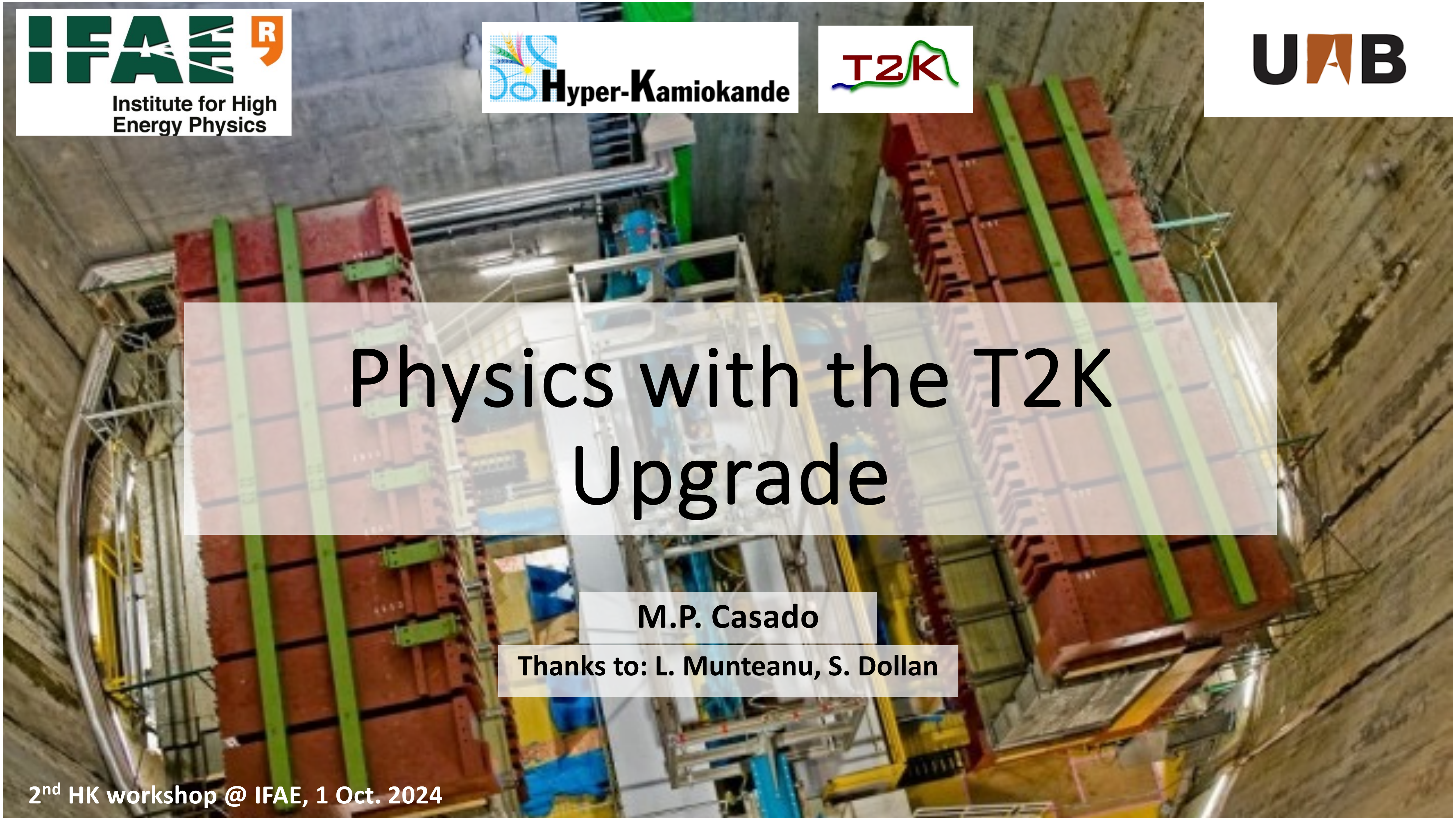


Physics with the T2K Upgrade

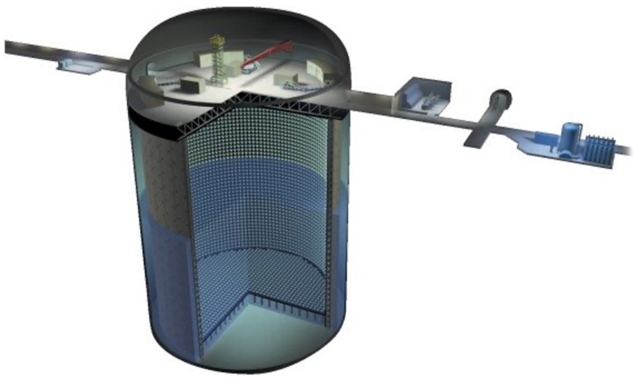
M.P. Casado

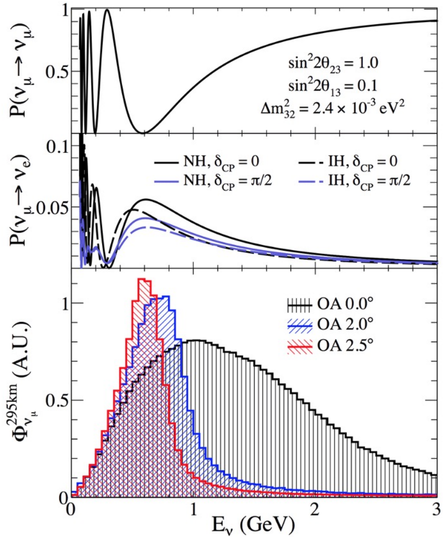
Thanks to: L. Munteanu, S. Dollan

2nd HK workshop @ IFAE, 1 Oct. 2024

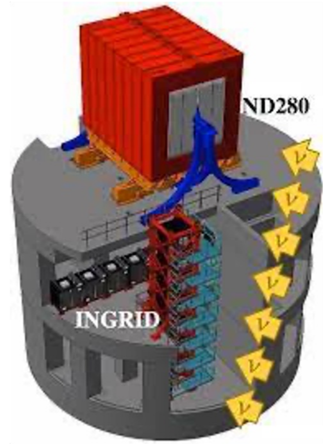
The T2K Experiment

Far detector: Super-Kamiokande

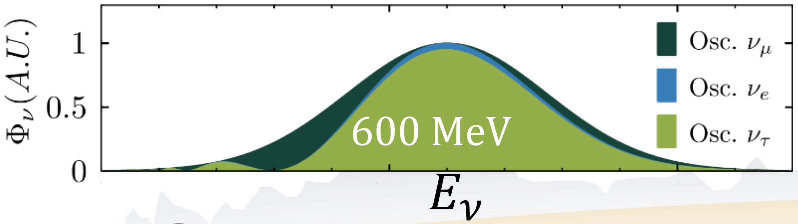




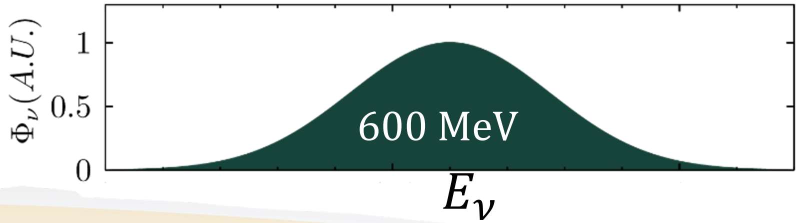
Near detector complex

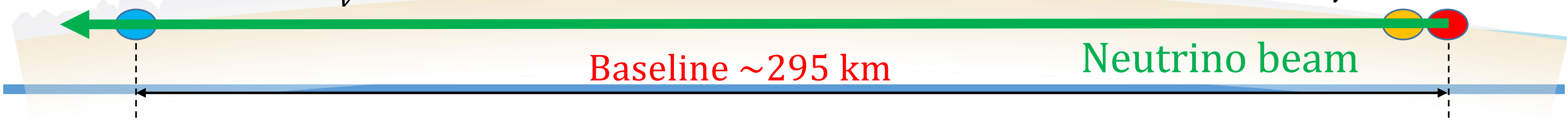


$$N_{\nu_{\mu/e}}(E_\nu) = P_{\nu_\mu \to \nu_{\mu/e}}(E_\nu)\Phi(E_\nu)\sigma(E_\nu)\epsilon(E_\nu)$$



