Sensitivity of the T2K Near Detector Upgrade to constrain CCQE uncertainties

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Outline

- Introduction
- Improved detectors: T2K Near Detector Upgrade
- Improved neutrino interaction models
- Projected constraints with T2K ND Upgrade
- Summary

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

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

What do Long-Baseline Experiments measure?

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$c_{ij} = \cos(\theta_{ij})$
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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
→ CP violation!

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

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What do Long-Baseline Experiments measure?

$U_{\alpha i}\,|\nu_\alpha\rangle$

$c_{ij} = \cos(\theta_{ij})$
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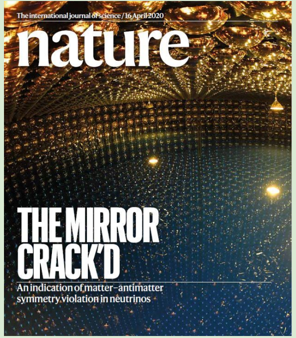
$c_{12} \quad s_{12} \quad 0$
$-s_{12}$
0

ance

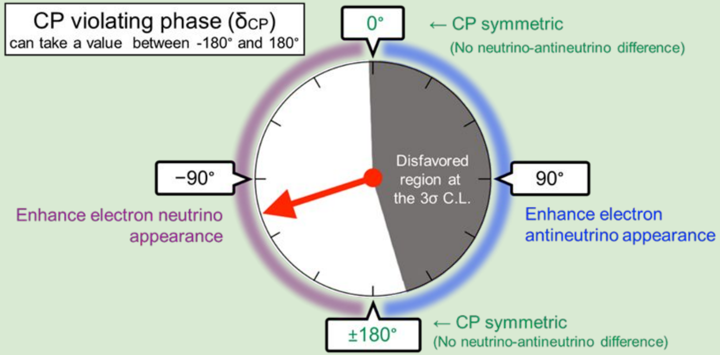
$(\mp) O(\delta_{CP})$

First hints by T2K

April 2020



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



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$\longrightarrow$ CP violation!

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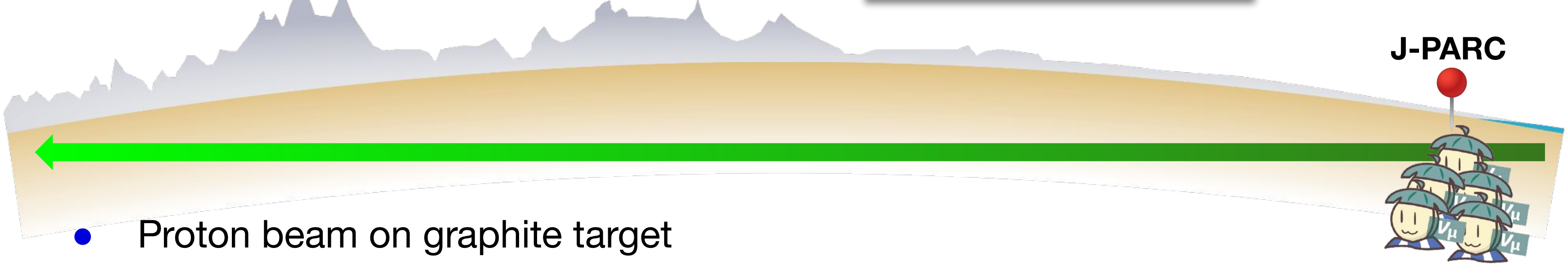
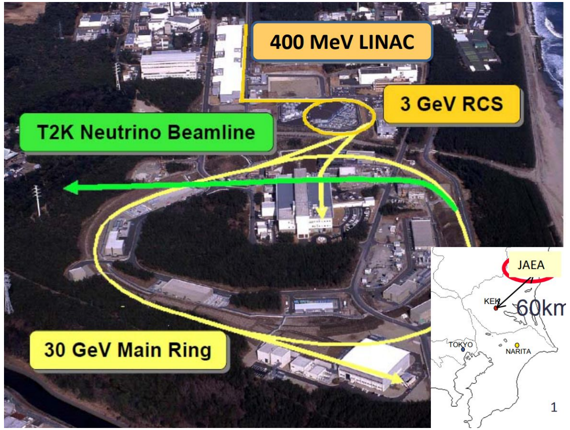
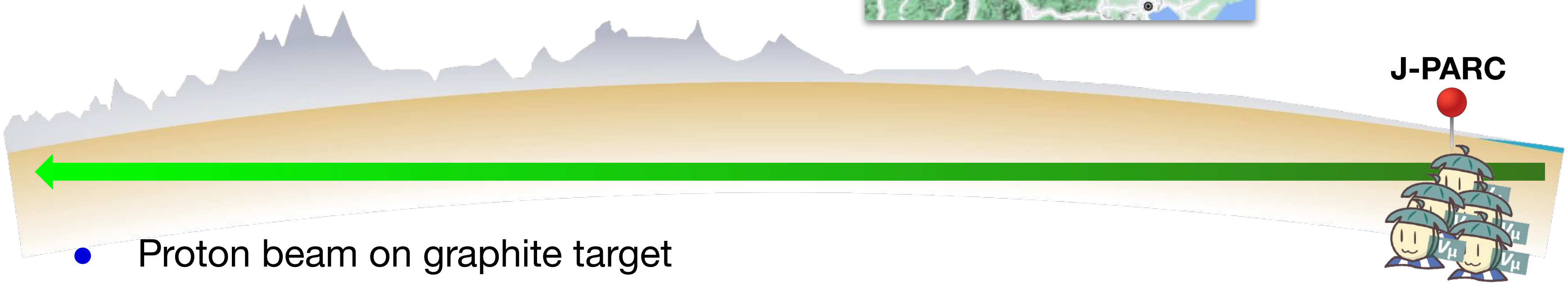
T2K Experiment



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



T2K Experiment



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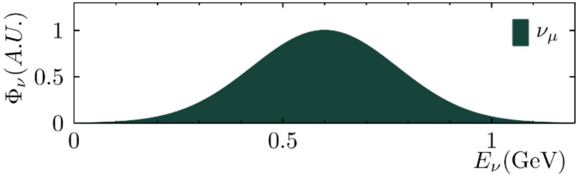
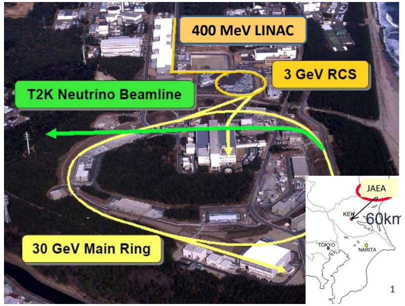
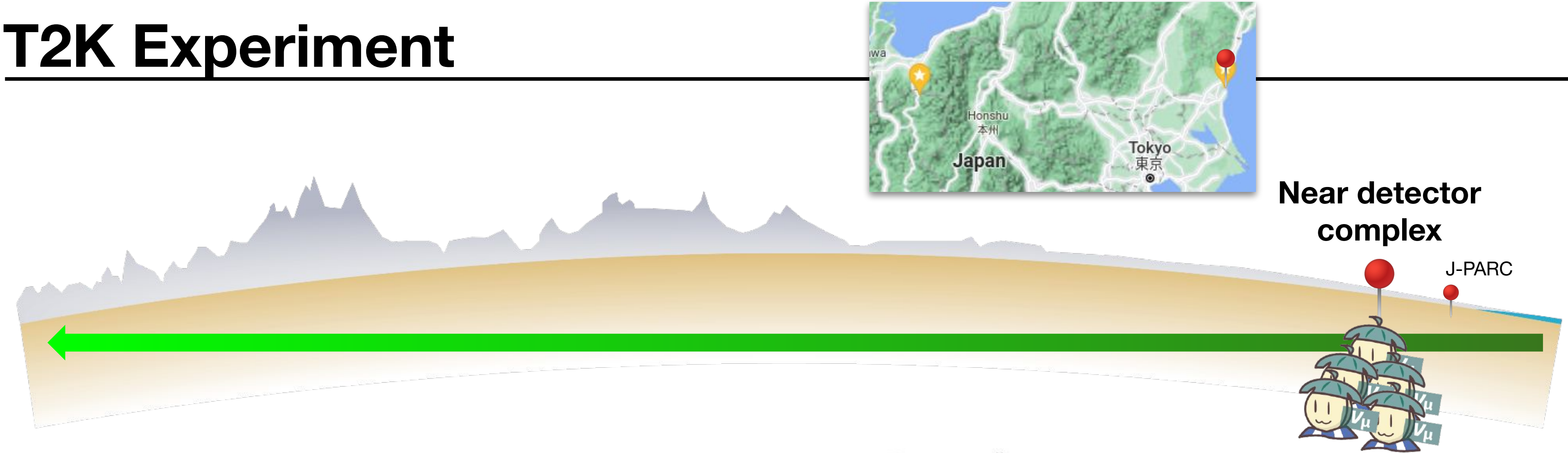
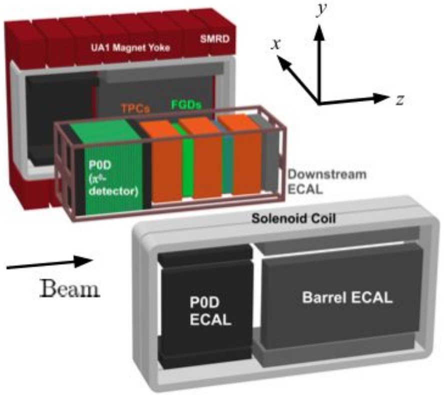


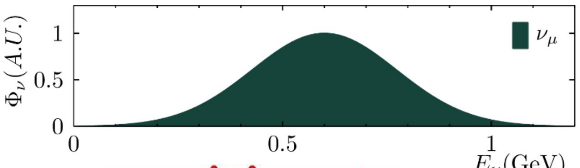


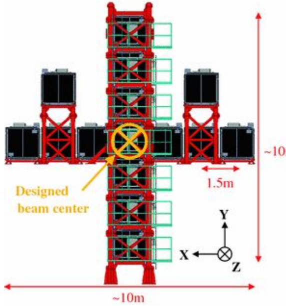
T2K Experiment



Near detector complex





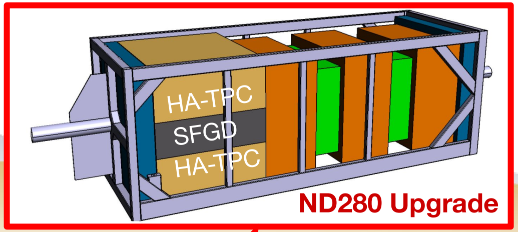


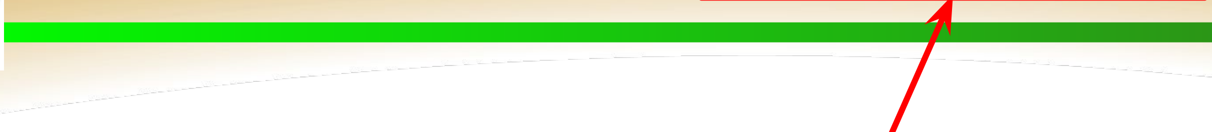
- Measure unoscillated neutrino flux:
  - Electron neutrino and wrong-sign contaminations
  - Neutrino-nucleus interactions

⟶ Reduce **systematic uncertainties**

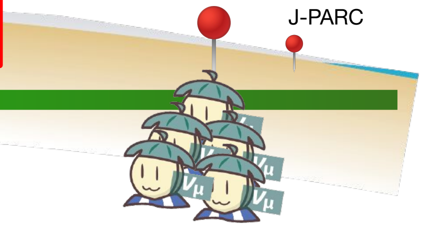
T2K Experiment

- Ongoing upgrade of the ND for improved constraints on systematic uncertainties





Near detector complex



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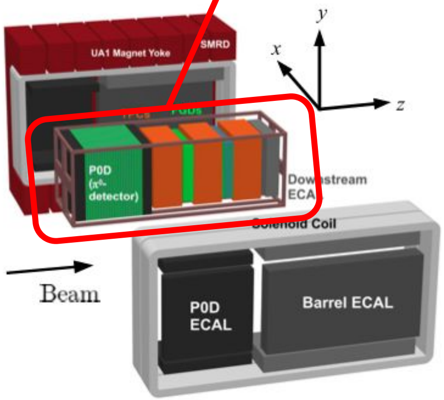
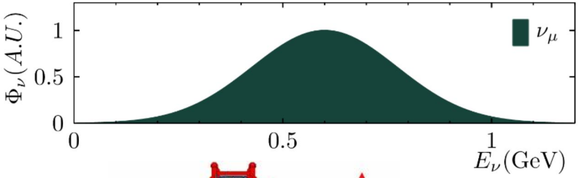
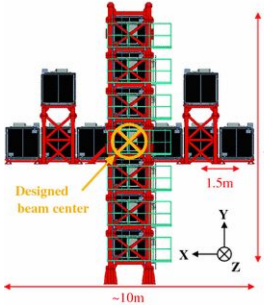
→ Reduce **systematic uncertainties**



