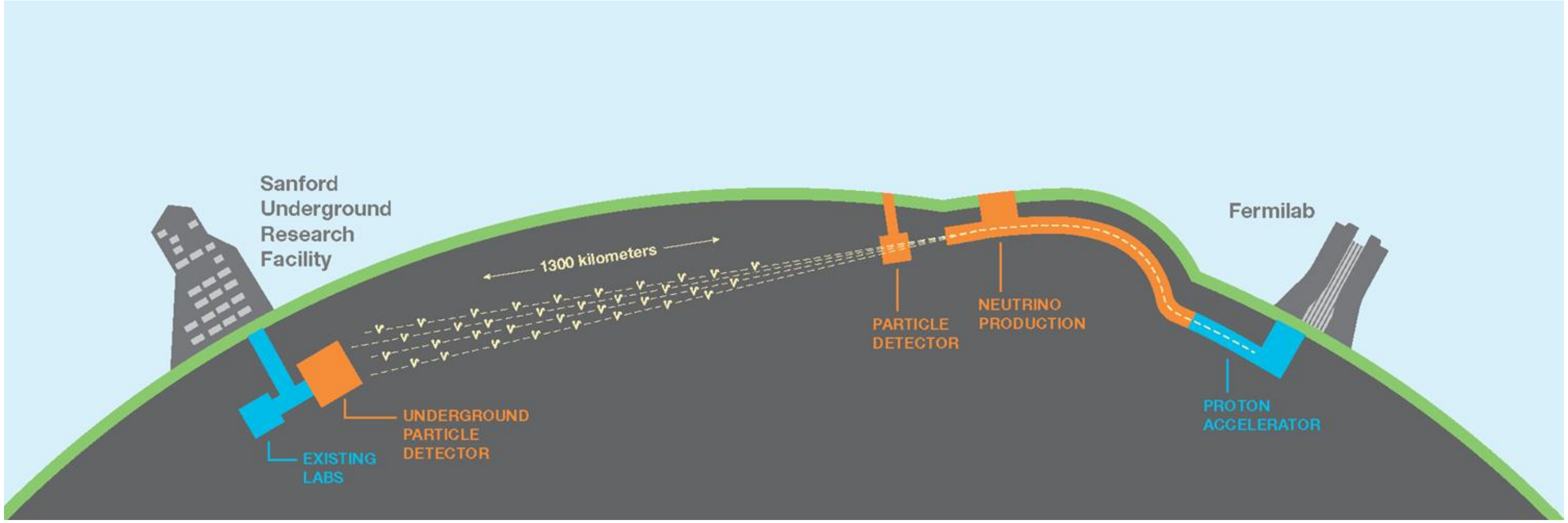
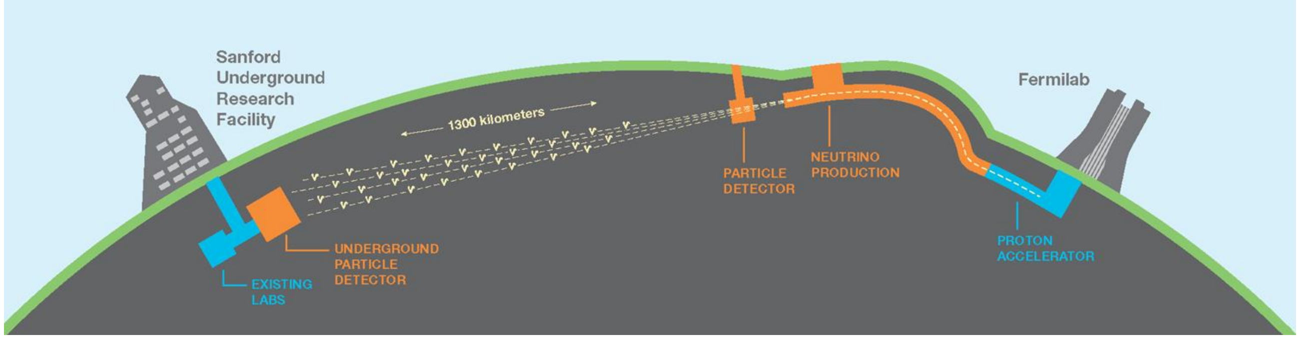
Deep Underground Neutrino Experiment

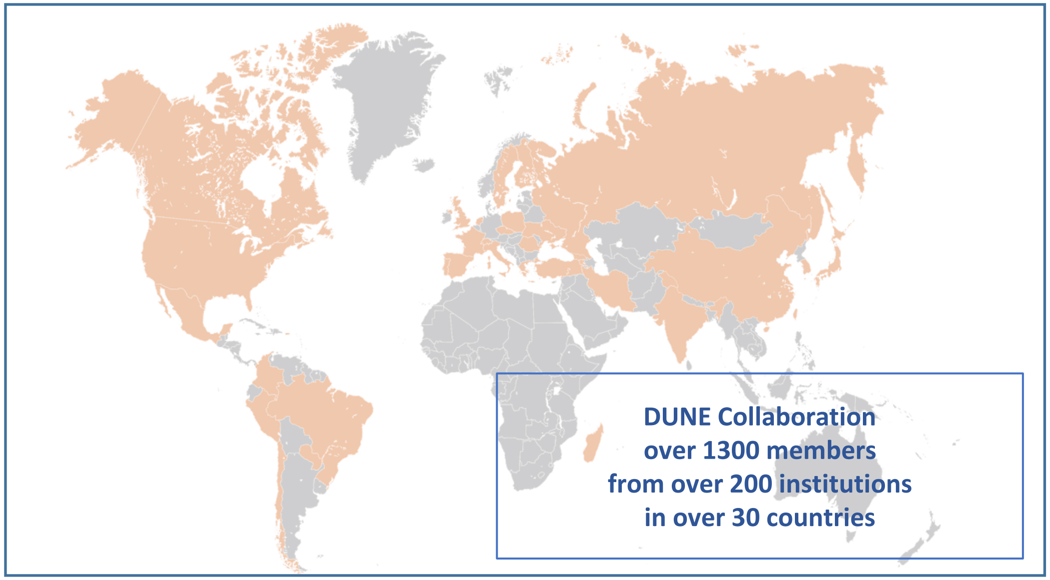


Kim Siyeon
Chung-Ang University

Naju Meeting
KSHEP 2023 Fall
November 23, 2023

Deep Underground Neutrino Experiment





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

Korean members of DUNE Collaboration (2023년 12월 1일 현재)

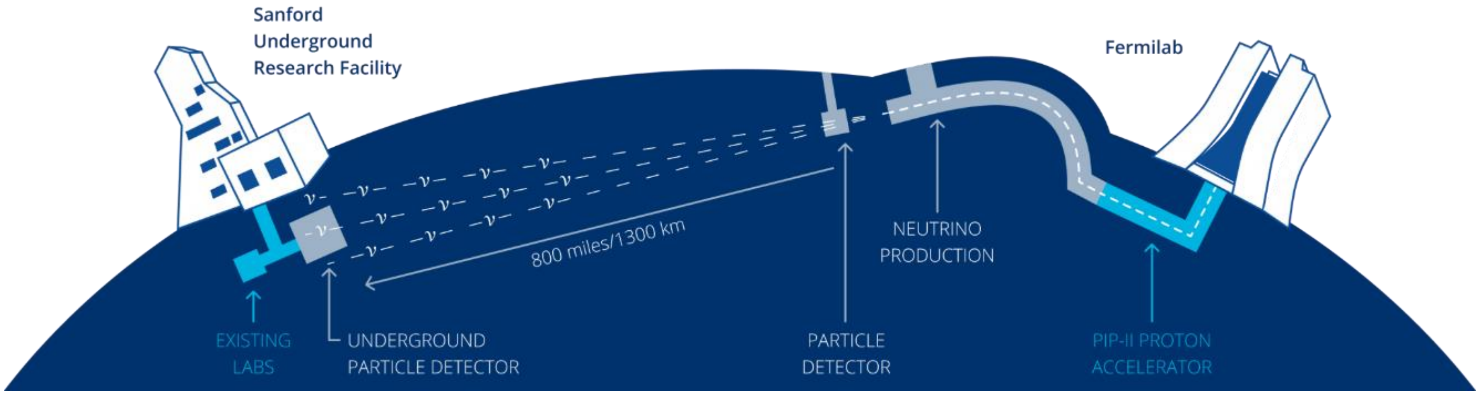
Chung-Ang University
: Gwon, Sunwoo (Ph.D, NBD),
: Masud, Mehedi (Research Fellow)
: Park, Juseong (Graduate Student)
: Kim, Siyeon (Professor, IR)

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

KISTI
: Cho, Kihyeon (Professor, IR)

UNIST
: Chung, Moses (Professor, IR)

Activities of K-DUNE Groups



DUNE Collaboration

Collaboration Resource Board
Gary Baker (U. of Warwick)

Institutional Board
Alfons Weber (Rutherford Lab.)

DUNE Administration
Maxine Hronek(Fermilab)

Fermilab Neutrino Div. Head
Steve Brice (Fermilab)

Computing Coordinator
Mike Kirby (BNL)

DUNE Cospokesperson
Mary Bishai (BNL)
Sergio Bertolucci (U. of Bologna)

Moses Chung (UNIST)

Accelerator and Neutrino interphase

Kim Siyeon (CAU)

Neutrino interaction, Sim/Rec, Oscillation Analysis

Mehedi Masud (CAU)

BSM Search

Seodong Shin (JBNU),
Kihyeon Cho (KISTI)

BSM, DM Search

Physics issues of DUNE

원거리 검출기

진동거리 1300 km
지하 1.5 km
극저온 LAr TPC 40 kton

근거리 검출기
페르미랩 내에 하이브리드 범용

L-Ar, G-Ar TPC
SAND(on axis), PRISM(off axis)

양성자 가속과 중성미자 빔

Proton Improvement Plan II (PIP II)
휘도, 초점 Optimization
입자, 반입자의 생성

비표준 모형,
암흑물질 탐색

우주론과 천체물리

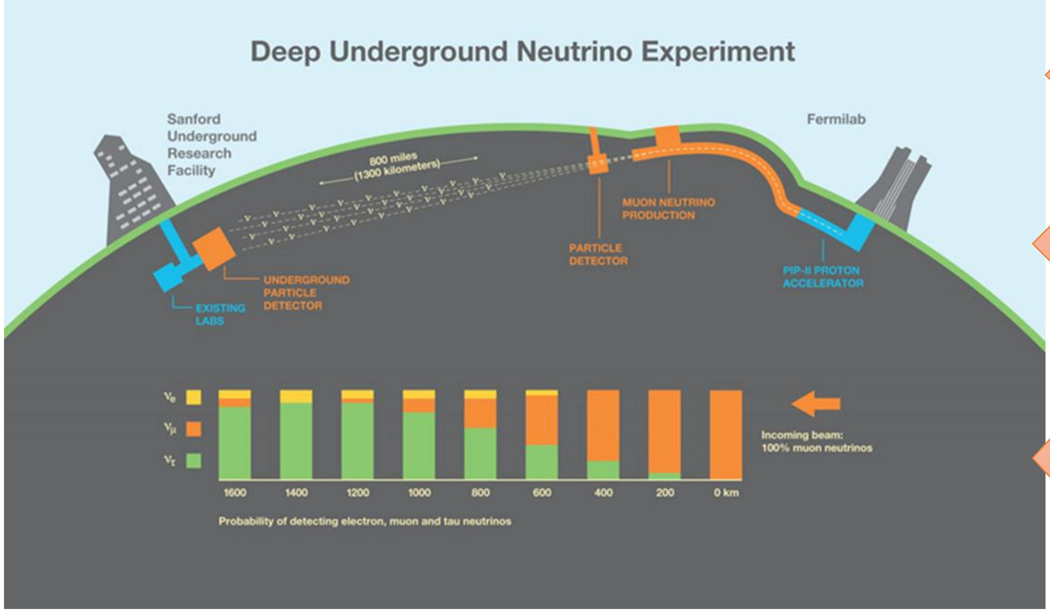
고에너지 중성미자
우주 잔재 중성미자
비활성 중성미자

중성미자 질량과 CP

3세대 중성미자 검증
CP 비대칭 위상
질량의 순서

중성미자 상호작용

QE, DIS, RES,
X-section



빔 라인

진동분석을 위한 개선
(Optimized Beam)

근거리 검출기

진동 전 중성미자 선속 측정,
오차 개선
중성미자 상호작용 단면적
비표준 상호작용 탐색

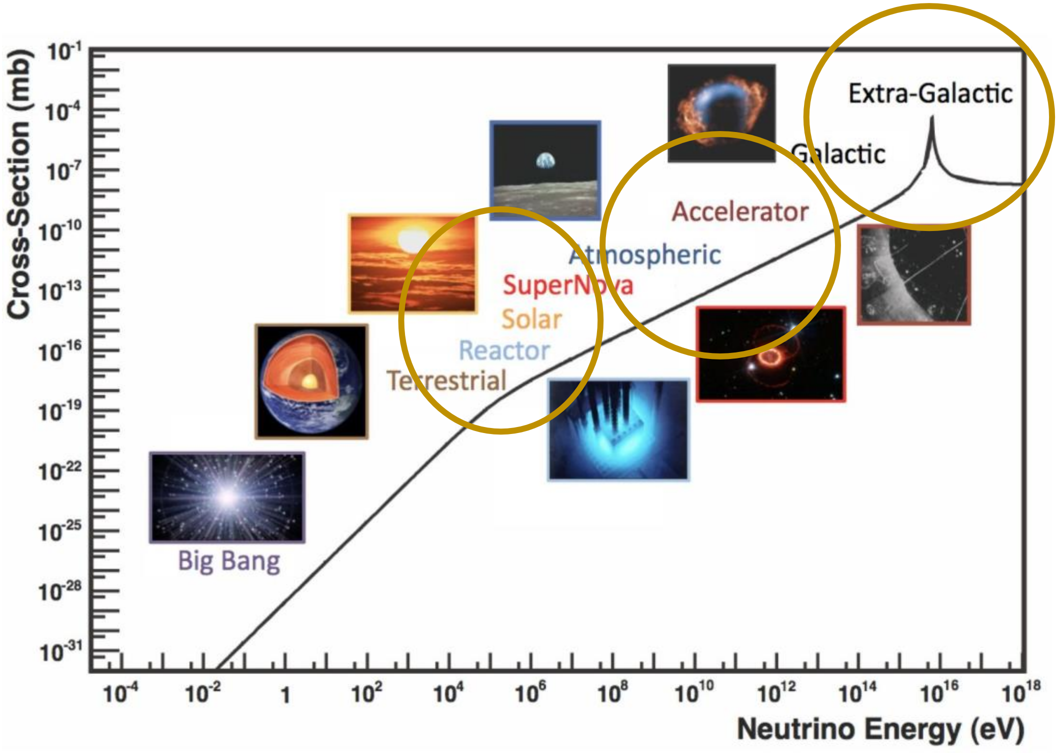
원거리 검출기

진동효과의 측정

대기, 태양 중성미자 관측
초신성 폭발 대기,
양성자 붕괴

Physics goals of Neutrino experiments

- Low energy(~100MeV)
  - CEvNS, SNB, Solar neutrinos. Reactor neutrinos
  - BSM: sterile neutrinos, light DM, NSI, precision tests of SM
  - Astrophysics: Supernova bursts and solar models
  - Tests of neutrino mixing models



- Intermediate energy (.1 ~20 GeV)
  - Accelerator neutrinos, Atmospheric neutrinos
  - BSM: ….. + Proton decays
  - 3-nu oscillation: mass hierarchy, CPV, tests of 3-nu paradigm.

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**

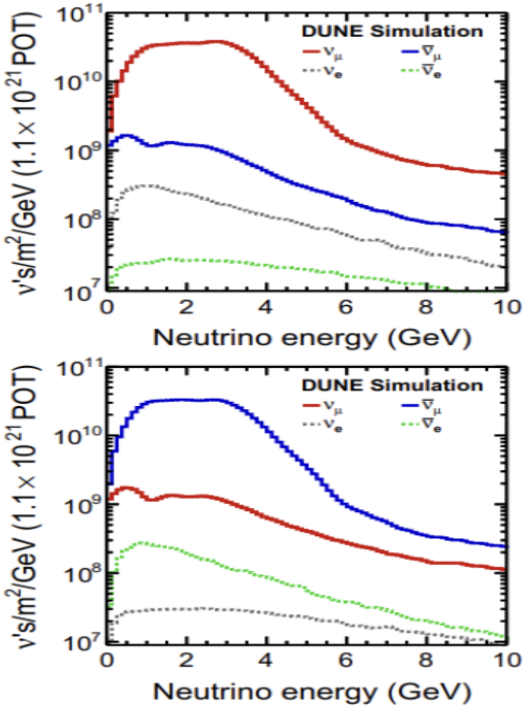
  GeV-scale non-accelerator physics: atmospheric neutrinos, nucleon decays and other signals where atm neutrinos are a background.

