Precision measurements of Semileptonic Asymmetry a_{sl} at the future high-luminosity Z-factory: Roadmap

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Motivation

- In the Standard Model, CP violation from quark mixing is too small to account for the abundance of matter.
- CP violation in neutral meson system is one of the most important ingredients to determine the CP phase in the SM.
- 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

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

Standard Model predictions[1]

- $a_{sl}^d = -(4.7 \pm 0.6) \times 10^{-4}$
- $a_{sl}^s = +(2.22 \pm 0.27) \times 10^{-5}$

[1] M. Artuso et al., Rev. Mod. Phys. 88, 045002

D0 experiment[2,3]

- Relevant decays:
  $B^0 \to \mu^+ \nu D^- X$ with $D^- \to K^+ \pi^- \pi^-$
  $B^0 \to \mu^+ \nu D^{*-} X$ with $D^{*-} \to \bar{D}^0 \pi^-$, $\bar{D}^0 \to K^+ \pi^-$
  $B_s^0 \to D_s^- \mu^+ X$ where $D_s^- \to \phi \pi^-$ and $\phi \to K^+ K^-$
- Results:
  $a_{sl}^d = [0.68 \pm 0.45(\text{stat.}) \pm 0.14(\text{syst.})]\%$
  $a_{sl}^s = [-1.12 \pm 0.74(\text{stat.}) \pm 0.17(\text{syst.})]\%$

[2] V.M. Abazov et al. (D0 collaboration), Phys. Rev. D86, 072009 (2012), arXiv:1208.5813 [hep-ex]

[3] V. Abazov et al. (D0 collaboration), Phys. Rev. Lett. 110, 011801 (2013), arXiv:1207.1769 [hep-ex]

LHCb experiment[4,5]

- Relevant decays:
  $B^0 \to D^- \mu^+ \nu_\mu X$ where $D^- \to K^+ \pi^- \pi^-$
  $B^0 \to D^{*-} \mu^+ \nu_\mu X$ where $D^{*-} \to \bar{D}^0 (\to K^+ \pi^-) \pi^-$
  $B_s^0 \to D_s^- \mu^+ \nu_\mu X$, where $D_s^- \to K^+ K^- \pi^-$
- Results:
  $a_{sl}^d = (-0.02 \pm 0.19(\text{stat.}) \pm 0.30(\text{syst.}))\%$
  $a_{sl}^s = (+0.39 \pm 0.26(\text{stat.}) \pm 0.20(\text{syst.}))\%$

[4] R. Aaij et al. (LHCb collaboration), Phys. Rev. Lett. 114, 041601 (2015), arXiv:1409.8586 [hep-ex]

[5] R. Aaij et al. (LHCb collaboration), Phys. Rev. Lett. 117, 061803 (2016), arXiv:1605.09768 [hep-ex]

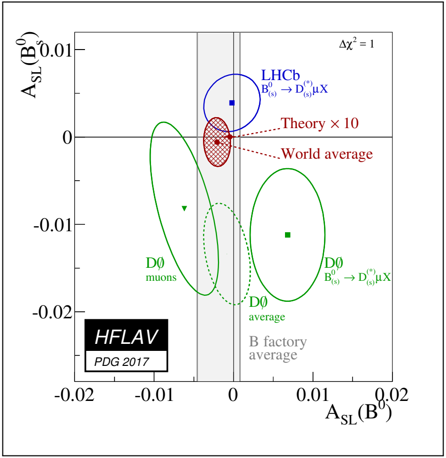

Figure 1. Semileptonic asymmetry measurements from different experiments. World average results[6]: $a^d_{sl} = -0.0021 \pm 0.0017$ and $a^s_{sl} = -0.0006 \pm 0.0028$

[6] Heavy Flavor Averaging Group (HFAG), arXiv: 1612.07233v1 [hep-ex] (2016)

Estimation of a_{sl} statistical uncertainty at FCC-ee

Z decays at FCC-ee

- Process: $e^+e^- \to \gamma/Z$ where $Z \to b\bar{b}$ where $b \to B^0/\bar{B}^0$
- Z decays at FCC: 10^{13}

Computation of total number of events (N_T)

- $N_{Z^0} = (10^{13}) \times BF_{(Z\to b\bar{b})} \times 2(b \to B^0)\times$
  $2(BF_{B^0\to D^-\mu^+\nu_\mu X/B^0\to D^{*-}\mu^+\nu_\mu X})\times$
  $(BF_{D^-\to K^+\pi^-\pi^-/D^{*-}\to \bar{D}^0(\to K^+\pi^-)\pi^-})\times \epsilon_{\text{tagging}} \times \epsilon_{\text{selection}}$
- Branching fractions[7]:
  $Z \to b\bar{b} = (15.12 \pm 0.05)\%$
  $b \to B^0 = (40.5 \pm 0.6)\%$
  $b \to B^0_s = (10.1 \pm 0.4)\%$

[7] C. Patrignani et al. (Particle Data Group), Chin. Phys. C, 40, 100001 (2016) and 2017 update

Computation of N_T for a_{sl}^d (LHCb and D0)

- Decay channel and branching fractions[8]:
  $B^0 \to \mu^+\nu D^- X = (4.95 \pm 0.23)\%$ where
  $D^- \to K^+\pi^-\pi^- = (8.98 \pm 0.28)\%$
  $B^0 \to \mu^+\nu D^{*-} X = (4.07 \pm 0.20)\%$ where
  $D^{*-} \to D^0\pi^+ = (67.7 \pm 0.5)\%$ and $D^0 \to K^-\pi^+ = (3.89 \pm 0.04)\%$

Computation of N_T for a_{sl}^s (LHCb and D0)

