Precision (Anti)Neutrino Interaction Measurements with SAND at DUNE

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University of Bologna and INFN Bologna

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ALMA MATER STUDIORUM
UNIVERSITÀ DI BOLOGNA

Outline

In this presentation:

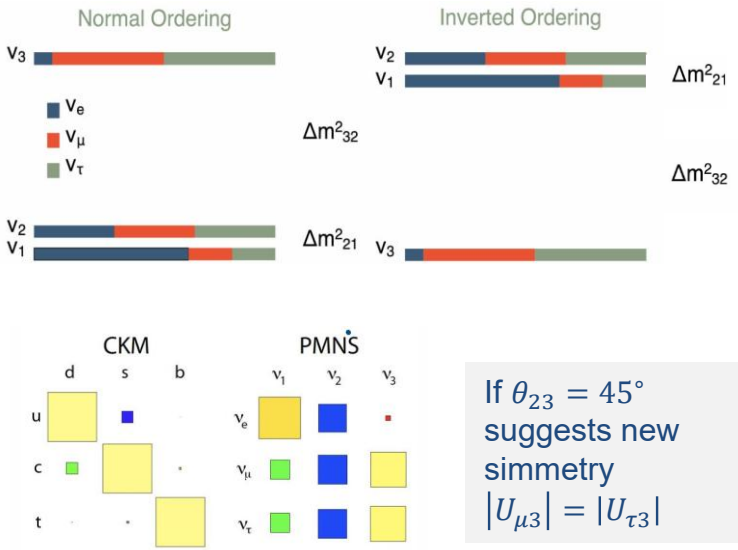
- Overview of the **DUNE experiment**, its physics goals, scope and composition
- Overview of the **SAND Near Detector**
- Introduction to the '**Solid Hydrogen**' technique in SAND: obtain a sample of neutrino interactions on hydrogen, devoid of nuclear effect systematics, by statistical subtraction
- Preliminary results from a 'Solid Hydrogen' **study** in the $\bar{\nu}_\mu$ **CCQE channel**

Neutrino physics: Open questions

- Mass-less in the Standard Model
- Evidence of flavour oscillations

→ **Mass** **Mixing**

- Many **open questions** still exist:
  - What is the neutrino mass ordering?
  - Is there leptonic CP violation?
  - Is θ_{23} mixing maximal?
  - Is the PMNS matrix unitary?
  - What is the neutrino absolute mass scale?
  - Are neutrinos Majorana particles?

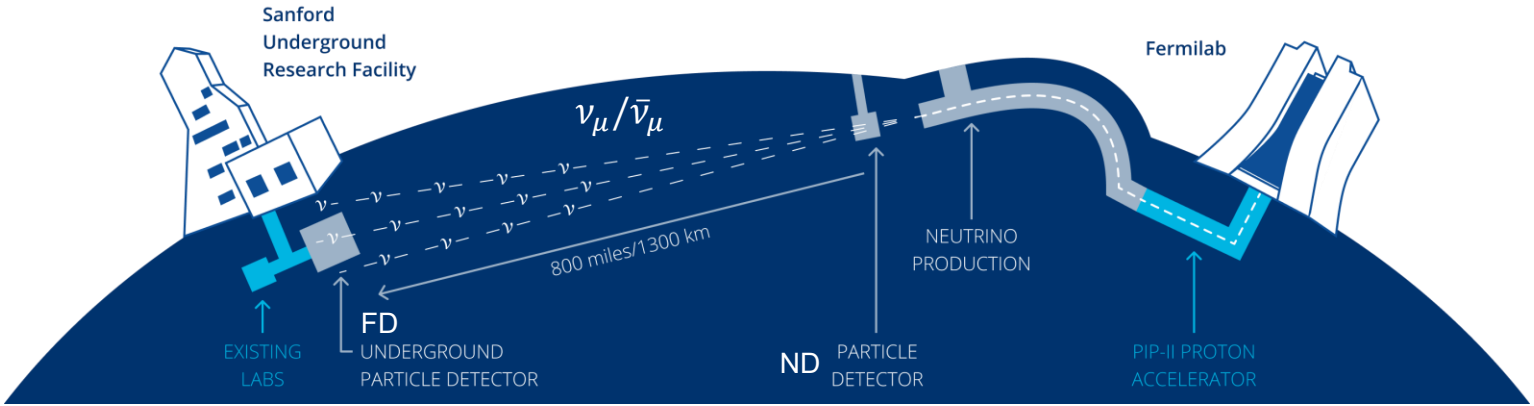


If $\theta_{23} = 45°$ suggests new simmetry $|U_{\mu 3}| = |U_{\tau 3}|$

Can be investigated in oscillation experiments

Need other dedicated experiments

The Deep Underground Neutrino Experiment



A new generation Long Baseline – 1300 km – neutrino oscillation experiment based on:

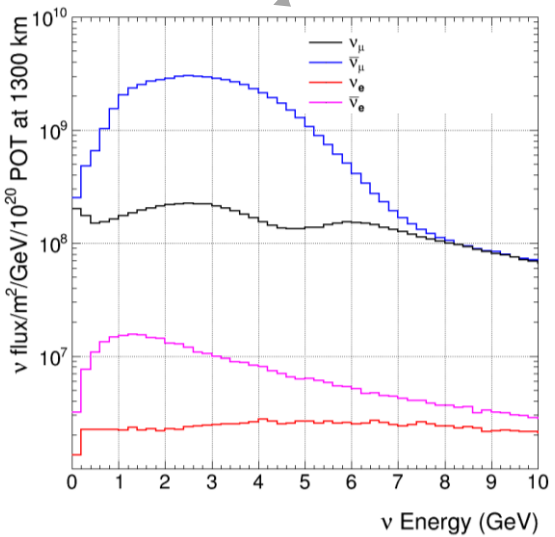
- a wide band high intensity (1.2 MW upgradable to 2.4 MW) $\nu/\bar{\nu}$ neutrino beam produced at Fermilab
- a large total mass (~70 kton) Far Detector at the Sanford Underground Neutrino Facility (SURF) 1.5 km underground exploiting the Liquid Argon Time Projection Chamber (LArTPC) technology
- a Near Detector complex (ND) at Fermilab providing control of systematic uncertainties, enabling a rich physics program

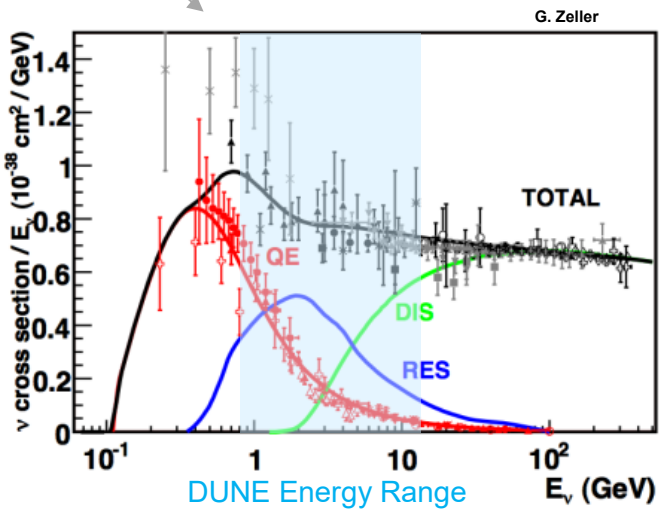
What do we actually measure?

