Electroweak precise measurements at the Tevatron

Liang HAN
Department of Modern Physics, University of Science and Technology of China, Hefei 230026, China

The fundamental parameters of the Standard Model of particle physics, i.e. the W-boson mass M_W, the top-quark mass m_t and the effective mixing angle $\sin^2\theta^l_{\text{eff}}$, have been intensively measured by the CDF and D0 experiments at the Fermilab Tevatron Collider. Published results from RunII (2001-2011) $9.7 fb^{-1}$ data of $p\bar{p}$ collisions at $\sqrt{s} = 1.96$TeV are combined, and RunI (1992-1996) results of $\sqrt{s} = 1.96$TeV collisions are also used if available. The preliminary combinations yield legacy Tevatron average values as $M_W = 80387 \pm 16$MeV, $m_t = 174.30 \pm 0.65$GeV and $\sin^2\theta^l_{\text{eff}} = 0.23179 \pm 0.00035$.

1 Introduction

In the standard model of particle physics(SM), the electroweak interactions is described by the $SU(2) \times U(1)$ gauge group and the Higgs mechanics of spontaneous symmetry breaking. The theory predicts strict correlations between fundamental physical parameters, especially the fine-structure constant α, the Fermi coupling constant G_F, the Z and W weak vector boson masses M_Z and M_W, the weak mixing angle $\sin^2\theta_W$, the top quark mass m_t, and the Higgs scalar boson mass M_H. These parameters can be independently measured, and thus have the SM electroweak theory over-constrained and be able to precisely tested [1]. For example, the value of M_H can be calculated from M_W, $\sin^2\theta_W$ and m_t, when the values of α, G_F and M_Z are given. Any significant deviation of these parameters between experimental observations and electroweak theory predictions implies new interactions beyond the SM. This paper presents the latest results of M_W, m_t and $\sin^2\theta_W$ measured by the CDF and D0 experiments during the Fermilab Tevatron $p\bar{p}$ collider RunII (2001-2011) at $\sqrt{s} = 1.96$TeV with an integrated luminosity of 9.7 fb^{-1} data, and the combination with results of RunI (1992-1996) at $\sqrt{s} = 1.8$TeV with an integrated luminosity of 0.1 fb^{-1} data,if available.

2 The W-boson mass

At the Tevatron, the W-boson mass is determined by using three kinematic variables perpendicular to the beam direction derived in single W boson production and leptonic decay $p\bar{p} \to W \to l\nu + X$ events, where the charged leptons $l = e, \mu$ are electrons and muons: the transverse momentum of the charged lepton p^l_T, the missing transverse energy $\not{E}^\nu_T$ originating from the neutrino, and the transverse mass $m^l_T = \sqrt{2p^l_T \not{E}^\nu_T(1 - \cos\Delta\phi)}$, where $\Delta\phi$ is the opening angle between the vectors of the p^l_T and $\not{E}^\nu_T$ in transverse plane. The distributions observed from low-background data are compared with those predicted by detector-based Monte Carlo (MC) simulations parameterized as a function of M_W, and the W-boson mass is extracted from

Table 1: Latest Tevatron M_W results: the CDF $2.2fb^{-1}$ $W \to e\nu/\mu\nu$ and the D0 $5.3fb^{-1}$ $W \to e\nu$ measurements.

	$M_W \pm \sigma_{stat.} \pm \sigma_{syst.}$
CDF-II	$80387 \pm 12 \pm 15$ MeV
D0-II	$80376 \pm 11 \pm 20$ MeV

maximum-likelihood fits between data observations and MC templates. Details of the experimental methods of extracting M_W are discussed in Ref.[2].

The latest Tevatron M_W measurements were derived by CDF experiment using $W \to e\nu$ and $W \to \mu\nu$ events collected with $2.2fb^{-1}$ RunII integrated luminosity[3], and D0 experiment using $W \to e\nu$ events collected with $5.3fb^{-1}$ RunII data[4], respectively, as shown in Table 1.

The dominant systematic uncertainties are raised from the parton distribution functions (PDFs) of the W-boson production in the interacting protons and antiprotons and the modeling of W-boson transverse momentum p_T^W, and the detector responses to lepton energy and hadronic recoil, which are calibrated with J/ψ, Y and Z-boson decay into dilepton final states.

