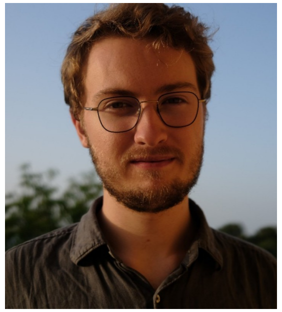
Future sensitivity of the T2K experiment

with its upgraded neutrino beam and optimisation of the neutrino-antineutrino running modes



Pierre Boistier
CEA Saclay/IRFU, FRANCE

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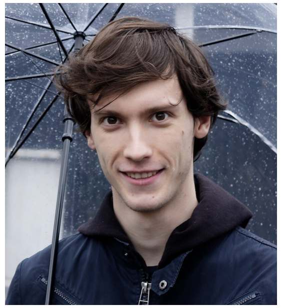
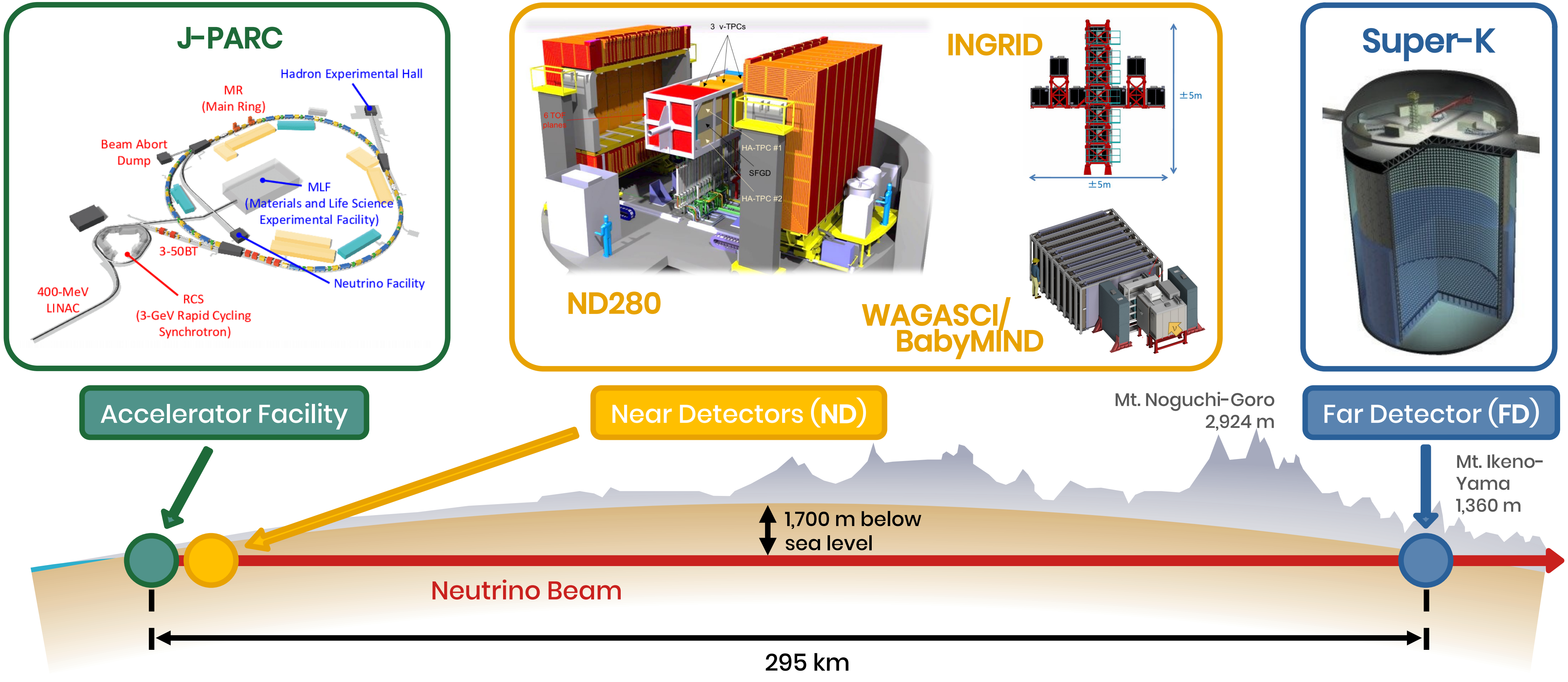


on behalf of the T2K COLLABORATION

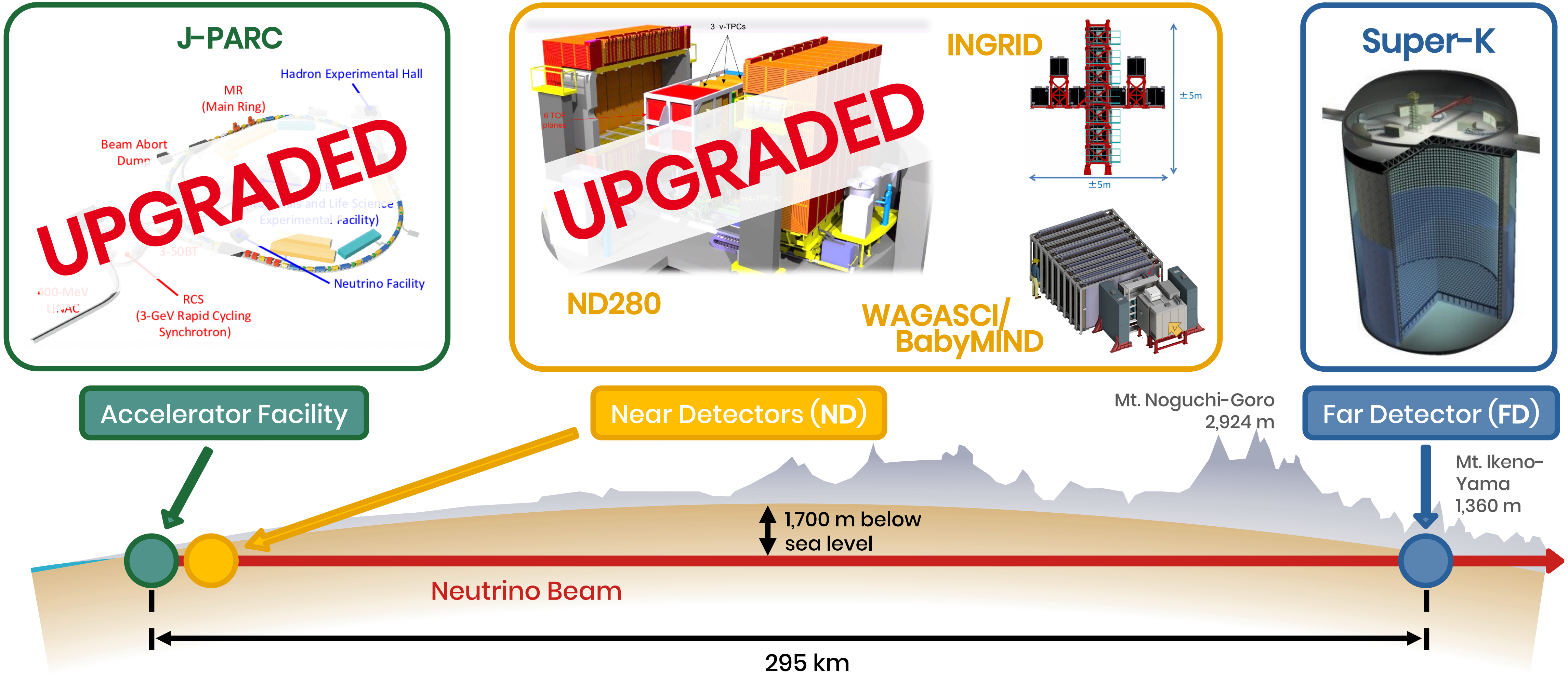
IRN Neutrino Nov. 2025
LPNHE, Paris

1. Introduction

The T2K experiment



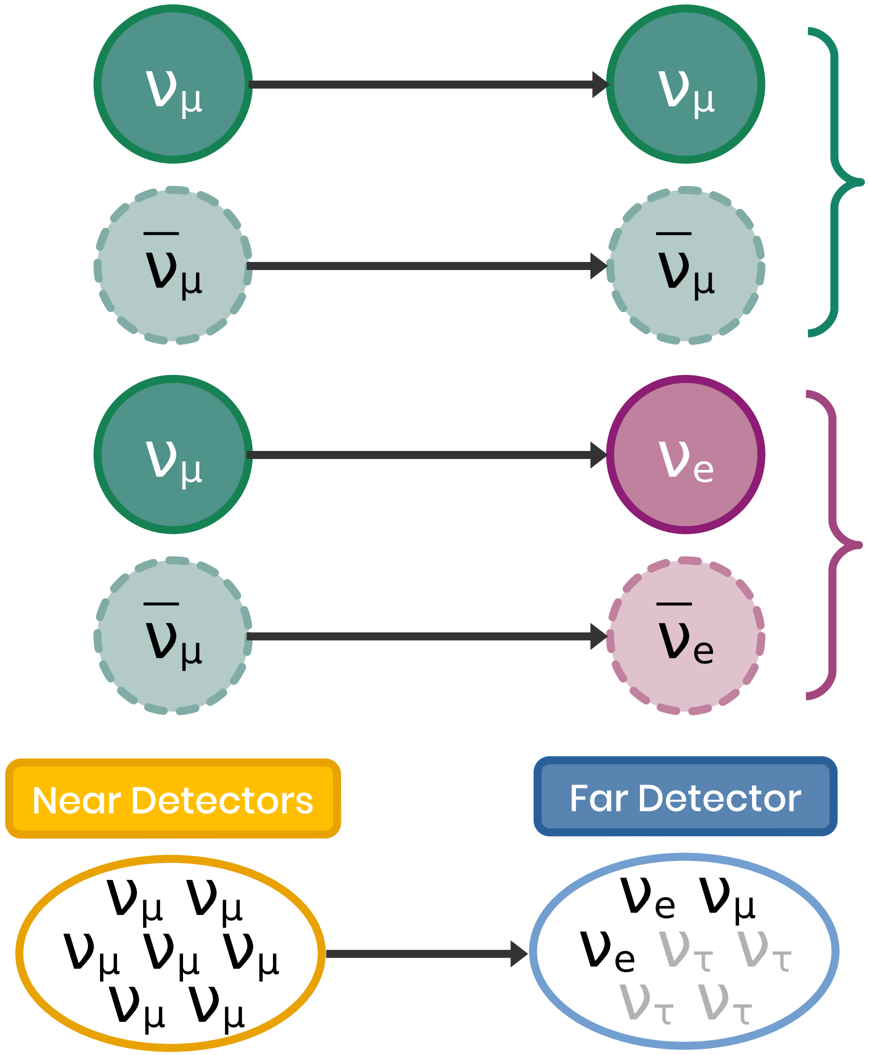
The T2K experiment



The T2K experiment

Important **French contribution** on **building and running all near detectors.** Strong involvement in data analysis, including **neutrino oscillations**, **SK atmospherics** and **DSNB search.**

Oscillation channels at T2K



Disappearance channels

at first order:

Δm^2_{32} and θ_{23}

Appearance channels

at first order:

δ_{CP} and θ_{13}

Combination of the 4 channels to resolve degeneracies between different oscillation parameters

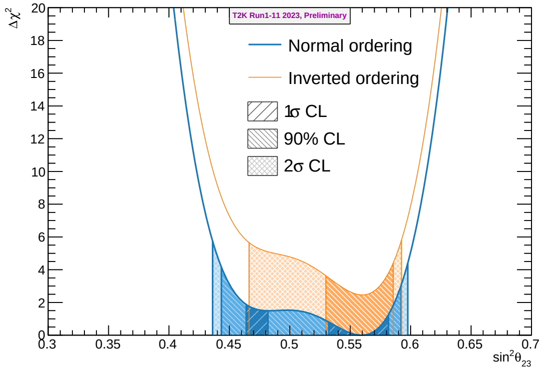
→ **Especially the $\nu/\bar{\nu}$ ratio**

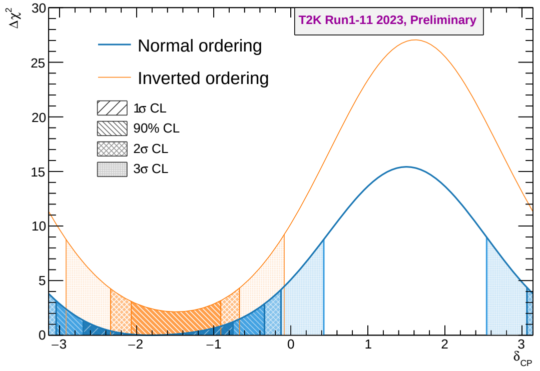
T2K oscillation physics:

- → CP violation;
- → Δm^2_{32} (NO) / $|\Delta m^2_{31}|$ (IO)
- → θ_{23} octant
- → oscillation interpretation beyond PMNS (unitarity tests…)
- → *Mass Ordering* ; θ_{13}

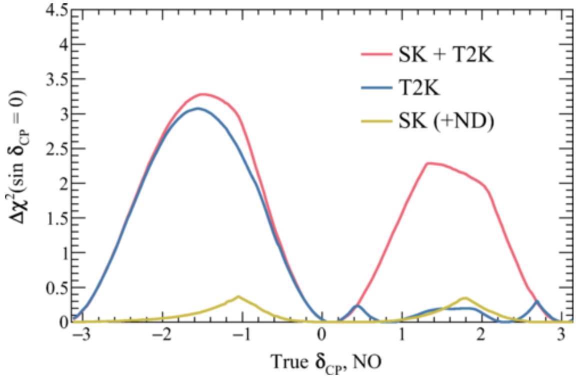
T2K: most recent results

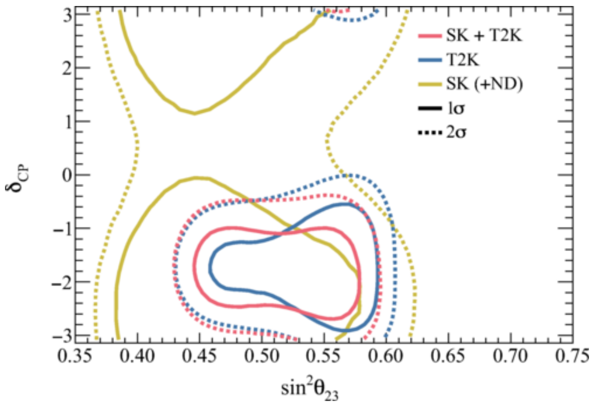
See T2K plenary talk by Y. Prabhu at NuFact2025 for more details and latest results



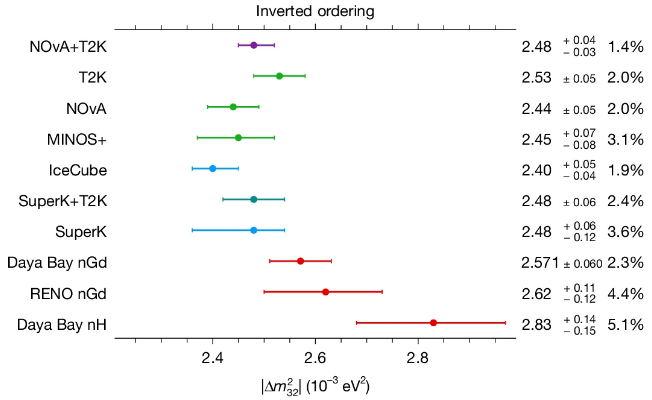


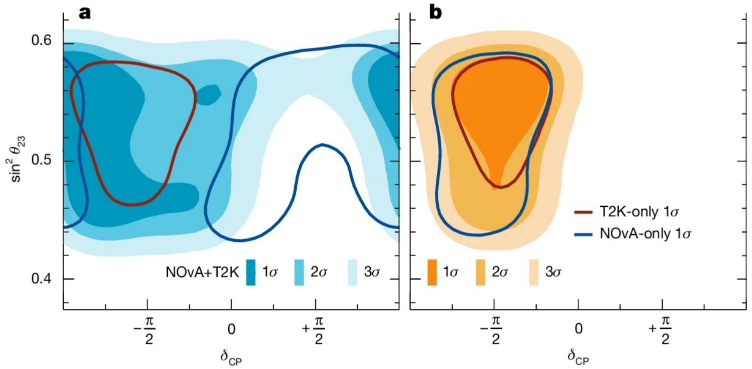
Y. Prabhu, NuFact 2025





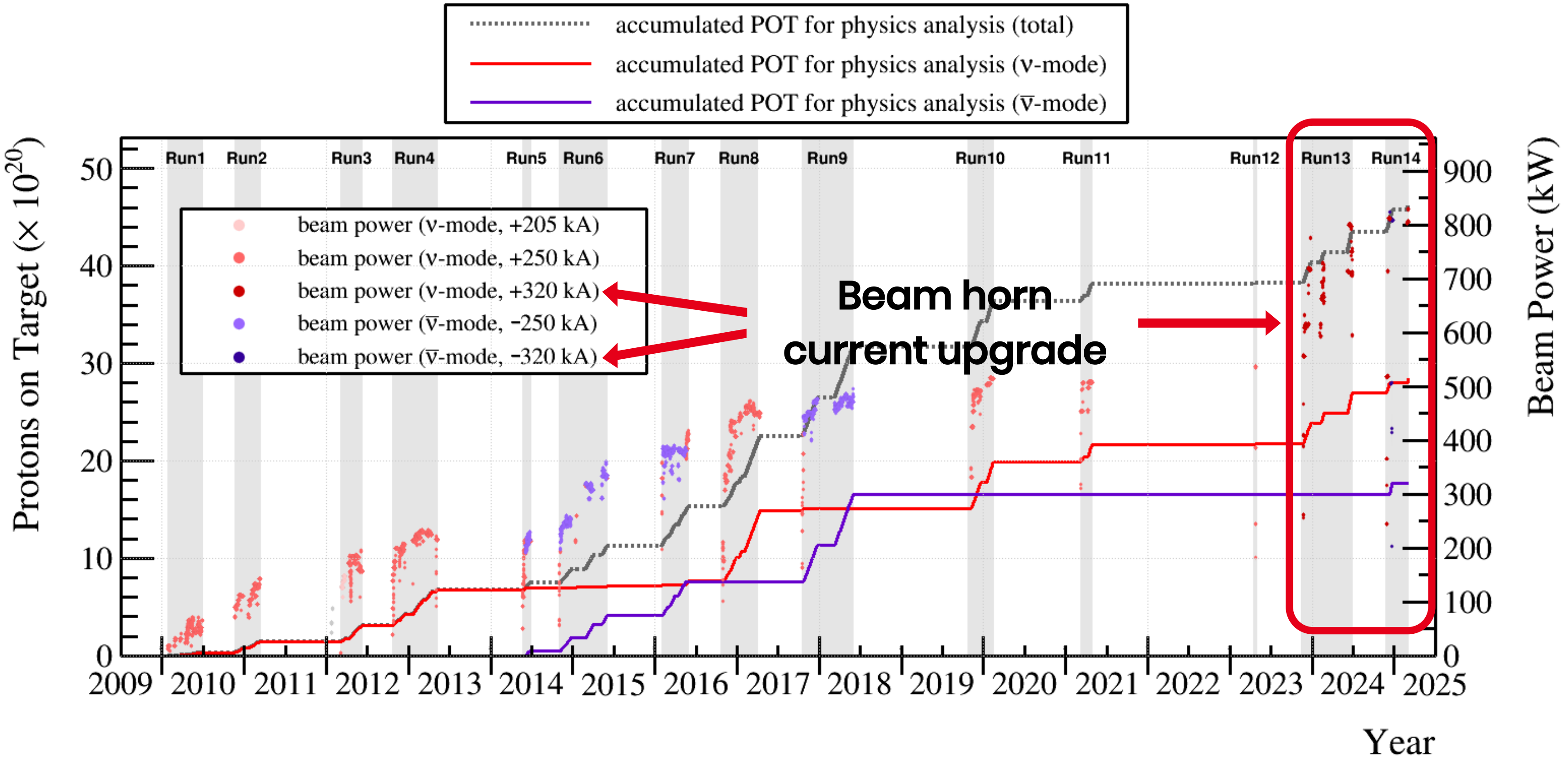
Phys. Rev. Lett. 134 (2025) 011801





Nature 646, 818–824 (2025)

