Neutrino interactions and neutrino oscillations in the T2K experiment

Tomasz Wąchała
Department of Cosmic Rays and Neutrinos

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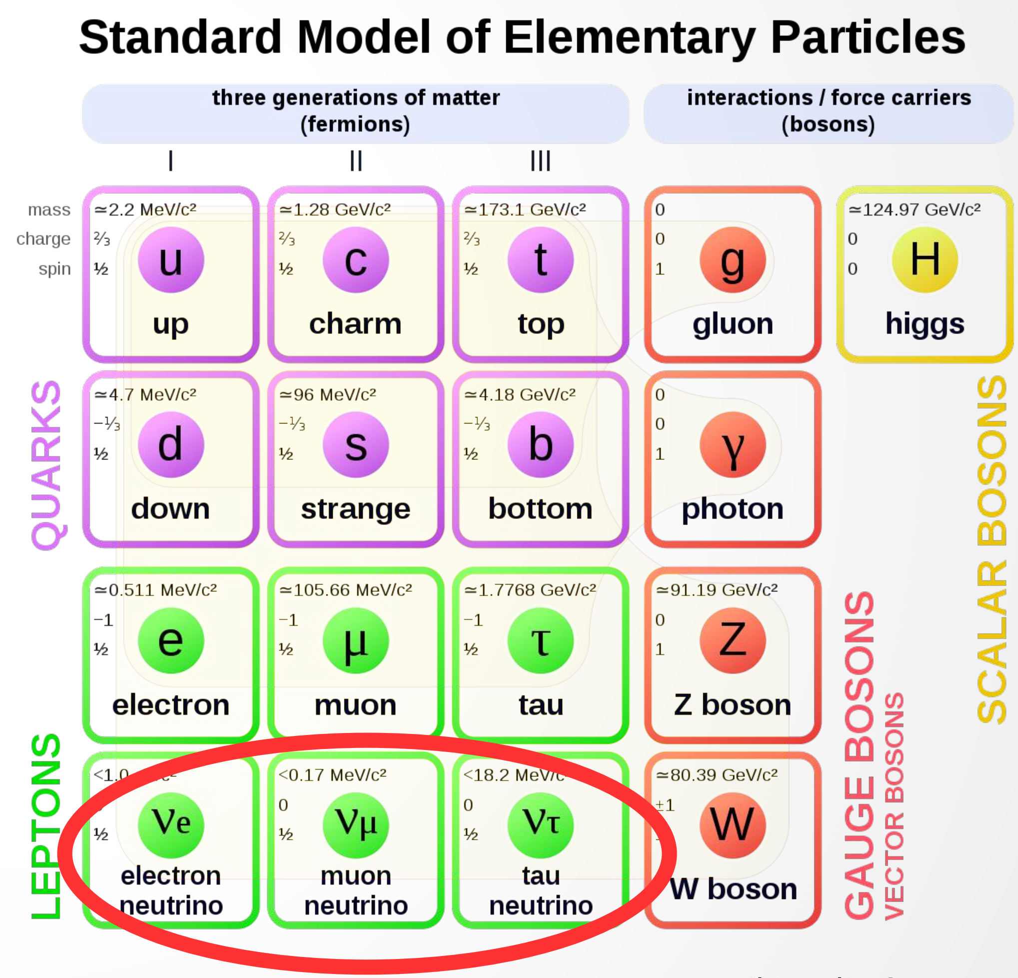
Outline

1. Neutrinos and their oscillations
2. T2K experiment
3. Why neutrino oscillations need neutrino cross sections?
4. Selected measurements of neutrino cross sections
5. Summary

Neutrinos in Standard Model

- Neutrinos in the Standard Model are elementary particles with the following properties:
  - Fermions, interacting only via weak interactions
  - Neutral (no electric charge)
  - Massless
  - Come in three flavor states: electron neutrino: ν_e, muon neutrino: ν_μ, taon neutrino: ν_τ). LEP experiment results are consistent with the three neutrino flavors (Z^0 boson width measurement).



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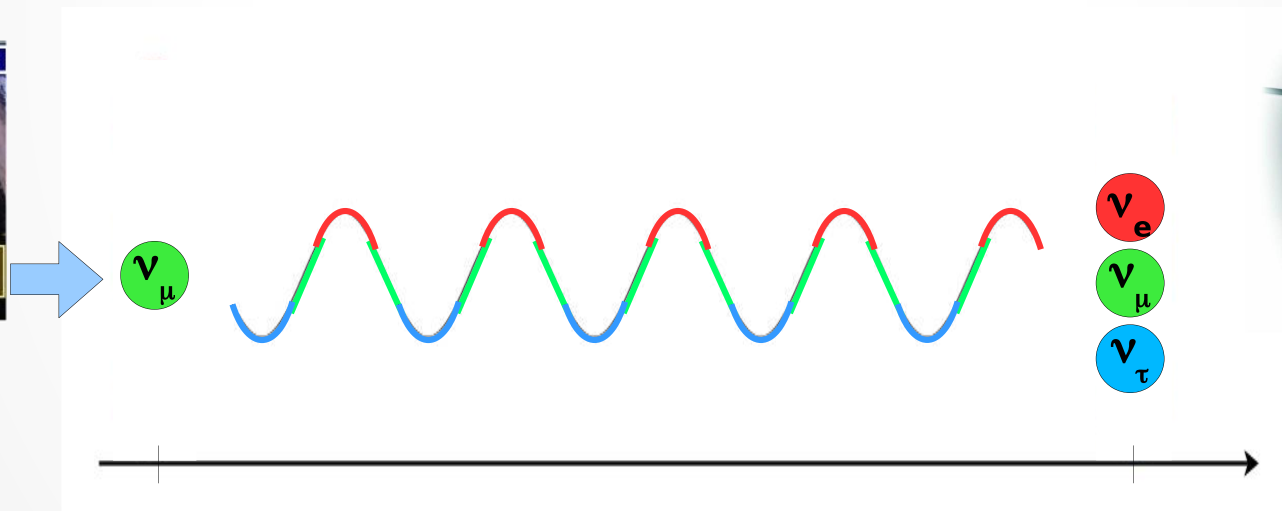
Neutrino oscillations

- Neutrino oscillations phenomenon→ experimentally confirmed for neutrinos by a number of experiments: Super Kamiokande (1998), K2K, SNO, KamLAND, MINOS, Daya Bay, T2K,...
- Neutrinos are produced and detected via weak interactions but propagate as the linear superpositions of the mass eigenstates.
- Discovery of neutrino oscillations → neutrinos have mass!

Source of muon neutrinos with energy E (produces neurinos of one flavor) eg. accelerator



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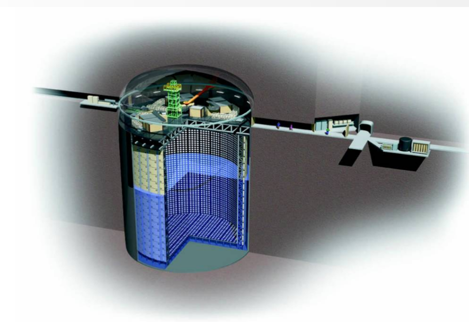


Detector (detects neutrinos of all three flavors)

Neutrino oscillations (PMNS model)

- 1958 B. Pontecorvo proposes the idea of neutrino oscillations
- 1962 Z. Maki, M. Nakagawa, S. Sakata introduce mixing matrix (PMNS matrix) to explain neutrino oscillations predicted by Pontecorvo
- Common PMNS matrix parametrization (3-neutrino paradigm) uses 4 parameters → PMNS model

Flavor eigenstates Mass eigenstates

$$\begin{bmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{bmatrix} = U_{PMNS}\begin{bmatrix}\nu_1\\ \nu_2\\ \nu_3\end{bmatrix}$$

1 complex phase (CP phase)

3 mixing angles (i=1,2,3 j=1,2,3)

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

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

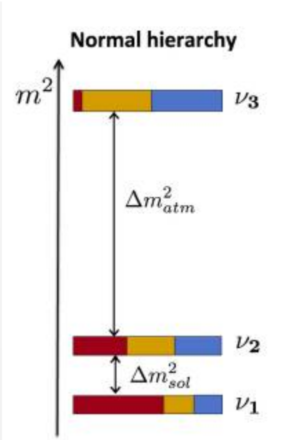
- Transition (probability) between two neutrino flavors depends not only on U_{PMNS}, but also on Δm^2_{ij},$=m_i^2-m_j^2$, energy and distance via $\sin^2\left(\frac{\Delta m^2_{ij} L}{4E}\right)$ term → oscillations

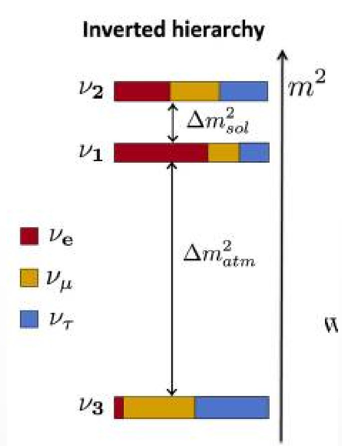
Knowns and unknowns in neutrino oscillations

P.A. Zyla et al. (Particle Data Group), Prog. Theor. Exp. Phys. 2020, 083C01 (2020) and 2021 update

NO	Best Fit Ordering	
Param	bfp $\pm 1\sigma$	3σ range
$\frac{\sin^2\theta_{12}}{10^{-1}}$	$3.20^{+0.20}_{-0.16}$	$2.73 \to 3.79$
$\theta_{12}/^\circ$	$34.5^{+1.2}_{-1.0}$	$31.5 \to 38.0$
$\frac{\sin^2\theta_{23}}{10^{-1}}$	$5.47^{+0.20}_{-0.30}$	$4.45 \to 5.99$
$\theta_{23}/^\circ$	$47.7^{+1.2}_{-1.7}$	$41.8 \to 50.7$
$\frac{\sin^2\theta_{13}}{10^{-2}}$	$2.160^{+0.083}_{-0.069}$	$1.96 \to 2.41$
$\theta_{13}/^\circ$	$8.45^{+0.16}_{-0.14}$	$8.0 \to 8.9$
$\delta_{CP}/^\circ$	218^{+38}_{-27}	$157 \to 349$
$\frac{\Delta m^2_{21}}{10^{-5}\ \mathrm{eV}^2}$	$7.55^{+0.20}_{-0.16}$	$7.05 \to 8.24$
$\frac{\Delta m^2_{32}}{10^{-3}\ \mathrm{eV}^2}$	2.424 ± 0.03	$2.334 \to 2.524$

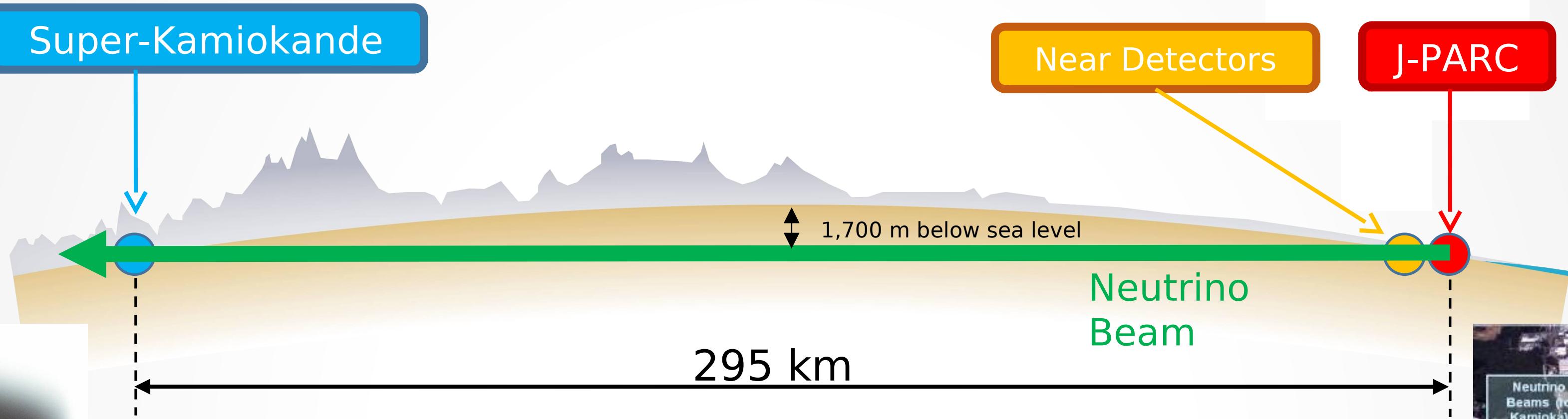
IO	$\Delta\chi^2 = 11.7$	
$\frac{\sin^2\theta_{12}}{10^{-1}}$	$3.20^{+0.20}_{-0.16}$	$2.73 \to 3.79$
$\theta_{12}/^\circ$	$34.5^{+1.2}_{-1.0}$	$31.5 \to 38.0$
$\frac{\sin^2\theta_{23}}{10^{-1}}$	$5.51^{+0.18}_{-0.30}$	$4.53 \to 5.98$
$\theta_{23}/^\circ$	$47.9^{+1.0}_{-1.7}$	$42.3 \to 50.7$
$\frac{\sin^2\theta_{13}}{10^{-2}}$	$2.220^{+0.074}_{-0.076}$	$1.99 \to 2.44$
$\theta_{13}/^\circ$	$8.53^{+0.14}_{-0.15}$	$8.1 \to 9.0$
$\delta_{CP}/^\circ$	281^{+23}_{-27}	$202 \to 349$
$\frac{\Delta m^2_{21}}{10^{-5}\ \mathrm{eV}^2}$	$7.55^{+0.20}_{-0.16}$	$7.05 \to 8.24$
$\frac{\Delta m^2_{32}}{10^{-3}\ \mathrm{eV}^2}$	$-2.50\pm^{+0.04}_{-0.03}$	$-2.59 \to -2.39$

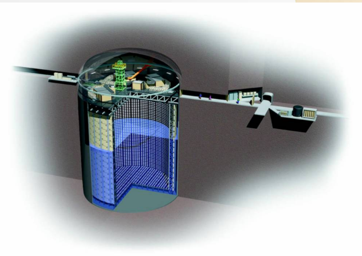




- Open questions:
  - Is $\delta_{CP} \neq$ 0,+-π (CP symmetry violation in neutrino sector) ?
  - Is there a normal: **m_3>m_2**>m_1 (N.O. or N.H.) or inverted: m_2>**m_1>m_3** (I.O. or I.H.) mass ordering?
  - Is θ_{23} = 45° (called 'maximal mixing'), if not then what is θ_{23} octant?

