FUTURE NEUTRINO PROGRAMME

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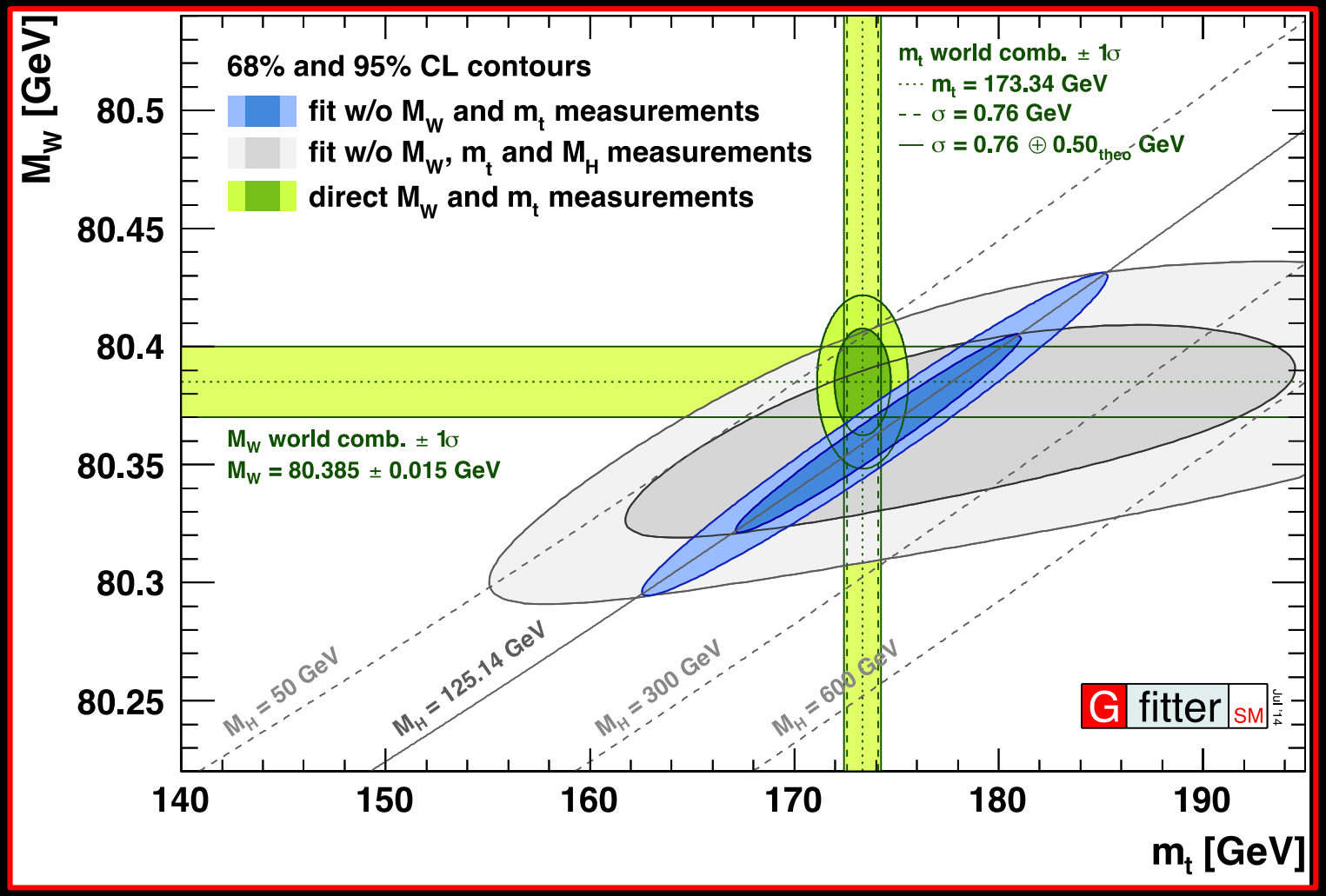
The Standard Model



- Taught, robust, predictive …

Neutrinos indicate SM is incomplete

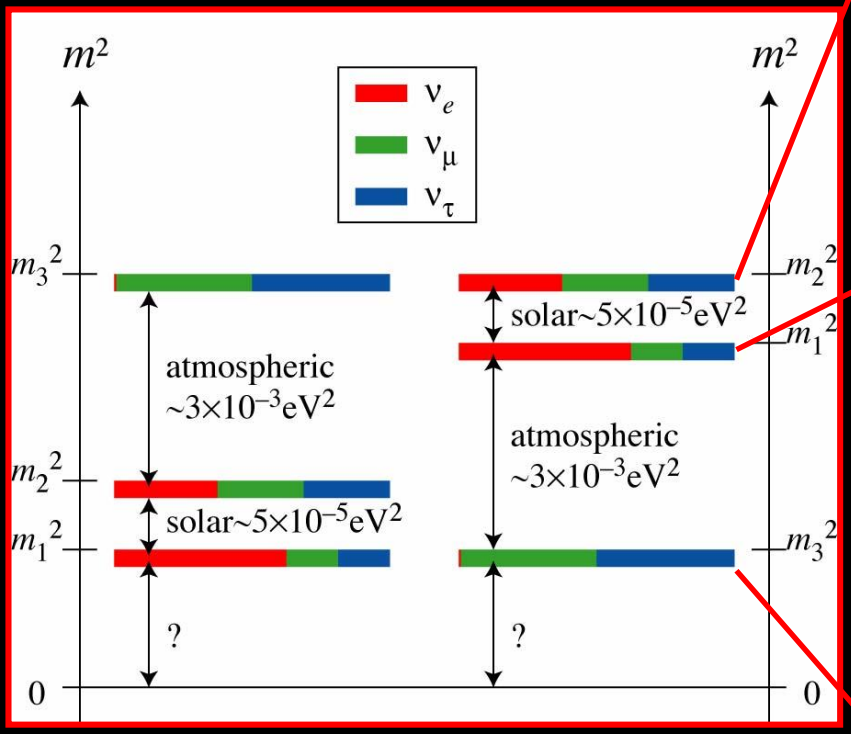
- Neutrino oscillations imply:
  - Neutrinos have mass; mass states mix to make flavour states
- Neutrino mass ➔ new degrees of freedom:
  - Right-handed neutrinos or Majorana neutrinos
  - New interactions?
- Mixing among three neutrinos:
  - CP-invariance violation in lepton sector
  - Origin of matter-dominated Universe?
- Possible cosmological impact:
  - Inflation;
  - Galaxy and star formation;
  - Dark matter

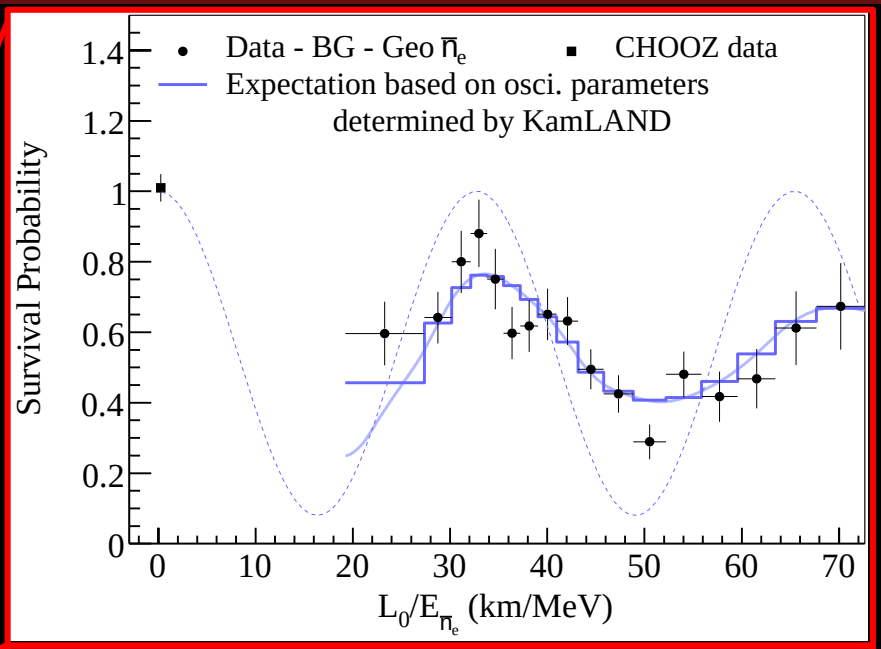
Flavour		Mass
ν_e	$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \mathcal{U}_{\rm PMNS} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$	ν_1
ν_μ		ν_2
ν_τ		ν_3

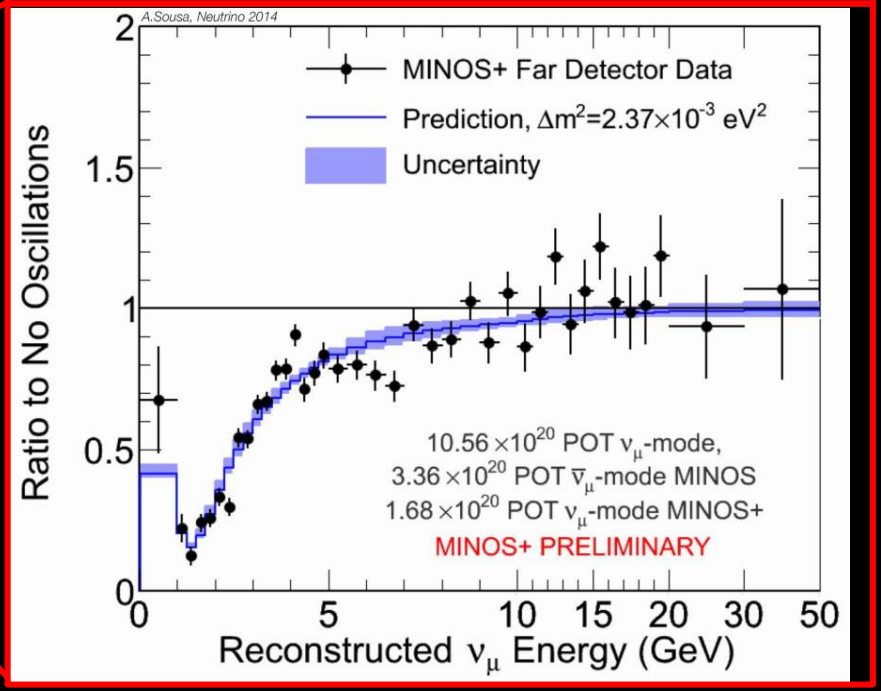
$$\mathcal{U}_{\rm PMNS} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \times \mathrm{diag}\left(1, e^{i\phi_1}, e^{i\phi_2}\right)$$

“Standard Neutrino Model (SvM)”

$$P(\nu_\alpha \to \nu_\beta) = \sum_{i,j} \omega_{\alpha\beta}(\theta_{ij}, \delta, \cdots) e^{-i\frac{(m_i^2 - m_j^2)}{2}\frac{L}{E}}$$



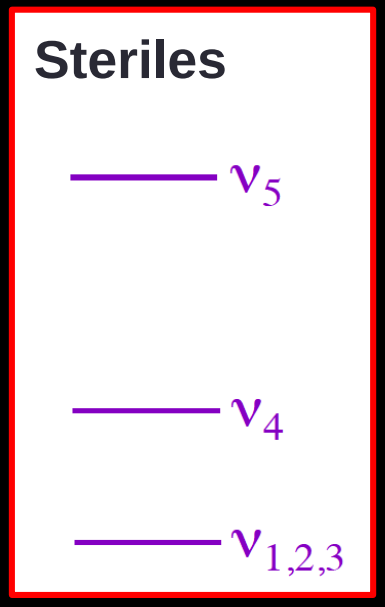




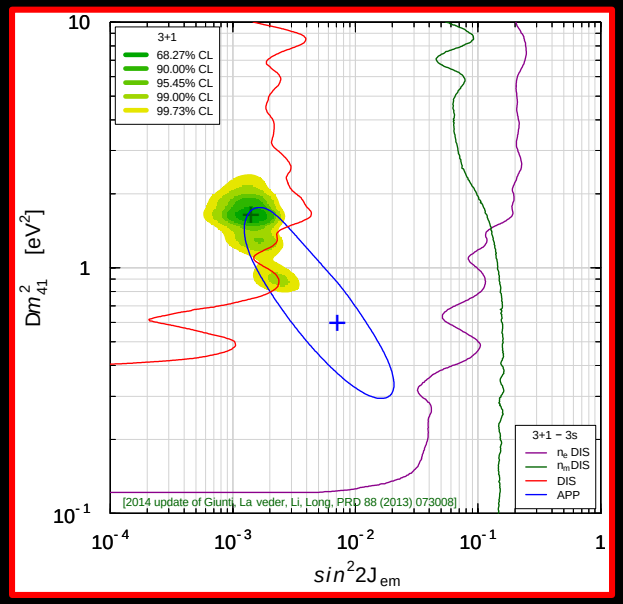
Anomalies; light-sterile neutrinos?

- Wide variety of data described by the SvM
- Anomalous behaviour in a variety of channels:

Data inconsistent with SνM					
Appearance			**Disappearance**		
LSND	$\bar{\nu}_\mu \to \bar{\nu}_e$	$\sim 4\sigma$	Reactor	$\bar{\nu}_e \to \bar{\nu}_X$	$\sim 3\sigma$
MiniBooNE	$\nu_\mu \to \nu_e$	$\lesssim 3\sigma$	Gallium	$\nu_e \to \nu_X$	$\sim 3\sigma$



- Global analysis gives:
  - Consistent description of:
    - Appearance alone;
    - Disappearance alone
  - But:
    - Tension between appearance and disappearance



Future programme, specification

- Complete the “Standard Neutrino Model” (SvM):
  - Determine the mass hierarchy
  - Search for (and discover?) leptonic CP-invariance violation

- Establish the SvM as correct description of nature:
  - Determine precisely the degree to which θ_{23} differs from $\pi/4$
  - Determine θ_{13} precisely
  - Determine θ_{12} precisely

- Search for deviations from the SvM:
  - Provide redundant measurements of sufficient precision to:
    - Test the unitarity of the neutrino mixing matrix
    - Seek relationships within SvM or between neutrinos and quarks
  - Search for sterile neutrinos, non-standard interactions, …

Plan

- Sterile neutrinos
- Standard Neutrino Model and beyond
- Cross sections
- Scanning the horizon

STERILE NEUTRINOS

Light sterile neutrinos

- Present, inconclusive, data on:
  - $\nu_\mu \rightarrow \nu_e$ [LSND, MiniBooNE]
  - $\nu_e \rightarrow \nu_X$ [Reactor flux, gallium source]
- Ideally study:

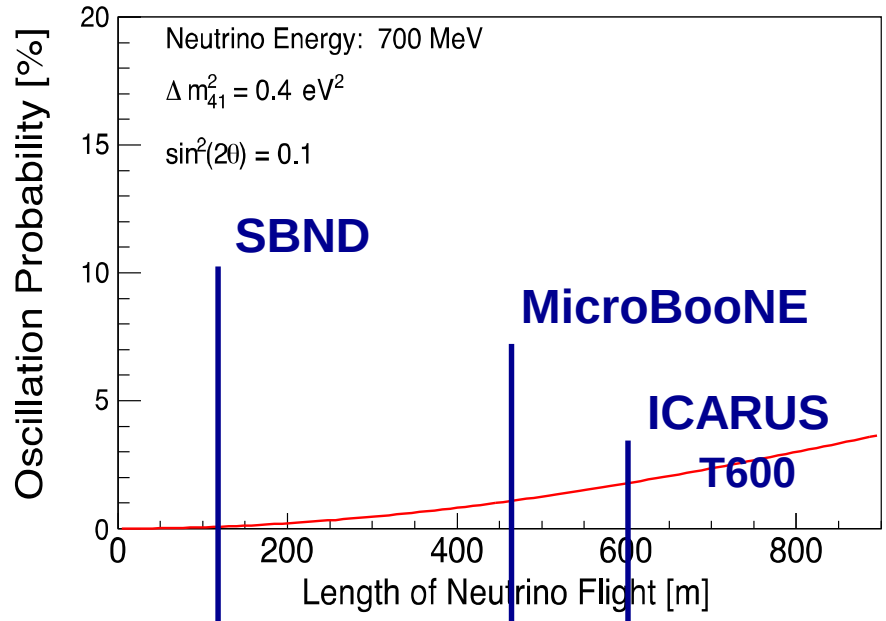
	Transition	Conjugate
Appearance	$\nu_e \rightarrow \nu_\mu$ $\bar{\nu}_e \rightarrow \bar{\nu}_\mu$	$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ $\nu_\mu \rightarrow \nu_e$
Disappearance	$\nu_e \rightarrow \nu_X$ $\bar{\nu}_e \rightarrow \bar{\nu}_X$	$\bar{\nu}_\mu \rightarrow \bar{\nu}_X$ $\nu_\mu \rightarrow \nu_X$

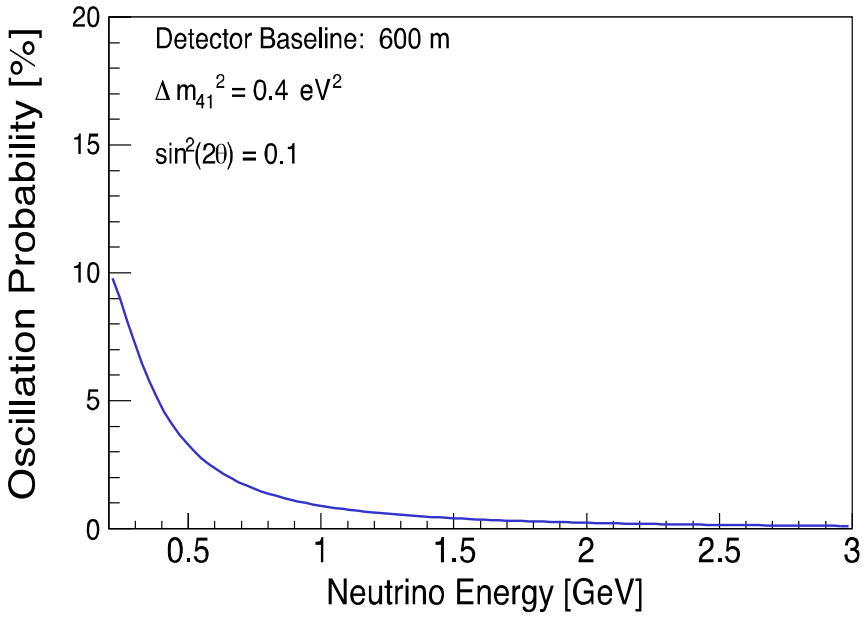
and

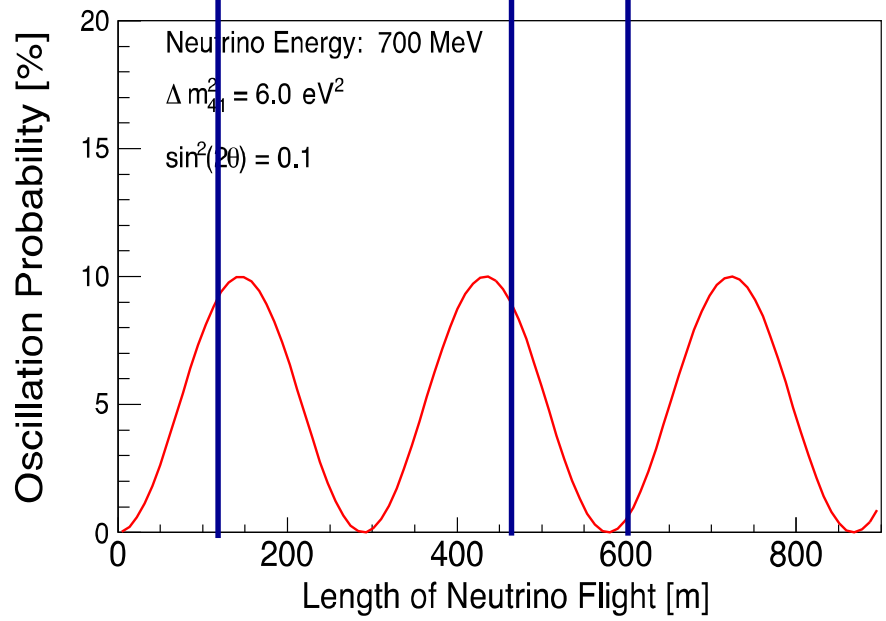
- Determine neutral current rate
  - Oscillation to steriles changes neutral-current rate
- Study $\nu_e N$ and $\nu_\mu N$ scattering
  - Including hadronic final states to eliminate hadronisation uncertainties

