Physics and status of SuperFGD detector for T2K experiment

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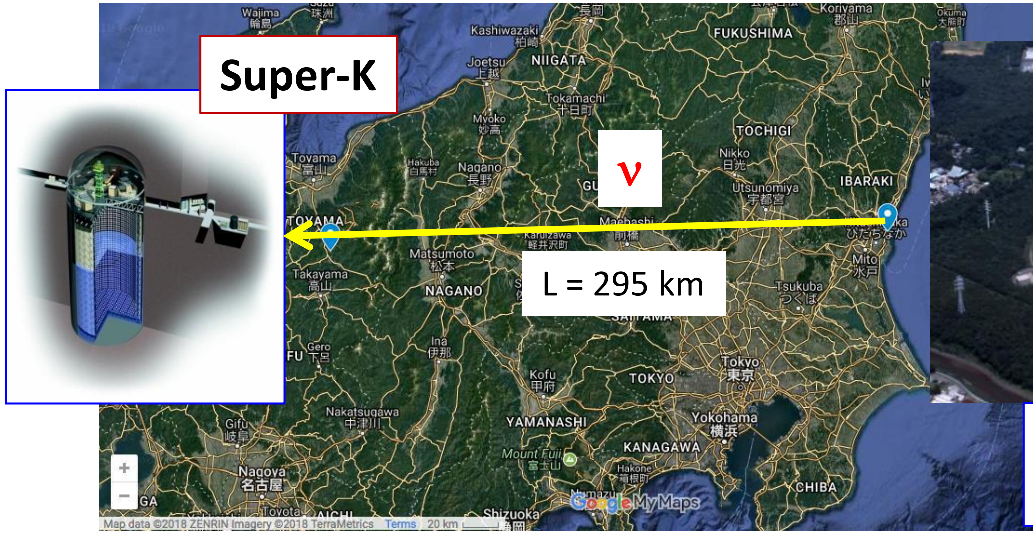
Tokai-to-Super-Kamiokande (T2K)

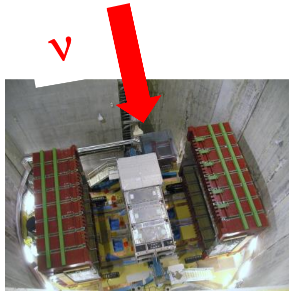
Main goals:
- **search for CP violation**
- **measurement of neutrino oscillation parameters**



J-PARC

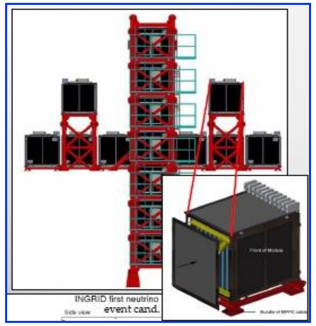
Proton beam :
30 GeV, 0.52 MW, spill 5μs, cycle 2.46 s

Off-axis near neutrino detector



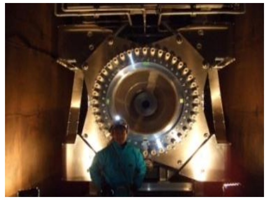
Near neutrino detector at 280 m from target

Neutrino monitor INGRID



Decay tunnel

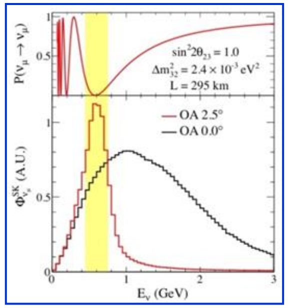
Horn



Target

Neutrino beam elements

Off-axis neutrino beam

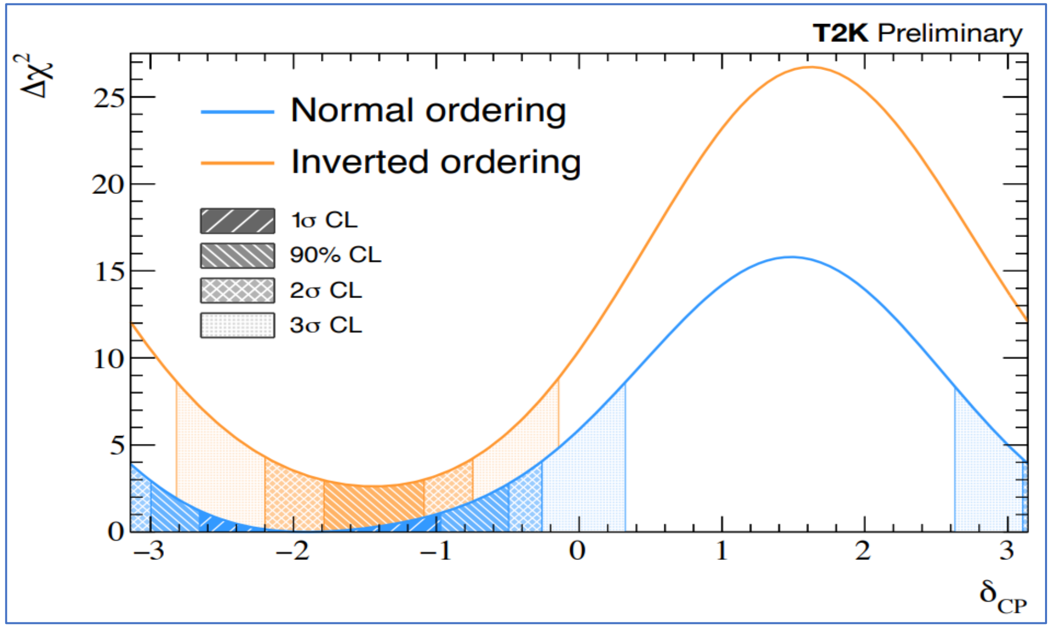


J-PARC neutrino beam 2.5°off-axis, peak energy 600 MeV (oscillation maximum)

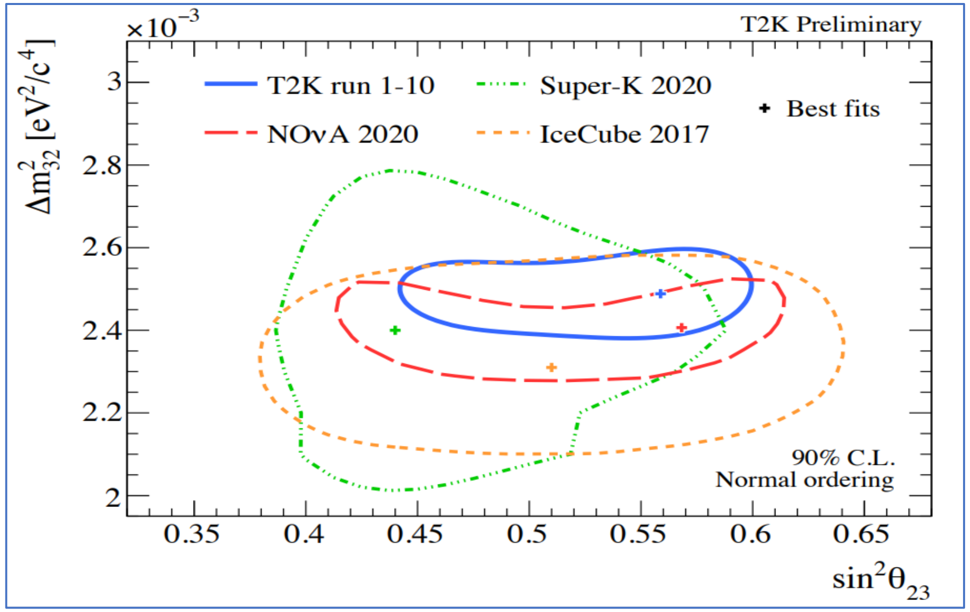
T2K results

T.Vladisavljevic, T2K talk on 20 August

CP conservation ($\delta_{CP} = 0, \pm\pi$) excluded at 90% CL
Large fraction of δ_{CP} excluded at 3σ level
Preference for maximal CP violation ($\delta_{CP} = -\pi/2$)



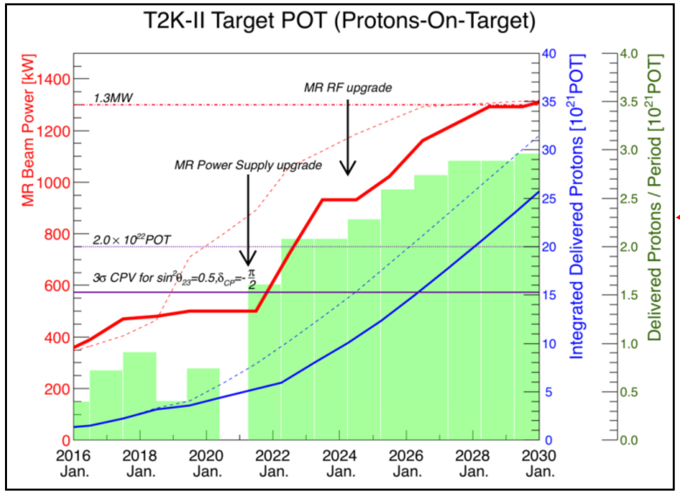
Best constraint on $\sin^2\theta_{23}$
Compatible with maximal mixing $\sin^2\theta_{23}$ = 0.5