- **Low-Energy Neutrinos**

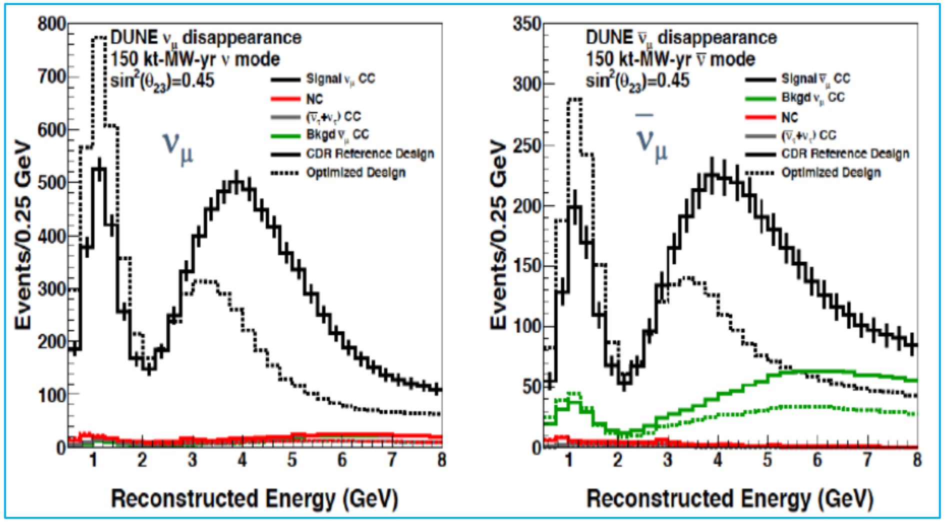
  1-10 MeV-scale physics: SN, Solar nu, Natural radioactivity background

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

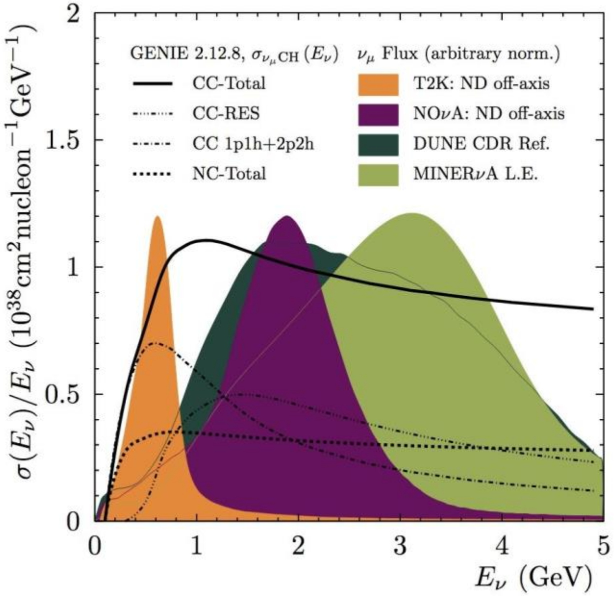


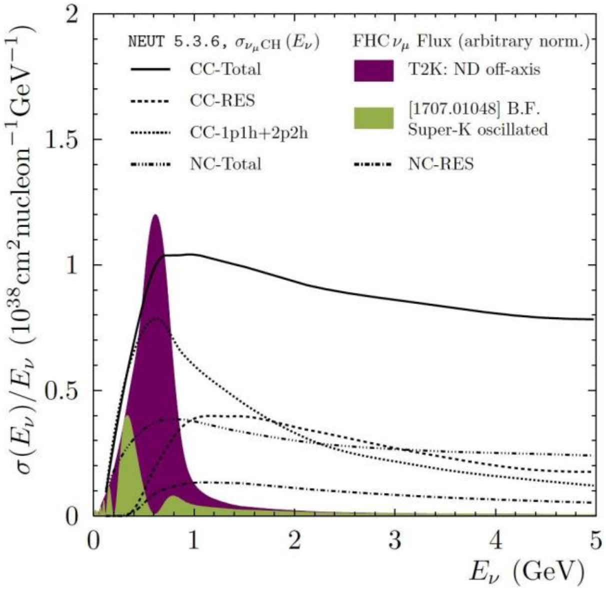
Beam Optimization

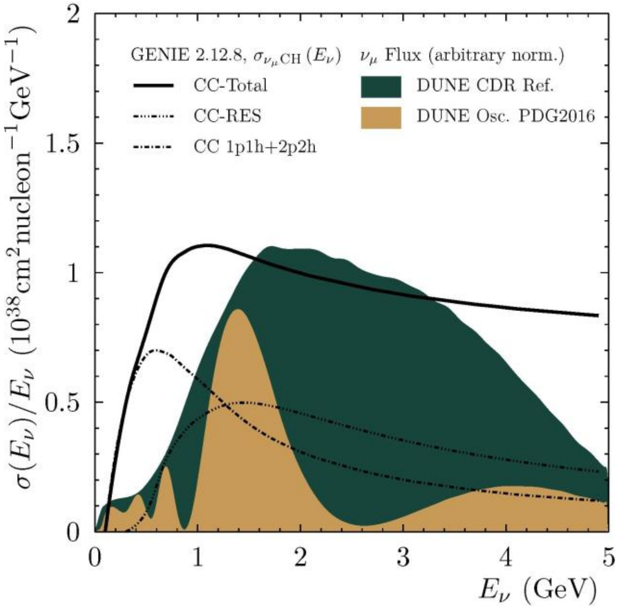


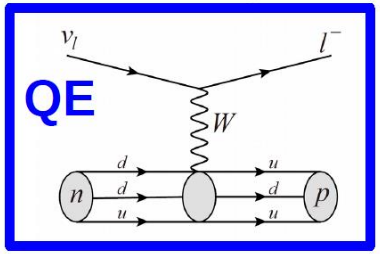
Neutrino Interactions

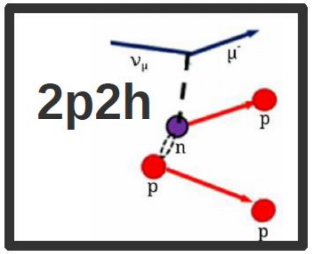
Kendall Mahn

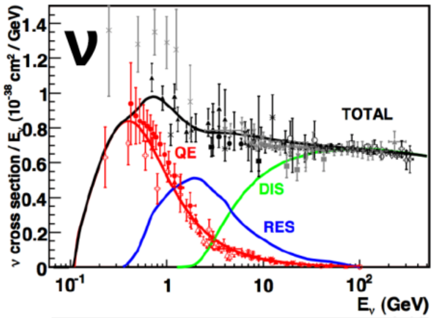


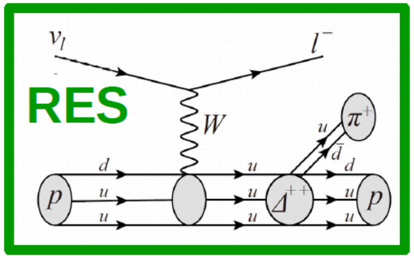


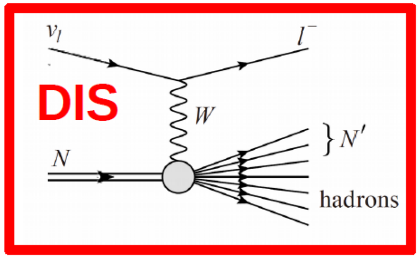


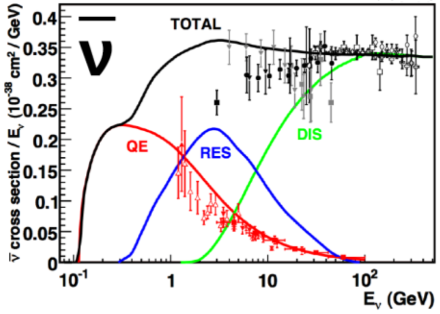








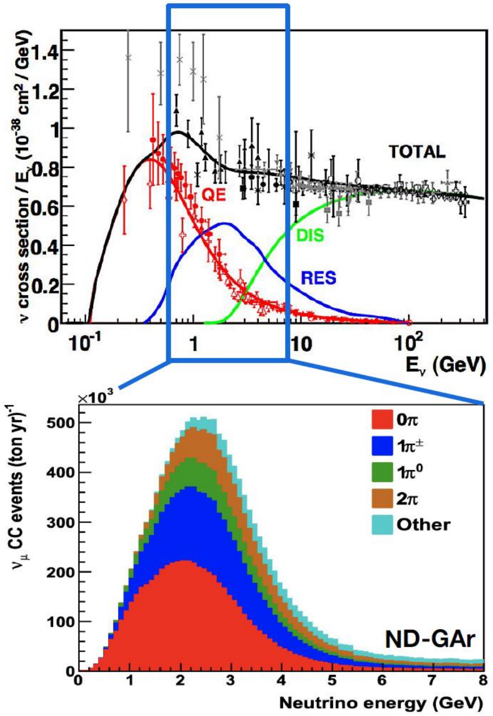


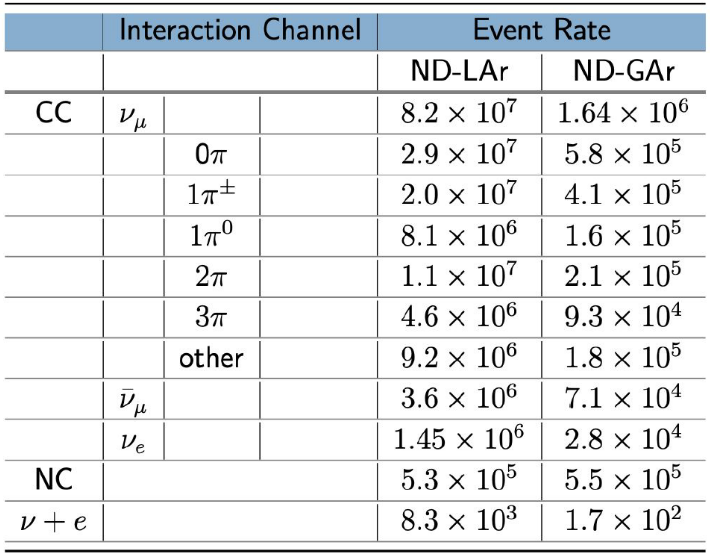


Neutrino Interaction Physics & the DUNE Near Detector

Mateus F. Carneiro on behalf of the DUNE Collaboration

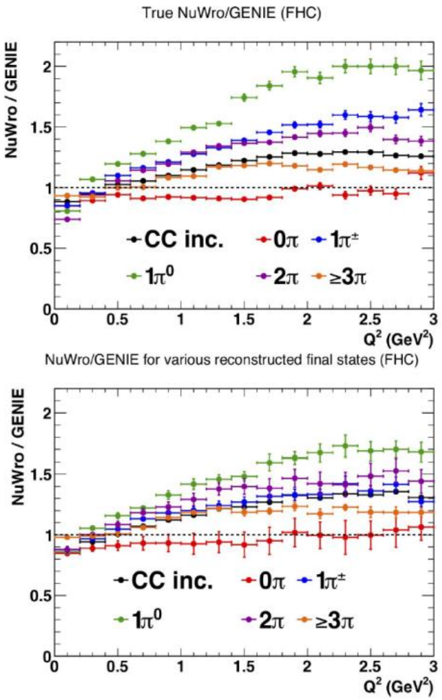
- Multi-scale problem
  - We have neutrino energy range .5 ~5 GeV and energy transfers from nearly zero to about 1 GeV
  - Nuclear response
    - Elastic
    - Metastable excitations
    - Quasi-elastic
    - Inelastic
  - The separation of processes failed.





	Interaction Channel			Event Rate	
				ND-LAr	ND-GAr
CC	ν_μ			8.2×10^7	1.64×10^6
		0π		2.9×10^7	5.8×10^5
		$1\pi^\pm$		2.0×10^7	4.1×10^5
		$1\pi^0$		8.1×10^6	1.6×10^5
		2π		1.1×10^7	2.1×10^5
		3π		4.6×10^6	9.3×10^4
		other		9.2×10^6	1.8×10^5
	$\bar{\nu}_\mu$			3.6×10^6	7.1×10^4
	ν_e			1.45×10^6	2.8×10^4
NC				5.3×10^5	5.5×10^5
$\nu + e$				8.3×10^3	1.7×10^2

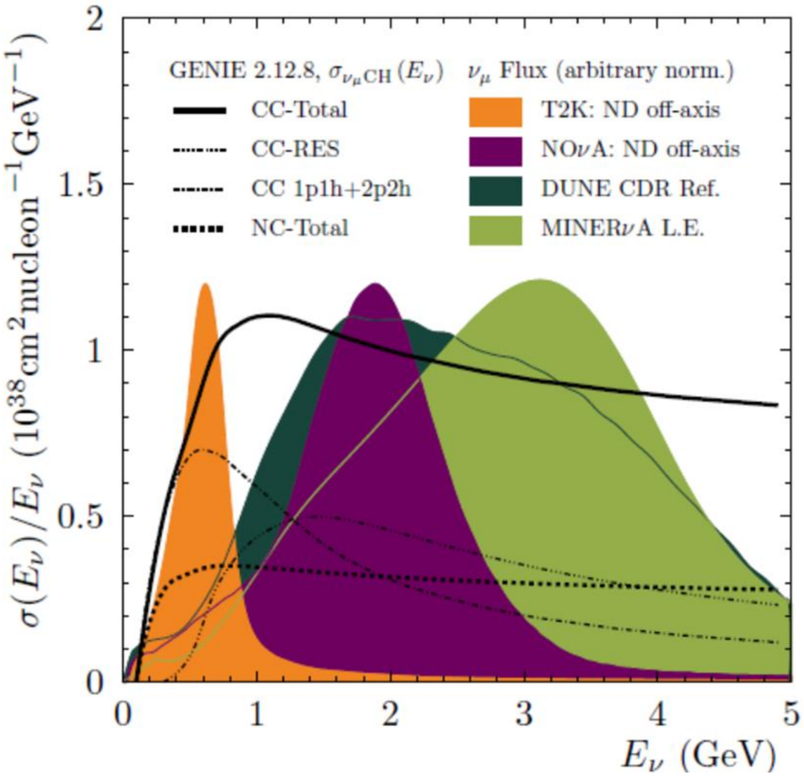
Events per year (1.1×1021 POT)

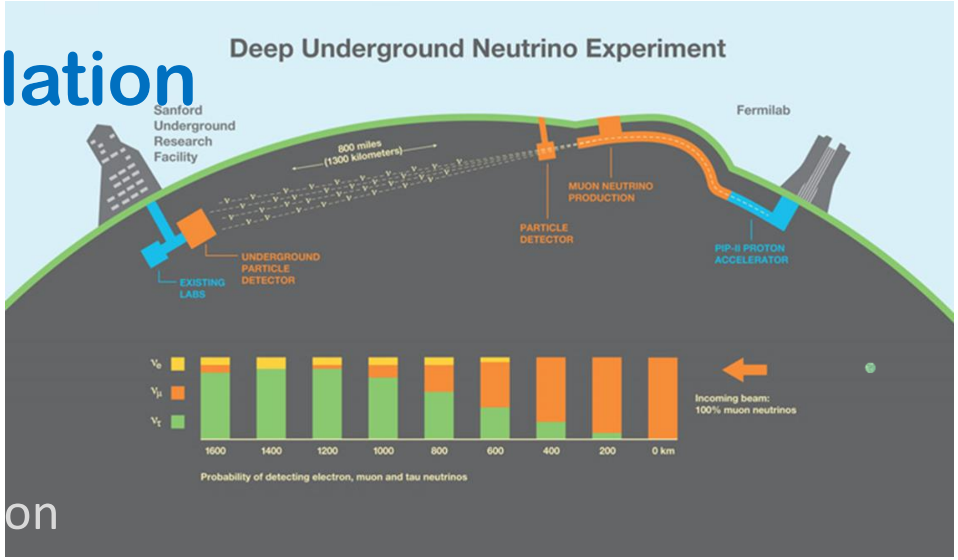

True NuWro/GENIE (FHC)

NuWro/GENIE for various reconstructed final states (FHC)

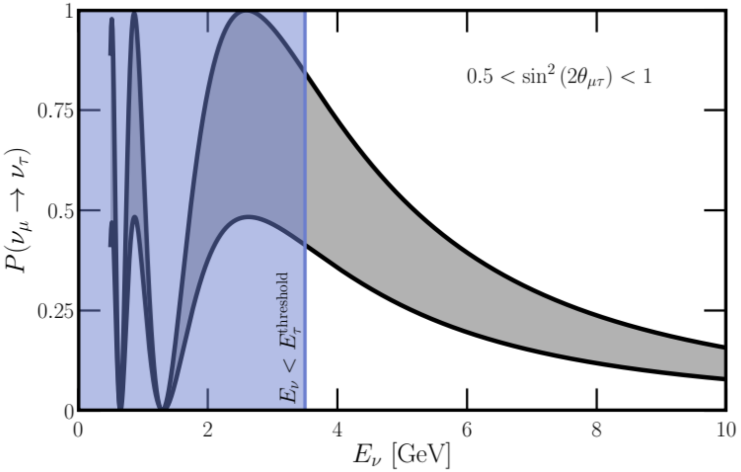
Physics Targets of DUNE

- **Long-baseline oscillation**
- Neutrino interactions
- Beyond Standard Model



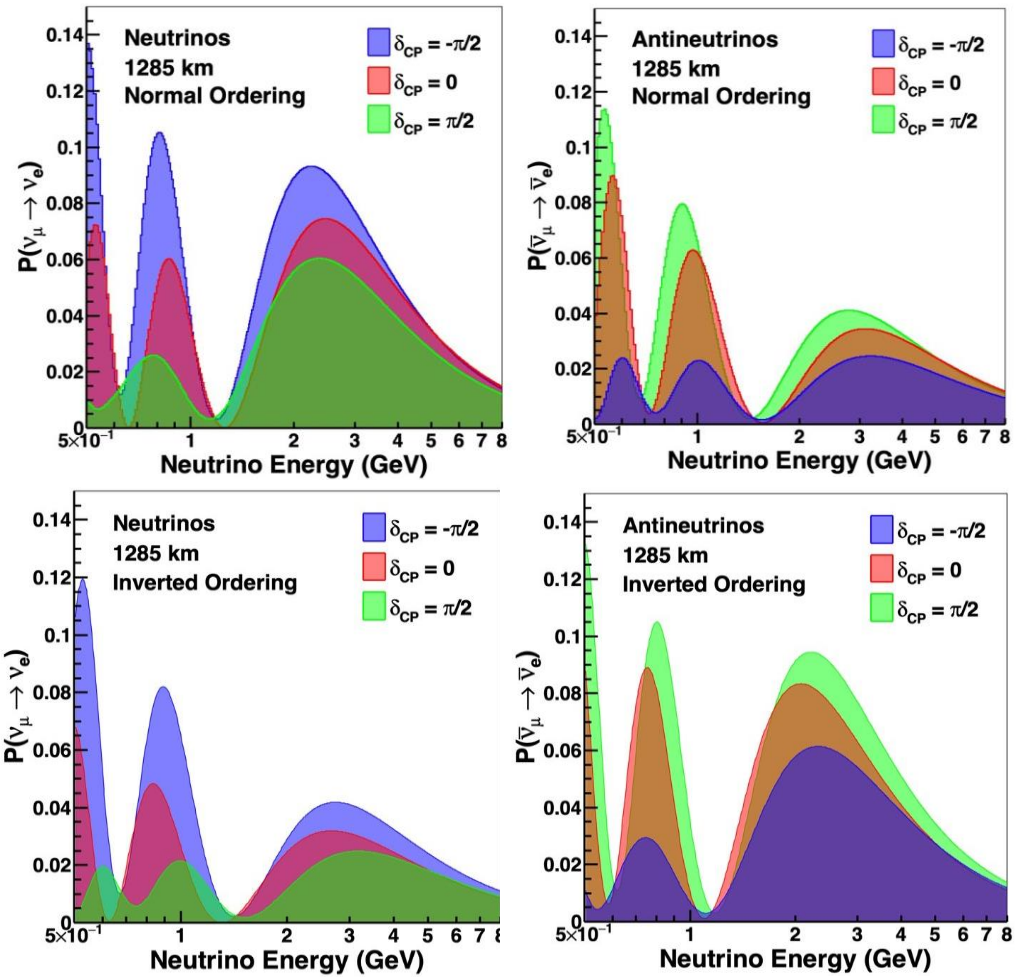


on



Neutrino-antineutrino asymmetry: P($\nu_\mu \rightarrow \nu_e$) vs. P($\nu_\mu \rightarrow \nu_e$)

