Electroweak Precision Measurements and Direct Higgs Searches at the Tevatron

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The latest electroweak precision measurements and direct Higgs boson search results from the Tevatron are reviewed. Emphasis is placed on measurements for which the Tevatron is still competitive with the LHC. In the case of certain results, notably the precision measurements of the W boson and top quark masses, the Tevatron results will remain world leading for a considerable period of time.

1 Introduction

Tevatron Run II ran from March 2001 until September 2011, delivering approximately 12 fb^{-1} of $p\bar{p}$ data at $\sqrt{s} = 1.96$ TeV to the CDF and DØ experiments. The recently released Higgs search results are based mainly on the full dataset and are almost final, with modest improvements expected for the 2012 summer conferences. Newly released measurements of the W mass use only a fraction of the total Run II dataset and, while rapidly becoming systematically limited, will be updated with the full statistics in forthcoming years.

The Tevatron is no longer at the energy frontier, and the LHC has taken over the search for the direct production of new particles. The Tevatron detectors are very well understood after more than a decade of analysis, and so they remain competitive in the precision measurement of m_W and m_{top}. In the search for the Higgs boson the Tevatron remains competitive especially at low masses and in complementary channels to those with the greatest sensitivity at the LHC. Is is therefore particularly timely and interesting to compare the Tevatron Higgs search results with those of the LHC.

More details on many of the results discussed here can be found in parallel session contributions by Head, Knoepfel, Peters, Riddick, Soustruznik and Vellidas.

2 W Mass Measurement

The W mass receives radiative corrections quadratic in the top mass m_{top} and logarithmic in the Higgs mass m_H. A precise measurement of m_W, in conjunction with a precise measurement of m_{top} and other electroweak Standard Model observables, therefore yields information on the missing parameter m_H. In the event of a Higgs discovery at the Tevatron or LHC, a precise measurement of m_W yields a powerful consistency check that may indicate the presence of physics beyond the Standard Model.

Both CDF and DØ have recently released new measurements of m_W using much larger datasets [1, 2]. Both experiments use leptonic W decays, electrons (CDF & DØ) and muons (CDF). The key observables are the lepton 4-momentum and the hadronic recoil in the transverse plane, $\vec{u}_T$. The neutrino transverse momentum is then inferred from $\vec{p}_T^{\,\nu} = -\left(\vec{p}_T^{\,\ell} + \vec{u}_T\right)$. The greatest information on m_W comes from fitting the transverse mass, defined as :

$$m_T = \sqrt{2 p_T^\ell p_T^\nu \left(1 - \cos(\Delta\phi^{\ell\nu}\right))}$$

although it should be noted that the missing-E_T and lepton p_T distributions are separately fit and combined with the m_T fit taking into account correlations, in order to extract the maximum sensitivity to m_W. The fits to the muon channel in CDF and electron channel in DØ are shown in figures 1 and 2 respectively. The CDF analysis begins with a determination of

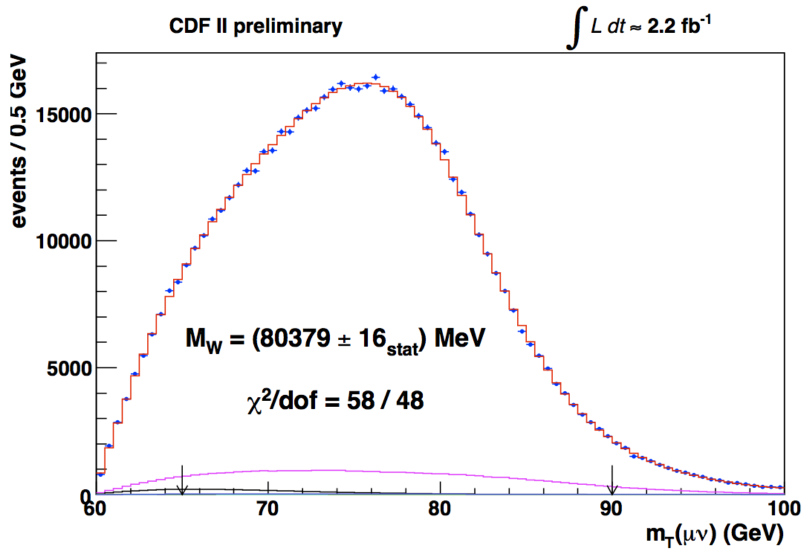

Figure 1: The transverse mass distribution in $W \to \mu\nu$ events in CDF. The data are compared to the summed signal and background (red histogram) with the background contributions indicated by the lower curves.

