Neutrino experiments

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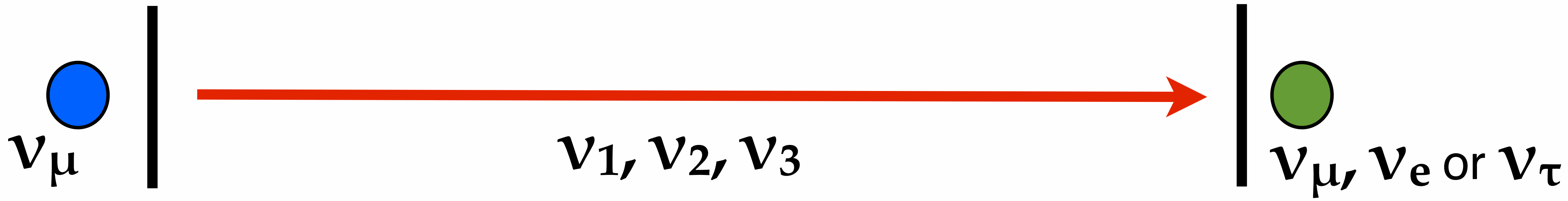
v1

Outline

- Recent T2K results
- Recent NOvA results
- Recent reactor results
- Recent atmospheric neutrino results from IceCube
- Next generation experiments

Neutrino flavour oscillations

- The Standard Model is the best theoretical model that can describe the electro-weak and strong forces but did not anticipate neutrino masses.
- Expect 3 mass-less active light neutrinos, but observed oscillations between flavors: at least 2 out of the 3 active neutrinos have mass
- Produced as flavor states (ν_e, ν_μ, ν_τ), propagate in space as mass states (ν_1, ν_2, ν_3) and possibly detected as different flavor state
- Neutrino oscillations could violate the CP symmetry



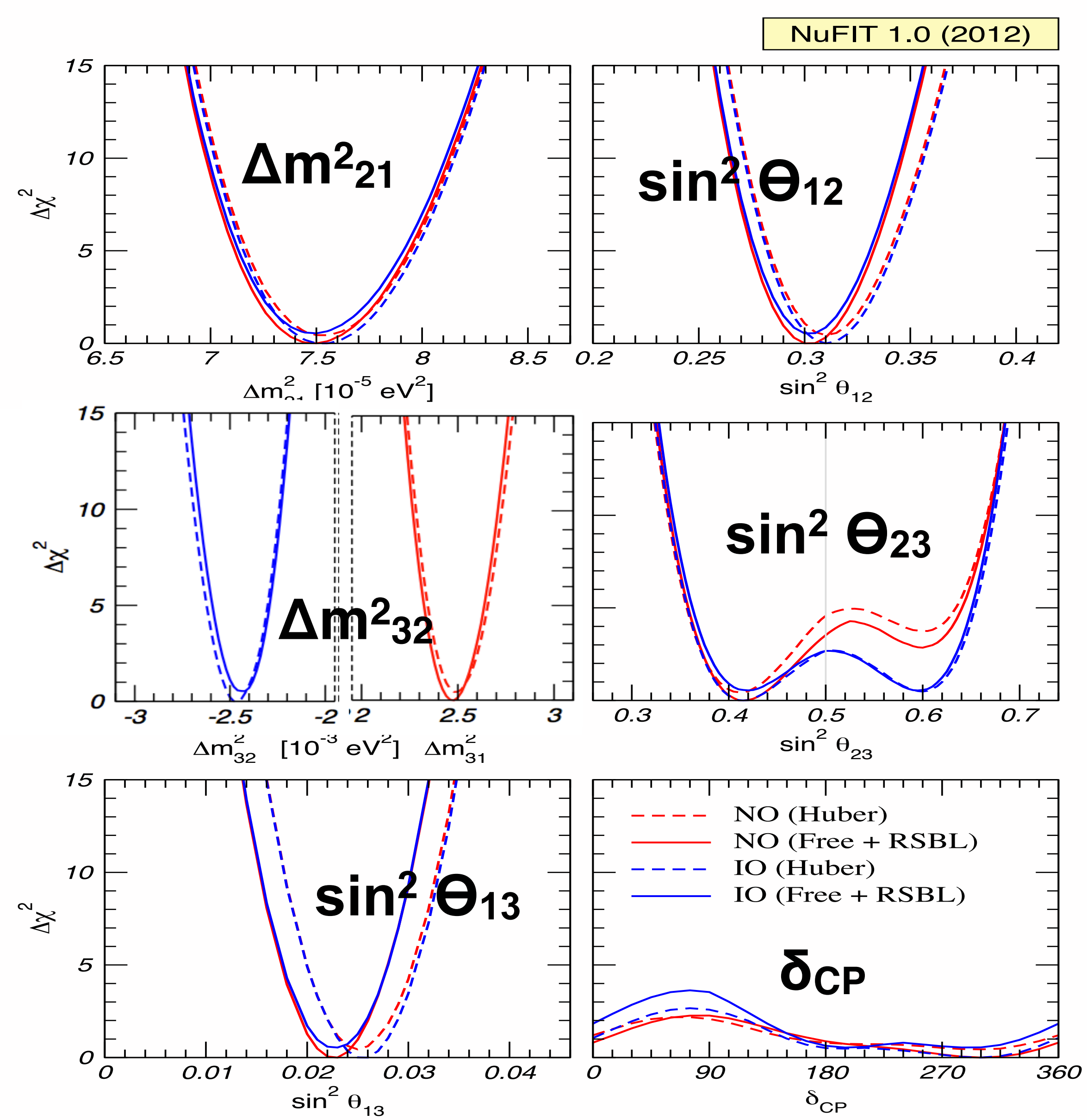
$$P_{\nu_\alpha \to \nu_\beta}(L,E) = \delta_{\alpha\beta} - 4 \sum_{i>j} Re\left[U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j}\right] \sin^2\left(\frac{\Delta m^2_{ij} L}{4E}\right)$$
$$- 2 \sum_{i>j} Im\left[U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j}\right] \sin\left(\frac{\Delta m^2_{ij} L}{2E}\right)$$

B. Pontecorvo, J. Exp. Theor. Phys. 6, 429 (1957); 7, 172 (1958); 26, 984 (1968); Z. Maki, M. Nakagawa, and S. Sakata, Prog. Theor. Phys. 28, 870 (1962).

Pontecorvo-Maki-Nakagawa-Sakata (PMNS) mixing 3x3 matrix **U**

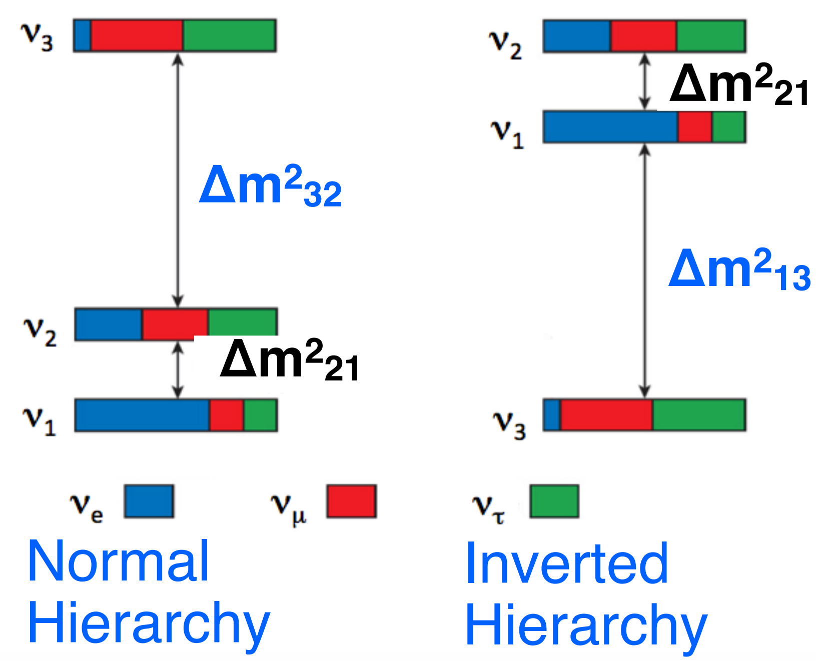
$\Delta m^2_{ij} = m^2_i - m^2_j$ (i,j=1,2,3)

The 3νSM paradigm

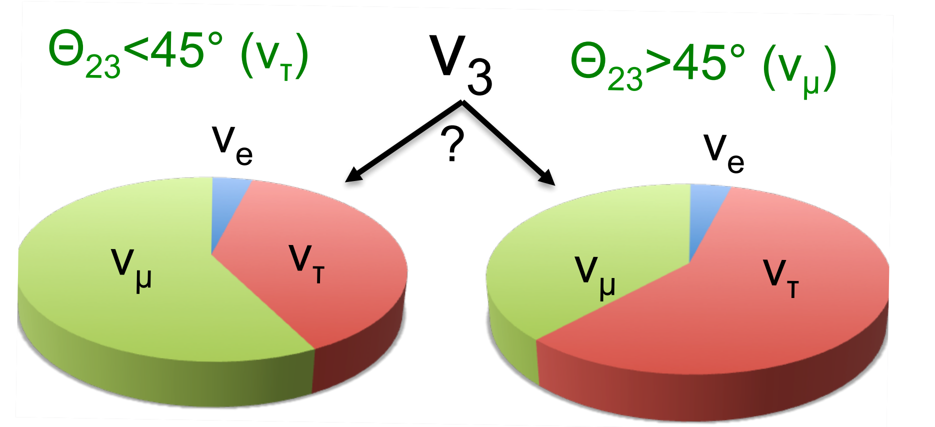


- Combining all solar, atm, reactor, and accelerators experiments that took place during the years 1998 until now, all the parameters of PMNS have been well measured except δ_{CP} and the **mass hierarchy**

$$\Delta m^2_{21} \simeq 3\% |\Delta m^2_{32}|$$



$$U = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \times \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{bmatrix} \times \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$



The octant of θ_{23} is also not well determined

T2K (Tokai-to-Kamioka) experiment

At the atmospheric $\Delta m^2_{32} \sim 10^{-3}$ eV^2, a beam of ν_μ will:

"disappear" into other neutrino flavors

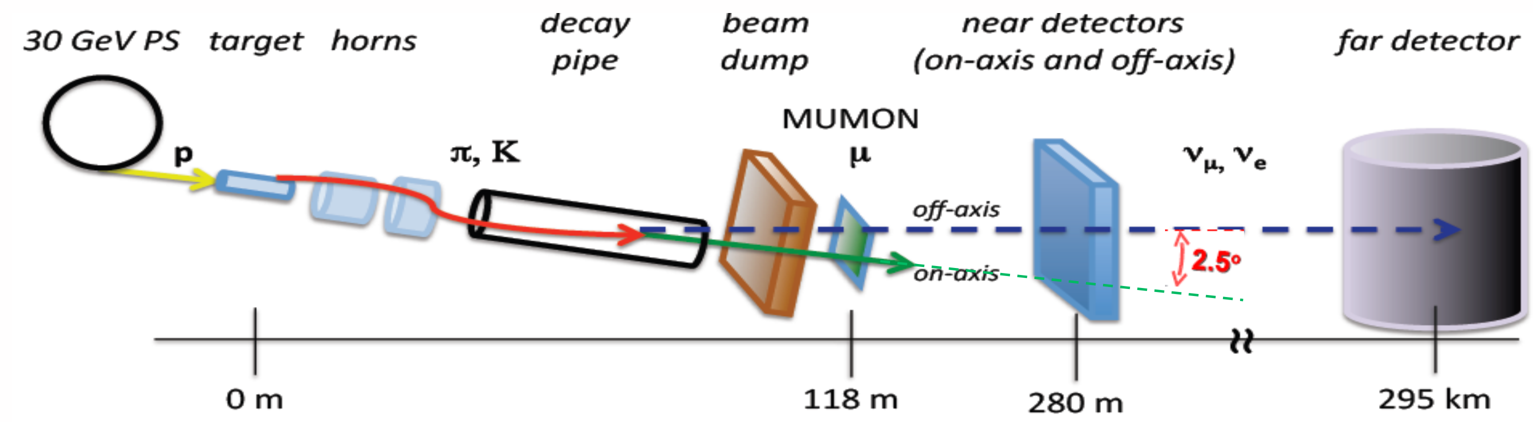
$$\boxed{P(\nu_\mu \to \nu_{x\neq\mu}) \cong \sin^2 2\theta_{23} \sin^2\left(\frac{\Delta m^2_{32} L}{4E}\right)}$$

A small fraction of ν_e will "appear"

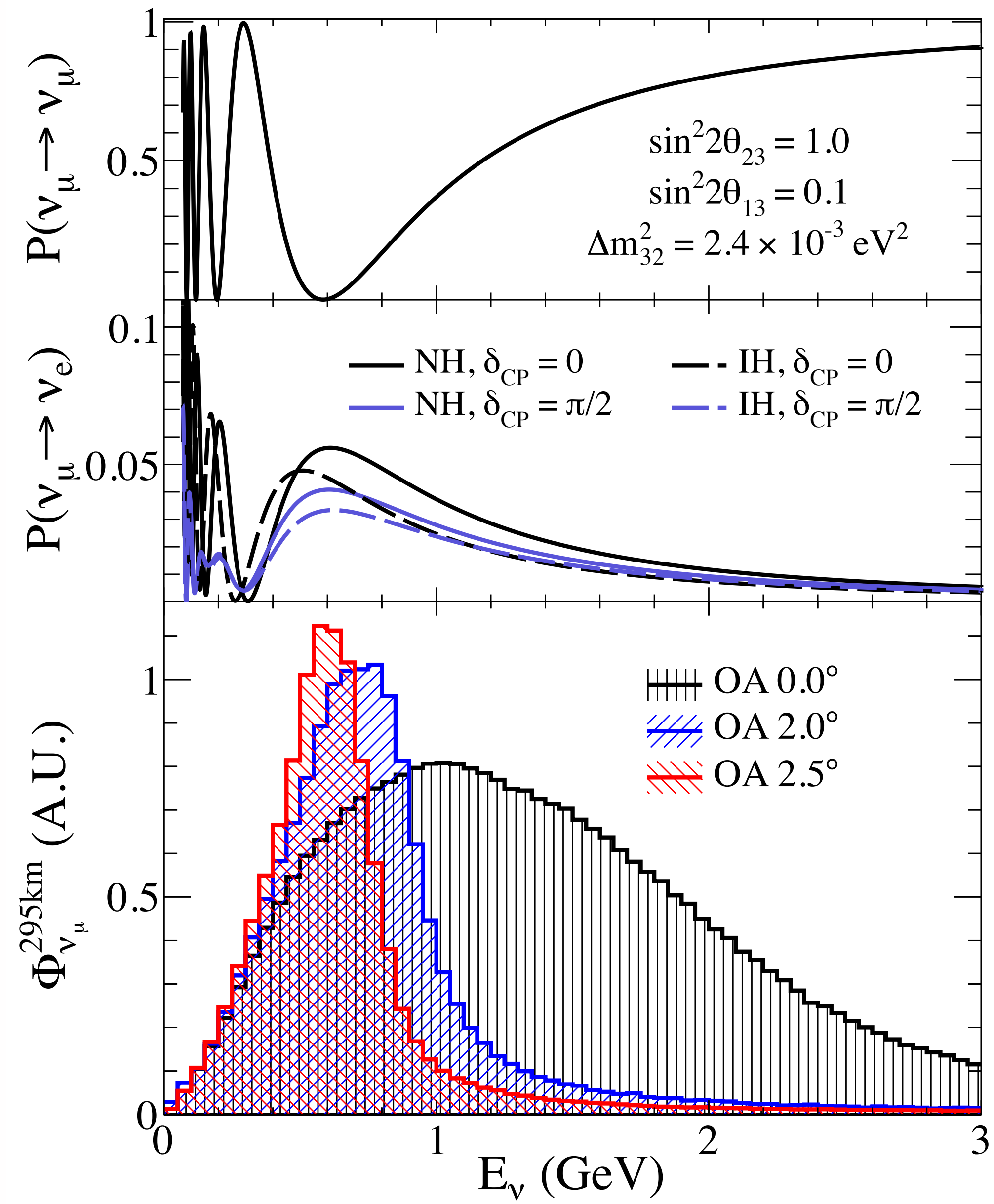
$\Delta m^2_{31} \sim \Delta m^2_{32}$

$$\boxed{P(\nu_\mu \to \nu_e) \cong \sin^2 2\theta_{13} \sin^2\theta_{23} \sin^2\left(\frac{\Delta m^2_{31} L}{4E}\right)}$$

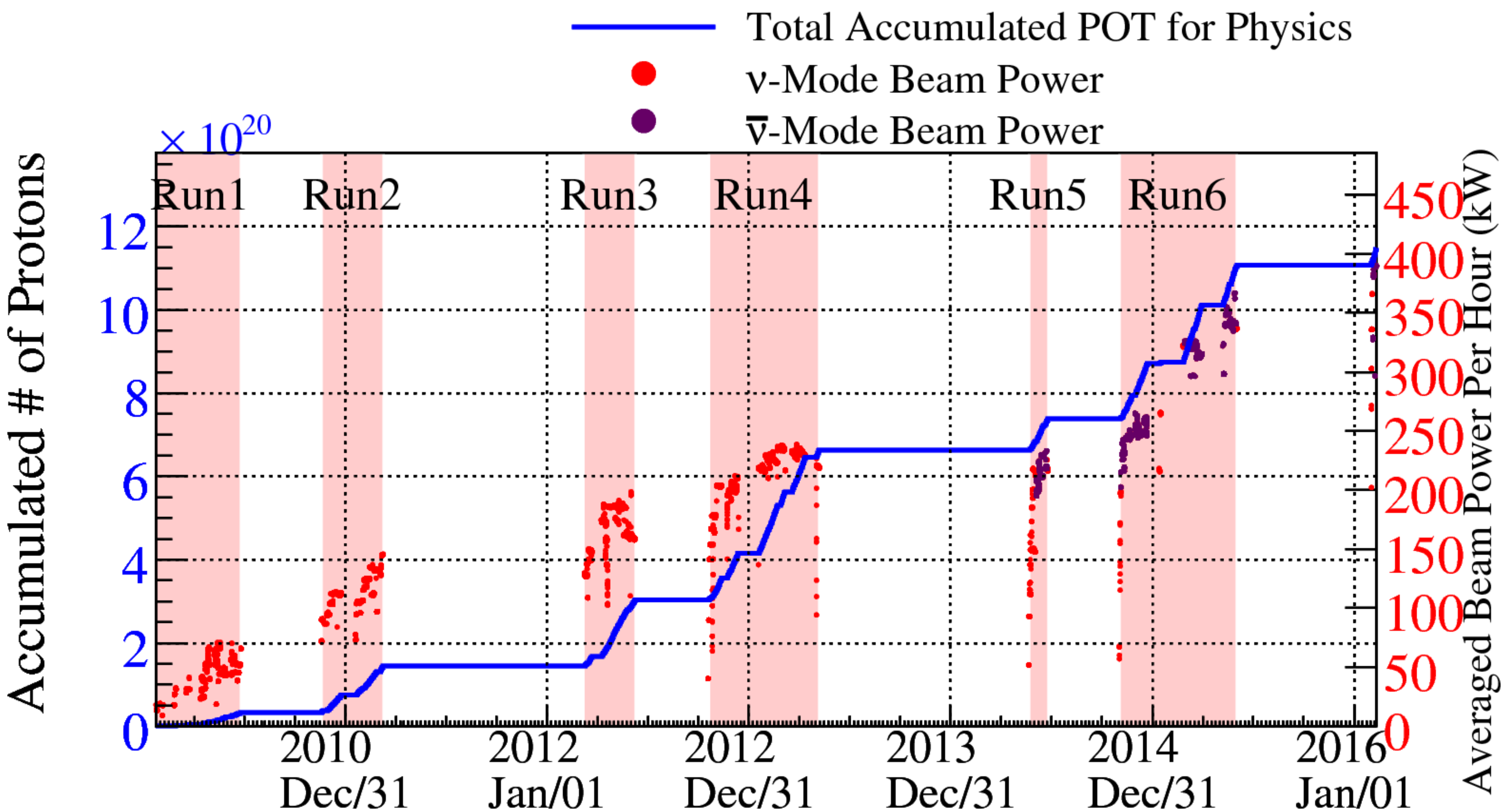
JPARC/T2K neutrino beam



- 30 GeV proton beam on C target (90 cm)
- 3 magnetic horns (250kA)
- **ν_μ from π^+ decay (~96m decay pipe)**
- **Small ν_e contamination from μ and K (<1%)**
- **Muon Monitor (MUMON)**
  - measure the beam profile and intensity
  - monitor the on-axis beam direction
- Beam dump to stop hadrons
- **2.5° off-axis neutrino beam**
  - low-energy narrow band
  - peak at oscillation maximum
  - decrease high-energy background



T2K - Data collection



Muon Neutrino mode: **6.9×10^{20} POT** (Run 1-4)

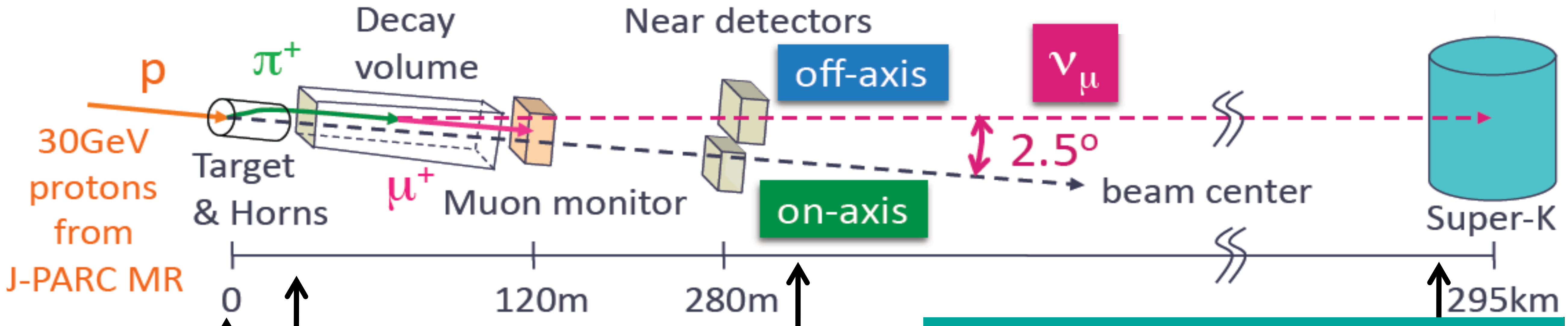
Muon AntiNeutrino mode: **4.1×10^{20} POT** (Run 5-6)

Beam power has been increased up to **390 kW**

Operation with a world record of **1.2×10^{14} proton per pulse**

<1mrad beam direction stability (<2% beam energy shift)

T2K analysis strategy



Tracking inside horns and He vessel

GEANT3+GCALOR

Proton beam interaction in the target

→Hadron production

FLUKA, NA61, etc.

Φ

Near detector data

Fit

Constrained Φ σ

σ

Neutrino-nucleus interactions (NEUT)

MiniBooNE, MINERvA

SK data and uncertainties (detector and uncorrelated σ)

Fit

Measured oscillation parameters

Predicted Φ and correlated σ at SK

$$\Phi^{SK} \cdot P_{osc} \cdot \sigma^{H2O}_{reaction} \cdot \varepsilon_{SK} dE_{\nu}$$

Recent T2K results

- Electron neutrino appearance discovery (PRL 112, 061802 (2013))
  - 28 electron-like events; BG = 4.64±0.53
  - Measured: $\sin^2 2\theta_{13} = 0.150^{+0.039}_{-0.034}(NH)$ $\sin^2 2\theta_{13} = 0.182^{+0.046}_{-0.040}(IH)$
  - **7.3σ significance for non-zero θ_{13}**
- Muon neutrino disappearance meas'ment (PRL 112, 181801 (2014))
  - **120 events observed (446±22.5 w/o osc)**
  - Measured $\sin^2 2\theta_{23} = 0.514^{+0.055}_{-0.056}(NH)$ $\sin^2 2\theta_{23} = 0.511^{+0.055}_{-0.055}(IH)$
    $\Delta m^2_{23} = (2.51 \pm 0.10) \times 10^{-3} eV^2 (NH)$ $\Delta m^2_{23} = (2.48 \pm 0.10) \times 10^{-3} eV^2 (IH)$
- Joint neutrino appearance & disappearance + combined with reactor (CPV) (PRD 91, 072010 (2015))

$$\sin^2 \theta_{23} = 0.524^{+0.057}_{-0.059}(NH),\ 0.523^{+0.055}_{-0.065}(IH)$$

$$\sin^2 \theta_{13} = 0.042^{+0.013}_{-0.021}(NH),\ 0.049^{+0.015}_{-0.021}(IH)$$

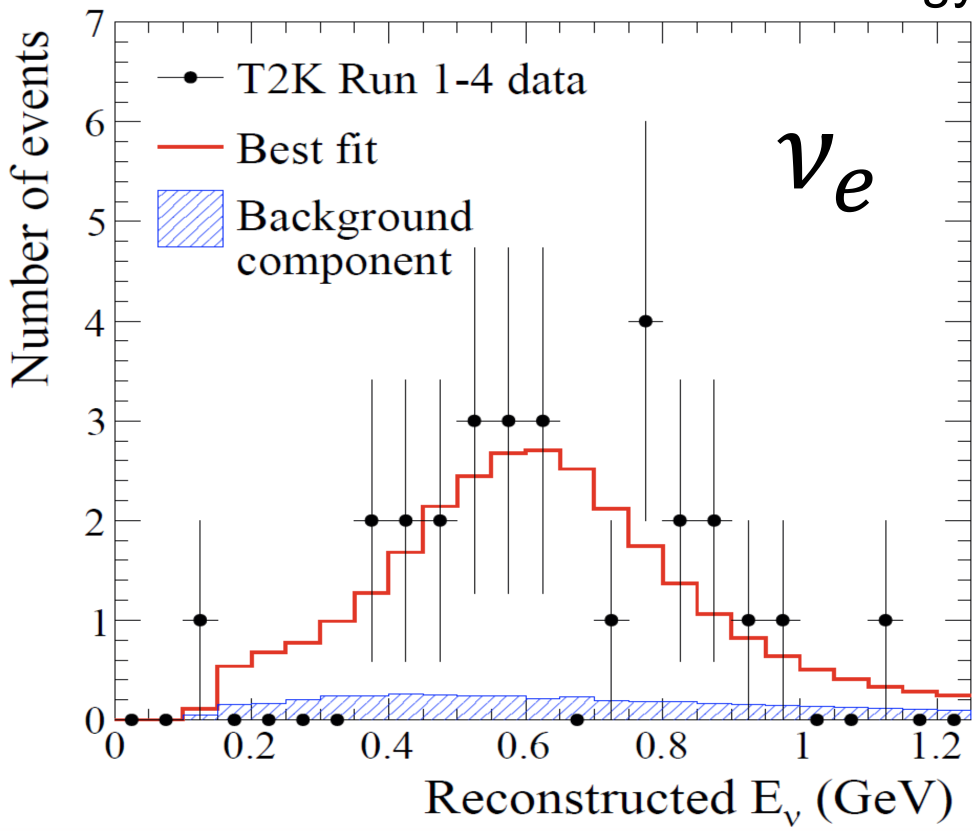
Combining T2K + reactor

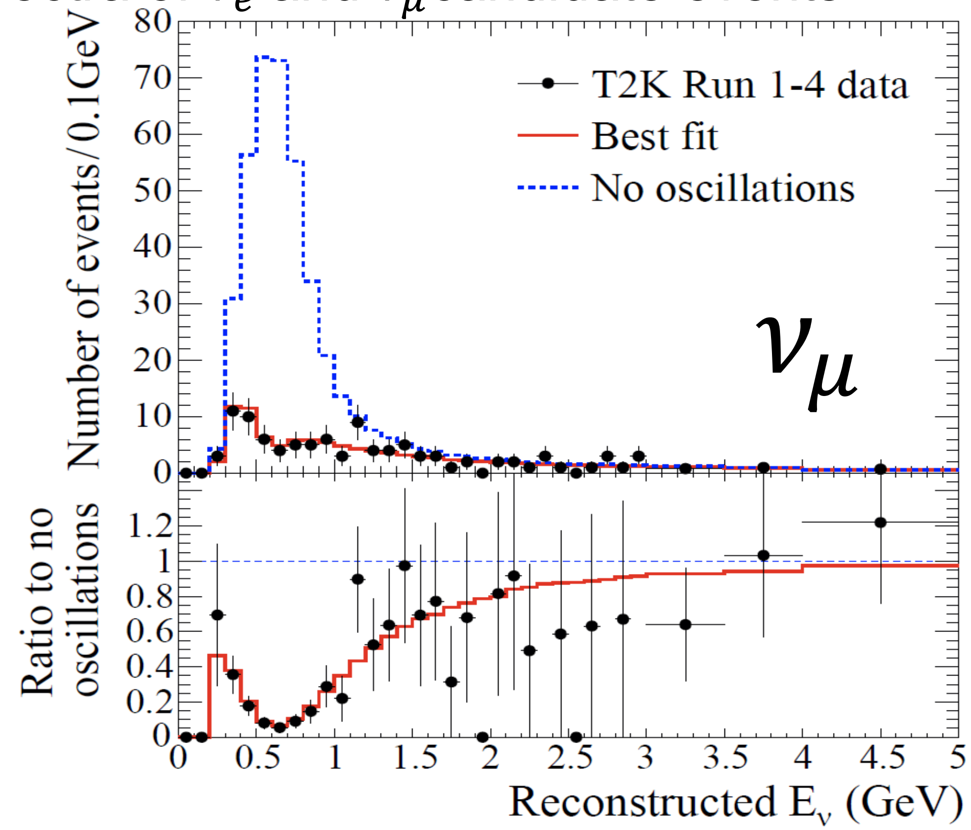
Some hints on δ_{CP} and MH !

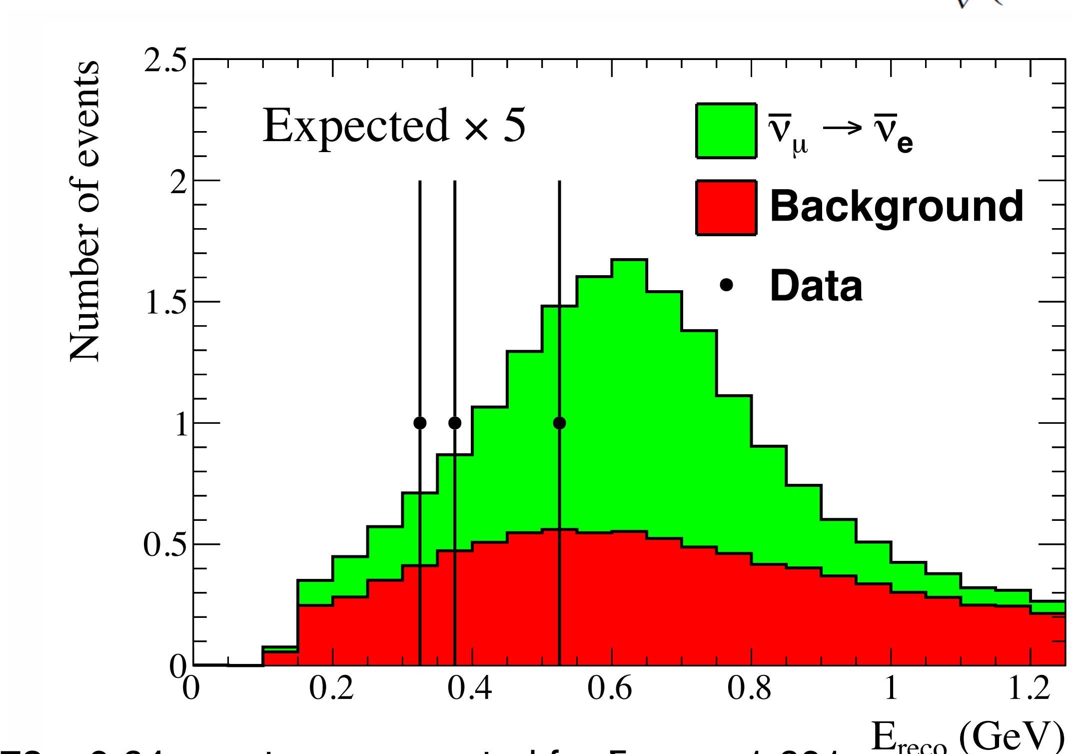
- Antineutrino oscillation analyses (arxiv:1512.02495)
  - **34 mu-like observed** (103.6 w/o osc); **3 positron-like** (consistent)

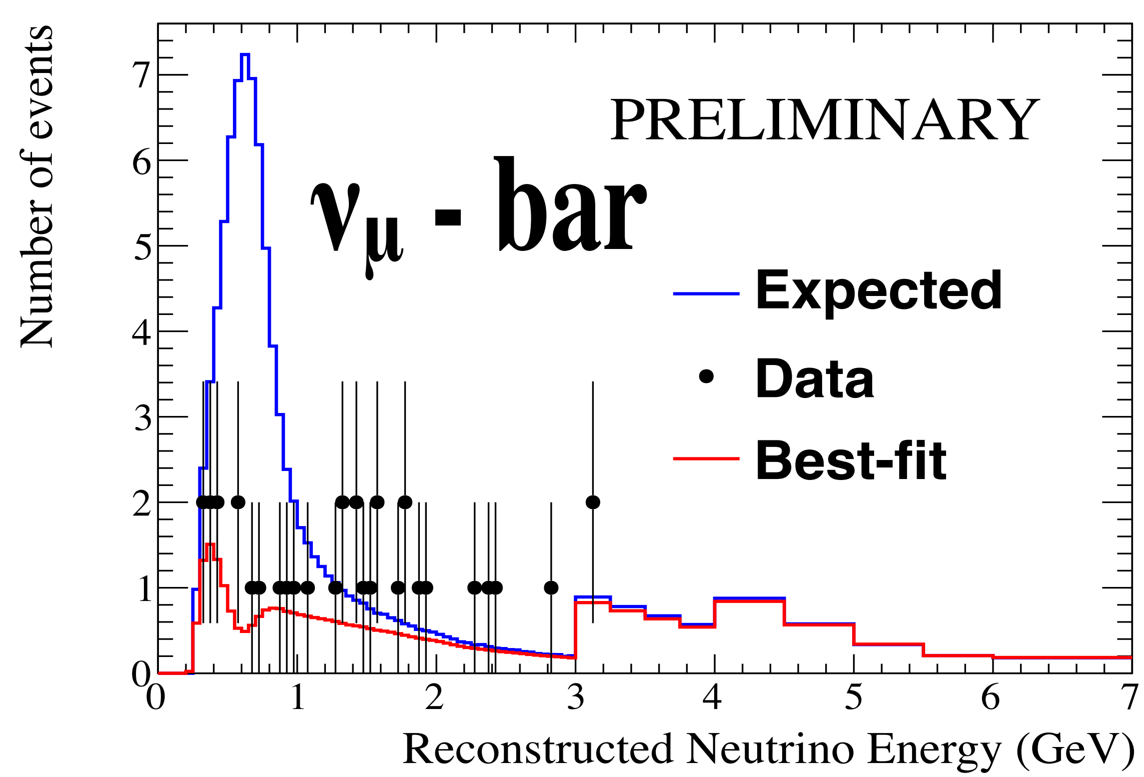
T2K: neutrino&antineutrino results

Reconstructed neutrino energy spectra of ν_e and $\nu_\mu$candidate events









3.73 ± 0.64 events are expected for δ_{CP} = -1.601
(best-fit of 2014 analysis)

T2K: neutrino&antineutrino results

Including subleading terms:

ν_μ (ν_μ-bar) disappearance → measure $\sin^2\theta_{23}$ and Δm^2_{32}

$$\boxed{P(\nu_\mu \to \nu_\mu)} \simeq 1 - (\cos^4\theta_{13}\boxed{\sin^2 2\theta_{23}} + \sin^2 2\theta_{13}\sin^2\theta_{23})\sin^2\left(\frac{\boxed{\Delta m^2_{31}}L}{4E}\right)$$

ν_e (ν_e-bar) appearance → measure $\sin^2\theta_{13}$ and δ_{CP}

$$\boxed{P(\nu_\mu \to \nu_e)} \simeq \boxed{\sin^2 2\theta_{13}}\sin^2\theta_{23}\sin^2\left(\frac{\Delta m^2_{31}L}{4E}\right)$$

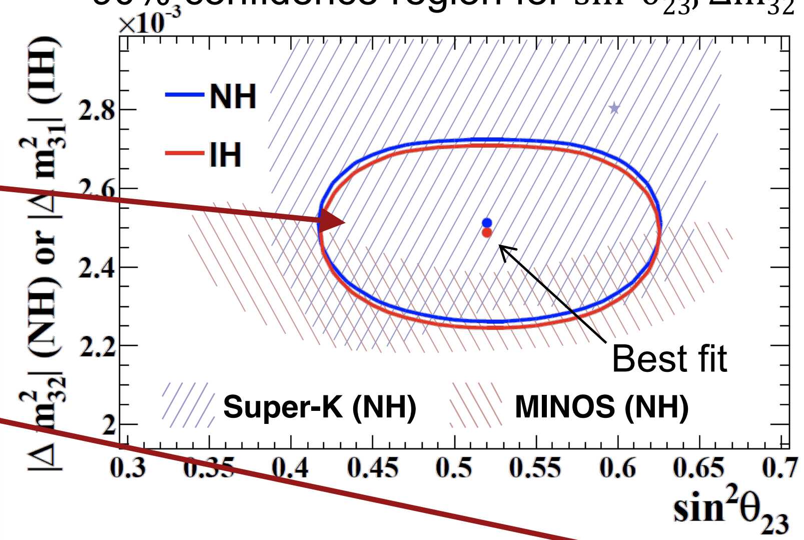
$$\pm \frac{\sin 2\theta_{12}\sin 2\theta_{23}}{2\sin\theta_{13}}\sin\left(\frac{\Delta m^2_{21}L}{4E}\right)\sin^2 2\theta_{13}\sin^2\frac{\Delta m^2_{31}L}{4E}\boxed{\sin\delta_{CP}}$$

- $\sin^2\Theta_{13}$ is constrained with reactor measurements (0.0219 ± 0.0012)

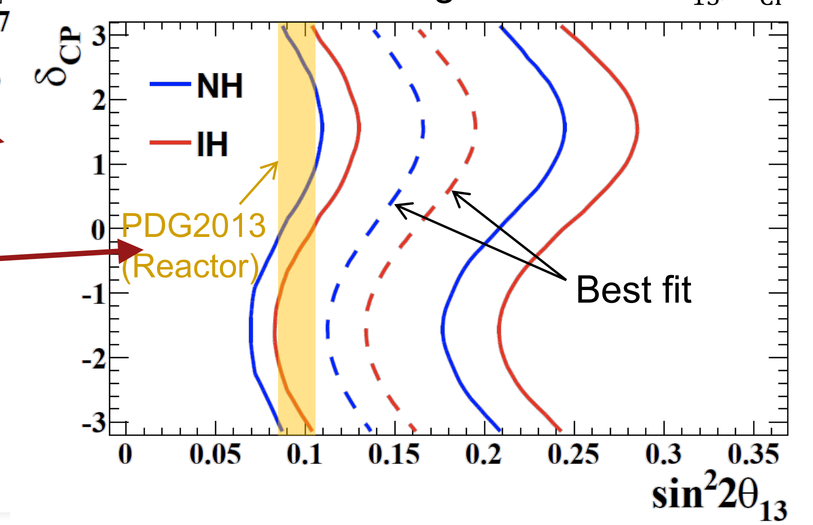
$\bar{\nu}_e$ survival probability from reactor

$$\boxed{P(\bar{\nu}_e \to \bar{\nu}_e) \cong 1 - \sin^2 2\theta_{13}\sin^2\frac{\Delta m^2_{31}L}{4E}}$$

90% confidence region for $\sin^2\theta_{23}$, Δm^2_{32}

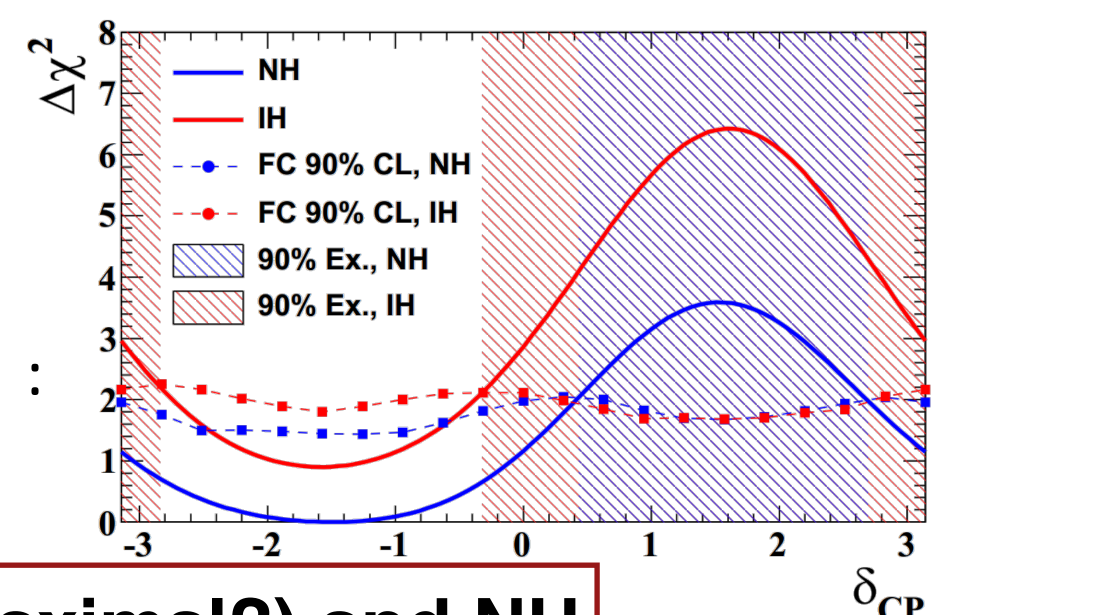


90% confidence region for $\sin^2 2\theta_{13}$, δ_{CP}



- Add constraint on $\sin^2 2\theta_{13}$ by reactor experiments to the fit.
- Improve precision on $\sin^2\theta_{23}$ and Δm^2_{32}.
- 90% C.L. excluded region of δ_{CP}: $0.15\pi < \delta_{CP} < 0.83\pi$ (NH) $-0.08\pi < \delta_{CP} < 1.09\pi$ (IH)

