



# NEUTRINO PHYSICS FROM PARTICLE BEAM

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# OUTLINE

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- Introduction
  - Motivations
  - Current Particle Beams
  - CERN neutrino platform
- Current long baseline neutrino experiment
  - T2K, NOvA
- Reducing the Systematic Errors: on cross sections and beam
  - T2K, MicroBoone
- Future Expectations
  - DUNE, Hyper-Kamiokande
- Beyond the SM
  - SBN, ICARUS, SHIP, FASER
- Next facilities
  - Enubet,  $\nu$ STORM, ESS $\nu$ SB
- Conclusions

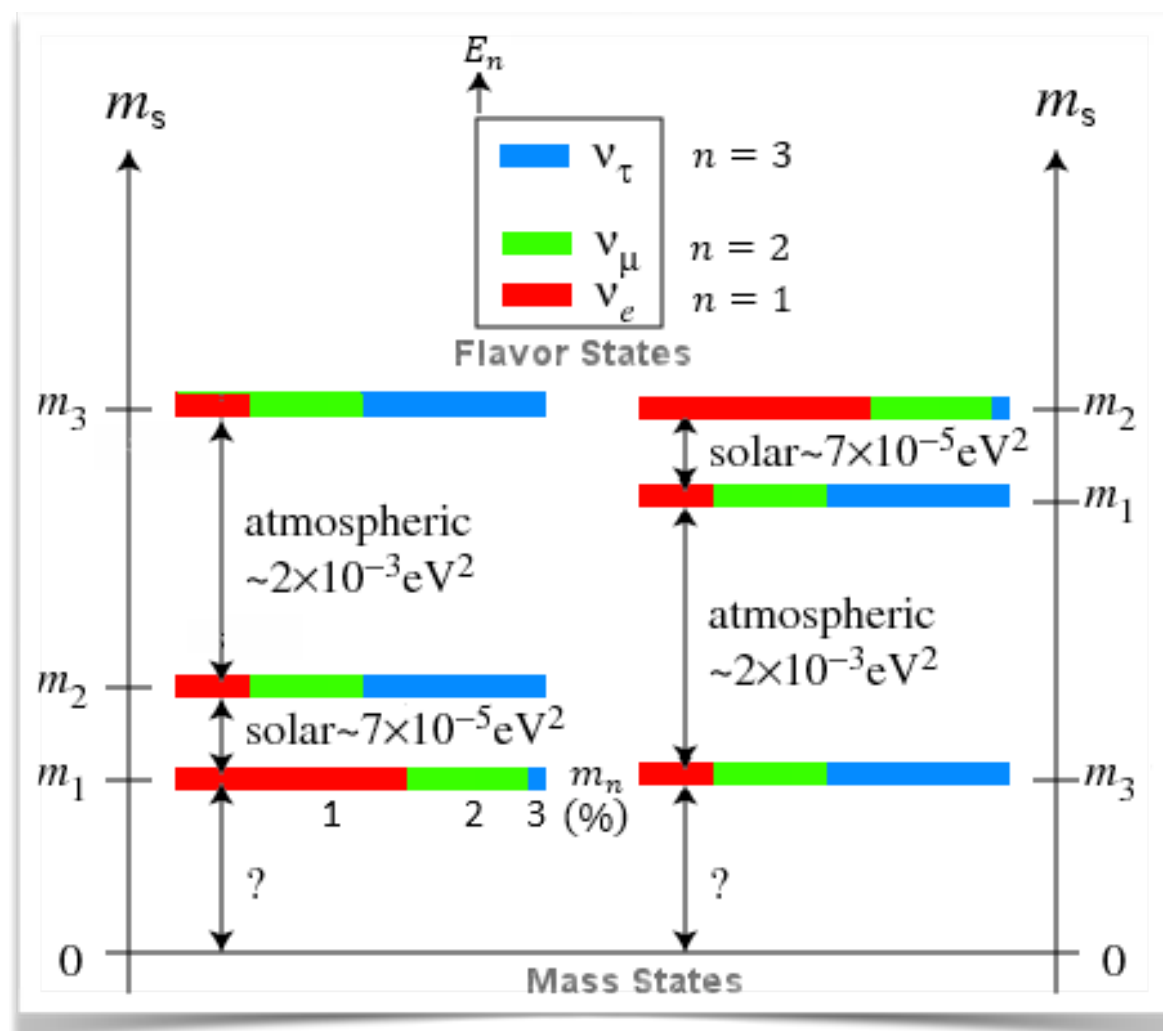
*Thanks to all collaborations and colleagues who provided important input to write this talk!*



# MOTIVATIONS

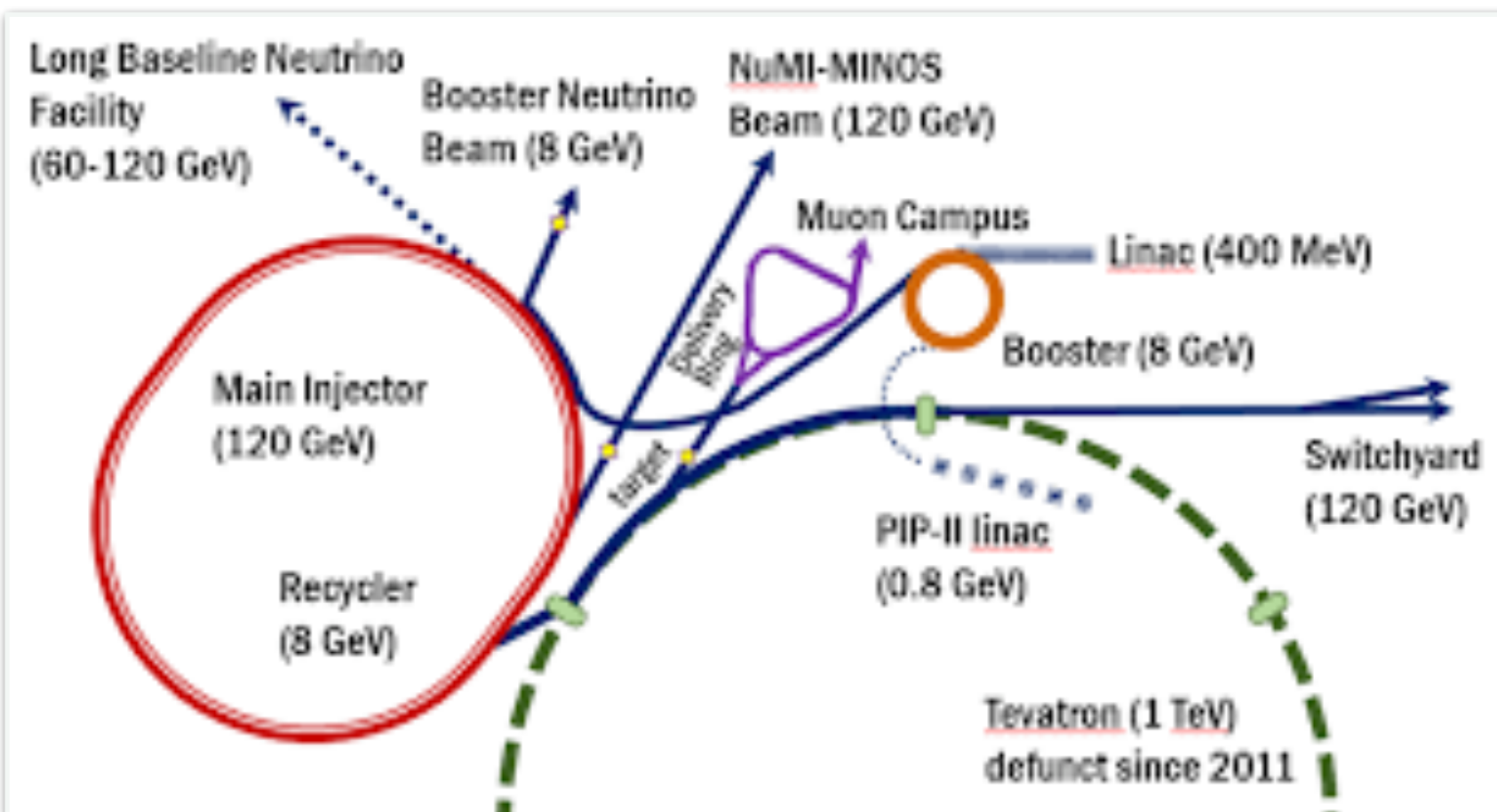
$$\begin{array}{c}
 \text{Flavour} \qquad \qquad \text{Atmospherics} \qquad \qquad \text{Accelerator/Reactor} \qquad \qquad \text{Solar} \qquad \qquad \text{Mass} \\
 \left( \begin{array}{c} \nu_e \\ \nu_\mu \\ \nu_\tau \end{array} \right) = \left( \begin{array}{ccc} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{array} \right) \left( \begin{array}{ccc} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{array} \right) \left( \begin{array}{ccc} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{array} \right) \left( \begin{array}{c} \nu_1 \\ \nu_2 \\ \nu_3 \end{array} \right)
 \end{array}$$

Normal Hierarchy (NH)      Inverted Hierarchy (IH)



- What is the value of  $\delta_{CP}$ ??
- What is the mass hierarchy?
- Is mixing matrix parametrisation correct?
- What is the absolute mass scale?
  - Why so small??
- What is the nature of neutrino mass?
  - Dirac or Majorana?

# FERMILAB NEUTRINO BEAM LINES

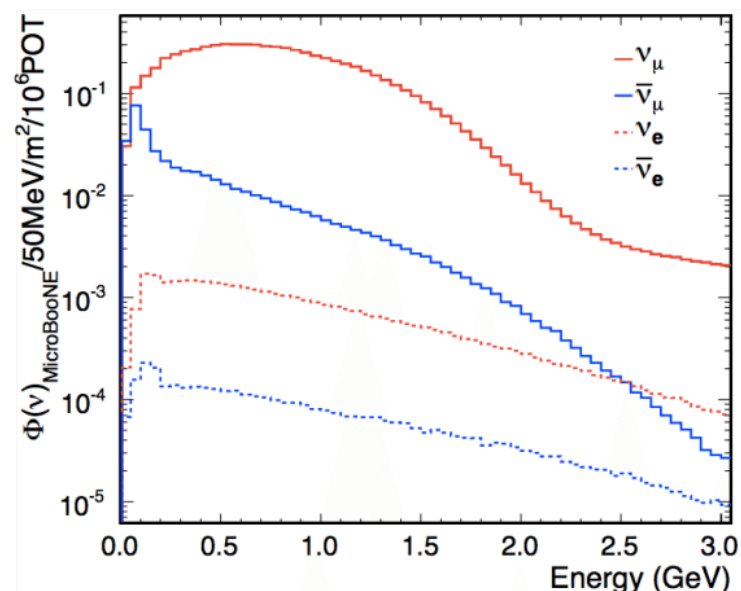


Three neutrino beam lines:

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

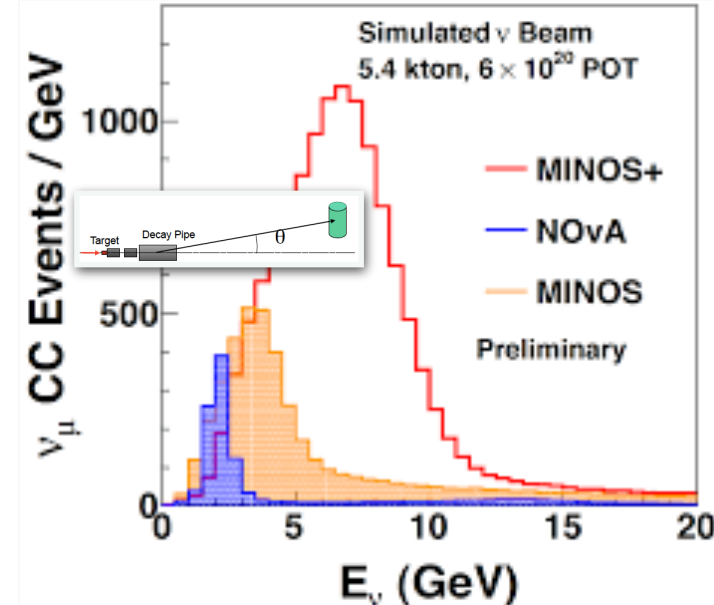
arXiv:1709.00146v1

BNB



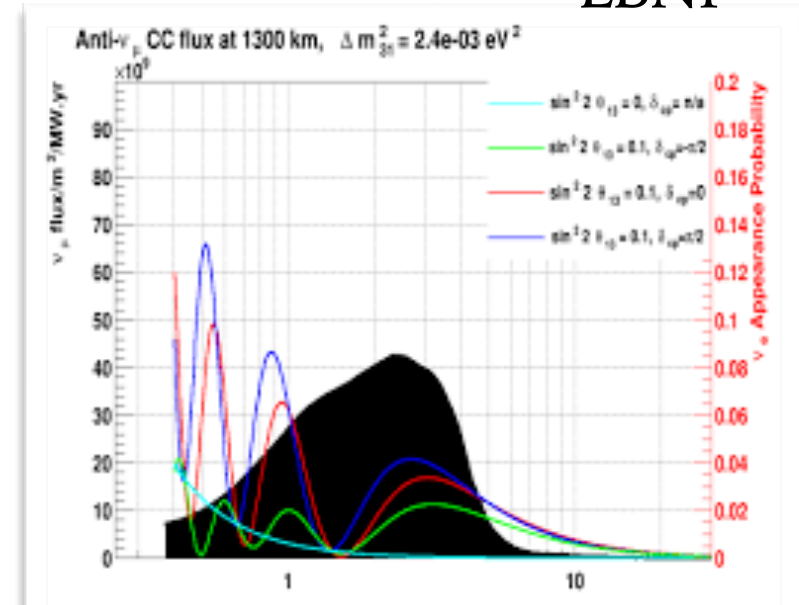
arXiv:1502.07715v2

NuMi



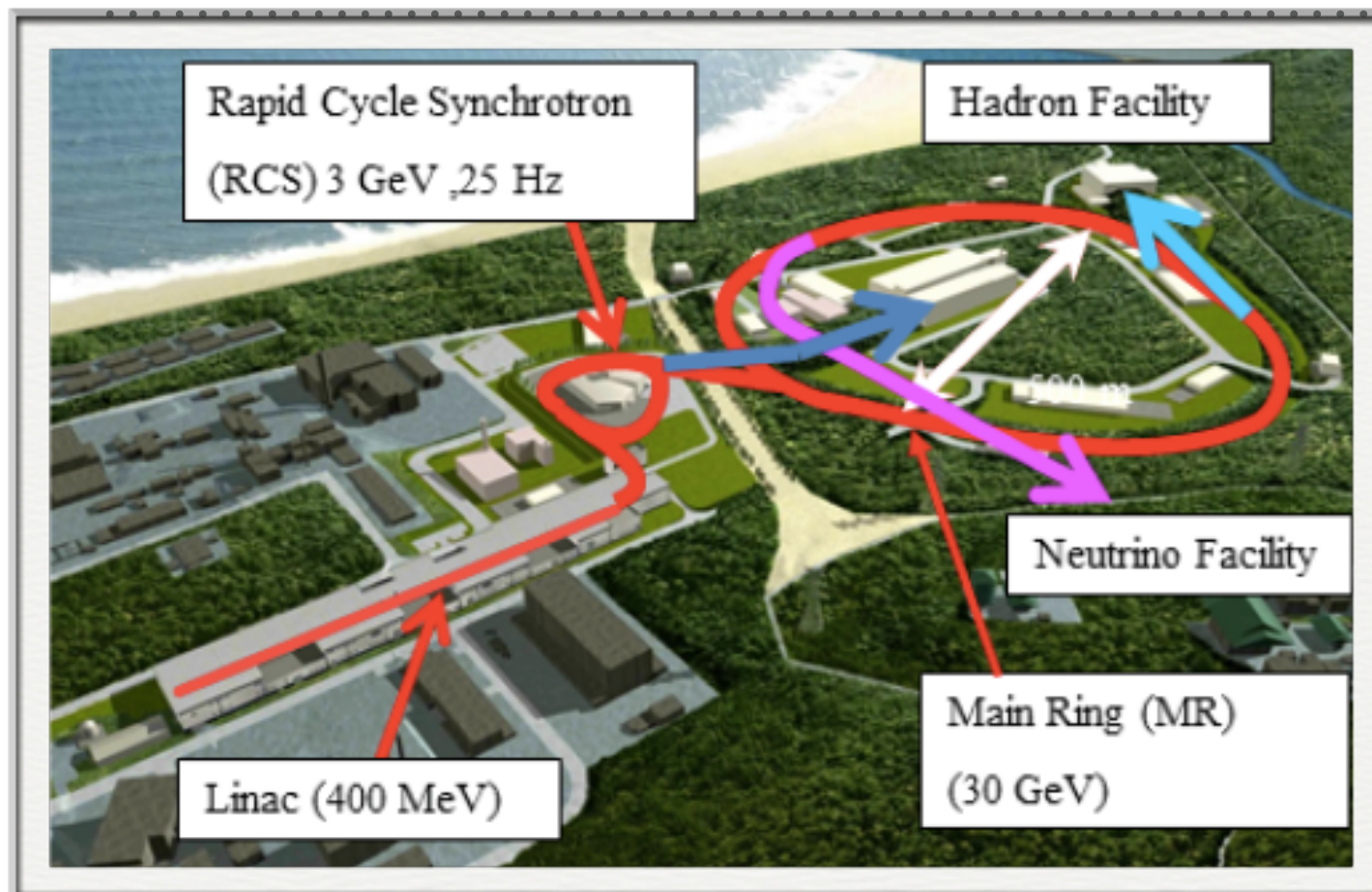
Letter of intent P-1062

LBNF

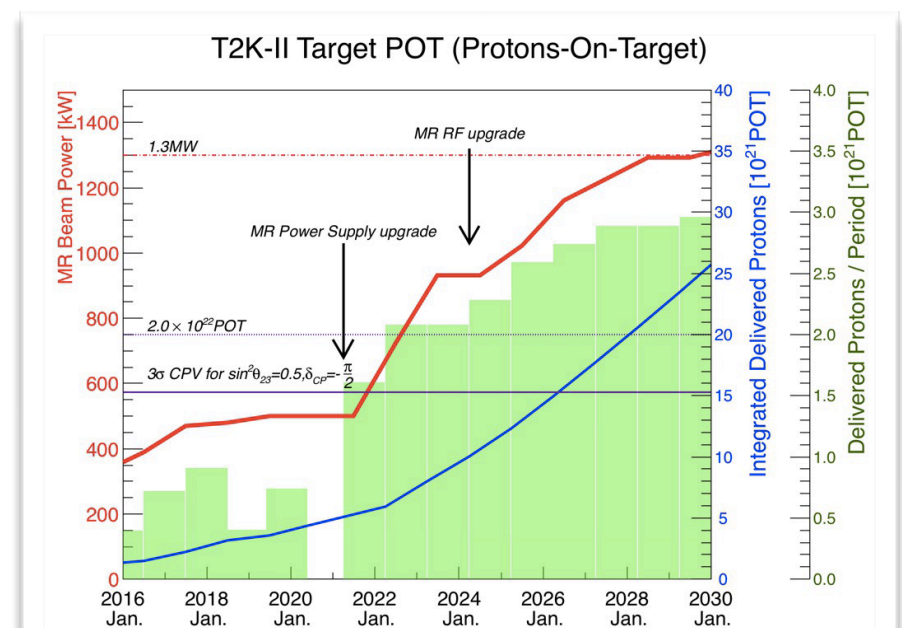
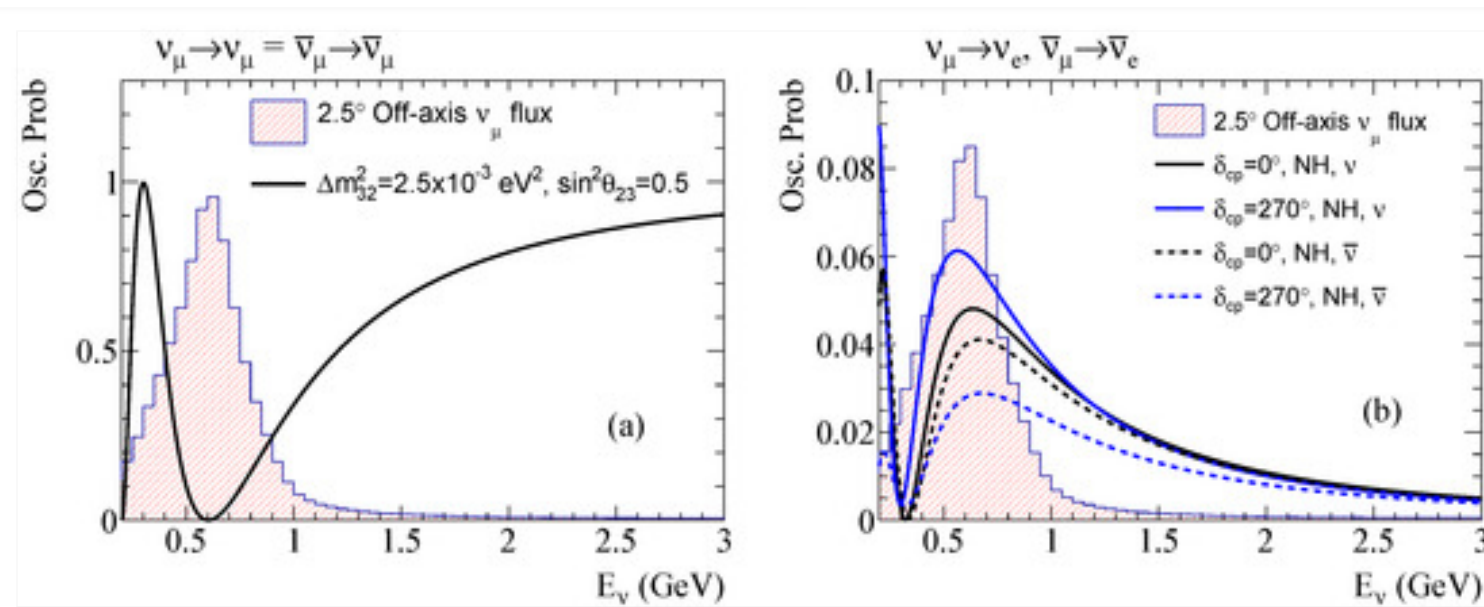




# J-PARC NEUTRINO BEAM LINE



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





# CERN “ACCELERATOR” NEUTRINO PLATFORM

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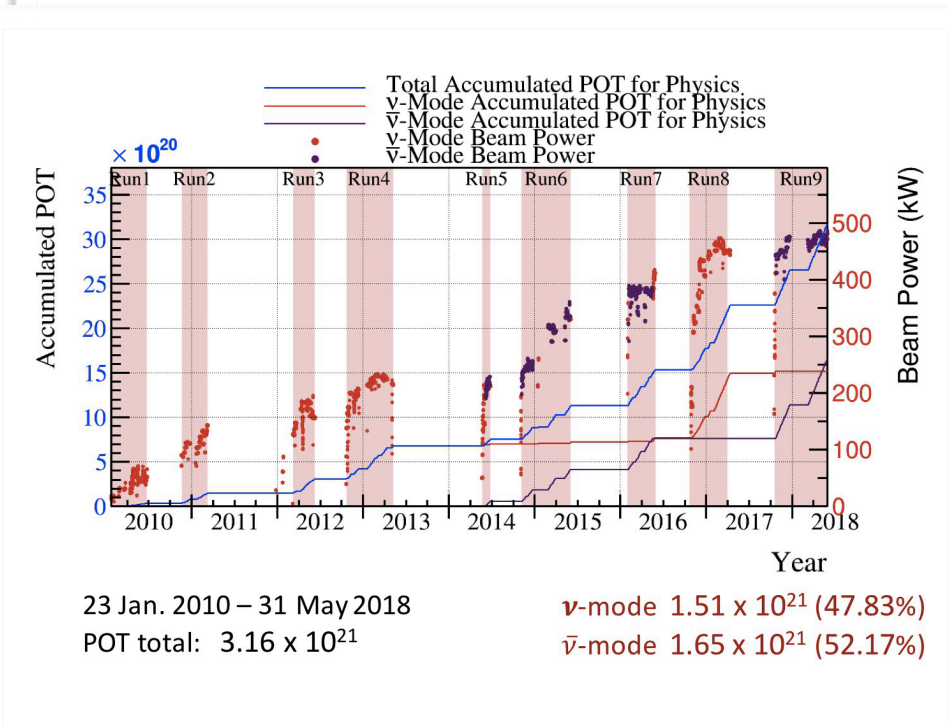
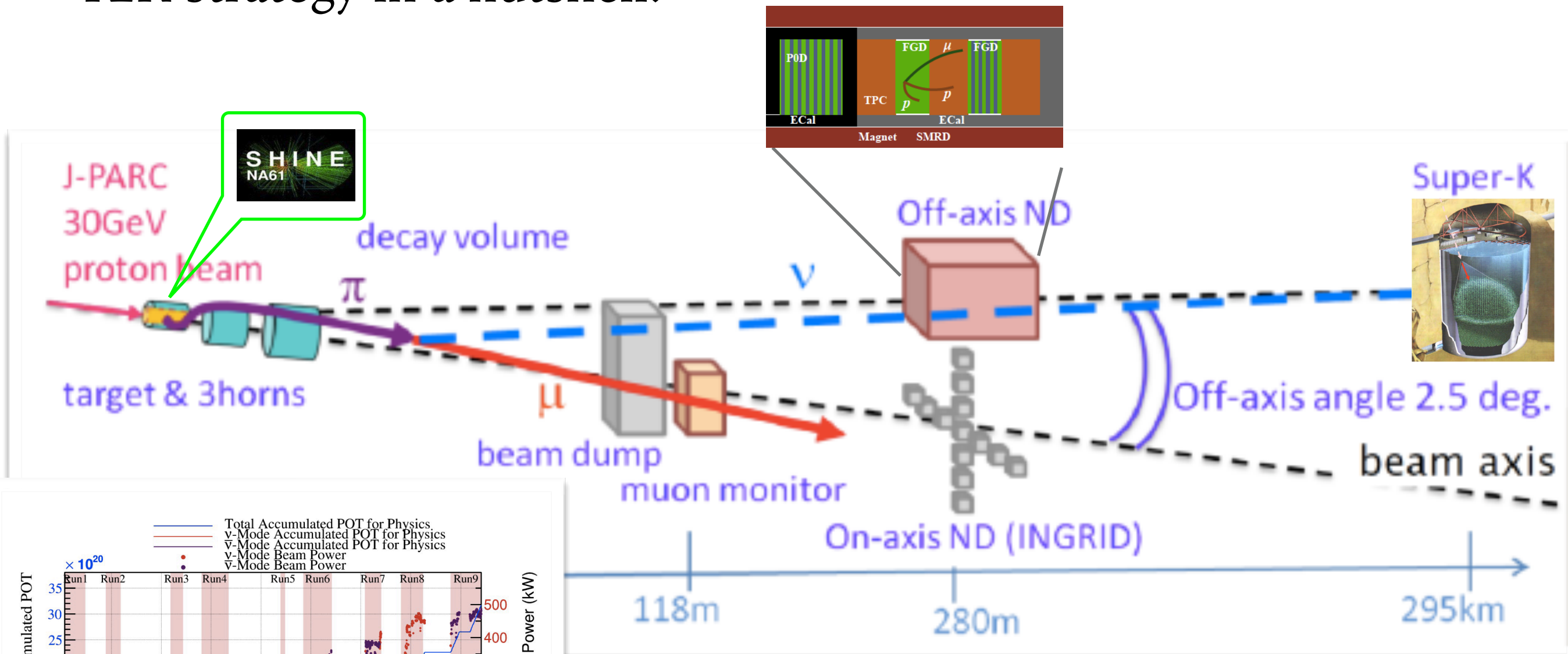
- European Strategy for Particle Physics 2013: “CERN should develop a neutrino programme to pave the way for a substantial European role in future long-baseline experiments”
- Part of the CERN Medium Term Plan (since 2015). CERN acts as a hub for R&D on future technologies (HW and SW) and partner in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

# TOKAI-2-KAMIOKA (T2K)

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

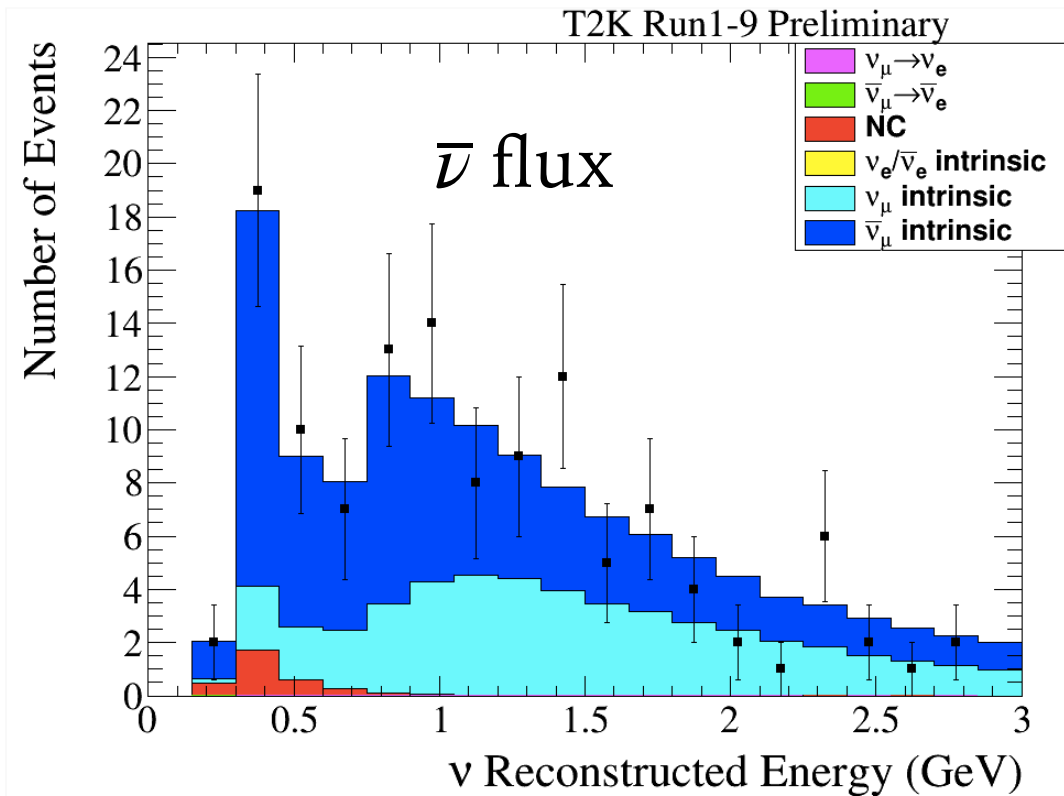
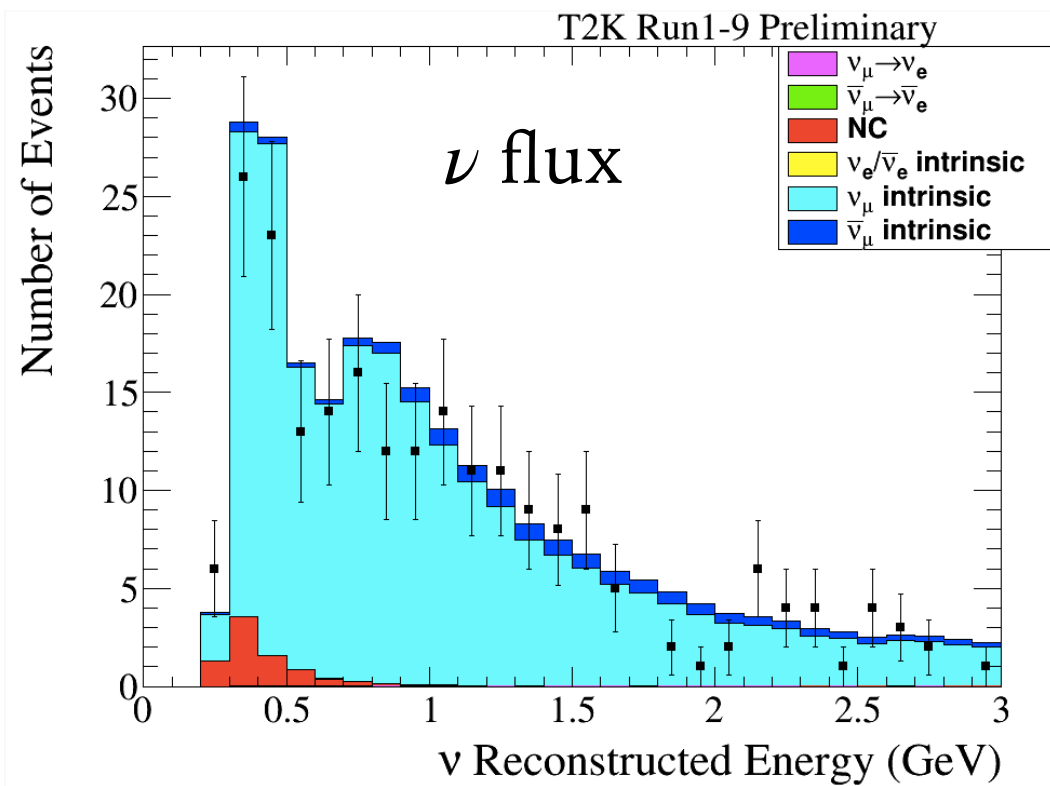
$$\Phi_{\nu\text{far}}(E, \theta, \Delta m^2, \delta) \cdot \sigma_{\text{far}}(E, Q_2) \cdot \varepsilon_{\text{far}}(E)$$

## ► T2K strategy in a nutshell:



- Total proton on target (POT) collected:  $3.1 \times 10^{21}$  POT
  - $1.5 \times 10^{21}$  POT in  $\nu$  mode
  - $1.6 \times 10^{21}$  POT in  $\bar{\nu}$  mode
- Beam power 500 kW!

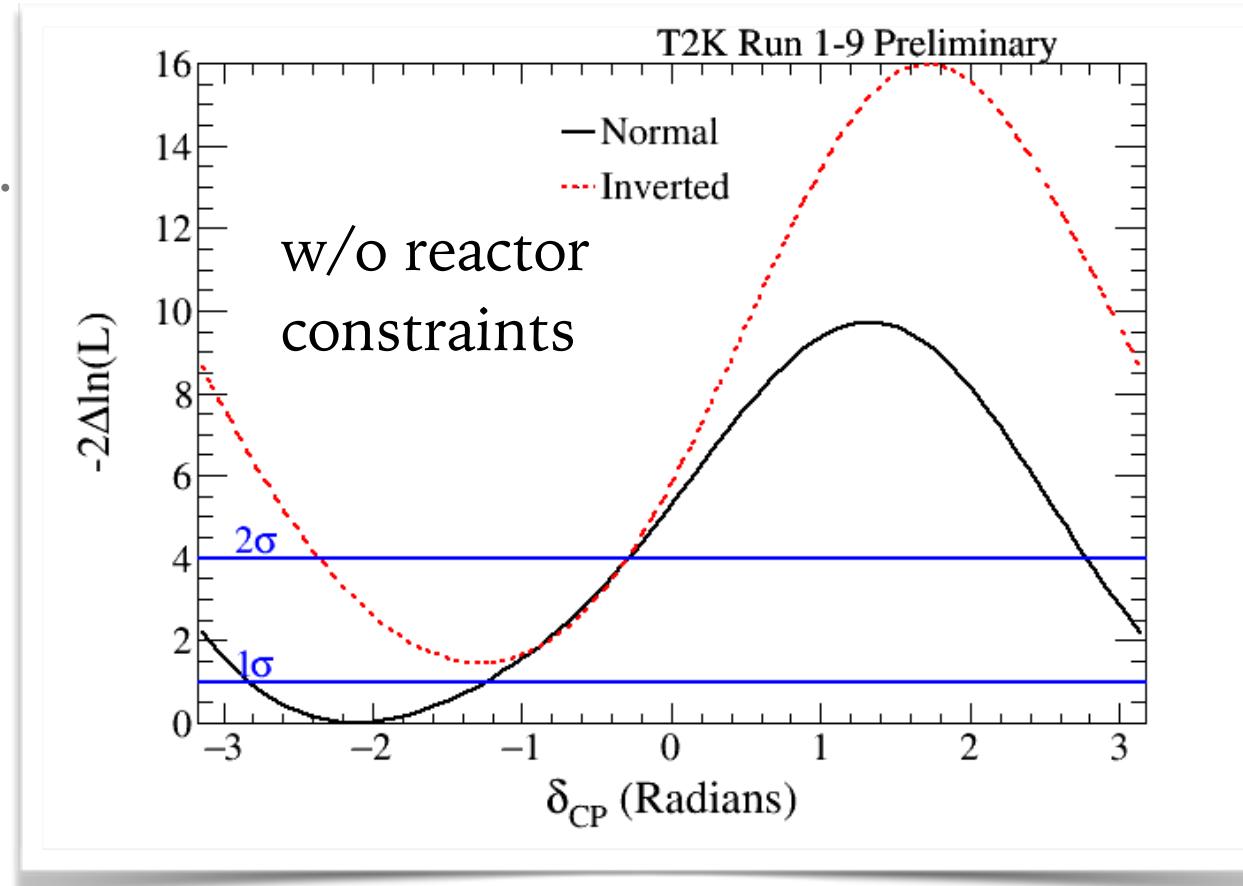
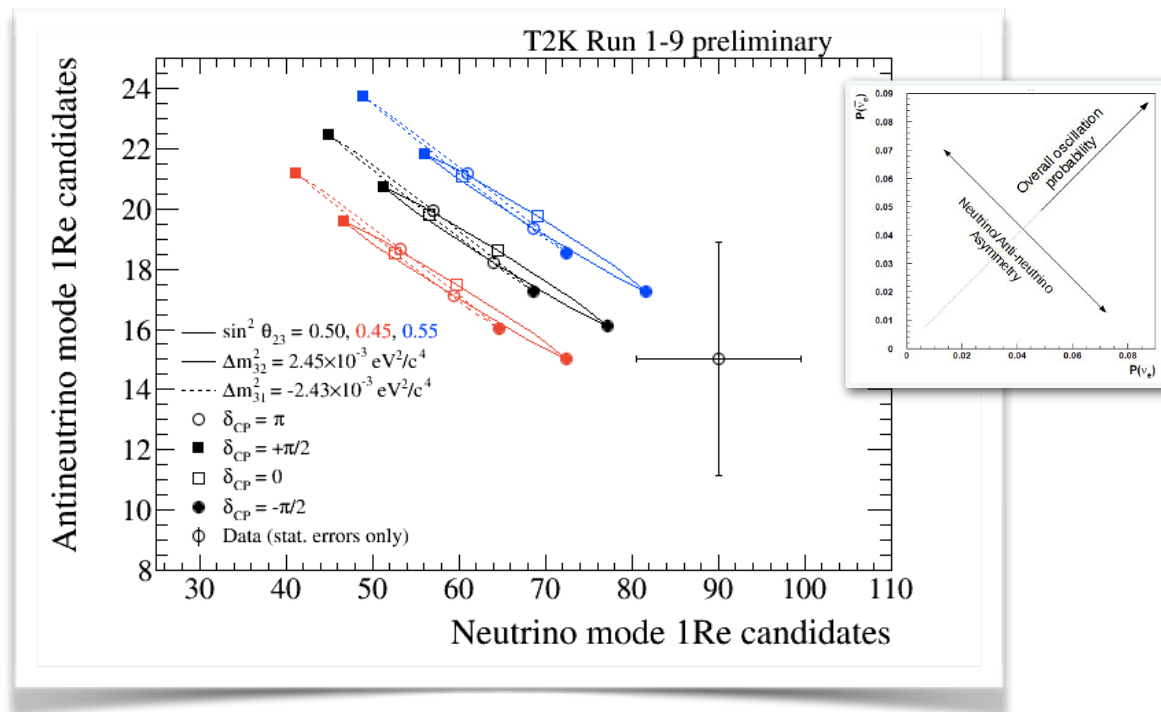
# OBSERVED EVENTS AT SUPER-KAMIOKANDE



	Observed	$\delta = -\pi/2$	$\delta = 0$	$\delta = +\pi/2$	$\delta = \pi$
$e$ -like $\nu$ mode	75	74.4	62.2	50.6	62.7
$e$ -like+ $1\pi^+$ $\nu$ mode	15	7.0	6.1	4.9	5.9
$e$ -like $\bar{\nu}$ mode	15	17.1	19.4	21.7	19.3
$\mu$ -like $\nu$ mode	243	272.4	272.0	272.4	272.8
$\mu$ -like $\bar{\nu}$ mode	140	139.2	139.2	139.5	139.9



