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FERMILAB-Conf-99/365-E
CDF

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January 2000

Published Proceedings of the *UK Phenomenology Workshop on Collider Physics*,
Durham, England, September 19-24, 1999

Operated by Universities Research Association Inc. under Contract No. DE-AC02-76CH03000 with the United States Department of Energy

CDF/ANAL/ELECTROWEAK/CDFR/5190
12^{th} Dec 1999

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Abstract. The current experimental status of vector boson p_T measurements is reviewed. The recent Monte-Carlo implementations of vector boson p_T distributions are compared to the data and the issues involved in making a meaningful comparison are outlined. The method used by CDF to obtain a W p_T distribution from the measured Z p_T distribution is also described.

1. Introduction

The study of quark anti-quark annihilation producing high mass γ^*, Z and W bosons is a rich area for QCD studies. QCD radiation from the initial state quarks means that the final state has a finite p_T. Measurements of the final state p_T distribution can thus be compared to QCD predictions. These predictions contain fixed order perturbation theory at high p_T and gluon resummation formalisms, which sum perturbative contributions from multiple soft and collinear gluon emissions, at low p_T. High p_T calculations are available to $\mathcal{O}(\alpha_s^2)$ [1]. The low p_T calculations have recently been improved to include sub-leading logarithms [2] whilst both the HERWIG [3] and PYTHIA [4] Monte-Carlos have recently been improved at high p_T by augmenting the parton shower prediction with an explicit matrix element calculation.

A detailed knowledge of the p_T distribution of W bosons is a vital ingredient in the W mass measurements performed at hadron colliders. Indeed for Run II at the Tevatron, where the statistical contribution to the W mass error will be $\sim$ 10 MeV, the uncertainties in the W p_T distribution could become one of the limiting W mass error sources. A precise description of W and Z production is also important in understanding the backgrounds to processes beyond the Standard Model.

2. Available Data

Low energy data from Drell-Yan events in the $\sqrt{\mathrm{s}}$ range, $20 < \sqrt{\mathrm{s}} < 63$ Gev from the E288, E605 and R209 [5] experiments provide much information about the behaviour of vector bosons at low p_T ($p_T < 5$ GeV). Collider data from both CDF and DØ at $\sqrt{s}$ = 1.8 TeV allow comparisons to be made with QCD predictions up to p_T values of $\sim$ 200 GeV. The low energy data is fully corrected for all experimental effects and can be compared directly to theoretical predictions. The Tevatron data has been published in three ways, not all of which are immediately amenable to comparsion with QCD predictions. Firstly, CDF has published [6] a corrected W p_T distribution, based on 4 pb^{-1} of integrated luminosity from the 1988/89 run. Secondly, DØ has published a comparison of their uncorrected W p_T distribution [7] with a theoretical prediction which has then been passed through a complete detector simulation. Finally, both CDF and DØ have recently published [8] high statistics measurements of the Z p_T distribution which have been fully corrected for all experimental effects. These measurements based on 110 pb^{-1} of integrated luminosity supercede the CDF 1988/89 measurement [9] which has previously been used in comparisons with QCD.

3. Correcting for Experimental Effects

At the Tevatron, the p_T distribution of Z bosons is determined by measuring the two final state decay leptons. The p_T of the Z can be determined with a resolution of 1–2 GeV, because at these energies the energy and momentum resolution of the calorimeter and tracking chambers, $\frac{\Delta E}{E}$, $\frac{\Delta p_T}{p_T}$, are typically $< 5\%$. In figure 1, the p_T of the two final state leptons is compared to the true Z p_T. This small amount of smearing can be reliably simulated with little or no bias such that one can obtain a robust measurement of the true Z p_T distribution.

