Upgrade of P-theta from T2K to HK

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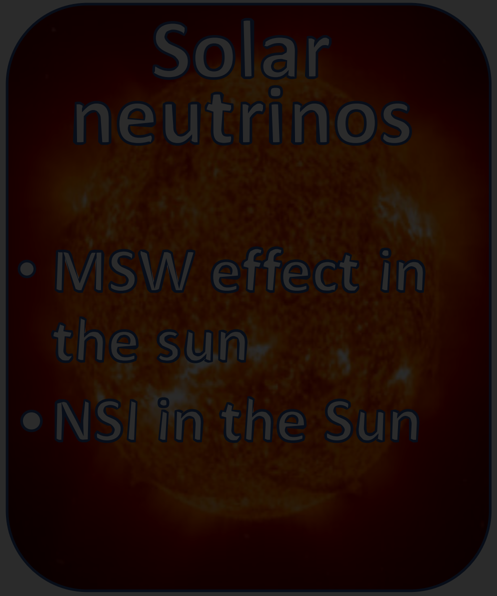
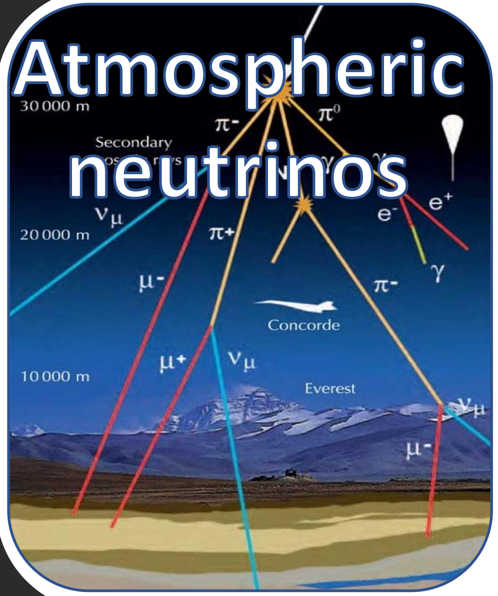
The HK collaboration meeting

LLR Group meeting – 02.05.2023

HyperK has an extensive physics program





Large physics program ⇒ Strong requirements on electronics

HK = challenging measurements:
- complex topologies: e.g. multiring samples
- large energy range: from SN to HE physics
- Michel-electron tagging
- neutron tagging

HK = challenging systematics:
- PMT response.
- Water transparency
- Direct vs indirect light
- Huge scale

Strong requirements on electronics:
- on charge measurements
- on timing measurements
- on hit rate and dead time

Large physics program ⇒ And analysis software as well !

HK = challenging measurements:
- complex topologies: e.g. multiring samples
- large energy range: from SN to HE physics
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- neutron tagging

HK = challenging systematics:
- PMT response.
- Water transparency
- Direct vs indirect light
- Huge scale

Advanced efficient far detector fitter software

Introduction

The current situation of HK-LBL far detector fitters:

- **Official FD fitters**: **Valor and Osc3++**
  Based on **OA2018** systematics and inputs with applied HK reweighs

- Now **P-theta** and **Mach3** are being adapted for HK era **basing on OA2020**

The goal is to officialize the P-theta framework with 2020 syst model for the HK experiment

Part I: P-theta framework

Five SK samples are used in T2K OA2020:

- Two samples with 1 μ-like ring for ν and $\overline{\nu}$ modes
- Two samples with 1 e-like ring for for ν and $\overline{\nu}$ modes
- One ν_e sample with $1\pi^+$ in final state

Samples binning (specifically for P-theta):

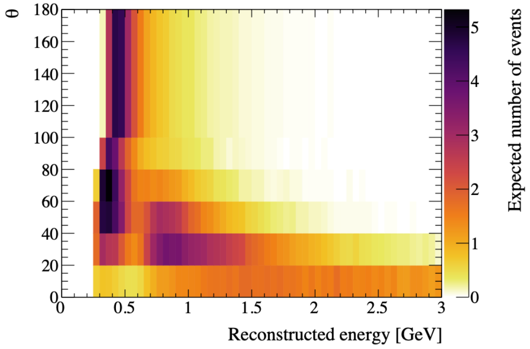
- $E_{rec} - \theta$ for μ-like samles
- $p - \theta$ for e-like samles (*the origin of the name*)

$p - \theta$ distribution of reconstructed electrons (positrons) is different for the signal and background categories

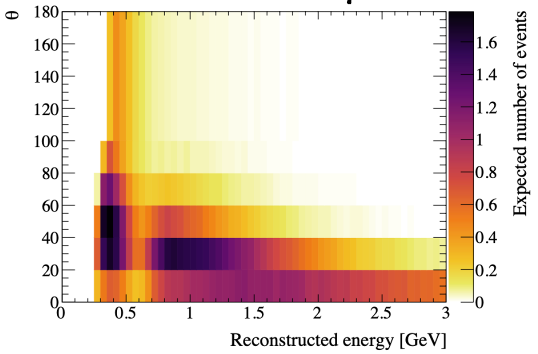
⬇

additional power to distinguish between signal and background events

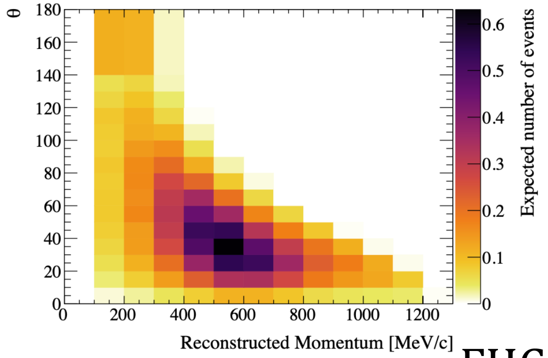
FHC $1R\mu$



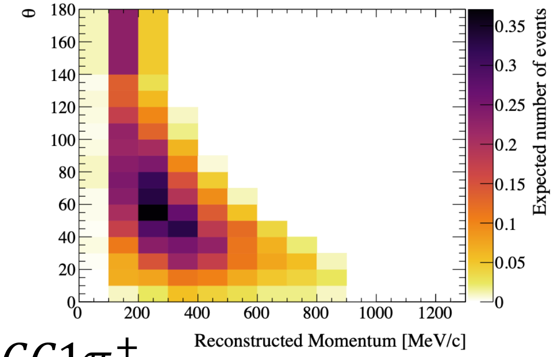
RHC $1R\mu$

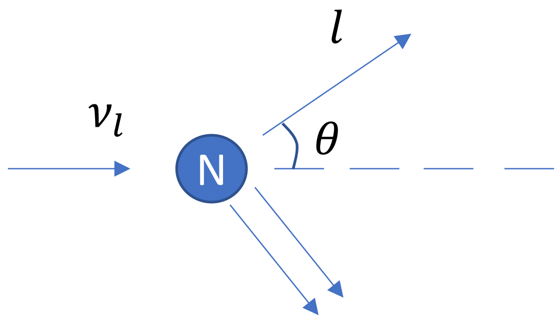


FHC $1Re$



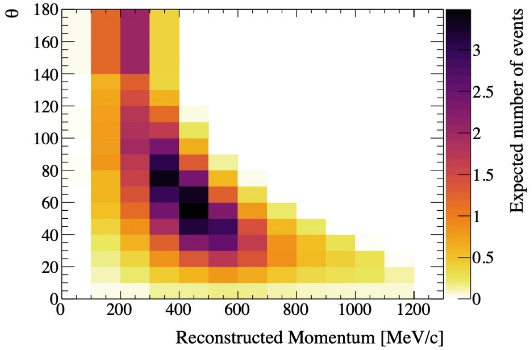
RHC $1Re$





adronic part

FHC $\nu eCC1\pi^+$



Part II: Reweighing from T2K to HK

The 5 event samples used are the Super-K event samples, with the MC scaled up to HK statistics

HK inputs = SK inputs(2020) X HK reweighs

HK reweighs:

1) Mass scaling

- Bulk events which pass a 2 m fiducial volume cut - scaled by volume: factor ~ 8.3
- Surface events - scaled by surface: factor ~ 3.1

2) Flux scaling

- tune from 250 kA to 320 kA
- reweigh to different far detector location

3) POT scaling

- $2.7 \cdot 10^{21}$ POT per HK-year (6 months, power 1300 kW, spills 1.16s)
- Ratio between FHC and RHC runs: $\nu_\mu : \overline{\nu}_\mu = 1:3$