ND280





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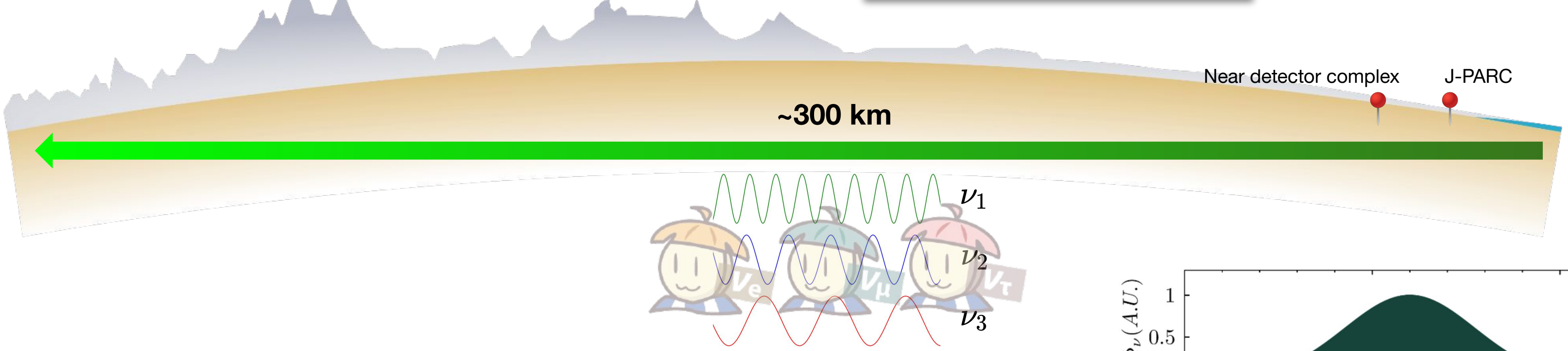
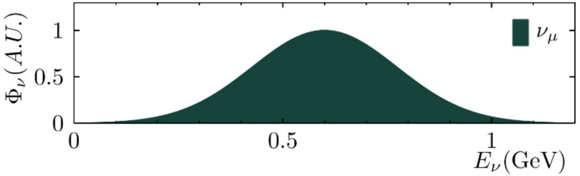
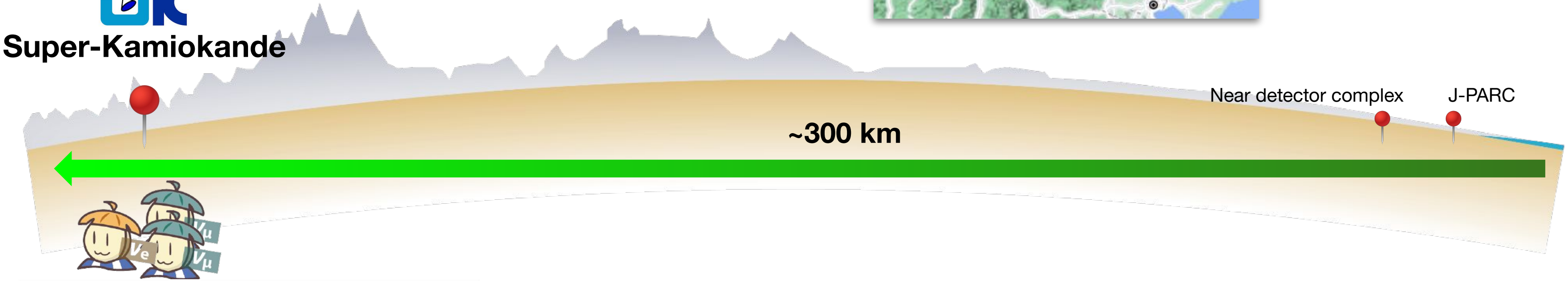
T2K Experiment

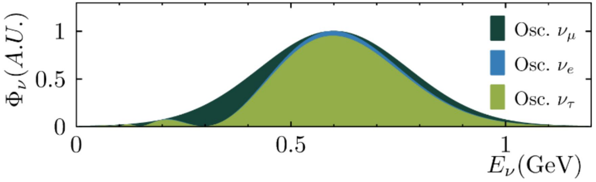


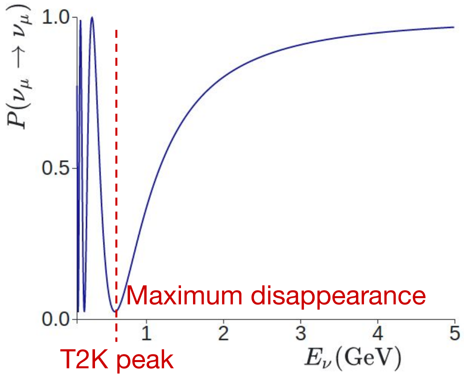
$$|\nu_i\rangle = \sum_{\alpha=e,\mu,\tau} U_{\alpha i} \, |\nu_\alpha\rangle$$

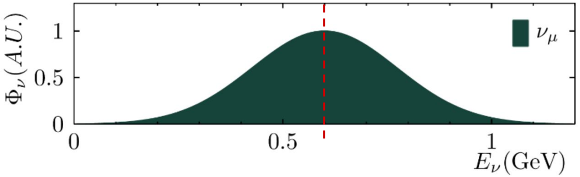


T2K Experiment



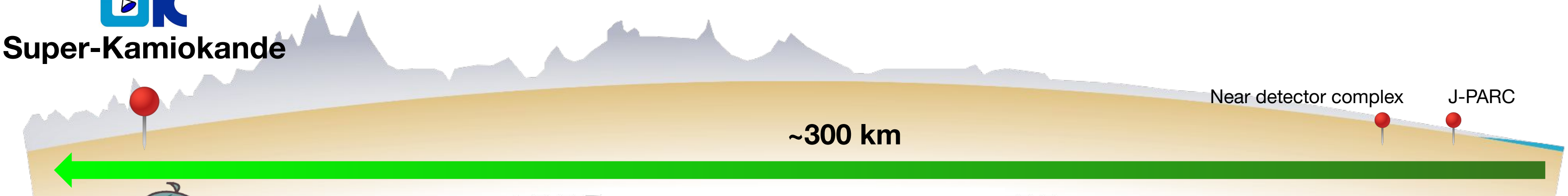


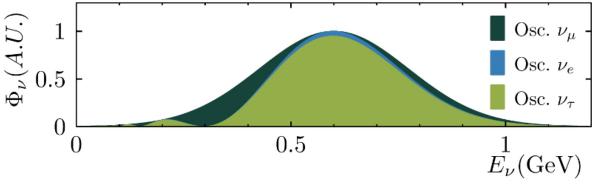


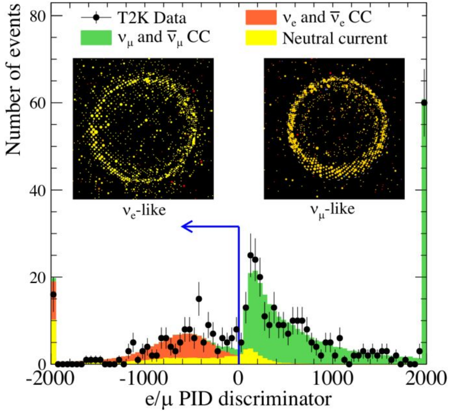


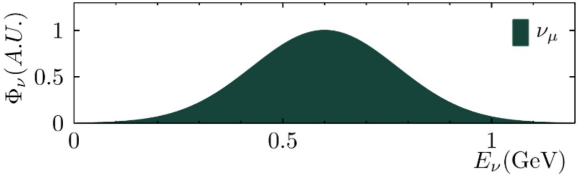
T2K Experiment

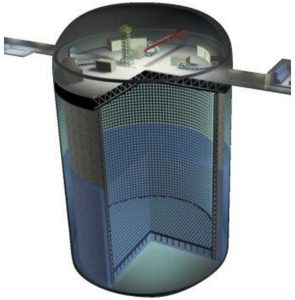
Super-Kamiokande





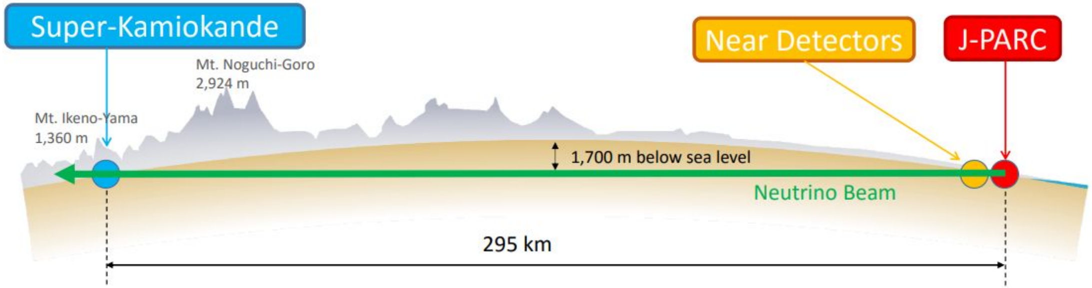






- 50 kt water Cherenkov detector
- Measurement of:
  - Electron neutrino vs. muon neutrino PID by ring pattern
  - Neutrino energy

T2K Oscillation Analysis strategy



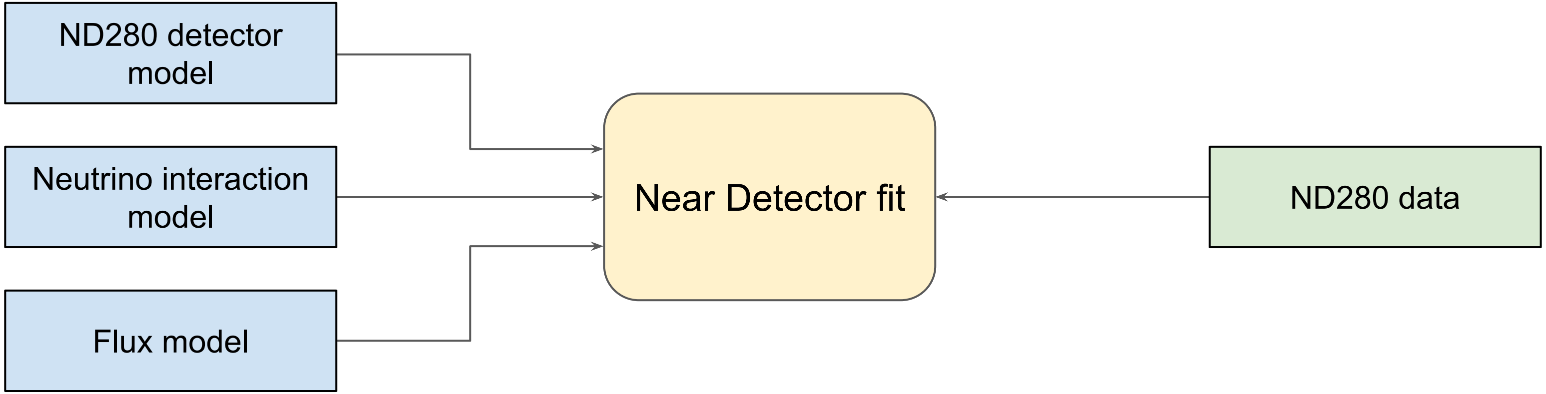
Flux model **Detector model** **Neutrino interaction model**

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

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

- **Far/Near ratio does not fully cancel systematic uncertainties:**
  - Flux model different at ND vs. FD due to geometry and oscillation
  - Different detectors, i.e. different acceptance, efficiencies, targets…
  - Mainly muon neutrinos at ND interacting with CH → use model to infer interactions with electron neutrino interactions and with H2O

