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Measurements and combination of $sin^2\theta_{\rm eff}^{\rm lept}$ at the Tevatron and extraction of the W mass

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We present the combination of measurements of the effective-leptonic weak mixing angle parameter $sin^2\theta_{\rm eff}^{\rm lept}$ from the CDF and D0 experiments using the full Tevatron data sets, corresponding to 9-10 fb^{-1} of $p\bar{p}$ collisions. The inference of the standard model weak mixing angle parameter $sin^2\theta_W$ and equivalent indirect measurement of M_W based on ZFITTER calculations is also made, yielding the combination results

$$\begin{aligned} \sin^2\theta_{\rm eff}^{\rm lept} &= 0.23148 \pm 0.00033, \\ \sin^2\theta_W &= 0.22324 \pm 0.00033, \text{ and} \\ M_W &= 80.367 \pm 0.017 \text{ GeV}/c^2. \end{aligned}$$

These Tevatron measurements are consistent with the world-best measurements from electron-positron colliders. The uncertainties include statistical and systematic contributions and represent the best precision from hadron colliders, which nearly matches that of the best electron-positron individual measurements.

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1. Introduction

At Fermilab's Tevatron, Drell-Yan lepton pairs [1] are produced through the reaction $q\bar{q} \to \gamma^*/Z \to \ell^+\ell^-$ in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV. The polar angle distribution of the lepton pairs is related to the weak-mixing angle through the Born-level Z boson vector coupling, $g_V^f = I_3 - 2Q_f sin^2\theta_W$. To all orders of the on-shell renormalization scheme, $sin^2\theta_W = 1 - M_W^2/M_Z^2$, and with M_z known to high precision (± 0.0021 GeV/c^2 [2, 3]), a $sin^2\theta_W$ inference is equivalent to an indirect M_W measurement. The Born-level couplings are altered by weak-interaction radiative corrections of a few percent to give the effective weak-mixing parameter, $sin^2\theta^{\rm lept}_{\rm eff}$. The world average of six individual measurements is 0.23149 ± 0.00016. However, there is a 3.2 standard-deviation difference between the two most precise measurements from LEP-1 and SLD [2, 3]. Consequently, there is a strong motivation for an accurate determination of $sin^2\theta^{\rm lept}_{\rm eff}$ by the Tevatron experiments.

The angular distribution of leptons is analyzed in the Collins-Soper rest frame of the γ^*/Z, in which the polar angle ϑ is defined as the angle of the ℓ^- relative to the incoming quark direction [4]. Events are designated forward (backward) if $\cos\vartheta \geq 0$ ($\cos\vartheta < 0$). The angular distribution expression consisting of nine helicity cross section terms reduces to $dN/d\Omega \propto 1 + \cos^2\vartheta + A_4\cos\vartheta$ [5, 6] after integrating over the azimuthal angle at zero transverse momentum. The forward-backward asymmetry as a function of the dilepton mass, M, is

$$A_{\rm fb}(M) = \frac{\sigma^+(M) - \sigma^-(M)}{\sigma^+(M) + \sigma^-(M)} = \frac{3}{8}A_4(M), \tag{1.1}$$

where $\sigma^{+(-)}$ is the forward (backward) cross section, and the parity violating A_4 is sensitive to the weak mixing angle through Z vector-axial vector self-interference.

The CDF [7] and D0 [8, 9, 10] detectors are general-purpose instruments for hadron collision measurements. They feature central charged-particle tracking in solenoid fields, electromagnetic and hadronic calorimetry, and outer muon identification systems. Both experiments measure $A_{\rm fb}$ using high-$p_{\rm T}$ electron and muon pairs. Each of the four separate analyses is carried out in four steps: measure $A_{\rm fb}$ in bins of M, produce simulation templates of $A_{\rm fb}(M, sin^2\theta_W)$ at several values of the weak-mixing angle, perform full corrections to data and simulation, and extract $sin^2\theta^{\rm lept}_{\rm eff}$ with a χ^2 comparison to determine the prediction that best fits the measured $A_{\rm fb}(M)$ distribution.