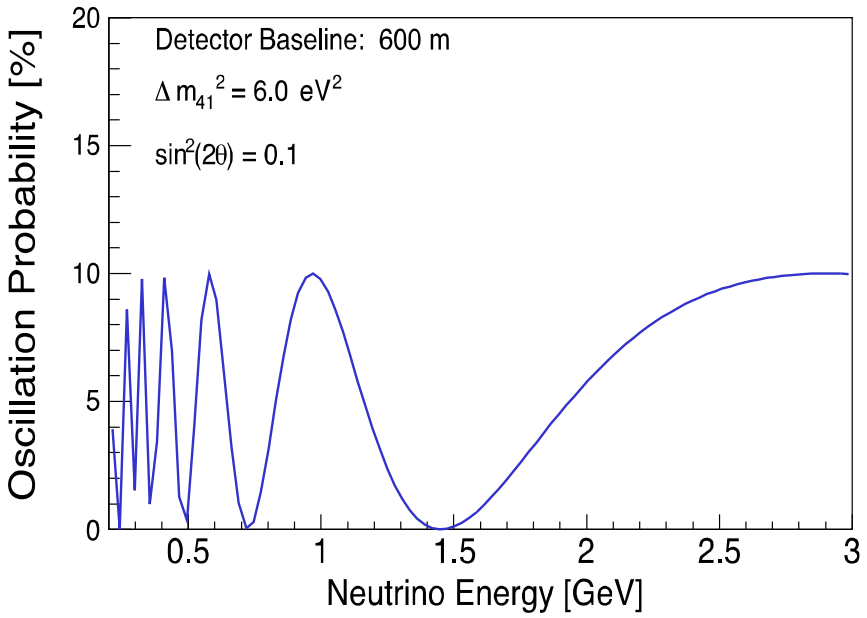
Short Baseline Neutrino programme

- Definitive search for $\Delta m^2 \sim 1\text{eV}^2$ sterile neutrinos:
  - Exploit *L*, *E* and *L*/*E* modulation; detectors at three baselines
    - Appearance, $\nu_\mu \rightarrow \nu_e$, *and*, disappearance, $\nu_\mu \rightarrow \nu_X$
  - Exploit 3 LAr detectors; minimise inter-detector systematics
- Robustly address backgrounds and uncertainties:
  - ν_e contamination in FNAL Booster Neutrino Beam
  - Photons produced by NC νN and cosmic rays
  - External ν interactions in earth or experimental hall


Neutrino Energy: 700 MeV
Δ m²41 = 0.4 eV²
sin²(2θ) = 0.1
SBND
MicroBooNE
ICARUS
T600
Oscillation Probability [%]
Length of Neutrino Flight [m]

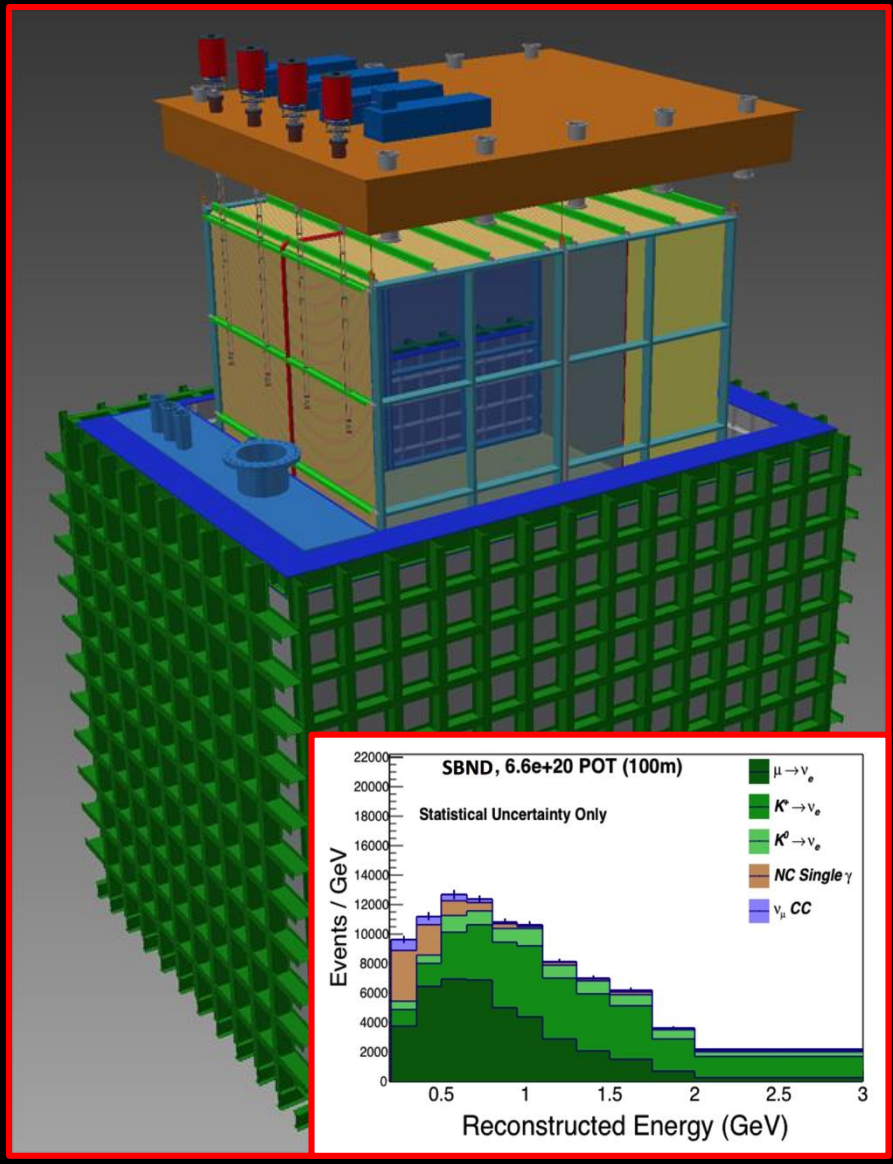

Detector Baseline: 600 m
Δ m²41 = 0.4 eV²
sin²(2θ) = 0.1
Oscillation Probability [%]
Neutrino Energy [GeV]


Neutrino Energy: 700 MeV
Δ m²41 = 6.0 eV²
sin²(2θ) = 0.1
Oscillation Probability [%]
Length of Neutrino Flight [m]


Detector Baseline: 600 m
Δ m²41 = 6.0 eV²
sin²(2θ) = 0.1
Oscillation Probability [%]
Neutrino Energy [GeV]

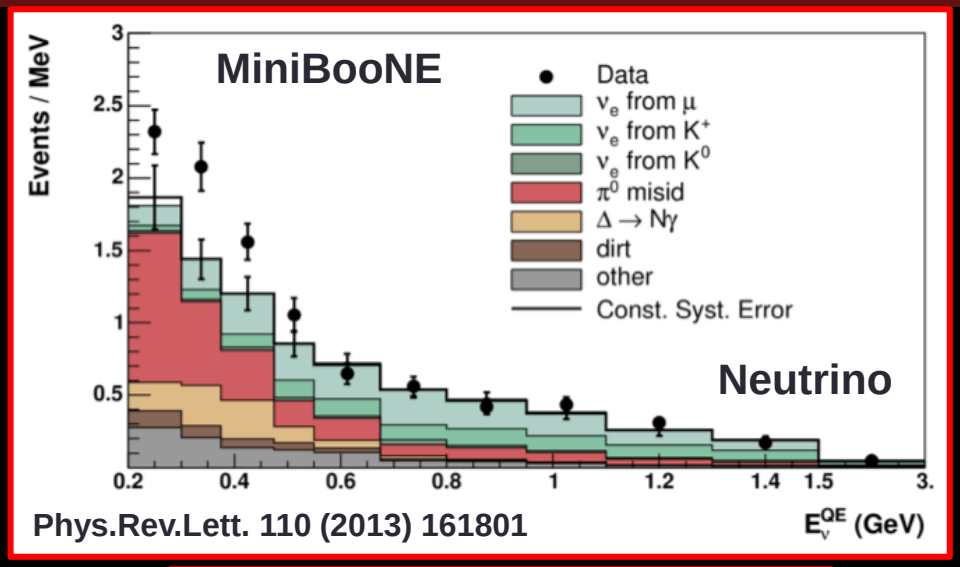
Short Baseline Near Detector

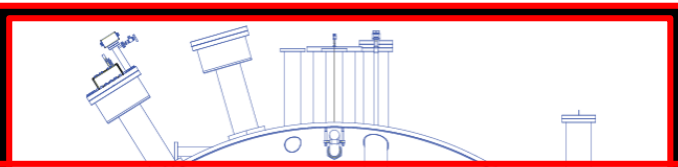
- 275 T LAr TPC @ L = 110m
  - Characterise beam before oscillation
  - Address many dominant systematic uncertainties
- Neutrino scattering
  - Total νN sample: ~7×10^6
    - From 6.6×10^{20} pot (~3 years)
  - Inclusive ν_e samples:
    - Charged current: ~37×10^3
    - Neutral current: ~14×10^3
  - High-statistics studies:
    - Cross sections
    - Final states

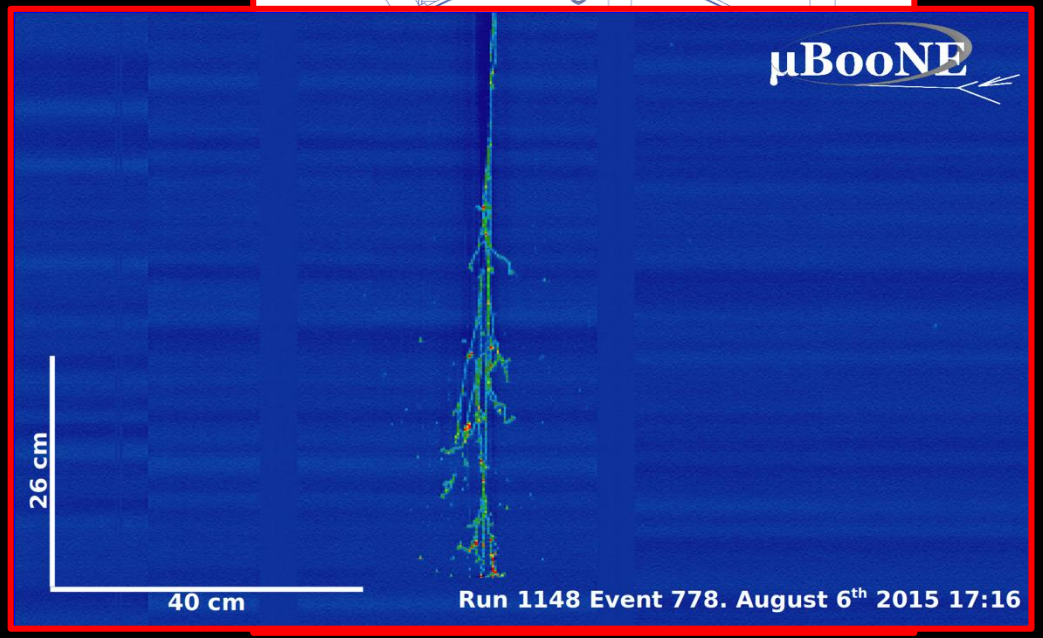


MicroBooNE

- 170 T LAr TPC @ *L* = 470
- Solo capabilities:
  - Investigate MiniBooNE low-energy ν_e excess;
  - Measure neutrino cross sections (BNB & NuMI)
  - LAr detector R&D
- Neutrino scattering
  - Total νN sample: ~2.5×10^5
    - From 6.6×10^{20} pot (~3 years)
  - Inclusive ν_e samples:
    - Charged current: ~1.5×10^3
    - Neutral current: ~0.5×10^3
  - Further studies of:
    - Cross sections/final states

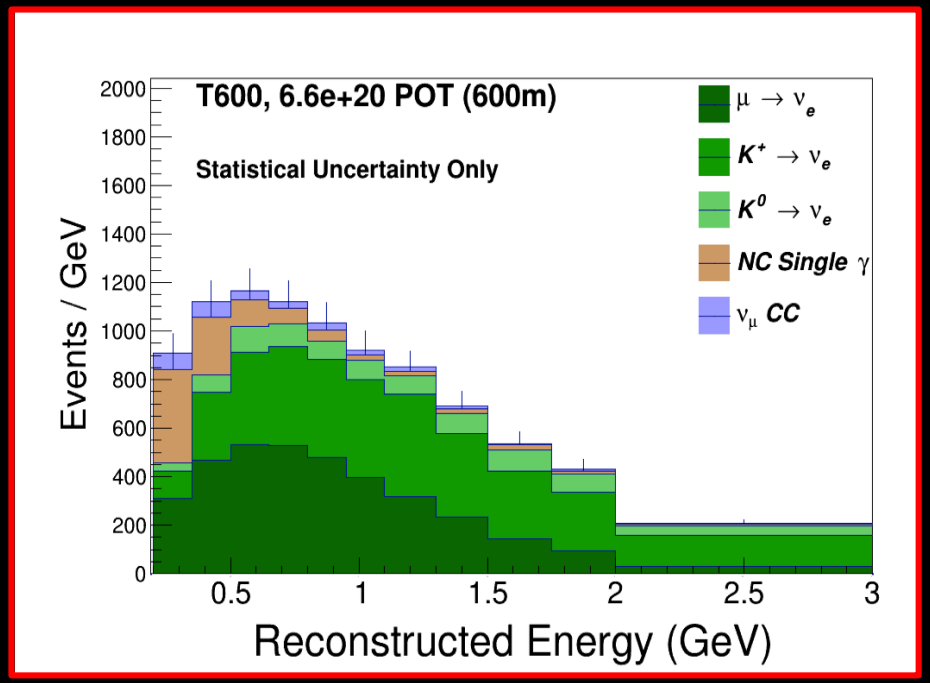






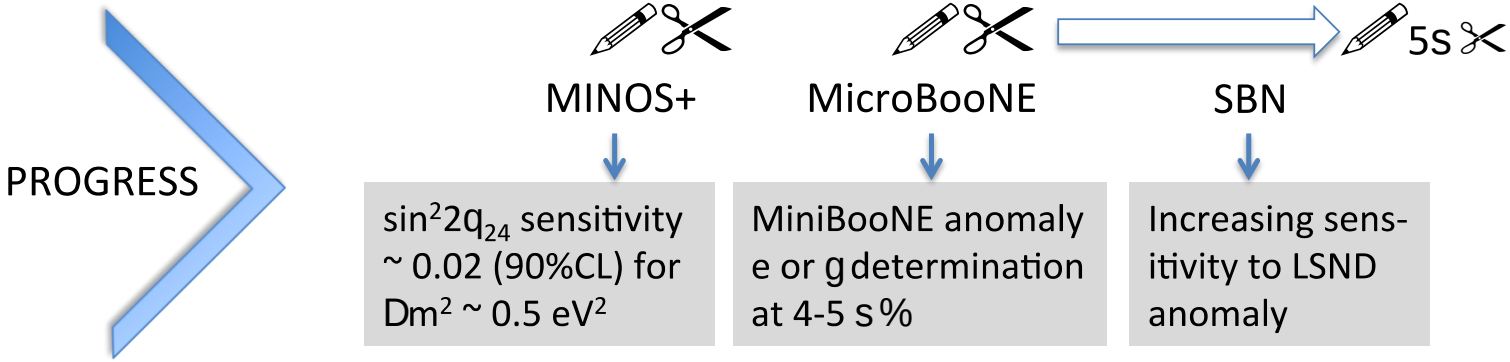
ICARUS T600

- 760 T LAr TPC @ 600 m
  - Large mass gives good ν_e rate
- Exposed to:
  - Booster Neutrino Beam; and
  - Off-axis to NuMI beam
- Refurbishment; WA104:
  - Part of CERN Neutrino Platform programme
  - Both T300 modules transported from Gran Sasso to CERN
  - Scheduled to arrive at FNAL early 2017



SBN Program Timeline !

EPOC%	EXPT%	2015%	2016%	2017%	2018%	2019%	2020%
NOW	MINOS+	RUN					
NOW	MicroBooNE	RUN 1			RUN - SBN		
NEXT	SBND	BUILD + INSTALL *			RUN - SBN		
NEXT	ICARUS	REFURBISH+INSTALL*			RUN - SBN		
NEXT+	?					decide	????