Part II: Reweighing from T2K to HK

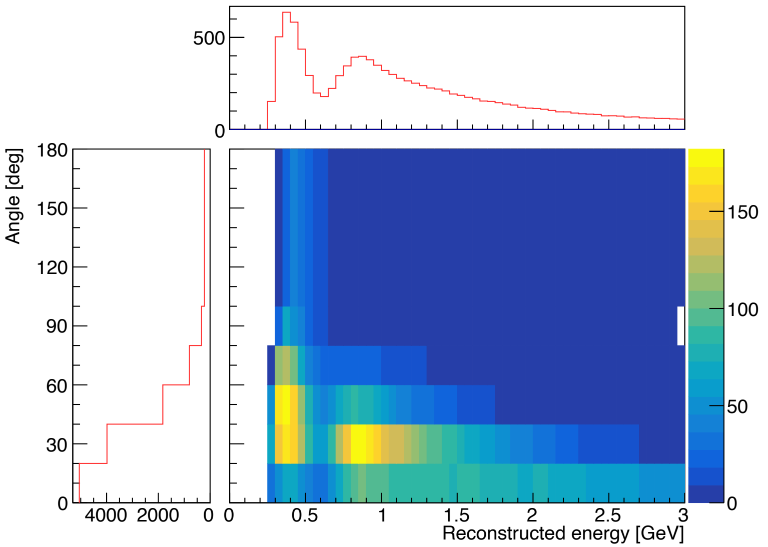
AsimovA
10 HK years

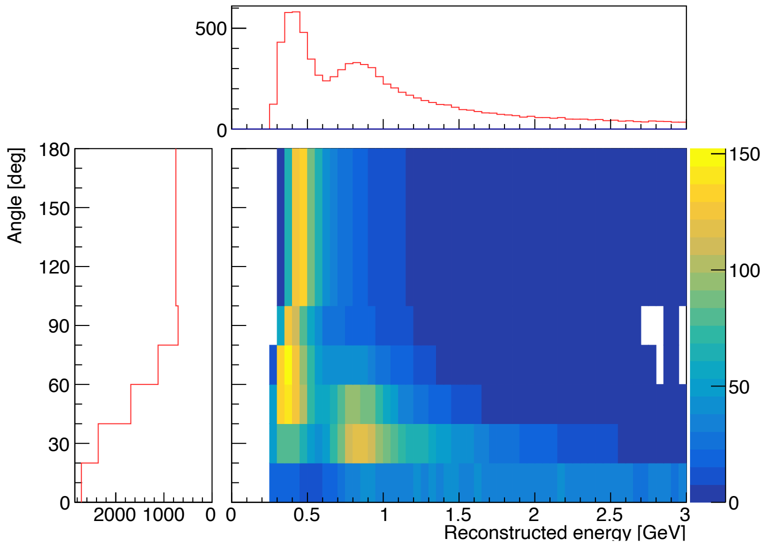
Reweighted FD samples

$FHC\ 1R$ | $RHC\ 1R$

$\mu-\text{like}$

$E_{rec}-\theta$

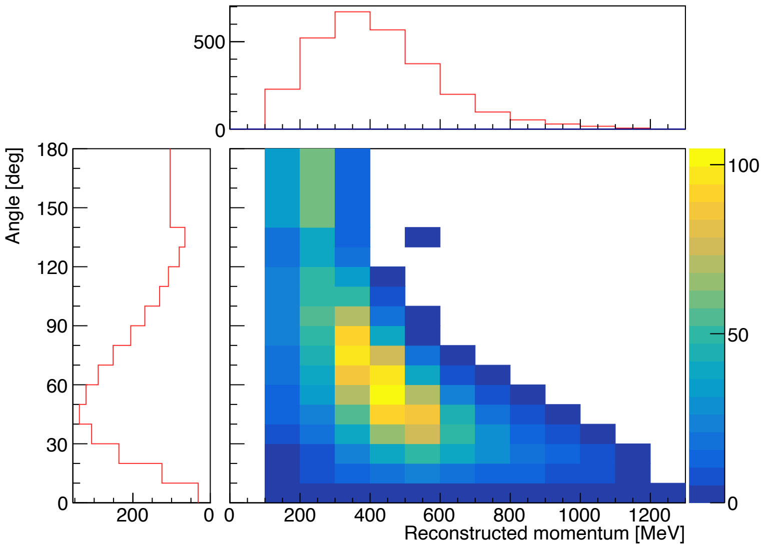


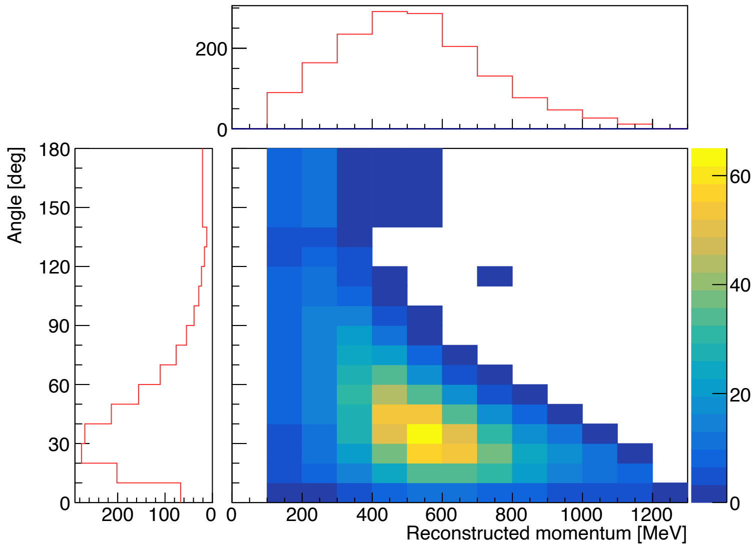


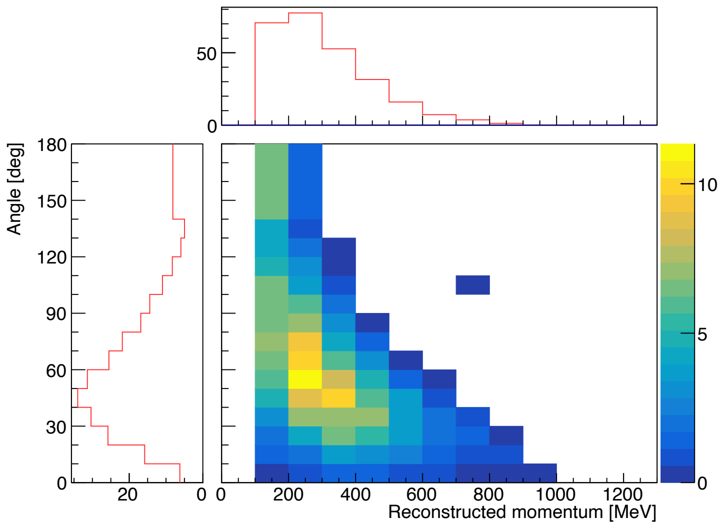
$FHC\ 1R\ 1de$

$e-\text{like}$

$p-\theta$

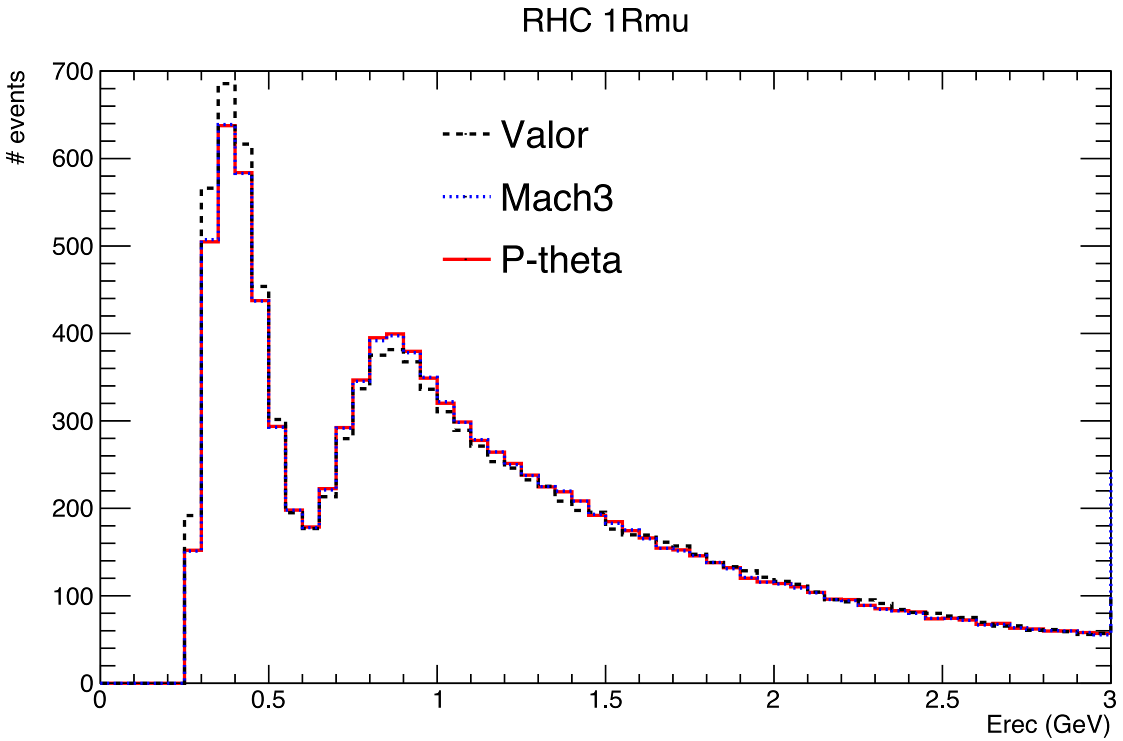


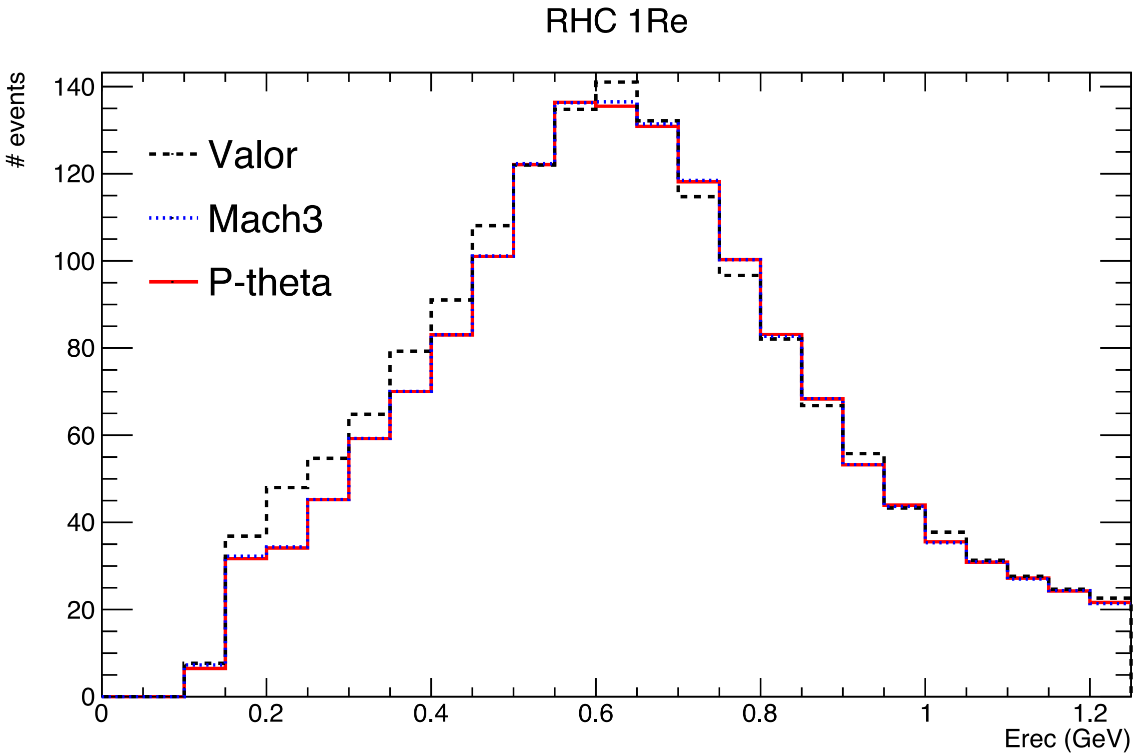




