Hyper-Kamiokande

Preparation of the Hyper-Kamiokande experiment

A next generation neutrino detector

LPNHE PARIS

SORBONNE UNIVERSITÉ

Claire Dalmazzone - réunion hebdomadaire du LPNHE

Excavation reached center of cavern dome in July

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Hyper-Kamiokande

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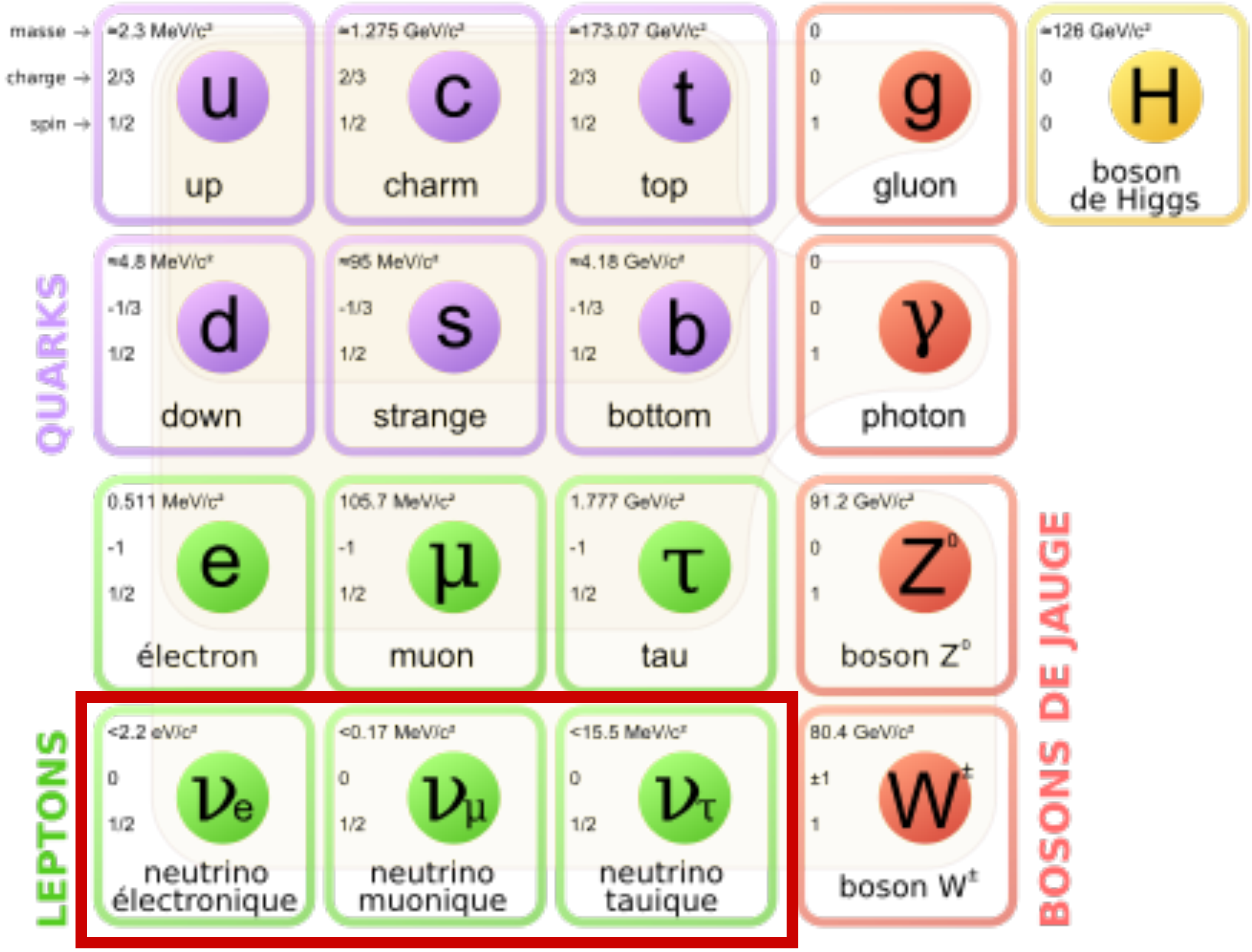
- Reducin neutrino flux uncertainties with NA61/SHINE
- Sensitivity studies for HK long baseline program
- Timing distribution in HK
- Conclusion: Plans

Introduction:
Neutrinos in the standard model and detection with Water Cerenkov detectors

Introduction

Neutrinos in the standard model



What we know:
- Neutral lepton
- Left handed
- 3 generations/flavours
- Lightest fermions of the SM
- Flavour oscillation (see next slide)

What we don't know:
- Are they Dirac or Majorana ($\nu = \bar{\nu}$) particles?
- What are their respective masses?
- Why are they so light? Where do their masses come from?
- Are there sterile, right handed neutrinos?

Water Cherenkov detectors

Hyper-Kamiokande

Principle

But detecting neutrinos is challenging due to their very low interaction cross-section!!

$\longrightarrow$ Use large (tens of kT) Water Cherenkov detector

Cherenkov effect:

A charged particle in a dielectric medium going faster than light, in the medium, emits "Cherenkov radiation"

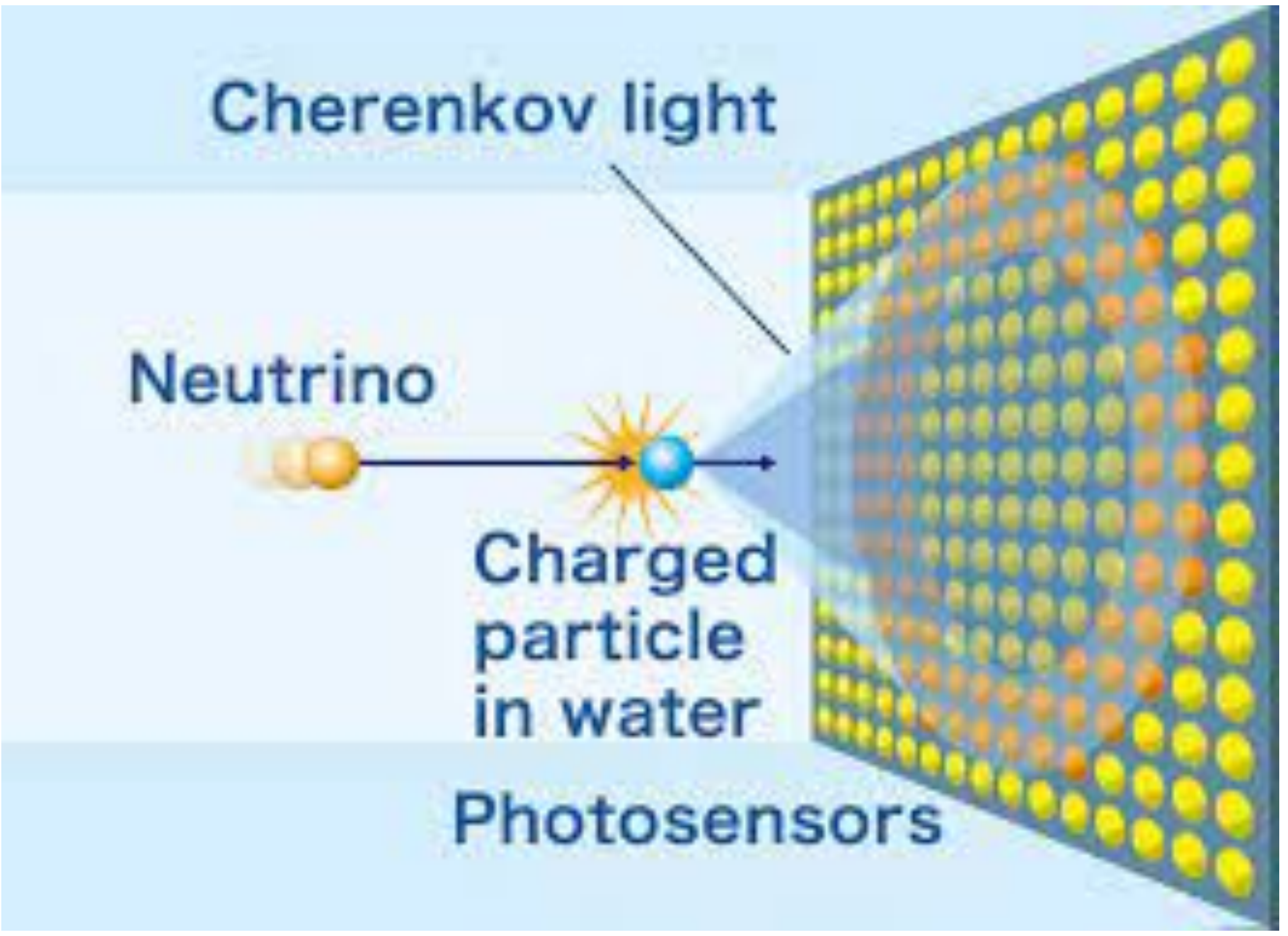
Emission angle:

$$\cos\theta = \frac{c}{nv}$$

Speed of light (c)

Particle's speed (v)

Refractive index (n)



Principle of neutrino detection in Water Cherenkov detectors: from the **shape of the signal and the time arrival** of the photons, it is possible to reconstruct **the direction and the interaction vertex.**

Water Cherenkov detectors

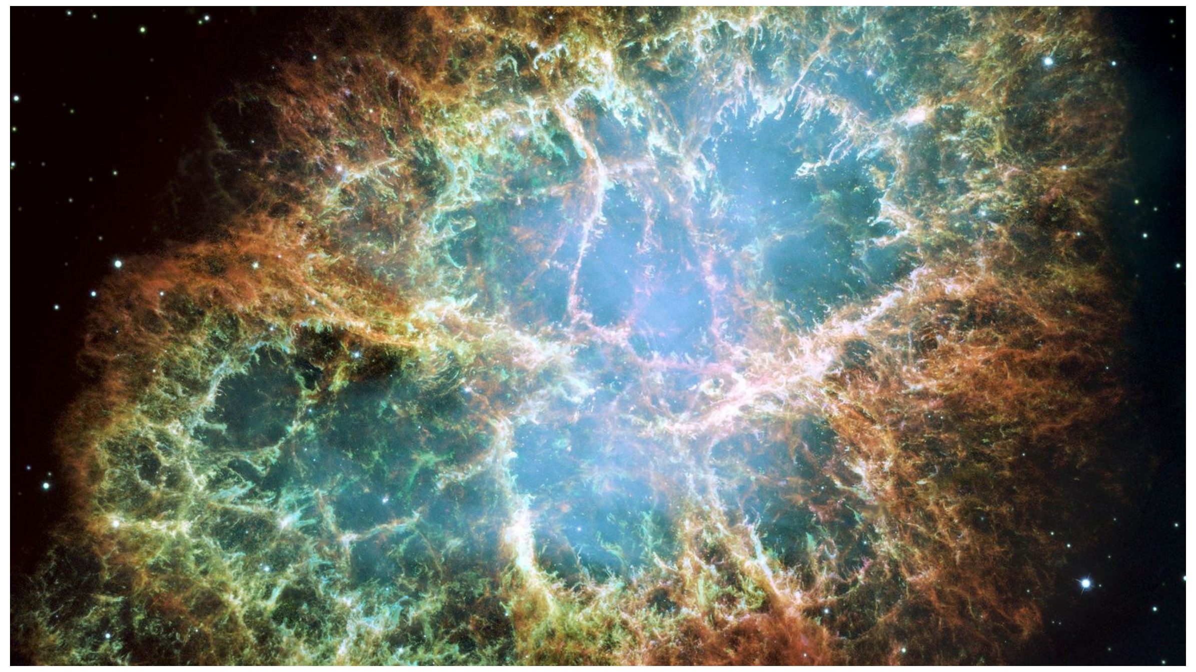
From Kamiokande to Hyper-Kamiokande

- **Kamiokande** detected ~15 neutrinos from the supernova **SN1987a**
- **SK** has been running since 1996 and notably lead to the **discovery of neutrino flavour oscillation in 1998**.
- But faster accumulation of statistics is always wanted hence the **Hyper-Kamiokande project: same principle but ~10 times larger volume!**
- The construction is ongoing and data-taking will start in **2027**

Water Cherenkov detectors

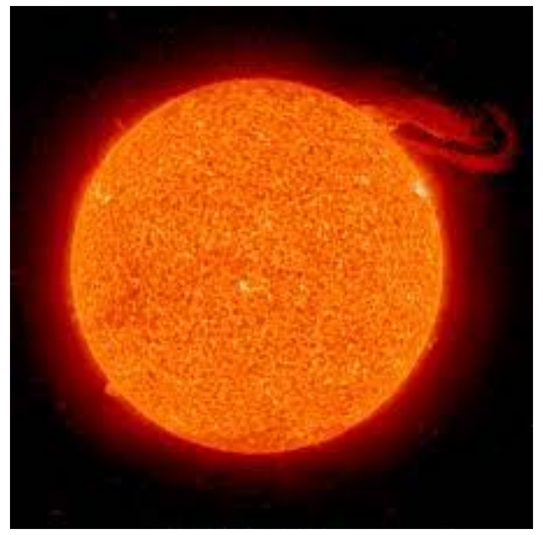
Applications

Astrophysics

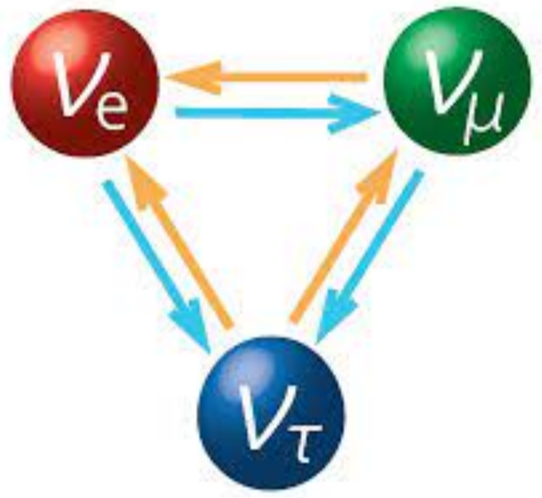


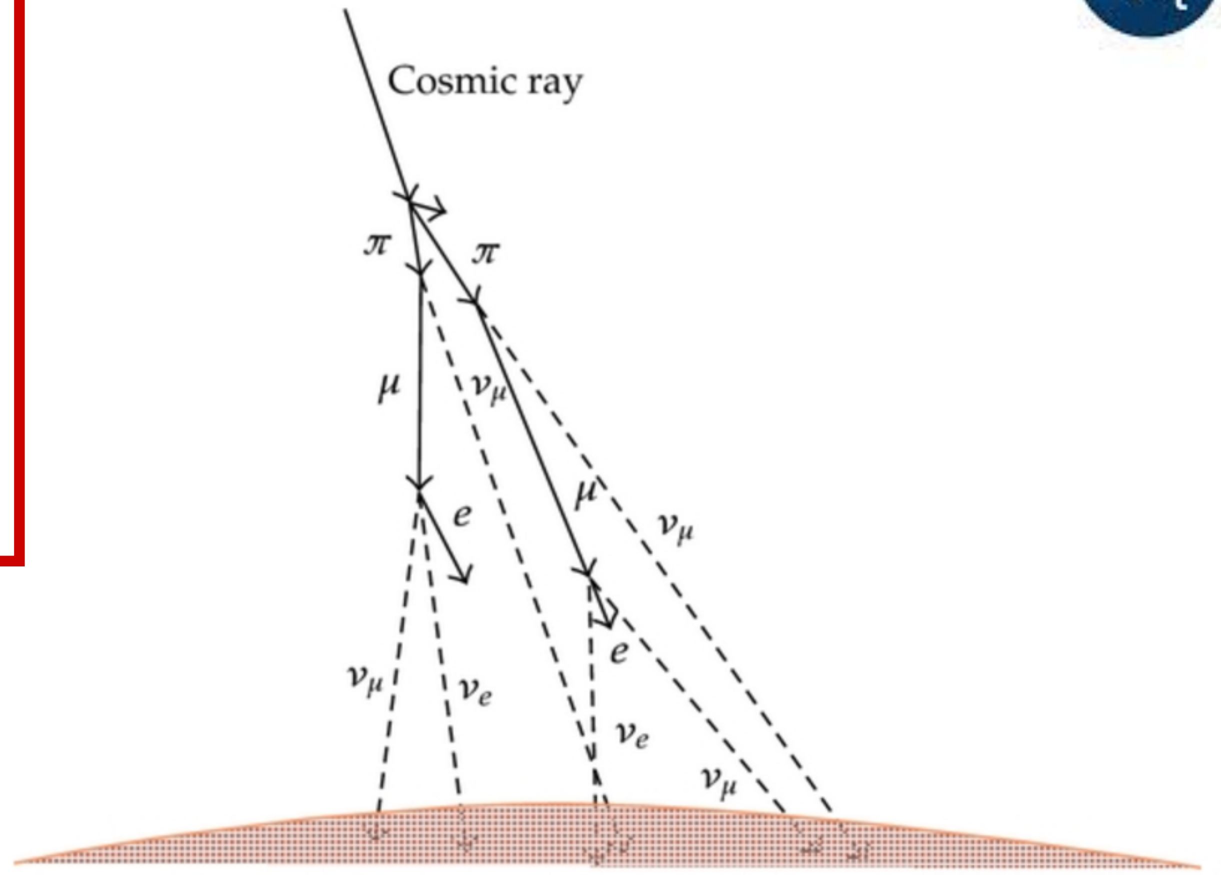
Supernovae neutrinos

Solar neutrinos

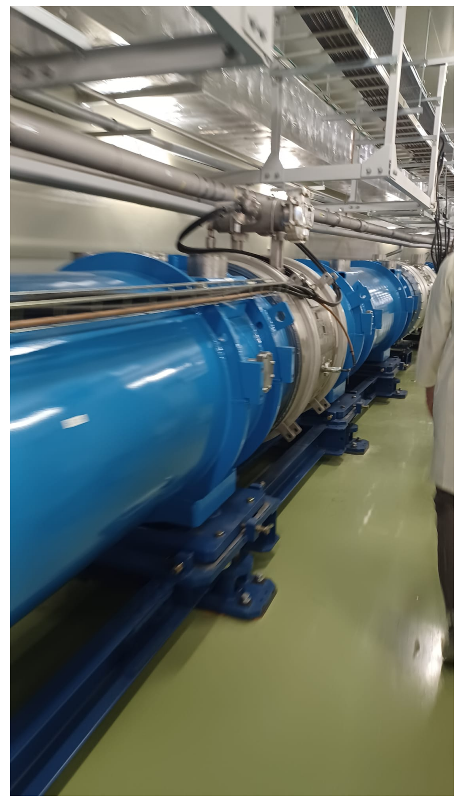


Flavour oscillation

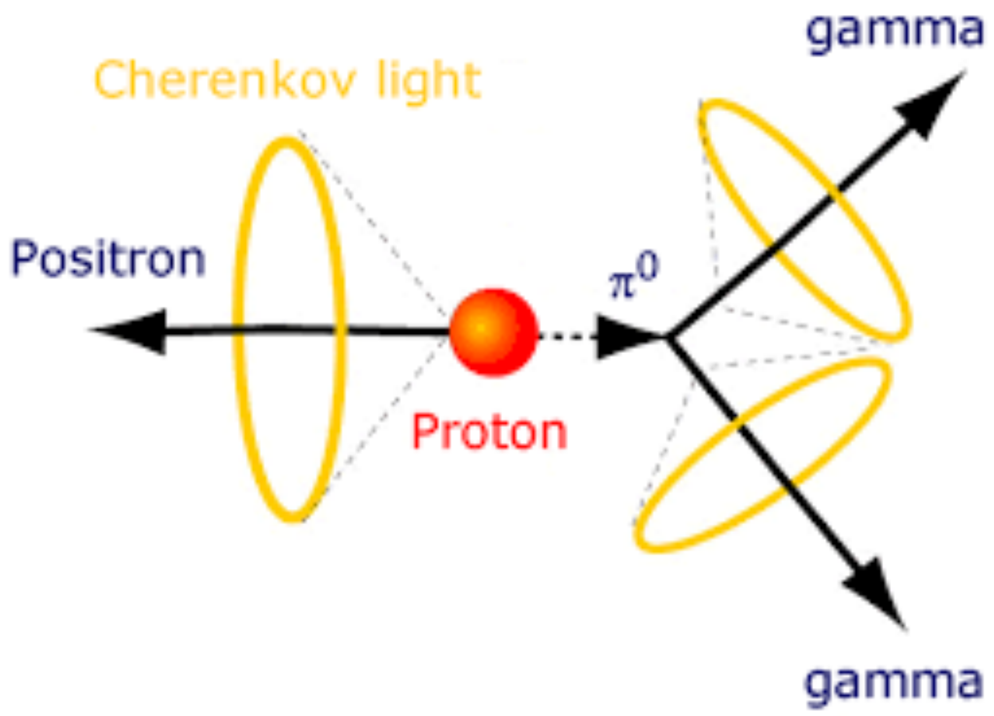




Atmospheric neutrinos



Accelerator neutrinos
(See next slide)

