T2K Near Detector Upgrade

Jaafar Chakrani
On behalf of the T2K collaboration
Laboratoire Leprince-Ringuet (LLR)
<jaafar.chakrani@polytechnique.edu>

Neutrino Oscillation Workshop 2022
Ostuni, Brindisi, Italy
September 6th, 2022

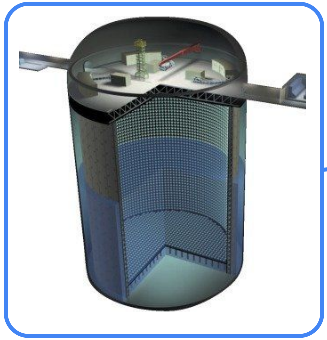
Outline

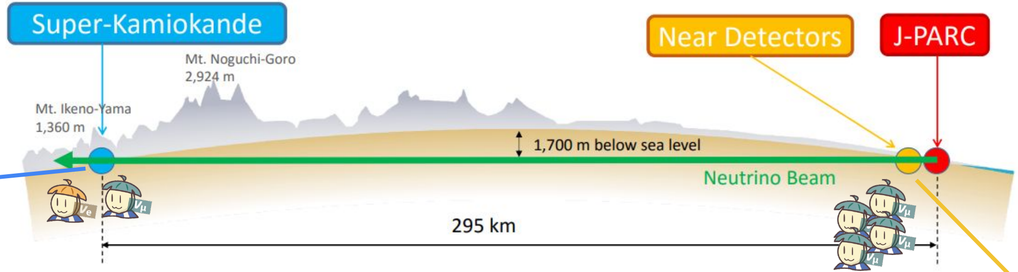
- Introduction
- T2K Near Detector Upgrade
- Physics with the Upgrade
- Summary and prospects

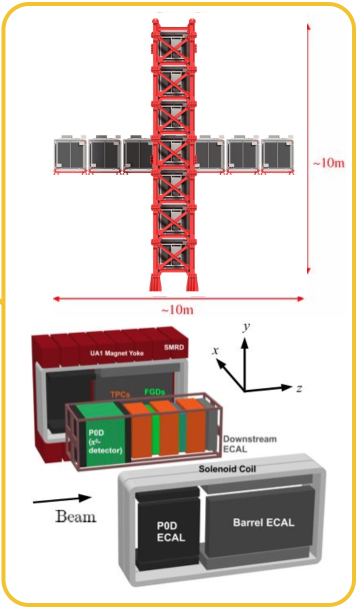
Introduction

T2K Experiment

See talk by Lukas Berns (Monday)



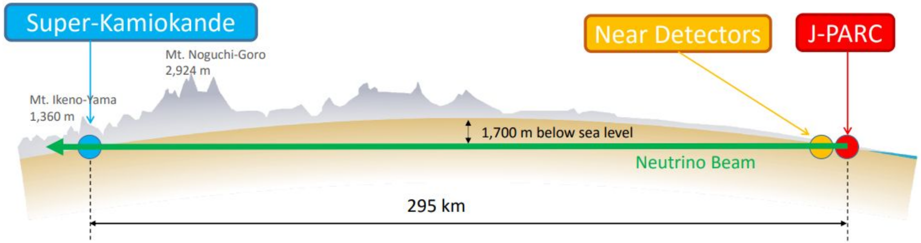




- Main goals:
  - Measure $\nu_e/\bar{\nu}_e$ appearance: sensitive to $(\delta_{CP}, \theta_{13})$
  - Measure $\nu_\mu/\bar{\nu}_\mu$ disappearance: sensitive to $(\theta_{23}, \Delta m^2)$
- How?
  - Produce an intense ν_μ (or $\bar{\nu}_\mu$) beam
  - Measure the unoscillated flux at the near detector complex to monitor the beam and constrain systematic uncertainties
  - Measure the oscillated flux at Super-Kamiokande

T2K Oscillation Analysis strategy

See talk by Lukas Berns (Monday)



Flux model · Detector model · Neutrino interaction model

$$N^{ND}_{\nu_\alpha}(E_\nu) = \Phi^{ND}_{\nu_\alpha}(E_\nu) \times \epsilon^{ND}(E_\nu) \times \sigma^{ND}_{\nu_\alpha}(E_\nu)$$

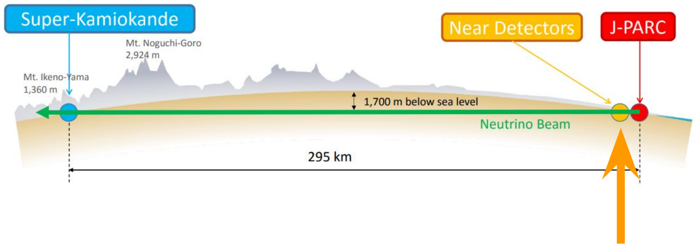
$$N^{FD}_{\nu_\beta}(E_\nu) = \Phi^{FD}_{\nu_\beta}(E_\nu) \times \epsilon^{FD}(E_\nu) \times \sigma^{FD}_{\nu_\beta}(E_\nu) \times P_{\nu_\alpha \to \nu_\beta}(E_\nu)$$

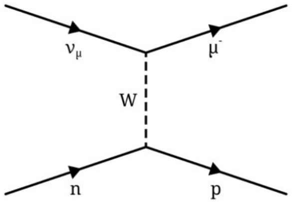
- Far/Near ratio does not fully cancel systematic uncertainties, *e.g.*:
  - Flux model different at ND vs. FD due to geometry and oscillation
  - Different detectors, *i.e.* different acceptance and efficiencies
  - Mainly $\nu_\mu(\bar{\nu}_\mu)$ at ND interacting with CH $\longrightarrow$ use model to infer interactions of $\nu_\mu/\nu_e(\bar{\nu}_\mu/\bar{\nu}_e)$ on H_2O

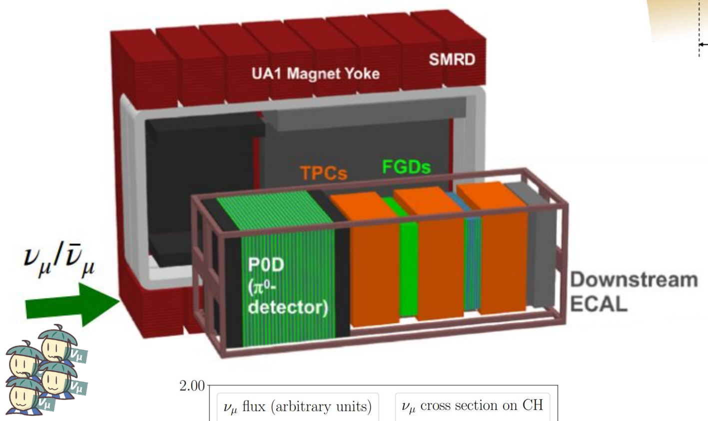
Also see talks by:
** Kevin McFaland (Monday)*
** Stephen Dolan (Wednesday)*

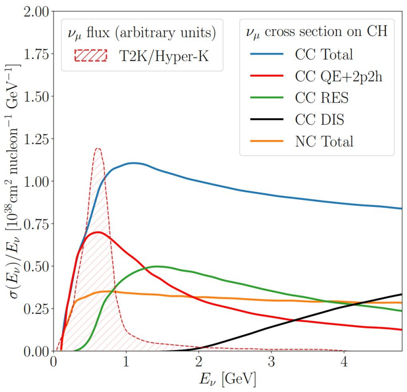
↪ **T2K's approach is to propagate the constraints on the flux and the neutrino interaction models from the ND to the FD**

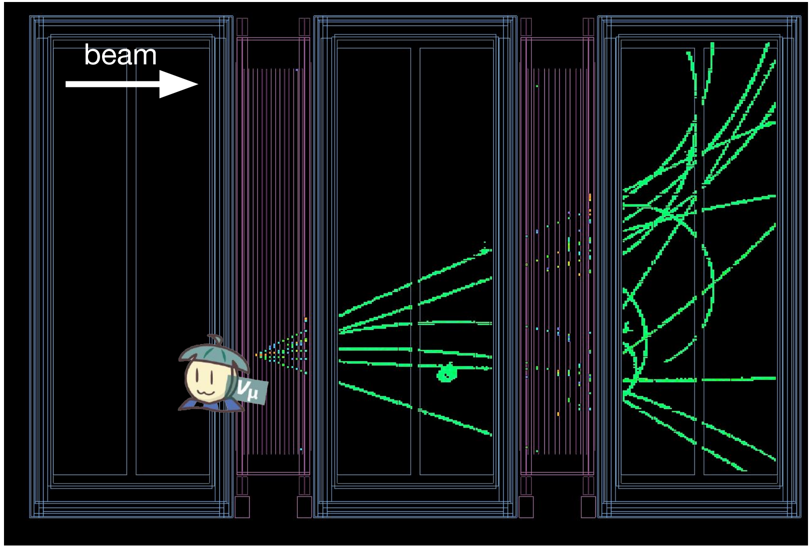
Off-axis Near Detector at 280m (ND280)





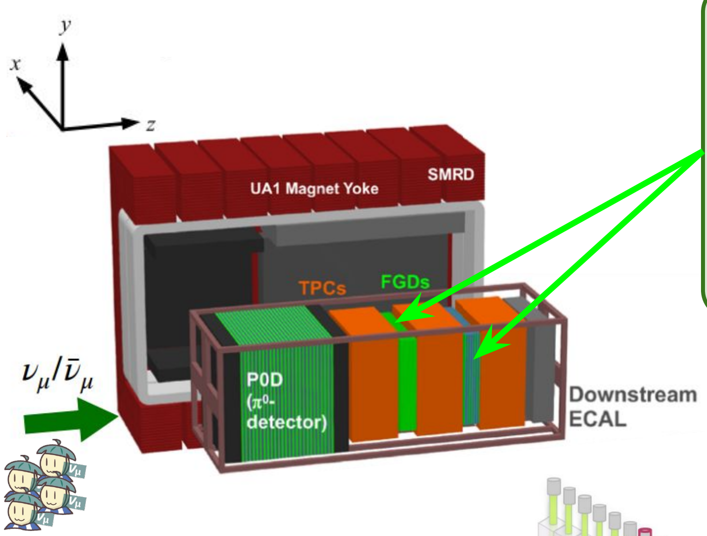






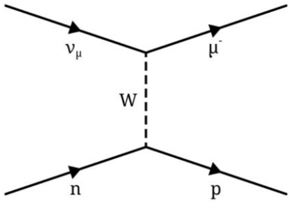
Deep Inelastic Scattering event display

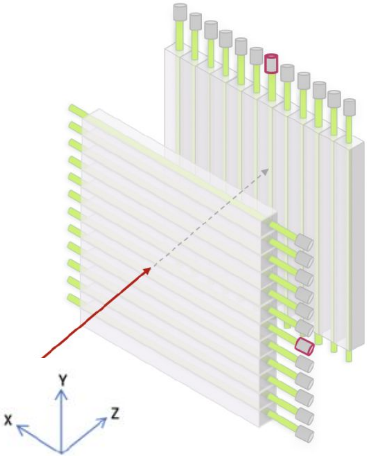
Off-axis Near Detector at 280m (ND280)

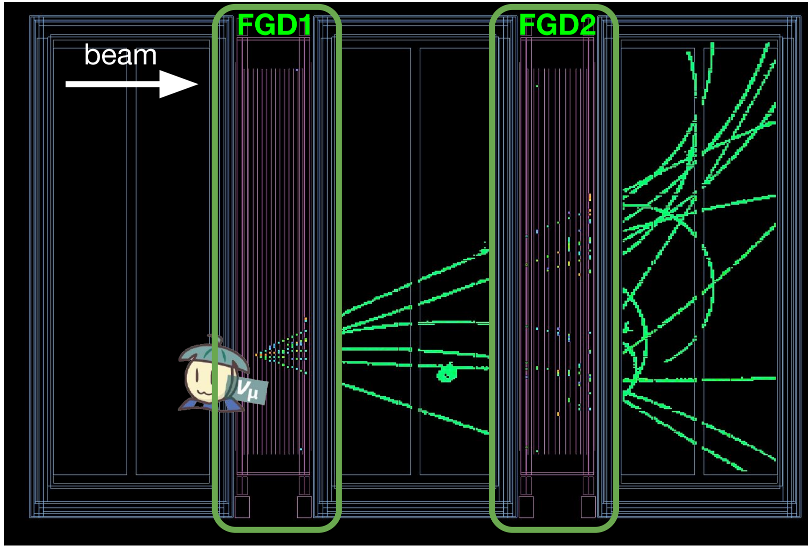


Fine Grained Detectors (FGDs):

- Plastic scintillator tracker
- Target for neutrino interactions 
- FGD2 has water target layers







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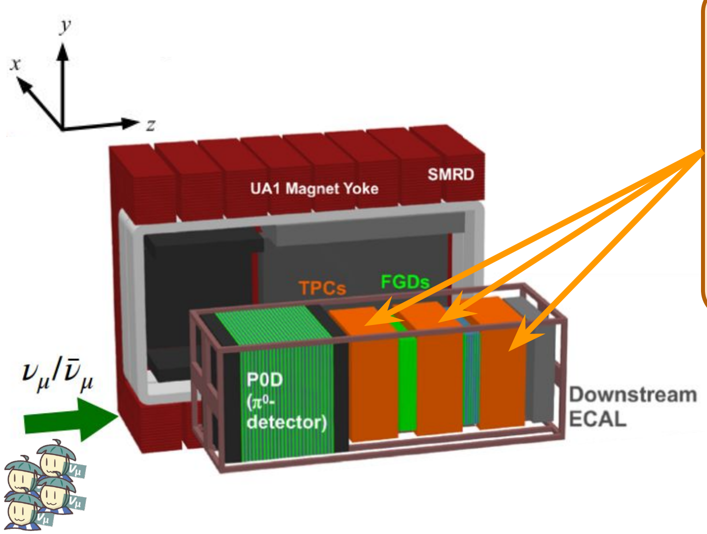
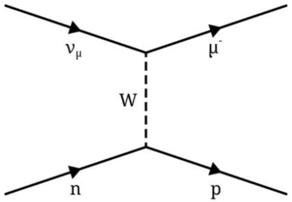
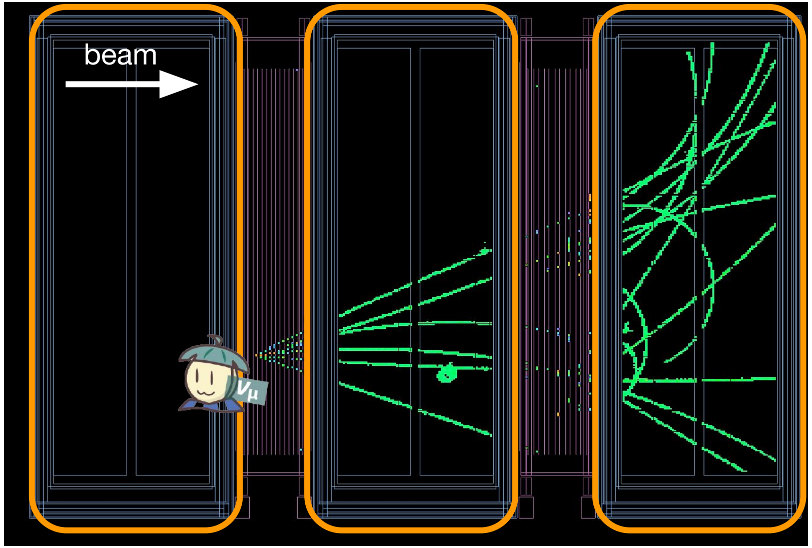


