IFAE

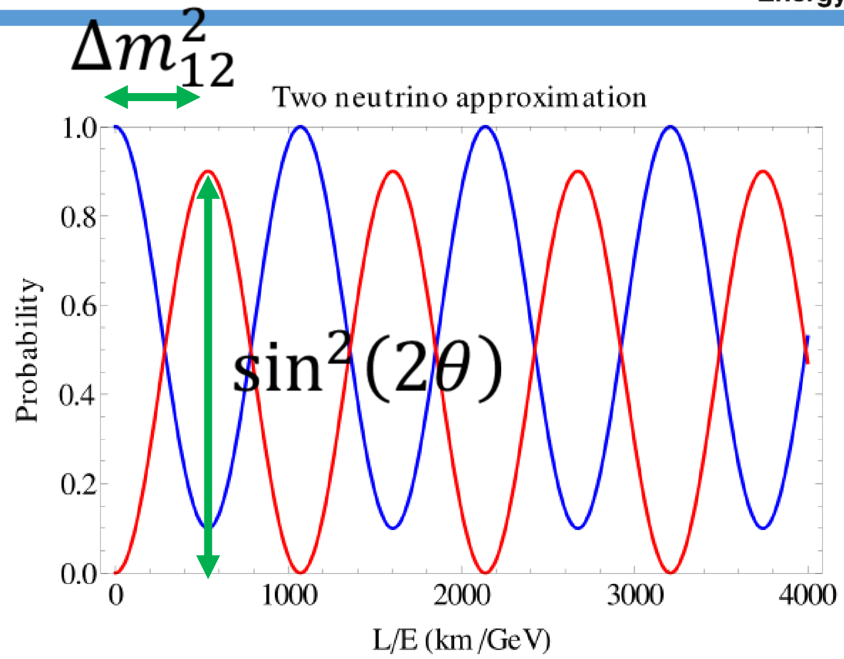
Institute for High
Energy Physics

Long-Baseline Neutrino Oscillation Experiments
and
the Role of the Near Detector

Thorsten Lux

Quick Reminder: 2 Neutrino Oscillations

$$P(\nu_\mu \rightarrow \nu_e) = \sin^2(2\theta)\,\sin^2\left(1.27\,\frac{\Delta m_{12}^2 L}{4E_\nu}\right)$$

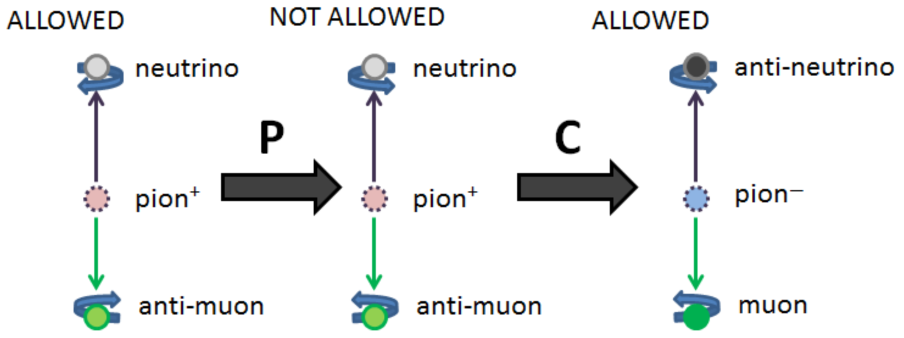


What would CP Violation imply?

$$P\left(\vartheta_\mu^L \rightarrow \vartheta_e^L\right) \neq P\left(\overline{\vartheta_\mu^R} \rightarrow \overline{\vartheta_e^R}\right)$$

⇒ Measure oscillations with neutrinos and anti-neutrinos

⇒ Might help to understand why more matter than anti-matter in the Universe



M. Strassler 2013

Quick Reminder: Oscillation Probabilities for 3ν

$$P\left(\nu_\mu \rightarrow \nu_e\right) = \sin^2 2\theta_{13} \sin^2 \theta_{23} \frac{\sin^2([1-x]\Delta)}{[1-x]^2}$$

Leading term

$$-\alpha \sin \delta_{CP} \sin^2 2\theta_{12} \sin 2\theta_{13} \sin 2\theta_{23} \sin \Delta \frac{\sin[x\Delta] \sin([1-x]\Delta)}{x[1-x]}$$

CP violating term

$$+\alpha \cos \delta_{CP} \sin 2\theta_{12} \sin 2\theta_{13} \sin 2\theta_{23} \cos \Delta \frac{\sin[x\Delta] \sin([1-x]\Delta)}{x[1-x]}$$

CP conserving term

For $P\left(\overline{\vartheta_\mu^R} \rightarrow \overline{\vartheta_e^R}\right)$:

- “-” => “+”
- replace δ and x with -δ and -x

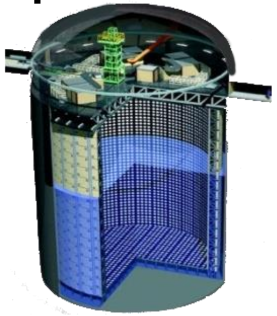
$$x = \frac{2\sqrt{2} G_F n_e E_\vartheta}{\Delta m_{31}^2}, \alpha = \left|\frac{\Delta m_{21}^2}{\Delta m_{31}^2}\right| \cong \frac{1}{30}, \Delta = \frac{\Delta m_{31}^2 L}{4E_\vartheta}$$

δ_{CP} = 0 implies violating tem vanishes!

LBNO Experiment Concept

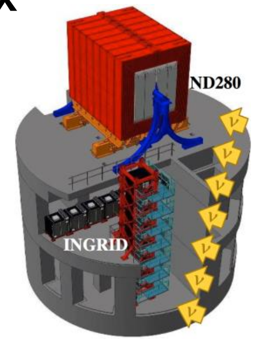
Far detector

Super Kamiokande



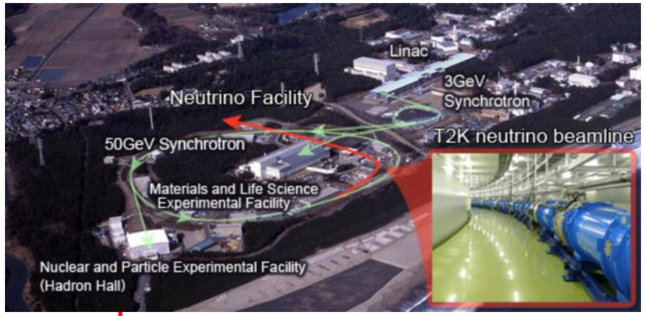
Near detector

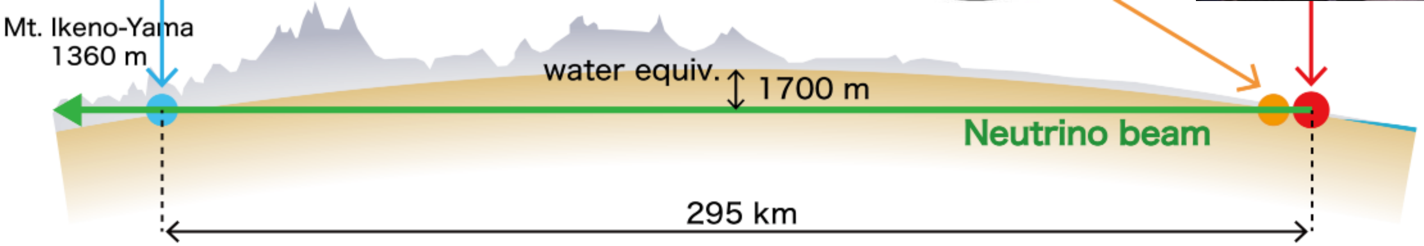
complex



J-PARC

Neutrino Beam





@SK

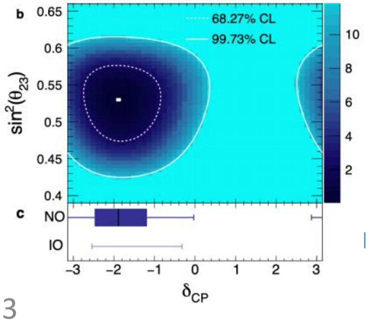
Measure oscillated beam ←

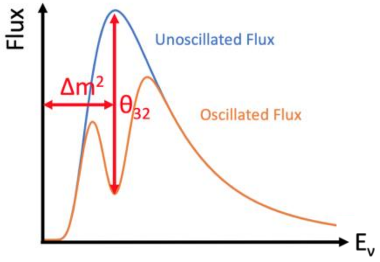
@ND280

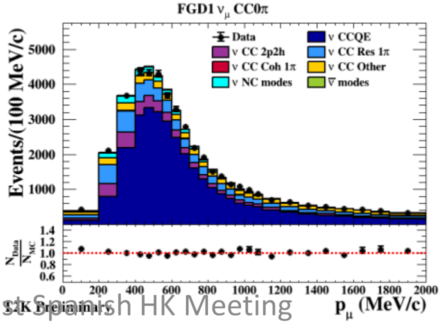
Characterize beam and ν interactions ←

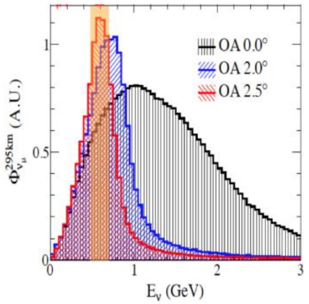
@J-PARC

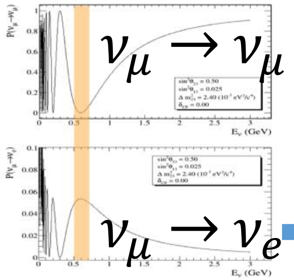
Create Neutrino's off-axis beam ν_μ or $\bar{\nu}_\mu$











What do we need?

- To extract the oscillation parameters, we need the oscillation probability
- We should measure:
  - Disappearance probability: $P(\nu_\alpha \rightarrow \nu_\alpha)$
  - Appearance probability: $P\left(\nu_\alpha \rightarrow \nu_\beta\right)$ ($\beta=\tau$ normally not accessible)
- Wide range of E_ν to measure the shape of ***P*** well
- Ideal would be pure ν_α flux initially
- ***P*** is in fact not directly measurable but is given by: $P_{\nu_\alpha \rightarrow \nu_\beta} = \frac{\Phi_\beta}{\Phi_\alpha^{no\ osc}}$
- Some problems:

Flux also not direct observable, no pure ν_α flux, we also do not know so well E_ν and more …

What do we have (ideally)?

- Detectors provide event rates:

$$dN/dE_\nu = \Phi\sigma N_{target}$$

Number of target isotopes given by detector

Neutrino flux, depends on E_ν

Cross-section (interaction probability), depends on E_ν, target isotope

Takes into account geometrical differences

- ND provides the no oscillated flux on the FD via: $\Phi_{FD}^{no\ osc} = \Phi_{ND} F_{FD/ND}$
- Then ***P*** is given by:

$$P_{\nu_\alpha \to \nu_\beta} = \frac{\frac{dN_\beta^{FD}}{dE_\nu}}{\frac{dN_\alpha^{ND}}{dE_\nu}} \frac{N_{target}^{ND}\sigma_\alpha^{ND}}{N_{target}^{FD}\sigma_\beta^{FD}} \frac{1}{F_{FD/ND}}$$

What do we have (ideally)?

- Detectors provide event rates:

Number of target isotopes given by detector

$$dN/dE_\nu = \Phi\sigma N_{target}$$

Neutrino flux, depends on E$_\nu$

Cross-section (interaction probability), depends on E$_\nu$, target isotope

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$$P_{\nu_\alpha\to\nu_\beta} = \frac{\frac{dN_\beta^{FD}}{dE_\nu}}{\frac{dN_\alpha^{ND}}{dE_\nu}}\frac{N_{target}^{ND}\sigma_\alpha^{ND}}{N_{target}^{FD}\sigma_\beta^{FD}}\frac{1}{F_{FD/ND}}$$

No, not at all! We have detector effects!

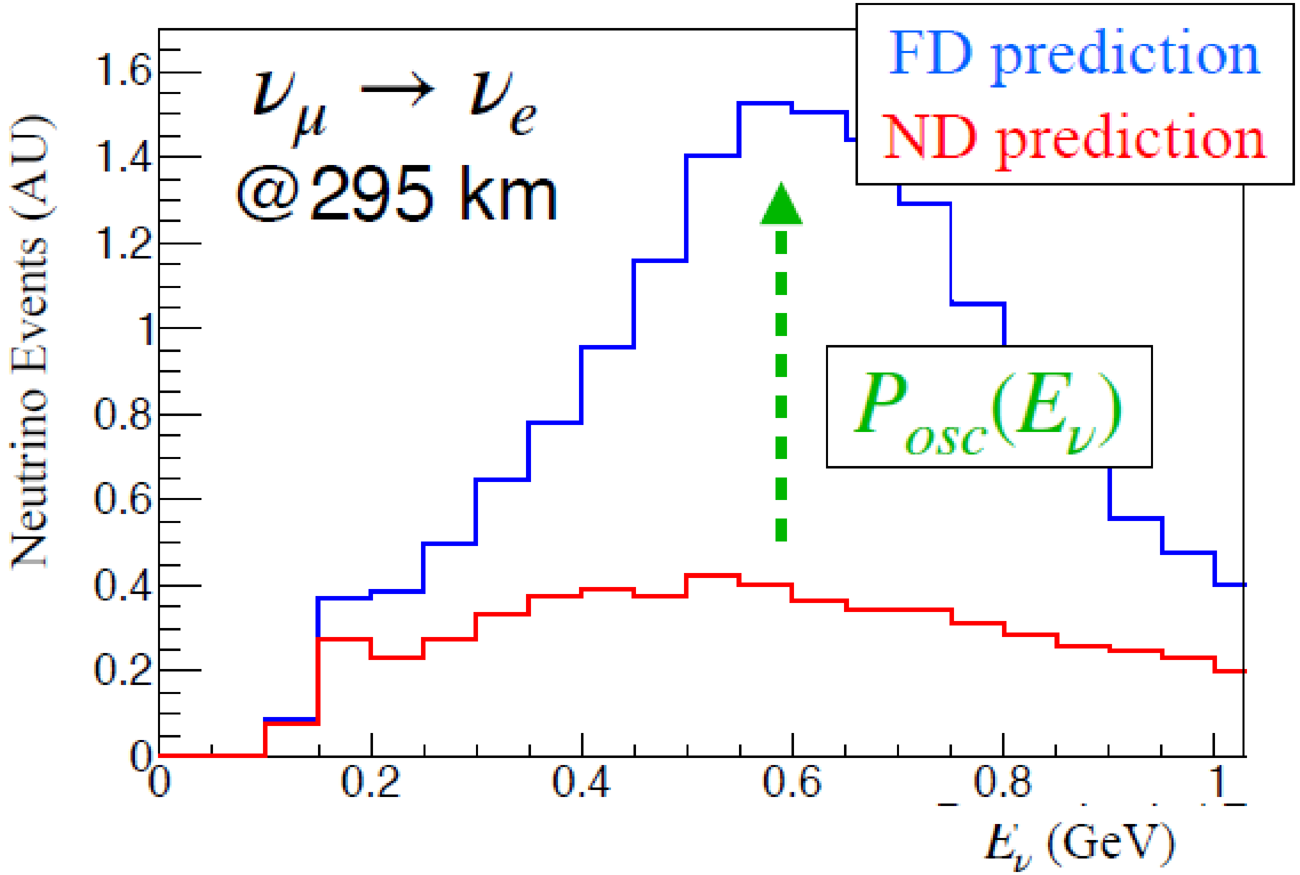
Real World Detector

- ***P*** depends on true E_ν but a detector provides E_ν^{reco}
- Energy migration described by matrix: $T(E_\nu, E_\nu^{reco})$
- Additional detector effects/efficiencies which depend on E_ν/E_ν^{reco}: $\epsilon(E_\nu, E_\nu^{reco})$
- Both require an excellent understanding of the detector response
- Different for every interaction process
- Event rate at FD is then: $\frac{dN_\beta^{FD}}{\Delta E_\nu^{reco}} = N_{target}^{FD} \sum_i \int_{E_{min}}^{E_{max}} \Phi^{ND}(E_\nu) F_{\frac{FD}{ND}}(E_\nu) \sigma_i^{FD}(E_\nu) T_i^{FD}(E_\nu, E_\nu^{reco}) \epsilon_i(E_\nu, E_\nu^{reco}) P_{\nu_\alpha \to \nu_\beta}(E_\nu) dE_\nu$
- Event rate at ND is then:

$$\frac{dN_\beta{}^{ND}}{\Delta E_\nu^{reco}} = N_{target}^{ND} \sum_i \int_{E_{min}}^{E_{max}} \Phi^{ND}(E_\nu) \sigma_i^{ND}(E_\nu) T_i^{ND}(E_\nu, E_\nu^{reco}) \epsilon_i(E_\nu, E_\nu^{reco}) dE_\nu$$

More complicated but you still extract the oscillation parameters from comparing the near detector and the far detector neutrino spectrum!

Analysis Concept: νe Appearance

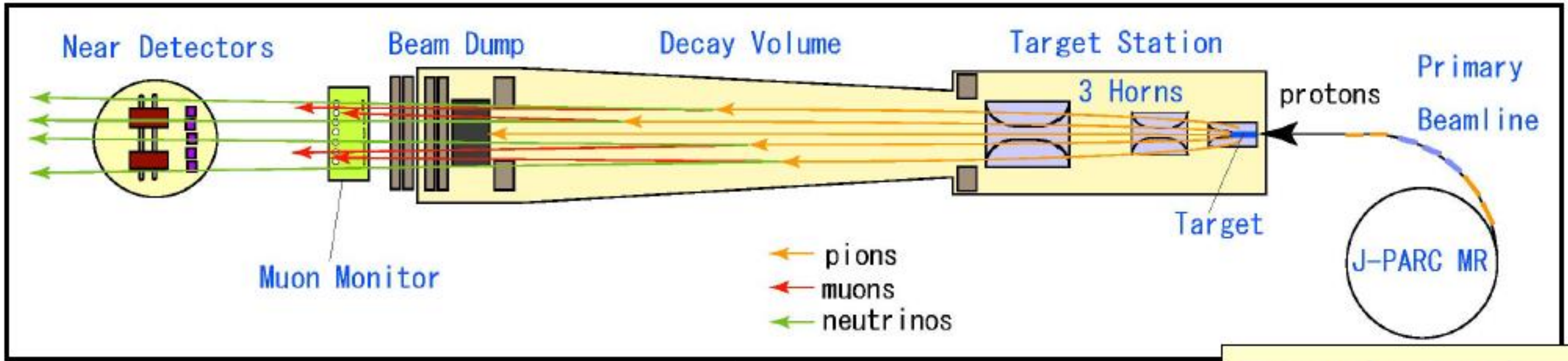


A lot of uncertainties have to be taken into account!

Neutrino Beam Generation

- Neutrino beam is tertiary beam
- Proton beam, hadron production, magnetic horn system, … contribute to neutrino flux uncertainties
- Some of these uncertainties controlled by beam monitors and external experiments

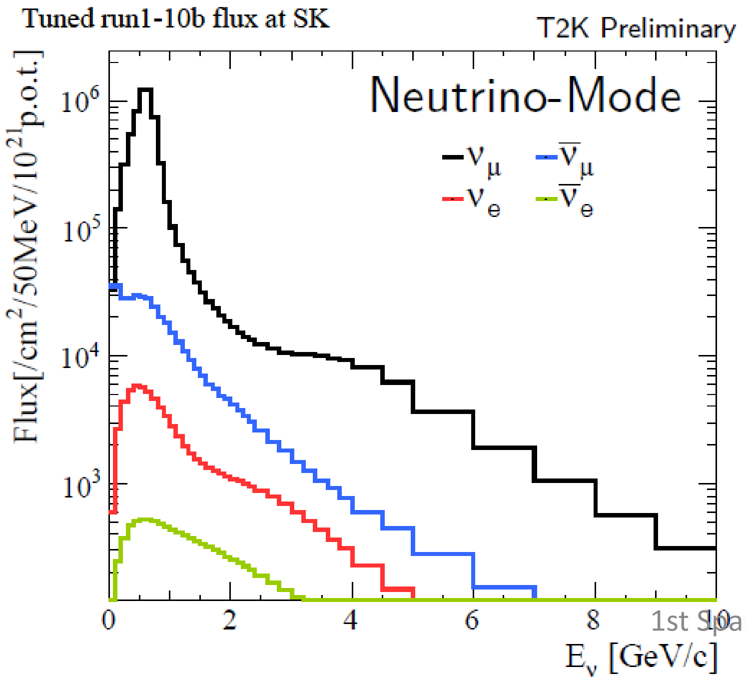
Hard work to reduce uncertainties in knowledge of neutrino flux!