- Decay channel and branching fractions[8]:
  LHCb: $B_s^0 \to D_s^- \mu^+\nu X = (7.9 \pm 2.4)\%$ where
  $D_s^- \to K^+K^-\pi^- = (5.45 \pm 0.17)\%$
  D0: $B_s^0 \to D_s^- \mu^+\nu X = (7.9 \pm 2.4)\%$ where
  $D_s^- \to \phi(\to K^+K^-)\pi^- = (2.27 \pm 0.08)\%$

[8] All branching fractions were taken from *Patrignani et al. (Particle Data Group), Chin. Phys. C, 40, 100001 (2016) and 2017 update* except for $B^0 \to \mu^+\nu D^- X$, $B^0 \to \mu^+\nu D^{*-} X$ (CERN-THESIS-2015-354) and $B_s^0 \to D_s^- \mu^+\nu X$ (CERN-THESIS-2017-255)

Estimation of a_{sl} statistical uncertainty at FCC-ee

- The asymmetry is given by $A = \frac{N-\overline{N}}{N+\overline{N}}$ where N - number of particles and $\overline{N}$ - number of anti-particles.
- The estimated uncertainty is $\sigma_A = \sqrt{\frac{1-A^2}{N_T}}$ where $N_T = N + \overline{N}$.
- Assuming the efficiencies at FCC-ee to be $\epsilon_{\text{tagging}} \sim 10\%$ and $\epsilon_{\text{selection}} \sim 90\%$, we obtain $N_T \approx 10^8 - 10^9$.
- The resulting a_{sl} statistical uncertainty is about “few 10^{-5}” for both B^0 and B_s^0.
- Considering the world average uncertainty is in the order of 10^{-3} thus FCC-ee can significantly improve this value.

FCC-ee simulation

- Process: $e^+e^- \to \gamma/Z$ where $Z \to b\bar{b}$ where $b \to B^0/\bar{B}^0$
- Center-of-mass energy: 91.118 GeV
- Decay channel: $B^0 \to D^-\mu^+\nu_\mu X$ where $D^- \to K^+\pi^-\pi^-$
- Event generator: Pythia 8 and EvtGen
- FCC packages:
  PODIO - C++ library for the creation and handling of data in particle physics
  FCC-EDM - event data model based on PODIO which is used to generate, write and read data models from configuration files
  HEPPY - python based software for the analysis of collision

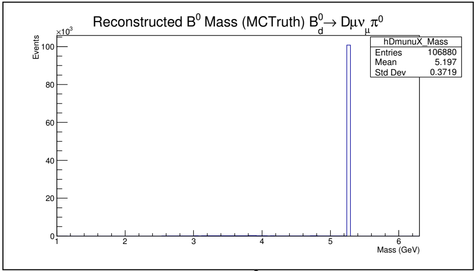

Figure 2. Reconstructed B^0 mass (MCTruth)

- Decay chain of B^0:

$B^0 \to D^- \mu^+ \nu_\mu$
$B^0 \to D^{*-} \mu^+ \nu_\mu$
$B^0 \to D_0^{*-} \mu^+ \nu_\mu$
$B^0 \to D_1^{'-} \mu^+ \nu_\mu$
$B^0 \to D_1^- \mu^+ \nu_\mu$
$B^0 \to D_2^{*-} \mu^+ \nu_\mu$
$B^0 \to D^- \pi^0 \mu^+ \nu_\mu$
$B^0 \to D^- \pi^0 \pi^0 \mu^+ \nu_\mu$
$B^0 \to D^- \pi^+ \pi^- \mu^+ \nu_\mu$
$B^0 \to D^{*-} \pi^0 \mu^+ \nu_\mu$
$B^0 \to D^{*-} \pi^0 \pi^0 \mu^+ \nu_\mu$
$B^0 \to D^{*-} \pi^+ \pi^- \mu^+ \nu_\mu$
$B^0 \to D^- \tau^+ \nu_\tau$
$B^0 \to D^{*-} \tau^+ \nu_\tau$
$B^0 \to D_1^- \tau^+ \nu_\tau$
$B^0 \to D_1^{'-} \tau^+ \nu_\tau$
$B^0 \to D_2^{*-} \tau^+ \nu_\tau$

Final state:
$B^0 \to D^-(\to K^+ \pi^- \pi^-) \mu^+ \nu_\mu X$

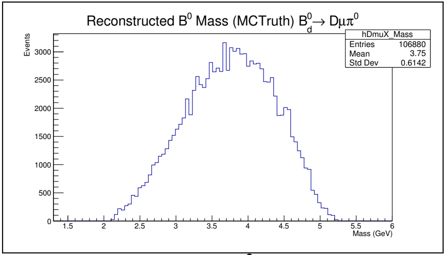

Figure 3. Reconstructed B^0 mass (MCTruth)

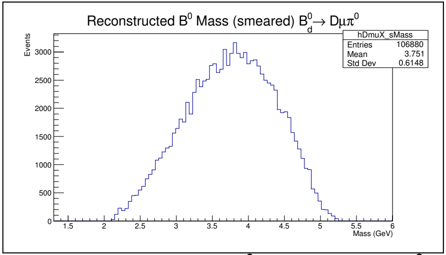

Figure 4. Reconstructed B^0 mass (smeared)[9]

Note: Smearing is not yet applied to π^0.

[9] The smearing is applied to momentum resolution and assumed to be 10%.

Summary

- The statistical uncertainty of a^d_{sl} and a^s_{sl} will improve by two orders of magnitude with the expected 10^{13} Z decays in FCC-ee. Hence, the SM values could potentially be measured.
- Next, it is necessary to see whether systematic uncertainties can be controlled at that level. These systematic uncertainties include detection and tracking asymmetry, B^+ and Λ_b background.
- Development of software packages for FCC-ee is still on going for initial physics studies.

End