine

$$\frac{A^2}{1 - \Delta r} = m_W^2(1 - \frac{m_W^2}{m_Z^2}). $$

Table III shows the results from UA1 and UA2 for these quantities using the $W$ and $Z$ mass measurements. From these cross section x branching ratio measurements, limits can be obtained on the number of neutrino types, etc.47

The angular distribution for the leptons in $Z^0$ decay is given by

$$\frac{d\sigma}{d\cos \theta^*} = (V_i^2 + A_i^2)(V_f^2 + A_f^2)(1 + \cos^2 \theta^*) + 8A_iV_iA_fV_f \cos \theta^*$$

with $A_f = \pm 1$, $V_f = \pm (1 - 4|Q_f| \sin^2 \theta_W)$ for $\pm$ charge fermions. The asymmetry in the $\cos \theta^*$ distribution for all lepton decay modes from the UA1 experiment shown in Figure 47 can be related, assuming standard model couplings for the quarks and leptons, to $\sin^2 \theta_W$ to provide another, independent measure of $\sin^2 \theta_W$. The UA1 finds the asymmetry is $0.30 \pm 0.15$, which yields $\sin^2 \theta_W = 0.18 \pm 0.04$, consistent with the previous results.
TABLE III

UA Electroweak Parameters*

<table>
<thead>
<tr>
<th></th>
<th>UA1</th>
<th>UA2</th>
</tr>
</thead>
<tbody>
<tr>
<td>$m_W$ (GeV)</td>
<td>83.5 ± 1.1 ± 2.7</td>
<td>80.2 ± 0.6 ± 0.5 ± 1.3</td>
</tr>
<tr>
<td>$m_Z$ (GeV)</td>
<td>93.0 ± 1.4 ± 3.0</td>
<td>91.5 ± 1.2 ± 1.7</td>
</tr>
<tr>
<td>$\sin^2 \theta_W$:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>UA alone</td>
<td>.194 ± .032</td>
<td>.232 ± .025 ± .01</td>
</tr>
<tr>
<td>Use $A^2/(1 - \Delta r)$</td>
<td>.214 ± .006 ± .015</td>
<td>.232 ± .003 ± .001</td>
</tr>
<tr>
<td>Low energy neutrinos</td>
<td>.232 ± .004 ± .003</td>
<td></td>
</tr>
<tr>
<td>$m_Z - m_W$</td>
<td>9.5 ± 1.8 ± .5</td>
<td>11.3 ± 1.3 ± .5 ± .8</td>
</tr>
<tr>
<td>$\Delta r$:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>UA alone</td>
<td>.068 ± .087 ± .030</td>
<td></td>
</tr>
<tr>
<td>Using low energy neutrino results</td>
<td>.068 ± .022 ± .032</td>
<td></td>
</tr>
<tr>
<td>$\rho$</td>
<td>1.026 ± .037 ± .019</td>
<td>1.001 ± .028 ± .006</td>
</tr>
<tr>
<td>$\Gamma_W$ (90% C.L.)</td>
<td>6.5 GeV</td>
<td>7.0 GeV</td>
</tr>
<tr>
<td>$\Gamma_Z$ (90% C.L.)</td>
<td>8.3 GeV</td>
<td>5.6 GeV</td>
</tr>
</tbody>
</table>

* First error quoted is purely statistical, followed by the systematic error estimates. In the case of the UA2, two systematic errors are reported for the mass fit and calorimeter calibration.
Fig. 47. Center of mass scattering angle distribution from the UA1 experiment for $Z^0$ decays detected into either electrons or muons. The curves are standard model expectations for various $\sin^2 \theta_W$ values.
The $k_t$ spectrum of the produced $W^\pm$ and $Z^0$ is dominated at low $k_t$ by recoil of the $W^\pm$ or $Z^0$ against the low momentum 'spectator' particles in the event, and dominated at high $k_t$ by recoil against jets. The full $k_t$ spectrum is calculable in QCD, even at low $k_t$. Furthermore, at very high $k_t$, recoil against more than one jet is expected. The $Z^0$ decays to leptons provide the most direct measurement of the $k_t$ spectrum, since the $k_t$ is determined from the two leptons ($e$ or $\mu$). In the $W^\pm$ decays, the $p_t$ of the missing neutrino is measured by measuring the missing $p_t$ in the rest of the event, as outlined above. In the case of the UA2 experiment, this measurement has uncertainties dominated by the lack of coverage of the detector for hadrons at small angles. In the UA1 case, since the recoil is measured from a large number of particles distributed over a large rapidity range, the $p_t$ uncertainty is dominated by the uncertainty in the calorimeter response. The $k_t$ spectrum measurement with the least uncertainty is provided by the $Z^0$ decays into leptons. As in the dijet case, the UA2 experiment has broken down the $k_t$ measurement from the two leptons into a component along the $p_t - p_t$ axis ($p_t$) and a component perpendicular to that axis ($p_n$), see Figure 15. The $p_t$ component shown in Figure 48 provides the best possible boson $k_t$ measurement, since it is dominated by the angular resolution of the apparatus, not the energy resolution. The curves in Figure 48 are standard model predictions for two different choices of structure function parameterization. The statistics are still low for $p_t > 10$ GeV, but future running will provide higher statistics.

