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DOE HEP Closeout Report
from
Ashutosh Kotwal, Duke University
to
Department of Energy Office of Science

Project Title: W Boson Mass Measurement at CDF

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PROJECT DESCRIPTION

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1 Executive Summary

This is the closeout report for the grant for experimental research at the energy frontier in high energy physics. The report describes the precise measurement of the W boson mass at the CDF experiment at Fermilab, with an uncertainty of ≈ 12 MeV, using the full dataset of ≈ 9 fb^{-1} collected by the experiment up to the shutdown of the Tevatron in 2011. In this analysis, the statistical and most of the experimental systematic uncertainties have been reduced by a factor of two compared to the previous measurement with 2.2 fb^{-1} of CDF data. This research has been the culmination of the PI's track record of producing world-leading meassurements of the W boson mass from the Tevatron. The PI performed the first and only measurement to date of the W boson mass using high-rapidity leptons using the D0 endcap calorimeters in Run 1. He has led this measurement in Run 2 at CDF, publishing two world-leading measurements in 2007 and 2012 with total uncertainties of 48 MeV and 19 MeV respectively. The analysis of the final dataset is currently under internal review in CDF. Upon approval of the internal review, the result will be available for public release.

2 Introduction

One of the main research efforts of Kotwal's career has been the measurement of the W boson mass. This measurement, together with the top quark mass and other precision electroweak observables, is sensitive to the radiative corrections induced by the Higgs boson and possibly other new particles such as supersymmetric particles or composite Higgs constituents. It is a very interesting measurement now that the Higgs boson has been found at the LHC, but all of its properties have not been measured yet and the LHC continues to search for beyond-Standard Model physics. Increasing the precision of the W boson mass is one of the best possible ways to check the consistency of the 125 GeV Higgs boson with the Standard Model.

2.1 Summary of Funding

We include in Table 1 a summary of the funds received from this grant. The funds were used to support graduate student Sourav Sen as a research assistant.

	2013	2014
CDF	$43K	$50K

Table 1: Summary of funds received at Duke in 2013 and 2014. In addition, $7K ($4K) were received in 2013 (2014) in the Fermilab Service account for CDF travel related to this project.

3 W Mass Analysis with 8.8 fb^{-1} of CDF Data

Kotwal and his ex-postdoc Hays (now Lecturer at Oxford University) completed the final, and most accurate alignment of the drift chamber with cosmic rays for the full dataset. The methodology and results from this alignment study, including improvements to the drift model, electrostatic and gravitational deflections of the wires and deformation of the end plates has been published in a detailed article in **Nuclear Instrum. Meth. Phys. Res. A 762, 85 (2014)** .

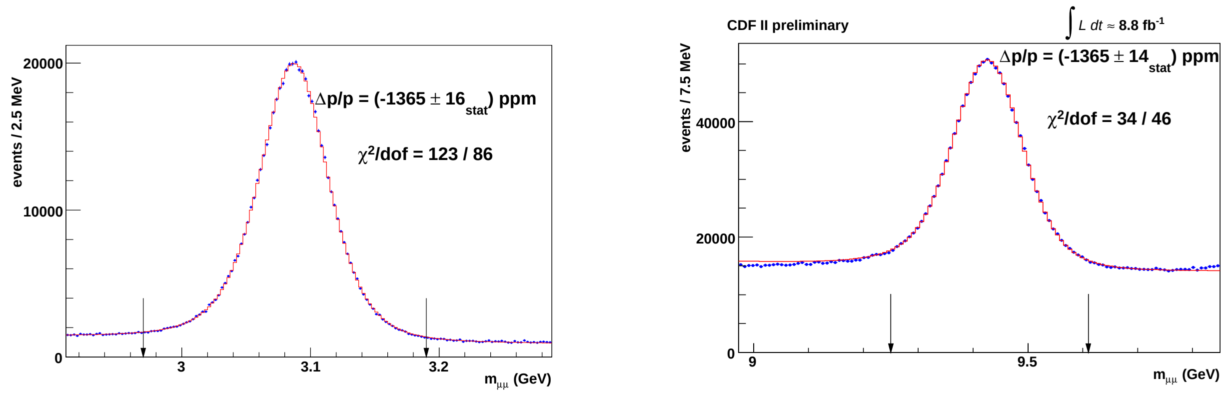

Figure 1: Tracker momentum calibration using the $J/\psi \to \mu\mu$ data in a bin of muon momentum (left) and using the inclusive $\Upsilon \to \mu\mu$ data (right).

