SPAATIND 2020– 26TH NORDIC PARTICLE PHYSICS MEETING

SKEIKAMPEN 2-7 JANUARY 2020

Neutrinos - Part I

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BRIEF HISTORY OF NEUTRINOS

Credit to APS

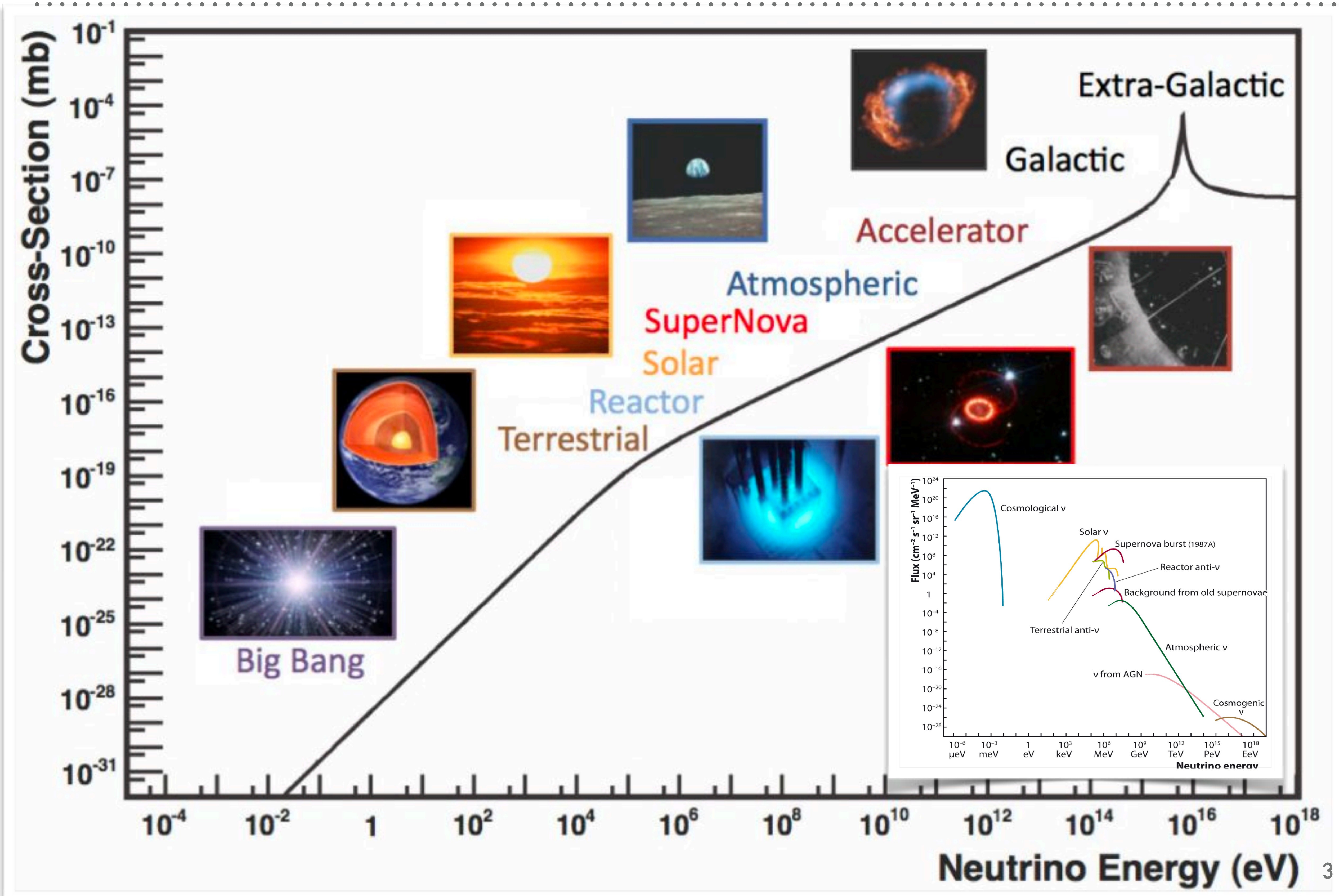
The Growing Excitement of Neutrino Physics

- 1930: On-paper appearance as "desperate" remedy by W. Pauli
- 1956: $\bar{\nu}_e$ first experimentally discovered by Reines and Cowan
- 1962: ν_μ existence confirmed by Lederman *et al.*
- 1998: Atmospheric neutrino oscillations discovered by Super-K
- 2000: ν_τ first evidence reported by DONUT experiment
- 2001: Solar neutrino oscillations detected by SNO (KamLAND 2002)
- 2011: $\nu_\mu \rightarrow \nu_\tau$ transitions observed by OPERA
- 2011-13: $\nu_\mu \rightarrow \nu_e$ by T2K, $\bar{\nu}_e \rightarrow \bar{\nu}_e$ deficit observed by Daya Bay(2012)
- 2015: Nobel prizes for ν oscillations, Breakthrough prize (2016)

Pauli predicts the Neutrino
Fermi's theory of weak interactions
Reines & Cowan discover (anti)neutrinos
2 distinct flavors identified
Davis discovers the solar deficit
Kamioka II confirms solar deficit
LEP shows 3 active flavors
SAGE and Gallex see the solar deficit
Kamioka II and IMB see atmospheric neutrino anomaly
Kamioka II and IMB see supernova neutrinos
Nobel Prize for discovery of distinct flavors!
LSND sees possible indication of oscillation signal
Nobel Prize for ν discovery!
Super K sees evidence of atmospheric neutrino oscillations
Super K confirms solar deficit and "images" sun
SNO shows solar oscillation to active flavor
Nobel Prize for neutrino astroparticle physics!
KamLAND confirms solar oscillations
K2K confirms atmospheric oscillations
Daya Bay observe theta 13 at 5 sigma
T2K observe $\nu_\mu \rightarrow \nu_e$ appearance
Nobel & Breakthrough for ν oscillations

1930 1955 1980 2015

NEUTRINO SOURCES



OUTLINE

- Part I
  - What we know about neutrinos
  - Matter Antimatter Asymmetry & the role of Neutrinos
  - Study of Neutrinos using Long Baseline Neutrino Experiments
- Part II
  - Study of Neutrinos using Reactor Experiments
  - How we can measure the neutrino mass?
  - What is the nature of neutrinos? Dirac or Majorana?
  - Astrophysical neutrinos
  - Sterile neutrinos

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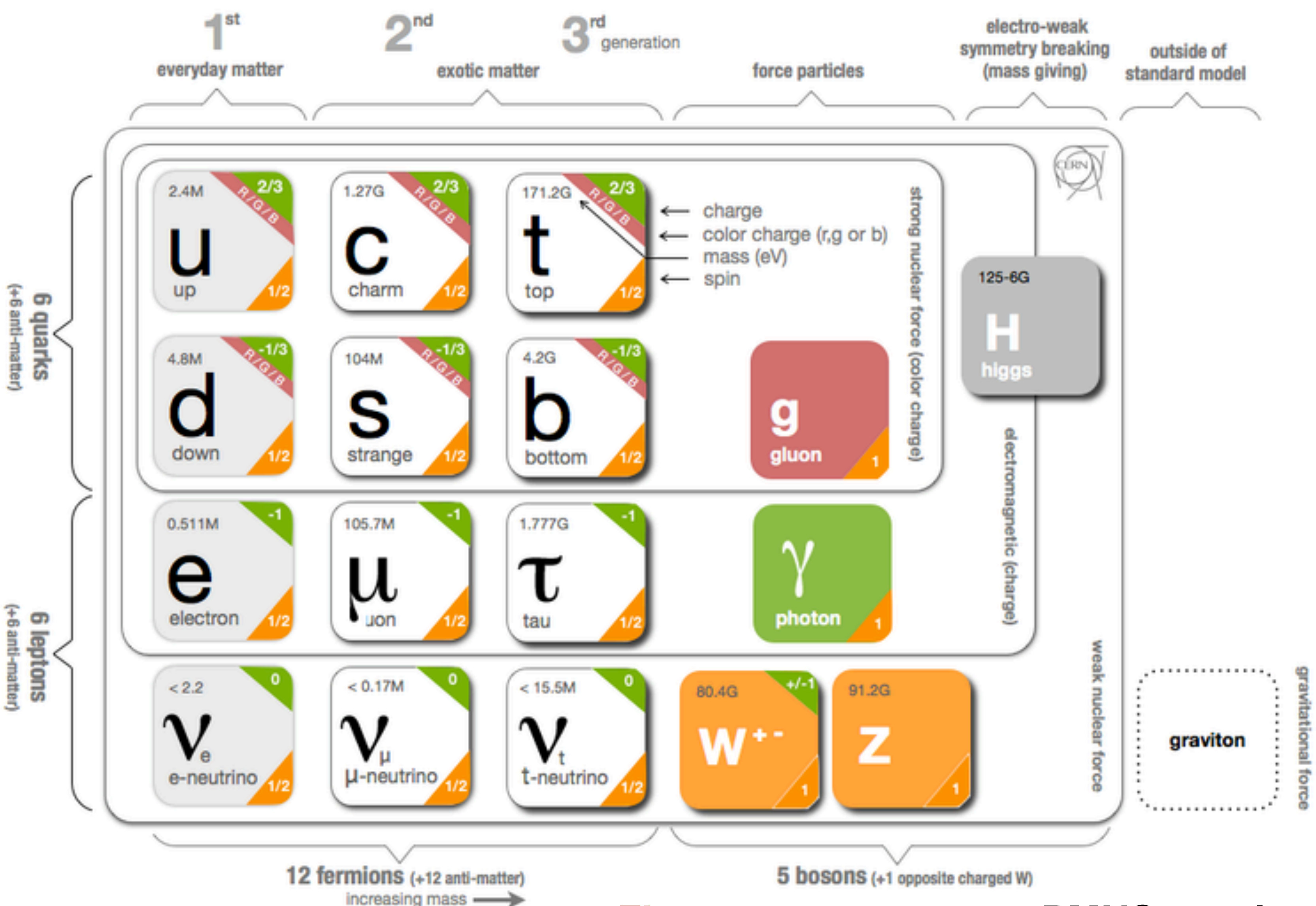
WHAT DO WE KNOW ABOUT NEUTRINOS?



Standard Model

- ➤ Neutrinos interact through the weak interaction
- ➤ The lepton flavour is strictly conserved
- ➤ Neutrinos have zero mass

Neutrino oscillations

- ➤ Indicate massive neutrinos
- ➤ Mix flavour and mass eigenstates (PMNS matrix)
- ➤ Beyond Standard Model

Flavour **PMNS matrix** **Mass**

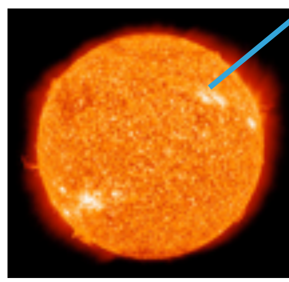
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

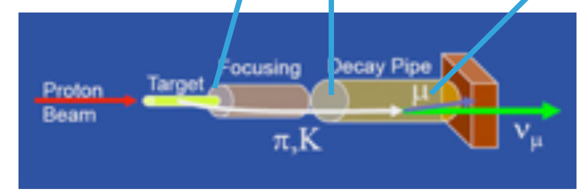
NEUTRINO OSCILLATION FRAMEWORK

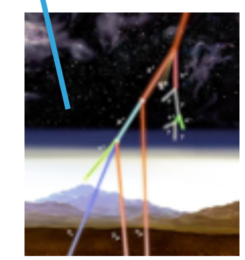
$c_{ij}=\cos\theta_{ij}$ $s_{ij}=\sin\theta_{ij}$

Solar — Accelerator/Reactor — Atmospherics

$$\begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} \end{pmatrix} = \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}$$







- Free parameters usually written in terms of three rotation angles and 1 complex phase: θ_{12}, θ_{23}, θ_{13}, δ_{CP}

Neutrino oscillations

- In the two-flavour approximation:

$$P_{\alpha\beta} = \sin^2(2\theta)\sin^2\left(1.27\Delta m^2[eV^2]\frac{L[km]}{E[GeV]}\right)$$

- $\Delta m^2_{ij} = |m^2{}_i - m^2{}_j|$ [eV²] - L=distance to source - E=neutrino energy
- Flavour change doesn't alter total neutrino flux
- If $\Delta m^2 = 0$ then neutrinos don't oscillate
- If there is no mixing (if $U_{\alpha,j} = 0$) neutrinos don't oscillate

NEUTRINO OSCILLATIONS

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

$$P(\nu_\mu \to \nu_e) = 4c_{13}^2 s_{13}^2 s_{23}^2 \cdot \sin^2\Delta_{31}$$

Leading term θ_{13}

CP conserving $+8c_{13}^2 s_{12} s_{13} s_{23} (c_{12} c_{23} \cos\delta_{CP} - s_{12} s_{13} s_{23}) \cdot \cos\Delta_{32} \cdot \sin\Delta_{31} \cdot \sin\Delta_{21}$

CP violating $-8c_{13}^2 c_{12} c_{23} s_{12} s_{13} s_{23} \sin\delta_{CP} \cdot \sin\Delta_{32} \cdot \sin\Delta_{31} \cdot \sin\Delta_{21}$

$\delta \to -\delta$ for $P(\bar{\nu}_\mu \to \bar{\nu}_e)$

Solar $+4s_{12}^2 c_{13}^2 (c_{12}^2 c_{23}^2 + s_{12}^2 s_{23}^2 s_{13}^2 - 2c_{12} c_{23} s_{12} s_{23} s_{13} \cos\delta_{CP}) \cdot \sin^2\Delta_{21}$

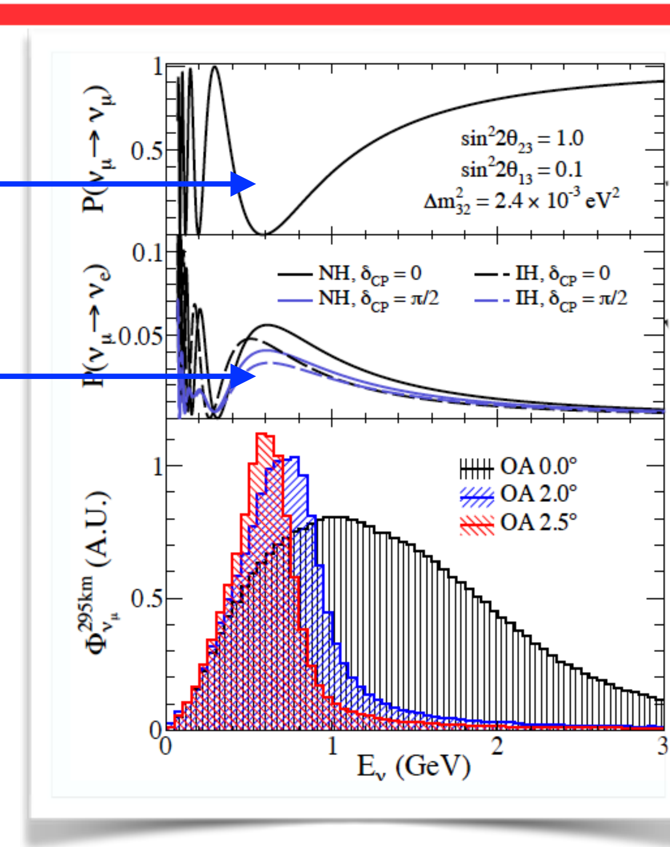
Matter

$$-8c_{13}^2 s_{13}^2 s_{23}^2 \cdot \frac{aL}{4E_\nu}(1 - 2s_{13}^2) \cdot \cos\Delta_{32} \cdot \sin\Delta_{31}$$

$$+8c_{13}^2 s_{13}^2 s_{23}^2 \frac{a}{\Delta m_{31}^2}(1 - 2s_{13}^2) \cdot \sin^2\Delta_{31},$$

where Δ_{ij} is $\Delta m_{ij}^2 L/4E_\nu$, and $a = 2\sqrt{2} G_F n_e E_\nu = 7.56 \times 10^{-5} [\mathrm{eV}^2] \times \rho[\mathrm{g/cm}^3] \times E_\nu[\mathrm{GeV}]$.

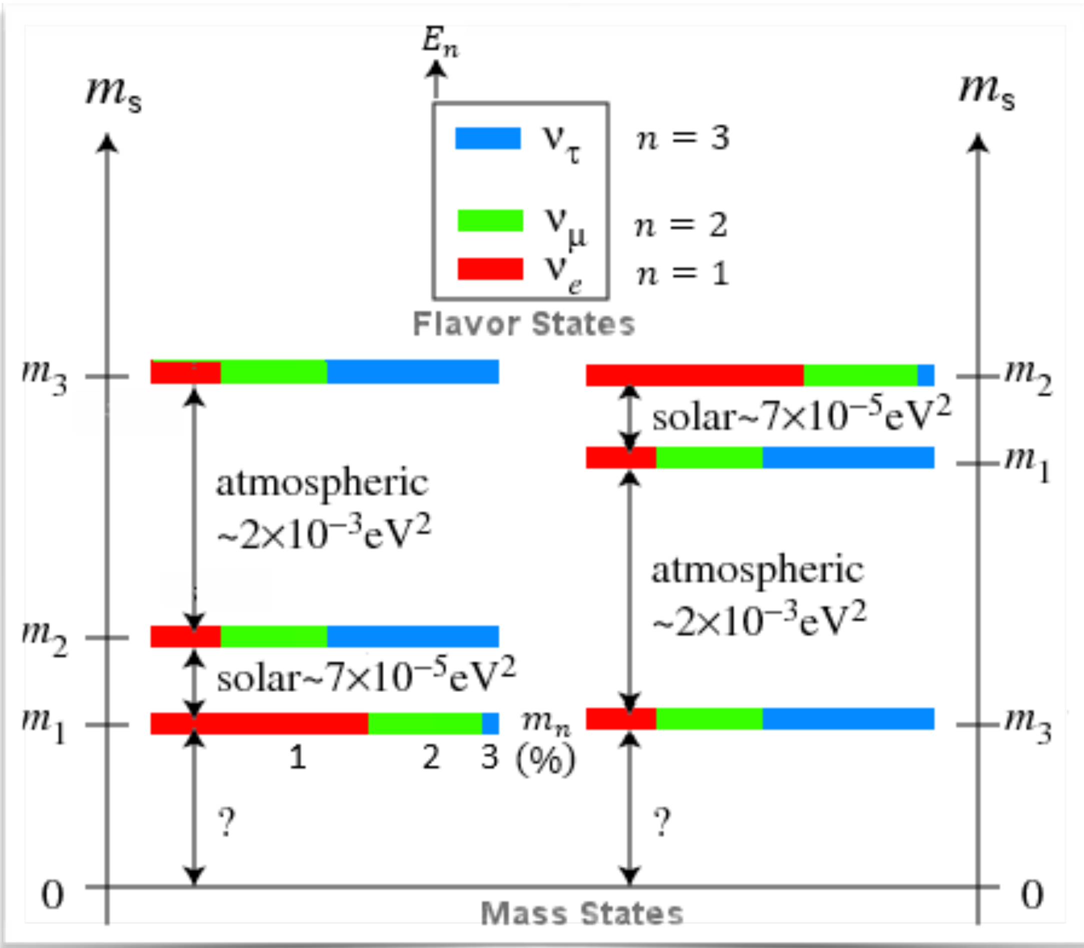
- Starting with ν_α either see if they disappear (disappearance) or look for ν_β (appearance)
- δ_{CP} measured comparing neutrinos and antineutrinos



NEUTRINO MASSES

- $\Delta m^2_{12} << \Delta m^2_{32}$ implies at least 3 massive neutrinos

Normal Ordering (NO) Inverted Ordering (IO)



- Δm^2_{12} from solar neutrinos - sign known
- $|\Delta m^2_{32}|$ from atmospheric neutrinos - sign not known
- Matter interaction needed to solve ambiguity

$$m_1 = m_{\text{min}}$$
$$m_2 = \sqrt{m_{\text{min}} + \Delta m^2_{21}}$$
$$m_3 = \sqrt{m_{\text{min}} + \Delta m^2_{31}}$$

$$m_3 = m_{\text{min}}$$
$$m_1 = \sqrt{m_{\text{min}} + |\Delta m^2_{32}| - \Delta m^2_{21}}$$
$$m_2 = \sqrt{m_{\text{min}} + |\Delta m^2_{32}|}$$

NEUTRINO MASSES

There are three limiting cases:

- Normal Hierarchical spectrum (NH): requires Normal Ordering (NO) and $m_1 \sim 0$

$$m_1 \ll m_2 \simeq \sqrt{\Delta m^2_{21}} \ll m_3 \simeq \sqrt{\Delta m^2_{31}}$$

- Inverted Hierarchical spectrum (IH): requires Inverted Ordering (IO) and $m_3 \sim 0$

$$m_3 \ll m_1 \simeq m_2 \simeq \sqrt{\Delta m^2_{32}}$$

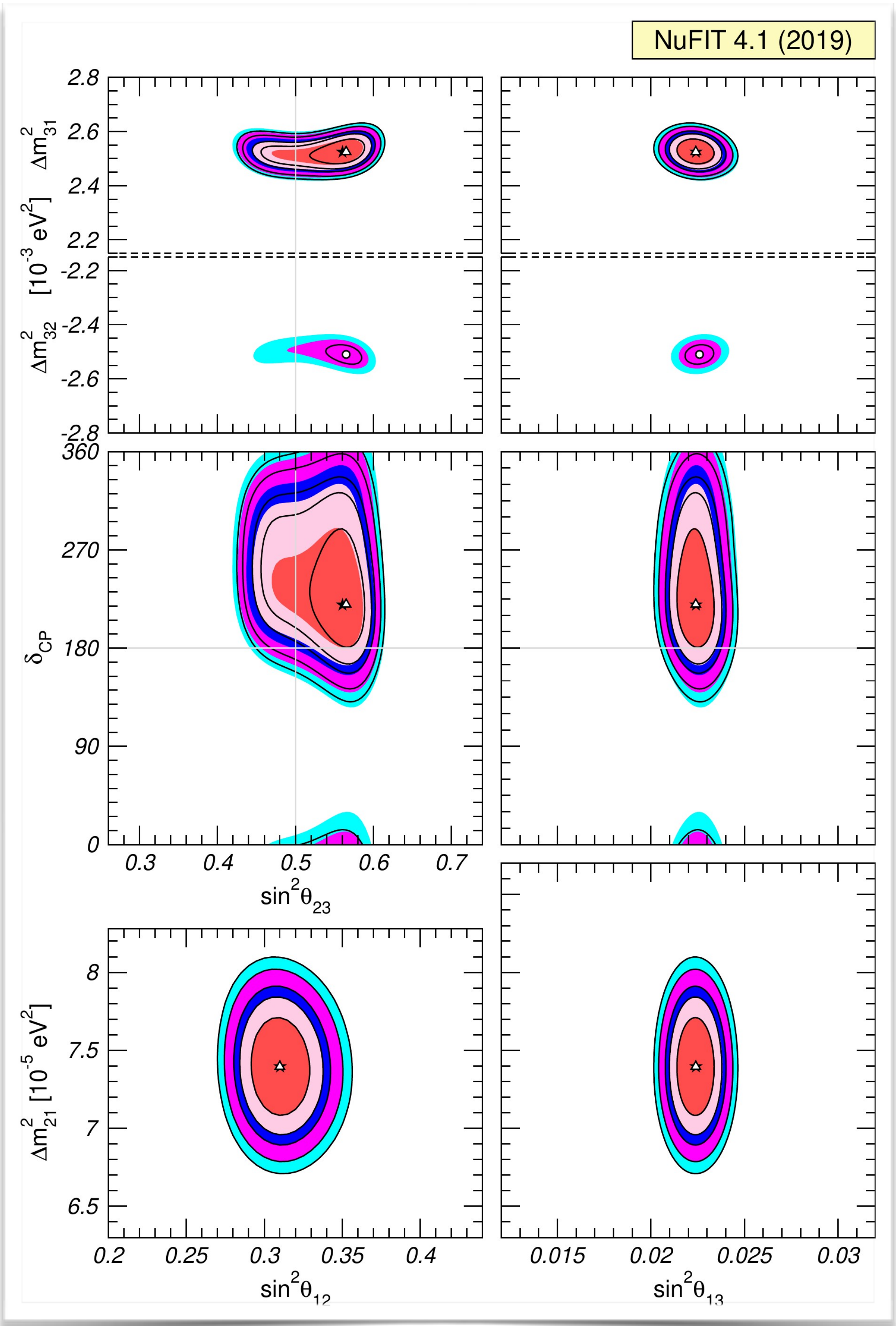
- Quasi Degenerate spectrum (QD): for $m_1 > 0.1$eV

$$m_1 \simeq m_2 \simeq m_3 \gg \sqrt{\Delta m^2_{32}}$$

Measuring the masses requires:

- The mass scale: m_{min}
- The mass ordering, i.e. either NO or IO

OSCILLATIONS



Global 6-parameter fit (2019)

Best determined:

- $\theta_{12}, \theta_{13}, \Delta m^2_{21}, |\Delta m^2_{3l}|$
  - $|\Delta m^2_{3l} = \Delta m^2_{31} > 0(NO)$
  - $\Delta m^2_{3l} = \Delta m^2_{32} < 0(IO)|$

Pending issues:

- θ_{23} maximality/octant
- Mass ordering
- CP phase: $>\pi$?

NEUTRINOS – WHERE WE STAND

NuFIT 4.1 (2019)

		Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 6.2$)	
		bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range
without SK atmospheric data	$\sin^2\theta_{12}$	$0.310^{+0.013}_{-0.012}$	$0.275 \to 0.350$	$0.310^{+0.013}_{-0.012}$	$0.275 \to 0.350$
	$\theta_{12}/^\circ$	$33.82^{+0.78}_{-0.76}$	$31.61 \to 36.27$	$33.82^{+0.78}_{-0.76}$	$31.61 \to 36.27$
	$\sin^2\theta_{23}$	$0.558^{+0.020}_{-0.033}$	$0.427 \to 0.609$	$0.563^{+0.019}_{-0.026}$	$0.430 \to 0.612$
	$\theta_{23}/^\circ$	$48.3^{+1.1}_{-1.9}$	$40.8 \to 51.3$	$48.6^{+1.1}_{-1.5}$	$41.0 \to 51.5$
	$\sin^2\theta_{13}$	$0.02241^{+0.00066}_{-0.00065}$	$0.02046 \to 0.02440$	$0.02261^{+0.00067}_{-0.00064}$	$0.02066 \to 0.02461$
	$\theta_{13}/^\circ$	$8.61^{+0.13}_{-0.13}$	$8.22 \to 8.99$	$8.65^{+0.13}_{-0.12}$	$8.26 \to 9.02$
	$\delta_{CP}/^\circ$	222^{+38}_{-28}	$141 \to 370$	285^{+24}_{-26}	$205 \to 354$
	$\frac{\Delta m^2_{21}}{10^{-5}\ \text{eV}^2}$	$7.39^{+0.21}_{-0.20}$	$6.79 \to 8.01$	$7.39^{+0.21}_{-0.20}$	$6.79 \to 8.01$
	$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \text{eV}^2}$	$+2.523^{+0.032}_{-0.030}$	$+2.432 \to +2.618$	$-2.509^{+0.032}_{-0.030}$	$-2.603 \to -2.416$

Neutrino have masses and mix!

Current knowledge of neutrino properties:

- 2 neutrino mass squared differences
- 3 sizeable mixing angles
- some hints of CP violation in favour of NO

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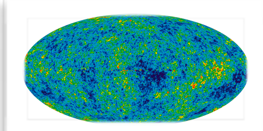
A TINY PARTICLE FOR A BIG MYSTERY

- The current Universe is matter-dominated.
- Evidence from several sources (non-observation of gamma ray emission, direct searches for antimatter, CMB anisotropy, LSS and nucleosynthesis, etc.



- The modern perspective is that the excess of matter developed dynamically through a processes called "baryogenesis."
- There are three conditions that any model of Baryogenesis must satisfy: Sakharov's conditions
  - Baryon number violation
  - C- and CP-violation
  - Out-of-equilibrium

- **Leptogenesis: Generation of baryon asymmetry from lepton asymmetry**

MINIMAL SCENARIO OF LEPTOGENESIS

- Leptogenesis takes place in the context of see-saw models
- The minimal seesaw mechanism is Type-I.
  - Introduce a right handed neutrino **N**
  - Couples to the Higgs and has a Majorana mass ($\nu = C\bar{\nu}^T$)
- The mass of the light Majorana neutrinos is predicted correctly if the mass scale of the heavy Majorana neutrino is 10^{10} GeV.

$$m_\nu = \frac{Y_\nu^2 v_H^2}{M_N} \sim \frac{1 \text{ GeV}^2}{10^{10}\text{GeV}} \sim 0.1 \text{ eV}$$

Minkowski; Yanagida; Glashow; Gell-Mann, Ramond, Slansky; Mohapatra, Senjanovic

- See-saw type I models can be embedded in GUT and explain the baryon asymmetry via leptogenesis. HNL masses can go from eV to GUT scale.

DIRAC OR MAJORANA?

- Massive neutrinos can be **Majorana** or **Dirac** particles.
- In the SM only neutrinos can be Majorana as neutral particles.

Majorana condition: $\nu = C\bar{\nu}^T$

- Dirac particle are distinguished from their antiparticles due to some conserved charge (e.g. electron from positron).
- The nature of neutrinos is linked to the conservation of lepton (L) number
- This is crucial information to unveil the **Physics BSM: with or without L-conservation**?
- Lepton Number Violation (LNV) is a necessary condition for **Leptogenesis**.
- Test of LNV: neutrinoless double beta decay.

OPEN QUESTIONS IN NEUTRINO PHYSICS

- Is there leptonic CP-violation?
  - ➡ Long baseline neutrino experiments
- What are the precise values of mixing angles?
  - ➡ Long baseline neutrino experiments, reactor experiments
- What are the values of the masses?
  - Absolute scale
    - ➡ Direct Neutrino Mass Experiments
  - Mass Ordering
    - ➡ Long baseline neutrino experiments, reactor experiments, neutrino observatories
- What is the nature of neutrinos?
  - ➡ Neutrinoless Double Beta Decays Experiments
- **Is the standard picture correct?** Are there NSI? Sterile neutrinos? Other effects?
  - ➡ Reactor experiments, short baselines experiments etc.

Very exciting experimental programme now and for the future!!