Current and future statistics



Now

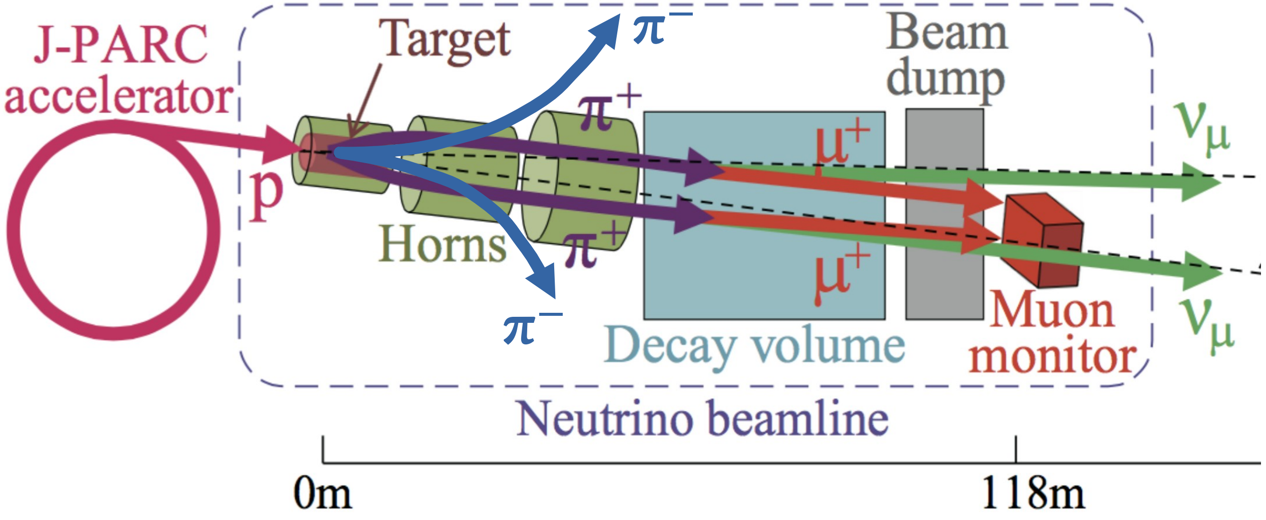
4.62 $\times 10^{21}$ POT

Nominal plan by end of 2027

10.0 $\times 10^{21}$ POT

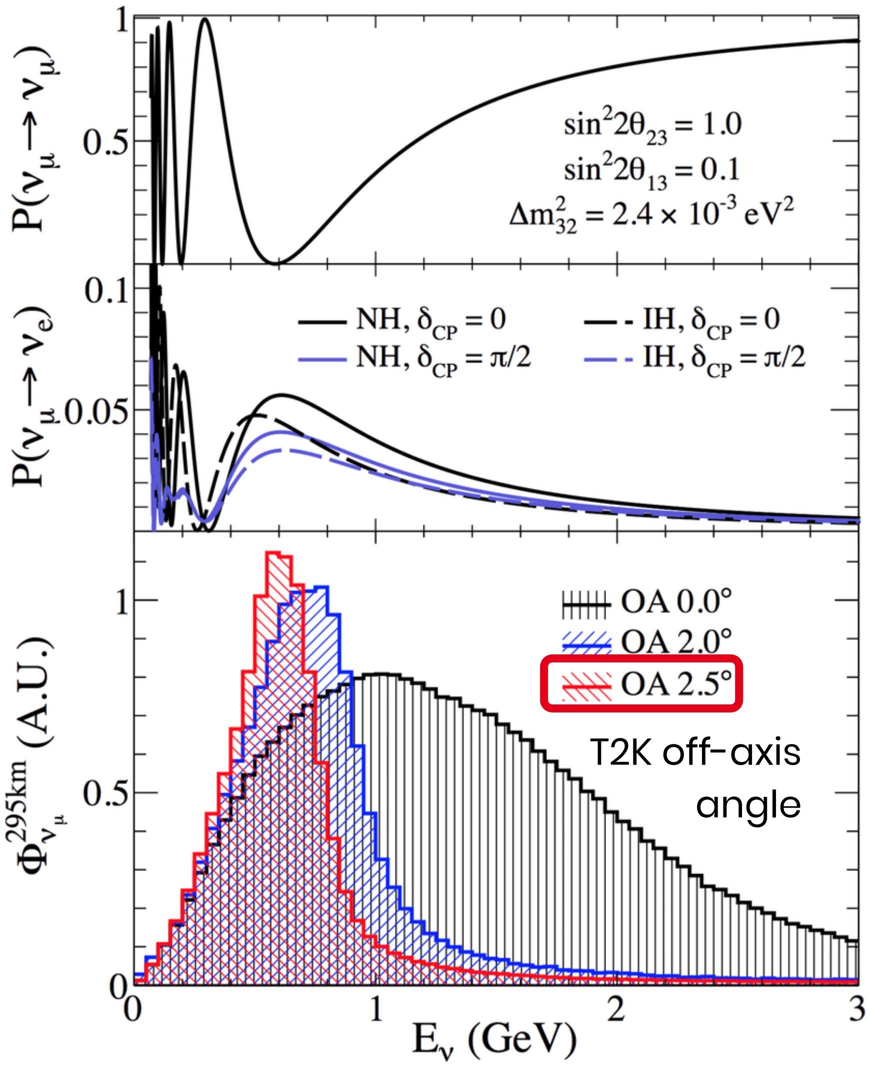
- POT = "Protons On Target" (= statistics)
- 2 years of data to go before Hyper-K takes over (in 2028)

Producing neutrinos at T2K



Mesons focused/defocused by 3 electromagnetic horns
→ **neutrino mode** (“Forward Horn Current”, **FHC**)
→ **antineutrino mode** (“Reversed Horn Current”, **RHC**)

UPGRADE: from **250 kA** to **320 kA**



Oscillated neutrinos at SK: beam upgrade impact

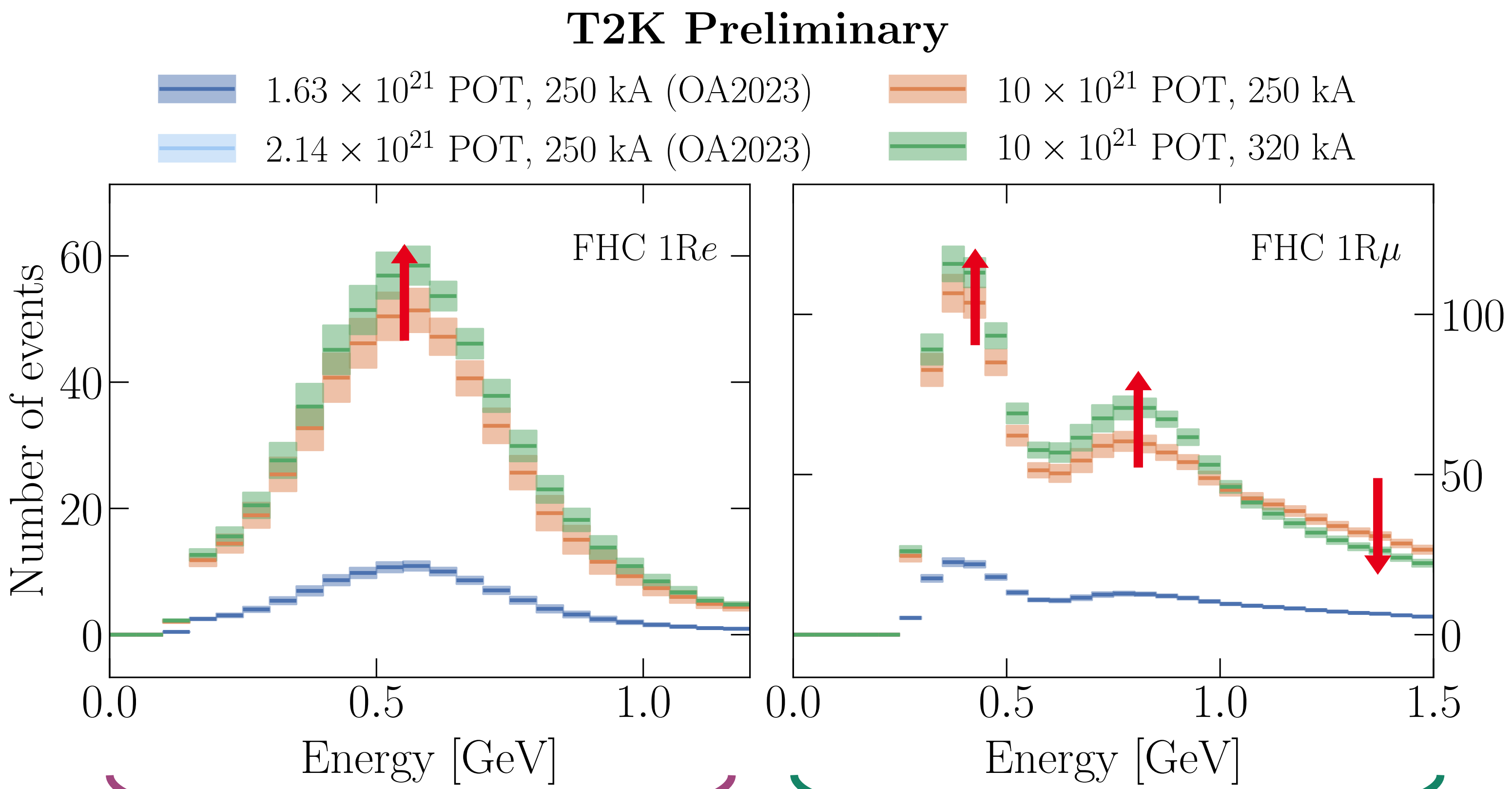
Today

Future (old beam config.)

Future (upgrad. beam config.)

+13.01%

oscillated ν_e events (1Re)



Appearance channels (e-like)

Disappearance channels (μ-like)

Neutrino mode

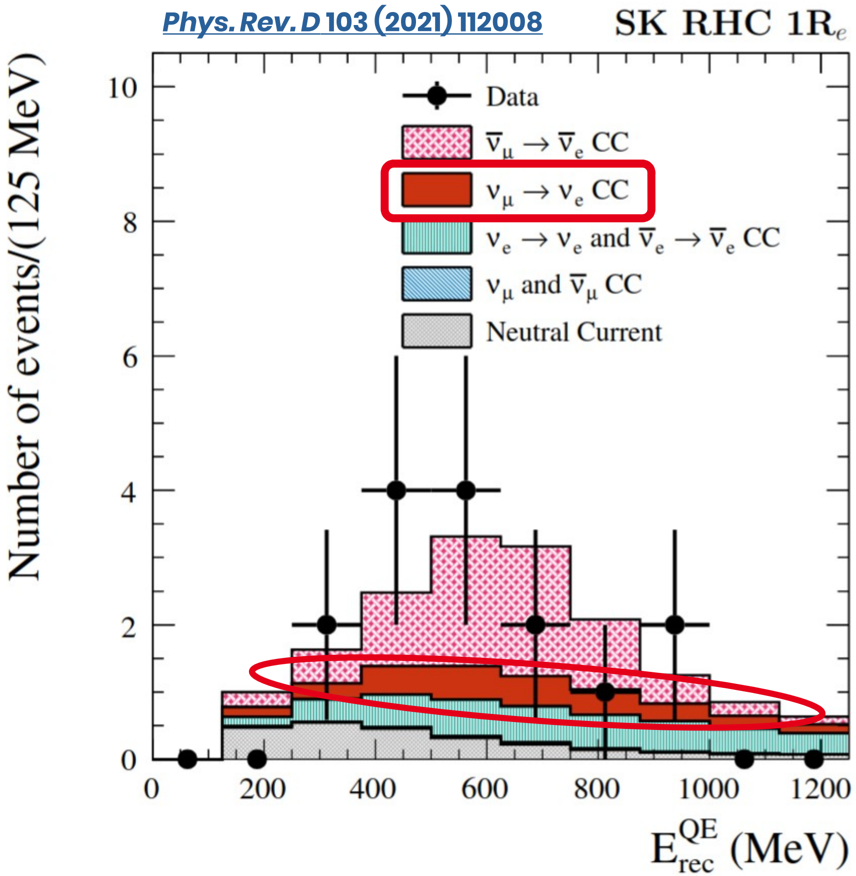
- Global **increase in total number of events**, specifically **appearance** channels
- Increase events at oscillation maximum, decrease at high energies → **narrower energy range**

Upgraded beam: increased purity

Appearance channels (e-like)
Antineutrino mode

+14.01%
oscillated $\bar{\nu}_e$ events (1Re)

40.61% → 32.55%
wrong-sign bkg/signal $\bar{\nu}_e$ events (1Re)



- better focusing of right-sign mesons (signal) and defocusing of wrong-sign mesons (main background) → **better purity**
- CP violation sensitivity from ν_e / $\bar{\nu}_e$ **asymmetry** → need to reduce **wrong-sign background**

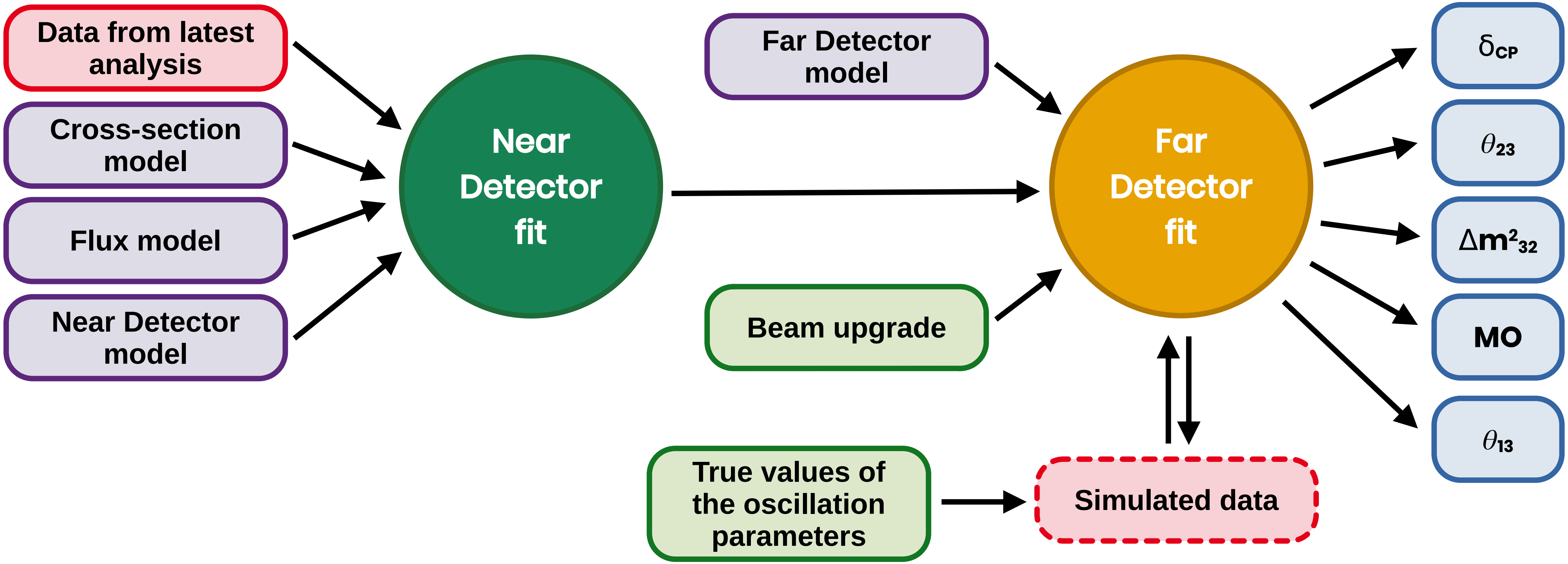
2. Strategy of the study

Scope and approximations of the study

GOAL

ESTIMATE THE FUTURE SENSITIVITY OF THE T2K EXPERIMENT

as a function of **statistics**; and as a function of **neutrino/antineutrino running ratio**



Scope and approximations of the study

GOAL

ESTIMATE THE FUTURE SENSITIVITY OF THE T2K EXPERIMENT

as a function of **statistics**; and as a function of **neutrino/antineutrino running ratio**

Scaled with **statistics** and ND280Upgrade **new fiducial mass**
→ ND fit is not performed again!

Far Detector model

Beam upgrade

Far Detector fit

True values of the oscillation parameters

Scaled with **statistics** and **$\nu/\overline{\nu}$ ratio**

δ_{CP}

θ_{23}

Δm^2_{32}

MO

θ_{13}

Scope and approximations of the study

True values of the oscillation parameters →

Parameter	Set A22	
Δm^2_{21}	7.53×10^{-5} eV^2/c^4	
Δm^2_{32} [NO] / $\lvert\Delta m^2_{31}\rvert$ [IO]	2.494×10^{-3} eV^2/c^4	
$\sin^2\theta_{23}$	0.561	→ θ_{23} upper octant
$\sin^2\theta_{12}$ ($\sin^2 2\theta_{12}$)	0.307 (0.851)	
$\sin^2\theta_{13}$ ($\sin^2 2\theta_{13}$)	0.0220 (0.0861)	
δ_{CP}	-1.601 rad	→ max CP violation
Earth matter density	2.6 g/cm^3	
Baseline length	295 km	
Mass ordering	Normal	→ Normal Ordering

A22 → near T2K best-fit in 2022

3. CP violation sensitivities

CPV search : appearance channel

At T2K, the 3 leading terms are:

$$P_{\mu e} = 4s^2_{23}s^2_{13}c^2_{13}\sin^2\Delta_{31}$$ **Leading term** (sensitivity to Δm^2 and θ_{23})

$$\boxed{\mp} J_{\mathrm{CP}}\sin\Delta_{32}\sin\Delta_{31}\sin\Delta_{21}$$ **CP violating term** (about 30% effect → δ_{CP})

$$\boxed{\pm} 8a(1-2s^2_{13})s^2_{23}s^2_{13}c^2_{13}\frac{\sin\Delta_{31}}{\Delta m^2_{31}}(\sin\Delta_{31}-\Delta_{31}\cos\Delta_{32})$$ **Matter effects** (10% → MO)

$$+\cdots\ ,$$

with the Jarlskog invariant:

$$\boxed{J_{\mathrm{CP}} = s_{13}c^2_{13}s_{12}c_{12}s_{23}c_{23}\sin\delta_{\mathrm{CP}}}$$

$$c_{ij} = \cos\theta_{ij}$$
$$s_{ij} = \sin\theta_{ij}$$
$$\Delta_{ij} = \frac{\Delta m^2_{ij}L}{4E}$$
$$a = 2\sqrt{2}G_F n_e E$$

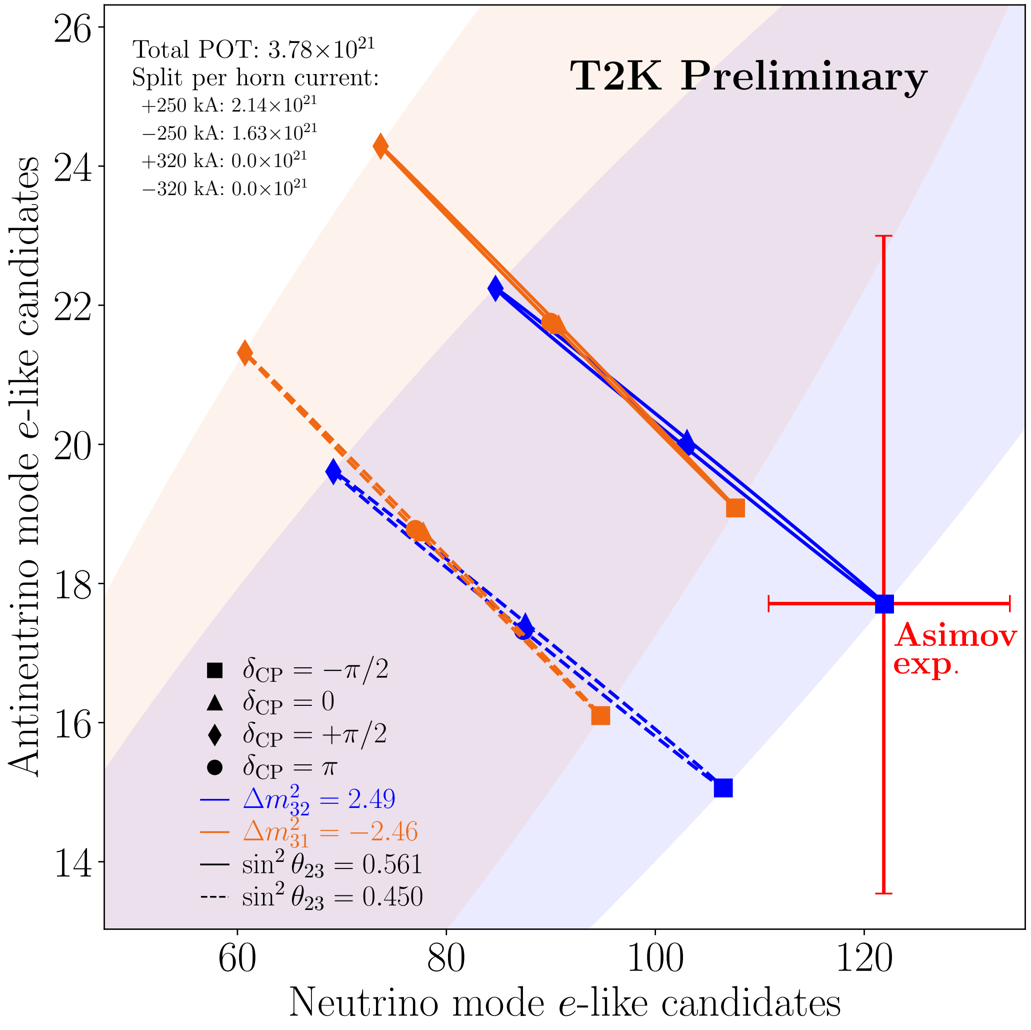
CPV search : bi-event plot

2 CP violating term

$$\mp J_{CP} \sin\Delta_{32} \sin\Delta_{31} \sin\Delta_{21}$$

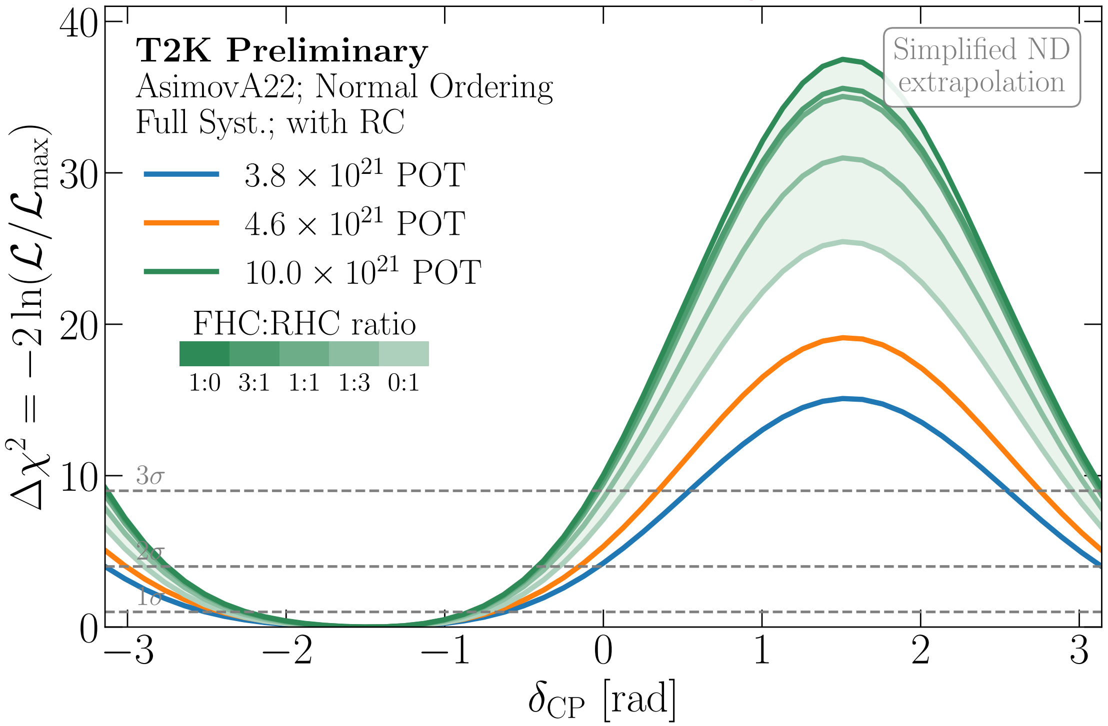
$$J_{CP} = s_{13}c_{13}^2 s_{12}c_{12}s_{23}c_{23}\boxed{\sin\delta_{CP}}$$

term sensitive to CP violation and
$\sin\delta_{CP}$: but many degeneracies...
bi-event plot!