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



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 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

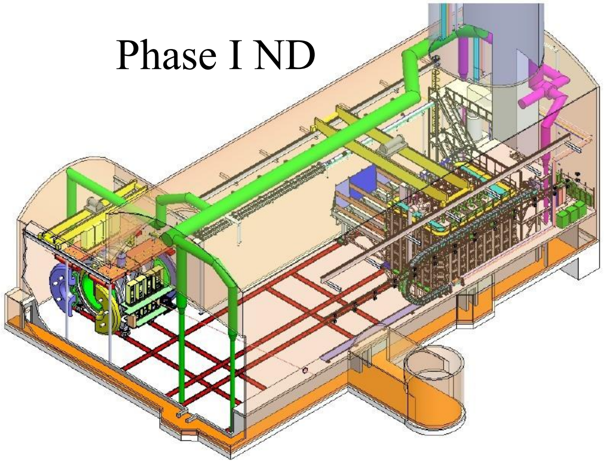
- FD3 + FD4
- ND-Gar replaces TMS.
- 2.4 MW beam power

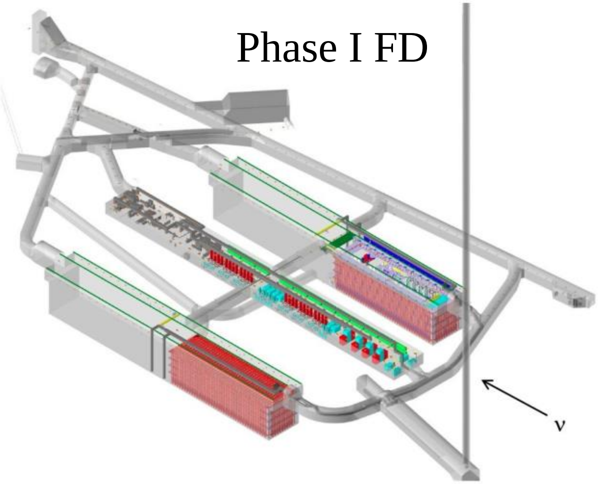
Staged year
1 (2026) with 20 kt-1.2MW
2 (2027) with 30 kt-1.2 MW
4 (2029) with 40 kt-1.2 MW
7 (2032) with 40 kt-2.4 MW

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

Getting there: phased construction

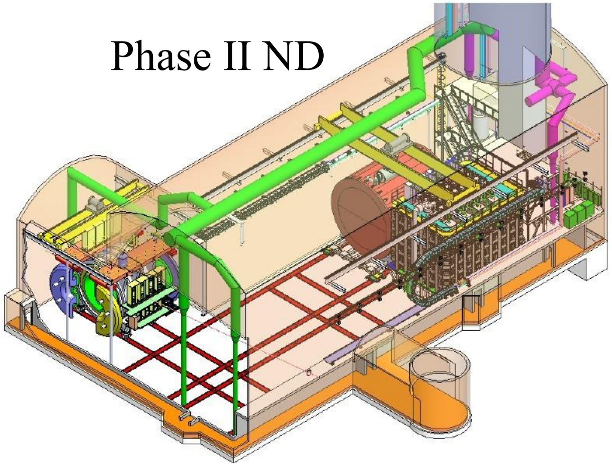
- As was always envisioned, DUNE construction is phased
- DUNE Phase I:
  - Neutrino beam with 1.2 MW intensity
  - Two 17kt LAr TPC FD modules, but underground facilities and cryogenic infrastructure to support four modules
  - Near detector: ND-LAr + TMS (movable), SAND
- Construction schedule is funding limited → changes to the funding profile have a significant impact on the schedule
- Current CD1-RR schedule has FD 1&2 taking physics data in 2029, beamline and ND by 2031
- The US DOE scope of Phase I was reviewed last week in CD1-RR



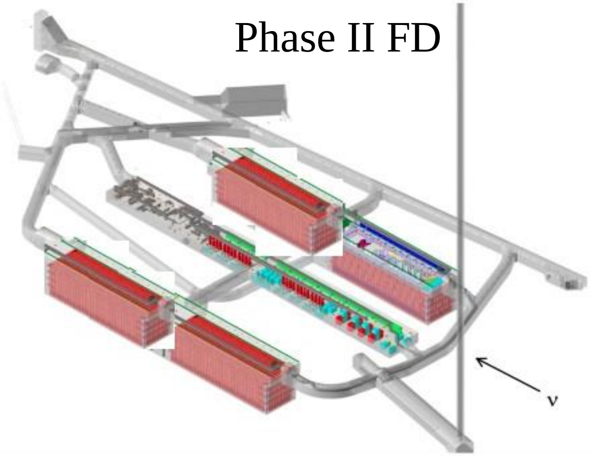


Getting there: Phase II upgrades

- DUNE Phase II:
  - Fermilab proton beam upgrade to 2.4 MW
  - Two additional 17kt FD modules
  - Near detector: ND-LAr + MCND (movable), SAND
- Beam upgrade benefits all Fermilab experiments: dedicated session Wednesday on Booster replacement options (AF2-AF5-NF)
- ND upgrade is driven by improved performance at reducing systematics → talk on ND-GAr in Wednesday session (NF)
- Opportunities to expand physics scope with 3rd & 4th FD modules: dedicated session Wednesday (NF)

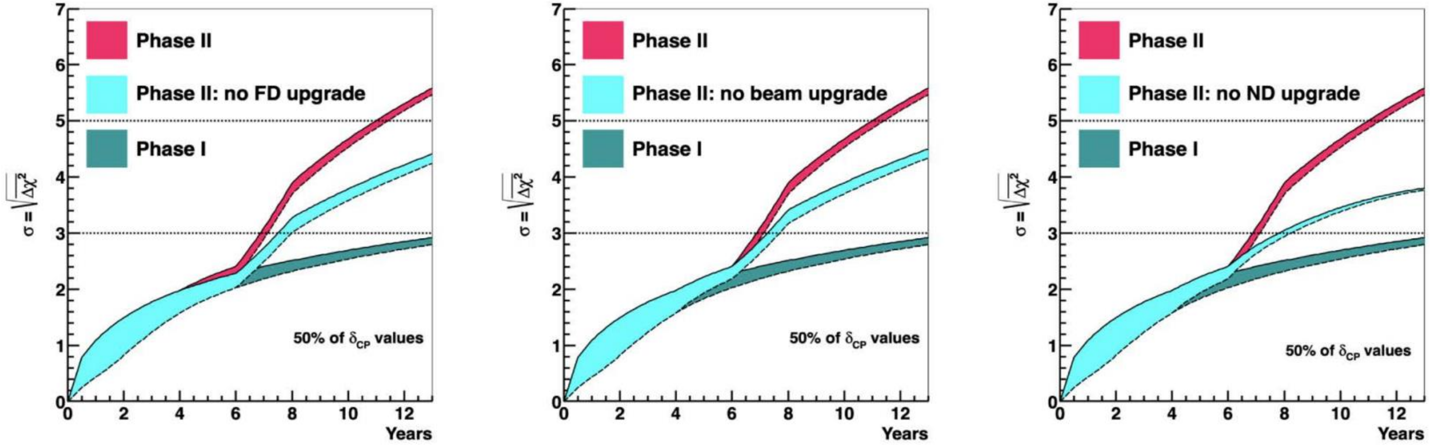


Phase II ND



Phase II FD

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**

LBNF: intense beam, underground facilities and infrastructure

- 1.2 MW neutrino beam from PIP-II proton beam, upgradeable to 2.4 MW

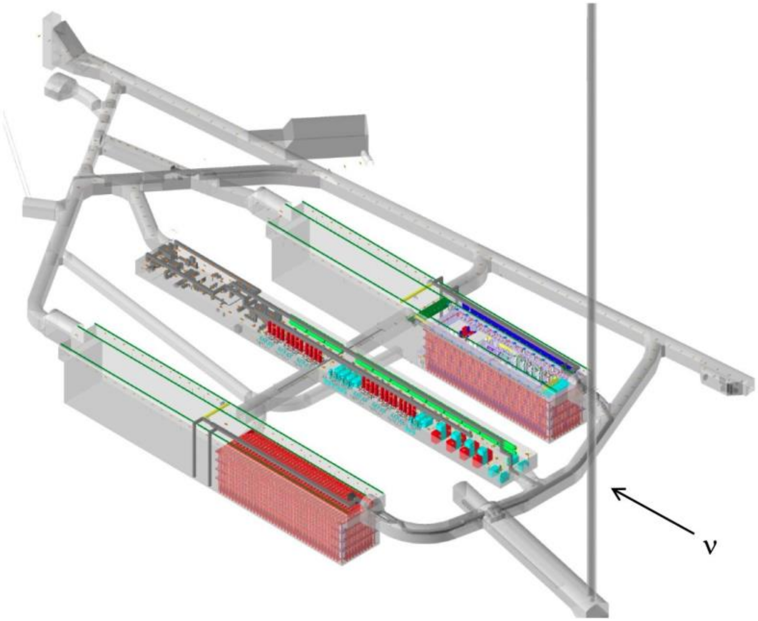
Boosted BSM searches
→ high intensity beam and capable ND

LBNF: intense beam, underground facilities and infrastructure

Deep underground far site to accommodate four 17-kiloton detector modules

DUNE FD has excellent low-energy neutrino and BSM sensitivity:

- Large mass | Deep underground | High resolution | Low thresholds



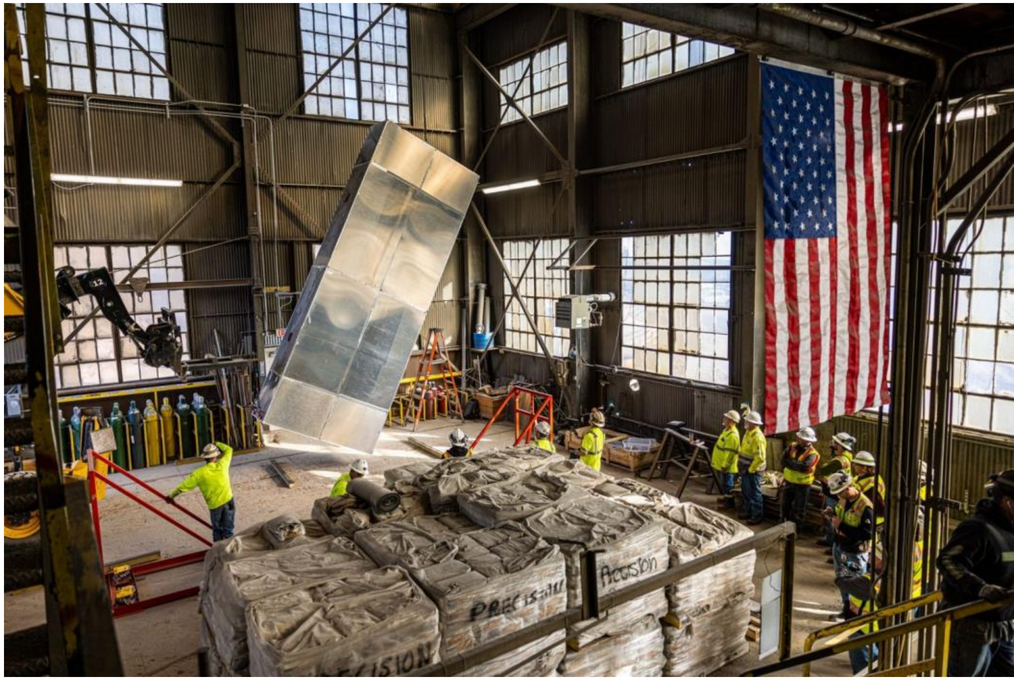
LBNF: intense beam, underground facilities and infrastructure

- Construction is underway at both SURF and Fermilab

North cavern breakthrough January 2022

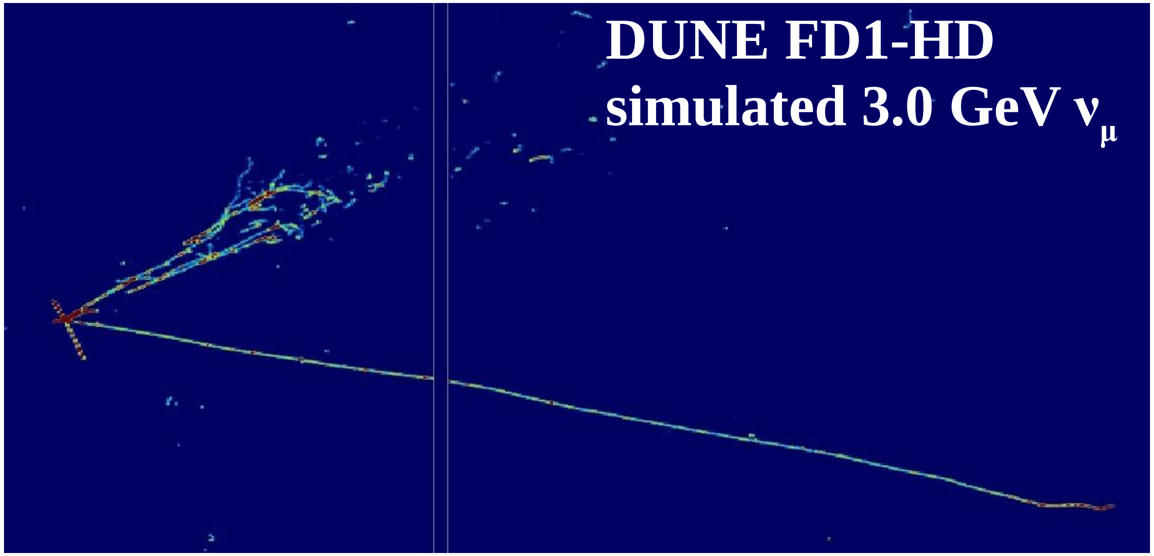
PIP-II construction May 2022

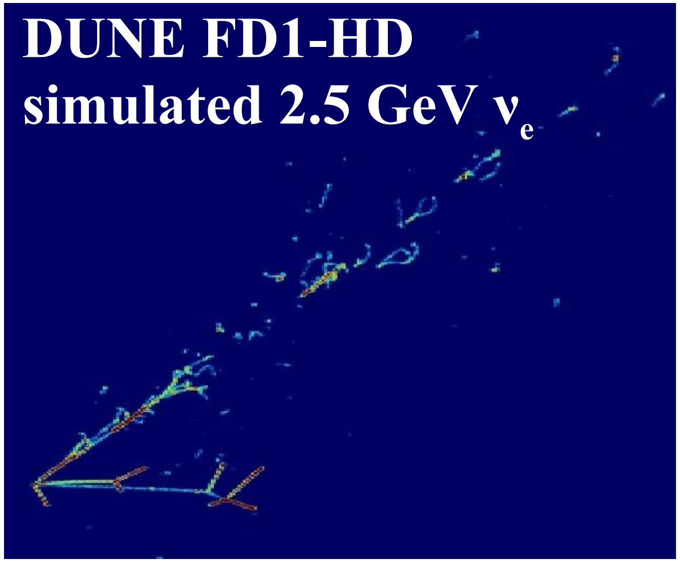
This was a test of the entire logistics chain —
from the UK, to Switzerland, to Illinois, and finally to South Dakota. (December 6, 2022)
In total, 150 APAs will be built for DUNE: 136 from the UK and 14 from the US.