T2K experiment overview

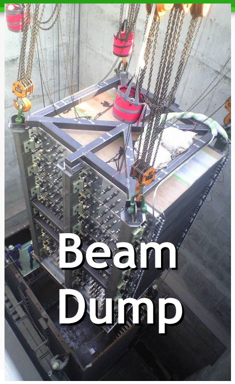


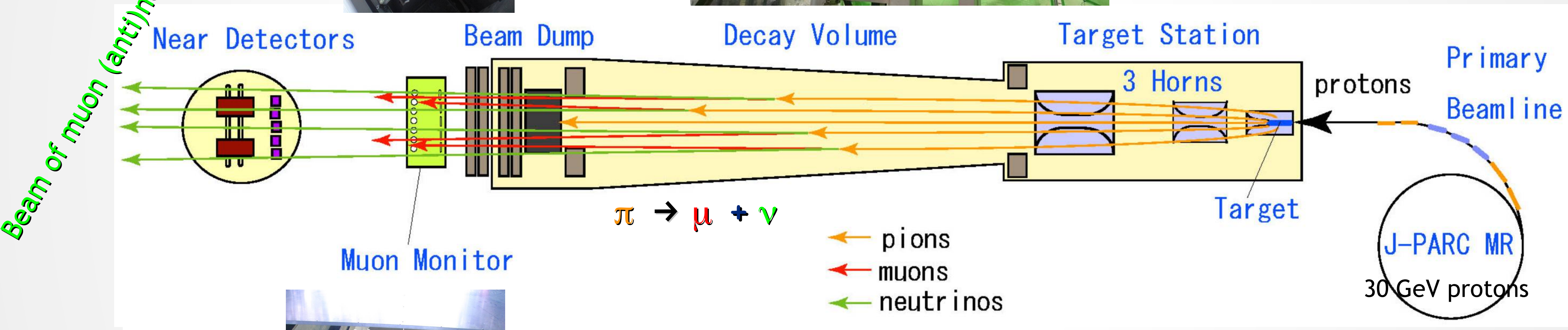


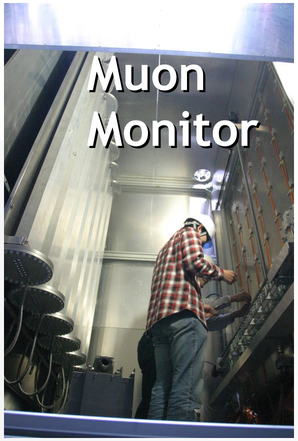
~500 people from 12 countries, 66 institutions

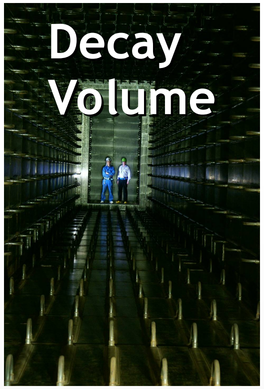
- High intensity beam produced at Japan Proton Accelerator Research Complex (J-PARC) working in two modes: producing neutrinos (ν_μ) and antineutrinos (anti-ν_μ)
- Super-Kamiokande as a far detector to measure neutrino oscillations at 295 km
- Beam with narrow energy spectrum peaked at 0.6 GeV but extending to several GeV (so called sub-GeV region)
- Main goals:
  - Measure neutrino oscillations: originally designed to discover ν_e appearance, currently: exclude CP conservation at 3σ if δ_{CP} is maximal

Producing neutrinos in T2K

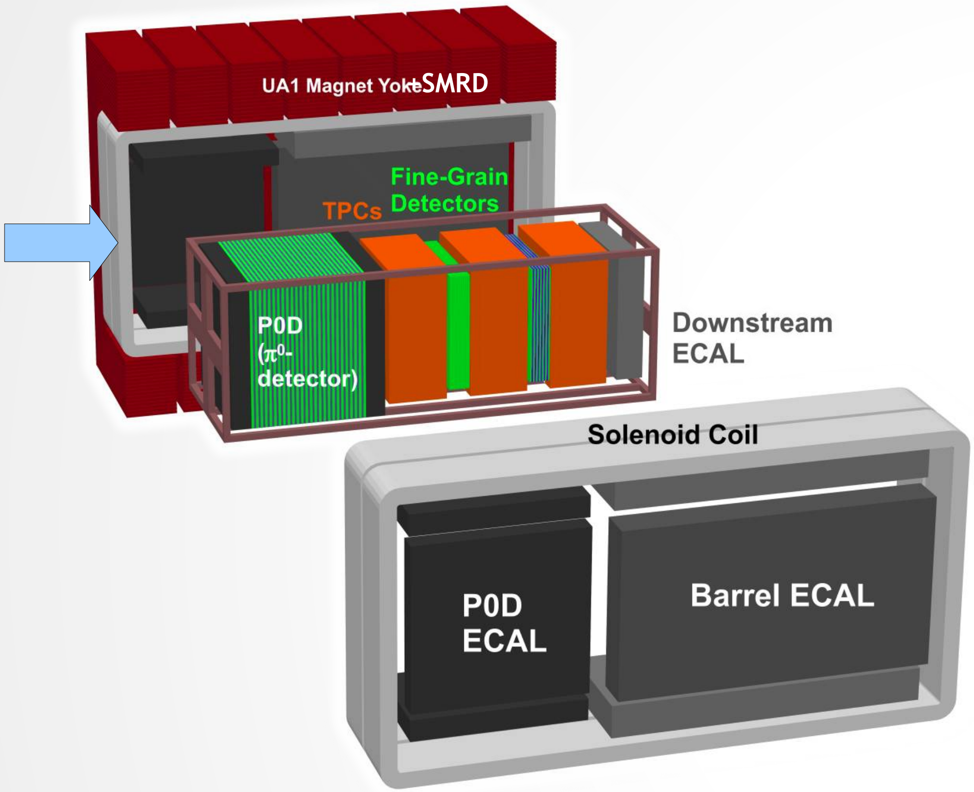




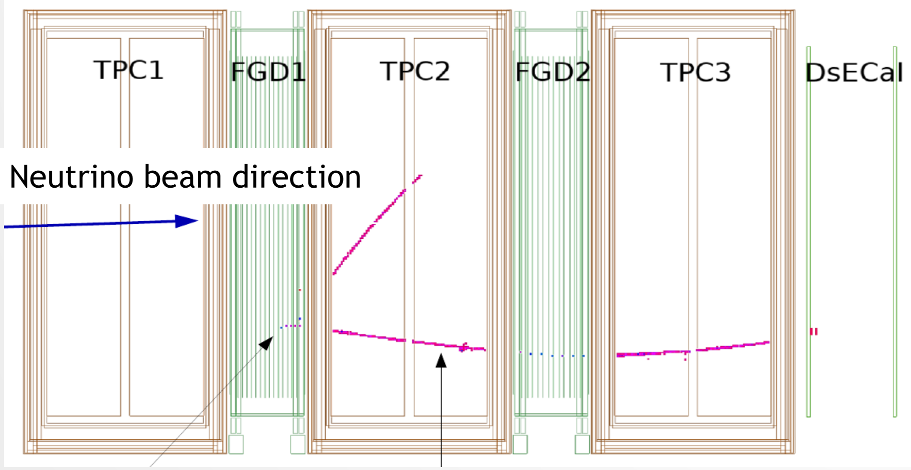




T2K off-axis near detector



- ND280 off-axis near detector:
  - Consists of several sub-detectors in 0.2T magnetic field:
    - Tracker (TPCs & Fine-Grain Detectors), Pizero Detector (P0D), Electromagnetic Calorimeter (ECAL), Side Muon Range Detector (SMRD)
  - **Goals: Measure neutrino spectrum before the oscillation occurs**
  - Measure neutrino-nucleus cross sections



Muon anti-neutrino interaction in the FGD1 part of ND280 with positive muon and negative pion detected

CP symmetry violation in neutrino oscillations?

- We know that there is a Charge-Parity (CP) symmetry violation in the quark sector
- CP symmetry violation in neutrino oscillations would occur if:

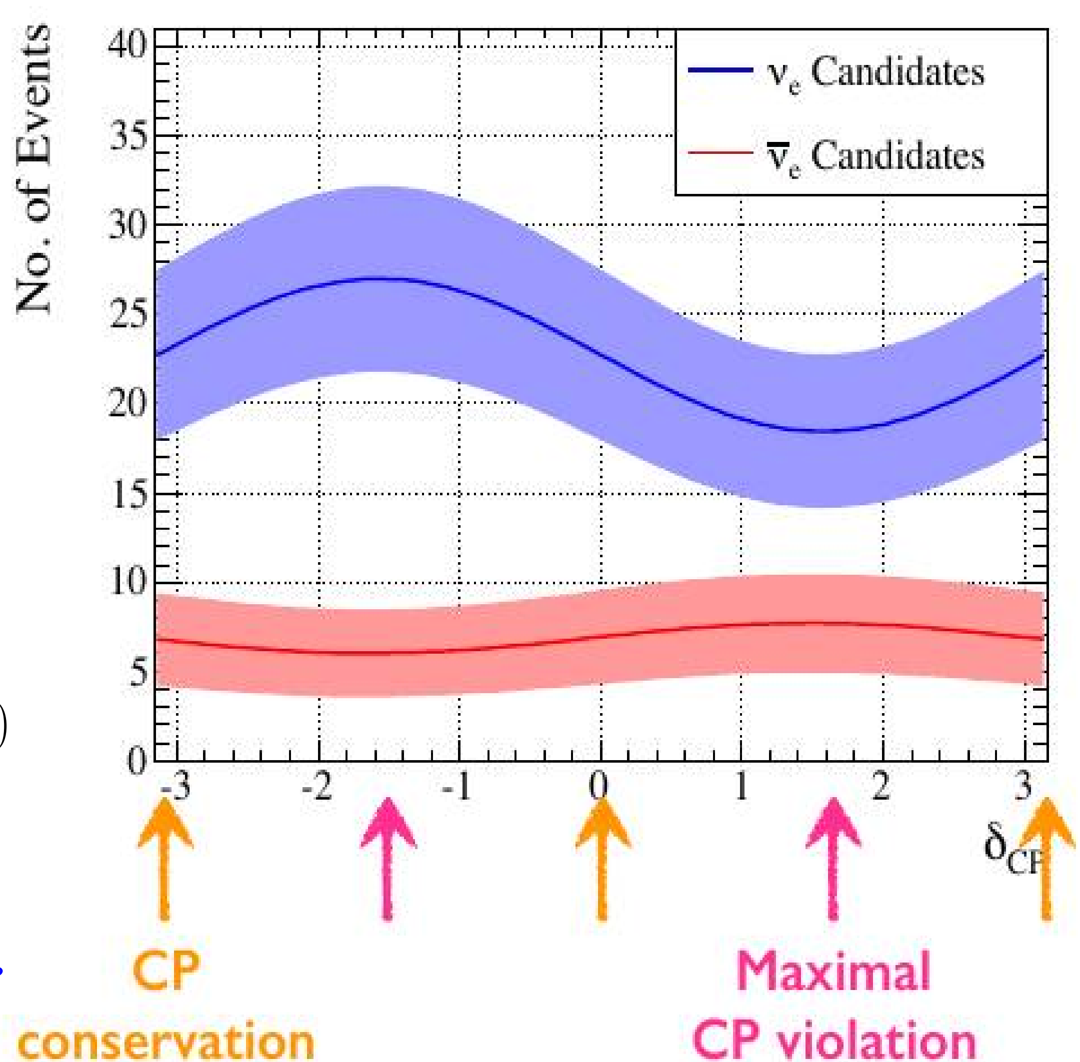
$$P(\nu_\mu \rightarrow \nu_e) \neq P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$$