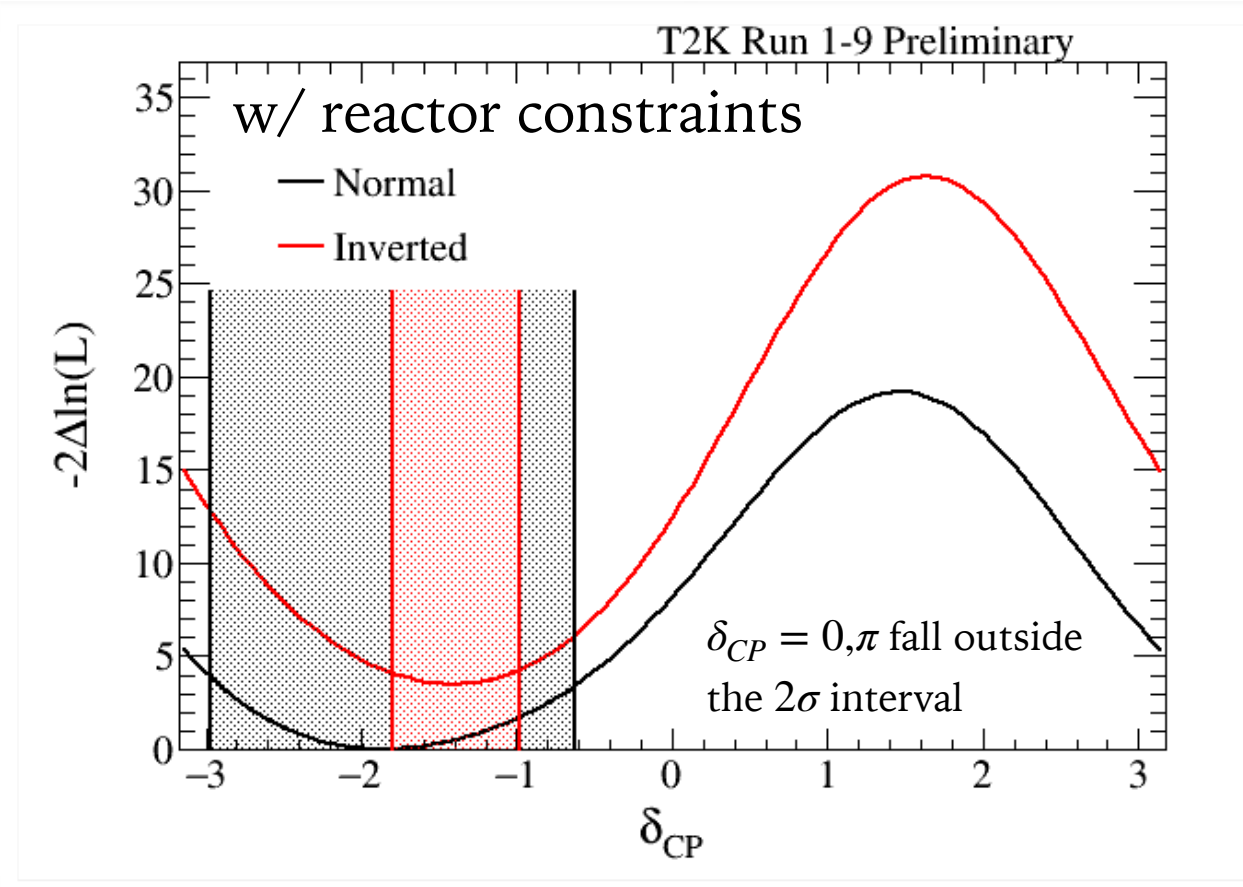
# $\delta_{CP}$ MEASUREMENT



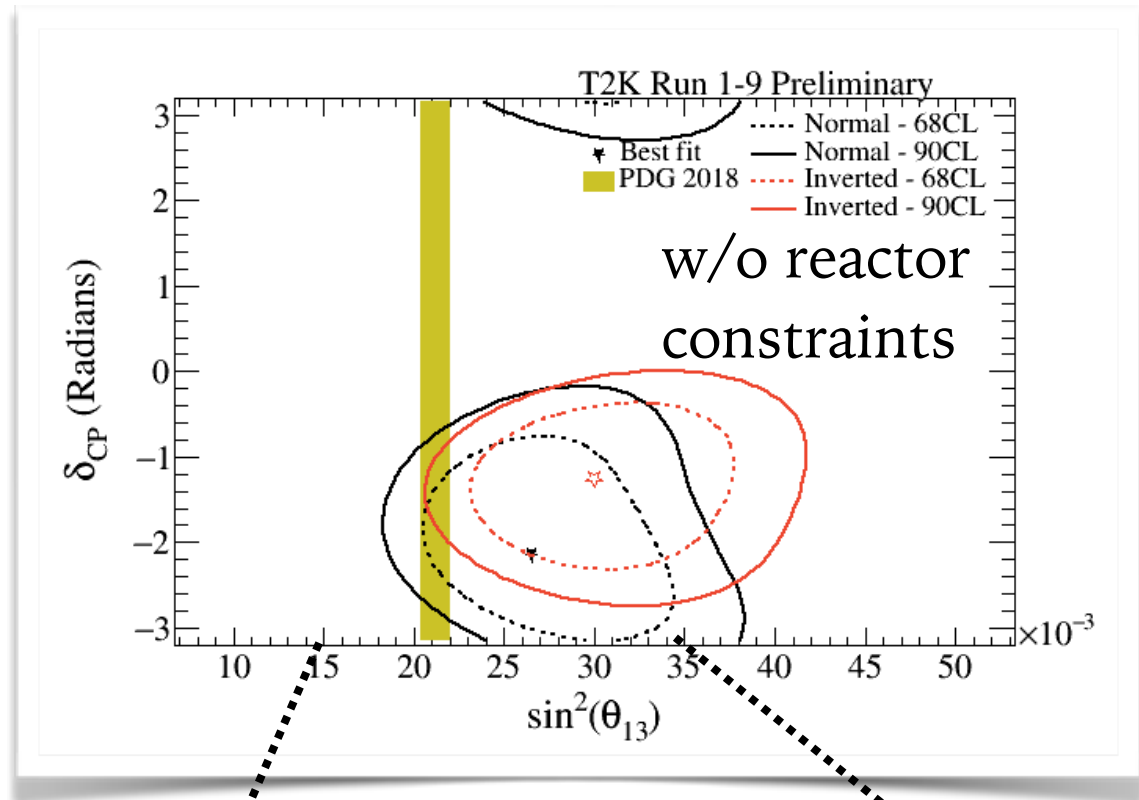
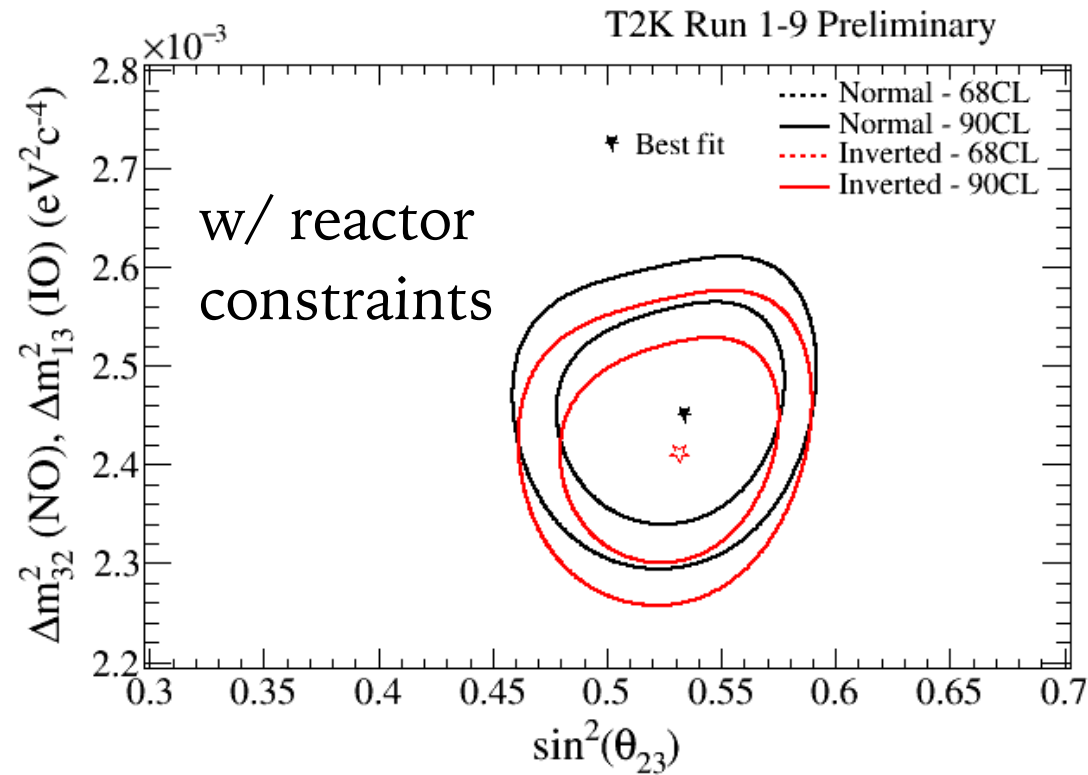
T2K data prefer values of  $\delta_{CP} \sim -\frac{\pi}{2}$ : mostly driven by the large number of events observed in the e-like sample in neutrino mode.

CP conservation ( $\delta_{CP} = 0, \pi$ ) disfavoured at  $2\sigma$  for both mass hierarchies.

C.L.	Normal hierarchy	Inverted hierarchy
68%	[-2.51, -1.26]	-
90%	[-2.80, -0.84]	-
2 $\sigma$	[-2.97, -0.63]	[-1.78, -0.98]

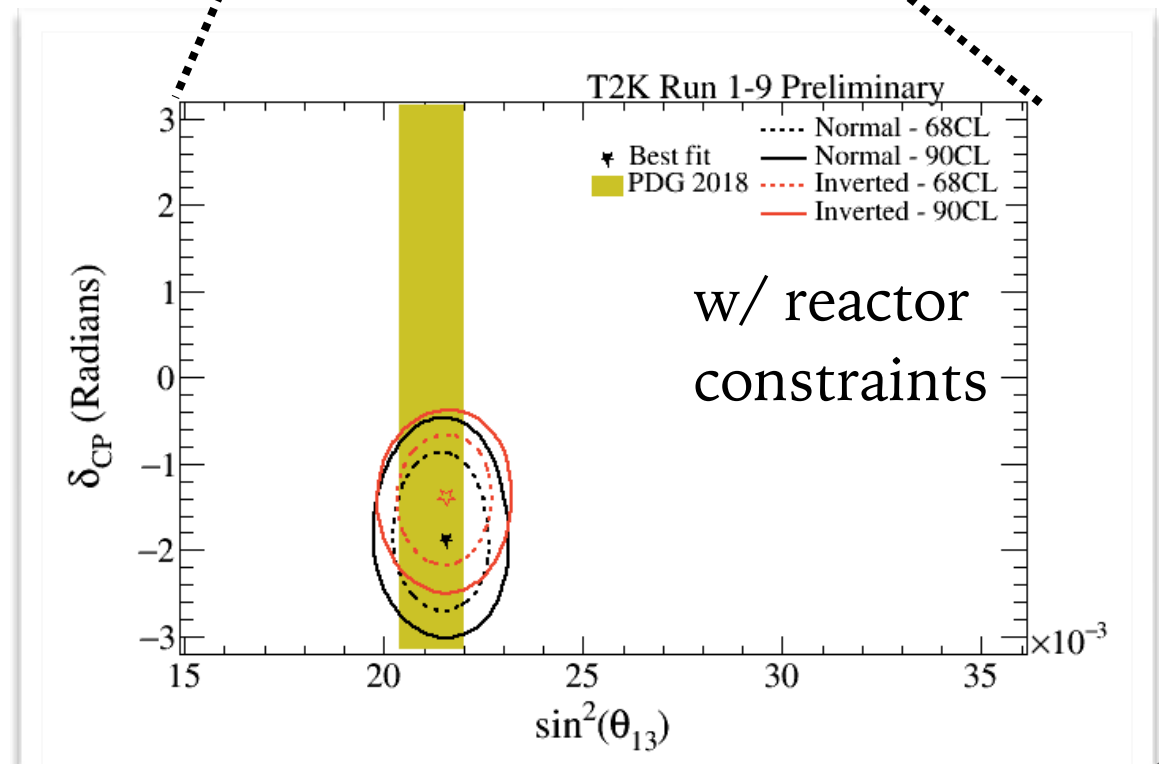


# OSCILLATION RESULTS ( $\theta_{23}$ , $|\Delta m_{23}^2|$ , $\theta_{13}$ , $\delta_{CP}$ )



T2K data compatible with maximal mixing

Parameter	Best Fit NH (IH)	$\pm 1\sigma$ NH (IH)
$\sin^2\theta_{32}$	0.54 (0.53)	[0.490,0.558] ([0.496,0.560])
$ \Delta m_{32}^2  \text{ (} 10^{-3}\text{eV}^2/\text{c}^4\text{)}$	2.46 (2.43)	[2.370,2.498] ([2.362,2.502])
$\sin^2\theta_{13}$	0.0268 (0.0305)	[0.0222,0.0319] ([0.0253,0.0369])



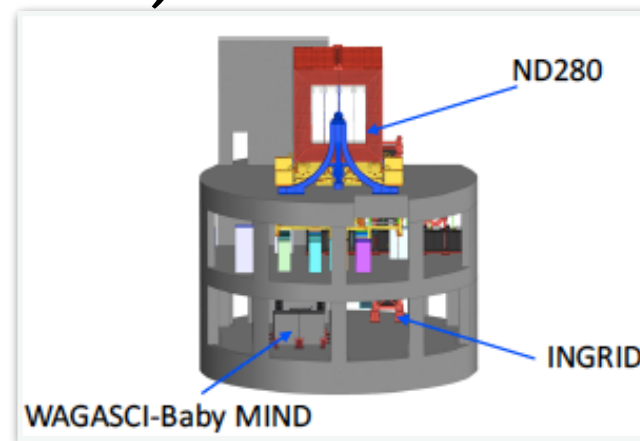
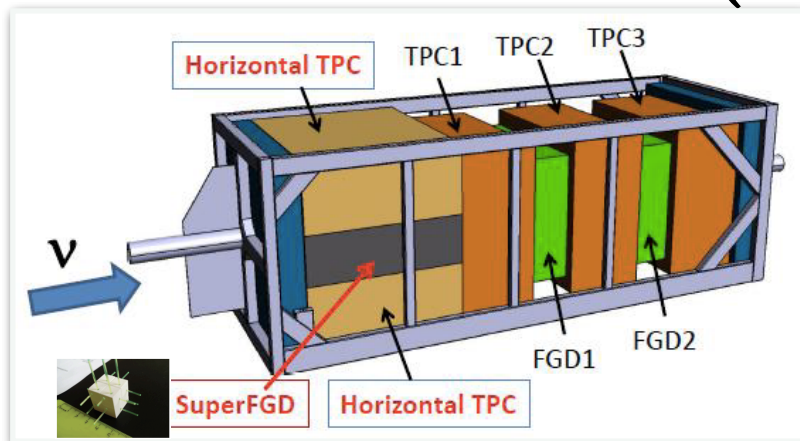
# T2K IN THE NEXT DECADE (*aka* T2K-II): UPGRADED BEAM & DETECTORS

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  $\sim 4\%$

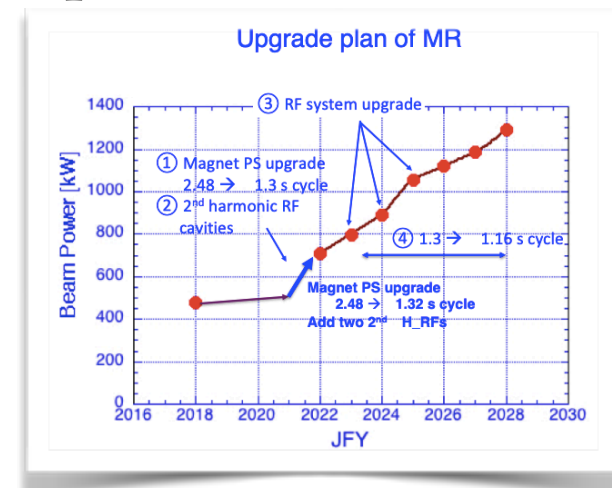
Near detector suite (at 280m):



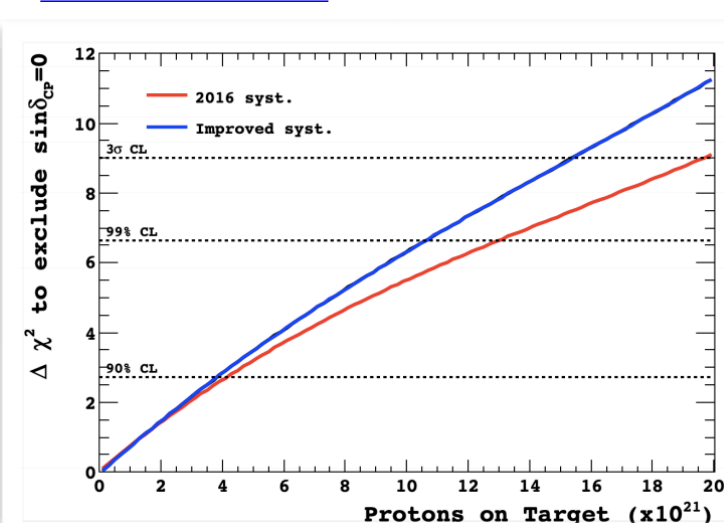
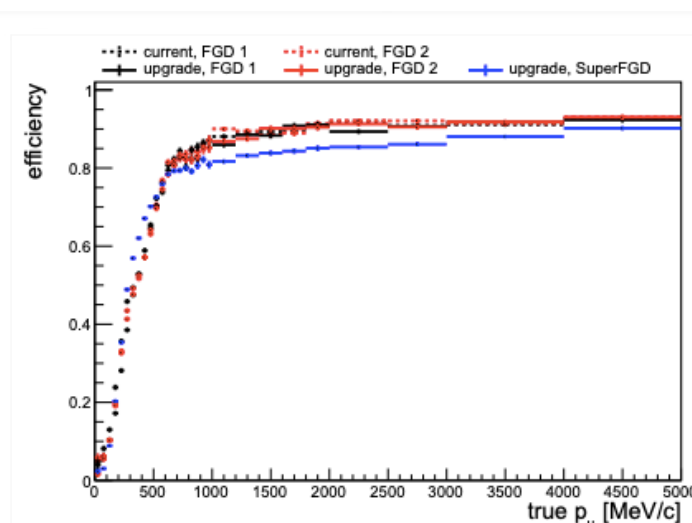
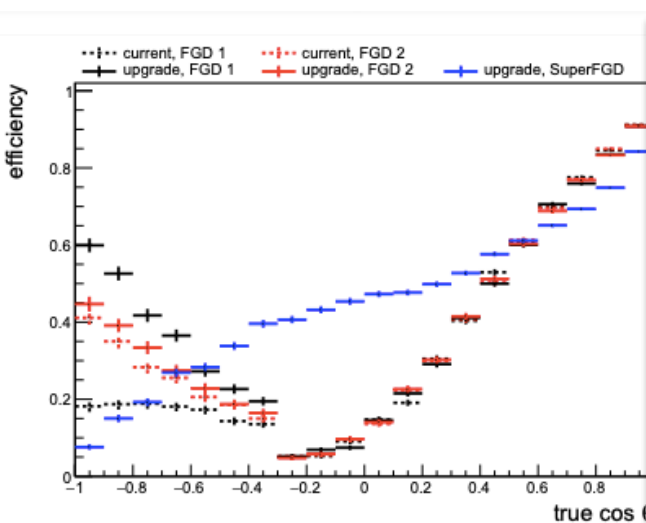
Super-Kamiokande

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

Beam power schedule



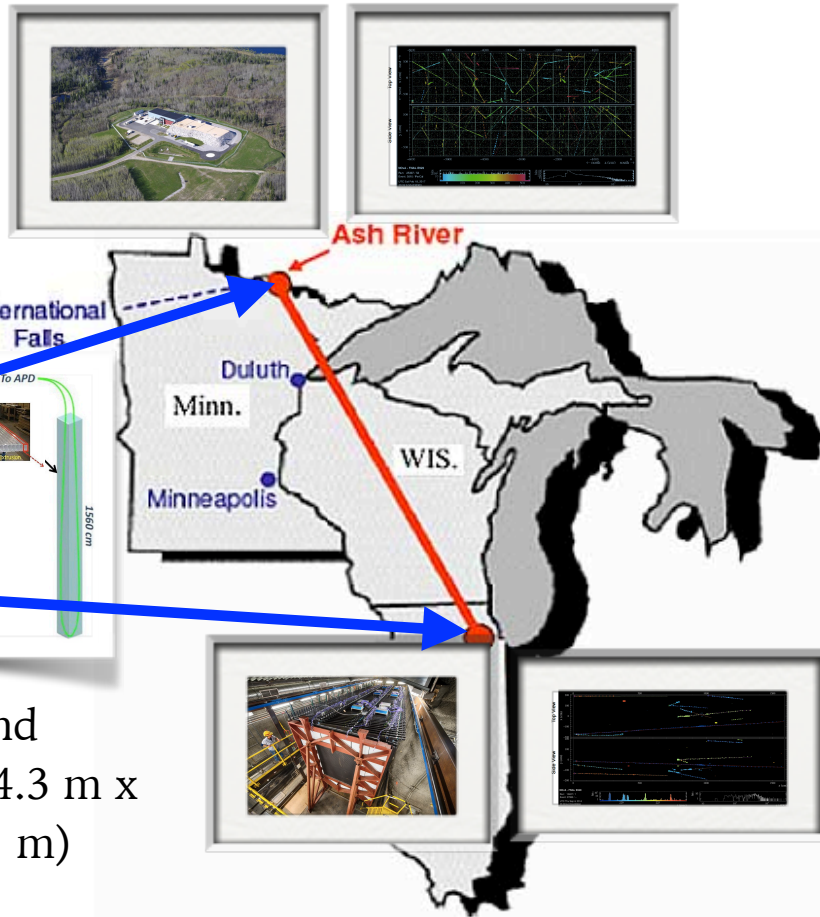
[arXiv:1901.03750](https://arxiv.org/abs/1901.03750)





# NOVA

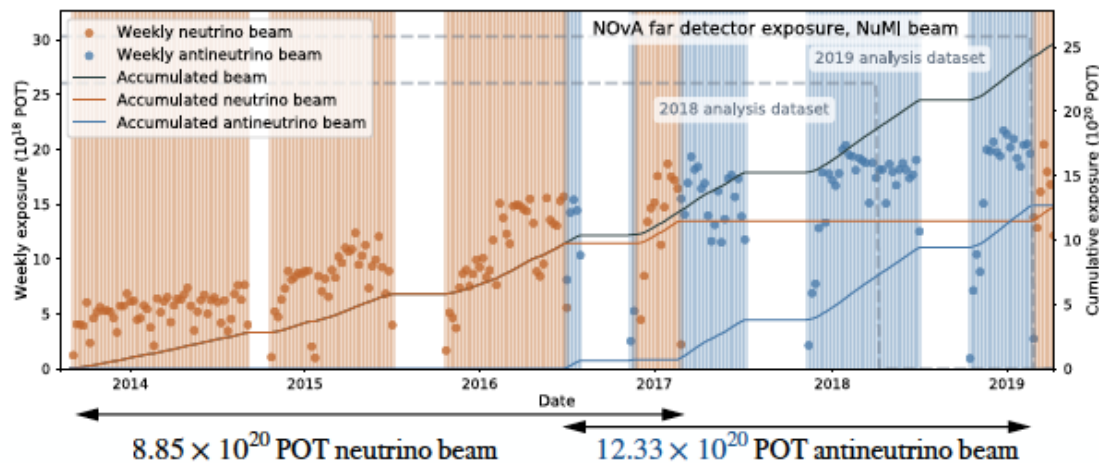
on the surface  
14 kton (60 m x  
15.6 m x 15.6 m)



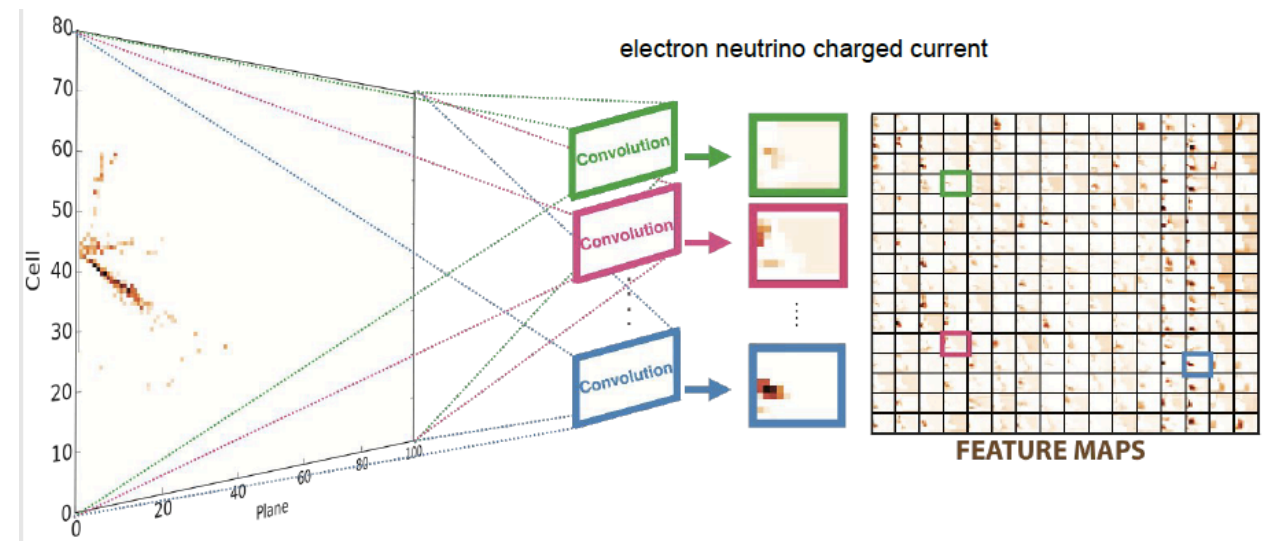
underground  
300 ton (14.3 m x  
4.1 m x 4.1 m)

Sensitivity to mass hierarchy thanks to  
matter effect  $\Rightarrow$  determine sign of  $\Delta m_{23}^2$

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

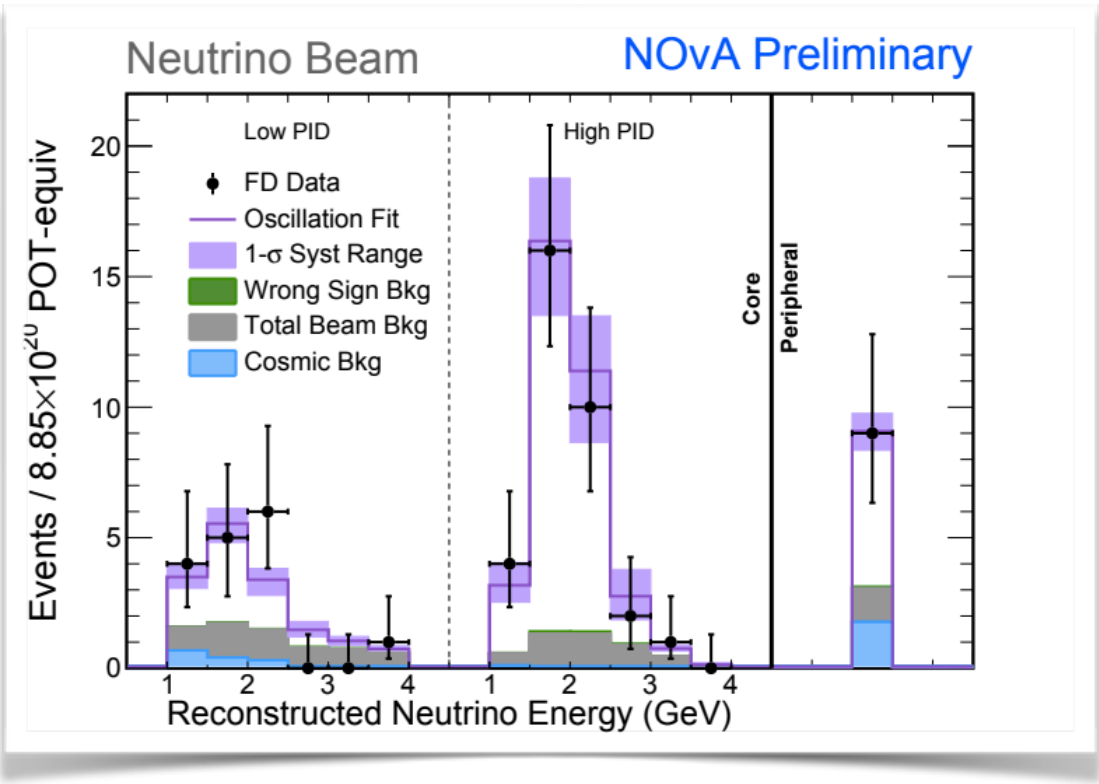


- Functionally identical near and far detector
- Events are classified using a Convolutional Neural Network



# NOVA FAR DETECTOR DATA

$\nu_e$  sample



$\nu_e$  sample

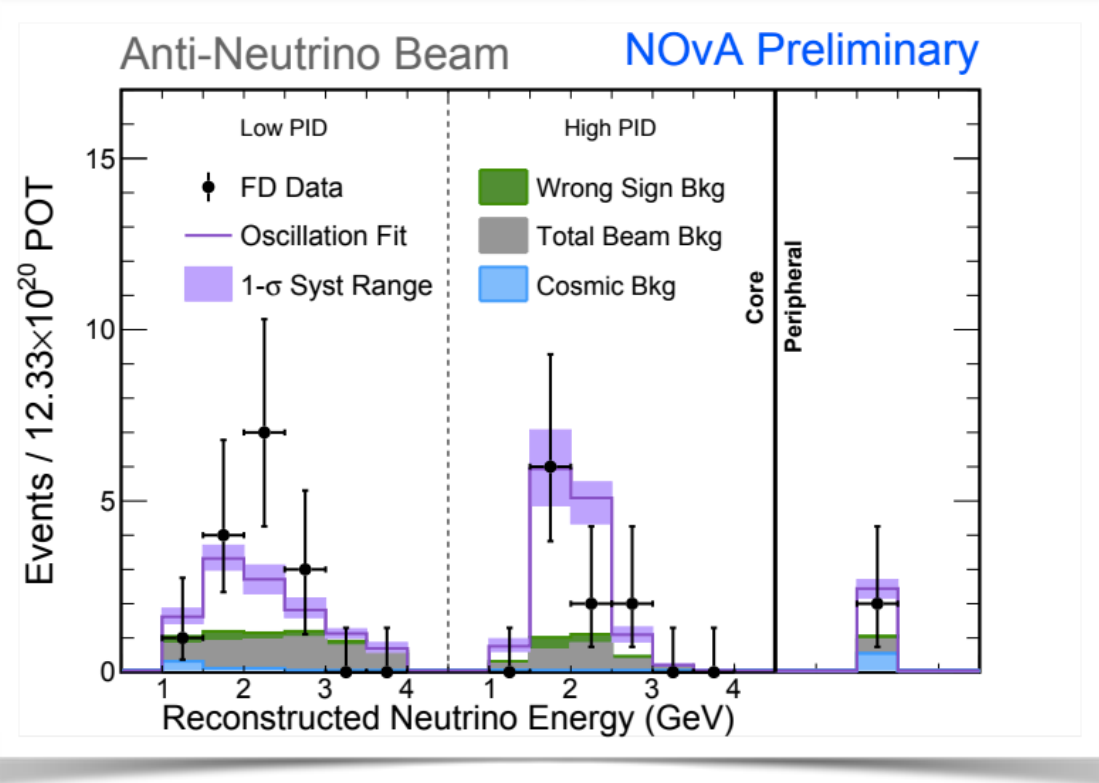
neutrino beam

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

$\nu_\mu$  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	27
Best Fit prediction	27
Total bkgd	10.3
Cosmic bkg	1.1
Beam bkg	7.0
Wrong sign ( $\nu_e$ app.)	2.2

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  $4.4\sigma$

# NOVA OSCILLATION RESULTS

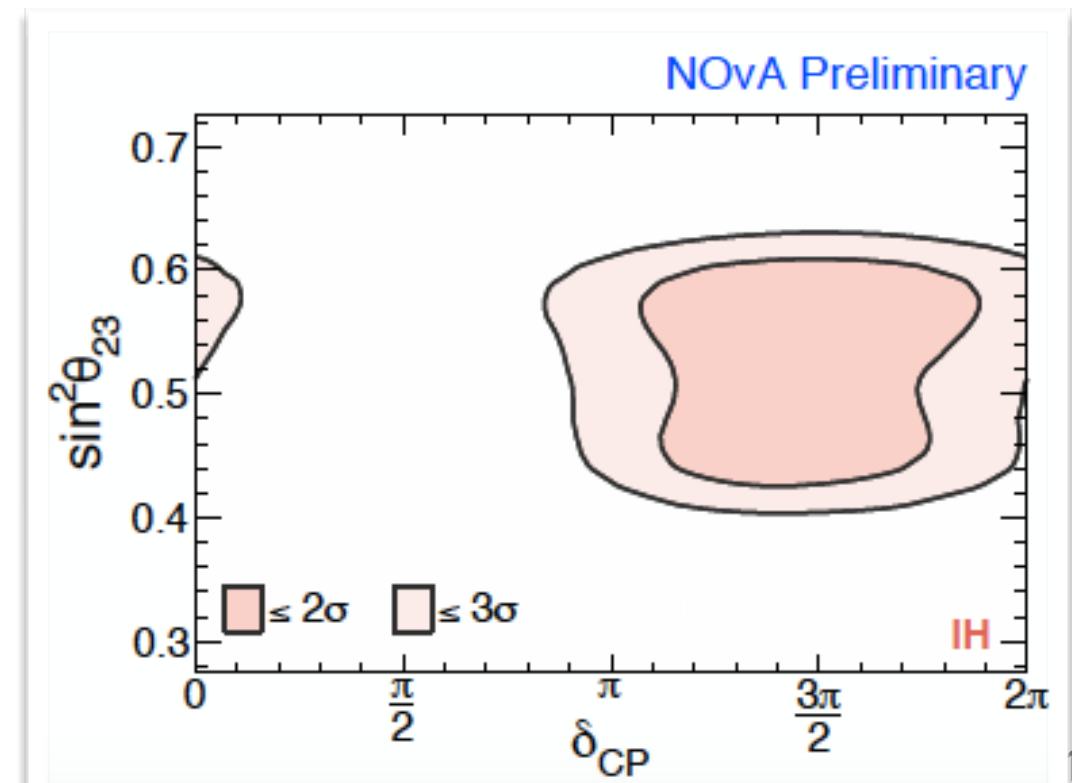
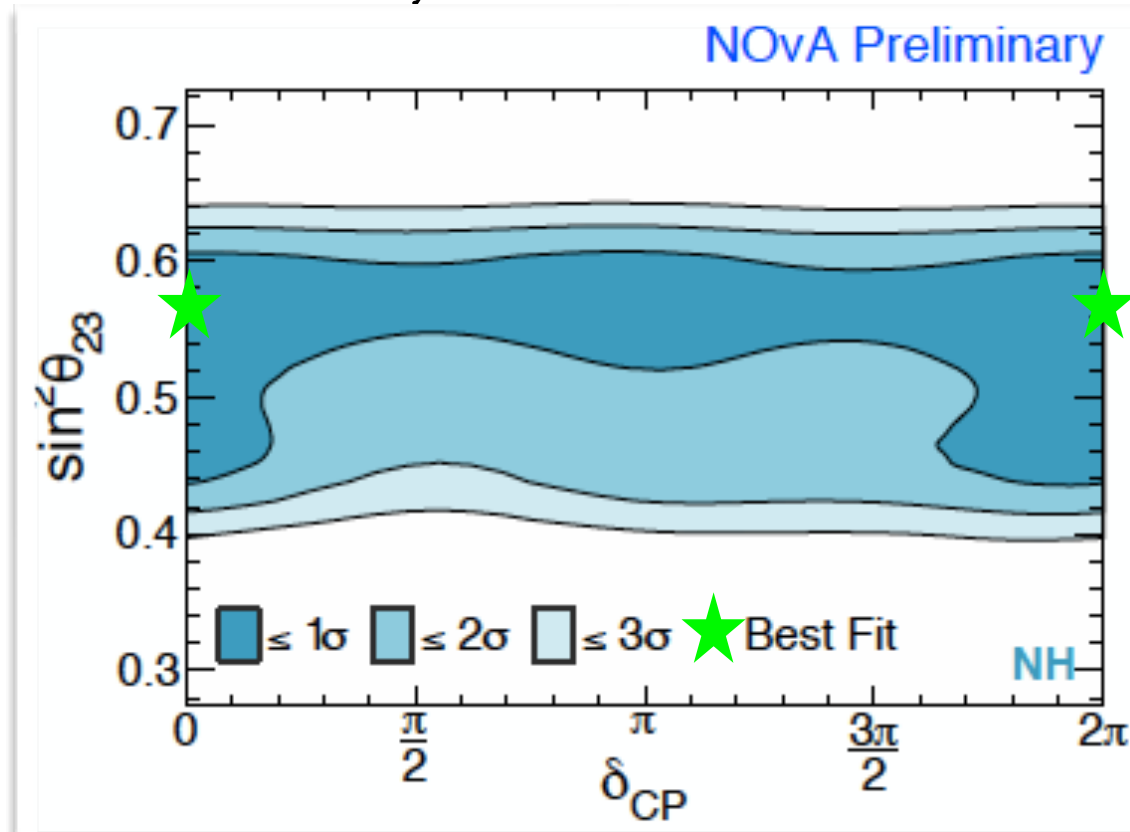
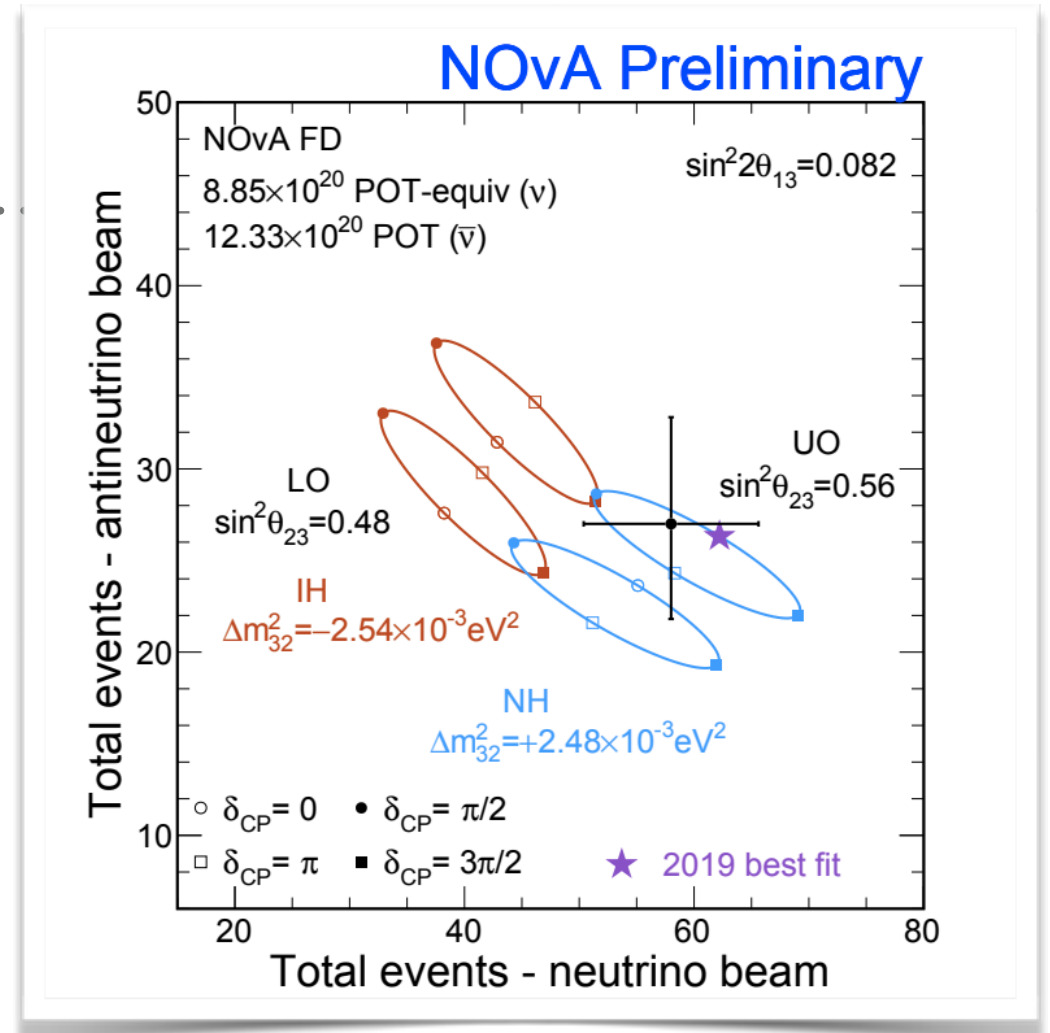
Best fit:

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

$$\Delta m_{32}^2 = +2.48 \times 10^3 \text{ eV}^2 \text{ (NH)}$$

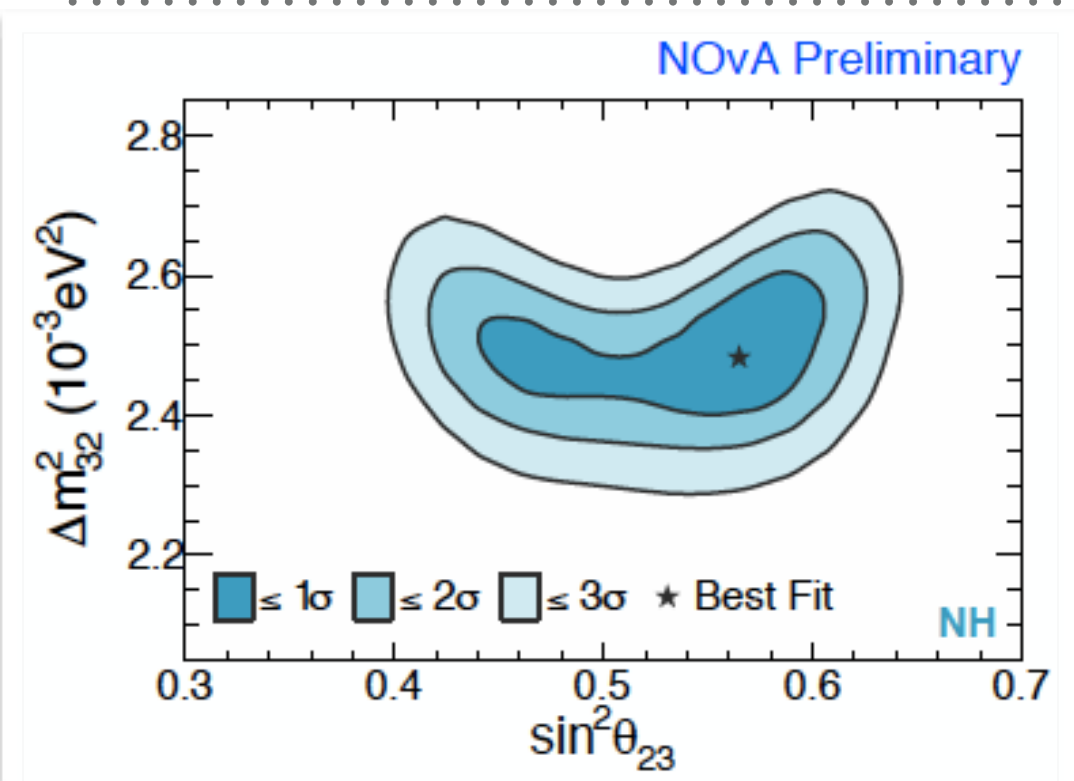
$$\delta_{CP} = 0.0^{+1.3}_{-0.4} \pi$$

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

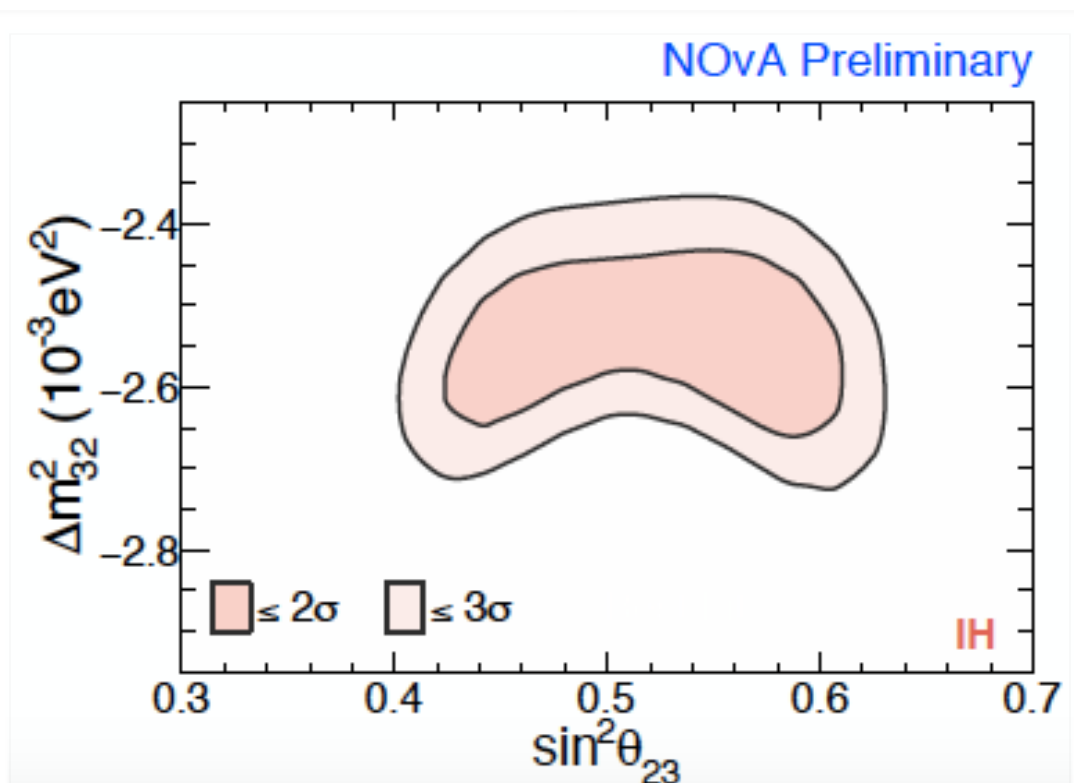
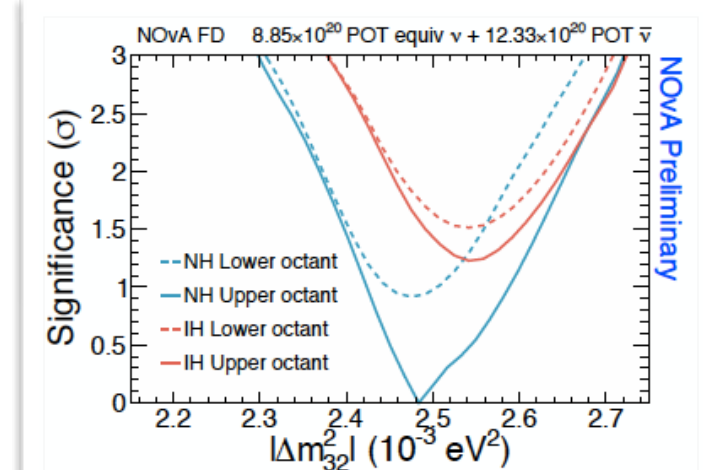
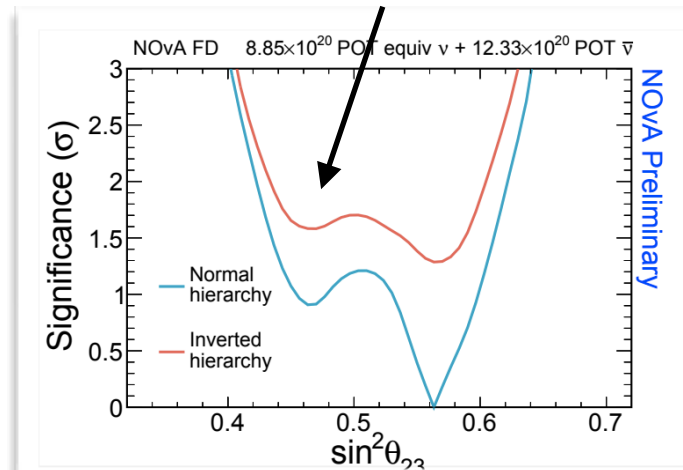




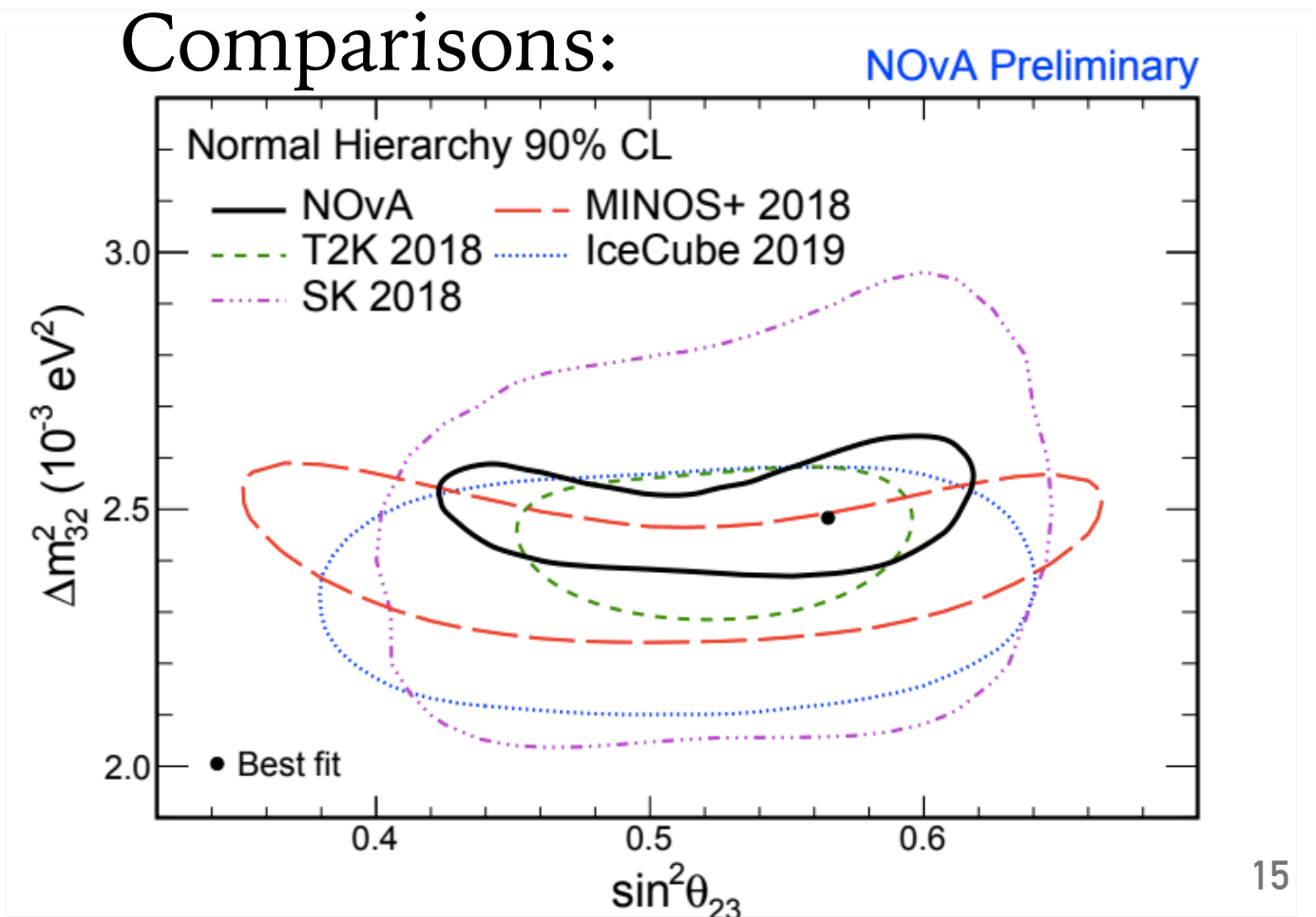
# NOVA OSCILLATION RESULTS



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

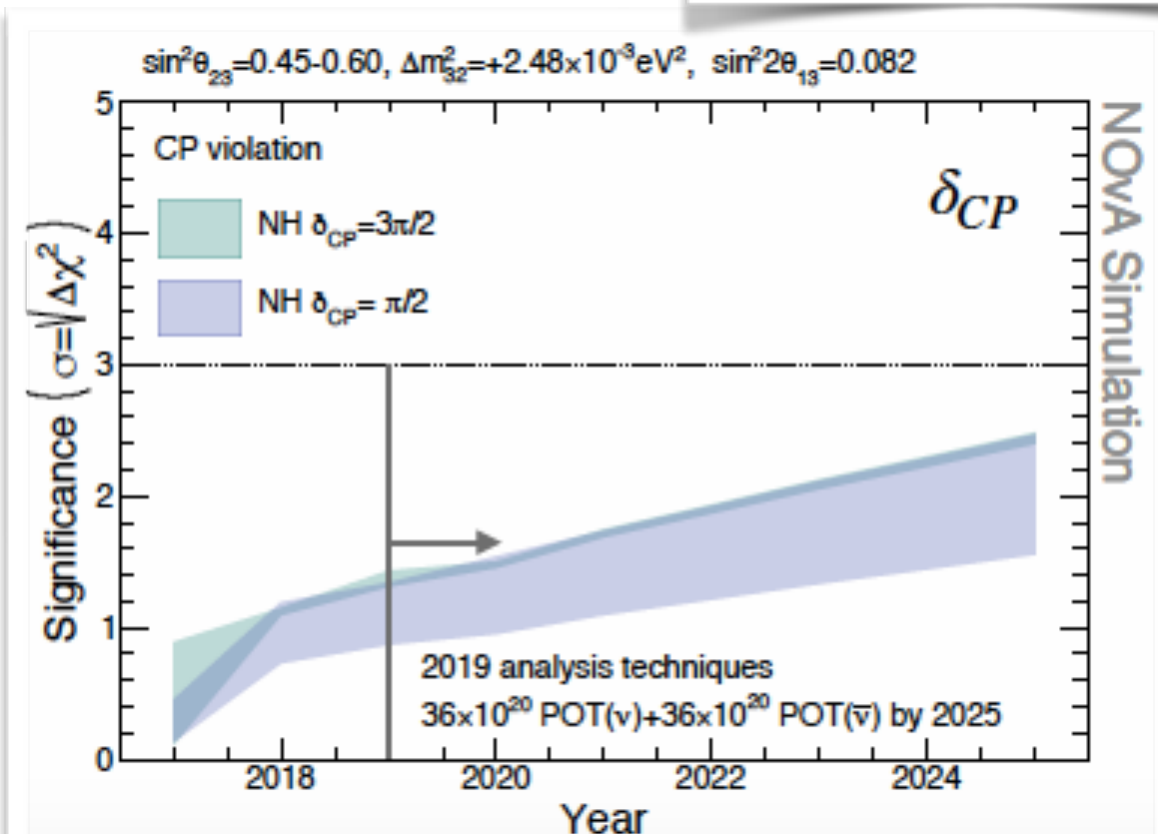
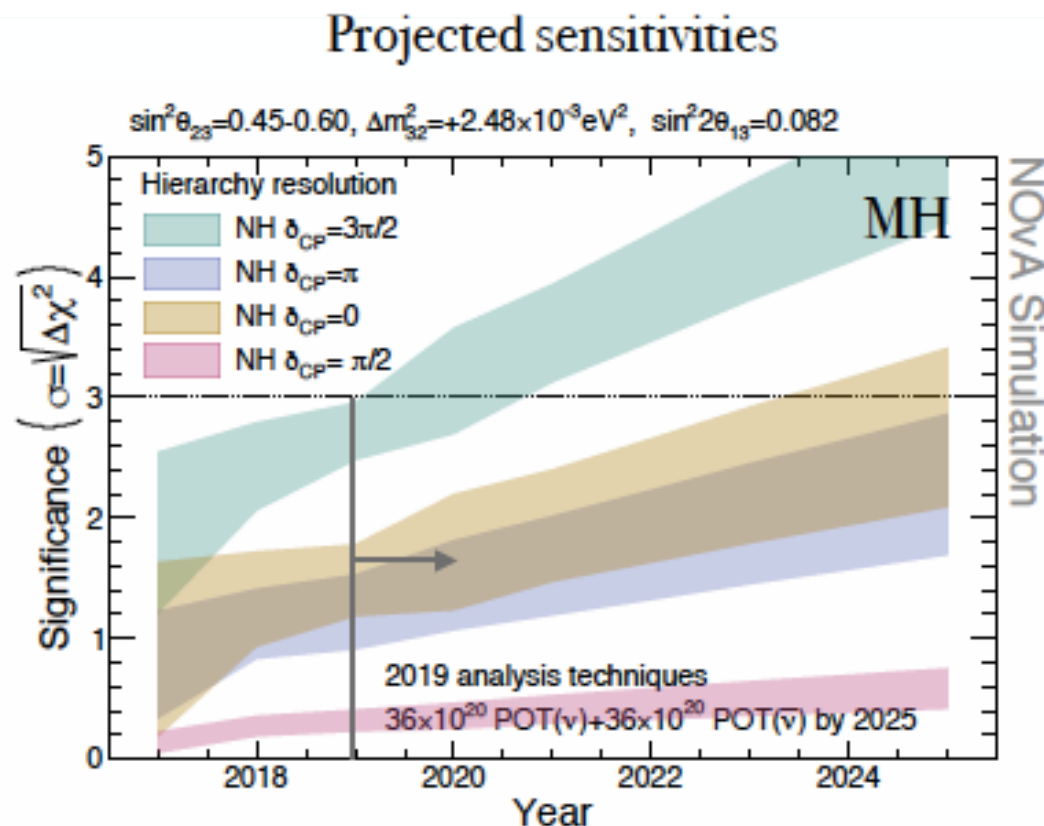
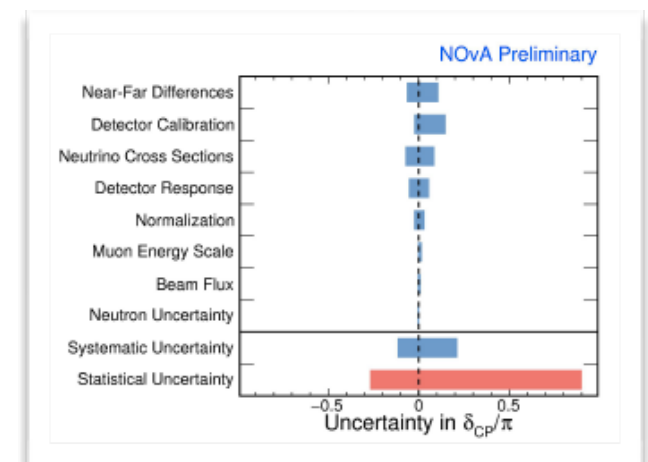


## Comparisons:



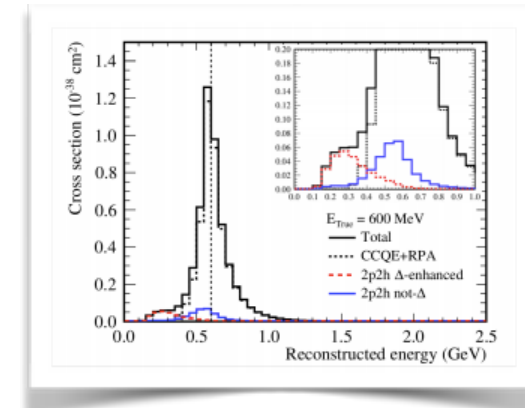
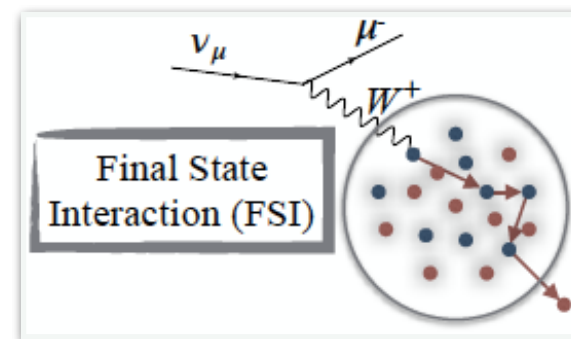
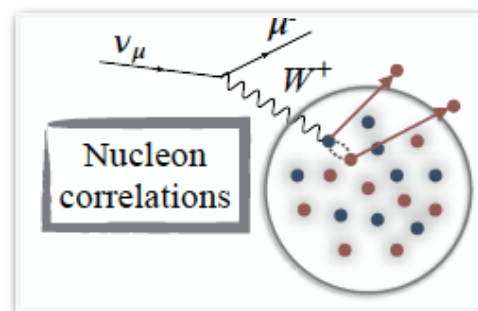
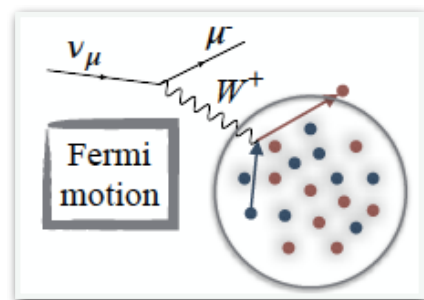
# NOVA FUTURE RUNNING

- 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



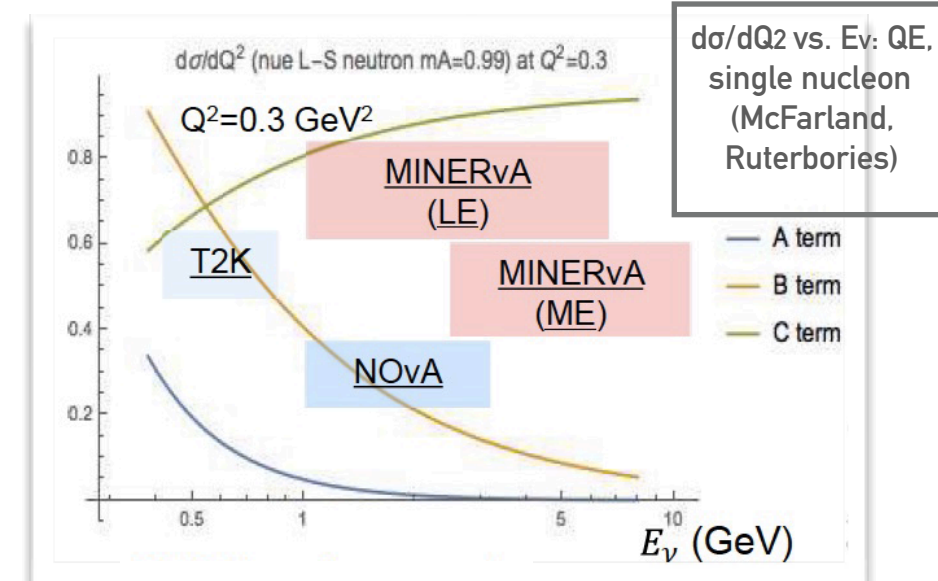
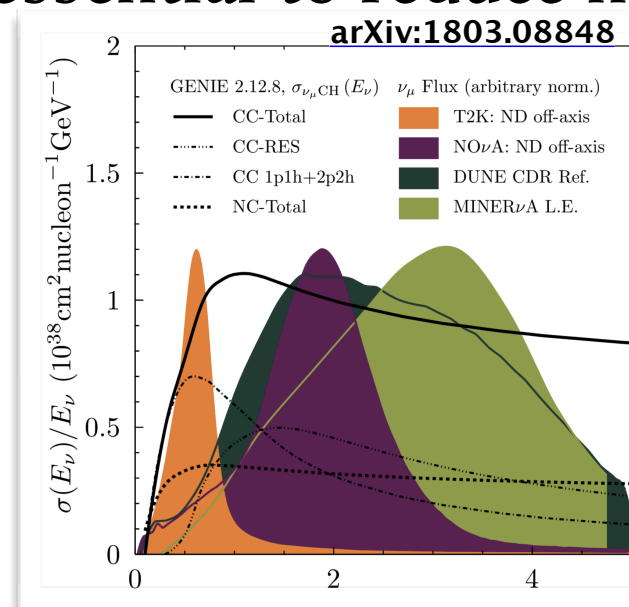
# NEUTRINO-NUCLEON INTERACTIONS

Neutrinos interact with nucleons bound in the nuclei  $\Rightarrow$  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
- Need a global program of measurements of diverse type of interactions on different target materials at various range of neutrino energies and flavours

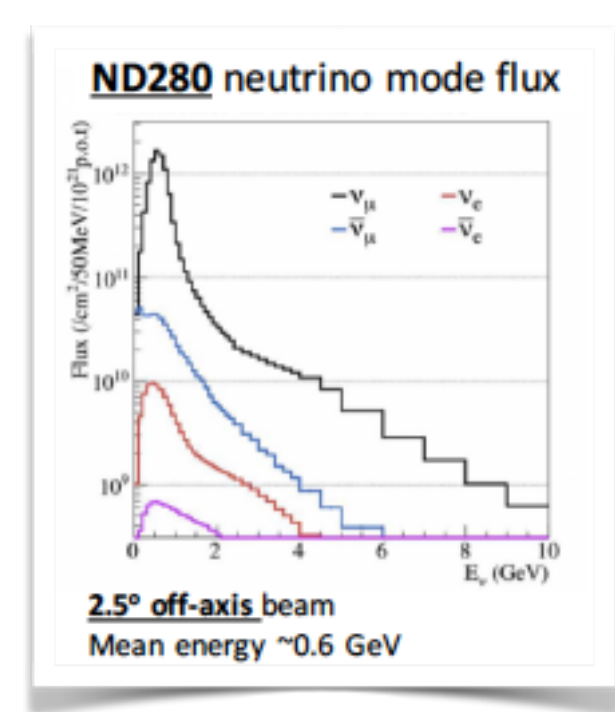
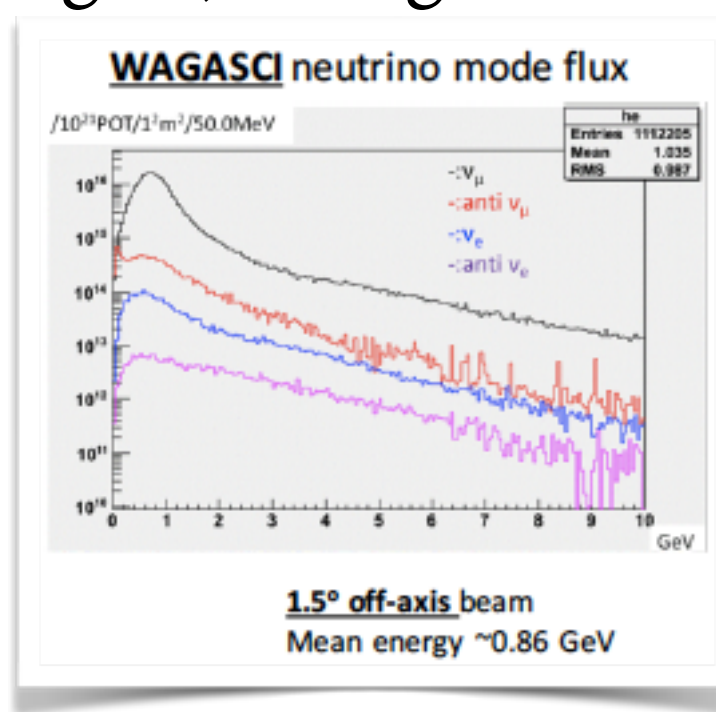
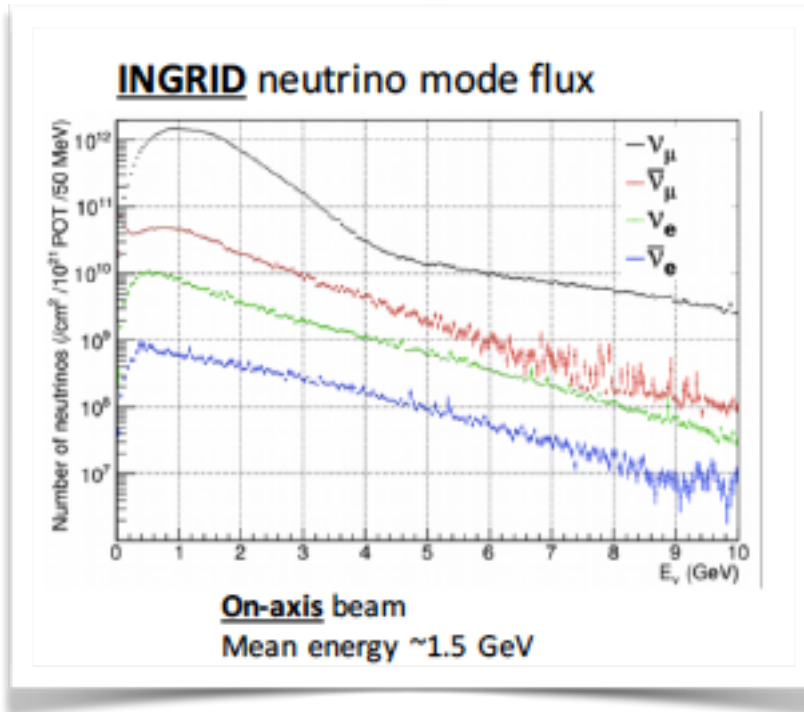


Osc experiment	Target	cross sections from
T2K, NOvA	Scintillator	T2K, NOvA ND, MINERvA LE, HE
T2K, SK, IceCube	Water	T2K (INGRID, WAGASCI, ND280), MINERvA
DUNE	Ar	T2K ND upgrade, MicroBooNE/SBN, MINERvA



# T2K CROSS SECTIONS 2019 HIGHLIGHTS

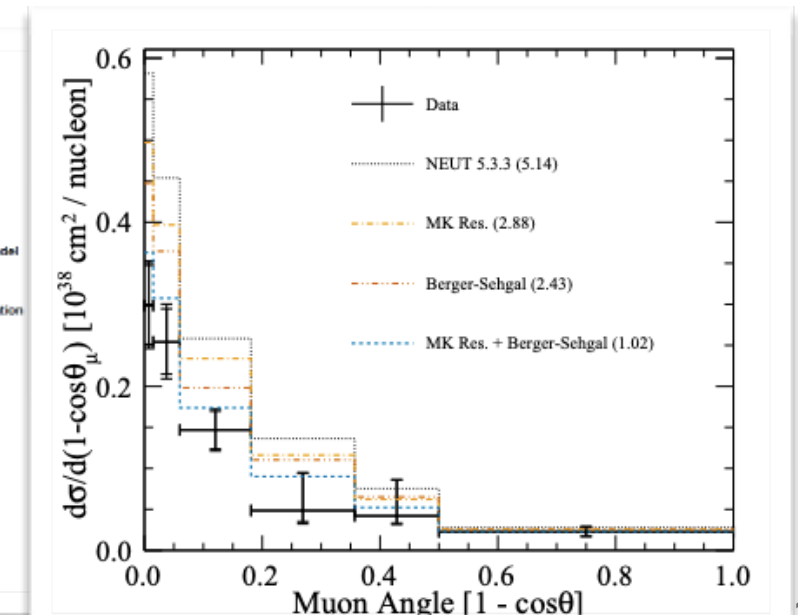
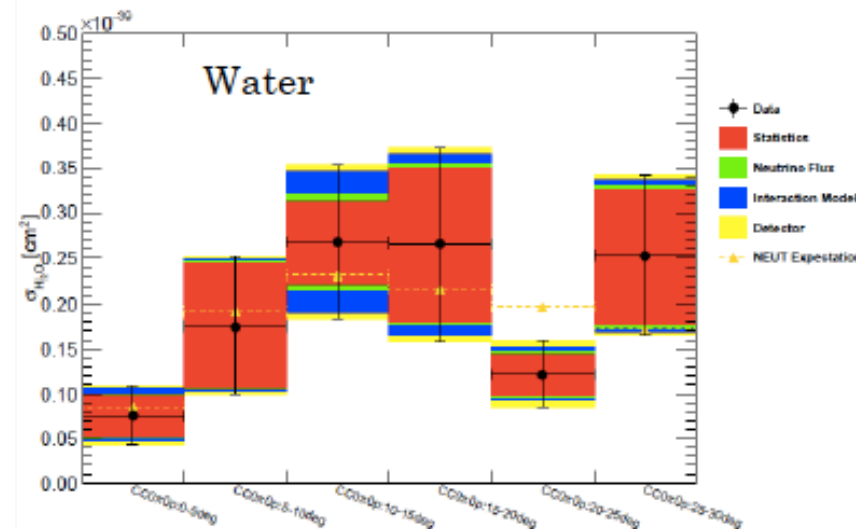
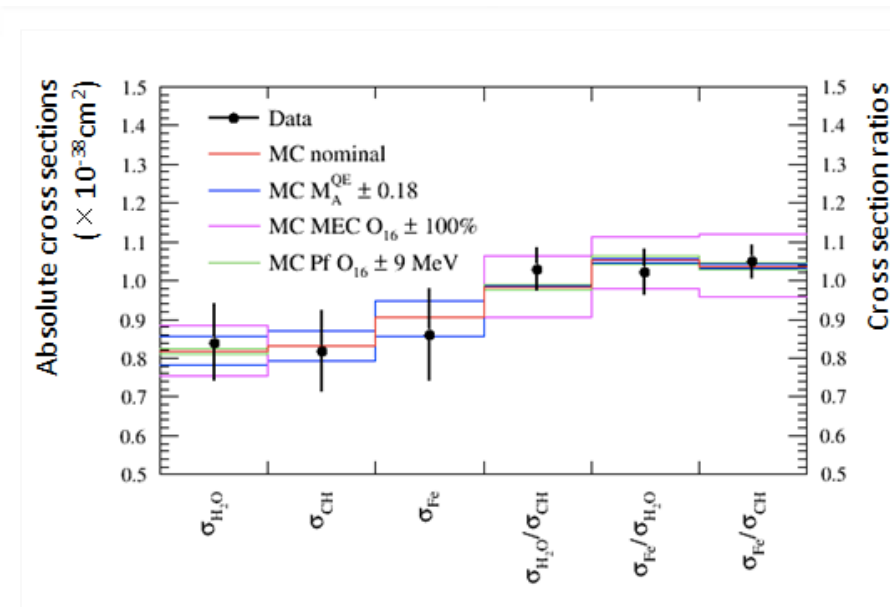
Three different off-axis angles, energies and detectors



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

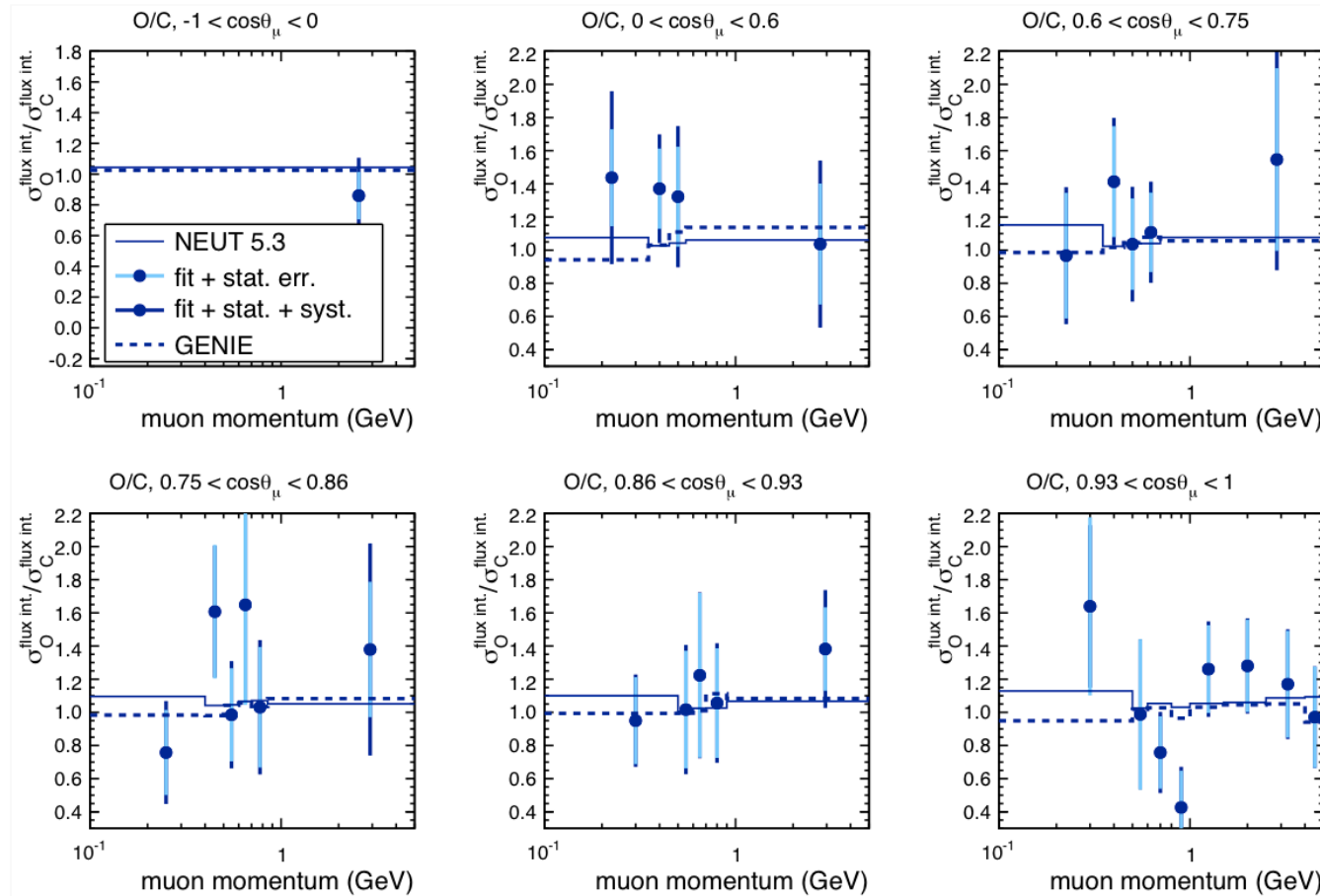
CC $\bar{\nu}_\mu 0\pi 0p$  cross section on plastic and water

