IL NUOVO CIMENTO **47 C** (2024) 253
DOI 10.1393/ncc/i2024-24253-2

COMMUNICATIONS: SIF Congress 2023

Prospects for measuring A^b_{FB} at the ATLAS experiment at the LHC and at the FCC-ee

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received 20 February 2024

Summary. — Standard Model parameter determinations are still not satisfactory from LEP measurements, which can be better defined with the new measurements performed with ATLAS. Preliminary studies based on simulated events and part of the LHC Run-2 data collected by the ATLAS experiment are presented, where the suggestion of a new experimental determination of the asymmetry A^b_{FB} is given. Furthermore a feasibility study on the A^b_{FB} measurement in the production of a $b\bar{b}$ pair from a decaying Z boson at the FCC-ee, with a parametric detector simulation tuned to the current design parameters of the IDEA detector and of the FCC-ee accelerator are also discussed. All these studies show that measurements competitive or even more precise than that at LEP are in reach.

1. – Introduction

In the electroweak sector of the Standard Model, some discrepancies are still present due to the lack of precision in the LEP measurements. For example, the two most precise determinations of the Weinberg angle, $\sin^2\theta_W$, are in $\sim 3\sigma$ tension with each other, the largest deviation in global electroweak fits [1,2]. They come from the LEP measurement of the b-quark forward-backward asymmetry at the Z-boson pole, A^b_{FB}, and from the SLD measurement of the parameter A_ℓ. To shed light on this discrepancy, a new experimental determination of A^b_{FB} will certainly be beneficial. A possible measurement of A^b_{FB} at the LHC will be discussed, considering the process $pp \to Zb$, with $Z \to e^+e^-, \mu^+\mu^-$, explaining the possibility of identifying the b-jet charge either using constituent tracks information or exploiting the charge of soft muons from B-hadron decays.

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2. – The b-quark forward-backward asymmetry in the Standard Model

In the SM, the b-quark forward-backward asymmetry can be defined in the process $e^+e^- \to Z \to b\bar{b}$, taking advantage of parity violation in the decay of the Z boson, causing the emitted anti-fermion ($\bar{b}$) being directed preferentially along the direction of the Z-boson spin, with the fermion (b) in the opposite direction. It is defined as

$$A^b_{\rm FB} = \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B}, \tag{1}$$

where σ_F is the cross-section for fermions emitted in the hemisphere centred along the direction of the electron beam, while σ_B is for fermions in the opposite hemisphere. It can also be expressed in terms of the Z-boson chiral couplings with left-handed and right-handed fermions, g_L and g_R, using the relation $A^b_{\rm FB} = \frac{3}{4}\mathcal{A}_e\mathcal{A}_b$, with $\mathcal{A}_b = \frac{2g_{V_b}/g_{A_b}}{1+g_{V_b}/g_{A_b}}$, where the subscript b indicates the bottom flavour [3].

Experimentally, the forward-backward asymmetry at $\sqrt{s} = m_Z$ in the process $e^+e^- \to Z \to b\bar{b}$ can be determined either by measuring the cross-section in the forward and backward hemispheres and then computing $A^b_{\rm FB}$ according to the definition in eq. (1), or by fitting the data to the differential angular distribution

$$\frac{{\rm d}\sigma}{{\rm d}\cos\theta} = \sigma^{\rm tot}_{b\bar{b}}\left[\frac{3}{8}(1+\cos^2\theta) + A^b_{FB}\cos\theta\right], \tag{2}$$

where θ is the polar scattering angle between the outgoing quark and the incoming electron flight direction in the centre-of-mass reference frame.

Although the natural strategy for a precise measurement of the $A^b_{\rm FB}$ asymmetry is waiting for the construction of a new, powerful accelerator like FCC-ee, an about 92 kilometers long electron-positron circular collider currently being designed [4], it is also possible to perform the measurement at the Large Hadron Collider (LHC), by probing the interaction between the Z boson and the b quark with a competitive determination of $A^b_{\rm FB}$ at the ATLAS experiment [5]. In this context, a novel approach is investigated, exploiting the measurement of the asymmetry $A^{b,{\rm LHC}}_{\rm FB}$ in the associated production of a b quark with a leptonically decaying Z boson, using the data collected by the ATLAS detector at the LHC [6]. This observable can be used for an accurate determination of the A^b_{FB} investigated at LEP and proposed for FCC-ee, as they differ by a kinematic factor $k = A^{b,{\rm LHC}}_{\rm FB}/A^b_{\rm FB}$ [7].

3. – A^b_{FB} measurement at the ATLAS experiment

For the $A^b_{\rm FB}$ analysis at the LHC using ATLAS data being presented here, the process $pp \to Z + b$, with $Z \to l^+l^-$ is considered. Then, the asymmetry $A^{b,{\rm LHC}}_{\rm FB}$ can be actually extracted from the angle θ^* between b and l^+ or equivalently between $\bar{b}$ and l^-, in the $Z \to l^+l^-$ centre-of-mass rest frame.