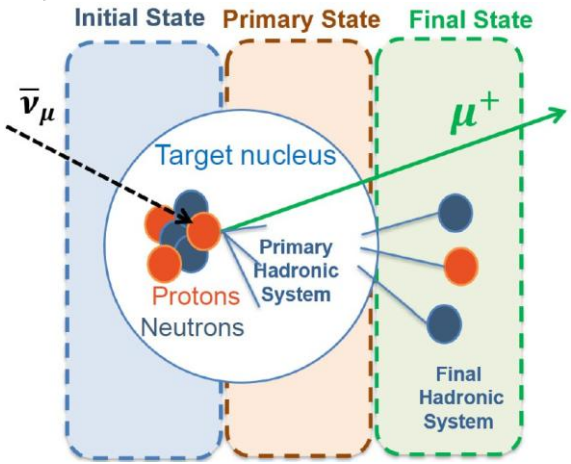
The **number of events N_x** at the Near/Far Detector for a process x, which is given by:

$$N_x(E_\nu) = \int P_{osc}(E_\nu)\, \Phi_{\bar{\nu}}\, \sigma_x(E_\nu)\, R_{phys}(E_\nu, E_{vis})\, \underline{R_{det}\,(E_{vis}, E_{rec})}\, \underline{\epsilon_x\,(E_{rec})}\, dE_\nu$$

Neutrino **flux** | **cross section** | **nuclear smearing** | **detector response** | **selection efficiency**





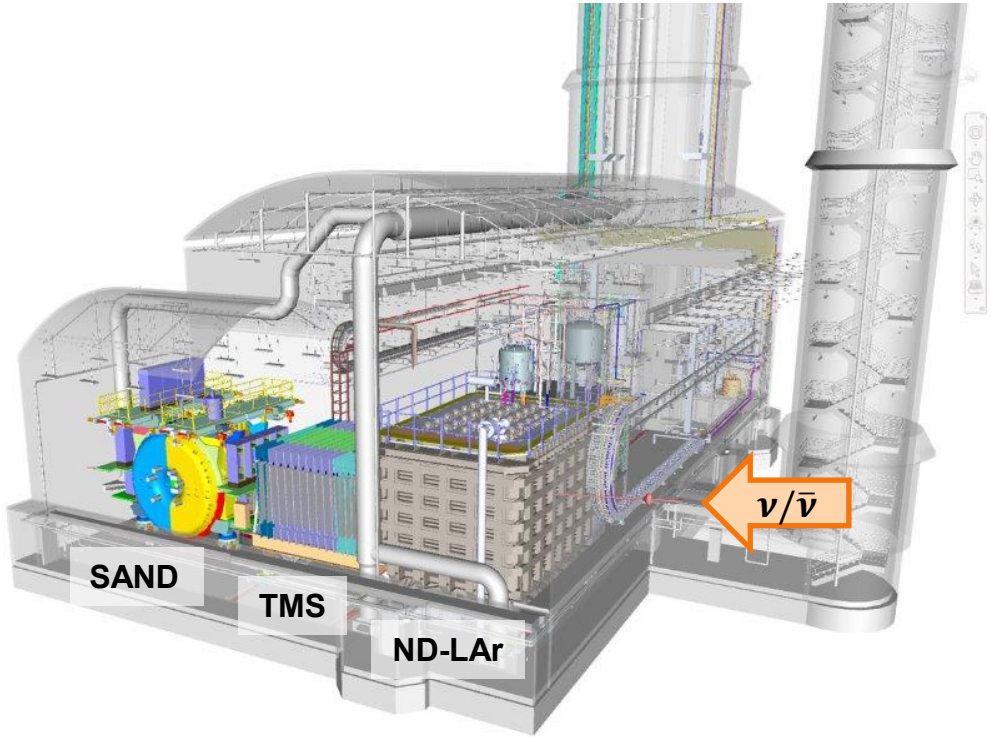


The Near Detector Complex

ND Hall : 574 m from LBNF target
60 m underground

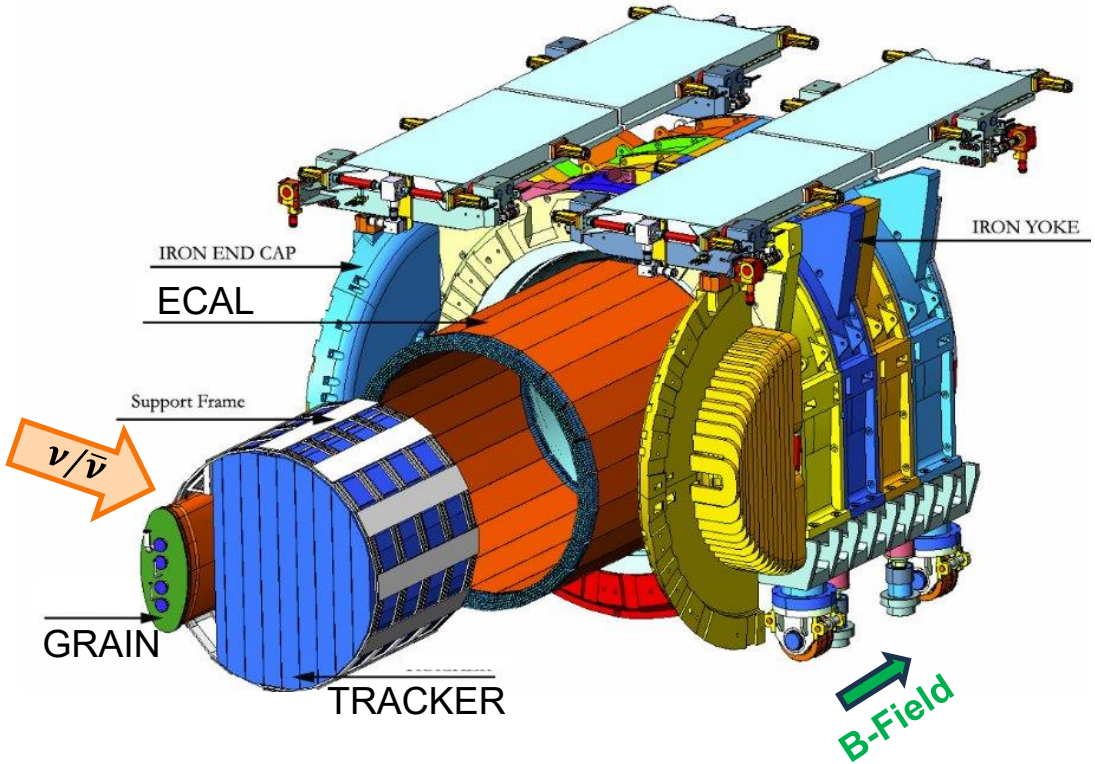
Configuration (Phase I):

- **ND-LAr:** 7 x 5 array of modular 1x1x3 m^3 LArTPC with pixel readout
- **TMS:** Magnetized steel range stack for measuring muon momentum/sign from ν_μ CC interactions in ND-LAr
- **DUNE-PRISM: ND-LAr + TMS** move up to 28.5 m off-axis to access narrow neutrino spectrum
- **SAND:** On-axis magnetized neutrino detector



The SAND (System for on-Axis Neutrino Detection)

