Status and physics with new T2K near detector SuperFGD

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INR RAS

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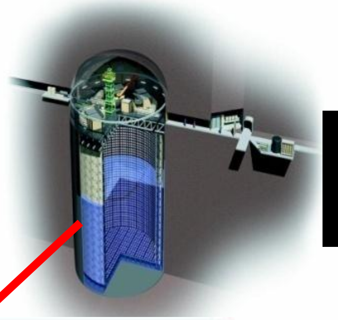
Supported by the RSF grant # 24-12-00271

> 550 members
76 institutions
from 14 countries
Russai: INR, JINR

Long-Baseline Neutrino Oscillation Experiment

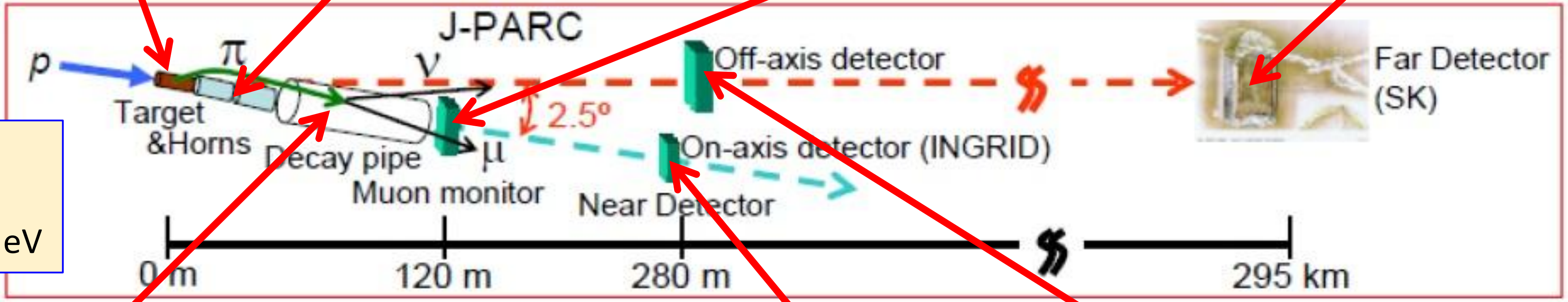
Experiment T2K

T2K collects data since 2010



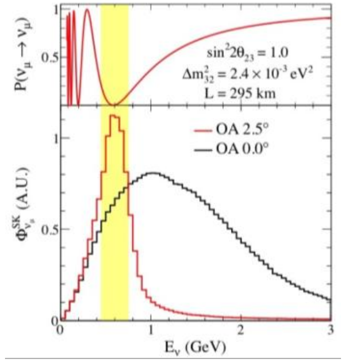
Far neutrino detector SuperKamiokande

L = 295 km
Off-axis ν beam
Peak energy 600 MeV

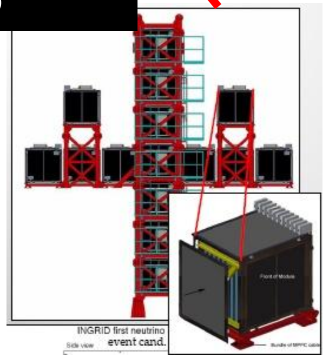


Decay tunnel

Off-axis neutrino beam

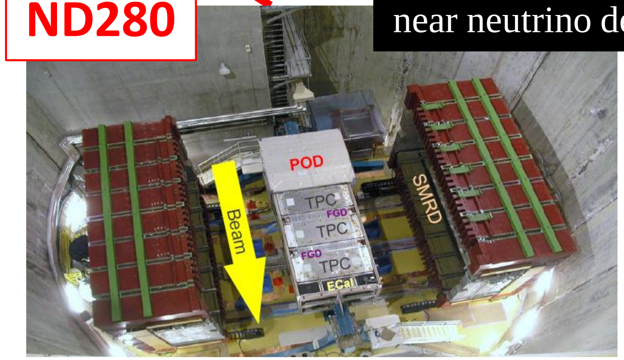


Neutrino monitor INGRID



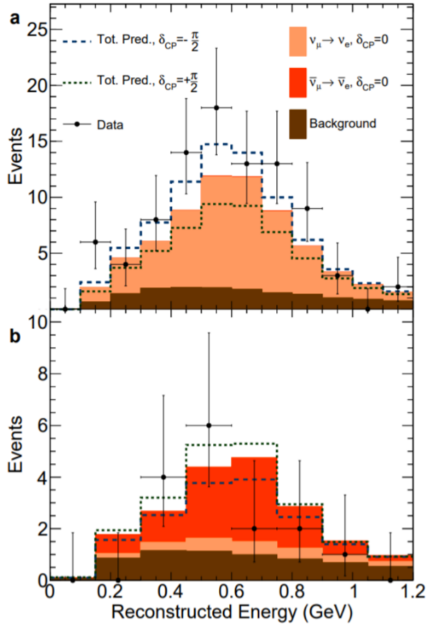
ND280

Off-axis near neutrino detector



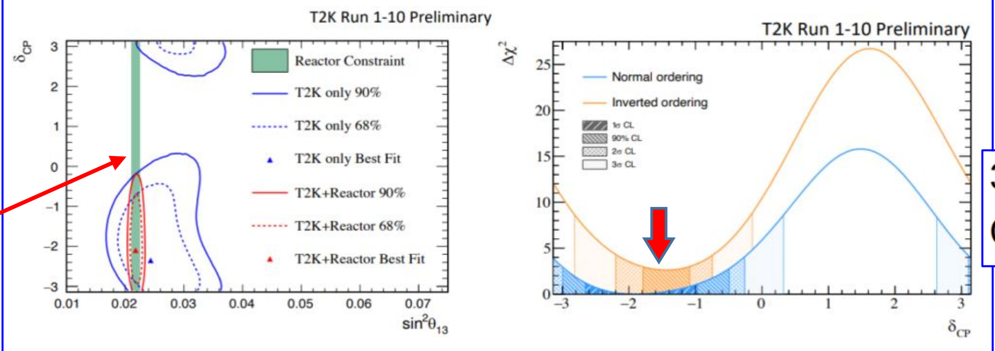
Main T2K Results

Discovery of $\nu_\mu \to \nu_e$ oscillations



Constraints on CP violating parameter δ_{CP}

$$A_{CP} = \frac{P(\nu_\mu \to \nu_e) - P(\bar{\nu}_\mu \to \bar{\nu}_e)}{P(\nu_\mu \to \nu_e) + P(\bar{\nu}_\mu \to \bar{\nu}_e)} \sim \sin\delta_{CP}$$

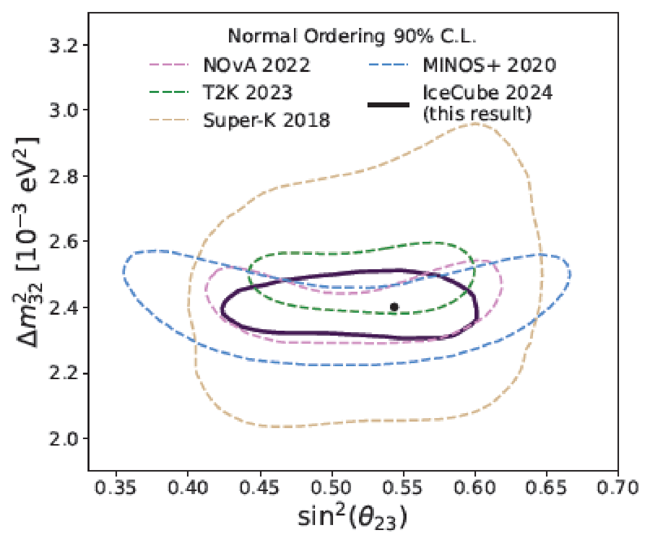


Constraint on θ_{13} from reactor experiments Daya Bay, RENO, DChooz

Indication of maximal CP violation in neutrino oscillations $\delta_{CP} \sim -\pi/2$

Measurements of oscillation parameters $\sin^2(\theta_{23})$ and Δm^2_{32}

arXiv:2405.02163

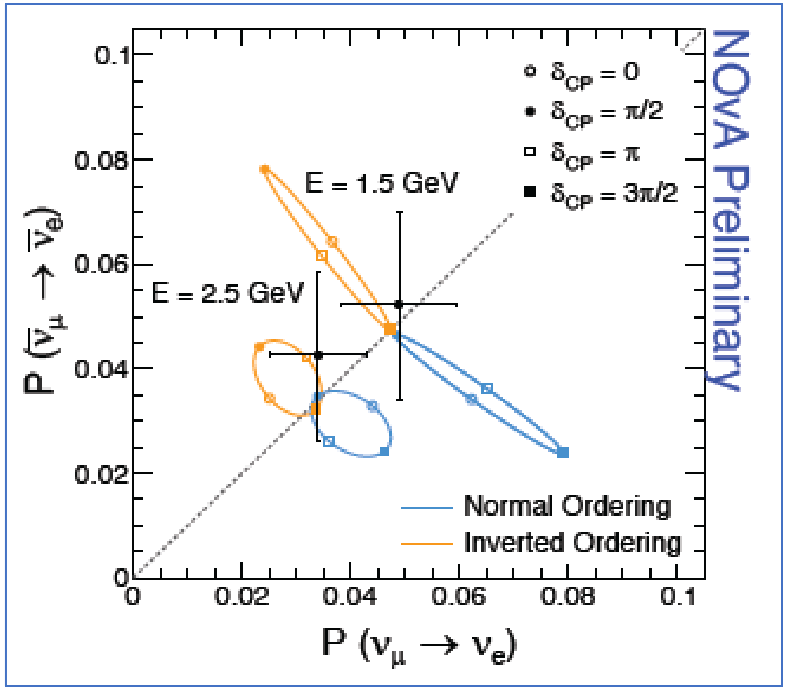


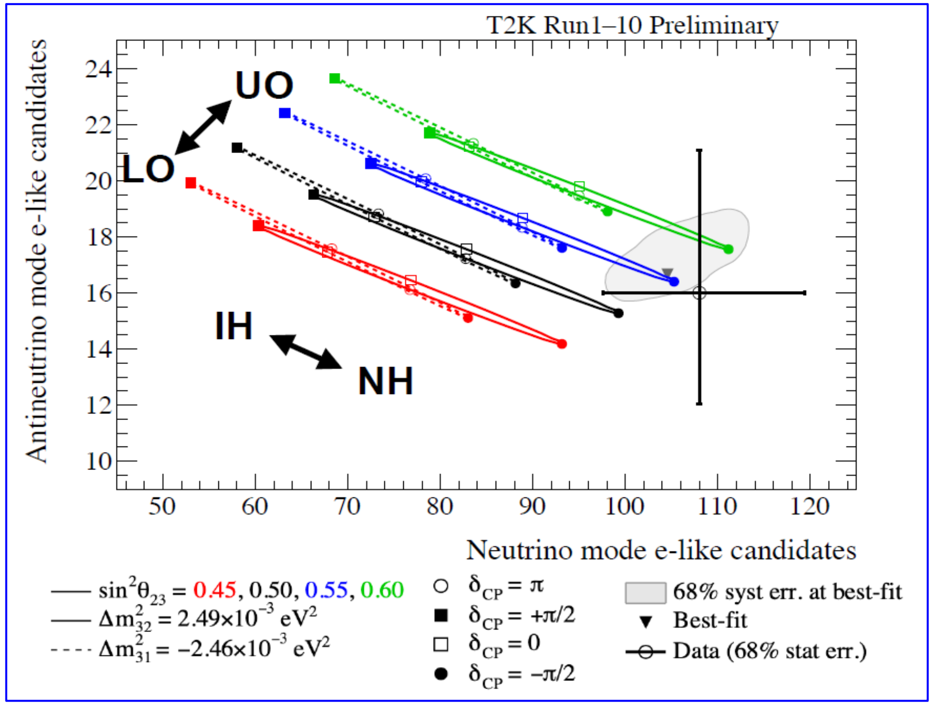
35% of δ_{CP} values excluded at 3σ marginalized over hierarchies
CP conserving values ($\delta_{CP} = 0, \pi$) excluded at >90%

Normal mass ordering is preferred at 80% CL

CP violation: T2K and NOvA

T2K Preliminary





NOVA ($\nu+\bar{\nu}$) prefers:
NO
CP conservation
octants ~degenerate

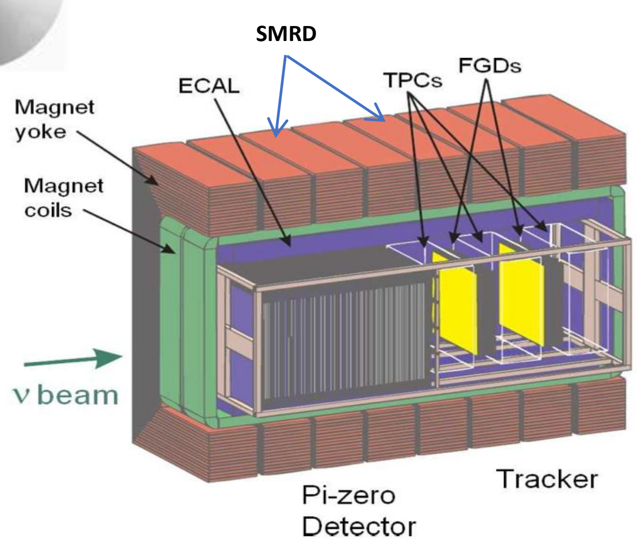
T2K → δ = $-\pi/2$ favored
Large range of values of δ around $+\pi/2$ excluded at 99.7%

NOvA → Best fit δ = 0.82π
Exclude IH δ = $\pi/2$ at > 3σ
Disfavor NH δ = $3\pi/2$ at $\sim 2\sigma$

T2K ($\nu + \bar{\nu}$) prefers
NO
$\delta \sim -\pi/2(\frac{3\pi}{2})$ (~max CPV)
2nd octant

