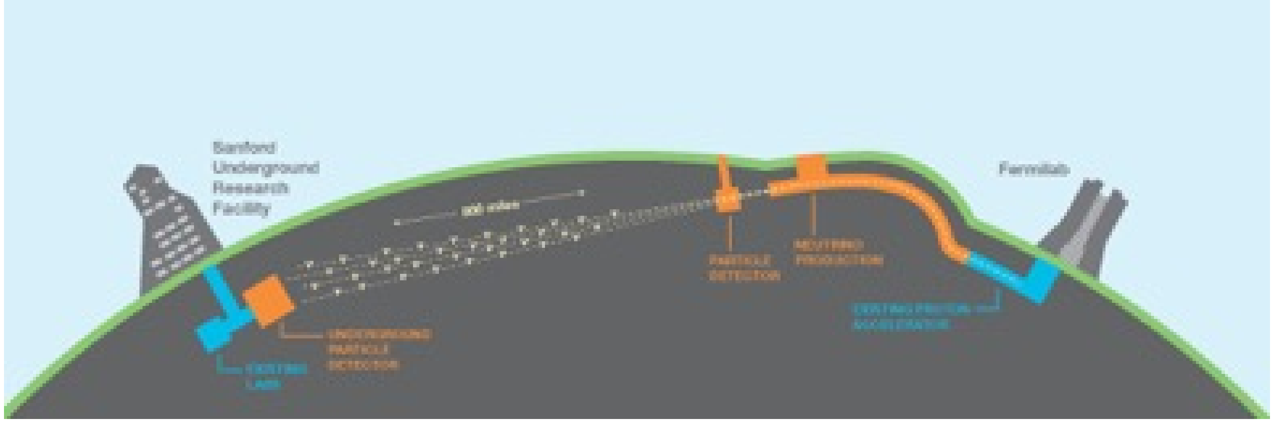
Next Generation neutrino Experiments at Accelerators: the DUNE Experiment at FNAL



Sergio Bertolucci
University of Bologna and INFN
Pisa 21/07/2021

Looking for “unknown unknowns”

Needs a synergic use of:

- High-Energy colliders
- neutrino experiments (solar, atmospheric, cosmogenic, short/long baseline, reactors, $0\nu\ \beta\beta$ decays, masses)
- cosmic surveys (CMB, Supernovae, BAO, Dark E)
- gravitational waves
- dark matter direct and indirect detection
- precision measurements of rare decays and phenomena
- dedicated searches (WIMPS, axions, dark-sector particles)
- …..

From the P5 Report (USA)

Recommendation 12 : In collaboration with international partners, develop a coherent short- and long-baseline neutrino program hosted at Fermilab.
The minimum requirements to proceed are the identified capability to reach an exposure of at least **120 kt*MW*yr by the 2035 timeframe**, the far detector situated **underground** with cavern space for expansion **to at least 40 kt LAr fiducial** volume, and **1.2 MW beam power upgradable to multi megawatt** power. The experiment should have the demonstrated capability to search for **supernova (SN) bursts** and for **proton decay**, providing a significant improvement in discovery sensitivity over current searches for the proton lifetime.

From the European Strategy Document

f) Rapid progress in neutrino oscillation physics, with significant European involvement, has established a strong scientific case for a long-baseline neutrino programme exploring CP violation and the mass hierarchy in the neutrino sector.

CERN should develop a neutrino programme to pave the way for a substantial European role in future long-baseline experiments.

Europe should explore the possibility of major participation in leading long-baseline neutrino projects in the US and Japan.

From Japan HEP Community

The committee makes the following recommendations concerning large-scale projects, which comprise the core of future high energy physics research in Japan.

……….

Should the neutrino mixing angle $\boldsymbol{\theta}_{13}$ be confirmed as large, **Japan should aim to realize a large-scale neutrino detector through international cooperation**, accompanied by the necessary reinforcement of accelerator intensity, so allowing studies on CP symmetry through neutrino oscillations.
This new large-scale neutrino detector should have sufficient sensitivity to allow the search for proton decays, which would be direct evidence of Grand Unified Theories.

Standard Three Neutrino Paradigm

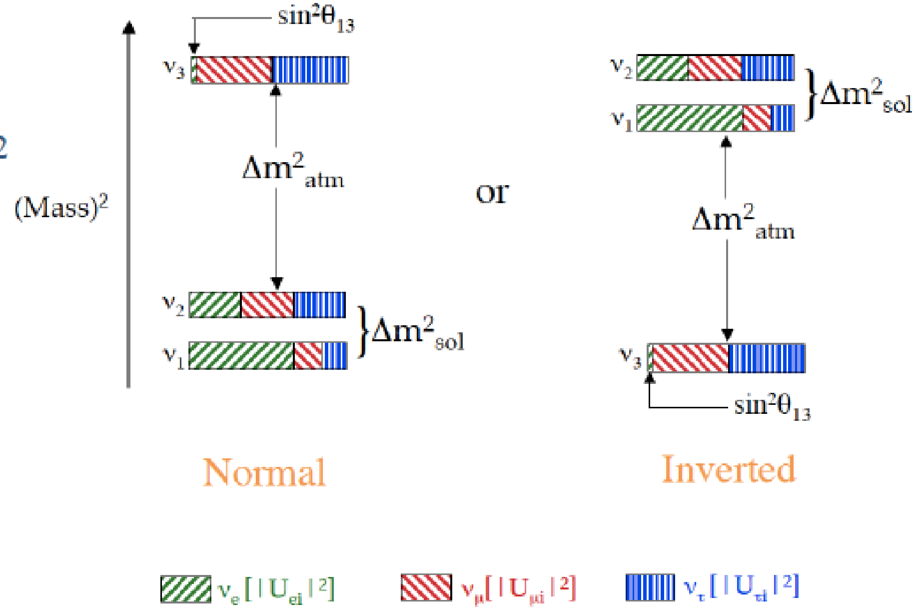
Unitary PNMS matrix described by 3 Euler angles ($\theta_{12}, \theta_{13}, \theta_{23}$) and 1 complex phase ($\delta$). $\delta \neq \{0, \pi\}$ → **CP Violation**

$$U_{\rm PMNS} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} = \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}}_{\theta_{23} \sim 45^\circ} \underbrace{\begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix}}_{\theta_{13} \sim 9^\circ} \underbrace{\begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{\theta_{12} \sim 30^\circ}$$

$$s_{ij} = \sin\theta_{ij}\ ;\ c_{ij} = \cos\theta_{ij}$$

$\Delta m^2_{atm} \sim 2.5 \times 10^{-3}$ eV^2

$\Delta m^2_{sol} \sim 7.5 \times 10^{-5}$ eV^2

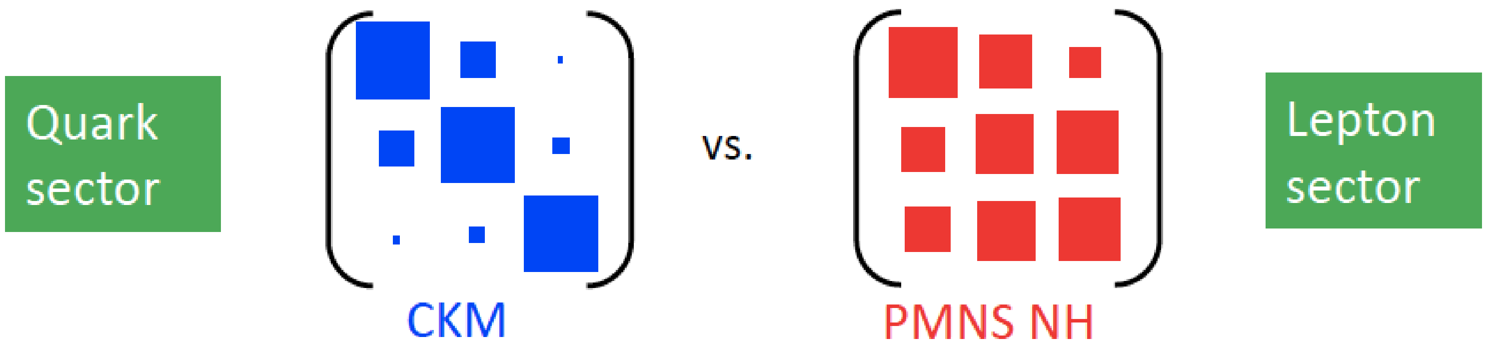


Key Questions in Neutrino Physics

- Do neutrinos violate CP symmetry?

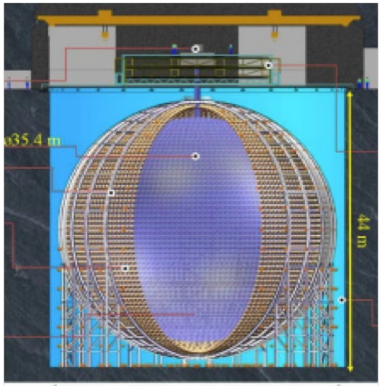
$$P(\nu_\mu \to \nu_e) - P(\bar{\nu}_\mu \to \bar{\nu}_e) = -16 s_{12} c_{12} s_{13} c_{13}^2 s_{23} c_{23} \sin\delta \sin\left(\frac{\Delta m_{12}^2}{4E} L\right) \sin\left(\frac{\Delta m_{13}^2}{4E} L\right) \sin\left(\frac{\Delta m_{23}^2}{4E} L\right)$$

- What is the mass ordering?
- Why are the quark and neutrino mixing matrices so different?



- Are there additional neutrino states?
- Are neutrinos their own antiparticles?
- What is the neutrino mass?

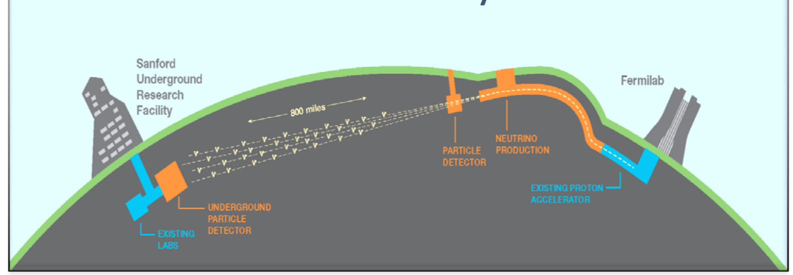
An Exciting Global Initiative to Understand the Most Abundant Known Matter Particle in the Universe

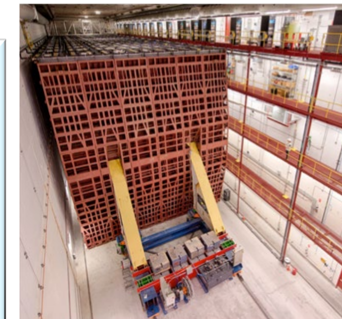


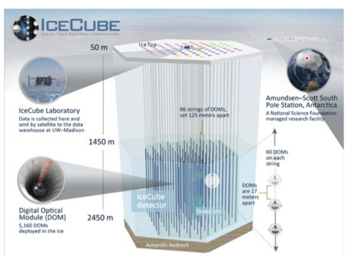
Deep Underground Neutrino Experiment

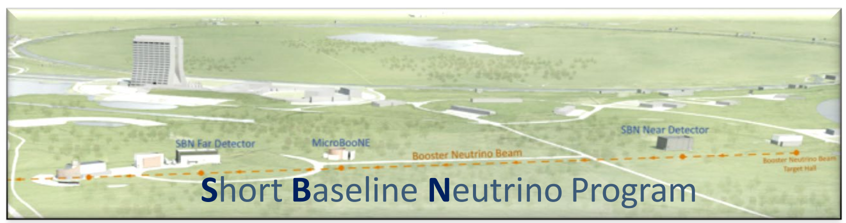
at the

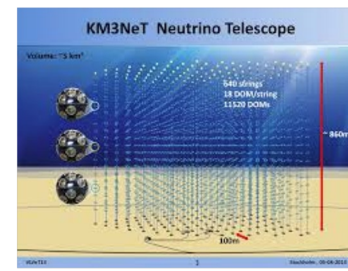
Long Baseline Neutrino Facility

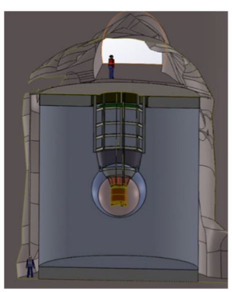


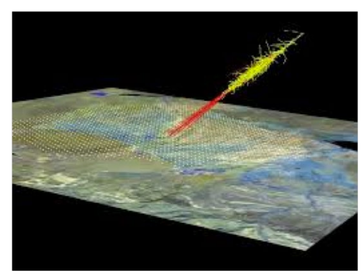


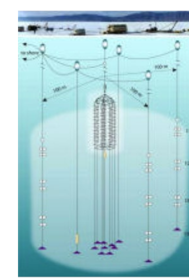












How to search for CP violation

- Compare oscillation oscillation rates for νs and $\bar{\nu}$s

$$P(\nu_\mu \to \nu_e) - P(\bar{\nu}_\mu \to \bar{\nu}_e) = -16 s_{12} c_{12} s_{13} c_{13}^2 s_{23} c_{23} \sin\delta \sin\left(\frac{\Delta m_{12}^2}{4E} L\right) \sin\left(\frac{\Delta m_{13}^2}{4E} L\right) \sin\left(\frac{\Delta m_{23}^2}{4E} L\right)$$

(in vacuum)

- As in quark sector, CP violating effects $\propto J \equiv c_{12} c_{23} c_{13}^2 s_{12} s_{23} s_{13} \sin\delta$, and require no degenerate masses

- We know mixing angles and mass differences, so we can measure $P(\nu_\mu \to \nu_e) - P(\bar{\nu}_\mu \to \bar{\nu}_e)$ and determine δ, but there is a complication...

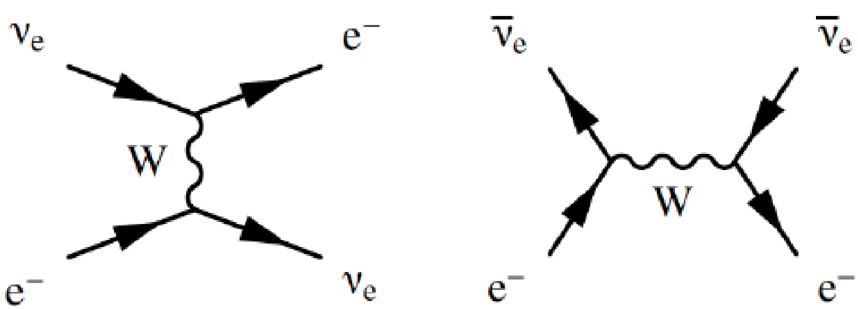
Matter Effects

- In real experiments, even in the absence of CPV,

$$P(\nu_\mu \rightarrow \nu_e) - P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) \neq 0$$

Neutrinos travel through material that is not CP symmetric, i.e., matter not antimatter

- In vacuum, the mass eigenstates $\nu_1,\ \nu_2,\ \nu_3$ correspond to the eigenstates of the Hamiltonian:
  - they propagate independently (with appropriate phases)
- In matter, there is an effective potential due to the forward weak scattering processes. **Effect depends on Mass Hierarchy**



$$V = \pm\sqrt{2}G_F n_e$$

Different sign for ν_e vs $\bar{\nu}_e$

Possible Experimental Strategies

EITHER:

- Keep L small (~200 km): so that matter effects are insignificant
  - First oscillation maximum:

$$\frac{\Delta m^2_{31} L}{4E} \sim \frac{\pi}{2} \Rightarrow E_\nu < 1\,\mathrm{GeV}$$

  - Want high flux at oscillation maximum

➡ **Off-axis beam:** narrow range of neutrino energies

OR:

- Make L large (>1000 km): measure the matter effects (i.e., MH)
  - First oscillation maximum:

$$\frac{\Delta m^2_{31} L}{4E} \sim \frac{\pi}{2} \Rightarrow E_\nu > 2\,\mathrm{GeV}$$

  - **Unfold CPV from Matter Effects through E dependence**

➡ **On-axis beam:** wide range of neutrino energies

Possible Experimental Strategies

EITHER:

- Keep L small (~200 km): so that matter eff… are insignificant
  - First oscillation maximum:

$$\frac{\Delta m^2_{31} L}{4E} \sim \frac{\pi}{2}$$

  - Want hi… …tion maximum

➡ **Off-… …eam:** narrow range of neutrino energies

Hyper-Kamiokande

OR:

- Make L large (>1000 km): measure the …atter effects (i.e., MH)
  - First oscillation maximum:

$$\frac{\Delta m^2_{31} L}{4E} \sim \frac{\pi}{2}$$

  - **Unfold CPV from Ma… …ts through E dependence**

➡ **On-axis beam:** w…de range of neutrino energies

DUNE

It's not only statistics....

