τ neutrino physics in the DUNE experiment and recent activities related to the Liquid Argon Time Projection Chamber Vertical Drift design

Thomas Kosc, 02/11/2021

PhD student 2018-2021 at IP2I (Lyon) already involved in DUNE

Post-Doc LPSC on DUNE 2021-2023

Outline

- **Motivations for τ neutrino physics**
- **D**eep **U**ndeground **N**eutrino **E**xperiment (DUNE)
- Contribution during my thesis on τ neutrino physics
- Perspectives for the LPSC neutrino group

THESE DE DOCTORAT DE L'UNIVERSITE DE LYON
opérée au sein de
l'Université Claude Bernard Lyon 1

Ecole Doctorale N°52
PHAST : Physique et Astrophysique de Lyon

Spécialité de doctorat : Physique des Particules

Soutenance prévue à huit clos le 06/09/2021, par:
Thomas Kosc

Kinematic search for τ neutrino appearance in the DUNE experiment

Devant le jury composé de :

JOLLET	Cécile	Maître de Conférences - CENBG Bordeaux	Rapporteure
MARCHIONNI	Alberto	Senior Scientist - Fermilab (USA, Illinois)	Rapporteur
DAVESNE	Dany	Professeur des Universités - IP2I Lyon	Examinateur
NEDELEC	Patrick	Professeur des Universités - IP2I Lyon	Examinateur
AUTIERO	Dario	Directeur de Recherche CNRS - IP2I Lyon	Directeur de Thèse
CHEYNIS	Brigitte	Chargée de Recherche CNRS - IP2I Lyon	Invitée

Neutrino group and activities at LPSC

- **STEREO**: neutrino experiment investigating possible sterile neutrino signature at short baselines (ILL)
  - Jean-Sébastien Réal, Jacob Lamblin, Anne Stutz, Jean-Stéphane Ricol, Matthieu Licciardi (post-doc)

- **RICOCHET**: measuring coherent neutrino-nucleus elastic scattering with reactor neutrinos (ILL)
  - Jacob Lamblin, Corinne Goy, Guillaume Chemin (PhD)

- **DUNE**: next generation of long-baseline experiment to study unresolved questions of neutrino oscillations
  - Jean-Sébastien Réal, Jean-Stéphane Ricol, Arnaud Robert, Thomas Kosc (post-doc), Joël Dai (PhD)

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Status on PMNS matrix

$$\nu_\alpha = \sum_{i=1}^{3} \nu_i$$ Neutrino mixing

- PMNS matrix has 3 mixing angles and 1 complex phase

$$U = \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}}_{\text{atmospheric}} \underbrace{\begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{CP}} & 0 & c_{13} \end{pmatrix}}_{\text{reactor}} \underbrace{\begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{\text{solar}}$$

http://www.nu-fit.org/?q=node/228

without SK atmospheric data		Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 2.7$)	
		bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range
	$\sin^2\theta_{12}$	$0.304^{+0.013}_{-0.012}$	$0.269 \to 0.343$	$0.304^{+0.013}_{-0.012}$	$0.269 \to 0.343$
	$\theta_{12}/^\circ$	$33.44^{+0.78}_{-0.75}$	$31.27 \to 35.86$	$33.45^{+0.78}_{-0.75}$	$31.27 \to 35.87$
	$\sin^2\theta_{23}$	$0.570^{+0.018}_{-0.024}$	$0.407 \to 0.618$	$0.575^{+0.017}_{-0.021}$	$0.411 \to 0.621$
	$\theta_{23}/^\circ$	$49.0^{+1.1}_{-1.4}$	$39.6 \to 51.8$	$49.3^{+1.0}_{-1.2}$	$39.9 \to 52.0$
	$\sin^2\theta_{13}$	$0.02221^{+0.00068}_{-0.00062}$	$0.02034 \to 0.02430$	$0.02240^{+0.00062}_{-0.00062}$	$0.02053 \to 0.02436$
	$\theta_{13}/^\circ$	$8.57^{+0.13}_{-0.12}$	$8.20 \to 8.97$	$8.61^{+0.12}_{-0.12}$	$8.24 \to 8.98$
	$\delta_{CP}/^\circ$	195^{+51}_{-25}	$107 \to 403$	286^{+27}_{-32}	$192 \to 360$
	$\frac{\Delta m^2_{21}}{10^{-5}\ \text{eV}^2}$	$7.42^{+0.21}_{-0.20}$	$6.82 \to 8.04$	$7.42^{+0.21}_{-0.20}$	$6.82 \to 8.04$
	$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \text{eV}^2}$	$+2.514^{+0.028}_{-0.027}$	$+2.431 \to +2.598$	$-2.497^{+0.028}_{-0.028}$	$-2.583 \to -2.412$

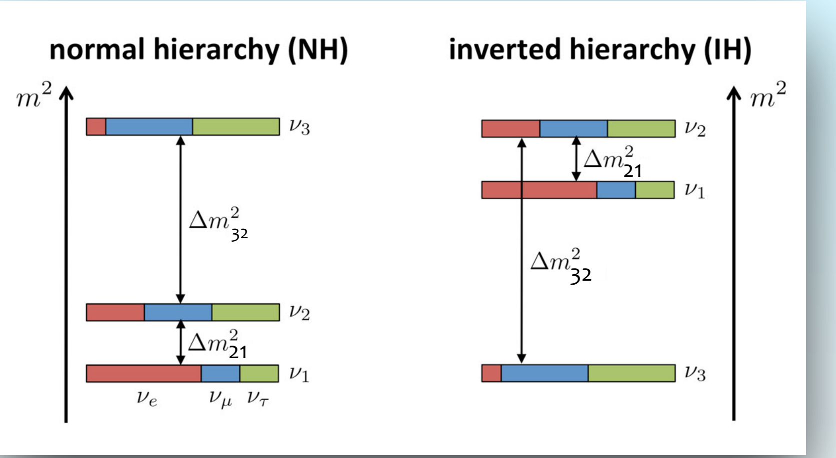
θ_{23} is large (~45°) and octant unkown

θ_{13} is small but non-zero: allows for subleading atmospheric $\nu_\mu \longrightarrow \nu_e$ oscillations (~10%)

δ_{CP} very poorly constrained

- There exists an ambiguity in the mass hierarchy, sign of Δm^2_{31}

- Unitarity very poorly constrained



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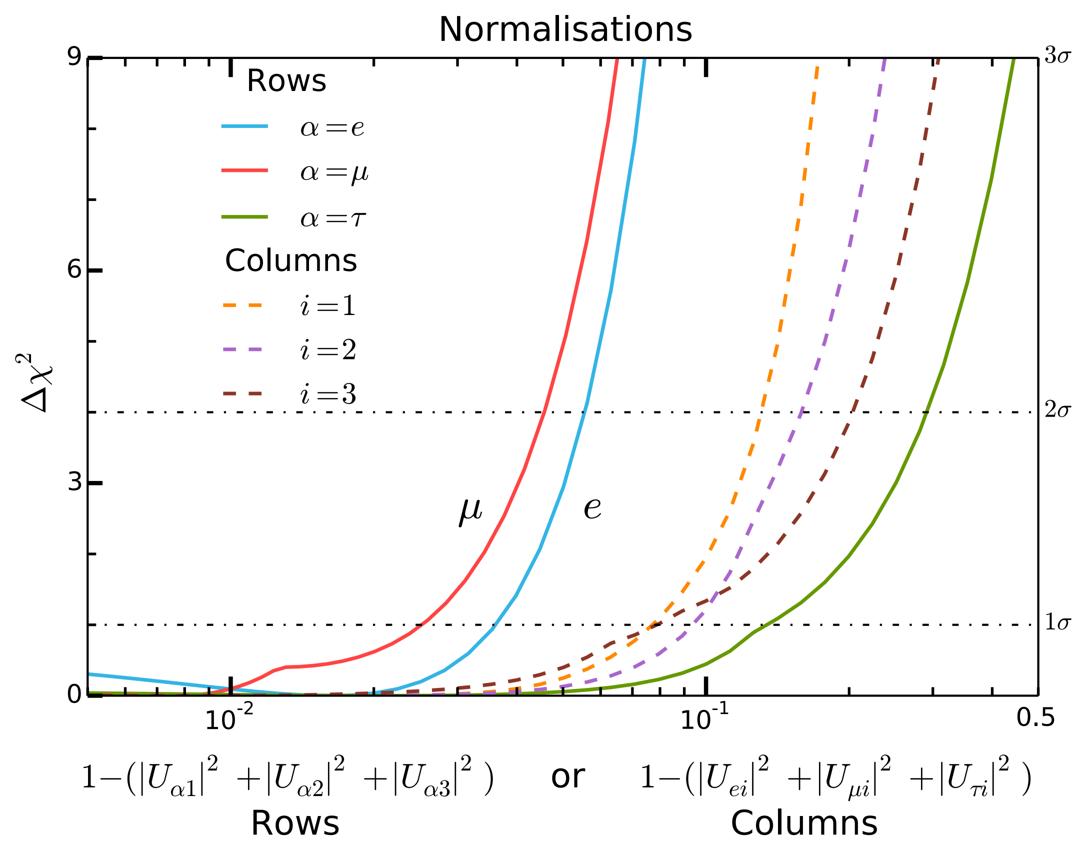
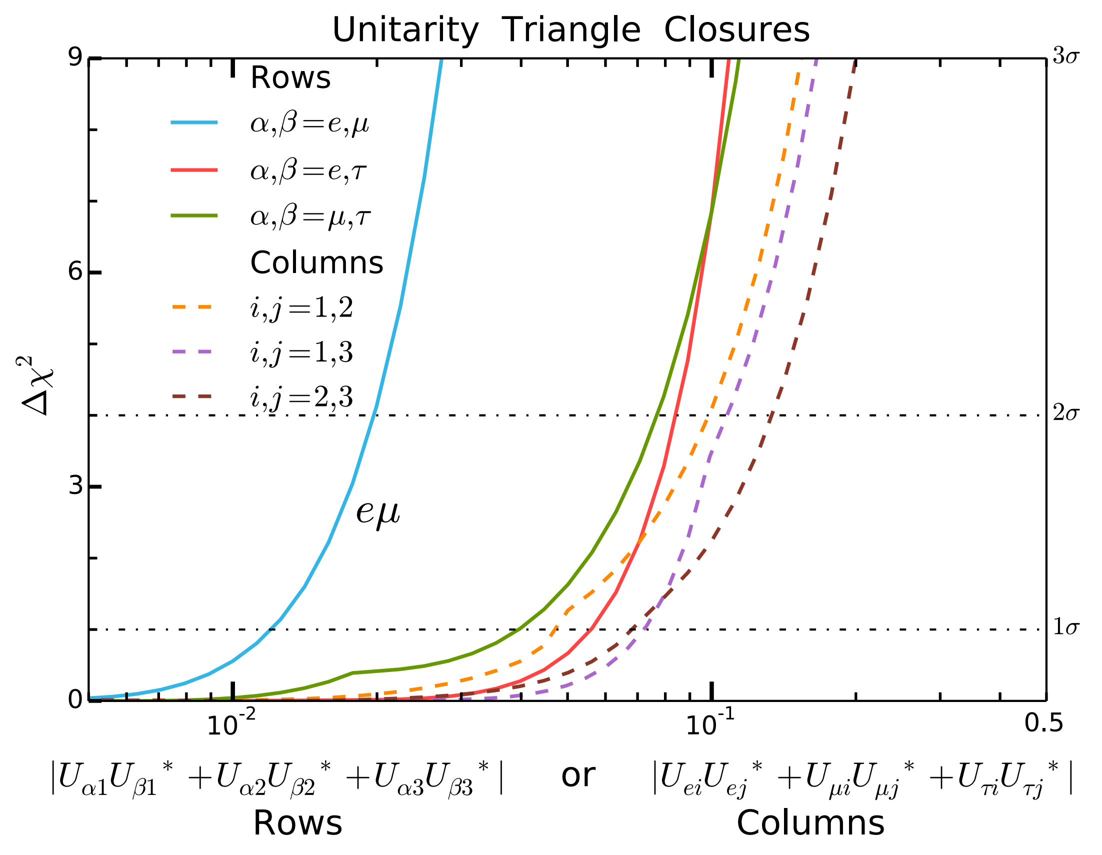
PMNS unitarity

- Knowledge on τ neutrino comes from PMNS unitarity (for oscillations) and leptonic universality (for cross-section).