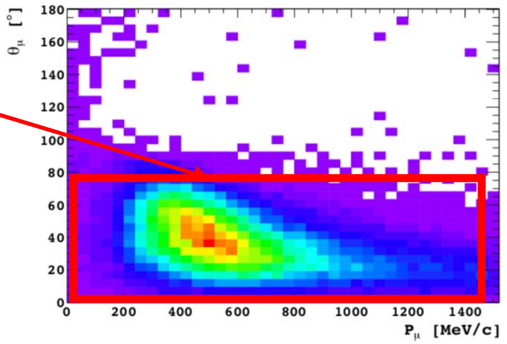
T2K Near Detector ND280

- Placed at 280 m from the target
- Measures the flux, flavor content, energy spectrum of the neutrino beam, studies neutrino-nucleus interactions



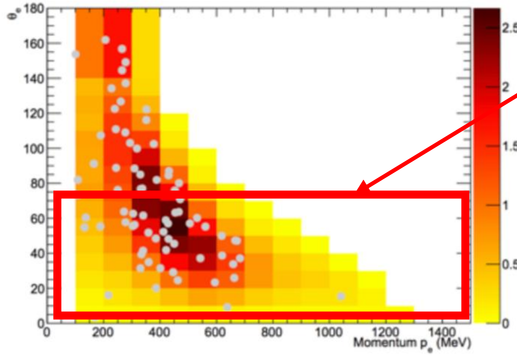
Muons in ND280:
- forward direction

ND280

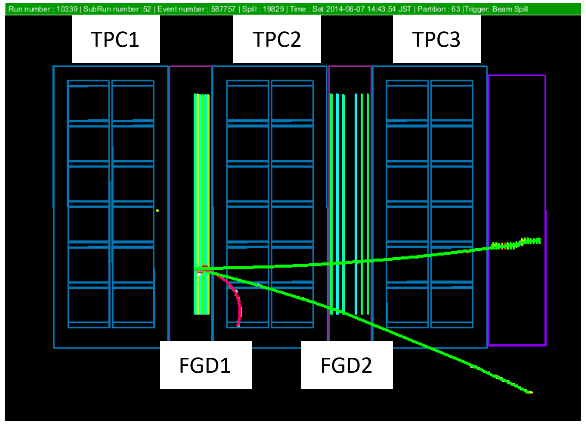


ν_e detection in SuperK:
- 4π acceptance

ND280

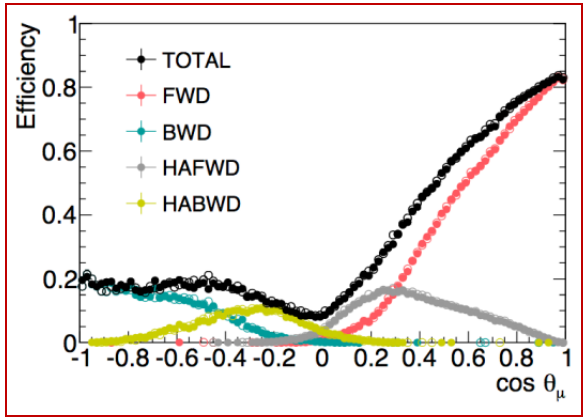


ν interaction in ND280



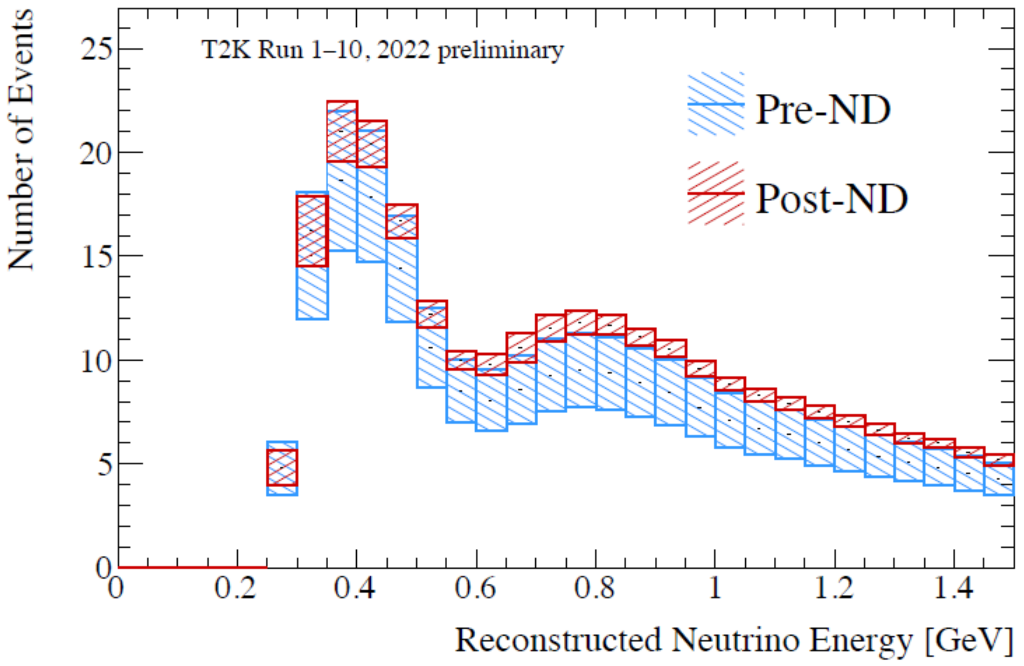
Current ND280

- Momentum threshold for protons 450 MeV/c (100 MeV kinetic energy);
- Non-CCQE interaction (2p2h, FSI) observed as CCQE;
- Acceptance for tracks in forward direction, SuperKamiokande - 4π acceptance;
- Larger oscillation systematic uncertainties due to tracks not measured by TPCs
- No capability to detect neutrons

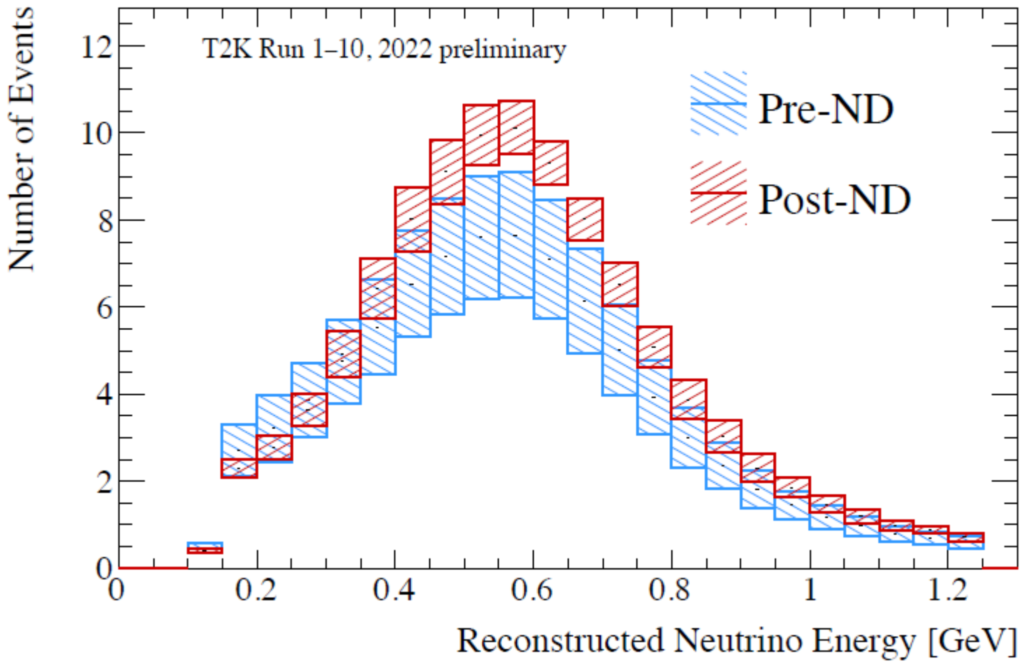


ND280 constraints of systematics

ν_μ spectrum at SuperK



ν_e spectrum at SuperK

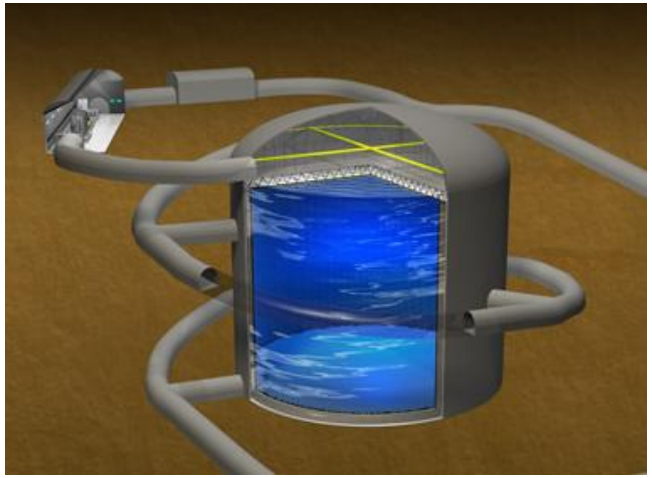


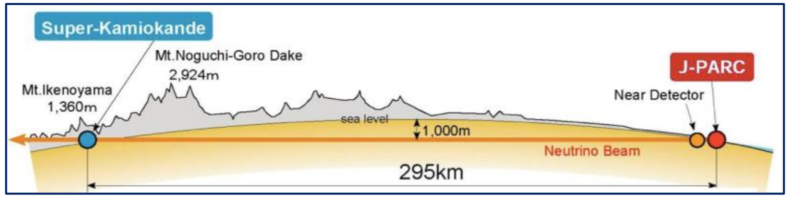
$\nu_\mu \rightarrow \nu_\mu$ and $\nu_\mu \rightarrow \nu_e$: systematic uncertainties reduced from $\sim 15\%$ to $\sim 5\%$ using ND280 data

HyperK: Sensitivity to CP violation

HyperK, arXiv:1805.04163

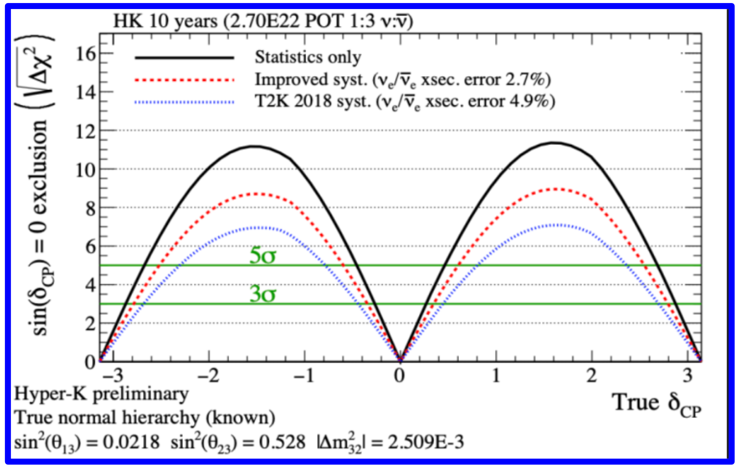
Water Cherenkov detector
71 m (height) x 68 m (diameter)
Total mass **260** kt
Inner Detector:
20000   50 cm PMTs + mPMTs
Outer Detector:
~4000   7.5 cm PMTs + WLS plates





Projected HyperK sensitivity to CP violation

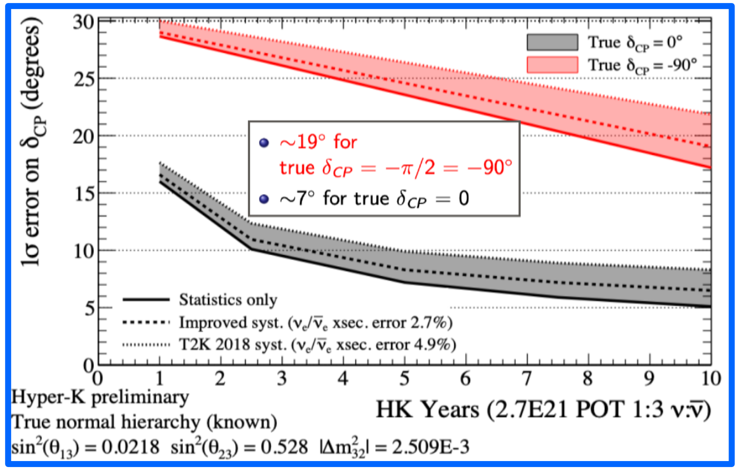
- 10 years of data taking
- 1.3 MW beam power → 2.7×10^{22} POT



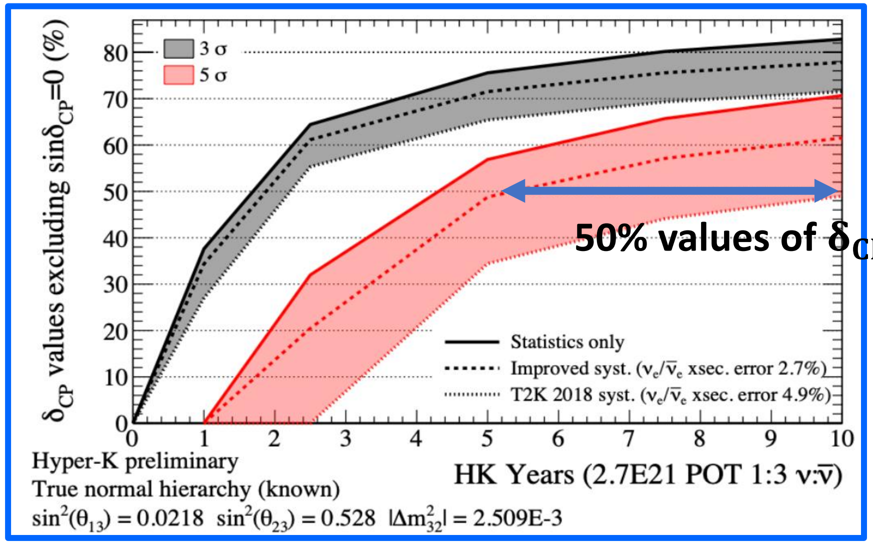
Expected number of events at HyperK for $\nu_e : \bar{\nu}_e = 1:3$ and $\sin\delta_{CP} = 0$