In the experiment we measure:

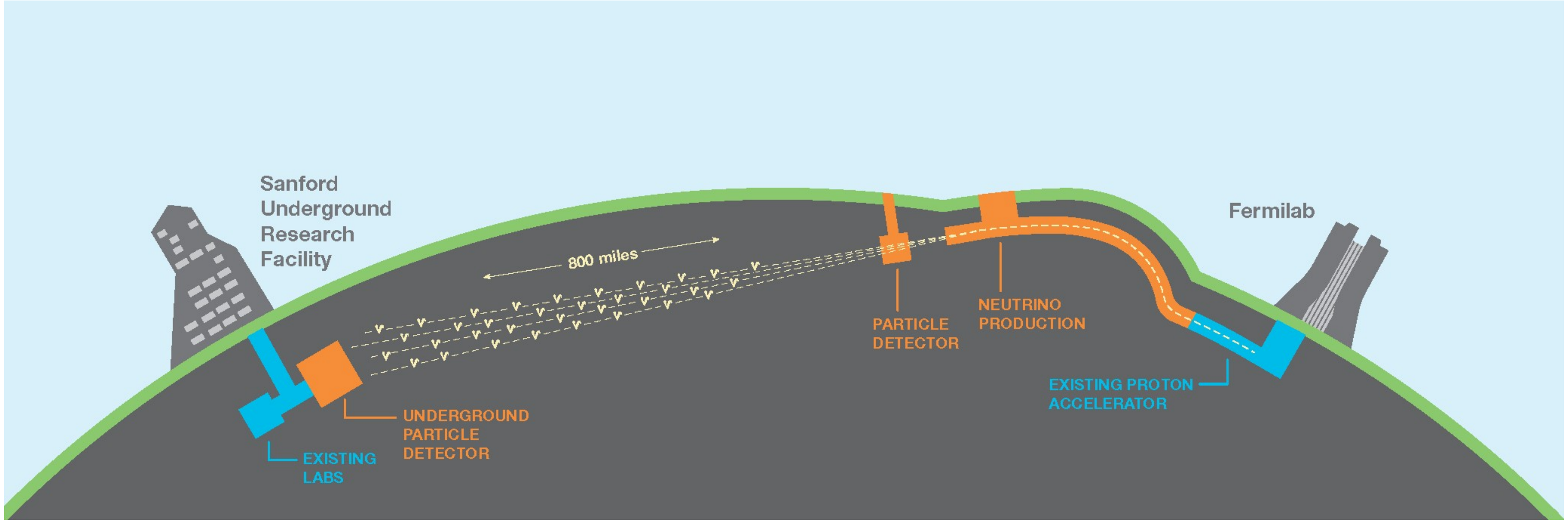
$$\frac{\frac{dN_{\nu_e}^{far}}{dE_{rec}}}{\frac{dN_{\nu_\mu}^{near}}{dE_{rec}}} = \frac{\int P_{\nu_\mu\rightarrow\nu_e}(E_\nu) * \phi_{\nu_\mu}^{near}(E_\nu) * F_{far/near}(E_\nu) * \sigma_{\nu_e}^{Ar}(E_\nu) * D_{\nu_e}^{far}(E_\nu, E_{rec})\ dE_\nu}{\int \phi_{\nu_\mu}^{near}(E_\nu) * \sigma_{\nu_\mu}^{Ar}(E_\nu) * D_{\nu_\mu}^{near}(E_\nu, E_{rec})\ dE_\nu}$$

In order to get the physical quantities, we have to control flux, energy distribution/geometry of the beam, efficiencies, acceptances, etc..

Need one (or more) sophisticated Near Detector to control beam and systematics

Long-Baseline Neutrino Facility

The biggest international project hosted in the US



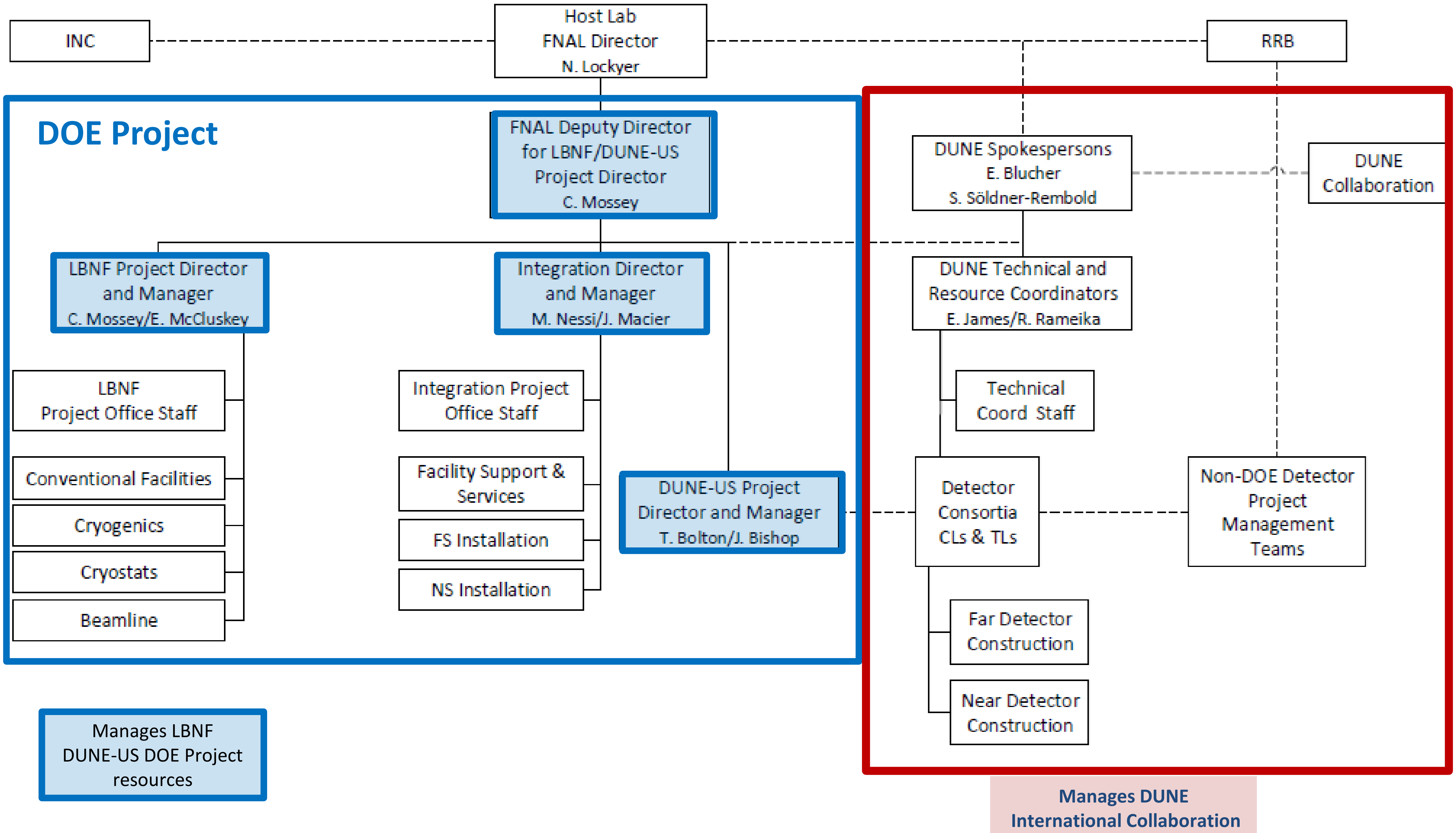
DUNE Far Detector

DUNE Near Detector
Neutrino Beam Source

DUNE Collaboration

- 1180 collaborators from 198 Institutions in 33 Countries
- 628 faculty/scientists, 199 postdocs, 119 engineers, 234 PhD students

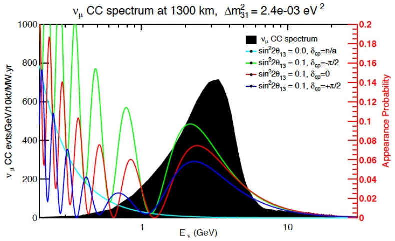
LBNF/DUNE Project Management



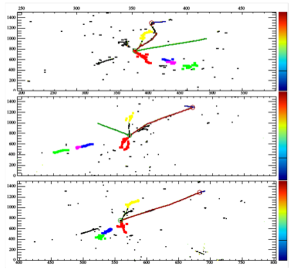
Far Detector Technical Design Report (Feb. 2020)

https://arxiv.org/abs/2002.02967
https://arxiv.org/abs/2002.03005
https://arxiv.org/abs/2002.03008
https://arxiv.org/abs/2002.03010

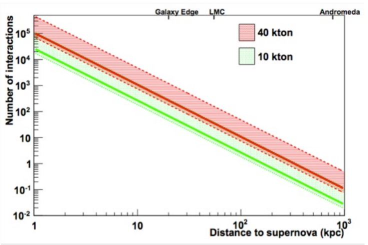
DUNE Primary Science Goals



- Testing the Neutrino Three-Flavor Paradigm
  - CP Phase/CP Violation
  - Mass Ordering

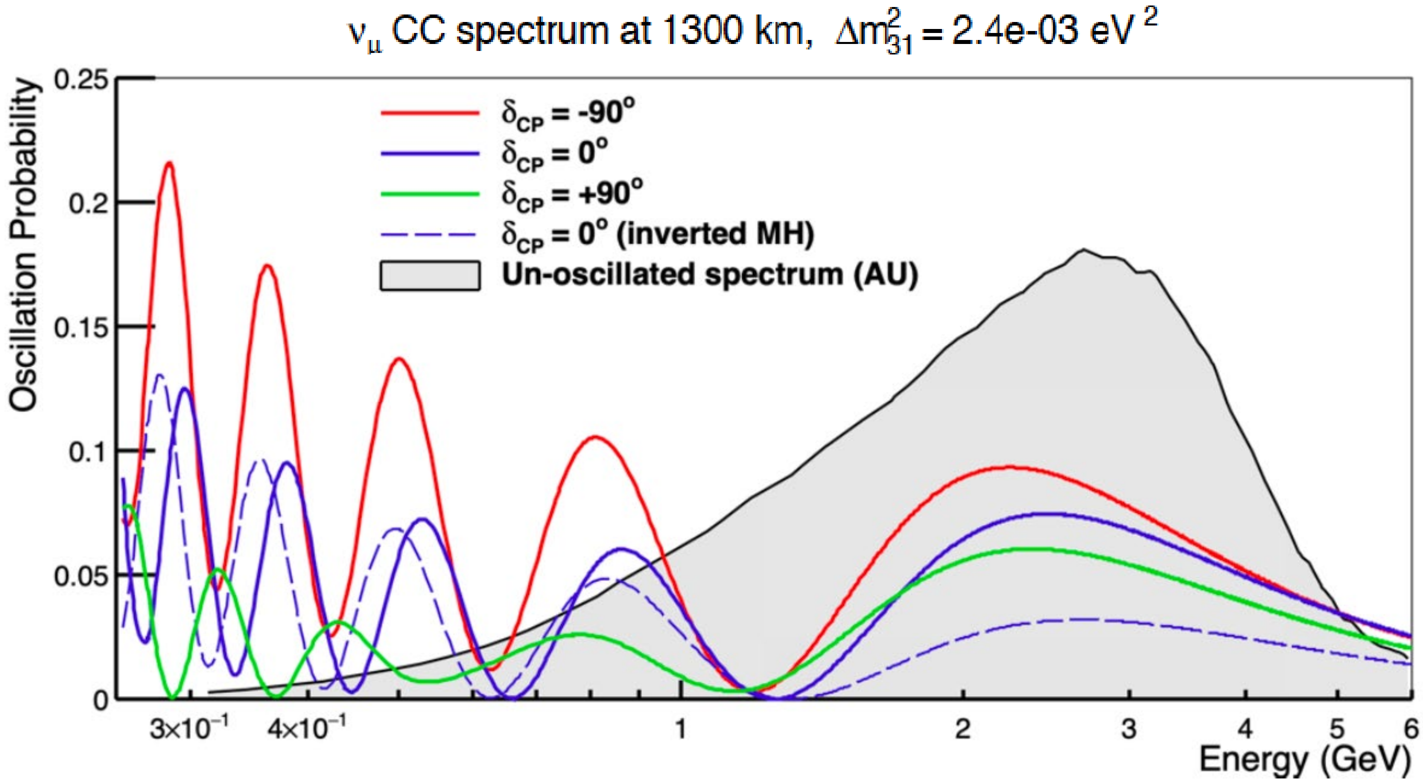


- Baryon Number Violation and Grand Unification
  - Nucleon Decay
  - Neutron/Anti-Neutron Oscillation



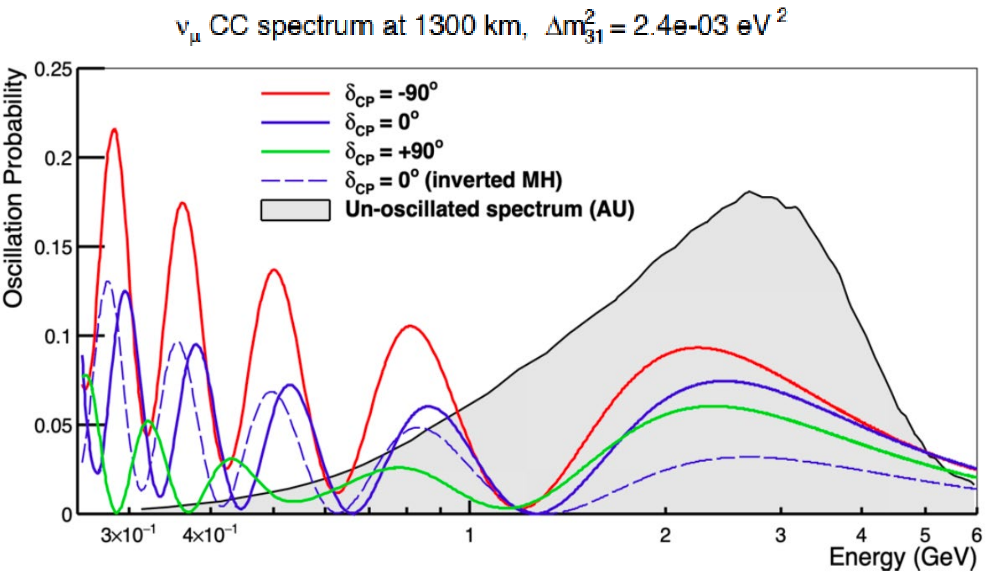
- Neutrino Astrophysics
  - Supernova Burst Neutrinos

Testing the Neutrino Three-Flavor Paradigm



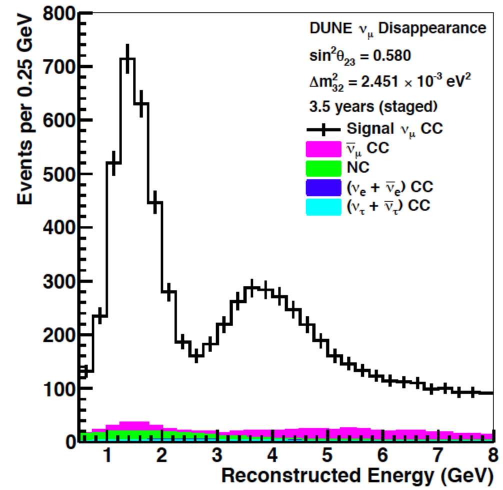
- Oscillation probability depends on the ratio of distance travelled (L) and neutrino energy (E): L/E
- Lines shows ν_e appearance probability for a pure ν_μ beam for L = 1300 km for three values of CP violating phase δ_{CP}
- Filled in curve shows ν_μ energy spectrum at L if there were no oscillations