CC $1\pi^+$  per nucleon

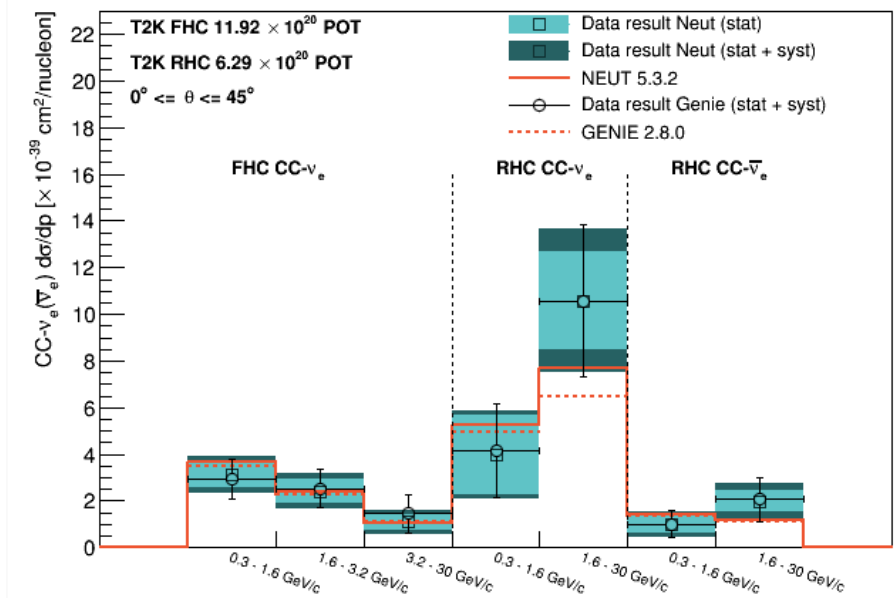


# T2K ND280 CROSS SECTIONS 2019 HIGHLIGHTS

## CC0 $\pi$ Water/Plastic ratio

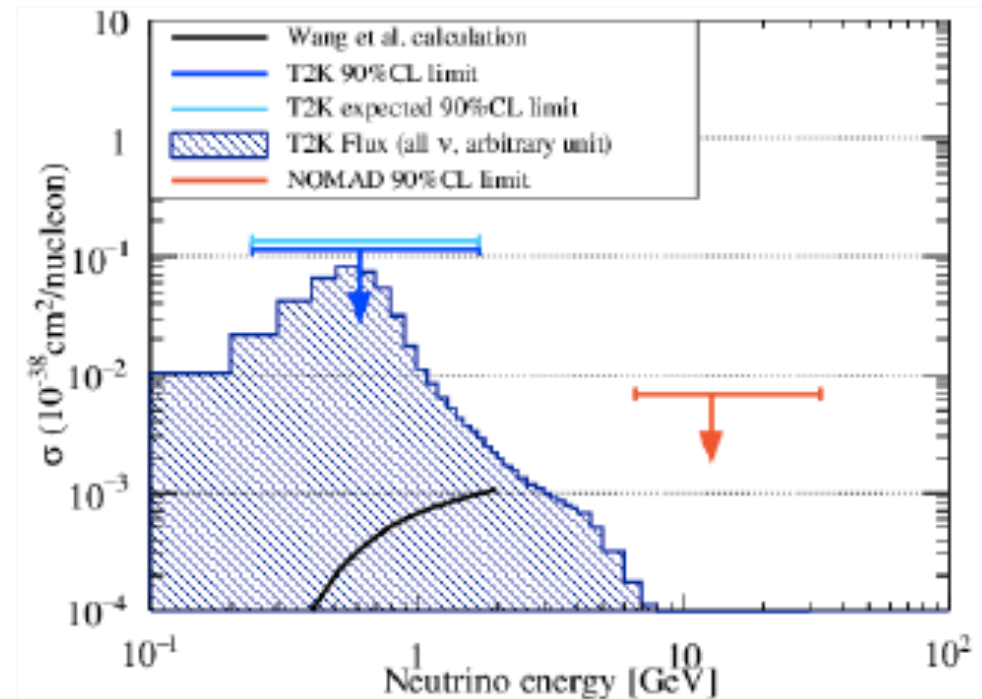


## CC $\nu_e$ , CC $\bar{\nu}_e$ inclusive cross section on plastic

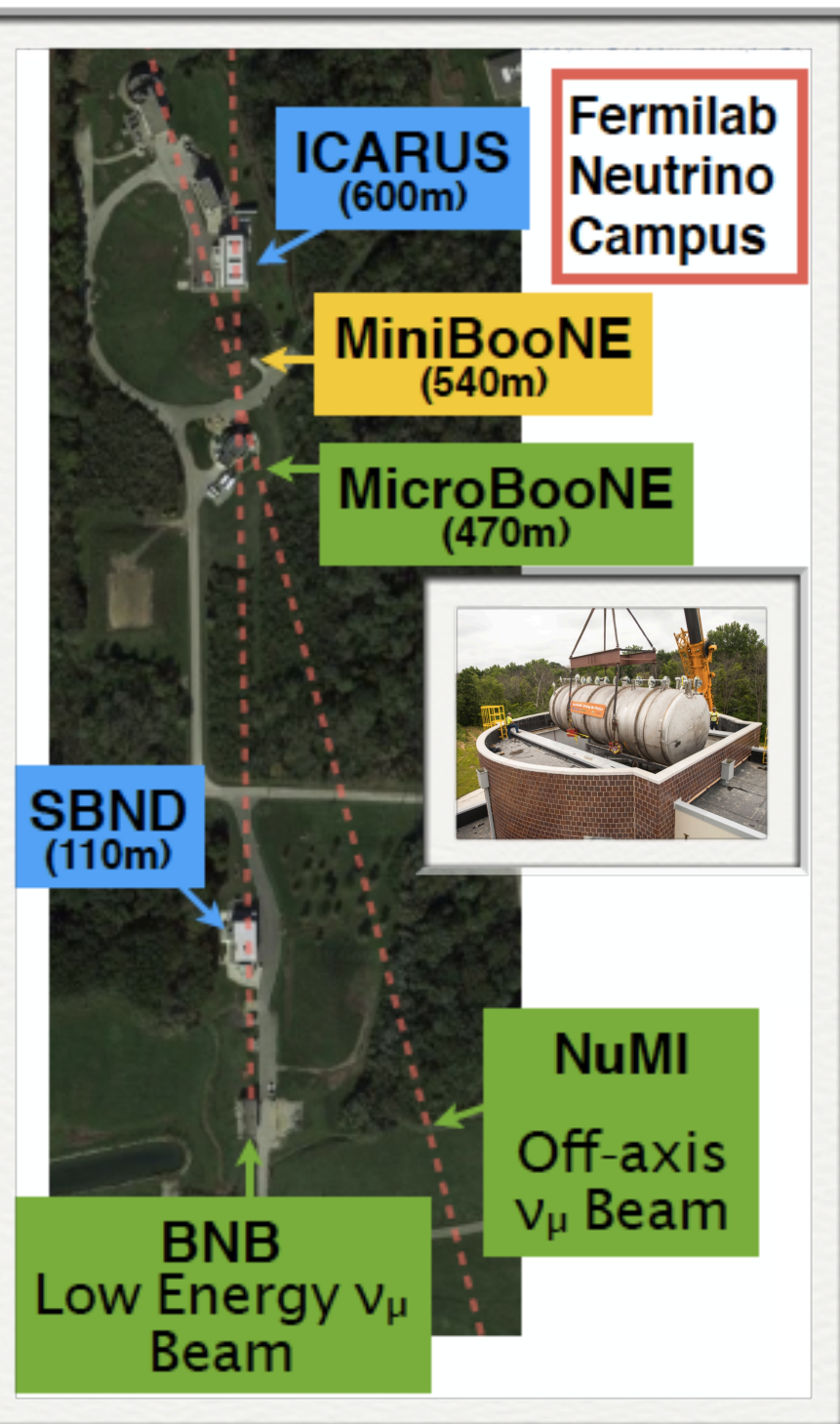


## NC1 $\gamma$ off-axis flux of neutrinos

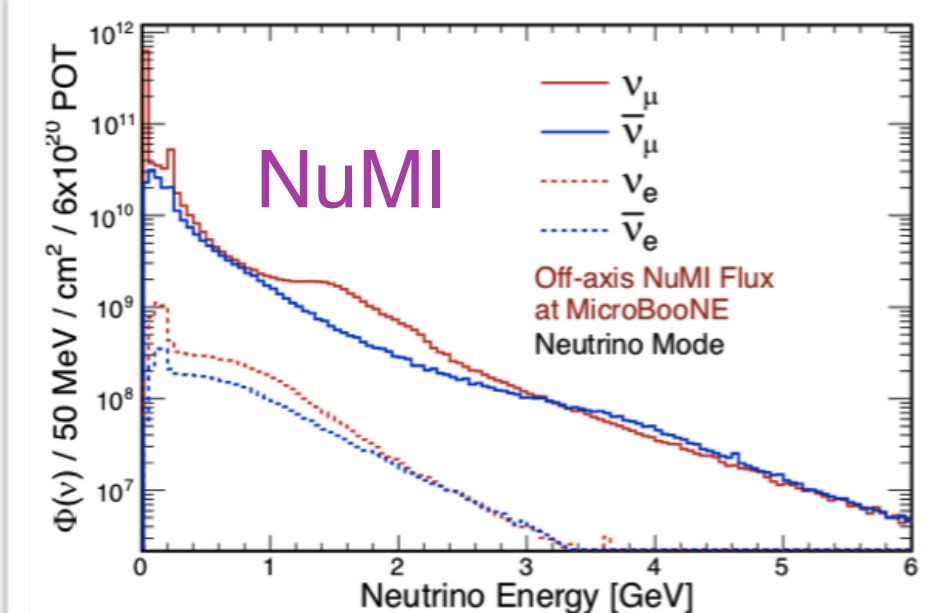
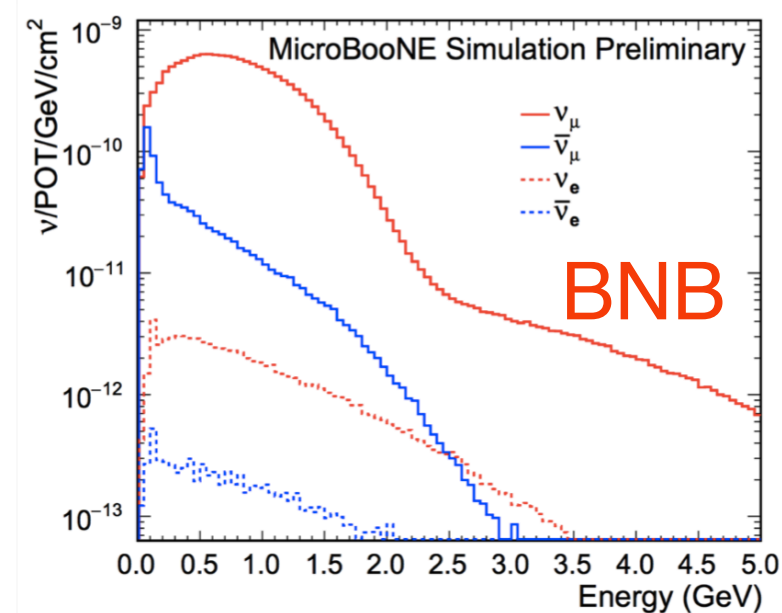
J. Phys. G 46, 08LT01 (2019)



# MICROBOONE OVERVIEW

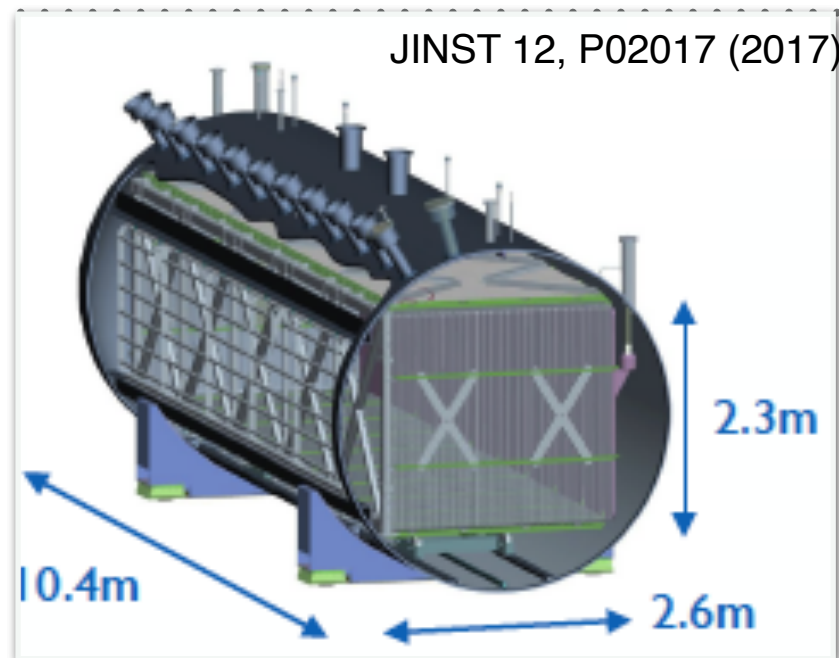


- **Past:** MiniBooNE
- **Present:** MicroBooNE
- **Future:** SBN Program
  - Over the next couple of years two additional detectors, ICARUS and SBND, will come online joining MicroBooNE
  - The goal of this program is to definitively investigate the LSND allowed space.

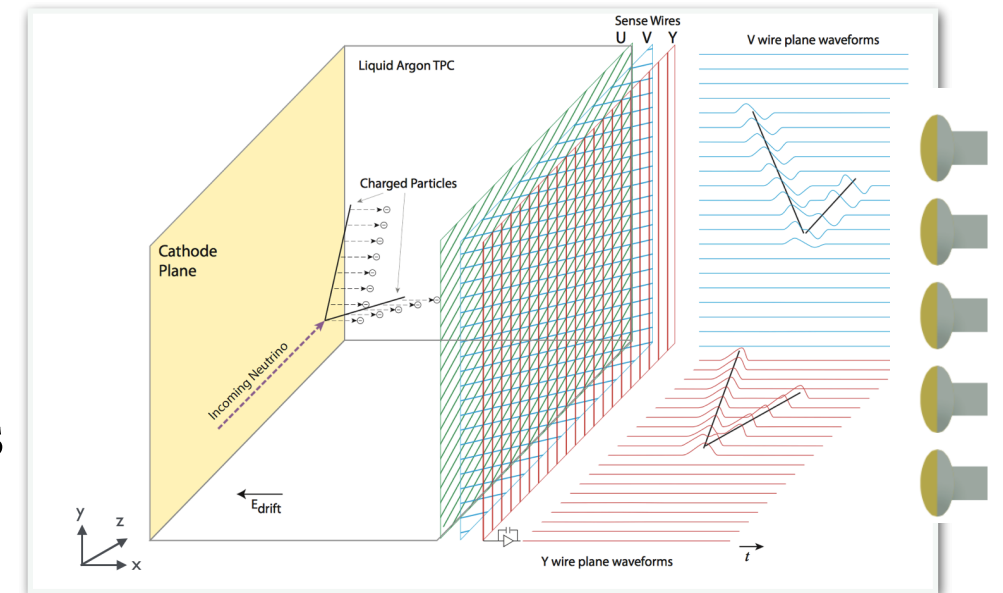




# MICROBOONE LAR TPC



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

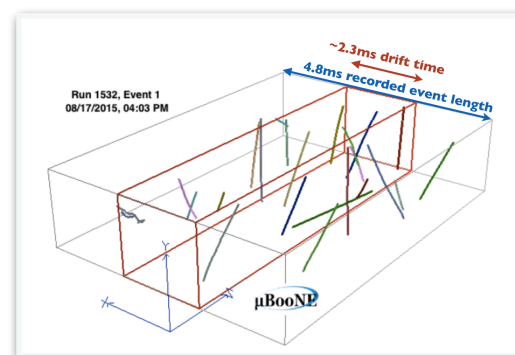


- Sensitive to many detector effects
- Using data to perform direct calibrations of each
- It's relevant for all LAr programme.
- Some already adopted by ProtoDUNE



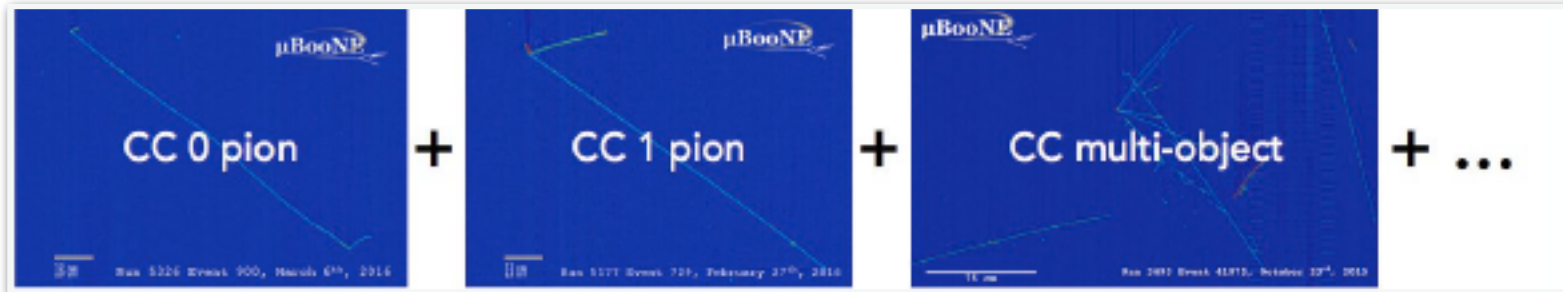
1. Localized electric field distortions  
[MICROBOONE-NOTE-1055-PUB](#)
2. Detector response functions  
[JINST 13, P07007 \(2018\)](#)
3. Readout uniformity  
[MICROBOONE-NOTE-1048-PUB](#)
4. Electro-negative contamination  
[MICROBOONE-NOTE-1026-PUB](#)
5. Induced charge responses  
[JINST 13, P07006 \(2018\)](#)
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.

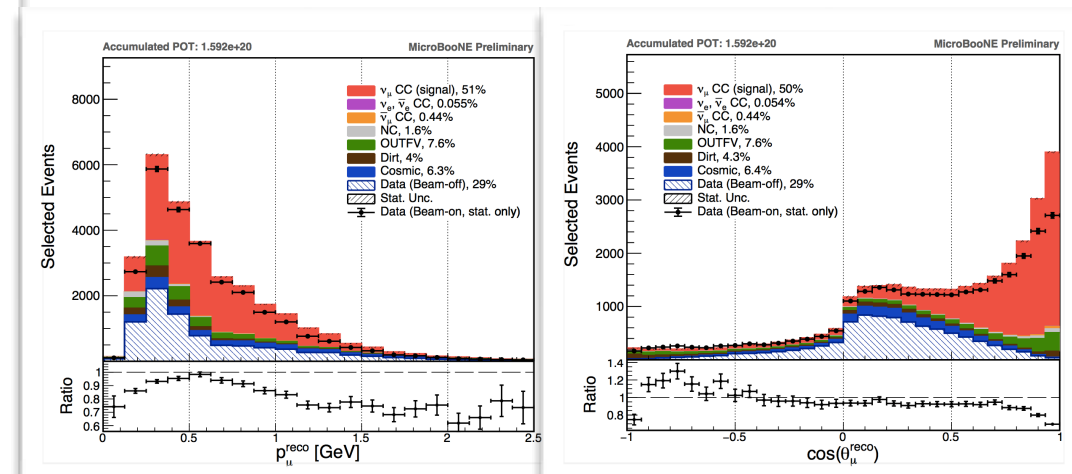
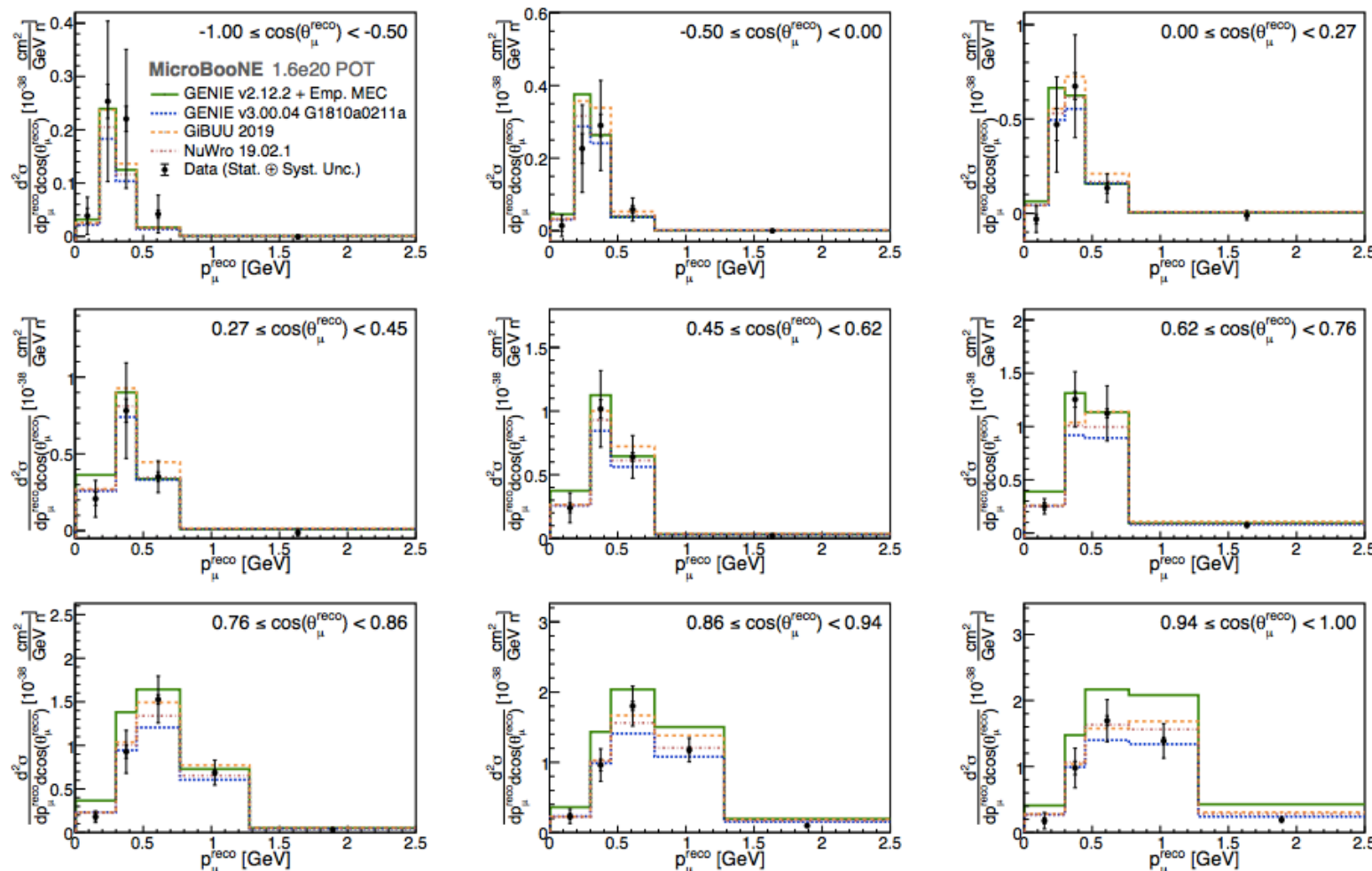


# MICROBOONE RESULTS

- First absolute cross section measurement from MicroBooNE: CC0 $\pi$
- Recent  $\nu_\mu$  CC inclusive cross section



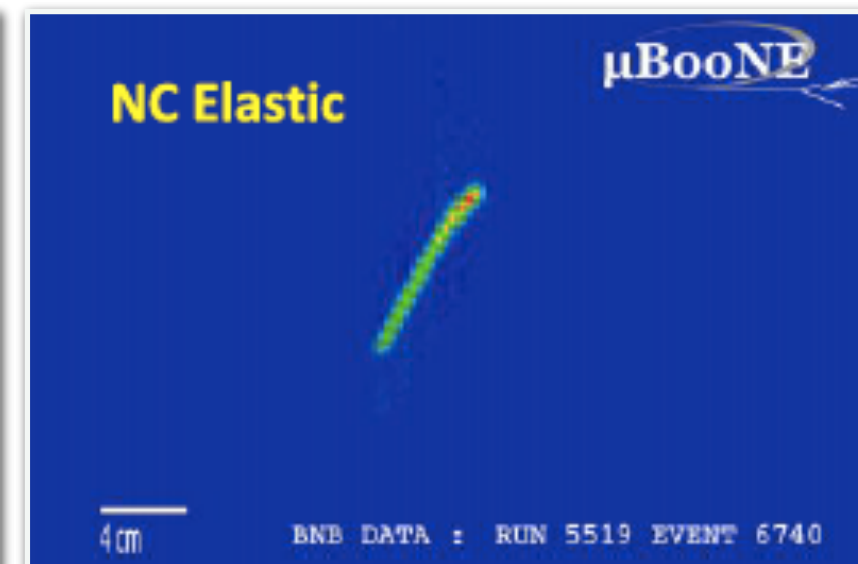
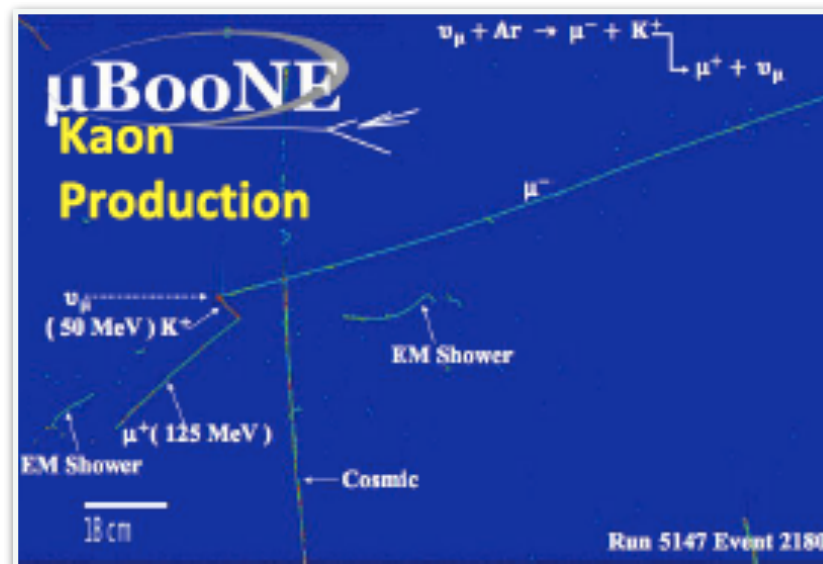
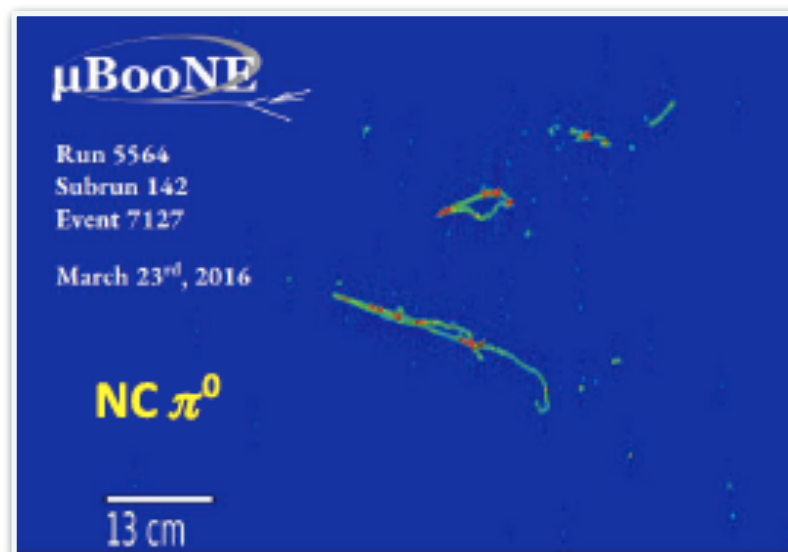
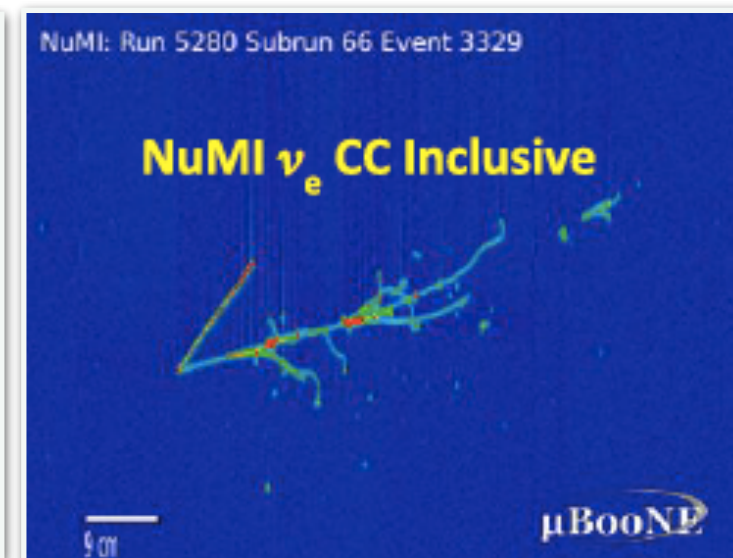
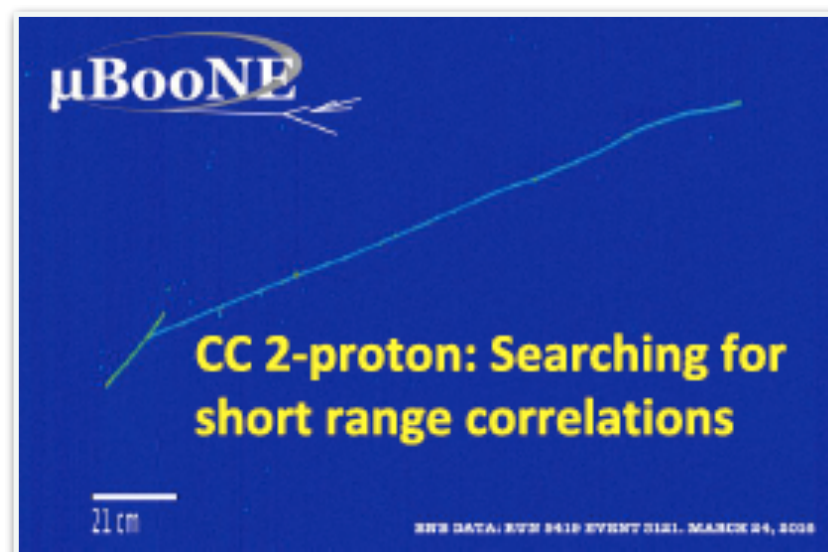
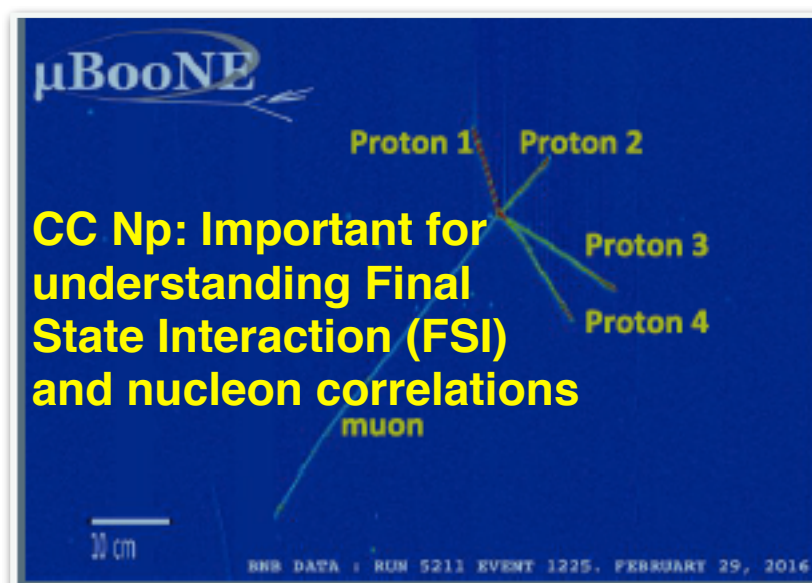
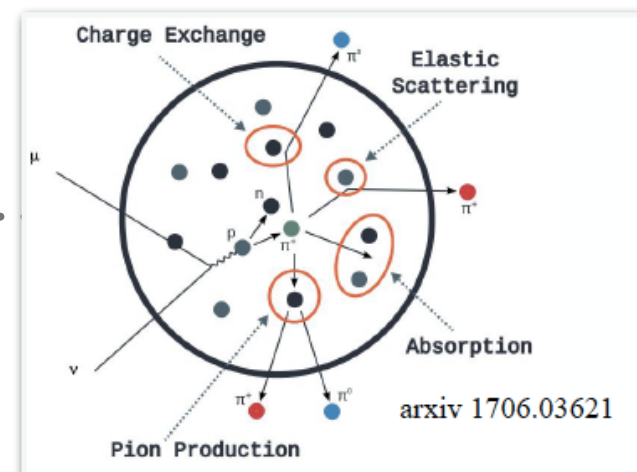
- First -Ar double differential cross section measurement
- Uncertainty is dominated by:
  - Detector model (16.2%)
  - Beam flux (12.2%)
  - Out-of-FV neutrino modelling (10.9%)





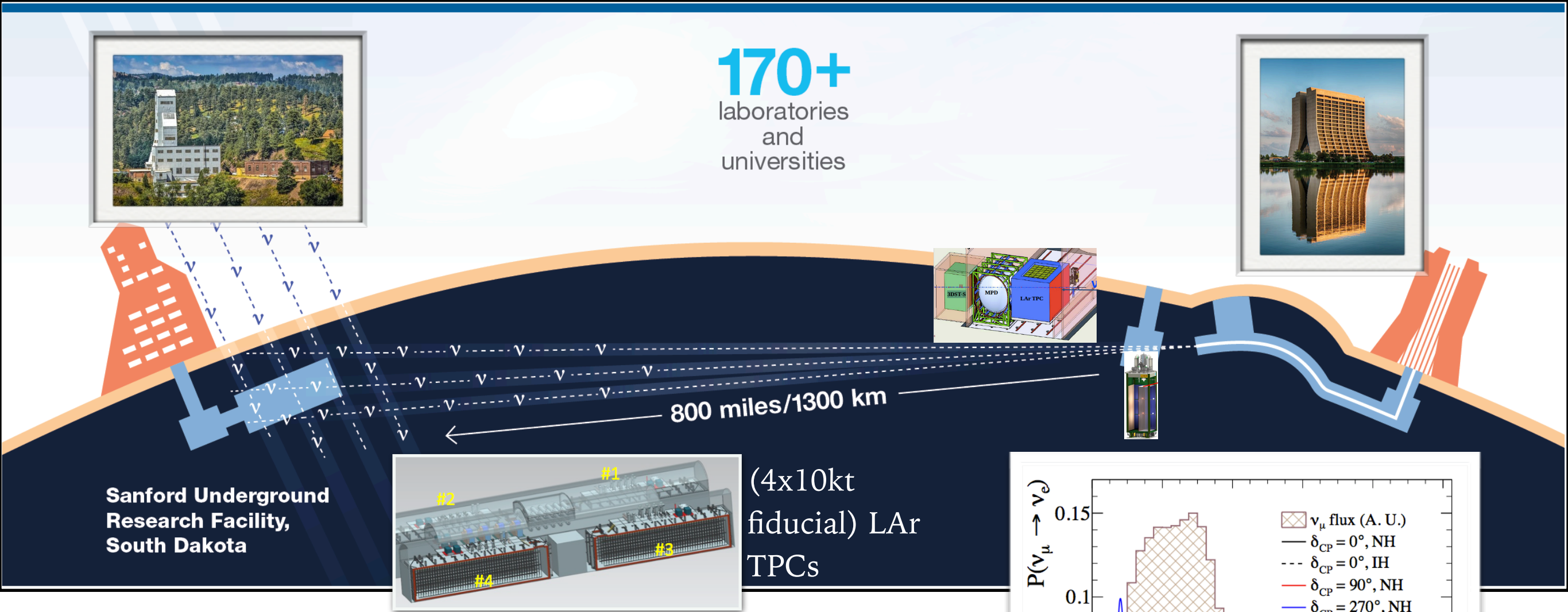
# MICROBOONE

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

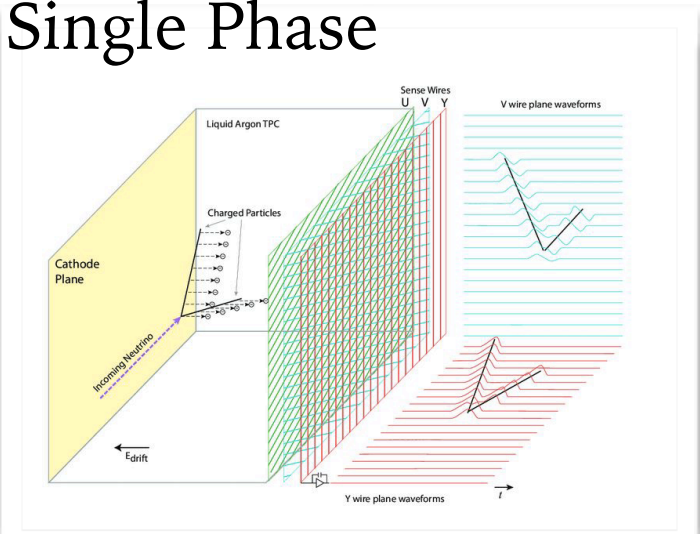




# DUNE

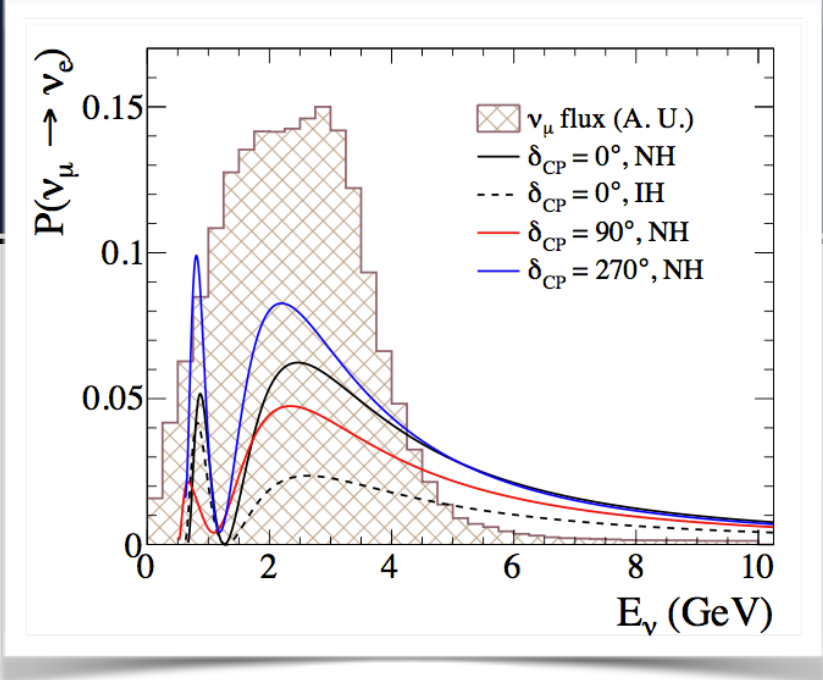
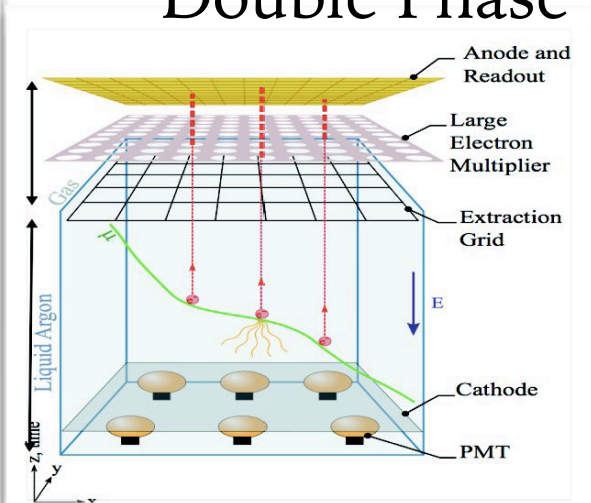


Two detector technologies:  
Single Phase



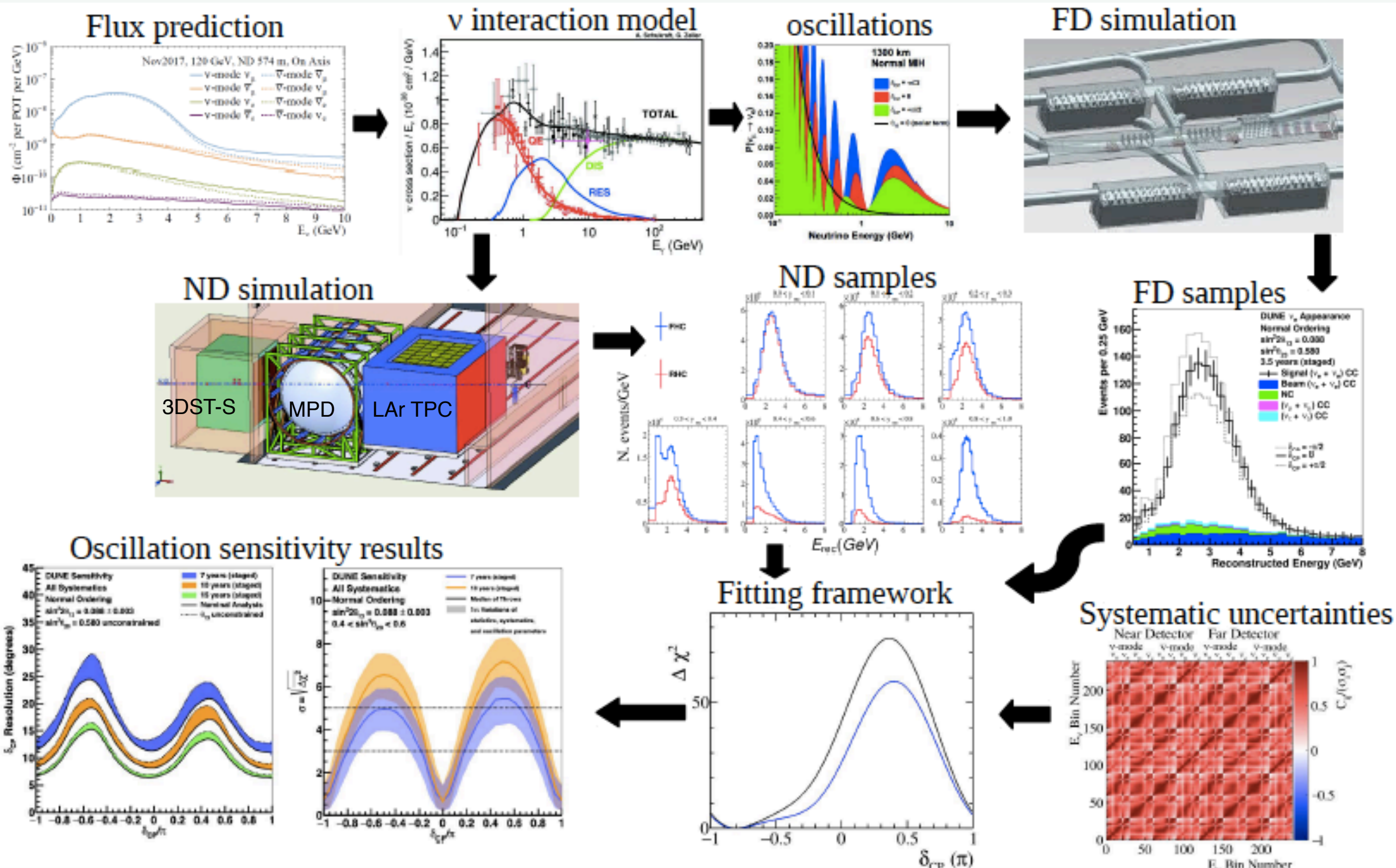
arXiv:1807.10334, 1807.10327,  
1807.10340)