Time Projection Chambers (TPCs)

- Tracking detectors
- Charged particle momentum
- Particle ID





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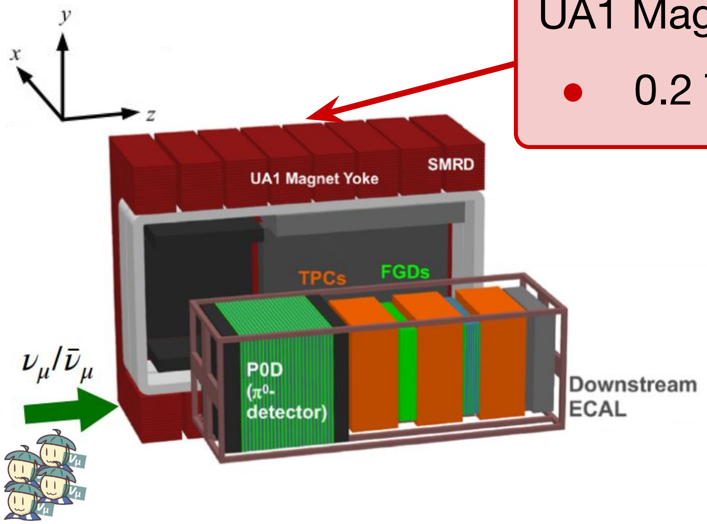
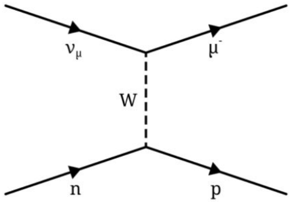
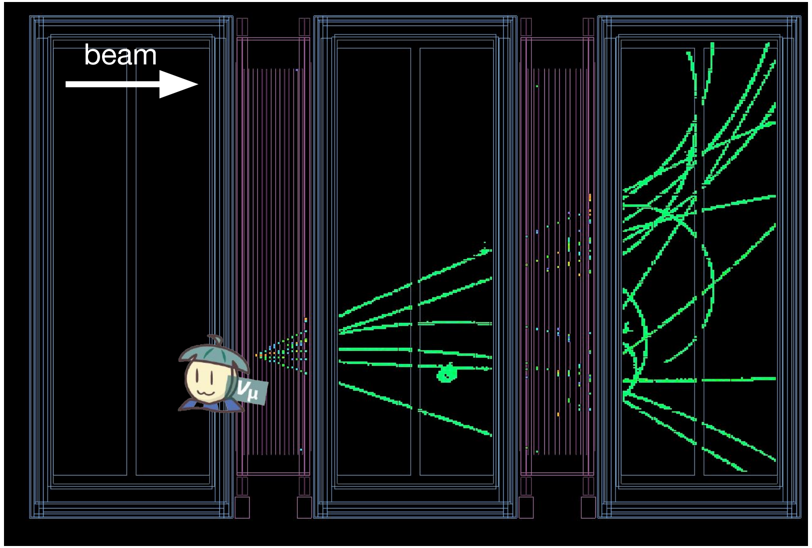
Off-axis Near Detector at 280m (ND280)

UA1 Magnet:

- 0.2 T magnetic field for charge identification







Deep Inelastic Scattering event display

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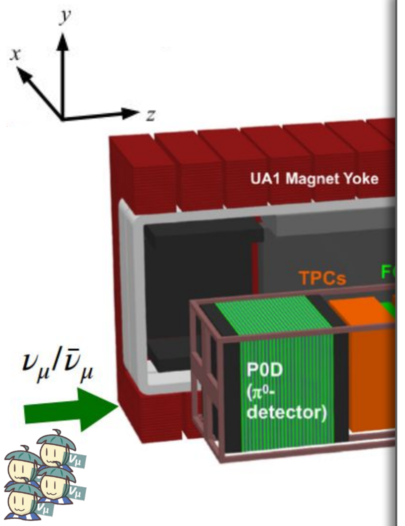

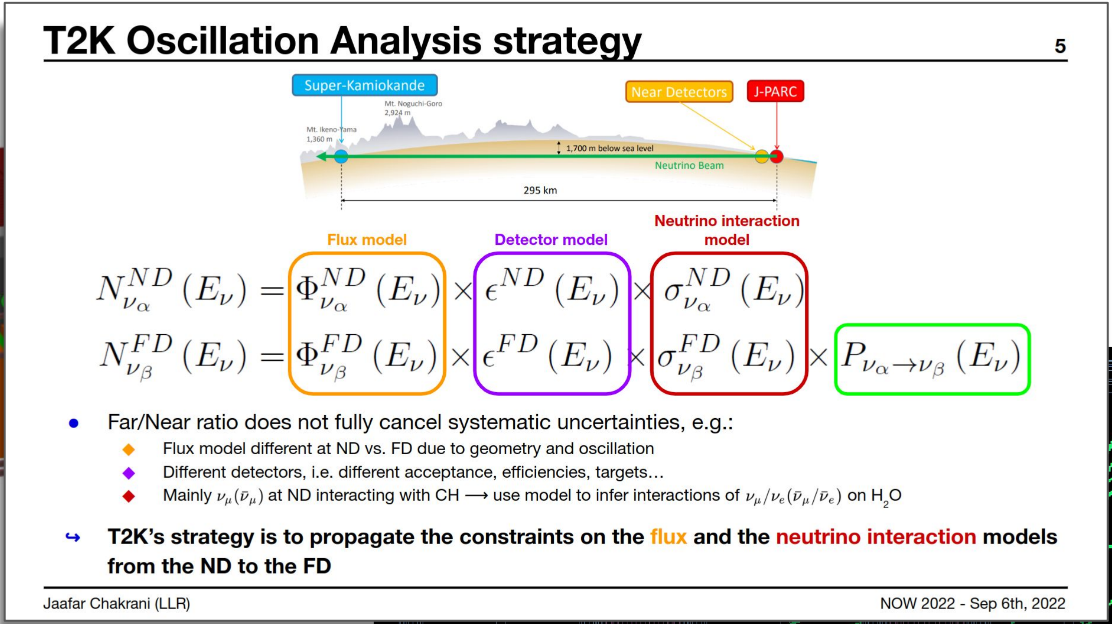

T2K Oscillation Analysis strategy

5

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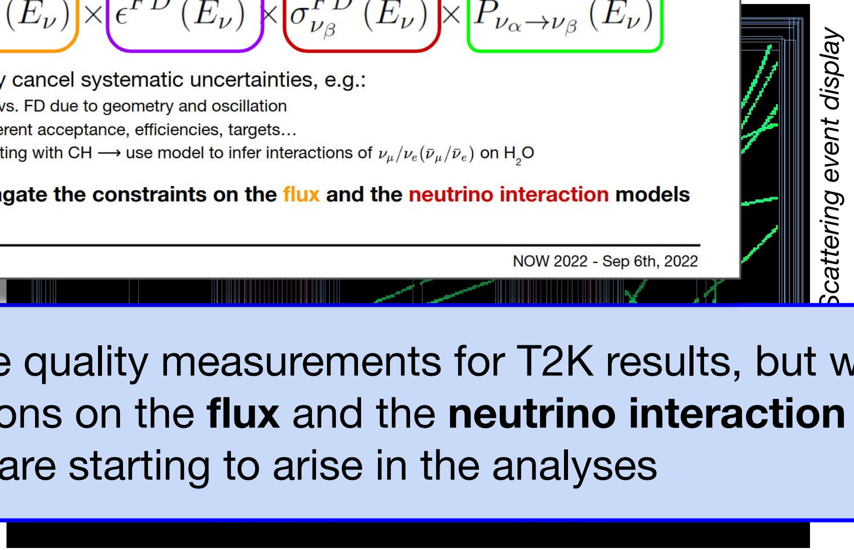
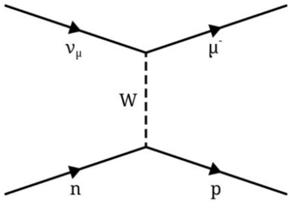
Jaafar Chakrani (LLR) NOW 2022 - Sep 6th, 2022

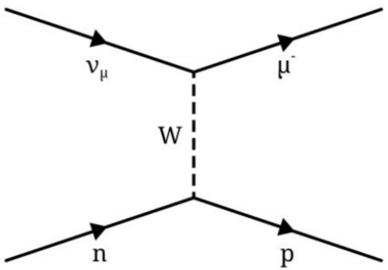




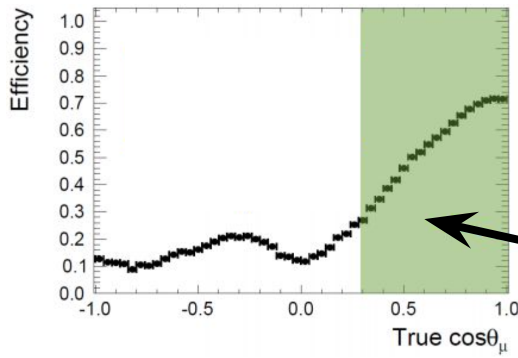
ND280 has been able to provide quality measurements for T2K results, but with the **increasing statistics** its limitations on the **flux** and the **neutrino interaction model uncertainties** are starting to arise in the analyses

Limitations of current ND280

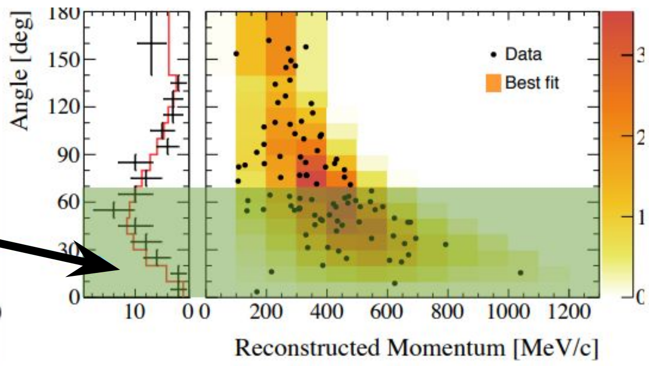
- Non-isotropic efficiency (unlike Super-Kamiokande)
- High momentum proton threshold (~450 MeV/c)
- For the oscillation analysis, neutrino interactions are characterized in **muon kinematics only**



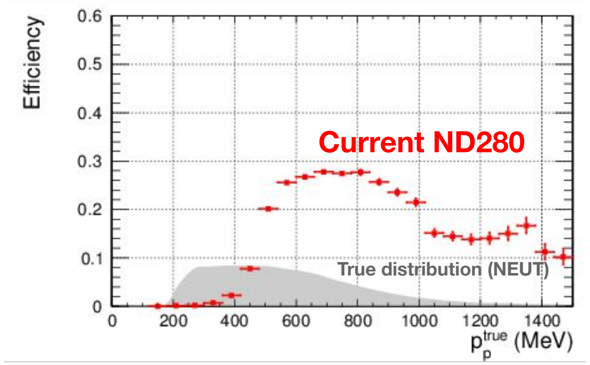
Muon detection efficiency at ND280



ν_e candidates at Super-K



Proton detection efficiency

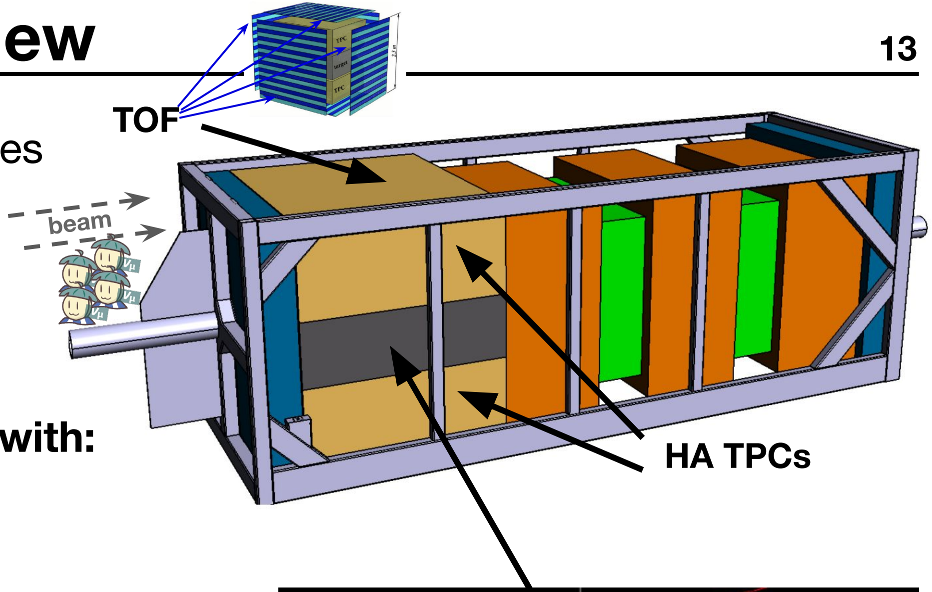


⇒ T2K is currently upgrading ND280 to overcome these limitations

T2K Near Detector Upgrade

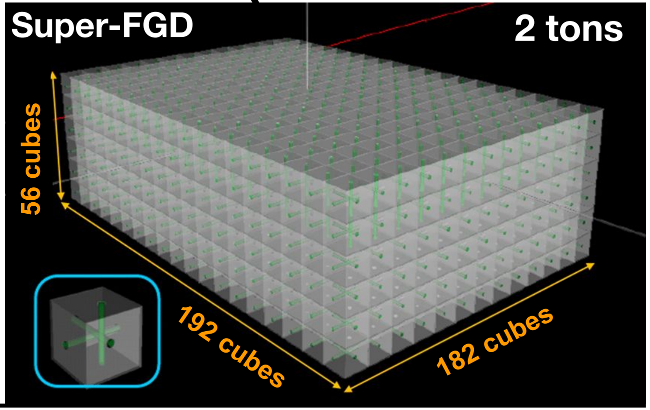
T2K ND280 Upgrade Overview

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



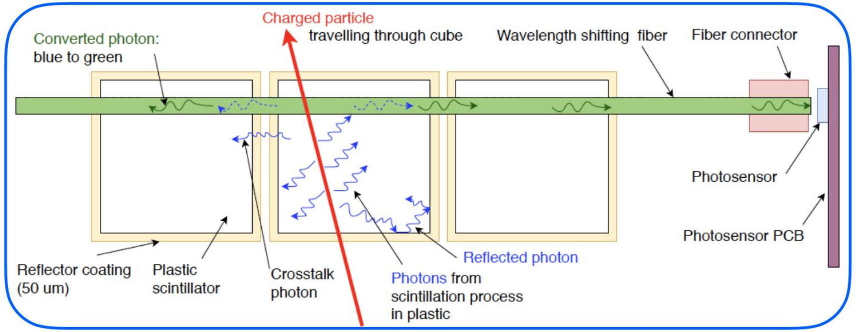
The goal is to reduce the ND systematics with:

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

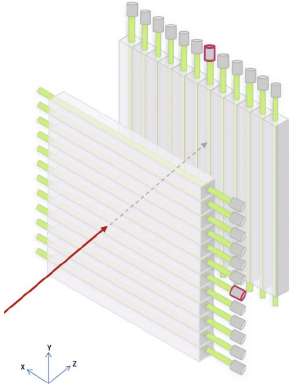


Super-FGD [JINST 13 P02006 (2018)]

- ~2 million 1x1x1 cm3 cubes made of plastic scintillator ⟶ ~2 tons
- Cubes covered by reflector will be read out with 3 orthogonal WLS fibres each with MPPC on one end
⟶ total of 56,382 fibers

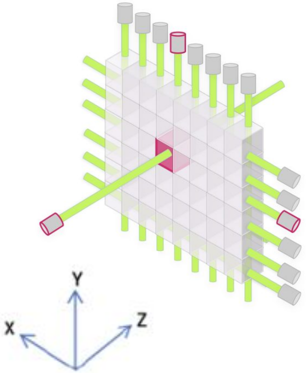


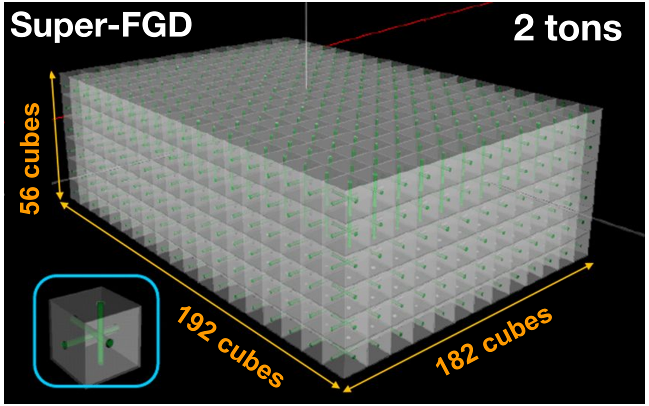
FGD1&2



vs.

Super-FGD

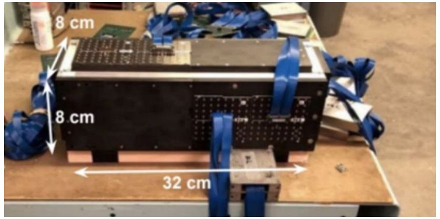




Super-FGD prototypes

- Multiple beam tests with prototypes have been performed to confirm the Super-FGD concept:

Super-FGD prototype (8x24x48 cm)



US-Japan prototype (8x8x32 cm)

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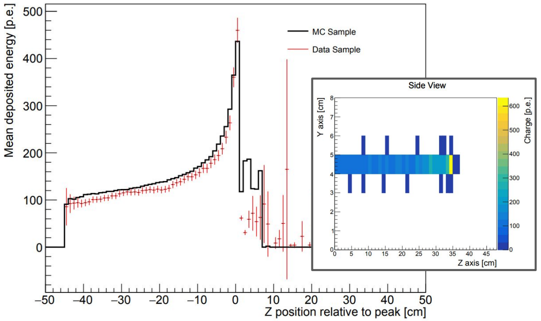
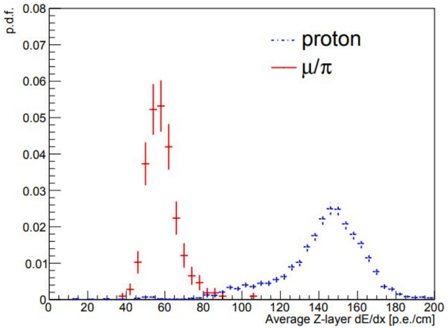
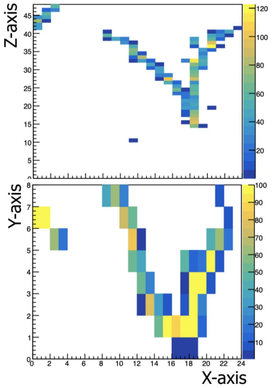
Bragg peak from a stopping proton



dE/dx measured for different particles



Electron-gamma separation



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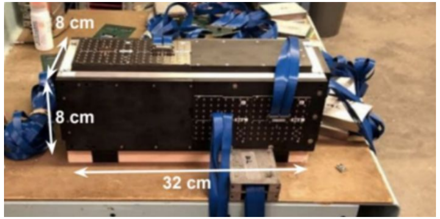

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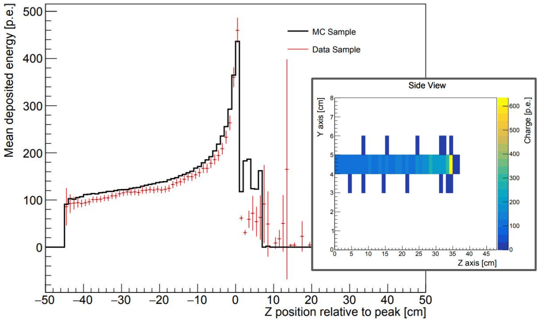

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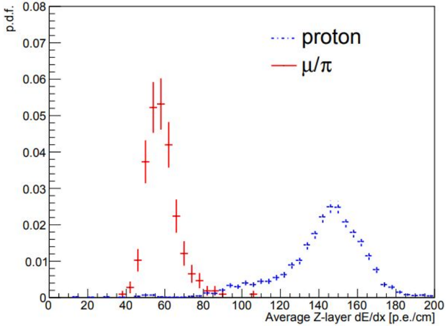

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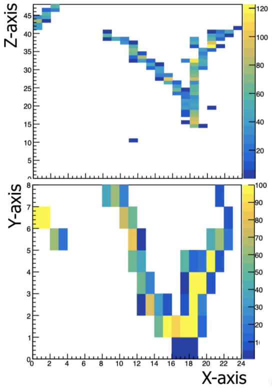

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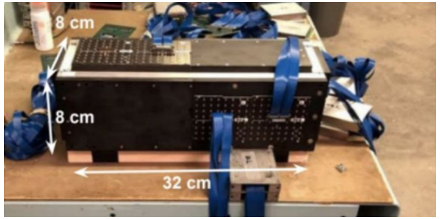

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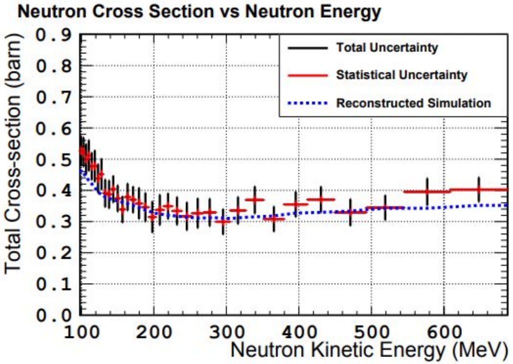
  - At LANL with neutrons: [arxiv:2207.02685]()
    - Measurement of the total cross section as a function of the neutron kinetic energy using event rate depletion along the beam axis: $N\left(z\right) = N_0 e^{-T\sigma_{\rm tot} z}$



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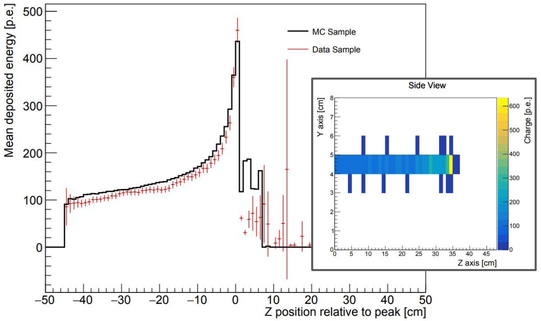

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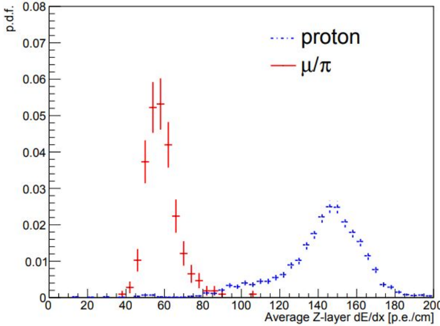

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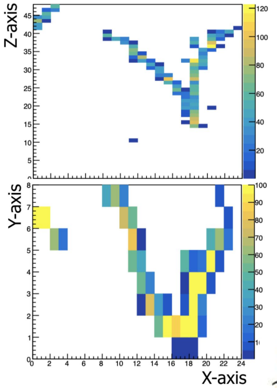

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↪ The tests show that this concept meets the requirements

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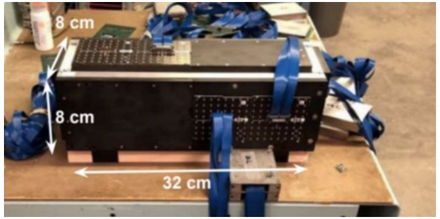

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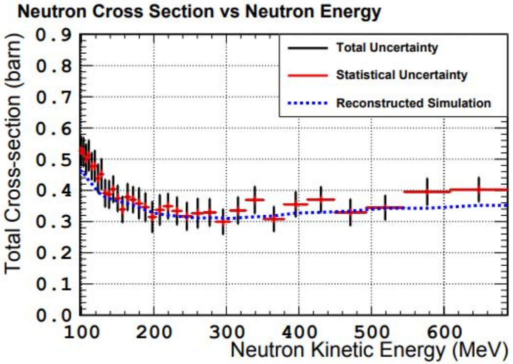

Super-FGD ongoing work

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At J-PARC

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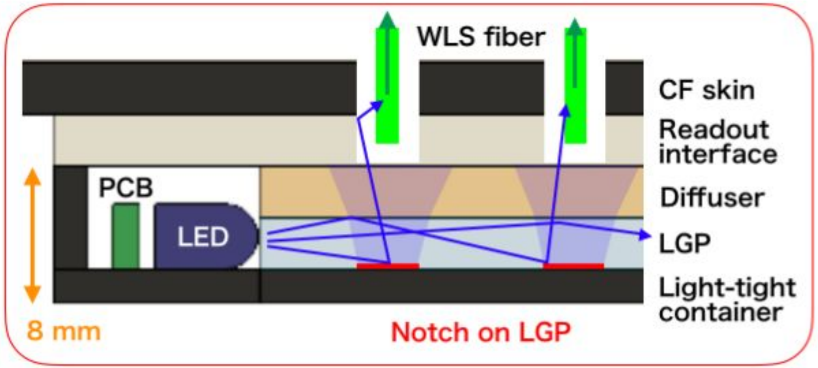

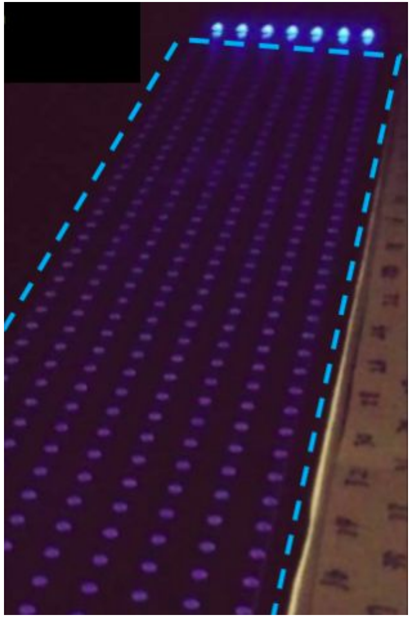

Light Guide Plate (LGP)

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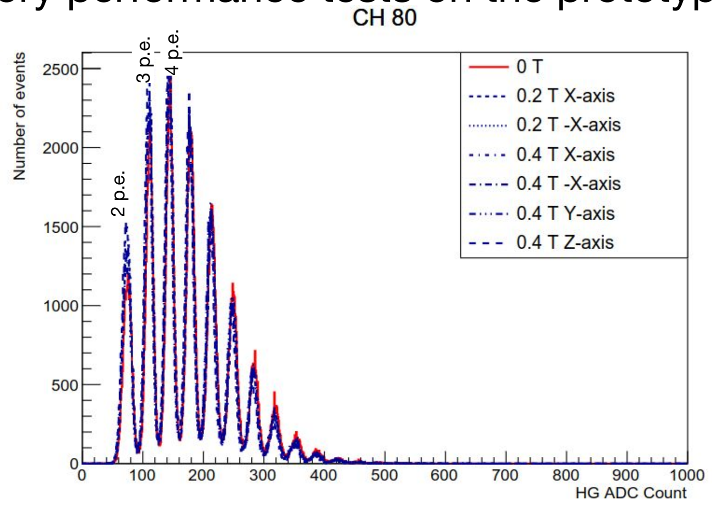
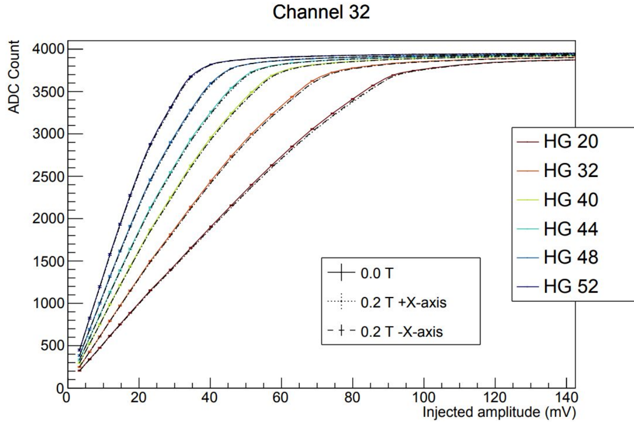
- Assembly with fibers by replacing the fishing lines will start soon
- LED calibration system QC and assembly to begin this Autumn
- The production of the front-end electronics to read the 56,382 channels is also starting soon after satisfactory performance tests on the prototypes (linearity, crosstalk, timing resolution, …)