T2K Oscillation Analysis strategy



ND280 detector model

Neutrino interaction model

Flux model

Near Detector fit

ND280 data

$$N_{\nu_\alpha}^{ND}(E_\nu) = \Phi_{\nu_\alpha}^{ND}(E_\nu) \times \epsilon^{ND}(E_\nu) \times \sigma_{\nu_\alpha}^{ND}(E_\nu)$$

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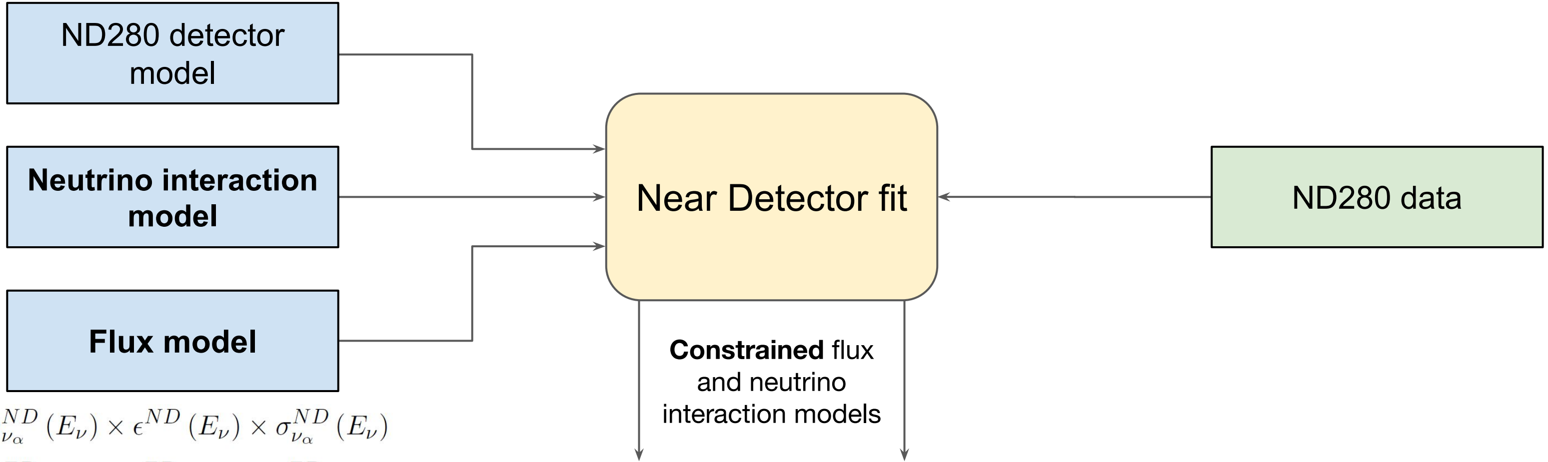
T2K Oscillation Analysis strategy



ND280 detector model

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ND280 data

Constrained flux and neutrino interaction models

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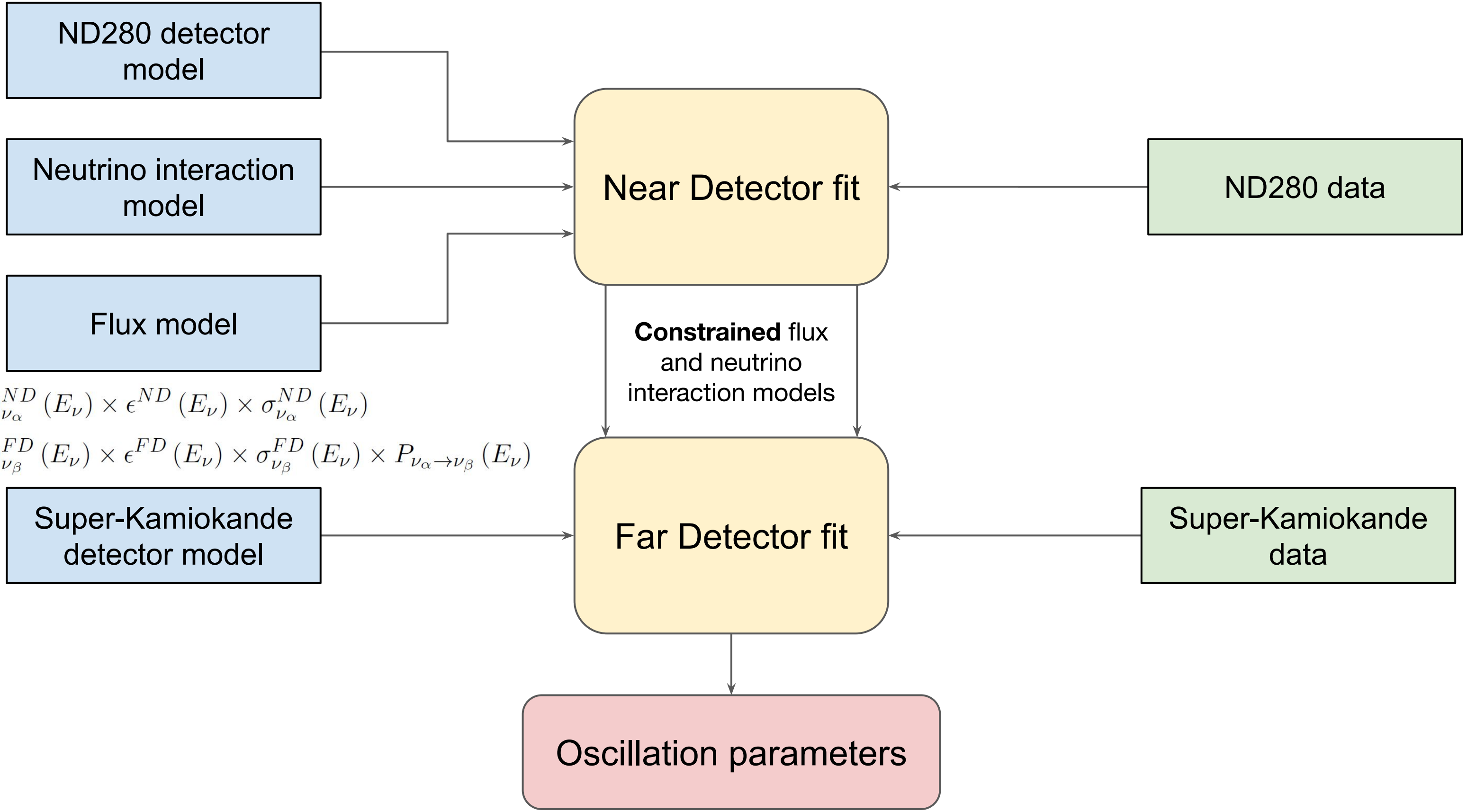
T2K Oscillation Analysis strategy



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Super-Kamiokande detector model

Far Detector fit

Super-Kamiokande data

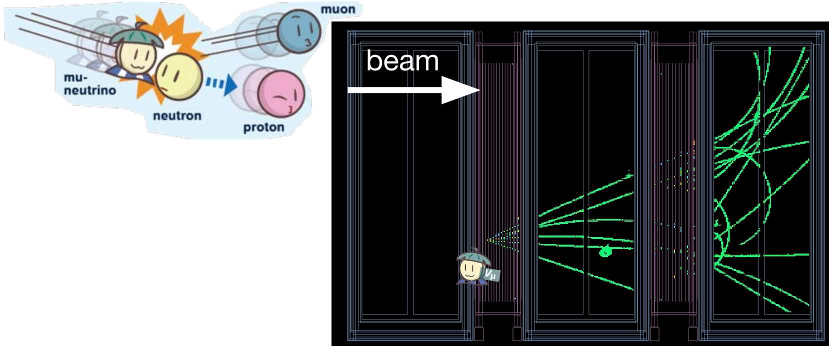
Oscillation parameters

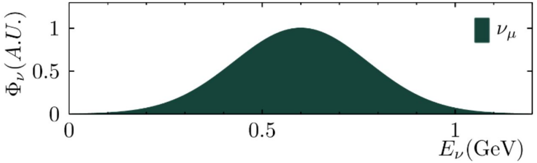
Neutrino energy reconstruction

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

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

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





Neutrino energy reconstruction

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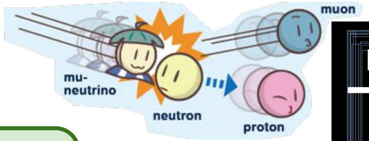
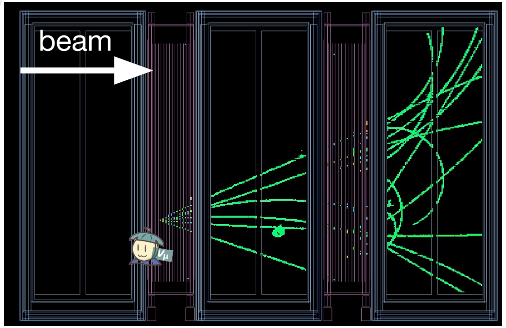
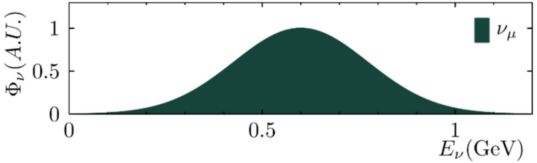
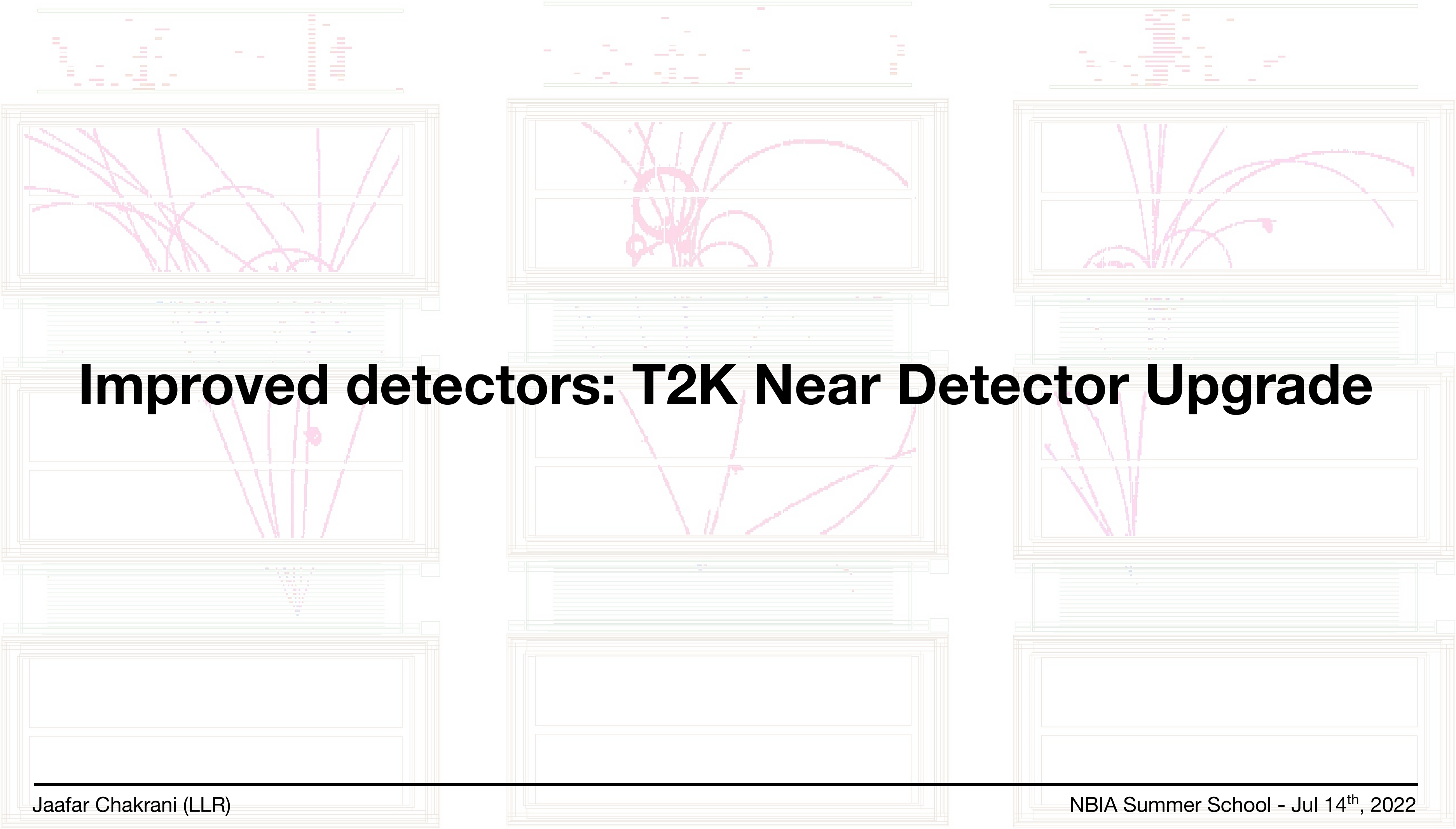