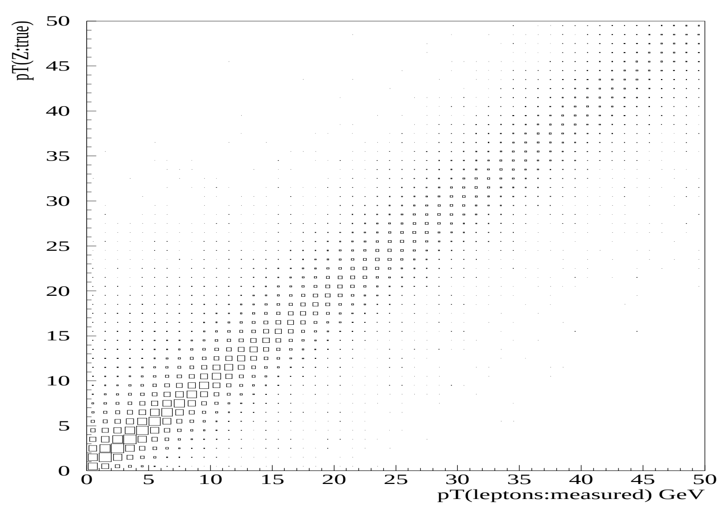

Figure 1. A comparison of the Z p_T measured from the final state leptons with the true (unsmeared) Z p_T.

This however is not the case for W events where the p_T of the final state neutrino has to be inferred by imposing the condition of transverse momentum balance. In effect this means that the W p_T is inferred from a measurement of the non-leptonic p_T in the event, i.e. one actually measures the fragmentation products of the initial state QCD radiation to determine the W p_T. This has three associated problems. Firstly, because the products of the initial state QCD radiation are typically at low momentum and the Tevatron detectors are not 100% hermetic, only ~ 50 % of the original W p_T is actually detected. Furthermore, the measurement has a poor resolution because it is based on a low energy hadronic calorimetry measurement. Secondly, the initial state QCD radiation contribution to the non-leptonic p_T of the event cannot be separated (on an event-by-event basis) from the underlying event energy, the energy from final-state photons and the contribution from additional minimum bias events, whose contribution varies with the instantaneous luminosity. One thus has to make corrections to the data to account for the acceptance loss, the smearing due to resolution effects and the additional contributions to the non-leptonic p_T in the event. These large corrections must be unfolded by deriving corrections from Monte-Carlo event samples. However, it is found that these corrections depend quite strongly on the assumed form of the W p_T, i.e. precisely the quantity we are trying to extract. Recent attempts by both DØ and CDF to circumvent this unfolding problem have not been very successful. This has become more apparent as the Tevatron experiments have accumulated more data. The first Tevatron measurements had large statistical uncertainties and so the large systematic uncertainty arising from this unfolding correction was less apparent. Subsequent Tevatron measurements of the W p_T have thus been "uncorrected", i.e. what is plotted is just the non-leptonic p_T of the event. Such "W p_T" distributions can only be compared to QCD predictions if these predictions are passed through a complete detector and event simulation. This detector and event simulation includes the effects of detector acceptance and resolution, QED final state photons and the contribution of underlying and minimum bias event energy. Comparing "W p_T" distributions that have not been through a detector simulation with the raw "uncorrected" data distributions can lead to erroneous conclusions being drawn. For example in the paper of [4], such a comparison was made and it was concluded that a large instrinsic k_T was needed to achieve a reasonable description of the data. However this large intrinsic k_T was compensating for the acceptance and resolution effects which had not been simulated. This is illustrated in figure 2 where, for Monte Carlo events, the true p_T of the W is compared with the non-leptonic p_T (the so-called "uncorrected" W p_T).

The best measurements for comparing with QCD predictions are the corrected Z p_T measurements. They do not require a detector simulation and the corrections applied to the data are small, such that the systematic errors of the measurement remain small.

4. Fits to Data

The Z data measurements are used to compare with QCD predictions and to generate W p_T distributions for use in the W mass analysis. The most recent quantitative analysis of Z p_T distributions was done by Ladinsky and Yuan [10] following on from work done by Davies, Webber and Stirling [11]. Much of this work has centred on the form of the non-perturbative function used in the resummed part of the p_T calculation. This is