LArTPC technology provides exquisite resolution

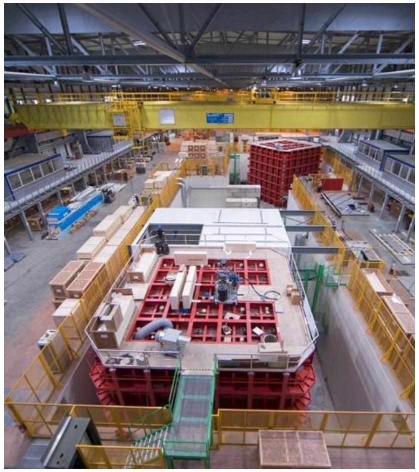
- Clean separation of ν_μ and ν_e charged currents
- Precise energy reconstruction over broad E_ν range
- Low thresholds: sensitivity to few-MeV neutrinos, hadrons

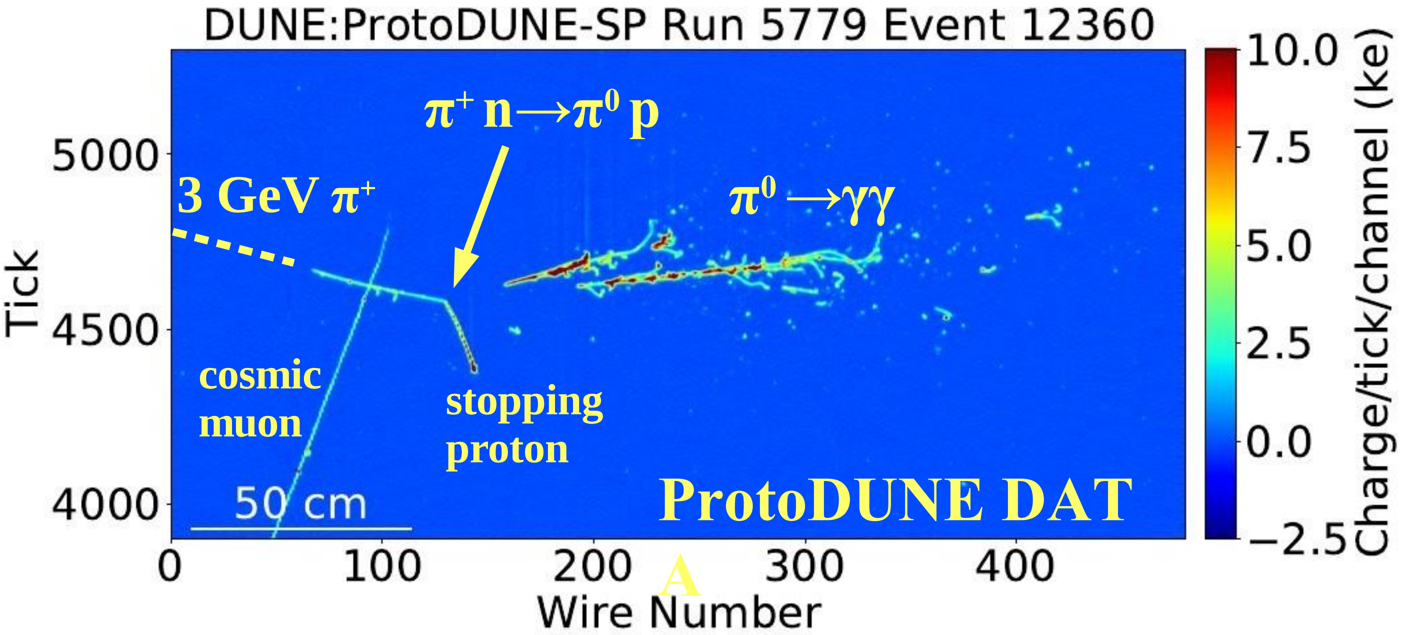




LArTPC technology provides exquisite resolution

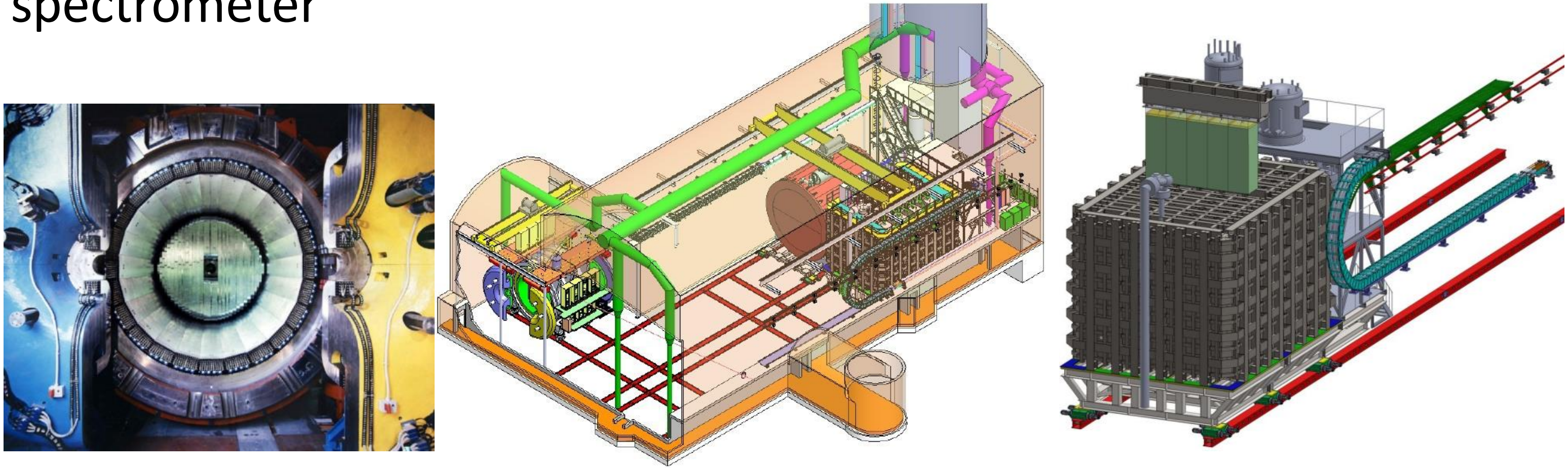
- ProtoDUNE is full scale in the drift direction
- Successful operation at CERN: low noise, stable HV, high purity → demonstrates LArTPC technology and DUNE design



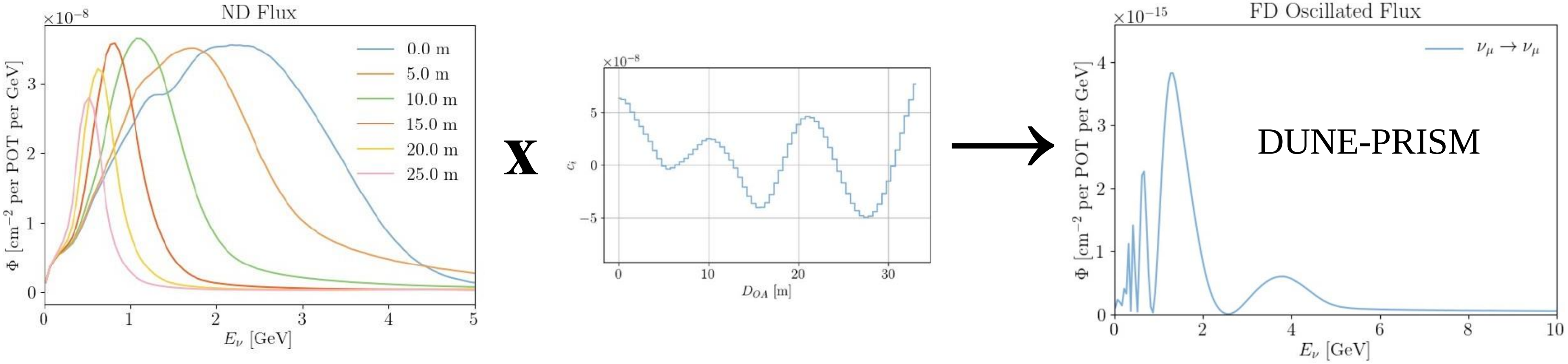


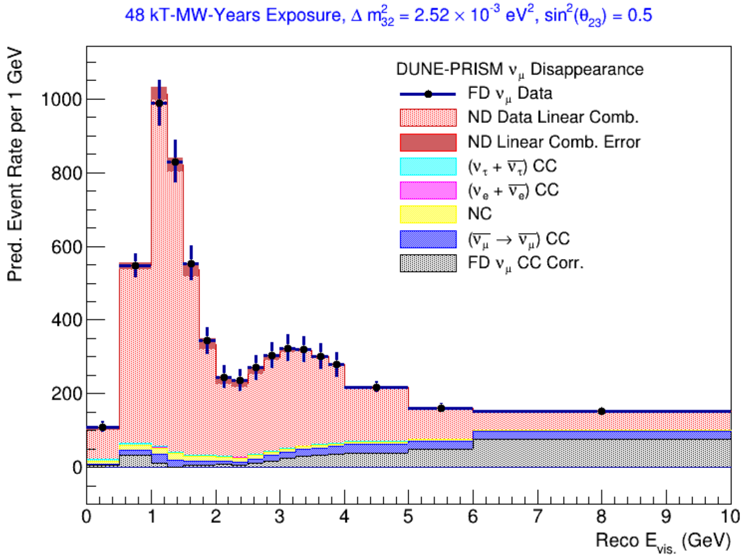
Near Detector: constraints to enable precision measurements

- LArTPC detector: same nuclear target and detector technology near & far
- Movement system to facilitate measurements in different neutrino fluxes
- On-axis magentized low-density tracker and spectrometer



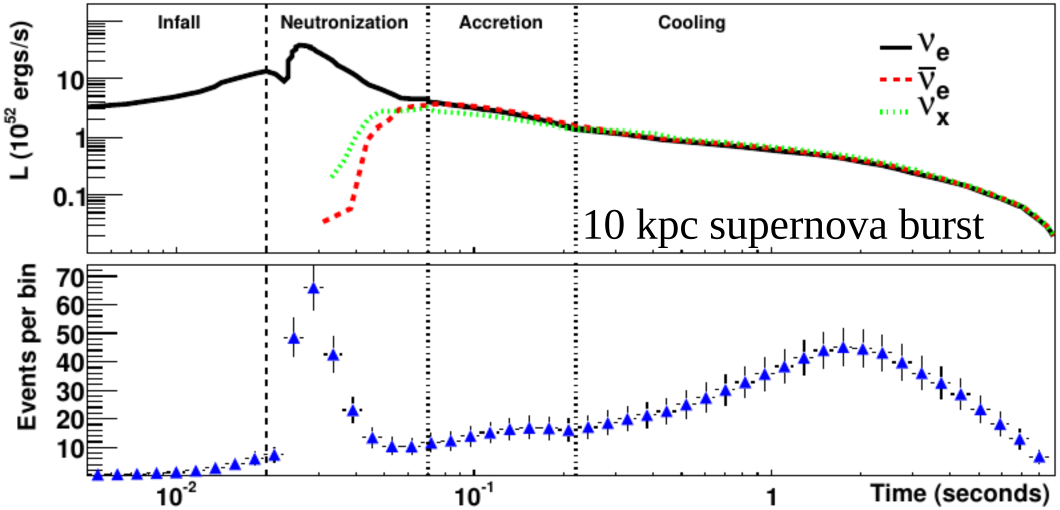
PRISM plays a critical role in DUNE’s precision



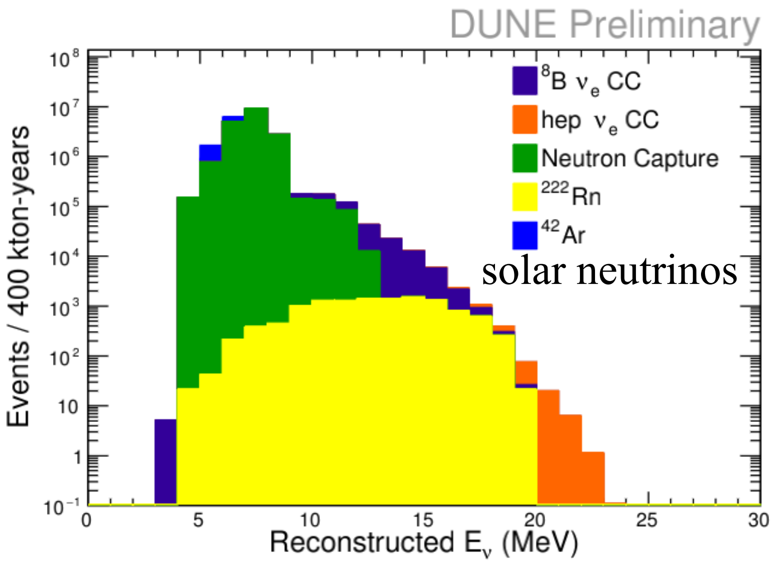


- FD flux ≠ ND flux → uncertainties in energy dependence of flux, cross sections
- ND flux changes with angle → take ND data in different fluxes→build linear combination to match FD *oscillated* spectra
- For LBL: robust analysis approach with very minimal dependence on interaction modeling
- Also extends dark matter sensitivity

MeV-scale physics: unique opportunities with ν_es



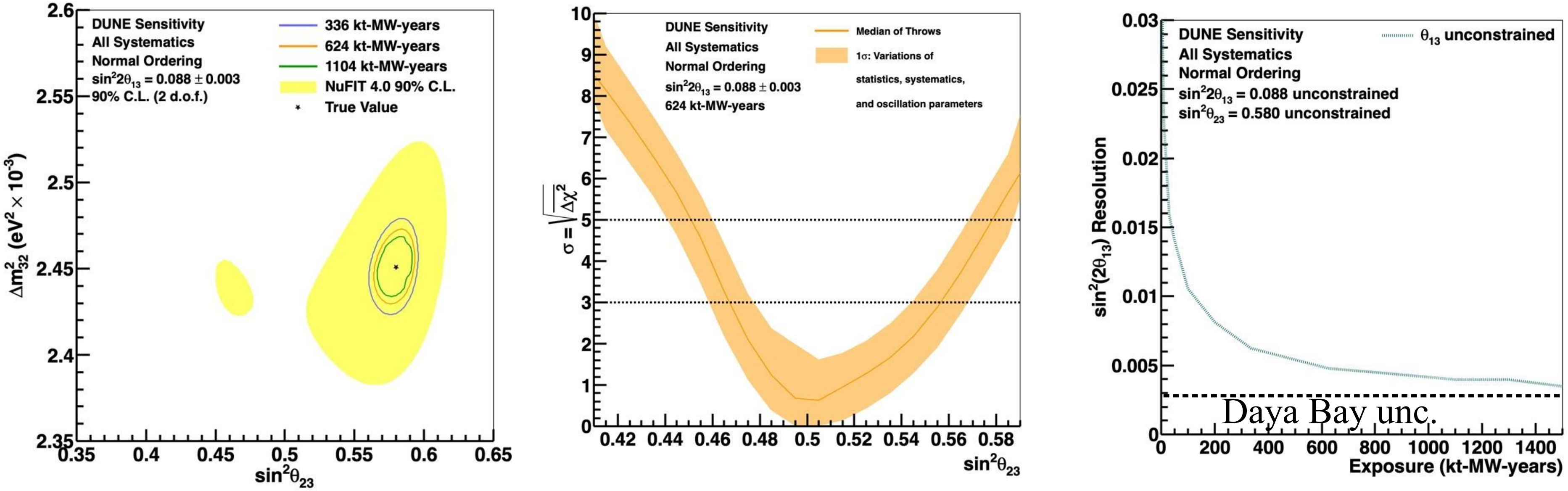
10 kpc supernova burst



solar neutrinos

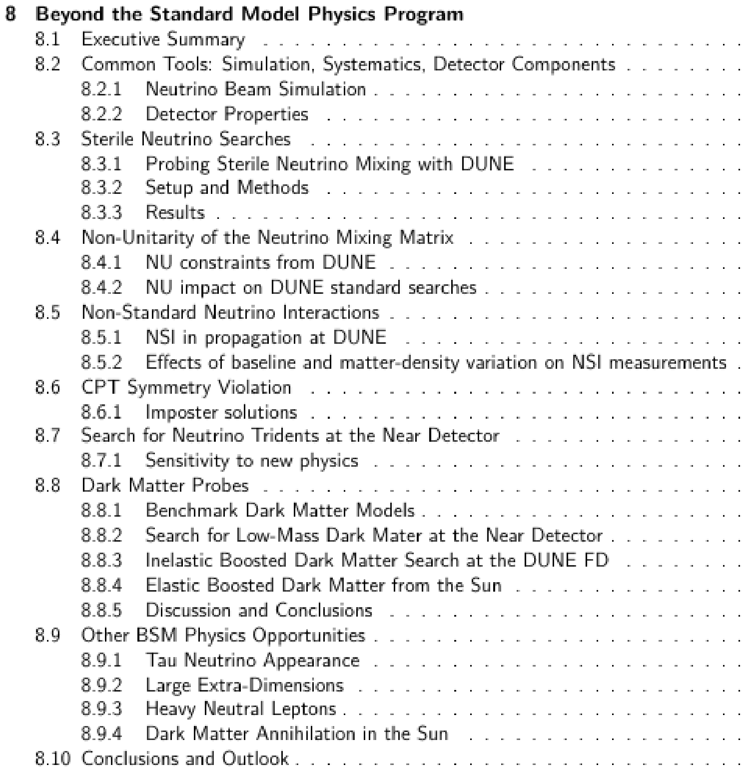
- Large detector + underground + low thresholds = sensitivity to supernova neutrinos
- Ar target makes DUNE uniquely sensitive to ν_e flux → measure neutronization burst, and highly complementary to other water/hydrocarbon detectors which measure predominantly $\bar{\nu}_e$
- Solar neutrino sensitivity to ^{8}B and discovery potential of hep flux, with capability to measure solar mixing parameters θ_{12} and Δm^2_{12}

Physics potential:
Precision measurements,non-unitarity tests



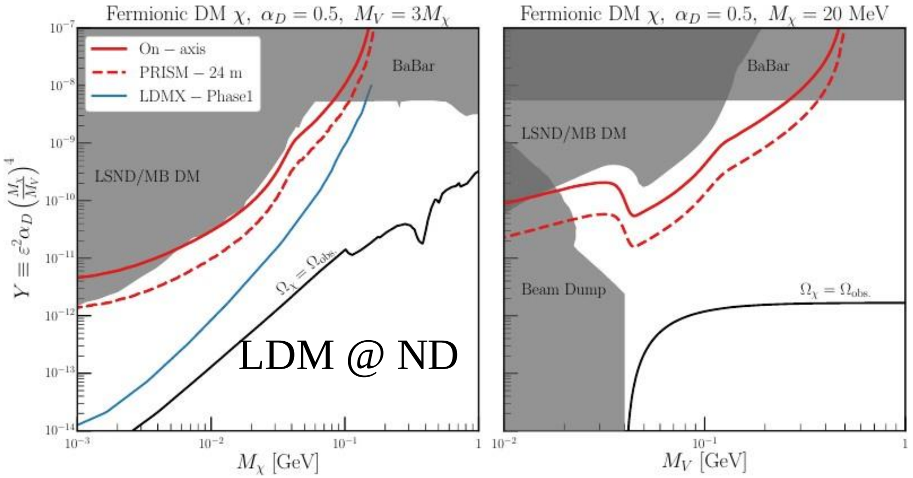
- Excellent on Δm^2_{32} and θ_{23} , including octant, and unique PRISM measurement technique that is less sensitive to systematic effects
- Ultimate reach does not depend on external θ_{13} measurements, and comparison with reactor data directly tests PMNS unitarity