S. Park & M. Ross-Lonergan, Phys. Rev. D 93, 113009 (2016)

- Lack of experimental data on τ neutrino (appearance+disappearance) limitates the unitarity measurements.

My thesis in DUNE - search for τ neutrinos at the simulation level

- Growing interest concerning DUNE sensitivity to $\nu_\mu \longrightarrow \nu_\tau$ appearance at far detector site, with O(30) ν_τ charged current events / year / 10kTon.

  Ghoshal, Giarnetti, Meloni , J. High Energ. Phys. 2019 (2019)   A. de Gouvêa *et al*, PRD100, 010004 (2019)

- Current data: 8 from DONUT (2008), 10 from OPERA (2018) (+T2K and IceCUBE) —> 18 directly observed candidates.

- **Motivations ?** 3-flavour phenomenology, PMNS unitarity, 3+1 neutrino paradigm, cross-section, non-standard neutrino interaction

- Workshop on Tau neutrino Sep. 27 to Oct. 1 2021, White Paper in prep.

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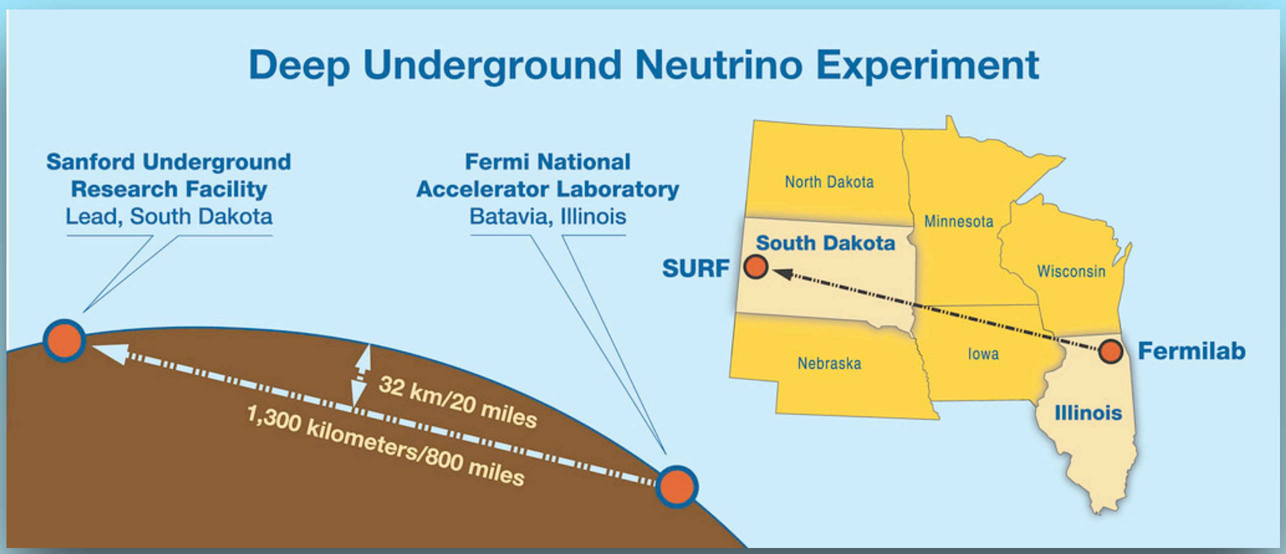
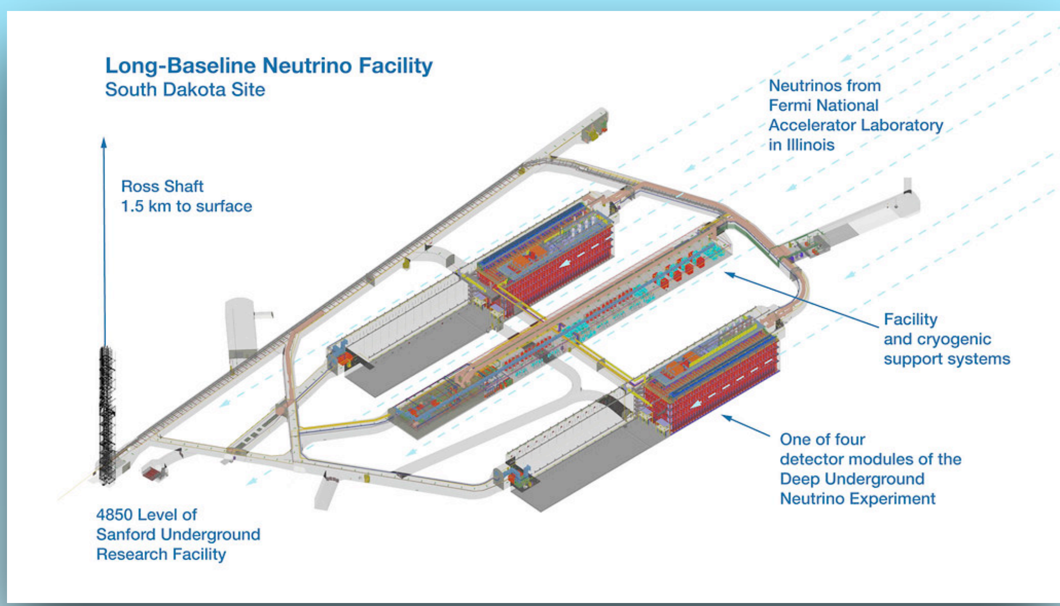
Deep Underground Neutrino Experiment

- Future long-baseline (1285 km) beam neutrino experiment between Fermilab and Sanford. Start by the end of the decade. Joint LBNO & LBNF in 2015.



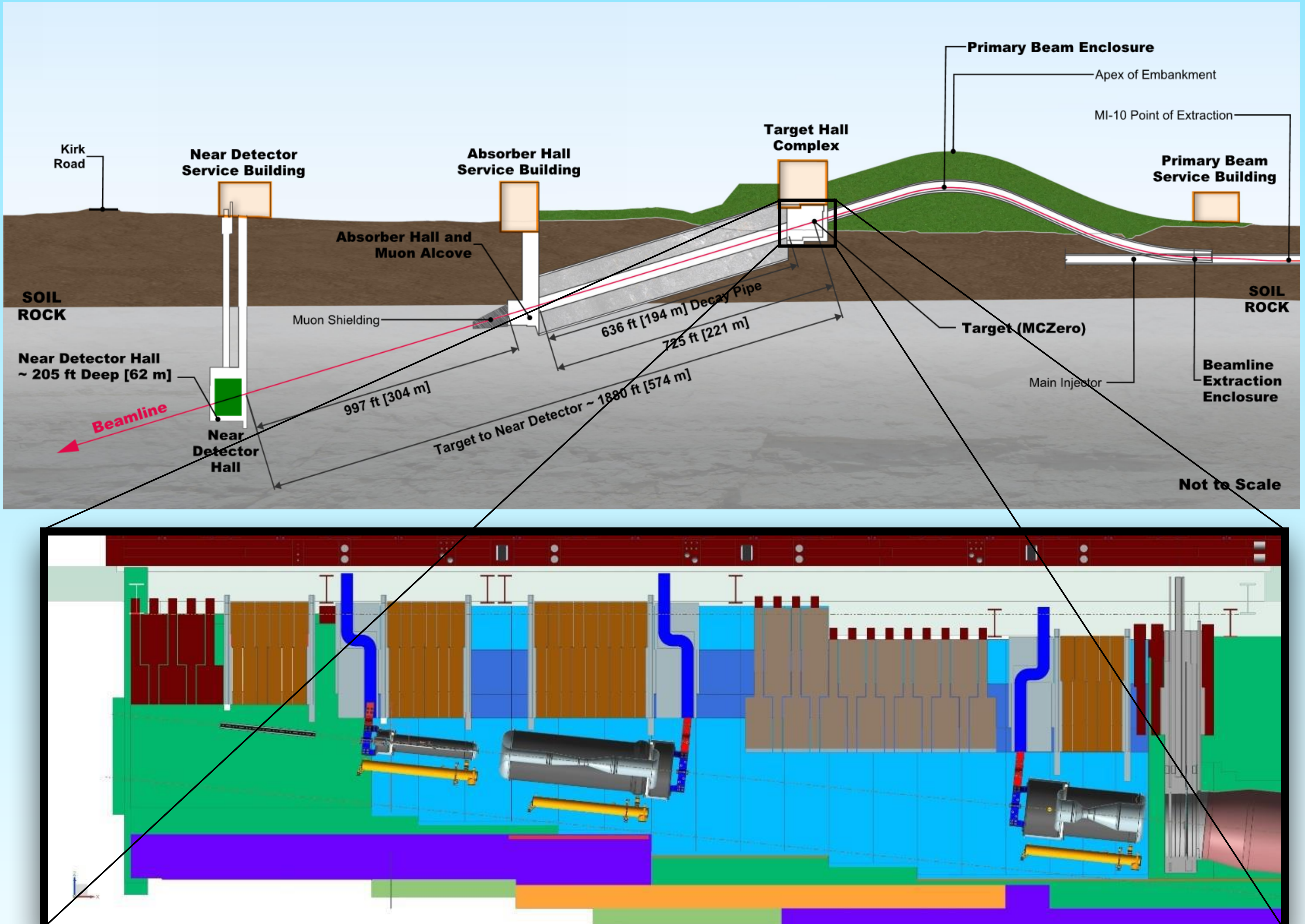


- Characteristics:
  - 1.2 MW beam (upgradeable to 2.4 MW)
  - Near detector hall (Fermilab)
  - four 10 kTons (fiducial mass) modules at far detector site