Prospects
T2K will continue data taking until start of HyperKamiokande
More statistics will be accumulated with beam power increase from 500 kW to 1.3 MW
Extensive T2K upgrade in progress

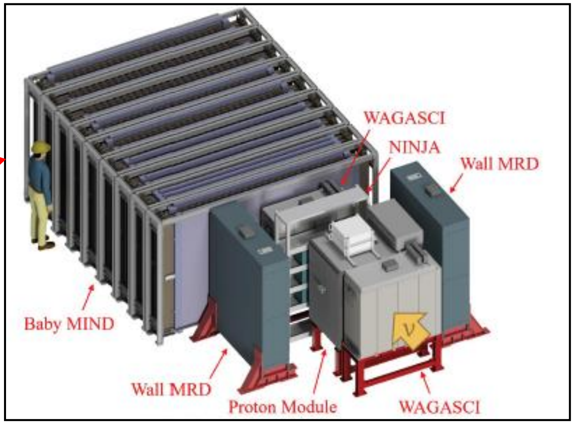
T2K upgrade

J-PARC beam upgrade

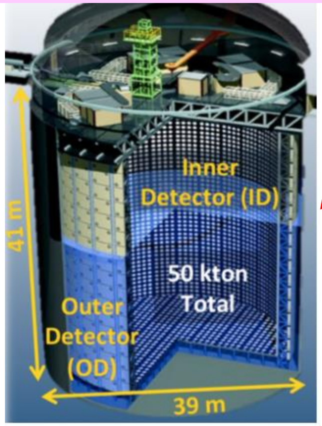


Intensive upgrade program

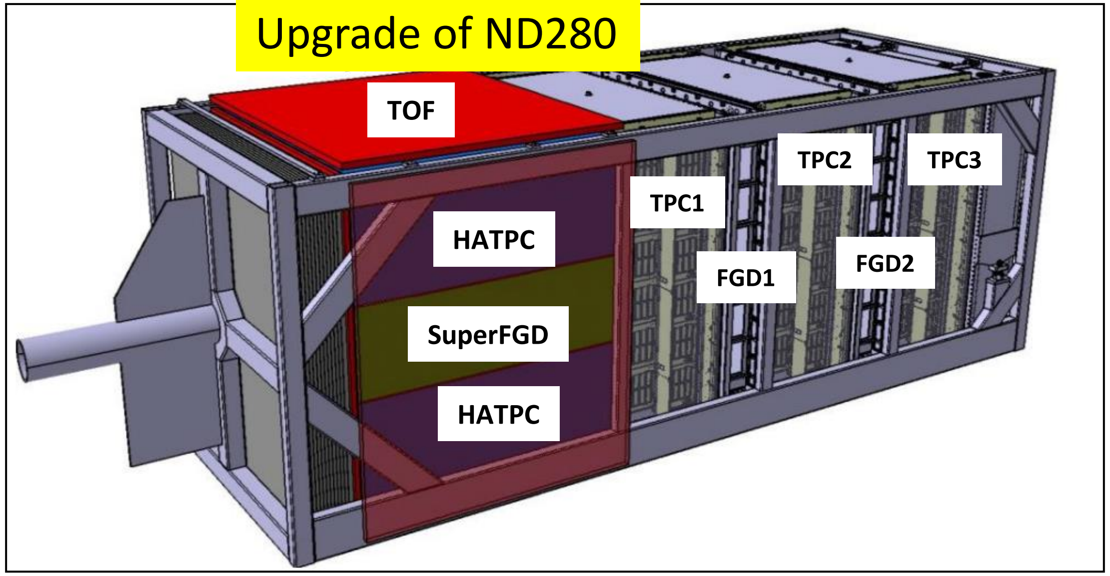
WAGASHI/Baby-MIND detectors



SuperK upgrade: Gd loading for neutron tagging



Upgrade of ND280



ND280 upgrade

New upstream tracker:
- Two Horizontal TPCs
- One 3D fine-grained scintillator target SuperFGD
- TOF system around new tracker

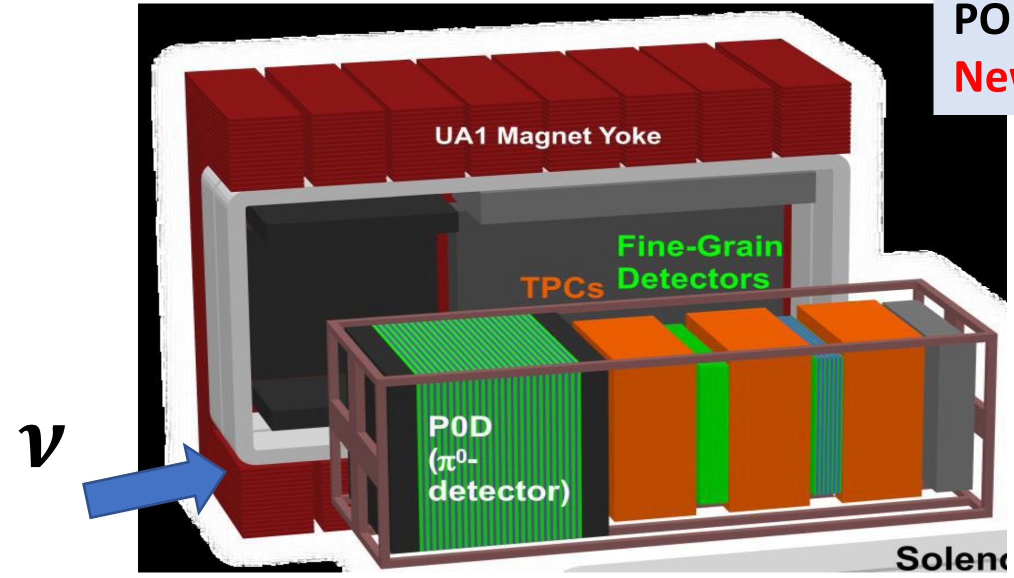
- Fully active detector
- 4π acceptance for charged particles
- Detection of low energy protons and pions
- Electron/gamma separation
- Electron neutrino studies
- Detection of neutrons

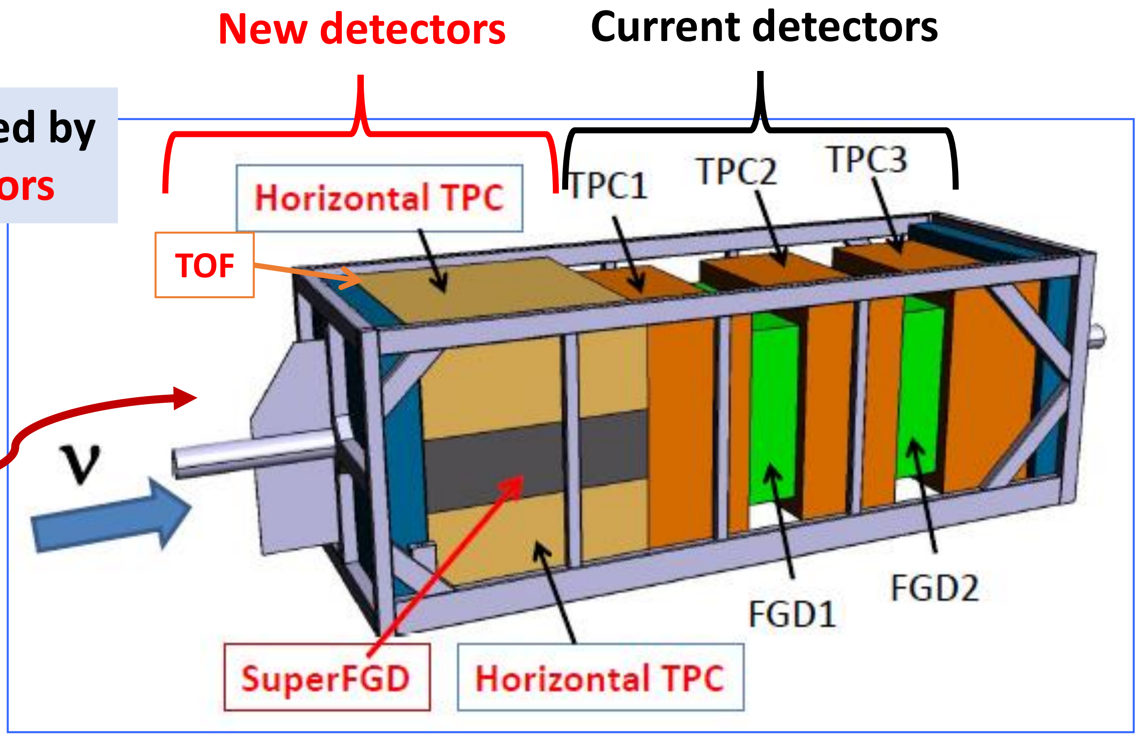
arXiv:1901.03750

T2K upgrade group
~ 90 participants
from 10 countries

Current ND280 complex

POD replaced by New detectors





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

On average the error on the systematic parameters can be reduced by about 30% in the ND280 upgrade configuration

