Precision Measurements at Long-Baseline Oscillation Experiment

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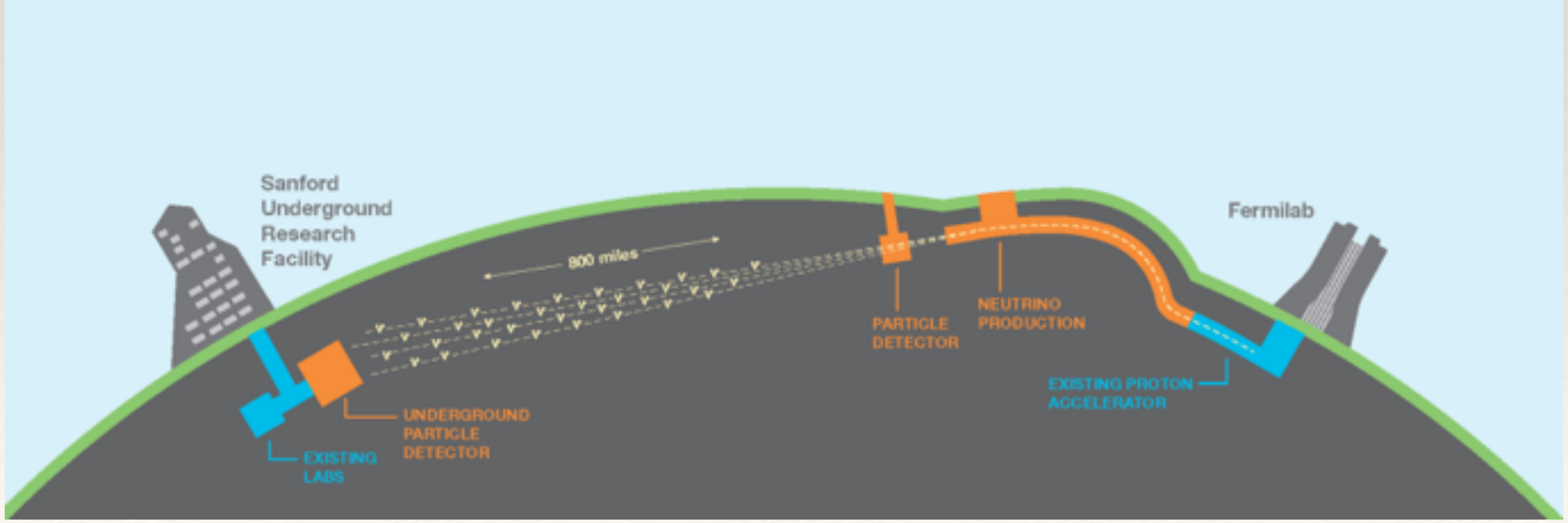
Long Baseline Experiment-DUNE

These experiments search for $\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_\mu$ $\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e$

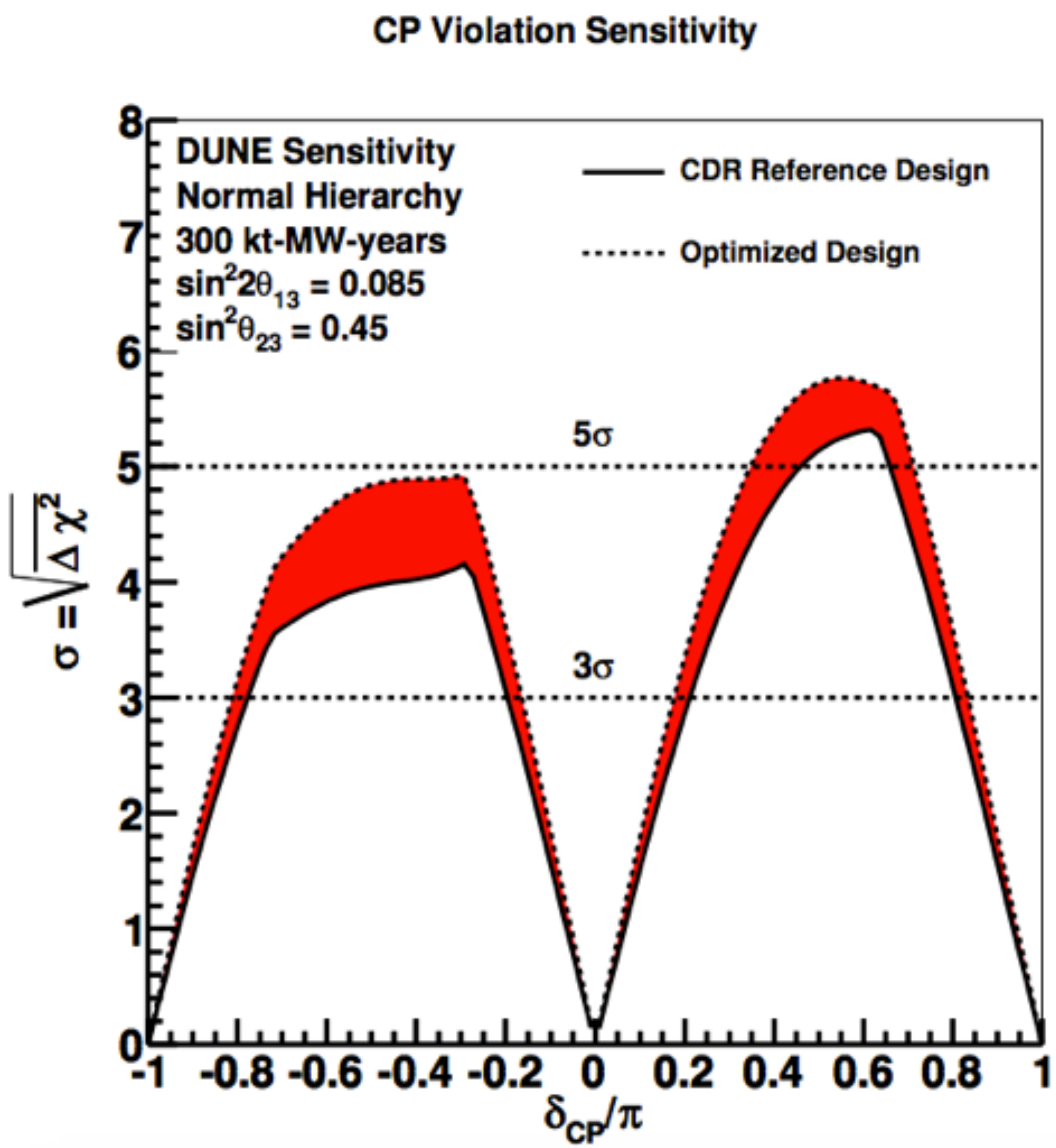
	L (km)	Detector (kt)	Beam Power	E_p (GeV)	Flux peak
LBNE	1300	LAr - 34	1.2 MW	120	3 GeV
DUNE		LAr - 40		80	