2300 ν_e 1300 $\bar{\nu}_e$

Measurement of δ_{CP}



Exclusion of CP conservation



Motivation for ND280 upgrade

- Uncertainties of current T2K oscillation measurements are dominated by statistics
- However, systematics will limit T2K (and HyperK) sensitivity in future

Post-fit errors of the most significant systematic parameters

Parameter	Current ND280 (%)	Upgrade ND280 (%)
SK flux normalisation ($0.6 < E_\nu < 0.7$ GeV)	3.1	2.4
MA_{QE} (GeV/c^2)	2.6	1.8
ν_μ 2p2h normalisation	9.5	5.9
2p2h shape on Carbon	15.6	9.4
MA_{RES} (GeV/c^2)	1.8	1.2
Final State Interaction (π absorption)	6.5	3.4

The systematic error can be reduced by about 30% in the ND280 upgrade configuration

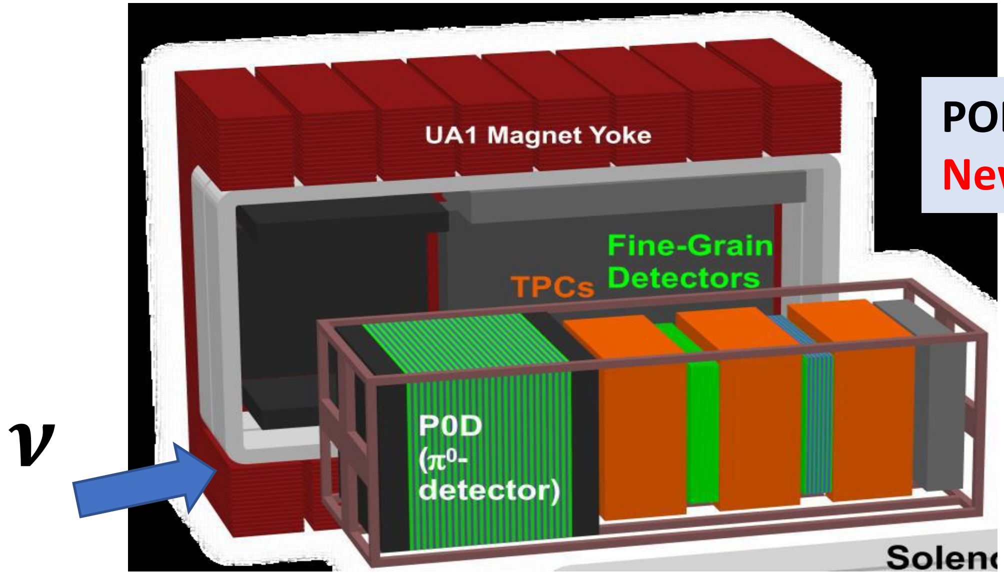
- Important to measure neutrino interactions in all phase space
- Precisely detect particles produced at any angle
- Reduce detection threshold, measure protons with low threshold
- Measure neutrons in anti-ν_μ interactions
- Reduce background, obtain better track identification using TOF
- Provide electron/gamma separation
- Reduce total systematics to ~ 3% level for appearance modes

ND280 upgrade

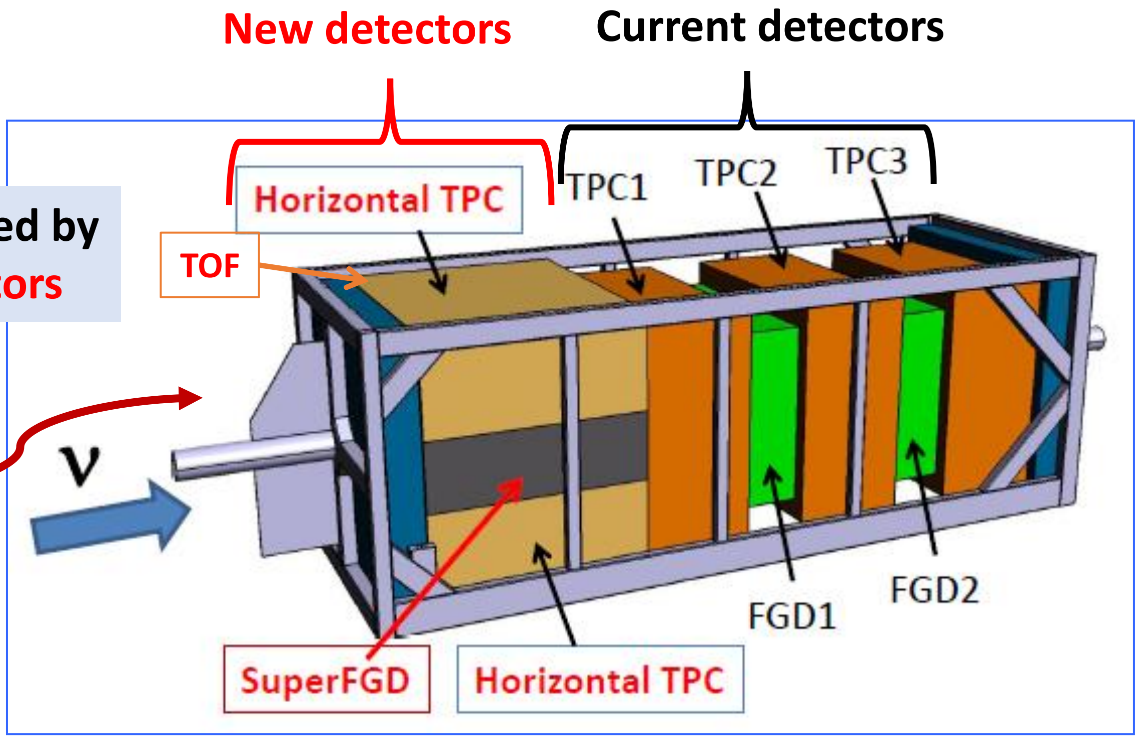
New upstream detectors
- **3D fine-grained scintillator target/detector SuperFGD**
- **Two Horizontal TPCs**
- **TOF system around new tracker**

arXiv:1901.03750

Current ND280 complex



POD replaced by New Detectors



SuperFGD

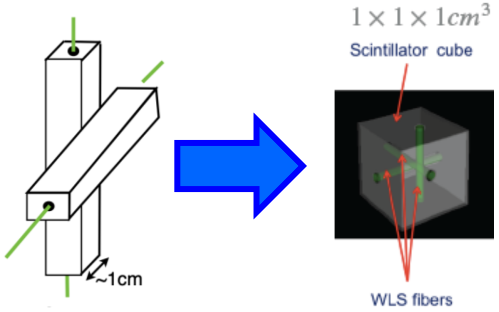
JINST 13 (2018) 02006

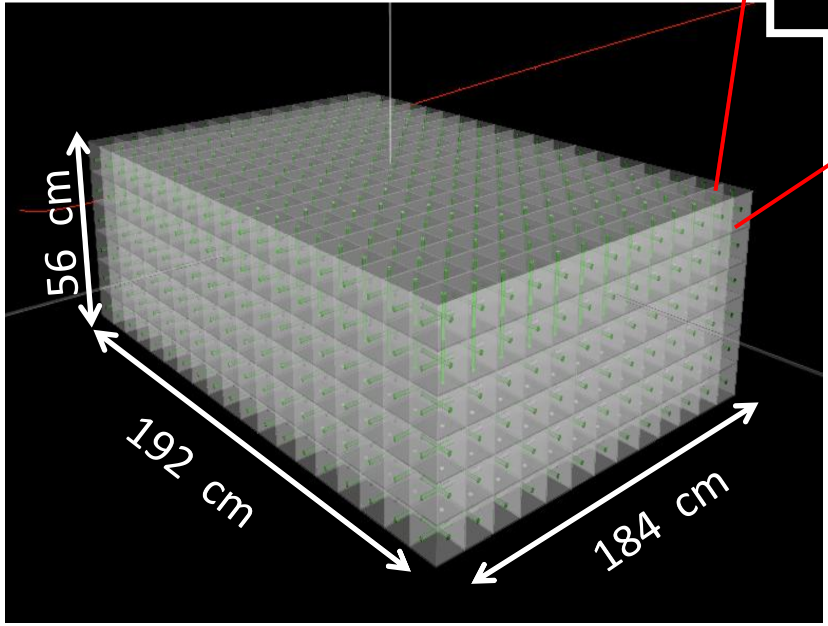
- Volume ~192 x 184 x 56 cm^3
- ~2 x 10^6 scintillator cubes , each 1 x 1 x 1 cm^3
- Each cube has 3 orthogonal holes of 1.5 mm diameter
- 3D (x,y,z) WLS readout
- About 60000 readout WLS/MPPC channels
- Total active weight about 2t

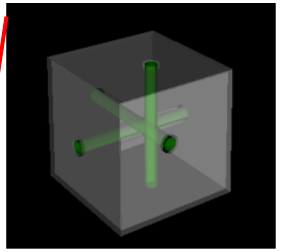
Fully active, highly granular, 4π scintillator neutrino detector with 3D WLS/MPPC readout - proposed, and constructed at INR

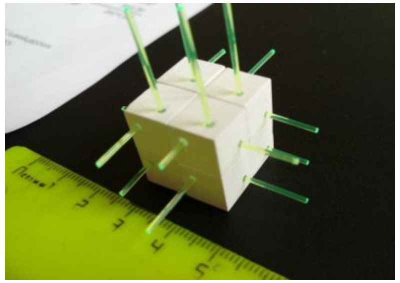
SuperFGD project: about 100 participants from 6 countries
Russia: INR, JINR, LPI

ND280 FGD → **SuperFGD**

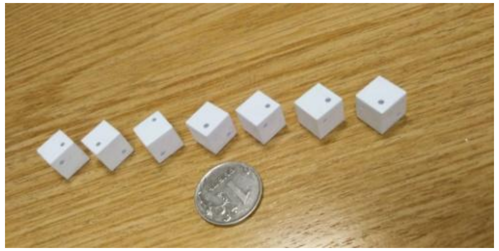


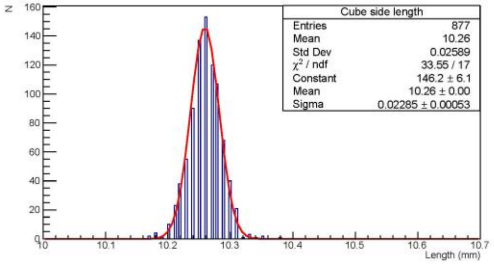


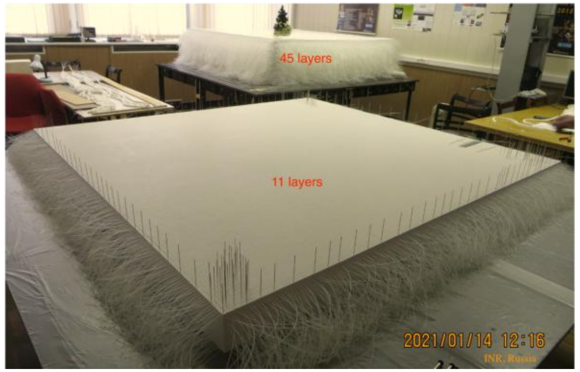




- Cubes produced by injection molding at OOO Uniplast, Vladimir
- Covered by chemical reflector
-Tolerance (each side) about 30 microns







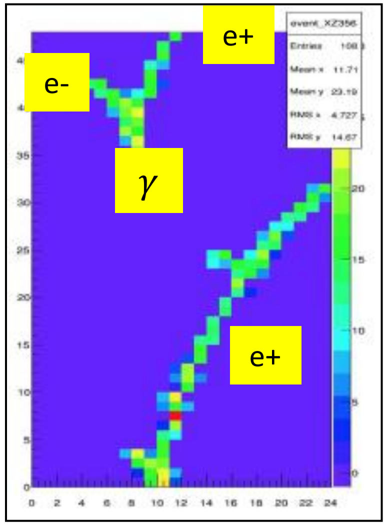
Talks on 21 May:
A.Chvirova
D.Fedorova
A.Shvartsman

SFGD prototypes: beam tests (I)

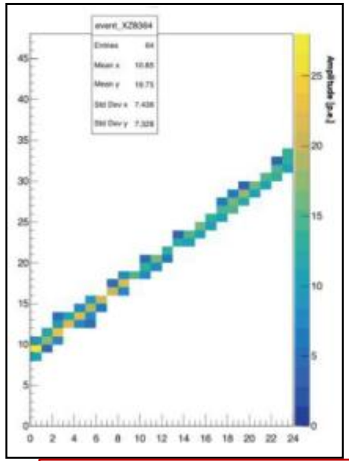
SFGD prototypes were tested:
- with charged particles beams (e, μ, π, p) at CERN
- with neutron beam at LANL

JINST 15 (2020) 12, P12003

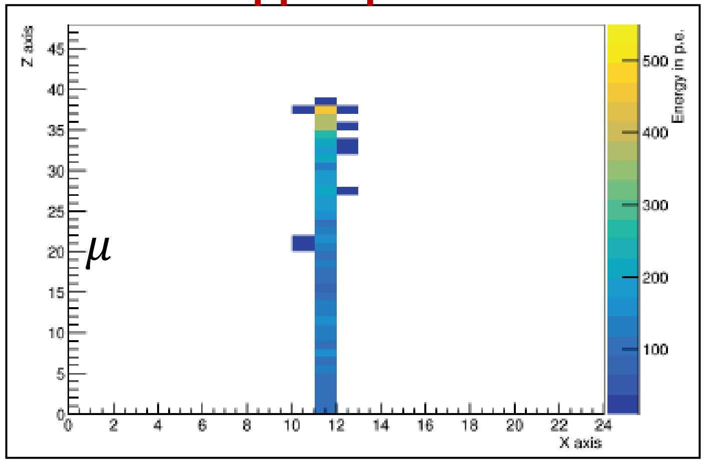
e+, B=0.2T

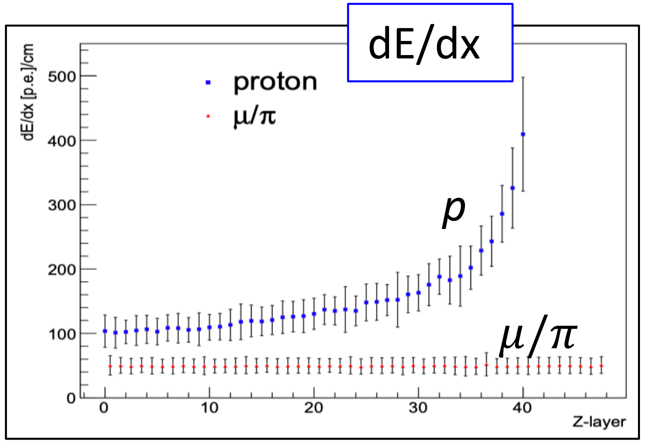


Muons



Stopped protons

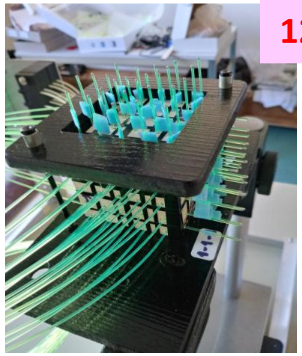




Parameters of the SFGD prototype obtained in the beam tests at CERN:

- **Light yield of one cube** 50-60 p.e./MIP, 1 fiber readout
- **Light yield of one cube** 150-180 p.e./MIP for sum of 3 orthogonal fibers
- **Time resolution** ~1 ns for MIP and 1 fiber readout
- **Dark rate of MPPCs:** 50-70 kHz (th=0.5 p.e.), 0.5 kHz (th=1.5 p.e.)

