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NEW TEVATRON MEASUREMENTS OF THE W BOSON MASS

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New measurements of the W boson mass from the two Tevatron experiments, CDF and DØ, are presented. The results are from the 1994–1995 Tevatron run, and based on integrated luminosities of 82 pb^{-1} (DØ) and 90 pb^{-1} (CDF), from $p\bar{p}$ collisions at $\sqrt{s} = 1.8$ TeV. These new measurements when combined with previous published measurements yield a Tevatron W mass value of 80.450 ± 0.063 GeV.

1 Introduction

A precise W mass measurement allows a stringent test of the SM beyond tree level where radiative corrections lead to a dependence of the W mass on both the top quark mass and the mass of the, as yet unobserved, Higgs boson. The dependence of the radiative corrections on the Higgs mass is only logarithmic whilst the dependence on the top mass is quadratic. Simultaneous measurements of the W and top masses can thus ultimately serve to constrain the Higgs mass and potentially indicate the existence of particles beyond the Standard Model. To achieve the same sensitivity to the Higgs mass which the current uncertainty on the top mass[1] provides, a W mass measurement with an uncertainty of $\mathcal{O}(40)$ MeV is required.

From data taken in 1992–1993, the two Tevatron experiments, CDF and DØ, have published W mass measurements[2] with a combined uncertainty of 150 MeV. The data sample from the 1994–1995 run is approximately four times larger and allows both a reduction in the statistical uncertainty of the W mass measurement and a more detailed understanding of the systematic uncertainties associated with the measurement e.g. the uncertainties associated with the model used for the W production. DØ has published a W mass measurement[3] based on this data sample using "central electrons" i.e. events where the W is detected via its $e\nu$ decay-mode and the electrons are confined to the rapidity region : $|\eta| < 1$. CDF has also presented a preliminary measurement[4] based on central muons. In this paper, these results are augmented by further measurements. DØ has completed an analysis based on "end-cap electrons", where the electrons are detected not in the central calorimeter but in the two end-cap calorimeters which cover the rapidity region $1.5 < |\eta| < 2.5$, and CDF has completed its analysis of the $W \rightarrow e\nu$[5] channel and has also reduced its systematic uncertainty in the $W \rightarrow \mu\nu$ analysis.

2 Measurement Technique

W and Z bosons are produced at the Tevatron through quark–anti-quark annihilation. The cross section is dominated by valence quarks and receives a contribution of $\sim$ 30% from $\mathcal{O}(\alpha_s)$ processes. Owing to the small backgrounds and superior resolution, the W mass is measured from its leptonic decay. CDF uses W samples where the W decays to $e\nu$ and $\mu\nu$ whilst DØ utilises only the electron channel.

At the Tevatron one cannot determine the longitudinal neutrino momentum since a significant fraction of the products from the p$\bar{\rm p}$ interaction are emitted at large rapidity where there is no instrumentation. Consequently, one must determine the W mass from transverse quantities[6] namely : the transverse mass ($\rm M_T$), the charged lepton $\rm P_T$ ($\rm P^{\it l}_T$) or the missing transverse energy ($\not\!\!E_{\rm T}$). $\not\!\!E_{\rm T}$ is inferred from a measurement of $\rm P^{\it l}_T$ and the remaining $\rm P_T$ in the detector, denoted by $\vec{\rm U}$ i.e.

$$\vec{\not\!\!E}_{\rm T} = -(\vec{\rm U} + \vec{\rm P}^{\it l}_{\rm T}) \qquad \text{and } \rm M_T \text{ is defined as}$$

$$\rm M_T = \sqrt{2P^{\it l}_T \not\!\!E_T (1 - \cos\phi)} \qquad \text{where } \phi \text{ is the angle between } \vec{\not\!\!E}_{\rm T} \text{ and } \vec{\rm P}^{\it l}_{\rm T}$$

$\vec{\rm U}$ receives contributions from two sources. Firstly, the so-called W recoil i.e. the particles arising from initial state QCD radiation from the q$\bar{\rm q}$ legs producing the hard-scatter and secondly contributions from the spectator quarks (p,$\bar{\rm p}$ remnants) and additional minimum bias events which occur in the same crossing as the hard scatter. This second contribution is generally referred to as the underlying-event contribution. Experimentally these two contributions cannot be distinguished. Owing to the contribution from the underlying-event, the missing transverse energy resolution has a significant dependence on the instantaneous p$\bar{\rm p}$ luminosity. $\rm M_T$ is to first order independent of the transverse momentum of the W ($\rm P^W_T$) whereas $\rm P^{\it l}_T$ is linearly dependent on $\rm P^W_T$. For this reason, and at the current luminosities where the effect of the $\not\!\!E_{\rm T}$ resolution is not too severe, the transverse mass is the preferred quantity to determine the W mass. However, the W masses determined from the $\rm P^{\it l}_T$ and $\not\!\!E_{\rm T}$ distributions provide important cross-checks on the integrity of the $\rm M_T$ result since the three measurements have different systematic uncertainties.