- In T2K we measure:

$$P(\overset{(-)}{\nu}_\mu \rightarrow \overset{(-)}{\nu}_e) \approx \sin^2(2\theta_{13})\sin^2(\theta_{23})\sin^2(\frac{1.27\Delta m^2_{32}L}{E})$$

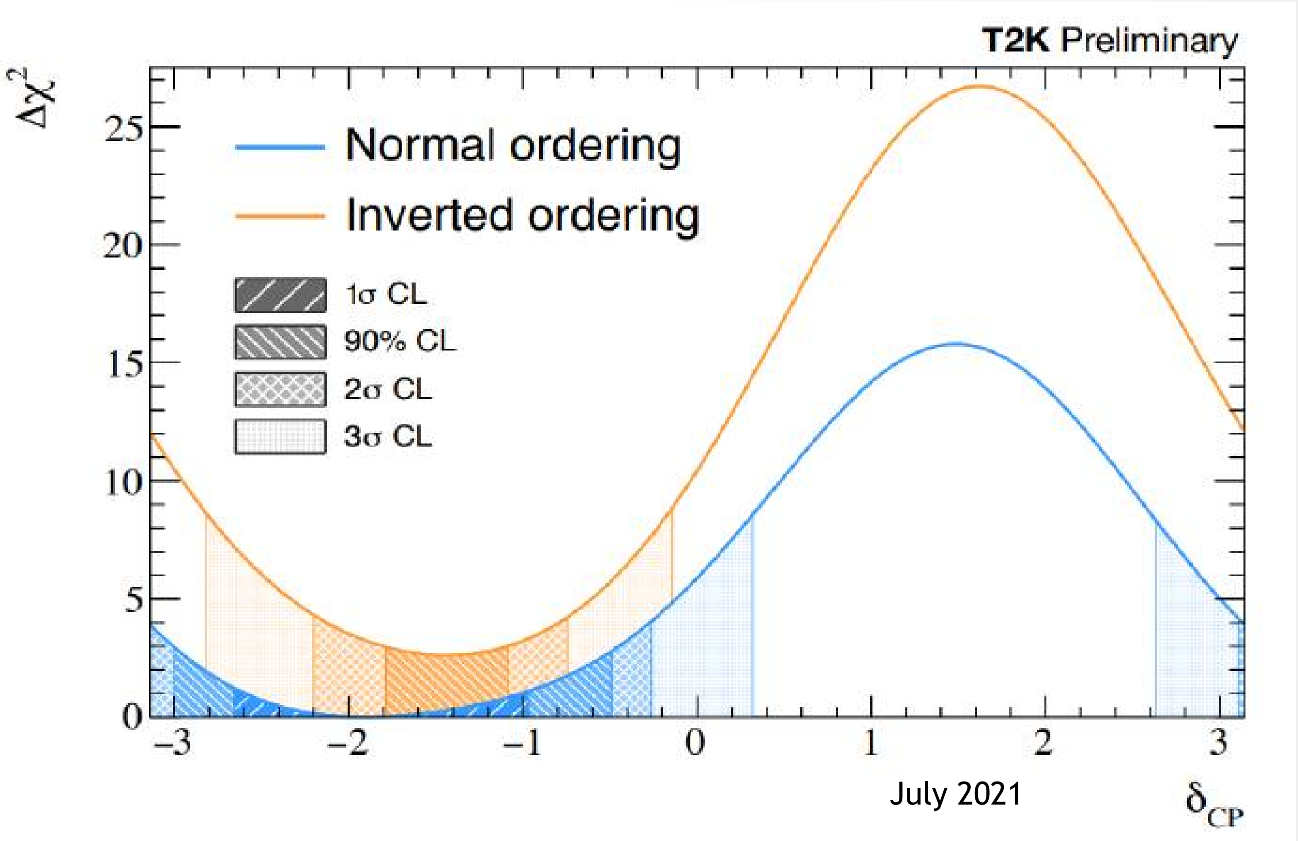
$$\mp \frac{1.27\Delta m^2_{21}L}{E} 8 J_{CP} \sin^2(\frac{1.27\Delta m^2_{32}L}{E})$$

$$J_{CP} = \frac{1}{8}\cos\theta_{13}\sin(2\theta_{12})\sin(2\theta_{23})\sin(2\theta_{13})\sin\delta_{CP}$$



CP phase measurement in T2K

- First measurement of the CP phase was done in T2K
- T2K also provided the best estimate of δ_{CP} so far.
- Large region of CP phase values excluded by T2K at 3σ C.L.
- CP conservation ($\delta_{CP}=0,\pm\pi$) excluded at 90% C.L. → preference for maximal CP violation



Why neutrino oscillations need neutrino cross sections?

- Total number of detected neutrino interactions of channel *a* in T2K:

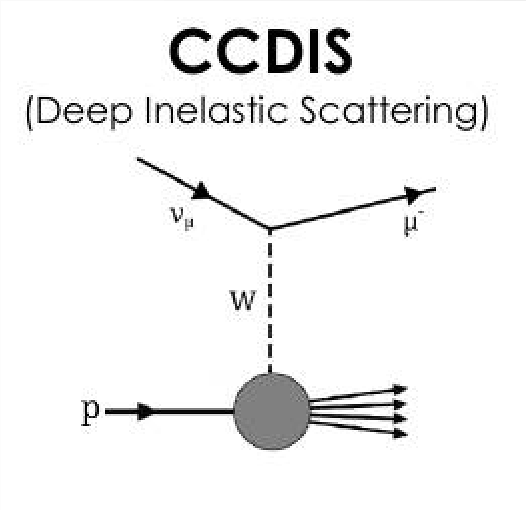
$$N_{a\ \ detected} = \sigma_a \cdot \Phi \cdot T \cdot \epsilon \cdot P_{oscillation}$$

where: σ_A - neutrino interaction cross section, Φ - neutrino flux, T – number of targets, ε – detection efficiency, $P_{oscillation}$ – oscillation probability

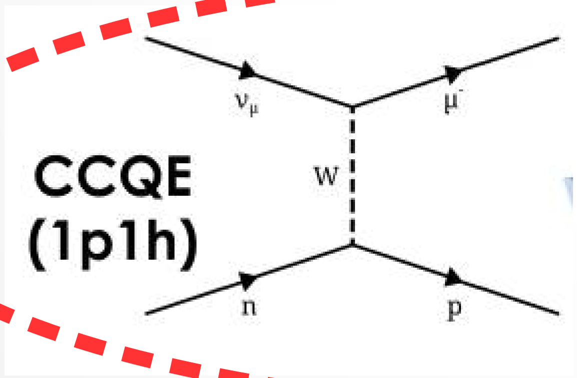
- The measurements of neutrino cross sections σ_a are crucial to reduce systematic uncertainties in neutrino oscillations
- Cross-section has currently assigned the largest systematic uncertainty (up to 3.82% for T2K) in neutrino oscillation analysis
  - Precise δ_{CP} measurement requires further reduction of this uncertainty
- Neutrino cross section measurements are also important to verify the existing neutrino interaction models

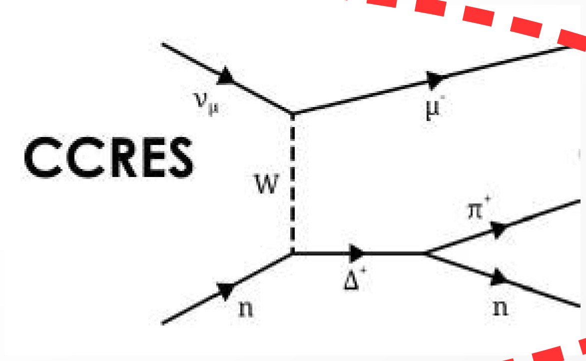
Neutrino interactions – reaction?

- Two main types of neutrino interactions:
  - Charge Current (CC) → mediated by W^{+-} boson
  - Neutral Current (NC) → mediated by Z^0 boson
- Further classification: historically based on neutrino-nucleon reactions (also called primary interactions):
  - QE - quasi-elastic: lepton + nucleon in the final state
  - RES - resonance production: lepton + resonance. Resonance decays into meson(s), mainly pion(s) and nucleon
  - DIS - deep inelastic scattering: lepton + more than one pion in the final state

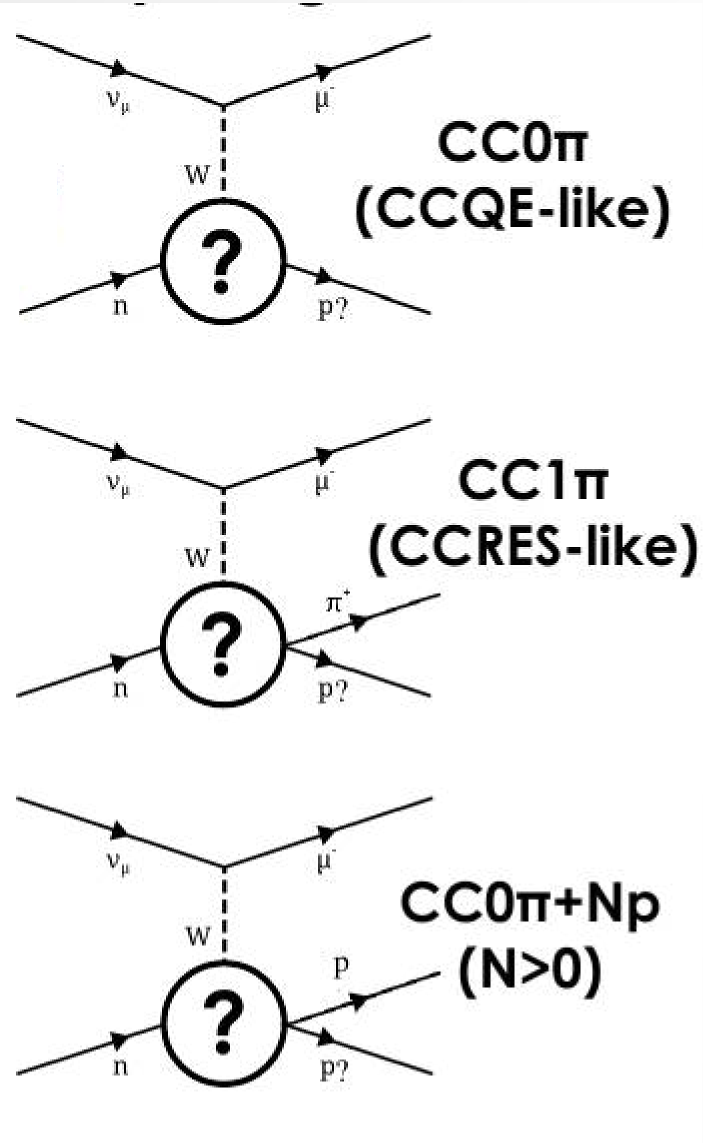


Dominant for T2K energy regime

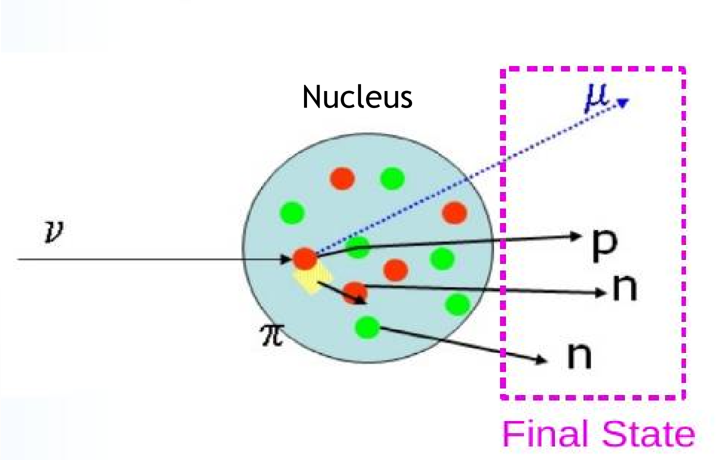




Topology, not reaction!