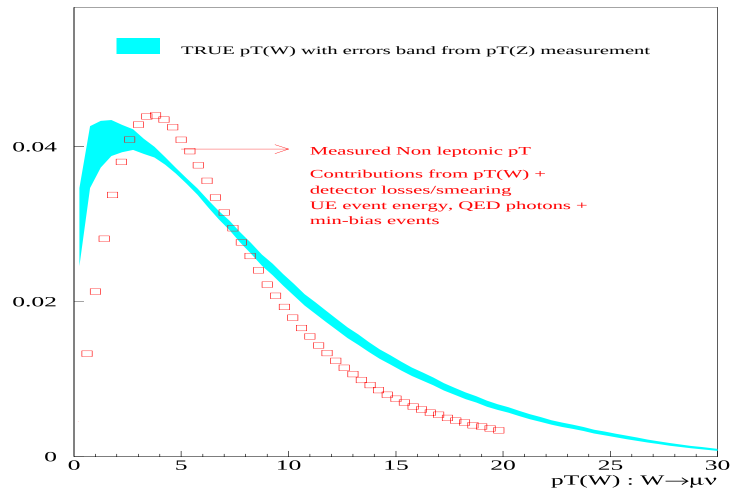

Figure 2. A comparison of the measured non leptonic p_T with the true W p_T. The shaded region of the true W p_T shows how well the W p_T can be determined from a fit to Z data (see section 4).

particular important because, owing to the superior resolution and reduced backgrounds, the W mass measurement is made in the region of W p_T< 30 GeV where the resummed part of the cross section dominates. Ladinsky and Yuan found that to accomodate a satisfactory description of both the low energy Drell-Yan and Tevatron data they needed to introduce an x dependence into the form of the non-perturbative function i.e.

$$F^{\rm N\it P} = exp\left[-g_2 b^2 ln\left[\frac{Q}{2Q_0}\right] - g_1 b\left(b + g_3 ln\left[\frac{x_a x_b}{x_o^2}\right]\right)\right]$$

where x_a and x_b are the Bjorken-x values of the quark and anti-quark and b is the impact parameter i.e. Fourier conjugate of p_T.

The form of the x dependence : $ln\left[\frac{x_a x_b}{x_o^2}\right]$ was arbitrary. This parametric form had two of the parameters fixed : $x_0 = 0.1$ and $Q_0 = 1.6$ GeV and fits to the Tevatron and low energy DY data were made to determine g_1, g_3 and g_2. Correlations between g_2 and g_1, g_3 were neglected and two separate fits were performed to determine g_2 and then g_1, g_3.

Recently a NLO calculation [12] has become available where both the resummed calculation and the perturbative calculation are performed in p_T-space. Previously the resummed calculation was performed in b-space and the perturbative in p_T-space. This made matching the two calculations troublesome and moreover even at high p_T, where the resummed calculation should be of no importance, the resummed calculation retains an influence since the b-space calculation in effect involves an integration over all p_T-space. The latest p_T-space calculation has a much simpler and more intuitive non perturbative parameterisation using only 2 parameters. However, it was found that this simple 2 parameter form did not have sufficient flexibility to describe the Tevatron Z p_T data at the level of accuracy required for the W mass analysis.

Furthermore, both the b-space and p_T space calculations are quite time consuming which makes the logistics of doing a multi-parameter fit somewhat difficult. For each choice of parameter (and this could run to thousands in a typical minimisation) a new prediction has to be generated. Consequently in the CDF W mass analysis, the Z p_T distribution was fitted using the following ad-hoc four parameter function :

$$\frac{X^{P_4}}{\Gamma(P_4+1)}\left[(1-P_1)P_2^{P_4+1}e^{-P_2X}+P_1P_3^{P_4+1}e^{-P_3X}\right]; \quad X=p_T/50.0$$

This function could be generated quickly for each choice of parameter set. The best fit compared to the data is shown in figure 3. The figure also shows the Z p_T measured from the decay leptons compared to the true Z p_T; this again illustrates that the measurement receives only a moderate smearing correction, which is trivial to correct for.

