Uncertainty of Semileptonic Asymmetry a_{sl}^{s} at the future high-luminosity Z-factory

Dennis C. Arogancia[1], Jan Mickelle V. Maratas[1] and Stephane Monteil[2]

[1]MSU-Iligan Institute of Technology
Iligan City, Philippines
[2]Université Clermont Auvergne
Clermont-Ferrand, France

December 1, 2021

Outline

Introduction

- In the SM, no mechanism yet to account for the abundance of matter in the universe from the measured values of *CP* violation.
- *CP* violation in neutral meson system is an important ingredient to determine the *CP* phase in the SM. Precision measurements of *CP* violating asymmetries will test the SM and deviations can reveal indirect signs of BSM physics.
- Neutral *B* meson system provides an excellent opportunity to explore new physics. Studies on the *B* meson mixing and decay have been performed in the collider experiments of Belle, Babar, D0, CDF and recently at LHCb.
- No CP violation in the mixing of B mesons have been observed to date. Limits are however consistent with the SM predictions.

Neutral meson mixing

- Neutral mesons (K^0, B^0, D^0) can oscillate into their own anti-particle through mixing.
- Since SM CP-violating effects are expected to be highly suppressed in B^0 system thus they are sensitive to new physics.
- CP violation in mixing can be measured by looking at flavour-specific decays defined by

$$a_{fs} = \frac{\Gamma(\bar{B}_q^0 \to B_q^0 \to f) - \Gamma(B_q^0 \to \bar{B}_q^0 \to \bar{f})}{\Gamma(\bar{B}_q^0 \to B_q^0 \to f) + \Gamma(B_q^0 \to \bar{B}_q^0 \to \bar{f})} \quad (1)$$

Standard Model predictions[1]

- $a_{sl}^d = -(6.5^{+1.9}_{-1.7}) \times 10^{-4}$
- $a_{sl}^s = +(0.29^{+0.09}_{-0.08}) \times 10^{-4}$

[1] https://arxiv.org/abs/1106.4041

State of the art

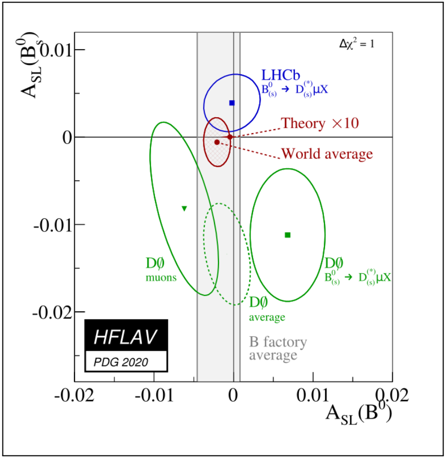

Figure 1: Semileptonic asymmetry measurements from different experiments. World average results[2]: $a^d_{sl} = -0.0021 \pm 0.0017$ and $a^s_{sl} = -0.0006 \pm 0.0028$.

[2]Heavy Flavor Averaging Group (HFAG), arXiv: 1909.12524v2 [hep-ex] 1 Nov 2019

a_{sl}^s measurement at LHCb

- The SM prediction of a_{sl}^s is at the order magnitude of 10^{-5}. The smallness of this CP violating effect makes this process an excellent laboratory to probe new CPV phases. At the future colliders like the FCC-ee, we can further explore the precision of this measurement by determining the uncertainty of a_{sl}^s.
- At LHCb, the semileptonic asymmetry is measured using the exclusive B_s^0 and $\bar{B}_s^0$ to $D_s^{\mp}\mu^{\pm}\overset{(-)}{\nu}_{\mu}X$ decays where $D_s^{\mp} \to K^{\mp}K^{\pm}\pi^{\mp}$. It is expressed as

$$a_{sl}^s = \frac{2}{1-f_{bkg}}(A_{raw} - A_D - (1 - f_{sig})A_{bkg}) \text{ where}$$

$$A_{raw} = \frac{N(D_s^- \mu^+) - N(D_s^+ \mu^-)}{N(D_s^- \mu^+) + N(D_s^+ \mu^-)}, \quad A_D \text{ - detection asymmetry,}$$

A_{bkg} - production asymmetry of the backgrounds and

f_{sig} - fraction of signal events given by $f_{sig} = \frac{N_{sig}}{N_{sig}+N_{bkg}}$.

- We explore the capability of FCC-ee by looking at these B_s^0 decays.