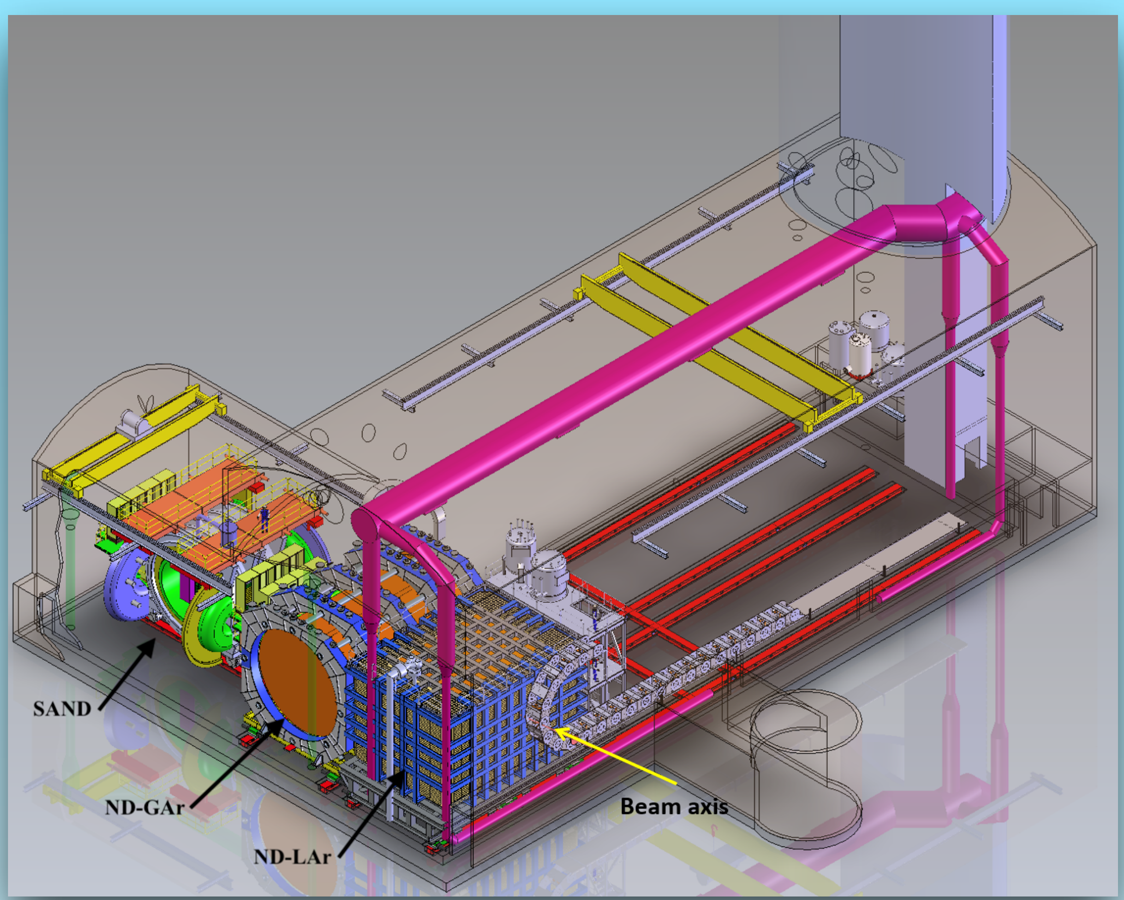
Deep Underground Neutrino Experiment

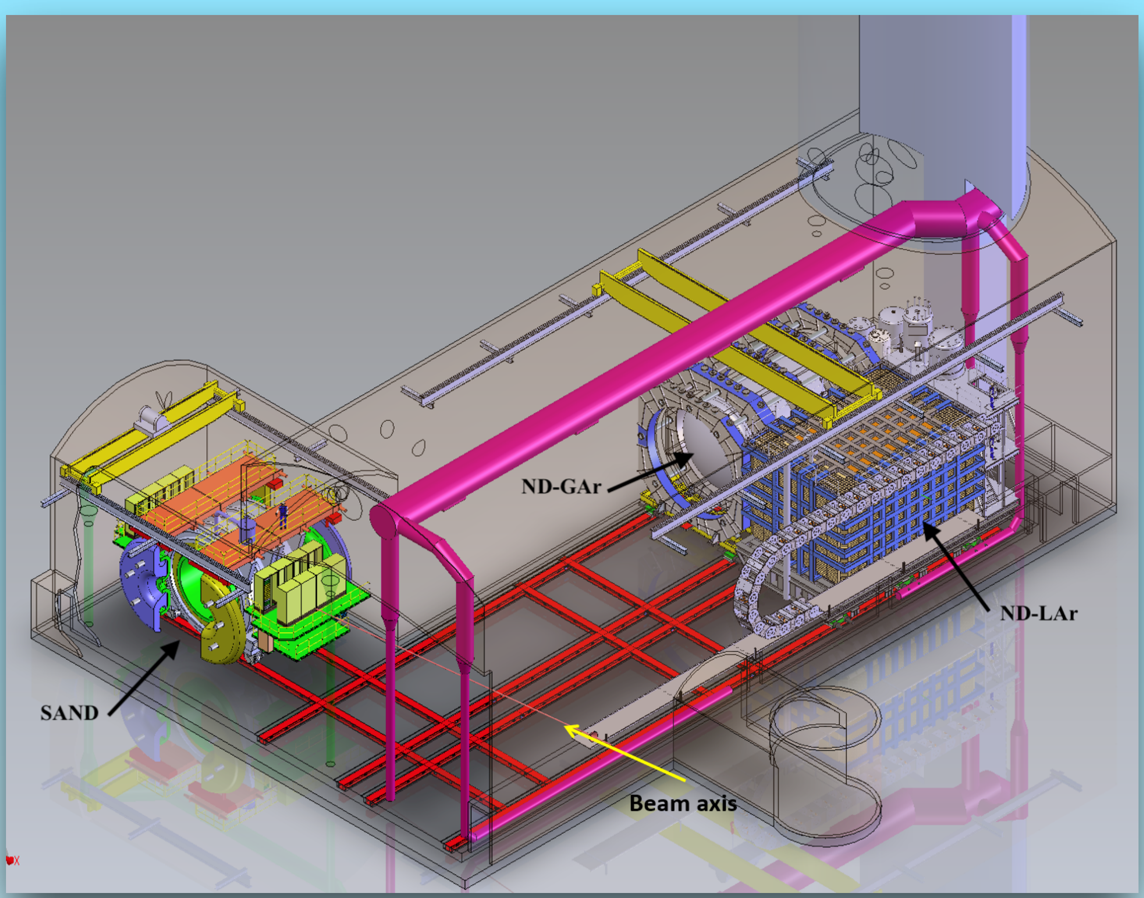
- Tuned to study subleading $\nu_\mu \longrightarrow \nu_e$ oscillations (~10%) sensitive to last unconstrained PMNS parameter δ_{CP}, related to possible CP violation
- Rich program
  - Neutrino oscillations (mass hierarchy, octant of θ_{23}, CP violation study)
  - Neutrino astrophysics (supernovae, solar)
  - BSM studies
- >1000 physicists, >30 countries, >200 research institutions

Near site facility



Near site facility - Detector





- Liquid argon + High pressure gas argon detectors to monitor the neutrino beam.
- DUNE-PRISM (**P**recision **R**eaction-**I**ndependent **S**pectrum **M**easurement) to perform off-axis measurements (flux and cross section deconvolution).
- SAND (**S**ystem for on-**A**xis **N**eutrino **D**etection) detector to perform on-axis monitoring 100% of the time.

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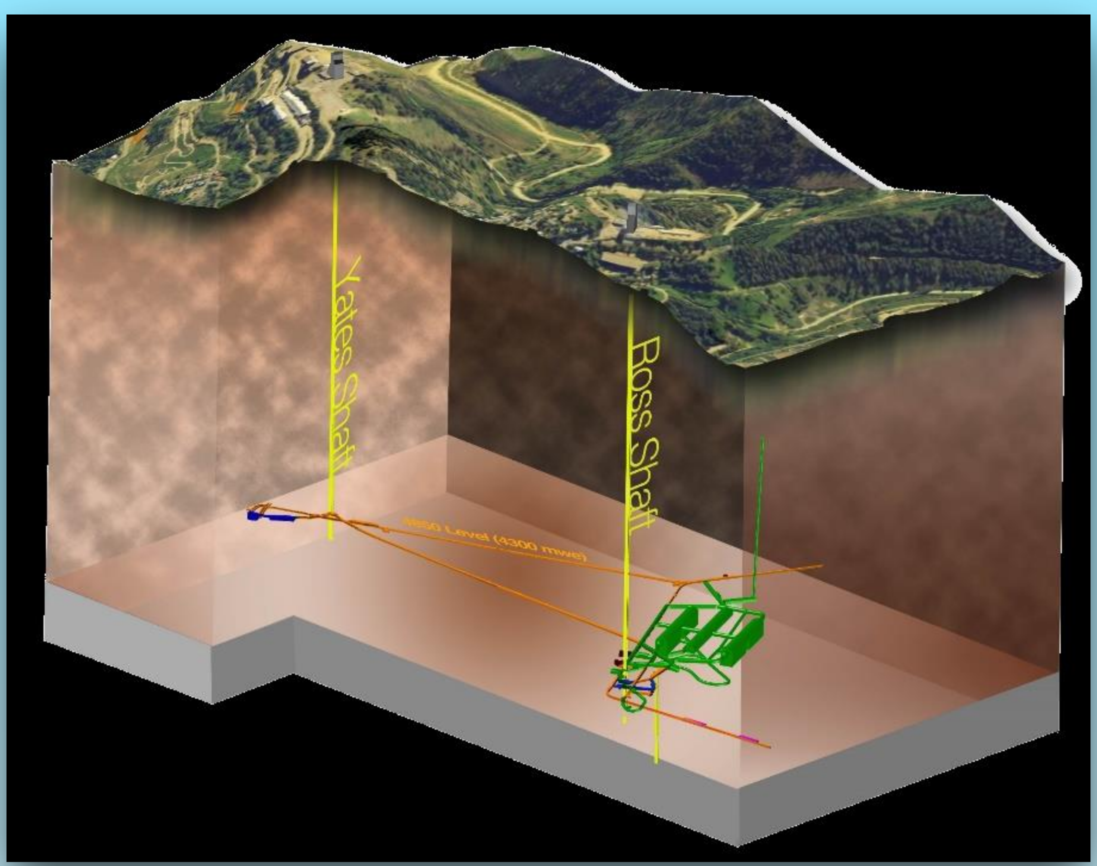
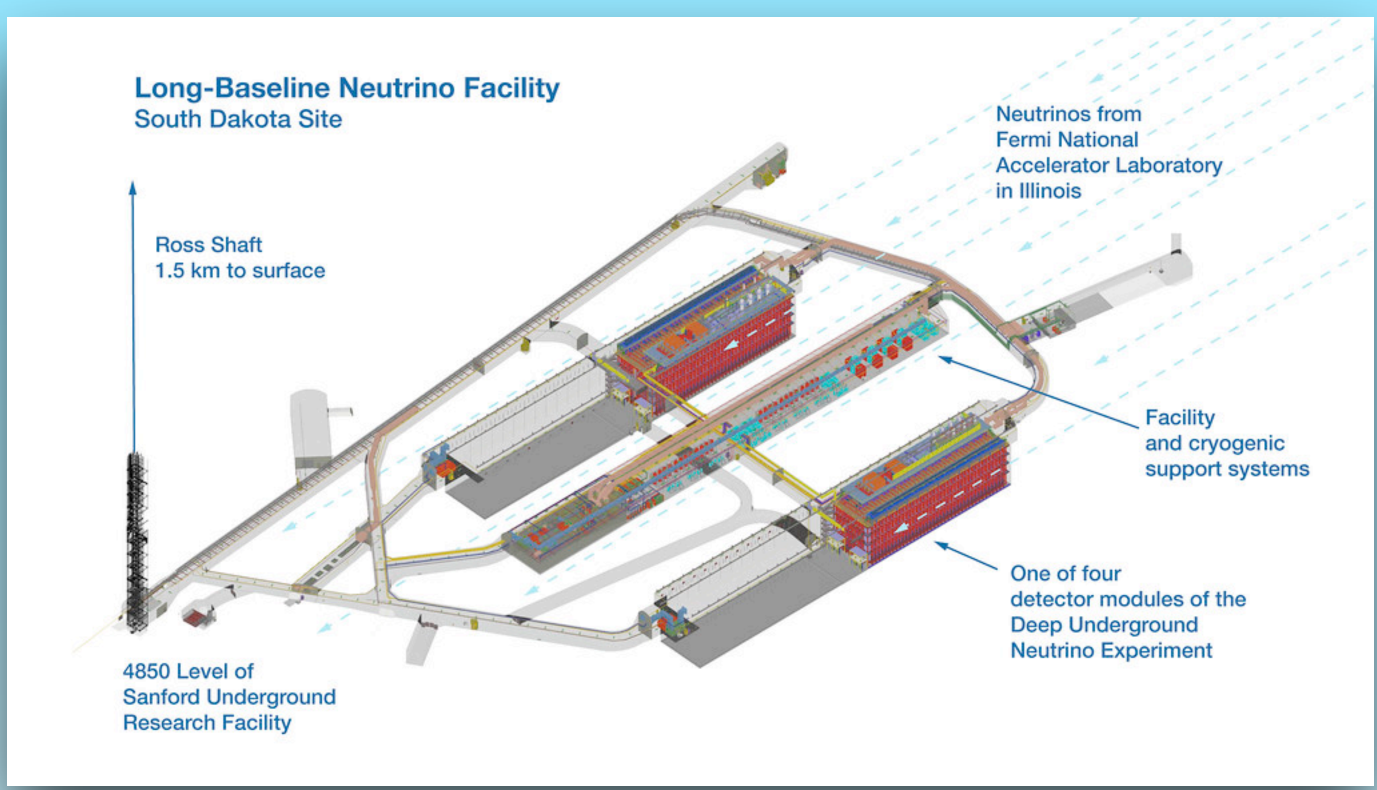
Far site facility