Two ways to improve the neutrino energy reconstruction:

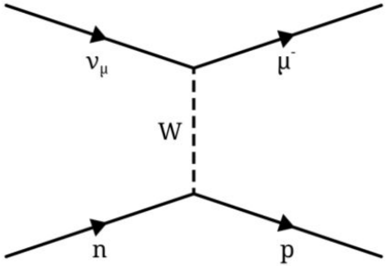
- Improve the detectors
- Improve the nuclear model

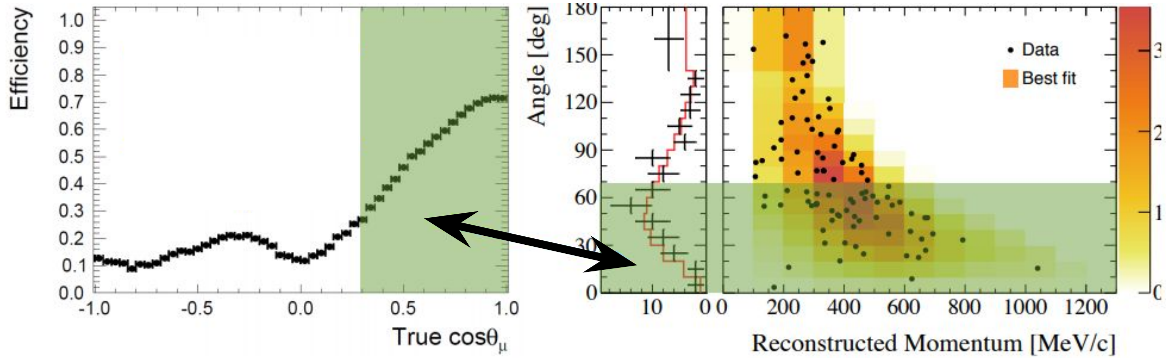


Improved detectors: T2K Near Detector Upgrade

Limitations of current ND280

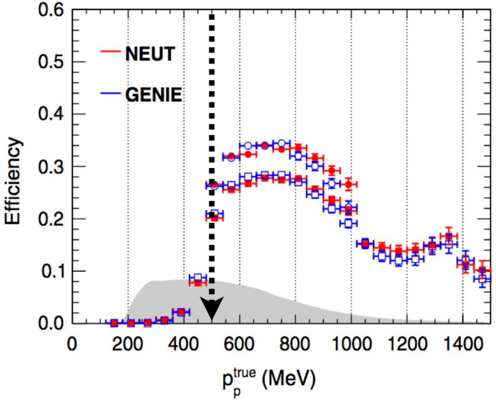
- Non-isotropic efficiency (unlike Super-Kamiokande)
- High momentum proton threshold (~450 MeV/c)
- For the oscillation analysis, neutrino interactions are characterized in **muon kinematics only**





Muon detection efficiency at ND280

ν_e candidates at Super-K



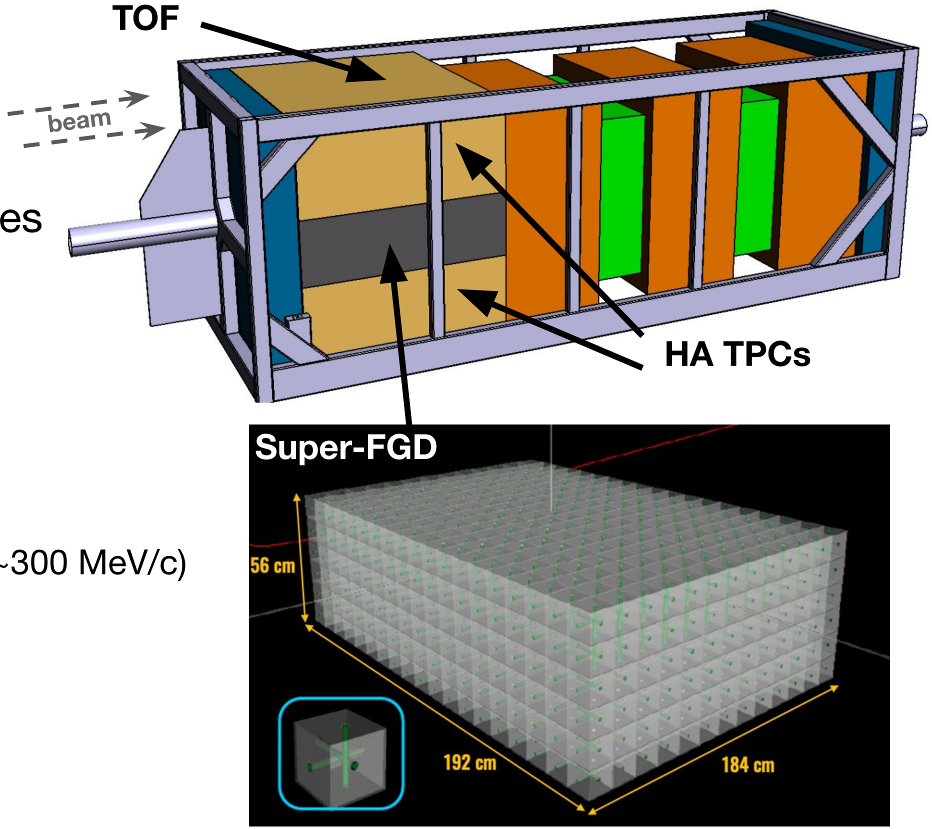
Proton detection efficiency

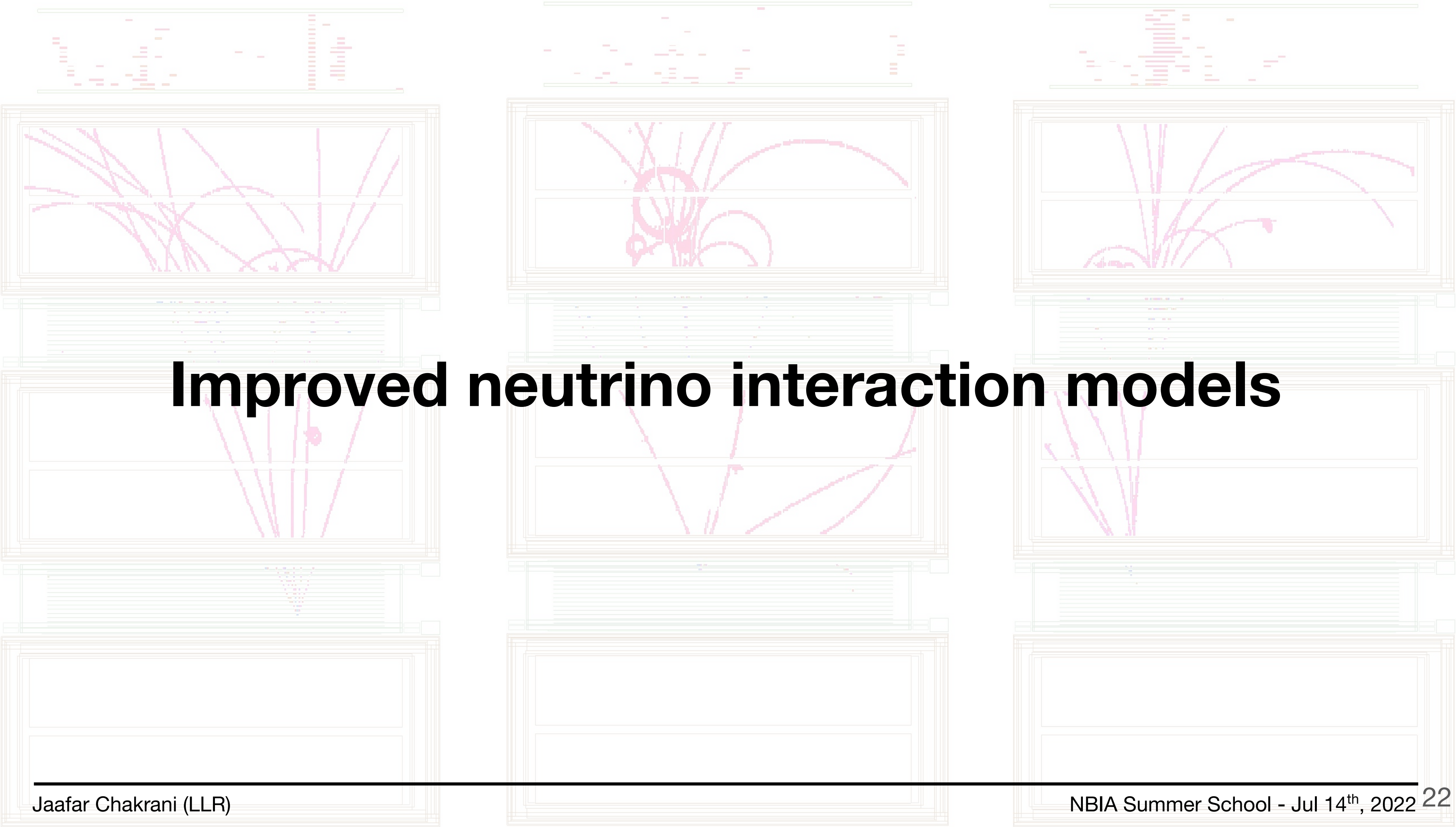
ND280 Upgrade

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

What to expect:

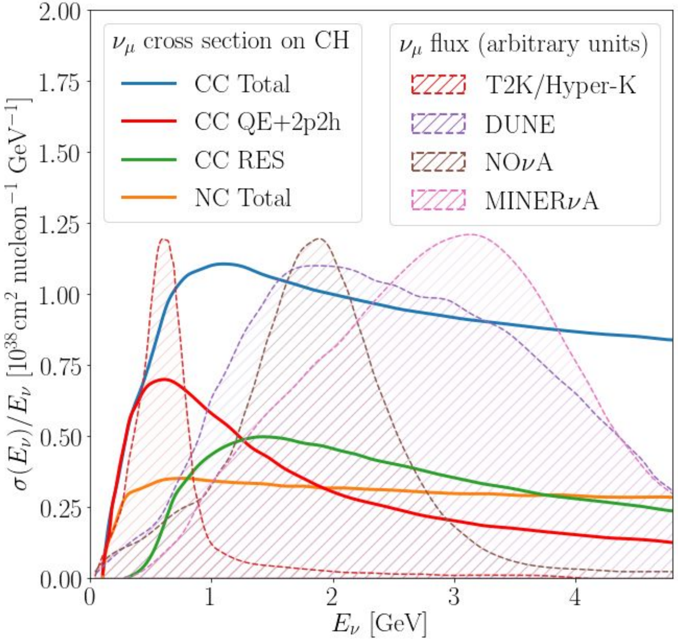
- Fully active target
- **4π acceptance** for charged particles
- **Lower proton momentum threshold** (~300 MeV/c)
- **Neutron detection**



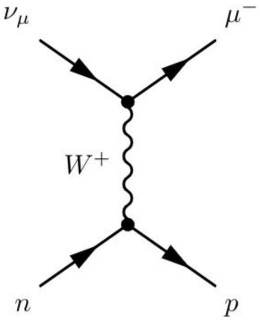


Improved neutrino interaction models

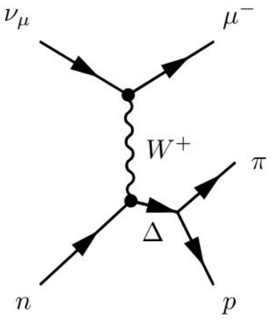
Neutrino interactions



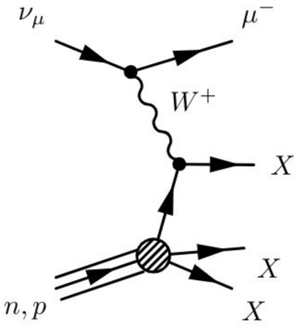
Quasi-elastic
(CCQE)



