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Forward-backward asymmetry in $Z \to \mu^+\mu^-$ and determination of the effective electroweak mixing angle

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Summary. — The LHCb experiment offers a complementary phase space region to ATLAS and CMS to study electroweak processes, thanks to the precision in the forward acceptance, corresponding to the pseudo-rapidity range $2 < \eta < 5$. Here the measurement of the leptons asymmetry in the decay $Z \to \mu^+\mu^-$, performed using data collected by LHCb during the LHC Run I data taking, is presented. By studying this asymmetry LHCb determined the effective electroweak mixing angle, with the highest precision of the LHC experiments.

1. – Introduction

The electroweak mixing angle θ_W is a fundamental parameter of the Standard Model electroweak Lagrangian: it quantifies the relative strength between the electromagnetic and the weak forces. It can be measured at experiments such as those at colliders. Therefore, the experimental measurement can be used as input value of the Standard Model, in order to produce predictions for precision Physics.

θ_W governs the couplings of the Z boson with fermions: these couplings differ for right-handed and left-handed fermions. This difference leads to an asymmetry in the angular distribution between negative and positive leptons.

By studying the lepton asymmetry it is possible to measure the quantity $\sin^2\theta_W^{\text{eff}}$, where θ_W^{eff} is called effective electroweak mixing angle. $\sin^2\theta_W^{\text{eff}}$ is also defined by the axial and vector-axial coupling constants of the Z boson to the fermions and it is proportional to $\sin^2\theta_W$ [1].

$\sin^2\theta_W^{\text{eff}}$ has been measured by several experiments: a summary of these measurements is presented in fig. 1. The most precise measurements have been performed at electron-positron colliders, in particular by the LEP experiments [1] and by the SLD experiment

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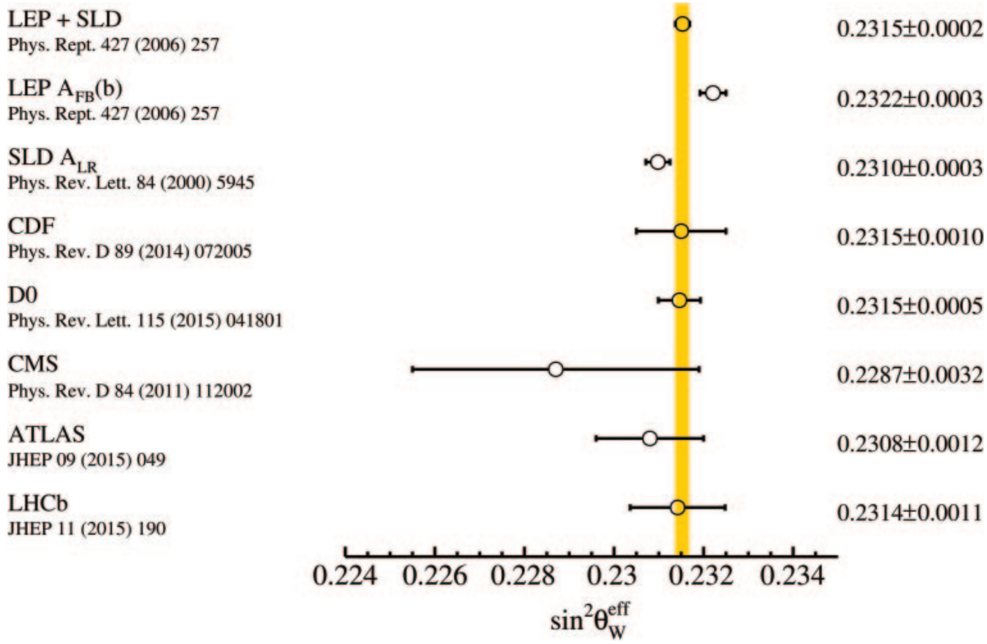

Fig. 1. – Summary of $\sin^2\theta_W^{\rm eff}$ measurements.

at SLAC [2]. $\sin^2\theta_W^{\rm eff}$ has been measured also at the hadron colliders: at the Tevatron, by CDF [3] and D0 [4] collaborations, and at the LHC, by ATLAS [5], CMS [6] and LHCb [7] collaborations.

The $\sin^2\theta_W^{\rm eff}$ measurement performed by LHCb [8], using data collected in 2011 and 2012, corresponding to an integrated luminisity of $1.0\,{\rm fb}^{-1}$ at $\sqrt{s} = 7\,{\rm TeV}$ and $2.0\,{\rm fb}^{-1}$ at $\sqrt{s} = 8\,{\rm TeV}$, is described in this article.