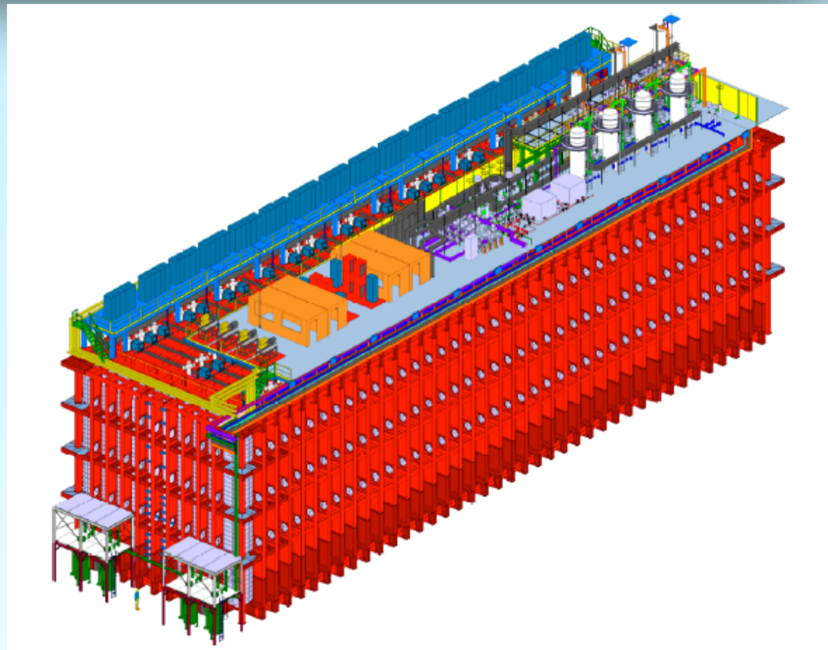
- 1.5 km underground at SURF (South Dakota), old gold mine





- 12 x 12 x 60 m^3 fiducial volume (~10 kTon mass)

- **L**iquid **Ar**gon **T**ime **P**rojection **C**hamber (LArTPC) technology



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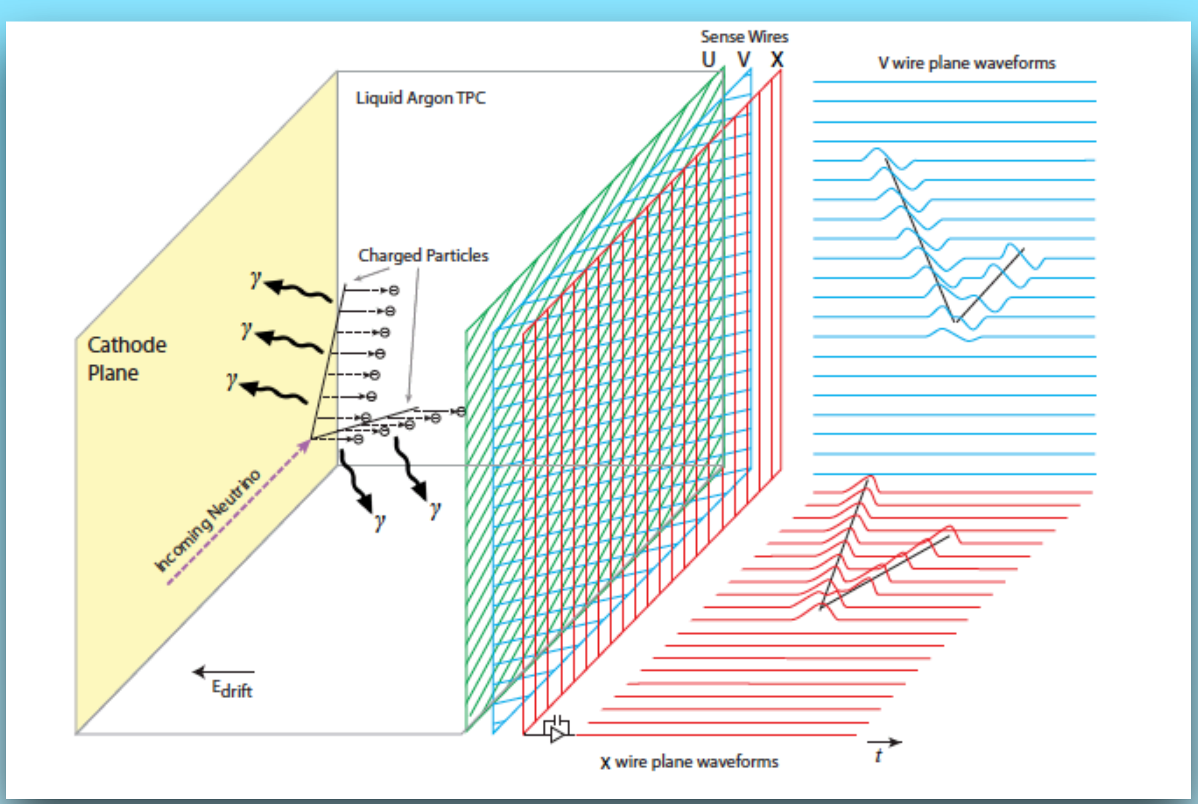
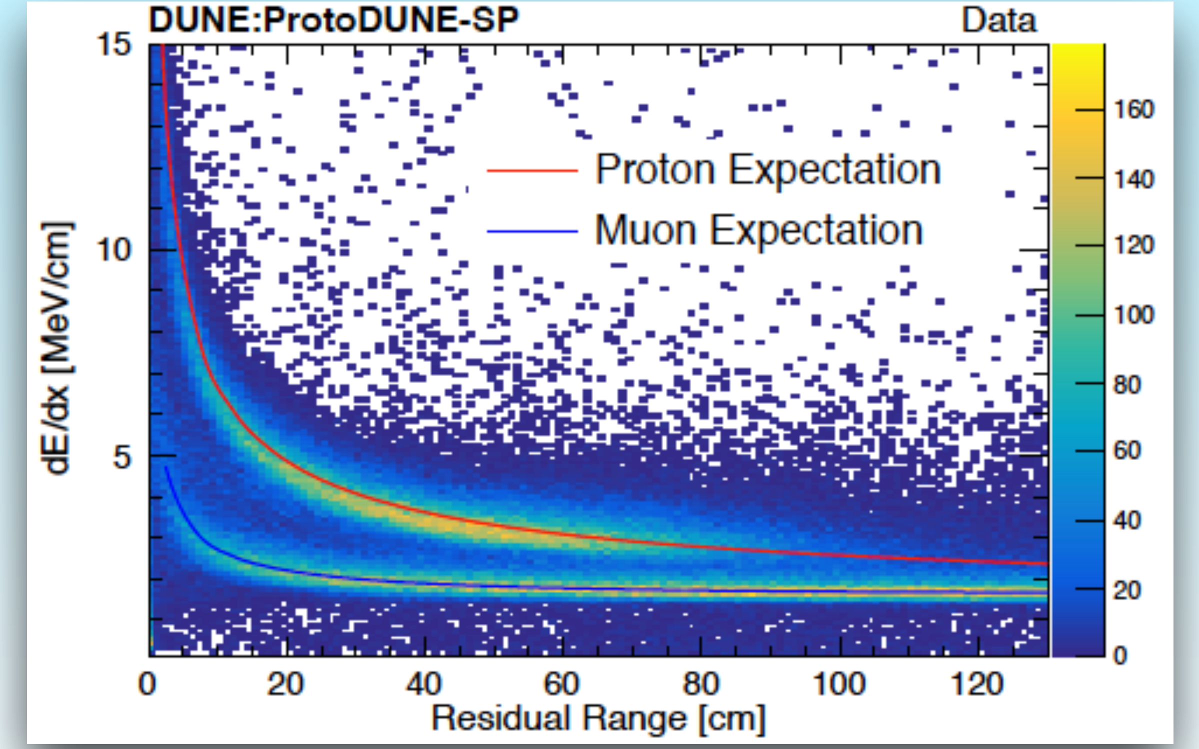
LArTPC technology

- Far detector chosen technology:
  - Excellent spatial resolution
  - Excellent calorimetric response

- Charged particle ionize argon. Freed electrons drifted: electronic bubble chamber !