the momentum scale in the tracker to better than one part in 10,000 using $J/\psi \to \mu\mu$, $\Upsilon \to \mu\mu$ and $Z \to \mu\mu$ samples, where the Z data is only combined after a blinded Z mass measurement is found to be in good agreement with the World Average value. The precise momentum scale is transferred to an electron energy scale by fitting the E/p distribution in $W \to e\nu$ events. Again, the $Z \to ee$ calibration is added after a successful Z mass measurement shows that there is no bias or mid-modelled non-linearity in the electromagnetic energy scale. DØ does not have a high precision momentum scale and so the analysis proceeds only in the electron channel, using the $Z \to ee$ sample to directly calibrate the electron energy scale.

The hadronic event includes contributions from the hadrons balancing the W transverse momentum, the underlying event and any overlapping $p\bar{p}$ collisions in the same bunch crossing. A recoil model simulates the reconstructed highly smeared $\vec{u}_T$ and is calibrated from $Z \to \ell\ell$ and minimum-bias data.

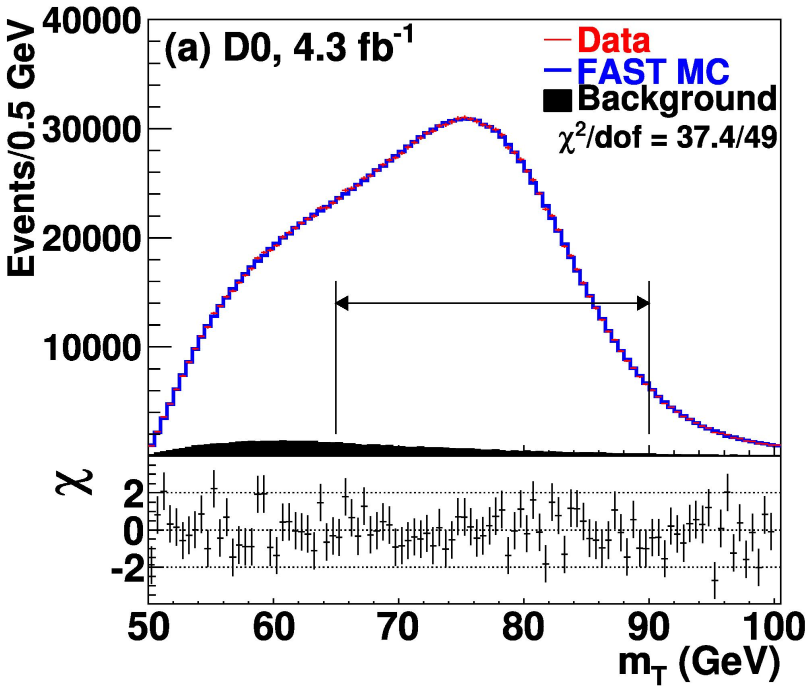

Figure 2: The transverse mass distribution in $W \to e\nu$ events in DØ. The lower signed-χ plot shows the level of agreement between data and simulation.

Signal modelling includes a description of the W and Z production in both the transverse plane (vector boson p_T due to hard and soft gluon emission) and the longitudinal axis (PDF's). QED and electroweak corrections, dominated by final state photon radiation from the charged leptons, are also modelled.

All the aspects of the analysis listed above require painstaking work to ensure that no biases are present and this has taken several years' work by both collaborations. The good χ^2 values evident in figures 1 and 2 are an indication of the success of this program, but hundreds of separate distributions in both signal and control samples are checked during the analysis.

The final results for both CDF and DØ, combined with earlier Run II results, are :

$$m_W = 80387 \pm 19 \text{ MeV} \quad (\text{CDF})$$
$$m_W = 80375 \pm 23 \text{ MeV} \quad (\text{DØ})$$

The CDF measurement is, by itself, more sensitive than the previous world average. These results are compared with other measurements in figure 3, which also indicates a new preliminary world average of $m_W = 80387 \pm 16$ MeV. This represents a 30% smaller uncertainty than the previous world average value of $m_W = 80399 \pm 23$ MeV. This is a major leap in precision and the Tevatron measurements are now clearly dominating the world average for this electroweak observable. The impact of this measurement on indirect determinations of the Higgs mass is discussed in the Conclusions.