$\Delta\chi^2$ as a function of δ_{CP} with critical limit



T2K+reactor hint $\delta_{CP} \approx -\pi/2$ (maximal?) and NH

Other T2K results

Physics	Title	Journal / Status
Sterile oscillation	Search for short baseline νe disappearance with the T2K near detector	Phys. Rev. D 91, 051102(R) (2015)
PMNS oscillation	Neutrino Oscillation Physics Potential of the T2K Experiment	Prog. Theor. Exp. Phys. 043C01 (2015)
Cross-section	Measurement of the muon neutrino CCQE cross section with ND280 at T2K	Phys. Rev. D 92, 112003 (2015)
Cross-section	Measurement of the electron neutrino charged-current interaction rate on water with the T2K ND280 pi0 detector	Phys. Rev. D 91, 112010 (2015)
Cross-section	Measurement of the muon neutrino charged current quasi-elastic cross-section on carbon with the T2K on-axis neutrino beam	Phys. Rev. D 91, 112002 (2015)
Cross-section	Measurement of the muon neutrino inclusive charged-current cross section in the energy range of 1-3 GeV with the T2K INGRID detector	Accepted by PRD arXiv:1509.06940
Neutrino mass	Upper bound on neutrino mass based on T2K neutrino timing measurements	Phys. Rev. D 93, 012006 (2016)
Cross-section	Measurement of double-differential muon neutrino charged-current interactions on C8H8 without pions in the final state using the T2K off-axis beam	Submitted to journal arXiv:1602.03652

Many more nearing publication – all publications, conference talks etc. at http://t2k-experiment.org/for-physicists/

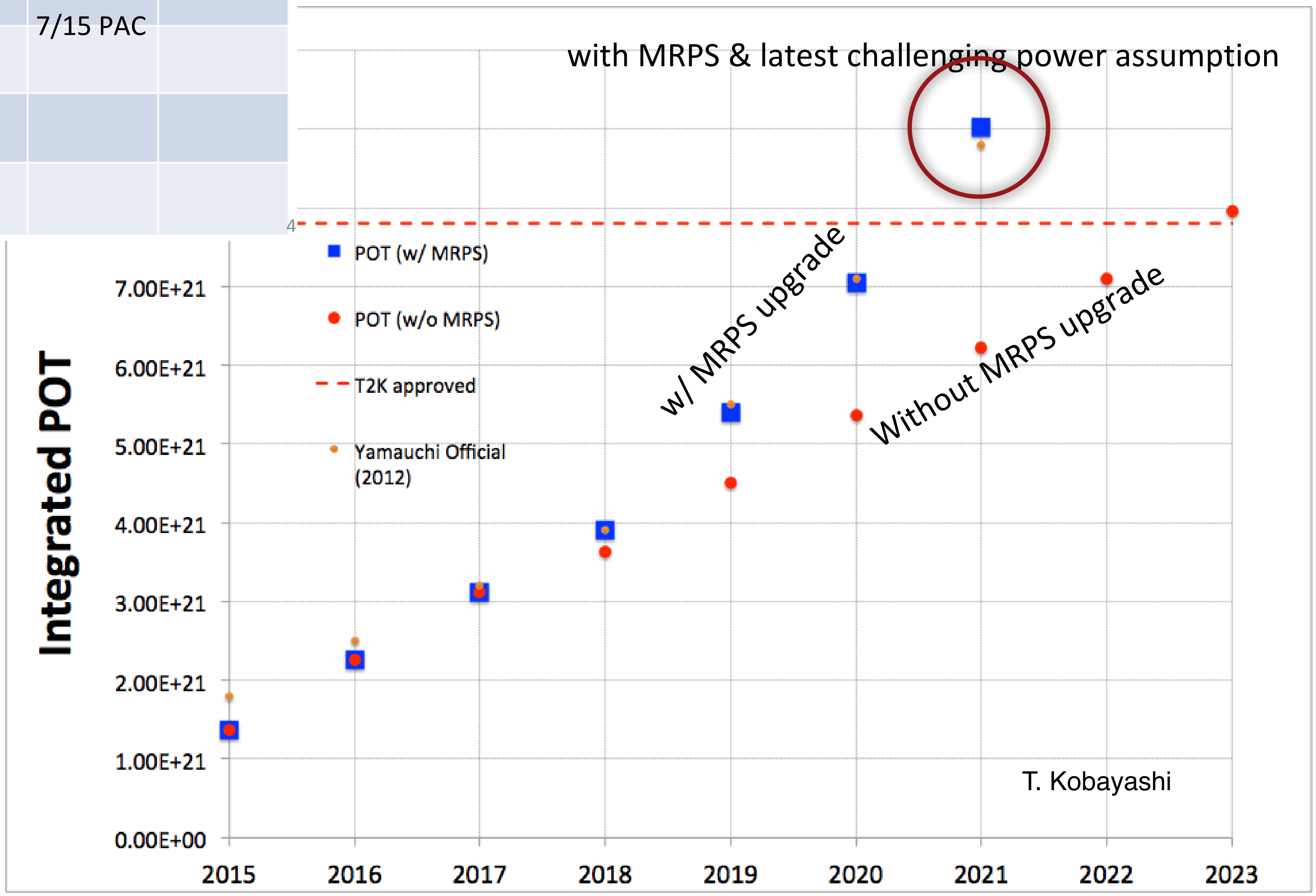
T2K - power & pot projection

JFY	2014	2015	2016	2017	2018	2019	2020
Event	Li. current 30 -> 50		New PS Buildings		New power projection		
FX [kW] (study/trial) SX [kW] (study/trial)	240-320 -	>360 30~40	400 50	450 50~70	700 50~70	800 100	900 100
Period of magnet PS New magnet PS	2.48 s R&D	Large prototype	Mass production		1.3 s	1.3 s	1.25 s
Present RF system High grad. rf system 2nd harmonic cavity VHF cavity	Manufacture, installation & test						
Ring collimators	Back to JFY2012 (2kW)	Add. colli. C,D	Add. colli. E,F				
Injection system FX system	Kicker PS improve., Septa manufac. /test Kicker PS improve., LF & HF septa manufac. /test					7/15 PAC	
SX collimator / Local shields			Local shields				
Ti ducts Ti chamber for SX	Beam ducts	ESS	24				

From 2011-2016 (Run1-6): accumulated 11×10^{20} POT

T2K is approved for 78×10^{20} POT

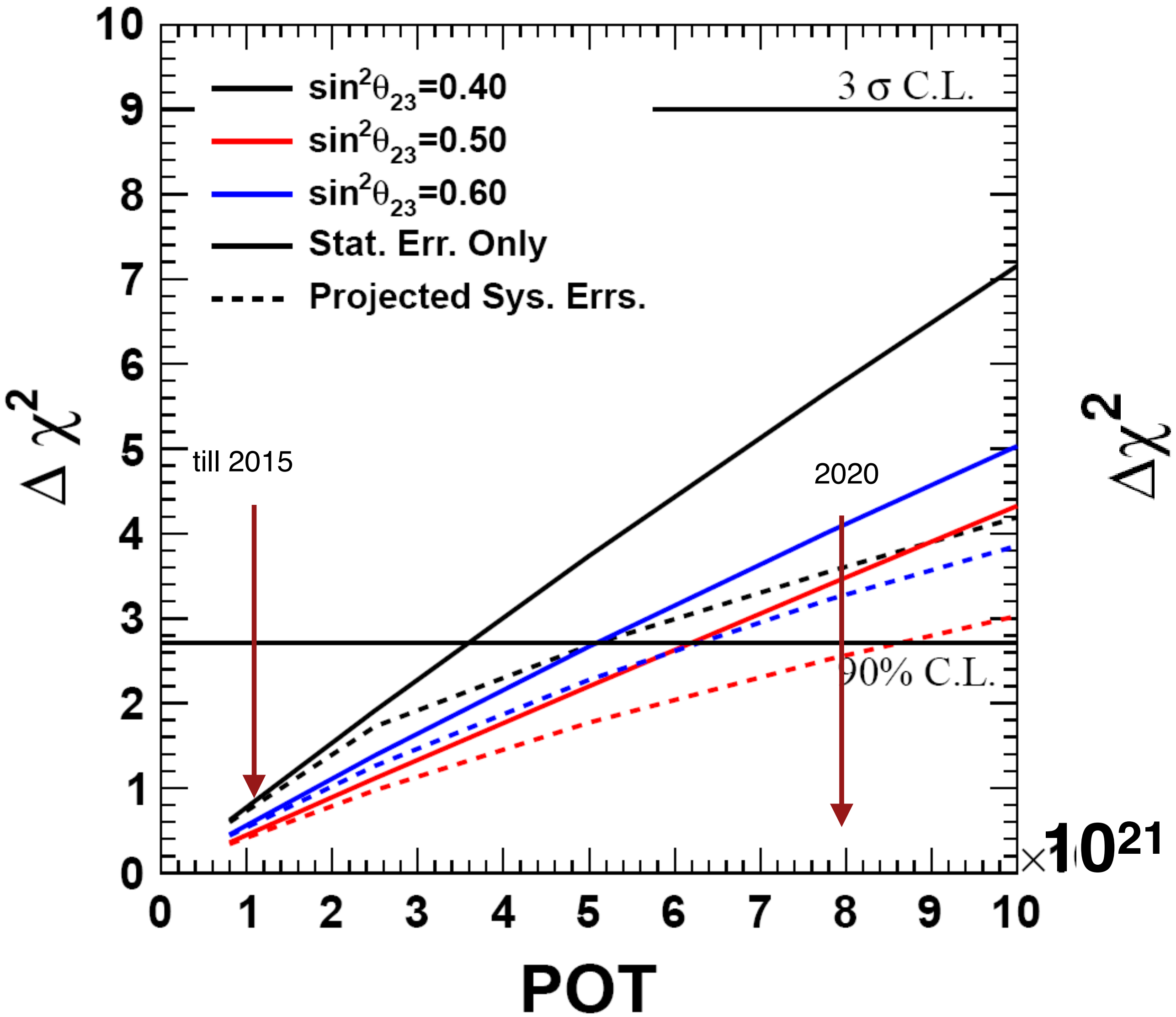
- With JPARC/MR power supply upgrade (approved) expect to reach T2K approved statistics by ≈2020

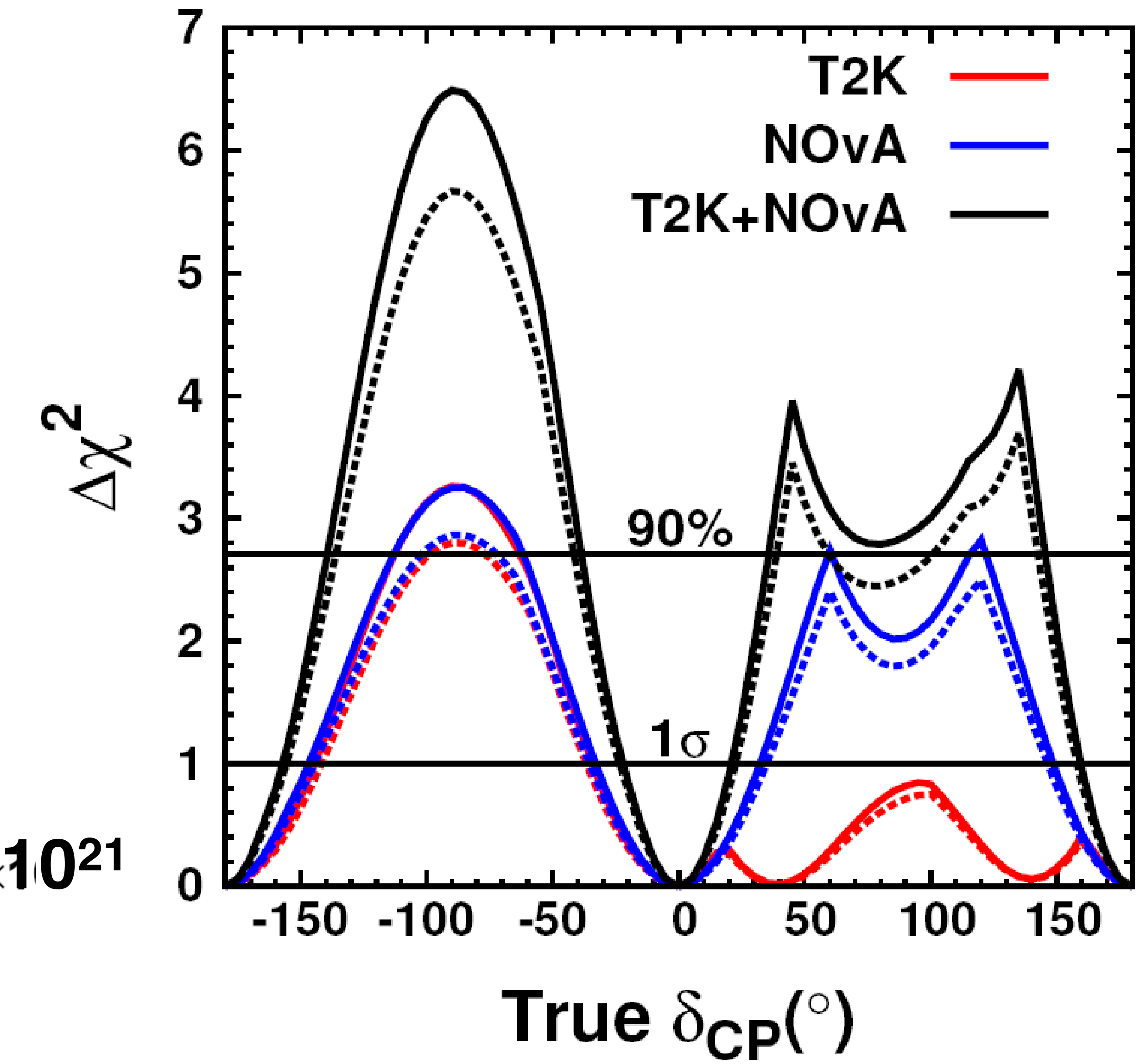


T2K - ultimate CP sensitivity

T2K should reach 78x10^{20} POT by ≈2020

Assume true $\delta_{CP}=-\pi/2$ then $\Delta\chi^2$ exclude $\sin\delta_{CP}=0$



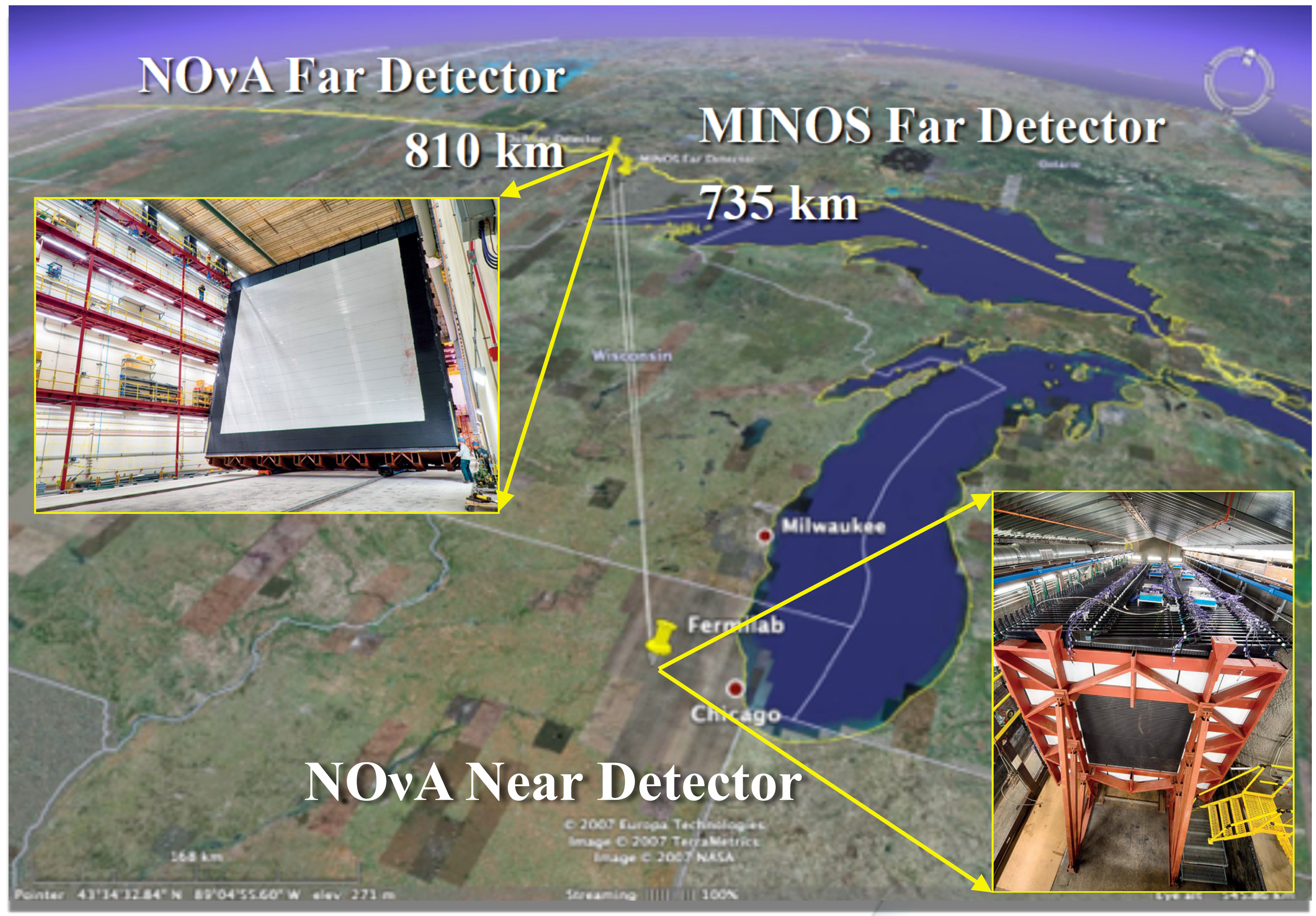


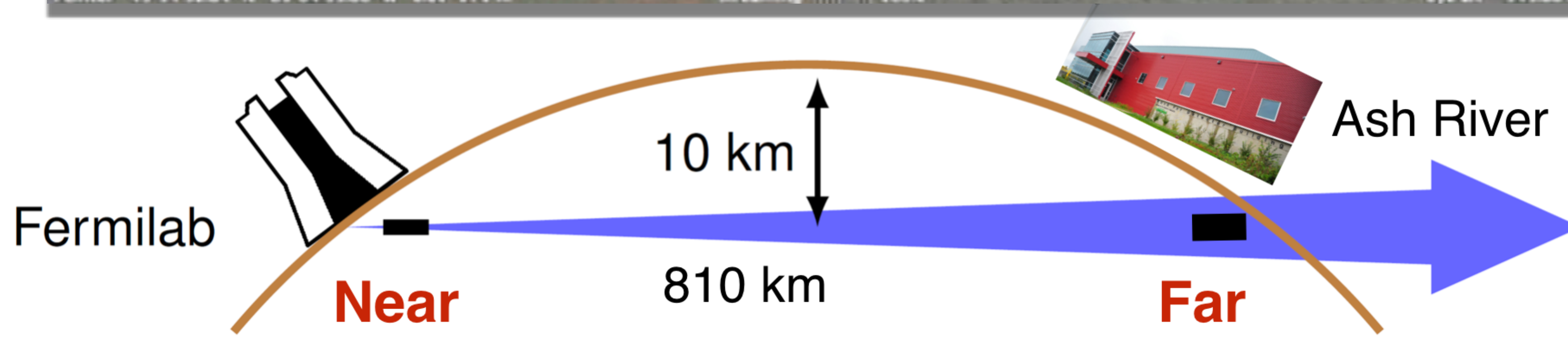
- Plots assume 1:1, $\nu:\bar{\nu}$ running, for normal mass hierarchy
- T2K-only, left, assumes δ_{CP} = -90°
- T2K + NOvA reach 90% sensitivity to $\delta_{CP} \neq 0$

The NOvA Experiment

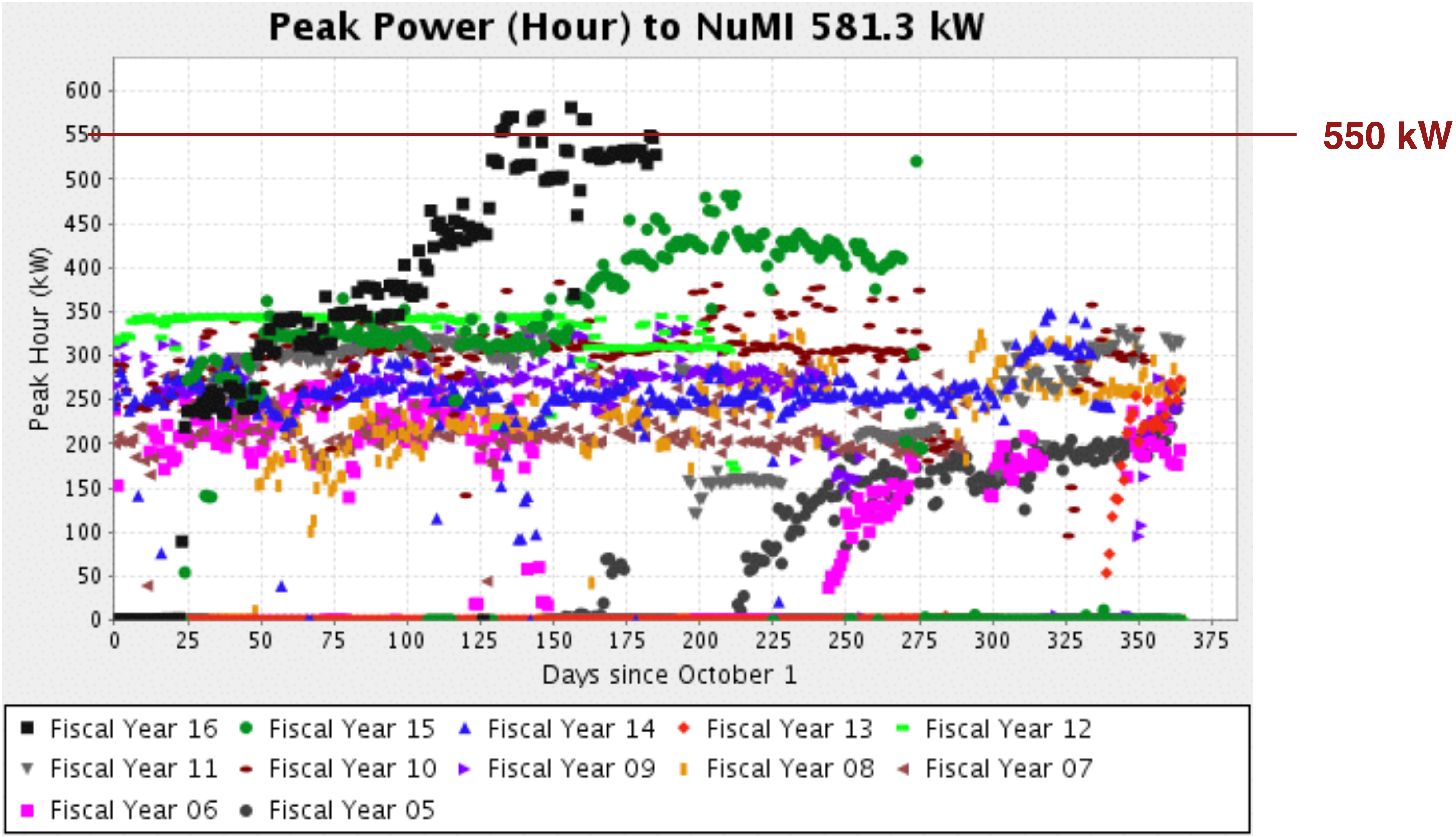
NuMI Off-Axis ν_e Appearance Experiment

- 810 km baseline from Fermilab to Ash River, MN
- 700 kW NuMI neutrino beam at Fermilab
- Near and Far Detectors placed 14 mrad off the NuMI beam axis
- Measure $\nu_\mu \rightarrow \nu_e$, $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ to:
  - Determine ν mass hierarchy
  - Determine the θ_{23} octant
  - Constrain δ_{CP}
- Use $\nu_\mu \rightarrow \nu_\mu$, $\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu$ to:
  - make precise measurements of θ_{23} and Δm^2_{32}
- Many other physics topics:
  - ν cross sections at the ND
  - Sterile neutrinos
  - Supernova neutrinos
  - …





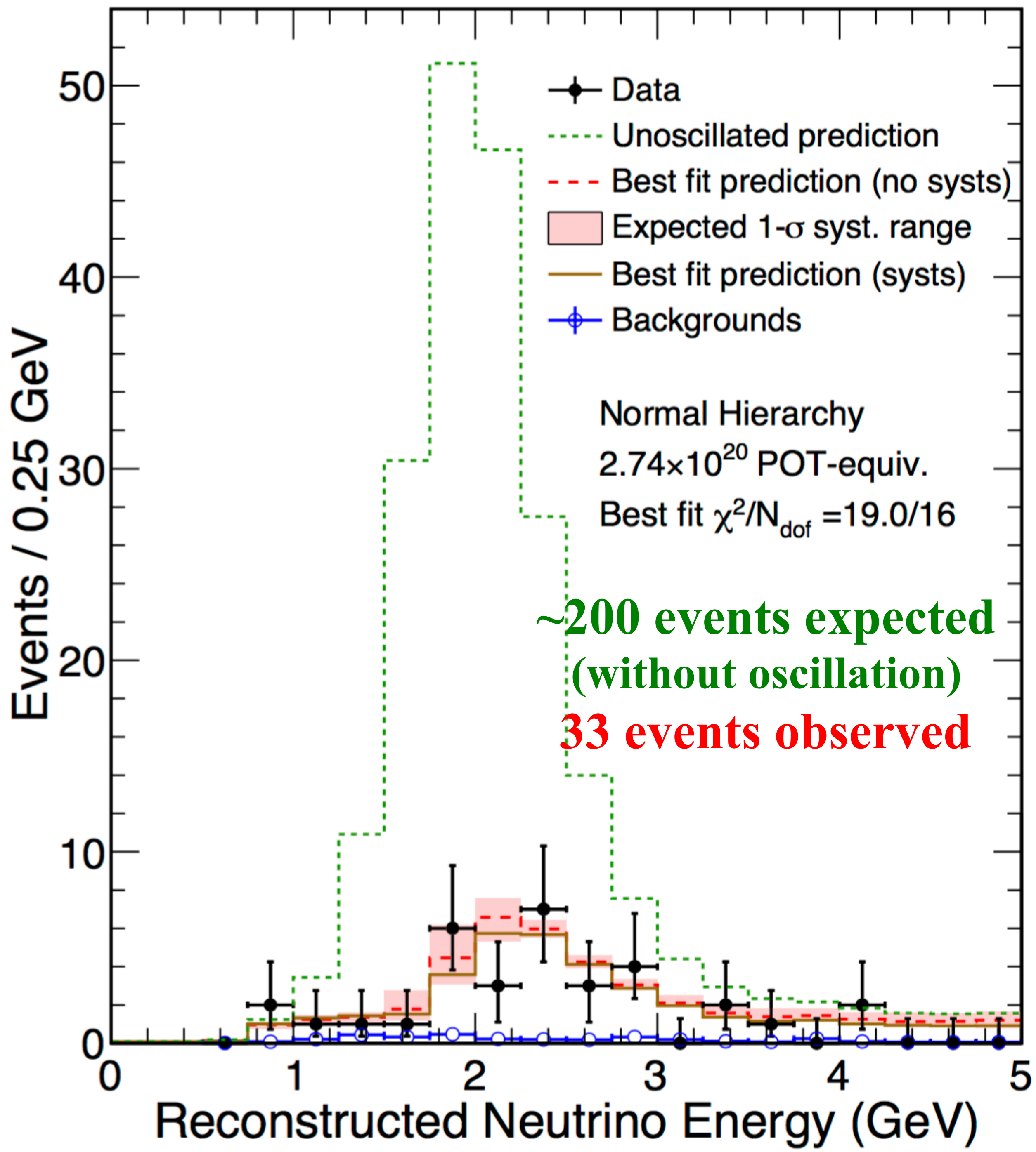
FNAL/NUMI beam power

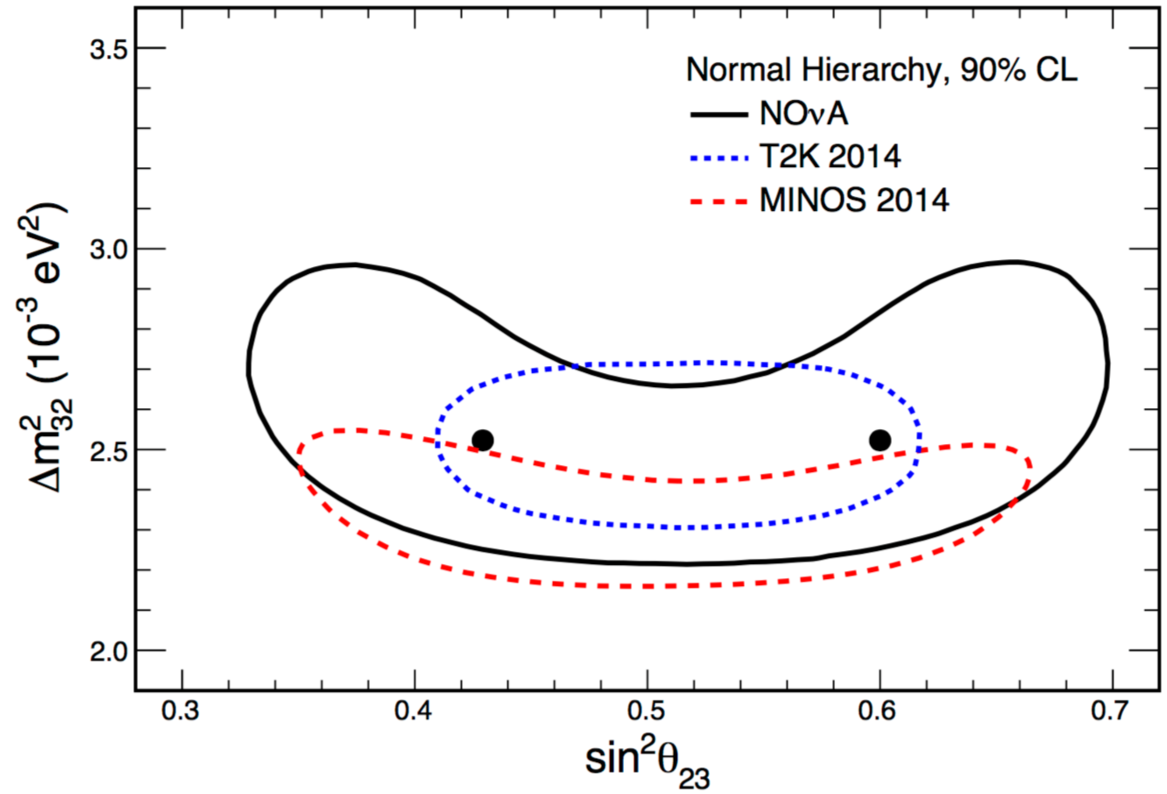


Integrated beam to NUMI : 2.5e21 pot @ 120 GeV

NOvA results based on : 2.74e20 pot-equiv

NOvA muon disappearance





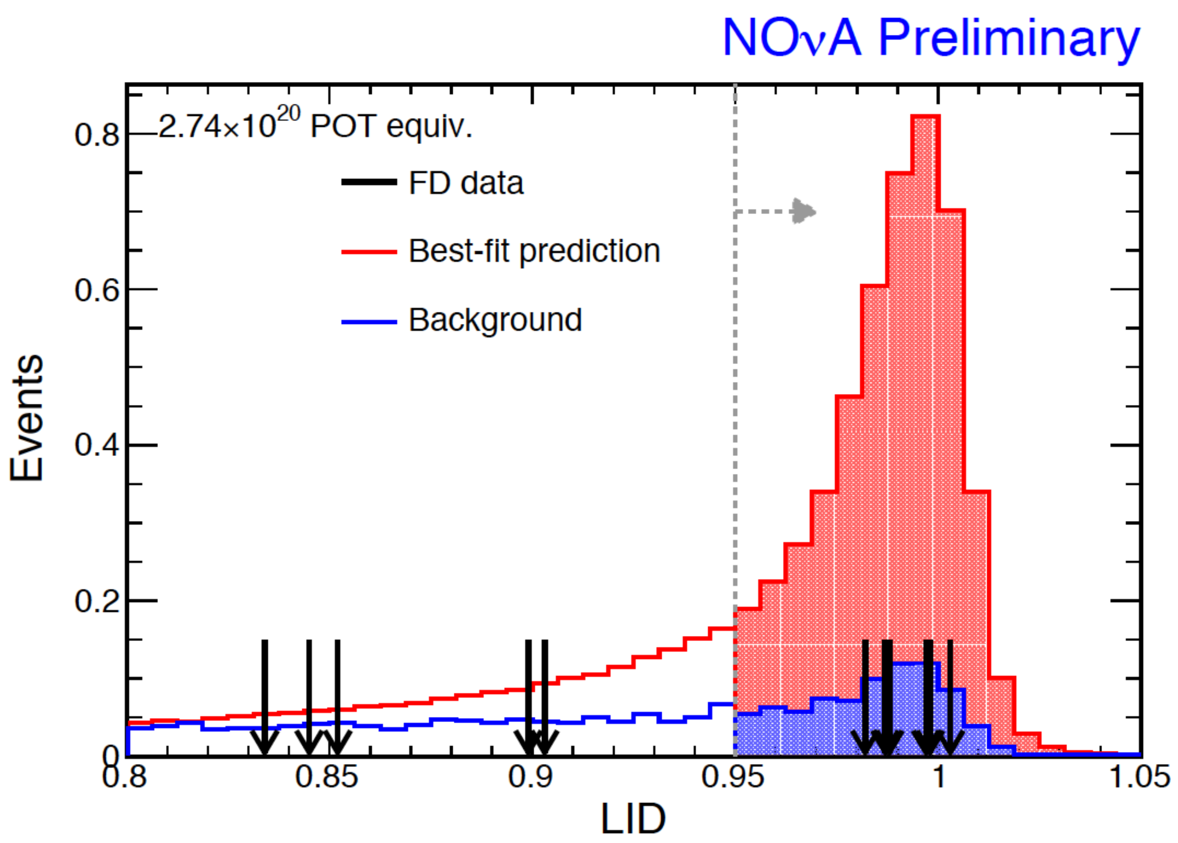
$$0.38 < \sin^2\theta_{23} < 0.65$$
$$\Delta m^2 = 2.52^{+0.20}_{-0.18}\ \mathrm{meV}^2 \quad (68\%\ \mathrm{C.L.})$$

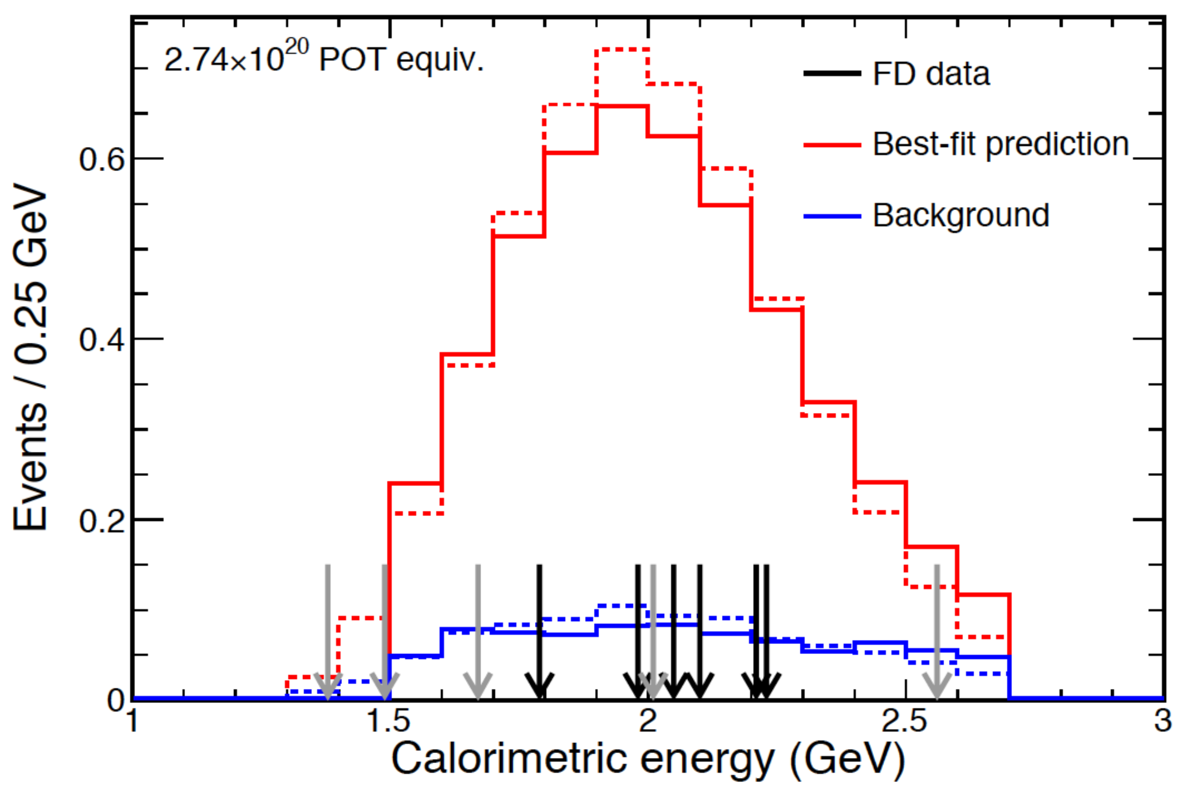
arXiv:1601.05037

Accepted for publication

33 events observed
NOvA sees ν_μ disappearance consistent with oscillations

ν_e CC Selected Events





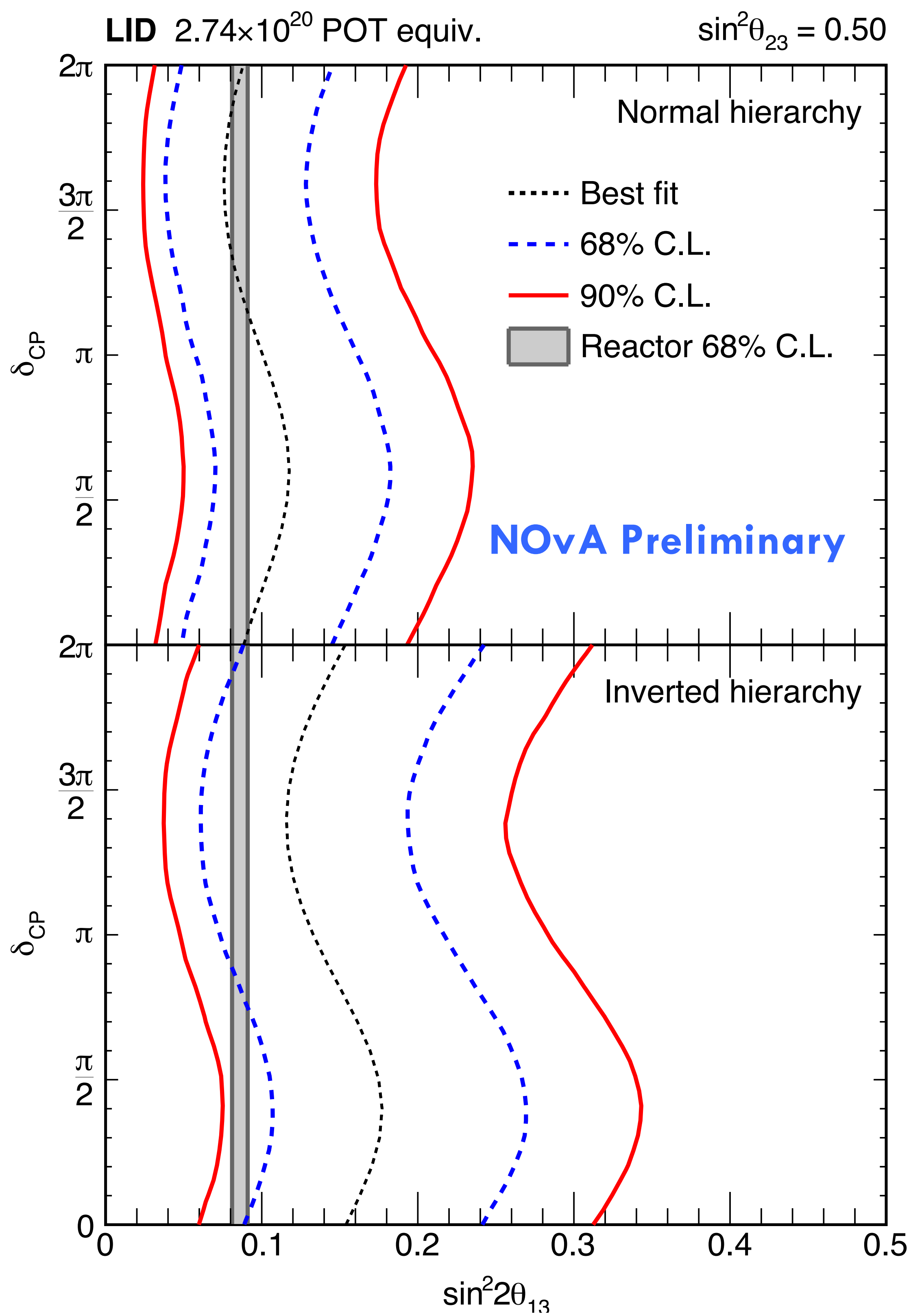
Two independent particle IDs: "LID" and "LEM"

- LID:
  - **Select 6 events**
  - **3.3σ evidence for ν_e appearance**
- LEM:
  - **Select 11 events**
  - **5.5σ for ν_e appearance**
- All 6 LID-selected events are also selected by LEM
  - The trinomial probability for observing 11 events with a (LID-only/LEM-only/Both) distribution is **P(11:0/5/6) = 9.2%**