SFGD prototypes



125 cubes

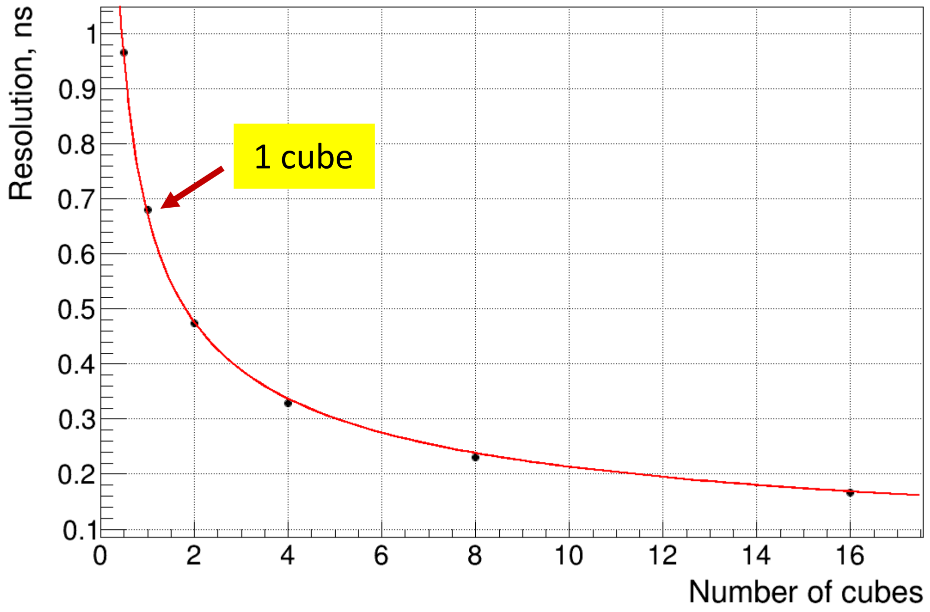
9216 cubes
1728 Y11 WLS fibers
and MPPCs

2048 cubes

SFGD prototypes: beam tests (II)

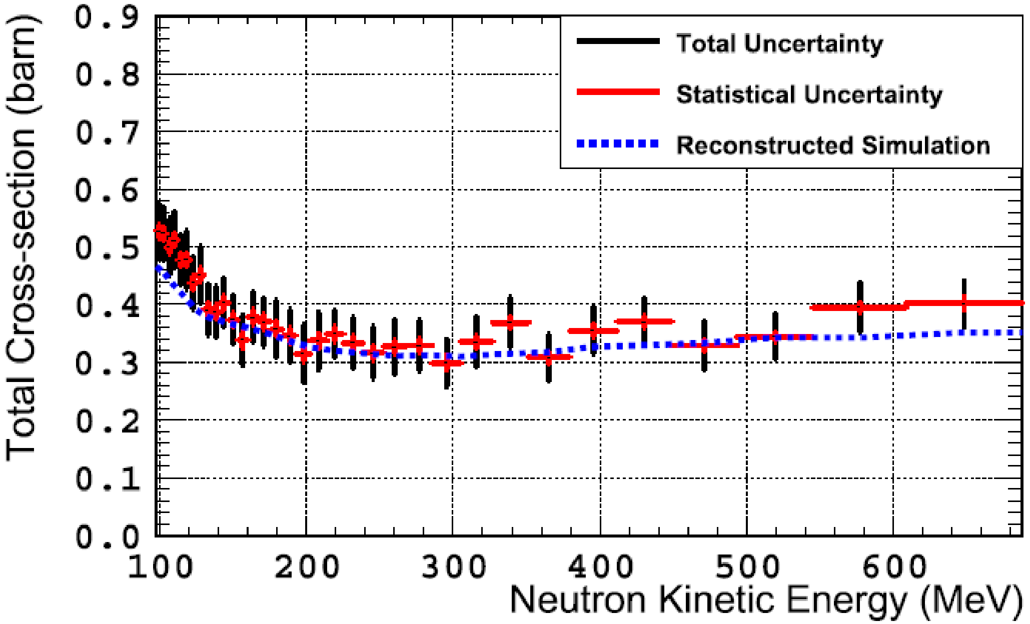
JINST 18 (2023) P01012

SuperFGD time resolution for MIPs



PLB 840 (2023) 137843

Neutron cross-section measurements at LANL with SuperFGD prototypes

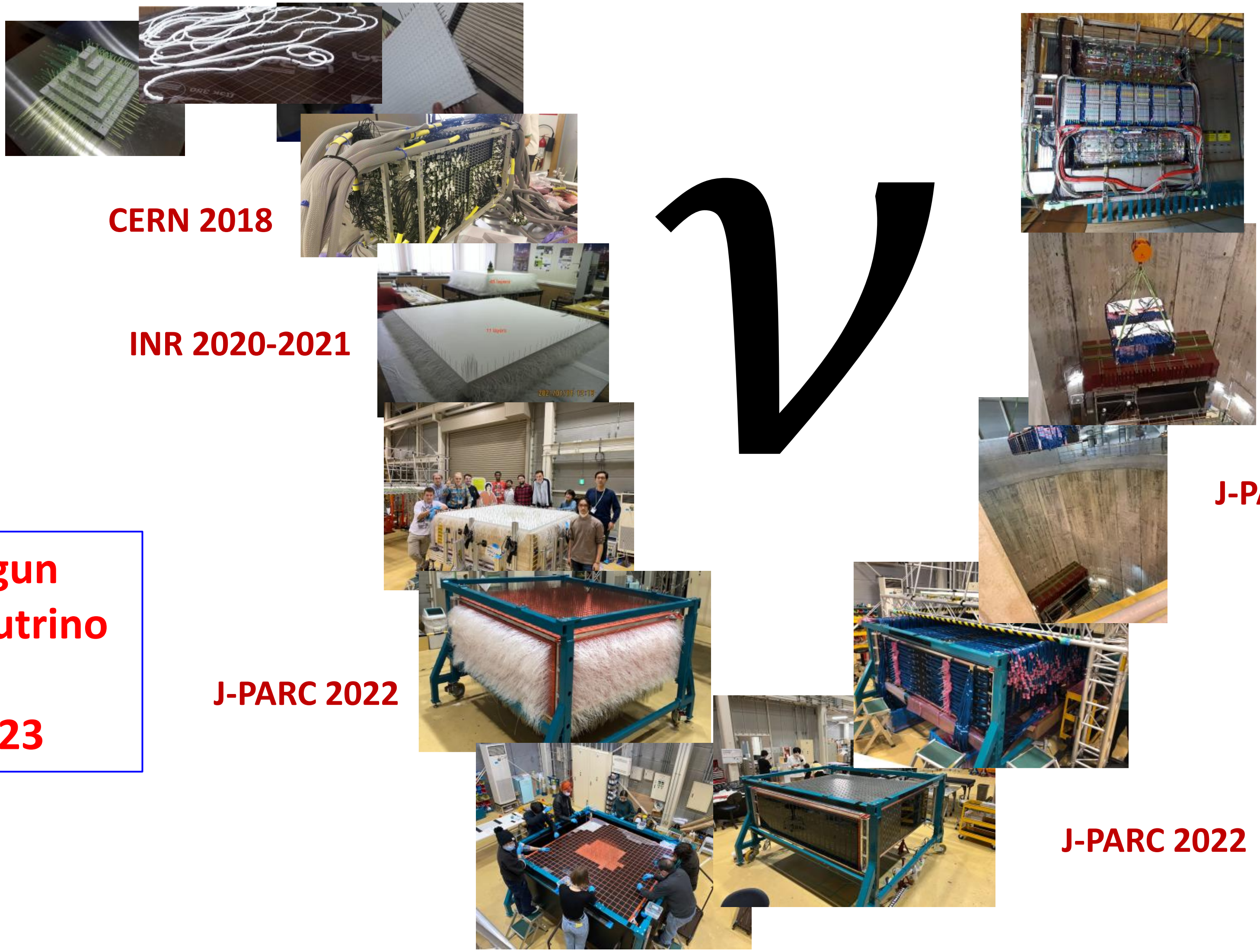


Milestones of SuperFGD

Start
INR 2017

CERN 2018

INR 2020-2021



J-PARC 2022

J-PARC 2022

J-PARC 2023

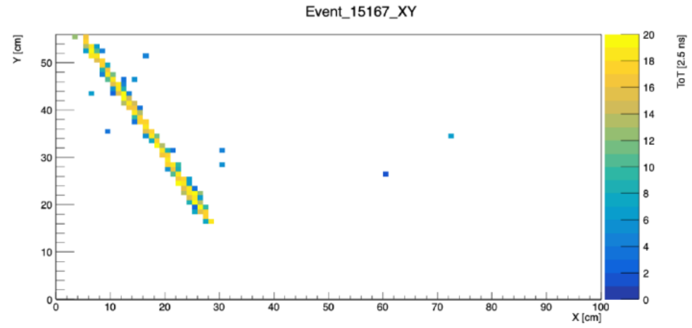
J-PARC 2024

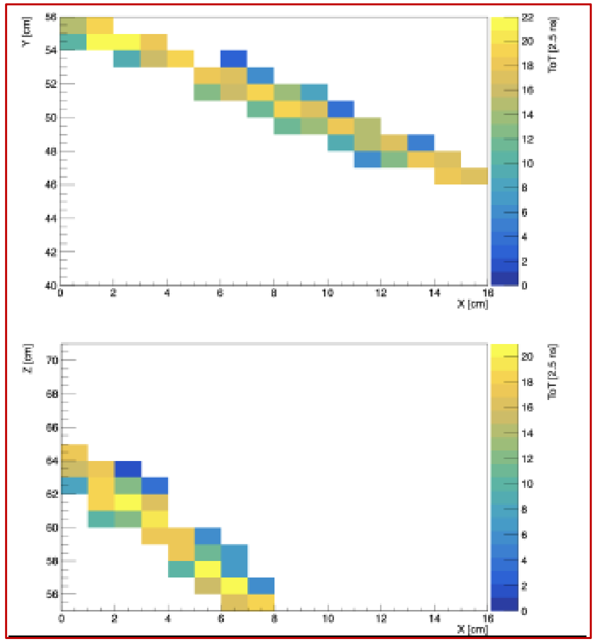
SuperFGD begun collecting neutrino data in November 2023

