Improved near detectors and nuclear models for present and future neutrino oscillation experiments

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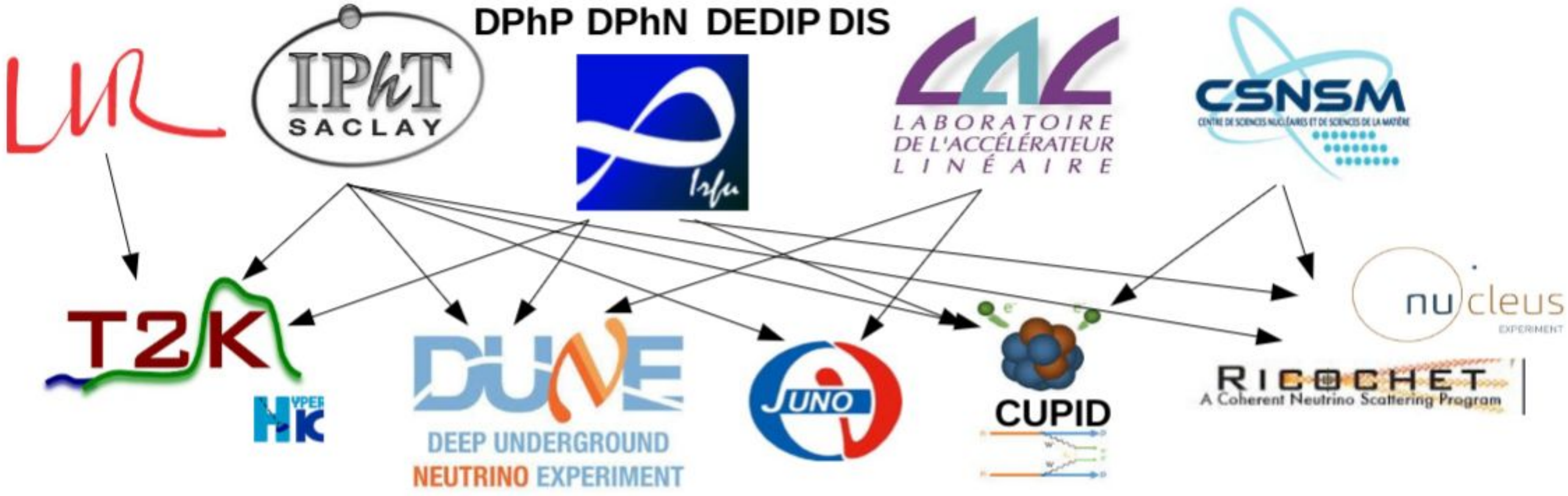
Journée du LabEx P2IO
Laboratoire de Physique des Solides, Orsay
November 26th, 2021

Outline

- Introduction:
  - BSM-Nu project
  - Neutrino oscillations and long-baseline experiments
- T2K Near Detector Upgrade
- Improved nuclear models
- Summary and prospects

Introduction

The BSM-Nu project



BSM-Nu: federation of all the actors of neutrino physics inside the P2IO perimeter. Very new kind of group in the field: neutrino+nuclear physicist + theoreticians + engineers from different neutrino experiments working together and sharing expertise towards the precision era in nu physics.

Goal: Neutrino nature (Majorana?) and neutrino mixing (MH? δ_{CP}?) as a way to access BSM physics

Neutrino flavors and masses mixing

- Neutrino flavor states: $\nu_e\,, \nu_\mu\,, \nu_\tau \longrightarrow$ production and detection
- Neutrino mass states: $\nu_1\,, \nu_2\,, \nu_3 \longrightarrow$ propagation

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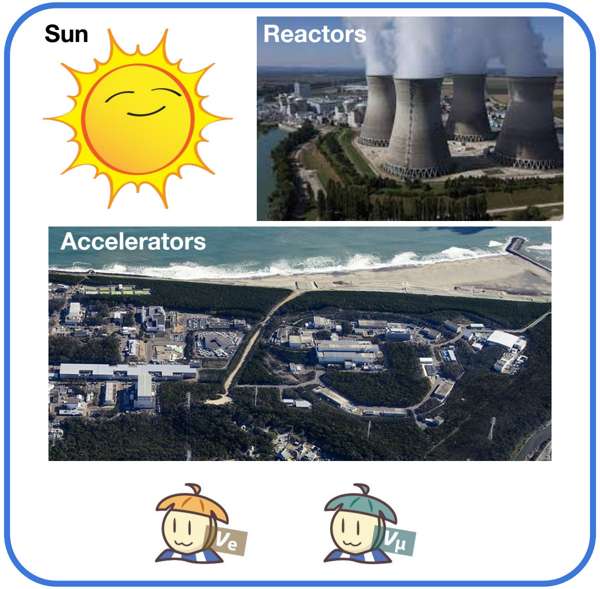

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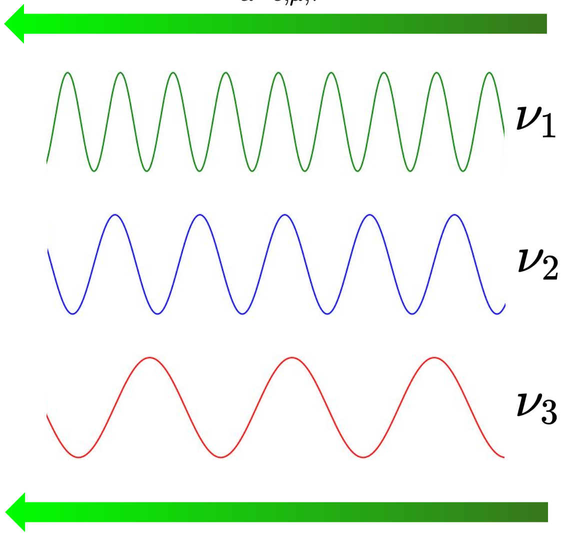

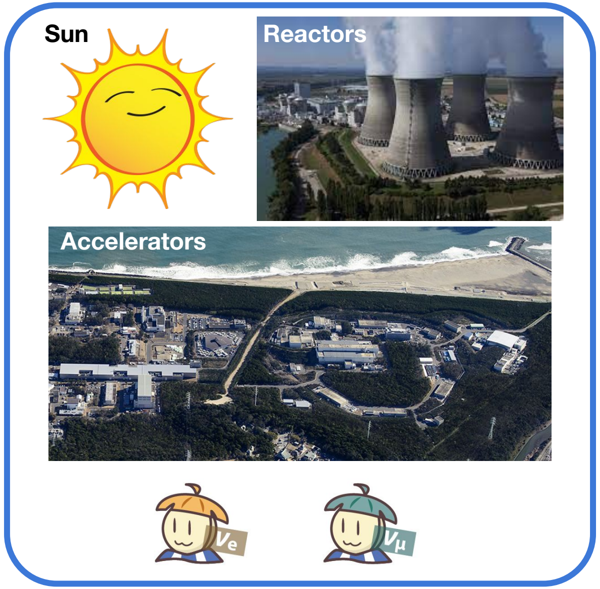

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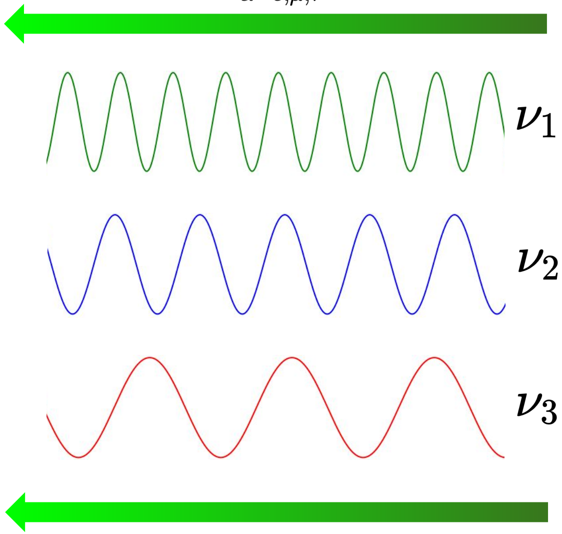

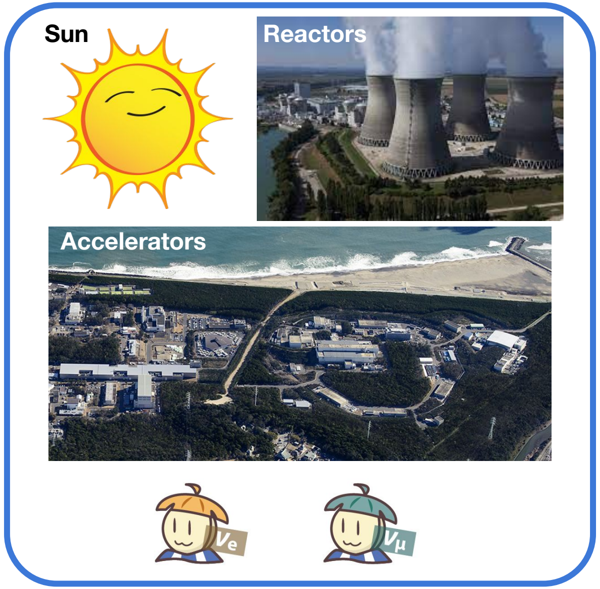

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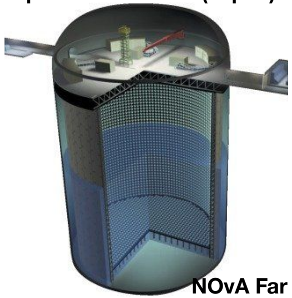
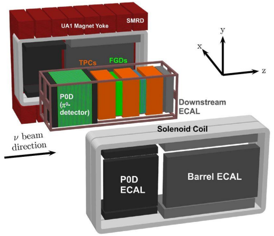
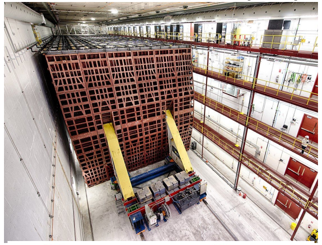
Super-Kamiokande (Japan)



T2K Near Detector (Japan)



NOvA Far Detector (USA)



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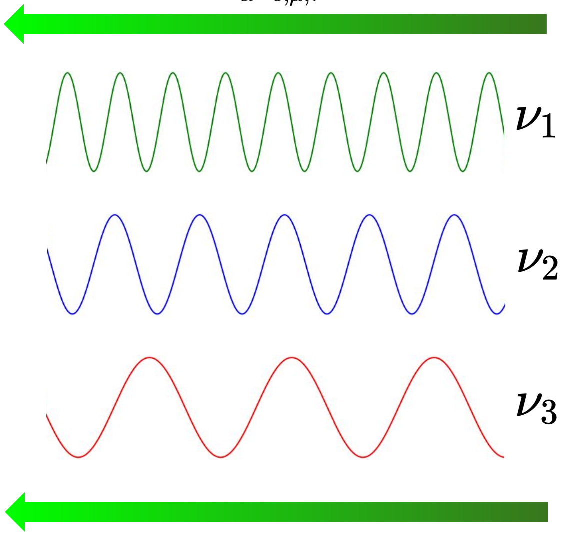
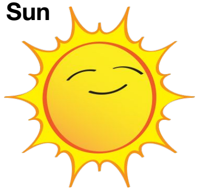


Sun



Reactors

Accelerators

What do Long-Baseline Experiments measure?