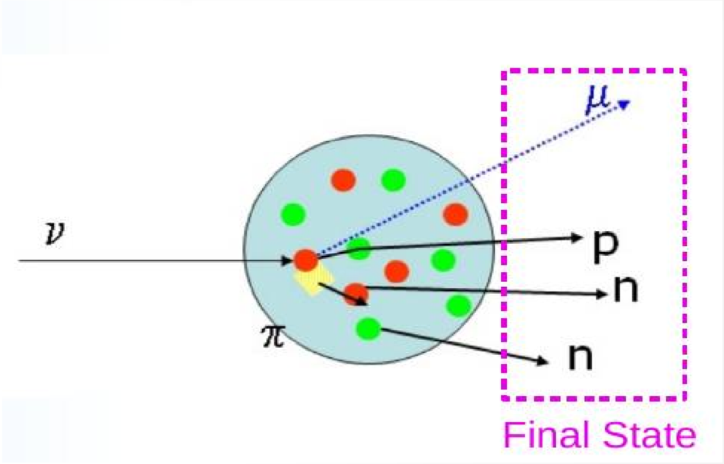


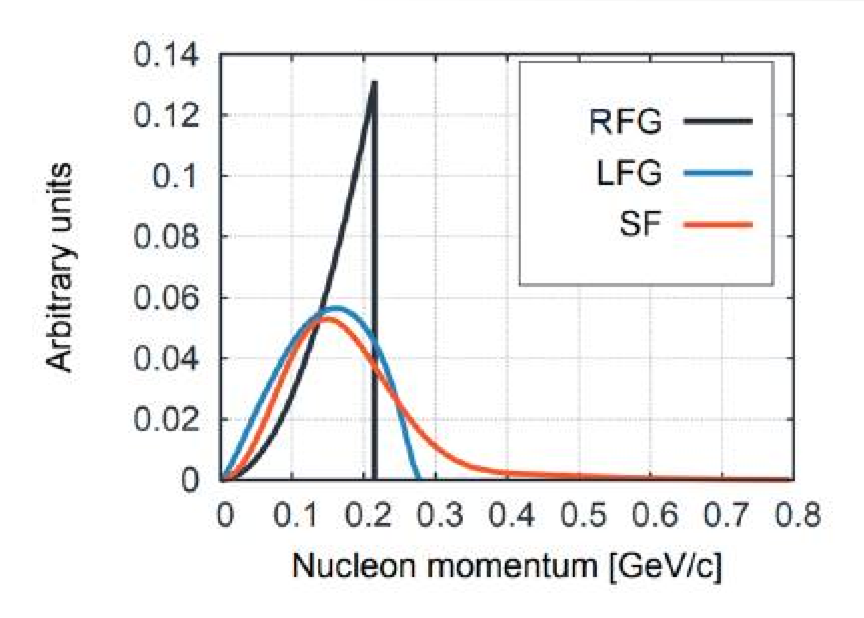
- All currently running accelerator neutrino experiments use nuclear targets (water, carbon, liquid argon) to increase the number of detected interactions
- 'Reaction' classification is no longer valid. 'Topology' is currently used in the neutrino interaction classification:
  - Particles can re-interact inside the nucleus and the final state can be different than the state after neutrino-nucleon interaction
  - 'Topology' classification takes into account particles in the final state which we see in the detector



Nuclear initial state

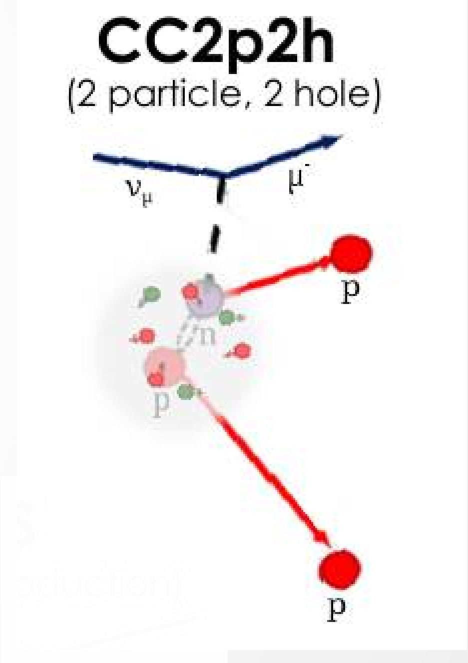
- Primary interactions (neutrino-nucleon) are not on free nucleon:
  - Fermi motion of the nucleons inside the nucleus needs to be taken into account
  - The energy loss in the nucleus (to extract struck nucleon from its shell) – called 'nuclear removal energy' needs to be considered
- Various models of nucleon momentum distribution before the interaction:
  - Relativistic Fermi Gas (RFG) – gas of non-interacting fermions in a constant nuclear potential (distance independent). A characteristic sharp cutoff ('Fermi cliff' is visible in the nucleon momentum distribution)
  - Local Fermi Gas (LFG) – nuclear potential depends on the local nuclear density
  - Spectral Function (SF) - the most realistic momentum distributions of nucleons, taking into account nucleon-nucleon interactions within the nucleus by O. Benhar et al. (*Nucl. Phys. A579 (1994) 493*)





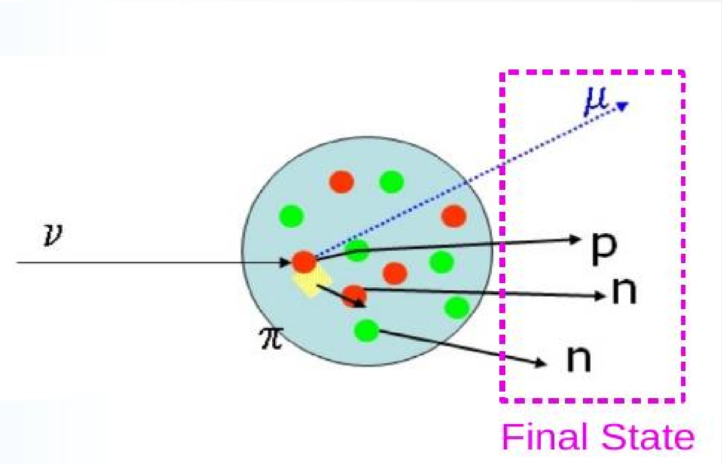
Correlations inside the nucleus

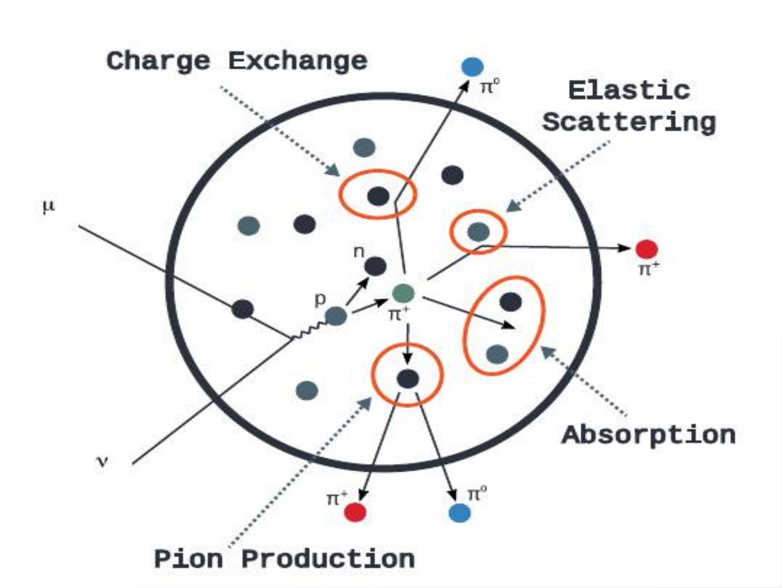
- Started to be considered after suprisingly high values of the axial mass parameter measured by MiniBooNE experiment (*Phys. Rev. D81 092005*)
- Incoming neutrino can interact not only with one nucleon (impulse approximation) but also with n nucleons simultaneously → called n particle – n hole interactions (npnh or np-nh)
- Martini and Nieves models (*Phys. Rev. C83 045501*, *Phys. Rev. C80 065501*) use multi-body expansion to explore multi-nucleon correlations and npnh interactions
- First term in their expansion refers to 1p1h and describes CCQE process
- Long range correlations are taken into account by Random Phase Approximation (RPA) approach → nuclear screening effect considered as a correction to RFG model



Final State Interactions

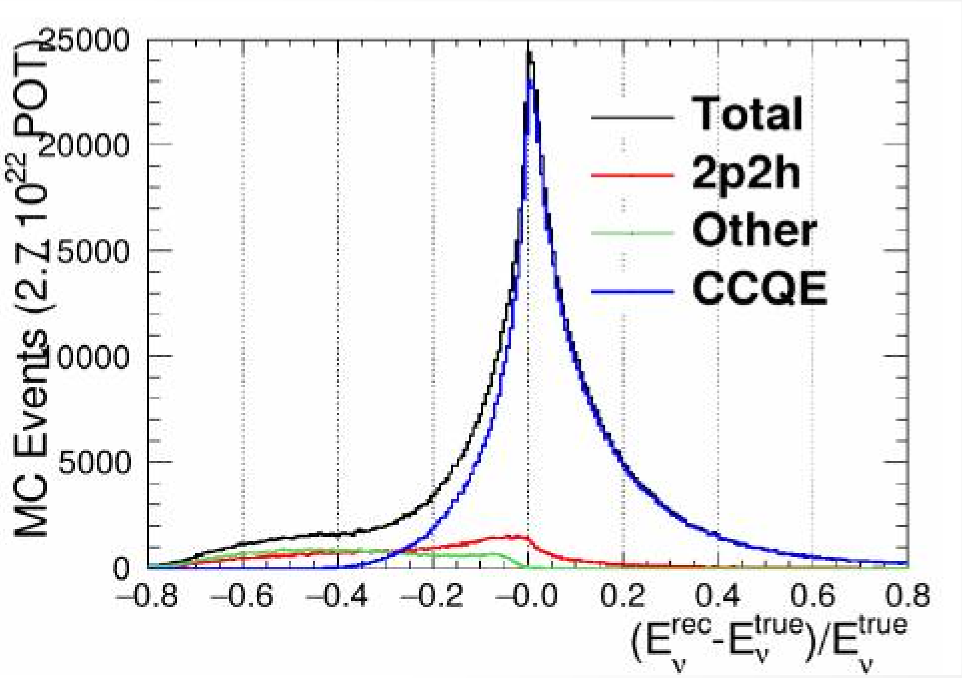
- Hadrons produced in the primary interaction of neutrino with the nucleon can re-interact in the nucleus → Final State Interactions (FSI)
- Common usage of intra-nuclear cascade model for FSI → classical billiard ball scattering in the nucleus
- In sub-GeV region pions are most often produced in the primary interactions and they can be absorbed, scattered or change their charge in FSI
- CC1π interactions can mimic CC0π and alter neutrino energy reconstruction



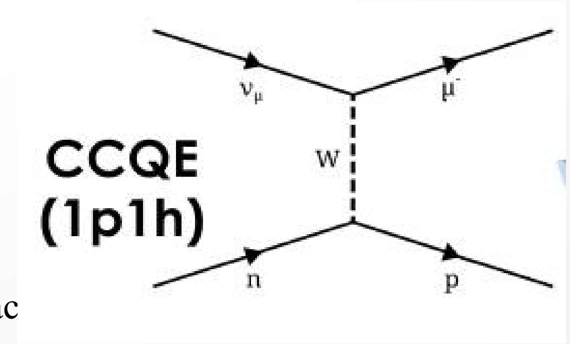


Neutrino energy reconstruction

- In neutrino oscillation experiments we need to measure energy spectrum of neutrinos
- But we don’t know the energy of neutrinos directly!
- Energy is reconstructed from the final state using the CCQE interaction assumption
- Nuclear targets increase the number of detected neutrino interactions but also introduce complications related to nuclear effects:
  - Fermi motion of the nucleons (smearing),
  - Nucleon removal energy (bias),
  - FSI and 2p2h interactions (further bias)

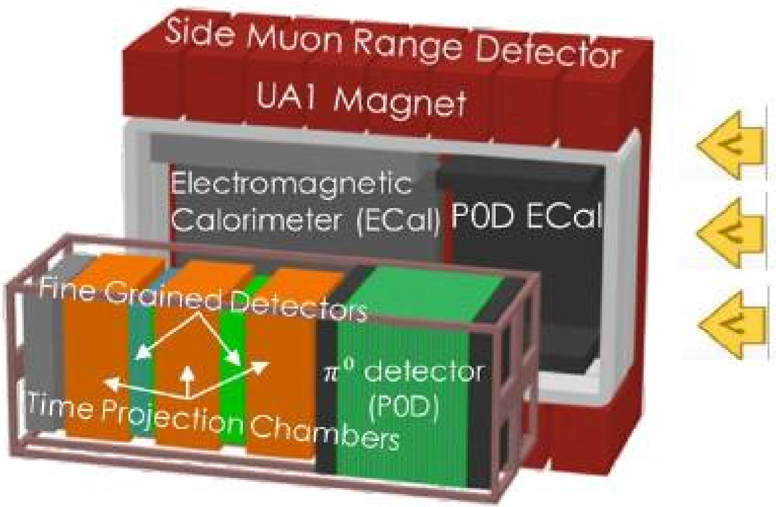


$$E_{\nu}=\frac{m_p^2-(m_n-E_b)^2-m_{\mu}^2+2(m_n-E_b)E_{\mu}}{2(m_n-E_b-E_{\mu}+p_{\mu}\cos\theta_{\mu})}$$