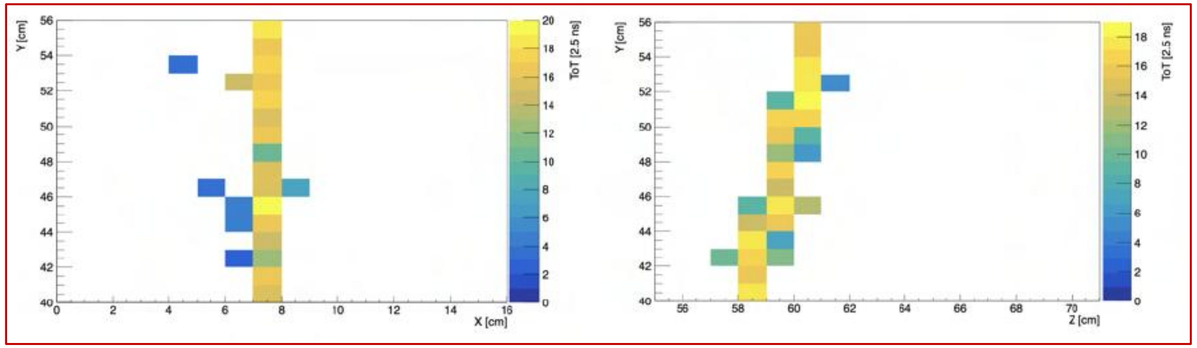
Calibration of SuperFGD

μ

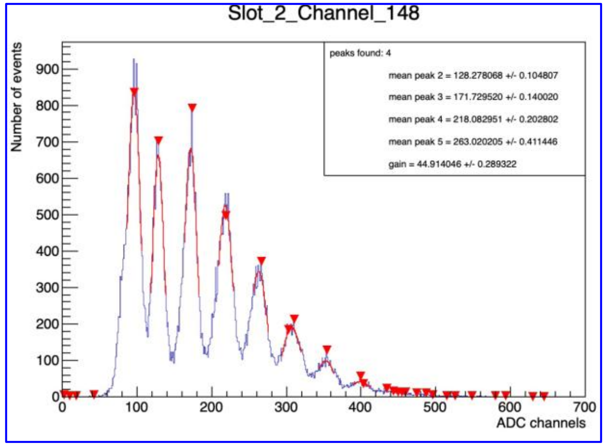
Cosmic events: muon tracks



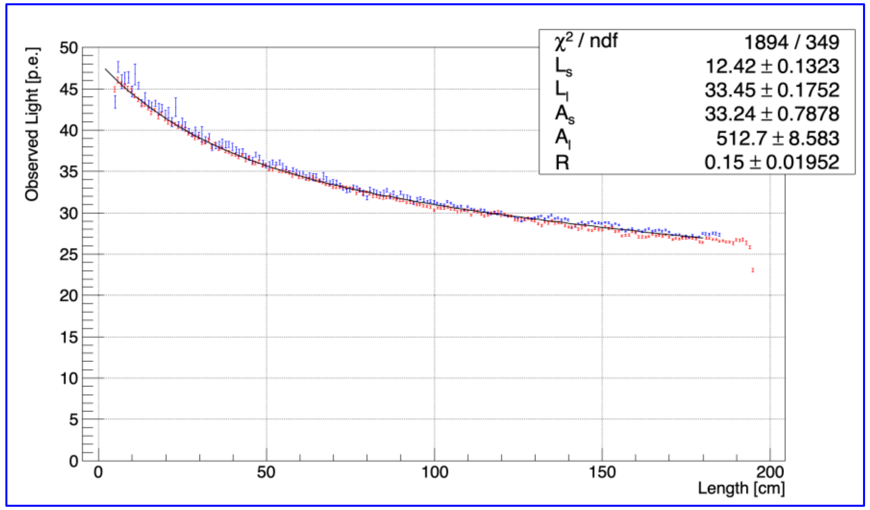




LED calibration in photoelectrons



LY per MIP and attenuation of WLS fibers

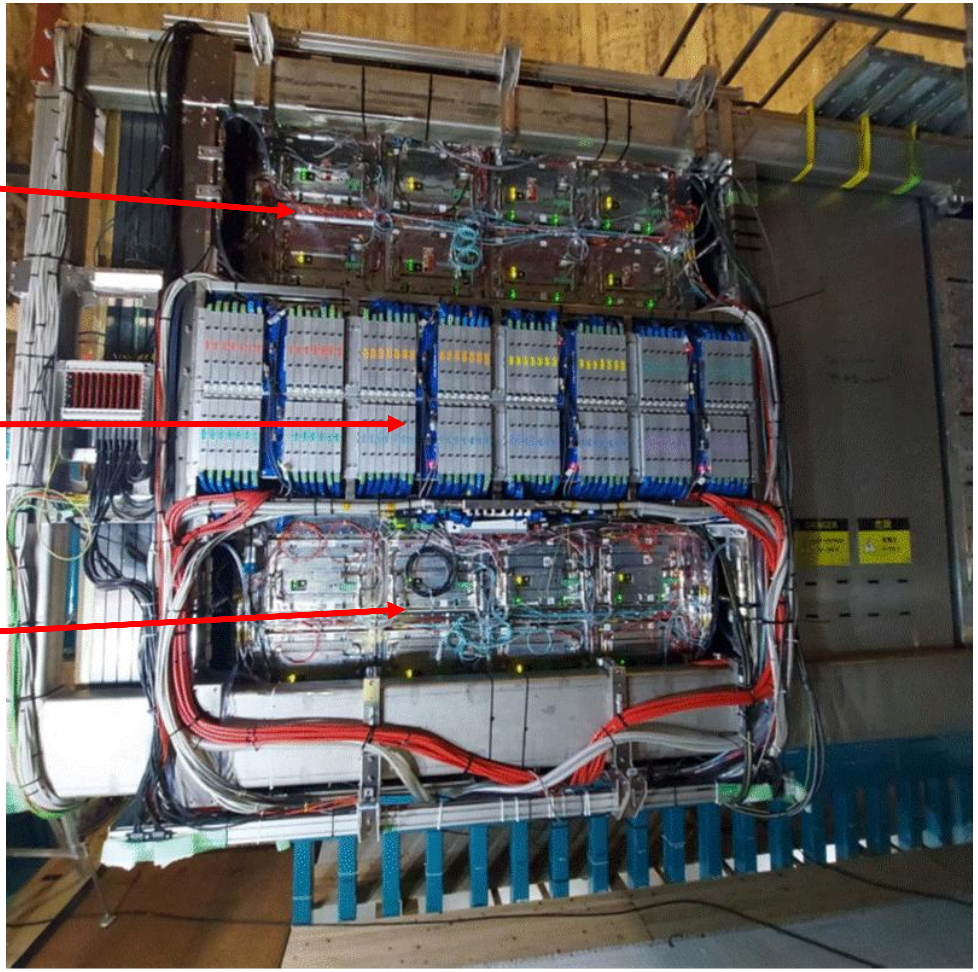


New ND280 detectors

TOP HA-TPC

SuperFGD

Bottom HA-TPC



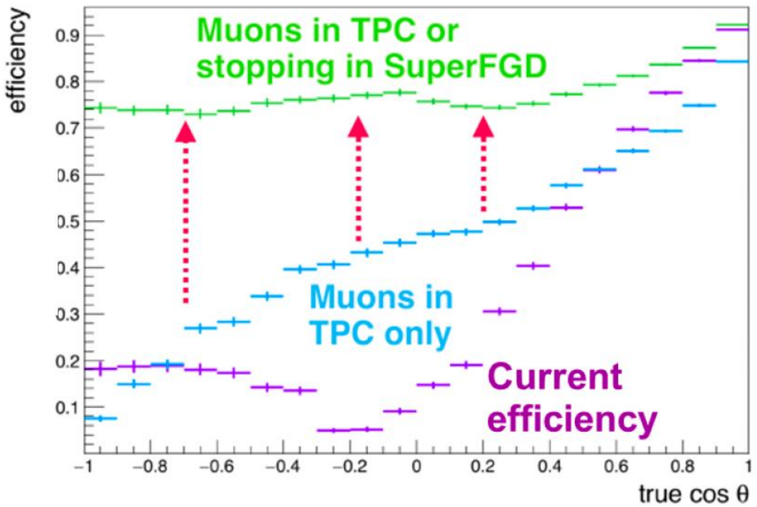
Installation of all detectors (SuperFGD, HA-TPC, TOF) into ND280 magnet completed in May 2024

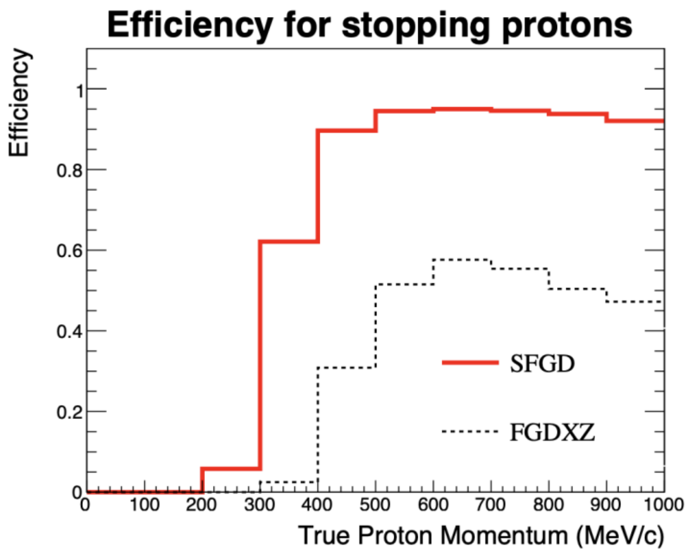
Features of upgraded ND280

Current ND280 ⇒ ***Upgraded ND280***

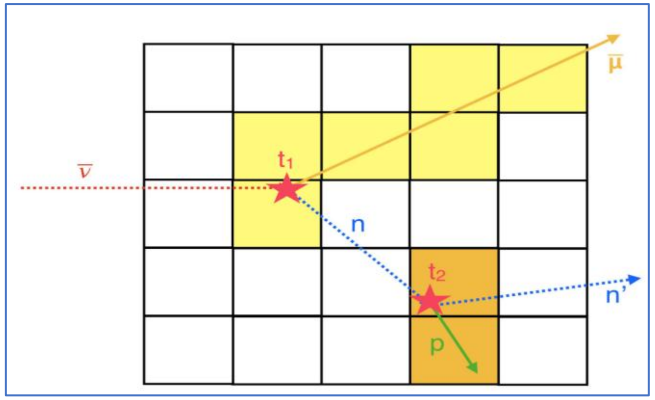
- **SuperFGD and HA-TPC improve acceptance for high angle and backward tracks**
- **SuperFGD provides a high precision probe of the nuclear effects responsible for some of the dominant systematics in neutrino oscillation analyses → reduced systematics**
- **High granularity of SuperFGD → detection of short proton tracks which is very important for T2K analysis**
- **SuperFGD provides reconstruction of the neutrino energy by time-of-flight**
- **TOF Detector separates background from outside SuperFGD and HA-TPC**

