W WIDTH AND W,Z CROSS SECTIONS AT THE TEVATRON

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The latest results on W and Z cross sections from $p\bar{p}$ collisions recorded by the CDF and DØ experiments at the Fermilab Tevatron collider, operating at a centre of mass energy of 1.96 TeV, are presented. These results have been used to used to validate (N)NLO QCD calculations, measure quark couplings, test lepton universality and constrain parton distributions functions. The width of the W boson has been obtained both directly from W events having a large transverse mass and indirectly from the ratio of W and Z cross sections. The possibility of using W events to determine the luminosity at the Tevatron and the future prospects for these measurements is also discussed.

Keywords: CDF, DØ, Tevatron, W width, W cross section, Z cross section

1. Introduction

Leptonically decaying W and Z events are one of the most incisive event samples for precision tests of the Standard Model (SM) at a hadron collider. They can be detected with a low background and their cross sections determined with an uncertainty of $\lesssim$ 2%. The motivation for precise W and Z cross section measurements is threefold. Firstly, they can be used to validate (N)NLO QCD calculations. The inclusive W and Z cross sections were amongst the first processes to be calculated to NNLO and the precision of both the measurements and the calculation allows a test of NNLO at the $\sim 3\%$ level. Measurements of the Z p_T distribution allow a test of the QCD NLO resummation techniques and a tuning of the Monte-Carlo (MC) parameters describing W and Z p_T distributions. This will be important at the LHC and is also critical to the W mass measurement where a very precise knowledge of the boson p_T at low p_T is crucial. At these low p_T values, one must invoke non perturbative QCD and the form of the p_T distribution is largely constrained by the data. Measurements of the rapidity distribution of the Z and W boson, particularly at large rapidity, provide stringent constraints on the parton distribution functions (PDFs) in kinematic regions not previously well measured and vital for LHC physics. Secondly, the cross section measurements allow the precise determination of SM parameters such as lepton to W couplings (to test lepton universality), quark couplings and the quark mixing CKM element, V_{cs}, and the W boson width. The latter can be determined directly from W events at high transverse mass and also indirectly from the W/Z cross section ratio. Thirdly, these events which have low background and whose kinematics are well defined can be used to optimise the detector response to leptons, both in terms of increasing the efficiency and acceptance region of their detection but also in optimising missing E_T measurements and background rejection techniques. Detector optimisation is particularly important for new physics searches at the Tevatron where the expected cross sections are small. Moreover Drell-Yan events at high mass are generally a background to new physics e.g. a new heavy Z boson and so a detailed understanding of these events around the Z pole, where the SM theory is precisely defined, is mandatory.

2. Data Samples and Detectors

The results presented here are from $p\bar{p}$ collisions recorded by the CDF and DØ experiments at the Fermilab Tevatron collider. The data was taken in 2002-2003 and the integrated luminosities used in the analyses vary from 72 to 350 pb^{-1} with average peak instantaneous luminosities of $\sim 2 \times 10^{31} cm^{-2} s^{-1}$. The CDF and DØ detectors are similar with regard their capabilities of detecting W and Z bosons. Both experiments can only measure the leptonic decay modes. Unlike at LEP, the enormous background from QCD processes swamps the hadronic decay mode at the Tevatron. Both detectors have calorimetry to $|\eta| < 4$ and combine inner silicon layers with large volume tracking to provide electron identification to $|\eta| < 3$, although precise momentum measurements are generally confined to the central region, $|\eta| < 1$. CDF has muon coverage to $|\eta| < 1$ while DØ has coverage to $|\eta| < 2$.