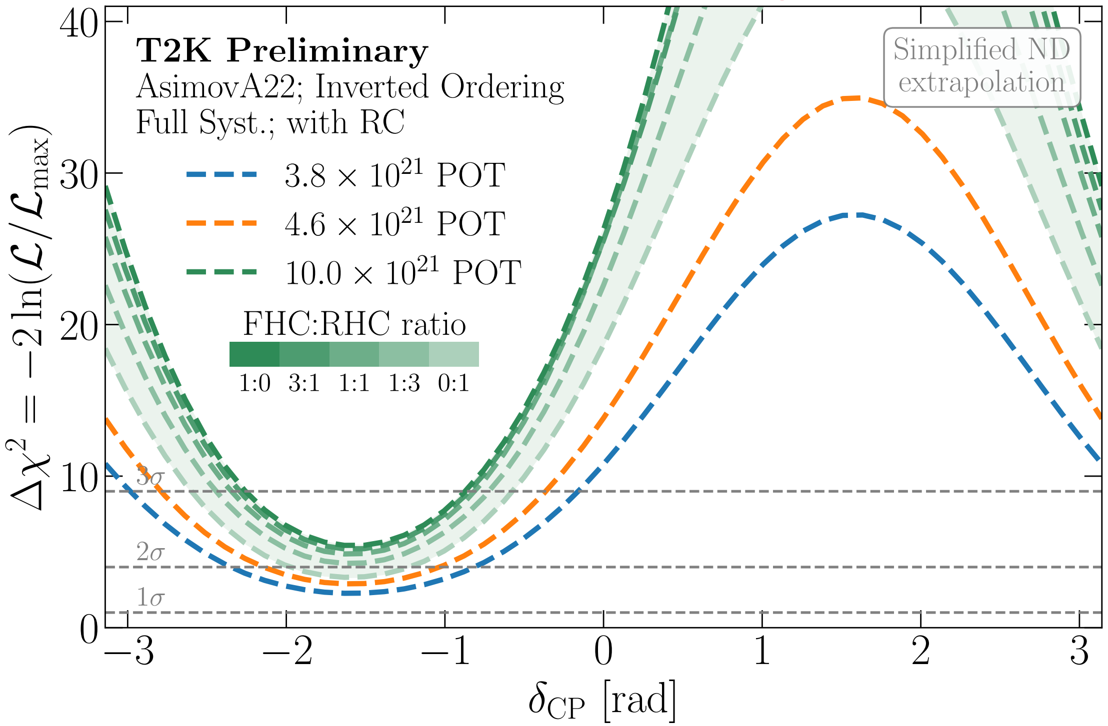


CPV search : δ_{CP} likelihood scan

Normal ordering

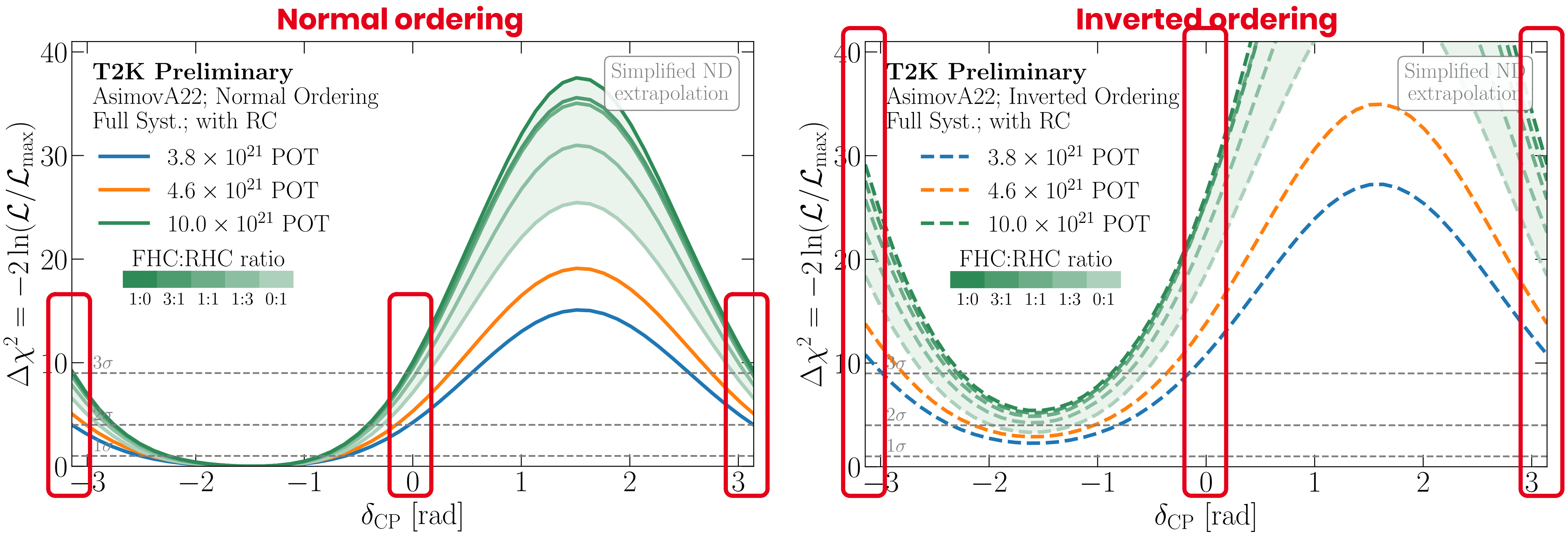


Inverted ordering



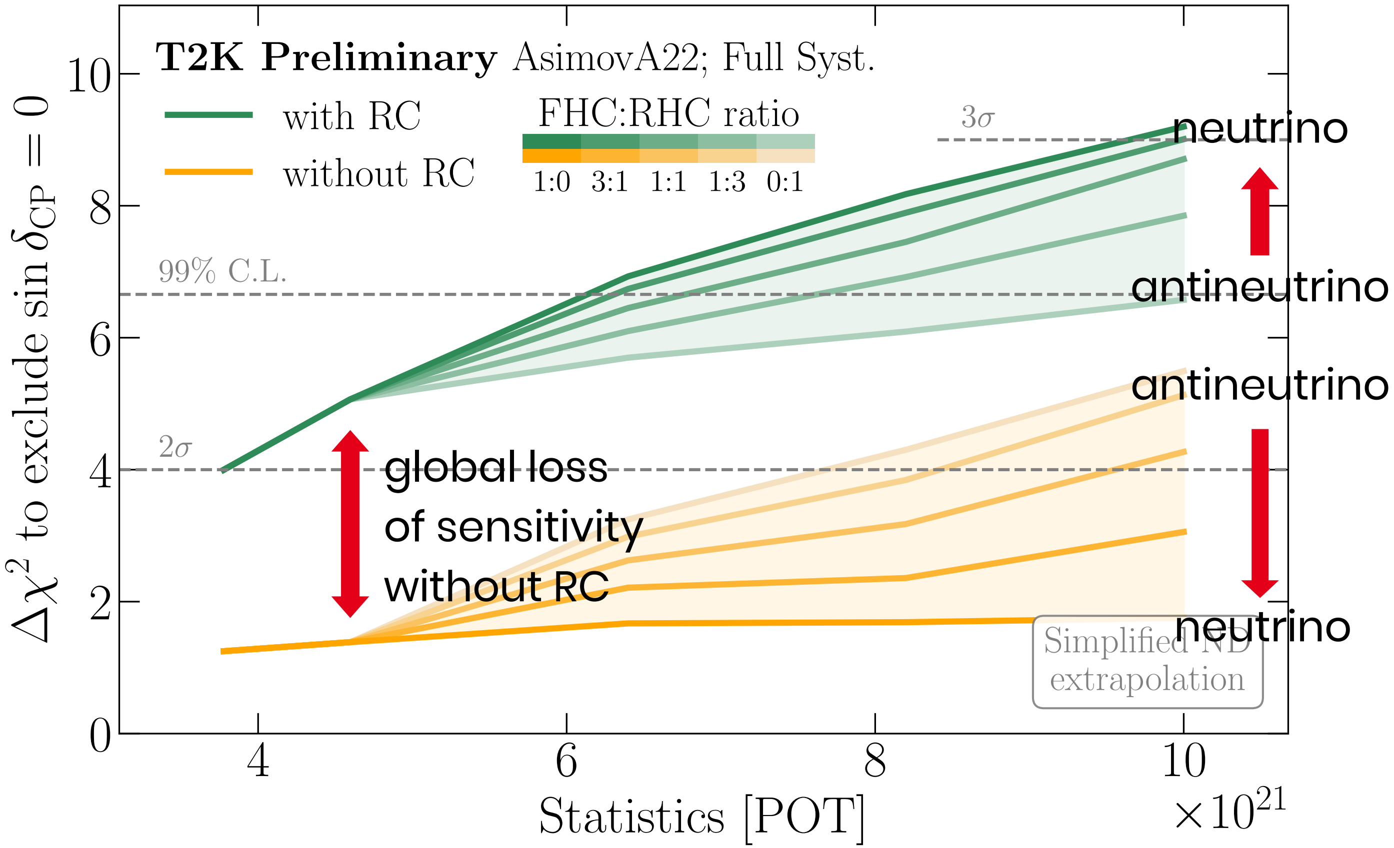
- good exclusion of the **sin δ_{CP} > 0** region;
- some sensitivity of excluding the **wrong ordering**;
- **full neutrino mode** is preferred since neutrino cross-section with matter about ~3 times higher than antineutrinos;

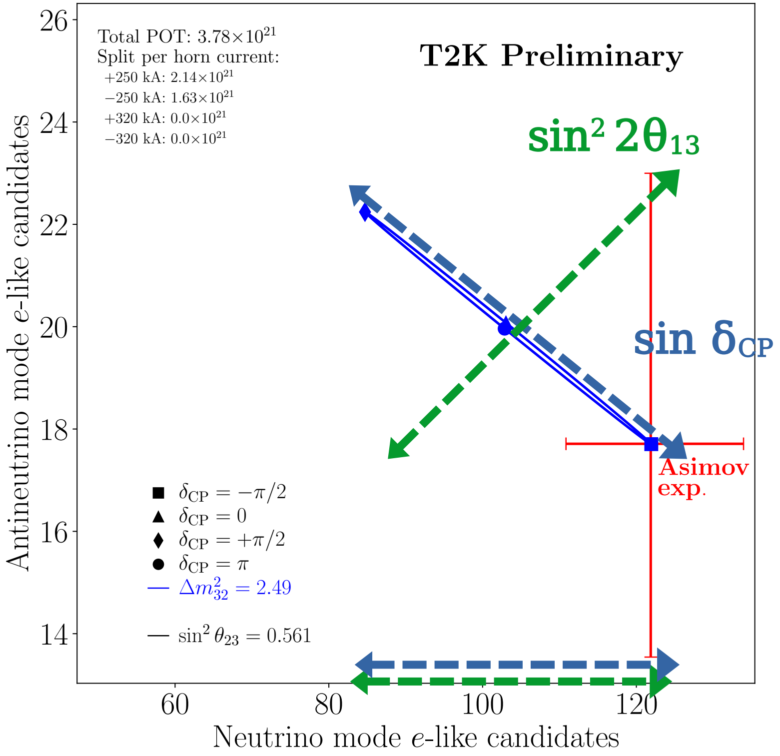
CPV search : CP conservation exclusion



CP conservation exclusion => **min $\Delta\chi^2$ to exclude $\sin \delta_{CP} = 0$**

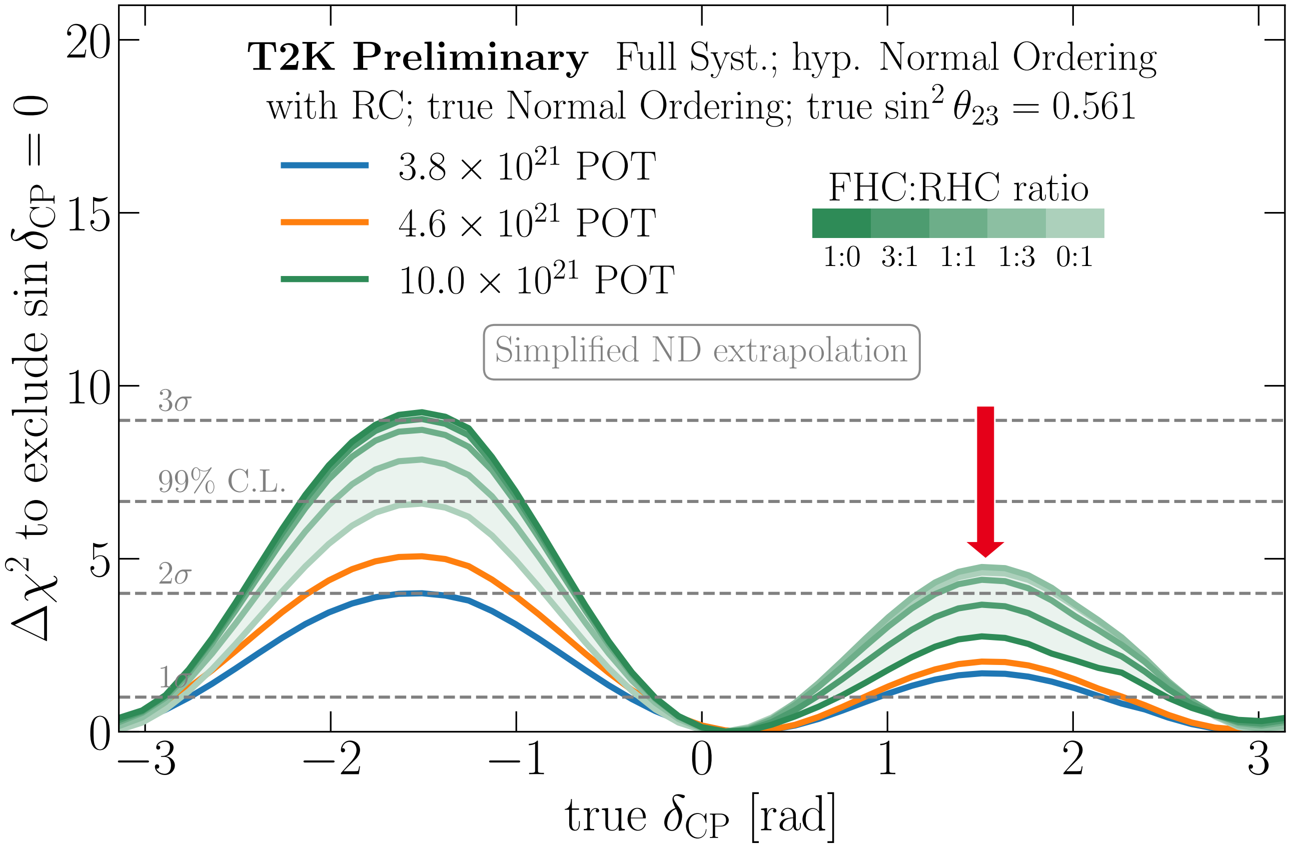
CPC exclusion: Reactor Constraint dependence

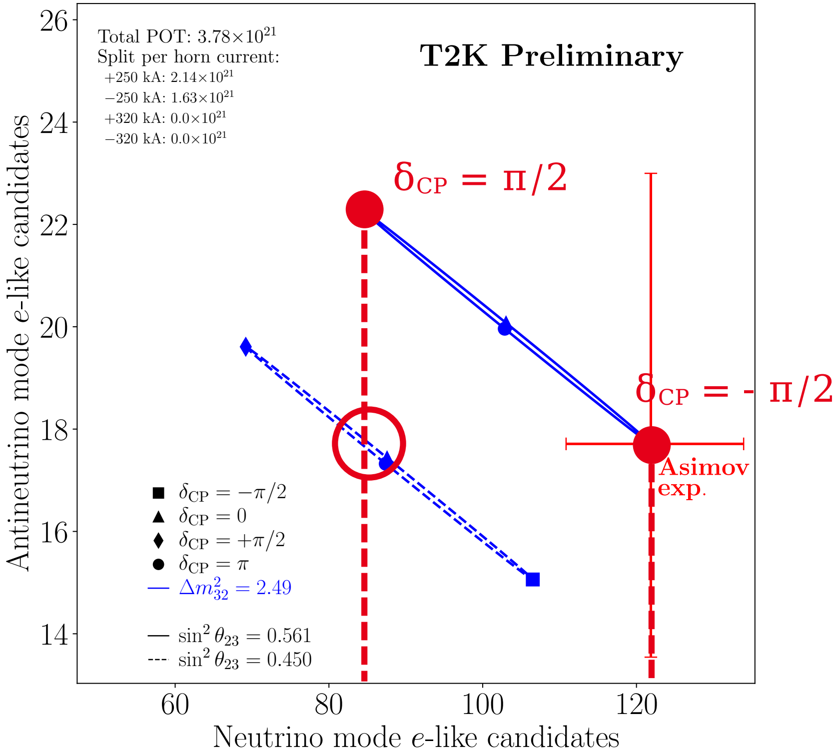




- **δ_{CP} – θ_{13} degeneracy** unresolved without RC → **antineutrino mode is needed to break it**, but more antineutrinos means also less statistics…

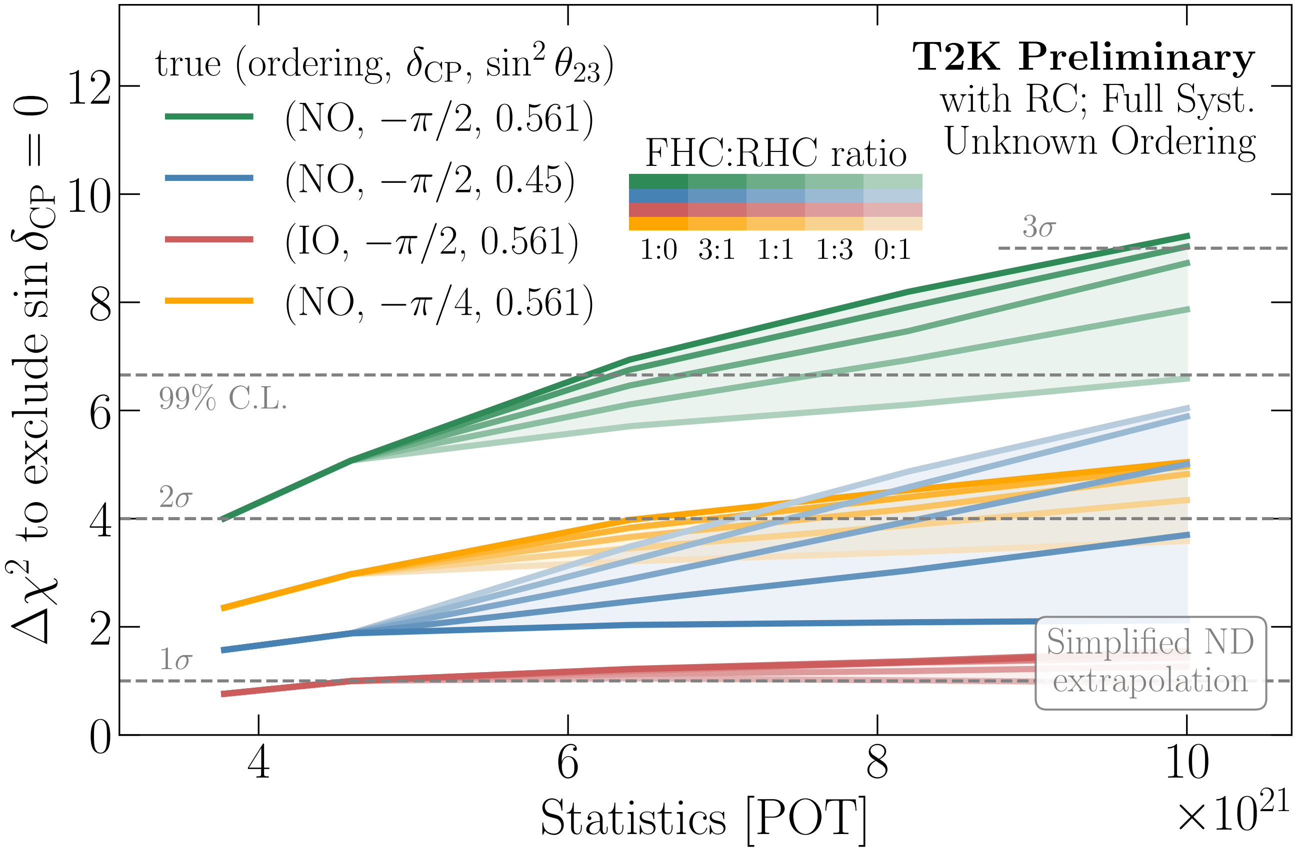
CPC exclusion: Normal Ordering hypothesis