Resonant
(CCRES)

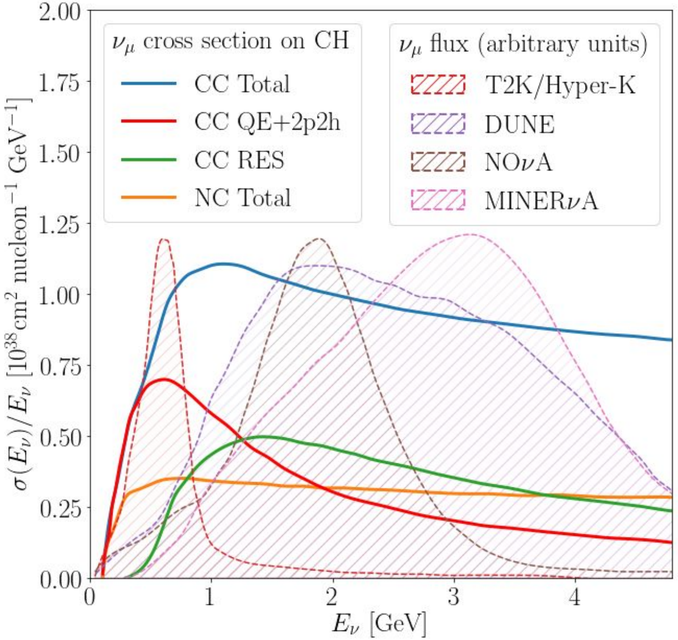


Deep Inelastic Scattering
(CCDIS)

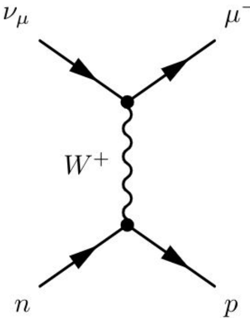


- In order to estimate neutrino energy, a good understanding of neutrino-nucleus interactions is necessary
- CCQE is the dominant interaction in T2K/Hyper-Kamiokande, and is a significant mode in NOνA, MINERνA and DUNE

Neutrino interactions

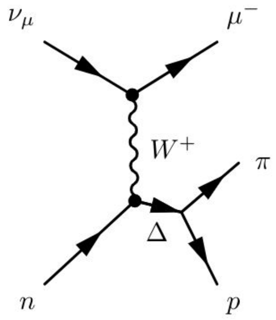


Quasi-elastic
(CCQE)

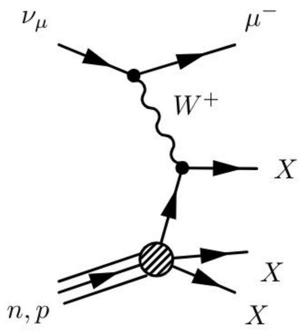


This talk

Resonant
(CCRES)



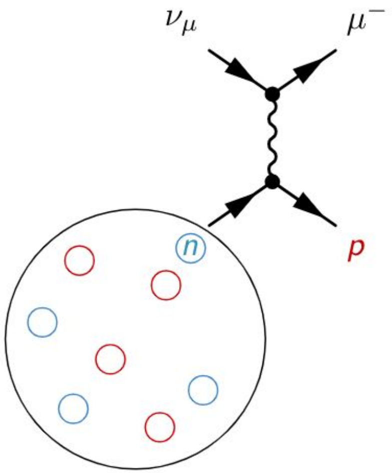
Deep Inelastic Scattering
(CCDIS)



- In order to estimate neutrino energy, a good understanding of neutrino-nucleus interactions is necessary
- CCQE is the dominant interaction in T2K/Hyper-Kamiokande, and is a significant mode in NOνA, MINERνA and DUNE

Initial state nucleons

- Neutrinos can interact with nucleons bound within nuclei (Carbon or Oxygen)
- Initial state nucleons are non-static: Fermi motion
- How to model this?



Initial state nucleons: Spectral Function model

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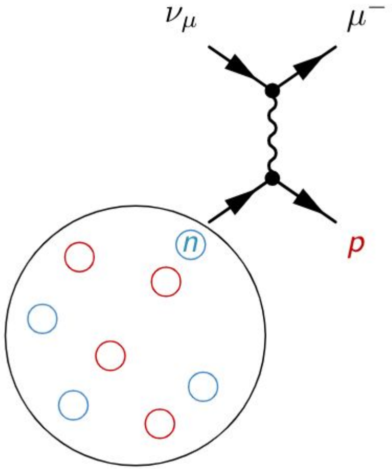


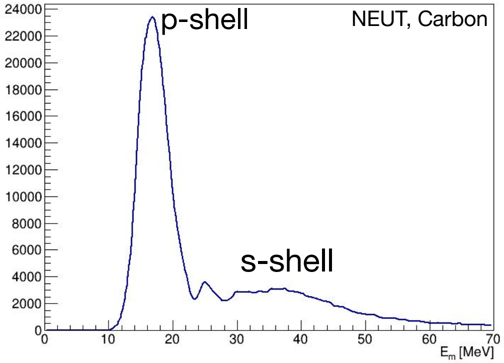
Spectral Function (SF)

The probability of removing of a nucleon with momentum p_m and leaving residual nucleus with excitation energy E_m

$$P(p_m, E_m) = \boxed{P_{MF}(p_m, E_m)} + P_{corr}(p_m, E_m)$$

Independent nucleons, moving in a mean-field potential within the shell-model picture → built from (e,e'p) data (~80%)

→ One outgoing nucleon is produced



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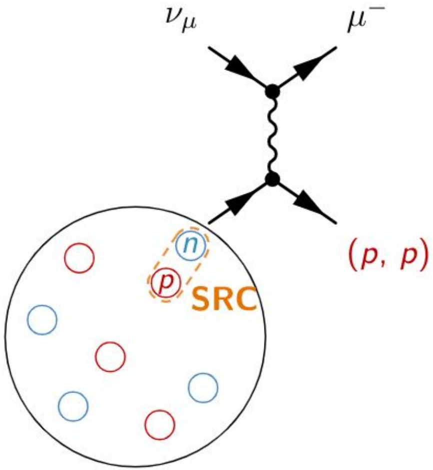

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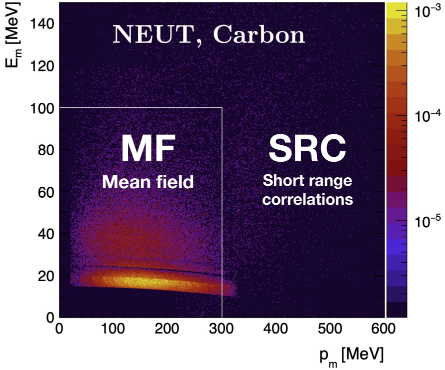

Initial state nucleons: Spectral Function model

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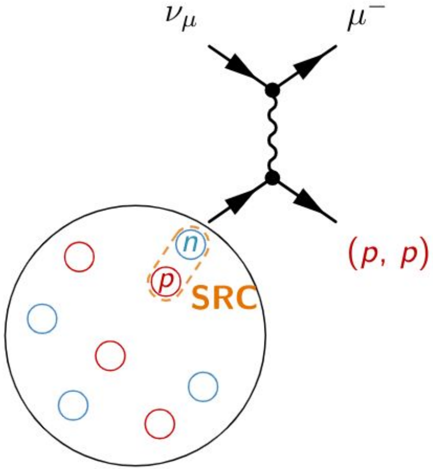
With uncertainties on :

- **Shell occupancies**
- **Shape of initial-state nucleon momentum distribution for each shell**
- **SRC**
- **…**



Used in T2K since 2020

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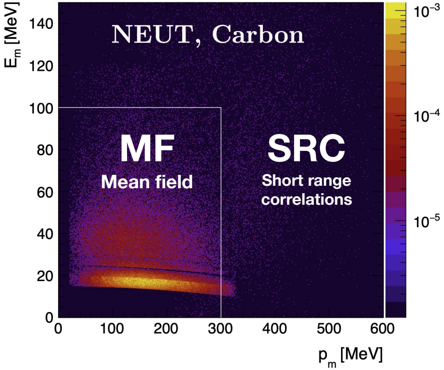

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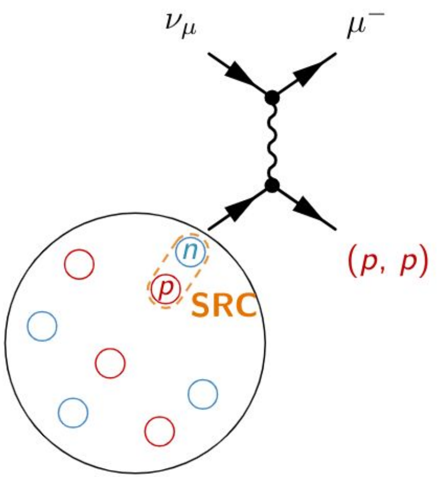