High angle acceptance



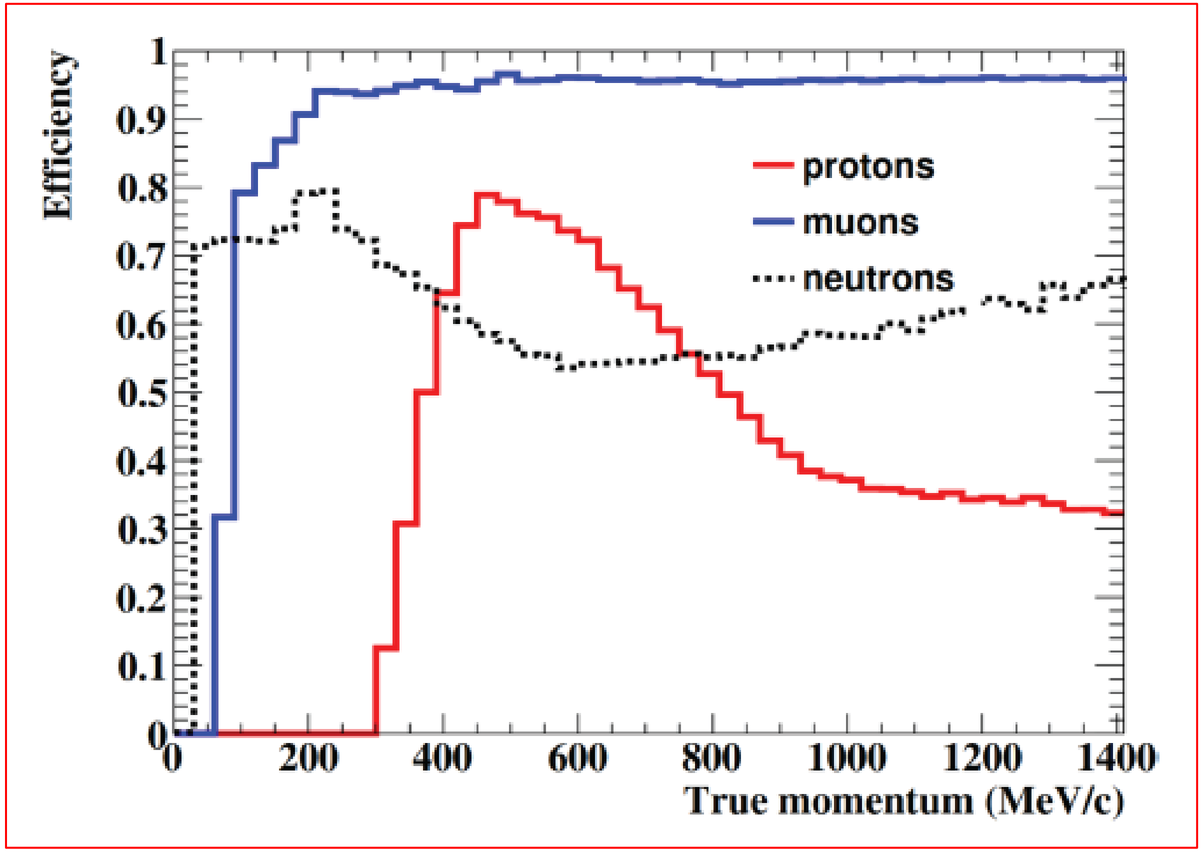


Neutron detection by SuperFGD using time-of-flight



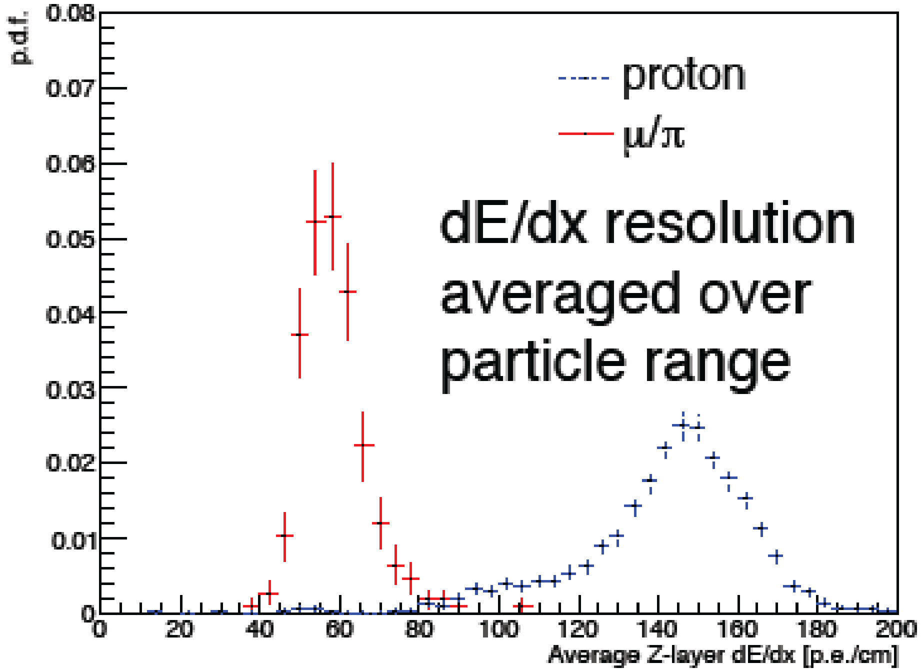
SFGD: efficiency of p, n, μ detection

Low detection threshold of protons neutrons, muons, and pions

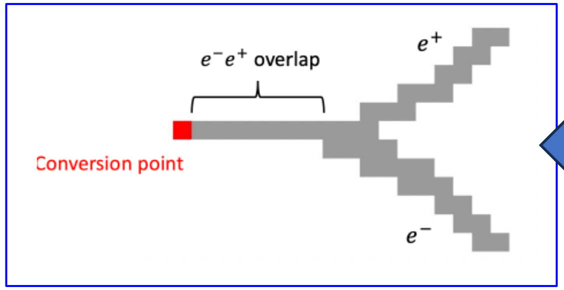


SFGD particle identification

proton vs muon/pion

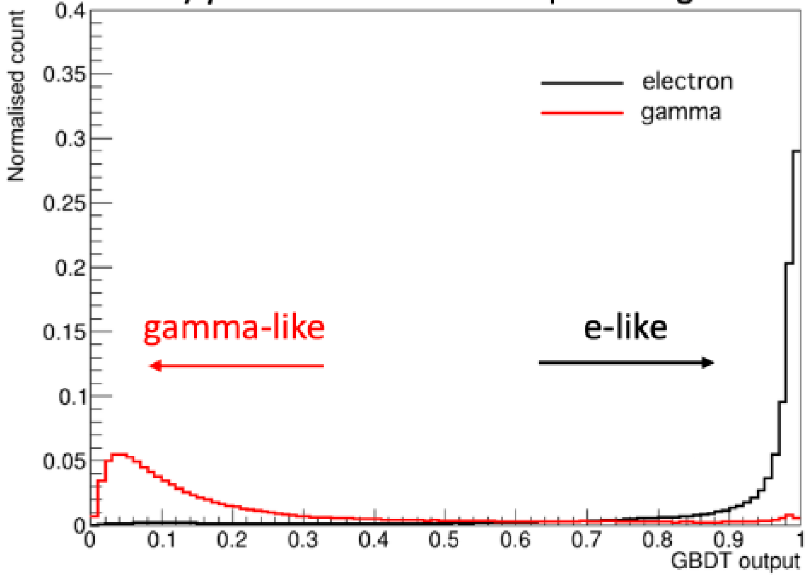


e/γ separation



L.y. in first cubes of EM shower/track about2 times larger for $\gamma's$

e/γ discrimination with particle gun



Neutrino energy reconstruction

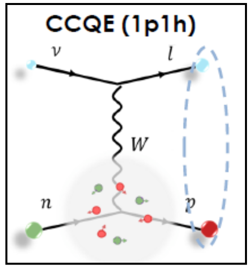
Muon neutrino CC0π

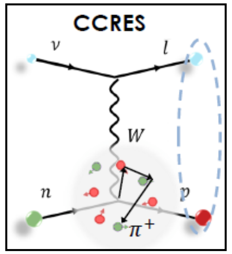
$$\nu_\mu + n \longrightarrow \mu^- + p$$

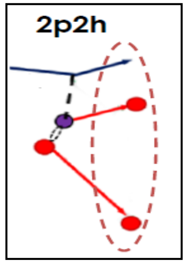
$$E_\nu = \frac{m_p^2 - (m_n - E_b)^2 - m_\mu^2 + 2(m_n - E_b)E_\mu}{2(m_n - E_b - E_\mu + p_\mu \cos\theta_\mu)}$$

$E_b \simeq 25$ MeV for carbon

Nuclei smearing and bias E_ν

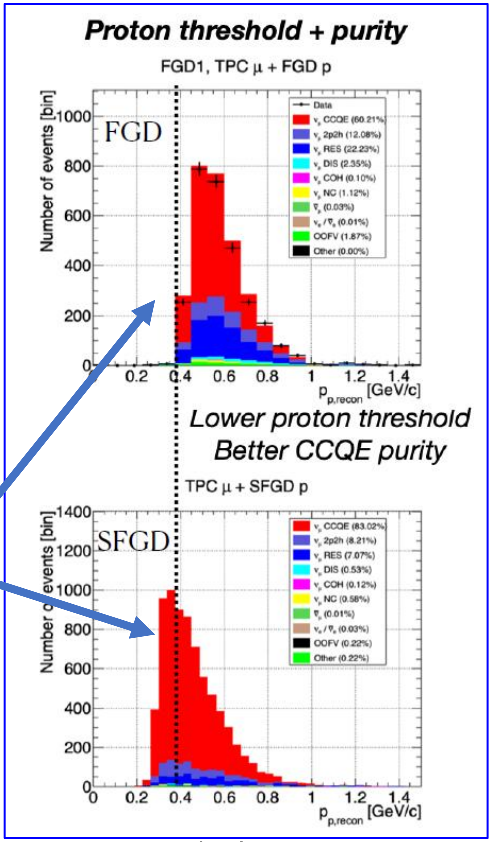




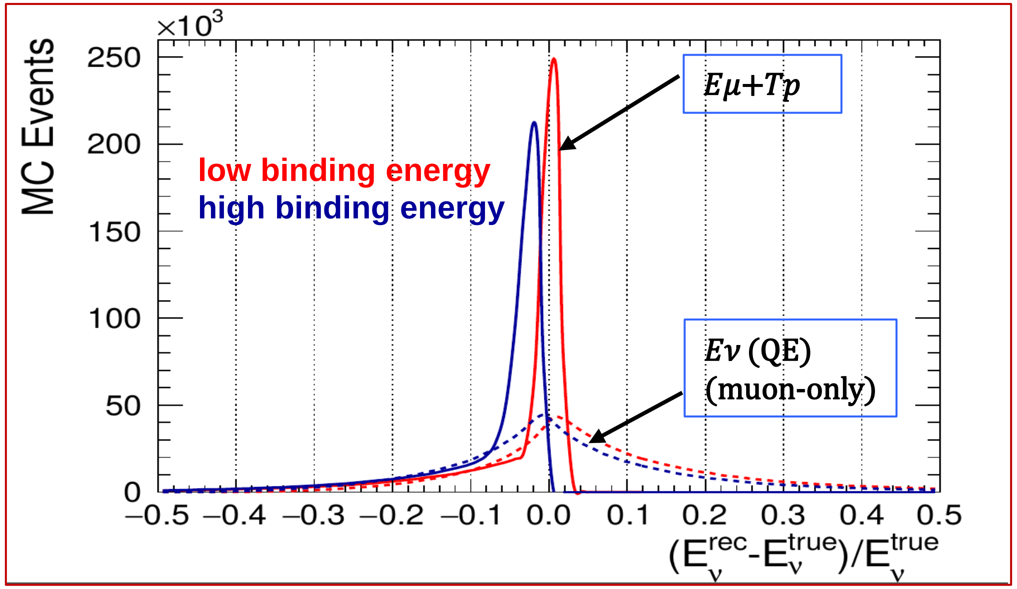


- Current ND280 uses muons for reconstruction of the neutrino energy and some protons with high threshold
- SuperFGD will provide reconstruction of the neutrino energy by measuring both the muon and proton energies
- More precise $E\nu$ reconstruction, more sensitive to oscillation physics

Proton momentum distribution from ν_μCC 1muon+1proton selection



S.Dolan, talk at HEP-EPS 2021



No detector smearing

Detection of neutrons

arXiv:1912.01511

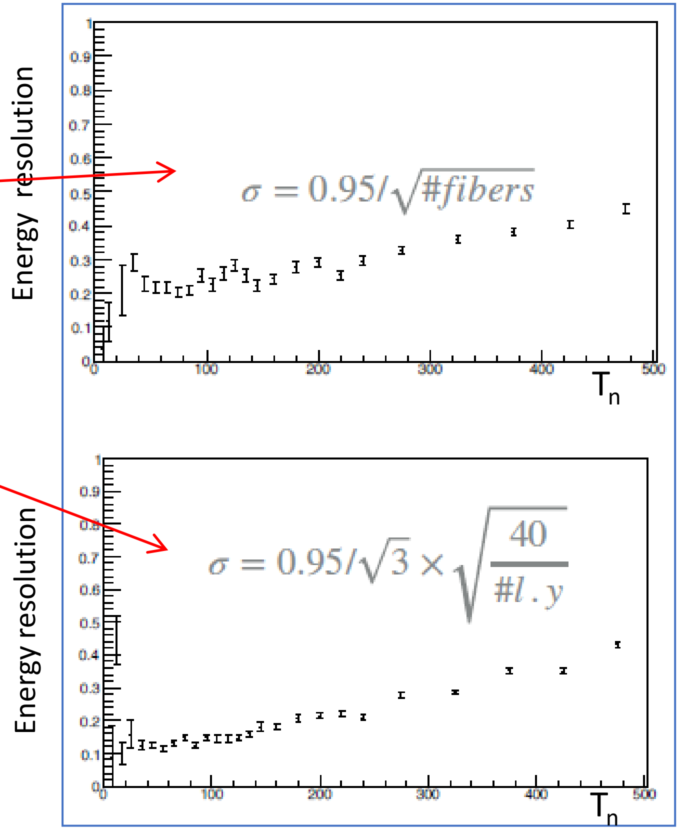
Antineutrino CCQE

$$\bar{\nu}_\mu + p \rightarrow \mu^+ + n$$

$$\sigma_t = 0.95ns/\sqrt{\#\ fibers}$$

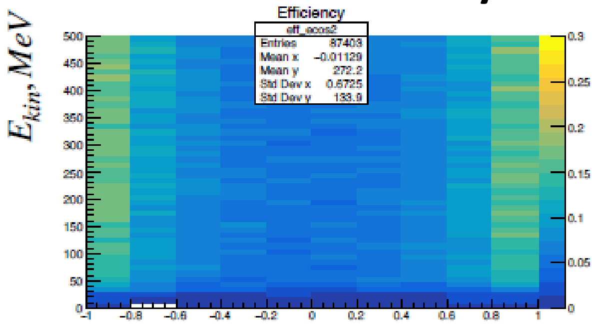
$$\sigma_t = \frac{0.95ns}{\sqrt{3}}\sqrt{\frac{40}{l.y.}}$$