Experimental results: T2K vs MINERvA

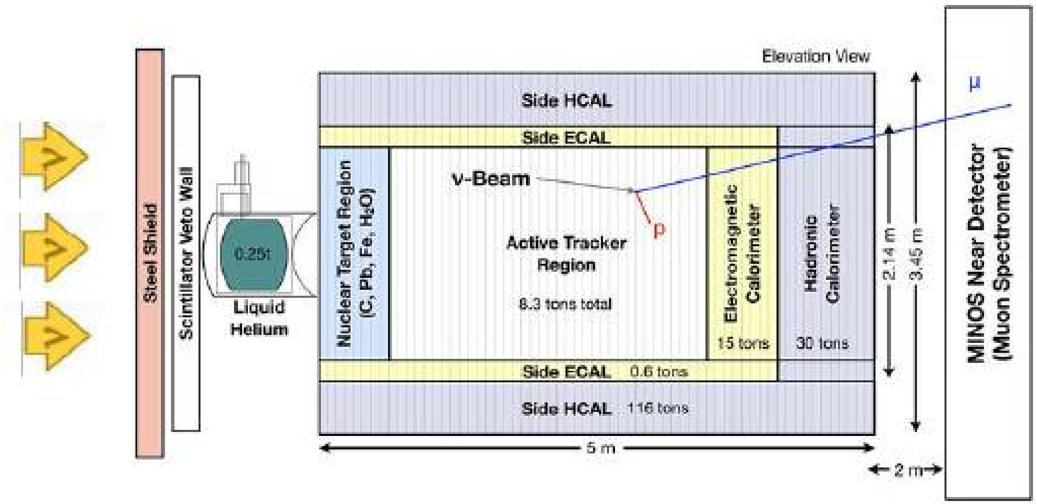
ND280 (Near detector for T2K)



Primary targets: CH, H_2O

Peak E_ν
- On Axis ~ 1.1 GeV
- Off Axis ~ 0.6 GeV

MINERvA

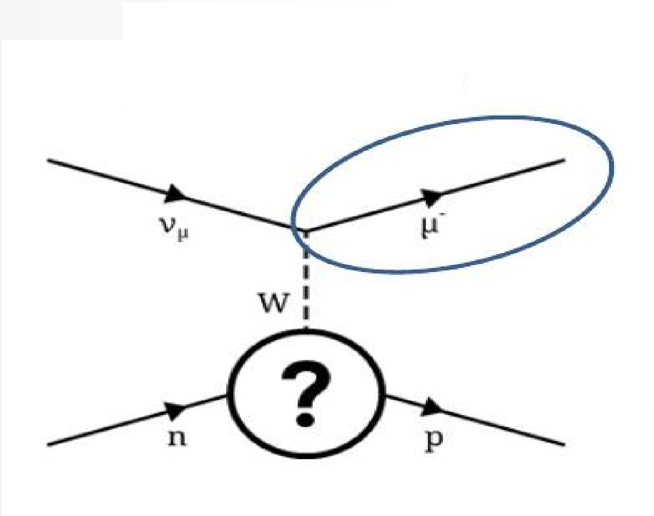


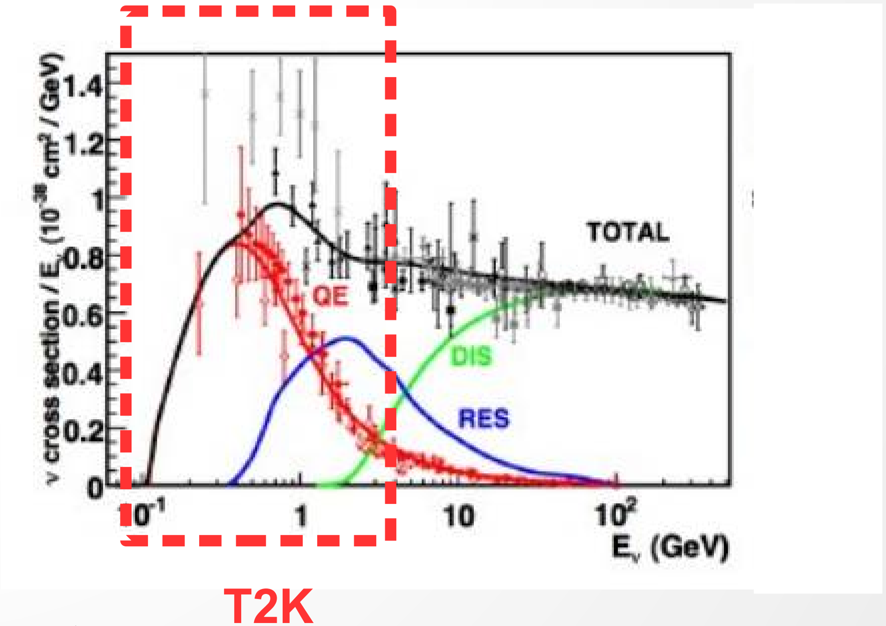
Primary targets: CH, Pb, Fe

Peak E_ν
- ME ~ 5.8 GeV
- LE ~ 3.2 GeV

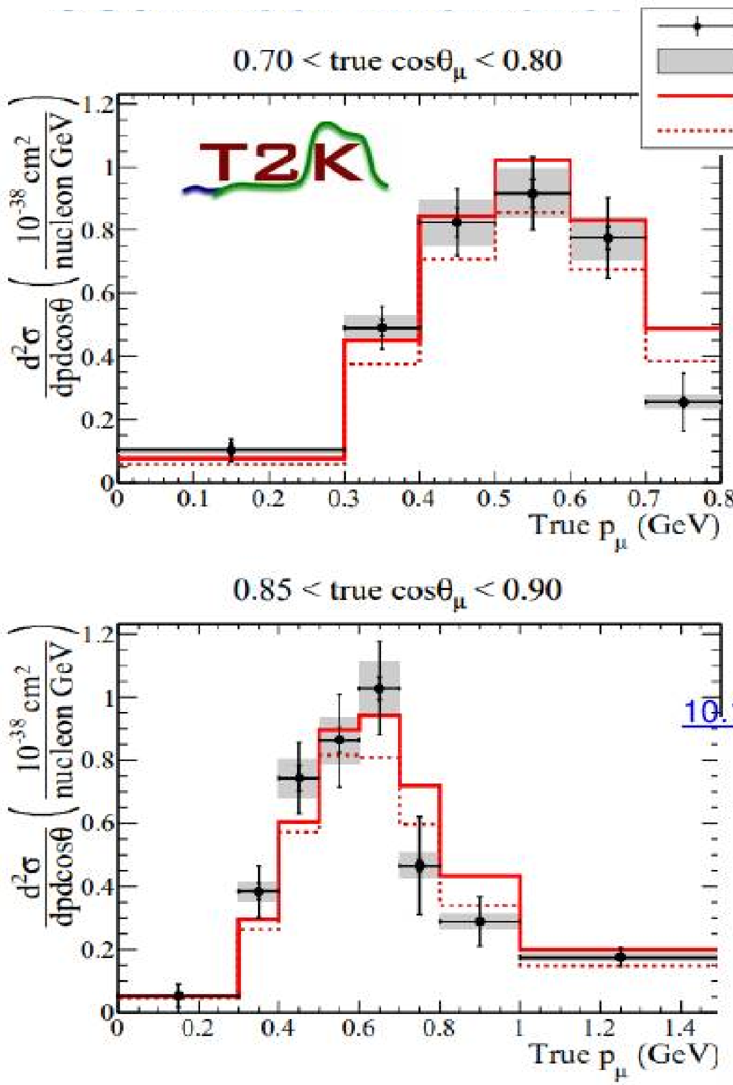
CC0π measurements

- It is the neutrino interaction channel which we know the best → focus in the community for the last 10 years
- Crucial for T2K experiment and its continuation Hyper-Kamiokande – dominant cross section at sub-GeV region → used as a signal for neutrino oscillations
- The simplest observables in which we can provide a cross section are the muon opening angle (or cosine of the angle) and muon momentum → aka 'muon kinematics'