- Solenoidal cryogenic magnet
  - Yoke of 475 t
  - **B field** of 0.6 T
- **Electromagnetic sampling calorimeter:**
  - 24 barrels modules of scintillating fibers and lead reused from KLOE
- Tracking system:
  - **Modular** and **low density** of about 5 t mass with overall 1 radiation length
- GRAIN (GRanular Argon for Interactions of Neutrinos)
  - 1 t liquid **argon** active target



‘Solid’ hydrogen concept

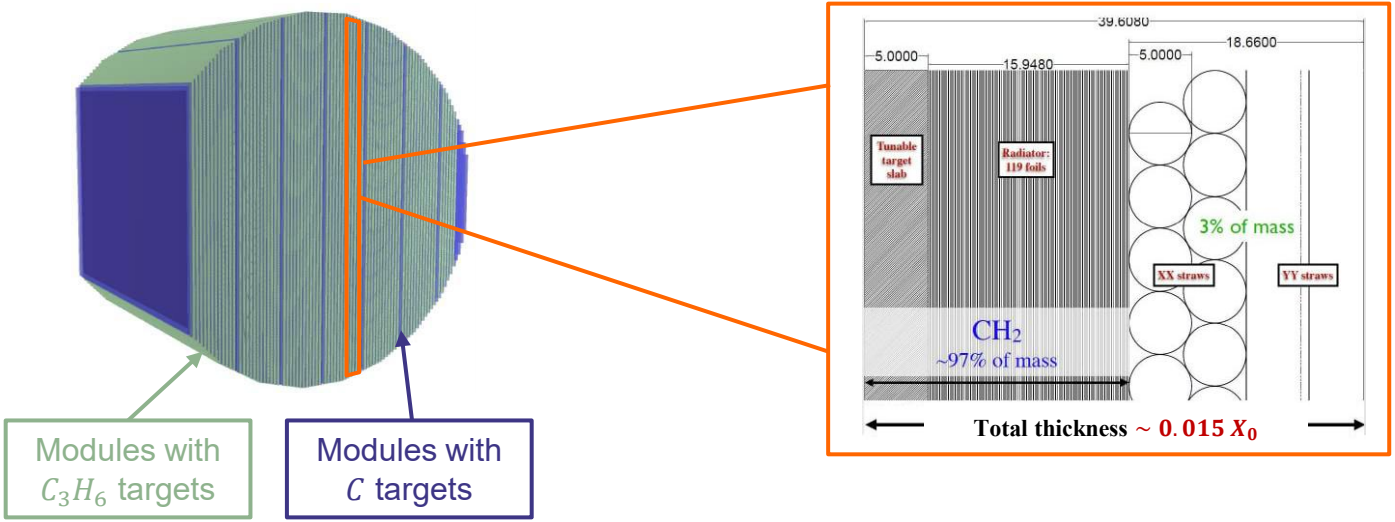
- Neutrino-hydrogen interactions are **free from nuclear effects** and thus are devoid of a major source of systematic uncertanties: $R_{phys}(E_\nu, E_{vis}) \equiv 1$
- It has been proposed that by using a neutrino detector that **alternates dedicated targets** of graphite (C) and polypropylene (C_3H_6), a sample of interactions on hydrogen can be obtained by **statistical subtraction**.
  - *“A Novel Approach to Neutrino-Hydrogen Measurements” H. Duyang, B. Guo, S.R. Mishra and R. Petti, https://doi.org/10.48550/arXiv.1809.08752*
- Selecting for a channel on Hydrogen for which the cross section is know, it should be possible to produce a **flux measurement unaffected by nuclear effect systematics**

The SAND detector tracker has been specifically designed to take advantage of this technique

The SAND tracker - Straw Tube Tracker

Straw Tube Tracker (baseline design) **:**

- Composed by a series of **passive target** slabs, and **active straw tube layers**
- 1 graphite target (pure C) for every 9 plastic (C_3H_6) targets
- Overall target mass: 4.7 t of plastic and 0.7 t graphite → **0.7 t of Hydrogen by subtraction!**



Solid Hydrogen Study

CC-QE Interaction

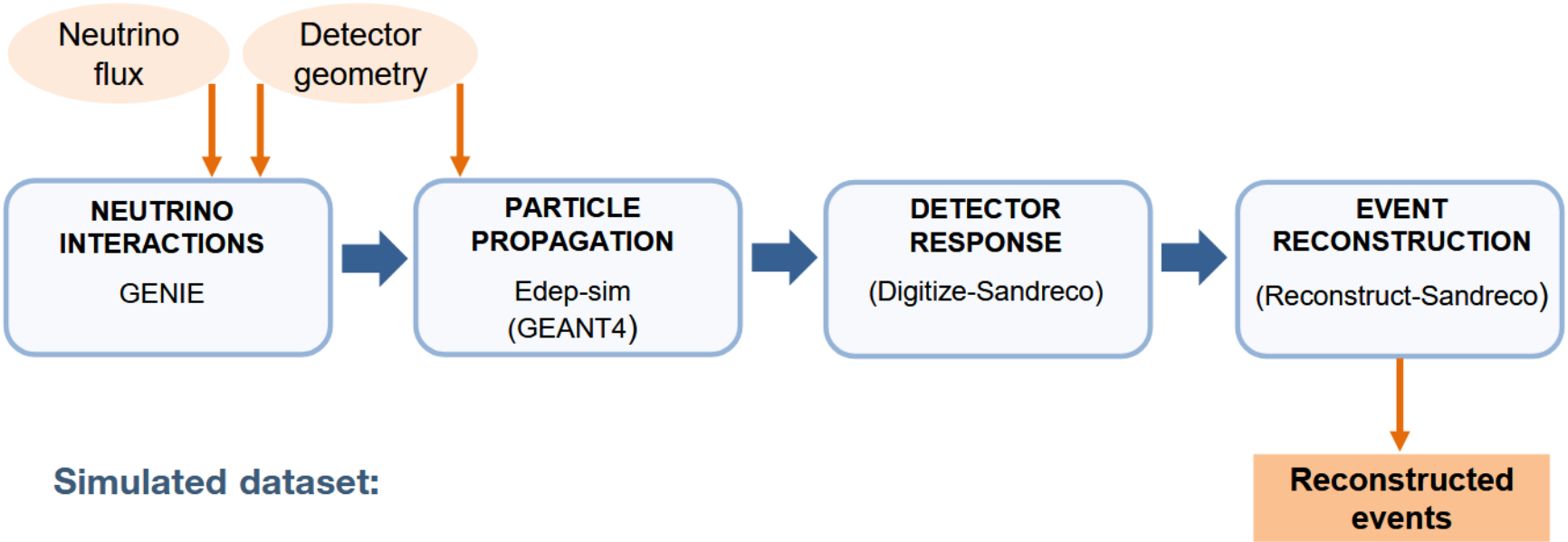
$$\bar{\nu}_\mu + H \rightarrow \mu^+ + n$$

Camilla Roselli, "Neutrino-hydrogen interactions in the SAND detector of the DUNE experiment", MsC thesis, University of Bologna. URL: https://amslaurea.unibo.it/id/eprint/37654/

Motivation:

- This is the simplest reaction in DUNE energy range for which we have a **theoretical parametrization** of the cross-section
- Muons can be reconstructed in charge and momentum in SAND's magnetized light tracker
- SAND's ECAL allows for a relatively straightforward tagging of neutrons with high efficiency and precision