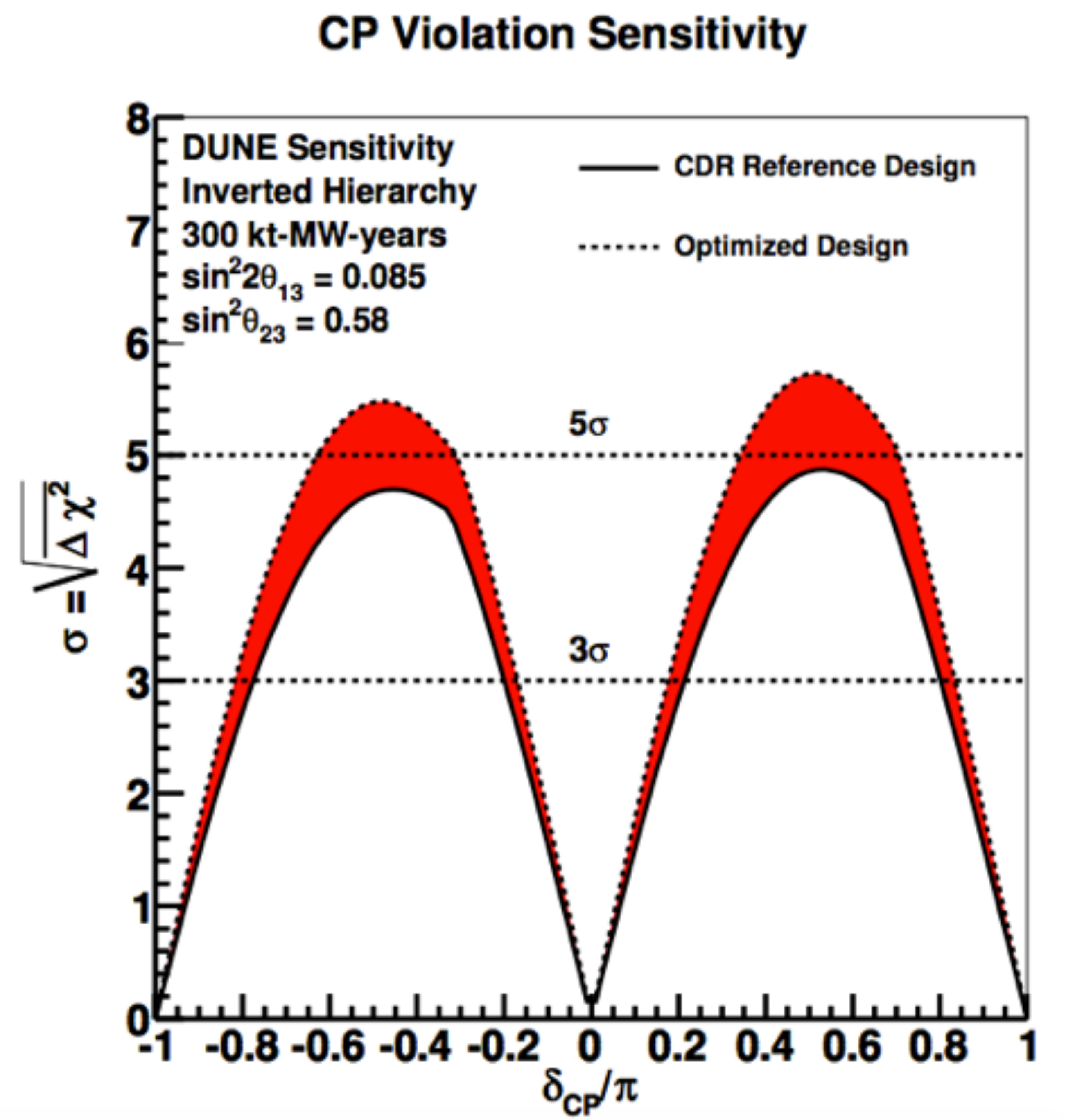


Introduction

- One of the key aims of DUNE is to check and measure the Dirac CPV phase in PMNS matrix.
- CPV phase is important to understand leptogenesis and flavour symmetry in lepton sector.
- One of the purposes to study the sensitivity is to know how to optimise the measurement.

Study on CPV sensitivity





θ_{12}=0.5843; Δm^2_{21}=7.5× 10-5eV^2; Δm^2_{31}(NH)=2.457× 10-3eV^2; Δm^2_{31}(IH)=-2.449× 10-3eV^2

cite from: DUNE/LBNF CDR V2

Analytical Study

- In analytical studies, we neglect the details of experimental setup, except for the baseline and neutrino energies.
- The analytical study can help us to understand how the sensitivity depends on the oscillation probability.

GLoBES

- We check the analytical result with a numerical simulation. We use GLoBES.
- General Long Baseline Experiment Simulator
- GLoBES is a sophisticated software package for the simulation of LBL experiments.
- GLoBES mainly allows to simulate the expected experiment outcome and provides C-library
  to obtain $\Delta\chi^2$ values.
- We use GLoBES to predict the uncertainty of oscillation parameter for the assigned experimental setup and the given true oscillation parameters.