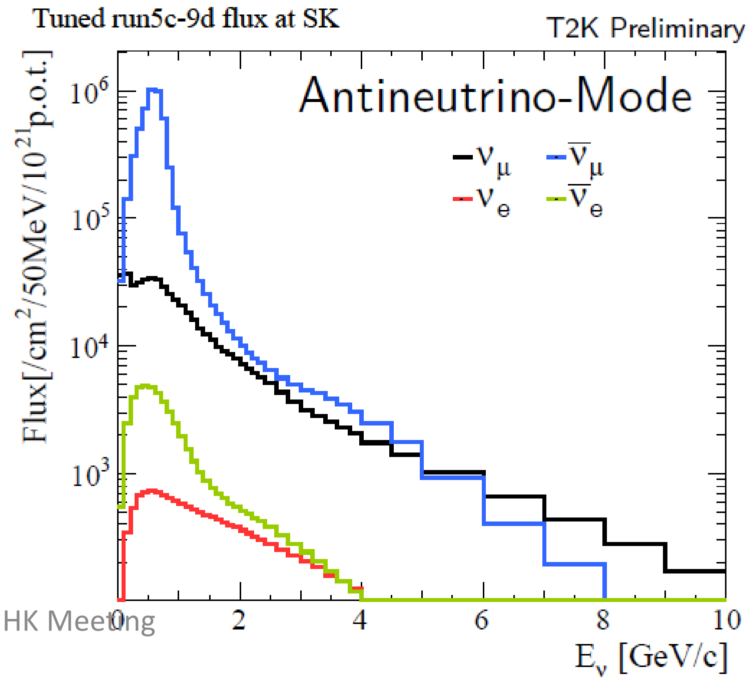


Example: T2K beam

T2K Neutrino Flux

- Neutrino flux not mono-energetic but shows broad spectrum
- No pure ν_μ beam but contaminations to be accounted for in analysis
- But: ν_e contamination useful to measure cross-section for appearance in FD
- Also wrong-sign contamination
- T2K/HK neutrino flux peaks at about 650 MeV

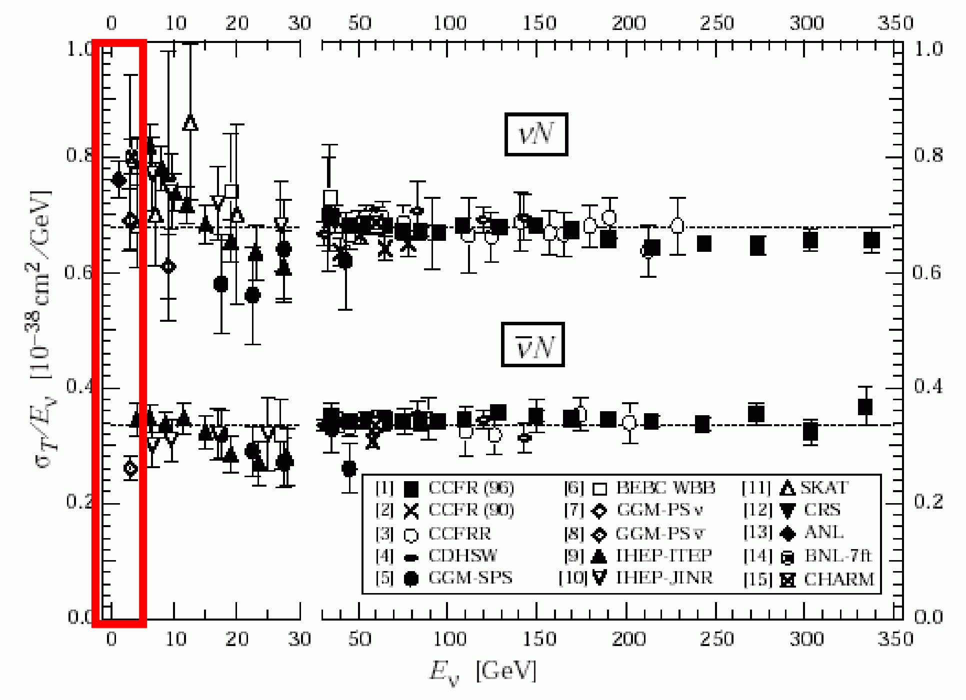




Neutrino Cross-Sections: Motivation

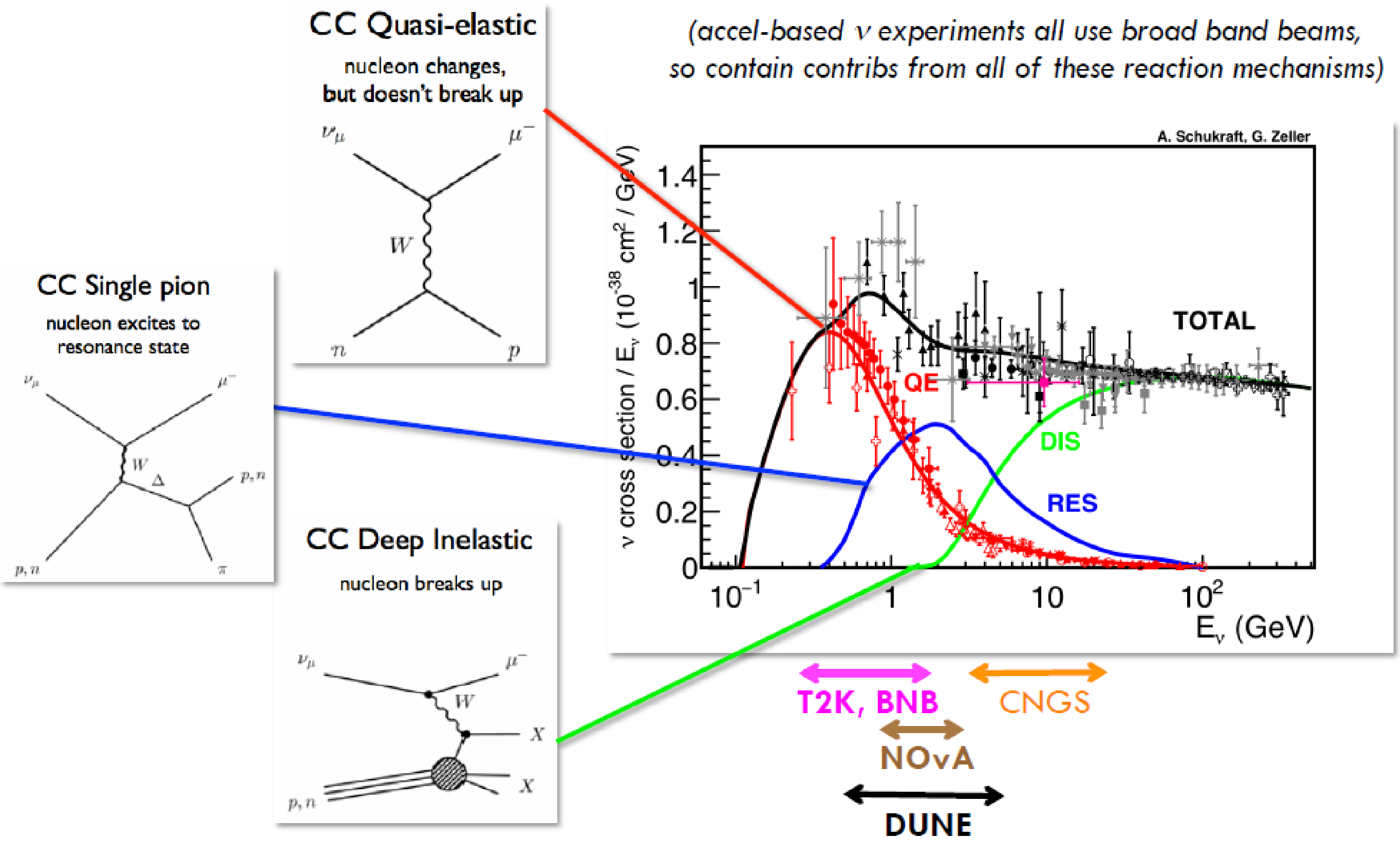
- Uncertainties in neutrino and anti-neutrino cross-sections affect CP Violation measurement
- Muon (anti-)neutrino cross-section well measured at ND and used to extrapolate to electron (anti-)neutrino cross-section at FD => enough for current experiments but not for future high statistics experiments
- Need <3% relative error on these cross-sections
- **Cross-sections depend on target material. ND280 measures mainly on CH => need to measure on water for future**

$$\mathcal{A}_{CP} = \frac{P(\nu_\mu \rightarrow \nu_e) - P(\overline{\nu}_\mu \rightarrow \overline{\nu}_e)}{P(\nu_\mu \rightarrow \nu_e) + P(\overline{\nu}_\mu \rightarrow \overline{\nu}_e)}$$



Neutrino Cross-Sections

(accel-based ν experiments all use broad band beams, so contain contribs from all of these reaction mechanisms)



CC Quasi-elastic

nucleon changes, but doesn't break up

CC Single pion

nucleon excites to resonance state

CC Deep Inelastic

nucleon breaks up

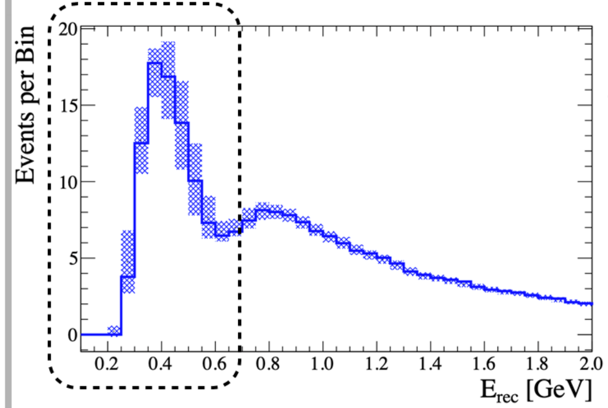
T2K Analysis: NC1π+

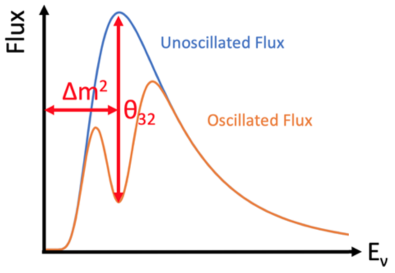
Why do we care about NC1π?

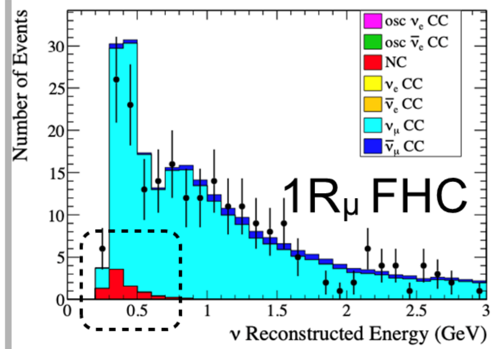
https://arxiv.org/pdf/2101.03779.pdf

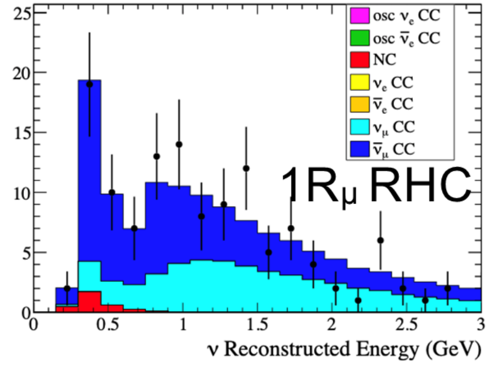
The NC1π+ 59% syst. compared to 5% for CC0π

5% 110 → ±5.5 events
60% 10 → ±6 events



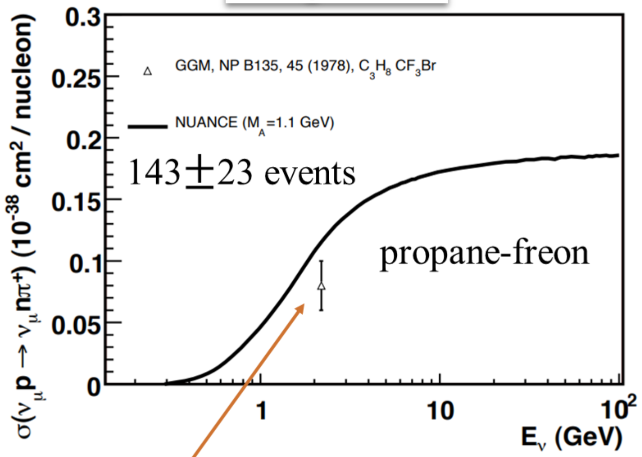






Existing published data

Gargamelle



143±23 events

propane-freon

$$\sigma^{GGM}_{nuc} = 0.056 \pm 0.011 \times 10^{-38}\ \mathrm{cm}^2\ ,$$

$$\sigma^{GGM}_{cor} = 0.08 \pm 0.02 \times 10^{-38}\ \mathrm{cm}^2\ .$$

Argonne National Laboratory

$$\sigma(\nu_\mu p \to \nu_\mu n \pi^+)/\sigma(\nu_\mu p \to \mu^- p \pi^+) = 0.17 \pm 0.08$$

$$\sigma(\nu_\mu p \to \nu_\mu n \pi^+)/\sigma(\nu_\mu p \to \mu^- p \pi^+) = 0.12 \pm 0.04$$

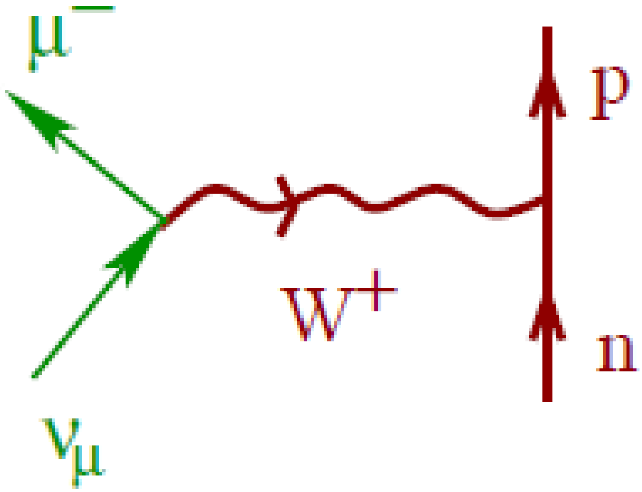
H_2, energy peak ~0.5 GeV long tail.

Energy Measurement: Could be so simple …

- **Remember: We need the oscillation probability as function of the true neutrino energy!**
- ν_μ/ν_μ enters the detector, exchanges a W-boson with a neutron/proton and in the final state we have a negative/positive muon and proton/neutron
- Energy reconstruction trivial for QE case:

$$E_{\text{rec}} = \frac{ME_\mu - m_\mu^2/2}{M - E_\mu + |\vec{p}_\mu|\cos\theta_\mu}$$

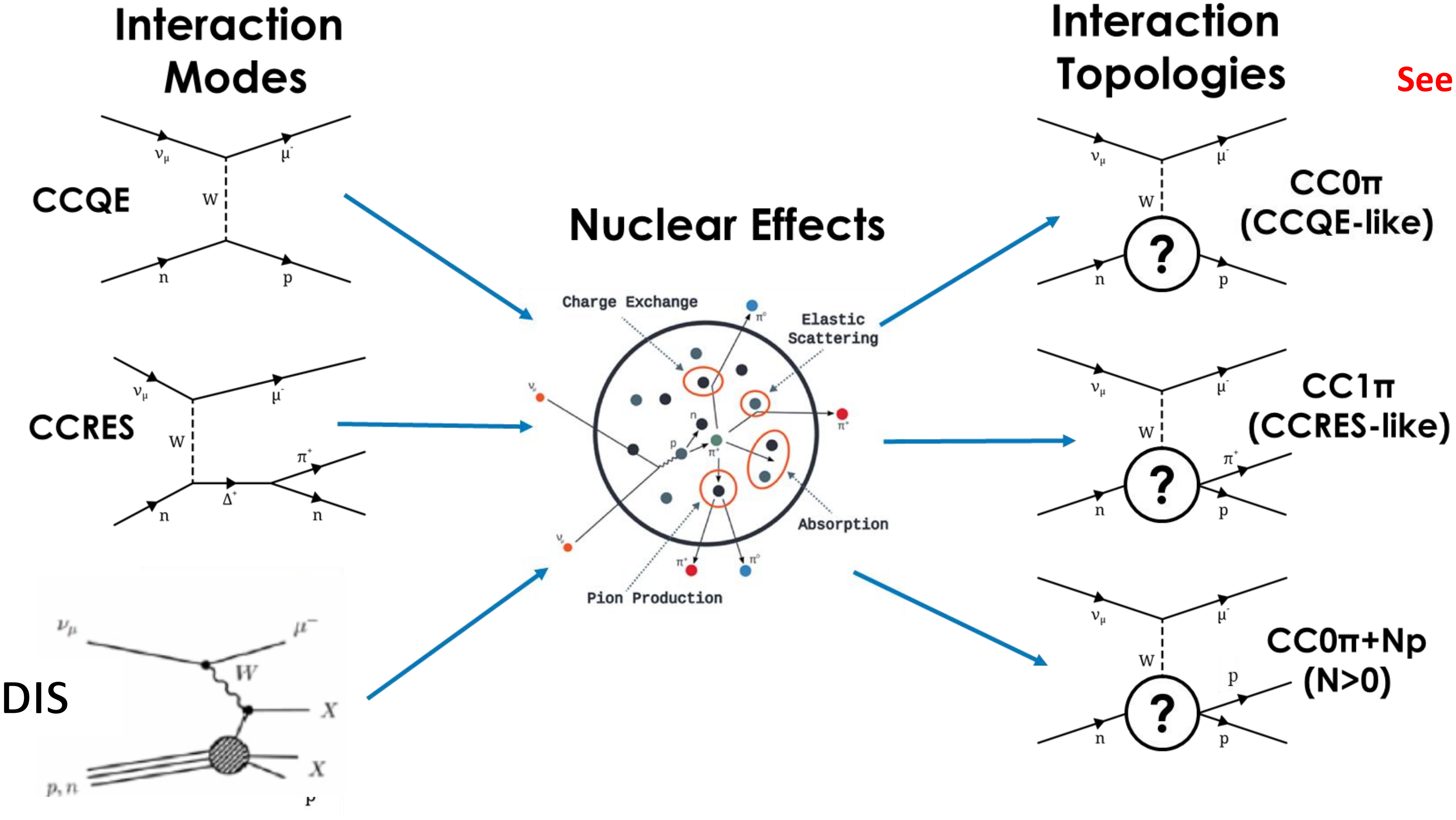
- Small but relevant problem: We have normally no H target and for sure no free neutrons!
- Interactions need to take into account many nuclear effects



Interaction Modes and Interaction Topologies

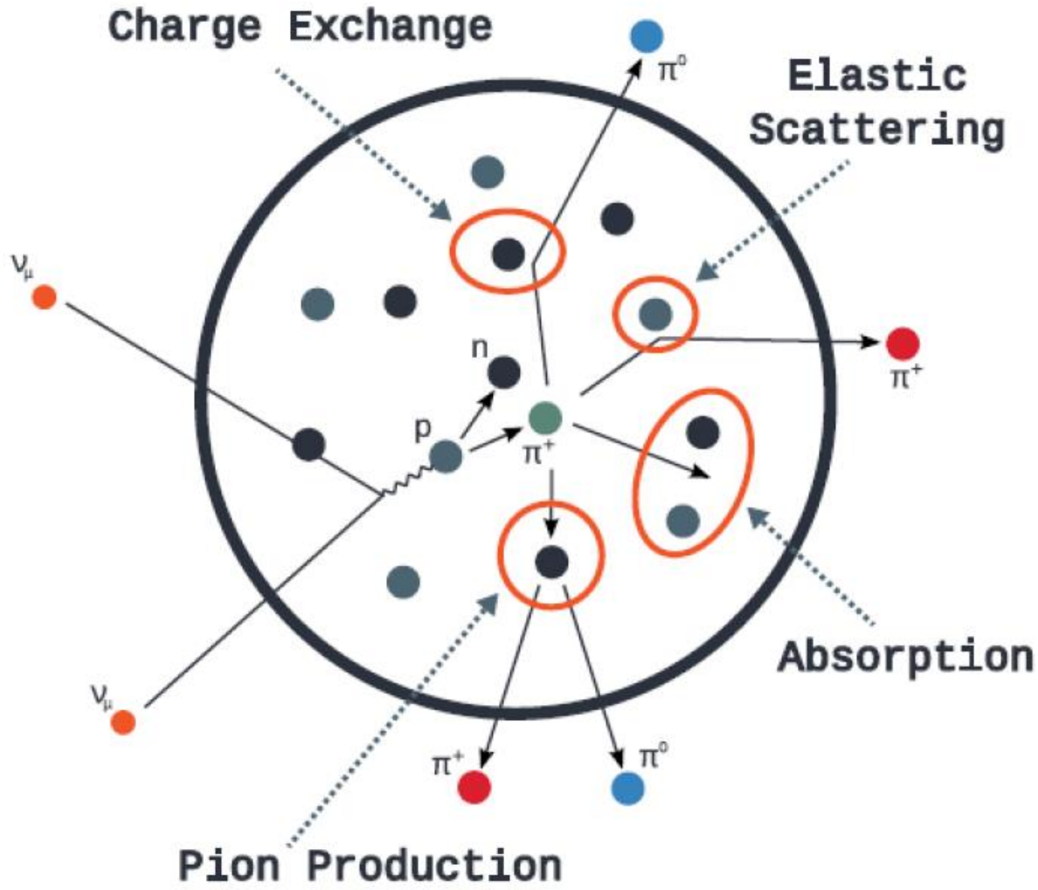
Relevant for neutrino oscillations

Seen by detector



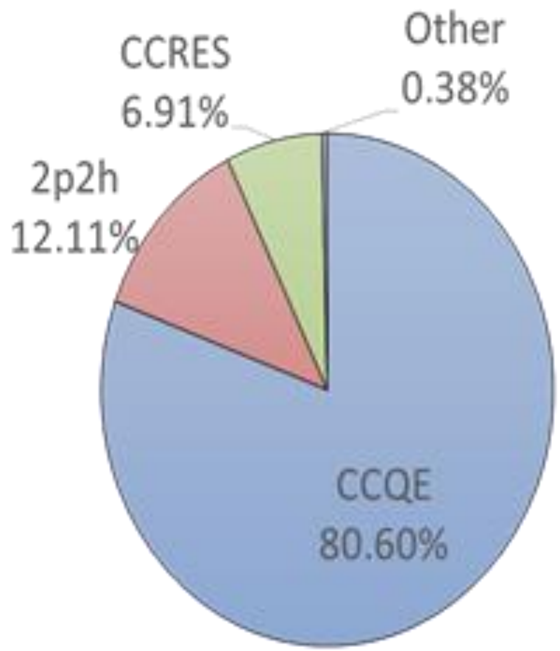
Final State Interactions

Probability depends on target! => Ideally measure with same target in ND and FD!



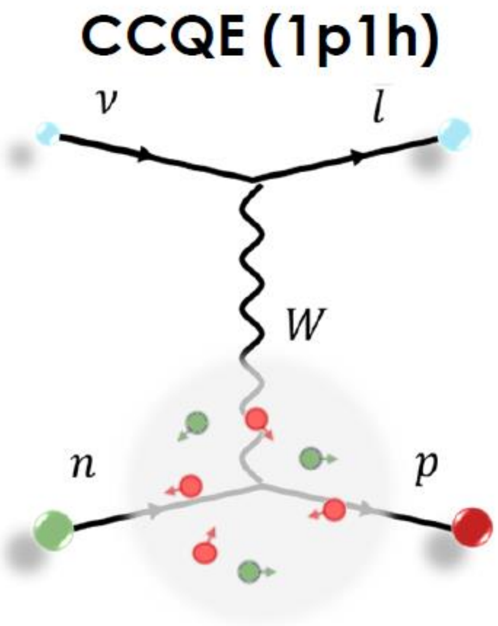
Might affect reconstructed neutrino energy

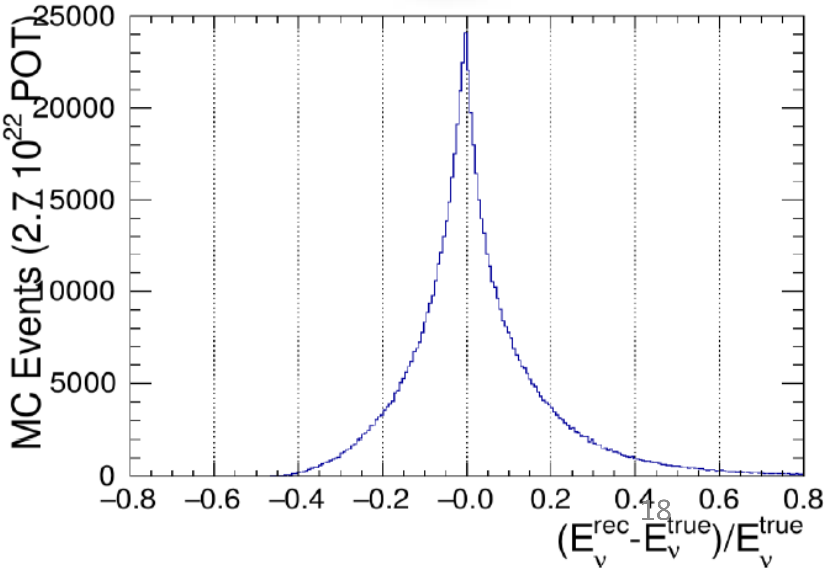
Interaction modes in CC0π topology: (NEUT, T2K ν_μ flux)



Fermi Motion

- Previous equations for energy reconstruction only valid for stationary nucleons
- Nucleons move inside nucleus => Fermi motion
- Energy at interaction vertex is not well defined
- Reconstructed energy is smeared around true value
- Large effect for small neutrino energies
- Several models for energy of nucleons in nucleus considered:
    - Relativistic Fermi Gas (RFG) => bad
    - Local Fermi Gas (LFG) => good
    - Spectral functions => very good



