Physics with near neutrino detectors of LBL accelerator experiments

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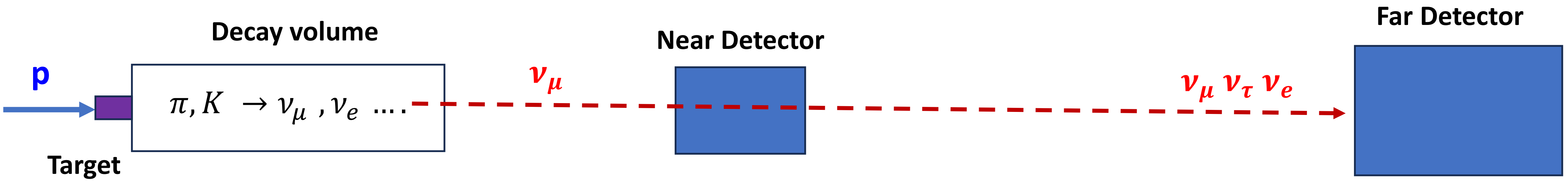
INR RAS

21 Lomonosov Conference, 24-20 August 2023,
MSU, Moscow, Russia

Scheme of LBL experiments



Main tasks of Near Detectors:

- Control of beam direction
- Measurement of neutrino spectra before oscillation
- Measurement of neutrino components
- Measurements of neutrino cross sections

+

Physics beyond the Standard Model

BSM: Hidden Sector

PhysRev D80 (2009) 095024

Mediator (Portal)

Standard Model ⟷ Dark Sector

Light Dark Sector coupled to Standard Model

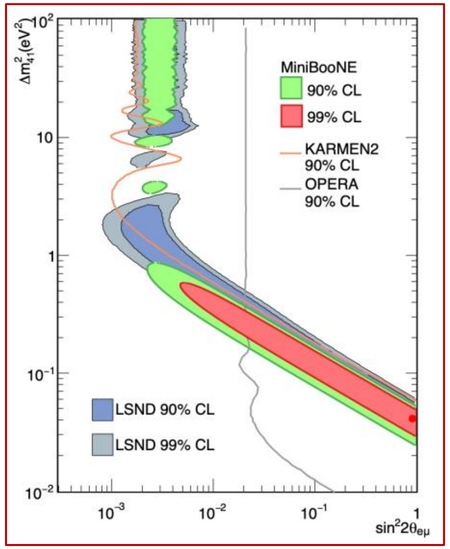
Possible portal interactions
- **Vector:** $\gamma', \; Z', \; MCP$
- **Neutrino: HNL**
- **Scalar: Dark Higgs**
- **Pseudo scalar: ALPs**

Light sterile neutrino

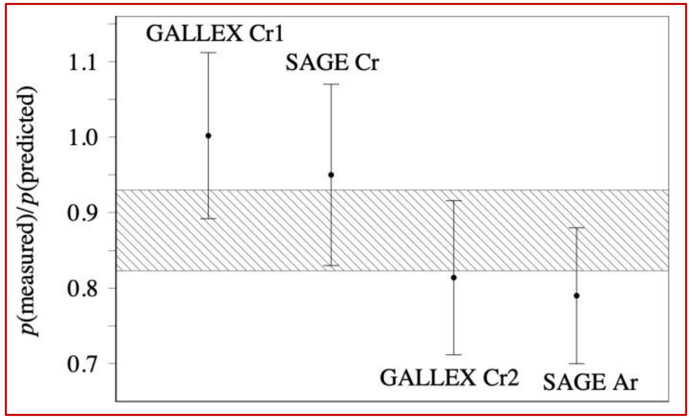
γ', Z' interchangeable

Light sterile neutrino

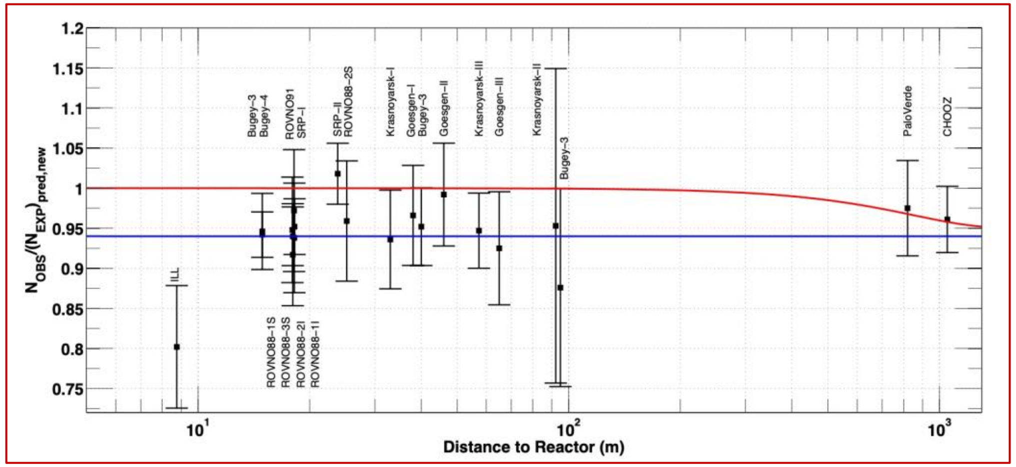
LSND/MiniBooNe anomaly



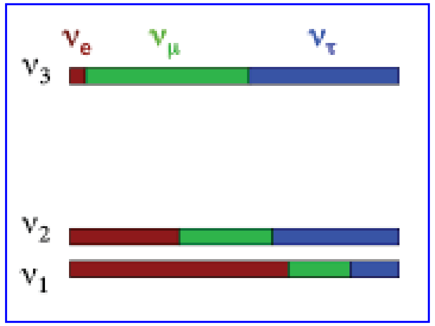
Ga anomaly



Reactor anomaly

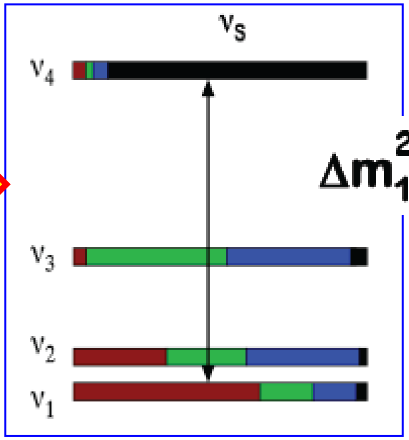


3ν, NO



?

$3\nu + 1\nu_s$



$\Delta m^2_{14} \sim 1$ eV^2

PMNS matrix

$$\begin{bmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\\ \nu_s\end{bmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4}\\ U_{\mu1} & U_{\mu2} & U_{\mu3} & U_{\mu4}\\ U_{\tau1} & U_{\tau2} & U_{\tau3} & U_{\tau4}\\ U_{s1} & U_{s2} & U_{s3} & U_{s4}\end{pmatrix} = \begin{bmatrix}\nu_1\\ \nu_2\\ \nu_3\\ \nu_4\end{bmatrix}$$

$$|U_{e4}|^2 = \sin^2\theta_{14}$$

$$|U_{\mu4}|^2 = \sin^2\theta_{24}\cdot\cos^2\theta_{14}$$

$$|U_{\tau4}|^2 = \sin^2\theta_{34}\cdot\cos^2\theta_{24}\cdot\cos^2\theta_{14}$$

Connection between Appearance and Disappearance channels

$$P_{\nu_e\to\nu_e} \simeq 1 - 2|U_{e4}|^2(1-|U_{e4}|^2)$$

$$P_{\nu_\mu\to\nu_\mu} \simeq 1 - 2|U_{\mu4}|^2(1-|U_{\mu4}|^2)$$

$$P_{\nu_\mu\to\nu_e} \simeq 2|U_{e4}|^2|U_{\mu4}|^2$$

$$\sin^2 2\theta_{e\mu} \simeq \frac{1}{4}\sin^2 2\theta_{ee}\ \sin^2 2\theta_{\mu\mu}$$

Dark Photon

Vector portal of extension of the Standard Model

$$\mathcal{L} = \mathcal{L}_{SM} - \frac{1}{4} F'_{\mu\nu} F'^{\mu\nu} + \frac{\epsilon}{2} F'_{\mu\nu} B^{\mu\nu} + \frac{m^2_{\gamma'}}{2} A'_\mu A'^\mu$$

$\pi^0 \to \gamma'\gamma,\ \ \eta \to \gamma'\gamma,\ \eta' \to \gamma'\gamma$

Mixing of dark photon with SM photon, ε – mixing parameter

$m_{\gamma'} \leq 0.4$ GeV

Partial decay width

$$Br\left(\pi^0 \to \gamma\gamma'\right) \simeq Br\left(\pi^0 \to \gamma\gamma\right) \cdot 2\varepsilon^2 \left(1 - \frac{m^2_{\gamma'}}{m^2_{\pi^0}}\right)^3$$

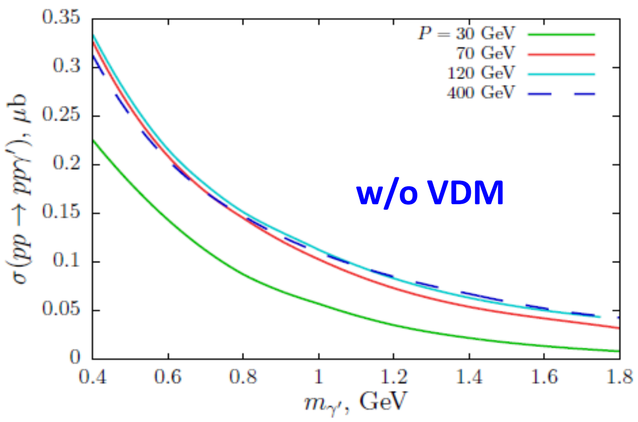
$$\Gamma_{\gamma' \to l^+ l^-} = \frac{1}{3} \alpha \varepsilon^2 m_{\gamma'} \left(1 + \frac{2m_l^2}{m^2_{\gamma'}}\right) \sqrt{1 - \frac{4m_l^2}{m^2_{\gamma'}}}$$

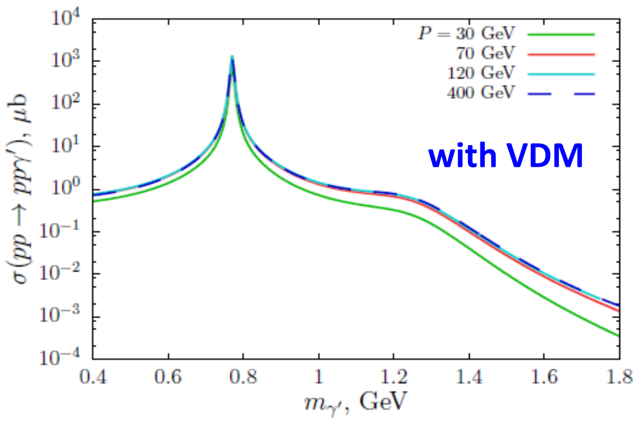
arXiv:1411.4007

$pp \to pp\gamma'$

Proton bremsstrahlung

$m_{\gamma'} \sim 0.4 - 1.8$ GeV





arXiv:2306.15800

Millicharged Particles

New particles with small electric charge can arise in extension of SM

- violate the quantization of charge
- can make up part of the dark matter in the Universe (millicharged dark matter)
- dark photons can connect to millicharged particles
- in extra-dimension scenarios MCPs receive mass from magnetic mixing effect

arXiv: 2005.01515

In case of massless γ' MCPs provide coupling between ordinary photon and dark sector

L. B. Okun et al. Phys. Lett.138B (1984) 115
B. Holdom, Phys.Lett. B166, 196 (1986)
S.Dubovsky et al. JETP Letter 79 (2004) 1
M.Fabbrichesi et al. arXiv:2005.01515
H.Liu et al. arXiv:1908.06986
G.Magill et al. arXiv:1806.03310

Heavy Neutral Leptons

νMSM – model

PLB 631 (2005)151

СМ + **3 нейтральных правых тяжелых лептона**

arXiv:0804.4542v2 [hep-ph]
arXiv:0901.0011v2 [hep-ph]

$$\nu_\alpha = \sum_{i=1}^{3} V_{\alpha i}\nu_i + \sum_{I=1}^{n} \Theta_{\alpha I} N_I \quad (\alpha = e, \mu, \tau)$$

$V_{\alpha i} \sim 1$

$|\Theta_{\alpha I}| = \mathcal{O}\left(\sqrt{\frac{m_\nu}{M_N}}\right) \sim 10^{-5}$

For $m_\nu \sim 0.1$ eV and $M_N \sim$ GeV

$V_{\alpha i}$ – elements of PMNS matrix
N_I – heavy neutral leptons
$\Theta_{\alpha I}$ - active-heavy mixing matrix
(α = e, μ, τ)

Meson decays:
$Br(M \rightarrow l_\alpha + N_I) \sim |\Theta_{\alpha I}|^2$

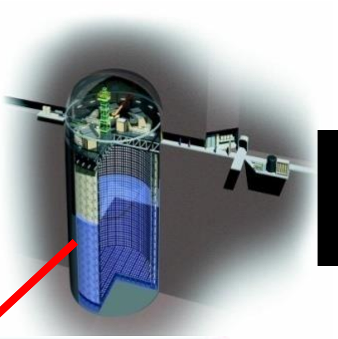
νMSM: n =3, $N_1 \leq$ 100 keV (dark matter candidate)
$N_{2,3} \sim$ GeV scale (baryon asymmetry)

T2K

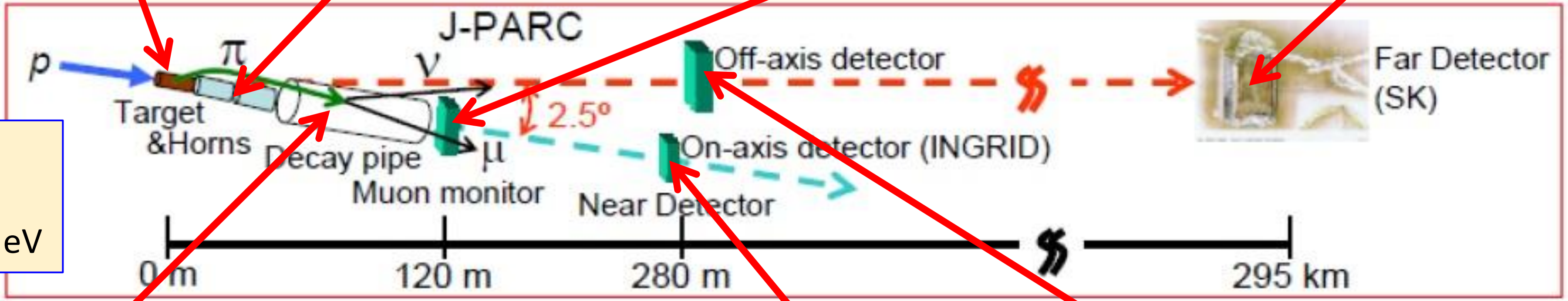
Long-Baseline Neutrino Oscillation Experiment

Experiment T2K

T2K collects data since 2010



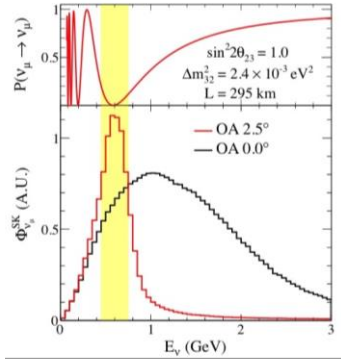
Far neutrino detector SuperKamiokande



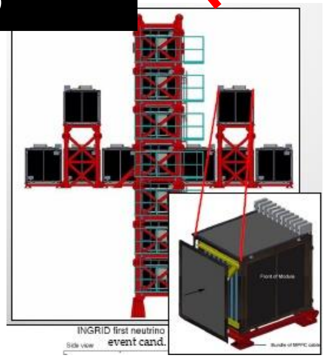
L = 295 km
Off-axis ν beam
Peak energy 600 MeV