3. Cross Section Measurements

The measured cross sections are shown in Fig. 1 and agree well with the NNLO predictions. For the electron and muon decay modes the measured cross sections are measured with a precision of $\sim 2\%$. The measurements are dominated by the systematic uncertainty which has contributions from three principal sources: PDFs, lepton identification efficiency and backgrounds. The measurements, along with all Tevatron cross section measurements, are also subject to a luminosity uncertainty of $\sim 6\%$. This error is due to uncertainties in the total $p\bar{p}$ cross section and the acceptance of the low angle luminosity detectors. Since the W cross section is known theoretically with an accuracy of 2% and can be measured with a similar precision, it is possible that future Tevatron cross sections will be quoted relative to the W cross section or will use the W events to determine the luminosity in order that the precision of cross section measurements is not limited by the luminosity uncertainty. For instance the present luminosity uncertainty on the CDF top quark production is 0.4 pb compared to the present systematic uncertainty of 0.6 pb. The τ channel has a larger error but is an interesting channel since it allows the experiments to test lepton universality and also optimise their τ finding algorithms, which is important for new physics searches where cross section enhancements are often found in decays to third generation particles e.g. in the decay of the MSSM Higgs boson. In W events, τs are identified from the hadronic decay channel using the distinctive one and three-prong decay modes and stringent track and calorimeter matching and isolation criteria are employed. In Z events, one τ is identified from its leptonic decay and one from the hadronic decay mode and invariant mass constraints are applied.

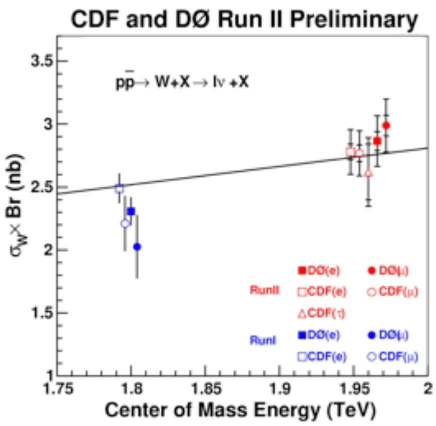

Fig. 1. The W cross sections measured by CDF[1] and DØ at a center of mass energy of 1.96 TeV compared to the NNLO[2] prediction using MRST2001[3] NNLO PDFS. The cross sections at 1.8 TeV are from the previous Tevatron run (1994-5), Run-1[4].

4. Determination of SM Parameters

The cross section measurements can be used to determine the W boson width, the CKM V_{cs} quark mixing element and test lepton universality. The W boson width can be determined using the measured ratio of leptonic W and Z cross sections, denoted by R, since:

$$R = \frac{\sigma_W}{\sigma_Z} \cdot \frac{\Gamma_Z}{\Gamma_{Z\to l^+l^-}} \cdot \frac{\Gamma_{W\to l\nu}}{\Gamma_W} \quad (1)$$

The first term is precisely determined (to $\pm$ 0.7%) from a NNLO calculation [2], the second term was measured at LEP-1 (to $\pm$ 0.07%) and $\Gamma_{W\to l\nu}$ is known within the SM to $\pm$0.1%. Using Eq. 1 CDF has determined Γ_W to be 2.092 $\pm$ 0.042 GeV, in good agreement with the SM prediction of 2092 $\pm$ 3 MeV[5]. The W width has also been measured in a direct, less model dependent manner by DØ using W events in the high transverse mass tail. The W transverse mass distribution has a sharp edge close to the value of the W mass. However owing to the finite width of the W boson, it is also possible for events to be measured with transverse mass values higher than the mass of the W boson. From a likelihood fit to the transverse mass distribution in the $100 < m_T < 200$ GeV, it is therefore possible to determine the W width. However events in the high transverse mass region can also arise due to the finite resolution of the detector and so a detailed understanding and modelling of resolution effects is a vital component of this analysis and indeed dominates the systematic uncertainty for the measurement. Using 177 pb^{-1} of data, and 625 W $\to$ eν events in the high transverse mass region, DØ have determined the W width to be 2011 $\pm$ 93 (stat) $\pm$ 107 (syst.) MeV. Tests of lepton universality have been made by CDF from their measured W cross sections. They determine $\frac{g_\mu^W}{g_e^W} = 0.991 \pm 0.012$ and $\frac{g_\tau^W}{g_e^W} = 0.99 \pm 0.042$. The former has a precision comparable to the LEP-2 determination and the τ channel is expected to have a similar precision when the analysis of the present datasets is concluded. V_{cs} is one of the least well determined CKM quark mixing matrix elements. Using world average values of the relevant other CKM elements ($V_{ud}, V_{us}, V_{cd}, V_{ub}, V_{cb}$), it is possible to extract V_{cs} using the relation:

$$\Gamma_W = 3\Gamma_{W\to l\nu}\left(1 + K_{QCD}(\alpha_s^3)\sum_{\text{no top}} |V_{qq'}|^2\right) \quad (2)$$

CDF determines V_{cs} to be 0.976 ± 0.03.