- Mass and flavor states mixing: $|\nu_i\rangle = \sum_{\alpha=e,\mu,\tau} U_{\alpha i} |\nu_\alpha\rangle$

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{CP}} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$$c_{ij} = \cos(\theta_{ij})$$
$$s_{ij} = \sin(\theta_{ij})$$

- Long-baseline experiments are sensitive to:
  - Atmospheric parameters $(\theta_{23}, \Delta m^2_{32})$ through $\nu_\mu/\bar{\nu}_\mu$ disappearance

$$P(\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_\mu) \approx 1 - \sin^2 2\theta_{23} \sin^2\left(\frac{\Delta m^2_{32} L}{4E}\right)$$

  - $(\delta_{CP}, \theta_{23})$ through $\nu_e/\bar{\nu}_e$ appearance

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If $P(\nu_\mu \to \nu_e) \neq P(\bar{\nu}_\mu \to \bar{\nu}_e)$ then matter and anti-matter could behave differently in the lepton sector
$\longrightarrow$ CP violation!

This could shed light on the matter/anti-matter asymmetry in the Universe

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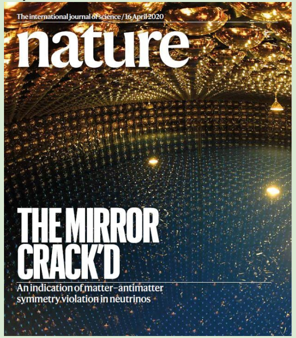
$\frac{{}_{32}^{2}L}{E}$

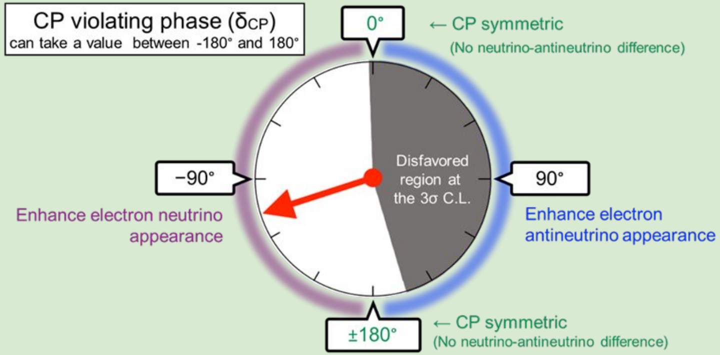
$(\mp) O(\delta_{CP})$

First hints by T2K

April 2020



- CP conservation is excluded at a 2σ level
- Preference for a ~maximal CP violation



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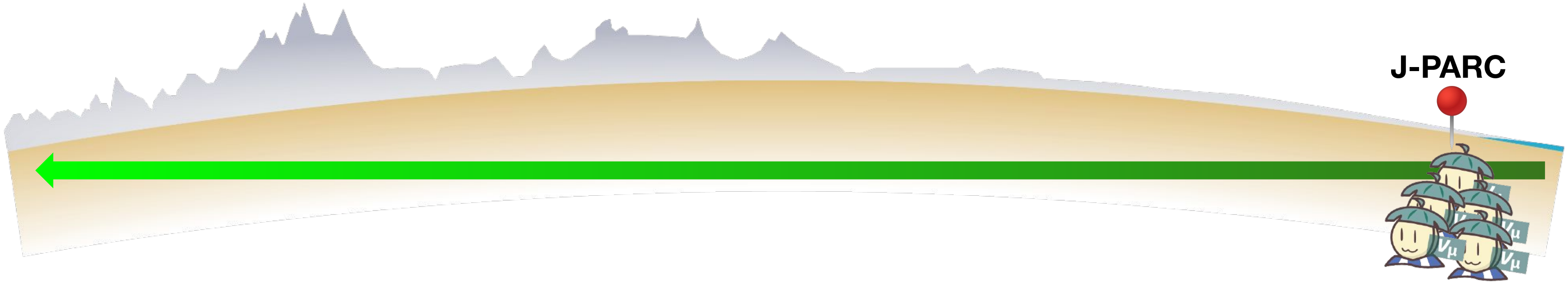
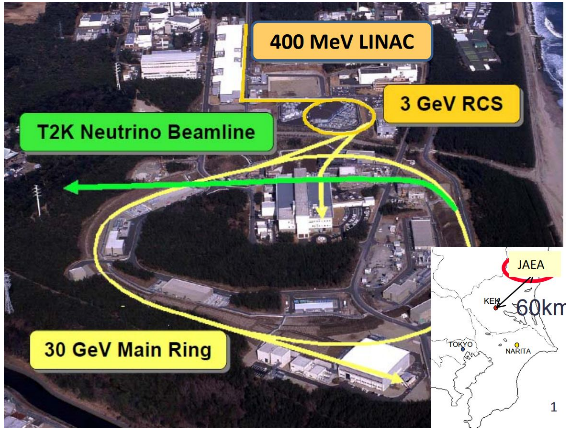
Long-Baseline Experiments: T2K



- Proton beam on graphite target
- Produced hadrons decay into muon (anti-)neutrinos



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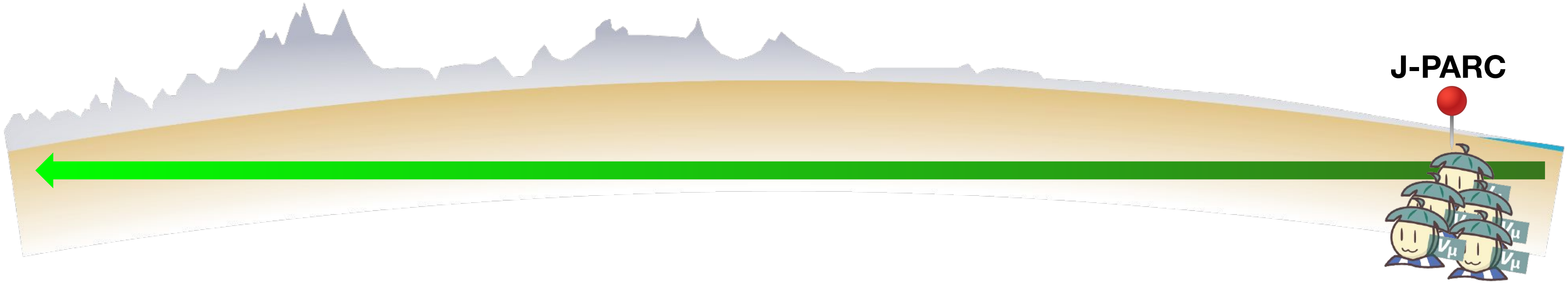

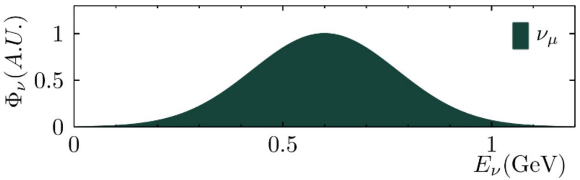

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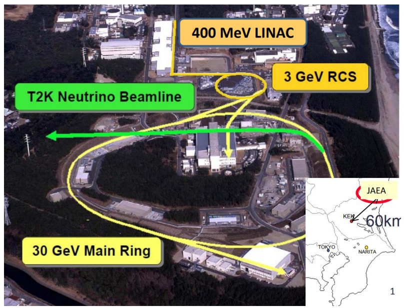
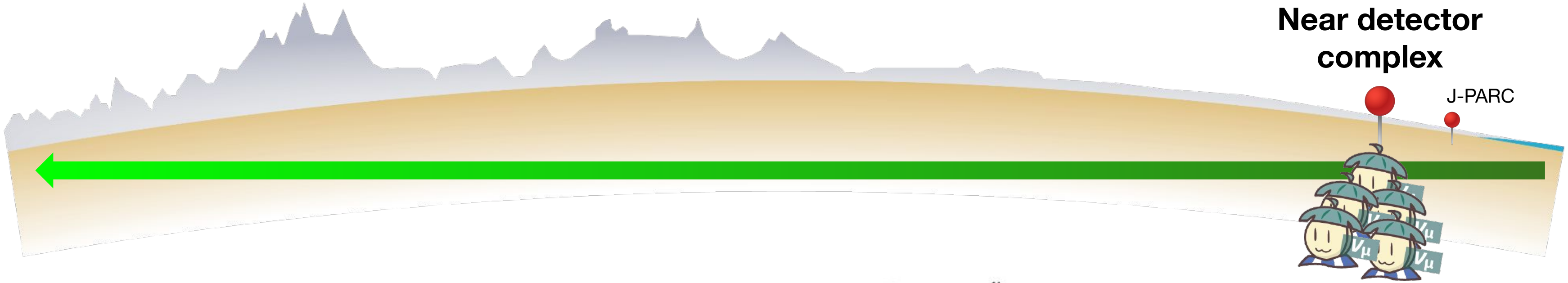
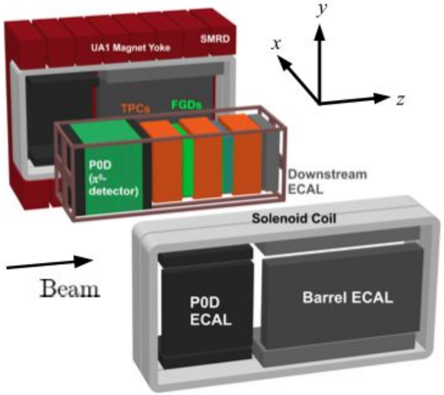
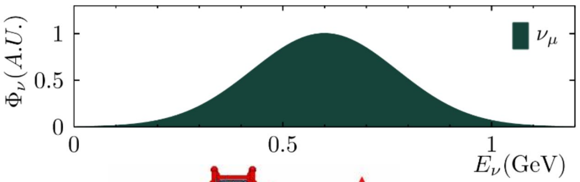


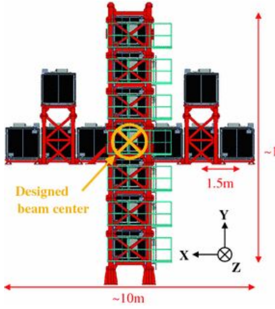
Long-Baseline Experiments: T2K

Near detector complex





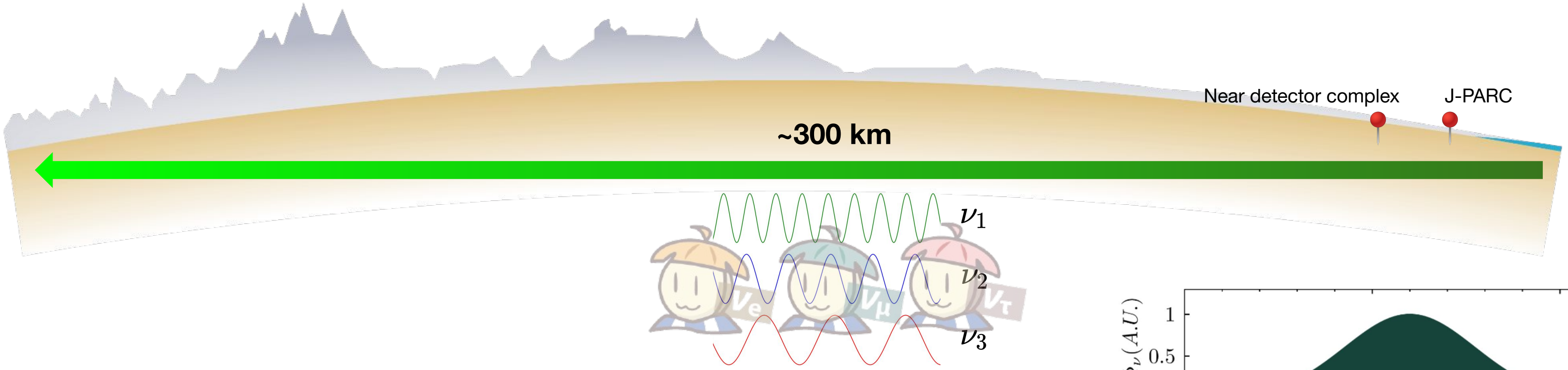




- Measure unoscillated neutrino flux:
  - Electron neutrino and wrong-sign contaminations
  - Neutrino-nucleus interactions