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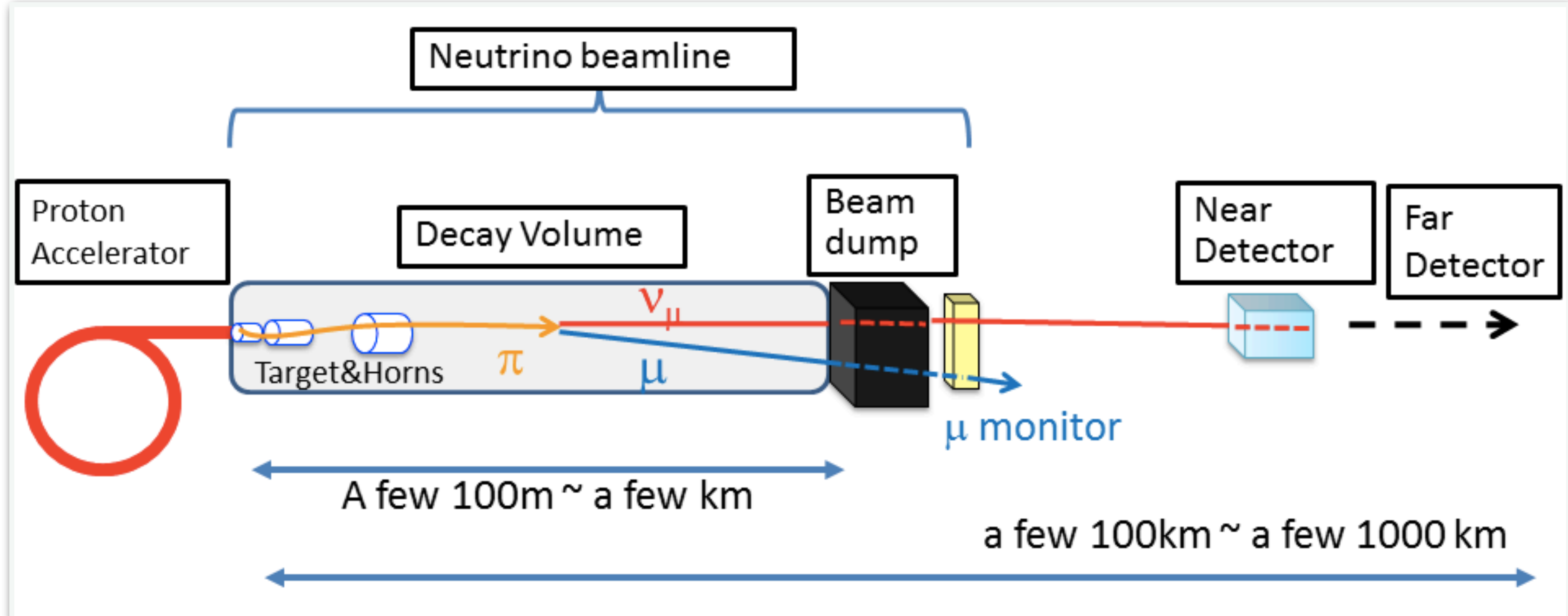
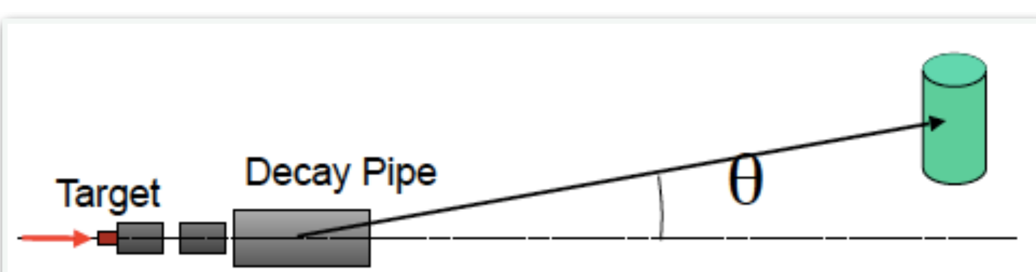
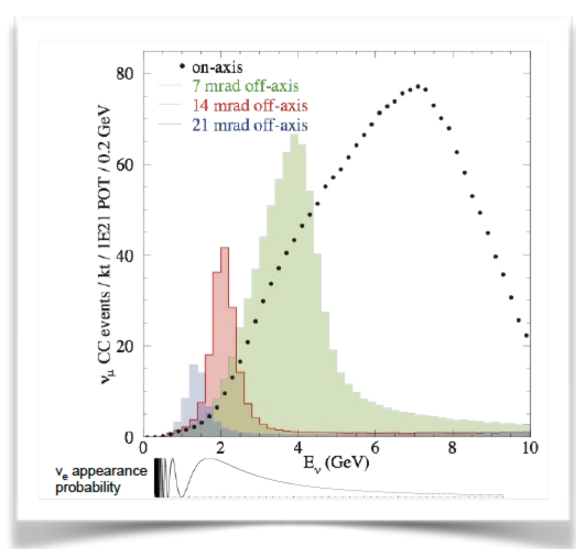
ACCELERATOR NEUTRINO EXPERIMENTS

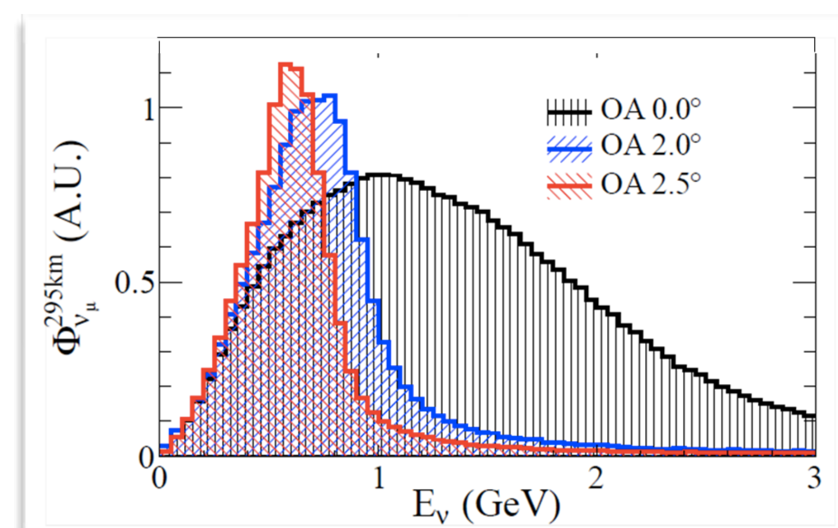
- Components of an accelerator neutrino experiment



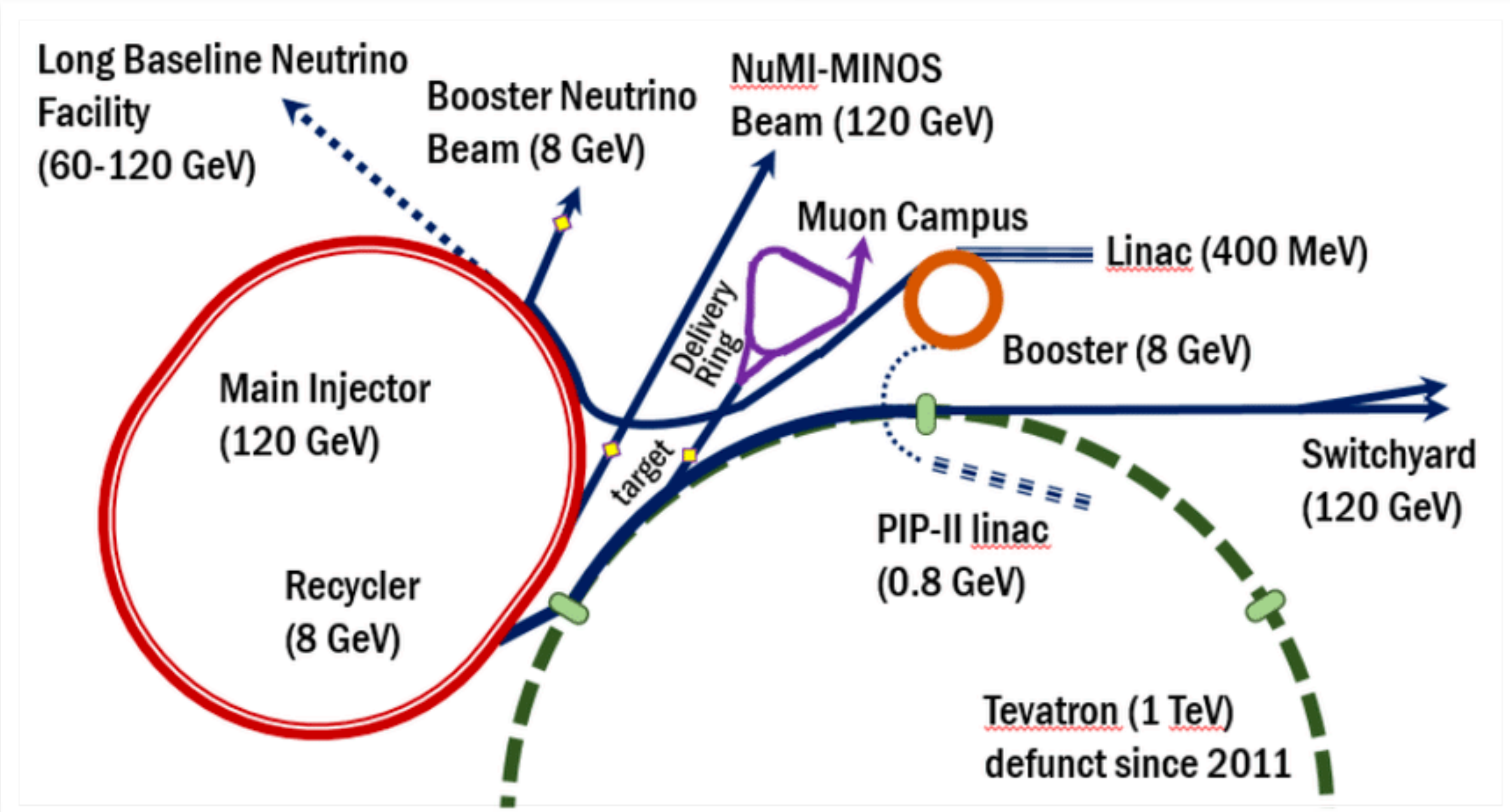
- On-axis neutrino energy tightly related to hadron energy
- Off-axis, neutrino spectrum is narrow-band and softened. Used by **NOvA (14 mrad)** and **T2K (2.5°)** Components of an accelerator neutrino experiment







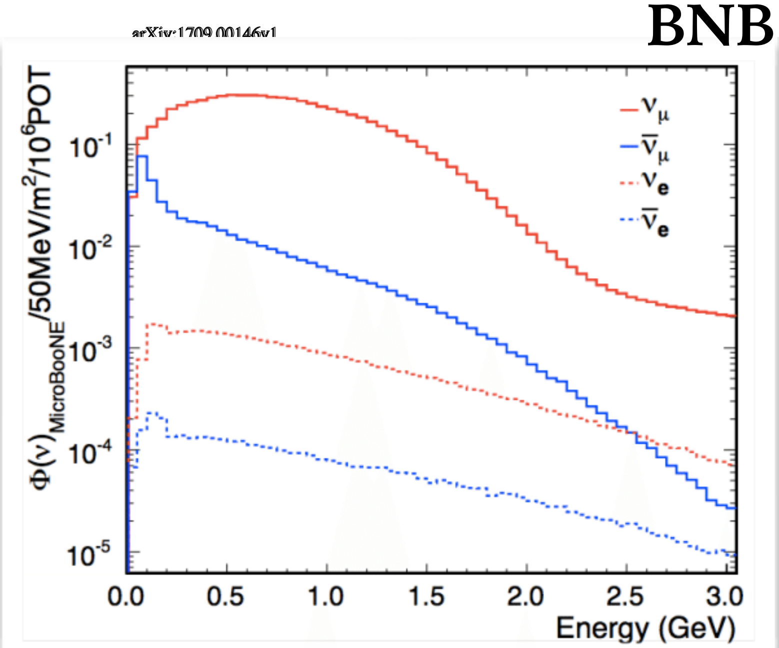
FERMILAB NEUTRINO BEAM LINES



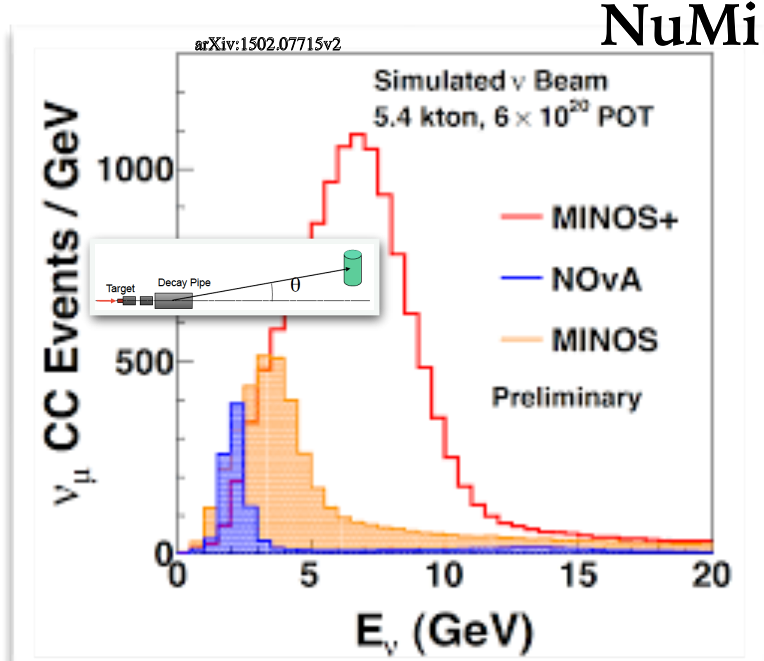
Three neutrino beam lines:

- Booster Neutrino Beam (**BNB**): short baseline neutrino program
- **NUMI**: MINOS+, MINERvA, NOvA
- **LBNF**: DUNE

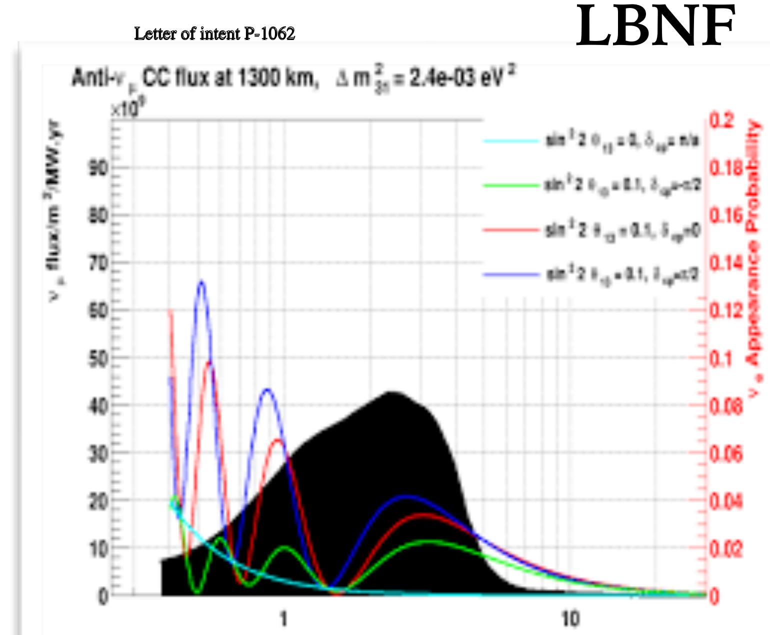
BNB



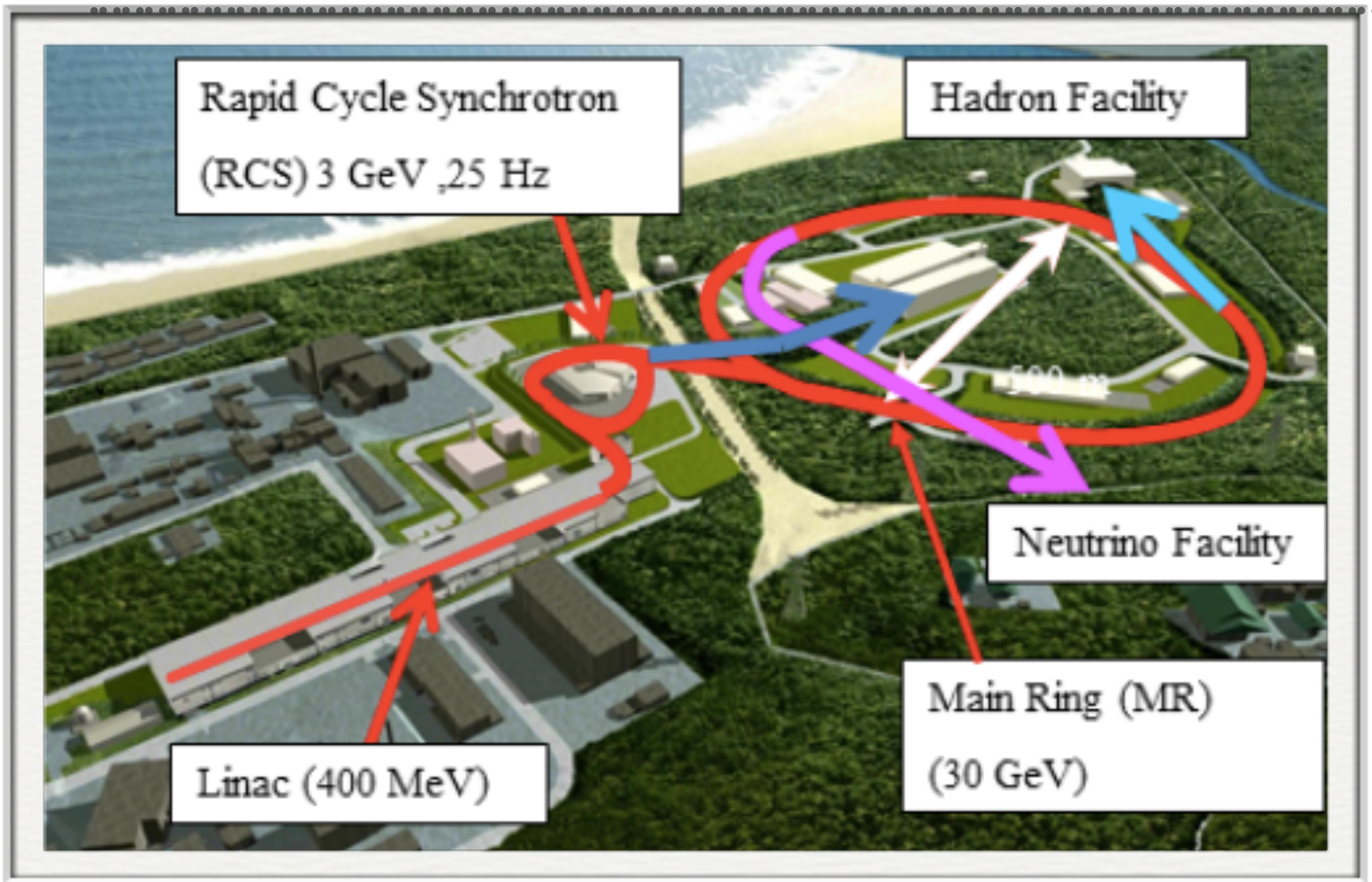
NuMi



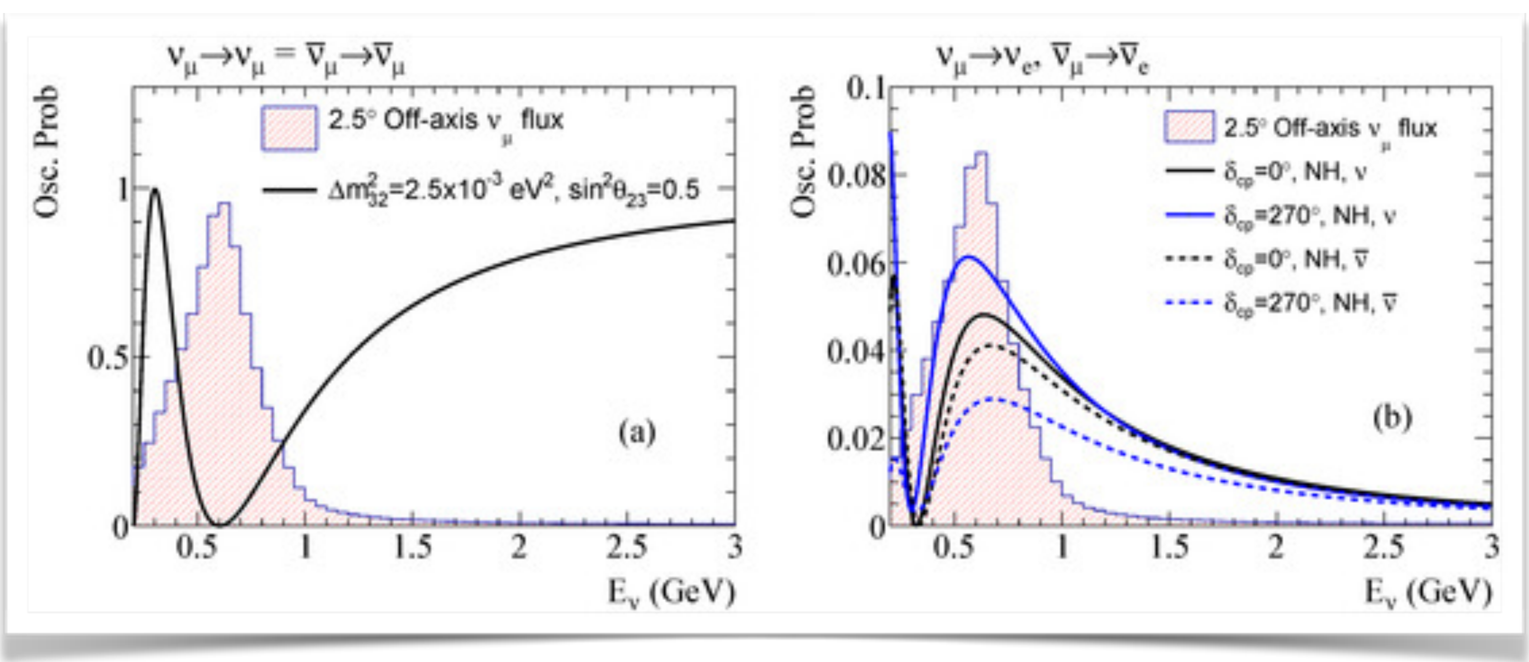
LBNF

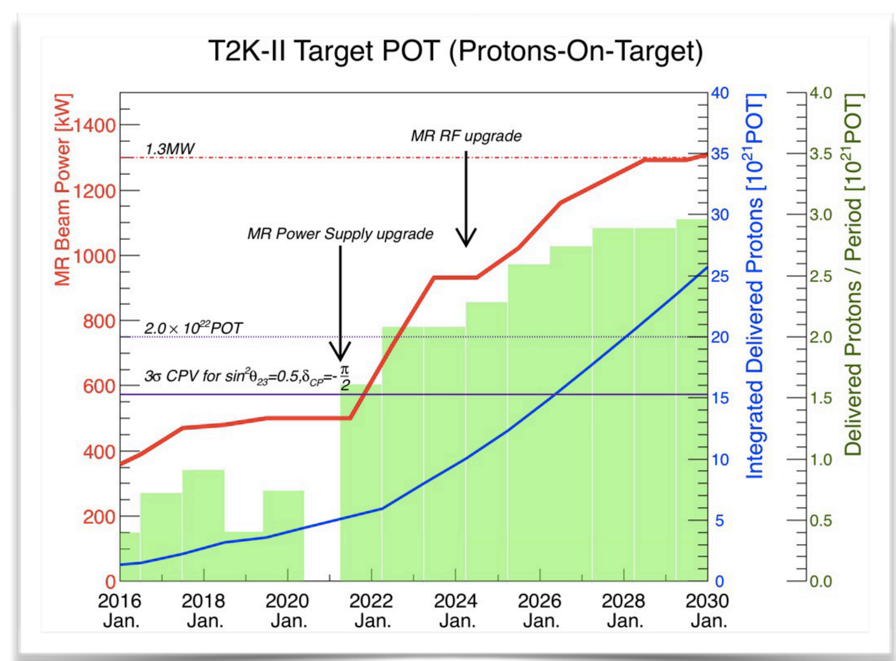


J-PARC NEUTRINO BEAM LINE



- 30 GeV proton beam from J-PARC Main Ring extracted onto a graphite target
- Detectors 2.5° off the direction of the beam centred around 0.6 GeV.
- Neutrino experiments:
  - T2K
  - Hyper-Kamiokande



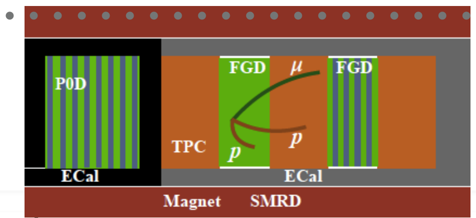


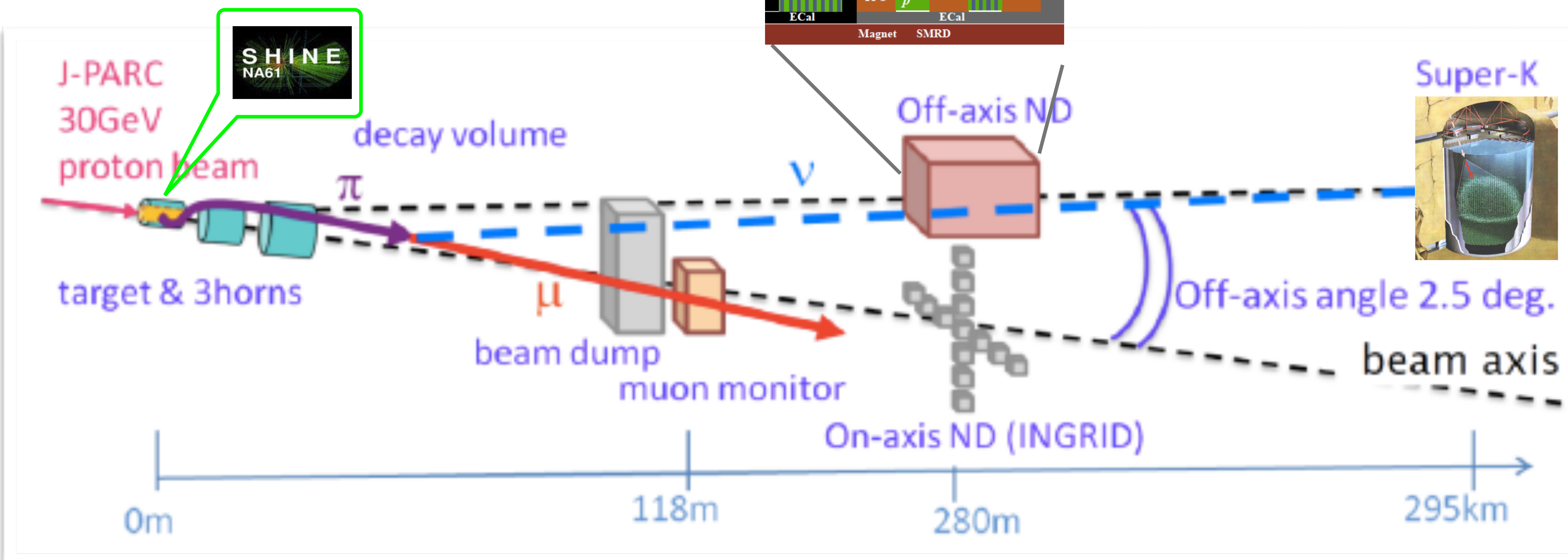
TOKAI-2-KAMIOKA (T2K)

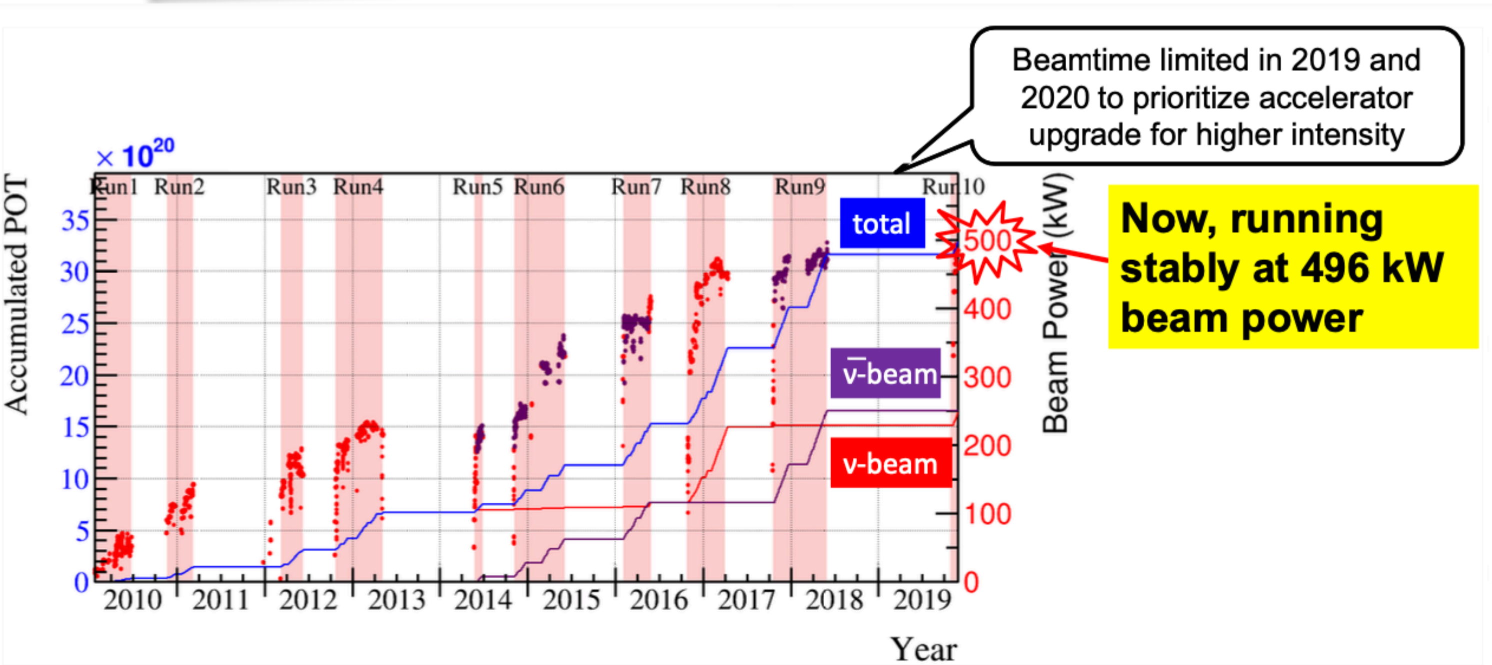
$$\Phi_{\nu near}(E)\cdot\sigma_{near}(E,Q_2)\cdot\varepsilon_{near}(E) \Leftrightarrow$$

$$\Phi_{\nu far}(E,\theta,\Delta m_2,\delta)\cdot\sigma_{far}(E,Q_2)\cdot\varepsilon_{far}(E)$$

- T2K strategy in a nutshell:







Total proton on target (POT) collected: 3.29×10^{21}

Collected

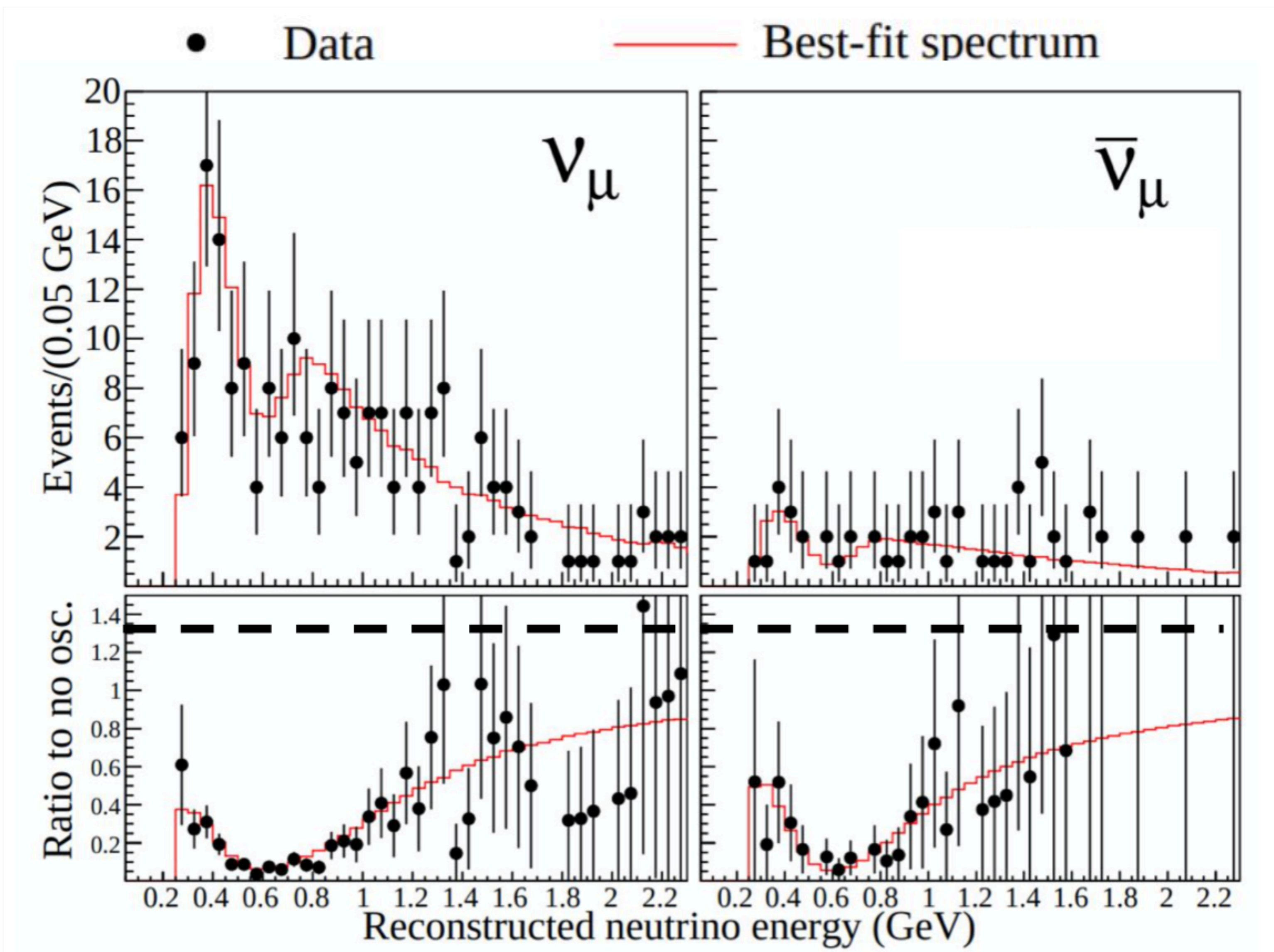
- 1.63×10^{21} POT in ν mode
- 1.65×10^{21}POT in $\bar{\nu}$ mode

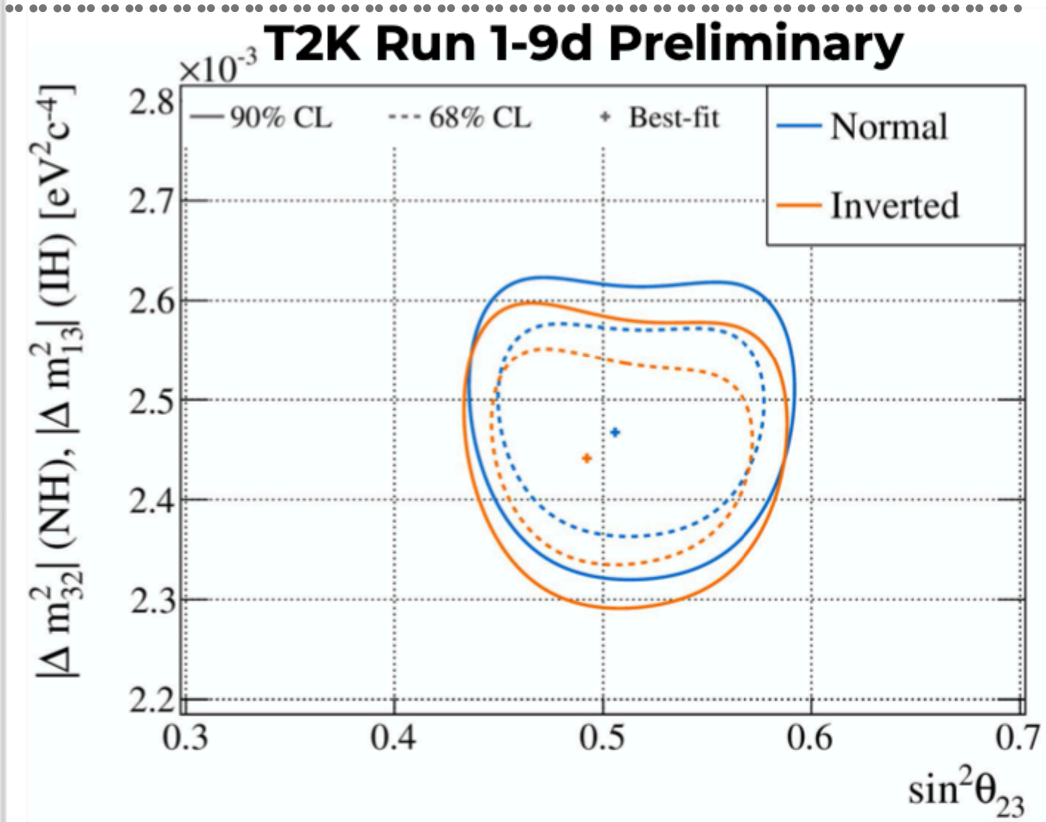
Analysed

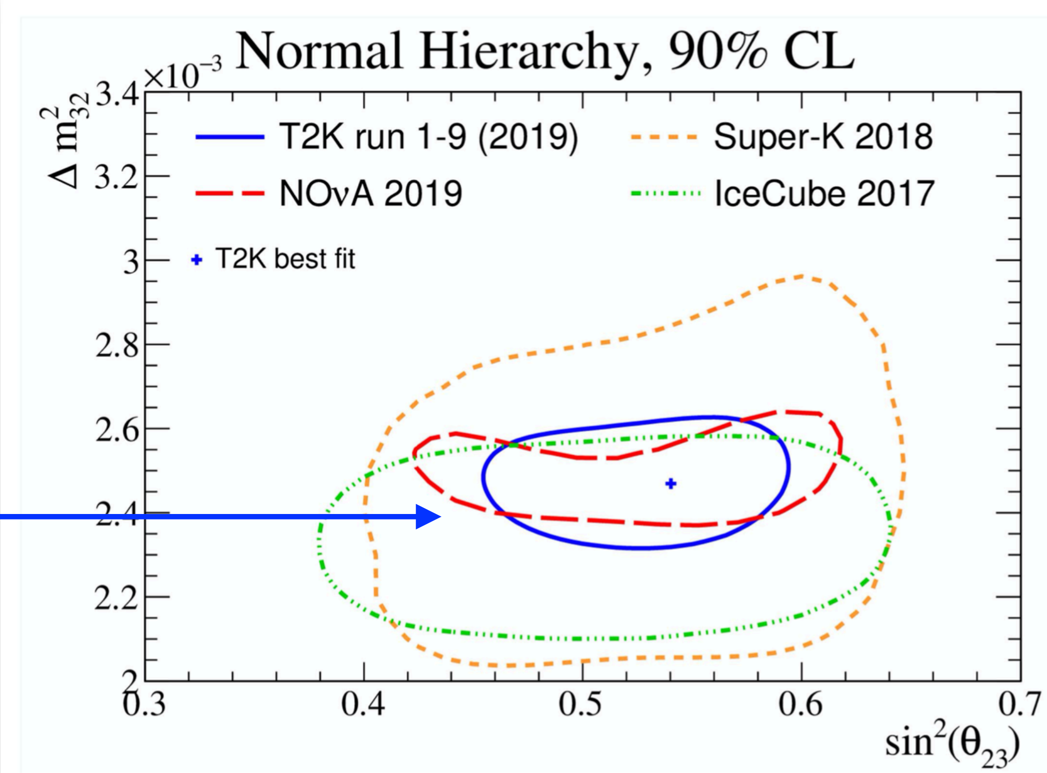
- 1.51×10^{21} POT in ν mode
- 1.65×10^{21}POT in $\bar{\nu}$ mode

Beam power 500 kW!