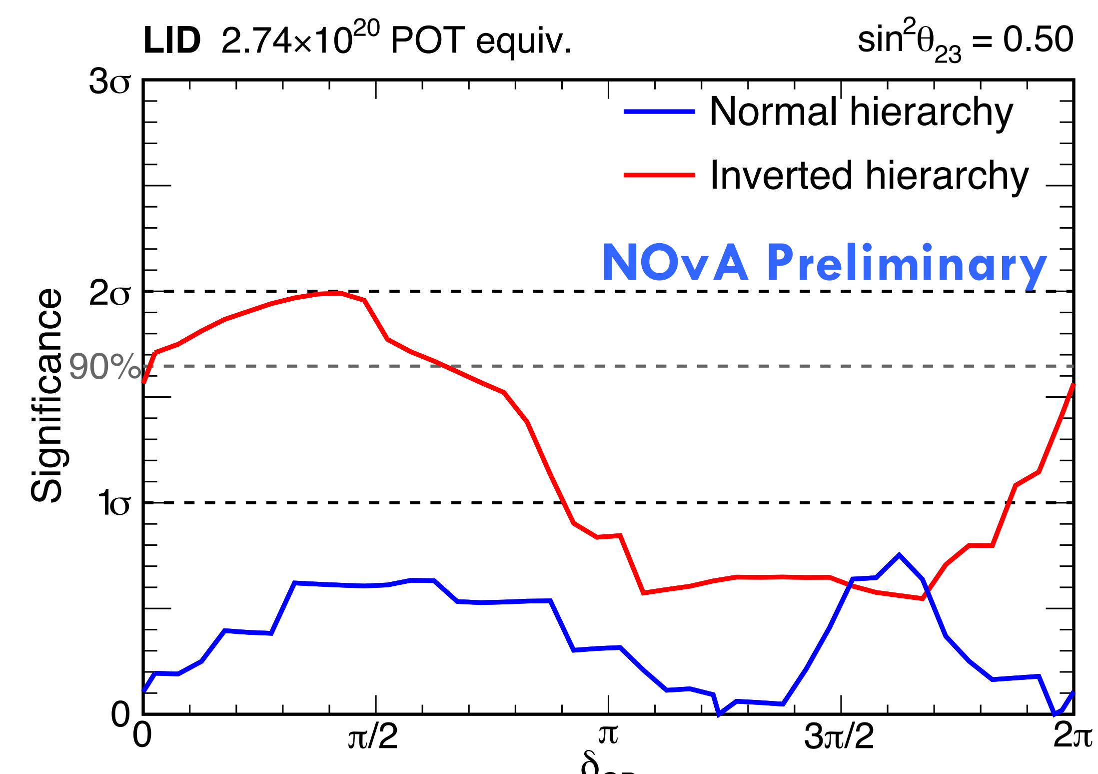
	Total Bkg	Beam ν_e	NC	ν_μ CC	ν_τ CC	Cosmic
LID	**0.94 ± 0.09**	**0.47**	**0.36**	**0.05**	**0.02**	**0.06**
LEM	1.00 ± 0.11	0.46	0.40	0.07	0.02	0.06

	NH $\delta_{CP}=3\pi/2$	IH $\delta_{CP}=\pi/2$
LID	**5.62 ± 0.72**	**2.24 ± 0.29**
LEM	5.91 ± 0.59	2.34 ± 0.23

NOvA result on CP-phase



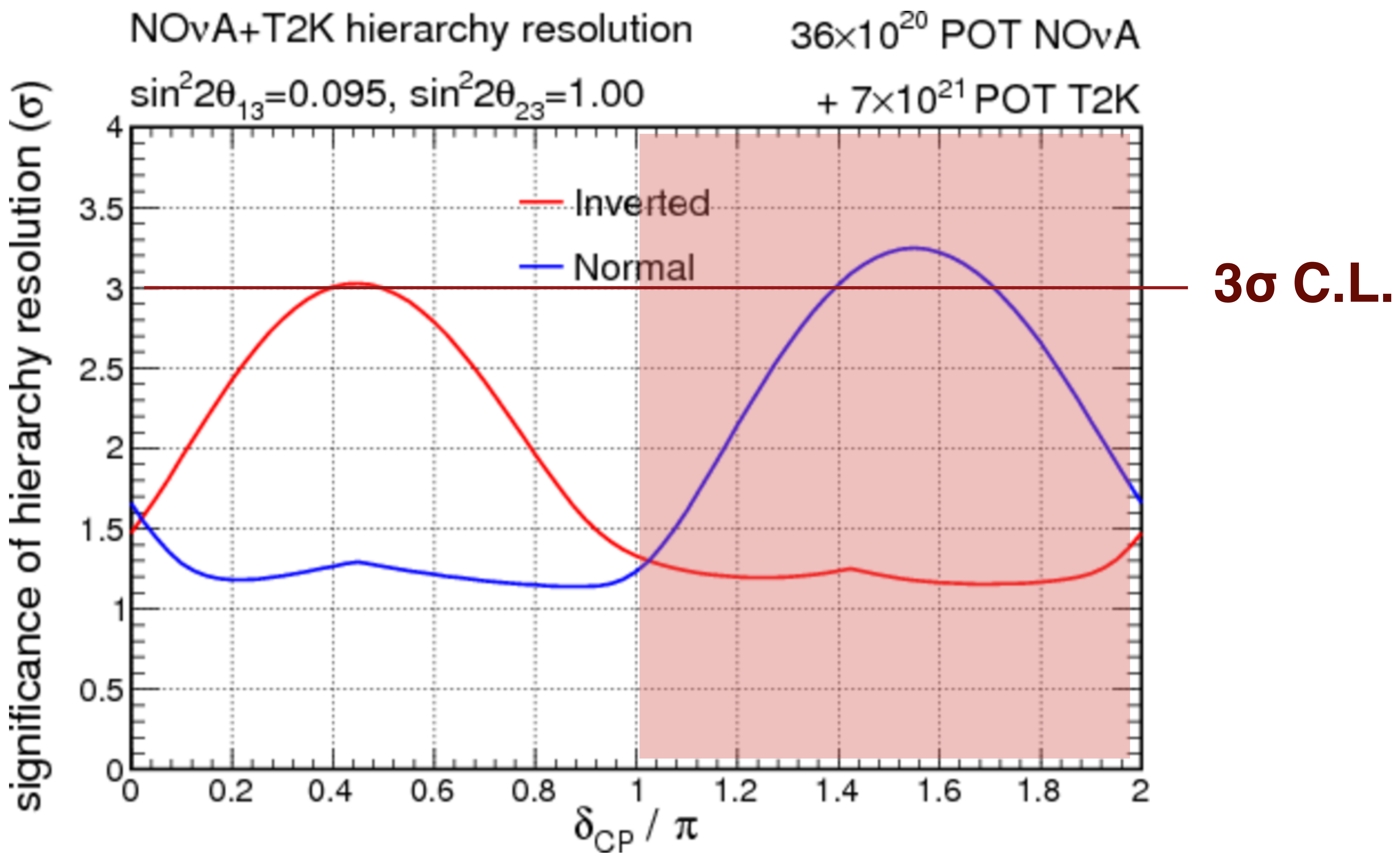
- Use reactor measurement of **$\sin^2 2\theta_{13}$=0.086±0.05** as input to understand how NOvA's results favor choices of mass hierarchy or δ_{CP}
  - Both LID and LEM prefer **NH** with δ_{CP} between π and 2π
  - LID shows some tension with **IH** for $0 < \delta_{CP} < 0.8\pi$
  - LEM disfavors **IH** at greater than 2σ for all values of δ_{CP}



NOvA δ_{CP}+MH hints consistent with T2K

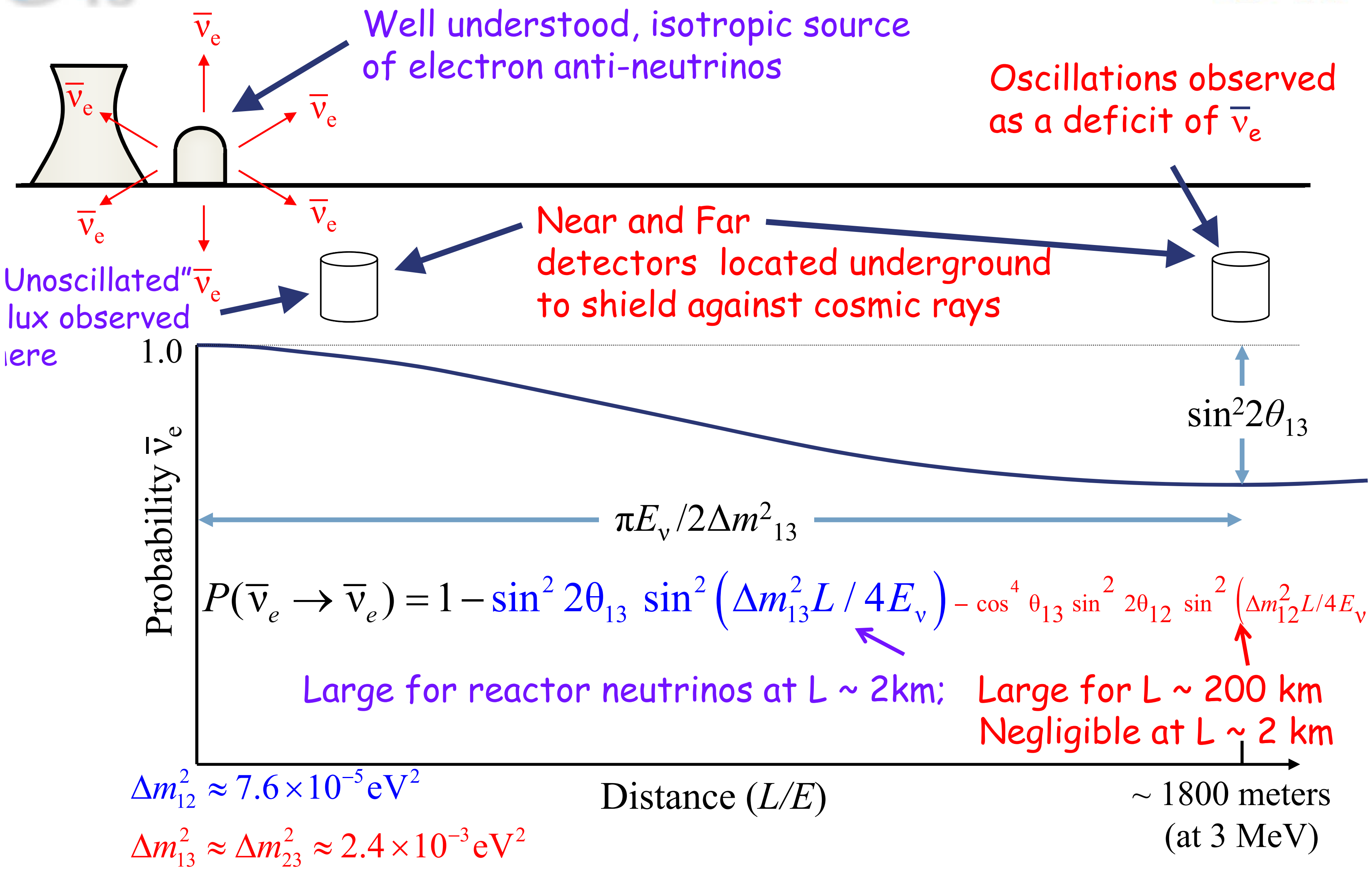
ETH Eidgenössische Technische Hochschule Zürich Swiss Federal Institute of Technology Zurich

NOvA sensitivity on MH



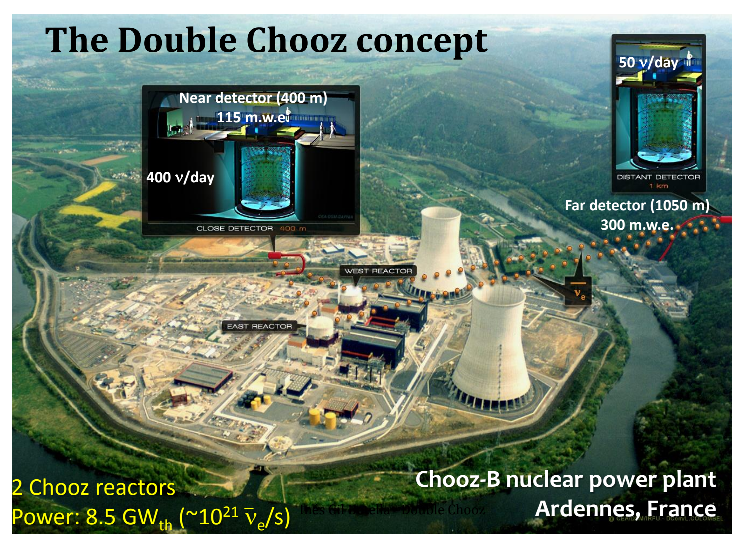
NOvA+T2K reach 3σ C.L. on MH for favoured region and true NH

Reactor experiments: disappearance



Daya Bay at Ling Ao & Daya Bay (China)

http://dayawane.ihep.ac.cn



Latest results from Daya Bay

217 days x 6AD + 404 days x 8AD

The most precise measurement of θ_{13} (6%)

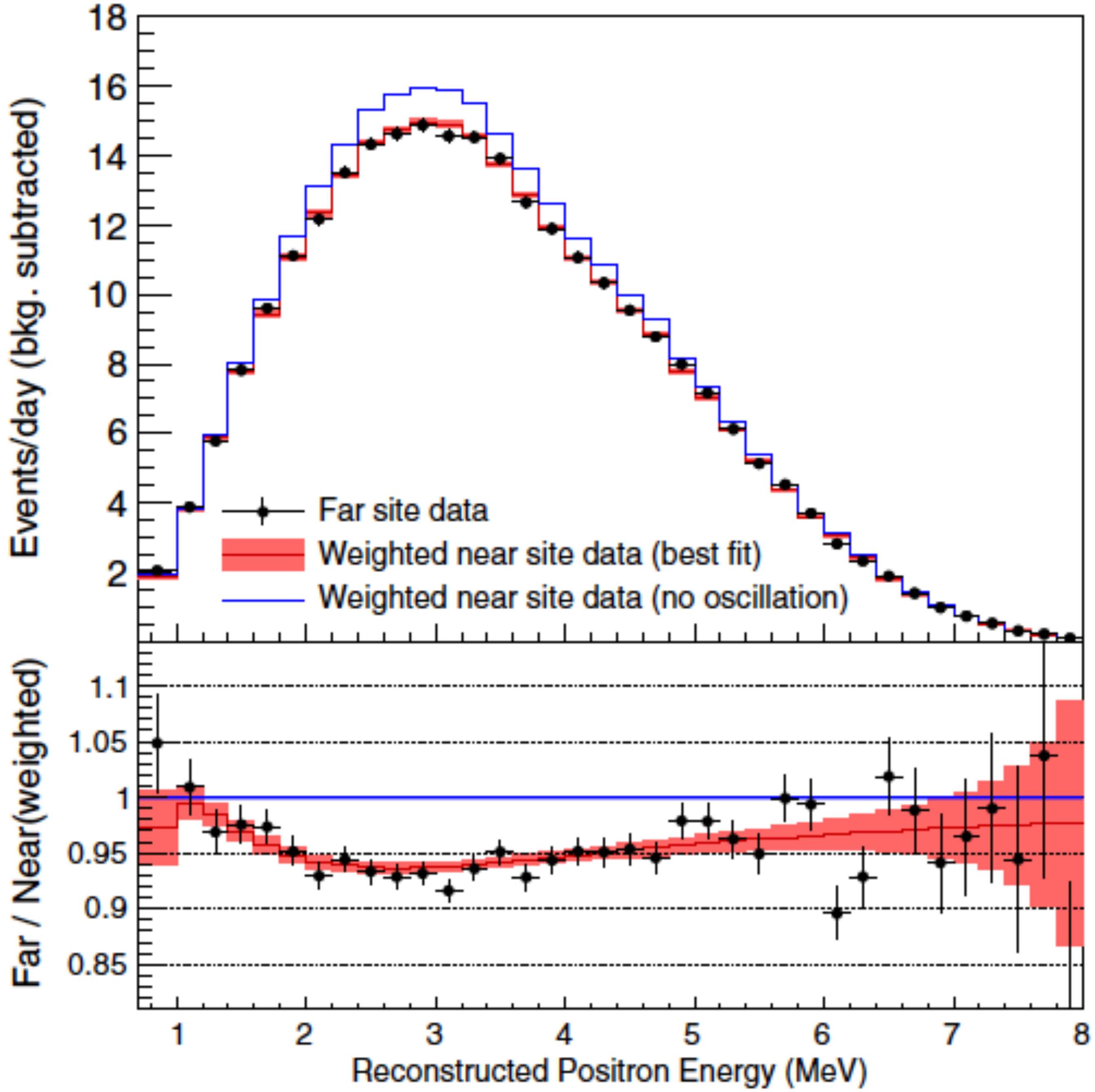
Using near/far comparison:

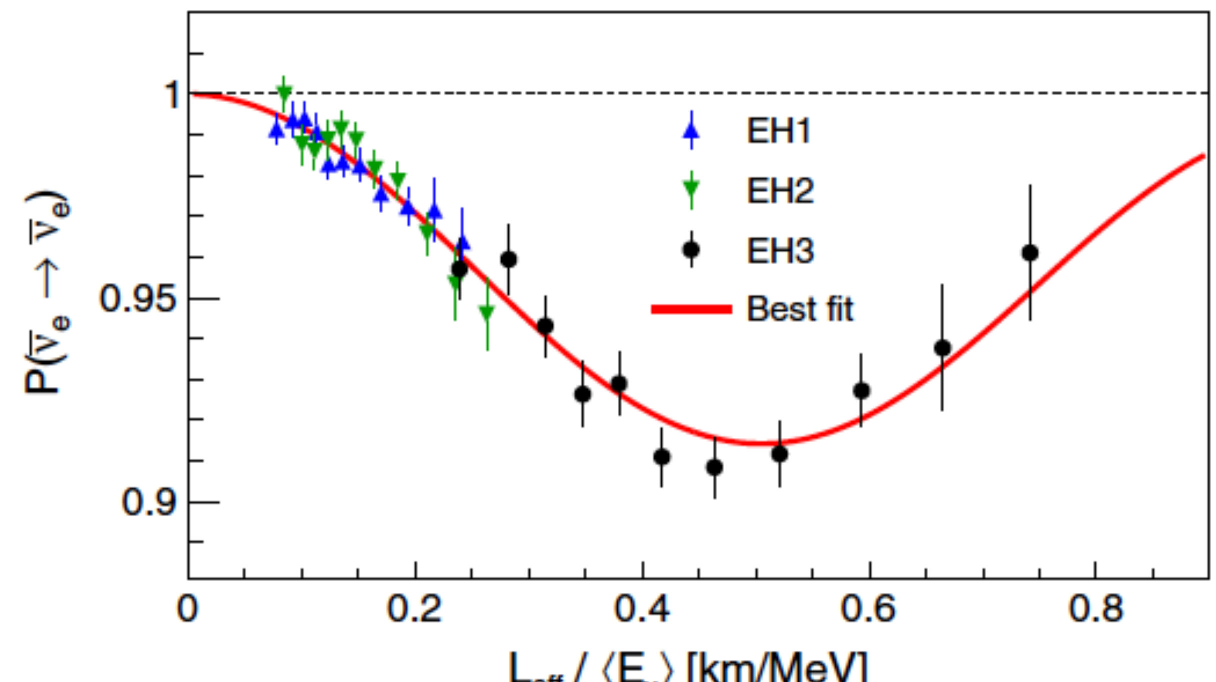
$$\sin^2 2\theta_{13} = 0.084^{+0.005}_{-0.005}$$

$$|\Delta m^2_{ee}| = 2.44^{+0.10}_{-0.11} \times 10^{-3}\mathrm{eV}^2$$

$$\chi^2/NDF = 134.7/146$$

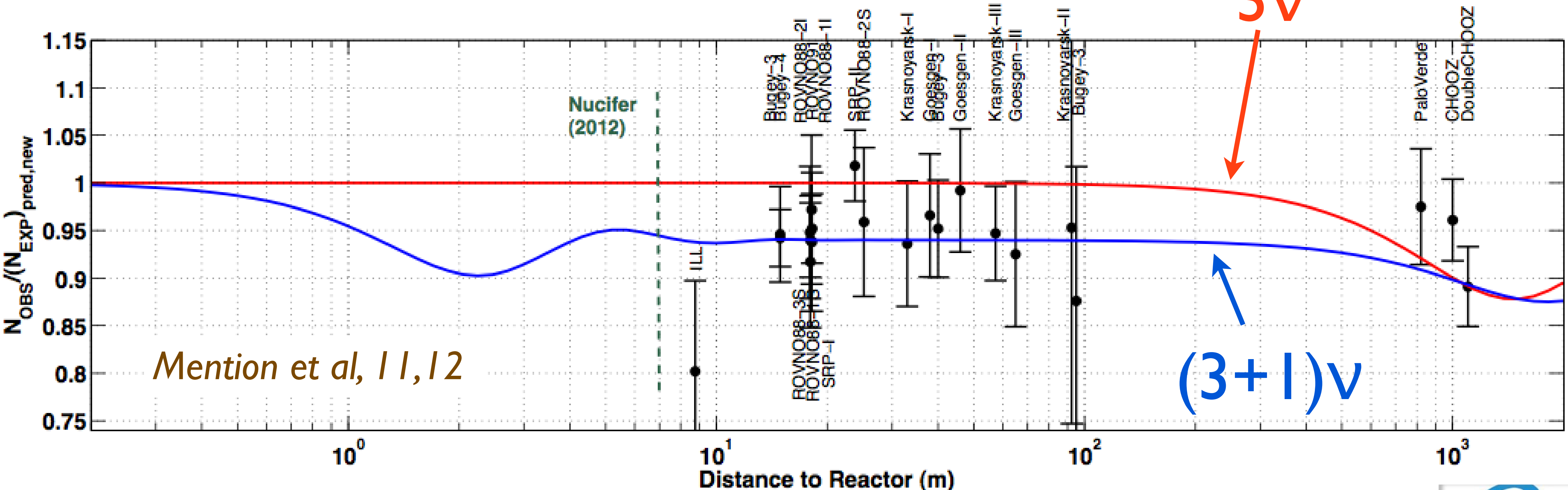
PRL 115, 111802 (2015)





Similar results from RENO and Double-CHOOZ

Reactor anomaly ?



<u>Data Bay latest analysis:</u>

Compare to flux models

- Data/Prediction (Huber+Mueller)

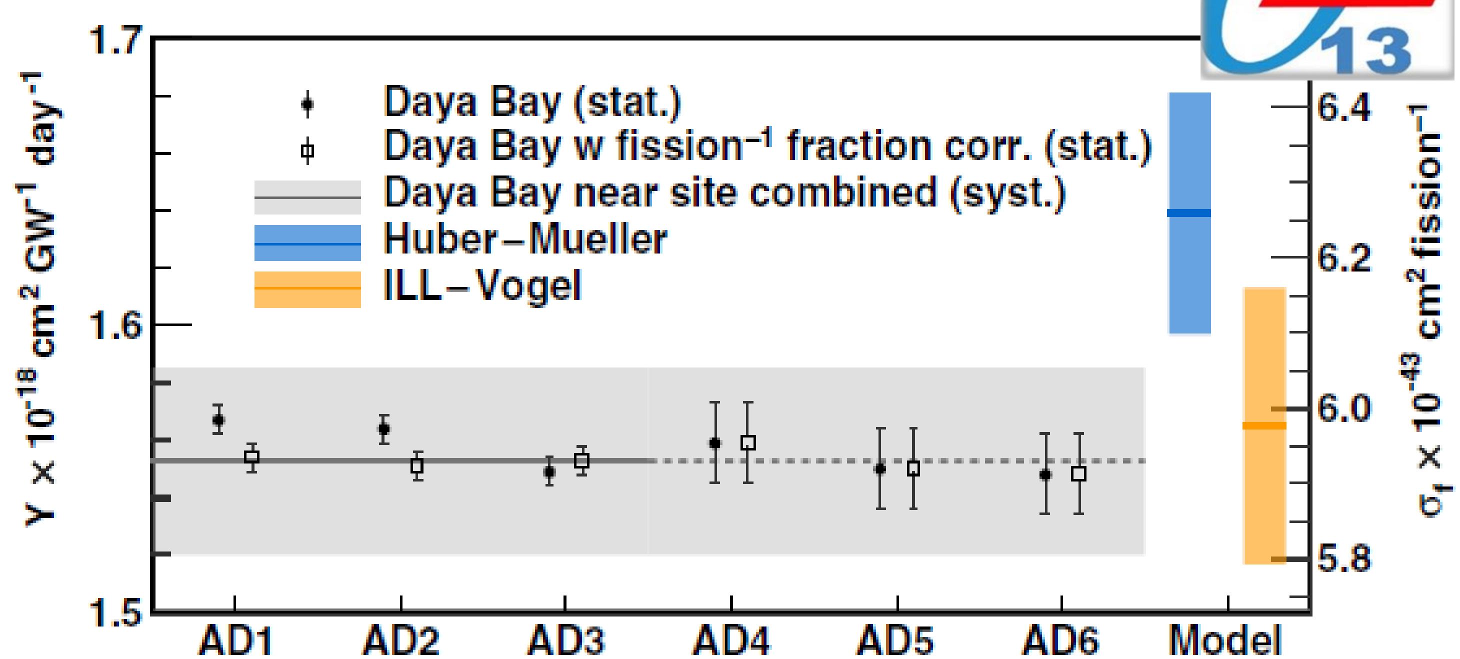
  0.946 ± 0.022

- Data/Prediction (ILL+Vogel)

  0.991 ± 0.023

Anomaly depends on theoretical flux chosen

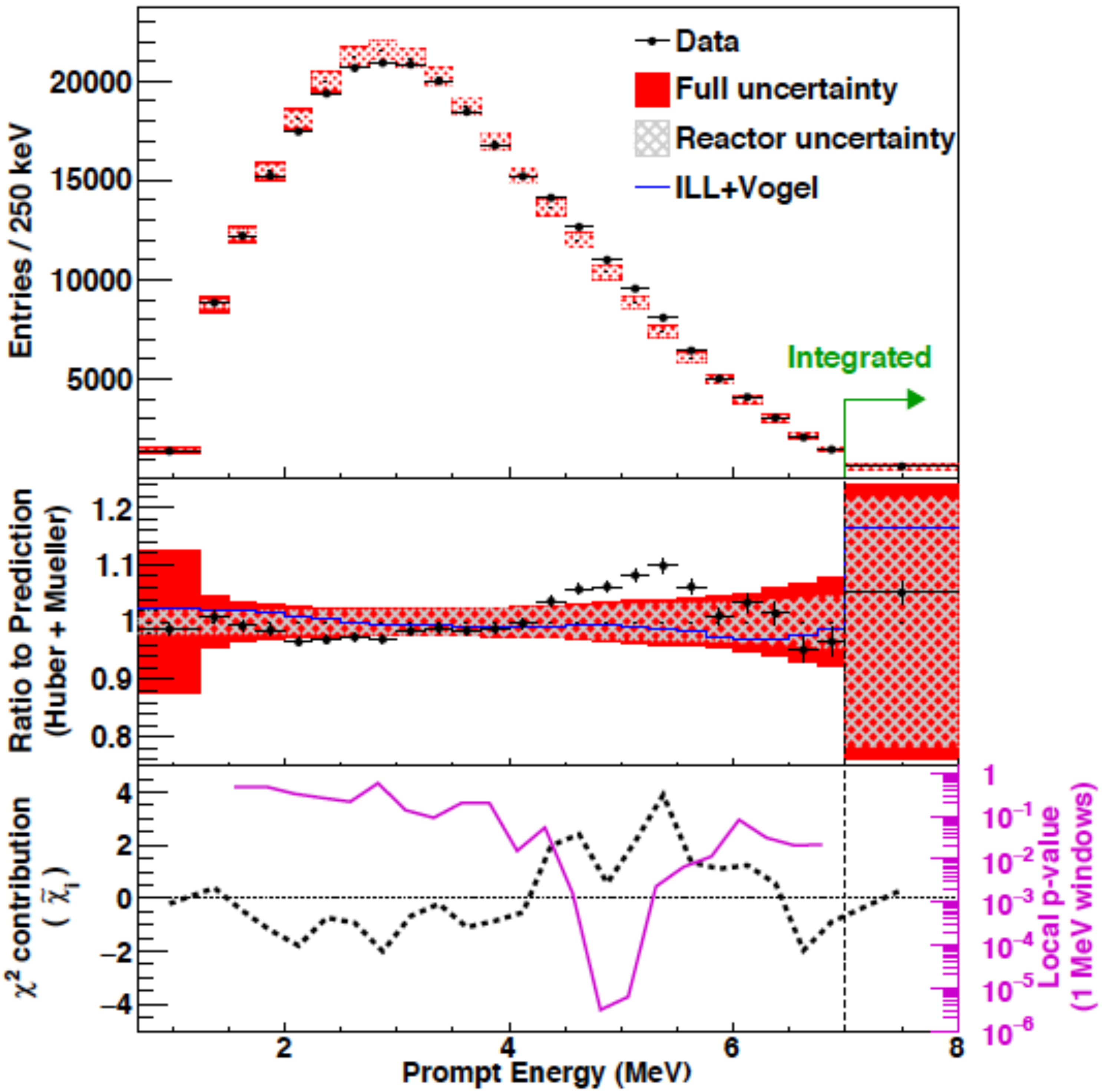
PhysRevLett.116.061801



Hint for discrepancies with theoretical reactor neutrino predictions

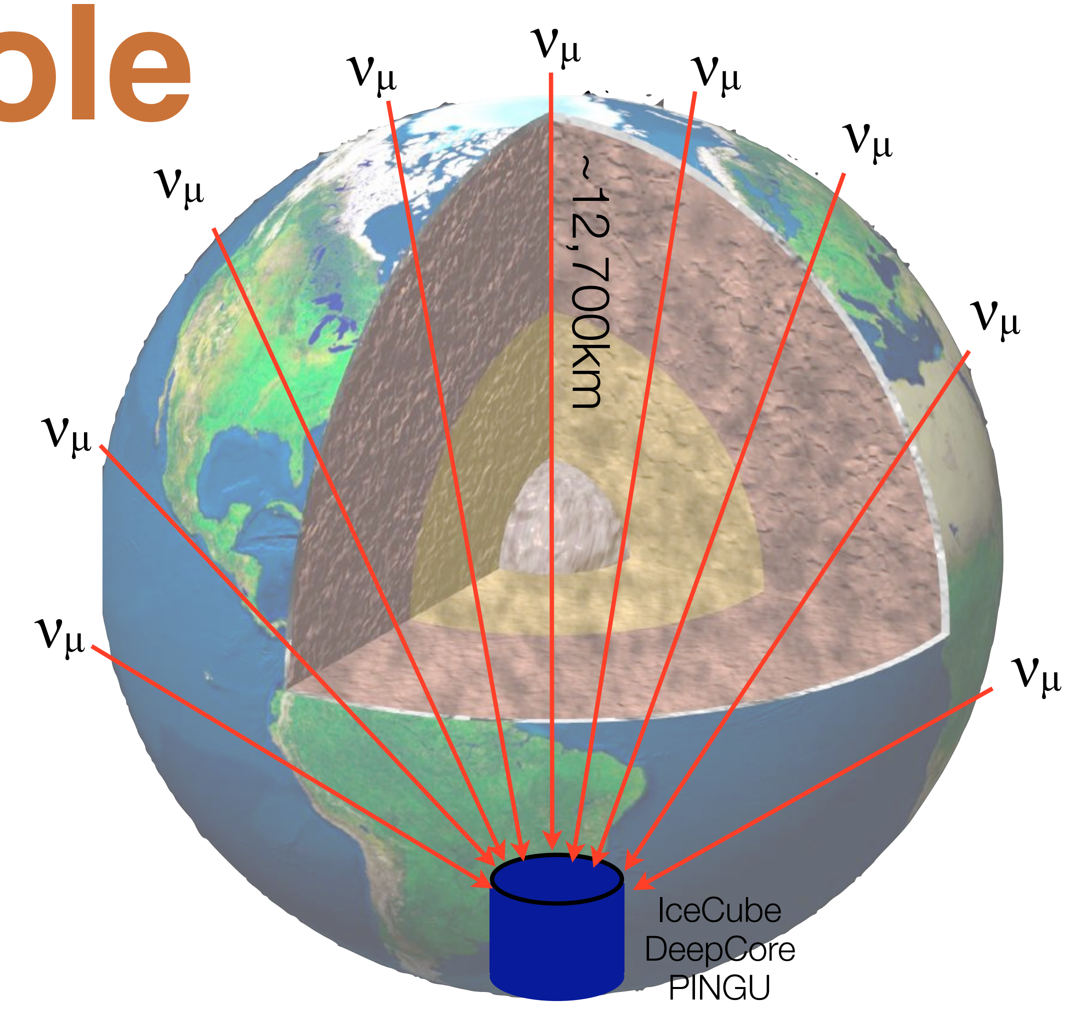
- Observation of a **2.6σ discrepancy** in the 0.7-12MeV range (**4.4σ in range 4-6MeV**)
- Possibilities to explain the discrepancy:
  - error in flux prediction
  - bias in experiments (unlikely)
  - new physics

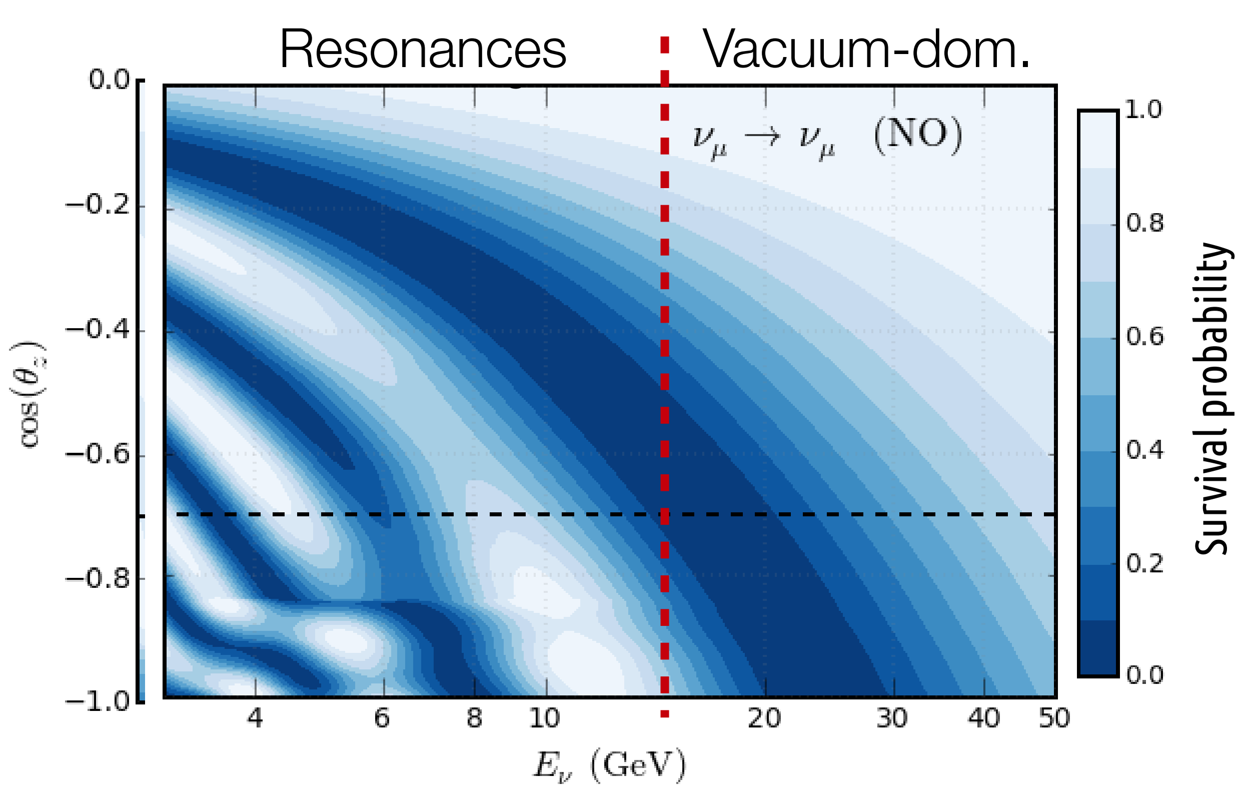
"Theoretical reactor flux not fully understood"



IceCube @ South Pole

- **Very Large Volume Neutrino Telescopes in deep ice**
  - Primary goal: neutrino astronomy (Understanding the sources of cosmic rays)
  - Secondary goal: DM, atm neutrino oscillations
- **Atmospheric neutrinos measurable over a wide range of energies and baselines**
  - oscillations + matter effects produce distinctive patterns in E & angle (i.e. baseline) phase space
  - control systematics by comparing E & angle (trade statistics for systematics)

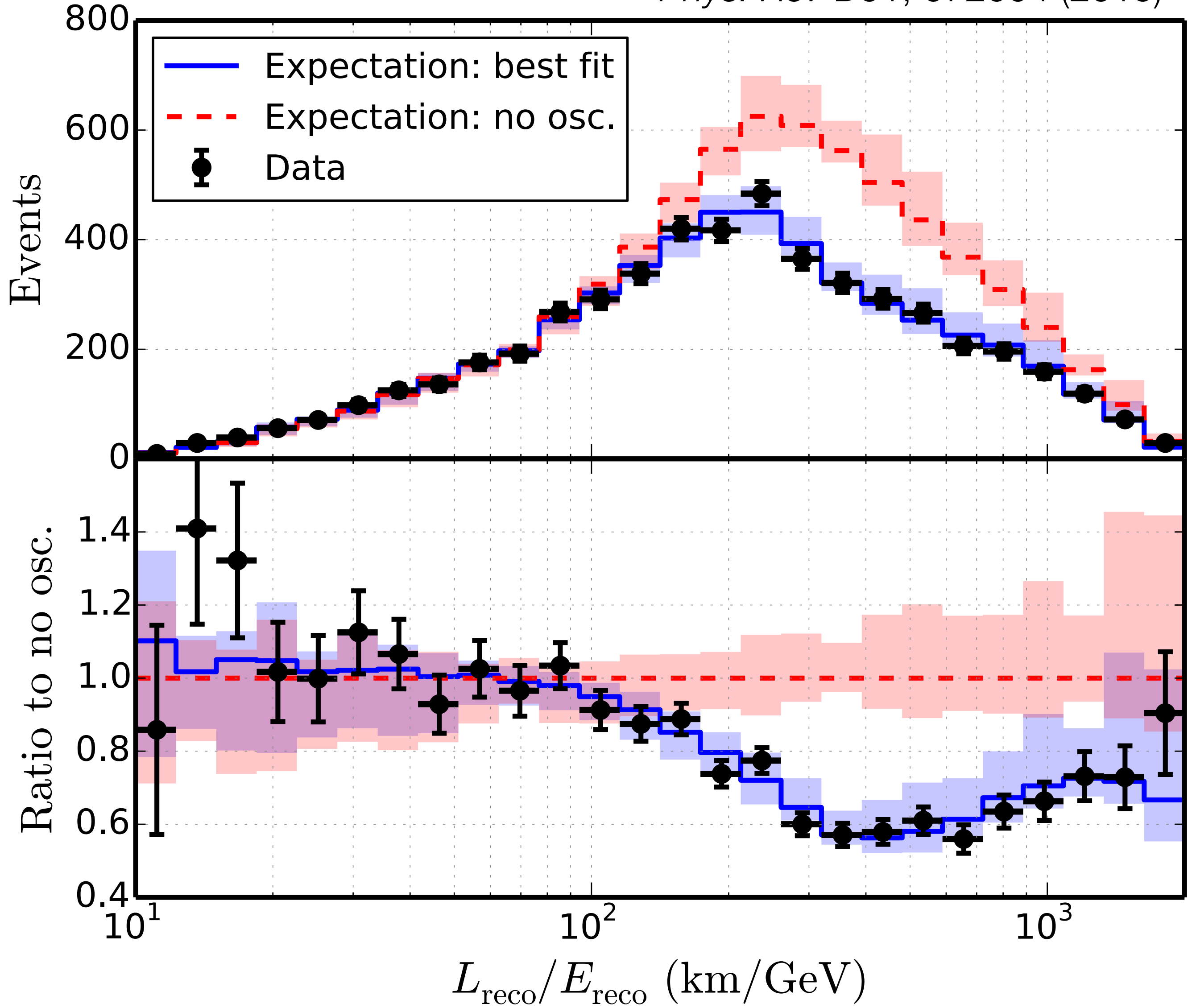




Below ~15 GeV, matter resonances (MSW) depend on MH

IceCube atmospheric result

Phys. Rev D91, 072004 (2015)

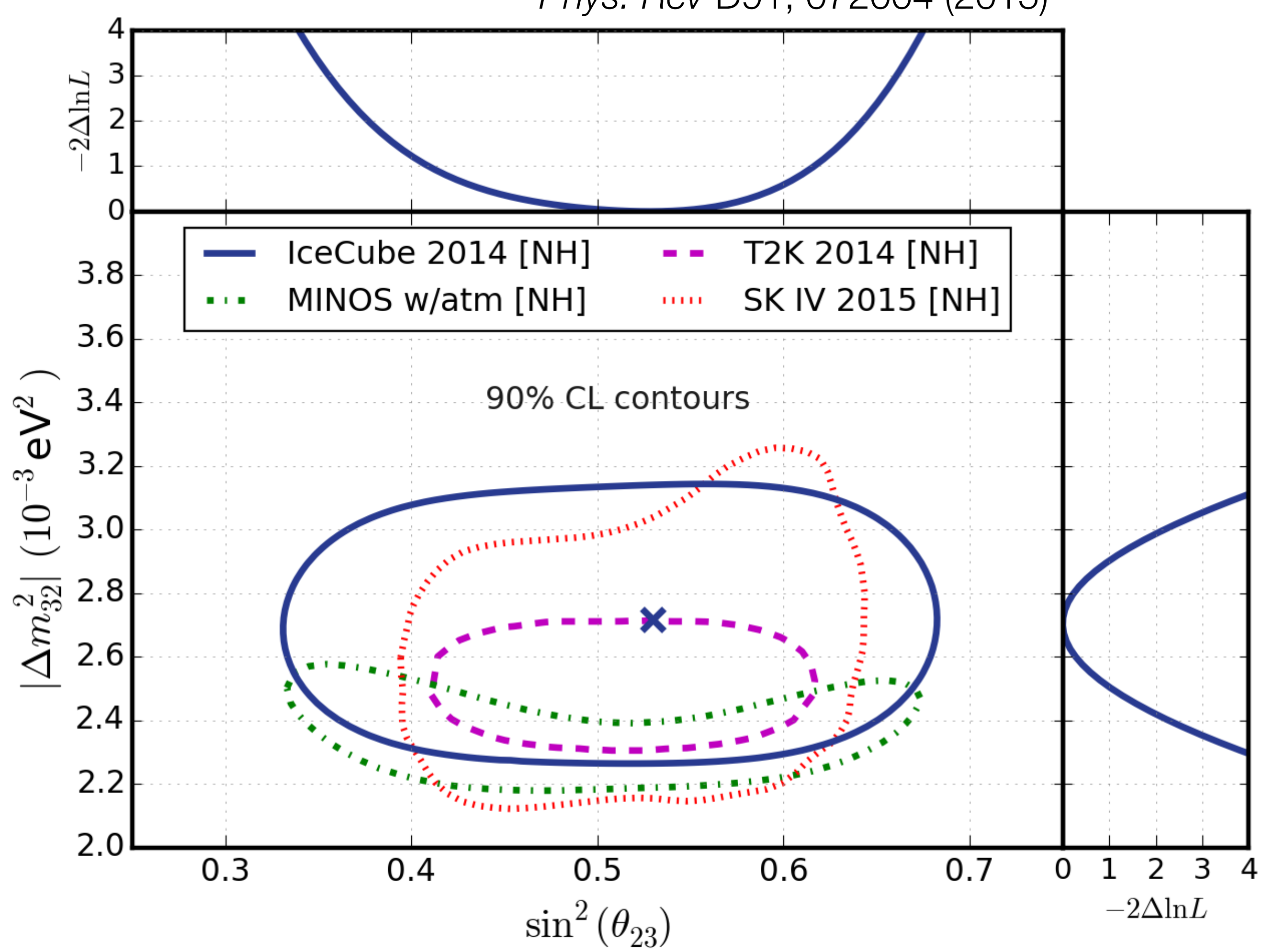


Measure atmospheric parameters (Δm^2, θ_{23}) at high energies

Precision comparable with LBL

Results compatible with LBL & SK

Phys. Rev D91, 072004 (2015)



Shaded range shows allowed systematics with constraints from current data

The 3νSM study programme

- **Establish the 3νSM as the correct description of nature**
  - Determine precisely all parameters (<5%), e.g. the degree to which θ_{23} differs from $\pi/4$
  - Test matter effects through Earth
- **Complete the three active neutrinos 3νSM model (PMNS)**
  - Determine the mass hierarchy and the complex CP-phase
  - Test (and discover?) CPV in the leptonic sector
- **Search for deviations from the 3νSM model**
  - Test the unitarity of the PMNS neutrino mixing matrix
  - Search for non-standard interactions
  - Is this picture affected by new sterile neutrinos ?