* Important contributions from CERN Neutrino Platform and European funding agencies (INFN, STFC, SNSF)

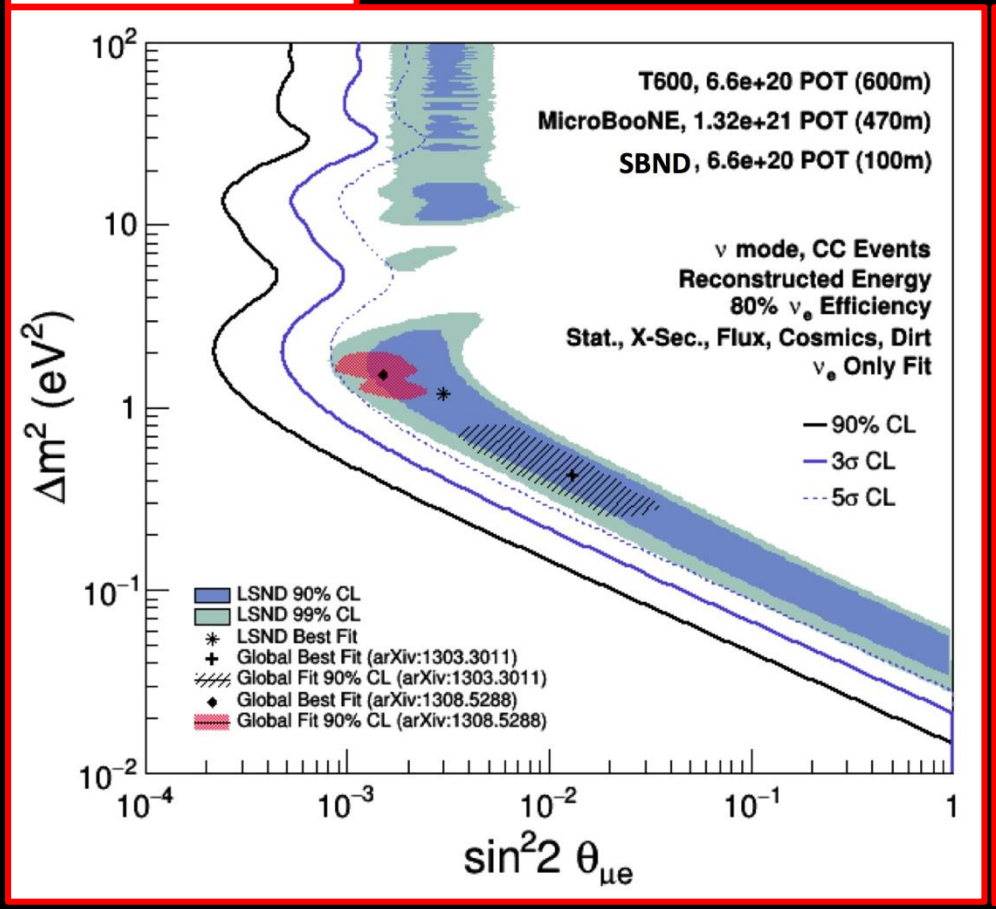
Source of information: January 2015 Fermilab PAC meeting; presentations & Report:

Steve Geer presented at ICFA Neutrino panel (18 April 2015)

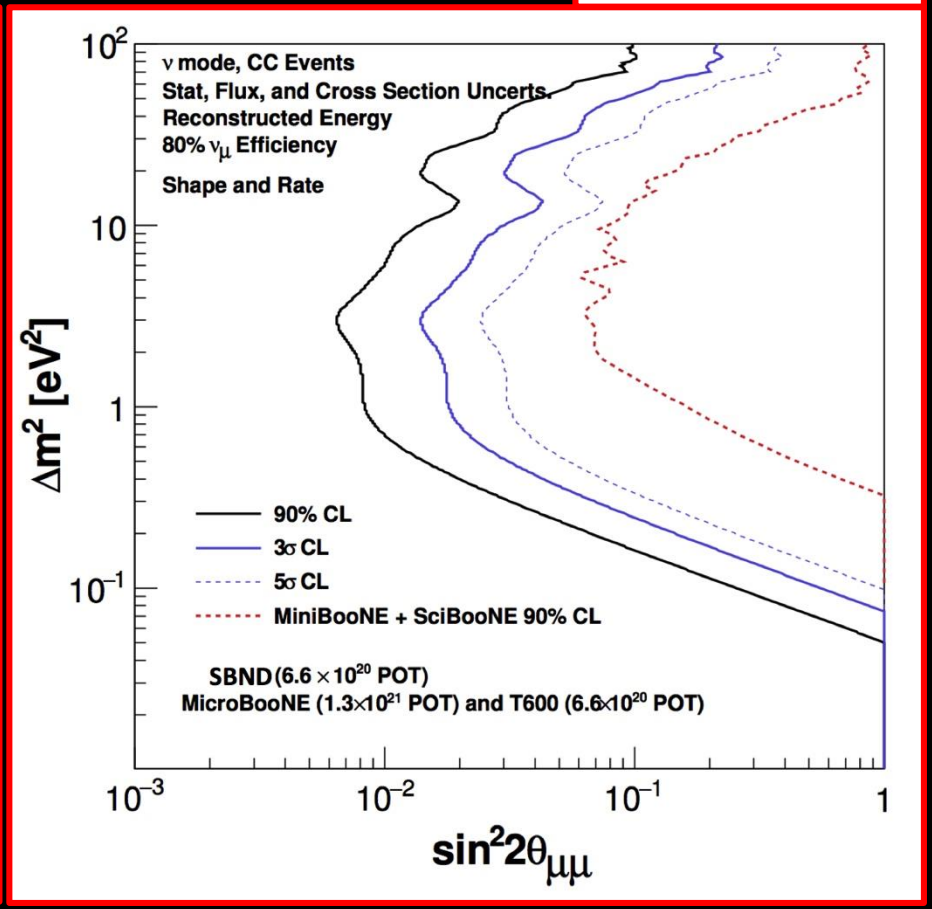
Fermilab

Short Baseline Neutrino sensitivity

$\nu_\mu \rightarrow \nu_e$



$\nu_\mu \rightarrow \nu X$



- **Region of interest can be addressed at 5σ**

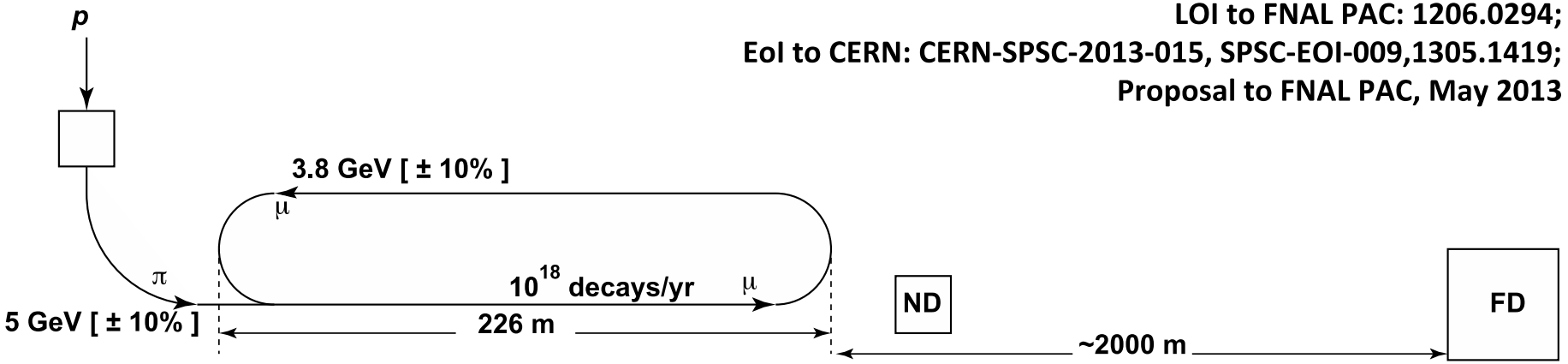
Capability to build on discovery?

- Confirmation would be a major discovery;
  - One that would change the direction of the field
- Therefore, essential to develop capability to go beyond the performance of the present generation
- Innovation in beam to observe:
  - Oscillation
    - ISODAR: observe oscillation using isotope decay at rest.
  - As many channels as possible …

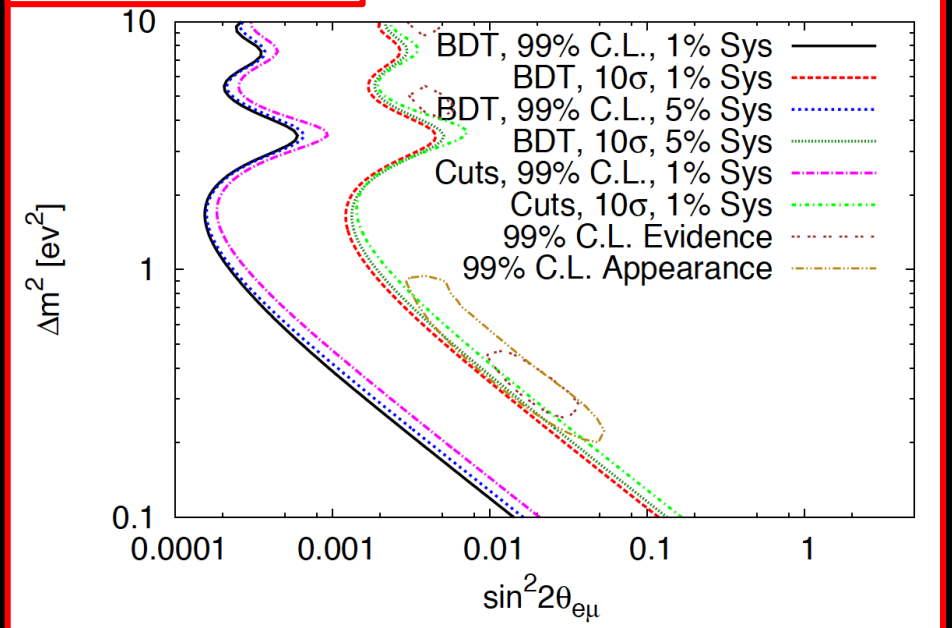
nuSTORM

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

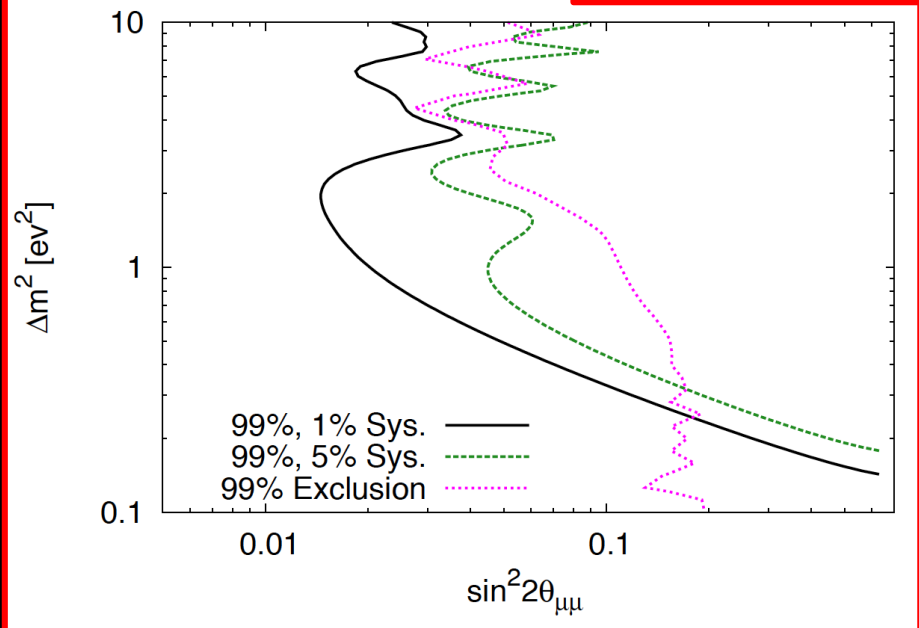
LOI to FNAL PAC: 1206.0294;
EoI to CERN: CERN-SPSC-2013-015, SPSC-EOI-009,1305.1419;
Proposal to FNAL PAC, May 2013



$\nu_\mu \rightarrow \nu_e$



$\nu_\mu \rightarrow \nu X$

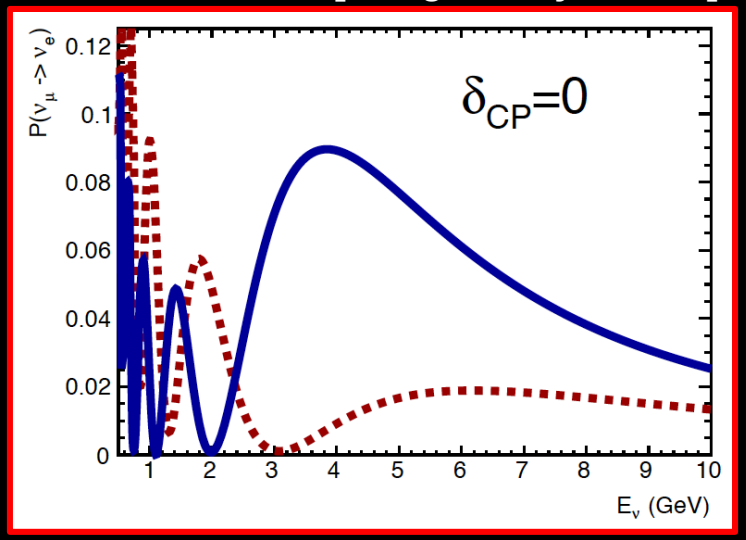


STANDARD NEUTRINO MODEL AND BEYOND

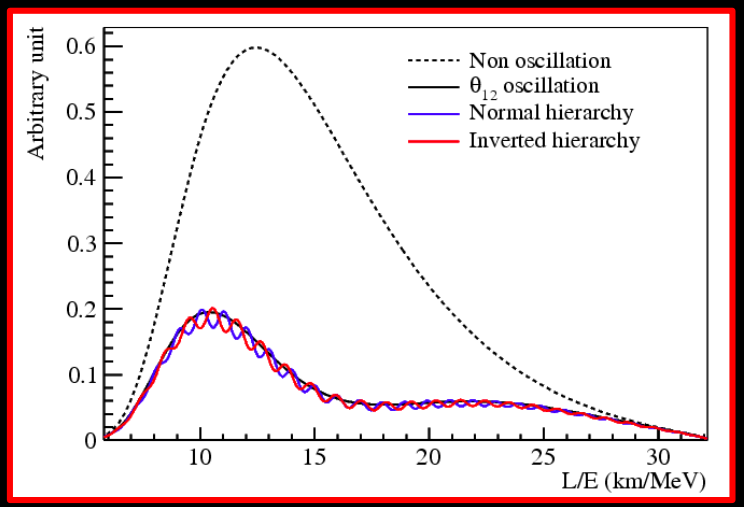
Completing the SvM

P. Shanahan:
Atmospheric: INO, PINGU, ORCA
LBL: NOvA, DUNE [design study, CHIPS]

- **Mass hierarchy:**
  - **Two approaches:**
    - **Exploit the "matter effect"**
    - **Exploit *L/E* dependence**



- CP-invatiance violation:
  - Two approaches:
    - Direct observation
    - Exploit *L/E* dependence

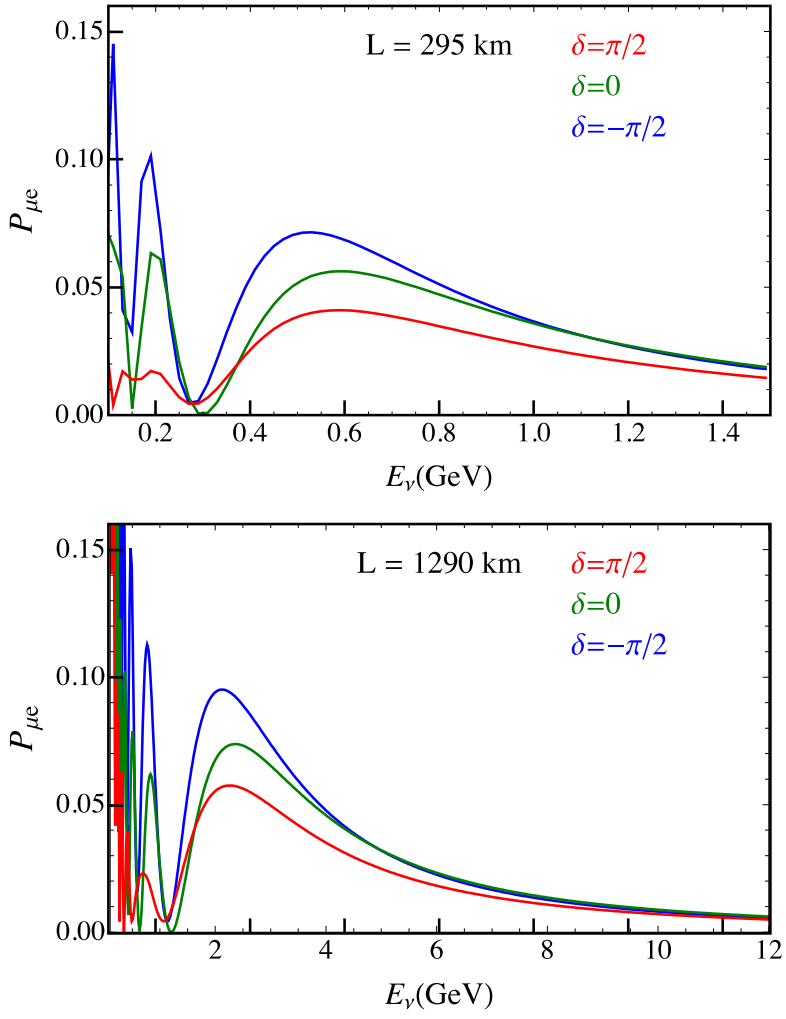


A. Stahl:
Reactor: JUNO, RENO-50

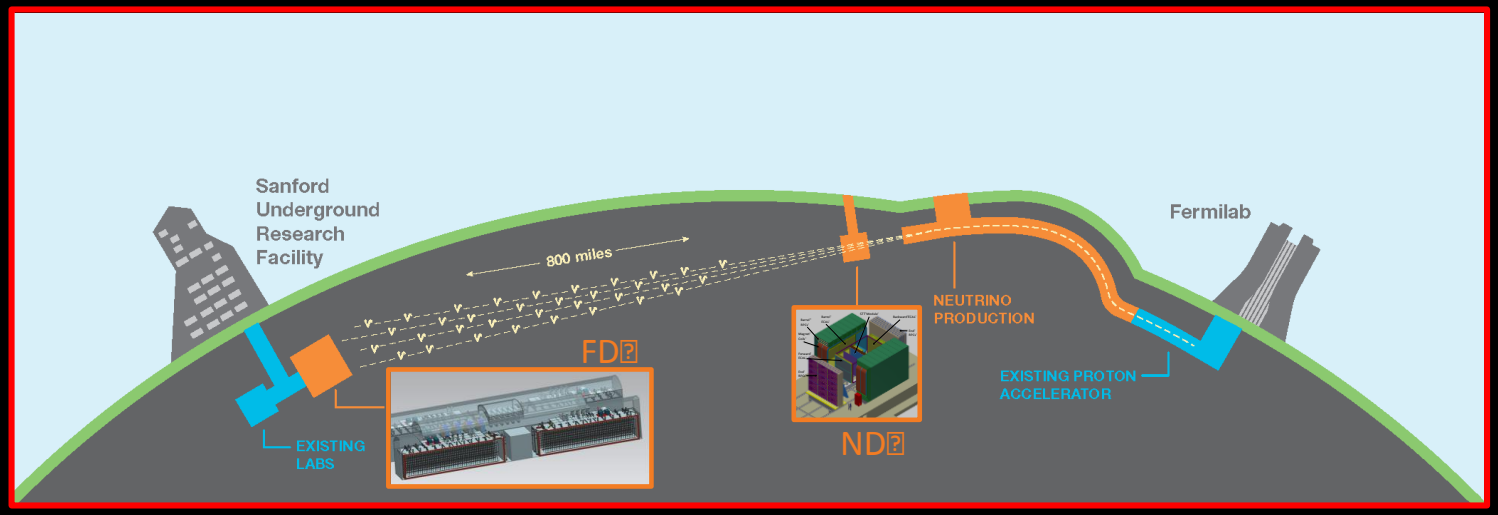
Completing the SvM

- Mass hierarchy:
  - Two approaches:
    - Exploit the “matter effect”
    - Exploit *L*/*E* dependence
- CP-invariance violation:
  - Two approaches:
    - Direct observation
    - Exploit *L*/*E* dependence
      - DAEδALUS:
        - π+ decay at rest:
          - 1307.6465, 1307.2949, 1006.0260