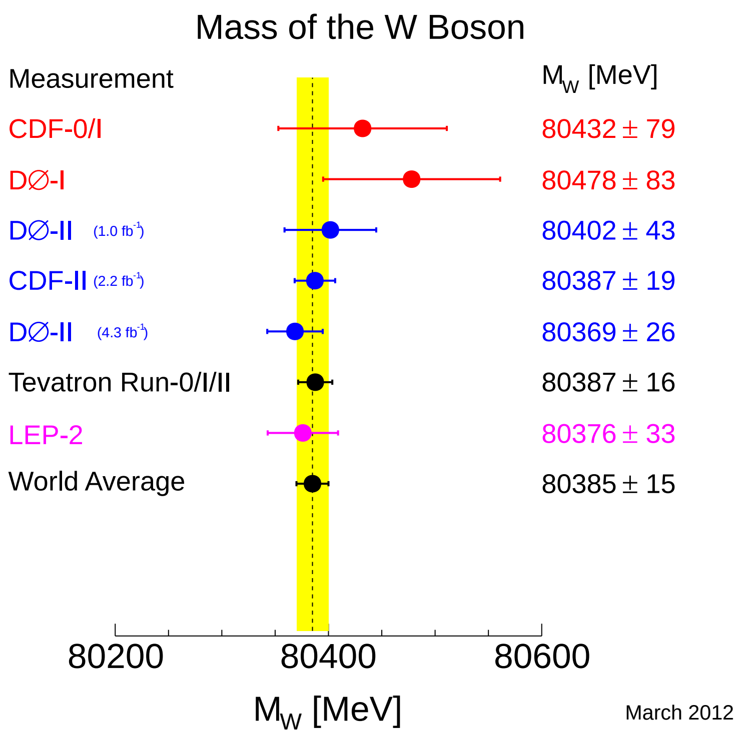

Figure 3: W mass measurements including the new measurements from CDF and DØ and with a preliminary new world average combination. From [3].

The new measurements are compared in precision with earlier Tevatron measurements in figure 4. The measurements lie broadly on a trajectory that scales statistically with a small systematic floor. The CDF Run II measurements are systematically better than the Run I measurements extrapolated to the same luminosity due to essential analysis improvements - most notably agreement between the electron energy scales determined from the W sample via E/p and the $Z \to ee$ sample. The fact that the precision is improving as would be expected statistically does *not* imply that the analyses have been easily updated with larger datasets. In reality whenever a larger dataset is analysed, all of the systematics need to be re-evaluated in order to maintain the observed scaling behaviour. Crucially, the analyses are now beginning to be dominated by production modelling systematics that cannot straightforwardly be reduced with more data. Most importantly, PDF's now represent a common systematic of 10 MeV across experiments and decay channels. Other modelling systematics such as QED are also non-negligible at the $4-7$ MeV level. Therefore future W mass measurements at the Tevatron using the full and final datasets will not continue to scale with luminosity until such systematics can be addressed. In the case of PDF's this may require new parton distributions incorporating new datasets from the Tevatron, LHCb or perhaps other experiments.