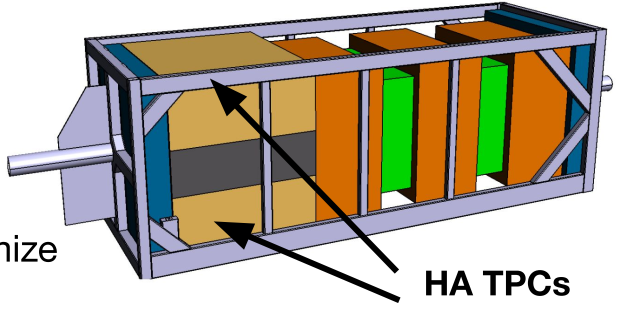


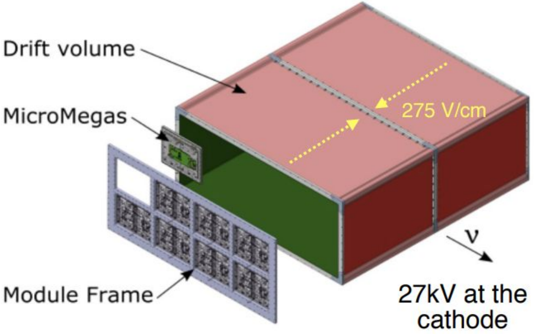


High-Angle Time Projection Chambers

- Two new TPCs will be added:
  - Similar design as current TPCs
  - High resolution tracking and particle identification

- New additions w.r.t. current TPC design:
  - New field cage design to minimize dead space and maximize the tracking volume





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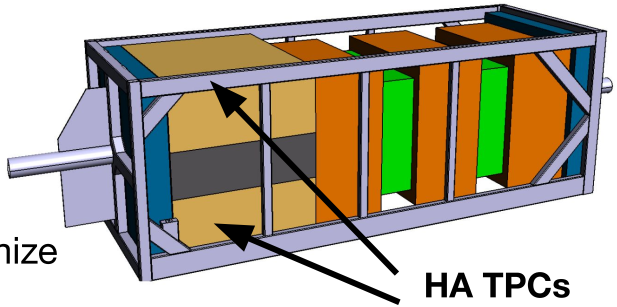
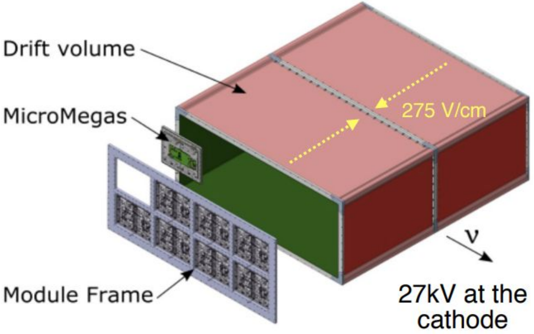
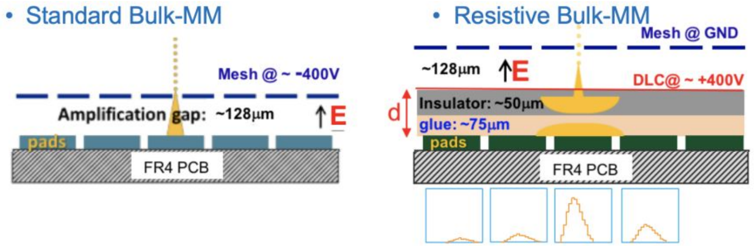
  - Similar design as current TPCs
  - High resolution tracking and particle identification



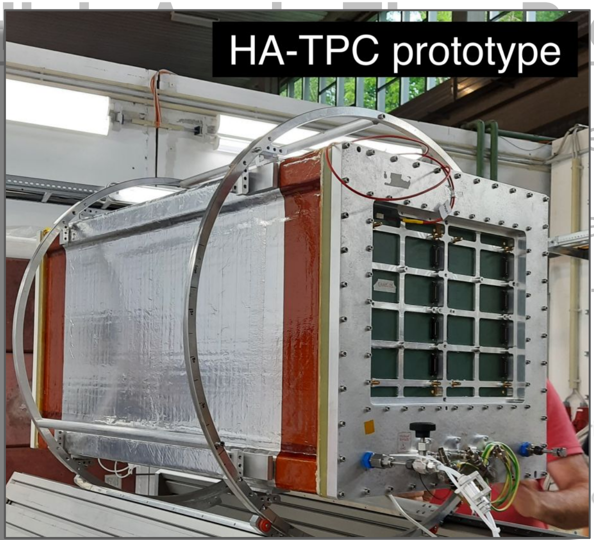
- New additions w.r.t. current TPC design:
  - New field cage design to minimize dead space and maximize the tracking volume



  - Replace the standard bulk-MicroMegas with new resistive MicroMegas Modules:
    - Signal induced on multiple pads thanks to the resistive layer
      ⟶ better spatial resolution with less pads



H ojection Chambers



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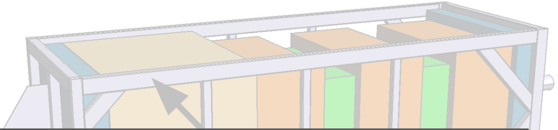
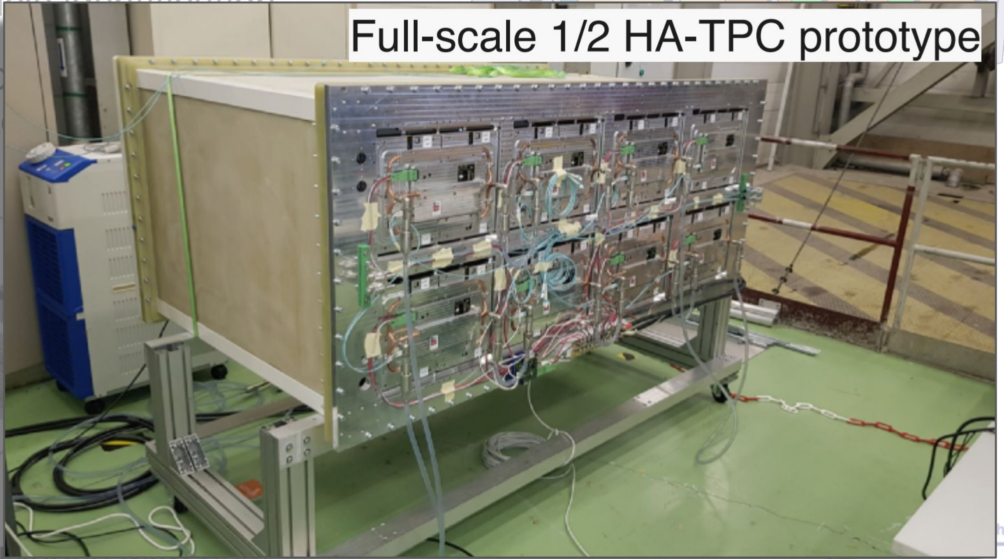
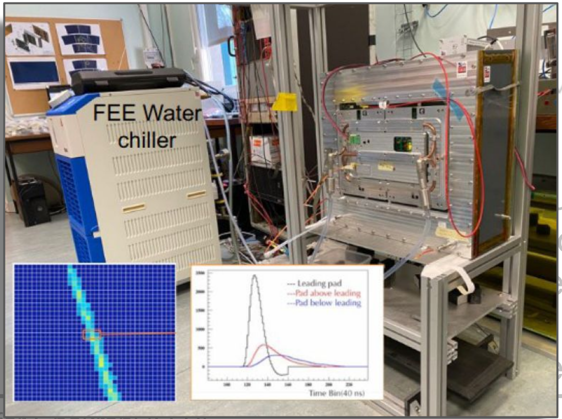


ift volume
croMegas
Module Frame



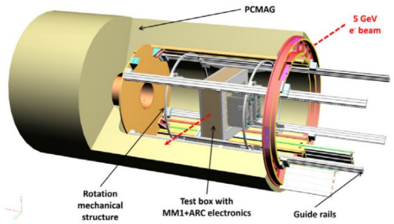


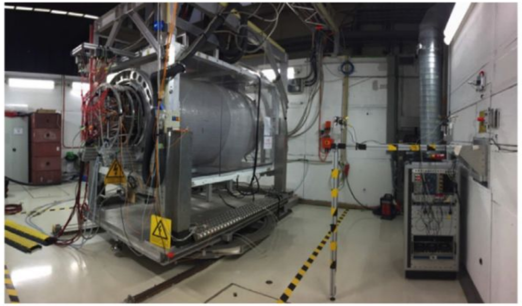
ulk-MicroMegas with new
odules:
e on multiple pads with a
esolution with less pads

High-Angle Time Projection Chambers

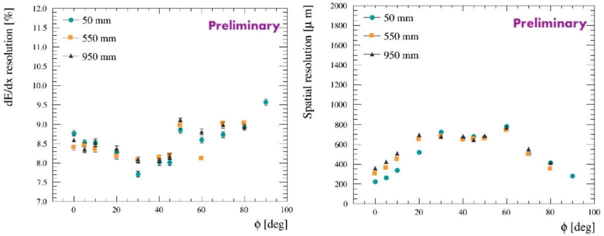
- Multiple beam tests to:
  - Test the setup stability
  - Characterize the charge spreading and study resistive foil uniformity
  - Measure spatial and energy resolution
- Past beam tests with various charged particles:
  - CERN 2018 [NIMA 163286 (2019)]
  - DESY 2019 [NIMA 166109 (2021)]
  - DESY 2021 (analysis ongoing)
  - CERN November 2021 (analysis ongoing)
- Results confirm that the requirements are fulfilled:
  - Spatial resolution for a hit < 0.8 mm
  - dE/dx resolution < 10%
- Reconstruction algorithms are being optimized in light of the beam tests

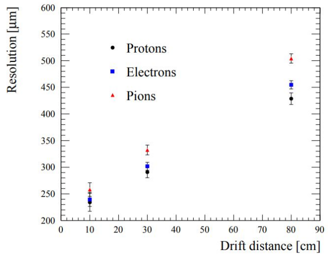
Setup at DESY





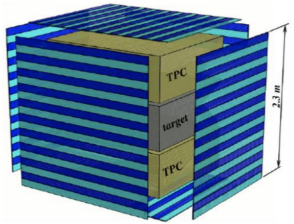
Inclined tracks with varying drift distance



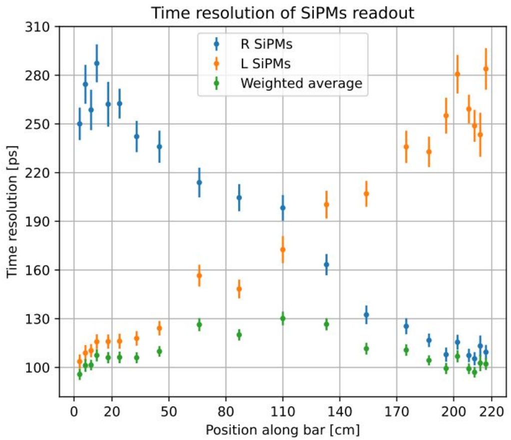


Time-of-Flight (ToF) detector [JPS Conf. Proc. 27, 011005 (2019)]

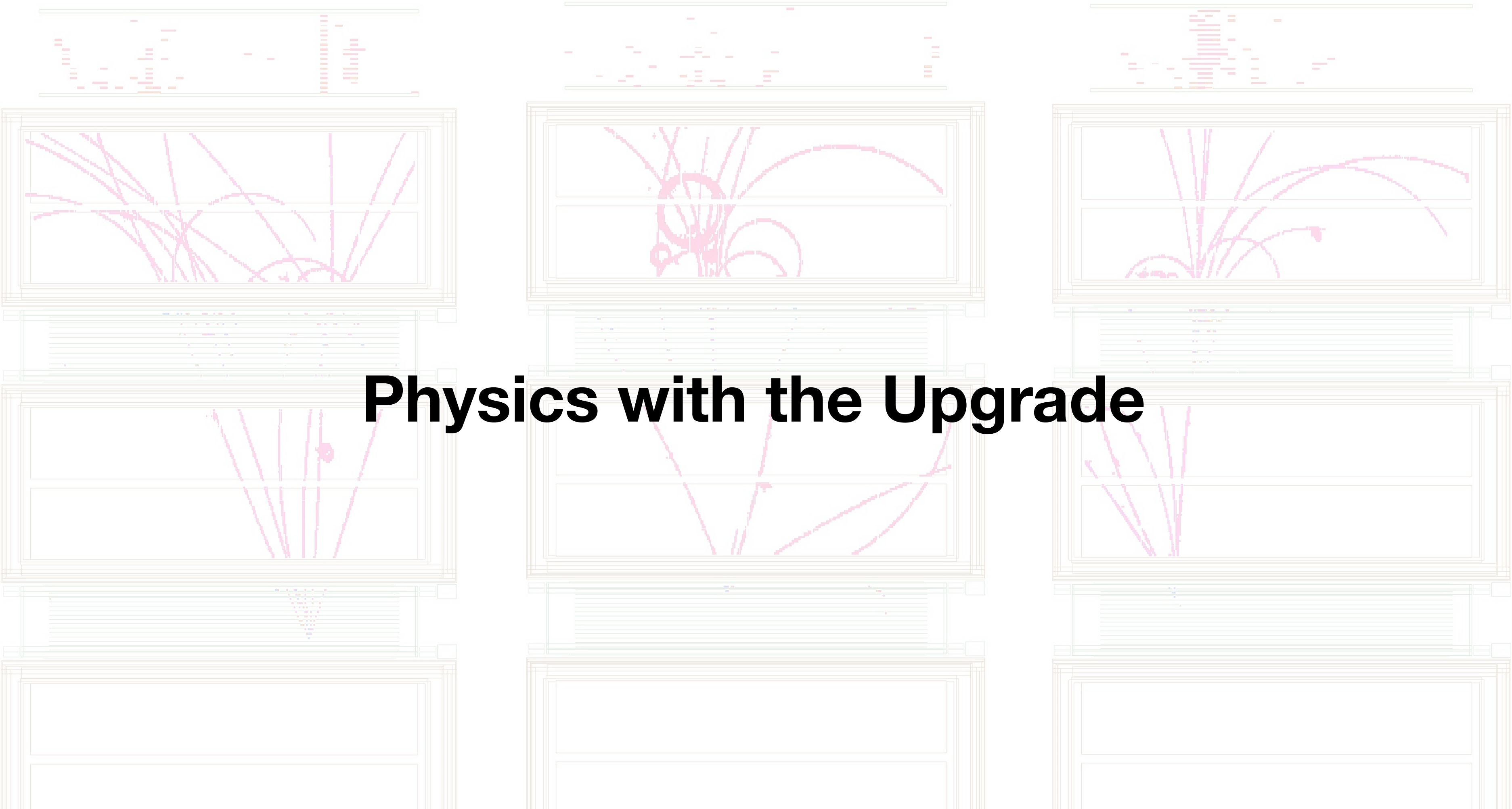
- 6 ToF planes fully covering the 2 HA-TPC and Super-FGD
  - Each plane of consists of 20 scintillator bars (EJ200)
  - Readout with 16 MPPCs at both ends of each bar
  - Fully built and tested, currently finalizing DAQ



- **Goals:**
  - precisely measure the **crossing time** of charged particles
  - ↪ Separate inward going background from products of neutrino interactions in fiducial volume
  - ↪ Can be used as cosmic trigger for the calibration of Super-FGD and HA-TPCs
  - ↪ Could also improve particle identification with timing information



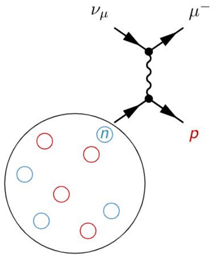
- **Performances:**
  - Excellent timing resolution ~ 130 ps