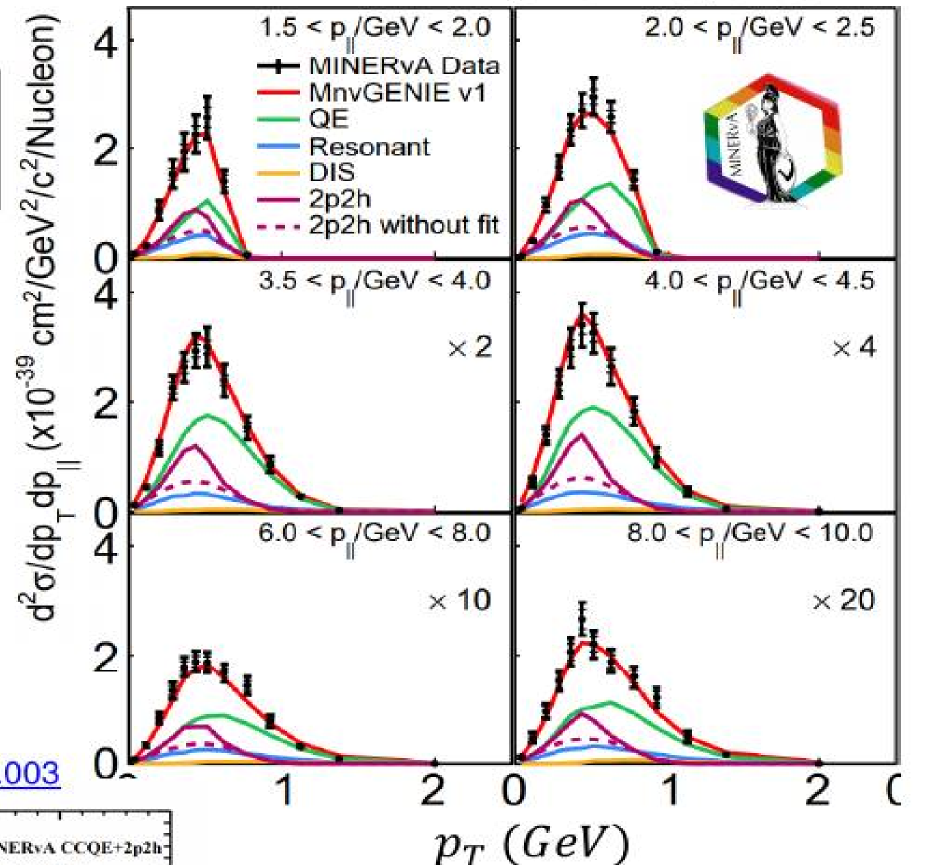




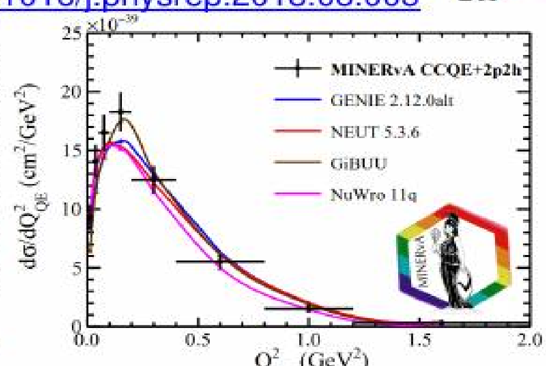
CC0π measurements



Phys. Rev. D **99**, 012004



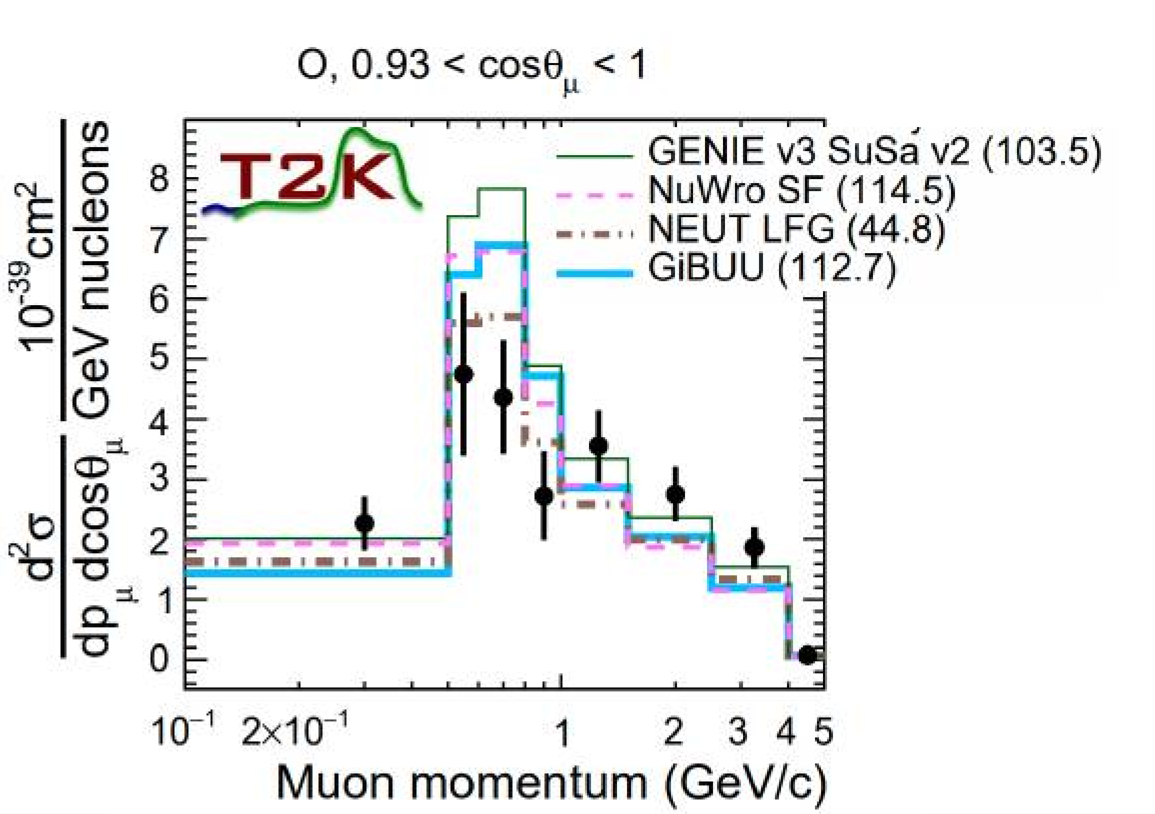
10.1016/j.physrep.2018.08.003



Good agreement between data and model predictions

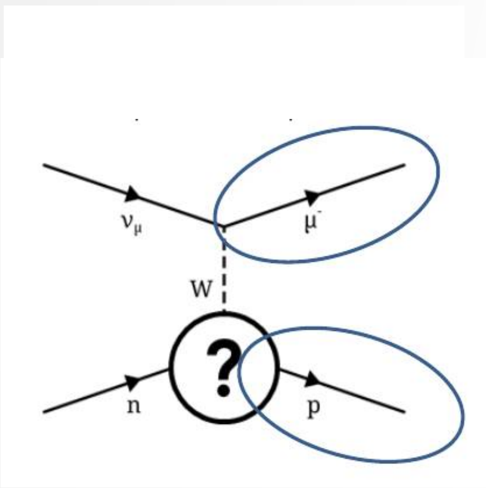
CC0π measurements

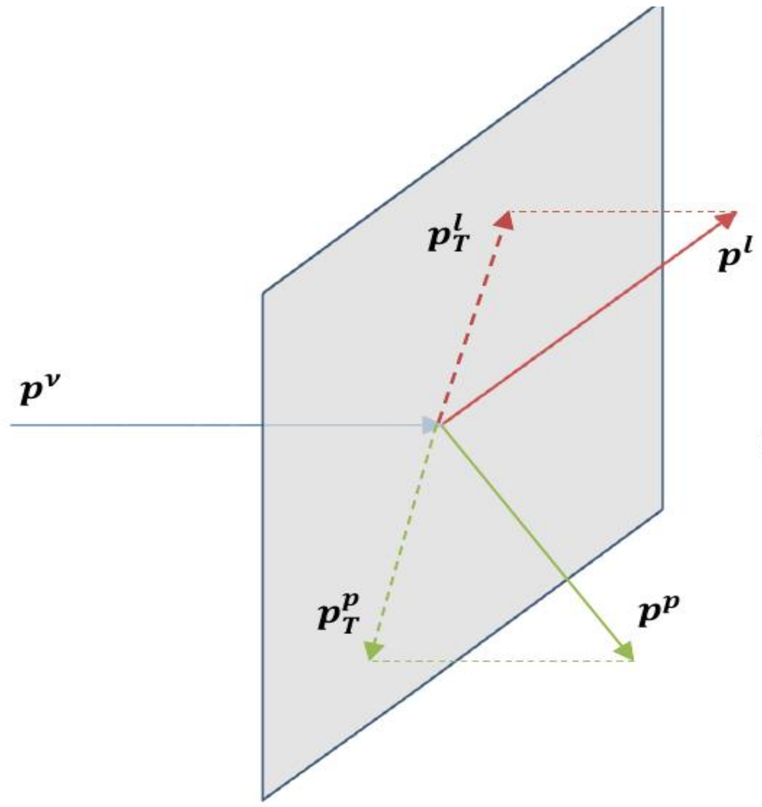
- ...but poor agreement in the 'very forward region' (small muon opening angles)

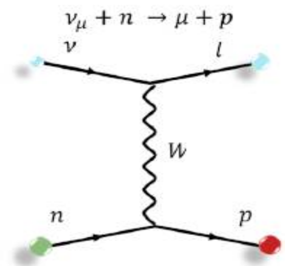


CC0π – nuclear effects

- An idea (*Phys. Rev. C 94, 015503 (2016)*) to look for nuclear effects in CC0π interactions via Single Transverse Variables (STV)





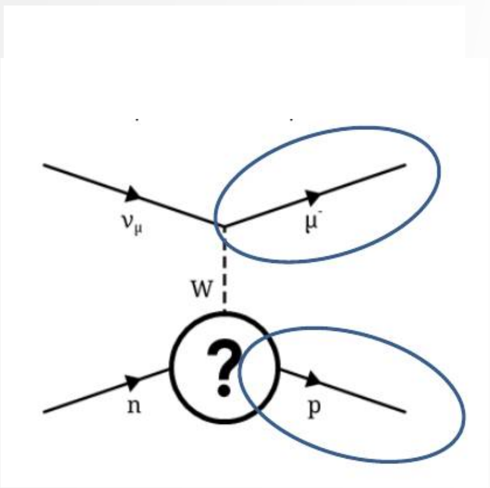


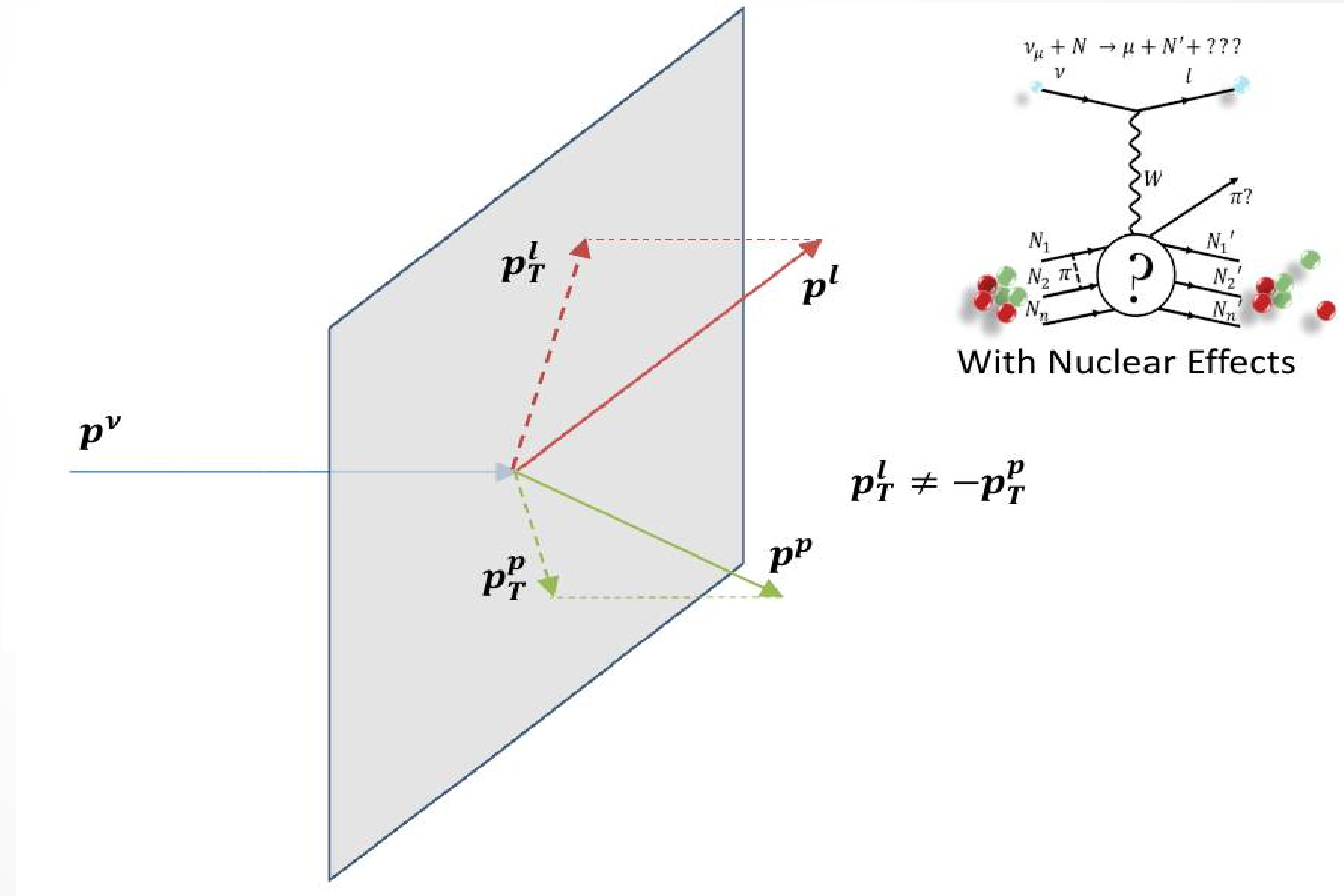
No nuclear Effects

$$p^l_T = -p^p_T$$

CC0π – nuclear effects

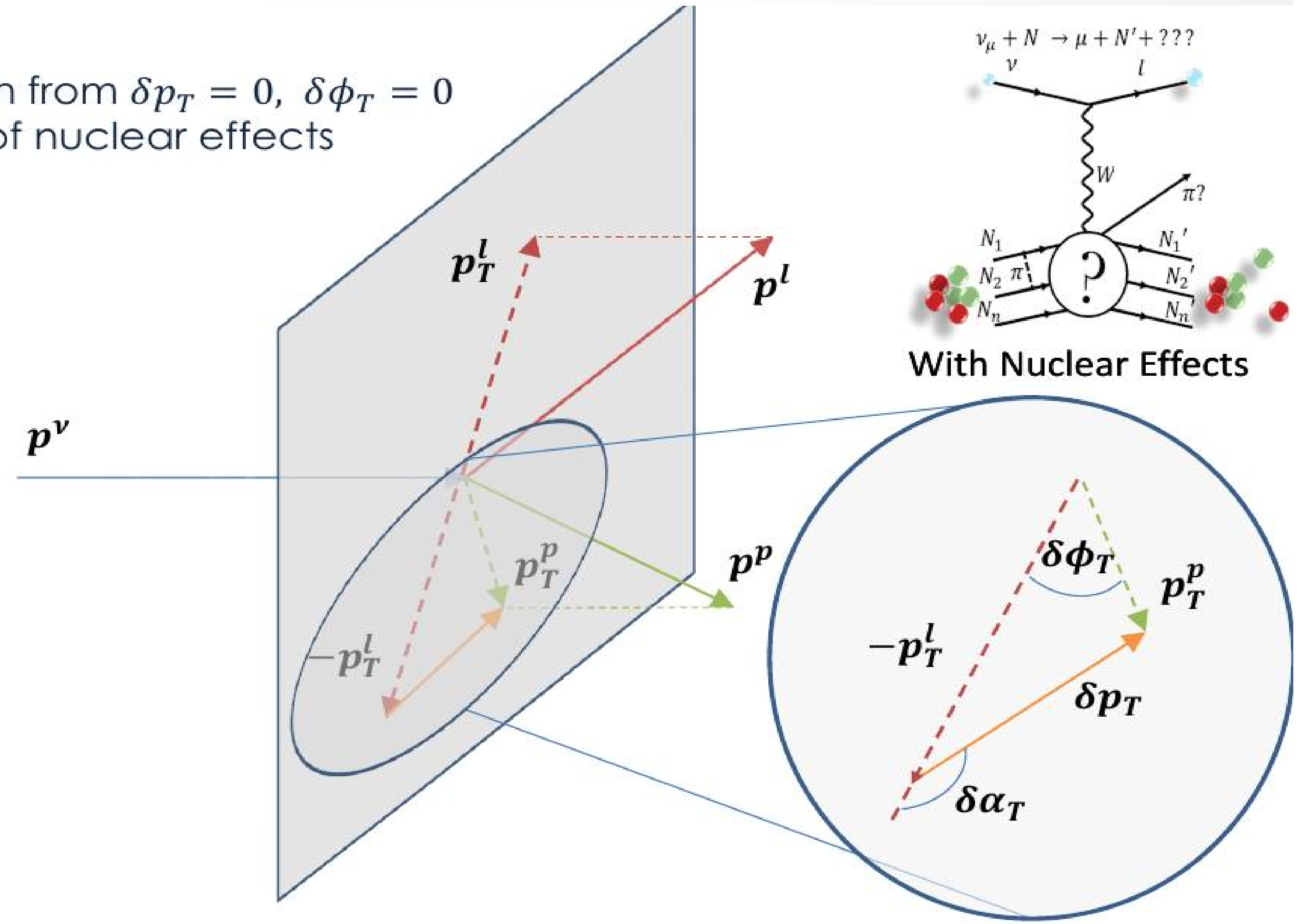
- An idea (*Phys. Rev. C 94, 015503 (2016)*) to look for nuclear effects by looking at proton(s) kinematics in CC0π interactions via Single Transverse Variables (STV)