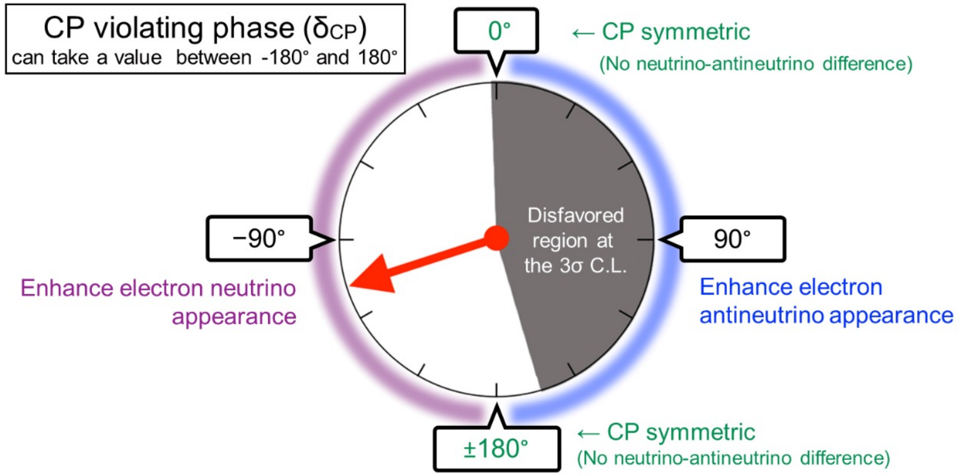
$$N_{\nu_\mu}(E_\nu) = \Phi(E_\nu)\sigma(E_\nu)\epsilon(E_\nu)$$





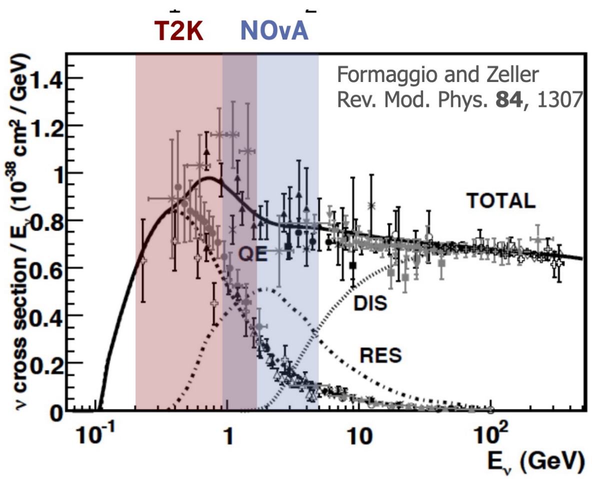
Physics program

- Neutrino oscillations



Nature 580, 339–344 (2020)
(T2K collaboration)

- Neutrino cross-sections
  - CC0π, CC1π, TKI, CCCoh
  - Particular focus on joint measurements ($\nu_\mu/\bar{\nu}_\mu$, $\nu_e/\bar{\nu}_e$, C/O, on/off-axis)



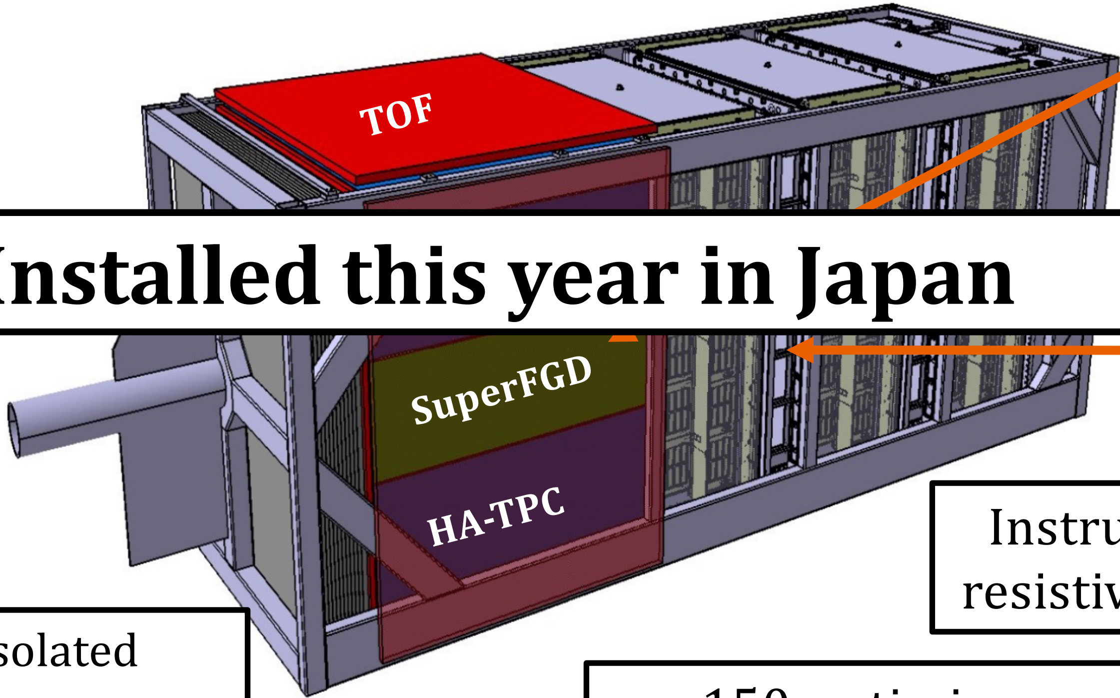
- Exotic searches (HNLs)

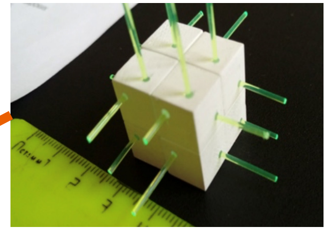
The T2K ND280 Upgrade project

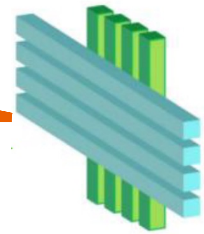
[ND280 Upgrade TDR](#)