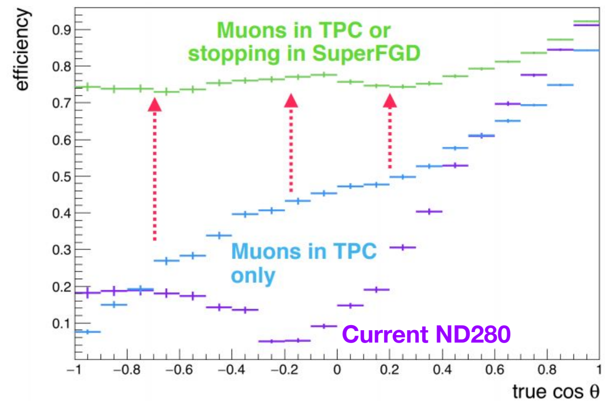


Physics with the Upgrade

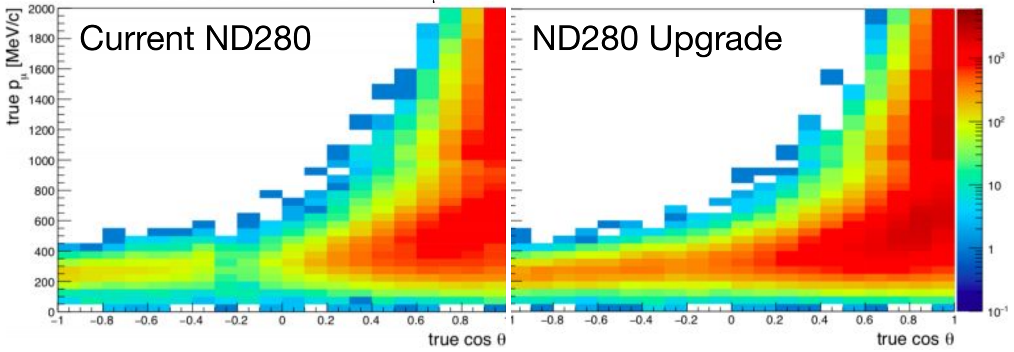
Improvements with the ND280 Upgrade

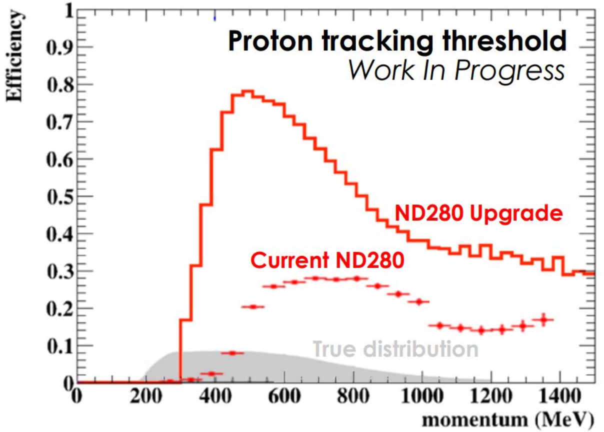
- Improved reconstruction at high and backward angles $\longrightarrow$ better constraints on the neutrino interaction model
- Increased target mass (x2 current ND280) $\longrightarrow$ more statistics
- Better reconstruction of outgoing nucleons $\longrightarrow$ access to new observables
- Neutrino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





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



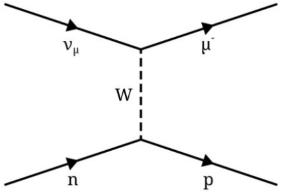


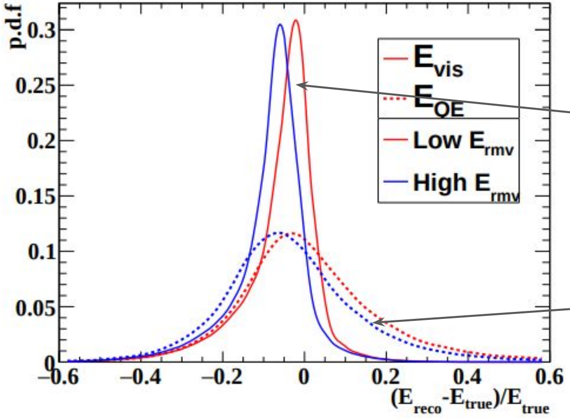
New observables: visible energy

- 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 $E_{\text{vis}} = E_\mu + T_p$





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

Bias due to nuclear effects

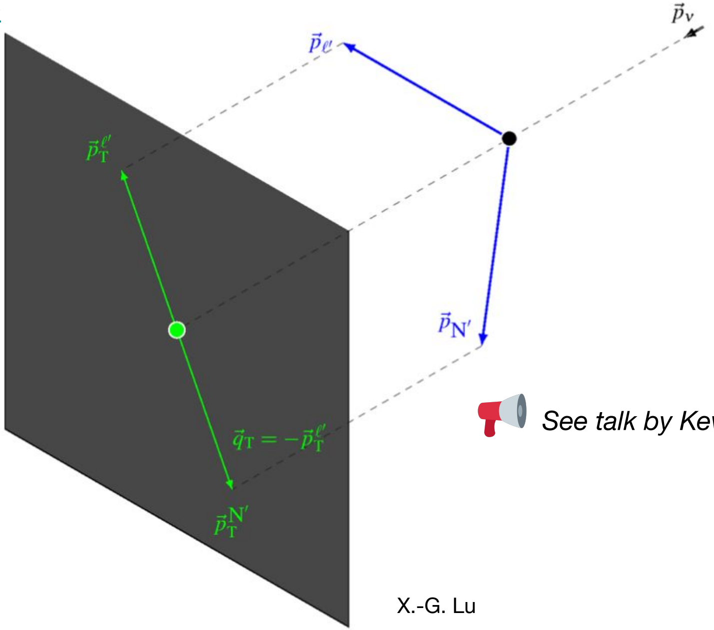
Using lepton information only
$E_\nu^{QE} = \frac{m_p^2 - (m_n - E_b)^2 - m_\mu^2 + 2(m_n - E_b)E_\mu}{2(m_n - E_b - E_\mu + p_\mu \cos\theta_\mu)}$

[Phys. Rev. D 105,032010]

New observables: transverse kinematic imbalance

For more details, see:
* *[Phys Rev C 94, 015503]*
* *[Talk by X.-G. Lu at NEUTRINO2022]*

Static nucleon target



X.-G. Lu

📢 *See talk by Kevin McFaland (Monday)*

New observables: transverse kinematic imbalance

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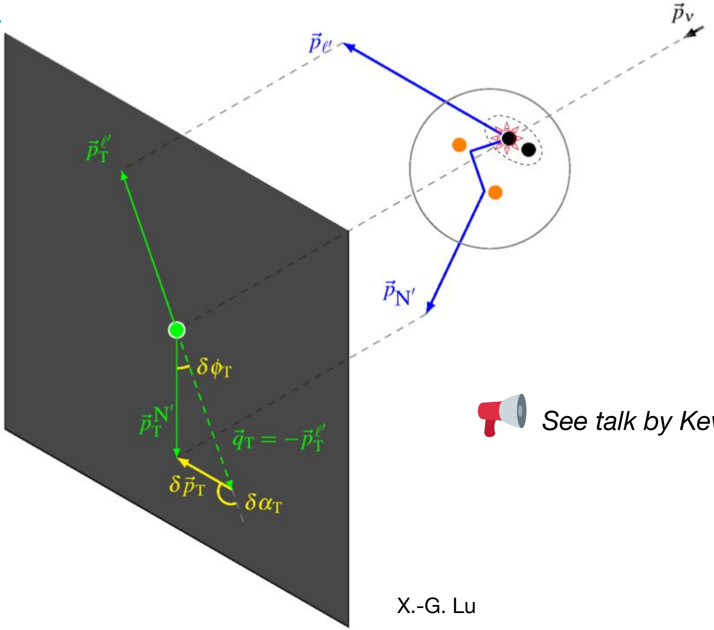
Nucleon bound within nuclear target



X.-G. Lu

See talk by Kevin McFaland (Monday)

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- Probe nuclear effects (Fermi motion, FSI, ...)

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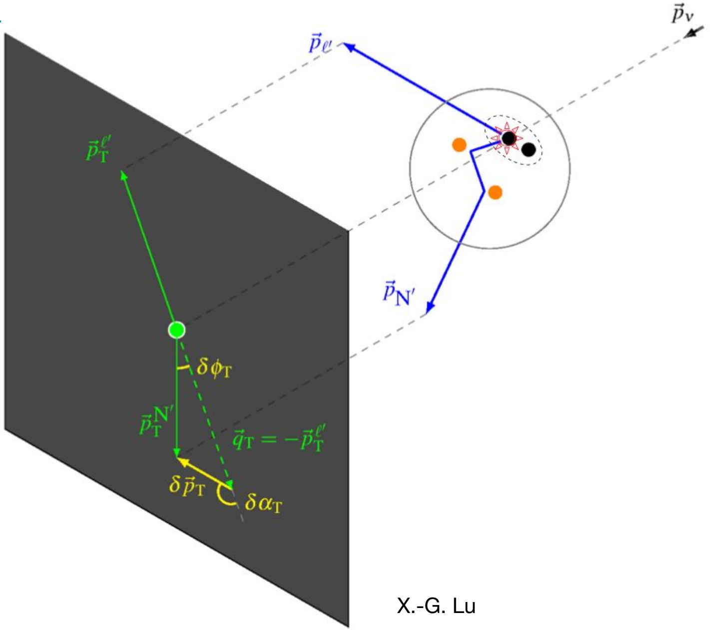
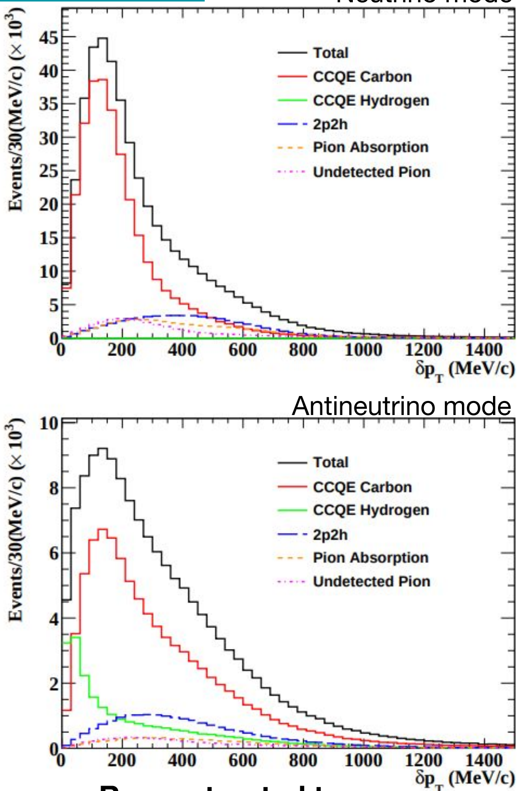


X.-G. Lu

Phys. Rev. D 105,032010



Reconstructed transverse momentum imbalance δp_T

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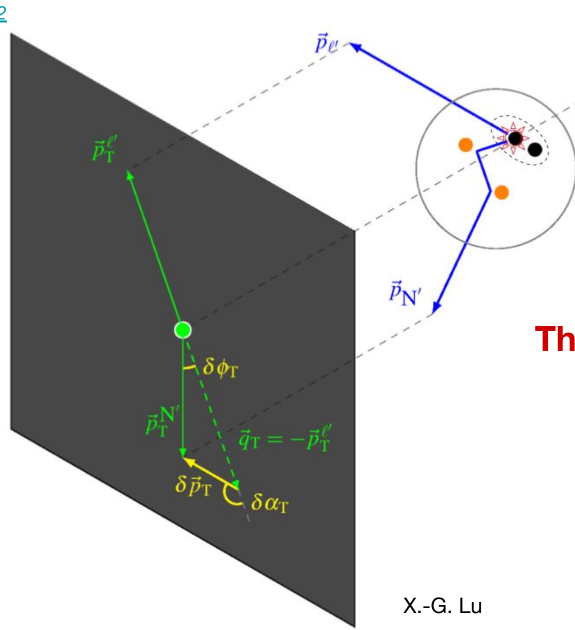
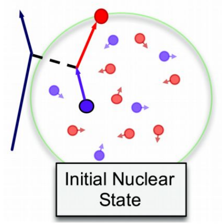
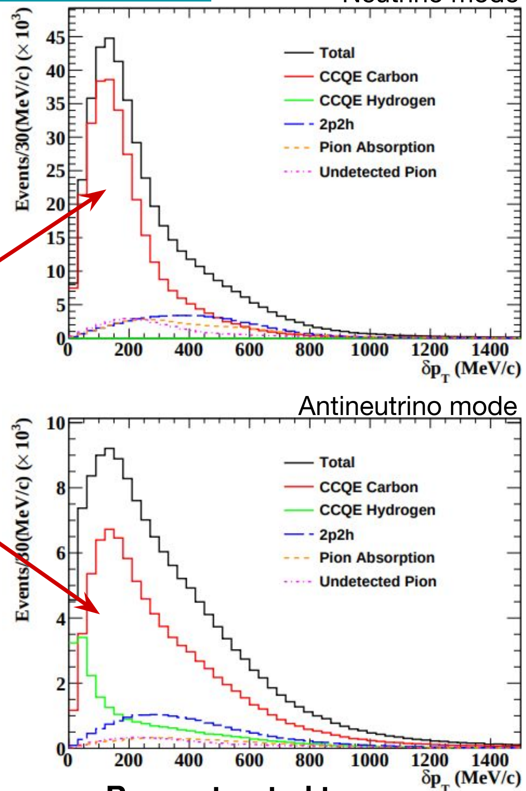


