A_{CP} and P($\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e$) measurement technote

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Contents

1 Introduction

This technote is devoted to the technique of CP asymmetry and oscillation probabilities extracted from the Far Detector real data collected up to 2020 (Fig. 1). For this goal we use unoscillated FD prediction for $\nu_e(\bar{\nu}_e)$. The ratio was made with signal extracted from data (Fig. 3). For error bar calculations the technique of the playing experiment was used. Systematic and oscillation parameter uncertainties were taken into account along with statistical uncertainty for background. See the procedure described in the following sections.

2 Calculation of central values

Oscillation probabilities are calculated in FHC and RHC in the following way per each bin:

$$P = (\text{data - predicted bkg})/(\text{signal prediction with P = 1}) \tag{1}$$

Wrong sign component is treated as background. Total background is shown in the Figure 2. (Signal prediction with P = 1) is collapsed 2D trueE-recoE histogram from PredictionExtrap (Fig. 4 - 5). Getting the fact that stat. fluctuations are still large, it was decided to use one recoE spectrum instead of two separate Low and High CVN bins. For all inputs (Fig. 3 and 5) Low and High CVN bins were merged. Final inputs are in the Figure 6.

With obtained oscillation probabilities the following expression is calculatedd:

$$A_{CP} = \frac{P(\nu_\mu \to \nu_e) - P(\bar{\nu}_\mu \to \bar{\nu}_e)}{P(\nu_\mu \to \nu_e) + P(\bar{\nu}_\mu \to \bar{\nu}_e)} \tag{2}$$

All resulted plots are shown in Figure 7. Central values are the final result of this section. The procedure for error bar calculation is in the following section.

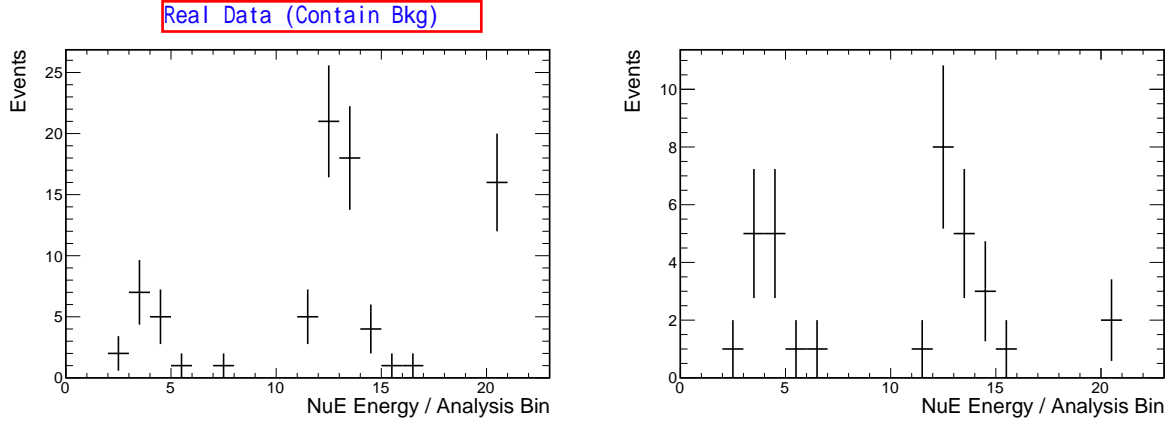Pay attention: A_CP is not strictly the same as delta_CP

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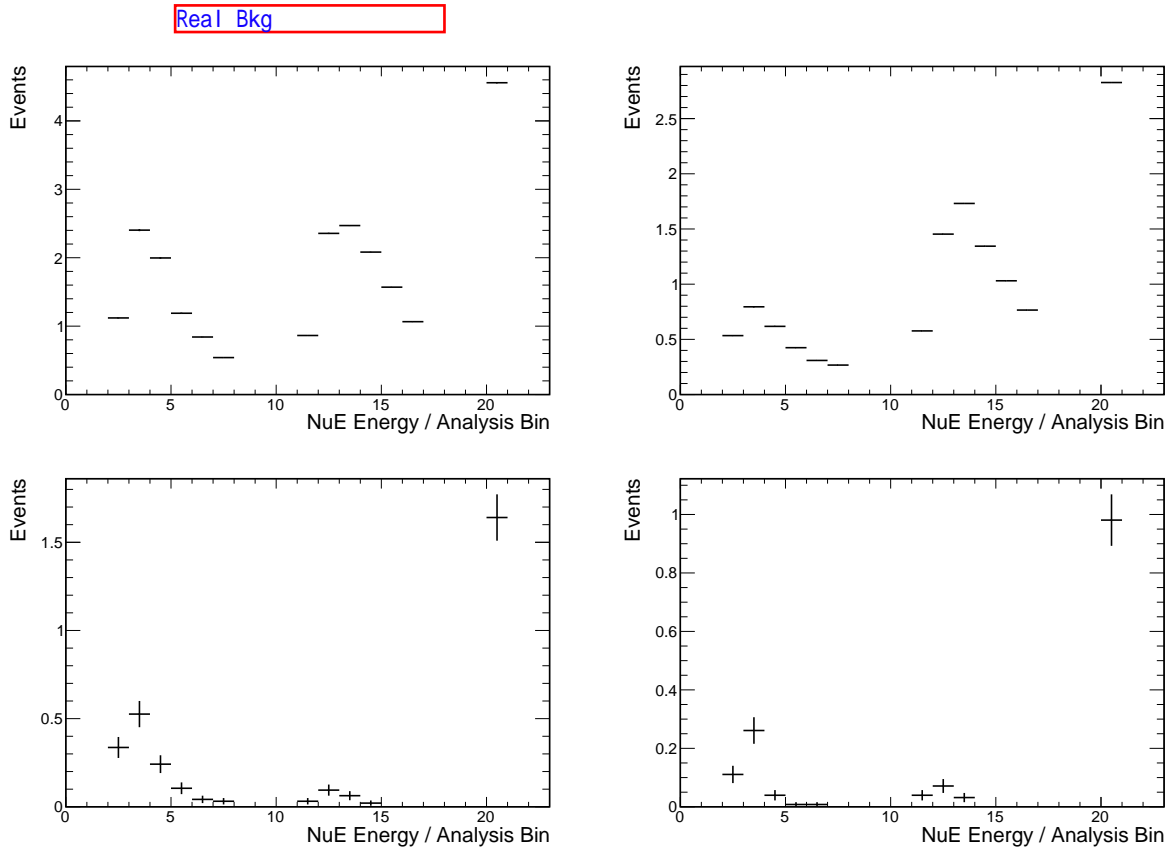Figure 1: Real FD data as inputs for the procedure. FHC is on the left and RHC is on the right.