Part III: Validation

Energy spectra comparison

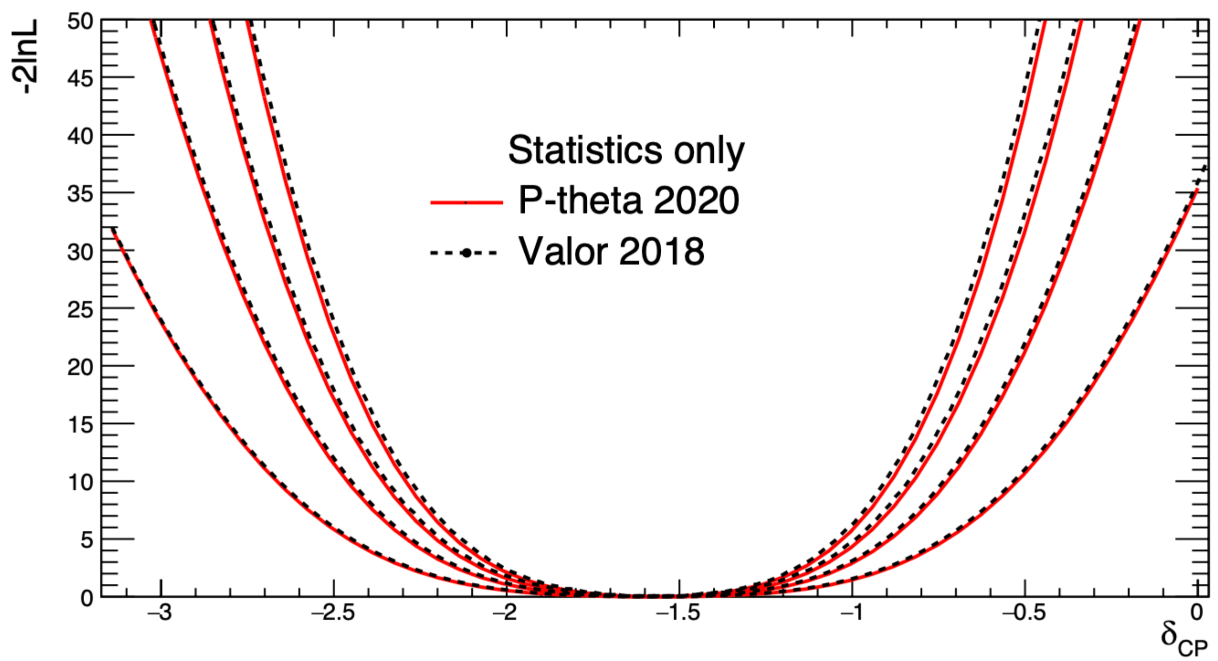




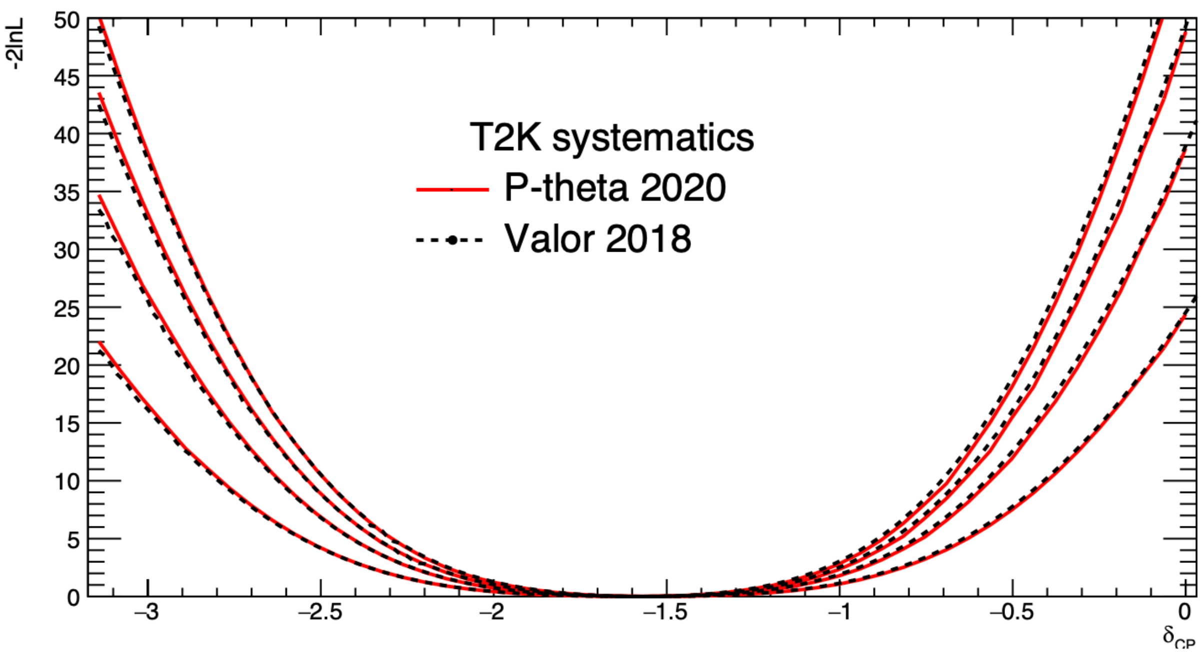
Good agreement

Part III: Validation

Statistic only



T2K systematics

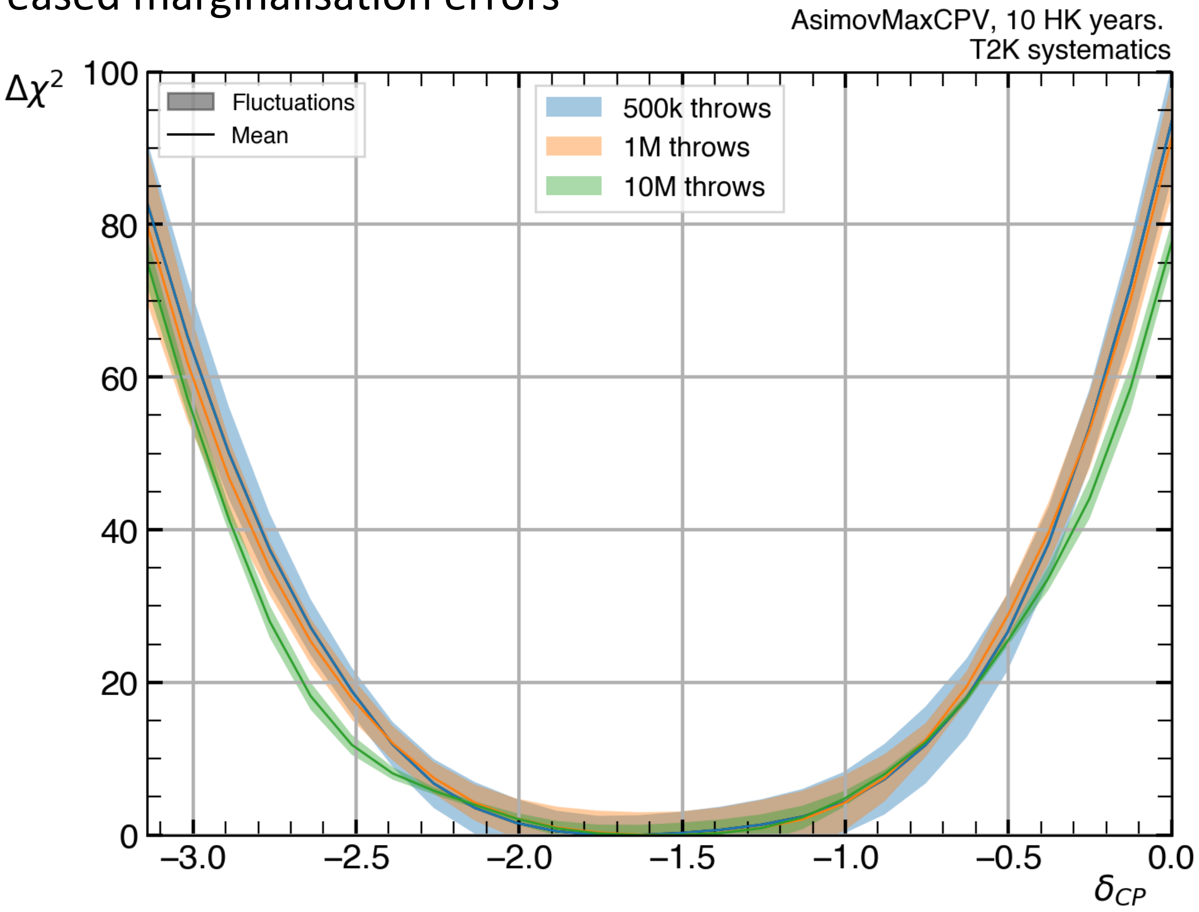


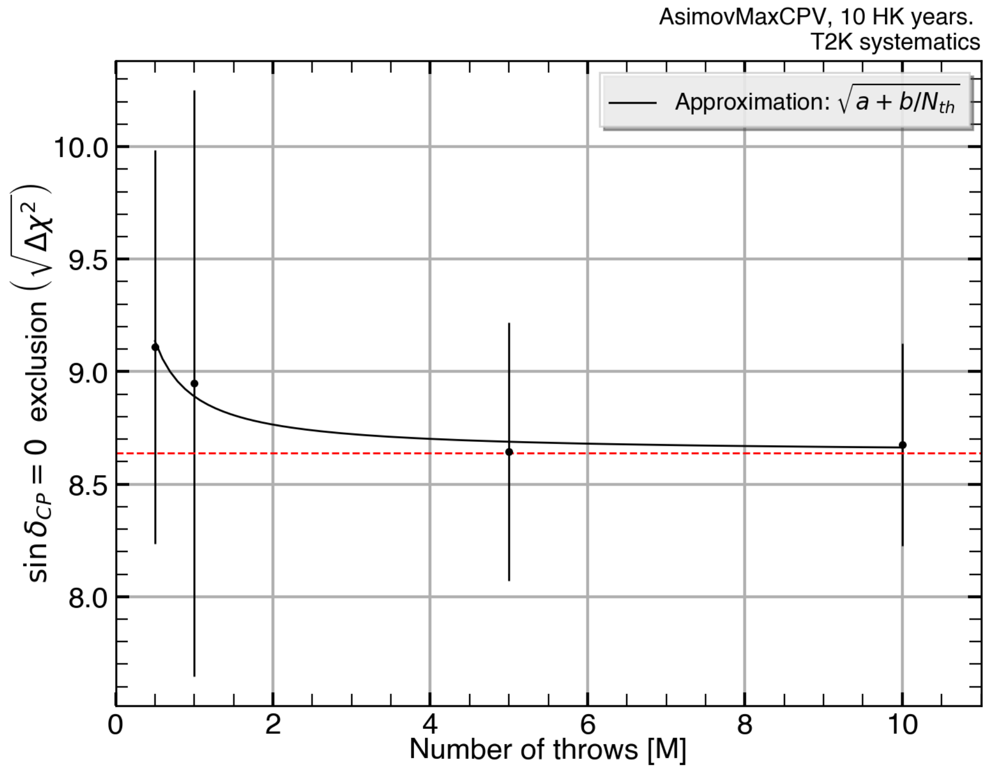
2.5, 5, 7.5 and 10 HK years

Part IV: Marginalisation errors

Number of throws in **T2K** 2020: **100.000**
For high HK statistics this number should be increased to compensate increased marginalisation errors