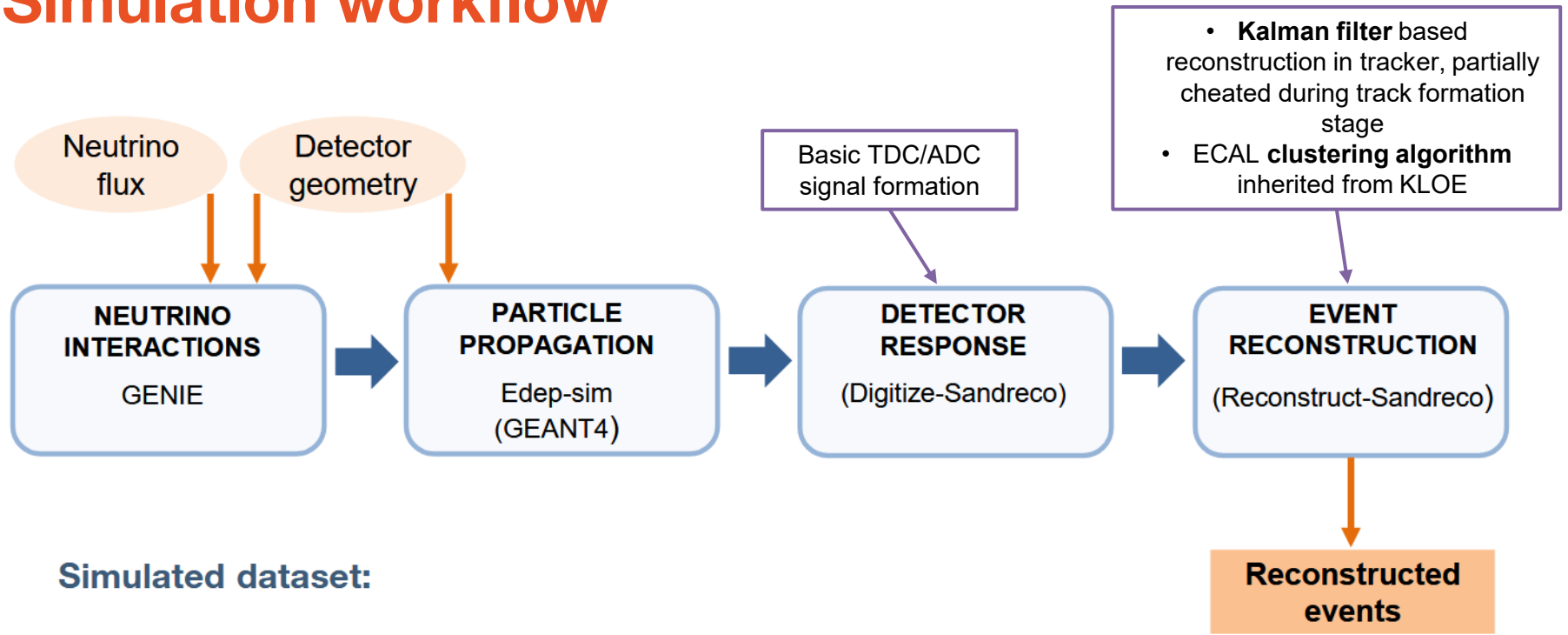
Simulation workflow



Simulated dataset:

- 1.6M $\bar{\nu}_\mu$ CC interactions in SAND tracker
- Five months of data taking at 1.2 MW

Simulation workflow



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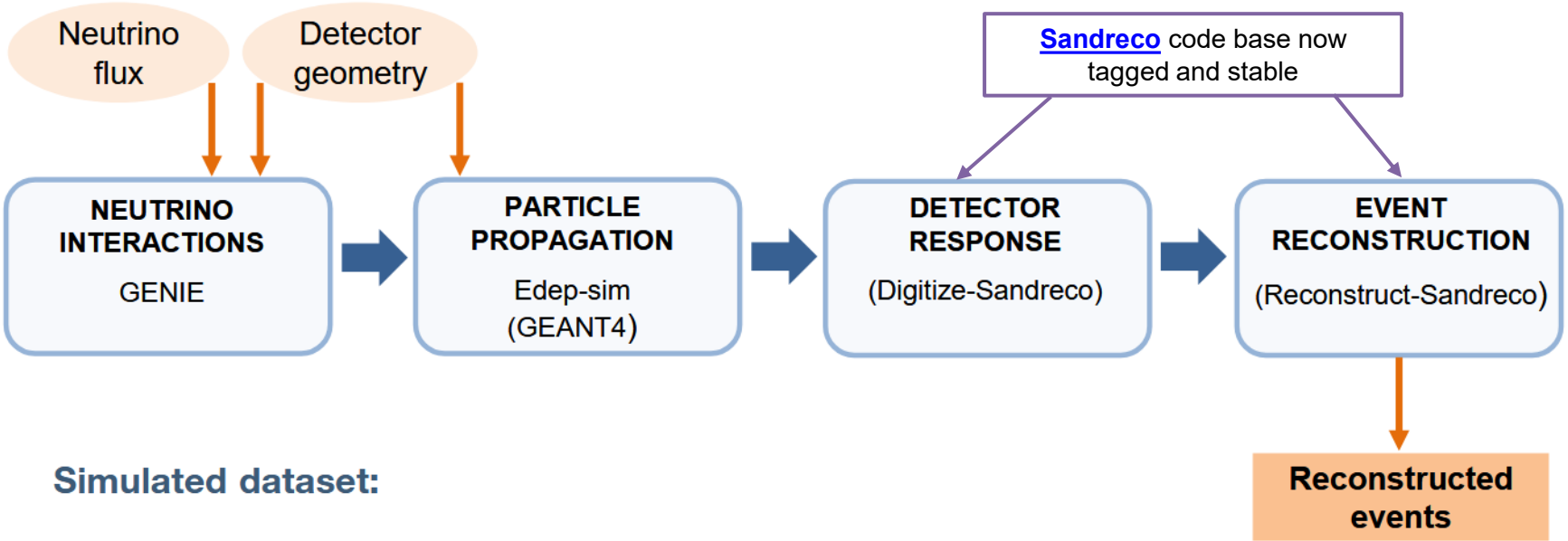


Simulated dataset:

- 1.6M $\bar{\nu}_\mu$ CC interactions in SAND tracker
- Five months of data taking at 1.2 MW

Selection of $\bar{\nu}_\mu + H \rightarrow \mu^+ + n$ in SAND

Selection method:

- ν-H interactions are perfectly balanced on the plane transverse to the neutrino direction
- The kinematics can be fully determined from the beam direction and the μ+ reconstructed 4-momentum:

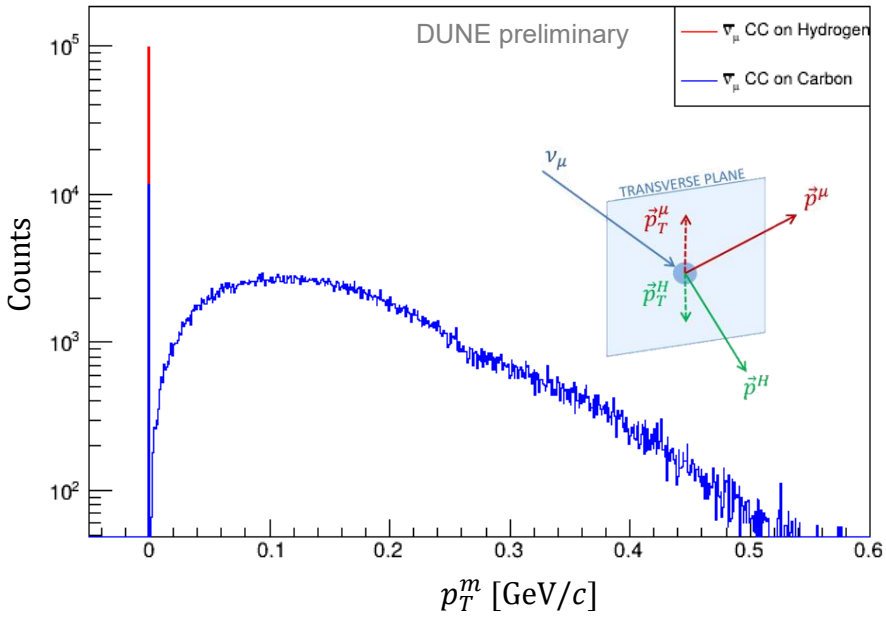
$$E_{\bar{\nu}_\mu}^{reco} = \frac{M_n^2 - m_\mu^2 - M_p^2 + 2M_p E_\mu^{reco}}{2(M_p - E_\mu^{reco} + p_\mu^{reco}\cos\theta_\mu^{reco})}$$

$$E_n^{pred} = E_{\bar{\nu}_\mu}^{reco} + M_p - E_\mu^{reco}$$

$$\vec{p}_n^{pred} = \vec{p}_\nu - \vec{p}_\mu$$

- The neutron is tagged in the ECAL from its starting position, direction and time of flight

Missing Transverse Momentum $p_m^T = \sum p_i^T$



Sample selection

SELECTION CRITERIA

- Neutrino vertex in the **fiducial volume**
- μ+ **reconstructed** in the tracker with >70 wires
- 1 charged particle associated with the neutrino vertex
- >1 ECAL hit consistent with the expected **neutron in time and position**

SELECTED SAMPLE

Sample on plastic C_3H_6 targets :

- **Signal:** - CCQE on H: $\bar{\nu}_\mu + H \rightarrow \mu^+ + n$
- **Bkg:** - CCQE on C: $\bar{\nu}_\mu + p \rightarrow \mu^+ + n$
  - CCRES on C: $\bar{\nu}_\mu + p(n) \rightarrow \mu^+ + n + \pi^0(\pi^-)$
  - Other CC on H, like RES: $\bar{\nu}_\mu + H \rightarrow \mu^+ + n + \pi^0$

Control sample on graphite C targets:

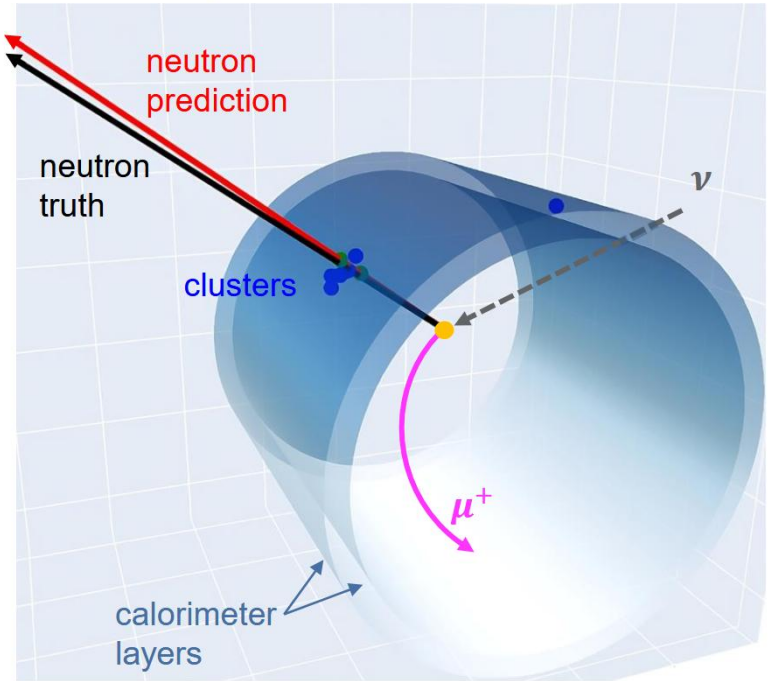
- **Signal:** - CCQE on C: $\bar{\nu}_\mu + p \rightarrow \mu^+ + n$
  - CCRES on C: $\bar{\nu}_\mu + p(n) \rightarrow \mu^+ + n + \pi^0(\pi^-)$

Sample selection

SELECTION CRITERIA

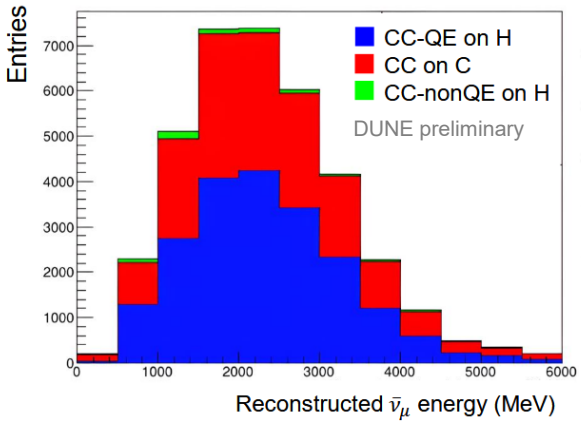
- Neutrino vertex in the **fiducial volume**
- μ+ **reconstructed** in the tracker with >70 wires
- 1 charged particle associated with the neutrino vertex
- >1 ECAL hit consistent with the expected **neutron in time and position**

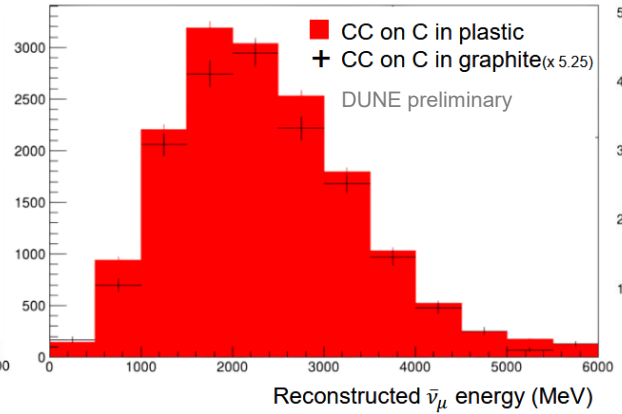
Display of a signal event

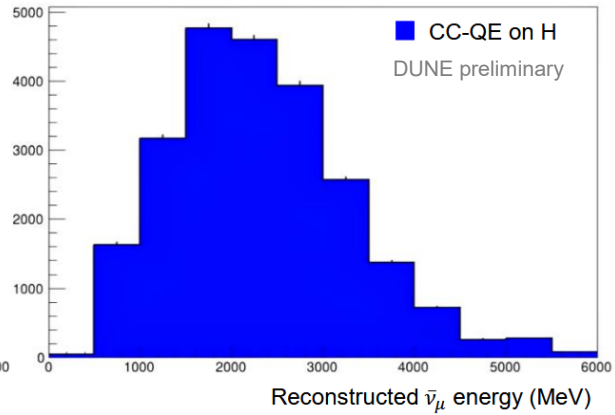


Statistical Subtraction

- **Solid Hydrogen technique:** the **reconstructed signal rate** as function of the **neutrino reconstructed energy,** is obtained from a **statical subtraction** of the measured background giving the (nearly) same detector acceptances.