DISAPPEARANCE SAMPLES/PARAMETERS

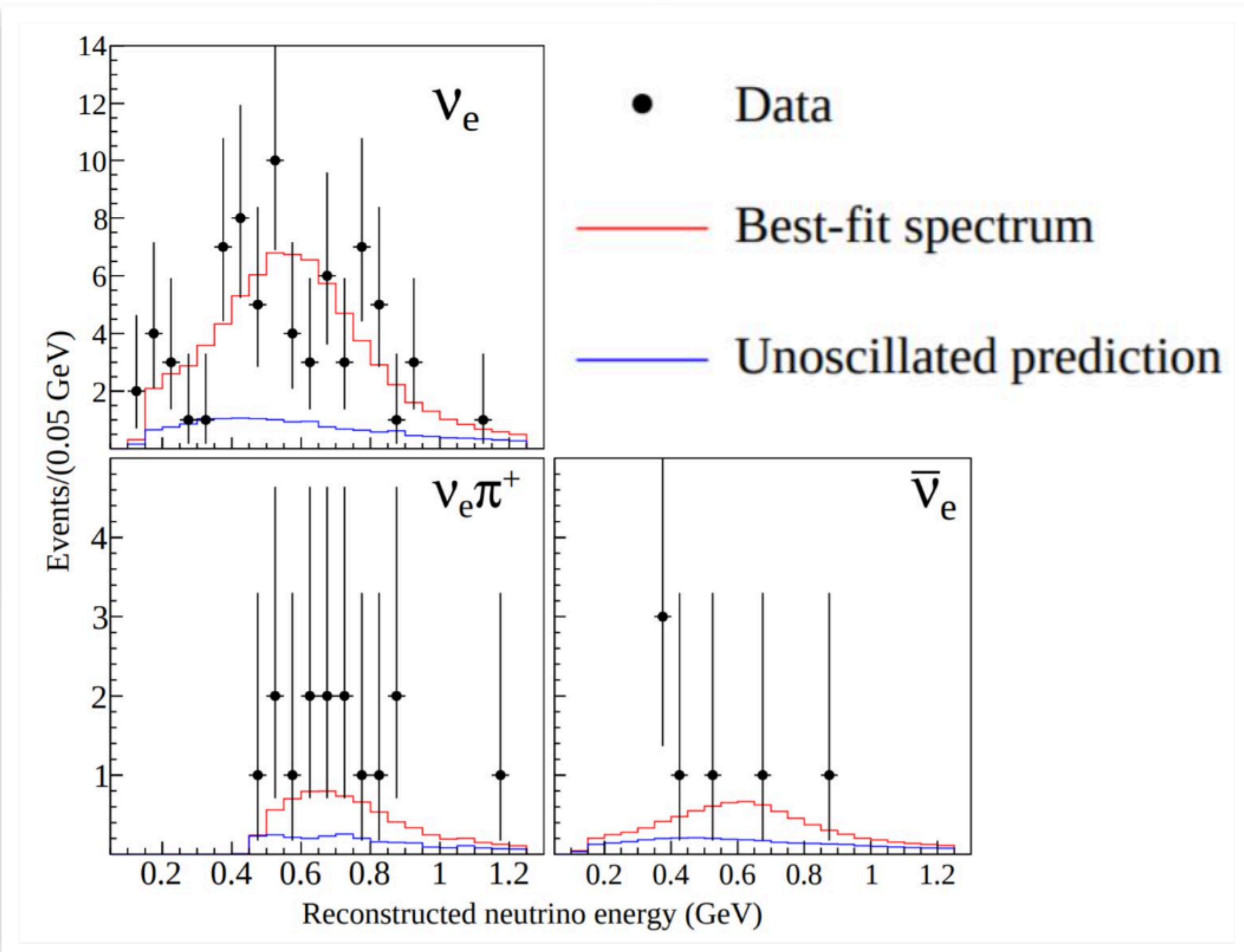


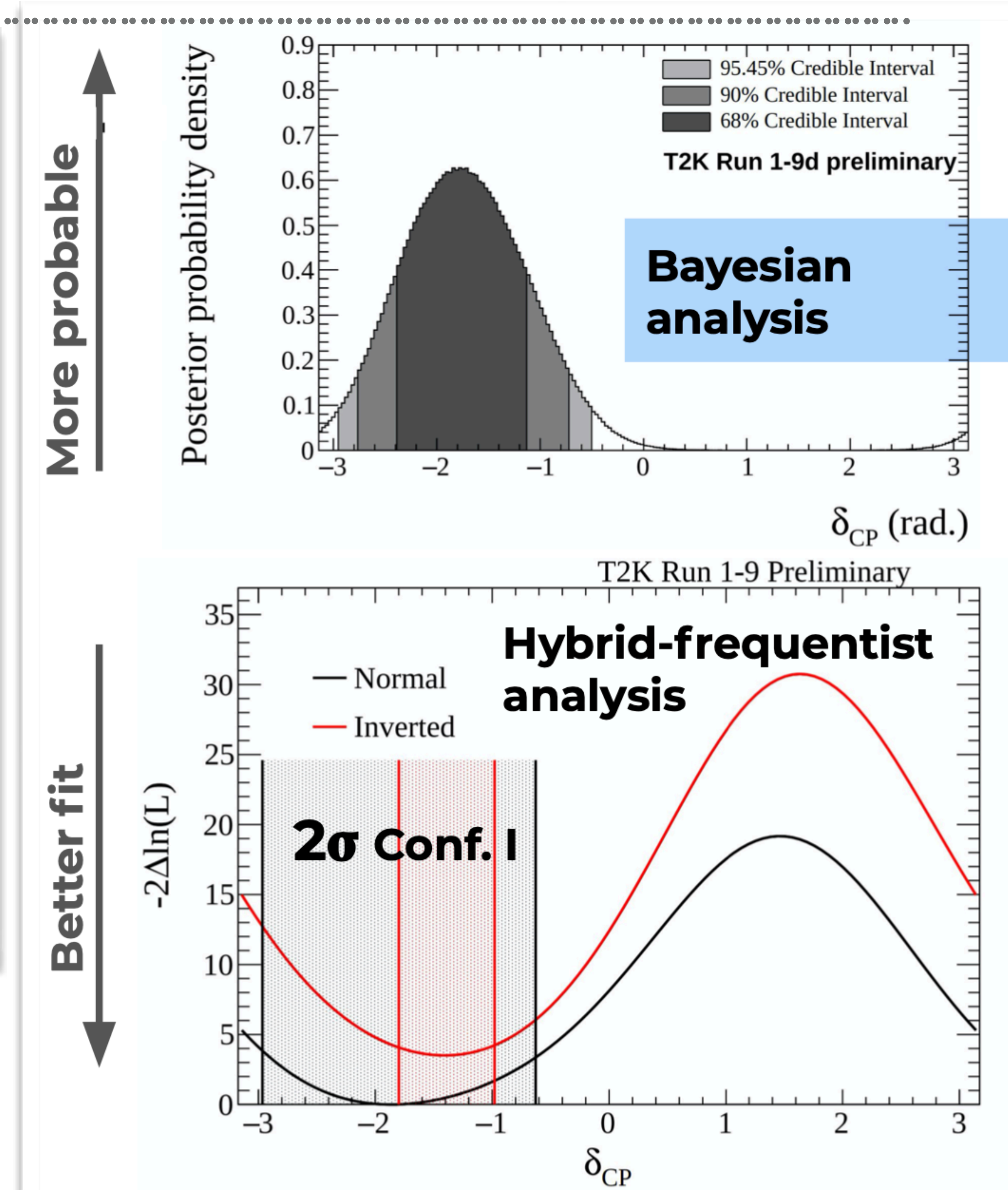




- World-leading constraint on atmospheric mixing angle.
- $\sin^2\theta_{23} = 0.53^{+0.03}_{-0.04}$ for both mass orderings.
- Consistent with maximal mixing (45°)

APPEARANCE



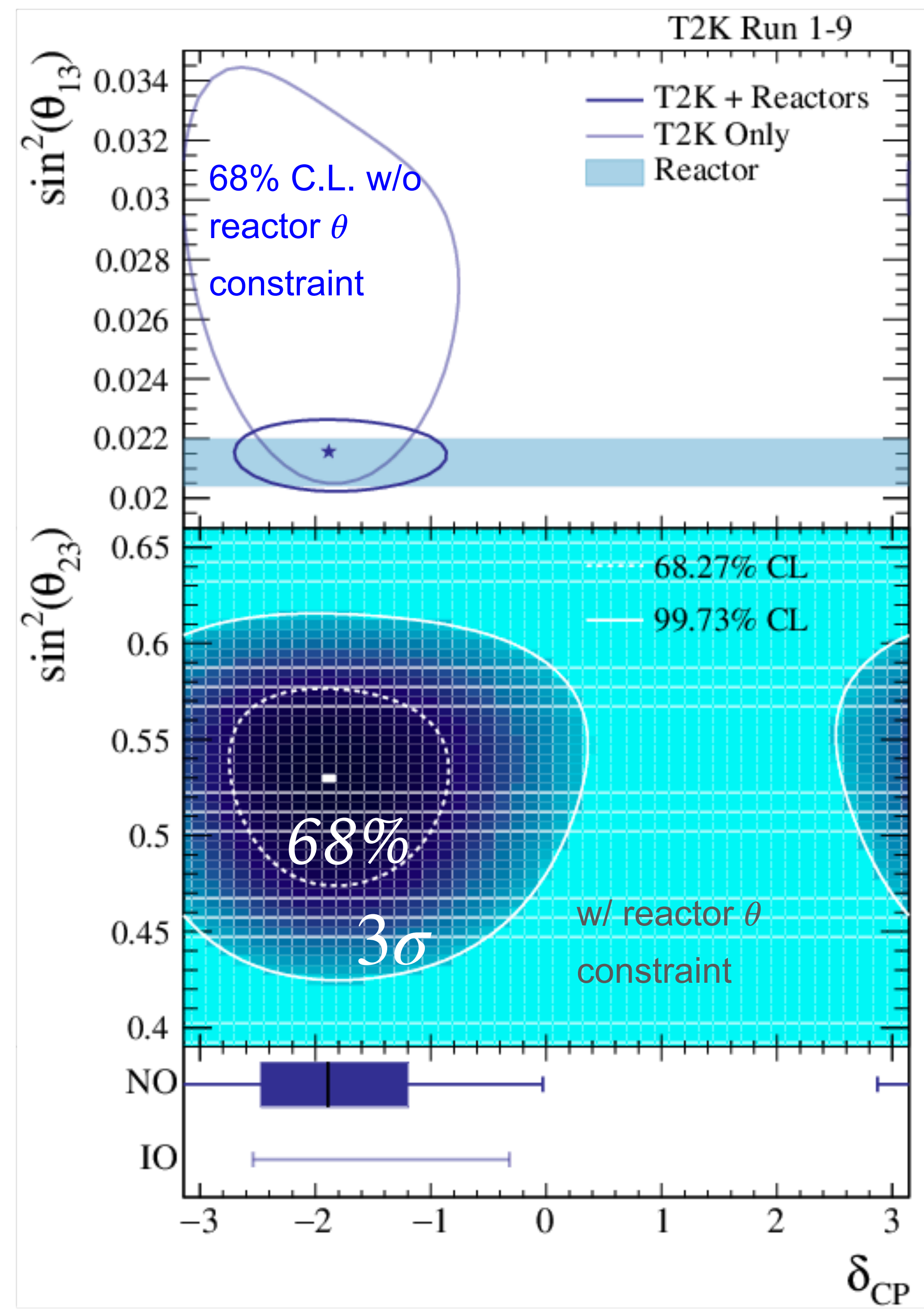


- δ_{CP} best fit value and 68% (1σ) C>L. for NO (IO): $-1.89^{+0.70}_{-0.58}(-1.38^{+0.48}_{-0.54})$.
- Statistical uncertainty dominating .
- CP conserving values lie outside the 2**σ** contour for both **bayesian** and **hybrid-frequentist** analyses.

δ_{CP} : 3σ EXCLUSION

1910.03887 [hep-ex]

- 2D confidence intervals at the 68.27% confidence level for δ_{CP}vs $\sin^2\theta_{13}$in the normal ordering.
- 2D confidence intervals at the 68.27% and 99.73% confidence level for δ_{CP} vs $\sin^2\theta_{23}$ from the T2K + Reactors fit in the normal ordering.
- 1D confidence intervals on δ_{CP} from the T2K + Reactors fit in both the normal (NO) and inverted (IO) orderings.
  - CP conserving points, $\delta_{CP} = 0$ and $\delta_{CP} = \pi$, are ruled out at 95%C.L.
  - NO 3σ C.L.: [-3.41;-0.03]
  - IO 3σ C.L: [-2.54;-0.32]



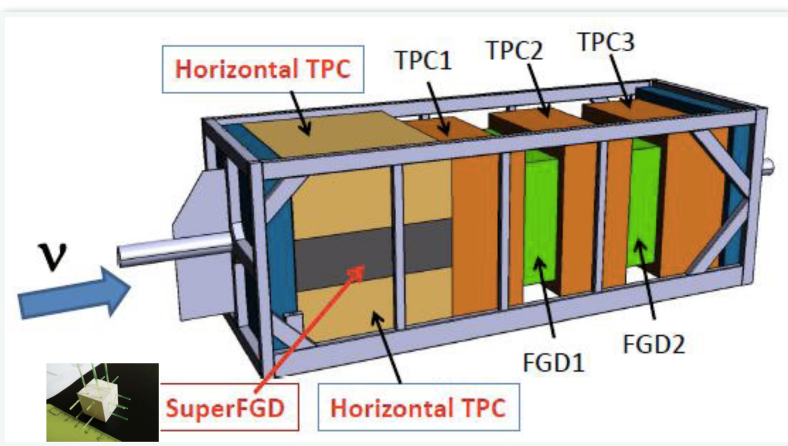
T2K IN THE NEXT DECADE (*aka* T2K-II): UPGRADED BEAM & DETECTORS

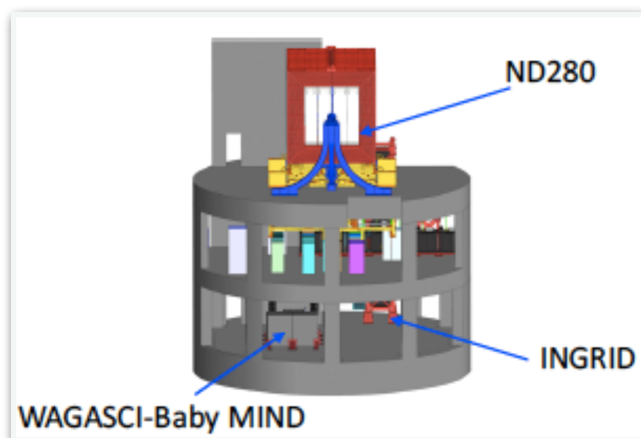
Running up to when Hyper-Kamiokande starts

- **Including more final states in analysis**
- **Use results from T2K replica target at NA61**
- **Upgraded near detector suite (installation 2021)**

Goal: reduce systematics to ~4%

Near detector suite (at 280m):

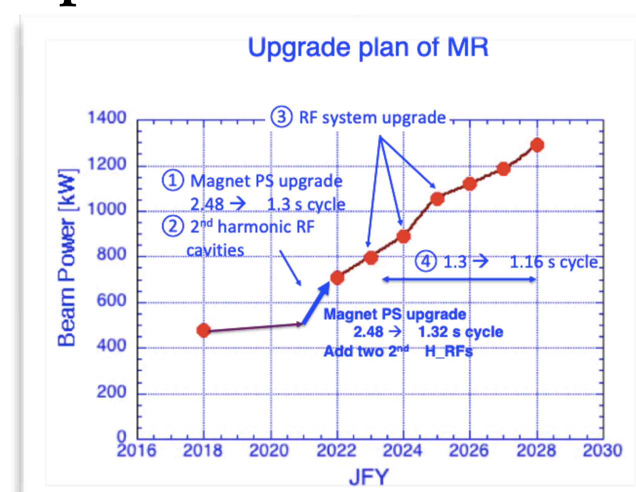


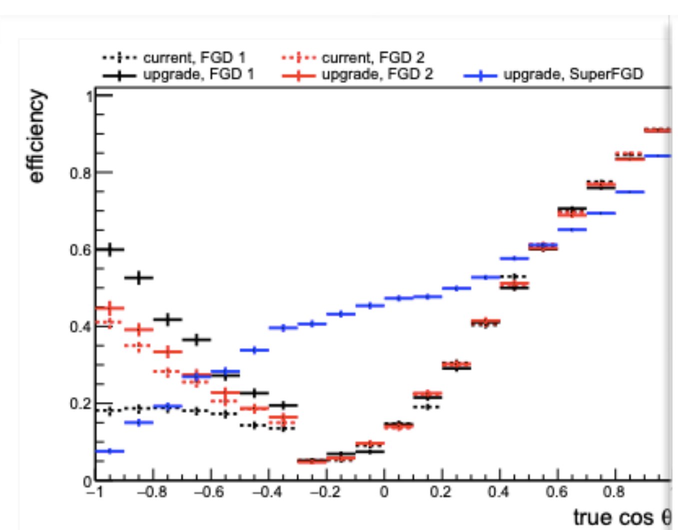


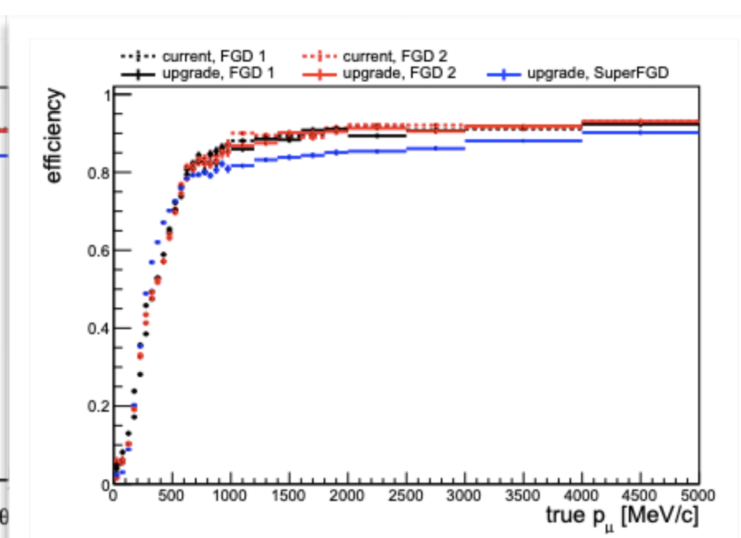
Super-Kamiokande

- Gadolinium doping (SK-Gd)
- Gd enhances neutron detection
- It can help with $\bar{\nu}_e$ wrong sign background rejection

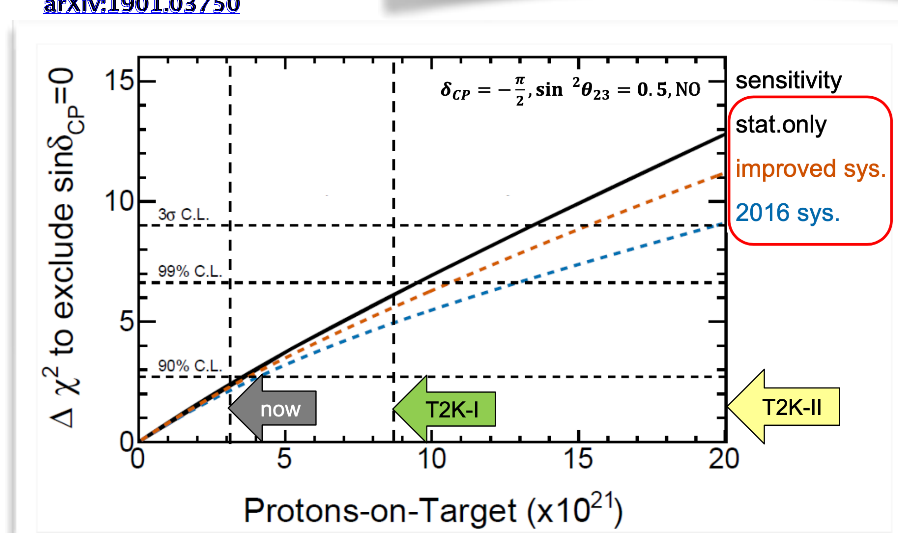
Beam power schedule





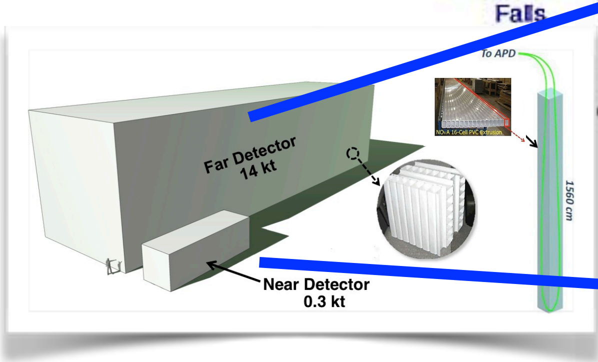


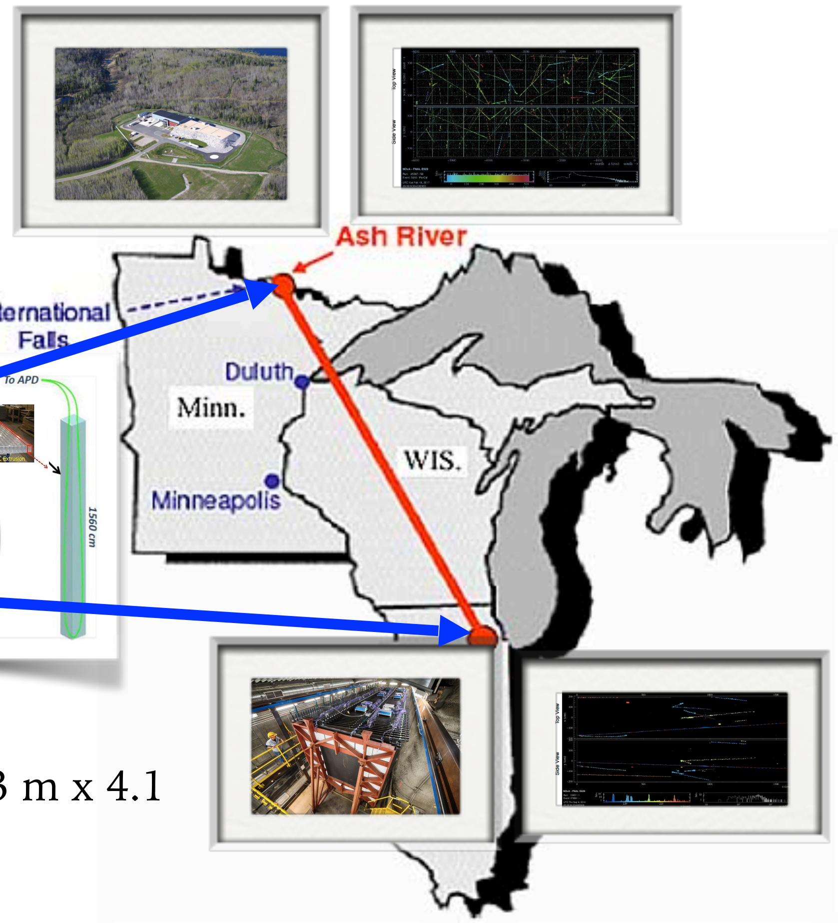
arXiv:1901.03750



NOVA

on the surface
14 kton (60 m x 15.6 m x 15.6 m)



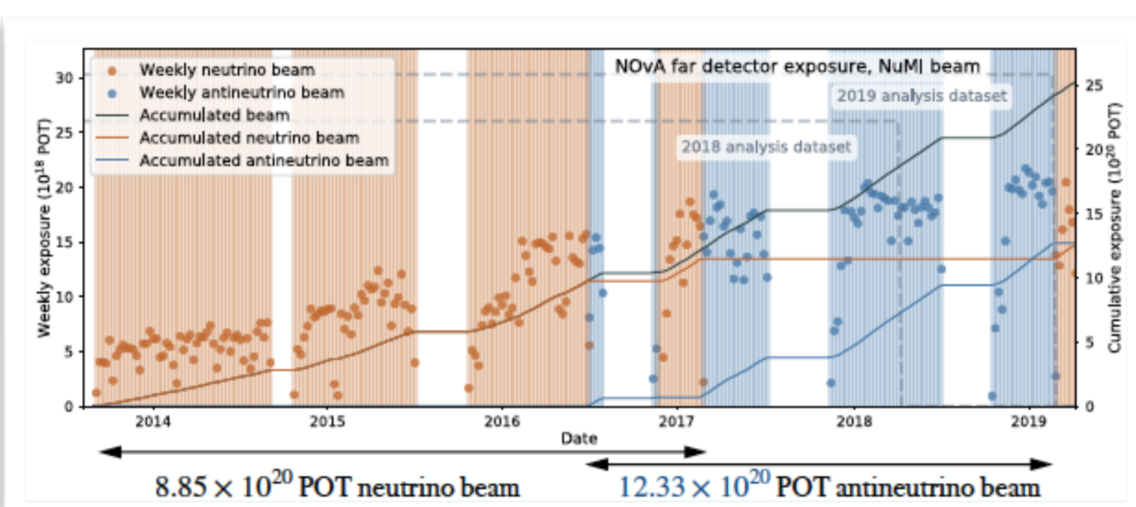


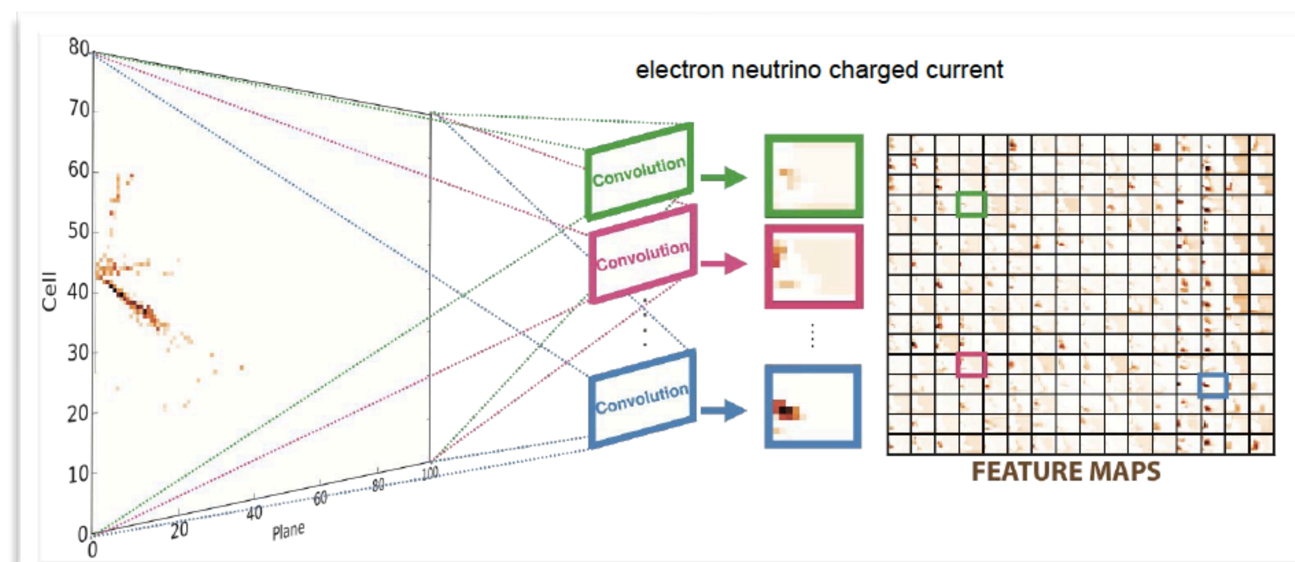
underground
300 ton (14.3 m x 4.1 m x 4.1 m)

Sensitivity to mass hierarchy thanks to matter effect ⇒determine sign of Δm^2_{23}

- Functionally identical near and far detector
- Events are classified using a Convolutional Neural Network

- Running at 700 kW since January 2017.
- 78% increase in exposure in 2018-2019

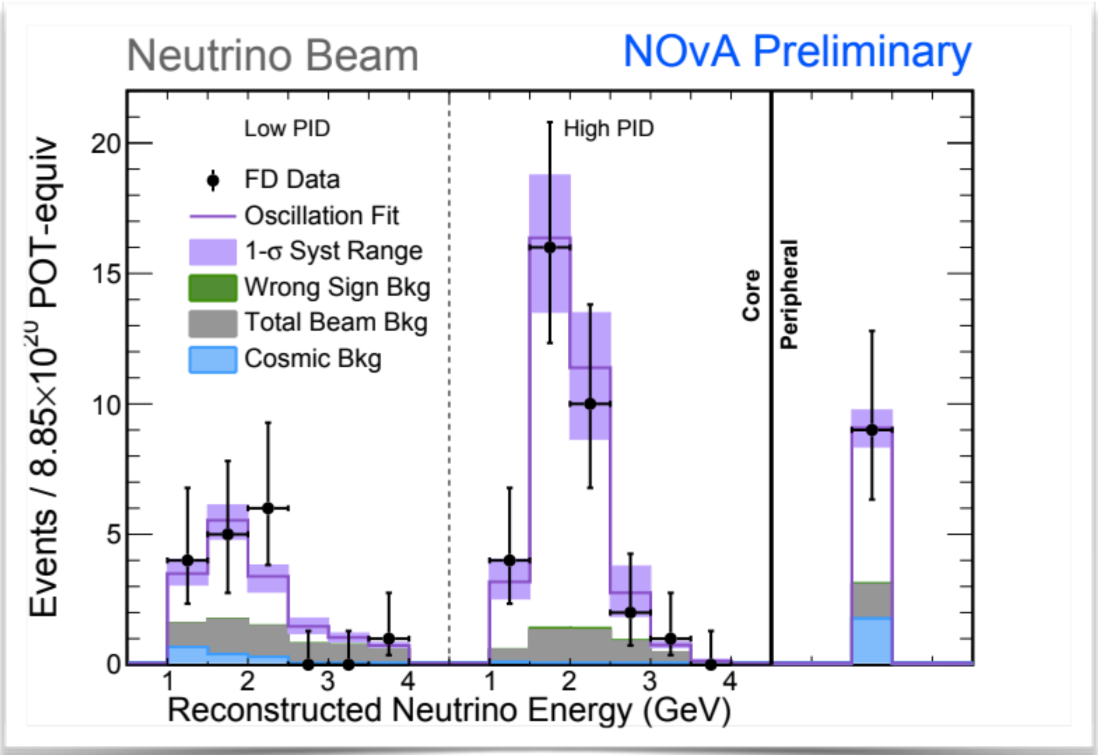


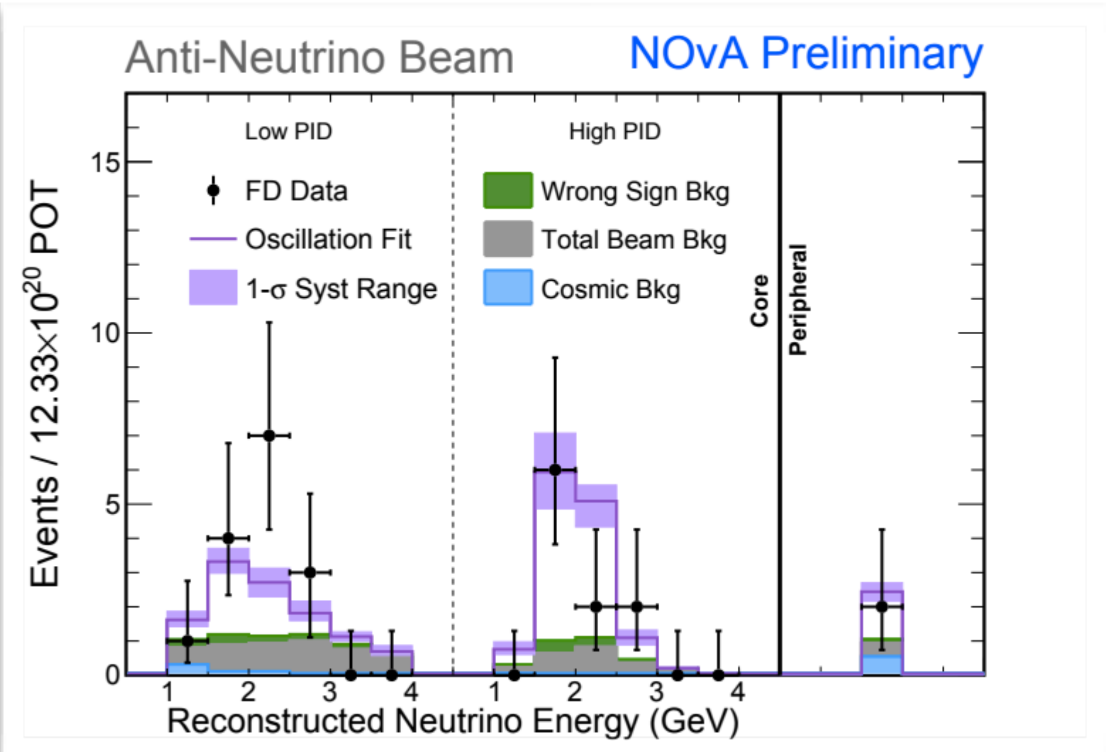


[arXiv:1906.04907 for more details]

