

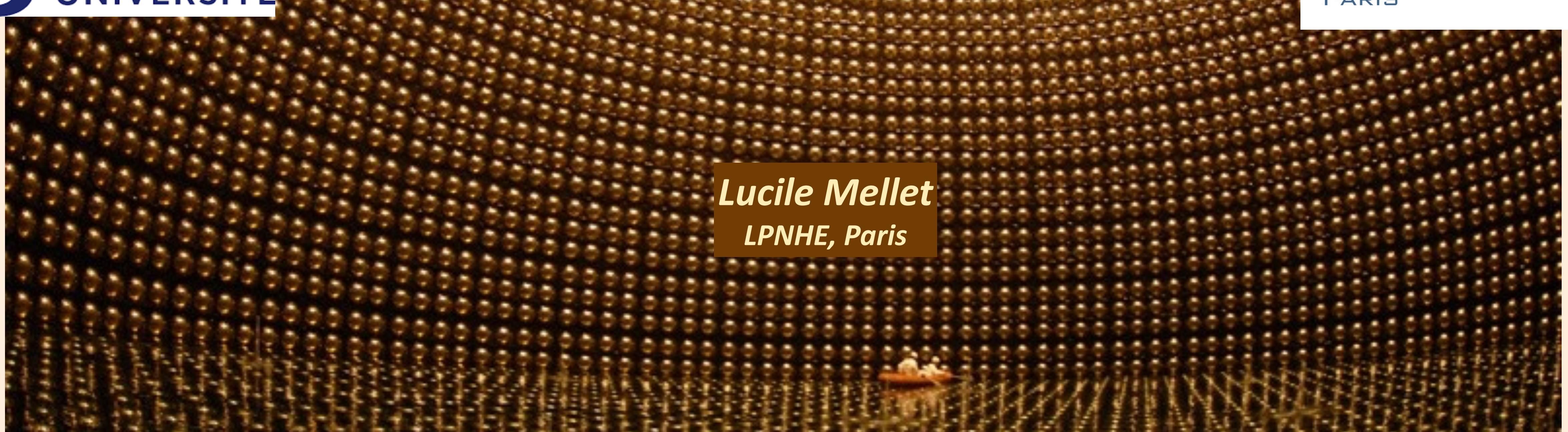
Analysis and R&D preparation for Hyper-Kamiokande experiment towards precise measurement of neutrino oscillation parameters



Advisors : Mathieu Guigue and Boris Popov



*Lucile Mellet
LPNHE, Paris*



Analysis and R&D preparation for Hyper-Kamiokande experiment towards precise measurement of neutrino oscillation parameters

Overview:

- ▶ Remaining open questions on neutrinos
- ▶ The T2K experiment
- ▶ T2K analysis
- ▶ Hyper-Kamiokande
- ▶ Clock synchronization
- ▶ Perspectives
- ▶ Conclusion

Neutrino Physics overview & open questions

- Flavour states $\nu_e \nu_\mu \nu_\tau$
- Mass states $\nu_1 \nu_2 \nu_3$

$$|v_\alpha\rangle = \sum_i U_{\alpha i}^* |v_i\rangle$$

Oscillation /non-oscillation probability
 —> Observable = number of neutrinos
 of a certain flavour at a specific energy

$$U = \begin{pmatrix} c_{12}c_{13} & s_{12}s_{13} & s_{13}e^{-i\delta_{CP}} \\ -s_{12}c_{23} - c_{12}s_{13}s_{23}e^{i\delta_{CP}} & c_{12}c_{23} - s_{12}s_{13}s_{23}e^{i\delta_{CP}} & c_{13}s_{23} \\ s_{12}s_{23} - c_{12}s_{13}c_{23}e^{i\delta_{CP}} & -c_{12}s_{23} - s_{12}s_{13}c_{23}e^{i\delta_{CP}} & c_{13}c_{23} \end{pmatrix} P$$

$$P(v_\mu \rightarrow v_e) = \sin^2\theta_{32} \sin^2 2\theta_{31} \sin^2 \left(\frac{\Delta m_{31}^2 L}{4E} \right)$$

(pour $\Delta m_{12}^2 \ll \Delta m_{31}^2 \approx \Delta m_{32}^2$ et $\frac{\Delta m_{12}^2 L}{E} \ll 1$)

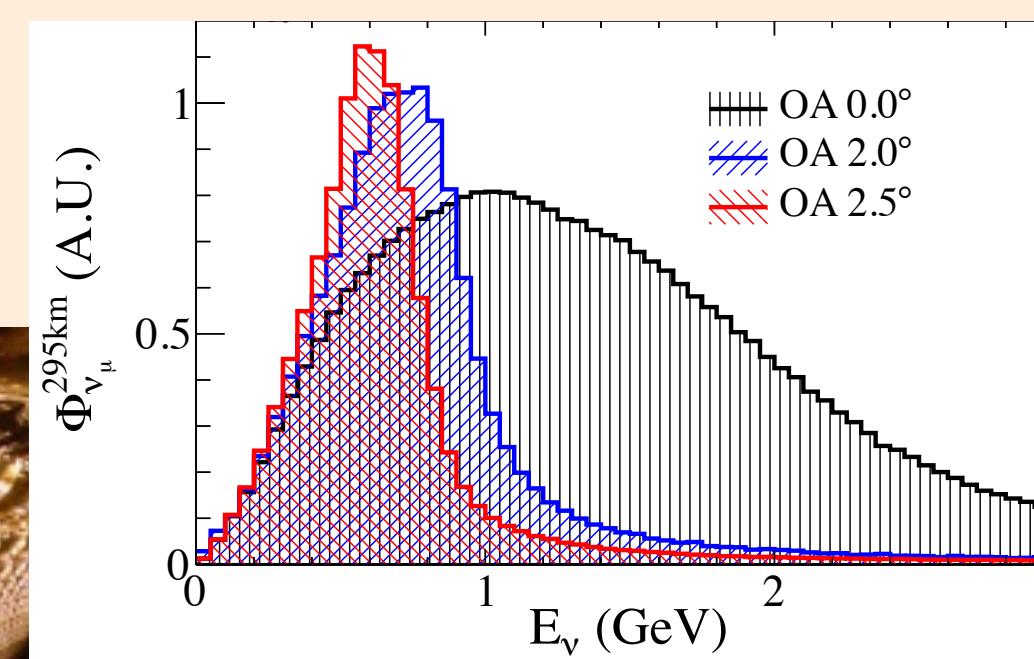
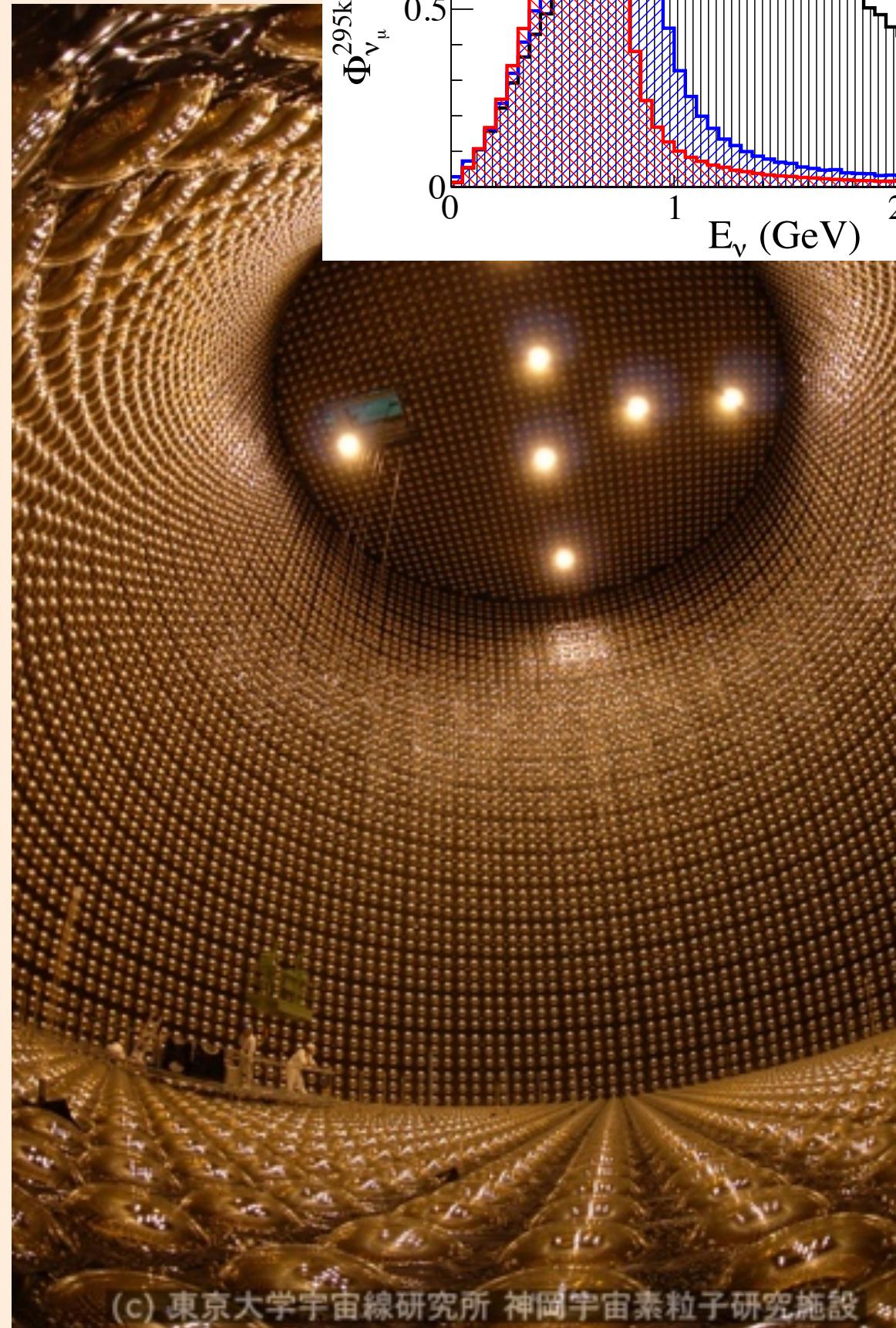
+ Asymmetry $\nu/\bar{\nu}$ (matter effects)

$$P(\nu_\mu \rightarrow \nu_e) - P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) \propto \sin(\delta_{CP})$$

Open questions :

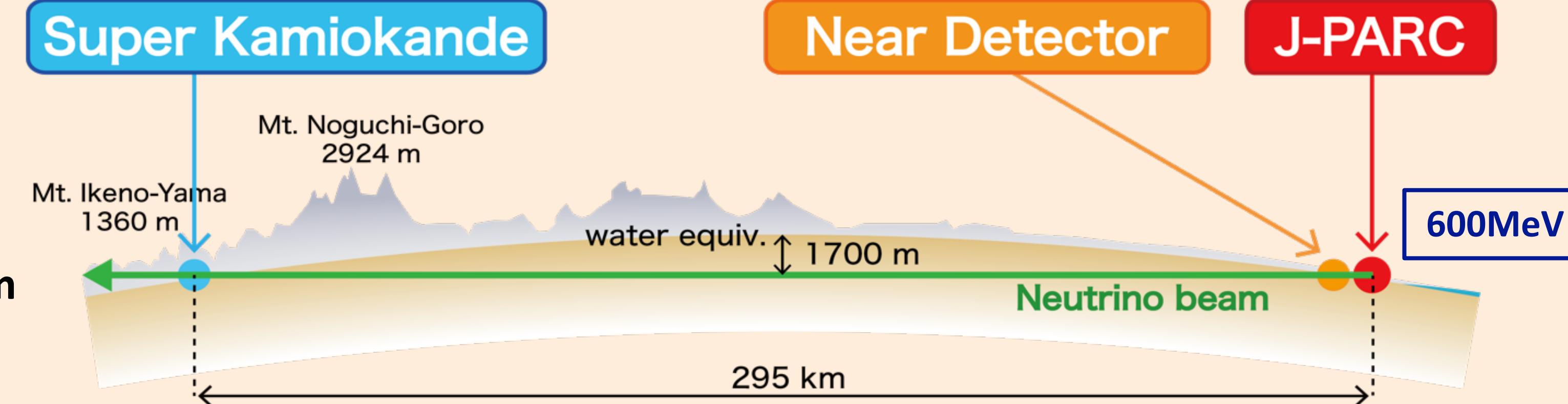
- Dirac/Majorana
- Absolute masses
- ~ Mass ordering
- $\sin(\theta_{13})$ et Δm_{12}^2
- ✓ $\sin(\theta_{23})$ et Δm_{23}^2
- ✓ δ_{CP}

ν_μ flux at 295km in arbitrary units (from K. Abe et al., "T2K neutrino flux prediction," Phys. Rev. D, 2013)

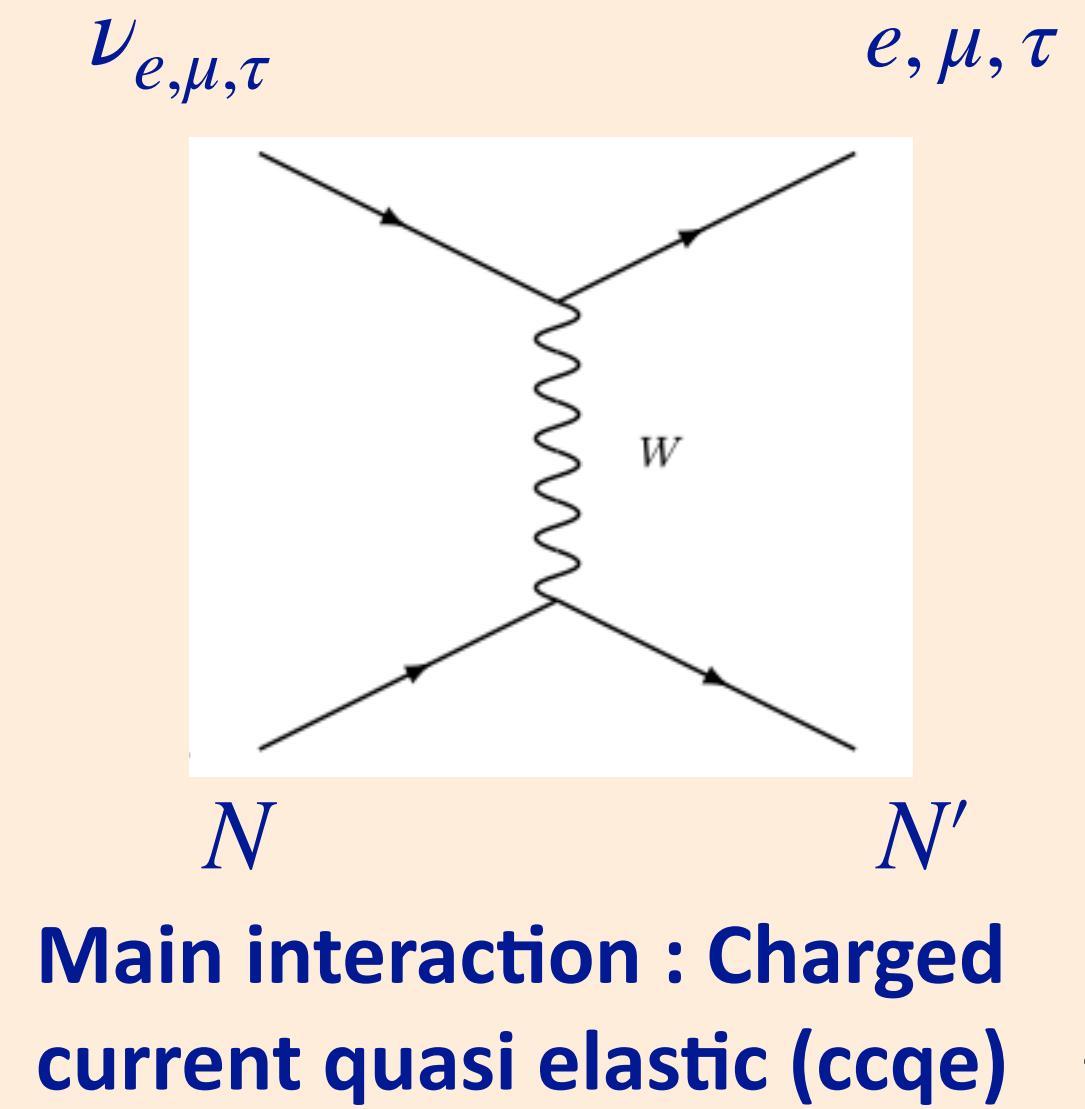


Tokai to Kamioka (T2K)

*Super-Kamiokande (1996), Mozumi mine (1000m), Kamioka, Japan
Tokai to Kamioka (2010)*

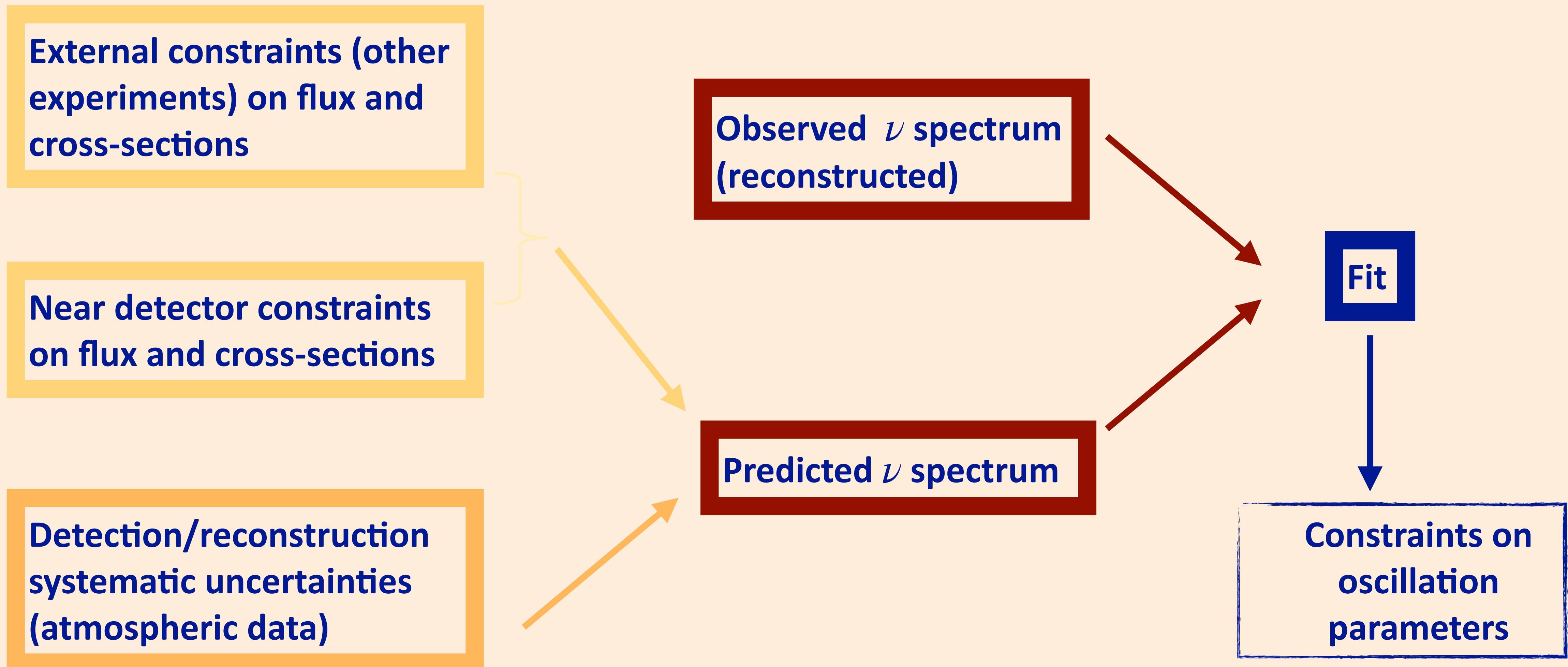


- Beam, two modes ν_μ or $\bar{\nu}_\mu$
- Cherenkov light detection
- 50 kTons of ultra-pure water
- 11000 photo-multiplier tubes (PMT)
- What we measure: flavor, lepton energy, lepton/ ν angle