Figure 2: Predicted backgrounds: total beam bkg (top row) and cosmic bkg (bottom row). FHC is on the left and RHC is on the right.
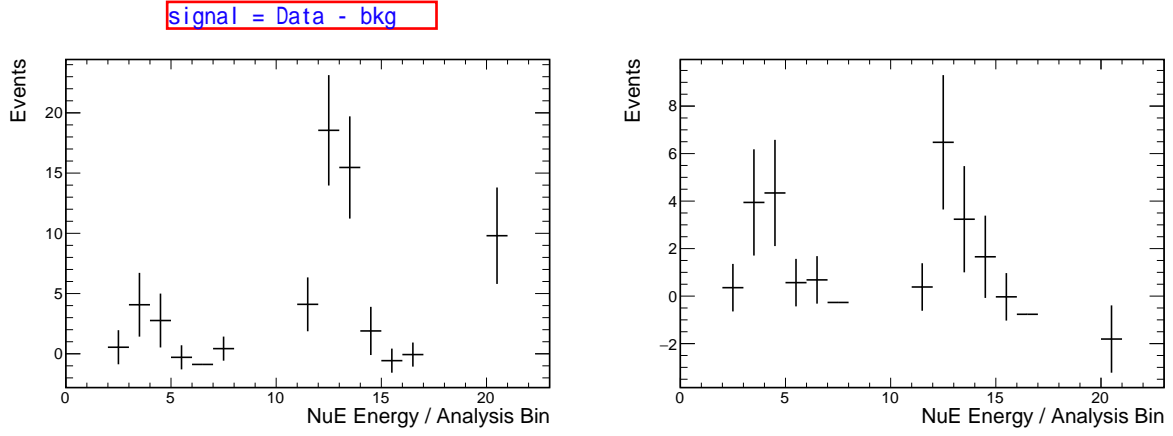
signal = Data - bkg

Figure 3: Signal extracted from data.