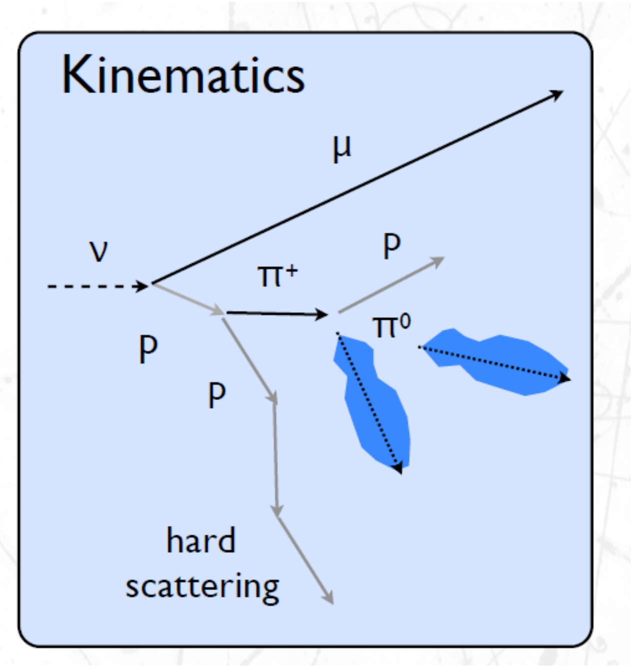


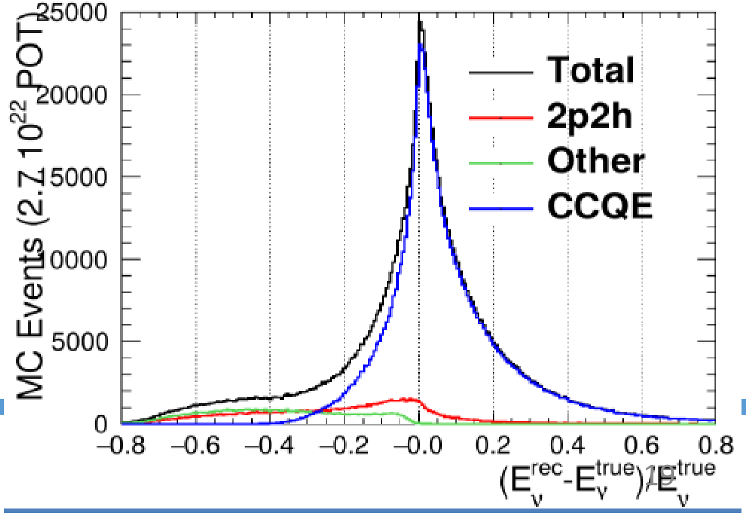
Energy Reconstruction

Kinematic approach:

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

- Simple and nice but only useful for CCQE events
- Does not take into account FSI effects
- Some particles might be “invisible” eg below Cherenkov threshold
- Ideal method for WCD



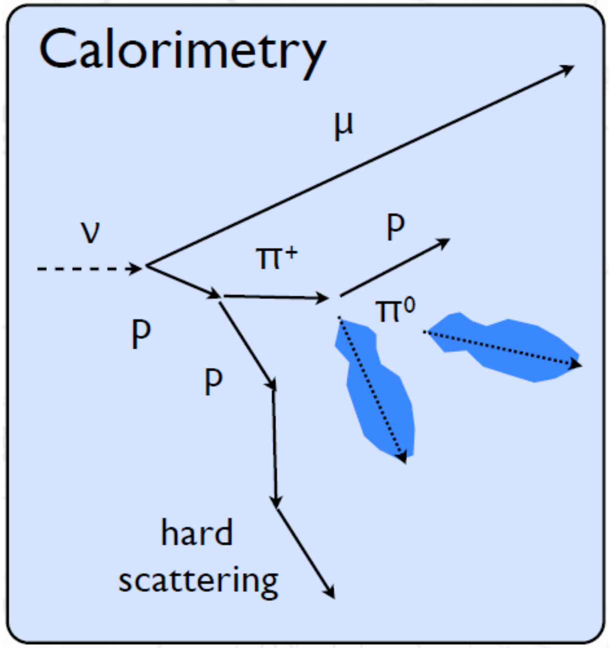


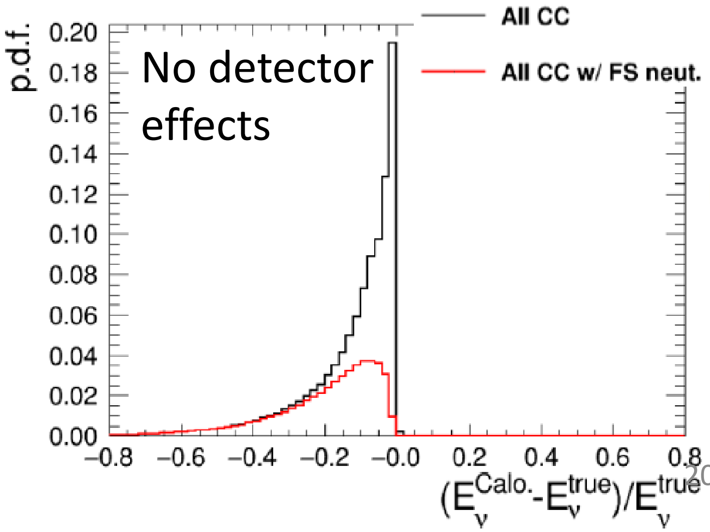
Energy Reconstruction

Calorimetric approach:

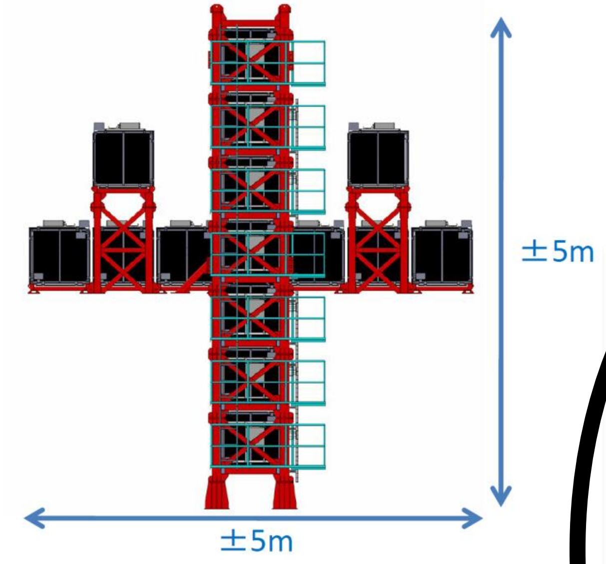
$$E_\nu^{calo} = E_\ell + E_{had.} = E_\ell + \Sigma T_p + \Sigma T_{\pi^\pm} + \Sigma E_\gamma$$

- Measure the energy of all outgoing particles and sum them to reconstruct neutrino energy
- Better estimation but far from perfect
- Problem are neutral particles, especially neutrons, carrying away energy undetected
- LAr TPC approach (DUNE) and ND280

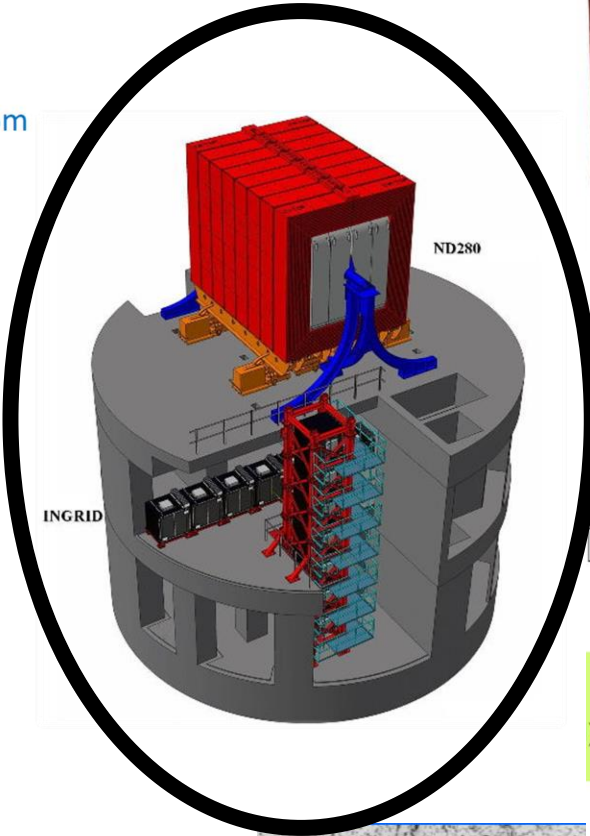


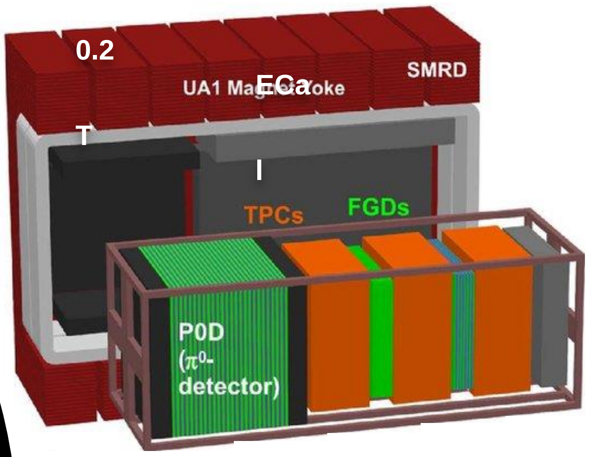


Several T2K Near Detectors

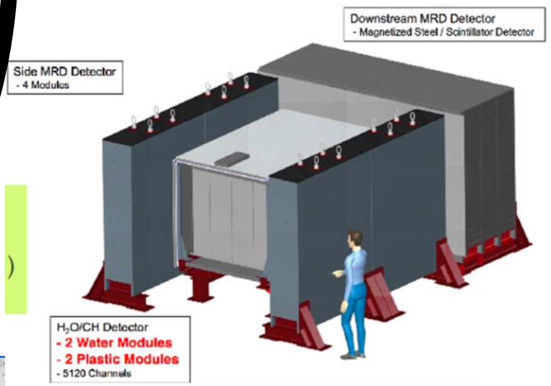


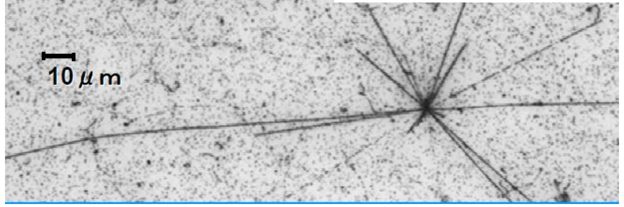
INGRID:
- On-axis
- Monitoring beam direction and flux





ND280:
- Off-axis 2.5
- Magnetized
- Cross-sections
- 2+2 tonne target mass (mainly CH)

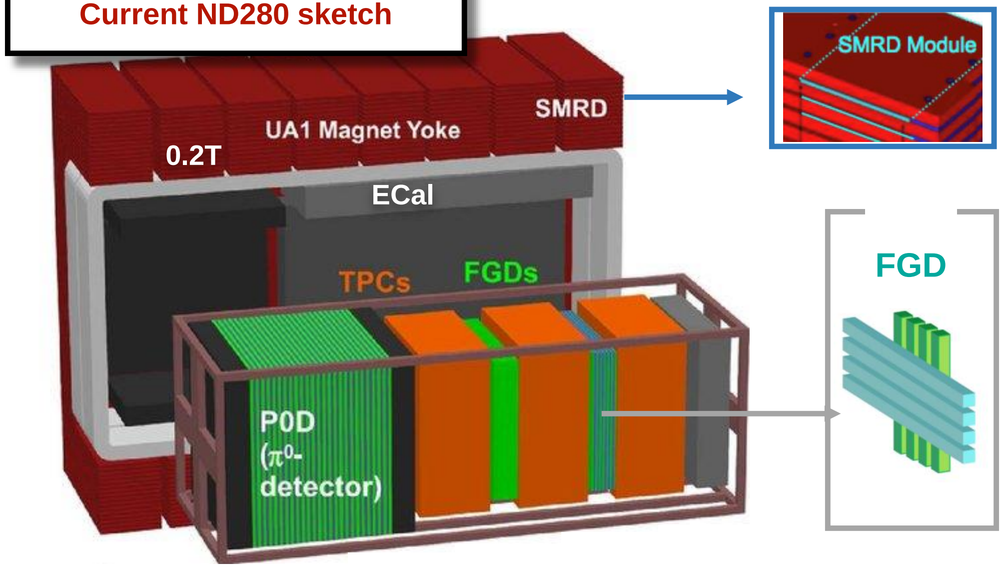




Others:
- WAGASCI
- NINJA
- Off-axis 1.5

The ND280 detector (2009-2022)

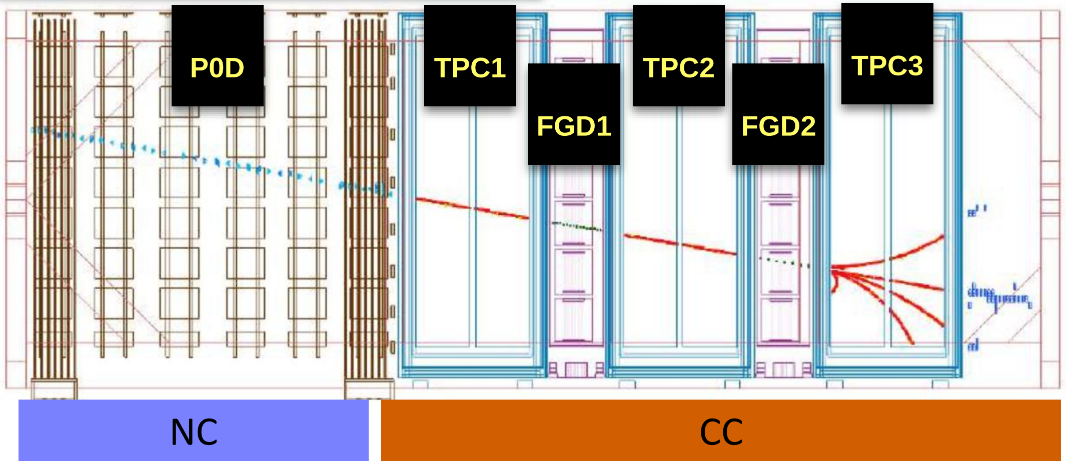
Current ND280 sketch

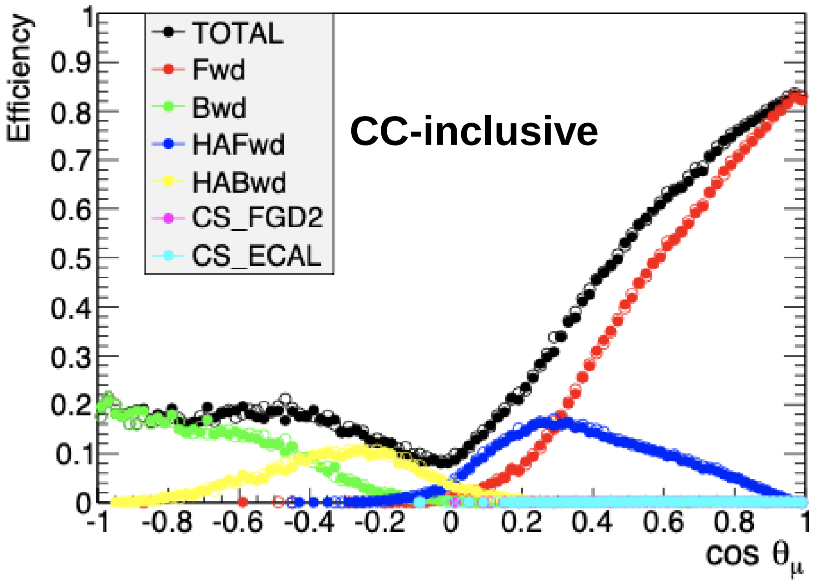


Current limitations

- Tracks w/o TPCs (high angle).
- Tracks w/o TPCs (low momentum).
- Limited timing information => no direction information
- No neutron info
- Poor electron/photon separation
- High detection threshold for protons

Event display of basket elements

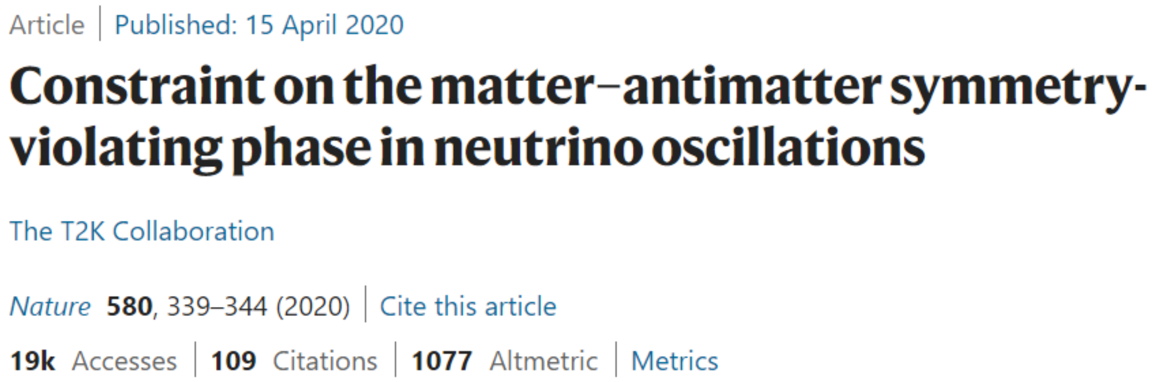




Some T2K Results

Institute for High Energy Physics

- T2K experiments reported first measurement of δCP
- Large region of δCP>0 rejected at 99.7% level
- Best fit result close to maximal CP violation
- δCP=0 excluded at 3σ, δCP=180 excluded at >2σ
- More key results in the past: First νe appearance measurement (Phys. Rev. Lett. **112**, 061802)



Article | Published: 15 April 2020

Constraint on the matter–antimatter symmetry-violating phase in neutrino oscillations

The T2K Collaboration

Nature **580**, 339–344 (2020) | Cite this article

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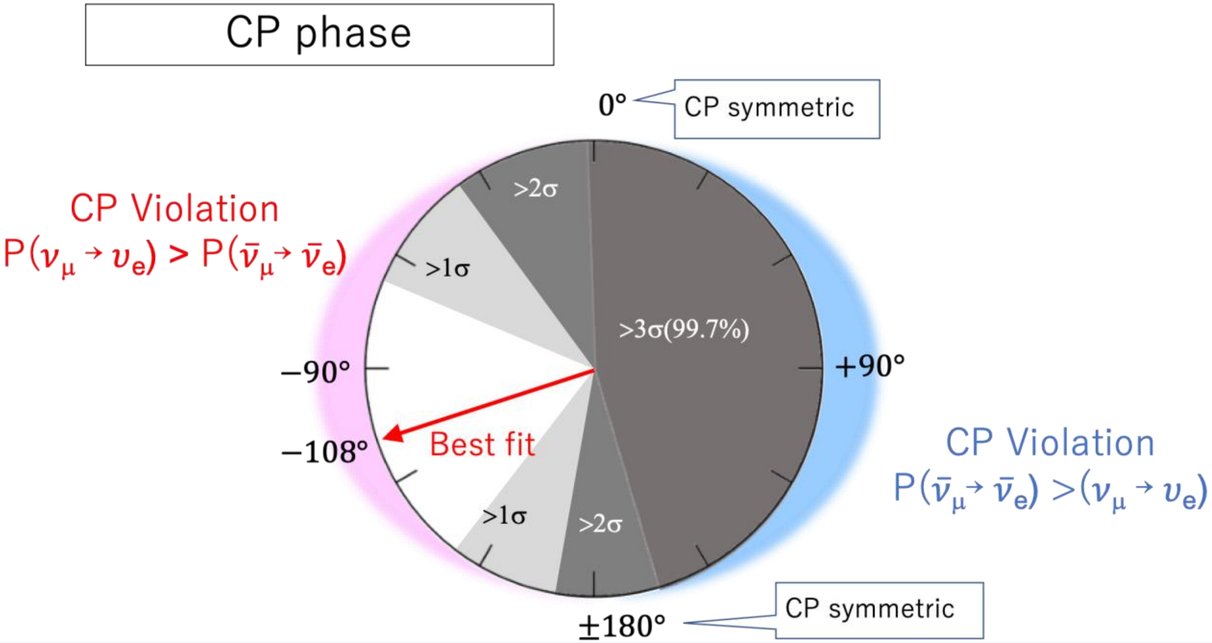
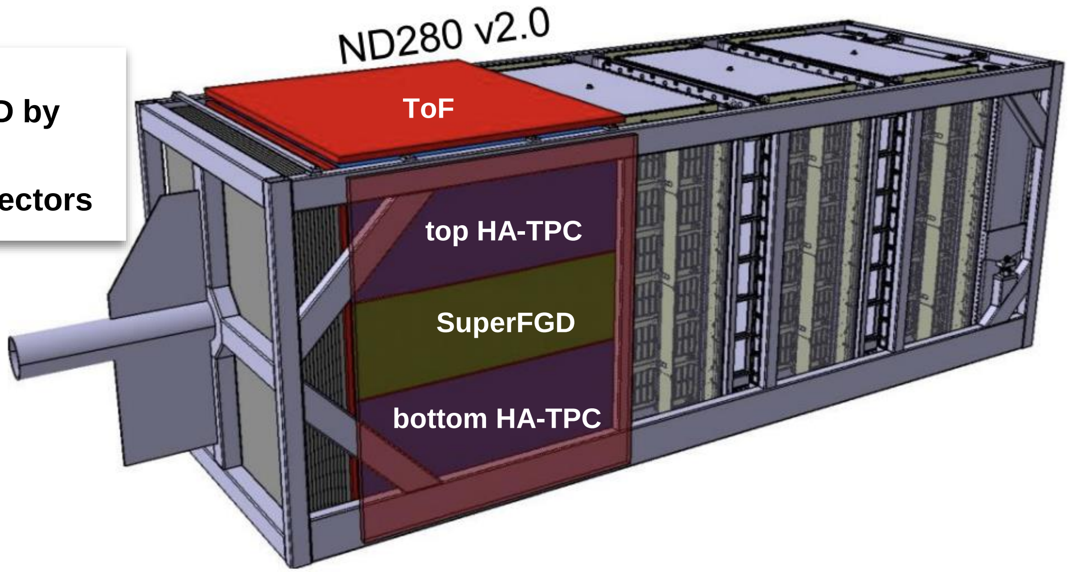


The upgraded ND280 detector

Replace P0D by

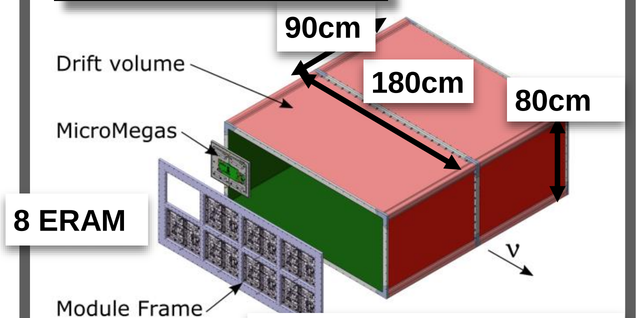
new subdetectors



Milestones

- ✦ 2018 → TDR arXiv:1901.03750
- ✦ 2023 installation

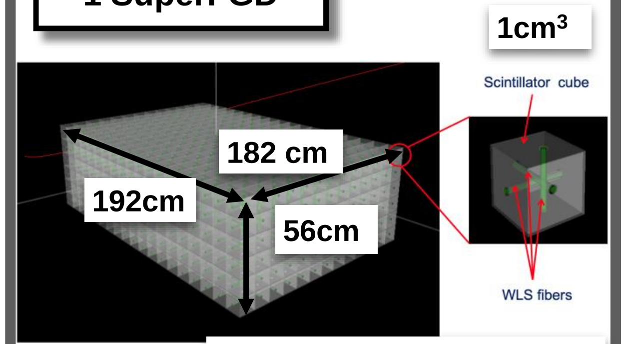
2 High Angle TPCs



New read-out concept

NIM A 957 163286 (2020)

1 SuperFGD



Novel detector concept

JINST 13, P02006 (2018)
JINST 15 P12003 (2020)

6 ToF panels

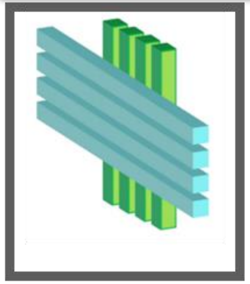
150 ps time resolution resolution

JPS Conf. Proc. 27, 011005 (2019)

