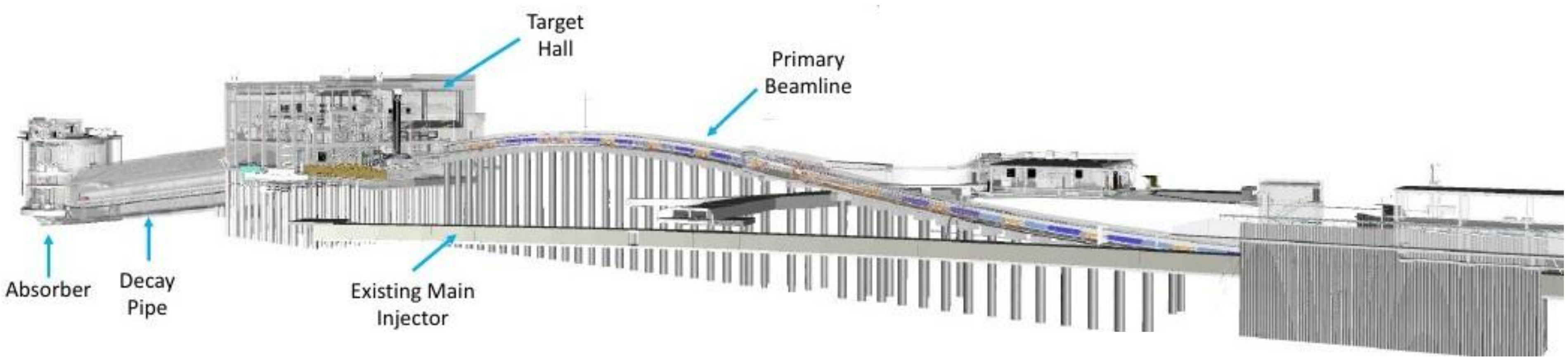
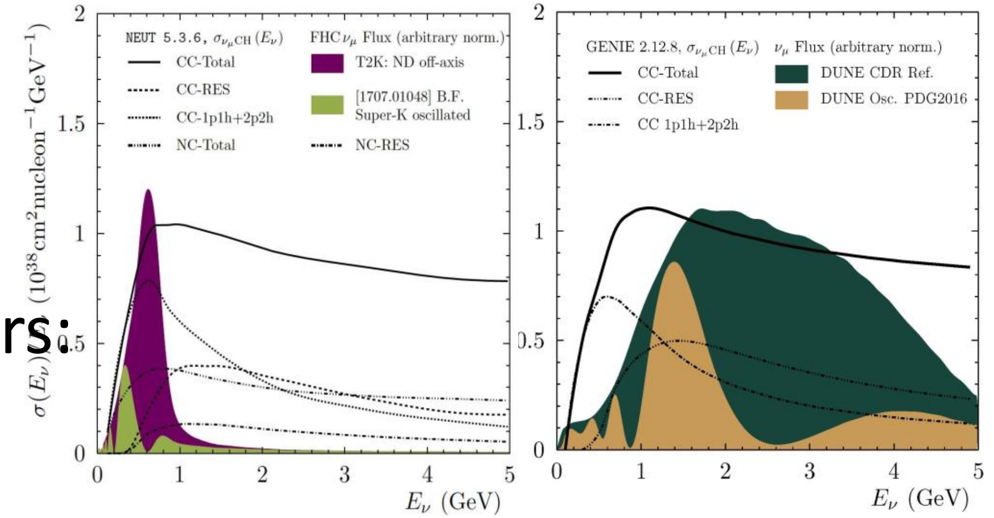
Accelerator-based Neutrino Experiments



Kim Siyeon
Chung-Ang University

Division of Particles and Fields, KPS
December 21, 2023

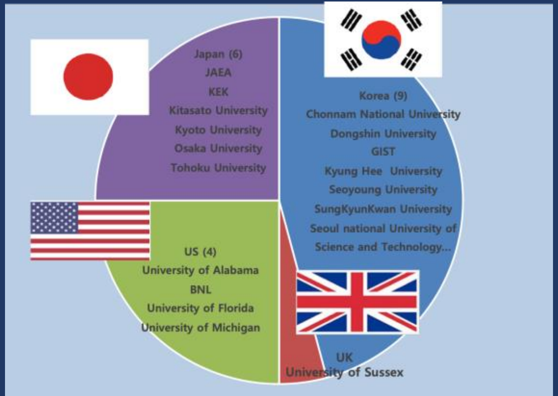
Accelerator Neutrinos



- Intense neutrino beams using proton accelerators:
  - J-PARC | CERN | Fermilab

Experiment	Beam Source	Detector (threshold)	Interaction	Flavors		
JSNS^2	Spallation Neutron Source (3GeV)	Liquid Scintillator (1.8 MeV)	CC	$\nu_\mu\ \bar{\nu}_\mu$ (Bg: $\nu_e\ \bar{\nu}_e$)	Oscillation	Operation
SND@LHC	LHC (TeV)	Emulsion (>10 GeV)	CC, NC	$\nu_e\ \nu_\mu\ \nu_\tau$	Scattering	Operation
T2HK	J-PARC (1 GeV)	Water Cerenkov (200 MeV)	CC, NC	$\nu_e\ \nu_\mu\ \bar{\nu}_e\ \bar{\nu}_\mu$	Oscillation	Construction
DUNE	PIP-II NuMI (0.5~10 GeV)	L-Ar Time Projection Chamber, NC, CC, ES (around 10 MeV)	NC, CC, (ES)	all	Oscillation Interaction	Construction

JSNS2 : J-PARC Sterile Neutrino Search at J-PARC Spallation Neutron Source (E56)



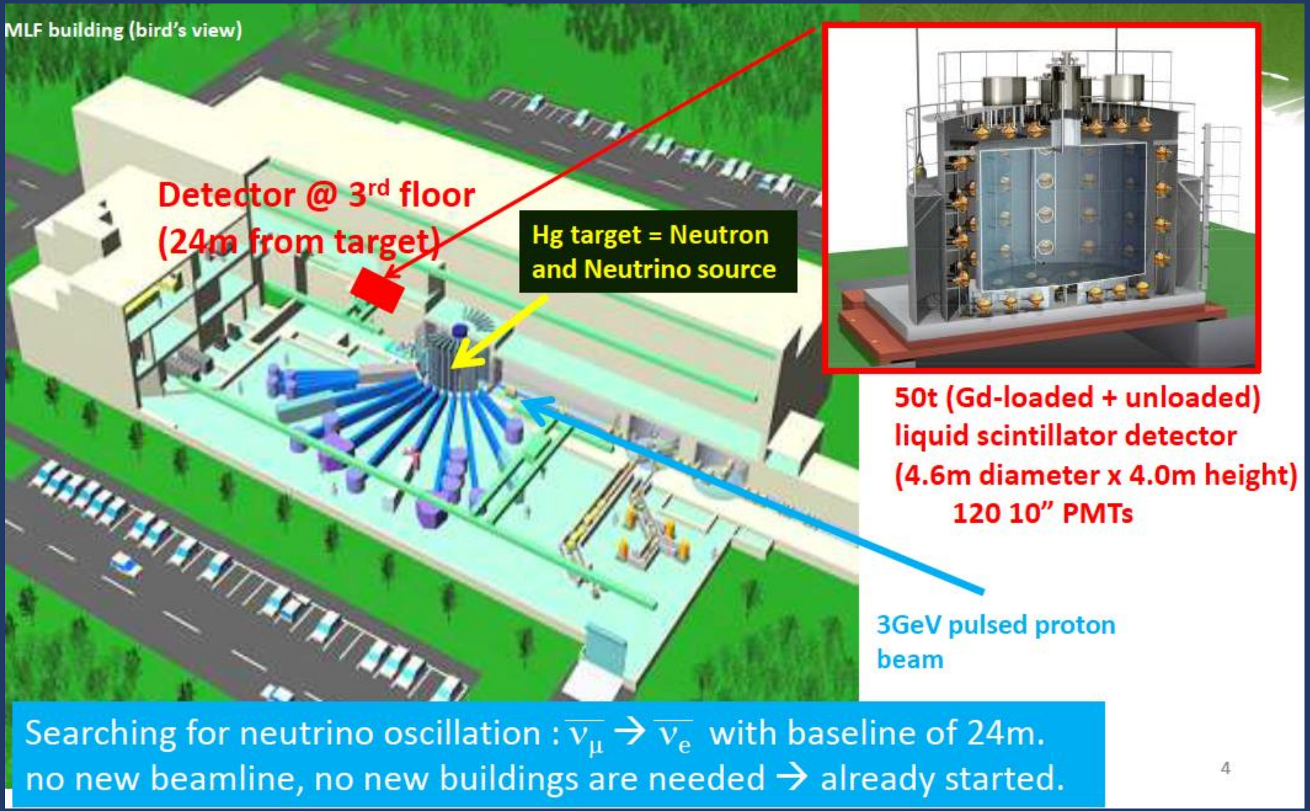
Neutrino anomalies from LSND

- **LSND reported an an excess of 87.9±22.4±6.0 anti-electron neutrino events (3.8σ) in 2001.**
- **Sterile neutrino hint**

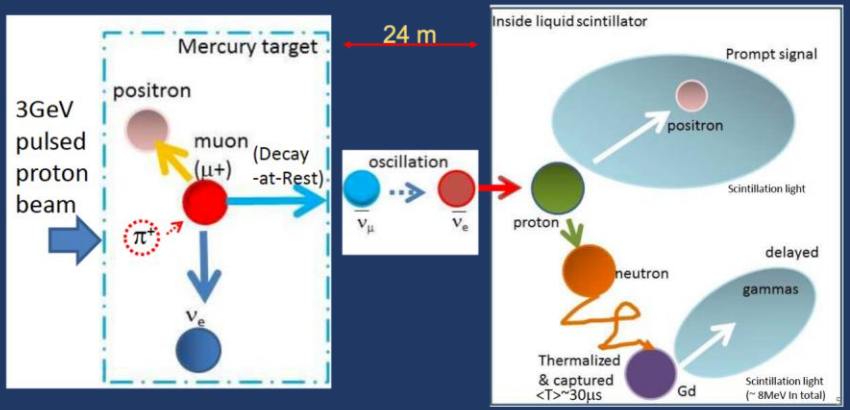
✓ **There are contradicted results from experiments : need to test LSND result <u>using same environment</u> ⇨ motivation**

	JSNS^2	LSND
Target mass	**17 tons**	**167 tons**
Baseline	**24 meters**	**30 meters**
Beam energy	**3 GeV**	**0.8 GeV**
Beam duty factor	**0.8/40,000**	**1/14**
Liquid scintillator	**Gd loaded LS + LS**	**small number of scintillating light, no Gd**
Delayed signal	**Etot ~ 8 MeV, Δt~30μs**	**Etot ~ 2.2 MeV, Δt~200 μs**
ΔE/E	**2.4% @ 45 MeV**	**7% @ 45 MeV**
Fast neutron rejection	**Pulse shape discrimination**	**Cerenkov**
Number of IBD signal events	**~20 events/yr @ LSND best fit**	**15 events/yr**

MLF : world best environment

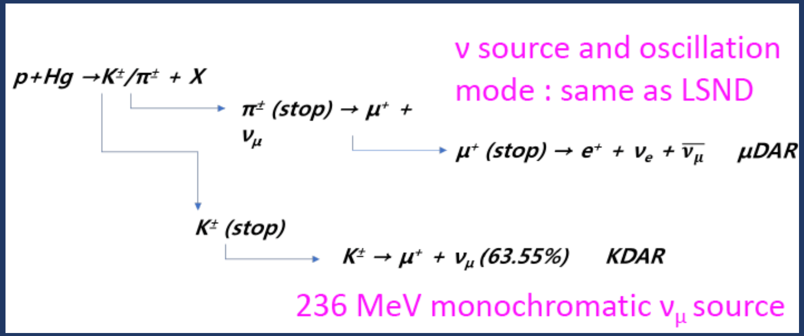


$\overline{\nu_\mu} \rightarrow \overline{\nu_e}$

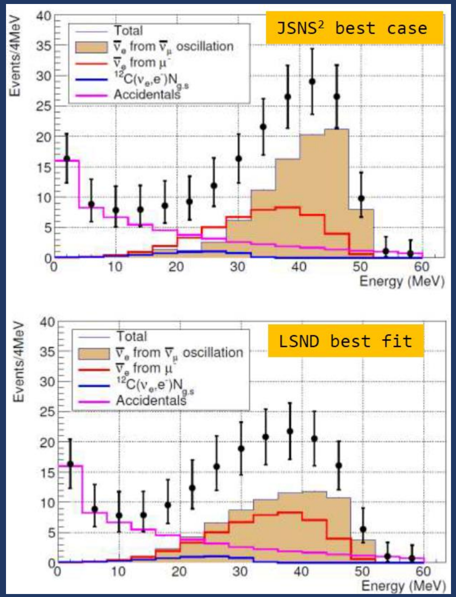


Detection : Inverse Beta decay (IBD)

Unique condition to reduce beam induced background using pulsed 3 GeV proton beams from RCS, J-PARC.

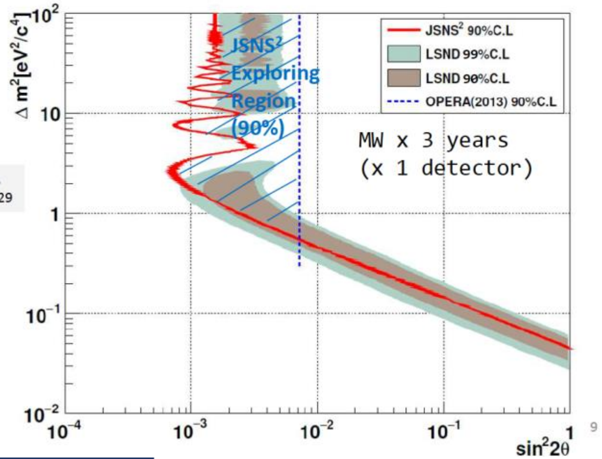


Energy Spectrum and Sensitivity and KDAR analysis (MC)

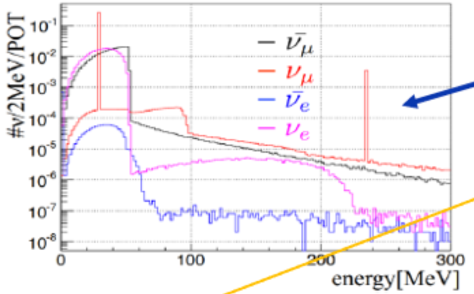


- Left: Energy spectrum; (Top: Δm^2=2.5eV², Bottom; 1.2eV² $\sin^2 2\theta$ = 0.003)
- Right: Sensitivity of 3 years physics running of JSNS² with one detector.