GLoBES http://www.mpi-hd.mpg.de/personalhomes/globes/index.html

Analytical Study On CPV-Phase Sensitivity

Matter In matter, the maxima of the oscillation probability for neutrinos and antineutrinos do not coincide. It is sensible to assume that most of the information in the neutrino channel comes from the bin where the neutrino probability maximizes, *i.e.* $(1-\hat{A})\Delta = \pi/2$, while in the antineutrino channel it comes from the bin where the antineutrino probability maximizes, *i.e.* $(1+\hat{A})\Delta = \pi/2$. The contribution to the error of both such bins is

$$(\Delta\delta)_\pm = \frac{\frac{\pi}{2}\frac{\hat{A}}{(1\mp\hat{A})}}{\sin\left[\frac{\pi}{2}\frac{\hat{A}}{(1\mp\hat{A})}\right]}\frac{1}{\sin\left(\frac{\pi}{2}\frac{1}{(1\mp\hat{A})}\mp\delta\right)}, \qquad (3.11)$$

$$\Delta\delta \simeq \left(\sqrt{\frac{1}{(\Delta\delta)_+^2}+\frac{1}{(\Delta\delta)_-^2}}\right)^{-1}$$

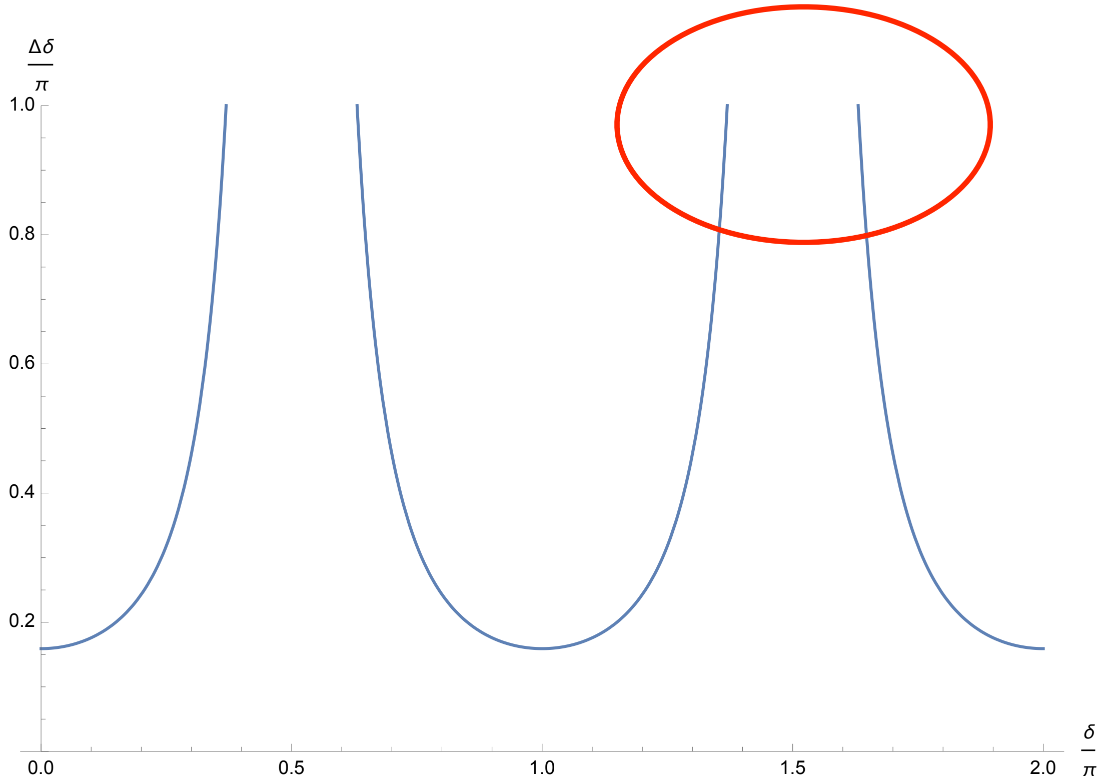
$$\Delta \equiv \frac{\Delta m_{13}^2 L}{4E}, \quad \Delta_{12} \equiv \frac{\Delta m_{12}^2 L}{4E}, \quad \hat{A} \equiv \frac{\sqrt{2}G_F n_e L}{2\Delta},$$