2. CDF measurements

The CDF measurements include results from the muon [11] and electron [12] channels using the full Tevatron Run II data set consisting of 9 fb^{-1} of integrated luminosity. A key feature of the $A_{\rm fb}$ measurements is a data-driven event-weighting method [13], which effectively combines individual measurements in bins of $|\cos\vartheta|$. The asymmetry in a given bin is

$$A_{\rm fb} = \frac{N^+/(\varepsilon A)^+ - N^-/(\varepsilon A)^-}{N^+/(\varepsilon A)^+ + N^-/(\varepsilon A)^-}, \tag{2.1}$$

where $N^{+(-)}$ and $(\varepsilon A)^{+(-)}$ are the event count, and the efficiency and acceptance product, respectively, of forward (backward) lepton pairs. Because the detector is charge symmetric to first order, and interchanging the lepton charges reverses the sign of $\cos\vartheta$ without changing the detector cells traversed by the pair or the lepton momentum in a cell, the (εA) dependence cancels so that

$$A_{\text{fb}} = \frac{N^+ - N^-}{N^+ + N^-}\,. \tag{2.2}$$

Event weights in the numerator and denominator remove angular dependencies and provide the appropriate statistical weight for combining events across $|\cos\vartheta|$ regions. To maintain sufficiently low statistical uncertainty with the event-weighting method, the kinematic acceptance is limited in the muon channel to the central pseudorapidity region ($|\eta_{\text{det}}| < 1$) for both muons. In the electron channel, one electron must be central ($0.05 < |\eta_{\text{det}}| < 1.05$) while the other can be either in the central or forward ($1.2 < |\eta_{\text{det}}| < 2.8$) region.

Drell-Yan event simultion uses PYTHIA 6.2 [14], CTEQ5L [15] PDFs, and PHOTOS 2.0 [16] to generate events, followed by a GEANT-3 and GFLASH [17] detector simulation. The data and simulation energy scales are calibrated to a common standard following Ref. [18]. Additional tuning is done to enable an accurate detector-resolution unfolding of A_{fb} in mass and $\cos\vartheta$ for the data, which removes the effects of resolution smearing and QED FSR. Backgrounds from W+jets, $\gamma^*/Z \to \tau\tau$, diboson (WW, WZ, and ZZ), and $t\bar{t}$ events are estimated with PYTHIA 6.2. QCD dijet backgrounds are determined from data. The overall background level is 0.5% for the muon channel and 1.1% for the electron channel. The A_{fb} templates are calculated using next-to-leading-order (NLO) POWHEG-BOX [19, 20] with PYTHIA 6.41 [21] and NNPDF 3.0 [22] next-to-next-to-leading order (NNLO) PDFs. An enhanced Born approximation (EBA) to the electroweak couplings is provided by ZFITTER 6.43 [23] form factor corrections for the effective couplings.

The muon-channel [11] result is $\sin^2\theta^{\text{lept}}_{\text{eff}} = 0.2315 \pm 0.0009(\text{stat}) \pm 0.0002(\text{syst}) \pm 0.0004$ (PDF), and the result is $\sin^2\theta^{\text{lept}}_{\text{eff}} = 0.23248 \pm 0.00049(\text{stat}) \pm 0.00004(\text{syst}) \pm 0.00019(\text{PDF})$ for the electron channel [12]. In both cases, the PDF uncertainty dominates the other systematic uncertainties which include contributions from the energy scale and resolution, the backgrounds, and the QCD scale. The CDF result combining electron and muon channels [12] is

$$\sin^2\theta^{\text{lept}}_{\text{eff}} = 0.23221 \pm 0.00043(\text{stat}) \pm 0.00007(\text{syst}) \pm 0.00016(\text{PDF}). \tag{2.3}$$

3. D0 measurements

The D0 measurement consists of $\sin^2\theta^{\text{lept}}_{\text{eff}}$ results in the electron [24] and muon [25] channels using 9.7 fb^{-1} and 8.6 fb^{-1} of recorded luminosity, respectively. Leptons are accepted over wide η_{det} ranges for electrons ($|\eta_{\text{det}}| < 1.1$ in the central calorimeter (CC) and $1.5 < |\eta_{\text{det}}| < 3.2$ in the end calorimeter (EC)) and muons ($|\eta_{\text{det}}| < 1.8$), resulting in very high statistics samples.