$\longrightarrow$ Reduce **systematic uncertainties**

Long-Baseline Experiments: T2K



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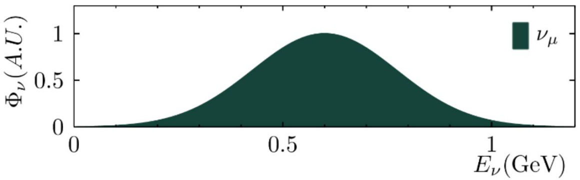

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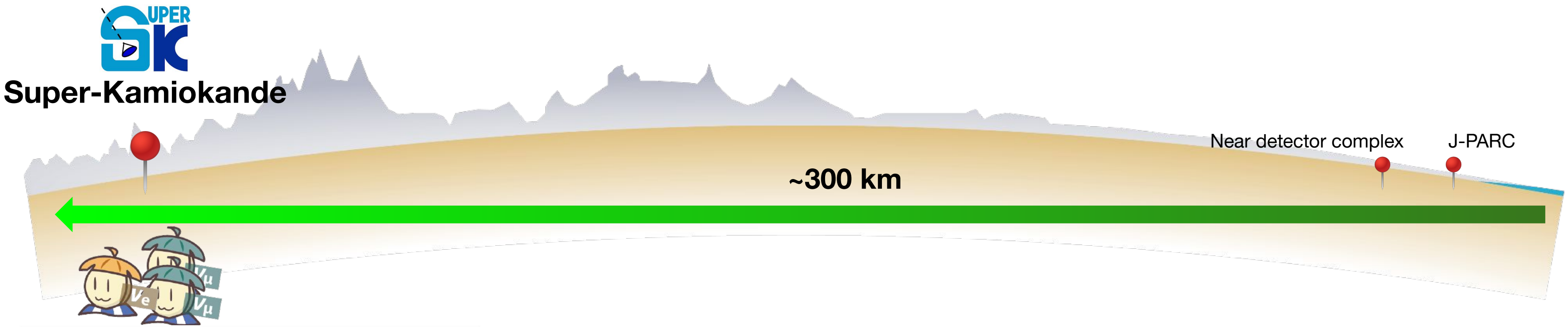
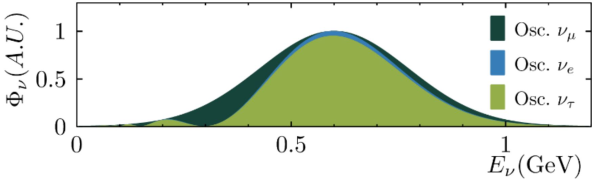
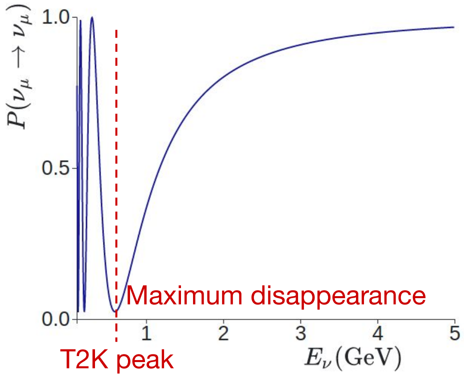
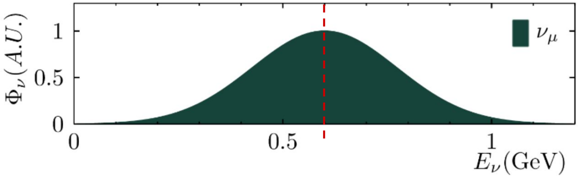


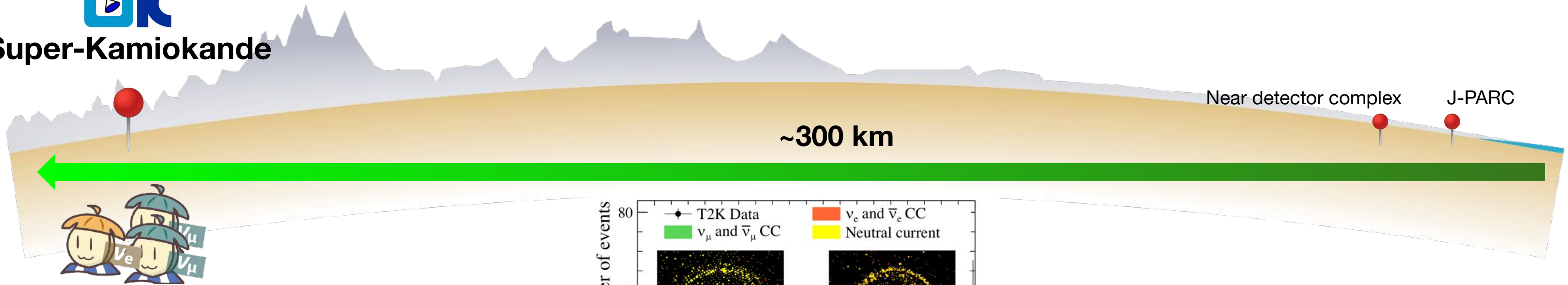


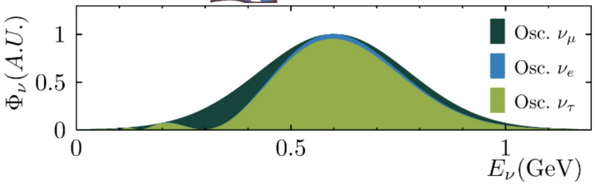


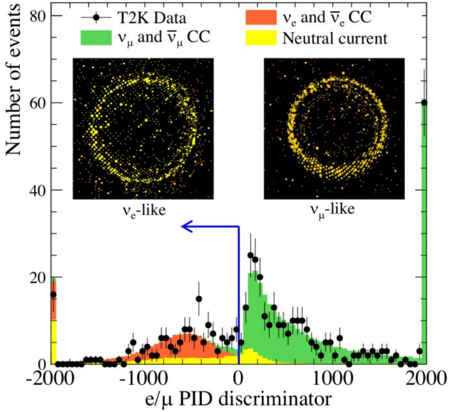


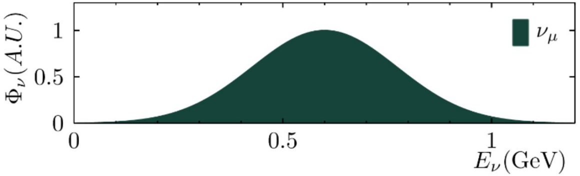
Long-Baseline Experiments: T2K

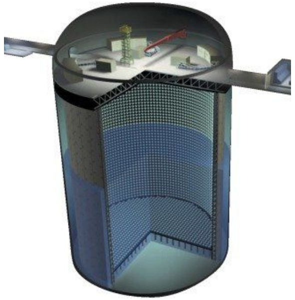
Super-Kamiokande











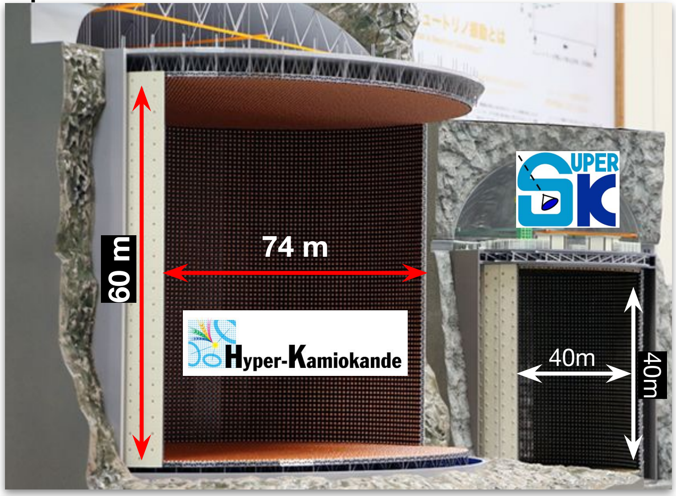
- 50 kt water Cherenkov detector
- Measurement of:
  - Electron neutrino vs. muon neutrino PID by ring pattern
  - Neutrino energy

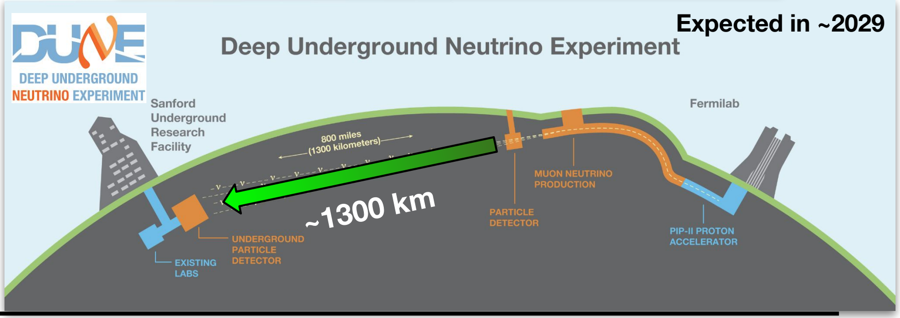
Long Baseline Experiments

- Currently:

- Next generation:

Expected in 2027



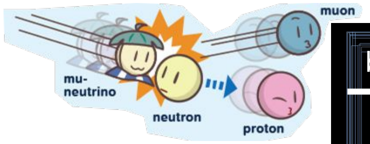


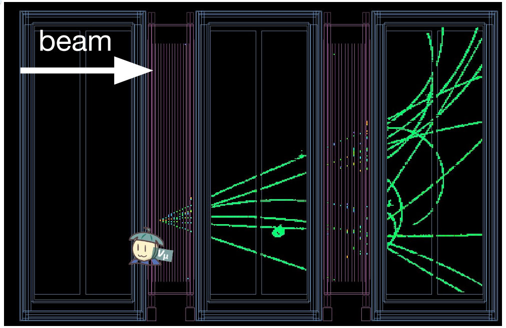
Neutrino energy reconstruction

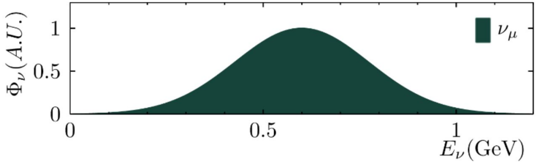
- To measure the oscillation parameters, the **neutrino energy** needs to be determined precisely

$$P(\overset{(-)}{\nu}_\mu \rightarrow \overset{(-)}{\nu}_e) \approx \sin^2 2\theta_{13} \sin^2 \theta_{23} \sin^2 \left(\frac{\Delta m^2_{32} L}{4E} \right) (\mp) O(\delta_{CP})$$

- An accurate reconstruction of the **neutrino energy** from the **outgoing particles** requires a precise **neutrino-nucleus interaction model**







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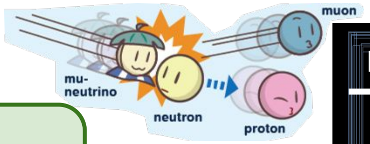
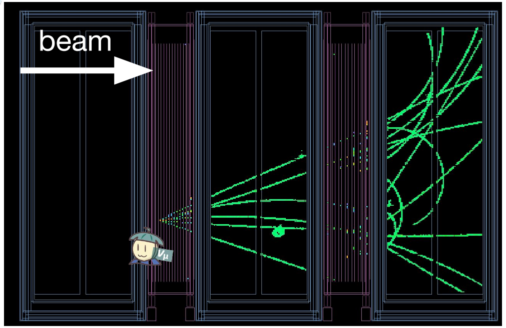
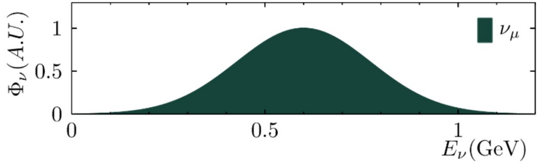