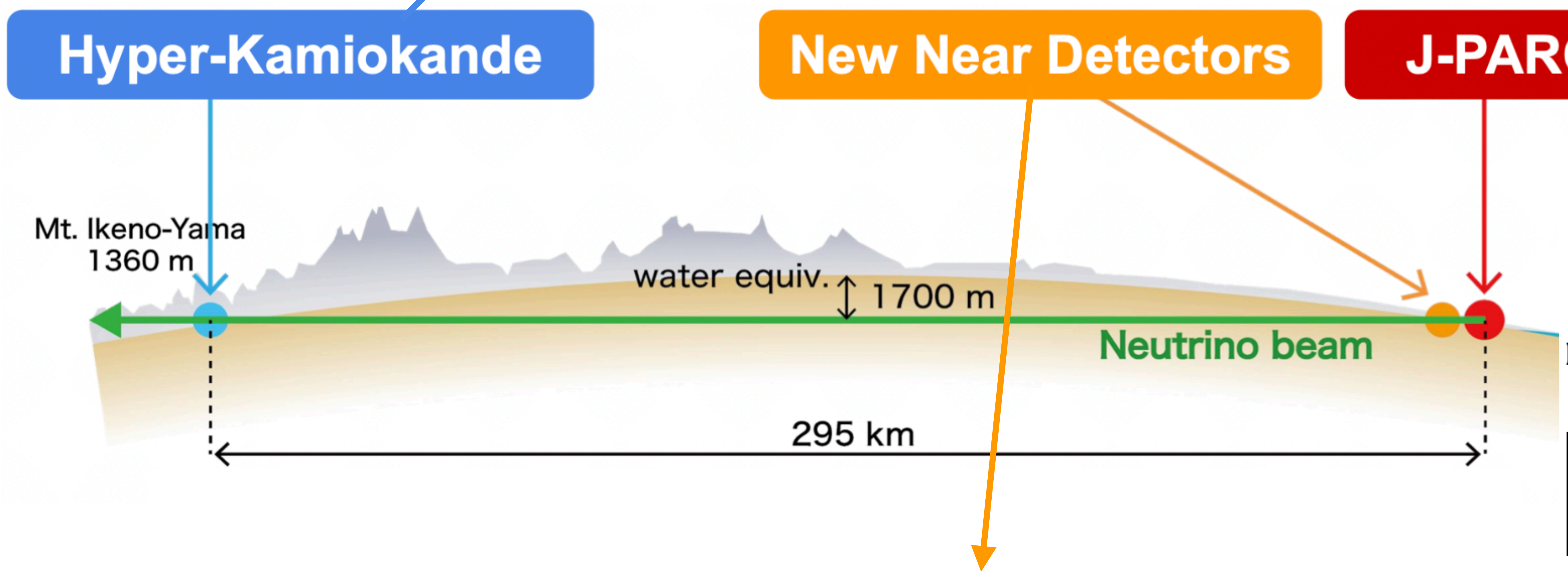


Nucleon decay search
Historical purpose of Kamiokande

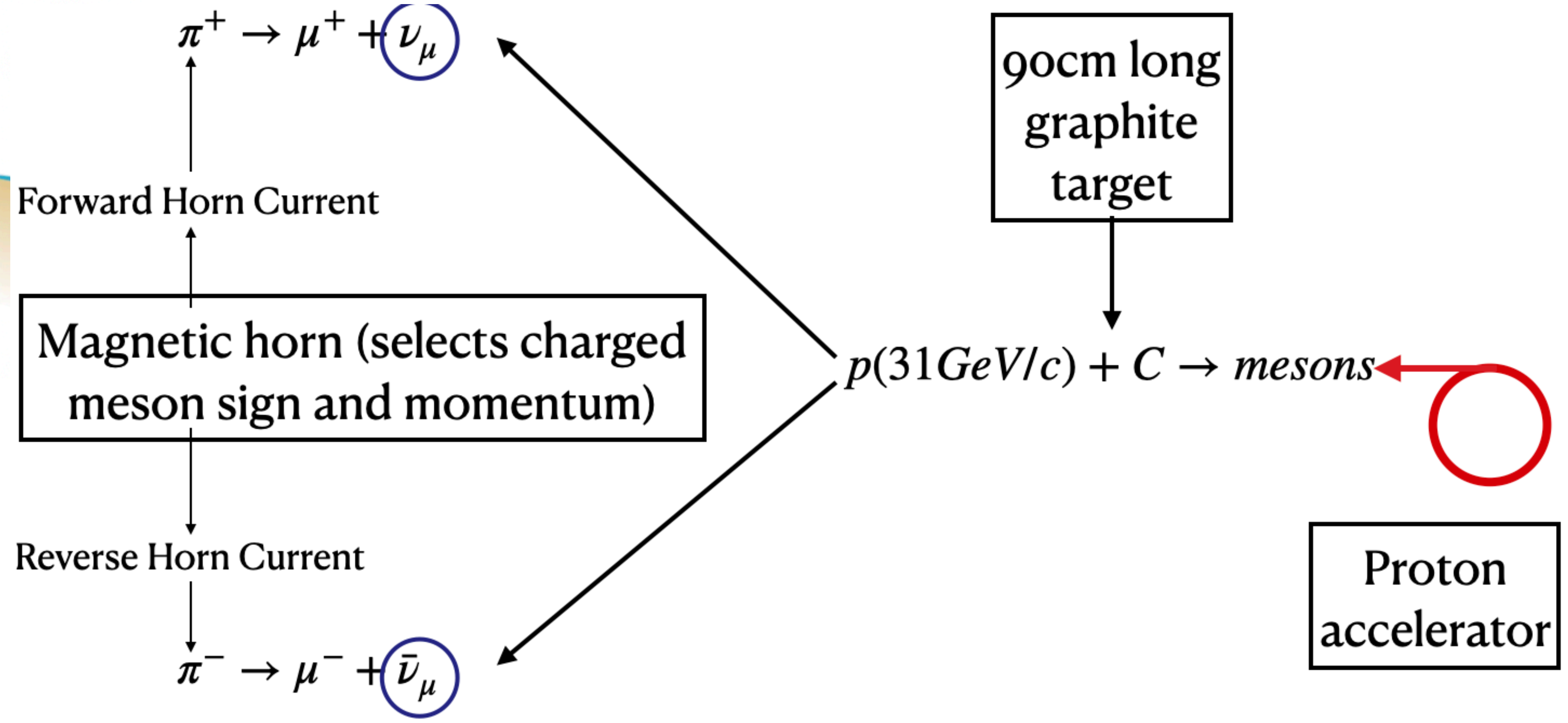
The T2(H)K experiment

Overview

Measures the appearance of $\nu_e(\bar{\nu}_e)$ in a beam of f $\nu_\mu(\bar{\nu}_\mu)$



Beam production at J-PARC accelerator facility



Measure neutrino flux and interaction cross-section before oscillation (constrains systematic effects)

The T2(H)K experiment

Systematic uncertainties

Hyper-Kamiokande

As we accumulate statistics, measurements become more sensitive to systematic effects

Simultaneously measured in the Near Detectors

Flux in detector

Interaction cross-section

Event rate measured in detector

$$N = F \times \sigma \times \epsilon$$

Detector efficiency

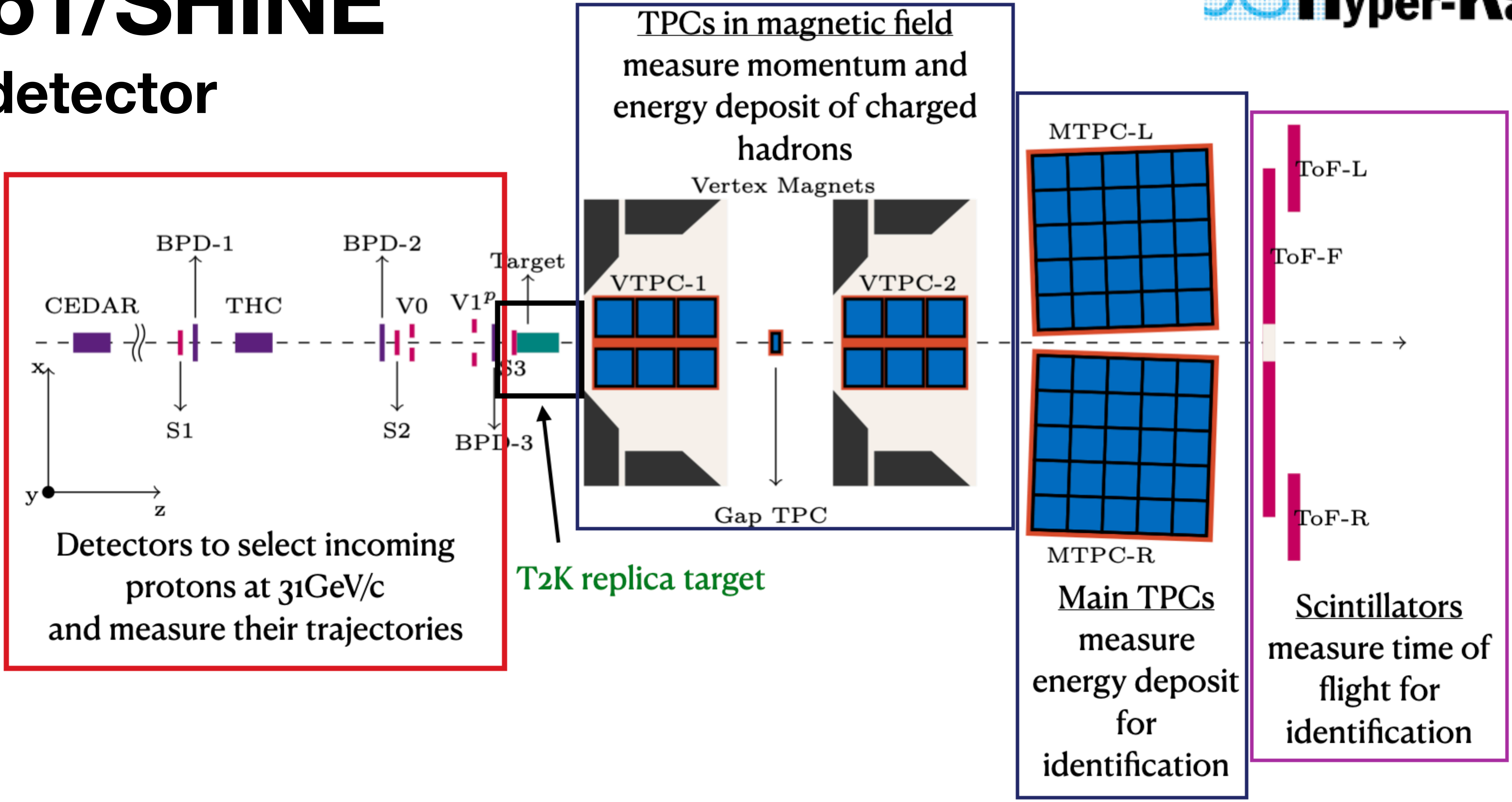
Near detectors are a key tool to constrain most of the systematic effects!

NA61/SHINE experiment:
How to reduce neutrino flux uncertainties

Systematic uncertainties can also be constrained by external measurements.
For instance, the NA61/SHINE hadron production measurements allow to reduce the neutrino flux uncertainties.