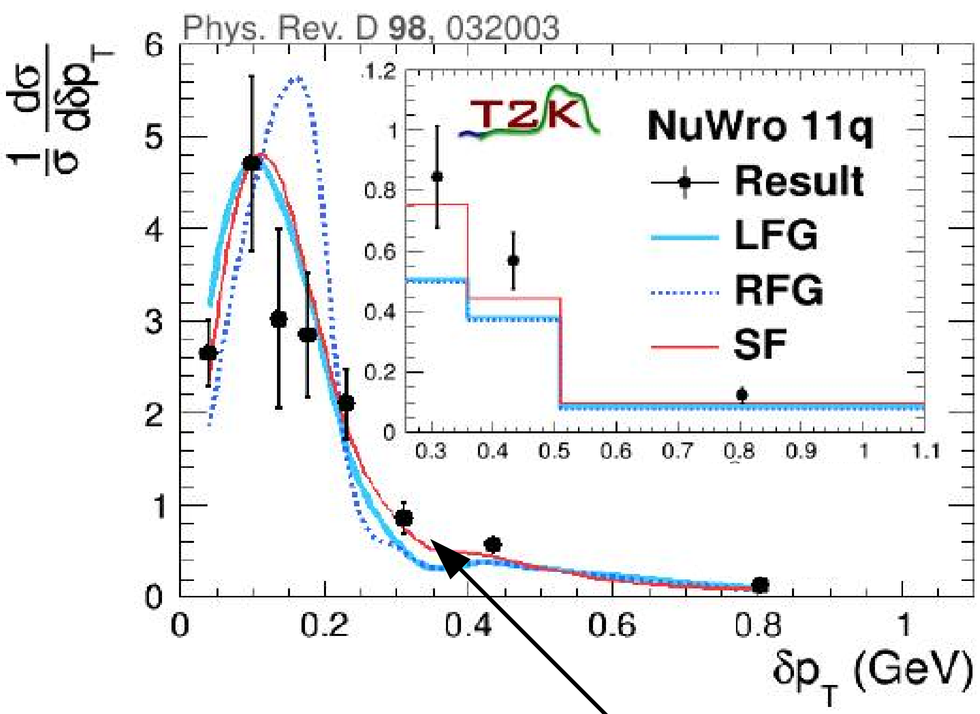


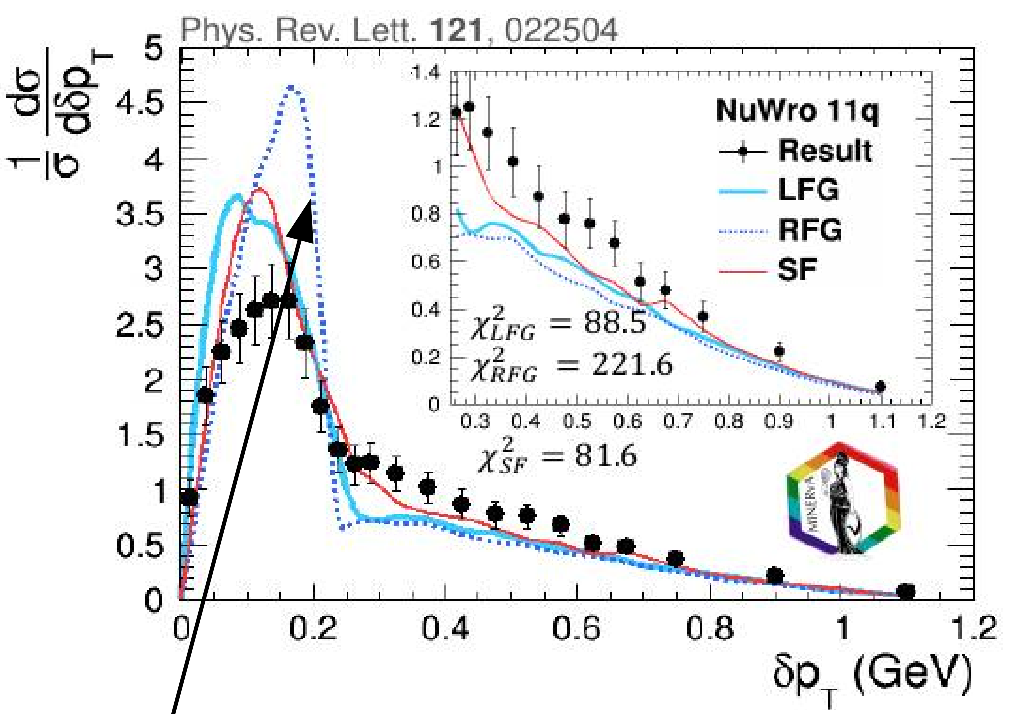
CC0π – nuclear effects

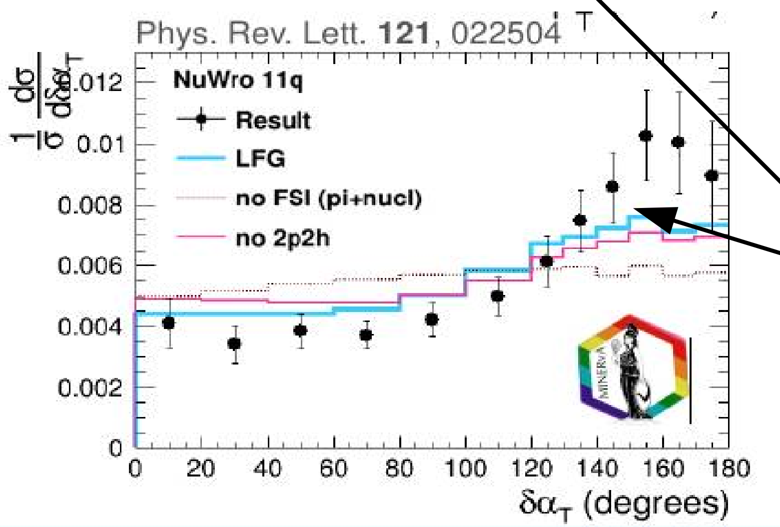
- Any deviation from $\delta p_T = 0,\ \delta\phi_T = 0$ is indicative of nuclear effects



CC0π – nuclear effects



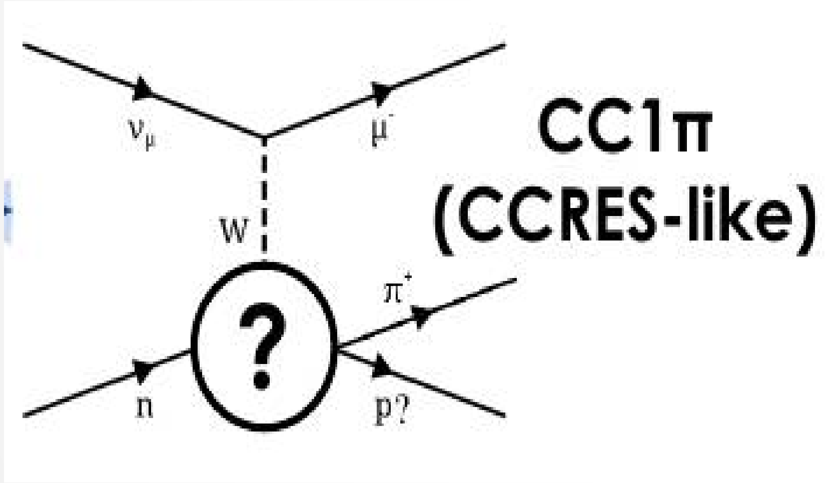


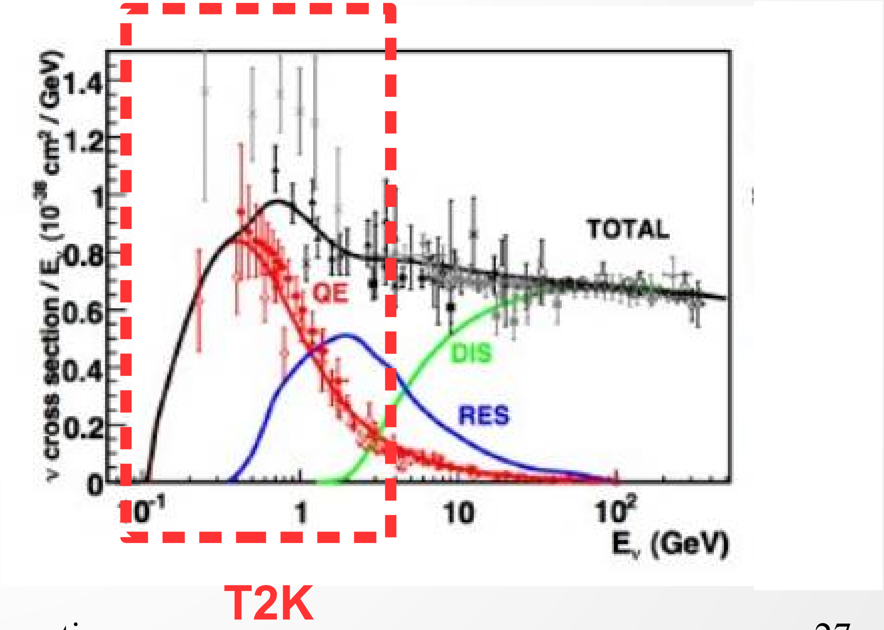


- We don't see a characteristic 'Fermi-cliff' → RFG model is rejected
- SF model desribes well the 'dip' region
- The need for 2p2h and FSI is clearly visible
- But none of the models is able to fully describe the data

CC1π measurements

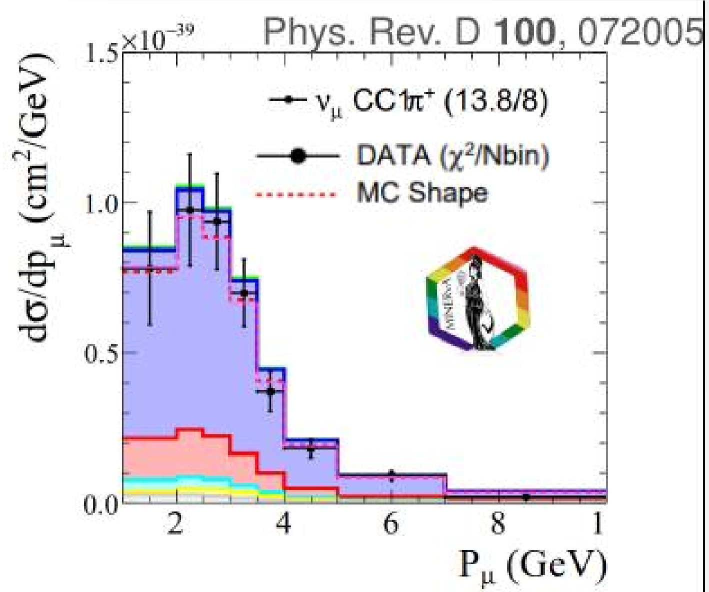
- Important contribution to total cross section in sub-GeV region and background in neutrino oscillations
- Can look into cross section in terms of muon opening angle, momentum and pion opening angle, momentum

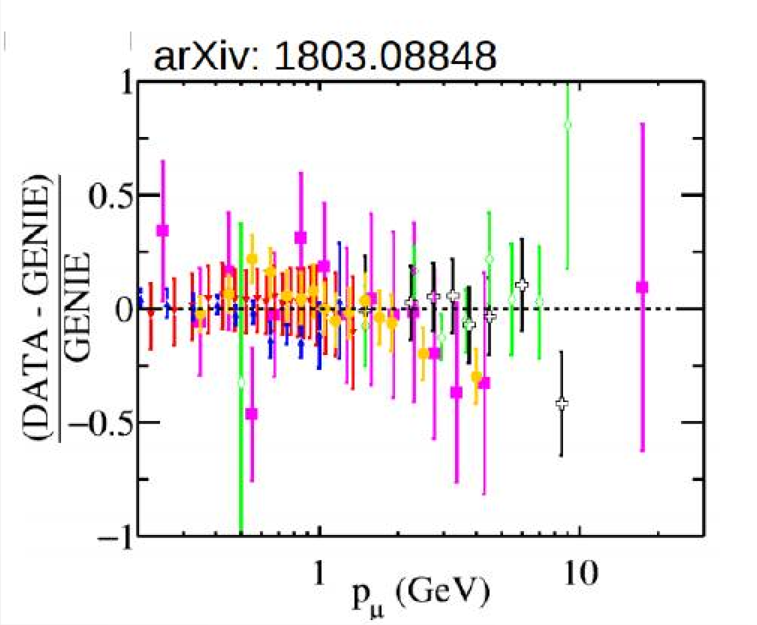


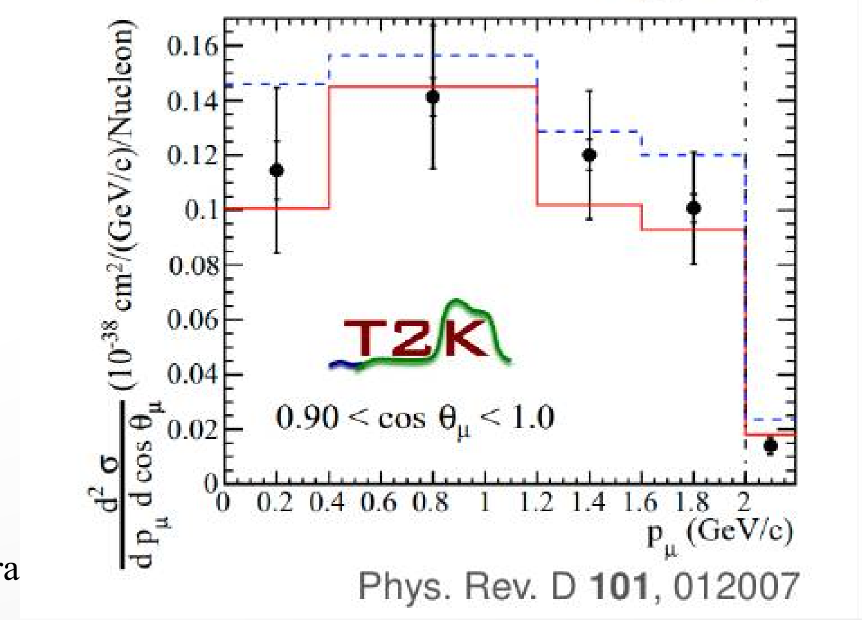


CC1π measurements

- Total cross sections and cross sections in terms of muon kinematics agree with Monte Carlo predictions