2. – LHCb detector and experimental setup

The LHCb detector [8] is a single-arm forward spectrometer covering the pseudo-rapidity range $2 < \eta < 5$. The detector includes a tracking system consisting of a silicon-strip vertex detector, a large-area silicon-strip detector located upstream of a dipole magnet with a bending power of about 4 Tm, and three stations of silicon-strip and straw drift tubes located downstream of the magnet. The resolution on charged particles momentum is 0.8% at high momentum [9]. LHCb includes also a particle identification system consisting of two ring imaging cherenkov detectors, of a calorimeter system composed of a pre-shower scintillating-pad detector, an electromagnetic calorimeter and a hadronic calorimeter, and of a system of gas chambers for muons identification. The muon identification efficiency is of about 97% [9].

3. – Forward-backward asymmetry in $Z \to \mu^+\mu^-$

The determination of the effective electroweak mixing angle by LHCb has been performed by measuring the forward-backward asymmetry in the decay $Z \to \mu^+\mu^-$. The

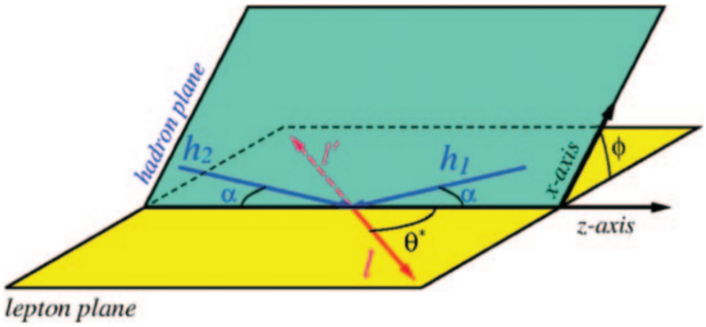

Fig. 2. – Schematic representation of the Collins-Soper frame. The angle θ^*, the two leptons and the two interacting hadrons are indicated.

contribution of virtual photons decaying into two muons is not negligible and it is included in the measurement. The asymmetry is measured in the Collins-Soper frame [10], represented in fig. 2: the angle θ^* is defined as the angle between the negatively charged muon momentum vector and the z-axis, in the dimuon rest frame; the z-axis is defined by the direction that bisects the quark momentum vector and the negative of the anti-quark momentum vector. The differential Z cross section as a function of θ^*, at leading order in the Standard Model, is given by the following expression:

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\cos\theta^*} = A(1+\cos^2\theta^*) + B\cos\theta^*; \quad (1)$$

where A and B depend on the dimuon mass, the quarks color charge and the couplings. The forward-backward asymmetry is proportional to B, and it is defined as

$$A_{\mathrm{FB}} = \frac{N_{\mathrm{F}} - N_{\mathrm{B}}}{N_{\mathrm{F}} + N_{\mathrm{B}}}; \quad (2)$$

where N_{F} is the number of forward decays, with $\cos\theta^* > 0$, and N_{B} is the number of backward decays, with $\cos\theta^* < 0$.

At LHC the direction of the incoming parton is not known, and the z axis of the Collins-Soper frame is taken parallel to the bisection of the two vector momenta of the colliding protons. However, the main processes of Z production are $u\bar{u} \to Z$ and $d\bar{d} \to Z$, where one valence quark at high transverse momentum interacts with a sea anti-quark with low transverse momentum: the Z boson tends to be produced boosted along the quark direction. As the Z boson in the forward acceptance has a larger boost than in the central acceptance, the LHCb experiment, measuring a larger A_{FB}, has a better sensitivity to $\sin^2\theta_W^{\mathrm{eff}}$ with respect to ATLAS and CMS.

4. – Events selection

The events selection is described in [11]. Two opposite charge particles identified as muons are selected as dimuon events. Each muon is required to have a pseudo-rapidity in the $2.0 < \eta < 4.5$ range, and a transverse momentum greater than 20 GeV. The dimuon invariant mass must be in the $60 < M_{\mu\mu} < 160$ GeV range. The $Z/\gamma^* \to \mu^+\mu^-$ sample selected with these criteria has a purity of 99%, estimated using a combination

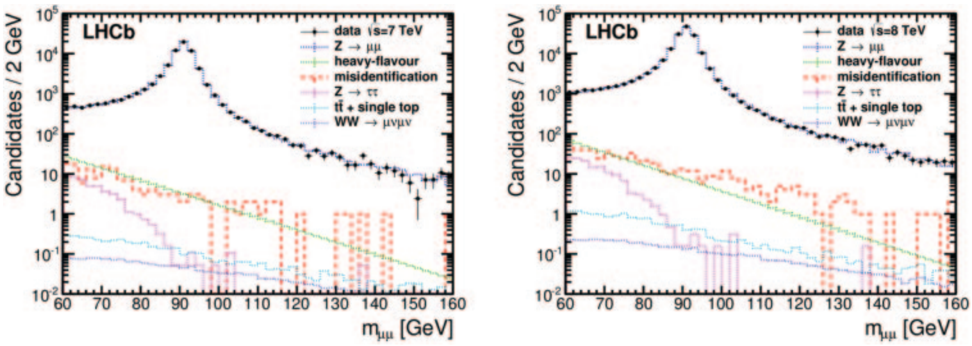

Fig. 3. – Invariant-mass distribution of selected $Z/\gamma^* \to \mu^+\mu^-$ events from the 7 TeV and 8 TeV dataset. Distributions of main background sources are displayed.