[Design study: ESSnuSB]

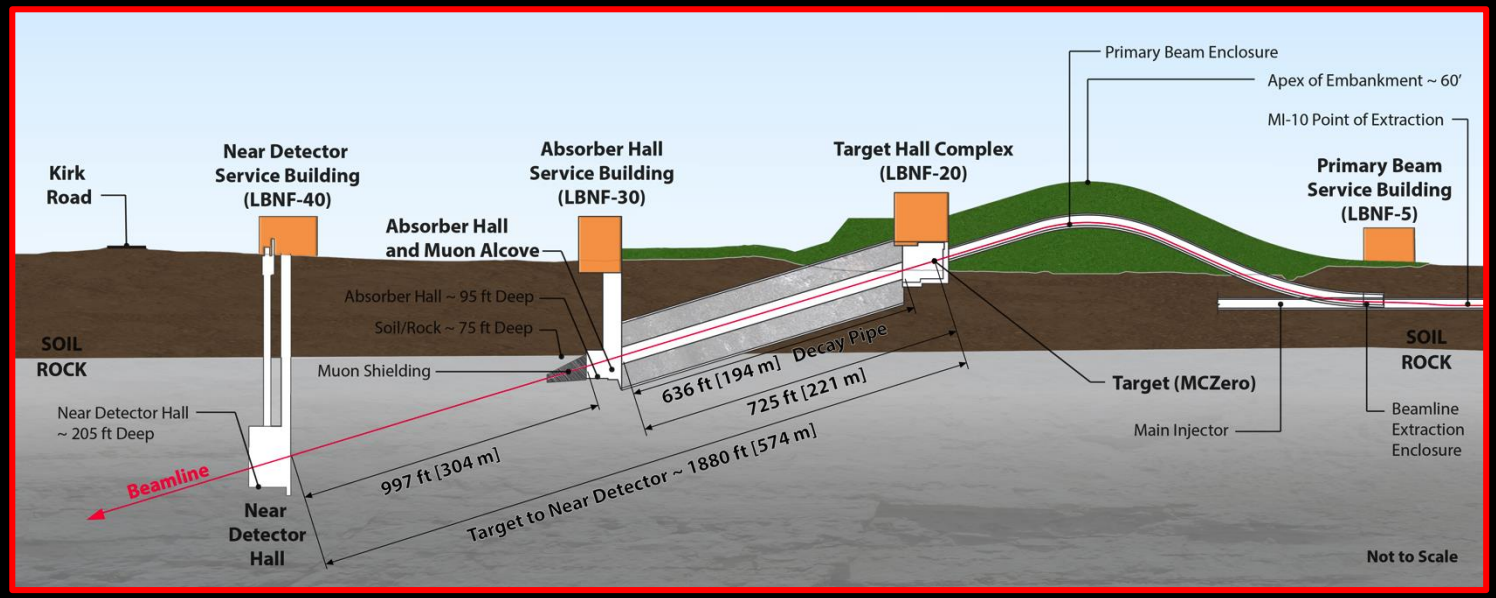


Deep Underground Neutrino Experiment



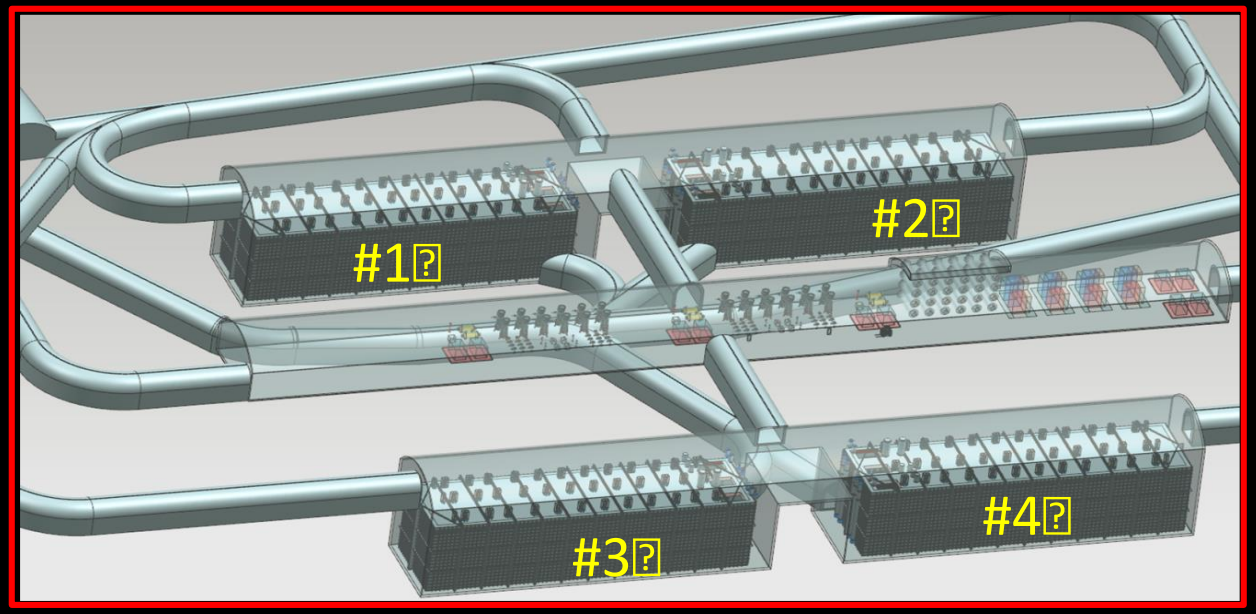
- Principal objectives:
  - CP-invariance violation
  - Mass hierarchy
  - Precision osc. physics:
    - Parameter measurement
    - “Beyond SvM” search
  - Near-detector physics:
    - Part of osc. programme
    - Neutrino scattering
- Additional opportunities:
  - Nucleon decay search
  - Supernova search
  - Astroparticle physics
  - Dark matter search
- Collaboration:
  - DUNE ⊃ LBNE, LBNO + others
  - Global:
    - 776 people, 114 institutions, 26 countries

Long Baseline Neutrino Facility



- New neutrino beam on Main Injector:
  - Horn-focused, wide-band beam
  - Peak in E_ν ~ 3 GeV; matched to 1300 km baseline
  - Main Injector, with PIP II, delivers 1.07 MW @ 80 GeV
- PIP II: 800 MeV s/c linac:
  - 1.2 MW @ 120 GeV; 1.07 MW @ 80 GeV – baseline for LBNF/DUNE
- PIP III: u/g 3 GeV s/c linac [2.4 MW @ 120 GeV]

DUNE: far detector strategy



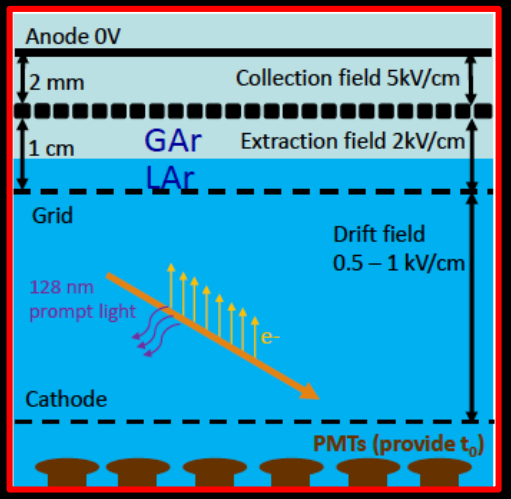
- Sanford Underground Research facility (SURF)
- 40 kT LAr TPC:
  - Modular approach: 4 caverns, 4 independent 10 kT modules
  - Approach allows:
    - Staged build
    - Flexibility to exploit advancements in LAr TPC technique

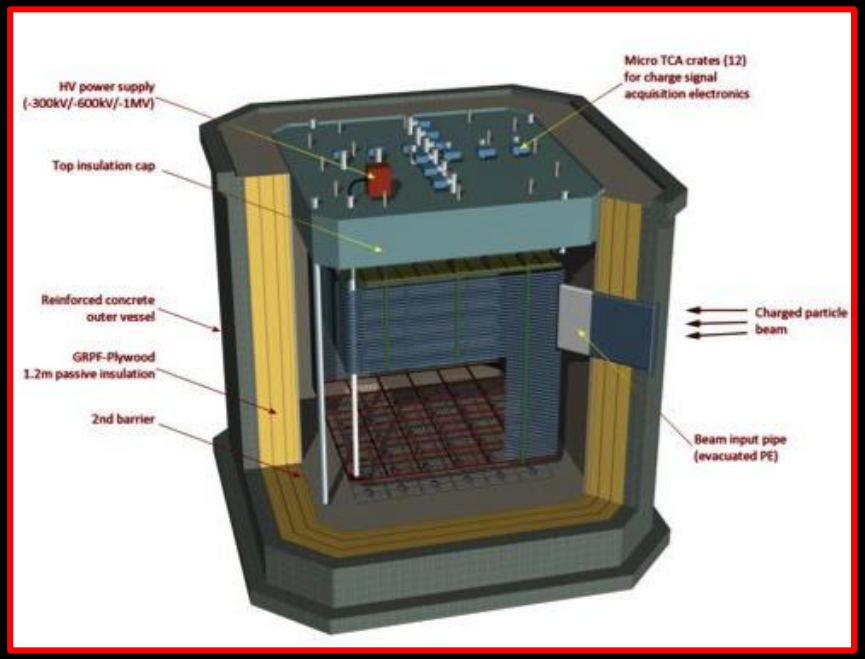
DUNE: far detector reference

- Single-phase LAr TPC
  - Development of ICARUS
  - Design presented in CDR
  - Reviewed in “CD1 refresh”
- Single-phase prototype:
  - “ProtoDUNE”; to be tested in CERN Neutrino Platform
- Development programme:
  - 35 T prototype – 2015
  - MicroBooNE – 2015
  - SBND/ICARUS – 2018

DUNE: far detector alternative

- Dual phase LAr TPC:
  - Electron drift in liquid
  - Amplification in Ar gas
  - Potential benefits:
    - Fully active LAr volume
    - Improved signal to noise
  - Presented in CDR, reviewed in CD1 refresh
- Prototypes:
  - WA105 @ CERN Neutrino Platform
    - Insulated membrane tank
    - Active area 36 m^2
    - Mass 705 T
  - 3x1x1 m^3 WA105 prototype:
    - Test of GTT membrane technology
      - Cryostat completed!
    - Operation 2016; important milestone!



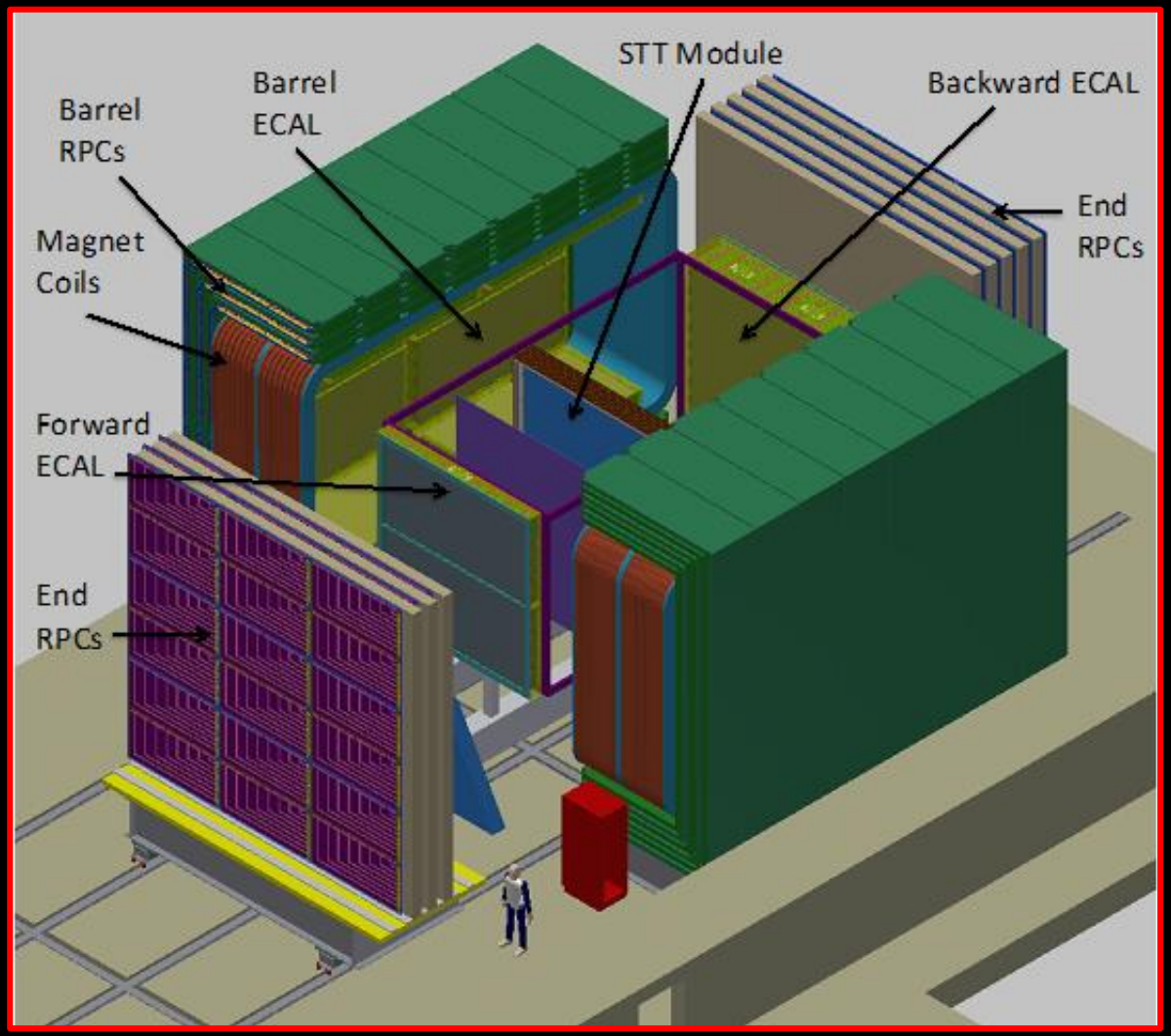


DUNE: near detector

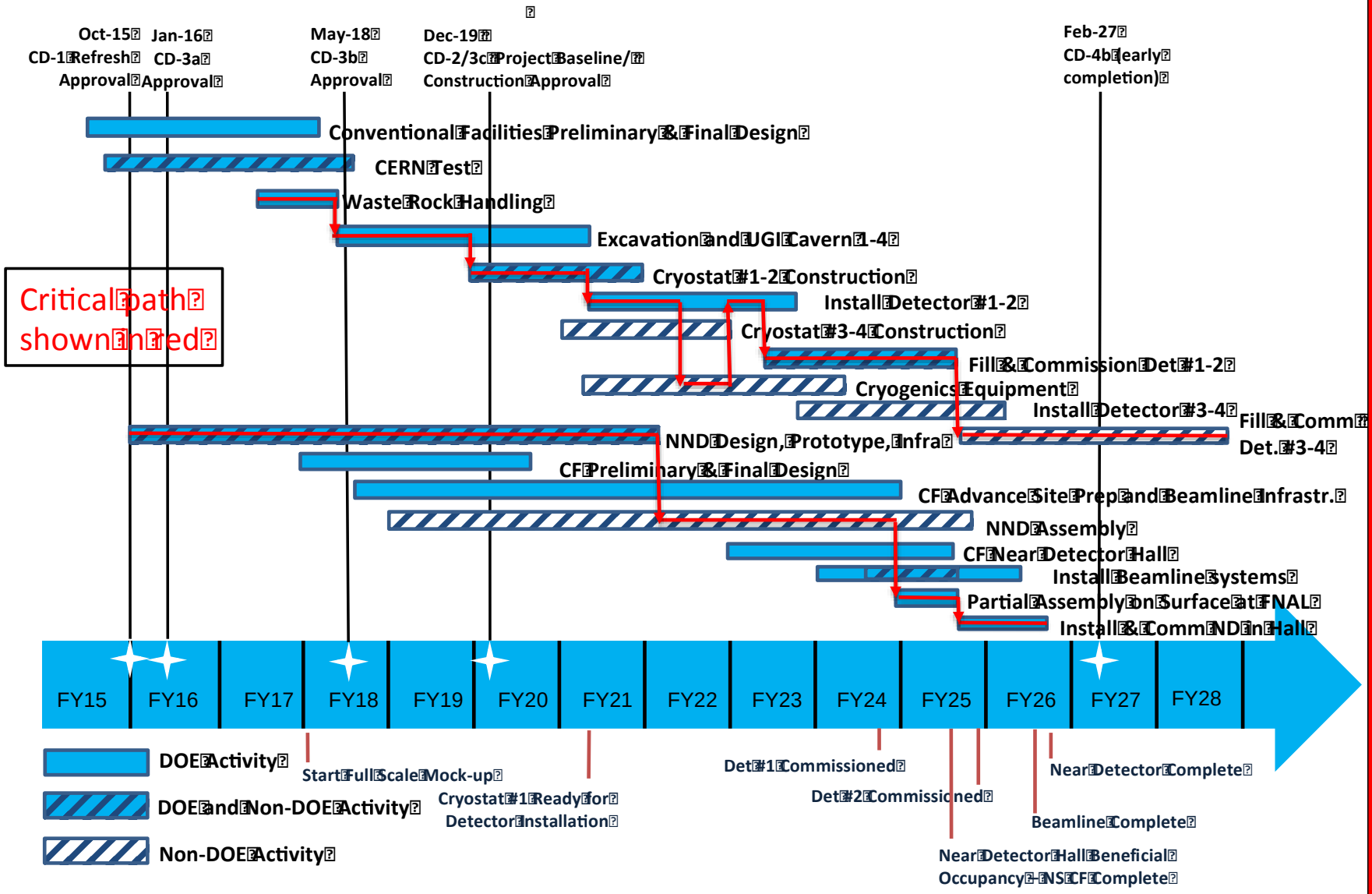
- Fine-grained detector:
  - Central straw-tube tracker
  - Pb/scintilator ECAL
  - Dipole magnet
  - RPC-based muon detectors