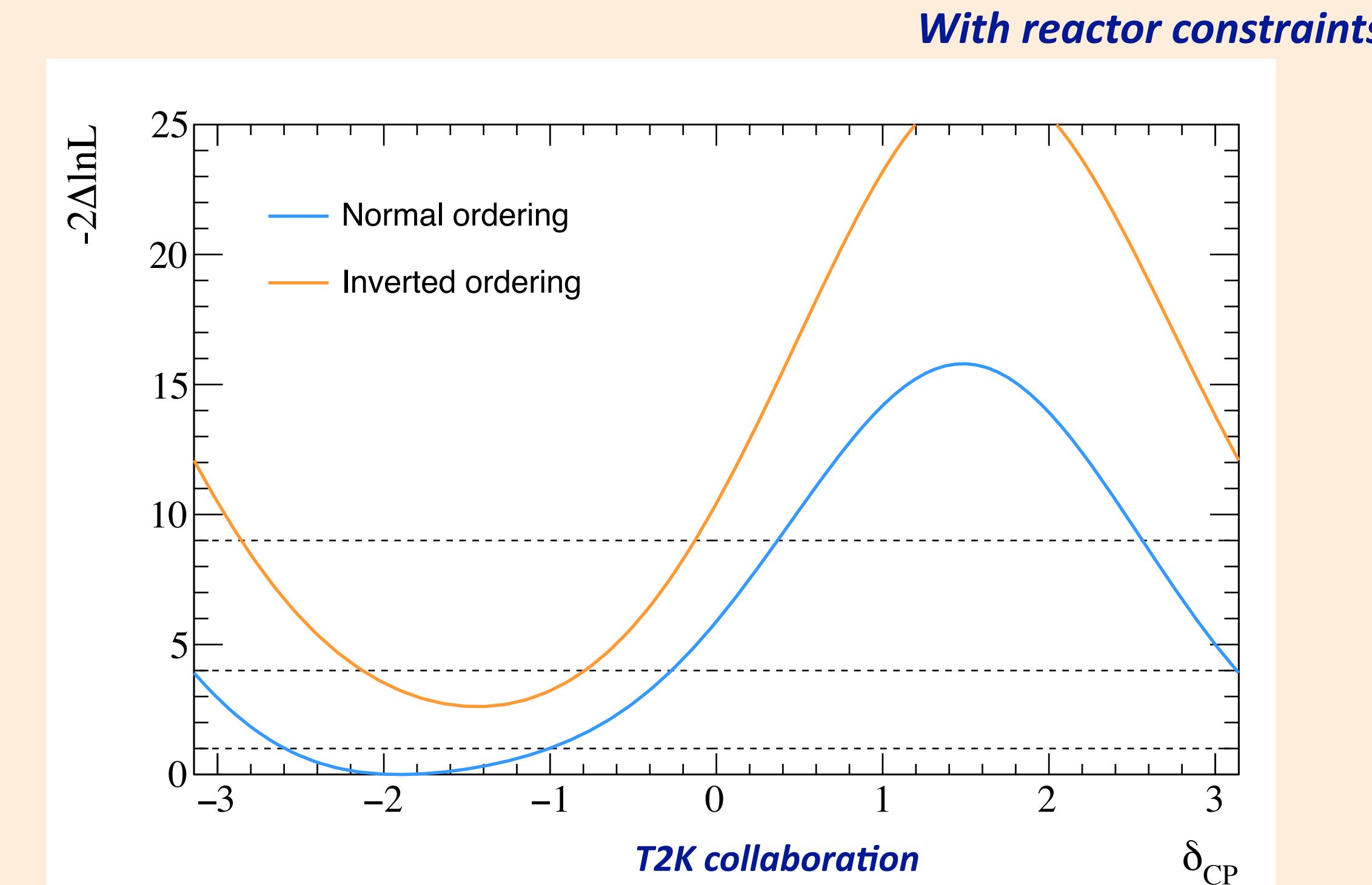
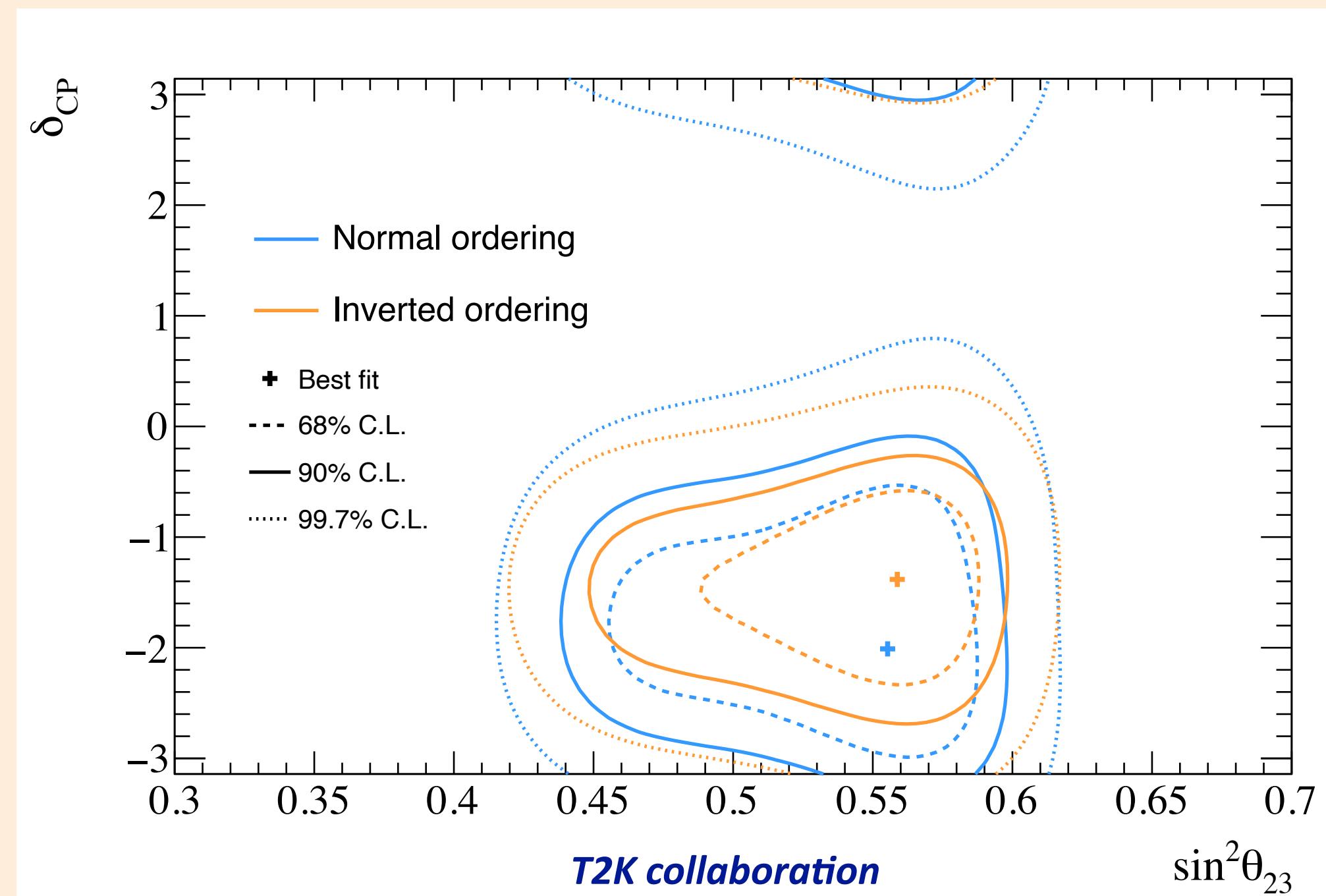
Analysis method in T2K

Global strategy



Tokaiï to Kamioka (T2K)

2020 analysis sensitivity
→ goal : better constraints on those parameters



T2K analysis : example of contribution to systematic effects studies

Short term

Improve the experiment sensitivity -> taking systematics into account more precisely

Focus on Eb (nucleon binding energy for CCQE interactions) : uncertainty results in a shift of outgoing lepton momentum

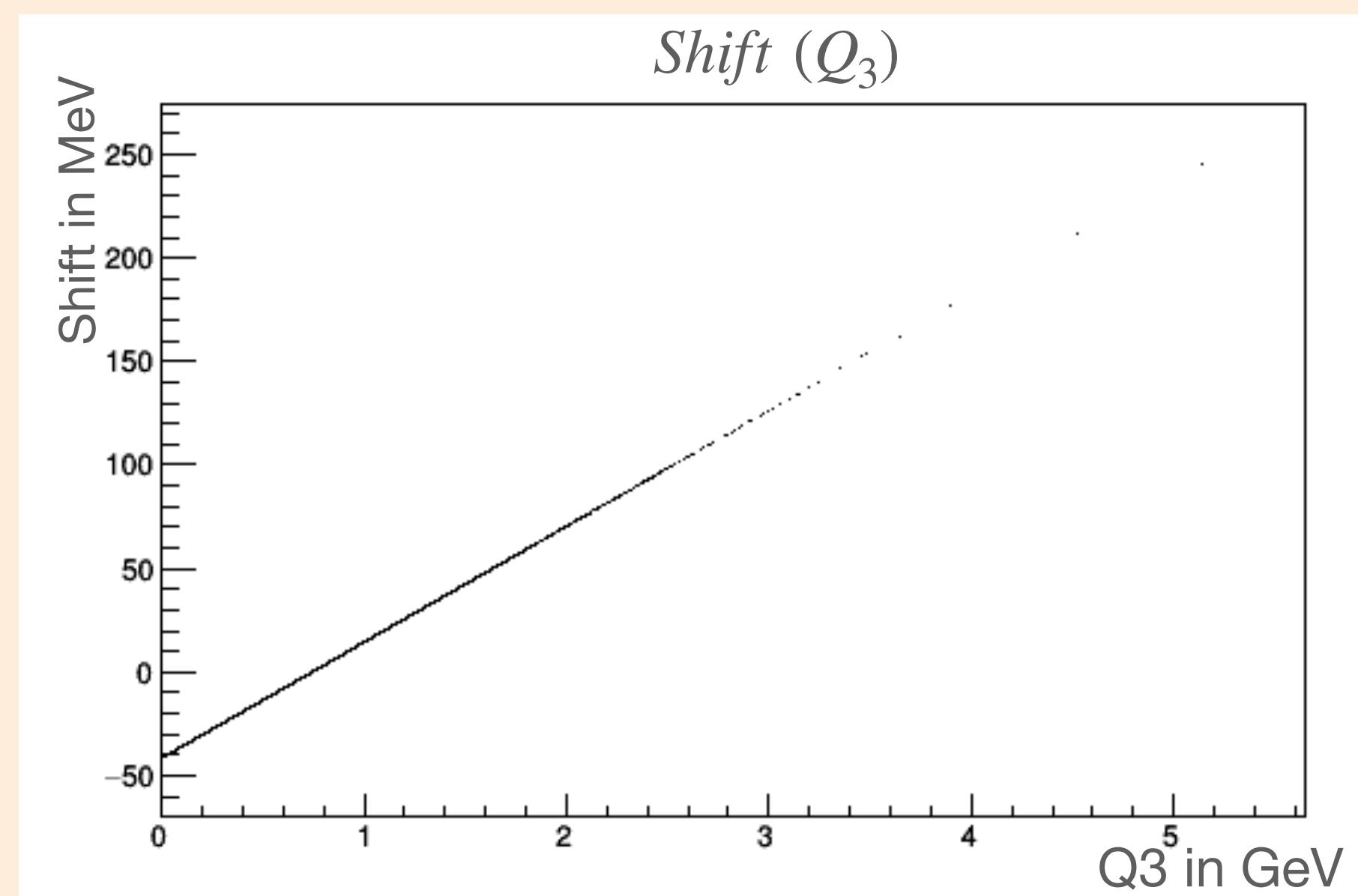
$$Q_3 = \sqrt{p_\nu^2 + p_l^2 + p_\nu p_l \cos\theta}$$

$$\text{Shift } (Q_3) = m * Q_3 + c$$

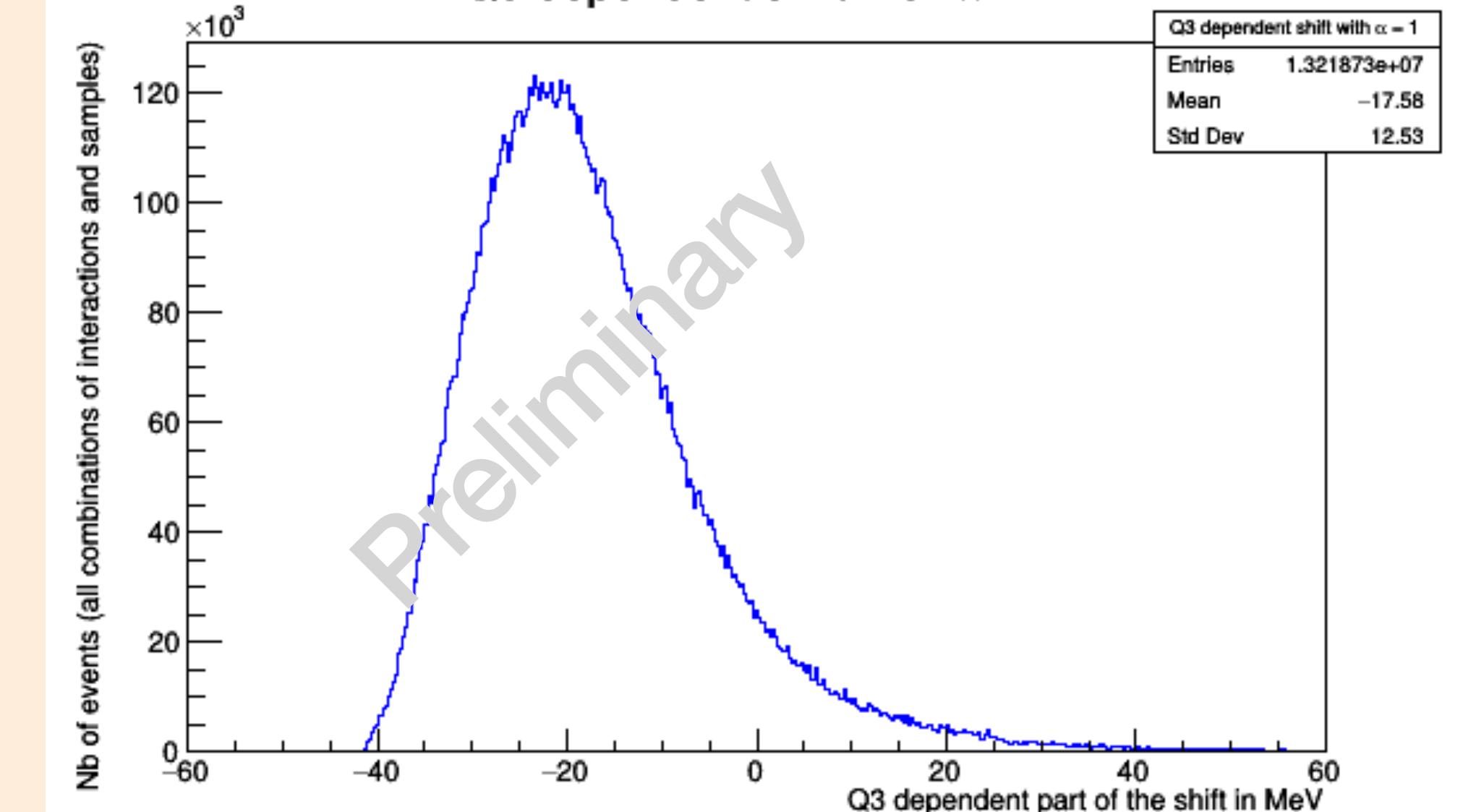
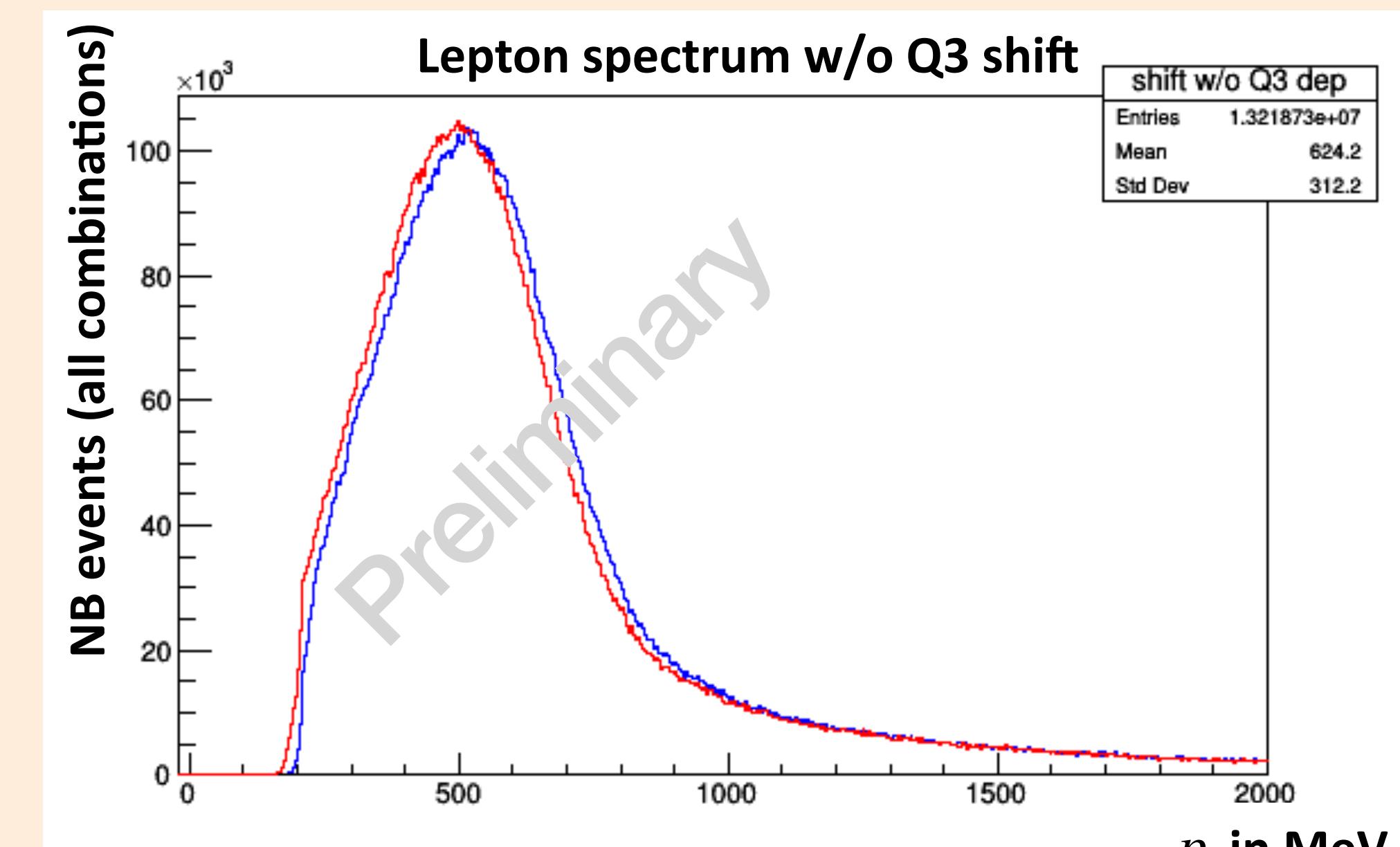
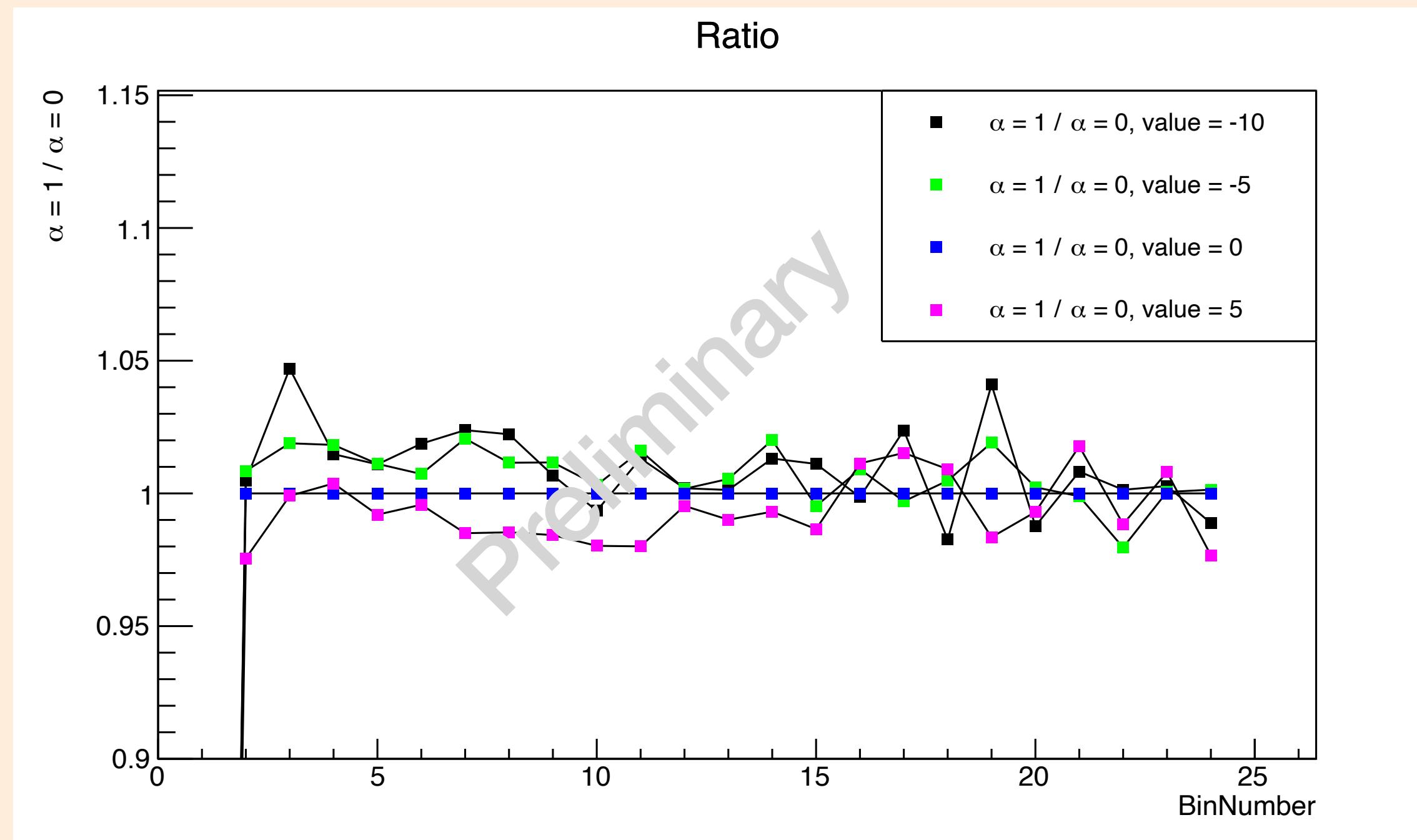
m and c constant, estimated by a fit



- No hadronic state detection after interaction (at SK)
- Used nuclear model (spectral functions): no outgoing lepton kinematics dependance
- Other models (RMF: Relativistic Mean-Field Model): Q3 (3-momentum transfer) dependance predicted
—> must be added



T2K analysis : example of contribution to systematic effects studies



Work in progress: Implementation of a directly Q3 dependent Eb uncertainty instead of a additional momentum shift