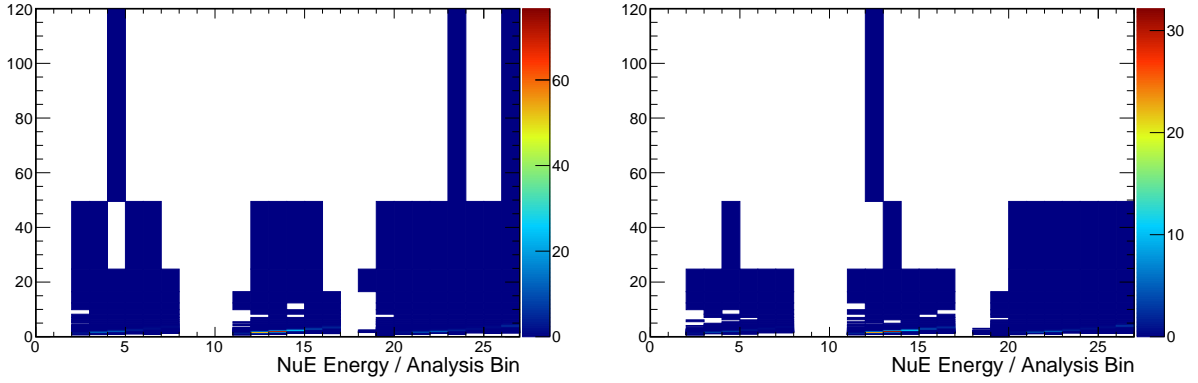Figure 4: 2D histogram from PredictionExtrap CAFAna class with P = 1. Y axis is true energy and X axis is reconstructed energy.
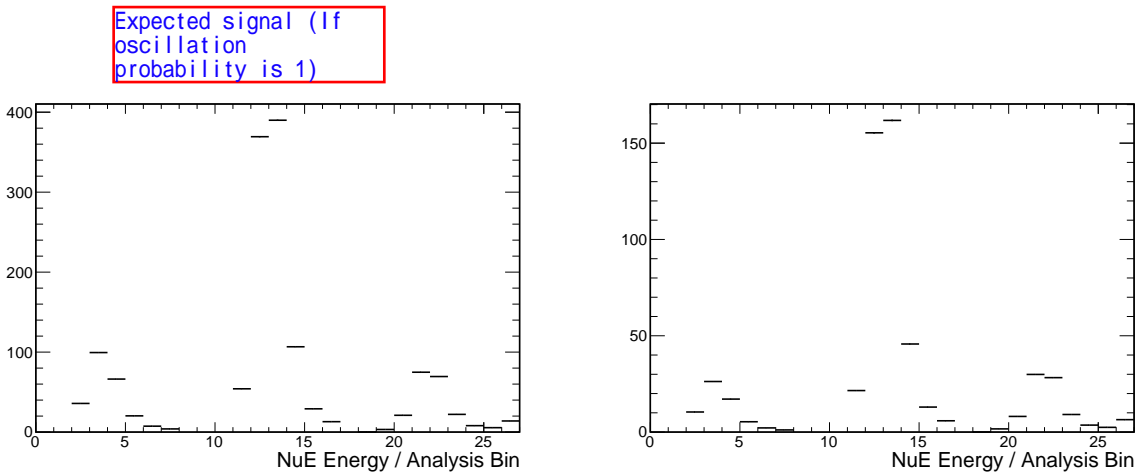
Expected signal (If oscillation probability is 1)

Figure 5: 2D prediction histogram projection on X axis. For the final prediction, the peripheral sample was collapsed into one bin.

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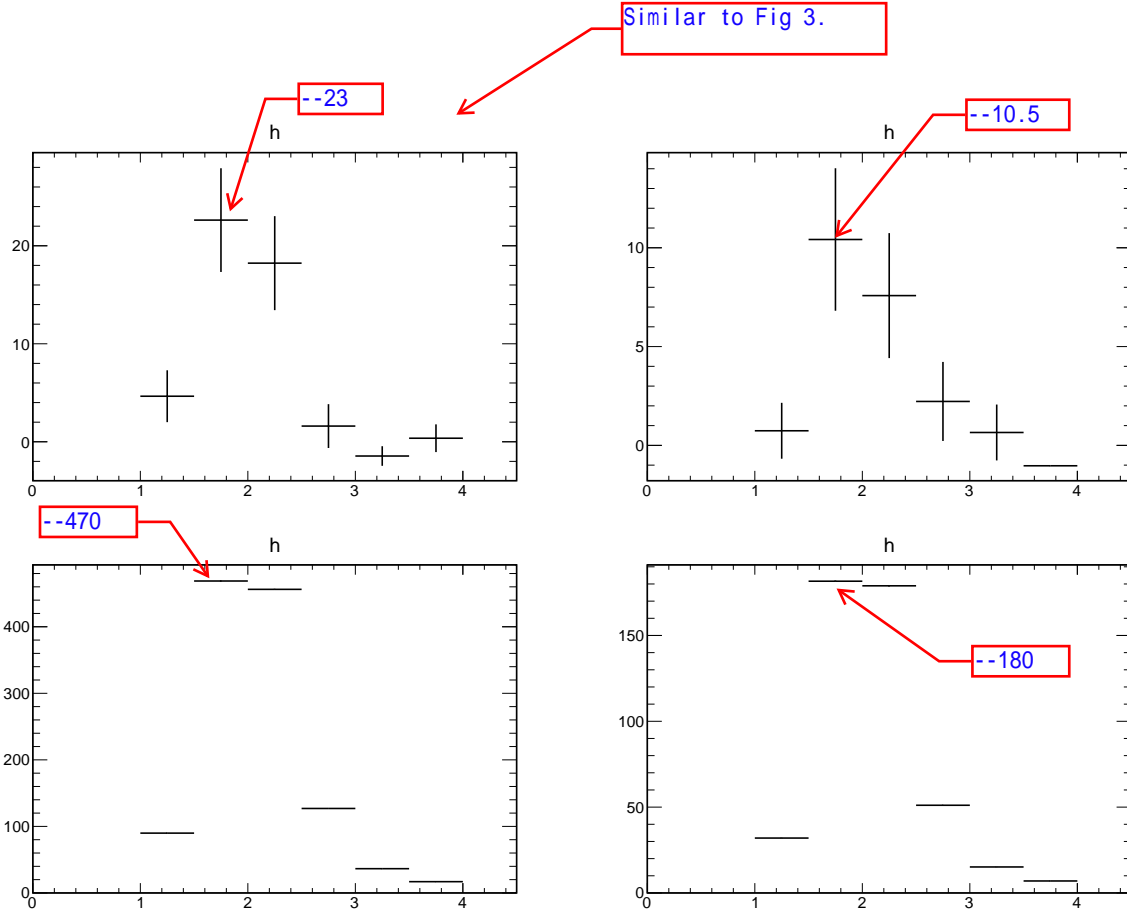Figure 6: Final inputs with merged Low and High CVN bins. Top raw is signal and bottom raw is the denominator for osc. calculation.