S. Ajimura *et al.* arXiv:1705.08629



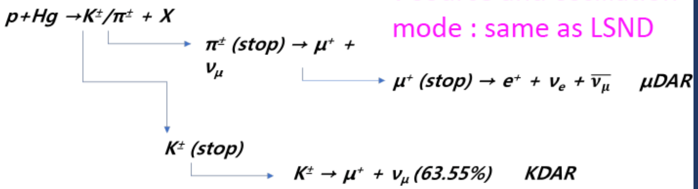
KDAR Neutrino Measurement



The monoenergetic KDAR ν In the J-PARC MLF flux.
$K^+ \rightarrow \mu^+ + \nu_\mu\ [BR = 63.5\ \%]$
$E_\nu = 236\ MeV$

- The first physics analysis via the KDAR neutrino interaction has been started.

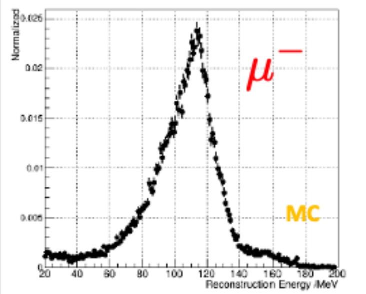
ν source and oscillation mode : same as LSND

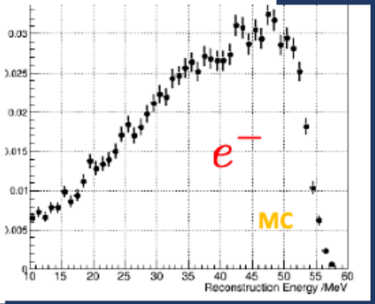


236 MeV monochromatic ν_μ source

$$\nu_\mu + ^{12}C \rightarrow ^{13}N_{gs} + \mu^-$$

$$\mu^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu$$

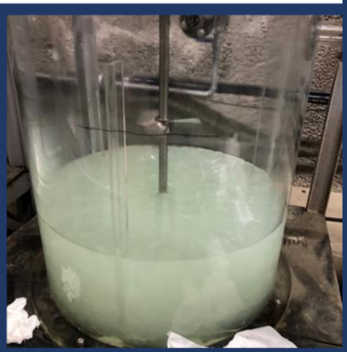


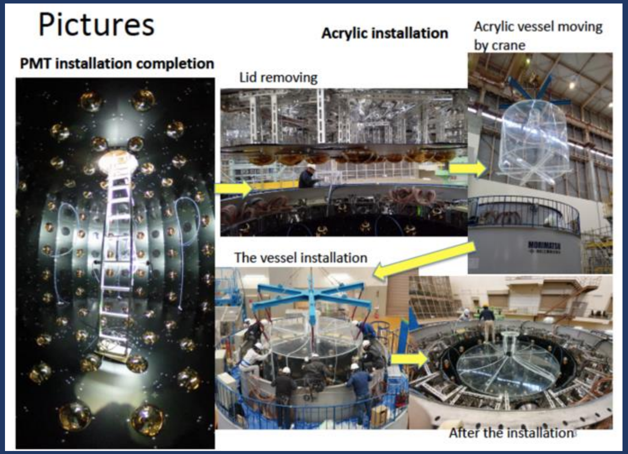


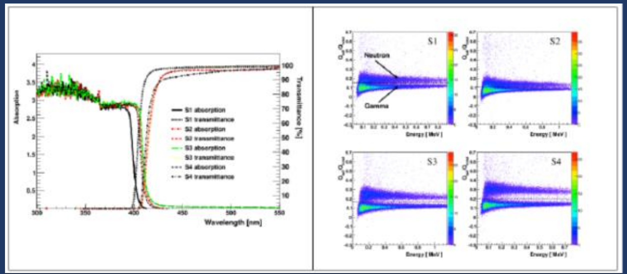
Contribution to JSNS2

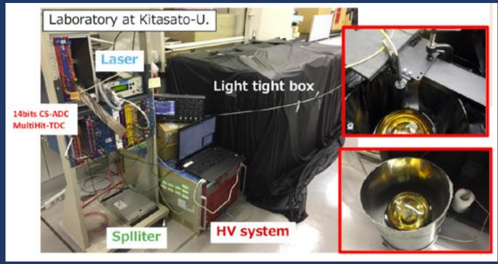
Korean Contributions

- ***Detector construction (finished)***
- ***~80% of PMTs (100PMTs were delivered)***
- ***35 tons of Liquid scintillator (delivered)***
- ***Slow monitoring system (delivered)***
- ***HV control software (installed)***
- ***Development of DAQ and monitoring/display codes (installed)***
- ***MC and analysis code (working)***
- ***Calculation of ν-nucleus cross section (working)***
- ***Beyond standard model phenomenology (working)***







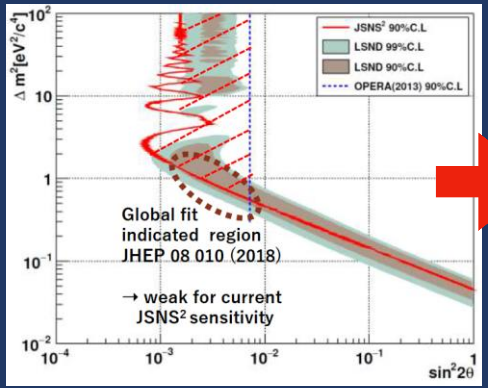


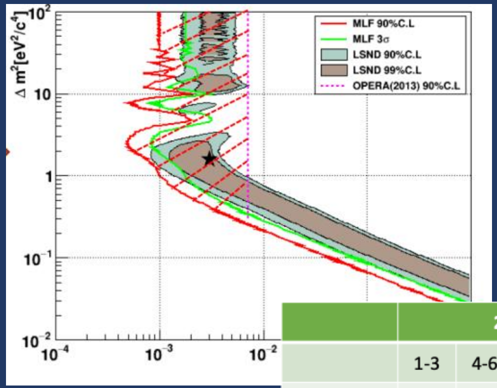
Korean Activity and JSNS2-II

Present and Future

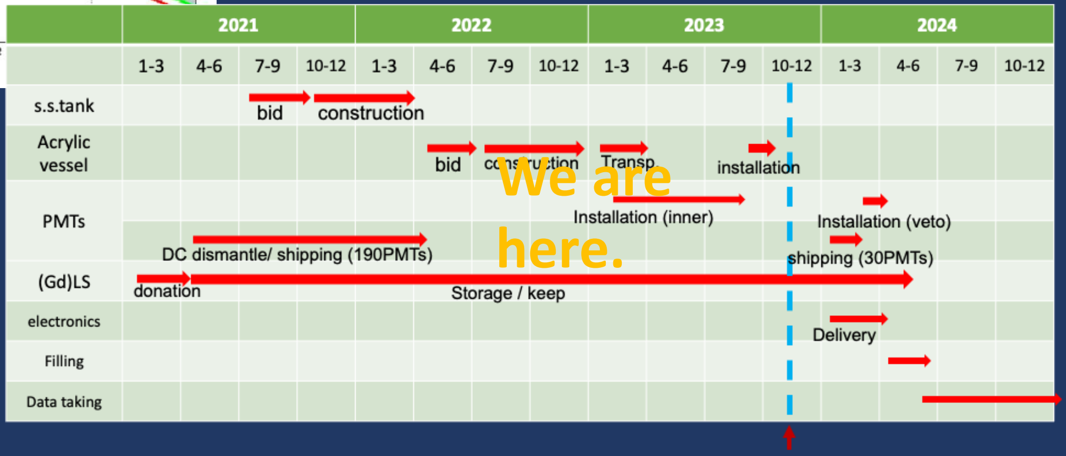
The contribution of the Korean group in JSNS2 has been significant, and we expect that the activities will continue in the future.

- Through the 2020-2021 experiment, background reactions were effectively provided, and IBD reaction candidates corresponding to 59 ± 8 events were obtained, of which 55.9 ± 2.7 events were identified as reactions by cosmic-rays neutrons.
- First long-term physics run data acquisition (Jan–June 2021)
- Second long-term physics run data acquisition (Jan–June 2022)
- Third long-term physics run data acquisition (Apr–June 2023)





JSNS2-I (24 m) + JSNS2-II (48 m) can improve the sensitivity of sterile neutrino search.



SND@LHC
& SHiP

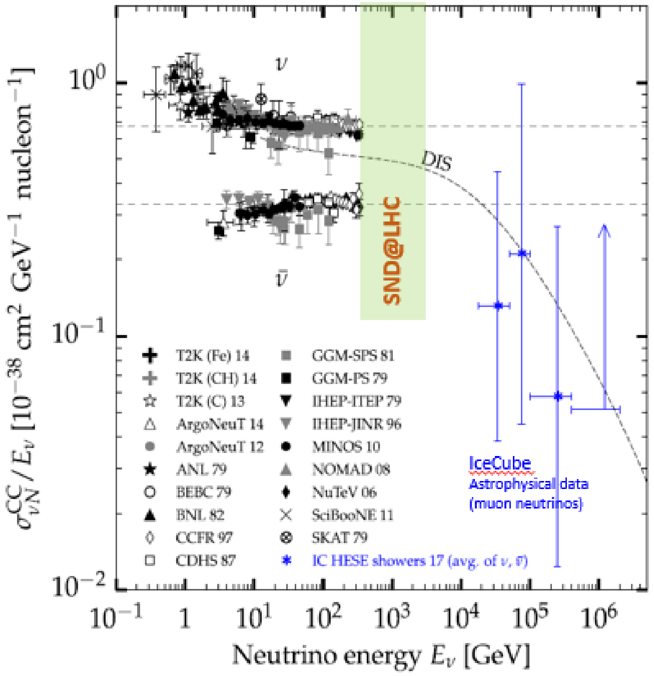
SND@LHC

Study of high energy neutrino interactions

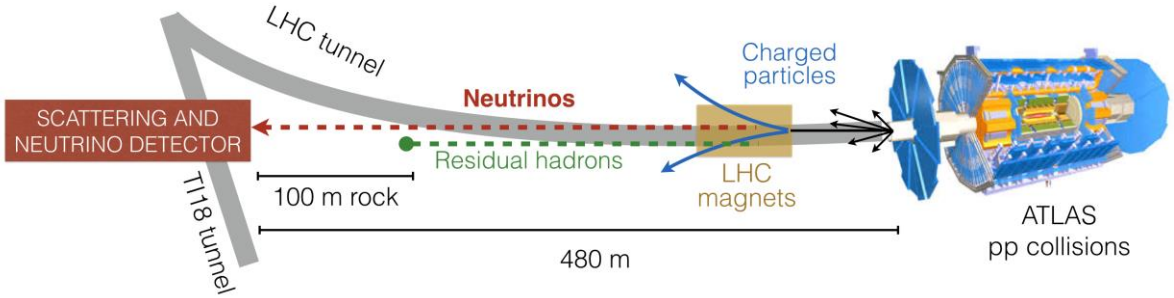
- LHC can create huge numbers of high-energy neutrinos in the **forward direction**.
- Measure ν interactions in unexplored energy range (~TeV) and unexplored pseudo-rapidity region ($7.2 < \eta < 8.4$)

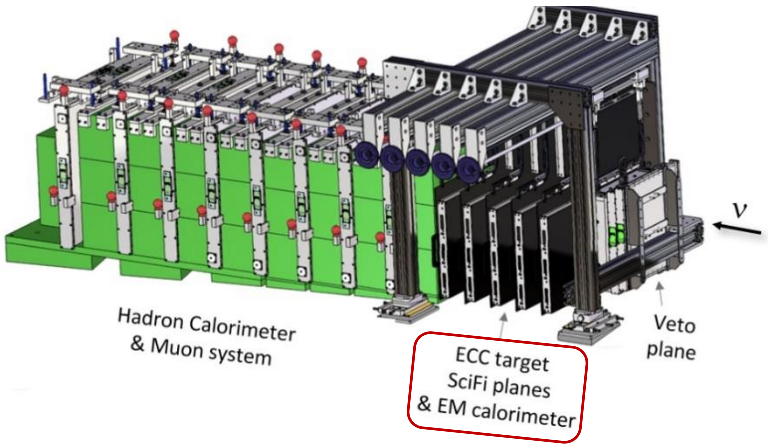
Search for FIPs

- Search for the **Feebly interacting particles** decaying within the detector or scattering off the target (HNL, Dark photon, ALP, Light dark matter etc.).



LoI: Aug 2020
Technical Proposal: Jan 2021
Approval in March 2021
Data taking from Apr 2022
when Run 3 started



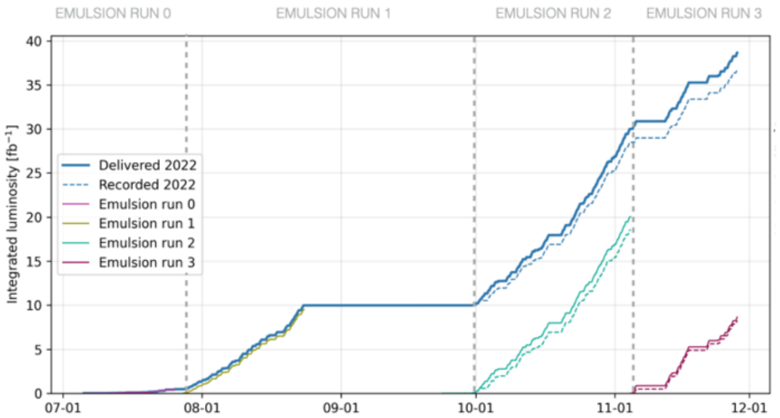


All 3 flavors of neutrinos can be identified in the ECC target.