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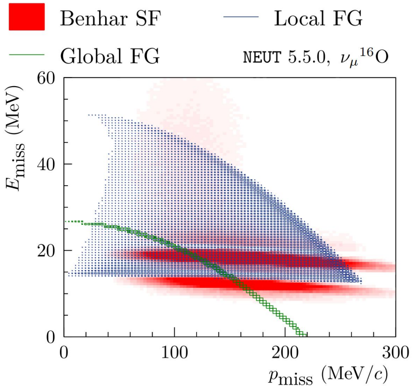
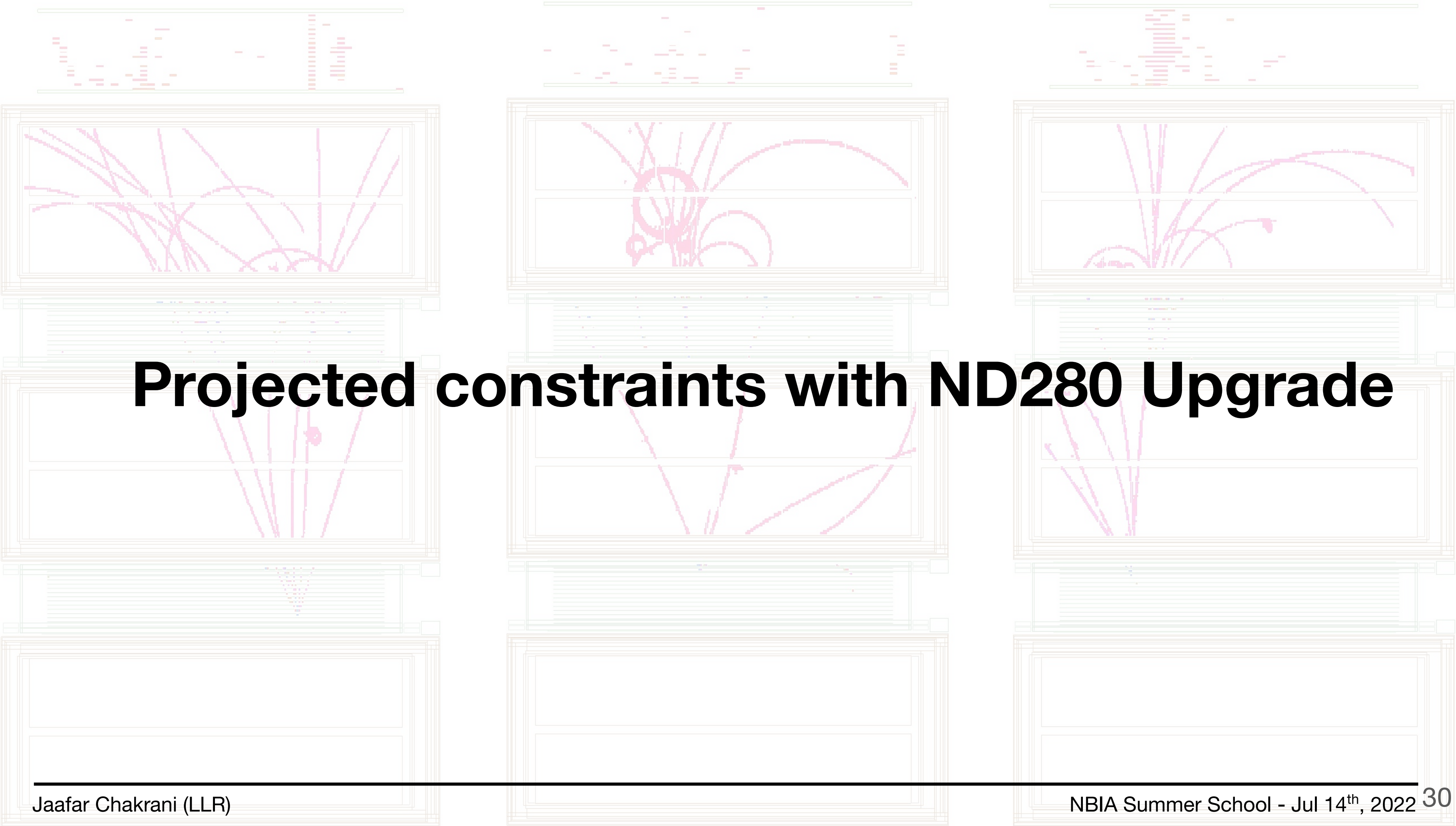
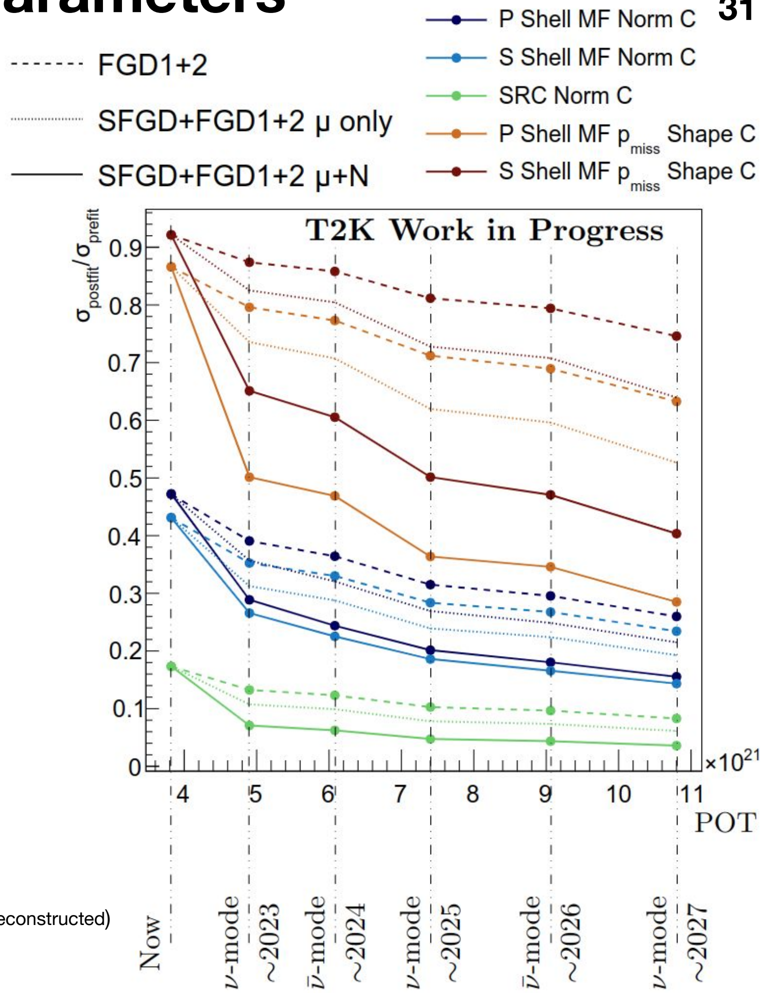




Projected constraints with ND280 Upgrade

Expected improvement: Carbon SF parameters



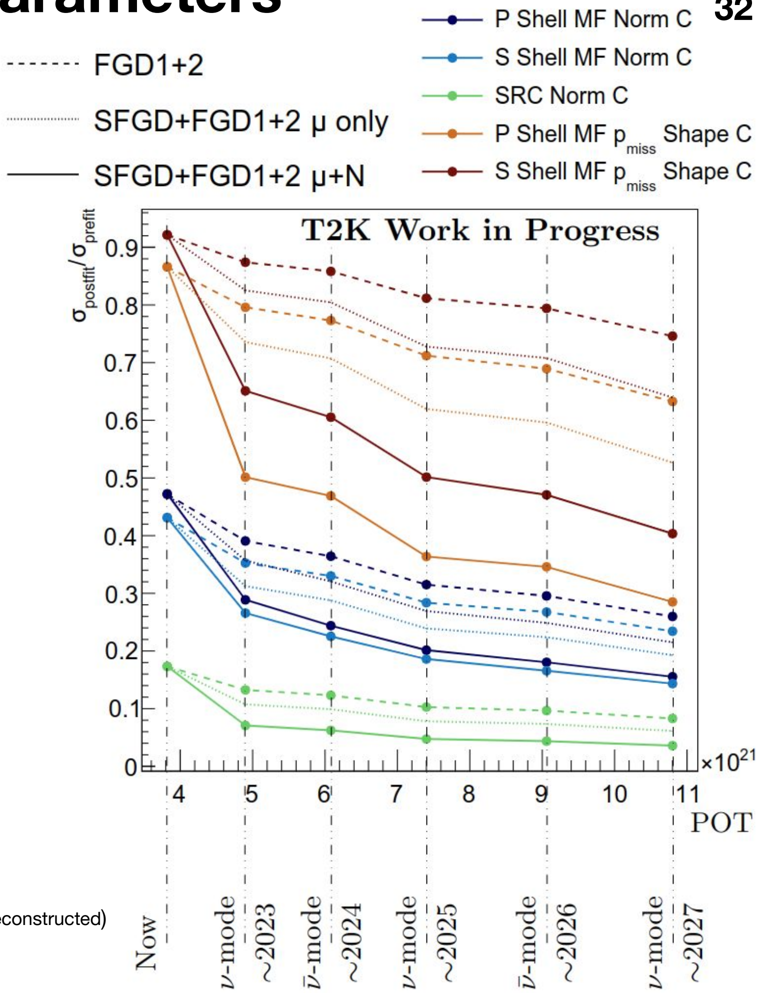
- - - - - - FGD1+2 : Current ND280 (with muon kinematics only)

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

——— SFGD+FGD1+2 μ+N : ND280 Upgrade using also nucleon information (when reconstructed)

Expected improvement: Carbon SF parameters

- Significant improvement with respect to the current ND configuration
- The use of nucleon information allows better constraints



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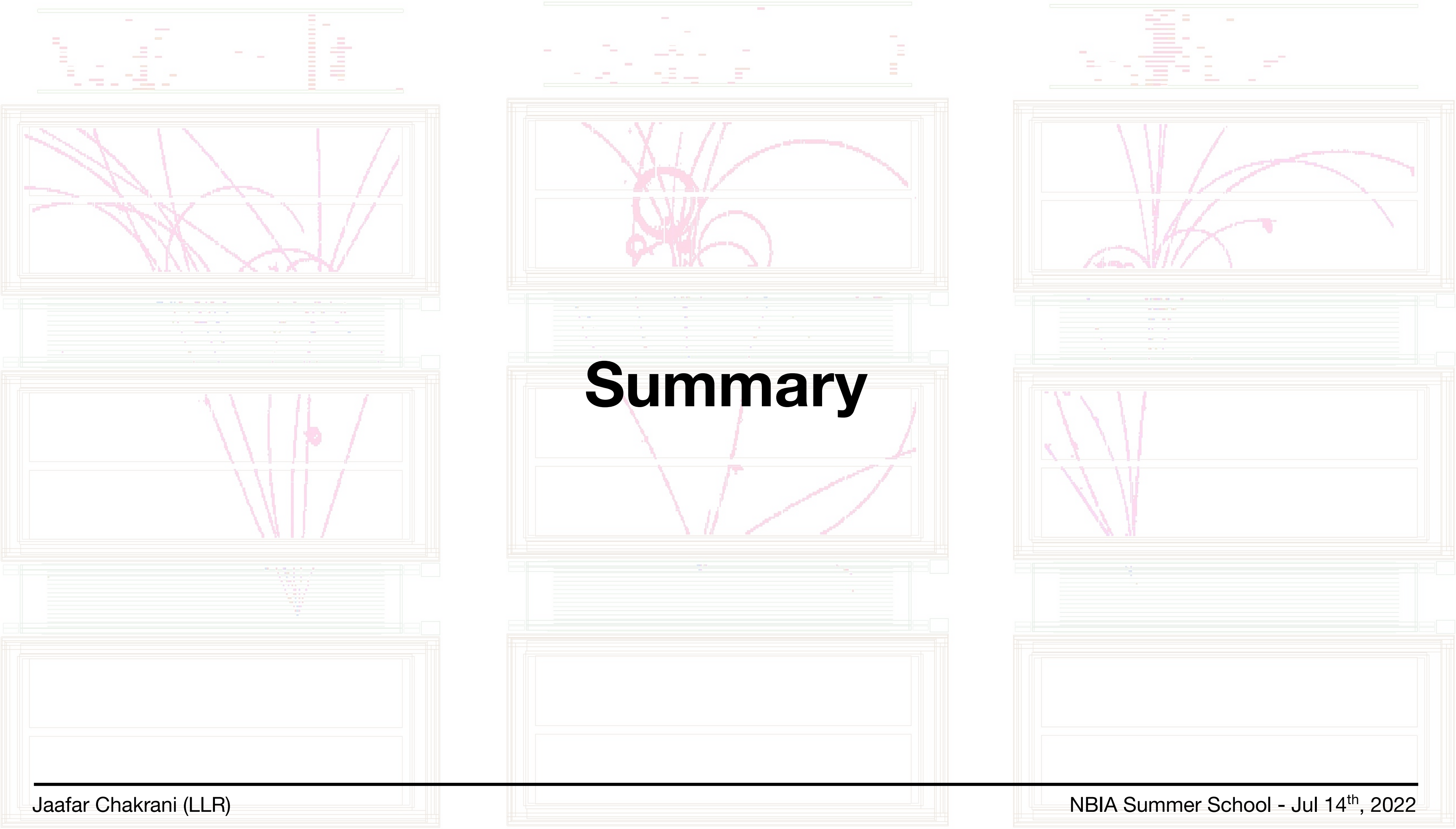
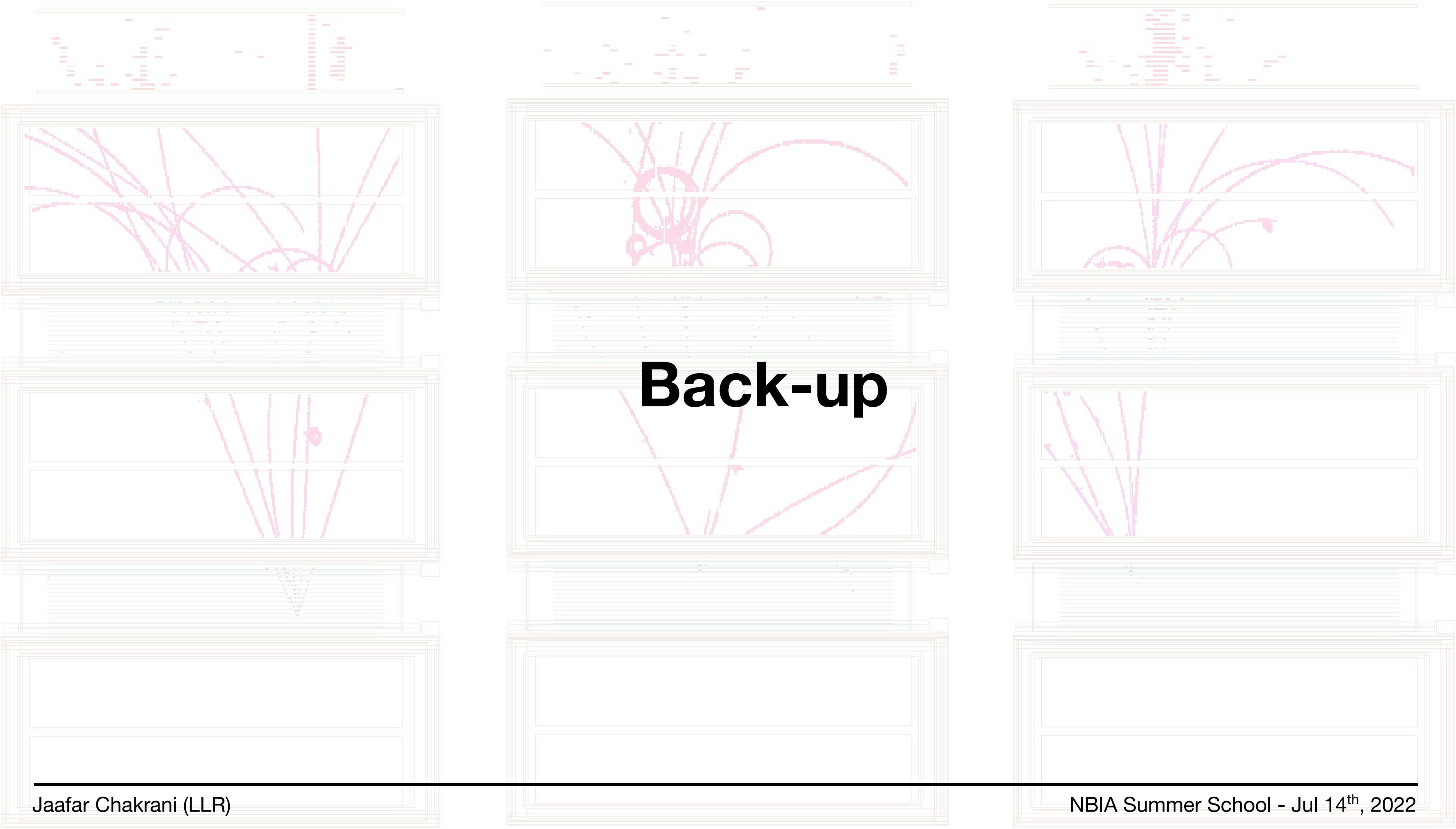