Replace P0D by new suite of detectors

>100 researchers
22 institut
7 countri







Installed this year in Japan

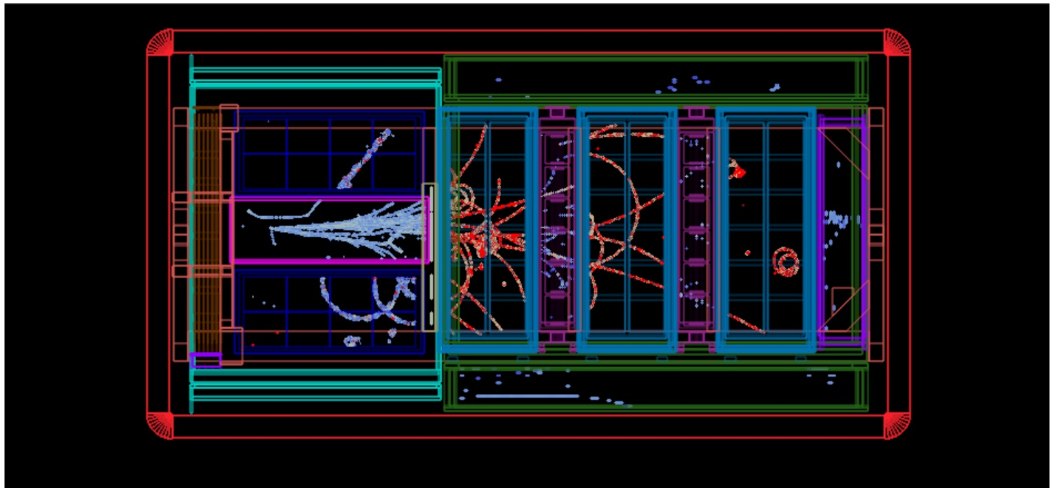
Instrumented with resistive Micromegas

150 ps timing resolution for PID

2M 1cm^3 optically isolated scintillator cubes
2x fiducial mass of current FGDs

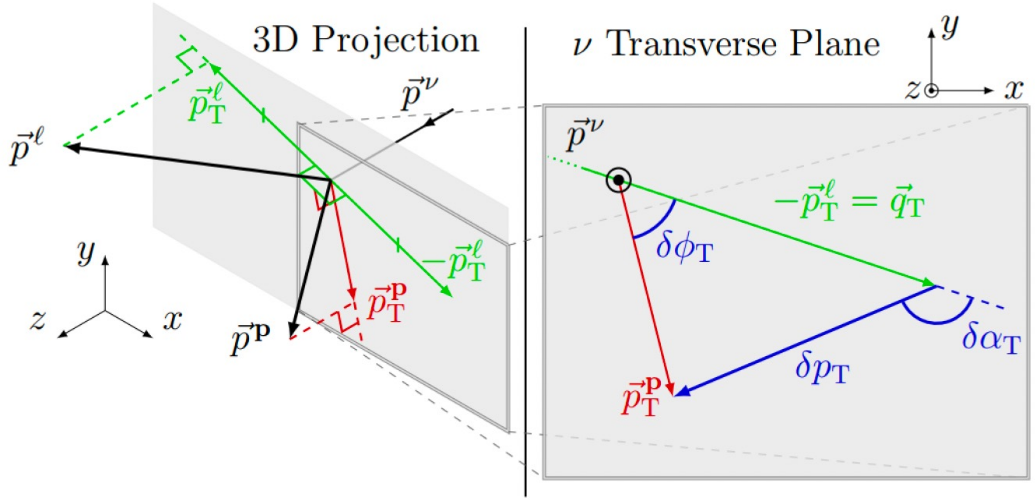
Physics with the Upgrade – this talk

- New kinematical regions with upgraded detectors



Top view of ND280 event, June 2024

- Transverse and nuclear variables

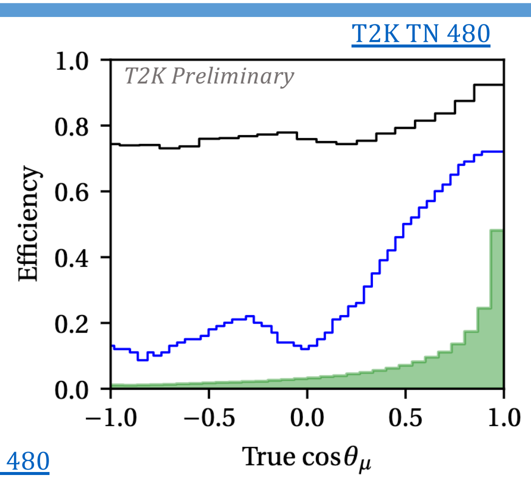


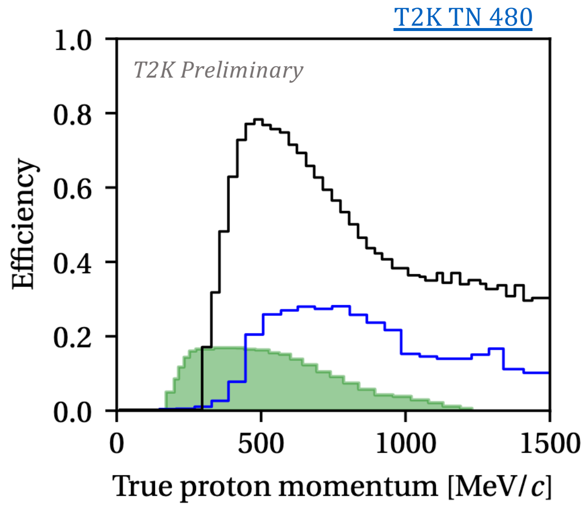
- Oscillation analysis sensitivity

New kinematical regions

- 4π acceptance for charged leptons (as in SK)
  - μ detection will be crucial
- Detect protons with lower momentum
  - Access to nuclear effects
- Tag and reconstruct neutrons!
  - Expect 50% efficiency, 30% resolution.

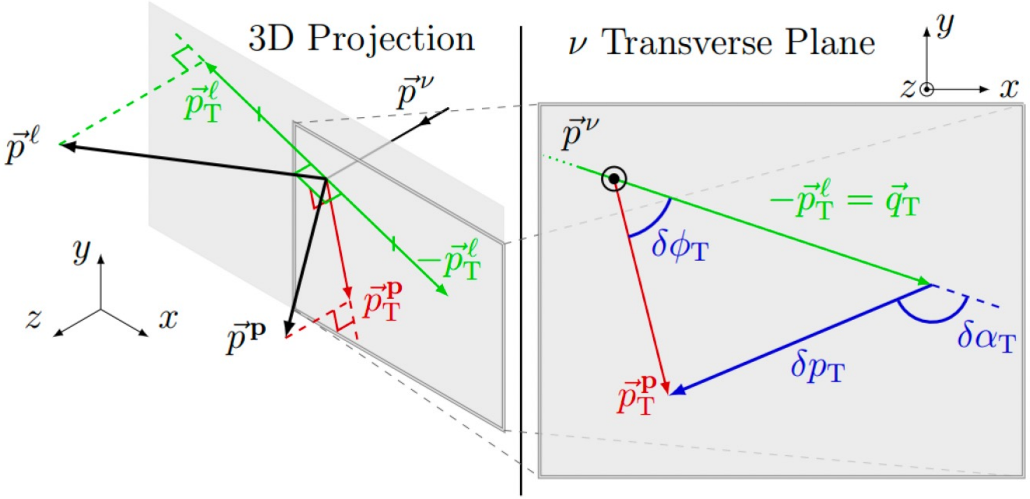
- NEUT prediction
- Classical ND280
- Upgraded ND280



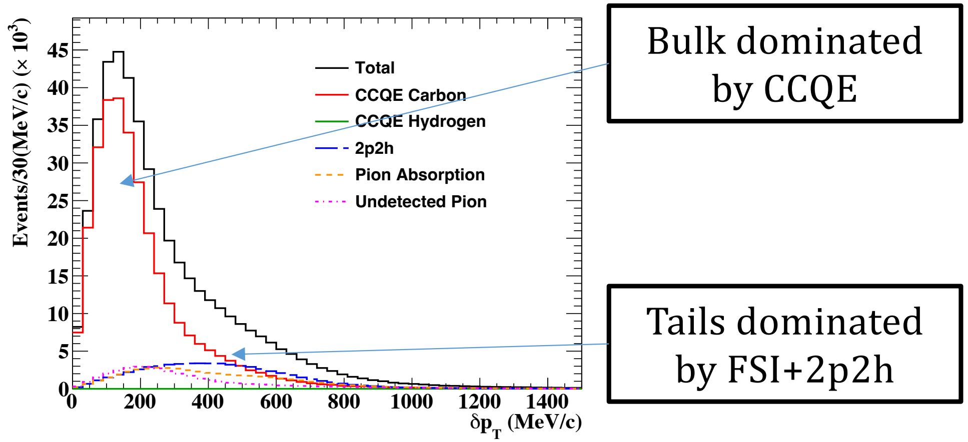


Transverse and nuclear variables

- Transverse plane to neutrino direction



- $\delta\vec{p}_T$=Tranverse momentum imbalance in final state

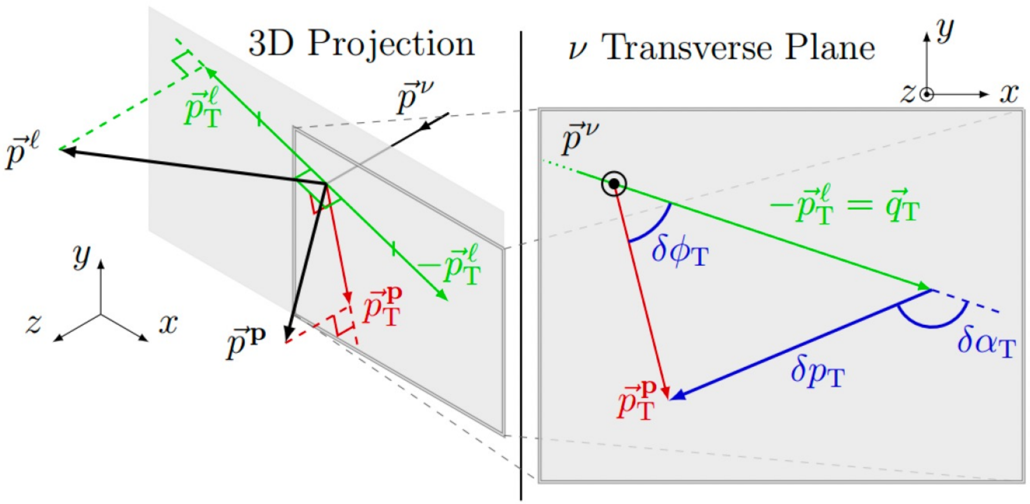


Phys. Rev. D 105, 032010

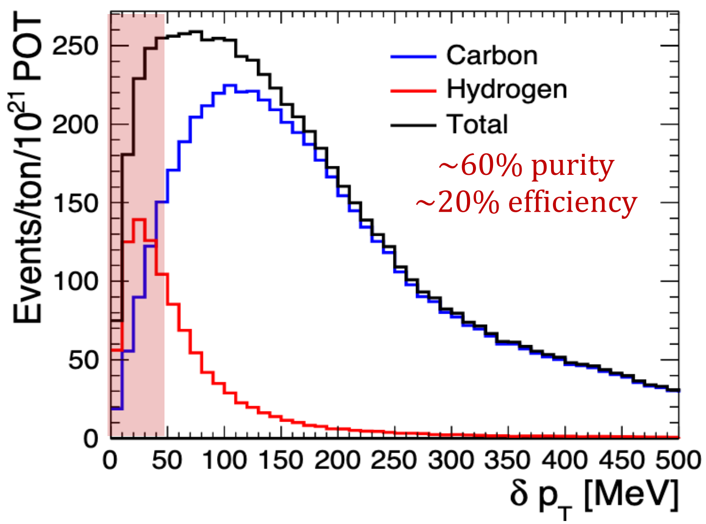
- Probe nuclear effects at high $\delta\vec{p}_T$