ECC: Emulsion Cloud Chamber (Emulsion + Tungsten)

SND: Scattering and Neutrino Detector (ECC+SciFi)

Beam exposure to ECC target



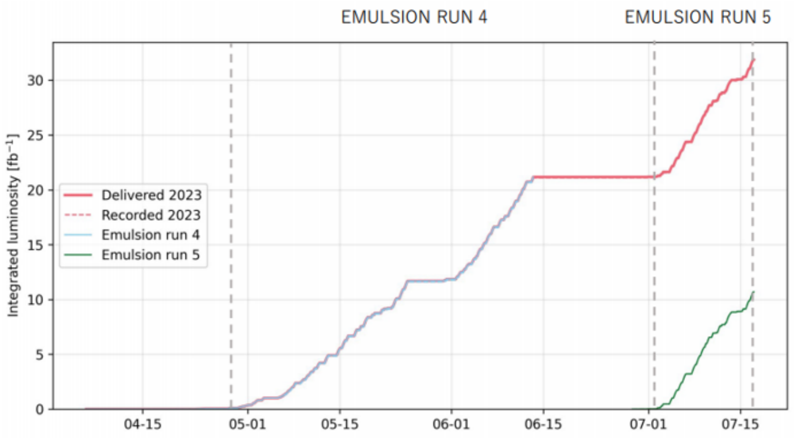
2022

- 3 ECC target replacements
- Total recorded luminosity: **38.5 fb^{-1}**

16 ECC Brick walls assembled (2422 kg)

3522 emulsion films developed (140 m^2)

Assembled ECC targets



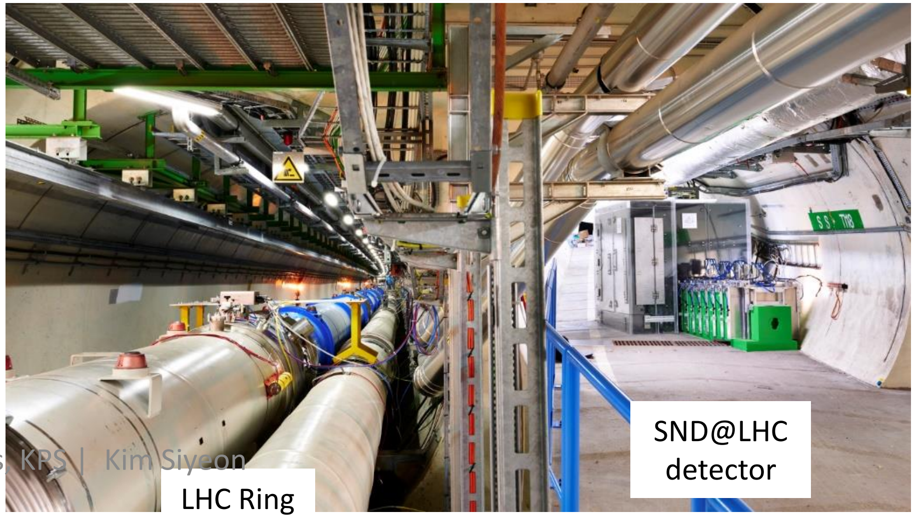
2023

- 4 ECC target replacements expected (Expected luminosity: 80 fb^{-1})
- LHC machine trouble happened on 17th July → pp run was terminated
- Total recorded luminosity: **31.9 fb^{-1}**

10 ECC Brick walls assembled (1581 kg)

2300 emulsion films developed (92 m^2)

2000 L disposed chemical solutions



LHC Ring

SND@LHC detector

Emulsion tasks at CERN

ECC assembly (Tungsten plates + Emulsion films) – ECC target installation – Beam exposure – Extraction – Development – Drying – Packing

Emulsion plates after development

July, Aug 2023

Chemicals and tanks for Emulsion development

First physics result (2022 run) – only by electronic detector

The first observation of Collider Neutrinos: **8 ν_μ CC events**

Estimated background : $(8.6 \pm 3.8) \times 10^{-2}$ events
Significance : 6.8 σ

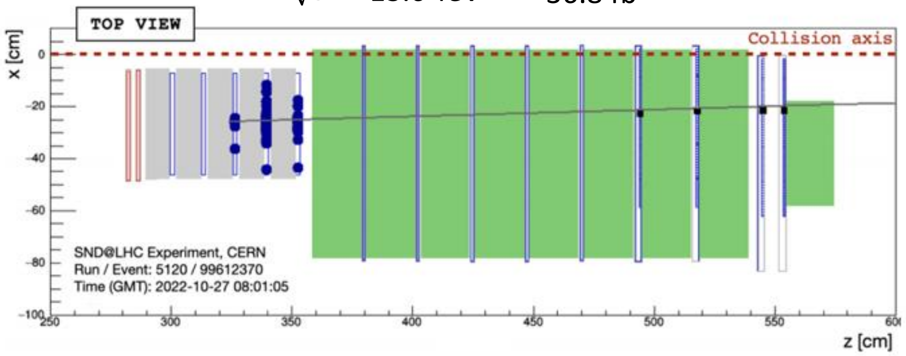
PRL 131, 031802 (2023)

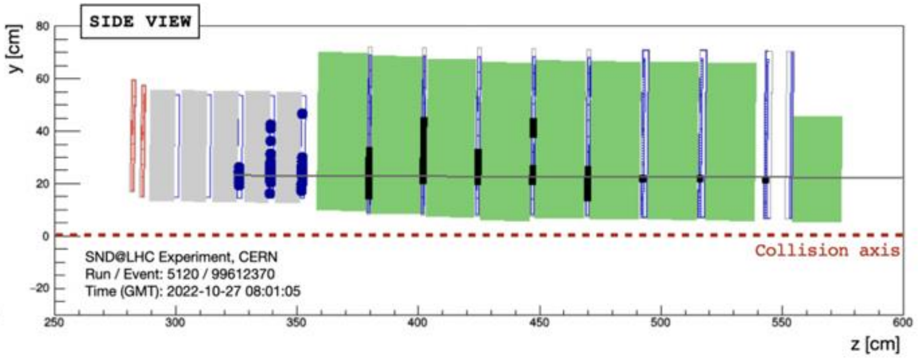
Editors' Suggestion | Open Access

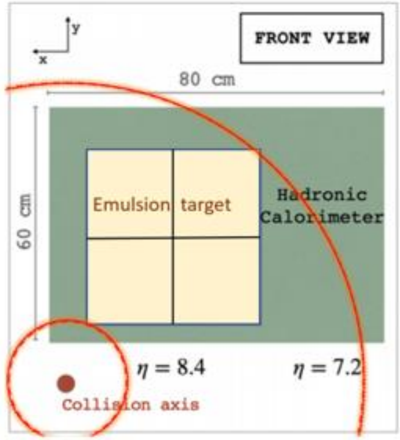
Observation of Collider Muon Neutrinos with the SND@LHC Experiment

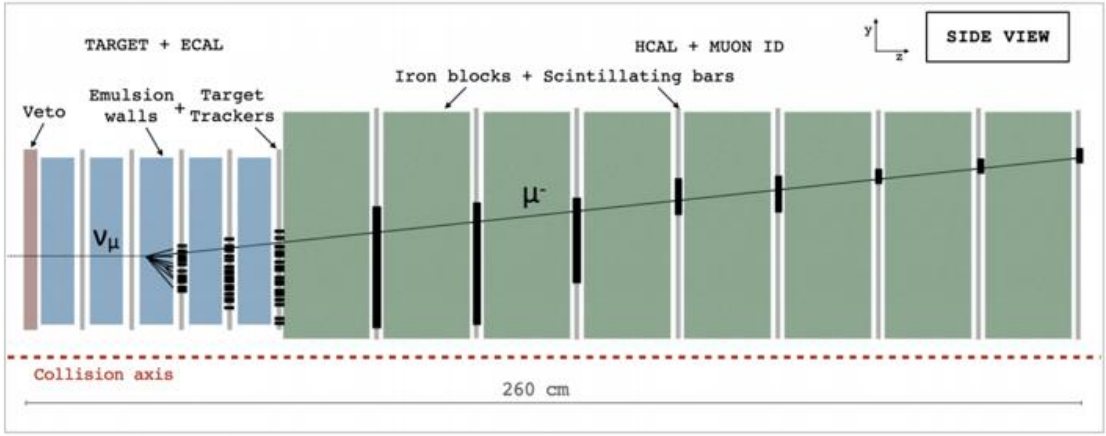
R. Albanese *et al.* (SND@LHC Collaboration)
Phys. Rev. Lett. **131**, 031802 – Published 19 July 2023

$\sqrt{s}$ = 13.6 TeV   36.8 fb^{-1}





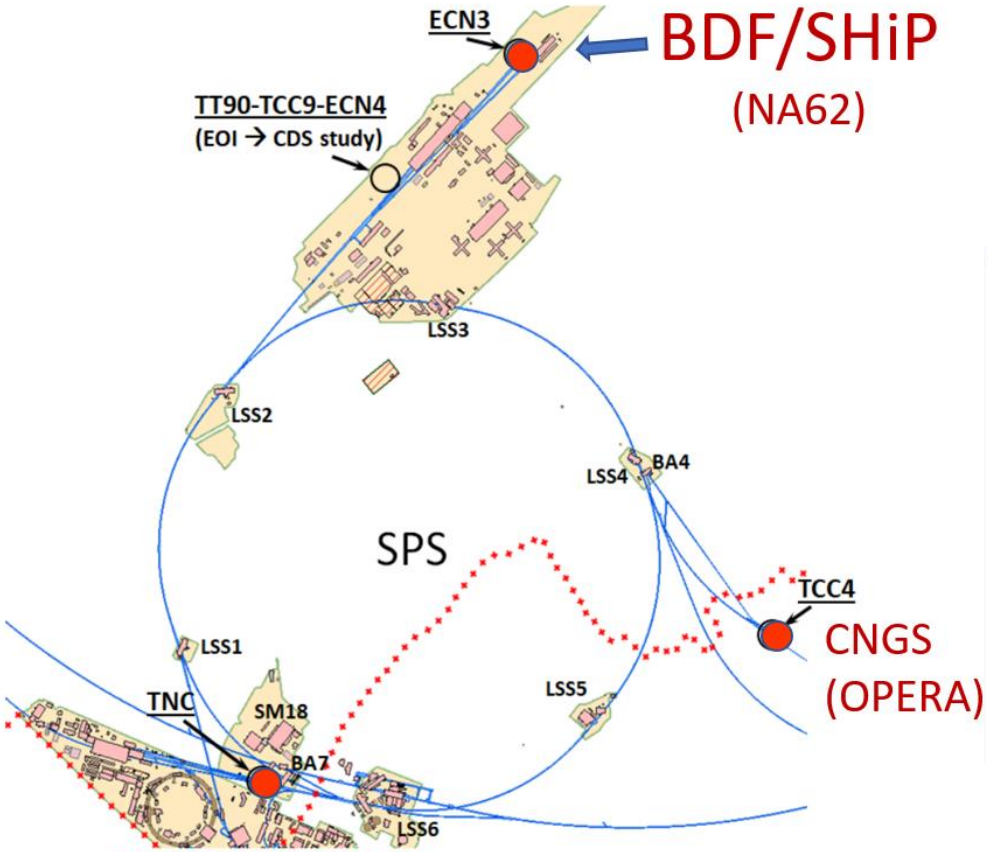


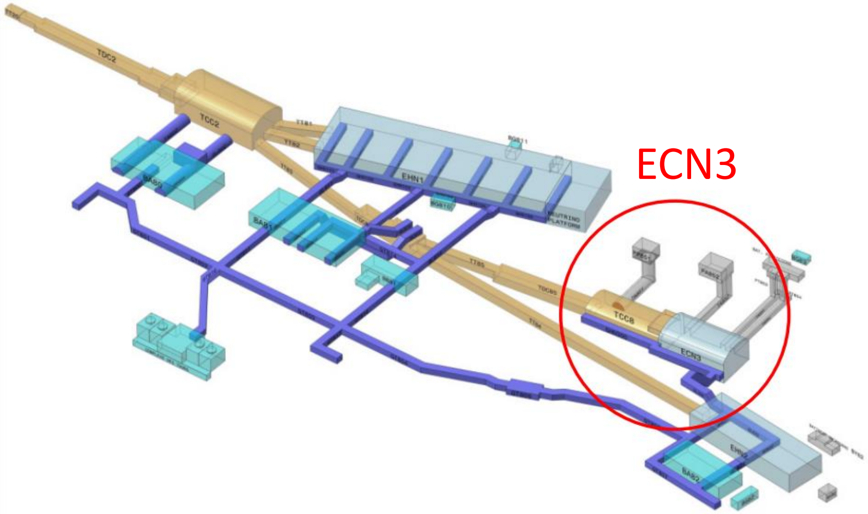


Currently, **33 ν_μ CC events**: 16 in 2022 run and 17 in 2023 run

SHiP
Search for Hidden Particles

New site: ECN3 in SPS North Area
High intensity proton beam
(6×10^{20} pot in 15 years)

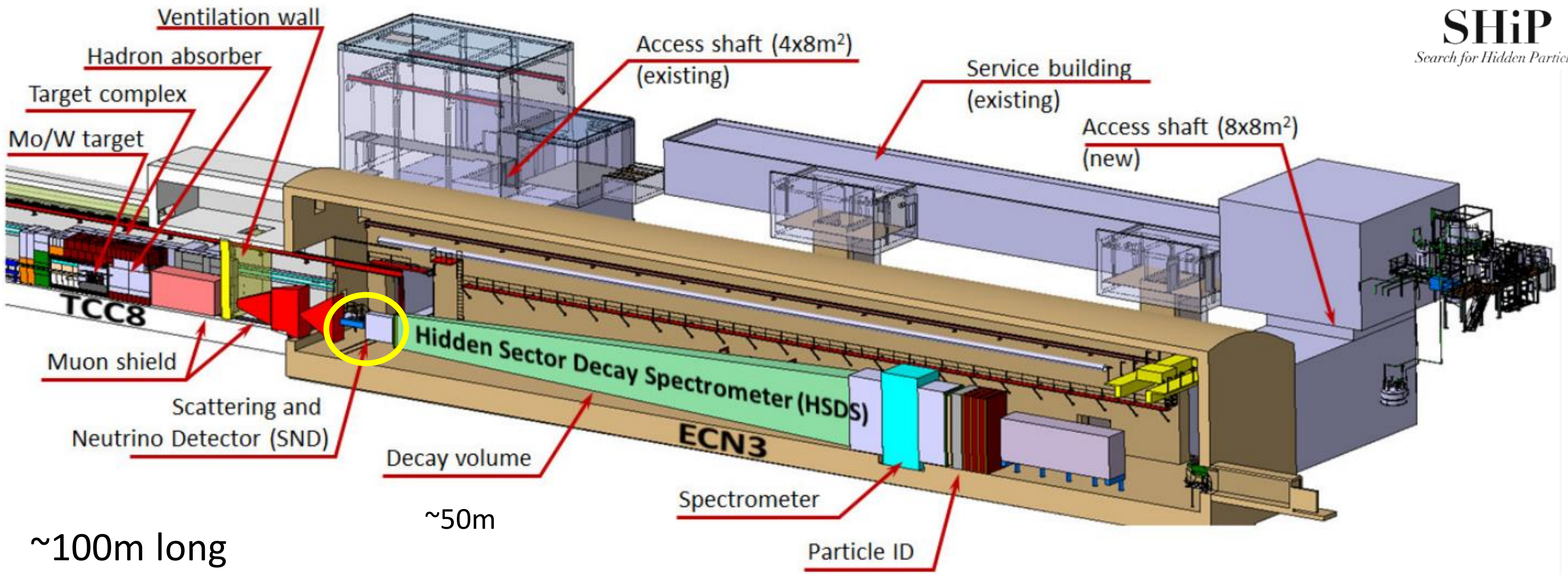




- Currently hosting NA62
- Profit a lot from existing infrastructure
- 6×10^{20} pot for SHiP in 15 years