The W mass itself is determined through a precise simulation of the transverse mass line-shape, which exhibits a Jacobian edge at $\rm M_T \sim M_W$. The simulation of the line-shape relies on a detailed understanding of the detector response and resolution to both the charged lepton and the recoil particles. This in turn requires a precise simulation of the W production and decay. The similarity in the production mechanism and mass of the W and Z bosons is exploited in the analysis to constrain many of the systematic uncertainties in the W mass analysis. The lepton momentum and energy scales are determined by a comparison of the measured Z mass from $\rm Z \rightarrow e^+e^-$ and $\rm Z \rightarrow \mu^+\mu^-$ decays with the value measured at LEP. The simulation of the W $\rm P_T$ and the detector response to it are determined by a measurement of the Z $\rm P_T$ which is determined precisely from the decay leptons and by a comparison of the leptonic (from the Z decay) and non-leptonic $\rm E_T$ quantities in Z events. The reliance on the Z data means that many of the systematic uncertainties in the W mass analyses are determined by the statistics of the Z sample.

The W and Z events in these analyses are selected by demanding a single isolated high $\rm P_T$ charged lepton in conjunction with missing transverse energy (W events) or a second high $\rm P_T$ lepton (Z events). Depending on the analyses, the $\not\!\!E_{\rm T}$ cuts are either 25 or 30 GeV and the lepton $\rm P_T$ cuts are similarly 25 or 30 GeV. The number of events used in the analyses are listed in Table 1.

D0(EC)		CDF(μ)		CDF(e)	
W	Z	W	Z	W	Z
11090	1687	14740	1830	30115	1541

Table 1: Events samples used in the W mass analyses.

3 Lepton Scale Determination

Unlike the determination of the W mass at LEP2, where the experiments can exploit the beam energy constraint, the Tevatron experiments have no such constraint and any uncertainties in the lepton scale determination enter directly as a corresponding uncertainty in the W mass. The lepton scales for the analyses are determined by comparing the measured Z masses with the LEP values. The mean lepton P_T in Z events ($P_T \sim 42$ GeV) is ~ 5 GeV higher than in W events, consequently in addition to setting the scale one also needs to determine the non-linearity in the scale determination i.e. to determine whether the scale has any P_T dependence. DØ does this by comparing the Z mass measured with high P_T electrons with J/ψ and π^0 masses measured using low P_T electrons as well as by measuring the Z mass in bins of lepton P_T. In the determination of CDF's momentum scale the non-linearity is constrained using the very large sample of $J/\psi \rightarrow \mu\mu$ and $\Upsilon \rightarrow \mu\mu$ events which span the P_T region : $2 < P_T < 10$ GeV. The non-linearity in the CDF transverse momentum scale is consistent with zero (see Fig. 1). This fact in turn can be exploited to determine the non-linearity in the electron transverse energy scale through a comparison of the measured E/p with a MC simulation of E/p where no E_T non-linearity is included. The lepton scale uncertainties form the largest contribution to the W mass systematic error. The non-linearity contribution to the scale uncertainty is typically $\sim 10\%$ or less.

The Z lineshape is also used by both experiments to determine the charged lepton resolution functions i.e. the non-stochastic contribution to the calorimeter resolution and the curvature tracking resolution in the case of the CDF muon analysis.