Detection of neutrons by time-of-flight

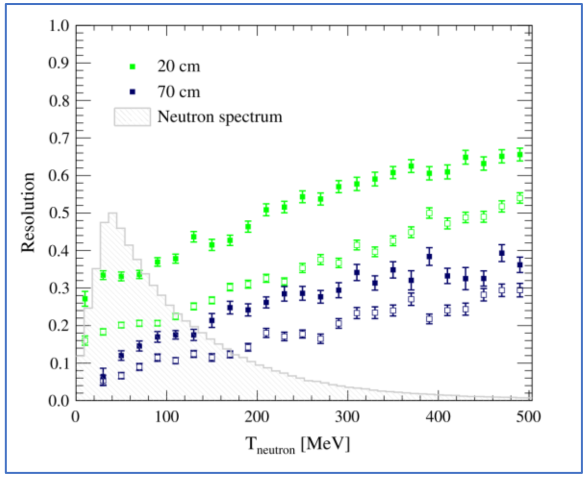


Monte Carlo study

Detection efficiency

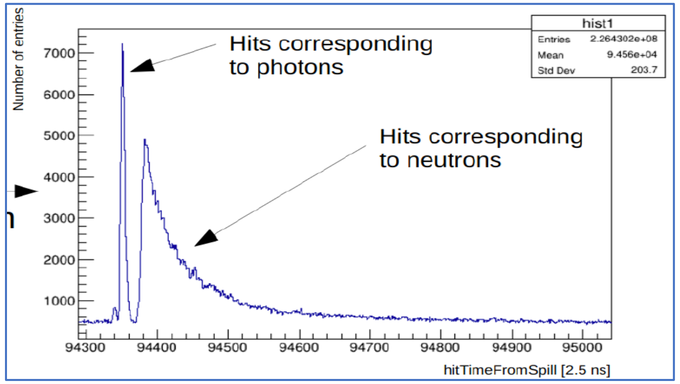


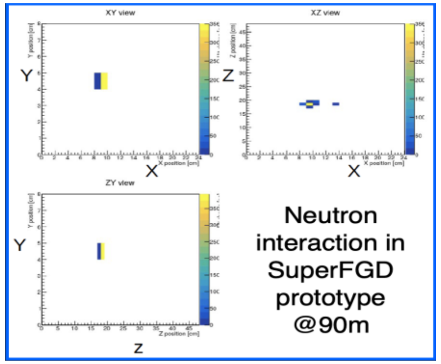
Energy resolution of neutrons



PLB 840 (2023) 137843

Beam tests with neutrons of SFGD prototype at LANL

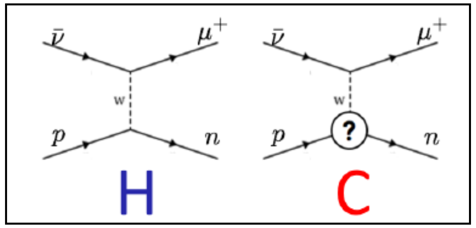




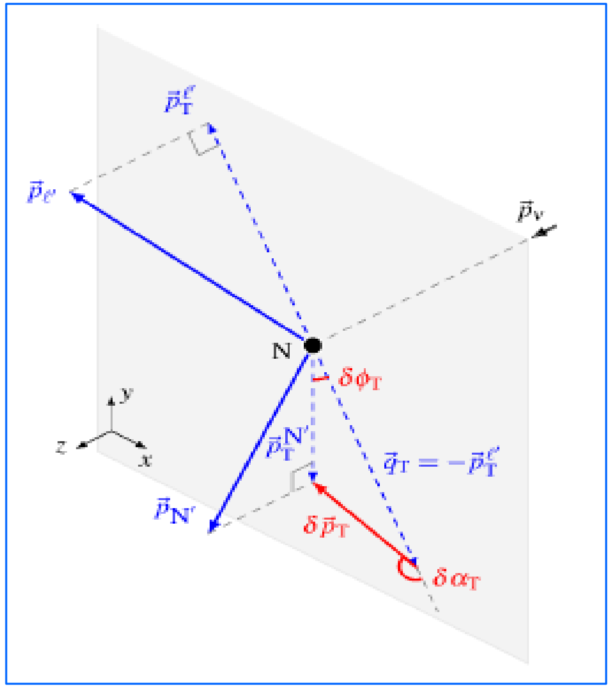
Anti-neutrino energy reconstruction

Muon antineutrino CCQE

$$\bar{\nu}_\mu + p \longrightarrow \mu^+ + n$$



Transverse kinematic imbalance

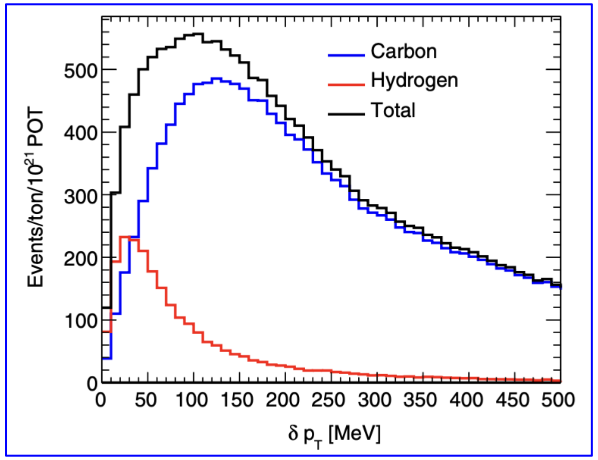


$$\delta p_T = |\vec{p}_T^{\,l} + \vec{p}_T^{\,n}|$$

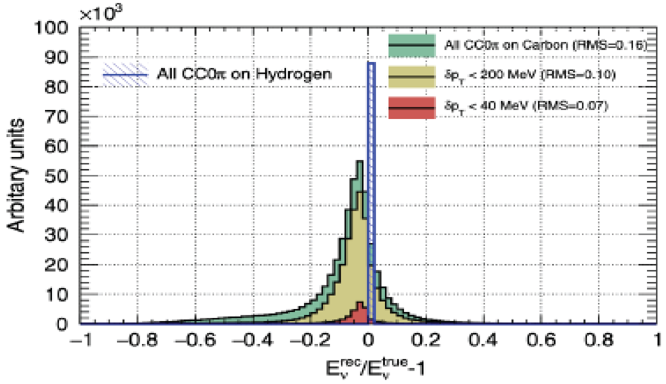
Transverse kinematic imbalance due to Fermi motion, FSI, 2p2h, pion absorption…

For free proton $\delta p_T = 0$

Very low δp_T – signature of neutrino interaction with hydrogen

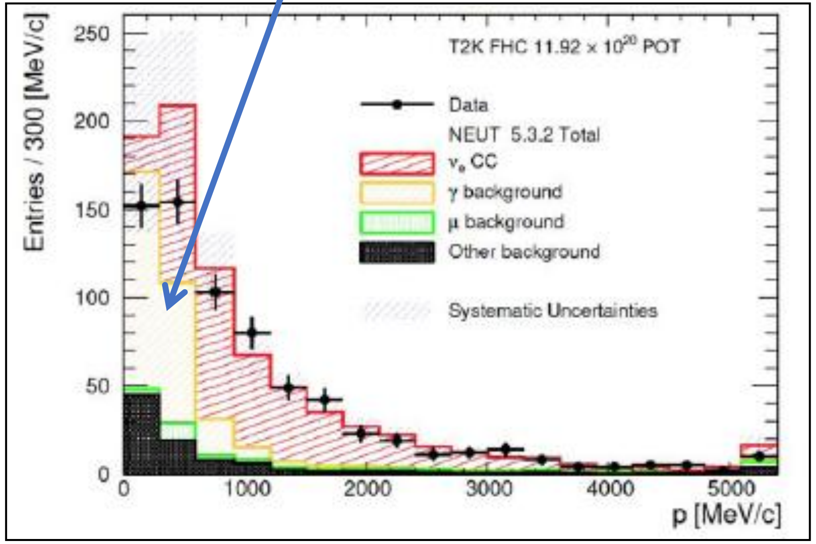


Improvement in reconstruction of $E_{\bar{\nu}}$ using detected neutron

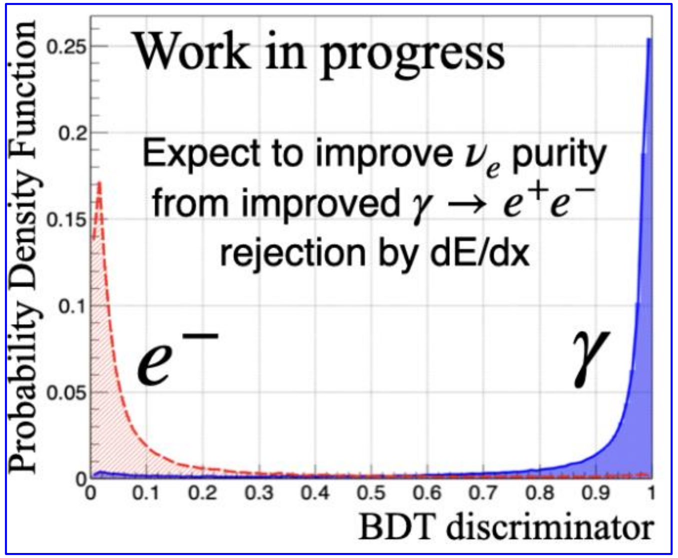


ν_e constraints

ND280: large contributions from photons in ν_e spectrum



SuperFGD: expected excellent electron/photon separation



- ν_e contamination in ν_μ beam

- Understanding of difference between $\sigma(\nu_e)$, $\sigma(\bar{\nu}_e)$, $\sigma(\nu_\mu)$, $\sigma(\bar{\nu}_\mu)$ - crucial for a search for CP violation in neutrino oscillations and measurements of oscillation parameters

Measurement of double ratio:

$$[\sigma(\nu_\mu)/\sigma(\nu_e)] / [\sigma(\bar{\nu}_\mu)/\sigma(\bar{\nu}_e)]$$

Search for ν_s in T2K ND280

Total proton number on target
5.9×10^{20} POT

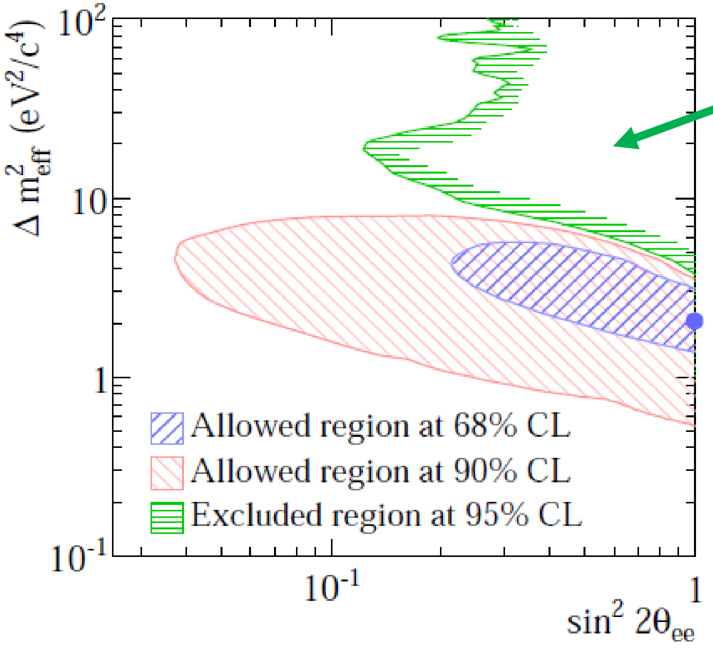
$$P(\nu_e \to \nu_e) = 1 - \sin^2 2\theta_{ee} \sin^2\left(1.27\frac{\Delta m^2_{eff} L}{E}\right)$$

Phys.Rev.D 91 (2015) 051102

ν_μCC interactions at ND280 are used to constrain neutrino flux and cross sections assuming no ν_μ disappearance
ν_e flux: 1.1% of total -> 614 ν_e CC candidates were detected

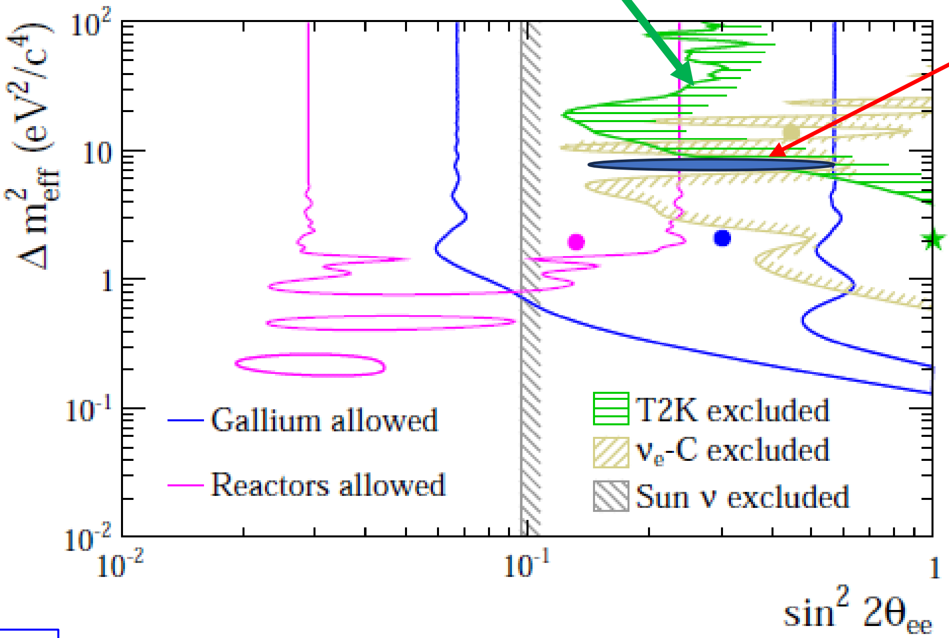
Δm^2_{eff} > 7 eV² $\sin^2 2\theta_{ee}$ > 0.3 (95% CL)

T2K excluded



T2K exclusion limit

Neutrino4



- ND280 statistics increased by a factor of 2
- SuperFGD will add more ν_e events

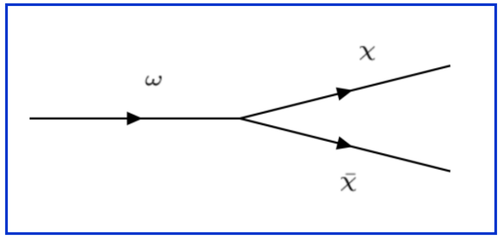
Sensitivity to $\Delta m^2_{eff} \sim 5$ eV²

Meson decays into MCPs

New particles with small electric charge can arise in some extensions of SM

Source of MCPs: decays of mesons produced by intense proton beam of 30 GeV at J-PARC

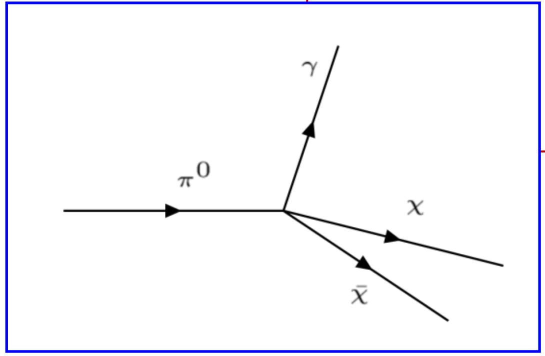
Light vector mesons ρ, ω, ϕ decay into MCP pair $\chi\bar{\chi}$



$$\mathrm{Br}(V \to \chi\bar{\chi}) = \epsilon^2 \cdot \mathrm{Br}(X \to e^+e^-) \cdot \left(1 + 2\frac{m_\chi^2}{M_V^2}\right)\sqrt{1 - 4\frac{m_\chi^2}{M_V^2}}, \quad V \in \{\rho, \omega, \phi\}$$

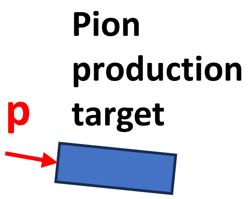
Pseudoscalar mesons π^0, η, η' decay into MCP $\chi\bar{\chi}$ pair through three-body decays

$$\mathrm{Br}(X \to Y\chi\bar{\chi}) = \epsilon^2 \cdot \mathrm{Br}(X \to Y\gamma) \cdot \frac{2\alpha}{3\pi} f_{X\to Y} \int_{4m_\chi^2}^{m_\chi^2} \frac{dm_{\chi\chi}^2}{m_{\chi\chi}^2}\left(1 + 2\frac{m_\chi^2}{m_{\chi\chi}^2}\right)\left(1 - 4\frac{m_\chi^2}{m_{\chi\chi}^2}\right)^{\frac{1}{2}} \times \left(\left(1 + \frac{m_{\chi\chi}^2}{M_X^2 - M_Y^2}\right)^2 - 4\frac{m_{\chi\chi}^2 M_X^2}{(M_X^2 - M_Y^2)^2}\right)^{\frac{3}{2}} |F_{XY}(m_{\chi\chi}^2)|^2,$$