NOVA FAR DETECTOR DATA

$\nu_e$sample





$\nu_e$sample

neutrino beam

Total Observed	58
Best Fit prediction	59
Total bkgd	15.0
Cosmic bkg	3.3
Beam bkg	11.1
Wrong sign ($\bar{\nu}_e$ app.)	0.7

antineutrino beam

Total Observed	27
Best Fit prediction	27
Total bkgd	10.3
Cosmic bkg	1.1
Beam bkg	7.0
Wrong sign (ν_e app.)	2.2

$\nu_\mu$sample

neutrino beam

Total Observed	113
Best Fit prediction	124
Total bkgd	4.2
Cosmic bkg	2.1
Beam bkg	2.1
Unoscillated prediction	730

antineutrino beam

Total Observed	102
Best Fit prediction	96
Total bkgd	2.2
Cosmic bkg	0.8
Beam bkg	1.4
Unoscillated prediction	476

78% more antineutrino running

Evidence for $\bar{\nu}_e$ appearance at 4.4σ

NOVA OSCILLATION RESULTS

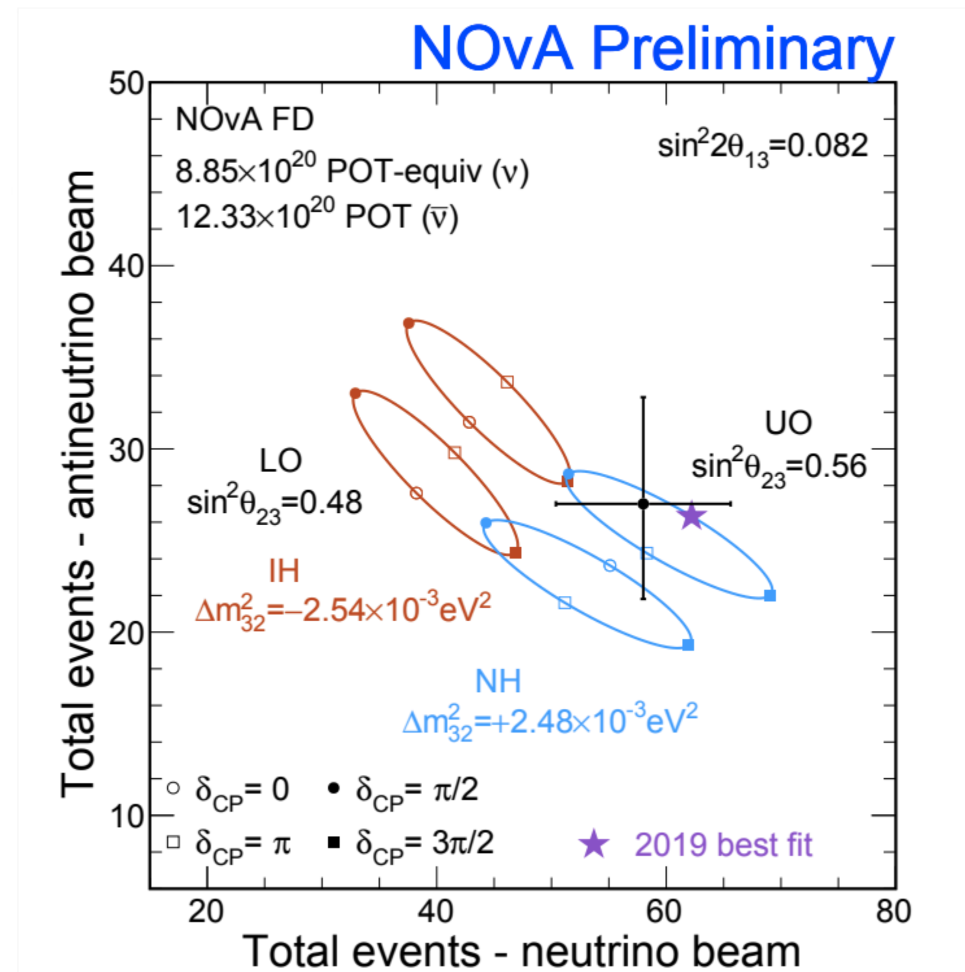
Best fit:

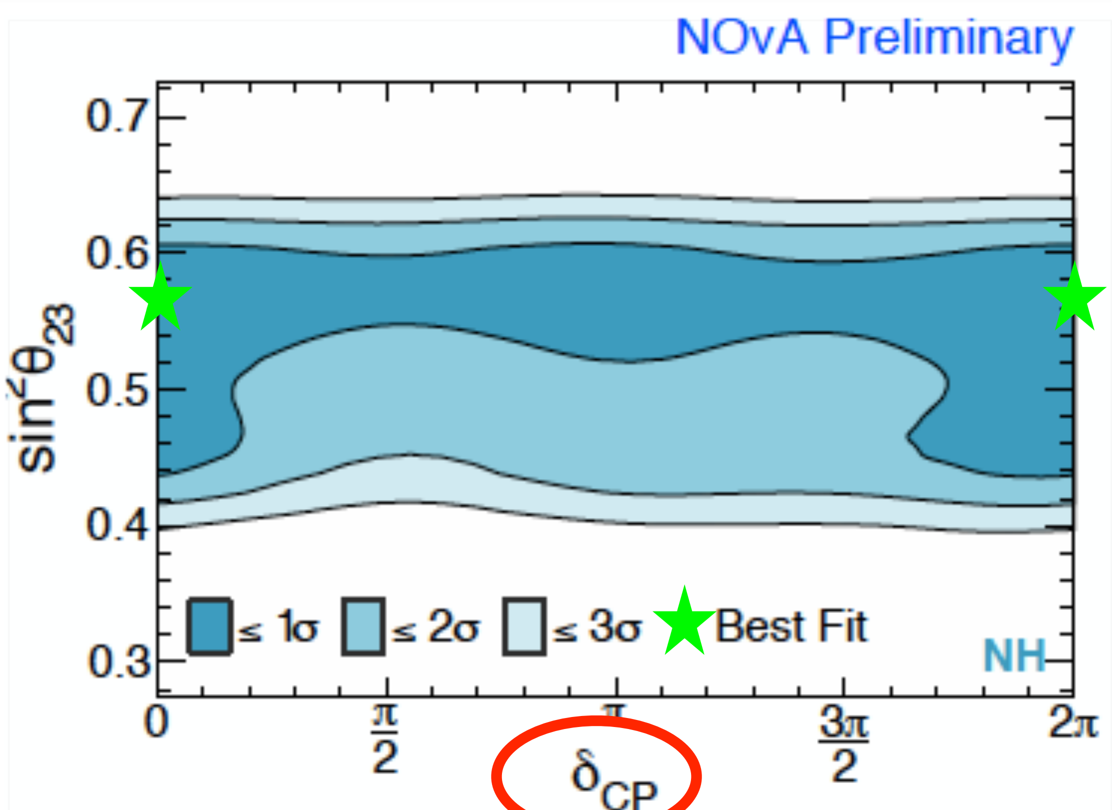
$\sin^2\theta_{23} = 0.56^{+0.04}_{-0.03}$

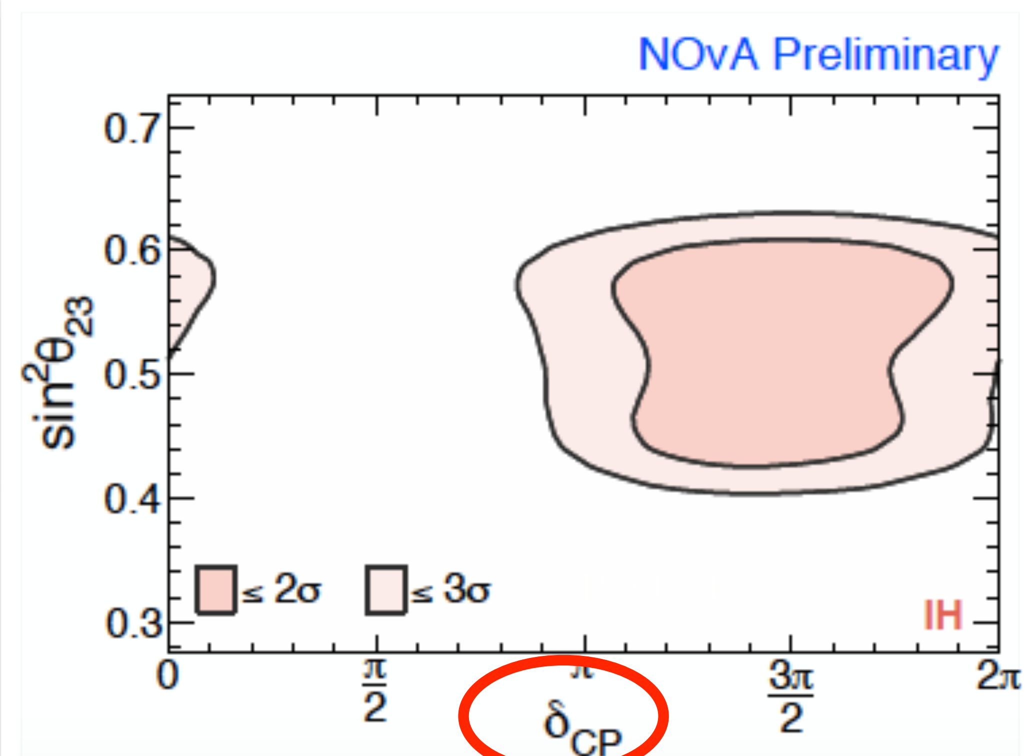
$\Delta m^2_{32} = +2.48 \times 10^3 eV^2$ **(NH)**

$\delta_{CP} = 0.0^{+1.3}_{-0.4}\pi$

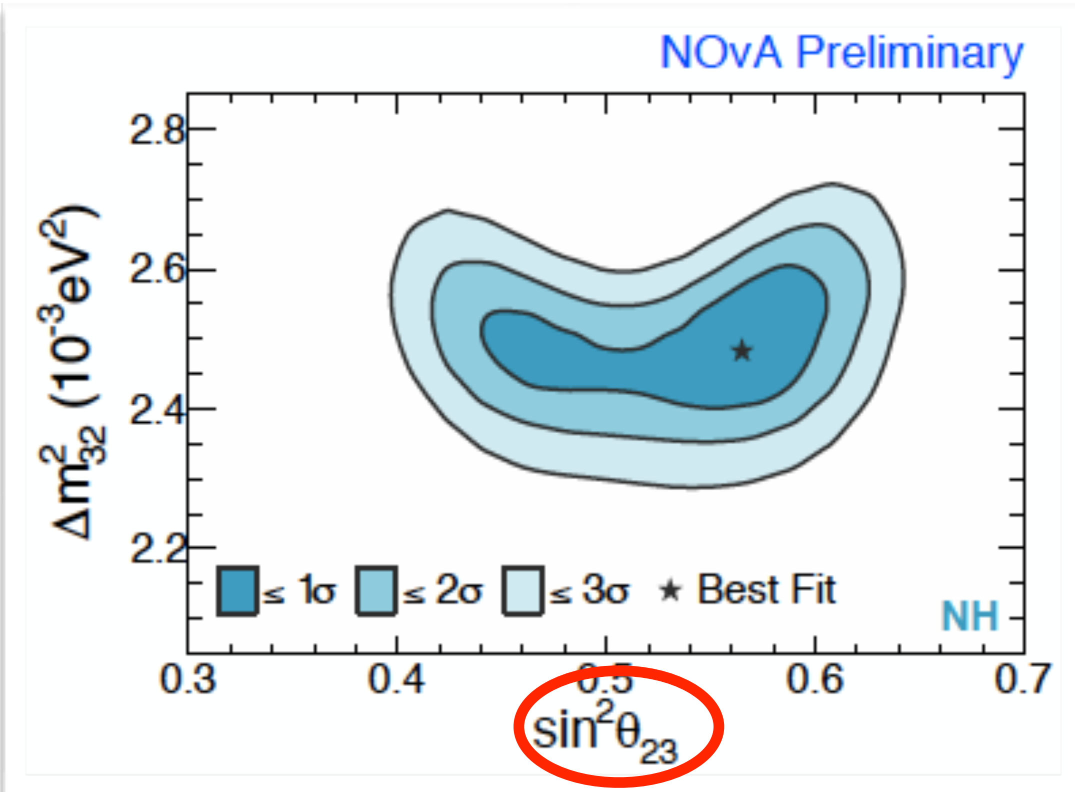
- All values of δ_{CP} are allowed at 1.1σ (NH, Upper octant).
- IH, $\delta_{CP} = \dfrac{\pi}{2}$ is ruled out > 4σ.
- **Inverted Hierarchy is disfavoured at 1.9σ.**



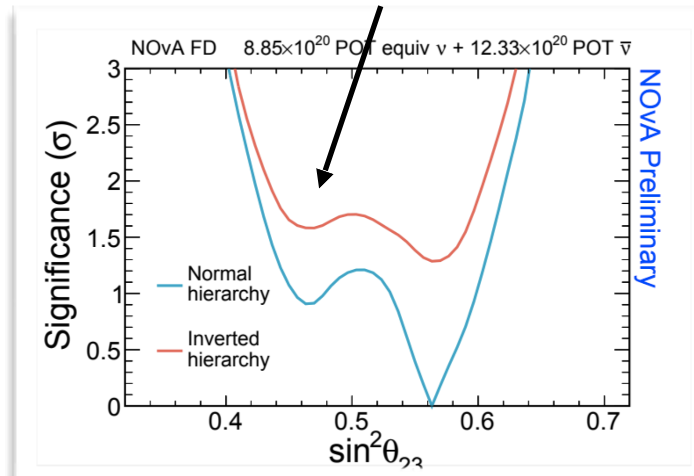


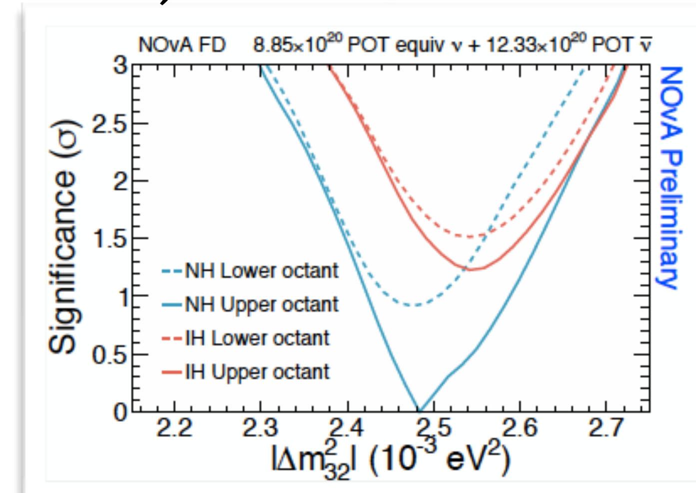


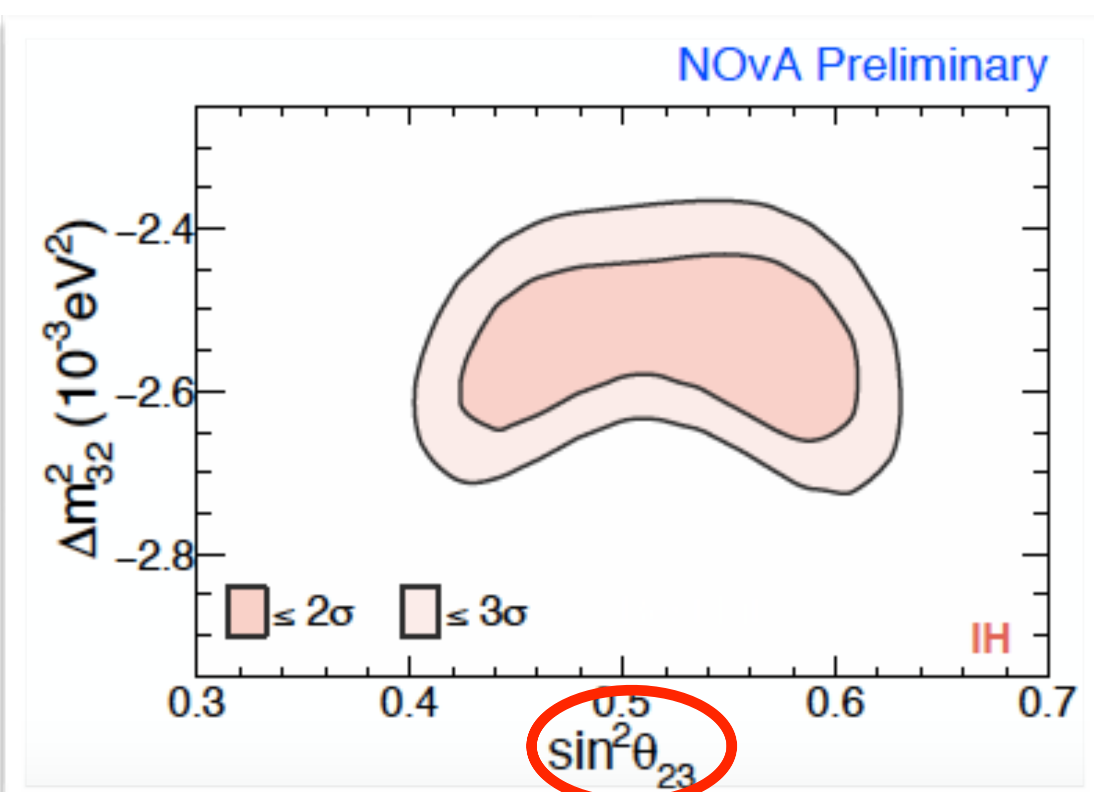
NOVA OSCILLATION RESULTS



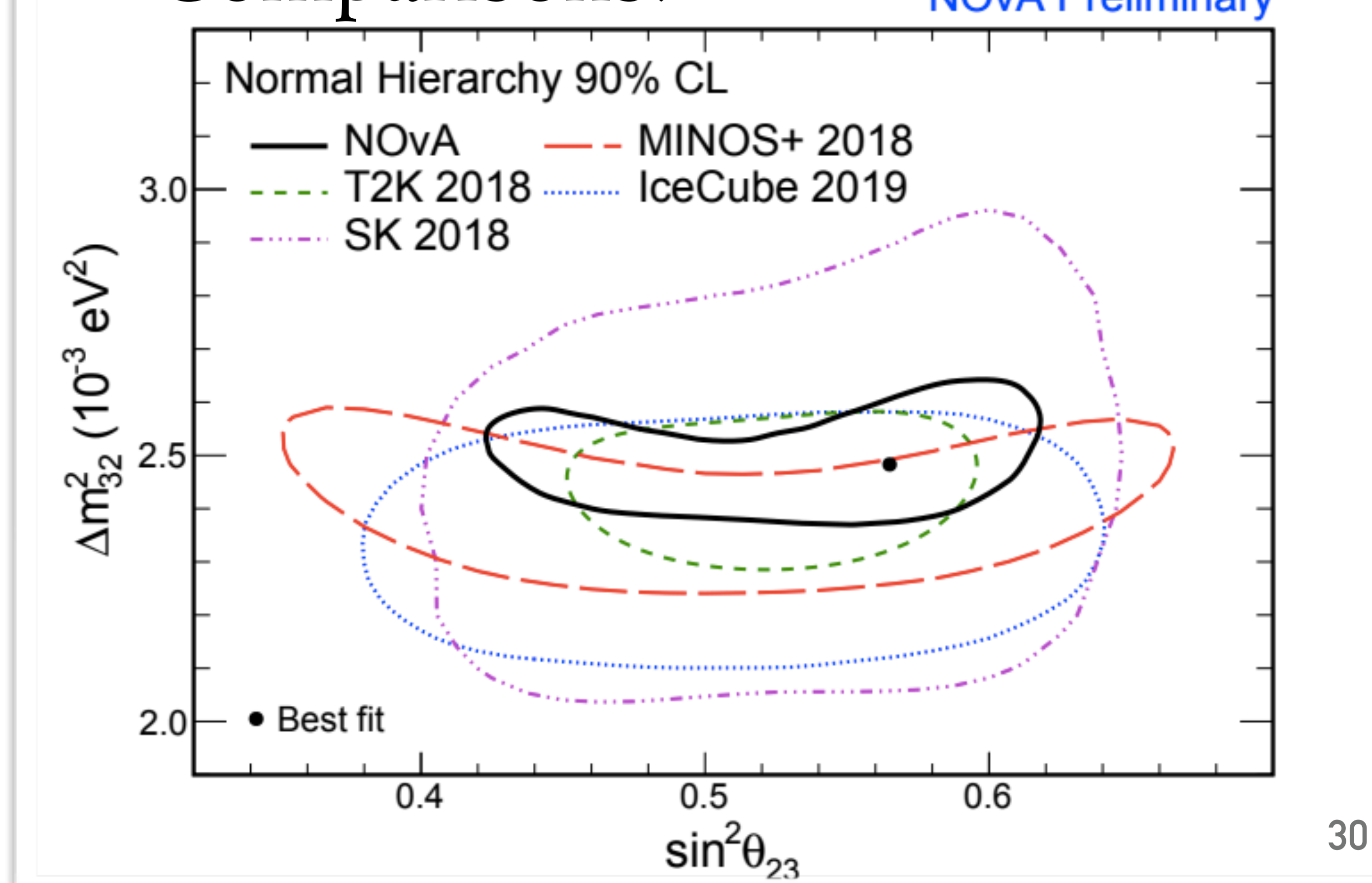
Lower octant ($\sin\theta_{32} < 0.5$) disfavoured at 1.6σ







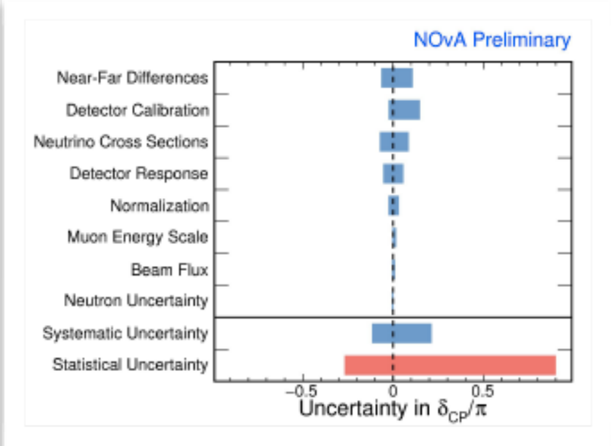
Comparisons:

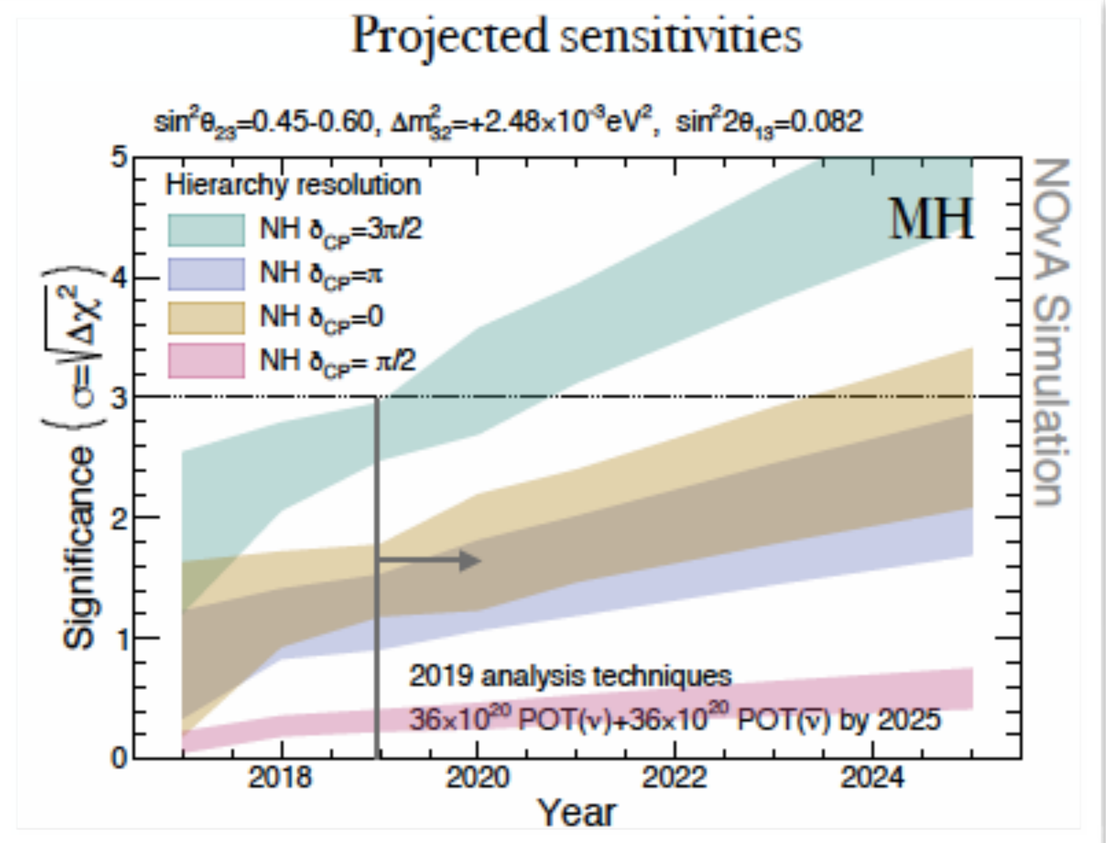


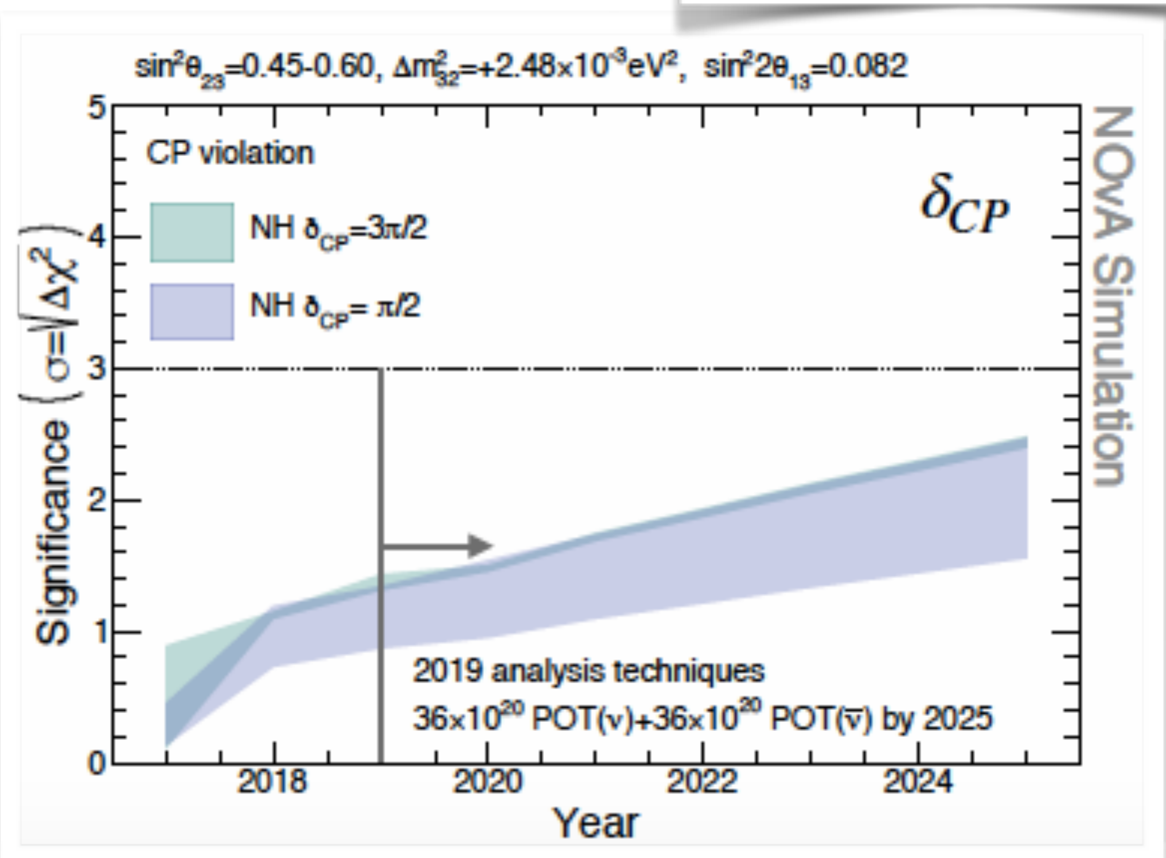
NOVA FUTURE RUNNING

- Expected running up to 2025.
- Expected improvements for upcoming analyses:
  - Accelerator beam intensity (50:50 neutrino:antineutrino running)
  - Analysis improvements
  - Test beam (measurements

  are still statistically limited)
- Projections with current analysis



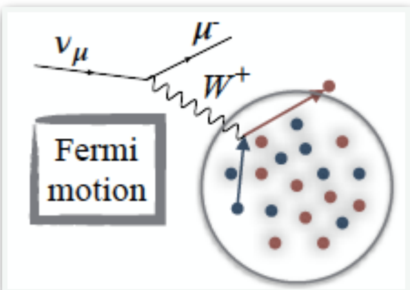


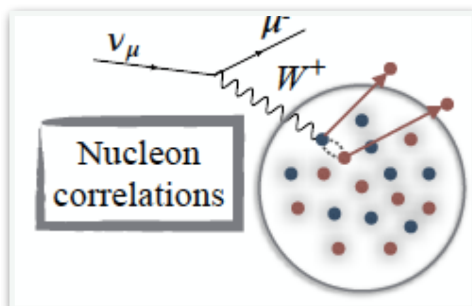


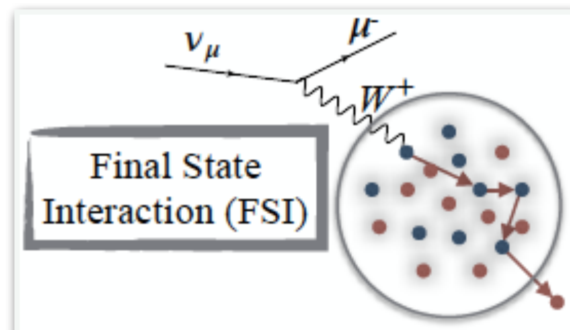
NEUTRINO-NUCLEON INTERACTIONS

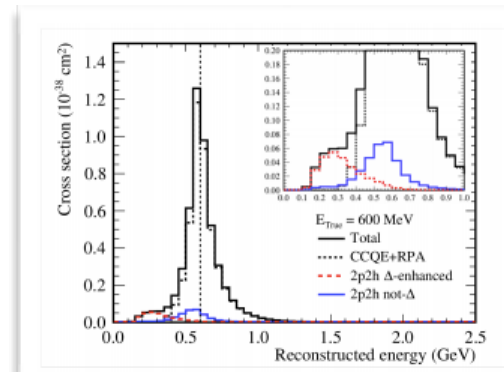
Neutrinos interact with nucleons bound in the nuclei ⇒ nuclear effects.

Nuclear effects also introduce a bias in energy reconstruction.