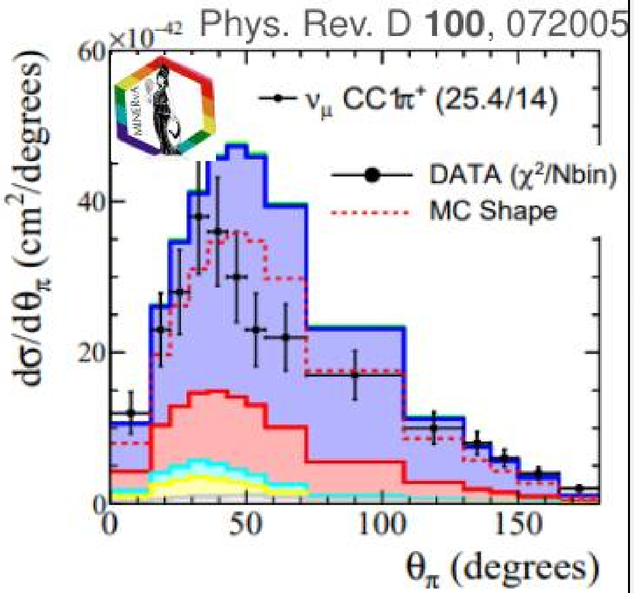


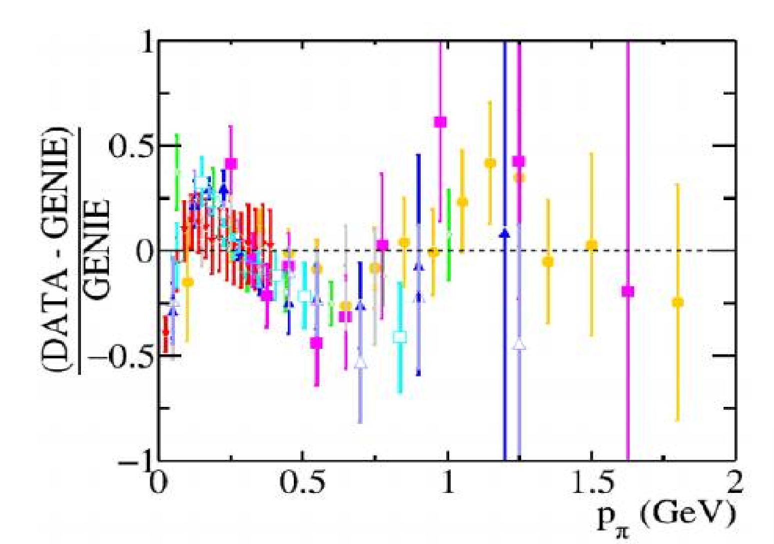


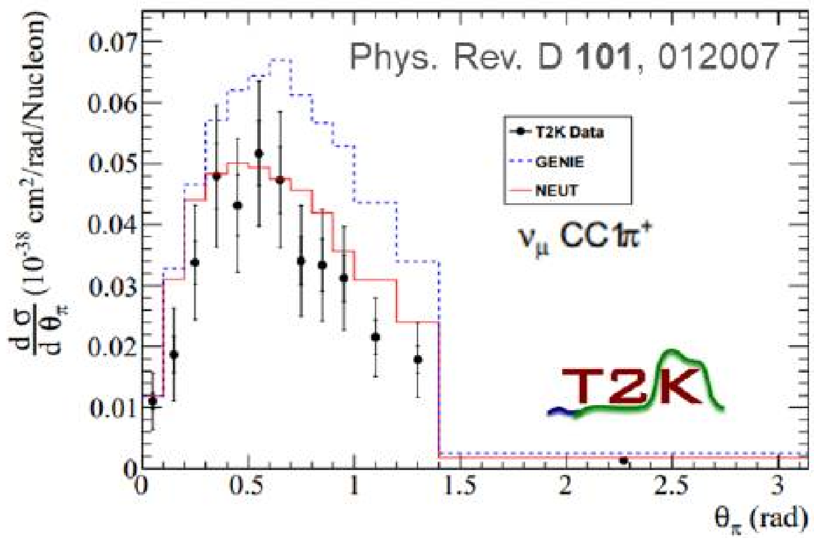


CC1π measurements

- But we are not able to reproduce the cross section as a function of pion kinematics at all...

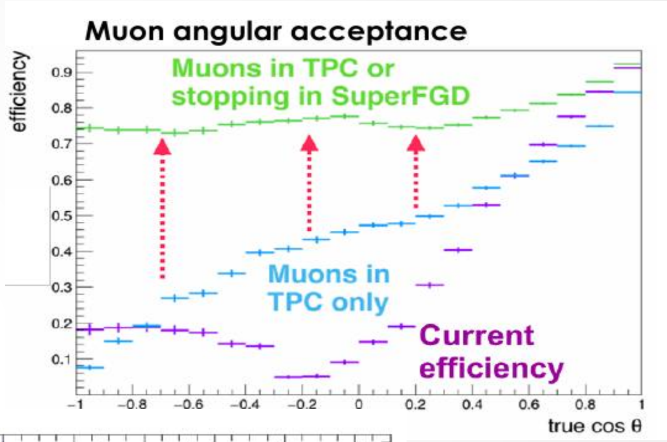


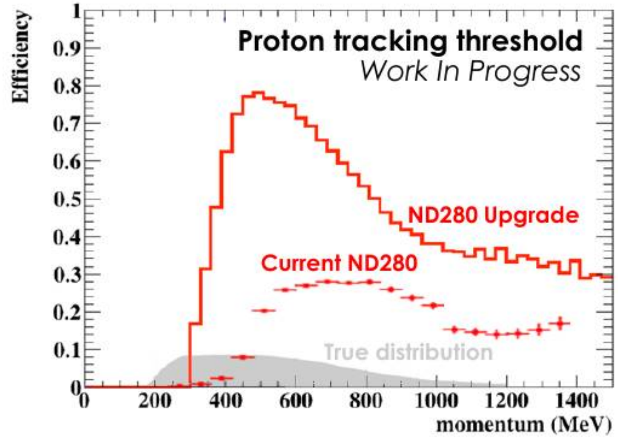




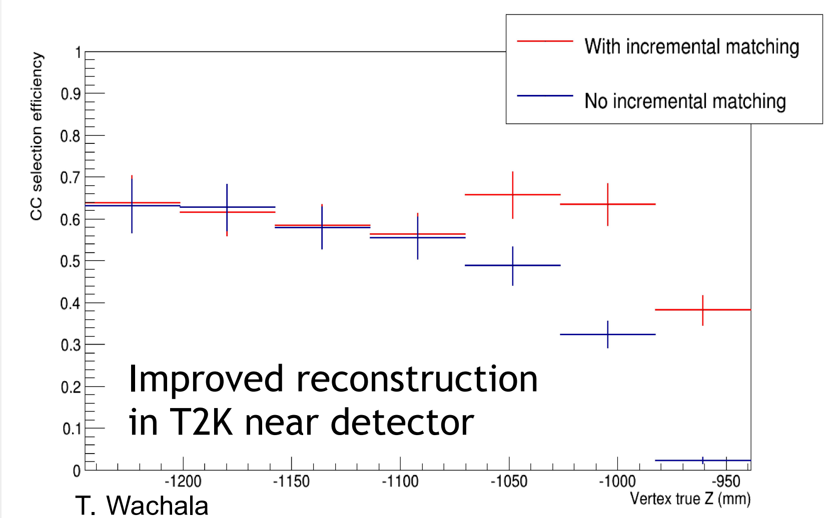
Future measurements in T2K

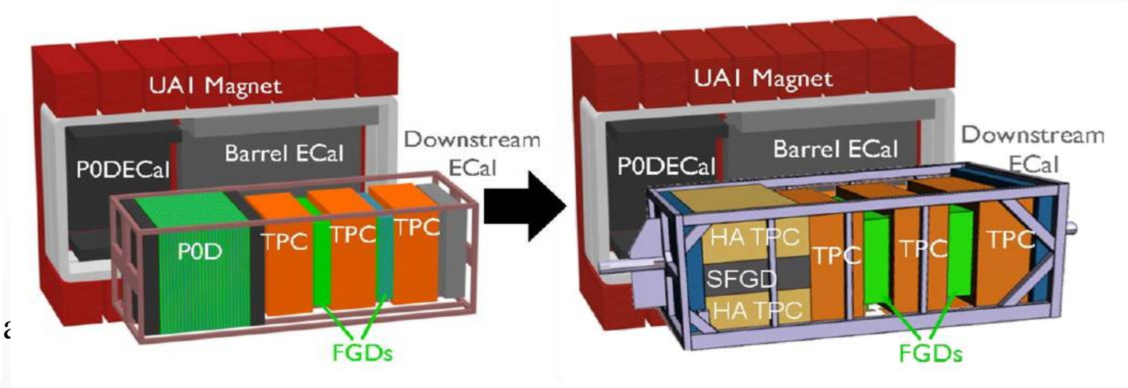
- More measurements from the current and upgraded T2K setup are coming:
  - Cross sections on different nuclear targets (eg. lead) wiil provide more hints on nuclear effects.
  - New event reconstruction techniques will increase the number of detected neutrino interactions and reduce systematic errors.
  - Joint fits to off-axis and on-axis detectors
  - Upgraded ND280 detector will greatly help in this effort → improved angular acceptance, tracking threshold and 3d reconstruction





ND280 upgrade





T. Wachala
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Summary of experimental results

- We describe muon kinematics in CC0π measurements quite well with most models:
  - Impulse approximation is reasonable
  - Inclusive 2p2h models are reasonable
  - The details of the hadron kinematics don't matter so much
  - The impact of FSI is small
- Forward going muon kinematics description is poor in CC0π measurements:
  - Impulse approximation is not reliable, but most of our models use it
  - Models with RPA do better because they provide some modelling of physics beyond the impulse approximation
- We describe nucleon kinematics badly
  - All of our models rely on ad-hoc model combinations to predict nucleon kinematics
  - SF models do better here because they use less approximations in predictions of nucleon kinematics
- Pion kinematics description is poor:
  - Generators using old models such as Reign-Seghal (*Ann. Phys. 133 (1981) 79*)
  - New model (MK model, *Phys. Rev. D 102, 053009*) is currently being developed in T2K. Uses ie. new vector-current form factors and fits to the latest electron-proton scattering data.

Progress in understanding neutrino interactions

- 2001: Nuclear effects are not taken into account in neutrino interactions at all...
- 2010: ,,Most of our knowledge in neutrino cross sections in 0.1 – 20 GeV range comes from the early experiments conducted in 1970s and 1980s” (Rev. Mod. Phys. 84.1307)
- 2010-2013: Axial mass = 1.3 GeV (MiniBooNE)? 2p2h interactions are started to being considered...
- 2016-2018: Precision measurements of hadron kinematics in the CCQE/CC0pi interactions are crucial to understand nuclear effects!
- 2021-2022: Many new measurements probing various interaction channels, energy regimes and nuclear targets.

- Progress in the neutrino cross section measurements is clearly more rapid than in the models of neutrino event generators
- We need to better understand neutrino interactions for future experiments such as DUNE and Hyper-K, but we do not need to have this tomorrow (DUNE, HK start ~2028)
- But, the measurements and theory developments have to start now!

Summary

- Understanding even subtle details of neutrino interactions is crucial for precision measurements in neutrino oscillations
- Using nuclear targets introduced additional complications, eg. in neutrino energy reconstruction
- Currently none of the models is able to fully describe two main channels of neutrino interaction in the sub-GeV region
- Large effort towards improving the modelling of neutrino interactions:
  - New models, tuning neutrino event generators, using electron scattering data,...
  - Experimental campaign to measure neutrino-nucleus cross sections more precisely:
    - T2K, MINERvA, NOvA,
    - Future experiments: T2K-II, MicroBooNE, ICARUS, SBND

Credits: Presentations by S. Dolan at INSS, EPS-HEP

Thank you