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Monte Carlo Study of Inclusive W^+ Production at CBA

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Introduction

The UA1 and UA2 experiments¹ at the CERN SPS $\bar{p}p$ collider observed several events which they have interpreted to be the leptonic decay of the charged intermediate vector boson, $W^+ \rightarrow e^+ \nu$. All of these events have an electron with large transverse momentum and large missing transverse energy. The experiments had remarkably little background in the region of large transverse momentum of the electron (P_{Te}). In this report we examine the possibility of doing a high statistics experiment producing several million W 's per year. Large statistics are necessary to obtain a precise measurement of the W^+ mass and of the Z^0 - W mass difference. We use the Jacobian peak in the electron P_T distribution to obtain the W^+ mass. This mass determination is discussed fully in a later section. Large statistics are also essential for the study of $W^+ \gamma$ production because of its small cross section. This reaction which tests the non-Abelian character of the weak-electromagnetic gauge theory is discussed in a separate report.² We examine in detail the P_T distribution of the electron produced by the leptonic decay of the $W^+ \rightarrow e^+ \nu$. We investigate backgrounds to this reaction from the pileup of minimum bias events, from leading π^+ 's in light quark jets simulating electrons and from the decay of heavy quark jets producing electrons.

The BNL Colliding Beam Accelerator (CBA) will have a center of mass energy of 800 GeV and a luminosity of $10^{33} \text{ cm}^{-2} \text{ sec}^{-1}$. In one year of operation (10^7 sec) the integrated luminosity will be $10^{40} / \text{cm}^2$ and one

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production of 5×10^6 W^+ events which subsequently decay to $e^+\nu$. In this report we simulate this reaction and the appropriate backgrounds using the ISAJET³ Monte Carlo program. This program generates W^+ 's by the Dreil-Yan mechanism. The ISAJET program includes the intrinsic transverse momentum of the quarks inside the hadron in the p_T of the W . However, various models predict different sizes for the intrinsic transverse momentum. If it is much broader than expected it will smear the Jacobian peak of the W^+ and affect the mass measurement discussed below.

The Detector

For these studies, we have chosen as a detector a calorimeter segmented into towers with azimuthal and polar widths of 5° . The calorimeter has an electromagnetic and a hadronic part in each tower so that one can read out both the electromagnetic energy and the total energy. The resolution for the electromagnetic (hadronic) energy is $0.15(0.40)/\sqrt{E}$. These resolutions are representative of the Axial Field Spectrometer at the CERN ISR. The detector has a magnetic field which is used to check the consistency of the momentum of a single track (presumably an electron) with the electromagnetic energy in the calorimeter cell. Charged particles with momentum less than 300 MeV/c are presumed trapped by the field and not used in the calculation of deposited energy. In the present analysis the propagation of tracks through a magnetic field is ignored. The detector is equipped with a transition radiation system which can provide 100 to one rejection of charged hadrons.

The calorimeter covers the entire 4π solid angle with the exception of a 5° cone⁴ in the forward and backward hemisphere to allow for the beam pipes. The primary trigger in this experiment is an energetic electromagnetic shower. All calorimeter cells with polar angle between 15° and 165° are scanned for a deposit of greater than 20 GeV of electromagnetic energy where the electromagnetic component is greater than 80% of the total deposited energy. This trigger accepts particles in the rapidity range $-2 < y < 2$. Figure 1 shows the cell trigger rate as a function of p_T . It arises primarily from π^0 's in light quark jets. Superimposed on the plot is experimental π^0 data from CCOR⁵ and Owens, Raya and Gluck.⁶ The trigger rate for a particular p_T is the luminosity times the integral from p_T to infinity of da/dp_T (Figure 1). The trigger rate as a function of p_T is given in Figure 2. With a trigger at 20 GeV one could expect a rate of ~ 100 events per second. The low primary trigger rate allows more complicated secondary triggers to be used. These could employ the transition radiation system and could require a consistency of the entry point of a charged track in the calorimeter and an electromagnetic shower vertex. A particularly useful secondary trigger for $W^+ \rightarrow e^+\nu$ is to require large unbalanced transverse momentum corresponding to the missing neutrino.

The luminosity of $10^{33} \text{ cm}^{-2} \text{ sec}^{-1}$ expected at CBA yields an event every ~ 20 nanoseconds. It is likely that a fast calorimeter could be designed to use this high rate effectively by the time the machine is turned on. However in this analysis we choose a conservative time resolution of 150 nanoseconds which is representative of many existing

calorimeters. In this time period one would expect ~ 7.5 minimum-bias events to overlap an event of interest. The effect of this "pile-up" background is analyzed in the next section.