C_3H_6 − k · C = ‘Solid’ Hydrogen

Unfolding of the event rate on Hydrogen

- The **reconstructed** signal rate differs from the **true** rate by the convoluted effect of the **detector resolution** and signal selection **efficiency.**

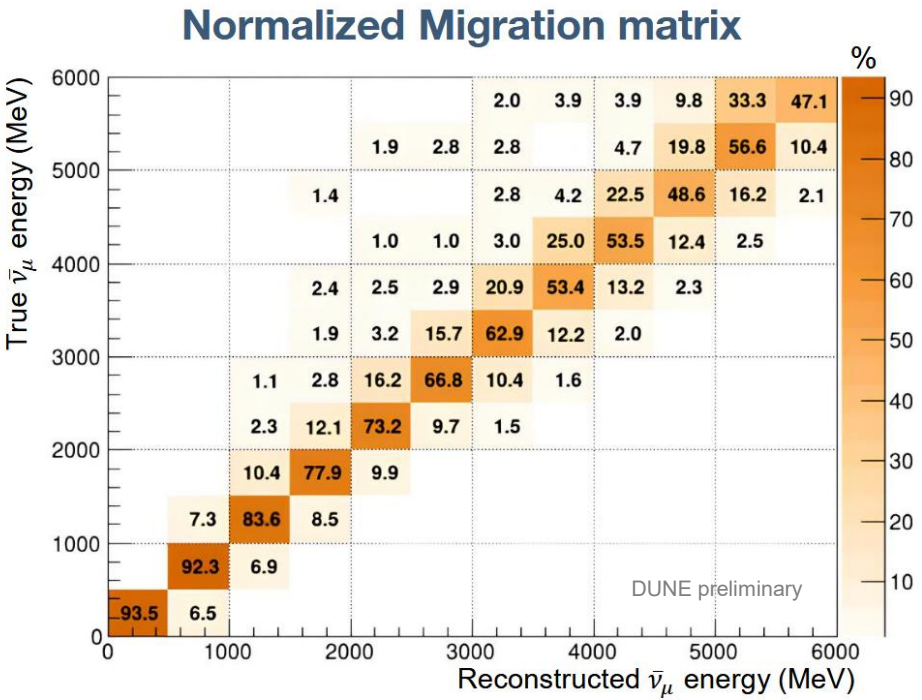
$$x_{reco} \sim \Phi \otimes \sigma \otimes \epsilon \otimes R$$

flux · cross section · selection efficiency · detector response

- The **unfolding** procedure corrects the reconstructed signal rate for the effect of the detector response and efficiencies

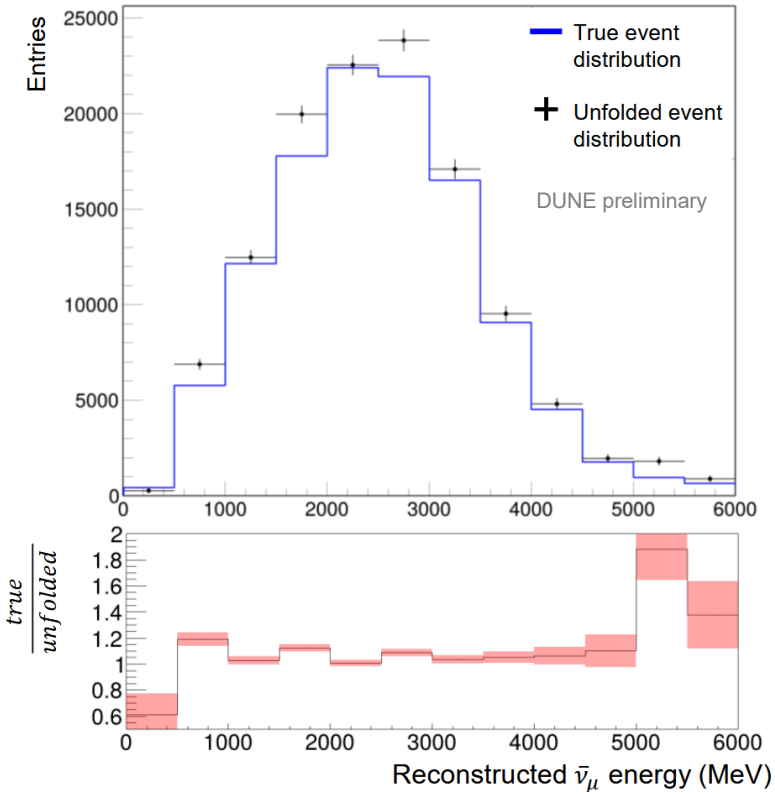
$$x_{\text{unfolded}} \sim M\, x_{reco} \sim \Phi \otimes \sigma$$

Migration matrix: filled with signal events that pass the event selection



Unfolding of the interaction rate

- The systematic uncertainties are obtained from the ratio between the unfolded event rate and the true event rate
- The systematic uncertainties are estimated to be less than 10% in the energy range (3-5) GeV



Conclusions and Outlooks

Summary

- To achieve DUNE's physics goals, SAND needs to constrain the systematic uncertainties
- To constrain systematic uncertainties, SAND will extract through statistical subtraction a target of Hydrogen which is free from nuclear effects
- This preliminary study, which focuses on the $\bar{\nu}_\mu$ CC-QE channel, achieves less than 10% systematic uncertainties of the subtraction technique with a simulated sample equivalent to ~ 5 months of data taking at 1.2 MW

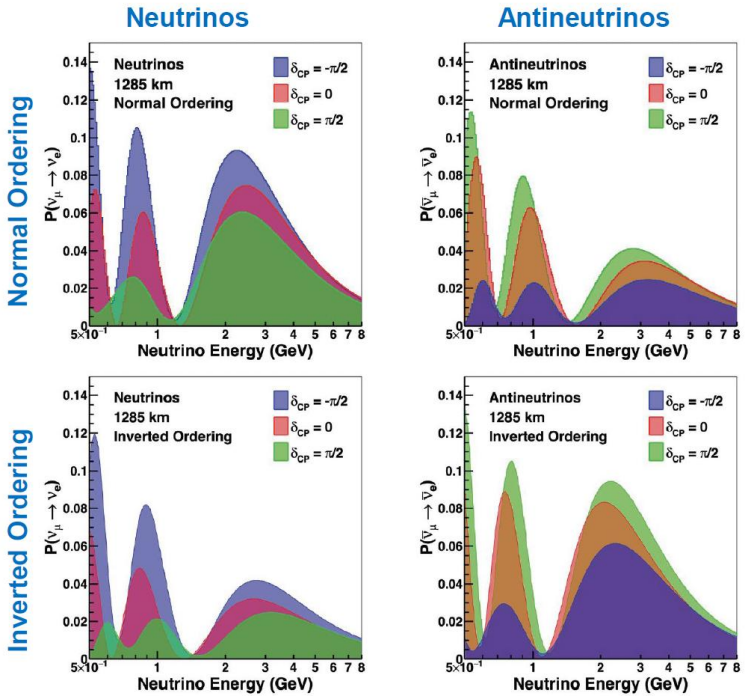
Outlook & Conclusions

- **Current uncertainty is not sufficient, but the estimate is limited in statistics**: with more than 5 month of data, uncertainties should improve by a few percent
- **Several steps can and will be improved**, this is only to be taken as a **proof of concept** (better muon reconstruction, enhanced hit reconstruction on the calorimeter, better selection methods etc.)