- Advantages of addition of:
  - LAr TPC; and/or
  - High-pressure Ar TPC

under discussion



LBNF/DUNE Schedule Summary Overview



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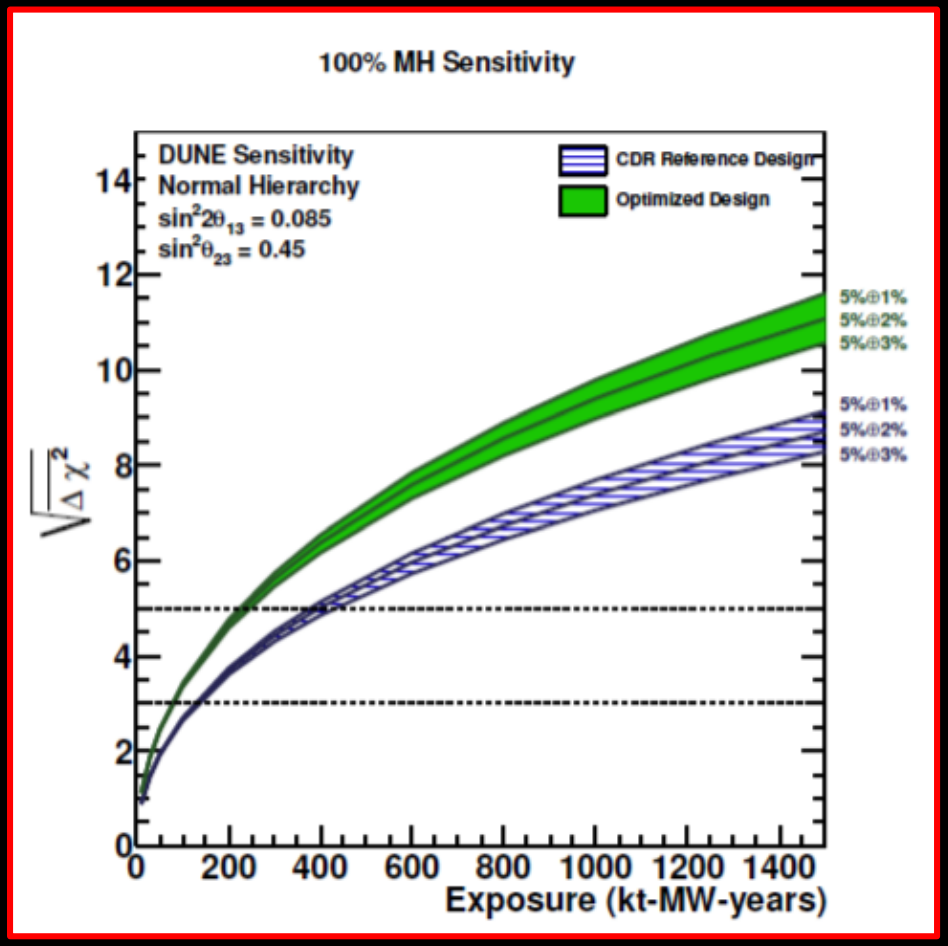
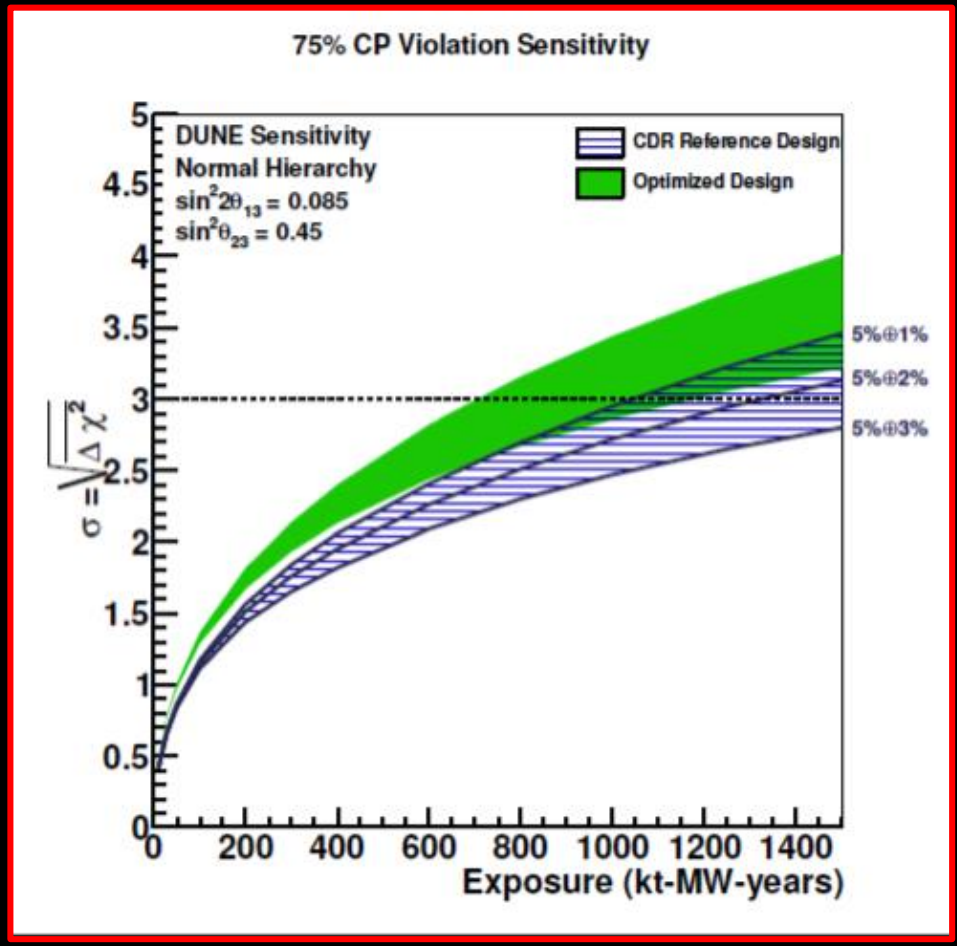
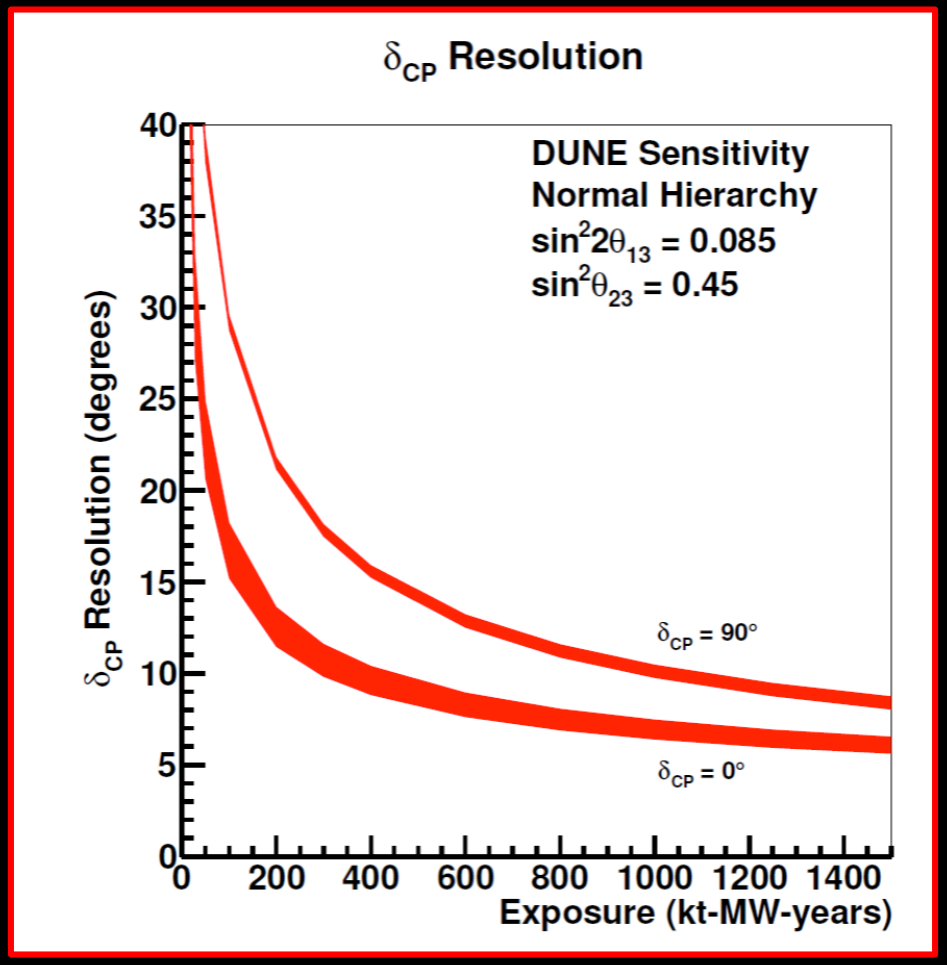
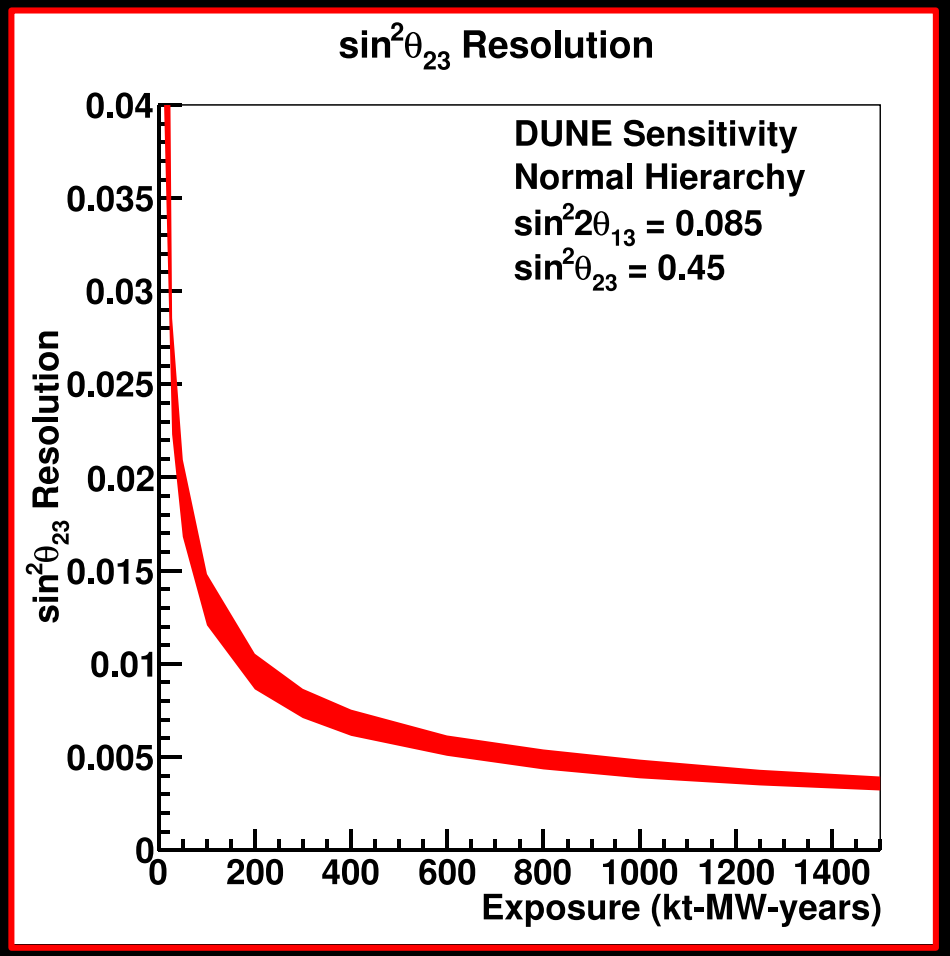
DUNE: sensitivity



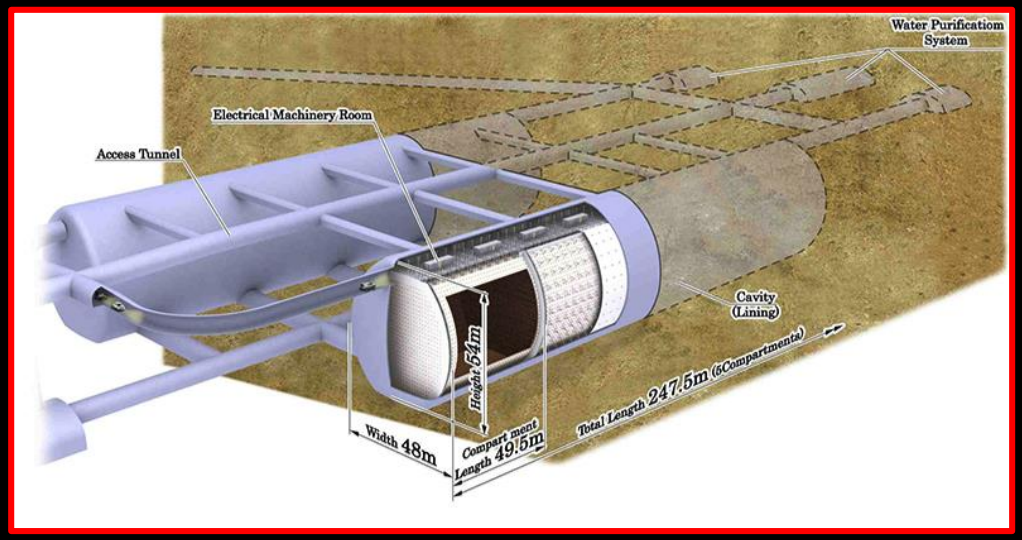


DUNE: precision



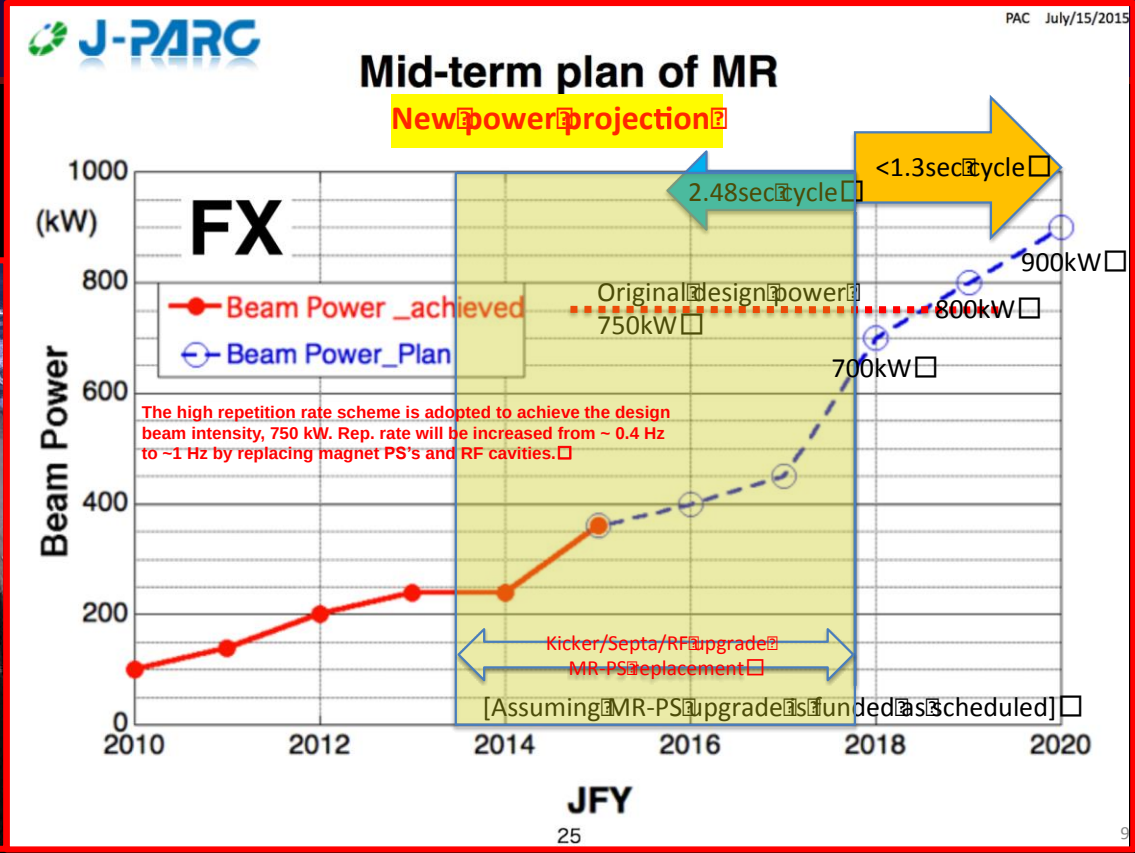


J-PARC to Hyper-K



- Accelerator neutrinos:
  - CP-invariance violation
  - Precision osc. physics:
    - Parameter measurement
    - "Beyond SvM" search
  - Near-detector physics:
    - Part of osc. programme
    - Neutrino scattering
- Additional opportunities:
  - Atmospheric and solar neutrinos
  - Proton decay
  - Astroparticle physics
- Collaboration:
  - Proto-collaboration Jan15
  - Global:
    - 240 scientists; 70 institutes; 12 countries

J-PARC



- **Neutrino beam:**
  - **Horn focused, narrow-band;**
  - **2.5° off axis:**

    Peak in $E_\nu \sim 0.6$ GeV; matched to 295 km baseline
  - **Delivers 0.35 MW on target**

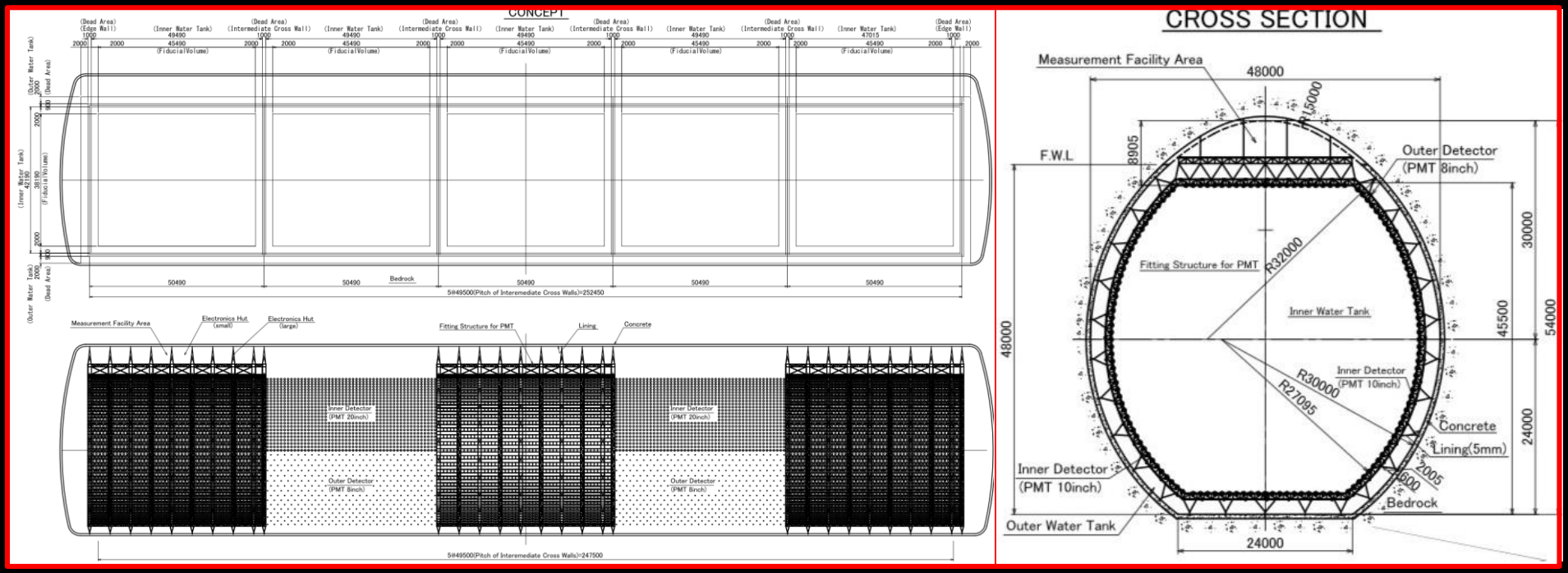
- **Upgrade path:**
  - **➔ 2020:**
    - **Main Ring PS upgrade:**
      - **1 Hz operation**
    - **High-gradient cavity upgrade**
      - **High impedance core**
  - **Considering run to 2024/5**