Double Phase



- 1.2 MW initial beam power
- Upgradeable to 2.4 MW

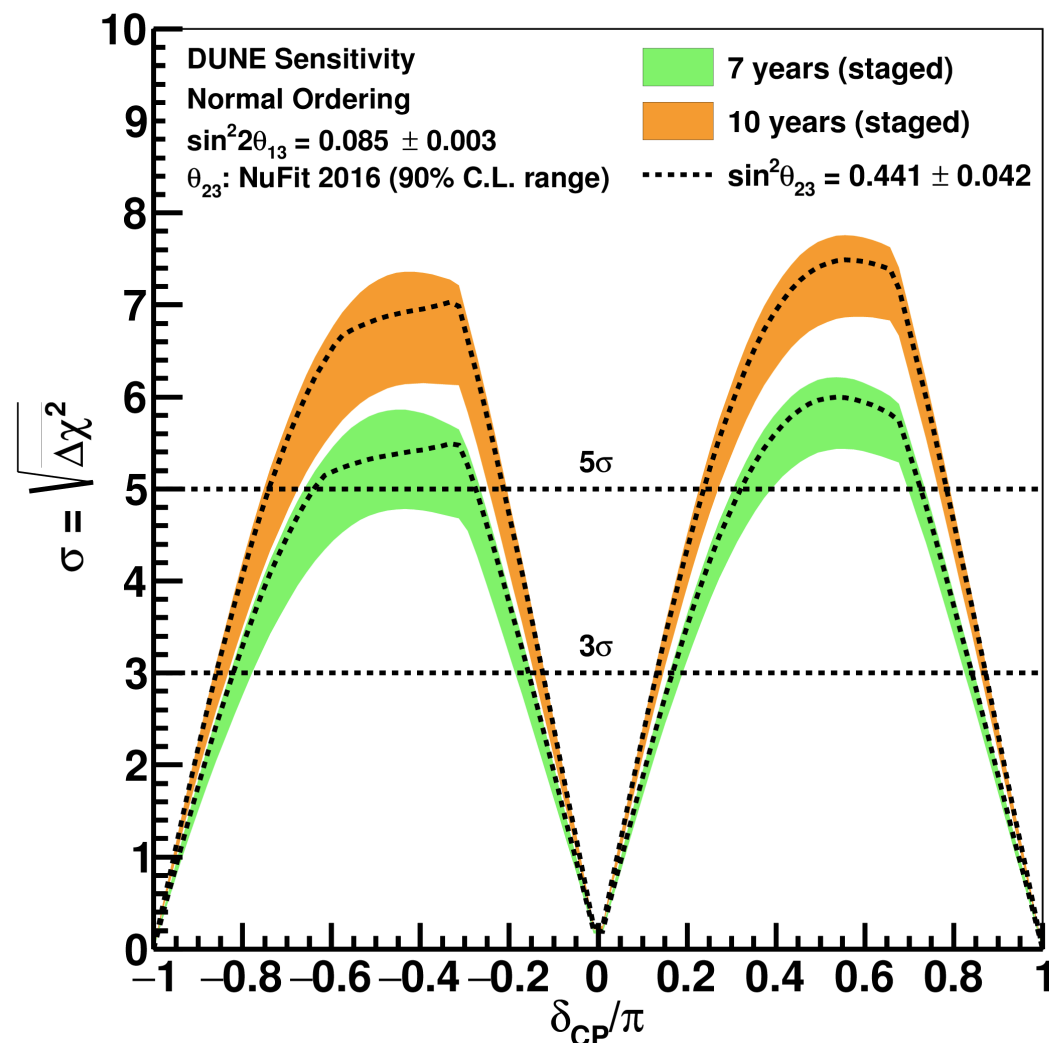
# DUNE LONG BASELINE OSCILLATION ANALYSIS OVERVIEWS





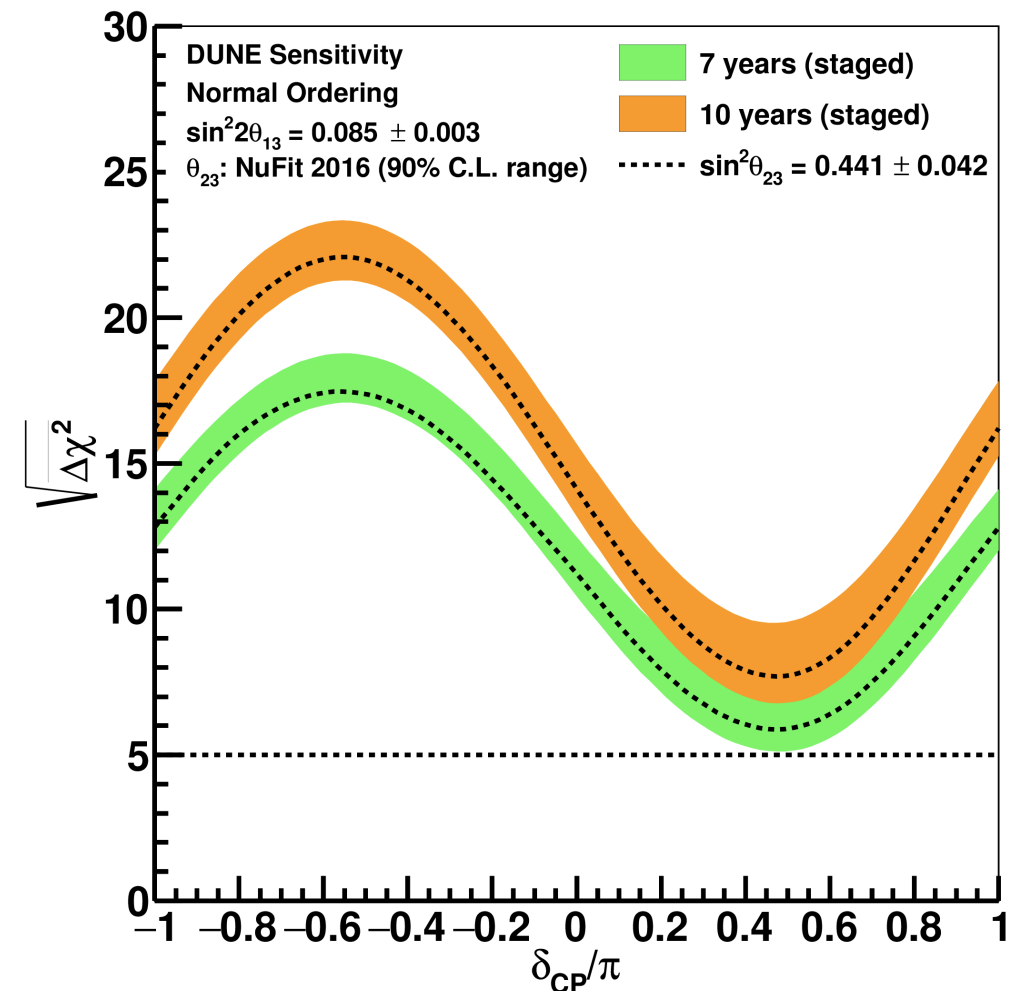
# DUNE SENSITIVITIES

## CPV sensitivity, Normal Ordering



Width of bands indicates variation in possible central values of  $\theta_{23}$

## MH sensitivity, Normal Ordering



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

Updated analysis with full FD simulation & reconstruction, detailed systematic uncertainties, including ND samples in progress, will be included in TDR (2 August 2019)

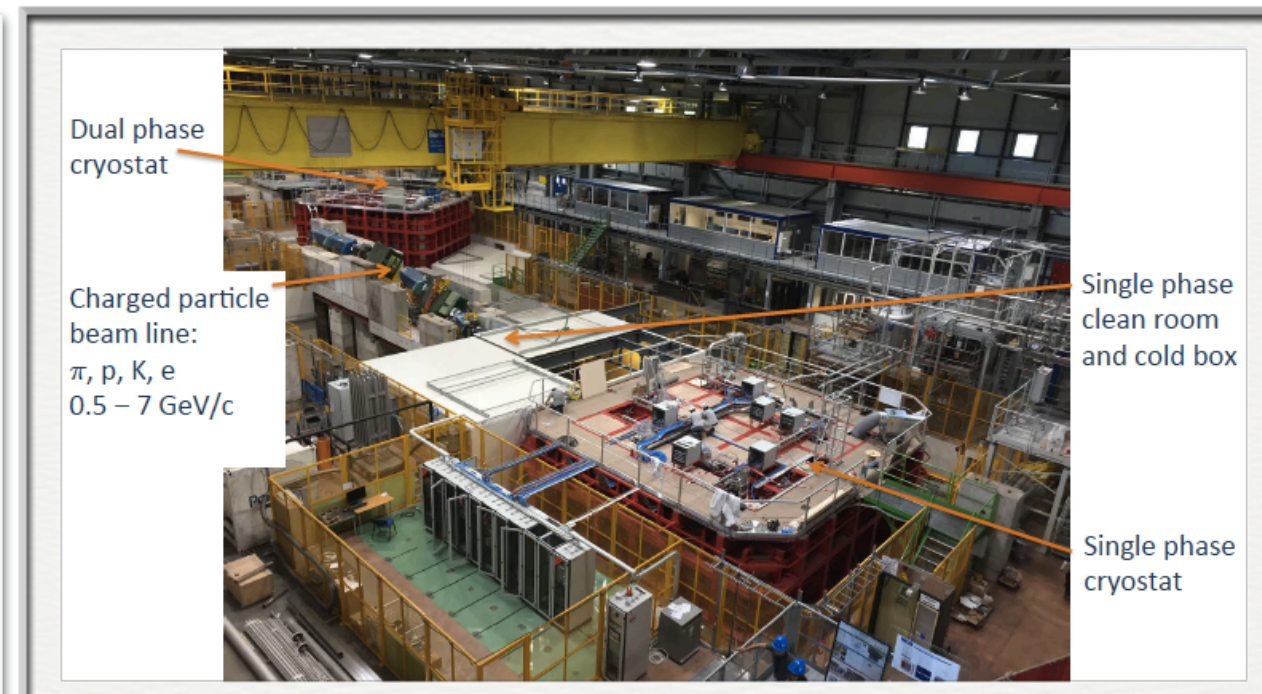
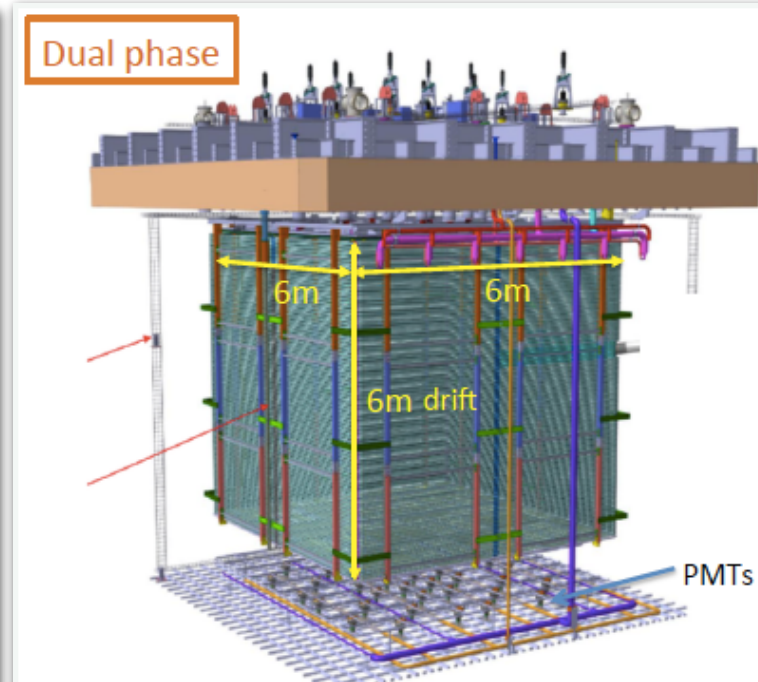
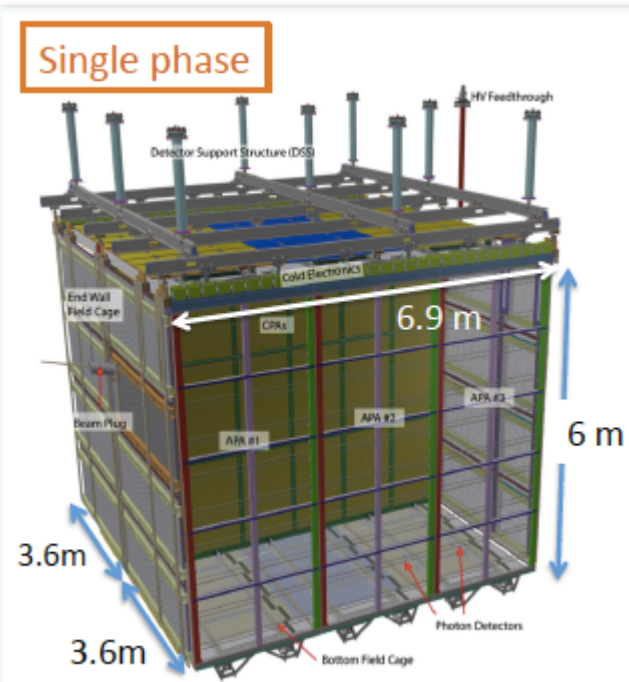
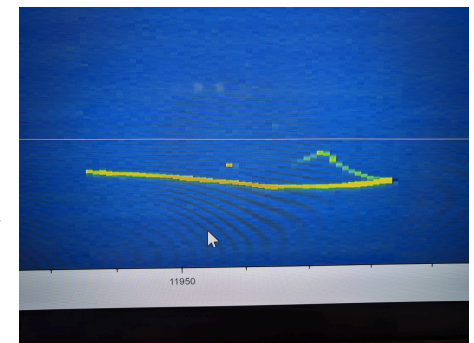


# PROTODUNE: PROTOTYPING THE DUNE FAR DETECTOR DESIGN

Two prototype detectors located at CERN neutrino platform

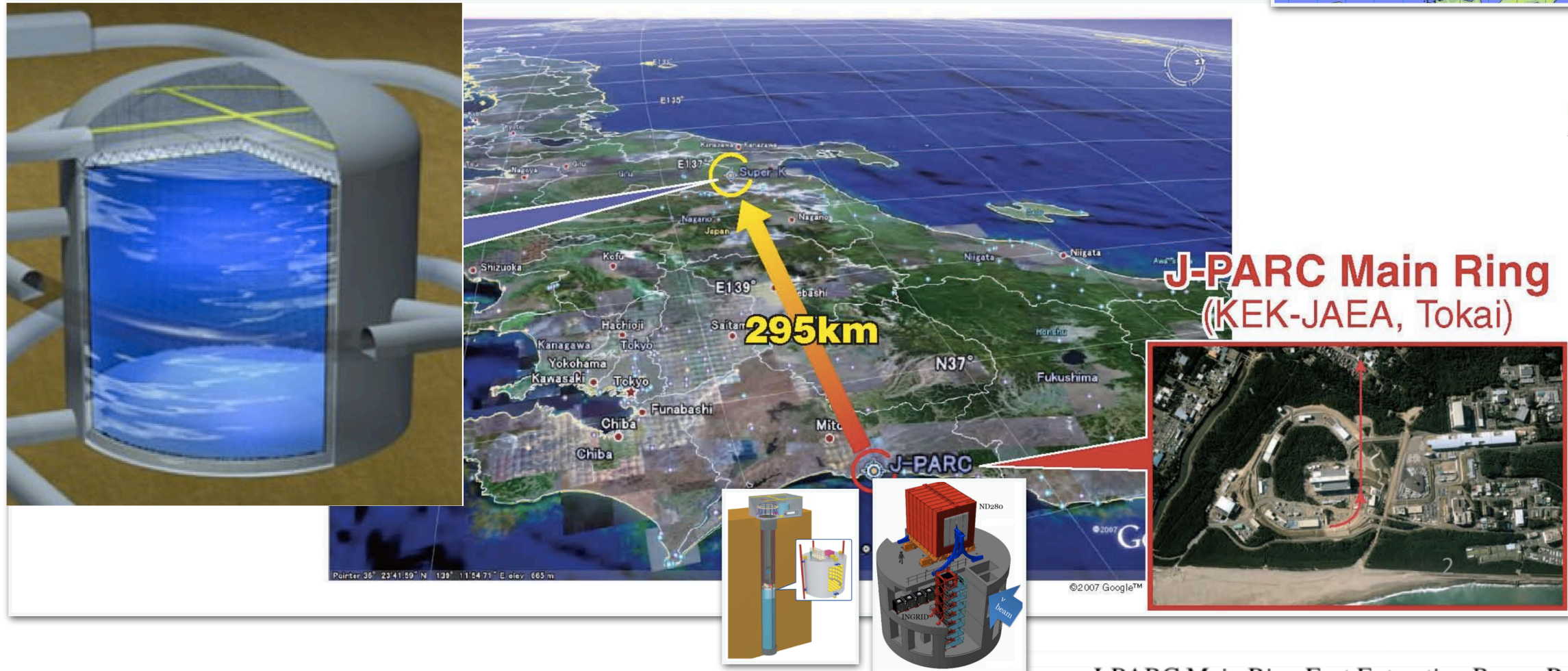
- Single phase and dual phase
- Test detector engineering, and demonstrate long-term operational stability
- Measurements with beam:
  - towards demonstrating calibration
  - 0.5 — 7 GeV particle beams ( $e$ ,  $\pi$ ,  $p$ ,  $K$ )
  - beam time limited by availability of CERN accelerators
- ProtoDune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

September 19 2018:  
first track recorded



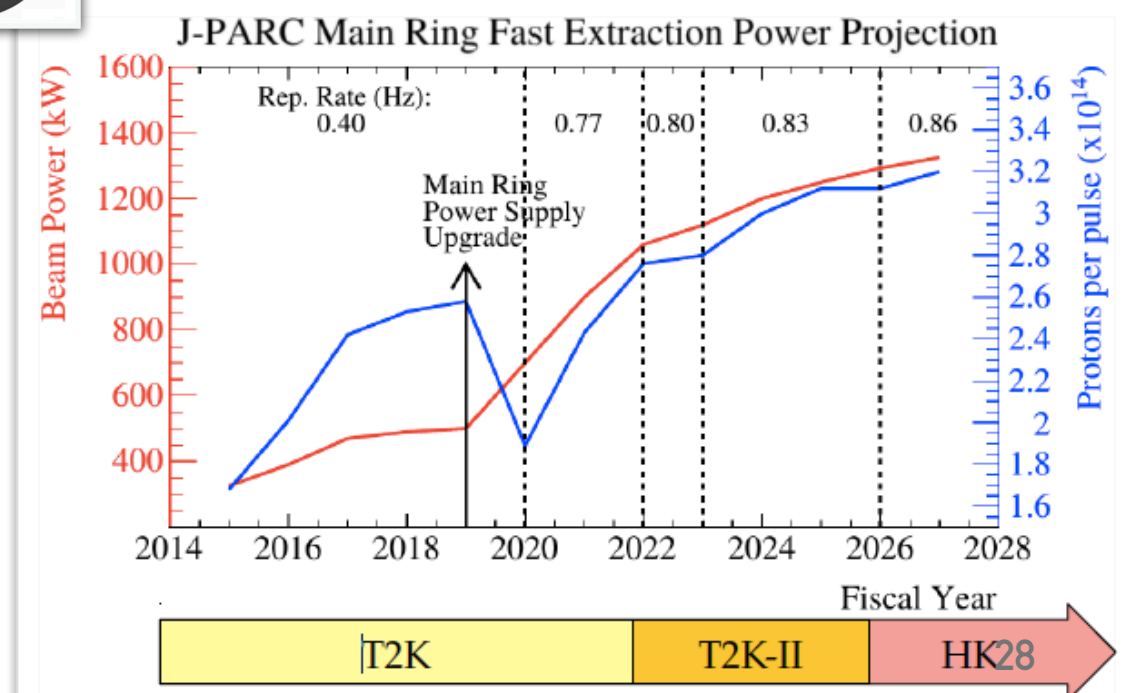


# HYPER-KAMIOKANDE



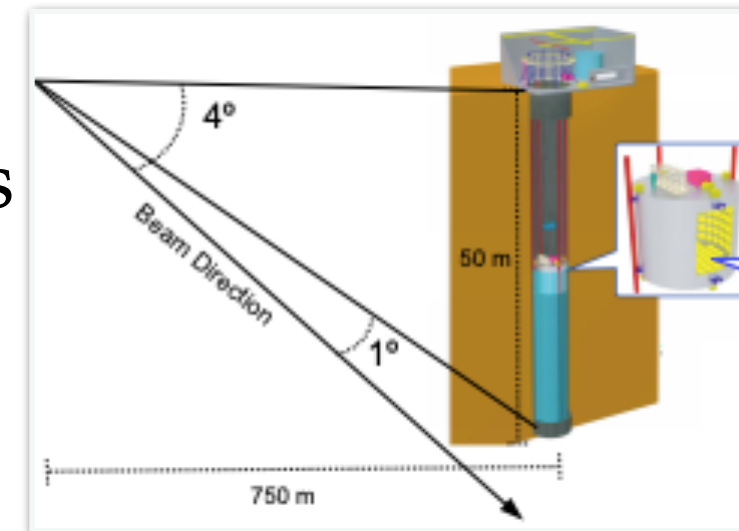
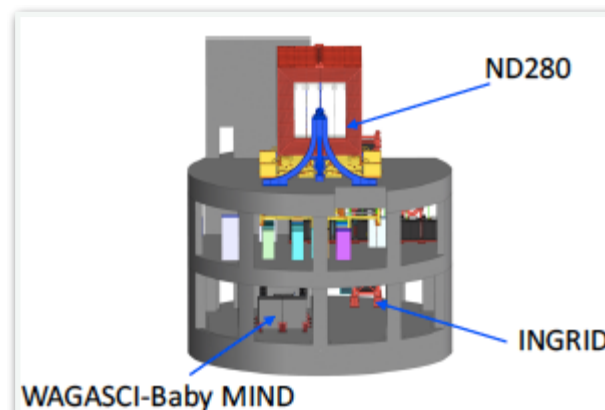
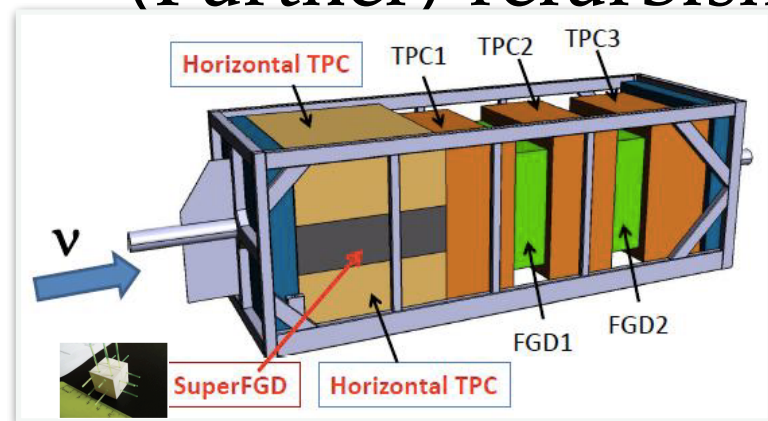
Next generation of neutrino observatory in Japan

- Water Cherenkov detector
- Construction 2020-26
- 260 kton water  $\Rightarrow$  Fid. Volume:  $\sim 8 \times$  Super-K
- Photocoverage: 40% ( $\times 2$  SK sensitivity)
- Second staged detector possibly in Korea ( $> 200\text{km}$  baseline, second oscillation maximum)

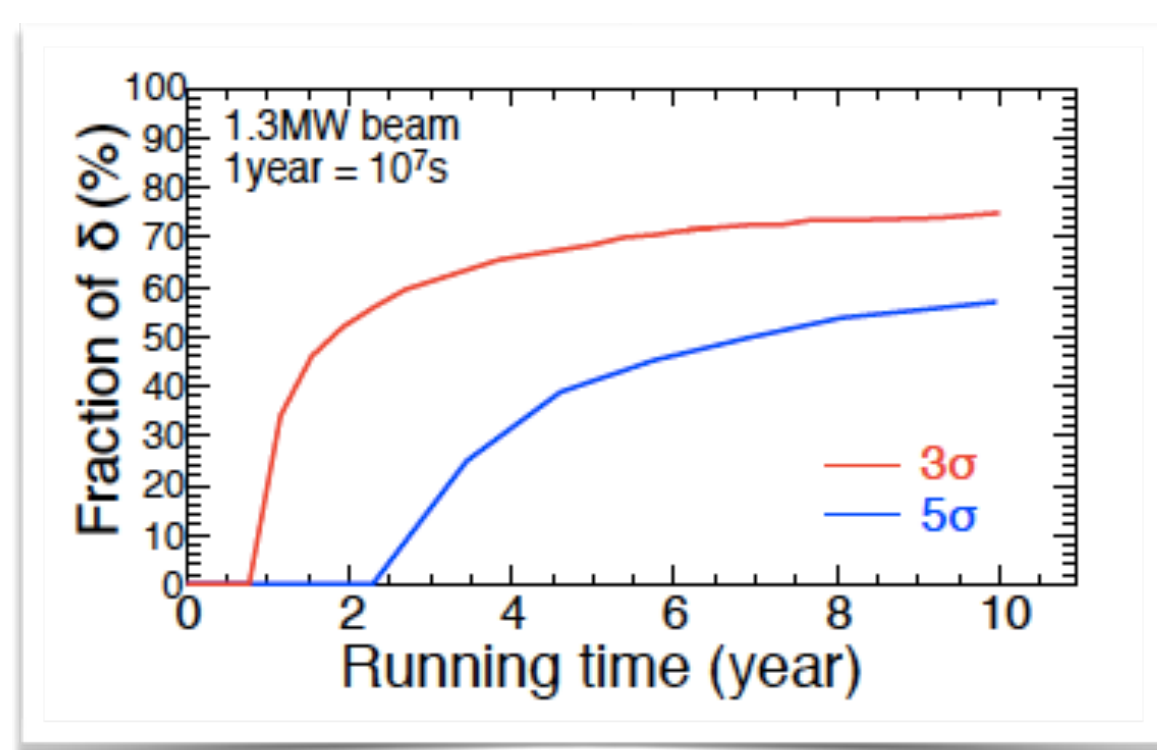
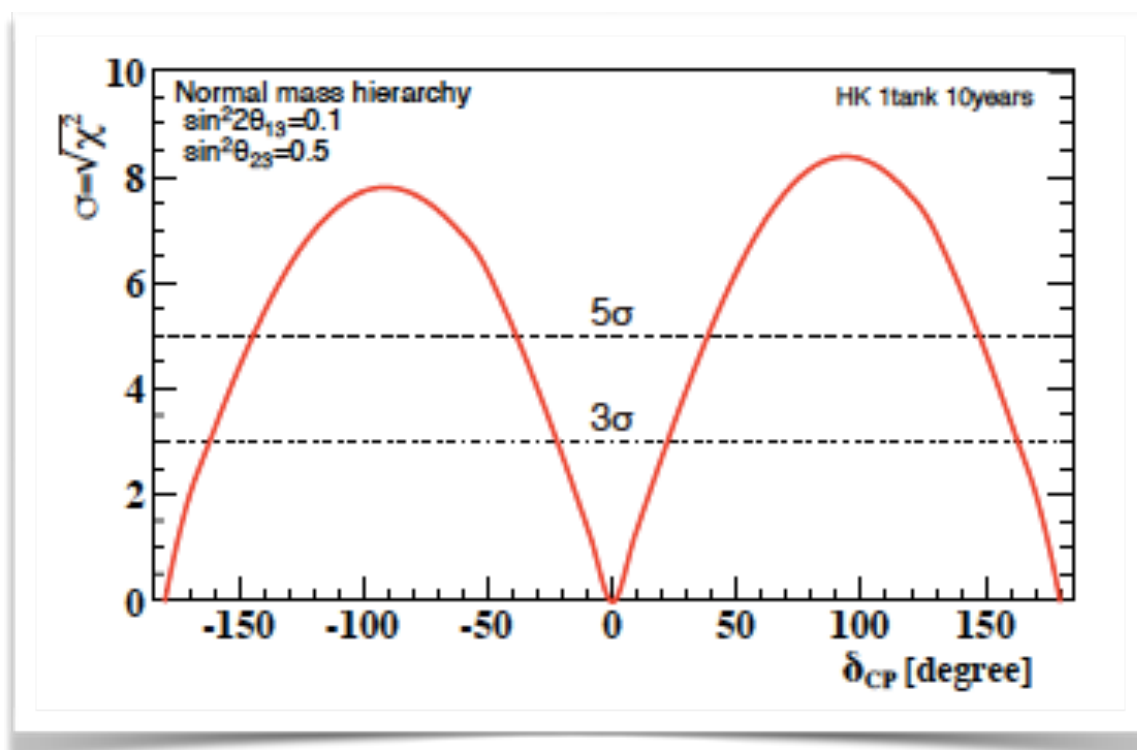


# HYPER-KAMIOKANDE WITH BEAM ONLY

- Aim to reduce systematics down to 3%
- Crucial suite of new detectors
  - New WC detector @  $\sim 750\text{m}$
  - (Further) refurbished on- and off-axis detectors



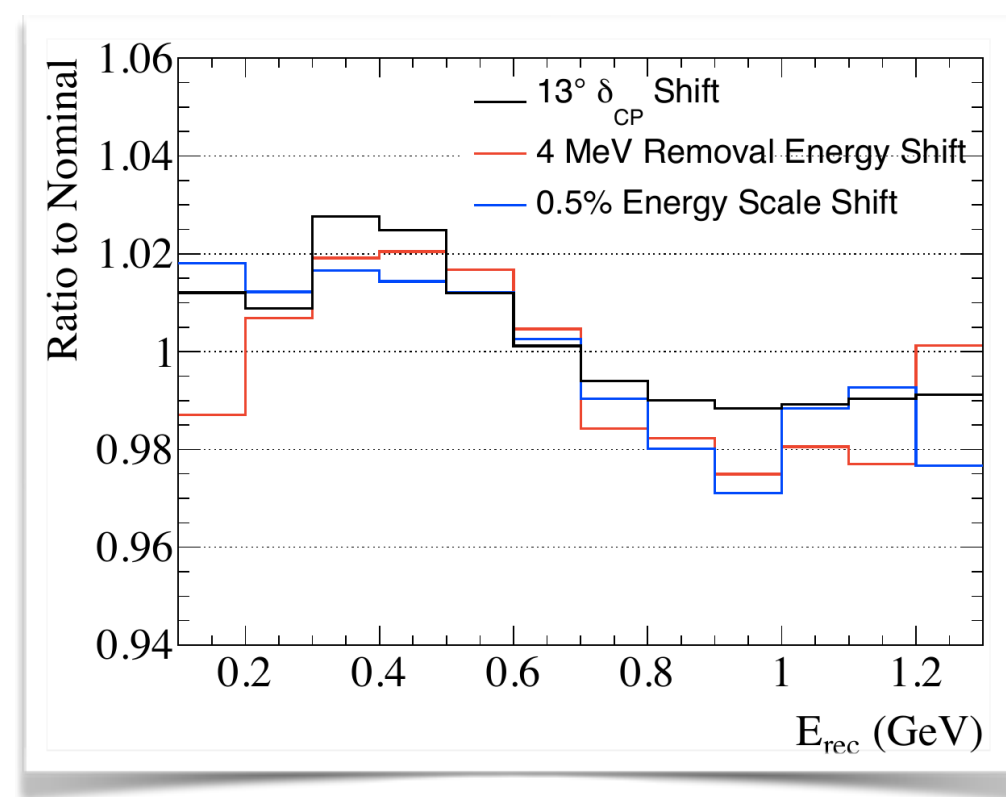
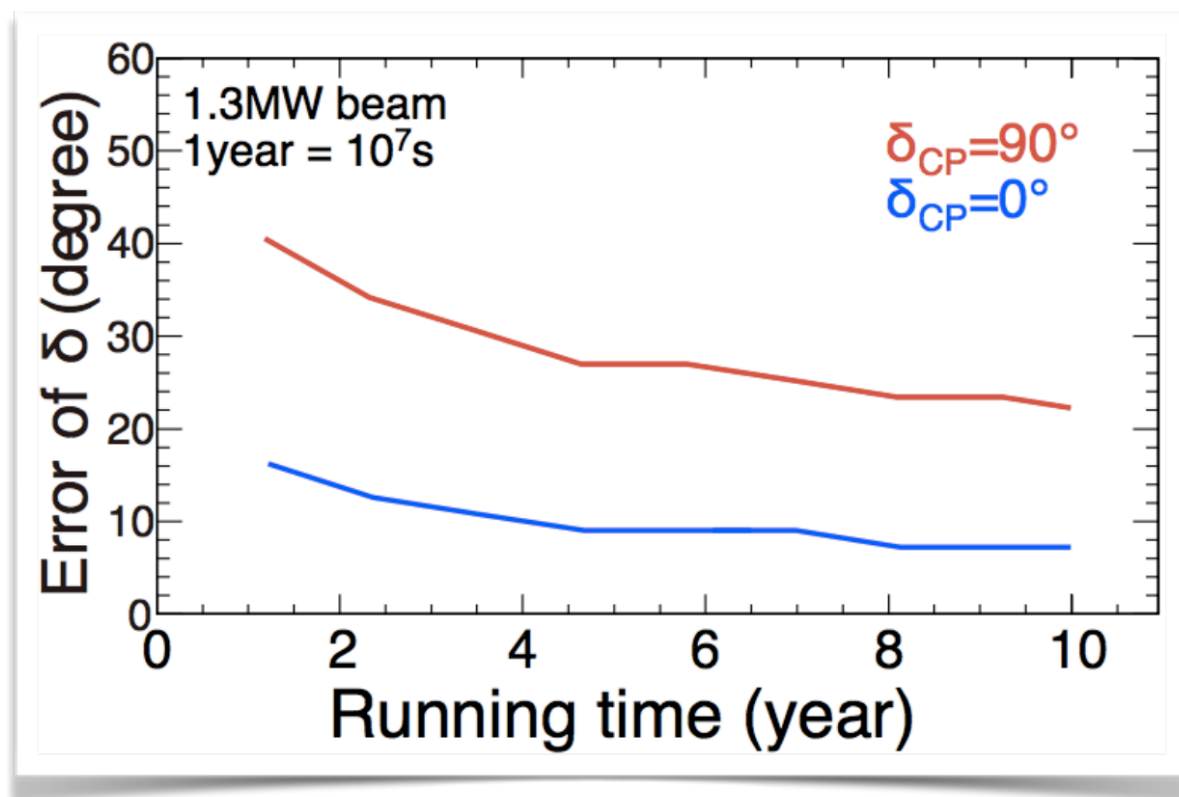
Expected significance to exclude  $\sin\delta_{CP} = 0$  plotted as a function of true  $\delta_{CP}$  assuming NH



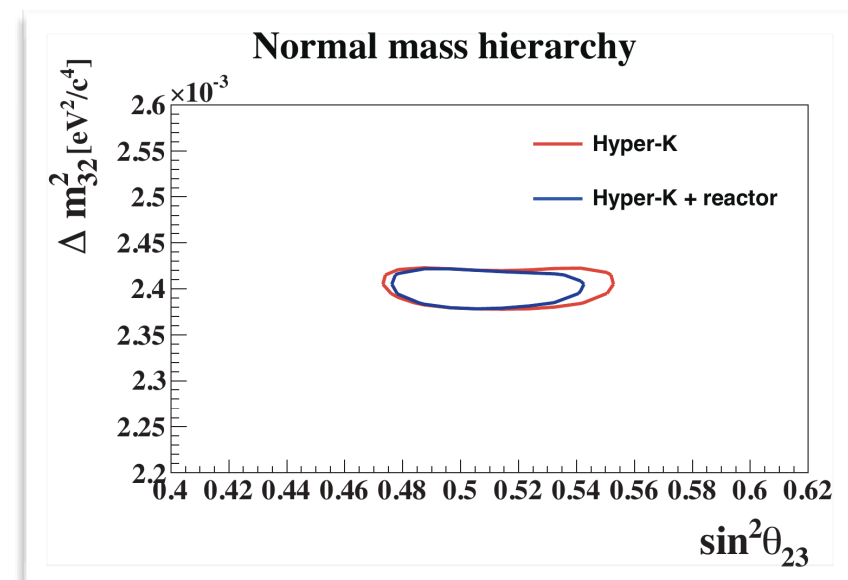


# HYPER-KAMIOKANDE WITH BEAM-ONLY

- After CPV is determined, accurate measurement of  $\delta_{CP}$  will be crucial
- Sensitivity is limited by systematics  $\Rightarrow$  near detectors

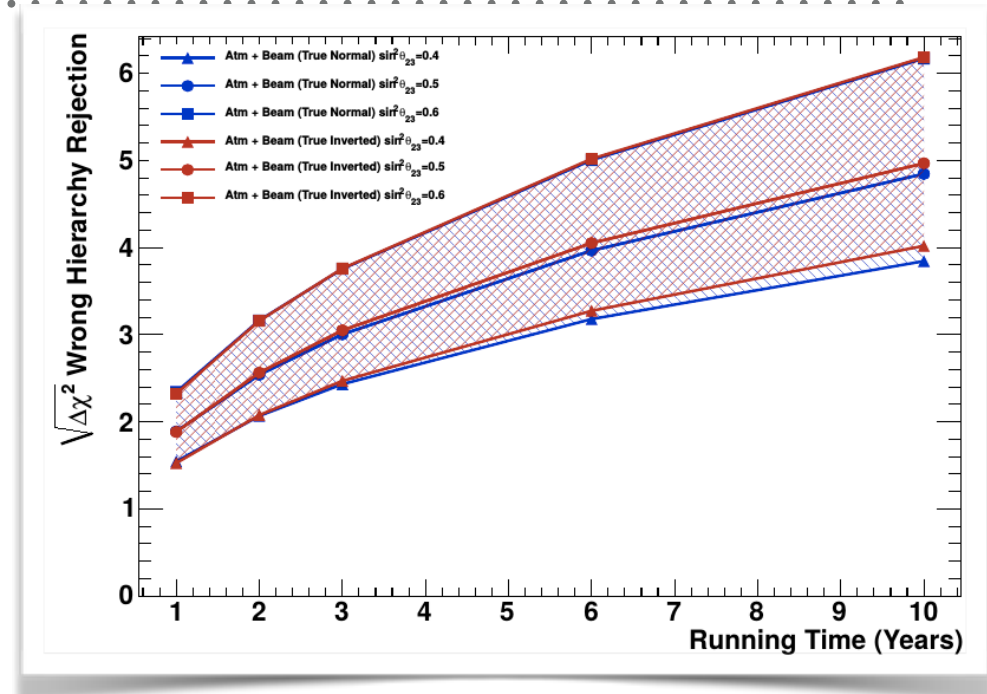


- The 90% CL allowed regions in the  $\sin^2 \theta_{23}$  and  $\Delta m_{23}^2$  plane.
- The true values are  $\sin^2 \theta_{23} = 0.5$  and  $\Delta m_{32}^2 = 2.4 \times 10^{-3} eV^2$

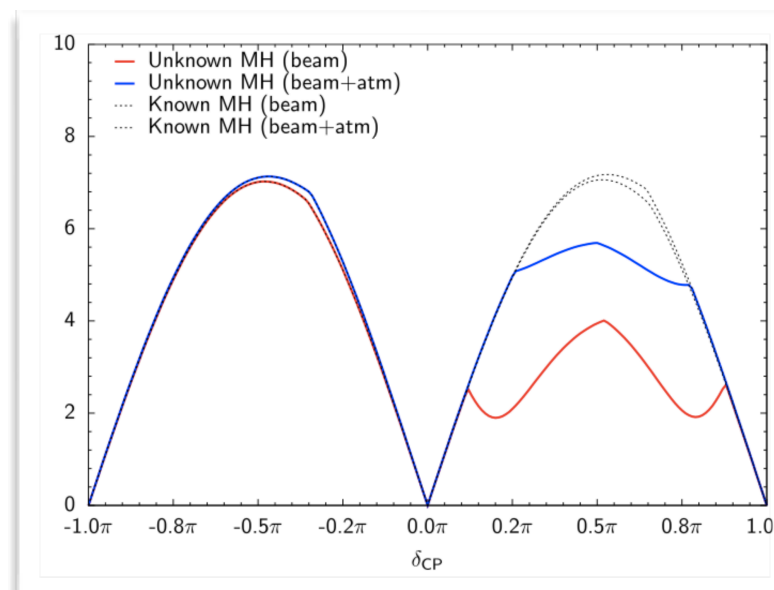


# HYPER-KAMIOKANDE WITH BEAM AND ATMOSPHERICS

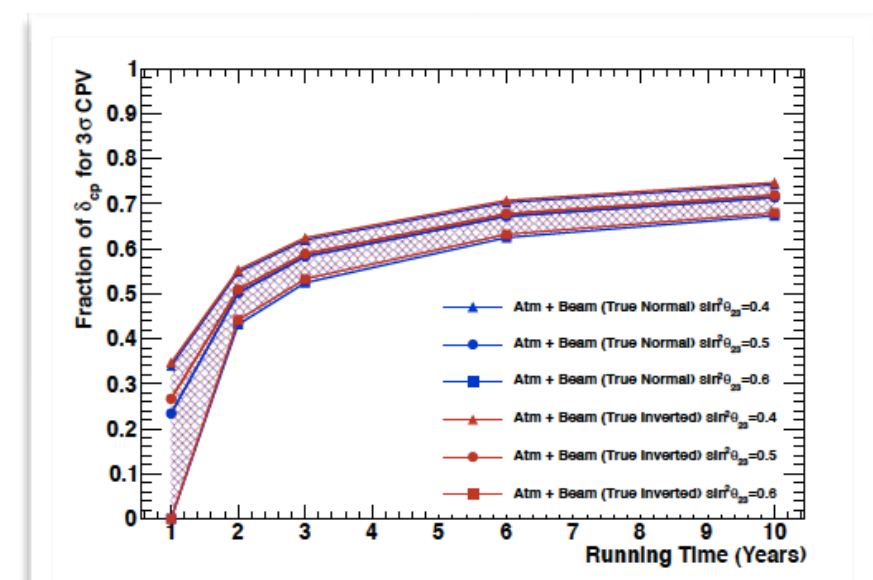
- Expected sensitivity to the mass hierarchy as a function of time
- Even if MH not determined at that time, HK-only can determine the MH at  $5\sigma$  after  $\geq 6$  years.
- The sensitivity highly depends on  $\theta_{23}$  value.