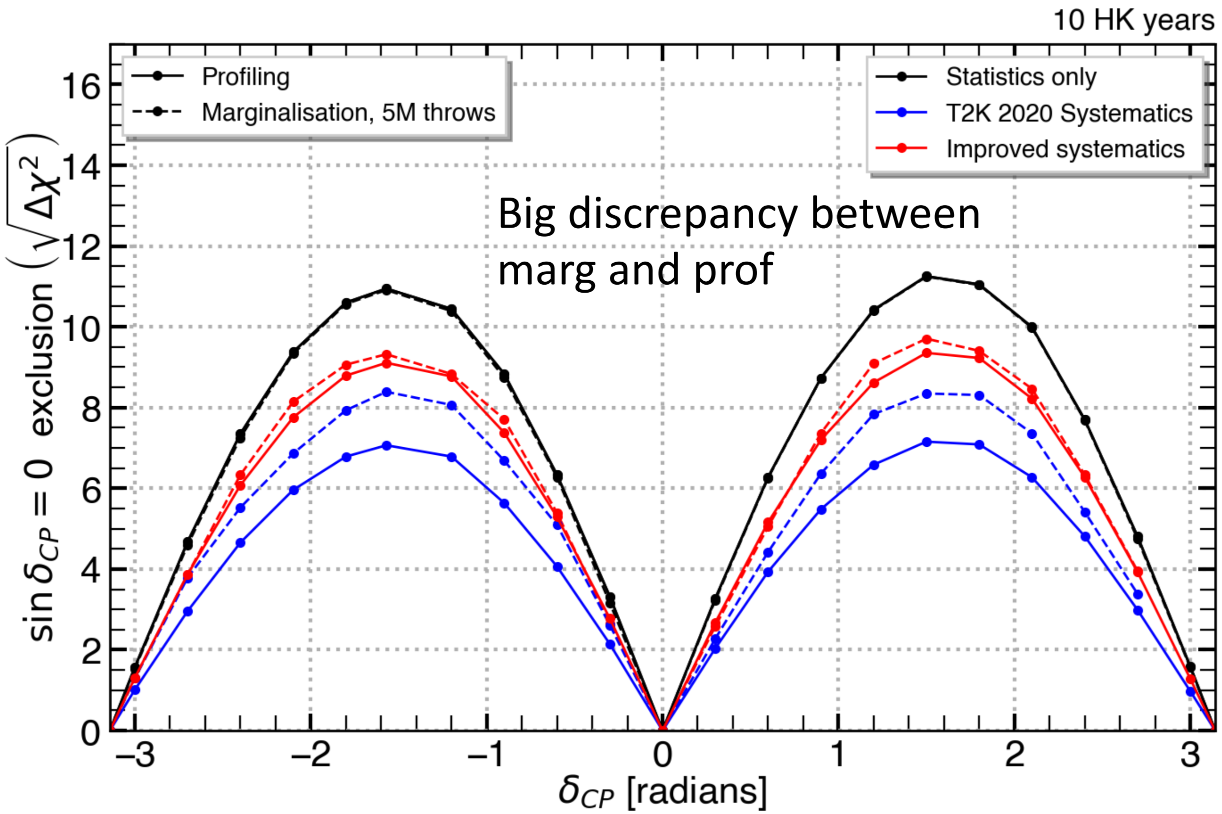
δ_{CP}
T2K systematics

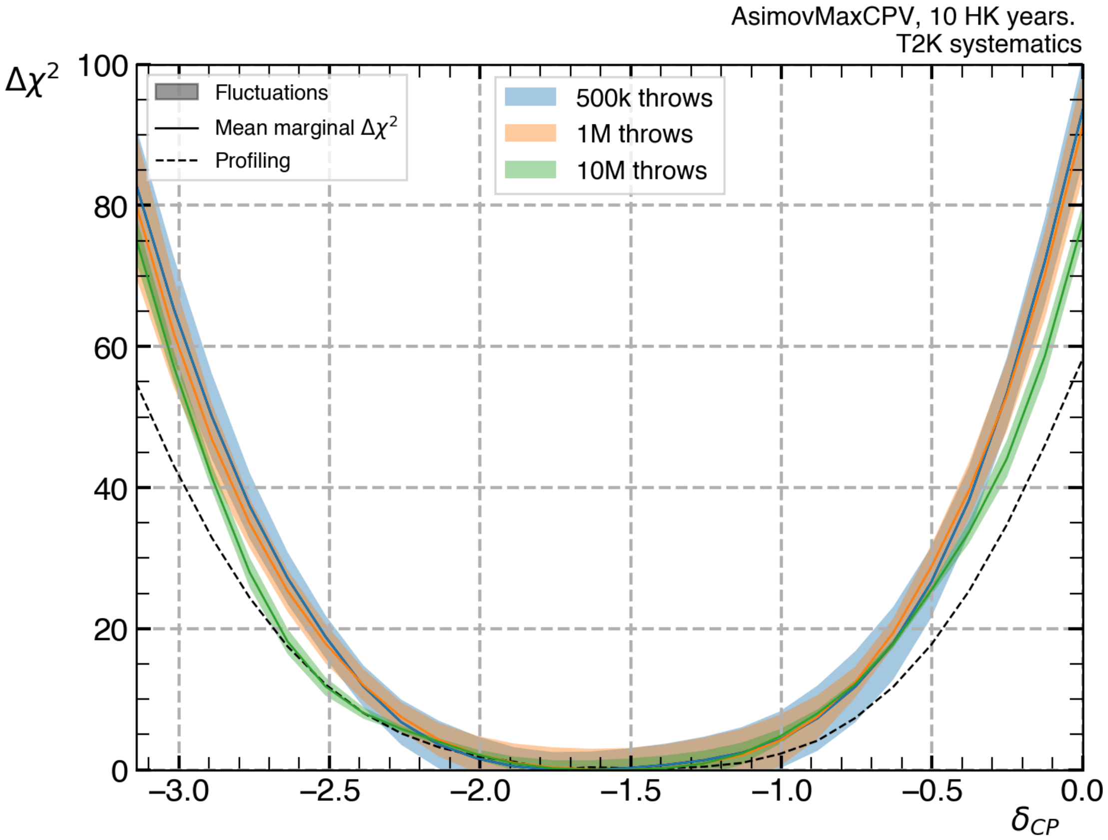




Optimal value of N_{th}: $10\ M$ (for T2K systematics) $\Delta\chi^2$

Part IV: Marginalisation vs Profiling comparison





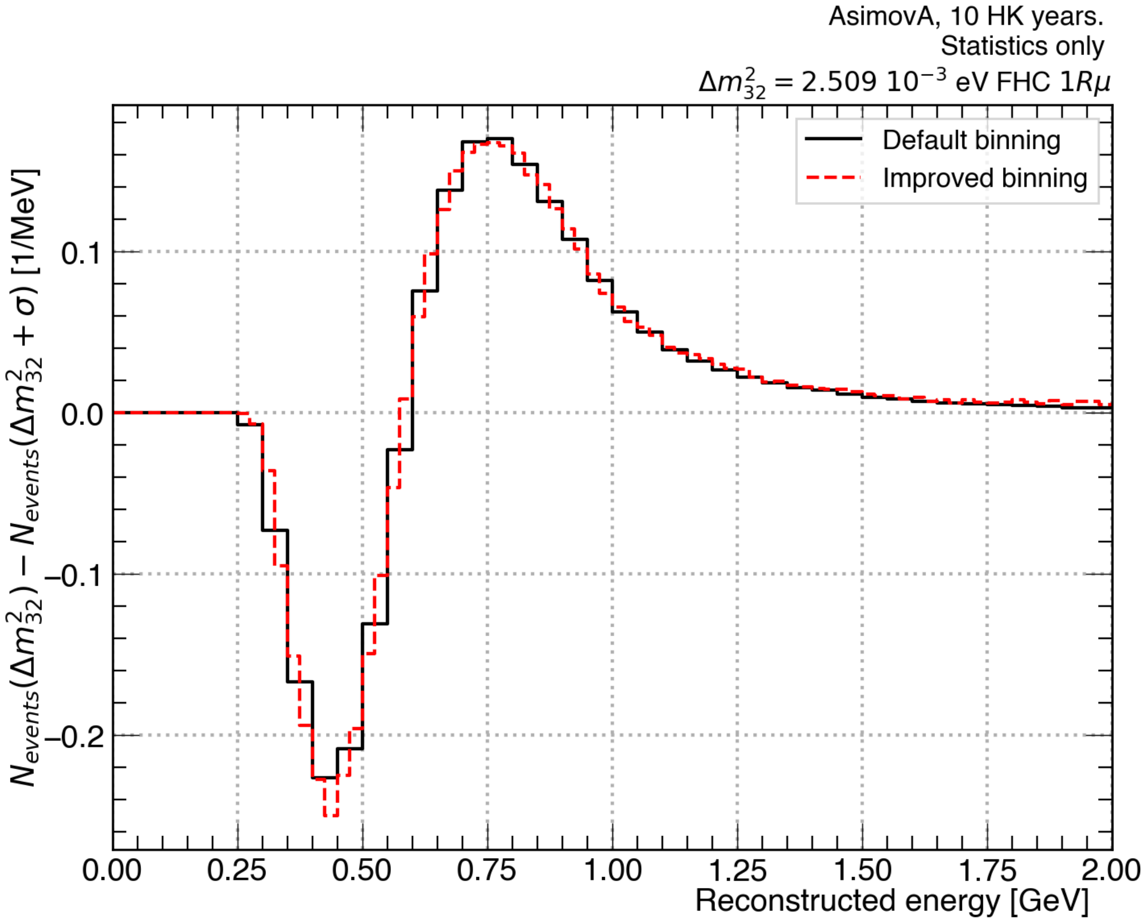
Conclusion: Different treatment of nuance parameters causes difference in profiled and marginal $\Delta\chi^2$.
Better systematical contraints – less discrepancy between curves.