Two ways to improve the neutrino energy reconstruction:

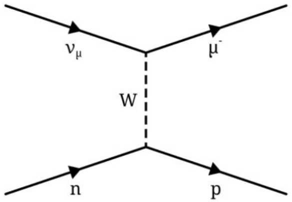
- Improve the detectors
- Improve the nuclear model

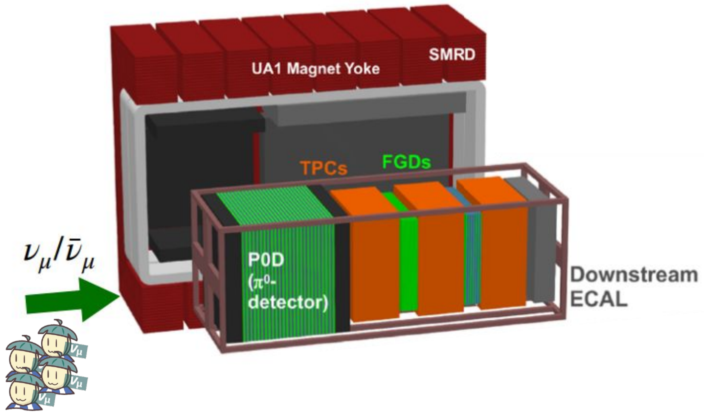
⟶ **Focus of BSM-Nu WP2**

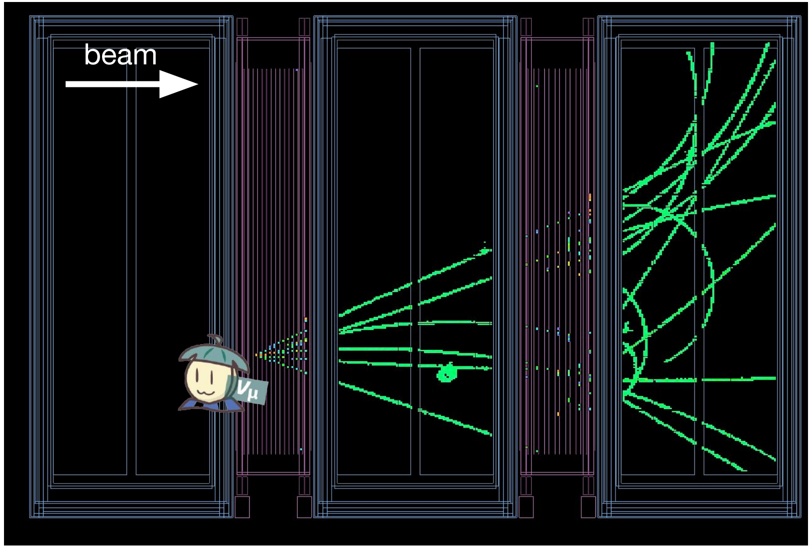


T2K Near Detector Upgrade (T2K-II)

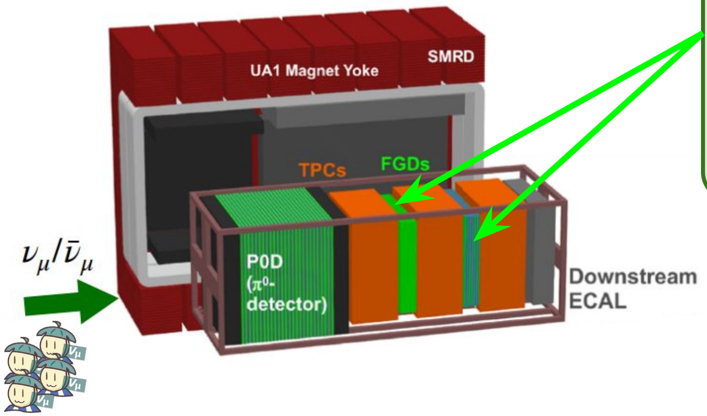
Off-axis Near Detector at 280m (ND280)





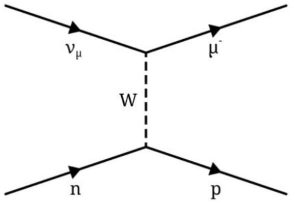


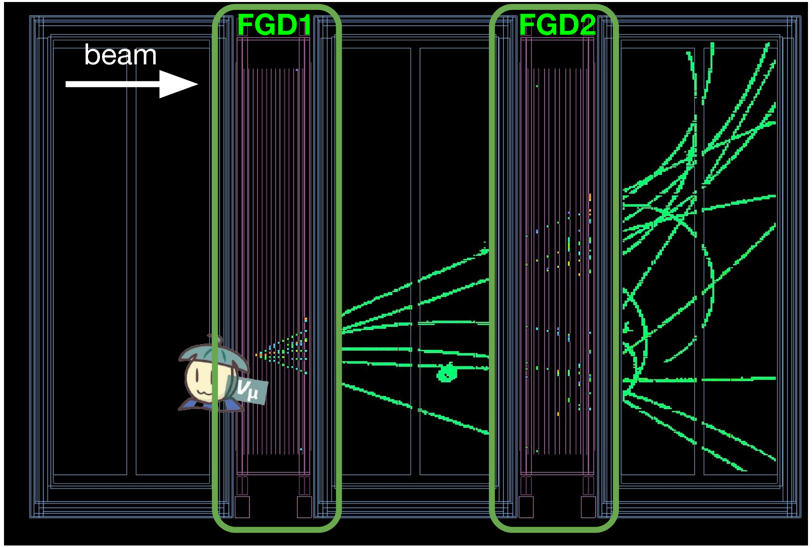
Off-axis Near Detector at 280m (ND280)



Fine Grained Detectors (FGDs):

- Plastic scintillator tracker
- Target for neutrinos
- FGD2 has water target layers





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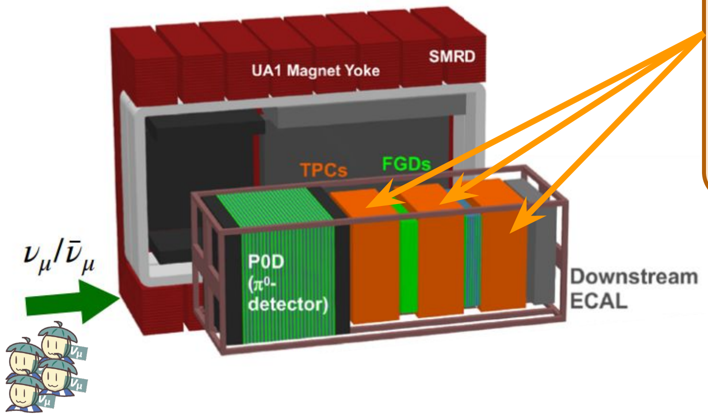
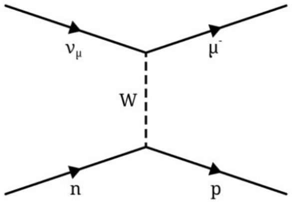
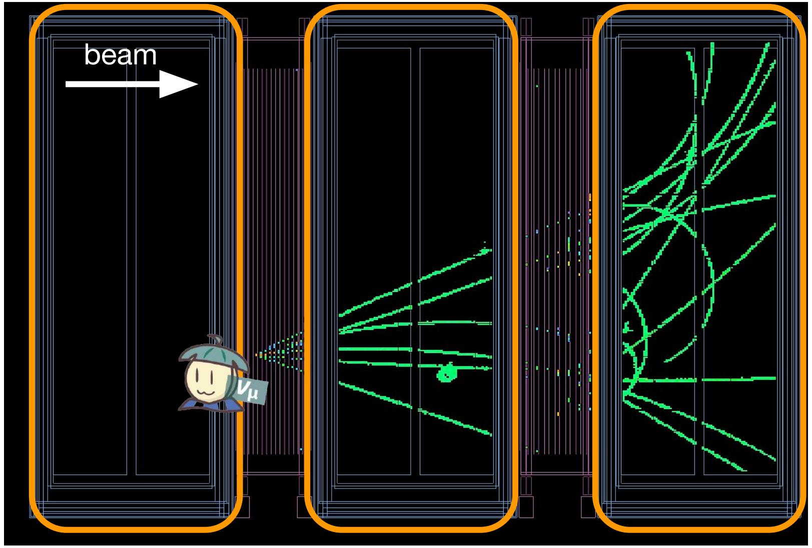


Time Projection Chambers (TPCs)

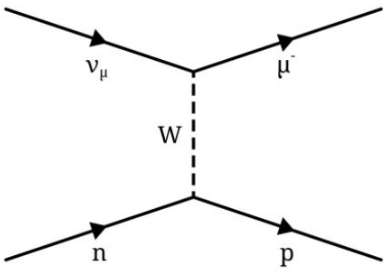
- Tracking detectors
- Charged particle momentum
- Particle ID



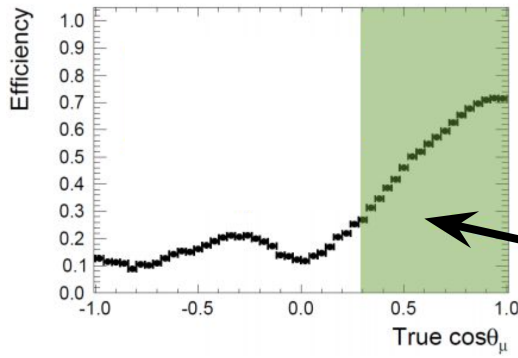


Limitations of current ND280

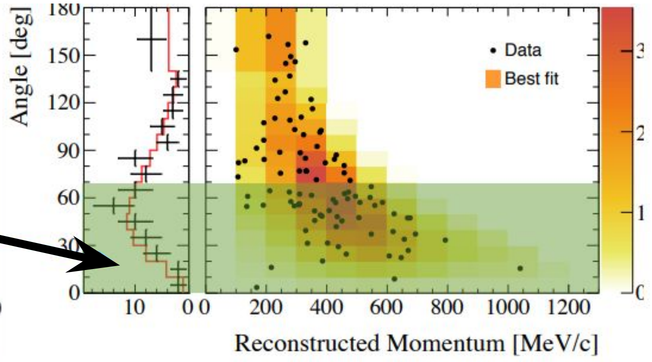
- Non-isotropic efficiency (unlike Super-Kamiokande)
- High momentum proton threshold (~450 MeV/c)
- For the oscillation analysis, neutrino interactions are characterized in muon kinematics only