NA61/SHINE

The detector

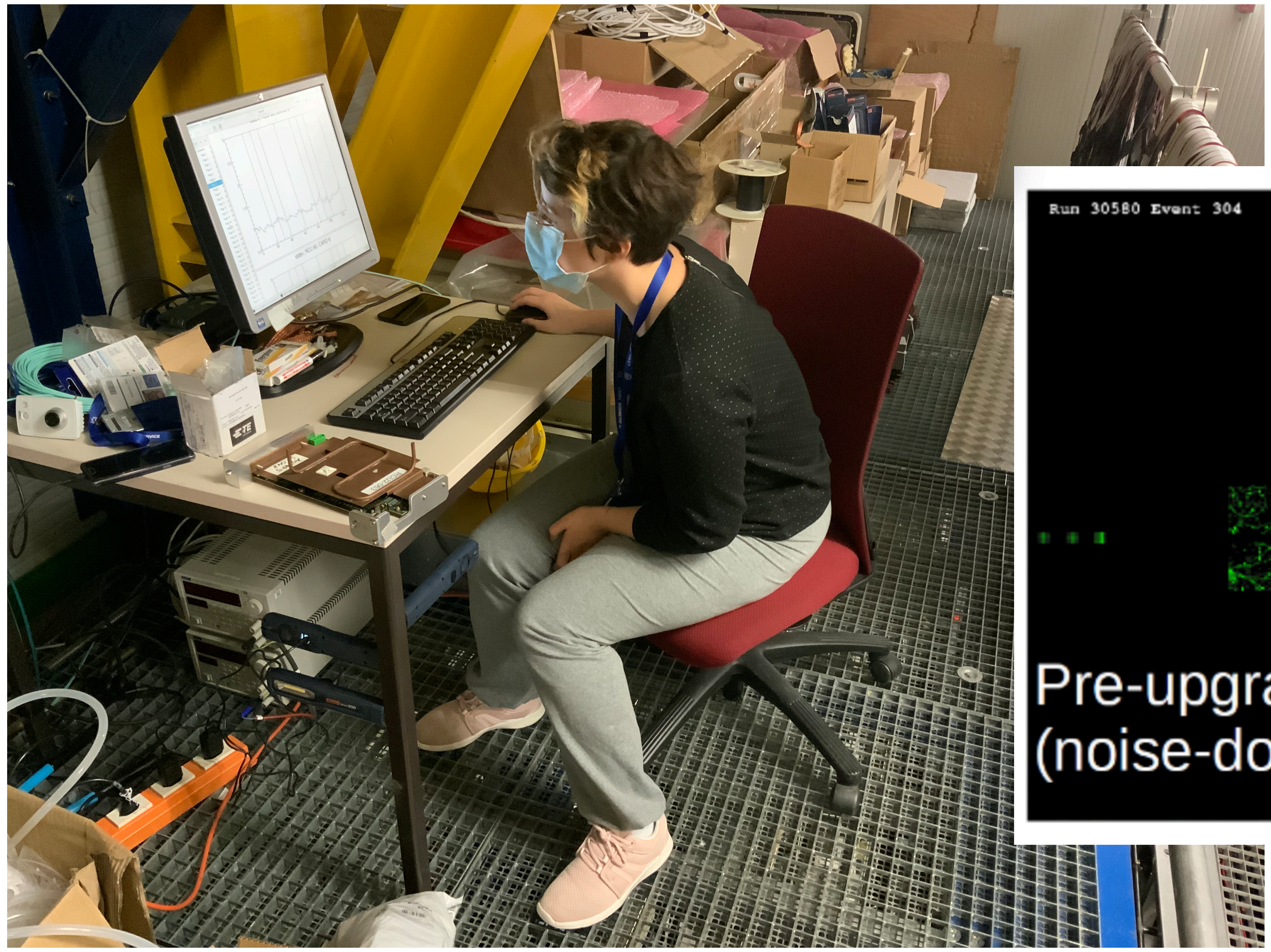


NA61/SHINE

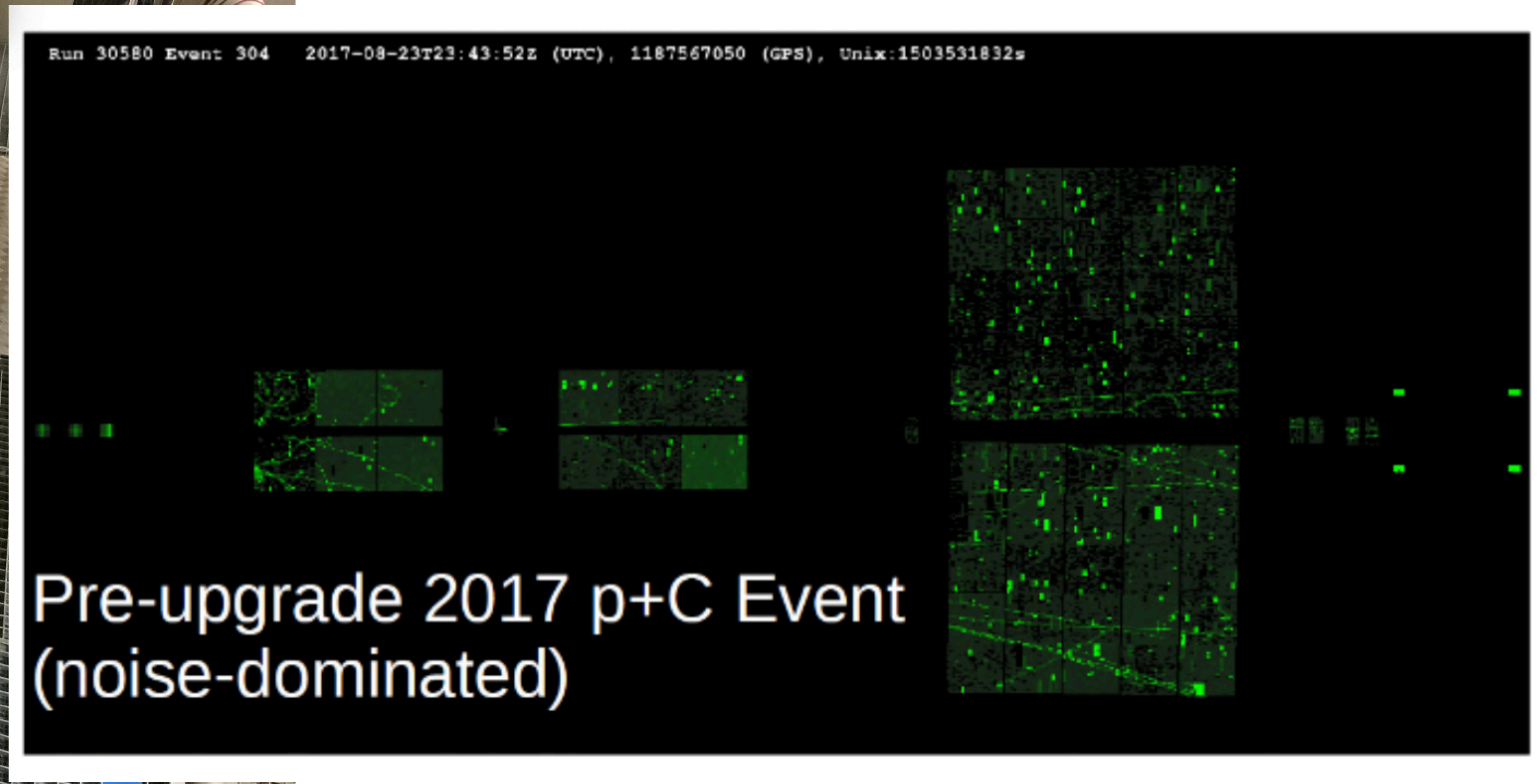
The detector

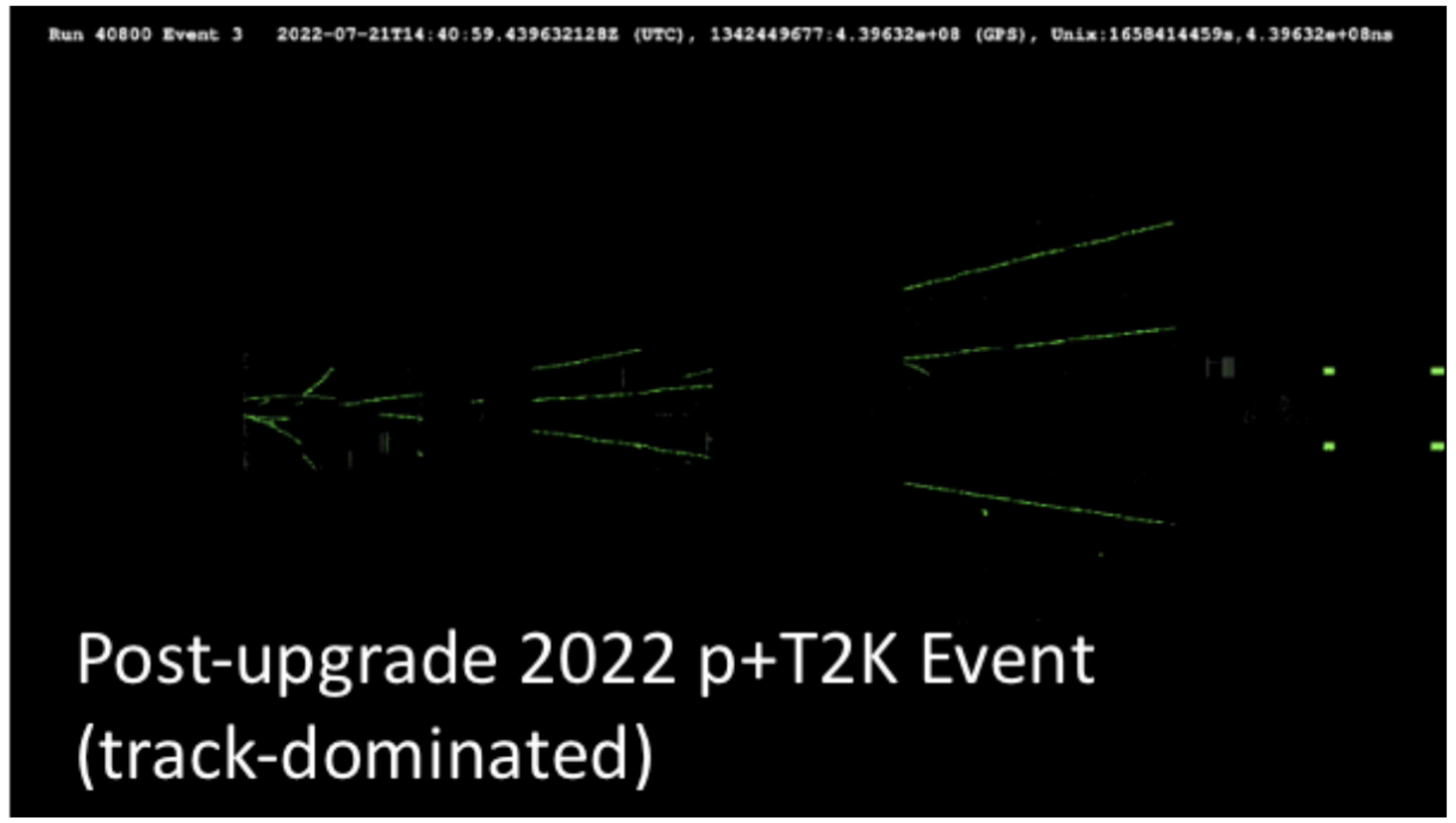
Hyper-Kamiokande

The detector was upgraded in 2021-2022 to allow a faster trigger rate



November 2021, testing the response of the TPCs with the new electronics

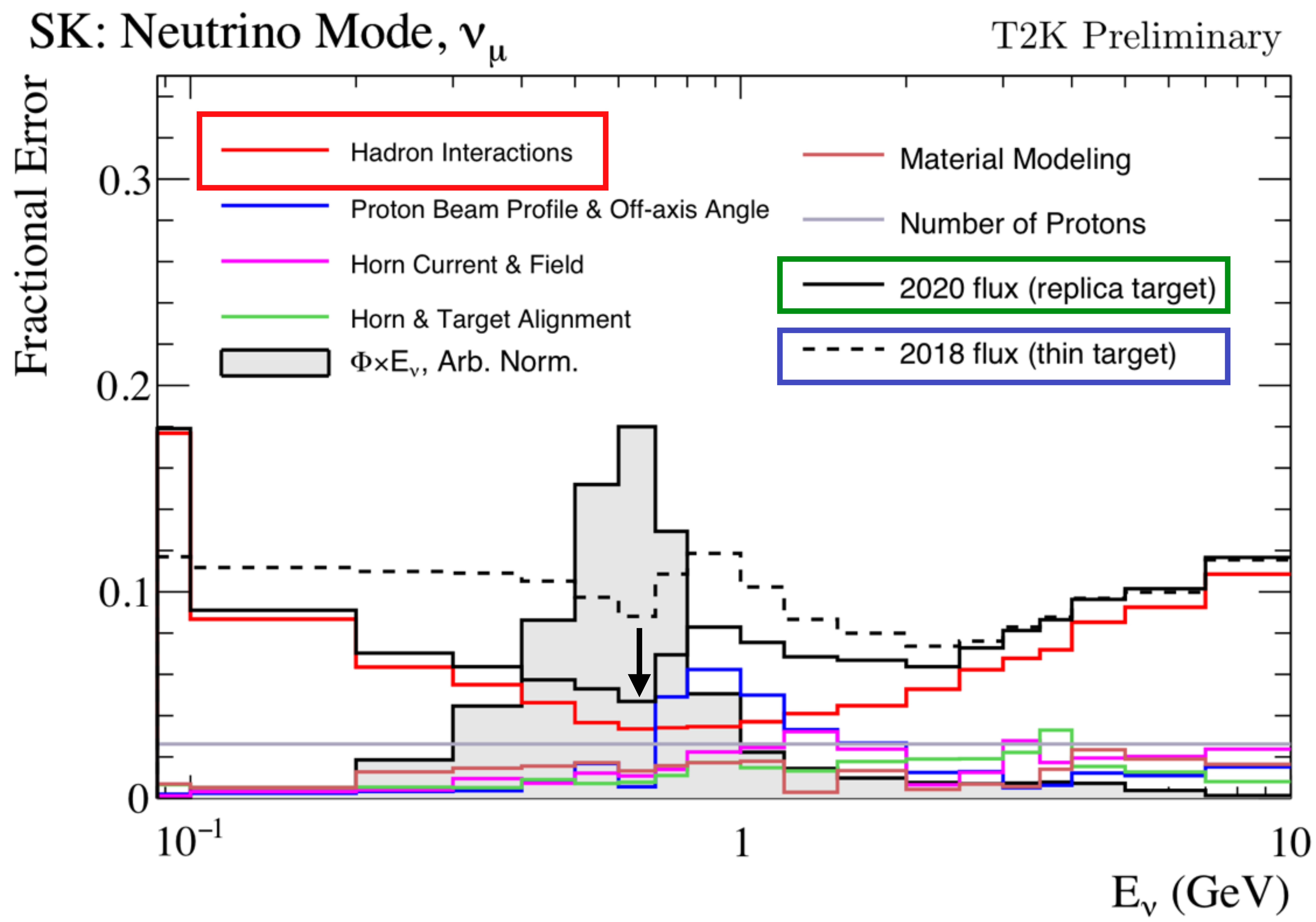




NA61/SHINE

Reducing the flux uncertainties

- Main uncertainty on flux: **hadron interaction uncertainties**.
- The last **replica target** measurements allowed to reduce the uncertainty to **5% at the flux peak**!
- **New NA61/SHINE data with replica target in 2022**: measure charged hadron + K_S^0 production in T2K target
- **My task**: calibration (in progress) and analysis of the new dataset

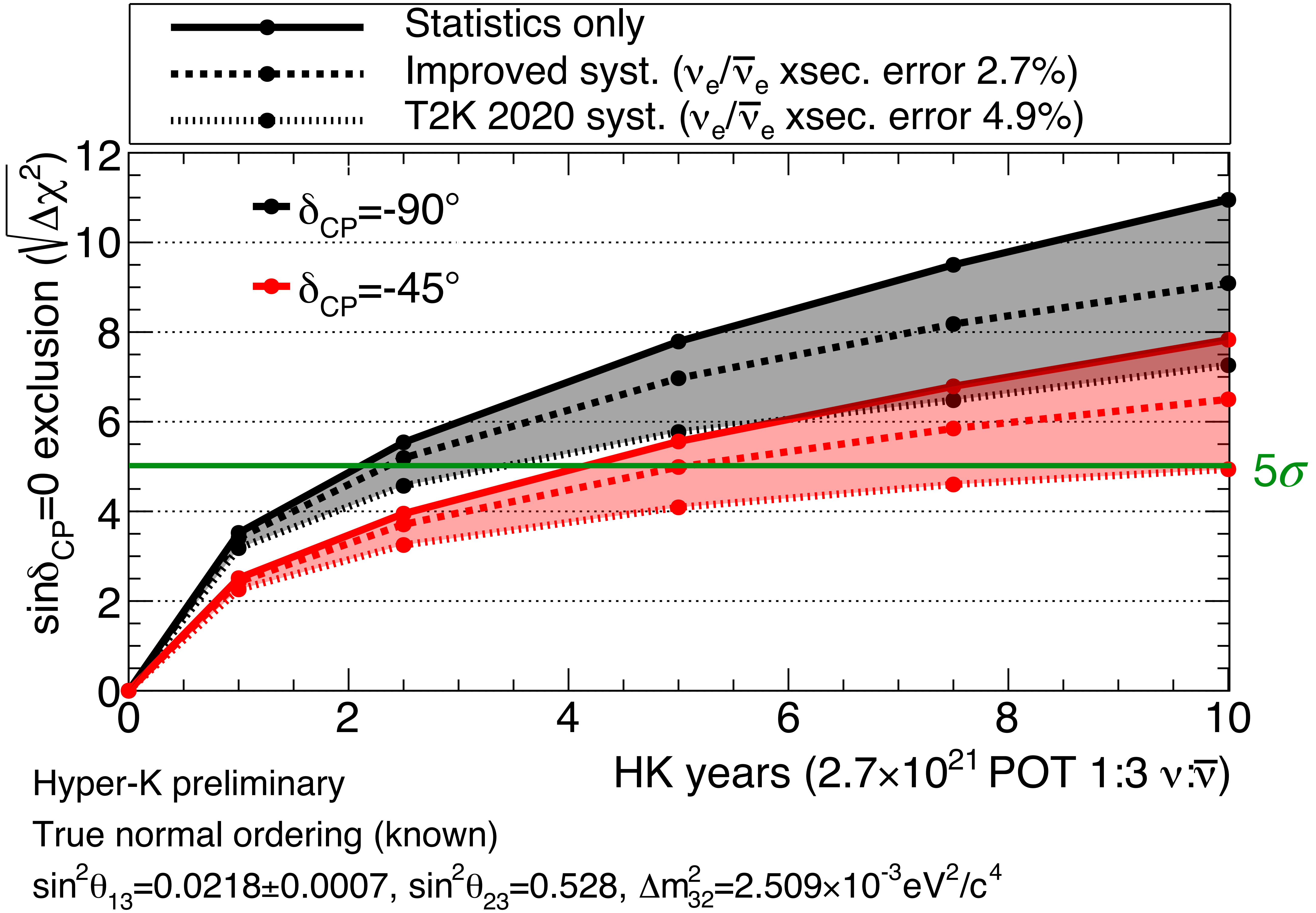


HK long baseline program: Sensitivity studies

One application of HK will be to detect the neutrinos produced at an accelerator facility 295km away to measure flavour oscillation parameters. This is the long baseline program, the foreseen evolution of the T2K experiment.

HK sensitivity studies

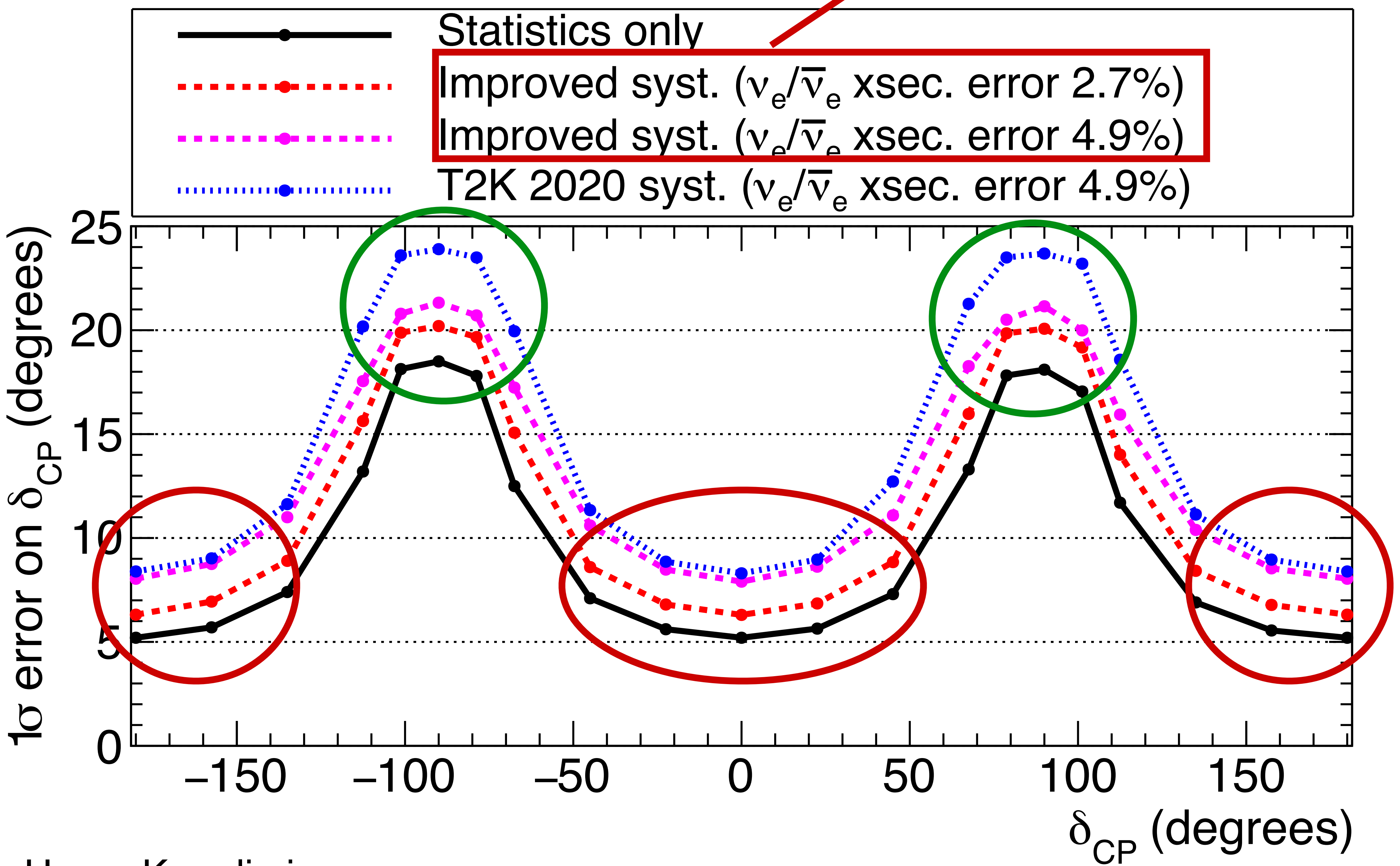
- **T2K** latest results gave **hint at 2σ** that neutrino flavour oscillation **violates** the symmetry between matter and anti-matter (**CP** symmetry).
- This is quantified by the CP violation phase parameter δ_{CP}.
- To confirm that neutrino oscillation violates CP, we want to exclude $\sin\delta_{CP} = 0$ at 5σ
- **HK could do that after a few years** depending on systematic effects



HK sensitivity studies

Only difference is the uncertainty on the ratio $\sigma(\nu_e)/\sigma(\bar{\nu}_e)$

The uncertainty on the ratio $\sigma(\nu_e)/\sigma(\bar{\nu}_e)$ is dominant for $\sin\delta_{CP} \approx 0$



Hyper-K preliminary

True normal ordering (known), HK 10 Years (2.7×10^{22} POT 1:3 ν:$\bar{\nu}$)

$\sin^2\theta_{13}=0.0218\pm0.0007$, $\sin^2\theta_{23}=0.528$, $\Delta m^2_{32}=2.509\times10^{-3}\mathrm{eV}^2/c^4$

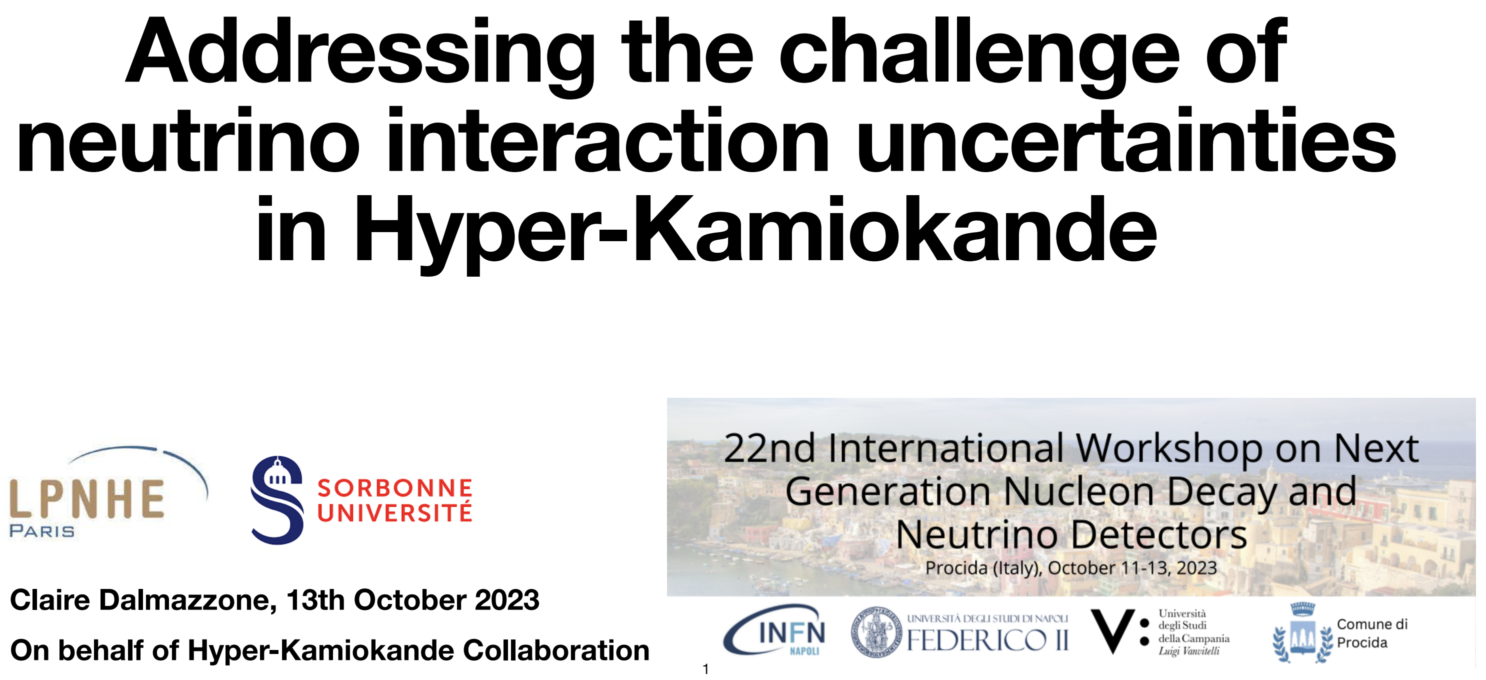
Other systematics are dominant for $|\sin\delta_{CP}| \approx 1$ (favoured by T2K results)

HK sensitivity studies

Officialisation

The results were presented on different occasion

- Poster at the CP2023 workshop (Les Houches, February 2023)
- Talk at the Neutrino International Research Network (Nantes, June 2023)
- Talk at the NNN23 (Procida, October 2023)



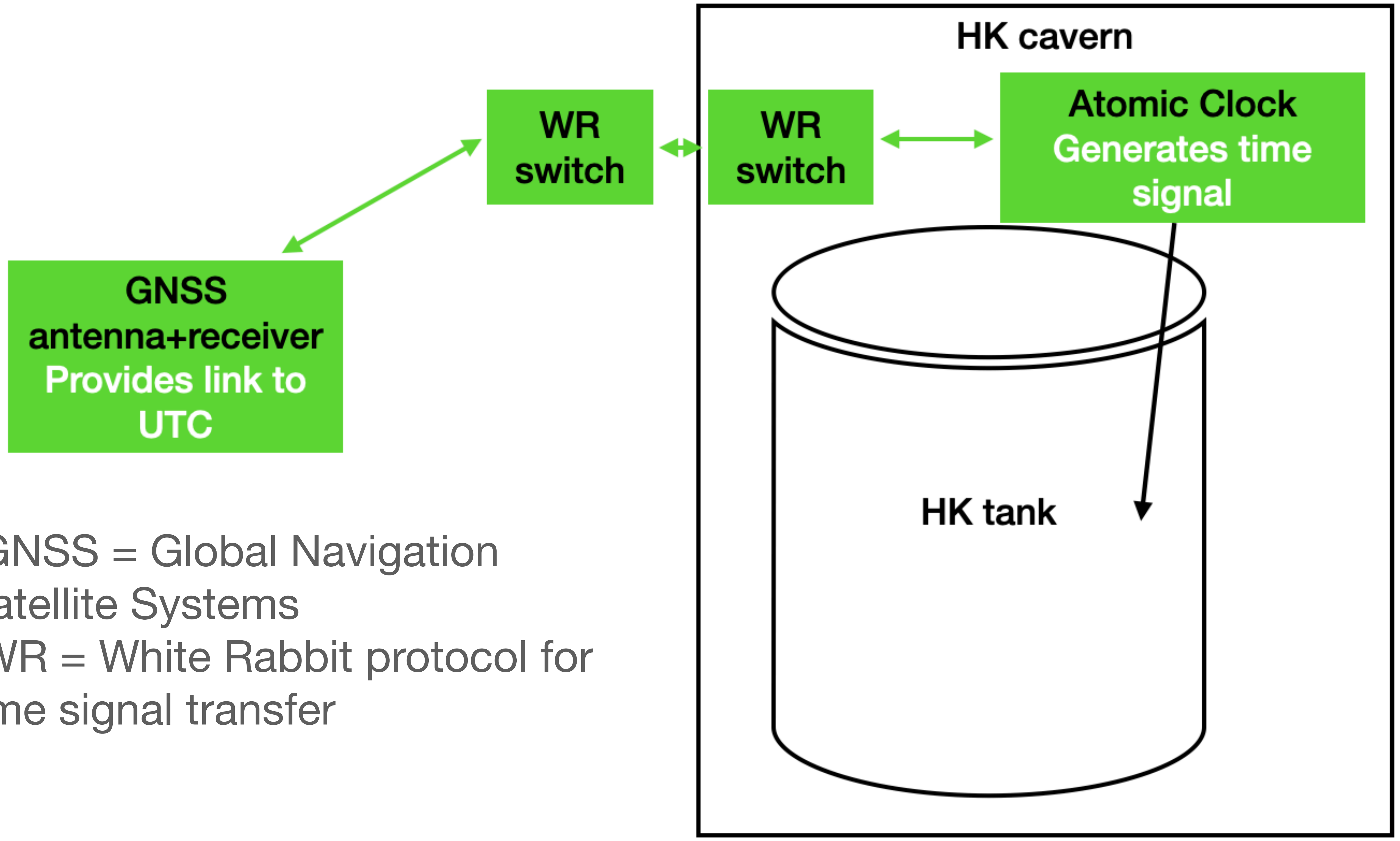
Timing distribution in HK

The accelerator neutrinos are selected in HK in particular thanks to the timing of the events.
The signal reconstruction in Water Cherenkov detectors necessitate a good synchronisation between the PMTs.
For multi messenger observations, the events in HK should be time-tagged with UTC*.
—> Timing is a very important aspect of the experiment!!