Summary

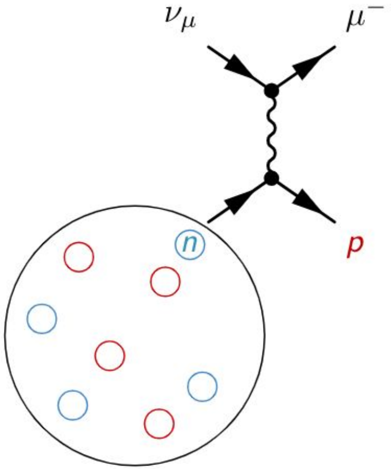
Summary

- T2K is currently upgrading its near detector to reduce systematic uncertainties and increase the sensitivity to the CP-violating phase
- The T2K ND Upgrade will allow for an improved reconstruction of low-momentum protons and even neutron detection
- The impact of the ND Upgrade on constraining the neutrino interaction model is estimated ⟶ Next is to check the impact on the sensitivity to the oscillation parameters



Back-up

Initial state nucleons: Fermi gas models



- Neutrinos can interact with nucleons bound within nuclei (Carbon, Oxygen, Argon...)
- Initial state nucleons are non-static: Fermi motion
- How to model this?

Fermi gas

Relativistic Fermi Gas (RFG)

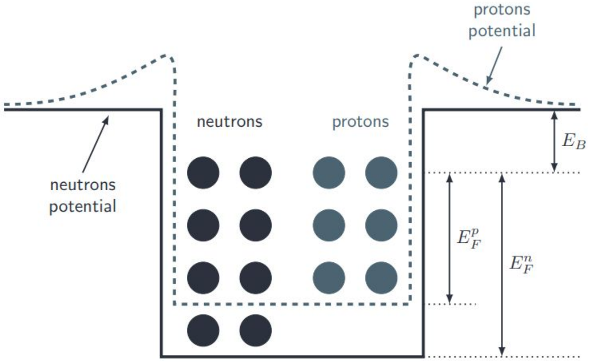
Nucleons move freely in a constant binding energy within the nuclear volume

$$p_F = \left(3\pi^2 \rho \frac{Z}{A}\right)^{1/3}$$

Local Fermi Gas (LFG)

The nucleus is described with the local density approximation

$$p_F(r) = \left(3\pi^2 \rho(r) \frac{Z}{A}\right)^{1/3}$$



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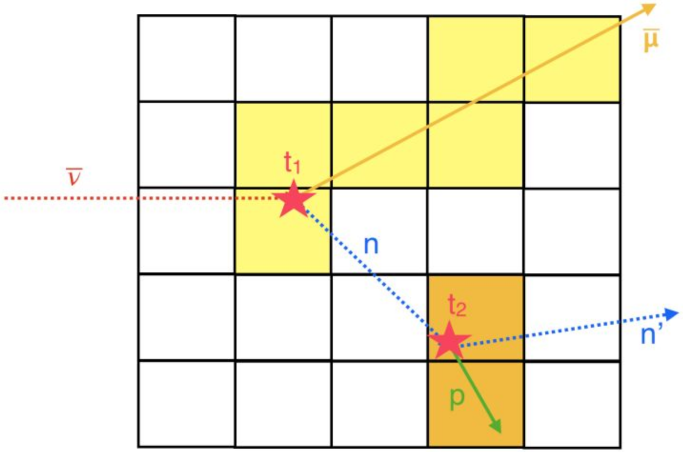
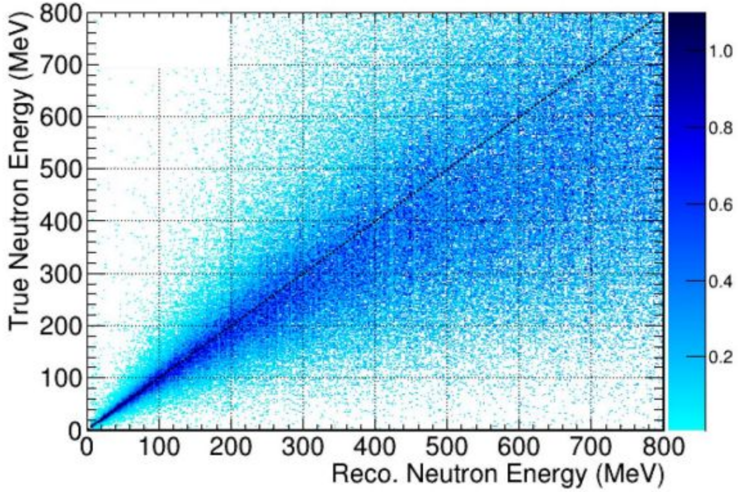
Neutron detection in the Super-FGD



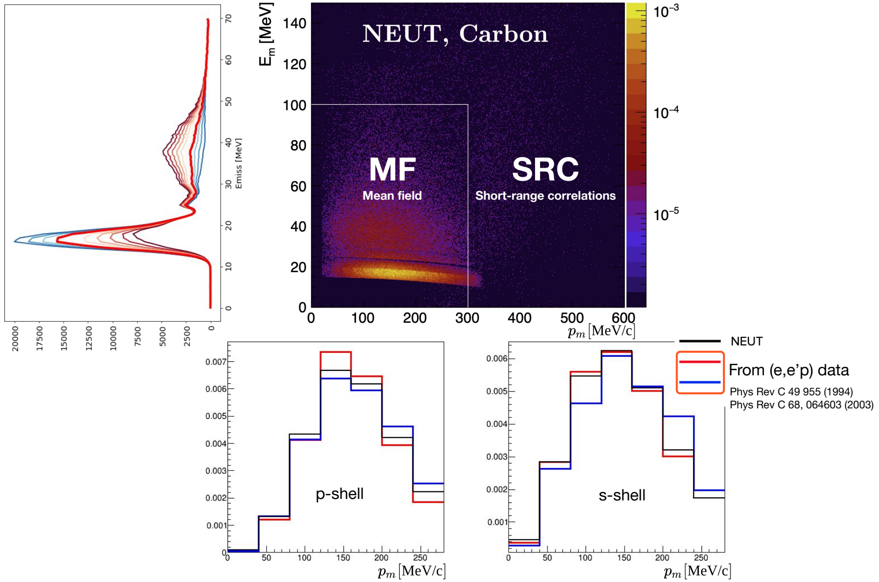


- In the Super-FGD, we can look for neutrons via their re-interaction within the detector
- If the path is long enough (> 20 cm), the neutron energy can be measured using time-of-flight with a resolution between 15% and 30%
- A neutron beam test was performed at LANL, results to be published soon!

Systematic uncertainties in CCQE interactions

PoS(NuFact2021)235

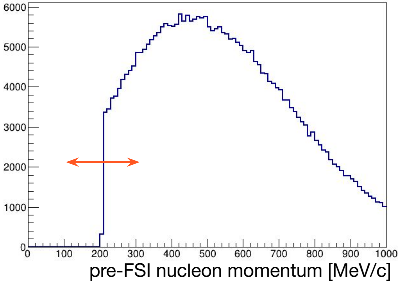
Initial state parameters



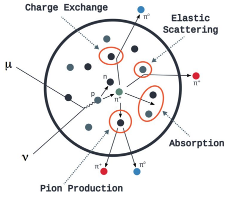
- Change the shape of the missing energy distribution by altering the shell occupancies
- Change the missing momentum distribution shape
- Change the contribution of SRC

Pauli Blocking parameter

- Change Pauli Blocking threshold on the pre-FSI nucleon momentum



FSI parameters

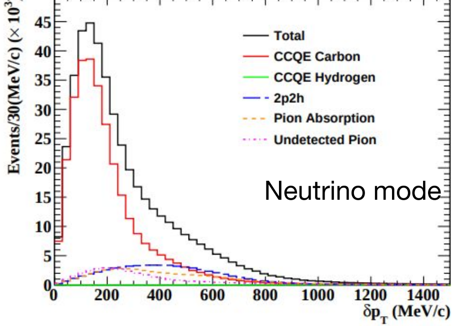


- <u>Outgoing nucleon:</u> Change the amount of events undergoing FSI w.r.t. no FSI *(see Anna's presentation for ways to improve)*
- <u>Outgoing lepton:</u> Change the lepton kinematics with an optical nuclear potential (Phys. Rev. D 91, 033005 (2015))

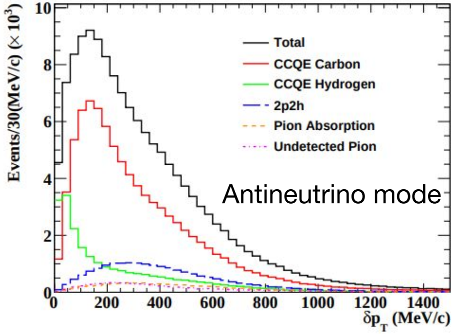
This parameterisation was implemented in NUISANCE and applied on NEUT 5.4.0 neutrino event generator (*arxiv:2106.15809*)

Future Oscillation Analysis?