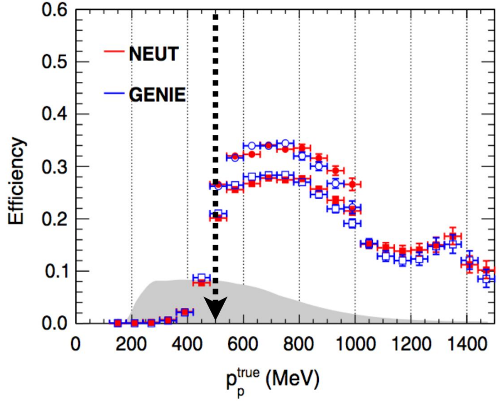
Muon detection efficiency at ND280



ν_e candidates at Super-K



Proton detection efficiency

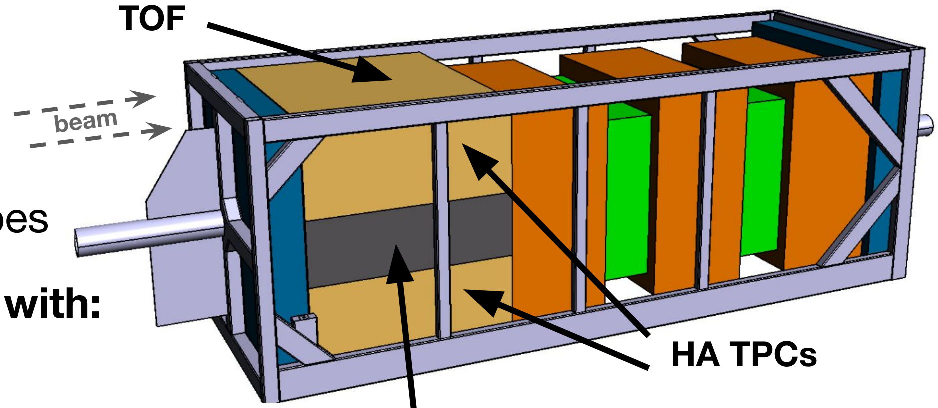


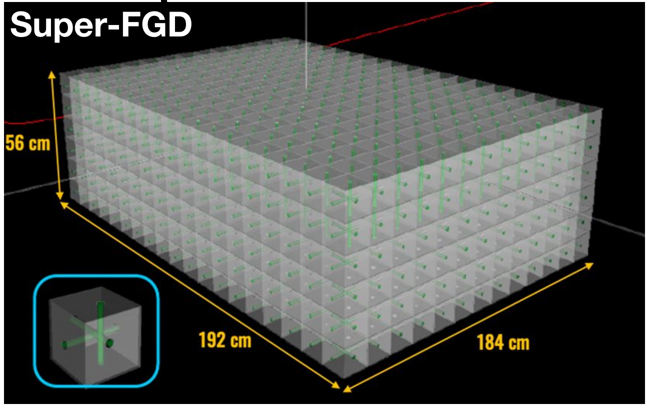
ND280 Upgrade

- New high-angle TPCs
- New Time Of Flight detector
- Super-FGD: 2.10^6 1 cm^3 scintillator cubes

The goal is to reduce the ND systematics with:

- Fully active target
- 4π acceptance for charged particles
- Lower proton momentum threshold (~300 MeV/c)
- Neutron detection





ND280 Upgrade

New high-angle TPCs

Beam test at CERN in 2018
Prototype tested at DESY in 2019 & 2021
Ongoing tests at CERN

arXiv:2106.12634

- New Time Of Flight detector
- ...scintill...

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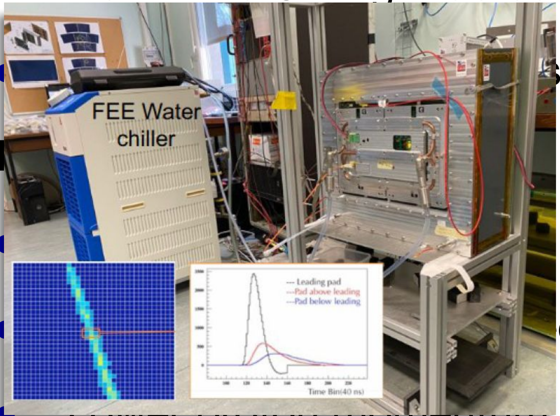
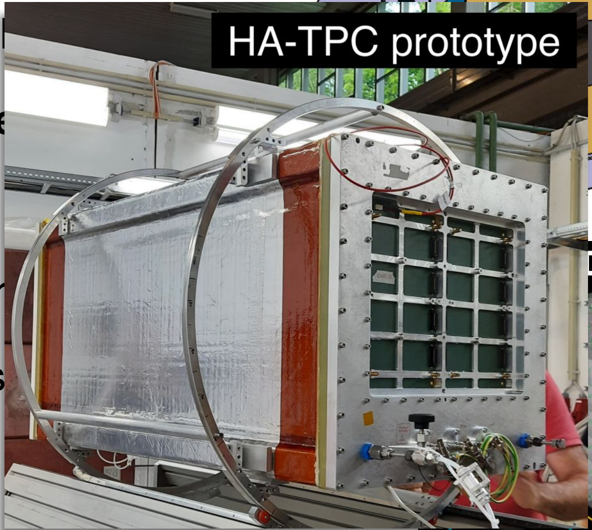
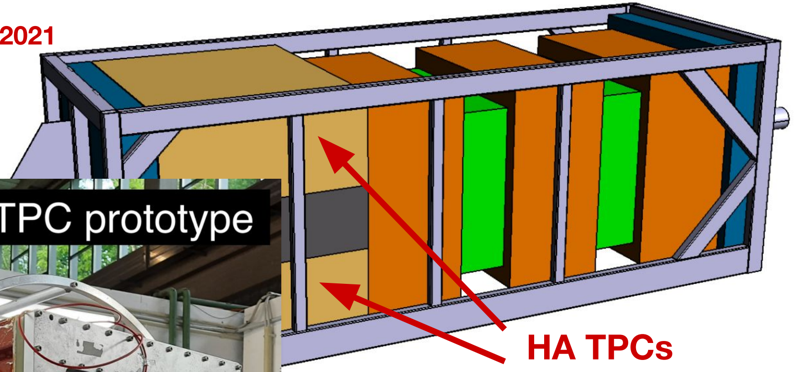
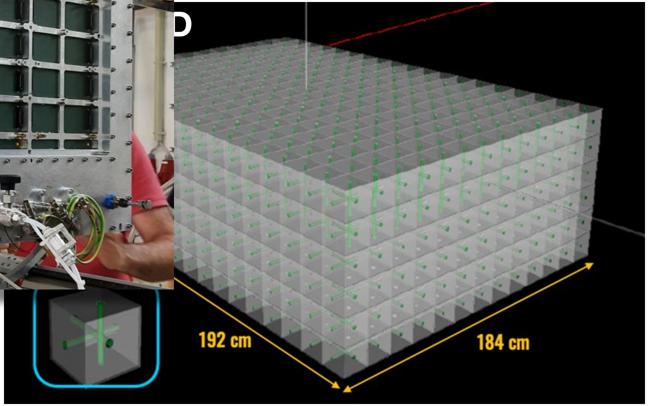
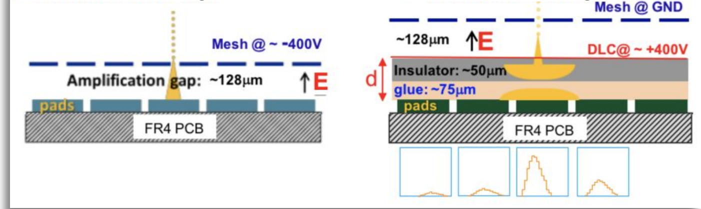
- ...
- ...d par...
- Lower proton momentum thres...





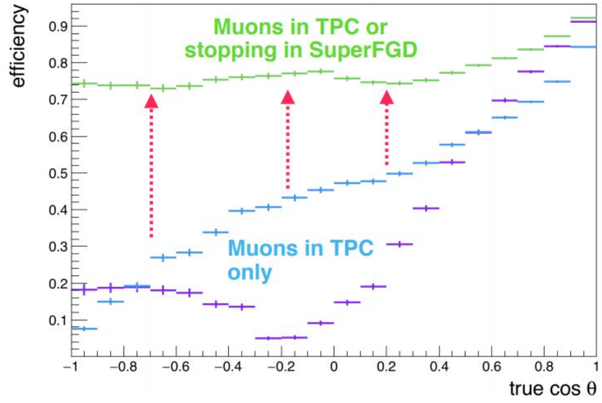




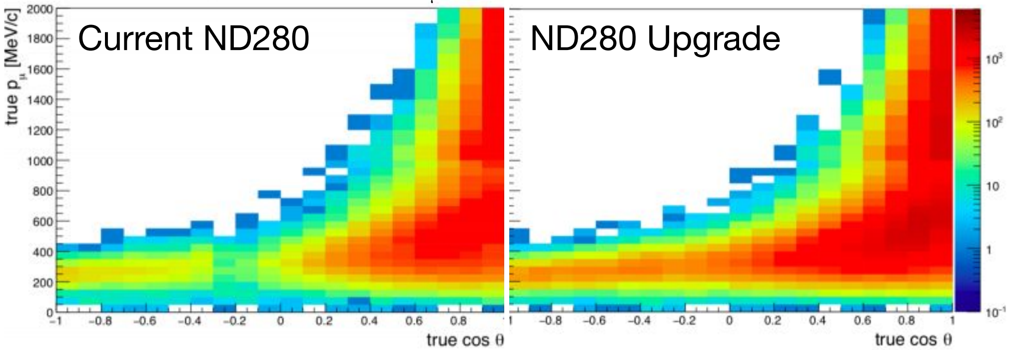


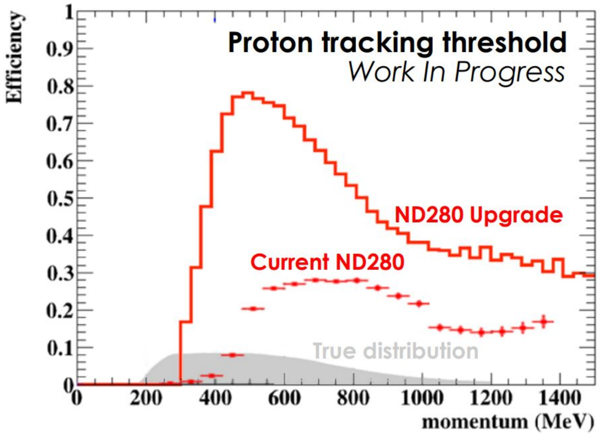
Improvements with the ND280 Upgrade

- Improved reconstruction at high and backward angles ⟶ better constraints on the neutrino interaction model
- Increased target mass (x2 current ND280) ⟶ more statistics
- Better reconstruction of outgoing nucleons ⟶ access to new observables
- Neutrino interaction measurements beyond p_μ, $\cos\theta_\mu$ (exclusive and multidimensional analyses)



Selected $\nu_\mu CC$ events (NEUT MC)



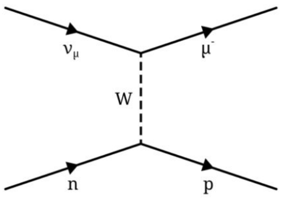


New observables: visible energy

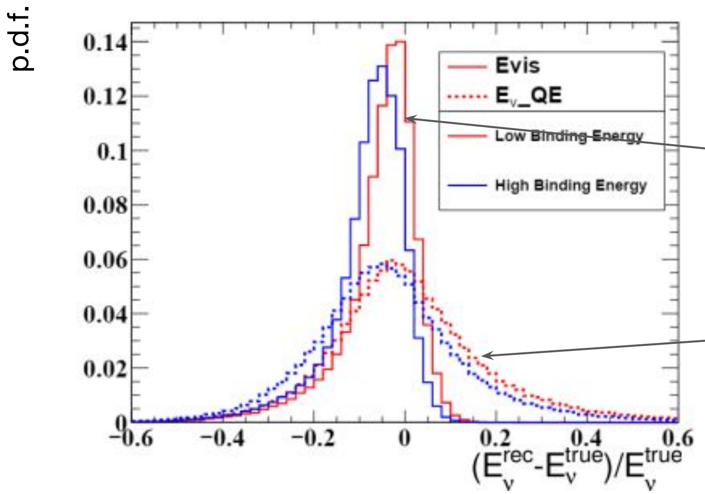
- The neutrino energy can be estimated using the lepton kinematics only under the assumption of a quasi-elastic interaction on a static initial state nucleon

$$E_\nu^{QE} = \frac{m_p^2 - (m_n - E_b)^2 - m_\mu^2 + 2(m_n - E_b)E_\mu}{2(m_n - E_b - E_\mu + p_\mu \cos\theta_\mu)}$$