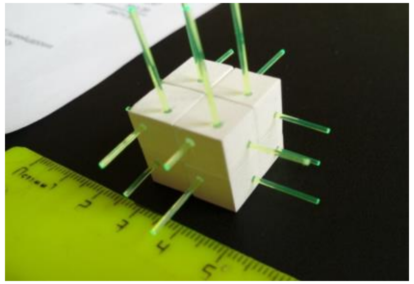
- Important to measure neutrino interactions in all phase space
- Precisely detect particles produced at any angle
- Reduce detection threshold, measure protons with low threshold
- Measure neutrons in anti-ν_μ interactions
- Reduce background, obtain better track identification using TOF
- Provide electron/gamma separation
- Reduce total systematics to **≤ 4%** level (from current ~ 6%) for appearance modes

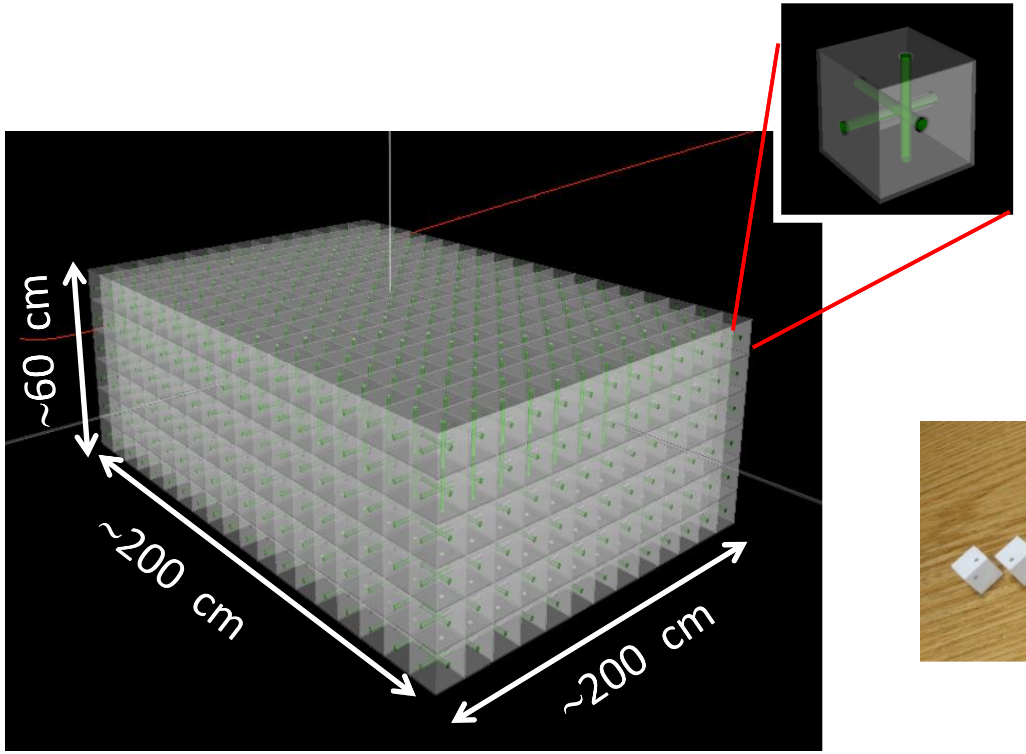
SuperFGD

JINST 13 (2018) 02006

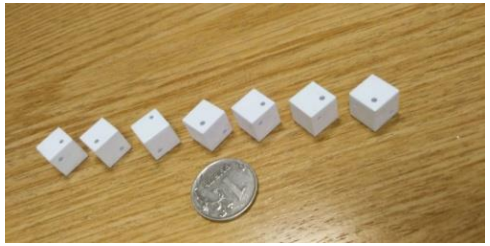
- Volume ~200 x 200 x 60 cm^3
- **~2 x 10^6** scintillator cubes , each 1 x 1 x 1 cm^3
- Each cube has orthogonal 3 holes, diameter 1.5 mm
- 3D (x,y,z) WLS readout
- About **60000** readout WLS/MPPC channels
- Total active weight about **2 t**

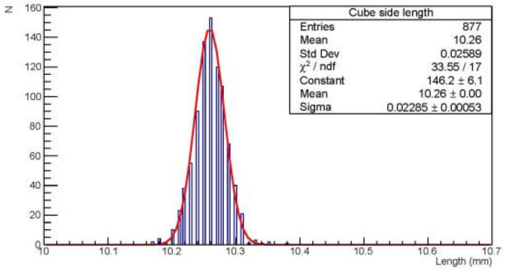
Fully active, highly granular, 4π scintillator neutrino detector with 3D WLS/MPPC readout





- Scintillator cubes (polystyrene based) produced by injection molding at Uniplast, Vladimir, Russia
- Covered by chemical reflector
- Tolerance (each side) about 30 microns





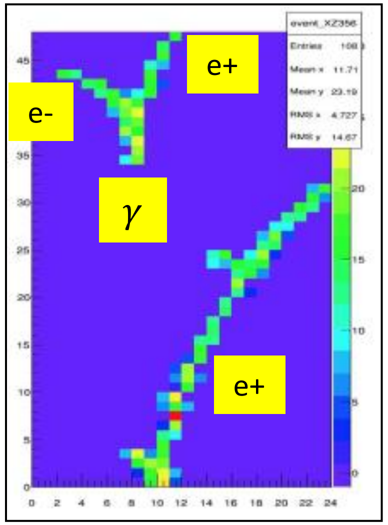
3 holes in each cube drilled with the tolerance of 50-70 microns

Performance in beam tests

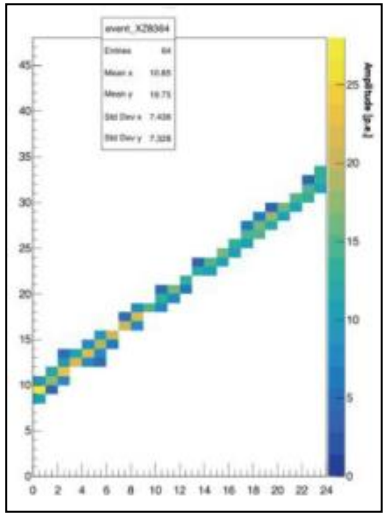
Tests of two SFGD prototypes in charged particles beams (e, μ, π, p) at CERN