Signal events are generated using PYTHIA 6.23 [14] with NNPDF 2.3 [26] PDFs for the electron channel and NNPDF 3.0 PDFs for the muon channel, followed by a GEANT-based detector simulation [27]. At D0, solenoid and toroid magnet polarities are reversed every two weeks on average, so samples for the four different polarity combinations are generated and used to model the corresponding data samples separately. Samples are weighted to correspond to equal luminosity exposures for each polarity combination, providing cancellation of asymmetries due to detector response and acceptance variations. New methods of electron energy and muon momentum calibration are developed, including scale and offset parameters applied to electron energy as functions of

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$\eta_{\rm det}$ and instantaneous luminosity, and a muon momentum scale factor dependent on charge, $\eta_{\rm det}$, and solenoid polarity. These reduce energy and momentum modeling systematic uncertainties to negligible levels. The combination of backgrounds from multijet events determined from the data and $W+$jets, $\gamma^*/Z\to\tau\tau$, diboson, and $t\bar{t}$ events estimated with ALPGEN [28] and PYTHIA 6.23 find overall background levels in the electron and muon channels to be 0.35% and 0.88%, respectively. The $A_{\rm fb}$ templates are calculated using PYTHIA 6.23 with NNPDF 2.3 (electron channel) and NNPDF 3.0 (muon channel), and reweighted to incorporate higher-order QCD effects. Electron channel $A_{\rm fb}$ distributions are obtained separately for CC-CC, CC-EC, and EC-EC event categories.

The electron-channel result obtained from combining the three electron event categories is $\sin^2\theta^{\rm meas}_{\rm eff}=0.23139\pm0.00043({\rm stat})\pm0.00008({\rm syst})\pm0.00017({\rm PDF})$. Non-PDF sources of systematic uncertainty include energy calibration and smearing, backgrounds, and charge and electron misidentification [24]. The extraction from the muon channel gives $\sin^2\theta^{\rm meas}_{\rm eff}=0.22994\pm0.00059({\rm stat})\pm0.00005({\rm syst})\pm0.00024({\rm PDF})$. Systematic uncertainties stem from momentum calibration and smearing, backgrounds, and muon misidentification [25]. The CDF and D0 analyses differ in the methods used for weak-interaction radiative corrections and in the use of NNPDF 2.3 for the D0 electron-channel measurement. Corrections are applied to the D0 $\sin^2\theta^{\rm lept}_{\rm eff}$ values above to standardize the Tevatron results for combination.

The D0 $A_{\rm fb}$ templates are calculated with PYTHIA, which uses the same fixed $\sin^2\theta_{\rm eff}$ value for all fermions. The CDF templates use ZFITTER weak-interaction corrections and the fermion-loop correction to the photon propagator, which are complex valued and mass-scale dependent. The difference between the two approaches is found to be $\Delta\sin^2\theta^{\rm lept}_{\rm eff}({\rm ZFITTER})=+0.00022\pm0.00004$. A D0 study comparing NNPDF 2.3 and NNPDF 3.0 ensembles finds a difference in extracted $sin^2\theta^{\rm lept}_{\rm eff}$ values requiring a correction, $\Delta\sin^2\theta^{\rm lept}_{\rm eff}({\rm PDF})=-0.00024\pm0.00004$, to standardize the D0 NNPDF 2.3 electron measurement to one made with NNPDF 3.0. Applying $\Delta\sin^2\theta^{\rm lept}_{\rm eff}({\rm PDF})$ to the electron-channel result and $\Delta\sin^2\theta^{\rm lept}_{\rm eff}({\rm ZFITTER})$ to both channels, yields the corrected values of $\sin^2\theta^{\rm lept}_{\rm eff}=0.23137\pm0.00043({\rm stat})\pm0.00009({\rm syst})\pm0.00017({\rm PDF})$ for electrons and $\sin^2\theta^{\rm lept}_{\rm eff}=0.23016\pm0.00059({\rm stat})\pm0.00006({\rm syst})\pm0.00024({\rm PDF})$ for muons. Combining the corrected D0 electron- and muon-channel results gives

$$\sin^2\theta^{\rm lept}_{\rm eff}=0.23095\pm0.00035({\rm stat})\pm0.00007({\rm syst})\pm0.00019({\rm PDF}). \tag{3.1}$$

4. CDF and D0 combination

The final CDF and D0 results are combined using the "best linear unbiased estimate" (BLUE) method [29], yielding a Tevatron combination value of

$$\sin^2\theta^{\rm lept}_{\rm eff}=0.23148\pm0.00027({\rm stat})\pm0.00005({\rm syst})\pm0.00018({\rm PDF}). \tag{4.1}$$