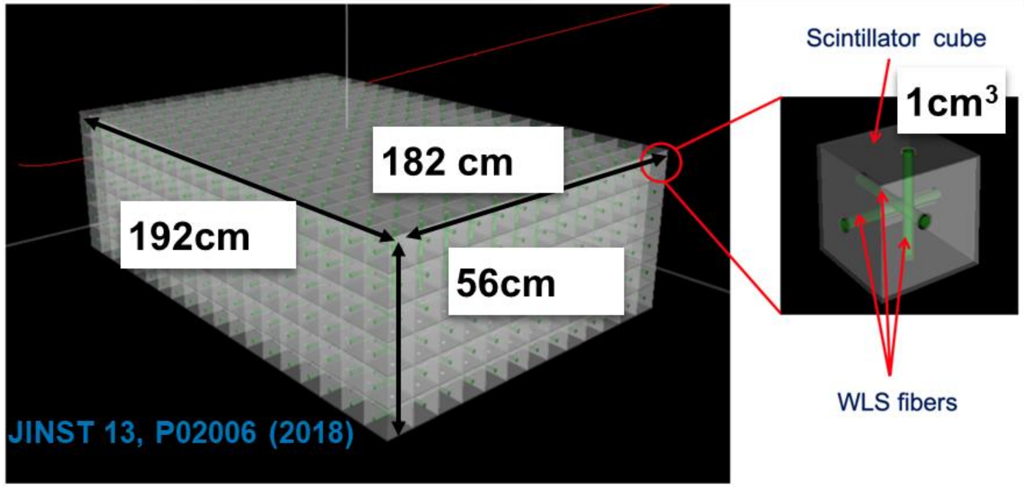
SuperFGD

- Novel scintillator tracker based on 2 million cubes
- Allows 3D reconstruction of the events
- 60k fibers/MPPC (as much as the current ND280)
- Assembly was a challenge including key material from Russia
- 2 tonne neutrino target (double as now)

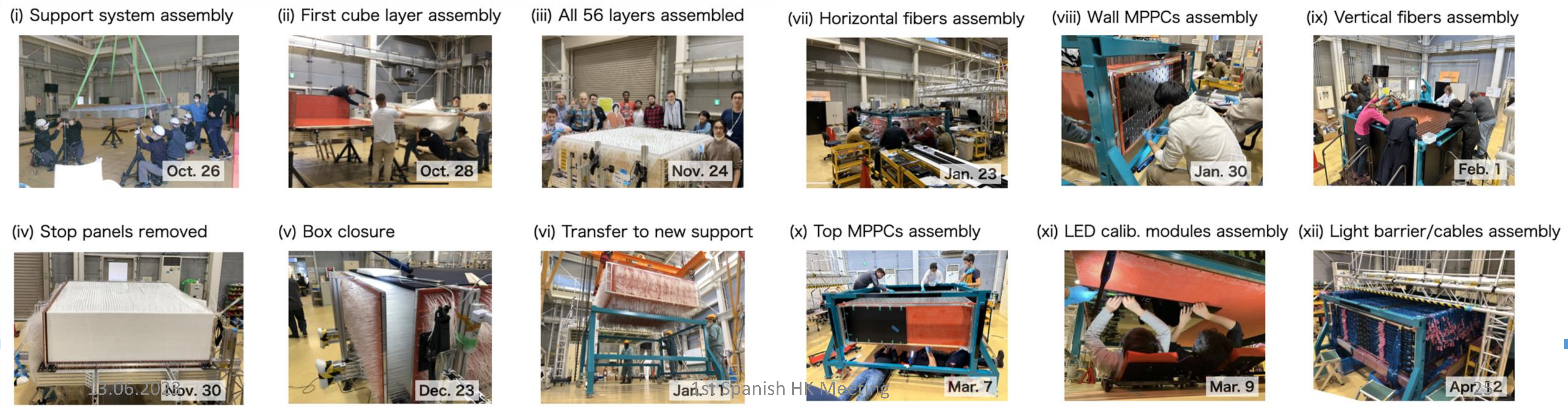
FGD concept



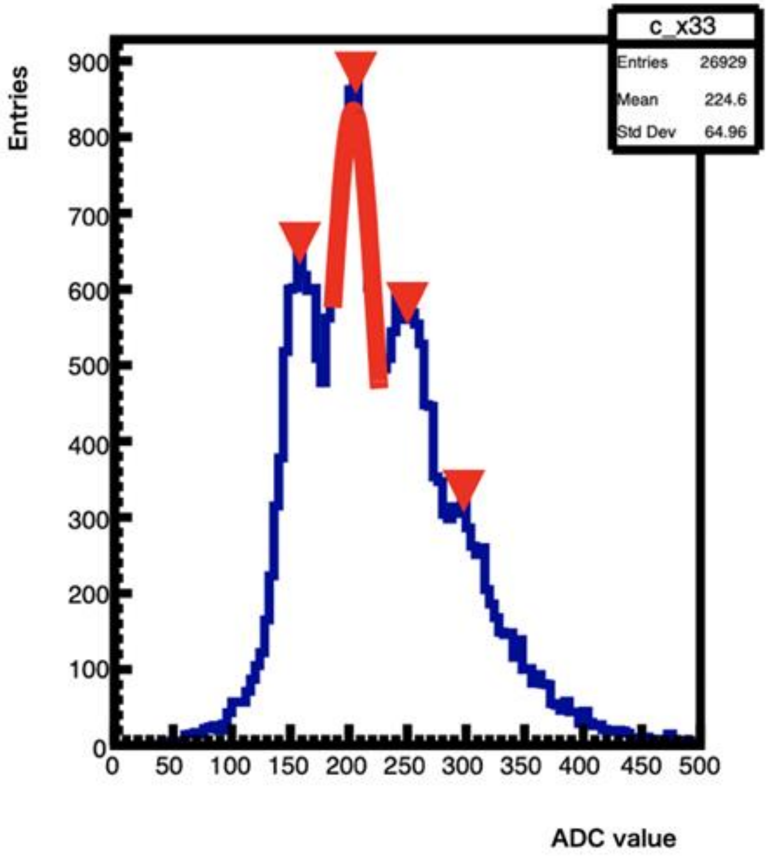
SuperFGD concept

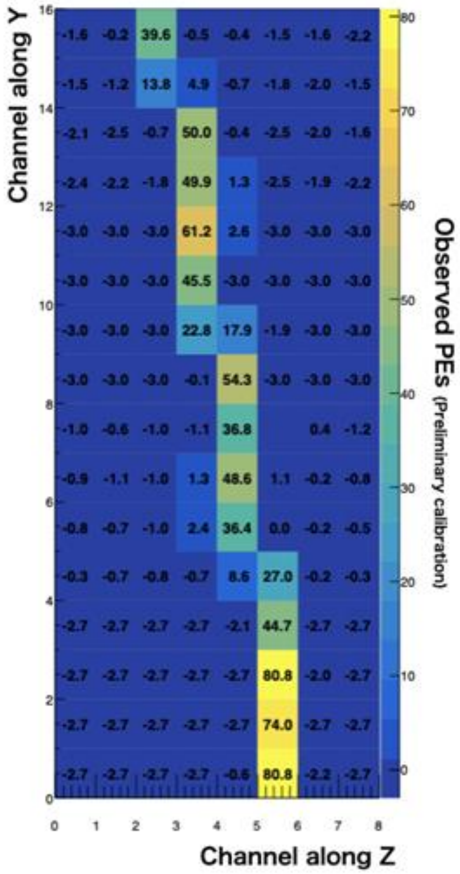


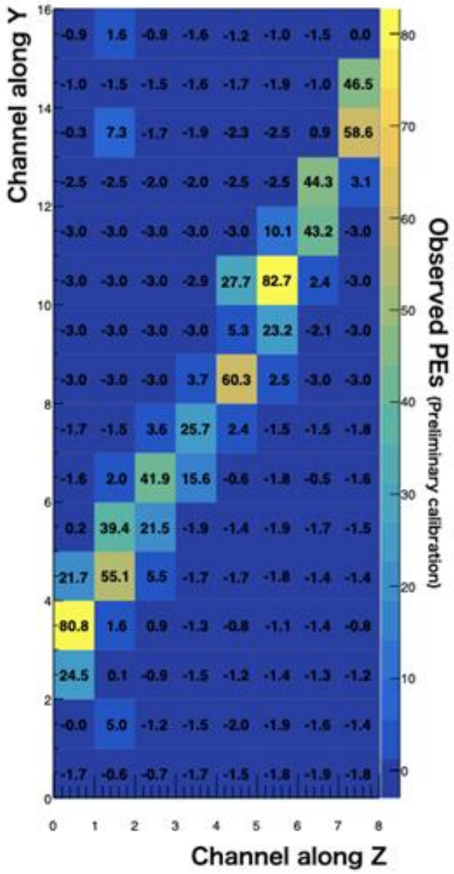
JINST 13, P02006 (2018)


(i) Support system assembly
(ii) First cube layer assembly
(iii) All 56 layers assembled
(vii) Horizontal fibers assembly
(viii) Wall MPPCs assembly
(ix) Vertical fibers assembly
(iv) Stop panels removed
(v) Box closure
(vi) Transfer to new support
(x) Top MPPCs assembly
(xi) LED calib. modules assembly
(xii) Light barrier/cables assembly

It works! First cosmics seen in April 2023!

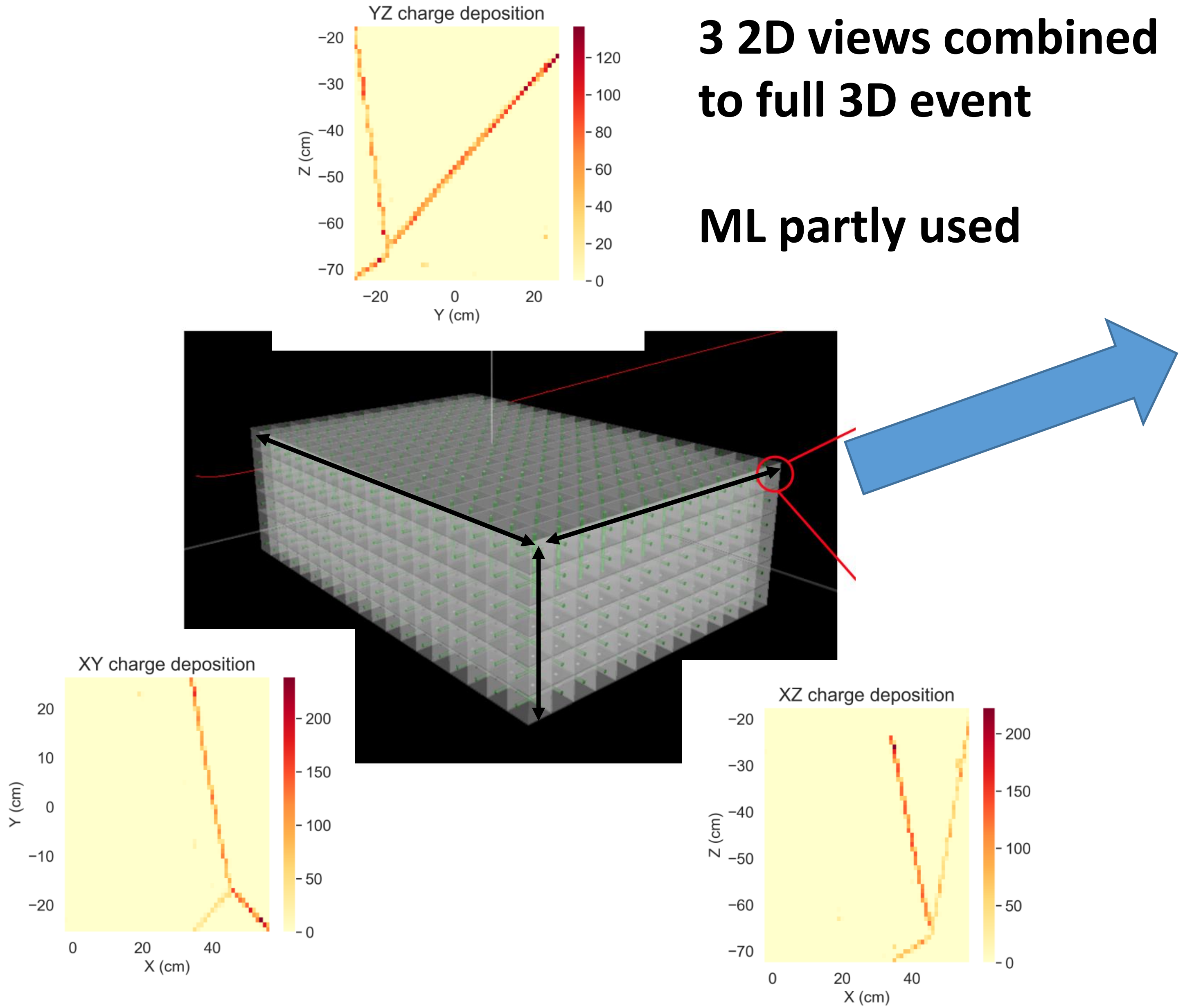


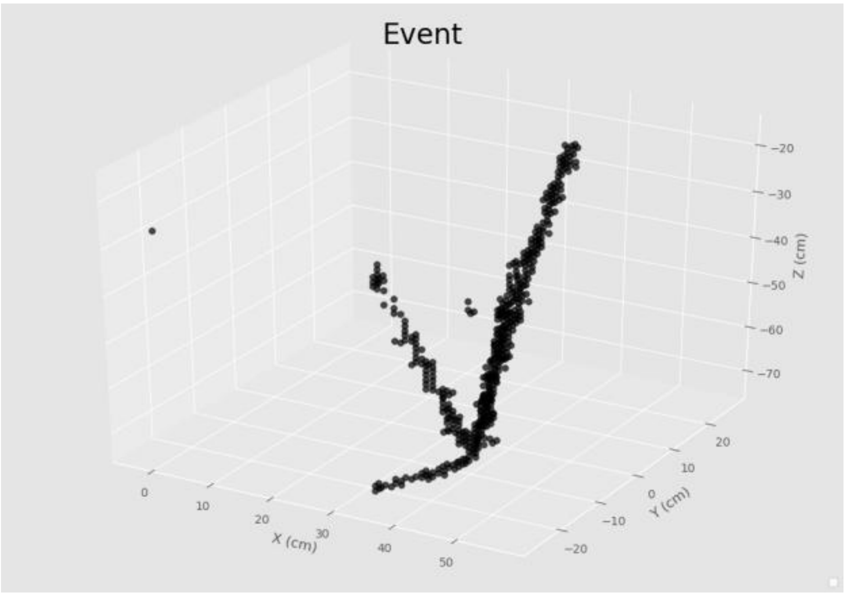




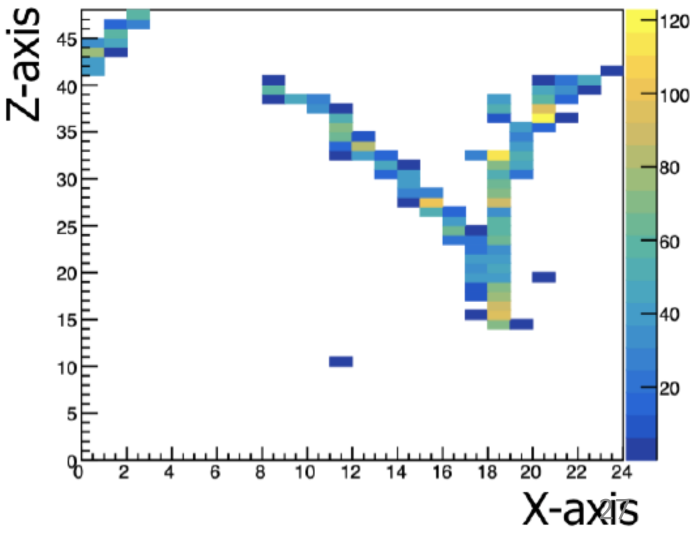
3 2D views combined to full 3D event

ML partly used





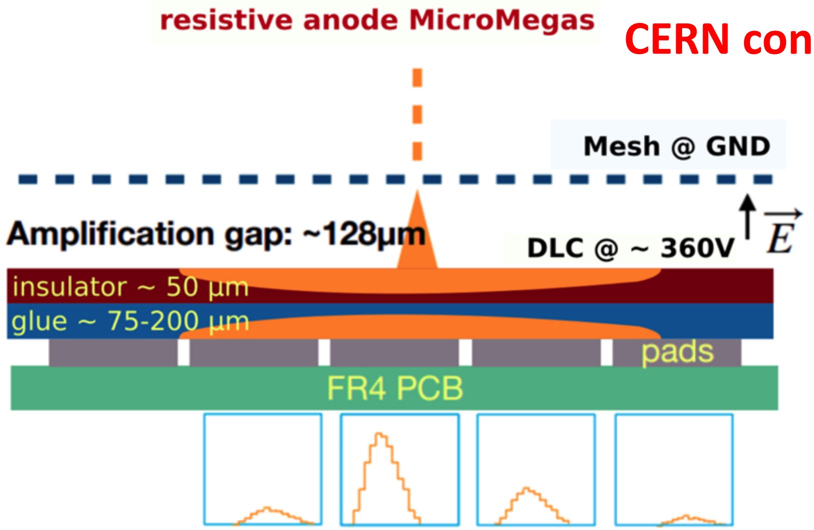
Testbeam event

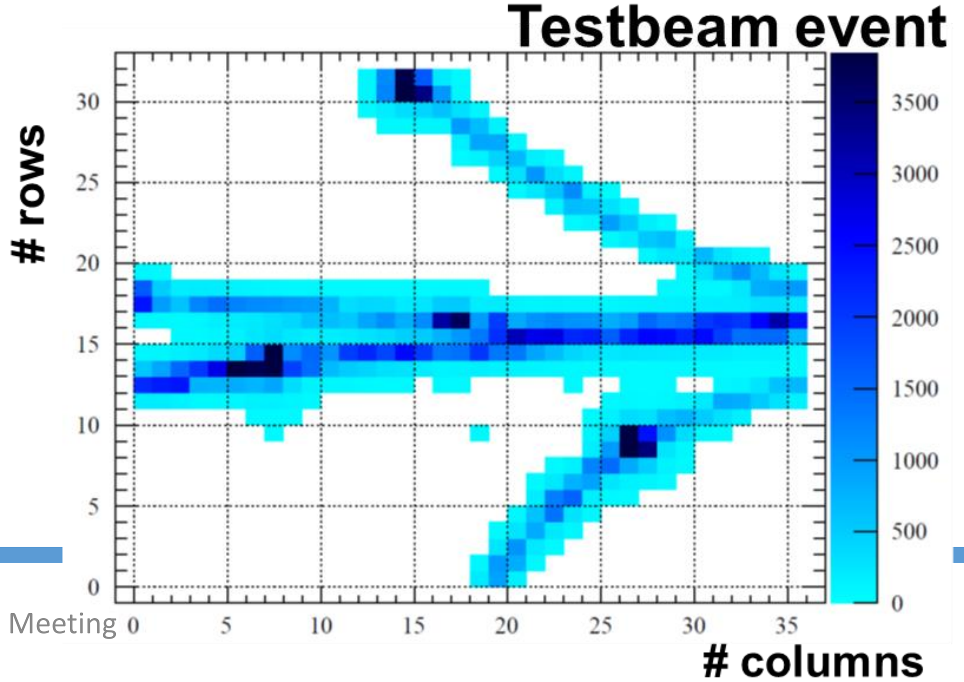


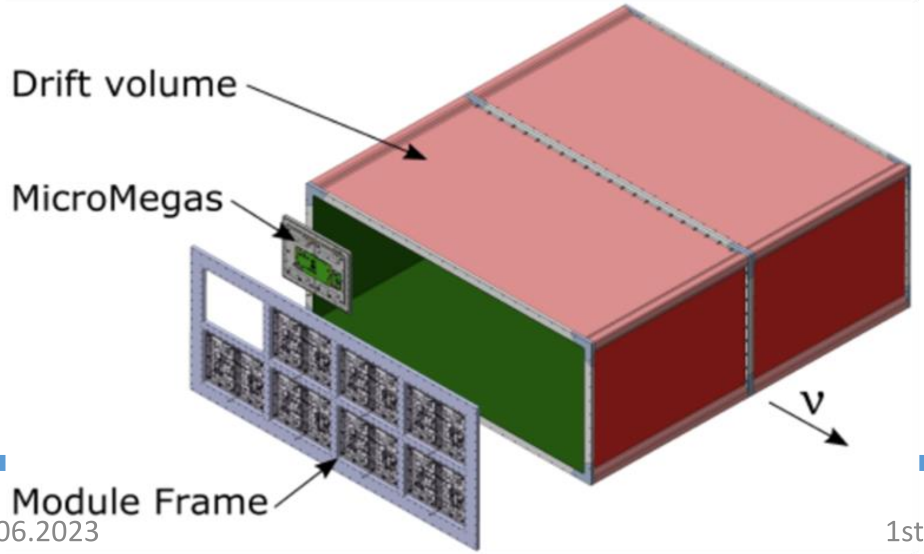
HA-TPC

- 2 HA-TPCs assembled out of field cage halves with central cathode
- **Resistive Anode MM (ERAM) readout**
- **Composite material walls**
- Both a novelties for full-size TPCs
- Particle identification + momentum measurement