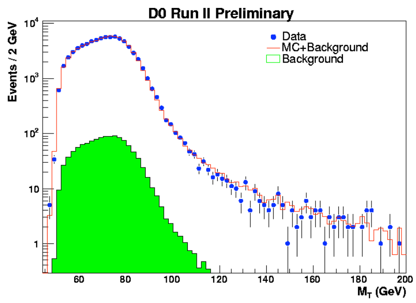

Fig. 2. The transverse mass of the DØ W $\to$ eν events used to determine the W width by a likelihood fit in the $100 < m_T < 200$ GeV region.

5. PDF constraints

PDF constraints can be obtained by measuring the rapidity distributions of W and Z bosons. In the W case, one has two constraints on PDFS: the lepton charge asymmetry [6] as a function of lepton rapidity and the ratio of W cross sections in the central region ($|\eta| < 1$) to the forward region ($1 < |\eta| < 3$). The latter has been measured by CDF, in the electron channel, using 223 pb^{-1} of integrated luminosity to be 0.925 ± 0.033 which compares favourably with the predictions based on CTEQ6 [7] (0.924 ± 0.037) and MRST[3] (0.941 ± 0.012) PDFs. The Z rapidity distribution which is sensitive to PDFs in the high x region has been measured by DØ in the electron channel using 337 pb^{-1} of integrated luminosity. At present in the interesting region beyond $\eta > 2.0$, where statistics are low, the experimental uncertainties are approximately twice as large as the PDF uncertainties; but with more data this measurement is expected to provide PDF constraints that will reduce theoretical uncertainties at the LHC.

6. Outlook

The results presented here are based on data taken in 2002-2003 with integrated luminosities in the range 72 to 350 pb^{-1}. Since that time the experiments have accumulated an additional $1000\mathrm{pb}^{-1}$ of data which is presently being analysed. The extraction of SM parameters and PDF constraints in the analyses presented here are dominated by statistical uncertainties. In the next round of analyses the statistical uncertainty will be reduced considerably allowing the measurements to supercede the precision of the LEP2 measurements and further constrain the PDFs. Indeed at the present luminosities both experiments are accumulating $\sim$ 20,000 W and $\sim$ 2000 Z bosons a week. However to maximise the statistical power of this data it will be necessary to make further progress in reducing the systematic sources of error. In the W and Z cross section ratio measurement, which determines the W width, CDF has demonstrated that the PDF and lepton identification uncertainties can be significantly reduced by selecting a single event sample using only one charged lepton and discriminating the W and Z events using either the missing $\mathrm{E_T}$ or the charged lepton $\mathrm{p_T}$ distribution. This has the side effect of increasing the backgrounds but owing to the large statistics it is hoped that this can be mitigated by using tighter cuts (e.g. on the recoil energy). In the extraction of PDF constraints it will be necessary to improve the simulation of lepton identification at high rapidity and also improve the efficiency and purity of their detection.

7. Conclusion

The first round of run-2 W and Z cross section analyses have been completed by both Tevatron experiments. They are presently the most precisely determined cross sections at the Tevatron with uncertainties (excluding luminosity) of $\sim$ 2% and they are the standard on which much of the search programme for exotic physics is underpinned. These cross section measurements are already providing determinations of SM parameters (Γ_W, V_{cs}, W-lepton couplings) which are the world's best and beginning to provide PDF constraints in the high-x region of interest to the LHC. Reductions of at least a factor of 2 in the uncertainties presented here are expected in the next round of analyses through developments in reducing systematic errors and using datasets with significantly larger integrated luminosities.

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