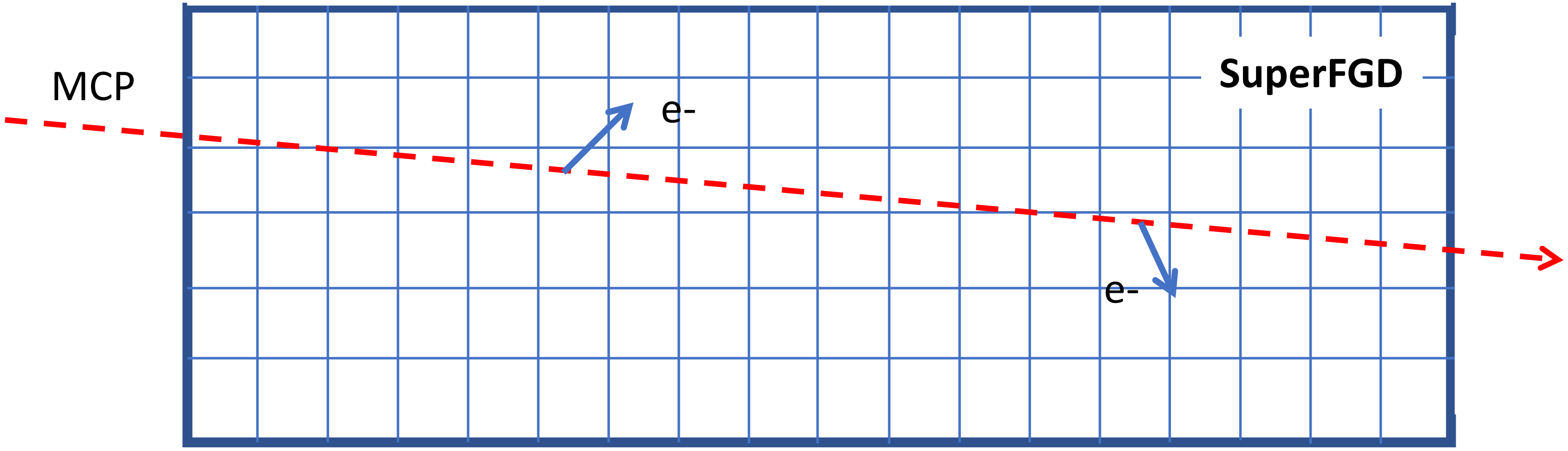
$$X \to Y \in \{\pi \to \gamma, \eta \to \gamma, \eta' \to \gamma, \omega \to \pi^0, \phi \to \pi^0, \phi \to \eta\}$$
$$f_{\pi\to\gamma} = f_{\eta\to\gamma} = f_{\eta'\to\gamma} = 1, \quad f_{\omega\to\pi^0} = f_{\phi\to\pi^0} = f_{\phi\to\eta} = \frac{1}{2}$$

Detection MCPs in SuperFGD



MCP interacts twice in the detector SuperFGD

arXiv:1902.03246
ArgoNeut, PRL 124 (2020) 131801



Detection threshold of knock-on electron = 100 keV

MCP free path in detector $\lambda \simeq 1.2 \times 104 \times \left(\frac{10^{-3}}{\varepsilon}\right)^2 \times \left(\frac{E_r^{min}}{100\ keV}\right)$ m

Probability for 2 hits:

$$P_{2h} = \frac{1}{2}\left(\xi\,\frac{L}{\lambda}\right)^2 = \frac{1}{2}\left(\frac{0.96 \times \left(\frac{\xi}{0.96}\right)\, 1.84\,\mathrm{m}}{\left(\frac{10^{-3}}{\epsilon}\right)^2\left(\frac{E_r^{min}}{100\,\mathrm{keV}}\right) 12\,\mathrm{km}}\right)^2 \approx 1.1 \times 10^{-8} \times \left(\frac{\epsilon}{10^{-3}}\right)^4$$

For E_r^{min} = 100 keV

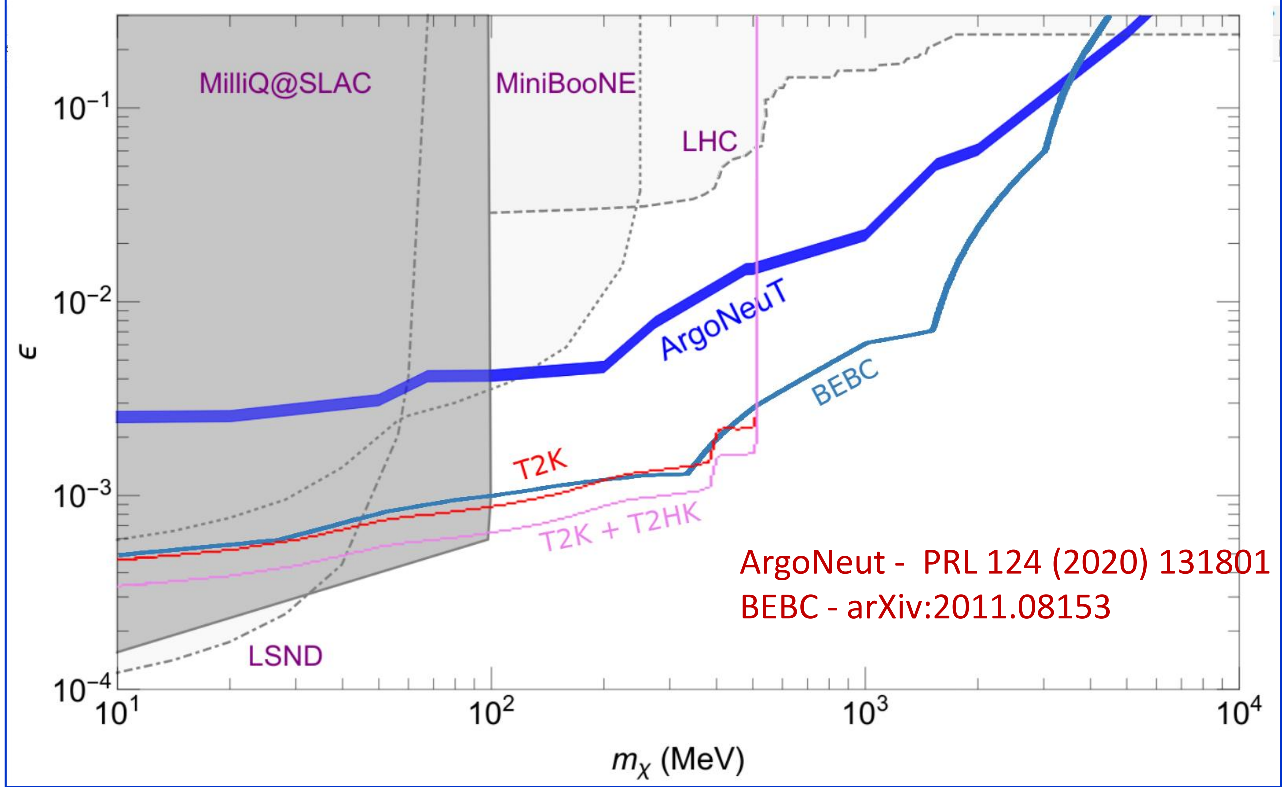
SFGD threshold = 2-3 p.e.

Expected sensitivity to MCPs

T2K: 0.5x10^{22} POT
HyperK: 2.7x10^{22} POT
No background

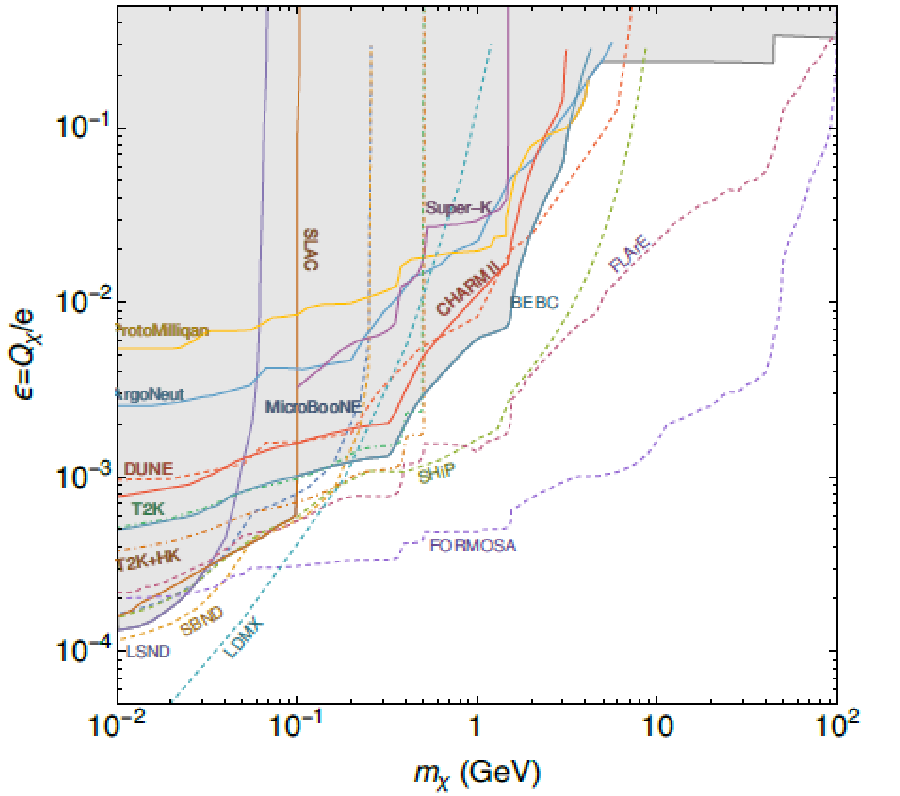
Phys.Lett.B 822 (2021)

90% CL exclusion regions



ArgoNeut - PRL 124 (2020) 131801
BEBC - arXiv:2011.08153

T2K, HyperK and DUNE



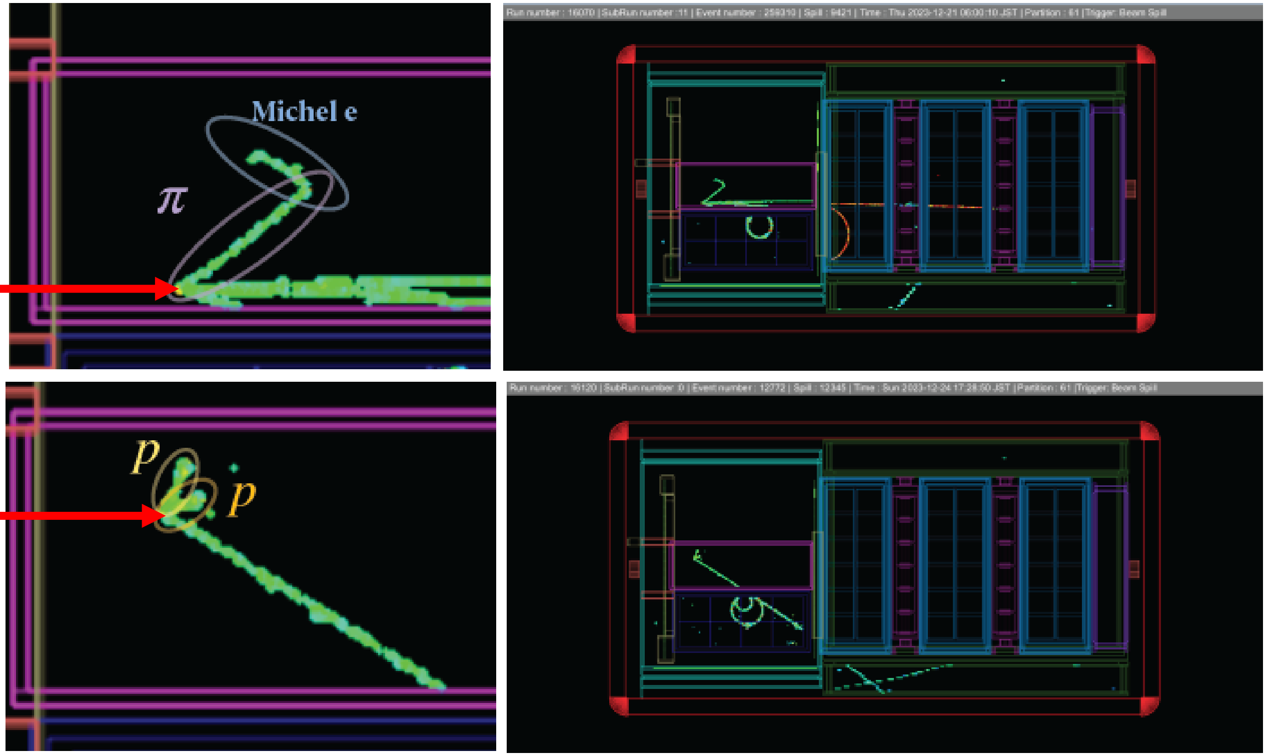
Neutrino interactions in SuperFGD

SuperFGD **ND280**

First run with neutrinos November 2023

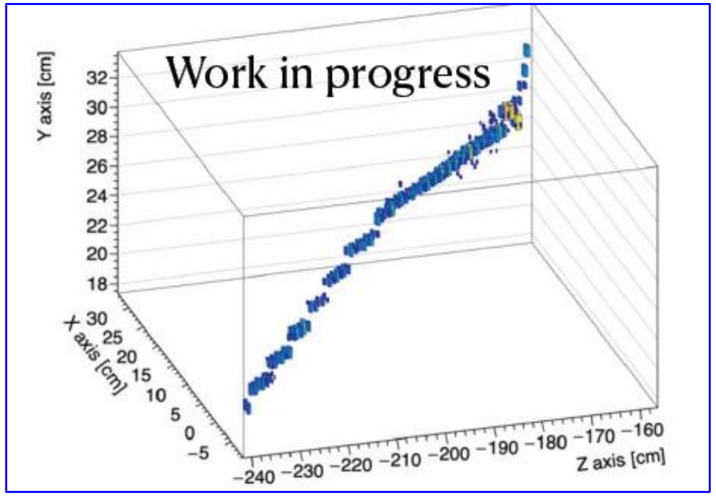
ν_μ

ν_μ



T2K muon neutrino beam, CC events

3D reconstructed tracks



Conclusion

- Reduction of systematic uncertainties – crucial for CP-violation search and oscillation measurements in T2K and HyperK
- Upgrade of T2K near detector ND280 with a new neutrino target-detector SuperFGD is completed
- SuperFGD will be a central near neutrino detector in T2K and HyperK experiments
- SuperFGD is one of key instruments in a CP violation search
- Rich neutrino interaction physics
- Search for exotics: sterile neutrinos, MCPs, HNLs….
- SuperFGD begun to accumulate data in T2K neutrino beam

Thank you very much for your attention