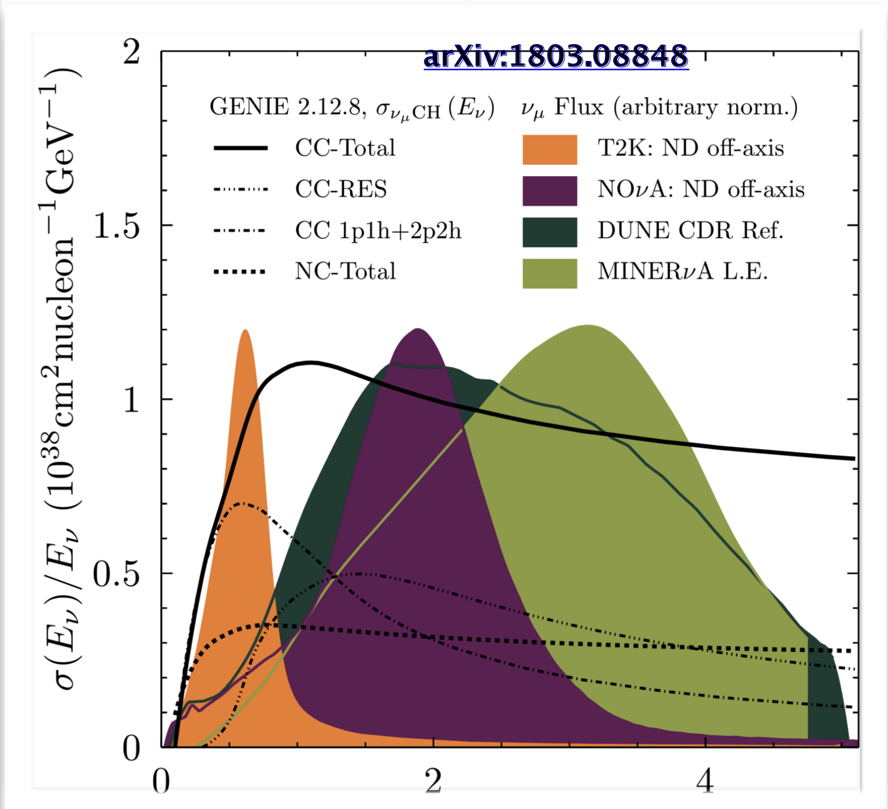


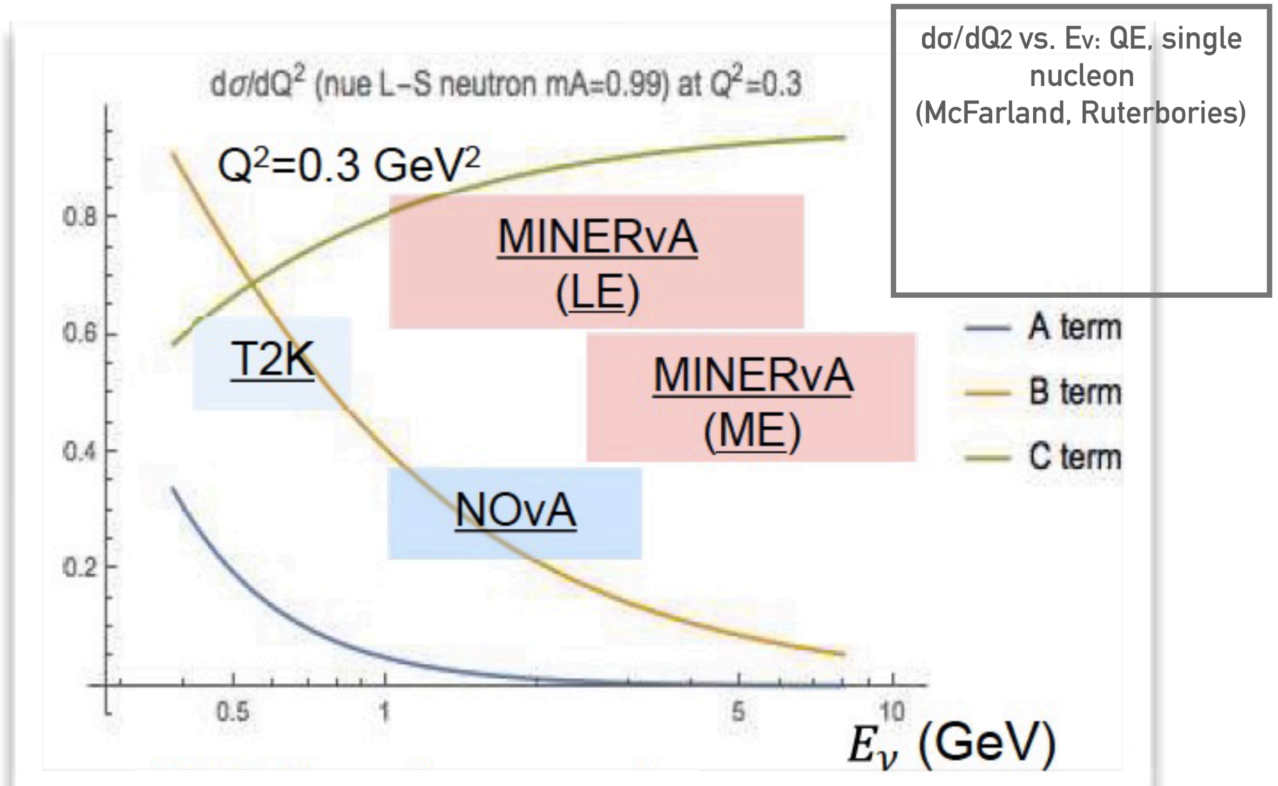
Phys. Rev. D 96, 092006 (2017)

- Neutrino interaction model is essential to reduce neutrino oscillation systematic uncertainties
- Current measurements are statistics limited, but not for long!
- Largest systematics related to neutrino-nucleus interactions
- Essential total systematic uncertainty <3% for DUNE/HK

	1-Ring e			
Error source	FHC	RHC	FHC 1 d.e.	FHC/RHC
SK Detector	2.83	3.80	13.15	1.47
SK FSI+SI+PN	3.00	2.31	11.43	1.57
Flux + Xsec constrained	3.24	3.10	4.09	2.67
E_b	7.13	3.66	2.95	3.62
$\sigma(\nu_e)/\sigma(\bar{\nu}_e)$	2.63	1.46	2.61	3.03
NC1γ	1.09	2.60	0.33	1.50
NC Other	0.15	0.33	0.99	0.18
Osc	2.69	2.49	2.63	0.77
All Systematics	8.81	7.13	18.38	5.96
All with osc	9.19	7.57	18.51	6.03

NEUTRINO-NUCLEON INTERACTIONS



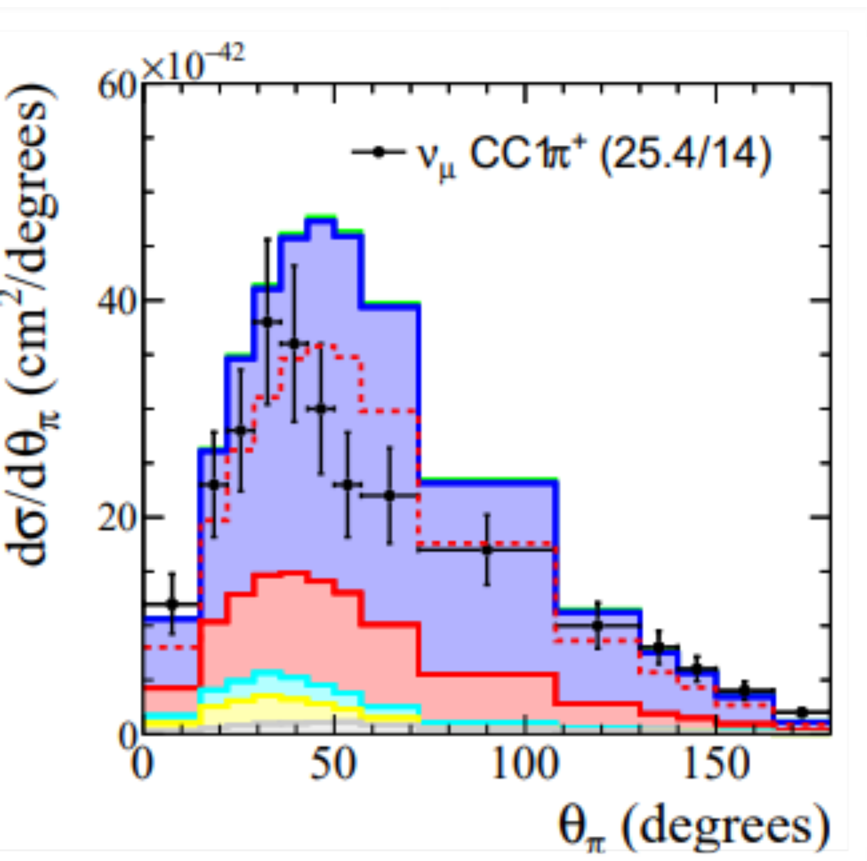


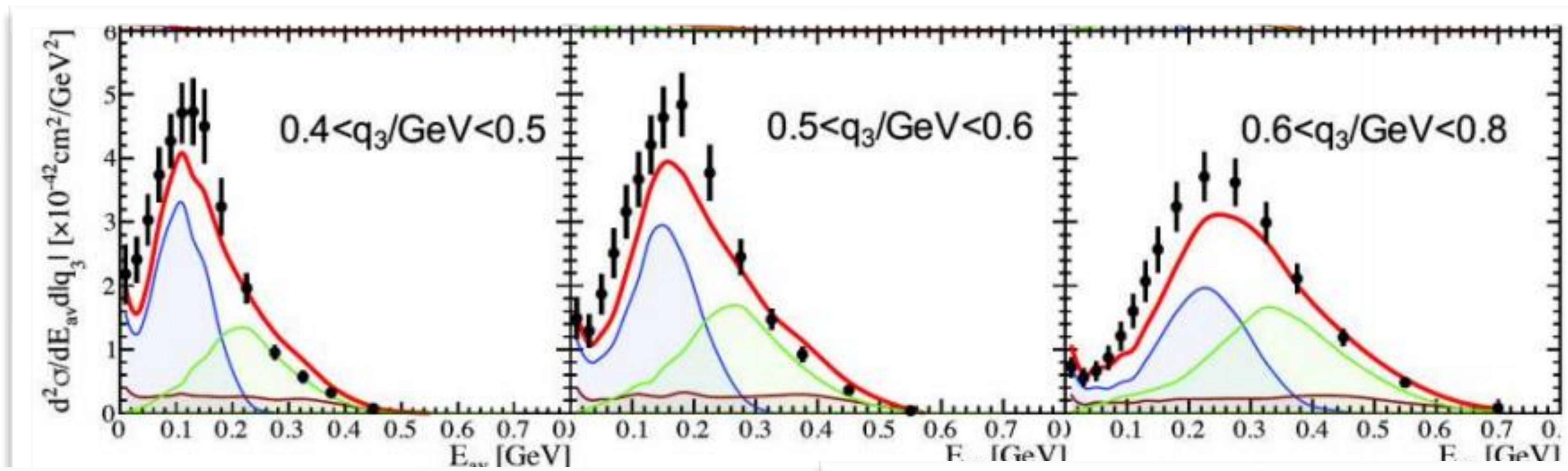
➤ Ongoing global program of measurements of diverse type of interactions on different target materials at various range of neutrino energies and flavours

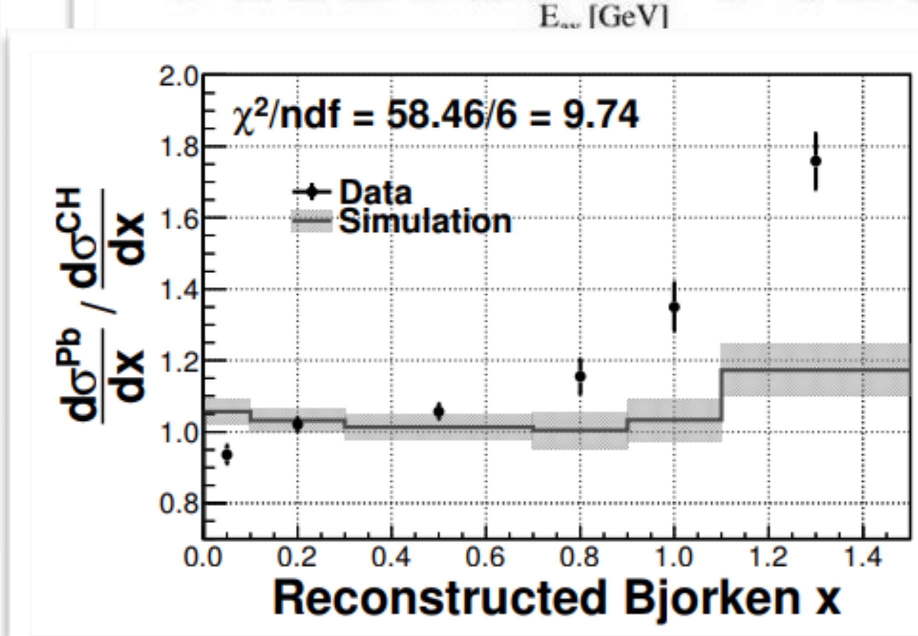
Osc experiment	Target	cross sections from
T2K, NOvA	Scintillator	T2K, NOvA ND, MINERvA LE, HE
T2K, SK, IceCube	Water	T2K (INGRID, WAGASCI, ND280), MINERvA
DUNE	Ar	T2K ND upgrade, MicroBooNE/SBN, MINERvA

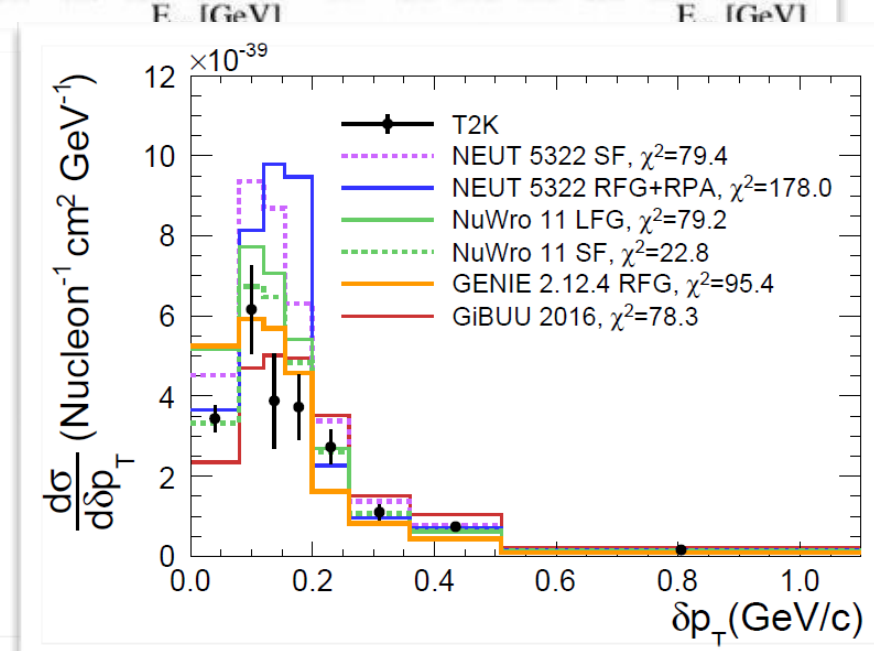
EXPERIMENTAL XSECTION STATUS

- T2K, MINERvA and others have made a wide range of innovative cross-section measurements aimed to target the nuclear physics most pertinent to future oscillation analyses.
- None of our current simulations are able describe more than the lepton kinematics …







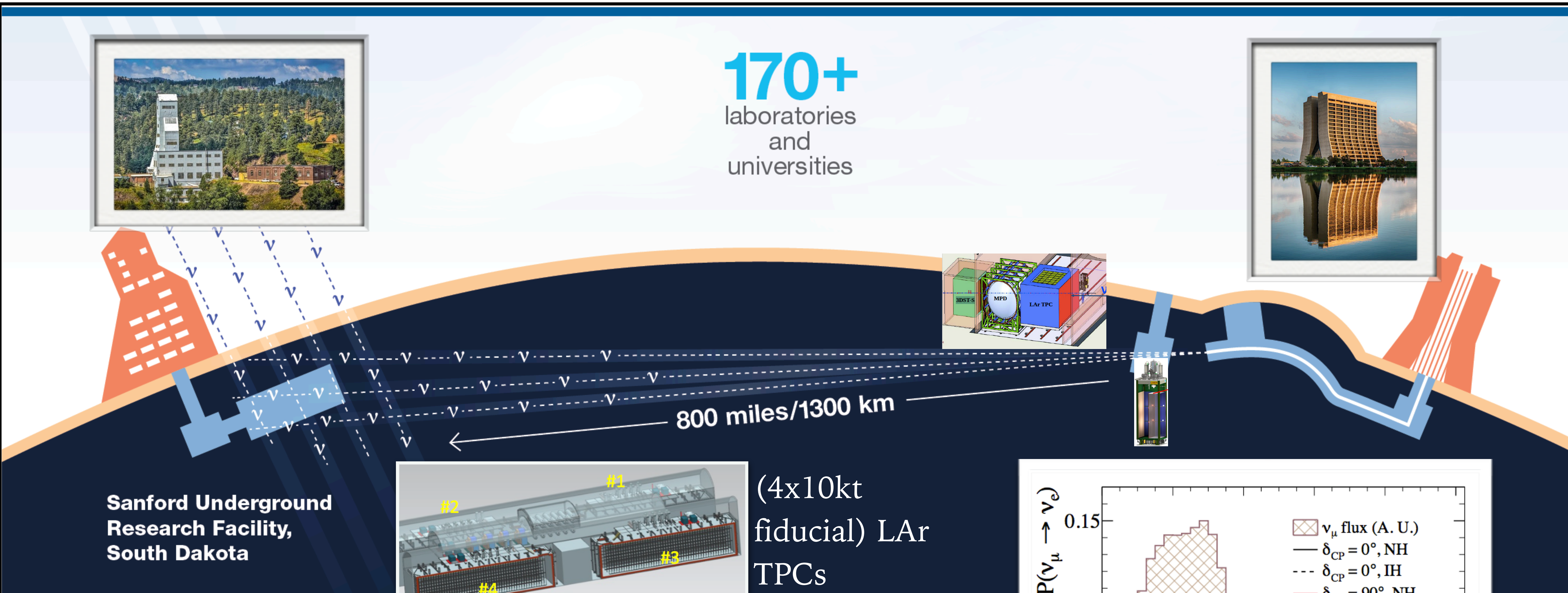


S. Dolan, NuPhys2019

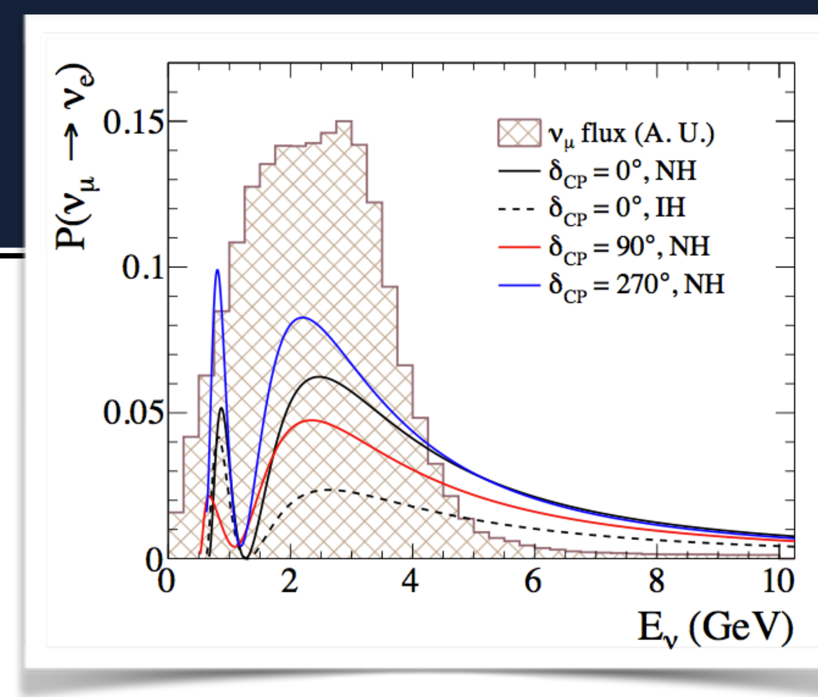
WHAT NEXT?

- Input from and collaboration between experimentalists and theorists is fundamental to overcoming these challenges.
- "Experiments have outstripped the oversimplified models in generators". (K. McFarland, NuInt18)
- U. Mosel, NEUTRINO18.
  - Precision era of neutrino physics requires more sophisticated generators and a dedicated joint effort in nuclear theory and generator development
  - This joint effort has to be funded as integral part of experiments

DUNE



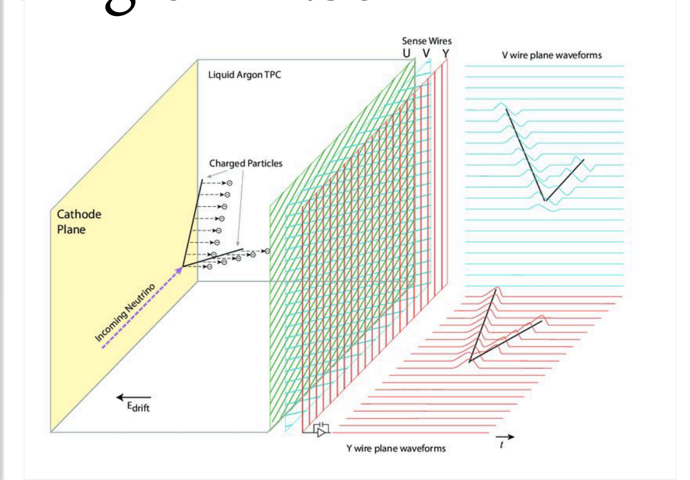
(4x10kt fiducial) LAr TPCs



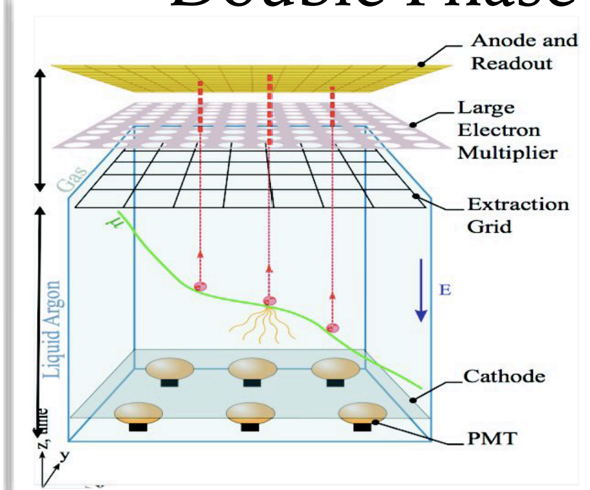
Two detector technologies:

arXiv:1807.10334, 1807.10327, 1807.10340)

Single Phase

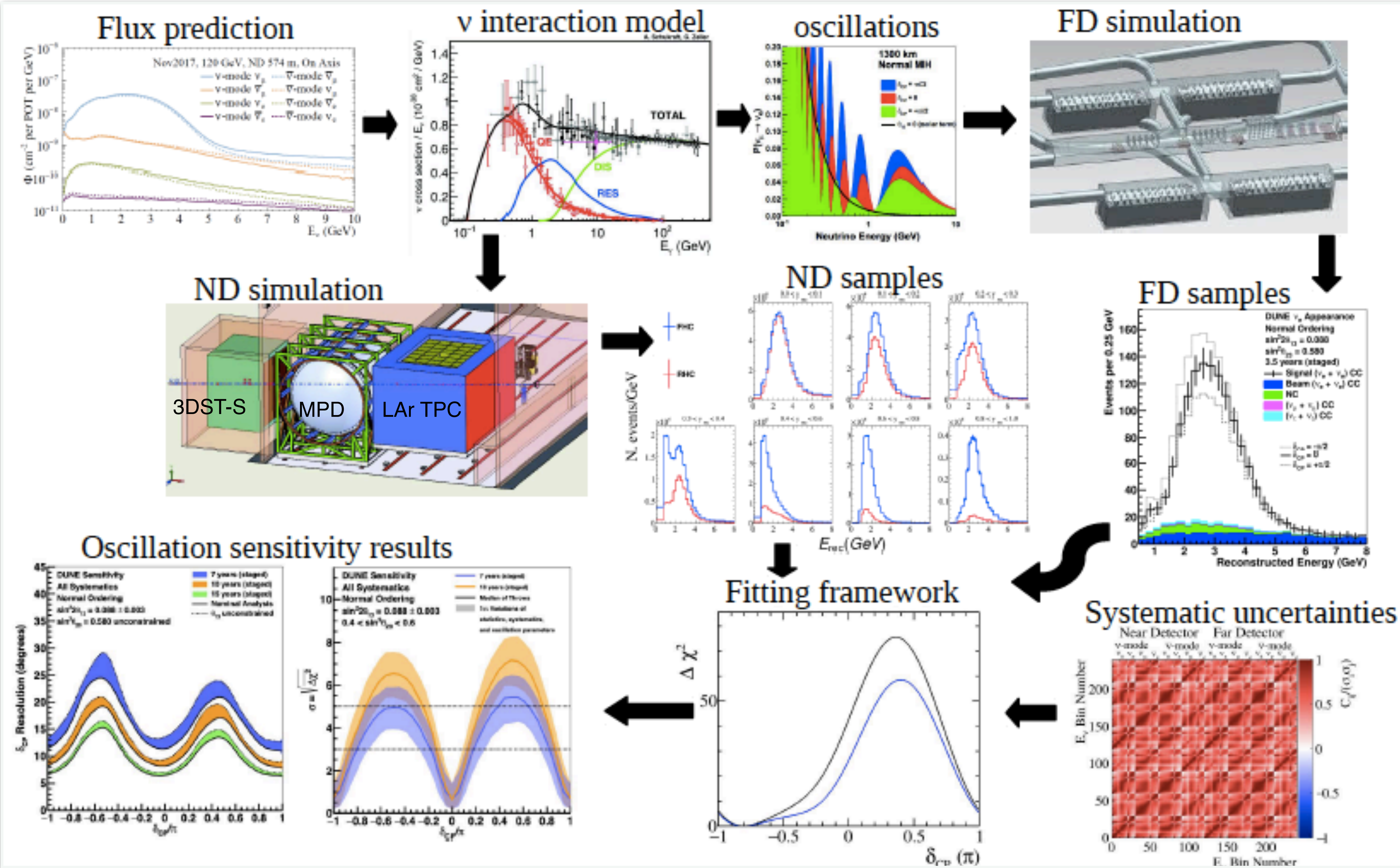


Double Phase

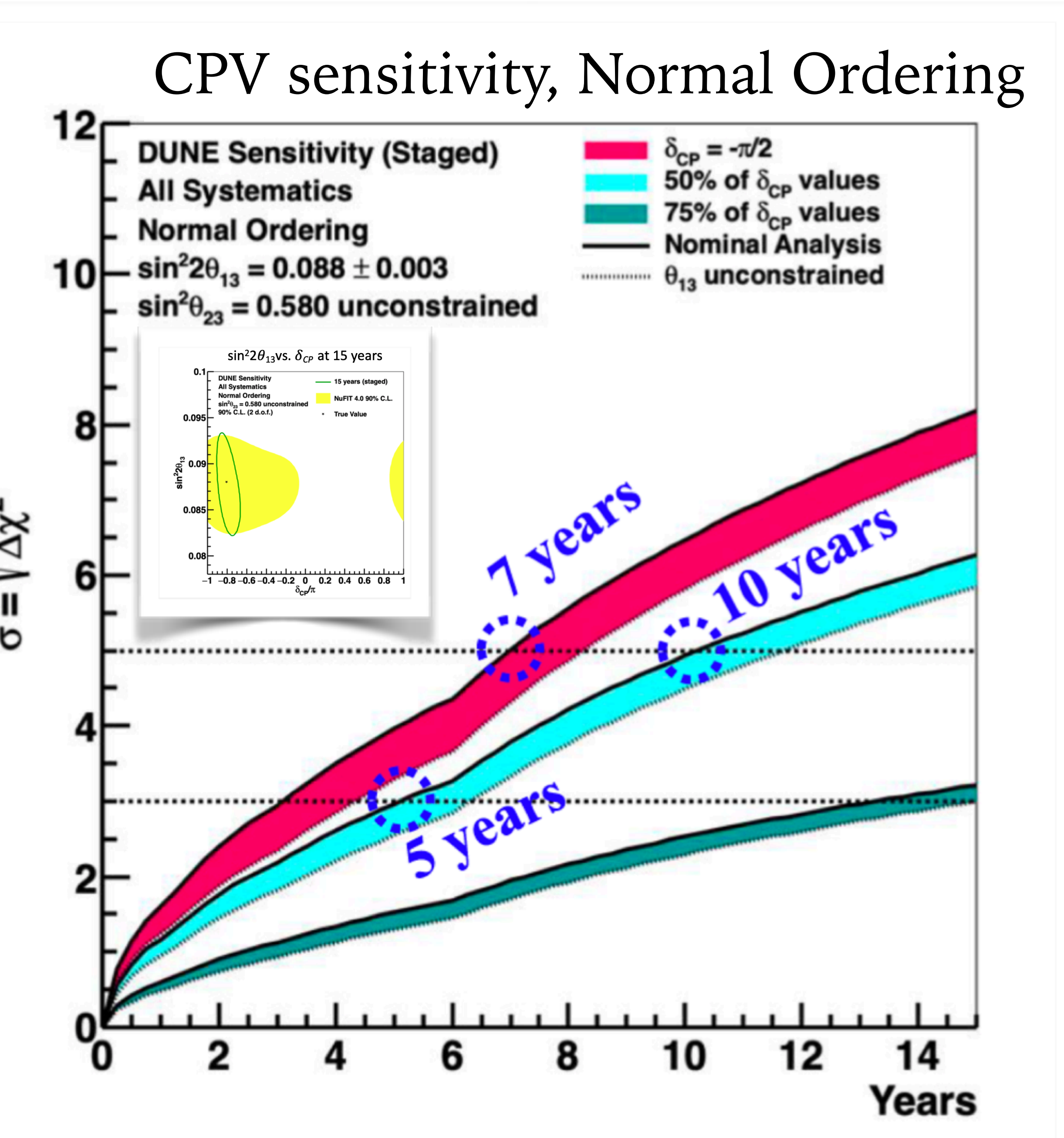


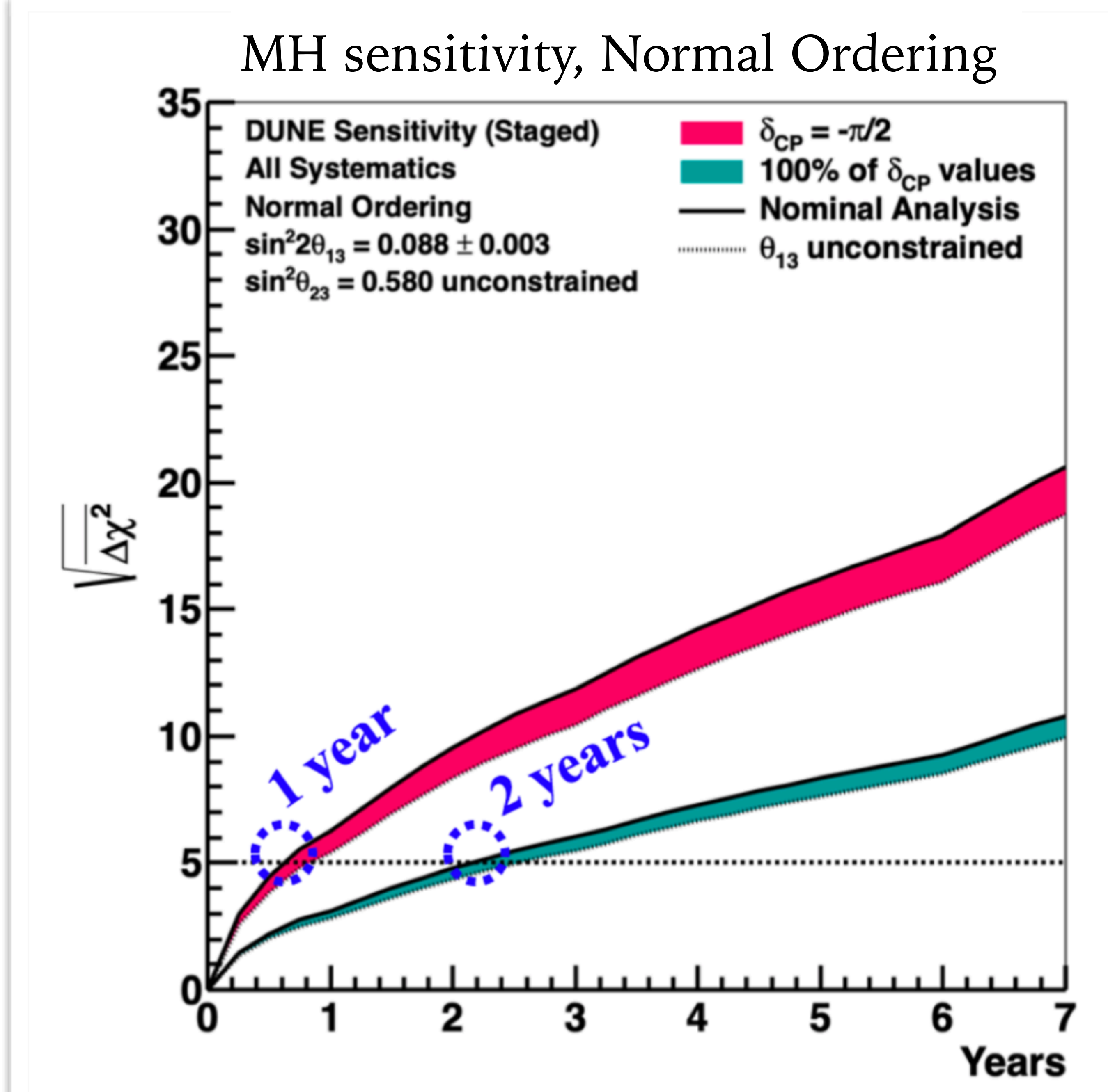
- 1.2 MW initial beam power
- Upgradeable to 2.4 MW

DUNE LONG BASELINE OSCILLATION ANALYSIS OVERVIEWS



DUNE SENSITIVITIES





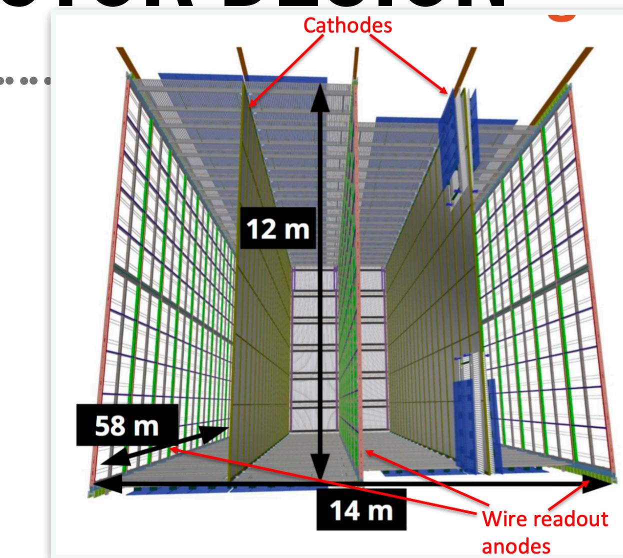
Width of bands indicates variation in possible central values of θ_{23}