P. Coloma at. el. (arXiv:1203.5651)

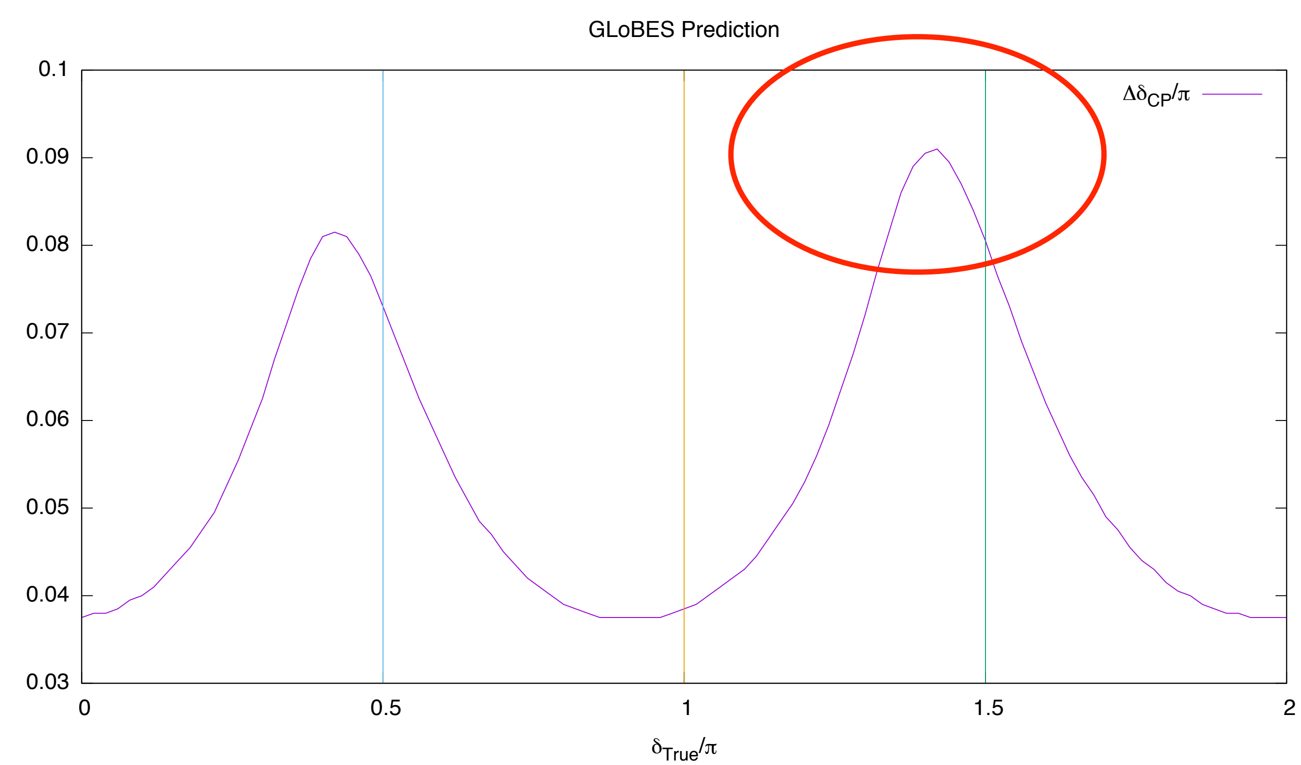
Go Beyond the First Maximum

For DUNE, studying $\nu_\mu \rightarrow \nu_e$ in matter, with baseline=1300 km and wide band bin around the first maximum,we need to consider more than the oscillation maximum.

By using the approximation in arXiv:1203.5651



By GLoBES



To go beyond the first-oscillation-maximum approximation, we look at

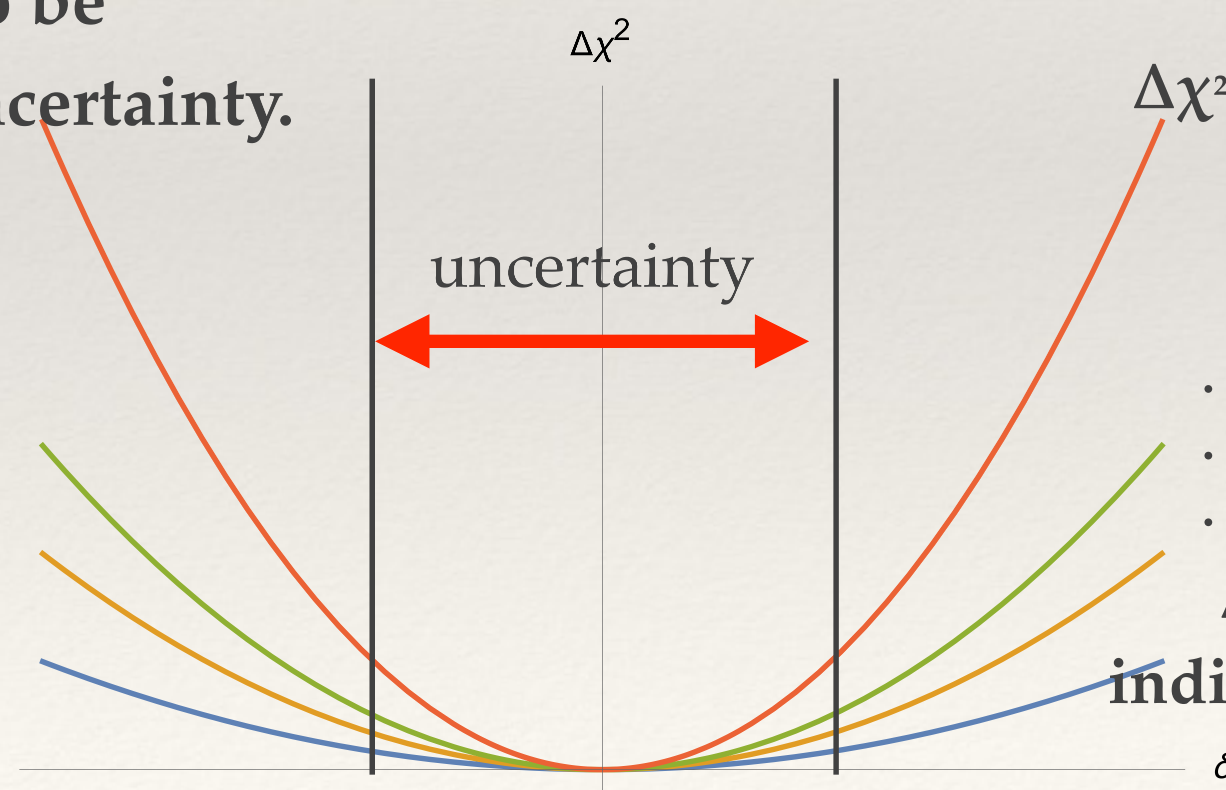
Poison distribution; Best Fit=True Value

$$\Delta\chi^2 = \Sigma_i \Delta\chi_i^2 = \Sigma_i \frac{(\hat{n}_i - n_{i,hypothesis})^2}{n_{i,hypothesis}} = \Sigma_i \frac{(\hat{n}_{i,\delta}\Delta\delta_A)^2}{\hat{n}_i}$$

Good Sensitivity; Taylor Expansion; we neglect the higher order terms

n_i is the event number of bin i.
$n_{i,\delta}$ is the derivative of n_i w.r.t. δ_{CP}.

$\Delta\chi^2(\Delta\delta)$ and $\Delta\chi^2_i(\Delta\delta)$ are assumed to be quadratic equations within the uncertainty.



$$\Delta\chi^2 = \Sigma_i \Delta\chi_i^2 = \Sigma_i \frac{(\hat{n}_i - n_{i,hypothesis})^2}{n_{i,hypothesis}} = \Sigma_i \frac{(\hat{n}_{i,\delta}\Delta\delta_A)^2}{\hat{n}_i}$$

We are interested in the precision at 1 σ (1 d.o.f), requiring $\Delta\chi^2$ =1. Then, we rearrange the above equation as follows.