Upgrade for Hyper-K era

Component	Beam power/parameter	
Target	3.3×10^{14} ppp	
Beam window	3.3×10^{14} ppp	
Horn		
Cooling for conductors	2 MW	
Stripline cooling	1∼2 MW	(400 kW)
Hydrogen production	1∼2 MW	(300 kW)
Horn current	320 kA	(250 kA)
Power supply repetition	1 Hz	(0.4 Hz)
Decay volume	4 MW	
Hadron absorber/beam dump	3 MW	
Water cooling facilities	∼2 MW	(750 kW)
Radiation shielding	4 MW	(750 kW)
Radioactive air leakage to the target station ground floor	∼2 MW	(500 kW)
Radioactive cooling water treatment	∼2 MW	(600 kW)

- **Proposed programme to deliver 1.3 MW to target**

Hyper-K



- 560 kT fiducial mass ring-imaging H_2O Cherenkov
  - Two independent modules; each with a total mass of 495 kT
  - Inner detector:
    - 99k 20-inch PMTs; 20% photo-cathode coverage
  - Outer detector:
    - 25k 8-inch PMTs

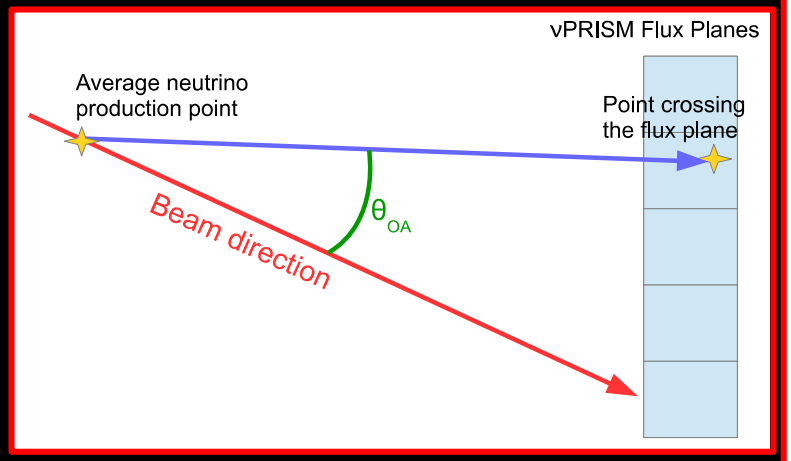
Hyper-K near detectors

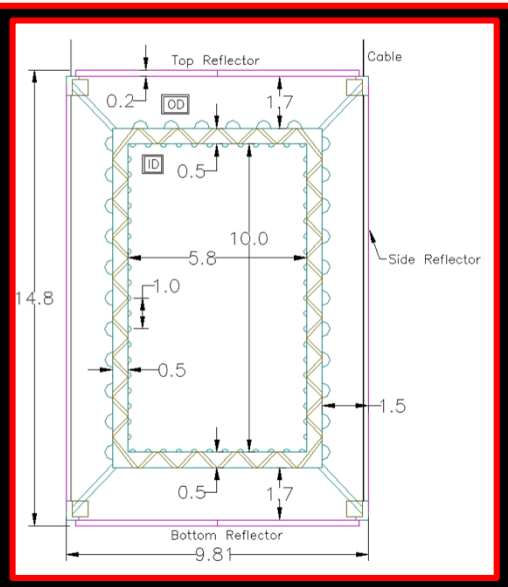
- Essential to constrain flux and cross sections
  - $\nu_\mu N$ and $\nu_e N$
- Upgrades to present ND280 detector considered:
  - 3D grid water detector (WAGASCI, J-PARC T59)
  - High-pressure Ar TPC [*]
  - Water-based liquid scintilaltor [NIM A660 51 (2011)]
  - Emulsion detector (J-PARC T60)

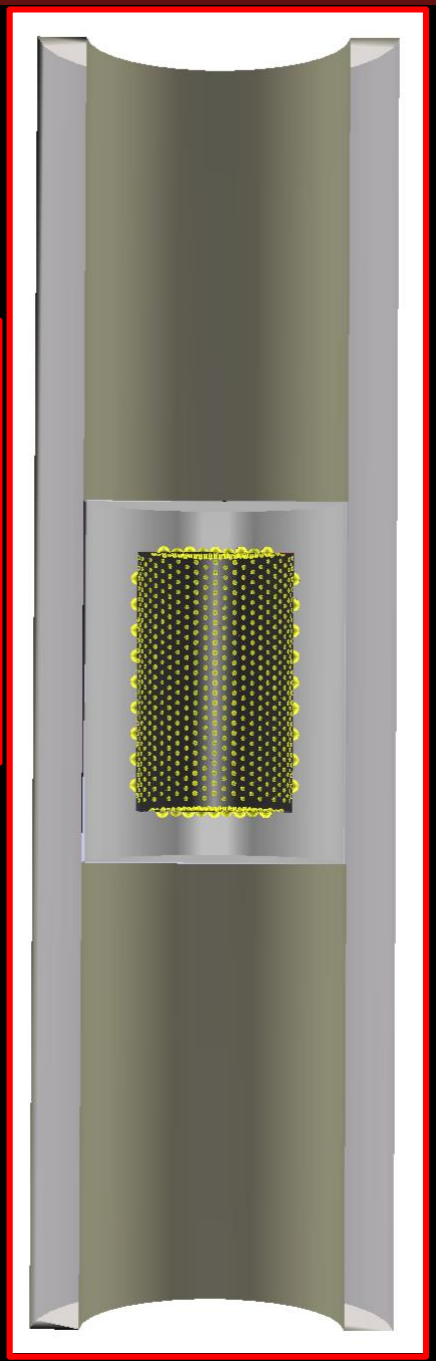
- Intermediate detectors under consideration:
  - TITUS [arXiv:1504.08272]:
    - 2 kT, Gd doped, H2O Cherenkov
    - Placed at ~2 km so that flux shape is similar to that at Hyper-K
  - nuPRISM [arXiv:1412.3086]:
    - Measure νN as a function of o.a. angle …

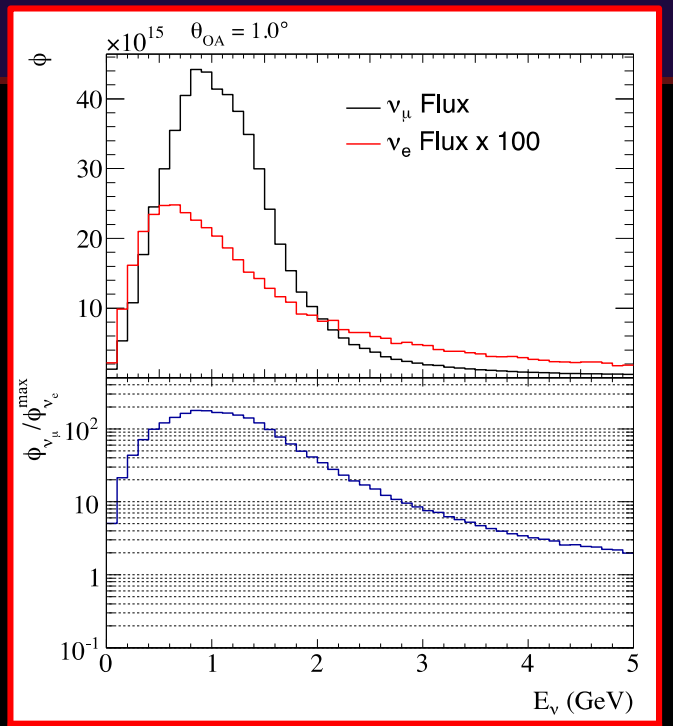
nuPRISM

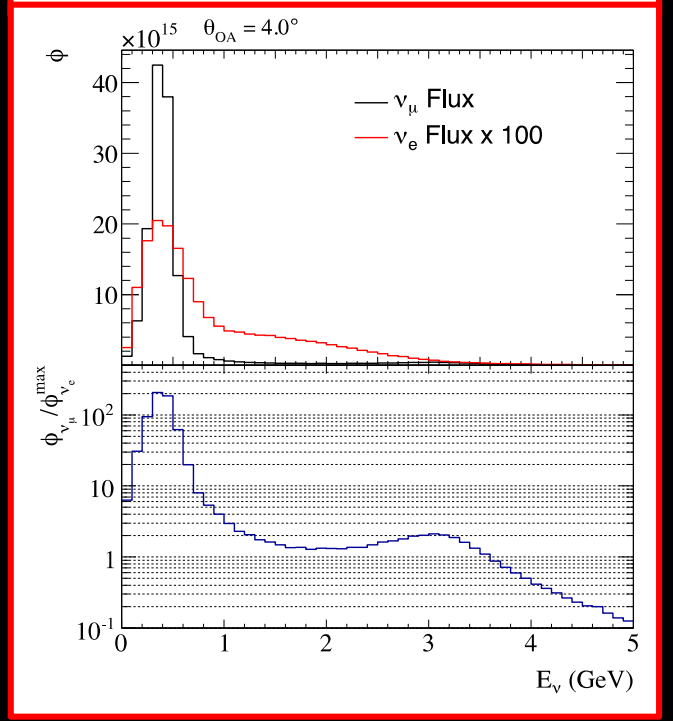
- Off-axis: $\langle E_\nu \rangle = f(\theta)$



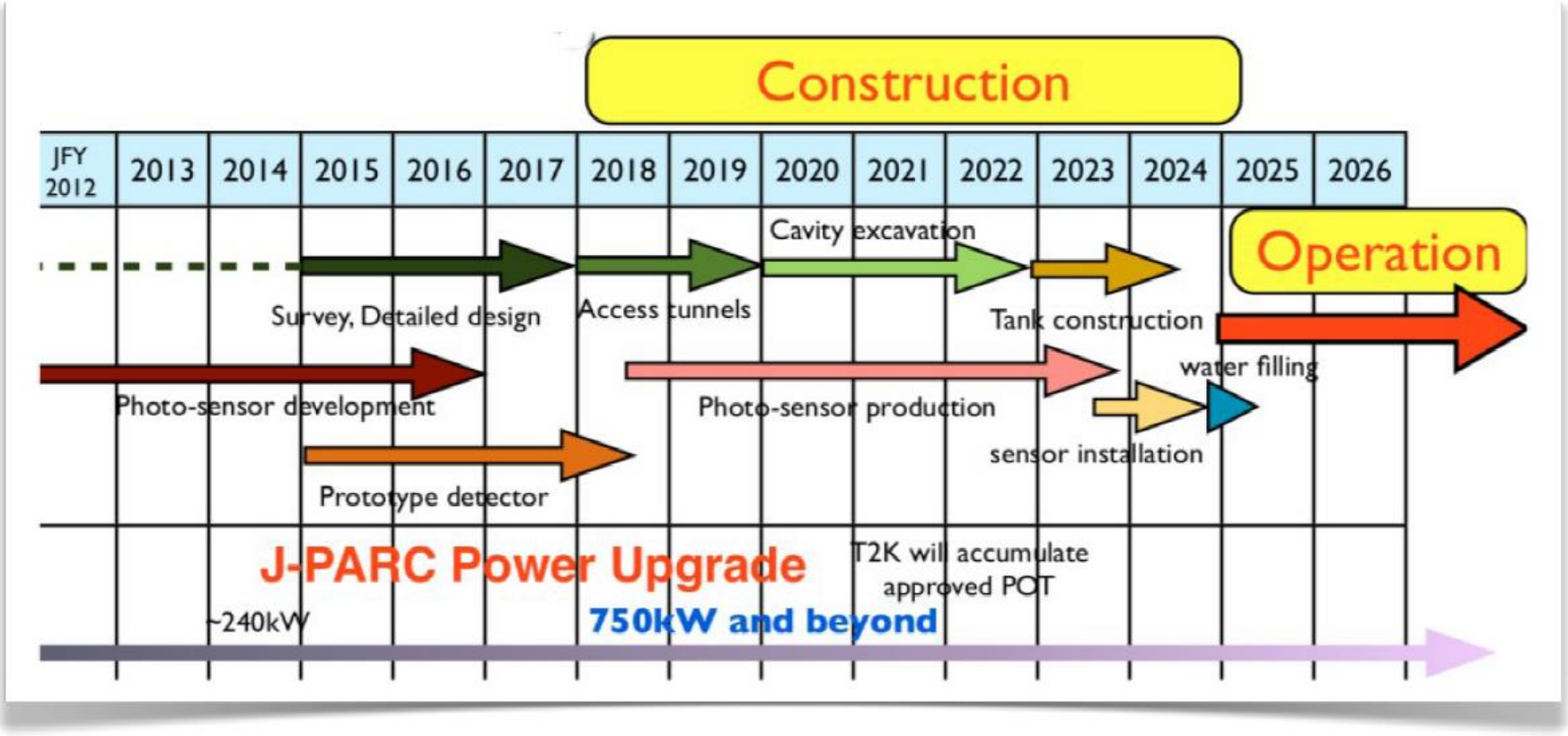






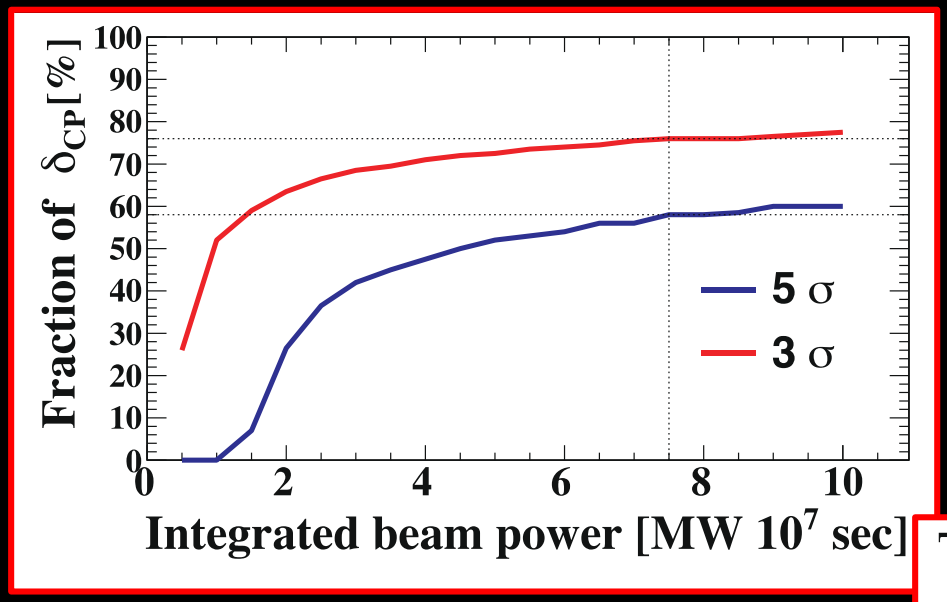


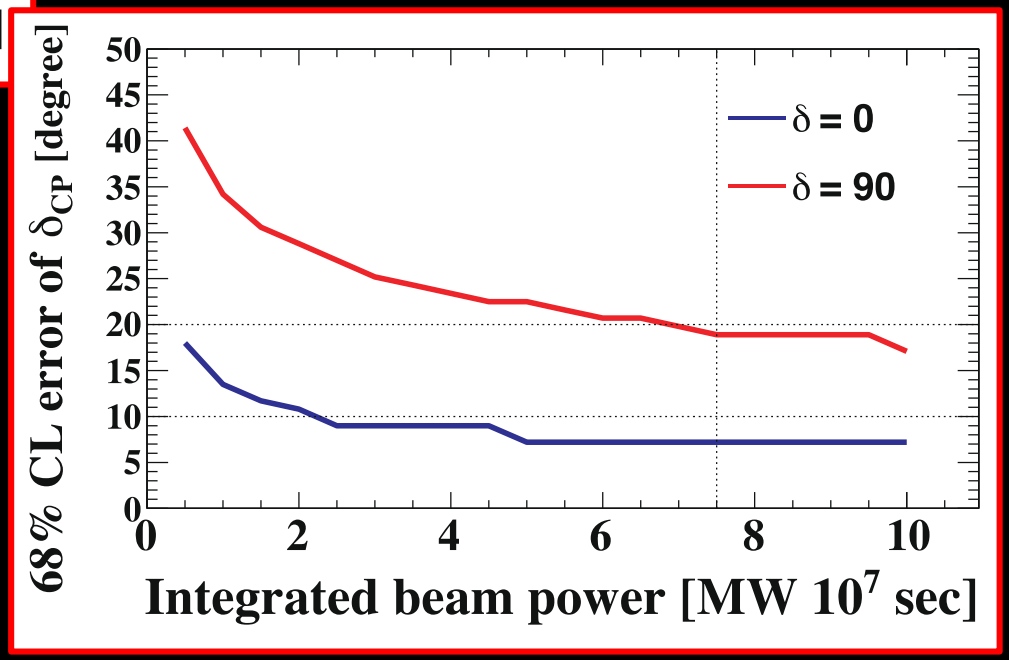
The Hyper-Kamiokande Timeline



~2017 Major design decisions finalized
~2018 Construction starts
~2025 Data taking start
> 2025 Discoveries!