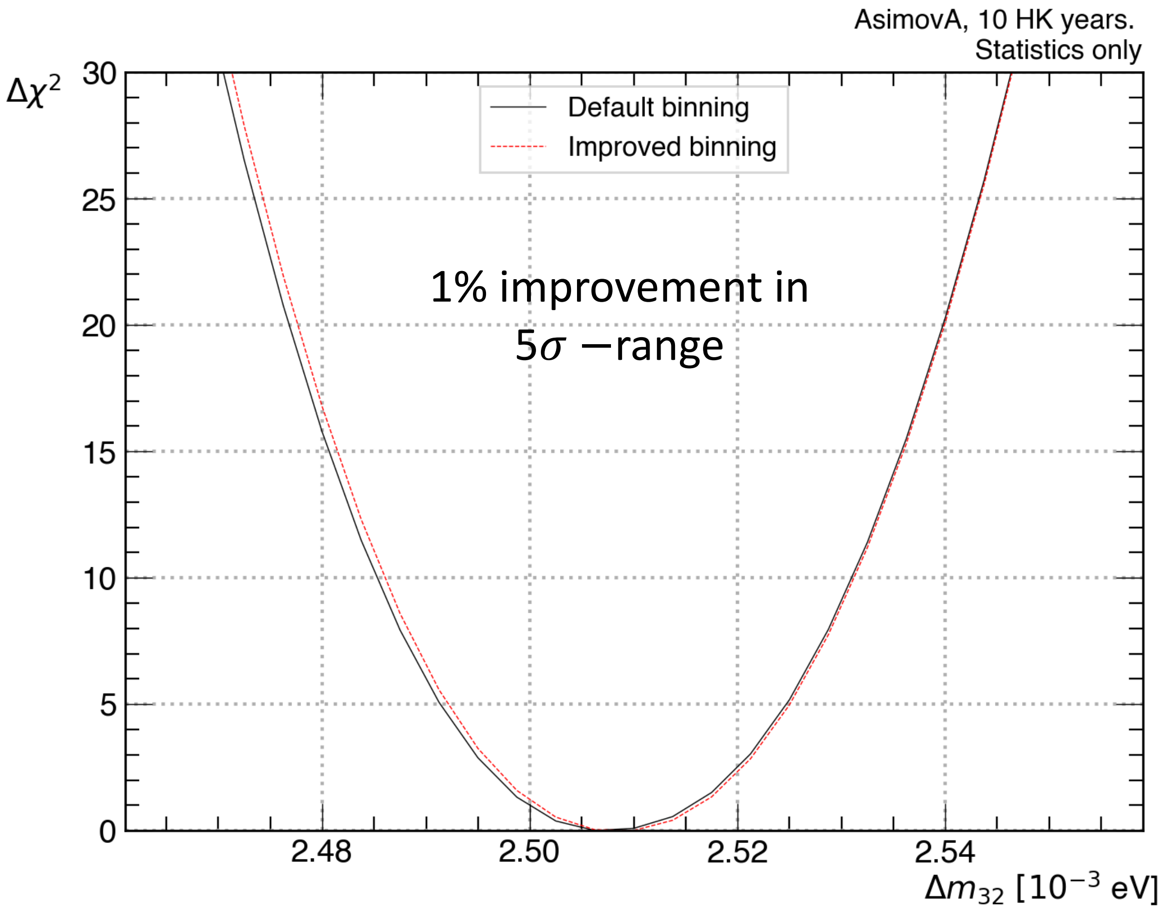
During validation period **profiling will be used**
Marginalisation vs profiling studies continue

See Claire's presentation for additional studies

Part V: Binning effect on sensitivity

Default binning: bin size = 50 MeV
“Improved” binning: bin size = 25 MeV (take extreme case for test)

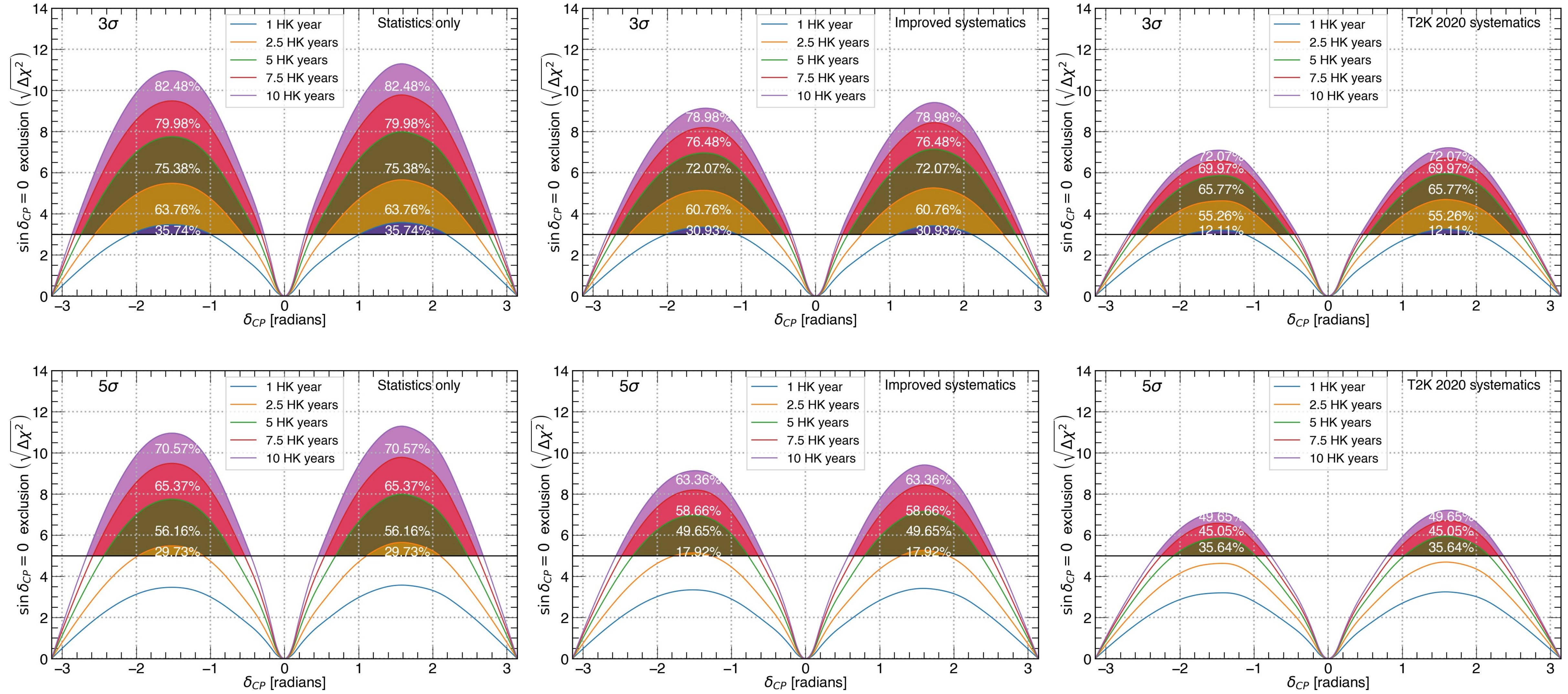




Binning size has a **small** impact on sensitivity to Δm^2_{32}. Most sensitivity comes from the **bin counts**