From Fig 6, we can calculate the result around E = 1.5GeV
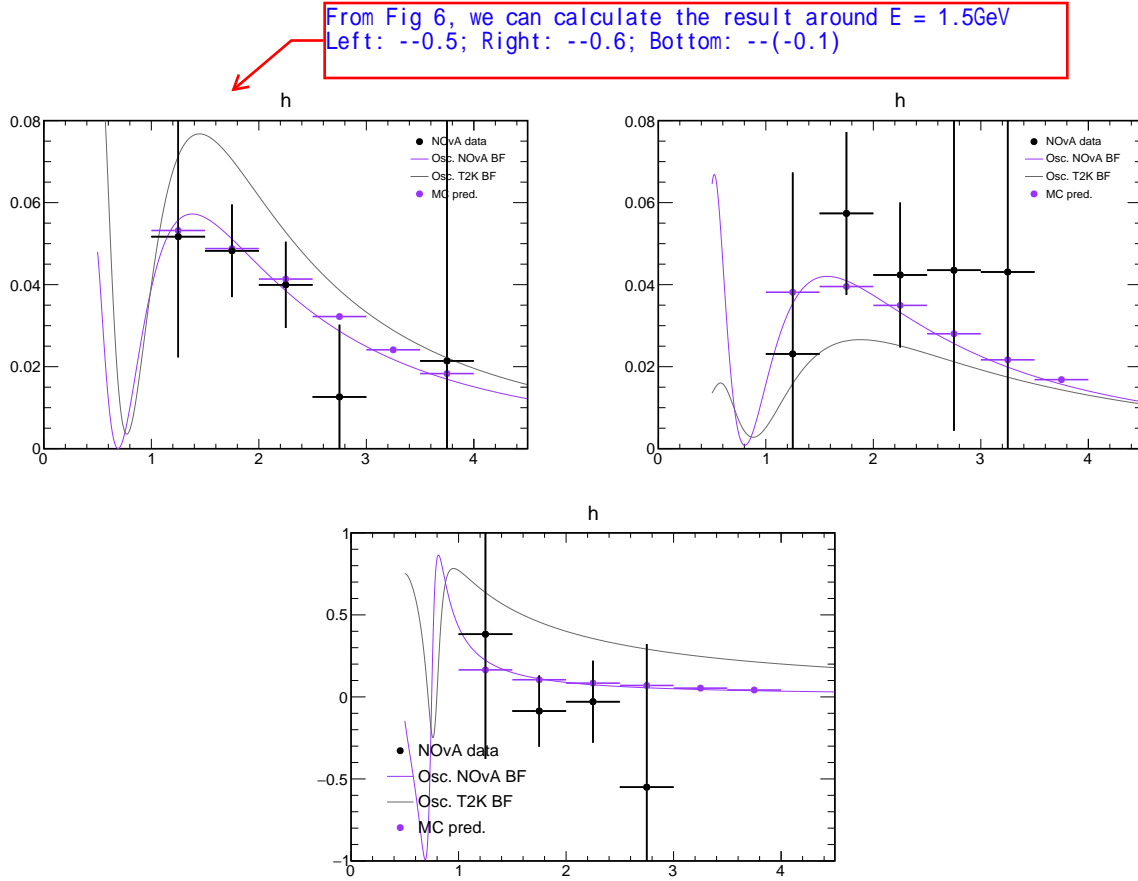Left: --0.5; Right: --0.6; Bottom: --(-0.1)

Figure 7: Result of osc. probability and A_{CP} calculation. Don't pay attention to the black dots error bars, they're gaussian. Violet marker is a result with MC prediction for the signal at 2020 BF point.

3   Calculation of error bars

NB: in this section, the mock data universe was treated as real data. Everything will be replaced with real data-based plots once it is allowed.

It was decided to use Poisson fluctuations and assign the region with 68% of experiments to the error bar. Each experiment goes throw the chain described in the previous section. In order to calculate the background rate for each experiment, each mock data universe is fitted like it's described in **?**. In total 5'000 mock experiments were played.

Obtained distribution examples for "signal" and oscillation probabilities per bin for FHC are shown in the Figures 8 - 10.

Final plots with statistical error bars calculated with this procedure for "data" are shown in Figure 11.

In order to take into account also the systematic variations the following steps were done during the background calculation stage:

- for individual best fit oscillation parameters were played with gaussian 1 sigma taken as error size in 2020 (3% for Δm^2_{32} and 7% for θ_{23}. For $\delta_{CP} \pm 1\pi$ range was used)

- total systematic error for the background was taken as 6% for FHC and RHC. The scaling factor for histogram was played around 1 with this value as 1 sigma error.

- after all these changes Poisson fluctuations were applied to the total background histogram.

