Using Drell-Yan A_{FB} to constrain PDFs

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We show that measurements of the forward-backward charge asymmetry ($A_{FB}(M,y)$) of Drell-Yan dilepton events produced at hadron colliders provide a new powerful tool to constrain Parton Distribution Functions (PDFs). PDF uncertainties are the dominant source of systematic error in precision measurements at hadron colliders (e.g. $\sin^2 \theta_{eff}(M_Z)$, $\sin^2 \theta_W = 1 - M_W^2/M_Z^2$ and the mass of the W boson). We show that the χ^2 values of fits to extract $\sin^2 \theta_{eff}^{lept}(M_Z)$ from $A_{FB}(M,y)$ with different PDF replicas can be used to place additional constraints on PDFs. In turn, using these constrained PDFs significantly reduces the PDF errors in precision measurements of electroweak parameters. The measurement of the on-shell $\sin^2 \theta_W = 1 - M_W^2/M_Z^2$ is equivalent to an indirect measurement of the W mass. The errors in this indirect measurement of the W mass are competitive with direct measurements. For example, with 200 fb^{-1} at 13 TeV, the expected error in the indirect measurement of the W mass is ± 9 MeV.

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Within the standard model, measurements of the mass of the *Z* boson and top quark, in combination with the mass of the Higgs boson, can be used to predict the mass of the W boson. At present, the average of all direct measurements of the mass of the W boson (80385±15 MeV) is about one standard deviation higher than the prediction of the standard model. Predictions of supersymmetric models for the W mass are also higher than the predictions of the standard model. Therefore, more precise measurements of the mass of the W boson are of great interest.

Alternatively, the W mass can also be extracted indirectly from measurements of the on-shell electroweak mixing angle $\sin^2\theta_W$ by using the relation $\sin^2\theta_W = 1 - M_W^2/M_Z^2$. Measurements of the forward-backward charge asymmetry in Drell-Yan dilepton events produced at hadron colliders (in the region of the *Z* pole) have been used to measure the value of the *effective* electroweak (EW) mixing angle $\sin^2\theta_{eff}^{lept}(M_Z)$[1, 2, 3, 4]. In addition, by incorporating electroweak radiative corrections in the analysis the CDF collaboration has also measured the *on-shell* EW mixing angle $\sin^2\theta_W$[1, 2]. An error of ±0.00030 in the measurement of $\sin^2\theta_W$ is equivalent to an indirect measurement of the W mass to a precision of ±15 MeV. However, the PDF error quoted in the most recent measurement of $\sin^2\theta_{eff}$ by the ATLAS collaboration[4] at the LHC is ±0.00090. Therefore, a significant reduction in the PDF errors is needed. Here, we show how A_{FB} data (both at the Tevatron and LHC) also provide a new powerful tool to constrain PDFs. Addition details can be found in Ref. [5].
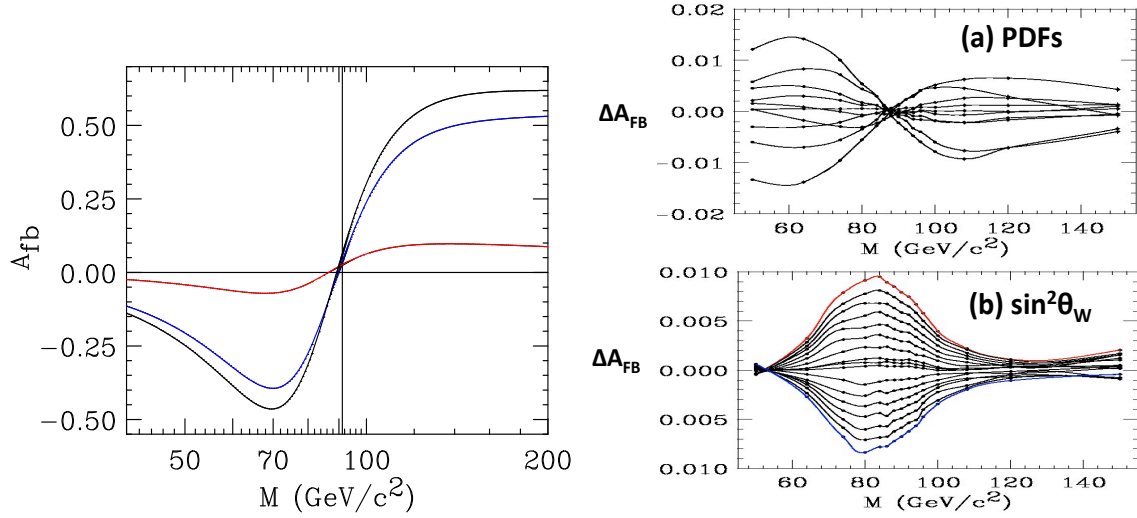