- When reconstructing the proton as well, the *visible energy* can be a better estimation of the neutrino energy $$E_{\text{vis}} = E_\mu + T_p$$



arXiv:2108.11779

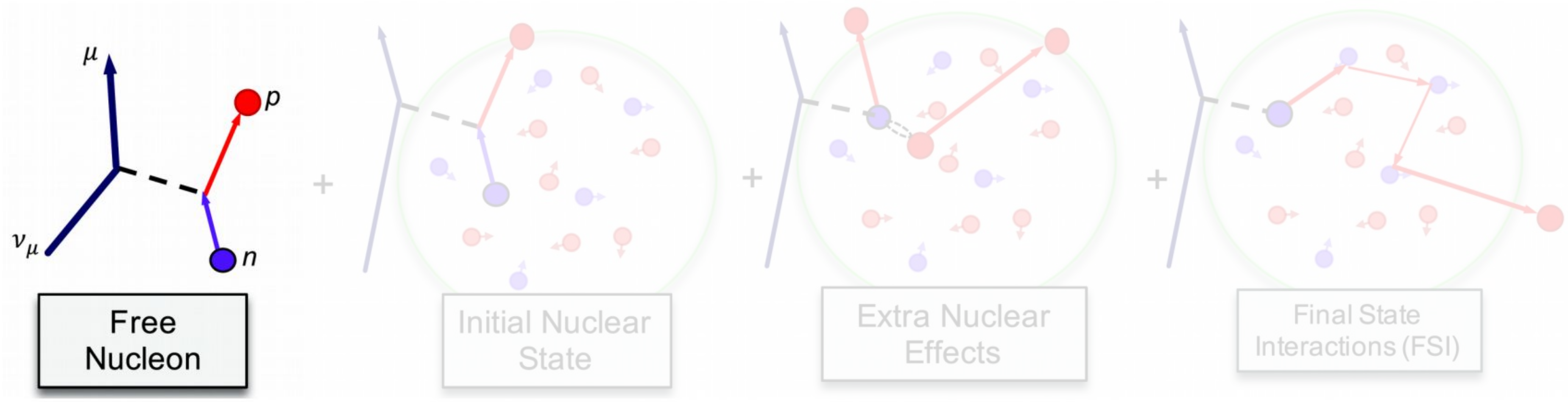


Using proton & lepton information
$E_{\text{vis}} = E_\mu + T_p$

Using lepton information only
$E_\nu^{QE} = \frac{m_p^2 - (m_n - E_b)^2 - m_\mu^2 + 2(m_n - E_b)E_\mu}{2(m_n - E_b - E_\mu + p_\mu \cos\theta_\mu)}$

Improved nuclear models

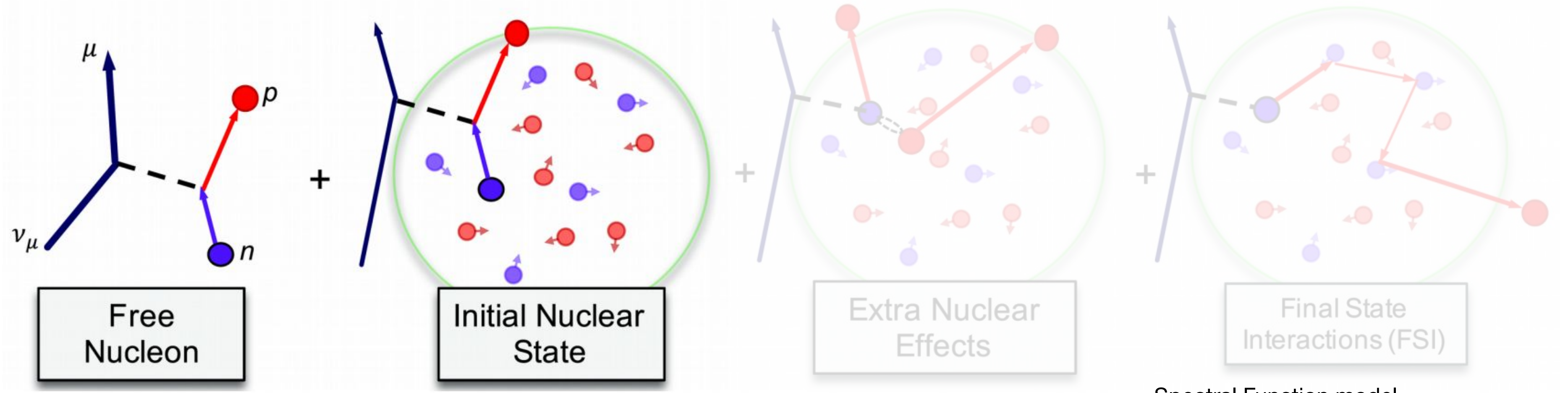
Nuclear effects



$$E_\nu^{QE} = \frac{m_p^2 - (m_n - E_b)^2 - m_\mu^2 + 2(m_n - E_b)E_\mu}{2(m_n - E_b - E_\mu + p_\mu \cos\theta_\mu)}$$

is an accurate estimation of the neutrino energy using muon kinematics only

Nuclear effects



Nucleons are bound within nuclei (Carbon & Oxygen in T2K).

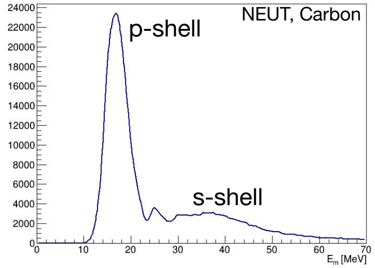
Need to account for:

- Removal energy
- Fermi motion

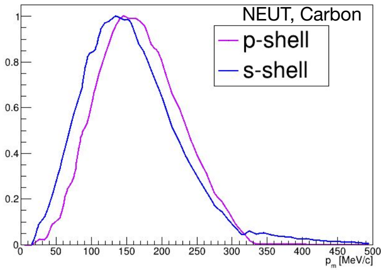
T2K now uses the sophisticated **Spectral Function model**

➔ Development of systematic uncertainties in this new framework for the oscillation analysis

Spectral Function model

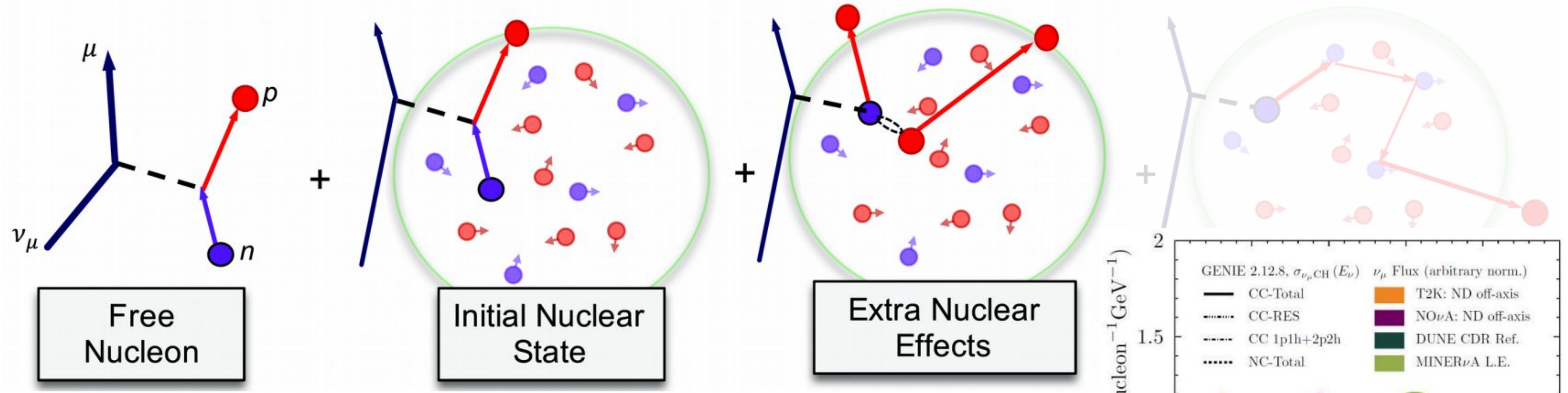


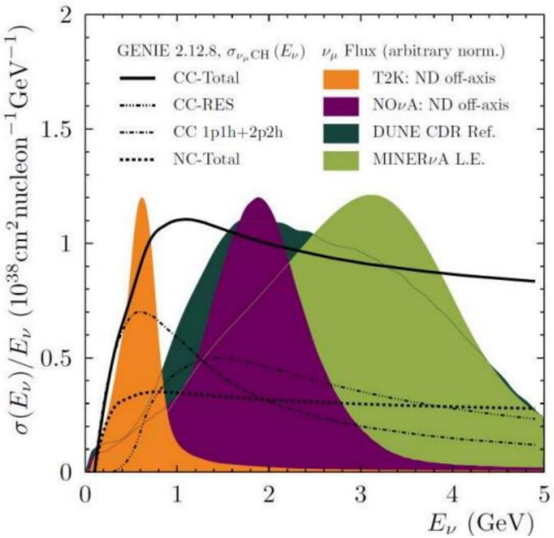
Initial state nucleon energy distribution



Initial state nucleon momentum distribution

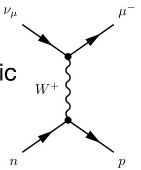
Nuclear effects



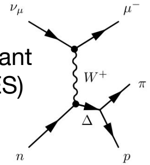


- Other nuclear effects can bias the reconstruction of neutrino energy like short-range correlations, 2p2h interactions...

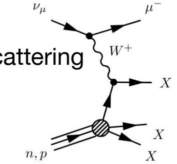
Quasi-elastic (CCQE)



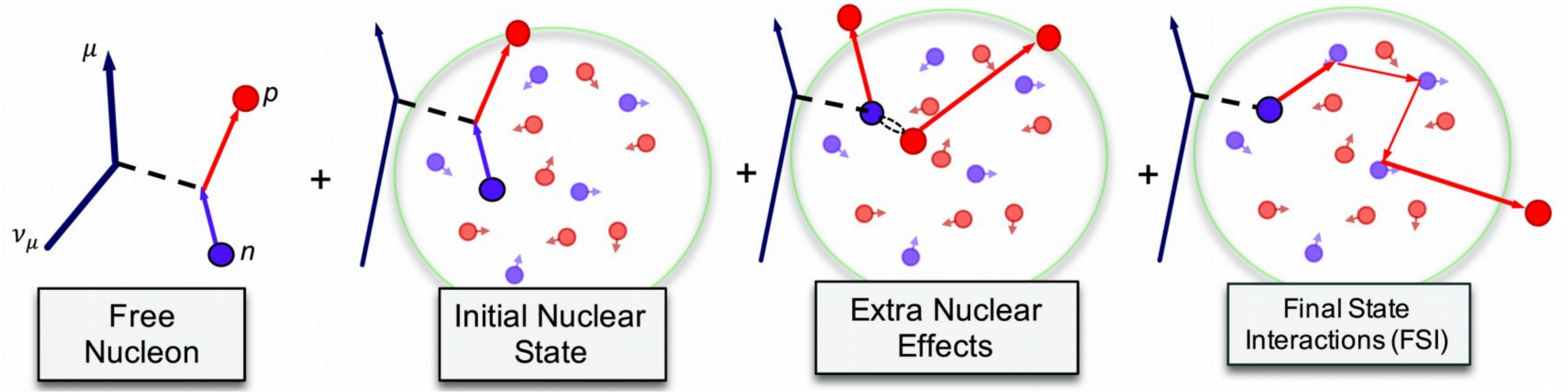
Resonant (CCRES)



Deep Inelastic Scattering (CCDIS)