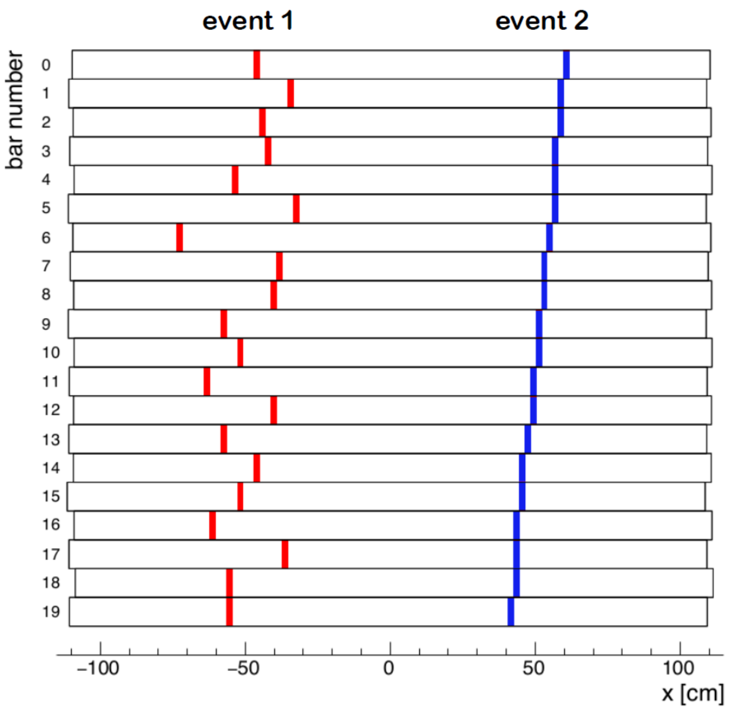
CERN contribution



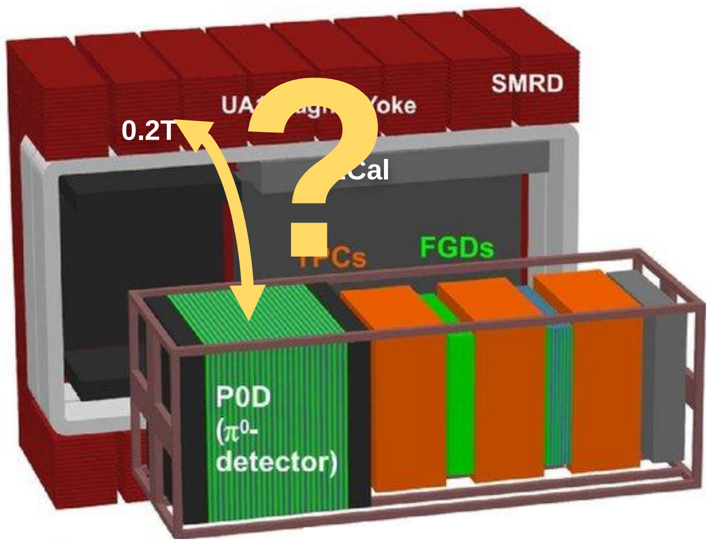


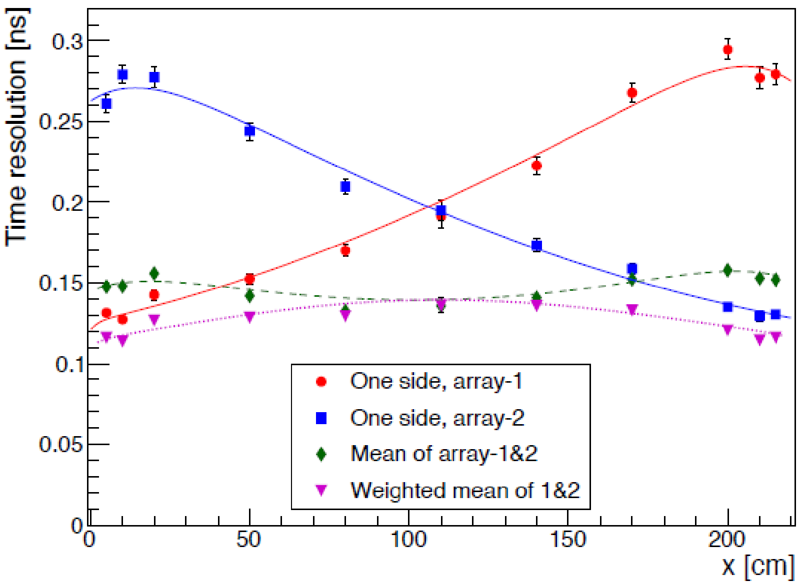


TOF



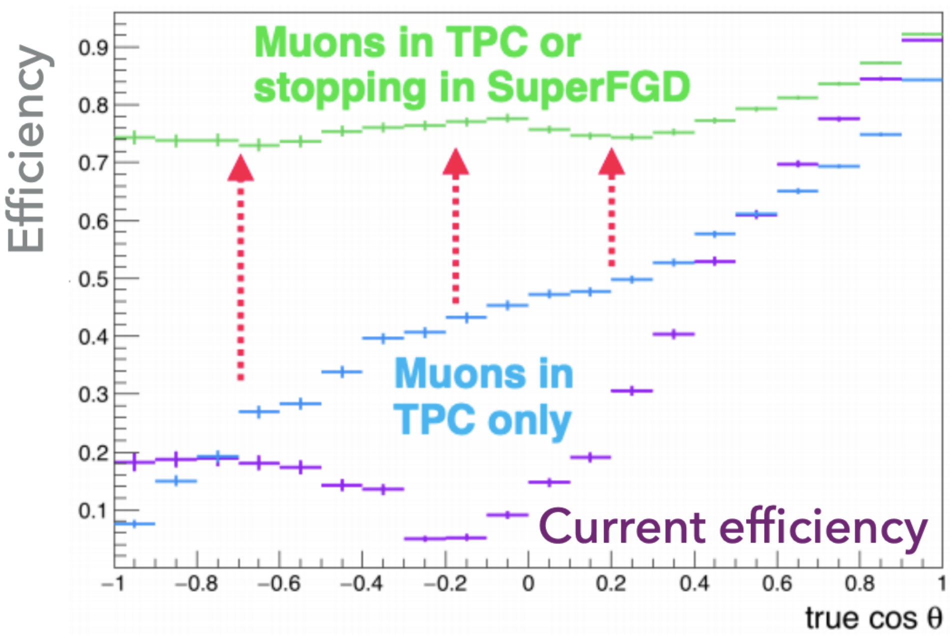
- 6 modules (2.3x2.5 m2) mounted each with 20 bars
- Double sided readout with 12 SiPMs per side
- Tested in several testbeams
- Excellent time resolution of 150 ps achieved
- Currently quality control of all modules using cosmics
- Important to determine direction of particles



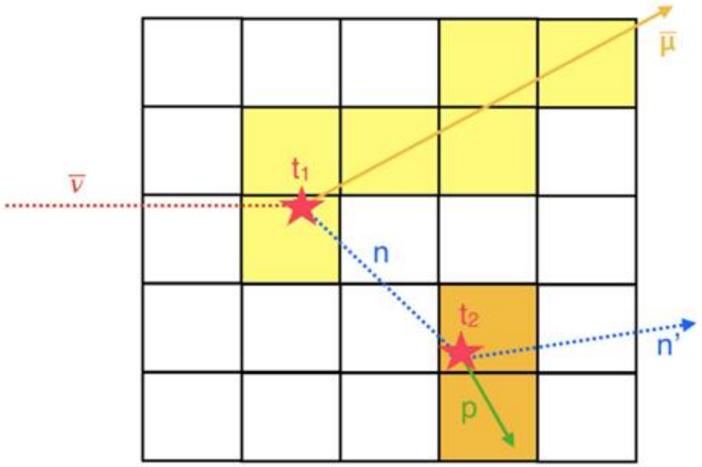


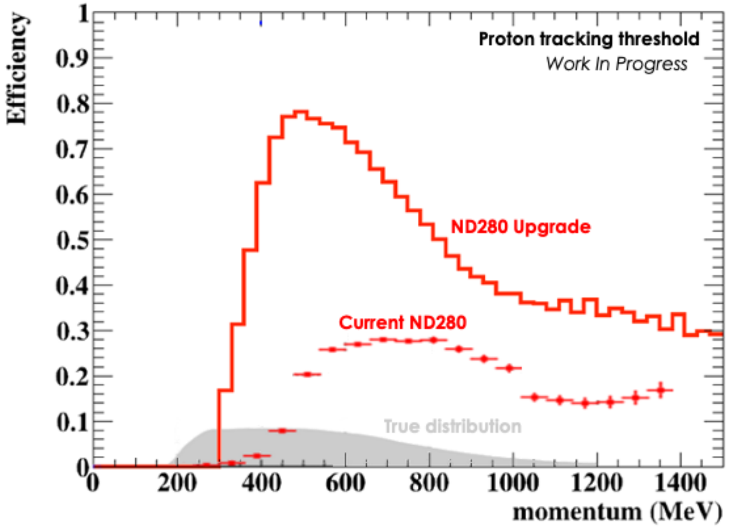
Physics Impact

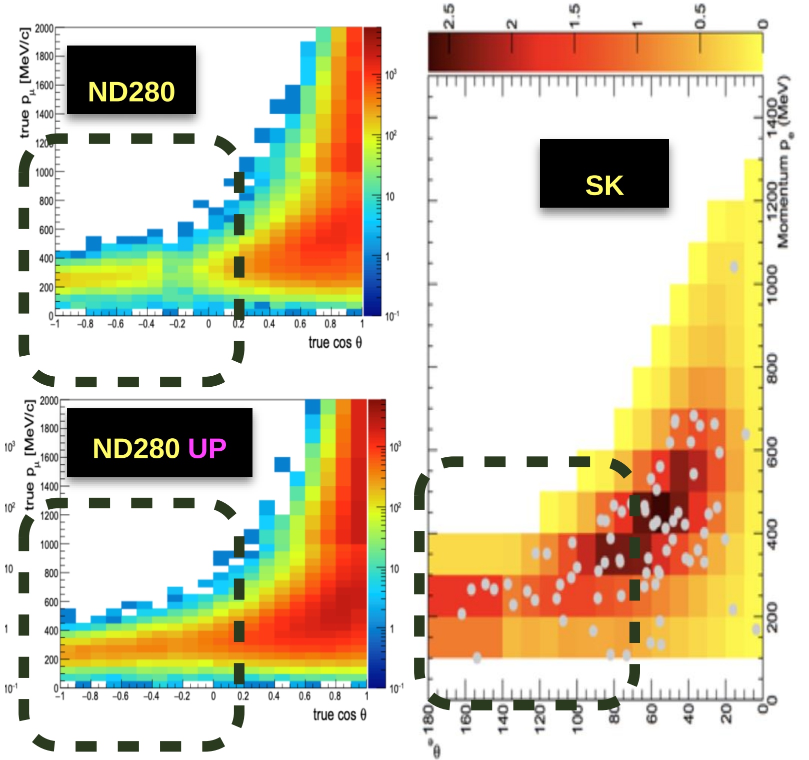
- Upgraded ND280 covering similar phase space coverage as SuperKamiokande
- Significant lower energy threshold
- Neutron detection capability
- Systematic uncertainty reduced from 6 to 4%



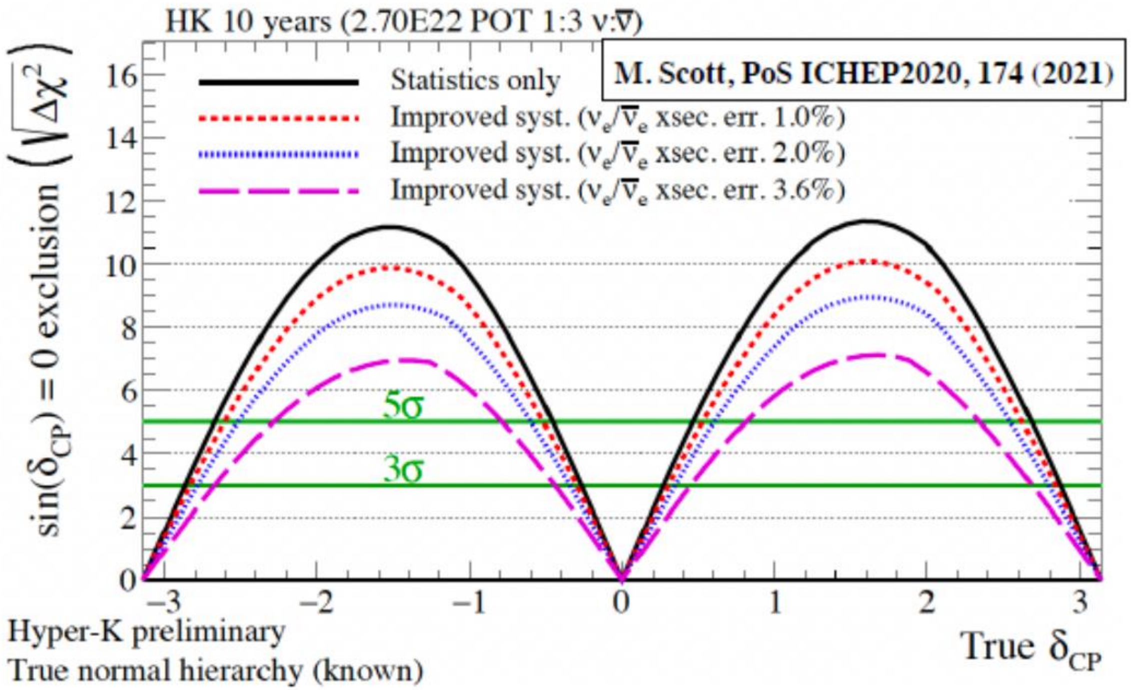
Much better cross section measurements and FSI understanding!

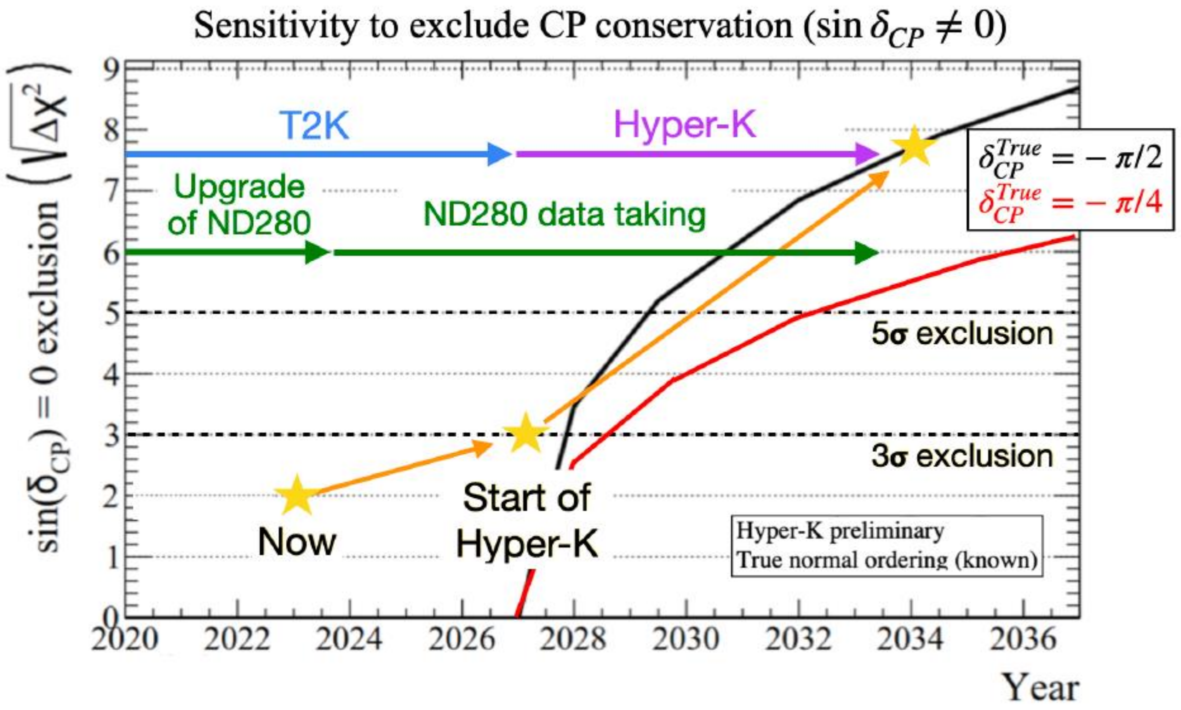






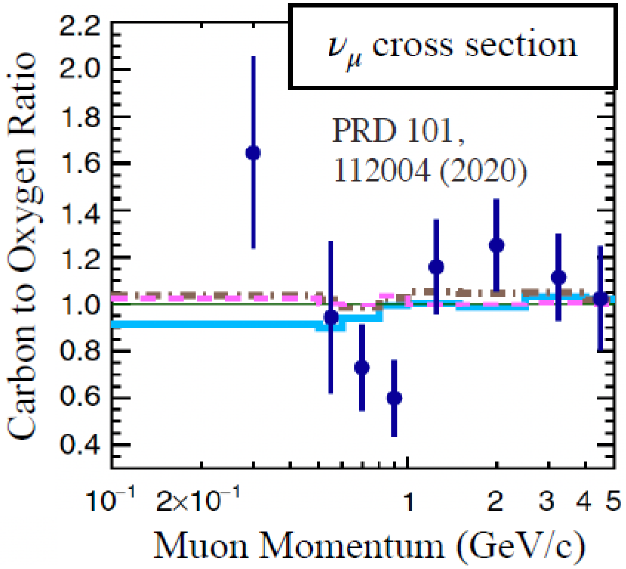
Delta CP in HyperK

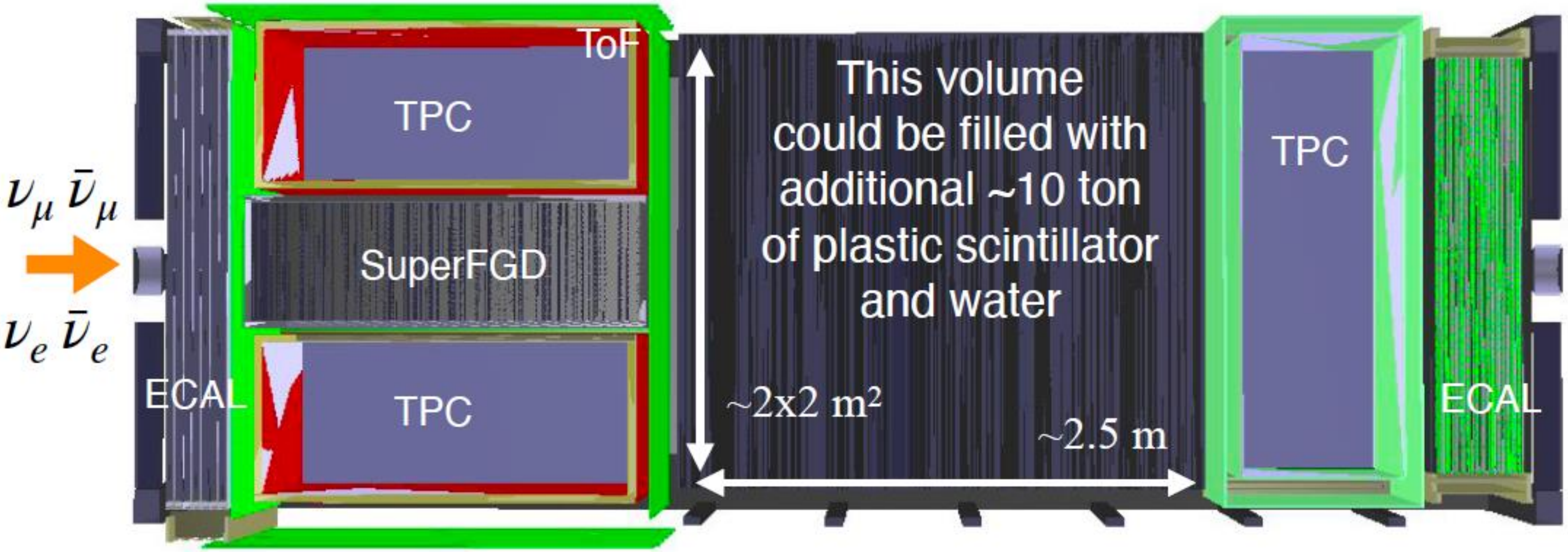




HK and ND280: What is needed?

- $\sigma(\nu_e)/\sigma(\nu_\mu)$ and $\sigma(\nu_e)/\sigma(\bar{\nu}_e)$ must be measured at theoretical uncertainty of 3%
- Cross section on water instead of carbon as in current ND280
- Work on HK ND280++ Upgrade slowly starting

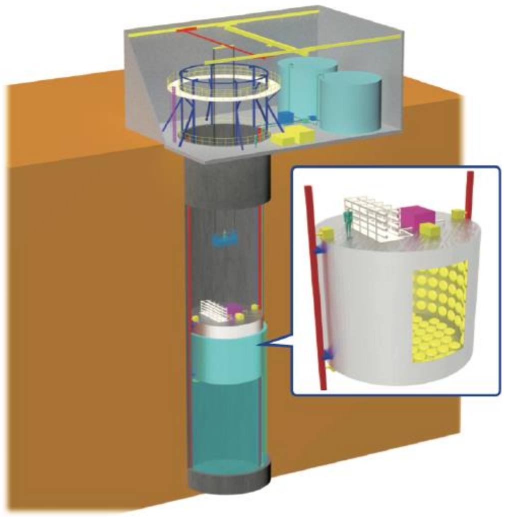


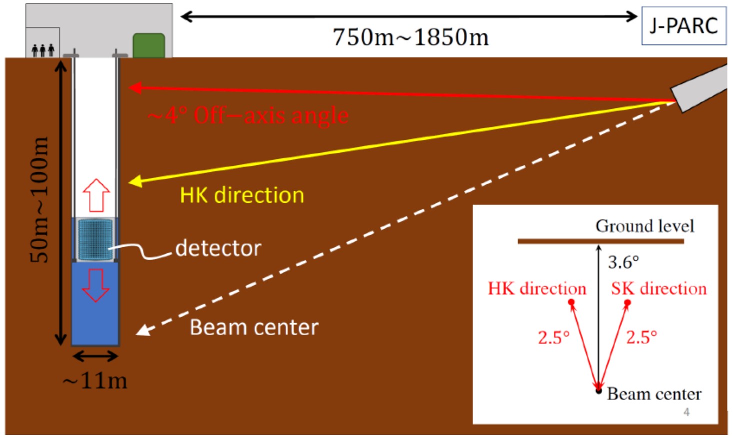


ND280 vs IWCD

	ND280++	IWCD	Advantages
Target	CH + H2O	H2O	H2O gives less systematics but not fully sensitive
Mass	4t (now) / 10t (++)	**300t**	Larger mass more statistics
Magnet	**Yes**	No	Better Particle Identification
Energy threshold	**Low**	High	Low helps to study FSI
Distance	280 m	**800 m**	Larger distance less extrapolation uncertainty to FD
Angle	Fixed (2.5°)	**Moveable**	Measure cross-sections and flux at different angles reduces uncertainties
Technology	Multi-detectors	WCD	WCD might introduce less detector uncertainties

ND280 and IWCD are complementary!





Summary

- Extracting oscillation parameters and CP violating phase from data, is highly complex process
- Near detector is the crucial detector for CP Violation measurement (cross-sections, energy reconstruction, FSI effects, background (eg NC1pi+), …)
- Upgraded ND280 will provide important information e.g. with more information about FSI crucial for energy reconstruction
- IWCD will be very useful to reduce uncertainties further and complementary to ND280
- HK will be a high statistics experiment and in contrast to now being limited by systematic uncertainties
- ND280 Upgrade++ for HK is under consideration
- There are possibilities to join the efforts e.g. on event reconstruction level

Backup

Neutrino Oscillation Theory

Based on some basic assumptions:

- 3 mass eigenstates ("true neutrinos"): $\nu_{1,2,3}$ relevant for transport
- 3 flavour eigenstates: $\nu_{e,\mu,\tau}$ relevant for production/detection via weak force
- Relation between both eigenstates defined by PMNS matrix $\boldsymbol{U}$

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

- PMNS matrix: 3 mixing angles, 1 CP violating phase
- Flavour oscillations possible if $m_{1,2,3} \neq 0$ and not identical

PMNS Matrix

- Useful representation of the PMNS matrix:

Pontecorvo-Maki-Nakagawa-Sakata

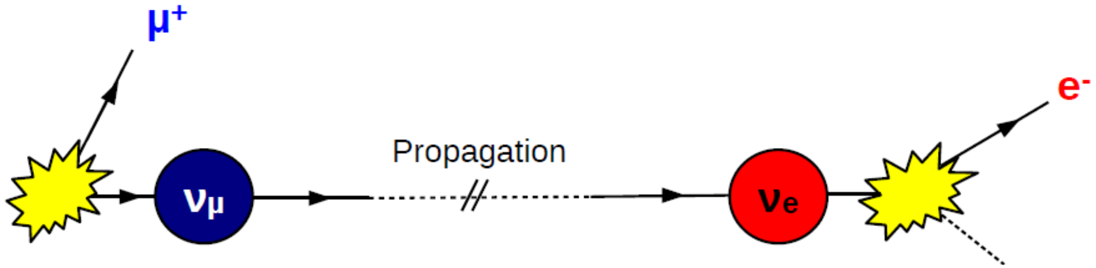
$$U_{\mathrm{PMNS}} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} = \underset{\text{Atmospheric}}{\overset{\theta_{23} \sim 45^\circ}{\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}}} \underset{\text{Reactor/accelerator}}{\overset{\theta_{13} \sim 9^\circ}{\begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix}}} \underset{\text{Solar}}{\overset{\theta_{12} \sim 30^\circ}{\begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}}$$

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

- Probability of oscillation from flavour α to flavour β after distance L:

$$P_{\nu_\alpha \to \nu_\beta} = |\langle \nu_\beta(L) | \nu_\alpha \rangle|^2$$

$$= |\sum_i U^*_{\alpha i} U_{\beta i} e^{-i\frac{m_i^2 L}{2E_\nu}}|^2$$

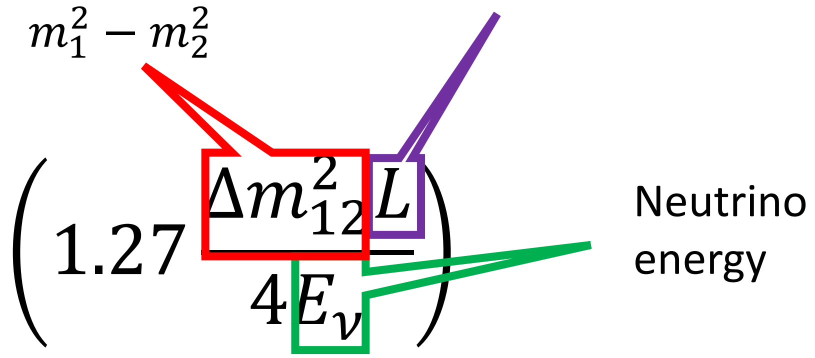


2 Neutrino Oscillations

- Reasonable simplification in many cases: 2 neutrino oscillations
- Instead of 3 mixing angles only one:

$$\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

- Starting with pure ν_μ beam we might detect after distance, L, ν_e in the beam
- Probability:



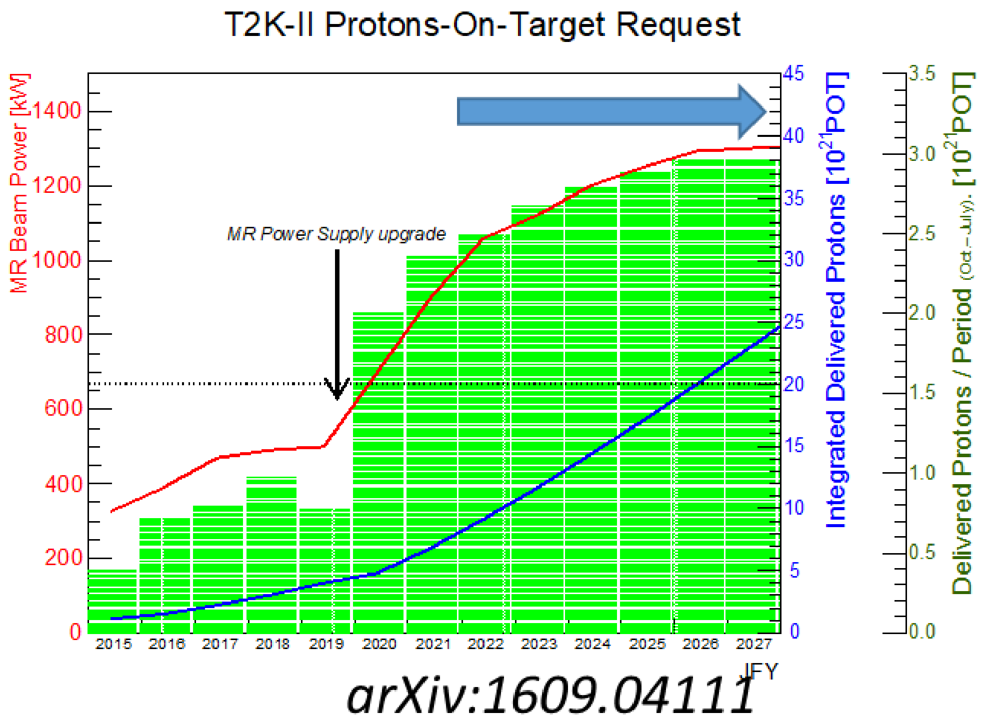
$$P(\nu_\mu \to \nu_e) = \sin^2(2\theta)\sin^2\left(1.27\frac{\Delta m_{12}^2 L}{4E_\nu}\right)$$

$m_1^2 - m_2^2$

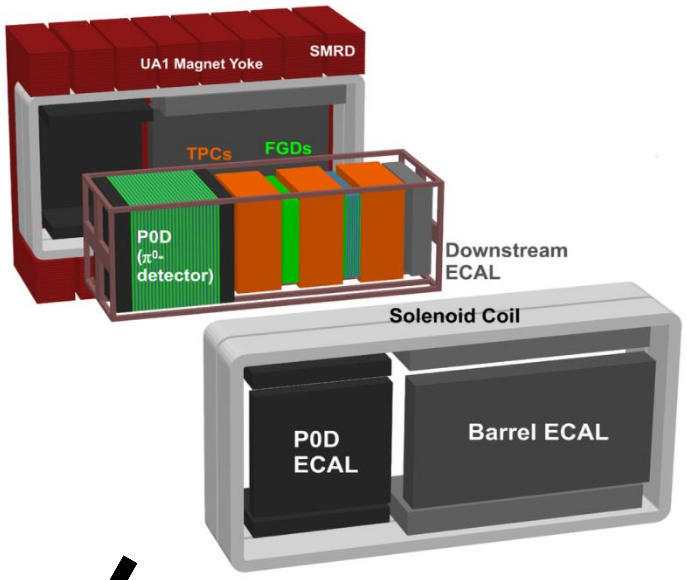
Neutrino energy

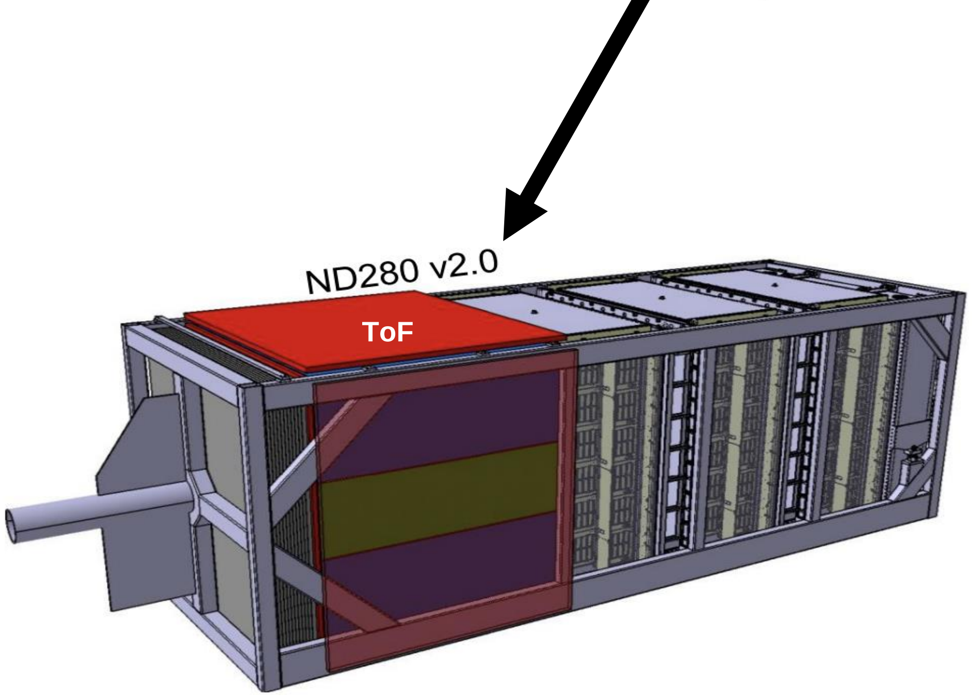
T2K-II (2023-2026)

- New subdetectors for ND280
- beam power upgrade: 0.5 MW → 750 kW (→ 1.3 MW HyperK)
- statistics: 3E21 POT (2018) → 1E22 POT (2026)
- aim: systematics from 5-6% to 4%
- Aim for CPV observation in optimal scenario at 3σ



arXiv:1609.04111





More complications: Matter Effects

- Even without CP violation, there is:

$$P\left(\vartheta_\mu^L \rightarrow \vartheta_e^L\right) \neq P\left(\overline{\vartheta_\mu^R} \rightarrow \overline{\vartheta_e^R}\right)$$

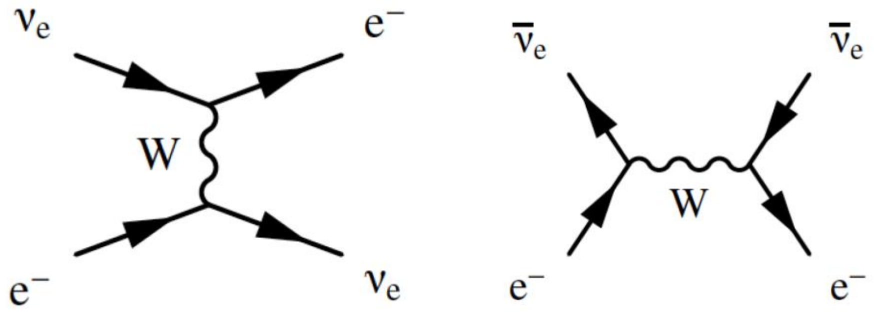
- Neutrinos cross the Earth and there are only electrons but no positrons!
- Corresponds to additional potential V:

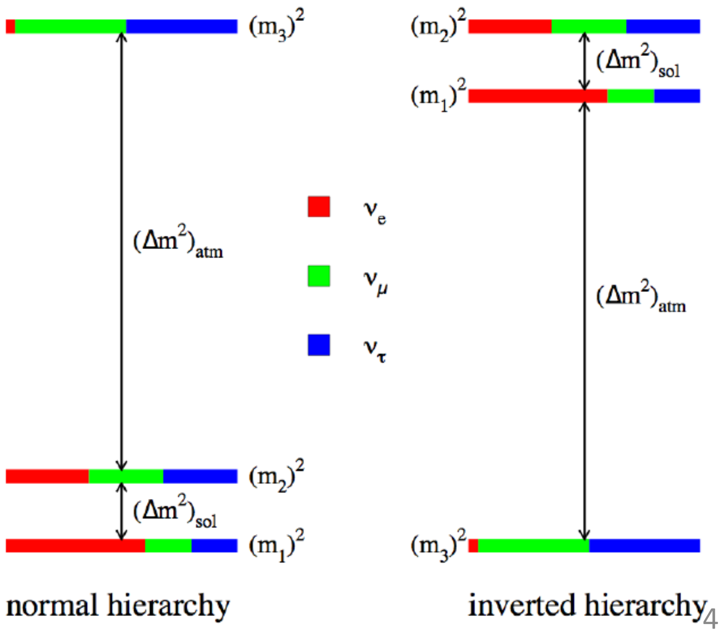
$$\mathrm{V} = \pm\sqrt{2}G_F n_e$$

GF: Fermi const., ne: electron number, sign depends on neutrinos or anti-neutrinos

- Depends on mass hierarchy in addition: normal preferred at 3σ level by SK atmospheric neutrinos

Weak forward scattering

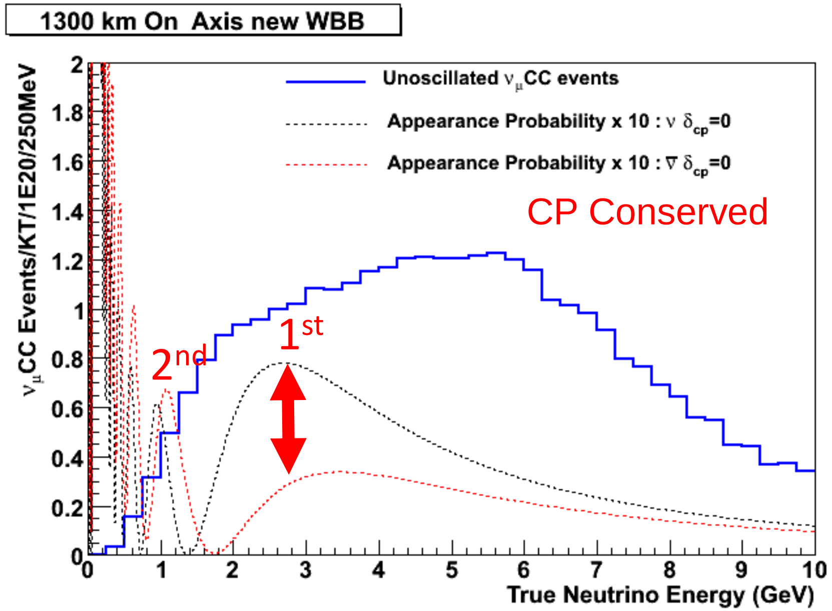


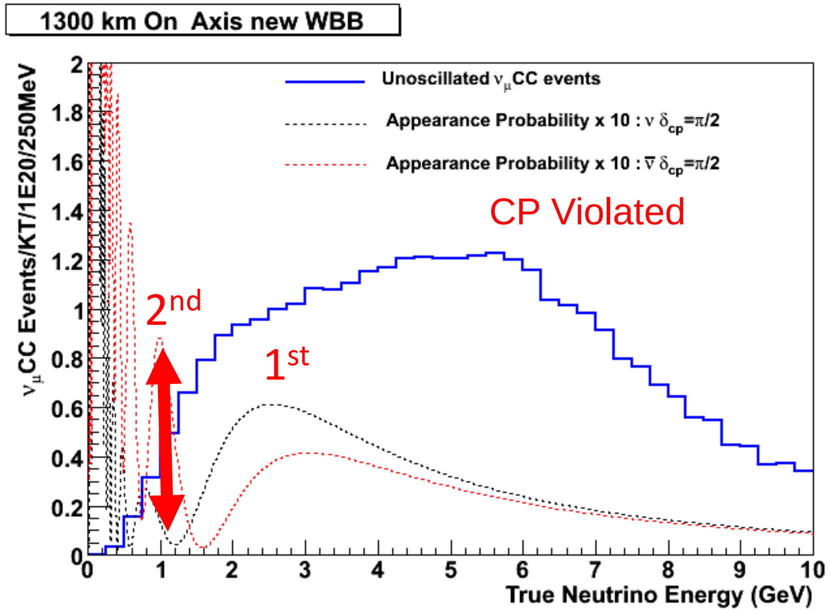


2 Approaches: Large Baseline

L > 1000 km

- Use wideband neutrino energy beam => on-axis
- Use high energy (E_ν>2 GeV) 1st maximum for mass hierarchy
- Use low energy 2nd maximum for CP violation

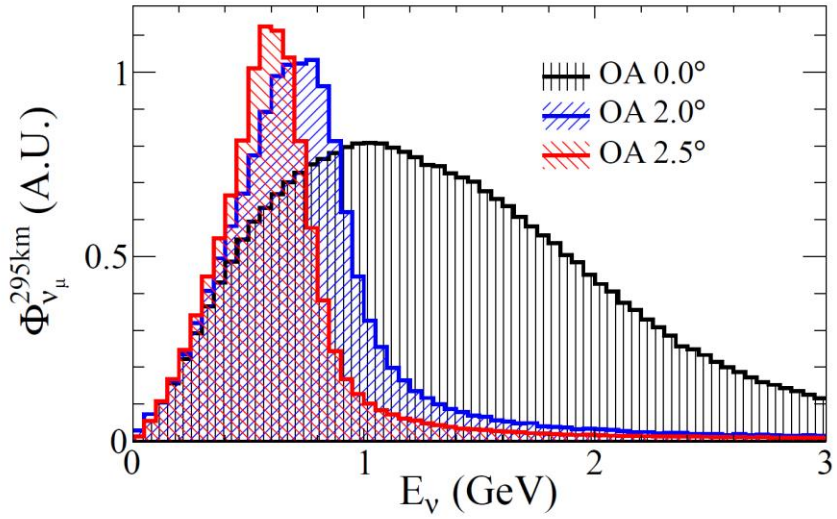




2 Approaches: Shorter Baseline

L ≈ few hundred km

- Baseline so short that matter effects have almost no impact
- Focus on 1st maximum => E_ν<1 GeV
- Aim on maximal flux at E_ν^{max} => off-axis configuration
- To improve sensitivity use mass hierarchy from other measurements or add another detector at larger L



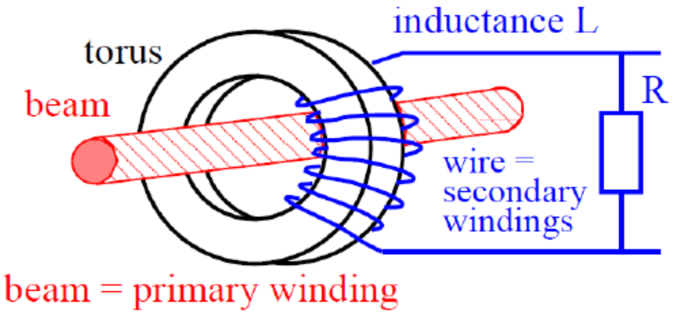
(Hyper-KK)

Near Detector and Uncertainties

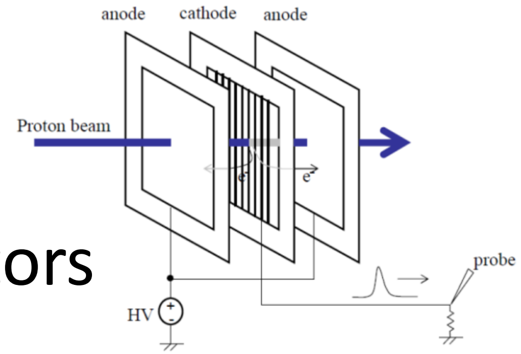
- More complicated to extract but ND provides: $\Phi\sigma$
- To measure cross-sections, we need to now the neutrino flux
- One single ND, cannot provide both independently
- Best approach constraint flux initial uncertainty by external data
- ND also provides information about Final State Interactions (see later)
- Significant uncertainties which can be grouped in 3 types:
  - Flux uncertainties
  - Cross-section uncertainties
  - Detector uncertainties

Proton Beam

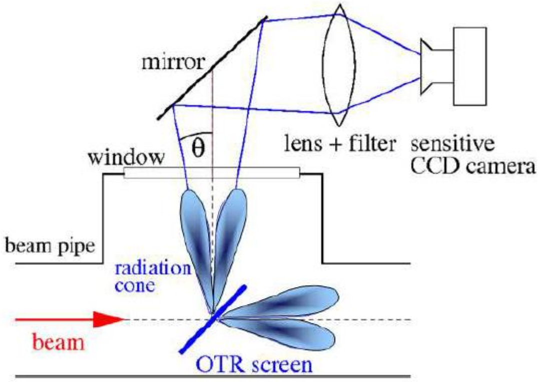
- The quality of the proton beam affects the neutrino flux
- 3 most relevant parameters are:
  - Beam intensity
  - Beam position
  - Beam profile



- Intensity: e.g. by current transformers with precision < 0.5% (NUMI), < 2.7% (T2K, aiming on 2%)

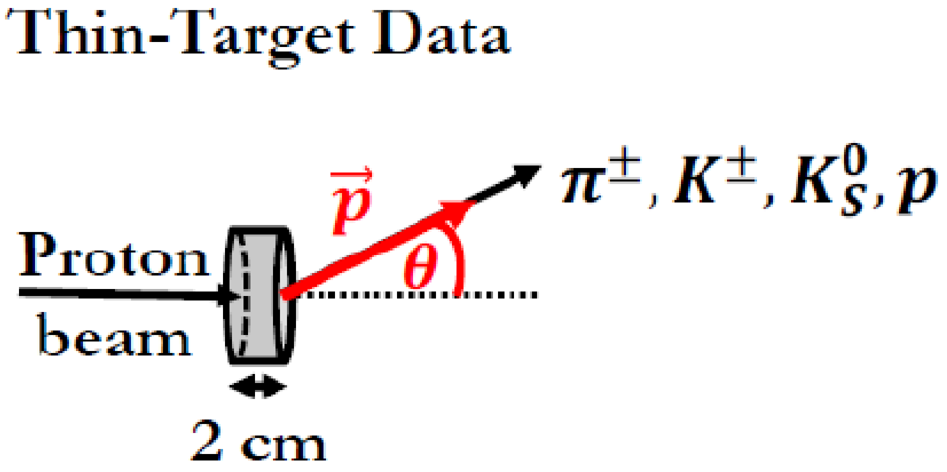


- Positon and profile: by segmented secondary emission monitors with precision on 100-200 μm level or by optical transition radiation monitors < 500 μm
- Measurement close to target crucial

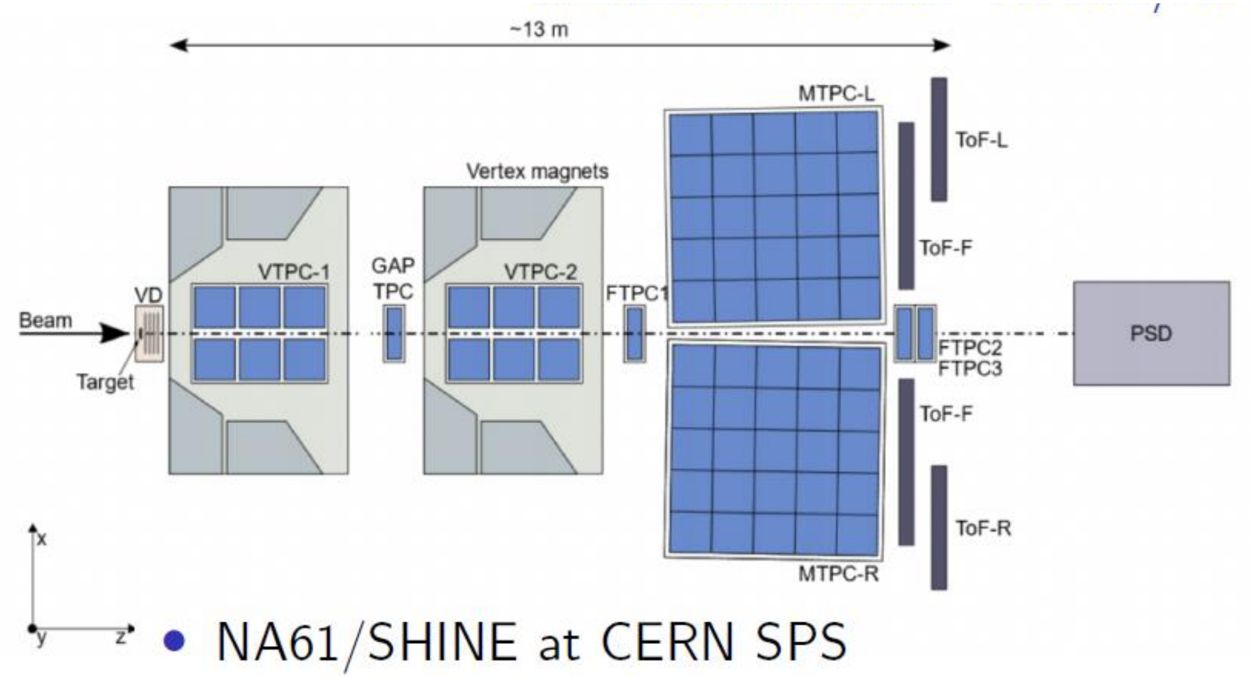


Hadron Production

- Hadron production is a major uncertainty for the neutrino flux
- Knowledge of meson production double differential cross-section in function of angle and momentum needed
- Cannot be obtained in-situ but dedicated experiments are needed
- Several experiments doing this measurement over the last decades with different targets and proton energies



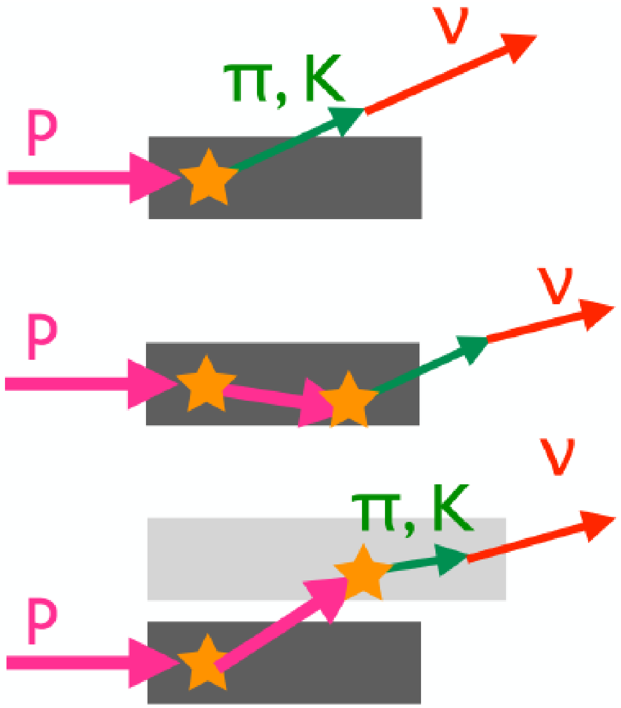
NA61/SHINE



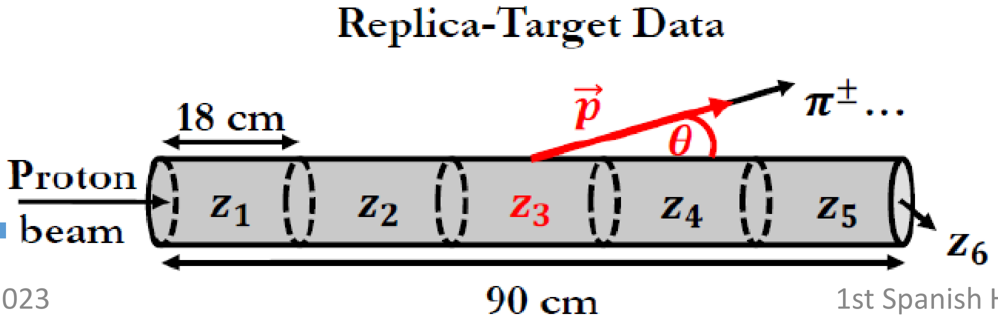
- NA61/SHINE at CERN SPS
- Secondary hadron beams between 13 GeV/c and 350 GeV/c
- Large acceptance for charged particles with good momentum and particle identification resolution
- Thin and replica target data
- Future upgrades to allow for <13 GeV/c proposed