*UTC: Universal Time Coordinated

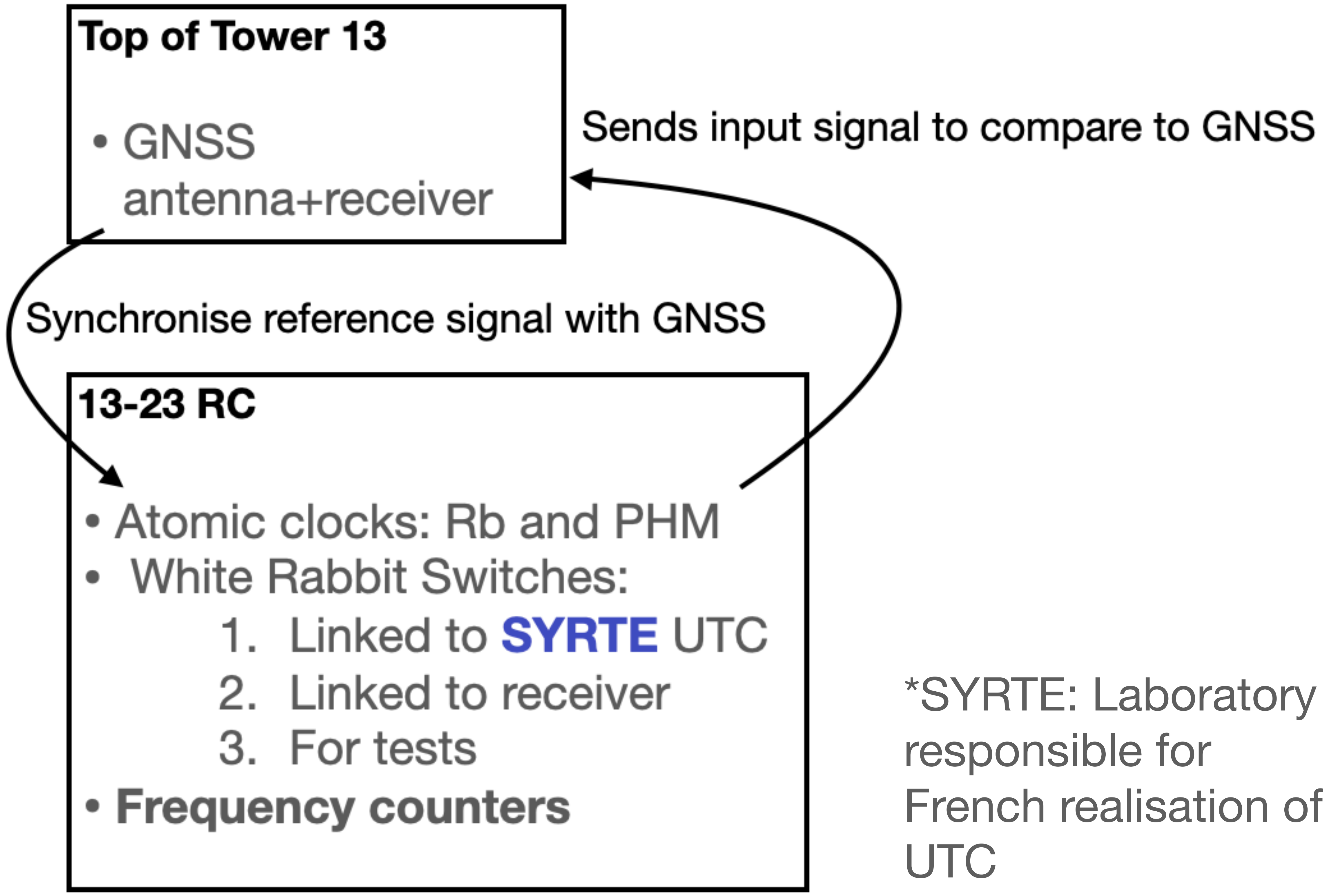
Timing distribution

Setups for the time generation



*GNSS = Global Navigation Satellite Systems
*WR = White Rabbit protocol for time signal transfer

Foreseen setup for HK



*SYRTE: Laboratory responsible for French realisation of UTC

Setup at LPNHE

Timing distribution

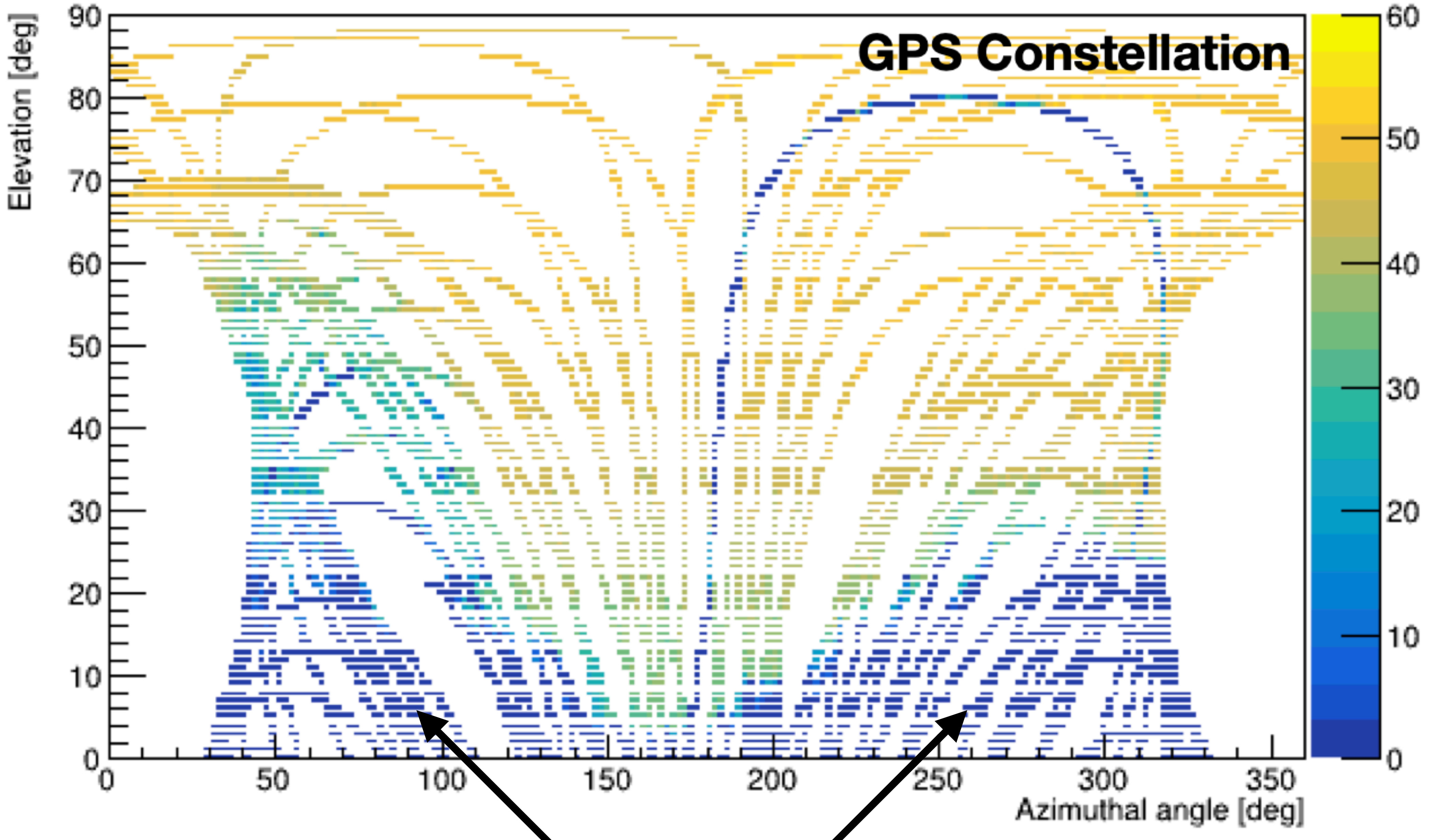
Tests in Japan

In summer 2023, we brought an antenna in Japan to check the reception of GNSS signals on site.

Credit: Mathieu Guigue

Tunnel to HK cavern

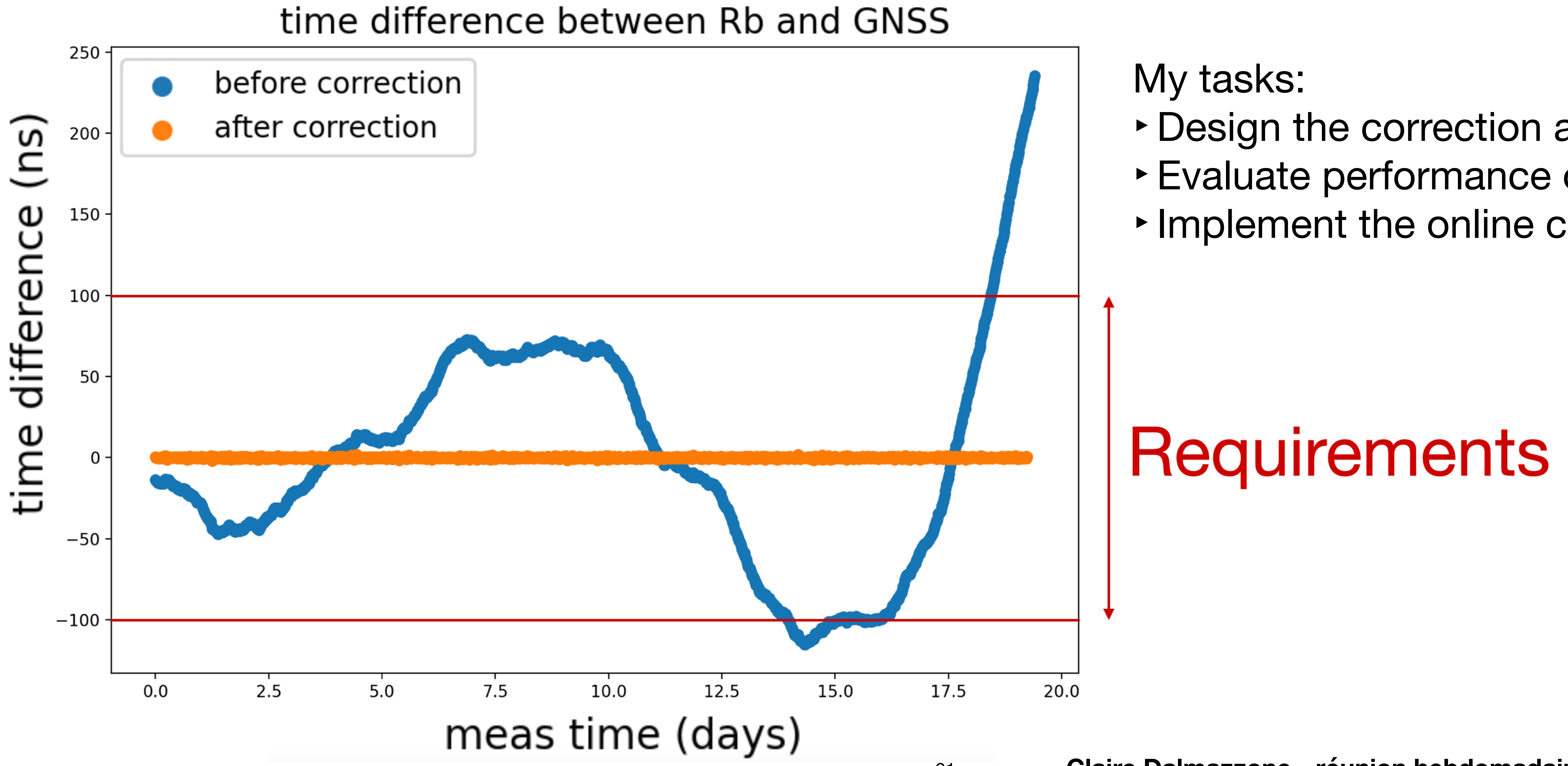
Our antenna



Low signal because of mountains!

Timing distribution

Rubidium clock signal correction



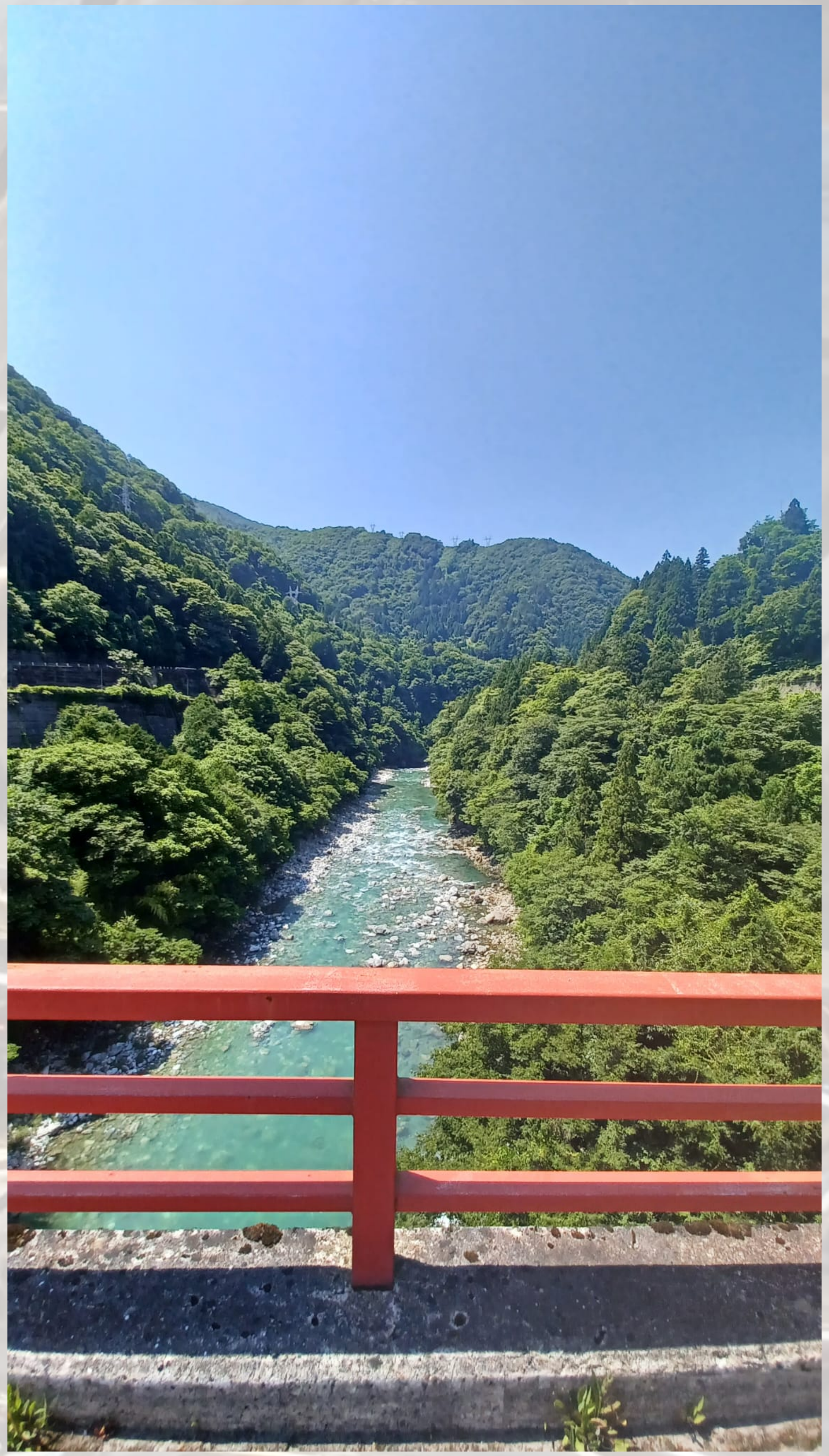
My tasks:

- Design the correction algorithm
- Evaluate performance of the correction
- Implement the online correction

Conclusion: Plans

- **Hyper-Kamiokande** will start in **2027**. My work involves different aspects the preparation.
- **Rubidium timing correction:**
  - Test correction on data (next months) plan to publish
  - Implement the online correction
- **New sensitivity studies** for the long baseline program using T2K's latest published results:
  - Results are official. publication is being considered
- Calibration and analysis of the new **NA61/SHINE T2K replica target dataset:**
  - Finishing the detectors calibration (~ 1 year)
  - Part of the analysis can begin before (MC studies)

Hyper-Kamiokande



Thank you!

Introduction

Neutrino flavour oscillation

Flavour oscillation: quantum effect due to the **mixing between the flavour states and the mass states**. Its existence means that neutrinos have **non zero mass**.

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \begin{pmatrix}1 & 0 & 0\\ 0 & \cos\theta_{23} & \sin\theta_{23}\\ 0 & -\sin\theta_{23} & \cos\theta_{23}\end{pmatrix}\begin{pmatrix}\cos\theta_{13} & 0 & \sin\theta_{13}e^{-i\delta_{CP}}\\ 0 & 1 & 0\\ -\sin\theta_{13}e^{i\delta_{CP}} & 0 & \cos\theta_{13}\end{pmatrix}\begin{pmatrix}\cos\theta_{12} & \sin\theta_{12} & 0\\ -\sin\theta_{12} & \cos\theta_{12} & 0\\ 0 & 0 & 1\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

PMNS* parametrisation of the mixing matrix: the three mixing angles (θ_{ij}) and the complex phase δ_{CP} are not predicted and **must be measured experimentally**.

If $\sin\delta_{CP} \neq 0$, neutrinos and anti-neutrinos don't have the same oscillation probability: neutrino oscillation violates CP

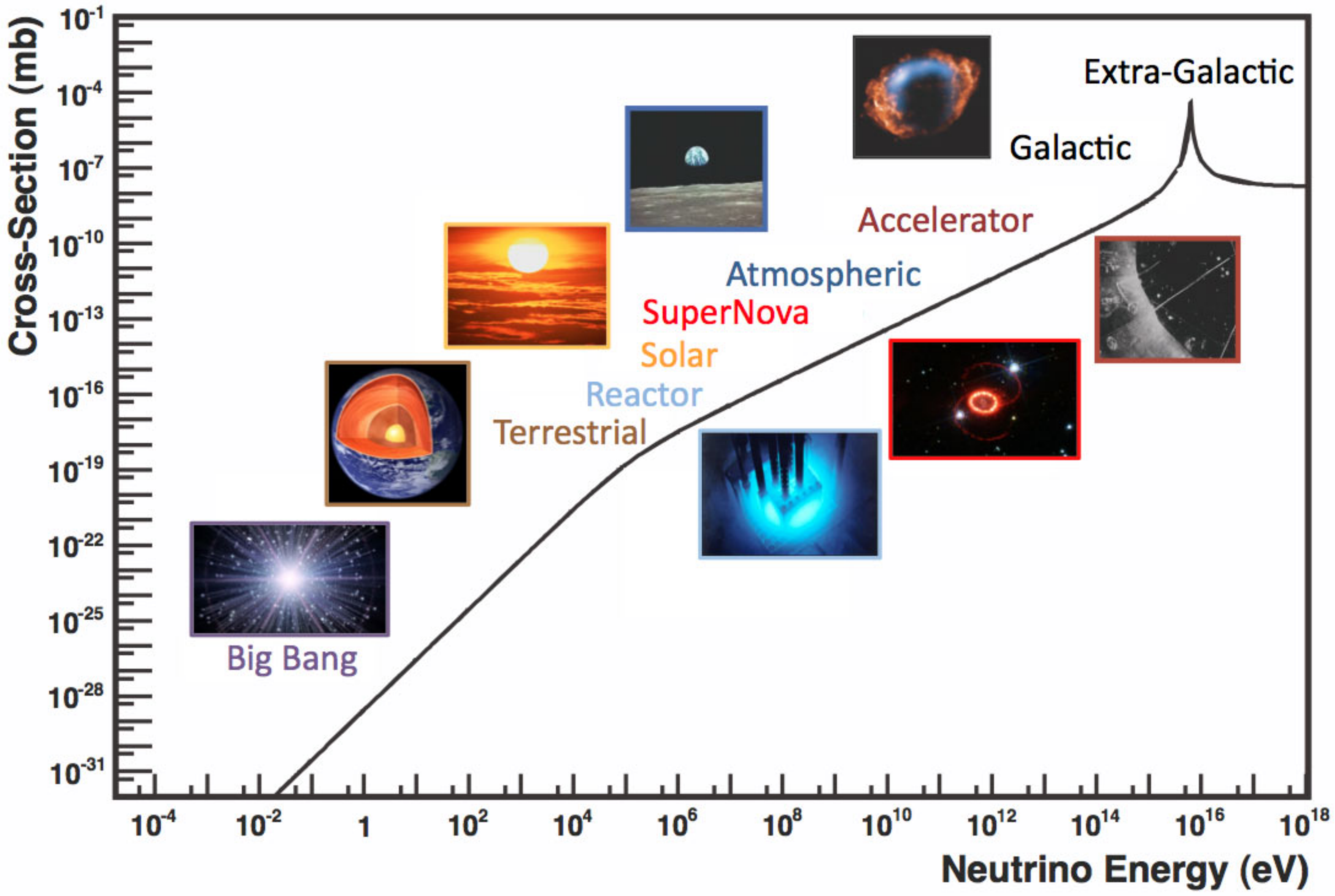
$$P(\nu_\alpha \to \nu_\beta, L, E) = \delta_{\alpha,\beta} - 4\sum_{j>k} \Re\{U^*_{\alpha j}U_{\beta j}U_{\alpha k}U^*_{\beta k}\}\sin^2\left(\frac{\Delta m^2_{jk}L}{4E}\right) + 2\sum_{j>k}\Im\{U^*_{\alpha j}U_{\beta j}U_{\alpha k}U^*_{\beta k}\}\sin\left(\frac{\Delta m^2_{jk}L}{2E}\right)$$

Oscillation probability depends on the propagation lenght, the energy, the mixing matrix U elements and the difference of neutrino masses squared $\Delta m^2_{jk} = m^2_j - m^2_k$

* PMNS for Pontecorvo-Maki-Nakagawa-Sakata

Introduction

Sources of neutrinos



Many natural and man-made sources of neutrinos. Detecting neutrinos allows to:

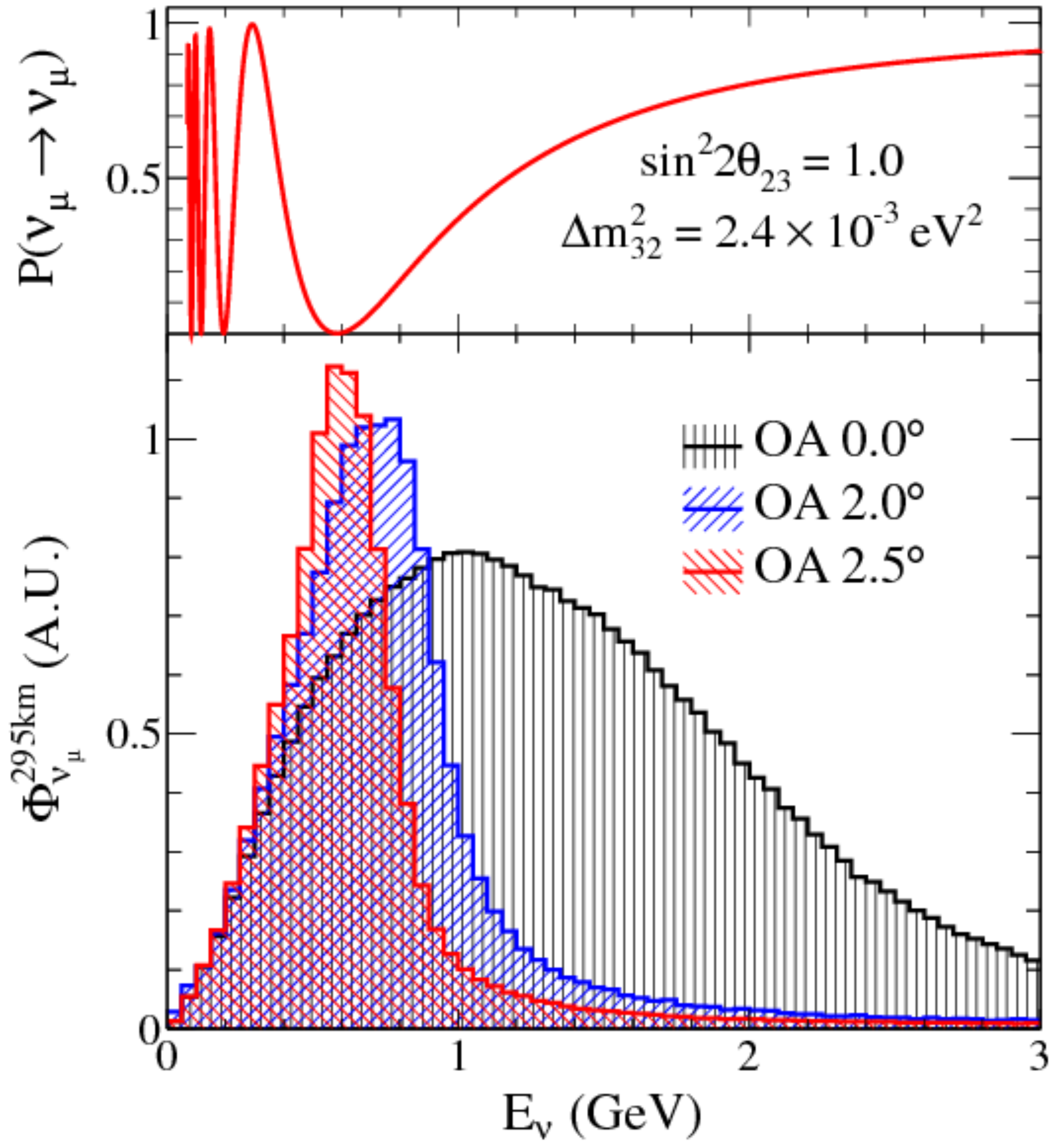
- Study **astrophysical** sources: neutrinos don't interact and can point to their source
- Test the **Standard Solar Model**
- Study quantitatively the **neutrino flavour oscillation**
- Study the **neutrinos properties**: mass measurement, Majorana particle?, etc.