X.-G. Lu

The bulk probes Fermi motion



Phys. Rev. D 105,032010



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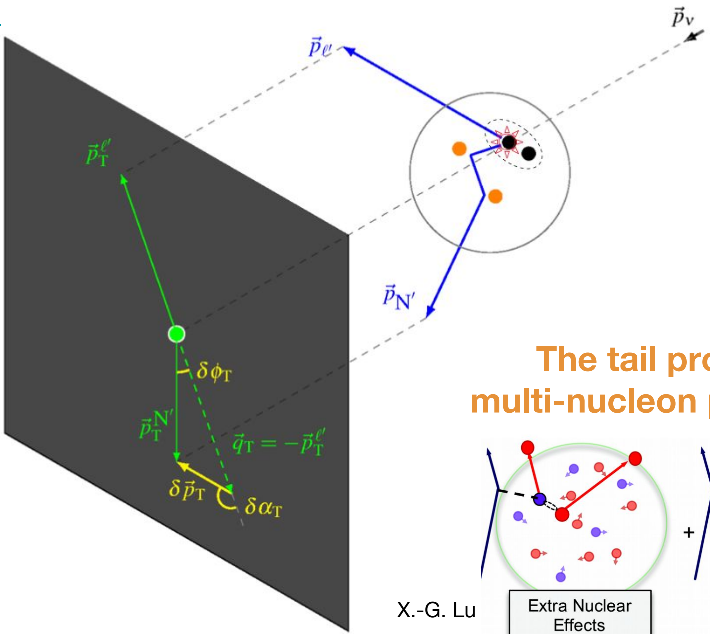
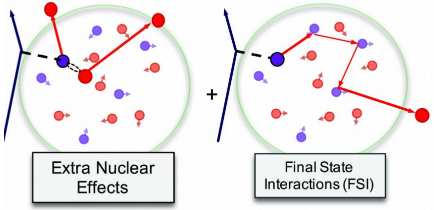
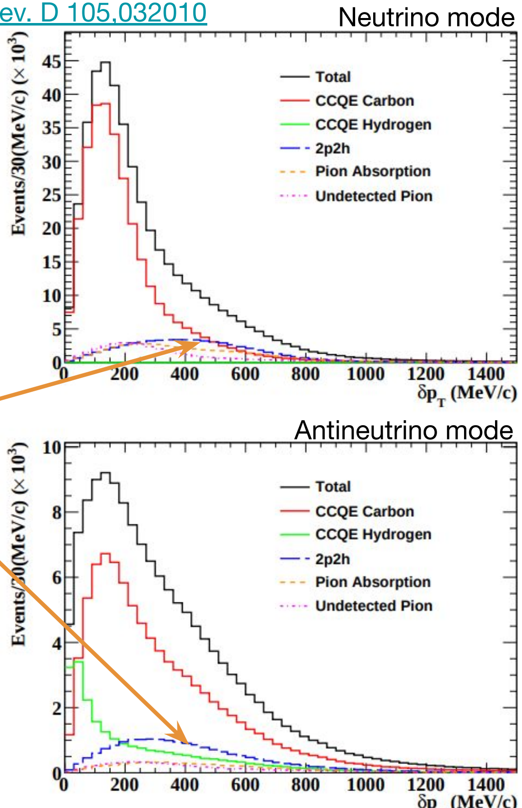


The tail probes FSI & multi-nucleon processes



Phys. Rev. D 105,032010



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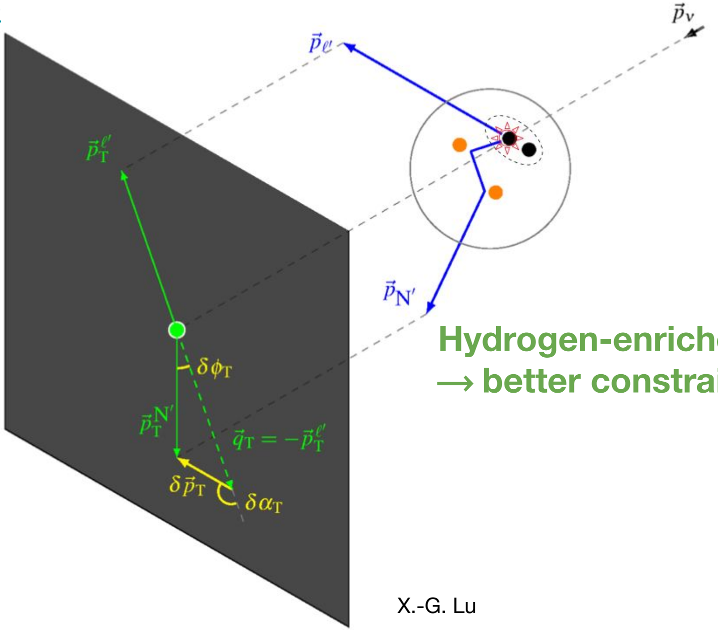
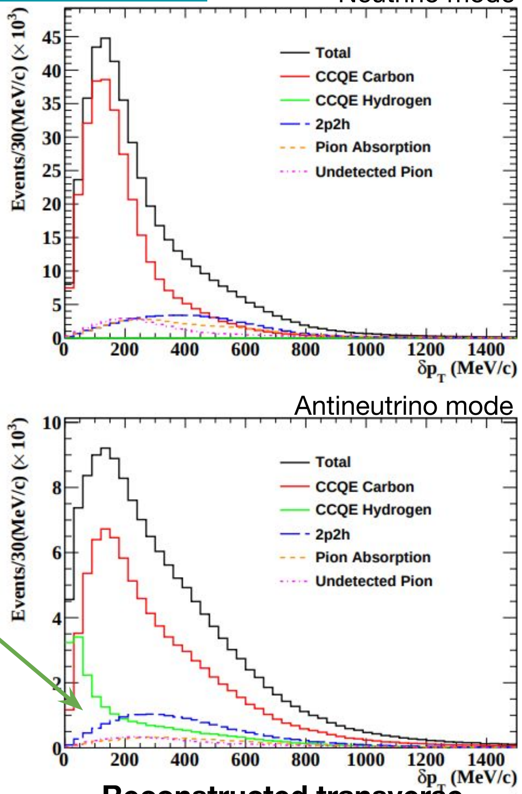


X.-G. Lu

Hydrogen-enriched region
⟶ better constraints on the flux

Phys. Rev. D 105,032010



Reconstructed transverse momentum imbalance δp_T

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Future Oscillation Analysis?

- Currently, T2K uses only lepton kinematics for the Oscillation Analysis (OA)

📢 *See talk by Lukas Berns (Monday)*

Future Oscillation Analysis?

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- With the ND280 Upgrade, we expect to obtain more precise measurements of the nucleons coming out from neutrino interactions
  ⟶ what will the impact be on the OA?

See talk by Lukas Berns (Monday)

Future Oscillation Analysis?

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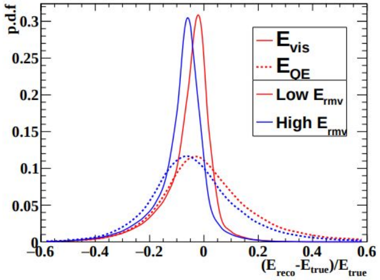
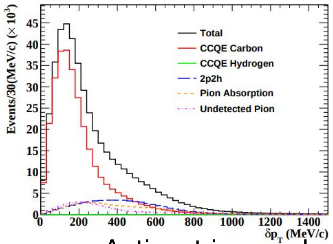
See talk by Lukas Berns (Monday)

- With the ND280 Upgrade, we expect to obtain more precise measurements of the nucleons coming out from neutrino interactions
  $\longrightarrow$ what will the impact be on the OA?

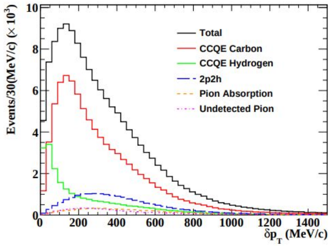
- With the nucleon information, we can introduce samples with new observables at the ND:
  - Transverse momentum imbalance
  - Visible energy:
    - $E_{\text{vis}} = E_\mu + T_p$ for ν_μ interactions
    - $E_{\text{vis}} = E_\mu + T_n$ for $\bar{\nu}_\mu$ interactions



Neutrino mode



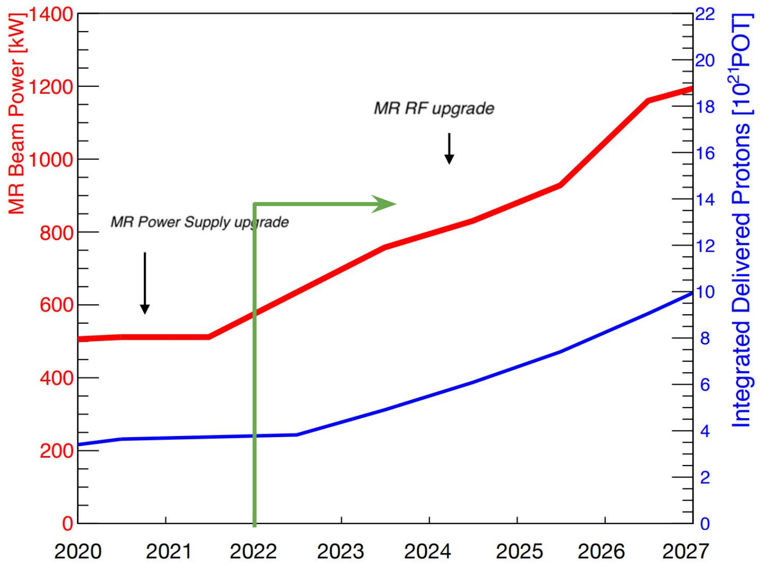
Antineutrino mode



Future Oscillation Analysis?

- We can use T2K projections of POT assuming a scenario where ν_μ and $\bar{\nu}_\mu$ beam modes are alternated yearly to evaluate the impact of adding such samples on the **neutrino interaction model uncertainties**

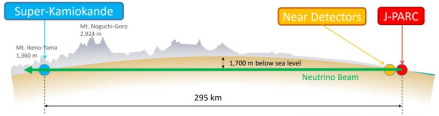
T2K Projected POT (Protons-On-Target)



Future Oscillation Analysis?

- We can use T2K projections of POT assuming a scenario where ν_μ and $\bar{\nu}_\mu$ beam … the … ties

T2K Oscillation Analysis strategy



Flux model — Detector model — Neutrino interaction model

$$N^{ND}_{\nu_\alpha}(E_\nu) = \Phi^{ND}_{\nu_\alpha}(E_\nu) \times \epsilon^{ND}(E_\nu) \times \sigma^{ND}_{\nu_\alpha}(E_\nu)$$

$$N^{FD}_{\nu_\beta}(E_\nu) = \Phi^{FD}_{\nu_\beta}(E_\nu) \times \epsilon^{FD}(E_\nu) \times \sigma^{FD}_{\nu_\beta}(E_\nu) \times \boxed{P_{\nu_\alpha \to \nu_\beta}(E_\nu)}$$

- Far/Near ratio does not fully cancel systematic uncertainties, e.g.:
  - Flux model different at ND vs. FD due to geometry and oscillation
  - Different detectors, i.e. different acceptance, efficiencies, targets…
  - Mainly $\nu_\mu(\bar{\nu}_\mu)$ at ND interacting with CH ⟶ use model to infer interactions of $\nu_\mu/\nu_e(\bar{\nu}_\mu/\bar{\nu}_e)$ on H_2O

↪ **T2K's strategy is to propagate the constraints on the flux and the neutrino interaction models from the ND to the FD**

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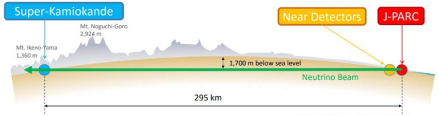

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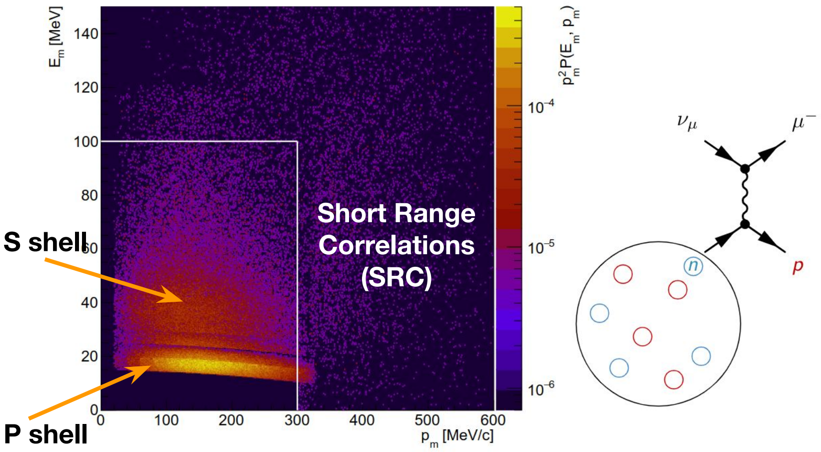
Jaafar Chakrani (LLR) NOW 2022 - Sep 6th, 2022



Carbon Spectral Function model for CCQE interactions

Future Oscillation Analysis?

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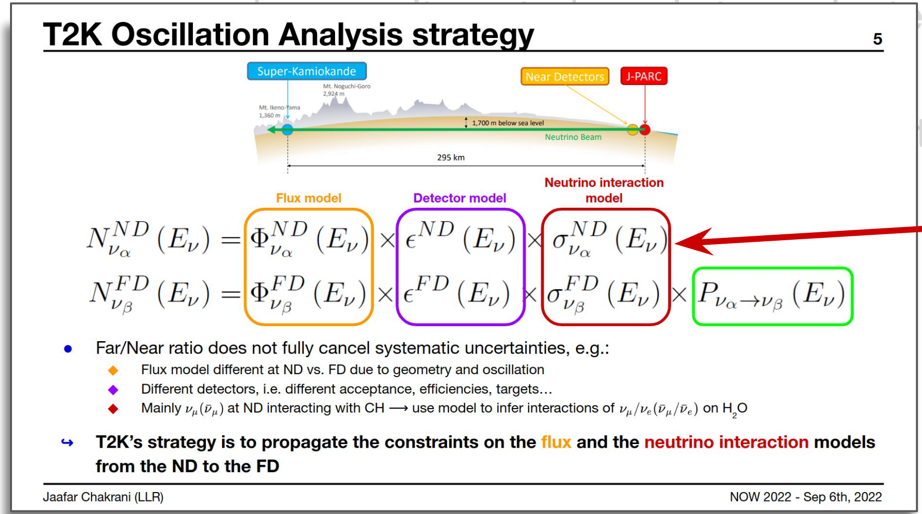

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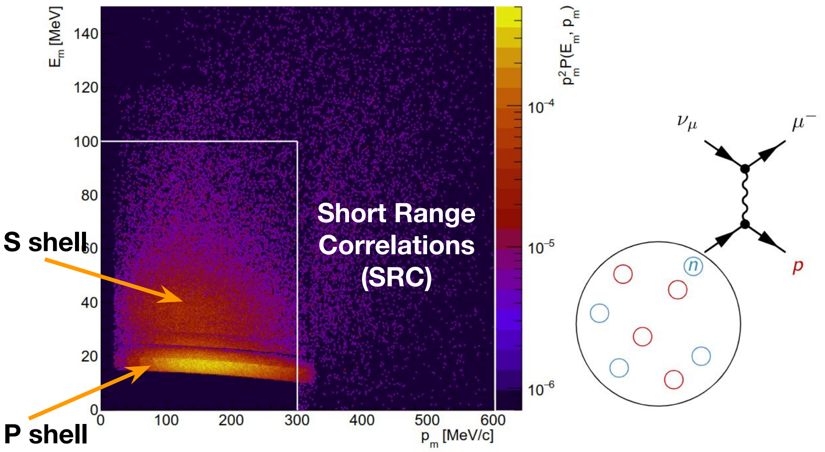