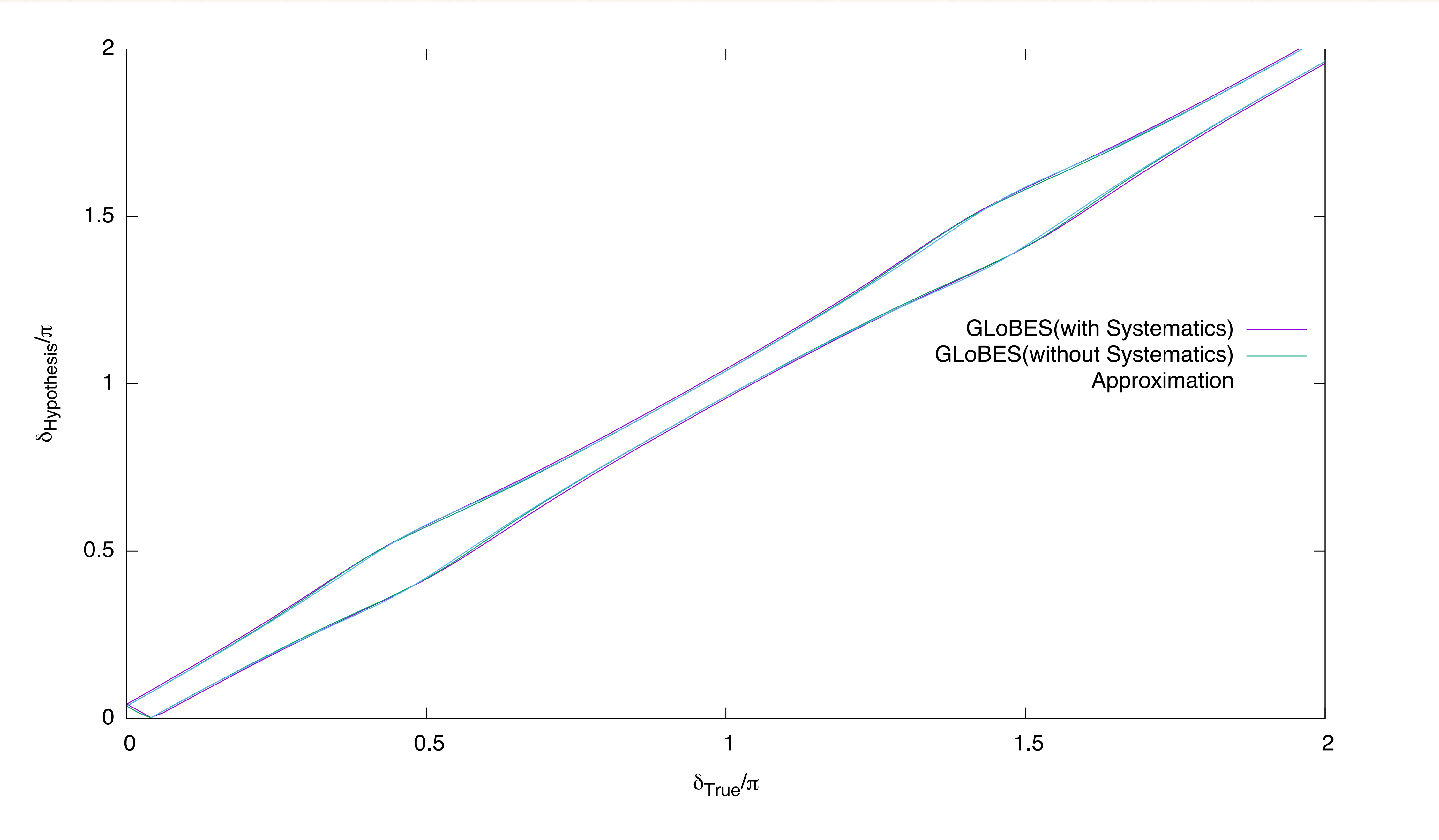
$$\Delta\delta_A = \frac{1}{\sqrt{\Sigma_i \frac{\hat{n}_{i,\delta}^2}{\hat{n}_i}}} \equiv \frac{1}{\sqrt{\Sigma_i \Delta_i^2}} \equiv \frac{1}{\sqrt{\Sigma_i \frac{1}{\Delta\delta_{A,i}^2}}}.$$

- If the derivative=0, the event number in bin i does not change significantly with delta and therefore this bin cannot give the contribution of CPV-phase sensitivity.

$$\Delta\delta_A = \frac{1}{\sqrt{\sum_i \frac{\hat{n}_{i,\delta}^2}{\hat{n}_i}}} \equiv \frac{1}{\sqrt{\sum_i \Delta_i^2}} \equiv \frac{1}{\sqrt{\sum_i \frac{1}{\Delta\delta_{A,i}^2}}}.$$

- The factor Δ_i^2 is proportional to the $\Delta\chi^2$-value of bin i at $\delta_{CP}+\Delta\delta_A$ or $\delta_{CP}-\Delta\delta_A$.
- $\Delta\delta_{A,i}$ is the analytically expected uncertainty for the bin i.
- The bin with a bigger value of Δ_i^2 (or a smaller value of $\Delta\delta^2_{A,i}$) contribute more to CPV-phase sensitivity.
- Δ_i^2 (or $\Delta\delta^2_{A,i}$) can help us to understand how a bin contributes to the sensitivity.