Backgrounds and Losses

The principal backgrounds for high P_T electrons from W decays are light quarks fragmenting into π^0 , heavy quarks decaying semileptonically, and Z^0 decays. Some secondary triggers or cuts that can be applied to reduce these backgrounds are the following: a transition radiation system which can distinguish electrons from hadrons with 1% inefficiency; a cut or trigger requiring a transverse momentum imbalance of greater than 15 GeV/c; a requirement that the total shower energy in the calorimeter cell is consistent with the momentum of a single particle tracked through the magnetic field.

The dominant background is from light quarks fragmenting to large P_T π^0 's. The π^0 can decay either into two photons (accompanied by some charged hadron from the jet) or by the Dalitz mode producing a real electron. Both modes may produce a signature of a charged track and a large fraction of electromagnetic energy. Transition radiation identifying an electron would reduce the $\pi^0 \rightarrow \gamma\gamma$ background by a factor of 100. Dalitz decays and early conversions, which can represent $\sim 4\%$ of the π^0 decays,⁷ produce real electron triggers that are not affected by transition radiation. A shower from a jet generally has a wider angular spread than a single electron. Energy from a jet should be distributed over a number of adjacent cells. To reduce light quark jet background we require that the sum of transverse energy in the two adjacent rings

around a triggered cell be less than 1.5 GeV. This reduces the raw π^0 signal by a factor of 0.25. The requirement that the momentum (from tracking in a magnetic field) of a single track carries 75% of the electromagnetic energy in a tower gives a factor of 0.3%. (This cut also affects the 2γ channels much more than the Dalitz channels.) The missing transverse momentum cut gives an additional factor of 0.3%. The effects of these cuts are illustrated in Figure 3. The signal for $W^+ \rightarrow e^+ \nu$ is included for comparison. The effect of the light quark's background is small above $P_T > 20$ GeV.

Heavy quark decays also produce e^+ 's. Since the energy of the heavy quark is shared by several particles, the average transverse momentum of the electron is less than for W^+ decays. The same techniques used on light quark jets are applied to the heavy quarks. Transition radiation does not help since real electrons are produced. Figure 4 illustrates how the cuts reduce the heavy quark background.

Large transverse momentum positrons can come from Z^0 decays. The electrons come in pairs; however, if the negative electron is not detected, this would be a source for W^+ background. In Figure 4 the P_T of the e^+ from those Z^0 decays where the e^- is at an angle of less than 5° with respect to the beam (where there is no calorimeter and is not detected) is shown. This background is not large.

To simulate the use of a calorimeter with time resolution of ~ 150 ns a number of minimum bias events (the number is determined from a Poisson distribution with $\langle n \rangle = 7.5$) are superimposed on each W^+ event. These pile-up events will spray hadronic energy into cells adjacent to a cell

containing the positron. Fig. 5 gives the sum of the transverse energy found in the two adjacent rings of cells around the trigger cell for the cases when the minimum bias events are included and when they are not. It is found that about 15% of the good events are lost due to pile-up because of the cuts that are used to separate electrons from jets. In Figure 6 the P_T distribution of the e^+ from W^+ is shown with and without the pile-up events included. There is a loss of approximately the same magnitude throughout the P_T distribution.

The total background to the $W^+ + e^+ \nu$ channel for the CBA collider is plotted on a linear scale in Figure 7. Above 20 GeV in transverse momentum, the backgrounds are very small. The effect of event pile-up is to cause a loss of events of the order of 15% but not to alter the shape of the distribution.

Measuring the $M_Z - M_W$ Mass Difference

We will have the ability at CBA to determine the mass difference $\Delta M \equiv M_Z - M_W$ reasonably well. The method used here is similar to that outlined in Bunce et al.⁷ which uses the Jacobian peak in the P_T distribution of the decay lepton. Other methods using transverse mass⁸ are being investigated and will be the subject of a later report. The method used here compares the P_T -distribution of single leptons from $W^\pm$ and Z^0 production in the neighborhood of the Jacobian peak. This distribution is controlled mainly by the parent boson mass - at least at the peak and beyond. Smearing effects that are present due to the P_T distribution of the parent bosons are expected to be similar for $W^\pm$ and Z^0 .