Figure 1: Left panel: $A_{FB}(M)$ at the Tevatron for $\bar{u}u$ (black), $\bar{d}d$ (red) and the sum of the two (blue). Right panel: (a) The difference between $A_{FB}(M)$ at the Tevatron for 10 NNPDF3.0 replicas and $A_{FB}(M)$ calculated for the default NNPDF3.0. Here $\sin^2\theta_W$ is fixed at a value of 0.2244. (b) The difference between $A_{FB}(M)$ for different values of $\sin^2\theta_W$ ranging from 0.2220 (shown at the top in red) to 0.2265 (shown on the bottom in blue), and $A_{FB}(M)$ for $\sin^2\theta_W$=0.2244. Here, the NNPDF3.0 default PDF is used.

For $\bar{p}p$ collisions, the direction of the quark is predominately in the proton direction, and the direction of the antiquark is predominately in the antiproton direction. Here, most of the cross section originates from the annihilation of quarks in the proton with antiquarks in the antiproton. Therefore, A_{FB} is measured under the assumption that the quarks originate form the proton, and the antiquarks originate from the antiproton.

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The extraction of $\sin^2\theta_{eff}^{lept}$ from $A_{FB}(M)$ at the Tevatron is sensitive to PDFs for two reasons. First, $A_{FB}(M)$ for up and down type quarks is different as shown in Fig. 1. The asymmetry at the Tevatron originates primarily from up quarks and is diluted by the fraction of down quarks in the proton because the asymmetry for down quarks is much smaller. In addition, there is a small fraction of events for which the annihilation is between sea antiquarks in the proton with a sea quarks in the antiproton. This also results in a dilution of the measured asymmetry.

The mass dependence of $A_{FB}(M)$ depends on both $\sin^2\theta_W$ and on PDFs In the region of the Z pole, $A_{FB}(M)$ is sensitive to the vector coupling, which depend on $\sin^2\theta_W$. At higher and lower mass $A_{FB}(M)$ is sensitive to the axial coupling and therefore insensitive to value of $\sin^2\theta_W$. In contrast, the magnitude of the dilution of $A_{FB}(M)$ depends on the PDFs. The sensitivity to PDFs is largest in regions where $A_{FB}(M)$ is large (i.e. away from the Z pole).
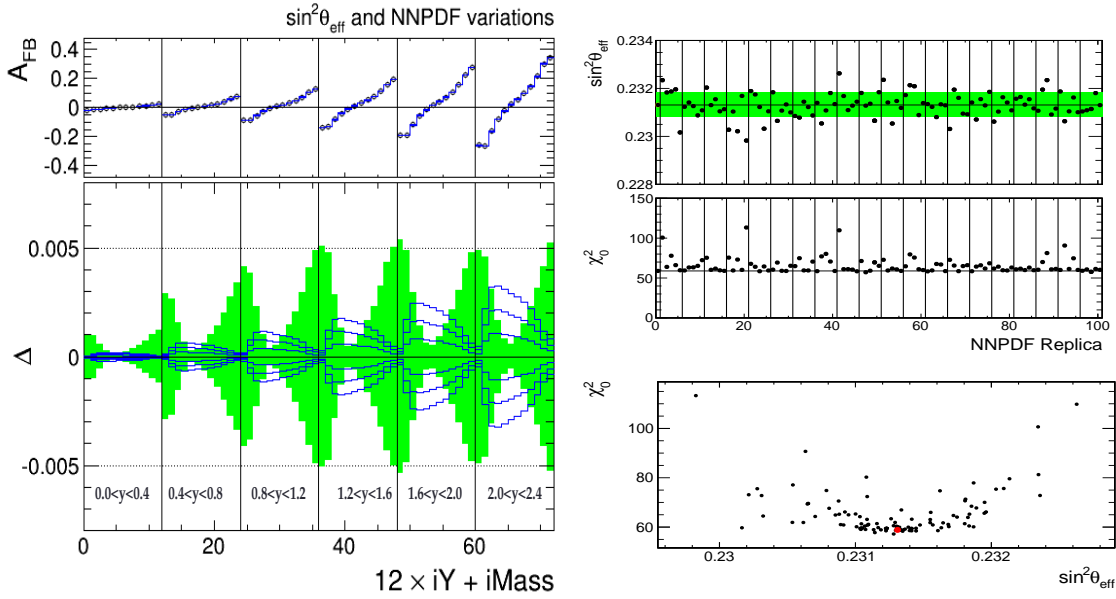