Decay tunnel

Off-axis neutrino beam

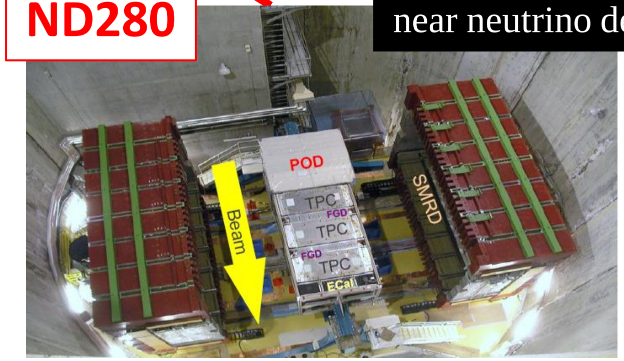


Neutrino monitor INGRID

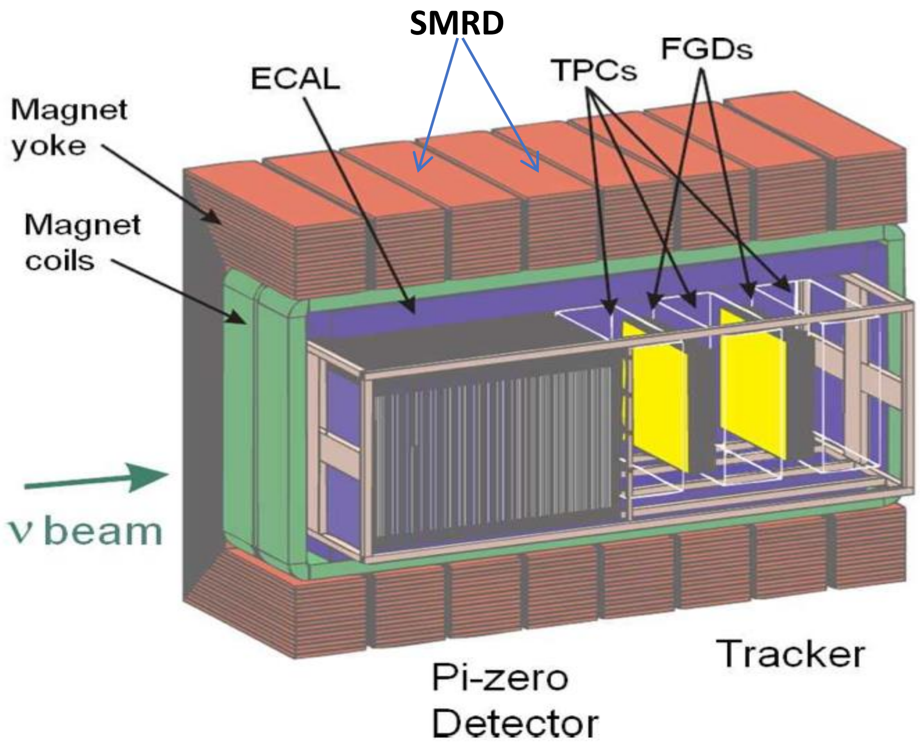


ND280

Off-axis near neutrino detector



T2K Near Detector ND280

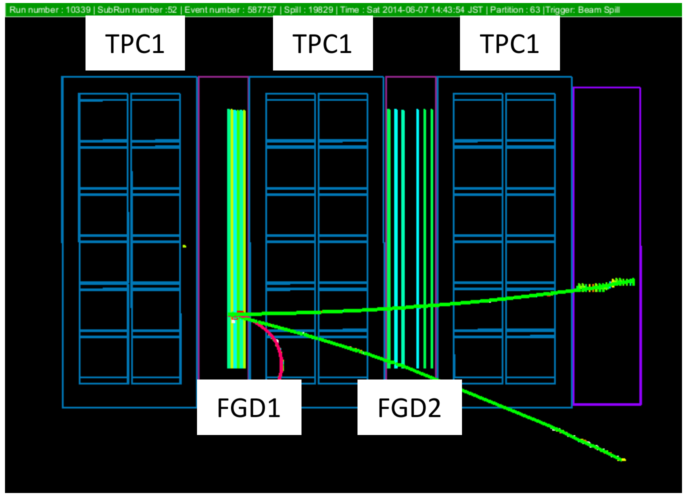


ND280

UA1/NOMAD magnet, 0.2 T

- π^0detector (Pi-Zero Detector)
- Electromagnetic calorimeter (ECAL)
- Tracker system:
  - Two fine grained detectors (FGDs) – ν active target
  - Three vertical time-projection chambers (TPCs)
- Side muon range detector (SMRD)

ν interaction in ND280

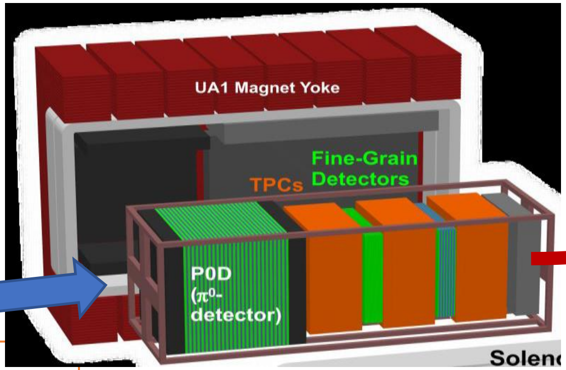


ND280 upgrade

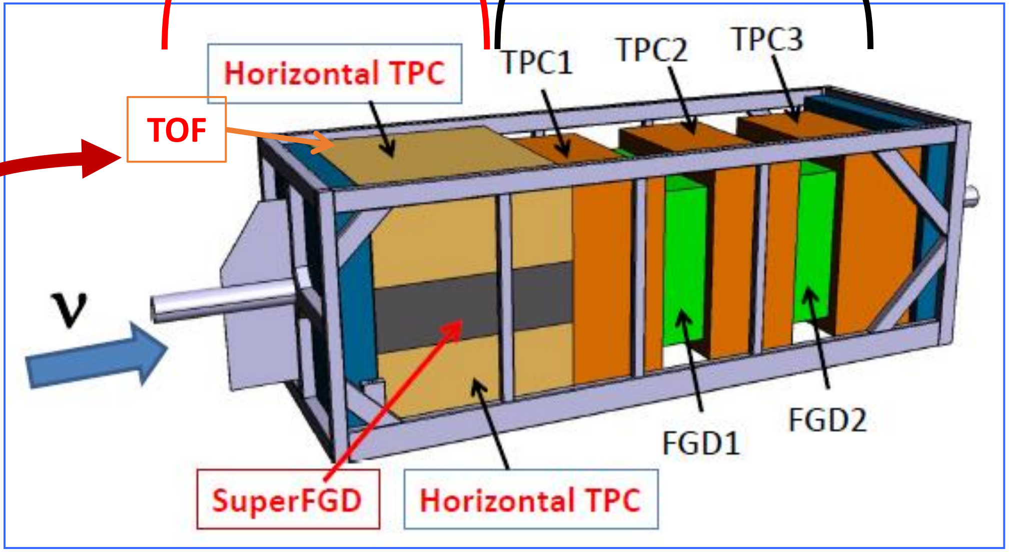
arXiv:1901.03750

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

Current ND280 complex

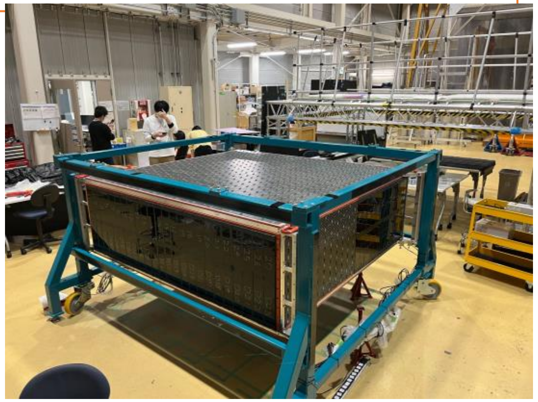


New detectors
Current detectors

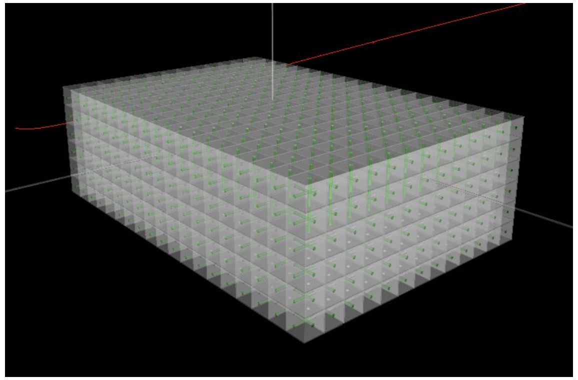


- Fully active detector
- 4π acceptance for charged particles
- Detection of low energy protons and pions
- Electron/gamma separation
- Electron neutrino studies
- Detection of neutrons

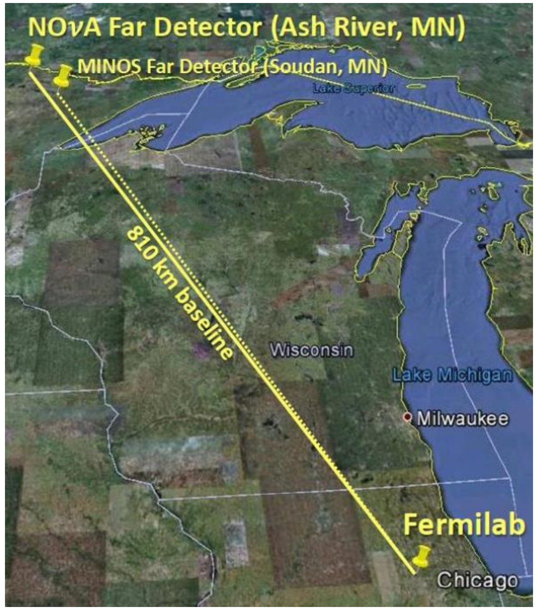
POD replaced by New Detectors



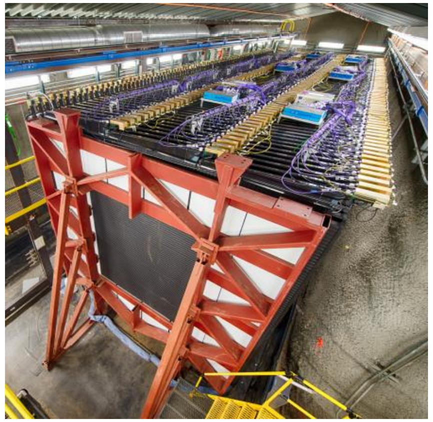
- Volume ~192 x 184 x 56 cm^3
- **~2 x 10^6** scintillator cubes , each 1 x 1 x 1 cm^3
- Each cube has 3 orthogonal holes of 1.5 mm diameter
- 3D (x,y,z) WLS readout
- About **60000** readout WLS/MPPC channels
- Total active weight about **2 t**



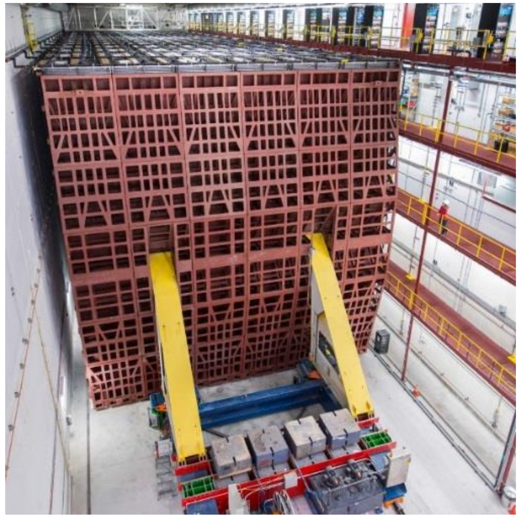
Experiment NOvA



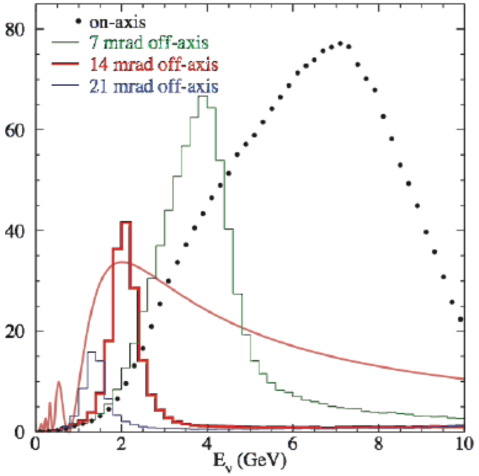
Near Detector



Far Detector



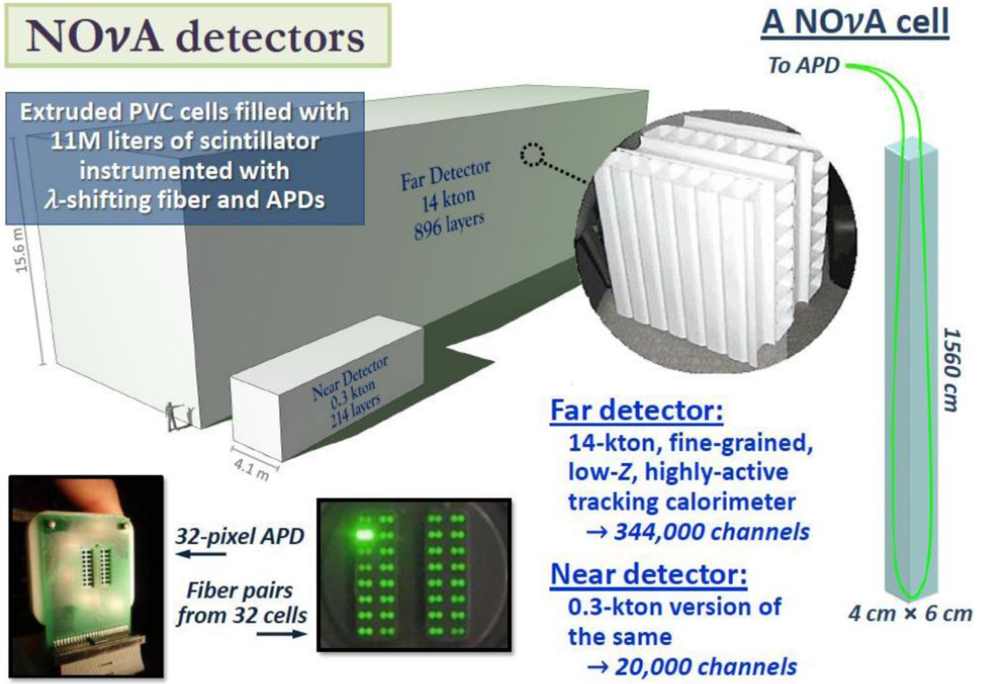
Neutrino beam



Taking data since Summer 2014

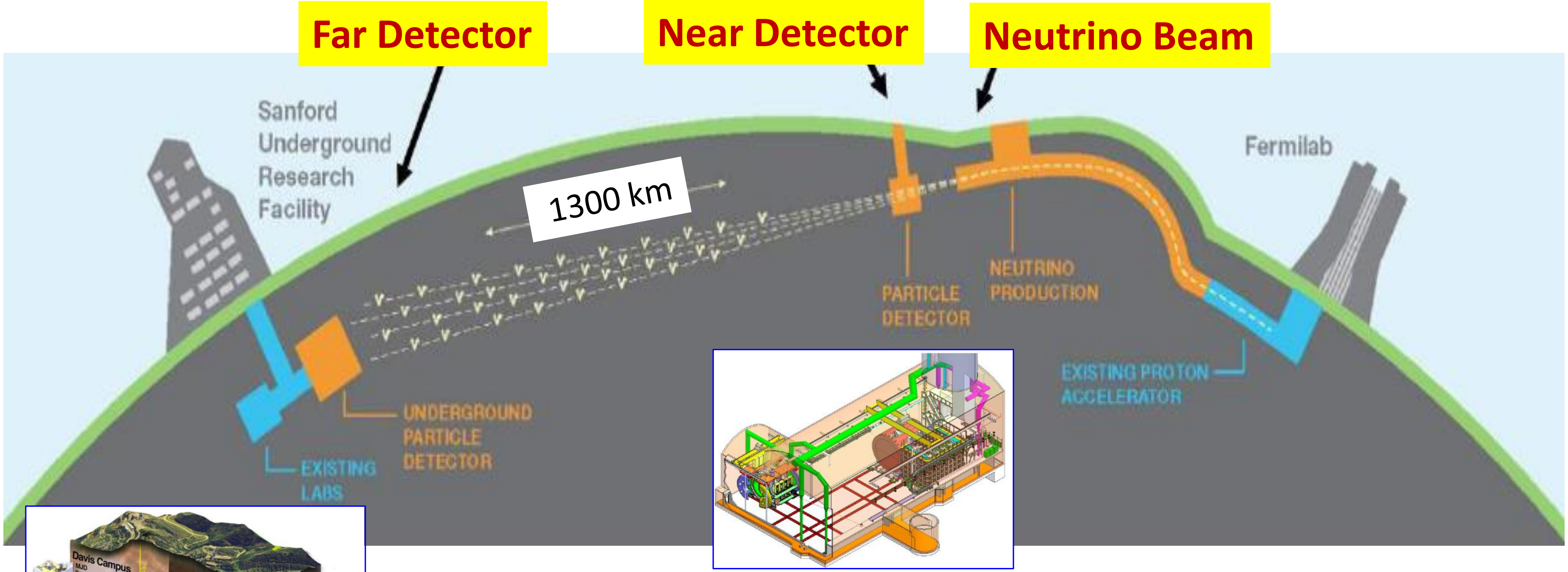
Study of $\nu_\mu \rightarrow \nu_\mu$ and $\nu_\mu \rightarrow \nu_e$ oscillations