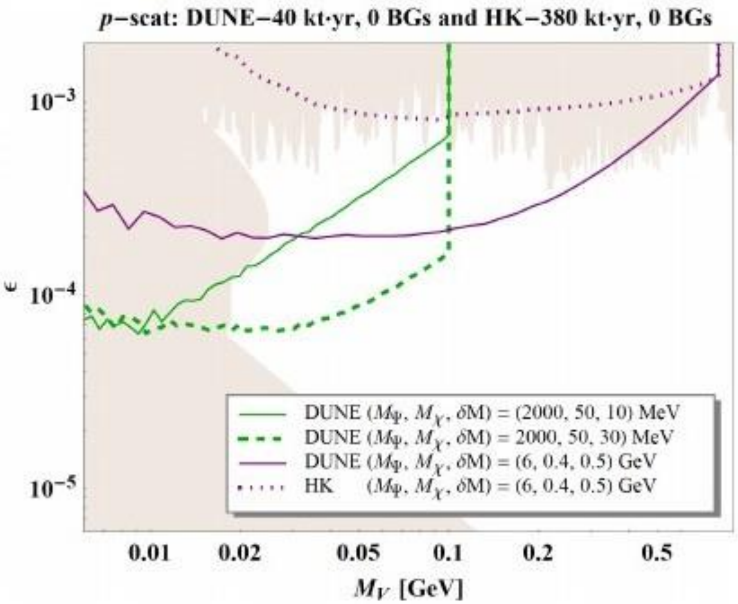
DUNE is an excellent BSM physics experiment



- For exotics of cosmic origin:
  - Large target mass
  - Deep underground → low background
  - Exquisite imaging, sensitivity to hadrons
- For exotics produced in hadron- nucleus collisions:
  - Very intense proton beam
  - Excellent detectors at ~500m, including a 150-ton detector (scattering), and a large, low density detector (decays)

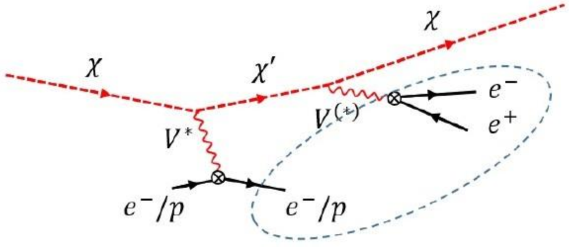
Dark matter at DUNE ND & FD



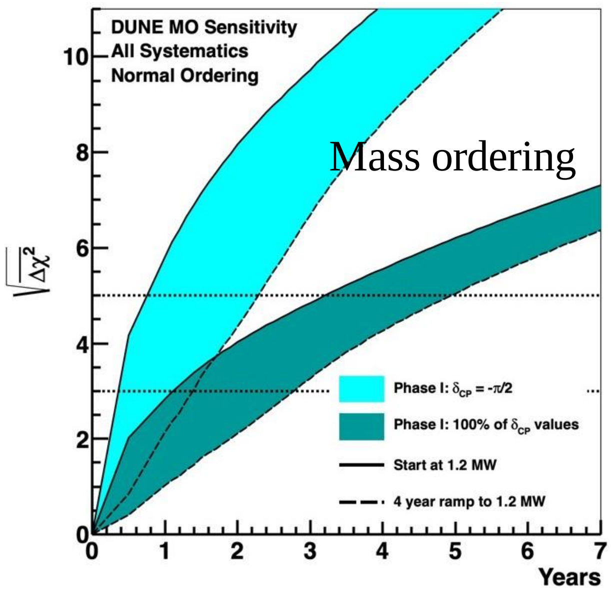


- ND-LAr is sensitive to DM produced in beamline, off- axis data helps to contro l SM backgrounds

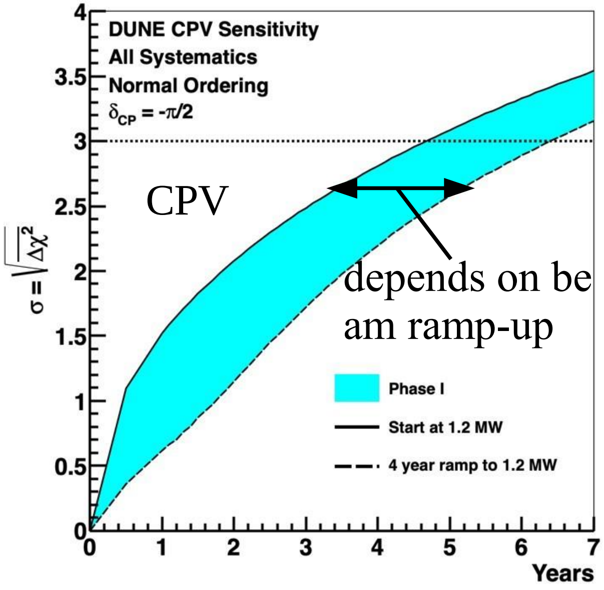
- FD is sensitive to inelastic dark matter of cosmic origin



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

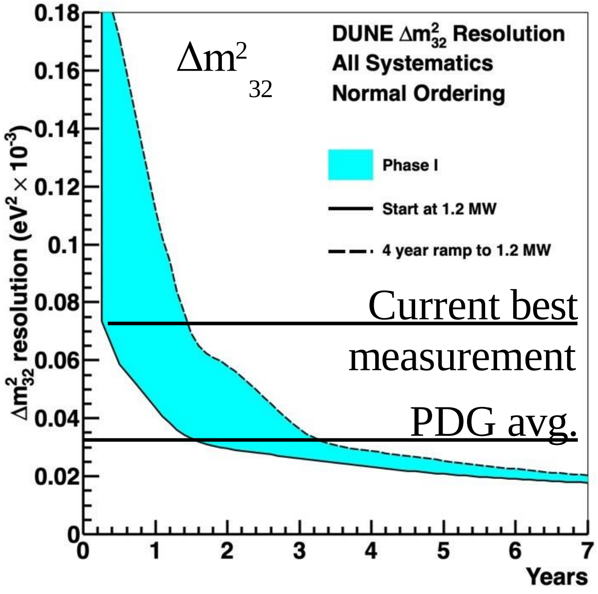


Mass ordering



CPV

depends on beam ramp-up



Δm^2_{32}

Current best measurement

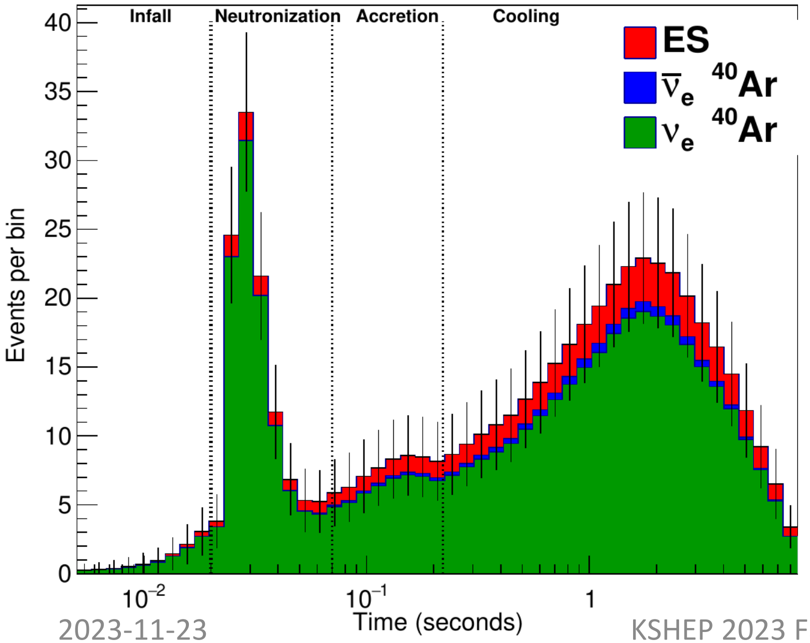
PDG avg.

- Phase I will do world-class long-baseline neutrino oscillation physics:
  - Only experiment with 5σ mass ordering capability regardless of true parameters Dis
  - covery 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)

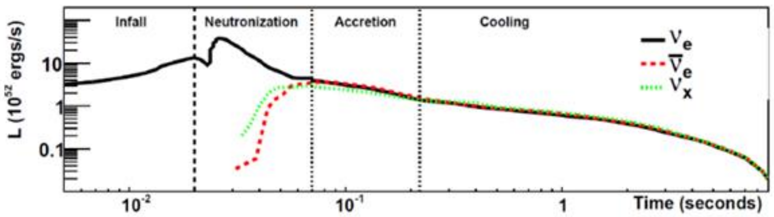
Non-beam physics with Phase I

DUNE is already very sensitive to a galactic supernova burst with Phase I

Shown is the time distribution for a hypothetical 10 kpc SNB with 20 kton fiducial mass



DUNE measures SNB ν_es; other experiments measure $\bar{\nu}_e$

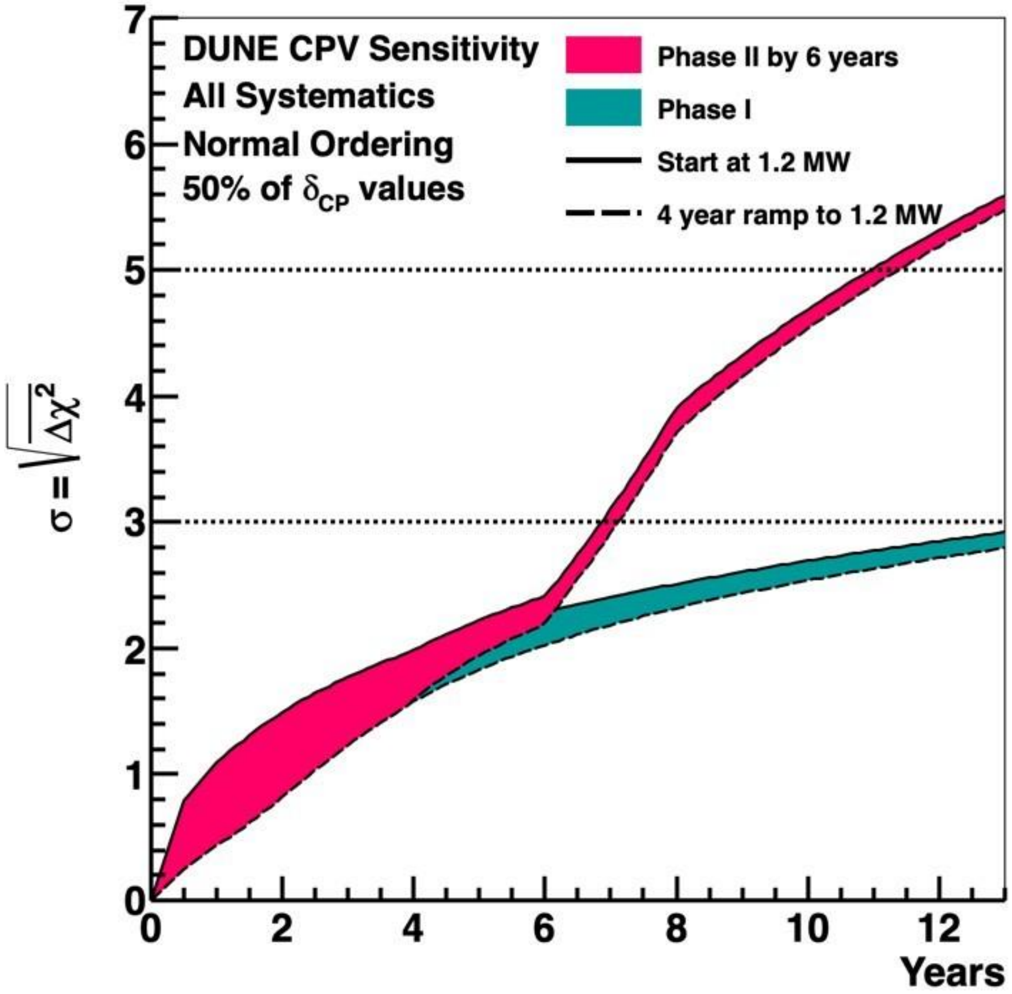


	ν_e	$\bar{\nu}_e$	ν_x
DUNE	89%	4%	7%
SK[1]	10%	87%	3%
JUNO[2]	1%	72%	27%

[1] Super-Kamiokande, *Astropart. Phys.* **81** 39-48 (2016)

[2] Lu, Li, and Zhou, *Phys Rev. D* **94** 023006 (2016)

DUNE’s long-term goals (Phase II)



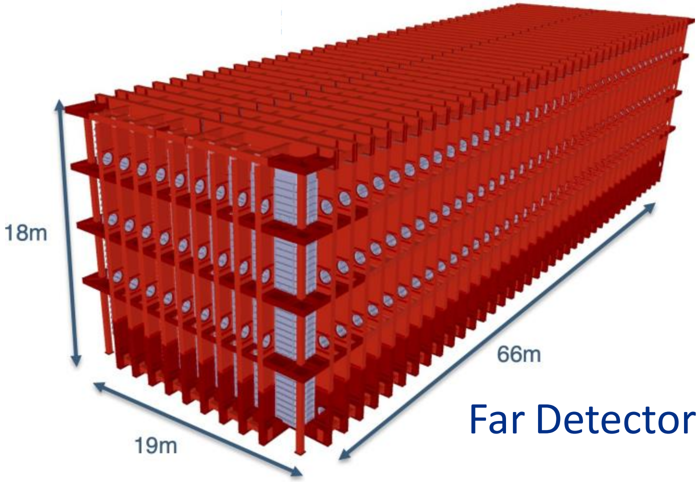
- DUNE needs full Phase II scope to achieve precision physics goals defined in P5 report
- CPV sensitivity for 50% of δ_{CP} values shown, precision measurements are similarly affected
- Timescale for precision physics is driven by achieving full scope on aggressive timescale, early ramp-up is not as relevant

Far Detector Dataflow and Trigger Records

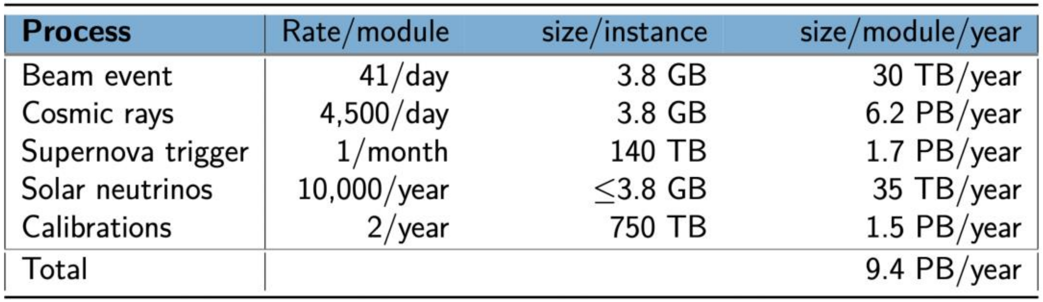
- beam coincidence events are extremely important, but of limited total volume
  - ~1 Hz beam rate
  - active online trigger in development
  - Region-of-Interest within module
  - online compression and zero-suppression being considered

- solar neutrino triggered events
- cosmic ray events and calibrations
- supernova readout events
  - ~140 TB in 100 seconds - one FD module
  - work w/ trigger primitives for immediate optical follow up
  - transfer out 4 hours and process in 4 hours for precision optical observations

- DUNE requirement - less than 30 PB/year total to permanent storage from all active FDs



Far Detector Cryostat

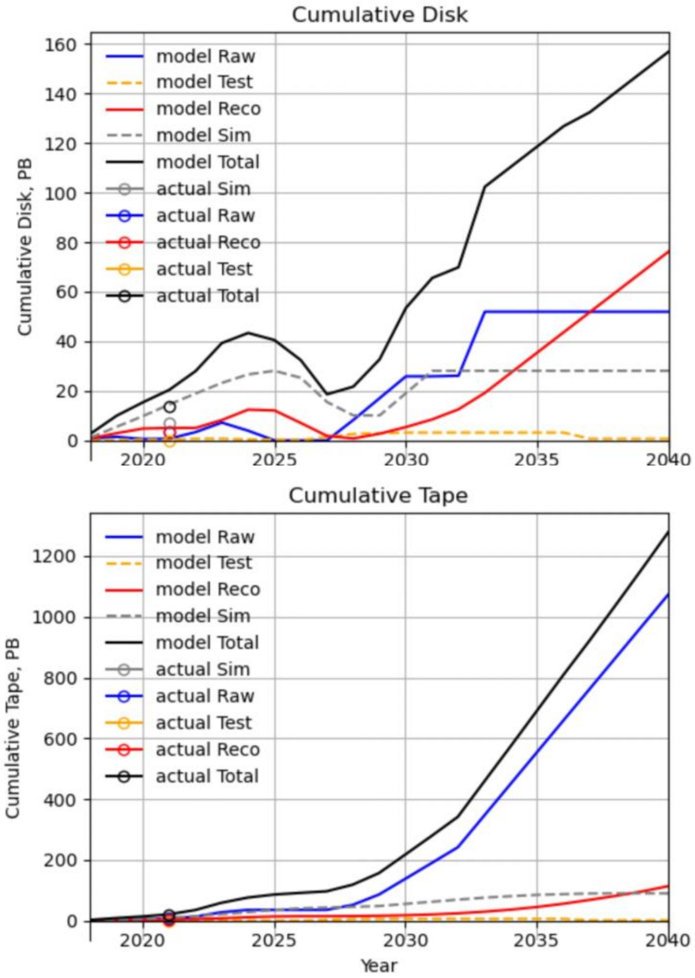


Process	Rate/module	size/instance	size/module/year
Beam event	41/day	3.8 GB	30 TB/year
Cosmic rays	4,500/day	3.8 GB	6.2 PB/year
Supernova trigger	1/month	140 TB	1.7 PB/year
Solar neutrinos	10,000/year	≲3.8 GB	35 TB/year
Calibrations	2/year	750 TB	1.5 PB/year
Total			9.4 PB/year