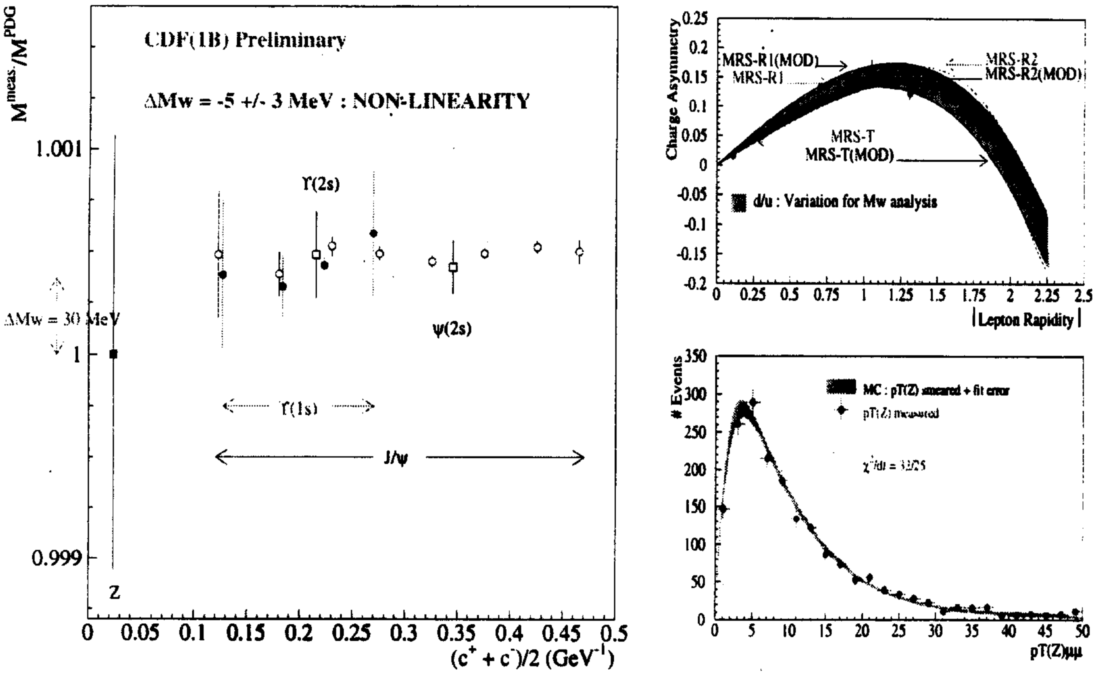

Figure 1: LEFT: The CDF determination of the momentum scale and non-linearity using dimuon resonances. RIGHT UPPER: The modified PDF sets used in the Mw analysis, which span CDF's *W* charge asymmetry measurement. RIGHT LOWER : The Z P_T distribution as measured by CDF in the $Z \rightarrow \mu^+\mu^-$ channel.

4 W Production Model

The lepton P_T and $\not{E}_T$ distributions are boosted by the non zero P_T^W and the $\not{E}_T$ vector is determined in part from the W-recoil products. As such a detailed simulation of the P_T^W spectrum and the detector response and resolution functions is a necessary ingredient in the W mass analysis. The W P_T distribution is determined by a measurement of the Z P_T distribution (measured from the decay leptons) and a theoretical prediction of the W to Z P_T ratio. This ratio is known with a small uncertainty and thus the determination of the W P_T is dominated by the uncertainty arising from the limited size of the Z data sample. The P_T^Z distribution of the CDF $Z \rightarrow \mu^+\mu^-$ sample is shown in Fig. 1. The detector response and resolution functions to the W-recoil and underlying event products are determined by both experiments using Z and minimum bias events. Since the W-recoil products are typically produced along the direction of the vector boson P_T and the underlying event products are produced uniformly in azimuth, the response and resolution functions are determined separately in two projections – one in the plane of the vector boson and one perpendicular to it. Typically one finds the resolution in the plane of the vector boson is poorer owing to the presence of jets (initial state QCD radiation from the quark legs) which are absent in the perpendicular plane where the resolution function matches closely that expected from pure minimum bias events. The parton distribution functions (PDFs) determine the rapidity distribution of the W and hence of the charged lepton. Both experiments impose cuts on the rapidity of the charged lepton and so a reliable simulation of this cut is necessary if the W mass determination is not to be biassed. On average the u quark is found to carry more momentum than the d quark resulting in a charge asymmetry of the produced W i.e. $W^{+(-)}$ are produced preferentially along the p ($\bar{p}$) direction. Since the V-A structure of the W decay is well understood, a measurement of the charged lepton asymmetry therefore serves as a reliable means to constrain the PDFs. To determine the uncertainty in the W mass arising from PDFs, MRS PDFs were modified to span the CDF charged lepton asymmetry measurements[7]. This is illustrated in Fig. 1.

5 Mass Fits

The W mass is obtained from a maximum likelihood fit of M_T templates generated at discrete values of M_W with Γ_W fixed at the SM value. The templates also include the background distributions, which are small (< 5%) and have three components : $W \rightarrow \tau\nu$, followed by $\tau \rightarrow \mu/e\nu\nu$, QCD processes where one mis-measured jet mimics the $\not{E}_T$ signature and the other jet satisfies the charged lepton identification criteria and finally Z events where one of the lepton legs is not detected. The transverse mass fits for the DØ end-cap electrons and the two CDF measurements are shown in Fig. 2. The uncertainties associated with the measurements are listed in Table 2. The uncertainties of the published DØ central-electron analysis are also listed. For both experiments the largest errors are statistical in nature, both from the statistics of the W sample and also the statistics of the Z samples which are used to define many of the systematic uncertainties e.g. the uncertainties in the lepton energy/momentum scales and the W P_T model. The CDF and DØ measurements are combined with a 25 MeV common uncertainty which accounts for the uncertainties in PDFs and QED radiative corrections which by virtue of being constrained from the same source are highly correlated. Together the two experiments yield a W mass value of 80.450 GeV with an uncertainty of 63 MeV. For the first time, both Tevatron experiments have measurements with uncertainties below 100 MeV and the combined uncertainty is comparable with the