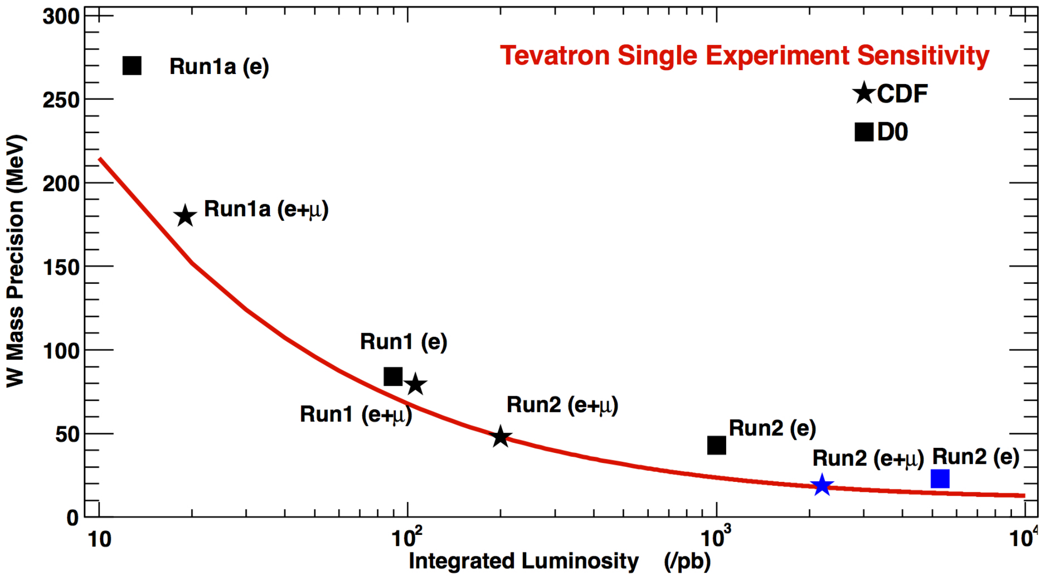

Figure 4: The precision of the measured W mass versus analysed integrated luminosity for a number of CDF and DØ Run I and Run II measurements.

3 Top Mass Measurement

The top quark mass has been directly measured at the Tevatron with significantly better accuracy than predicted at the outset of Run II, with a relative precision now approaching 0.5%. The most sensitive channel is lepton+jets, with one top decaying leptonically and the other hadronically. Dilepton events suffer from poorer statistics and weaker kinematic constraints due to the presence of two undetected neutrinos, while the all-hadronic channel suffers from poorer resolution and additional systematic uncertainties.

A major innovation in measuring the top mass at the Tevatron has been the development of an in-situ jet energy scale determination by applying the constraint that two of the jets in a hadronic top decay should have an invariant mass consistent with the mass of the decaying W boson. The additional constraint thus provided has reduced the jet energy scale systematic by a large factor. Developments have also been made over the years in fitting techniques, which broadly follow two approaches : (i) template fitting, for which a kinematic fit is performed to the $t\bar{t}$ event and a mass distribution is then compared to Monte Carlo templates similarly constructed; (ii) matrix-element methods, which determine the probability of observing kinematic configurations in data given a leading-order true kinematic distribution convolved with PDF's and detector-smearing functions.

The last combination of Tevatron top quark mass measurements was performed in the summer of 2011 and the results are shown in figure 5. The individual measurements used datasets up to 5.8 fb^{-1} in size. The Tevatron combination yields $m_{\rm top} = 173.2 \pm 0.6$ (stat) $\pm$ 0.8 (syst) $= 173.2 \pm 0.9$ GeV. In a similar fashion to the W mass measurement, many of the systematics are statistical in nature and improve with larger datasets. However signal modelling systematics - PDF's, initial & final state gluon radiation, colour-reconnection and