New design of SHiP detector - optimized for ECN3

SHiP
Search for Hidden Particles



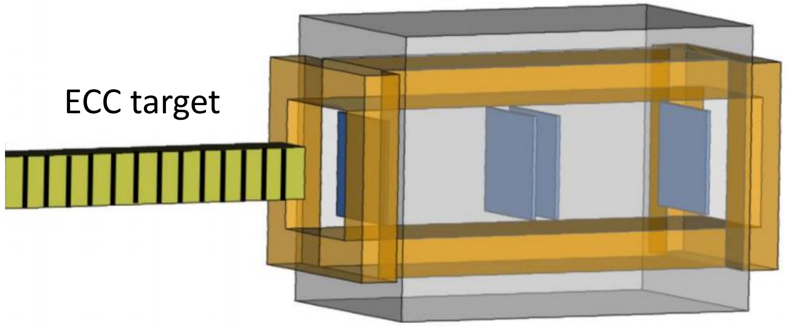
~100m long

~50m

SHiP SND

Muon spectrometer

ECC target



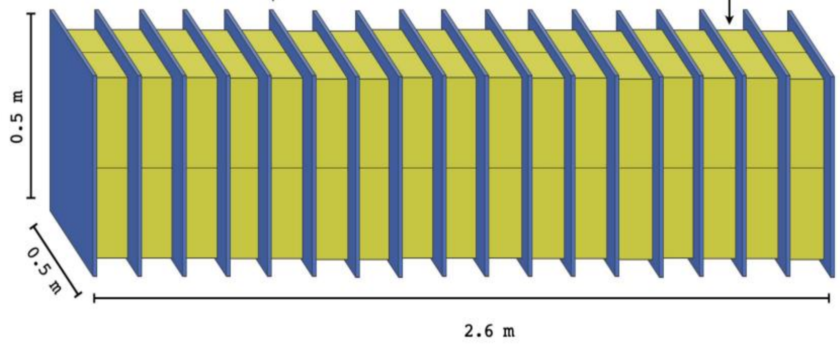
4 tracking stations inside dipole magnet

← ~ 6 m →

ECC target

SciFi

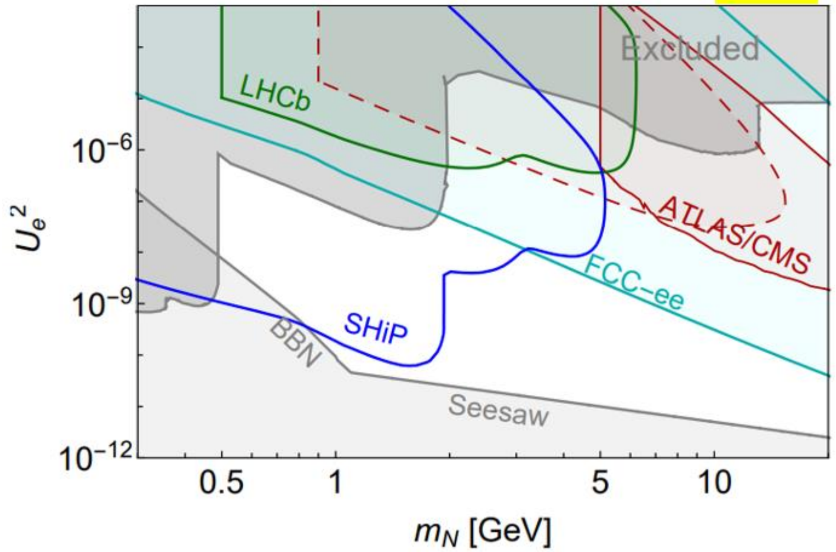
ECC



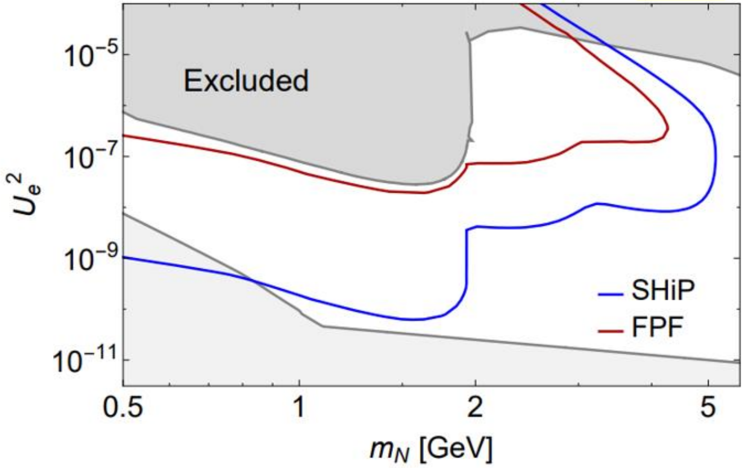
SHiP sensitivities in ECN3

6 x 10^{20} pot in 15 years

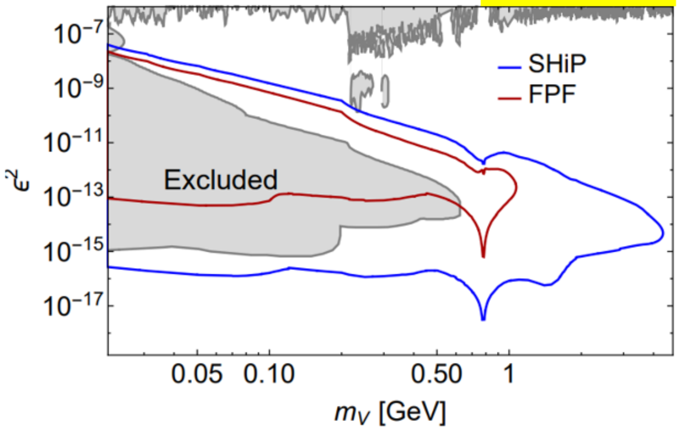
HNL

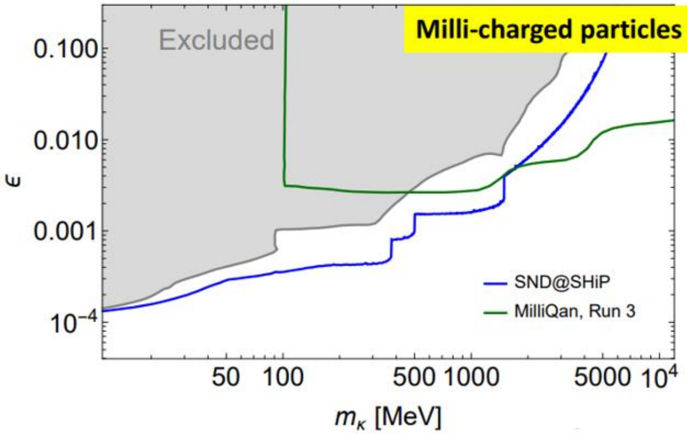


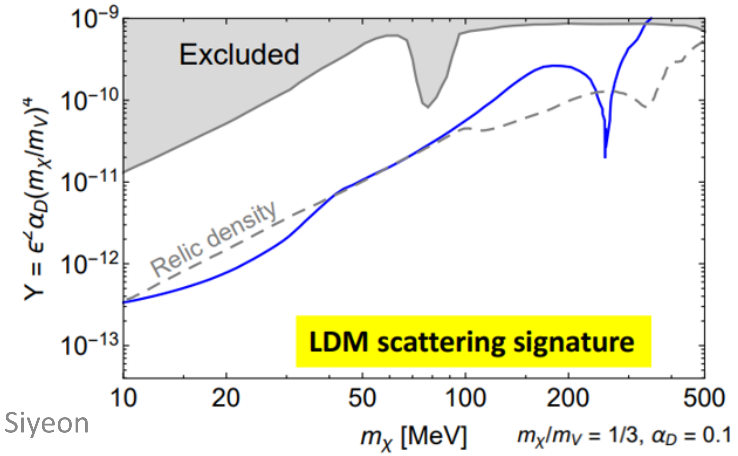
HNL



Dark photon

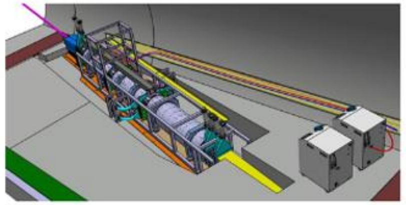






SND@LHC

- Accumulated **70.4 fb^{-1}** (2022: 38.5 + 2023: 31.9 fb^{-1})
- Due to LHC machine trouble, only two emulsion targets for 2023.
- The first physics result, **LHC neutrino observation**, published on PRL.
  → Both SND@LHC and FASERν results (Editors' suggestion)



Physics NEWS AND COMMENTARY

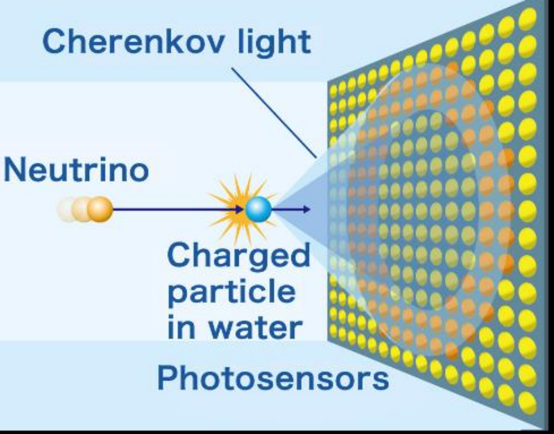
The Dawn of Collider Neutrino Physics

July 19, 2023

The first observation of neutrinos produced at a particle collider opens a new field of study and offers ways to test the limits of the standard model.

SHiP

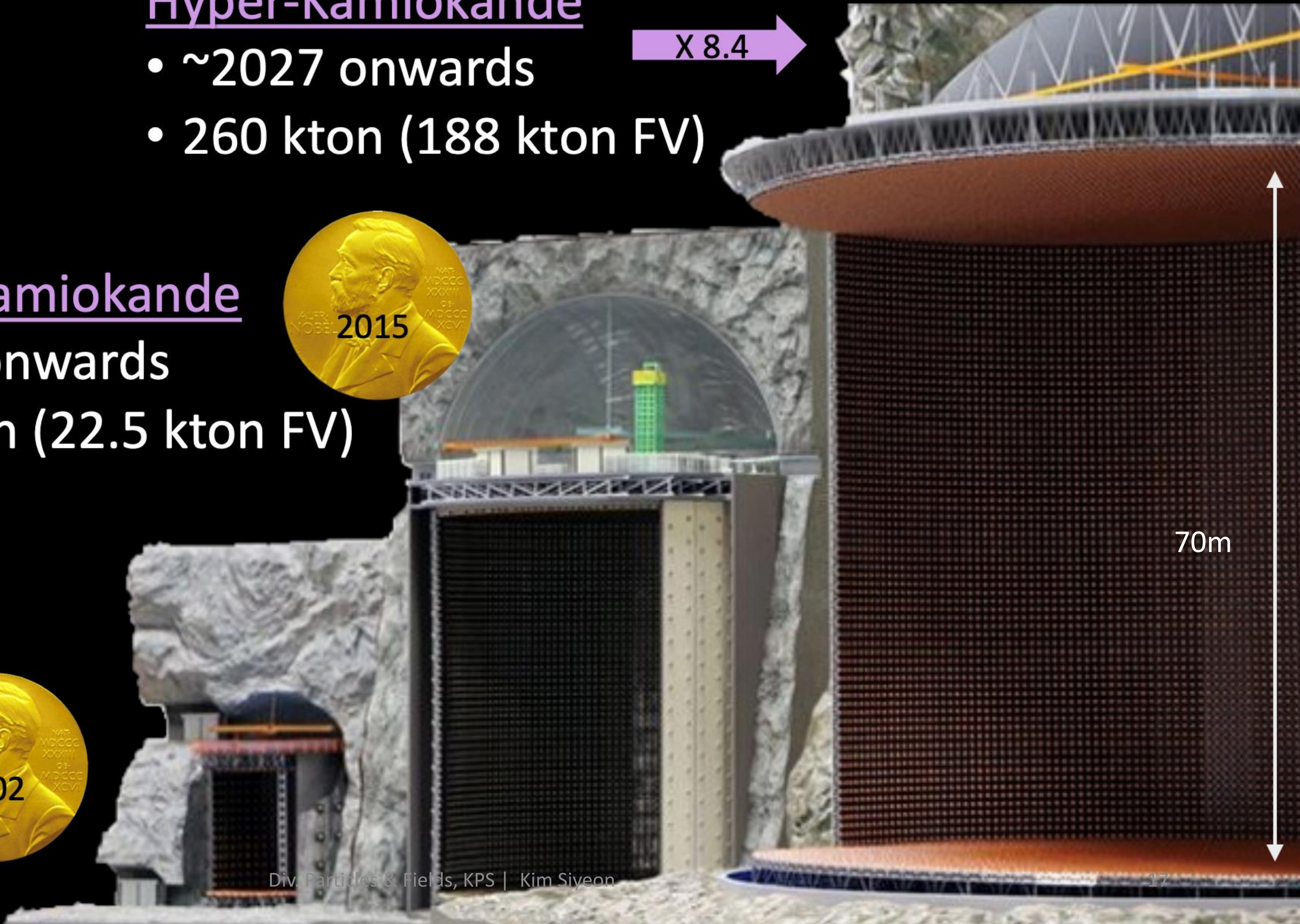
- **New proposal at North Area ECN3** was submitted in Aug 2023
  and under reviewing process at SPSC.
- HIKE/SHADOWS is the competitor. HIKE (Precision measurements of rare Kaon decays) and SHADOWS (FIP search) run simultaneously.
- **Final decision** on ECN3 by CERN RB (Mar 2024)



Hyper-Kamiokande

- ~2027 onwards
- 260 kton (188 kton FV)

X 8.4



Super-Kamiokande

X 20

- 1996 onwards
- 50 kton (22.5 kton FV)

Kamiokande

- 1983 – 1996
- 3 kton

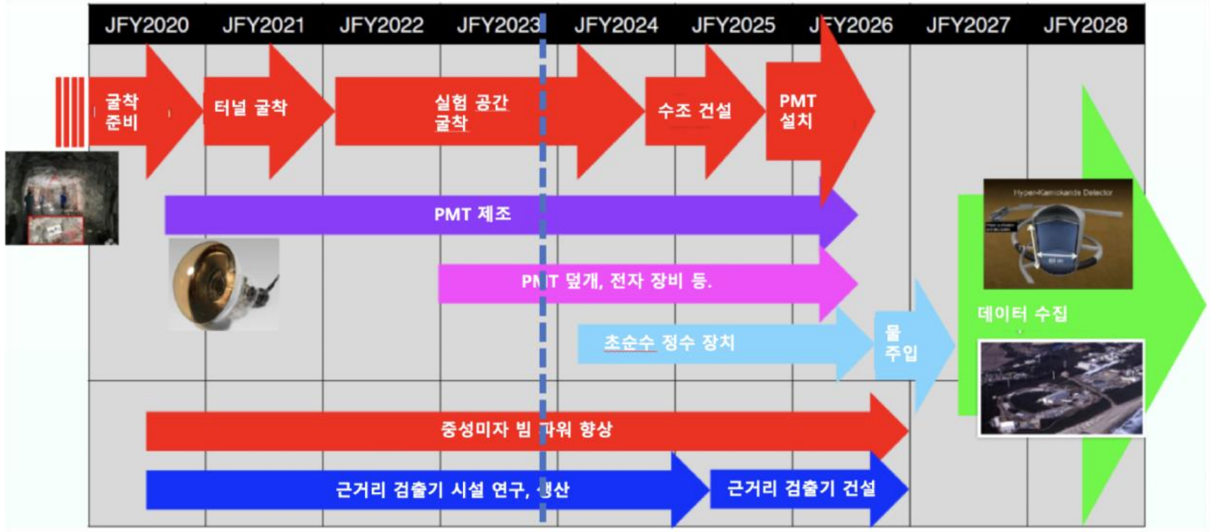
Korean Group in the Hyper-Kamiokande Experiment