XIII. MUON SIGNATURE

The electron signal is swamped by background in the present experiments at low $p_t$, but the muon signal, as will be shown below, is not. Standard model sources for both low and high $p_t$ muons are shown in Figure 49. As in the case for the electron analysis, clean muon identification requires that the muon be isolated from other energy in the event. Note that isolation criteria are sensitive to the production process and the mass of the decaying particle. Figure 50 shows schematically how the outgoing muon may have energy accompanying it in a cone about the muon direction. Standard model processes that tend to produce isolated muons (Figure 50a) include Drell-Yan and weak Drell-Yan processes (Figures 49a,b), and heavy quark decay for very heavy (top) quarks. Processes that produce non-isolated muons (Figure 50b) include $b$ and $c$ quark decays.

- UA1 Inclusive Muon Analysis

The UA1 muon detection system sits behind approximately nine interaction lengths of iron and covers about 70% of the solid angle in the pseudorapidity range $-2 < \eta < 2$ with a somewhat complicated geometry (Figure 8). The muon detector has two layers with four sets each of proportional tubes separated by 60
Fig. 48. $p_\eta$ component (see text) of the $k_t$ spectrum for $Z^0$ particles measured by the UA2 experiment. The curves are standard model predictions for two different choices of structure function parameterization.
Fig. 49. Standard model production process for low and high $p_T$ leptons. (a) Drell-Yan. (b) Weak-Drell-Yan. (c) Heavy quark production, 2-2 and 2-3, processes.
Fig. 50. Muon isolation. Some production processes (e.g., $Z^0 \rightarrow \mu^+ \mu^-$) make isolated muons (a), others (e.g., $e \rightarrow \mu \nu + x$) make non-isolated muons (b).
cm between the two layers. For muon candidate selection, the hardware trigger requires at least three of four possible hits in each projection and a pattern of hits such that the track points to the event vertex (±150 mr). The second level trigger (running on a 168E farm) requires a match between the muon stub and a central detector track with $p_t > 2$ GeV.

The 770 nb$^{-1}$ recorded by the UA1 experiment so far is recorded on about 10K tapes, of which about 40% are muon triggers. A filter is applied to remove cosmic rays, shower leakage through the calorimeter cracks, and central detector tracks with obvious kinks. After a cut requiring a single muon with $p_t > 6$ GeV and $|\eta| < 1.5$, about 10K events remain in the sample. A dimuon sample is made by requiring $p_t > 3$ GeV for each muon, $|\eta| < 2.0$ for each muon, with at least one muon satisfying $|\eta| < 1.3$, and mass of the muon pair $> 6$ GeV. With these cuts, about 1200 events remain in the dimuon sample.