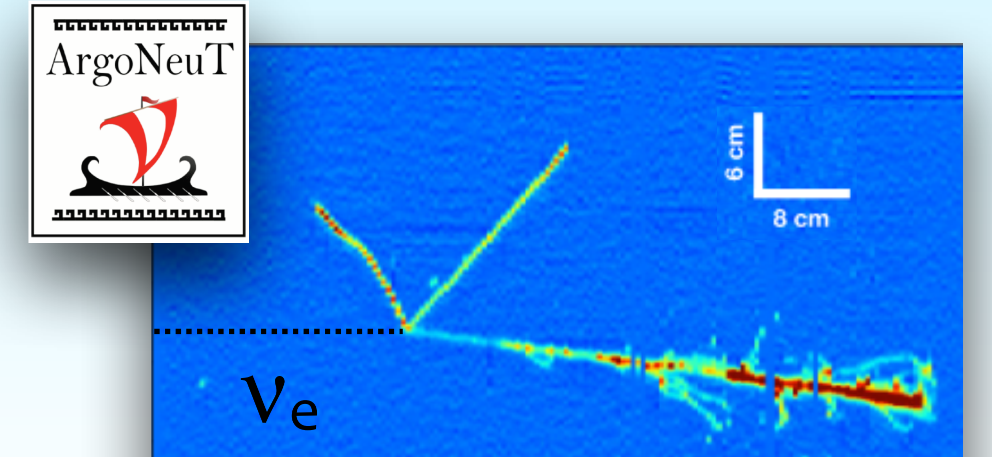


- Millimetric pitch + energy deposited measured



10.1088/1748-0221/15/12/P12004

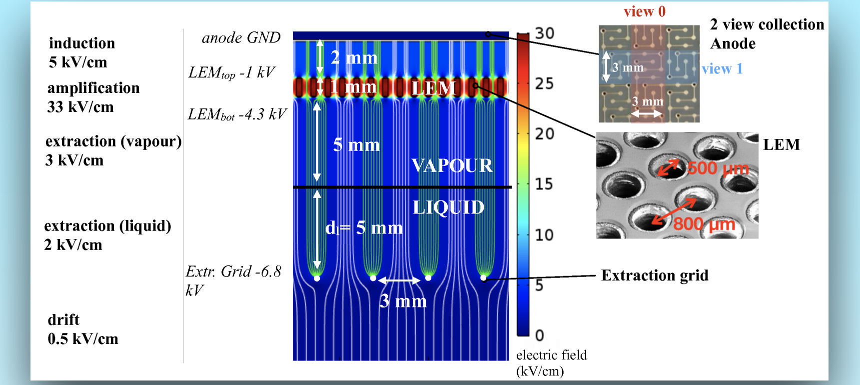
- Large scale detectors achievable

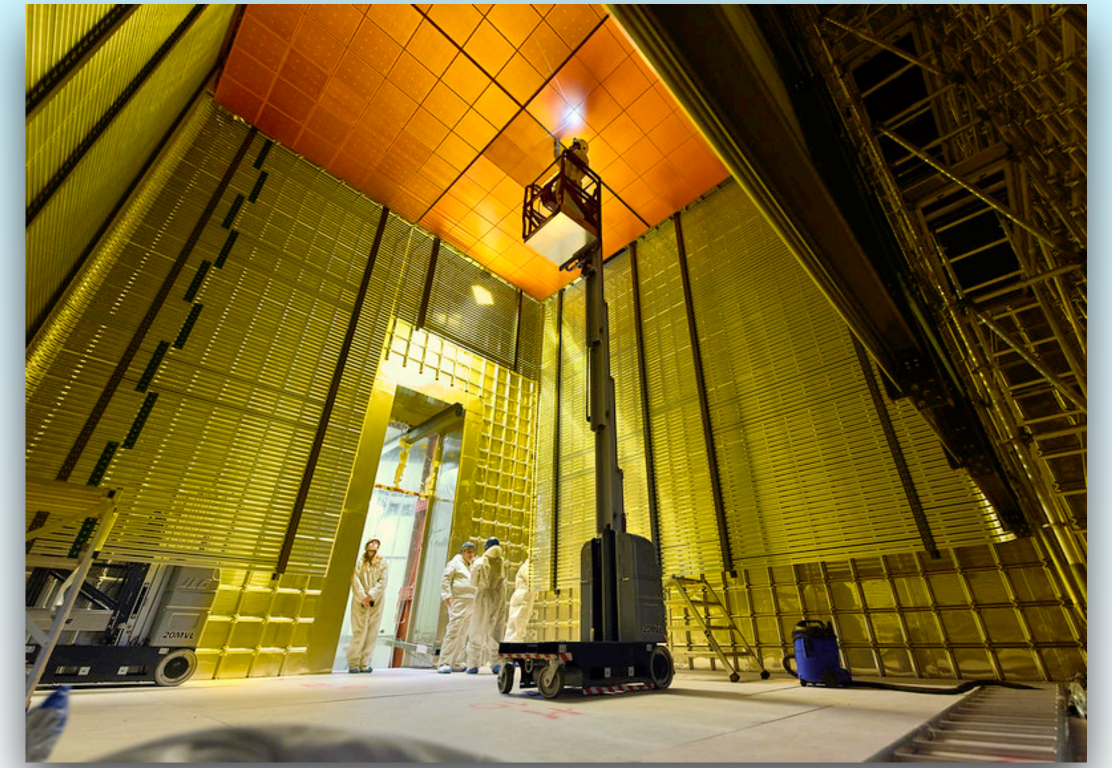


Phys. Rev. D 102, 011101(R)

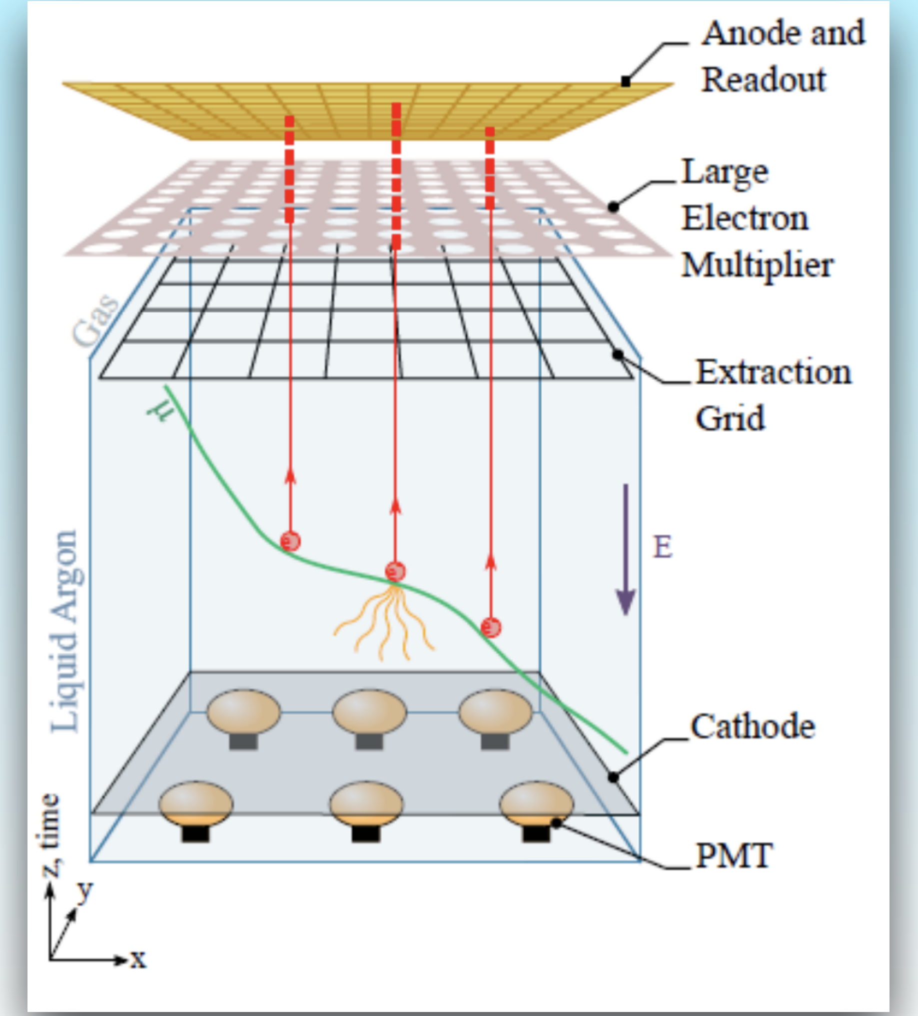
ProtoDUNEs 6x6x6 m3 (fiducial)

- Installed at CERN (2018) on neutrino platform.
- ProtoDUNE single-phase already shows excellent performance **http://arxiv.org/abs/2007.06722**





- ProtoDUNE double-phase evolved toward single-phase Vertical Drift design (2020)



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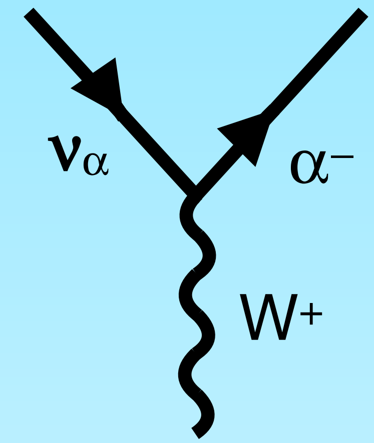
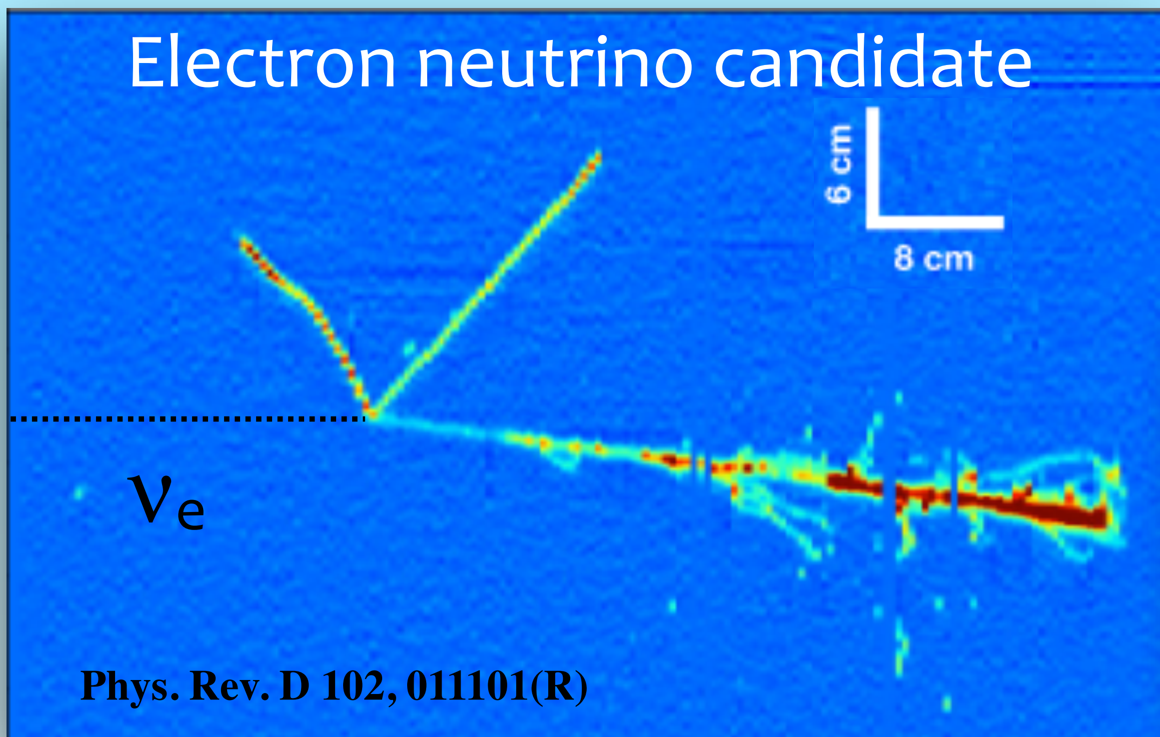
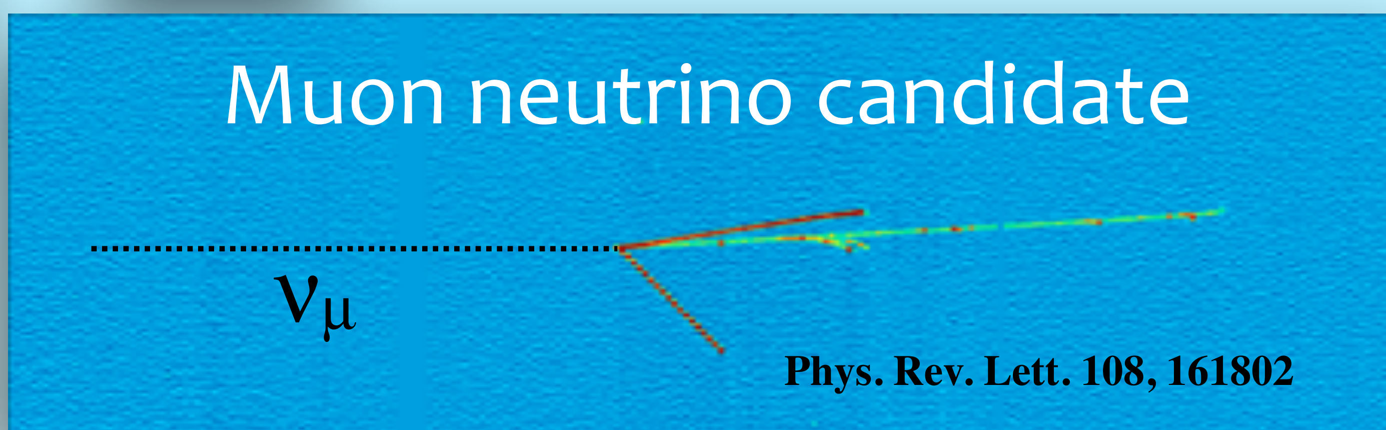
Neutrino flavour identification in LArTPC

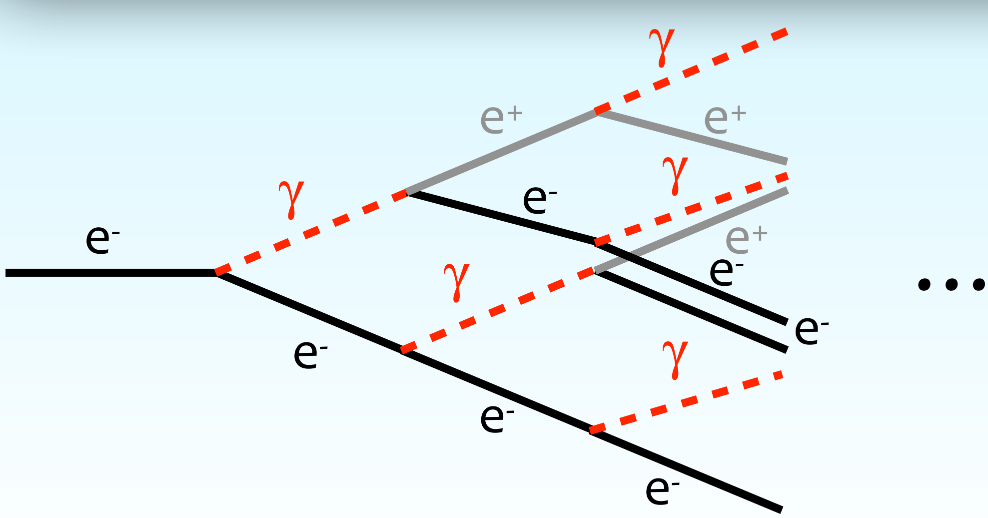
- Flavour identification of charged current interactions is a key element for oscillations experiments