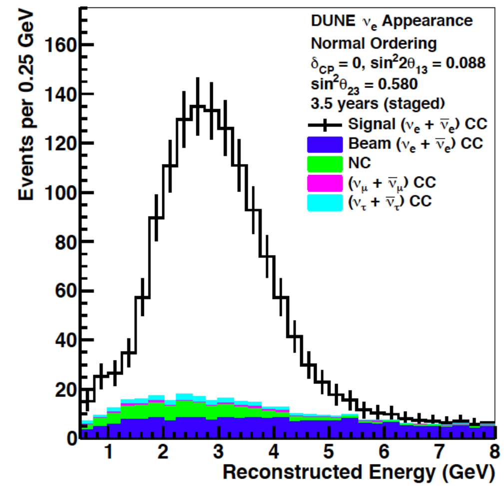
Experimental Method



disappearance

appearance

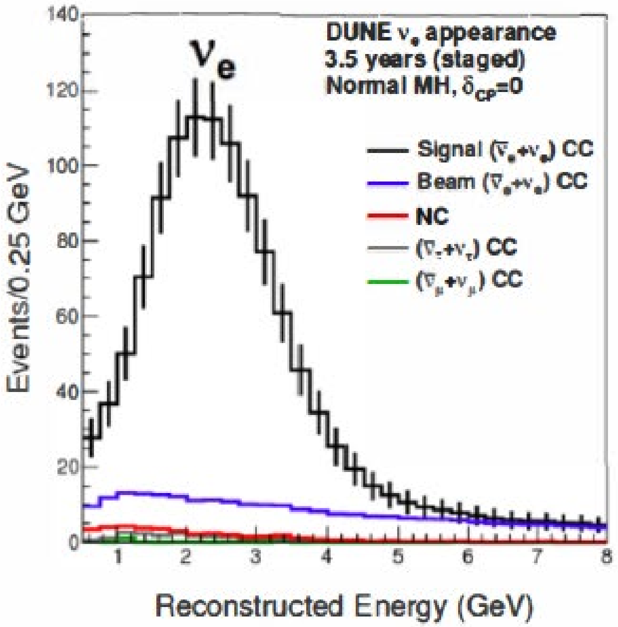




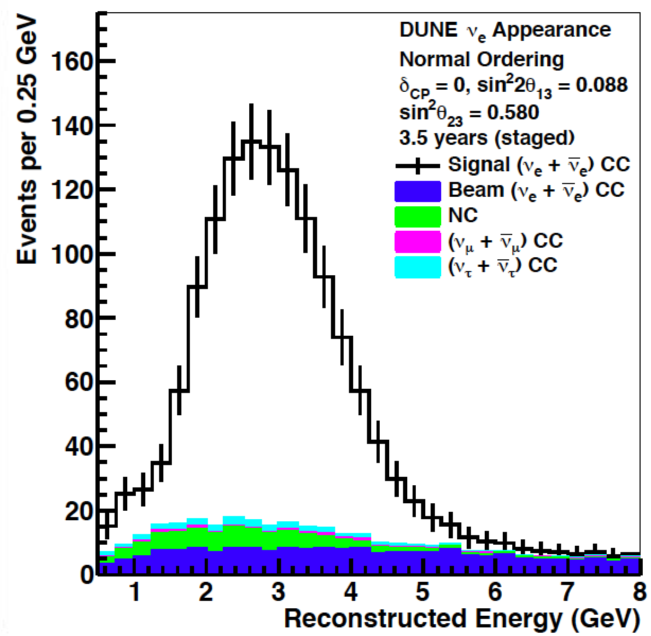
- Produce a pure on-axis ν_μ beam with spectrum matched to oscillation pattern at the chosen distance
- Measure spectrum of ν_μ and ν_e at a distant detector
- Do the same with anti-neutrinos
- **Fit all four spectra simultaneously**
- DUNE optimized the choice of beam and distance to have sensitivity to CP violation, CP phase, neutrino mass ordering, and other oscillation parameters ***in the same experiment***

Improving Our Tools

Conceptual Design Report (2016):
Parametrized detector response and estimated efficiency

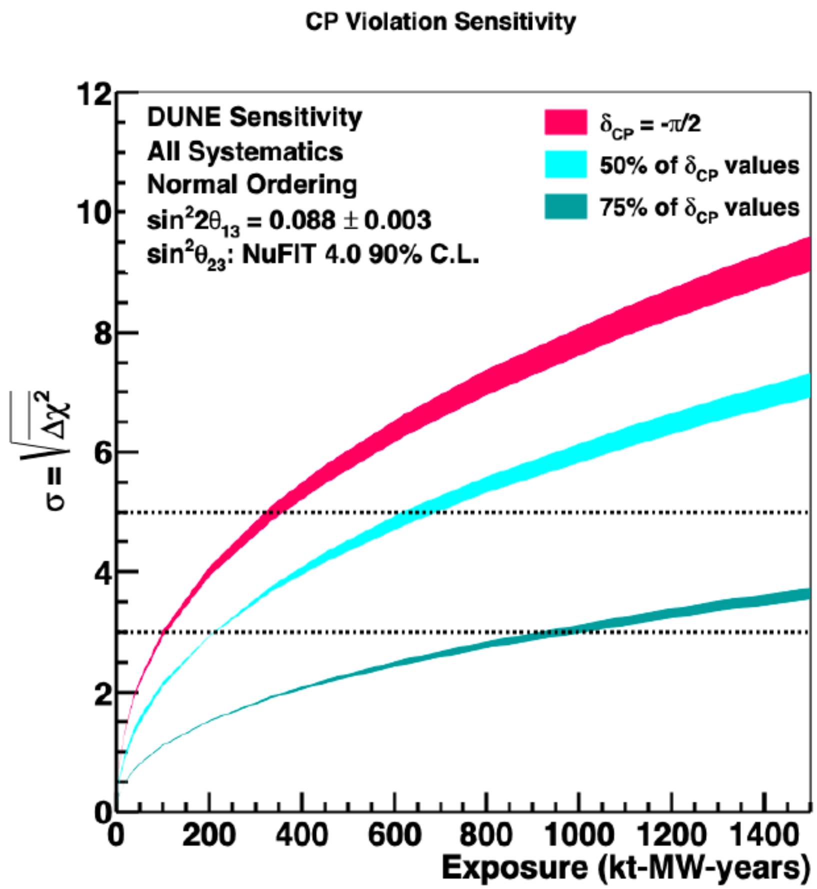


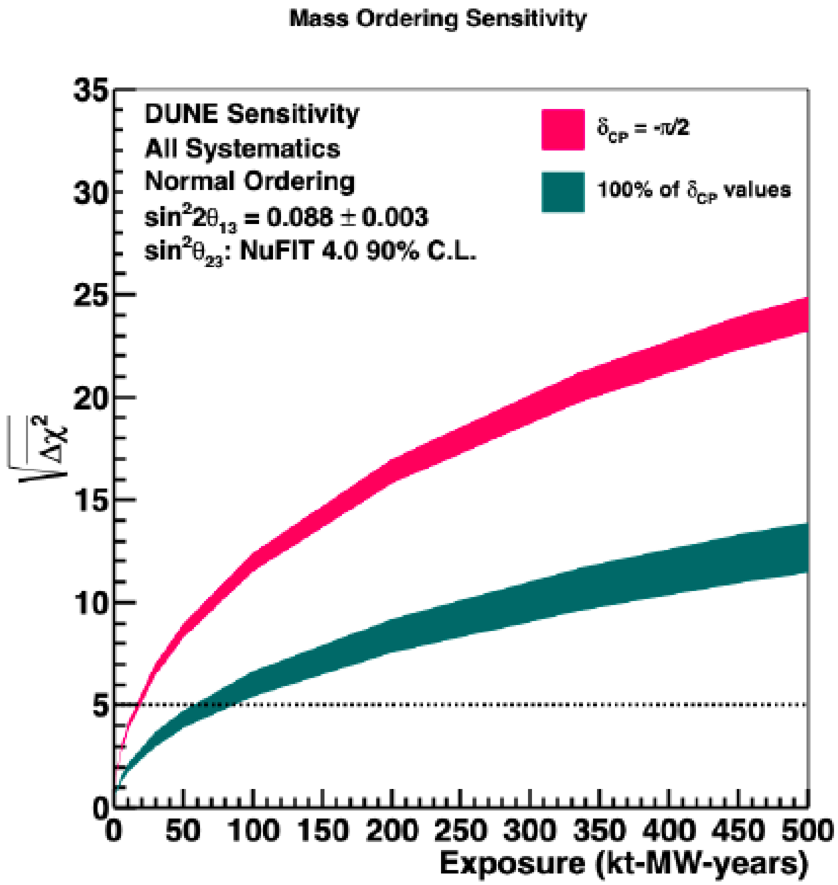
Technical Design Report(2020):
Full simulation reconstruction+ chain and CVN event selection



- Sensitivity from MC-based analysis with full reconstruction chain similar/better than in Conceptual Design Report (CDR)
- Sensitivity plots have been updated for the TDR

CP Violation and MH Sensitivity

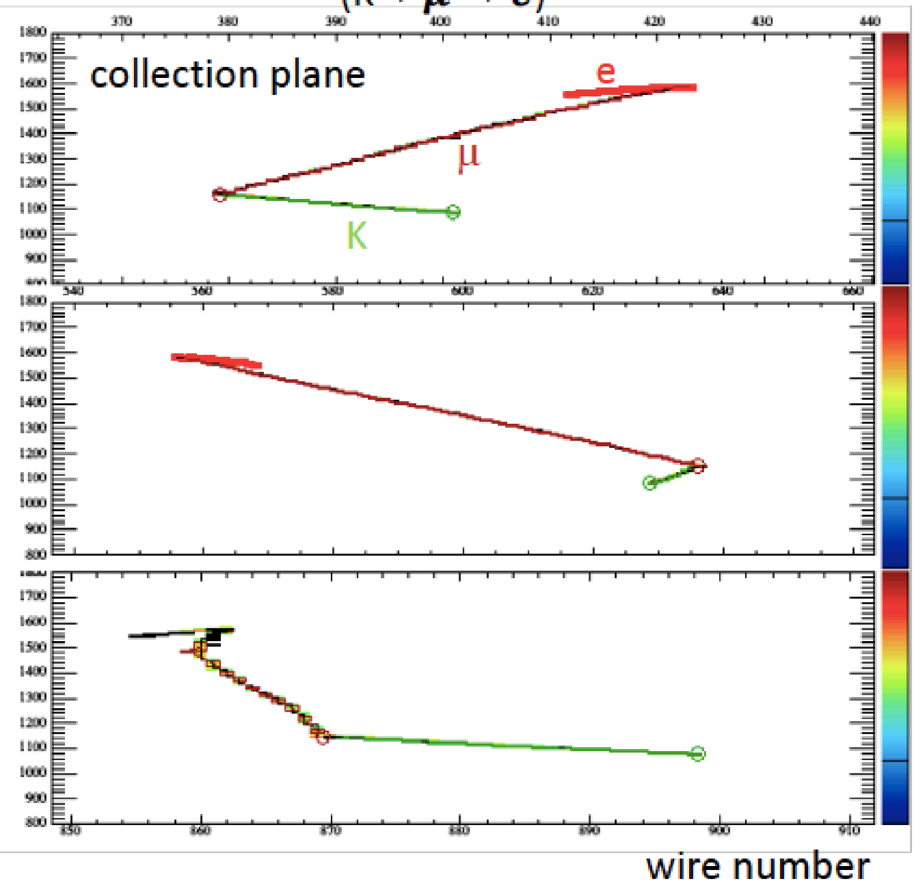




Baryon Number Violation

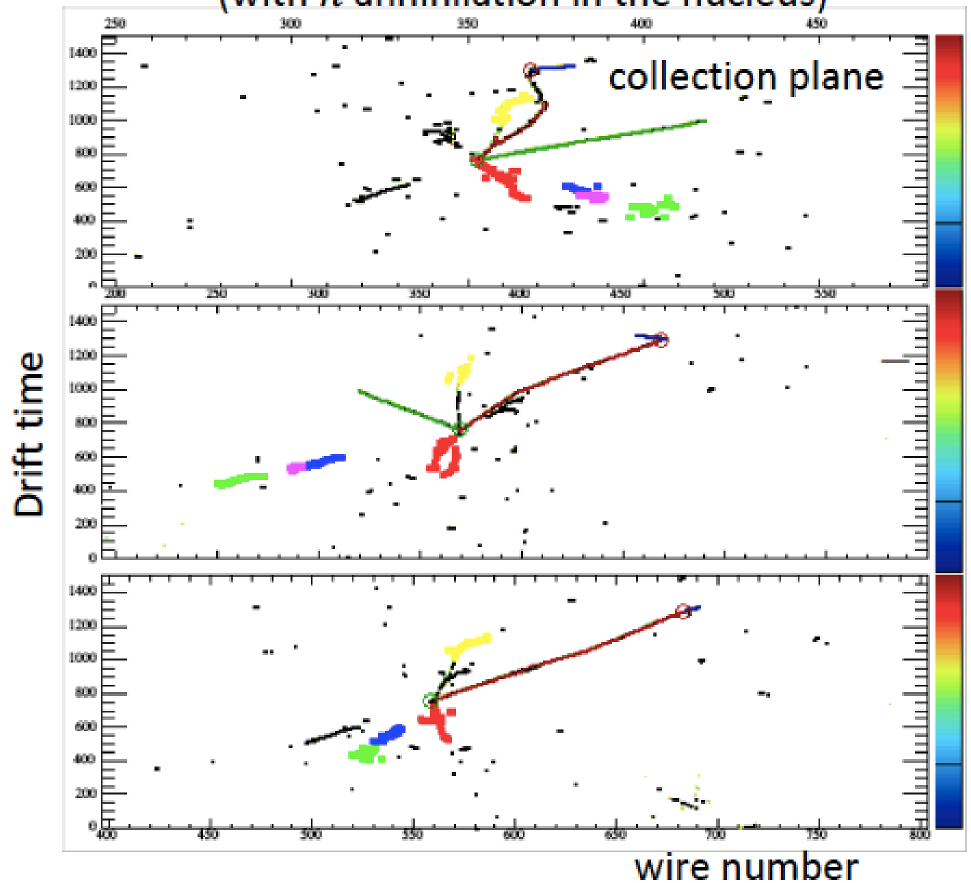
$p \rightarrow \bar{\nu} K$

(K→ $\mu \rightarrow e$)



$n - \bar{n}$ **oscillation**

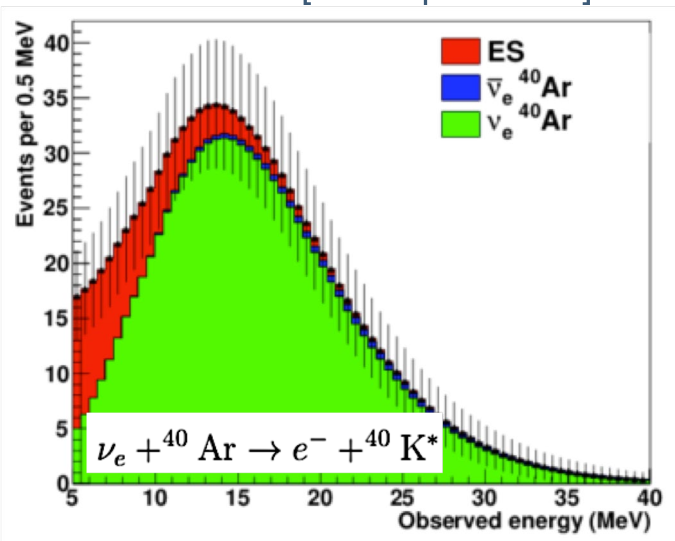
(with $\bar{n}$ annihilation in the nucleus)



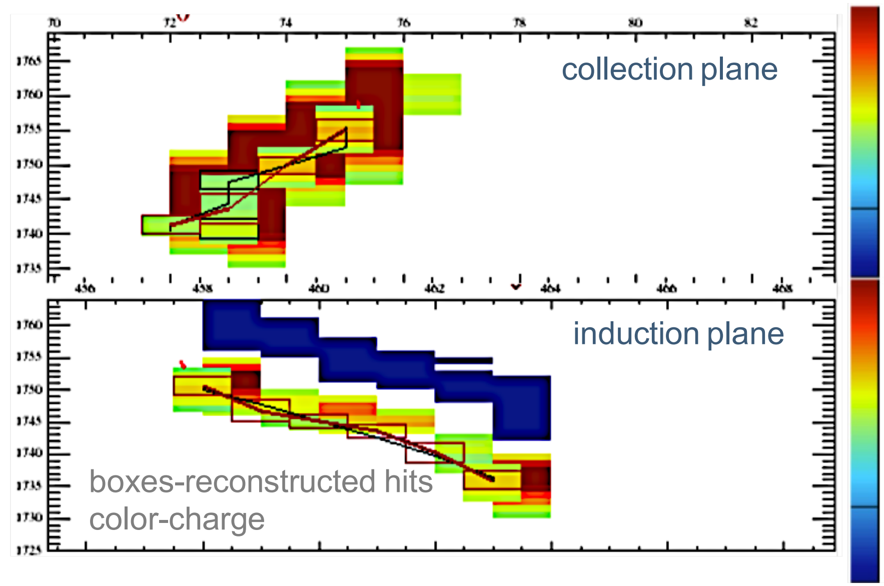
- Full simulation and reconstruction

Supernova Burst/Low Energy Neutrinos

Electron-capture SN at 10 kpc in
40-kt LArTPC [Huedepohl 2009]



10.25 MeV electron



- Sensitive to ν_e; complementary to water Cherenkov detectors
- Tracks only a few centimeters long but event-by-event energy reconstruction is possible in LAr
- Pointing may be possible using elastic scattering (ES) from electrons
- Triggering understood for SNB (100 sec readout buffer) but a challenge for solar neutrinos

INFN and DUNE

INFN intends to contribute **to both Near and Far Detectors**, to maximize the opportunities both on the core DUNE program as well as on the other physics measurements, which are enabled by the combination of a capable Near Detector with the unprecedented statistics.