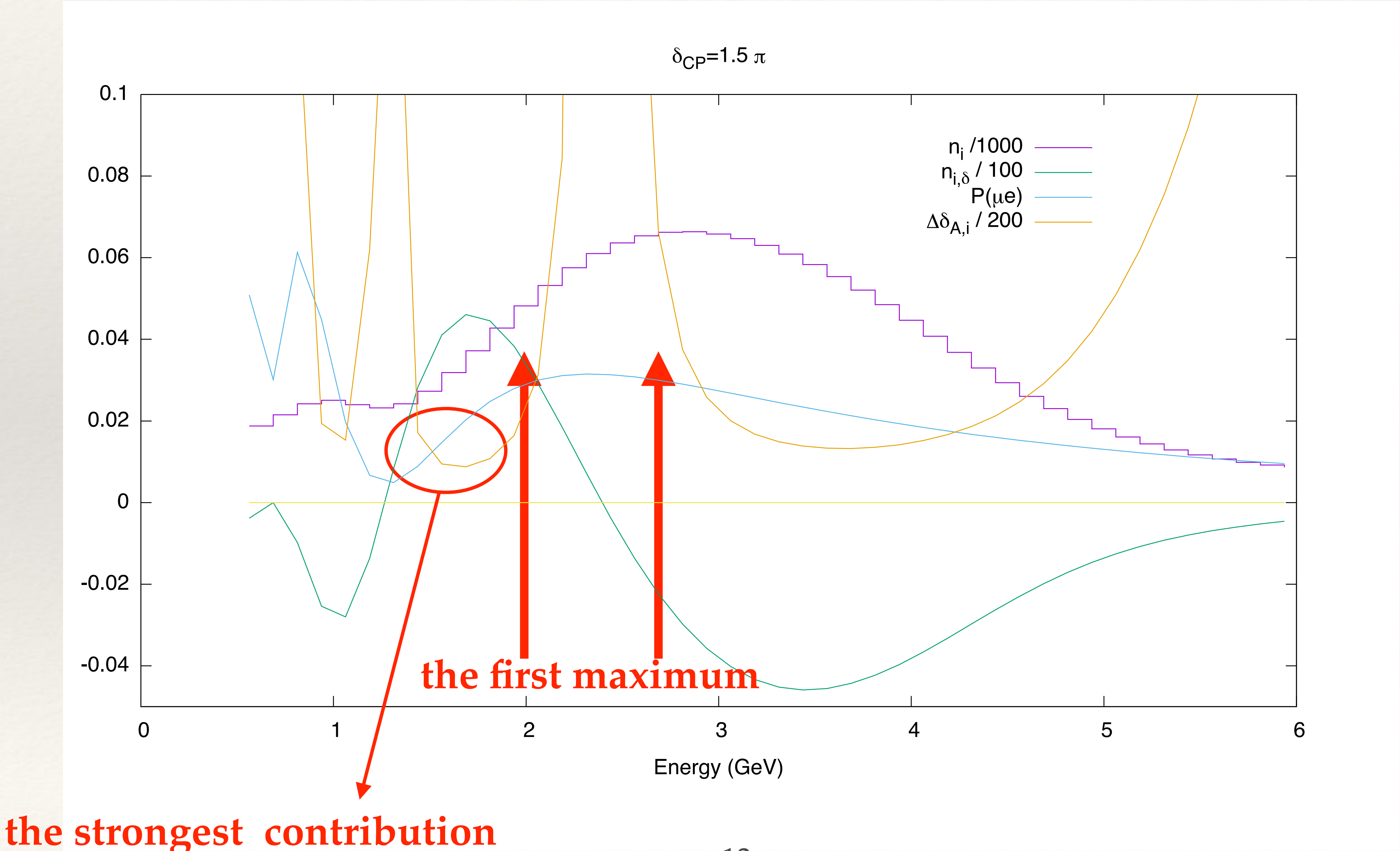
By using the same set of event numbers, we check the validity of $\Delta\delta_A$-approximation. We compare this approximation with GLoBES results.



ν + anti-ν

θ_{12}=33.48°; θ_{23}=42.3°; θ_{13}=8.52°; $\Delta m^2_{21}=7.5\times 10^{-5}\mathrm{eV}^2$; $\Delta m^2_{32}(\mathrm{IH})=-2.449\times 10^{-3}\mathrm{eV}^2$

We take an example (δ_{CP}=1.5π) to show the contribution of a bin to the measurement. We find that bins at the first maximum are hard to contribute to CPV-phase sensitivity, but the bins with energy between 1.5 GeV to 2 GeV give the strongest contribution.



Making an Analytical Tool

- For simplification, we assume background is negligible, and, at the same time, we collect flux, cross section, efficiency and mass of target to be a factor $N_i^{F.O.}$, which is the event number for oscillation probability = 1 (full oscillation). Note larger number of event -> smaller uncertainty.

Signal

Background

$$\hat{n}_i = \underline{\Phi_{\nu_\mu}(E_i)\sigma_{\nu_e}(E_i)}\mathrm{P}(\nu_\mu \to \nu_e; \vec{\theta}_{true}; E_i, L)\underline{\epsilon_e M} + \Sigma_{f=e,\mu,\tau}\Phi_\nu(E_i)\sigma_{\nu_f}(E_i)\epsilon_{f(e)}$$

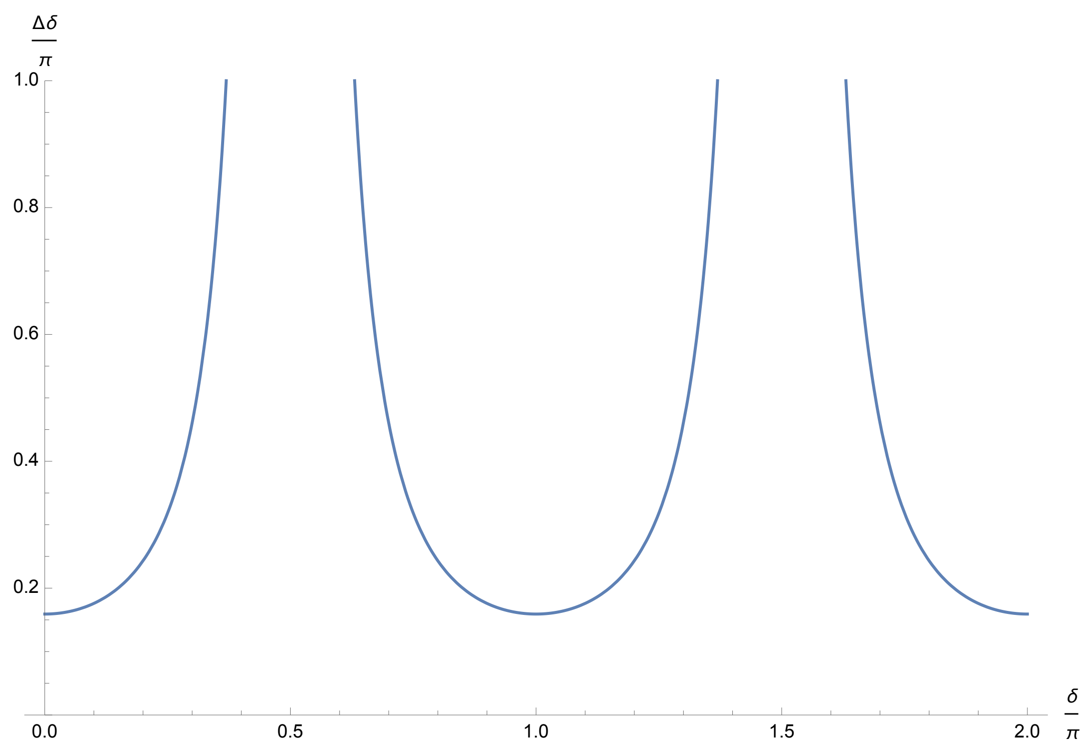
$$\approx \underline{N_i^{F.O.}}\mathrm{P}(\nu_\mu \to \nu_e; \vec{\theta}_{true}; E_i, L).$$

$$\Delta_i^2 = \frac{1}{\Delta\delta_{A,i}^2} = \frac{\hat{P}_i}{N_i^{F.O.} \times \hat{P}_{i,\delta}^2},$$