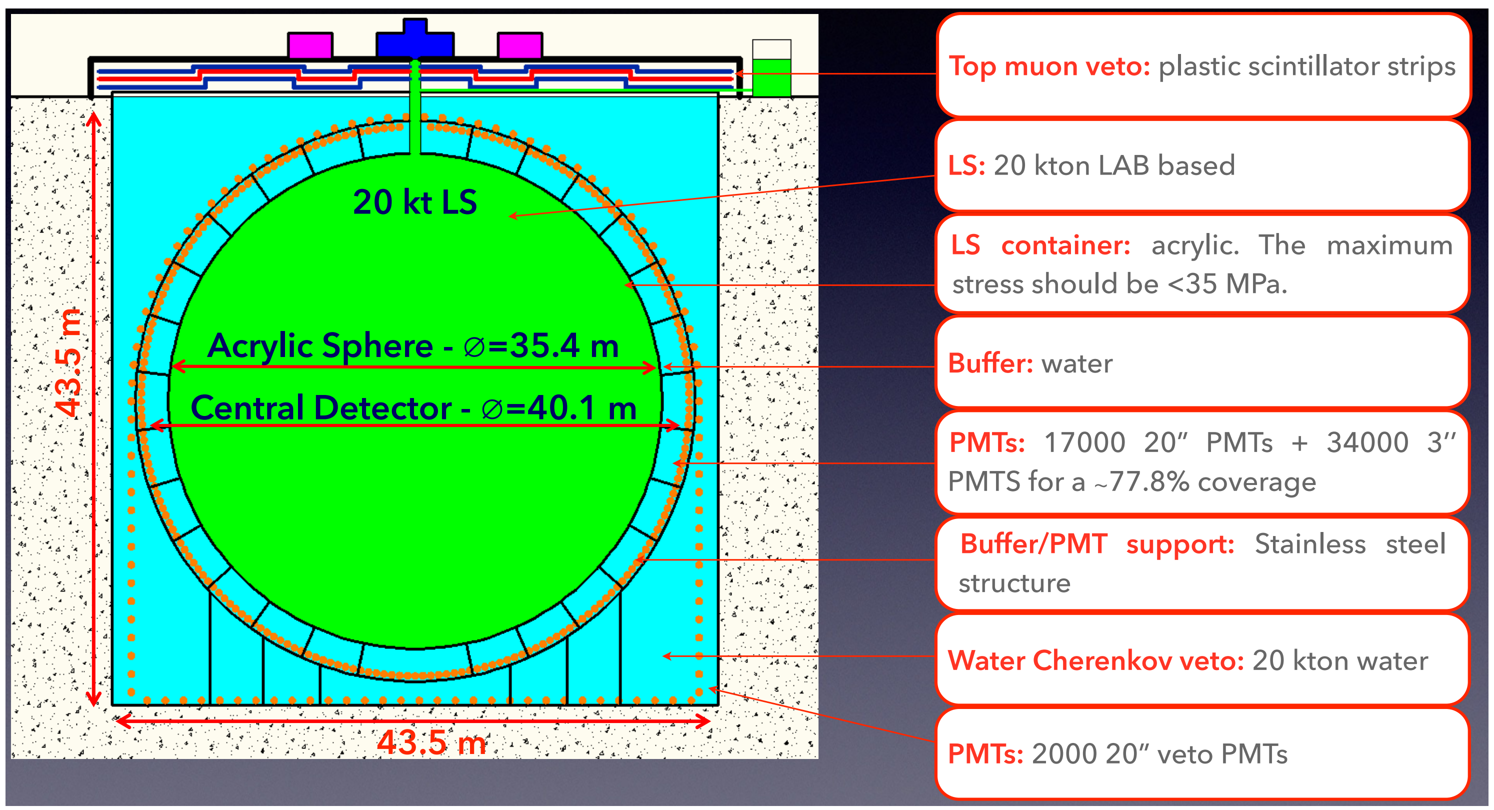
➠ ***Next generation of experiments !***

JUNO - Jiangmen Underground Neutrino Observatory

Start data taking in 2020

Next-generation Large Liquid Scintillator detector

- medium baseline reactors experiment (<L>=50 km)
- aim at much improved light yield and energy resolution ≈3%/√E(MeV)
- relatively shallow depth (700m overburden)



Performance:

- high yield scintillator, >20m attenuation length, low BG
- 75-80% photo coverage
- 30% QE PMTs

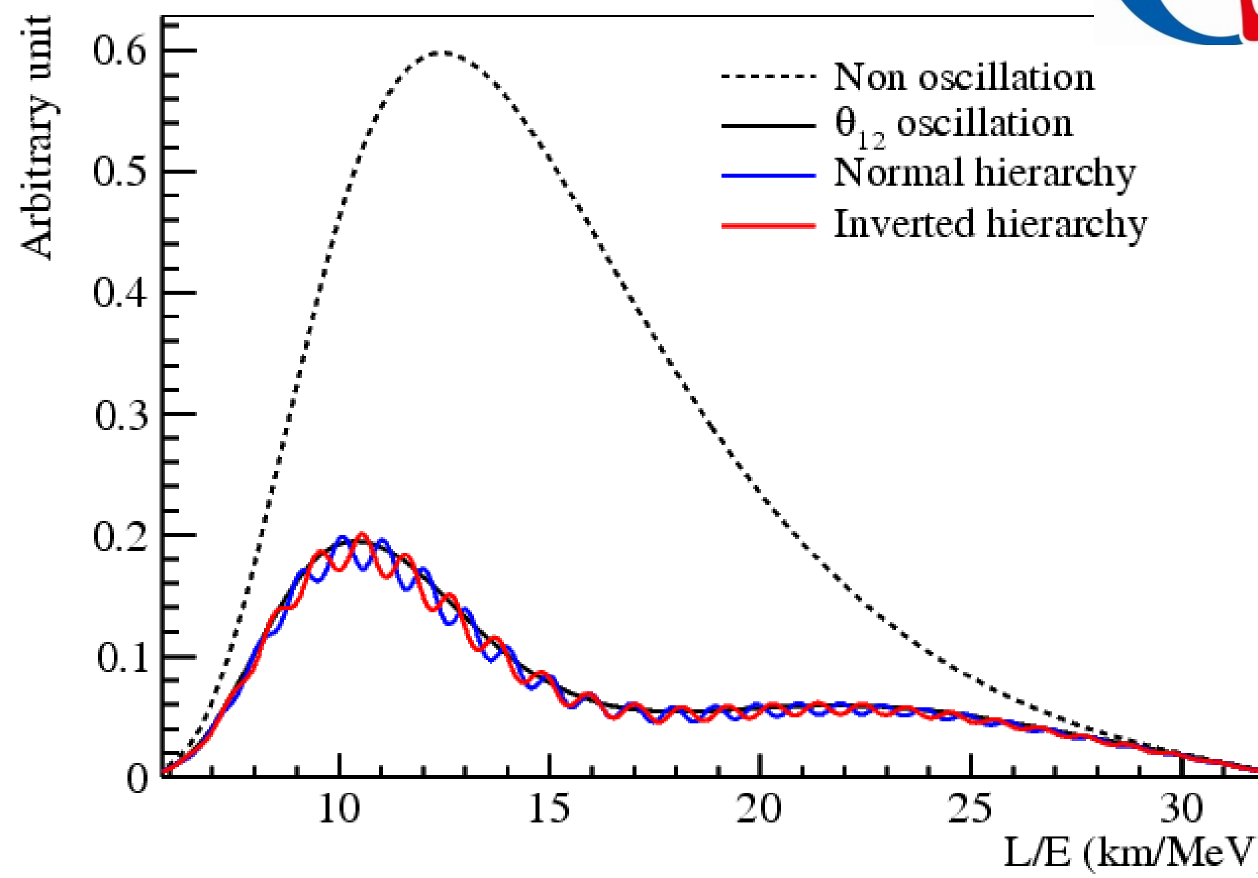
Calibration:

- energy scale at the sub-percent level with comprehensive calibration program for non-uniformity & non-linearity

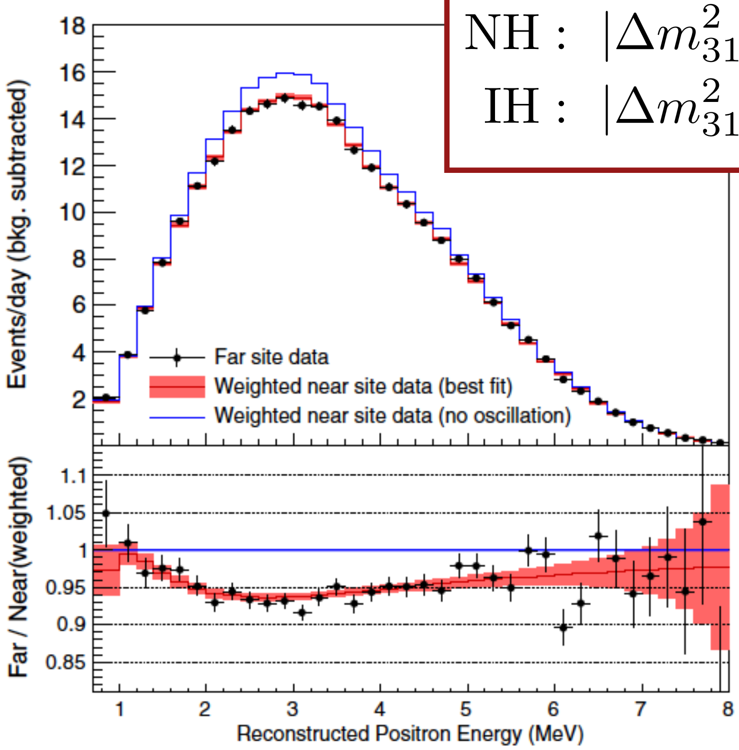
Experiment	Daya Bay	BOREXINO	KamLAND	JUNO
LS mass	20 ton	~300 ton	~1 kton	20 kton
Coverage	~12%	~34%	~34%	~80%
Energy resolution	~7.5%/√E	~5%/√E	~6%/√E	~3%/√E
Light yield	~ 160 p.e. / MeV	~ 500 p.e. / MeV	~ 250 p.e. / MeV	~ 1200 p.e. / MeV

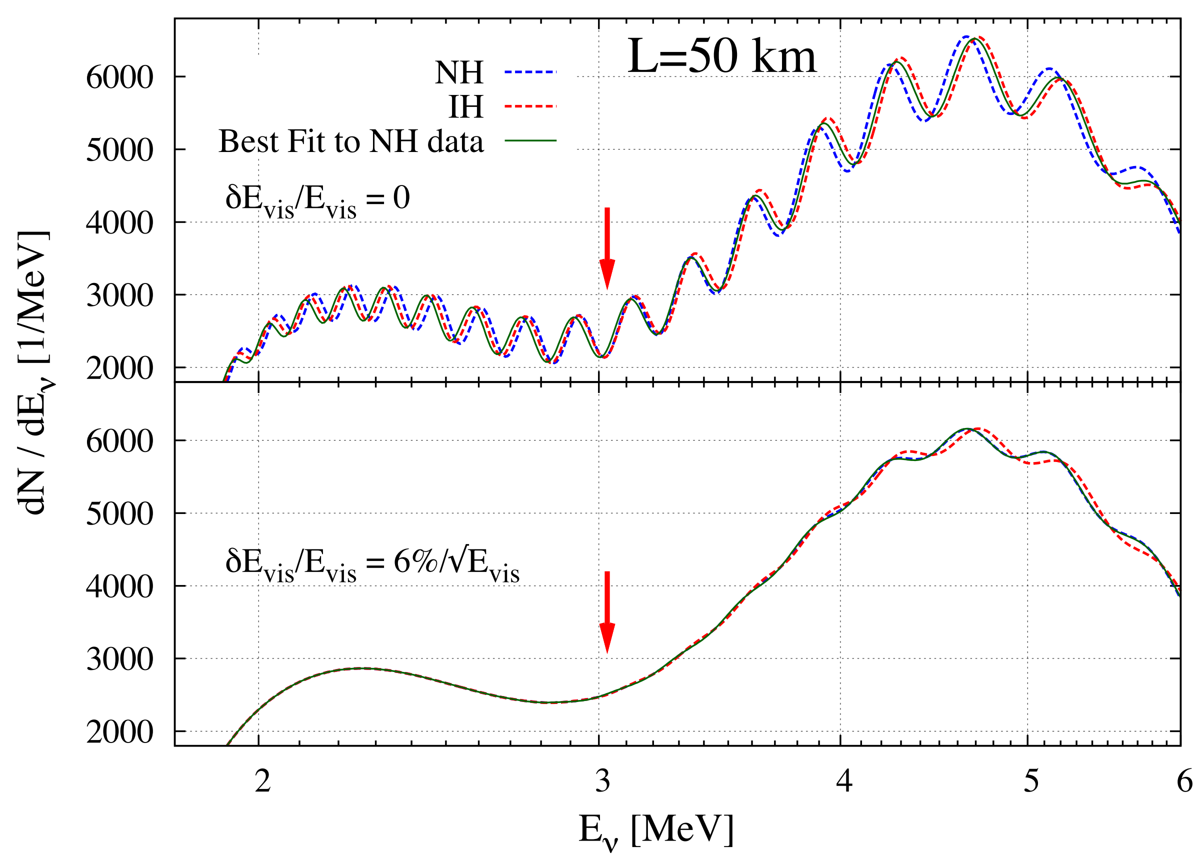
JUNO - Mass hierarchy determination

$$
\begin{aligned}
P_{ee}(L/E) &= 1 - P_{21} - P_{31} - P_{32} \\
P_{21} &= \cos^4(\theta_{13})\sin^2(2\theta_{12})\sin^2(\Delta_{21}) \\
P_{31} &= \cos^2(\theta_{12})\sin^2(2\theta_{13})\sin^2(\Delta_{31}) \\
P_{32} &= \sin^2(\theta_{12})\sin^2(2\theta_{13})\sin^2(\Delta_{32})
\end{aligned}
$$



$$
\boxed{
\begin{aligned}
\Delta m^2_{31} &= \Delta m^2_{32} + \Delta m^2_{21} \\
\mathrm{NH}: \ |\Delta m^2_{31}| &= |\Delta m^2_{32}| + |\Delta m^2_{21}| \\
\mathrm{IH}: \ |\Delta m^2_{31}| &= |\Delta m^2_{32}| - |\Delta m^2_{21}|
\end{aligned}
}
$$





Perfect resolution!

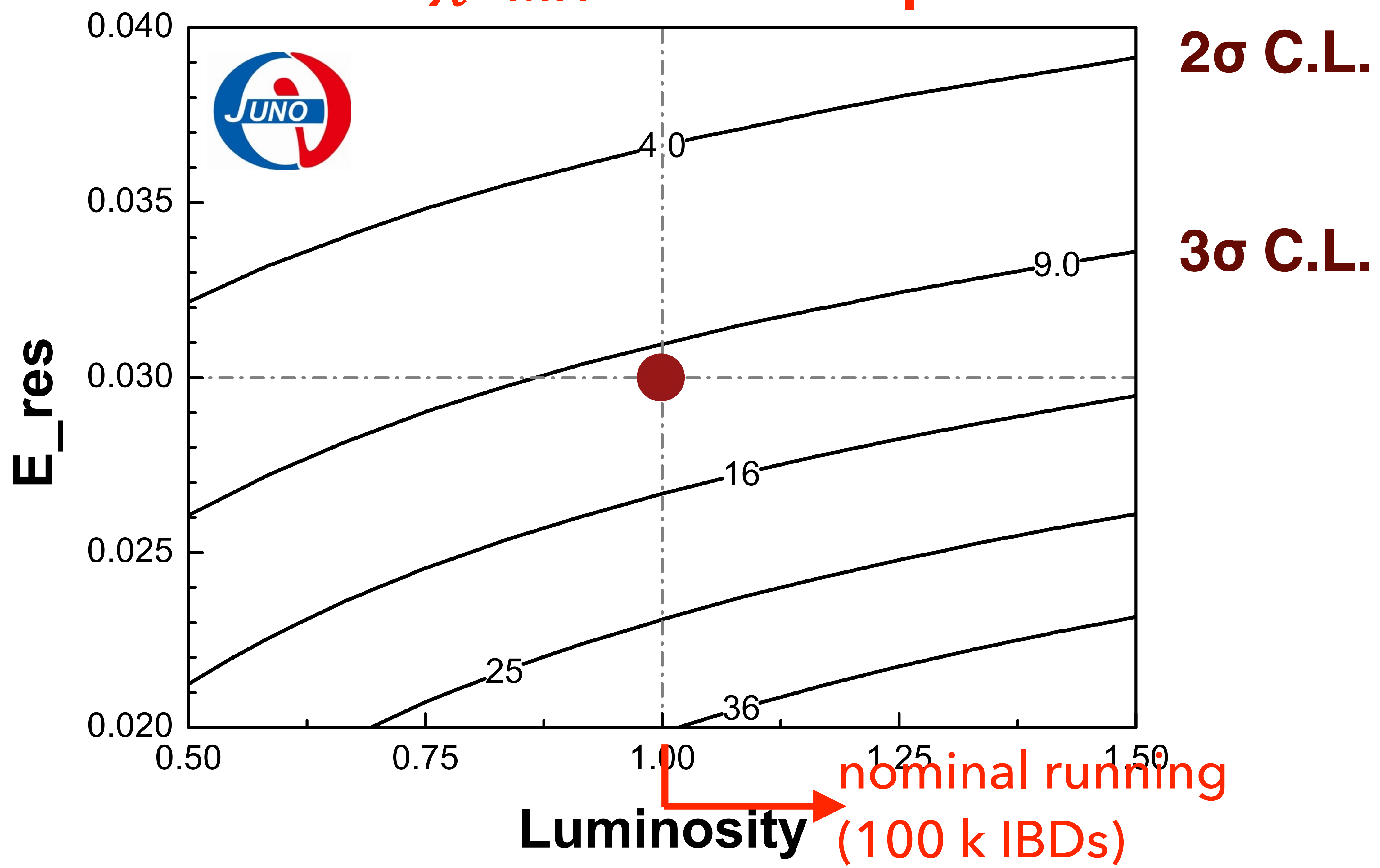
$$6\%/\sqrt{E(MeV)}$$

The energy resolution is a critical parameter in the achievable sensitivity

JUNO - Mass hierarchy determination

iso-$\Delta\chi^2_{MH}$ contour plot

$$\Delta\chi^2_{\rm MH} = |\chi^2_{\rm min}(\rm N) - \chi^2_{\rm min}(\rm I)|$$



3% resolution @ 1 MeV and 100 k IBDs = 20 ton * 35 GW * 6 years

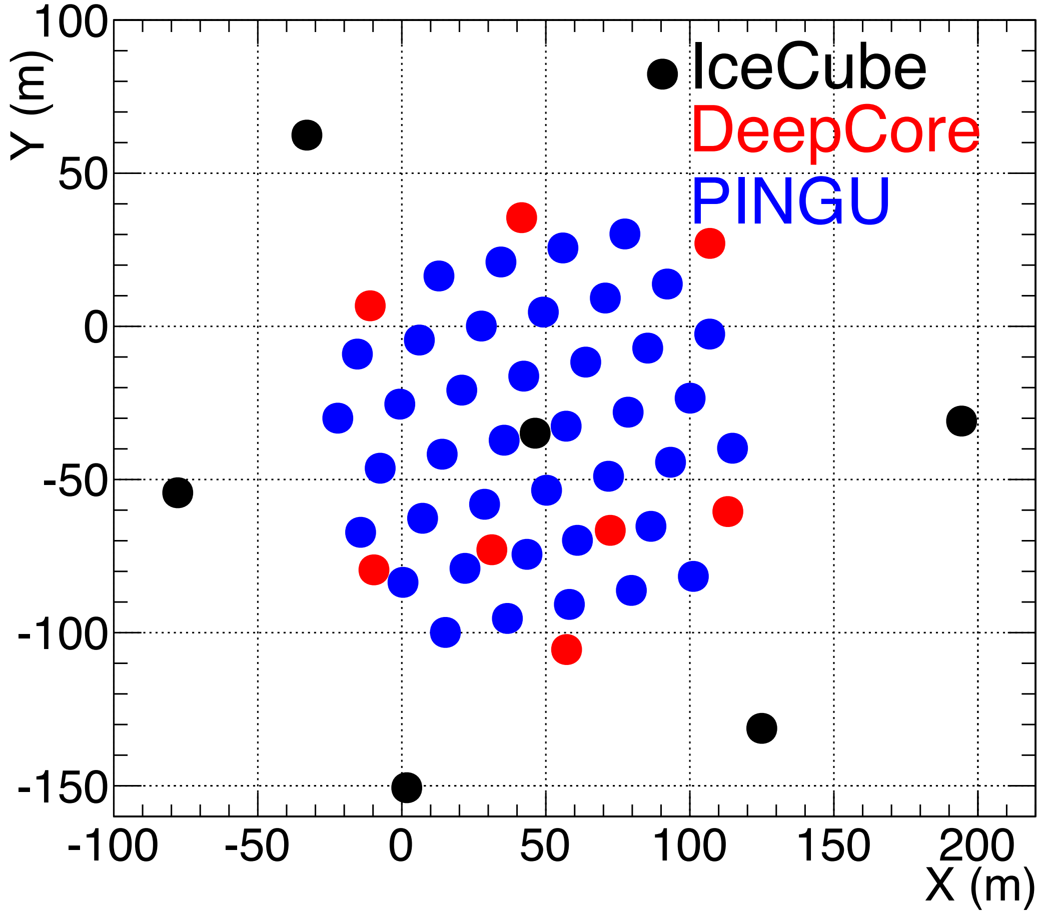
Projected sensitivity MH ordering at 3σ C.L. in 6 years

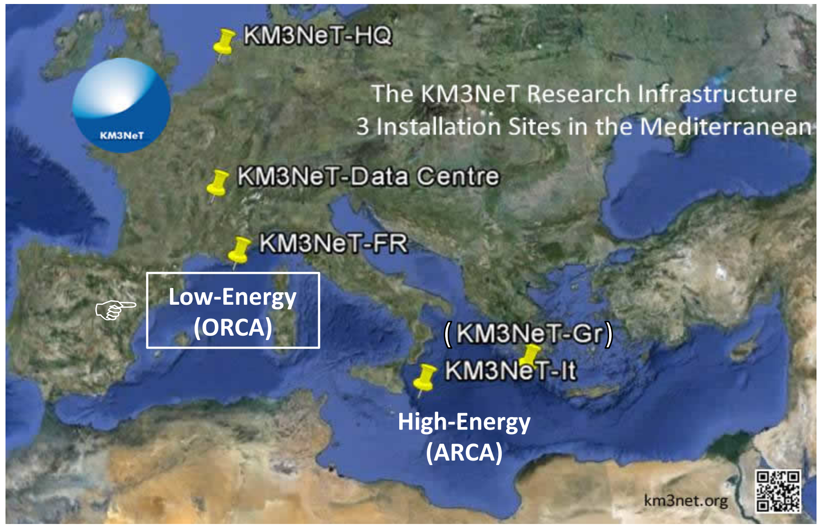
Atmospherics : PINGU/ORCA

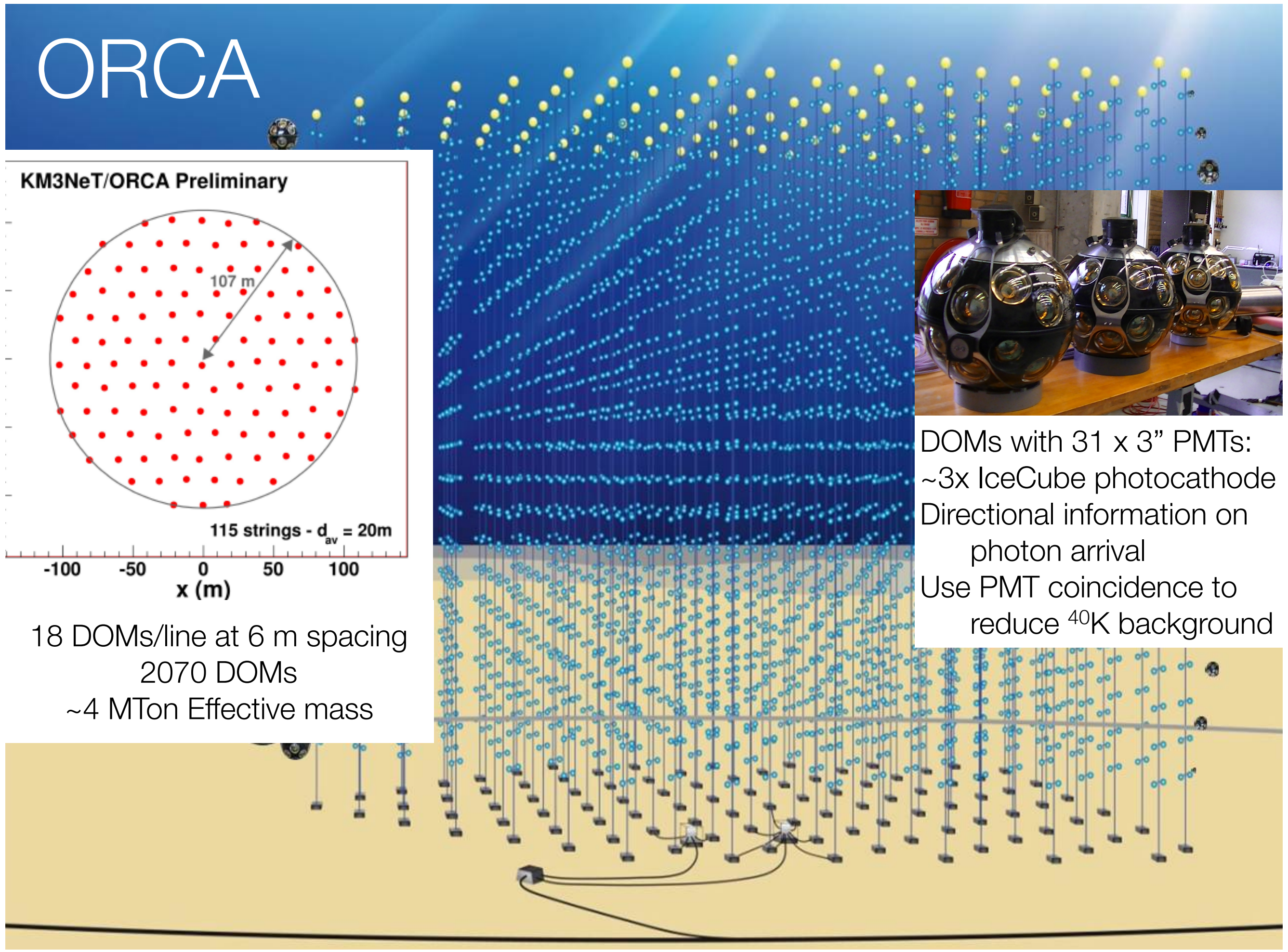
Start data taking in ≈2020

<u>South Pole:</u> 40 additional strings embedded in IceCube/DeepCore with 22 m spacing, 96 DOMs spaced vertically at 3 m → lower E threshold

Top view of the PINGU new candidate detector

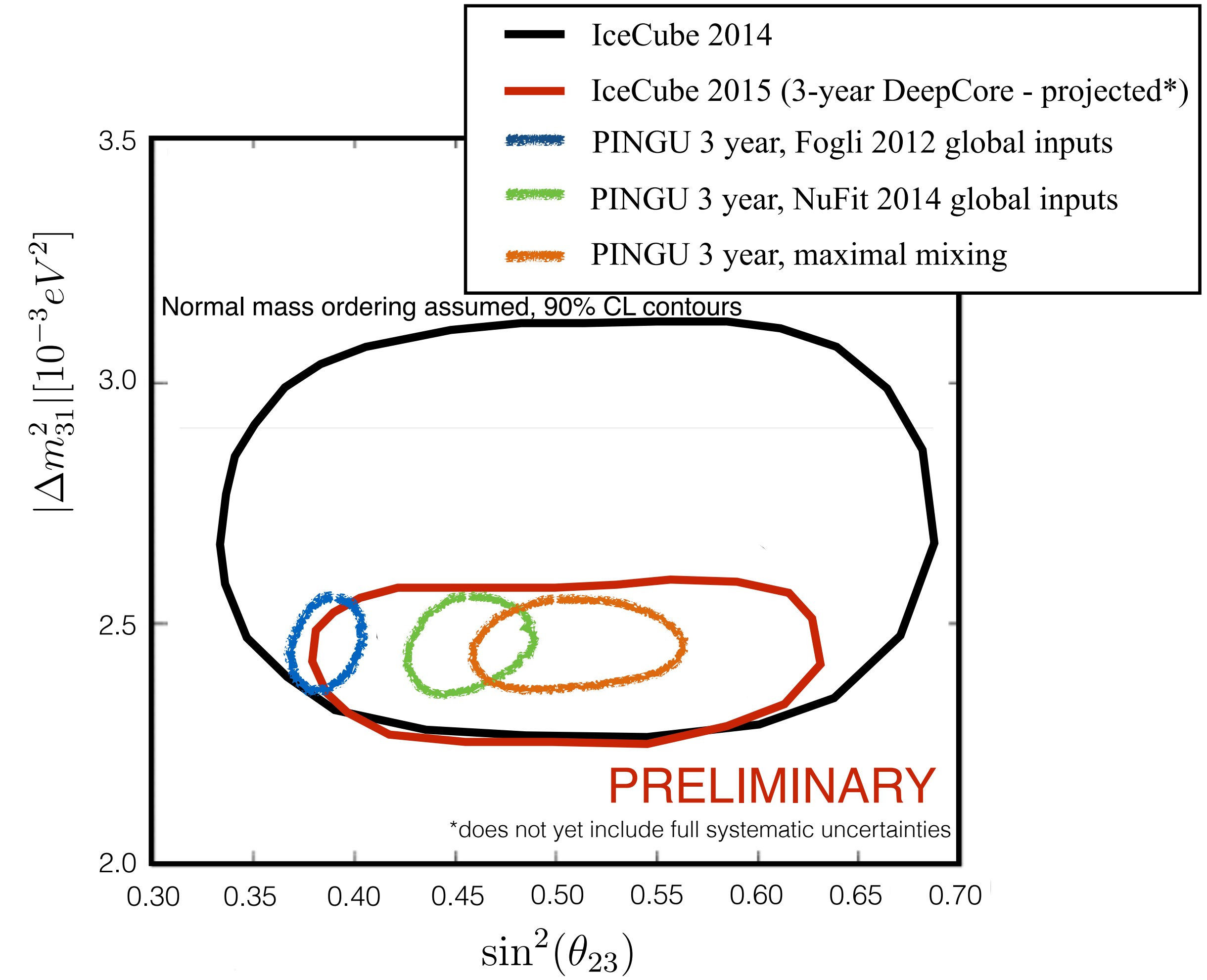


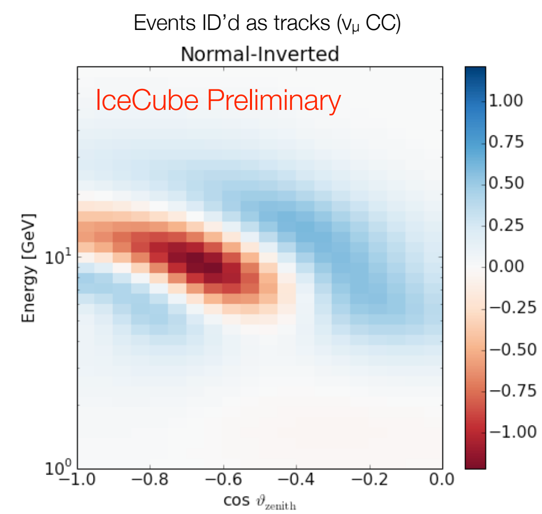


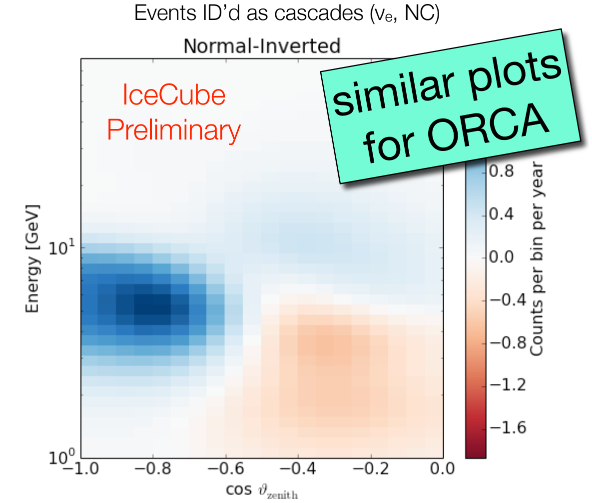


Atmospherics : PINGU/ORCA

- **PINGU**
  - Event rates, detector resolutions and efficiencies parametrized from full detector Monte Carlo
  - Expect ~50k (νμ+νμ̄) and ~40k (νe+νē) per year – largest sample ever in this energy range
  - No direct ν/ν̄ discrimination but $\sigma_{\nu N} \sim 2\sigma_{\bar{\nu}N}$
  - Sensitive to matter effects in Earth
- **Similar arguments for ORCA**





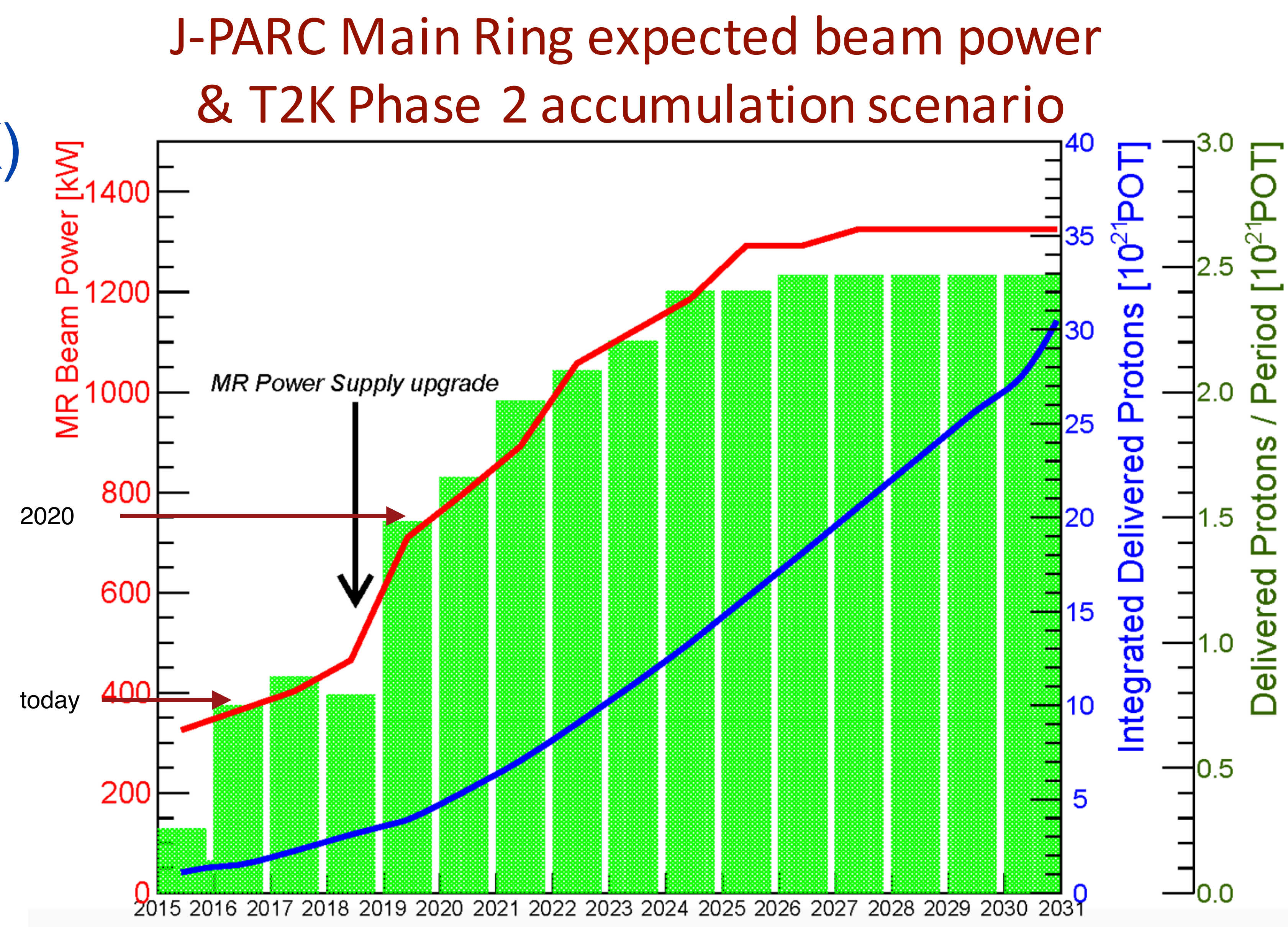


Projected sensitivity MH ordering at 3σ C.L. in 4 years

T2K phase II ?

Data taking window 2020-2026 ?

- Next generation LBL experiments (DUNE&HK) are expected to turn on around 2025
- **Proposal for T2K phase II** ⇒ continue to take data until 2026 beyond approved T2K program (7.8×10^{21} pot)
- Assume constant power increase until 1.3MW ⇒ accumulated POT reaches 20×10^{21} pot ?

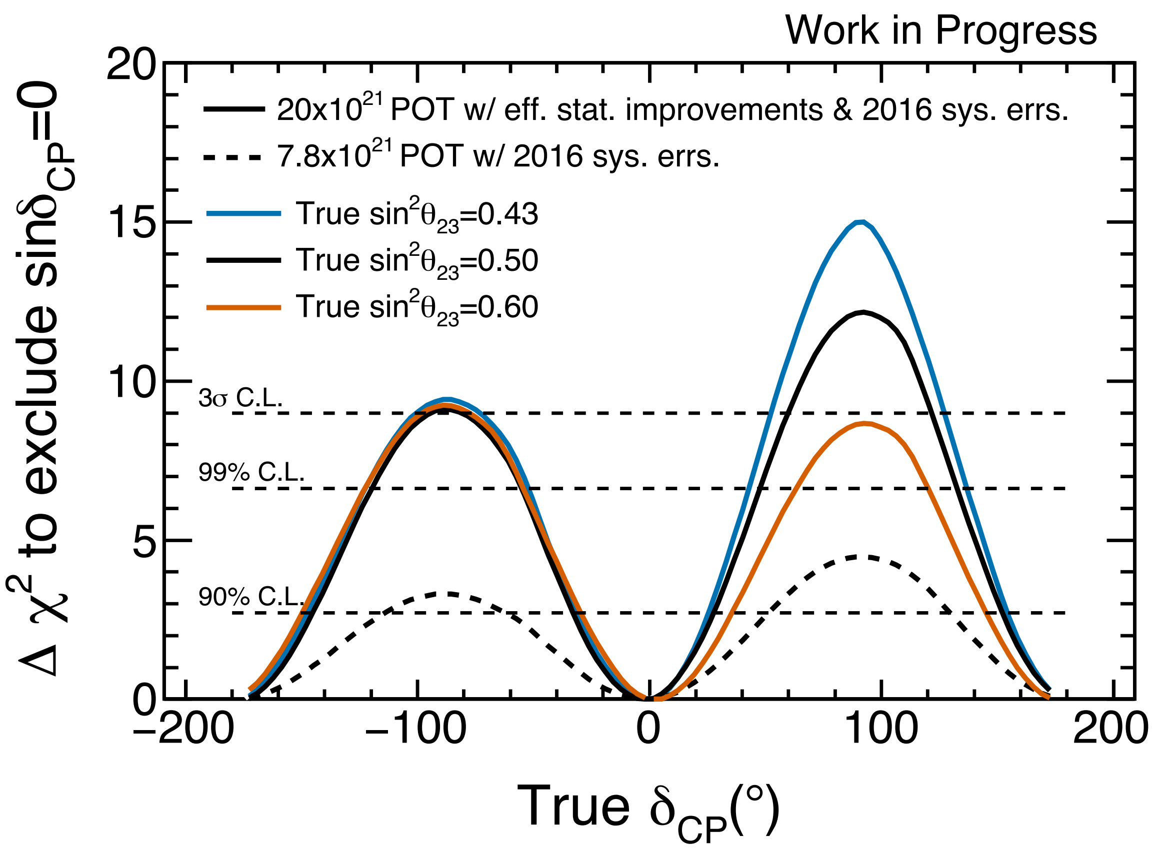


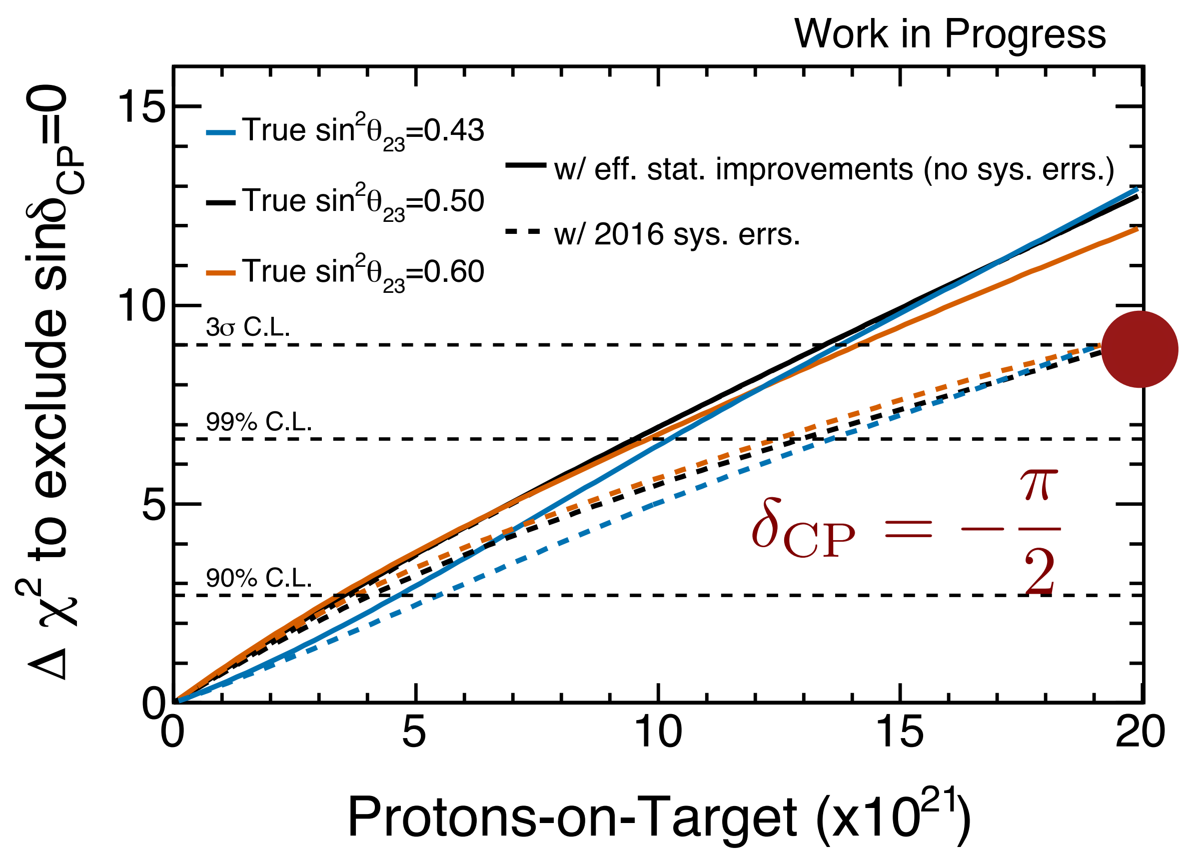
	True δ_{CP}	Total	Signal $\nu_\mu \to \nu_e$	Signal $\bar{\nu}_\mu \to \bar{\nu}_e$	Beam CC $\nu_e + \bar{\nu}_e$	Beam CC $\nu_\mu + \bar{\nu}_\mu$	NC
ν-mode	0	454.6	346.3	3.8	72.2	1.8	30.5
ν_e sample	$-\pi/2$	545.6	438.5	2.7	72.2	1.8	30.5
$\bar{\nu}$-mode	0	129.2	16.1	71.0	28.4	0.4	13.3
$\bar{\nu}_e$ sample	$-\pi/2$	111.8	19.2	50.5	28.4	0.4	13.3

T2K phase II ?