Thank you !

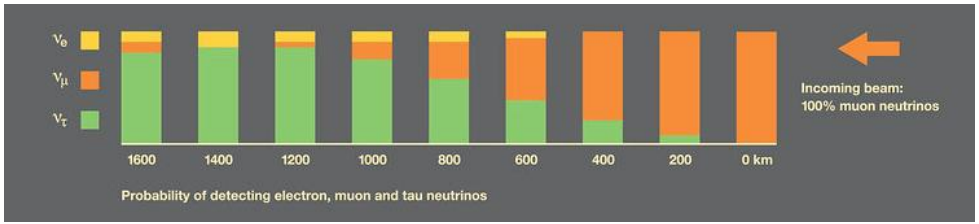
backup

The oscillation measurement



$\nu_e/\bar{\nu}_e$ **oscillation shapes**

$P(\nu_\mu \to \nu_e)$ **VS** $P(\bar{\nu}_\mu \to \bar{\nu}_e)$



- Mass ordering and CP violation induce **different shapes in $\nu_e/\bar{\nu}_e$ oscillation probabilities**
- **DUNE's unique capability** : with a **wide band beam** measures these shapes over more than a full period resolving degeneracies. Not simply a counting experiment!

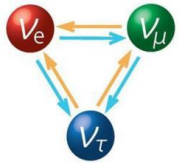
Mass ordering + CP violation + θ_{23} octant in a single experiment

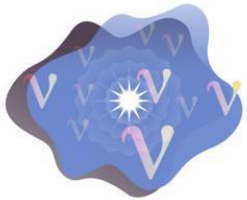
DEEP UNDERGROUND NEUTRINO EXPERIMENT

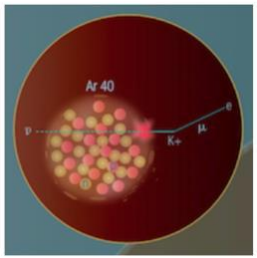
- 1300+ collaborators
- 36 countries
- 200+ institutions including CERN

DUNE Collaboration Meeting, CERN January 2023

DUNE's Physics program







Long-baseline wide-band neutrino beam

- Measurement of CP violation phase, mixing angles and neutrino mass ordering in a single experiment using spectral information

Underground location → access to astrophysical neutrinos

- Supernova neutrino burst detection–sensitive to the ν_e component
- Atmospheric neutrino – capability of ν_τ identification
- Solar neutrinos – potential for detection of hep flux

Massive detectors with tracking and calorimetric information

- Search for baryon number violating processes – $p \to \nu K^+, n\bar{n}$

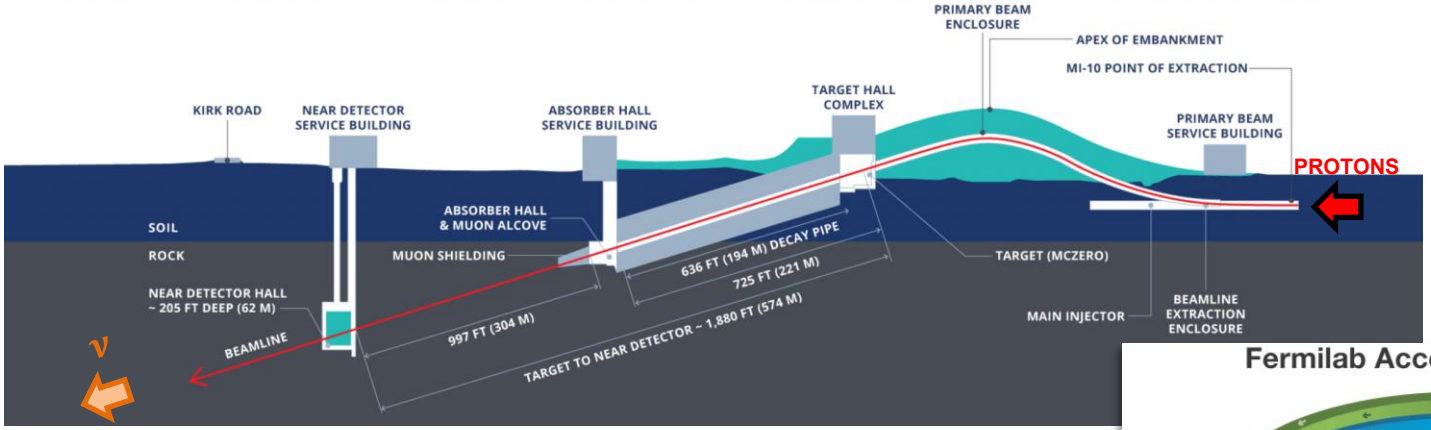
Long baseline + higher energy neutrino beam