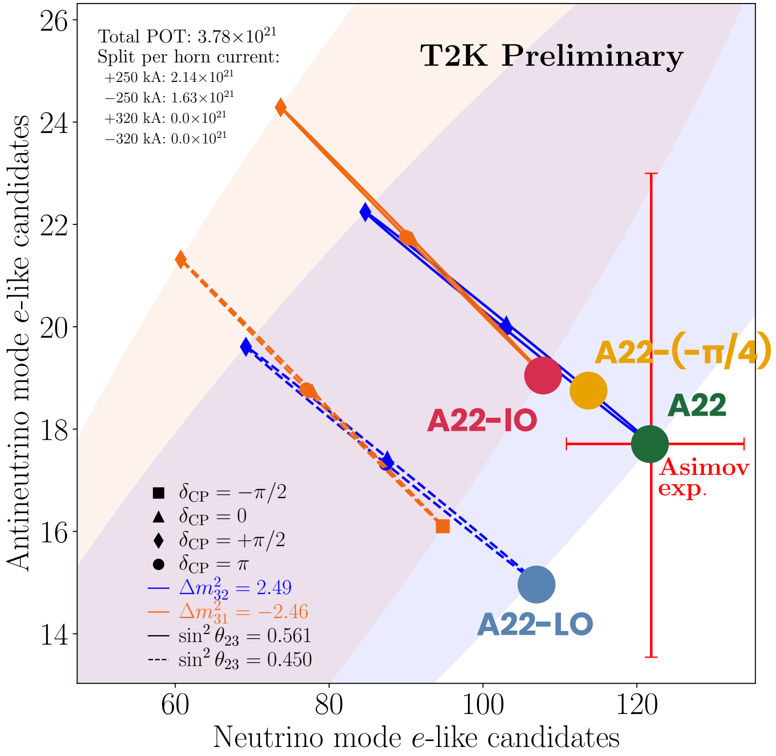




- **$\sin\delta_{CP} < 0$** ⟶ **full neutrino mode** preferred since **far from degeneracies**;
- **$\sin\delta_{CP} > 0$** ⟶ **full antineutrino mode** preferred as it helps solving the $\delta_{CP} - \theta_{23}$ octant degeneracy;

CPC exclusion: summary plot





- the further away from degeneracies ⟶ the better the sensitivity;
- the further away from degeneracies ⟶ **full neutrino mode** is preferred (in upper octant);

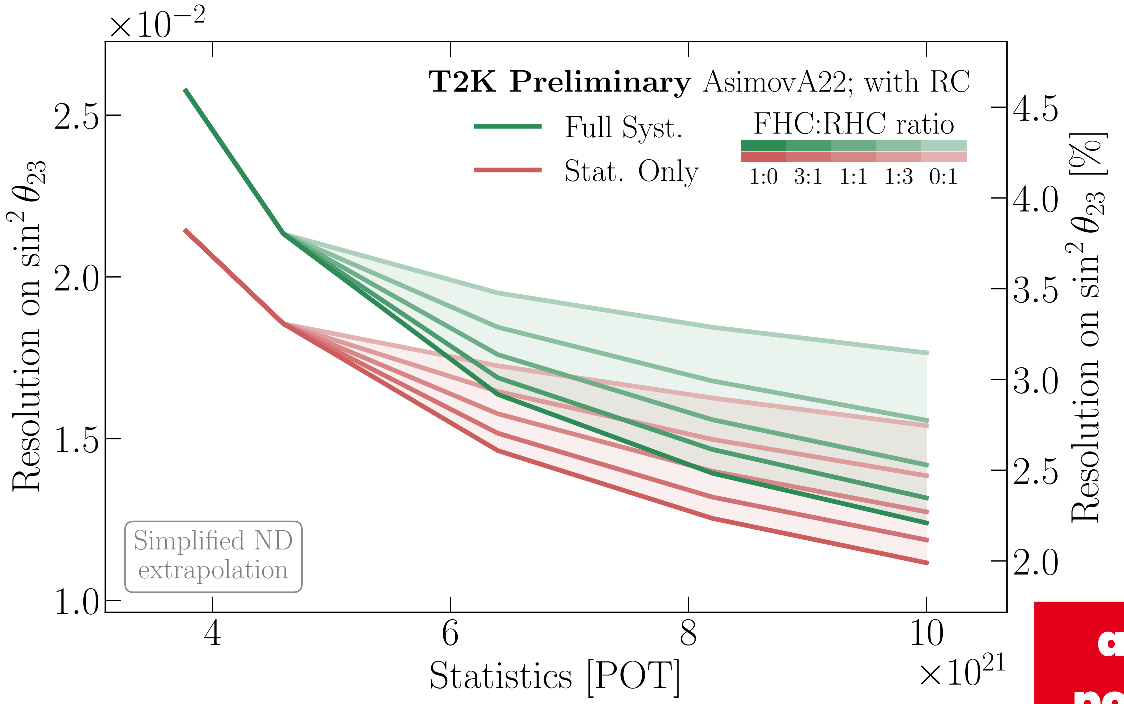
4. Δm^2 and θ_{23} sensitivities

θ_{23} sensitivity

Disappearance channels $\sin^2 \boxed{2}\theta_{23}$

Appearance channels $\sin^2\theta_{23}\,\sin^2 2\theta_{13}$

+ Reactor constraint on θ_{13}

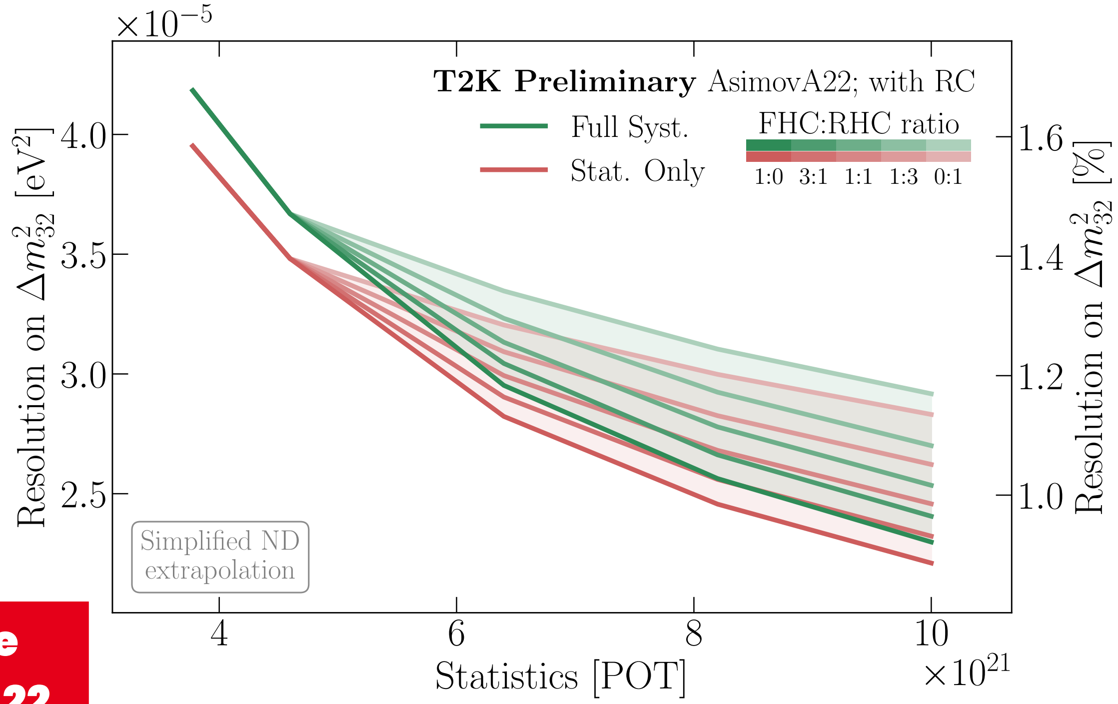


at true point A22

Δm^2 sensitivity

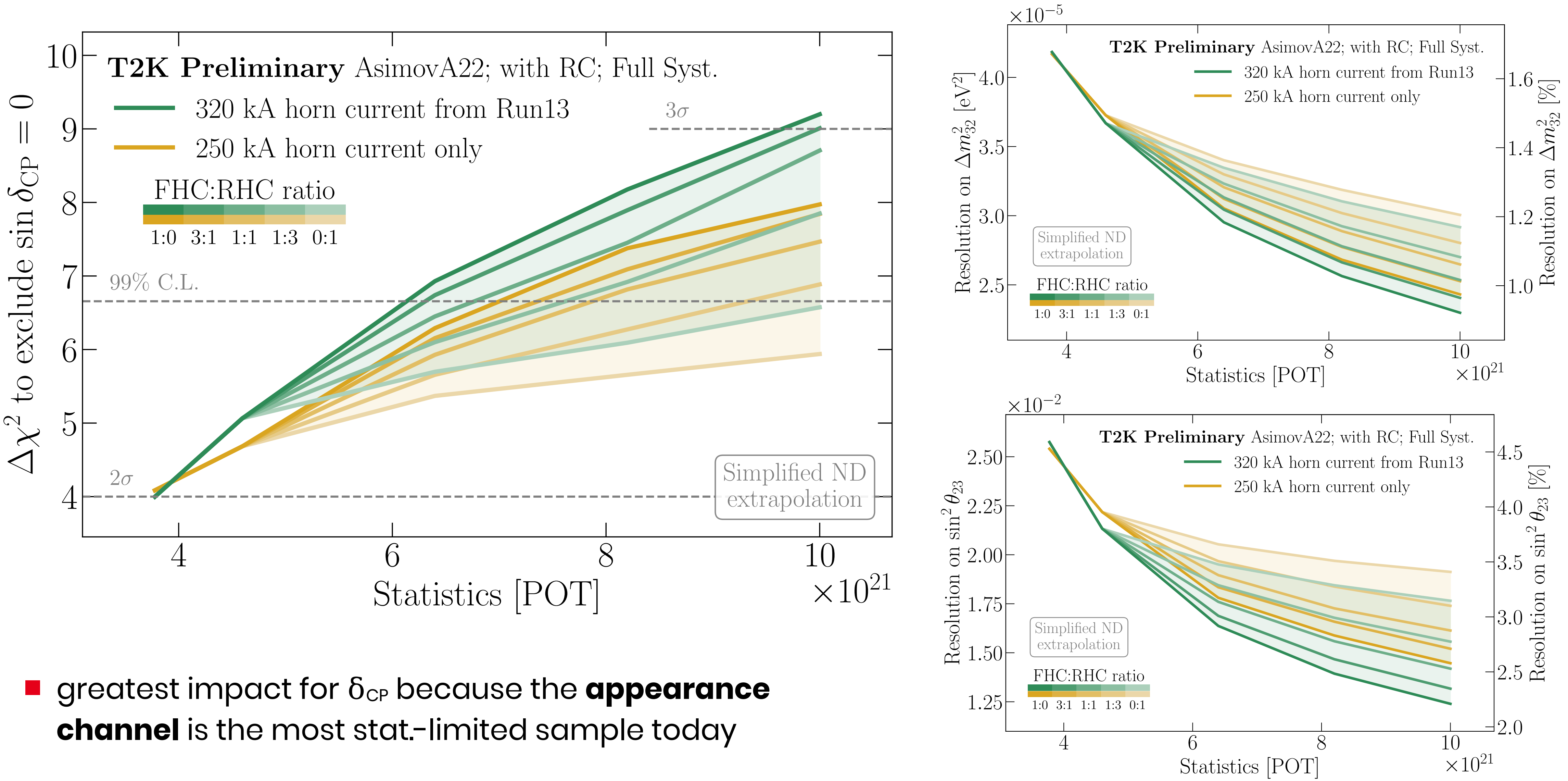
Disappearance channels $\sin^2\left(\frac{\Delta m^2_{\text{eff}} L}{4E}\right)$

$$\Delta m^2_{\text{eff}} \approx \Delta m^2_{32} \approx \Delta m^2_{31}$$



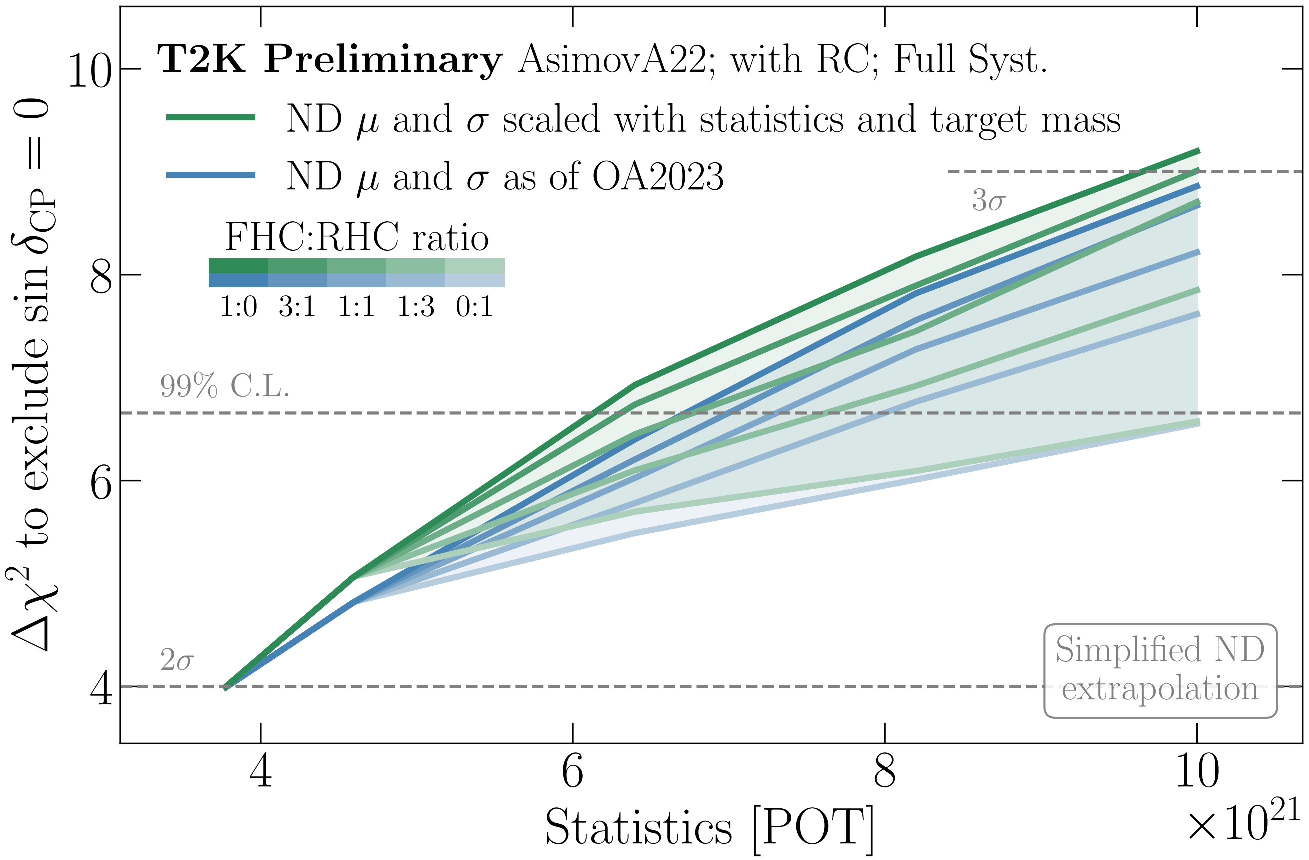
5. Impact of upgrades

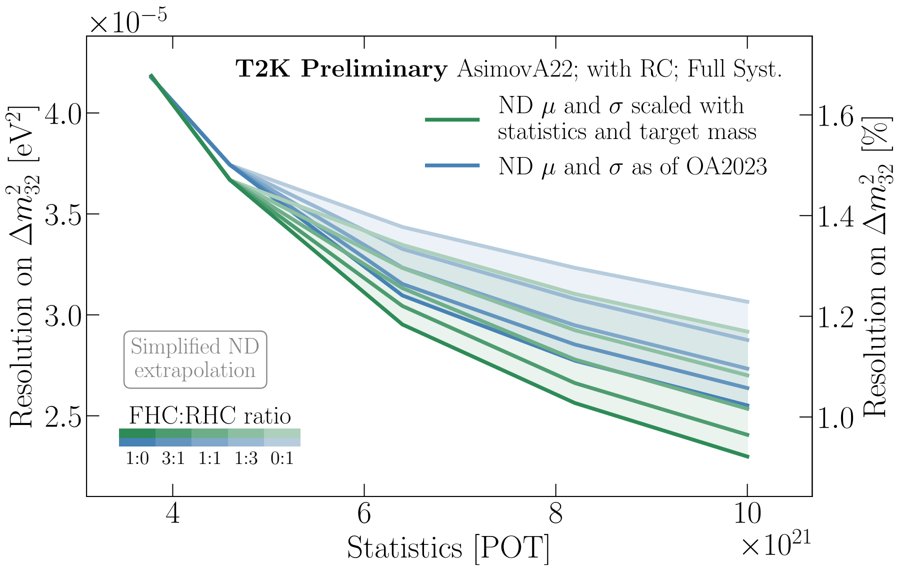
Impact of the upgraded neutrino beam

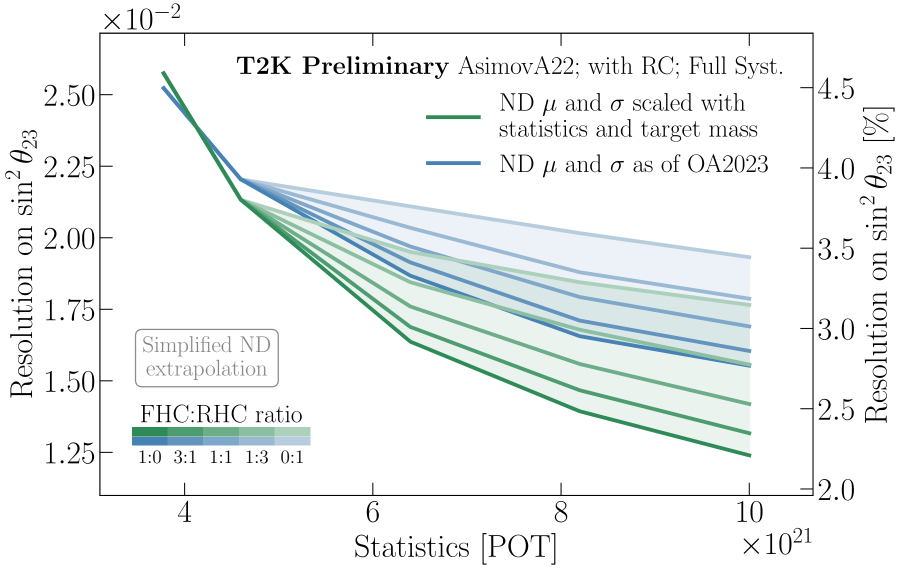


- greatest impact for δ_{CP} because the **appearance channel** is the most stat.-limited sample today

Impact of new ND statistics





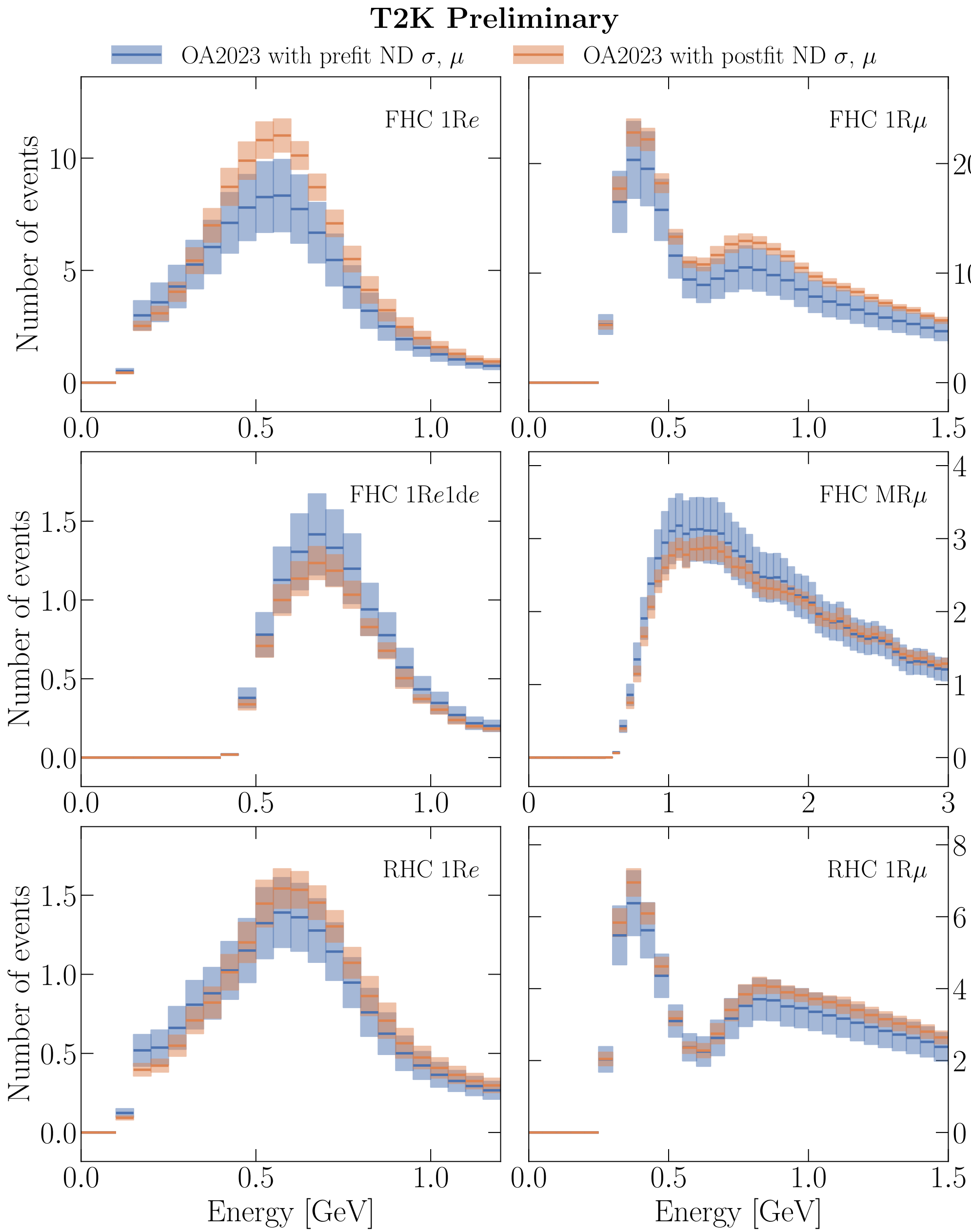


- greatest impact for $\sin^2\theta_{23}$ and Δm^2 because **systematic uncertainties** have a greater impact than they have for CPV