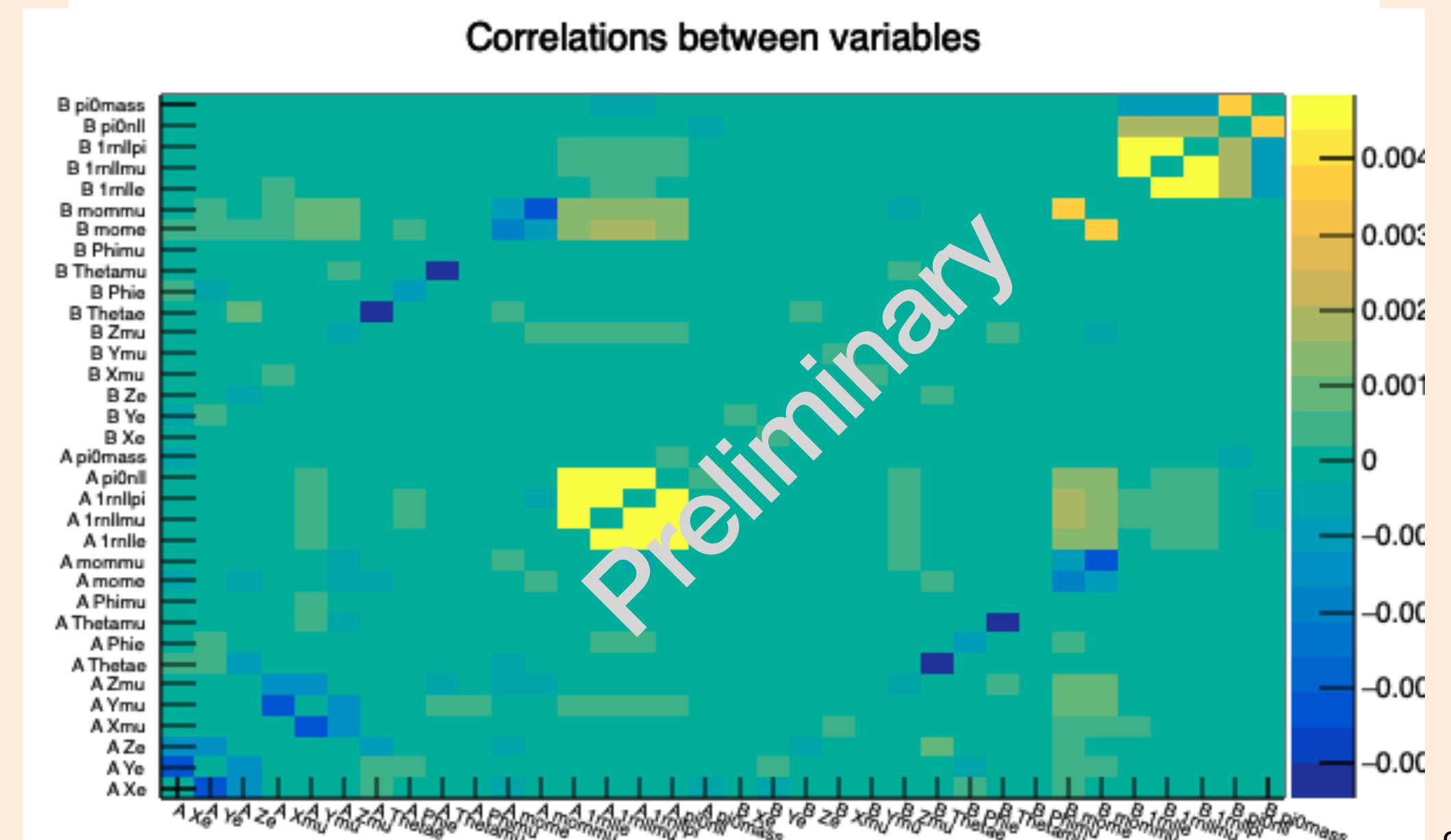
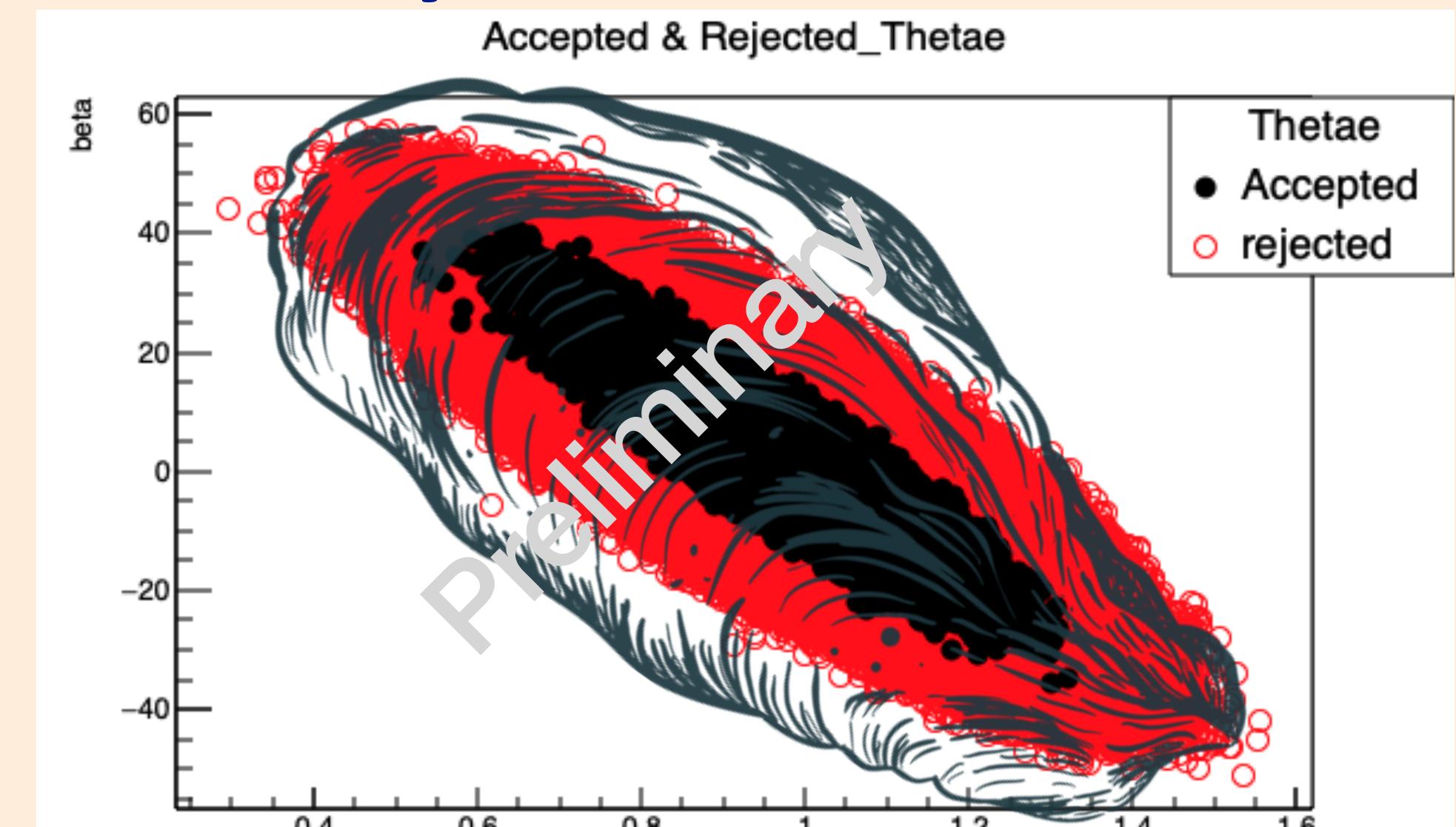
T2K analysis : another example of contribution to systematic effects studies

Long term

- ▶ Attempt to build a unified method for detection systematic uncertainty estimation, common to all parameters and both experiments : SK (atmospheric v) and T2K (beam v) —> framework of a joint analysis
- ▶ Metropolis Hastings Markov Chain Monte Carlo
- ▶ Vary the underlying variables involved in cuts (= in assigning an event to an analysis sample)
- ▶ 2 parameters per variable : additive and multiplicative —> smearing and shifting of distributions
- ▶ Likelihood (cuts/bins/samples)
$$proba = \min(1, e^{(LL_{tot} - LL[j-1])}) \rightarrow \text{Metropolis-Hastings}$$

if ($p \leq acc$) —> Accept. —> Random
- ▶ Random picking in prior distributions (Cholesky decomposition —> Oyster correlations)

Not validated and less « detailed » method than the current one, attempt of a proof of feasibility



T2K analysis : another example of contribution to systematic effects studies

Limitations :

- Run time
- convergence
- acceptance rate
- independence : **Markov chain specificity**

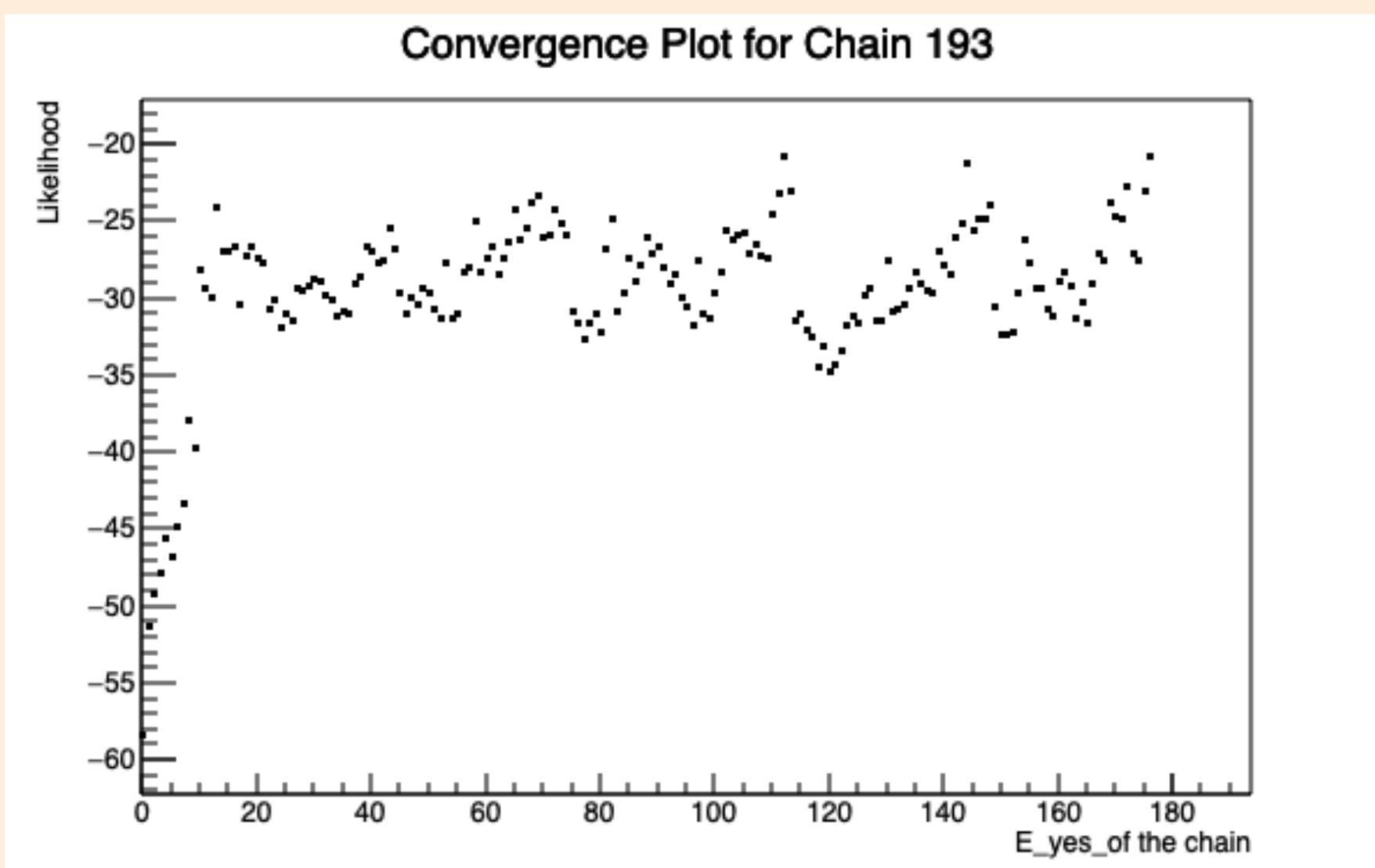
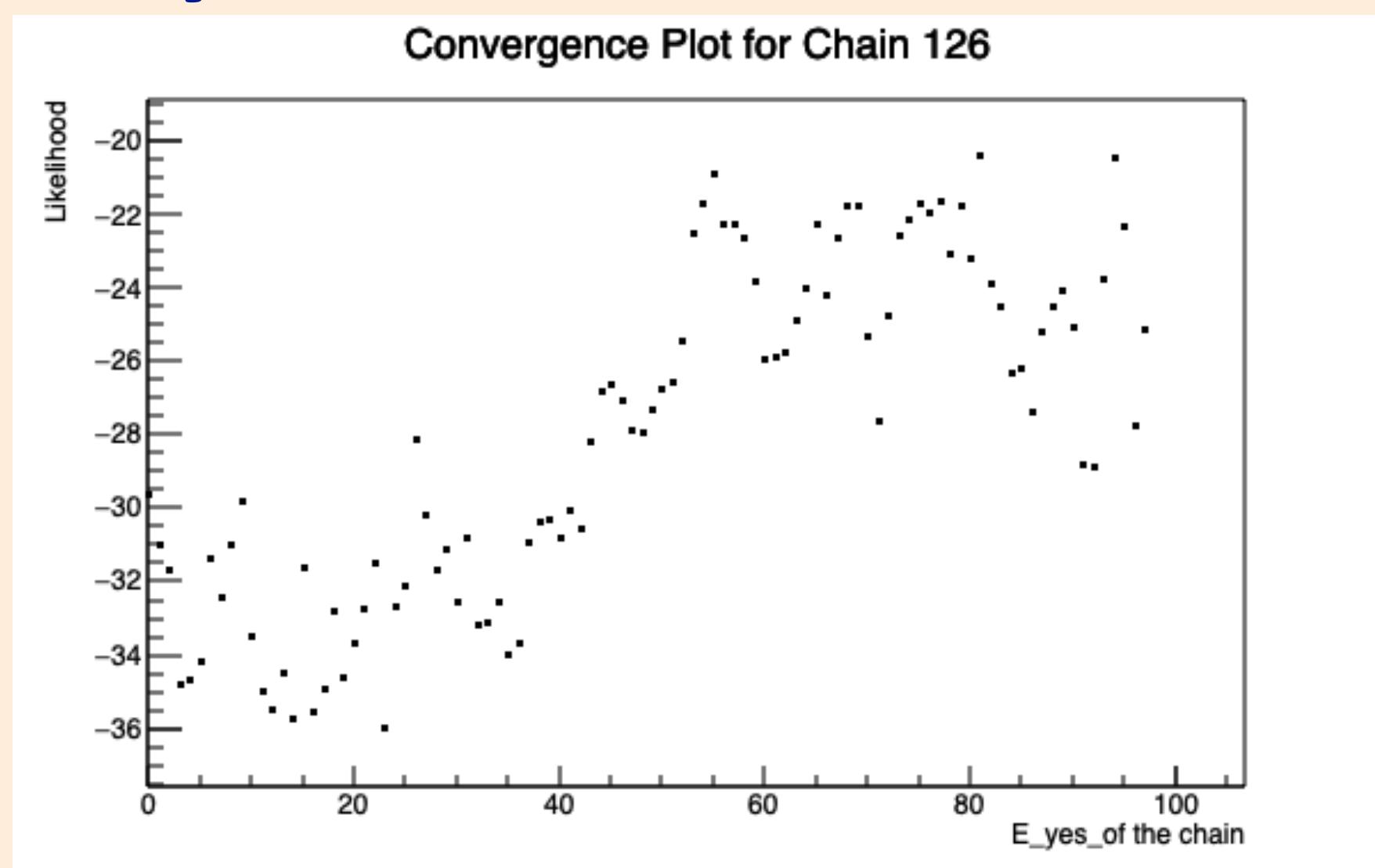
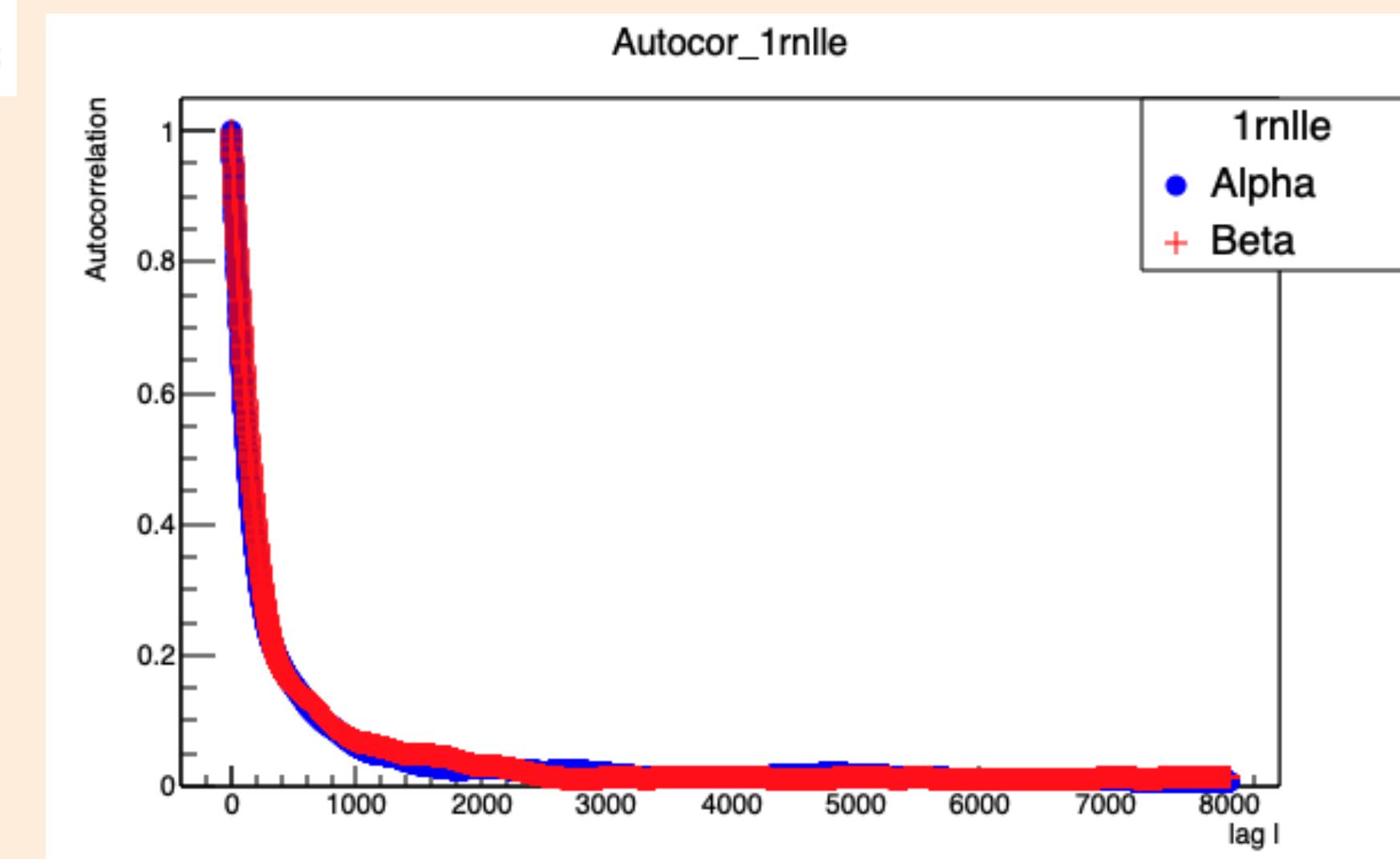
$$\rho_{lag} = \frac{\sum_i^{N-lag} (\theta_i - \bar{\theta})(\theta_{i+lag} - \bar{\theta})}{\sum_i^N (\theta_i - \bar{\theta})^2}$$

$$N_{\text{eff}} = \frac{N}{\sum_{t=-\infty}^{\infty} \rho_t} = \frac{N}{1 + 2 \sum_{t=1}^{\infty} \rho_t}$$