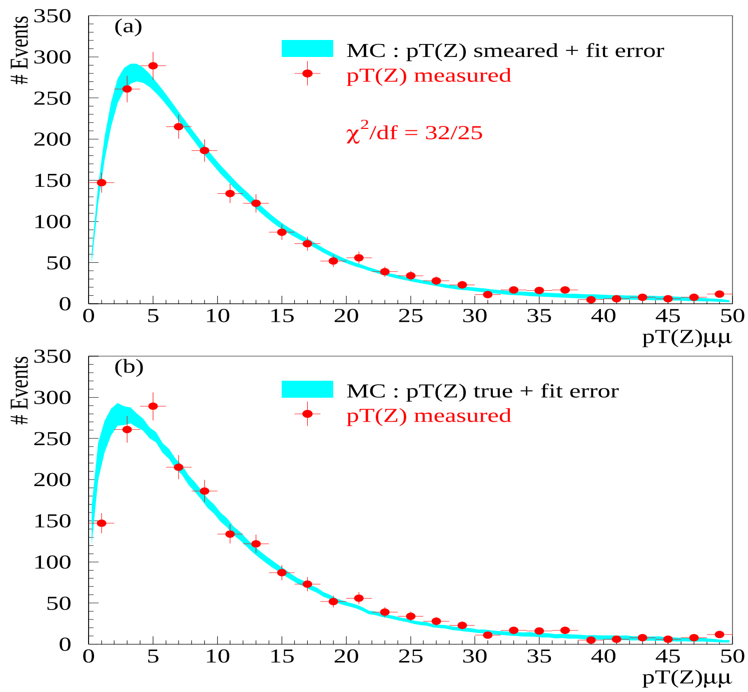

Figure 3. (a) A comparison of the Z p_T measured from the decay leptons with the best fit. (b) A comparison of the Z p_T measured from the decay leptons with the true Z p_T derived from the fit in (a). Note that the distributions in (b) are different at low p_T due to the smearing.

Figure 3 shows that one can obtain a very good description of the Z data with a very simple parameterisation. One can then use the QCD calculations to turn this Z p_T distribution into a W p_T distribution for use in the W mass analysis. This is done in two steps. Firstly, the above Z p_T distribution is weighted to allow for the fact that the fit is performed to data averaged over all rapidity (mean $|Y|=0.3$) but events need to be generated differential in both p_T and rapidity. This weighting function is taken from a theoretical calculation of $\frac{d\sigma}{dY\,dp_T}/\frac{d^2\sigma}{dY\,dp_T}|_{Y=0.3}$. Secondly, the Z p_T distribution differential in p_T and rapidity is re-weighted to a W p_T distribution differential in p_T and rapidity using a theoretical calculation of $\frac{d^2\sigma}{dY\,dp_T}|_{\mathrm{W}}/\frac{d^2\sigma}{dY\,dp_T}|_{\mathrm{Z}}$.

Since both of these functions are ratios one expects the uncertainty to be small. Indeed, by varying PDFs, α_s or the type of calculation (resummation done in b-

space or p_T space), the resulting uncertainty in W p_T is small in comparison to the uncertainty arising from the statistics of the Z sample which is used to orginally define the distribution.

5. Model Comparisons with data

Figure 4(a) shows that an acceptable description of the Z data can be obtained from the standard resummed calculations (e.g. RESBOS [13] which uses the Ladinsky-Yuan non-perturbative function) but not with the parton shower Monte Carlos. The parton shower Monte-Carlos generally fall below the data in the $p_T > 10$ GeV region unless they have been augmented with a matrix element calculation. The low p_T region ($p_T < 3$ GeV) can only be described with a relatively large intrinsic k_T of 2.0 GeV. However this intrinsic k_T then fails to describe the $3 < p_T < 10$ GeV region, which can then only be described with a very low intrinsic k_T (0.44 GeV), which in turn provides a very poor description of the data in the low p_T region. This is again highlighted in figure 4(b) where the uncorrected "W p_T" distribution is compared to the PYTHIA predictions where the W p_T has been generated using two different intrinsic k_T's and where the W p_T has been generated from the CDF fit to the Z data, as described in section 4. It is clear that the procedure of defining the p_T distribution from a fit to Z data and then using the QCD calculation to transform this to a W p_T distribution gives a much better description of the W data than the intrinsic k_T parton shower models. The use of such erroneous W p_T distributions would bias the determination of the W mass significantly. For example using the parton shower description, with the default PYTHIA intrinsic $k_T = 0.44$ GeV, would shift the W mass by ~ 100 MeV. This is a shift much larger than the current W mass uncertainty.