In this calculation we have investigated some of the systematic effects believed to contribute to errors on ΔM - in particular the small differences in the $W^\pm$ and the Z^0 P_T distributions and the sensitivity to the P_T cutoff chosen for the leptons. The analysis is restricted to leptons observed at large angles ($90^\circ \pm 50^\circ$ corresponding to rapidity $-1 < y < 1$) in order to minimize the effects of the different x -distributions in producing W and Z :

$$\begin{aligned} \bar{u}d &\rightarrow W^- \\ \bar{u}d &\rightarrow W^+ \\ \bar{u}u, \bar{d}d &\rightarrow Z^0 \end{aligned}$$

At small x , one expects the effects due to differences in $f(x)$ for u and d to be small.

We have generated 1.2×10^6 $W^\pm$ and 10^5 Z^0 according to the following prescription:

- a) $dN/dP_T (W^\pm)$ was taken from the distribution of ISAJET

$$\langle P_T^2 \rangle = 70 \text{ GeV}^2$$

$$dN/dP_T (W^\pm) \equiv f_W(P_T)$$

- b) $dN/dP_T (Z^0)$ was taken to be a similar function as used for $W^\pm$ with one additional parameter -

$$dN/dP_T (Z^0) = f_W(\lambda P_T)$$

with λ expected to be of the order $\lambda = (M_W/M_Z)^{1/2} = 0.95$ from QCD estimates. Thus the Z^0 has a slightly larger $\langle P_T^2 \rangle$ than the $W^\pm$.

Three cases of Z^0 were generated with $\lambda = 0.90$, $\lambda = 0.95$ and $\lambda = 1.0$.

- c) The x (or y) distributions were taken to be the same for Z^0 and $W^\pm$. The y distribution is generated in accordance with the ISAJET distributions - essentially flat in y for $|y| \leq 1$.
- d) Electrons were selected in the range $|y_e| \leq 1$. In the case of the Z^0 the other lepton was required to lie in the range $|y_{e'}| < 2.5$ in order to insure the Z^0 's identification.

The analysis of the resulting $W^\pm$ and Z^0 samples was performed as follows: The experimental lepton P_{Te} distribution of the Z^0 was scaled down in P_{Te} by a factor β . The χ^2 was computed as a function of β .

$$\chi^2 = \int_{P_{Tmin}}^{P_{Tmax}} \frac{(N^W(P_{Te}) - \alpha N^Z(\beta P_{Te}))^2}{\sigma^2} dP_{Te}$$

$$\sigma^2 = N^W(P_{Te}) + \alpha^2 N^Z(\beta P_{Te})$$

where $\alpha \equiv N_{TOT}(W^\pm)/N_{TOT}(Z^0)$ to normalize the two samples in the interval (P_{Tmin}, P_{Tmax}) . The χ^2 is found to have a minimum near $\beta = (M_W/M_Z)^2$. (In this study $M_W = 80$ GeV and $M_Z = 90$ GeV.)

Figure 7 shows the χ^2 distributions for the Z^0 samples with different λ scaling factors. The minima for the three cases are all at ~ 0.89 . The error in β is attained by finding the $\Delta\beta$ required to increase χ^2/χ_{min}^2 by 1. For the worse case ($\lambda = 1$) we find that $\beta = 0.8914 \pm 0.0063$. The error in β gives an error in mass difference of 570 MeV. If we restricted our analysis to the region of lepton P_T from 35 to 43 GeV/c, the corresponding uncertainty in ΔM is 260 MeV.

The mass difference can give a valuable measurement of $\sin^2\theta_W$ independent of those found in lepton scattering. Since $\sin^2\theta_W = 1 - M_W^2/M_Z^2$ we would expect that $\delta(\sin^2\theta_W) = \pm 0.011 (\pm 0.005)$ for the full (restricted) range⁹ in lepton P_T .

This analysis could be refined by fitting or correcting for the λ parameter at the same time as β . This could further reduce the error on ΔM .

Conclusion

From the results of the UA1 and UA2 experiments at CERN and the analysis made here we would expect the $W^\pm \rightarrow e^\pm \nu$ channel to be very clean, permitting detailed analysis. The so-called pile-up problem coming from poor calorimeter time resolution (at least in existing calorimeters) should not greatly compromise the analysis. It will cause a loss of only 15% of the events. We expect to be able to calculate the mass difference between the Z^0 and $W^\pm$ to a precision of $\sim 1/4$ GeV.

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