Assume known mass hierarchy (MH)
(baseline 295 km "too short")

Assumption: data-taking equally in ν-mode and $\bar{\nu}$-mode, known MH and reactor constraint used





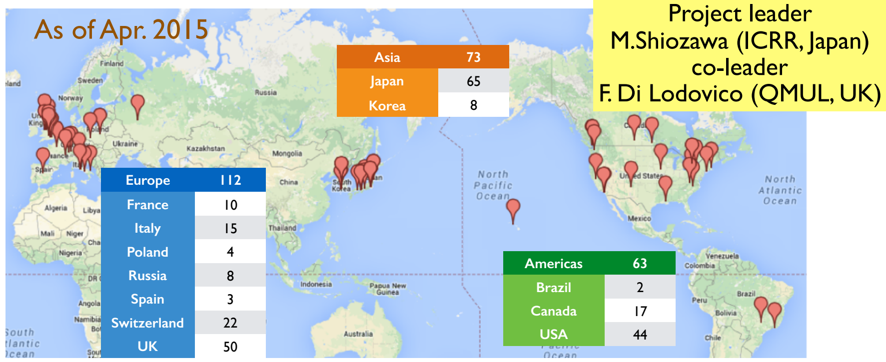
- ✧ 2016 work-in-progress systematic uncertainty is implemented
- ✧ ~ 3σ significance sensitivity to CP violation if δ_{CP}= - $\pi/2$
- ✧ 99% C.L. significance for more than 35% of the possible true values of δ_{CP}

HyperKamiokande

Data taking in 2026 ?

- 560 Kiloton Water Cherenkov Detector with a high intensity beam from J-PARC
- Multipurpose machine with all of the physics topics of Super-K and T2K, plus a few more
  - Solar and Supernova Neutrinos
  - Atmospheric Neutrinos
  - Nucleon Decay
  - Far detector for T2K

Hyper-K Proto-Collaboration



- Formed in Jan. 2015 as a step towards a full collaboration
- 13 countries, ~240 members and growing
- Governance structure has been defined
  - Active R&D ongoing over the world
  - Discussion on international contributions, task/cost sharing

R&D progress over the world

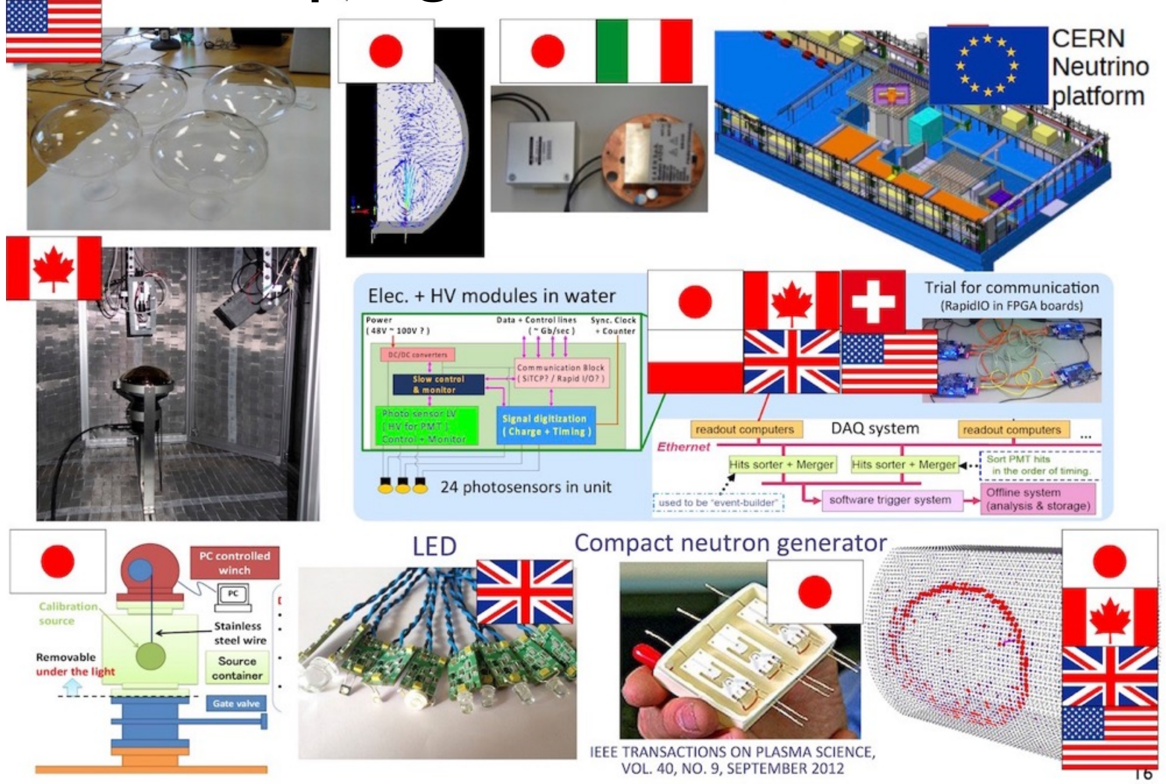
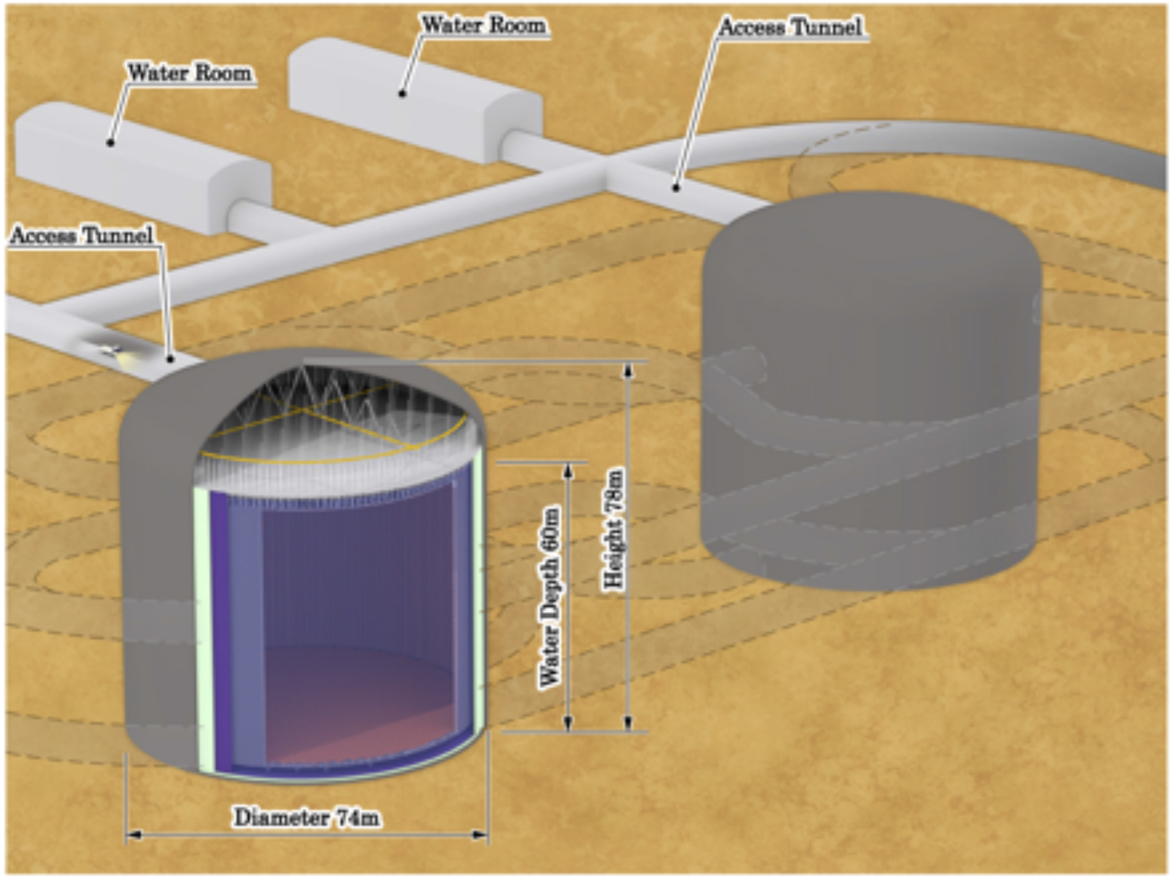


Photo-coverage 40%

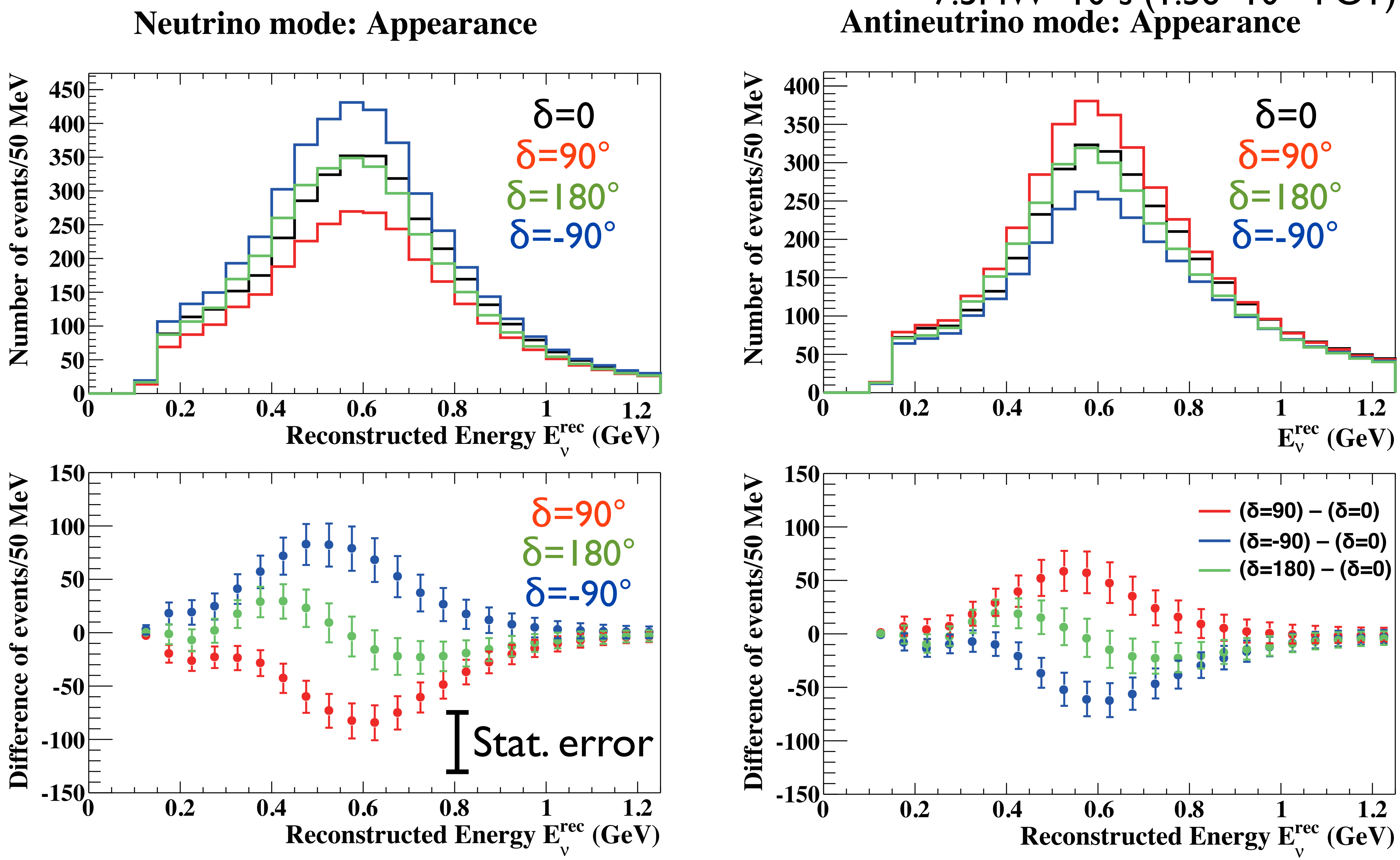


δ_{CP} dependence of observables

7.5MW×10^{7}s (1.56×10^{22} POT)

νe candidates

Difference from δ=0



Sensitive to all values of δ with numbers + energy spectrum shape

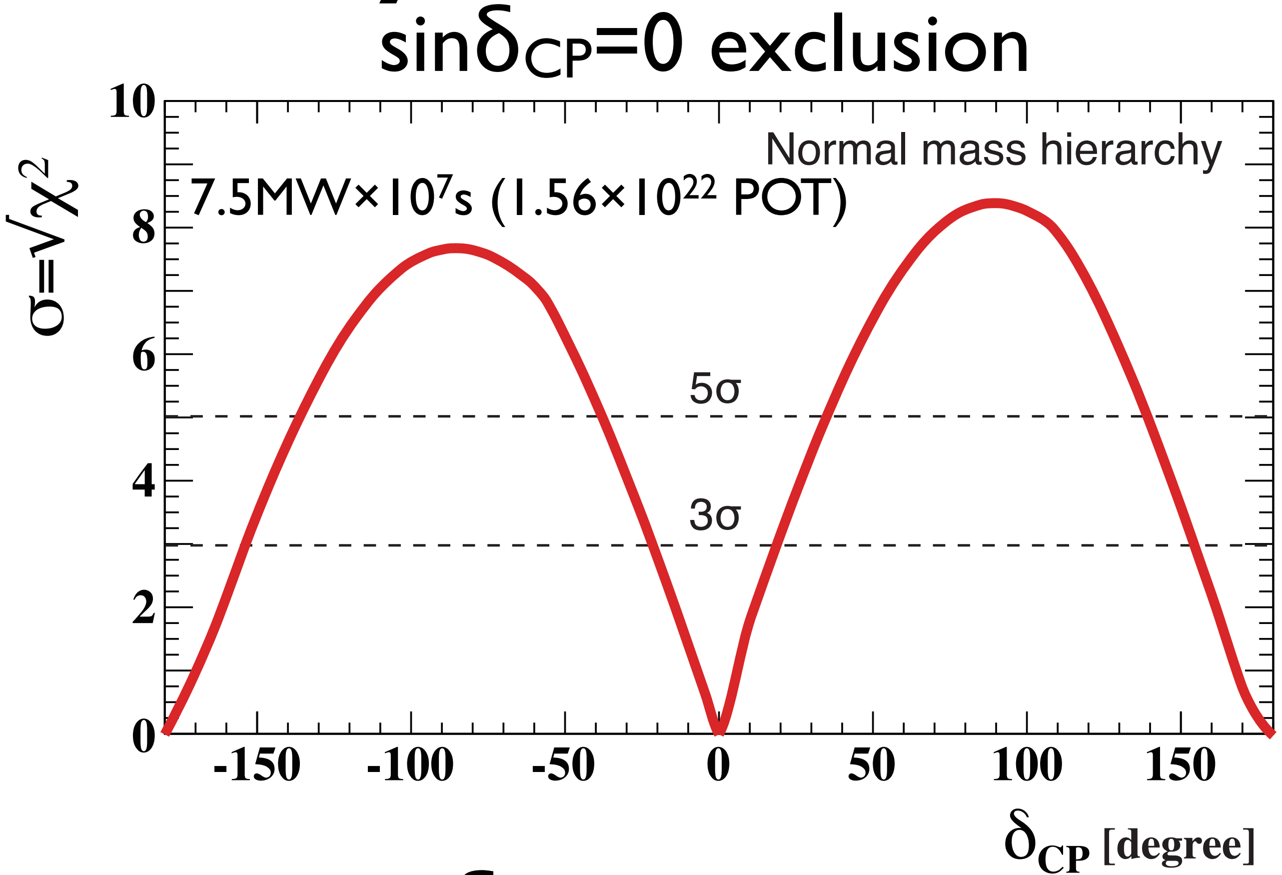
CPV sensitivity

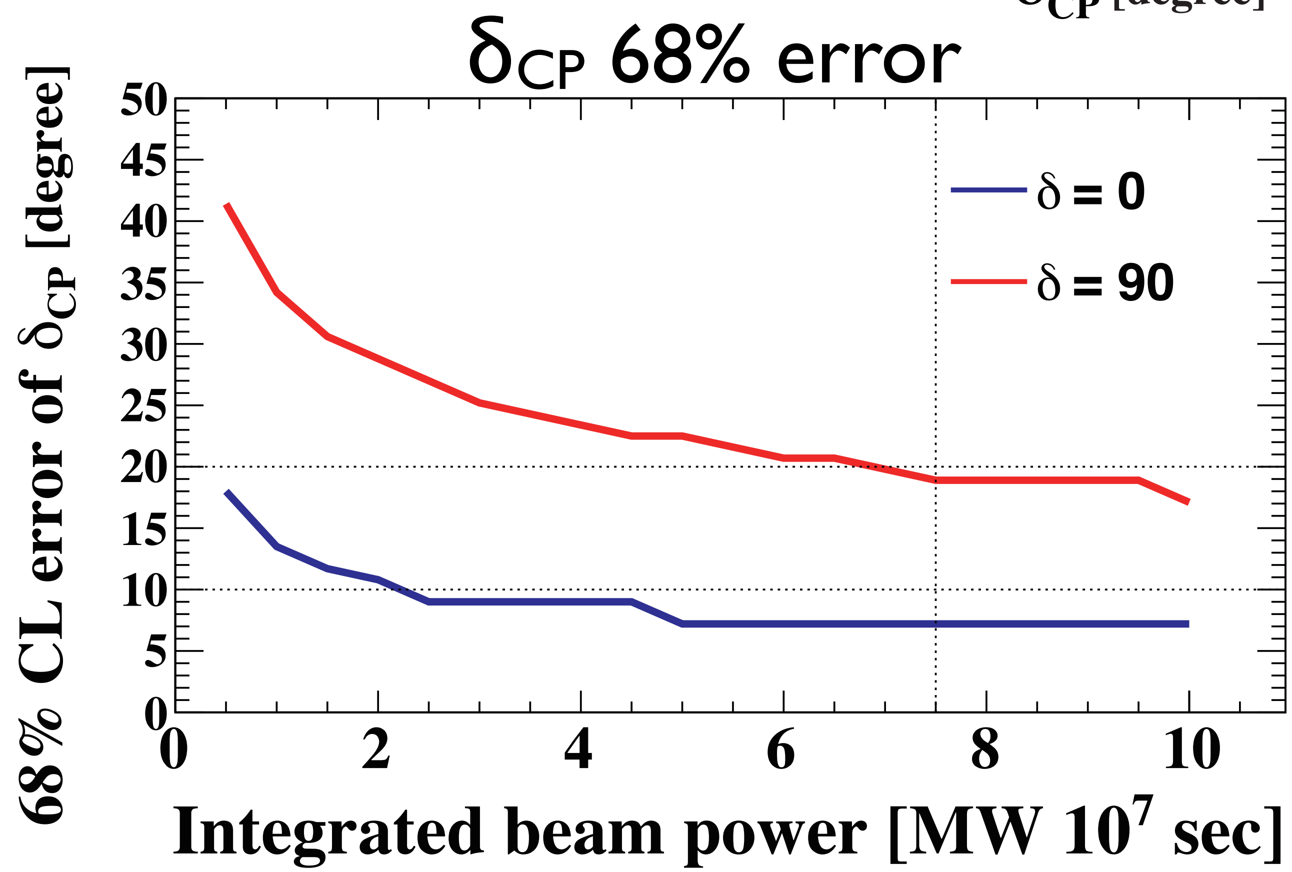
- Excellent sensitivity to CPV
  - >3σ for 78% of δ
  - >5σ for 56% of δ

- Based on a framework developed for T2K sensitivity study
  - Fit reconstructed E_ν distributions
  - Both ν_e and ν_μ samples, for ν and anti-ν run
  - Fit $\sin^2\theta_{23}$, Δm^2_{32}, $\sin^2 2\theta_{13}$, δ_{CP}
  - Assume known mass hierarchy (MH) (baseline 295 km "too short")

HK Fiducial volume = 560 kton
JPARC beam = 15.6×10^{21} pot

SK volume = 25 kton
JPARC beam = 7.8×10^{21} pot by 2020
(Runs 1-6 up to now 1.1×10^{21} pot)





International ν program hosted in USA

European Strategy for Particle Physics (2013):

CERN should develop a neutrino program to pave the way for a substantial European role in future long-baseline experiments. Europe should explore the possibility of major participation in leading long-baseline neutrino projects in the US and Japan.

Strategic USA «P5» report:

In collaboration with international partners, develop a coherent short- and long-baseline neutrino program hosted at Fermilab (LBNF).

Form a new international collaboration to design and execute a highly capable Long-Baseline Neutrino Facility (LBNF) hosted by the U.S.
To proceed, a project plan and identified resources must exist to meet the minimum requirements in the text. LBNF is the highest-priority large project in its timeframe.

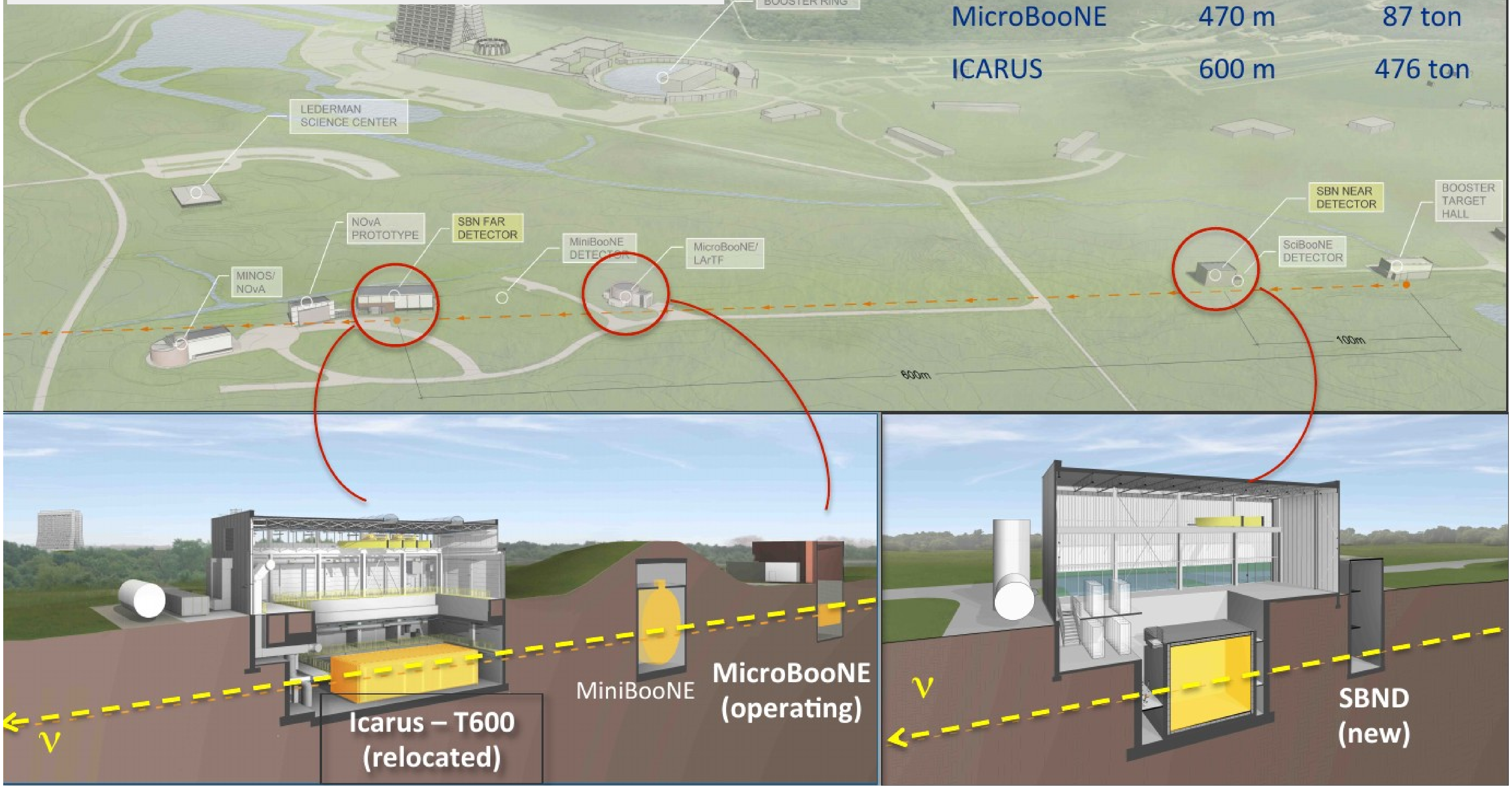
Select and perform in the short term a set of small-scale short-baseline experiments that can conclusively address experimental hints of physics beyond the three-neutrino paradigm. Some of these experiments should use liquid argon to advance the technology and build the international community for LBNF at Fermilab.

Short Baseline Program (SBN)

Data taking in 2018

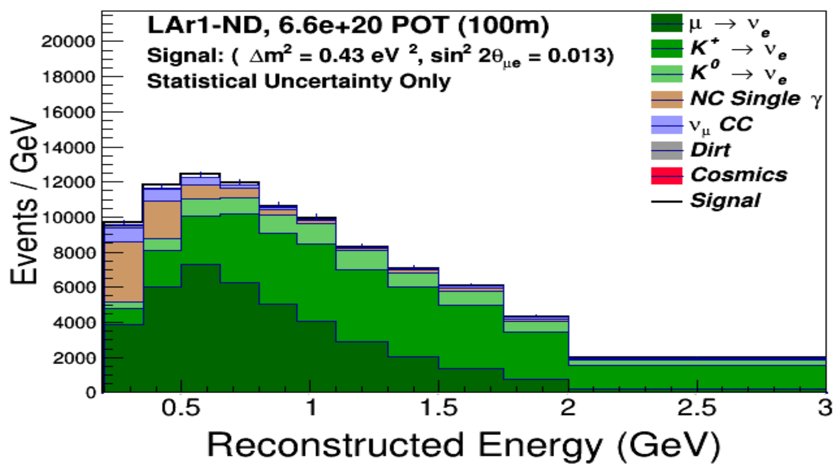
A Proposal for a Three Detector Short-Baseline Neutrino Oscillation Program in the Fermilab Booster Neutrino Beam
MicroBooNE and LAr1-ND and ICARUS-WA104 Collaborations
(M. Antonello (Gran Sasso) et al.). Mar 4, 2015. 209 pp.
e-Print: arXiv:1503.01520

Detector	Distance from BNB Target	Active LAr Mass
SBND	110 m	112 ton
MicroBooNE	470 m	87 ton
ICARUS	600 m	476 ton

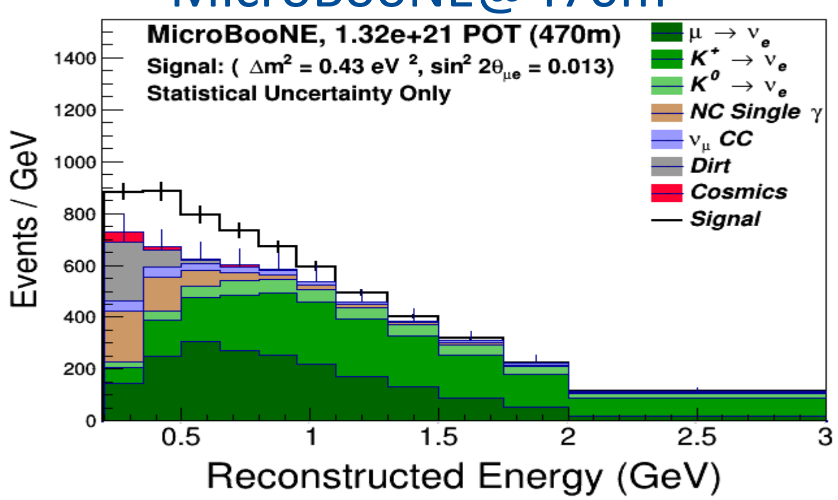


Sensitivity to test LSND

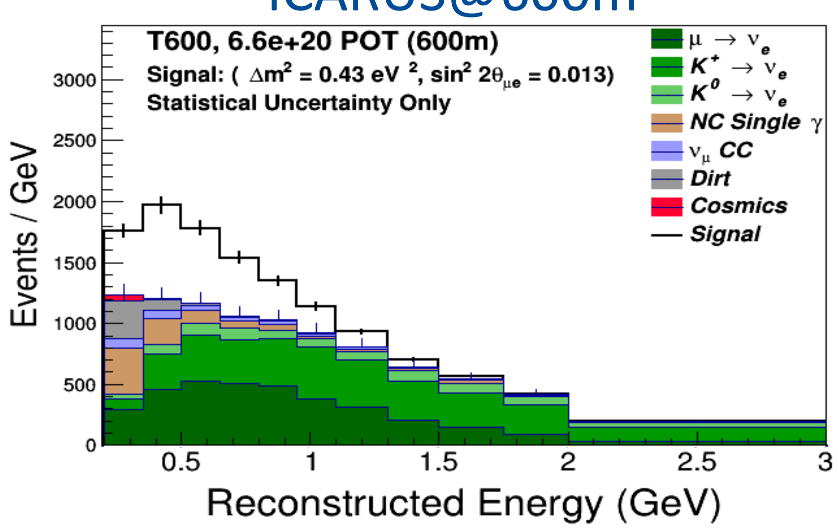
SBND@110m



MicroBooNE@470m

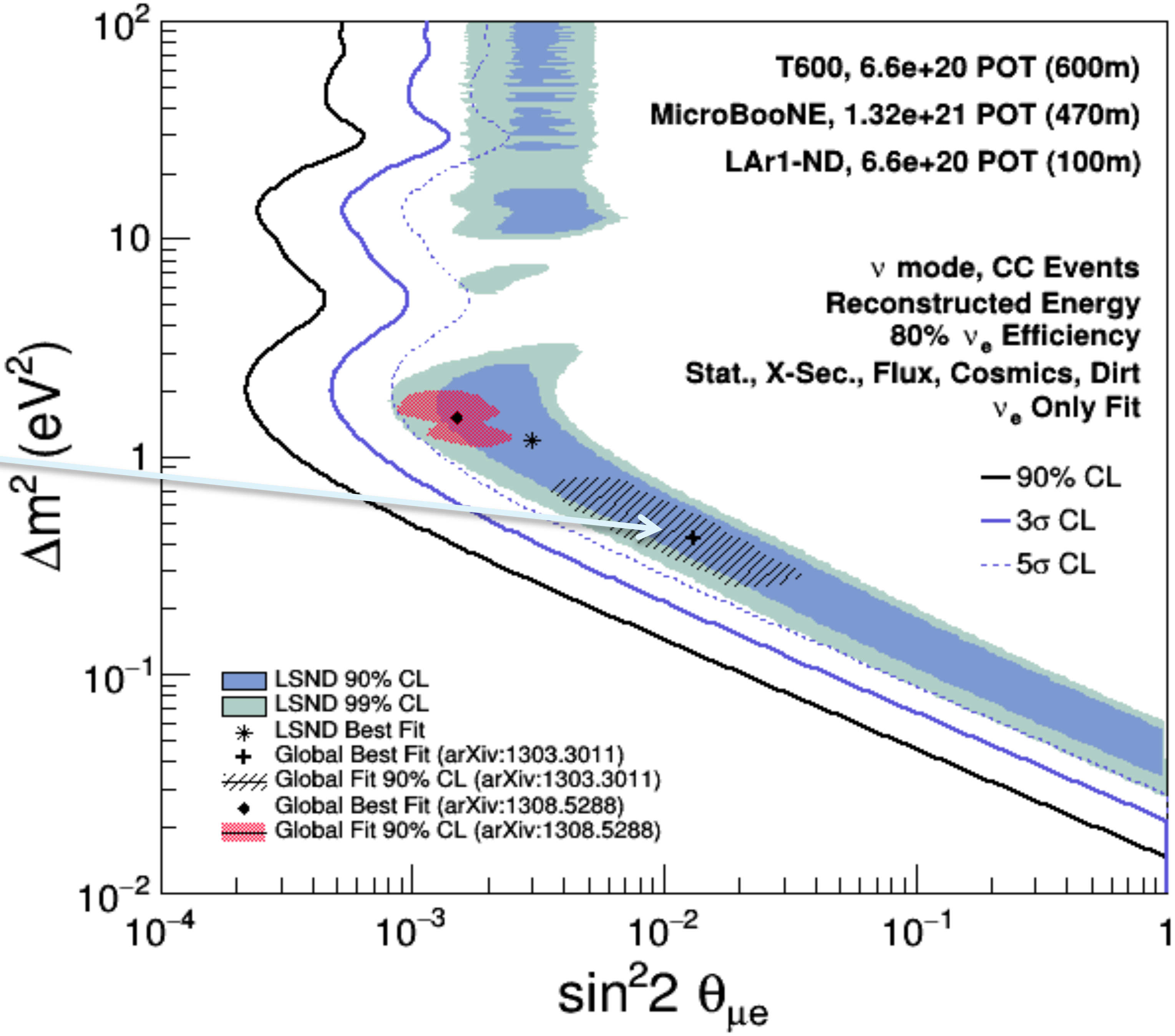


ICARUS@600m



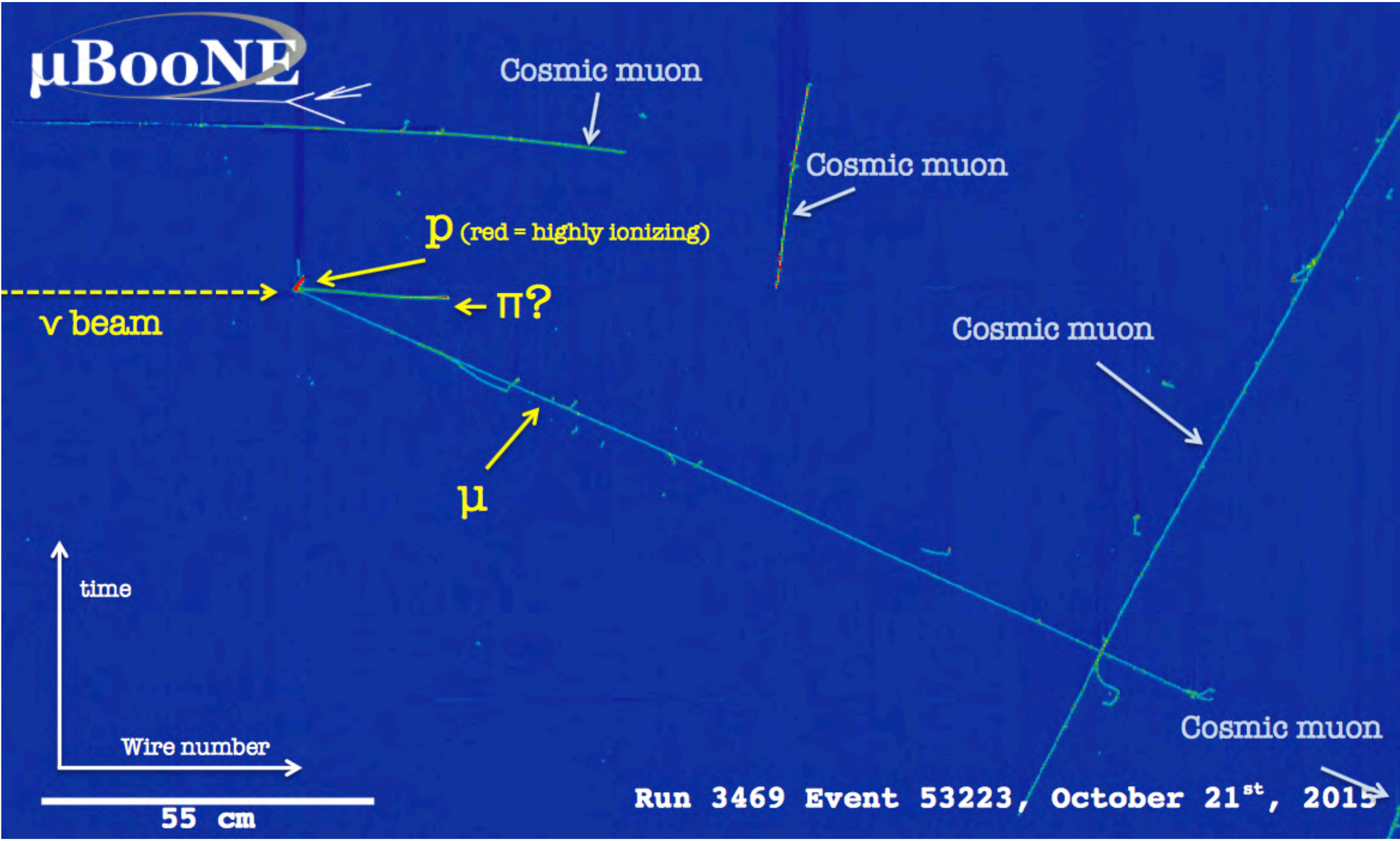
Example event dist. Δm^2=0.43eV^2 , $\sin^2 2\theta_{\mu e}$=0.013

~5σ coverage of LSND 99% CL Region for 6.6x10^{20} P.O.T. ~ 3 years (13.2x10^{20} for MicroBooNE)

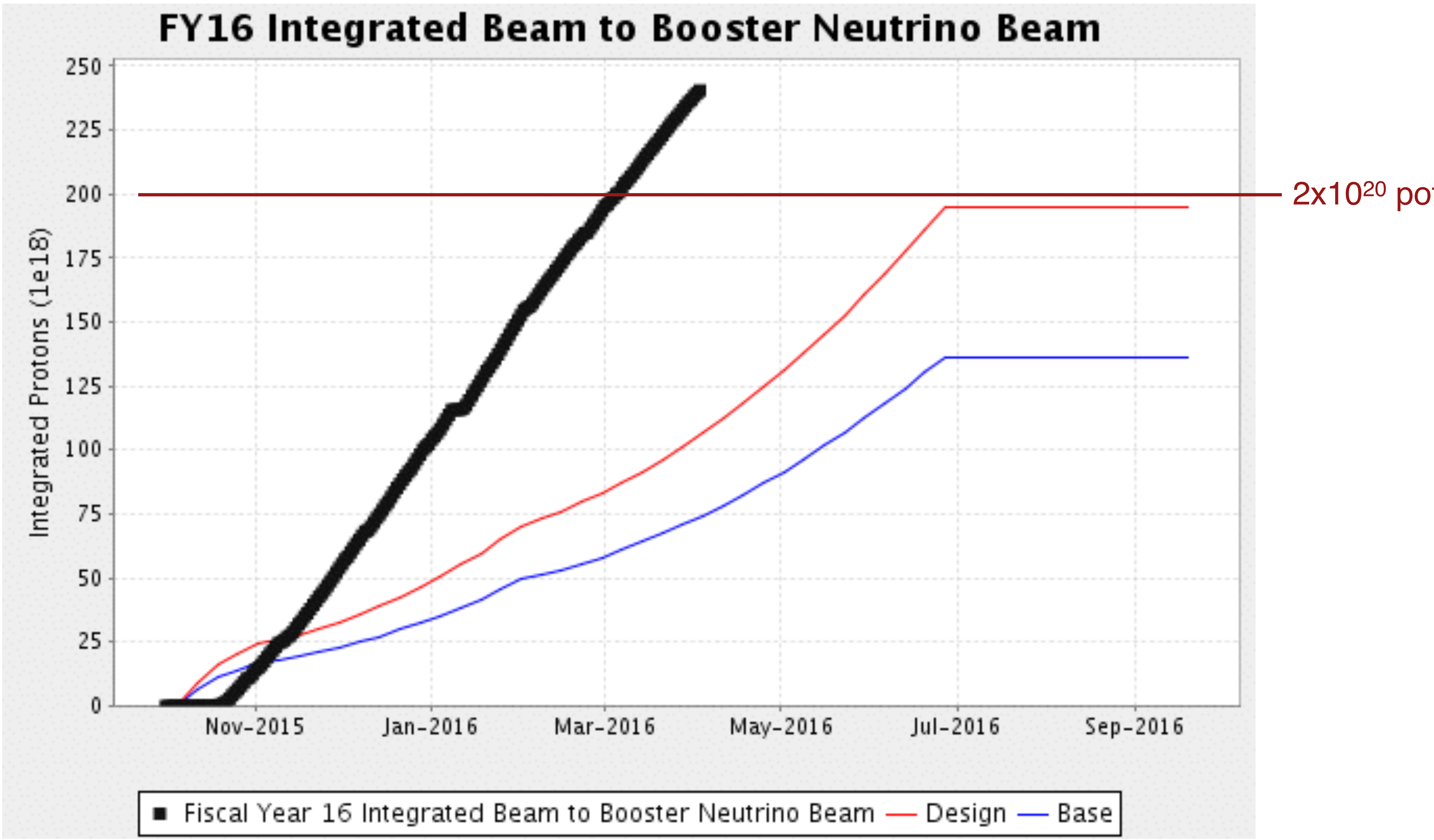


Neutrino candidate

MicroBooNE in operation



FNAL/Booster neutrinos

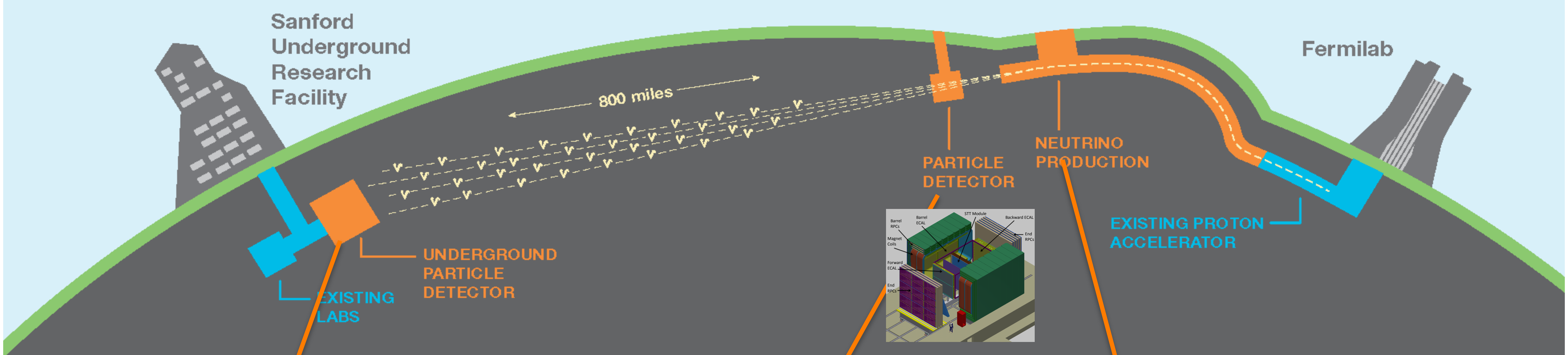


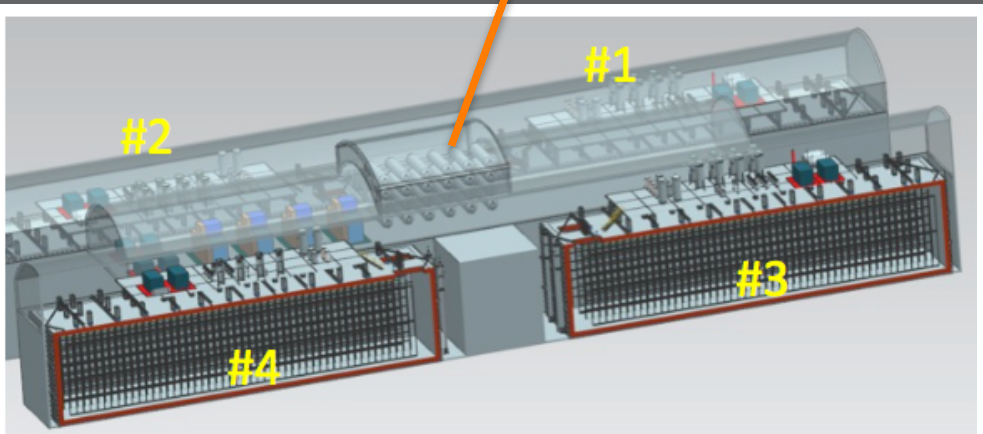
MicroBooNE collecting data (more than design)
First results expected within 2016

LBNF/DUNE

Data taking in 2026 ?