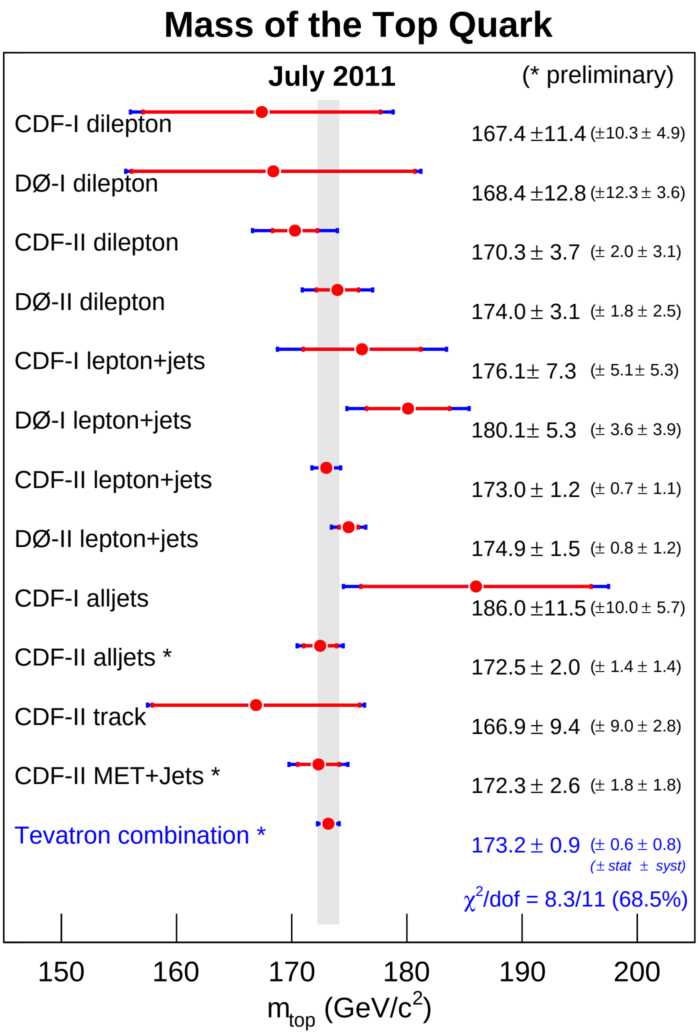

Figure 5: Top quark mass measurements including recent measurements from CDF and DØ with a preliminary world average combination. The individual measurements used datasets up to 5.8 fb^{-1} in size. From [4].

choice of generator - together account for approximately 0.5 GeV out of the total systematic of 0.8 GeV and will not improve in a straightforward way with the addition of more data.

There have been a number of updates in certain top mass measurement channels since the summer 2011 combination. For example the CDF lepton+jets analysis has been extended to 8.7 fb^{-1} and a DØ dilepton analysis on the same 4.3 fb^{-1} dataset has reduced the uncertainty using more sophisticated analysis techniques [5, 6]. Both these analyses show that improvements on the top mass uncertainty of order 10% can still be achieved, giving an indication of the likely size of the final Run II top mass precision.

4 Top Forward-Backward Asymmetry

If the top quark (anti-quark) in $t\bar{t}$ production events is reconstructed with a rapidity of y_t ($y_{\bar{t}}$) then the forward-backward asymmetry with respect to the rapidity difference $\Delta y = y_t - y_{\bar{t}}$ is defined as :

$$A_{FB} = \frac{N(\Delta y > 0) - N(\Delta y < 0)}{N(\Delta y > 0) + N(\Delta y < 0)} \quad .$$

Leading-order production mechanisms should give strictly zero A_{FB}, while new physics (for example a new flavour-changing $t-$channel exchange) can easily give rise to an observable asymmetry. The picture is complicated by the fact that higher-order QCD effects *can* give a small A_{FB} up to $6-7\%$ in the Standard Model. Both CDF and DØ have persistently measured a larger asymmetry than expected, at the $\sim 2-3\sigma$ level [7, 8].

A new analysis from CDF extends the measurement to the full Run II dataset and provides useful empirical parameterisations of A_{FB} as a function of the $t\bar{t}$ invariant mass and Δy [9]. Overall it remains to be seen whether this is really evidence for new physics, or a shortcoming in the analysis or Standard Model calculation of A_{FB}. It is of course interesting to note that no new physics affecting $t\bar{t}$ production has been found *directly* either at the Tevatron or LHC, although it is still conceivable that the different parton-level production sub-processes would make an anomaly more evident in Tevatron data than at the LHC.

5 Tevatron Higgs Searches

In March 2012, the Tevatron released an almost final combined Higgs search in the full Run II dataset [10]. 20 Higgs production and decay channels have been combined, the most important ones using the full luminosity. The result is the culmination of a large number of analysis improvements that have increased signal acceptance and $b-$tagging performance and have brought to bear highly optimised multi-variate analysis techniques. Importantly, a new analysis of Standard Model WZ/ZZ diboson production in identical decay modes to the Higgs signal provides an ideal 'standard candle' and demonstrates good experimental control of relevant experimental variables [11].