Error Source	DØ (EC)	DØ (C)	CDF (e)	CDF (μ)
Statistical	70	105	65	100
Lepton Scale+Resolution	70	185	80	90
P_T^W + $\not{E}_T$ Model	35	50	40	40
Other experimental	40	60	5	30
Theory (PDFs, QED)	30	40	25	20
Total Error	120	235	113	143
Mass Value	80.440	80.766	80.473	80.465
Combined Mass Values	80.497 ± 0.098 GeV		80.470 ± 0.089 GeV	

Table 2: The mass values and uncertainties of the CDF and DØ W mass analyses using the 1994–1995 data. The uncertainties are quoted in MeV. The mass values when the 1992–1993 data are included become : 80.474 ± 0.093 GeV for DØ and 80.430 ± 0.079 GeV for CDF.

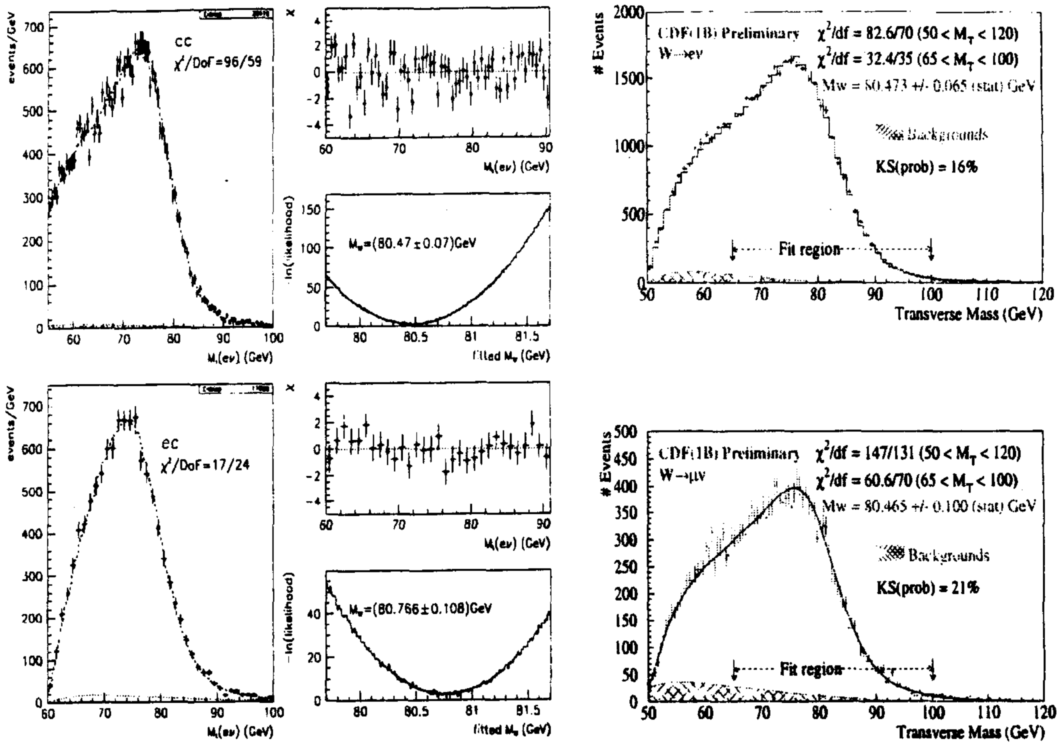

Figure 2: Transverse mass distributions compared to the best fit. LEFT : DØ's published central-electron analysis and preliminary end-cap analysis. RIGHT : CDF's electron and muon channel analyses. The fit likelihood and residuals are also shown for the two DØ distributions.

uncertainty recently attained by the combination of the four LEP experiments[8].

6 Conclusions

The two Tevatron experiments have updated their W mass measurements and now both report measurements with uncertainties < 100 MeV. These measurements are comparable with the uncertainties from LEP and when combined yield a world average W mass with an uncertainty of ~ 40 MeV. Together with the Tevatron top quark mass measurements and the precise electroweak measurements from LEP1 and SLC, these measurements indicate a preference for a light Higgs mass[9]. In the next Tevatron run, due to begin in the year 2000, both CDF and DØ expect to measure the W mass with a precision comparable to the final LEP2 uncertainty.

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