The latest CDF and D0 RunII results are then combined with previous RunI measurements, statistically independently and taking into account correlations among systematic uncertainties. The Tevatron combined value of the W-boson mass measurements[5] is

$$M_W(\text{Tevatron}) = 80387 \pm 16 MeV$$

Further combination of the above Tevatron measurements with the LEP M_W average[6] leads to a new world average, with a precision of 15 MeV, as shown in Fig. 1.

$$M_W(\text{World Average}) = 80385 \pm 15 MeV$$

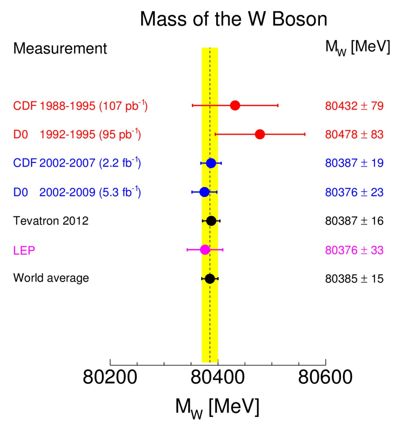

Figure 1 – The W-boson mass measurements performed at the Tevatron and LEP experiments and the new world-average combination

3 The top-quark mass

As the heaviest known elementary particle, the top quark raises the largest Yukawa coupling and play a critical role in the SM consistency check through radiative corrections to the masses of W and Higgs bosons. Therefore, a precise measurement of the top quark mass m_t is one of main physics goals of the Tevatron experiments. The dominant production of the top quark at the Tevatron is the process of top-antitop pair production via light quark annihilation $p\bar{p} \to q\bar{q} \to t\bar{t}$. The direct measurements of the top-quark mass are to extract the m_t value from parameterized MC simulations, based on the full kinematic and topological information in $t\bar{t}$ candidate events selected from data, under an assumption that the top and antitop quark masses are equal. Because of the 100% branching ratio of $t \to bW$ decay, the $t\bar{t}$ events can be catalogued into 4 different channels according to their W boson decay as:

- The "lepton+jets" channel (l+jets): one W boson decays leptonically $W \to l\nu$ ($l = e, \mu$) to an electron or a muon, while the other W boson decay hadronically into two jets. This channel has a branching ratio of around $\sim 30\%$ and a moderate background arising from W+jets, Z+jets and multijet processes;

- The "dilepton" channel (ll'): both W bosons leptonically decay into an electron or a muon final states. This channel is nearly free from background but has only a small fraction of branching ratio $\sim 4.5\%$;

- The “all jets” channel (ll'): both W bosons decay hadronically.This channel has the largest branching ratio of $\sim 46\%$, but suffers significant background from multijet production;
- The “tau-channel”: at least one W bosons decays into $\tau\nu$ final state, which has a branching ratio of $\sim 20\%$.

Due to the moderate yield and relatively low background, the first two channels listed above would provide more sensitivities to $t\bar{t}$ cross-section measurement and m_t extraction than the other channels. Hereinafter, I will present the direct top-quark mass measurements in lepton+jets [8] and dilepton [9] final states performed with D0 RunII data collected with $9.7fb^{-1}$ integrated luminosity as examples, while the CDF experiment has adopted the similar research strategies. These two sensitive channels, in which at least one W boson decays leptonically, require quite many common $t\bar{t}$ event selections: well spacial-separated and high p_T jets and electrons or muons; large $\not{E}_T$ due to escaping neutrinos; one or two jets should be identified as b jets. Good momentum resolution is required for all objects, especially the jet energy scale (JES) has to be known with high precision.

For the lepton+jets channel, 1502 electron and 1286 muon candidates are selected by the D0 experiment with RunII data, in which 918.1 ± 3.6 and 824.9 ± 3.5 $t\bar{t}$ signal events are expected respectively. To extract the value of m_t, event-based probability densities (PDs) are introduced, by using the matrix element (ME) technique [7] under both the $t\bar{t}$ signal and background hypotheses as

$$P_{\text{evt}} \propto f \cdot P_{\text{sig}}(\vec{x}; m_t, k_{\text{JES}}) + (1-f) \cdot P_{\text{bkg}}(\vec{x}; k_{\text{JES}})$$

where $\vec{x}$ represents the measured four-momenta of the four jets and the charged lepton, but not $\not{E}_T$ due to its limited experimental resolution. The signal fraction f is to be determined from data. The constant factor k_{JES} is introduced to reduce JES uncertainty by performing an in situ calibration, which exploits the hadronic $W \to q\bar{q}'$ decay by constraining the invariant mass of the dijet system to be consistent with $M_W = 80.4$ GeV. This in situ JES calibration, determined using light-quark jets, is applied to jets of all flavors associated with $t\bar{t}$ decay, and is propagated to the D0 RunII m_t measurements in dilepton channel. The signal PD function P_{sig} is described by the differential cross-sections of $p\bar{p} \to t\bar{t}$, assumed to be dominated by the ME of the partonic $q\bar{q} \to t\bar{t} \to b(l\nu)\bar{b}(q\bar{q}')$ hard scattering, where the unmeasured neutrino momentum components are integrated out in this computation. The background PD function P_{bgk} is described by the ME of the $q\bar{q} \to W$+jets partonic process. Thereafter, a likelihood function is constructed from the product of the individual P_{evt} values over all selected events. Two dimensional (m_t, k_{JES}) fits are performed on the likelihood function, and the result [8] is given as