The residual background in this sample is dominated by decays of pions and kaons into $\mu \nu$. In addition to backgrounds from misassociation of central detector and muon tracks ($\sim .07$/muon), other backgrounds include non-interacting punch-through hadrons, shower leakage, particles penetrating cracks, and residual cosmic rays (total $\sim .025$/muon without hand scanning events). The pion, kaon decay background is reliably estimated by folding the measured single hadron $p_t$ spectrum with the probability that a hadron of a given $p_t$ will decay to a muon with $p_t^\mu$. That is,

$$\frac{d\sigma^{\text{background}}}{dp_t^\mu} = \int \frac{d\sigma}{dp_t^{\text{hadrons}}} \, \text{Prob}(p_t^{\text{hadron}} \rightarrow p_t^\mu) \, dp_t^{\text{hadrons}}$$

where the probability $\text{Prob}(p_t^{\text{hadron}} \rightarrow p_t^\mu)$ is estimated using the Monte Carlo. Relative fractions of pions and kaons are taken from UA2 measurements. To obtain a sample of isolated dimuons, the UA1 calculates the summed transverse energy within cones of radius .7 in $\eta - \phi$ space (i.e. $R = [\Delta \phi^2 + \Delta \eta^2]^{1/2} \leq .7$) for each muon. Then the quantity

$$S = \left[ \left( \sum_{R \leq .7} E_t \right)^2_{\mu_1} + \left( \sum_{R < .7} E_t \right)^2_{\mu_2} \right]$$

is required to be $< 9$ GeV$^2$ for muon pairs defined to be isolated. Figure 51a shows the distribution of the summed transverse energy in a cone $R \leq .7$ for muons from randomly mixed $W$ decay events. The requirement $S < 9$ shown by the curve selects 82% of such events and gives an idea of the stringency of this cut. Figures 51b,c show the distributions of $S$ for the like sign and unlike sign (with $Z^0$ decay muons removed) dimuon samples. The muon pairs defined to be isolated are shown by the hatched area in the two histograms. Figure 52a shows the dimuon mass spectrum for the isolated dimuon sample, $S < 9$ GeV$^2$, along with events at lower masses from the $\psi$ region. There are 98 events with
Fig. 51. (a) Summed transverse energy within an $\eta - \phi$ cone of radius .7 about the muon direction for random pairs of $W$ events. (b) Distribution of $S$ (see text) for the unlike sign dimuon sample, with muons from $Z^0$ decay removed. (c) Distribution of $S$ (see text) for the like sign dimuon sample.
Fig. 52. (a) Dimuon mass distribution for isolated muon sample. (b) Dimuon mass distribution in the mass region 6–50 GeV with standard model predictions.
$m_{\mu\mu} > 6$ GeV with an estimated background of 7 events. Figure 52b shows the individual standard model contributions to the region $m > 6$ along with the background estimate. The cross section $\times$ branching ratio for the $T$ into muon pairs is measured to be $0.98 \pm 0.21 \pm 0.19$ nb, and the (Drell-Yan) cross section for muon pairs satisfying $m_{\mu\mu} > 11$ GeV is $0.25 \pm 0.08 \pm 0.05$ nb. Both these results are consistent with the standard model production.

In order to convert the background-subtracted measured single and dimuon $p_t$ spectra to inclusive cross sections, Monte Carlo simulation of the standard model production processes and the detector response is needed. Simulated events are generated, then passed through the UA1 detector simulation and the full reconstruction and analysis as was used for the real events. The heavy quark fragmentation and decay are adjusted to agree with $e^+e^-$ measurements. Figure 53 shows the muon $p_t$ spectra and model predictions for (53a) 2-2 and 2-3 processes, and (53b) for various top quark mass hypotheses. Top quark existence cannot be excluded by the inclusive distributions alone, because of the normalization uncertainty inherent in the QCD calculations.

However, Figure 54 shows a few example distributions that illustrate the detail of agreement obtained between the model and the data. Such distributions and such detailed understanding can be used as an effective tool to set limits with good sensitivity on production of new heavy quarks by investigating regions of the phase space not expected to be heavily populated by the known standard model processes. The sort of detailed understanding of the inclusive muon spectra in the UA1 muon analysis illustrates the type of groundwork that is necessarily laid in the search for new phenomenon—before an effect can be identified as being beyond the standard model, care must be taken to be sure that all standard model sources of the effect are taken into account.

- Summary, Electron and Muon Analyses at CERN

For electrons, the background, relative to the jet cross section, is about $2 \times 10^{-5}$ of jets, for an electron detection efficiency around 75%. The background is well measured in the $p_t$ range 10–20 GeV, but not yet simulated in detail by the Monte Carlo. The extrapolation of this background to detectors other than the UA and to other $\sqrt{s}$ is not completely clear, but it may be expected to remain of this order. The upgrade of the UA experiments at CERN and the CDF and DØ experiments at FNAL will gather large numbers of events from $W^\pm, Z^0$ production and subsequent decay including electrons, and the sample of large $p_t W, Z$ events will grow from 10s of events to 100s of events in the next few years.