of data-driven and simulation techniques [11]. The main background contributions come from heavy flavour semi-leptonic decays and hadrons mis-identified as muons. This last backgroud source can be originated by the hadronic punch-through from the calorimeters to the muon chambers. The punch-through is primarily due to pions and includes also pions decays in flight. Other background sources, such as $Z \to \tau^+\tau^-$, $t\bar{t}$, single top and $W^+W^- \to \mu^+\nu_\mu\mu^-\bar{\nu_\mu}$ are taken into account as well. The invariant mass distribution of selected data events, for the 7 TeV and the 8 TeV samples, together with the estimated background distributions, is displayed in fig. 3.

5. – Asymmetry unfolding

The raw asymmetry is determined by applying the forward-backward asymmetry definition to the selected data events. In order to obtain the measured true asymmetry, several corrections are applied.

First, the raw asymmetry is corrected for trigger, tracking and muon identification efficiencies: previous studies [11] on control data samples, performed using tag and probe techniques, have shown a dependence of these efficiencies from the muon pseudo-rapidity. It has been demonstrated that these corrections are almost negligible.

Momentum biases originating from remaining misalignments in the detector are corrected by studying the dependence of the Z mass peak on the azimuthal direction of the tracks [12].

An unfolding bayesian technique is applied to obtain the true asymmetry from the raw asymmetry [13]. The algorithm is trained on a $Z/\gamma^* \to \mu^+\mu^-$ simulation sample, after smearing the track momenta to reproduce the Z mass resolution observed in the data.

Finally background contributions to the asymmetry that are evaluated using simulation are subtracted. Even this last correction is almost negligible.

The main experimental systematic sources for the asymmetry measurement are related to the different steps presented above and they are displayed on table I: the dominant error is the one related to the momentum correction.

The measured asymmetry, obtained in bins of dimuon invariant mass with the procedure described above, is presented in fig. 4 for the 7 TeV and 8 TeV data sample, with experimental errors. The theoretical prediction, obtained with the POWHEG-BOX gen-

TABLE I. – *Summary of experimental systematic sources and their avarage effect on $A_{\rm FB}$.*

Source of uncertainty	$\sqrt{s} = 7\,$TeV	$\sqrt{s} = 8\,$TeV
curvature/momentum scale	0.0102	0.0050
data/simulation mass resolution	0.0032	0.0025
unfolding parameter	0.0033	0.0009
unfolding bias	0.0025	0.0025

erator [16], is also displayed in these plots: this prediction uses a $\sin^2\theta_W^{\rm eff}$ equal to the PDG world average [14]. Data are consistent with theory within the experimental and theoretical errors.

6. – Determination of the electroweak mixing angle

The determination of the effective electroweak mixing angle is done by comparing the measured forward-backward asymmetry with different predictions: several simulation samples are generated for different values of $\sin^2\theta_W^{\rm eff}$ [15]. Final State Radiation (FSR) effects are also applied to these samples. The generation has been performed using POWHEG-BOX [16] at Next-to-Leading-Order in QCD, interfaced with Pythia 8 [17], using NNPDF2.3 Parton Distribution Functions (PDFs) [18] and setting $\alpha_s(M_Z) = 0.118$ [14]. Changing generators does not give a significant change in the determined value of $\sin^2\theta_W^{\rm eff}$. A χ^2 comparison is made between these simulation samples and the measured $A_{\rm FB}$ as a function of the dimuon mass. The minimum χ^2 sets the favoured value of $\sin^2\theta_W^{\rm eff}$. Several sources of systematic error must be taken into account in the theoretical predictions: the uncertainties on the PDFs, the uncertainty on α_S, the uncertainties on the FSR corrections and the uncertainty on the renormalization and factorization scale. The effect of these systematic sources on the $A_{\rm FB}$ prediction are presented on table II: the dominant uncertainty is due to uncertainties in the PDFs.