Transverse and nuclear variables

- Transverse plane to neutrino direction



- Peak from $\bar{\nu}_\mu$ on H



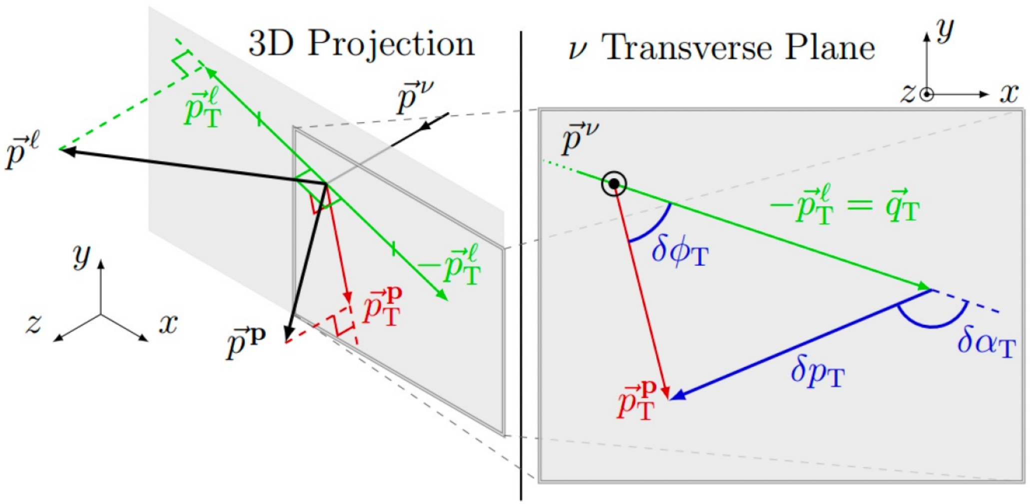
Phys.Rev.D 101, 092003 (2020)

Phys.Rev.D 110, 3, 032019 (2024)

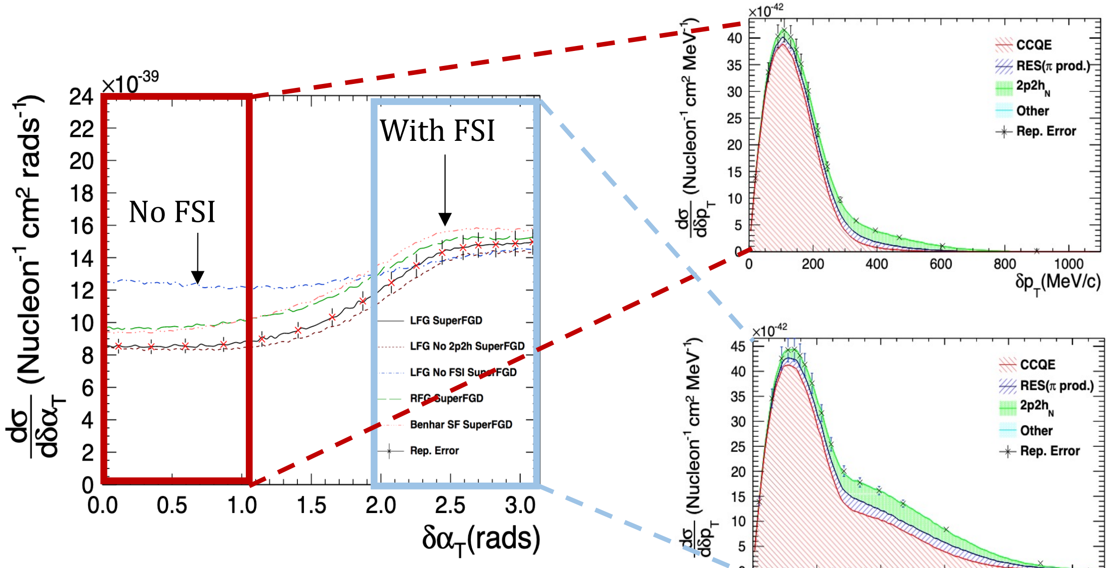
- No nuclear effects
- Thanks to neutron detection

Transverse and nuclear variables

- Transverse plane to neutrino direction



- $\delta\alpha_T$ = angle between lepton direction and imbalance momentum in final state



ND280 Upgrade TDR

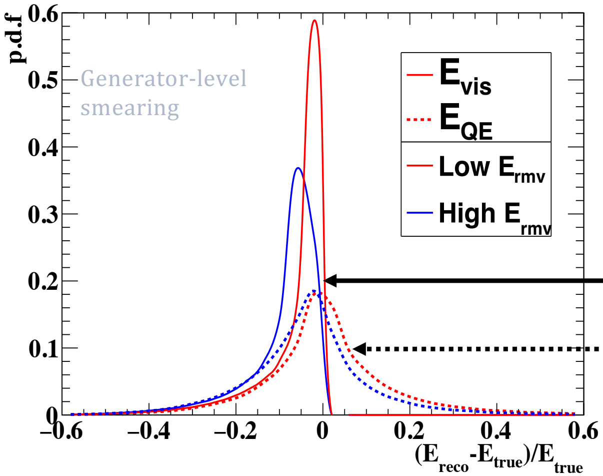
- Separate 2p2h and FSI effects

Transverse and nuclear variables

- Calorimetric estimator for neutrino energy

$$E_{vis} = E_\mu + T_N$$

Method used by NOvA & DUNE

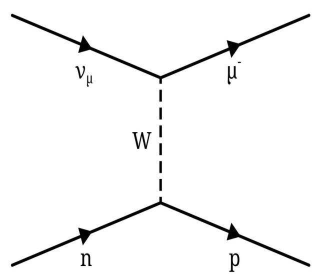


Phys. Rev. D 105, 032010

Reduced bias in neutrino energy reconstruction

$\boldsymbol{E_{vis}}$ bias dominated by **detector resolution**
$\boldsymbol{E_{QE}}$ dominated by **nuclear effects**

CCQE



If initial state nucleon is at rest: two body process → exact energy reconstruction

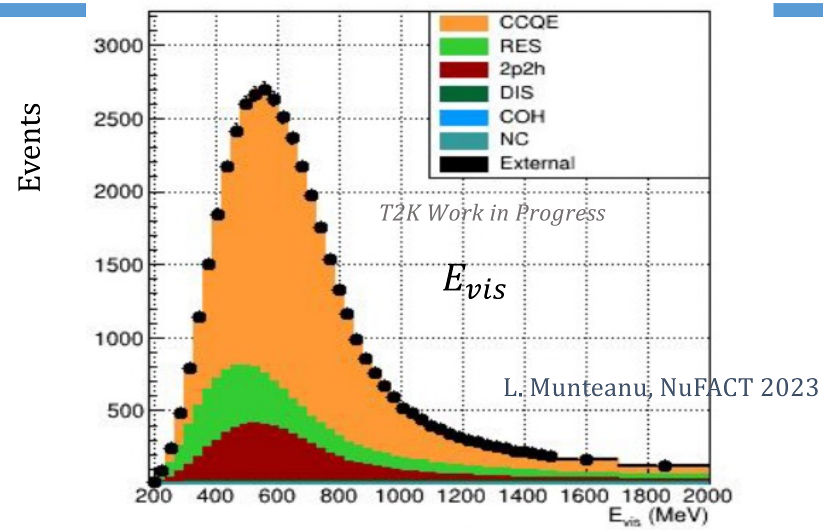
$$E_{QE} = \frac{m_p^2 - m_\mu^2 - (m_n - E_B)^2 + 2E_\mu(m_n - E_B)}{2(m_n - E_B - E_\mu + p_\mu^z)}$$