The further procedure is the same as previously. As a result of these steps, the change to the obtained error bars can be found in Figure 12.
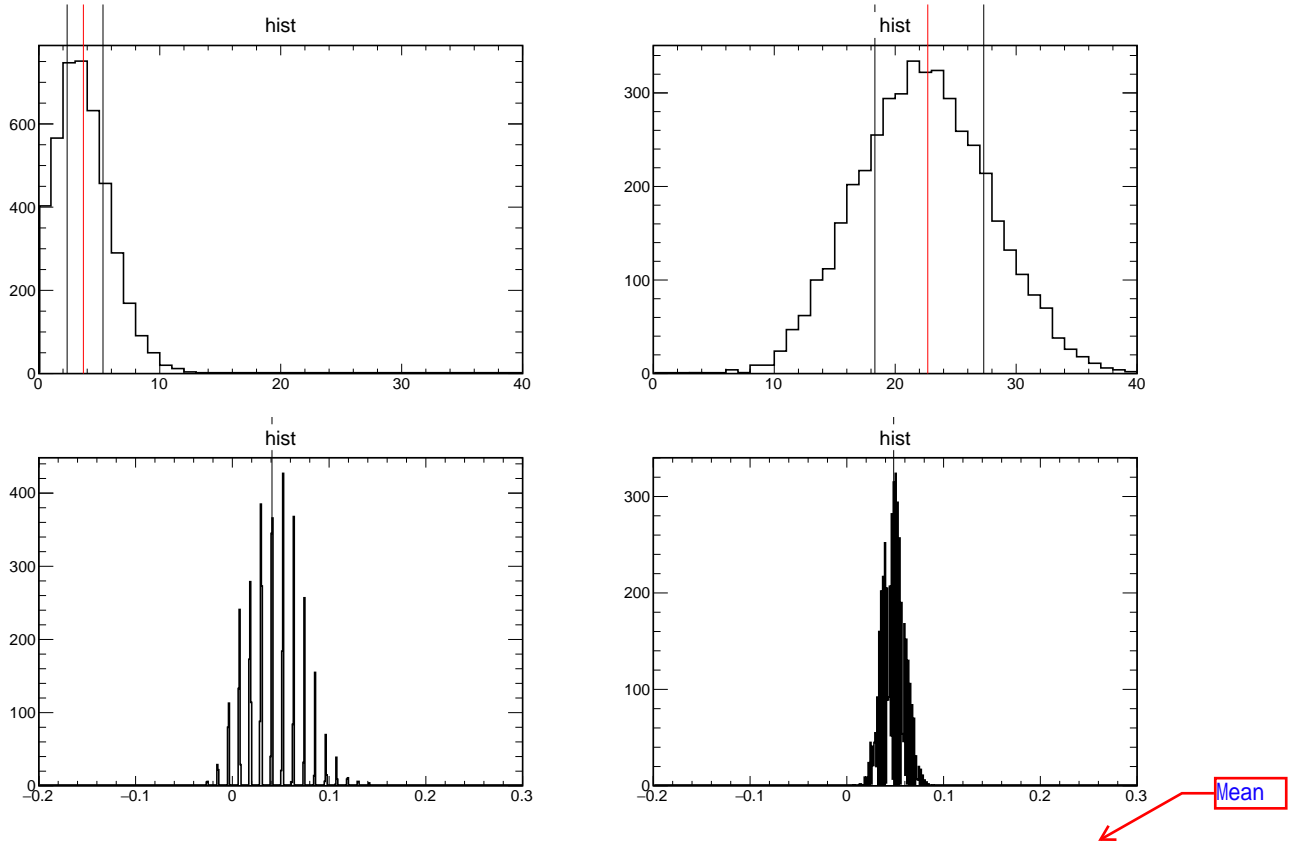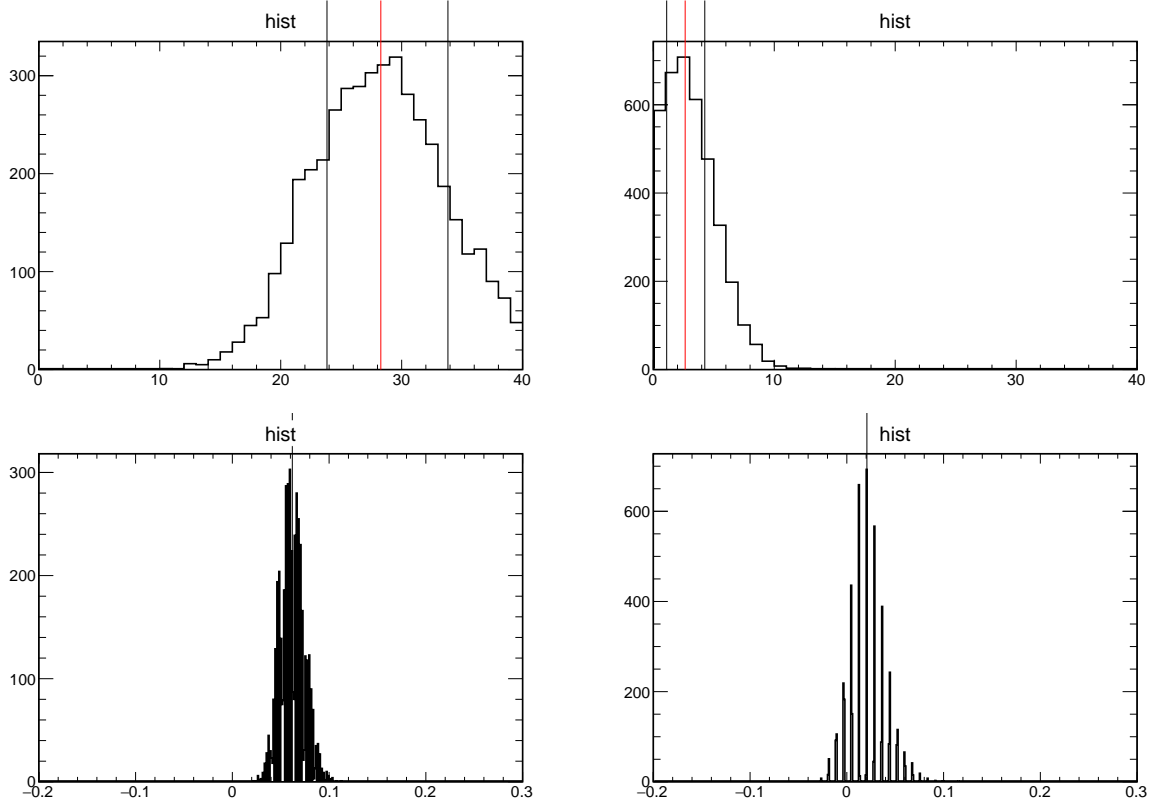
Figure 8: Top row: experiment's signal distributions for the bin. The Red line is the initial "data" value, black lines show 1 sigma calculated for this value. Bottom row: calculated oscillation probabilities for these experiments. a region that includes 68% experiments is assigned to the bin as an error. Bins: 1.0-1.5 GeV and 1.5-2.0 GeV.