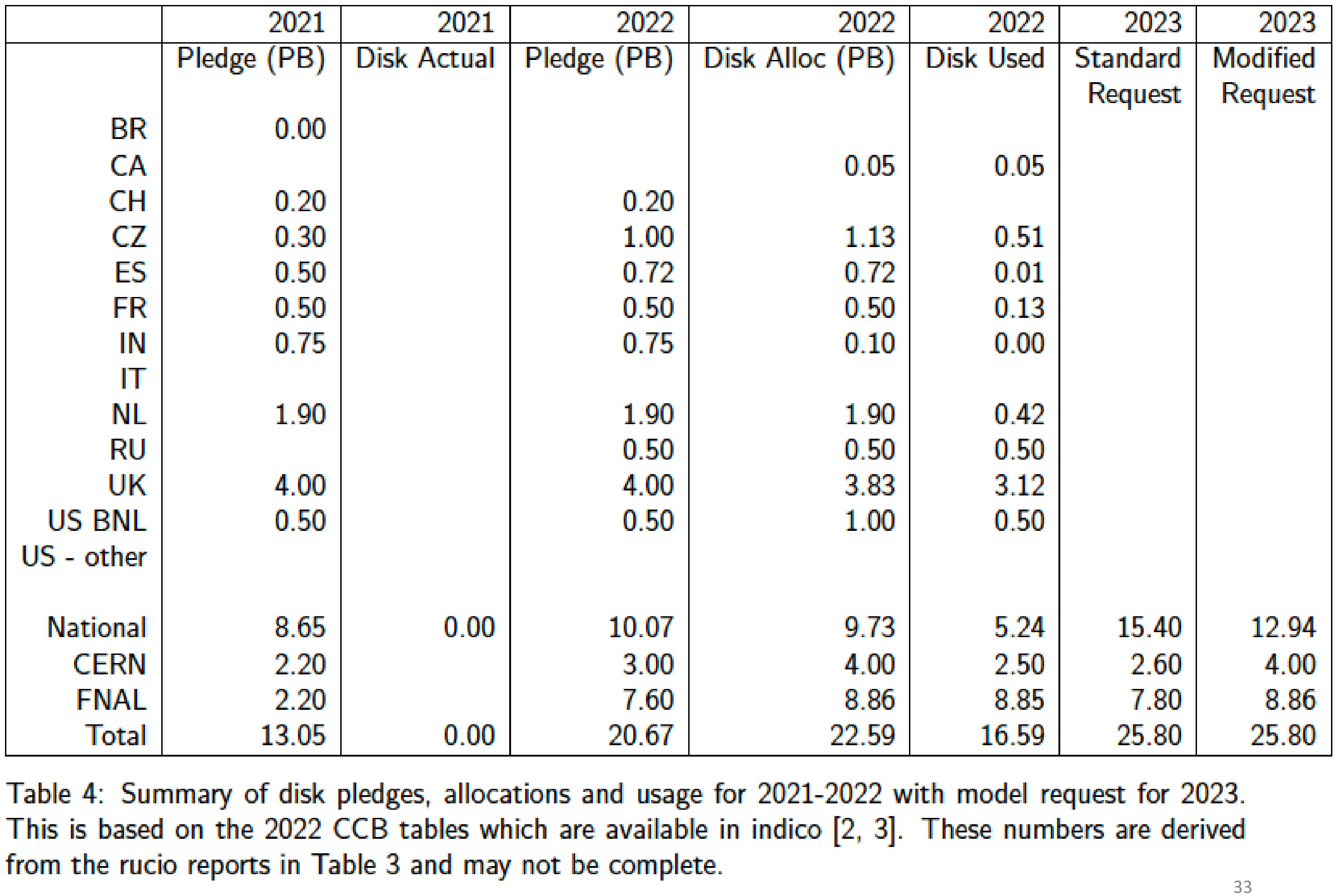
Recently published DUNE Computing CDR - https://arxiv.org/abs/2210.15665

Data Placement Strategy

- accomplished with Rucio and FTS3 - Scale tests of new DUNE data pipeline - S. Timm
- 2 copies of raw data on tape
  - one copy on each side of an ocean
  - 6 months on disk
- 1 replica of reco/sim on tape
  - distribute across global Rucio SEs
  - annual reco pass over all data
  - annual sim campaign to match
  - production resident on disk for 2 years
- Assume 2 disk copies of reco and sim
  - impose shorter lifetimes on tests & sim stages
  - R&D exploring data tiers and formats
- DUNE HDF5 Experience - B. Chowdhury



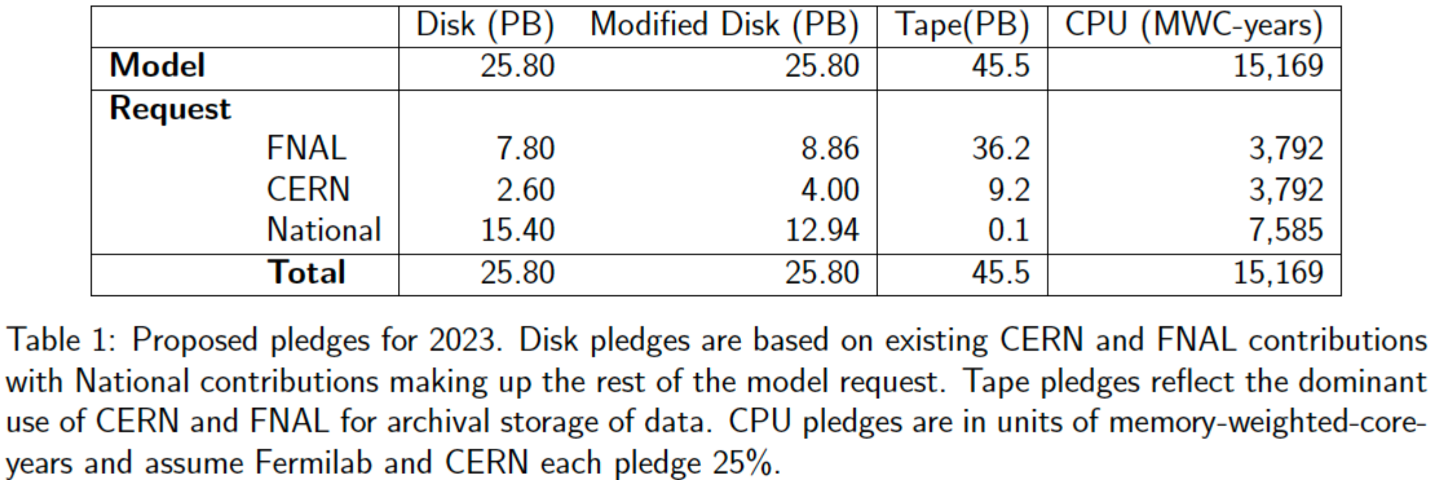
DUNE Computing CDR



	2021	2021	2022	2022	2022	2023	2023
	Pledge (PB)	Disk Actual	Pledge (PB)	Disk Alloc (PB)	Disk Used	Standard Request	Modified Request
BR	0.00						
CA				0.05	0.05		
CH	0.20		0.20				
CZ	0.30		1.00	1.13	0.51		
ES	0.50		0.72	0.72	0.01		
FR	0.50		0.50	0.50	0.13		
IN	0.75		0.75	0.10	0.00		
IT							
NL	1.90		1.90	1.90	0.42		
RU			0.50	0.50	0.50		
UK	4.00		4.00	3.83	3.12		
US BNL	0.50		0.50	1.00	0.50		
US - other							
National	8.65	0.00	10.07	9.73	5.24	15.40	12.94
CERN	2.20		3.00	4.00	2.50	2.60	4.00
FNAL	2.20		7.60	8.86	8.85	7.80	8.86
Total	13.05	0.00	20.67	22.59	16.59	25.80	25.80

Table 4: Summary of disk pledges, allocations and usage for 2021-2022 with model request for 2023. This is based on the 2022 CCB tables which are available in indico [2, 3]. These numbers are derived from the rucio reports in Table 3 and may not be complete.

Summary of request for 2023



		Disk (PB)	Modified Disk (PB)	Tape(PB)	CPU (MWC-years)
Model		25.80	25.80	45.5	15,169
Request					
	FNAL	7.80	8.86	36.2	3,792
	CERN	2.60	4.00	9.2	3,792
	National	15.40	12.94	0.1	7,585
	Total	25.80	25.80	45.5	15,169

Table 1: Proposed pledges for 2023. Disk pledges are based on existing CERN and FNAL contributions with National contributions making up the rest of the model request. Tape pledges reflect the dominant use of CERN and FNAL for archival storage of data. CPU pledges are in units of memory-weighted-core-years and assume Fermilab and CERN each pledge 25%.

- Disk request includes existing FNAL and CERN contributions
- Tape request reduced to 100 TB from National sites for testing, will increase in later years.
- CPU request is now memory-weighted, assumed data taking in 2023.

- ☐ **DUNE Computing is "internationalizing"**
  - This means DUNE will organize computing ~similar way to LHC experiments
  - Expect international contributions according to some sensible split
  - Expect a significant fraction of computing from outside of the USA (50% ?)

- ☐ **Main DUNE Computing sites are currently:**
  - USA
    - FNAL
    - BNL
    - Universities
  - Europe
    - UK -all GridPP
    - Czech Republic: FZU
    - NL: Sara
    - FR: IN2P3 Lyon
    - CH: CERN
    - ES: PIC
    - IT: INFN

- ☐ **Thus from network point of view**
  - Strong overlap with WLCG sites
  - We are well served by ESNET, Geant, and European NRENs

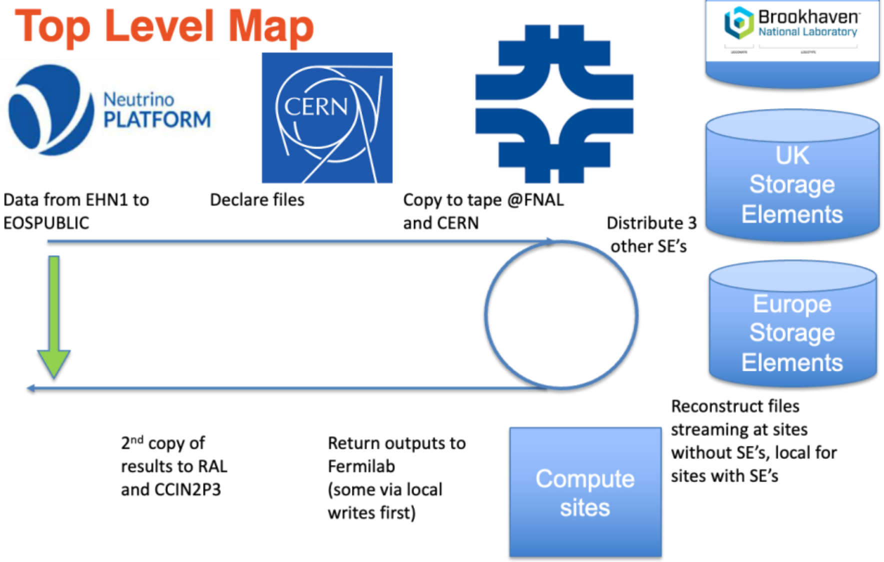
- ❑ In the future we will include computing in
  - Brazil
  - ? possibly others ?
- ❑ DUNE includes protoDUNE at CERN
  - 2018/19 data
  - Will run again in 22/23
  - Data transfer CERN ➔ FNAL
- ❑ DUNE also has a “different” network requirement to LHC
  - Connection from the SURF Lab in South Dakota → Fermilab
  - ESNET and FNAL are working on this.
- ❑ DUNE Computing Management, as a matter of policy, will work closely with FNAL Networking

- ❑ Latest DUNE CPU and storage estimates

	2020	2021	2022	2023	2024
CPU (Cores)	3600	6000	6000	8000	10000
Storage (PB)	12	20	25	~30	~40

Summer 2022 Data Challenge 4 - ProtoDUNE

- Goals of the Data Challenge 4 - test all the services and procedures that will be used in the forthcoming beam runs of PD-HD and PD-VD
- Phase 1 - Data Pipeline
  - Goal - test data path EHN1->CERN->FNAL
  - transfer, declare, and replicate “raw data” at needed scale
  - 3.6 GBytes/s achieved across atlantic
- Phase 2 - Data Processing
  - Goal - sustain 5000 concurrent jobs for keep up processing
  - significant drop in CPU efficiency for jobs where large input data files not located “near” job
  - The Workflow System (now “justIN”)
  - The Data Dispatcher



Top Level Map

Data from EHN1 to EOSPUBLIC

Declare files

Copy to tape @FNAL and CERN

Distribute 3 other SE’s

UK Storage Elements

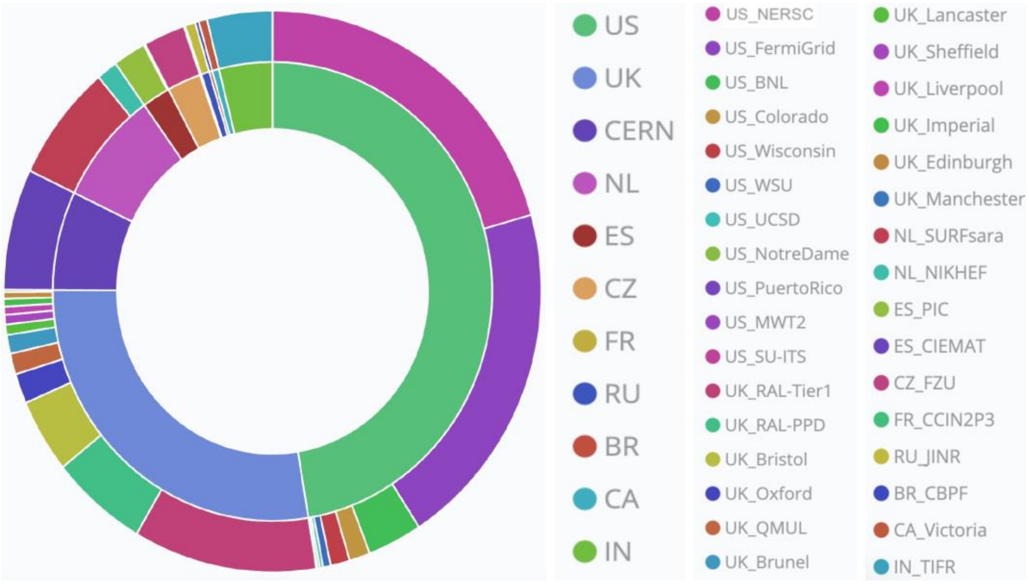
Europe Storage Elements

Reconstruct files streaming at sites without SE’s, local for sites with SE’s

Compute sites

Return outputs to Fermilab (some via local writes first)

2nd copy of results to RAL and CCIN2P3



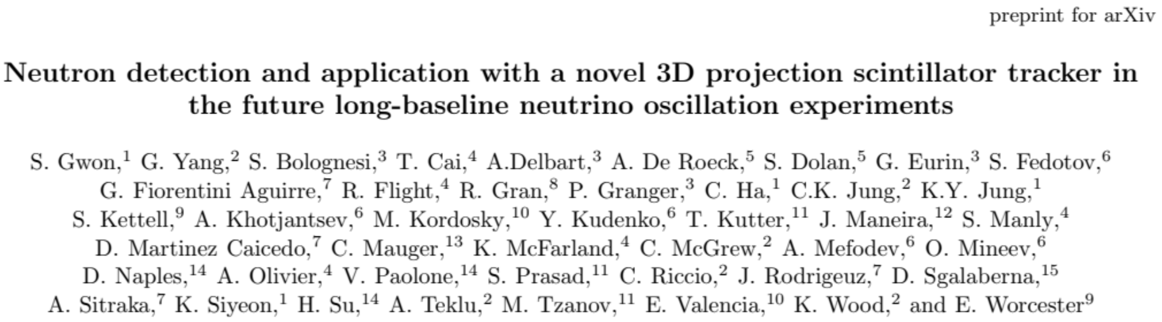
Korean DUNE Activities

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

최근 중요 실적 및 기여

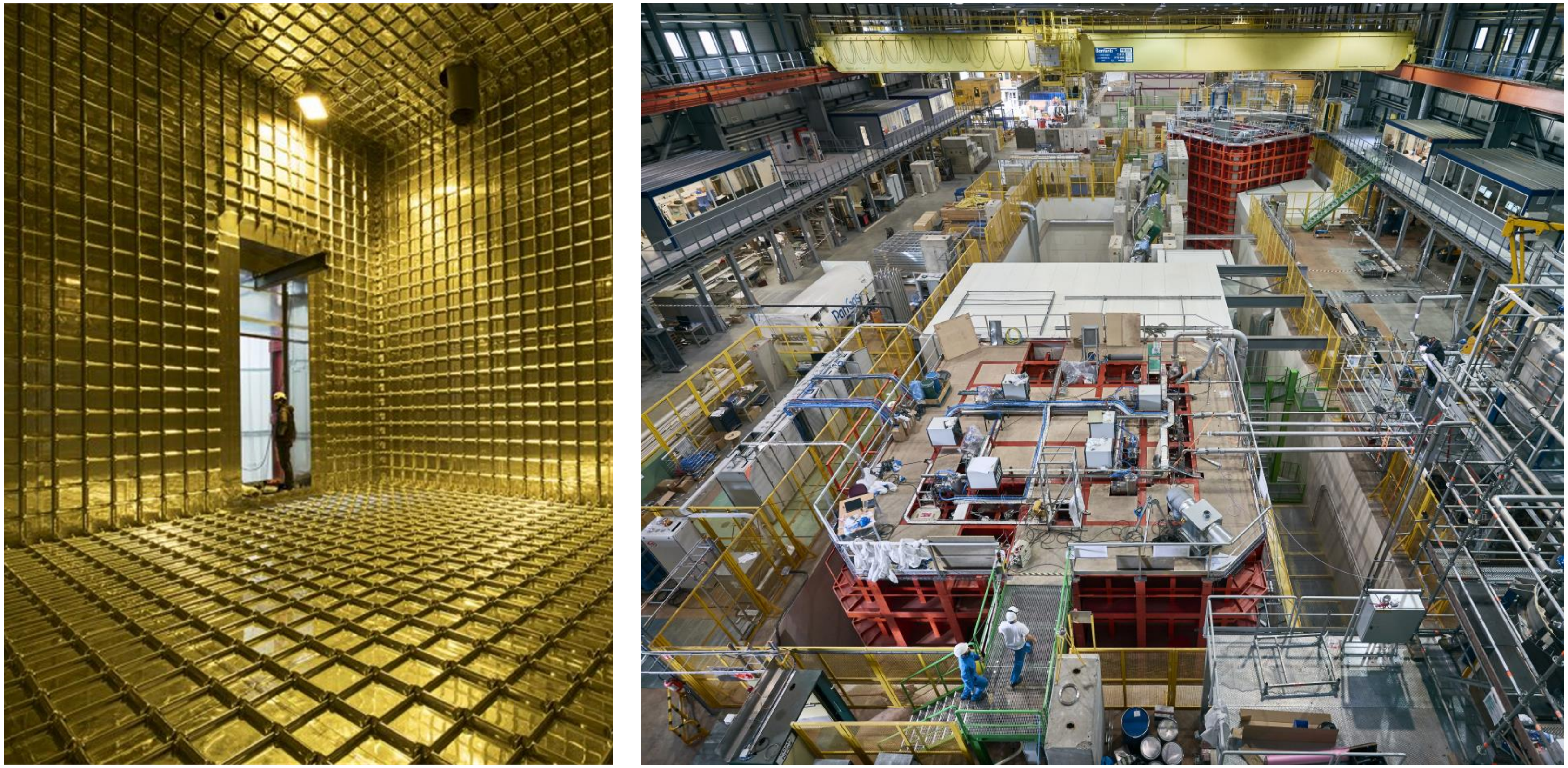
- 신서동(전북대):
  Prospects for beyond the Standard Model physics searches at the Deep Underground Neutrino Experiment, *Eur.Phys.J.C* 81 (2021) 4, 322,
  Boosted dark matter search 집필 기여
- 권순우(중앙대):
  Deep Underground Neutrino Experiment (DUNE) Near Detector Conceptual Design Report, *Instruments* 5 (2021) 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]



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

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

Concluding Remark

- Long baseline neutrino oscillation DUNE for CPV phase and mass ordering measurements.
- Staged year one is 2026 with neutrino beam, ND, and FD ready.
- Expected to produce a variety of new physics based on different types of interactions and different target materials.