Carbon Spectral Function model for CCQE interactions

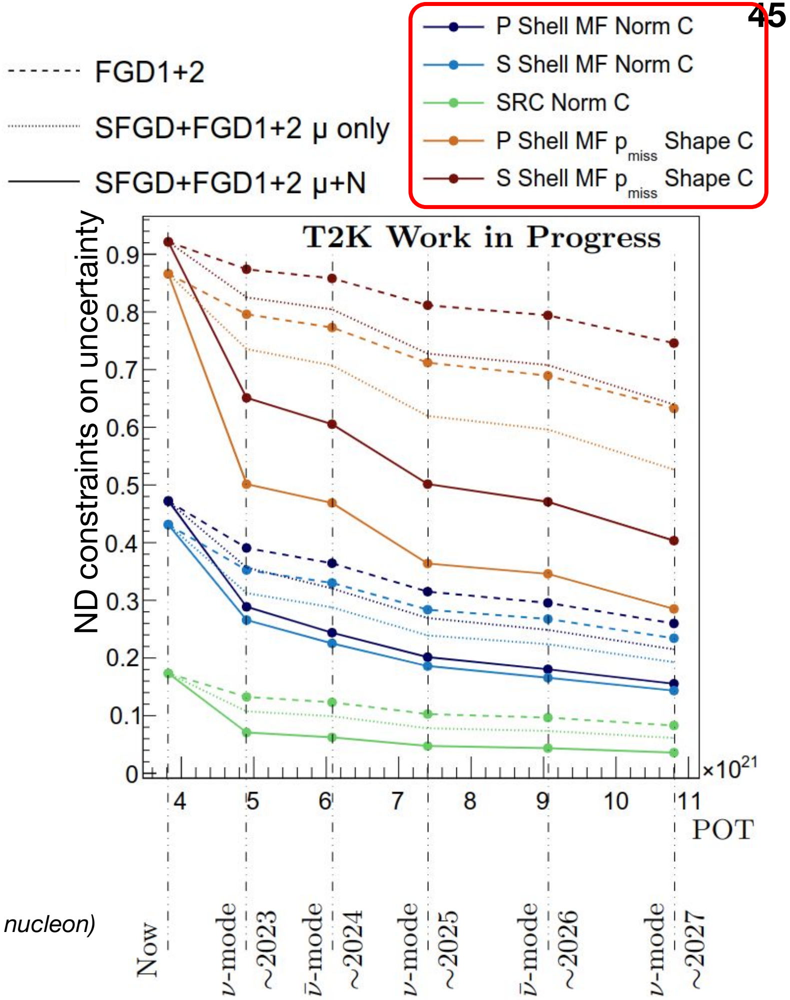
With uncertainties on:

- Shell occupancies (P and S shells for C)
- Shape of the initial state nucleon momentum distribution (Pmiss)
- SRC contributions
- …

Future Oscillation Analysis?

- We can use T2K projections of POT assuming a scenario where ν_μ and $\bar{\nu}_\mu$ beam modes are alternated yearly to evaluate the impact of adding such samples on the **neutrino interaction model uncertainties**

Carbon Spectral Function uncertainties



FGD1+2 : Current ND280 (no Upgrade)

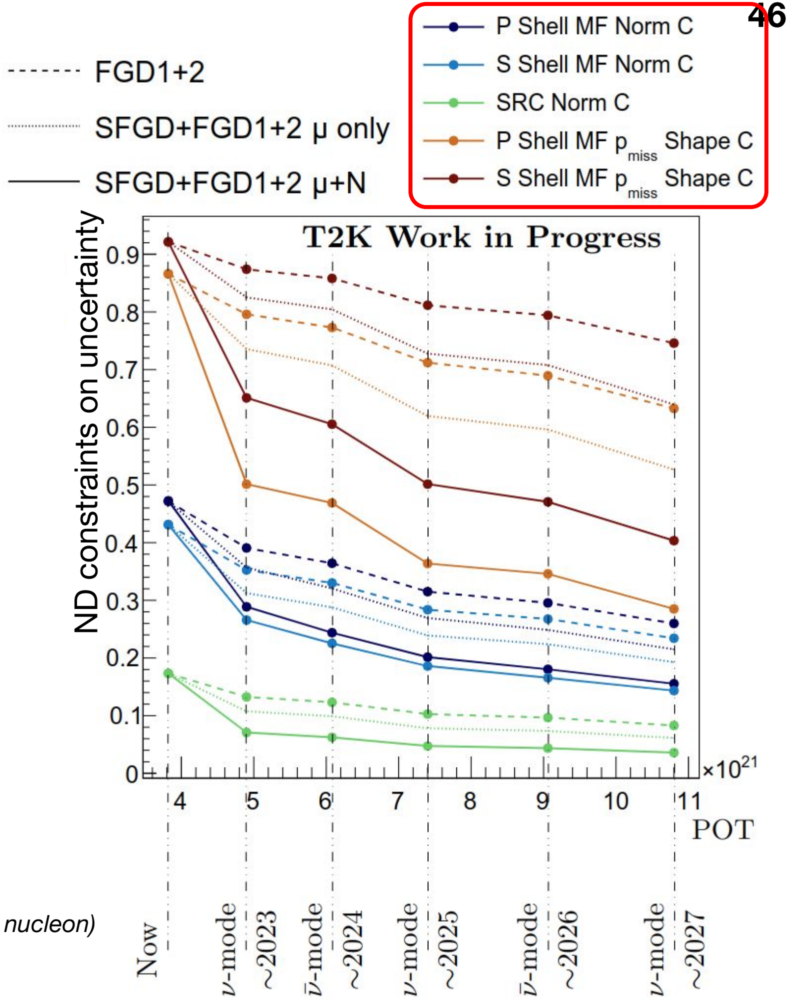
SFGD+FGD1+2 μ only : ND280 Upgrade using muon kinematics only

SFGD+FGD1+2 μ+N : ND280 Upgrade using (Evis, δp_T) *(when reconstructing a nucleon)*

Future Oscillation Analysis?

- We can use T2K projections of POT assuming a scenario where ν_μ and $\bar{\nu}_\mu$ beam modes are alternated yearly to evaluate the impact of adding such samples on the **neutrino interaction model uncertainties**
- Significant improvement is expected on constraining uncertainties at the ND with the Upgrade
- The use of nucleon information with (Evis, δp_T) allows larger constraints especially on the Fermi motion uncertainties

Carbon Spectral Function uncertainties



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Summary and outlook

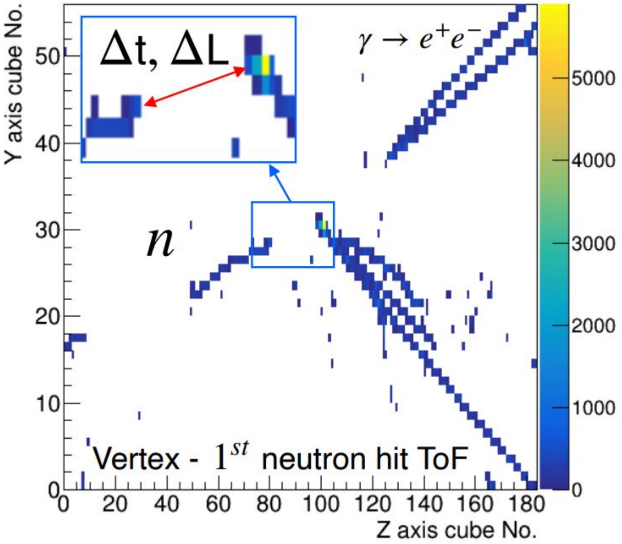
Summary and outlook

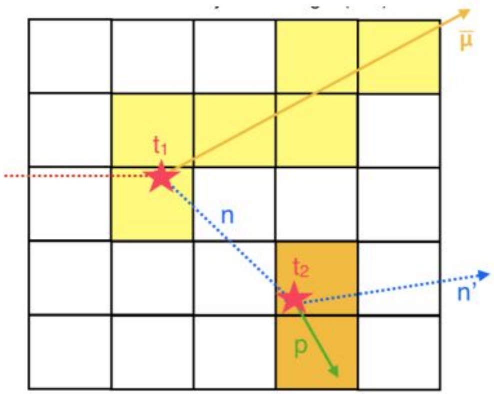
- T2K is currently upgrading its near detector ND280 to overcome limitations of the current ND configuration
- The goal is to reduce systematic uncertainties, particularly on neutrino-nucleus interactions, to further probe CP violation
- The ND280 Upgrade will be installed during 2023
- The performances of the Upgrade are expected to open the door to precisely probe nuclear effects at an unprecedented level, for current as well as next-generation experiments

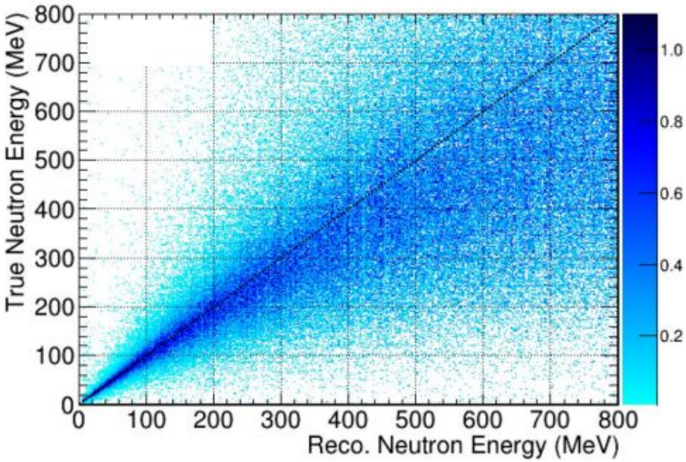
Back-up

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%







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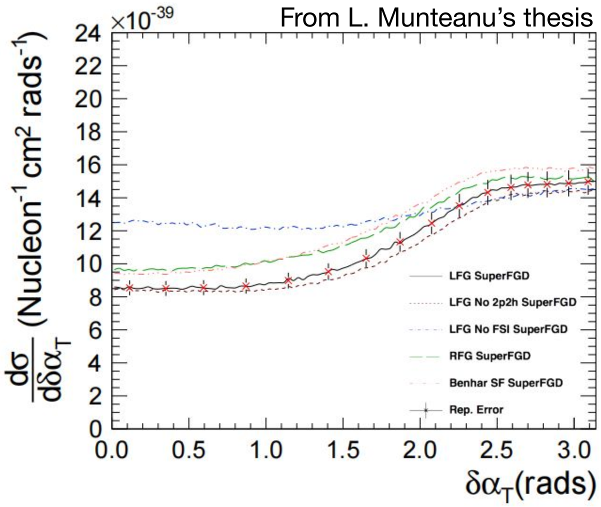
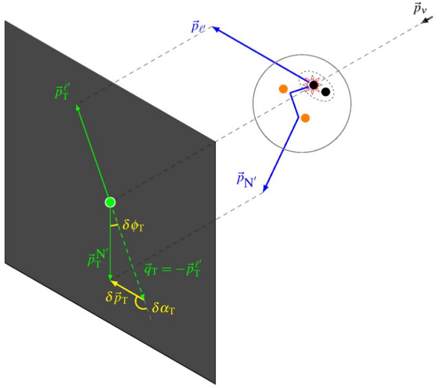
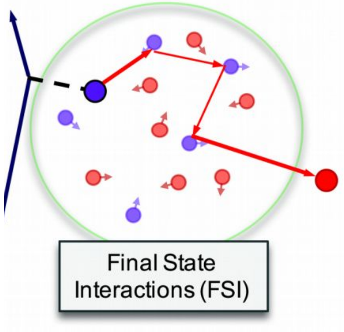
New observables: transverse kinetic imbalance

- $\delta\alpha_T$ is sensitive to FSI:
  - Higher values correspond to stronger FSI effect
  - Lower values correspond to less FSI







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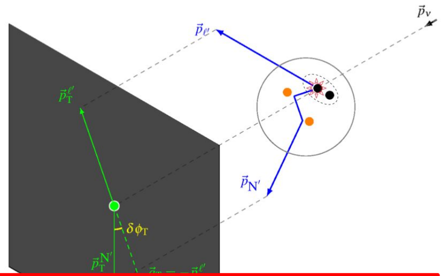
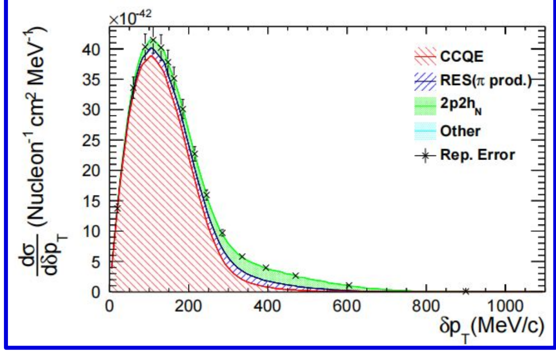
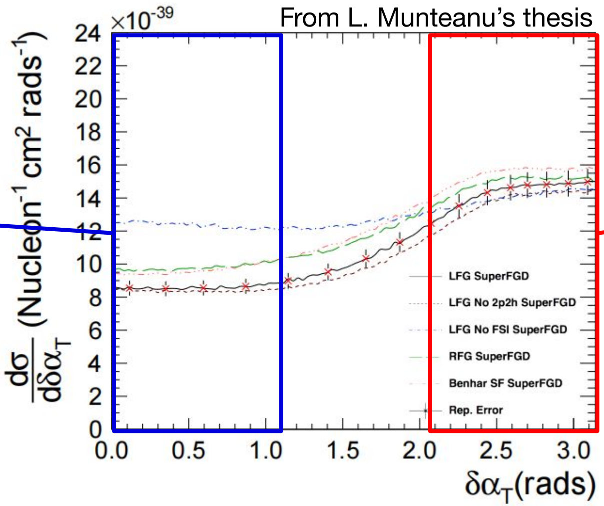
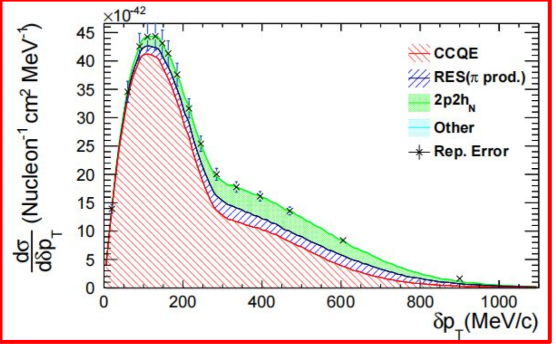


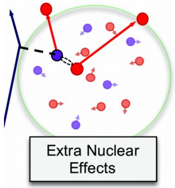
From L. Munteanu's thesis







Tail mostly due to multi-nucleon processes (2p2h)



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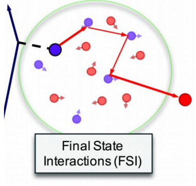

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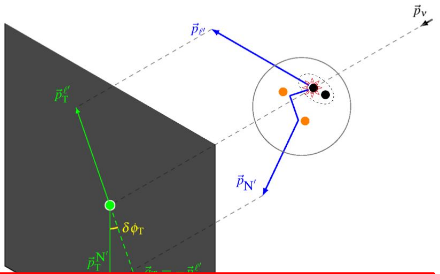