Hyper-K: sensitivity and precision





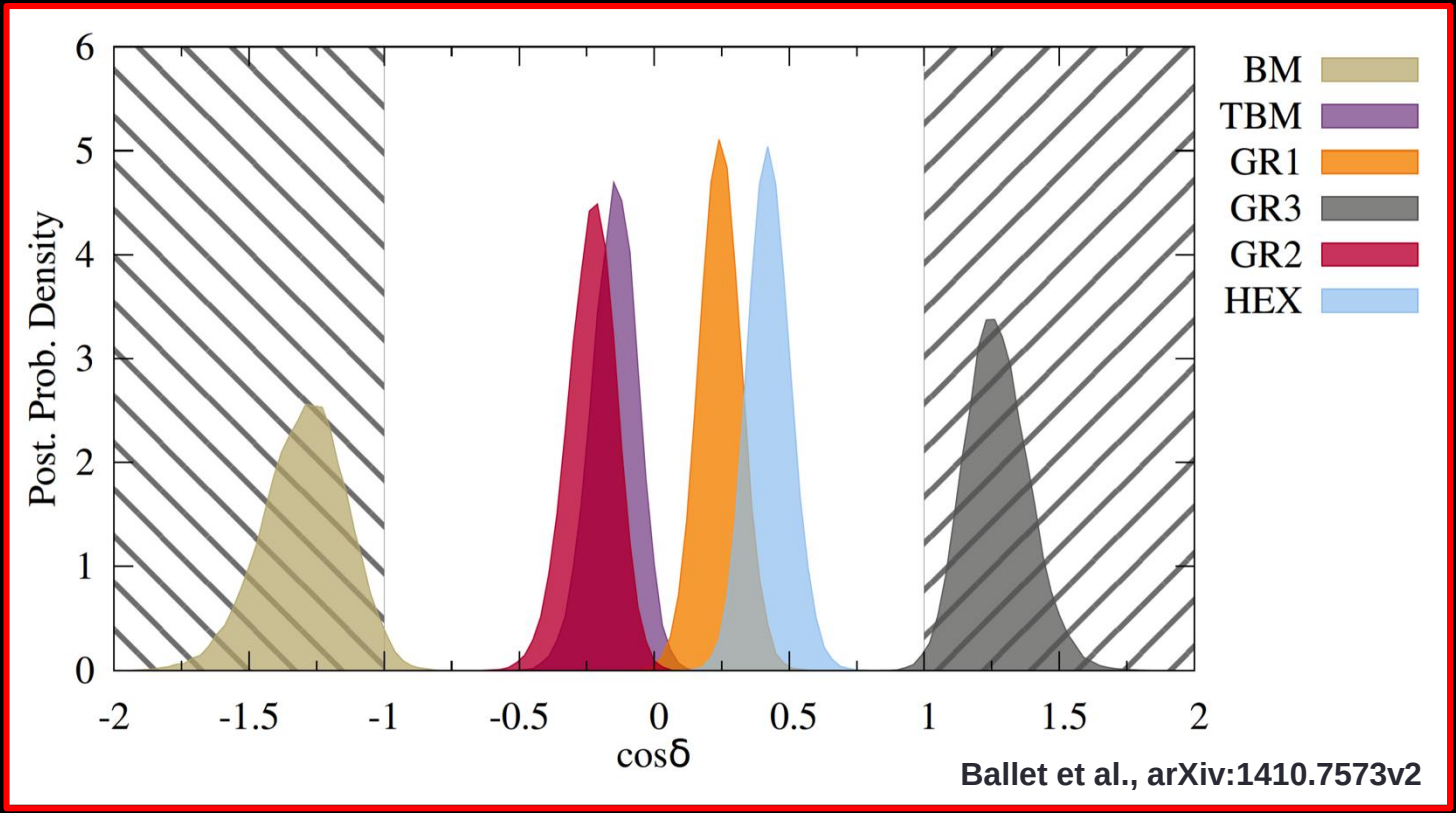
DUNE and Hyper-K

- T2K and NOvA:
  - Each has an excellent programme on its own;
  - Combined, sensitivity to (e.g.) δ enhanced
- DUNE and Hyper-K:
  - Each has an excellent programme on its own;
  - Combined, sensitivity to (e.g.) δ enhanced …

- ... additional, programmatic, benefits:
  - Optimised for same *L*/*E* at different *L* and *E*:
    - Allows SvM paradigm to be tested;
  - Different, *E*, *L*, technology:
    - Different matter effects;
    - Different systematics systematics

Beyond the SvM

- **Capability to go beyond the next generation required to:**
  - **Probe the SvM to elucidate the physics of flavour**



Beyond the SvM

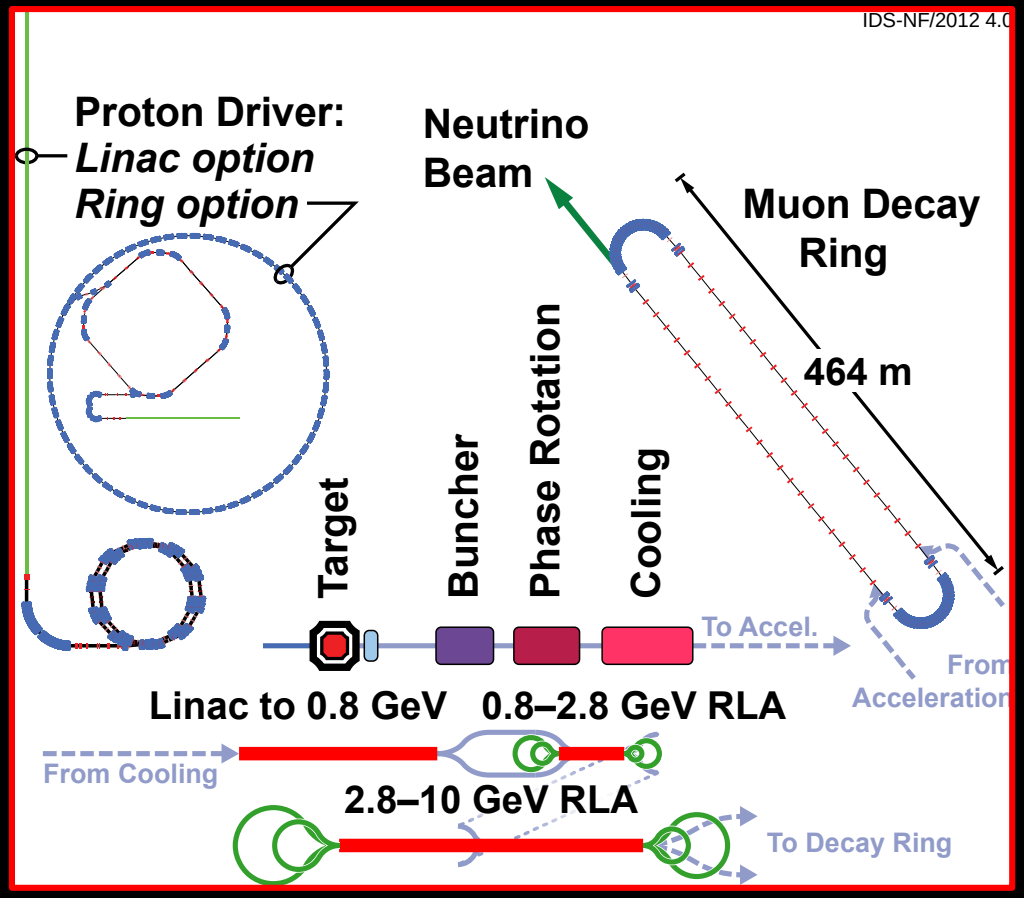
- **Capability to go beyond the next generation required to:**
  - **Probe the SvM to elucidate the physics of flavour**

- **Innovation in beam to:**
  - **Increase sensitivity and precision;**
  - **Allow detailed study of non-leading effects**

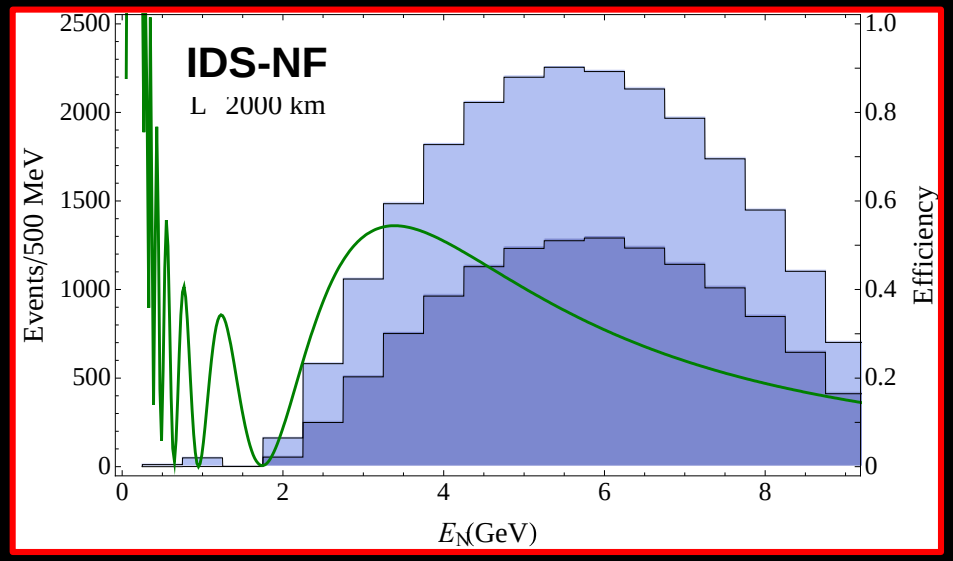
Neutrino Factory

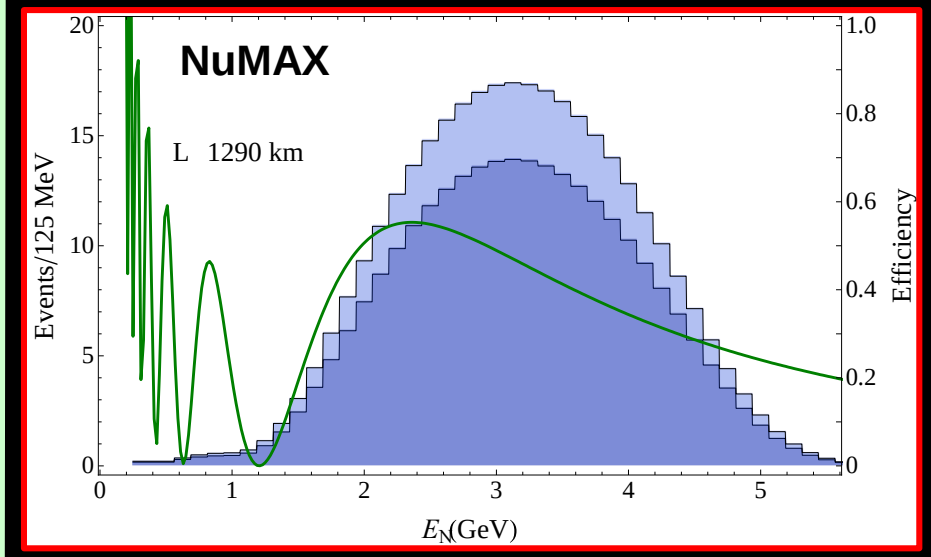
$$\mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu$$
$$\mu^- \rightarrow e^- \bar{\nu}_e \nu_\mu$$

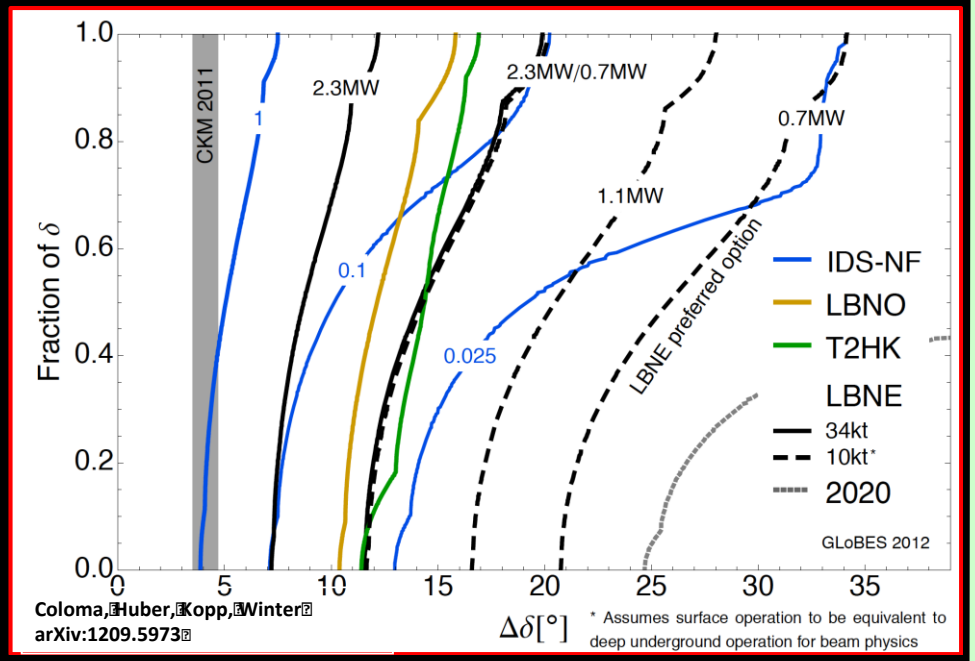
- Optimise sensitivity and precision:
  - Requirements:
    - Large ν_e ($\bar{\nu}_e$) flux
    - Detailed study of sub-leading effects
- Unique:
  - Large, high-energy ν_e ($\bar{\nu}_e$) flux
    - Muon-beam cooling huge advantage
  - Favourable rigidity allows:
    - Optimise *E* for given *L*

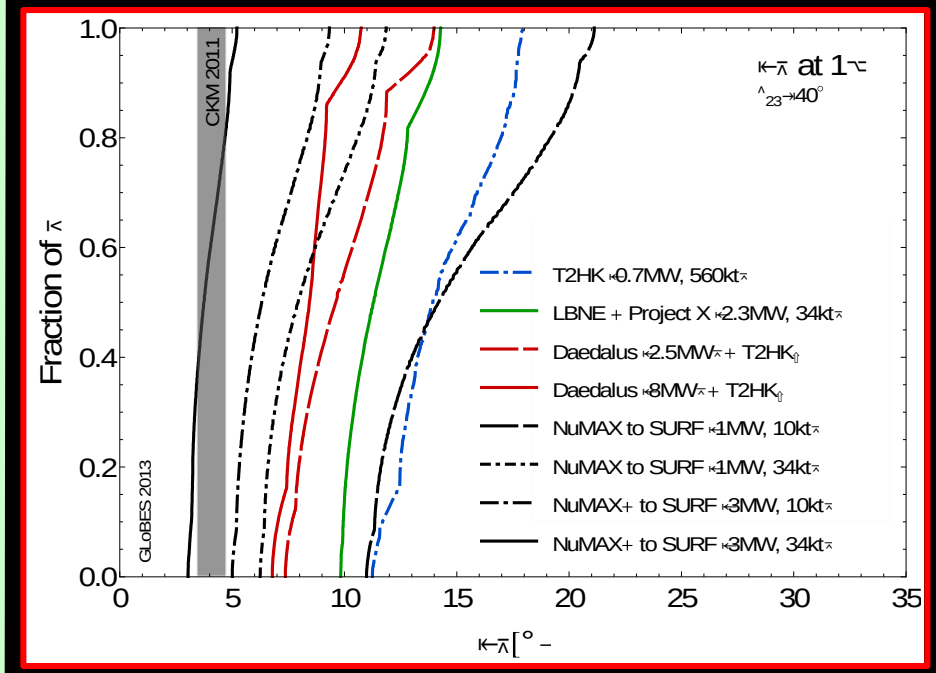


[See also MOMENT: "linear" NF]


IDS-NF
L 2000 km
Events/500 MeV
Efficiency
E_N(GeV)


NuMAX
L 1290 km
Events/125 MeV
Efficiency
E_N(GeV)

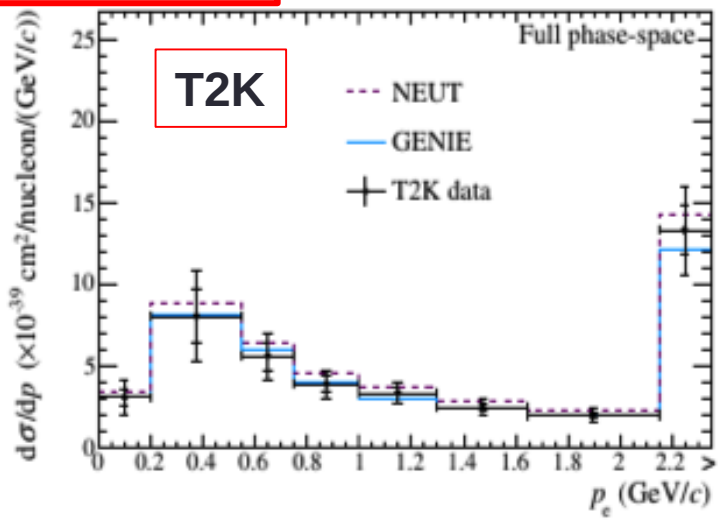

CKM 2011
2.3MW
2.3MW/0.7MW
0.7MW
1.1MW
1
0.1
0.025
LBNE preferred option
IDS-NF
LBNO
T2HK
LBNE
34kt
10kt*
2020
GLoBES 2012
Fraction of δ
Δδ[°]
Coloma, Huber, Kopp, Winter
arXiv:1209.5973
* Assumes surface operation to be equivalent to deep underground operation for beam physics

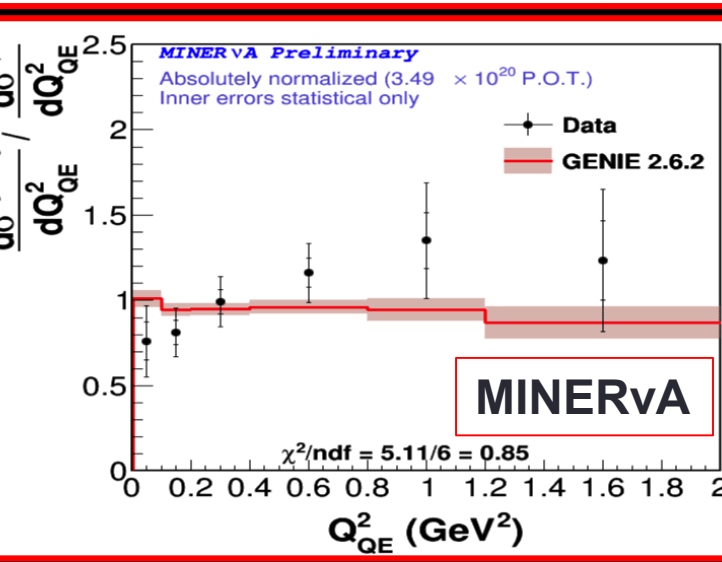

CKM 2011
GLoBES 2013
T2HK 0.7MW, 560kt
LBNE + Project X 2.3MW, 34kt
Daedalus 2.5MW + T2HK
Daedalus 8MW + T2HK
NuMAX to SURF 1MW, 10kt
NuMAX to SURF 1MW, 34kt
NuMAX+ to SURF 3MW, 10kt
NuMAX+ to SURF 3MW, 34kt