- Korean contributions for protoDUNE, ND/3DST detector, Neutron study for reconstruction of anti muon neutrinos.
- Plan to participate protoDUNE analysis.

- Both global and local activities are waiting for participation of young researchers and students .
- **CAU Neutrino Lab (Nu Int. Sim/Reco, Data analysis) Recruiting Postdocs (deadline: mid July, 2023)**

백업

중성미자 상호작용과 중성자 검출

Phys.Rev.D 107(2023) 3,032012
e-Print: 2211.17037
S. Gwon et al.

- Neutrino-nucleus interaction: nu-Ar, nu-C,H
  COH, QE, RES, DIS
- Neutrons in final states:
  Missing energy in neutrino detection
- Neutron identification:
  - Event-by-event Energy Reconstruction
- 3-dim Scintillator Tracker:
  - DUNE neutrino beam and CH target
  - CCQE-like (cc0pi) event analysis
  - Low-nu fitting for flux constraint
- LANL neutron beam test (3DST & SuperFGD/T2K):
  - Study of secondary neutrons

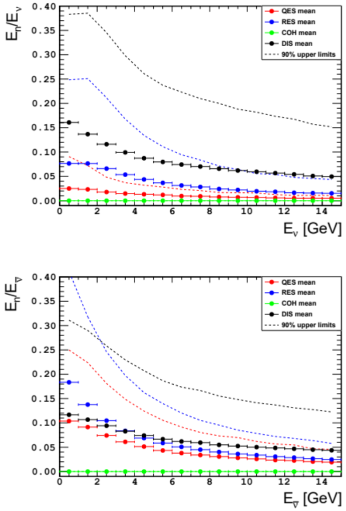
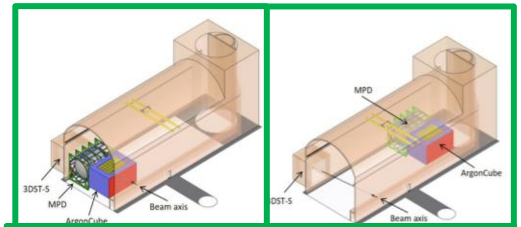
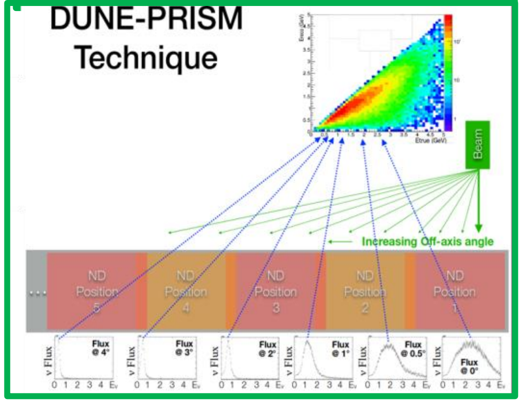


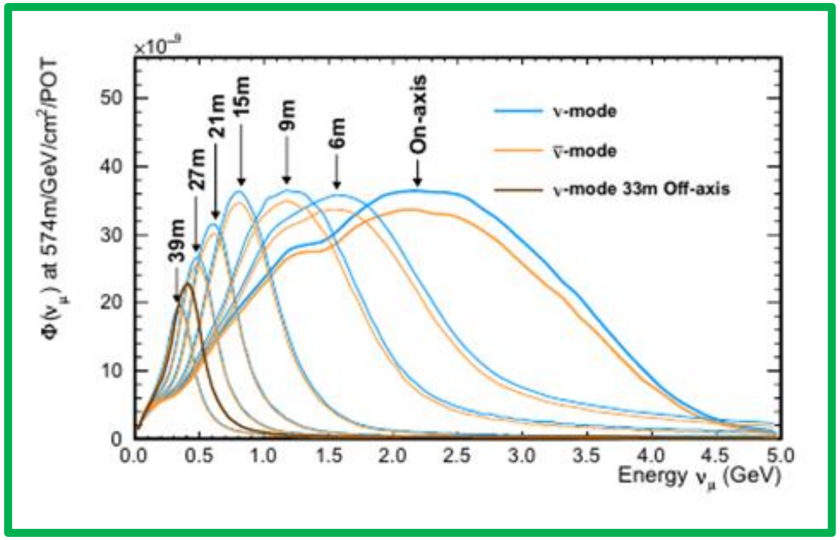
FIG. 1. Average energy fraction delivered to the primary neutrons relative to the neutrino energy(top) and the antineutrino energy(bottom). The average ratios E_n/E_ν are in comparison according to the CC Quasi-elastic (QES), CC resonant (RES), CC coherent (COH) and CC deep-inelastic scattering (DIS) interaction modes.

DUNE Detector Techniques

- Near Detector
  - DUNE Prism
  - LAr-TPC (ArgonCube) Segmented
  - Multi-Purpose Detector:
    Gas Argon TPC surrounded by Ecal and magnet
    Alice-type TPC, -> Reuse Alice Readout chamber
  - System for on-Axis Neutrino Detection
    - 3DST, Plastic Scintillator detector w/ 1cm x1cm 1cm cubes
    - Gas Ar TPC
    - KLOE magnet, and ECAL

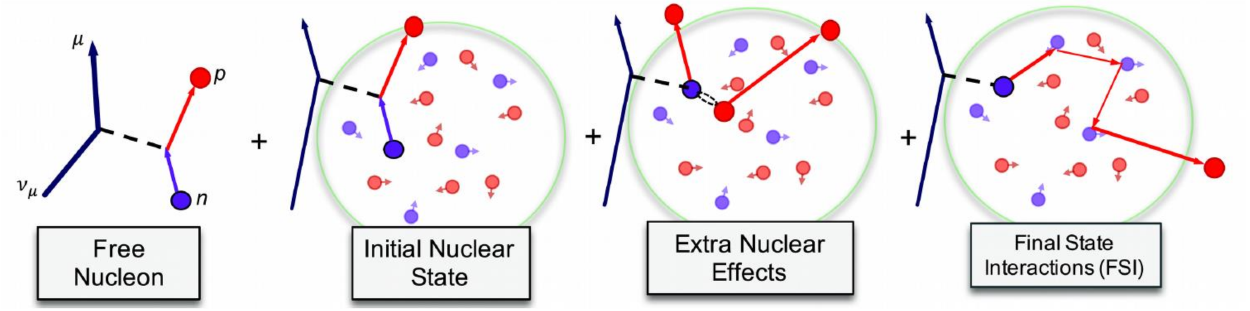






Neutrino Interaction Physics & the DUNE Near Detector

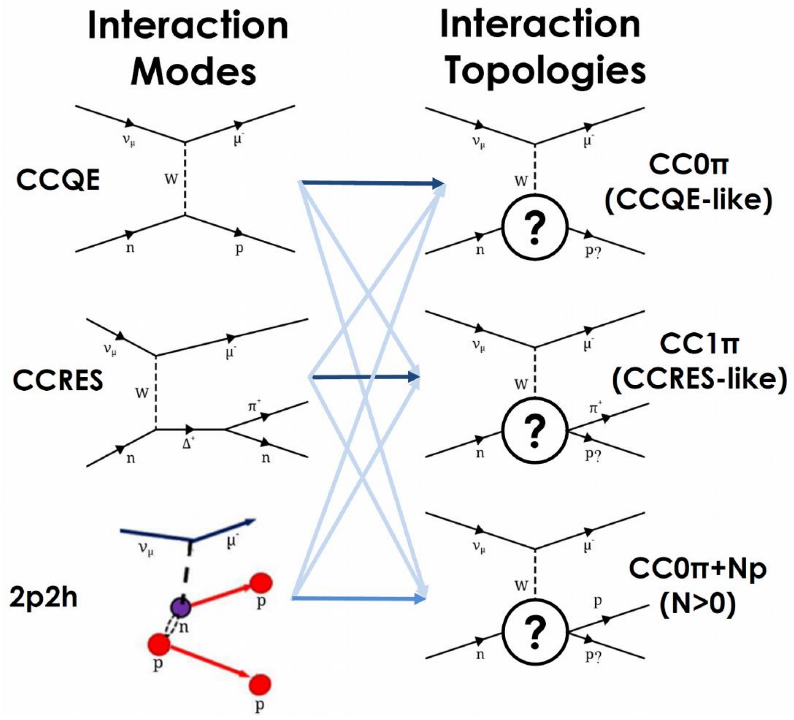
Mateus F. Carneiro on behalf of the DUNE Collaboration



$$R(\vec{\mathbf{x}}) = \Phi(E_\nu) \times \sigma(E_\nu, \vec{\mathbf{x}}) \times \epsilon(\vec{\mathbf{x}}) \times P(\nu_A \to \nu_B)$$

Final state particle content does not isolate initial interaction type!

What do we actually measure?



Graphic from S. Dolan

Many modes contribute to any measurement

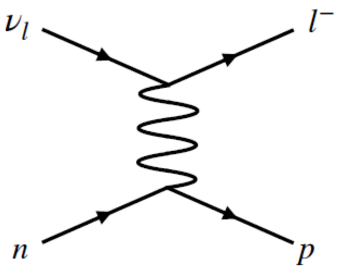
Integrated over broad ω region

Difficult to tune theory models!

Charged-current quasi-elastic scattering - the “golden channel”

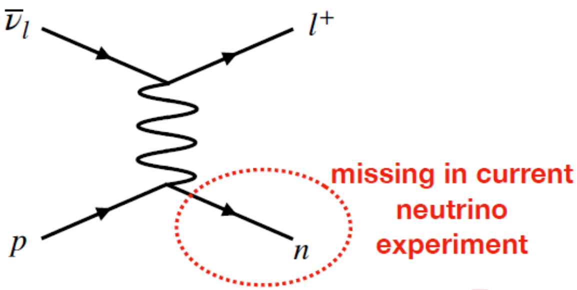
Why is this useful?

- Muon has constant $\mathrm{d}E/\mathrm{d}x$ (minimum-ionizing particle)
- Long, clear track: **easy to measure E_μ and θ_μ**
- $\bar{\nu}$ case - neutron hard to detect (neutral)
- Not affected by **final-state interactions**
  - Nucleons can re-interact in the nucleus.



neutrino CCQE interaction

2

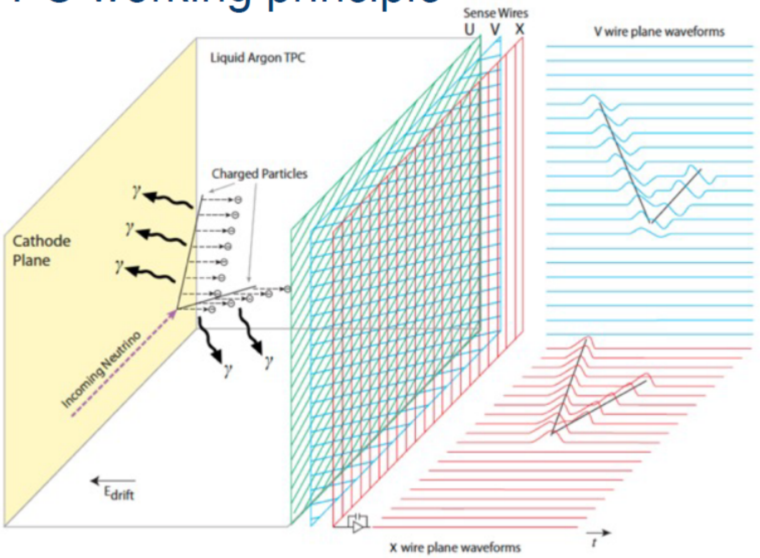


anti-neutrino CCQE interaction

What about anti-muon neutrinos?
What about neutrons?

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

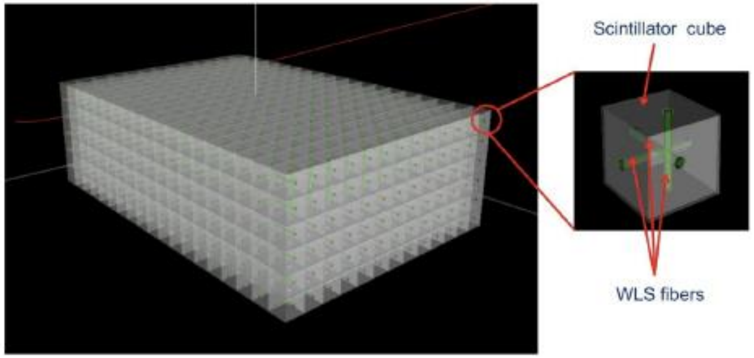
- Dense: 40% more than water
- Abundant primary ionization: 42 000 e^-/MeV
- High electron lifetime if purified → long drifts
- High light yield: 40k γ/MeV
- Easily available: ~1% of the atmosphere
- Cheap: $2/L ($3000/L for Xe, $500/L for Ne)

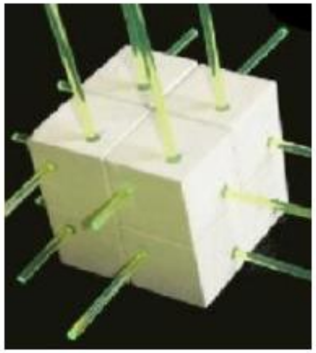
- Technological challenges
  - LAr continuous purification << 0.1 ppt O_2 eq. (>> 3 ms electron lifetime) for long drift
  - Imaging & anode planes
  - Very low noise front end amplifiers to detect ~ fC primary charge deposition
  - Large area photon detectors sensitive to 128 nm wave length
  - HV system 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

- Plastic scintillator detector with 1 cm x 1 cm x 1cm cubes
- Light collected by 3 wavelength shifting fibers
- Each cube etched chemically to keep light entrapped inside the cube
- Read out by MPPC at 3 faces
- 4π coverage, 300 MeV/c proton threshold, 0.5 ns timing for MIP