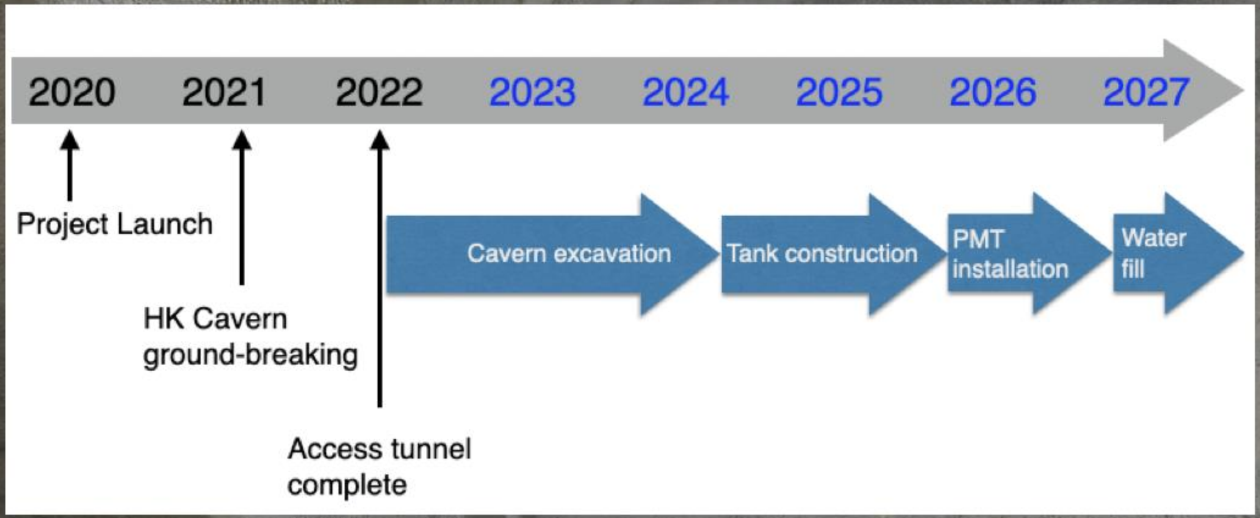
광주과기원, 경북대학교, 동신대학교, 서울대학교, 성균관대학교, 울산과기원, 전남대학교

한국그룹 대표: 유종희

HK Outer Detector Group Co-convener: 장지승

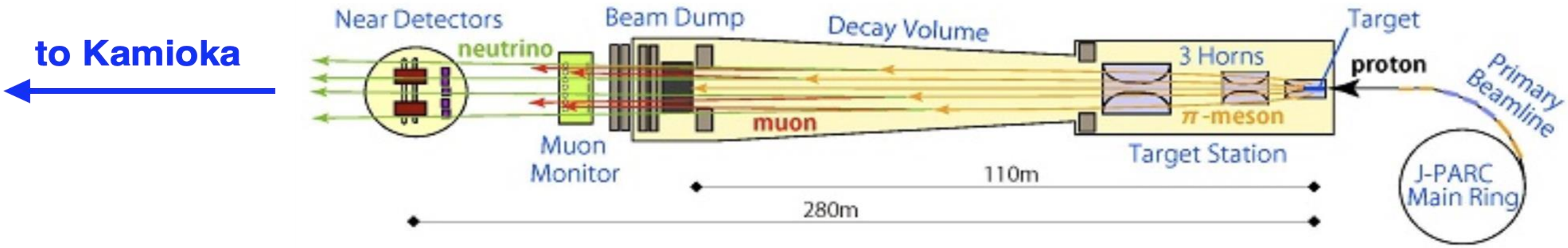
- **Proton decay**
- **CP-Phase Measurement**
- **Solar Neutrinos**
- **Atmospheric Neutrinos**
- **Dark Matter**
- **New Physics Search**



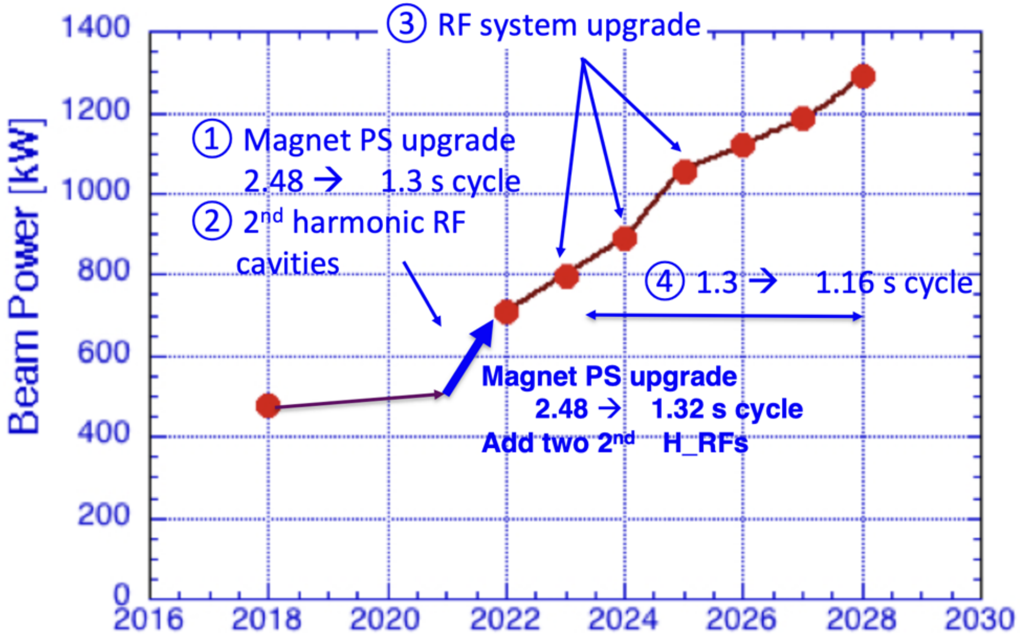


CP-measurement
Proton decay
Supernova neutrinos
Solar neutrinos
Atmospheric neutrinos
Dark matter search

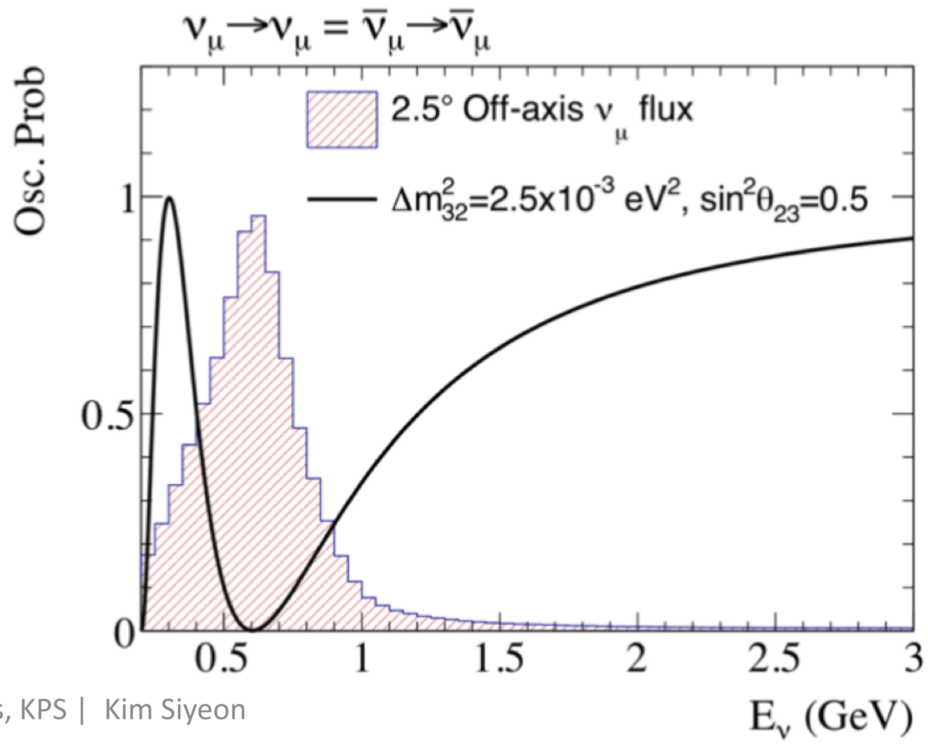
- HK operation will begin in 2027
- 1.3 MW upgraded neutrino beam from JPARC
- Upgraded and additional near detectors at JPARC



- **JPARC beam upgrade plan**



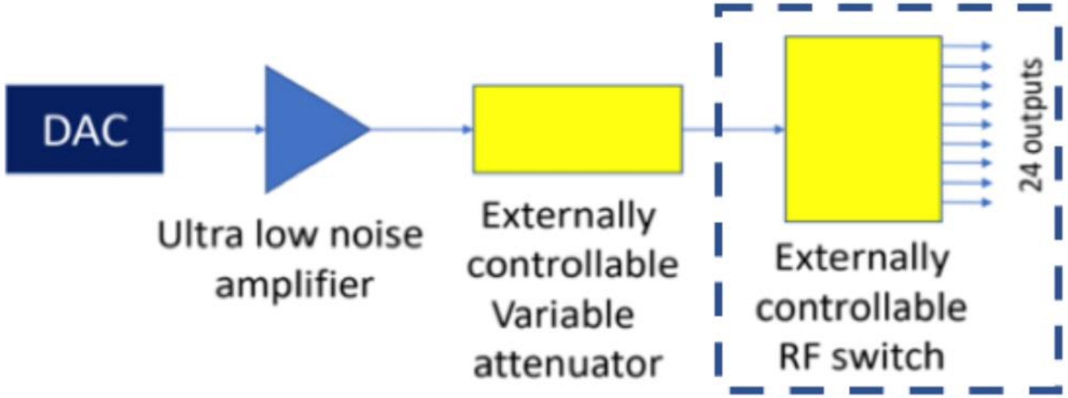
- **2.5-deg off-axis peak at 0.6 GeV**

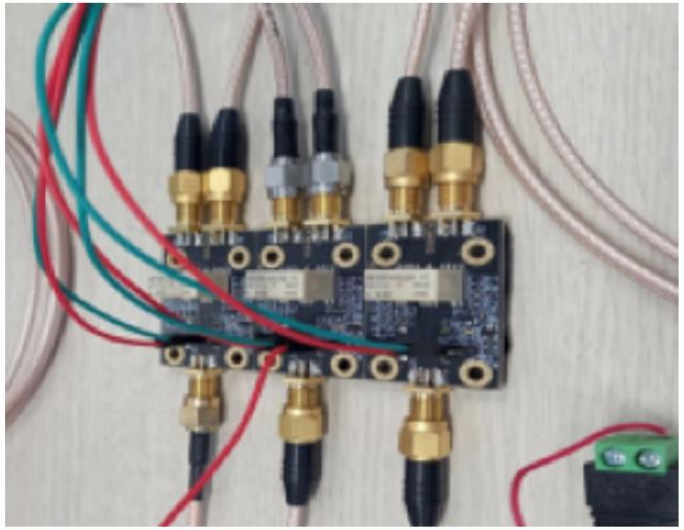


Korean Group in the Hyper-Kamiokande Experiment

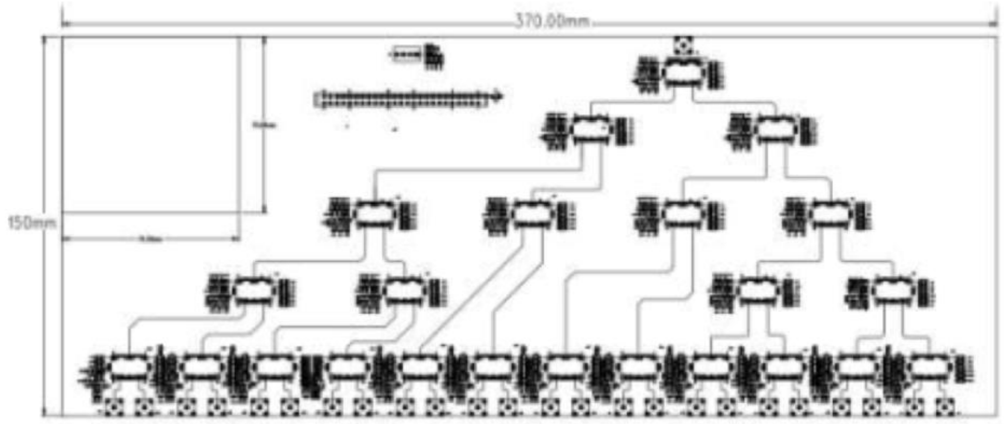
Calibration용 신호분배기 (경북대학교) 개발중

PMT 신호와
유사한
신호 생성

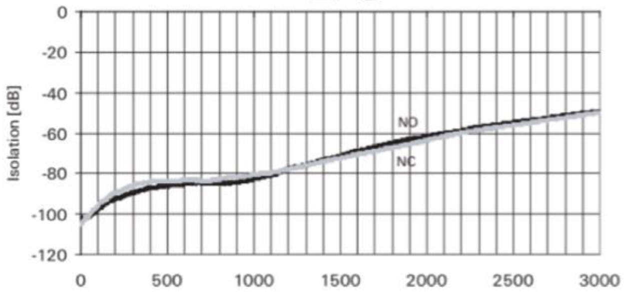




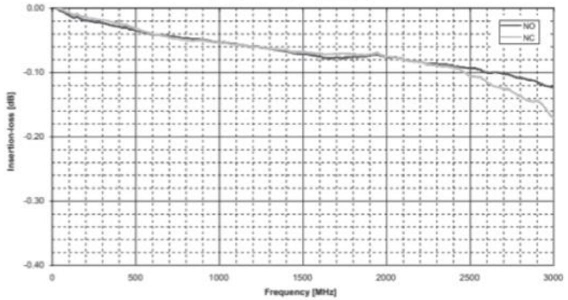
24채널 보드 설계



고립성



입력 손실



진동수 (MHz)