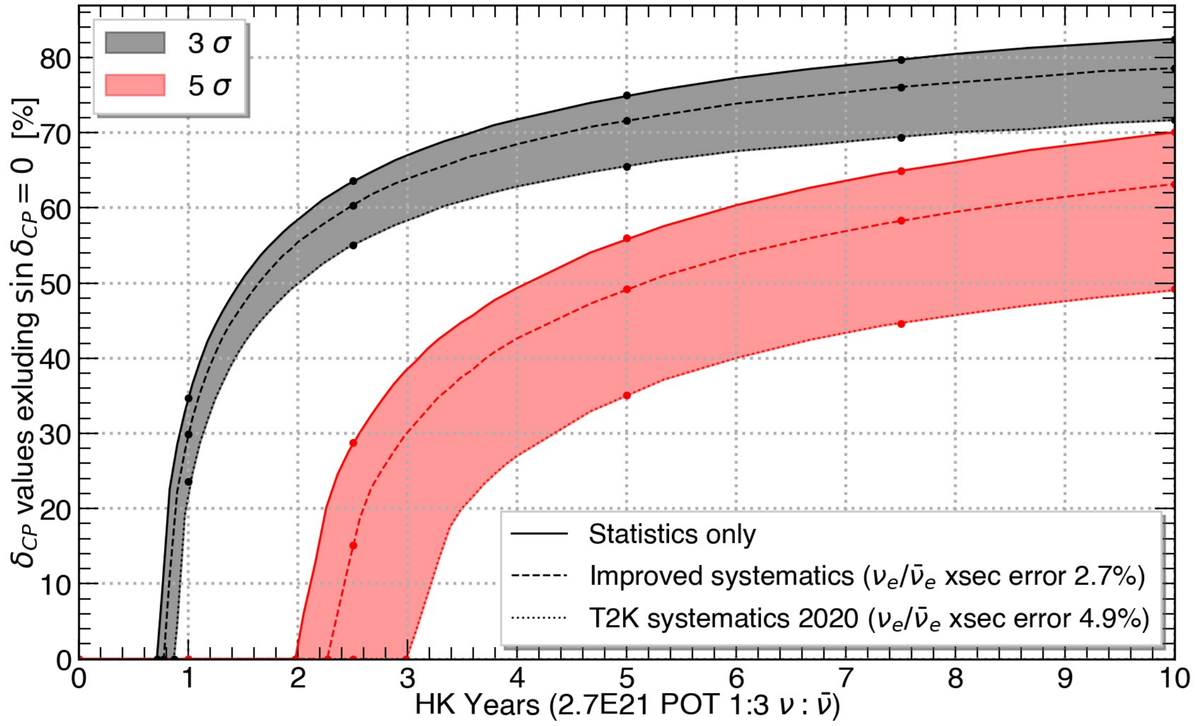
Part VI: Sensitivity studies

Proportion of δ_{CP} for different years

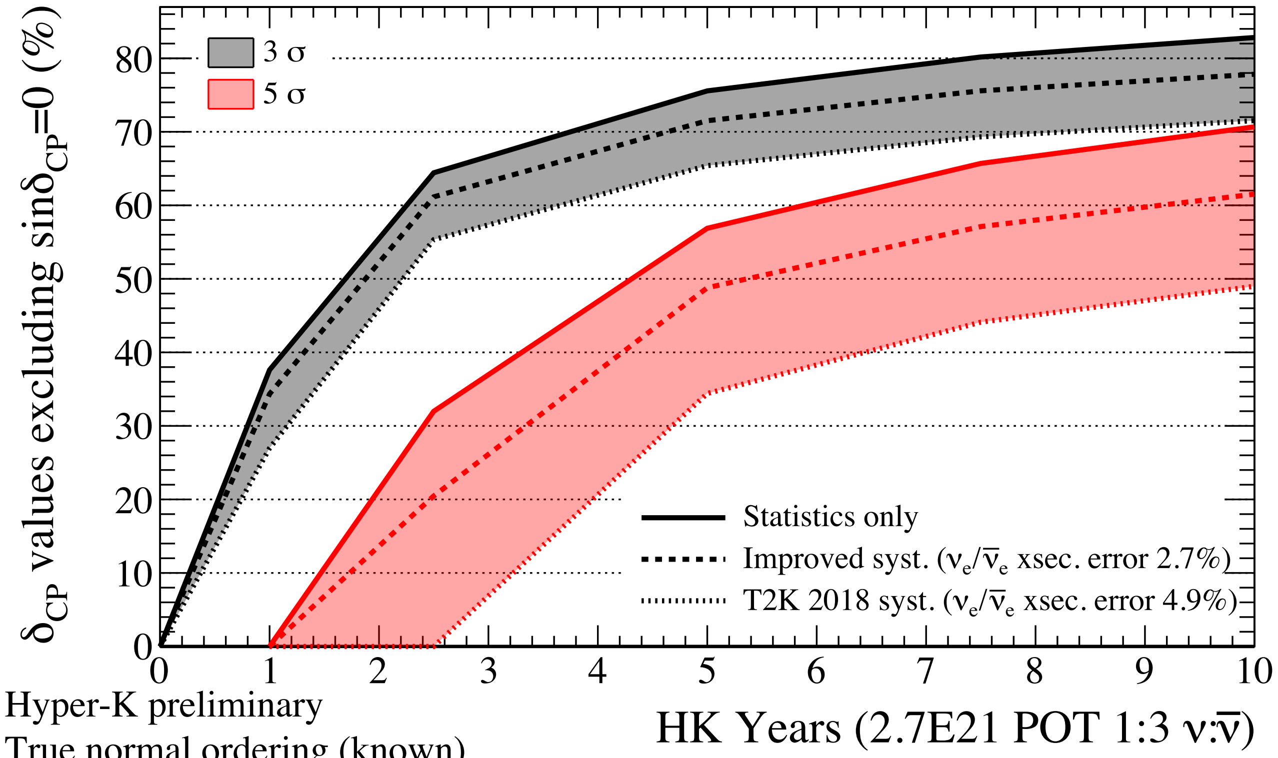


Part VI: Sensitivity studies

P-theta 2020



Valor 2018



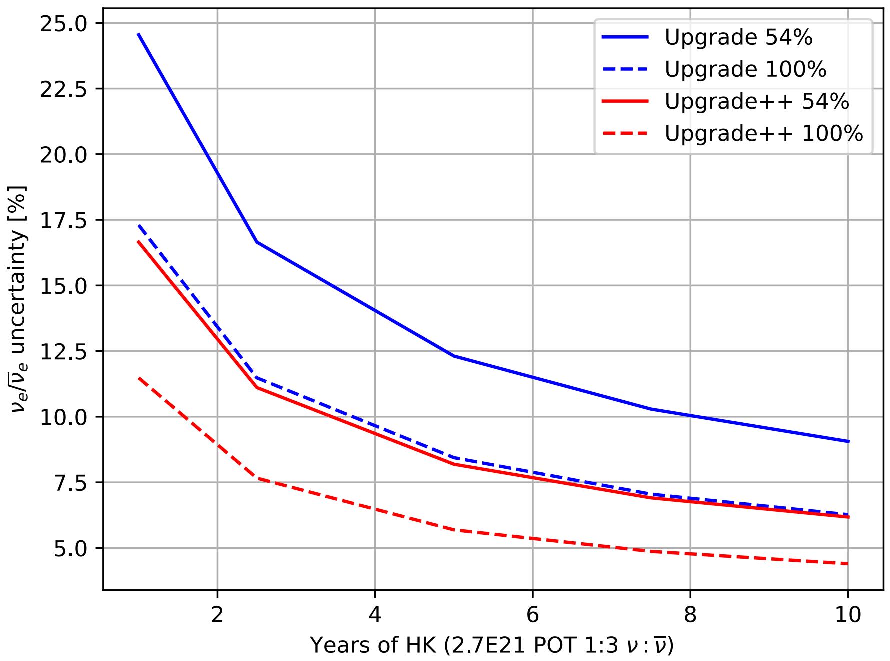
Hyper-K preliminary
True normal ordering (known)
$\sin^2(\theta_{13}) = 0.0218$ $\sin^2(\theta_{23}) = 0.528$ $|\Delta m^2_{32}| = 2.509\text{E-}3\ \text{eV}^2/\text{c}^4$

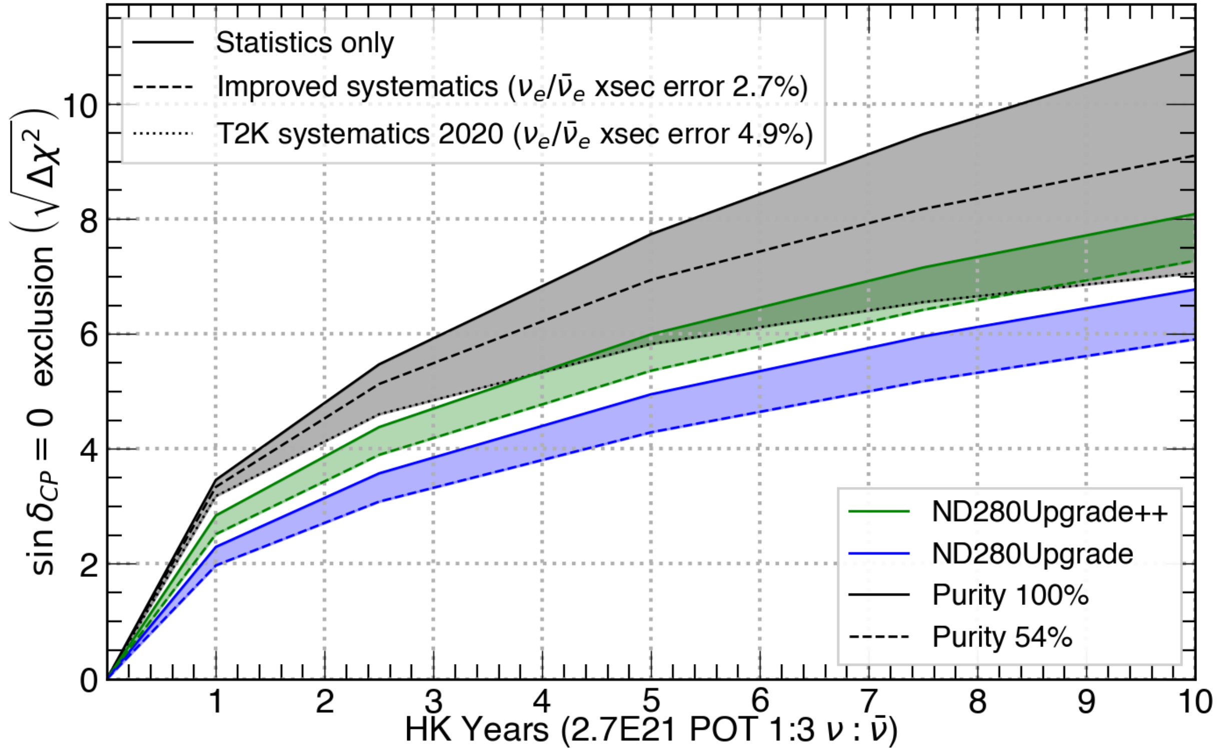
What CP-V sensitivity can we expect taking $\nu_e \backslash \bar{\nu}_e$ xsec constraints from ND measurements?

Expected CP-V sensitivity using **only** ND280 constraints, without relying on theory (See Ulysse's presentation)

Different scenarios are considered:
ND280Upgrade: FGD1+FGD2+SuperFGD (4 tons)
ND280Upgrade++: SuperFGD+HyperFGD (10 tons)

Preliminary studies





Conclusion: As $\nu_e \backslash \bar{\nu}_e$ xsec constraints from ND are worst than theoretical, sensitivity is reduced

Conclusion

- Reweighting from T2K to HK was performed and P-theta validation in on progress

- The impact of the marginalisation errors for HK statistics was studied, optimisation of number throws was performed

- Significant difference between two different methods of treatment nuisance parameters (marginalisation and profiling) was found

- Binning effects on sensitivity were quantified. The current binning does not introduce significant shape uncertainty even for 10 HK years.

- P-theta was already used for new studies.
  If we want to take $\nu_e \backslash \overline{\nu}_e$ xsec constraints from ND measurements:
  About 7σ of CP-violation significance can be expected from ND280Upgrade++ with 10 tons fiducial mass
  About 5.5σ of CP-violation significance can be expected from ND280Upgrade with 4 tons fiducial mass

Prospects

- To continue studies of marginalisation errors for Δm^2_{32} and $\sin^2\theta_{23}$
- Study the impact of systematical parameters: energy scale, the effect of ND constraints
- To study more deeply marginalisation vs profiling and to decide which treatment of nuisance parameters to use
- Finish the validation

Thank you for your attention!

Part I: P-theta framework

Analysis method:

- Poisson likelihood is used: $L(\boldsymbol{o},\boldsymbol{f}) = \prod_s [\left(N_{s,i}^{exp}(\boldsymbol{o}) - N_{s,i}^{obs}\right) + N_{s,i}^{obs} \times \ln\left(\frac{N_{s,i}^{obs}}{N_{s,i}^{exp}}\right)] \times L_{syst}(\boldsymbol{f})$
- Frequentist approach - Binned maximum likelihood method

Nuisance parameter treatment

- Marginalisation: $L_{marg}(\boldsymbol{o}) = \int L(\boldsymbol{o},\boldsymbol{o}',\boldsymbol{f})\, L_{pr}(\boldsymbol{o}') L_{pr}(\boldsymbol{f}) d\boldsymbol{f}\, d\boldsymbol{o}'$ (used in T2K for conf.int infering)

  Profiling can be also performed (used in T2K for best fit infering)

Monte-Carlo integration is used in practice : we are throwing (selecting) N_{th} times nuisance parameters $(\boldsymbol{o}_i', \boldsymbol{f}_i)$ according to their prior distributions and then we calculate average likelihood

$$L_{marg}(\boldsymbol{o}) = \int L(\boldsymbol{o},\boldsymbol{o}',\boldsymbol{f})\, L_{pr}(\boldsymbol{o}') L_{pr}(\boldsymbol{f}) d\boldsymbol{f}\, d\boldsymbol{o}' \longrightarrow L_{marg}(\boldsymbol{o}) = \frac{1}{N_{th}} \sum_{i=1}^{N_{th}} L\,(\boldsymbol{o},\boldsymbol{o}_i',\boldsymbol{f}_i)$$

This causes marginalisation errors (See later)

Part IV: Marginalisation errors

The exact quantitity

$$L_{marg}(\boldsymbol{o}) = \int L(\boldsymbol{o}, \boldsymbol{o}', \boldsymbol{f})\, L_{pr}(\boldsymbol{o}') L_{pr}(\boldsymbol{f}) d\boldsymbol{f}\, d\boldsymbol{o}'$$

Estimator

$$\text{ANLL} = -\ln \frac{1}{N_{th}} \sum_{i=1}^{N_{th}} L(o, \boldsymbol{o}_i', \boldsymbol{f}_i)$$

There are two uncertainties of average log-likelihood which are caused by finite number of throws : **fluctuations** and **bias**

1) Bias

Reason: Not linear function is applied on sample mean

$$\boldsymbol{b} := \text{E}[\text{ANLL(o)}] - (-\ln L_{marg}(o)) = \frac{1}{N_{th}} \frac{\sigma_L^2}{E^2(L)} + o(\sigma_L^2)$$