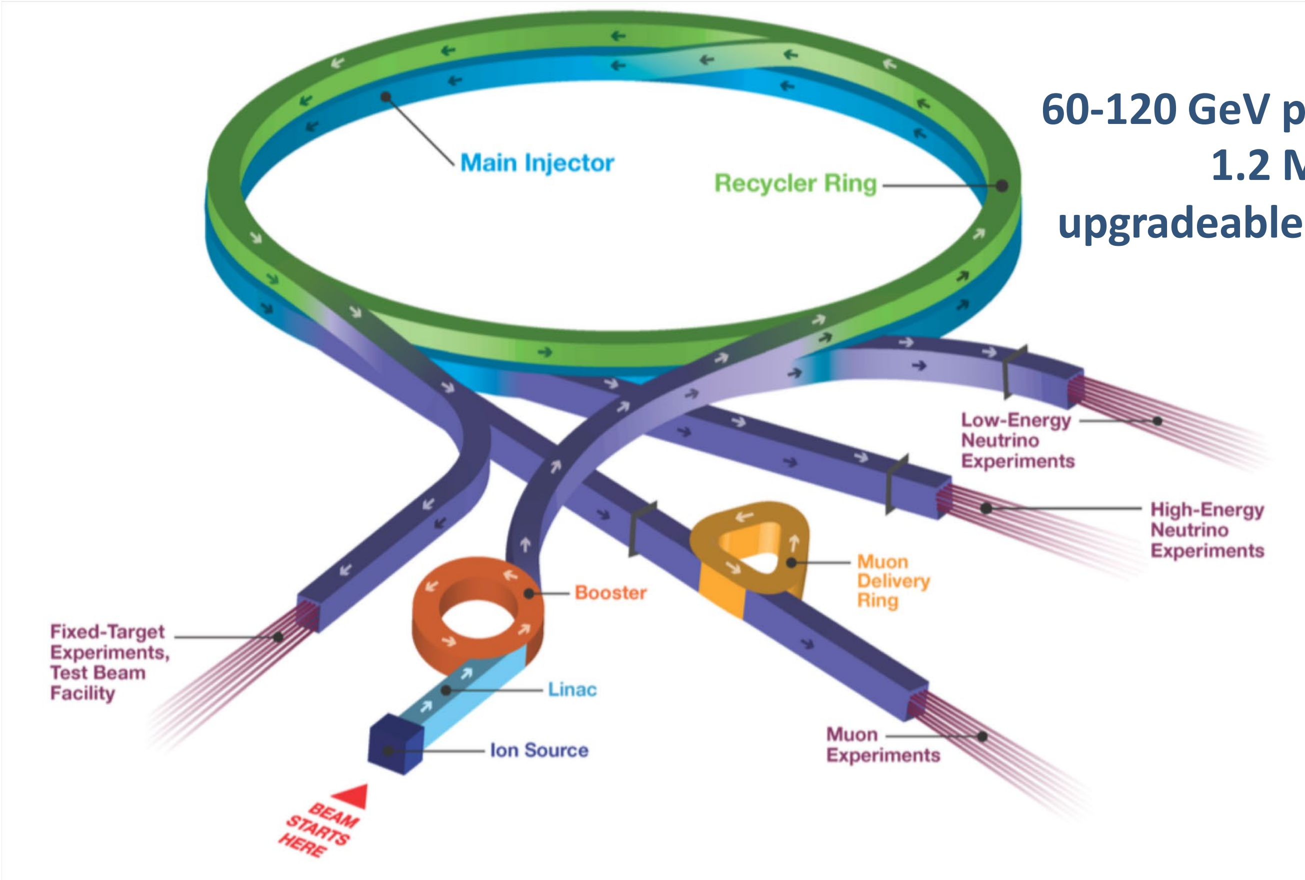
The Nu_at_FNAL project is summarized in two documents following the new schemes of INFN Project Management:

- a Conceptual Design Report for the Near Detector (SAND)
- a Technical Design Report for the Photon Detection System of the Far Detector (PDS)

Ancillary documents are also included in the same repositories.

INFN is also contributing to the upgrade of the neutrino beam.

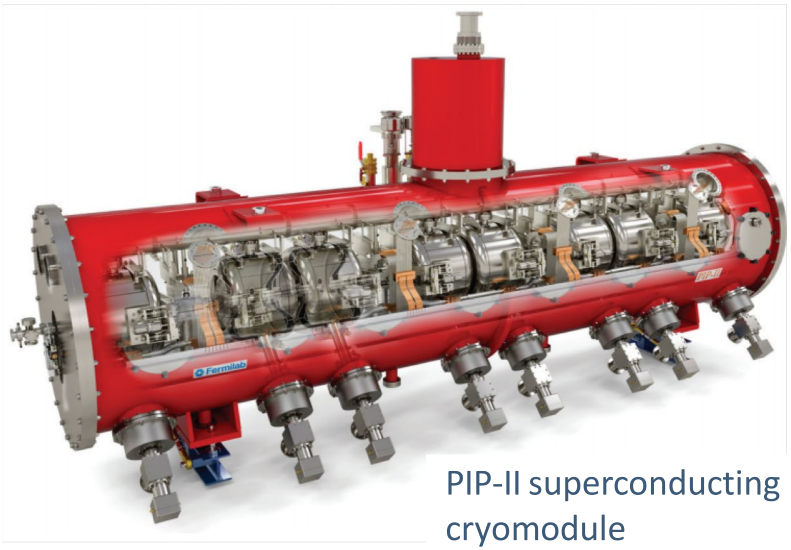
Fermilab Accelerator Complex



60-120 GeV proton beam
1.2 MW
upgradeable to 2.4 MW

- Reference design similar to existing NuMI (used for the NOvA experiment), optimized to improve sensitivity to oscillation measurements

Proton Improvement Plan



PIP-II superconducting cryomodule

- Megawatt proton beams
- 700-foot-long 800 MeV superconducting linear accelerator
- PIP-II Groundbreaking November 2019!

INFN and DUNE

The contributions to the Far and Near Detectors, **both substantial in terms of financial and human resources**, differ in nature: in the former case INFN will contribute to the Photon Detection System (**PDS**) of the first LAr module (Horizontal Drift), with the provision to contribute to the PDS of the second module (Vertical Drift), while for the latter INFN is contributing **the major part of a complete detector** previously used in the KLOE experiment at Frascati, consisting of a magnet yoke, a 0.6 T large bore superconducting solenoid and a 4π fine grained electromagnetic calorimeter.
The refurbished detector (**SAND**), complemented by a suitable **tracker** and a (small) **LAr active target**, will **permanently stay on the beam axis**, while the other two detectors of the ND complex, a largish LAr detector (ArgonCube) and a magnetized detector (ND-GAr) will move 50% of beam time off-axis.

Composition of INFN groups in DUNE

The table does not include technicians and the sections support services (electronics, mechanics, design, etc)

Institution	Researchers+ Technologists	FTE	Notes
BO	20	8.3	
FE	9	2.8	
GE	6	3.8	
LE	5	2.3	
LNF	*3*	*1.2*	*from 2022*
LNL	1	0.2	
LNS	7	1.6	
Mi	6	2.1	
MiB	18	8.3	
NA	7	1.8	
PD	1	0.3	
RM1	*3*	*0.9*	*from 2022*
Total	86	33.6	

INFN and DoE

INFN in-kind contributions:

i. The **magnet and calorimeter system** that were deployed in the KLOE experiment's detector at the DAΦNE collider at INFN's Frascati National Laboratory (hereinafter "KLOE Components"), it being understood that INFN's activities for the KLOE Components shall include their necessary refurbishment, maintenance, and subsequent delivery to Fermilab in accordance with the schedule to be developed by the DUNE Collaboration in consultation with the Participants. Once delivered, the refurbished KLOE Components shall form detector subsystems of the **SAND** detector;

ii. **Electronics, power supplies, and trigger systems** for the **SAND** calorimeter and magnet;

iii. **Design and construction activities of the superconducting magnet for the ND-GAr detector** in the DUNE ND experimental hall; and

iv. The DUNE **FD light collection system**, by providing **a share of the associated silicon photomultipliers and related electronics**. **The contribution may include the first Single Phase Module and possibly the second "Vertical Drift" Module**.

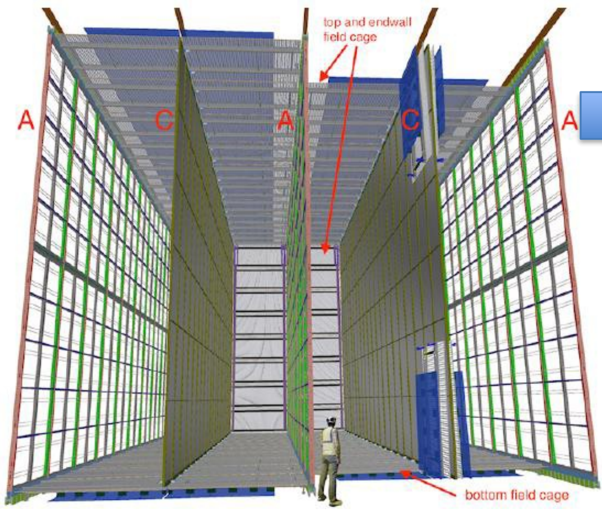
v. Contribution to the **development of the inner tracking system of SAND** and of an **active compact Liquid Argon target** to be installed within the KLOE volume.

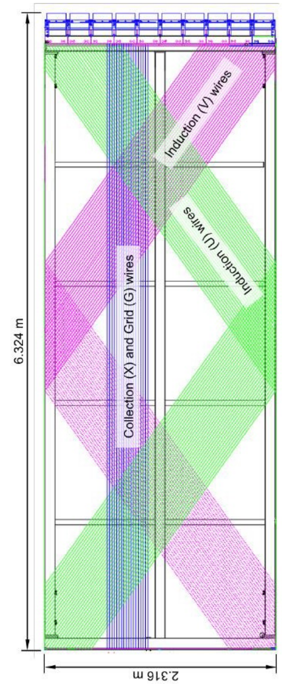
The PDS System

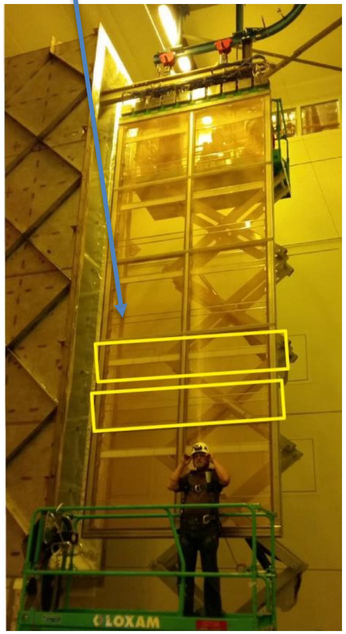
- The PDS of the **first module** of DUNE is technically and financially set. No special surprises:
  - Well in schedule despite the COVID pandemic
  - Latest achievements quite impressive
  - Medium and long-term resource-loaded schedule is complete
- The PDS of the **second module** of DUNE was in design phase six months ago:
  - The design phase is over and the CDR will be published very soon.
  - Tests of the most critical items are ongoing
  - We presented the INFN interest and potential commitments and the cost sharing is close to completion

Collecting charge and light

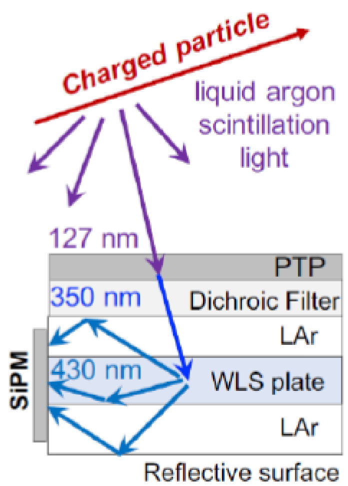
The first DUNE module is based on a horizontal drift, where the cathode is interspersed between two “anodic planes” (APA).
The natural place for the photon detectors is **inside the APA**



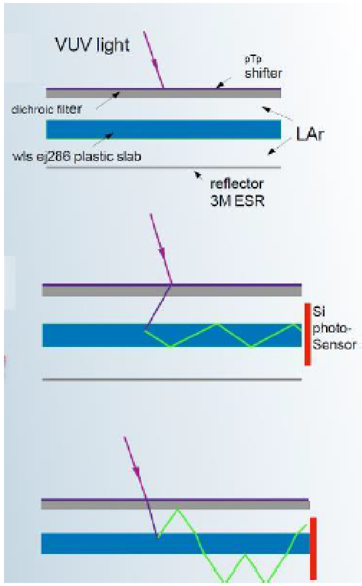




The DUNE Photon Detection System



The trapping system is a "poor man's lens" that increases the effective coverage of the Silicon Photomultipliers (SiPMs). It is **compact** and **modular**.



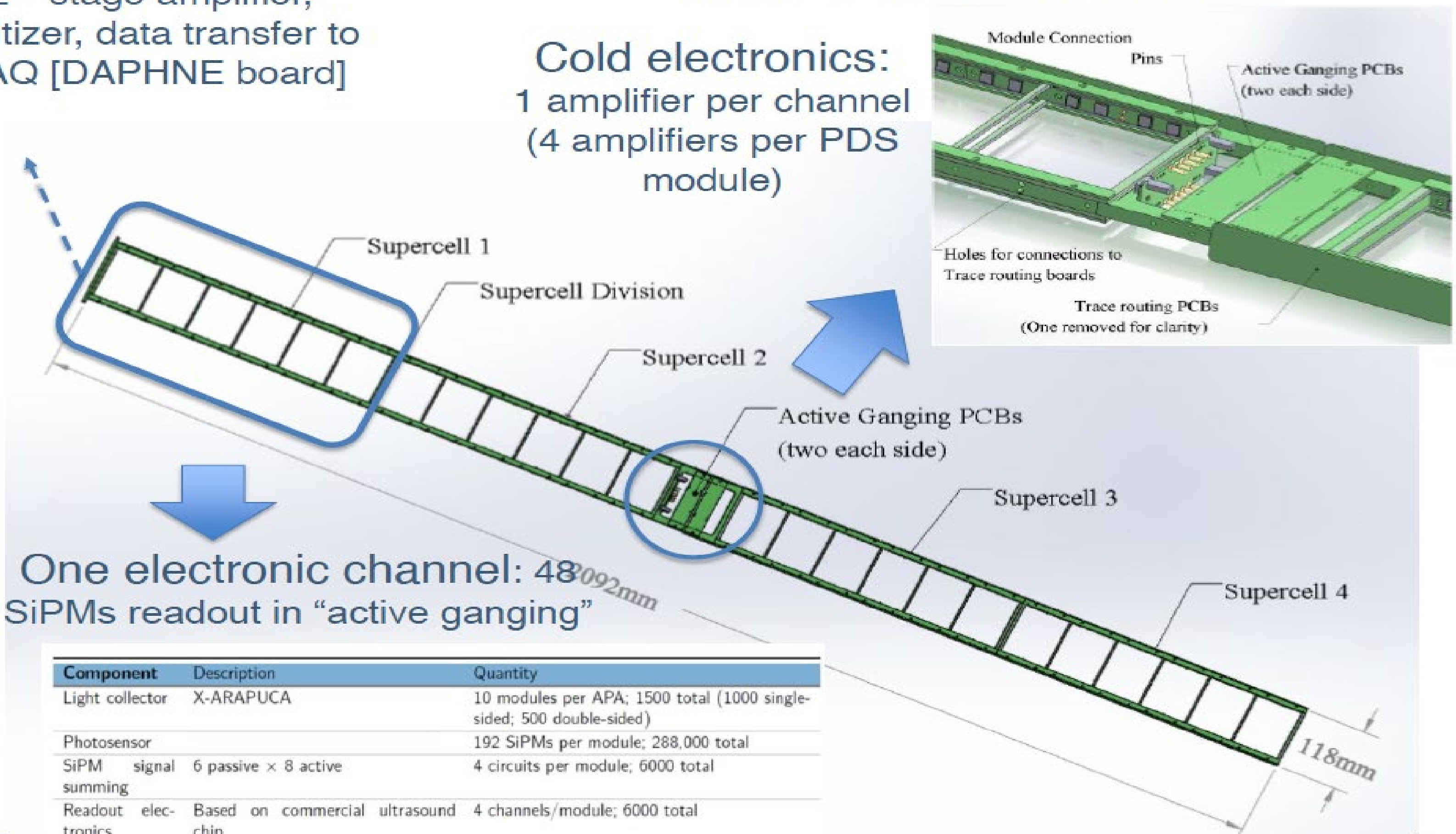
System tested:

- In Brazil with a dedicated setup
- In ProtoDUNE-SP but with without the WLS plate (early version with TPB)
- In ProtoDUNE-SP during the special Xe doping run with a "telescope" built at CERN+Brasil+Italy
- In Milano-Bicocca**: NEW!! See arXiv:2104.07548**

The PDS module

To Warm electronics:
2nd stage amplifier, digitizer, data transfer to DAQ [DAPHNE board]

Cold electronics:
1 amplifier per channel (4 amplifiers per PDS module)



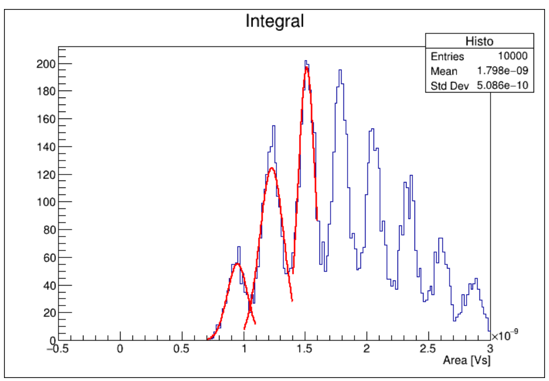
One electronic channel: 48 SiPMs readout in "active ganging"