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Figure 9: Top row: experiment's signal distributions for the bin. The Red line is the initial "data" value, black lines show 1 sigma calculated for this value. Bottom row: calculated oscillation probabilities for these experiments. a region that includes 68% experiments is assigned to the bin as an error. Bins: 2.0-2.5 GeV and 2.5-3.0 GeV.
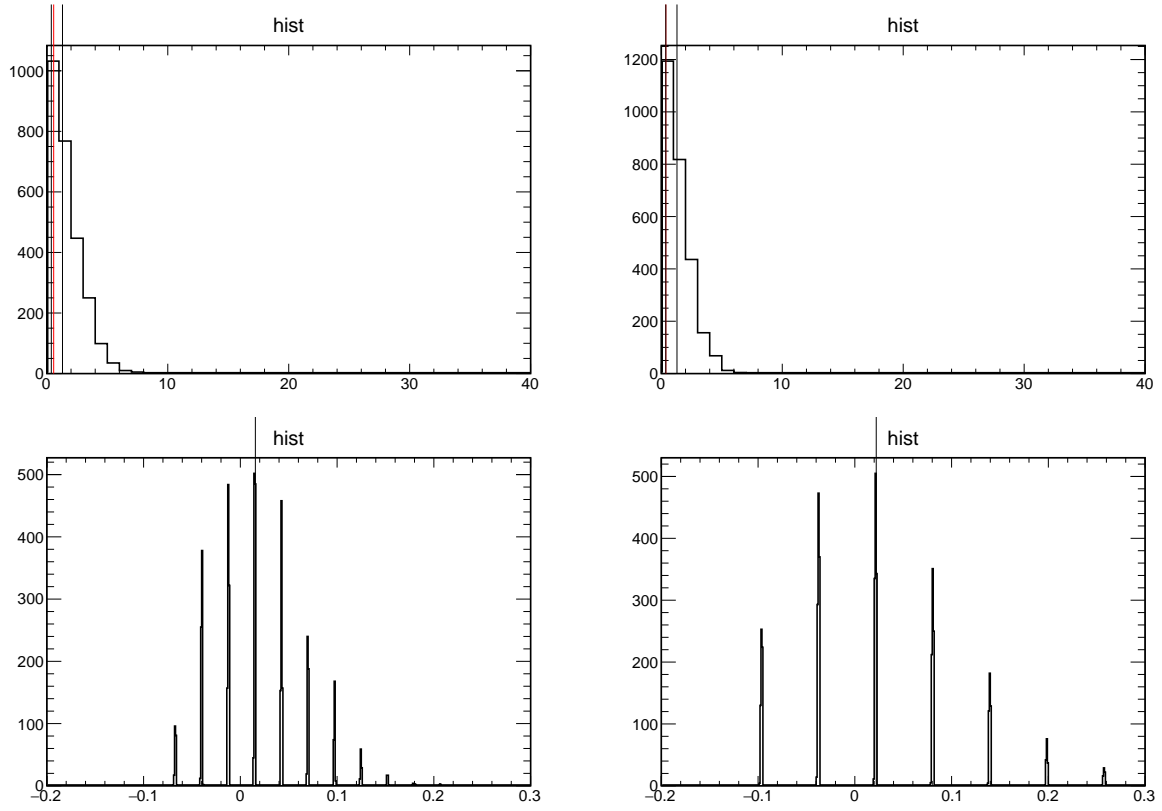