JINST 15 (2020) 12, P12003

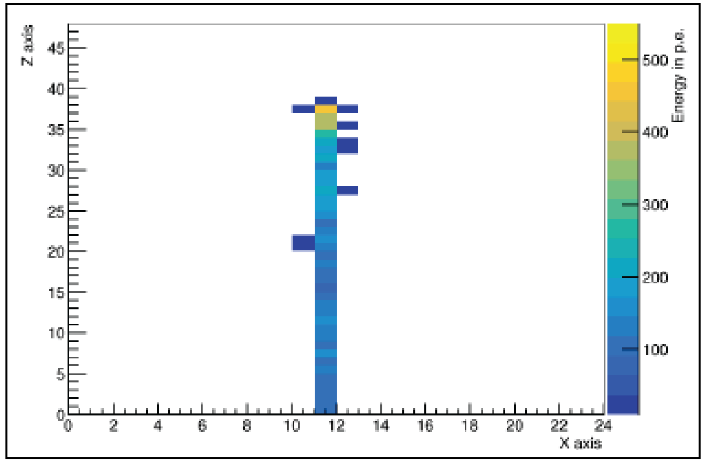
e+, B=0.2T



Muons

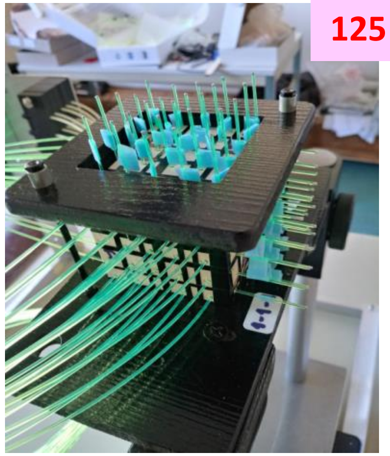


Stopped protons

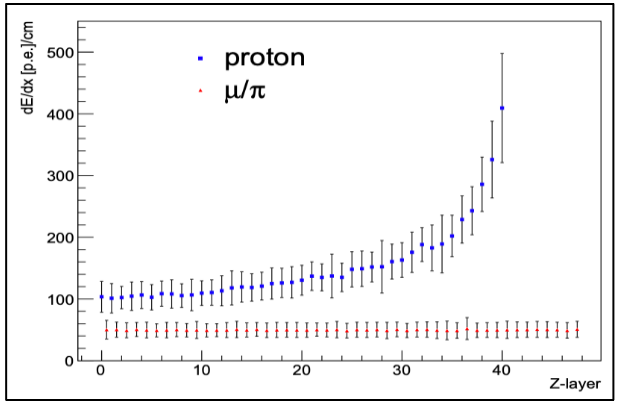


SFGD prototypes

125 cubes



dE/dx



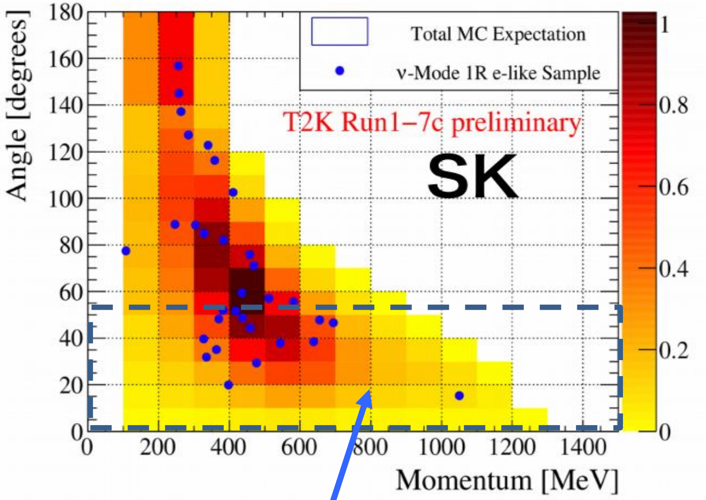
Parameters of the SFGD prototype obtained in the beam tests at CERN:

- 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.)

9216 cubes
1728 Y11 WLS fibers and MPPCs

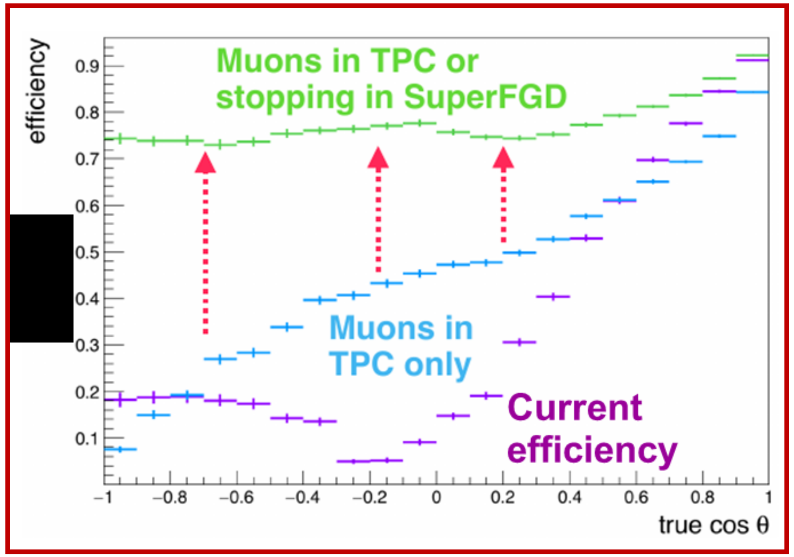
Detection of charged particles

Upgraded ND280

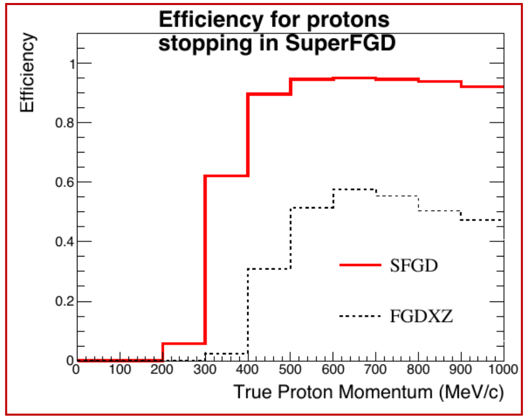


ND280 acceptance

4π acceptance for muons

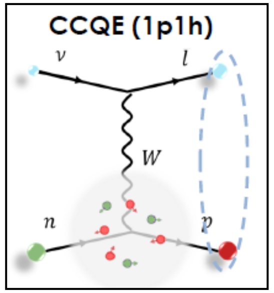


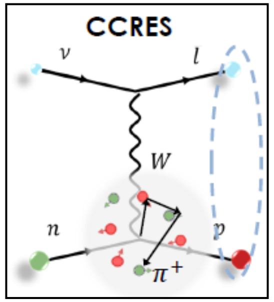
Detection of protons and neutrons in the final state will allow to test nuclear effects and to avoid biases in oscillation measurements

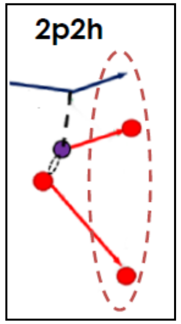


$$E_\nu = \frac{m_p^2 - (m_n - E_b)^2 - m_\mu^2 + 2(m_n - E_b)E_\mu}{2(m_n - E_b - E_\mu + p_\mu \cos\theta_\mu)}$$

E_b – nuclear binding energy



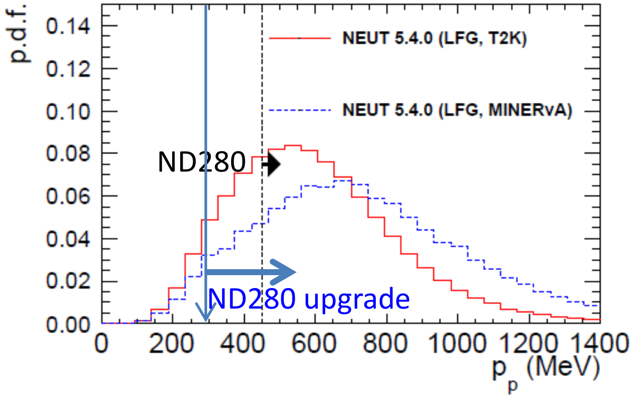




Nuclei smearing and bias E_ν

Nuclear effects which impact the oscillation measurements :

- **Fermi motion**
- **2p2h**
- **FSI**



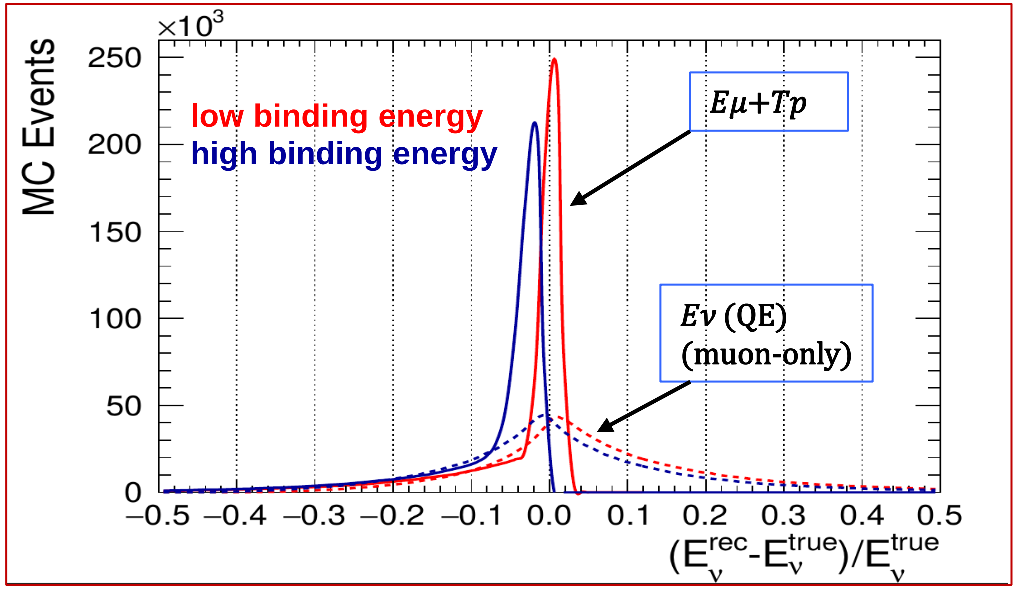
Neutrino energy reconstruction

Muon neutrino CC0π

$$\nu_\mu + \mathrm{n} \longrightarrow \mu^- + \mathrm{p}$$

S.Dolan, talk at HEP-EPS 2021

- Current ND280 uses only muons for reconstruction of the neutrino energy
- SuperFGD provides reconstruction of the neutrino energy by measuring both the muon and proton energies
- More precise E_ν reconstruction, more sensitive to oscillation physics

