Snowmass2021 - Letter of Interest

Measurement of the forward-backward charge asymmetry in the Z boson decay at LHC in the future

Thematic Areas: (check all that apply □/■)

□ (EF01) EW Physics: Higgs Boson properties and couplings
□ (EF02) EW Physics: Higgs Boson as a portal to new physics
□ (EF03) EW Physics: Heavy flavor and top quark physics
■ (EF04) EW Precision Physics and constraining new physics
□ (EF05) QCD and strong interactions: Precision QCD
□ (EF06) QCD and strong interactions: Hadronic structure and forward QCD
□ (EF07) QCD and strong interactions: Heavy Ions
□ (EF08) BSM: Model specific explorations
□ (EF09) BSM: More general explorations
□ (EF10) BSM: Dark Matter at colliders
□ (Other) *[Please specify frontier/topical group]*

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Abstract:

We present a study of the future measurements of the forward-backward charge asymmetry (A_{FB}) in $pp \to Z/\gamma^* \to \ell^+\ell^-$ events. At hadron colliders, A_{FB} relates to the precise determination of the leptonic effective weak mixing angle, and provides unique constraints on the parton distribution functions (PDFs). In the past decade, the A_{FB} measurements at hadron colliders, including the Fermilab Tevatron and the CERN Large Hadron Collider, are limited by the data samples. In few years, systematical uncertainties in precision measurements will be more dominating as data accumulates fast at the LHC. Besides, the A_{FB} measurement in the LHC's pp collisions has physical difference from that in the Tevatron's $p\bar{p}$ collisions. All these requires changes in not only the experimental measurement, but also the strategy of using A_{FB} in the global fitting. We will discuss the challenges in the A_{FB} measurements using future LHC data samples, and discuss how to perform the A_{FB} measurements under that situation.

The forward-backward charge asymmetry, A_{FB}, in the Z boson decay process, is one of the most valuable observables at hadron collider experiments for precision measurements. It can be used directly in the expreiment-theory comparison. At TeV-level hadron colliders, CDF collaboration at the Fermilab Tevatron performed the first measurement of A_{FB} around the Z boson mass pole in the electron final state in 2005[1]. In the past 15 years, D0 and CDF collaborations leads the record of the A_{FB} observation at hadron colliders. In 2018, the combined Tevatron measurement of the leptonic effective weak mixing angle, $\sin^2\theta^{\ell}_{\text{eff}}$, from the A_{FB} achieved a precision of 0.23179 ± 0.00033[2]. D0 and CDF also published their unfolded A_{FB} spectrum as a function of the dilepton mass, so that A_{FB} can be directly used in the experiment-theory comparison. For example, D0 has extracted the effective Z boson to u and d quark couplings from the A_{FB}[3] in 2011. Experiments at LHC, including ATLAS, CMS and LHCb also published their results using the data collected earlier. By now, the best journal published A_{FB} measurement at LHC comes from CMS collaboration. The corresponding uncertainty on the extracted $\sin^2\theta^{\ell}_{\text{eff}}$ is 0.00052[4]. In general, the precision of the A_{FB} measurements at hadron colliders is at $\mathcal{O}(0.1\%)$ level by now. The previous observations on A_{FB}, including efforts from Tevatron and early LHC and even from LEP and SLC, are limited by statistical fluctuation. For the LEP and SLC A_{FB} observations, systematic uncertainties are negligible compared to the statistical ones[5]. For the Tevatron case, statistical uncertainty on $\sin^2\theta^{\ell}_{\text{eff}}$ directly extracted from the A_{FB} is 0.00030, with respect to a total uncertainty of 0.00033[2]. At LHC, statistical uncertainty in the CMS 8 TeV results becomes less dominant, but still is the largest contribution in the total uncertainty[4].

LHC will provide us a large data sample and reduce the statistical uncertainties. However, measurements at LHC are far more complicated. A_{FB} is originally defined to describe the symmetry breaking in the Z boson decay, However, the initial state pp collisions at LHC is completely symmetrical. The forward and backward categories are separated according to the assumption that quarks statistically carry more energy than anti-quarks. Therefore, A_{FB} observed at LHC is significantly correlated with parton distribution functions (PDFs), causing not only a large PDF-induced uncertainty, but also a sensitivity loss due to mis-judge of the forward/backward category. As a result, measurements of A_{FB} at LHC highly rely on the events having large Z boson rapidity, and directions of final state leptons close to the beam. Due to the multiple hadron interactions at LHC, lepton reconstructions in these events are difficult. Meanwhile, studies have been made, indicating that the shape of the A_{FB} as a function of dilepton mass is needed to constraint the PDFs, in order to reduce the PDF-induced uncertainty at LHC[6;7]. That means A_{FB} should be precisely measured as a differential cross section instead of an average asymmetry around Z pole. In conclusion, even though the detectors of ATLAS, CMS and LHCb are far more advanced than those of D0 and CDF, the experimental uncertainties will extrapolate into the A_{FB} measurement more significantly at LHC than that at Tevatron.

The dominating systematics are not only an experimental issue. The unfolding procedure, which is to remove the detector effects from the collected data and provide an A_{FB} spectrum which could be directly compared to the theoretical calculations, is generally developed based on statistical assumptions. When systematics become dominating, the bin-by-bin correlated uncertainties are difficult to estimate. Improper correlation estimation will cause biases when using A_{FB} in electroweak global fittings, PDF global fittings, and extraction of some parameters such as $\sin^2\theta^{\ell}_{\text{eff}}$. An idea to avoid such bias is to changing the unfolding procedure into folding procedure, i.e., instead of removing the detector effects from the experimental observation, we can apply the parameterized detector modeling to the theoretical calculations. This is equivalent in experiment-theory comparison, but much easier in dealing with systematics. This needs studies and discussions between experimental and theoretical physicists.

There are other issues need to be discussed. For example, in the past years, combination of the individual A_{FB} observations in different decay channels and experiments are always an important task. However, when experimental systematics are more dominating, combination will not further improve the overall precision with respect to the most precise single measurement used in the combination. Besides, as all the standard model predicted fundamental particles have been experimentally fixed, the comparison in A_{FB} between different decay final state including electron, muon, τ, light quarks and heavy quarks is part of the global test itself. Following this, aiming for a higher precision of a specific measurement would be more important than considering an easier way to combine with others.

We are working on a series of studies on the above topics. In summary, the precision measurement of A_{FB} at future LHC is a topic needs direct cooperation between experiment and theory sides. This would be important and interesting to have joint-discussion between experimentalists and theoretical physicists.

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