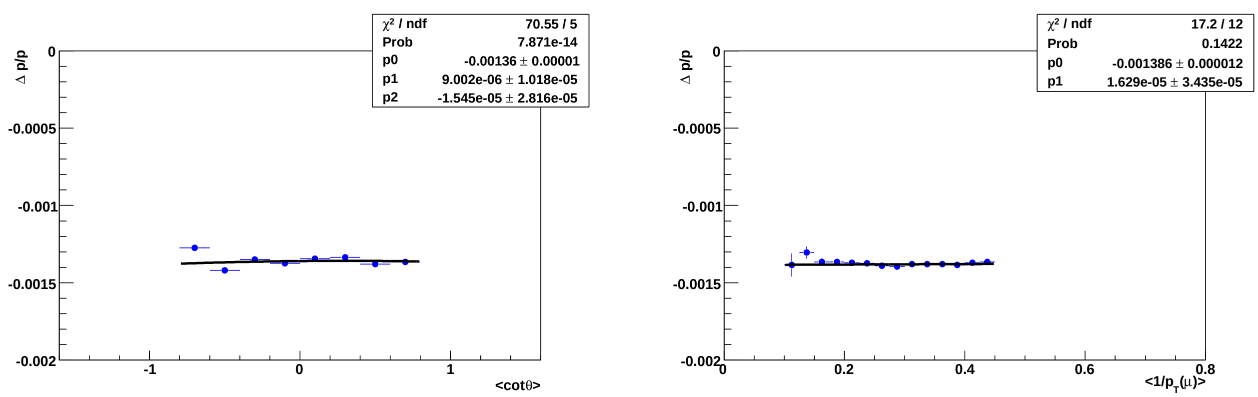

Figure 2: Calibration of the non-uniformity of the magnetic field (left) and the amount of passive material in the tracker (right) using the $J/\psi \to \mu\mu$ data.

In the next step of the alignment analysis, Kotwal and Hays removed the remaining weakly-constrained modes of the drift chamber deformation, based on the observed difference of $\langle E_{\rm cal}/p_{\rm track}\rangle$ between positrons and electrons from W-boson decays. Biases in the reconstruction of the beam line have also been removed using a combination of W-boson decays in the electron and muon channels. Biases as a function of time and as a function of the azimuthal and polar angles have been removed by updating the alignment and the

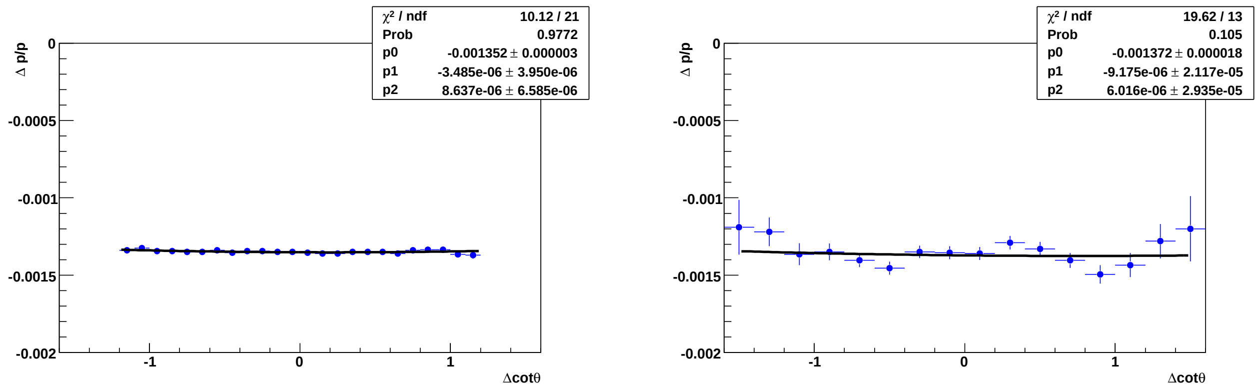

Figure 3: Calibration of the track polar angle measurement in the tracker using the $J/\psi \to \mu\mu$ data (left) and the $\Upsilon \to \mu\mu$ data (right).

electrostatic deflection model used at the reconstruction level, rather than applying ad-hoc corrections to track parameters as was done in the past.