Impact of the ND

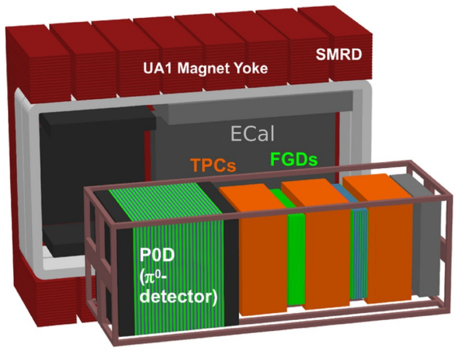
- uncertainty on xsec and flux model ⟶ not good enough model before a **ND data fit**.
  <u>Real role of the ND</u>: not only **shrinking systematics** but set **reliable central values for the model**
  (*e.g.* 2p2h xsec has no prior and is only constrained by the ND)

- in this study: assumption that future data will be in agreement with present data-tuned model
  BUT: with **ND280 Upgrade** ⟶ **better flux+xsec model**

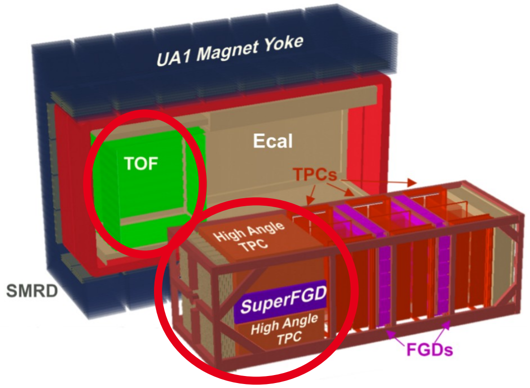


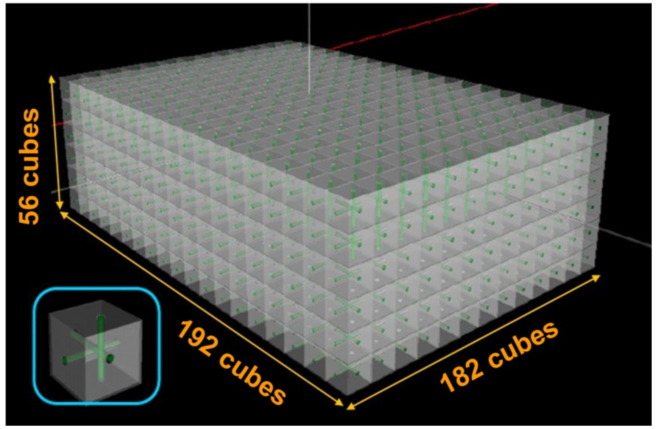
ND280 Upgrade

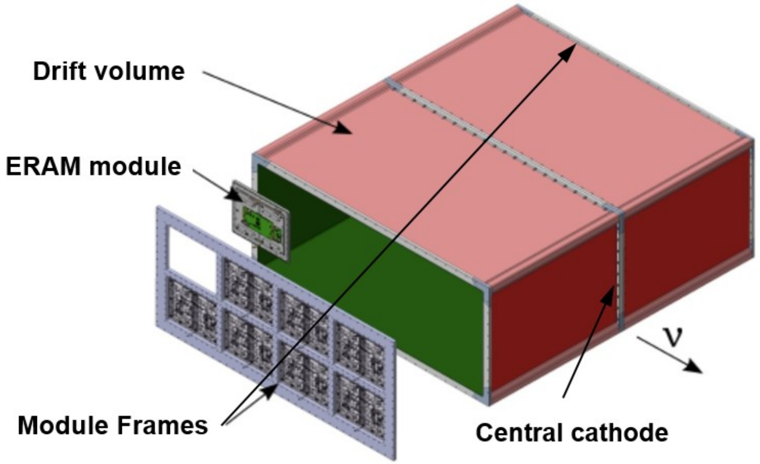
See T2K plenary talk by **T. Daret** at **NuFact2025** for more details and latest results

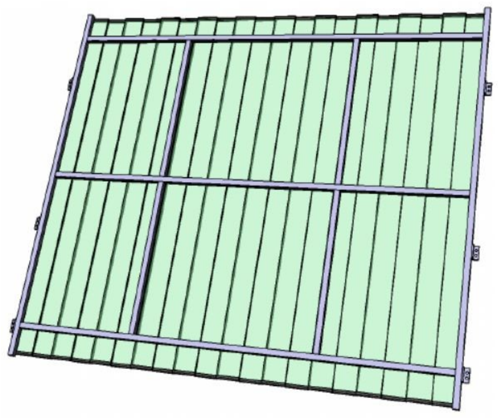


UPGRADE









Super-Fine Grained Detector

- → 2 tons of active target and tracker
- → 2 million 1 cm^3 scintillator cubes
- → isotropic hadron reco. at low p

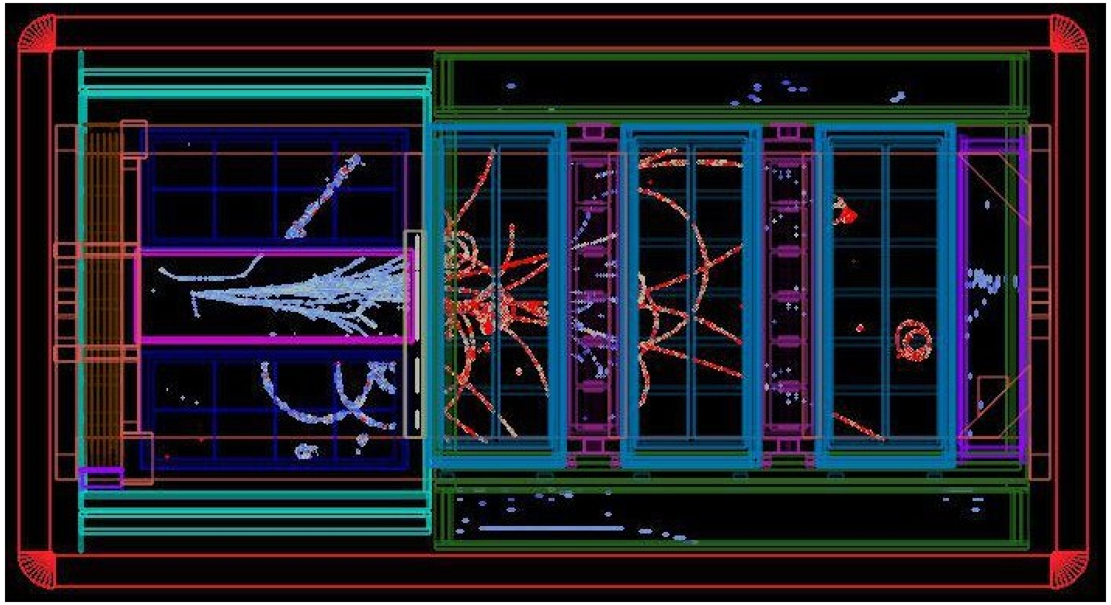
2 High Angle-TPC

- → innovative E field cage design
- → new resistive MicroMegas (ERAM)
- → high-angle scattering reco.

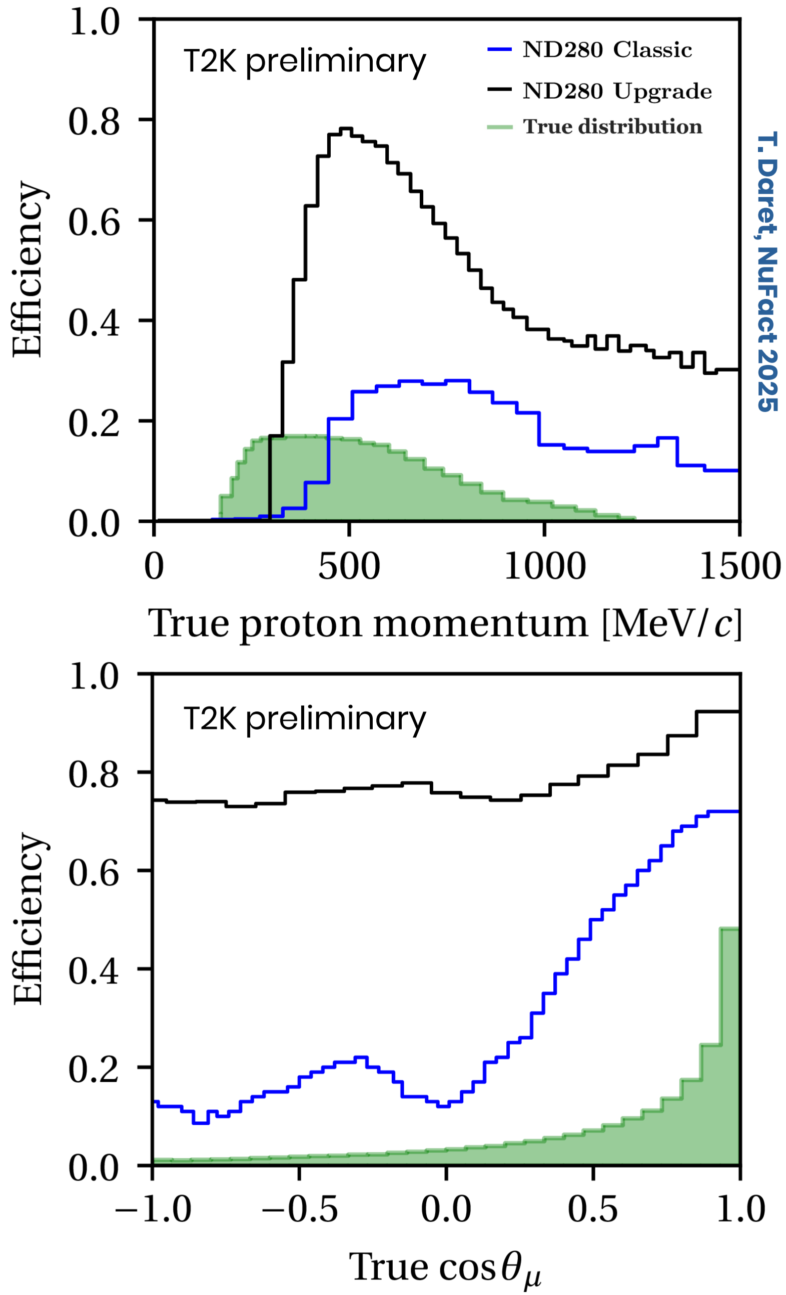
6 Time-of-Flight detectors

- → plastic scintillator bars
- → track orientation ~ 4π coverage
- → OOFV event rejection and PID

ND280 Upgrade



1. **larger angular acceptance**, especially important for muons
2. **lower threshold** for protons and pions
3. first measurement ever of **neutron kinematics** event by event
4. better **electron vs. gamma separation** at low electron momentum

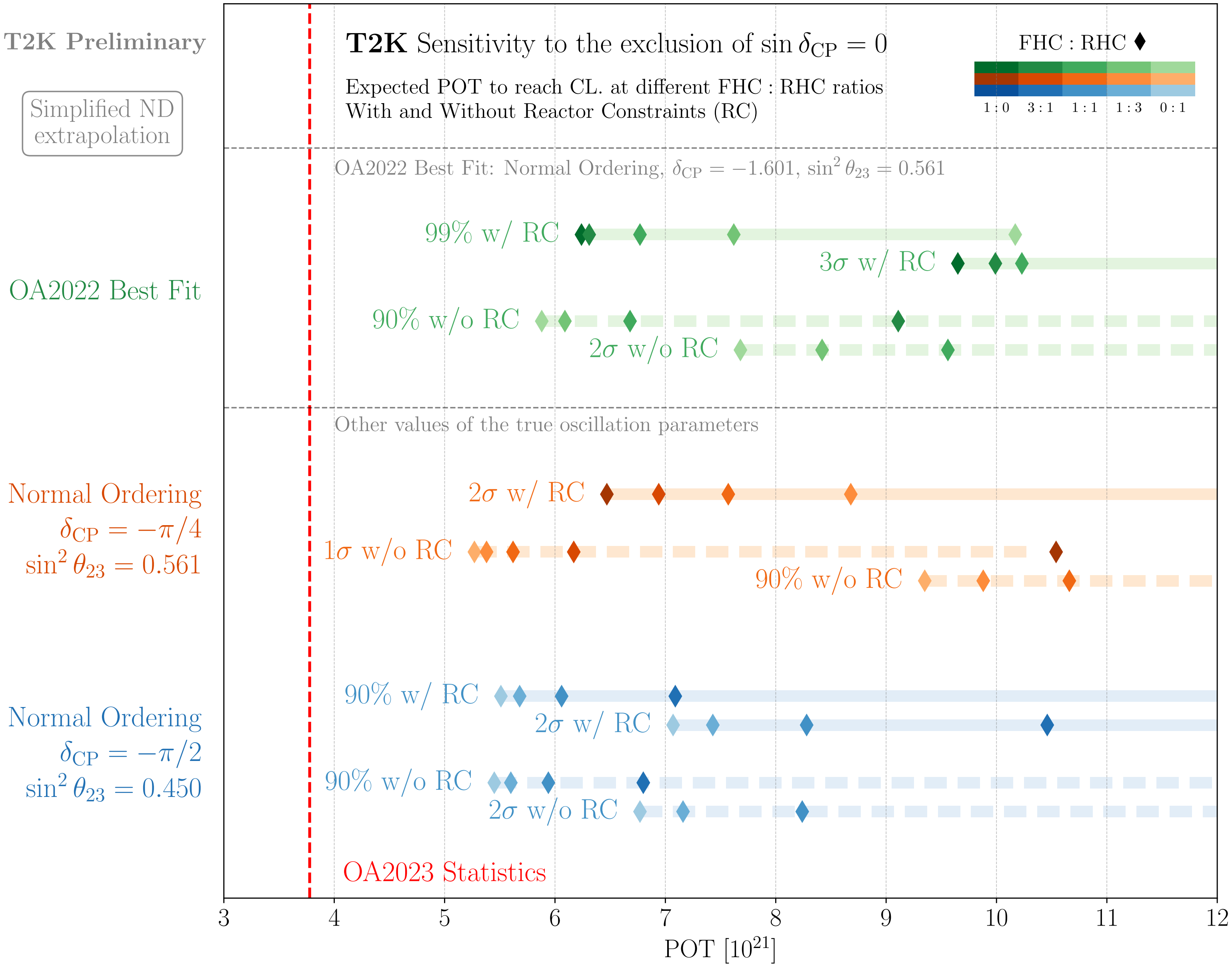


T.Daret, NuFact 2025

6. Conclusion

Conclusion

- beam upgrade has **significant impact** on the sensitivities;
- best neutrino/antineutrino is **highly dependent** on the true values of oscillation parameters;
- far from degeneracies, **full neutrino mode** is preferred (full antineutrino mode in θ_{23} lower octant for CPV);
- ND is essential in correcting for xsec*flux mismodelings, and **ND280Upgrade** will provide **a better tuning** which may differ from present predictions;



Thanks for listening!

X. Backup

Scope and approximations of the study

GOAL

ESTIMATE THE FUTURE SENSITIVITY OF THE T2K EXPERIMENT

as a function of **statistics**; and as a function of **neutrino/antineutrino running ratio**

STRATEGY

→ **based on latest oscillation analysis** for systematics and frequentist strategy

→ systematics from **ND Data fit** scaled with **total statistics** and new ND280 **target mass** (other syst. left unchanged: SK, ...)

→ **FD Asimov fit** performed at different **statistics** and **running ratio**

→ inclusion of the new **320 kA horn current**

APPROXIMATIONS

→ **simplified ND syst. treatment**:

- scaling with total stat, ratio kept fixed to current value (~ 1 : 1);
- scaling all syst. with SFGD mass (especially O xsec parameters);
- numerical/phys. boundary effects;
- no Fake Data Studies (FDS)

→ **simplified FD stat. treatment**: constant-$\Delta\chi^2$ method (no Feldman-Cousins)

→ **ND280 Upgrade** new physics capabilities not taken into account;

θ_{13} constraint from reactor experiments (RC) is applied unless stated otherwise

ND scaling method: scaling central values

Within the Gaussian approximation, we can model the ND fit by the following NLL minimization :

$$\mathrm{NLL}_{\mathrm{post}} = \mathrm{NLL}_{\mathrm{pre}} + \mathrm{NLL}_{\mathrm{ND}}$$

With, in the Gaussian approximation :

$$\mathrm{NLL}_{\lambda}(\boldsymbol{x}) = (\boldsymbol{x} - \boldsymbol{\mu}_{\lambda})^T \, \Sigma_{\lambda}^{-1} \, (\boldsymbol{x} - \boldsymbol{\mu}_{\lambda}) \ ,$$

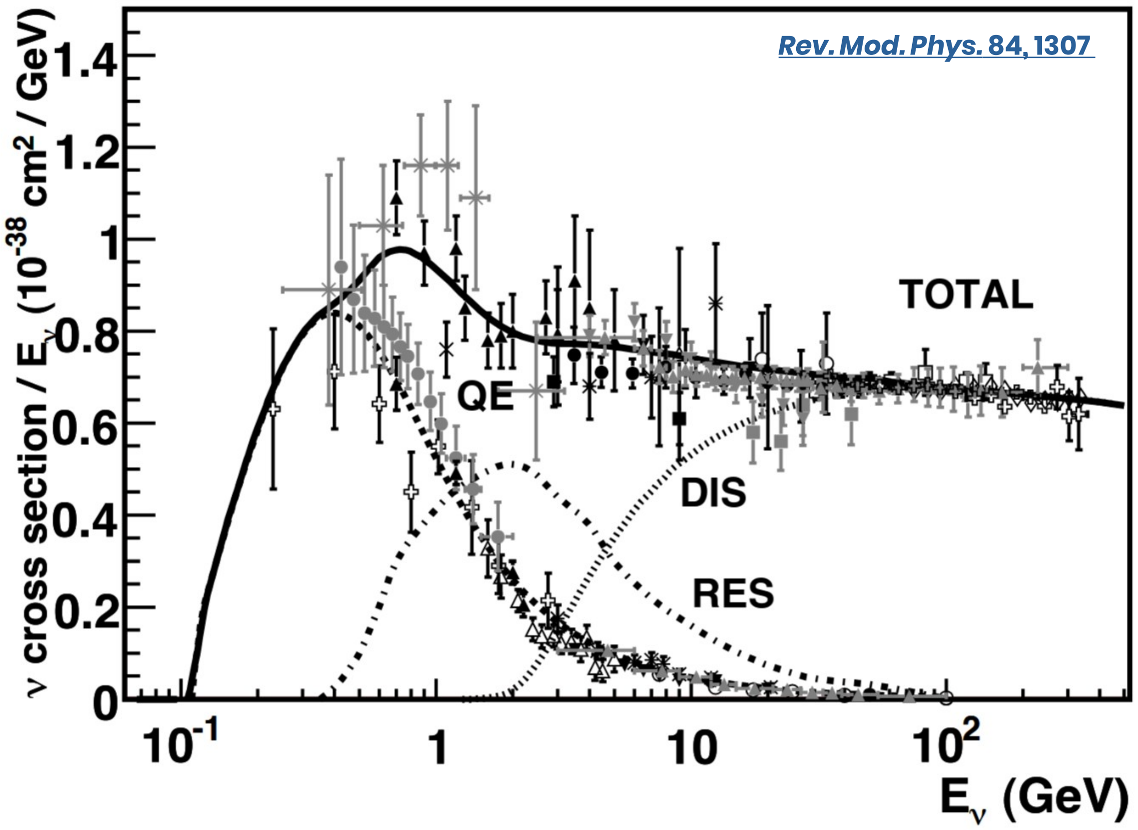
with $\boldsymbol{\mu}$ the central value vector, Σ the covariance matrix and Σ^{-1} the precision matrix.