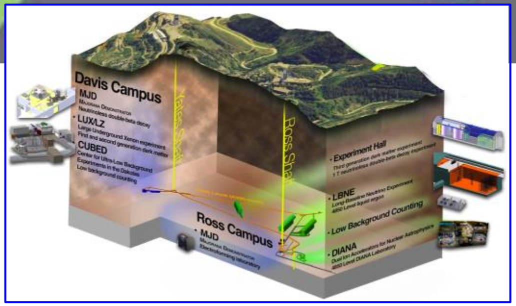
Neutrino beam from FNAL to Ash River
Baseline 810 km
Neutrino beam 14 mrad off-axis
Far detector : 14 kt fine-grained calorimeter
65% active mass
Near Detector: 0.3 kt fine-grained calorimeter



LBNF/DUNE

USA, Fermilab





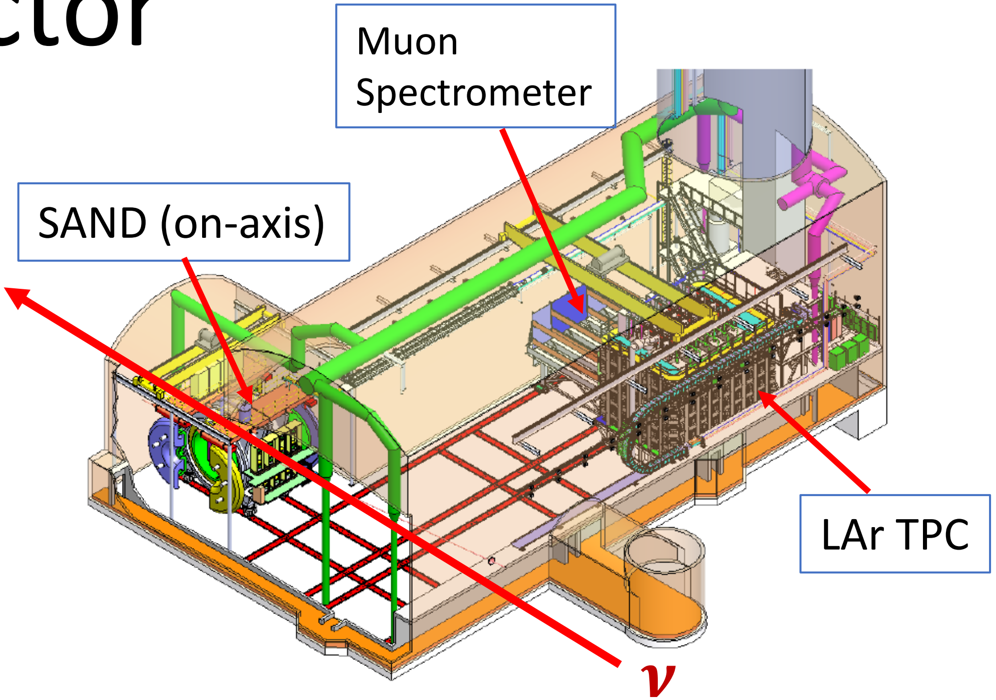
Far Detector at Sanford Underground Research Facility, South Dakota, 1.5 km underground

Phase I: 2x17kt modules in late 2020s, ND, proton beam 1.2 MW by 2031

Phase II: 4x17 kt modules, ND, proton beam 1.2 → 2.4 MW

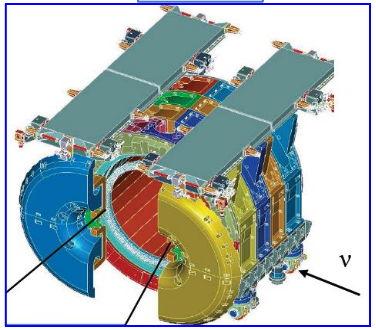
DUNE Near Detector

- ND-Lar TPC (+ TMS) uses the same technology as the FD → measure ν-Ar interactions with same medium and pixelated readout
- The Muon Spectrometer (TMS) measures muons that exit ND-LAr
- System for on-Axis Neutrino Detection (SAND) measures neutrino interactions on various targets (e.g. Hydrogen) and monitors the neutrino beam stability
- HP GAr TPC is also considered for Phase-II

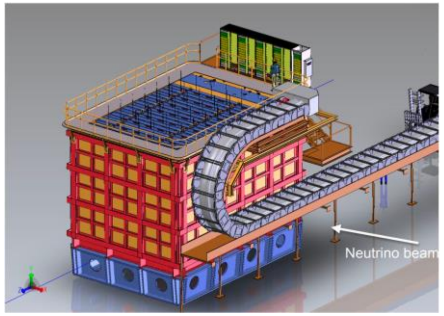


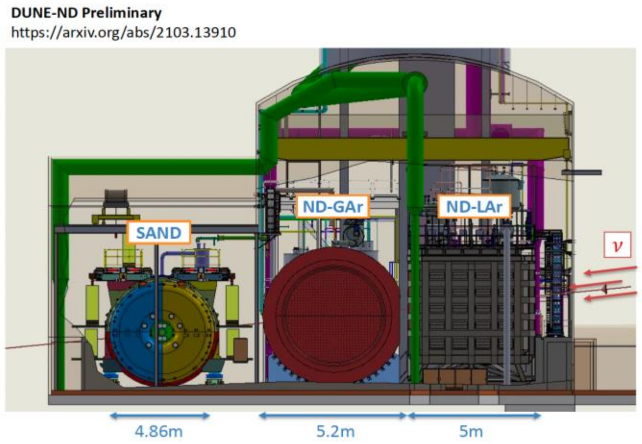
arXiv:2103.13910

SAND



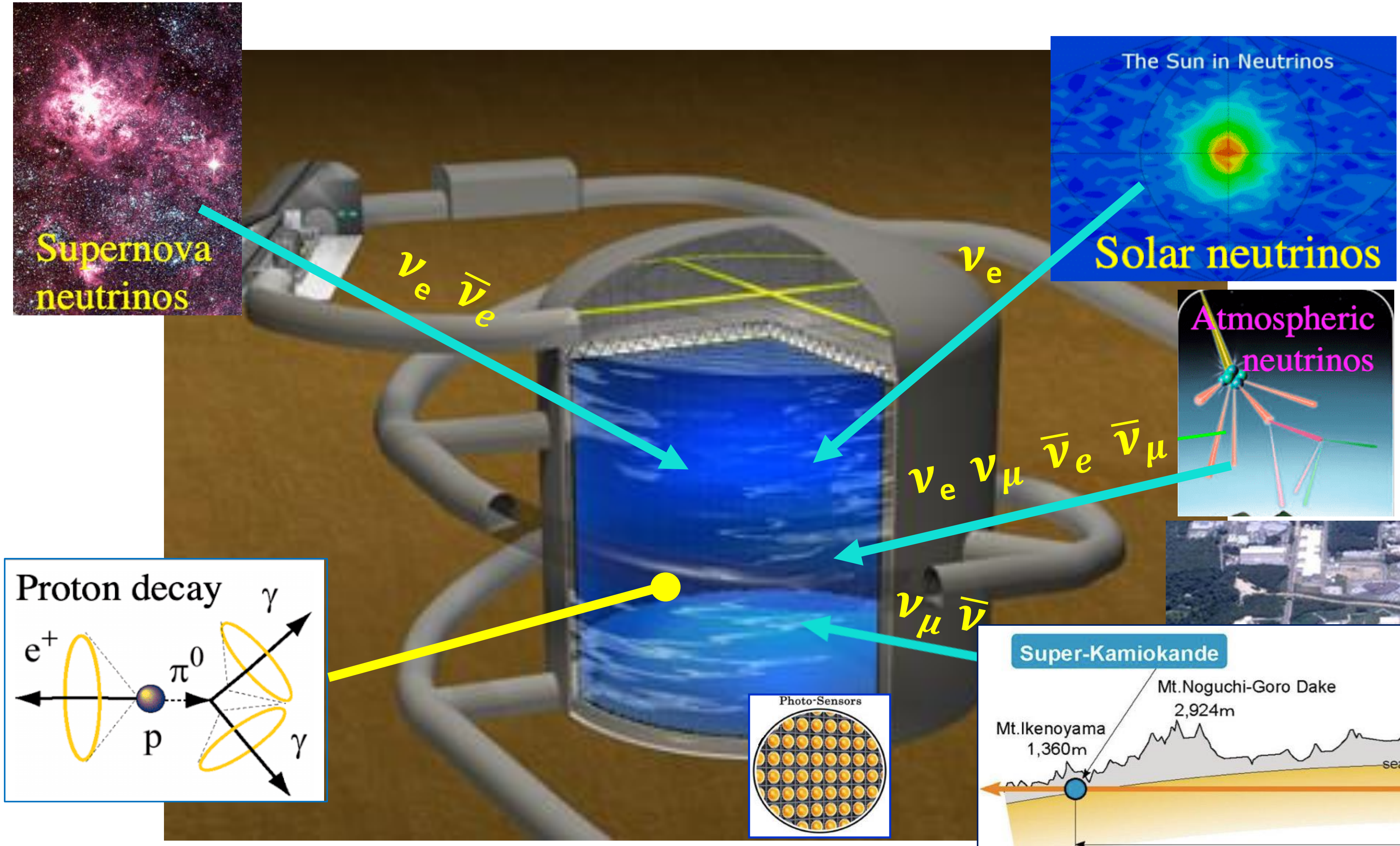
LAr TPC

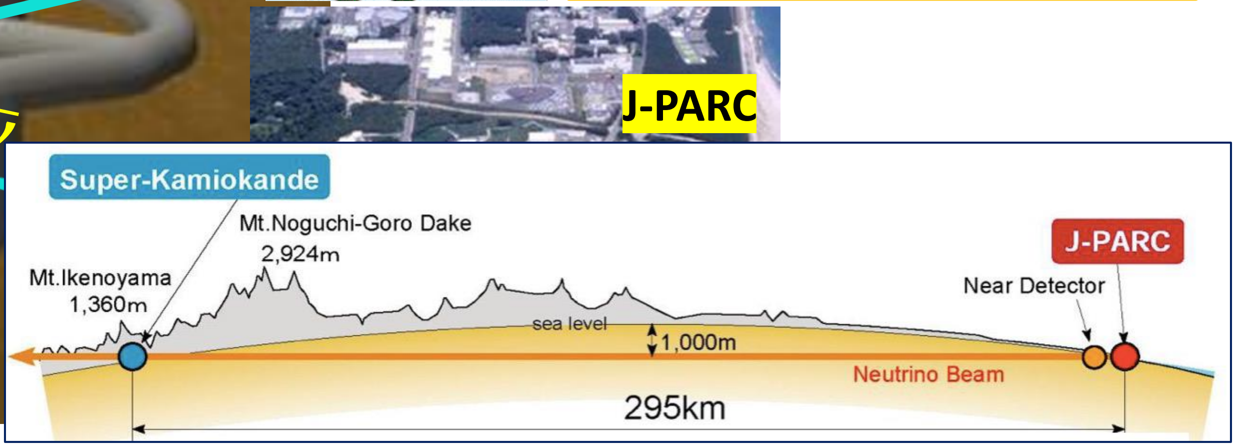




Hyper-Kamiokande

Japan. Construction begun in 2021, operation starts in 2027





Physics program:
- Search for CP violation
- Neutrino oscillations
- Proton decay
- Neutrino astrophysics

Water Cherenkov detector

71 m (height) x 68 m (diameter)

Total mass about 260 kt

Inner Detector:

20000   50 cm PMTs + mPMTs

Outer Detector:

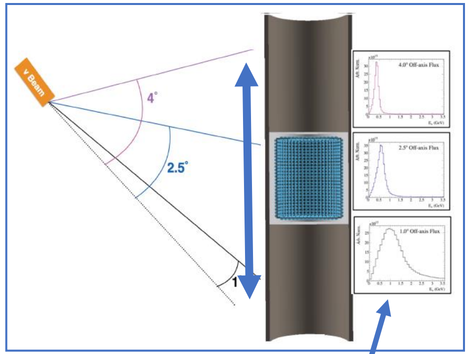
~7000   7.5 cm PMTs + WLS plates

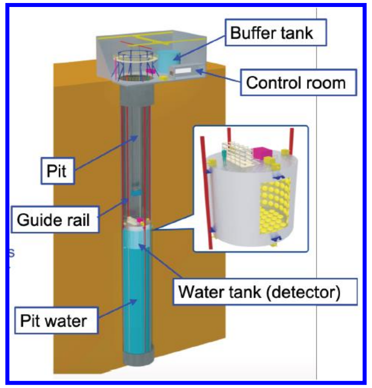
Near Detectors of HyperK

~1 km from target

IWCD: Movable water Cherenkov detector

IWCD





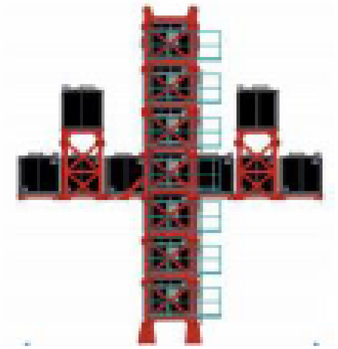
Neutrino spectra

IWCD: ~1 kT water Cherenkov detector muli-PMT modules

280 m from target

J-RARC beam
30 GeV
1.3 MW

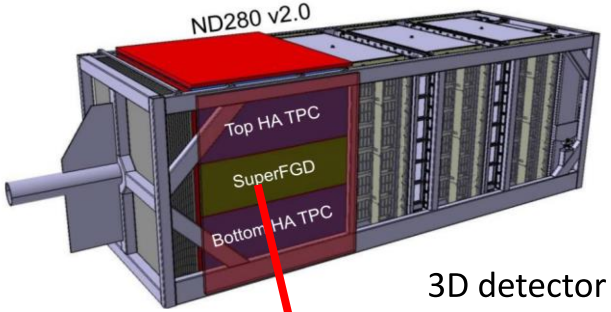
INGRID



Neutrino on/off axis beam monitor

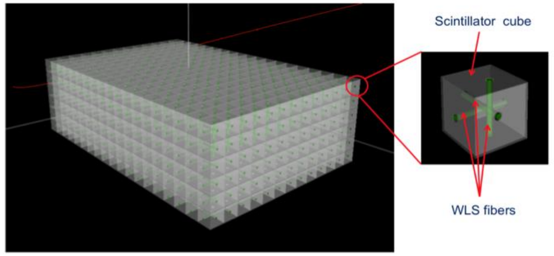
Upgraded ND280

Magnetized off-axis detector



3D detector SuperFGD:
$2x10^6$ scintillator cubes
each of $1cm^3$ with WLS readout

SuperFGD



Search for ν_s in T2K ND280

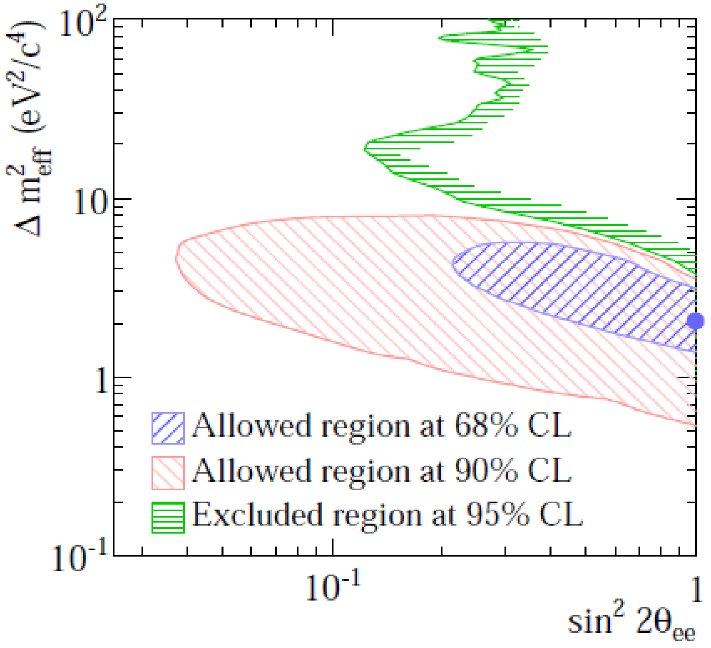
Total proton number on target
5.9×10^{20} POT