"Long-Baseline Neutrino Facility (LBNF) and Deep Underground Neutrino Experiment (DUNE) Conceptual Design Report Volume 2: The Physics Program for DUNE at LBNF" (arXiv:1512.06148)





high precision
near detector complex

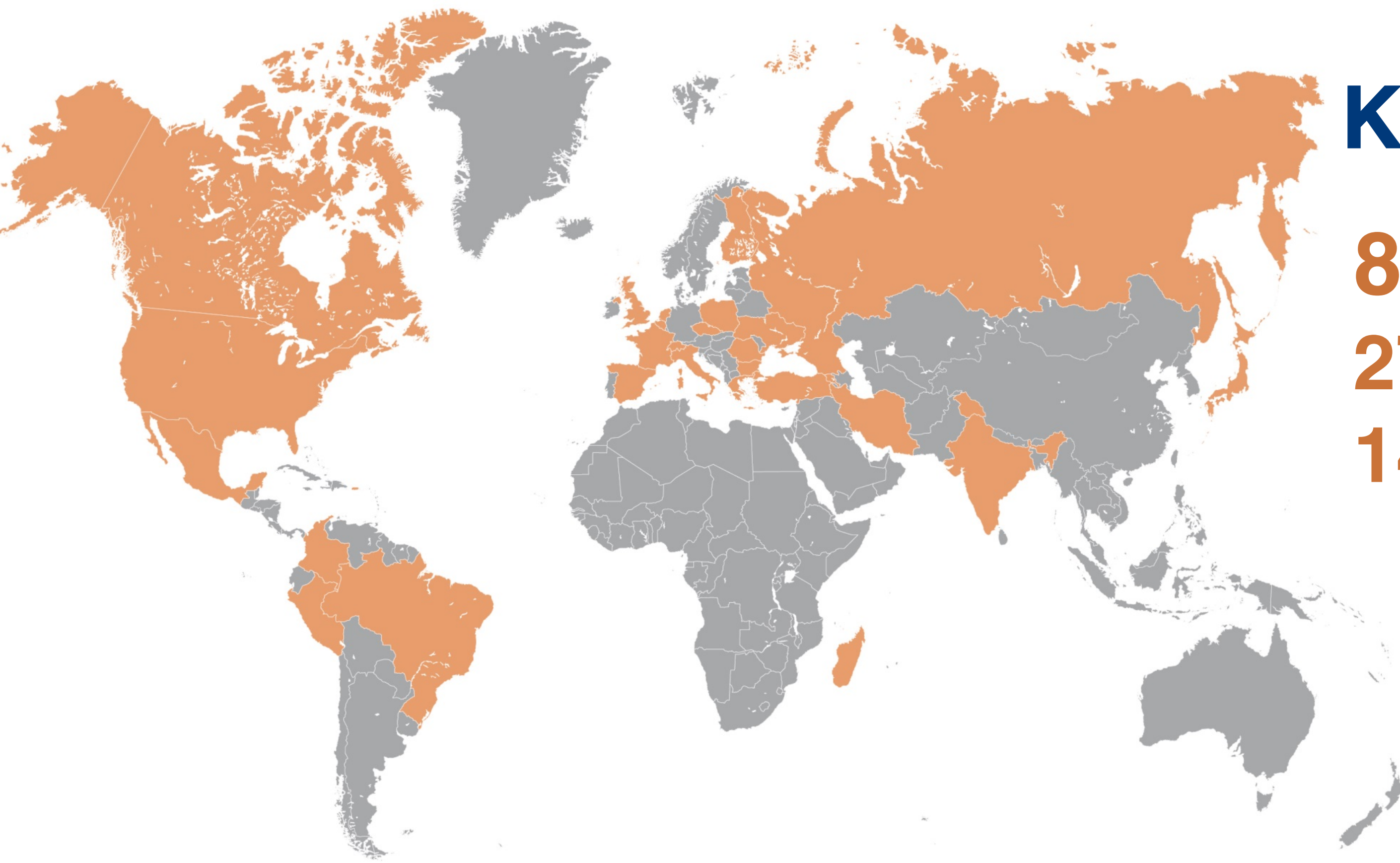
Wide band, high purity ν_μ beam with peak flux at 2.5 GeV operating at $\sim$1.2 MW and upgradeable

- four identical cryostats deep underground
- staged approach to four independent 10 kt LAr detector modules
- Single-phase and double-phase readout under consideration

"Conceptual Design Report Volume 4: The DUNE Detectors at LBNF" (arXiv:1601.02984)

The DUNE Collaboration

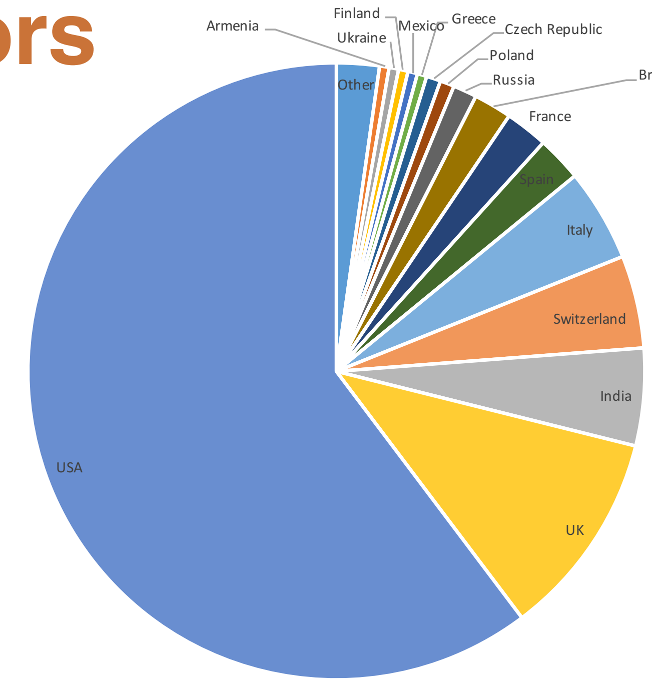
DEEP UNDERGROUND NEUTRINO EXPERIMENT



Keeps growing:

805 Collaborators
27 Nations
146 institutions

Greece and Finland recently joined



Armenia Yerevan Inst. for Theoretical Physics and Modeling
Belgium Univ. de Liege
Brazil Univ. Federal do ABC; Univ. Federal de Alfenas em Poços de Caldas; Univ. de Campinas; Univ. Estadual de Feira de Santana; Univ. Federal de Goias; Observatorio Nacional
Bulgaria Univ. of Sofia
Canada York University
Colombia Univ. del Atlantico
Czech Republic Charles University, Prague; Czech Technical University, Prague; Institute of Physics ASCR, Prague
France Lab. d'Annecy-le-Vieux de Phys. des Particules; Inst. de Physique Nucleaire de Lvon: APC-Paris: CEA/Sacla
Finland Jyväskylä
Greece Athens
India Aligarh Muslim University; Banaras Hindu University; Bhabha Atomic Research Center; Univ. of Delhi; Indian Inst. of Technology, Guwahati; Harish-Chandra Research Institute; Indian Inst. of Technology, Hyderabad; Univ. of Hyderabad; Univ. of Jammu; Jawaharlal Nehru University; Koneru Lakshmaiah; Univ. of Lucknow; Panjab University; Punjab Agri. University; Variable Energy Cyclotron Centre
Iran Inst. for Research in Fundamental Sciences
Italy Lab. Nazionali del Gran Sasso, Assergi; Univ. di Catania; Gran Sasso Science Institute; Univ. di Milano; INFN Sezione di Milano Bicocca; INFN Sezione di Napoli; Univ. of Padova; Univ. of Pavia, INFN Sezione di Pavia; CNI Pisa; Univ. di Pisa
Japan KEK; Kavli IPMU, Univ. of Tokyo
Madagascar Univ. of Antananarivo
Mexico Univ. de Colima; CINVESTAV
Netherlands NIKHEF
Peru PUCP
Poland Inst. of Nuclear Physics, Krakow; National Centre for Nuclear Research, Warsaw; Univ. of Warsaw; Wroclaw University
Romania Horia Hulubei National Institute
Russia Inst. for Nuclear Research, Moscow
Spain Inst. de Fisica d'Altas Energias, Barcelona; CIEMAT; Inst. de Fisica Corpuscular, Madrid
Switzerland Univ. of Bern; CERN; ETH Zurich
Turkey TUBITAK Space Technologies Research Institute
Ukraine Kyiv National University
United Kingdom Univ. of Cambridge; Univ. of Durham; Univ. of Huddersfield; Imperial College of Science, Tech. & Medicine; Lancaster University; Univ. of Liverpool; University College London; Univ. of Manchester; Univ. of Oxford; STFC Rutherford Appleton Laboratory; Univ. of Sheffield; Univ. of Sussex; Univ. of Warwick
USA Univ. of Alabama; Argonne National Lab; Boston University; Brookhaven National Lab; Univ. of California, Berkeley; Univ. of California, Davis; Univ. of California, Irvine; Univ. of California, Los Angeles; California Inst. of Technology; Univ. of Chicago; Univ. of Cincinnati; Univ. of Colorado; Colorado State University; Columbia University; Cornell University; Dakota State University; Drexel University; Duke University; Fermi National Accelerator Lab; Univ. of Hawaii; Univ. of Houston; Idaho State University; Illinois Institute of Technology; Indiana University; Iowa State University; Kansas State University; Lawrence Berkeley National Lab; Los Alamos National Lab; Louisiana State University; Univ. of Maryland; Massachusetts Institute of Technology; Michigan State University; Univ. of Minnesota; Univ. of Minnesota (Duluth); Univ. of New Mexico; Northwestern University; Univ. of Notre Dame; Ohio State University; Oregon State University; Pacific Northwest National Lab; Univ. of Pennsylvania; Pennsylvania State University; Univ. of Pittsburgh; Princeton University; Univ. of Puerto Rico; Univ. of Rochester; SLAC National Accelerator Lab; Univ. of South Carolina; Univ. of South Dakota; South Dakota School of Mines and Technology; South Dakota Science And Technology Authority; South Dakota State University; Southern Methodist University; Stanford University; Stony Brook University; Syracuse University; Univ. of Tennessee; Univ. of Texas at Arlington; Univ. of Texas at Austin; Tufts University; Virginia Tech; Wichita State University; College of William and Mary; Univ. of Wisconsin; Yale University

What is DUNE ?

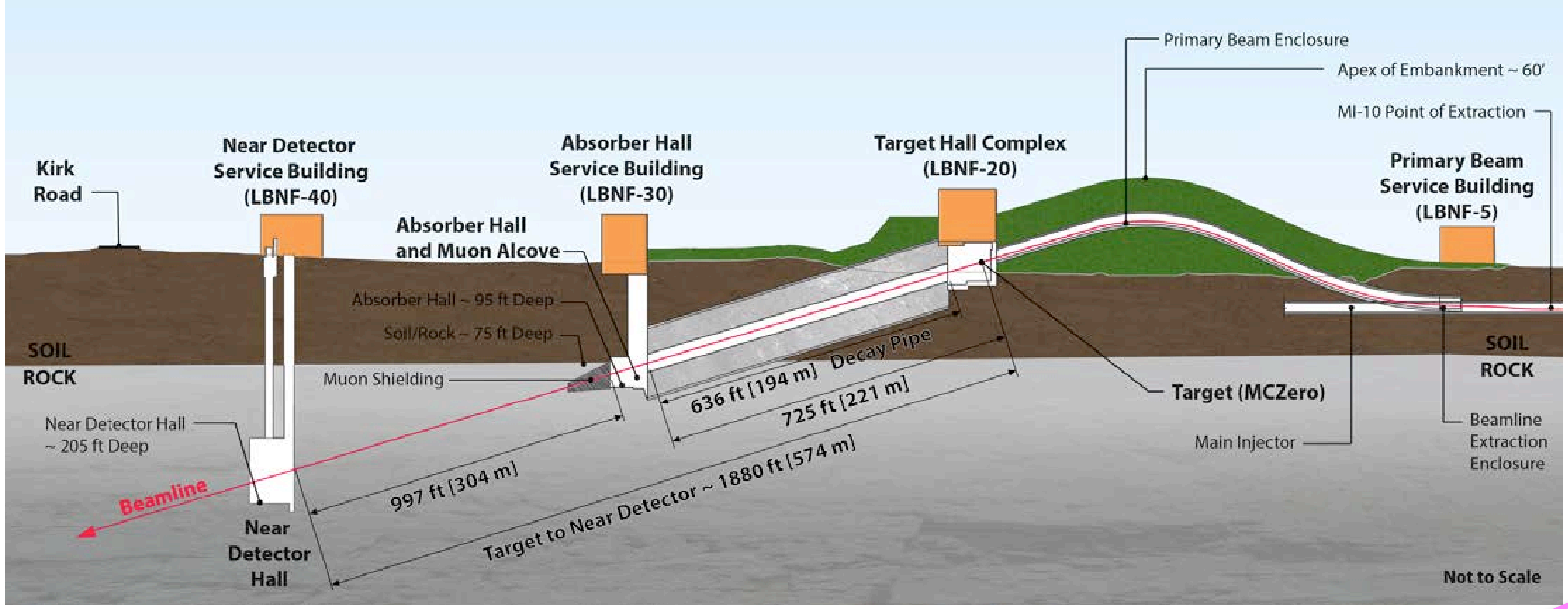
A rapidly evolving international scientific collaboration merging strengths and expertise from all previous efforts (LBNE, LBNO, others), built around the organisation model successfully implemented at the LHC

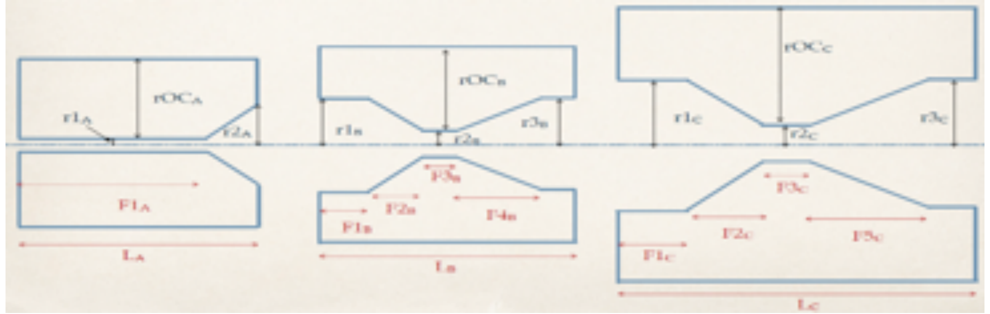
- **First formal collaboration meeting April 16^{th} - 18^{th} 2015**
- **Conceptual Design Report (4 volumes) June 2015**
- **Passed DOE CD-1 Review July 2015**
- **Second collaboration meeting September 2^{nd} - 5^{th} 2015**
- **DOE CD-3a Review December 2015 → CD3a will trigger FS excavation**
- **Third collaboration meeting UTA, Texas January 12^{th} - 15^{th} 2016**
- **Fourth collaboration meeting SDSMT, South Dakota May 2016**
- **Collaboration meetings at FNAL (Sep 16) & CERN (Jan 2017)**

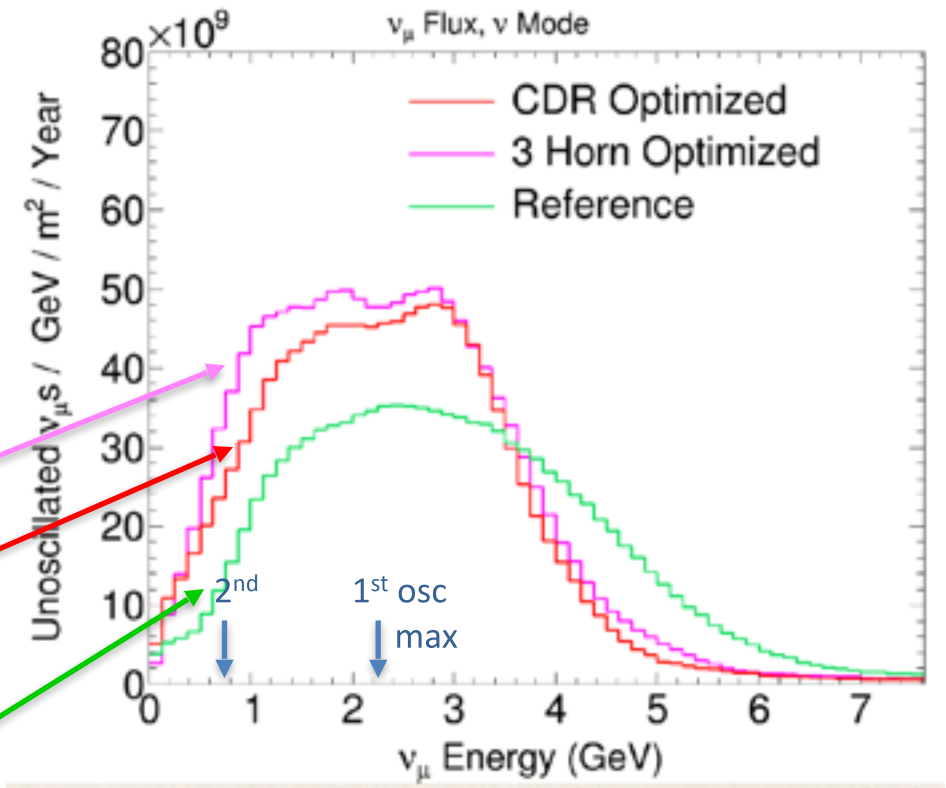
Photo taken during 2nd Collaboration meeting

LBNF neutrino beam

- **Primary 60-120 GeV proton beam** extracted from FNAL Main Injector
- Initial ≈**1.2 MW beam power** upgradable to ≈**2.4 MW** utilising improvements from PIP-II
- **Near detector hall @ 574 m**
- Fermilab-based design with input and ideas from the full international DUNE Collaboration







3-horn system,
CDR "Optimized" Design,
and the well-known NuMI-like Reference Design

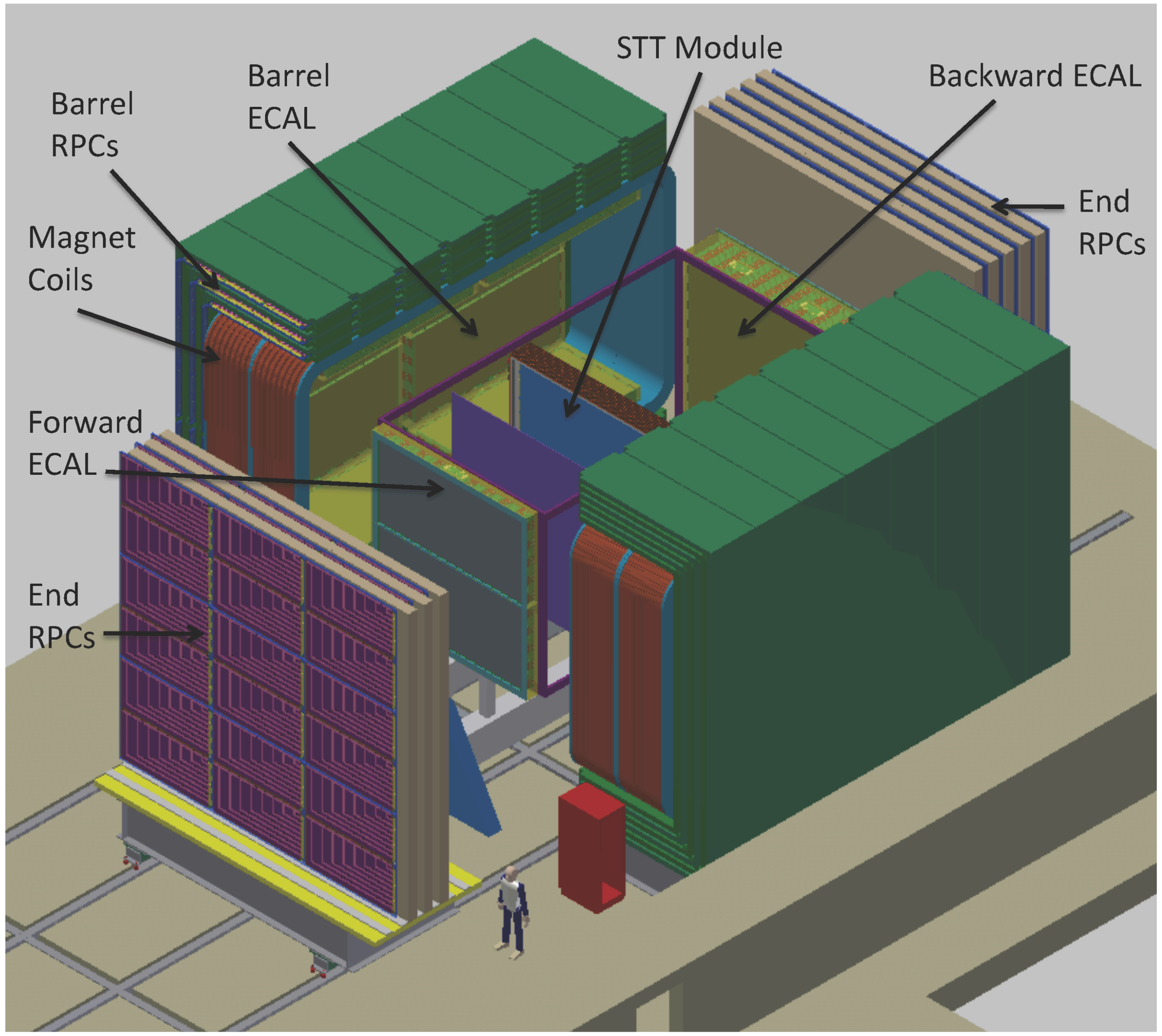
Neutrino energy (GeV)

➡ CP sensitivity optimisation maximises lower energies

DUNE Near Detector

The near detector will measure
- CC ν_μ events (normalization and energy spectrum)
- CC ν_e and NC pi0 (backgrounds)
- Neutrino interaction properties

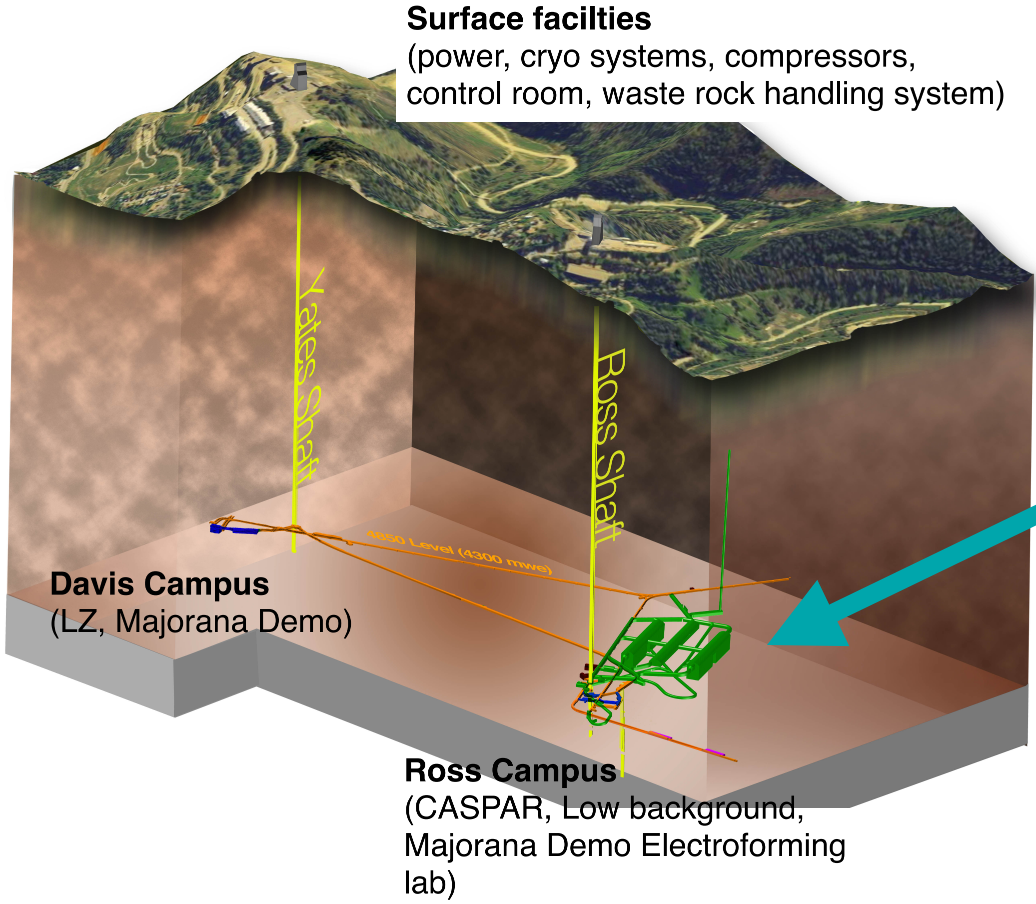
10^7 interactions per year - high precision!



Reference design
- Fine grained tracker inside 0.4T magnetic field (straw tubes)
- Lead-scintillator ECAL
- RPC muon tracker

Other designs under consideration
- Magnetized LArTPC
- High Pressure GArTPC

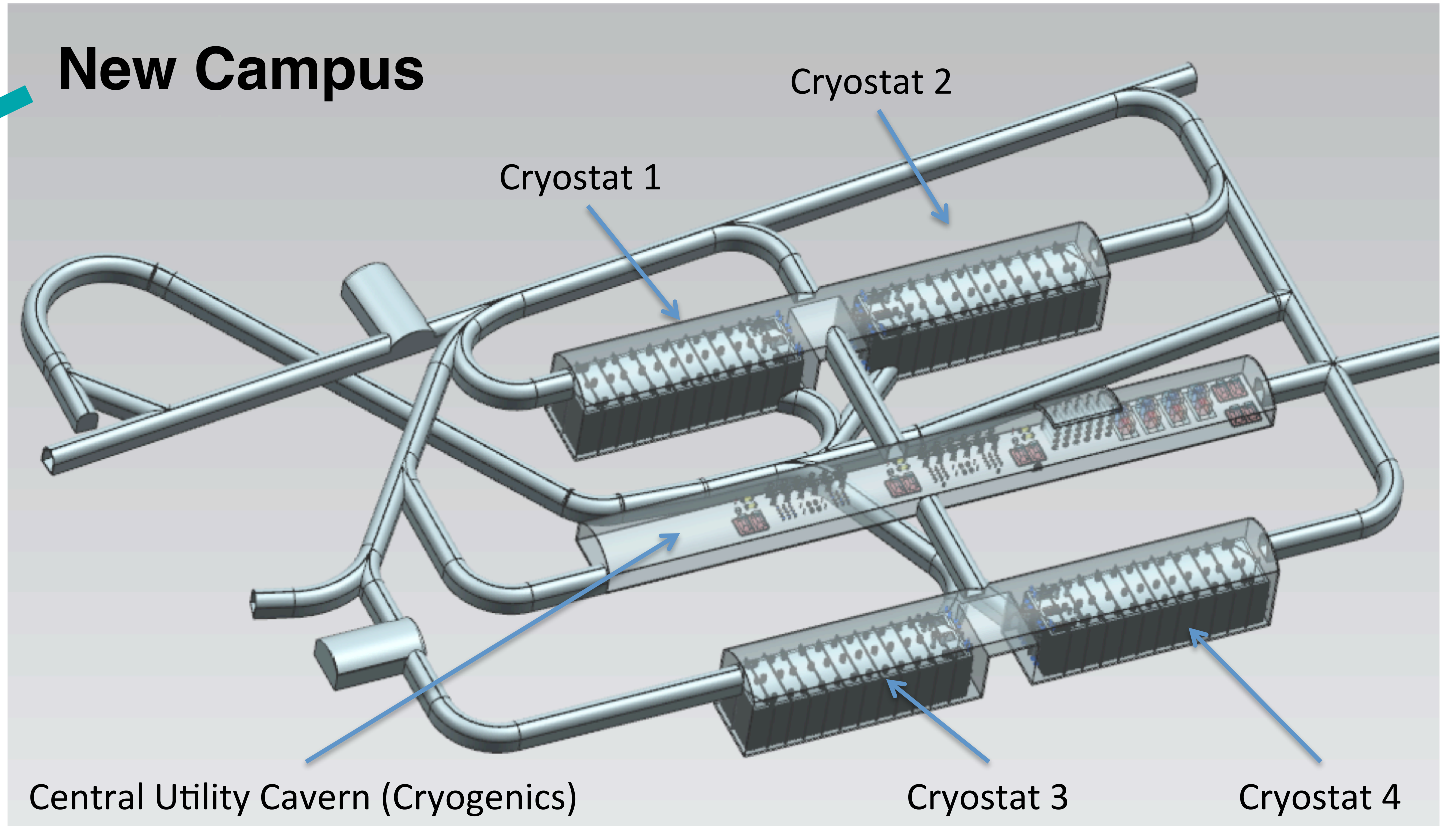
LBNF/DUNE Far Site @ SURF



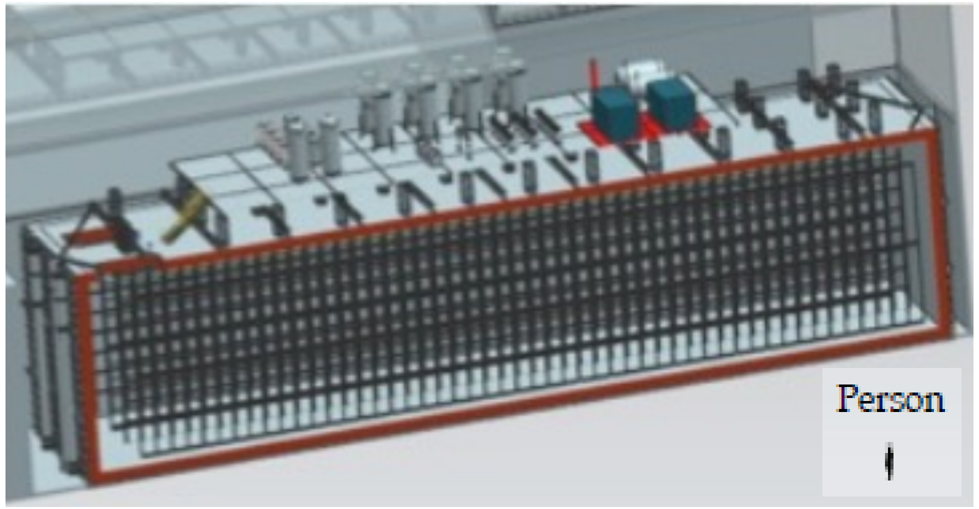
Sanford Underground Research Facility

http://sanfordlab.org

4850L Facilities (4300 mwe)



- Two parallel caverns each with two 10 kton detectors
- Separate cavern for utilities and cryogenics
- Four membrane tanks each 62m(L) x 14m(w) x 15m(h) with steel-frame exoskeleton designed by CERN
- Cryogenic system (w/ LAr purification) designed by joint FNAL and CERN
- Four independent and not necessary exactly identical 10 kton fiducial LAr TPCs. Two operating by 2026.



ETH Eidgenössische Technische Hochschule Zürich Swiss Federal Institute of Technology Zurich

DUNE Far Detector choice

Far detector is a 40 kt (fiducial mass) liquid argon TPC, a design optimized for:

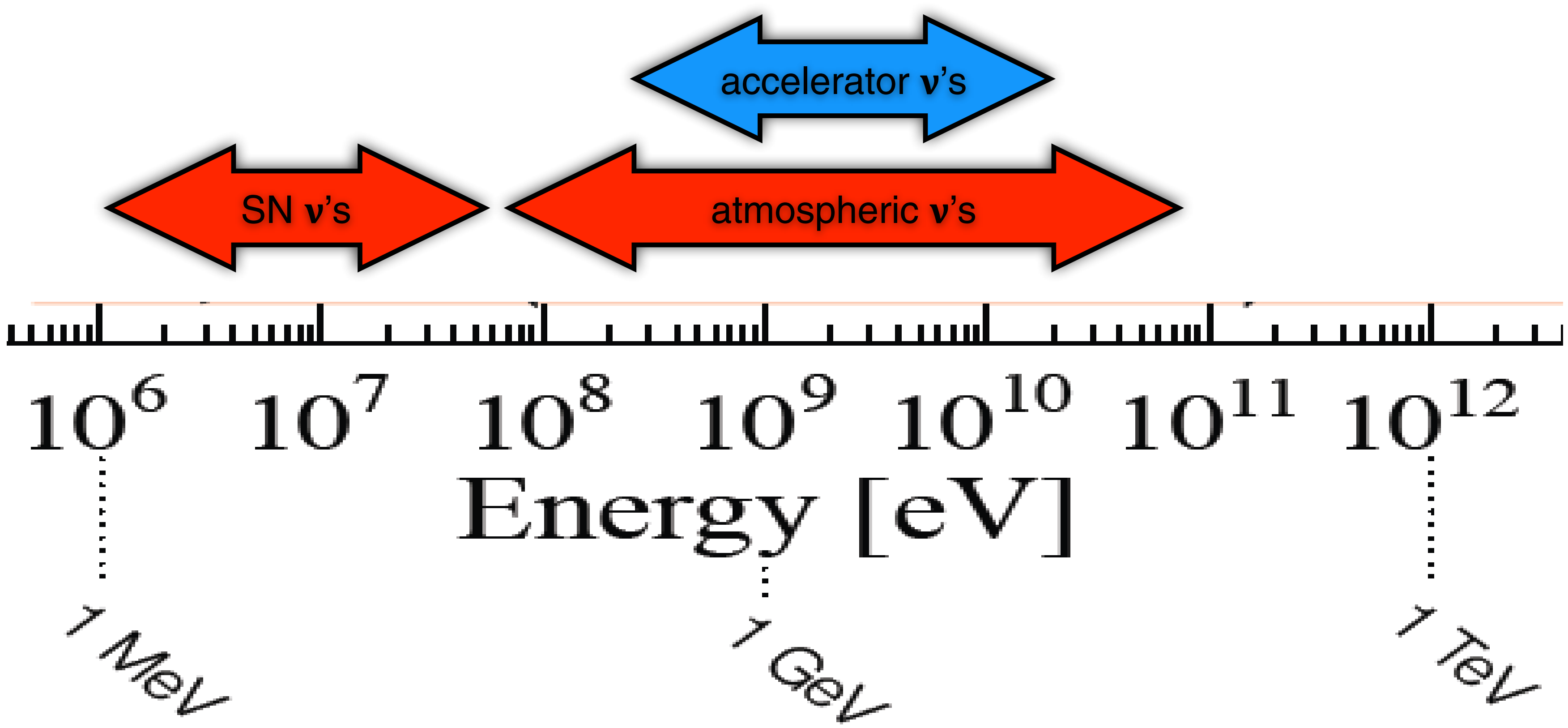
- Pattern recognition
- Energy measurement
- Particle ID

in energy range: few MeV – few GeV

LBNE
LBNO
→ **LAr-TPC**

LAr-TPC Far Detector technology gives:

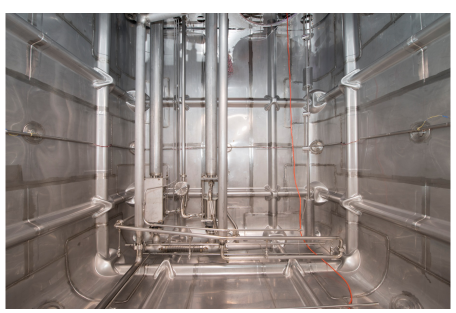
- Exquisite imaging capability in 3D
  - ~ few mm scale over large volume detector
- Excellent energy measurement capability:
  - totally active calorimeter
- Particle ID by dE/dx, range, event topology ,….