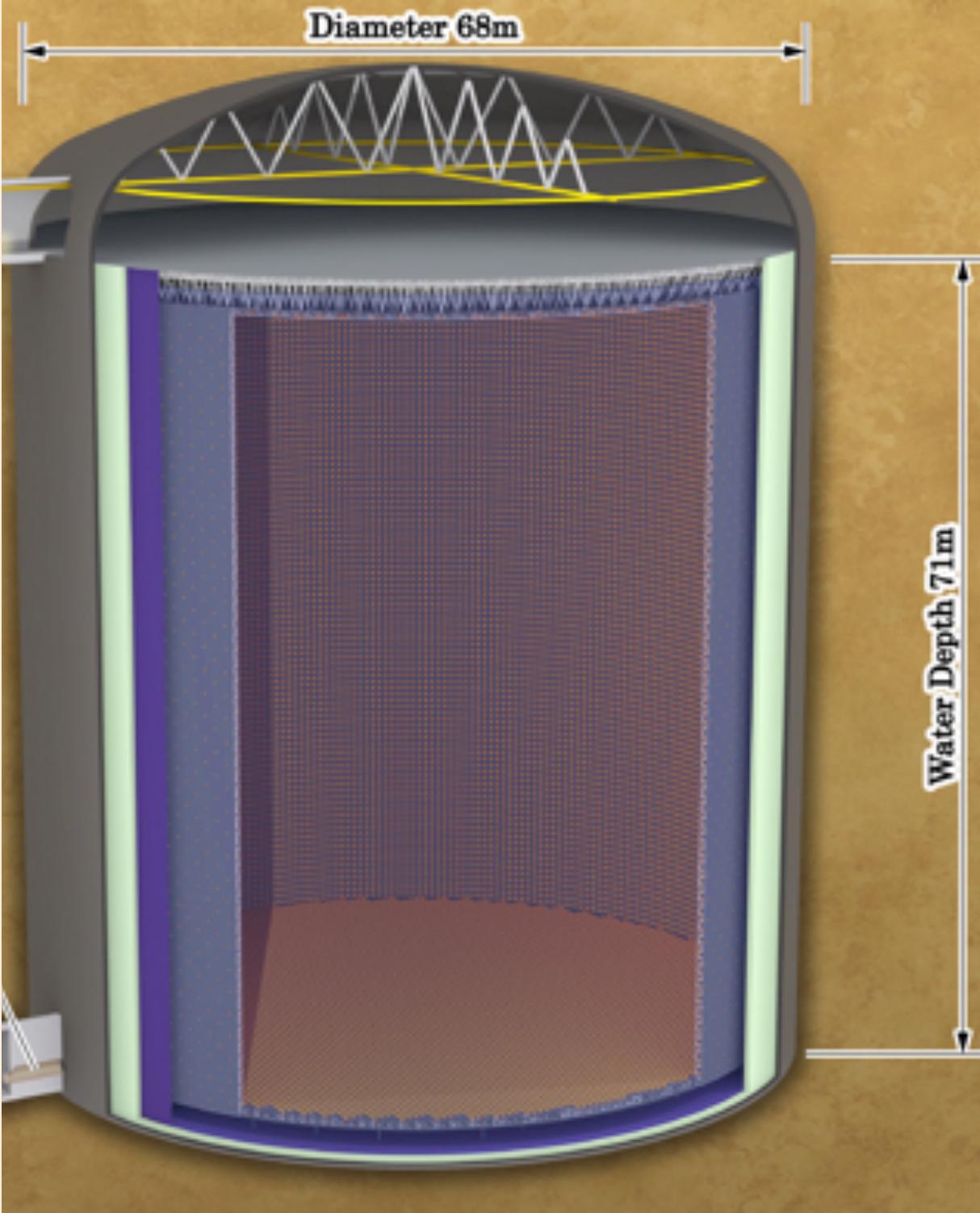
200 * 200 000 steps

Average acceptance rate = 0.106%

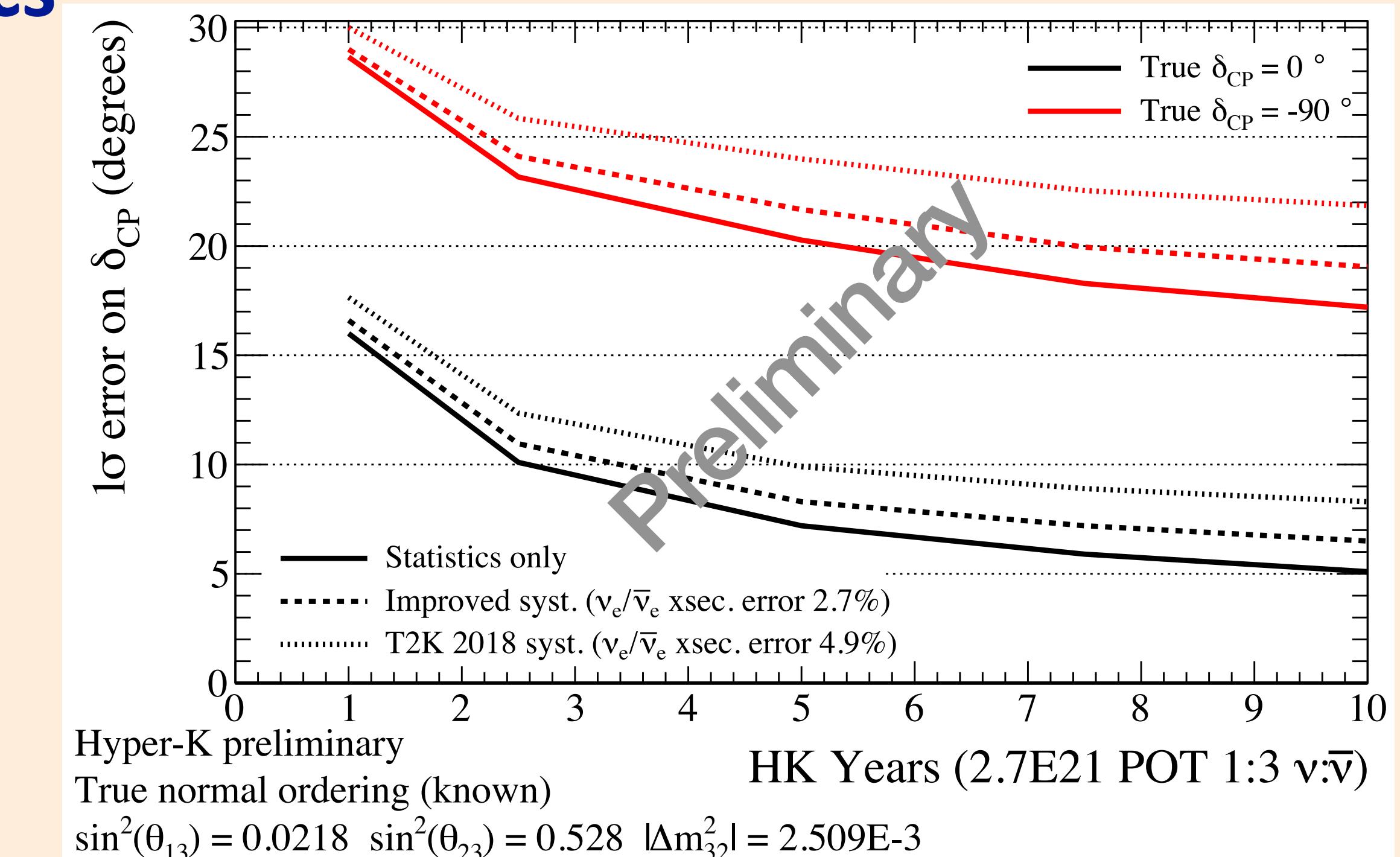
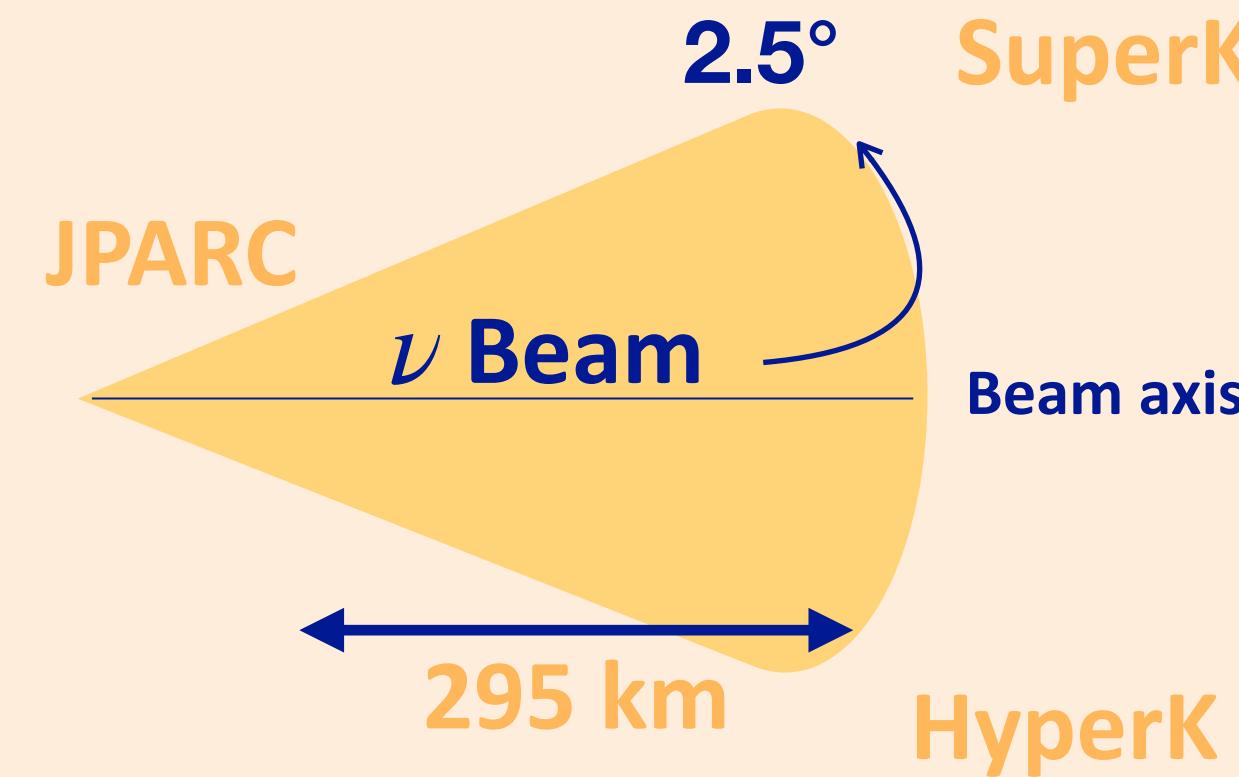
**Runtime on CCin2p3 for 1 chain:
26h24mn**



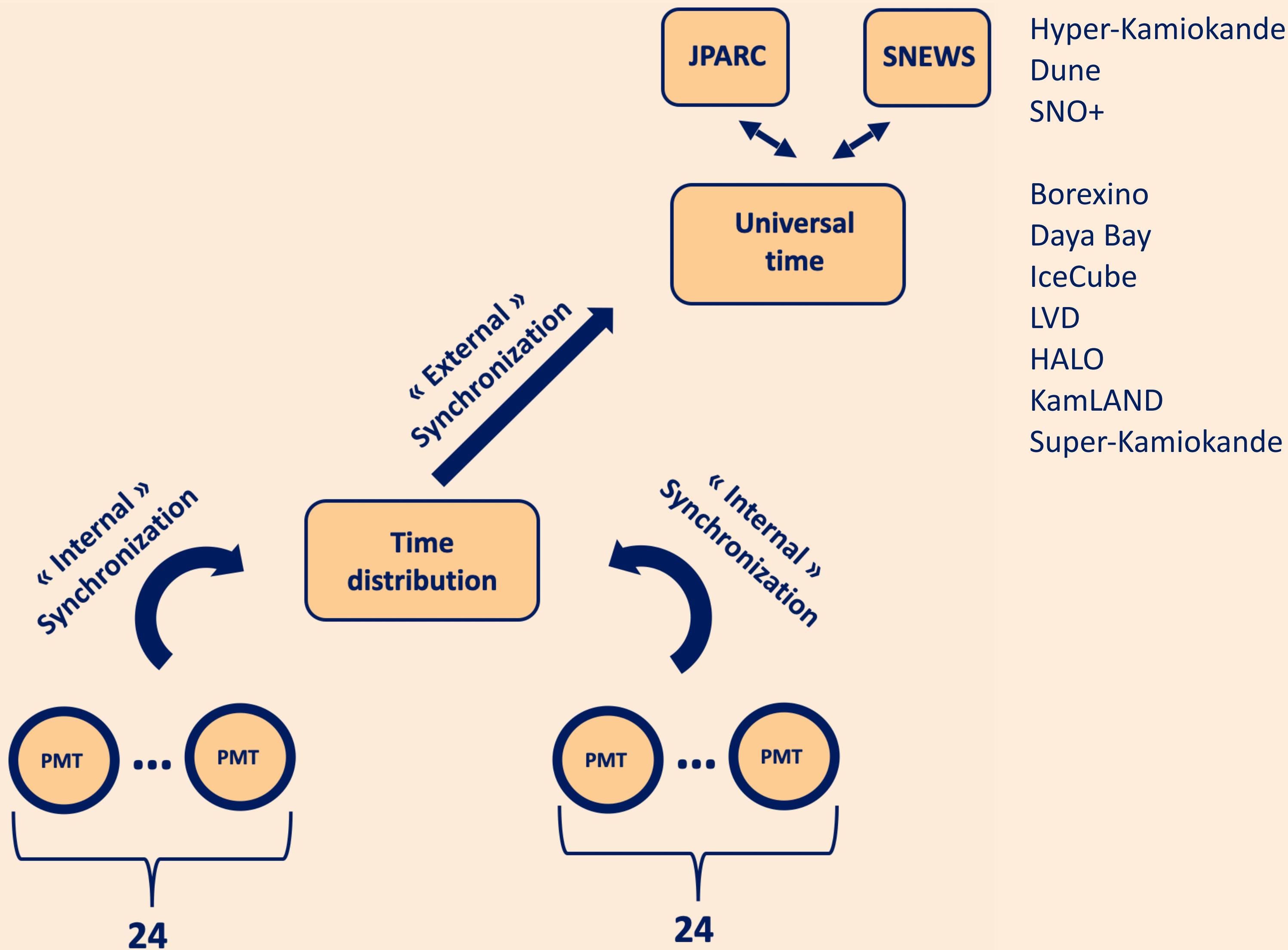
Hyper-Kamiokande experiment



- ▶ Data taking planned for 2027
- ▶ Tank 5x larger , fiducial volume x10
- ▶ New PMTs, time synchronisation system
- ▶ Increased statistics



Time synchronization system



R&D

Needs for time precision:

- Reconstruction: stability
- ‘Time stamp’ with beam : about 100ns
- bunchs window : 12 μ s
- Supernovae : 30s signal, time stamp for triangulation

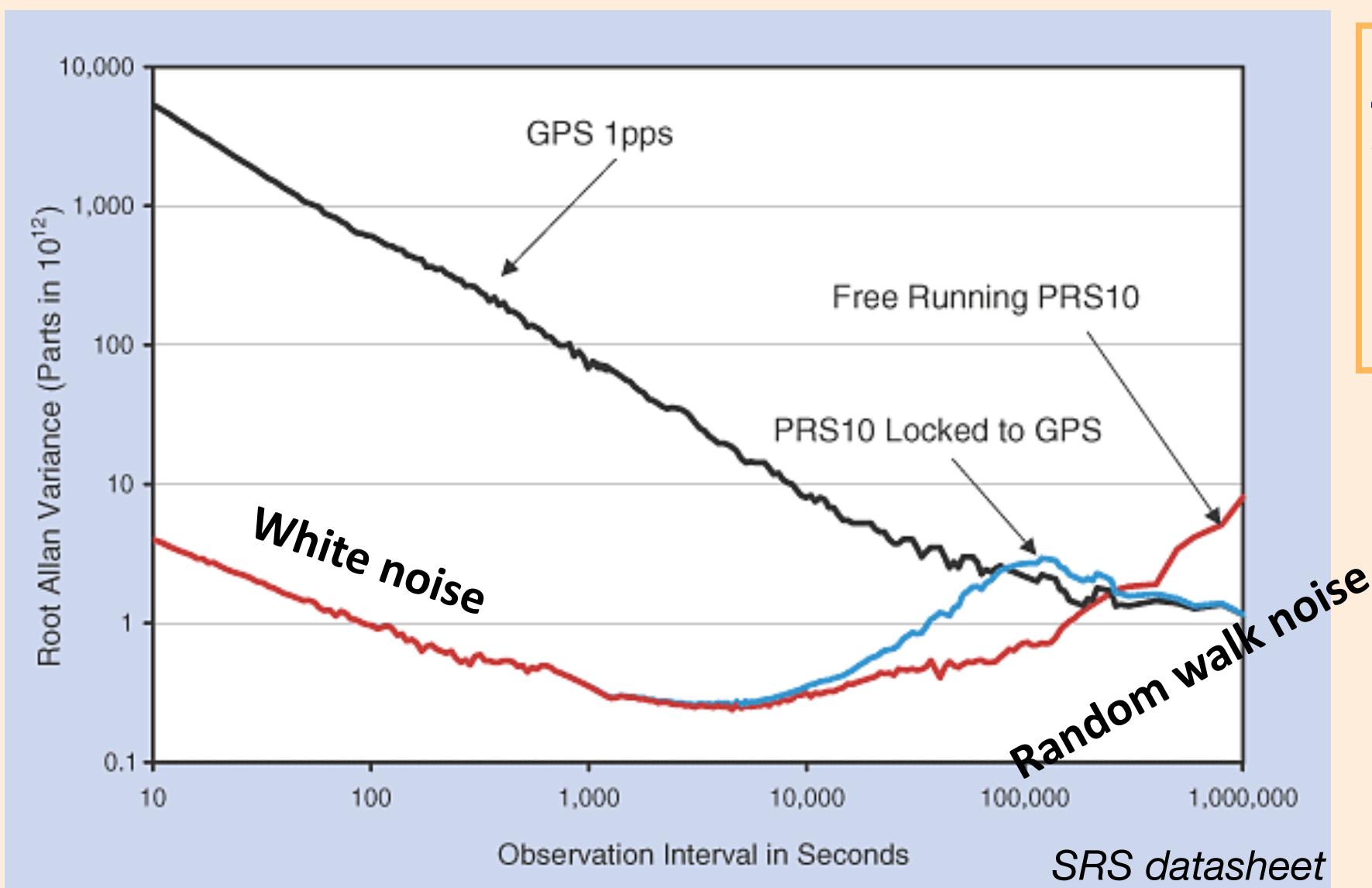
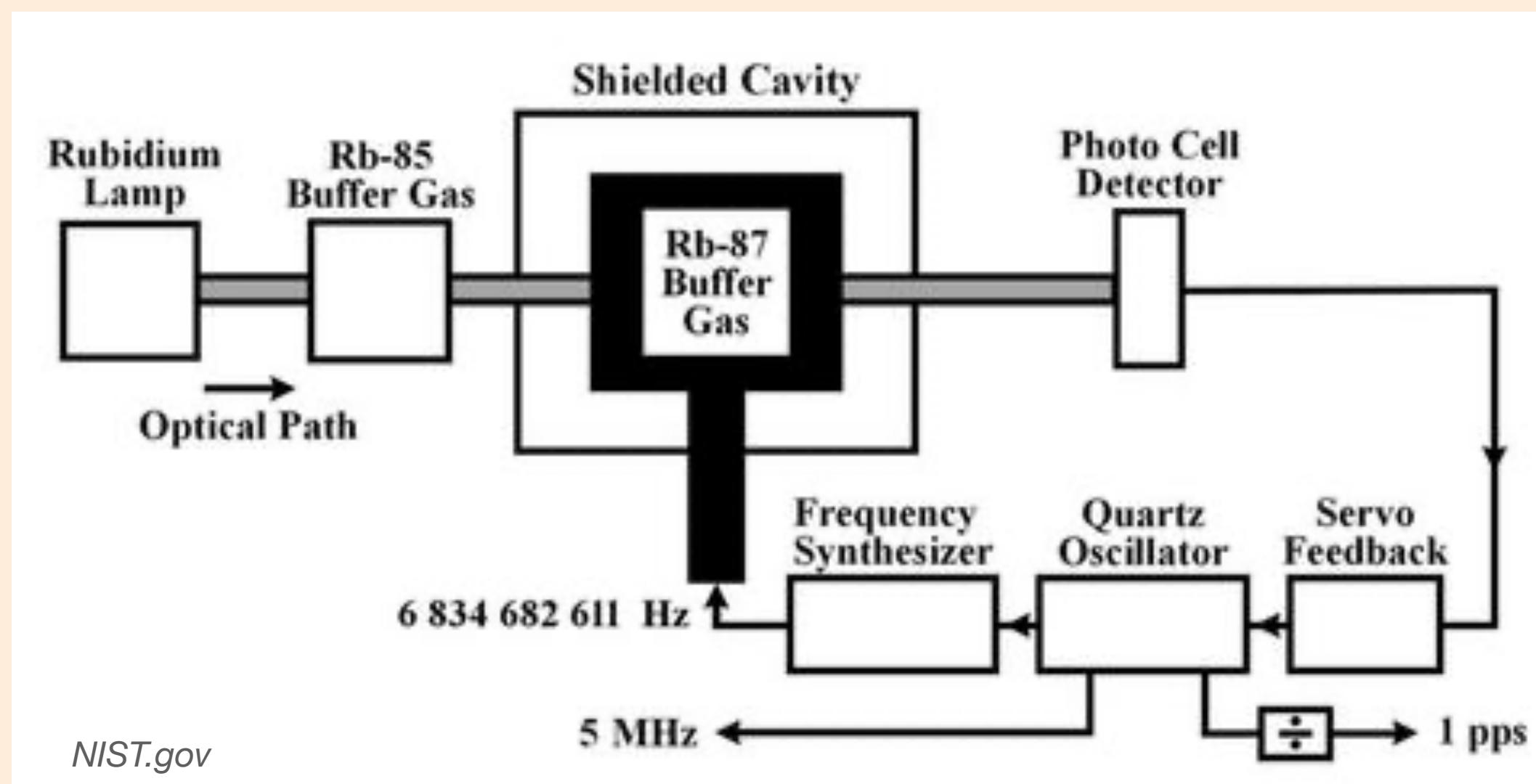
Tools: GNSS (long term stability) and atomic clocks (short term stability), optical fibers

Required precision wrt UTC: 100 ns
Required stability : 100ps (over the whole distribution)

Time synchronization system

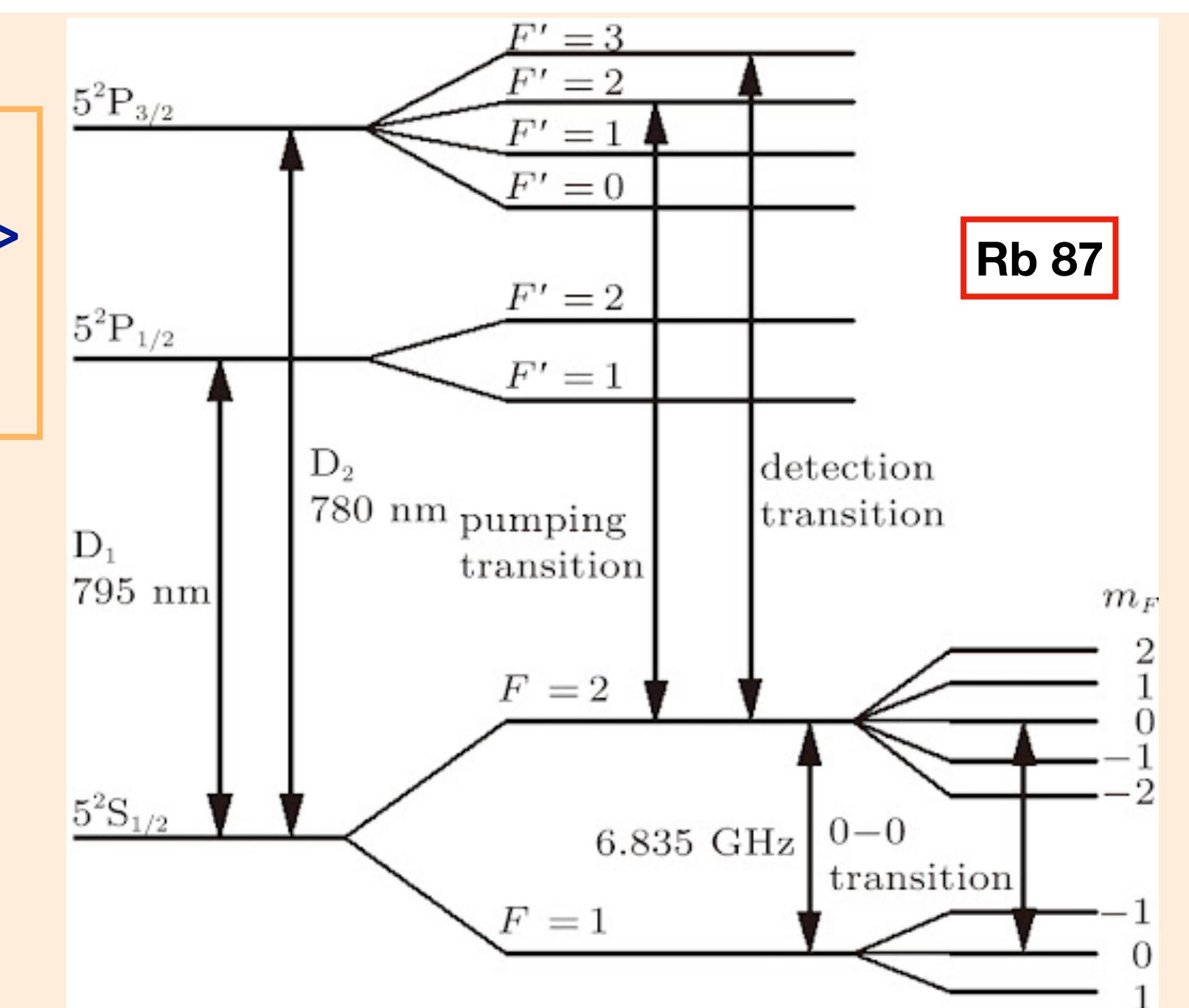
Rubidium clock principle : hyperfine structure (I and B coupling)