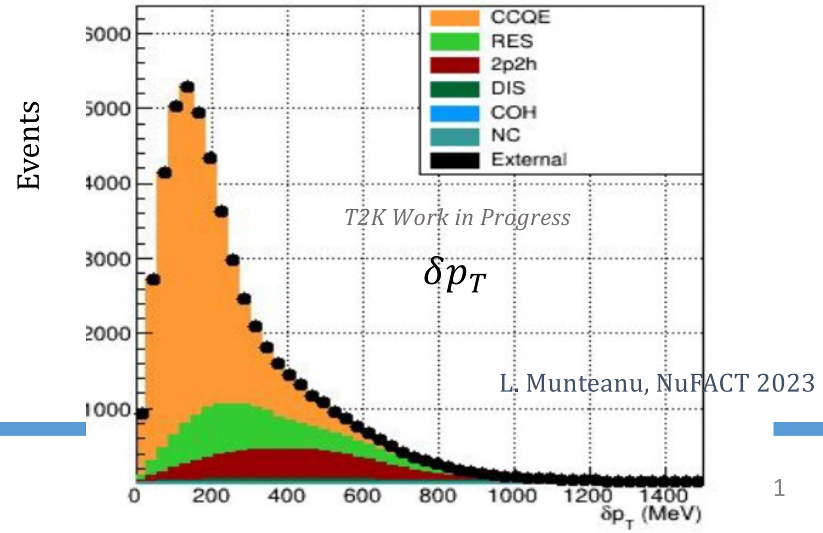
$\delta\vec{p}_T$, $\delta\alpha_{T}$, E_{vis} ≡ **exclusive variables**

Oscillation analysis sensitivity

- Preliminary impact on sesitivity to constrain systematic uncertainties using
  - Latest T2K interactions uncertainty model
  - Current ND280 samples binned in lepton kinematics
  - SFGD samples binned in ($\boldsymbol{E_{vis}}$, $\boldsymbol{\delta p_T}$)
  - Simplified (conservative) reconstruction effects
  - No detector systematics

CC0π + Np



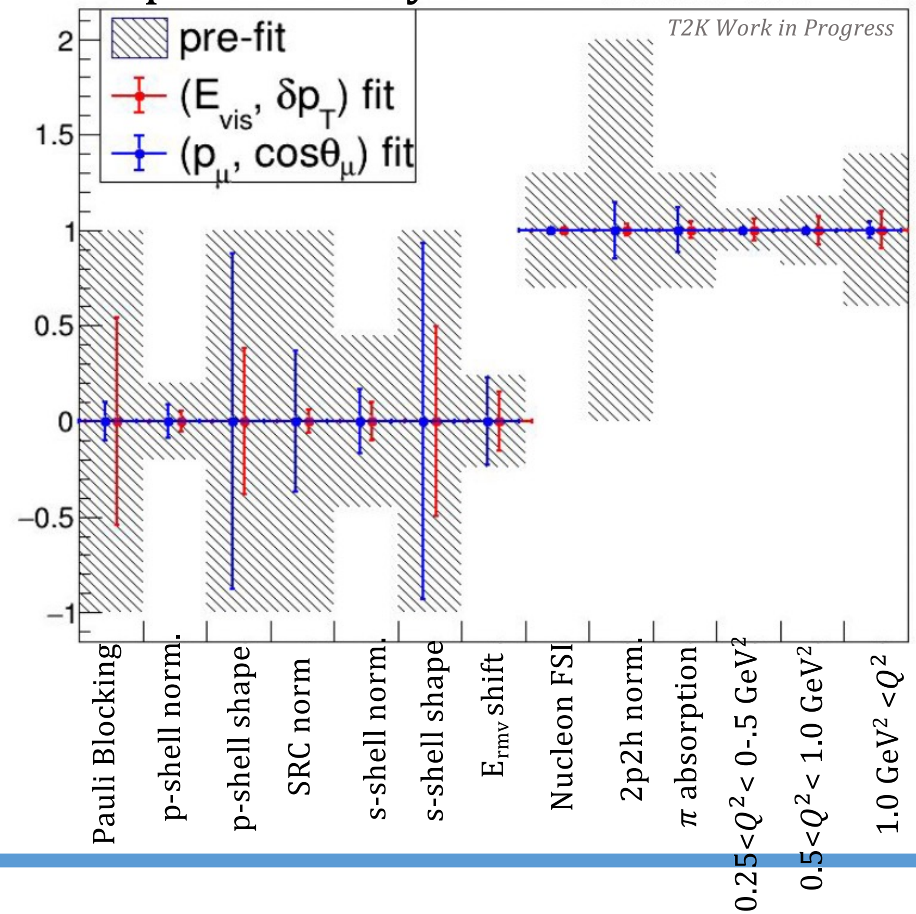


Impact of SuperFGD

- Impact with SuperFGD only
- Two different 2D binnings:
  - $(p_\mu, \cos\theta_\mu)$ – lepton only
  - $(E_{vis}, \delta p_T)$ – lepton + hadron information
- Check effect in post-fit uncertainties