$$\begin{aligned} m_t(\text{D0-II lepton+jets}) &= 174.98 \pm 0.58(\text{stat+JES}) \pm 0.49(\text{syst}) \text{ GeV} \\ &= 174.98 \pm 0.76 \text{ GeV} \end{aligned}$$

For the dilepton channel [9], around 340, 115 and 110 events are selected in the $e\mu$, ee and $\mu\mu$ final states respectively, within the full D0 RunII data. The presence of two undetected neutrinos with high p_T in the $t\bar{t}$ decay makes it impossible to fully constrain the kinematics of the final states. Therefore, a neutrino weighting (NW) technique is developed [9] to generate an event-based weight function ω, which is computed by comparing the $x-$ and $y-$components of the observed $\not{E}_T$ with the calculated p_T components of the neutrinos integrating over the neutrino rapidities, for a set of chosen values of hypothesized m_t. This way, a distribution function $\omega(m_t)$ is yielded, of which the first and second moments $[\mu_\omega, \sigma_\omega]$ are most sensitive and used to estimators for likelihood fitting to extract m_t as

$$\begin{aligned} m_t(\text{D0-II dilepton}) &= 173.32 \pm 1.36(\text{stat}) \pm 0.85(\text{syst}) \text{ GeV} \\ &= 173.32 \pm 1.60 \text{ GeV} \end{aligned}$$

All the D0 RunI and RunII direct top-quark mass measurements in the lepton+jets and dilepton channels are combined [10]. Taking the statistical and systematic uncertainties and their correlations among channels into account, the combined D0 average is given as

$$\begin{aligned} m_t(\text{D0 Average}) &= 174.95 \pm 0.40(\text{stat}) \pm 0.64(\text{syst}) \text{ GeV} \\ &= 174.95 \pm 0.75 \text{ GeV} \end{aligned}$$

Following the same combination strategy, the Tevatron average [11] of the CDF and D0 RunI and RunII measurements is derived as

$$\begin{aligned} m_t(\text{Tevatron Average}) &= 174.30 \pm 0.35(\text{stat}) \pm 0.54(\text{syst}) \text{ GeV} \\ &= 174.30 \pm 0.65 \text{ GeV} \end{aligned}$$

which is corresponding to a relative precision of 0.37%.

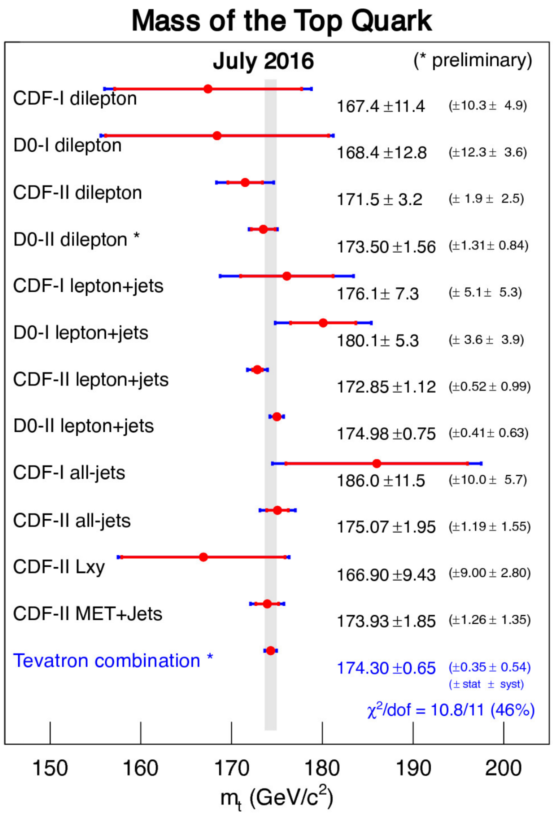

Figure 2 – The preliminary Tevatron combination of direct m_t measurements

4 The weak mixing angle

The weak mixing angle $\sin^2\theta_W$ is one of the fundamental parameters of the SM. It describes the mixing of the coupling constants of the $SU(2) \times U(1)$ gauge group, and consequentially the relative strength of the axial-vector couplings g_A^f to the vector couplings g_V^f in neutral-current interactions of a Z boson to fermions. At the Born level and in all orders of the on-shell renormalization scheme, the parameter is related to the W and Z boson masses as $\sin^2\theta_W = 1 - M_W^2/M_Z^2$. To include higher order electroweak radiative corrections, flavor-specified weak mixing angles are defined as