This work represents a significant improvement in the understanding and implementation of the alignment corrections, compared to previous W boson mass measurements. All of these corrections were used to reprocess selected and skimmed datasets used for this analysis, in order to minimize tracking uncertainties.

One of the significant systematic uncertainties in the previous analysis was a 0.02% discrepancy in the track momentum scale derived from Upsilon decays with and without the application of the beam-constraint to the reconstructed muon tracks. The source of this discrepancy was tracked down and the CDF reconstruction code was updated to fix this problem. We have demonstrated with the reprocessed datasets that this discrepancy has been eliminated, yielding a significant reduction in the uncertainty on the tracking momentum calibration.

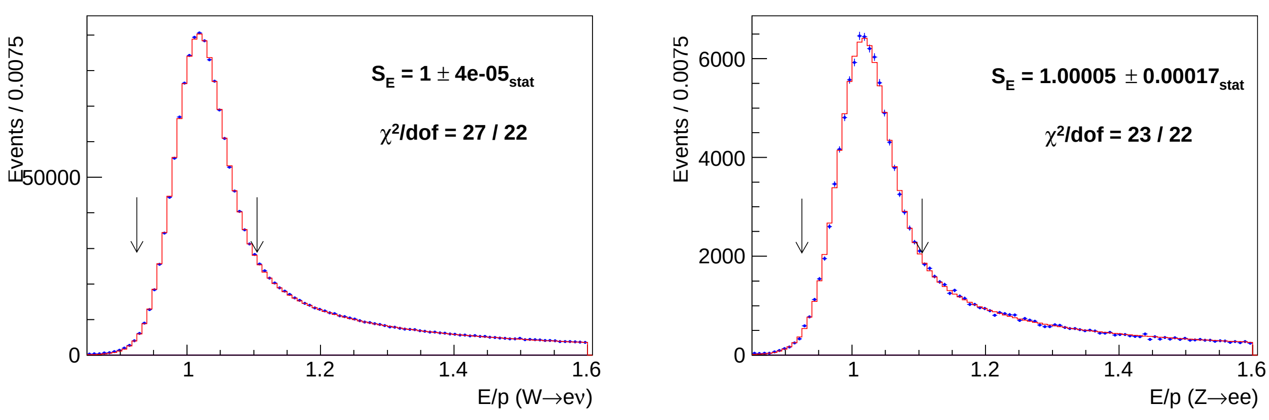

Figure 4: Calibration of the calorimeter energy scale from the $E_{\text{cal}}/p_{\text{track}}$ distribution of the $W \to e\nu$ data (left) and the $Z \to ee$ data (right).

The determination of the momentum calibration of the CDF magnetic tracker has been completed using $J/\psi \to \mu\mu$ and $\Upsilon \to \mu\mu$ data. Figure 1 shows the mass fits with consistent results and statistical errors equivalent to 1.1 MeV on the W boson mass. We have also completed the calibration of the amount of material in the tracker, the non-uniformity of the magnetic field, and the polar angle measurement. These calibrations have been performed by measuring the mass of these resonances as functions of track momentum and polar angle, and the results are shown in Figs. 2-3.