- Filter D2 only
- $\Delta F = -1, 0, +1 \rightarrow 6$ allowed transitions
- ^{85}Rb fundamental state with $F=2$ or $F=3 \rightarrow$ degeneracy in energy with transitions ^{87}Rb \rightarrow only γ to S ($F=1$) go through
- Resonant cavity with ^{87}Rb fundamental ($F=1$ or 2), excitation of $F=1$ then equiprobable desexcitation $\rightarrow +$ and $+ F=2$ until no more $F=1 \rightarrow$ cavity transparent to selected $\gamma \rightarrow$ optical pumping
- We « inject » a frequency f_0 close to f_{12} (2 steps) \rightarrow variations in luminosity/transparency \rightarrow servo control of f_0



Analysis tools for frequency stability : Allan variance = averages over different times $\tau \rightarrow$ discrimination of different noise types
Short term / long term drifts

$$\sigma_y^2(\tau) = \frac{1}{2} \langle (\bar{y}_{n+1} - \bar{y}_n)^2 \rangle$$

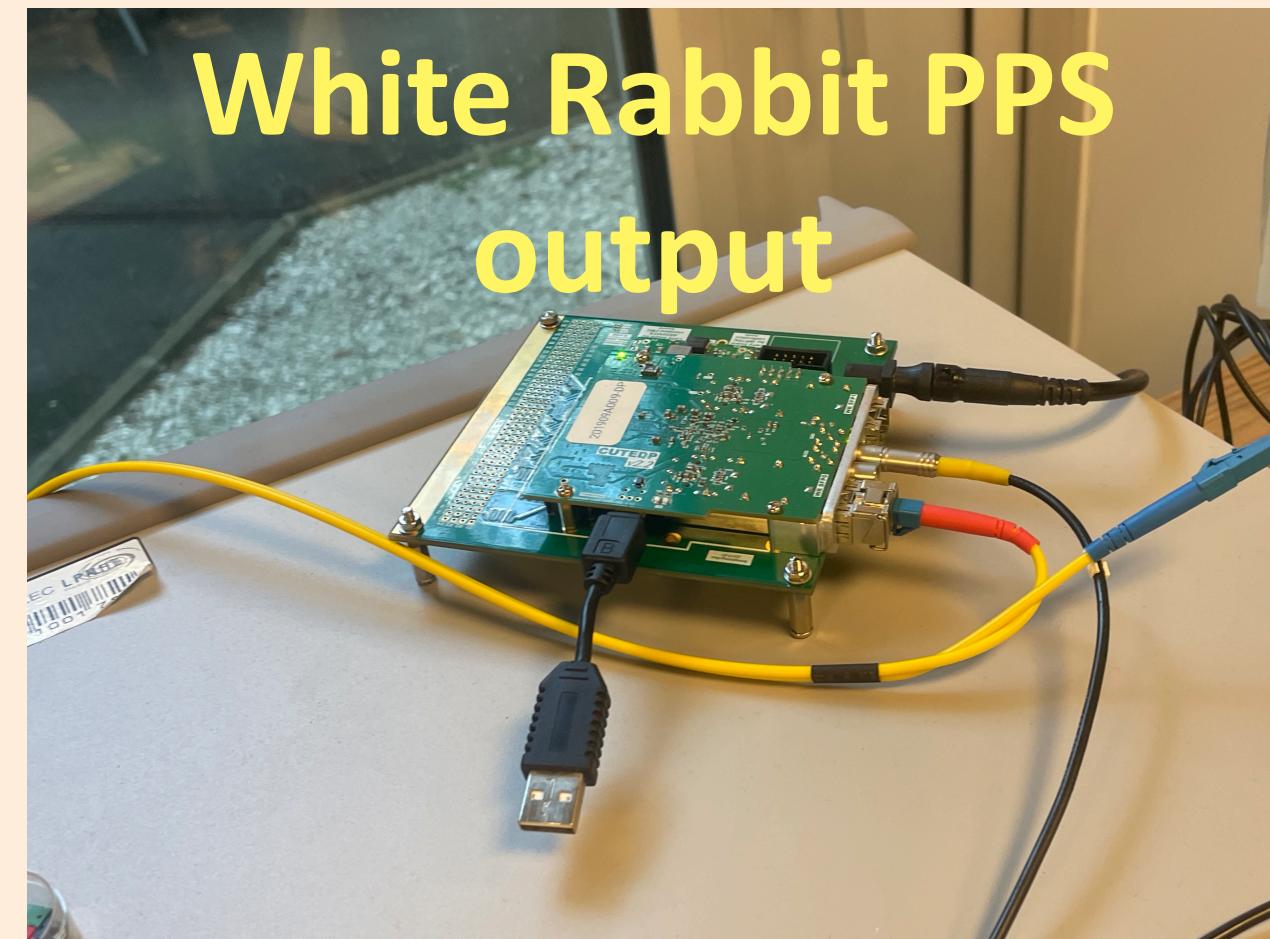
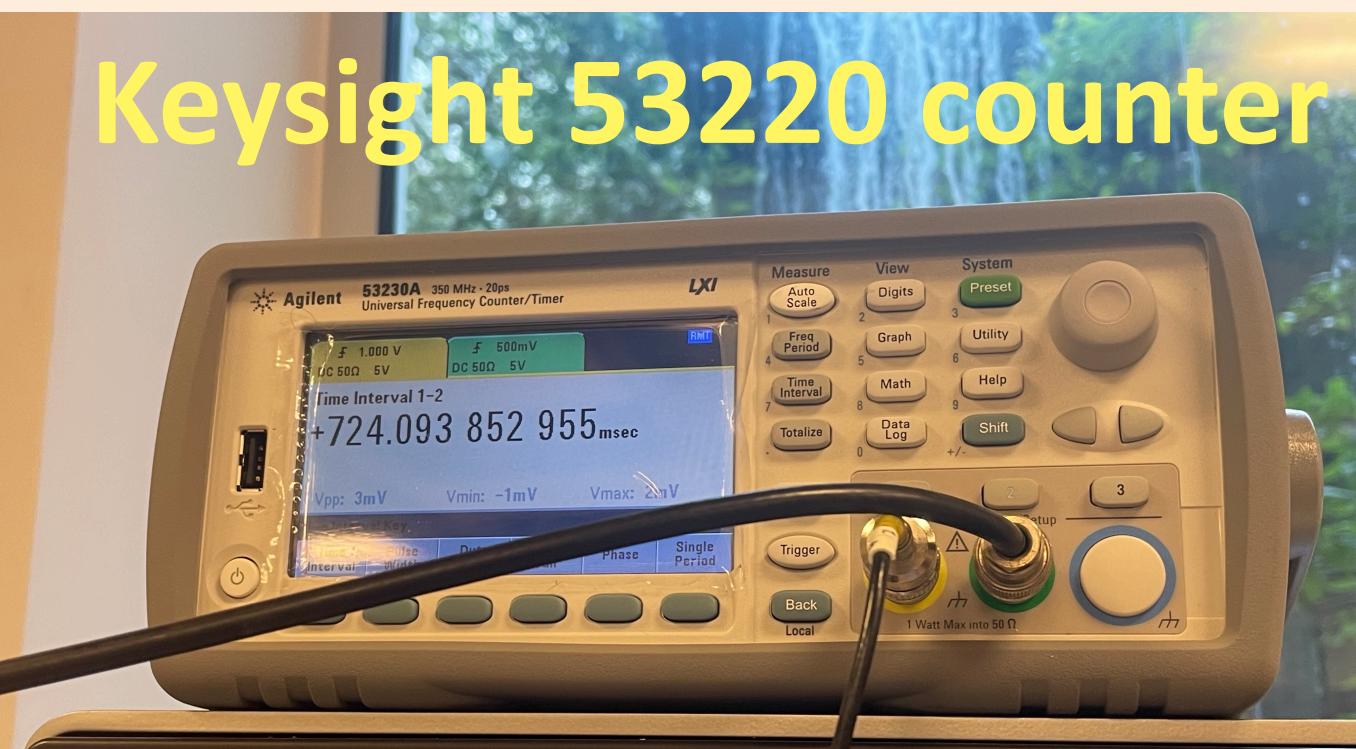
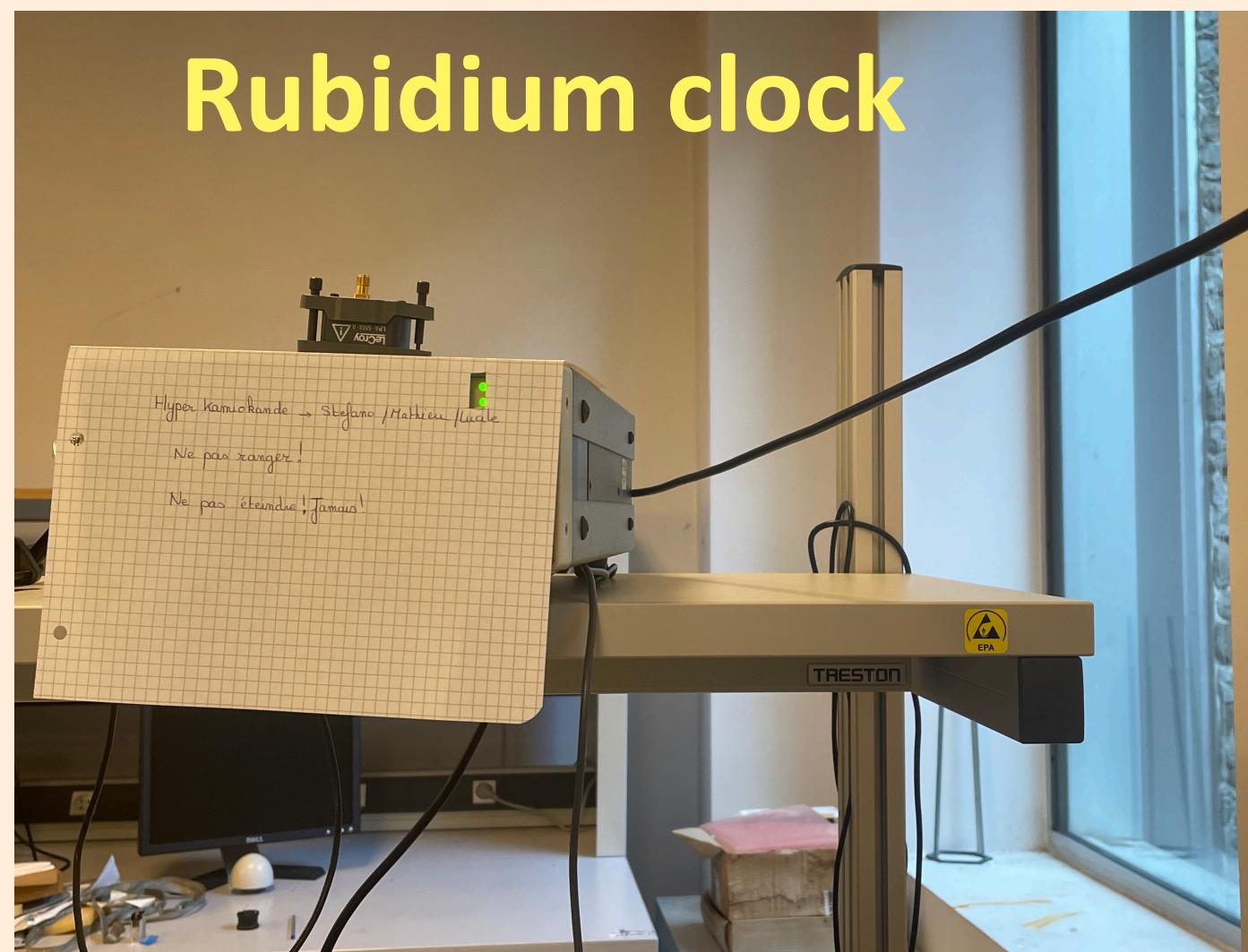


Time synchronization system

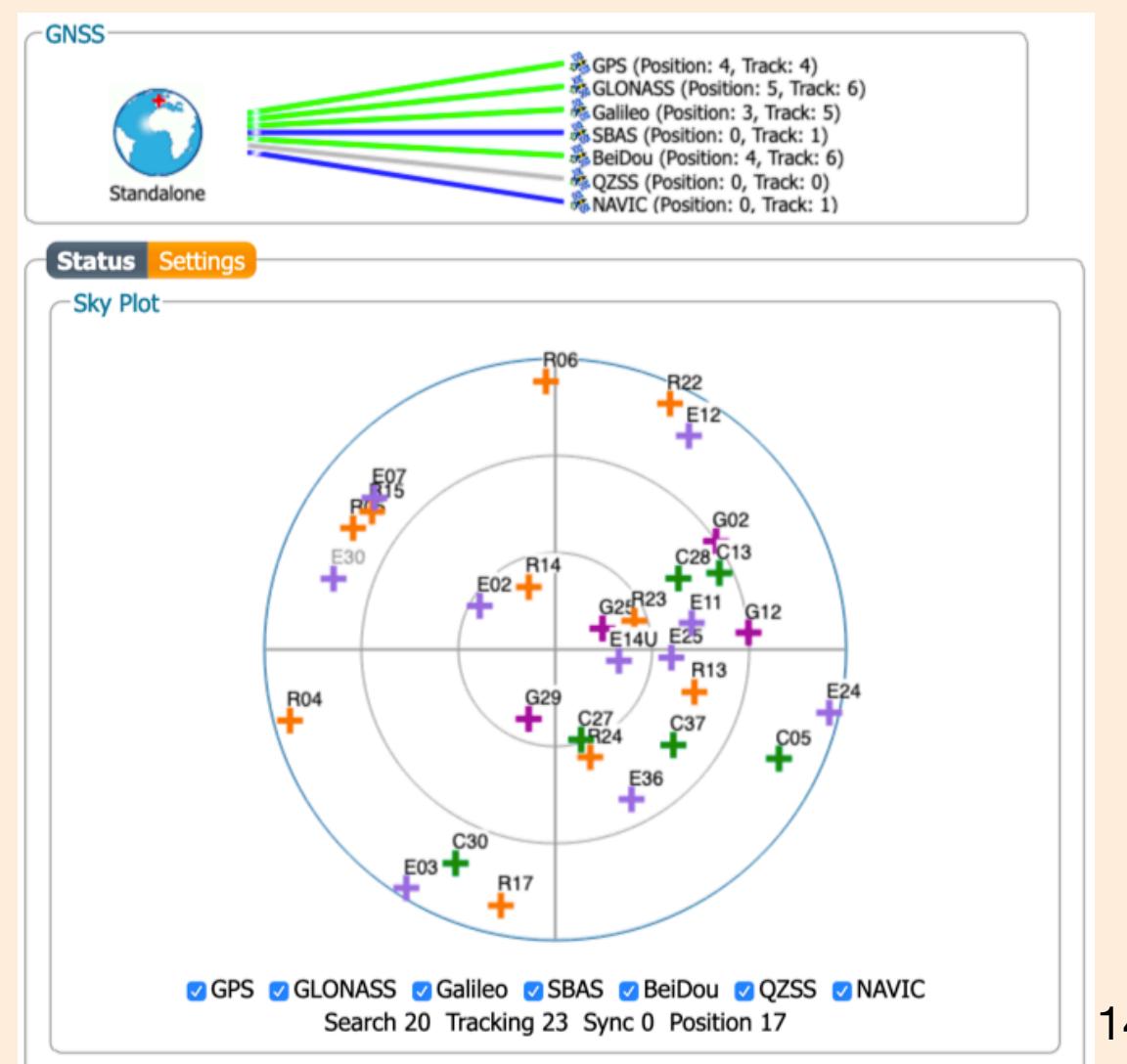


Systèmes de Référence Temps-Espace

In collaboration with SYRTE
compared to a more precise 1pps provided by SYRTE



Rubidium atomic clock
-> to be characterized and calibrated
GNSS receiver (reflections depending on
the surroundings and the sky view)