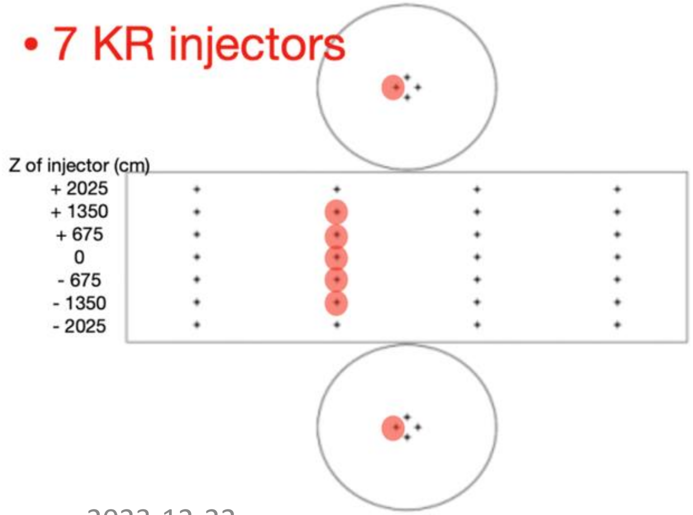
Korean Group in the Hyper-Kamiokande Experiment

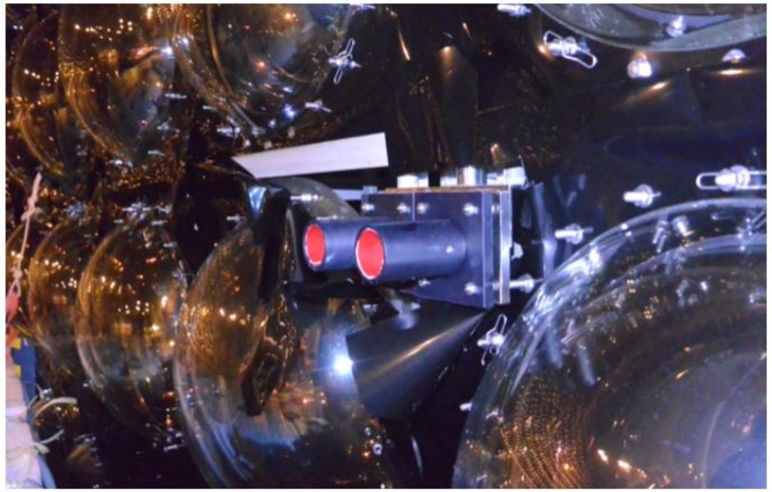
HK 구축사업 한국그룹 기여부분

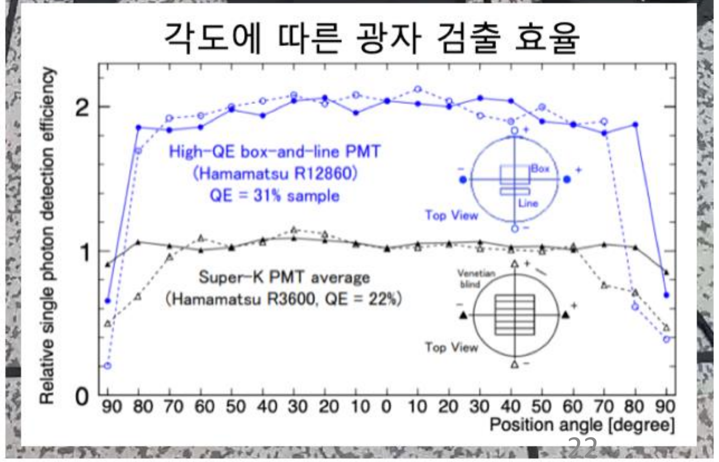
- **Outer Detector PMTs (Leader Group)**
- **Inner Detector / Outer Detector electronics system**
- **Inner Detector PMT (20-inch) pre-calibration**
- **Korean laser calibration system**
- **Computing support**

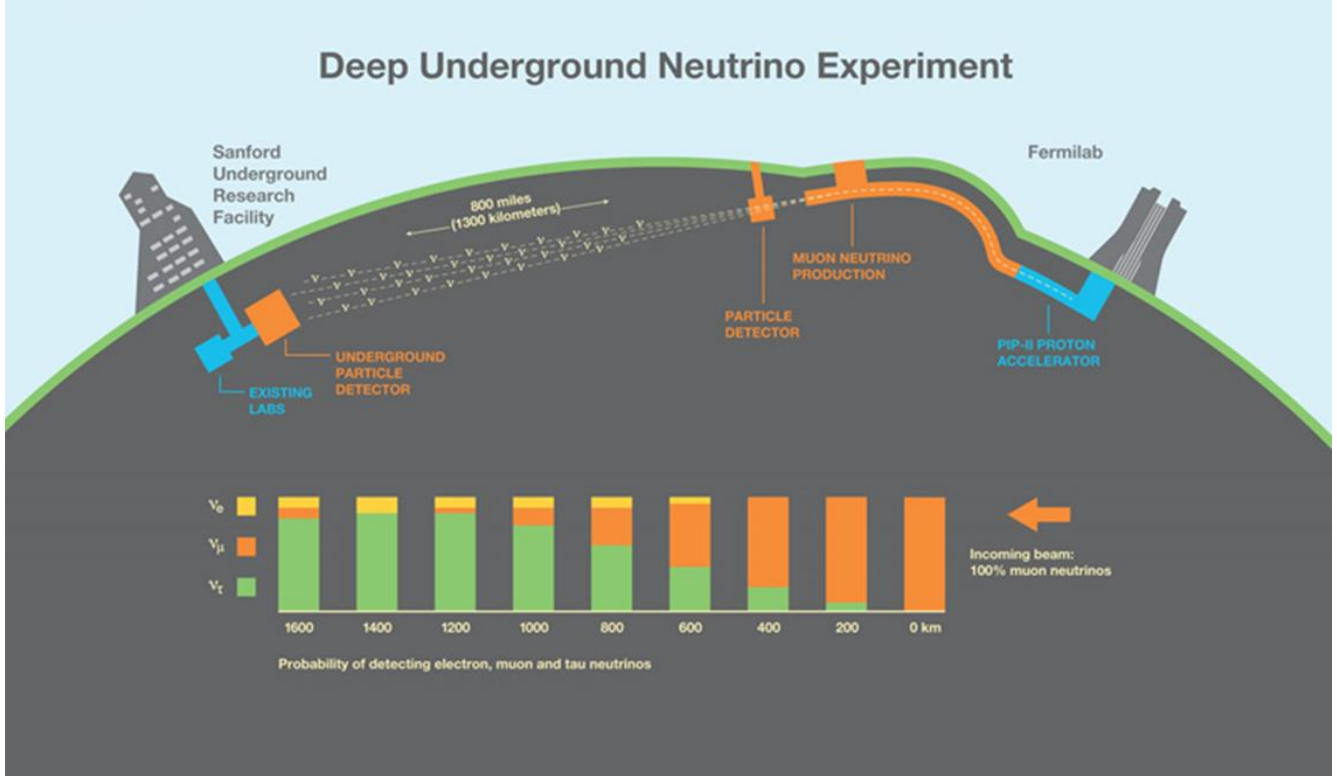
Korean laser system은 SK에서 약 20여년에 걸친 경험, 운용기술, 데이터 분석 기술로 거대 water Cherenkov 검출기의 확고한 보정시스템으로 자리잡음
(광주과기원, 울산과기원, 서울대학교, 전남대학교)

- 7 KR injectors









DUNE Collaboration
over 1300 members
from over 200 institutions
in over 30 countries

Korean members of DUNE Collaboration
(2024년 1월 1일 현재)

Chung-Ang University
: Kim, Siyeon (Professor, IR)
: Masud, Mehedi (Research Faculty)
: Gwon, Sunwoo (Post-doc, starting March 01)
: Masaku, Emar (Graduate)
: Kim, Suhyeon (Graduate)
: Park, Juseong (Graduate, starting March 01)

Neutrino Interaction, Sim/Rec.
Oscillation Analysis
ND Analysis, BSM

Jeon-Buk National University
: Shin, Seodong (Professor, IR)

BSM, DM Search

KISTI
: Cho, Kihyeon (Professor, IR)

BSM, Computing Facility

UNIST
: Chung, Moses (Professor, IR)

Accelerator and Neutrino Interphase

2018: ProtoDUNEs at CERN → 2019: FD TDR → 2020: Excavation starts → 2022(?): Installation of first module → First physics data: Atm, SN, & solar neutrinos. Proton decay. Calibration → 2026: ND & Neutrino beam available

DUNE Day 1 : When FD1 is filled and turned on, Science begins.

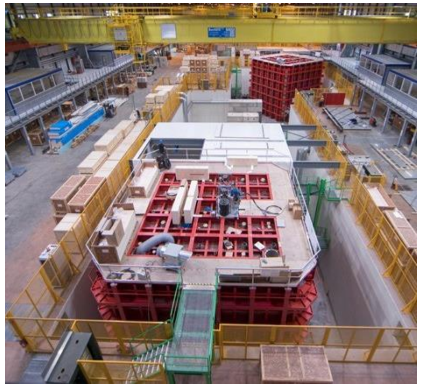
DUNE Phase I

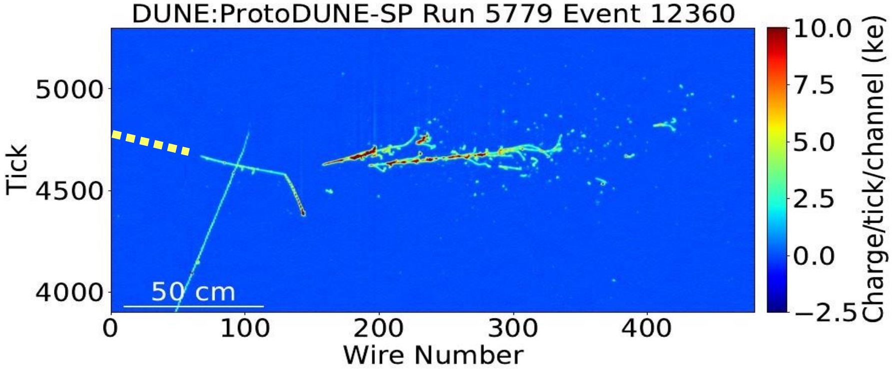
- 2 Far Detectors : Horizontal Drift (HD) + Vertical Drift (VD) LAr
- Near Detectors : ND LAr + TMS + SAND + PRISM
- 1.2 MW beam power

DUNE Phase II

- FD3 + FD4
- ND-Gar replaces TMS.
- 2.4 MW beam power

Staged year
1 (2026) with 20 kt-1.2MW
2 (2027) with 30 kt-1.2 MW
4 (2029) with 40 kt-1.2 MW
7 (2032) with 40 kt-2.4 MW





ProtoDUNE is full scale in the drift direction

Successful operation at CERN:
low noise, stable HV, high purity
→ demonstrates LArTPC technology and DUNE design

Vision of the 2023 Particle Physics Project Prioritization Panel (P5)

We recommend the following:

As the highest priority independent of the budget scenarios, complete construction projects and support operations of ongoing experiments and research to enable maximum science. This includes HL-LHC, the first phase of DUNE and PIP-II, the Rubin Observatory to carry out the Legacy Survey of Space and Time (LSST), and the LSST Dark Energy Science Collaboration.

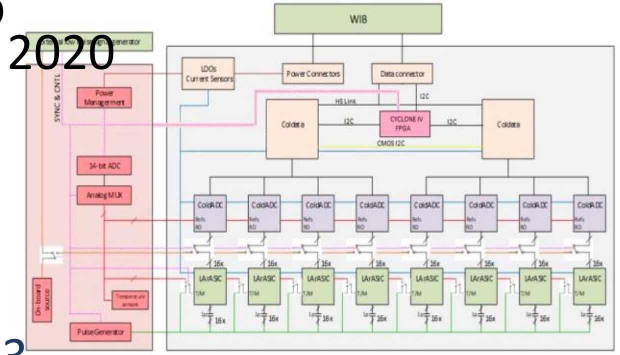
Construct a portfolio of major projects that collectively study nearly all fundamental constituents of our universe and their interactions, as well as how those interactions determine both the cosmic past and future.

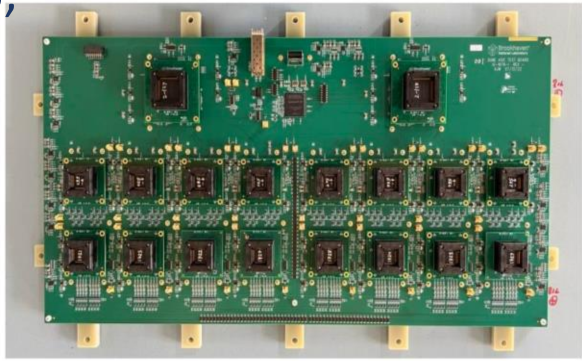
1. **CMB-S4**, which looks back at the earliest moments of the universe,
2. **Re-envisioned second phase of DUNE** with an early implementation of an enhanced 2.1 MW beam as the definitive long-baseline neutrino oscillation experiment,
3. **Offshore Higgs factory, realized in collaboration with international partners**, in order to reveal the secrets of the Higgs boson,
4. **Ultimate Generation 3 (G3) dark matter direct detection experiment** reaching the neutrino fog,
5. **IceCube-Gen2** for the study of neutrino properties using non-beam neutrinos complementary to DUNE and for indirect detection of dark matter.