Signal and background process

Process	Branching fraction (%)	$N_{events}(\times 10^9)$
$B_s^0 \to D_s^- \ell^+ \nu_\mu X$ (signal)	8.1 ± 1.3	2.57
Backgrounds:		
$B^- \to \bar{D}^{(*)0} D_s^{(*)-} X$	7.9 ± 1.4	1.20
$\bar{B}^0 \to \bar{D}^0 D_s^{(*)-} X$	5.7 ± 1.2	0.434
$\bar{B}^0 \to D^+ D_s^{(*)-} X$	4.6 ± 1.2	1.09
$B_s^0 \to D_s^{(*)-} D_s^{(*)+}$	4.5 ± 1.4	0.19
$\Lambda_b^0 \to \Lambda_c^+ D_s^{(*)-} X$	10.3 ± 2.1	0.25

Table 1: Branching fractions and expected number of events of signal and backgrounds for $N = 5.0 \times 10^{12}$ Z decays.

- At FCC-ee there is no production asymmetry, $A_P = 0$. This means that $A_{bkg} \equiv A_D$. Assuming that there is no correlation between the signal and background we estimated the statistical uncertainty of a_{sl}^s.

Event selection

- The signal and backgound events were generated using Pythia interfaced with EvtGen.
- The smearing values for momentum resolution and vertex are
  - Momentum resolution: $\sigma p_T/p_T = 3.0 \times 10^{-5}/p_T + 0.6 \times 10^{-3}$
  - Primary vertex: 3.0 μ m, Secondary vertex: 7.0 μ m
- Mass correction is applied to the reconstructed $D_s\mu$ mass using the expression

$$M_{corr} = \sqrt{M^2_{D_s\mu} + |p_T^{mis}|^2} + |p_T^{mis}|$$

  where p_T^{mis} is the missing transverse momentum relative to the flight direction of the B meson.
- Multivariate analysis is performed using Boosted Decision Trees (BDT) with the following input variables: μ impact parameter and transverse momentum, vertex fitting χ^2 of reconstructed $D_s\mu$ and $\Delta\chi^2[\chi^2_{D_s\mu h(\pi^\pm/K^\pm)} - \chi^2_{D_s\mu}]$.

Reconstructed $D_s\mu$ mass

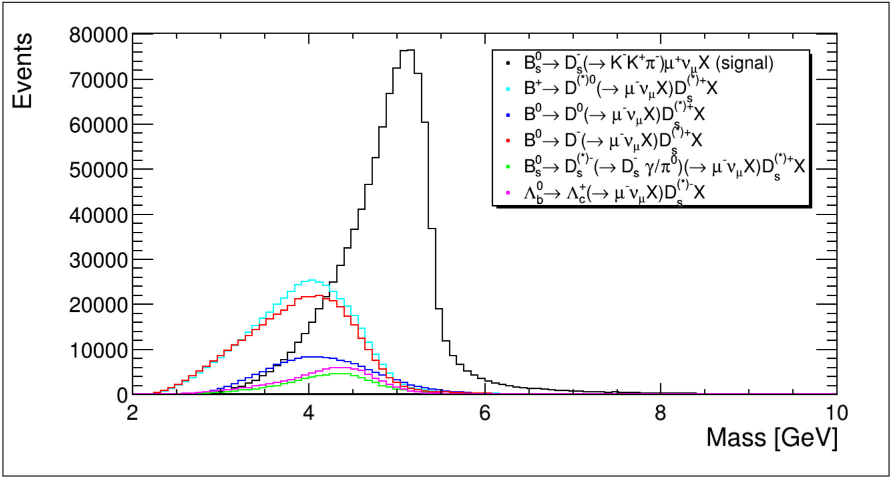

Figure 2: Reconstructed $D_s\mu$ distribution with mass correction.

BDT cut vs $\sigma_{a_{sl}^s}$

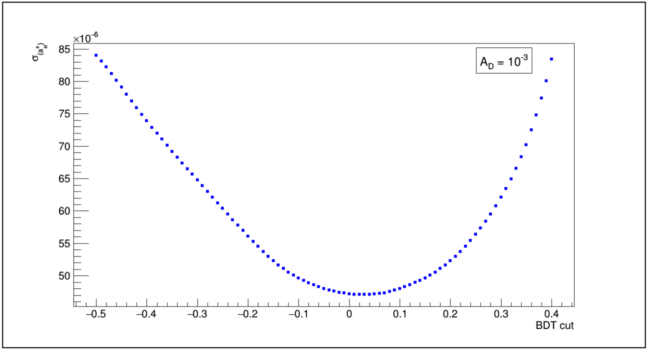

Figure 3: BDT cut vs $\sigma_{a_{sl}^s}$ ($A_D = 10^{-3}$).