For muons, the background is very detector-dependent, with the main component in the UA1 coming from pion and kaon decays within the track detector volume. The background and the standard model production processes are reasonably well simulated by the event generators and the detector simulation. Since the subprocesses contributing to the background are known and have been
Fig. 53. Corrected muon $p_t$ spectra for single (open circles) and dimuon (closed circles) event samples: (a) Standard model predictions for 2-2 process and 2-2 + 2-3 processes. (b) Predictions for various top quark mass hypotheses.
Fig. 54. (a),(b) Distribution of $p_t$ of the muon relative to the jet axis in unlike sign (a) and like sign (b) dimuon events. (c) Distribution of the dimuon azimuthal opening angle in non-isolated muon pair events along with ISAJET model predictions.
checked, reliable extrapolation to other $\sqrt{s}$ and other, similar, detectors should be possible.

Note also that the discussion in the introductory sections on quantities on which to filter the data glossed over an important detail: lepton identification efficiency depends upon the desired background rejection. The example provided by the electron analyses is particularly clear: many events must be examined, and the full information from the detector retained along candidate electron tracks. In general, for high rate signals, prescaled event samples can be used, and, for low rate signals, topological cuts (e.g. missing $p_t$, dileptons, etc.) can be used to reduce the data sample to a manageable size. In any case, almost all the analyses pass through a stage with a large data sample with large information to select the desired small data sample of rare process events. Computer resources (both cpu time and disk and tape space) should be consumed in the most economical way possible in this process. The capabilities of the experiment system are enhanced by pushing filtering decisions from the offline analysis into the online/hardware environment so that the volume of data that is necessary to handle at the later stages of the analysis is smaller. This overall problem requires a design of proper data structures, 'regional' track finding, etc., etc. Future work on solutions to these data handling problems may help convert the present experimental art to science, and extend the capabilities of the detector system.

XIV. NEUTRINOS AND LARGE MISSING $E_t$

- UA1 Missing $p_t$ Analysis

As in the $W$ analysis, the component of the missing energy vector transverse to the beams can be measured for each event. Note that since a large and variable amount of energy is lost along the beam direction, only the missing transverse energy can be measured in the experiment. This missing transverse energy will arise from standard model neutrino production (processes such as $p\bar{p} \rightarrow W \rightarrow ev$ or $Z+\text{jet with } Z \rightarrow \nu\nu$), from detector mismeasurements, or from non-$pp$ sources (cosmic rays, beam halo, etc.).

The hardware triggers used to define the input data sample for the UA1 missing $p_t$ analysis require either electromagnetic transverse energy $>10\text{ GeV}$, or hadronic transverse energy $>25\text{ GeV}$, within $|\eta| < 2.5$, or missing transverse energy $>17\text{ GeV}$, with at least one jet cluster, transverse energy $>15\text{ GeV}$. Many of the low missing transverse energy events in the resulting data sample come from dijets mismeasured due to shower fluctuations in the calorimeter. To obtain a measure of significance of the observed missing $E_t$, the quantity $N_{\sigma} = \frac{E_t^{\text{missing}}}{\sqrt{\Sigma E_t}}$ is calculated for each event. Figure 55 shows the distribution in $N_{\sigma}^2$, along with the expectation from a simple model based on the real data that fluctuates energies of jets in real events according to the expected resolution. This simple model describes the low $N_{\sigma}^2$ region well, and,
Fig. 55. Distribution in $N_2^2$ (see text) along with a jet fluctuation model prediction from the UA1 experiment.
after removal of the junk events, shows that the low missing \( E_t \) rate is dominated by the calorimeter measurement error.