But detecting neutrinos is challenging due to their very low interaction cross-section!!

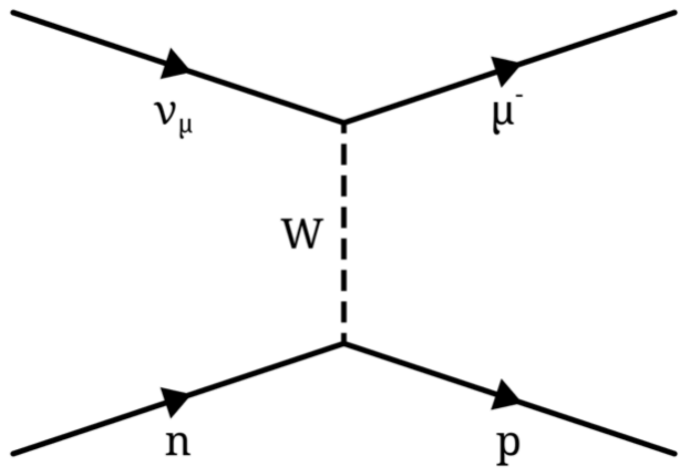
The T2(H)K experiment

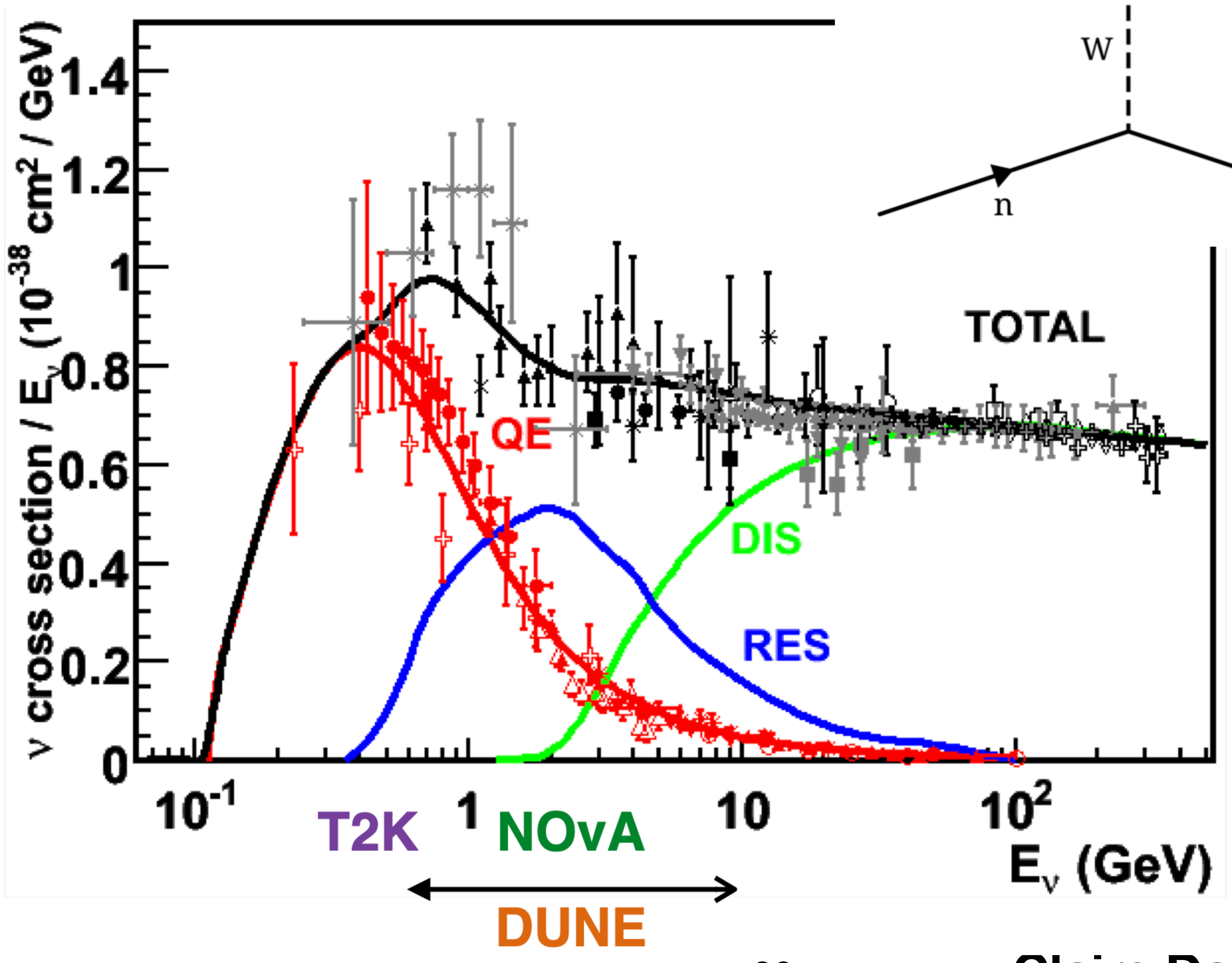
Overview

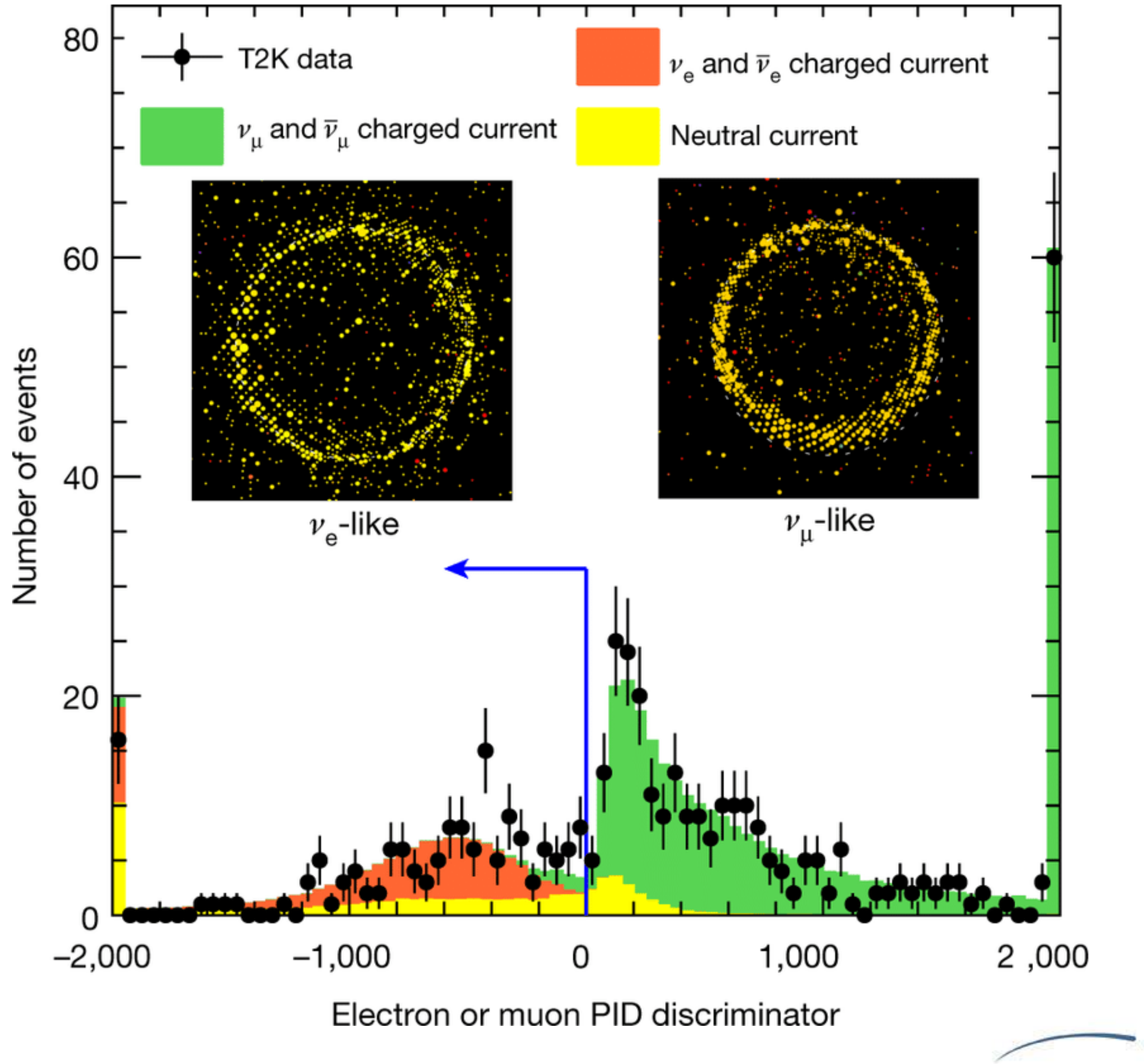
SK and HK are not aligned with the proton beam at J-PARC. The $2.5°$ off-axis angle allows to obtain in a narrow neutrino energy beam peaked at ~600MeV the survival probability minimum in the detector.



At these energies, most common interaction is QE: easier to reconstruct neutrino energy.





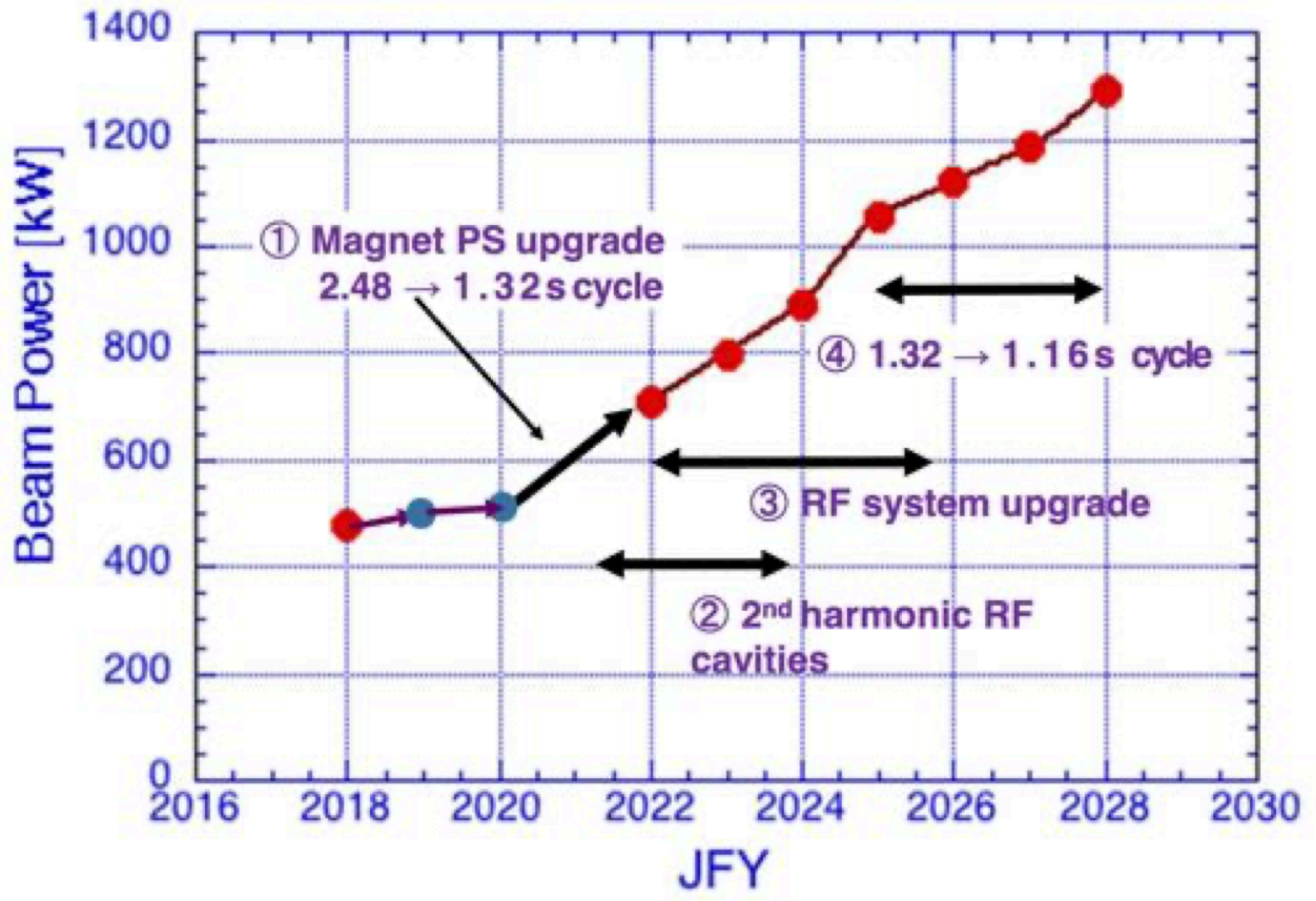


The T2(H)K experiment

From T2K to HK long baseline

HK long baseline is the future of the T2K experiment: the T2K baseline is being upgraded to accelerate the accumulation of statistics:

- Proton beam intensity increase at J-PARC
- New near detectors
- New far detector



Credit: Megan Friend, NuFact 2021

The T2(H)K experiment
From T2K to HK long baseline

HK long baseline is the future of the T2K experiment: the T2K baseline is being upgraded to accelerate the accumulation of statistics:

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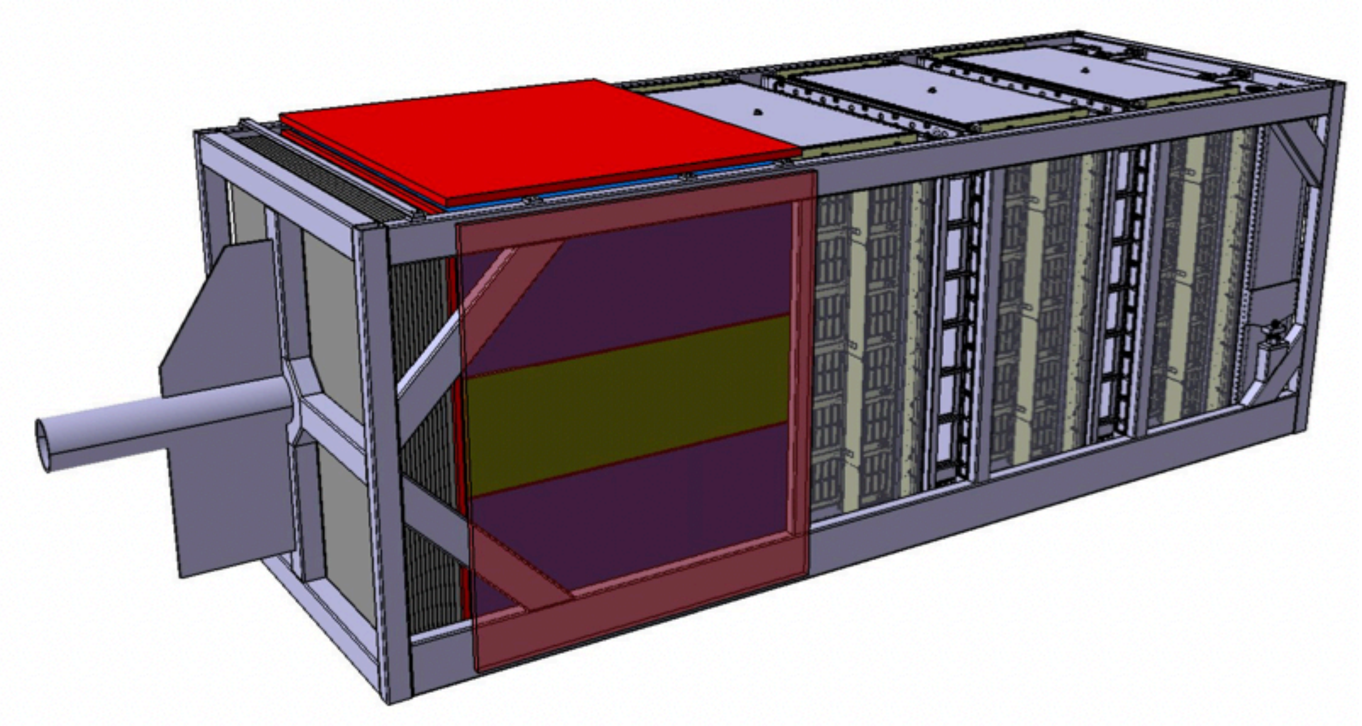
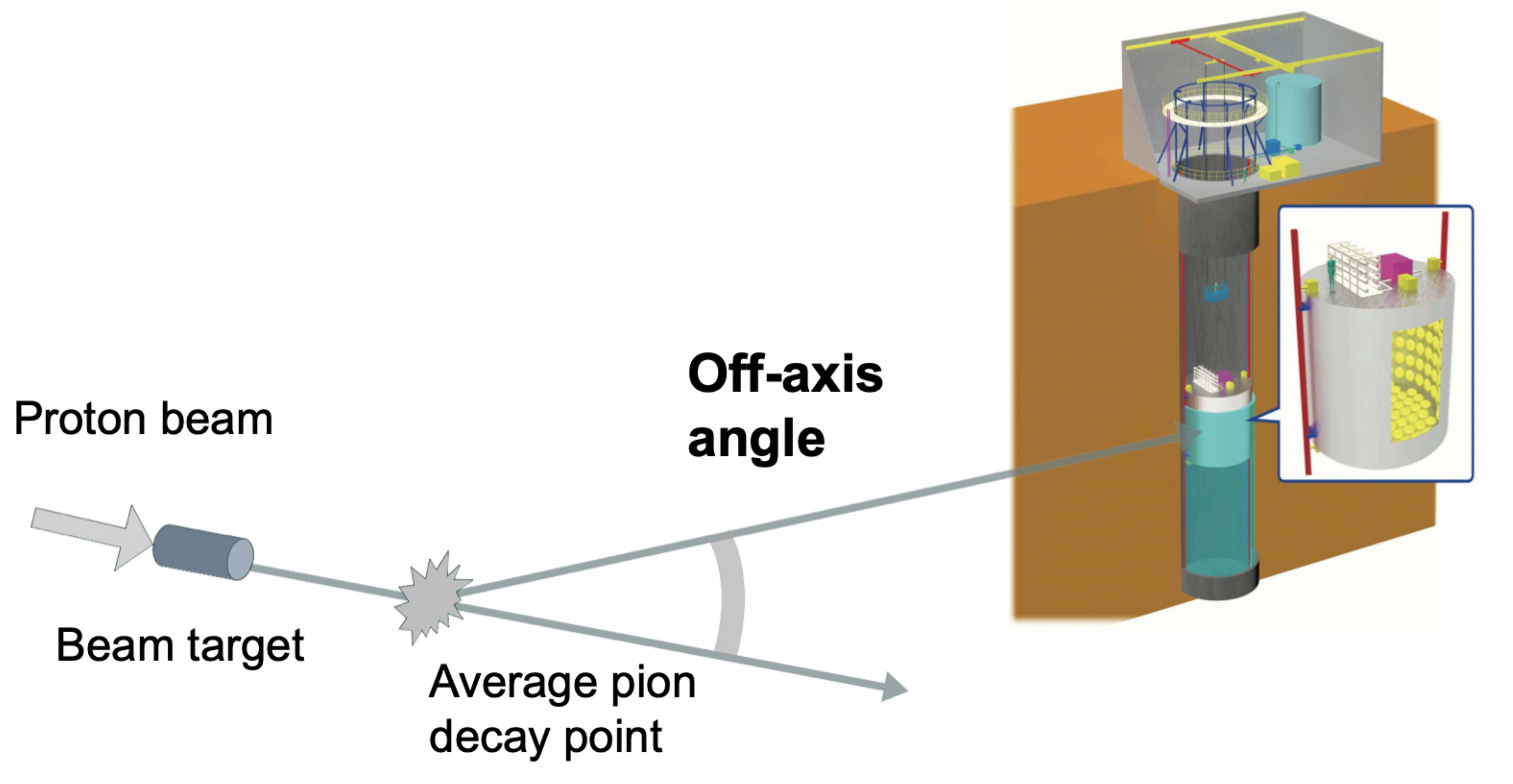