- An electron typically triggers an electromagnetic shower









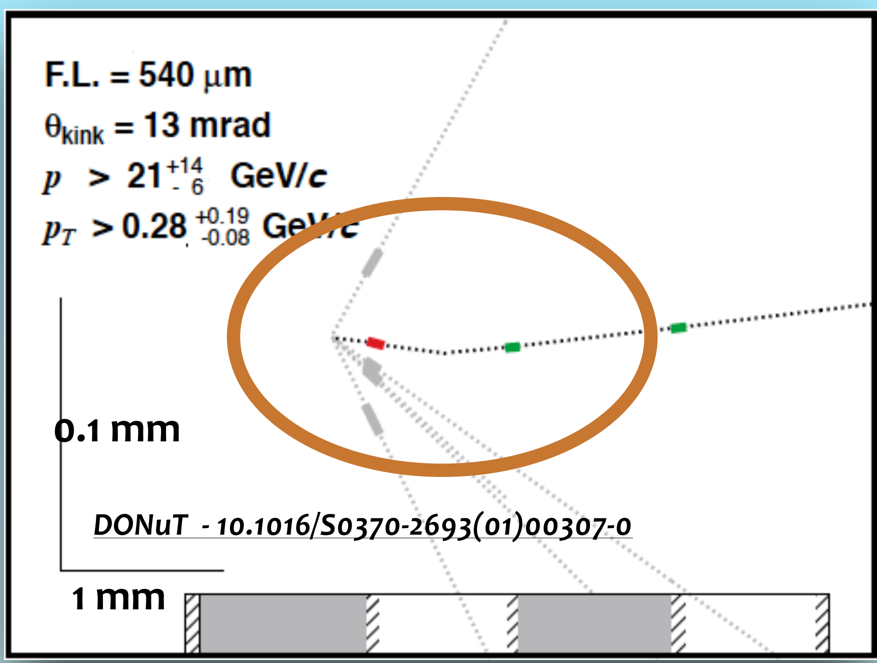
- Muons typically leave long and straight tracks

- LArTPC detectors very good at identifying and reconstructing electrons and muons which leave specific signatures

The τ neutrino problem(s)

- Charged lepton τ is short-lived (2.8×10^{-13} s) —> propagates on distances not resolvable by DUNE detectors !

- DONuT/OPERA relied on a high energy neutrino beam + high spatial resolution to resolve the kink of the τ decay.

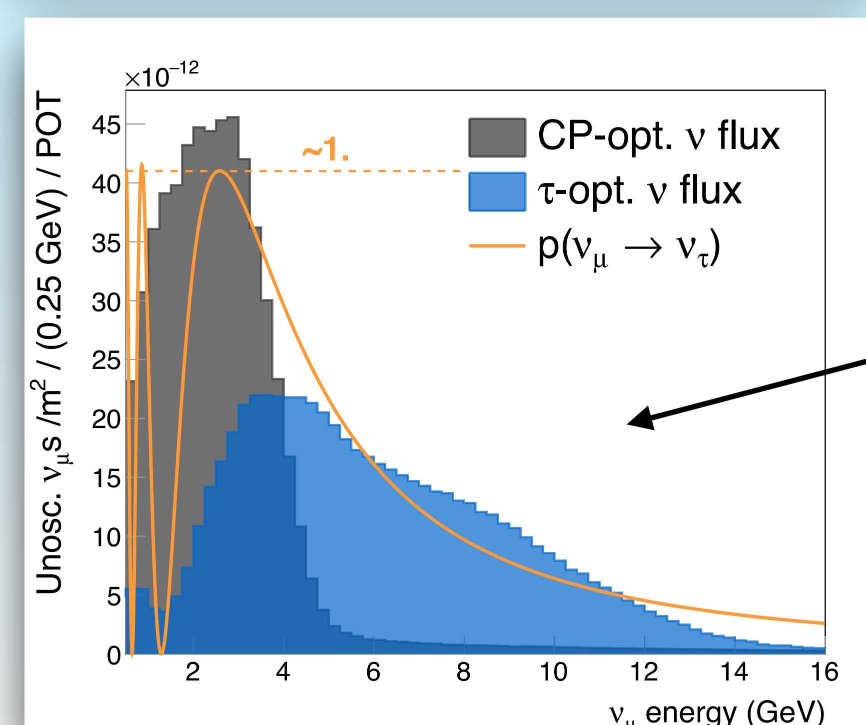


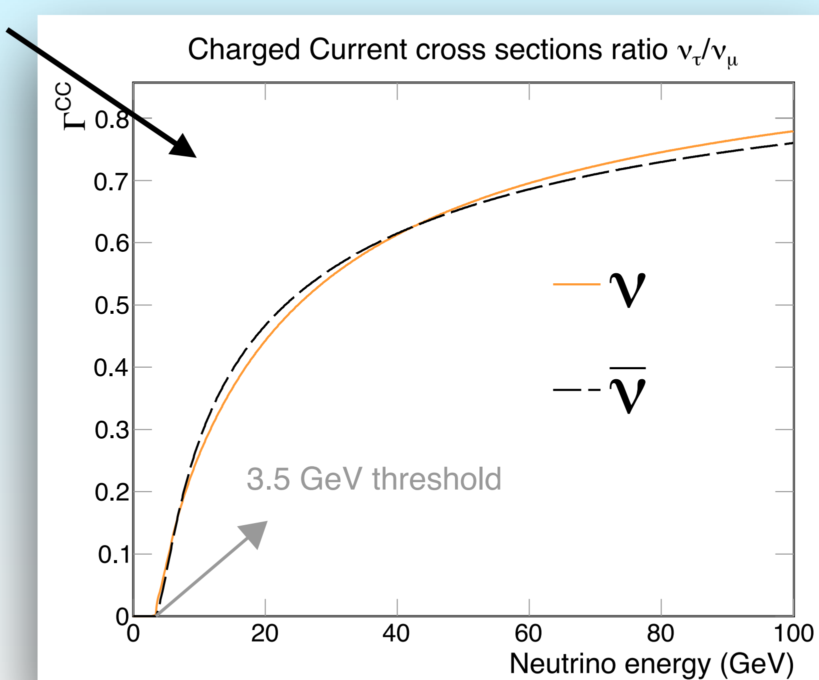
$\tau^- \to e^- \nu_e \nu_\tau$	$\tau^- \to \mu^- \nu_\mu \nu_\tau$	$\tau^- \to \rho^- \nu_\tau \to \pi^0 \pi^- \nu_\tau$	$\tau^- \to \pi^- \nu_\tau$
17.83±0.04%	17.41±0.04%	25.52±0.09%	10.83±0.06%

- Hence look for τ decay signatures, makes ν_τ interactions look like ν_e / ν_μ / neutral currents

- Large mass of the τ kills ν_τ CC cross-section in the 1 GeV - 10 GeV region (typical accelerator based neutrino experiment)

- Possible higher energy configuration for DUNE





Basics of τ neutrino physics (τ—>e + 2ν channel) I

$$\nu_\tau + Ar \rightarrow \tau^- + H \rightarrow (e^- + \bar{\nu}_e + \nu_\tau) + H$$

Leptonic system Hadronic system

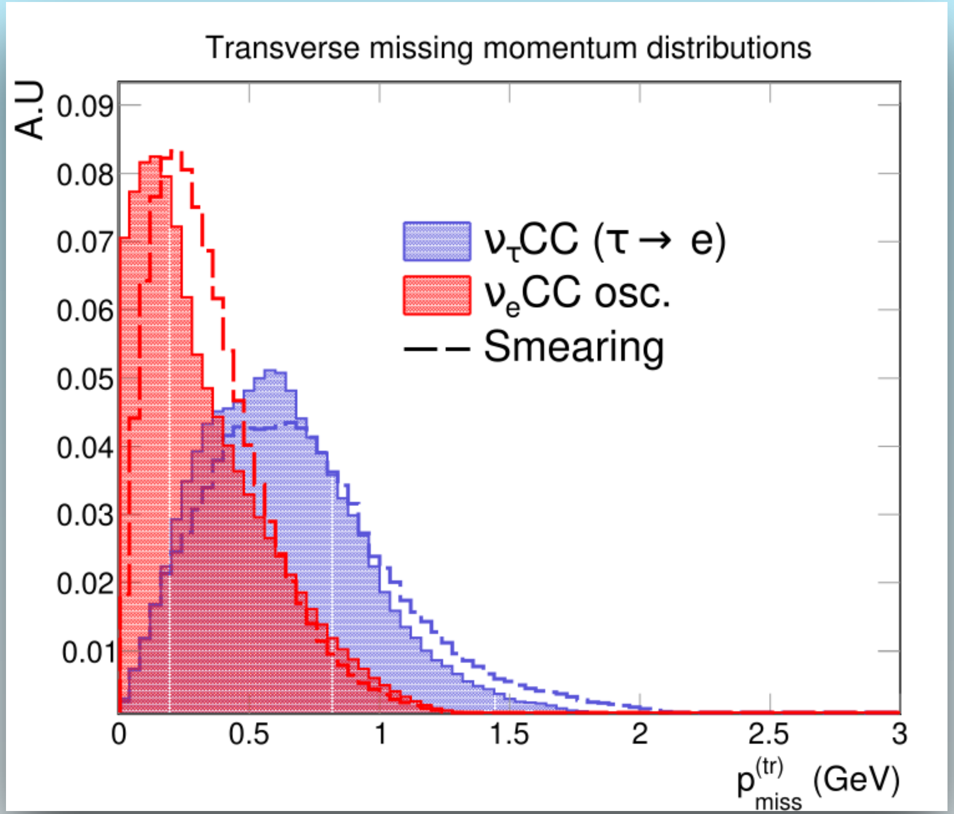
$$\nu_e + Ar \rightarrow e^- + H'$$

Leptonic system Hadronic system

Same final state topologies

- Large unbalance in energy-momentum conservation in transverse plane **(Albright & Shrock, 1978)** because of two undetected neutrinos.

$$\vec{p}_\nu = \vec{p}_{lep} + \vec{p}_{had} \Rightarrow 0 = \vec{p}_{lep}^{(tr)} + \vec{p}_{had}^{(tr)}$$