Korean DUNE Activities

- 2016.05 CAU joined DUNE Collaboration
- 2017 ~ 2018 ProtoDUNE L-Ar TPC Single Phase Cold Electronics Module test
- 2019.05 JBNU & UNIST joined
- 2018 ~ 2021 3DST Working Group,
  3DST (3-dim Scintillator Tracker) for SAND/ND
  - Joint consortium with T2K SuperFGD Group
  - Prototype LANL Neutron beam test 2019 & 2020
- 2022 ???
- 2023.01 ~ ProtoDUNE HD Data Analysis
  ProtoDUNE VD Cold Electronics

- ProtoDUNE II: Closing TCO in 2022.11, filling LAr in early 2023, OPS for 2023.06 to 2024.07
- ProtoDUNE II: February 2024, Data Available.
  DUNE Cold Electronics: Script and ASIC Chip Test,
  Water-based Liquid Scintillator for Module 4
  > Prototype Readout, Analysis





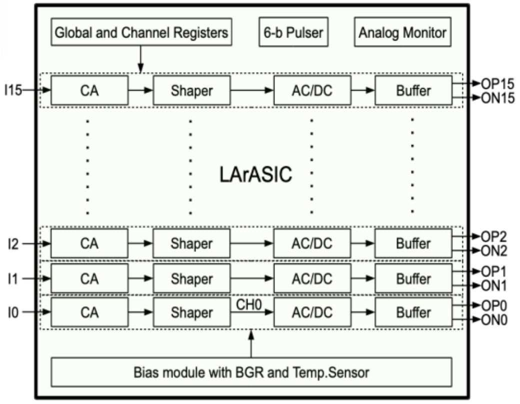


Fig. 1. Simplified block diagram of LArASIC

2023년 2월~3월, Brookhaven National Lab, USA

Issues of Korean DUNE

- Collaboration Size
  - CAU
  - KISTI (network, storage, computing)
  - JBNU and UNIST
- Collaboration Grant
- Common Fund (M&O)
- Participation to KNO
- Site Activities: BNL, Fermilab, CERN Neutrino Platform

BACK UP

Physics Issues of DUNE

- High-Energy Neutrinos
- Low-Energy Neutrinos
- Long-baseline oscillation
- Neutrino interactions
- Beyond Standard Model
- ProtoDUNE analysis
- And more…

- **High-Energy Neutrinos**

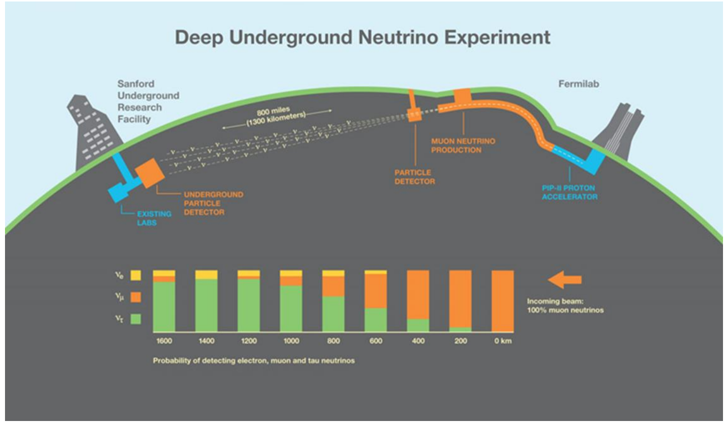
  GeV-scale non-accelerator physics: atmospheric neutrinos, nucleon decays and other signals where atm neutrinos are a background.

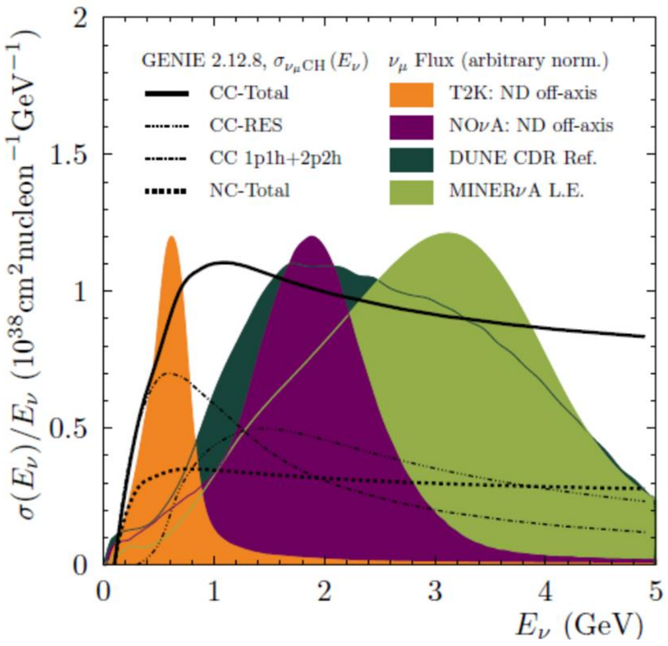
- **Low-Energy Neutrinos**

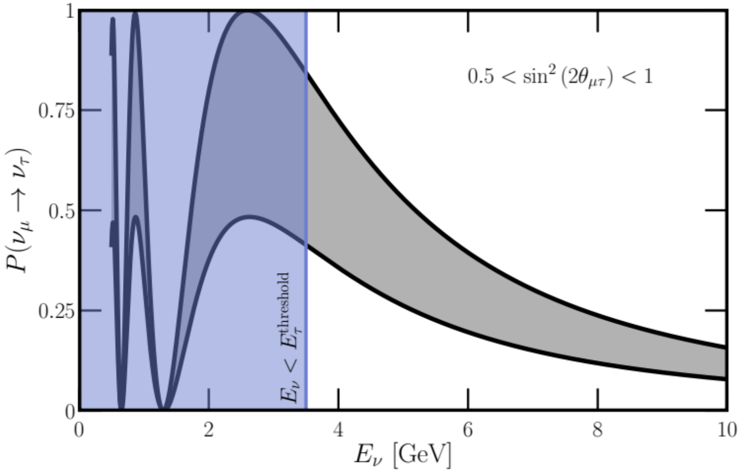
  1-10 MeV-scale physics: SN, Solar nu, Natural radioactivity background

Long-baseline oscillation

- 1285-km baseline
- Neutrino energy range Sub GeV ~ 10 GeV
- Neutrino mode(FHC) and antineutrino mode(RHC)
- Appearance of $\nu_e(\overline{\nu_e})$ and disappearance of $\nu_\mu(\overline{\nu_\mu})$ at FD

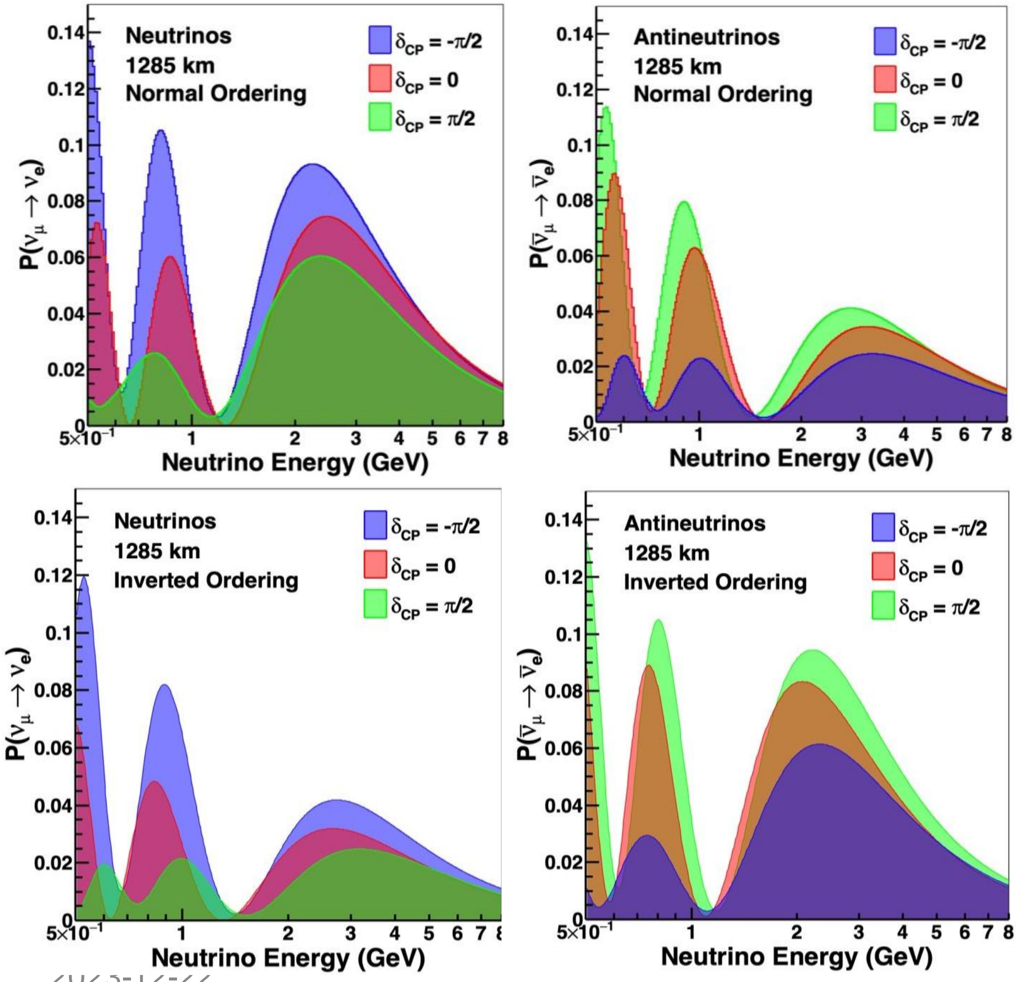




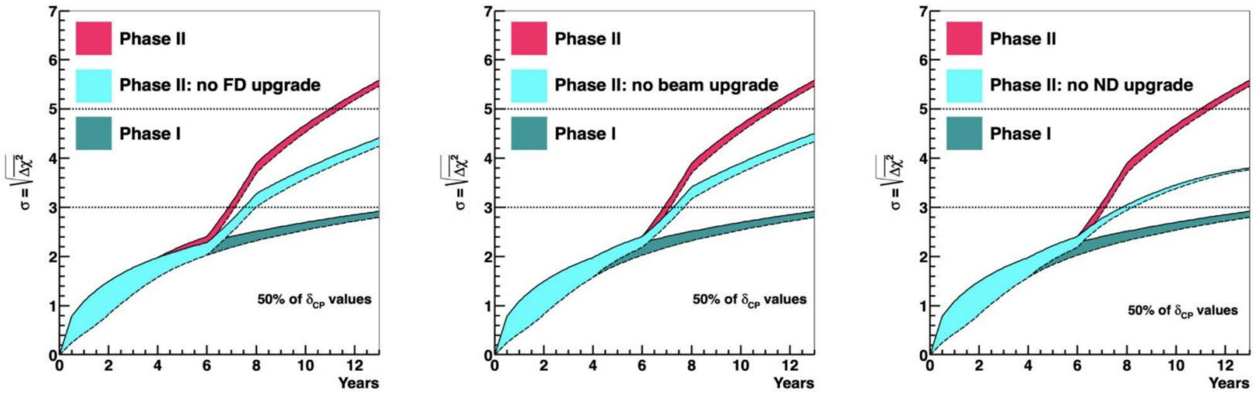


Neutrino-antineutrino asymmetry: $P(\nu_\mu \to \nu_e)$ vs. $P(\bar{\nu}_\mu \to \bar{\nu}_e)$

$$A_{CP} = \frac{P(\nu_\mu \to \nu_e) - P(\bar{\nu}_\mu \to \bar{\nu}_e)}{P(\nu_\mu \to \nu_e) + P(\bar{\nu}_\mu \to \bar{\nu}_e)} \sim \frac{\cos\theta_{23} \sin 2\theta_{12} \sin\delta_{CP}}{\sin\theta_{23}\sin\theta_{13}} \left(\frac{\Delta m^2_{21} L}{4E_\nu}\right) + \text{matter effects}$$



DUNE discovery potential for CP Violation and beyond



Start data taking with **2** detector modules then **4**

Fermilab proton power **1.2 MW** then **2.4 MW**

Phase one near detector and **Phase two near detector**

최근 중요 실적 및 기여

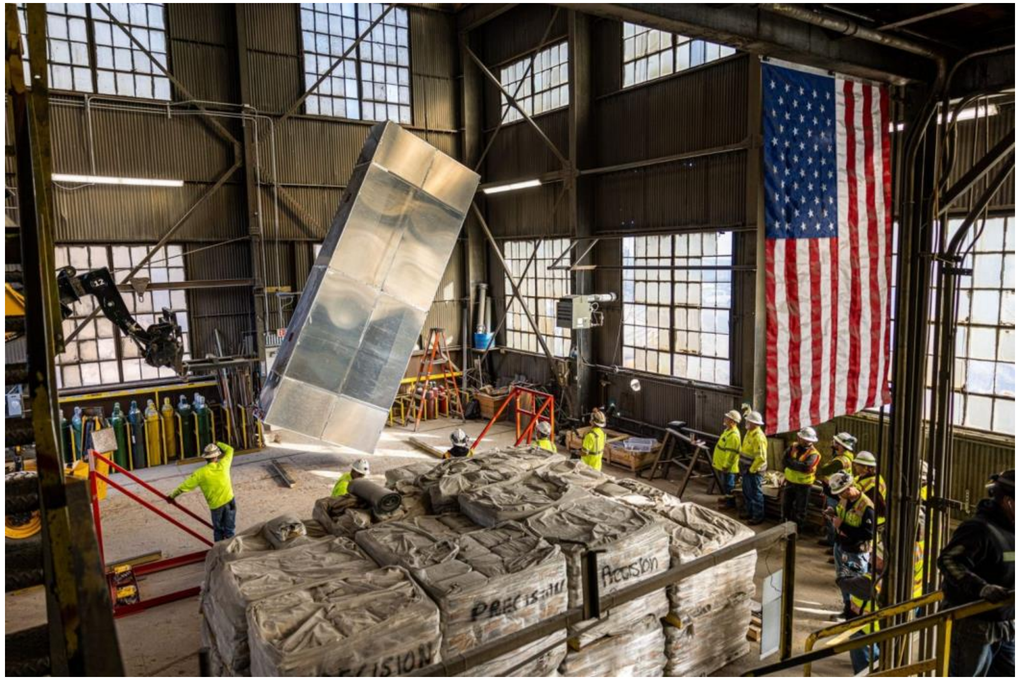
- 신서동(전북대):
  Prospects for beyond the Standard Model physics searches at the Deep Underground Neutrino Experiment, *Eur.Phys.J.C* 81 (2021) 4, 322,
  Boosted dark matter search 집필 기여
- 권순우(중앙대):
  Deep Underground Neutrino Experiment (DUNE) Near Detector Conceptual Design Report, *Instruments* 5 (2021) 4, 31,
  Neutron detection from antineutrino events in the 3DST, 분석결과 수록, 집필 기여
- 정기영(중앙대):
  Muon antineutrino CC 1 neutral pion interaction selection using the invariant mass, DUNE-doc-23681-v1,
  Technical note 작성
- 권순우(중앙대):
  Neutron detection and application with a novel 3D projection scintillator tracker in the future long-baseline neutrino oscillation experiments e-Print: 2211.17037 [hep-ex] -> Published in PRD.