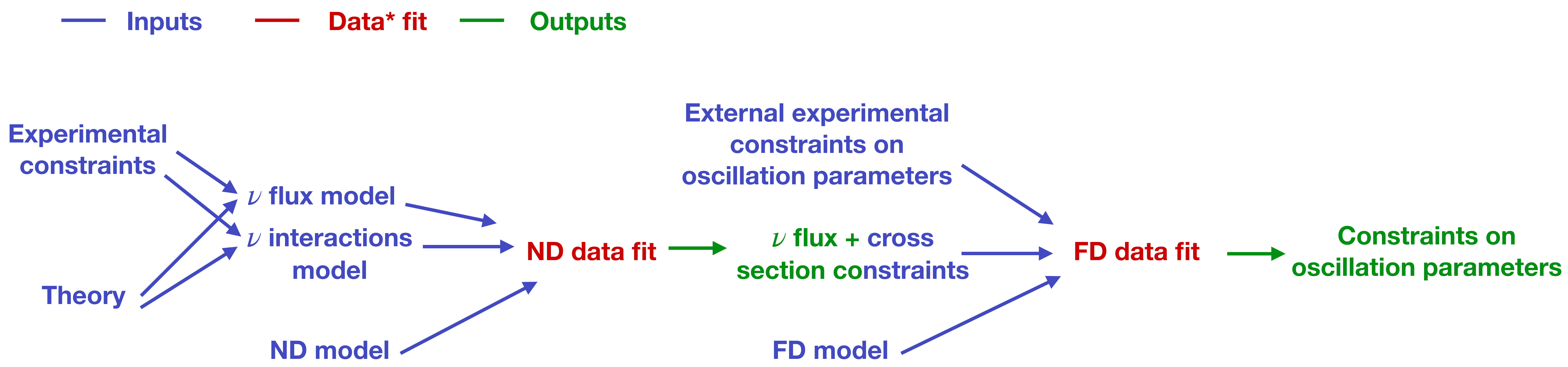
ND280 at 280m from T2K target:
Inherited from T2K
Is being upgraded for T2KII and might undergo further upgrades during HK data-taking



Intermediate Water Cherenkov Detector at ~1km from target:
New detector that will be built for HK long baseline

HK sensitivity studies

Overview of the oscillation analysis in T2K

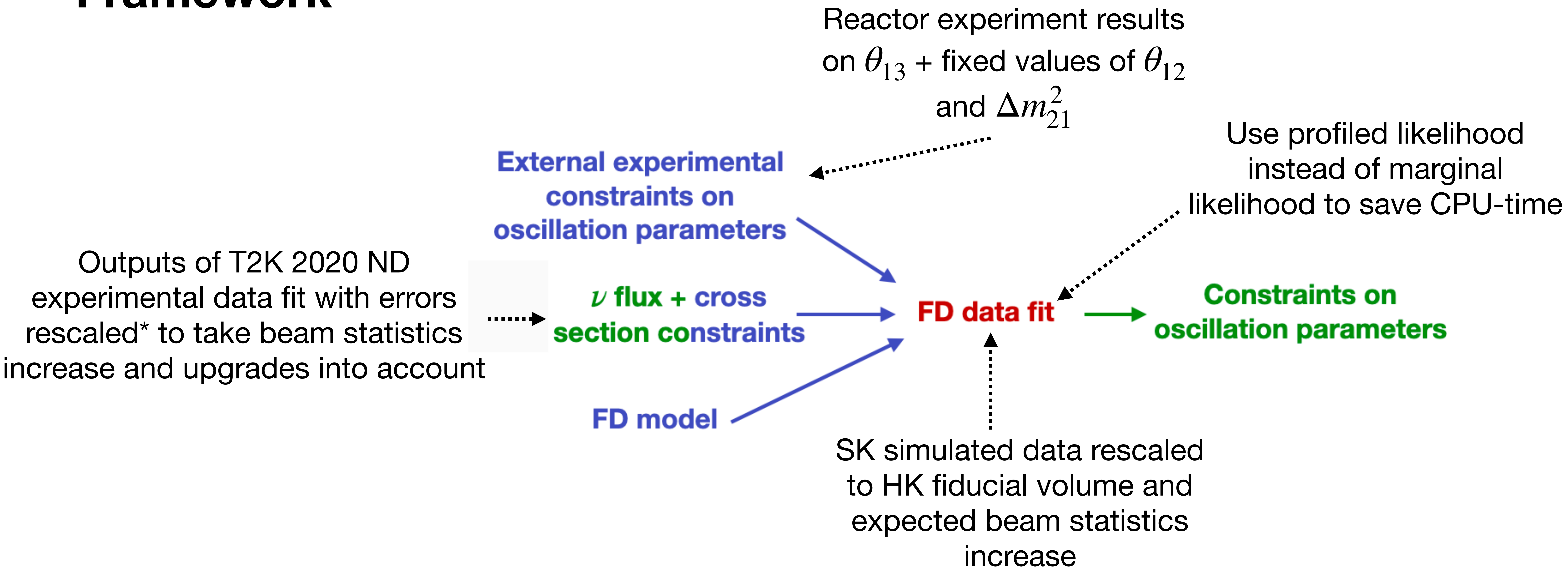


A similar framework was used to perform sensitivity studies for HK

*The data to fit can either be experimental data or simulated data (for sensitivity studies, fake data studies etc.)

HK sensitivity studies

Framework



*This predicted error model is called Improved systematics (VS T2K 2020 systematics)

HK sensitivity studies

Likelihood minimisation

Number of observed events

Systematic parameters

Expected number of events for given (o,f)

Use a Poissonian likelihood: $\ln \mathscr{L}_s(N^{obs}, x^{obs}, o, f) = -\sum_{\text{bin } i} \left((N_i^{exp}(o,f) - N_i^{obs}) + N_i^{obs} \times \ln(N_i^{obs}/N_i^{exp}(o,f)) \right)$

Kinematic variables measured

Oscillation parameters

Prior covariance matrix*

And a penalty for systematic effects: $\ln \mathscr{L}_{syst}(f) = -\frac{(f-f_0)^T V^{-1}(f-f_0)}{2}$

Prior central values**

$\chi^2 \equiv -2\ln\mathscr{L} = -2\ln\mathscr{L}_s - 2\ln\mathscr{L}_{syst}$ is minimised with gradient descent algorithm of Minuit 2

* For T2K 2020 or Improved error model

** Set to values that do not affect the Monte Carlo results or to the results of ND data fit

HK sensitivity studies

Marginal likelihood

$$\mathcal{L}_{prof} = \max_{\eta} \mathcal{L}(\eta)$$

$$\mathcal{L}_{marg} = \frac{1}{N}\sum_{i=1}^{N} \mathcal{L}(\eta_i)$$

Average over N realisations of the likelihood. The η_i are randomly thrown from a given distribution. This estimation of the marginal likelihood is biased with $B \sim 1/N$. The bias also increases with statistics, meaning that for HK it becomes much more cpu-consuming.

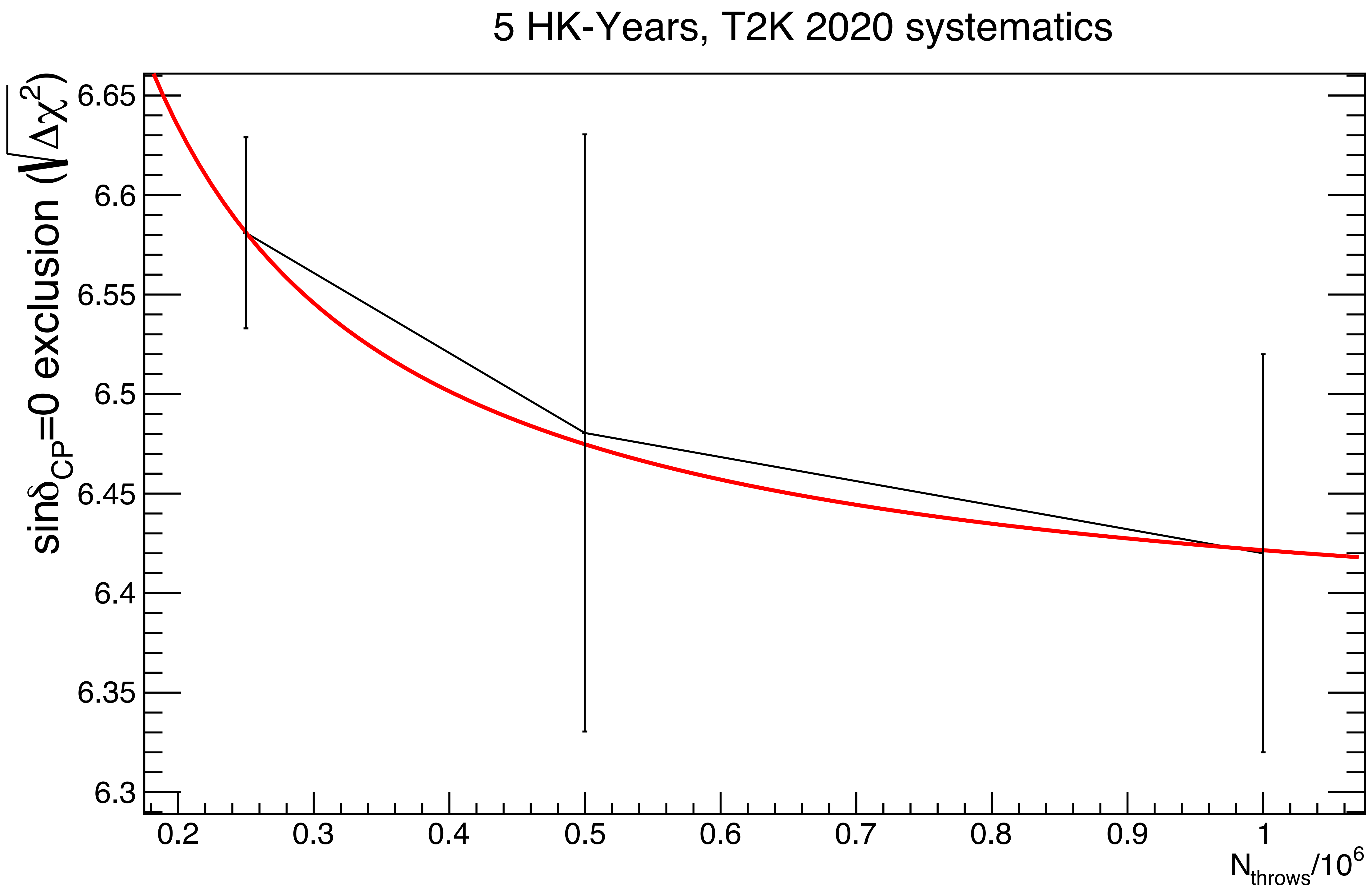


Illustration of the bias of the marginal likelihood behaving as 1/N

HK sensitivity studies

Systematic uncertainties

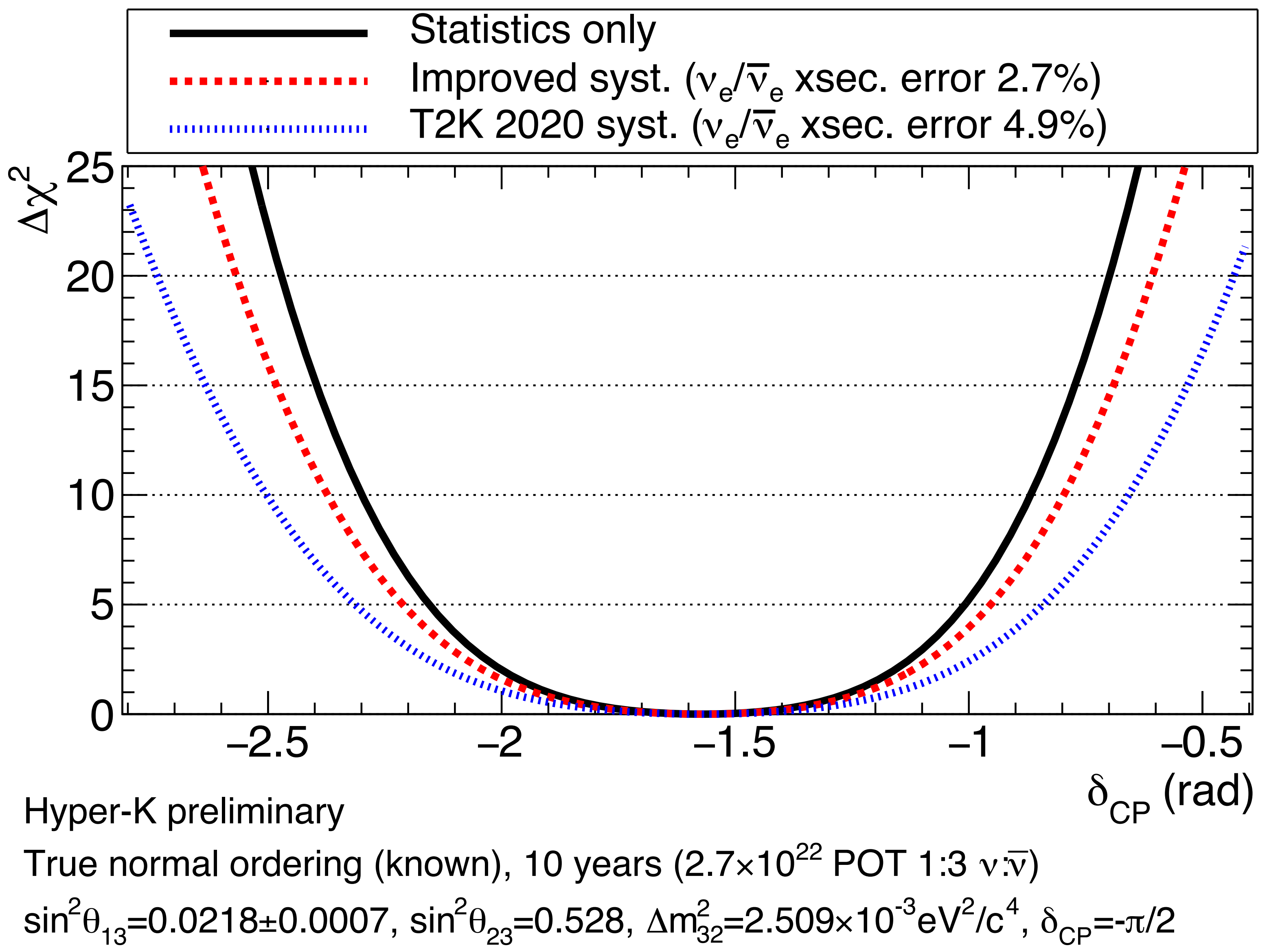
T2K 2020 Improved	Neutrino beam 1 electron ring	Neutrino beam 1 muon ring	Antineutrino beam 1 electron ring	Antineutrino beam 1 muon ring	Neutrino beam 1 electron ring + 1 decay electron
ND constrained flux + cross section	3.6% 1.8%	2.1% 0.9%	4.3% 1.6%	3.4% 0.9%	4.9% 1.8%
Other cross section	3.0% 1.6%	0.5% 0.4%	3.7% 1.4%	2.6% 0.4%	2.7% 1.6%
Detector	3.1% 1.1%	2.1% 0.8%	3.9% 1.5%	1.9% 0.7%	13.2% 4.9%
All	4.7% 2.1%	3.0% 1.2%	5.9% 2.2%	4.0% 1.1%	4.6% 2.0%

Systematic uncertainties on the event rates in HK per sample for the **T2K 2020** systematic and the **Improved** ones

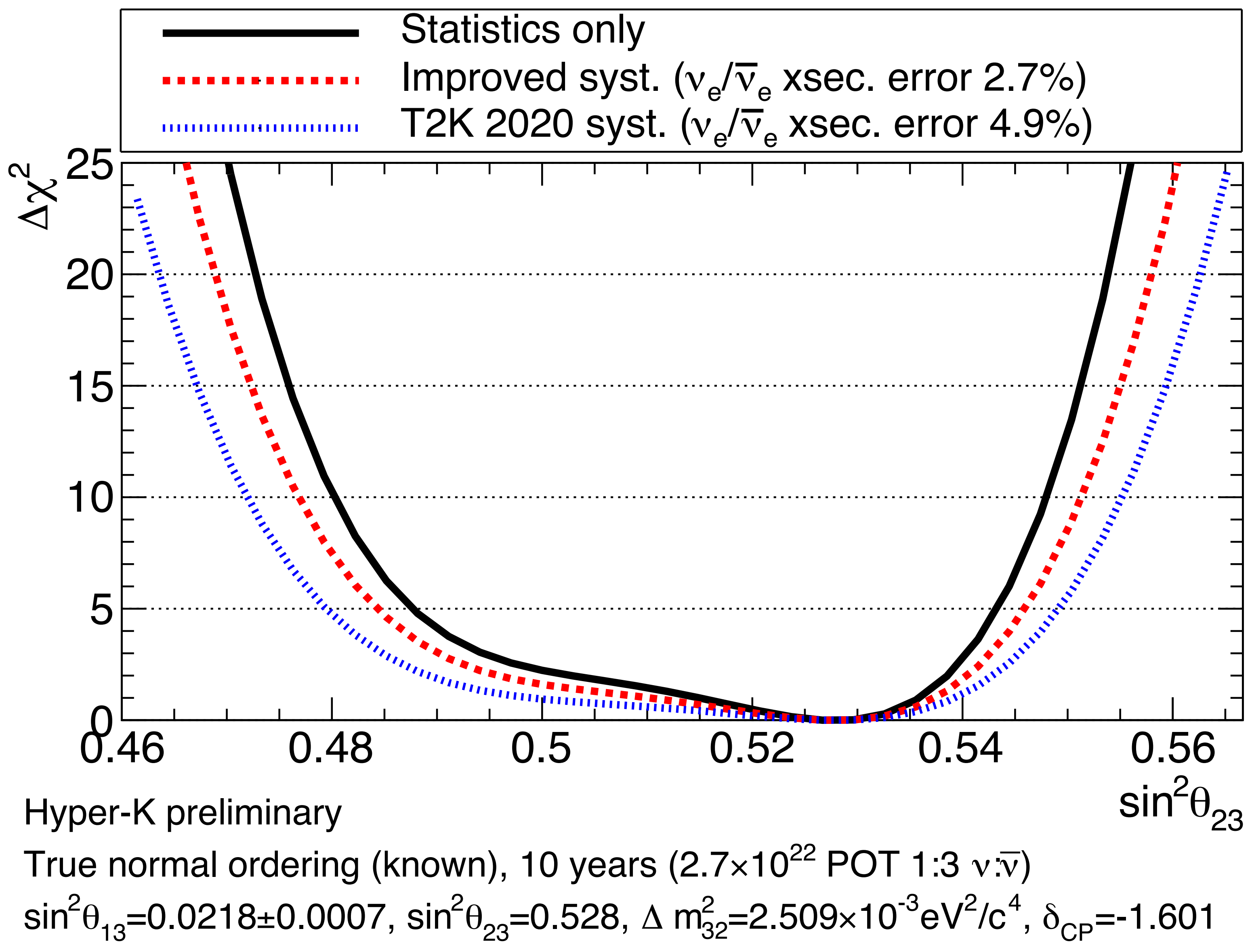
HK sensitivity studies

Results

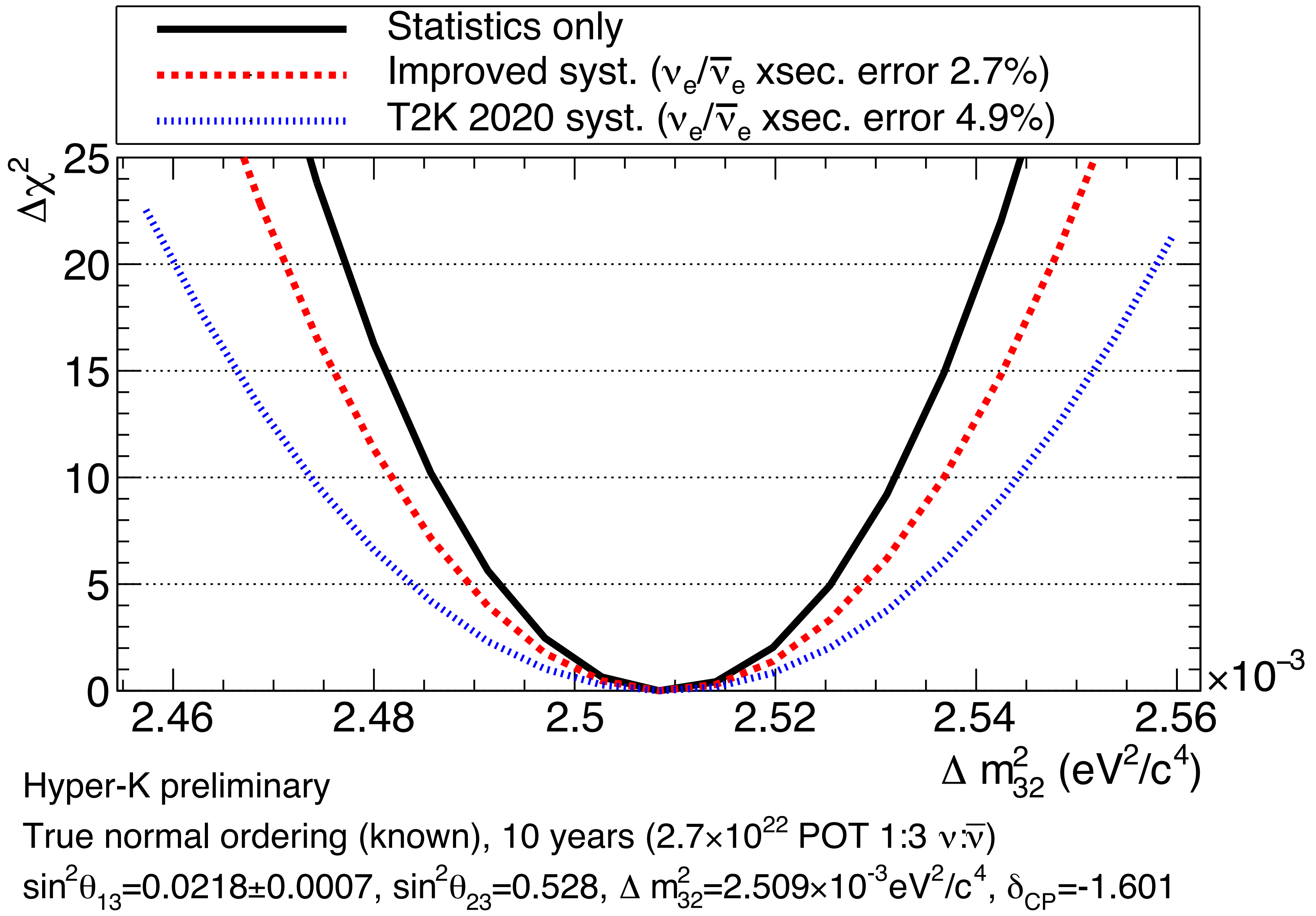
Sensitivity after 10 years of data-taking: $\Delta\chi^2$ curves