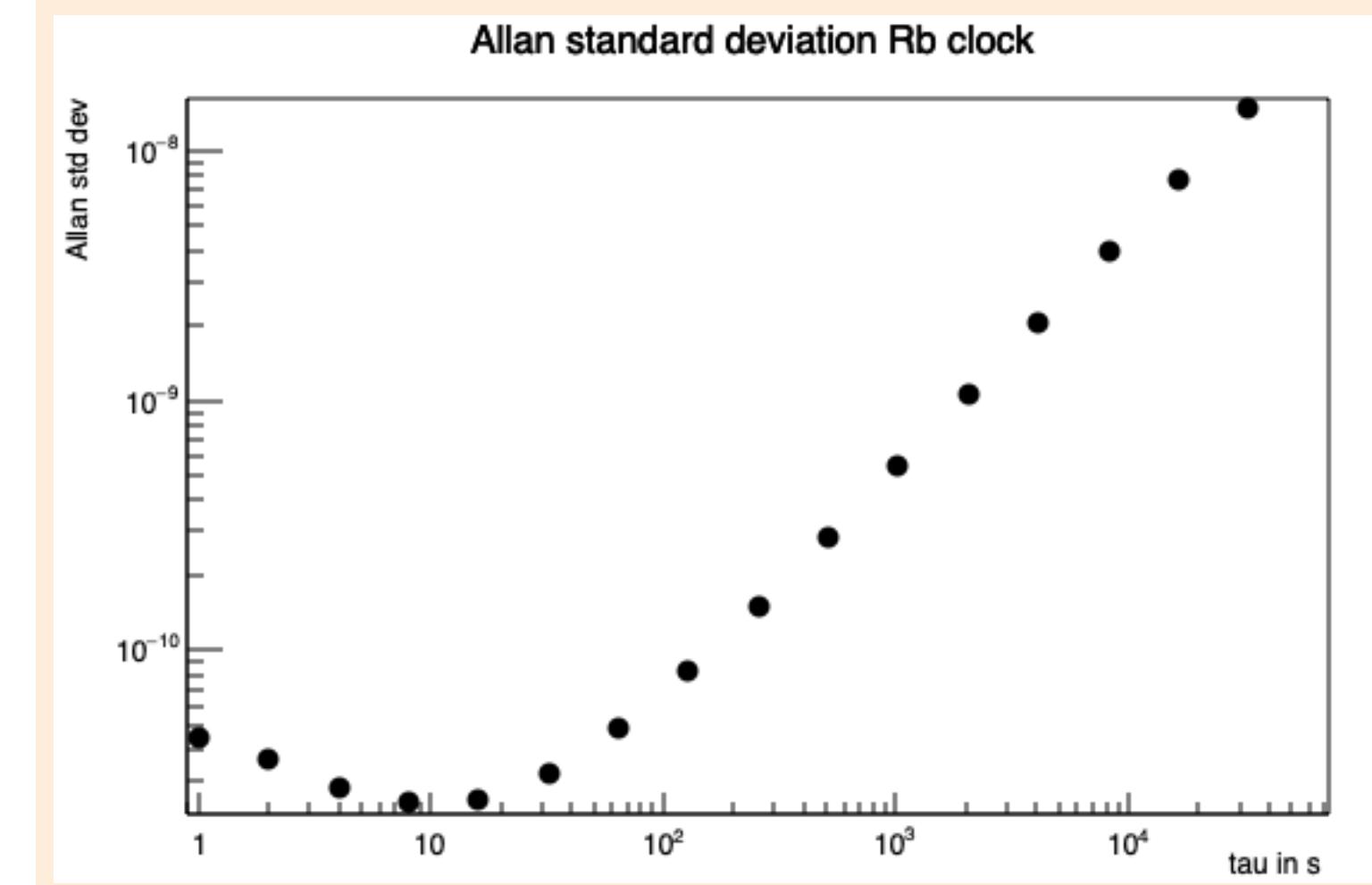
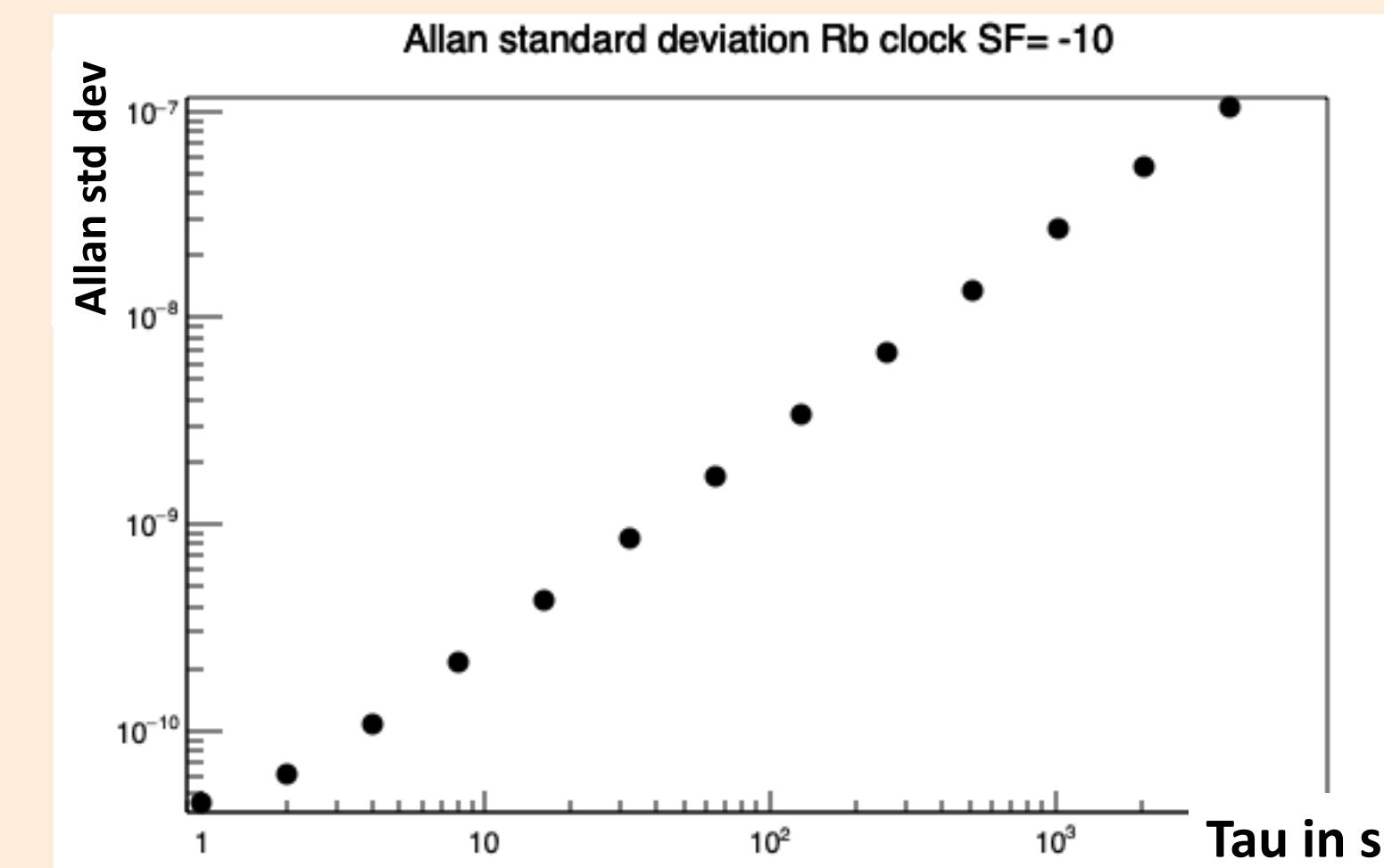
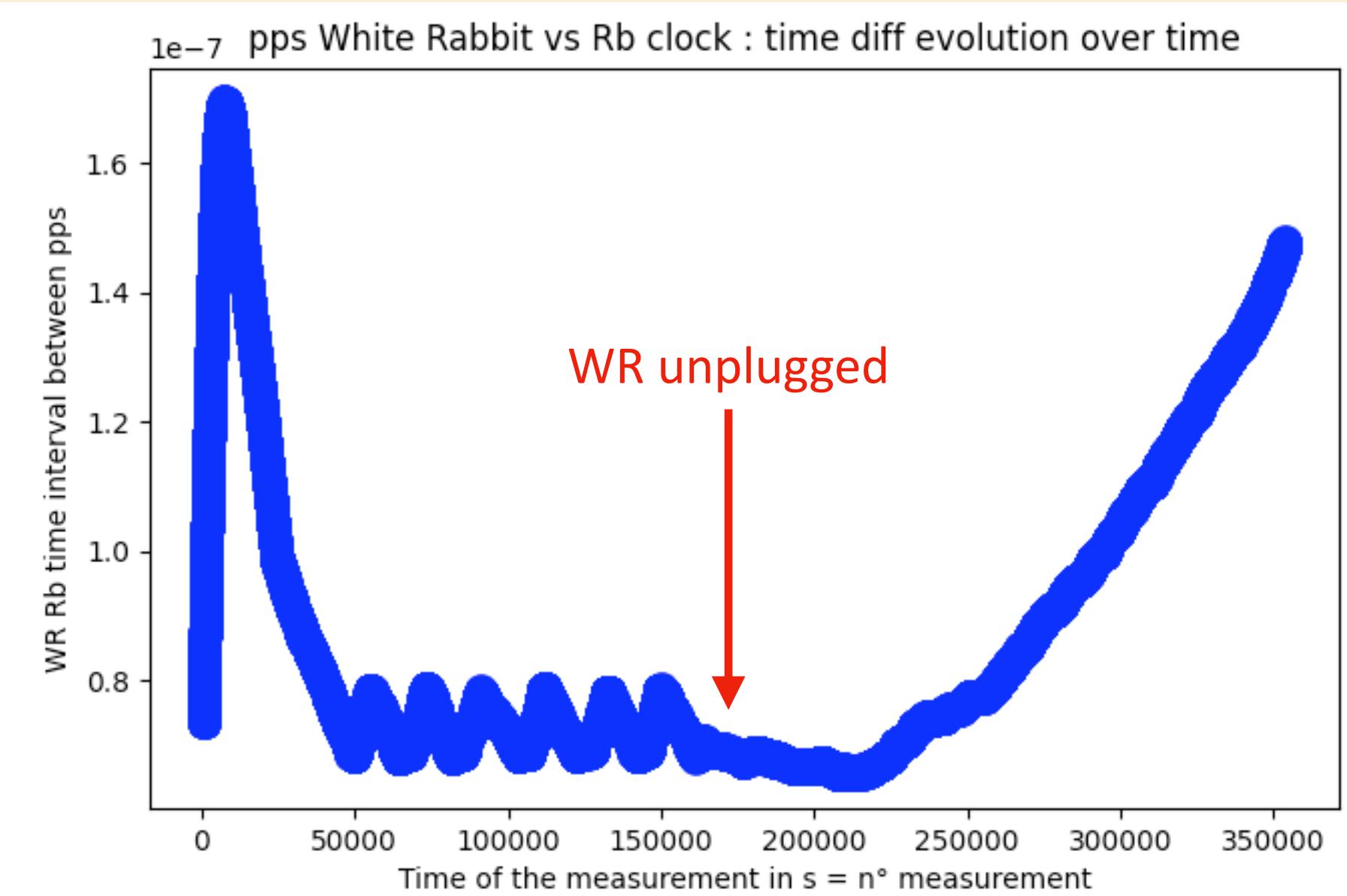
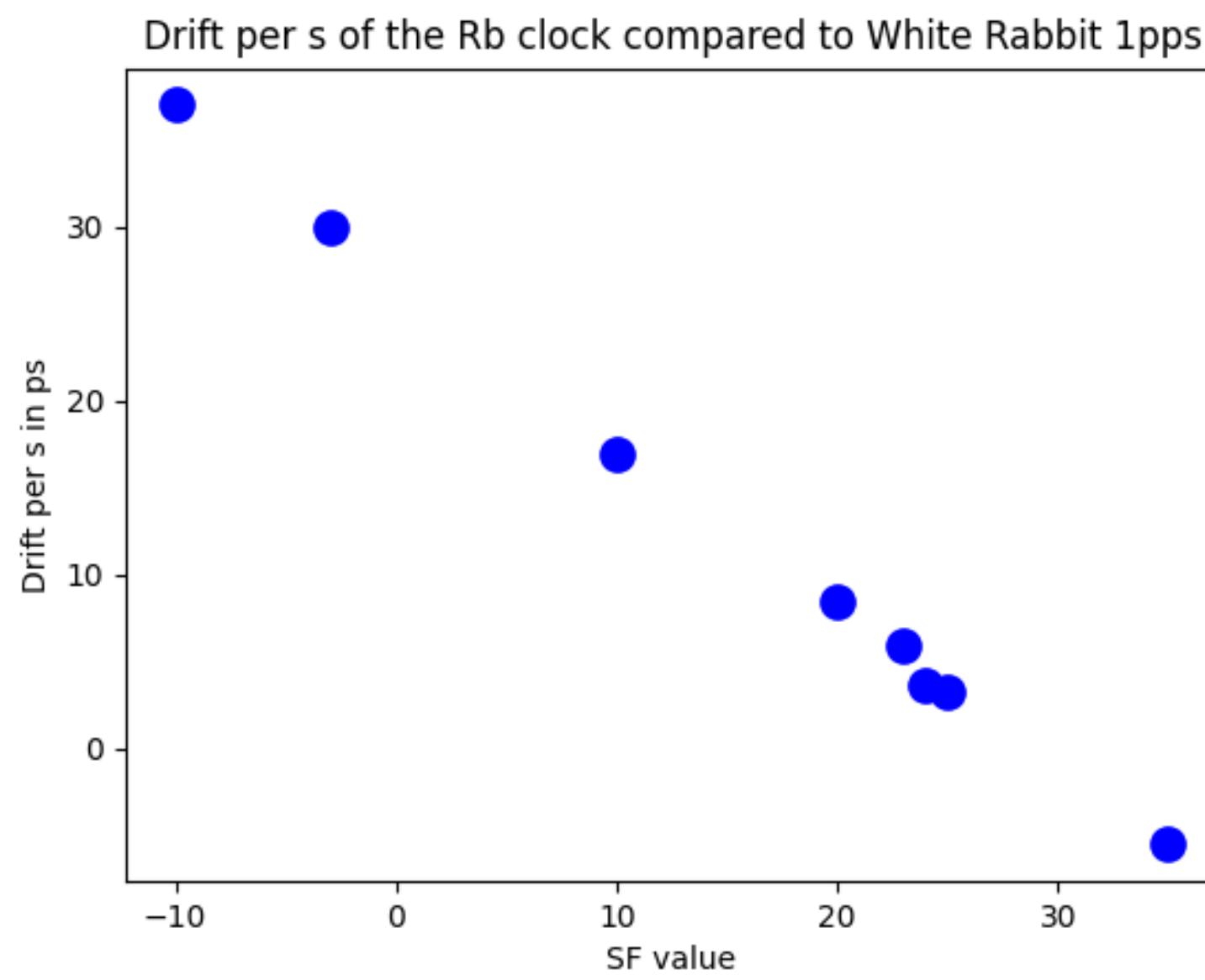


Time synchronization system

First tests and calibration:

Need for precise calibration → adjust SF parameter (tension->mag. field)
= output frequency offset

Phase ‘locking’ system on an external source



Time synchronization system

Next steps of the project :

- Construction of a test laboratory in preparation for HK (GNSS antenna, several atomic clocks models...)
- Characterize our equipment et assess the precision and stability that we can achieve
- Study the impact of the whole electronic chain time precision on HK sensitivity to oscillation parameters

Conclusion

- T2K and Super-Kamiokande detector already allowed a lot of progress on neutrino oscillations understanding
 - T2K II
- Preparation to Hyper-Kamiokande



HK tunnels excavation started in May 2021



Merci !



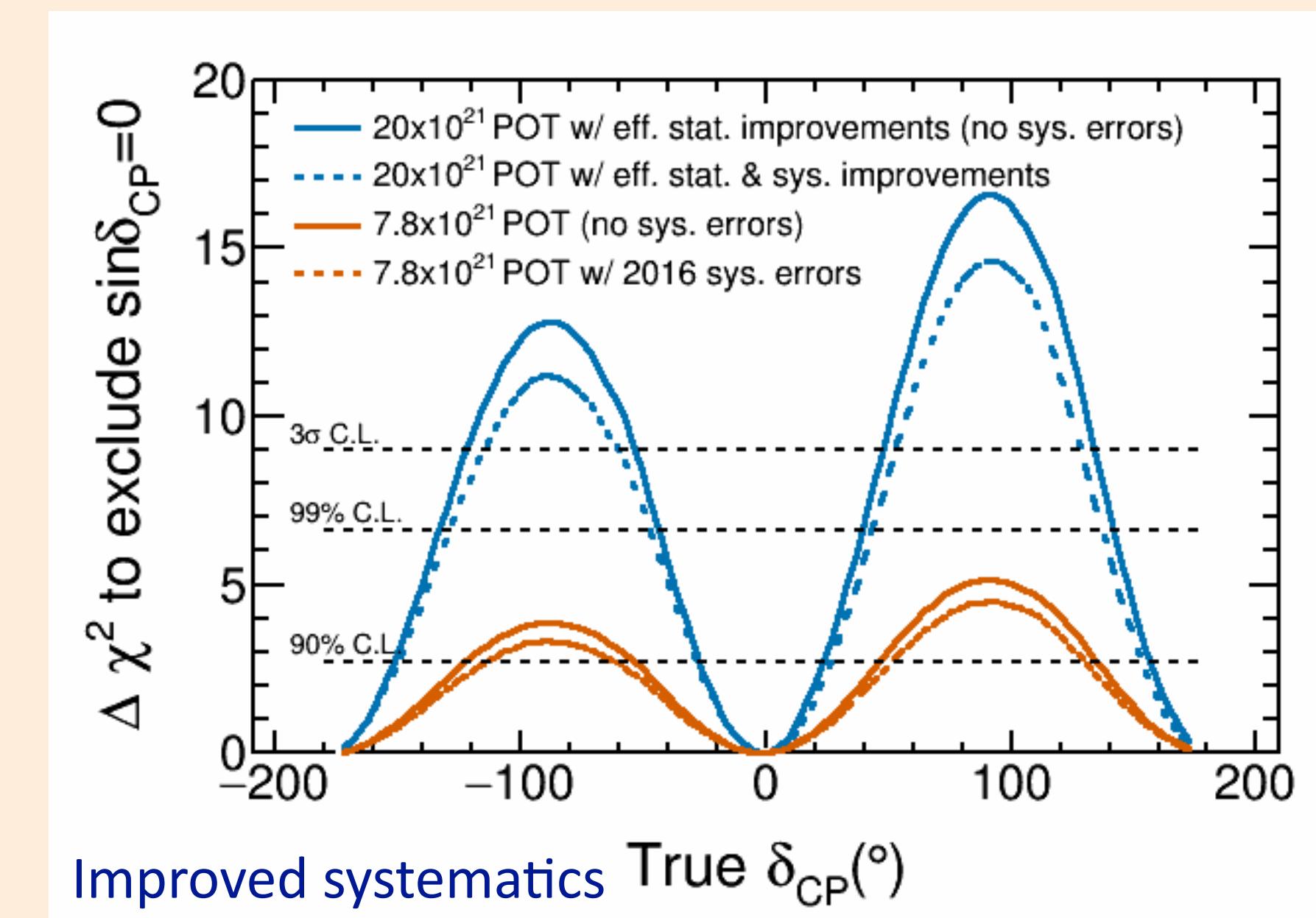
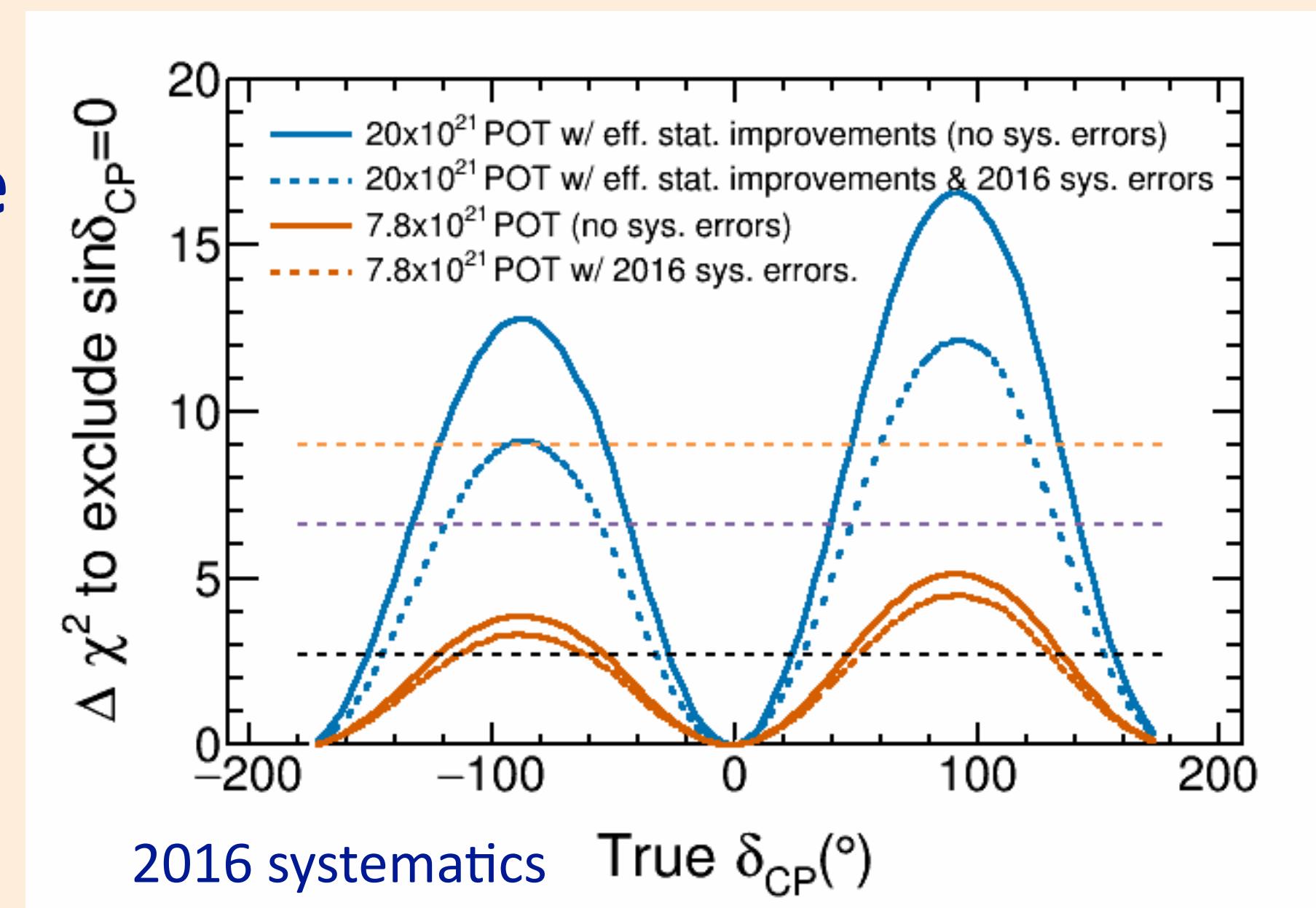
Back-up_Systematics effects : motivations

- ♦ T2K II :
 - near detector upgrade (start 2023)
 - beam power increase (500kW to 750kW)

- ♦ T2K-SK (beam/atmospheric v) joint analysis

- ♦ Hyper-Kamiokande

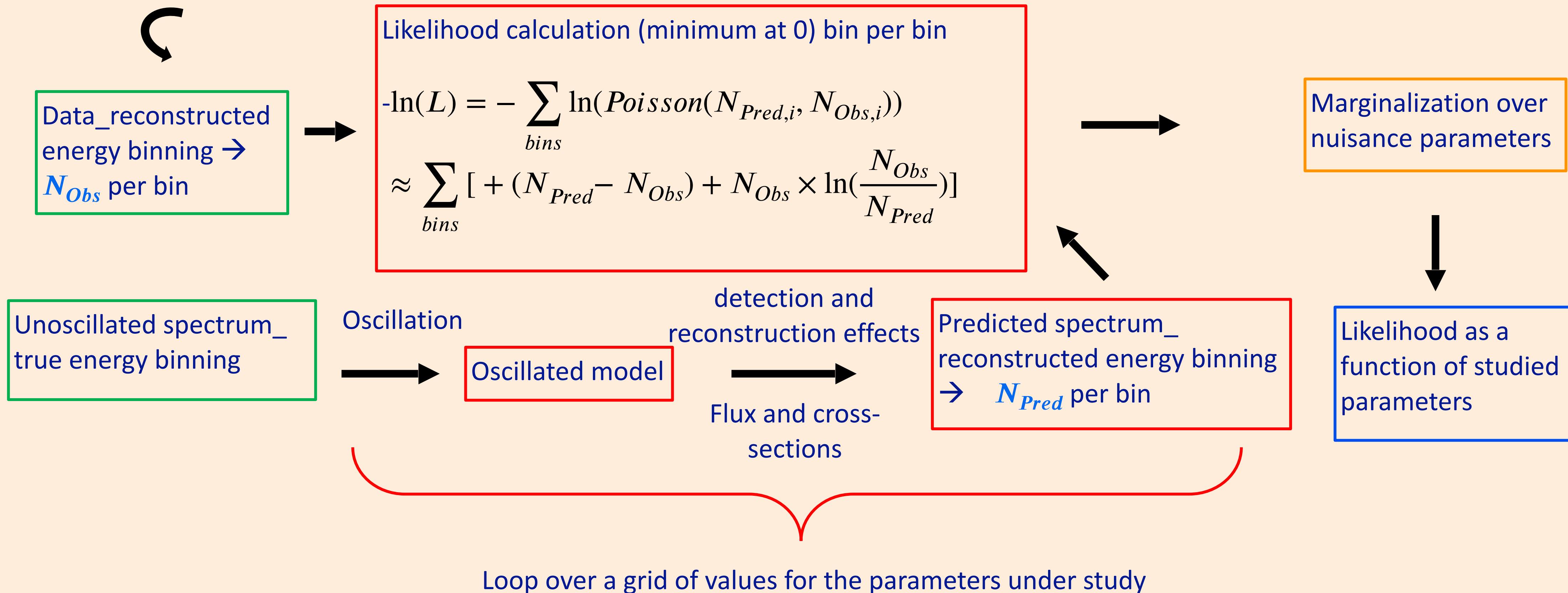
T2K II δ_{CP} sensitivity
Known mass hierarchy