Nuclear effects



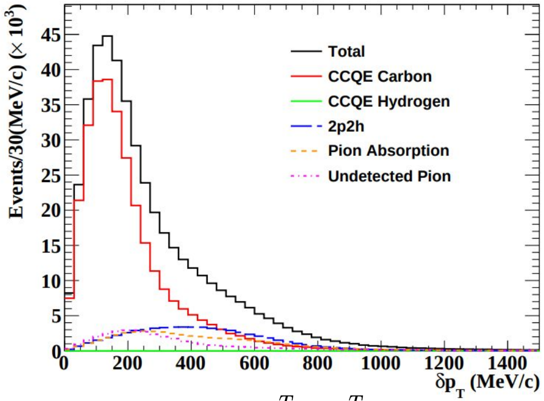
- The outgoing hadrons from a neutrino-nucleon interaction can re-interact with the remaining nucleus

- Ongoing work to improve the nuclear model for FSI of nucleons in neutrino simulations using INCL, one of the most predictive existing intranuclear-cascade models
  $\longrightarrow$ crucial for T2K Near Detector Upgrade & next generation experiments

Sensitivity with the Upgraded T2K Near Detector

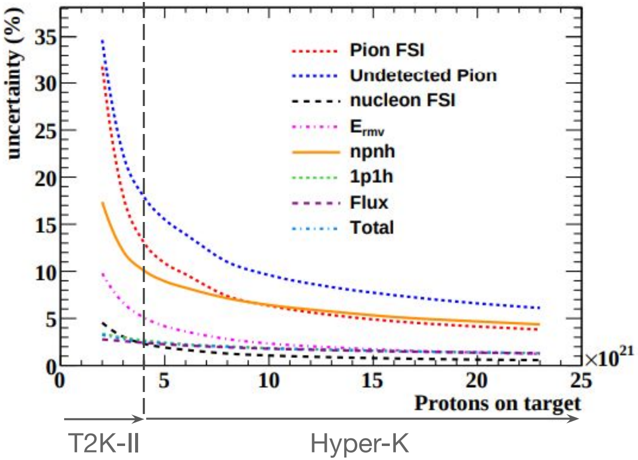
arXiv:2108.11779

Transverse momentum imbalance



$$\delta\vec{p}_T = \vec{p}_\mu^{\,T} + \vec{p}_p^{\,T}$$

Sensitivity to syst. uncertainties

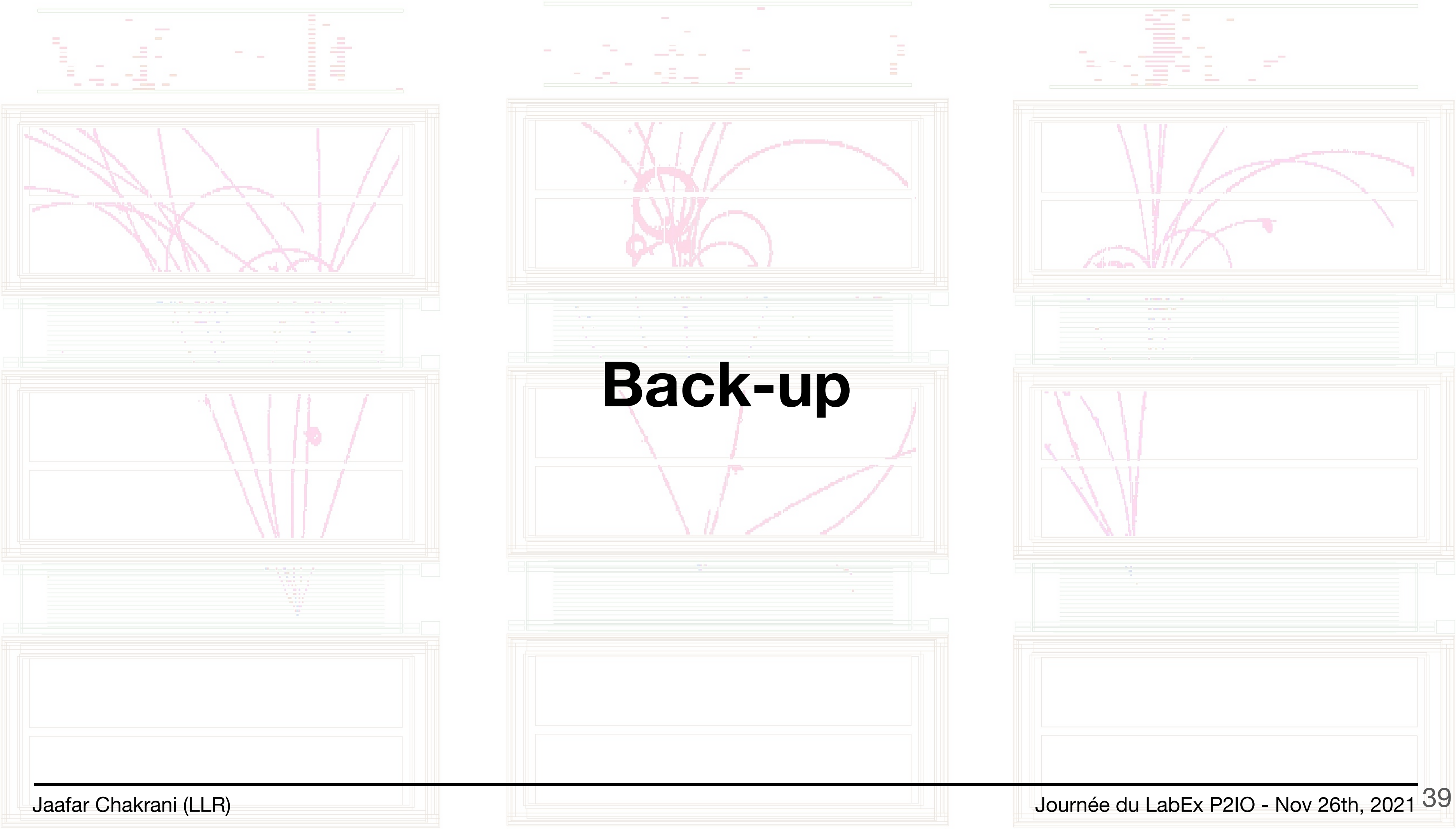


- Using the outgoing proton information (*eg. visible energy & transverse momentum imbalance*) allows a better reconstruction of the neutrino energy and constraint on systematic uncertainties
- The dominant systematic uncertainties can be constrained down to the few-% level as required by future oscillation analyses of T2K-II and next generation experiments

Summary and prospects

Summary and prospects

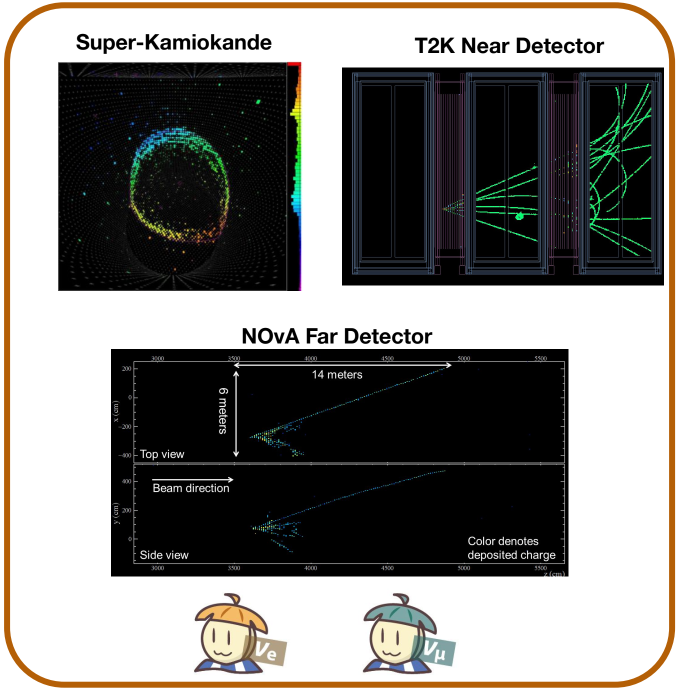
- BSM-Nu project regroups several neutrino experiments around a common goal: access BSM physics through the characterisation of neutrino nature and mixing
- Long-baseline experiments aim at measuring neutrino oscillation parameters
- To probe CP violation, we need to improve the current detector technologies as well as the modeling of neutrino-nucleus interactions
- Contributions of BSM-Nu WP2:
  - Detectors: T2K Near Detector upgrade → High-Angle TPCs
  - Neutrino-nucleus interaction model: improvement of the initial state nuclear model (Spectral Function model) and ongoing work to improve the modeling of final state interactions
- Prospects of BSM-Nu WP2:
  - Preparation of a new fitting framework for oscillation analyses with new samples and observables in the era of T2K-II and beyond
  - Installation and commissioning of T2K Near Detector Upgrade at the end of 2022



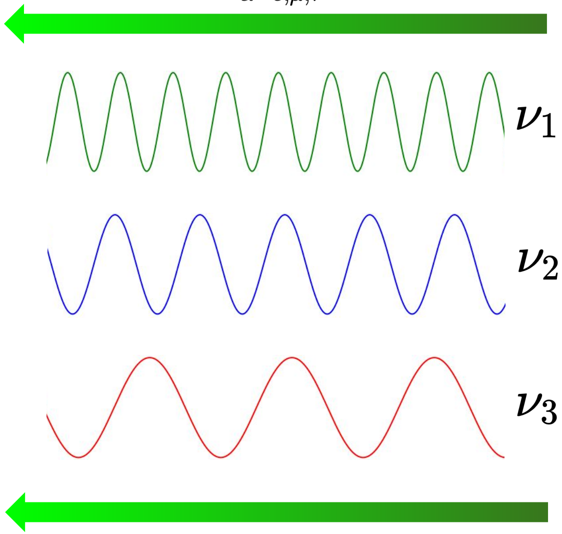
Back-up

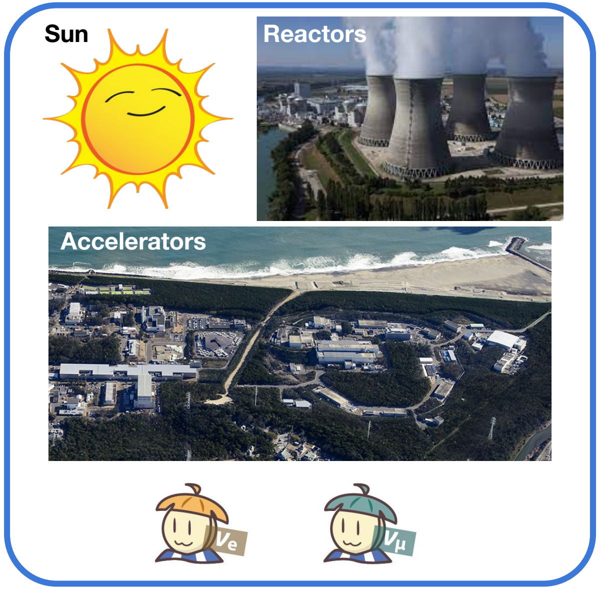
Neutrino flavors and masses mixing

- Neutrino flavor states: $\nu_e, \nu_\mu, \nu_\tau \longrightarrow$ **production** and **detection**
- Neutrino mass states: $\nu_1, \nu_2, \nu_3 \longrightarrow$ **propagation**