$$\sin^2\theta_{eff}^f = \frac{1}{4|Q_f|}\left(1 - \frac{g_V^f}{g_A^f}\right)$$

Table 2: Published Tevatron $\sin^2\theta^l_{\rm eff}$ measurements: the CDF results are given in the frame of NNPDF3.0 and running NLO radiative corrections, while the D0 is given with NNPDF2.3 and NLO electroweak corrections fixed at the Z-pole.

	$\sin^2\theta_W \pm \sigma_{stat.} \pm \sigma_{syst.} \pm \sigma_{PDF}$	Total uncertainty
CDF-II $Z(\mu\mu)$	$0.2315 \pm 0.0009 \pm 0.0002 \pm 0.0004$	± 0.0010
CDF-II $Z(ee)$	$0.23248 \pm 0.00049 \pm 0.00004 \pm 0.00019$	± 0.00053
D0-II $Z(ee)$	$0.23147 \pm 0.00043 \pm 0.00008 \pm 0.00017$	± 0.00047

It is customary to quote the charged lepton effective weak mixing angle $\sin^2\theta^l_{\rm eff}$, which has been accurately measured from CP-violating observables around the Z boson pole at the LEP and SLD e^+e^- experiments [12]. The combined LEP and SLD average gives a value of 0.23149 ± 0.00016. However, there is tension between the two most precise individual measurements: the LEP b-quark forward-backward charge asymmetry of 0.23221 ± 0.00029, and the SLD left-right polarization asymmetry of Z-boson production of 0.23098 ± 0.00026, differ by 3.2 standard deviations. Therefore, an independent determination of the effective weak mixing angle is an important precision test of the SM electroweak breaking mechanism.

At the Tevatron, the mixing angle can be measured in the Drell-Yan $p\bar{p} \to Z/\gamma^* \to l^-l^+$ ($l = e, \mu$) process, through a forward-backward charge asymmetry in the distribution of the emission angle θ^* of the negatively charged lepton momentum relative to the incoming quark momentum, defined in the rest frame of the dilepton final state. The number of events within $\cos\theta^* > 0$ are classified as forward N_F, while the number of events within $\cos\theta^* < 0$ as backward N_B, and the forward-backward charge asymmetry is defined by

$$A_{FB} = \frac{N_F - N_B}{N_F + N_B}$$

The A_{FB} distribution as a function of the invariant mass of the dilepton system measured from data, is compared with parameterized leading order (LO) simulation templates to extract the $\sin^2\theta_W$ at Born-level. This extracted value is further interpreted to the effective mixing angle with certain schemes of the PDF algorithm and the next-to-leading order (NLO) electroweak radiative corrections. The CDF and D0 Collaborations have achieved precise $\sin^2\theta^l_{\rm eff}$ measurements in $Z \to \mu\mu$ [13] and $Z \to ee$ [14,15] final states respectively, with the full Tevatron RunII data.

The CDF has its two measurements published in schemes of NNPDF3.0 and running NLO electroweak radiative corrections on the effective mixing angle;while the D0 result of electron channel is reported in schemes of NNPDF2.3 and NLO corrections fixed at the Z-pole. Converting the D0 result into the CDF PDF and NLO radiative correction schemes, the three measurements of the CDF electron and muon final states and the D0 electron channel are combined to give a Tevatron preliminary as

$$\begin{aligned}\sin^2\theta^l_{\rm eff}(\text{Tevatron Preliminary}) &= 0.23179 \pm 0.00030(stat.) \pm 0.00017(syst.)\\ &= 0.23179 \pm 0.00035\end{aligned}$$

Recently, the D0 experiment has finished the weak mixing angle measurement in $p\bar{p} \to Z \to \mu\mu$ events collected with RunII $8.6 fb^{-1}$ data. The effective mixing angle is extracted from the A_{FB} asymmetry as a function of the dimuon invariant mass around the Z pole, and interpreted with NNPDF3.0 and NLO electroweak corrections fixed at the Z-pole. The preliminary result [17] of the D0 dimuon measurement is given as

$$\begin{aligned}\sin^2\theta^l_{\rm eff}(\text{D0-II dimuon}) &= 0.23002 \pm 0.00059(stat.) \pm 0.00011(syst.) \pm 0.00027(PDF)\\ &= 0.23002 \pm 0.00066\end{aligned}$$