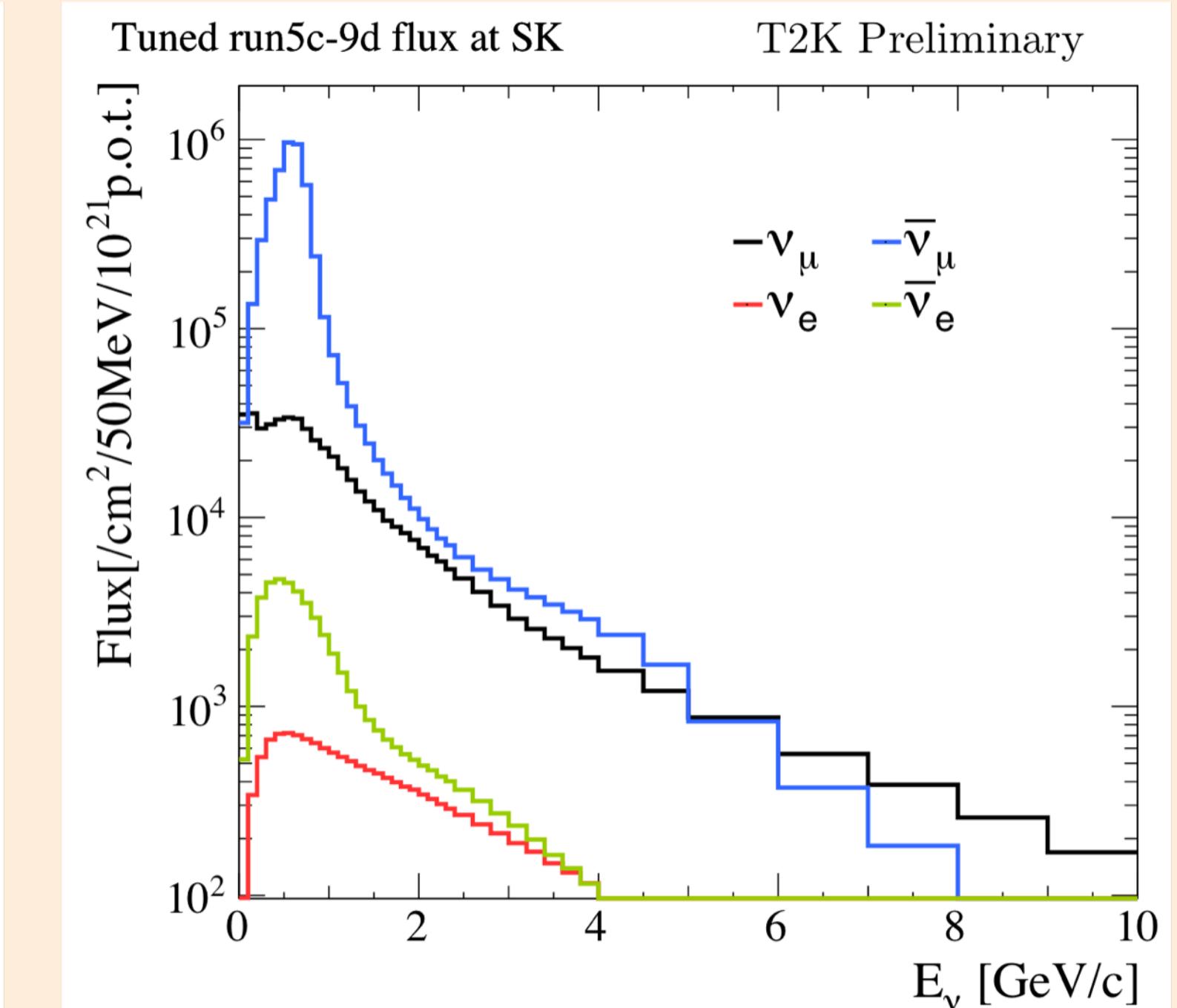
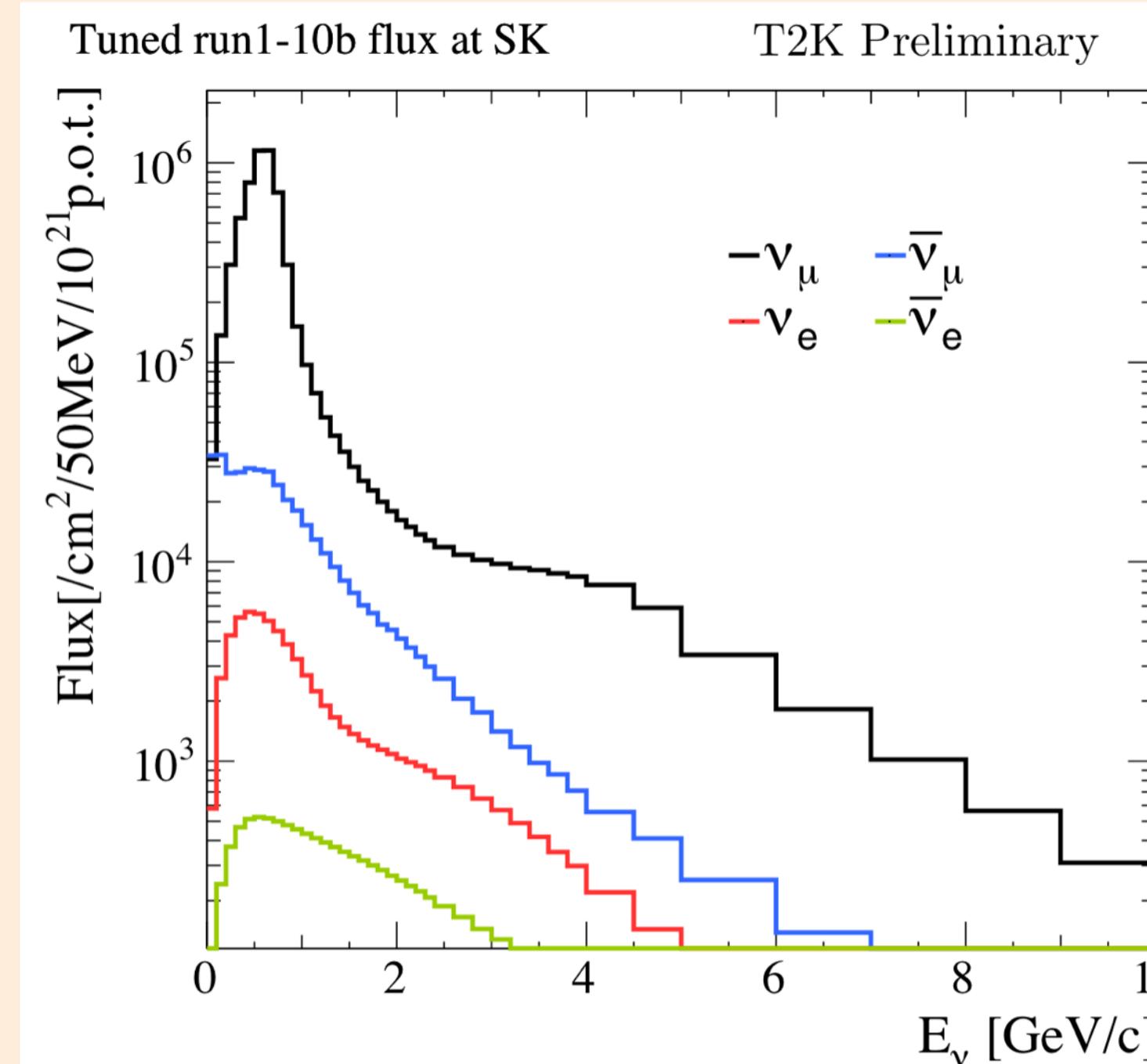
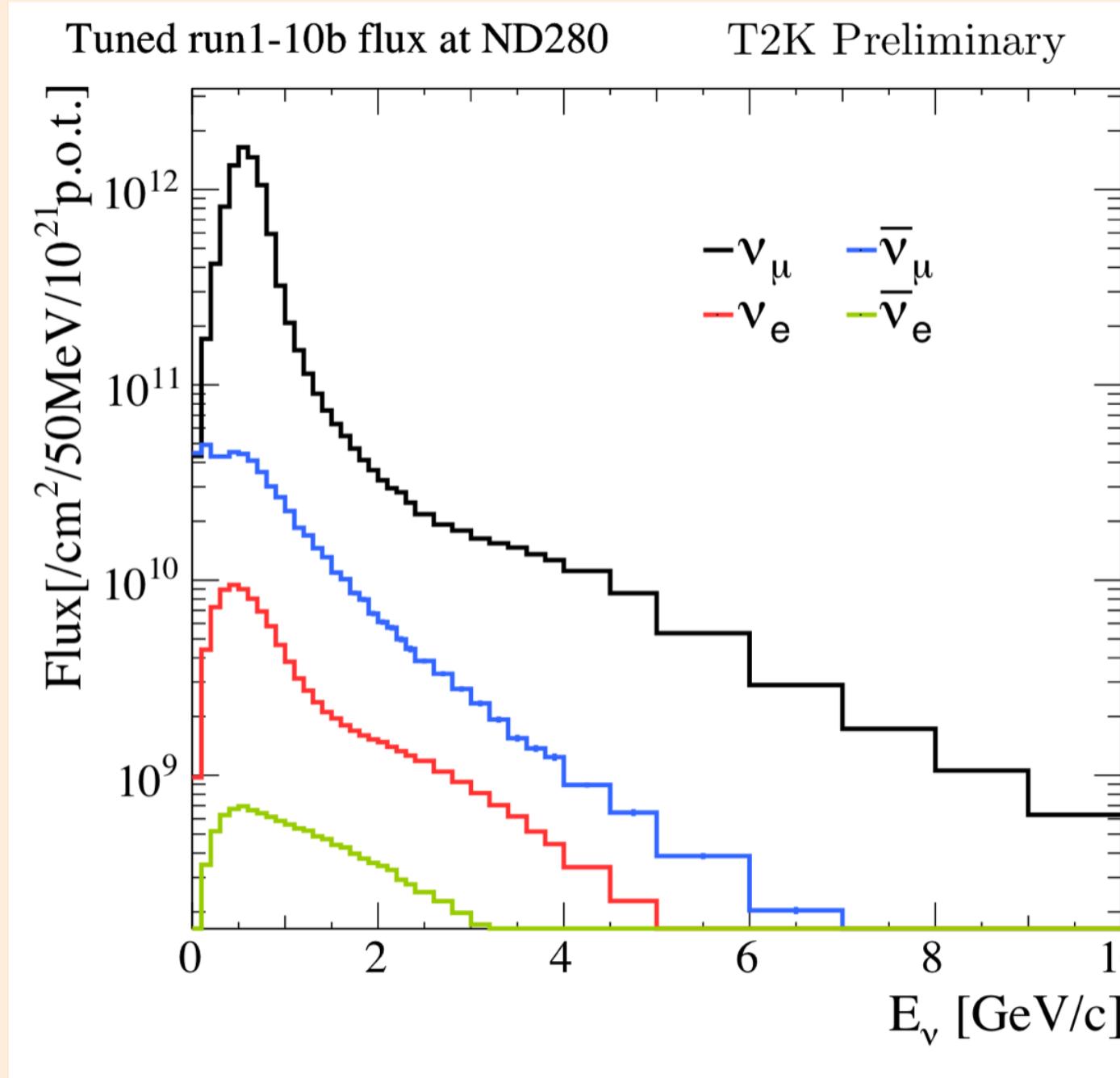
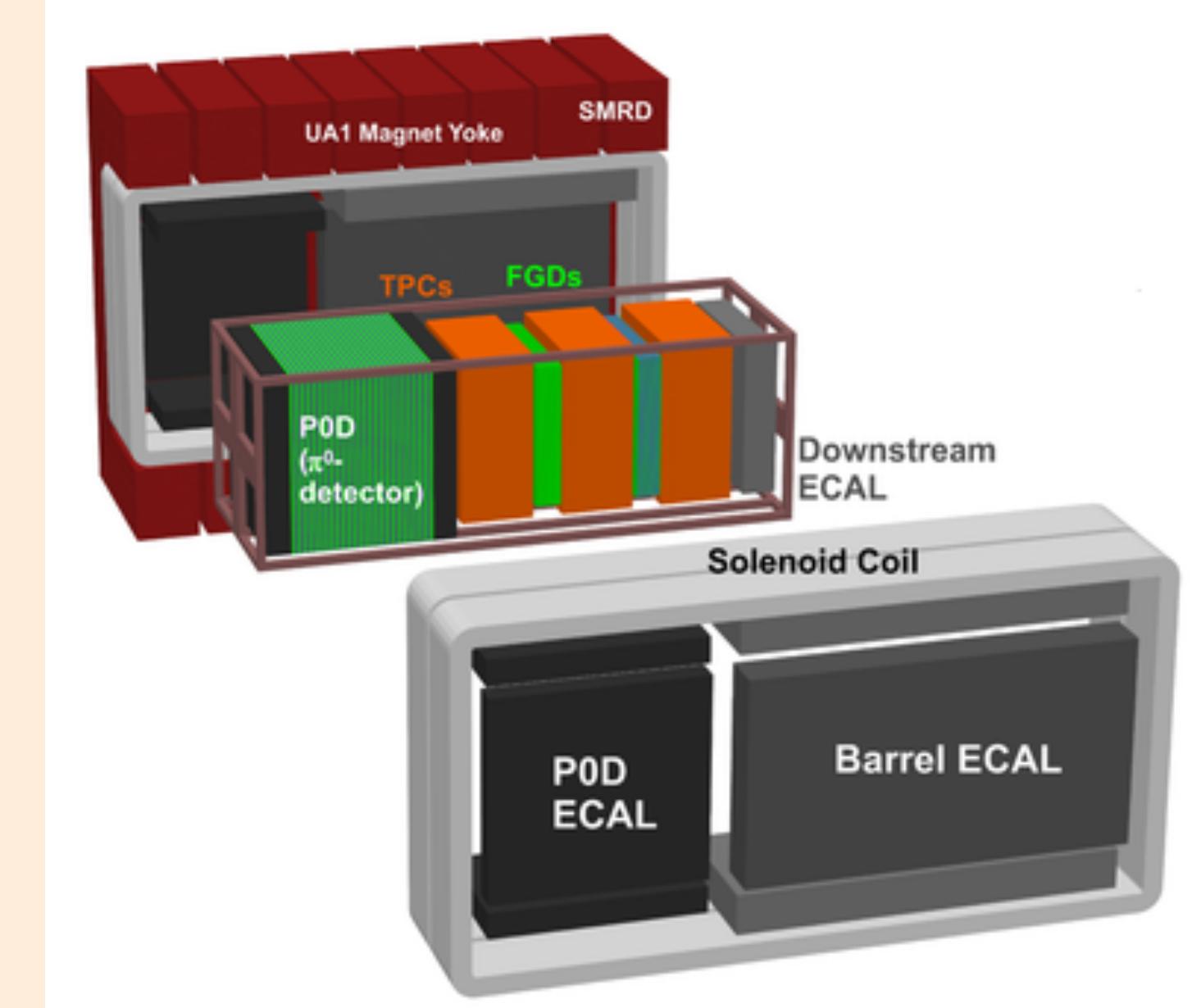
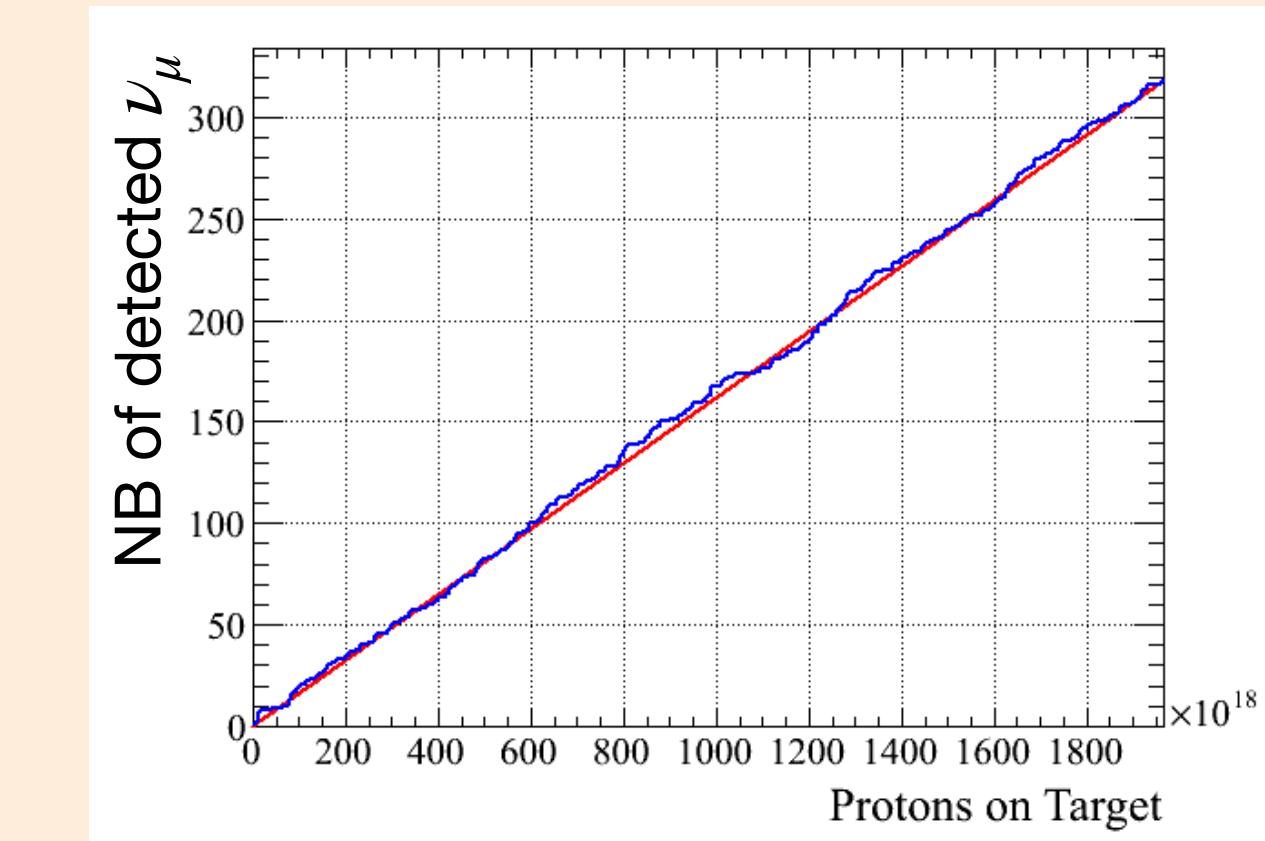
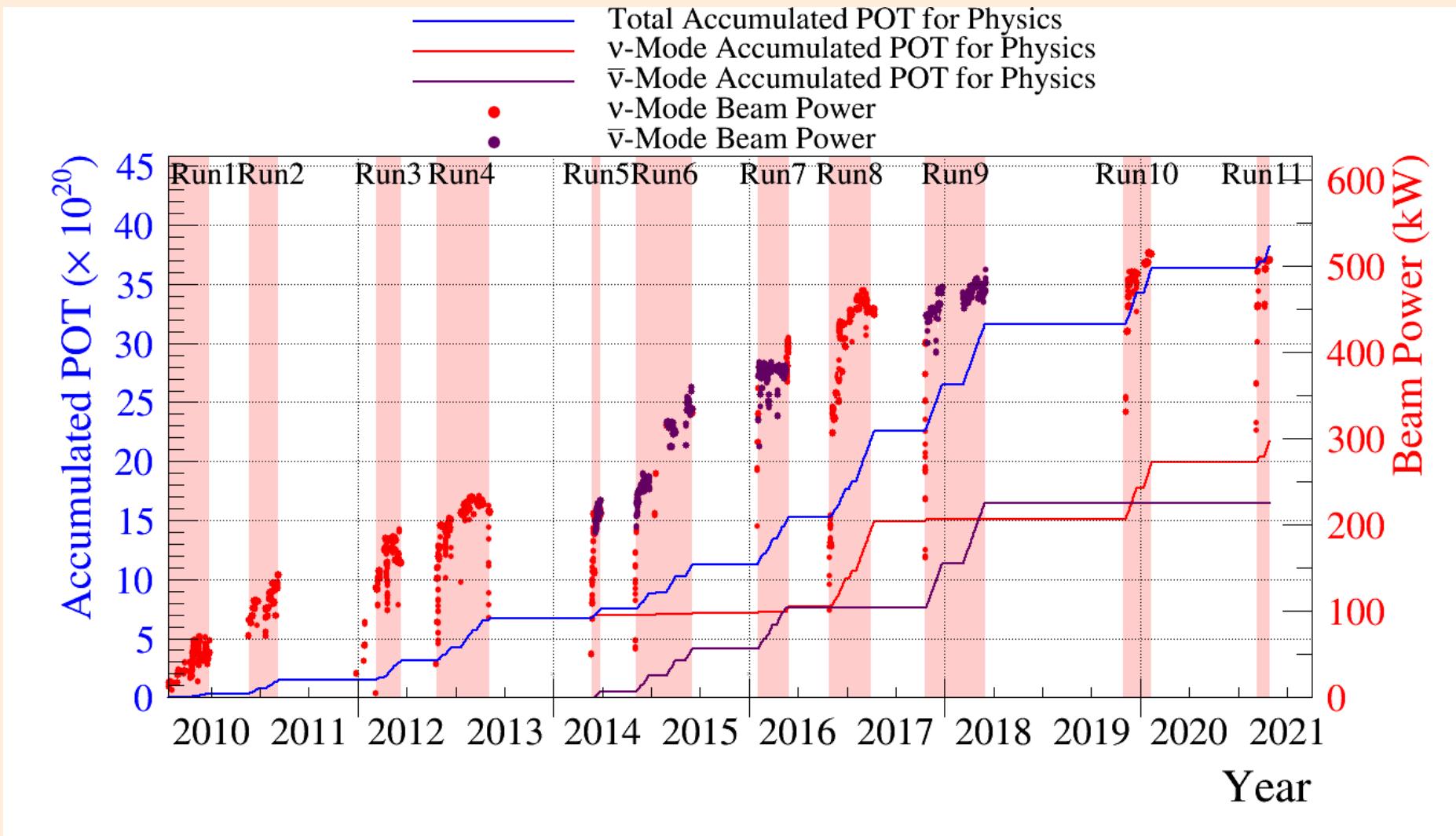
Back-up_T2K analysis method in the P-theta group