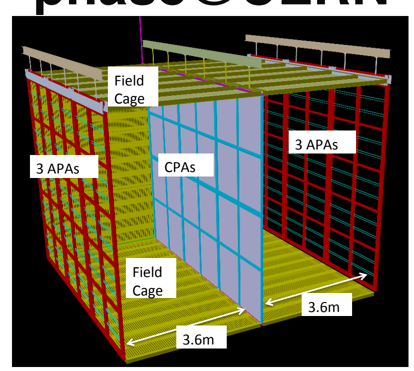
Far Detector Prototyping Program

- Basic technology demonstrated by ICARUS, ArgoNEUT/LArIAT, MicroBooNE, WA105 but **DUNE scale is very different** (each module is 40x ICARUS) and different in many details → **need strong prototyping**
- DUNE has well-developed plans for a series of detector prototypes that will provide input to the process leading to the final design(s) for the DUNE far detector modules.
- **ProtoDUNE single- and dual-phase 300 tons prototypes to operate in 2018.**

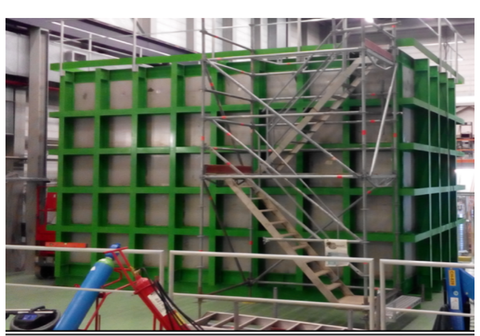
35T @ FNAL



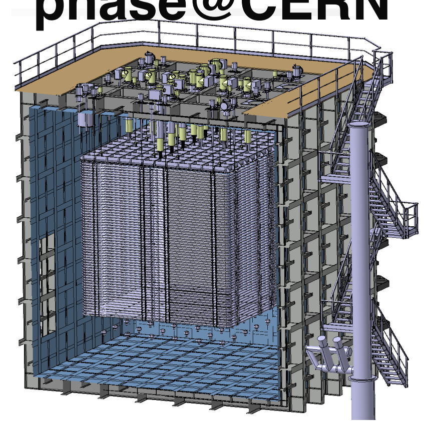
protoDUNE single phase@CERN



WA105 3x1x1@CERN

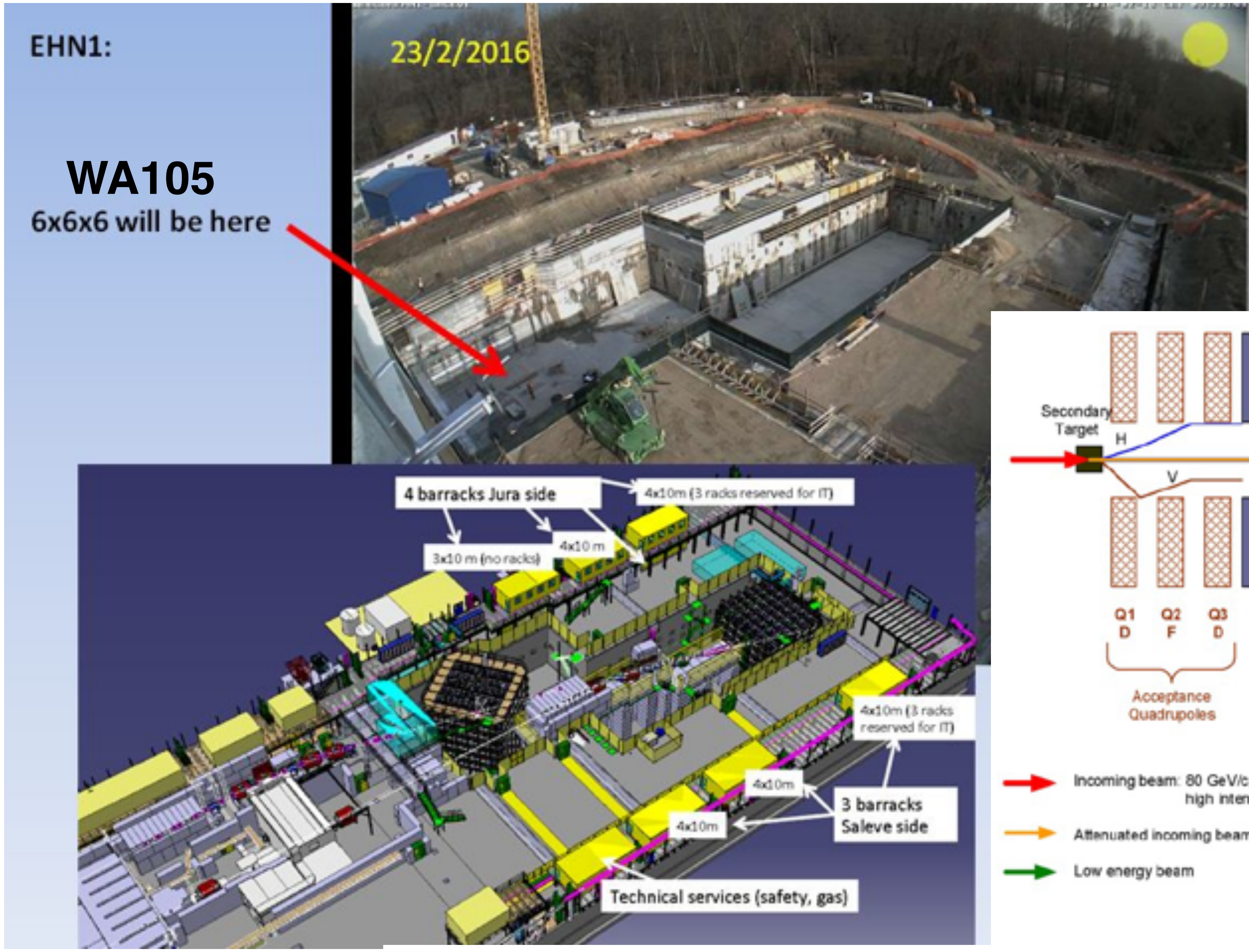


protoDUNE dual phase@CERN



- *Mitigation of risks associated with current detector designs*
- *Establishment of construction facilities required for full-scale production of detector components*
- *Early detection of potential issues with construction methods and detector performance*
- *Provide required calibration of detector response to particle interactions in charged particle test beams*

CERN EHN1 test beam extension



Ready for Data taking in spring 2018

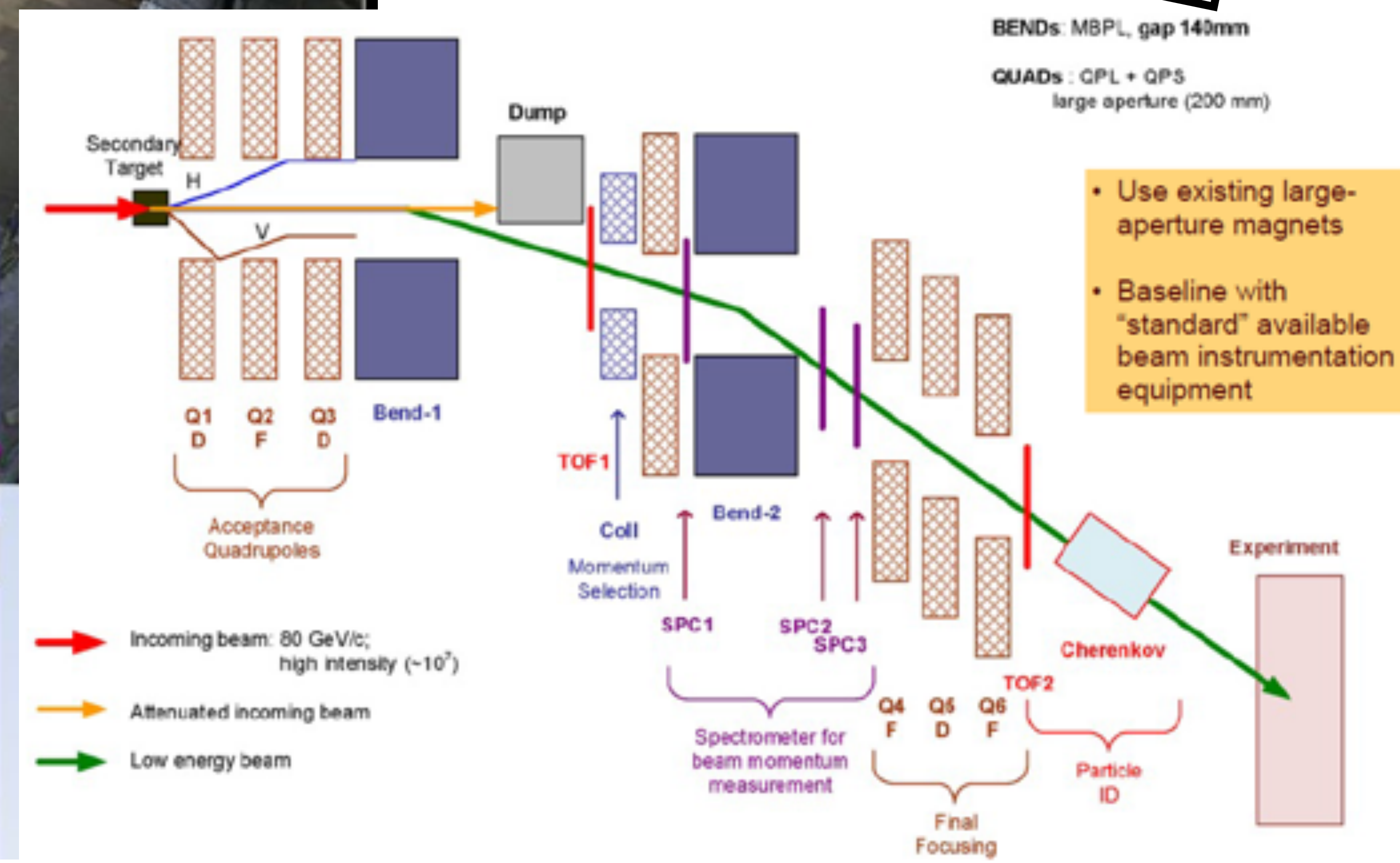


TABLE XIX: *Requirements for particles and their momenta. The particle rate here is the rate within a spill, regardless of the spill length, slow extraction is assumed.*

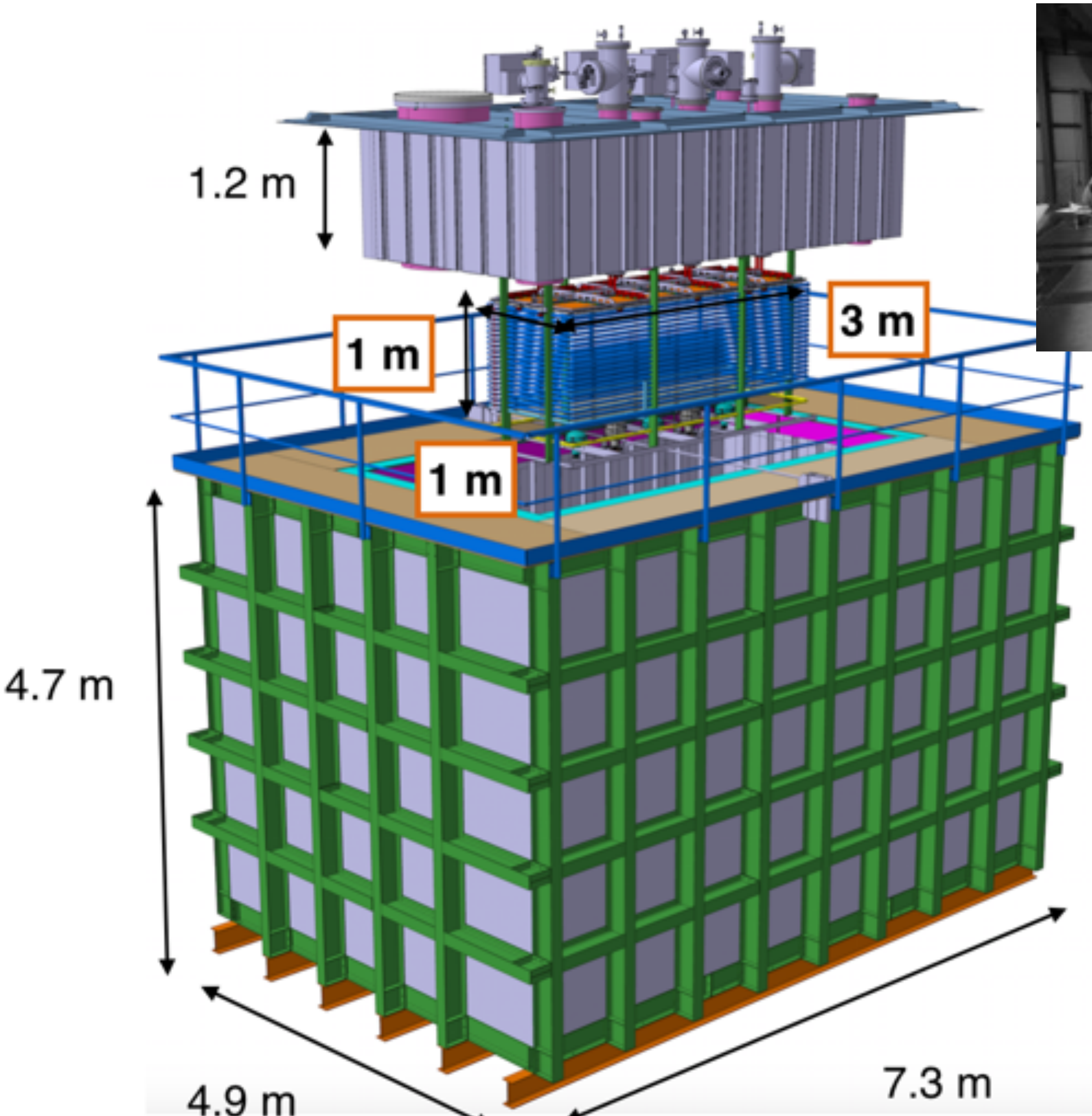
Type	Momentum [GeV/c]	Rate [kHz]	Total	Time est. [hrs]
Muon tracks				
$\mu^{+/-}$	0.8, 1.0, 1.5, 2.0, 5.0, 10.0, 20.0	0.1	$5\times10^6\times14$	200
Shower reconstruction				
$\pi^{+/-}$	0.5, 0.7, 1.0, 2.0, 5.0, 10.0, 20.0	0.1	$5\times10^6\times14$	200
e	0.5, 0.7, 1.0, 2.0, 5.0, 10., 20.0	0.1	$5\times10^6\times7$	100

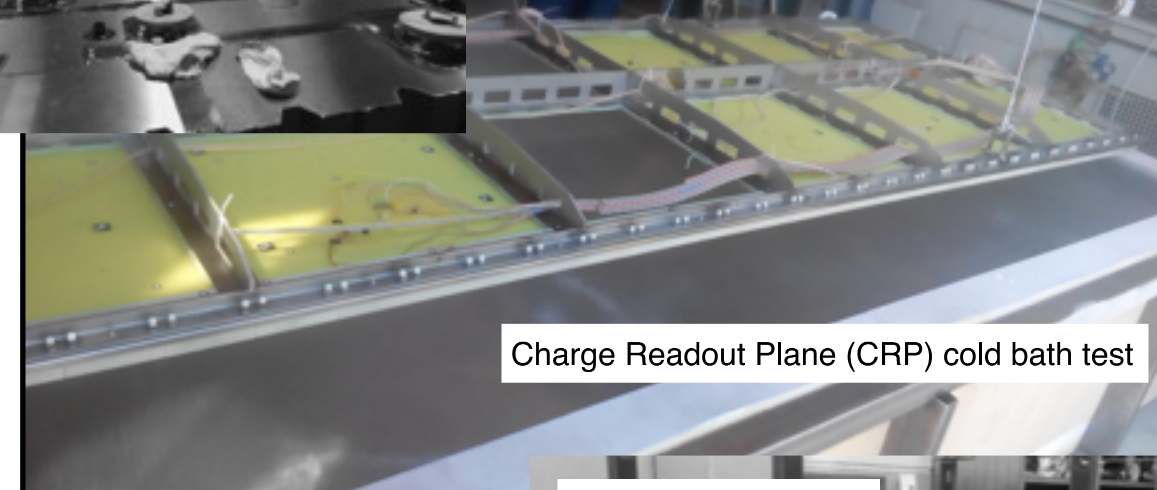
WA105 3x1x1 proto

10-ton scale Dual Phase LAr TPC

($3x1x1\ m^3$ active 24 ton LAr total)

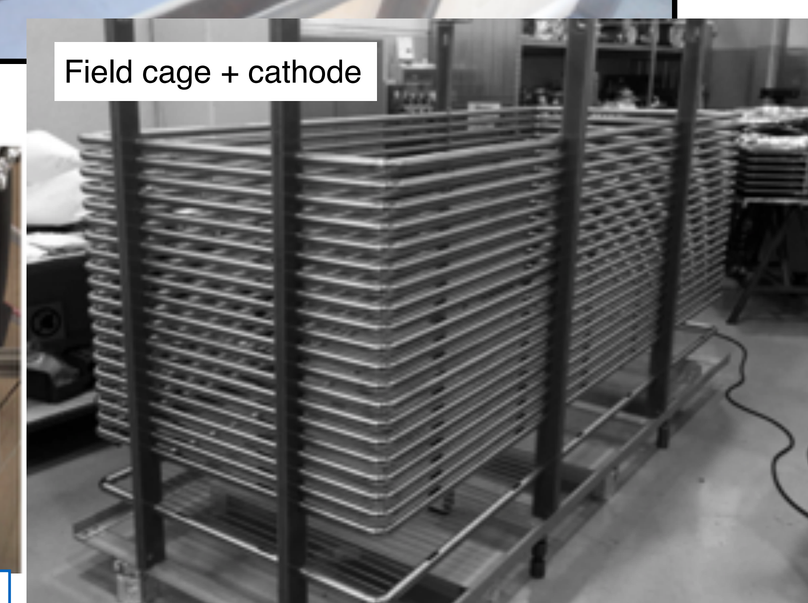
Detector integration in progress
Cryogenic Operation: September 2016





chimneys

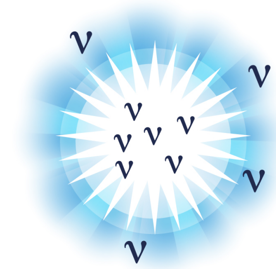
light readout



DUNE Primary Science Program

Focus on fundamental open questions in particle physics and astroparticle physics – aim for discoveries:

- **1) Neutrino Oscillation Physics**
  - CPV in the leptonic sector
    - "*Our best bet for explaining why there is matter in the universe*"
  - Neutrino Mass Hierarchy
    - "*Guaranteed determination of MH (>5sigmas)*"
  - Precision Oscillation Physics & testing the 3-flavor paradigm



- **2) Nucleon Decay**
  - Predicted in beyond the Standard Model theories
    - "*Probe the unification of the fundamental forces*"

- **3) Supernova burst physics & astrophysics**
  - Galactic core collapse supernova, unique sensitivity to ν_e
    - "*Information on neutron star or even black-hole formation*"

LBL oscillation strategy

- Precise measurement of the L/E behaviour for neutrinos and antineutrinos at L>1000 km
  $\mathcal{A} = P(\nu_\mu \to \nu_e) - P(\bar{\nu}_\mu \to \bar{\nu}_e) = \mathcal{A}_{CP} + \mathcal{A}_{Matter}$ with $\mathcal{A}_{CP} \propto L/E$; $\mathcal{A}_{Matter} \propto L \times E$
- **High discovery potential** for **leptonic CPV** and **guaranteed determination of MH**; test of 3-ν flavour oscillation paradigm; determine the sector of Θ_{23}
- Complete knowledge of PMNS matrix by precisely determining all parameters including CP-phase. Fundamental parameters of the SM → CKM and PMNS matrices to shed light on the **flavour problem**.

- **DUNE measures the energy dependence of electron-appearance and muon-disappearance oscillation probabilities, independently for neutrinos and antineutrinos**
- **High neutrino beam power and near + far detectors provide precise measurements with high statistics and low systematics**
  - **E.g. Appearance probability for neutrinos**

$$P(\nu_\mu \to \nu_e; L) \simeq 4c_{13}^2 s_{13}^2 s_{23}^2 \left\{1 + \frac{a}{\delta m_{31}^2}\cdot 2(1-2s_{13}^2)\right\} \sin^2\frac{\delta m_{31}^2 L}{4E}$$

$$+ c_{13}^2 s_{13} s_{23}\left\{-\frac{aL}{E} s_{13}s_{23}(1-2s_{13}^2) + \frac{\delta m_{21}^2 L}{E} s_{12}(-s_{13}s_{23}s_{12} + c_\delta c_{23}c_{12})\right\}\sin\frac{\delta m_{31}^2 L}{2E}$$

$$-4\frac{\delta m_{21}^2 L}{2E} s_\delta c_{13}^2 s_{13} c_{23} s_{23} c_{12} s_{12} \sin^2\frac{\delta m_{31}^2 L}{4E}$$

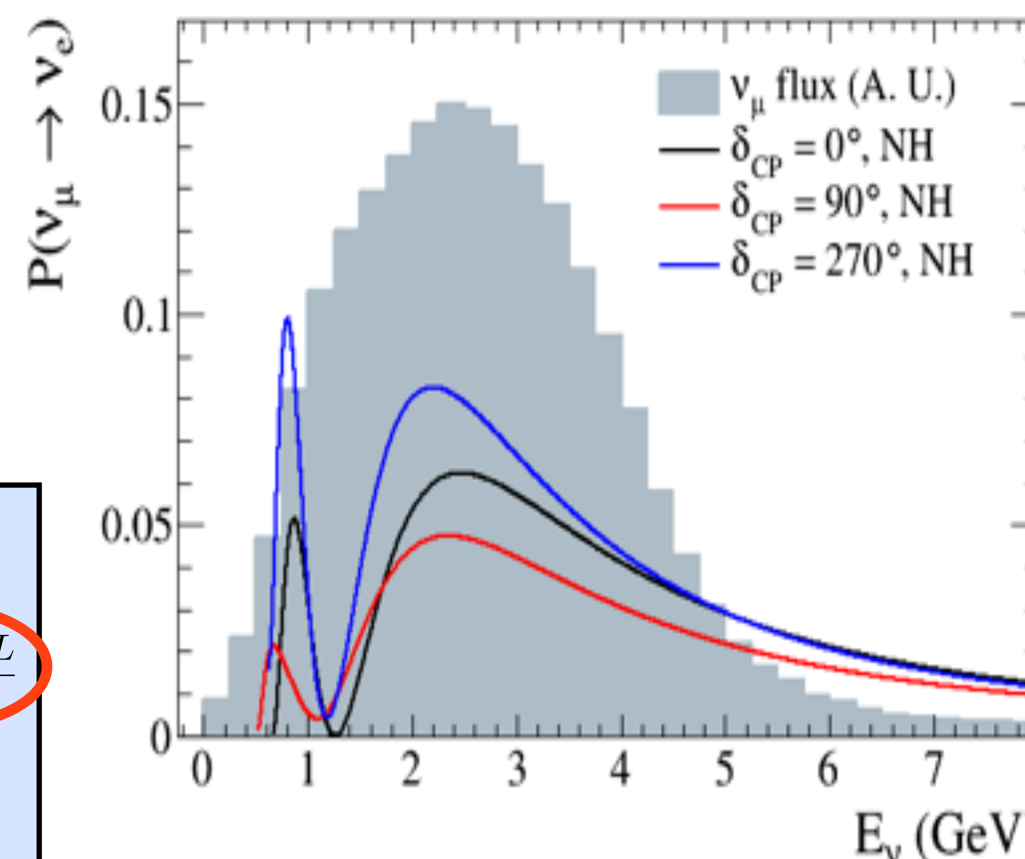
Matter terms∼a

CP-even

L/E dependence

CP-odd∼sinδ$_{CP}$

$$a \equiv 2\sqrt{2}G_F n_e E = 7.56\times10^{-5}\,\mathrm{eV}^2 \frac{\rho}{\mathrm{g\,cm^{-3}}}\frac{E}{\mathrm{GeV}}$$



Aim for discovery!

LBL oscillation strategy

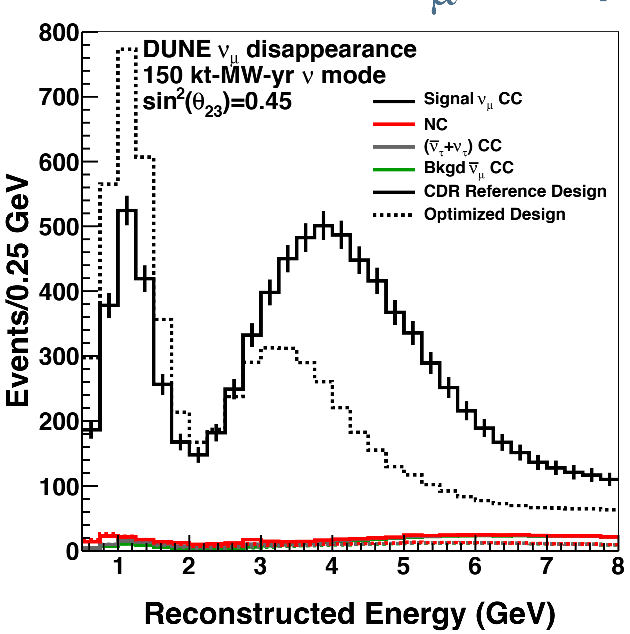
Measure neutrino spectra at 1300 km in a wide-band beam

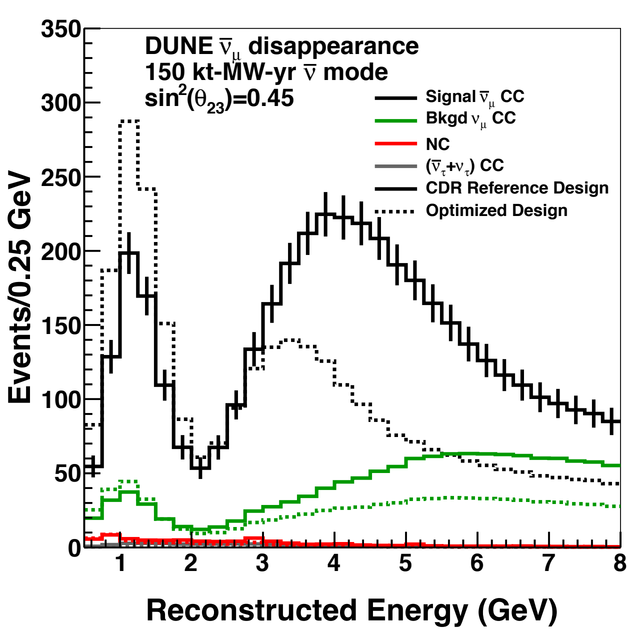
- **Determine MH and θ_{23} octant, probe CPV, test 3-flavor paradigm and search for ν NSI in a single experiment**
  - Long baseline:
    - Matter effects are large ~ 40%
  - Wide-band beam:
    - Study $\nu_\mu \rightarrow \nu_e$ ($\bar{\nu}_\mu \rightarrow \bar{\nu}_e$) and $\nu_\mu \rightarrow \nu_x$ ($\bar{\nu}_\mu \rightarrow \bar{\nu}_x$) over range of energies
    - MH & CPV effects are separable

Expected number of events in the far detector.
5 years running, δ_{CP}=0, normal MH (inverted)

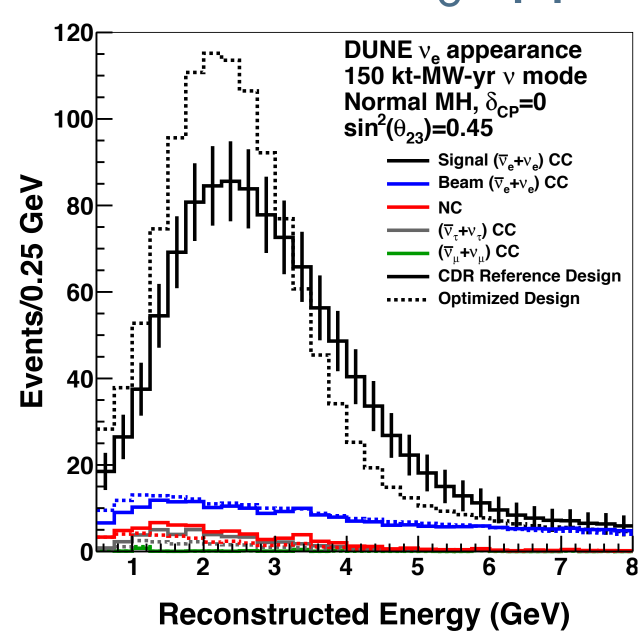
	Neutrino beam	Anti-neutrino beam
ν_μ signal	7929	2639
ν_μ background	29	18
ν_e signal	945(521)	168(436)
ν_e background	243	127

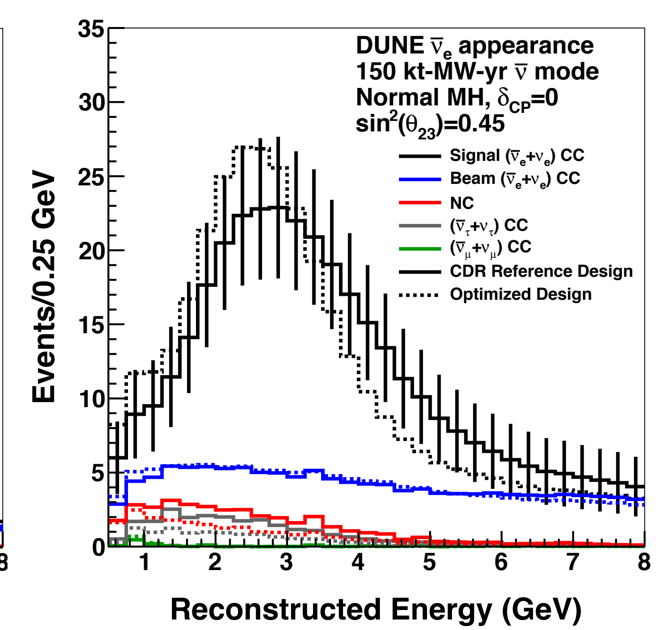
ν_μ disappearance





ν_e appearance





LBL science discovery potential

Rapidly reach scientifically interesting sensitivities:

- e.g. in best-case scenario for CPV ($\delta_{CP} = +\pi/2$) :
  - **Reach 3σ CPV sensitivity with 60 – 70 kt.MW.year**
- e.g. in best-case scenario for MH :
  - **Reach 5σ MH sensitivity with 20 – 30 kt.MW.year**

DUNE 40 kton * 1.2 MW beam
≈ 50 kt.MW.year per year

Physics milestone	Exposure kt · MW · year (reference beam)	Exposure kt · MW · year (optimized beam)
1° θ_{23} resolution ($\theta_{23} = 42^\circ$)	70	45
CPV at 3σ ($\delta_{\mathrm{CP}} = +\pi/2$)	70	60
CPV at 3σ ($\delta_{\mathrm{CP}} = -\pi/2$)	160	100
CPV at 5σ ($\delta_{\mathrm{CP}} = +\pi/2$)	280	210
MH at 5σ (worst point)	400	230
10° resolution ($\delta_{\mathrm{CP}} = 0$)	450	290
CPV at 5σ ($\delta_{\mathrm{CP}} = -\pi/2$)	525	320
CPV at 5σ 50% of δ_{CP}	810	550
Reactor θ_{13} resolution ($\sin^2 2\theta_{13} = 0.084 \pm 0.003$)	1200	850
CPV at 3σ 75% of δ_{CP}	1320	850

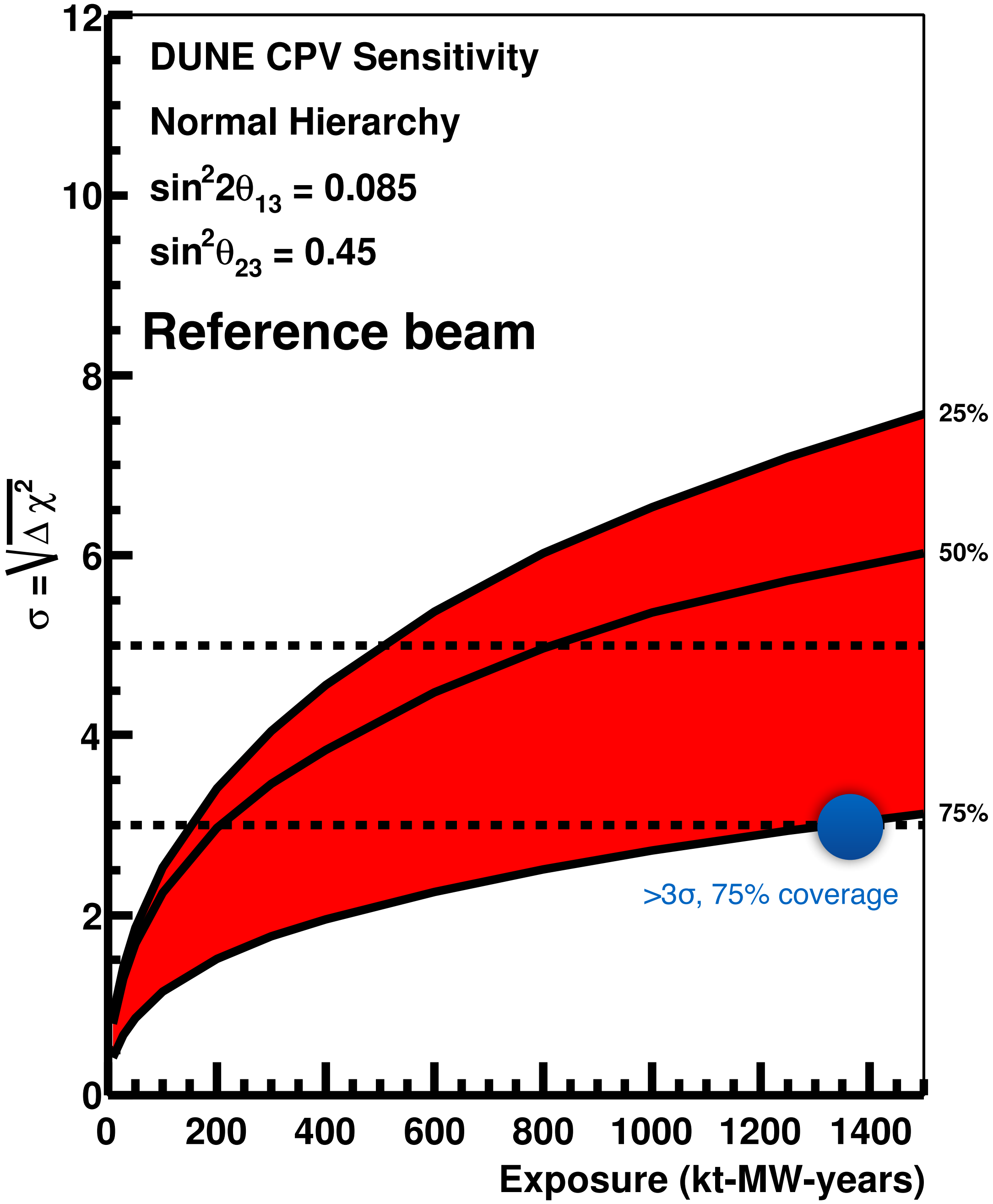
5σ CPV Discovery

Opportunities for early discoveries !

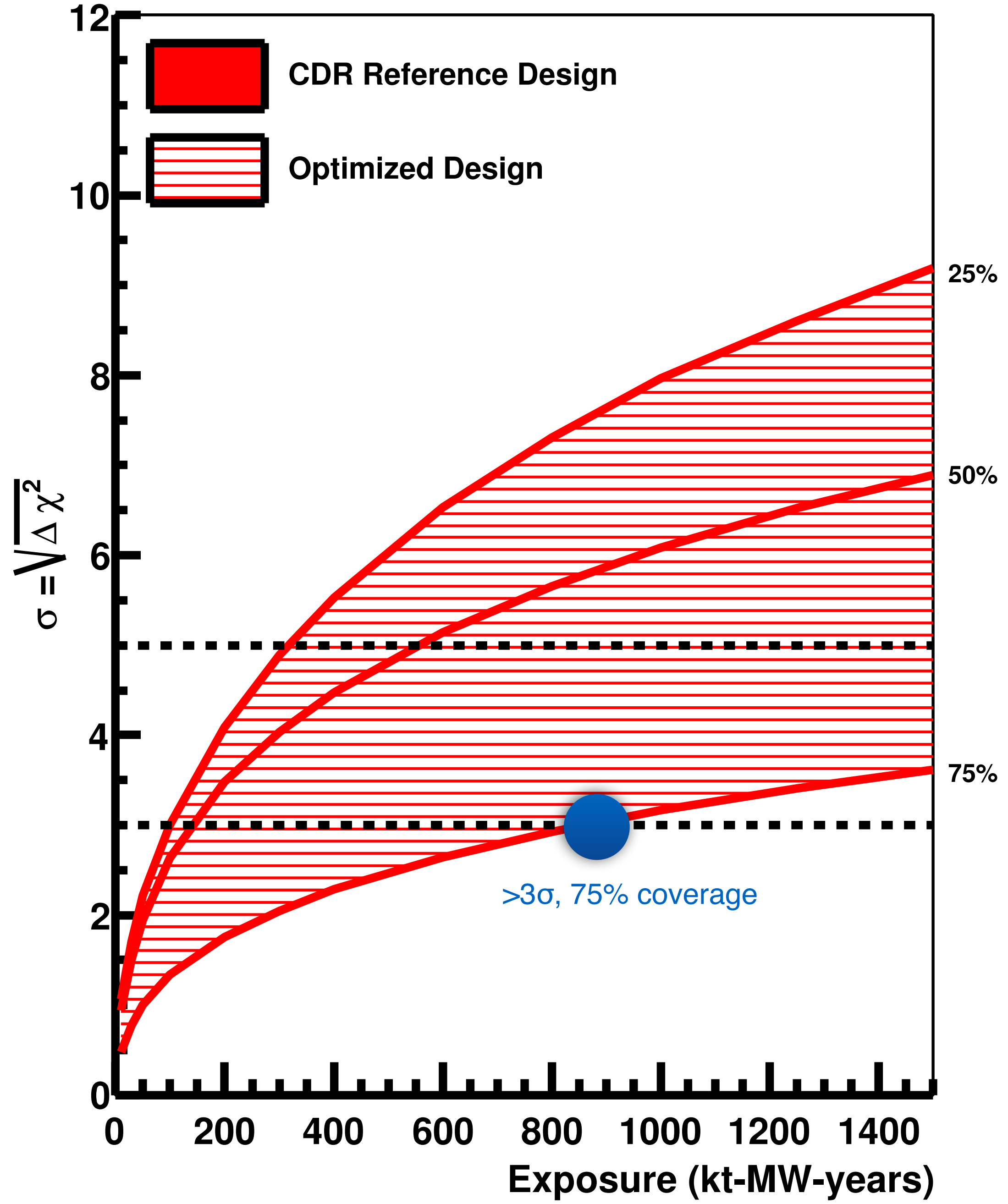
CPV sensitivity

★ Sensitivities depend on multiple factors:
- CPV parameter δ, other mixing angles e.g. θ_{23}
- Beam spectrum, …

CP coverage 25%, 50%, 75%



Beam focusing choice



Conclusions

- Very significant progress in experimental neutrino physics shedding light into the leptonic flavour sector and more generally improving our understanding of the Standard Model with three massive neutrinos.
  - Accelerator LBL (T2K & NOvA) collecting data for precision measurements, providing indirect information on CP violation & MH when combined with other global data
  - Reactor experiments to improve precision on θ_{13}, while studying potential anomalies
  - Atmospheric neutrinos measurements provide complementary information about oscillations

- Next generation international experiments are being planned/constructed to complete our understanding of 3νSM paradigm.

- It is important to keep in mind that the history of neutrino experiments has been full of surprises, so let's keep an open mind on anomalies, extra neutrinos, etc. as the new experiments deliver their data.