δ_{CP}



$\sin^2\theta_{23}$



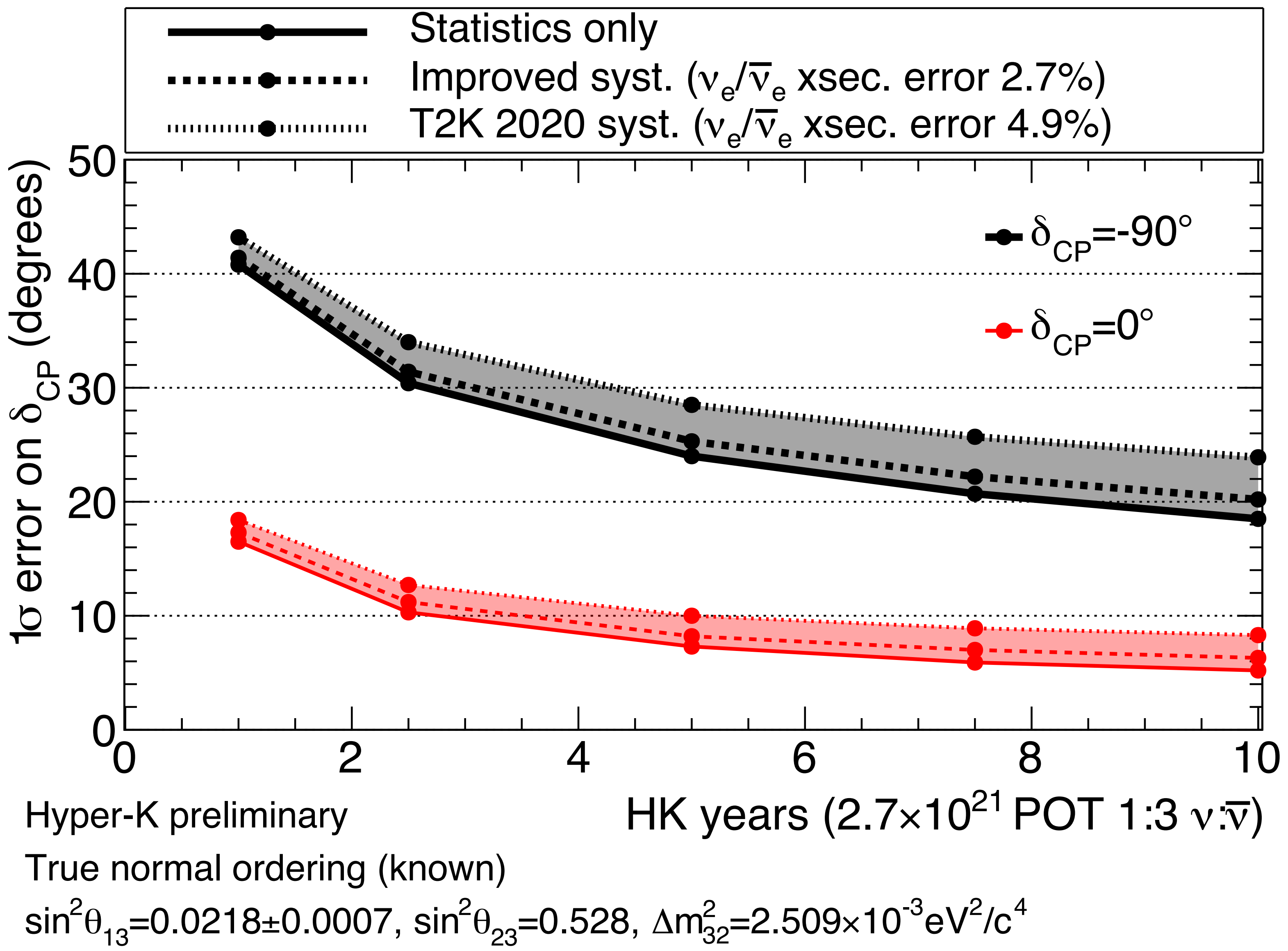
Δm^2_{32}

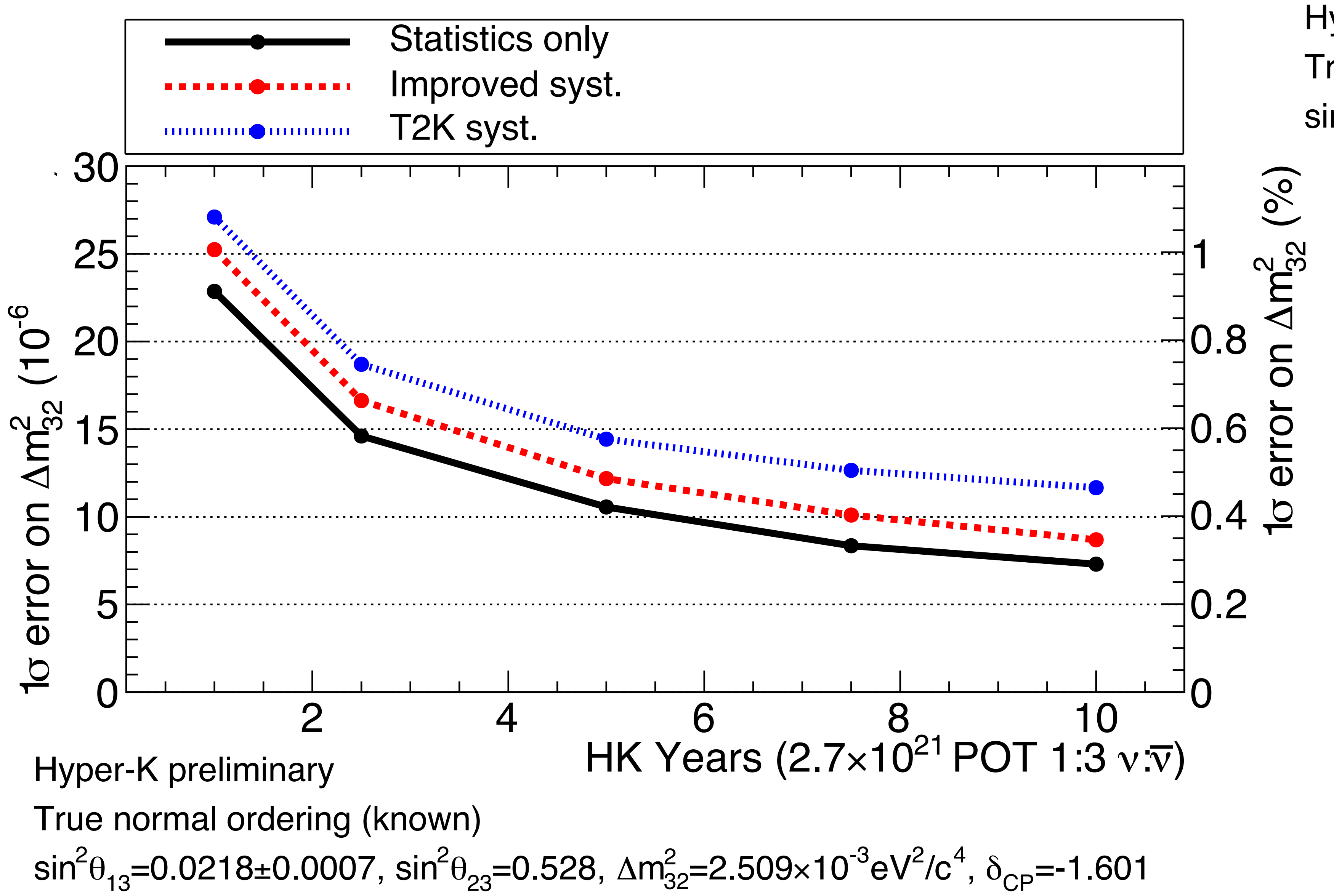
We estimate the resolution by taking the width of the curves at $\Delta\chi^2 = 1$

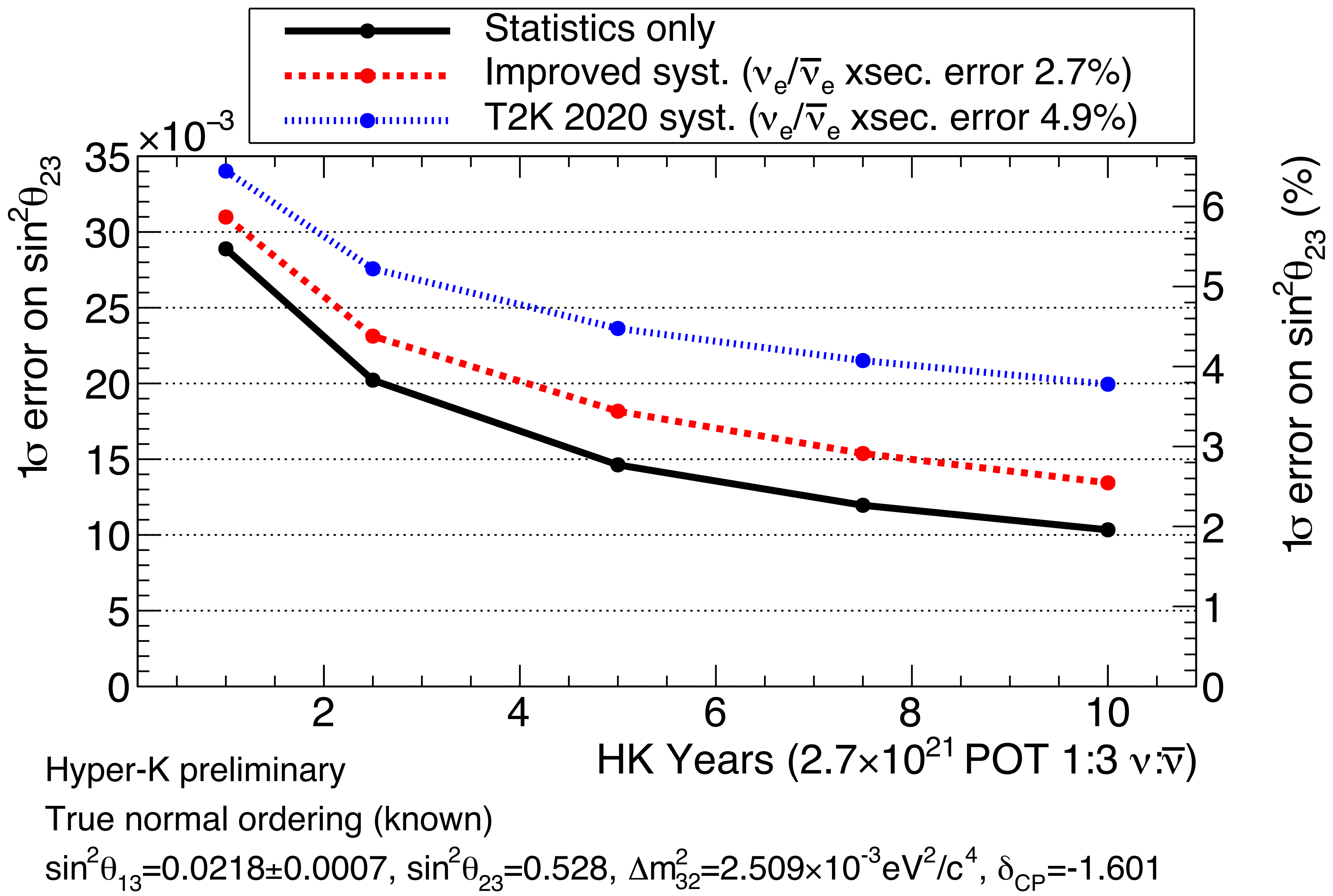
HK sensitivity studies

Results

Hyper-Kamiokande



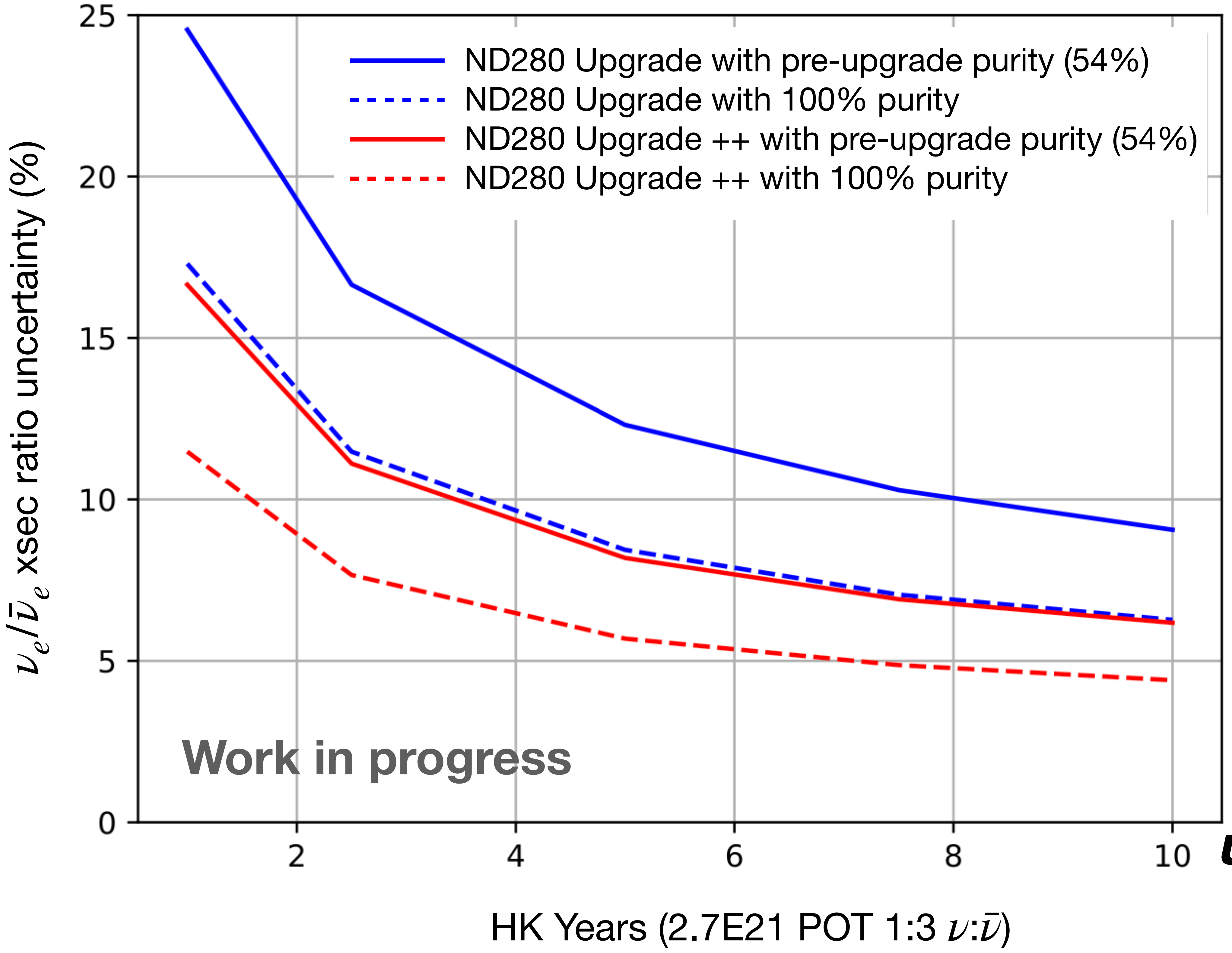




Plan to reduce systematics

Hyper-Kamiokande

Example: $\nu_e/\bar{\nu}_e$ cross-section ratio uncertainty



This measurement is challenging as the $\nu_e/\bar{\nu}_e$ contamination of the beam is very low (few percents)

With **only ND280 upgrade**, could reach a **~7.5%** uncertainty or below with the upgrade ++

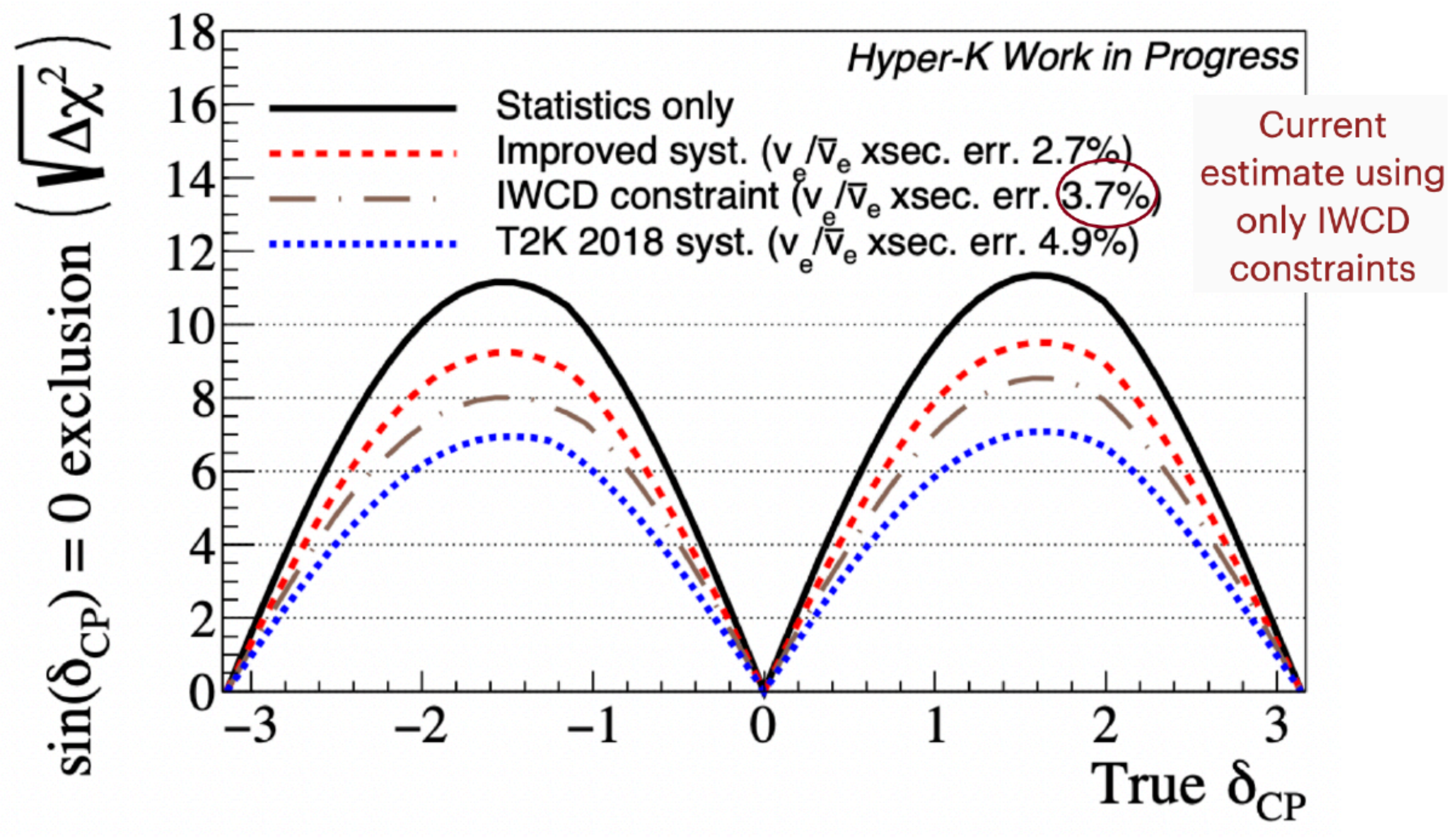
Estimation of ND280 constraint on $\sigma(\nu_e)/\sigma(\bar{\nu}_e)$ with upgrade or upgrade ++ mass, pre-upgrade efficiency and pre-upgrade or 100% purity.

Plan to reduce systematics

Example: $\nu_e/\bar{\nu}_e$ cross-section ratio uncertainty

With **only IWCD**, could reach a **∼3.7%** uncertainty

With **ND280 upgrade (++) and IWCD**, the goal is to go **below 3%** uncertainty after 10 years of HK-LBL

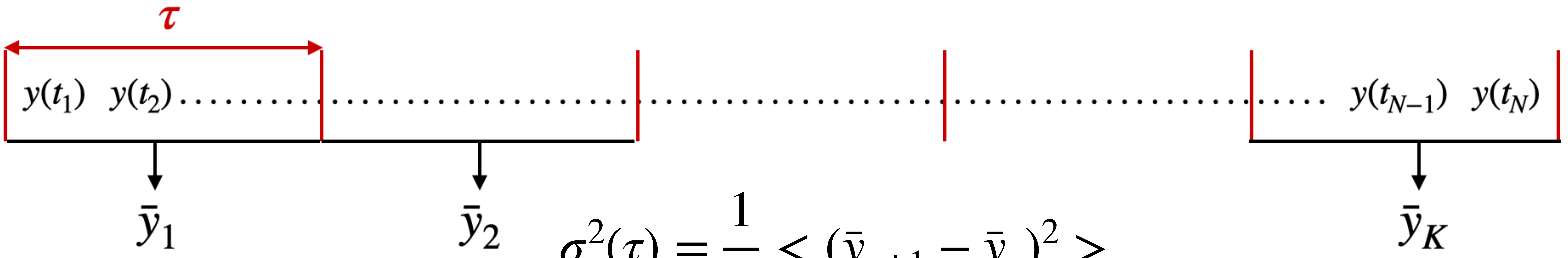


Significance level to exclude the CP-conserving values (0 and $\pm\pi$) of δ_{CP} after 10 years with HK.