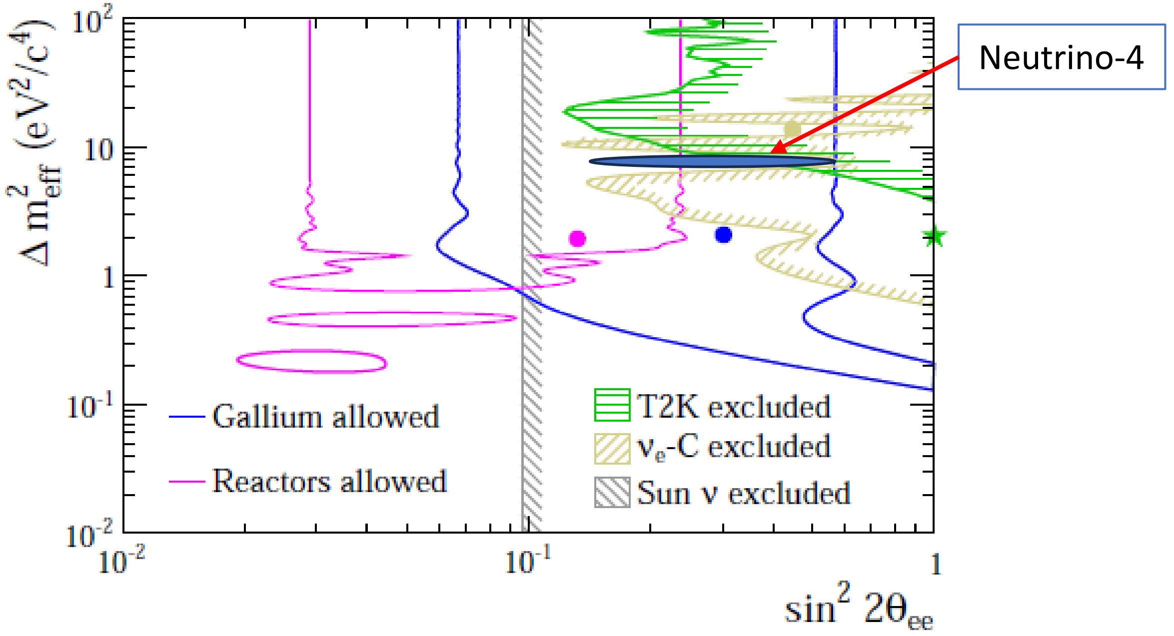
$$P(\nu_e \to \nu_e) = 1 - \sin^2 2\theta_{ee} \sin^2\left(1.27\frac{\Delta m^2_{eff} L}{E}\right)$$

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

$\Delta m^2_{eff} > 7$ eV^2 $\sin^2 2\theta_{ee} > 0.3$ (95% CL)





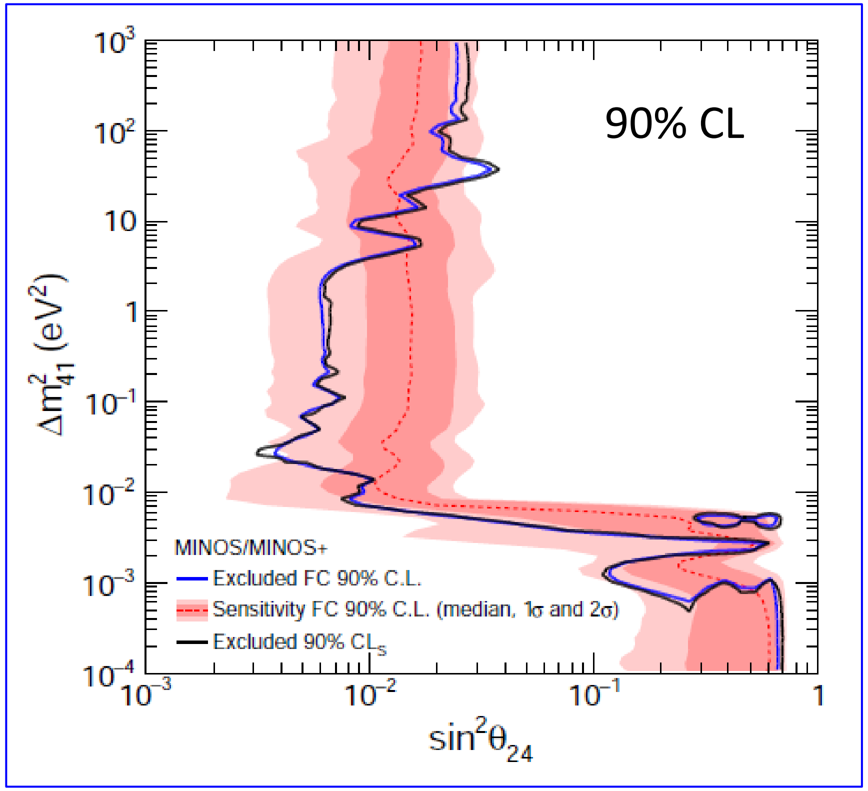
N280 statistics increased by a factor of 2, analysis in progress

Joint Analysis: MINOS, Daya Bay, Bugey-3

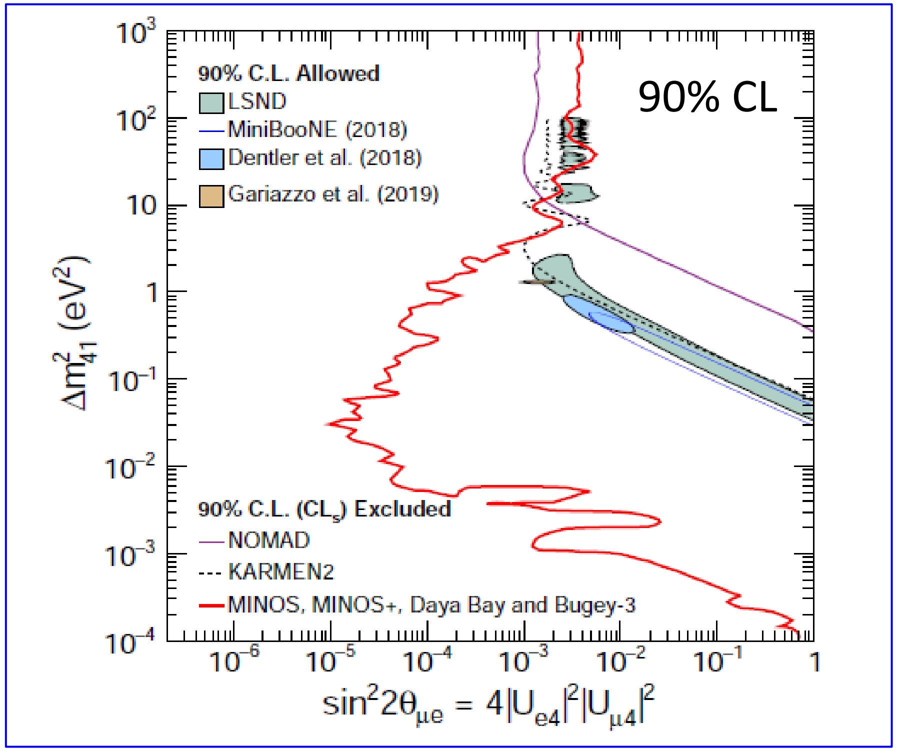
MINOS: $\nu_\mu \to \nu_\mu$ Daya Bay, Bugey-3: $\nu_e \to \nu_e$

PRL 125 (2020) 131802

MINOS



MINOS/Daya Bay/Bugey-3



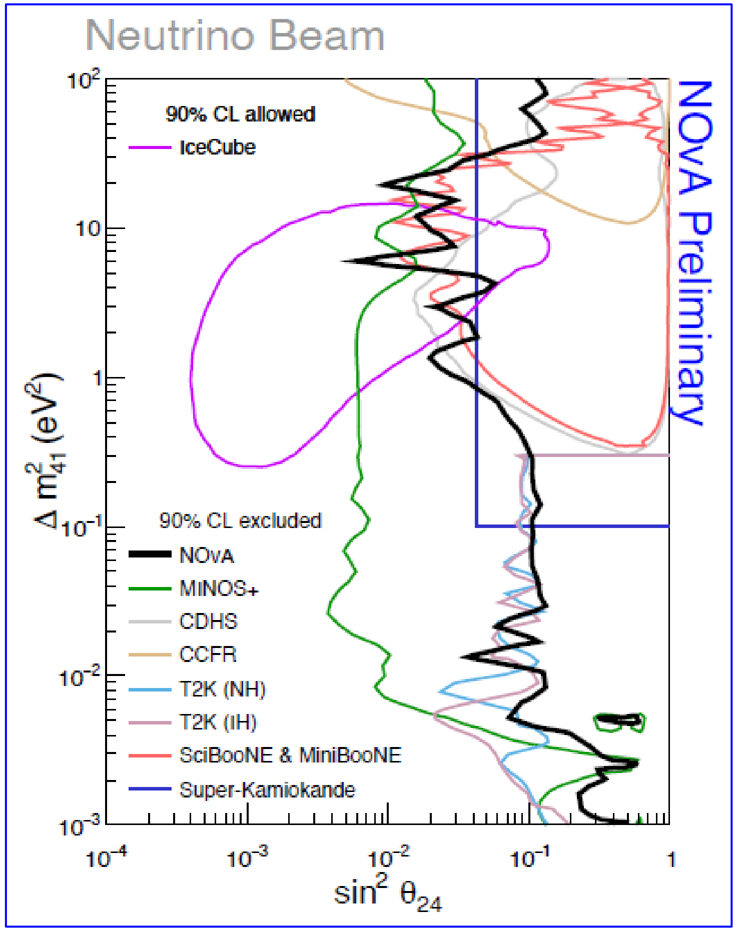
$$\sin^2 2\theta_{e\mu} \simeq \frac{1}{4} \sin^2 2\theta_{ee} \ \sin^2 2\theta_{\mu\mu}$$

Search for ν_s in NOvA ND+FD

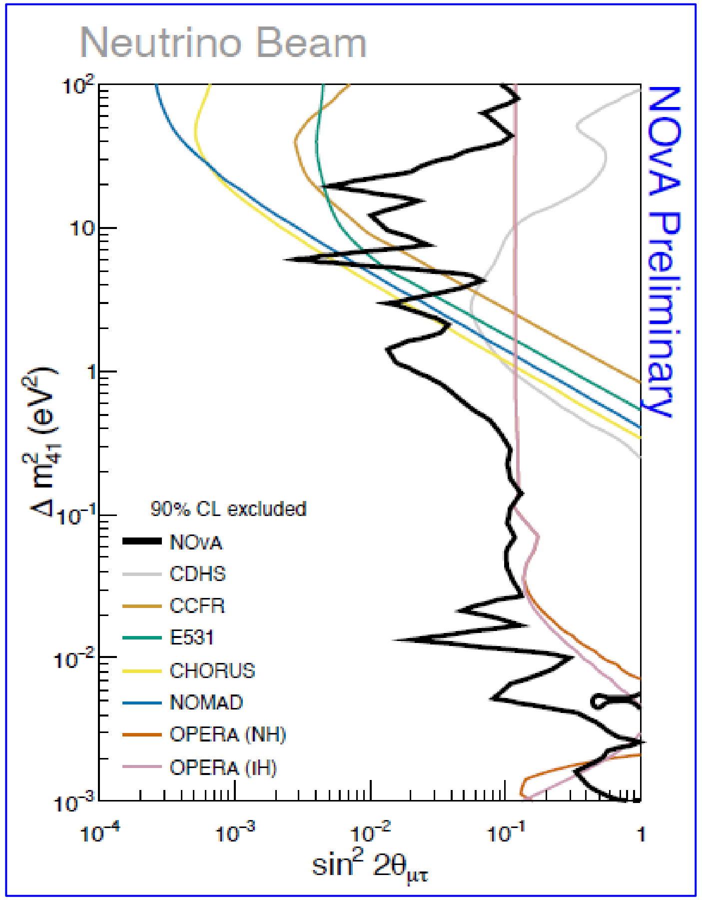
$\nu_\mu \rightarrow \nu_\mu$ CC disappearance measurement

ν_μ NC disappearance measurement

A.Sutton, talk at NuFACT2023



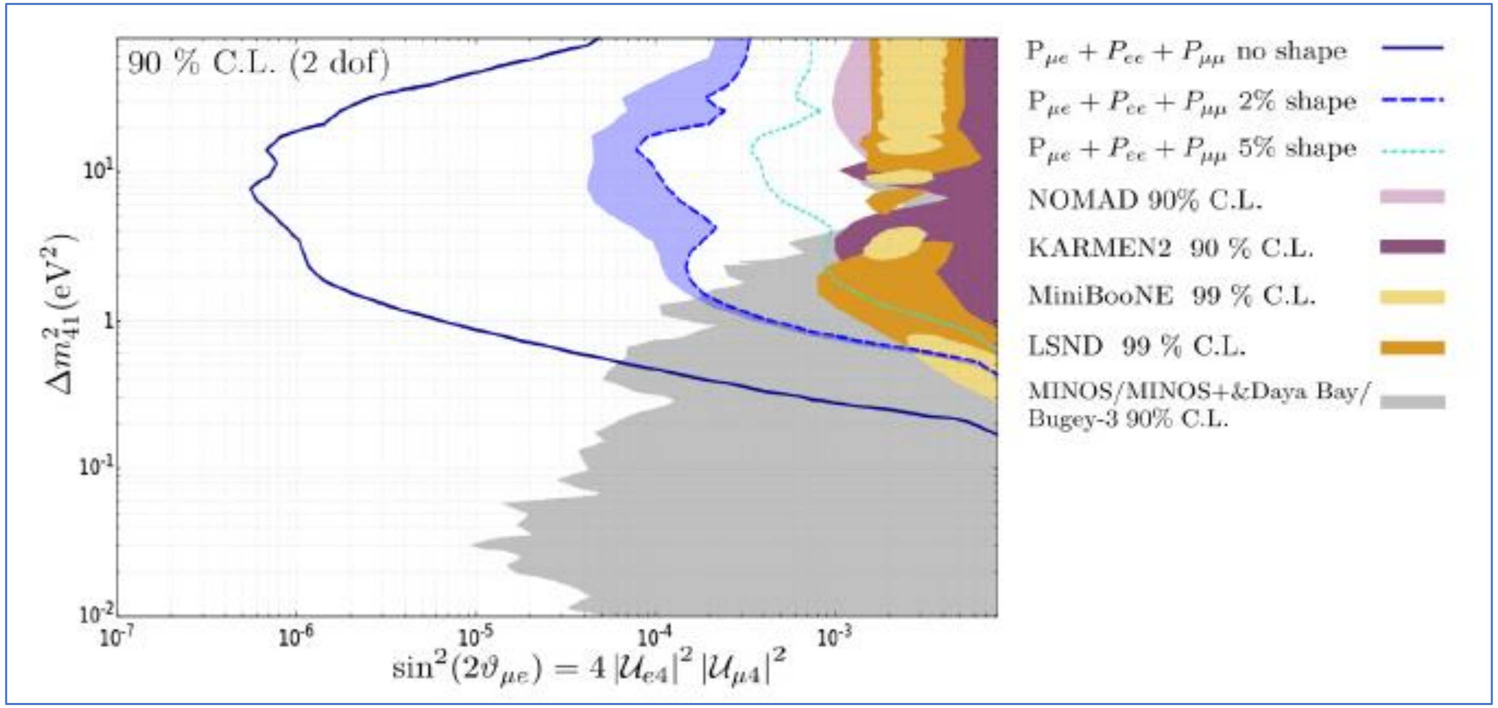
$\sin^2 2\theta_{\mu\tau} = \cos^4\theta_{14}\sin^2 2\theta_{24}\sin^2\theta_{34}$



DUNE: Expected sensitivity to ν_s

3.5 y data taking
Expected sensitivity to sterile neutrino
$\nu_\mu \rightarrow \nu_e$ appearance channel