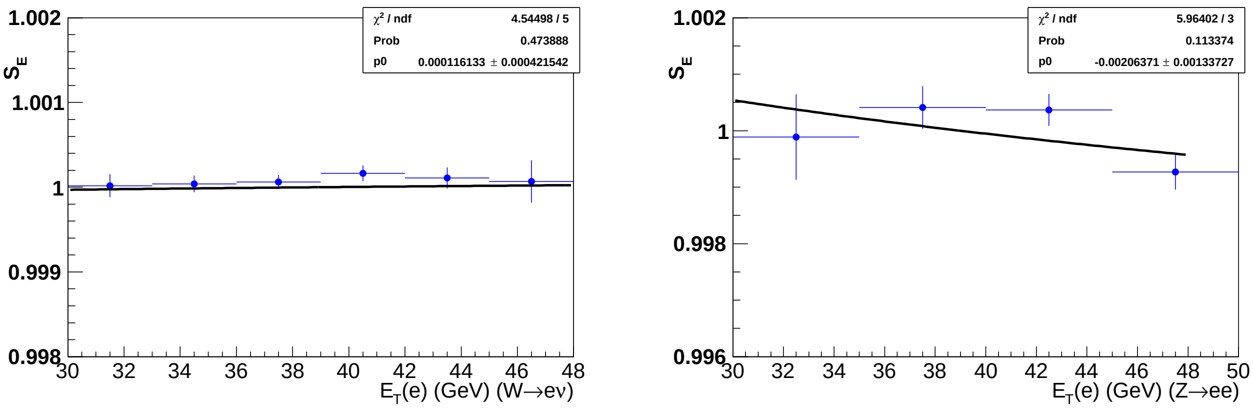

Figure 5: Calibration of the calorimeter non-linearity as a function of transverse energy, demonstrated using the $W \to e\nu$ data (left) and the $Z \to ee$ data (right).

The calibration of the calorimeter has been completed, using the ratio of the calorimeter energy and the track momentum for electrons from $W \to e\nu$ and $Z \to ee$ decays. The peak of the distribution of $E_{\rm cal}/p_{\rm track}$ is sensitive to the calorimeter response. Consistent calibrations have been obtained from the $W \to e\nu$ and $Z \to ee$ data, as shown in Fig. 4. The technique has been used to calibrate each tower in the calorimeter, and to smooth out the variations in the calorimeter response as a function of proximity to the tower edge. The non-linearity of the calorimeter response has also been calibrated, as shown in Fig. 5. Finally, the amount of radiative material in the tracker has also been calibrated from the radiative tail in the electron $E_{\rm cal}/p_{\rm track}$ distribution.

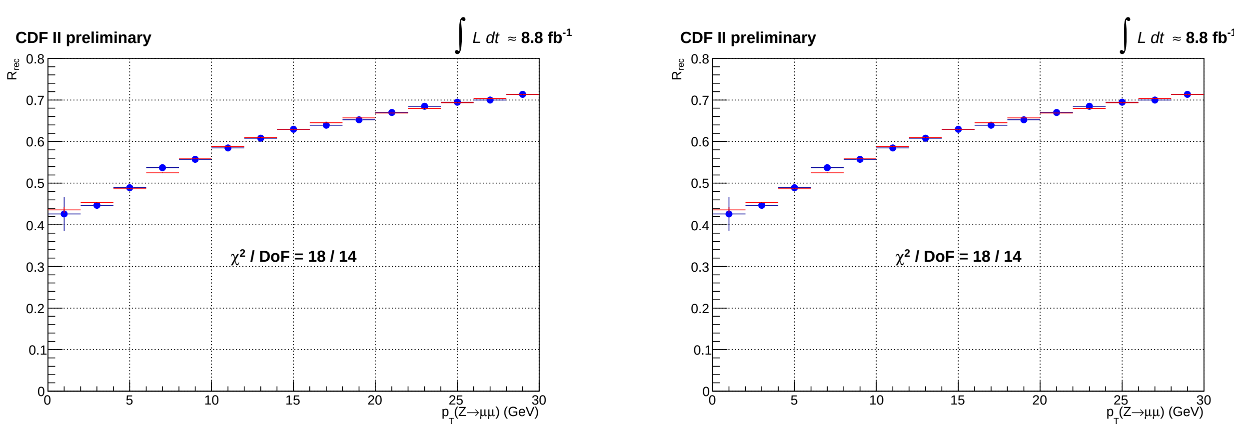

Figure 6: Calibration of the hadronic calorimeter response using the $Z \to \mu\mu$ data (left) and the $Z \to ee$ data (right). The data (simulation) are shown in blue (red).

The response and resolution of hadronic calorimeter has been measured and modeled precisely using p_T-balance in $Z \to \ell\ell$ decays. The excellent agreement between the measured and simulated response of the hadronic calorimeter is demonstrated in Fig. 6. The measurement of the energy contributions from spectator interactions and pileup have also been measured to a precision of 1-2 MeV.