The χ^2 parabolas for the 7 TeV data, the 8 TeV data and the combination of the two samples are displayed in fig. 5. The mininum of the combined χ^2, corresponding to the

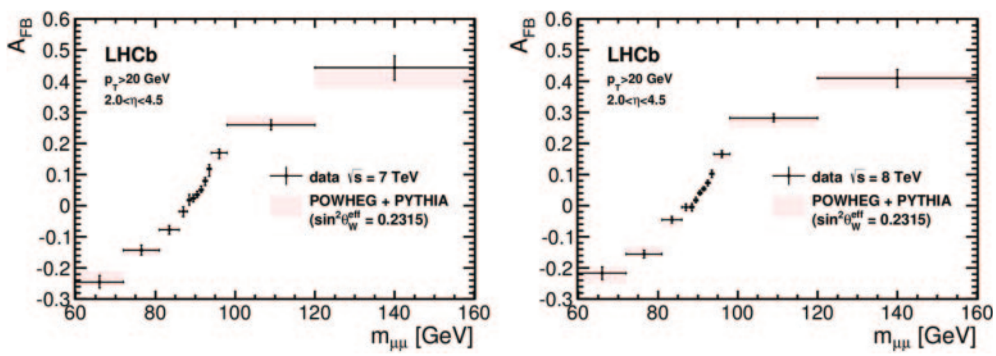

Fig. 4. – Measured asymmetry and theoretical prediction in bins of dimuon invariant mass, for the 7 TeV and the 8 TeV dataset. The prediction is obtained using a value of $\sin^2\theta_W^{\rm eff}$ equal to the world average.

TABLE II. – *Summary of theoretical systematic sources and their average effect on A_{FB} prediction.*

Uncertainty	Average $\Delta\lvert A_{\mathrm{FB}}^{\mathrm{pred}}\rvert$
PDF	0.0062
scale	0.0040
α_s	0.0030
FSR	0.0016

measured $\sin^2\theta_W^{\mathrm{eff}}$, with statistical, experimental and theoretical errors is

$$\sin^2\theta_W^{\mathrm{eff}} = 0.23142 \pm 0.00073(\mathrm{stat.}) \pm 0.00052(\mathrm{syst.}) \pm 0.00056(\mathrm{th.}). \tag{3}$$

7. – Conclusions

$\sin^2\theta_W^{\mathrm{eff}}$ has been measured by the LHCb experiment, for the 7 TeV dataset, the 8 TeV dataset and the combination of the two samples, by studying the forward-backward asymmetry in the $Z/\gamma^+ \to \mu^+\mu^-$ decay. The LHCb measurement is consistent with the PDG world average [14] and it is one of the most precise at hadron colliders: in particular it is the most precise measurement at the LHC, thanks to the forward acceptance. The uncertainty is expected to be reduced by updating the measurement with data collected during the LHC Run II campaign, since it is currently dominated by the statistical error. The theoretical error on the Parton Distribution Functions will be reduced after the release of new PDFs sets constrained with new LHC data. With increased statistics the measurement could be also performed in bins of Z boson rapidity, to increase the sensitivity to $\sin^2\theta_W^{\mathrm{eff}}$. On the other hand, the diluition of A_{FB} from knowledge of the

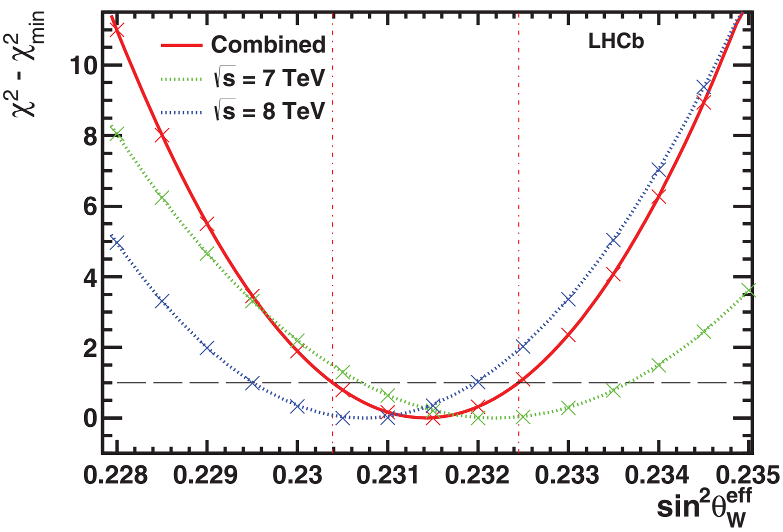

Fig. 5. – χ^2 obtained from the comparison between data and simulation samples generated with different values of $\sin^2\theta_W^{\mathrm{eff}}$, for the 7 TeV data, the 8 TeV data and the combination of the two samples.

direction of the initial state quark is expected to increase by about 5% between 8 TeV and 14 TeV proton-proton collisions.

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