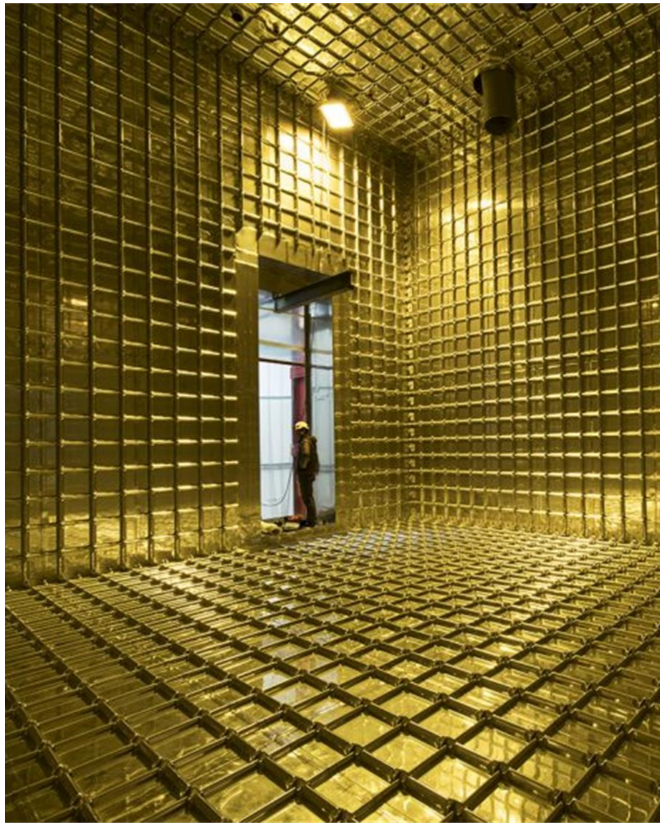
preprint for arXiv

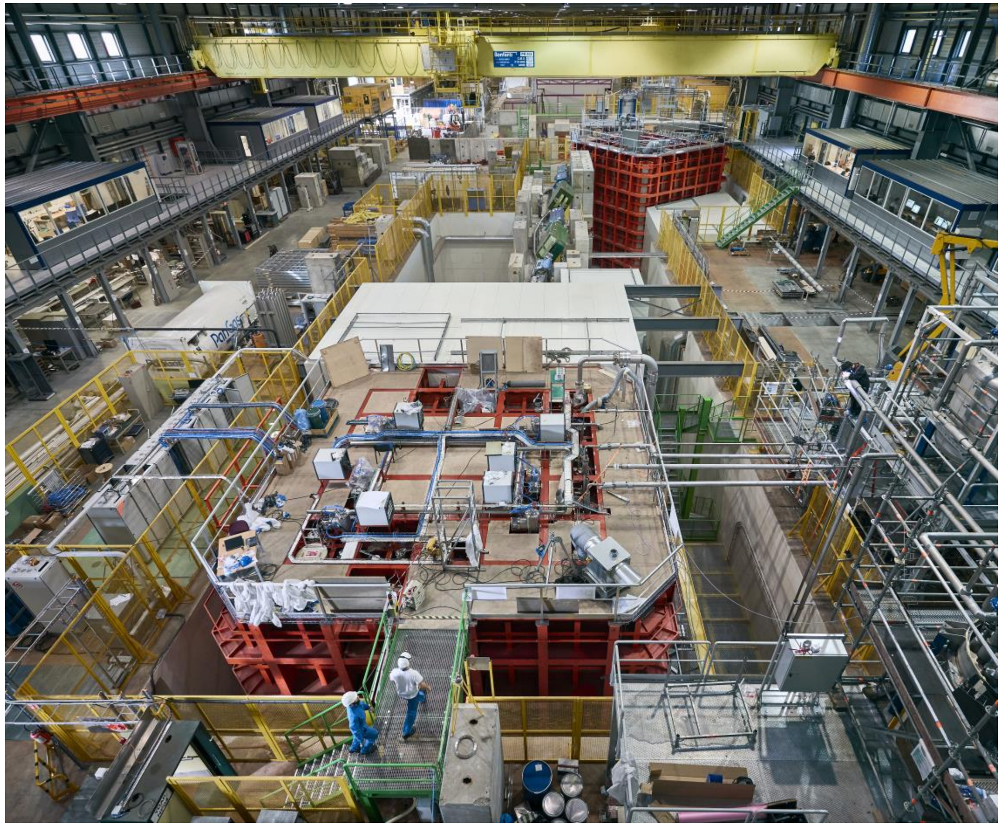
Neutron detection and application with a novel 3D projection scintillator tracker in the future long-baseline neutrino oscillation experiments

S. Gwon,[1] G. Yang,[2] S. Bolognesi,[3] T. Cai,[4] A.Delbart,[3] A. De Roeck,[5] S. Dolan,[5] G. Eurin,[3] S. Fedotov,[6] G. Fiorentini Aguirre,[7] R. Flight,[4] R. Gran,[8] P. Granger,[3] C. Ha,[1] C.K. Jung,[2] K.Y. Jung,[1] S. Kettell,[9] A. Khotjantsev,[6] M. Kordosky,[10] Y. Kudenko,[6] T. Kutter,[11] J. Maneira,[12] S. Manly,[4] D. Martinez Caicedo,[7] C. Mauger,[13] K. McFarland,[4] C. McGrew,[2] A. Mefodev,[6] O. Mineev,[6] D. Naples,[14] A. Olivier,[4] V. Paolone,[14] S. Prasad,[11] C. Riccio,[2] J. Rodrigeuz,[7] D. Sgalaberna,[15] A. Sitraka,[7] K. Siyeon,[1] H. Su,[14] A. Teklu,[2] M. Tzanov,[11] E. Valencia,[10] K. Wood,[2] and E. Worcester[9]

This was a test of the entire logistics chain —
from the UK, to Switzerland, to Illinois, and finally to South Dakota. (December 6, 2022)
In total, 150 APAs will be built for DUNE: 136 from the UK and 14 from the US.







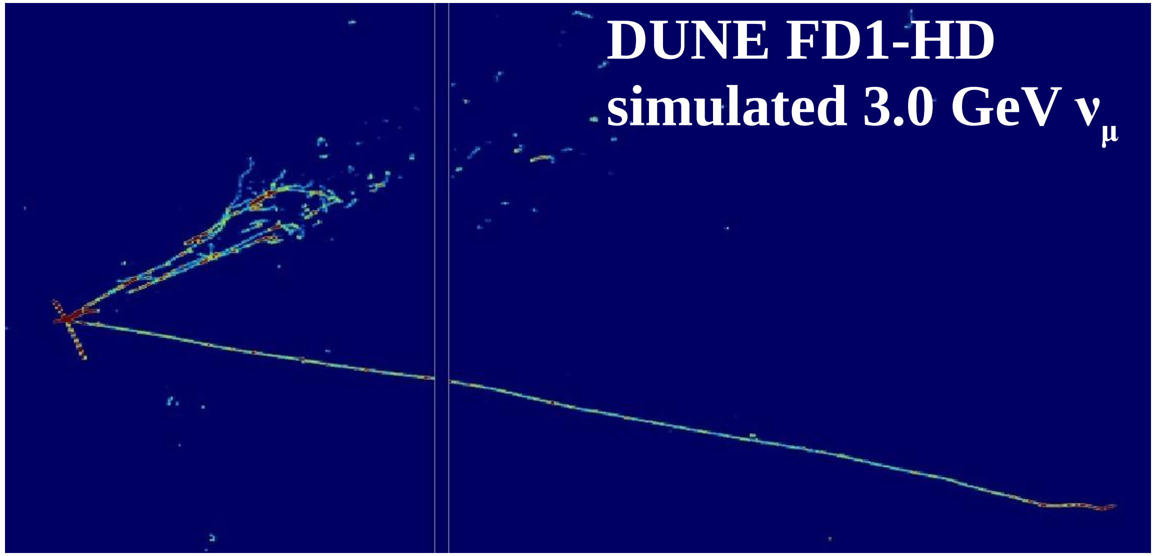
ProtoDUNE at CERN Neutrino Platform

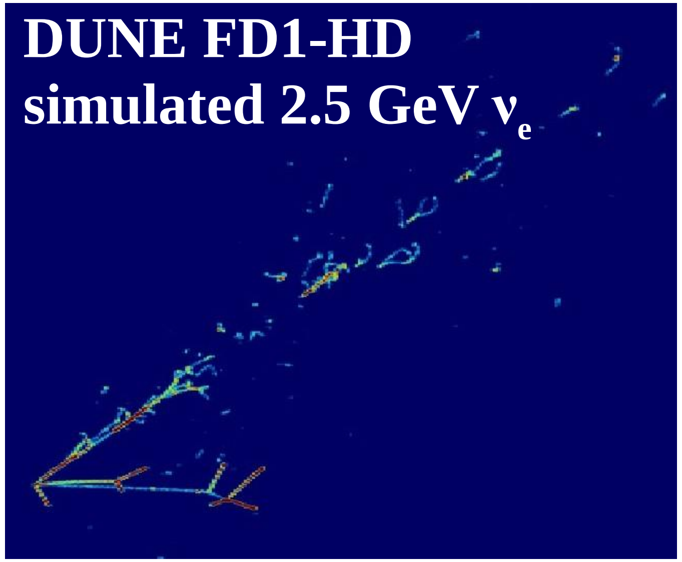
- ProtoDUNE II 의 목적:

- 원거리검출기의 각 성분의 수행능력과 검출기의 안정성 테스트
- 아르곤에 대한 강입자 크로스섹션을 측정
- 캘리브레이션 방법의 개발과 테스트: 레이저, 중성자 외 여러가지 저에너지 소스 활용
- 스케줄: 6~7월 중성미자 빔가동, 12월 빔데이터 수집, 데이터 분석

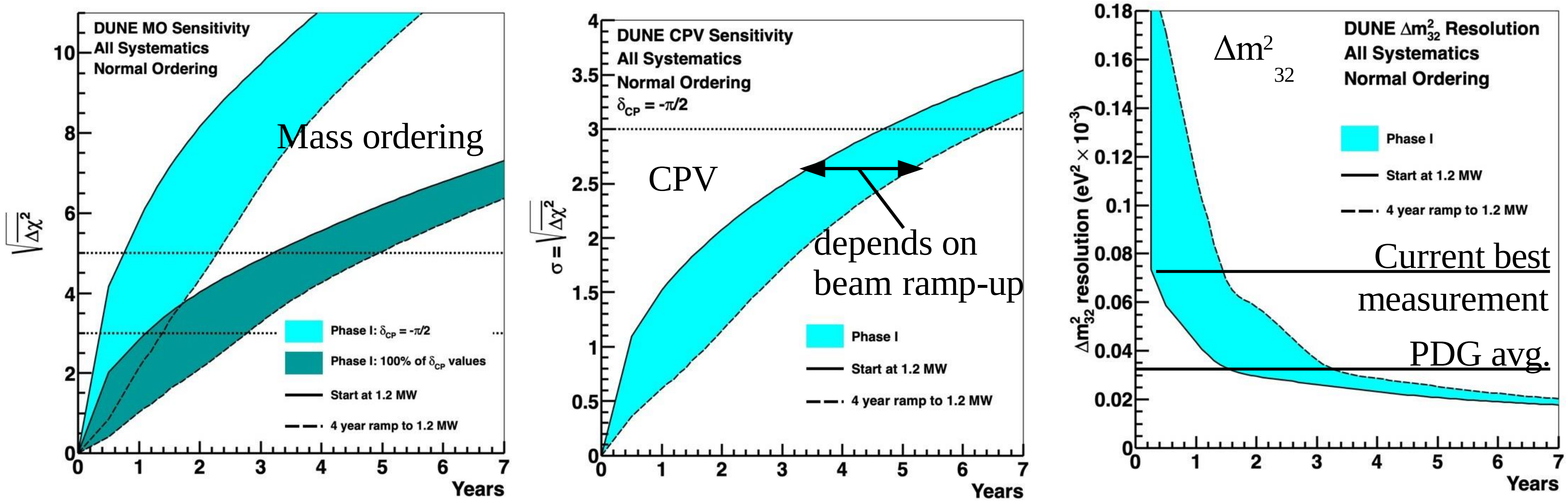
LArTPC technology provides exquisite resolution

- Clean separation of ν_μ and ν_e charged currents
- Precise energy reconstruction over broad E_ν range
- Low thresholds: sensitivity to few-MeV neutrinos, hadrons





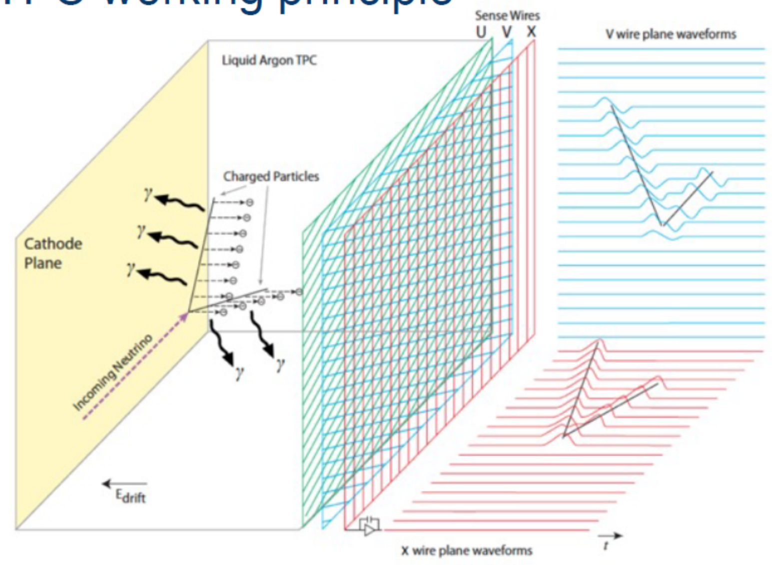
DUNE Phase I: world-leading MO, sensitivity to maximal CPV



- Phase I will do world-class long-baseline neutrino oscillation physics:
  - Only experiment with 5σ mass ordering capability regardless of true parameters
  - Discovery of CPV at 3σ if CP violation is large
  - High precision disappearance parameters, (e.g. surpass current Δm^2_{32} error in ~2-3 years)

The Single-Phase LAr-TPC

TPC working principle



- Ionization electrons [~5 fC/cm] drift to the anode in pure LAr & uniform E-field (~500 V/cm)
  - Few mm pitch and ~MHz sampling frequency
  - 3D via multiple 2D view (wire# vs drift time)
  - high imaging capabilities → kinematic reconstruction with mm-scale spatial resolution
  - Intrinsically excellent Calorimetry and Particle Identification (dE/dx) capability
- Prompt scintillation light (@128 nm)
  - T = 0, trigger, calorimetry

LAr as radiation detection medium

- Dense: 40% more than water
- Abundant primary ionization: 42 000 e^-/MeV
- High electron lifetime if purified → long drifts
- High light yield: 40k γ/MeV
- Easily available: ~1% of the atmosphere
- Cheap: $2/L ($3000/L for Xe, $500/L for Ne)

- Technological challenges
  - LAr continuous purification << 0.1 ppt O_2 eq. (>> 3 ms electron lifetime) for long drift
  - Imaging & anode planes
  - Very low noise front end amplifiers to detect ~ fC primary charge deposition
  - Large area photon detectors sensitive to 128 nm wave length
  - HV system to provide uniform/stable E-field in large drift volume
- Pioneered by ICARUS and adopted in present and next generation neutrino ezperiment (μBoone, SBND, DUNE)
  - DUNE: scaling to multi-kt size