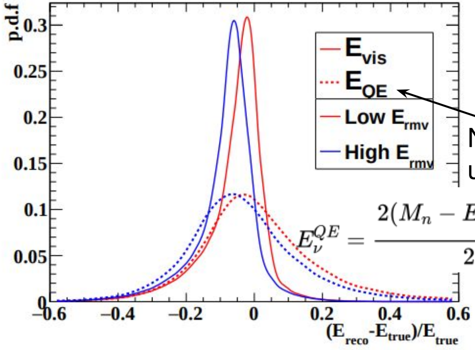
- Currently, T2K uses only lepton kinematics for the Oscillation Analysis (OA)
- With the ND280 Upgrade, we expect to obtain more precise measurements of the nucleons coming out from neutrino interactions
  → what will the impact be on the OA?
- With the nucleon information, we can introduce samples with new observables:
  - Transverse momentum imbalance
  - Visible energy:
    - $E_{\text{vis}} = E_\mu + T_p$ for neutrino interactions
    - $E_{\text{vis}} = E_\mu + T_n$ for antineutrino interactions
- We use T2K projections of POT assuming a scenario where nu and anti-nu beam modes are alternated on a yearly basis



Neutrino mode



Antineutrino mode



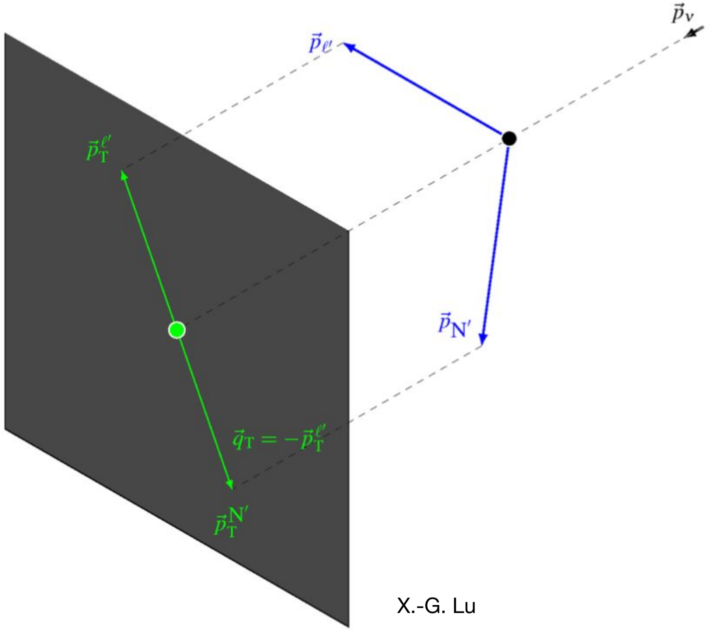
Neutrino energy estimator using lepton kinematics only:

$$E_\nu^{QE} = \frac{2(M_n - E_B)E_l - \left[(M_n - E_B)^2 + m_l^2 - M_p^2\right]}{2[M_n - E_B - E_l + p_l\cos\theta_l]}$$

Single Transverse Variables

Phys. Rev. C 94, 015503 (2016)

Static nucleon target

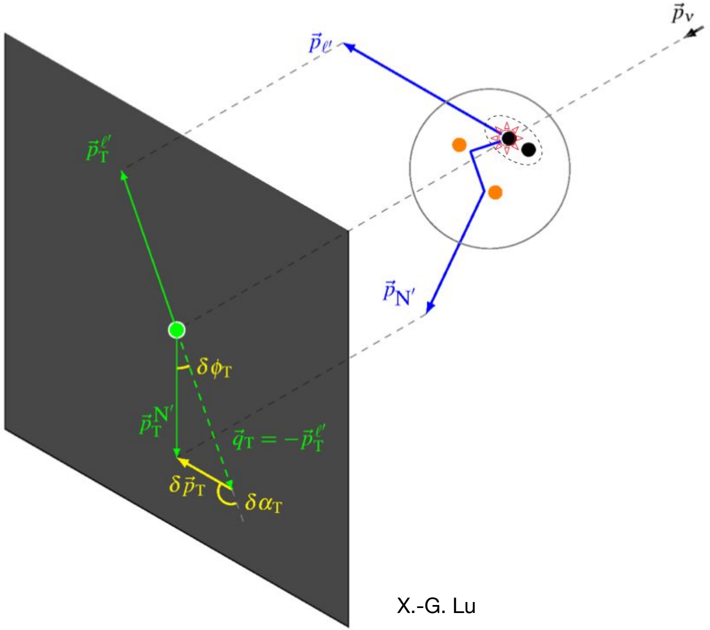


X.-G. Lu

Single Transverse Variables

Phys. Rev. C 94, 015503 (2016)

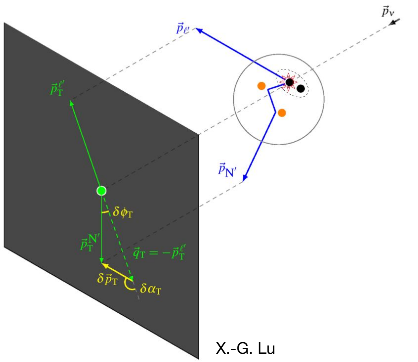
Nucleon bound within nuclear target



X.-G. Lu

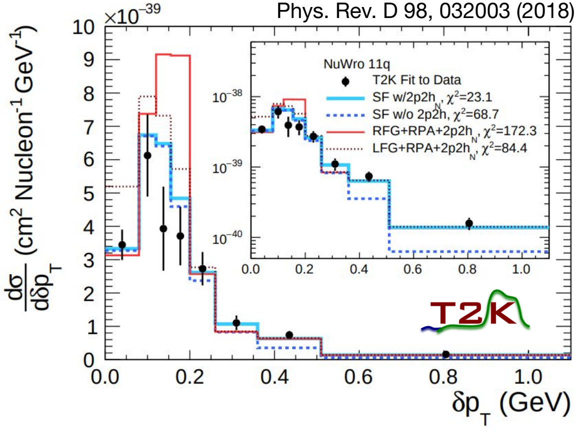
- Need the reconstruction of both muons and nucleons
- Probe nuclear effects (Fermi motion, FSI, ...)

Single Transverse Variables: δp_T Phys. Rev. C 94, 015503 (2016)



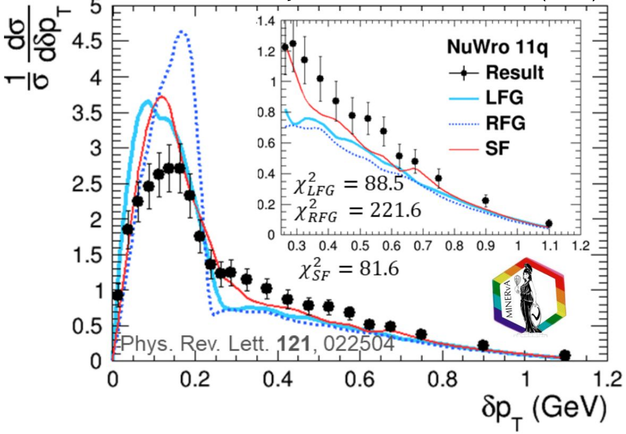
X.-G. Lu

T2K



Phys. Rev. D 98, 032003 (2018)

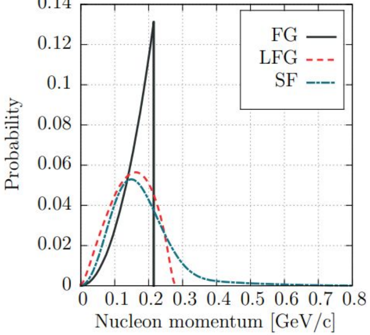
MINERνA



Phys. Rev. Lett. 121, 022504 (2018)

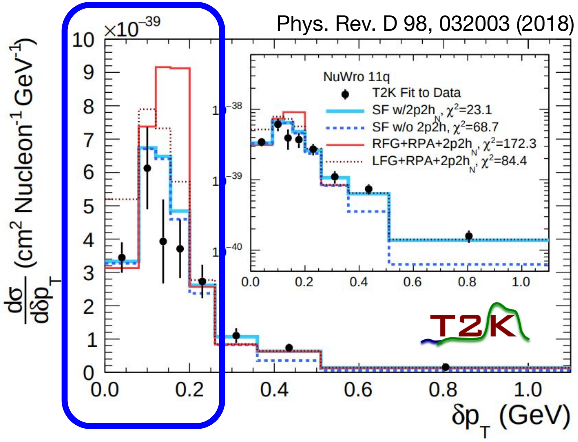
Single Transverse Variables: δp_T Phys. Rev. C 94, 015503 (2016)

- The bulk of the distribution is sensitive to the initial state nucleon momentum



T. Golan

T2K



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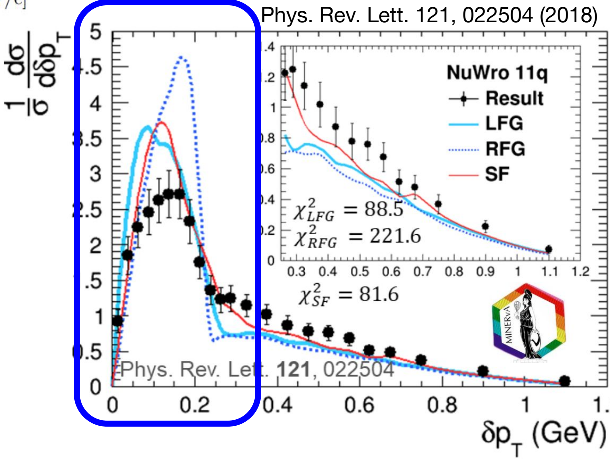

Phys. Rev. Lett. 121, 022504 (2018)

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Phys. Rev. C 94, 015503 (2016)

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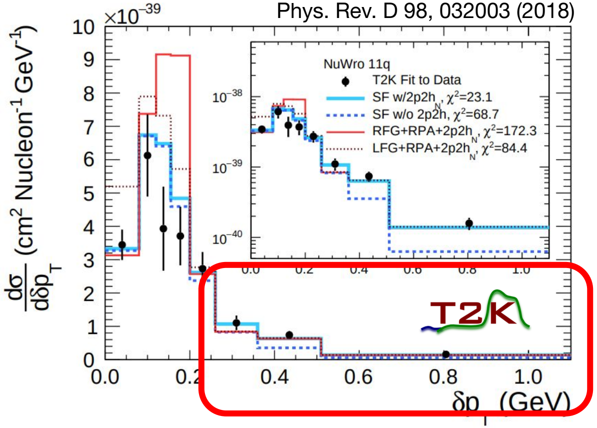
- The tail of the distribution is sensitive to FSI, SRC, 2p2h

T2K



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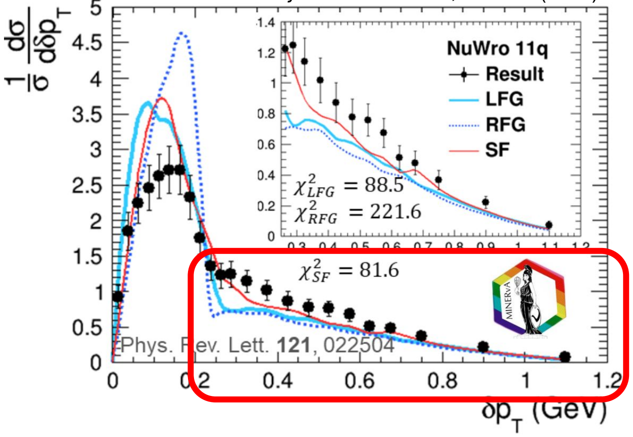
MINERνA



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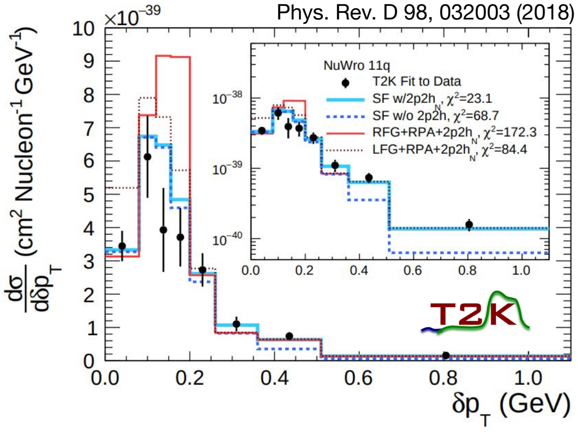
- The bulk of the distribution is sensitive to the initial state nucleon momentum
- The tail of the distribution is sensitive to FSI, SRC, 2p2h
- None of the models describe well the data...

T2K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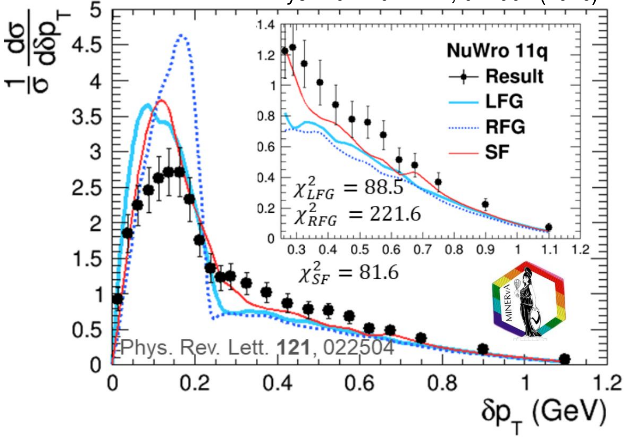
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