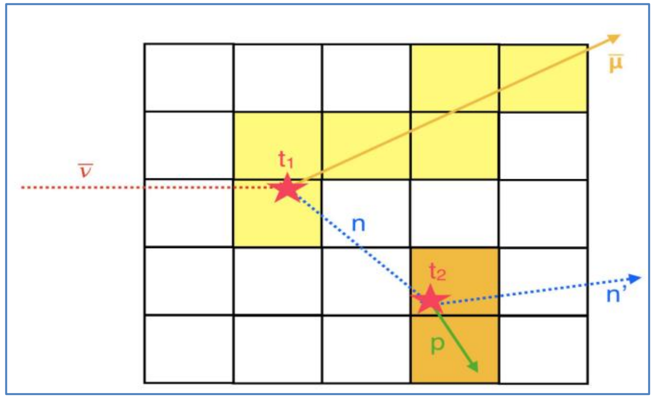


No detector smearing

Detection of neutrons

Antineutrino CCQE

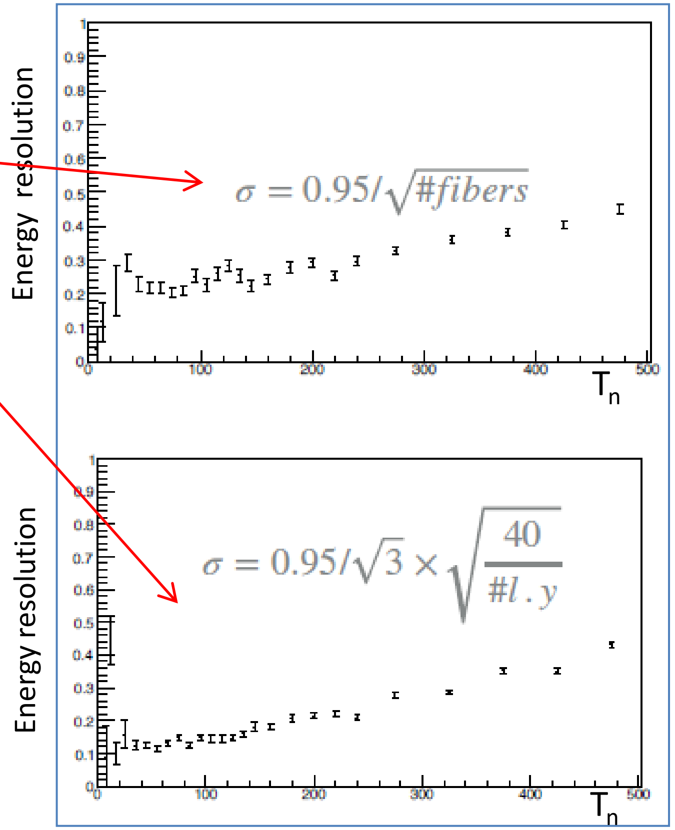
$$\bar{\nu}_\mu + p \rightarrow \mu^+ + n$$



Detection of neutrons by time-of-flight

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

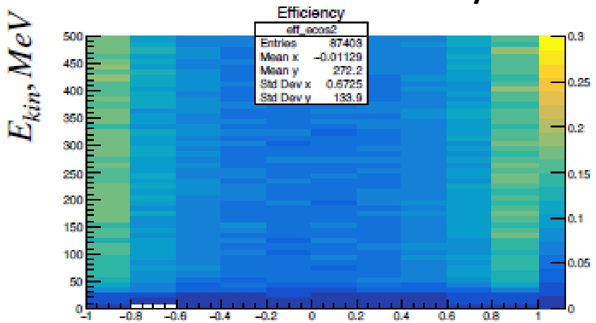
$$\sigma_t = \frac{0.95ns}{\sqrt{3}}\sqrt{\frac{40}{l.y.}}$$