SuperFGD only

Plot for 4.10^{21} *POT* =1 year



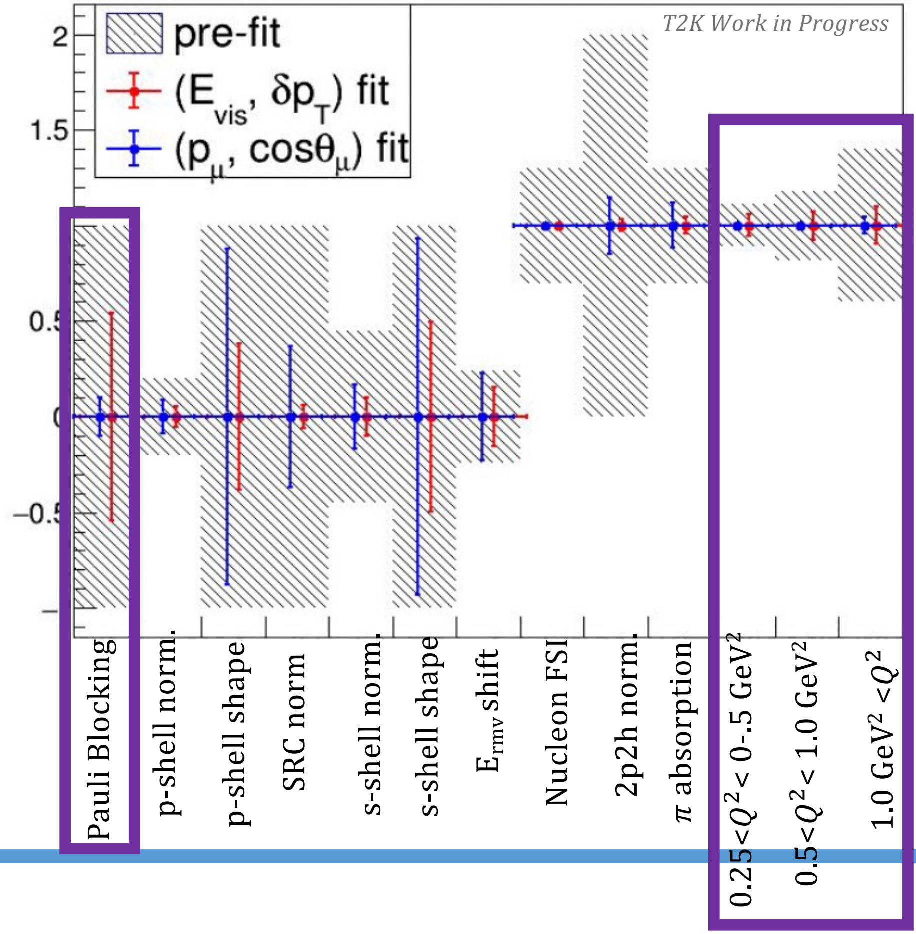
Impact of SuperFGD

- Pauli Blocking and high-Q2 shape freedom more sensitive to lepton only binning

L. Munteanu, NuFACT 2023

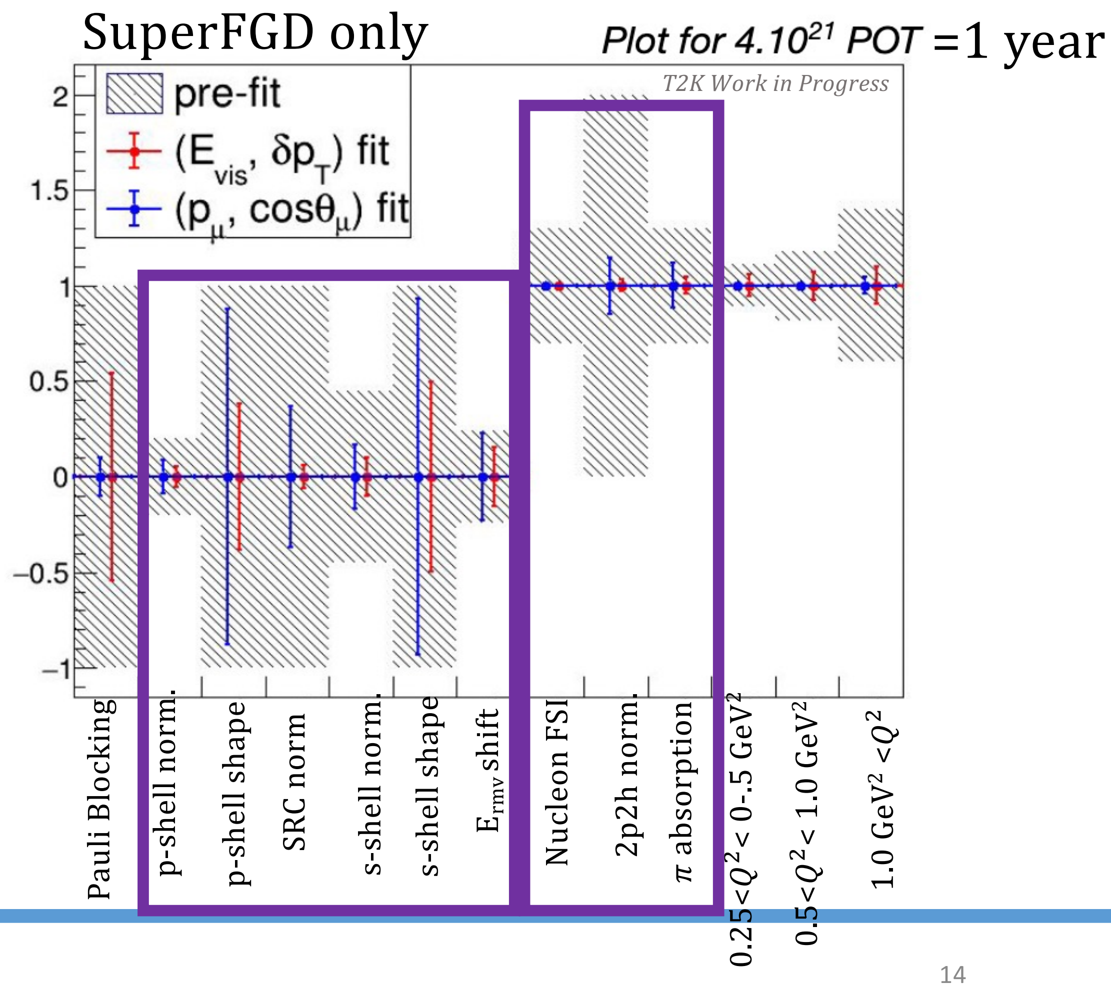
SuperFGD only

Plot for 4.10^21 POT =1 year



Impact of SuperFGD

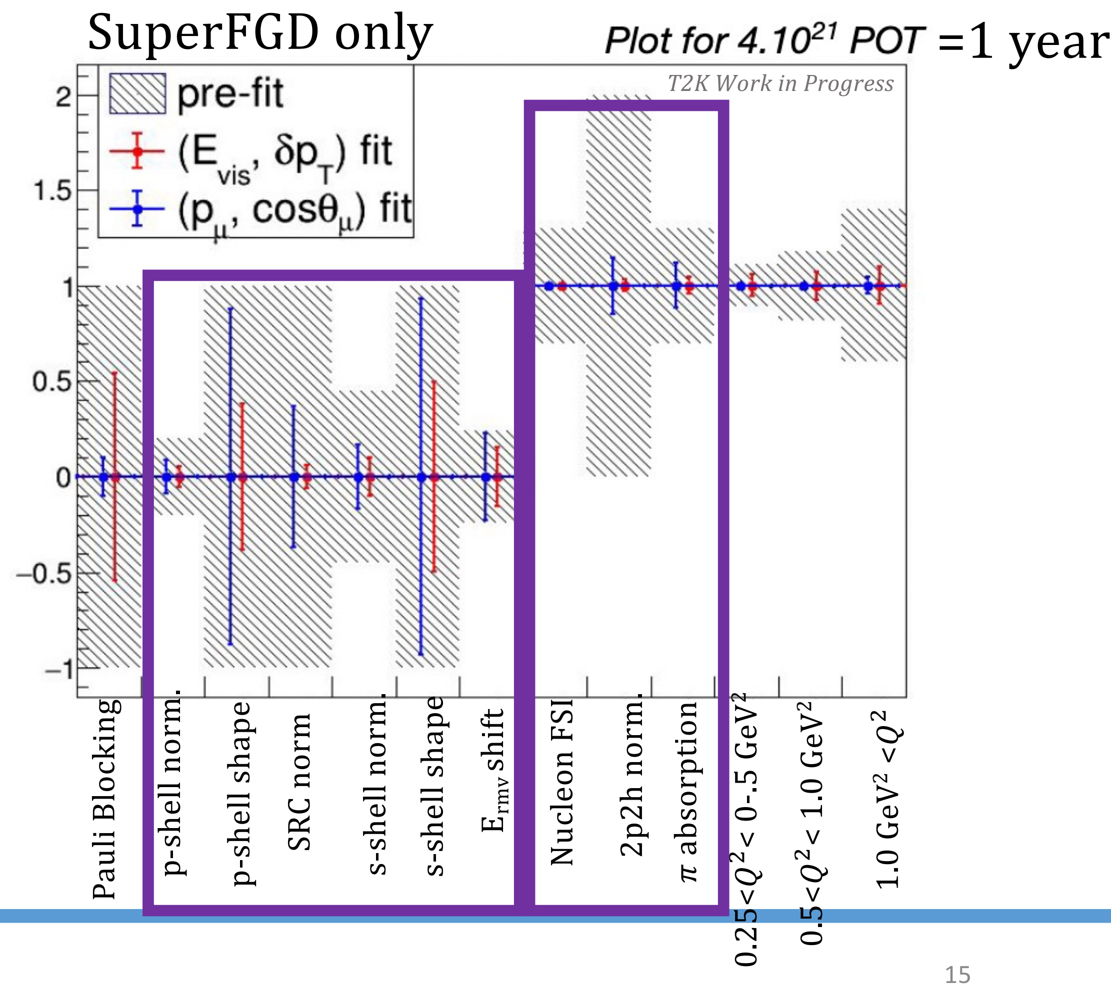
- Spectral function + 2p2h more sensitive to adding hadronic information



Impact of SuperFGD

- Spectral function + 2p2h more sensitive to adding hadronic information

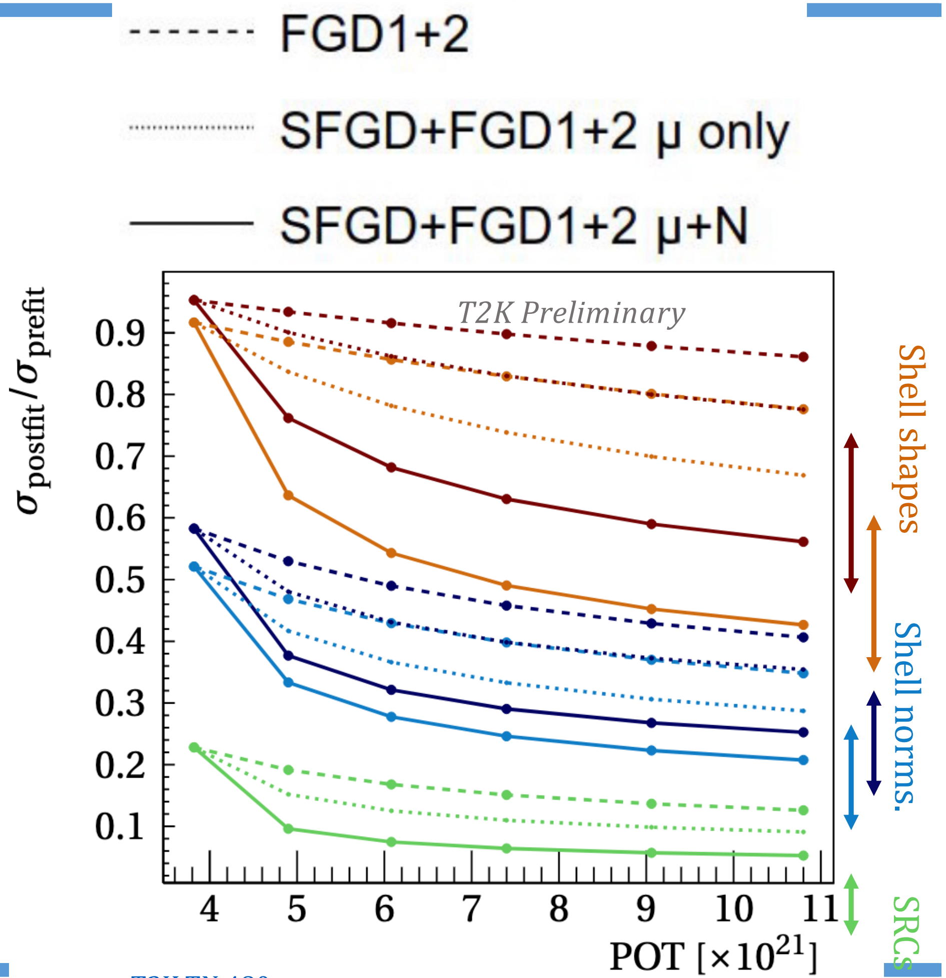
- Parameters with higher impact on Δm^2_{32} and $\sin\theta_{23}$.