* See ref. 4 for more details

Timing distribution
Equipment characterisation

The Allan Standard Deviation is used to characterise the stability of a signal compared to another using **frequency ratio** y. For N measurements, we split the measurement time into K time intervals of a given length τ.



$$\sigma^2(\tau) = \frac{1}{2} < (\bar{y}_{n+1} - \bar{y}_n)^2 >$$

Difference of the mean of y for two consecutive intervals of length τ

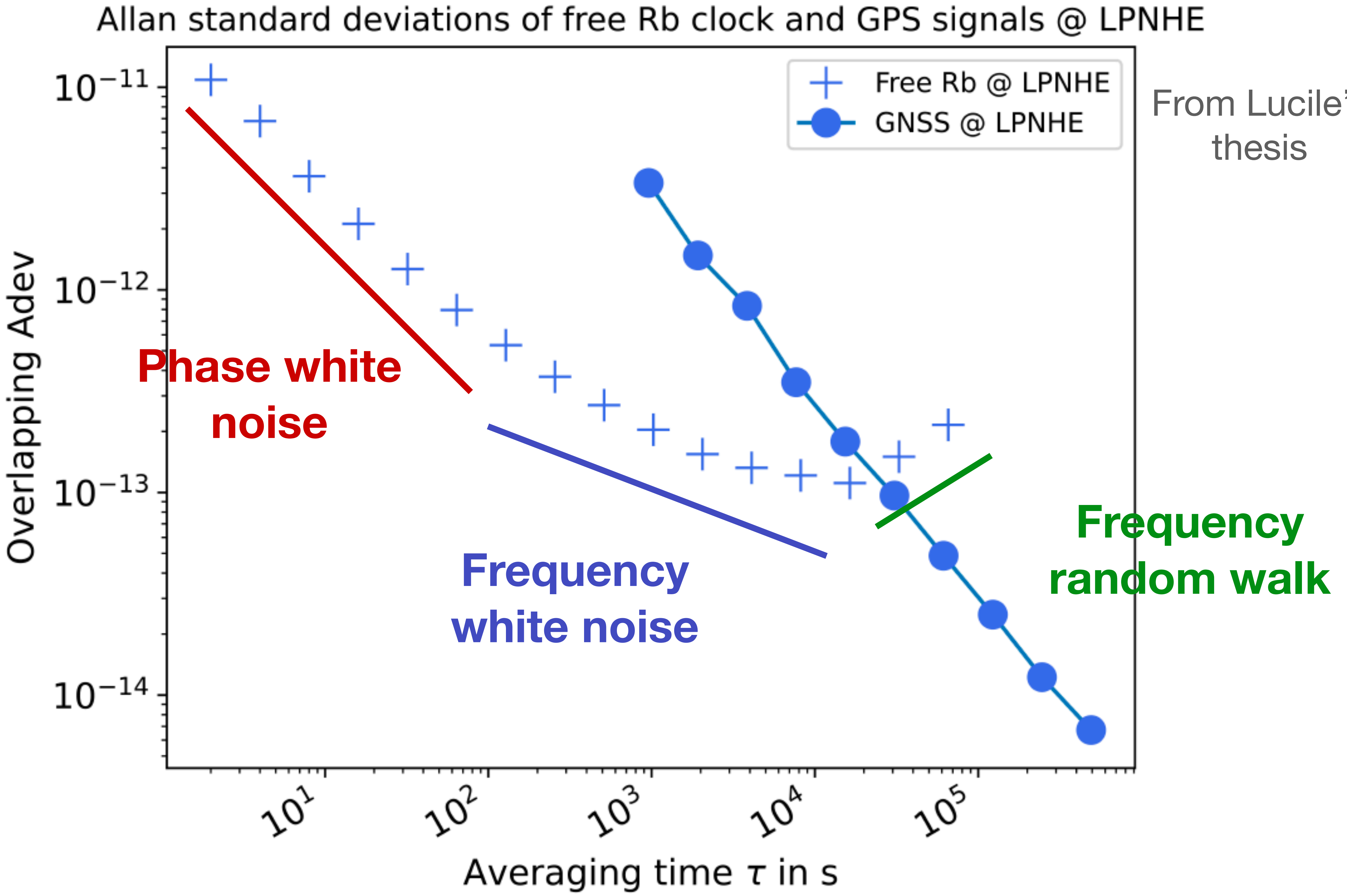
A similar formula can be derived for overlapping intervals and for time differences instead of frequency ratios

Timing distribution

Equipment characterisation

Hyper-Kamiokande

The ASD $\sigma(\tau)$ can then be plotted as function of τ. The dependency in τ depends on the type of noise in the signal.



From Lucile's thesis

The Rubidium signal is more stable than the GNSS at short term but gets worse at long term because of the frequency random walk.

Need to correct the long term instability due to the frequency random walk

From Lucile's thesis

Timing distribution

Rubidium clock signal correction

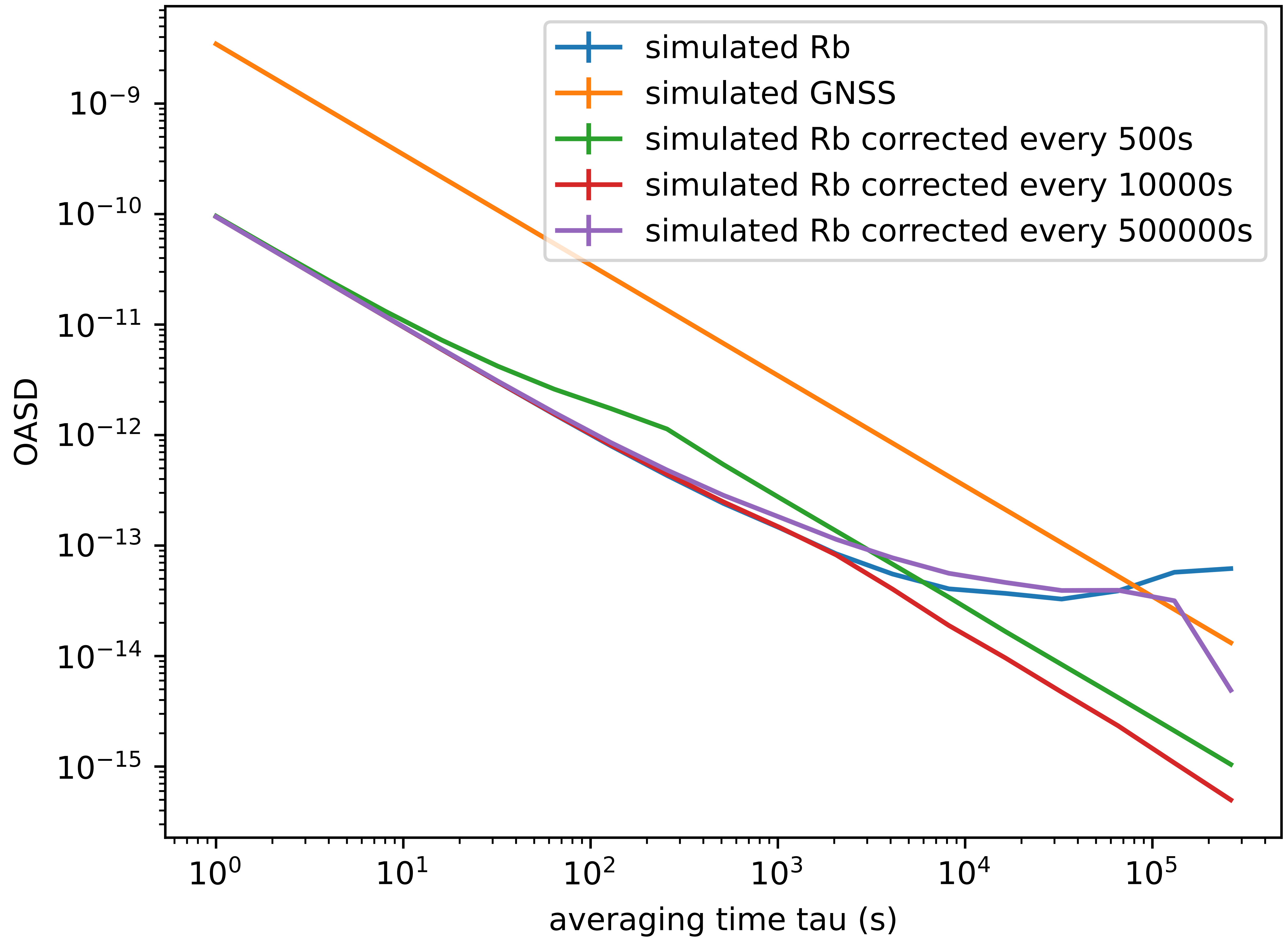
The frequency random walk leads to a polynomial time dependency of the time differences between the Rb and the GNSS PPS:

$$t^i_{Rb} - t^i_{GNSS} = a \times t_i^2 + b \times t_i + c \text{ for } i^{th} \text{ measurement}$$

So one can **regularly** fit $\Delta t_{Rb,GNSS}(t)$ and correct:

$$t^i_{Rb,corr} = t^i_{Rb} - (a \times t_i^2 + b \times t_i + c)$$

Measurement in progress to try the correction with experimental data.



NA61/SHINE

2022 replica target data calibration

Done:

- BPDs relative alignment
- Time stamp calibration

In progress:

- TPC position calibration
- Drift velocity calibration
- MC simulation

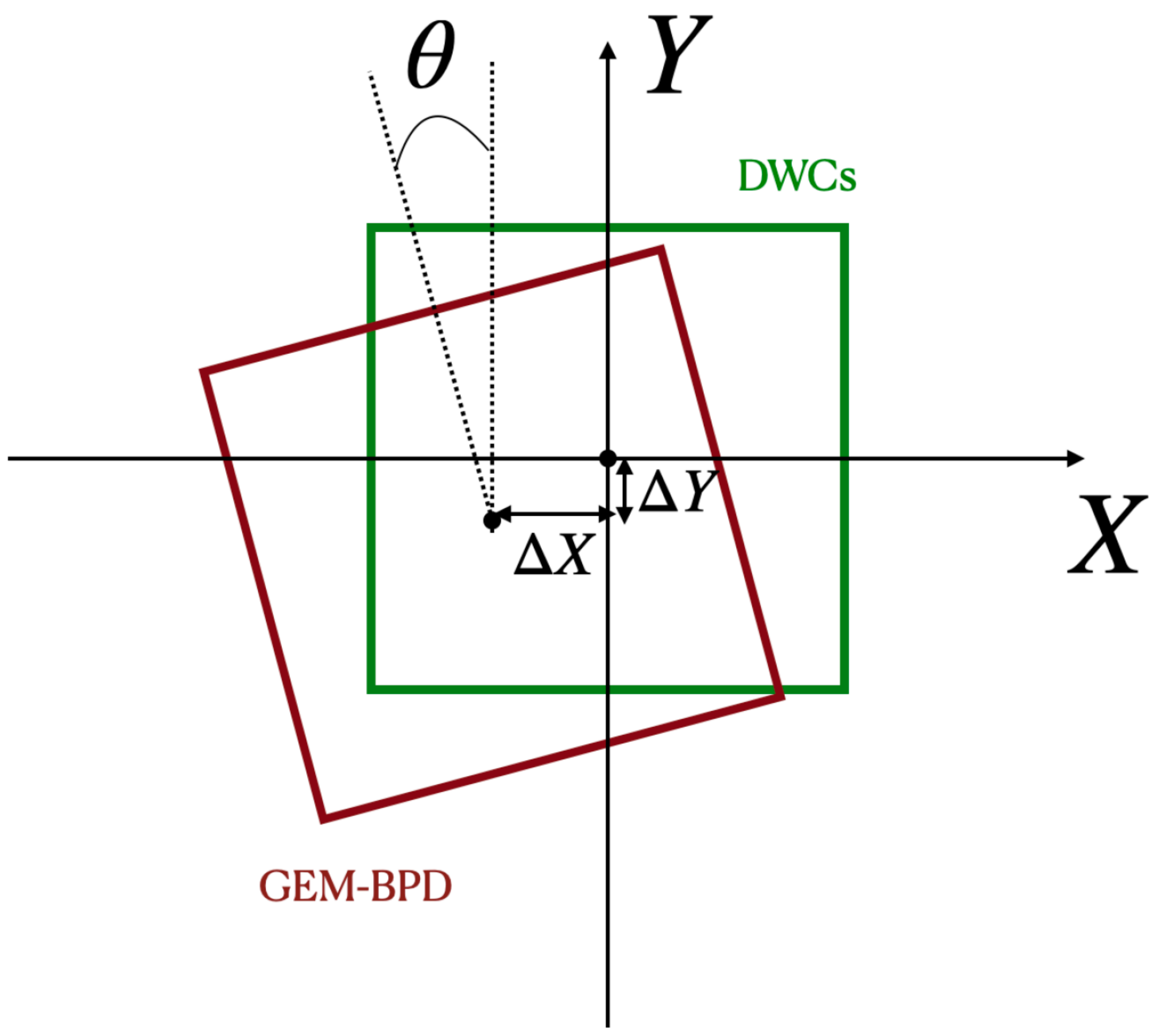
To be done:

- TPC alignment with other detectors
- Gain (or dEdx) calibration in TPCs
- TOF calibration
- Data analysis

NA61/SHINE

BPD alignment: done

Beam Position Detectors: three detectors along beam line that allow to reconstruct the beam particle tracks (essential to match with the interaction vertex in the target).
The three detectors have to be aligned!!



A special run was taken with two additional detectors (Delay Wire Chambers) along the beam line.
Idea: if we align each BPD with the two DWCs, then the BPDs will be aligned together.

3 degrees of freedom for each detector i:

- Shift in X: ΔX_i
- Shift in Y: ΔY_i
- Rotation around beam direction: θ_i

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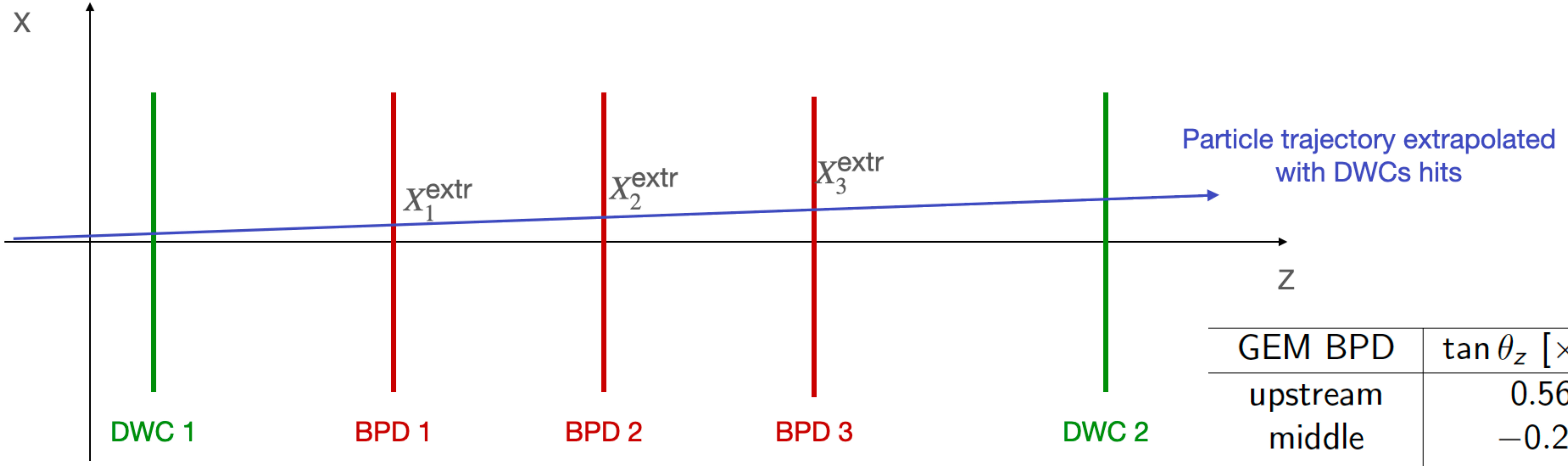
BPD alignment: done

The "misalignment parameters" are extracted by comparing the extrapolated and measured beam hits position at each BPD



GEM BPD	$\tan\theta_z$ $[\times 10^3]$	ΔX $[\mu m]$	ΔY $[\mu m]$
upstream	0.56	−3.7	5.5
middle	−0.22	1.2	−2.9
downstream	0.43	−3.0	4.8

Residual "misalignment" between each BPD and the two others after correction

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Drift velocity calibration: ongoing

The y position of clusters in the TPCs is extracted from the measured drift time:

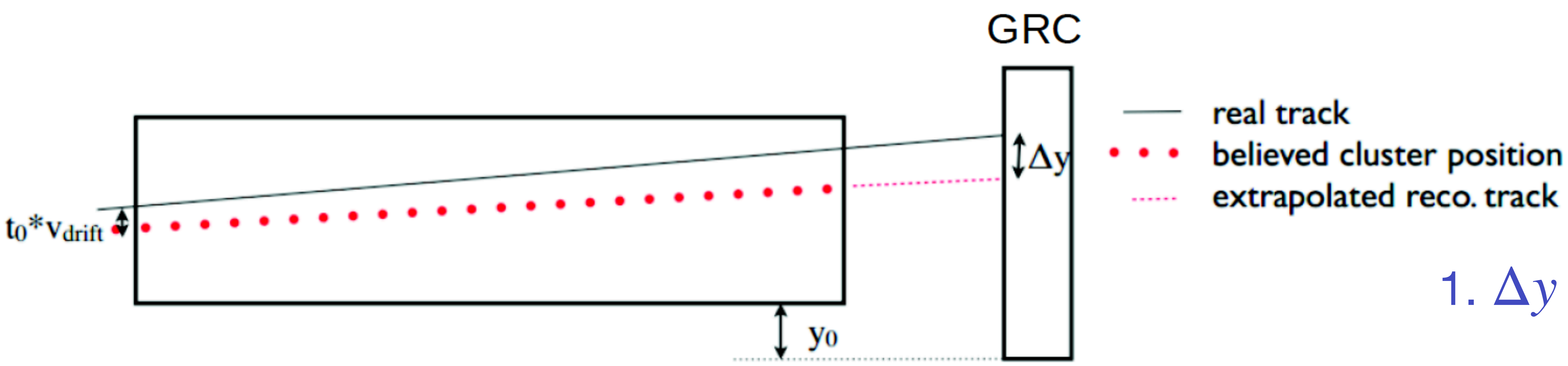
Quantities to calibrate

$$y = v_{drift} \times (t_{drift} - t_0) + y_0$$

Position offset (TPC position)

Drift velocity

Time offset (cable length)



(Segmented in y)

1. Δy against y gives v_{drift}^{true}

2. Δy against v_{drift} gives t_0^{true}

$$\Delta y = (v_{drift}/v_{drift}^{true} - 1) \times y + (y_0 - v_{drift} \times (t_0 - t_0^{true}) - v_{drift}/v_{drift}^{true} \times y_0^{true})$$

3. Residual Δy gives y_0^{true}

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2022 replica target data analysis

Once data is calibrated, move on to analysis. Once again, many steps needed:

- Track selection (beam+TPC)
- Particle Identification: use dEdx in TPC
- Corrections using MC
- Uncertainties estimation
- Etc.

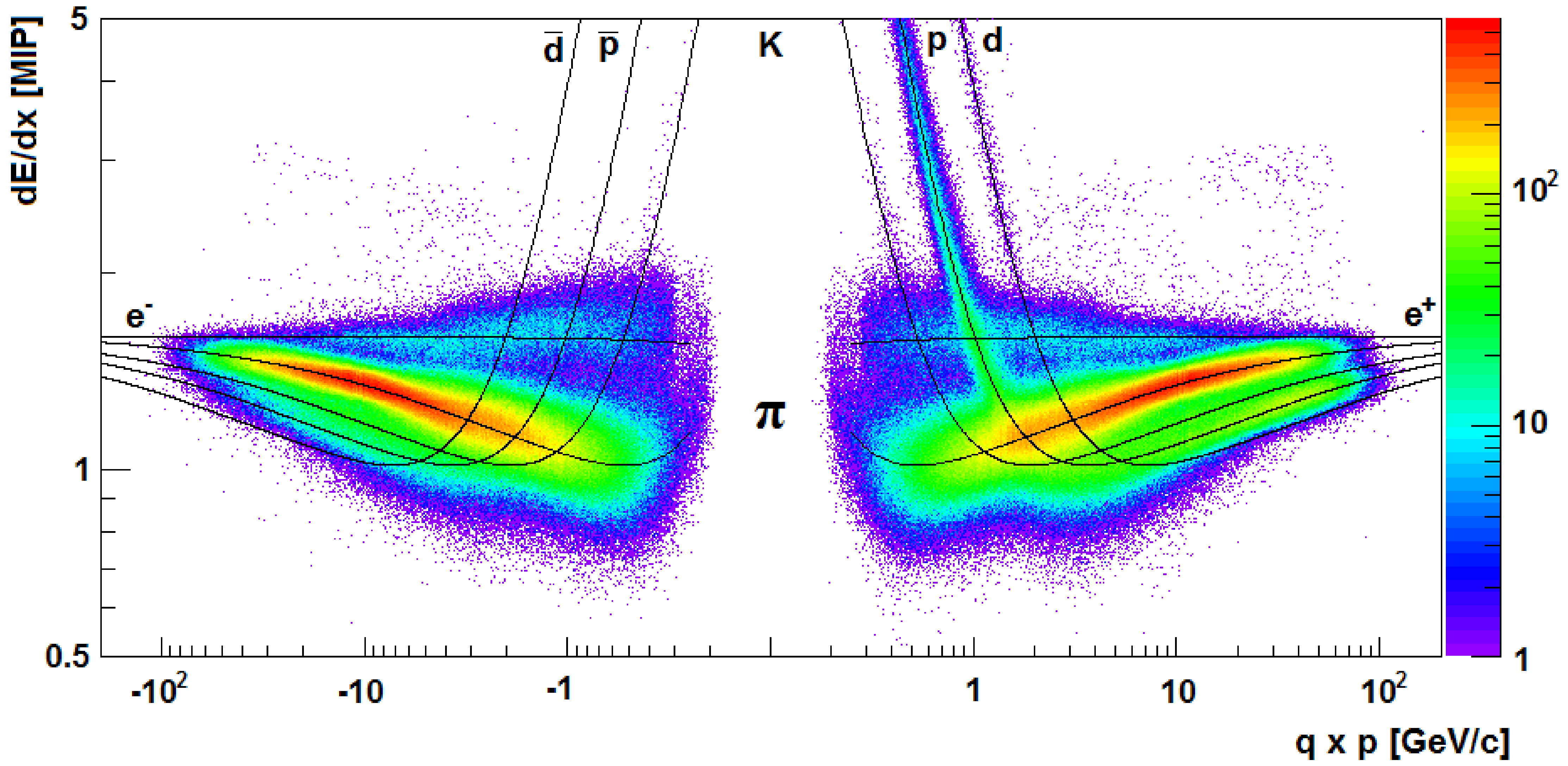

Illustration of the PID technique using dEdx