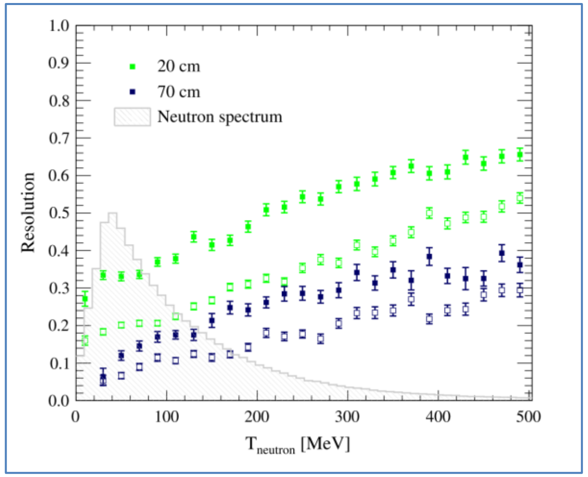
L.Munteanu et al. arXiv:1912.01511

Monte Carlo study

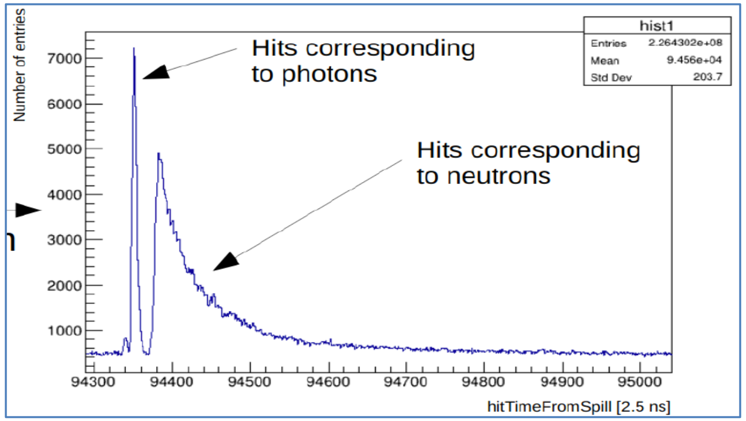
Detection efficiency

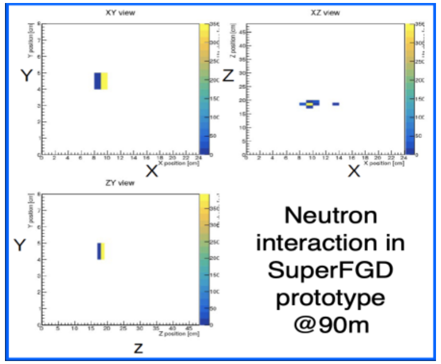


Energy resolution



Beam tests with neutrons of SFGD prototype at LANL

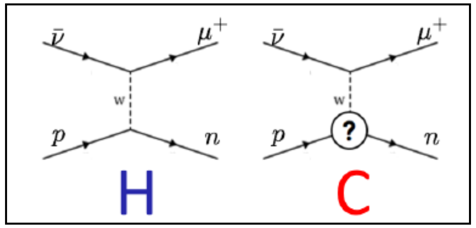




Anti-neutrino energy reconstruction

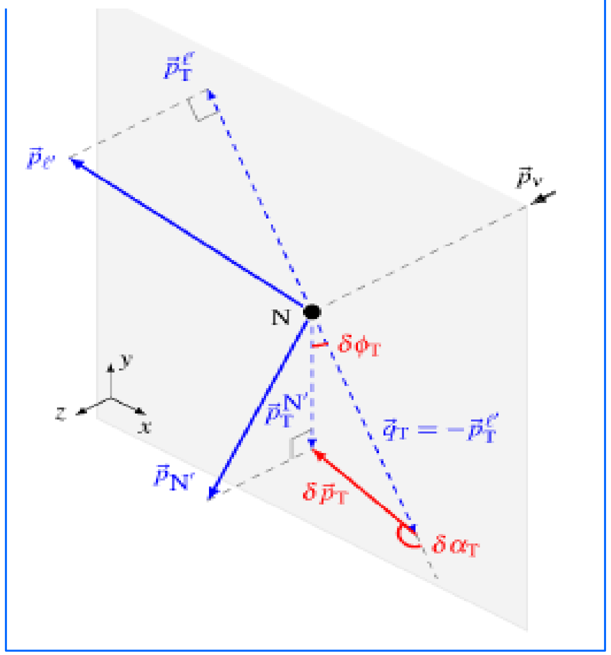
Muon antineutrino CCQE

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



Transverse kinematic imbalance

X.-G.Lu et al, arXiv:1512.05548

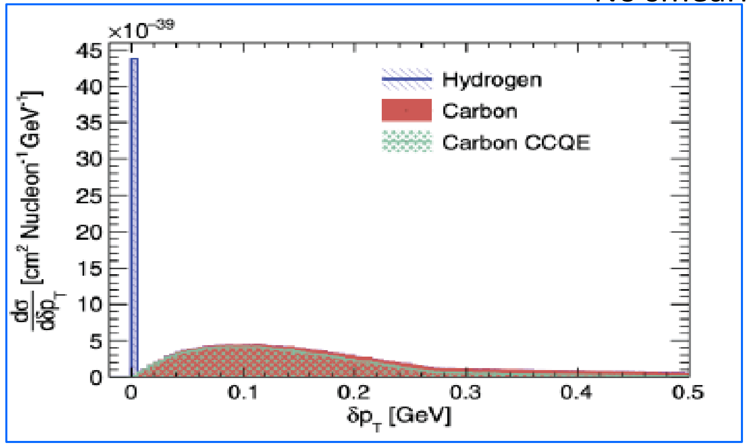


$$\delta p_T = |\vec{p}_T^{\,l} + \vec{p}_T^{\,n}|$$

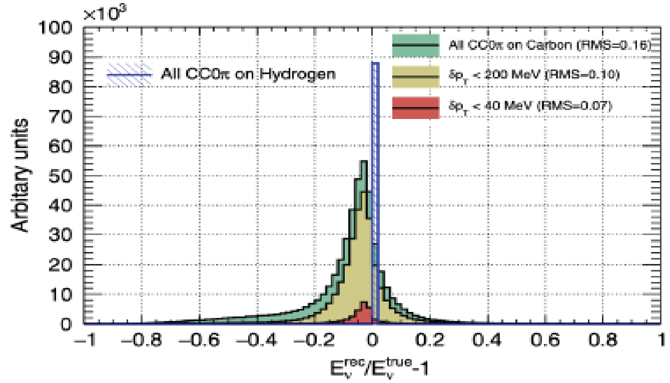
Transverse kinematic imbalance due to
Fermi motion, FSI. 2p2h,
pion absorption…
For free proton $\delta p_T = 0$

Very low δp_T – signature of neutrino interaction with hydrogen

No smearing



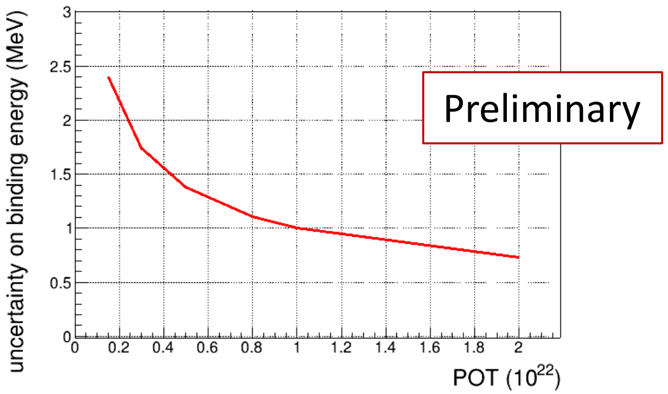
Improvement in reconstruction of $E_{\bar{\nu}}$ using detected neutron



Measurement of nucleons

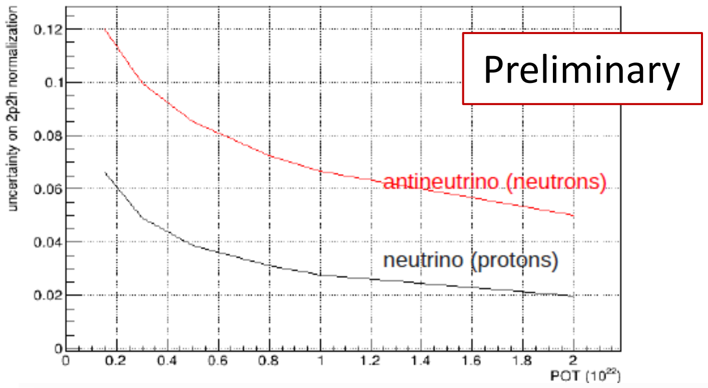
SuperFGD similiation
S.Bolognesi, S.Dolan, L.Muntenau

Measurement of protons helps to reduce E_b uncertainty

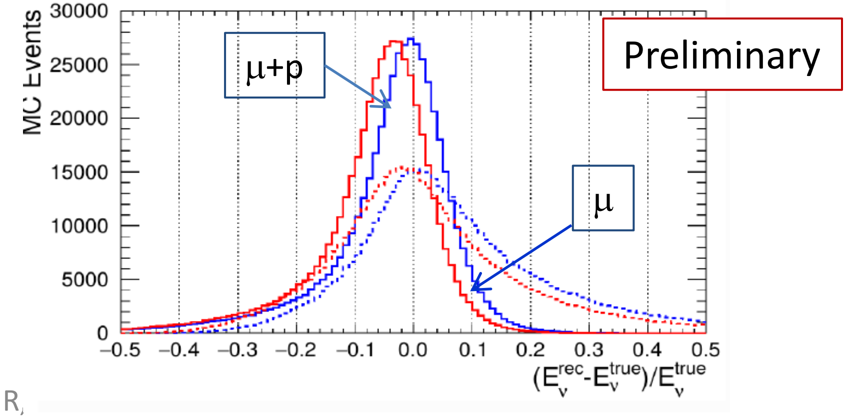


Neutron detection:
- 60% efficiency
- neutron path >50 cm
- energy resolution 15-30%

helps to reduce uncertainty on 2p2h contribution

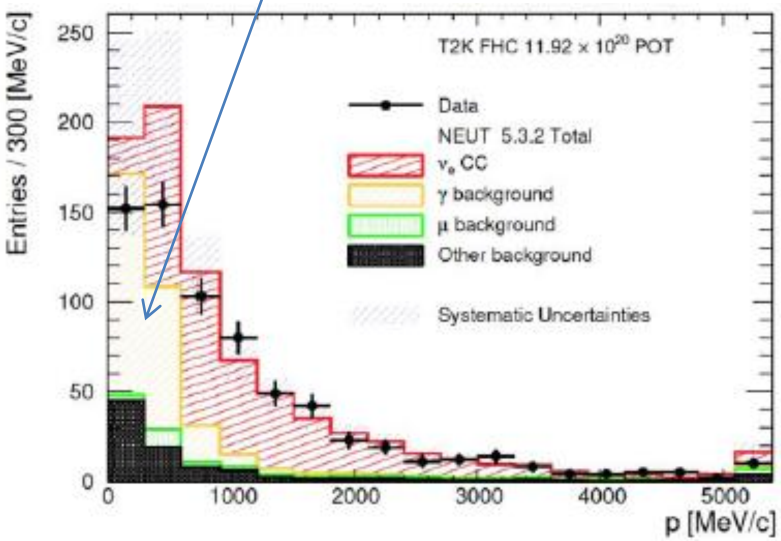


Eν reconstruction based on muon kinematics and Ep + Eμ with detector resolution

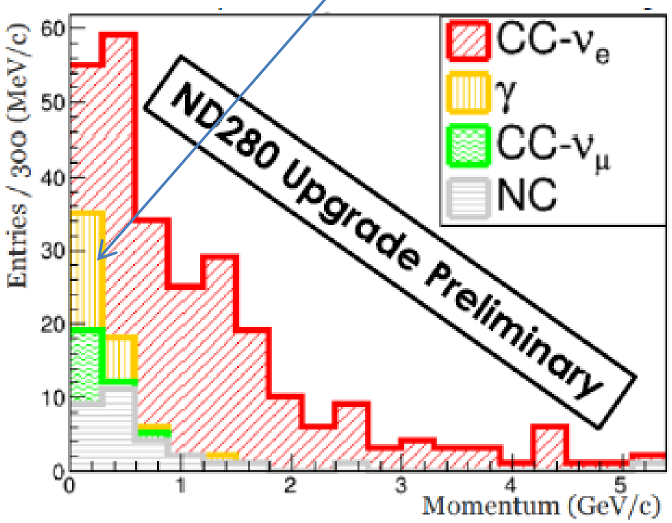


ν_e constraints

ND280: large contributions from photons in ν_e spectrum



SFGD: expected excellent photon rejection



Understanding of difference between $\sigma(\nu_e)$ and $\sigma(\nu_\mu)$ - crucial for oscillation measurements

Measurement of double ratio:

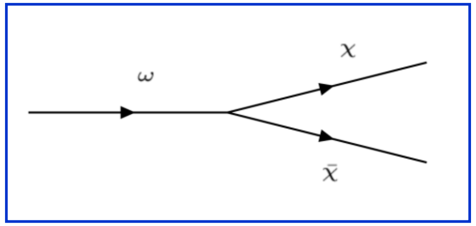
$$\boxed{[\sigma(\nu_\mu)/\sigma(\nu_e)] \,/\, [\sigma(\bar{\nu}_\mu)/\sigma(\bar{\nu}_e)]}$$