$> 5\sigma$ sensitivity for both orderings and the full range of δ_{CP}

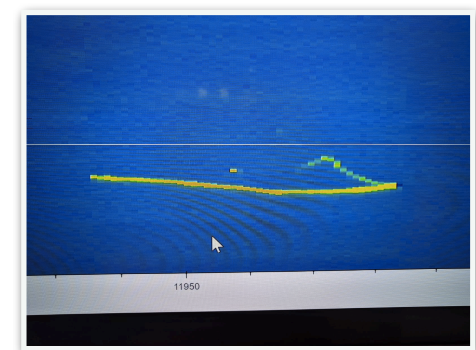
PROTODUNE: PROTOTYPING THE DUNE FAR DETECTOR DESIGN

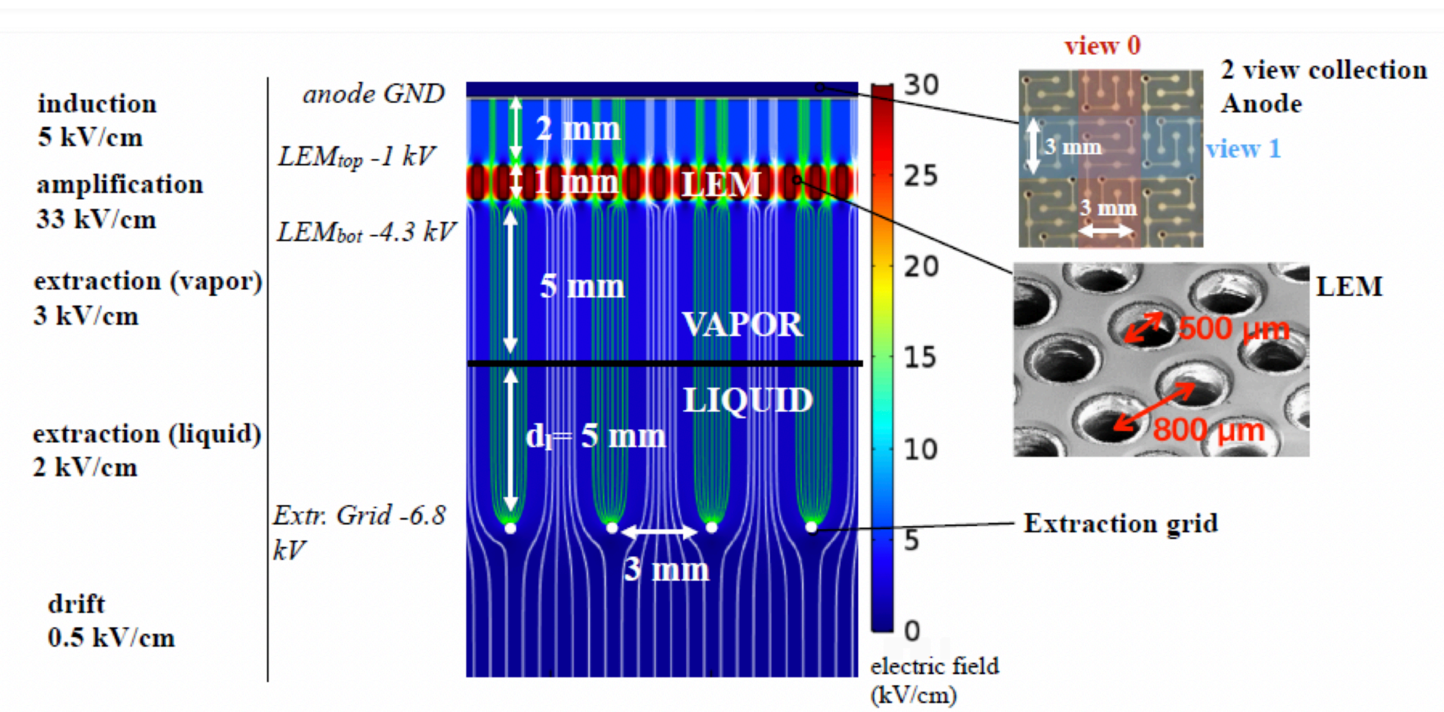
Two prototype detectors located at CERN neutrino platform

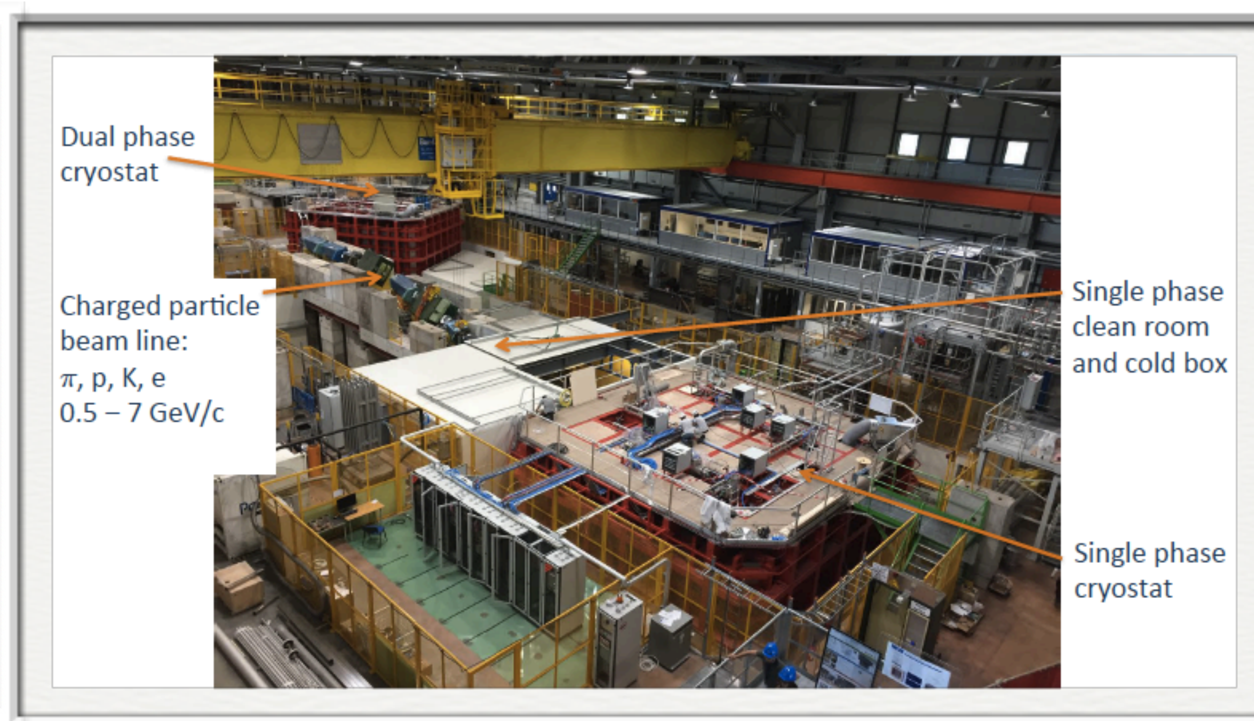
- Single phase and dual phase
- Test detector engineering, and demonstrate long-term operational stability
- Measurements with beam:
  - towards demonstrating calibration
  - 0.5 — 7 GeV particle beams (e, π, p, K)
  - beam time limited by availability of CERN accelerators
- ProtoDune Single Phase : data taking in August — November 2018 →
  - Currently taking cosmics
- ProtoDune Double phase:
  - Being filled with Ar.



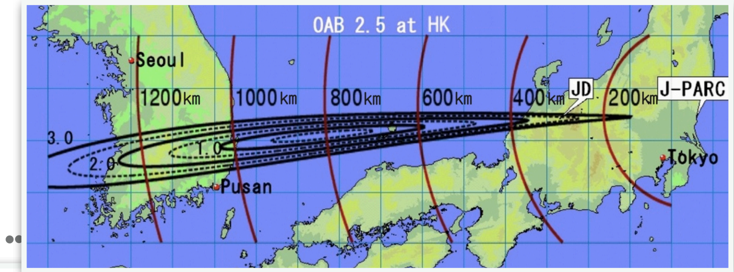
September 19 2018: first track recorded

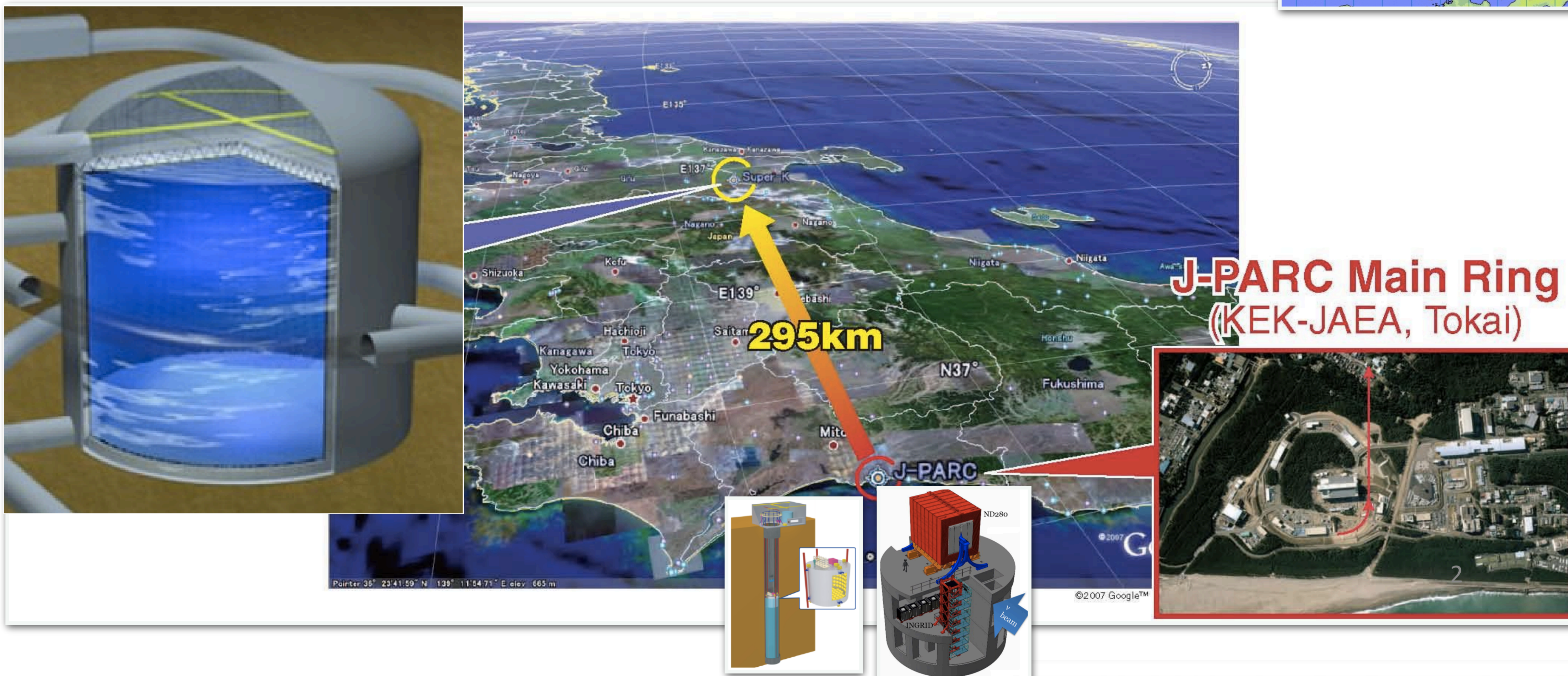






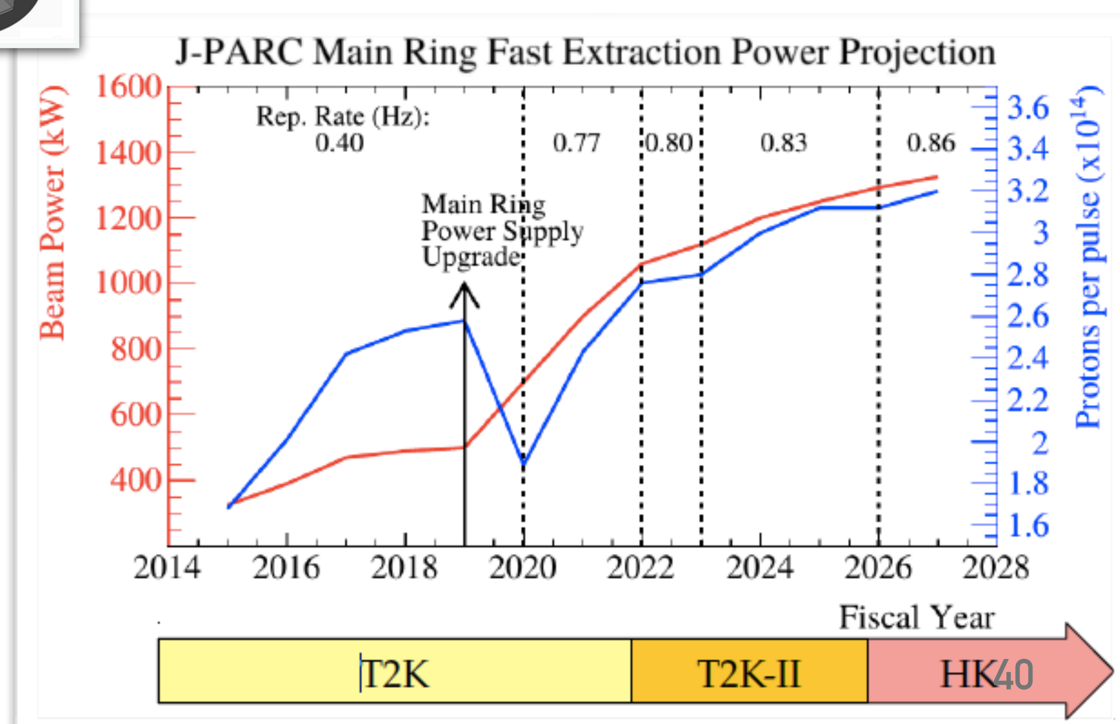
HYPER-KAMIOKANDE





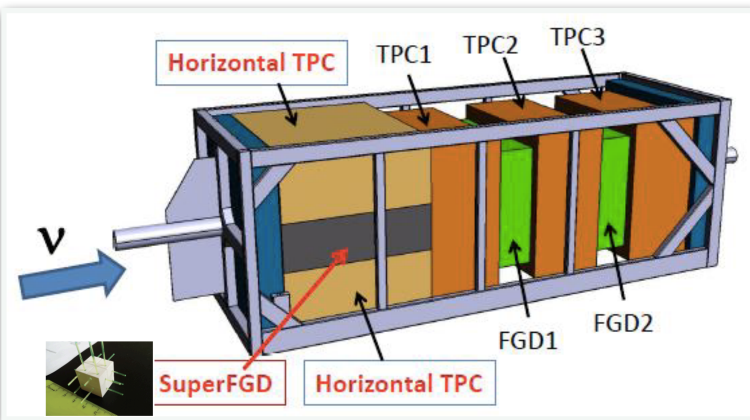
Next generation of neutrino observatory in Japan

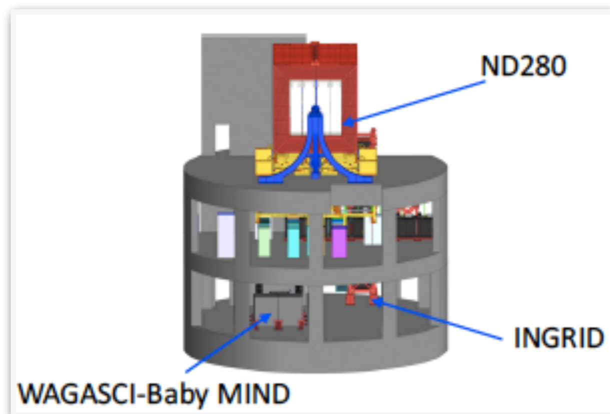
- Water Cherenkov detector
- Construction 2020-26
- 260 kton water ⇒Fid. Volume: ~ 8 x Super-K
- Photocoverage: 40% (x2 SK sensitivity)
- Second staged detector possibly in Korea (>200km baseline, second oscillation maximum)

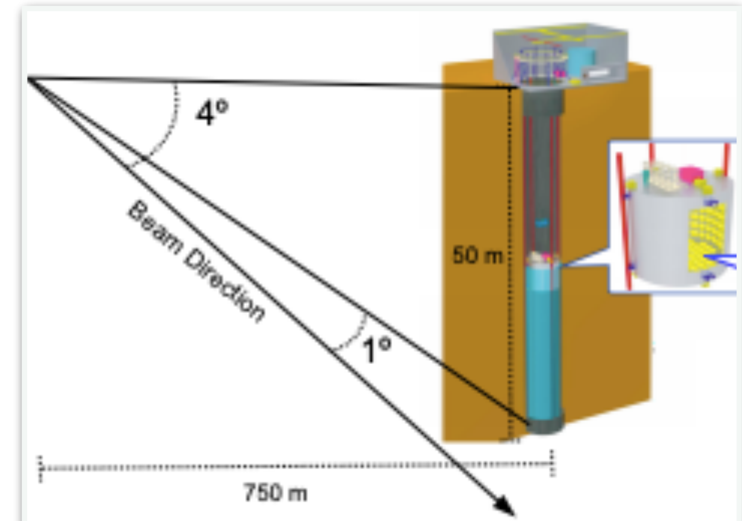


HYPER-KAMIOKANDE WITH BEAM ONLY

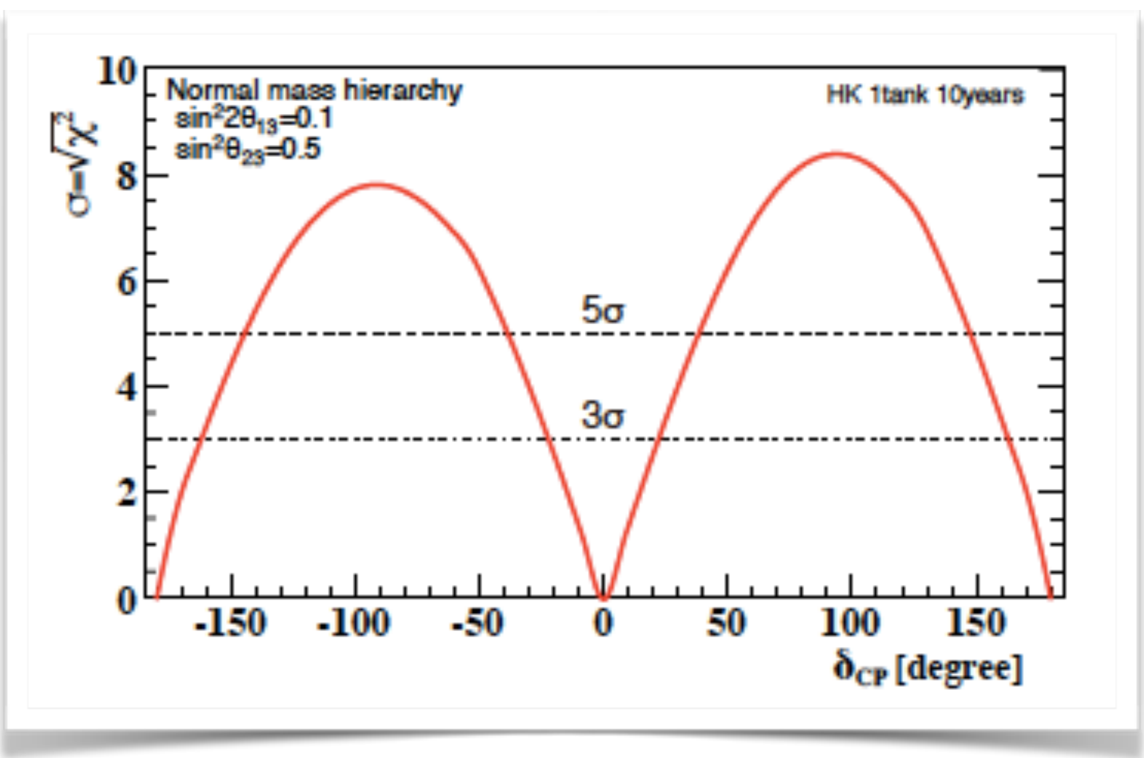
- Aim to reduce systematics down to 3%
- Crucial suite of new detectors
  - New WC detector @ ~750m
  - (Further) refurbished on- and off-axis detectors

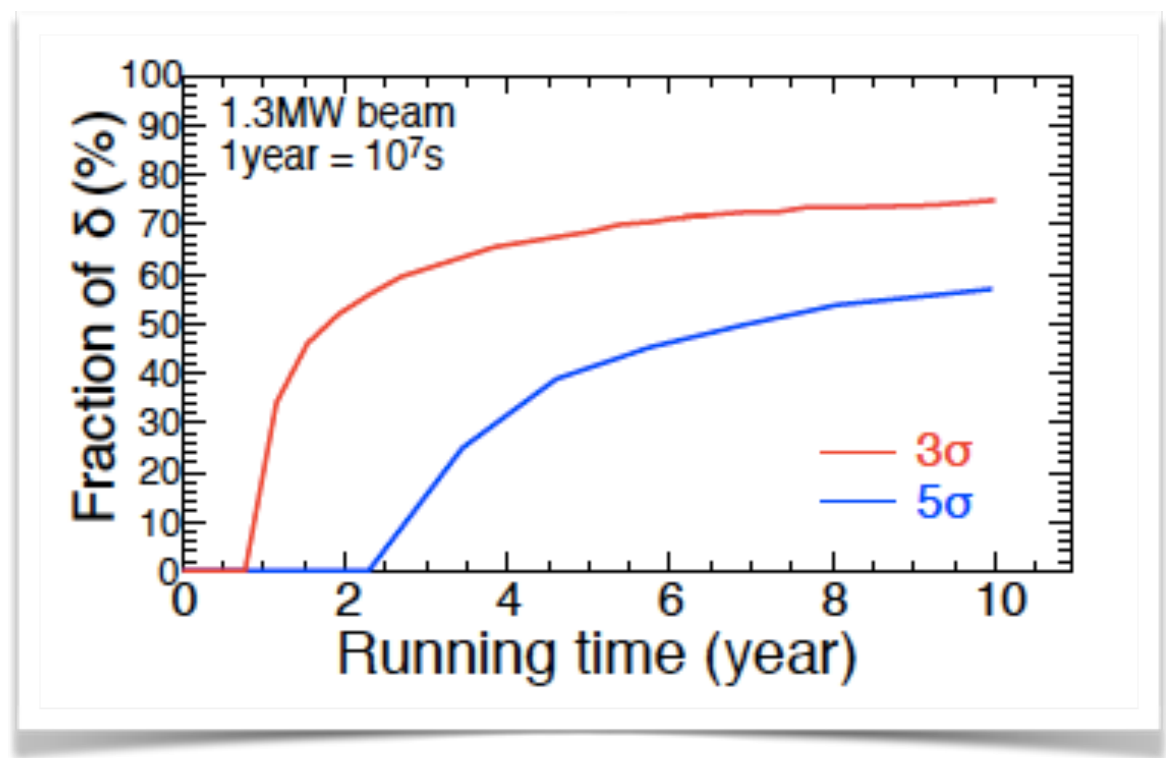






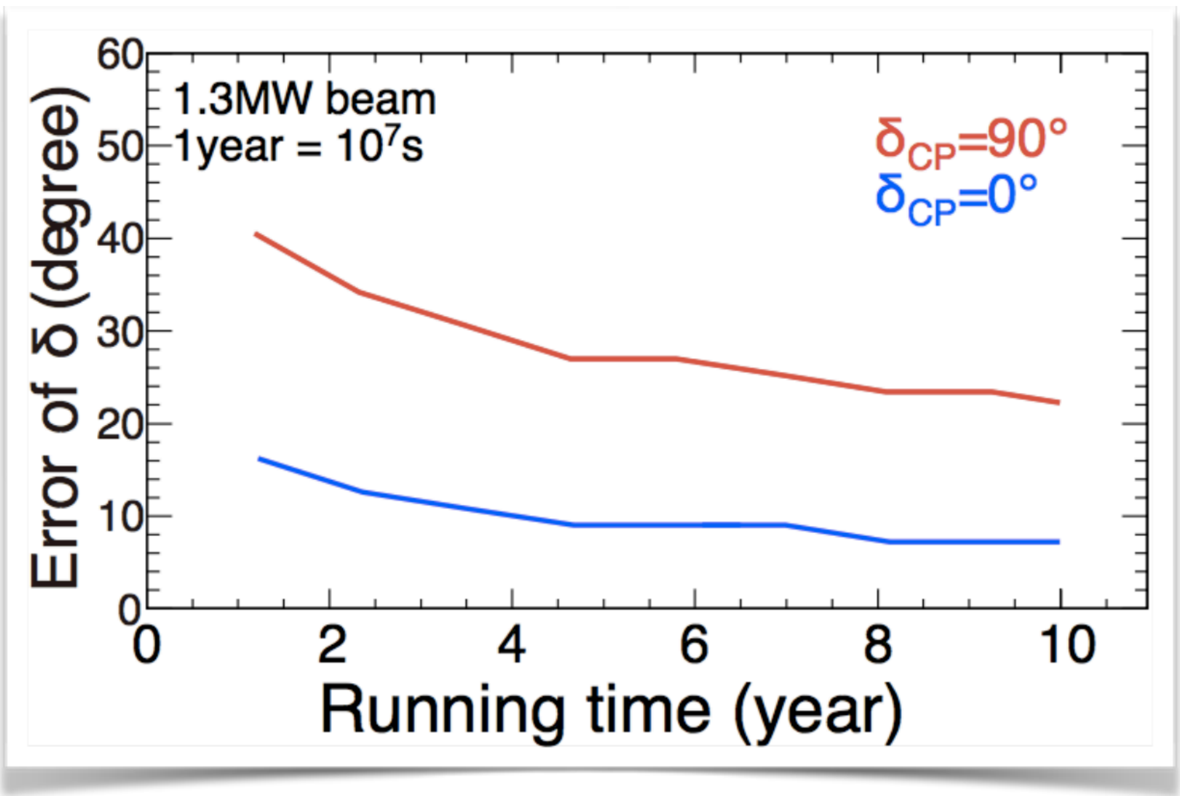
Expected significance to exclude $\sin\delta_{CP} = 0$ plotted as a function of true δ_{CP} assuming NH

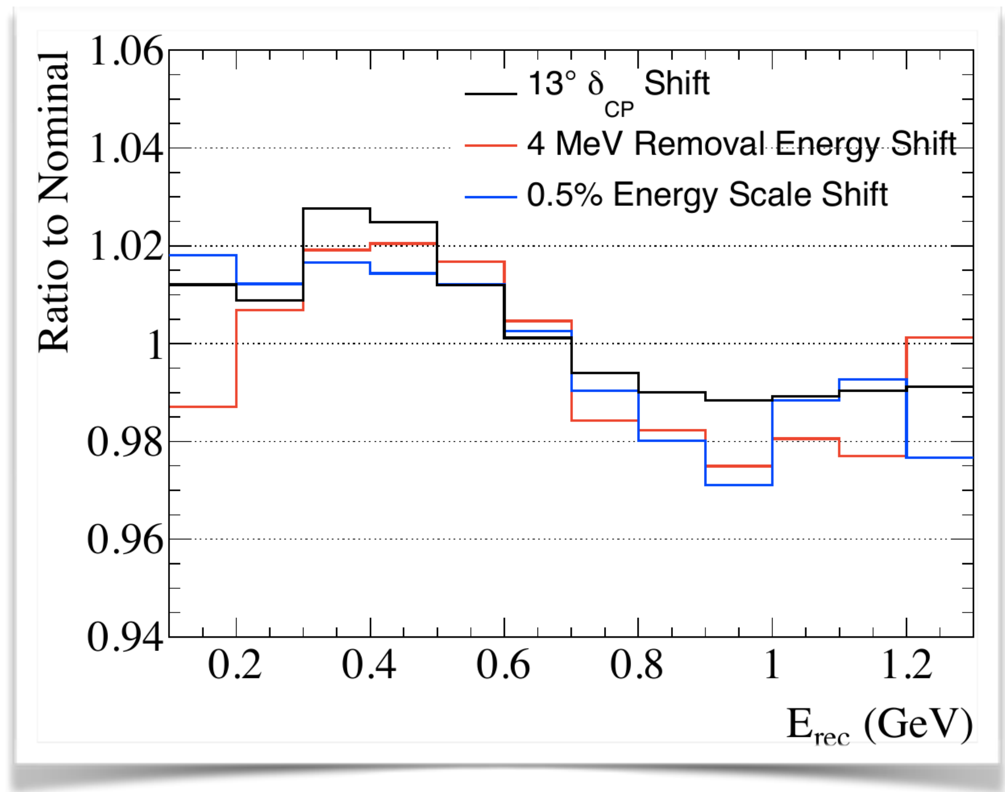




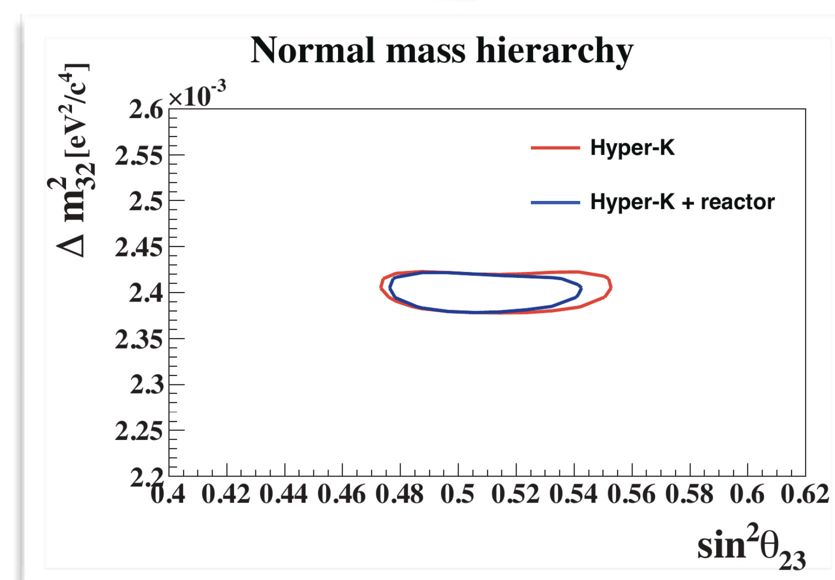
HYPER-KAMIOKANDE WITH BEAM-ONLY

- After CPV is determined, accurate measurement of δ_{CP} will be crucial
- Sensitivity is limited by systematics ⇒ near detectors



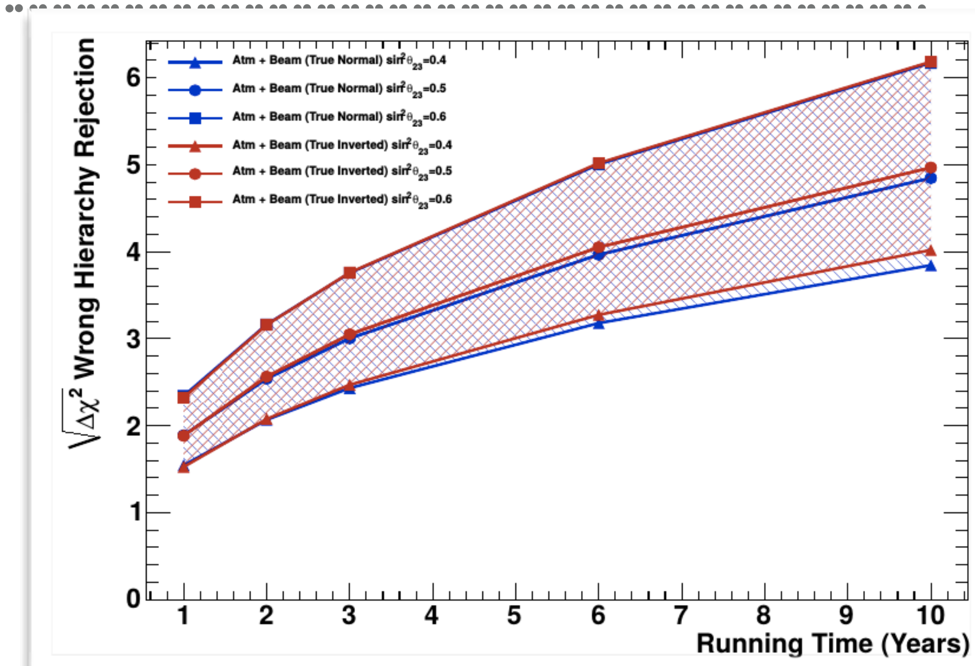


- The 90% CL allowed regions in the $\sin^2\theta_{23}$ and Δm^2_{23} plane.
- The true values are $\sin^2\theta_{23} = 0.5$ and $\Delta m^2_{32} = 2.4 \times 10^{-3} eV^2$

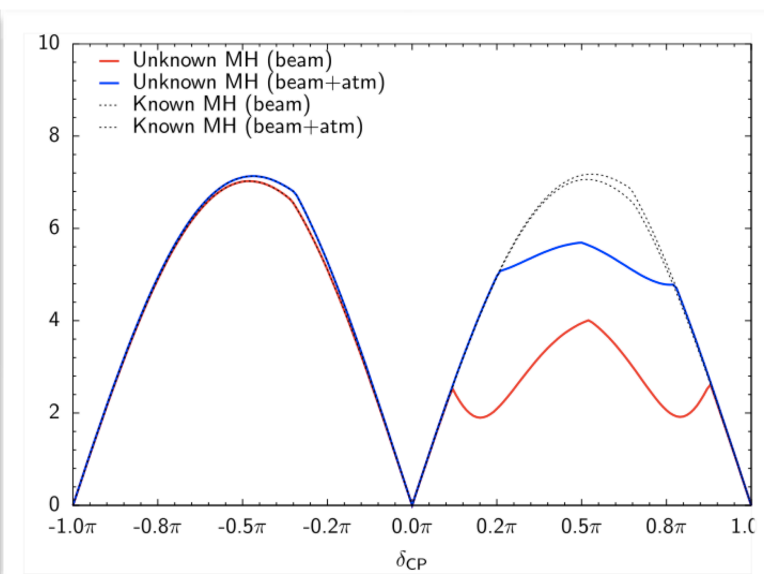


HYPER-KAMIOKANDE WITH BEAM AND ATMOSPHERICS

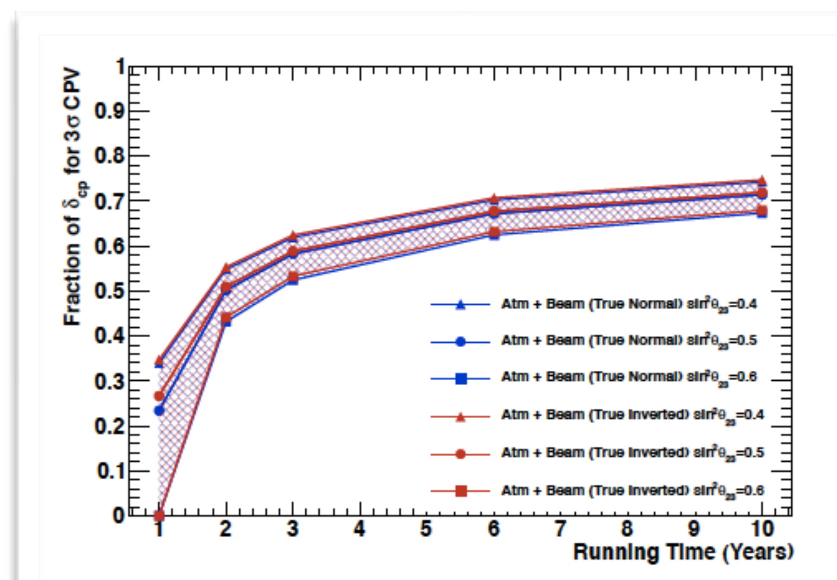
- Expected sensitivity to the mass hierarchy as a function of time
- Even if MH not determined at that time, HK-only can determine the MH at 5σ after ≥ 6 years.
- The sensitivity highly depends on θ_{23} value.