The definition of this asymmetry intrinsically requires some sensitivity both to the charge and to the cosine of the polar angle of the bottom quark/antiquark in the final state. To that purpose, the b and $\bar{b}$ quarks need to be distinguished via dedicated charge-tagging methods. Such experimental determination of the charge of the quark giving rise to a jet is a challenging task, and two general strategies already developed at LEP for heavy flavours are considered.

The first strategy is often called "jet charge" measurement, and its simplest realisation relies on calculating for each considered jet the weighted sum of the charge (namely q_i in eq. (3)) of all the inner-detector tracks within a certain angular distance within the jet, or associated with the jet in other ways([1]) [8-12], with the weights being the longitudinal momenta of the various tracks assigned to the jet

$$Q_{\rm jet} = \frac{\sum_i q_i p_{L,i}}{\sum_i p_{L,i}}. \quad (3)$$

A second strategy is to restrict the jet candidates to those containing a so-called "soft lepton", preferably a muon, that can clearly indicate a semi-leptonic decay of a B hadron, and to then infer the hadron charge from the clean measurement of the lepton charge [13-18].

The first approach is expected to be maximal efficient, since it is not statistically limited to semileptonic decays, but presents a relatively low purity due to emission of QCD final state radiation and strong dependence on jet shape and hadronization. On the other hand, the soft lepton tagging has a better purity but requires to minimize the crucial contribution from $b \to c \to \mu$ decay chain that mimics the same signature, with opposite charge. Once the b-jet charge is determined, the measurement of $A^{b,\rm LHC}_{\rm FB}$ can be extracted by reconstructing the detector-level distribution of $\cos\theta^*$, then applying an unfolding procedure and finally fitting the unfolded parton-level distribution, according to eq. (2).

3˙1. *Preliminary study in* MadGraph. – A simplified study based on the software MadGraph5_aMC@NLO [19] has been performed to evaluate the feasibility of the measurement. The process $gb \to bZ$, $Z \to e^+e^-$ in both s-channel and t-channel is considered and correspondent events at $\sqrt{s} = 13$ TeV and $\mathcal{L} = 36$ fb^{-1} are generated with a fast simulation of the ATLAS detector based on the software Delphes [20]. Ideal conditions are considered, assuming no background from c and light jets, perfect b-quark charge reconstruction and 100% in terms of acceptance and b-tagging efficiency. The truth-level $\cos\theta^*$ distributions for b and $\bar{b}$ quarks are built (fig. 1), and the value of $A^{b,\rm LHC}_{\rm FB}$ (eq. (1)) is extracted. Known the $A^b_{\rm FB}$ value with the same settings, the kinematic factor k is extracted from the simulation, turning to be around 0.55. A rough estimation of the statistical uncertainty in ideal conditions is computed, via error propagation, to be ~ 0.00042, to be compared with the uncertainty obtained in the $A^b_{\rm FB}$ LEP combination of ~ 0.0015 [1].

3˙2. *Pre-fit control plots.* – At the state of art of the analysis, 36 fb^{-1} of LHC Run 2 data at a centre-of-mass energy of 13 TeV collected by the ATLAS experiment are considered, and $Z + b$ final states are selected as signal. Events are required to have at least one b-jet, one soft muon and $E^{\rm miss}_T < 35$ GeV. The distributions of $\cos\theta^*$ and p_T of the selected b-jets and the soft muons are reported in fig. 2, showing that the main background contribution is related to $Z + c$ events.

([1]) The angular distance between the jet and a track in terms of pseudorapidity η and azimuthal angle ϕ is defined as $\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2}$. In the method implemented for this study, a track is assigned to a jet if its angular distance ΔR with respect to the jet is smaller than a certain value.

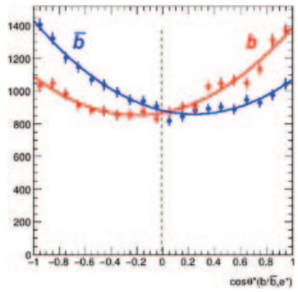

Fig. 1. – The parton-level distributions of $\cos\theta^*$ of the b and $\bar{b}$ quarks in $pp \to bZ$, $Z \to e^+e^-$ events at $\sqrt{s} = 13$ TeV simulated with MadGraph5_aMC@NLO.

4. – Prospects for the A^b_{FB} measurement at the FCC-ee

In parallel with the preliminary results of the analysis performed at the ATLAS experiment at the LHC, some prospects for the A^b_{FB} measurement at the FCC-ee are presented in this contribution.