Figure 2: LHC: Left-Top panel- A_{FB} at the LHC at $\sqrt{s}$=8 TeV for six rapidity bins. The horizontal scale for each of the six plots is the $\mu^+\mu^-$ invariant mass. Left-Bottom panel : The green bands span the difference between $A_{FB}(M,y)$ calculated for the 100 NNPDF3.0 replicas and $A_{FB}(M,y)$ calculated for the central default NNPDF3.0 for the six $\mu^+\mu^-$ rapidity bins. The blue lines are the differences between $A_{FB}(M,y)$ calculated with different values of $\sin^2\theta_{eff}$ and the values calculated with nominal $\sin^2\theta_{eff}$=0.23120. Right-Top panel. Analysis of one of the 64 LHC pseudo experiments The top two panels show the extracted $\sin^2\theta_{eff}$ and corresponding χ^2_{AFB} values from fits to $A_{FB}(M,y)$ versus replica number for the 100 NNPDF3.0 replicas. The Right-Bottom panel shows the same results in the form of a scatter plot of χ^2_{AFB} values versus $\sin^2\theta_{eff}$ for one pseudo experiment.

The right panel of Fig. 1 shows the sensitivity of $A_{FB}(M)$ at the Tevatron to PDFs. Also shown is the sensitivity of $A_{FB}(M)$ at the Tevatron to $\sin^2\theta_W$. There is a large difference in the $A_{FB}(M)$ predictions for PDF sets with different $\frac{d}{u}(x)$ and $\frac{\bar{u}}{u}(x)$ in regions where $A_{FB}(M)$ is large and positive (M>100 GeV). The changes in $A_{FB}(M)$ in regions where $A_{FB}(M)$ is large and negative (M<80 GeV) are the opposite direction. In contrast, different values of $\sin^2\theta_W$ change $A_{FB}(M)$ primarily in the region near the Z pole. However, here the change is in the same direction above

and below the Z pole. Therefore, if we extract $\sin^2 \theta_W$ from $A_{FB}(M)$ data using different PDFs, PDFs with poor values of χ^2 are less likely to be correct.

The Left-Top panel of Fig. 2 shows $A_{FB}(M,y)$ at the LHC at $\sqrt{s}$=8 TeV for six rapidity bins (i=1 to 6) with average y values of 0.2, 0.6, 1.0, 1.4, 1.8 and 2.2. The horizontal scale for each of the six plots is the $\mu^+\mu^-$ invariant mass. The calculations are done with the POWHEG MC generator. The version of POWHEG that is used does not include electroweak radiative corrections. Therefore, POWHEG requires an input value of $\sin^2 \theta_{eff}$ for the calculation of A_{FB}. The green bands span the difference between $A_{FB}(M,y)$ calculated with the 10 NNPDF3.0 replicas and $A_{FB}(M,y)$ calculated with the default NNPDF3.0 PDF. The blue lines are the differences between $A_{FB}(M,y)$ calculated for several values of $\sin^2 \theta_{eff}$ and $A_{FB}(M,y)$ for the nominal $\sin^2 \theta_{eff}$=0.23120. For all of the blue lines, $A_{FB}(M,y)$ is calculated with the default NNPDF3.0 PDF.

At the LHC, as for the Tevatron, the dependence of $A_{FB}(M,y)$ on $\sin^2 \theta_{eff}$ and on PDFs is different. In the region of the Z pole, $A_{FB}(M,y)$ is sensitive to the vector coupling, which are functions of $\sin^2 \theta_{eff}$. At higher and lower mass $A_{FB}(M,y)$ is sensitive to the axial coupling and therefore insensitive to value of $\sin^2 \theta_{eff}$. As is the case for the Tevatron, the magnitude of the dilution of $A_{FB}(M)$ is larger in regions where the absolute value of $A_{FB}(M)$ is large (i.e. away from the Z pole). At the LHC the dilution depends on both M and y. The combined mass and rapidity dependence of the dilution at the LHC provides more stringent constraints on PDFs than $A_{FB}(M)$ measurements at the Tevatron.