Proton Interactions

	in-target primary int.	other than the in-target primary int. (out of target int.)
ν_μ	63.2%	36.8% (12.4%)
$\bar{\nu}_\mu$	41.5%	58.5% (45.1%)
ν_e	61.7%	38.3% (12.7%)
$\bar{\nu}_e$	54.0%	46.0% (27.2%)



- Most data in the past was taken with thin data
- Real target is long
- High probability of secondary integrations in target
- Or in surrounding material
- Large effect for wrong-sign neutrinos
- Solution: take data with exact replica of neutrino target


Replica-Target Data

Magnetic Horn System

- Mesons leaving the target are mixture of matter and anti-matter
- Need a system to be able to select one charge polarity
- Magnetic horn developed by *S. van der Meer*
- Creates a magnetic field focussing one polarity and defocussing the other polarity depending on current orientation
- Suppresses wrong-sign flux contribution to below 1%
- Normally several horns in series for better flux quality

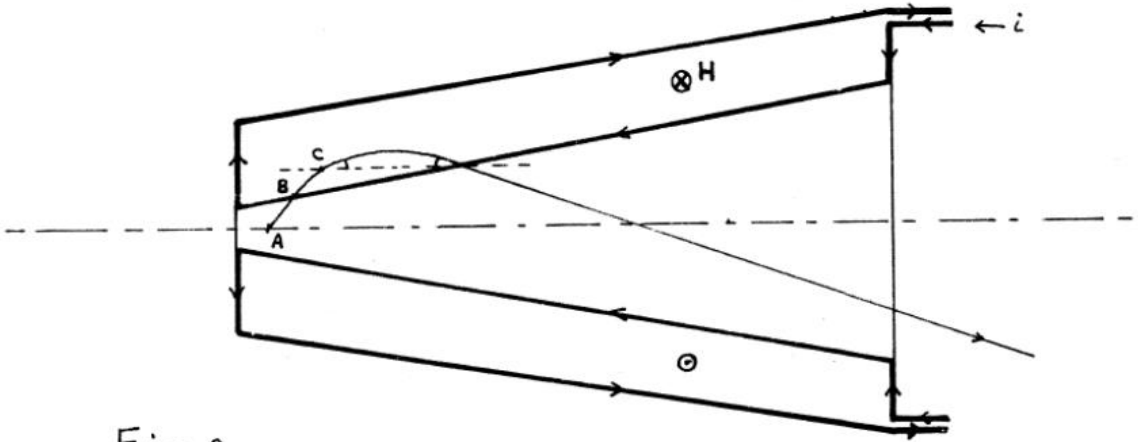
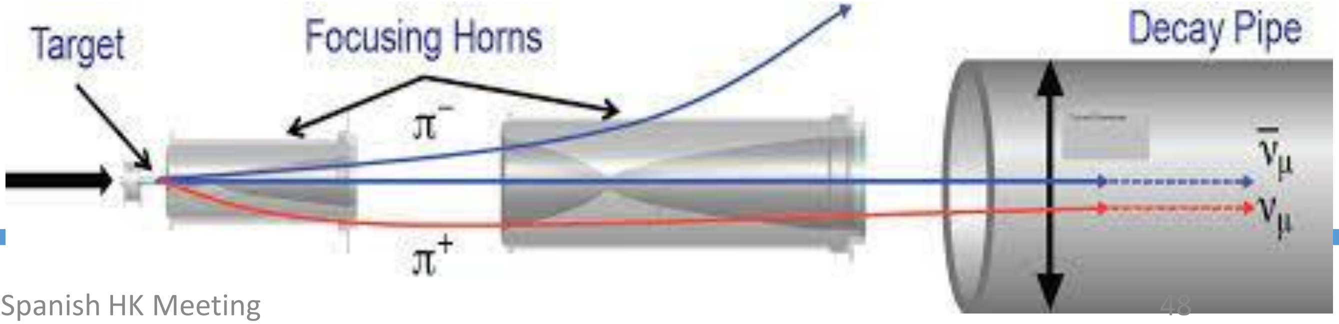
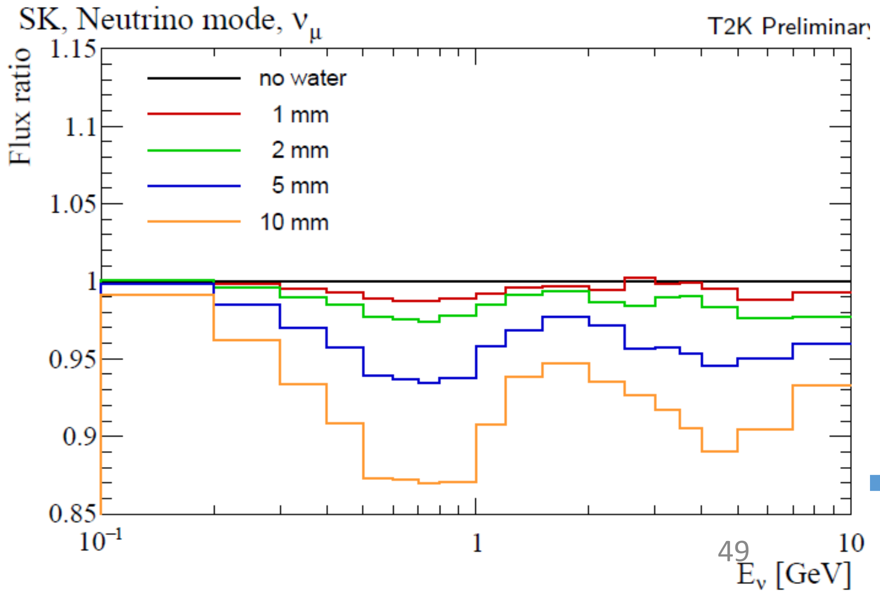


Fig.2



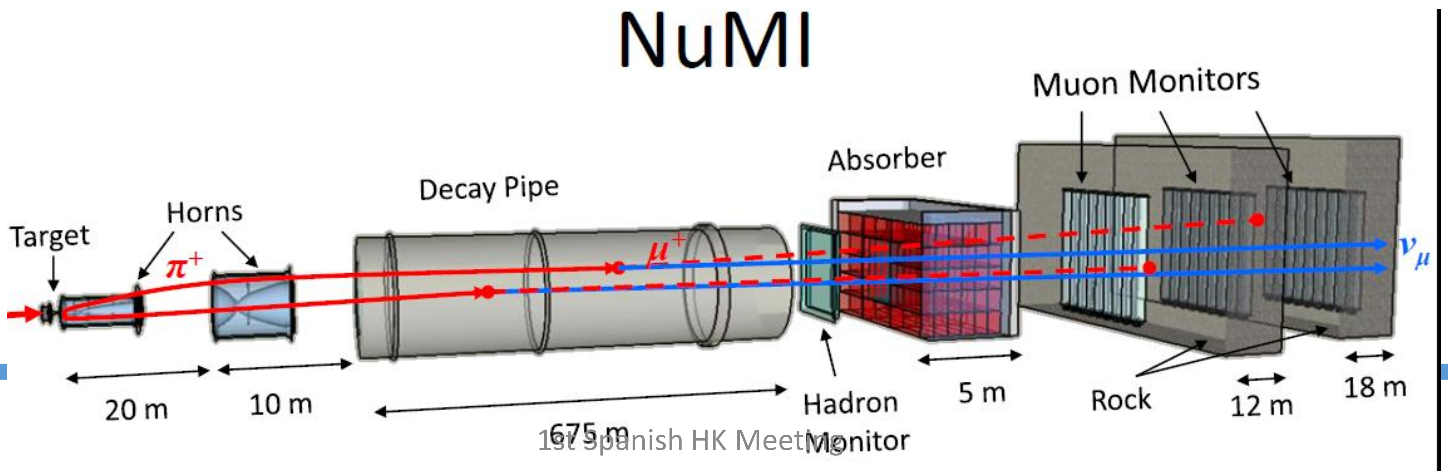
Magnetic Horn System: Uncertainties

- Usual flux uncertainties are coming from mis-alignment of horns, current variations 320 kA +/- 1 kA
- Minor contribution to flux uncertainty
- But started to look in two possible new sources:
  - Horn needs to be cooled and water can accumulate in horn and not easy to measure in-situ => water absorbs/scatters pions
  - Huge amount of charge particles produced => might change magnetic field locally



Decay Tunnel

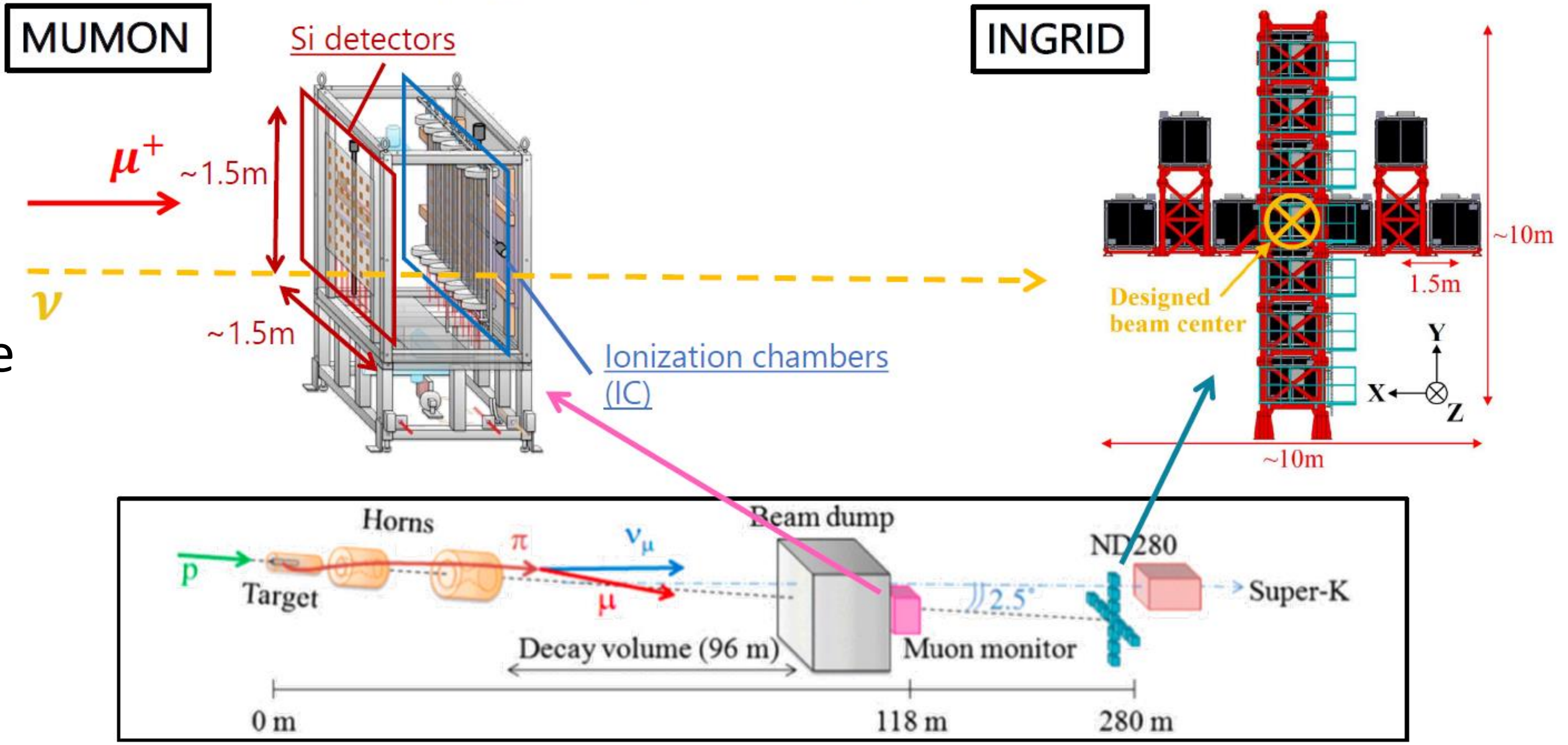
- Behind horns, a decay tunnel is situated
- Length depends on beam energy: 675 m for NUMI beam peaking 2 GeV, 100 m for T2K beam peaking at 0.6 GeV
- Either vacuum or filled with He to minimize interactions in tunnel
- Might introduce uncertainties depending on E_ν for $F_{FD/ND}$
- ND sees extended tunnel, while FD sees point source
- Depends ultimately on position of ND



Secondary Beam Monitors

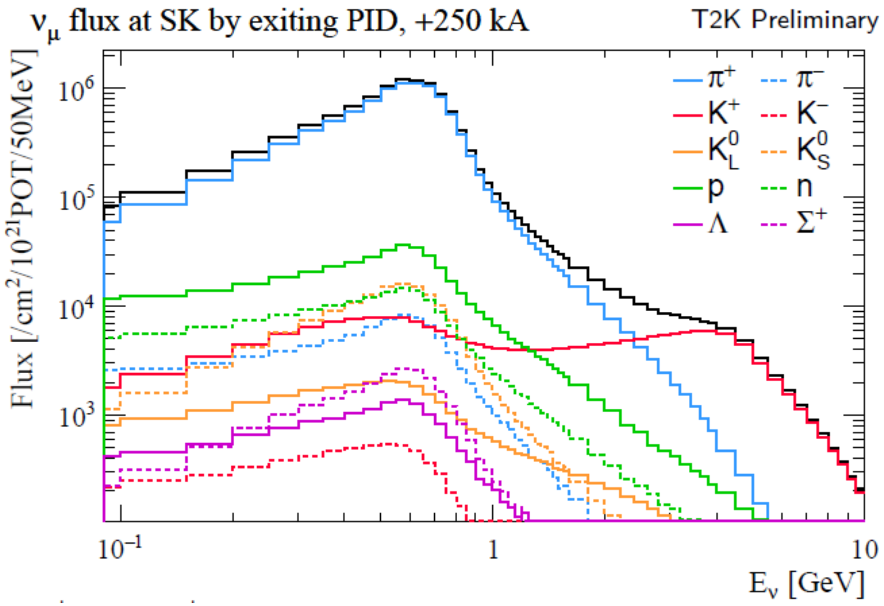
- Beam dump stops all particles except muons and neutrinos
- Si and IC detectors to monitor muon flux and profile
- Hadron monitors normally not possible due to radiation
- R&D on new muon beam monitors ongoing e.g. CT to estimate wrong-sign component

- Two monitors play complementary roles.



Neutrino Parent Particles

- Most of the beam neutrinos are produced from pions/kaons directly from primary proton interaction
- But significant fraction also from secondary interactions
- Kaons contribute mainly to high energy tail of E_ν
- Several, well known decay channels contribute to neutrino flux production



$$\pi^{\pm} \rightarrow \mu^{\pm} + \nu_\mu(\bar{\nu}_\mu) \text{ (BR=99.99\%) (right-sign low-E } \nu_\mu\text{'s)}$$

$$K^{\pm} \rightarrow \mu^{\pm} + \nu_\mu(\bar{\nu}_\mu) \text{ (BR=63.6\%) (right-sign high-E } \nu_\mu\text{'s)}$$

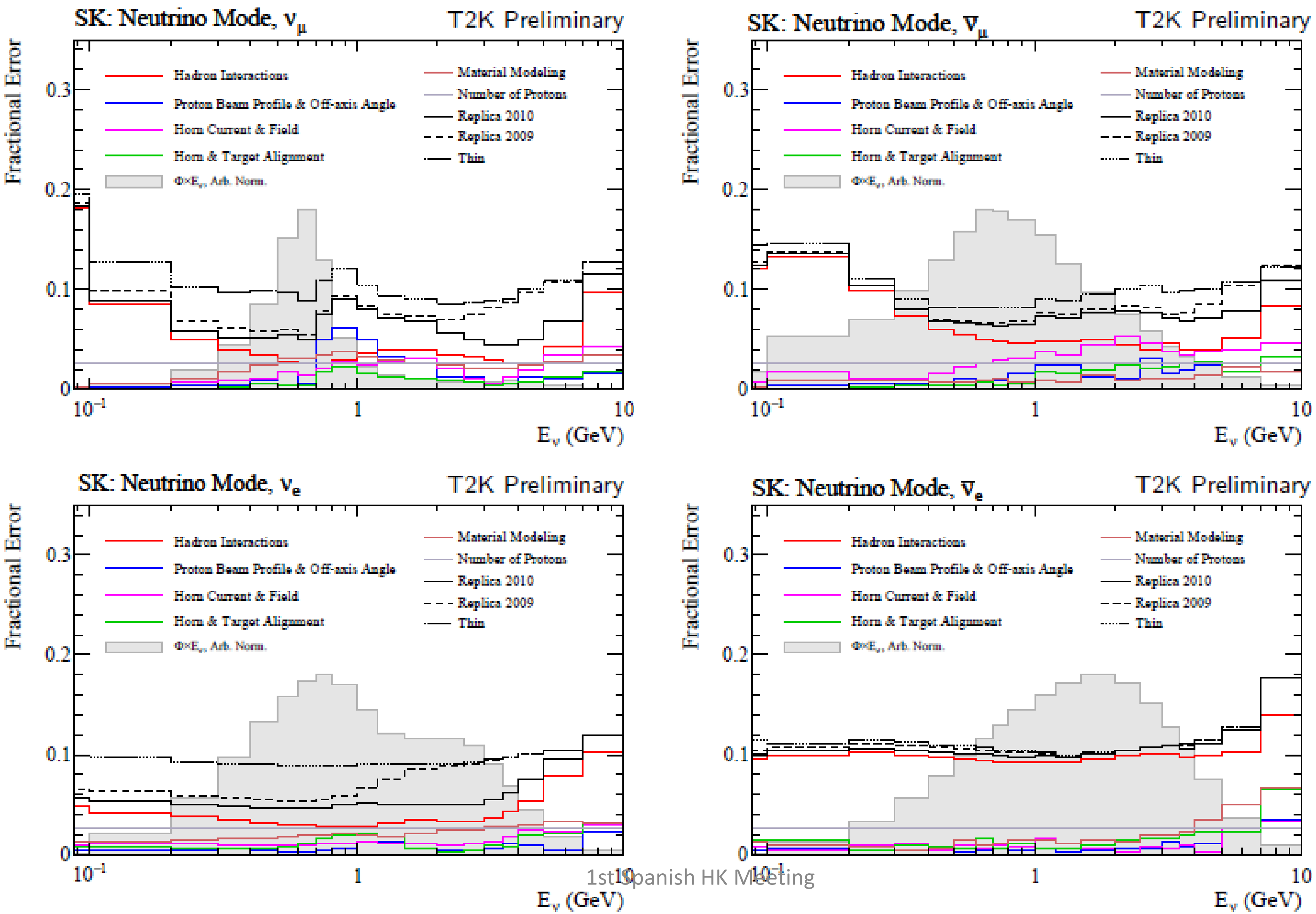
$$\Lsh\ \mu^{\pm} \rightarrow e^{\pm} + \bar{\nu}_\mu(\nu_\mu) + \nu_e(\bar{\nu}_e) \text{ (BR=100\%) (right-sign } \nu_e\text{'s)}$$

$$K_L \rightarrow \pi^{\pm} + \mu^{\mp} + \bar{\nu}_\mu(\nu_\mu) \text{ (BR=27.0\%) (right- and wrong-sign } \nu_\mu\text{'s)}$$

$$K_L \rightarrow \pi^{\pm} + e^{\mp} + \bar{\nu}_e(\nu_e) \text{ (BR=40.6\%) (right- and wrong-sign } \nu_e\text{'s)}$$

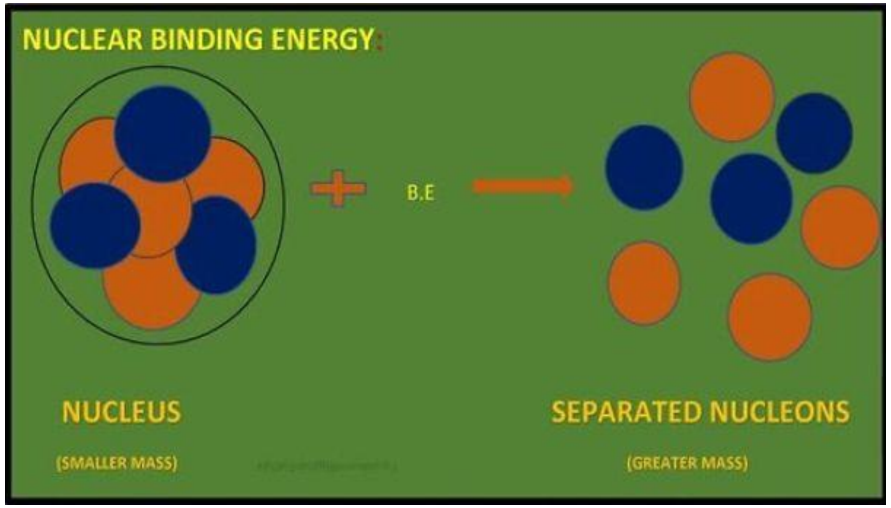
!