For $m_H < 125$ GeV, the Tevatron sensitivity to the Higgs boson is through associated production with a W or Z boson, $VH \to \ell\nu b\bar{b}, \ell^+\ell^- b\bar{b}, \nu\bar{\nu}b\bar{b}$. For higher masses, the decay mode $H \to W^{(*)}W^{(*)}$ provides greatest sensitivity, and is sufficiently distinctive experimentally that the much larger $gg \to H$ production cross section can be exploited. All search channels are carefully combined, taking care not to dilute high-purity search regions with lower-purity regions. No significant signal is evident and therefore an upper limit on the Higgs production cross section is set across the mass range, as shown in figure 6. A particular Higgs mass hypothesis is excluded when the 95% C.L. upper limit on the cross section falls below the Standard Model cross section. This results in the following mass regions being excluded by the Tevatron :

$$100 < m_H < 106 \text{ GeV} \;\; ; \;\; 147 < m_H < 179 \text{ GeV} \quad \text{(observed)}$$
$$100 < m_H < 119 \text{ GeV} \;\; ; \;\; 141 < m_H < 184 \text{ GeV} \quad \text{(expected)}$$

As can be seen, the observed exclusion is somewhat poorer than that expected. The cross section limit is clearly worse than expected for Higgs masses in the range $\sim 110-140$ GeV

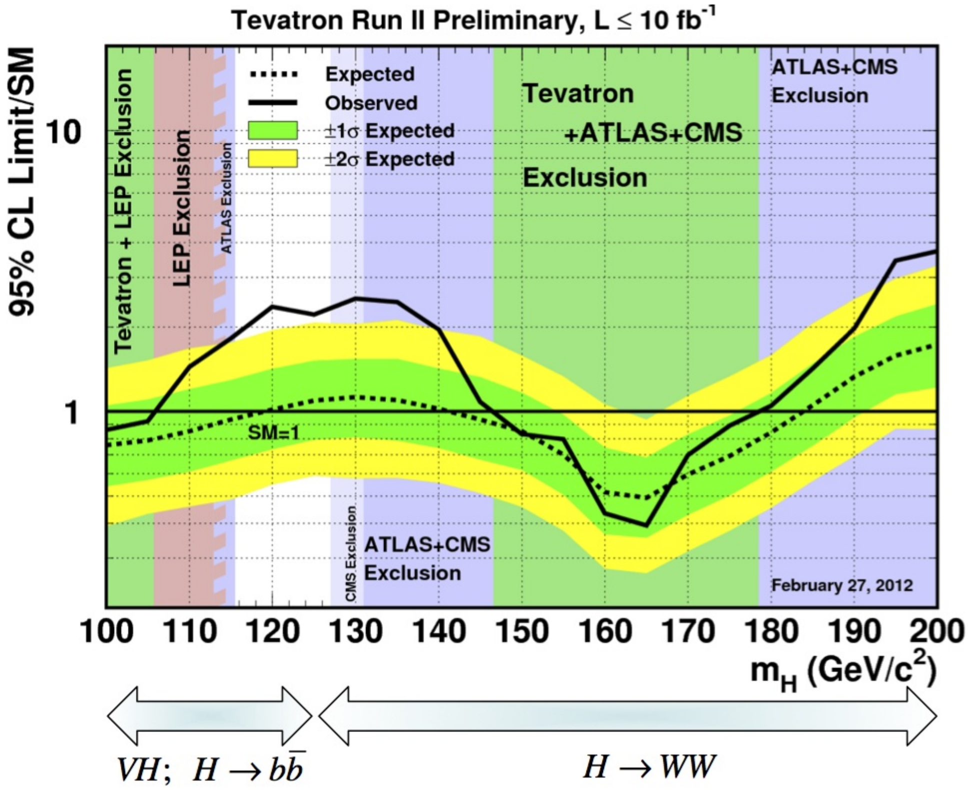

Figure 6: Combined Tevatron 95% C.L. upper limits on the Higgs boson production cross section as a function of Higgs mass, in units of the Standard Model cross section. Also indicated are mass regions already excluded by searches at LEP and the LHC. The arrows beneath the graph indicate the production and decay channels that dominate the sensitivity for different putative Higgs masses at the Tevatron. From [4], annotated.

and this of course would be expected in the presence of a signal, since the expected limits assume *no* signal. The biggest discrepancy is for a Higgs mass of 120 GeV and the probability of a background-only model fluctuating to give an excess at least as large as that observed in the data corresponds to 2.7σ. Taking account of the 'look-elsewhere effect' reduces this discrepancy to approximately 2.2σ, where it is interesting to note that because of the much poorer mass resolution of the low-mass Higgs decay channels exploited at the Tevatron, this statistical penalty is considerably smaller than at the LHC. It is of course extremely intriguing that the mass region of the Tevatron excess is similar to that observed at ATLAS and CMS.