L. Munteanu, NuFACT 2023

SuperFGD + current FGDs

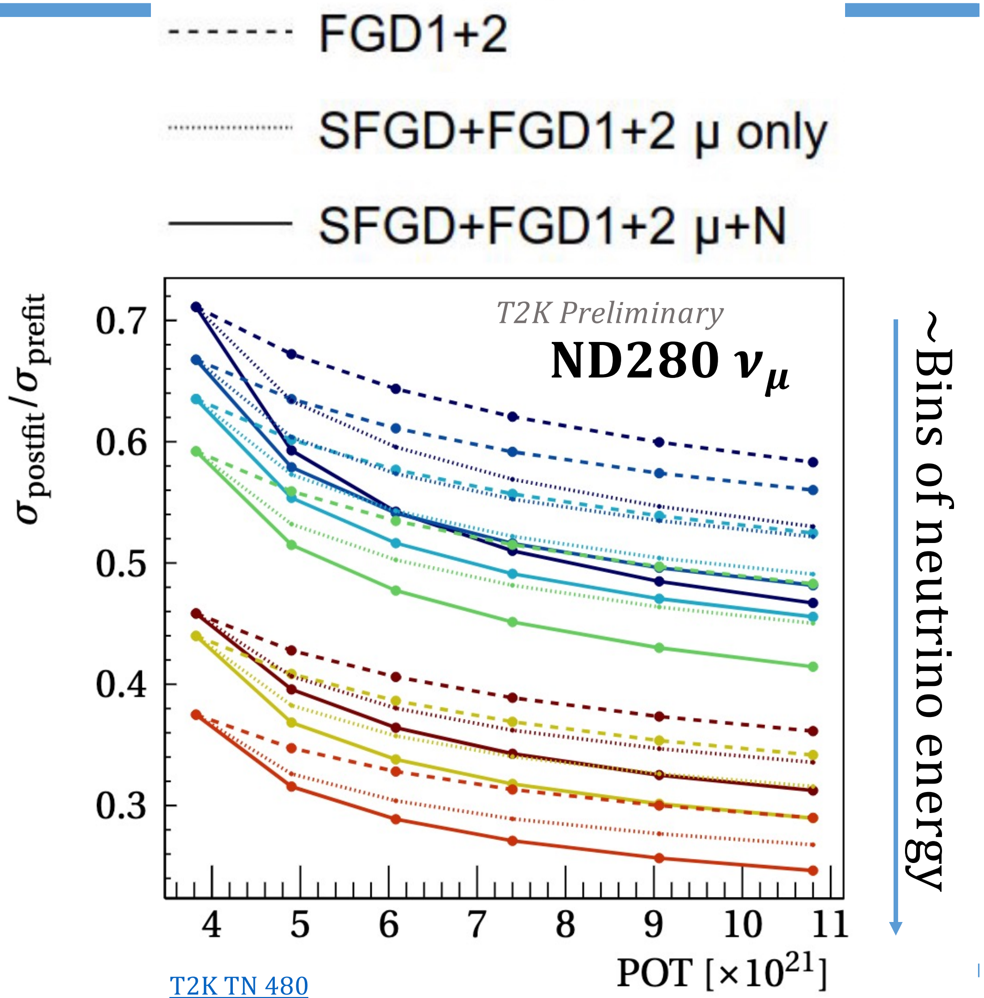
- Assume all T2K ND280 POTs to date (3.6 x 10^{21} POTs), (ν:ν ratio 1:1)
- Two different 2D binnings:
- (p_{μ}, $cos\theta_{\mu}$) binning for FGD samples
- (E_{vis}, δp_T) binning for SFGD samples
- *Spectral Function C-shell parameters*
- *Big improvement with hadronic variables, key in oscillation measurements*



T2K TN 480

SuperFGD + current FGDs

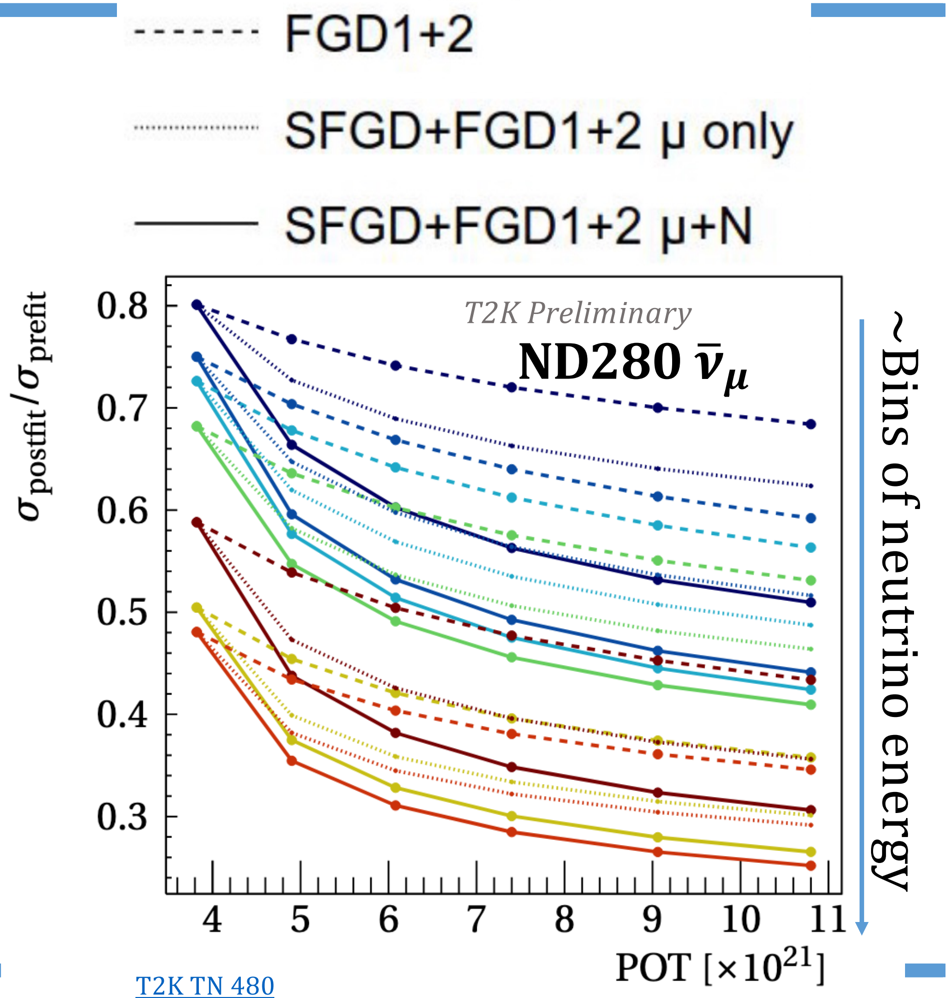
- Assume all T2K ND280 POTs to date (3.6×10^{21} POTs), (ν:ν ratio 1:1)
- Two different 2D binnings:
- (p_{μ}, $\cos\theta_{\mu}$) binning for FGD samples
- (E_{vis}, δp_T) binning for SFGD samples
- E_{vis} is a more accurate estimator of neutrino energy



T2K TN 480

SuperFGD + current FGDs

- Assume all T2K ND280 POTs to date (3.6×10^{21} POTs), ($\nu:\nu$ ratio 1:1)
- Two different 2D binnings:
- (p_{μ}, $\cos\theta_{\mu}$) binning for FGD samples
- (E_{vis}, δp_T) binning for SFGD samples
- E_{vis} is a more accurate estimator of neutrino energy
- Larger effect for $\bar{\nu}$ (neutron information)