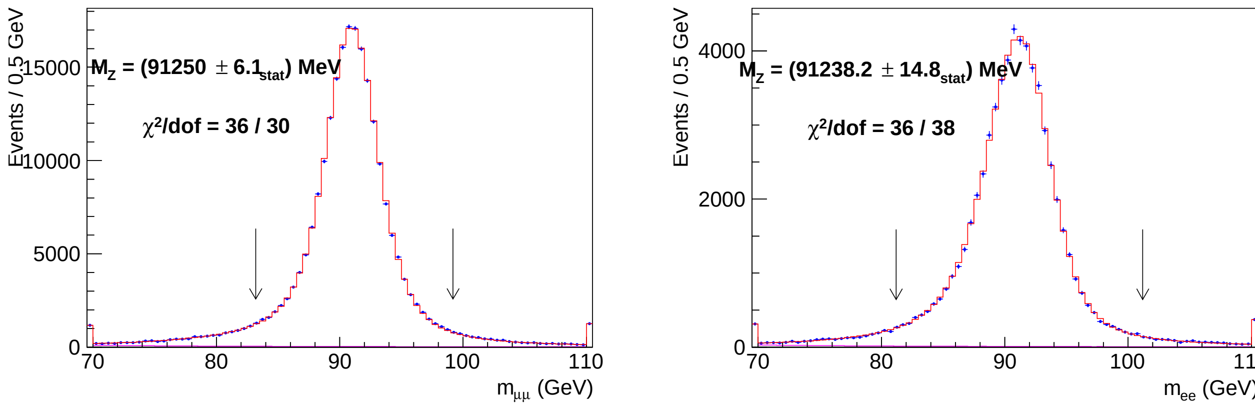

Figure 7: Blinded mass fits to the $Z \to \mu\mu$ data (left) and the $Z \to ee$ data (right). The data (simulation) are shown in blue (red). The printed mass values contain an unknown random offset.

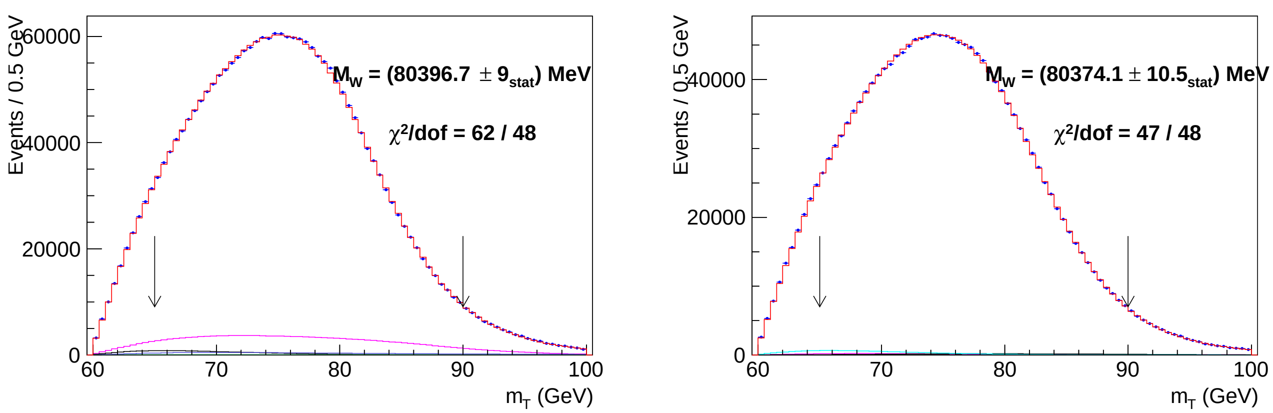

Figure 8: Blinded mass fits to the $W \to \mu\nu$ data (left) and the $W \to e\nu$ data (right) transverse mass distributions. The data (simulation) are shown in blue (red). The printed mass values contain an unknown random offset.

The evaluation of the QCD-jet background in the W boson sample has been completed. Graduate student Sourav Sen resurrected the artificial neural network code written by Kotwal's ex-graduate student Yu Zeng. Due to higher instantaneous luminosity and resulting pileup compared to the 2.2 fb^{-1} analysis, the distributions of isolation energy around the muon track were different in the final dataset. The neural network was retrained on the new data to regenerate the templates of the neural network output for pure signal, pure background and the W boson data. A linear combination of the signal and background templates fitted to the data was used to measure the background fraction. The determination of the $\pi \to \mu\nu$ decay-in-flight background, and the Z boson backgrounds has also been completed. Kotwal incorporated the modeling of these backgrounds in the custom simulation in order to reduce their uncertainties, as compared to past determinations from the standard CDF simulation.