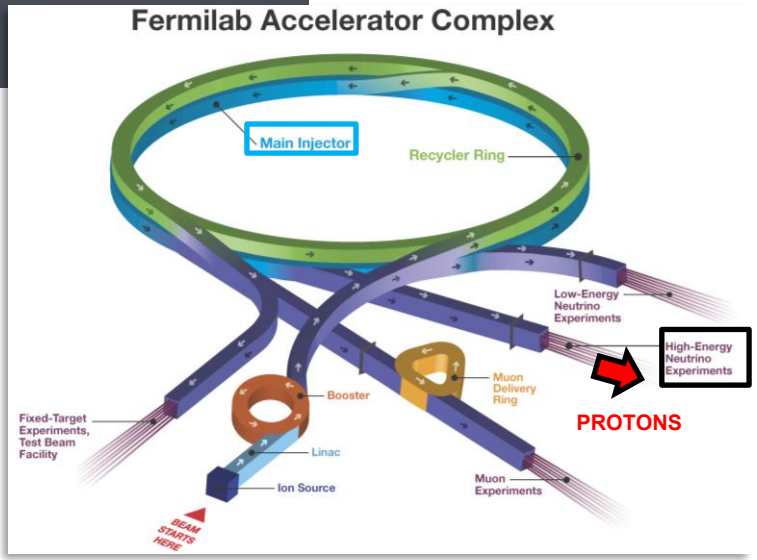
- ν_τ appearance, NSI searches

Capable Near Detector Complex

- Precise neutrino physics (cross sections, nuclear effects)
- BSM searches

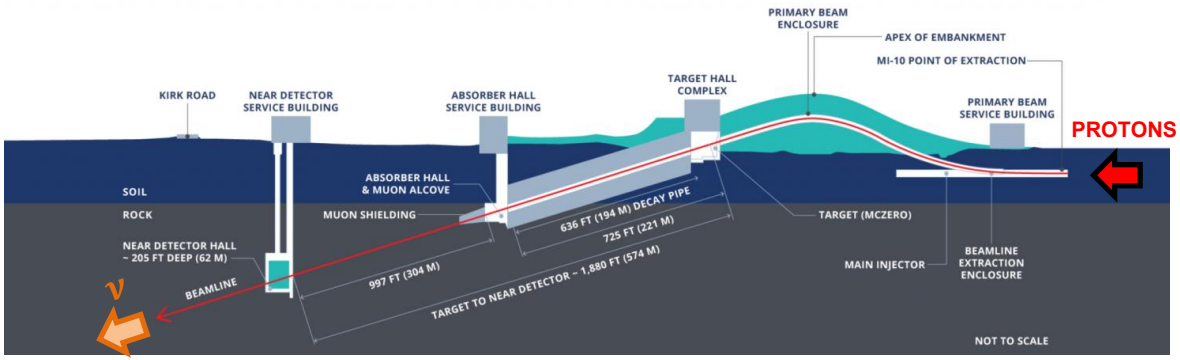
The LBNF beam

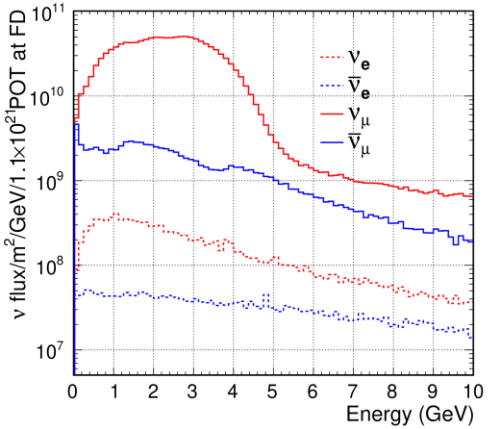




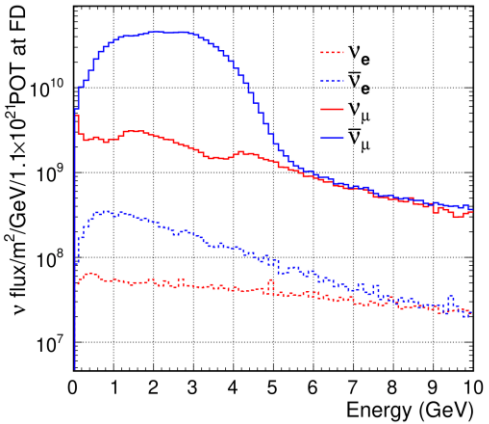
- LBNF will use accelerated protons from the Main Injector: start at 1.2 MW (Phase I) and then upgraded to 2.4 MW (Phase II)
- Primary proton beam (60-120 GeV) on a graphite target at 5.8° slope: $(1.1 - 1.9)10^{21} \frac{pot}{yr}$

The LBNF beam





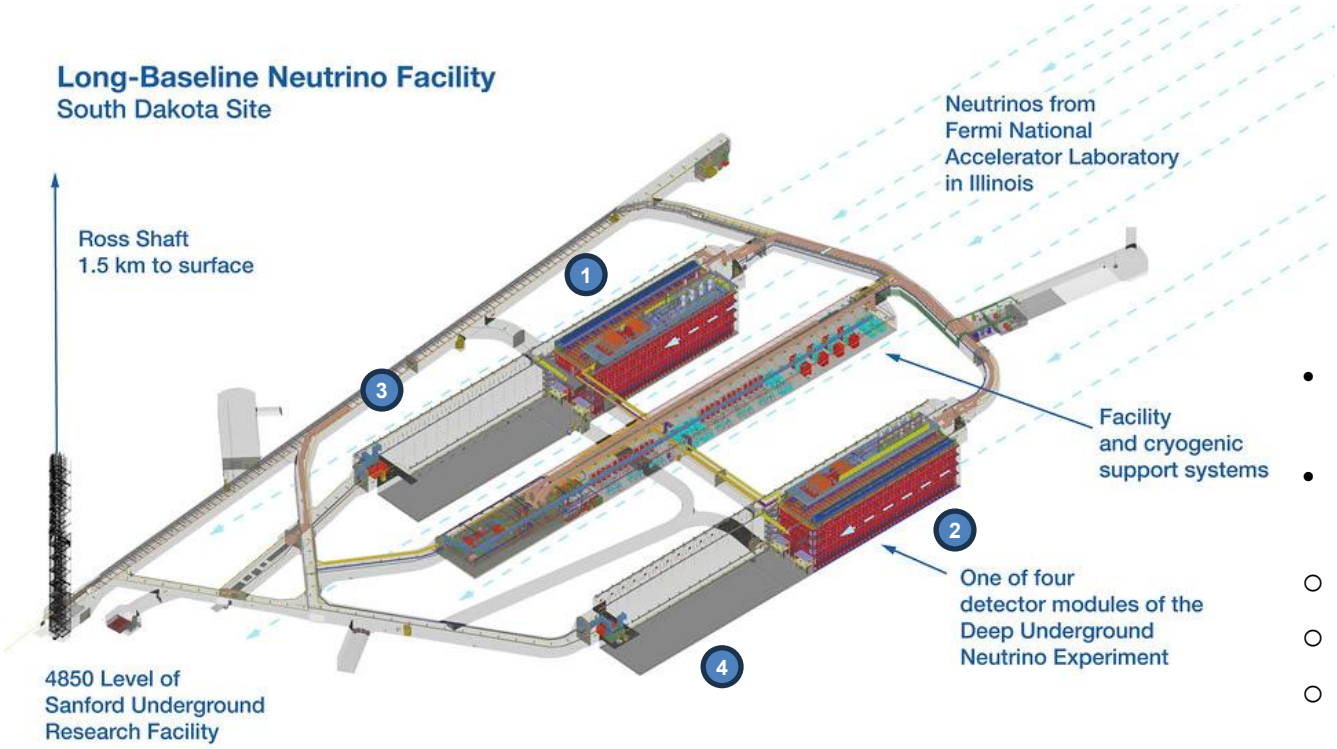
FHC
ν-mode

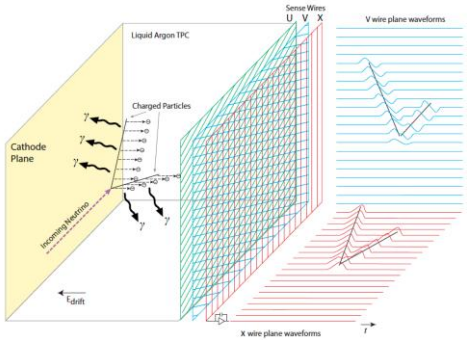


RHC
$\bar{\nu}$-mode

- LBNF will use accelerated protons from the Main Injector: start at 1.2 MW (Phase I) and then upgraded to 2.4 MW (Phase II)
- Primary proton beam (60-120 GeV) on a graphite target at 5.8° slope: $(1.1 - 1.9)10^{21}\frac{pot}{yr}$
- Forward Horn Current (FHC): neutrino enhanced
- Reverse Horn Current (RHC): antineutrino-enhanced

The Far Detector Complex at SURF





LArTPC: best particle imaging at kton scale

- Sanford Underground Research Facility in Lead, South Dakota
- 4 x 17-kt LAr TPC modules, located 1.48 km underground
  - **FD1** – Horizontal Drift LArTPC
  - **FD2** – Vertical Drift LArTPC
  - Phase-2 - **FD3** (decision 2027) - **FD4** module of opportunity (decision 2028)

The Far Detector Complex at SURF

Caverns excavations completed in 2024 on budget and on-schedule!