By means of a simulation based on the official FCCSW framework and tuned on the FCC-ee parameters, Monte Carlo samples at a centre-of-mass energy of $m_Z = 91.1778$ GeV are generated for the signal $e^+e^- \to b\bar{b}$ in the EDM4hep [21] format. Hadronization and parton shower are performed with the Pythia 8 software [22]. The IDEA concept [23] is in the software Delphes [20] to account for detector modelling and response. The jets are reconstructed with ee-KT Durham clustering algorithm. A simplified Delphes b-tagging is applied for the jet identification, including a flat 80% efficiency and c- and light-mistagging efficiencies of 10% and 1%, respectively. A selection is applied in order to require exactly two b-tagged jets with opposite charge in the final state, with the charge reconstructed with the same strategies planned for the ATLAS measurement (the "jet charge" and the soft lepton methods), as described in sect. **3**.

Truth-level and reconstructed-level distributions for the observable $\cos\theta^*$ are built from the MC events, and the response matrices and the efficiency vectors b-quarks and b-quark-jets are built on top of them. The generated events are re-scaled to the event number to match the expected integrated luminosity at Z-boson pole, corresponding to a data-taking period of four years: $\mathcal{L}_{Z-pole} = 150$ ab^{-1}.

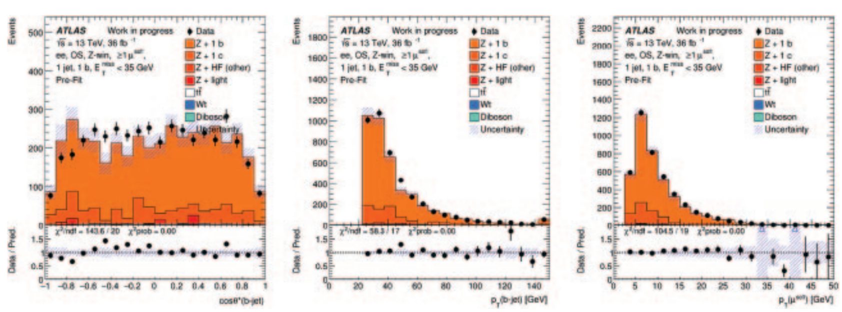

Fig. 2. – Comparisons between data and Monte Carlo simulation for the variables $\cos\theta^*$ and p_T of the selected b-jets and the soft muons. The hatched area corresponds to the statistical uncertainties of the MC simulations.

In order to calculate A_{FB}^b, the unfolding procedure on the variable $\cos\theta^*$ is applied [24] with a simple 10×10 matrix inversion, in order to be independent of the detector structure and the reconstruction effects. To this end, the A_{FB}^b value is extracted by fitting on the unfolded differential cross-section in eq. (2), considering 10 bins in both lepton-based and jet-charge–based study.

4·1. *Statistical and systematic uncertainties.* – To calculate the statistical uncertainty, the reconstruction level distributions of $\cos\theta$ are scaled in order to match the expected integrated luminosity at the Z-boson pole, $\mathcal{L} = 150\ \mathrm{fb}^{-1}$; then statistical fluctuations are produced on top of the reconstruction-level distributions, and a set of 1000 new replicas of each of the histograms is created; finally, each of the replicas of the parton-level distributions (obtained via unfolding from the reconstructed ones) is fitted according to eq. (2) and the A_{FB}^b values are extracted for each replica. The statistical uncertainty on A_{FB}^b is then obtained as the root mean squared (RMS) of the distribution of these measured A_{FB}^b values.

The main sources of systematic uncertainty on the measurement are investigated as well: the modelling of b-quark and b-hadron fragmentation in the Lund-Bowler function in Pythia [25, 26]; the emission of QCD final state radiation; the comparison between standalone Pythia and Dire parton shower models; finally, the effect of variation of b-tagging and c-mistagging efficiency, with a relative uncertainty on them assumed to be 5%. For each of them, new $e^+e^- \to b\bar{b}$ samples are generated by changing (*i.e.,* scaling up and down) the parameters used to the FCCSW framework to describe the correspondent phenomena. The total systematic uncertainty is provided by the sum in quadrature of the different contributions mentioned above.

4·2. *Feasibility study results.* – At the state of art, the present world average for the b-quark forward-backward asymmetry measured at LEP at the Z pole is $A_{\mathrm{FB}}^b = 0.0992 \pm 0.0015\,(\mathrm{syst.}) \pm 0.0007\,(\mathrm{stat.})$, with the statistical being of the same order of the systematic uncertainties [1]. For the measurement of the A_{FB}^b asymmetry at the FCC-ee, with an integrated luminosity $\mathcal{L} = 150\ \mathrm{ab}^{-1}$ at Z-boson pole, the statistical contribution is of the order of 10^{-5}. The systematic uncertainty is estimated to be around 0.0049 for the lepton-based method, and around 0.0030 for the jet charge method. For both methods, the statistical uncertainty is expected to be of the order of 10^{-5}, thanks to the expected larger data set [2], and can be considered totally negligible. Although it will be crucial to minimize the contribution of the systematic uncertainty, the results clearly confirm that a measurement at FCC-ee competitive with LEP is in reach.

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