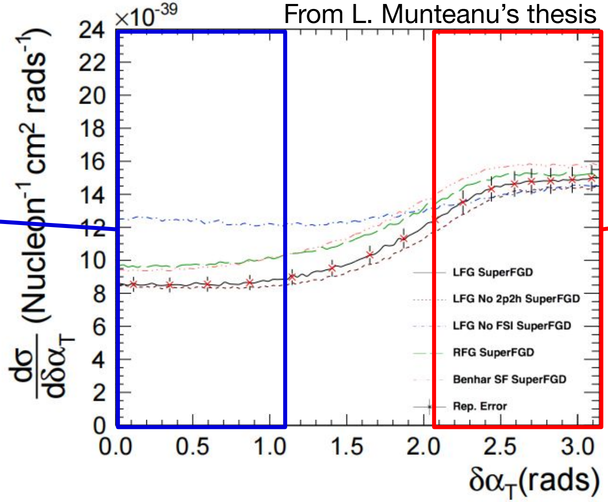

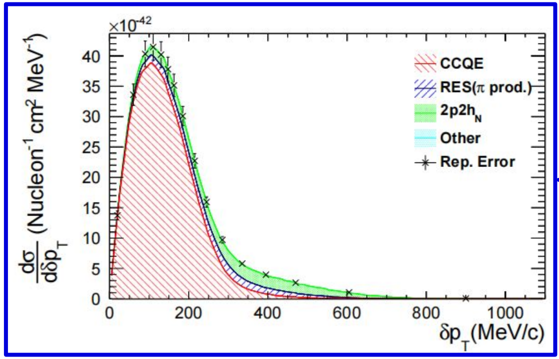

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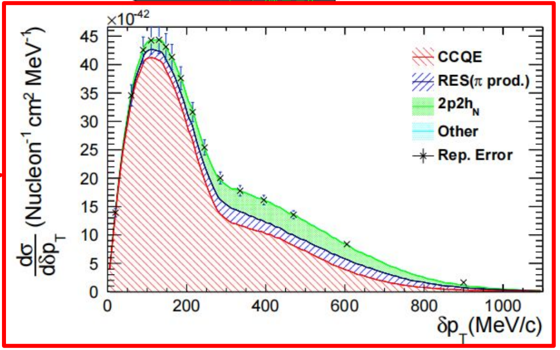
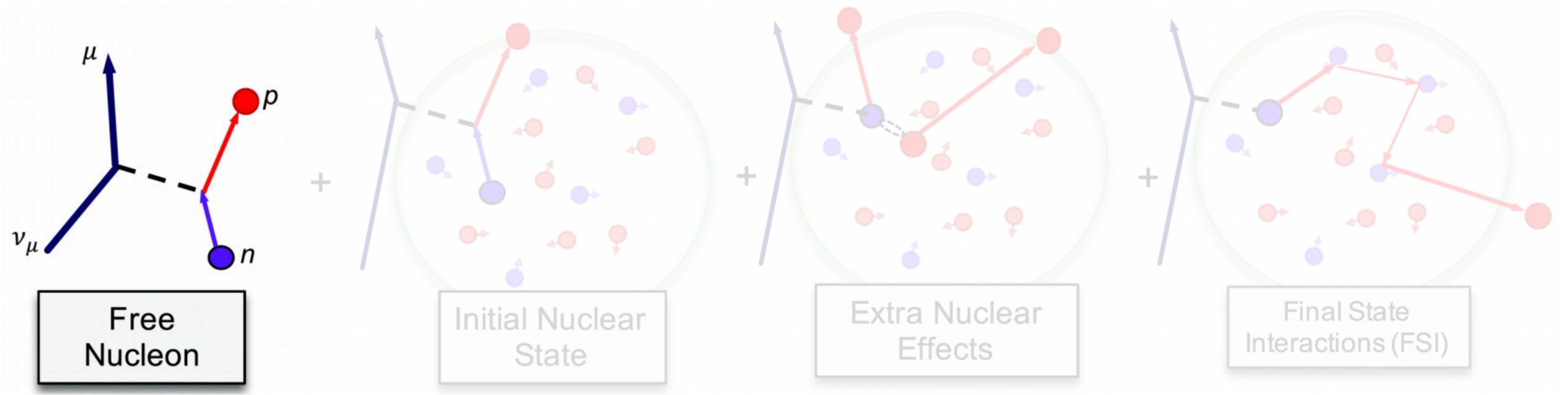


Tail mostly due to FSI

⟹ The Upgrade will open the door to new multi-dimensional analyses (e.g. δp_T in bins of $\delta\alpha_T$)

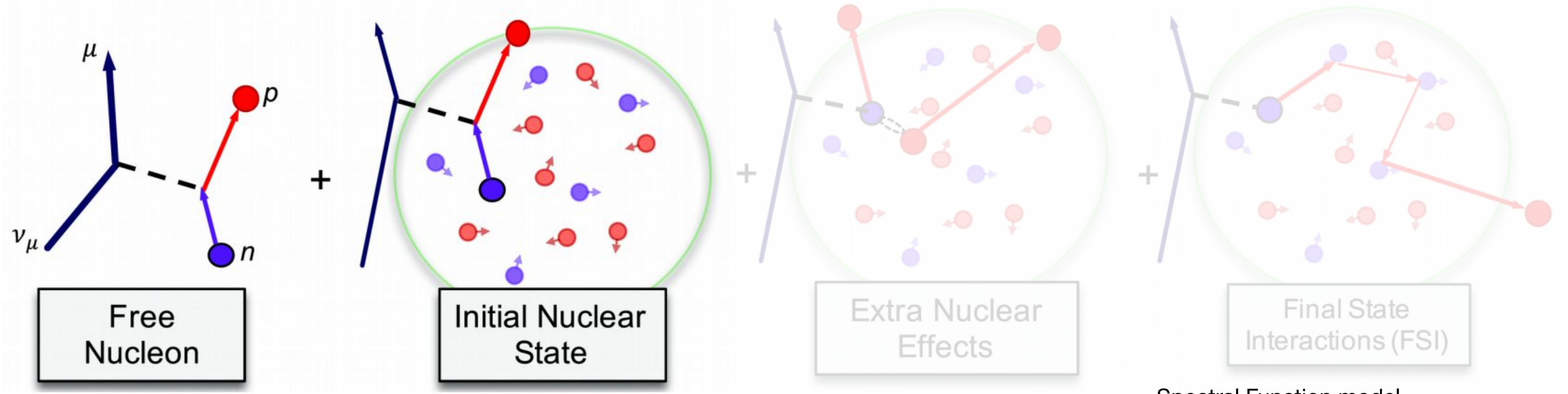
Nuclear effects



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

is an accurate estimation of the neutrino energy using muon kinematics only if the initial state nucleon is static

Nuclear effects



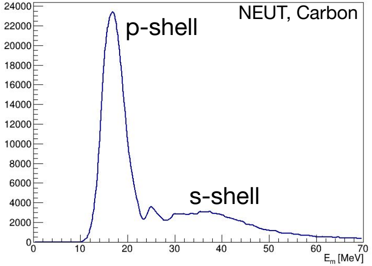
Nucleons are bound within nuclei (*e.g.* C & O in T2K) and are not static

↪ Need to account for:

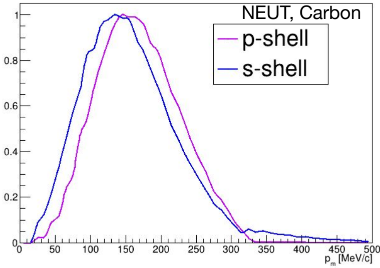
- Removal energy
- Fermi motion

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

Spectral Function model

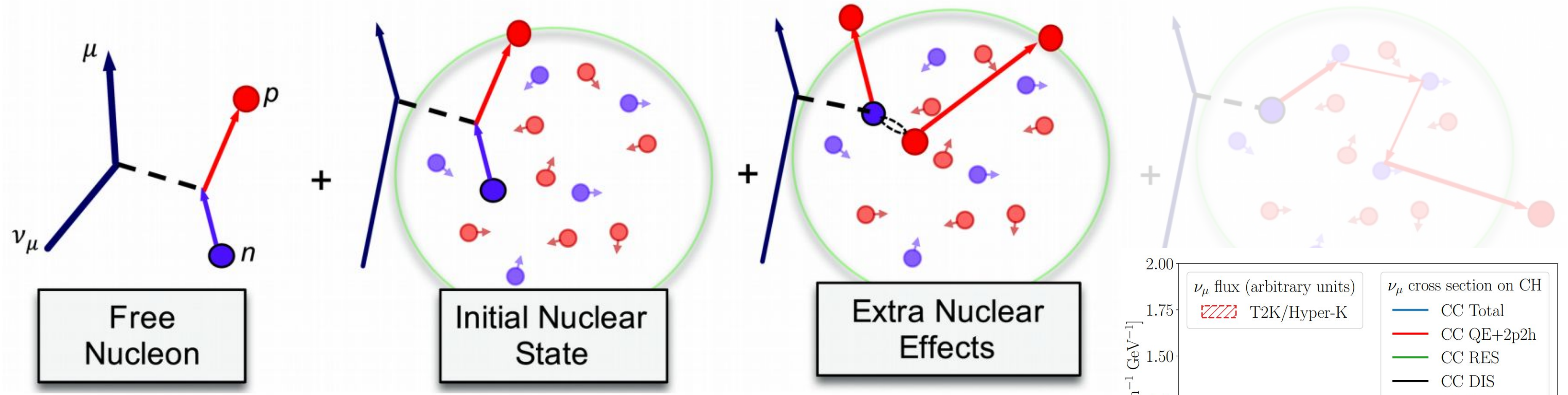


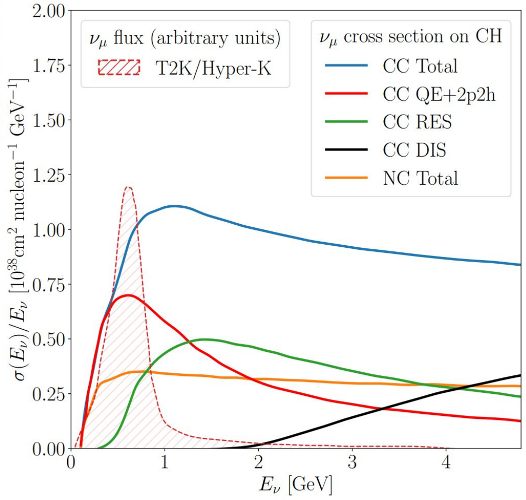
Initial state nucleon energy distribution



Initial state nucleon momentum distribution

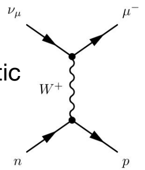
Nuclear effects



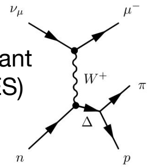


- Other nuclear effects can bias the reconstruction of neutrino energy like short-range correlations, 2p2h interactions...

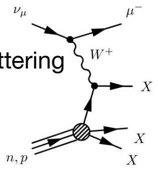
Quasi-elastic (CCQE)



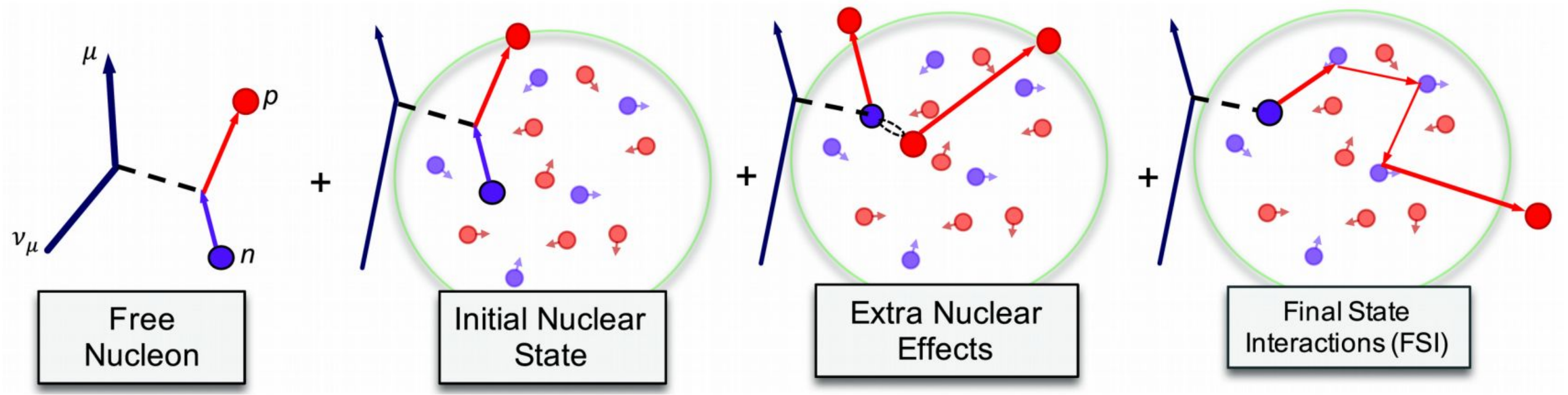
Resonant (CCRES)



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

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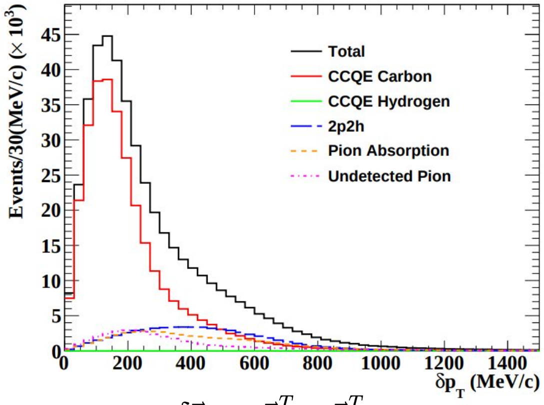
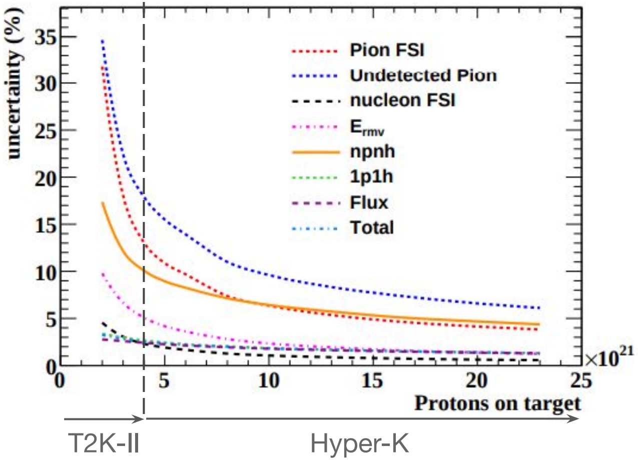
Transverse momentum imbalance



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

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 and next generation experiments