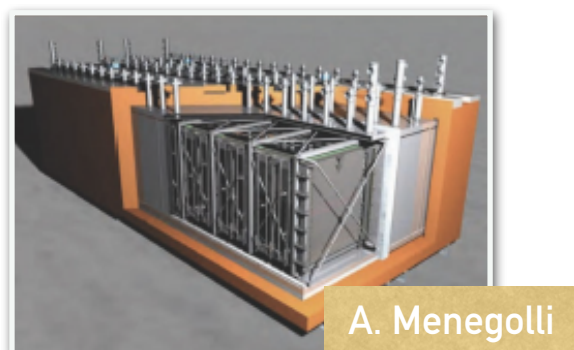
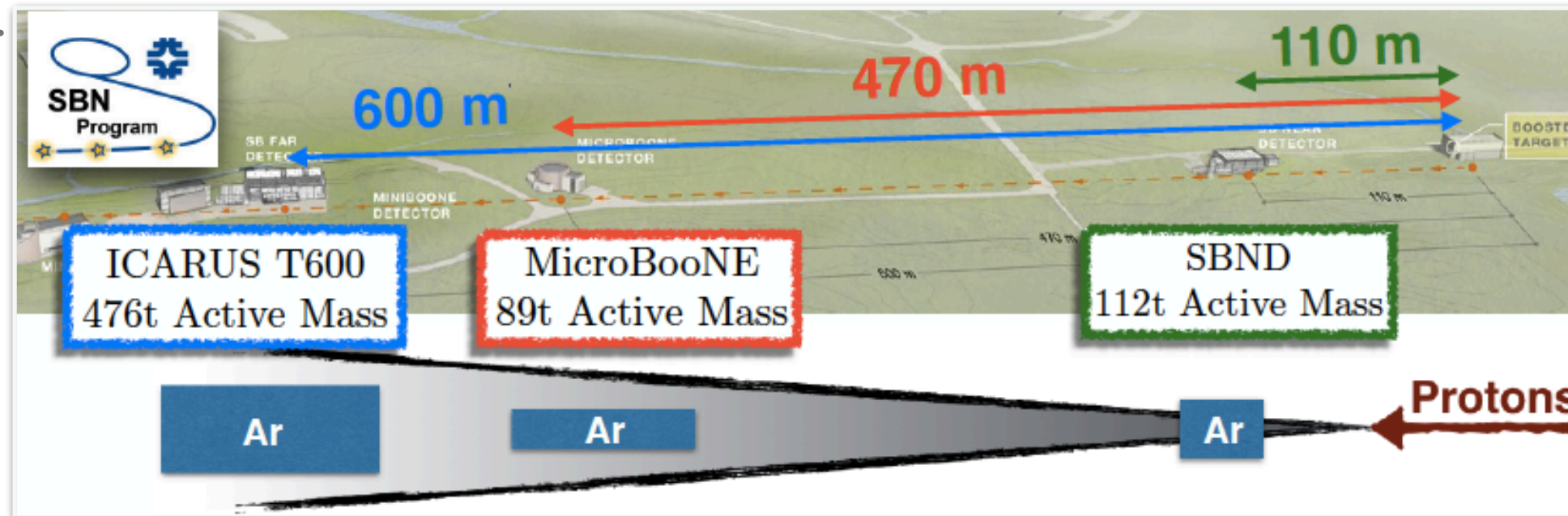
Expected significance to exclude  $\sin\delta_{CP}=0$  plotted as a function of true  $\delta_{CP}$  for beam-only and beam+atmospherics atmospheric neutrinos



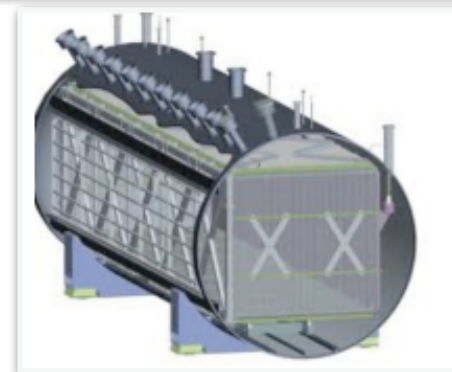
Fraction of  $\phi_{CP}$  phase space at which a  $3\sigma$  observation of CP violation can be made as a function of time for NH and IH



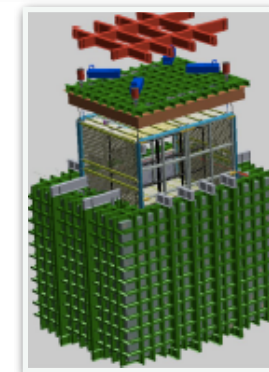
# SHORT BASELINE NEUTRINO (SBN) PROGRAMME



ICARUS- Being installed.  
Data taking by the end of  
the year.

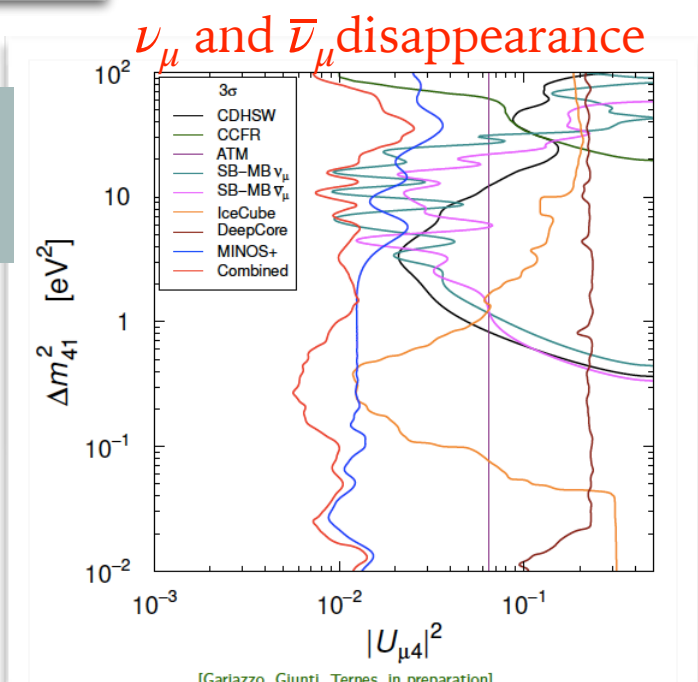


MicroBooNE  
Running



SBND  
Construction ongoing  
Commissioning in 2020  
Data taking in 2021

See review talk on  
sterile neutrinos  
by C. Giunti



SBN aims to:

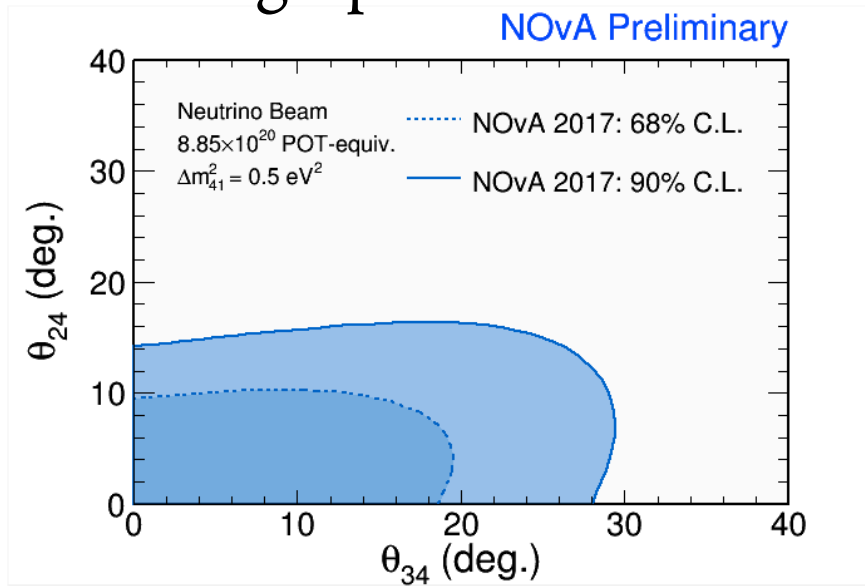
- study the baseline dependence of the appearance and disappearance channels.
- make a high precision measurement on  $\nu$ -Ar cross sections
- develop LArTPC technology for future large neutrino experiments like DUNE



# NOVA AND OPERA STERILE NEUTRINO SEARCHES

- **NOvA**: No evidence of neutral current disappearance and limits sets.
- Being updated with increased  $\bar{\nu}$  dataset and two-detector joint analysis.

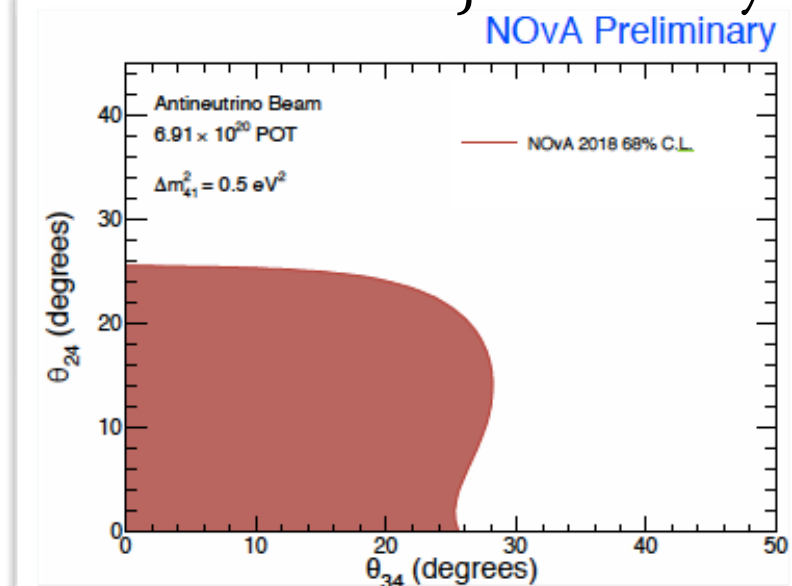
T. Alion



$$\theta_{24} < 16.2^\circ$$

$$\theta_{34} < 29.8^\circ$$

(90% C.L.)



$$\theta_{24} < 25.5^\circ$$

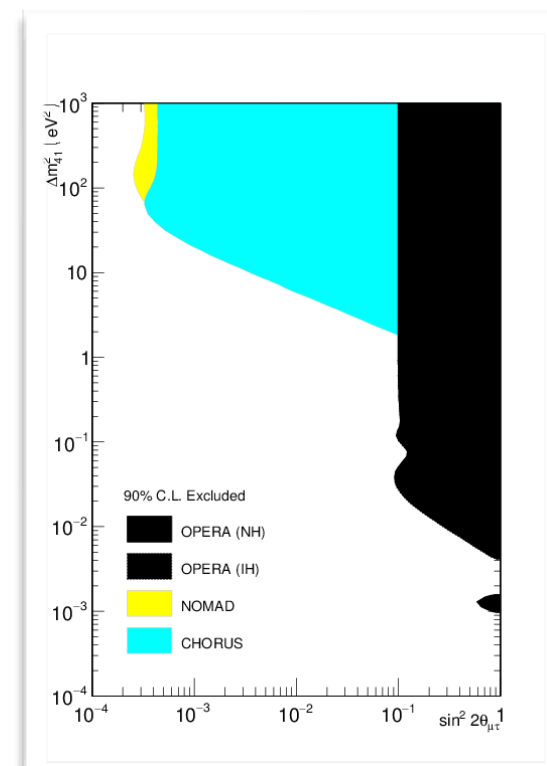
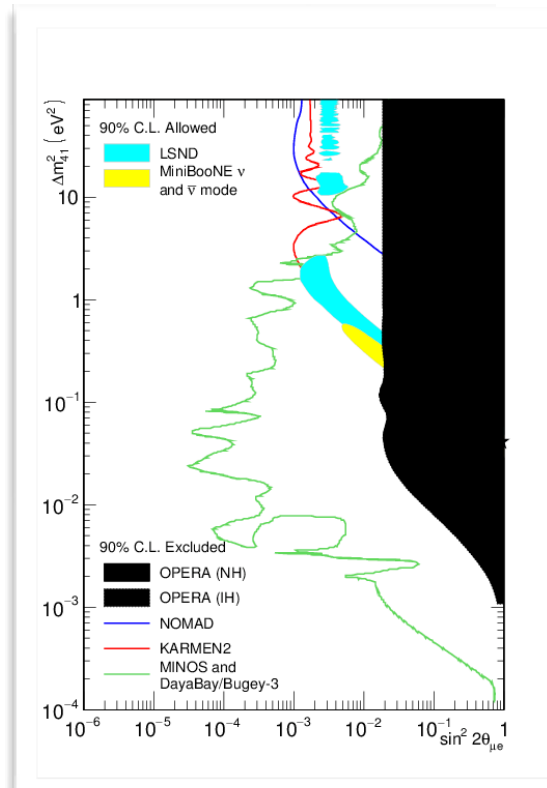
$$\theta_{34} < 31.5^\circ$$

(68% C.L.)

- **OPERA**: Final results
- $\nu_\tau$  and  $\nu_e$  appearance channels were combined for the first time to constrain parameters of the  $3 + 1$  sterile mixing model.
- For  $\Delta m^2_{41} > 0.1 \text{ eV}^2$ , upper limits on  $\sin^2 2\theta_{\mu\tau}$  and  $\sin^2 2\theta_{\mu e}$  are set to 0.10 and 0.019 for NH and IH. The MiniBooNE best-fit values are excluded with  $3.3\sigma$  significance.

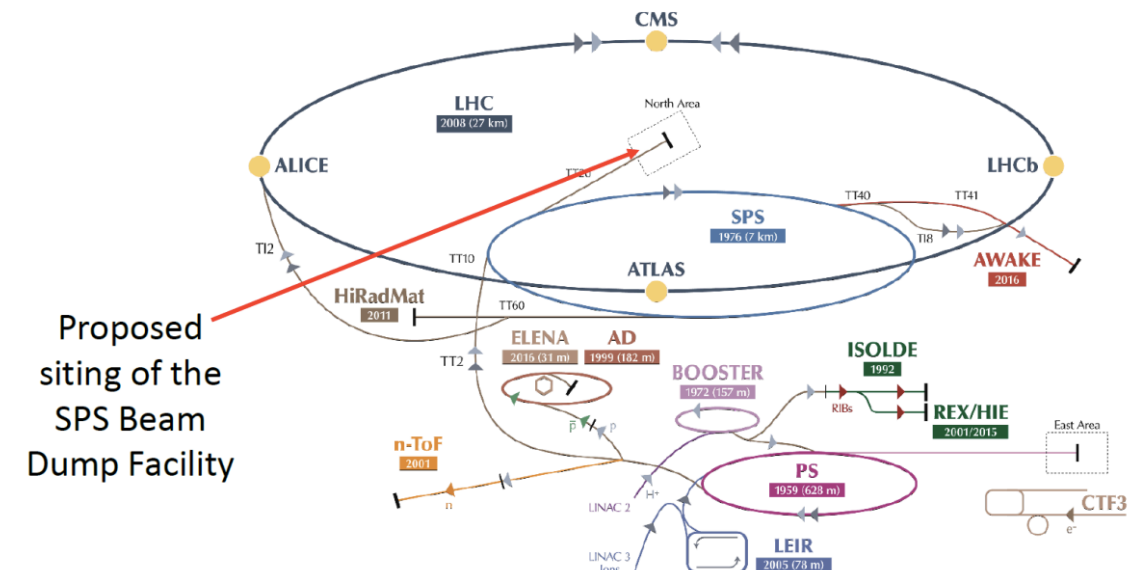
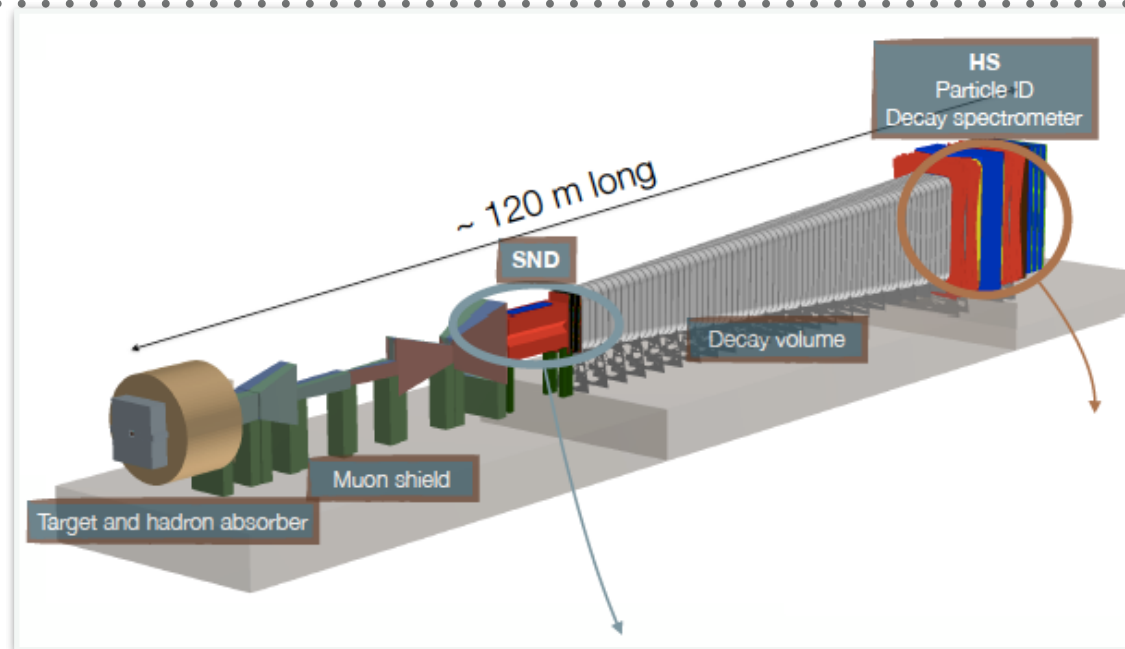
arXiv:1904.05686

G. Galati



# SHIP

arXiv:1504.04956, JINST 14(2019)03 P03025, CERN-SPSC-2019-010



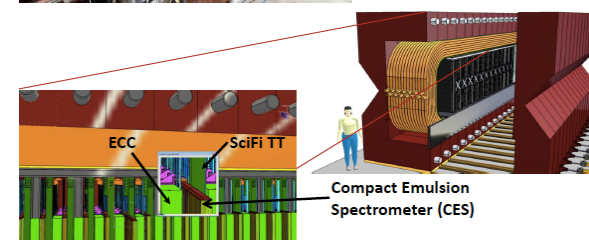
Planned SHIP CDS by 2019

Dual detector system:

- Hidden Sector detector (HS)  $\Rightarrow$  search for new, weakly coupled, long lived particles from the Hidden Sector
- Scattering and Neutrino Detector (SND)  $\Rightarrow$  neutrino physics and Light Dark Matter searches
- SND based on re-development of Opera concepts
- Magnet allows distinguishing between neutrino and anti-neutrino interactions



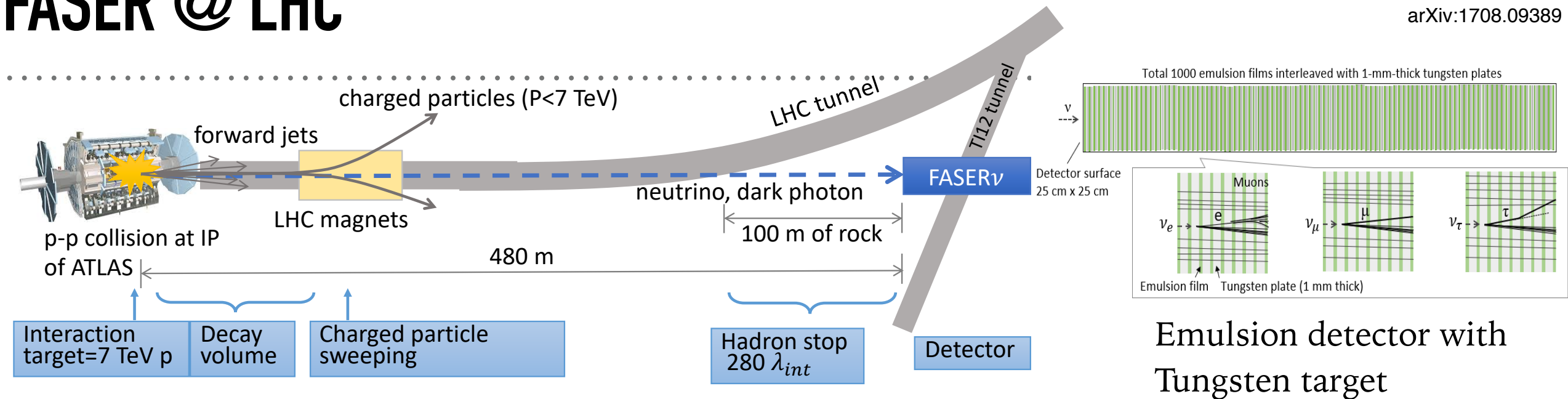
RPC prototypes built and successfully operated for muon flux and charm production measurement at SPS in 2018



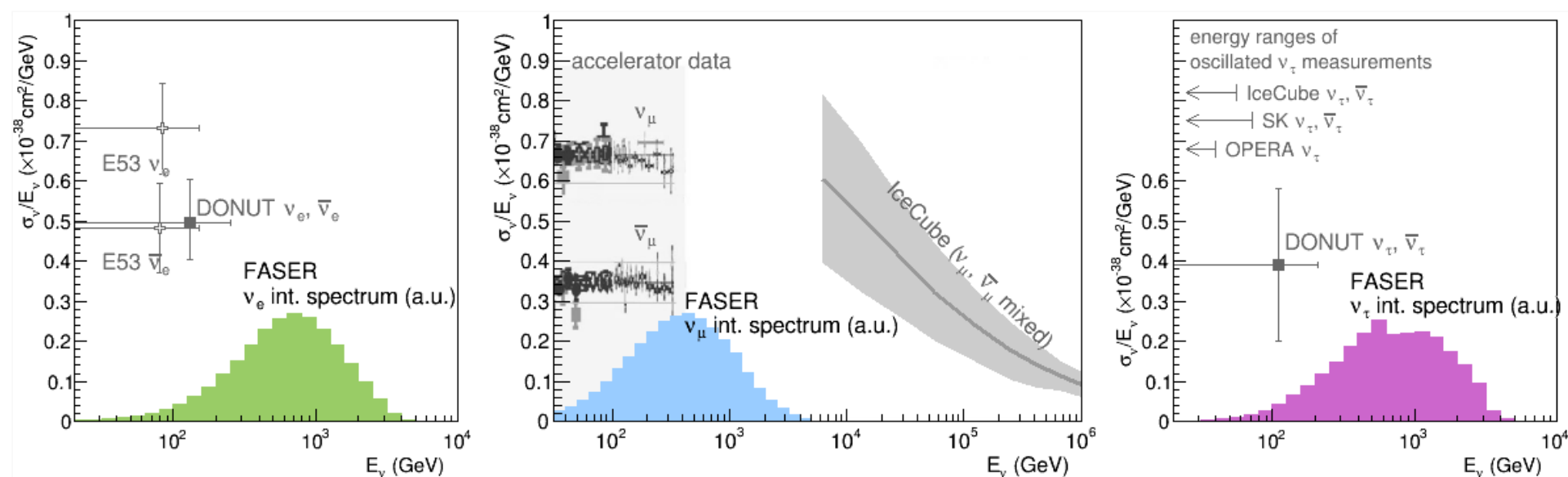
Testbeam at DESY in 2019

# FASER @ LHC

arXiv:1708.09389



- First neutrino project from colliders → **FASER $\nu$**
- 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



Expected Yield in  
2021-2023

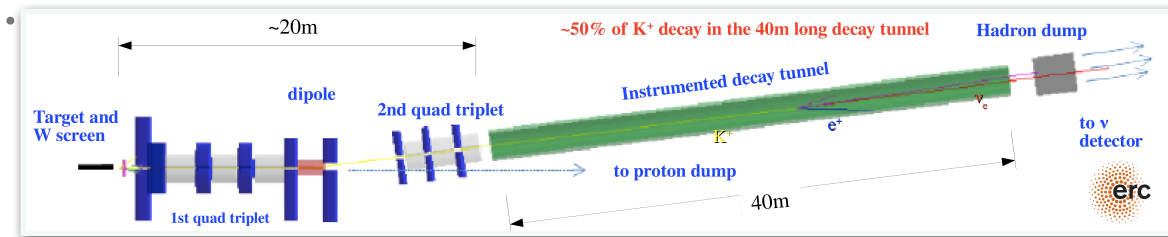
	# of	Mean
$\nu_{e+}$	1296	827
$\nu_{\mu+}$	20439	631
$\nu_{\tau+}$	21	965



# NEXT FACILITIES

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

protons  $\rightarrow (K, \pi) \rightarrow$  Kaon decays  $\rightarrow \nu_e \rightarrow$  neutrino detector



G. Brunetti

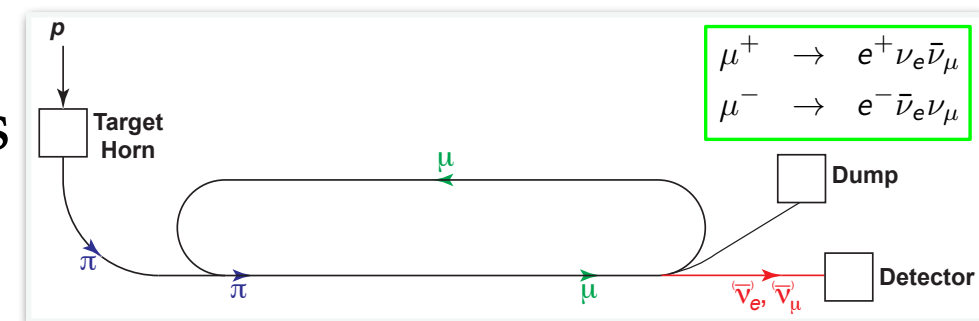
- Aim:  $\sim 1$  order of magnitude better  $\nu_e$  and  $\nu_\mu$  cross sections, search for New Phys.

- **$\nu$ STORM**: Physics goals:

- %o-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  $\nu_e$ ,  $\bar{\nu}_e$ ,  $\nu_\mu$ , and  $\bar{\nu}_\mu$ .



## ESS $\nu$ SB

J. Cederkall

- 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.

# ITEMS NOT COVERED

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Other relevant and very interesting contributions:

- First Sub-Percent Exploration of PMNS Unitarity with LiquidO? (A. Cabrera)
- Neutrino oscillation and CPT violation due to quantum decoherence at DUNE (F.N.D. Desposorio)
- Genuine, Matter-induced and Interference Components of CPV, TRV, CPTV Asymmetries for Neutrino Oscillations (J. Bernabeu)
- Coherent Meson Production in the NOMAD Experiment (C. Kullenberg)
- Non-Standard Neutrino interactions: Current Status and Future Prospects (M. Tortola)
- Probing Non-Standard Interactions with a Muon Decay-at-Rest Source (S. Raut)

# CONCLUSIONS

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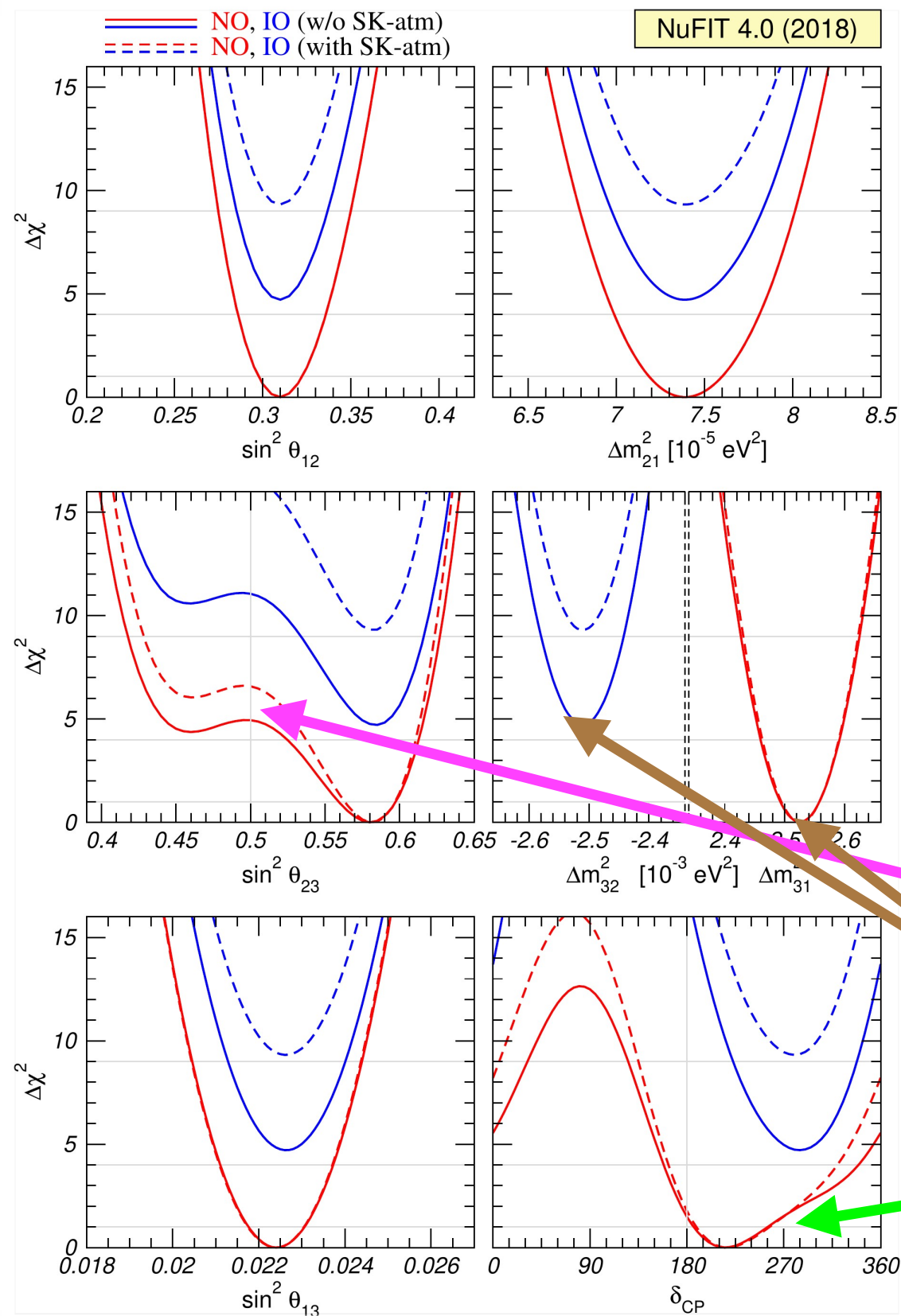
- Current and future experiments addressing open questions as:
  - CP violation
  - Mass hierarchy
  - Sterile and BSM particles
  - Other mixing parameters
- It is supported by a programme that aims to reduce systematics errors in cross section and flux
- Crucial support for current and future experiments from the CERN neutrino platform.



# ADDITIONAL SLIDES

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# GLOBAL FIT RESULTS: $3\nu$ FLAVOUR PARAMETERS



<http://www.nu-fit.org> I. Esteban, C. Gonzales-Garcia, A. Hernandez-Capezudo, M. Maltoni, W. Schwetz *JHEP* 01 (2019) 106

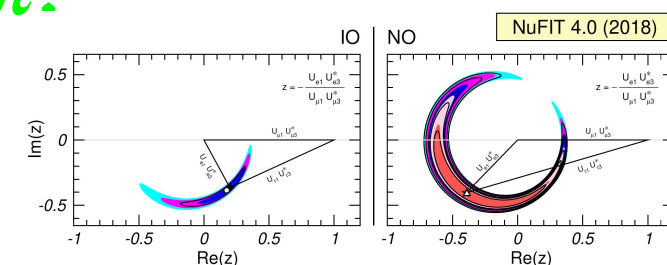
Global 6-parameter fit (November 2018)

Best determined:

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

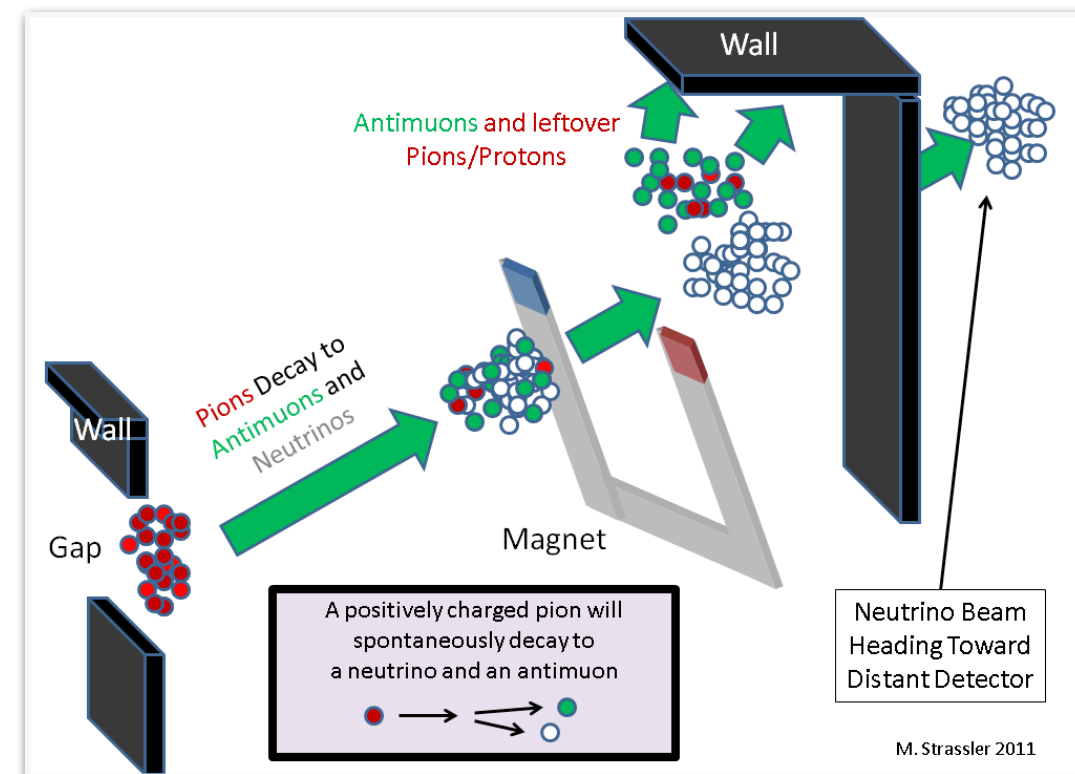
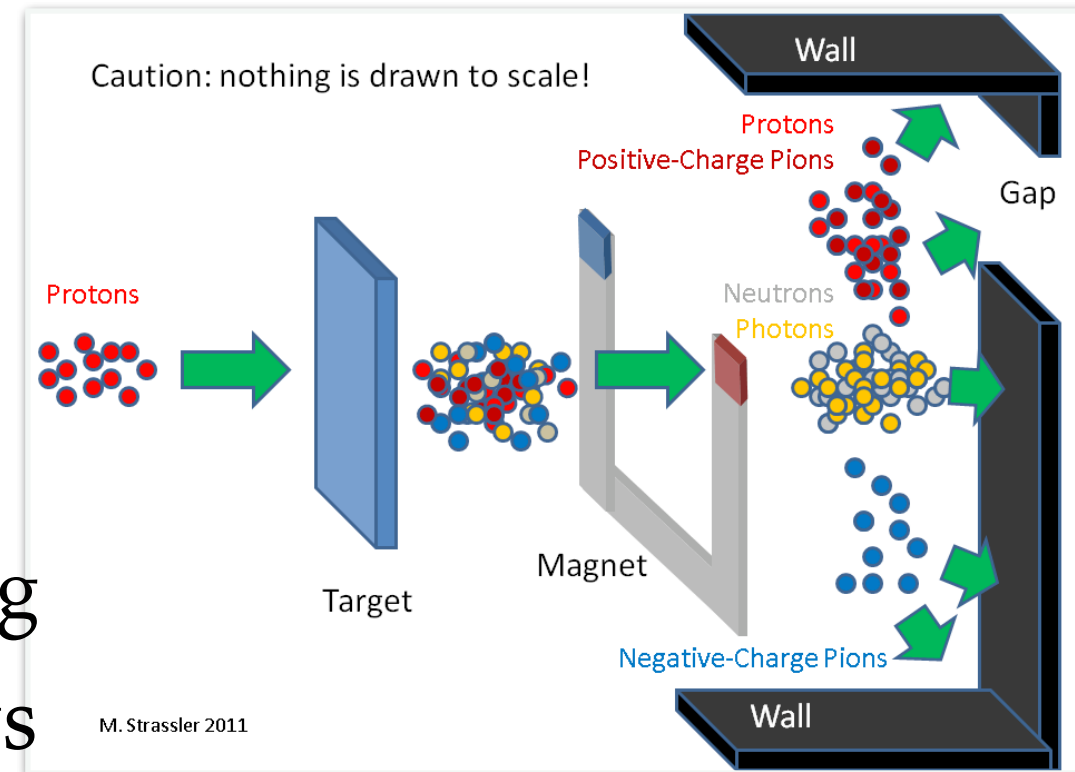
Pending issues:

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



# PARTICLE BEAMS

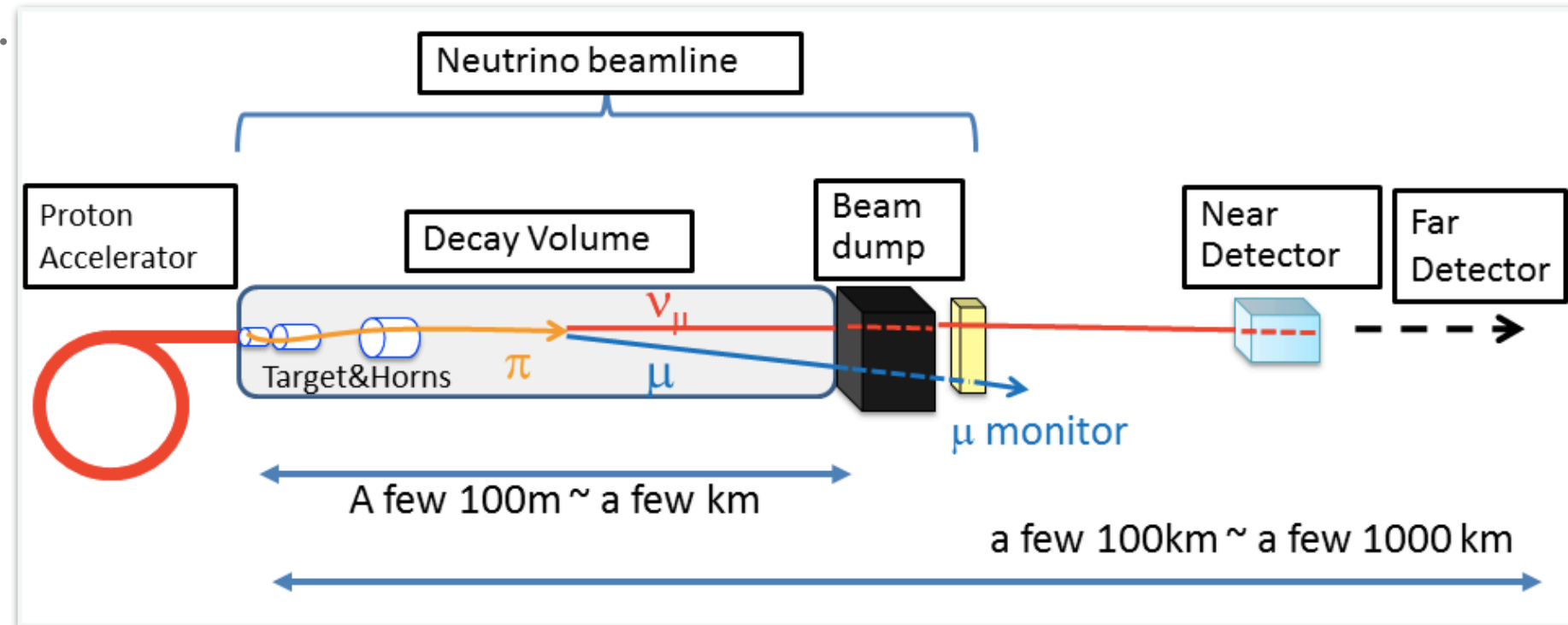
- I'll mainly focus on conventional neutrino beams, as described in this introduction
- Characteristics:
  - Well controlled in energy and timing
  - Neutrinos produced in  $\pi/K/\mu$  decays
- Dominant source is pion decay
  - $\pi \rightarrow \mu + \nu_\mu$  (BR  $\approx$  100%)
  - Simple 2 body decay in CM system
  - Neutrino energy:  $E_\nu \approx \frac{0.43E_\pi}{1 + \gamma^2\theta^2}$
- Neutrinos boosted in the direction of the proton beam.