The NNPDF3.0 PDF set is given in the form of N (e.g. 100 or 1000) replica PDFs. Each of the PDF replicas has equal probability of being correct. The central value of any observable is the average of the values extracted using each one of the N PDF replicas. The PDF error is the RMS of the values extracted using each of the N replicas.

One advantage of the PDF replica method is that constraints from new data can easily be incorporated in any analysis by using different weights for each replica. Replicas for which the theory predictions are in agreement with the new data are given higher weights, and replicas for which the predictions are in poor agreement are given lower weights. The weights are derived from the χ^2 values of the comparison between the new data and theory prediction using each of the PDF replicas. The central value of any observable is then the *weighted* average of the values extracted using each one of the N PDF replicas. The PDF error is the *weighted* RMS of the values extracted using each of the N replicas.

The procedure of constraining a PDF set with new data was initially proposed by Giele and Keller[8]. They proposed that each of the N PDF replicas be *weighted* by w_i, and the weights reduce the effective number of replicas[11] from N to N_{eff}. Here

$$w_i = \frac{e^{-\frac{1}{2}\chi_i^2}}{\frac{1}{N}\sum_{i=1}^{N} e^{-\frac{1}{2}\chi_i^2}}; \qquad N_{eff} = exp(\frac{1}{N}\sum_{i=1}^{N} w_i \, ln(N/w_i))$$

More recent discussions of the method can be found in references [6, 7, 9, 10, 11]. The mass and rapidity dependence of A_{FB} can be used to both provide additional constraints on PDFs and reduce the PDF error in measurements of $\sin^2 \theta_W$.

For studies of $A_{FB}(M,y)$ at the LHC we simulate Drell-Yan $\mu^+\mu^-$ data for 64 pseudo experiments for a CMS like detector at $\sqrt{s}$=8 TeV. The pseudo data is generated using the POWHEG NLO MC generator with the default NNPDF3.0 PDFs and $\sin^2 \theta_{eff}$=0.23120.

Table 1: Values of $\sin^2\theta_W$ with statistical errors and PDF errors expected for a 15 fb^{-1} Drell-Yan $\mu^+\mu^-$ sample at the LHC (at 8 TeV). The pseudo data is generated by the POWHEG MC generator with the default NNPDF3.0 PDF, and $\sin^2\theta_{eff}$=0.23120. The PDF error for a standard analysis is compared to the PDF error for an analysis with both χ^2_{AFB} *weighting* and $\chi^2_{AFB}+\chi^2_{Wasym}$ *weighting*. In addition, expected errors for larger statistical samples are shown.

input POWEG Default NNPDF3.0 (261000)	LHC CMS like Pseudo-Exp. 15 fb^{-1} 8 TeV 6.7M ($\mu^+\mu^-$) reconst. events	LHC CMS like Pseudo-Exp. 19 fb^{-1} 8 TeV 15M ($\mu^+\mu^-$, e^+e^-) reconst. events	LHC CMS like Pseudo-Exp. 200 fb^{-1} 13 TeV 120M ($\mu^+\mu^-$) econst. events
$\sin^2\theta_{eff}$ statistical error $\sin^2\theta_{eff}$ CT10 PDF error	±0.00050 $\pm$ 0.00080	±0.00034	±0.00011
NNPDF3.0 Average PDF error RMS	$N_{eff}=100$ ±0.00051		
χ^2_{AFB} *weighting* *weighted* PDF error RMS	$N_{eff}=46$ ±0.00029		
$\chi^2_{AFB}+\chi^2_{Wsym}$ *weighting* *weighted* PDF error RMS	$N_{eff}=21$ ±0.00026	$\pm$ 0.00022	±0.00014
$\Delta\sin^2\theta_{eff}$ Stat+PDF ΔM_W indirect Stat+PDF	±0.00056 ±28 MeV	±0.00040 $\pm$ 20 MeV	±0.00018 ±9 MeV

For each pseudo experiment, we generate a sample of 15.6 Million $\mu^+\mu^-$ events with $M_{\mu\mu} >$ 50 GeV, which corresponds to an integrated luminosity of 15.0 fb^{-1}. This is similar to the $\approx$19 fb^{-1} of integrated luminosity collected by CMS and ATLAS at 8 TeV. To this sample, we apply acceptance and transverse momentum cuts which are similar to a CMS-like detector. We also smear the events with a muon momentum resolution similar to a CMS-like detector. The final sample consists 6.7M reconstructed $\mu^+\mu^-$ events.