- Statistical uncertainty of a_{sl}^s will reach 4.7×10^{-5} with $N_Z = 5.0 \times 10^{12}$ events.
- Uncertainty of detection asymmetry, σ_{A_d}, must be at the same level or below $\sigma_{a_{sl}^s}$.
- Full simulation is needed to address A_d.

Dilepton charge asymmetry

- At D0 experiment[3], the like-sign dimuon charge asymmetry is defined as

$$A_{sl}^{b} = \frac{N^{++} - N^{--}}{N^{++} + N^{--}}$$

where N^{++} and N^{++} are events containing semileptonic decays of b hadrons producing two positive or negative muons respectively.

- The total asymmetry A_{sl} has contributions from B^0 and B_s^0 charge asymmetries a_{sl}^d and a_{sl}^s respectively

$$A_{sl} = C_d a_{sl}^d + C_s a_{sl}^s$$

where $C_d = \frac{f_d \chi_d}{f_d \chi_d + f_s \chi_s}$ and $C_s = 1 - C_d$. The production fractions f_d and f_s are for B^0 and B_s^0 respectively. The coefficient C_d was determined to be 0.583 ± 0.015. The total semileptonic asymmetry is $A_{sl} = (-0.496 \pm 0.153 \pm 0.072) \times 10^{-2}$. This differs by 2.8 standard deviations from SM expectation: $A_{sl}^{sm} = (-0.023 \pm 0.004) \times 10^{-2}$.

[3]Phys. Rev. D 89, 012002 (2014)

Dilepton charge asymmetry

- The same-sign dilepton signal events can be expressed as

$$N_{\ell_1\ell_2}^{\pm\pm} = N_{\ell_1\ell_2}(1 \pm a_{\ell_1} \pm a_{\ell_2} \pm A_{CP})$$

in the limit of $A_{CP} \ll 1$ and $a_{\ell_j} \ll 1$, where

$a_{\ell_j=\{\mu,e\}}$ - lepton charge asymmetry of detection and identification
$N_{\ell_1\ell_2}$ - total number of dilepton events coming from the semileptonic decays of different b hadrons including its mixing probabilities.
A_{CP} - dilepton charge asymmetry.

- At FCC-ee, we can estimate the signal yield by using the semileptonic decays of $B^0, B_s^0, B^\pm$ and Λ_b^0. The total signal dilepton events is about $N_{\ell\ell} = 5.48 \times 10^9$ events. The estimated statistical uncertainty of A_{sl}^b is at the level of 10^{-5}.

State of the art

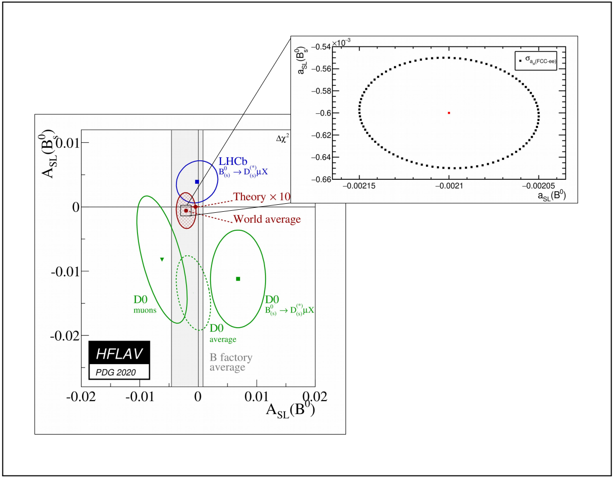

Figure 4: Semileptonic asymmetry measurements from different experiments. World average results[2]: $a_{sl}^{d} = -0.0021 \pm 0.0017$ and $a_{sl}^{s} = -0.0006 \pm 0.0028$. Inset: Level of statistical uncertainty at the order of 10^{-5} for FCC-ee .

[2] Heavy Flavor Averaging Group (HFAG), arXiv: 1909.12524v2 [hep-ex] 1 Nov 2019

Summary

- Using the quantities such as the μ impact parameter, transverse momentum of the μ, perpendicular component of the μ momentum along the B_s^0 direction and the vertex χ^2 in the multivariate analysis were able to significantly reduce the amount of background events.
- Controlling the uncertainty on the detection asymmetry of charged particles is however the name of the game for this kind of measurements. Full simulation in order..
- Uncertainty on the detection asymmetry still needs to be explored for its contribution to the statistical uncertainty of a_{sl}^s.
- The level of statistical uncertainty for the dilepton charge asymmetry is in the order of 10^{-5} however, here also, detector effects must be addressed.
- FCC-ee experiments are the best experimental environment to reach the precision to observe SM predictions.

End