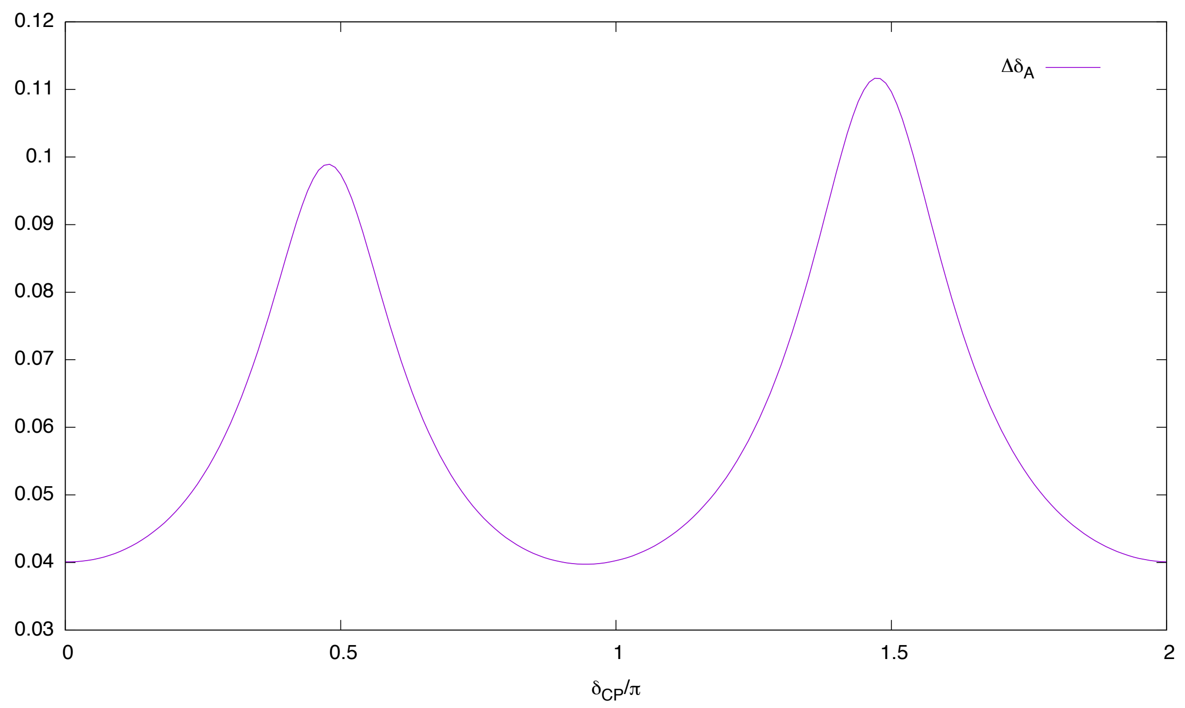
$$\Delta\delta_A = \frac{1}{\sqrt{\Sigma_i \frac{\hat{P}_{i,\delta}^2}{\hat{P}_i} N_i^{F.O}}}.$$

Compare two approximations.

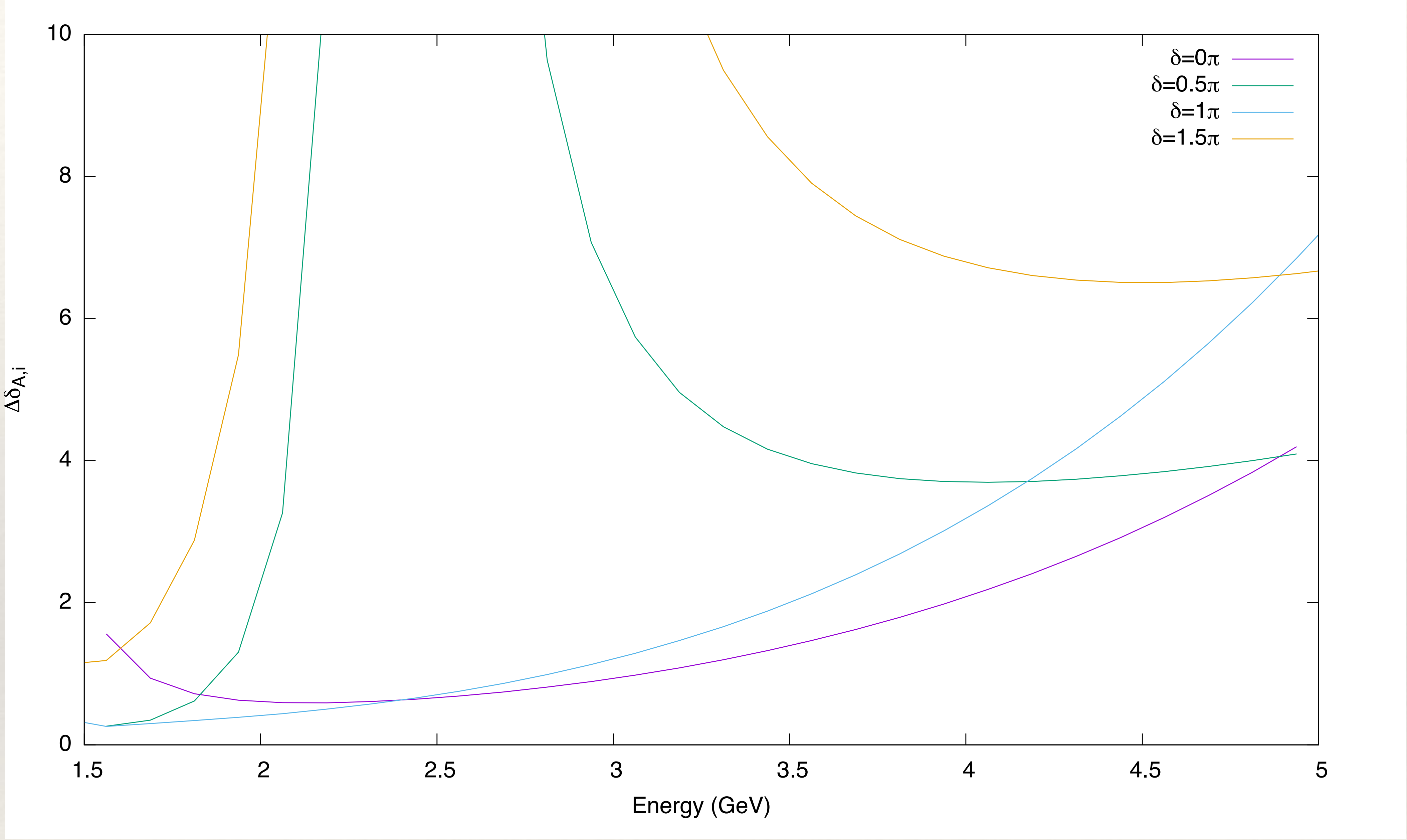
By using the approximation in arXiv:1203.5651 (Energy=E_{max})