Kotwal has completed the determination of the uncertainty from the QED radiative corrections by performing a high-statistics comparison of the PHOTOS and HORACE programs. There is interest in the wider community in understanding the subtle differences between such programs and their impact on the W mass extraction at the level of 1-2 MeV. These studies have been published (**Adv. High Energy Phys. 2016 (2016) 1615081**).

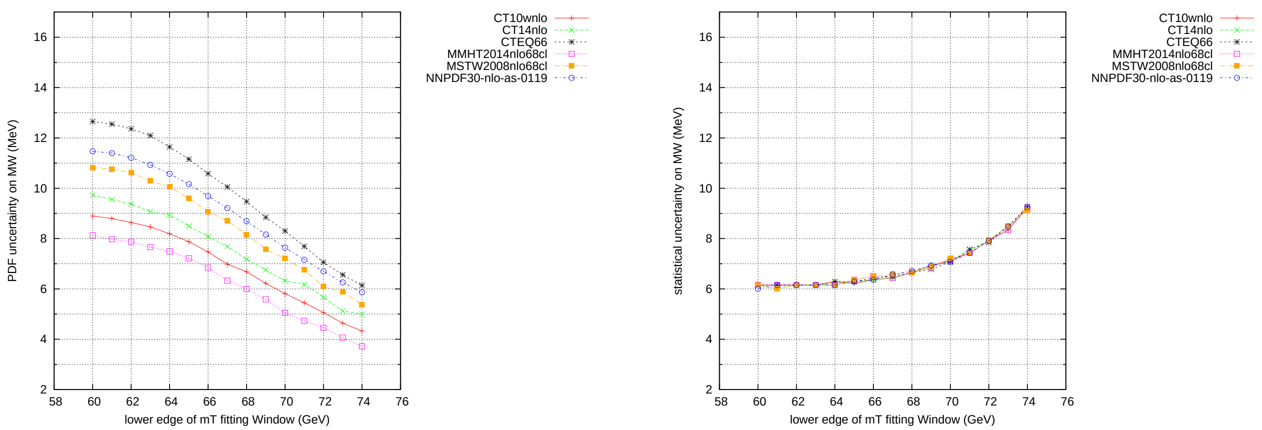

Figure 9: Variation of the PDF uncertainty (left) and the statistical uncertainty (right) on M_W from the fit to the transverse mass distributions of both the electron and muon channels. The variation is shown as a function of the lower limit of the kinematic range used in the fit.

The calibration of the tracker and calorimeter momenta will be confirmed upon unblinding the measurements of the Z boson masses in the di-electron and di-muon channels. These measurements will be unblinded when the internal review in CDF, currently ongoing, is completed. Similarly, the measurements of the W boson mass in both channels will also be unblinded upon final approval in CDF. The blinding is performed by adding an unknown random offset to the fitted values of the Z and W boson masses. The mass fits to the Z and W boson data, including the modeling of all theoretical and experimental effects and backgrounds, are shown in Figs. 7 and 8, respectively.

Sourav Sen performed the evaluation of the parton distribution functions (PDF) uncertainty. In the previous 2.2 fb^{-1} analysis, the PDF uncertainty was already the single largest source of systematic uncertainty. In order to obtain a robust estimate of the uncertainty, Sourav installed the POWHEG program and interfaced it to the LHAPDF library so that events could be generated simultaneously with the CTEQ, MSTW and NNPDF sets. This package was interfaced to the DukeSim fast simulation package which is used for the W boson mass measurement. With this full chain established, high-statistics pseudo-experiments were generated to evaluate the PDF uncertainty with high precision, and the results from different PDF sets were compared. The variation of the PDF uncertainty with kinematic cuts was also studied to optimize the combination of the PDF uncertainty and the statisti-