5 Summary

I have presented the combinations of measurements of the SM fundamental parameters M_W, m_t and $\sin^2\theta_W$ performed by the Tevatron CDF and D0 experiments, dominantly with RunII $9.7 fb^{-1}$ data and RunI results if available. These parameters are extracted by comparing sensitive experimental observables measured from data with those predicted by parameterized simulations:

the W-boson mass is extracted from lepton p_T, missing energy $\not{E}_T$ and transverse mass m_T distributions in the $W \to l\nu$ $(l = e, \mu)$ channels; the top-quark mass is measured by using full kinematic and topological information of $t\bar{t}$ events; and the effective weak mixing angle is measured from the forward-backward charge asymmetry distributions in Drell-Yan $p\bar{p} \to Z/\gamma^* \to l^-l^+$ final states. The preliminary results of Tevatron combinations are

$$
\begin{aligned}
M_W &= 80387 \pm 16 \text{ MeV} \\
m_t &= 174.30 \pm 0.65 \text{ GeV} \\
\sin^2\theta^l_{\text{eff}} &= 0.23179 \pm 0.00035
\end{aligned}
$$

Where the direct m_t measurements yield a relative precision of 0.37%; and the accuracies of the final Tevatron M_W and $\sin^2\theta^l_{\text{eff}}$ results are expected to be improved with the completeness of CDF and D0 W-boson mass measurements with the full RunII dataset, and by including the D0 effective mixing angle measurement in dimuon channel, respectively.

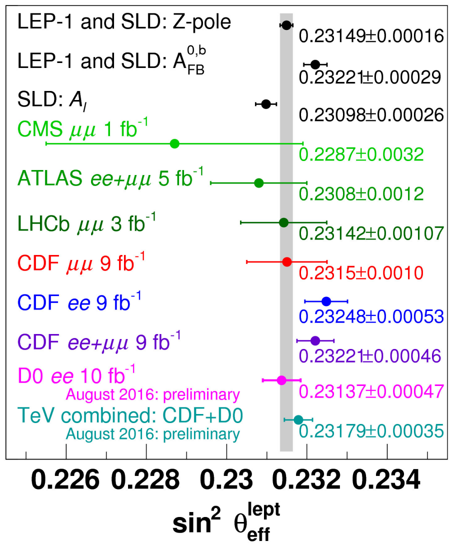

Figure 3 – The preliminary Tevatron combination of $\sin^2\theta^l_{\text{eff}}$ measurements and comparison to LEP/SLD and LHC experiments.

References

1. Particle Data Group, *Chin. Phys.* C **40**, 100001 (2016).
2. A.V. Kotwal and J. Stark, *Annu. Rev. Nucl. Part. Sci.* **58**, 147 (2008).
3. T. Aaltonen et al. (CDF Collaboration), *Phys. Rev. Lett.* **108**, 151803 (2012).
4. V. M. Abazov et al. (D0 Collaboration), *Phys. Rev. Lett.* **108**, 151804 (2012).
5. T. Aaltonen et al. (CDF and D0 Collaboration), *Phys. Rev.* D **88**, 052018, (2013).
6. S. Schael et al. (LEP and SLD Collaborations), *Phys. Rep.* **427**, 257 (2006).
7. K. Kondo, *J. Phys. Soc. Jpn.* **57**, 4126 (1988).
8. V. M. Abazov et al. (D0 Collaboration), *Phys. Rev.* D **91**, 112003 (2015).
9. V. M. Abazov et al. (D0 Collaboration), *Phys. Lett.* B **752**, 18 (2016).
10. V. M. Abazov et al. (D0 Collaboration), *arXiv:* **1703**.06994v1.
11. The CDF and D0 Collaborations, *arXiv:* **1608**.01881v1.
12. The LEP and SLD Collaboration, *Phys. Rept.* **427**, 257 (2006).
13. T. Aaltonen et al. (CDF Collaboration), *Phys. Rev.* D **89**, 072005 (2014).
14. T. Aaltonen et al. (CDF Collaboration), *Phys. Rev.* D **93**, 112016 (2016).
15. V. M. Abazov et al. (D0 Collaboration), *Phys. Rev. Lett.* **115**, 041801 (2015).
16. The CDF and D0 Collaborations, *Fermilab-Conf*-**16**-295-E.
17. The D0 Collaborations, *DØnote* **6497**-CONF.