ANLL **estimator is biased**

$$\boldsymbol{b} \sim \frac{\mathbf{1}}{\boldsymbol{N_{th}}}$$

2) Fluctuations

$$\textbf{STD} \approx \frac{1}{\sqrt{N_{th}}} \frac{\sigma_L}{\bar{L}}$$

$$\boldsymbol{STD(POT)} \sim \textbf{POT}^*$$

$$\boldsymbol{STD(N_{th})} \sim \frac{\mathbf{1}}{\sqrt{\boldsymbol{N_{th}}}}$$

Conclusion: $\boldsymbol{N_{th}}$ should be increased fot high statistics

Part III: Validation

Event rates comparison

P-theta 2020 vs Valor 2018

	nue1R, CC		nuebar1R, CC	
	P-theta	Valor	P-theta	Valor
$\nu_\mu \rightarrow \nu_e$	2276.64	2252.51	259.16	257.26
$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$	11.48	11.70	798.20	796.55
$\nu_\mu \rightarrow \nu_\mu$	7.27	6.53	3.22	3.24
$\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu$	0.26	0.23	5.74	4.99
$\nu_e \rightarrow \nu_e$	318.24	326.15	135.46	147.70
$\bar{\nu}_e \rightarrow \bar{\nu}_e$	11.02	12.34	227.27	236.90
NC	128.48	130.30	133.55	177.33
Total	2753.28	2739.76	1562.88	1623.97

Good agreement at the level of **4%** with **Valor**
Good agreement at the level of **1%** with **Mach3**

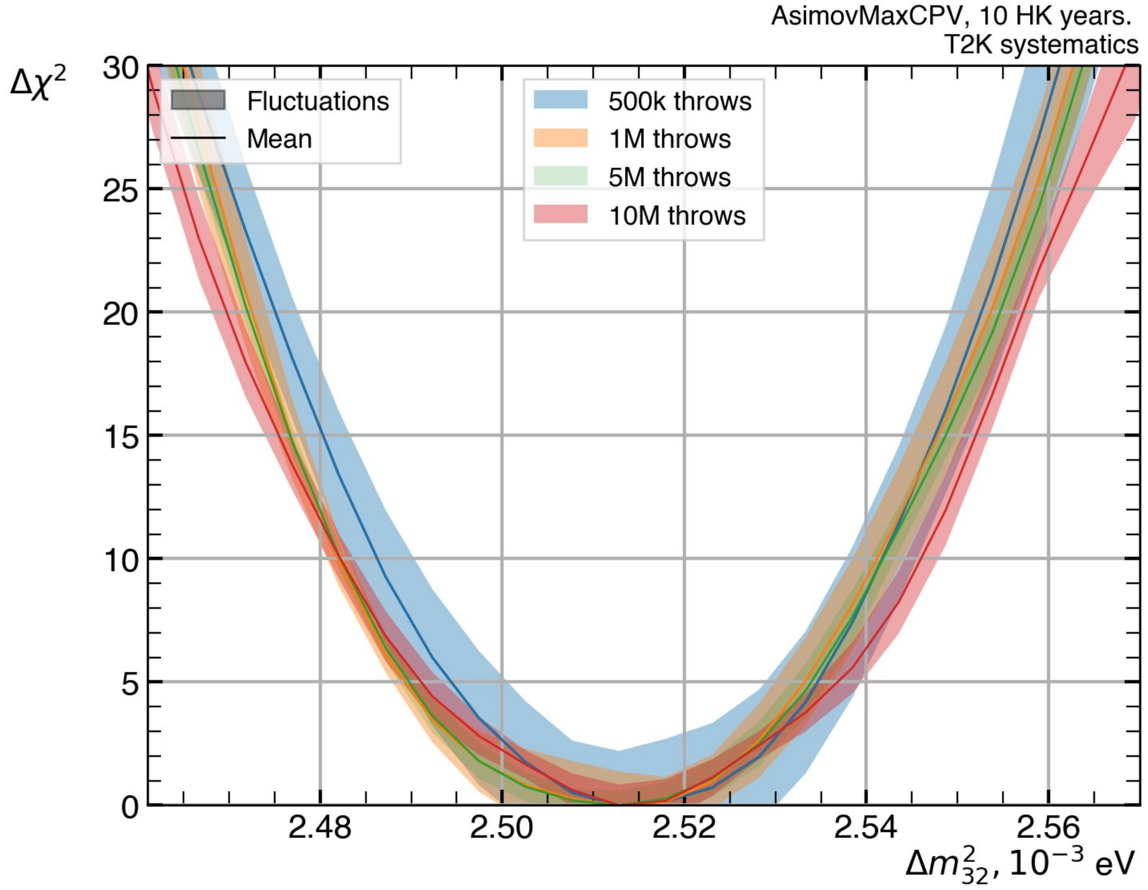
P-theta 2020 vs Mach3 2020

FHC 1Re

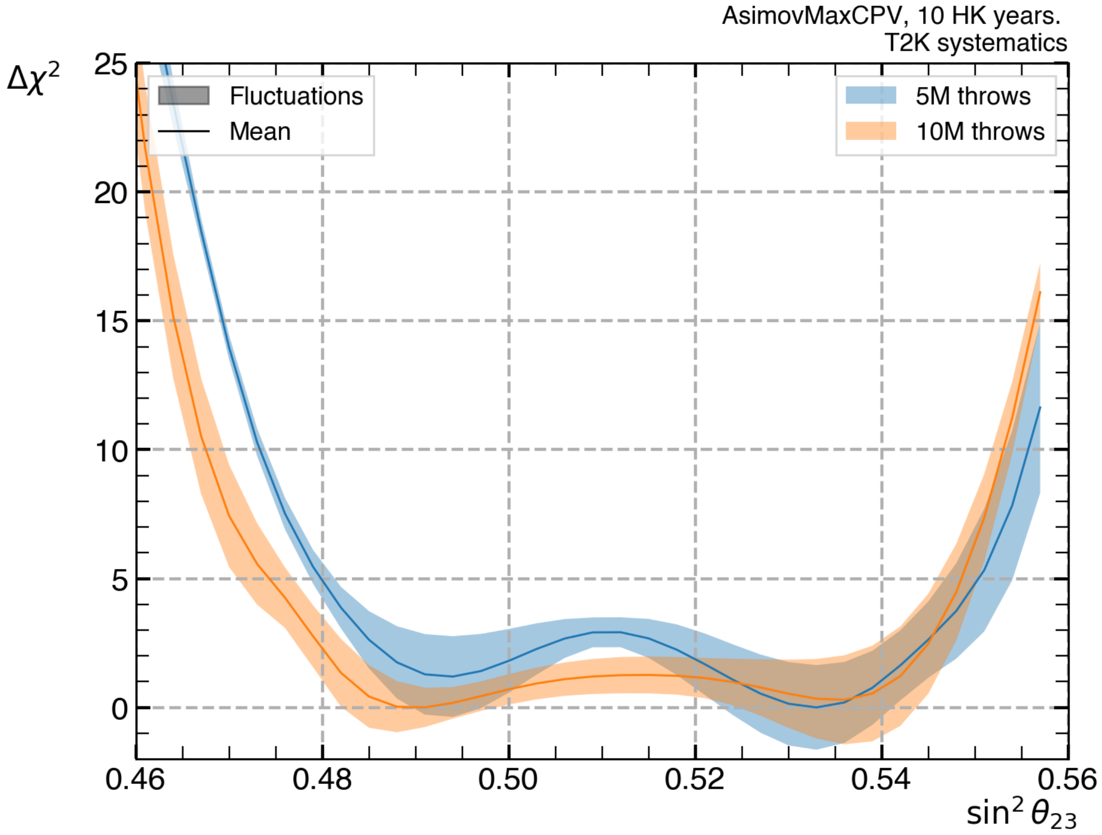
Mode	Mach3	P-Theta
CCQE	2034.53378	2036.23587
CC1pi	268.22455	266.18712
CCcoh	1.61489	1.61287
CCMpi	9.48062	9.28065
CCDIS	0.39237	0.39473
NC1pi0	50.23191	50.2058800
NC1pipm	8.18208	8.19138
NCcoh	9.28877	9.28912
NCoth	14.07806	14.06353
2p2h	319.70035	318.86587
NC1gam	46.83811	46.82927
CCMisc	1.58924	1.59290
Total:	2764.15472	2762.75000

Part IV: Marginalisation errors

Number of throws in **T2K** 2020: **100.000**
For high HK statistics this number should be increased to compensate increased marginalisation errors



Conclusion: For 10M $\Delta\chi^2(\Delta m^2_{32})$ is still biased.
More throws or throws optimisation are necessary