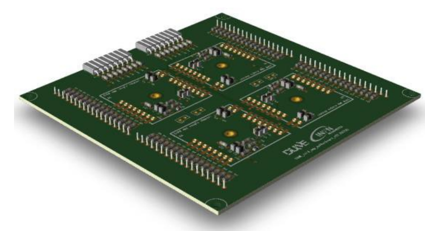
Component	Description	Quantity
Light collector	X-ARAPUCA	10 modules per APA; 1500 total (1000 single-sided; 500 double-sided)
Photosensor		192 SiPMs per module; 288,000 total
SiPM signal summing	6 passive × 8 active	4 circuits per module; 6000 total
Readout electronics	Based on commercial ultrasound chip	4 channels/module; 6000 total
Calibration and monitoring	Pulsed UV via cathode-mounted diffusers	45 diffusers/CPA side; 180 diffusers for 4 CPA sides

PDS Status

- Identify the best custom sensors (cryo-reliability, DCR, PDE, correlated noise…) in spec for DUNE for at least two vendors ("two vendor scheme"). **DONE**
  - **Fondazione Bruno Kessler (FBK): NUV-HD-CRYO-TT**
  - **Hamamatsu Photonics (HPK): S13160-6075HS-HQR**
- Test the ganging and cold amplifier. **DONE**
- Test the entire chain up to the warm amplifier: **in progress**
- In the next 8 months: produce, assemble and test the 40 modules for ProtoDUNE-SP Run II

Active ganging plot– 48X FBK





Long-term plan

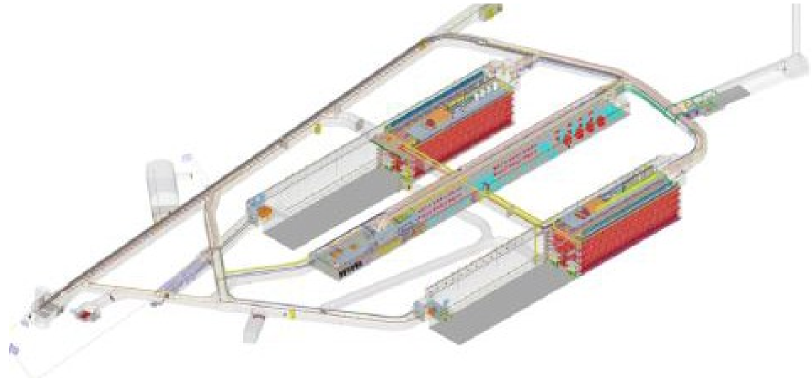
X-ARAPUCA Det. Support Calibration	SiPMs	Cold amplifiers	Warm electronics
Mechanics, dichroic filter, WLS LED system	SiPMs, side boards	Cold amplifiers, ganging	Warm amplifier, digitizer (DAPHNE)
Brasil US	**Leading institution: INFN** Spain Czech Rep.	**Leading institution: INFN** Spain	US Colombia Perù

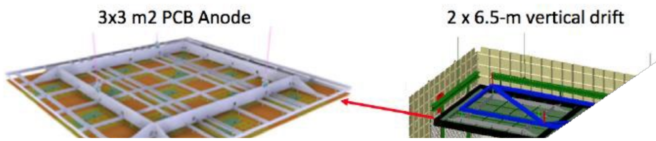
INFN roles in the PDS Consortium: **Convenors** (A. Montanari, P. Sala, **C. Cattadori**),
Management Board: F. Terranova (INFN repr.), A. Montanari, L. Patrizii
Technical coordinators: D. Warner, **F. Terranova**

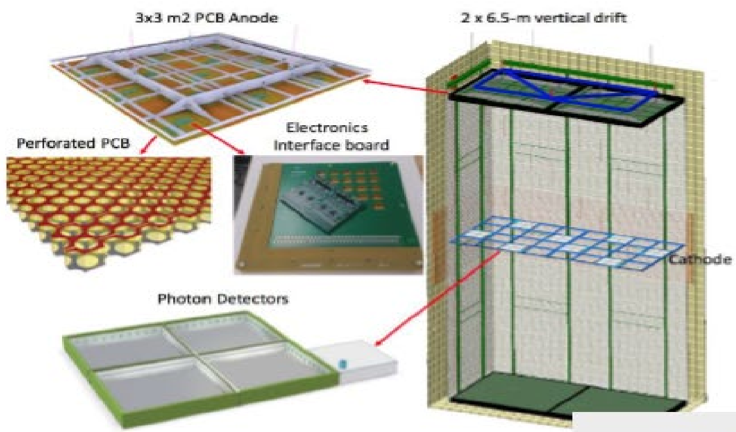
The DUNE second module (VD)

Several news since Dec 2020:

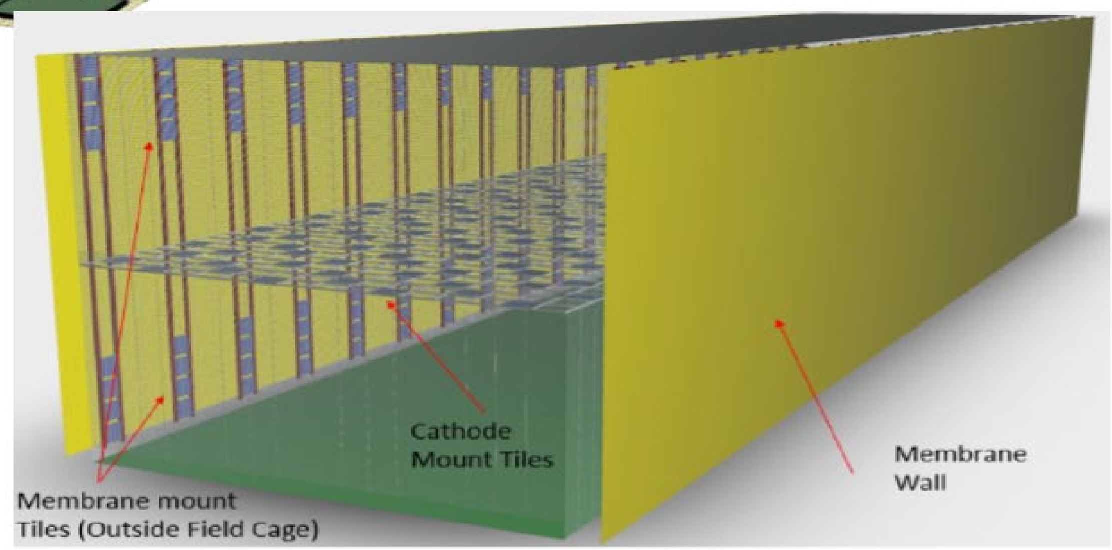
- The design of the whole second DUNE module has been finalized
- The CDR is ready but not yet publicly available (expected: summer 2021). I will show some parts that should be considered as confidential
- The cost sharing is well advanced
- The Photon Detection System of the second module (PDS-VD) is based on the same concept as the first module (X-ARAPUCA) with some differences (see below)
- The cost sharing for the PDS-VD is well advanced
- The role of INFN in the PDS-VD is well defined and resources have been requested accordingly







- Drift is <u>vertical</u> and the drift length is twice the first module: less electronic channels and, hence, less costs
- Cathode in the middle of the TPC
- Cold electronics in the top, accessible during data taking
- No wires, replaced by PCB strips (less costs)



Rationale:

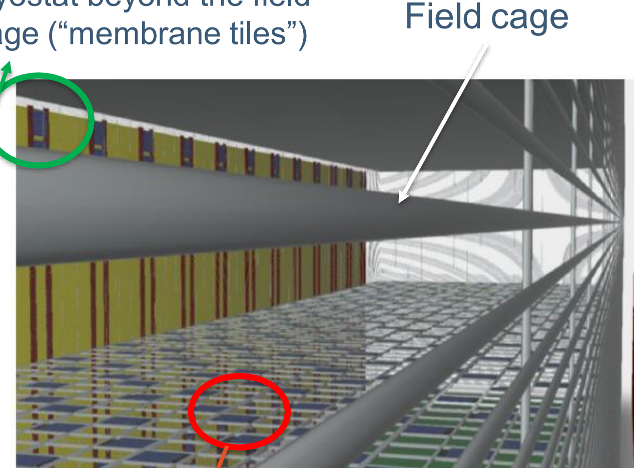
A detector that has the same performance as the first module but a reduced cost. It arises from the R&D done in ProtoDUNE-DP

The good and the bad…

Table 6.4: FD2-VD photon detector system components.

Item	Quantity	Detector Surface
X-ARAPUCA modules	320 double-side	Cathode plane
	320 single-side	Membrane long walls
Dichroic Filters	34,560	
WLS plates	640	
PhotoSensors (SiPMs)	51,200	Cathode plane
	51,200	Membrane long walls
Signal Channels	640	Cathode plane
	640	Membrane long walls
SiPMs per channel	80	
Optical Area	$115\ m^2 \times 2$	Cathode plane
	$115\ m^2$	Membrane long walls
Active coverage	14.8%	Cathode plane
	7.4%	Membrane long walls
	0%	Membrane end walls

Tiles hanging on the cryostat beyond the field cage ("membrane tiles")



Less SiPMs (110,000)
Better SiPM-WLS coupling

Cathode tiles have a "ground" of 320 kV!!

The cathode tiles are a very smart idea, but also a technical risk . Its full validation will be performed in 2022 (backup solution: increase the number of membrane tiles)

Not Only Hardware….

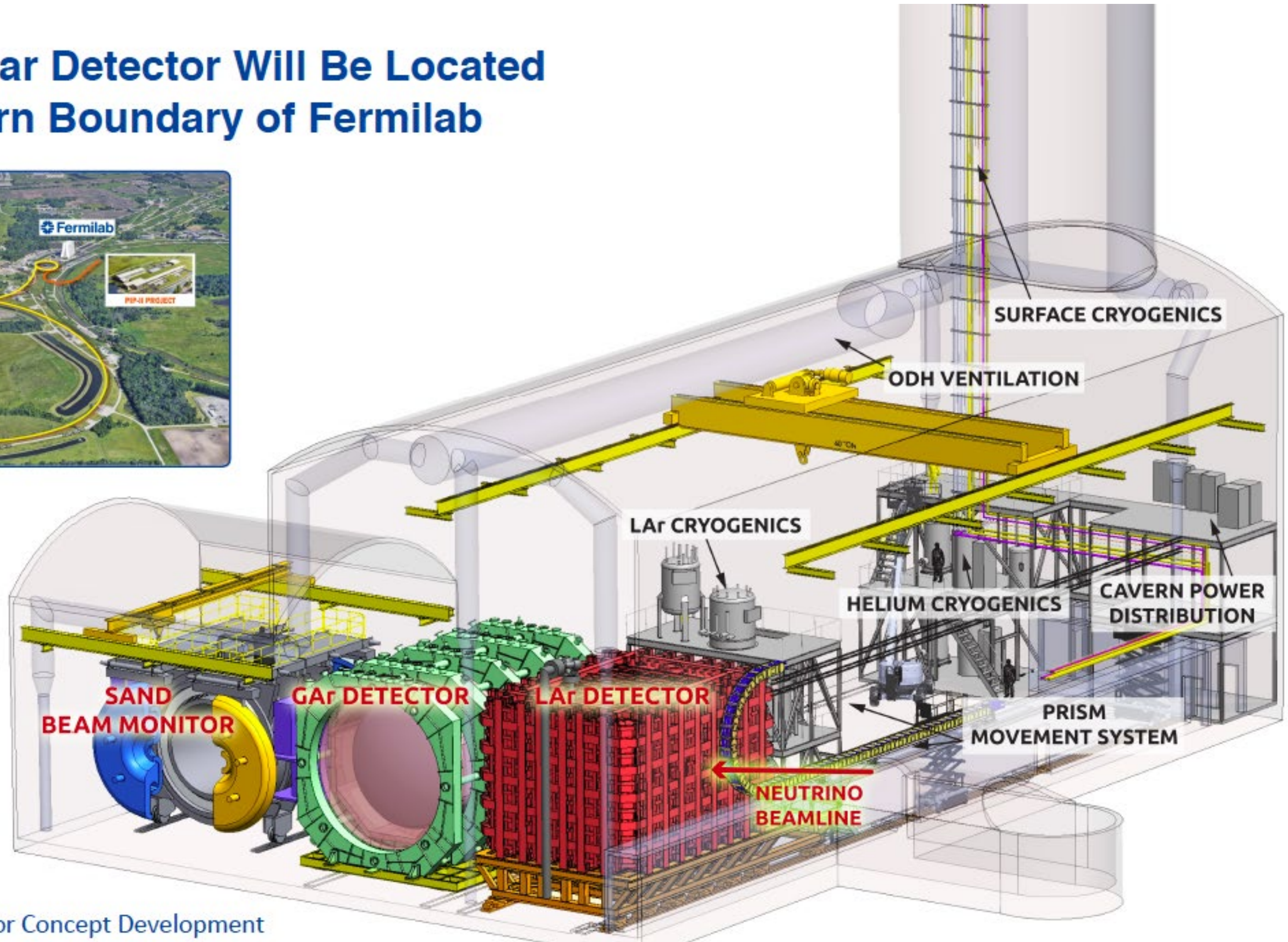
The US groups are extremely strong in the analysis, and we want to take full advantage of the investment done in the detector. Even if it seems “early”, we already took steps to fill the gap with the US groups, **especially in the PDS**.

- Since 2021, we have an analysis team of several post-docs + students at Master/PhD level that are very active (and recognized) in the DUNE Physics Groups
- We are currently the leader of the analysis of Xe-doping, which is a must for the second module (VD)
- We are the main group developing double calorimetry (charge+light) in DUNE from the GeV scale (beam events) to the MeV scale (supernove bursts, solar neutrinos)
- We played an important role in the simulation of the second DUNE module

The ND complex and SAND

The DUNE Near Detector Will Be Located At The Western Boundary of Fermilab

GAr and LAr Detectors off-axis for 50% of the time



DUNE-ND I&I Team
Supported Early Detector Concept Development

The Near Detector Mission

Summarized here:

$$\frac{\frac{dN^{far}_{\nu_e}}{dE_{rec}}}{\frac{dN^{near}_{\nu_\mu}}{dE_{rec}}} = \frac{\int P_{\nu_\mu \to \nu_e}(E_\nu) * \phi^{near}_{\nu_\mu}(E_\nu) * F_{far/near}(E_\nu) * \sigma^{Ar}_{\nu_e}(E_\nu) * D^{far}_{\nu_e}(E_\nu, E_{rec})\ dE_\nu}{\int \phi^{near}_{\nu_\mu}(E_\nu) * \sigma^{Ar}_{\nu_\mu}(E_\nu) * D^{near}_{\nu_\mu}(E_\nu, E_{rec})\ dE_\nu}$$

SAND Design Requirement

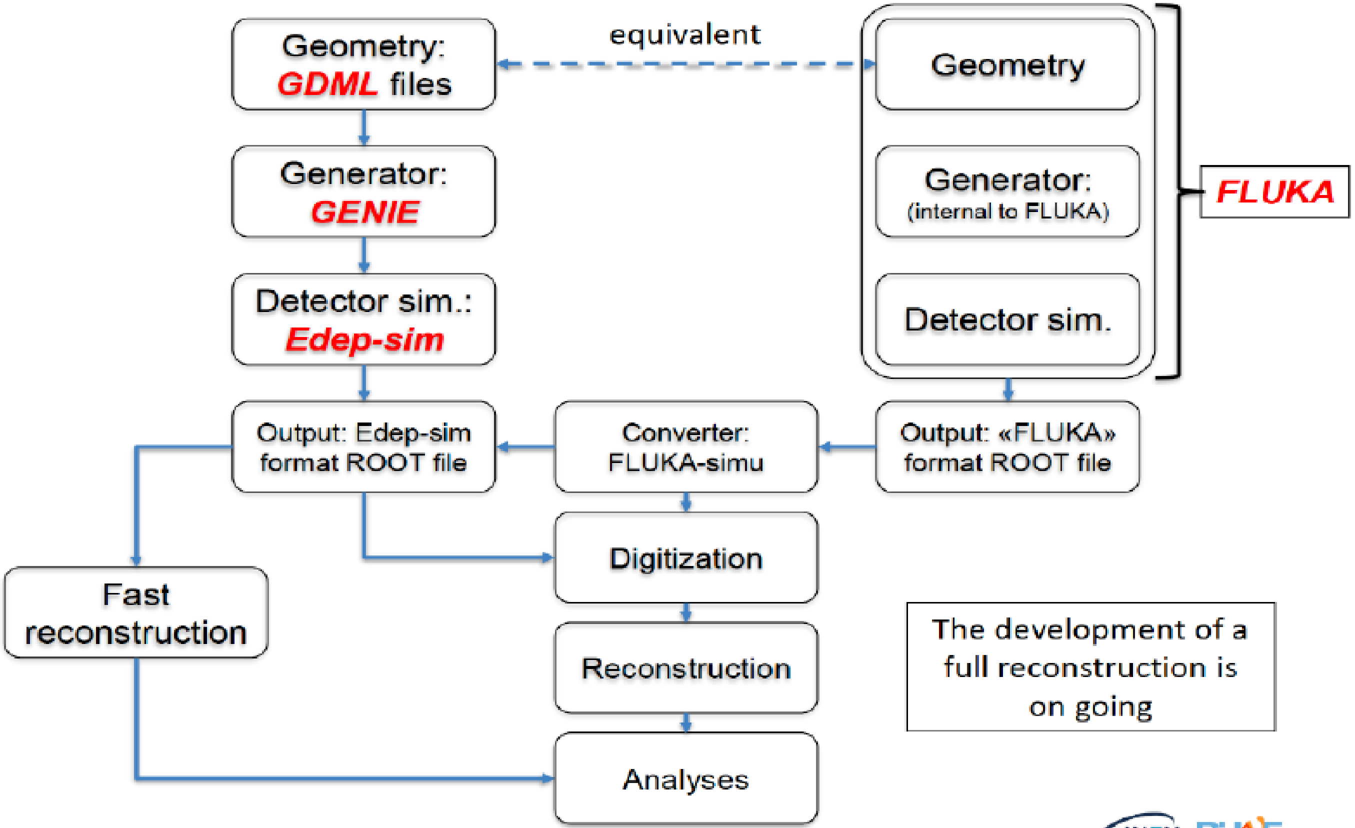
SAND is the **only detector** which will stay **on-axis all the time.**
As such we see SAND as a component of the ND complex, **NOT** a standalone detector to:

- **monitor** the beam changes **on a weekly basis** with high sensitivity;
- **provide an independent measurement of the flux;**
- **measure the flavour content** of the neutrino beam;
- contribute to **remove degeneracies** especially when the other components are off-axis;
- **add robustness** to the ND complex to keep systematics under control;
- **be capable to provide a reasonable control of the systematics** in the inauspicious case that it is the only available component on Day-1;
- exploit the unprecedented high statistics to perform a rich physics program besides oscillations **without any modification.**

INFN and SAND

It is evident that the fulfilment of these requirements hinges on the design of the inner target-tracker system, **whose choice must be primarily driven by physics performances supported by detailed and quantitative studies and then by a realistic assessment of technical feasibility, cost, funding, proponents, schedule, risks, etc. Politics should come as last criterion.**

SAND Design Tools

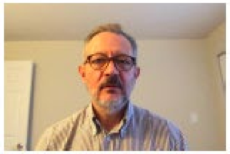


The development of a full reconstruction is on going

INFN and SAND

SAND Consortium setup in May 2020

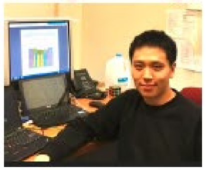
Appointed **Consortium Leader**: Luca Stanco
Appointed **Technical Leader**: Claudio Montanari



Boards: **Advisory** (Sergio Bertolucci, Sara Bolognesi, Chang Kee Jung, Marco Pallavicini, Laura Patrizii, Roberto Petti)

Steering and Physics (Lea Di Noto, Paola Sala, Davide Sgalaberna, Guang Yang)

....



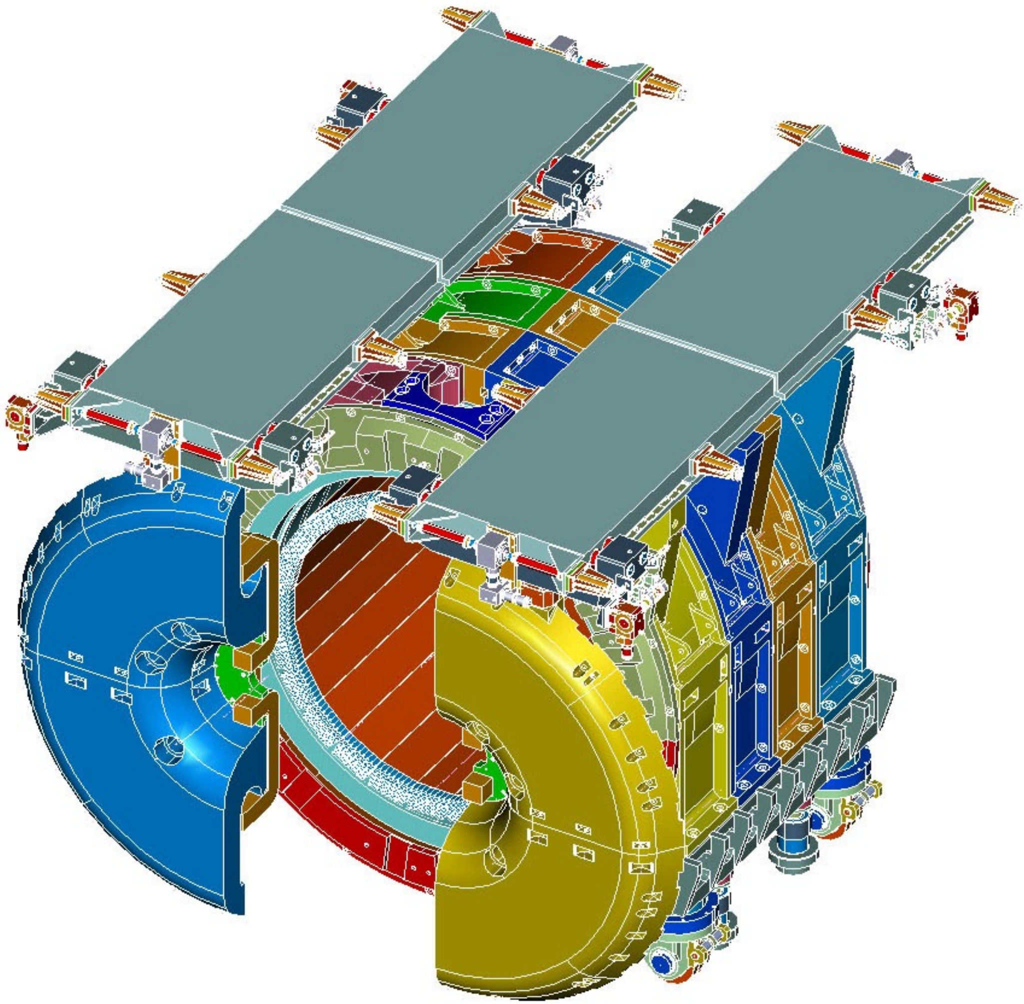
Software Coordinators: Clark McGrew

and Matteo Tenti

DAQ coordinators: Michele Pozzato and Matteo Tenti (deputy)

Slow Control: N. Moggi

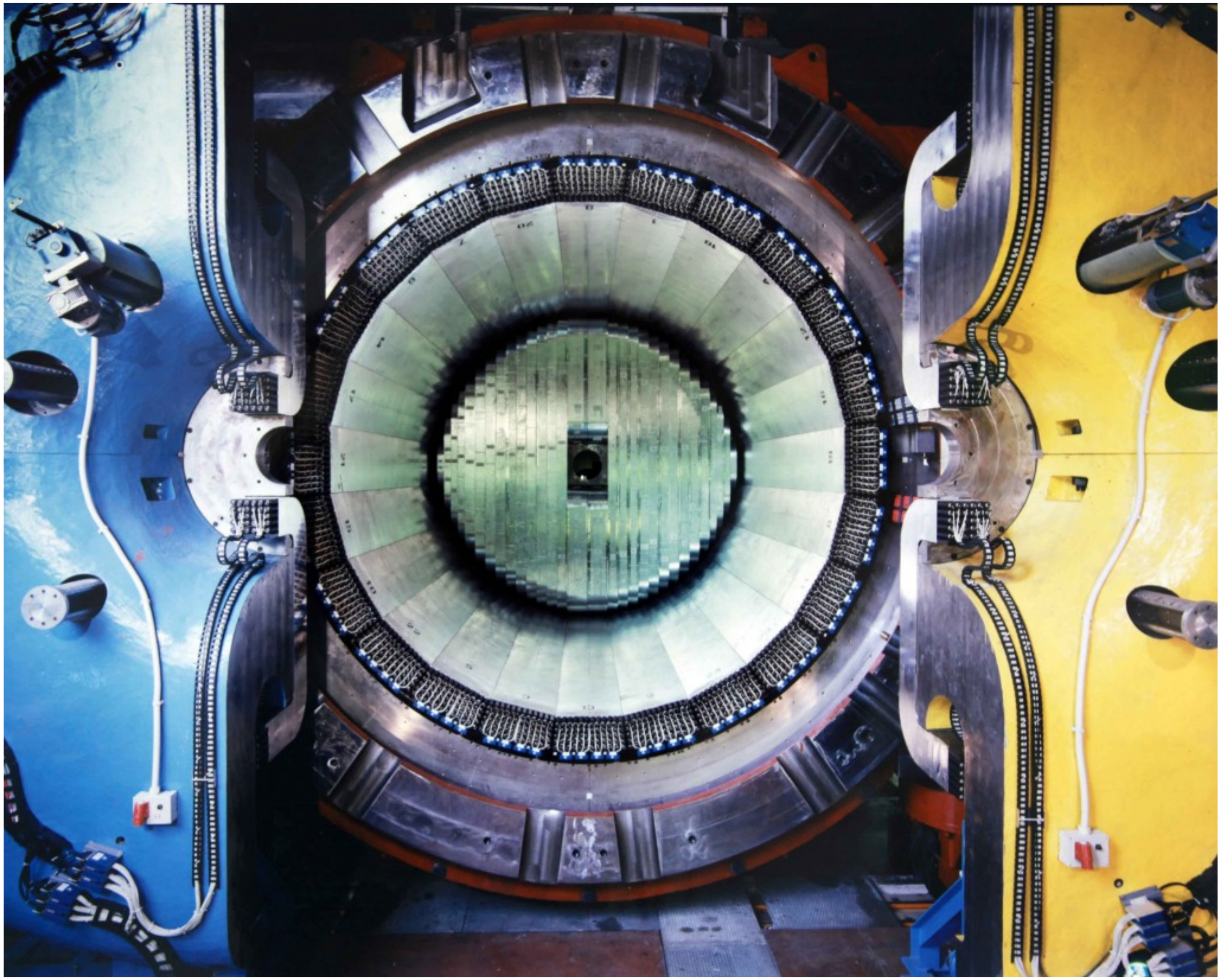
...



Supercond. Solenoid .6T

4π Pb-SciFi Calorimeter

43 m^3 of space available for a tracker



The KLOE calorimeter

KLOnE
KLOe Neutron Efficiency

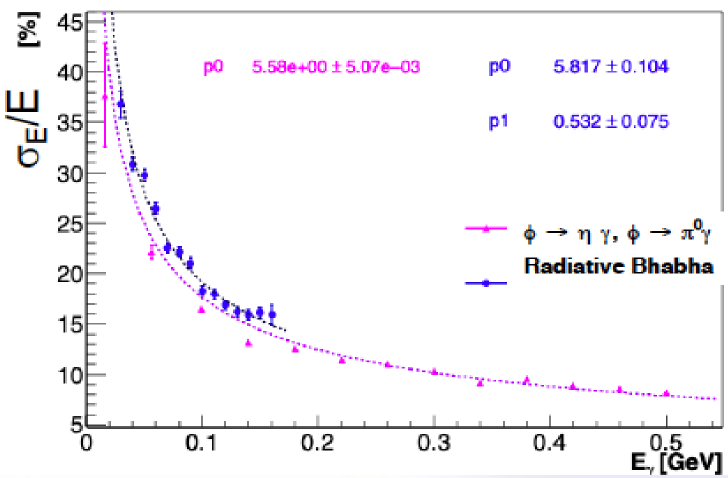
Operated from 1999 till 2018 with excellent performances for electron and photons and good capabilities for $\pi/\mu/e$ separation

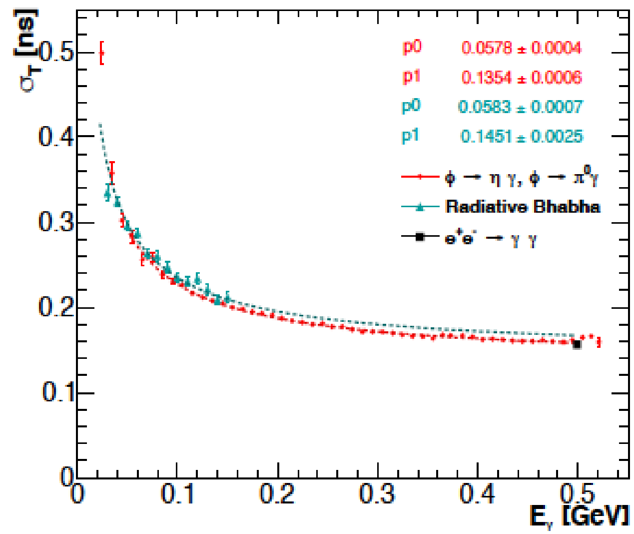
Also: good neutron detection efficiency due to the **small sampling fraction** and the **high sampling frequency.**

$\sigma_E/E \cong 5.6\% / \sqrt{E(GeV)}$

$\sigma_t \cong 58\ ps / \sqrt{E(GeV)} \oplus 135\ ps$

Check e.m. calorimeter performance
during KLOE-2 data taking (2015-2018):
compatible with known performance.





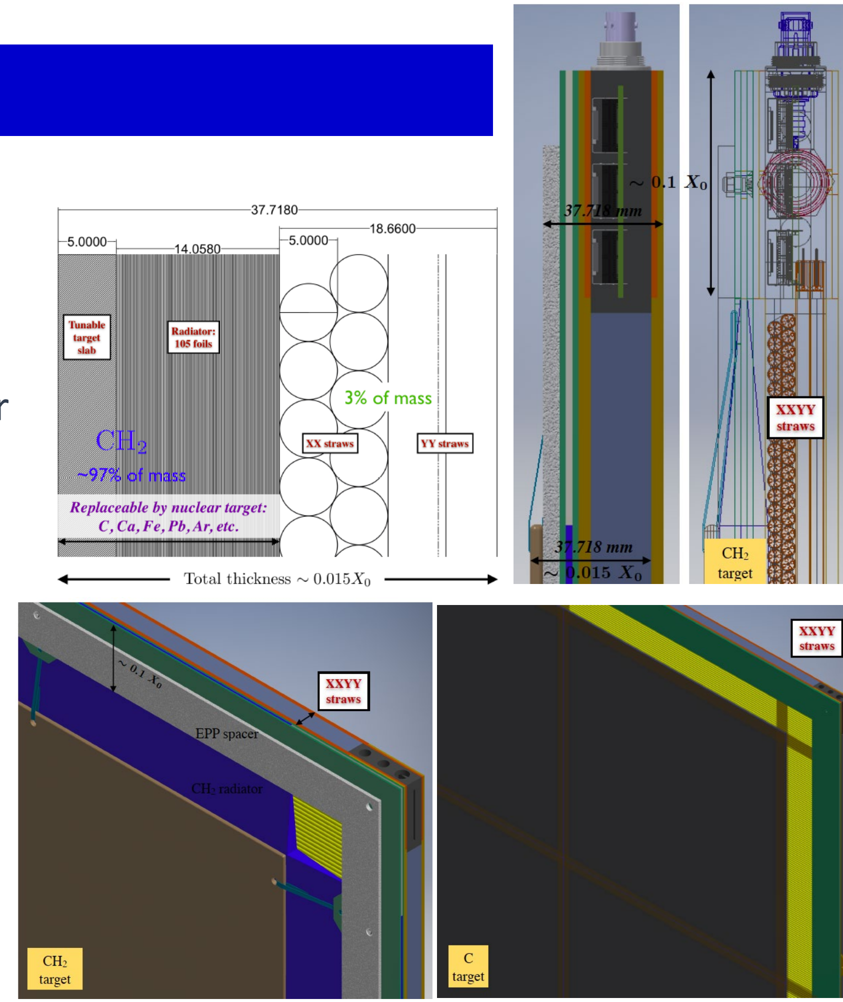
Tracker Design Criteria

- Provide enough mass to have sufficient statistics on ν interactions while still measuring kinematic quantities of charged particles with a good resolution.
- Maximize acceptance for particle produced both in the tracker and in the upstream ECAL.
- Retain a smooth efficiency across most of the volume.
- Be easy to calibrate.
- Have good PID capabilities.
- Be based on mature technologies (detector, FE, ancillary systems), to save time and reduce risks/delays.
- Have a proven extended lifetime.
- Be easy to build, install, maintain (modularity highly preferred)
- Minimize the need of bulky supporting structure, ease the integration with the other components.
- Have the needed expertise within the proponent group.
- Have a reasonable cost and realistic funding perspectives.