JHEP 08 (2021) 065



Sensitivity depends
on systematic uncertainties

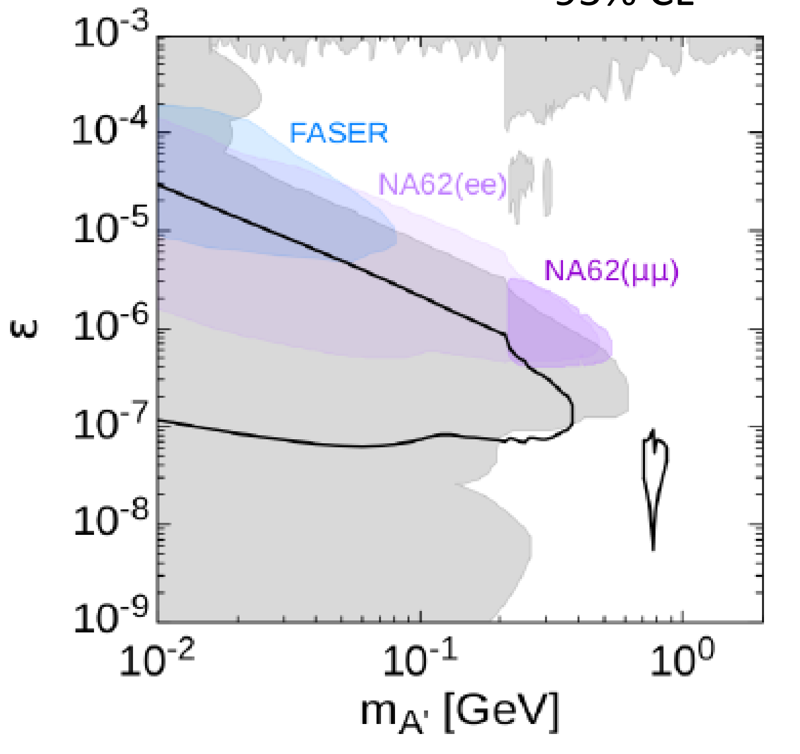
Dark Photons: T2K and DUNE

T2K: 3.8×10^{21} POT

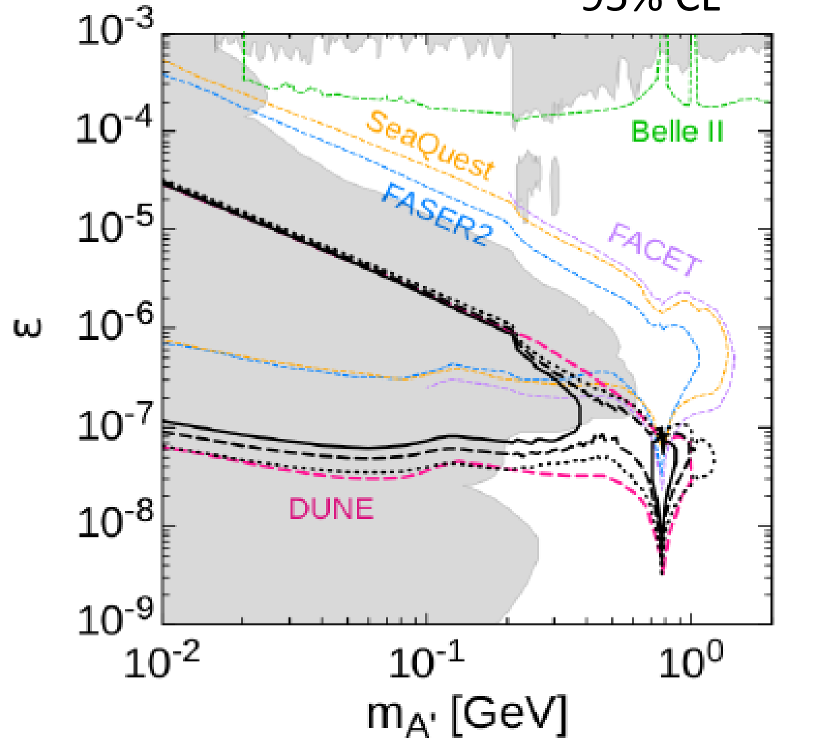
Expected sensitivity, analysis in progress

Expected sensitivity
DUNE (red): 10y data taking
T2K (black dotted): 3.7×10^{22} POT

95% CL



95% CL

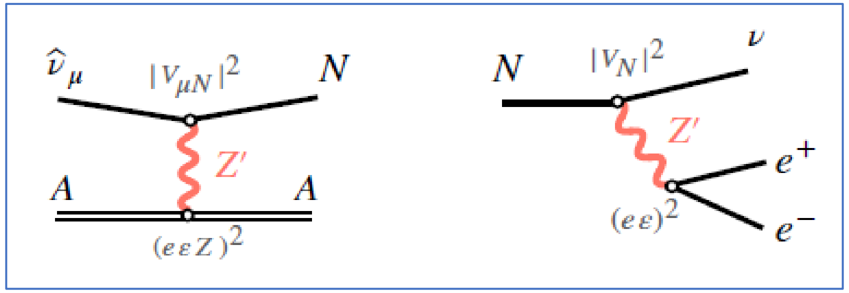


arXiv:2308.01565

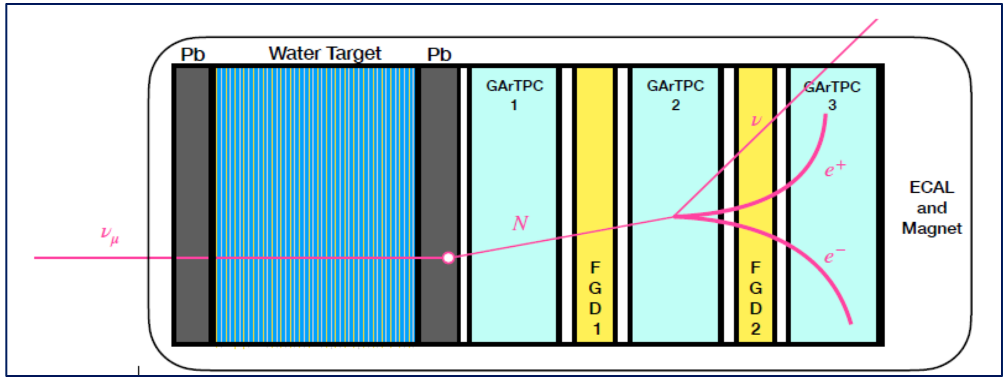
$\gamma' \to f\bar{f}$
$f = e^{\pm}, \mu^{\pm}, \pi^{\pm}$

Search for Dark Photon/Z’ in ND280

- Coherent neutrino up-scattering
- Heavy neutrino (HNL) decays

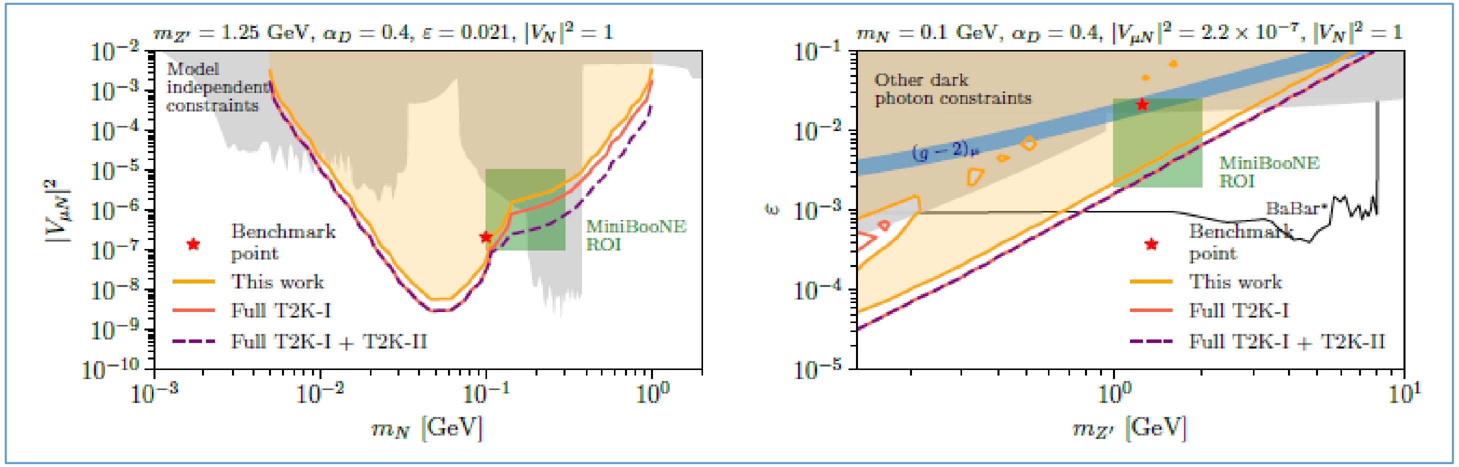


Process in ND280: muon neutrino interacts in POD – heavy (Pb) target

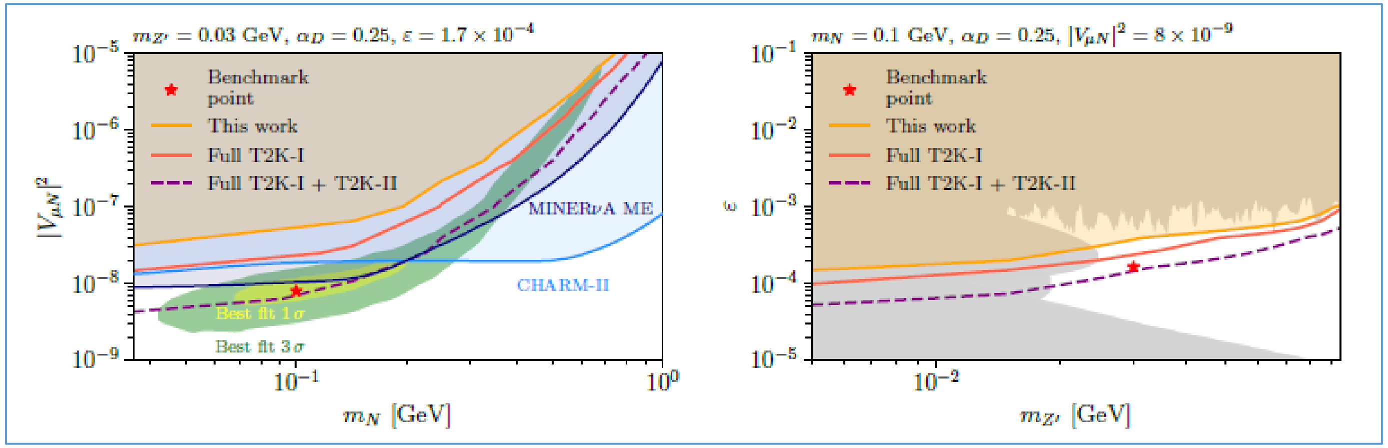


Estimated sensitivity arXiv: 2205.12273

Heavy dark photon



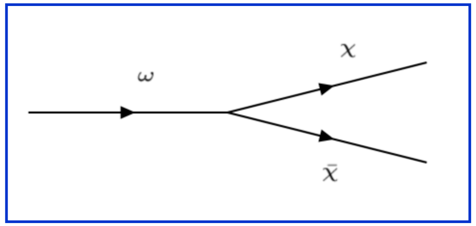
Light dark photon



Meson decays into MCPs

Source of MCPs: decays of mesons produced by intense proton beam

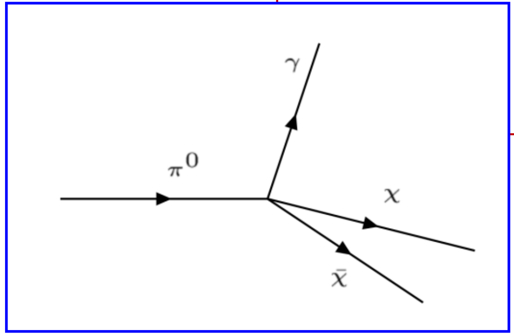
Light vector mesons ρ, ω, ϕ decay into MCP pair $\chi\bar{\chi}$



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

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

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

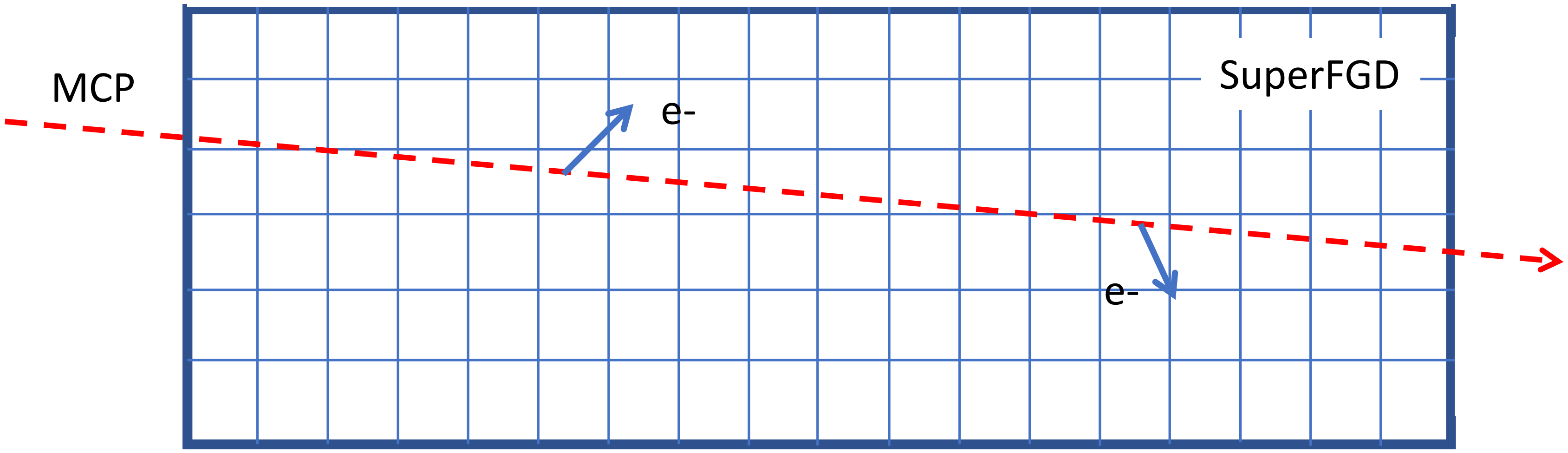


$$X \to Y \in \{\pi \to \gamma, \eta \to \gamma, \eta' \to \gamma, \omega \to \pi^0, \phi \to \pi^0, \phi \to \eta\}$$
$$f_{\pi\to\gamma} = f_{\eta\to\gamma} = f_{\eta'\to\gamma} = 1\,, \quad f_{\omega\to\pi^0} = f_{\phi\to\pi^0} = f_{\phi\to\eta} = \frac{1}{2}$$

Detection MCPs in upgraded ND280

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

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

Probability for 2 hits:

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

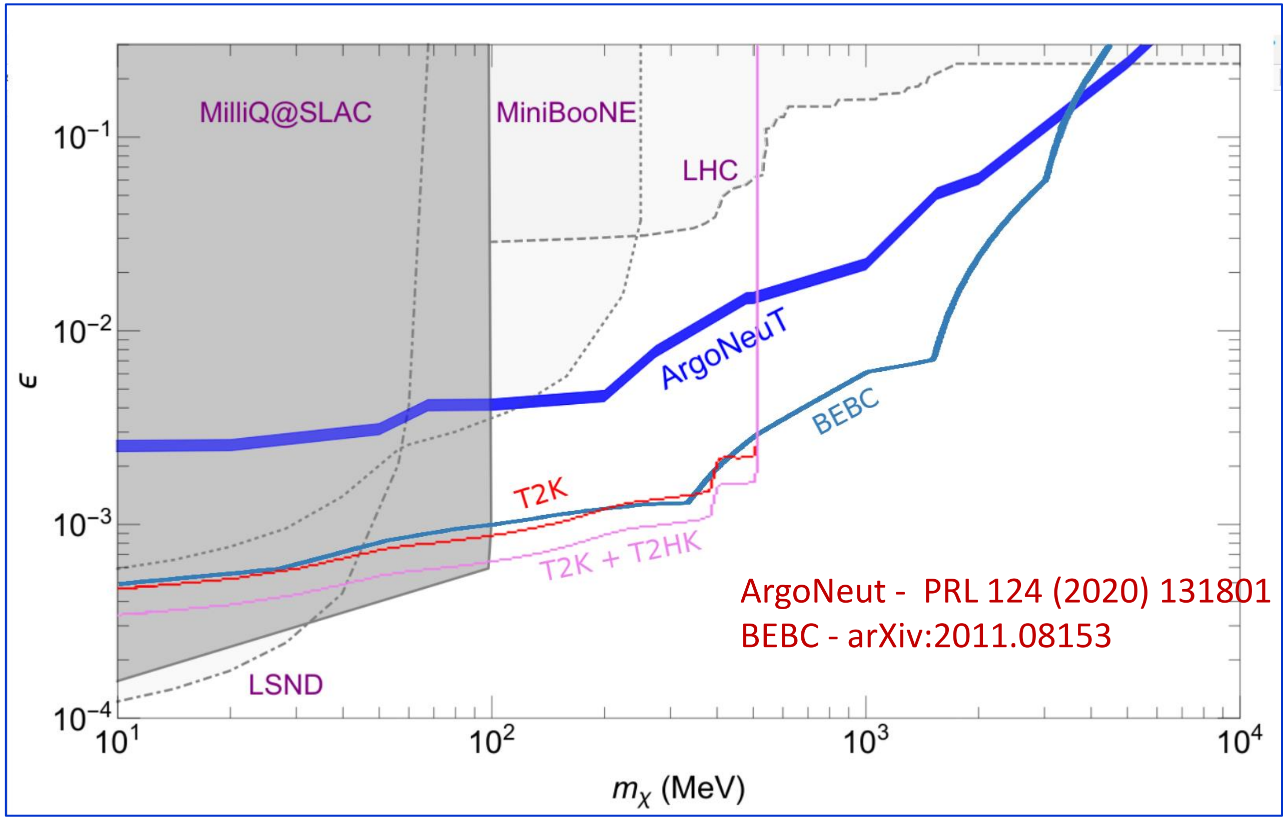
E_r^{min} = 100 keV

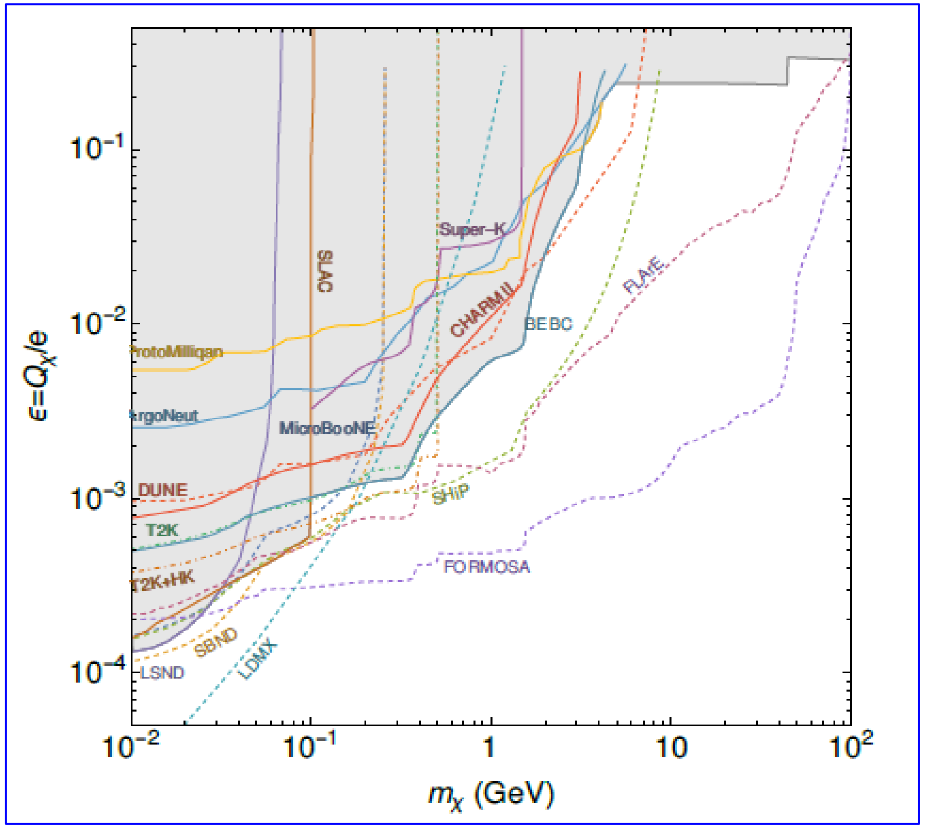
Expected sensitivity to MCPs

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

90% CL exclusion regions

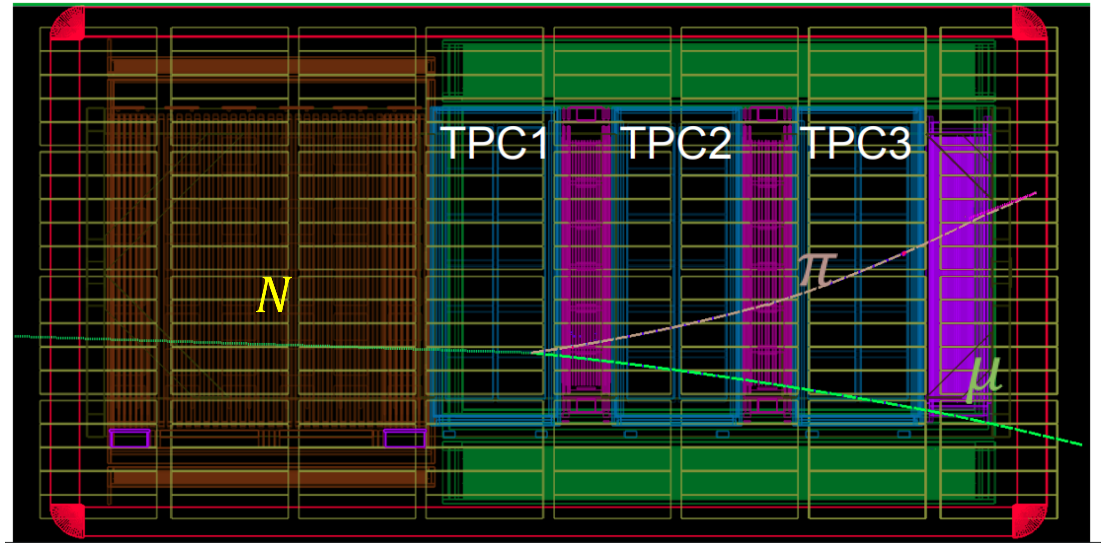
T2K, T2HK and DUNE

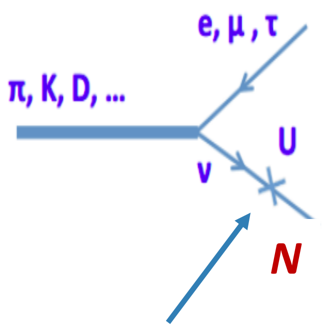




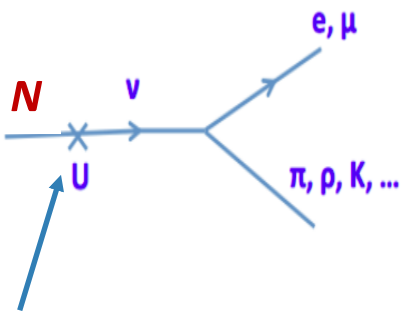
Search for HNL in T2K ND280

Almost background-free search





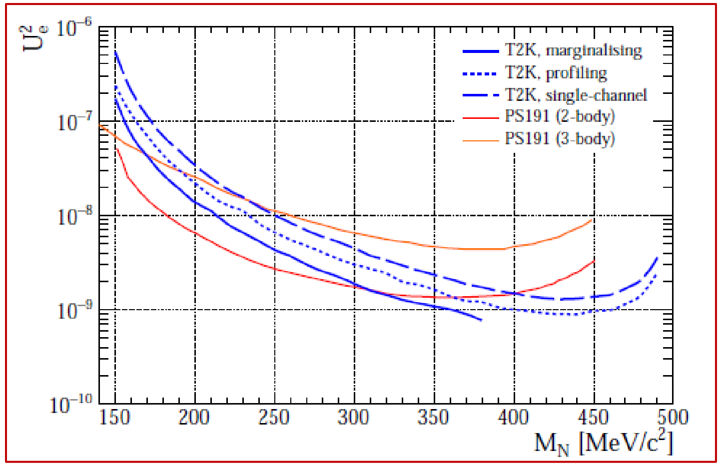
Production of HNL in decays of mesons

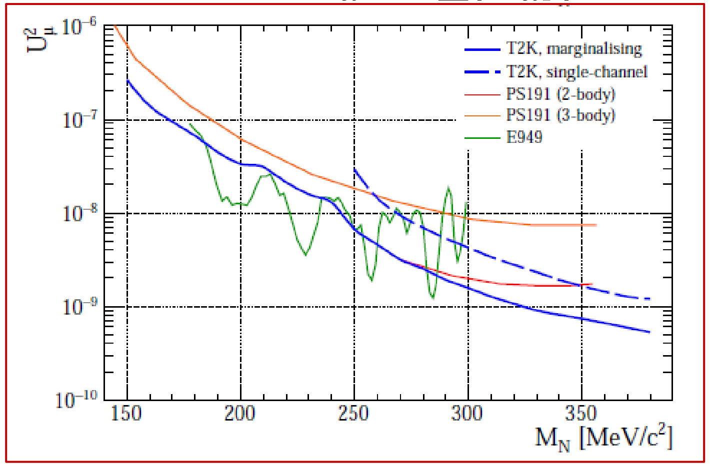


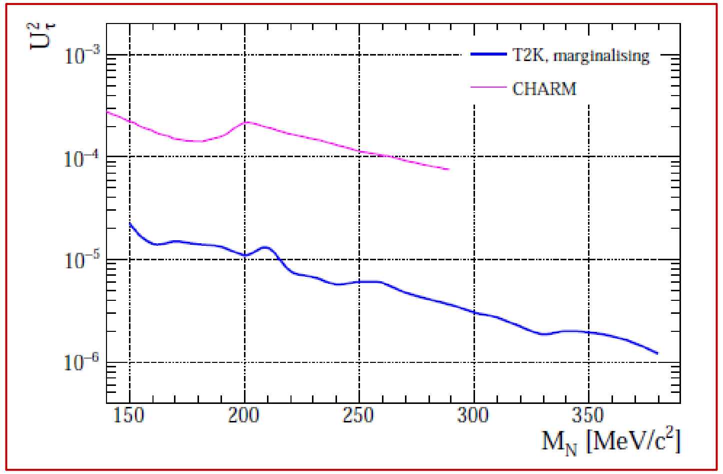
Mixing HNL with active neutrino

Decay of HNL into SM particles

$$U_\alpha^2 = \sum|\Theta_{\alpha I}|^2$$





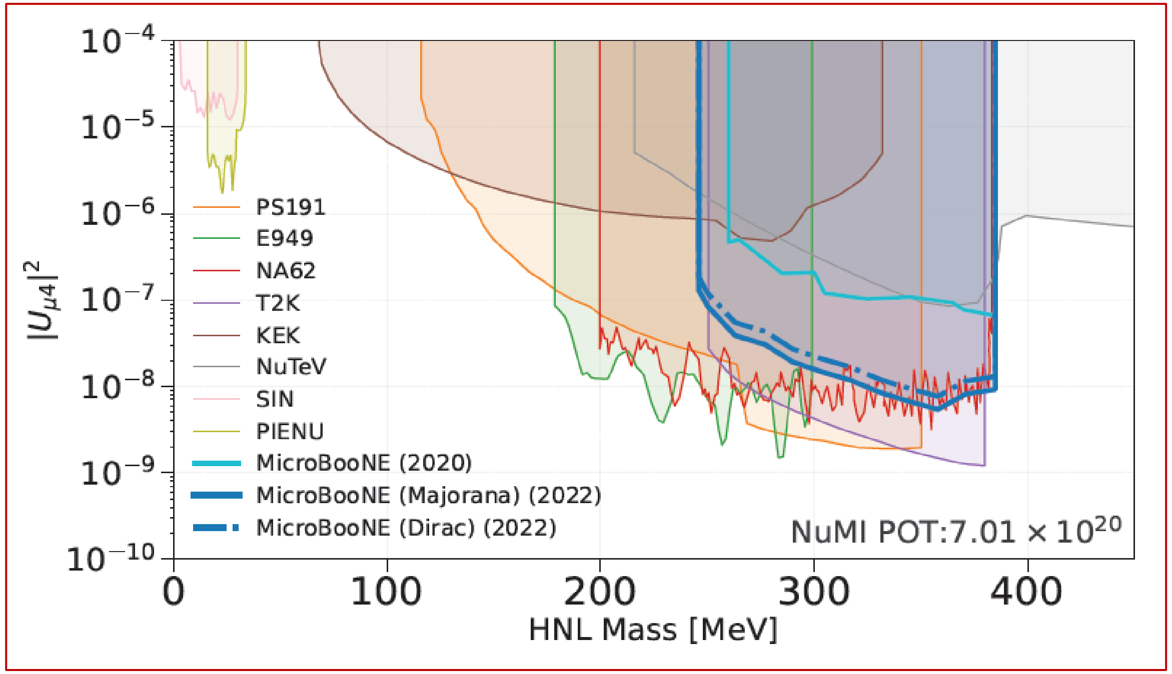


Search for HNL

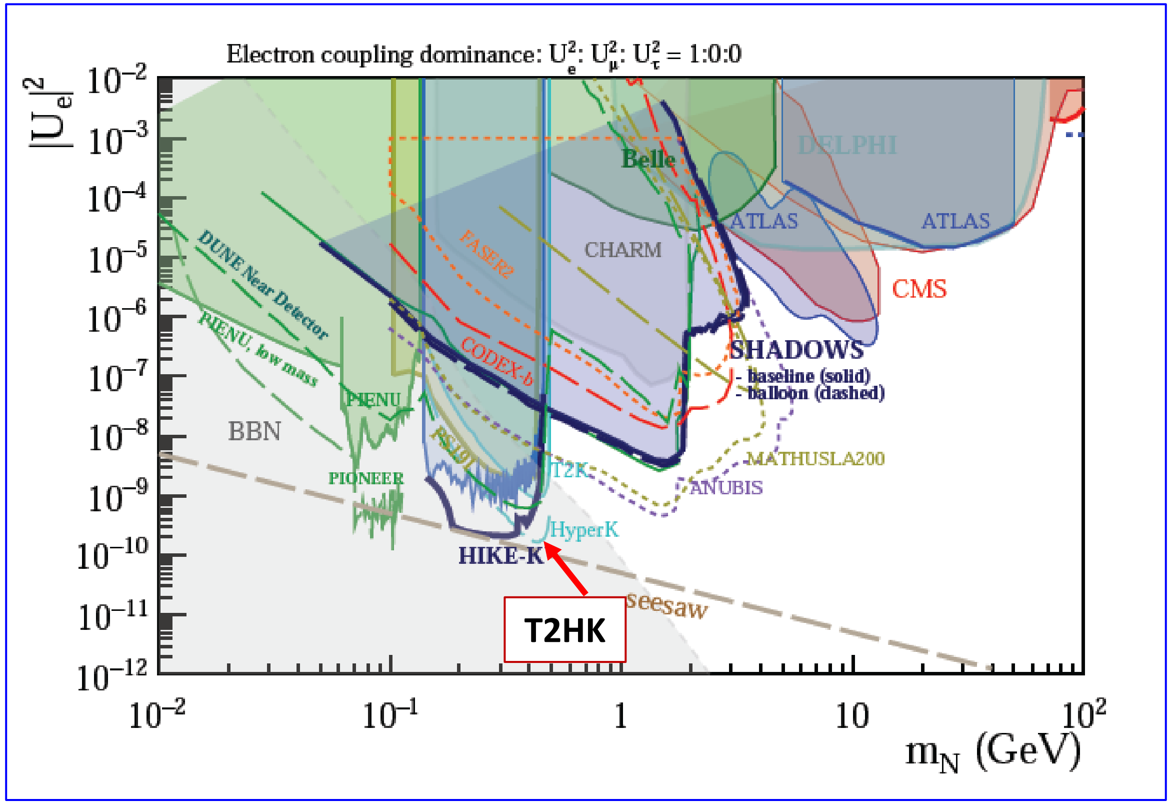
Past, current and future experiments

M_{HNL} < 500 MeV

arXiv: 2305.01715



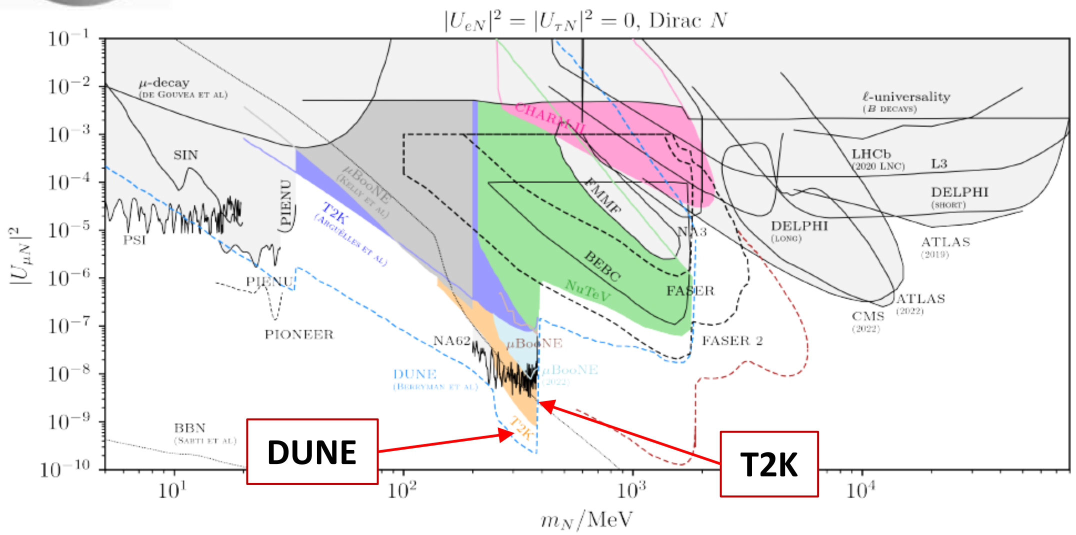
M_{HNL} < 100 GeV



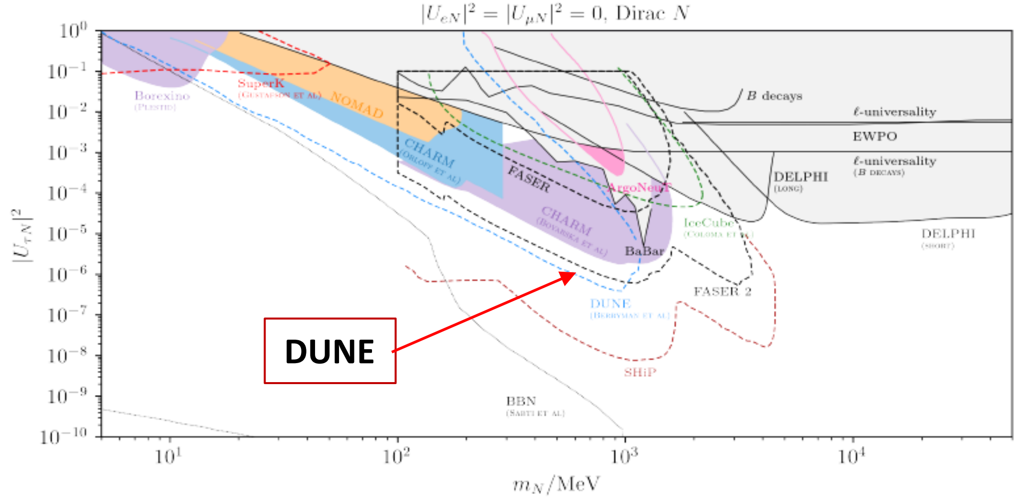
Sensitivity to HNL

arXiv: 2207.06898

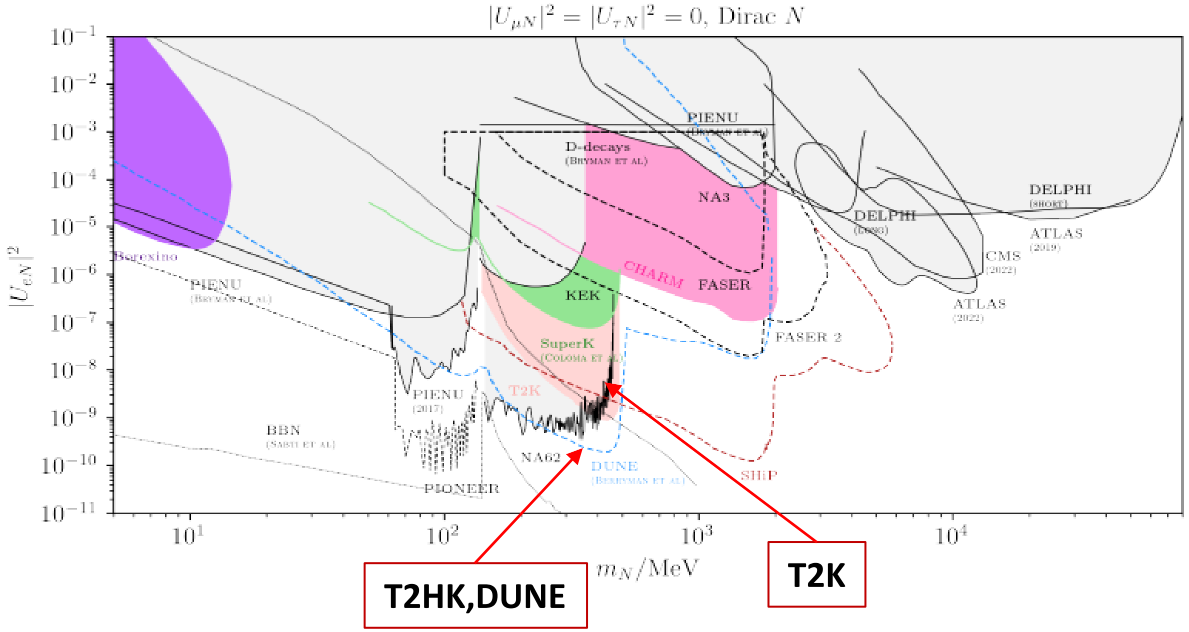
$|U_{\mu N}|^2 \neq 0$



$|U_{\tau N}|^2 \neq 0$



$|U_{eN}|^2 \neq 0$



Conclusion

Rich BSM physics using near detectors of LBL experiments