To define a high missing \( E_t \) sample, the following selections are made: \( E_t^{\text{missing}} > 15 \text{ GeV}; N_\sigma > 4 \); one or more jets with \( E_t > 12 \text{ GeV}, |\eta| < 2.5 \); one or more tracks, \( p_t > 1 \text{ GeV}, \) pointing to the calorimeter cluster within \( \Delta R = .4 \); the missing \( E_t \) direction is isolated (no calorimeter cluster within \( \pm 30^\circ \) in \( \phi \) of missing \( E_t \) direction); events with jets coplanar to the missing \( E_t \) direction are removed (\( 150^\circ - 210^\circ \) opposite in \( \phi \)); and all events with \( e \) or \( \mu \) candidates are removed from the sample. The distribution in \( N_\sigma \) of the surviving event sample is shown in Figure 56. The hatched area shows the contribution expected from the jet fluctuation model. The curve is the sum of the jet fluctuation model and the expected standard model contributions. The main surviving contribution for large \( N_\sigma \) comes from \( W \rightarrow \tau \nu \), but other contributions come from \( W \rightarrow c\bar{s}; Z^0 \rightarrow \tau \tau; Z^0 \rightarrow \nu \nu; Z^0 \rightarrow c\bar{c}, b\bar{b}; \bar{p}p \rightarrow c\bar{c}, b\bar{b}; W \rightarrow l\nu \) with the lepton misidentified; and jet fluctuations.

To obtain greater sensitivity to possible new physics processes, the \( W \rightarrow \tau \nu \) signal must be isolated and removed from the sample. To separate the \( W \rightarrow \tau \nu \) signal, use is made of the fact that \( \tau \) decay products appear as tightly collimated low multiplicity jets in the detector. A \( \tau \) likelihood is formed from the fraction of the jet energy within a cone of radius \( \Delta R = .4 \), the angular separation of the leading tracks and the cluster axis, and the mean charged multiplicity of tracks with \( p_t > 1 \text{ GeV} \) within \( \Delta R = .4 \). With a cut requiring the resulting likelihood \( L_\tau > 0 \), 78% of \( \tau \) decays are retained, while 11% of jet events are accepted. Figure 57 shows the missing \( E_t \) distribution and the transverse mass distribution for the \( L_\tau > 0 \) (\( \tau \) enriched) sample, along with the \( W \rightarrow \tau \nu \) expectations. The data are well described by the standard model. Figure 58 shows for the \( L_\tau < 0 \) sample the jet \( E_t \) and event missing \( E_t \) distributions along with the surviving standard model contribution. The predicted contributions include \( W \rightarrow \mu \nu \) (2. events), \( W \rightarrow \tau \nu \) (8. events), \( Z^0 \rightarrow \nu \nu \) (7.1 events), and jet fluctuations (3.4 events) for a total of \( 20.8 \pm 5.1 \pm 1.0 \) events to compared with 24 events observed. Again, the standard model explains the observed rate in terms of the known processes.

These distributions can be used to set limits on possible new phenomena such as production of new heavy leptons (via \( W \rightarrow L\nu \)); UA1 obtains \( M_L > 41 \text{ GeV} \) at 90% C.L. Also, limits on number of neutrinos, supersymmetry, etc., etc. follow.

XV. SUMMARY AND CONCLUSIONS

The CERN UA experiments have conclusively shown that ‘new’ particles and the detailed nature of their interactions can be studied at hadron colliders. The ‘discovery reach’ of present and future collider experiments depends for many reactions on the further understanding of multijet final states. The calculation of the multijet QCD background, the reconstruction resolution and
Fig. 56. $N_\sigma$ distribution for the UA1 large missing $E_t$ sample, with expected contributions from the jet fluctuation model (hatched area) and standard model processes shown.
Fig. 57. (a) Missing $E_t$ and (b) transverse mass distribution for the $\tau$ enriched missing $E_t$ sample from UA1 (see text).
Fig. 58. (a) Jet $E_t$ and (b) missing $E_t$ for the non-$\tau$ high missing $E_t$ events from UA1 (see text).
efficiency in multijet final states, and how tagging and topology cuts can be used to reduce standard model background all require further study in the upgraded UA and FNAL experiments. The state of the art with regard to detector description and physics processes is generally rather primitive in $\bar{p}p$, as compared to low $Q^2$ (e.g. $e^+e^-$) experiments. Generally, the capabilities and limitations of detector systems for the general purpose experiments can be understood in terms of how well the jets, leptons, and their combinations can be measured when produced by 'known' standard model processes. The ability of the detector system to measure 'known' processes determines how reliably they can be removed in the search for new phenomena. Clearly, physics processes are well enough understood to predict reliably many results—the question remains how far the detector system performance can be pushed, and how to obtain better performance with less effort.
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