T2K TN 480

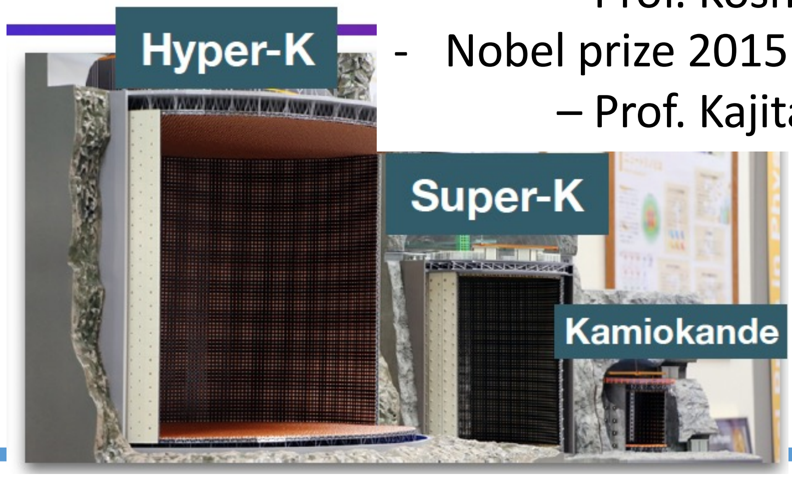
Oscillation measurements: next steps

- Being studied quantitative impact on oscillation measurements
- Key elements:
  - Error parametrization of kinematical variables – need to introduce error exclusive variables.
- Extrapolation of carbon constraints to oxygen
  - Crucial correlation between C and O
  - Close collaboration with nuclear physicists
  - More data with WAGASCI
- Understancing ν_e/ν_μ differences
- Complementarity with IWCD

Conclusions

- The upgraded ND280 detector opens a big window of new, interesting physics measurements
- Everything in place to have excellent results on neutrino oscillations from
  - increase acceptance in kinematical variables
  - access to new low momentum protons
  - measure neutrons from secondary interactions
- A discovery at some point? …
- If so, ND280 will be there

- Nobel prize 2002
  – Prof. Koshiba, Kamiokande
- Nobel prize 2015
  – Prof. Kajita, SuperKamiokande



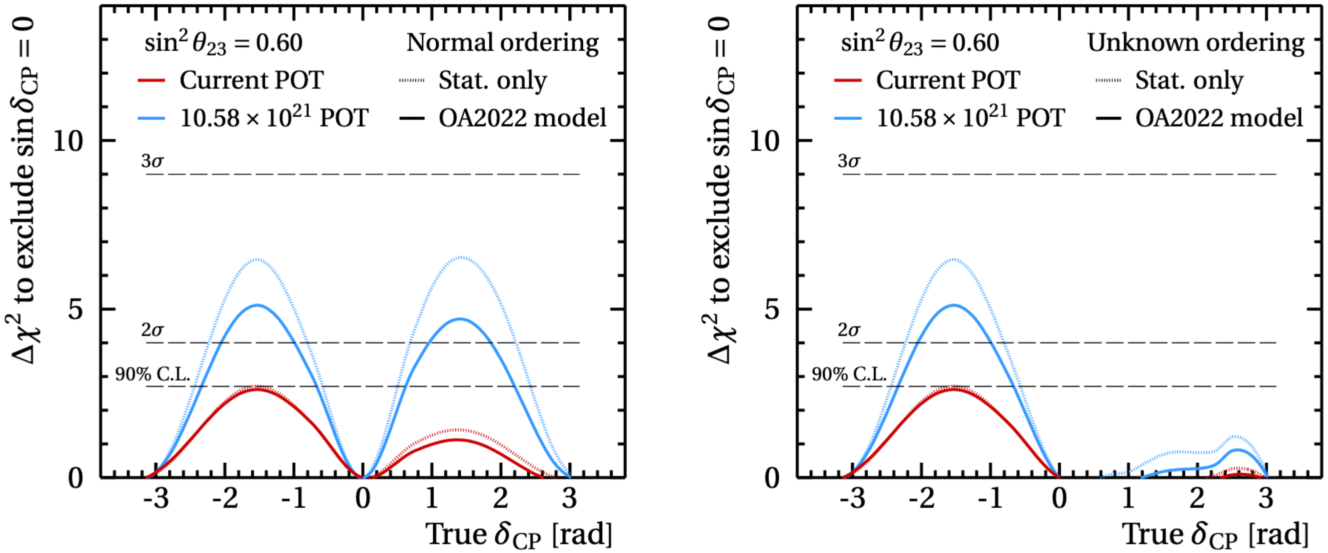
Institute for High Energy Physics

Thank you!

Back-up

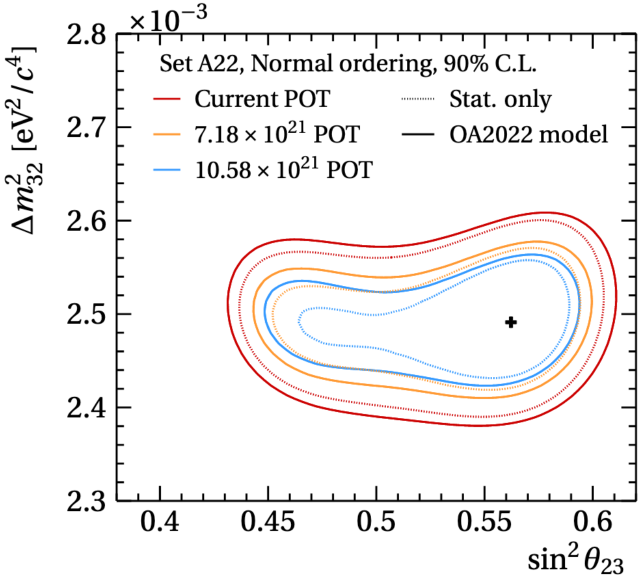
CP - violation sensitivities

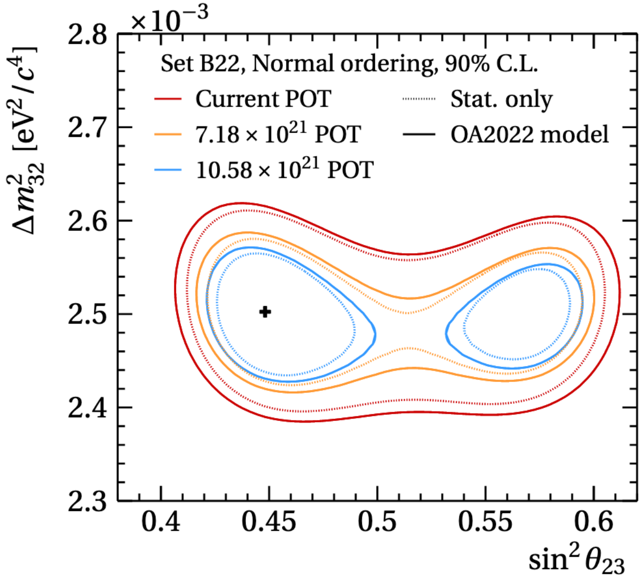
- Sensitivity to exclude CP conservation as a function of δ_{CP} for $\sin^2\theta_{23}$=0.60



Contours for $(\sin^2\theta_{23},\Delta m^2_{32})$

- 90% CL contours in $(\sin^2\theta_{23},\Delta m^2_{32})$ for normal ordering (Set A22, Set B22)





Detector details for Set A22

- Predicted rate in each of the six far detector simples for Set A22.

Sample	2022	2023	2024	2025	2026	2027
FHC 1Rμ	301.18	383.89	474.26	575.35	701.71	837.26
RHC 1Rμ	124.68	165.86	210.86	261.20	324.13	391.63
FHC 1Re	79.53	101.37	125.24	151.93	185.30	221.09
RHC 1Re	15.47	20.58	26.17	32.42	40.23	48.60
FHC 1Re1de	10.87	13.85	17.11	20.76	25.32	30.21
FHC multi-Rμ	116.25	148.17	183.05	222.07	270.84	323.16

Table 6. Predicted event rate in each of the six far detector samples at the Asimov Set A22 with the additional POT per year as shown in Table 1.

Detector details for Set B22

- Predicted rate in each of the six far detector simples for Set B22.

Sample	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**
FHC 1Rμ	305.92	389.93	481.72	584.39	712.74	850.42
RHC 1Rμ	125.49	166.95	212.25	262.92	326.26	394.20
FHC 1Re	57.97	73.89	91.28	110.74	135.06	161.15
RHC 1Re	15.42	20.52	26.08	32.31	40.09	48.44
FHC 1Re1de	8.12	10.34	12.78	15.50	18.91	22.56
FHC multi-Rμ	116.52	148.51	183.47	222.58	271.47	323.91

Table 7. Predicted event rate in each of the six far detector samples at the Asimov Set B22 with the additional POT per year as shown in Table 1.