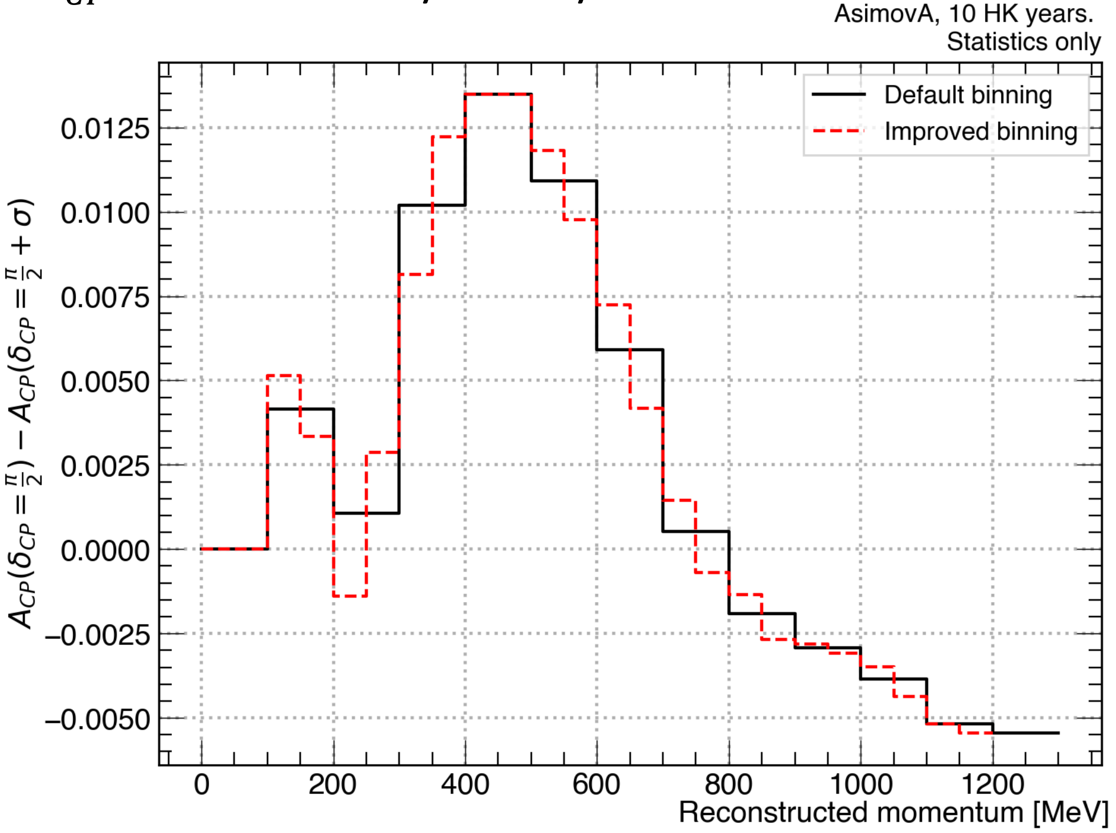


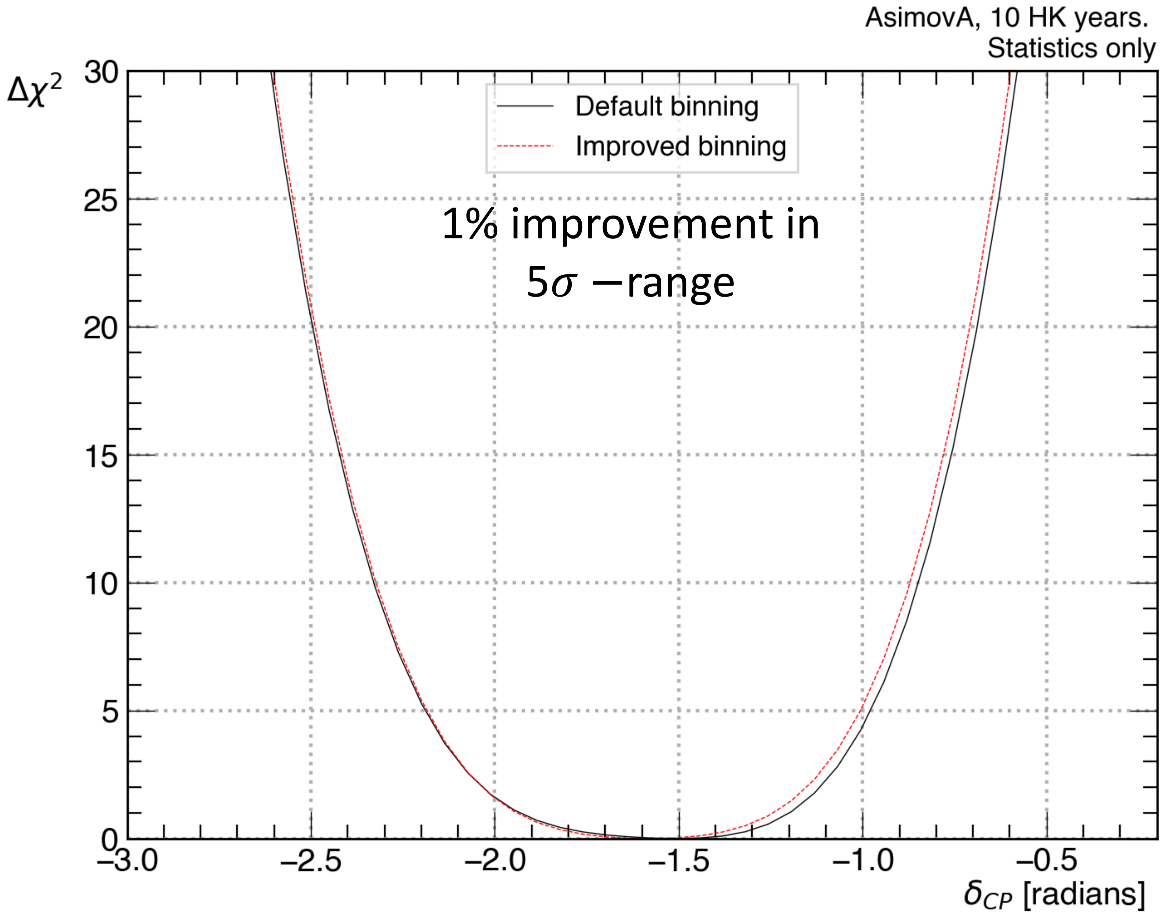
Conclusion: For 10M $\Delta\chi^2(\sin^2\theta_{23})$ is still fluctuated (octant can be wrongly determined)
More throws or throws optimisation are necessary

Part V: Binning effect on sensitivity

Default binning: bin size = 100 MeV
"Improved" binning: bin size = 50 MeV (take extreme case for test)

A_{CP} −relative CP asymmetry





Binning size has a **small** impact on sensitivity to δ_{CP}. Most sensitivity comes from the **bin counts**

Part V: Binning effect on sensitivity

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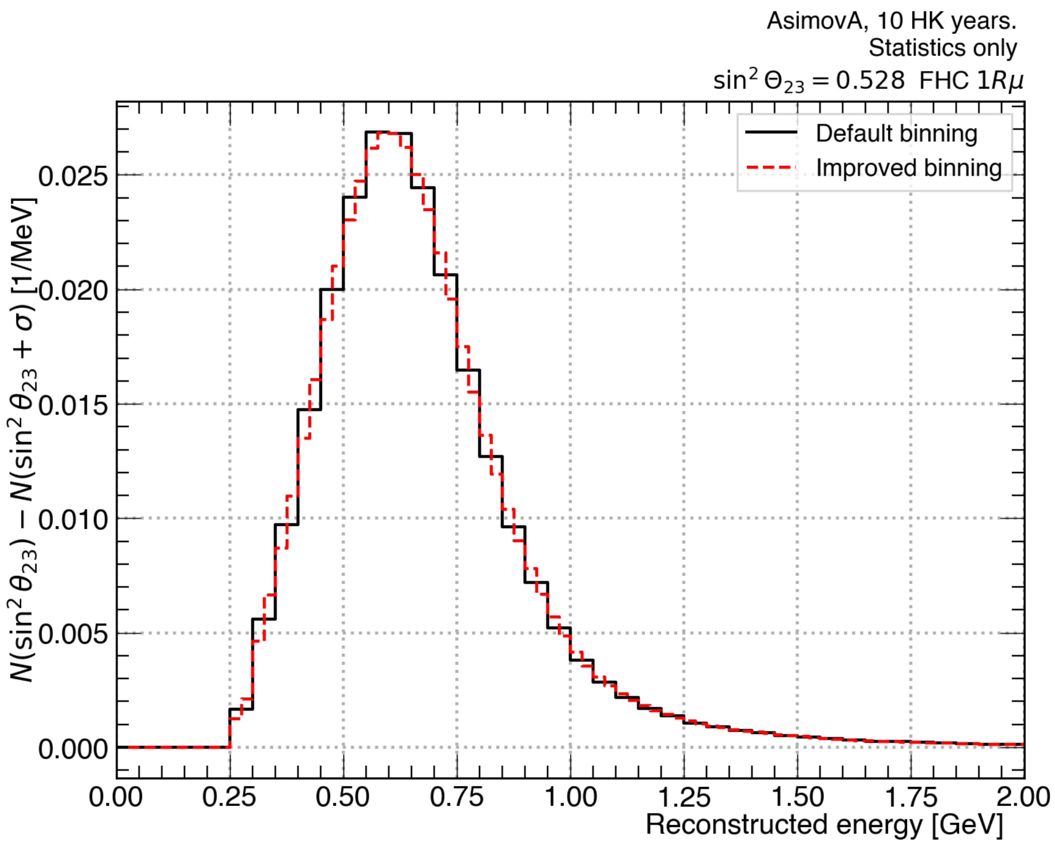
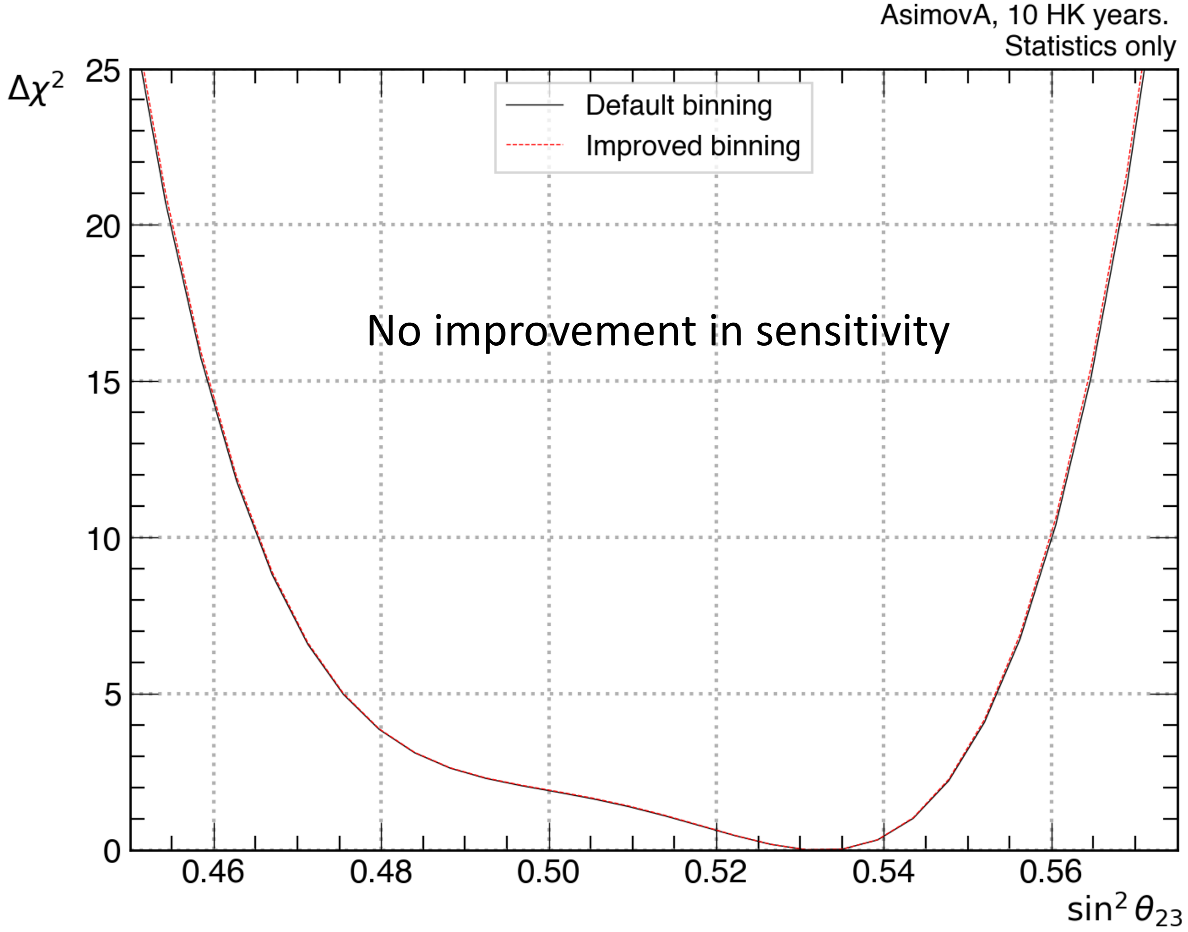
“Improved” binning: bin size = 25 MeV (take extreme case for test)





Binning size has **no impact** on sensitivity to $\sin^2\theta_{23}$. Rate parameter