Figure 10: Top row: experiment's signal distributions for the bin. The Red line is the initial "data" value, black lines show 1 sigma calculated for this value. Bottom row: calculated oscillation probabilities for these experiments. a region that includes 68% experiments is assigned to the bin as an error. Bins: 3.0-3.5 GeV and 3.5-4.0 GeV.
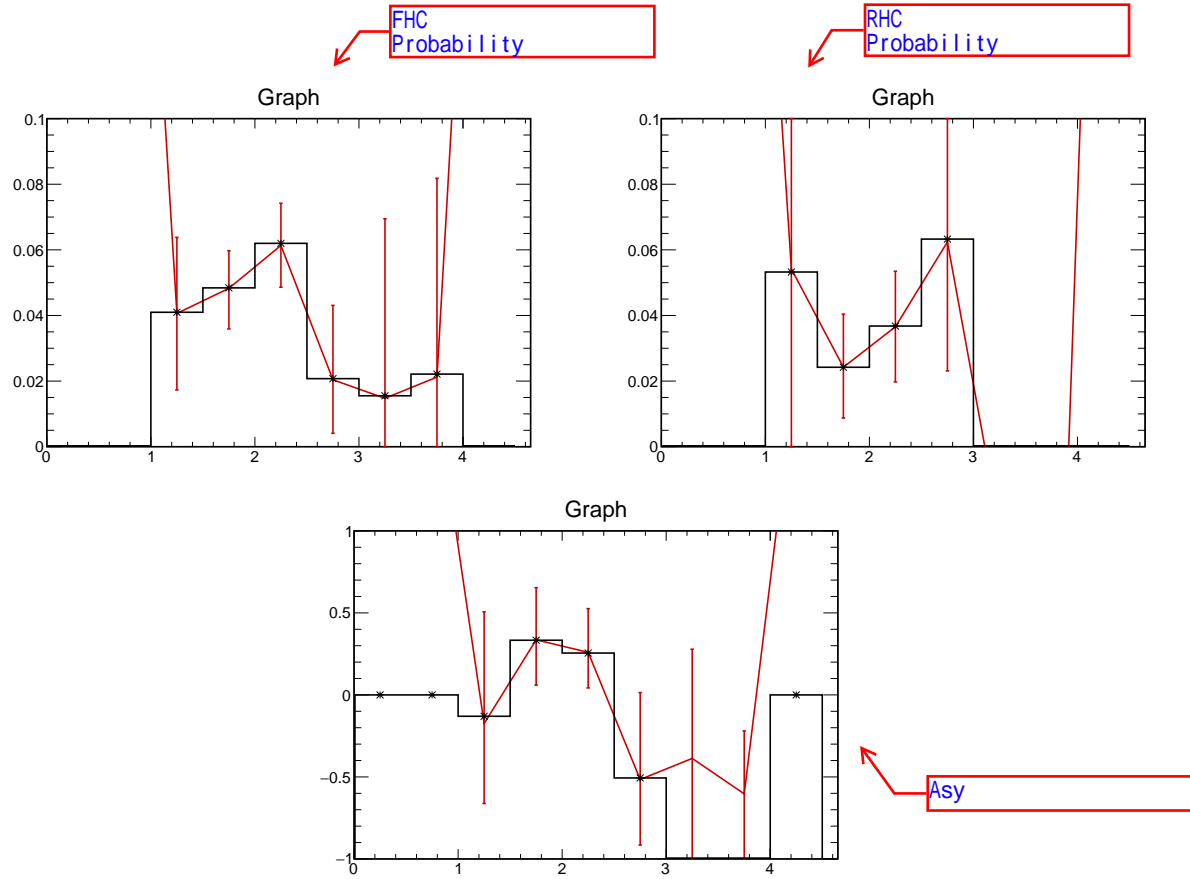
Figure 11: Result of statistical error bar calculation which represents the region with 68% of experiments. The black histogram is the initial "data"'s central value result.