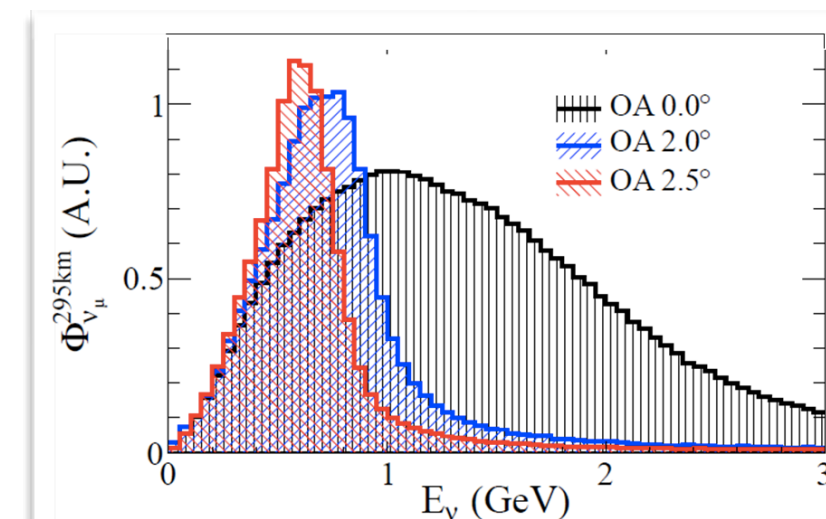
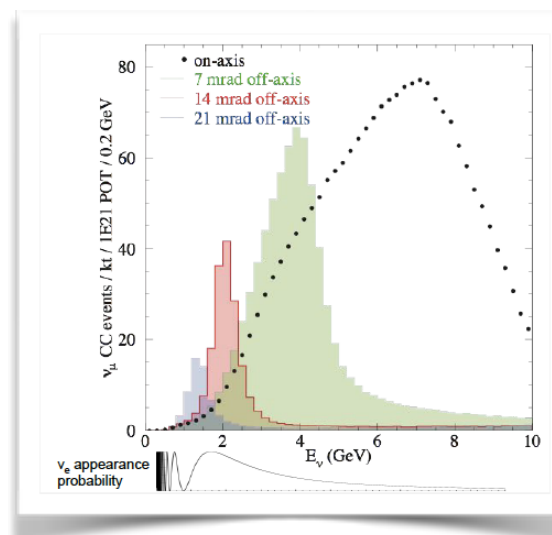
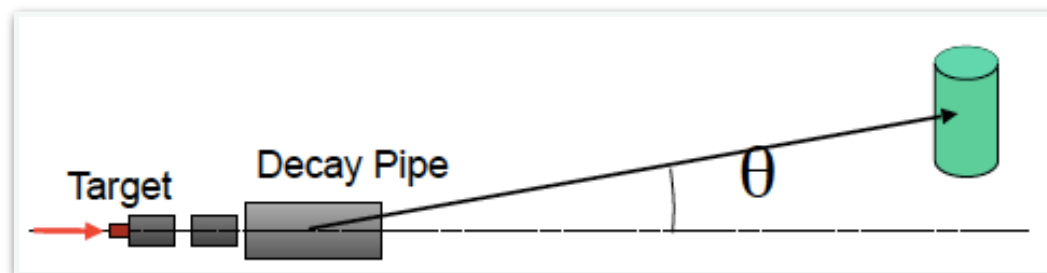


# ACCELERATOR NEUTRINO EXPERIMENTS

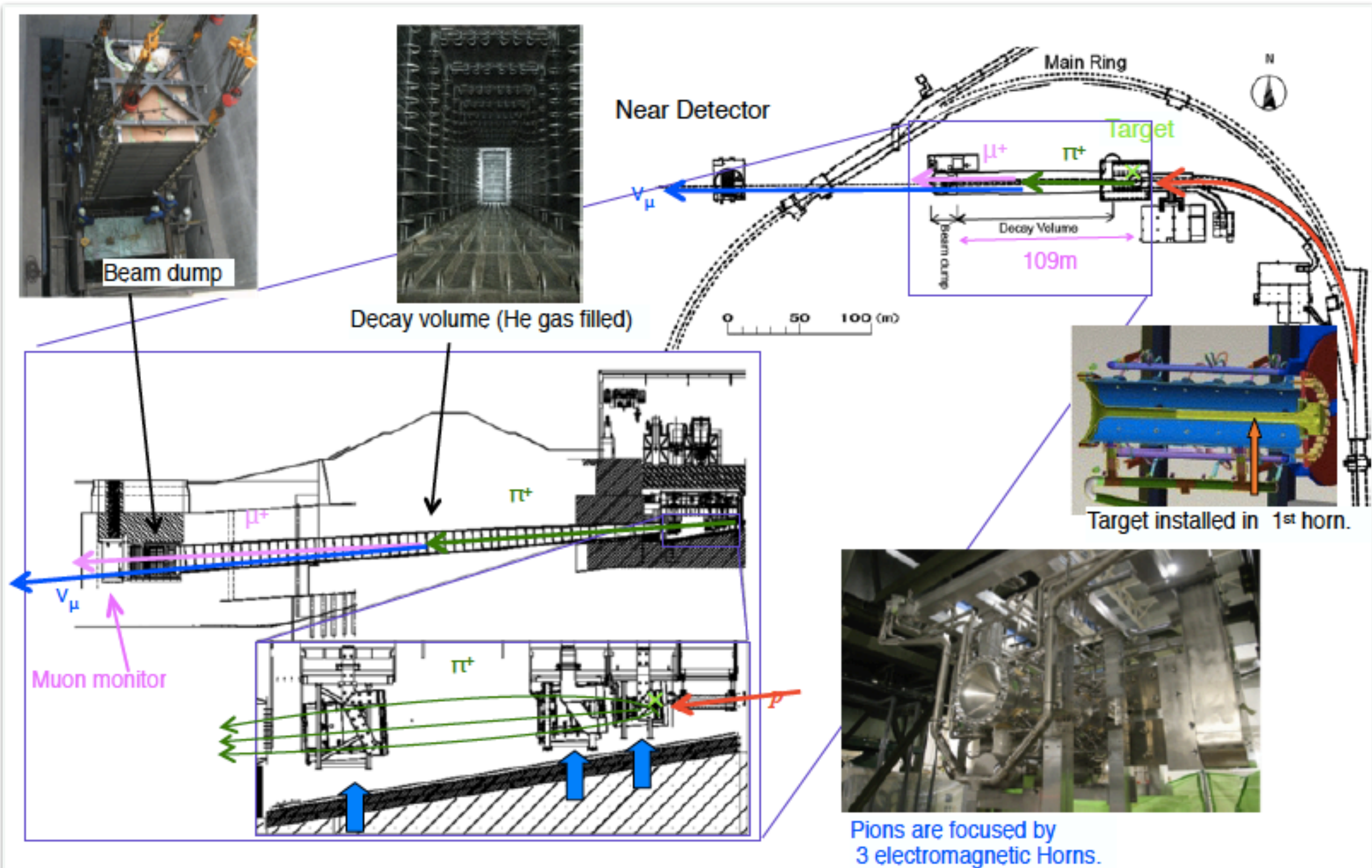
- Components of an accelerator neutrino experiment



- 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



# J-PARC NEUTRINO BEAM LINE

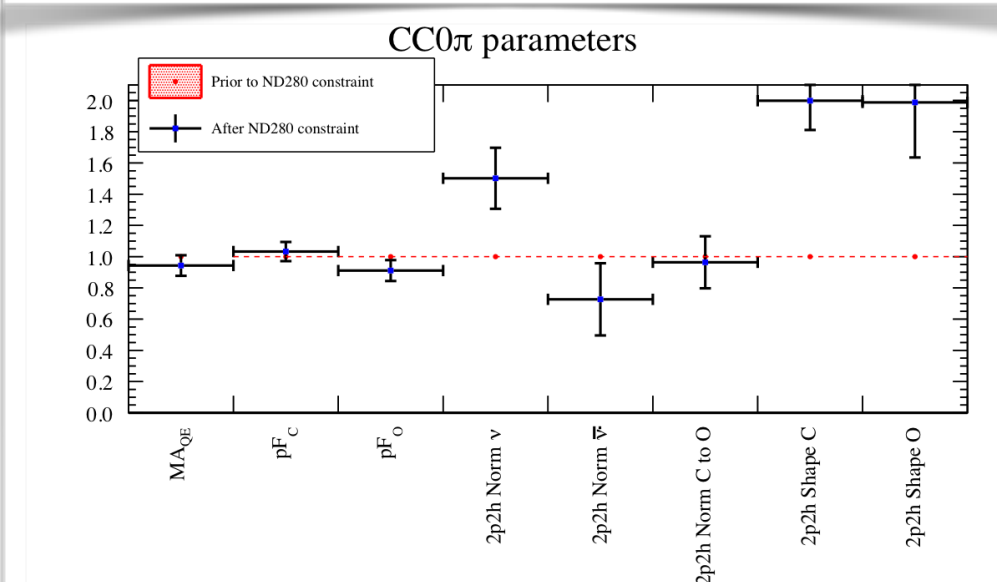
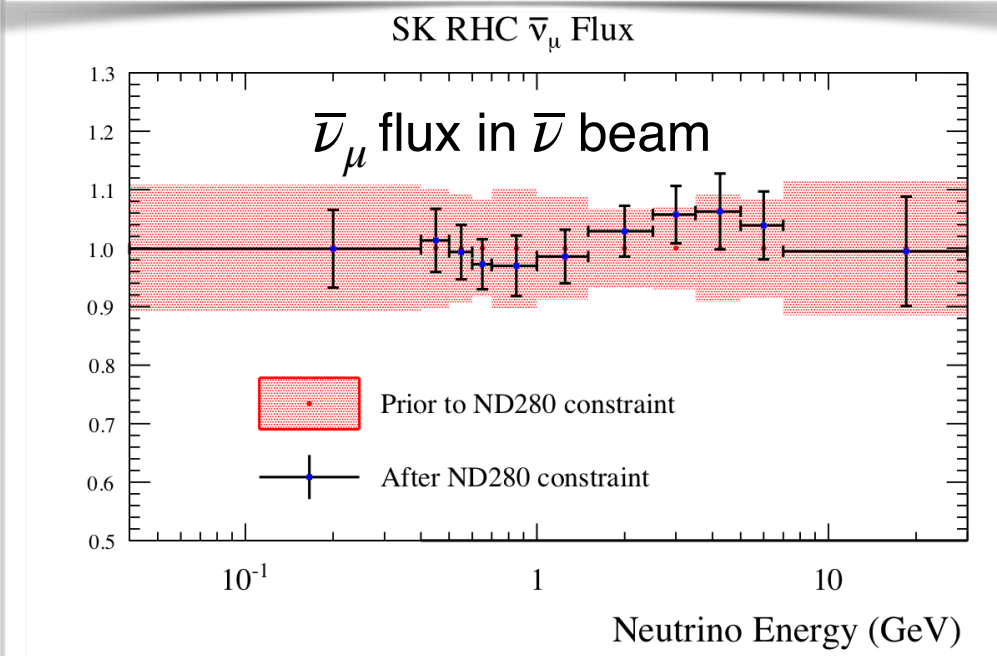
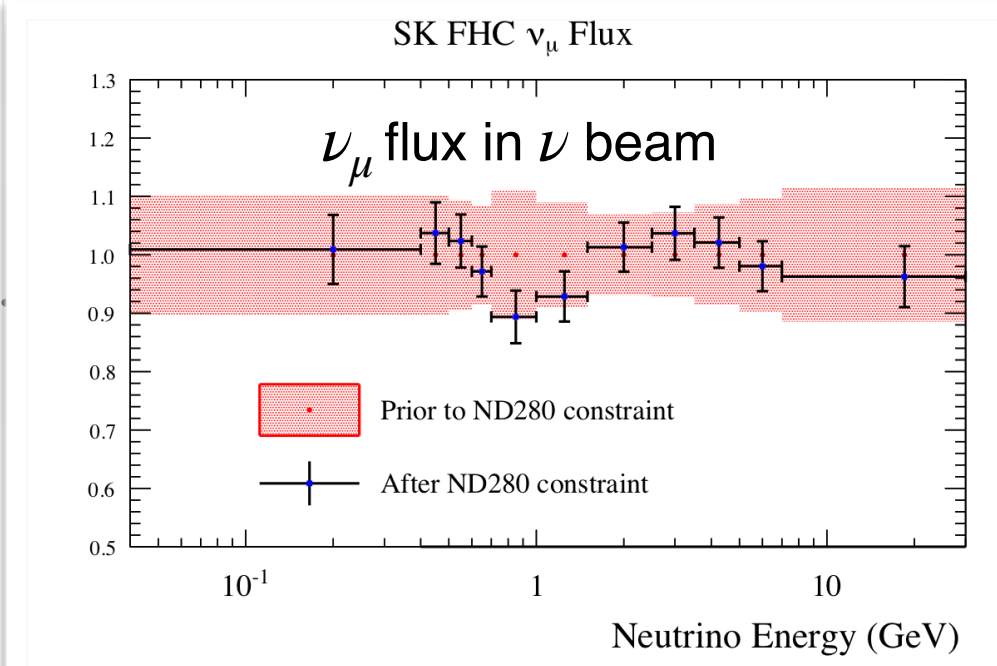


# ND280 DATA FITTING AND RESULTS

Parametrise cross section & flux models

- Constrain by fitting ND280 data
- Result of data fit reduces flux & interaction model uncertainties at Super-K
- Also measure  $\nu$ -nucleus cross sections
- Impact on Super-K:

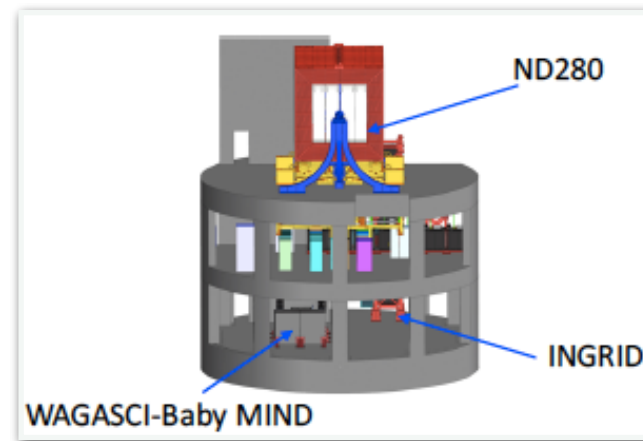
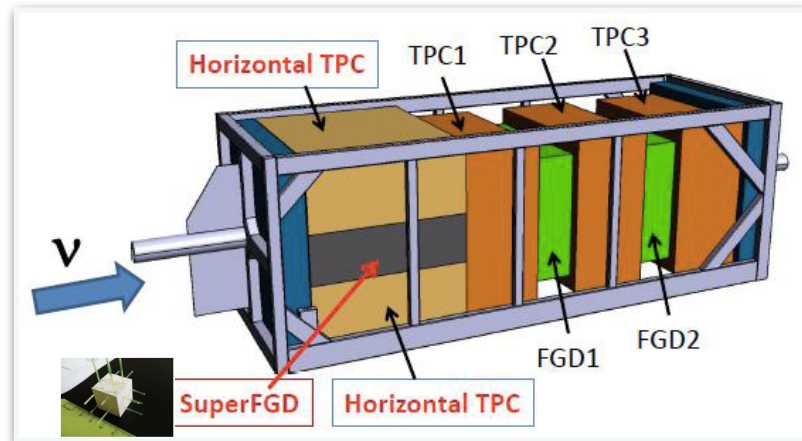
Sample	w/o ND280	w/ ND280
$\nu$ 1R $\mu$	14,6%	5,1%
$\bar{\nu}$ 1R $\mu$	12,5%	4,5%
$\nu$ 1Re	16,9%	8,8%
$\bar{\nu}$ 1Re	14,4%	7,1%
$\nu$ 1Re+1 $\pi^+$	22,0%	18,7%





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

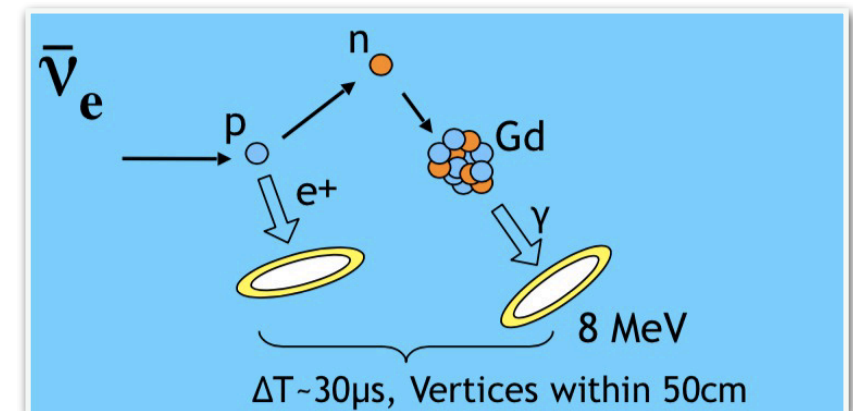
Near detector suite (at 280m):



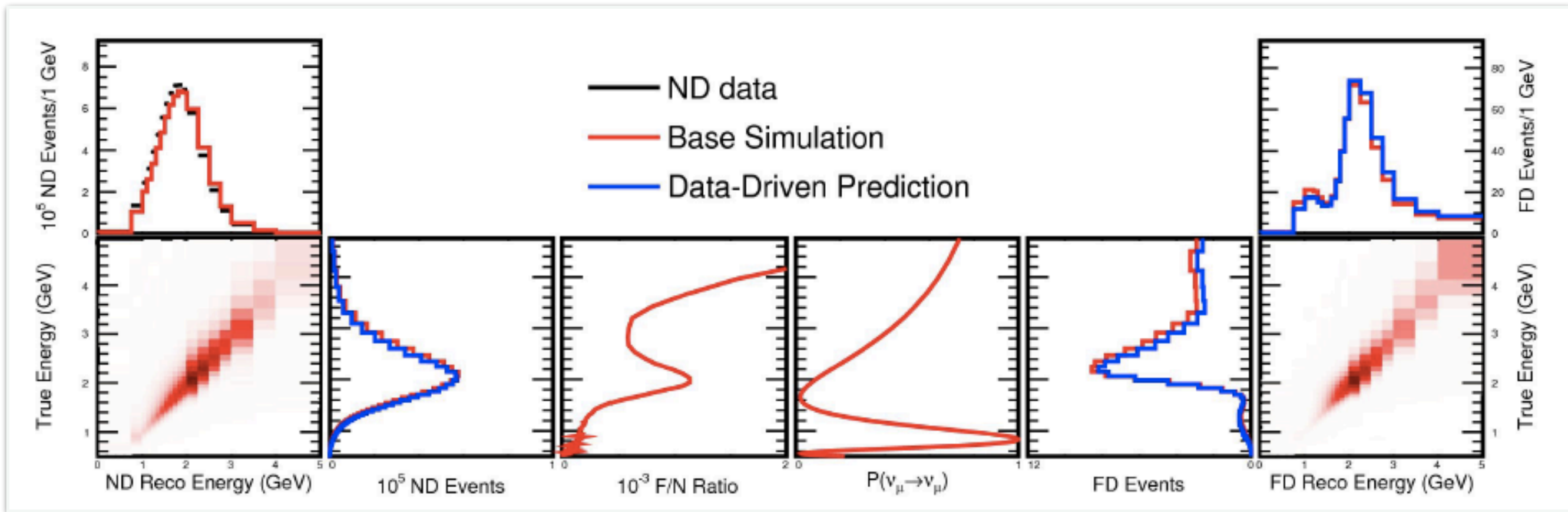
- Larger angular acceptance.
- Better reconstruction efficiency
- Approx. 2 more events expected
- Reduction of out-of-fiducial-volume background

Super-Kamiokande

- Gadolinium doping (SK-Gd)
- Refurbishment in 2018
- Start gradual addition of Gd in 2020
  - Gd enhances neutron detection
  - It can help with  $\bar{\nu}_e$  wrong sign background rejection



# CONSTRAINING PREDICTIONS

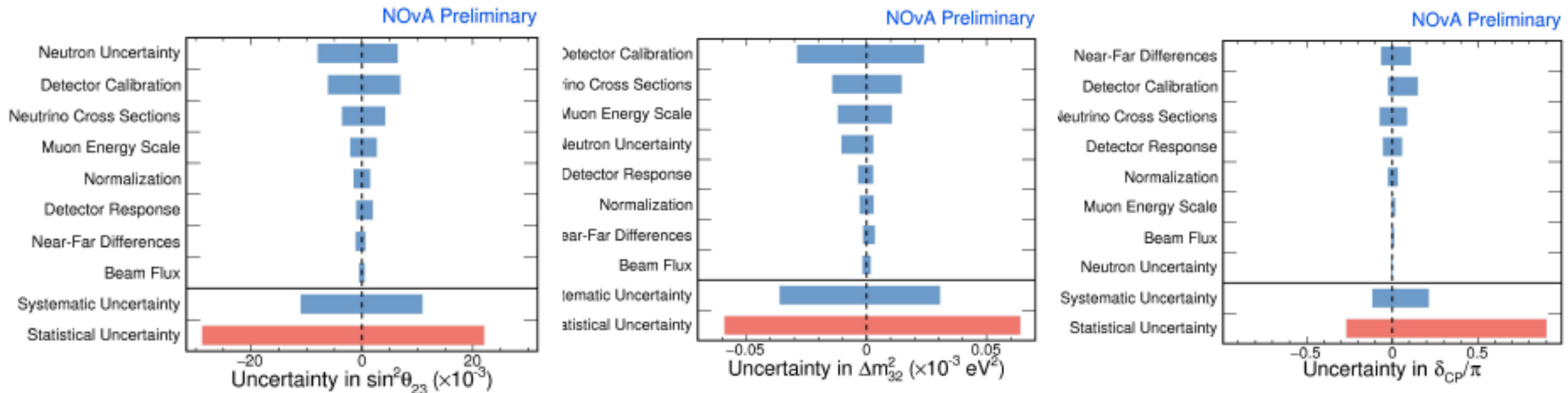


Extrapolate neutrino spectrum at the near detector to the spectrum at the far detector.

Multiply by the far-to-near flux ratio (shape of beam at far vs near detectors) and the oscillation probability to predict the true spectrum at the far detector.

Convert back to reconstructed energy to compare to far detector data

# NOVA SYSTEMATIC ERRORS



- Statistically limited
- The leading systematics are detector calibration, neutrino/antineutrino cross section uncertainties, and contributions from neutron response.
- Upcoming testbeam @ Fermilab will address many of these contributions.



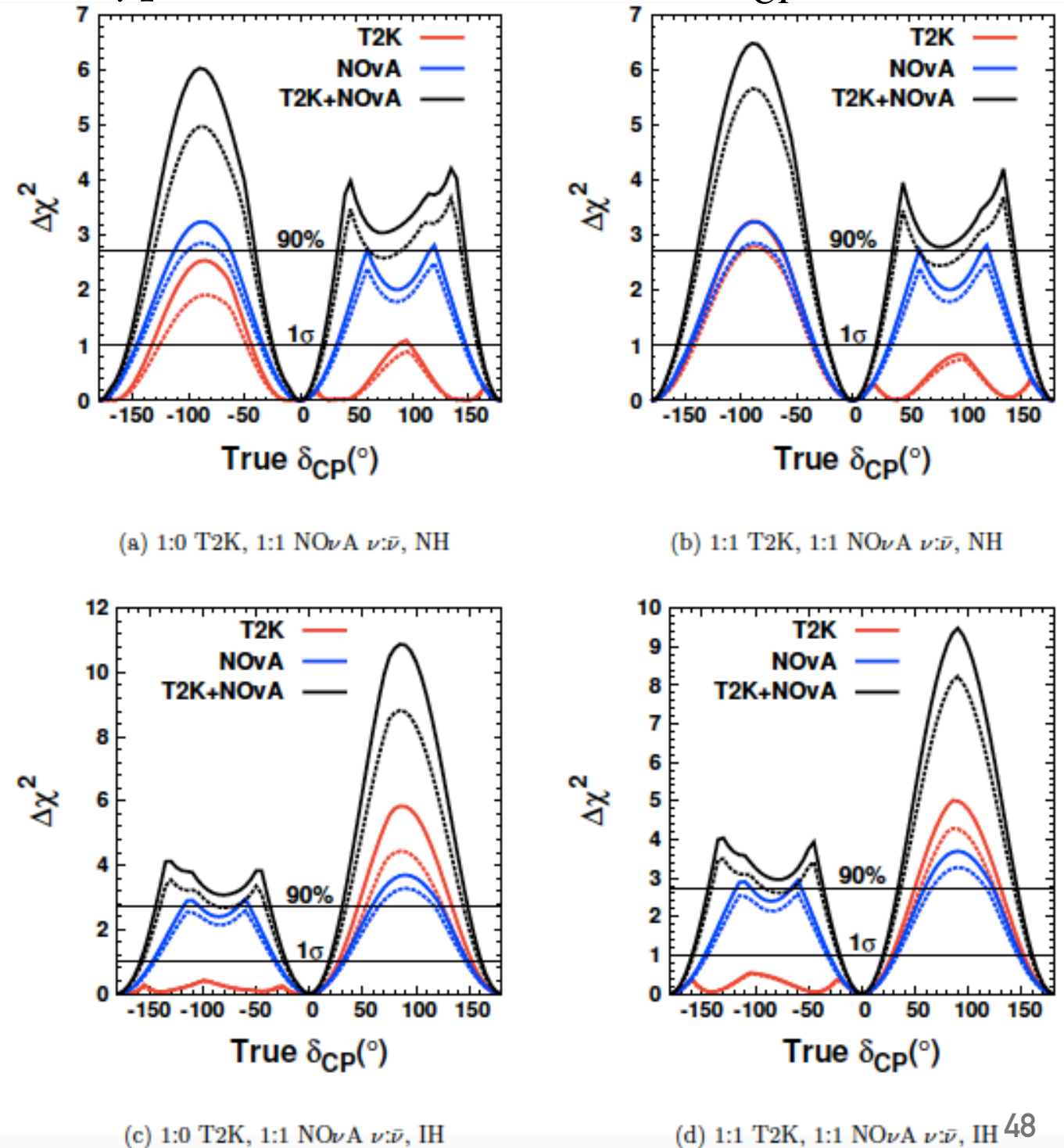


# T2K-NOVA COMBINATION

- T2K & NOvA combined results under way.
- Relevant correlations in the flux and cross section modelling will be accounted for.
- Combination breaks nearly degeneracy of T2K  $\nu_e$  appearance event rate predictions at SK in NH w/  $\delta_{CP} > 0$  compared to the prediction in IH w/  $\delta_{CP} < 0$ .
- Initial sensitivity studies in T2K future sensitivity paper.

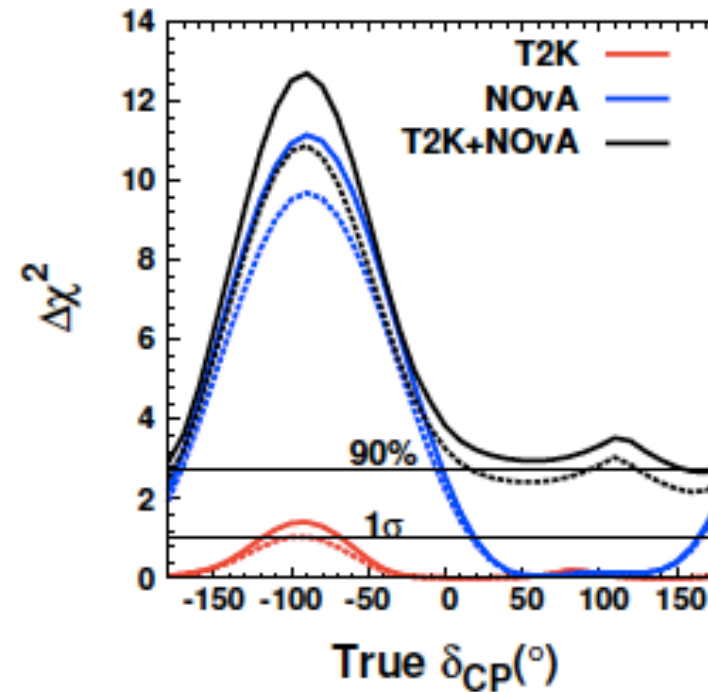
Dashed (solid) curves indicate studies where normalisation systematics are (not) considered.

Predicted  $\chi^2$  for rejecting the  $\sin \delta_{CP} = 0$  hypothesis, as a function of  $\delta_{CP}$

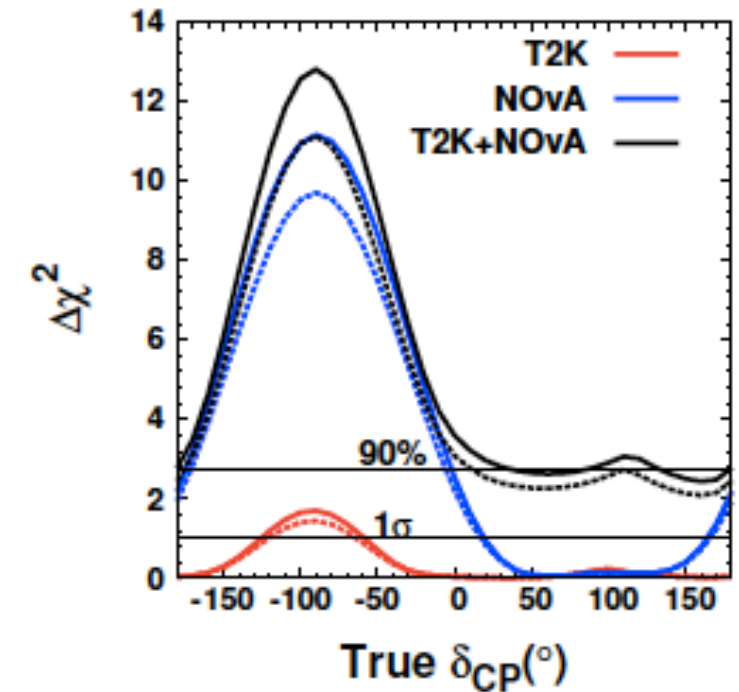


# T2K-NOVA COMBINATION

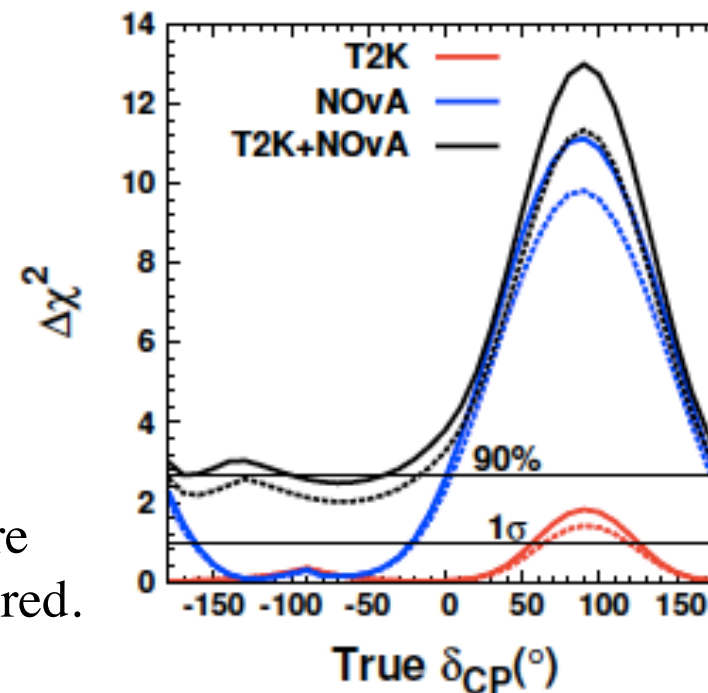
The predicted  $\chi^2$  for rejecting the incorrect MH hypothesis, as a function of  $\delta_{CP}$



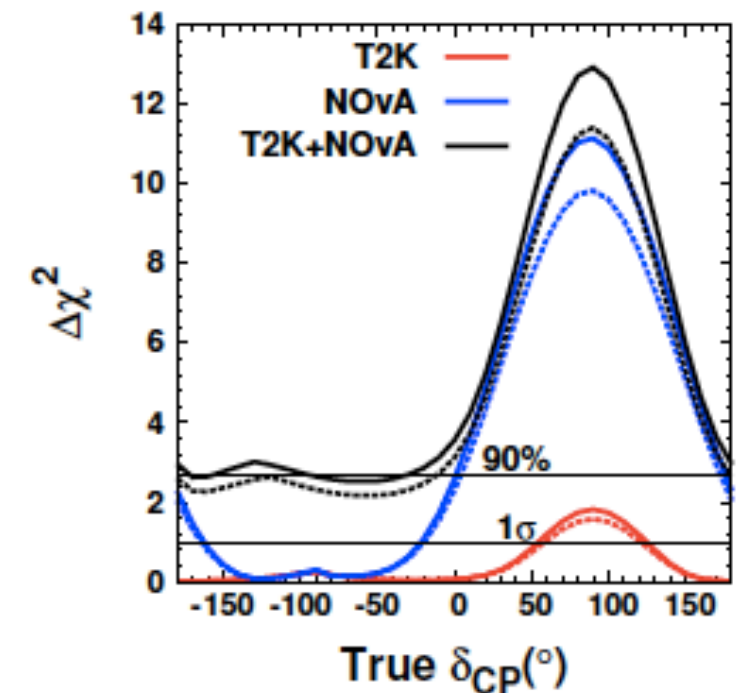
(a) 1:0 T2K, 1:1 NO $\nu$ A  $\nu:\bar{\nu}$ , NH



(b) 1:1 T2K, 1:1 NO $\nu$ A  $\nu:\bar{\nu}$ , NH



(c) 1:0 T2K, 1:1 NO $\nu$ A  $\nu:\bar{\nu}$ , IH



(d) 1:1 T2K, 1:1 NO $\nu$ A  $\nu:\bar{\nu}$ , IH

Dashed (solid) curves indicate studies where normalisation systematics are (not) considered.

# NEUTRINO INTERACTION ERROR IN OSCILLATIONS FOR T2K

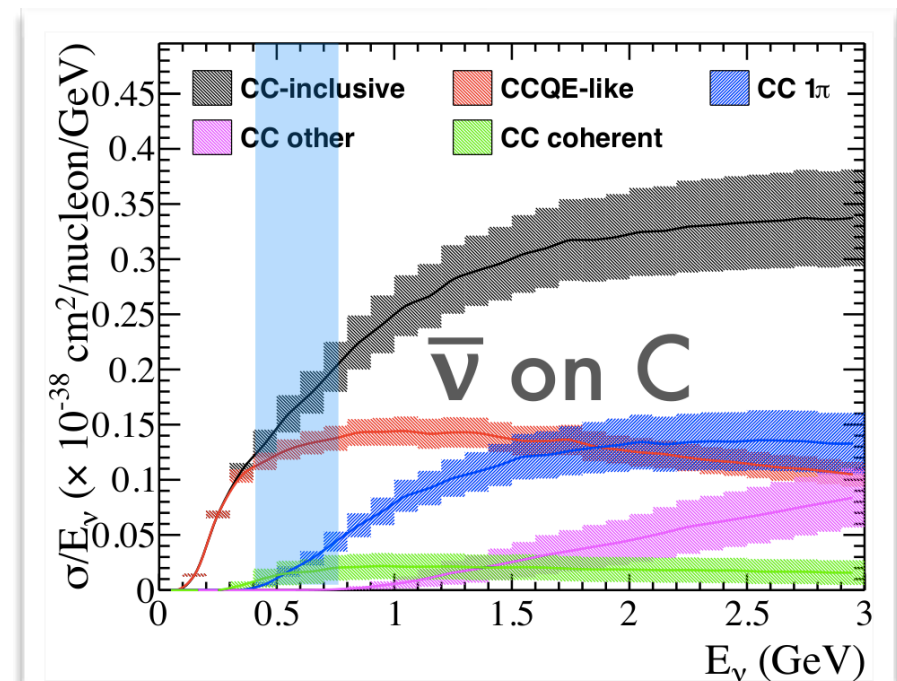
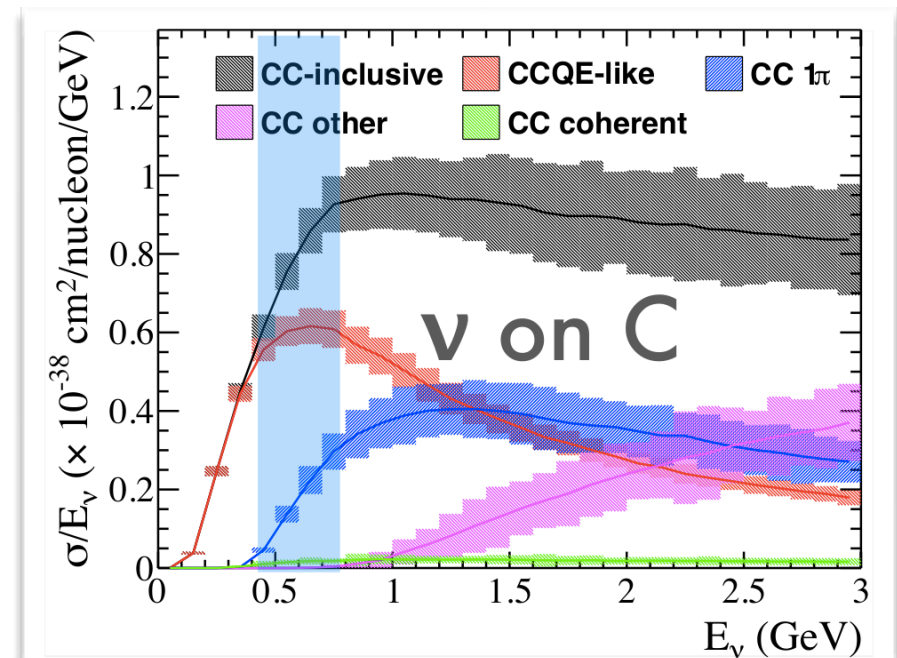
- Neutrino interaction model is essential to reduce neutrino oscillation systematic uncertainties
- Example from T2K:

Phys. Rev. Lett. 121, 171802, 2018

TABLE I. Systematic uncertainty on far detector event yields.