6. Issues for the W mass analysis

In the present hadron collider W mass analyses, the W p_T is essentially defined by constraining the form from a fit to a Z p_T distribution. One then relies on the theoretical calculations to convert this into a W p_T measurement. This calculation must take into account the different rapidity distributions of the W and Z events and the different PDFs, aswell as the obvious difference in Q^2. If there are any other differences between W and Z events which are not included in the theoretical calculations, then the resulting W p_T will be biassed with a consequent bias in the W mass. For example, is the form of the non perturbative function universal or does it have an energy (or x) dependence as implemented in the Ladinsky-Yuan paramaterisation ? This is particularly relevant for extrapolations to the LHC where the x values will be significantly lower than those at the Tevatron. Additionally in the W mass analysis the p_T values of the W are small, it thus also imperative that the calculation of $\frac{d^2\sigma}{dY dp_T}|_{\mathrm{W}} / \frac{d^2\sigma}{dY dp_T}|_{\mathrm{Z}}$ is robust as $p_T \rightarrow 0$.

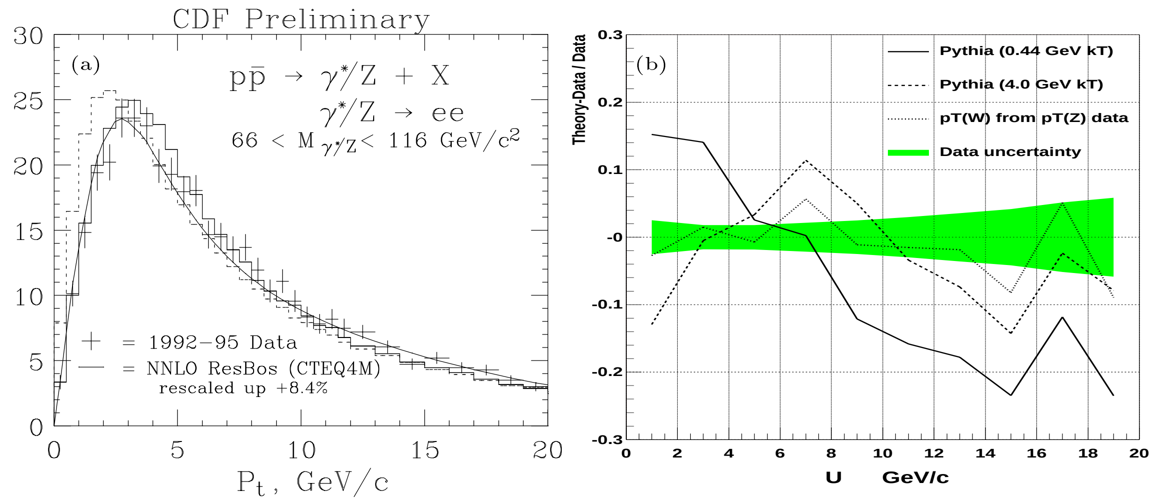

Figure 4. (a) : The fully corrected CDF Z p_T data is compared to the resummed RESBOS calculation (solid smooth line) and a parton shower description of Z p_T for two different intrinsic k_T values : 0.44 (dotted histogram) and 2.0 GeV (solid histogram). (b) : The uncorrected CDF "W p_T" distribution is compared to two types of prediction. One based on parton showers and the other based on a fit to the CDF Z p_T distribution.

7. Conclusion

Recently new measurements of W and Z p_T distributions have been produced by the Tevatron experiments. The Z distributions are completely corrected for all experimental effects and are thus the most amenable for comparison to QCD calculations. This is not the case for the recent W data and care must be exercised in making QCD comparisons with such data. Providing the non perturbative function has enough parameters the resummed calculations can provide a very good description of the available data. Parton shower Monte-Carlos which have an intrinsic k_T augmented by exact matrix element calculations at high p_T provide a reasonable description of the data. However for a precision W mass measurement they do not describe the data accurately enough and one must use the fits to Z data and a theoretical calculation to convert this into a W p_T distribution. It is important that all differences between W and Z production are included in these calculations if the W mass is not to be biassed.

Acknowledgents

We'd like to thank Willis Sakumoto for making available his comparisons of the Z p_T with RESBOS and PYTHIA (figure 4(a)).

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