The Straw Tube (Target) Tracker

- **90 modules with planes of 5 mm ϕ straw tubes arranged in XXYY(XX) layers and operated at 1.9 bar.**
  - **78 modules** with 5 mm CH_2 targets and radiator TRD foils operated with a mixture of Xe/CO_2 **(standard modules)**
  - **7 modules** with a 4 mm C target, interleaved among the CH_2 modules and operated with a Ar/CO_2 mixture **(C modules)**
  - **5 modules XXYYXX,** operated in Ar/CO_2, no targets, no radiators **(tracking modules)**

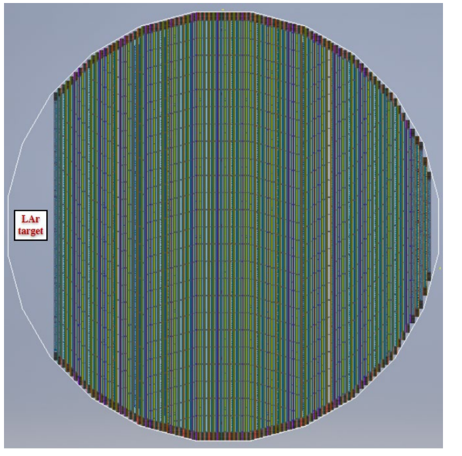
FV mass: 4.7 t CH_2, 557 kg C.

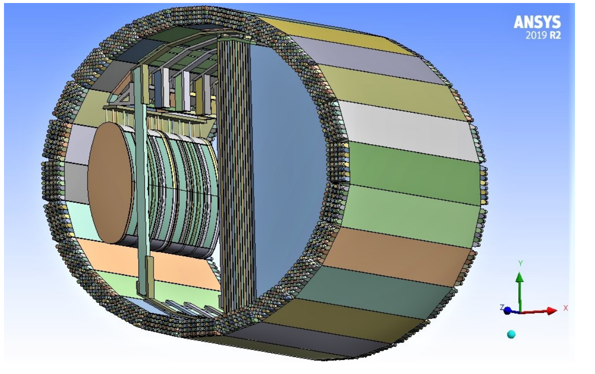


STT in SAND

The layout (starting from upstream):

- **A tracking module** with 6 straw layers XXYYXX, following the internal LAr target
- **Two blocks (supermodules, SM),** each composed of one C module followed by 11 standard modules
- **Two SM**, each composed of one C module and 12 standard modules
- **Two SM** , each composed of one C module and 11 standard modules
- **One SM** with one C module and 10 standard modules (the last one with 6 straw layers XXYYXX)
- **Four** tracking modules.





The total thickness of the STT in this configuration corresponds to about 1.34 X_0, including the straws and all target materials.

STT: a fully tunable/configurable precision instrument

◆**STT designed to offer a control of ν-target(s) similar to $e^{\pm}$ DIS experiments:**

- Thin (1-2% X_0) passive target(s) separated from active detector (straw layers);
- "Transparent" target/tracker system with total length ∼ **$1.3X_0$** ;
- Target layers spread out throughout tracker by keeping low density $0.005 \leq \rho \leq 0.18$ g/cm^3
- Replaceable targets of high chemical purity give ∼ 97% of STT mass (straws 3%).

◆**Accurate reconstruction of transverse plane kinematics from particle 4-momenta:**

- **$\Delta p/p \leq 3\%$, $\Delta\theta/\theta \leq 1.5$ mrad** (inspired to the NOMAD concept) [Nucl.Phys.B 611 (2001) 3-39]

◆**Combined particle ID & tracking over the entire STT volume**:

- Electron ID with Transition Radiation (TR) and **dE/dx =⇒ $\pi/e \sim 10^{-3}$** ;
- 4π detection of π^0 from γ conversions (∼ 49% within the STT volume);
- p/π/K ID with dE/dx and range.
- Good neutron event by event detection and reconstruction efficiency
- Good synergy with PID performances of ECAL.

STT: a fully tunable/configurable precision instrument

◆ **In-situ calibrations***:*

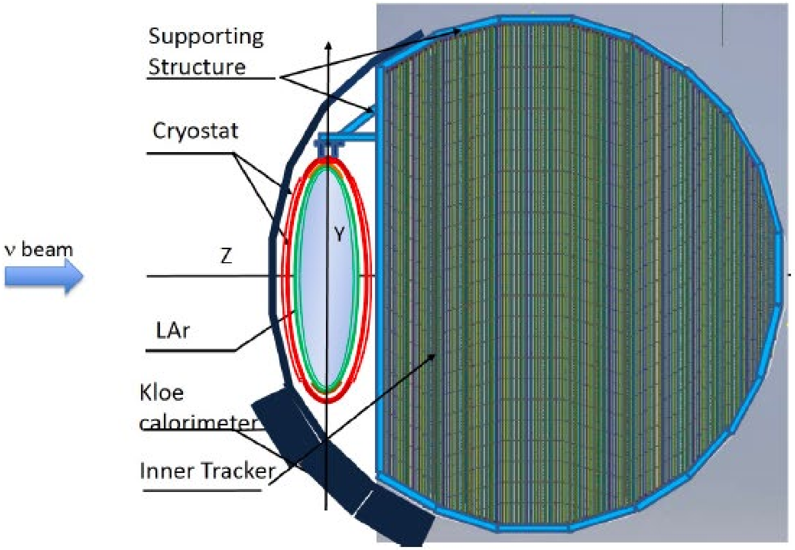
- Absolute momentum scale uncertainty from $K_0 \rightarrow \pi^+\pi^-$ in STT volume ($\Delta p < 0.2\%$) (337,000 in FHC);
- p reconstruction and identification, vertex, etc. from $\Lambda \rightarrow p\pi$ in STT volume (506,000 in FHC);
- $e^\pm$ reconstruction and identification from $\gamma \rightarrow e^+e^-$ in STT volume (8×10^6 in FHC).

◆ **"Solid" Hydrogen concept: (anti)ν-H from subtraction of CH_2 and C targets:**

- Exploits high resolutions & control of chemical composition and mass of targets in STT;
- Allows for **model-independent** data subtraction of dedicated C (graphite) target from main CH_2 target;
- Kinematic selection provides **large H samples** of inclusive & exclusive CC topologies **with 80-95% purity and 75-96% efficiency** before subtraction

A viable and realistic alternative to liquid H_2 detectors, a powerful tool for meeting the ND requirements

GRAIN (GRanular Argon for Interactions of Neutrinos)



inside SAND, example with STT

- Get ~ 50K events per week (in FV and FHC)
- in Liquid Argon neutrino interactions
- with full event reconstruction
- in a magnetized volume

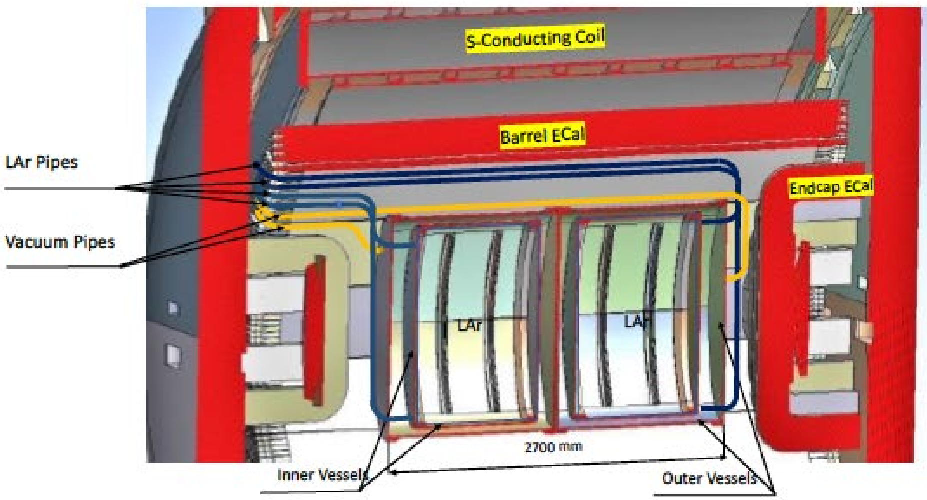
☞ Excellent perspective for inter-detector calibrations, and several other studies

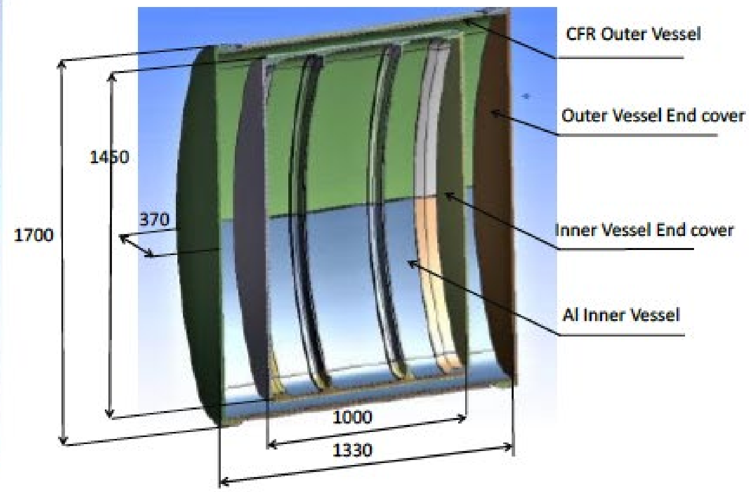
Main goals

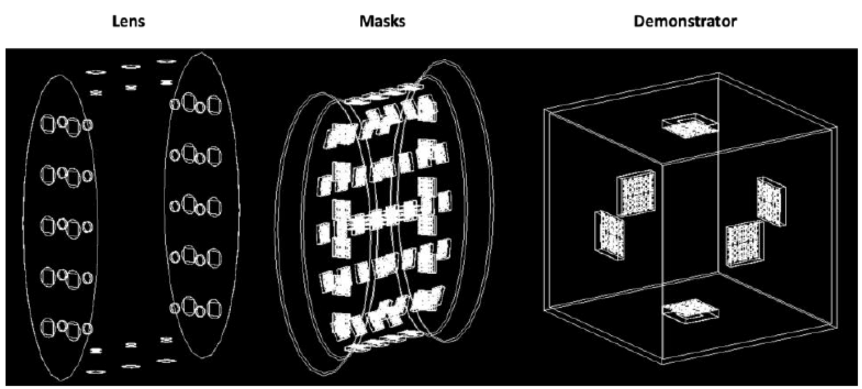
- Measure exclusive and inclusive channels in Ar
- Initial guidance for MC generators, from day-1
- Provide control samples for ND-Lar calibration and reconstruction from day-1
- Cross-calibration with the PRISM system with inclusive CC events
- Monitor variations of Ar measurements vs possible beam variations
- Constrain nuclear effects in Ar by comparing Ar events with H and C events within the same detector

What it cannot do: event topology and reconstruction as in FarDetector

GRAIN

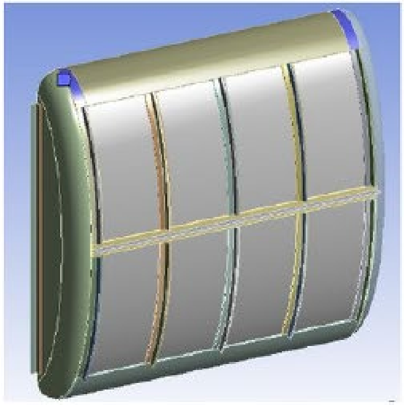

S-Conducting Coil
Barrel ECal
Endcap ECal
LAr Pipes
Vacuum Pipes
LAr
LAr
2700 mm
Inner Vessels
Outer Vessels

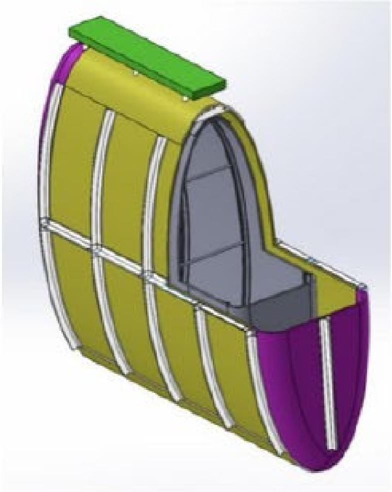

CFR Outer Vessel
Outer Vessel End cover
Inner Vessel End cover
Al Inner Vessel
1700
1450
370
1000
1330


Lens
Masks
Demonstrator

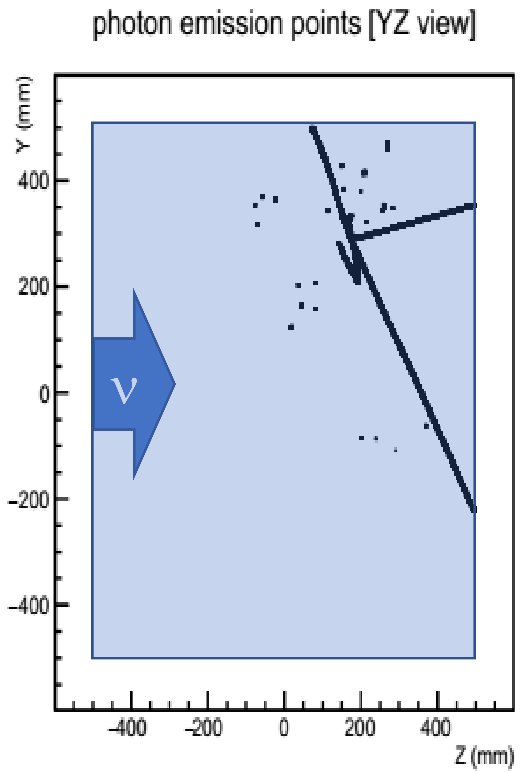
Active LAr target

- With all design options, a ~ 1 ton LAr target can be installed on the upstream part of SAND
- Target thickness ~ 1 X0
- Cryostat walls: C-composite + thin Aluminium foil
- An optical system considered in order to localize the intreaction in the LAr volume and provide t0.
- The combination of the inner tracker and ECAl used to fully reconstruct the neutrino interaction in LAr.

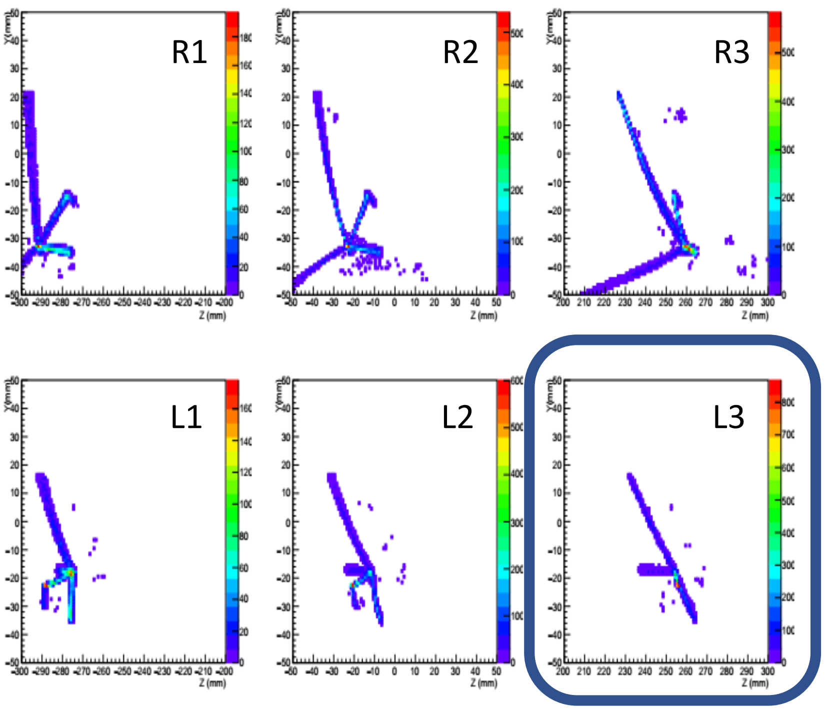




Lar Optical readout example:
ν_μCC with E_ν = 2.44 GeV [YZ view]



n. of photons/SiPM



SiPM size: 1 x 1 mm^2

Distance between lens and SiPM plane: 4.4 cm

SAND/STT Simulation and Performance Studies

- **Completed detector simulation with detailed geometry of all sub-detectors**
  - Option I: GEANT4 + GENIE + dunendggd;
  - Option II: FLUKA (with internal generator) + ROOT

- **Performed reconstruction using only detected quantities:**
  - Cluster reconstruction in KLOE ECAL for γ, π_0,n (validated with real data);
  - Track & vertex reconstruction in STT for charged particles;
  - **External backgrounds** from rock and magnet and **pileup** effects within spill;
  - Single particle reconstruction/identification & neutrino energy reconstruction.