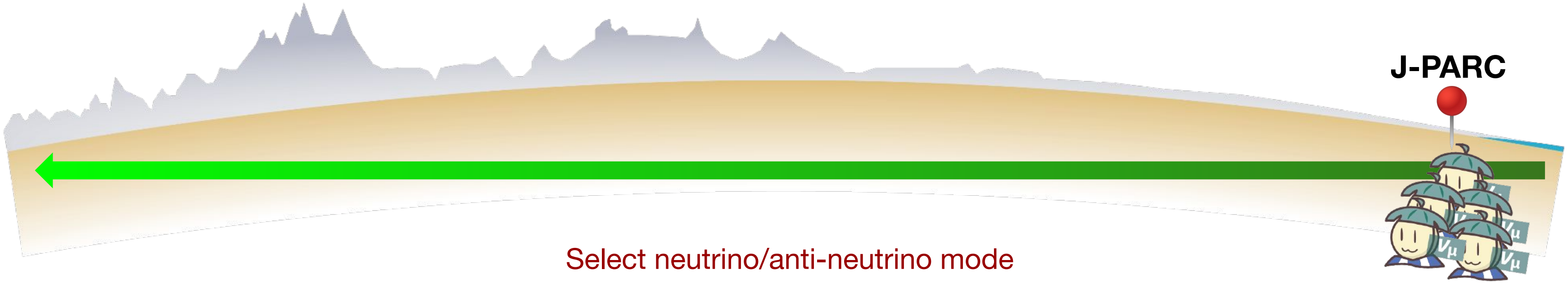


$$|\nu_i\rangle = \sum_{\alpha=e,\mu,\tau} U_{\alpha i} \, |\nu_\alpha\rangle$$

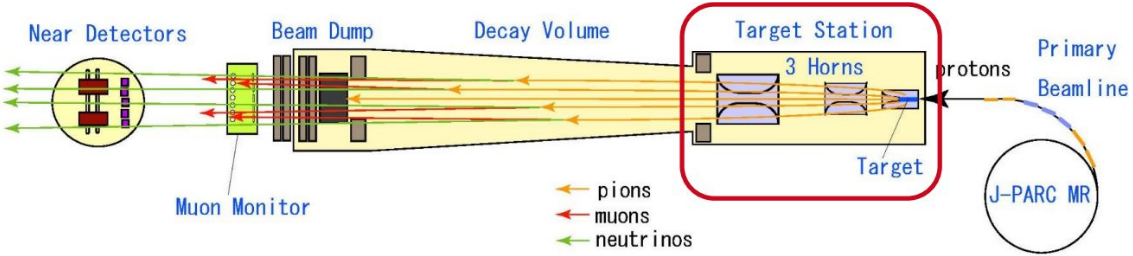


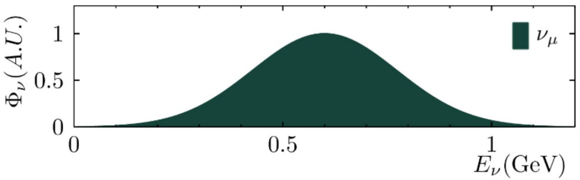


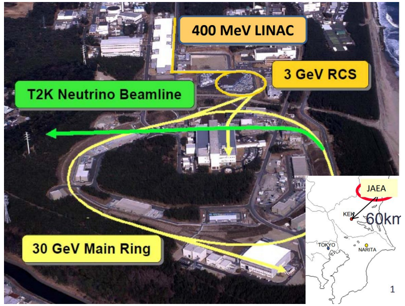
Long-Baseline Experiments: T2K



Select neutrino/anti-neutrino mode





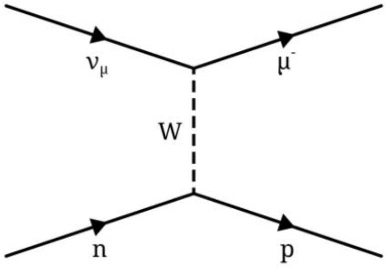


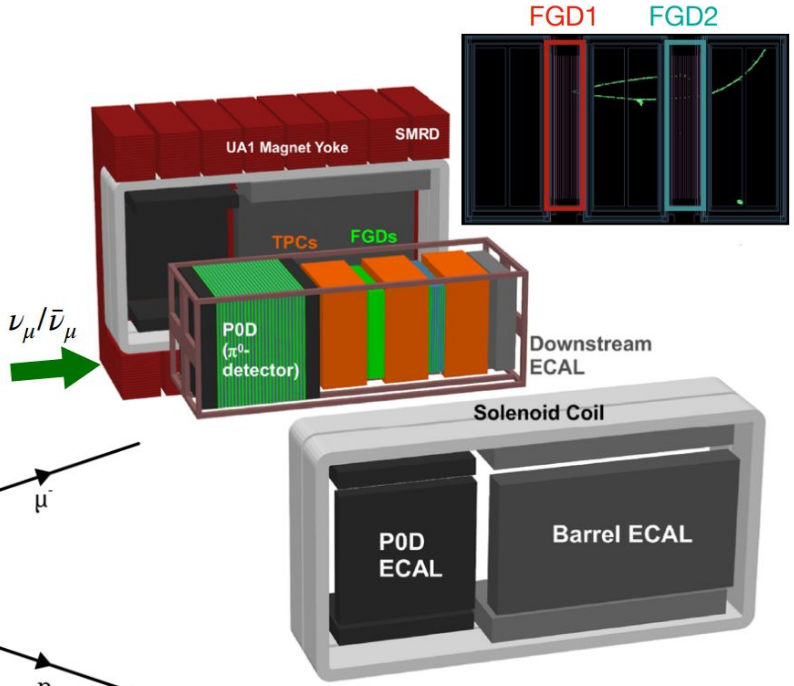
- Proton beam on graphite target
- Produced hadrons decay into muon (anti-)neutrinos

Off-axis Near Detector at 280m (ND280)

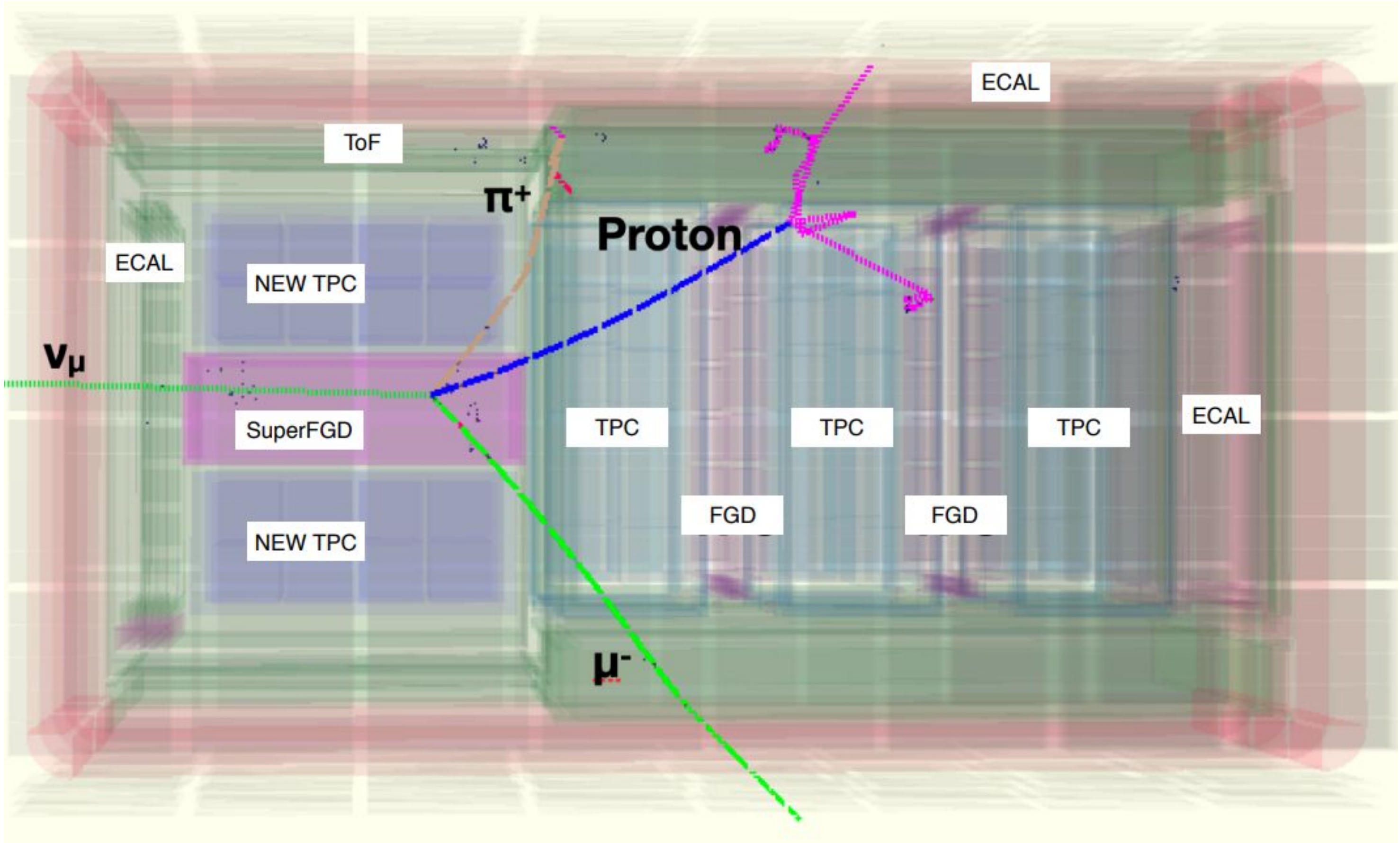
Off-axis detector (2.5 degrees, 0.6 GeV flux peak)

- Fine Grained Detectors (FGDs)
  - Plastic scintillator tracker
  - FGD1 & 2 carbon target (CH)
  - FGD2 has water target layers
- Time Projection Chambers (TPCs)
  - Tracking detectors
  - Charged particle momentum
  - Particle ID
- Very good measurements of muon kinematics



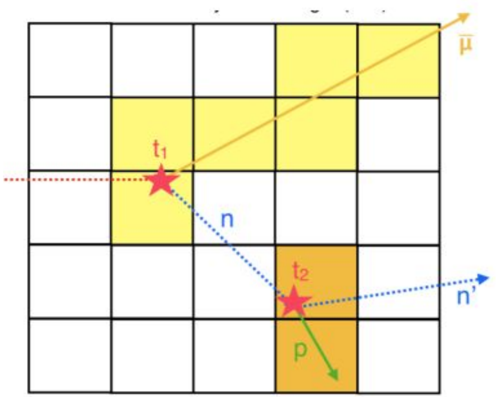


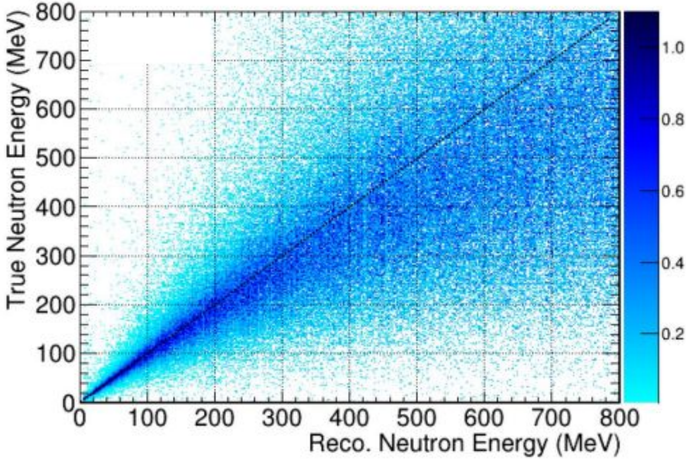
Event in the T2K Upgraded Near Detector



Neutron detection with the Super-FGD

- Neutrons can be detected via their re-interaction within the detector
- If the path is long enough, neutron energy can be measured using time of flight
- Resolution: ~15-30%





Phys. Rev. D 101, 092003