6 Conclusions

The Tevatron era is drawing to a close, but the experiments are still generating world-leading results. New measurements of the W mass from the Tevatron now dominate the world average and the precision in the measurement of the top quark mass that has been achieved in Run II

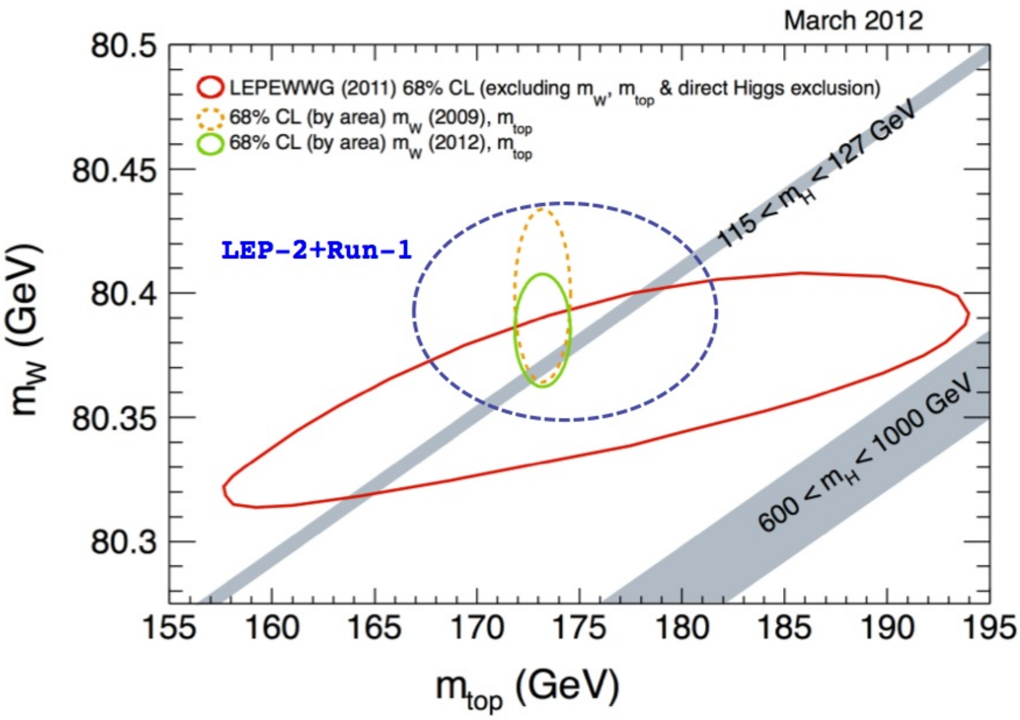

Figure 7: The small green ellipse shows the 1σ allowed region of the $m_W, m_{\rm top}$ plane including the latest direct measurements from the Tevatron. The taller yellow ellipse shows the corresponding constraint before the new 2012 measurements of the W boson mass from CDF and DØ. The large blue-dashed ellipse shows the situation that pertained with just the LEP-2 and Run I measurements, showing the dramatic improvements that have been made during Run II. The red ellipse shows the indirect constraints from other precision electroweak observables, and the grey bands show the allowed Higgs mass ranges from direct searches. All data are consistent with a light Standard Model Higgs.

is extraordinary. Figure 7 shows the impact of the latest measurements of m_W and $m_{\rm top}$ and the striking impact of Run II on these measurements is evident. Feeding the latest direct measurements of m_W and $m_{\rm top}$ into the electroweak fits results in a best fit value $m_H = 94^{+29}_{-24}$ GeV and an upper limit $m_H < 152$ GeV at 95% C.L. [12]. This mass range includes the excesses that are hinted at in direct Higgs searches at both the Tevatron and LHC.

As discussed above, there is scope for both $m_{\rm top}$ and especially m_W measurements from the Tevatron to continue to be improved, although both are now hitting quite hard theoretical systematic limits. They will remain amongst the most important and long-lived legacy measurements from the Tevatron.

7 Acknowledgements

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