Source [%]	$\nu_\mu$	$\nu_e$	$\nu_e \pi^+$	$\bar{\nu}_\mu$	$\bar{\nu}_e$
ND280-unconstrained cross section	2.4	7.8	4.1	1.7	4.8
Flux & ND280-constrained cross sec.	3.3	3.2	4.1	2.7	2.9
SK detector systematics	2.4	2.9	13.3	2.0	3.8
Hadronic re-interactions	2.2	3.0	11.5	2.0	2.3
Total	5.1	8.8	18.4	4.3	7.1

11 – 14 % before near detector constraints





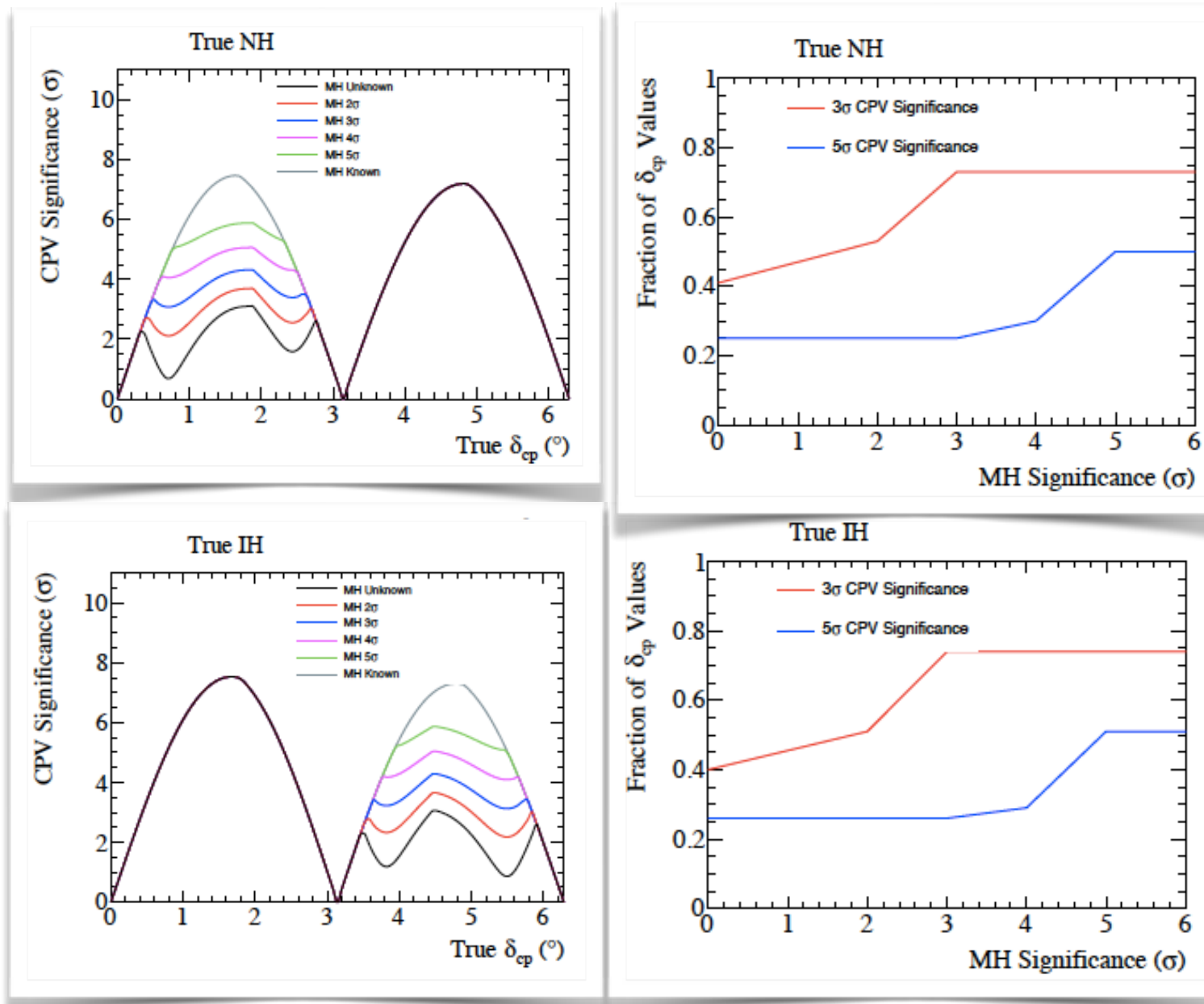
# DUNE SYSTEMATIC ERRORS

Source of Uncertainty	MINOS $\nu_e$	T2K $\nu_e$	DUNE $\nu_e$
Beam Flux after N/F extrapolation	0.3%	3.2%	2%
Interaction Model	2.7%	5.3%	$\sim 2\%$
Energy scale ( $\nu_\mu$ )	3.5%	included above	(2%)
Energy scale ( $\nu_e$ )	2.7%	2.5% includes all FD effects	2%
Fiducial volume	2.4%	1%	1%
Total	5.7%	6.8%	3.6 %
Used in DUNE Sensitivity Calculations			$5\% \oplus 2\%$

- DUNE Conceptual Design Report (CDR) arXiv:1512.06148
- The DUNE signal normalization uncertainty is taken to be 5% 2% in  $\oplus$  both neutrino and antineutrino mode, where 5% is the normalization uncertainty on the FD  $\nu_\mu$  sample and 2% is the effective uncorrelated uncertainty on the FD  $\nu_e$  sample after fits to both near and far detector data and all external constraints

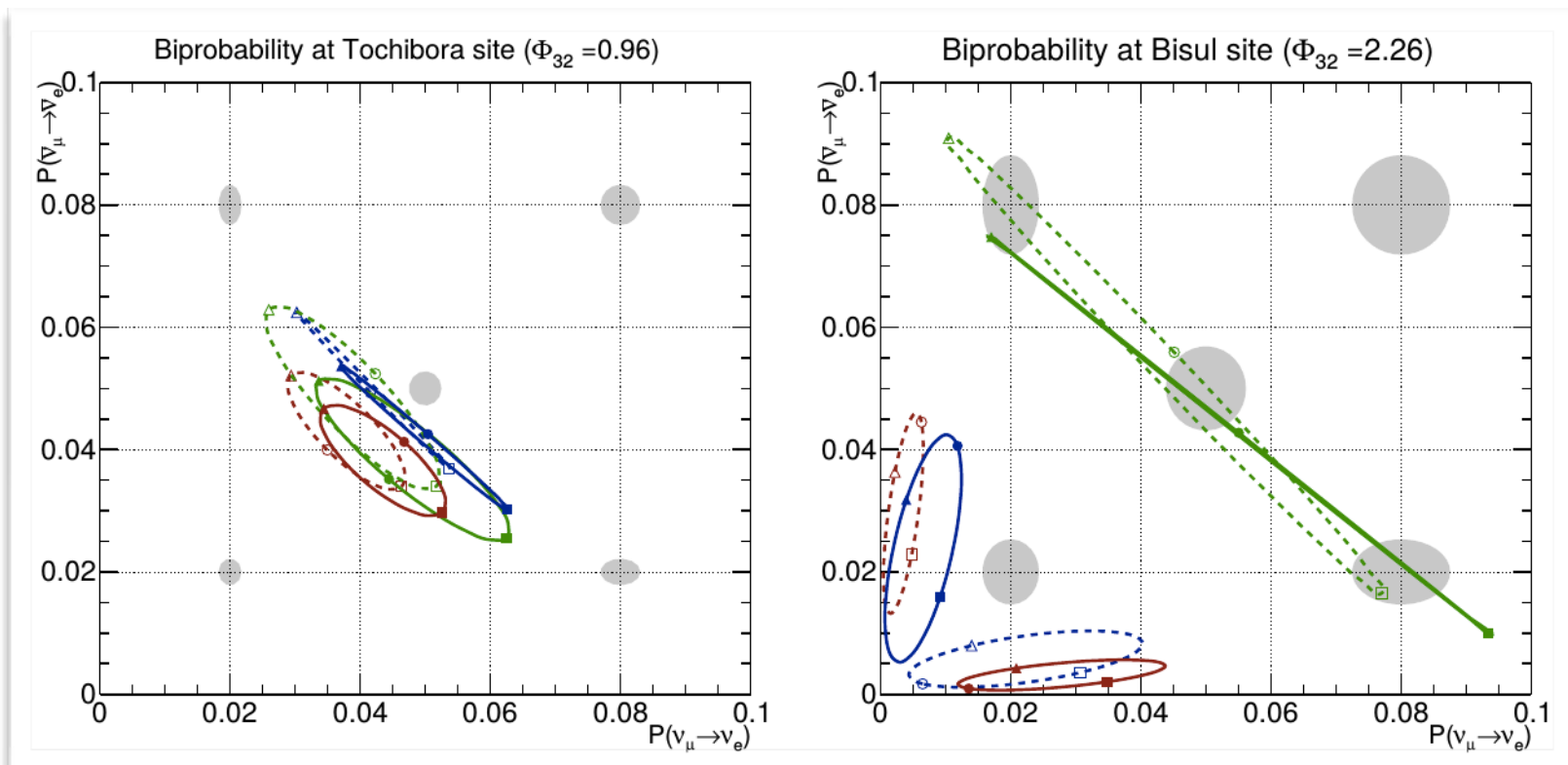
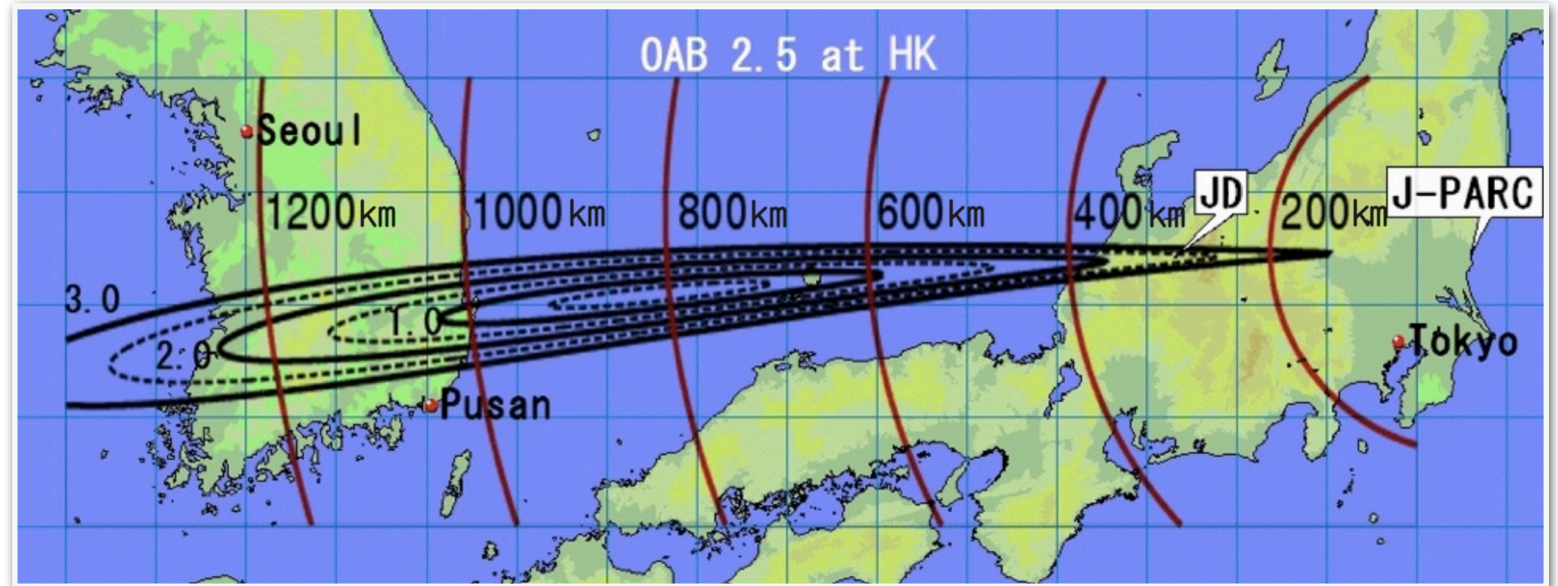
# HYPER-KAMIOKANDE WITH BEAM ONLY

- Expected significance to exclude  $\sin\delta_{CP}=0$  plotted as a function of true  $\delta_{CP}$  assuming different constraints on the MH
- For illustration purposes. It is not using the latest systematic errors and fitting program.



# SECOND FAR DETECTOR STAGING

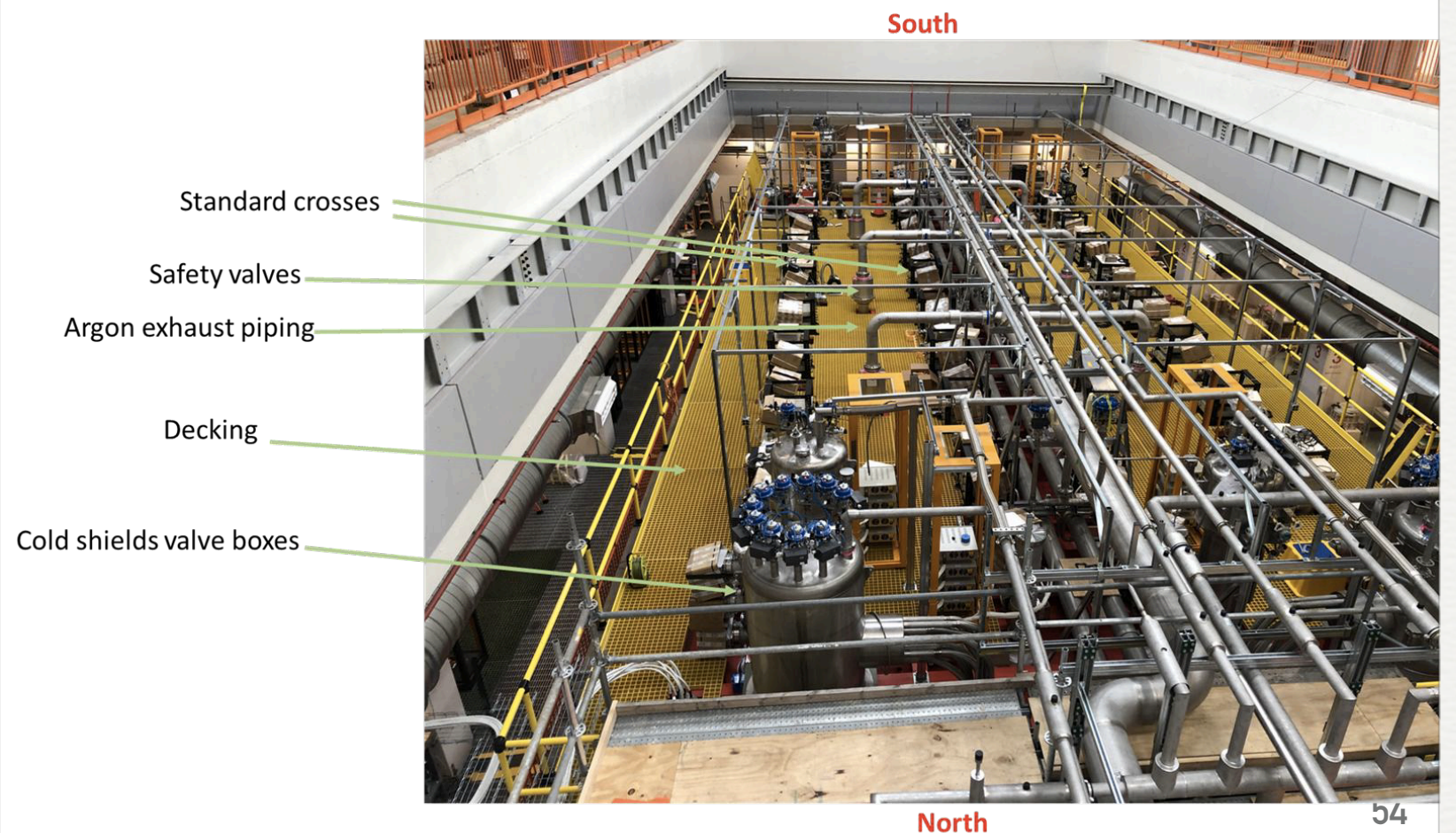
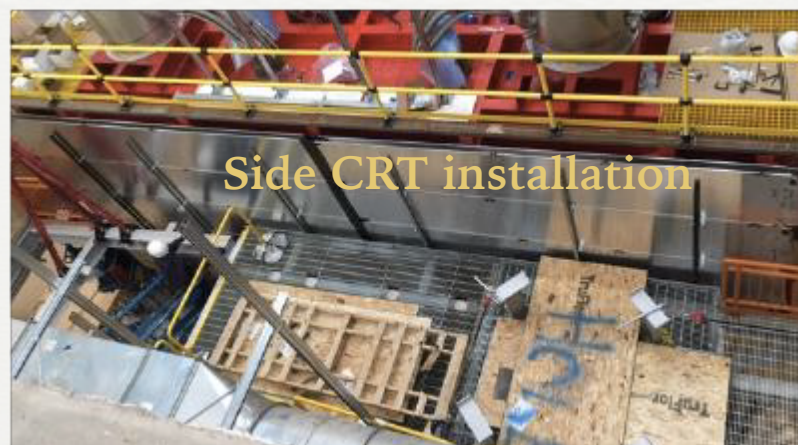
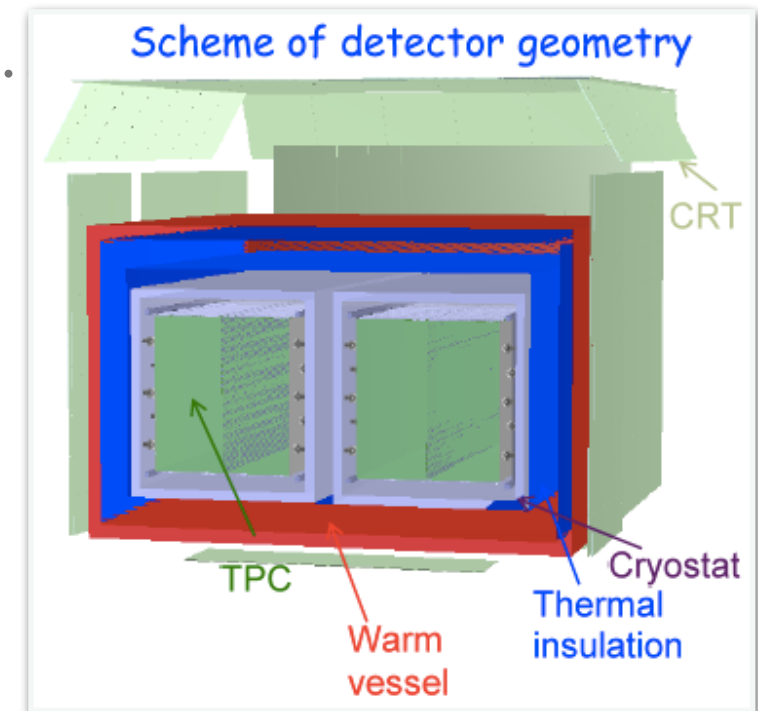
- Install a 2<sup>nd</sup> detector in Korea
  - Baseline > 1000 km
  - Off-axis angle could be  $1.3^\circ$ .
- Improved MH sensitivity
- Enhanced  $\delta_{CP}$  impact





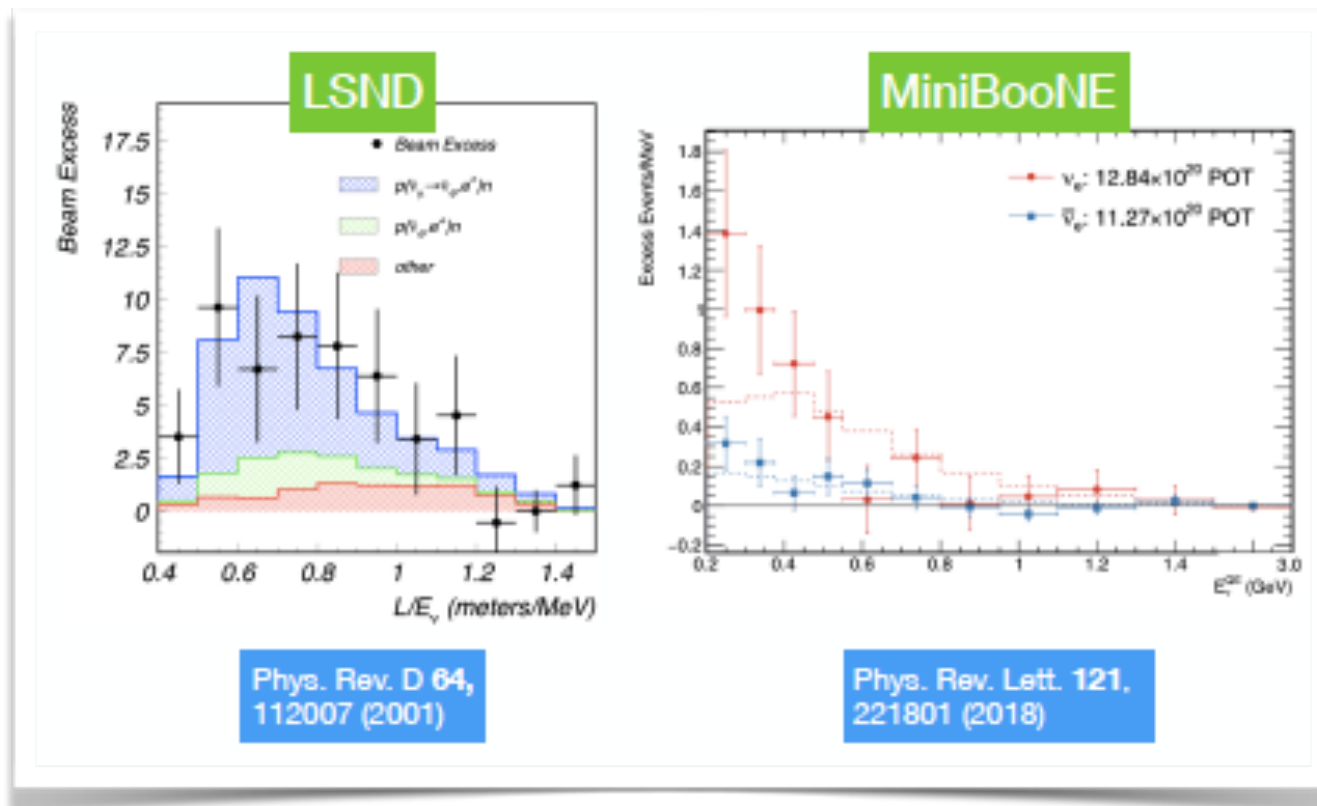
# ICARUS INSTALLATION AT FNAL STATUS

- Operational at LNGS from 2010 to 2013
- In 2015, sent to CERN for refurbishment
- Shipped to Fermilab in June 2017
- ICARUS Vacuum phase started on Jun5
- Cryostat installation ongoing
- Passed Director's review

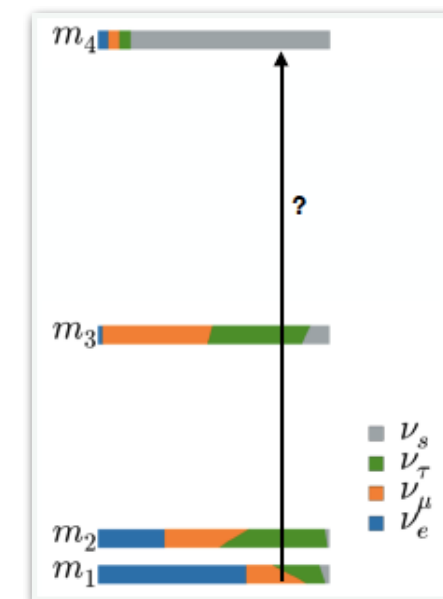
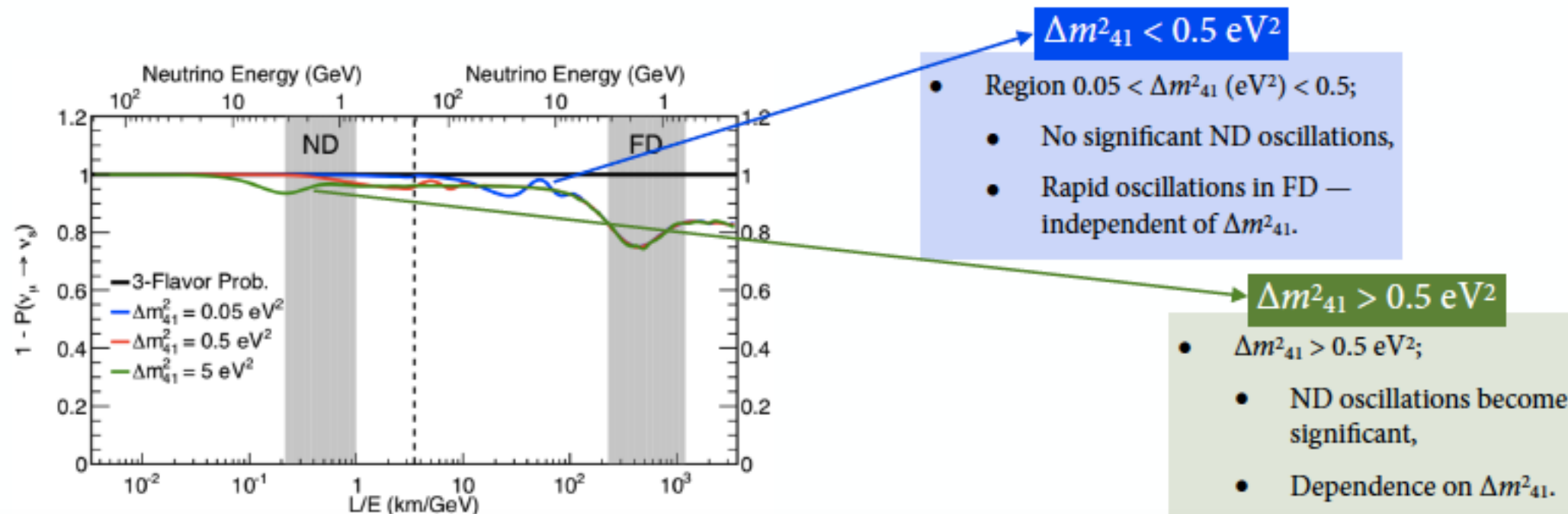




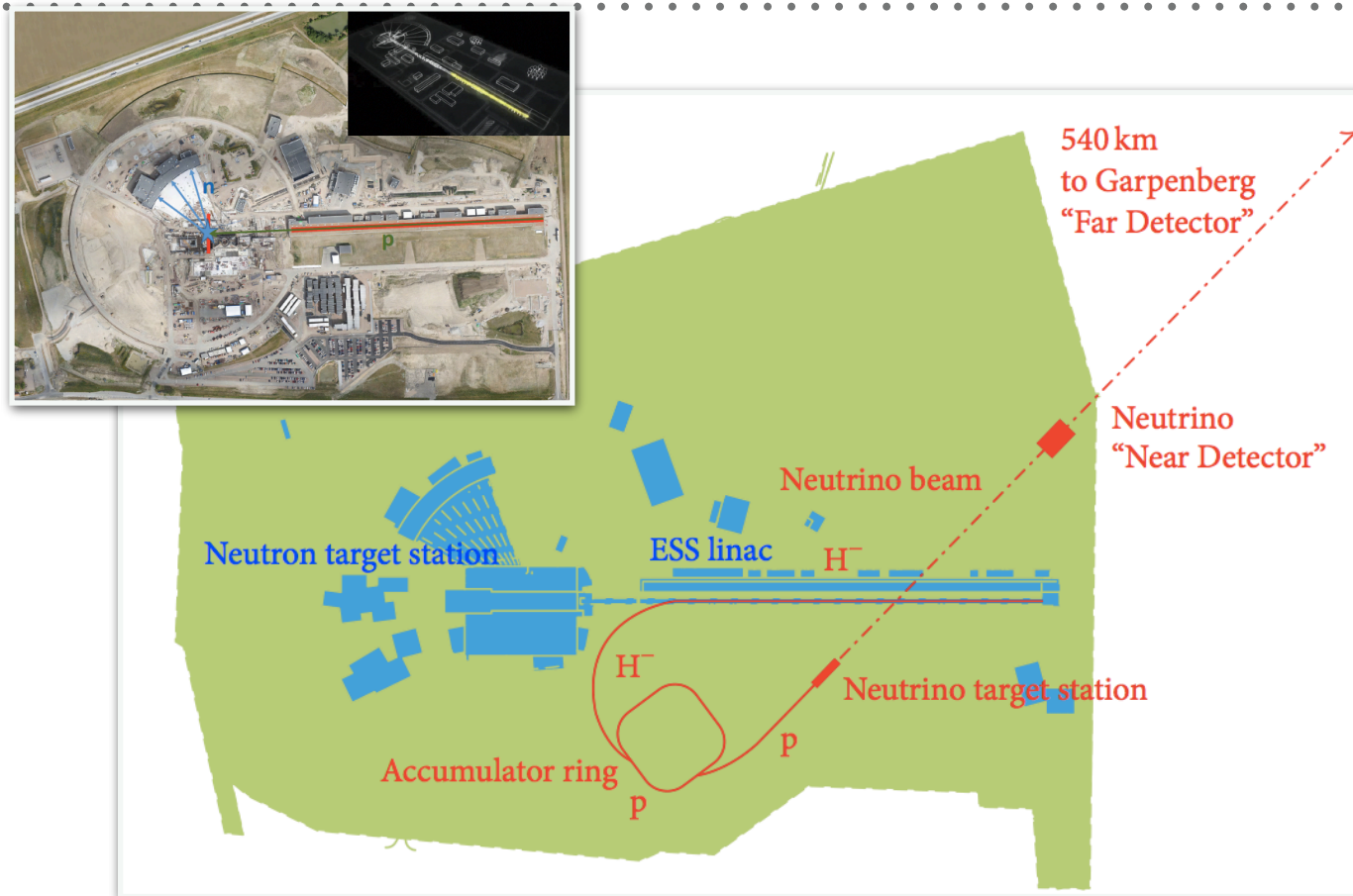
# STERILE NEUTRINOS AT NOVA



- LSND and MiniBooNE observed an excess of  $\nu_e(\bar{\nu}_e)$  events in  $\nu_\mu(\bar{\nu}_\mu)$  beams.
- Inconsistent with oscillations between three neutrino flavors => fourth neutrino with a mass splitting  $\Delta m^2 \sim 1 \text{ eV}^2$ .
- But from measurement  $\Gamma_Z$  at LEP the number of light neutrinos = 3
- Additional neutrinos must be sterile => simplest model (3+1 model).

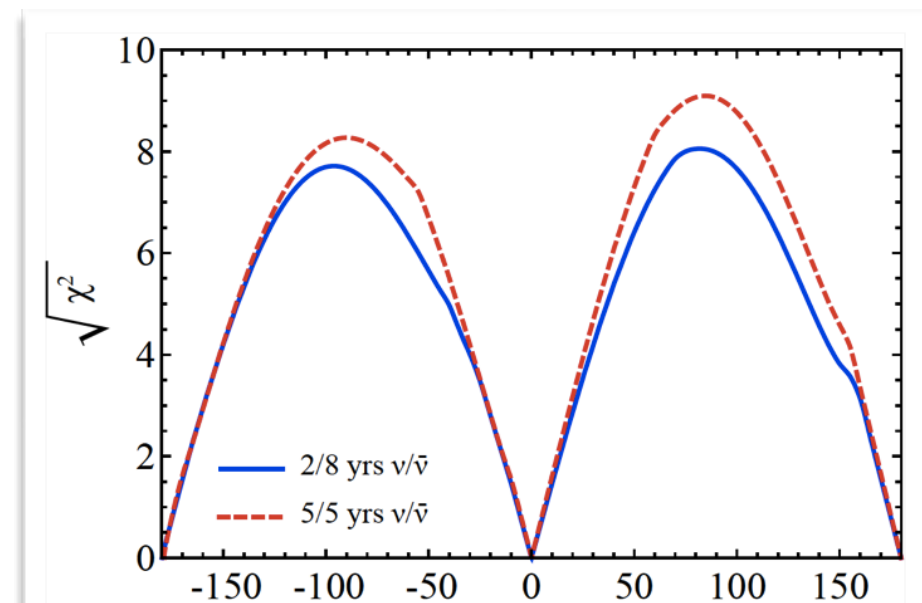
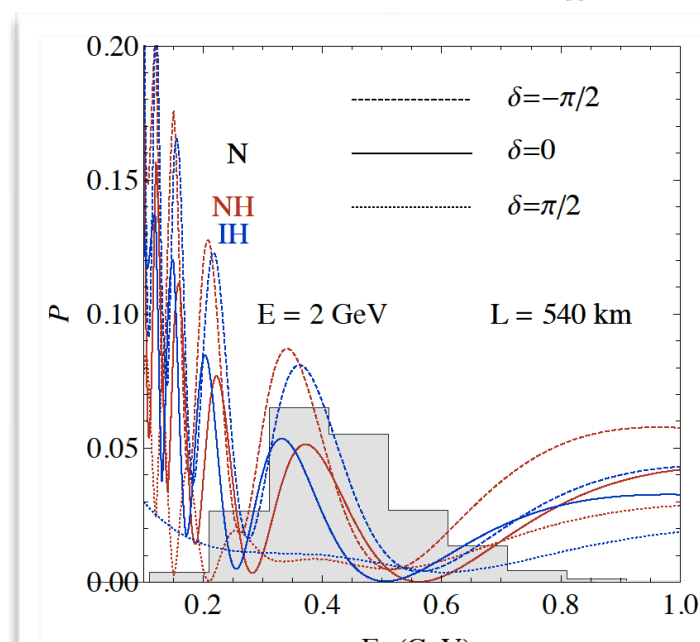


# NEXT (NEXT) GENERATION: ESS<sub>ν</sub>SB



- A design study for an experiment to measure CP violation at 2nd neutrino oscillation maximum.
- The ESS will be a copious source of spallation neutrons.
- 5 MW average beam power.
- Main challenge: modifications to ESS linac to produce neutrinos.

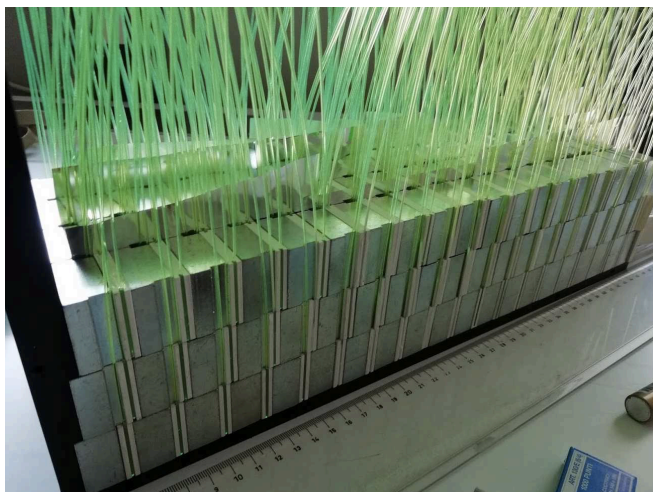
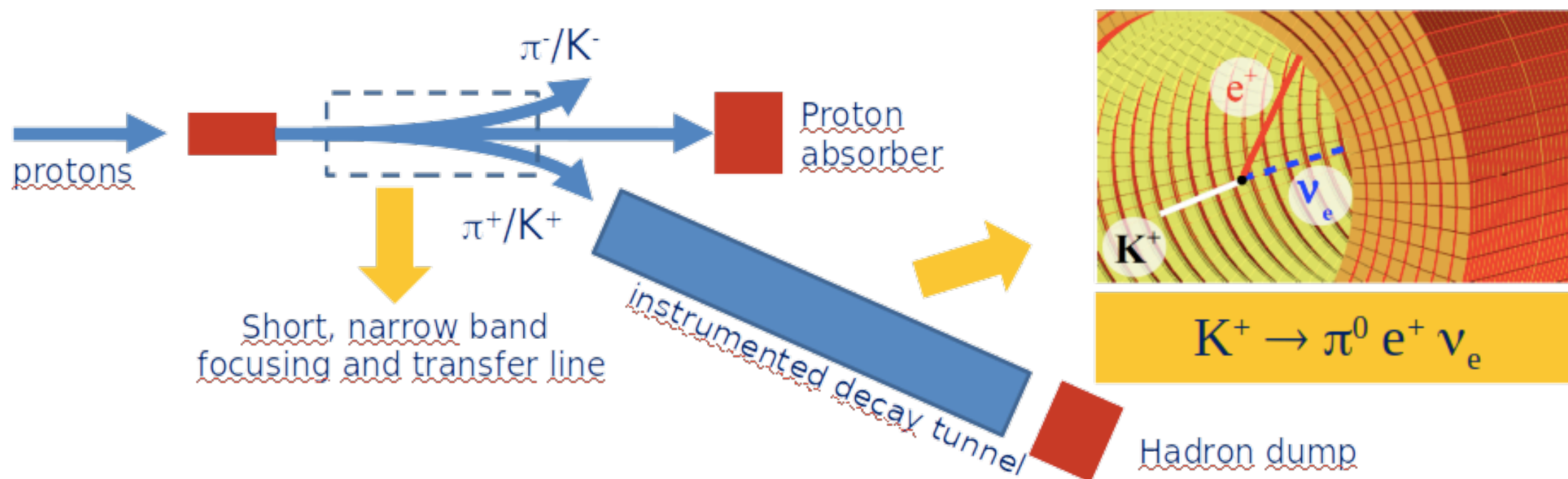
- The ESS proton pulse is too long for a conventional magnetic horn. => Accumulator (C~400 m) needed to compress to few  $\mu$ s the 2.86 ms proton pulses.



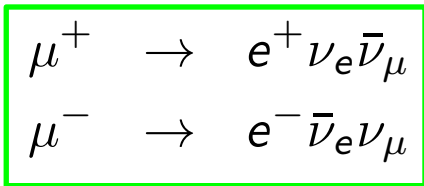


# ENUBET

- Based on conventional technologies, aiming for a 1% precision on the  $\nu_e$  flux  
 $\text{protons} \rightarrow (\text{K}, \pi) \rightarrow \text{Kaon decays} \rightarrow \nu_e \rightarrow \text{neutrino detector}$
- “By-pass” hadro-production, PoT, beam-line efficiency uncertainties  
 removing the leading source of uncertainty in  $\nu$  cross section measurements



- Fully instrumented K decay region
- $\nu_e$  flux prediction = e counting
- R&D ongoing on beamline/detector and work on software



- |  |   |  |
|--|---|--|
| <ul style="list-style-type: none"> <li>➤ Physics goals:             <ul style="list-style-type: none"> <li>➤ %o-level <i>electron</i> and muon neutrino cross-sections</li> <li>➤ Sterile neutrino searches, beyond SBN</li> </ul> </li> </ul> | <ul style="list-style-type: none"> <li>➤ Technology             <ul style="list-style-type: none"> <li>➤ Serve 6D cooling experiment &amp; muon accelerator test bed</li> <li>➤ Required in <i>p</i>-driven neutrino factory and muon collider</li> </ul> </li> </ul> | <p>CERN Option:</p> <ul style="list-style-type: none"> <li>➤ Extraction from SPS through existing tunnel</li> <li>➤ Siting of storage ring:             <ul style="list-style-type: none"> <li>➤ Allows measurements to be made 'on or off axis'</li> <li>➤ Preserves sterile search option</li> </ul> </li> </ul> |
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