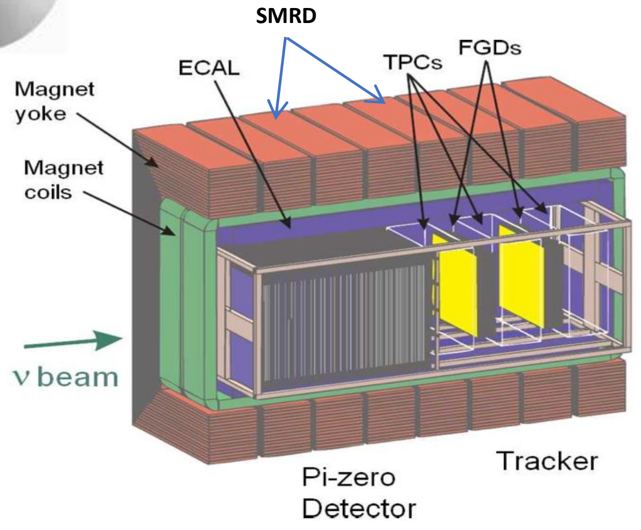
Near detectors most sensitive to vector and neutrino portals

Light sterile neutrinos can be also probed with good sensitivity

Thank you very much for your attention

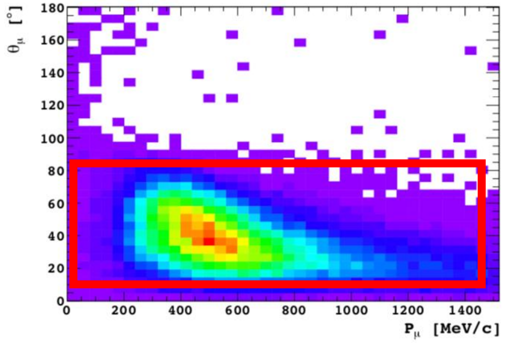
Backup slides

T2K Near Detector ND280

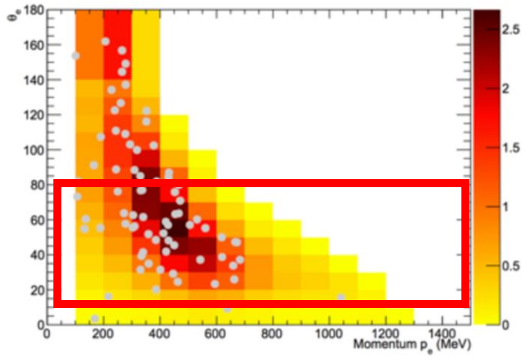


- Placed at 280 m from the target
- Measures the flux, flavor content, energy spectrum of the neutrino beam, studies neutrino-nucleus interactions

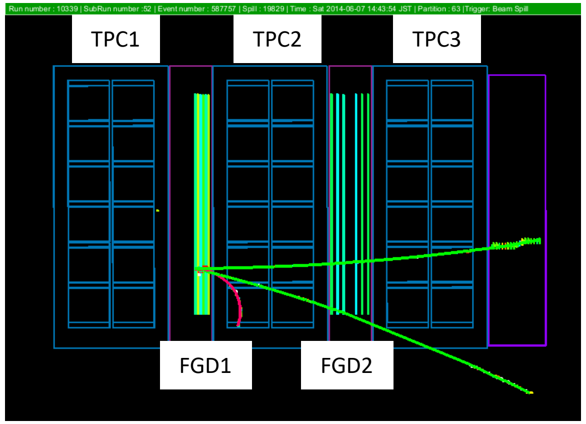
Muons in ND280:
- forward direction



Electrons in SuperK:
- 4π acceptance

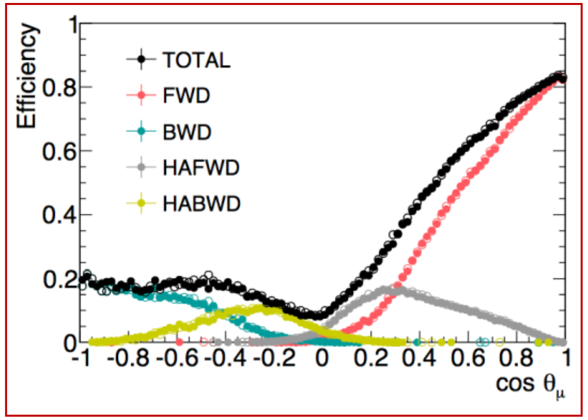


ν interaction in ND280



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, SuperK - 4π acceptance;
- Larger oscillation systematic uncertainties due to tracks not measured by TPCs
- No capability to detect neutrons



ND280 upgrade

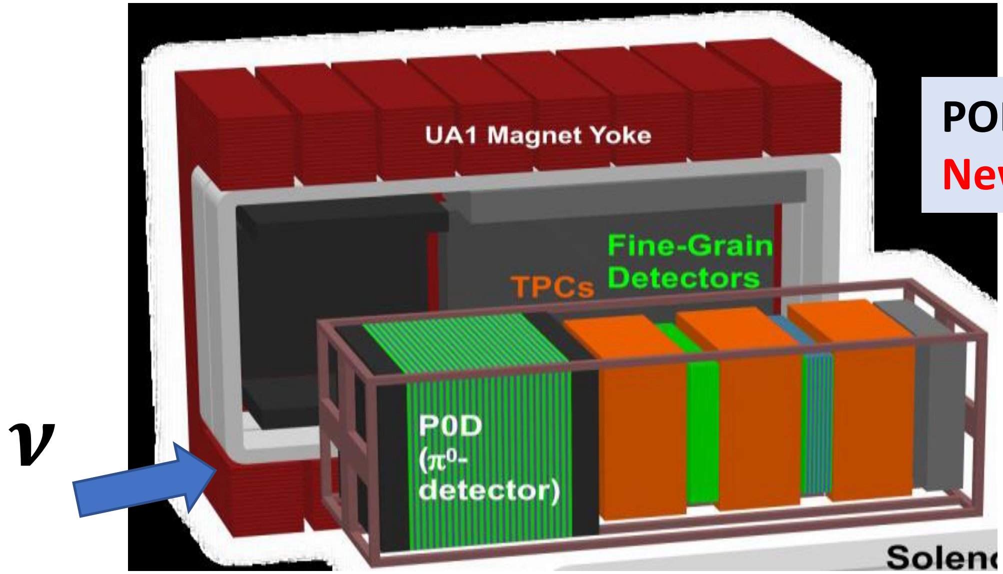
New upstream tracker:
- One 3D fine-grained scintillator target SuperFGD
- Two Horizontal TPCs
- TOF system around new tracker

- 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

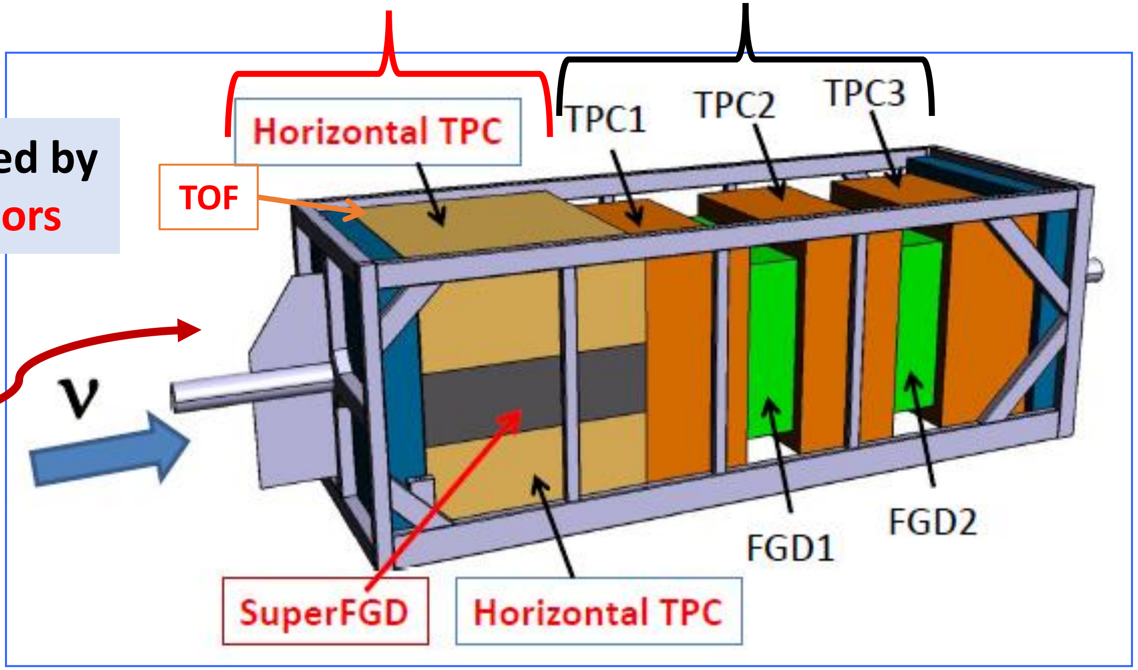
T2K ND280 upgrade group:
120 participants from
29 institutions and 11 countries
including CERN