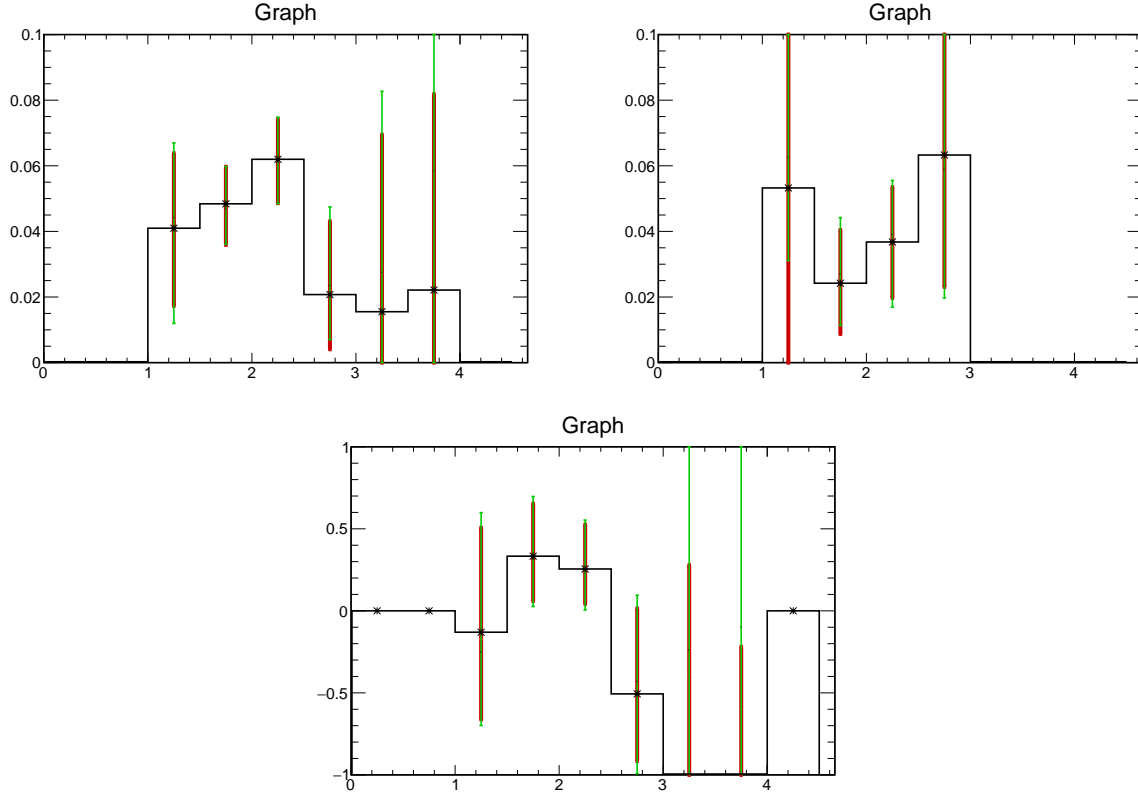
Figure 12: Result of statistical and systematical error bar calculation which represents the region with 68% of experiments. Red error bars stand for statistical error, green includes also systematic effects and background fluctuations.
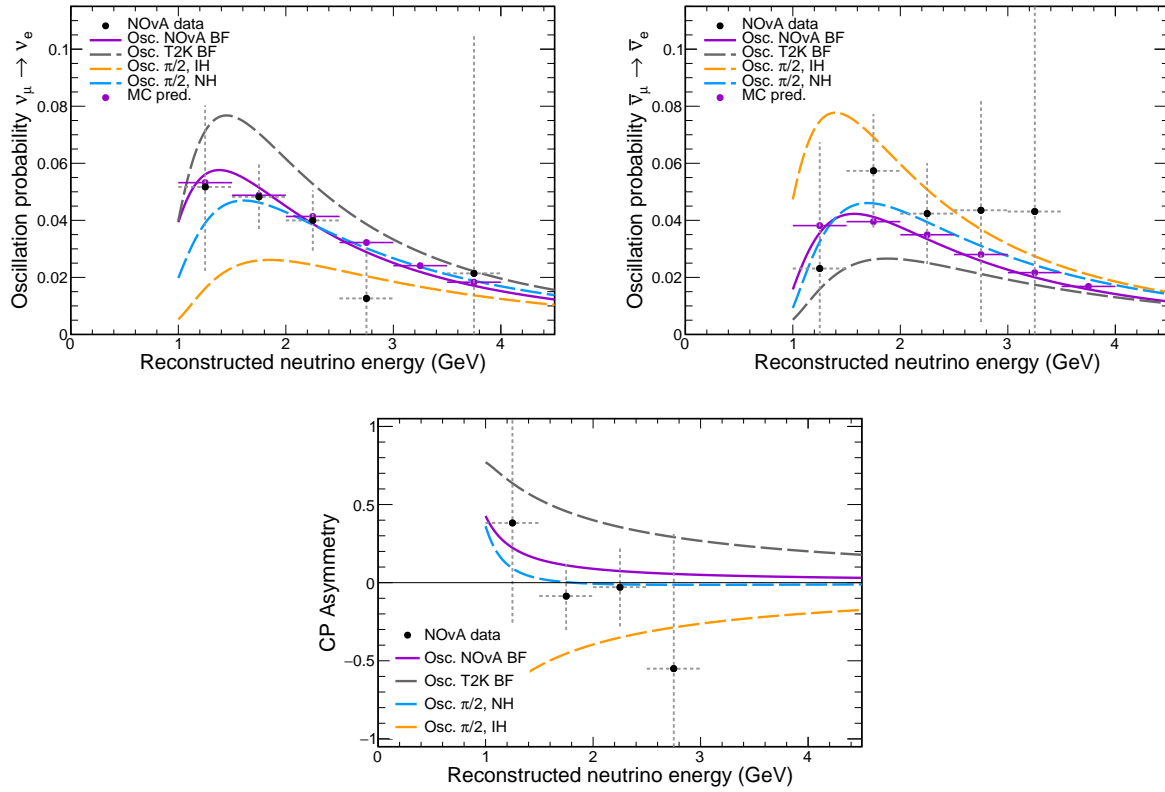
4 Results

Here will be final plots with real data and error bars made for them.

Figure 13: Final plots for blessing.