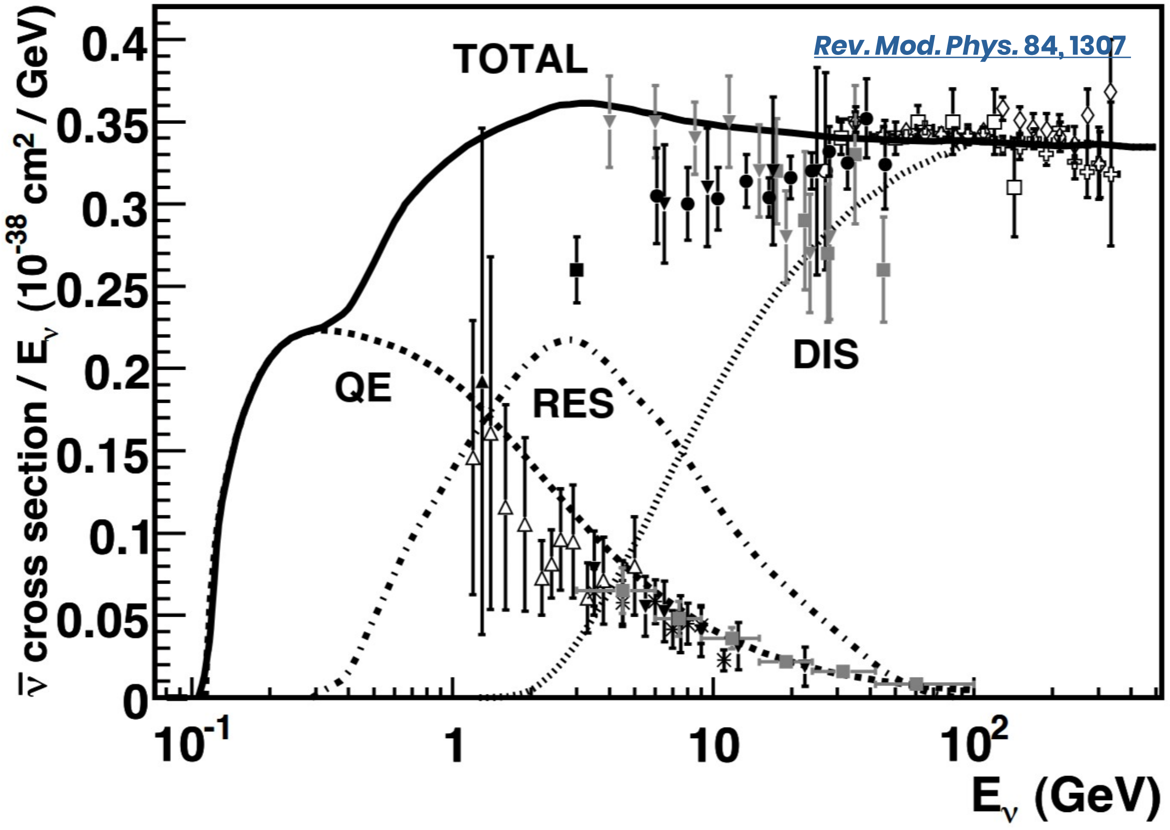
Differentiating this relation one gets :

$$\Sigma_{\mathrm{post}}^{-1} = \Sigma_{\mathrm{pre}}^{-1} + \Sigma_{\mathrm{ND}}^{-1} \quad \text{and} \quad \mu_{\mathrm{post}} \Sigma_{\mathrm{post}}^{-1} = \mu_{\mathrm{pre}} \Sigma_{\mathrm{pre}}^{-1} + \mu_{\mathrm{ND}} \Sigma_{\mathrm{ND}}^{-1} \ .$$

Finally, supposing that the ND will have the same fitting effect on future data we can both **estimate a posterior matrix for the new 320kA flux** and **estimate future new POT and ND280 target mass** effects by scaling the ND precision matrix.

Neutrino/Antineutrino cross-sections





Upgraded beam

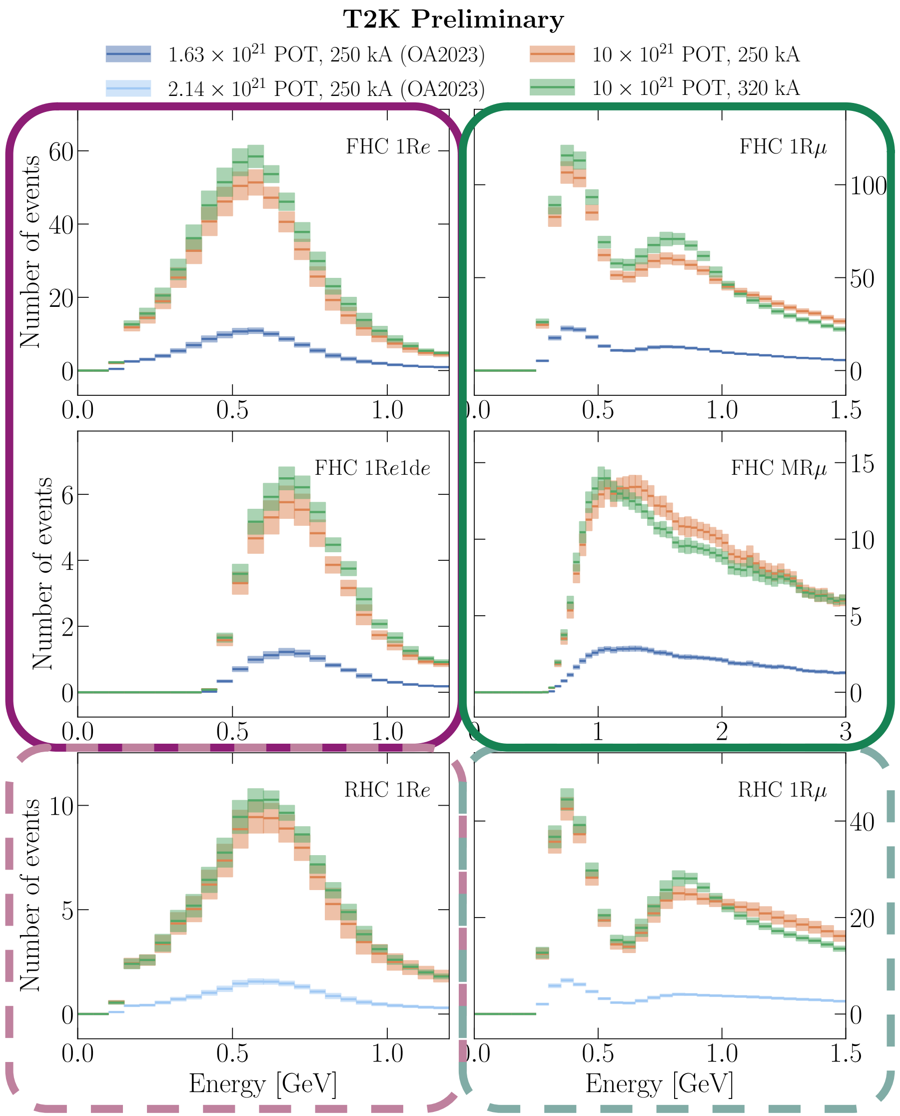
Today

Future (old beam config.)

Future (upgrad. beam config.)

+13.01% oscillated ν_e events (1Re)

+14.41% oscillated $\overline{\nu}_e$ events (1Re)



Neutrino mode

Antineutrino mode

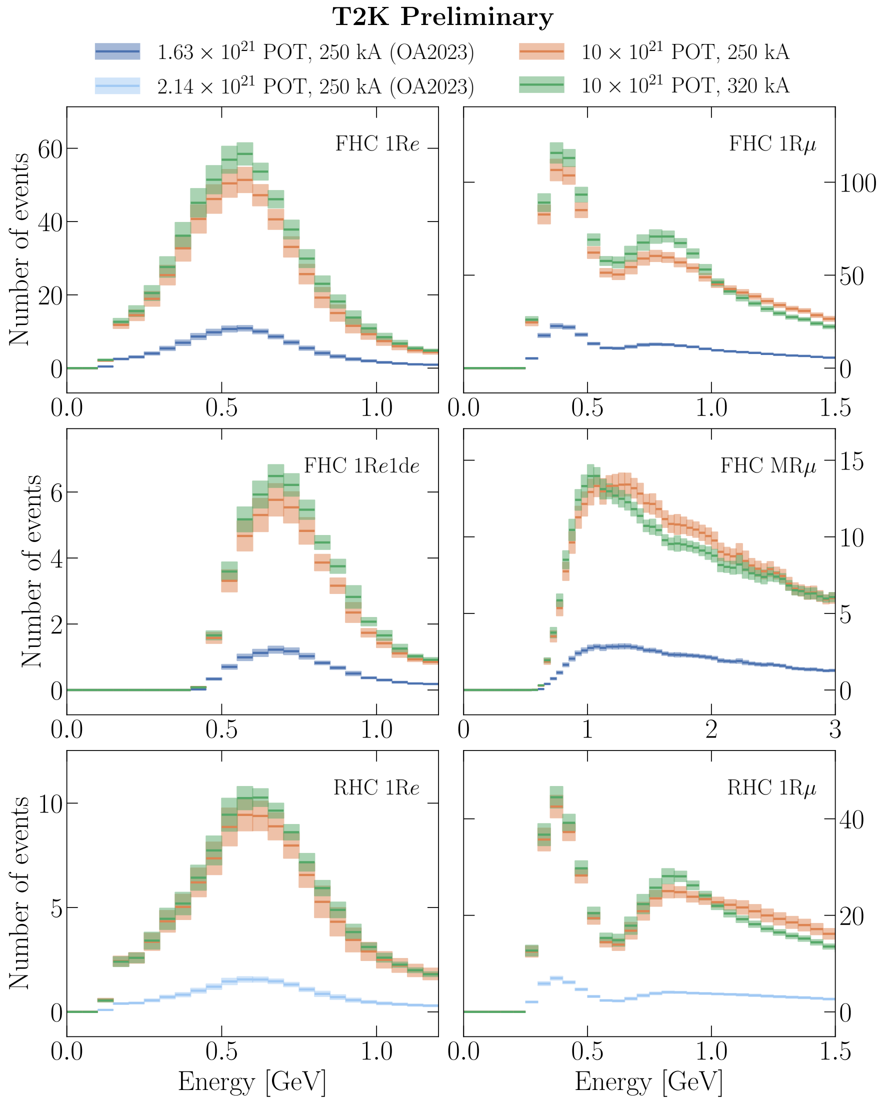
Appearance channels (e-like)

Disappearance channels (μ-like)

Impact of the upgraded beam

- Better focusing of right-sign mesons (signal) and defocusing of wrong-sign mesons (main background) → **better purity**

- Number of events increase around oscillation maximum, and decrease at high energies → **narrower energy range**



Sample		Rel. diff.
FHC 1Rμ	total	+3.02%
	signal (ν_μ)	*+3.79%*
RHC 1Rμ	total	−3.51%
	signal ($\overline{\nu}_\mu$)	*+1.01%*
FHC 1Re	total	+11.73%
	signal (osc. ν_e)	*+13.01%*
RHC 1Re	total	+5.62%
	signal (osc. $\overline{\nu}_e$)	*+14.41%*
FHC 1Re1de	total	+12.92%
	signal (osc. ν_e)	*+14.52%*
FHC MRμ	total	−1.40%
	signal (ν_μ)	*−1.07%*

Table. Relative difference between 250kA and 320kA predicted oscillated number of events at FD

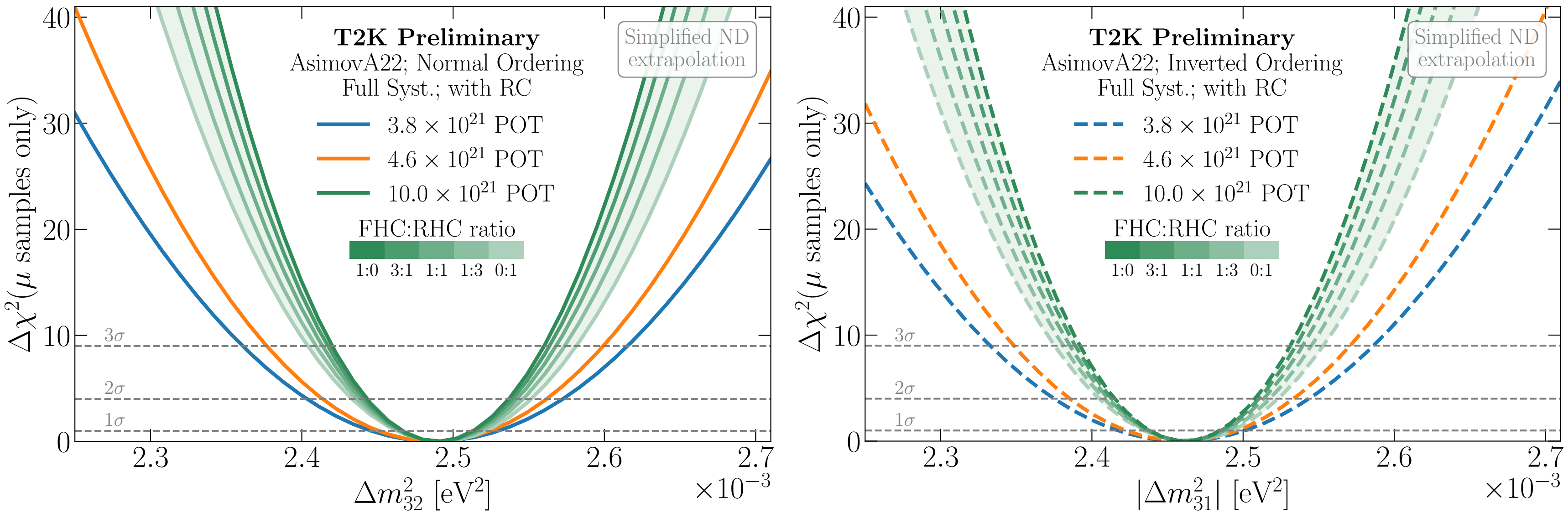
Impact of the disappearance channel

At T2K, 2-flavour approximation:

$$P_{\mu\mu} \simeq 1 - \sin^2 2\theta_{\text{eff}} \sin^2\left(\frac{\Delta m^2_{\text{eff}} L}{4E}\right)$$

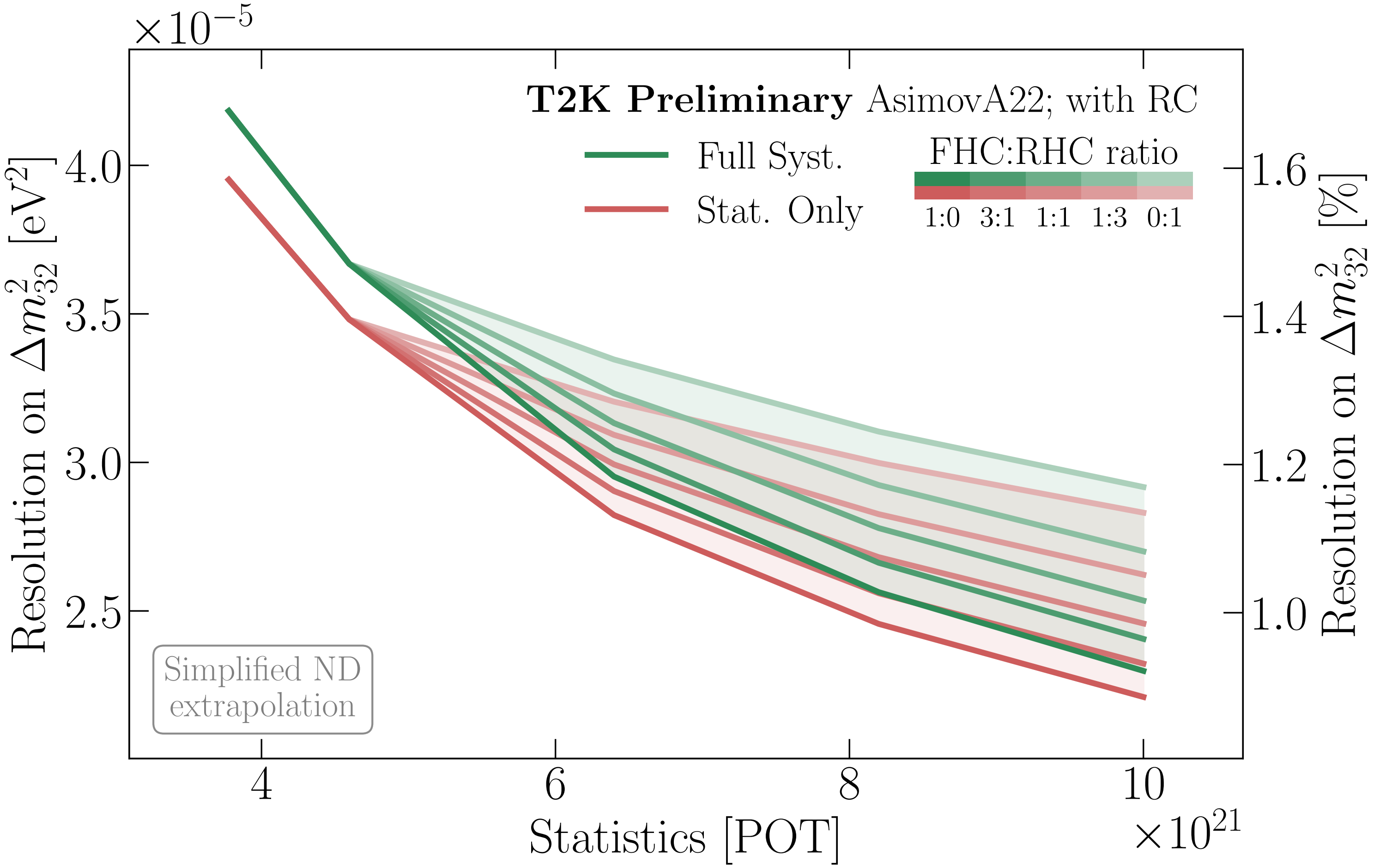
$$\sin^2 2\theta_{\text{eff}} = 4\cos^2\theta_{13}\sin^2\theta_{23}(1-\cos^2\theta_{13}\sin^2\theta_{23}) \qquad \Delta m^2_{\text{eff}} \approx \Delta m^2_{32}$$

Not sensitive to mass ordering + Independent of running mode (neutrino or antineutrino)
(at first order)



Neutrino mode is preferred since cross-section with matter is ~3x higher for neutrinos than for antineutrinos

Impact of the disappearance channel



Neutrino mode is preferred since cross-section with matter is ~3x higher for neutrinos than for antineutrinos

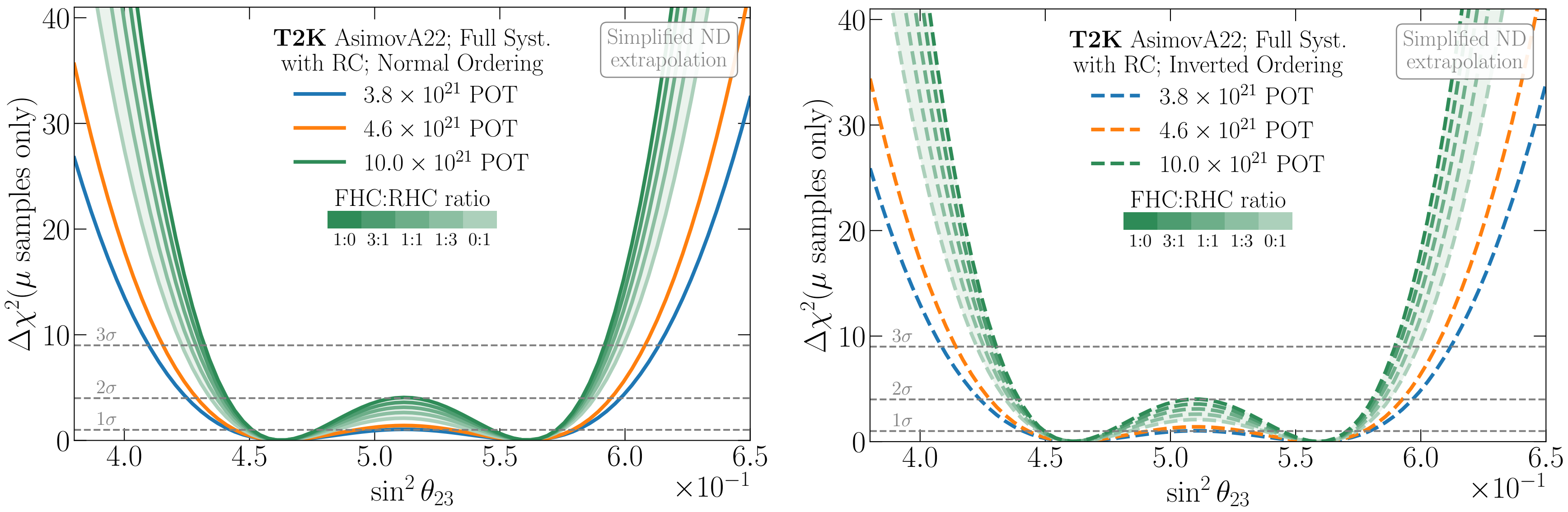
Impact of the disappearance channel

At T2K, 2-flavour approximation:

$$P_{\mu\mu} \simeq 1 - \sin^2 \boxed{2}\theta_{\text{eff}} \sin^2\left(\frac{\Delta m^2_{\text{eff}} L}{4E}\right)$$

$$\sin^2 2\theta_{\text{eff}} = 4\cos^2\theta_{13}\sin^2\theta_{23}(1-\cos^2\theta_{13}\sin^2\theta_{23}) \qquad \Delta m^2_{\text{eff}} \approx \Delta m^2_{32}$$

Total octant degeneracy



Impact of the appearance channel

At T2K, the 3 leading terms are:

$$P_{\mu e} = 4s_{23}^2 s_{13}^2 c_{13}^2 \sin^2 \Delta_{31}$$ 1 Leading term

$$\boxed{\mp} J_{\mathrm{CP}} \sin \Delta_{32} \sin \Delta_{31} \sin \Delta_{21}$$ 2 CP violating term

$$\boxed{\pm} 8a(1 - 2s_{13}^2) s_{23}^2 s_{13}^2 c_{13}^2 \frac{\sin \Delta_{31}}{\Delta m_{31}^2} (\sin \Delta_{31} - \Delta_{31} \cos \Delta_{32})$$ 3 Matter effects

$$+ \cdots ,$$

with the Jarlskog invariant:

$$J_{\mathrm{CP}} = s_{13} c_{13}^2 s_{12} c_{12} s_{23} c_{23} \sin \delta_{\mathrm{CP}}$$

$$c_{ij} = \cos \theta_{ij}$$

$$s_{ij} = \sin \theta_{ij}$$

$$\Delta_{ij} = \frac{\Delta m_{ij}^2 L}{4E}$$

$$a = 2\sqrt{2} G_F n_e E$$

Impact of the appearance channel

1 **Leading term**

$$4s_{23}^2 s_{13}^2 c_{13}^2 \sin^2 \Delta_{31}$$

sensitive to $\sin^2\theta_{23}$ can **resolve the octant degeneracy** from disappearance channel