CROSS SECTIONS

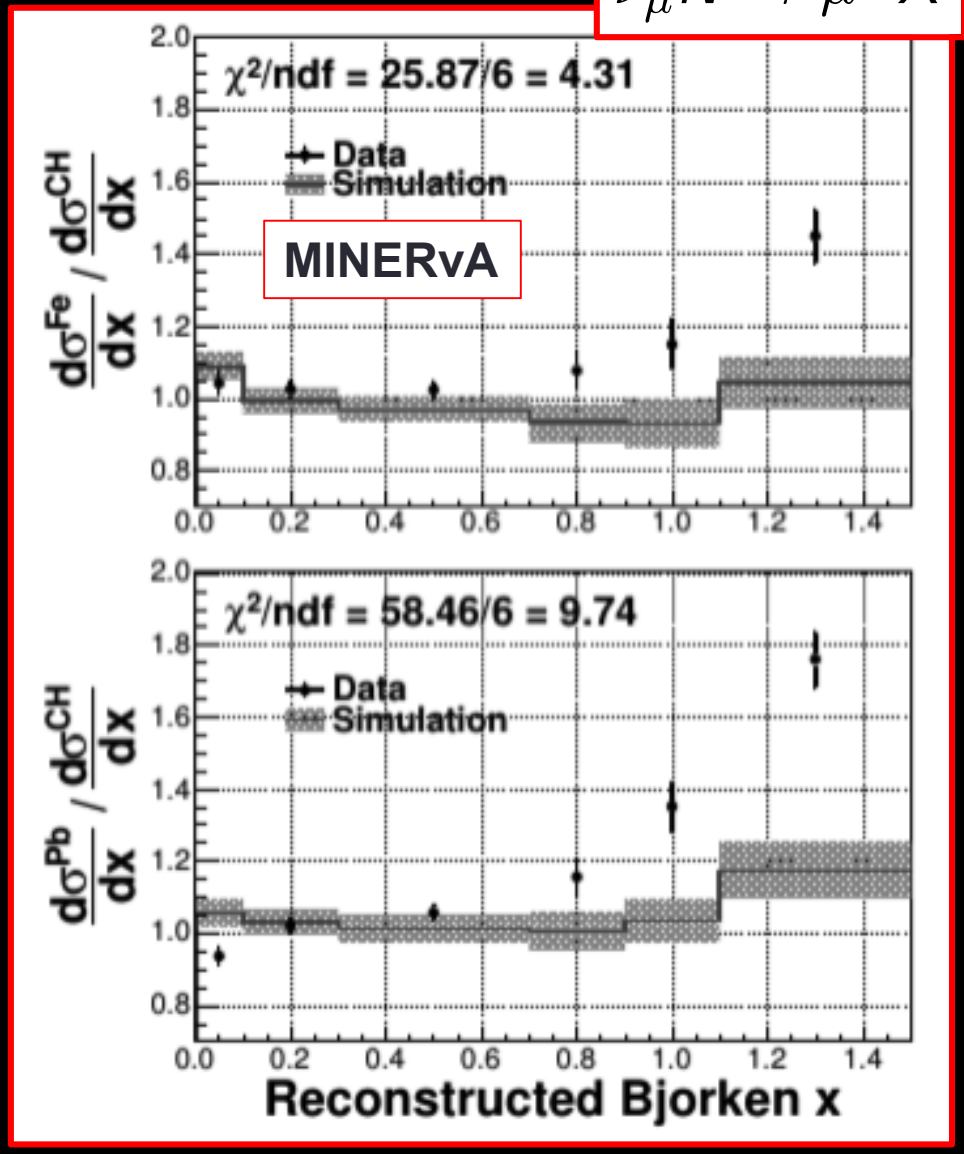
Cross-section measurement

$\nu_e C \to e^- X$



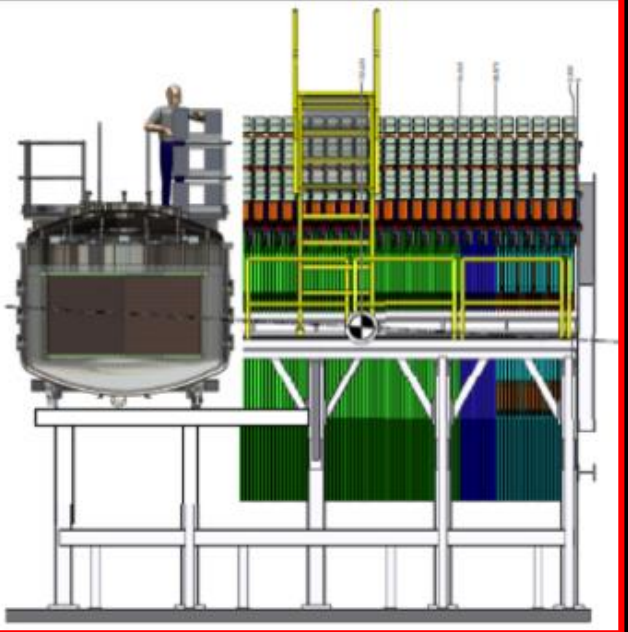


$\nu_\mu N \to \mu^- X$



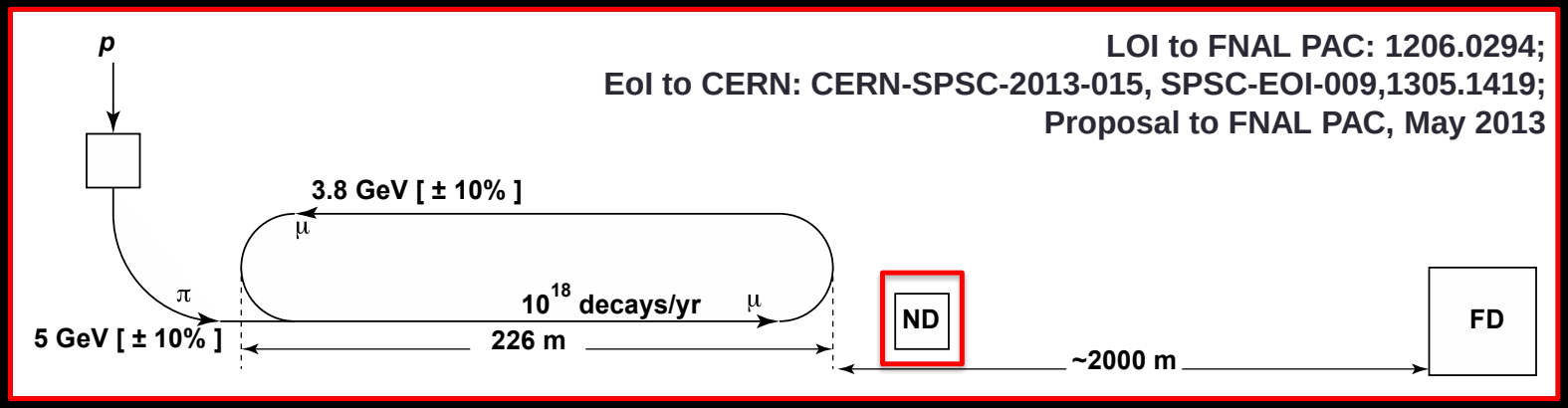
Cross-section measurement

- Lots of data to analyse and understand:
  - MINERvA, ND280, MINOS-ND, NOvA-ND
- Important advances in theory:
  - Complete, accurate description challenging
    - $\nu_e \neq \nu_\mu$: some aspects understood
  - $\nu \neq \nu$: vector-axial-vector interference
    - $\nu_e \neq \overline{\nu}_e$: pernicious!
- Additional measurements required:
  - CAPTAIN-MINERvA [arXiv:1309.1740]
  - SBN detectors:
    - SBND, MicroBooNE, ICARUS

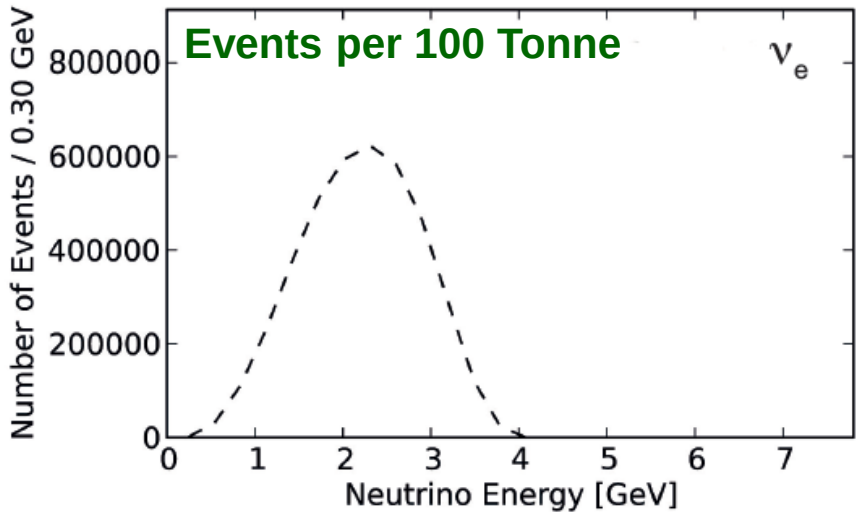


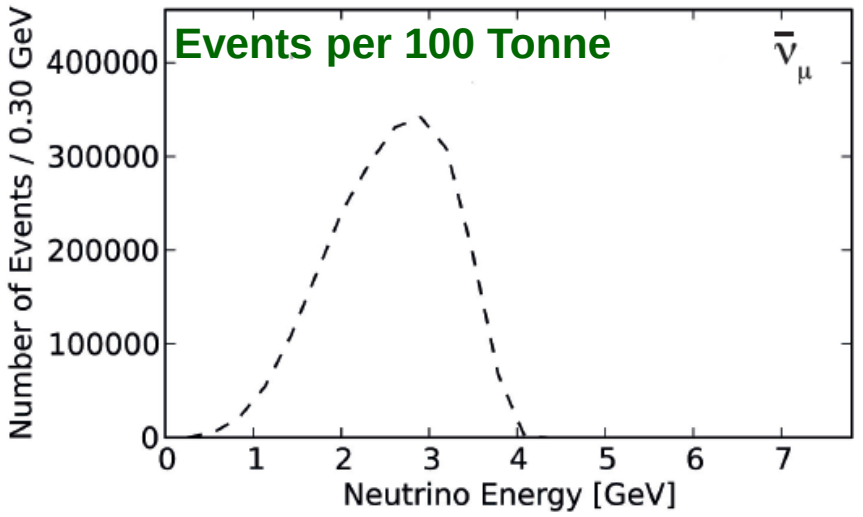
	Events w/ reco μ	Events w/ reco μ and charge
CCQE-like	916k	784k
CC1$\pi^{\pm}$	1953k	966k
CC1π^{0}	1553k	597k

nuSTORM and cross section measurement



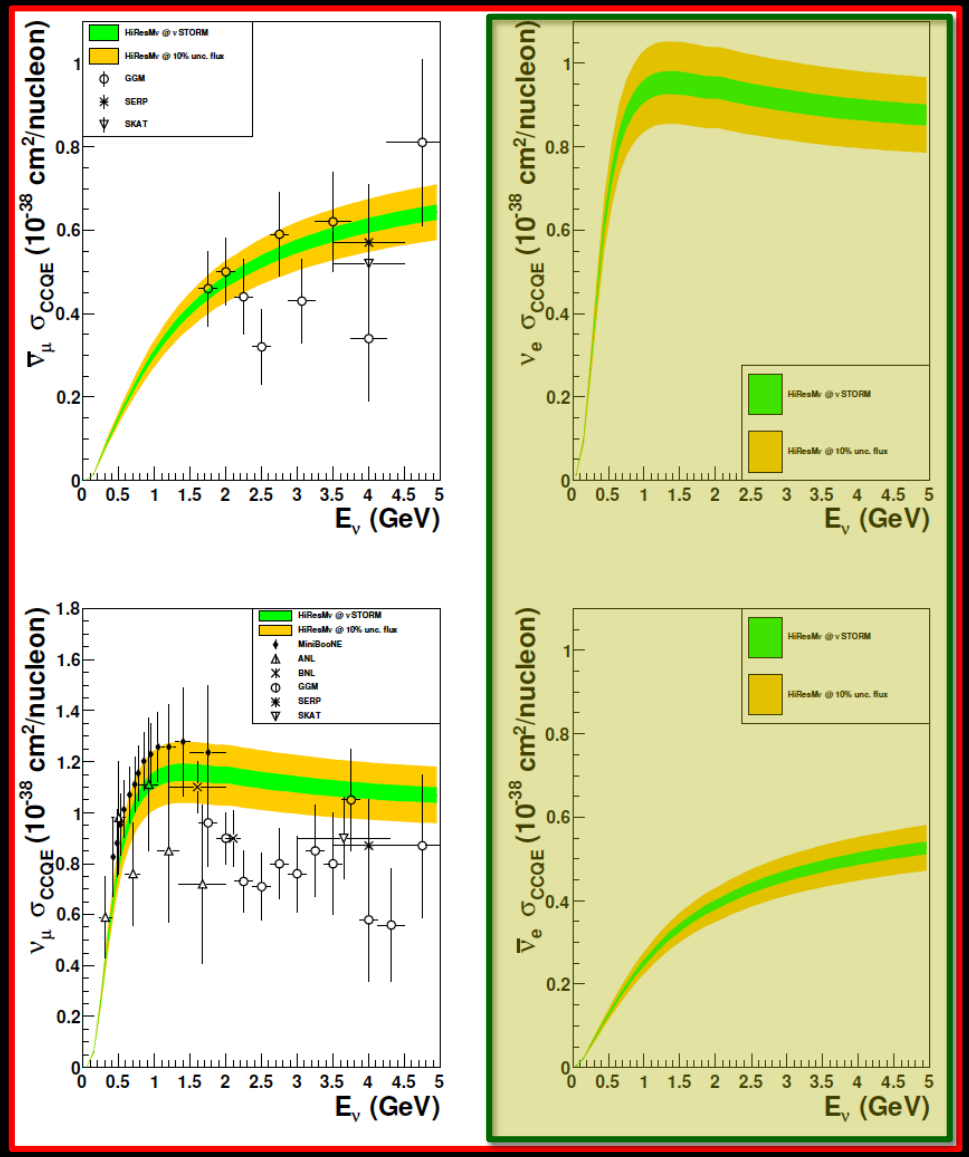
- **nuSTORM event rate is large:**
  - **Statistical precision high:**
    - **Can measure double-differential cross sections**





CCQE cross section measurement:

- Systematic uncertainties for CCQE measurement at nuSTORM:
  - Six-fold improvement in systematic uncertainty compared with “state of the art”
  - Electron-neutrino cross section measurement unique



SCANNING THE HORIZON

Future neutrino programme

- An exciting programme of discovery lies ahead:
  - DUNE and SBN at LBNF
  - Hyper-K at J-PARC
  - Reactor, atmospheric, astroparticle, solar

- Innovation and the development of capability:

Innovation in detector

- Energetic development of detector technique:
  - Large mass, LAr TPC:
    - DUNE prototypes, WA105, SBND, MicroBooNE, ICARUS, CAPTAIN
  - Near detectors for systematics and cross sections:
    - nuPRISM, TITUS, CAPTAIN, DUNE ND
- Supported by the CERN Neutrino Platform:

SvM: Accelerator-based contributions

CERN
Horn and bubble chamber
First neutrino beam

BNL
first neutrino "beam"

IHEP
SKAT, JINR

CERN
Horn #2 & Gargamelle

CERN
Gargamelle, Aachen/Padova, CDHS, CHARM, BEBC, CCFR, NOMAD, CHORUS

BNL/FNAL
CITF, HPWF, 7' BC, 15' BC, E605, E613, E734, E776, NuTEV

FNAL
MINOS, MINOS+, NOvA

CERN
OPERA, ICARUS

KEK/J-PARC
K2K, T2K

Global neutrino progamme
Hyper-K
LBNF/DUNE
CERN Neutrino Platform

1950 1960 1970 1980 1990 2000 2010 2020 2030

ν_μ discovery

ν_e/ν_μ universality

Neutral Current discovery

Development of E/w SM, QPM, QCD

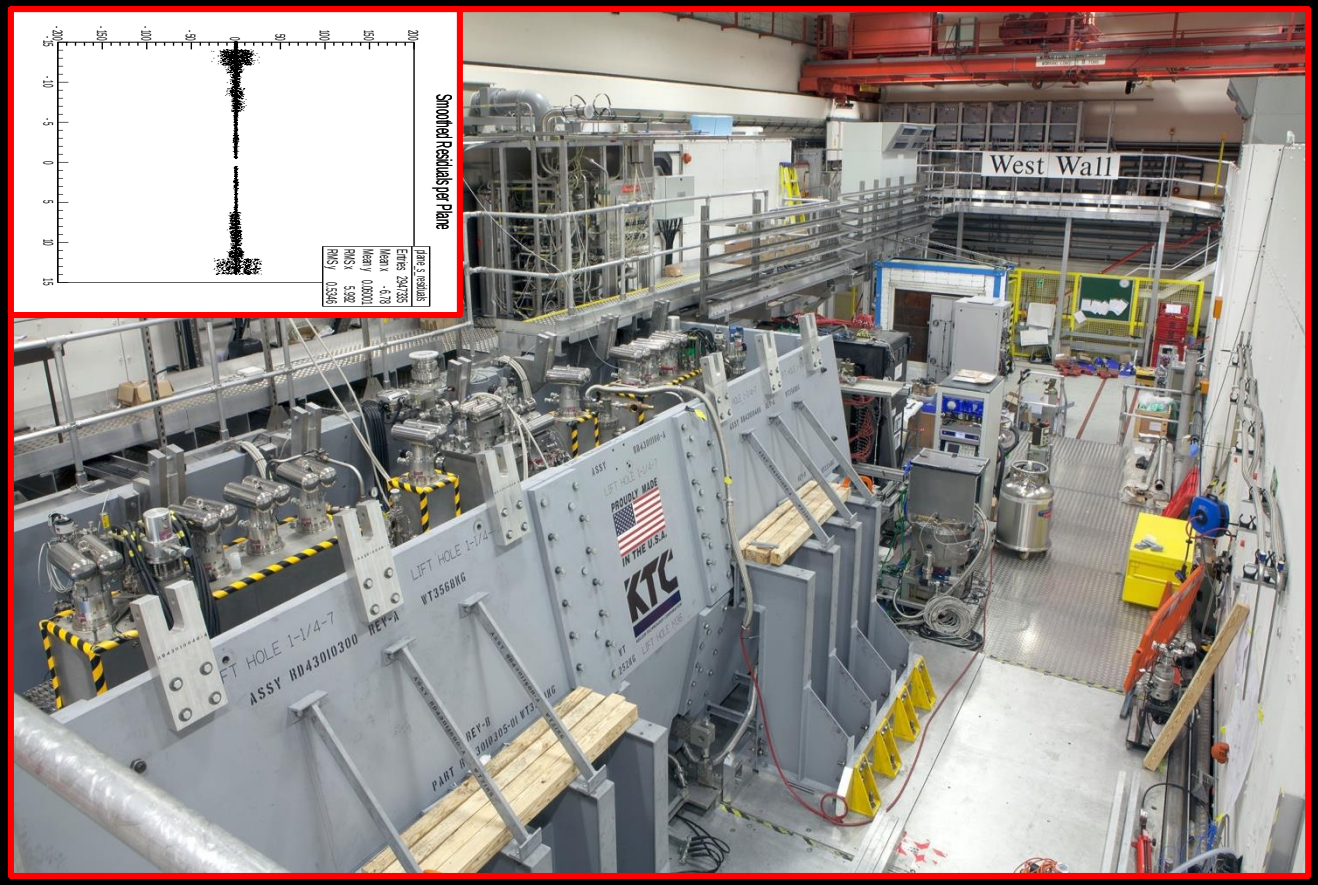
Development of Standard Neutrino Model

Discovery of CP-invariance violation?

Innovation in detectors to provide:
— High-precision
— Large data sets
— Control of systematics
Innovation in accelerators to go beyond

Innovation in neutrino beam

- Neutrino Factory offers un-paralleled performance
  - Essential R&D: demonstration of ionization cooling
    - MICE: Muon Ionization Cooling Experiment



- Commissioning:
  - Now!
- Study of factors affecting cooling:
  - Sep/Oct ‘15 …
- Reconfiguration start summer ‘16
- Ionization cooling demonstration:
  - Start summer ‘17

Future neutrino programme

- An exciting programme of discovery lies ahead:
  - DUNE and SBN at LBNF
  - Hyper-K at J-PARC
  - Reactor, atmospheric, astroparticle, solar

- Innovation and the development of capability:
  - Detector: to deliver the planned/future programme
  - Accelerator: to elucidate the physics of flavour
    - Beams derived from muon decay have unique potential

- Taken together we have a programme by which to:
  - Understand origin of neutrino mass and if a new scale exists;

and thereby open a new window on laws of nature!