We focus on
$1.5\text{GeV} \leq \text{bin energy} \leq 5\text{GeV}$
with the bin width of 0.125 GeV

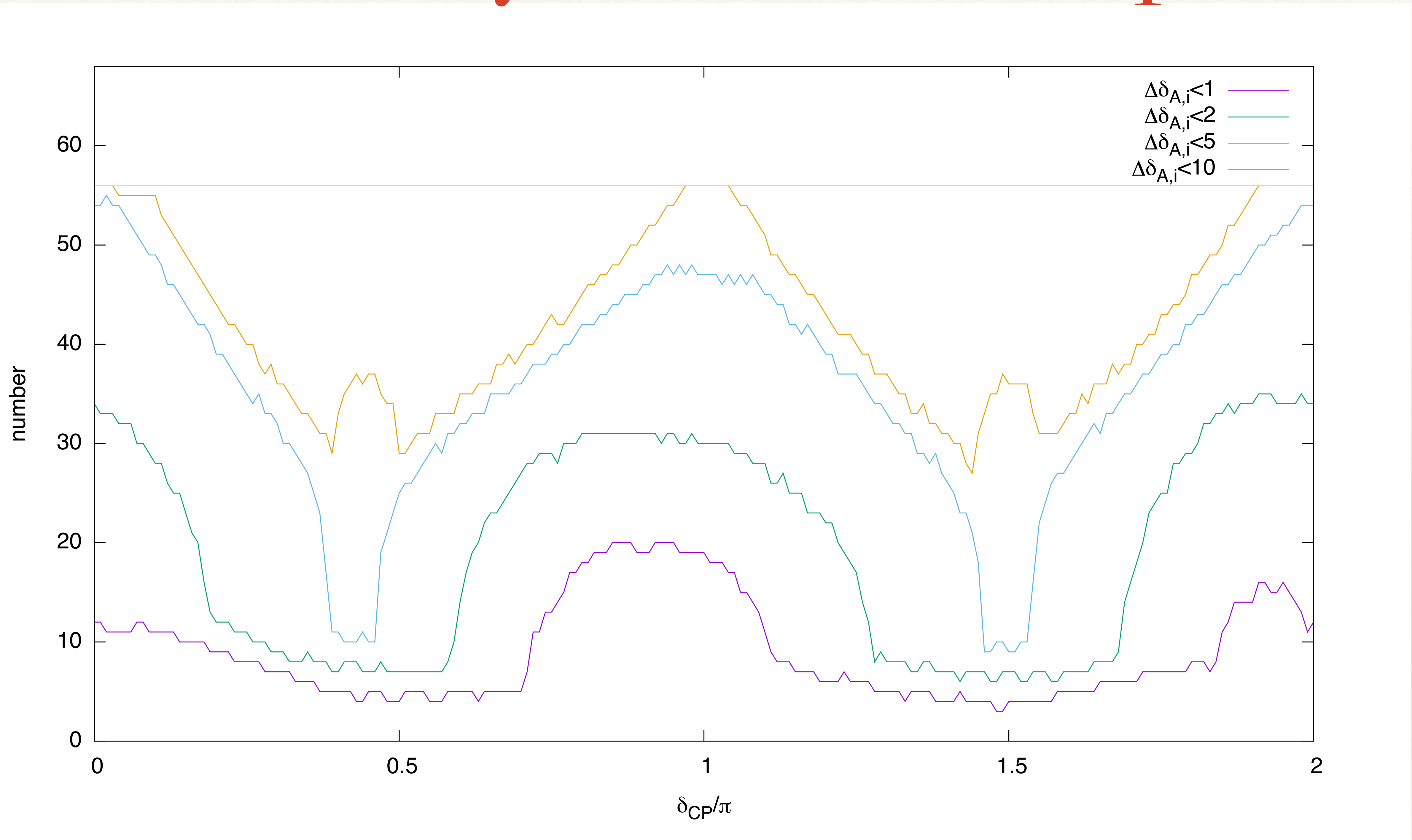


Detailed Study for Some CPV Phases



More than one bin contribute to CPV-phase sensitivity!

Detailed Analysis for all CPV phases



δ_{CP}=0.5,1.5π have the smaller number of bins with stronger contribution.

Conclusions and further work

- We have developed an analytical tool which can help us to understand the contribution of different energy bins to the precision achievable on delta.
- We have checked the approximation with numerical simulations run using GLoBES.
- We are now going to use the analytical tool and the numerical simulations to study the precision attainable in future LBL experiments focusing on the dependence on the oscillation parameters and on the optimisation of the experimental setups.

Thank you!!