Expected significance to exclude $\sin\delta_{CP} = 0$ plotted as a function of true δ_{CP} for beam-only and beam+atmospherics atmospheric neutrinos



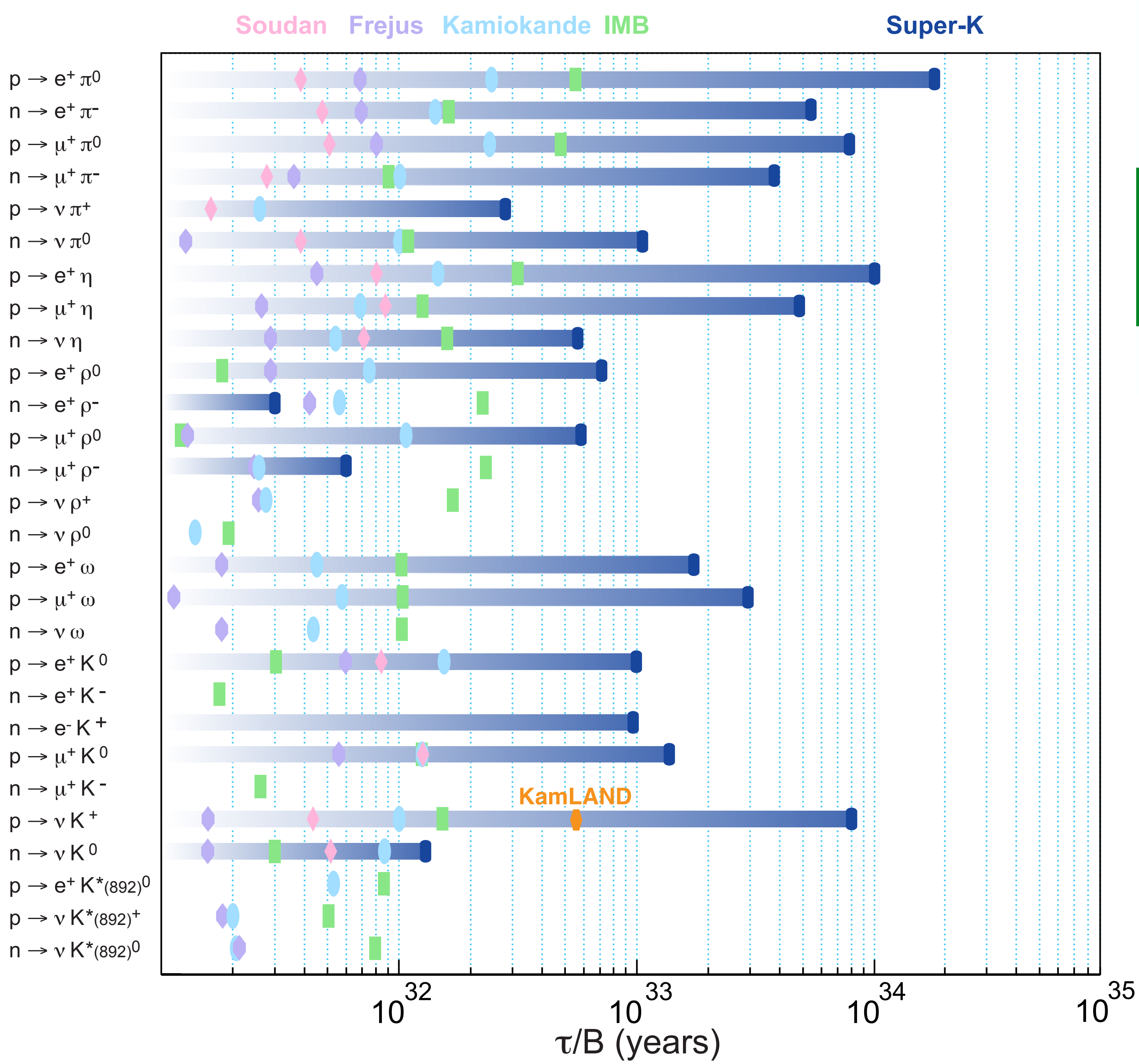
Fraction of $_{CP}$phase space at which a 3σ observation of CP violation can be made as a function of time for NH and IH



PROTON DECAYS

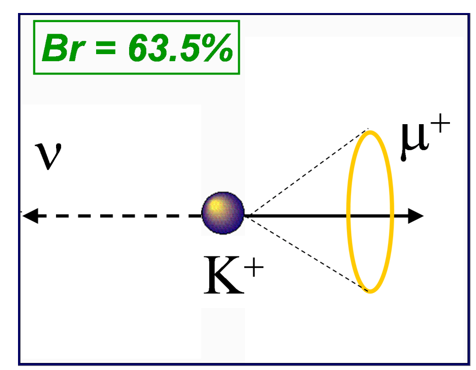
- Theories as Grand Unification Theories (GUT) suggest that the proton decay may exist and be observable.
- Large neutrino detectors are also good detector for proton decay searches!

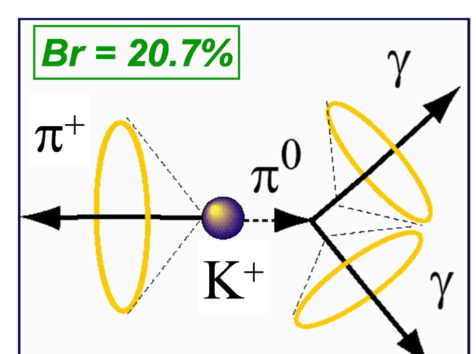
Current limits



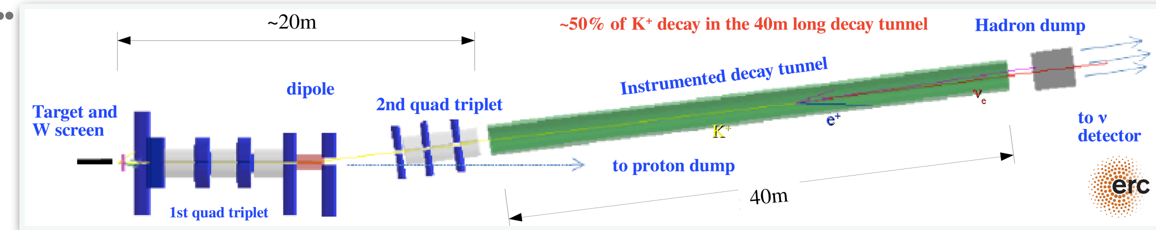
Future

	Hyper-K 190 kton		DUNE 40 kton		JUNO 20 kton	
	Eff. (%)	BG (/Mt y)	Eff. (%)	BG (/Mt y)	Eff. (%)	BG (/Mt y)
$e^+\pi^0$	40	0.7	45	1	-	-
νK^+	24	1.6	97	1	64	2.5
	arXiv:1805.04163		JHEP0704(2007)041; arXiv:1512.06148		arXiv:1507.05613	





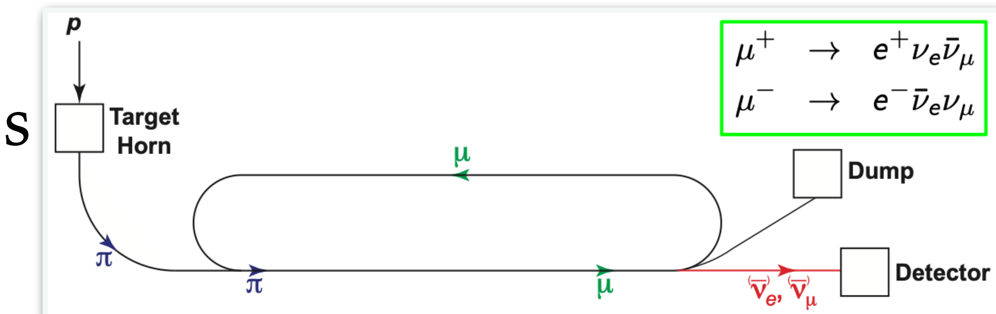
NEXT FACILITIES



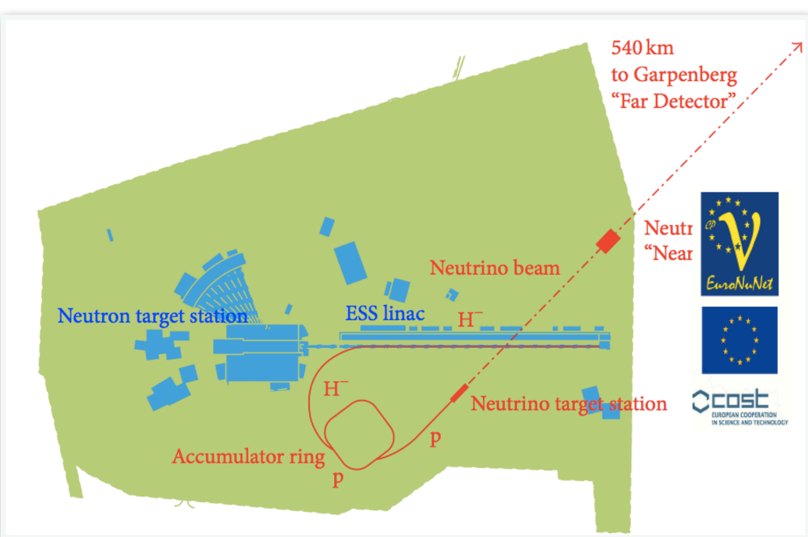
- **Enubet**: Based on conventional technologies
- Aiming for a 1% precision on the ν_e flux

protons →(K, π) →Kaon decays →ν_e→neutrino detector

- Aim: ~1 order of magnitude better ν_e and ν_μ cross sections, search for New Phys.



- **νSTORM**: Physics goals:
  - %-level electron and muon neutrino cross-sections
  - Sterile neutrino searches, beyond SBN
- Technology
  - Muon storage ring design that relies on R&D towards future Neutrino Factories.
  - Very well known fluxes of ν_e, $\bar{\nu}_e$, ν_μ, and $\bar{\nu}_\mu$.



ESSνSB

- A design study for an experiment to measure CP violation at 2nd neutrino oscillation maximum at ESS.
- Main challenge: modifications to ESS linac to produce neutrinos. Aim for a 5MW beam power.

CONCLUSIONS - PART I

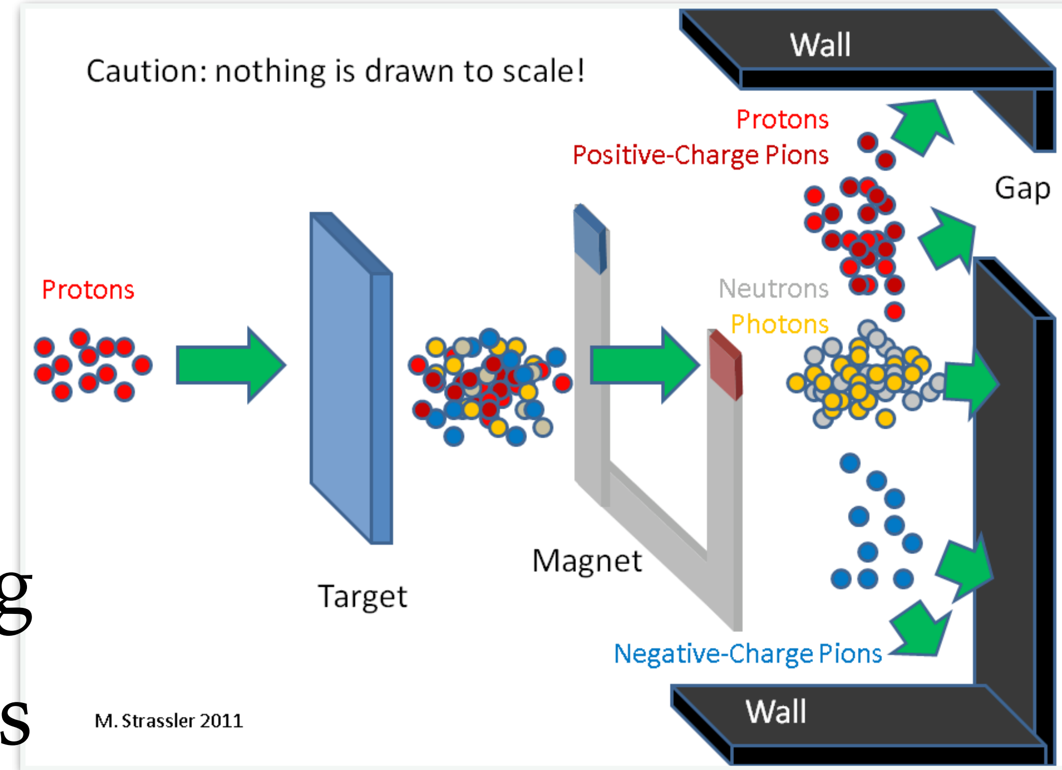
- Increase interest in neutrinos in the last decades.
- Tiny particles that may help to explain the current matter-antimatter asymmetry of the universe.
- Intense programme worldwide to understand the neutrino properties.
- Focus of the long-baseline neutrino experiments is on the measurement of the CP phase.
  - CP conserving values excluded at 2σ
  - Continuous programme running up to ~2025 with the current facilities.
  - New facilities starting in ~2026-2027

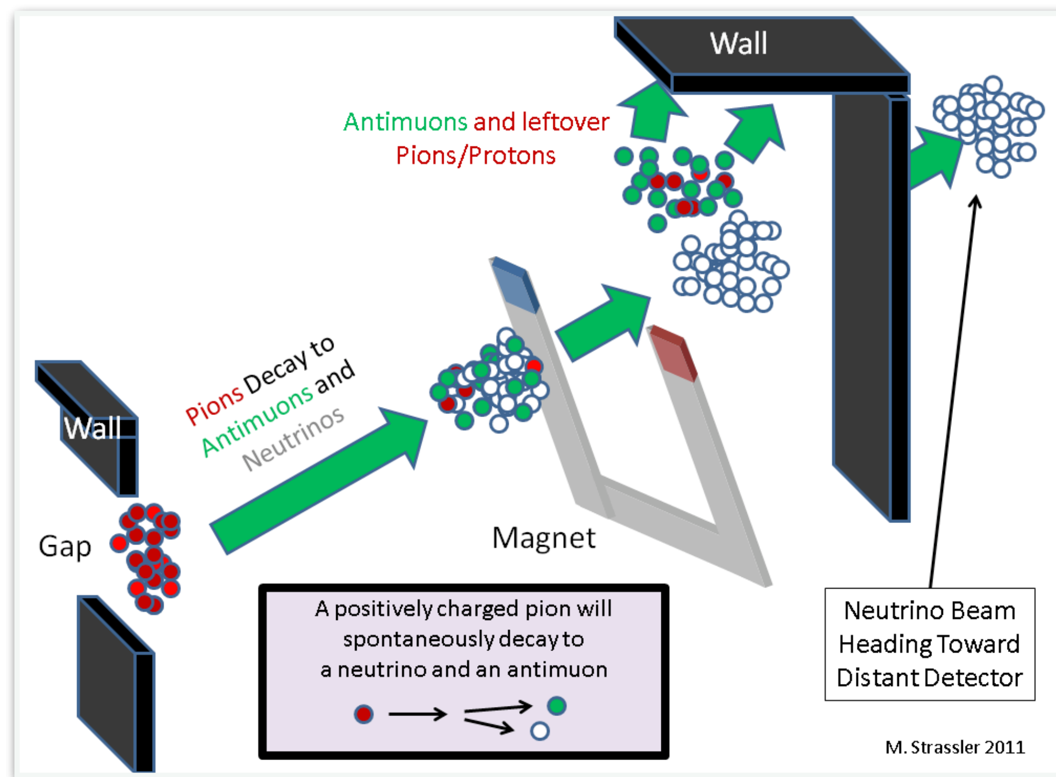
ADDITIONAL SLIDES

PARTICLE BEAMS

- I'll mainly focus on conventional neutrino beams, as described in this introduction
- Characteristics:
  - Well controlled in energy and timing
  - Neutrinos produced in $\pi/\mathrm{K}/\mu$ decays
- Dominant source is pion decay

  $\pi \to \mu + \nu_\mu$ (BR≈100%)
  - Simple 2 body decay in CM system
  - Neutrino energy: $E_\nu \approx \dfrac{0.43 E_\pi}{1+\gamma^2\theta^2}$
- Neutrinos boosted in the direction of the proton beam.

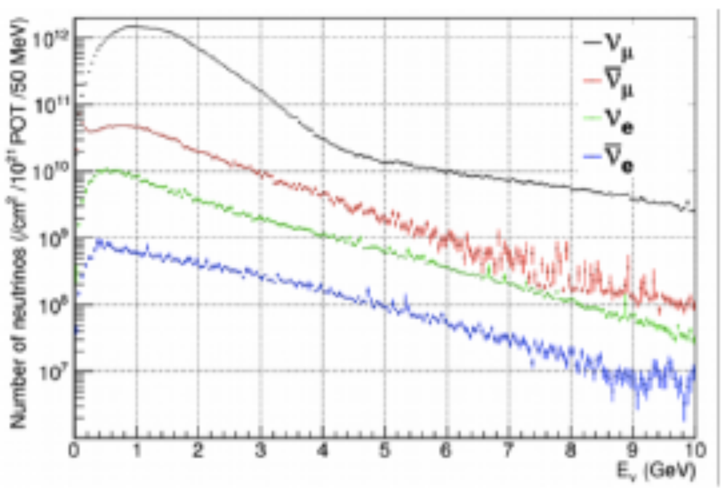




T2K CROSS SECTIONS 2019 HIGHLIGHTS

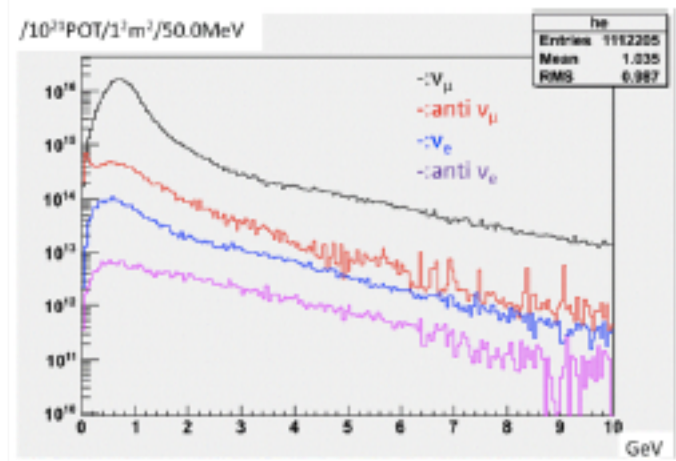
Three different off-axis angles, energies and detectors

INGRID neutrino mode flux



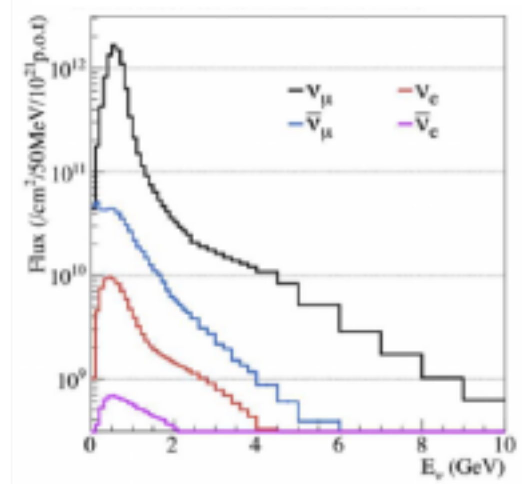
On-axis beam
Mean energy ~1.5 GeV

WAGASCI neutrino mode flux



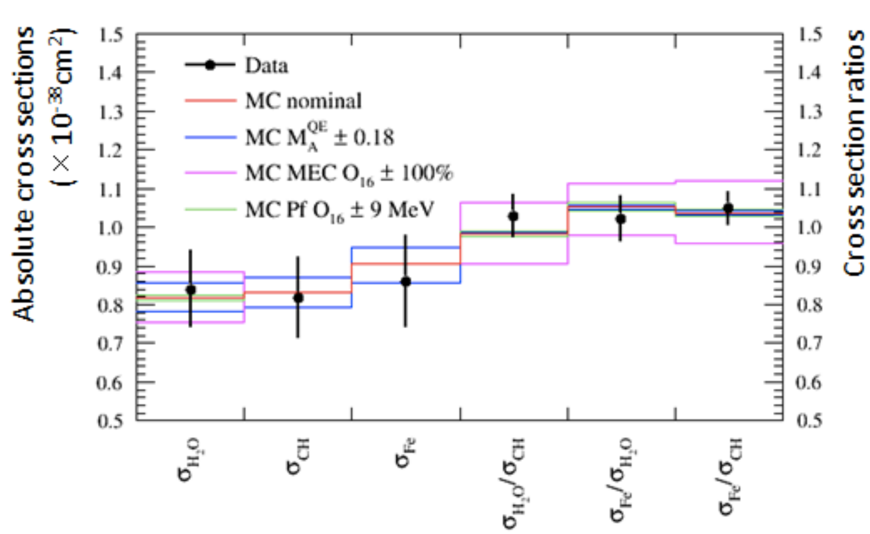
1.5° off-axis beam
Mean energy ~0.86 GeV

ND280 neutrino mode flux

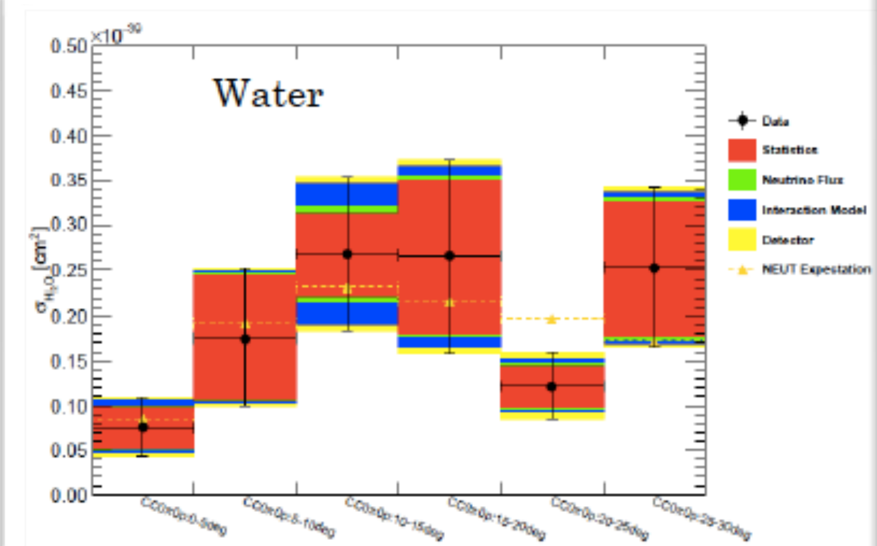


2.5° off-axis beam
Mean energy ~0.6 GeV

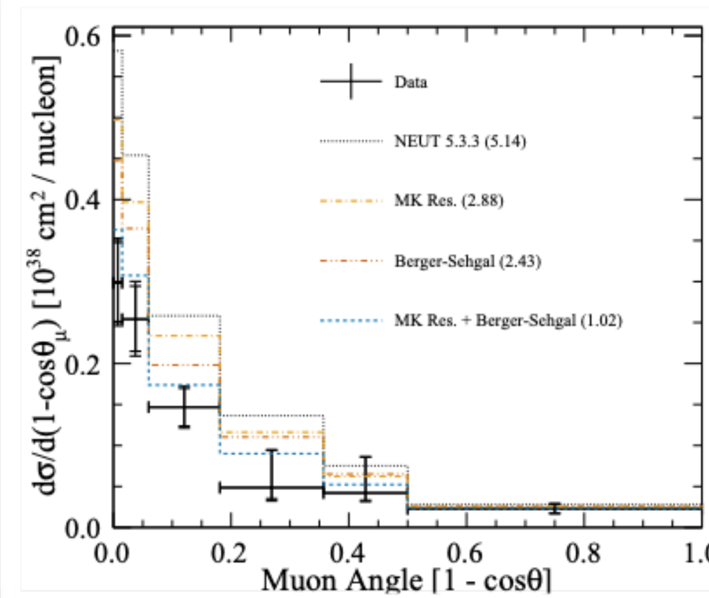
$CC\nu_\mu$ cross section on water, hydrocarbon and iron