- Intrisic limitations: Fermi momentum, final state interaction, neutrons…

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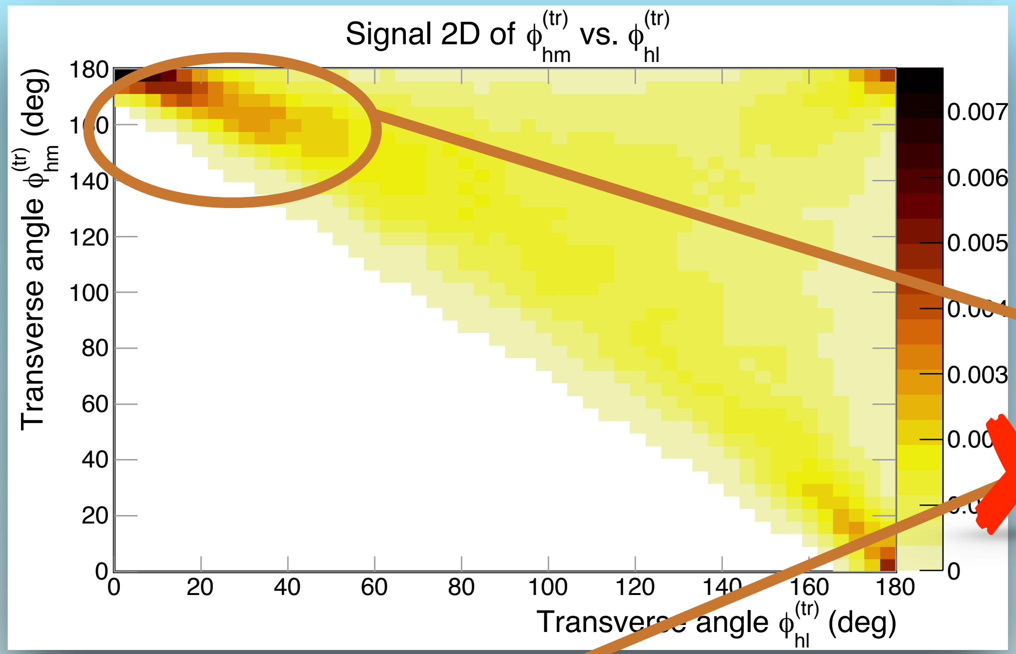
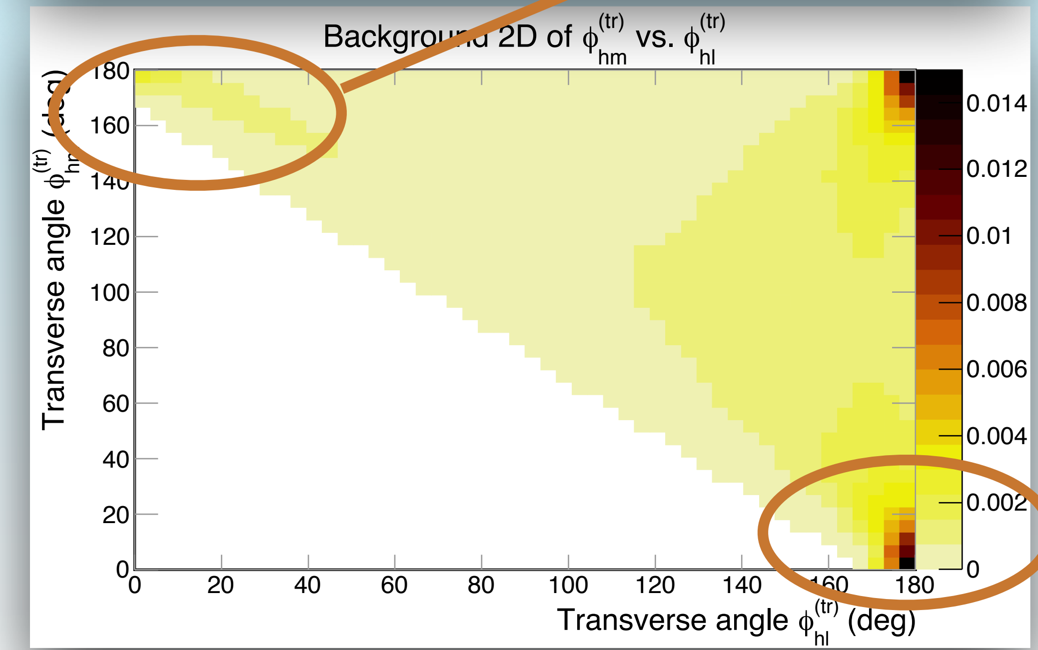
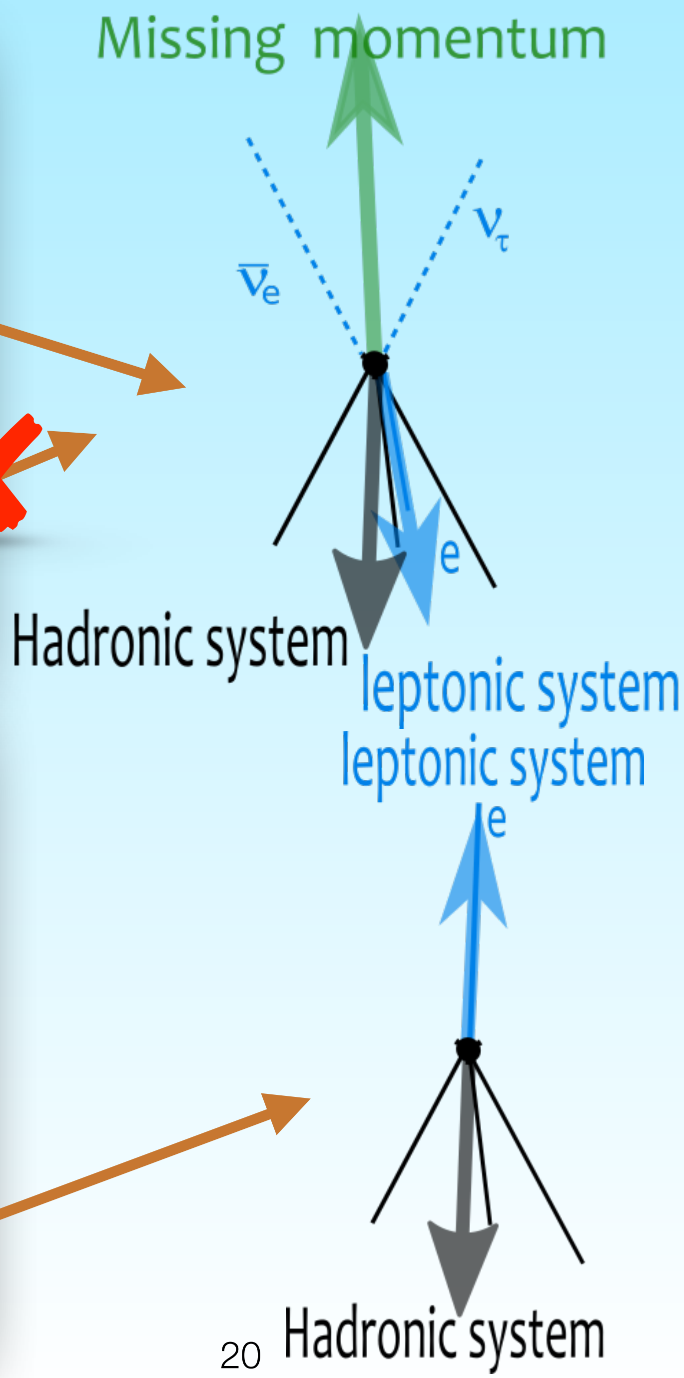
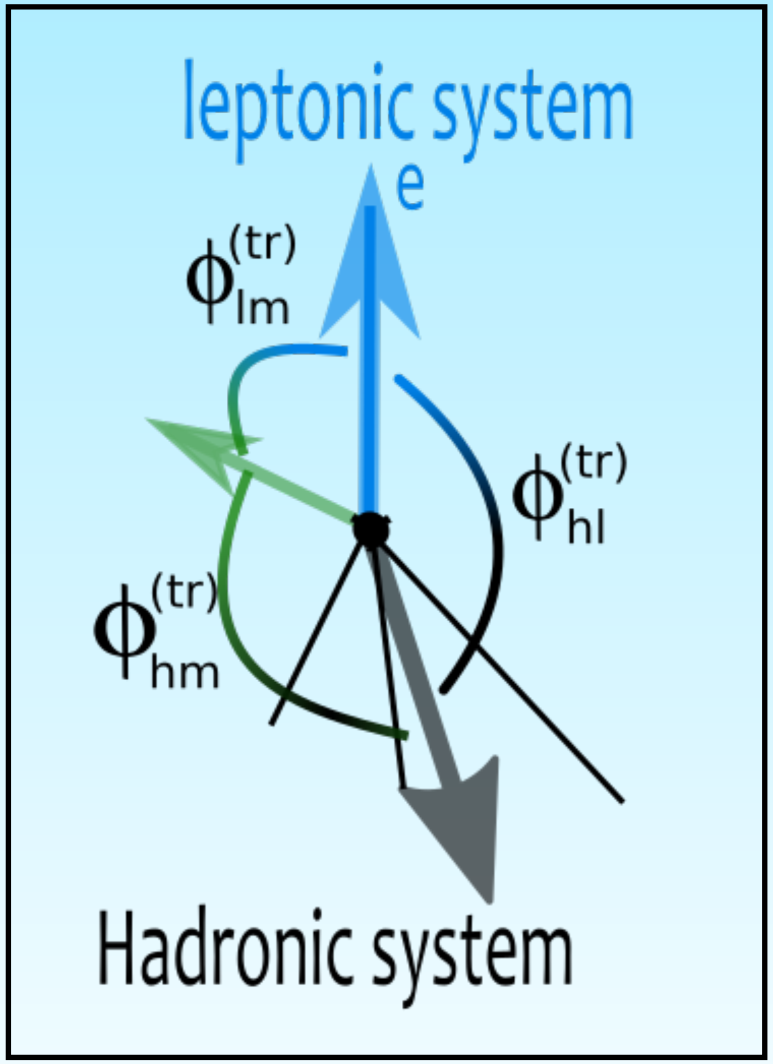
Basics of τ neutrino physics (τ—>e + 2ν channel) II

$$\vec{p}_\nu = \vec{p}_{lep} + \vec{p}_{had} \Rightarrow 0 = \vec{p}^{\,(tr)}_{lep} + \vec{p}^{\,(tr)}_{had}$$