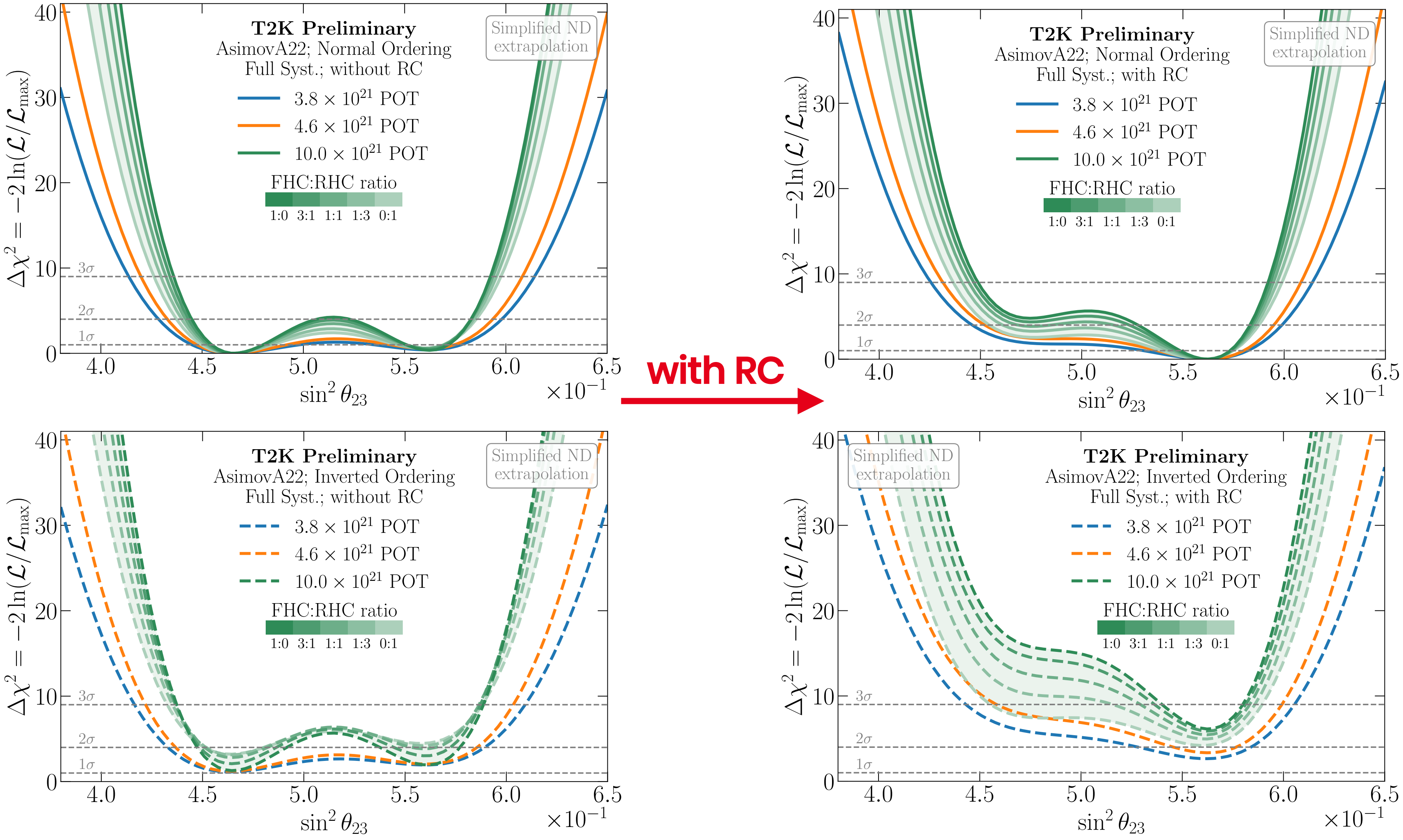
total degeneracy with $\sin^2 2\theta_{13}$

well constrained by disappearance channel

this can be solved by using the 1D θ_{13} **constraint from reactor experiments** (**RC**)

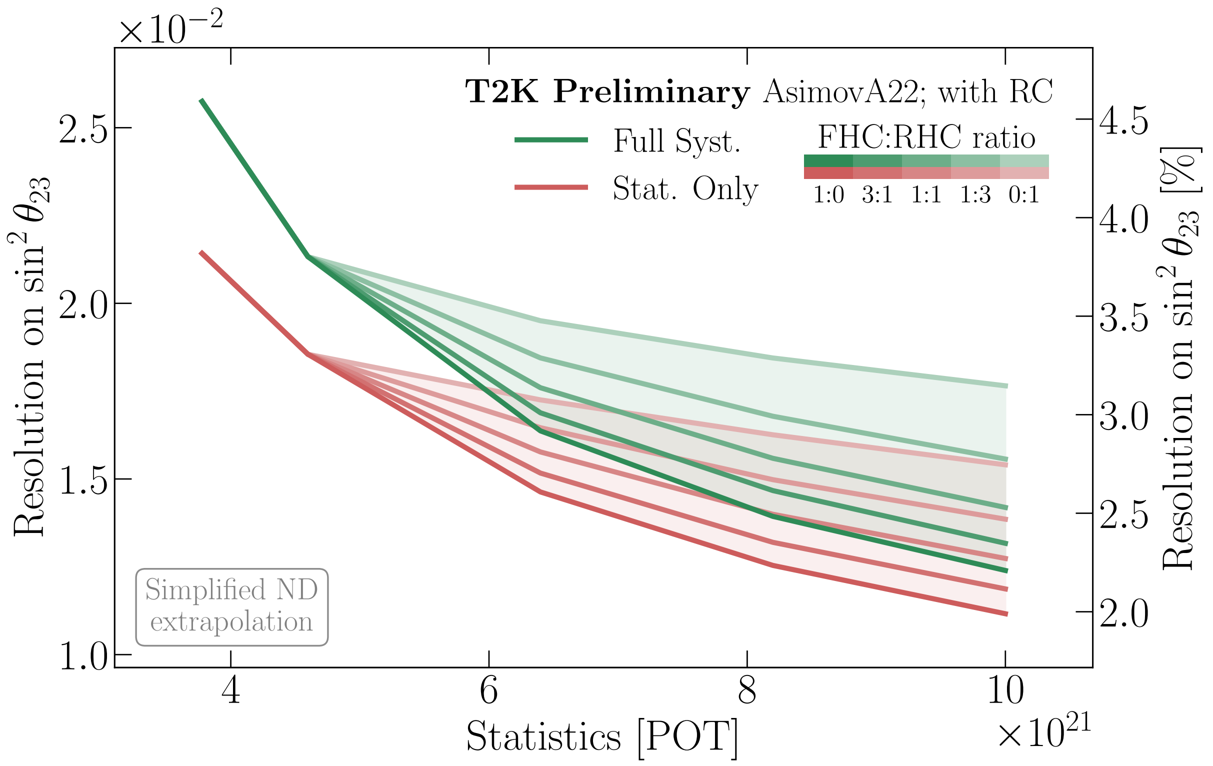
Parameter	**Prior distribution**
$\sin^2 2\theta_{13}$	Uniform$(0, 1)$
with PDG reactor constraint	Gaussian$(\mu = 0.0861, \sigma = 0.0027)$

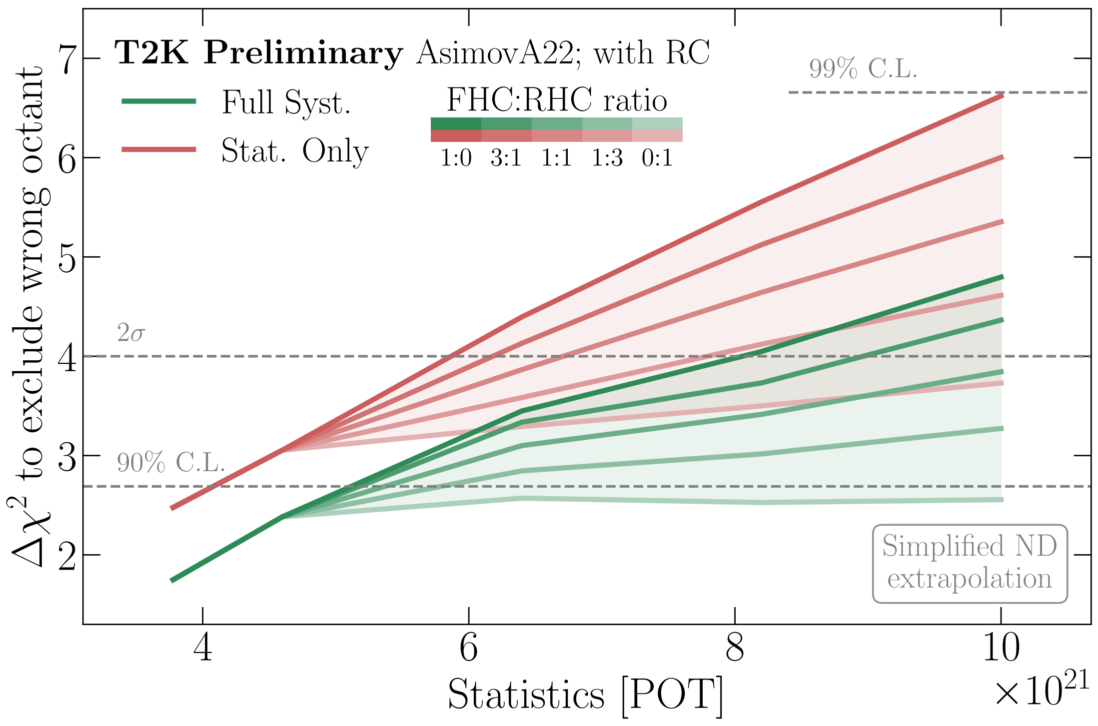
Impact of the appearance channel



- **upper octant** is preferred
- **neutrino mode** is preferred (disap.)

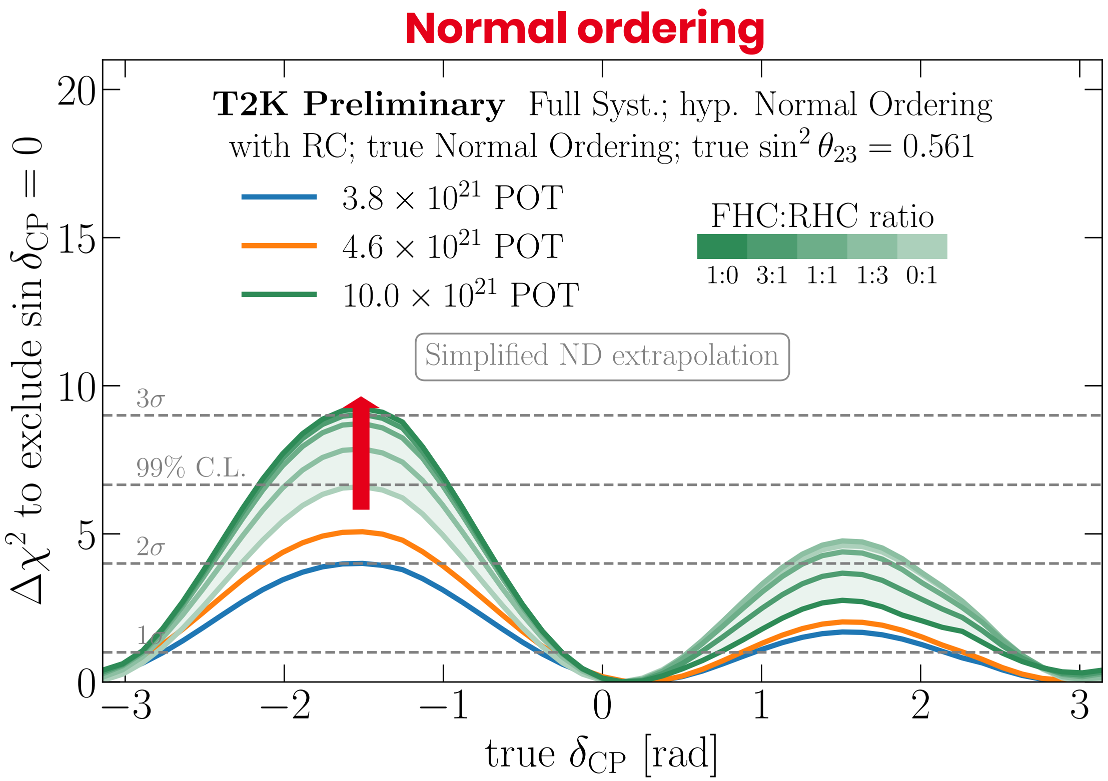
Impact of the appearance channel

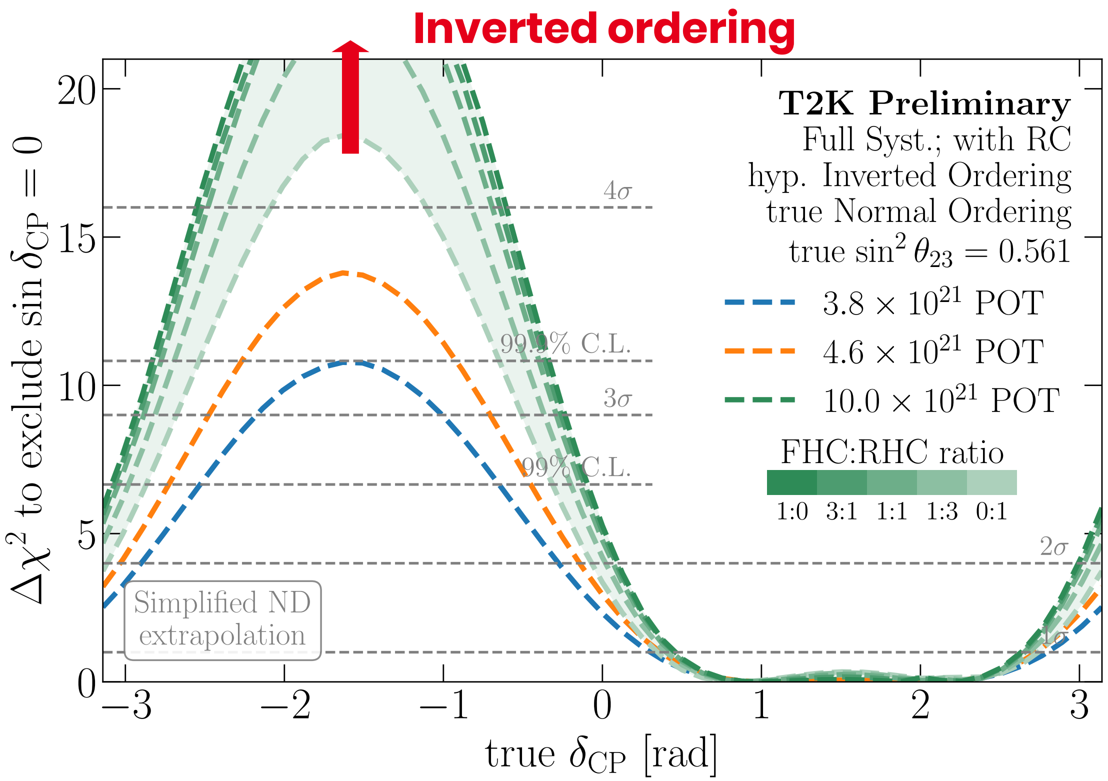




- we could **divide by 2** our resolution on $\sin^2\theta_{23}$;
- we could reach a **2σ exclusion** of lower octant… **for this specific value of true θ_{23}** !!

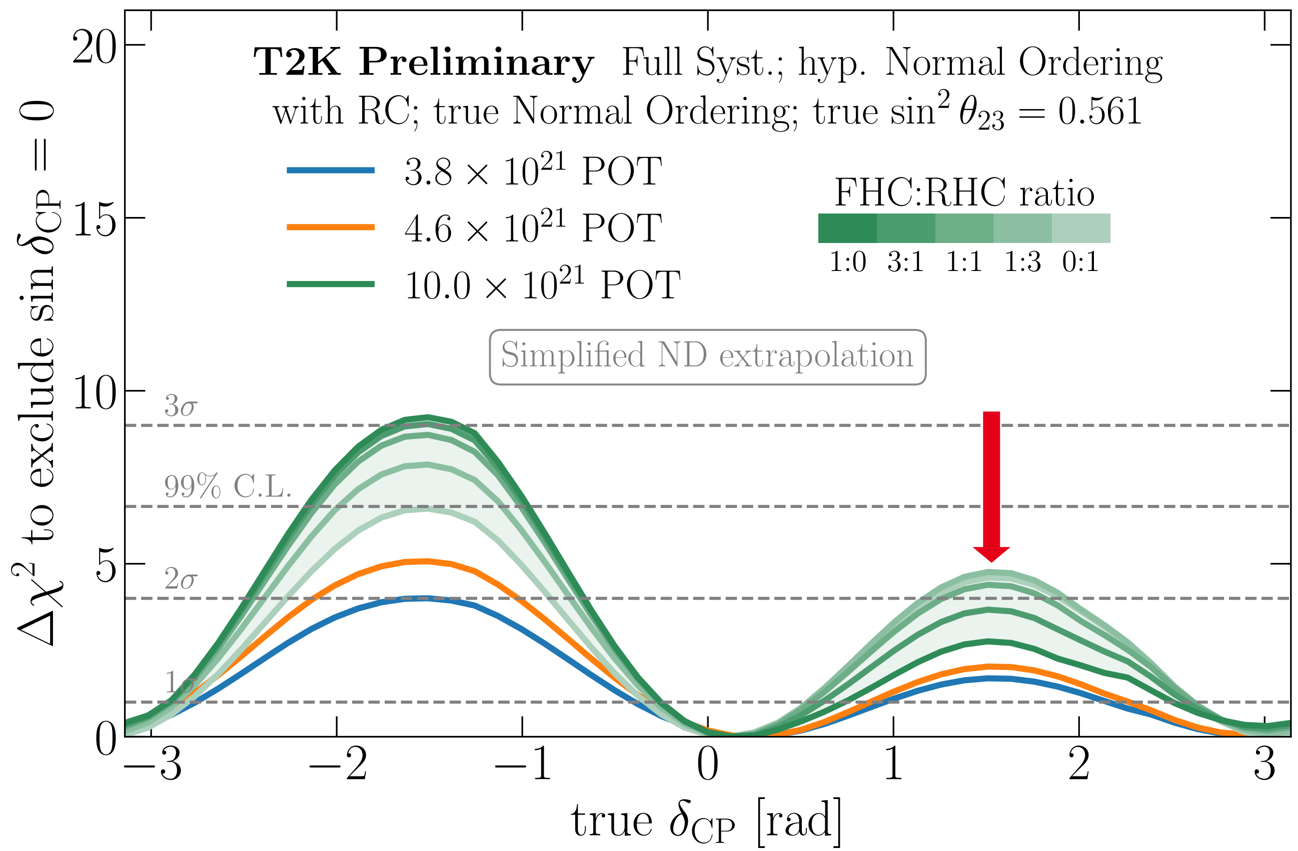
CPC exclusion: true δ_{CP} dependence

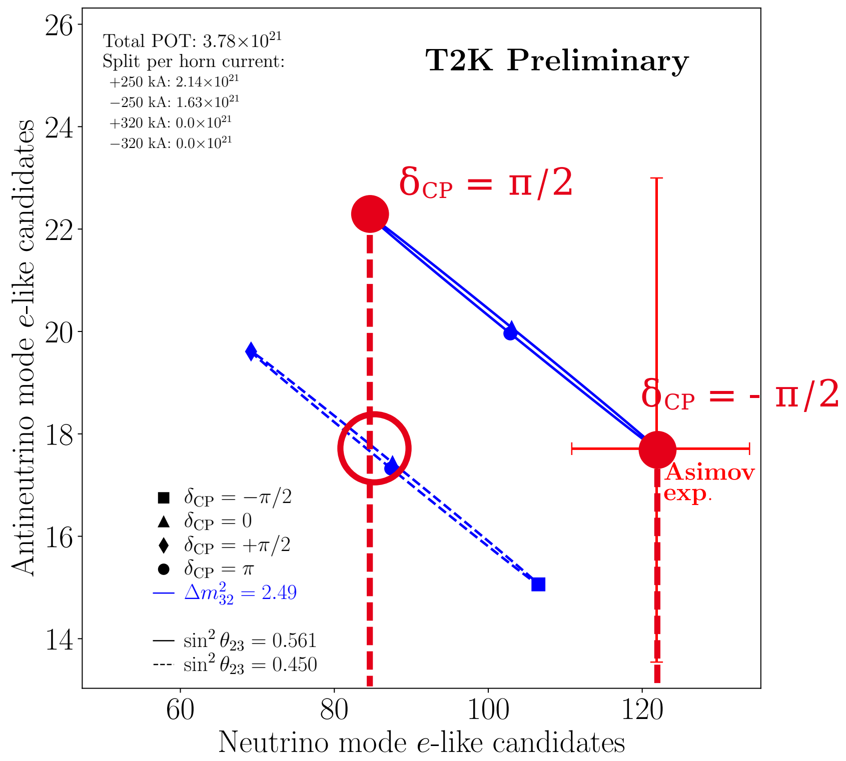




- **$\sin\delta_{CP} < 0$** ➡ far from degeneracies, good exclusion and **neutrino mode** is preferred;
- **$\sin\delta_{CP} > 0$** ➡ let's dig into the effects…