Beam Uncertainties

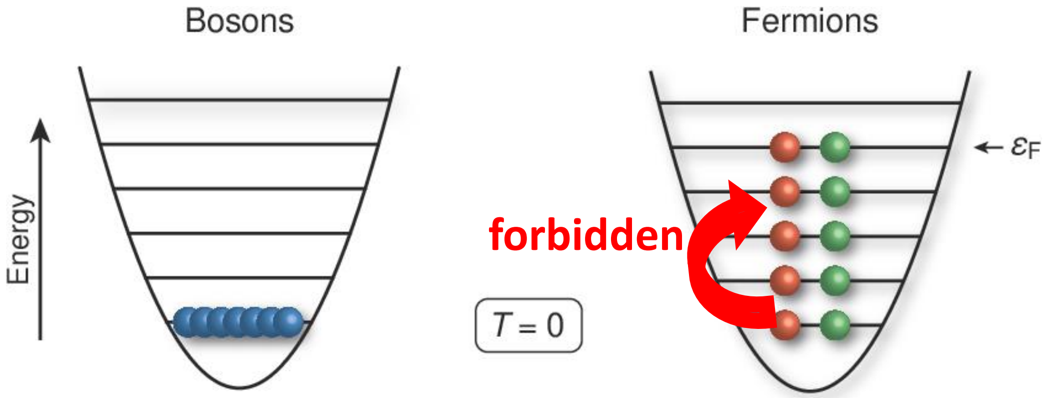


Binding Energy and Pauli Blocking

- Nucleons the neutrino interacts with are inside nucleus
- To kick them out a binding Energy is needed
- $E_b/\varepsilon_n \approx 25$ MeV => shift in reconstructed energy if not taken into account
- Cross-section altered by Pauli blocking
- Nucleons are fermions => forbidden to excite nucleons to fully occupied energy level



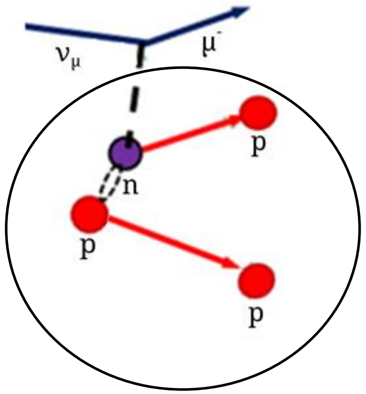
$$E_\nu = \frac{m_p^2 - (m_n - E_b)^2 - m_\mu^2 + 2(m_n - E_b)E_\mu}{2(m_n - E_b - E_\mu + p_\mu cos\,\theta_\mu)}$$

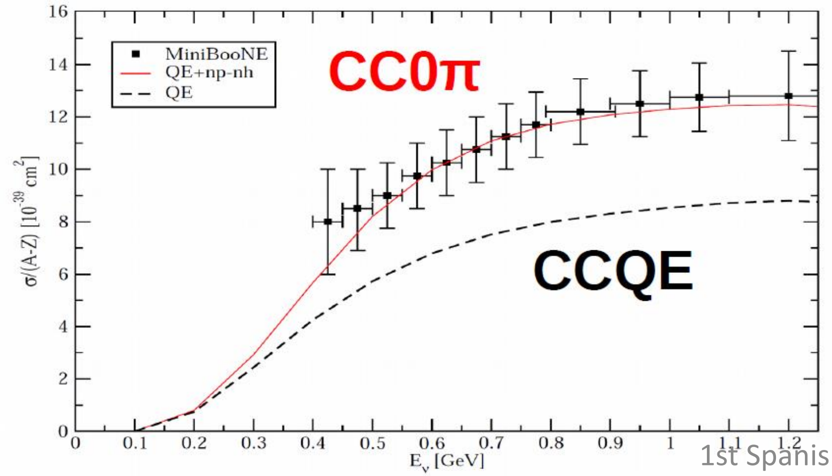


2p2h

Institute for High Energy Physics

- Previous measurements indicated too large CC0π cross-section
- Solution: neutrino not interacting with 1 nucleon but coherently with 2 (2 particle 2 holes)
- Significant cross-section contribution in the range of several hundred MeV to few GeV
- Affects energy reconstruction


2p2h



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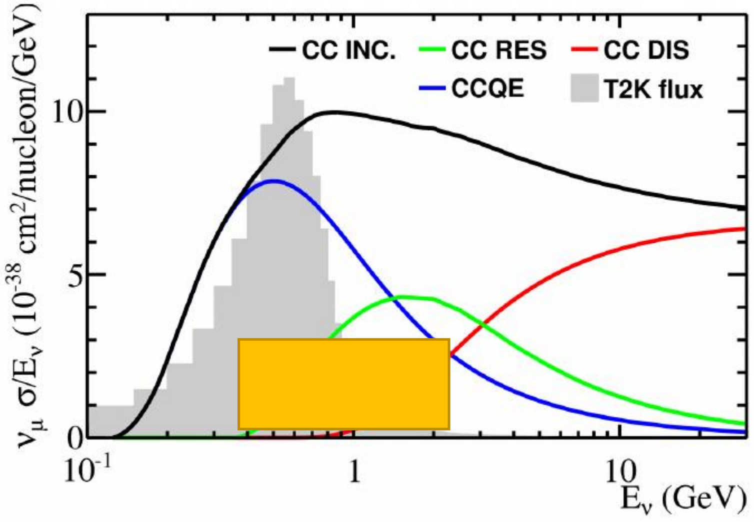
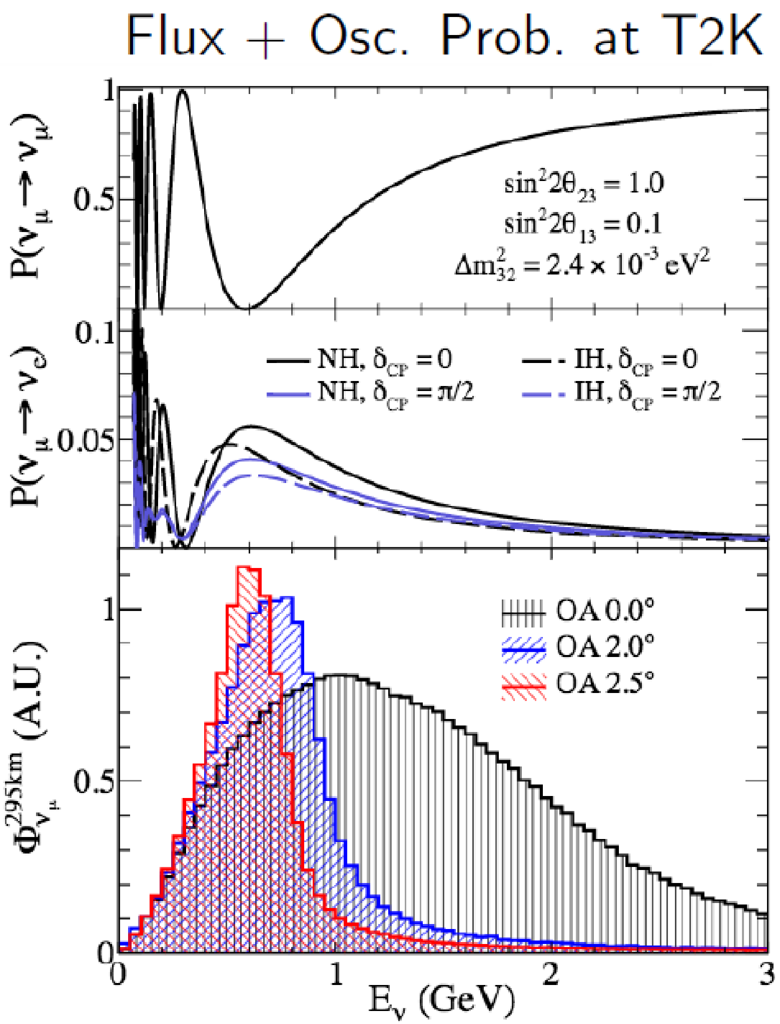


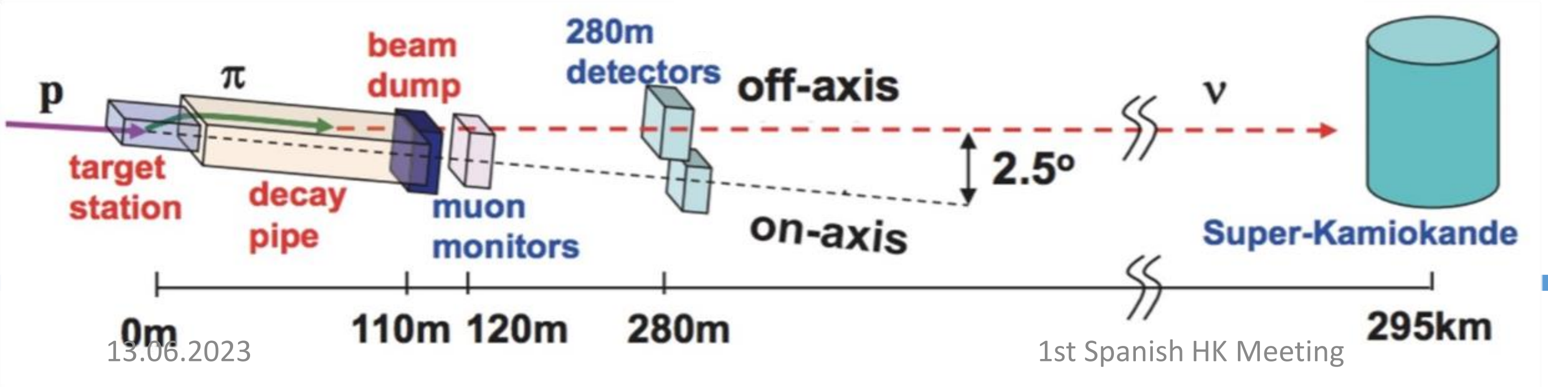
On-axis vs Off-axis flux

- On-axis means along the axis of the original proton beam
- E_ν spectrum depends on off-axis angle:

$$E_\nu = \frac{(1-(m_\mu/m_\pi)^2)E_\pi}{1+\gamma^2\theta^2} \quad \text{(for pions)}$$

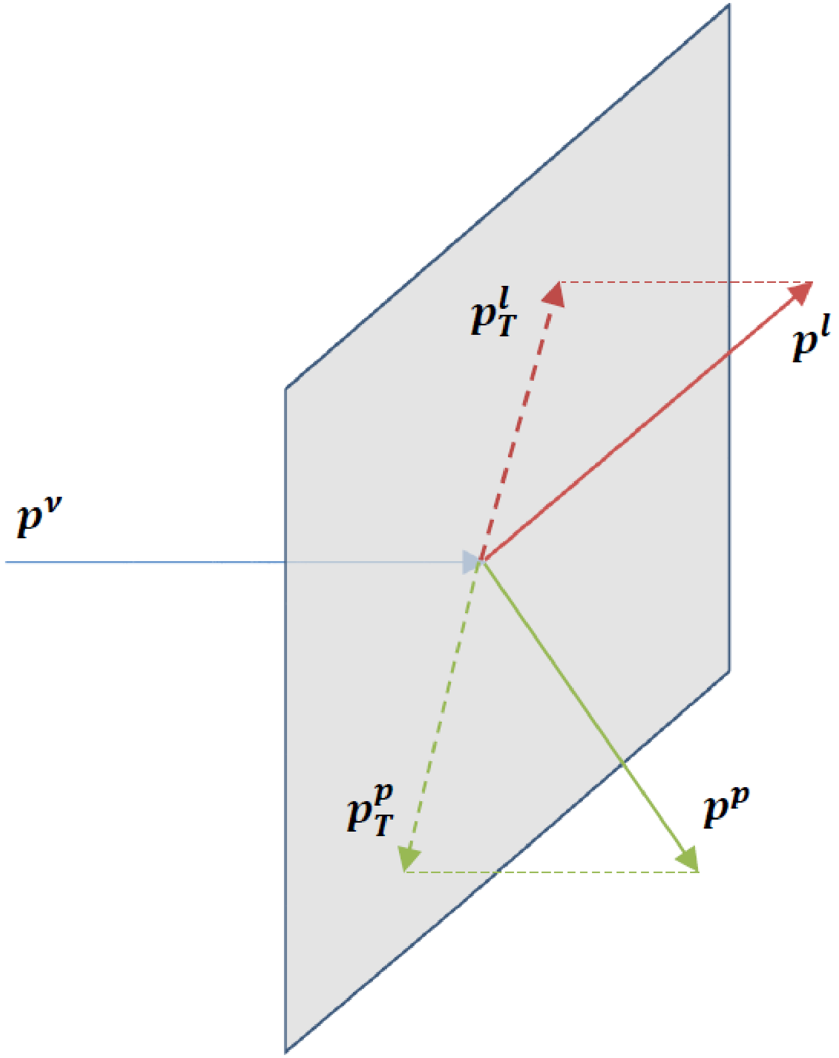
- Overall flux reduced but can be chosen to peak at expected oscillation maximum
- Contamination from Kaons at high energies suppressed
- Uncertainties: small error in beam direction, translates to relevant uncertainty in neutrino flux!

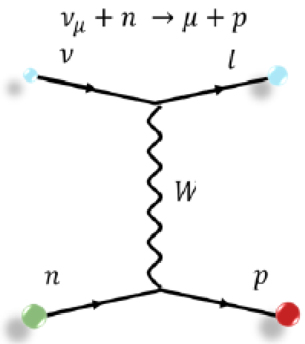




Studying FSI Effects

- Momentum conservation needs to be fulfilled
- Especially it must be valid: $p^l_T = - p^N_T$
- **IF** there are no nuclear effects
- Transverse kinematics variables allow to study FSI effects



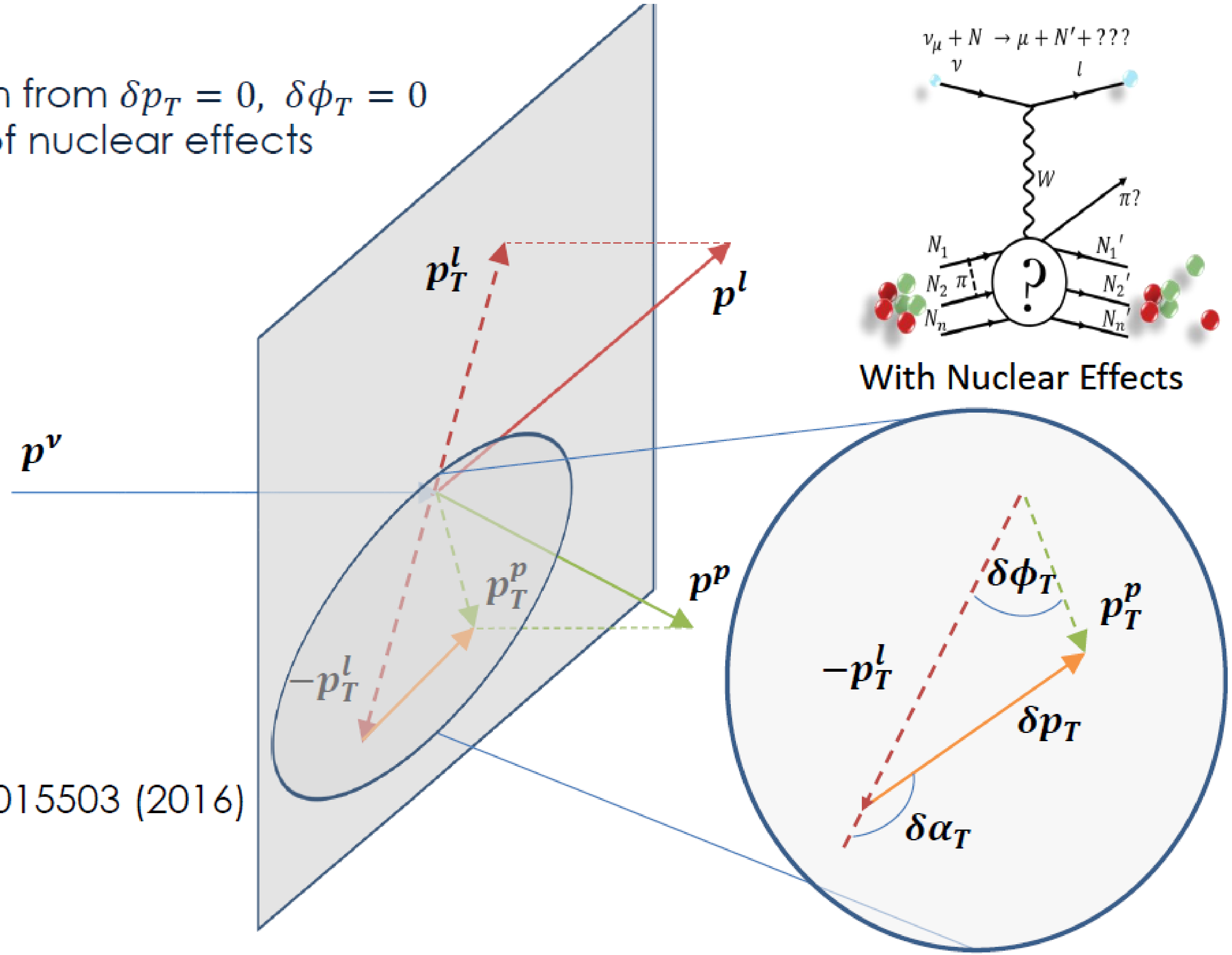


No nuclear Effects

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

Studying FSI Effects

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



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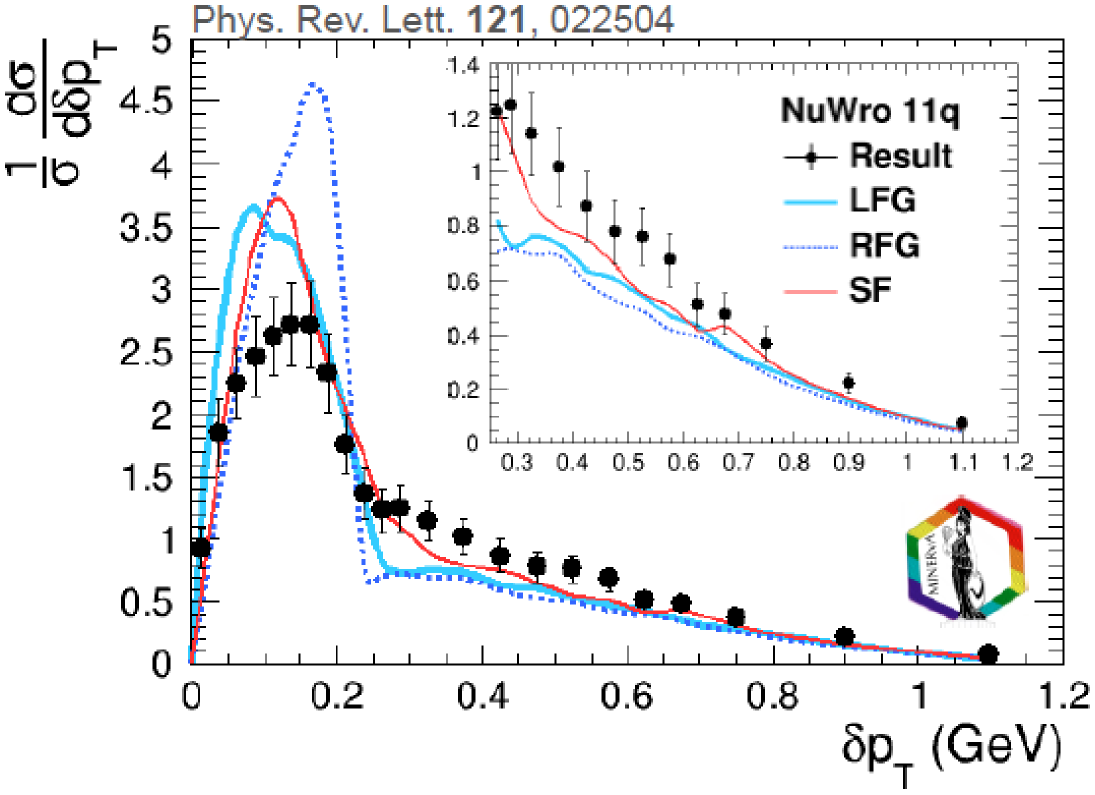
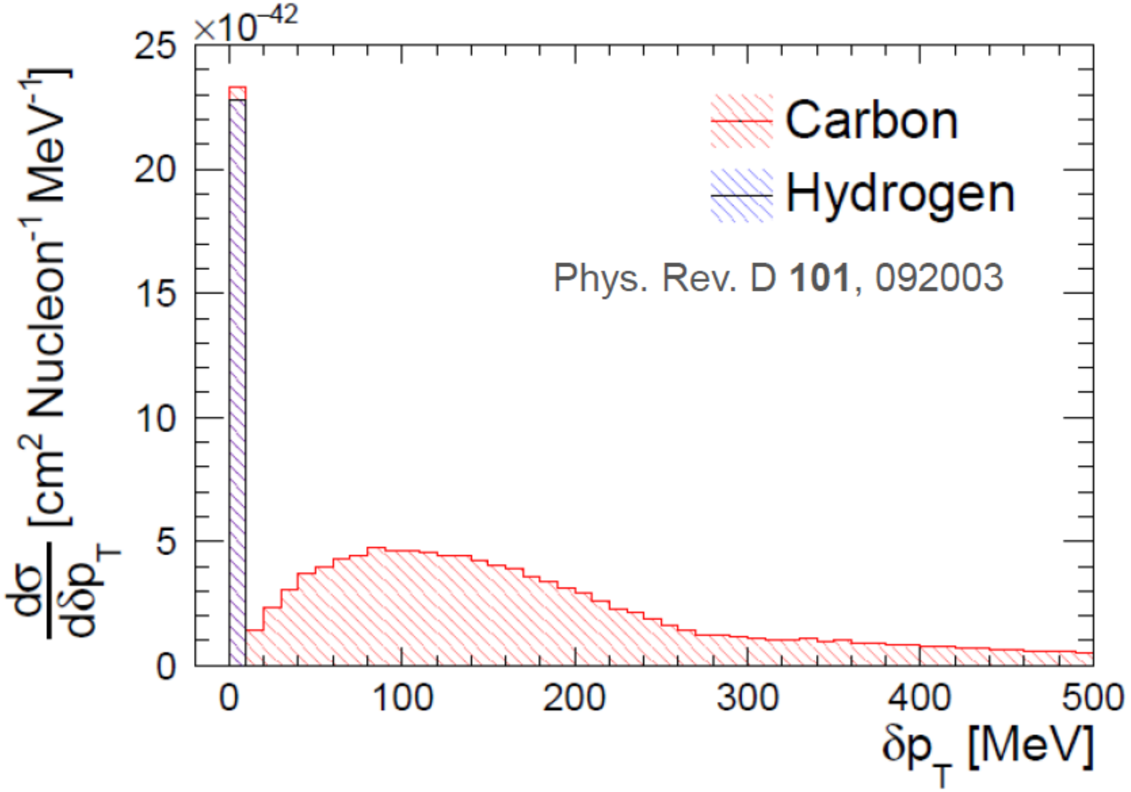
Studying FSI Effects

Theoretically could allow to separate interactions on H and C => but no detector effects in plot

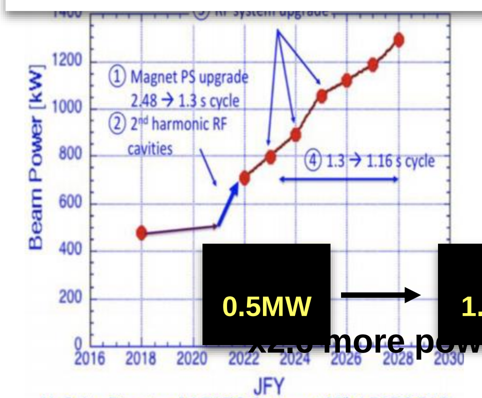




Physics benefits

Improvement in statistics

JPARC upgrades to increase beam power



N. Saito, Director of J-PARC Center, at 27th J-PARC PAC

0.5MW → **1.3MW**

x2.6 more power

Integrated POT

- ✦ 2010-20: ~$3 \cdot 10^{21}$ POT
- ✦ 2022-26: ~$1 \cdot 10^{22}$ POT

ND280 upgrade

target mass **1ton** → **2ton**

FGD1+FGD2: 2ton SuperFGD: 2ton

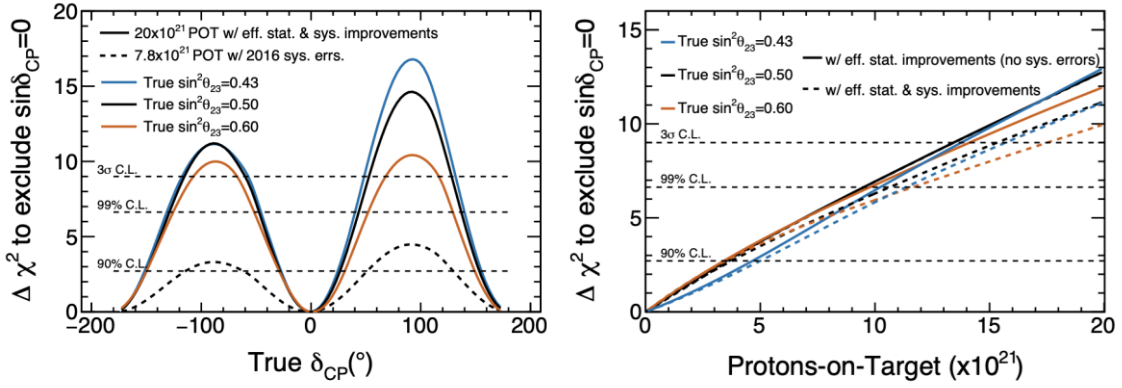
- ✦ ~8x more data than so far in ND280.
- ✦ good for OA but also a lot of data with upgraded modules to study ν interactions

Improvement in systematics

arXiv:1901.03750

PARAMETER	current ND280(%)	upgraded ND280(%)
SK flux norm. (0.6<Eν<0.7 GeV)	3.1	2.4
MA$_{QE}$	2.6	1.8
ν_μ 2p2h norm.	9.5	5.9
2p2h shape on C	15.6	9.4
MA$_{RES}$	1.8	1.2
FSI (π absorption)	6.5	3.4

~6% → **~4%**



- ✦ Key to rule out CP conservation 3σ and beyond!