1.5 cm x 1.5 cm x 1.5 cm

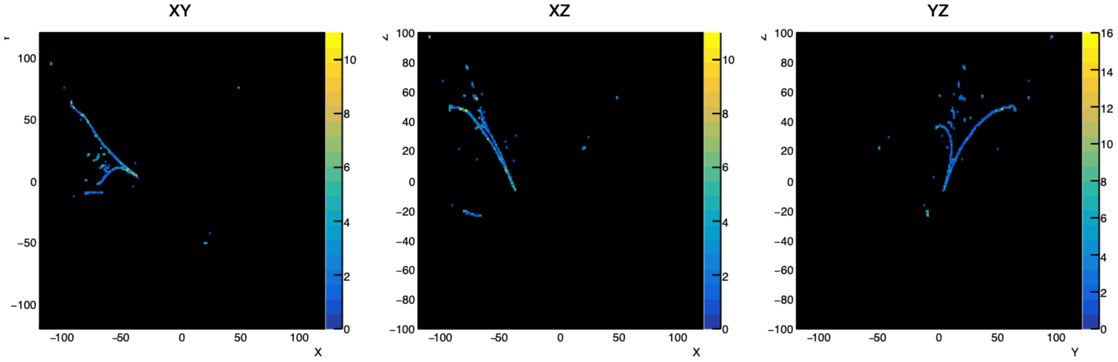
Sunwoo Gwon
for KPS 2020F



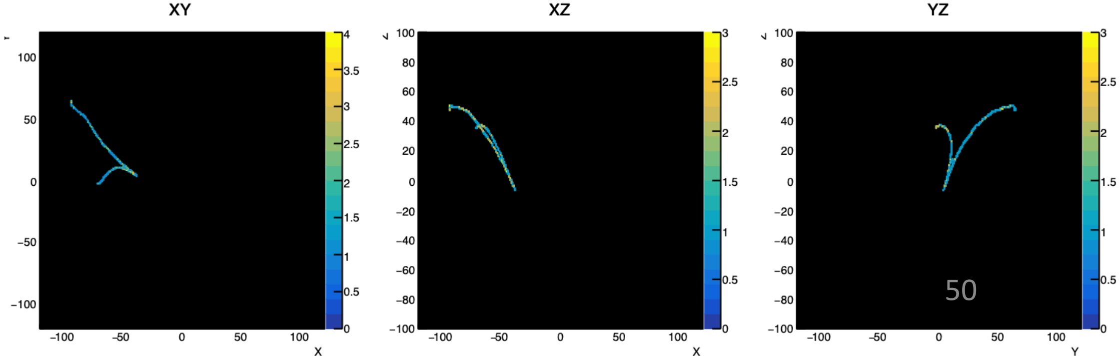


Event Display

contains all neutron, gamma induced hits

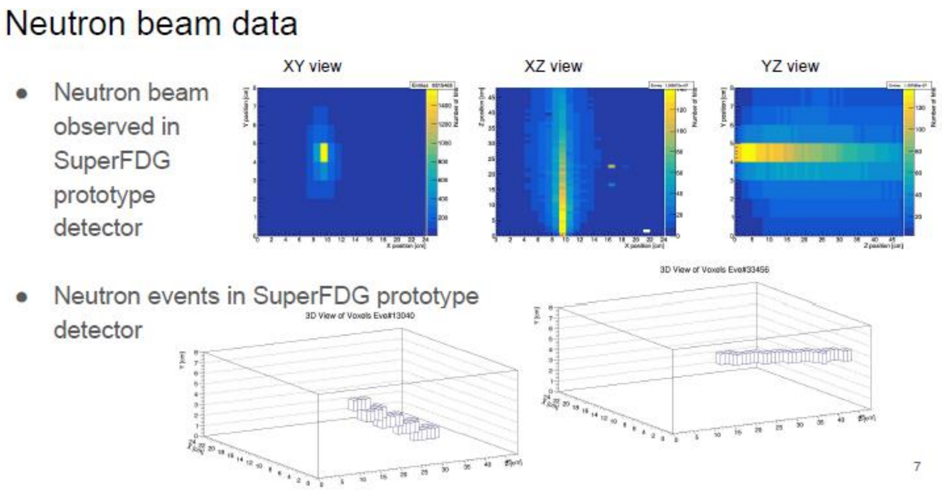


only the cluster



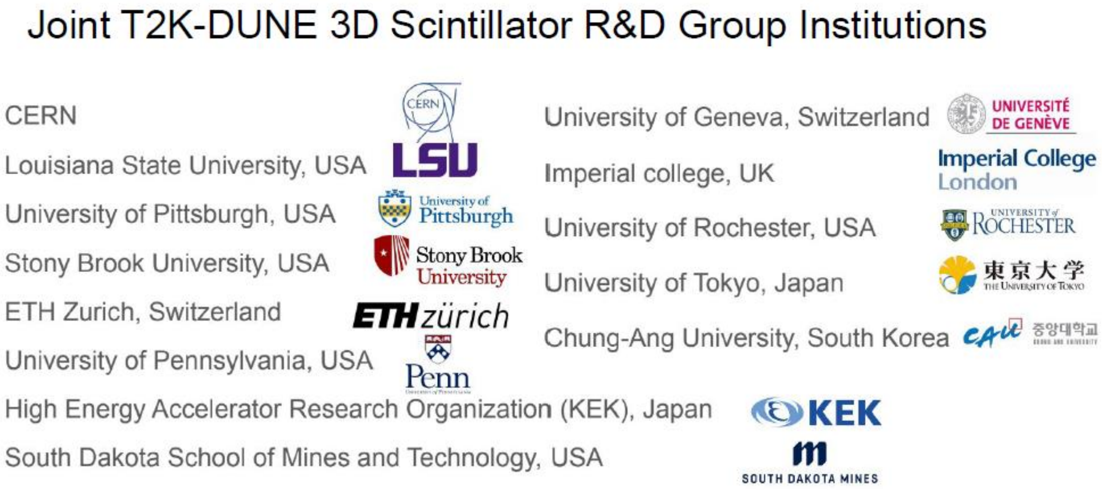
Los Alamos Neutron Beam test

- SuperFGD 24x8x48 (2019, 2020)
- 3DST prototype 8x8x32 (2020)



Neutron beam data

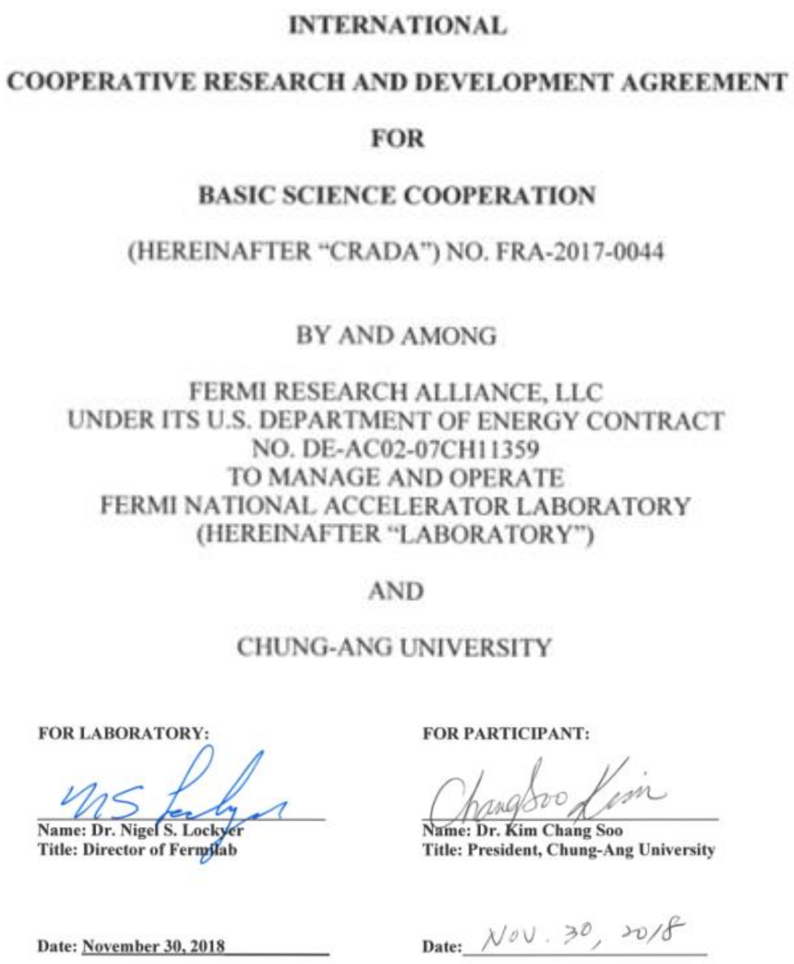
- Neutron beam observed in SuperFDG prototype detector
- Neutron events in SuperFDG prototype detector



Joint T2K-DUNE 3D Scintillator R&D Group Institutions

CERN
Louisiana State University, USA
University of Pittsburgh, USA
Stony Brook University, USA
ETH Zurich, Switzerland
University of Pennsylvania, USA
High Energy Accelerator Research Organization (KEK), Japan
South Dakota School of Mines and Technology, USA

University of Geneva, Switzerland
Imperial college, UK
University of Rochester, USA
University of Tokyo, Japan
Chung-Ang University, South Korea



INTERNATIONAL

COOPERATIVE RESEARCH AND DEVELOPMENT AGREEMENT

FOR

BASIC SCIENCE COOPERATION

(HEREINAFTER "CRADA") NO. FRA-2017-0044

BY AND AMONG

FERMI RESEARCH ALLIANCE, LLC
UNDER ITS U.S. DEPARTMENT OF ENERGY CONTRACT
NO. DE-AC02-07CH11359
TO MANAGE AND OPERATE
FERMI NATIONAL ACCELERATOR LABORATORY
(HEREINAFTER "LABORATORY")

AND

CHUNG-ANG UNIVERSITY

FOR LABORATORY:

Name: Dr. Nigel S. Lockyer
Title: Director of Fermilab

Date: November 30, 2018

FOR PARTICIPANT:

ChangSoo Kim

Name: Dr. Kim Chang Soo
Title: President, Chung-Ang University

Date: NOV. 30, 2018

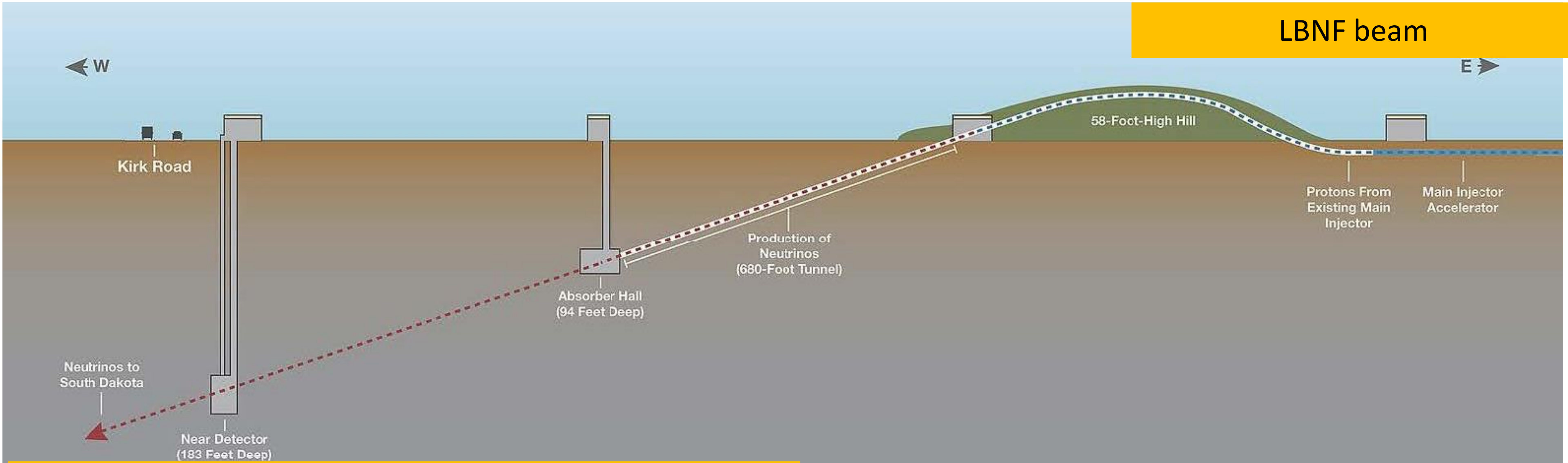
중앙대, 미 에너지부 산하 가속기 연구기관 '페르미랩'과 공동연구센터 설립

발행일 : 2020.04.07

[올쇼TV] IBM-코로나19 사태에 따른 상담 업무 환경의 변화 (4/24 생방송)

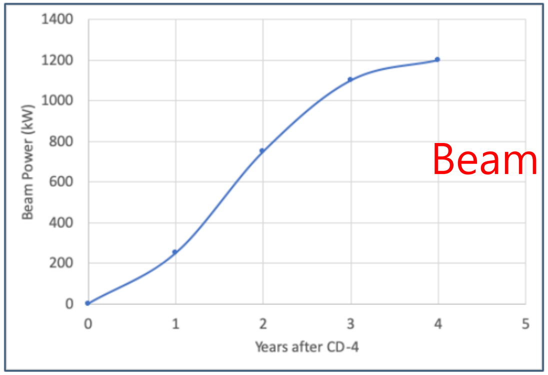
<중앙대 전경>

LBNF beam



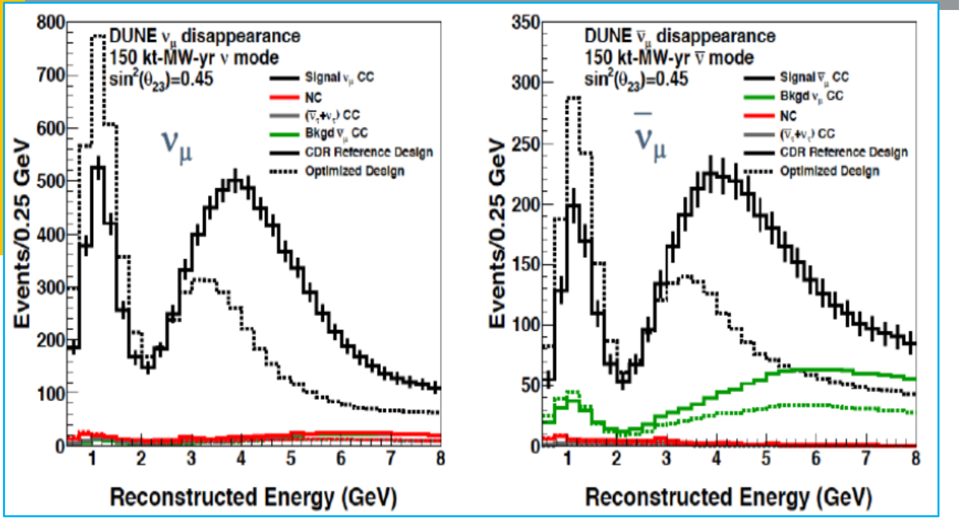
Long-Baseline Neutrino Facility

- Proton Improvement Plan (PIP-II)
- Initial 1.2 MW proton beam to be upgraded to 2.4 MW (proton energy 60-120 GeV)
- Beam optimization s. t. more flux at lower energies for better physics sensitivity
- Neutrino beam available in 2026

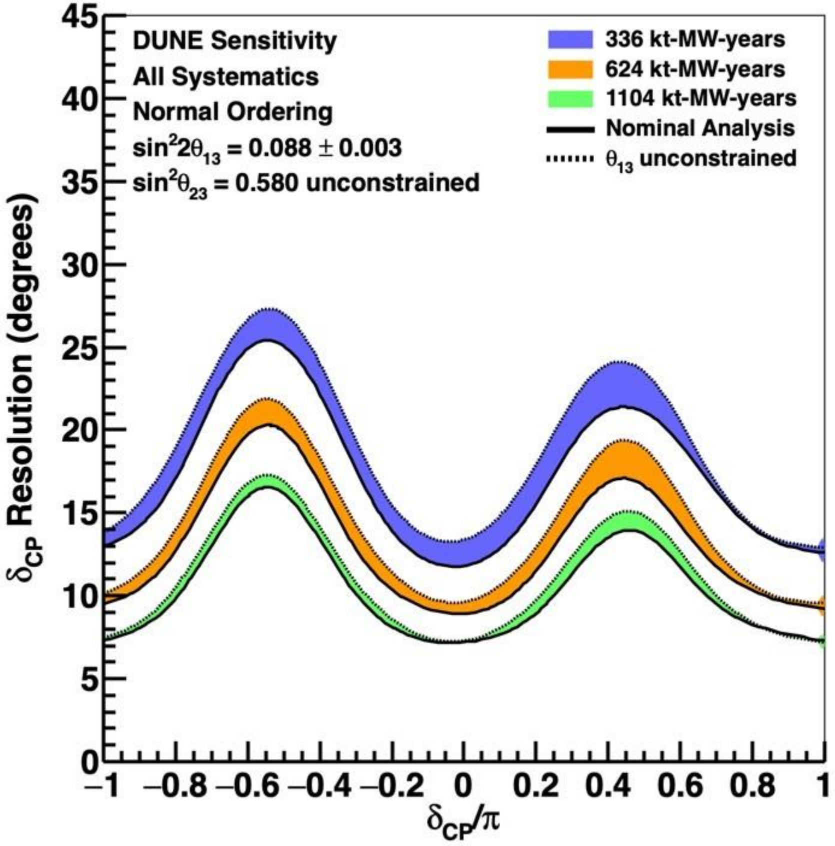


Beam Ramping plan

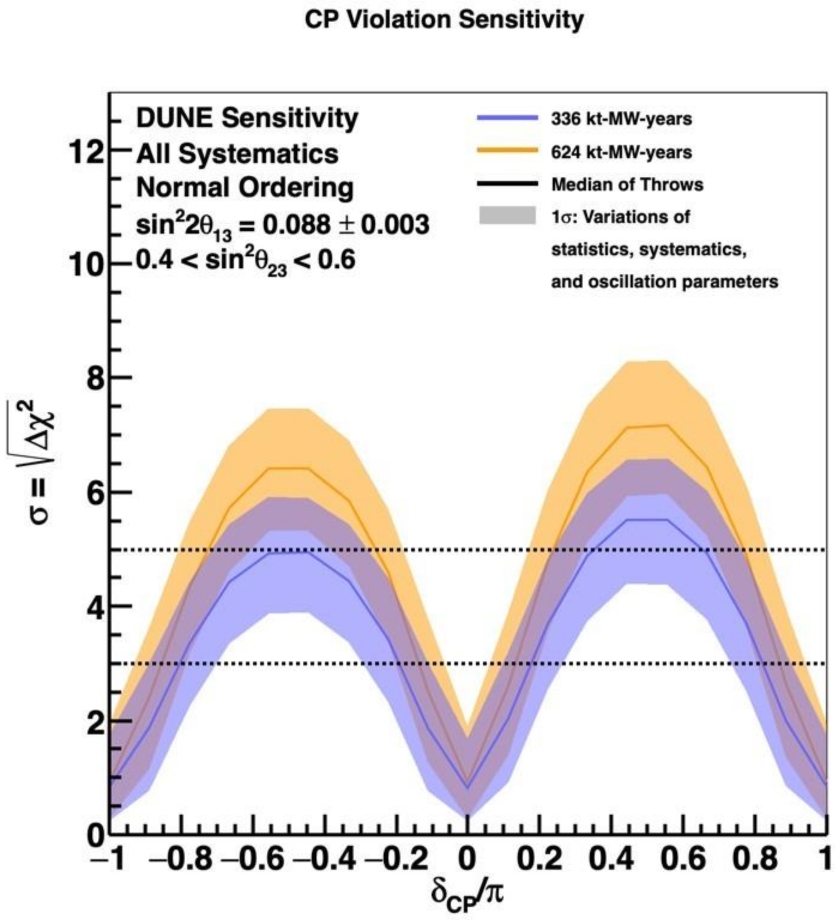
Beam Optimization



Physics potential: CP violation



CP Violation Sensitivity



- 7° resolution to δ_{CP} without dependence on other experiments, discovery sensitivity to CP violation over a broad range of possible values