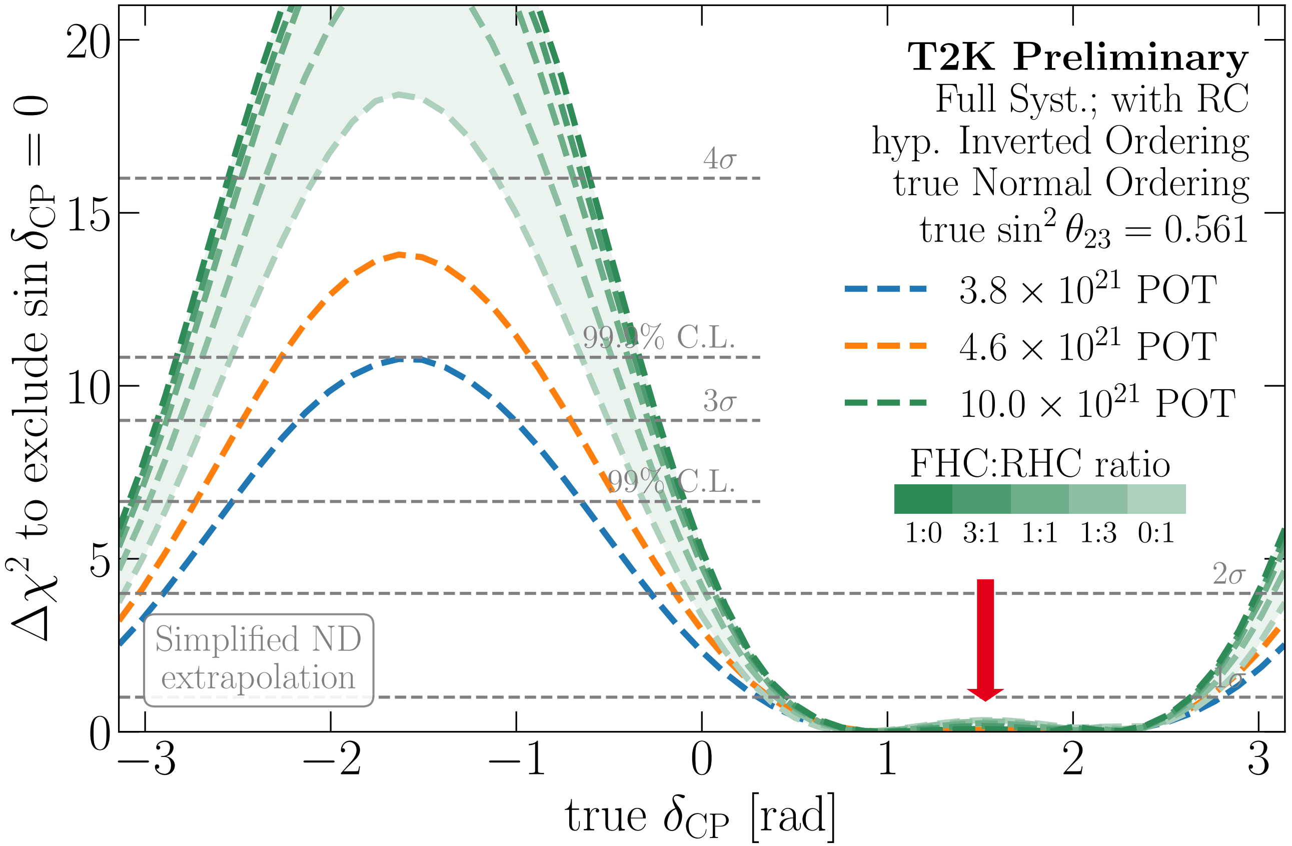
CPC exclusion: Normal Ordering hypothesis

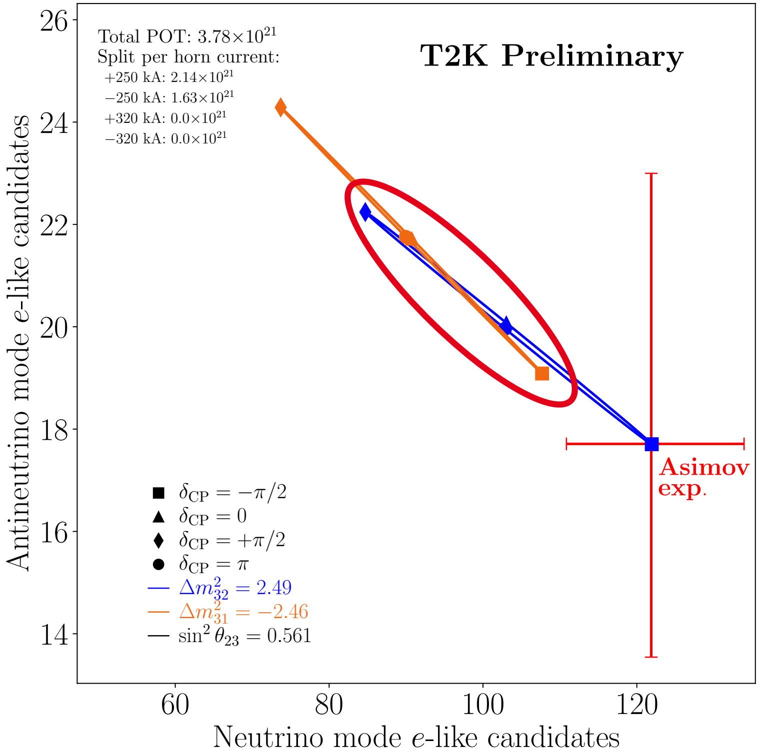




- **$\sin\delta_{CP} < 0$** ⟶ **full neutrino mode** preferred since **far from degeneracies**;
- **$\sin\delta_{CP} > 0$** ⟶ **full antineutrino mode** preferred as it helps solving the $\delta_{CP} - \theta_{23}$ octant degeneracy;

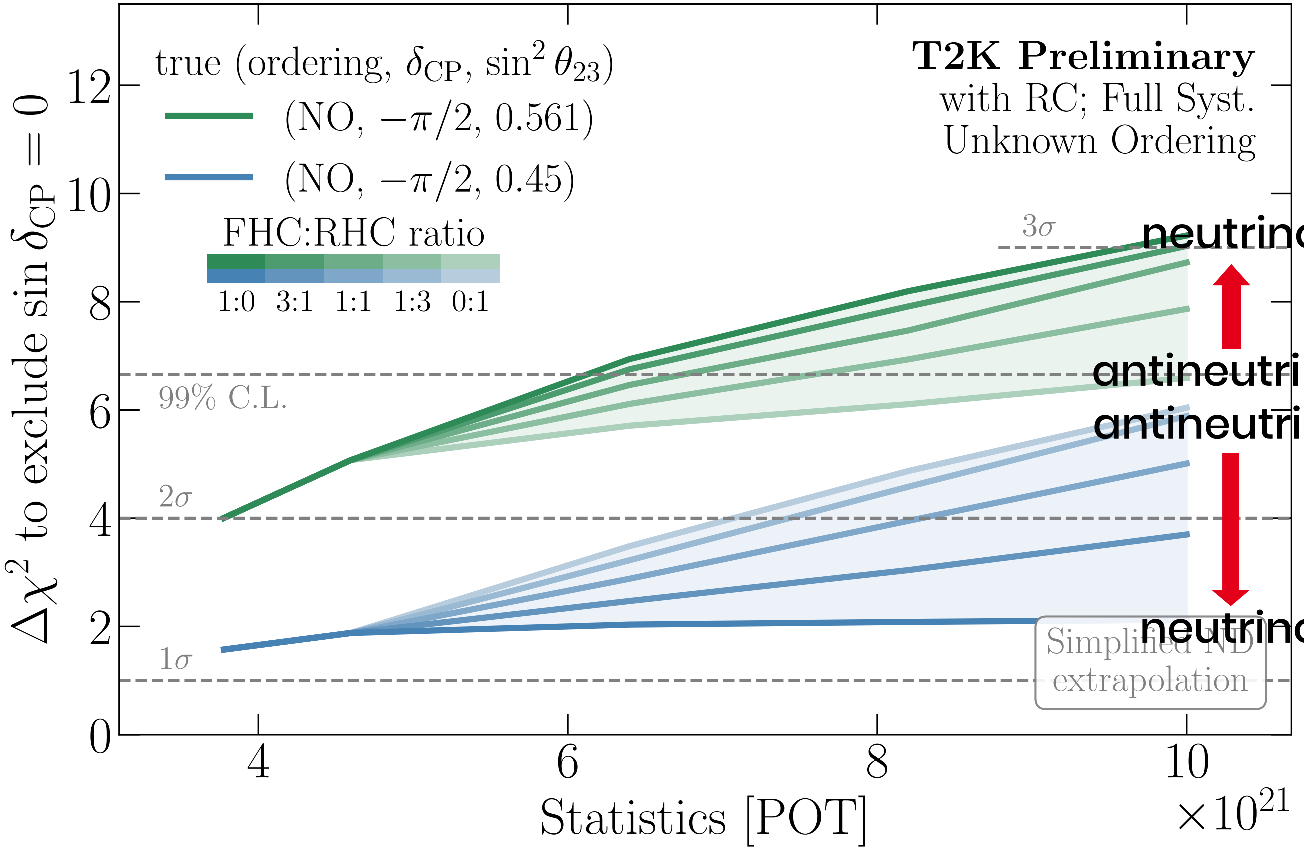
CPC exclusion: Inverted Ordering hypothesis

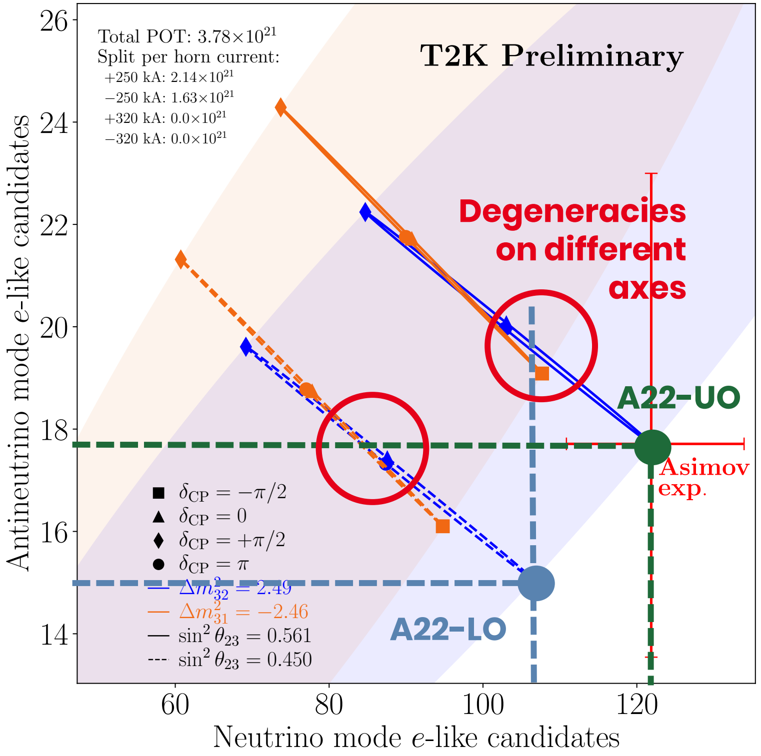




- **$\sin\delta_{CP} < 0$** ⟶ **full neutrino mode** preferred (as seen before) ;
- **$\sin\delta_{CP} > 0$** ⟶ fully degenerate with mass ordering…

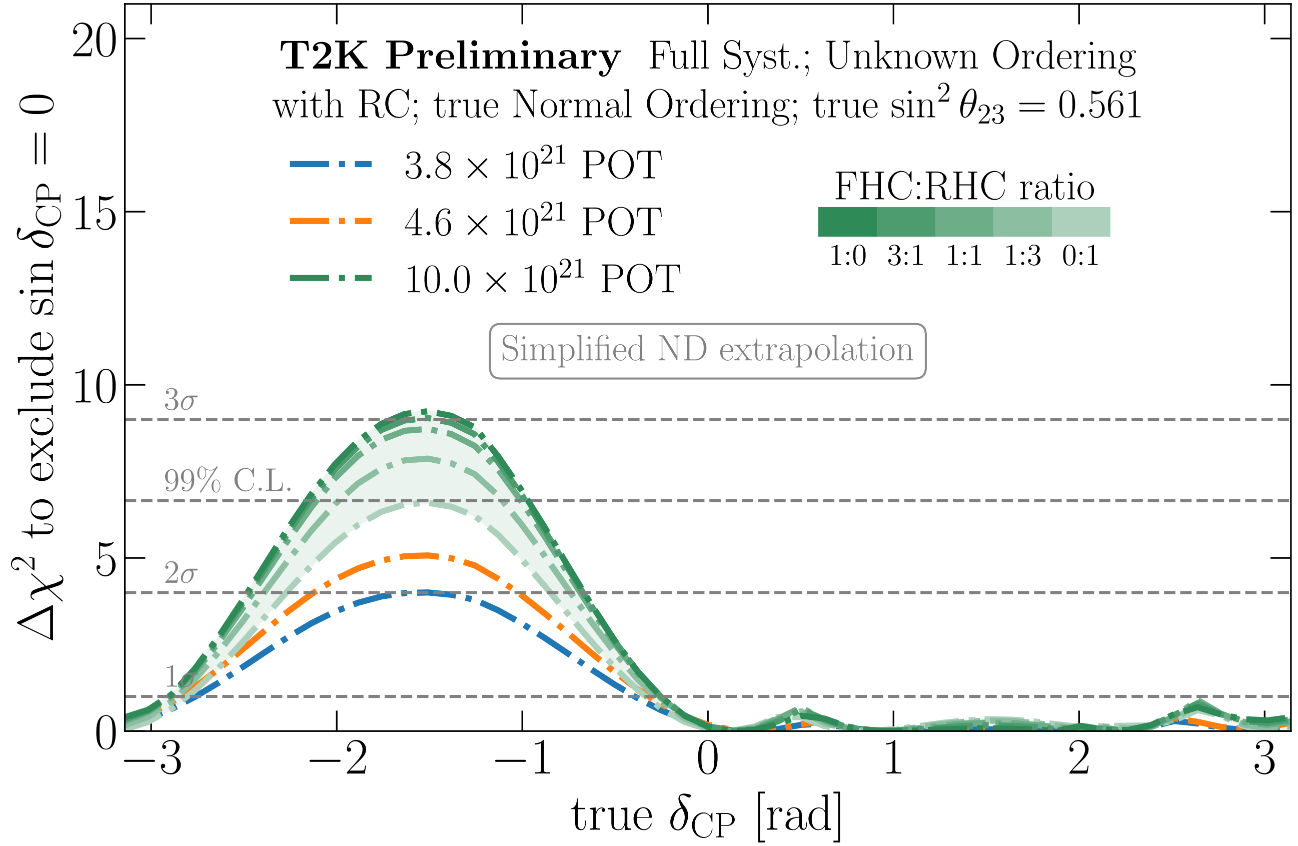
CPC exclusion: true octant dependence





- in **true upper octant**, no degeneracy in ν_e appearance : **neutrino mode is preferred** ;
- in **true lower octant**, degeneracy in ν_e appearance but not in $\bar{\nu}_e$ appearance : thus **antineutrino mode is preferred**, and sensitivity is reduced ;

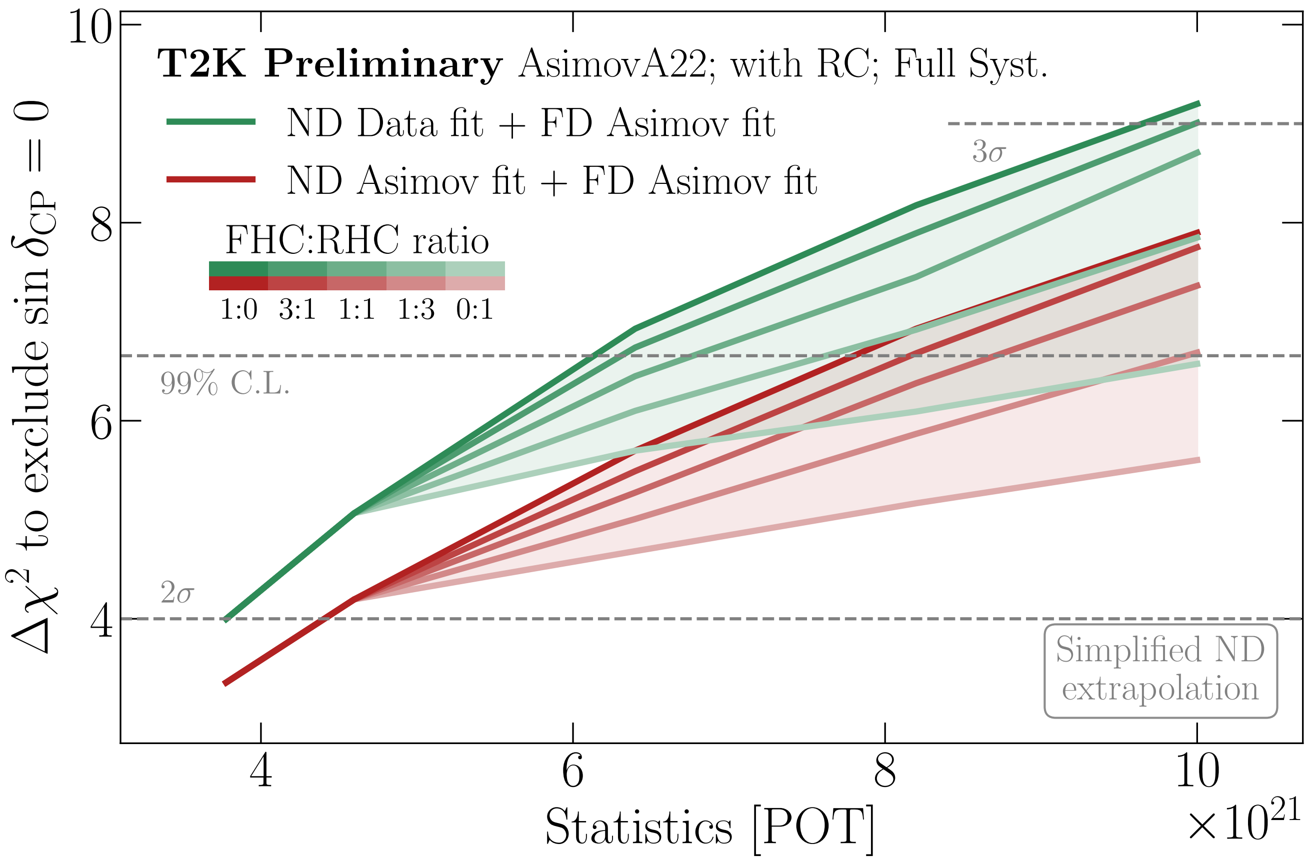
CPC exclusion: true δ_{CP} dependence

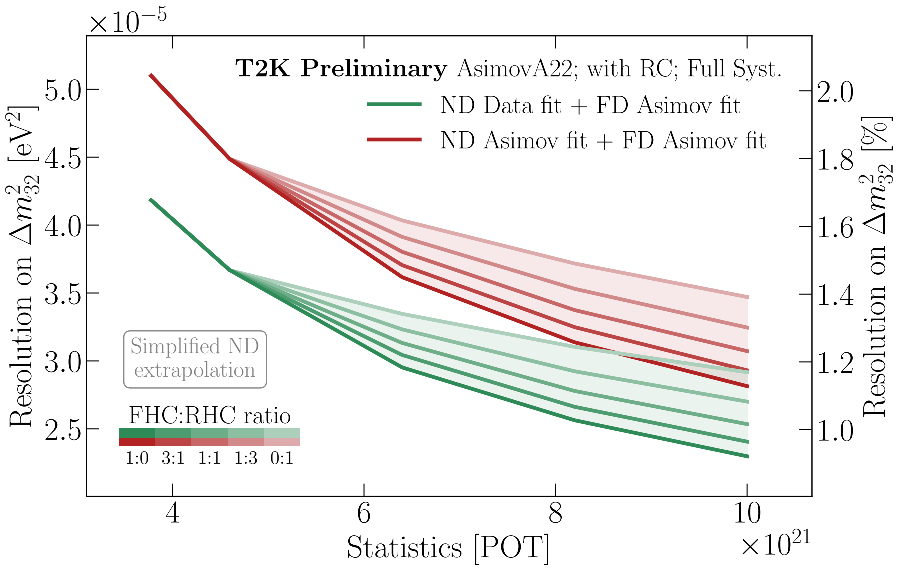


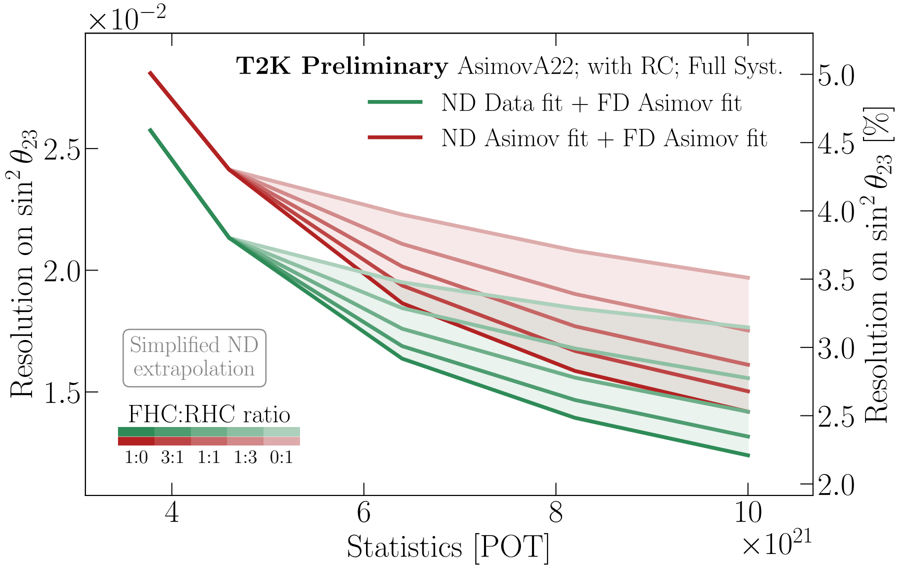
Summary plot: we profile over mass ordering (min of the two ordering hypotheses)

- **$\sin\delta_{CP} < 0$ ➡ full neutrino mode preferred;**
- **$\sin\delta_{CP} > 0$ ➡ no sensitivity;**

ND Data fit vs ND Asimov fit







- **ND Data fit has significant impact**, even today (first stat. point) where no scaling is applied, for **all channels**