Search for MilliCharged Particles

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

Millicharged particles (MCPs) source at J-PARC: decays of mesons produced by 30 GeV proton beam

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

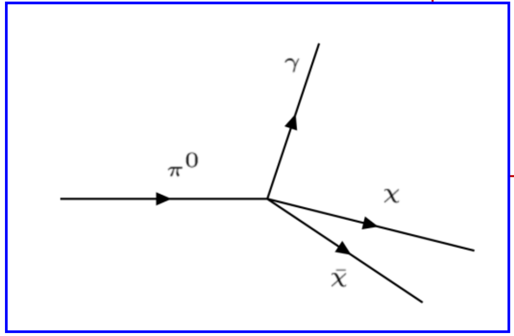


$$\mathrm{Br}(V \to \chi\bar{\chi}) = \epsilon^2 \cdot \mathrm{Br}(X \to e^+e^-) \cdot \left(1 + 2\frac{m_\chi^2}{M_V^2}\right)\sqrt{1 - 4\frac{m_\chi^2}{M_V^2}}\,, \qquad V \in \{\rho,\, \omega,\, \phi\}$$

MCP charge = ϵe

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

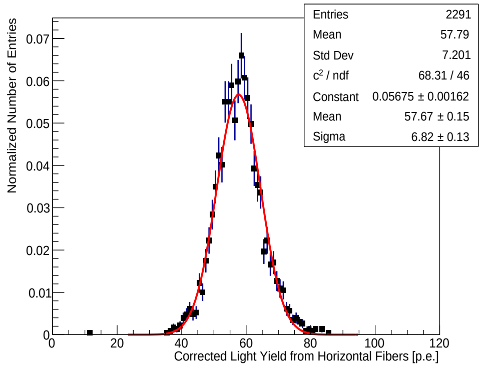
$$\mathrm{Br}(X \to Y\chi\bar{\chi}) = \epsilon^2 \cdot \mathrm{Br}(X \to Y\gamma) \cdot \frac{2\alpha}{3\pi} f_{X\to Y} \int_{4m_\chi^2}^{m_X^2} \frac{dm_{\chi\chi}^2}{m_{\chi\chi}^2}\left(1 + 2\frac{m_\chi^2}{m_{\chi\chi}^2}\right)\left(1 - 4\frac{m_\chi^2}{m_{\chi\chi}^2}\right)^{\frac{1}{2}}$$
$$\times\left(\left(1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



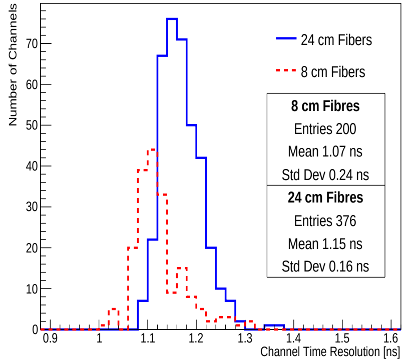
$$X \to Y \in \{\pi \to \gamma, \eta \to \gamma, \eta' \to \gamma, \omega \to \pi^0, \phi \to \pi^0, \phi \to \eta\}$$
$$f_{\pi\to\gamma} = f_{\eta\to\gamma} = f_{\eta'\to\gamma} = 1\,, \quad f_{\omega\to\pi^0} = f_{\phi\to\pi^0} = f_{\phi\to\eta} = \frac{1}{2}$$

Detection of MCPs

l.y./MIP ~ 60 p.e.



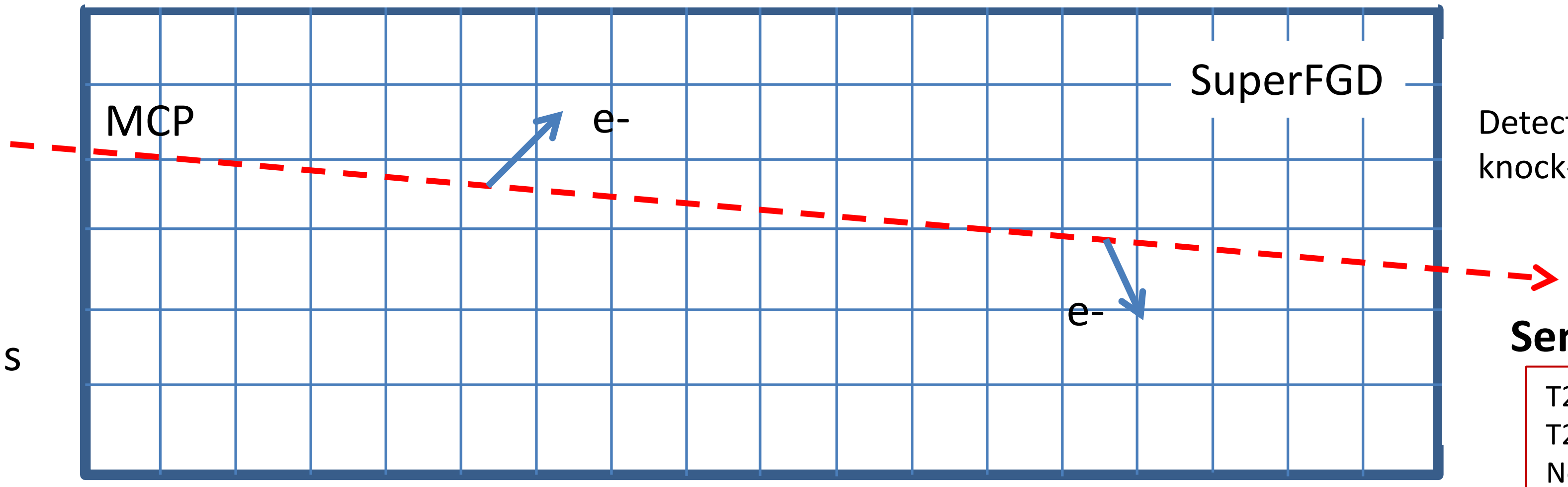
MIP time resolution σ~1 ns



SFGD: low threshold of ~100 keV for detection of charged particles

D.Gorbunov et al. arXiv:2103.11814

MCP interacts twice in SuperFGD



Detection threshold of knock-on electron = 100 keV

MCP free path in SFGD

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

Probability for 2 hits:

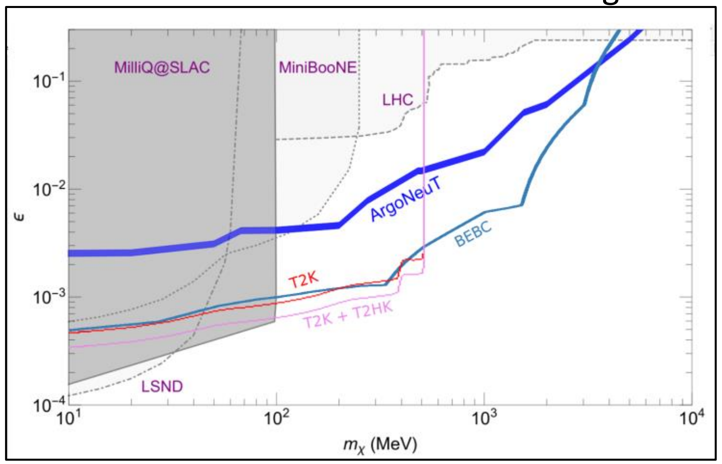
$$P_{2h} = \frac{1}{2}\left(\xi\frac{L}{\lambda}\right)^2 = \frac{1}{2}\left(\frac{0.96 \times \left(\frac{\xi}{0.96}\right) 1.84\,\mathrm{m}}{\left(\frac{10^{-3}}{\epsilon}\right)^2 \left(\frac{E_r^{min}}{100\,\mathrm{keV}}\right) 12\,\mathrm{km}}\right)^2 \approx 1.1 \times 10^{-8} \times \left(\frac{\epsilon}{10^{-3}}\right)^4$$

$$E_r^{min} = 100\ keV$$

Sensitivity to MCP

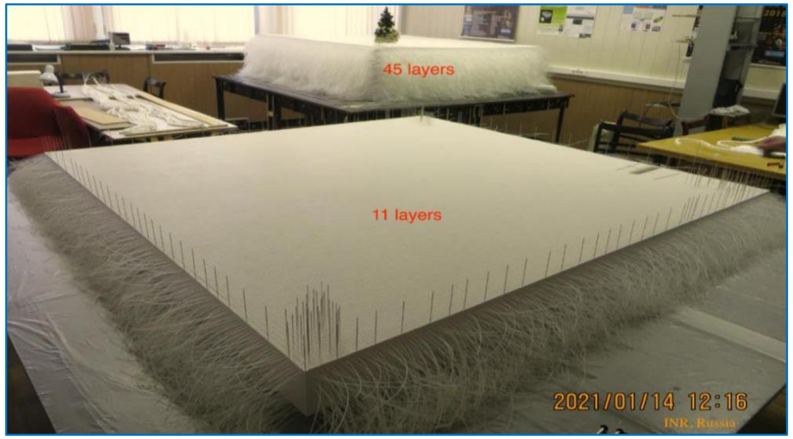
T2K: 0.5×10^{22} POT
T2HK: 2.7×10^{22} POT
No background