- **Performed physics sensitivity studies of key measurements for oscillation analyses**
  - Full simulation + fast reconstruction of digitized hits from parameterized resolutions & acceptances;

All work **documented** and **continually updated** in https://docs.dunescience.org/cgi-bin/sso/RetrieveFile?docid=13262&filename=A_Near_Detector_for_DUNE.pdf&version=7 **(104 authors)**

A few examples: beam flavor composition

Event type	Efficiency	Purity $(\nu_\mu+\bar{\nu}_\mu+\nu_e+\bar{\nu}_e)$ CC+NC	Wrong sign contamination
Tagging + WS veto + $\mu^\pm$ ID:			
FHC ν_μ CC with tagged μ^-	98.4 %	97.5 %	0.5 %
RHC $\bar{\nu}_\mu$ CC with tagged μ^+	97.9 %	97.8 %	0.3 %
RHC ν_μ CC with tagged μ^-	95.4 %	97.3 %	0.3 %
FHC $\bar{\nu}_\mu$ CC with tagged μ^+	95.4 %	94.2 %	2.6 %
Tagging + muon veto + $e^\pm$ ID:			
FHC ν_e CC with tagged e^-	82.6 %	99.4 %	
RHC $\bar{\nu}_e$ CC with tagged e^+	83.8 %	99.2 %	
RHC ν_e CC with tagged e^-	82.0 %	99.3 %	
FHC $\bar{\nu}_e$ CC with tagged e^+	84.3 %	93.6 %	

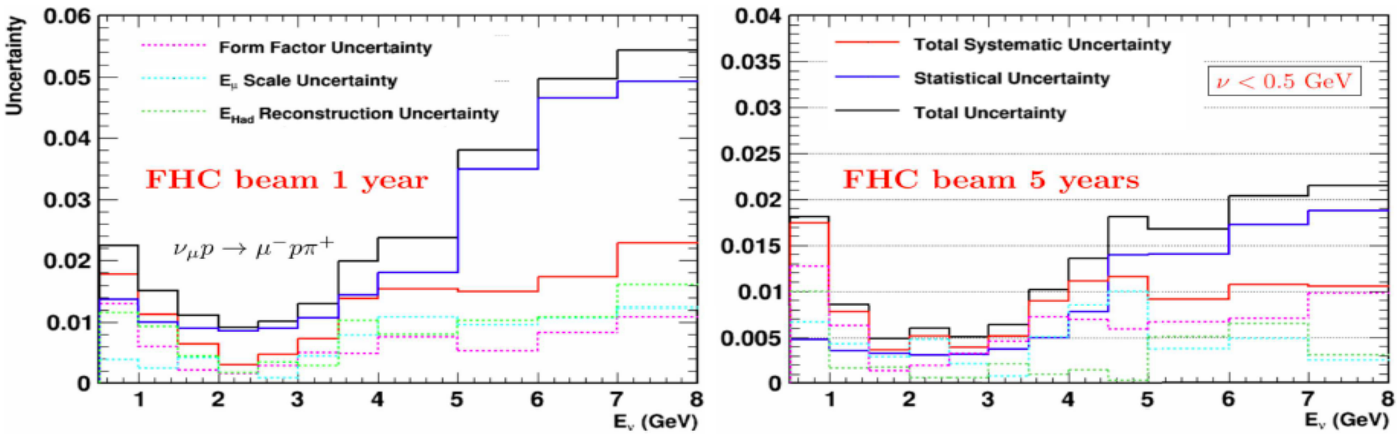
- Generic CC selections: purities can be further increased with tighter cuts.
- The selection of specific processes/topologies results in additional background rejection.
- For the selection of CC interactions on H only kinematic tagging needed: efficiency 99.1% in FHC and 99.3% in RHC with negligible NC backgrounds.

A few examples: “Solid Hydrogen” relative flux measurement

RELATIVE ν_μ FLUX WITH $\nu_\mu p \to \mu^- p \pi^+$ ON H

- *Relative ν_μ flux vs. E_ν from exclusive $\nu_\mu p \to \mu^- p \pi^+$ on Hydrogen:*
  - *Select well reconstructed $\mu^- p \pi^+$ topology on H ($\sim 93\%$ p reconstructable);*
  - *Cut $\boxed{\nu < 0.5 \text{ GeV}}$ flattens cross-sections reducing uncertainties on E_ν dependence;*
  - *Systematic uncertainties dominated by momentum scale ($\Delta p \sim 0.2\%$ from $K^0_s \to \pi^+\pi^-$).*

$\Longrightarrow$ *Dramatic reduction of systematics vs. techniques using nuclear targets*



PLB 795 (2019) 424, arXiv:1902.09480 [hep-ph]

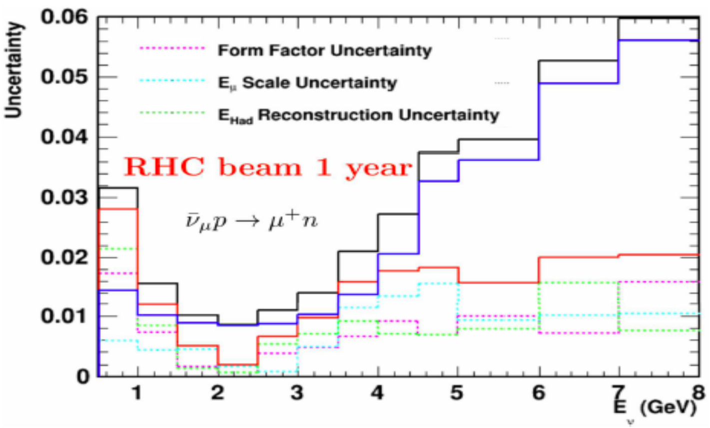
A few examples: "Solid Hydrogen" relative flux measurement

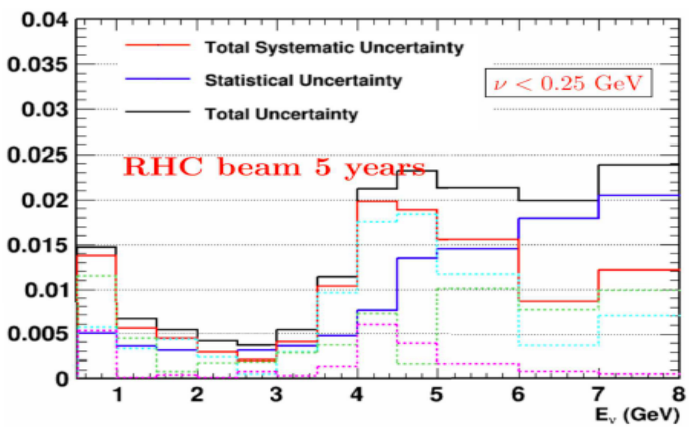
RELATIVE $\bar{\nu}_\mu$ FLUX WITH $\bar{\nu}_\mu p \to \mu^+ n$ ON H

✦ *Relative $\bar{\nu}_\mu$ flux vs. E_ν from exclusive $\bar{\nu}_\mu p \to \mu^+ n$ QE on Hydrogen:*

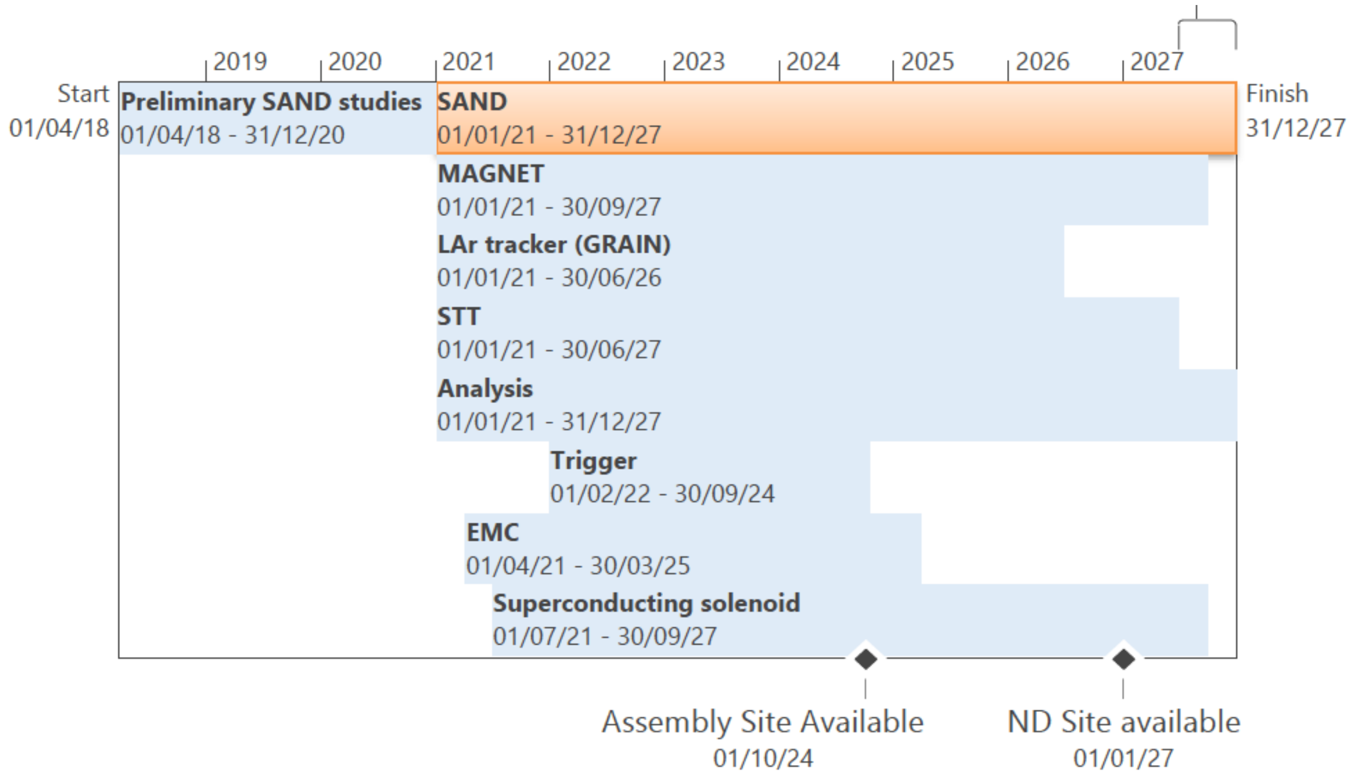
- *E_ν from QE kinematics + reconstructed direction of neutrons detected in STT+ECAL ($\sim 80\%$);*
- *Cut $\nu < 0.25$ GeV flattens cross-sections reducing uncertainties on E_ν dependence;*
- *Efficient rejection of random neutrons from external interactions (rocks, magnet) within the spill.*

$\Longrightarrow$ *Uncertainties comparable to relative ν_μ flux from $\nu_\mu p \to \mu^- p \pi^+$ on H*





SAND High Level Timeline



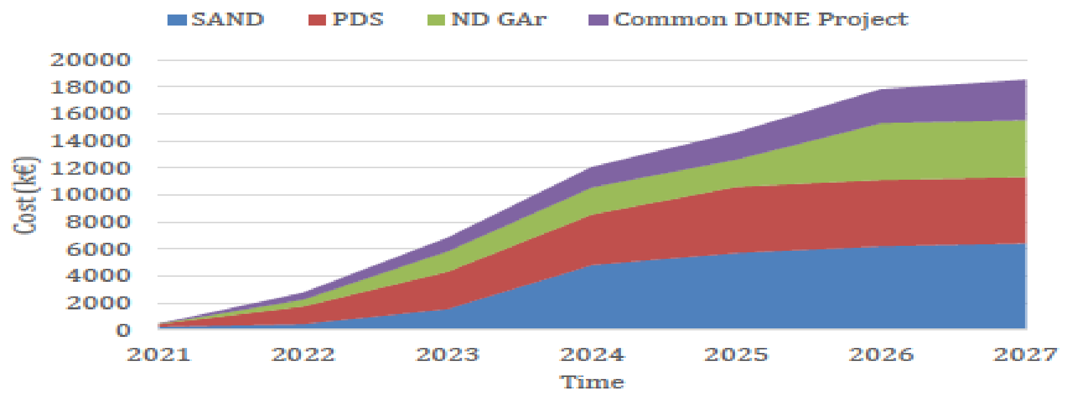
Resources: costs and spending profile Nu_at_FNAL

YEAR	TASK	2021	2022	2023	2024	2025	2026	2027	TOTAL	CSN II	INFN
	Dismounting and storage of the e.m Calorimeter	100							100	100	
	Magnet Power supply, Quench Prot System, Breakers	125							125		125
	Dismounting of KLOE magnet and Yoke			120					120	120	
NEAR DETECTOR	Shipping of all KLOE			1300					1300	1300	
	Assembly inside the cryostat of the calorimeter and the tracker of SAND at FNAL				80	40	30		150	150	
	Reassembly of YOKE, insertion of the instrumented cryostat,Installation of electronics, cabling, services							250	250	250	
	Calorimeter Photomultipliers spares		100	100	100				300	300	
	Calorimeter FE electronics				750				750		750
	Carorimeter HV					250			250		250
	LAr ND Meniscus			400	400	200	500		1500	1500	
	Contribution to the tracker, trigger, slow control			200	500	500	300		1500	1500	
FAR DETECTOR	Tender for 10% PDS SiPm	200							200		200
	Tender for the bulk supply of PDS Sipm		2800						2800		2800
	Participation to Vertical Drift PDS					2000			2000		2000
MPD	Possible contribution of INFN for the contruction of the coil of the MPD detector		500	1000	500		2200		4200		4200
GENERAL	Contribution to LAr		500	500	500	500	500	500	3000	3000	
ALL ITEMS/YEAR		425	3900	3620	2830	3490	3530	750	18545	8220	10325

DUNE Spending Profile

Table 12 Global spending profile of INFN core contribution.

Product	2021	2022	2023	2024	2025	2026	2027	Total
SAND	225	200	1120	3250	900	500	200	**6395**
PDS	200	1100	1454	992	1160	0	50	**4956**
ND GAr	20	500	1000	500	0	2200	0	**4220**
Common DUNE Project including Ar contribution to DUNE Far Module 2 (common Funds)	0	500	500	500	500	500	500	**3000**
Total	**445**	**2300**	**4074**	**5242**	**2560**	**3200**	**700**	**18521**



Our Next Steps

2021-2022 main activities:

PDS

- Prepare, install, commission and operate ProtoDune-II PDS
- Launch the SiPM tender for the HD module
- Complete the R&D on the VD PDS

SAND

- Complete the dismounting of the EMC, purchase spares for the calorimeter PM’s
- Continue R&D and prototype on the LAr Active target (GRAIN)
- Lead the design and the prototyping of the inner tracker

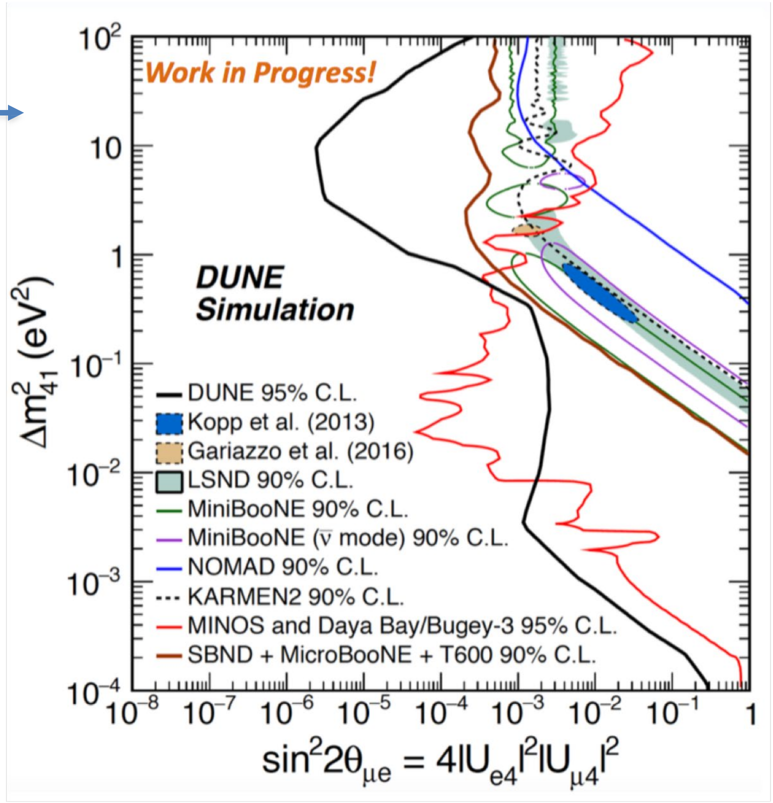
DUNE/LBNF Outlook

- LBNF
  - Far site pre-excavation work underway (rock disposal systems etc.); cavern excavation 2021-24
  - Near site construction starts 2021
  - Neutrino beam construction started
- DUNE
  - Far Detector TDR February 2020; Near Detector CDR fall 2020
  - Module 1 Single Phase installation begins end 2024
  - Followed immediately by a second module
  - Module 4 “module of opportunity” for a different design – a workshop later this year to begin exploration of ideas
- First module live ~2026 – SNB & atmospheric neutrino
- First beam end of 2028

Beyond Standard Model

- DUNE sensitive to many BSM particles and processes
- Sterile neutrinos
- Light dark matter
- Boosted dark matter
- Non-standard interactions, non-unitary mixing, CPT violation
- Neutrino trident searches
- Large extra dimensions
- Neutrinos from dark matter annihilation in sun

Sterile Neutrino Sensitivity
(ν_eCC appearance at Near Detector)



To conclude

- Since 1998, neutrinos have given us the most promising hints of BSM physics.
- Their nature and their properties are still a central questions in particle physics.
- A new generation of experiments is underway, with a substantial and strategic Italian involvement in DUNE
- DUNE/LBNF is heralding this effort addressing the challenge in a global context and enabling a long term, first class environment to enhance our understanding of Fundamental Physics.

Thank You

…and thanks to E. Blucher, F. Cavanna, E. Worcester, et al. for the looted material and many useful discussions.