Software/group P-theta : 1 of 3 T2K analysis groups

Unknown true values of
oscillation parameters



Back-up_T2K

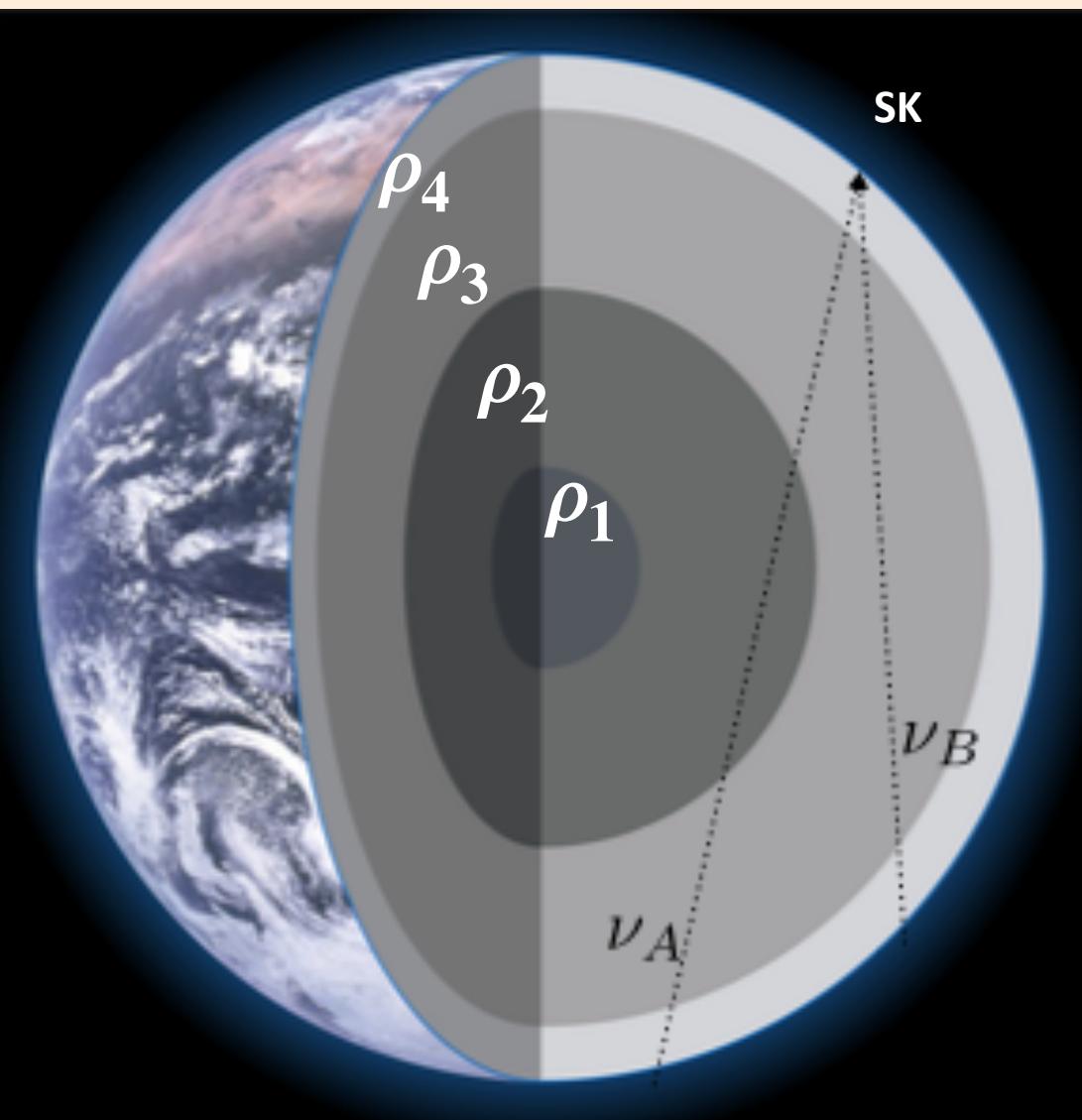


Back-up_T2K-SK

JointSK (atmospheric)/T2K (beam) analysis

P-theta framework

Perspective : Hyper-Kamiokande

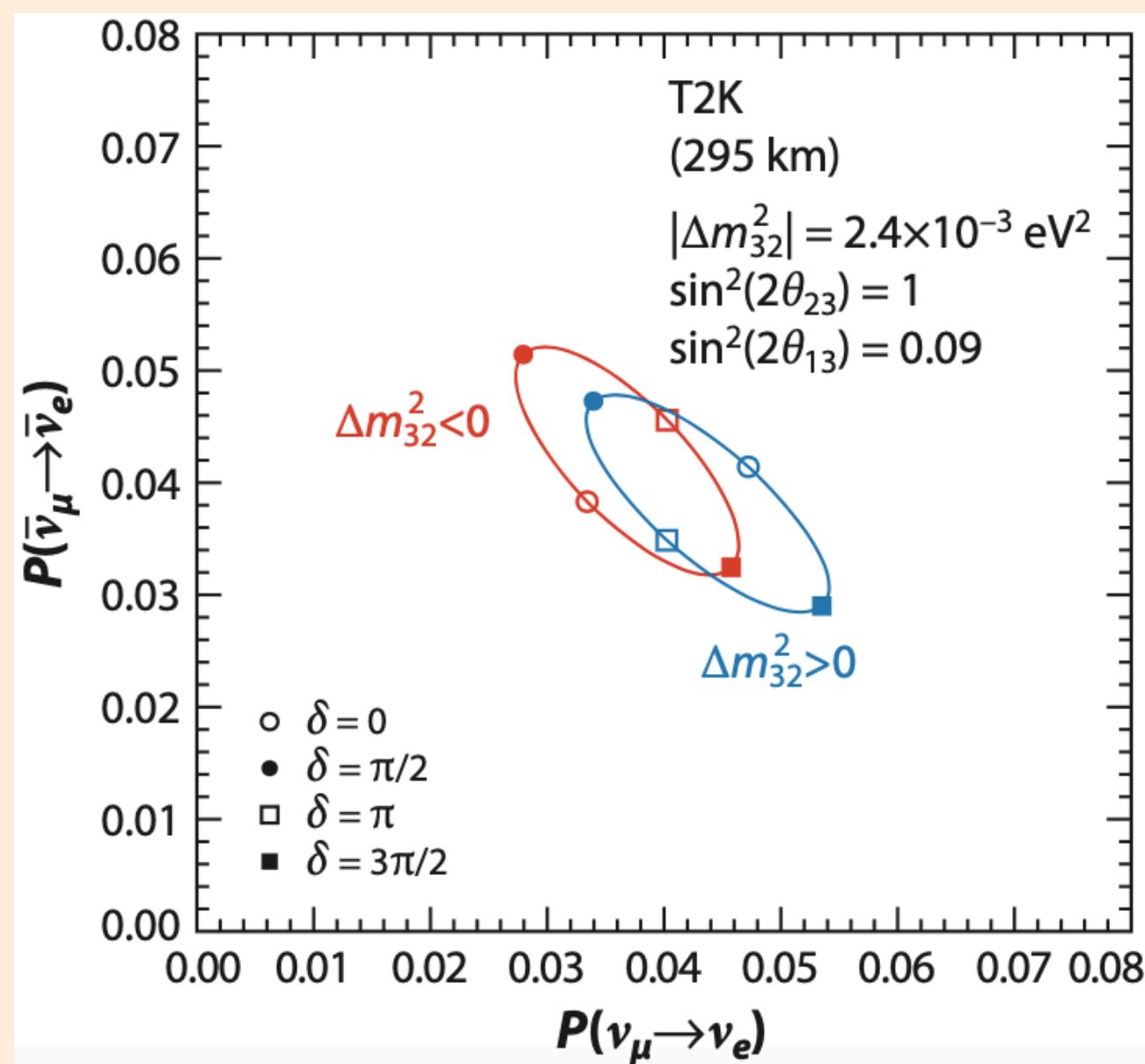


K. Abe et al., Phys. Rev. D, vol. 97, 2018

**Complementarity
of the 2 neutrino sources**

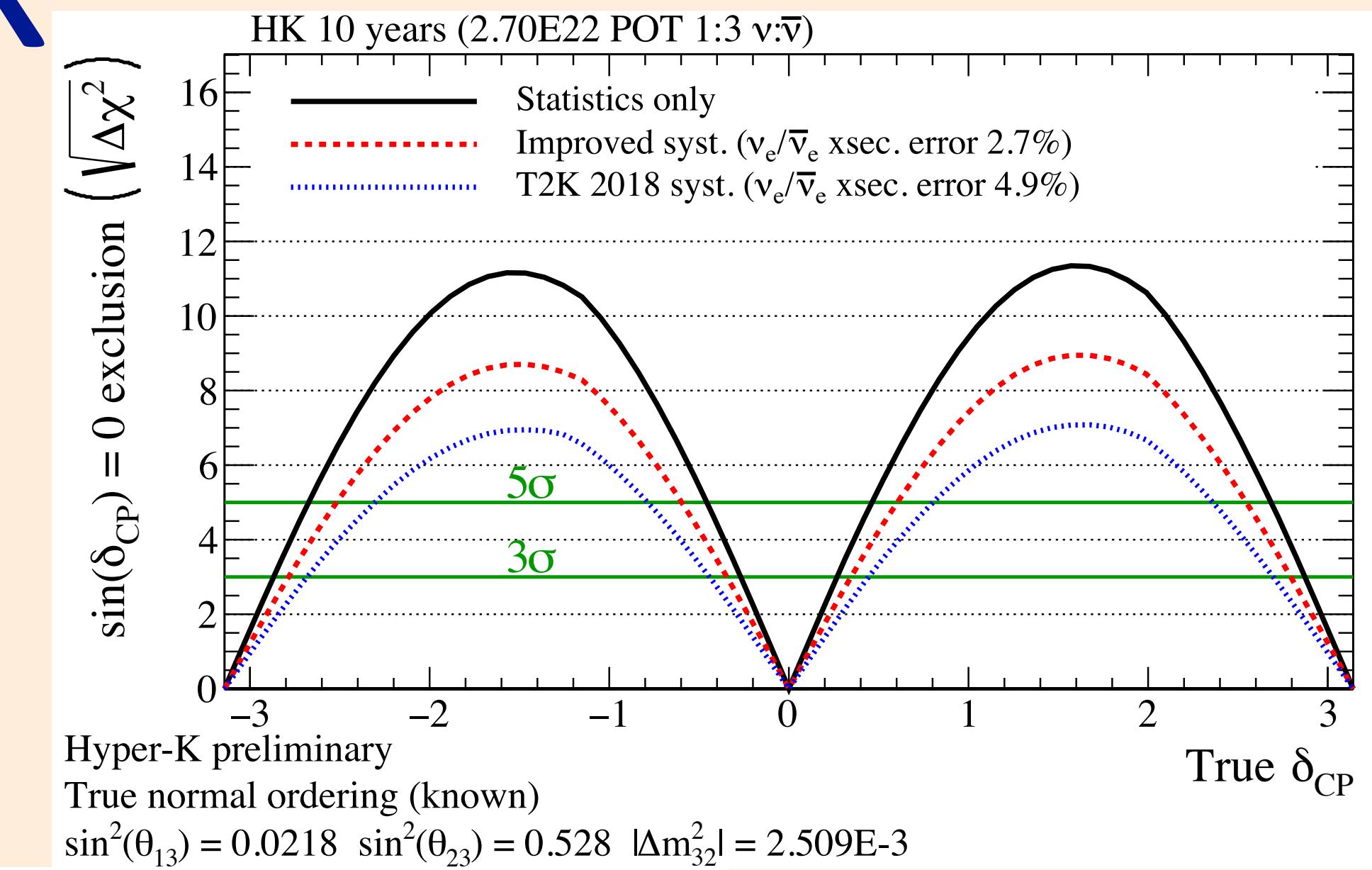
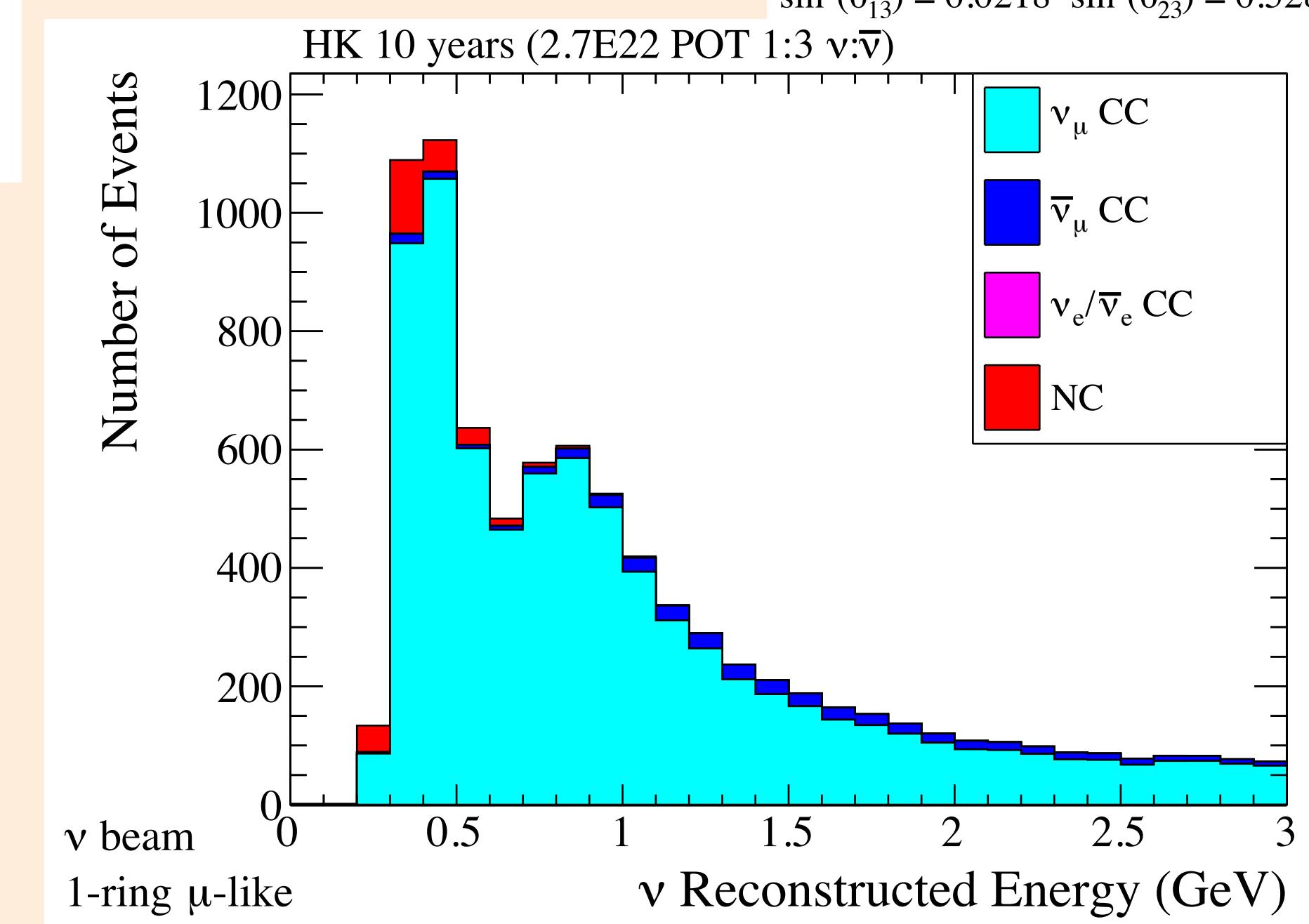
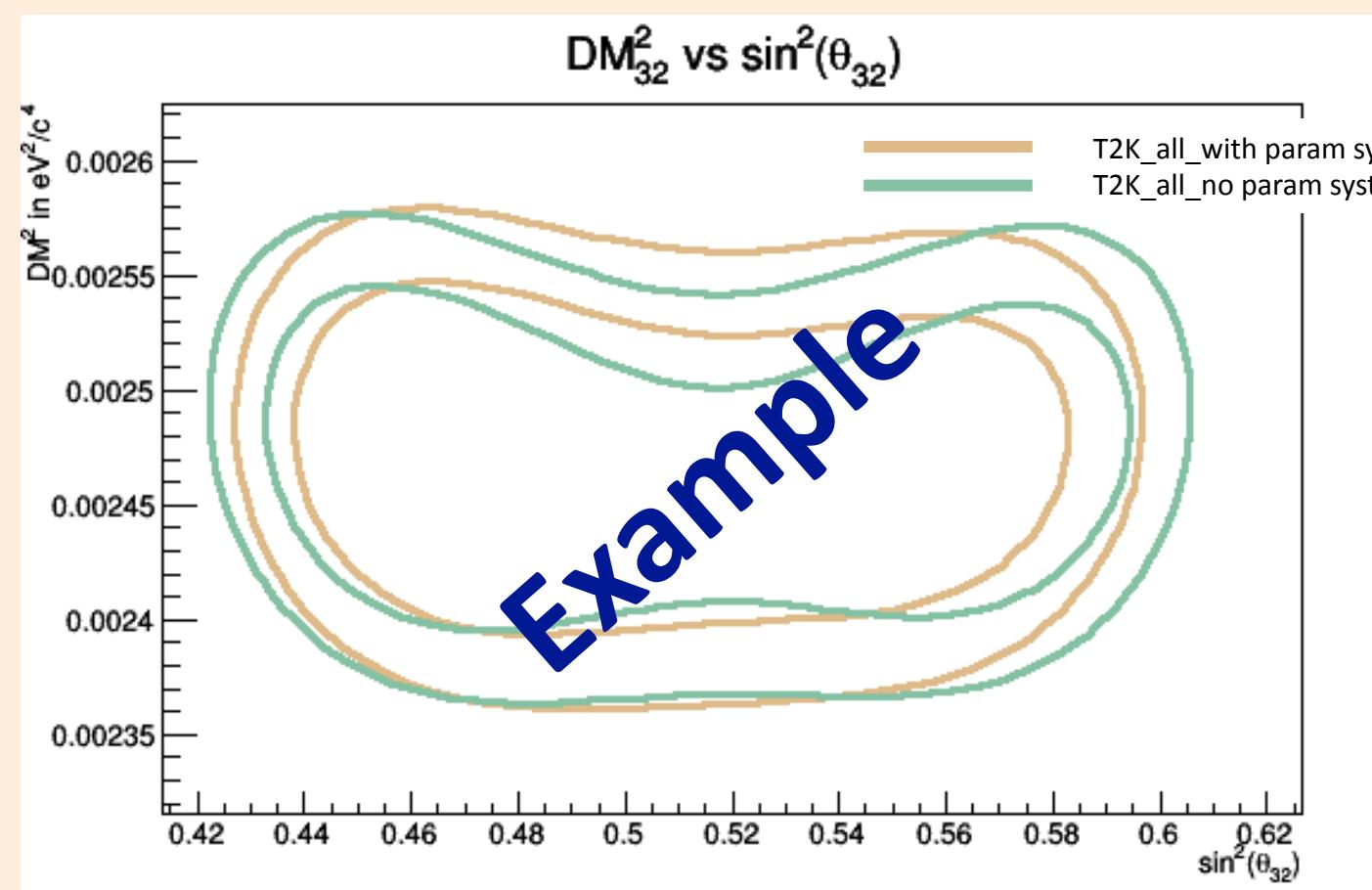
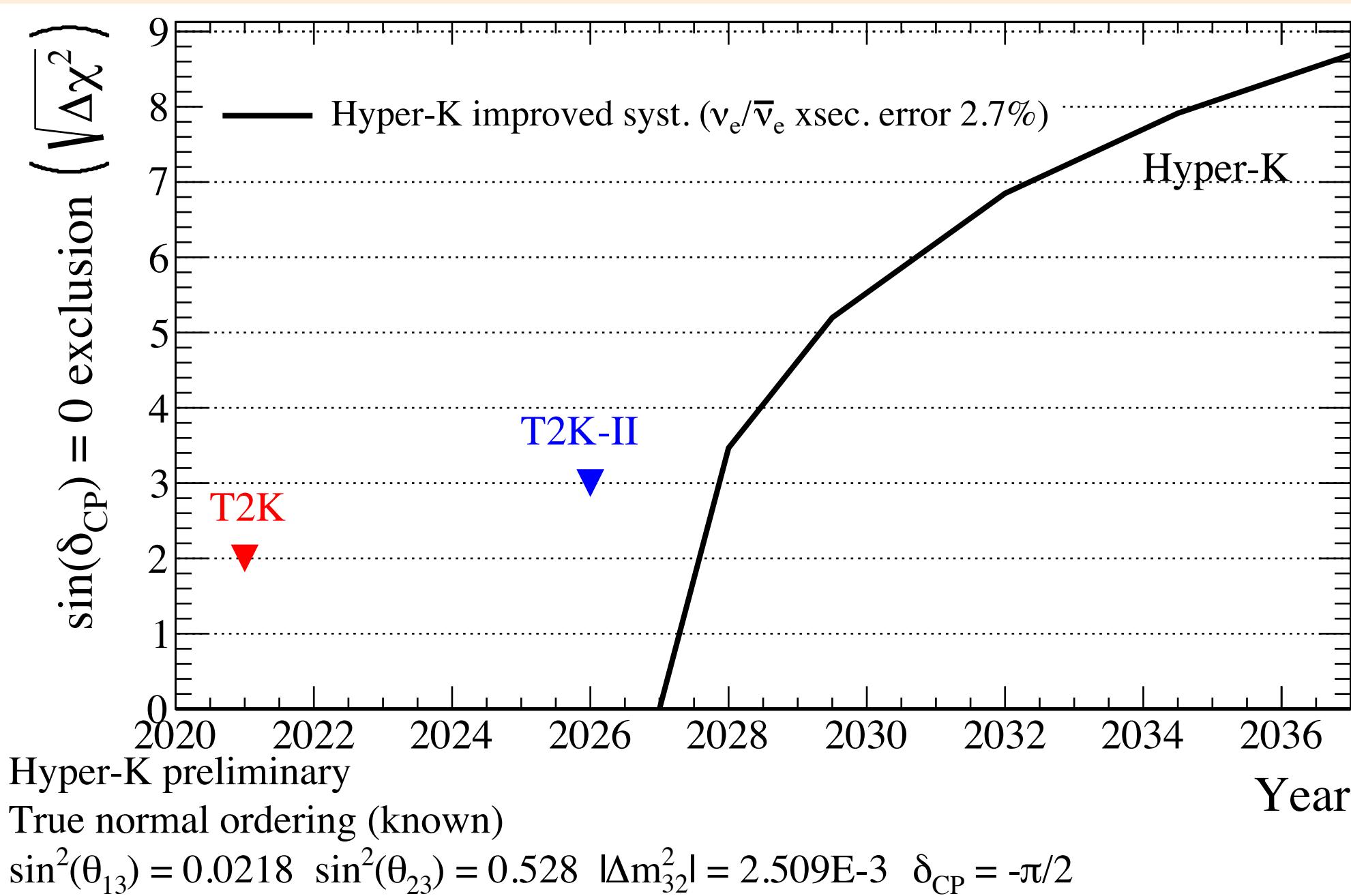
	Atmospheric v	T2K beam v
Baseline/path length	10-13000km	295km
Densities → matter effects	$\rho_1 = 13 \text{ g.cm}^{-3}$ to $\rho_4 = 3 \text{ g.cm}^{-3}$	$\rho = 2,6 \text{ g.cm}^{-3}$
Energies	100MeV à 100GeV	600MeV

→ Consistent estimation of detection systematic uncertainties between both experiments



R. B. Patterson , Annu. Rev. Nucl. Part. Sci., vol. 65 , . 2015

Back-up_HK



Back-up_MCMC

Samples and variables

Atmospheric MC

3 T2K samples : **1Re, 1Rmu, 1Re1de**

T2K Cut Flow (9 cuts) :

- **Wall**
- **To wall**
- **Electron momentum**
- Nb rings → discrete variable
- E/mu separation
- **Momentum**
- Nb of decay electrons → discrete variable
- **Separation with pion**
- **Reconstructed energy**

Continuous variables involved (6) :

- fq1rpos *3components *2PID
- fq1rdir *2 angles *2PID
- fq1rmom *2PID
- fq1rnll *3PID
- fqpi0nll
- fqpi0mass

17 α/β pairs

β is the shifting parameter
 α is the smearing parameter