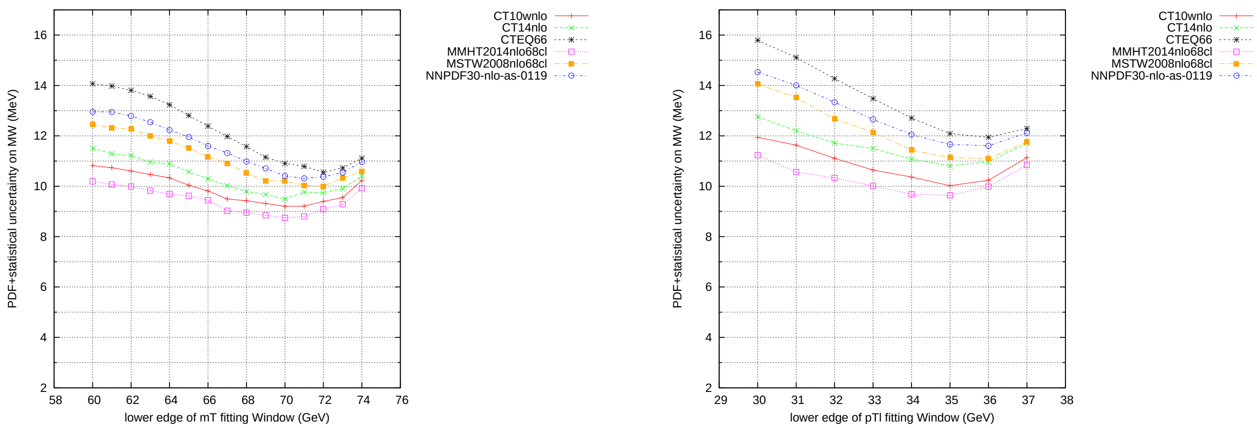

Figure 10: Variation of the combination of PDF uncertainty and the statistical uncertainty on M_W for the transverse mass fit (left) and the lepton p_T fit (right) of both channels. The variation is shown as a function of the lower limit of the kinematic range used in the respective fits.

cal uncertainty. We showed that as the kinematics cuts were raised, the PDF uncertainty reduced while the statistical uncertainty increased, as shown in Fig. 9. The combination of the PDF uncertainty and the statistical uncertainty is shown in Fig. 10, and shows the optimal kinematic range for the mass fits.

The statistical and estimated systematic uncertainties are summarized in Table 2. Despite the high instantaneous luminosity and the resultant degradation of efficiencies and resolutions, most experimental uncertainties have been reduced by about a factor of two relative to the previous publication. Thus, the latest analysis has been able to exploit the factor of four increase in the statistics of the data.

Source	Uncertainty (MeV)
Lepton energy scale and resolution	4
Recoil energy scale and resolution	3
Lepton removal	2
Backgrounds	3
$p_T(W)$ model	3
Parton distributions	7
QED radiation	3
W-boson statistics	7
Total	12.4

Table 2: Uncertainties for the combined result on M_W.

The PDF uncertainty has been determined using the global fits which were last published in 2014. The uncertainty has reduced by 30% as compared to 2012 when our previous W mass analysis was published. While this improvement is substantial, it has been outpaced by the improvement in our experimental analysis. However, further reduction of PDF uncertainty is expected after the publication of the final Tevatron results on the W charge asymmetry, the inclusion of LHC data published over the last four years, and other world data. As the PDF uncertainty is decoupled from our analysis of the experimental data, we plan to publish this analysis with the currently latest available PDF set and the corresponding uncertainty. The central value and PDF uncertainty can be easily updated by evaluating the relative M_W shift between the current and any future PDF set.

4 Conclusions

We have completed the analysis of 8.8 fb^{-1} of CDF data, the full dataset from the Tevatron Run 2, to measure the W boson mass with unprecedented precision. The result improves significantly upon the previous CDF publication and the world average. The total M_W uncertainty is $\approx$ 12 MeV and the analysis is under review within the CDF Collaboration. The central value of the measured M_W will be unblinded when the internal review is complete and the result is approved for publication.

5 Statement of current and pending support

Graduate student Sourav Sen was supported by the $93K that were received at Duke to support a graduate student under this grant. The grant has expired as of December 31, 2016.

6 Statement of unexpended funds

The grant has been spent down as close to zero as possible, within one day's worth of graduate student stipend.