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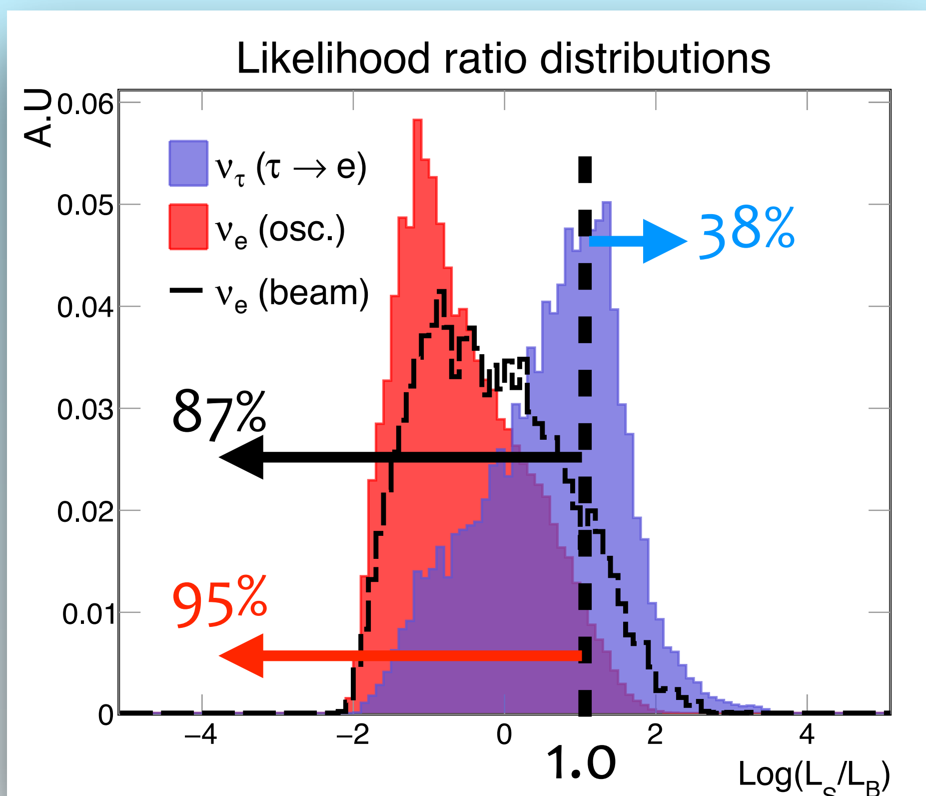
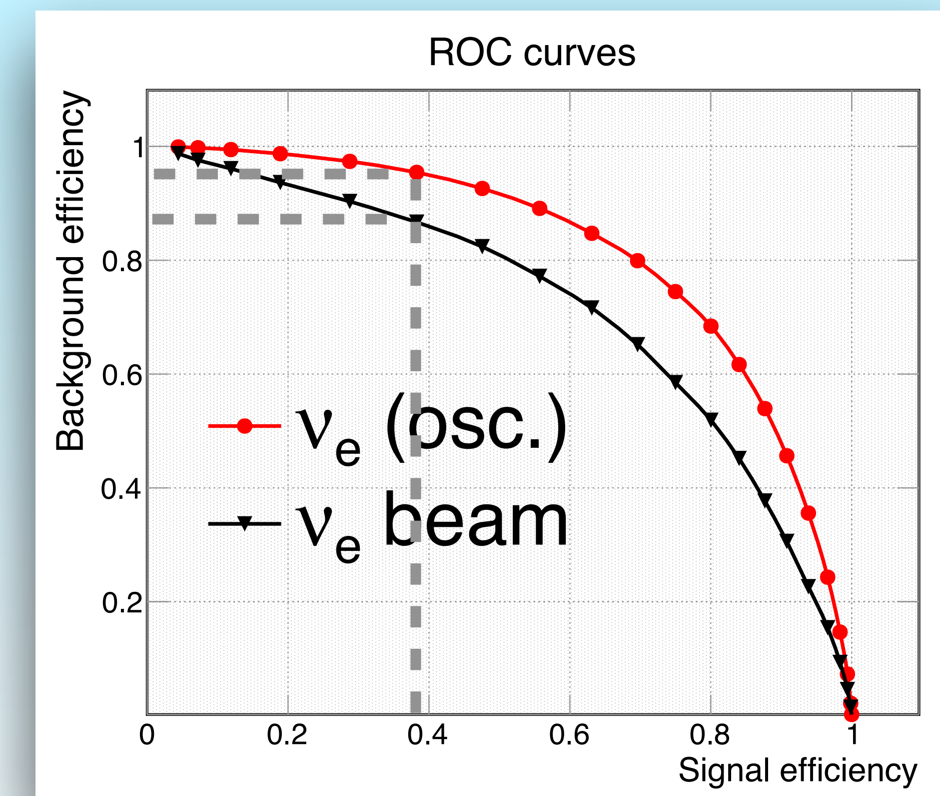
Traditionnal likelihood approach for τ—>e + 2ν decay mode

ν mode	
ν_e from osc.	1197
$\bar{\nu}_e$ from osc.	18
ν_e from beam cont.	365
$\bar{\nu}_e$ from beam cont.	57
ν_μ	9660
$\bar{\nu}_\mu$	741
ν_τ from oscillation	270
$\bar{\nu}_\tau$ from oscillation	25
NC	8832

Signal = $\nu_\tau(\tau \rightarrow e)$ // Background = ν_e

- ν_e from ν_μ oscillations and ν_e survival of intrisic beam contamination
- I optimize the search studying oscillated ν_e (majoritary by a factor of 3.3) and add beam ν_e afterwards





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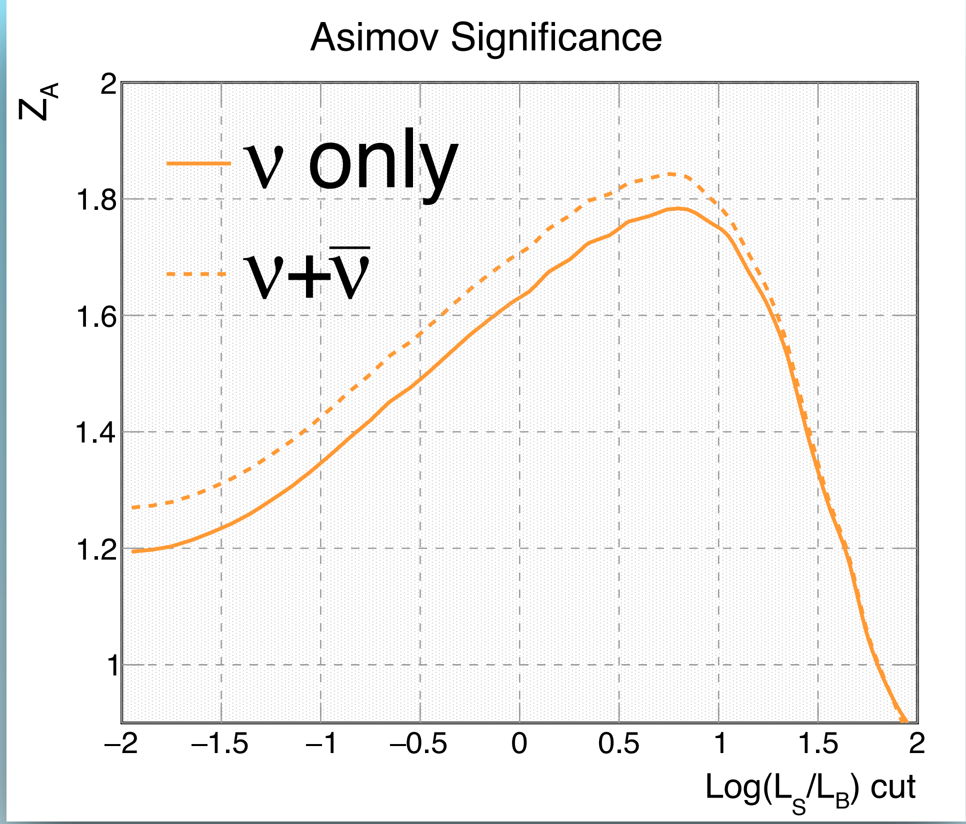
Pick a figure of merit !

- Observe S & B Poisson distributed, then Asimov significance (normalized to 3.5 years staged):

$$Z_A = \sqrt{2\left((S+B)\ln(1+\frac{S}{B}) - S\right)} \xrightarrow{S \ll B} \frac{S}{\sqrt{B}}$$

Experiments compare predicted B and observed N = S+B



- This tells you how statistically sensitive to ν_τ appearance your analysis would be.

Take home message

- ν_τ appearance search (ν_μ—>ν_τ) at the simulation level (GENIE) via the electron decay mode. Detector effects included.
- Quasi-elastic interactions, machine learning techniques…
- 3.5 years staged normalization ("referent" normalization in the collaboration) shows 1.8σ significance

More τ decay modes

- $\tau \longrightarrow e + 2\nu$ decay mode is ~18% of branching ratio, need for extended analysis ! $\tau \longrightarrow \mu + 2\nu$ is less sensitive because of the larger associated level of background ($\nu_\mu > \nu_e$)

- $\tau \longrightarrow \rho + 2\nu \longrightarrow \pi^{\pm}\pi_0 + 2\nu$ decay mode (25% BR): exploit large branching ratio and kinematic signature of ρ decay (invariant mass). Promising decay mode !

- $\tau \longrightarrow 1\pi + 2\nu$ decay mode (10% BR): exploit clean final state topology of quasi-elastic scatterings (half of ν_τCC interactions with the nominal DUNE neutrino beam)

- Traditionnal likelihood approach compared to modern machine learning tools, no improvement found.

- No systematics included. Quite large and deserve full treatment analysis.

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Vertical Drift configuration

- Argon purity reached by protoDUNEs lowers need for signal amplification, as allowed by the dual-phase technology. However appealing design for cost reduction: evolution toward single phase Vertical Drift configuration in 2020 !
  - Far detector 1 Horizontal Drift LArTPC
  - Far detector 2 Vertical Drift LArTPC (IN2P3 TGIR program)
- Test of the Vertical Drift design with a small prototype (ColdBox) in 2021 (filled with argon yesterday). Components then included in cryostat of NP02 (currently double-phase) with a beam test campaign.
- Tremendous work incoming for the ColdBox and VD-0 operations, as well as integrating the Vertical Drift configuration into simu/reco software **LArSoft.**
- LPSC agreed to participate to construction of the Charged Readout Planes of the Far Detector VD.

Cern Neutrino Platform

Joël and I cabling the argon level meters on top of the CRP roof

NP02 cryostat

Thank you !

Back-up

LArTPC detectors

Historical perspectives

1970 | 1975 | 1980 | 1985 | 1990 | 1995 | 2000 | 2005 | 2010 | 2015 | 2020 | 2025 | 2030

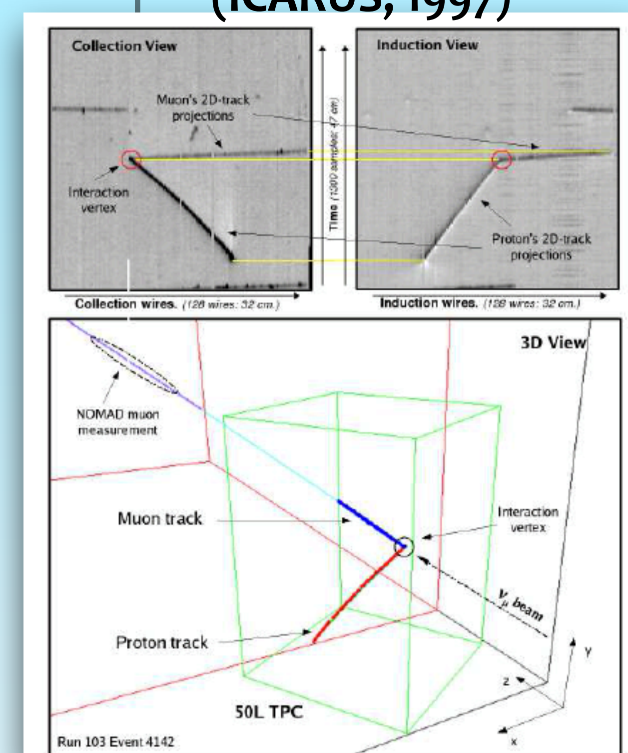
Willis, Radeka (1974)
Absorption of liquid argon and use in particle physics.

C. Rubbia (1977) / H.H. Chen (1978)
LArTPC as neutrino detectors
drift length ~ 30 cm
Several tons achievable (> bubble chambers)
Argon purity…

Aprile, Giboni, Rubbia (1985)
2 liters Liquid Argon TPC is built (10 cm drift)
Signal characterization (drift velocity, attenuation, purity of argon…) with cosmic rays
They also studied solid argon !

ICARUS (1994), 3t LArTPC

(ICARUS, 1997)

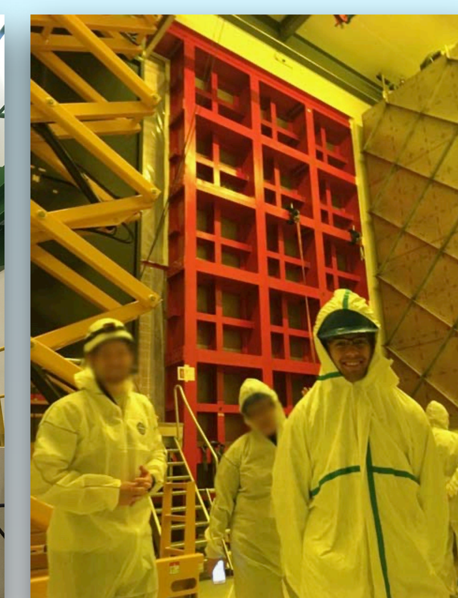


50 liters LArTPC exposed to CERN WANF beam

ICARUS (2003) 14t & (2004) 600t LArTPC

MicroBOONE (2015), 170t LArTPC
Dedicated to neutrinos physics

ProtoDUNEs 6x6x6 m^3



Attenuation length was 7.5 meters with 10 kV/cm