The PDF uncertainties are treated as 100% correlated and all other systematic uncertainties are considered to be uncorrelated. The combination weights are 0.42 for the CDF input and 0.58 for the D0 input, with the combination χ^2 probability being 2.6%. To infer $sin^2\theta_W$ (and equivaently, M_W) from the direct measurement of $sin^2\theta^{\rm lept}_{\rm eff}$, the relationship $\sin^2\theta^{\rm lept}_{\rm eff}={\rm Re}[\kappa_e(\sin^2\theta_W,M_Z^2)]\sin^2\theta_W$ and a ZFITTER calculation of the form factor ${\rm Re}[\kappa_e]$ are required. This gives the Tevatron combination values $\sin^2\theta_W=0.22324\pm0.00026\pm0.00019$ and $M_W=80.367\pm0.014\pm0.010$ GeV$/c^2$,

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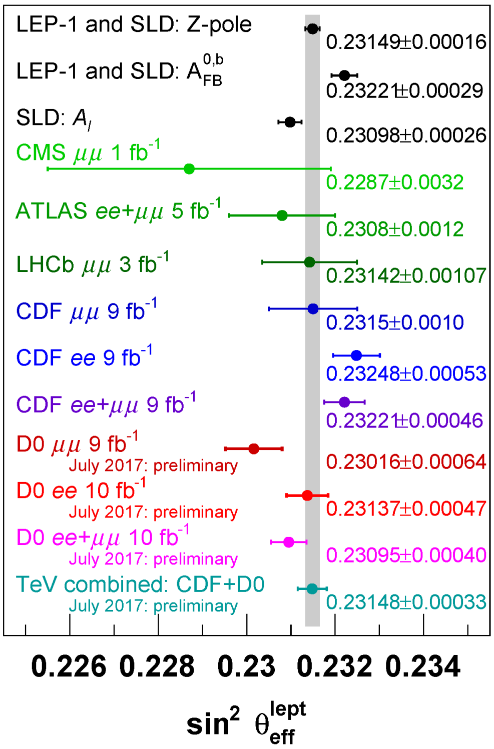

Figure 1: Comparison of experimental measurements of $\sin^2\theta^{lept}_{eff}$. The horizontal bars represent total uncertainties.

where the first contribution to each uncertainty is statistical and the second is systematic. The Tevatron measurements of $\sin^2\theta^{lept}_{eff}$ are compared with previous results in Fig. 1. The indirect W-boson mass determination is compared in Fig. 2 with previous direct and indirect measurements.

5. Conclusions

We report on the combination of $sin^2\theta^{lept}_{eff}$ measurements from the CDF and D0 experiments in both the electron and muon channels using the full Tevatron RunII data set. We also make indirect determinations of $sin^2\theta_W$ (M_W) based on standard model calculations. The combination results are

$$\sin^2\theta^{lept}_{eff} = 0.23148 \pm 0.00033, \quad (5.1)$$
$$\sin^2\theta_W = 0.22324 \pm 0.00033, \text{ and} \quad (5.2)$$
$$M_W = 80.367 \pm 0.017 \text{ GeV}/c^2 . \quad (5.3)$$

These represent the best precision from hadron colliders, nearly matching the best individual measurements from LEP-1 and SLD. While not resolving the long-standing 3.2σ difference between those results, the Tevatron value for $sin^2\theta^{lept}_{eff}$ perhaps removes some of the tension due to the fact that it falls squarely on the world average, and is consistent with both. The 17 MeV/c^2 uncertainty on the Tevatron indirect measurement of M_W comes very close to the uncertainty on the combination of direct measurements from the Tevatron and LEP-2.

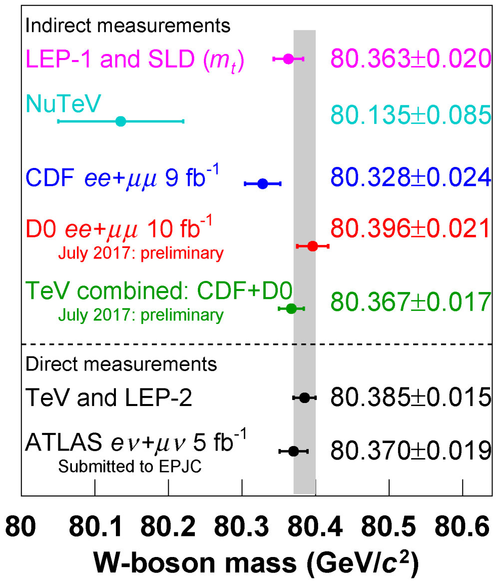

Figure 2: Comparison of experimental determinations of the W-boson mass. The horizontal bars represent total uncertainties.

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