The 8 TeV W asymmetry data at the LHC has not yet been incorporated into the most recent PDF fits. Therefore, in addition to $A_{FB}(M,y)$, we also use the default NNPDF3.0 PDF to generate pseudo data for the W decay muon asymmetry as a function of muon rapidity (for muon transverse momentum PT>25 GeV). This simulates the W asymmetry measurement at 8 TeV.

In the analysis of each of the 64 pseudo experiments generated with the default NNPDF3.0 PDF the simulated values of $A_{FB}(M,y)$ for each experiment are compared to $A_{FB}(M,y)$ templates. The templates are generated with the POWHEG MC for a range of values of $\sin^2\theta_{eff}$ for each of the 100 NNPDF3.0 PDF replica. For each replica we extract the best fit value of $\sin^2\theta_{eff}$, the corresponding statistical error and the fit χ^2_{AFB}.

In addition, we calculate χ^2_{Wasym} which is the χ^2 for the agreement between the predictions for the W lepton decay asymmetry and the W decay lepton asymmetry pseudo data at 8 TeV for each of the 100 PDF replicas.

The right panels of Fig. 2 shows the results from one of the 64 pseudo experiments at the

LHC. The top two panels on the right show the extracted $\sin^2 \theta_{eff}$ and corresponding χ^2_{AFB} values from fits to $A_{FB}(M, y)$ versus replica number for the 100 NNPDF3.0 replicas. The bottom panel on the right shows the same results in the form of a scatter plot of χ^2_{AFB} values versus $\sin^2 \theta_{eff}$ for one pseudo experiment. For each pseudo experiment we find the mean value and PDF error of $\sin^2 \theta_{eff}$ from the average and RMS of the $\sin^2 \theta_{eff}$ extracted values using each of the 100 PDF replicas. The average and RMS values are done in three ways: (1) Using the standard average and RMS of the $\sin^2 \theta_{eff}$ fit values. This analysis results in a standard PDF error of ± 0.00051 with 100 replicas. (2) Using the χ^2_{AFB} values of the fits to $A_{FB}(M, y)$ to form a *weighted* average and *weighted* RMS of the $\sin^2 \theta_{eff}$ values. This analysis results in a PDF error of ± 0.00029 with 46 effective replicas. (3) Using the combined $\chi^2_{AFB} + \chi^2_{Wasym}$ for the fits to Drell-Yan $A_{FB}(M, y)$ pseudo data and the fits to the W lepton decay asymmetry pseudo data to form the *weighted* average and *weighted* RMS of the $\sin^2 \theta_{eff}$ values. This analysis results in a PDF error of ± 0.00026 with 21 effective replicas.

Table 1 shows values of $\sin^2 \theta_W$ with statistical errors and PDF errors expected for a 15 fb^{-1} Drell-Yan $\mu^+ \mu^-$ sample at the LHC (at 8 TeV). The pseudo data is generated by the POWHEG MC generator with the default NNPDF3.0 PDF, and $\sin^2 \theta_{eff} = 0.23120$. The PDF error for a standard analysis is compared to the PDF error for an analysis with both χ^2_{AFB} *weighting* and $\chi^2_{AFB} + \chi^2_{Wasym}$ *weighting*. As shown in Table 1, the number of effective PDF replicas is reduced when we apply constraints from χ^2_{AFB} and χ^2_{Wasym}. Therefore, the analysis will be more robust if we start with 1000 PDF replicas.

Also shown are the expected errors for larger statistical samples. With larger statistical samples, the PDF constraints are more stringent, and the PDF errors are also reduced. The errors in this indirect measurement of the W mass are competitive with direct measurements. For example, with 200 fb^{-1} at 13 TeV, the expected error in the indirect measurement of the W mass is ± 9 MeV. Additional details and studies for both the Tevatron and LHC are give in ref. [5].

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