$CC\overline{\nu}_\mu 0\pi 0p$ cross section on plastic and water

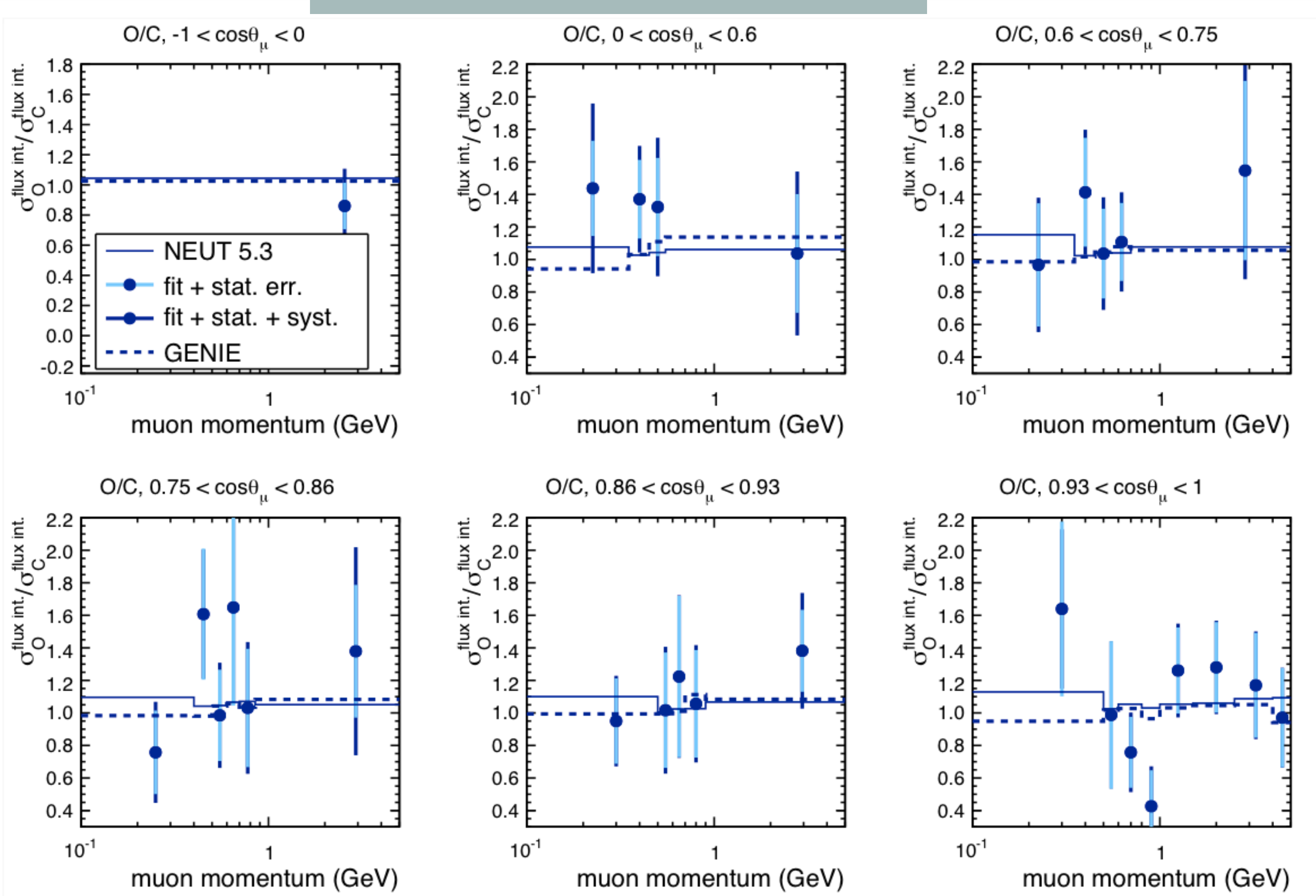


$CC1\pi^+$ per nucleon

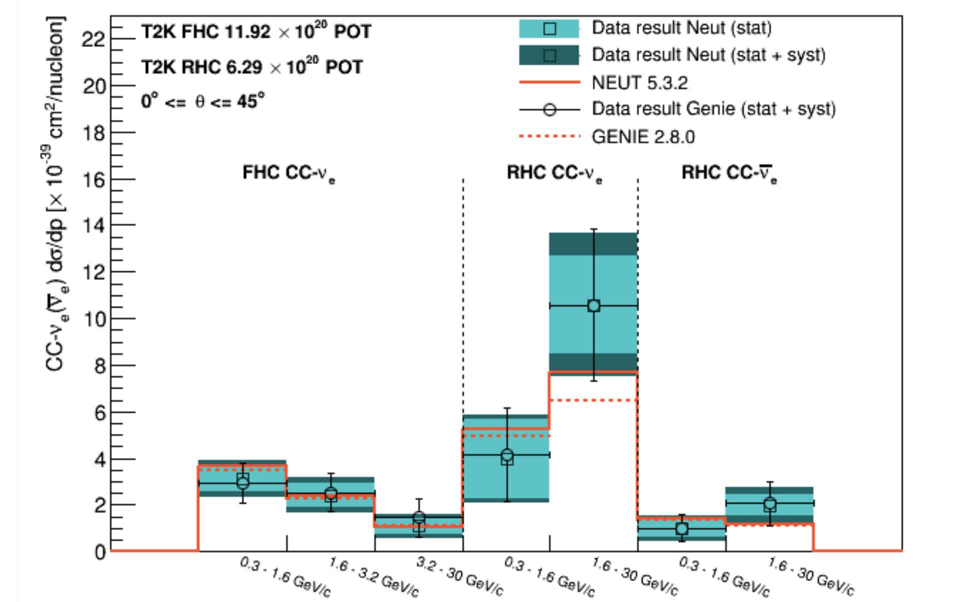


T2K ND280 CROSS SECTIONS 2019 HIGHLIGHTS

CC0π Water/Plastic ratio

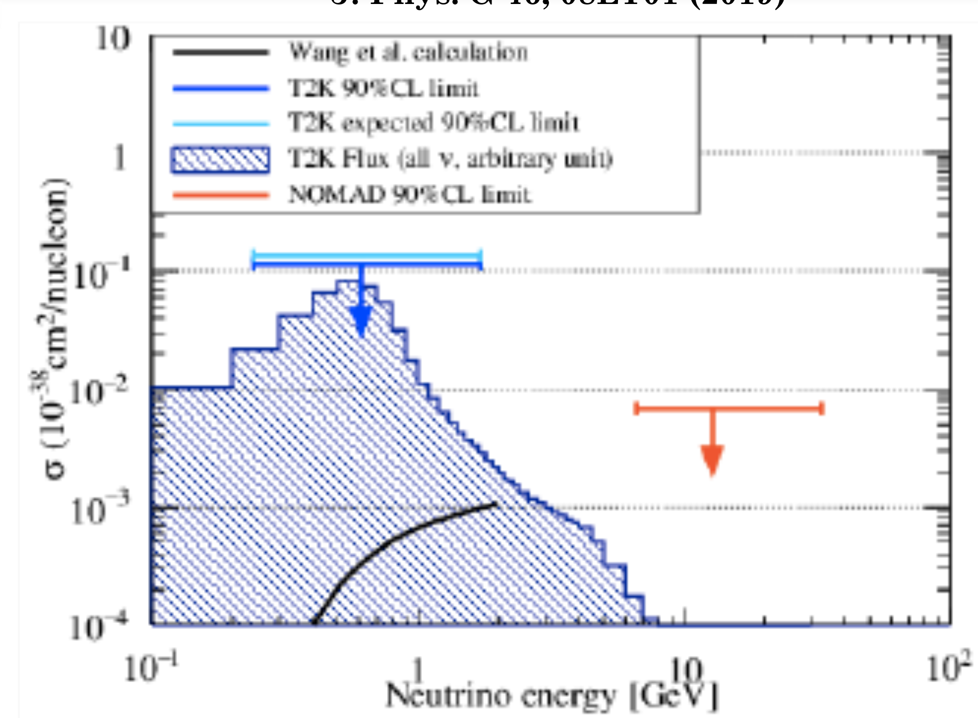


CCν_e, CC$\overline{\nu}_e$ inclusive cross section on plastic

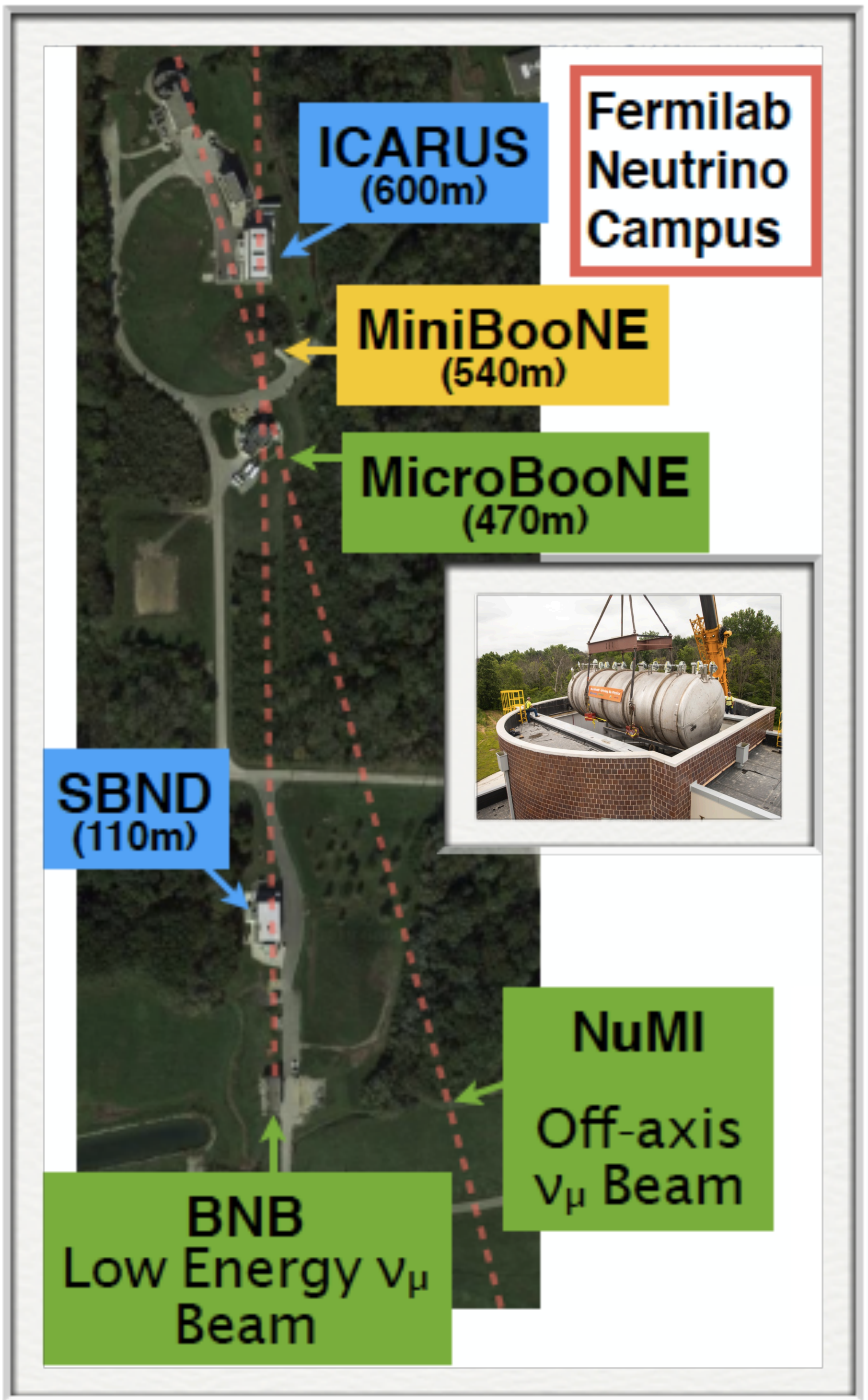


NC1γ off-axis flux of neutrinos

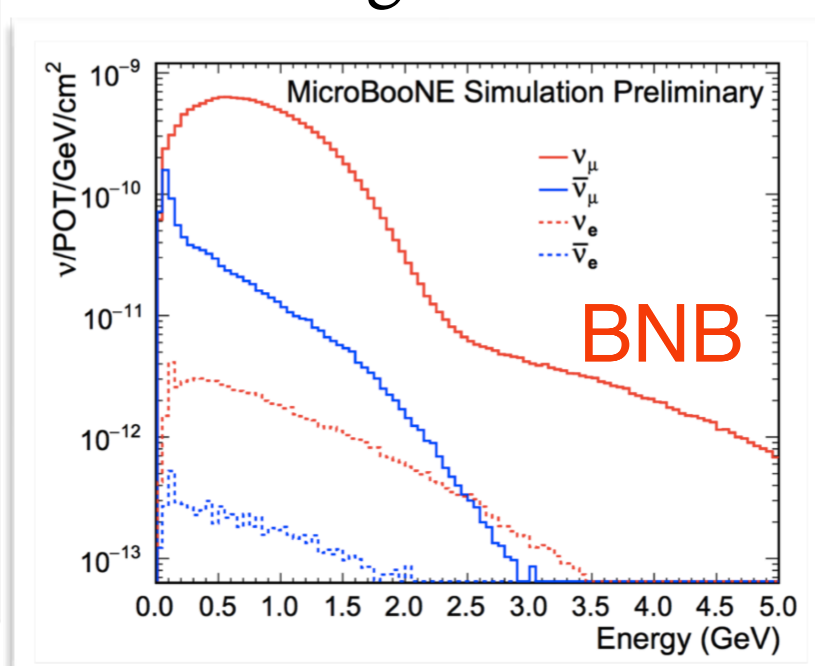
J. Phys. G 46, 08LT01 (2019)

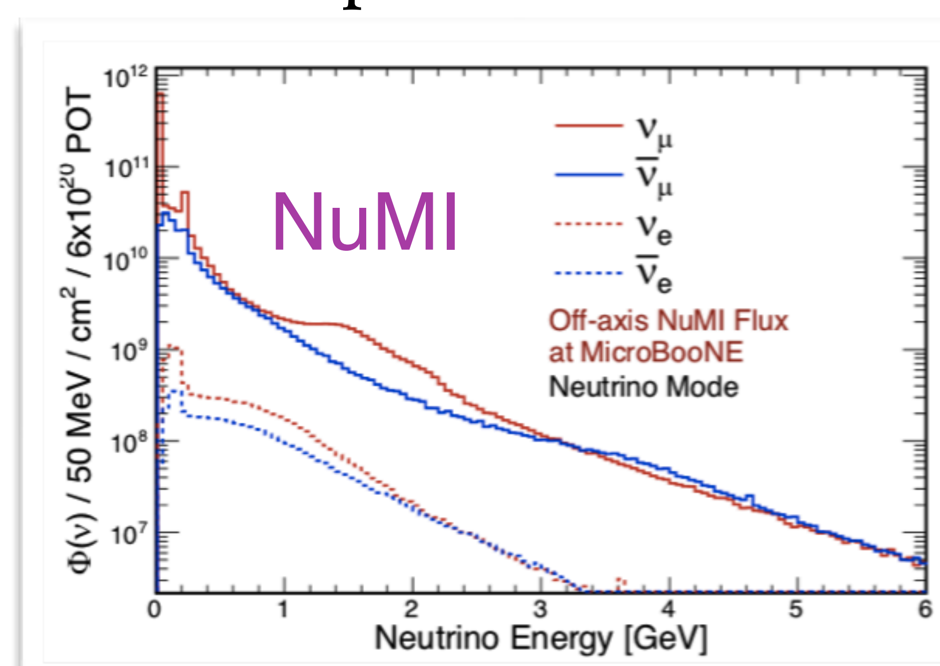


MICROBOONE OVERVIEW

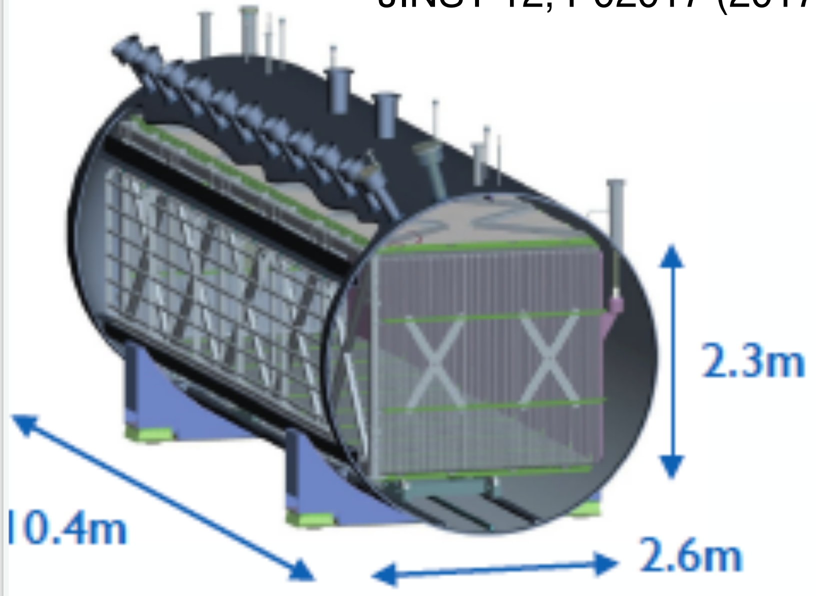


- Past: MiniBooNE
- Present: MicroBooNE
- Future: SBN Program
- Over the next couple of years two additional detectors, ICARUS and SBND, will come online joining MicroBooNE
- The goal of this program is to definitively investigate the LSND allowed space.



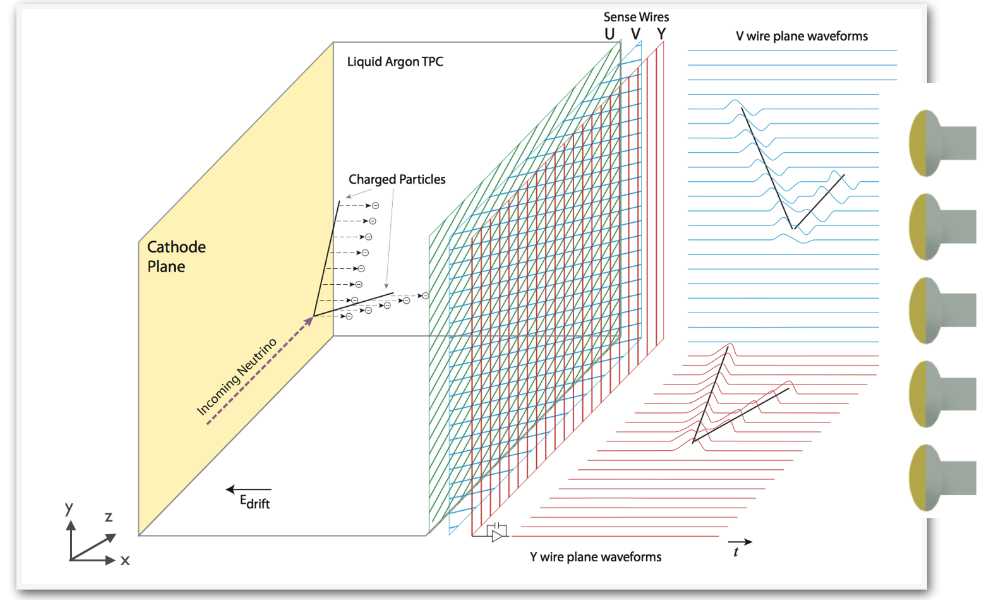


MICROBOONE LAR TPC



JINST 12, P02017 (2017)

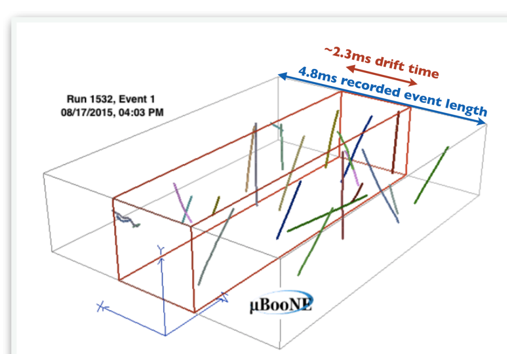
- ➤ 85-ton active volume Liquid argon TPC.
- ➤ 3 planes of sensing wires $(0^{\circ}, +/-60^{\circ})$
- ➤ System of 8-inch PMTs



- ➤ Sensitive to many detector effects →
- ➤ Using data to perform direct calibrations of each
- ➤ It's relevant for all LAr programme.
- ➤ Some already adopted by ProtoDUNE

1. Localized electric field distortions
   MICROBOONE-NOTE-1055-PUB
2. Detector response functions
   JINST 13, P07007 (2018)
3. Readout uniformity
   MICROBOONE-NOTE-1048-PUB
4. Electro-negative contamination
   MICROBOONE-NOTE-1026-PUB
5. Induced charge responses
   JINST 13, P07006 (2018)
6. Event-by-event channel status
   JINST 13, P07007 (2018)
7. Electronics noise mitigation
   JINST 12, P08003 (2017)
8. PMT Responses

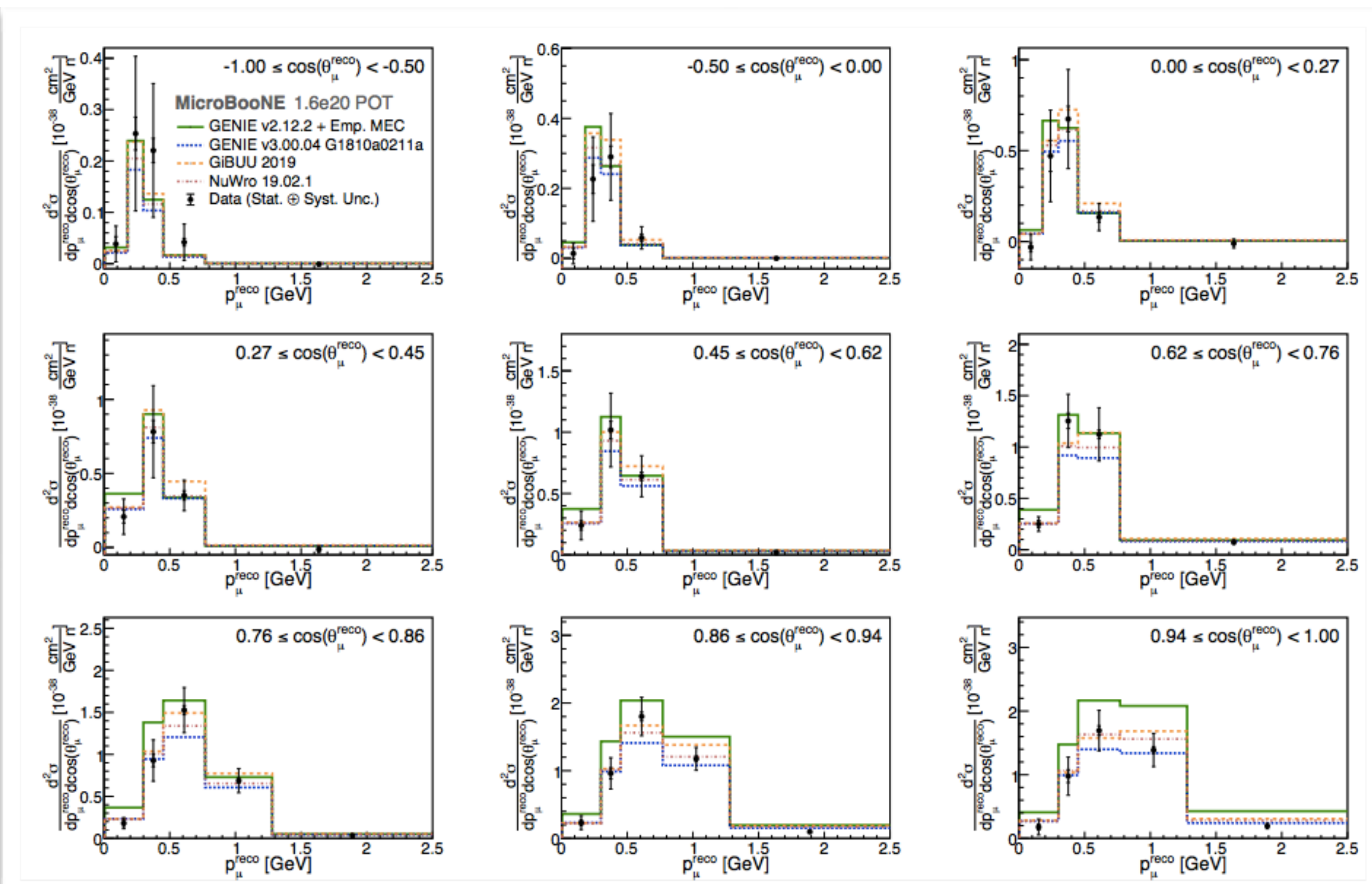
- ➤ Surface detector:
  - ✍ Main challenge is the cosmic rays background
  - ✍ 99.9% background reduction for analyses
  - ✍ Also source of important samples for calibration etc.

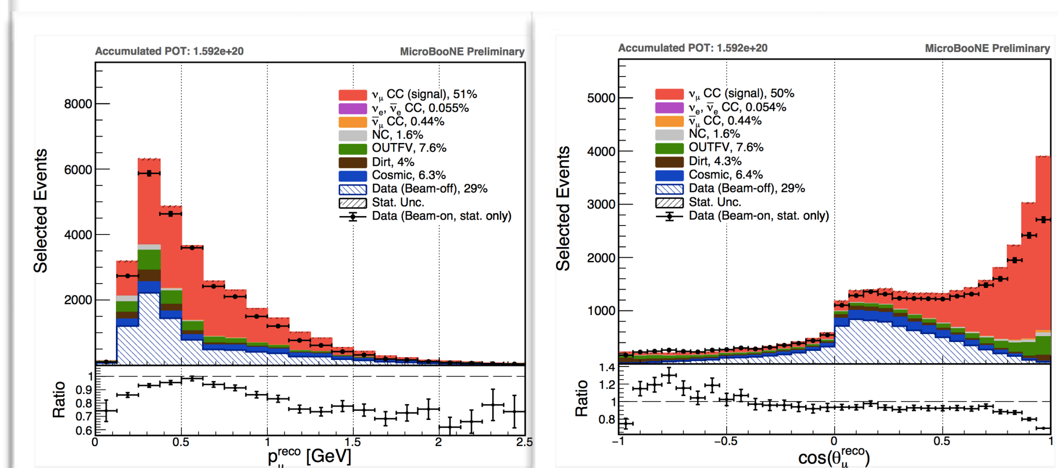


MICROBOONE RESULTS

- First absolute cross section measurement from MicroBooNE: CC0π
- Recent ν_μ CC inclusive cross section

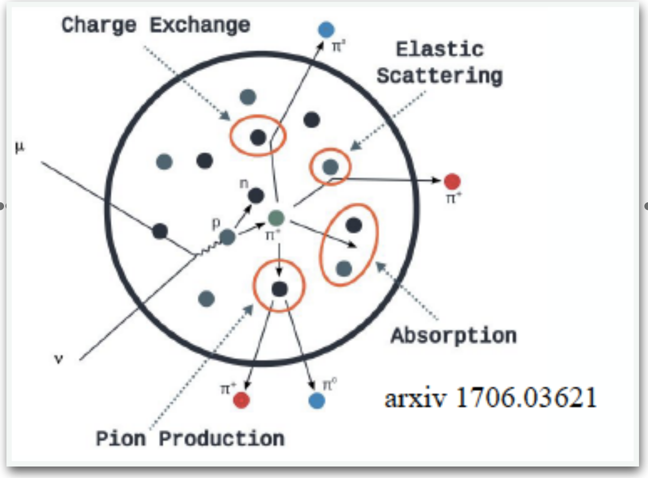
- First -Ar double differential cross section measurement
- Uncertainty is dominated by:
  - ✍ Detector model (16.2%)
  - ✍ Beam flux (12.2%)
  - ✍ Out-of-FV neutrino modelling (10.9%)

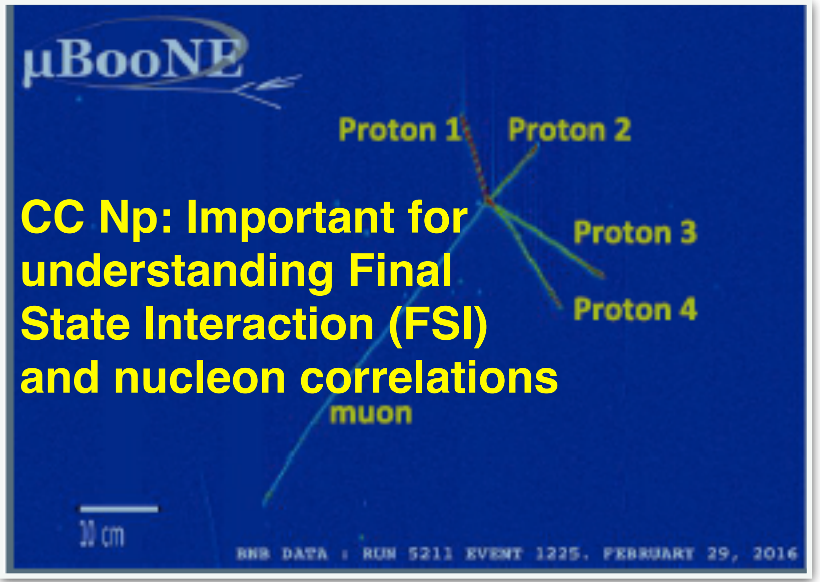


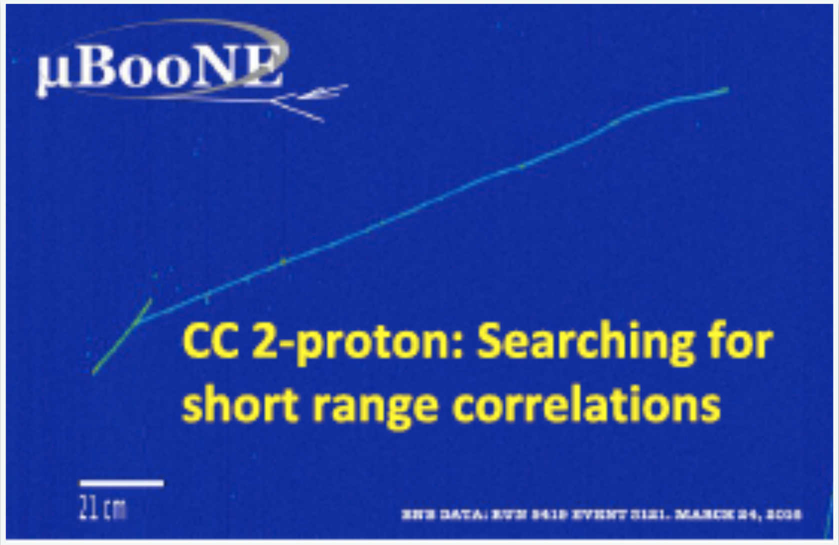


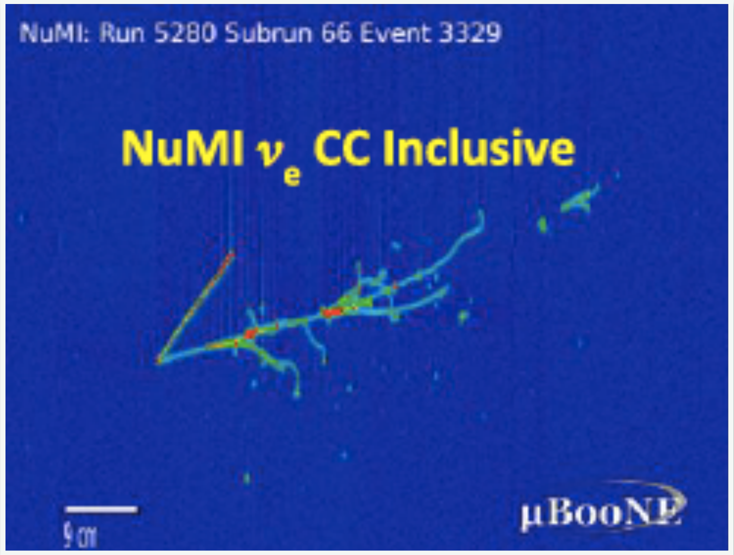
MICROBOONE

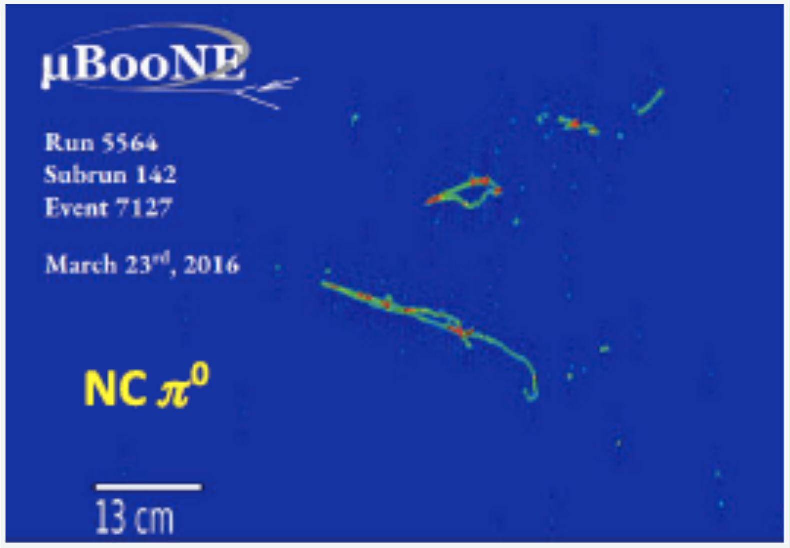
- Many ongoing measurements
- https://microboone.fnal.gov/public-notes/

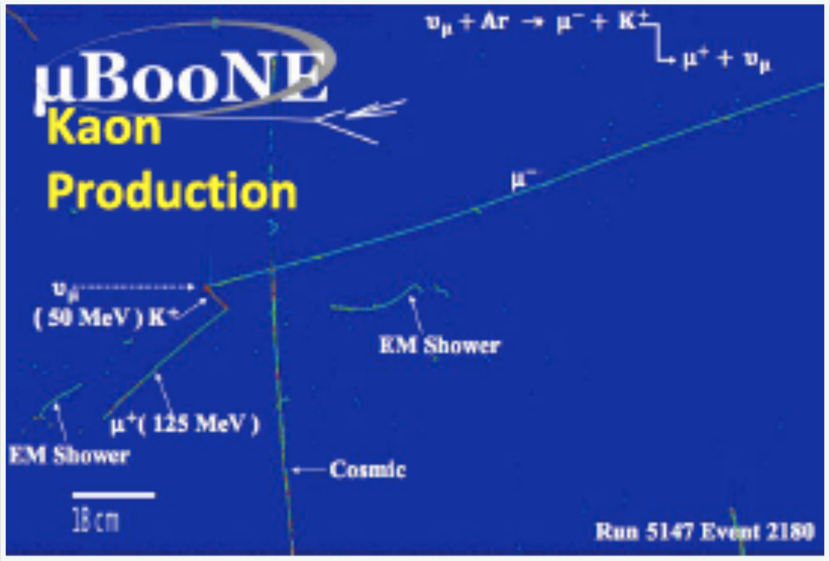


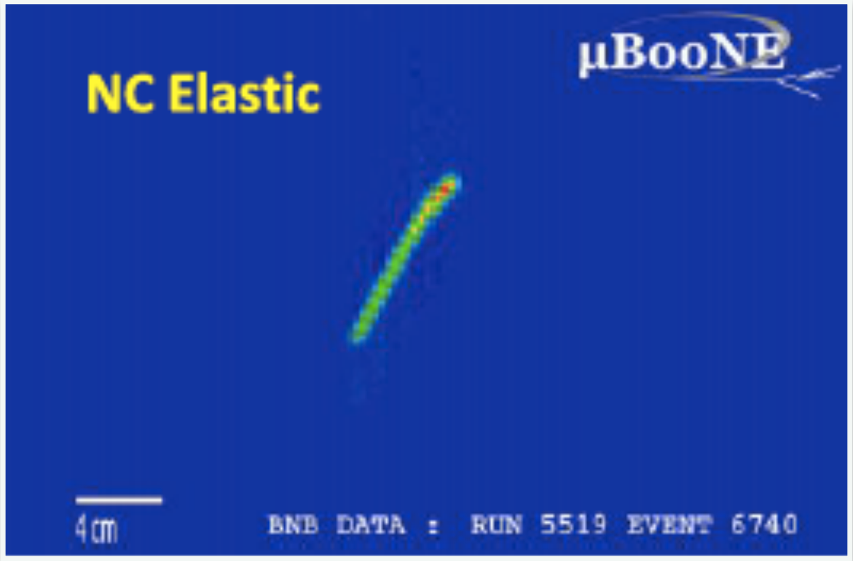










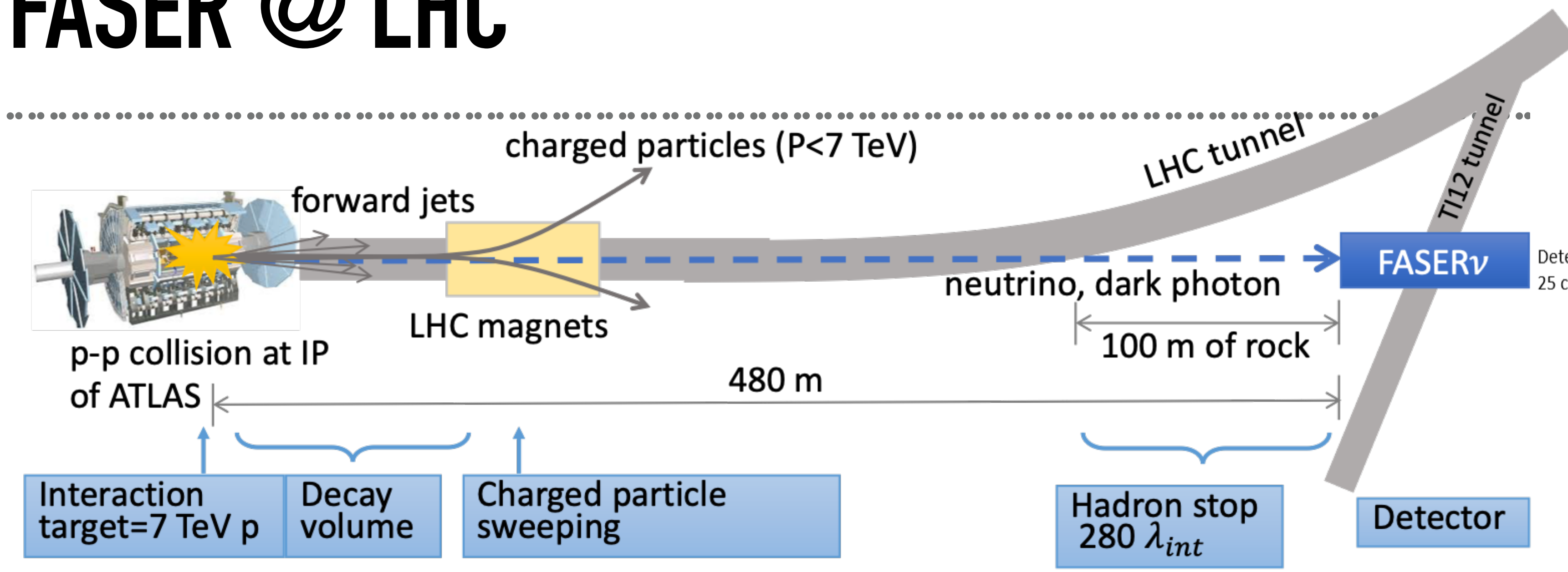


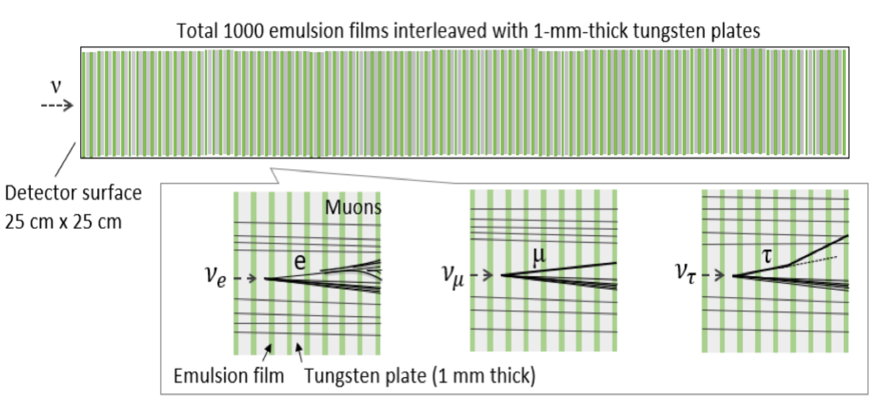
CERN "ACCELERATOR" NEUTRINO PLATFORM

- European Strategy for Particle Physics 2013:"CERN should develop a neutrino programme to pave the way for a substantial European role in future long-baseline experiments"
- Part of the CERN Medium Term Plan (since 2015). CERN acts as a hub for R&D on future technologies (HW and SW) and partner in several neutrino "accelerator" research programs
- Current activities:

- ENP01: ICARUS refurbishing and far detector in the SBN FNAL facility (now at FNAL almost ready for operation)
- NP02: LAr double phase TPC demonstrator (ProtoDUNE DP)
- NP03: PLAFOND –generic detectors R&D
- NP04: LAr single phase TPC demonstrator (ProtoDUNE SP)
- NP05: Baby Mind muon detector for T2K near (operational)
- NP06: ENUBET project (new in the NP)
- NP07: ND280 T2K near detector upgrade (new)
- + agreed active participation in the construction and exploitation of the LBNF/DUNE and SBN US programs
- + collaboration with DarkSide20k experiment

FASER @ LHC





Emulsion detector with Tungsten target

- First neutrino project from colliders → **FASERν**
- Pilot run in 2018. Preparing for physics run 2021.
- Possible studies with high energy neutrinos at the TeV scale
  - Cross-section measurements of all flavours in **unexplored energy region**
  - Search for new physics effects in high-energy neutrino interactions