95% CL exclusion regions

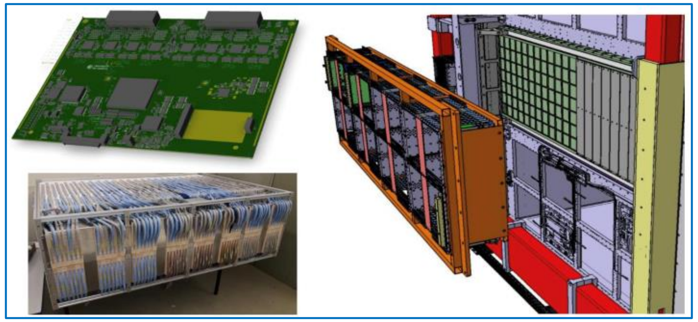


Status & Schedule

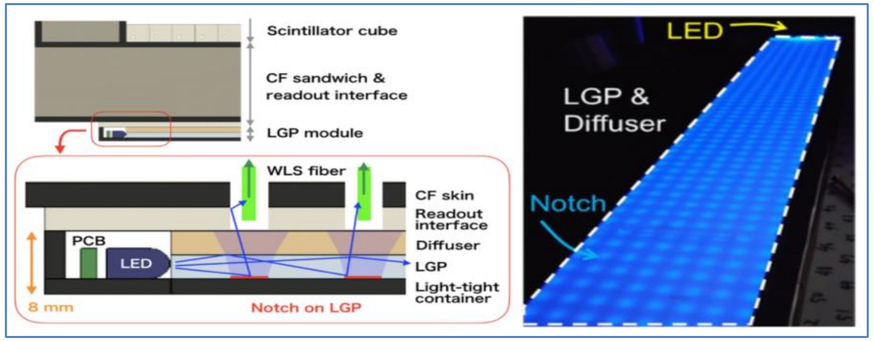
- 2M cubes are manufactured
- Assembled using fishing lines at INR
- Ready for shipment to JPARC



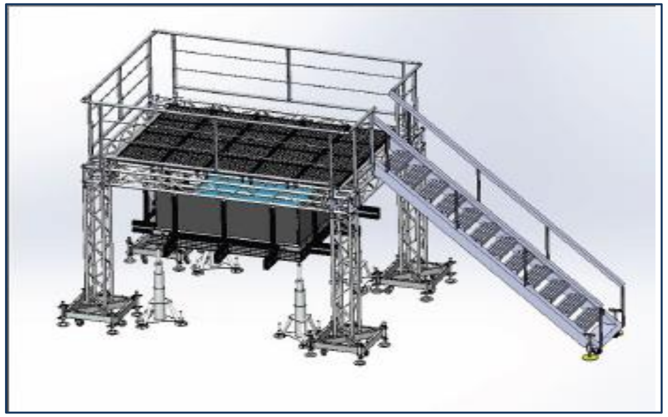
Design of electronics based on CITIROC chip is finished



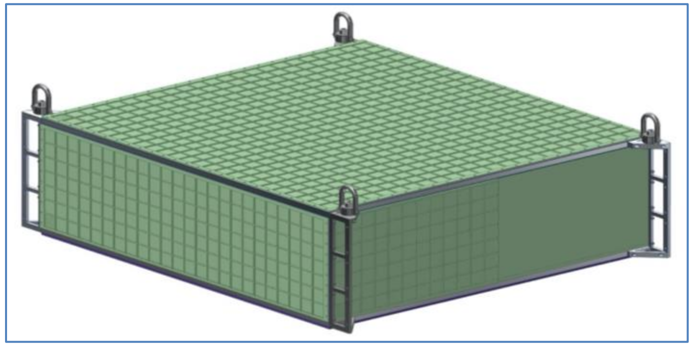
LED based calibration system allows to calibrate/control low dark rate MPPCs



SFGD Assembly platform



SFGD Box



Schedule

- Manufacturing all elements and mechanics - 10.2022
- SFGD assembly at JPARC - 10.2022
- Commissioning - 11.2022
- Installation in ND280 pit - 12.2022
- Ready to accept ν beam - 02.2023

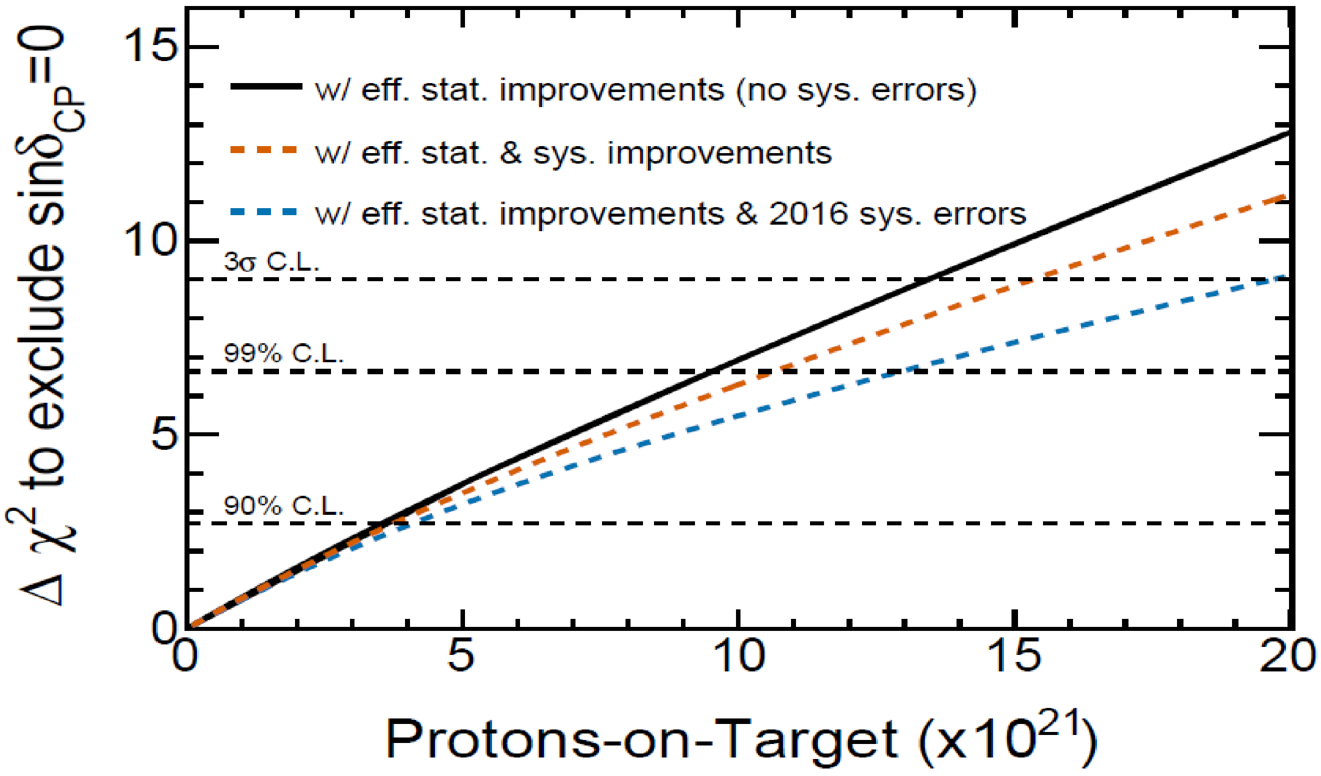
Conclusion

- Ambitious ND280 Upgrade is in progress
- Reduction of T2K systematic uncertainties – crucial for CP-violation search and oscillation measurements
- Rich neutrino interaction physics
- Assembly, installation and commissioning of SuperFGD at J-PARC - 2022
- Upgraded detector is to take data in early 2023

Backup slides

Sensitivity to CP violation

T2K sensitivity to exclude δ_{CP} =0



Test at CERN

SFGD prototype before installation into the magnet

MCPs

New particles with small electric charge can arise in extensions of SM
- violate the quantization of charge
- can make up part o the dark matter in the Universe (millicharged dark matter)
- Massless dark photons can connect to millicharged particles
- Extra-dimension scenarios MCPs receive mass from magnetic mixing effect

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B. Holdom, Phys.Lett. B166, 196 (1986)
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Meson decays
Into MCPs

Meson branching ratios
$\varepsilon^2 = 1$