Current ND280 complex

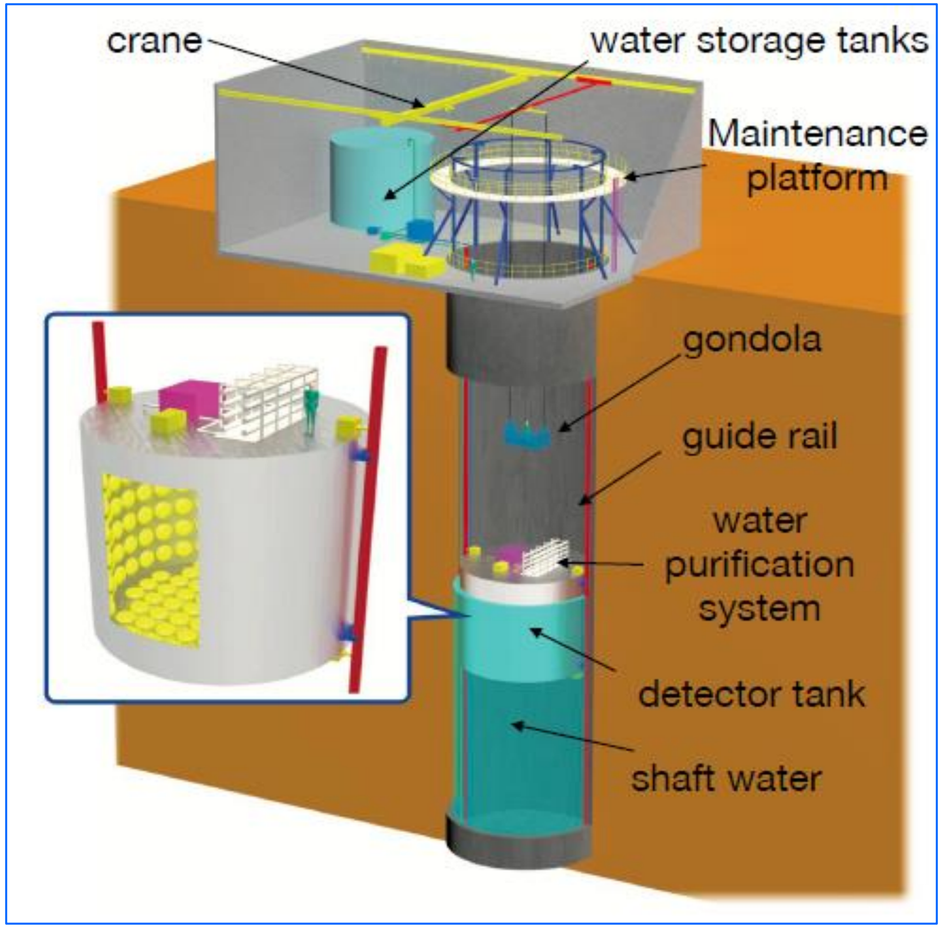


POD replaced by
New Detectors

New detectors **Current detectors**

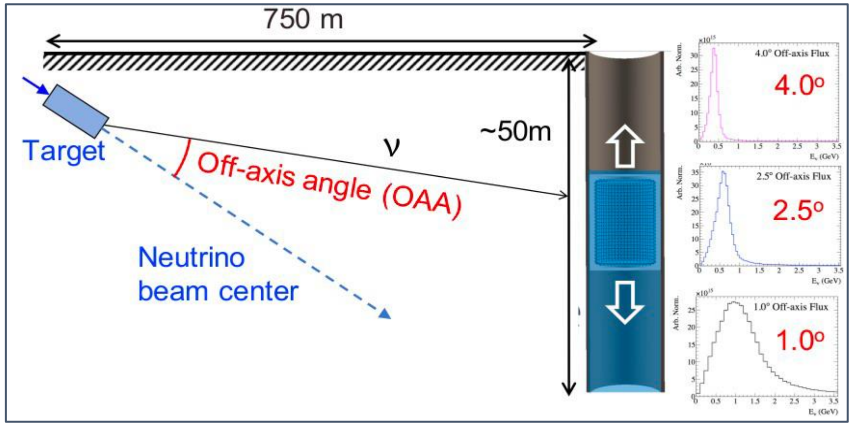


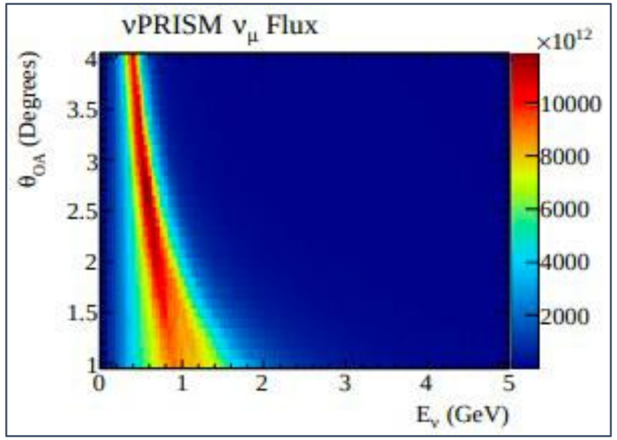
Intermediate Water Cherenkov detector



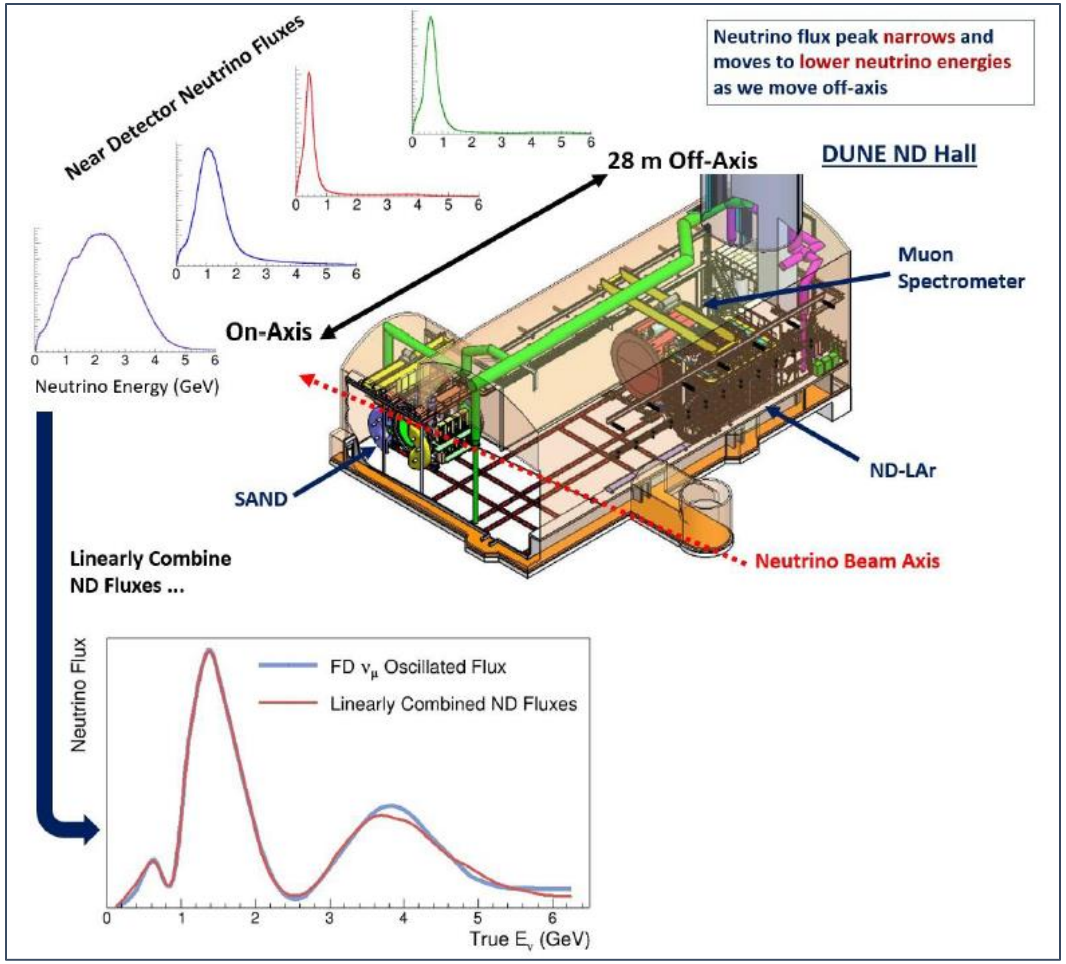
A 600 tonne water Cherenkov detector with diameter ~8 m and height ~6 m, located at ~ 1 km from the neutrino source

A vertically moving detector, allowing detections at different off-axis angles between 1-4 degrees



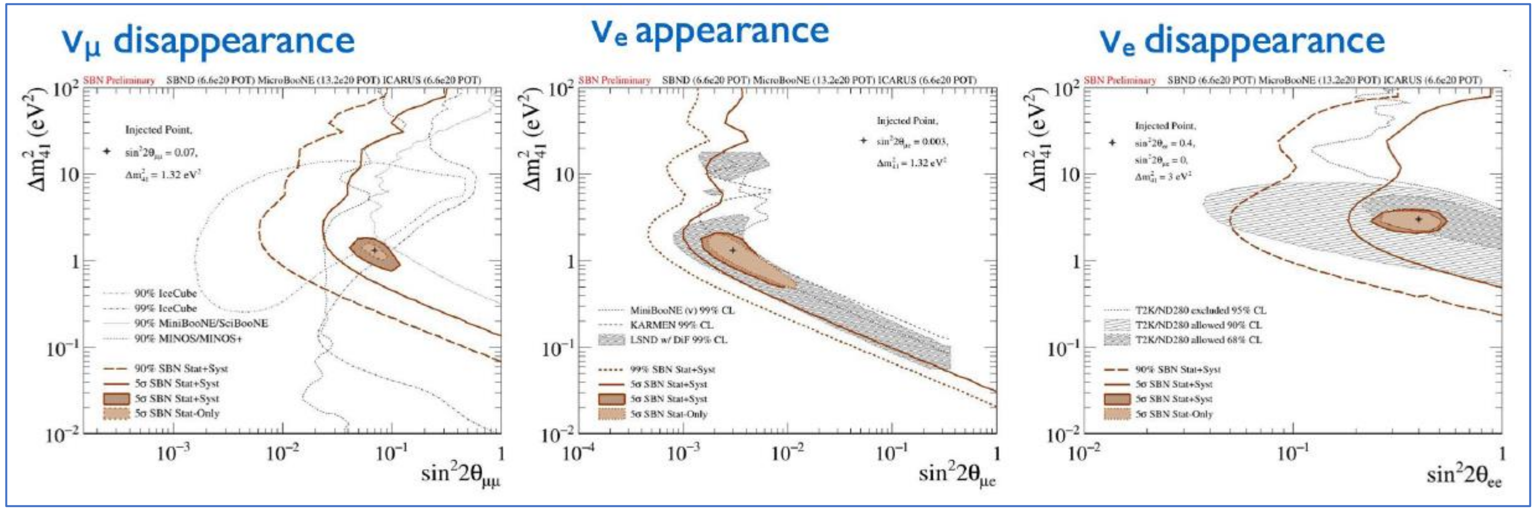


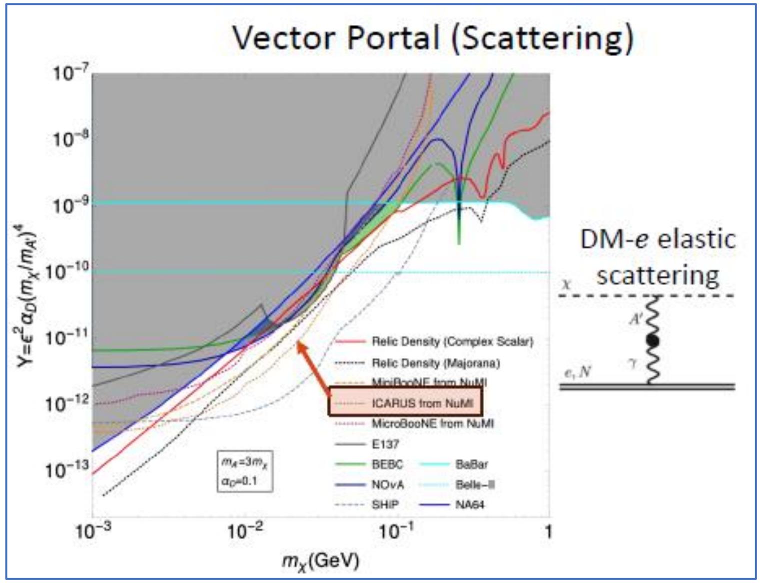
DUNE-PRISM



- Build a FD prediction **directly from ND data** by going off-axis
- Linearly combine many **ND fluxes** to **match the FD oscillated flux**
- Unknown or poorly modelled cross section effects **directly measured**
- Cancellation between ND and FD flux uncertainties

FNAL: Short Baseline ν Program

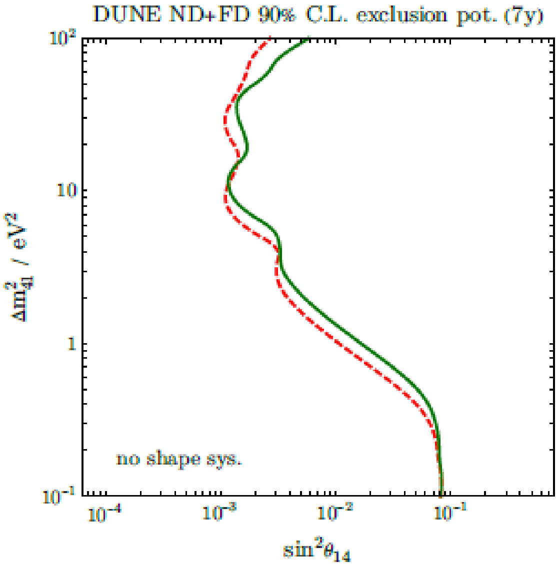


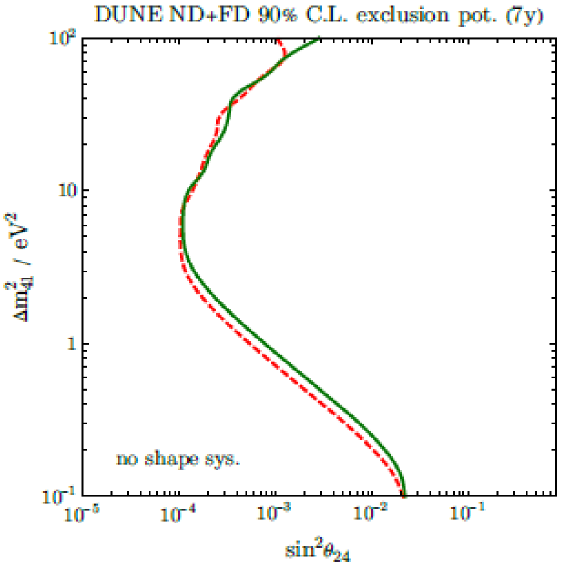


DUNE: Expected sensitivity to ν_s

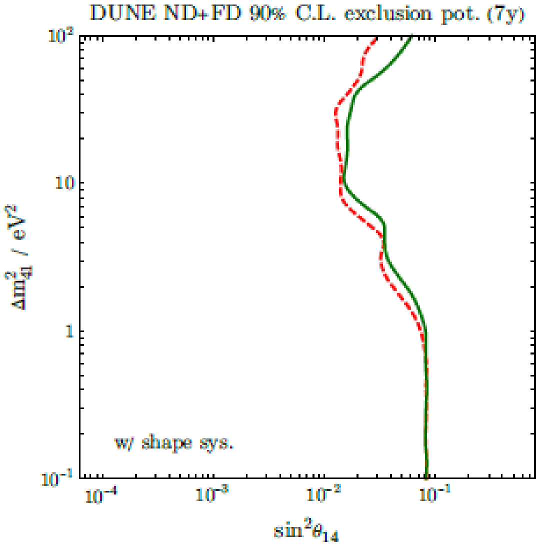
arXiv:2207.02331

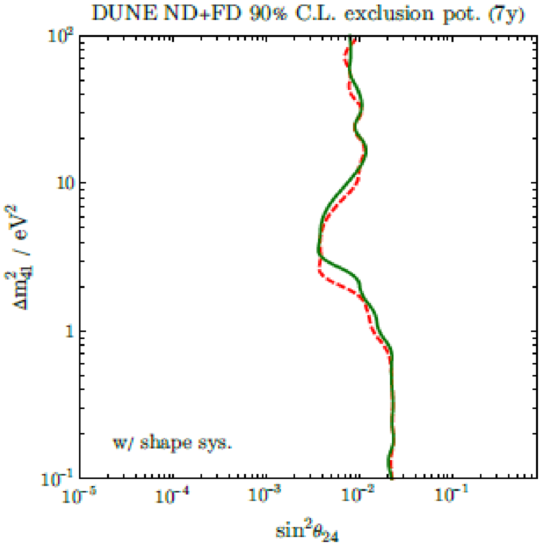
No systematics, 7y data taking



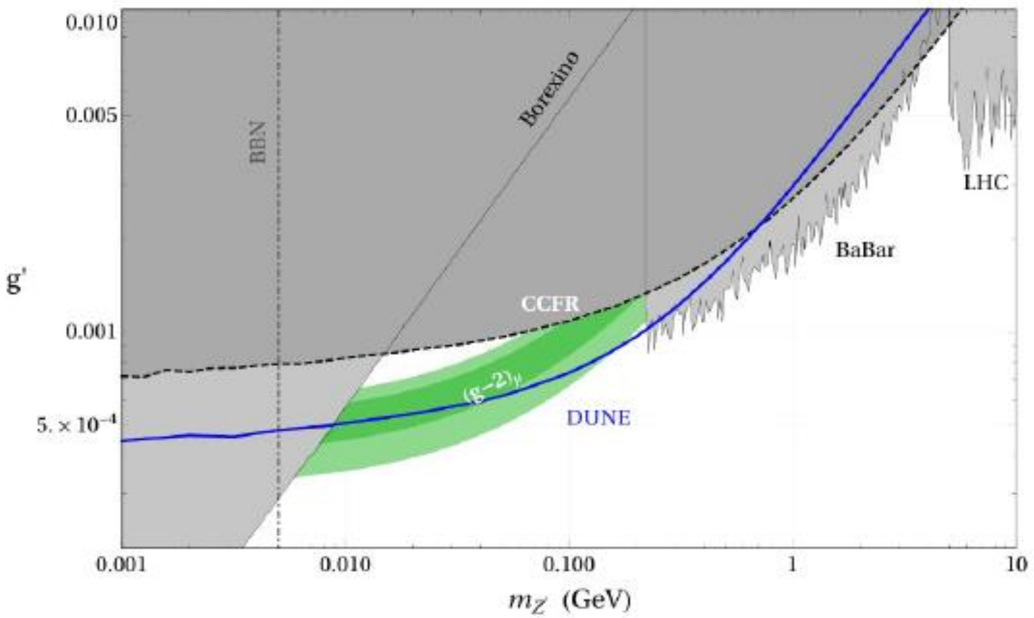


Systematics 5%, 7y data taking

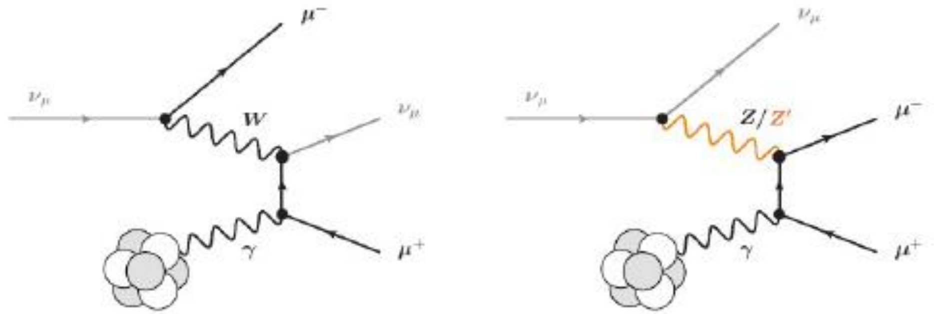




DUNE: Z’



0.010
0.005
0.001
5. × 10⁻⁴
g'
BBN
Borexino
CCFR
(g−2)μ
DUNE
BaBar
LHC
0.001
0.010
0.100
1
10
m_{Z} (GeV)



ν_μ
μ^-
W
ν_μ
γ
μ^+
ν_μ
ν_μ
Z / Z'
μ^-
γ
μ^+