Backup

Single phase protoDUNE

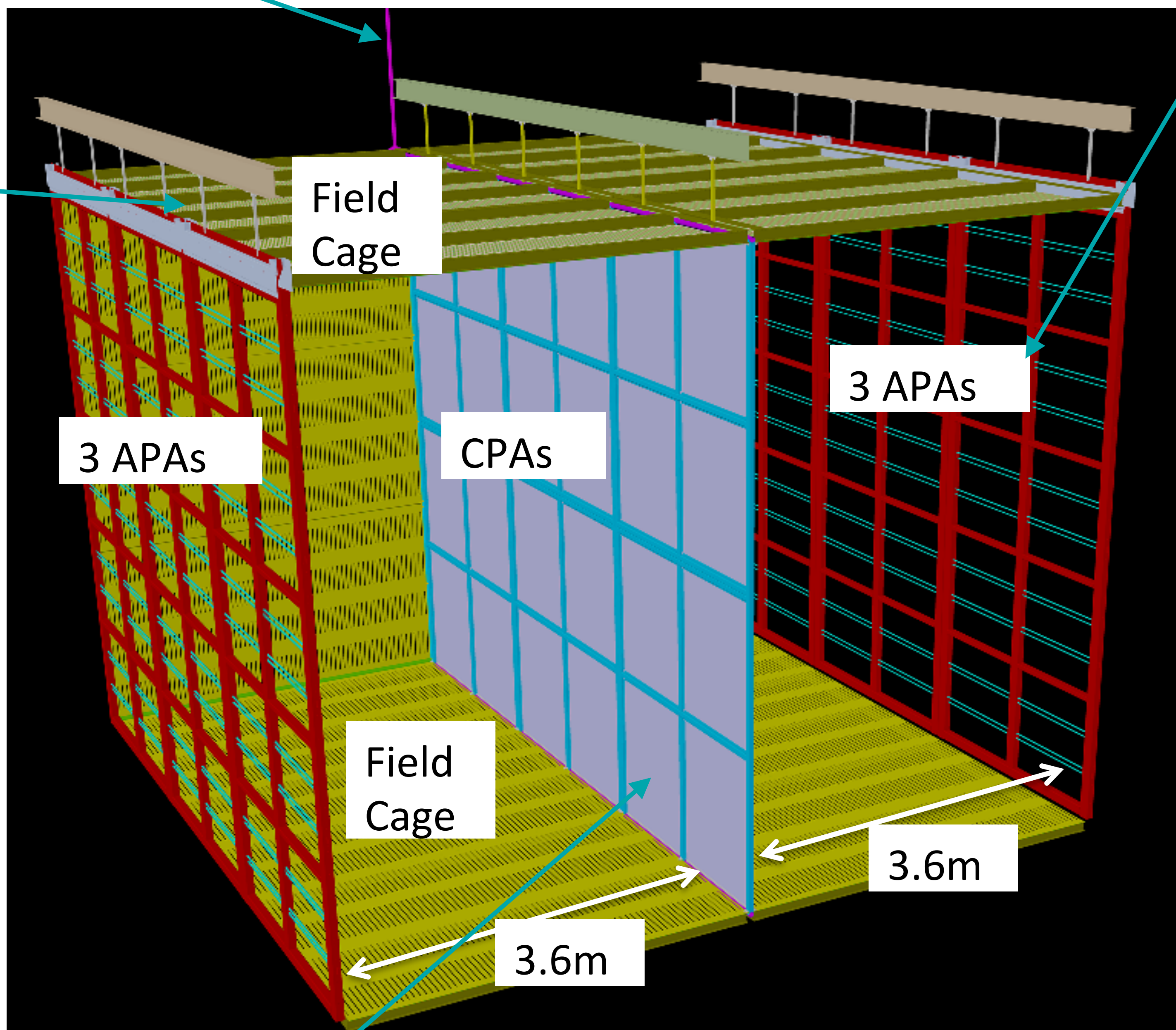
(Non-DOE funding under negotiation)

Drift HV system

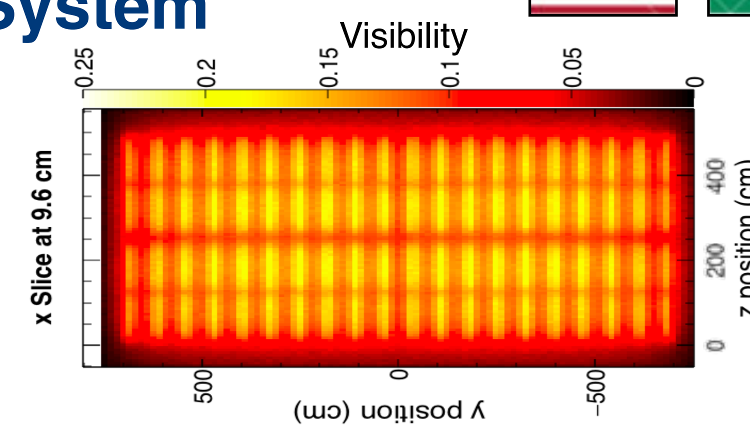
Signal feed-throughs

Anode Plane Assemblies (APA)

Field cage



Photon Detector System



Cold readout electronics

DAQ

Slow control

Cathode Plane Assemblies (CPA)

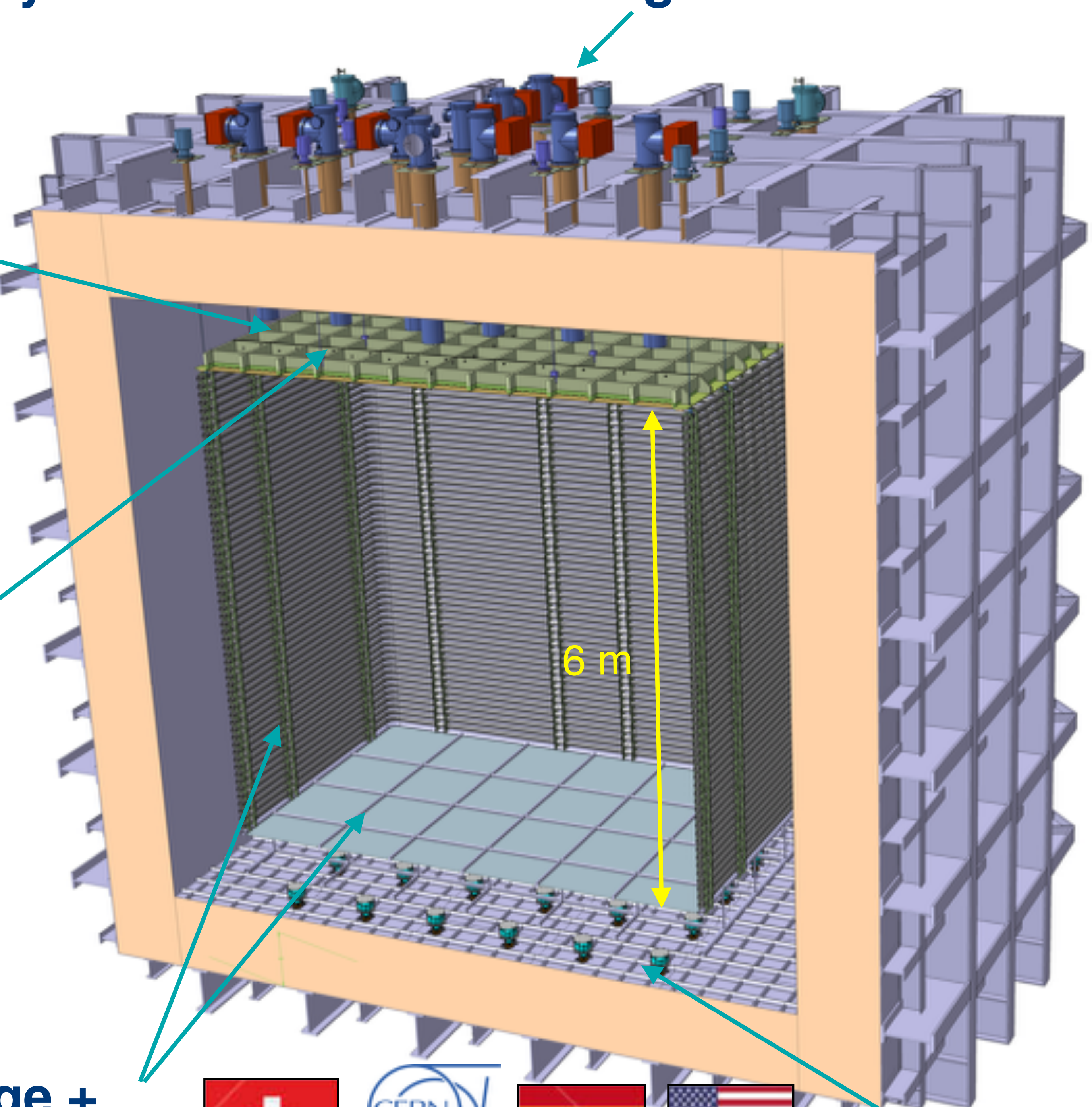
Dual phase protoDUNE - WA105 6x6x6m^3

(US contributions under discussion)

Drift HV system

Signal feed-throughs

CRP frame + hanging system



CRP readout planes

Drift cage + cathode plane

Photon Electronics

Cold readout electronics

DAQ

Online computing

Purity monitor

Slow control

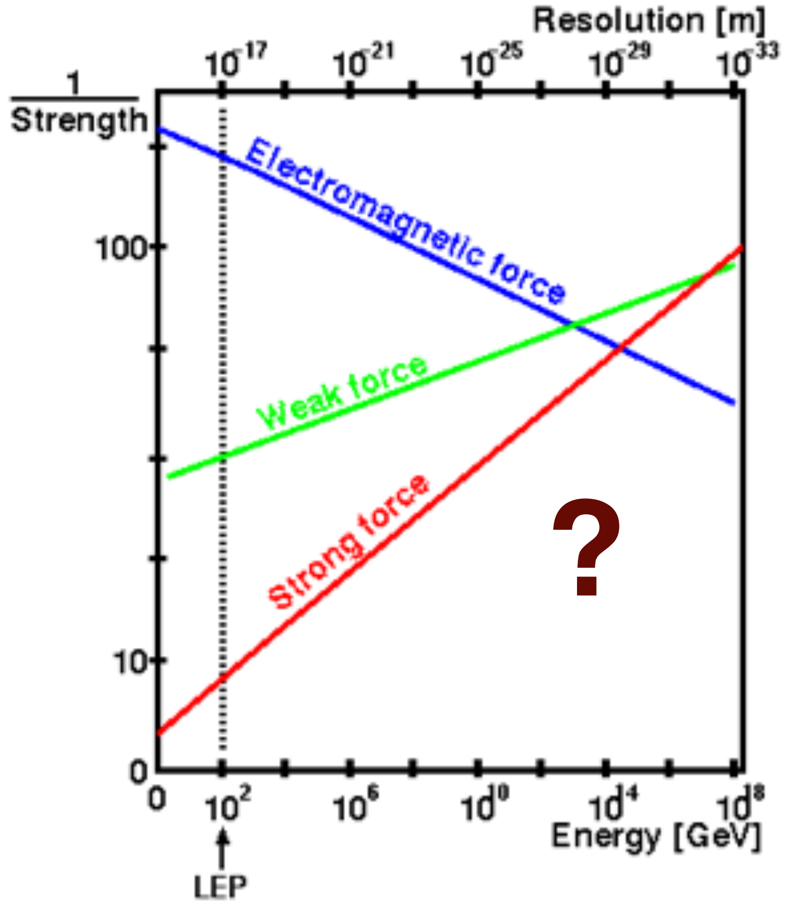
Cosmic tracker

Photon Detectors

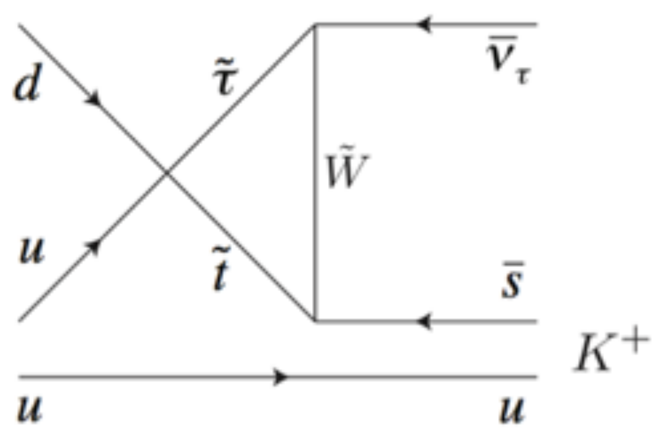
DUNE - Primary Science Programme

2. Nucleon Decay (and atmospheric neutrinos)

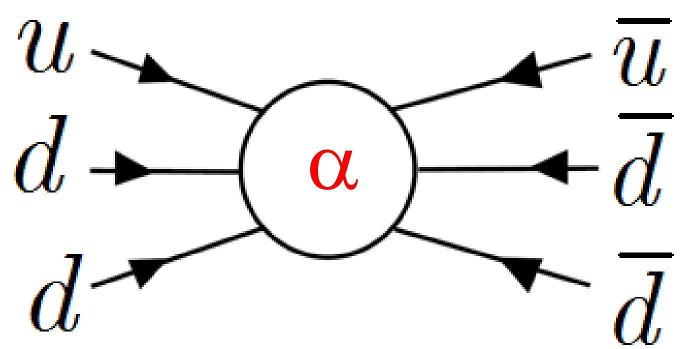
- EW+QCD are all local-gauge QFT with similar structure → GUT ? many hints exist in favour (high energy behaviour of couplings; Q_e=–Q_p, neutrino masses, …) but the **missing link** is the **direct observation of a nucleon decay**.
- Measurements of branching ratios inform GUT models (SUSY, non-SUSY).
- Signatures of annihilations from n-nbar oscillations can also be searched for.
- DUNE provides a generational advance in atmospheric neutrino detection and study.



SUSY dim-5



n-nbar oscillations



A discovery would be monumental !

DUNE - Primary Science Programme

3. **Neutrino astrophysics, including supernova detection**
   - SN burst to verify models of stars' explosions; but also neutrino physics
   - Measurement of the **neutrino energy spectra**, **time distributions** and **flavor composition** with **large statistics** from SN will provide information about:
     - Supernova physics:
       - Core collapse mechanism
       - Supernova evolution in time
       - Cooling of the proto-neutron star
       - Nucleosynthesis of heavy nuclei
       - Black hole formation
     - Neutrino flavour transformation and propagation physics:
       - Flavor transformation in SN core has rich physics affected by my phenomena, such as matter & collective effects, sterile neutrinos and in general neutrino properties (e.g. anomalous magnetic moment)
     - Early alert for astronomers

SN detection provides unique and broad science opportunities !

LBL oscillation strategy (II)

CPV & MH : Systematic errors presented in CDR

After fits to both near and far detector data and all external constraints.

Signal: **5%** (abs. $\nu\mu$ norm.) $\oplus$ **2%** (νe norm.) for both neutrinos and antineutrinos sample

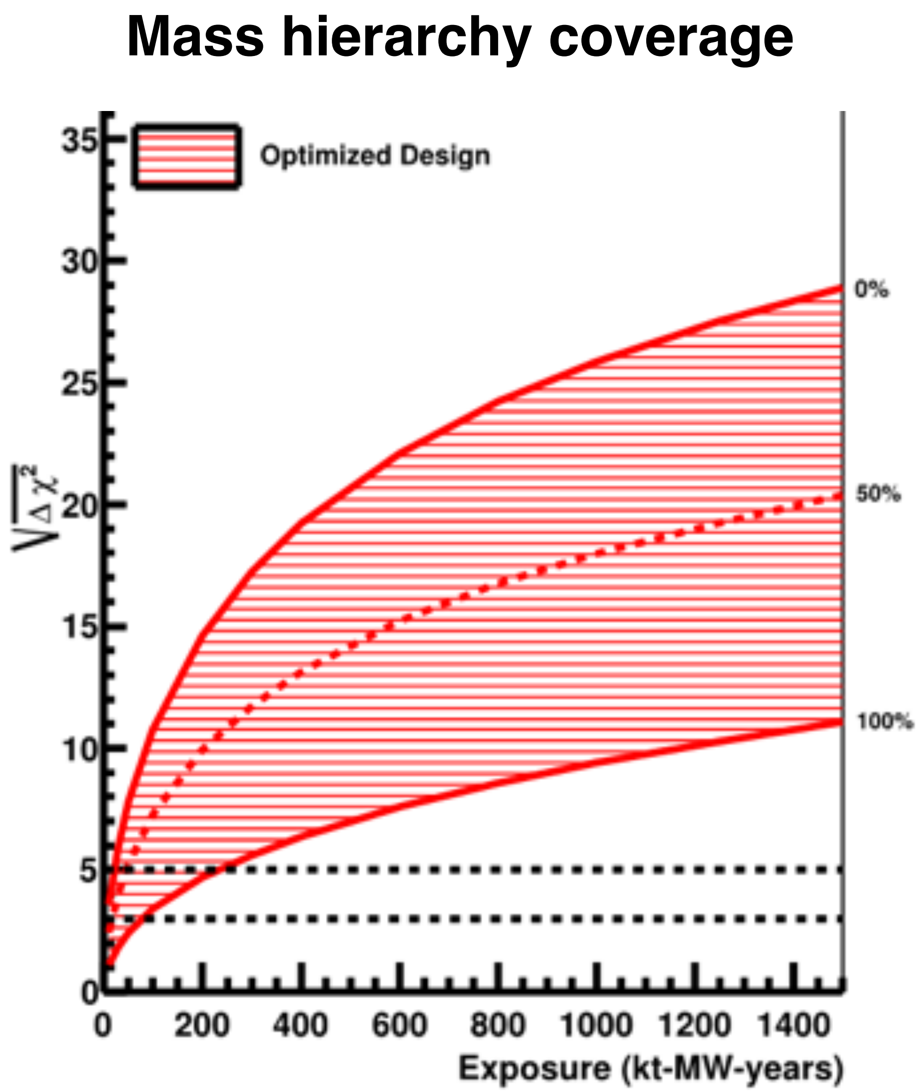
Background processes:

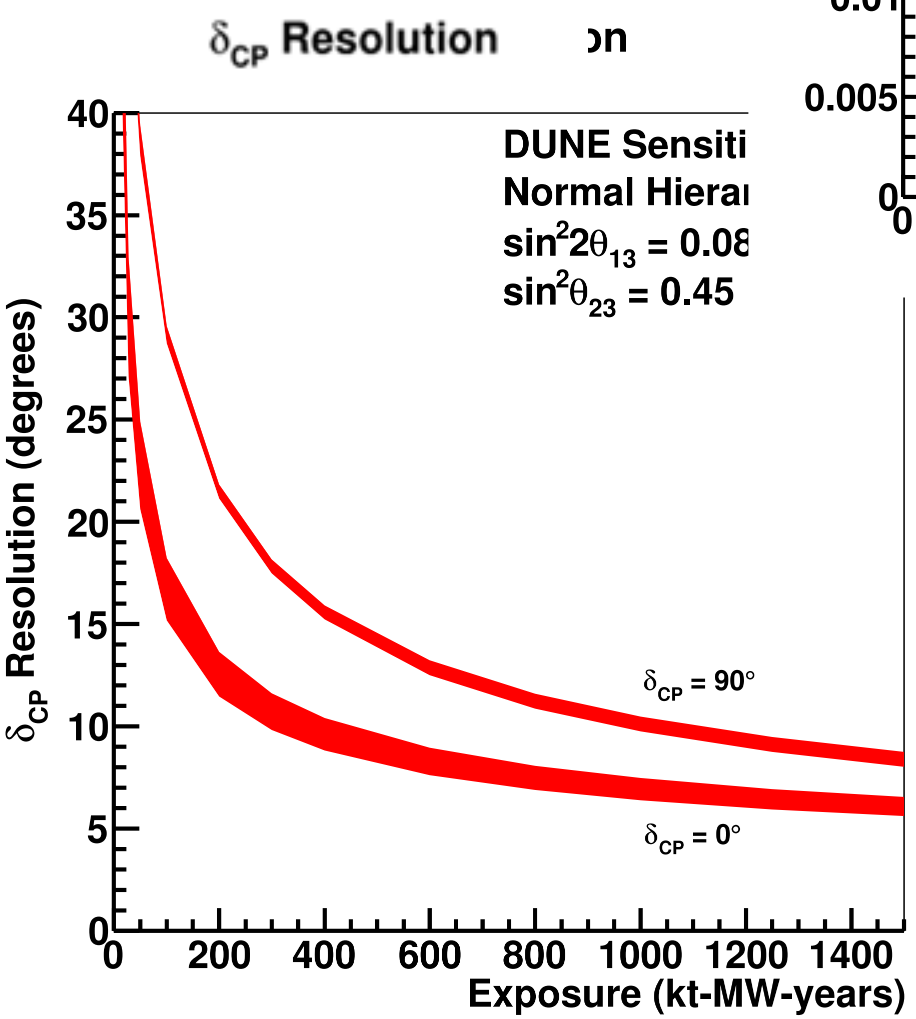
From CDR Volume 2 "Physics":

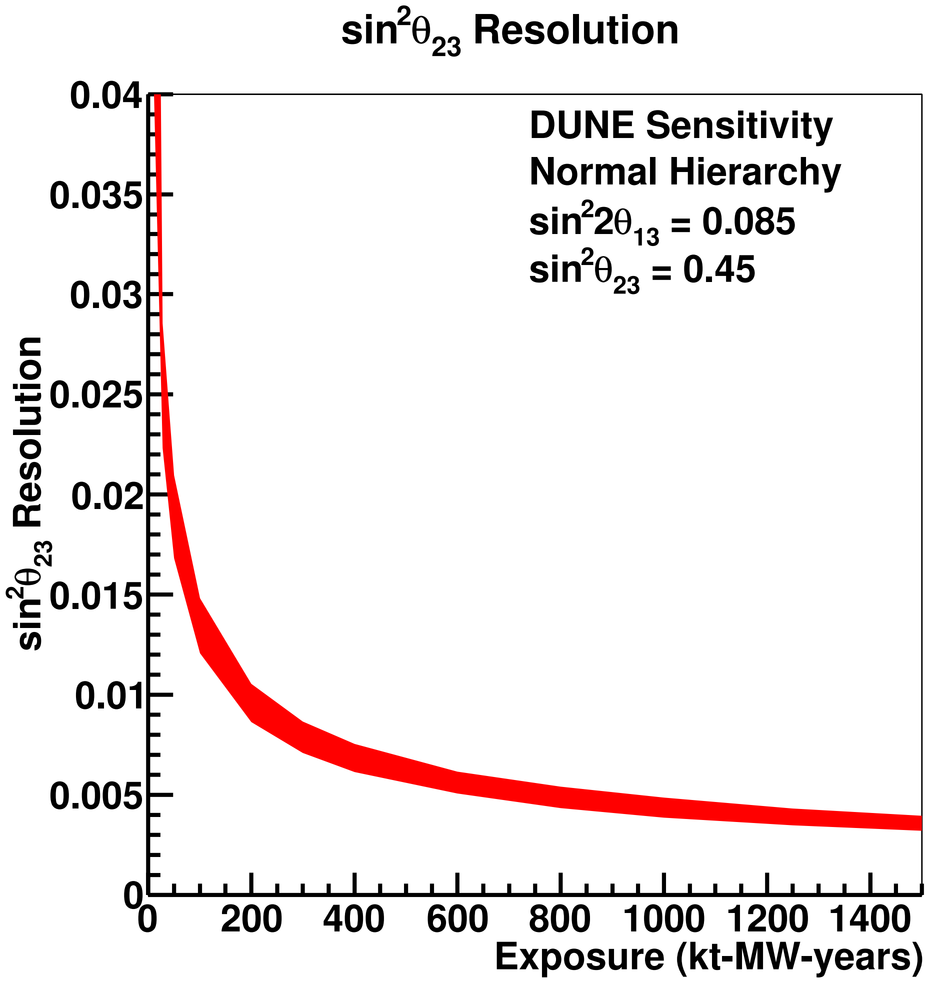
Background	Normalization Uncertainty	Correlations
For $\nu_e/\bar{\nu}_e$ appearance:		
Beam ν_e	5%	Uncorrelated in ν_e and $\bar{\nu}_e$ samples
NC	5%	Correlated in ν_e and $\bar{\nu}_e$ samples
ν_μ CC	5%	Correlated to NC
ν_τ CC	20%	Correlated in ν_e and $\bar{\nu}_e$ samples
For $\nu_\mu/\bar{\nu}_\mu$ disappearance:		
NC	5%	Uncorrelated to $\nu_e/\bar{\nu}_e$ NC background
ν_τ	20%	Correlated to $\nu_e/\bar{\nu}_e$ ν_τ background

External experimental and theoretical input (nu cross-sections, hadroproduction, detector test beams, SBN) and DUNE ND important ingredients to achieve these levels.

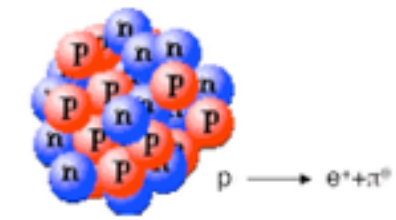
MH, δ_{CP} and $\sin^2\theta_{23}$ Sensitivities







Nucleon decay searches in DUNE



DUNE provides a generational advance in detection method:

Exploit tracking and calorimetry for unbiased, exclusive final state reconstruction of decay products with precise kinematics, low thresholds (no Cherenkov threshold)

- **Phenomenology is rich and there are many possible decay modes (≈90 identified)**
  - **Proton decay modes**
  - **Neutron decay modes**
  - **n-nbar oscillation modes**
- **Backgrounds can be calculated using atmospheric neutrino samples and estimated using side-bands**
- **Efficiencies involving π's in the final states are affected by nuclear uncertainties but constrained by neutrino cross-section measurements**
- **With LAr imaging & excellent kinematics, we find a ≈linear sensitivity improvement with exposure until 1000 kton×year… or 25 years of DUNE…**

For a 20kton exposure of 10 years (200 kton×year)

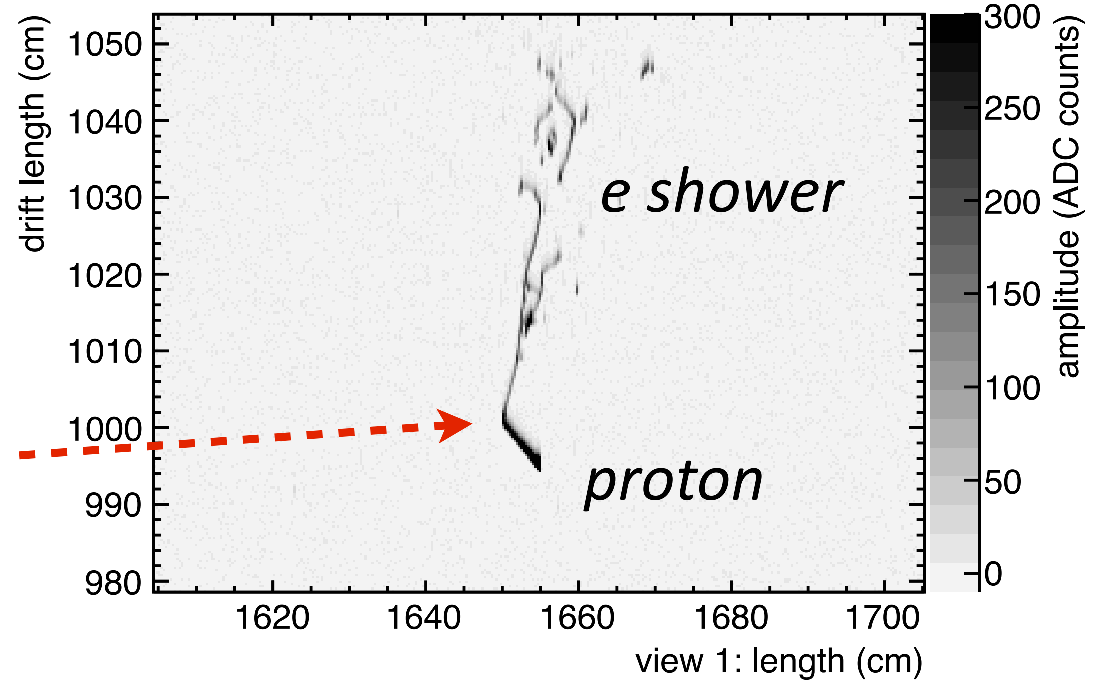
JHEP 0704 (2007) 041

Mode	Lifetime (90%C.L.)
$p\rightarrow\nu K^+$	**$>3\times10^{34}$ yrs**
$p\rightarrow e^+\gamma$, $p\rightarrow\mu^+\gamma$	**$>3\times10^{34}$ yrs**
$p\rightarrow\mu^-\pi^+K^+$	**$>3\times10^{34}$ yrs**
$n\rightarrow e^-K^+$	**$>3\times10^{34}$ yrs**
$p\rightarrow\mu^+K^0$, $p\rightarrow e^+K^0$	$>1\times10^{34}$ yrs
$p\rightarrow e^+\pi^0$	$>1\times10^{34}$ yrs
$p\rightarrow\mu^+\pi^0$	$>0.8\times10^{34}$ yrs
$n\rightarrow e^+\pi^-$	$>0.8\times10^{34}$ yrs

Atmospheric neutrinos in DUNE

Mode	Events/20kt/yr
ν_eCC	1440
$\bar{\nu}_e$CC	310
ν_μCC	2440(w/o osc)
$\bar{\nu}_\mu$CC	680(w/o osc)
νNC	640

MC: ν_eCC



- **Neutrino oscillation physics complementary to long baseline beam**
- Clean ν_e & ν_μ CC over all range of energies (GeV,MultiGeV)
- Good neutrino energy and angular reconstruction
- Recoil hadronic system on an event-by-event basis
- Statistical separation of ν and anti-ν by exclusive final states
- $\nu_\mu \rightarrow \nu_\tau$ appearance significance >3σ after 3 years exposure (≈12 ν_τ CC / year)

Low energy neutrinos in DUNE

hep-ph/0307222; JCAP 10 (2003) 009; JCAP 08 (2004) 001

- Elastic scattering (ES) on electrons

$$\nu + e^- \rightarrow \nu + e^-$$

- Charged-current (CC) interactions on Ar

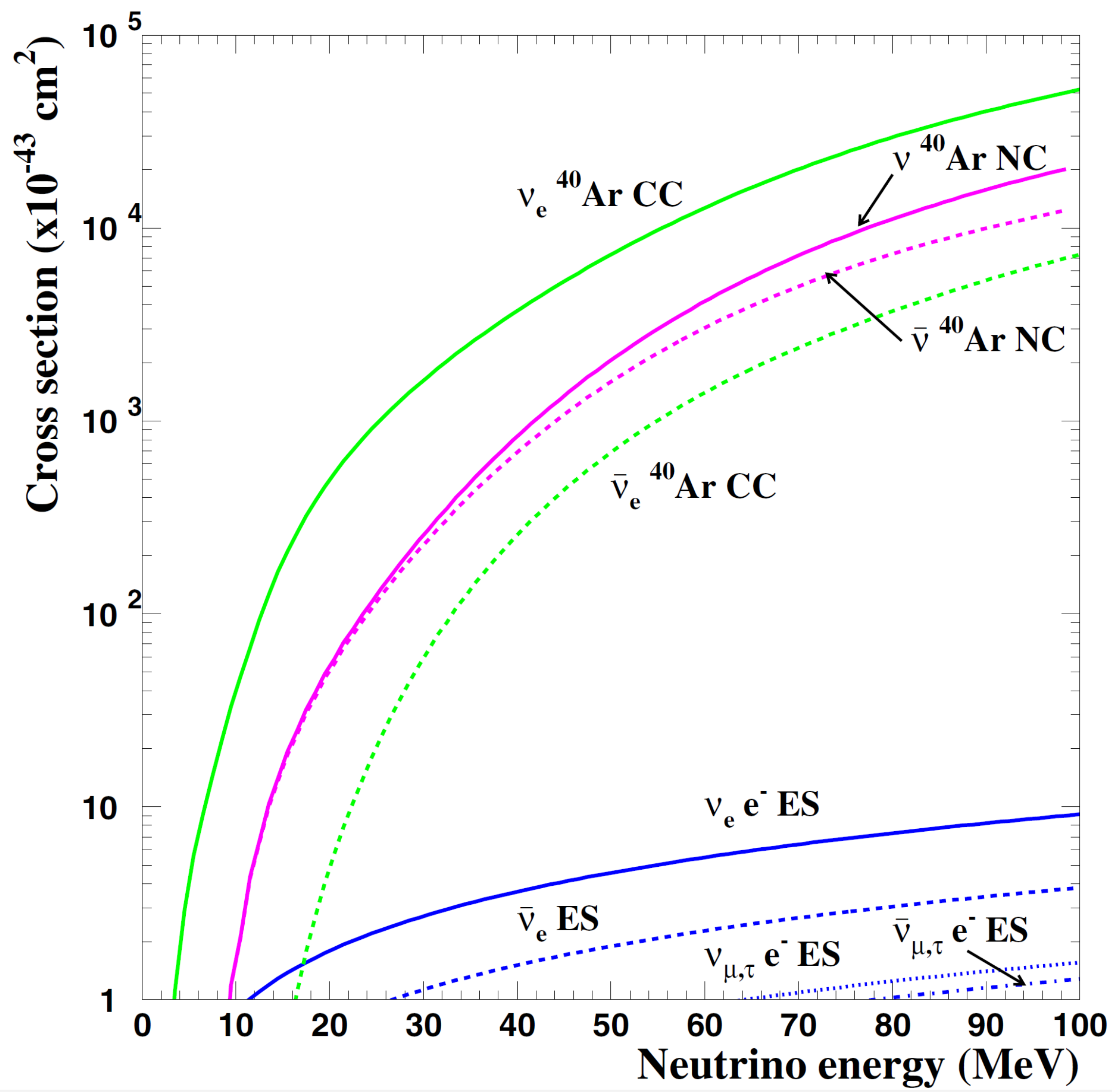
$$\nu_e + {}^{40}Ar \rightarrow {}^{40}K^* + e^-$$ $E\nu_e > 1.5$ MeV

$$\bar{\nu}_e + {}^{40}Ar \rightarrow {}^{40}Cl^* + e^+$$ $E\bar{\nu}_e > 7.48$ MeV

- Neutral current (NC) interactions on Ar

$$\nu + {}^{40}Ar \rightarrow \nu + {}^{40}Ar^*$$ $E\nu > 1.46$ MeV

SN ν cross sections on Ar



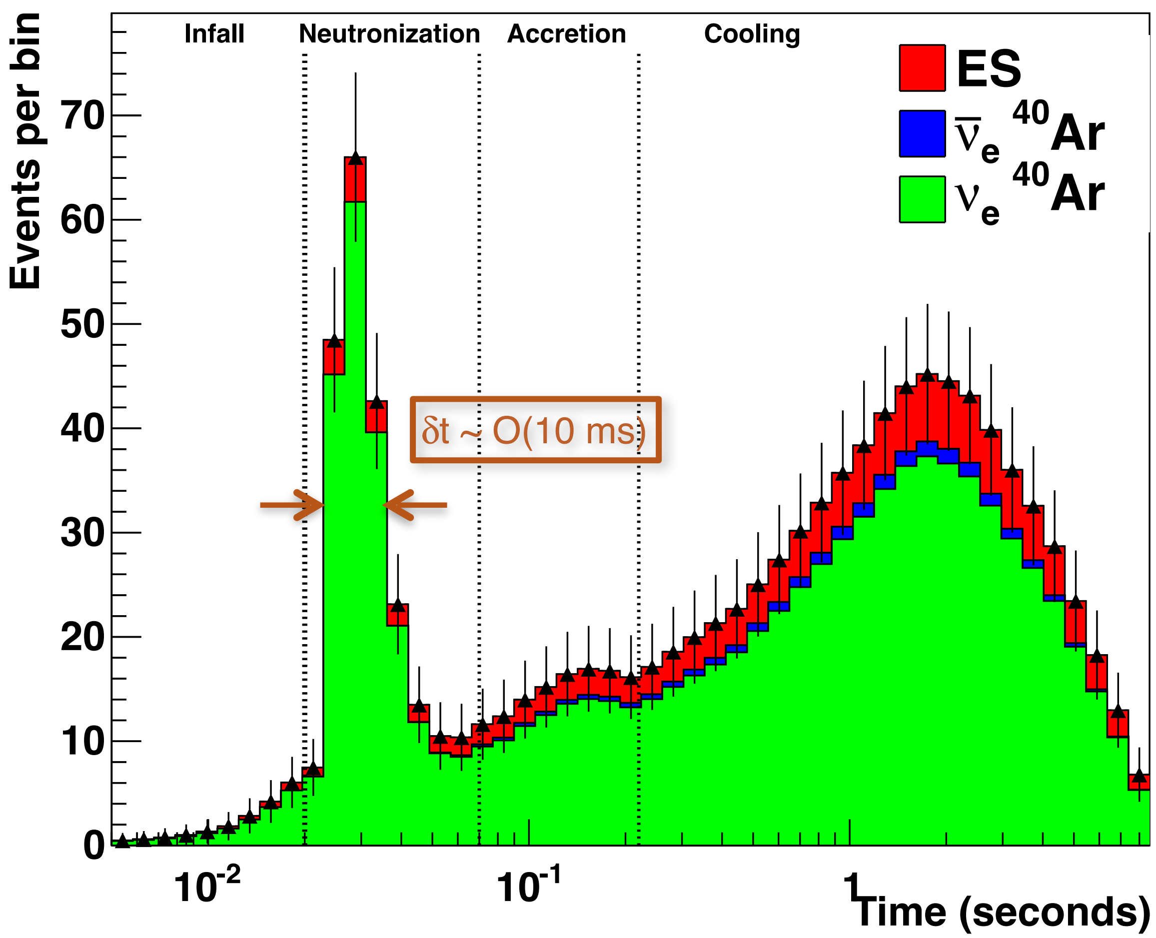
Possibility to separate the different channels by a classification of the associated photons from the K, Cl or Ar de-excitation (specific spectral lines for CC and NC) or by the absence of photons (ES)

Supernova burst neutrinos

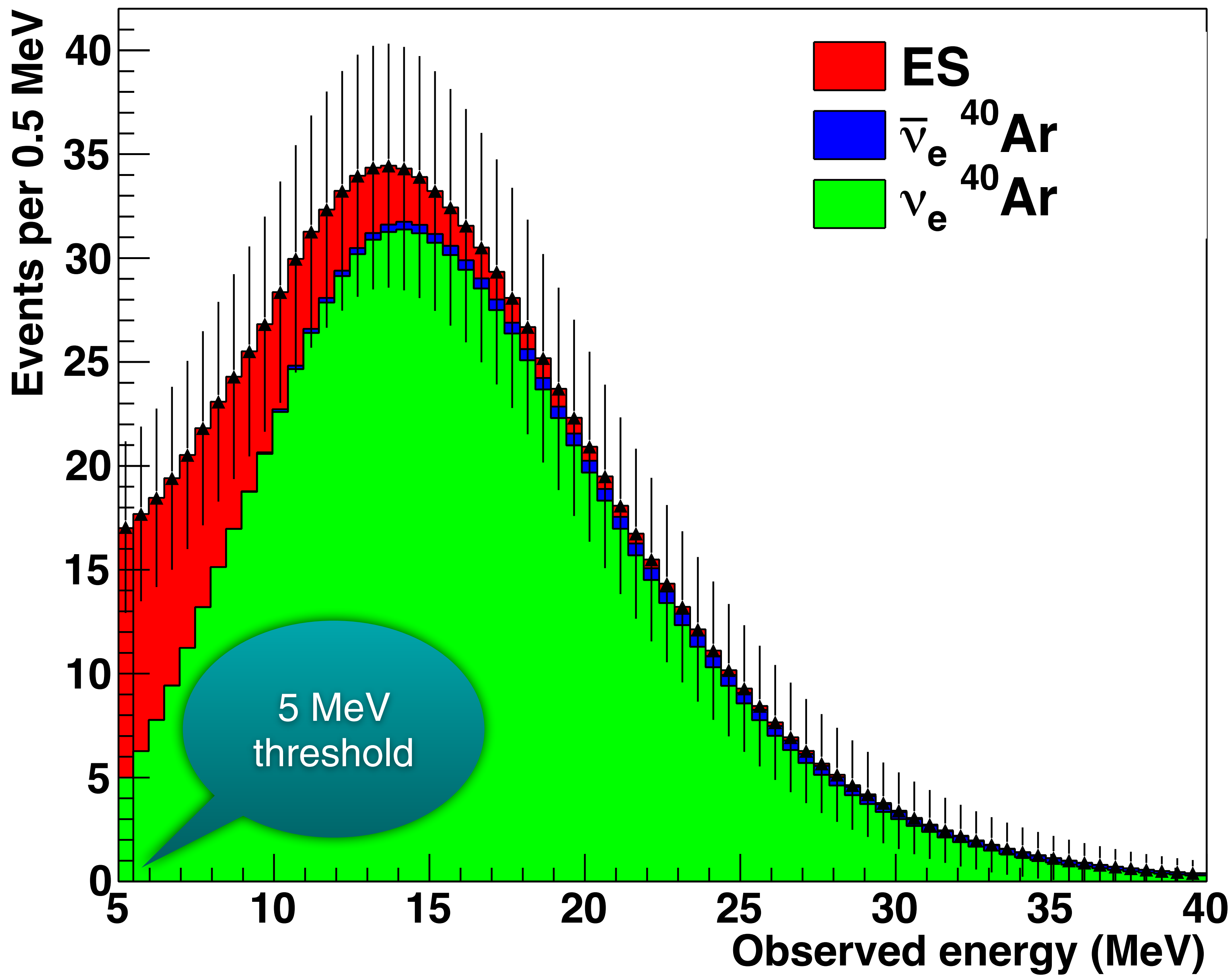
Expected event rates for 40 kton and SN at the distance of 10 kpc : (no oscillations included!)

Channel	Events "Livermore" model	Events "GKVM" model
$\nu_e +^{40}\mathrm{Ar} \to e^- +^{40}\mathrm{K}^*$	2720	3350
$\overline{\nu}_e +^{40}\mathrm{Ar} \to e^+ +^{40}\mathrm{Cl}^*$	230	160
$\nu_x + e^- \to \nu_x + e^-$	350	260
Total	3300	3770

- Unique sensitivity to electron neutrino flavour (most other SN-detectors detect inverse beta decays)
- Peak of neutronization (osc?)
- Combined analysis of all reaction modes – can NC reaction be observed ?
- Oscillation (both standard and collective) will potentially have a large effect
- Neutrino abs. mass via TOF

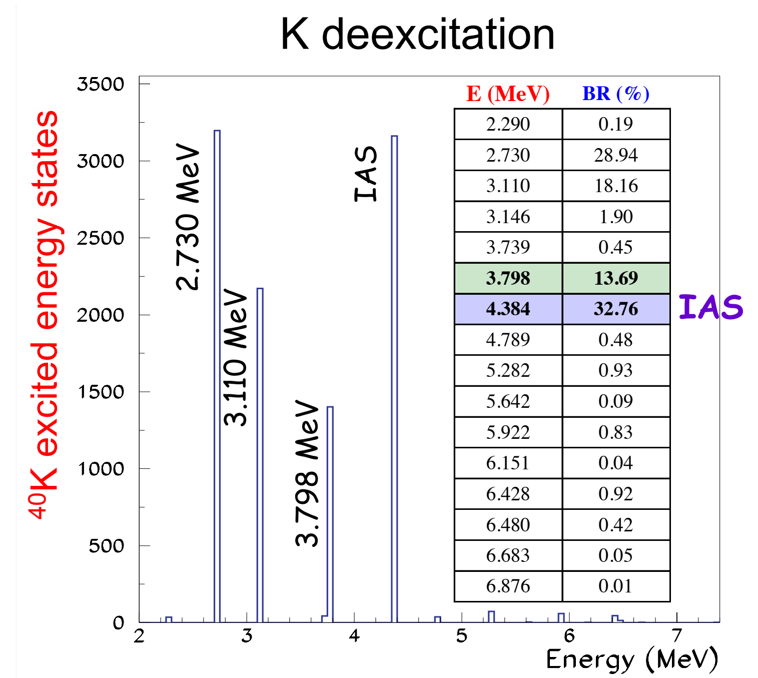


Energy spectrum



- Spectrum calculated with SNoWGloBES

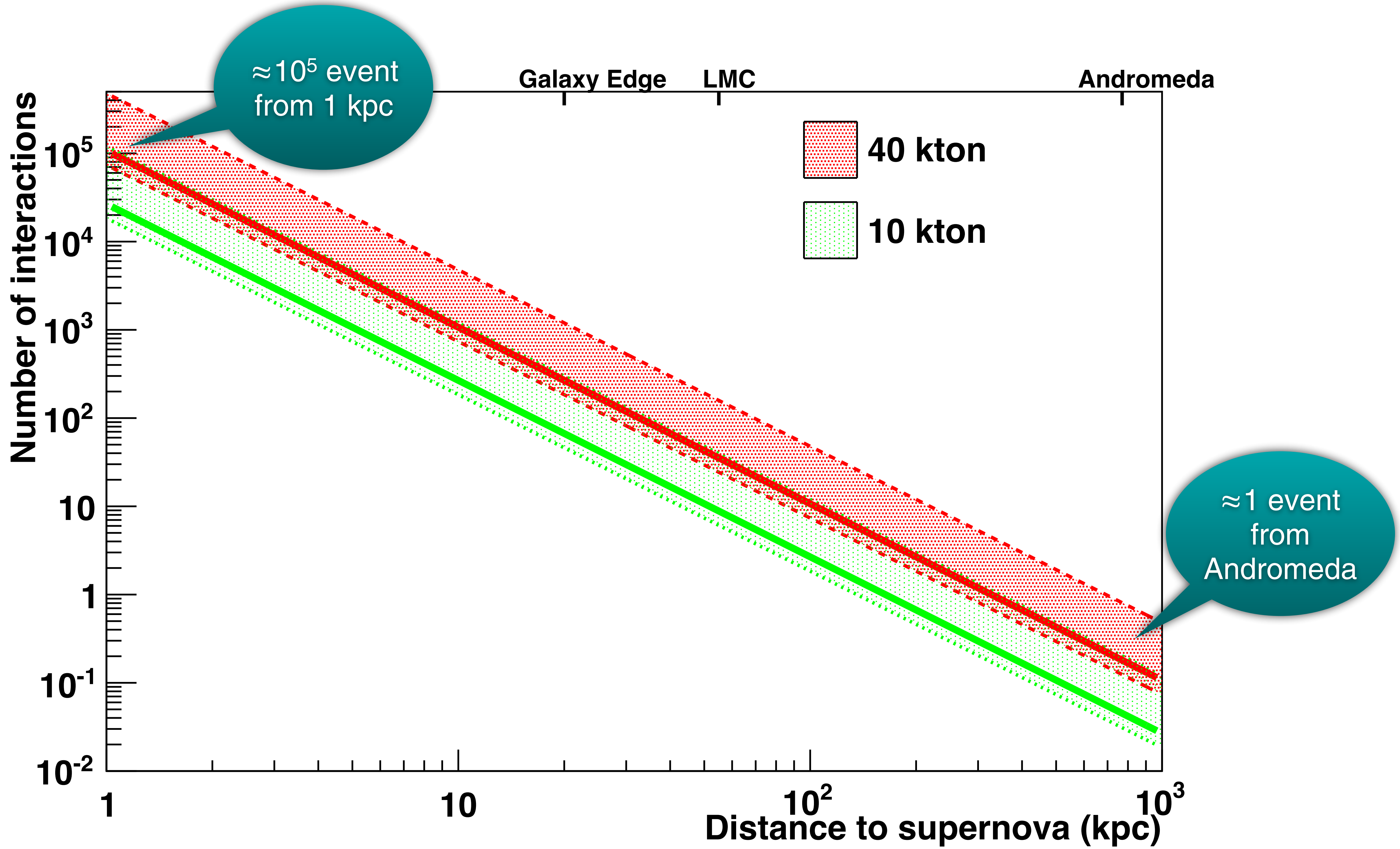
- Spectrum assumes final state energy is fully reconstructed
- Neutrino flavour classification assumes detection of **deexcitations photons**



E (MeV)	BR (%)
2.290	0.19
2.730	28.94
3.110	18.16
3.146	1.90
3.739	0.45
3.798	13.69
4.384	32.76
4.789	0.48
5.282	0.93
5.642	0.09
5.922	0.83
6.151	0.04
6.428	0.92
6.480	0.42
6.683	0.05
6.876	0.01

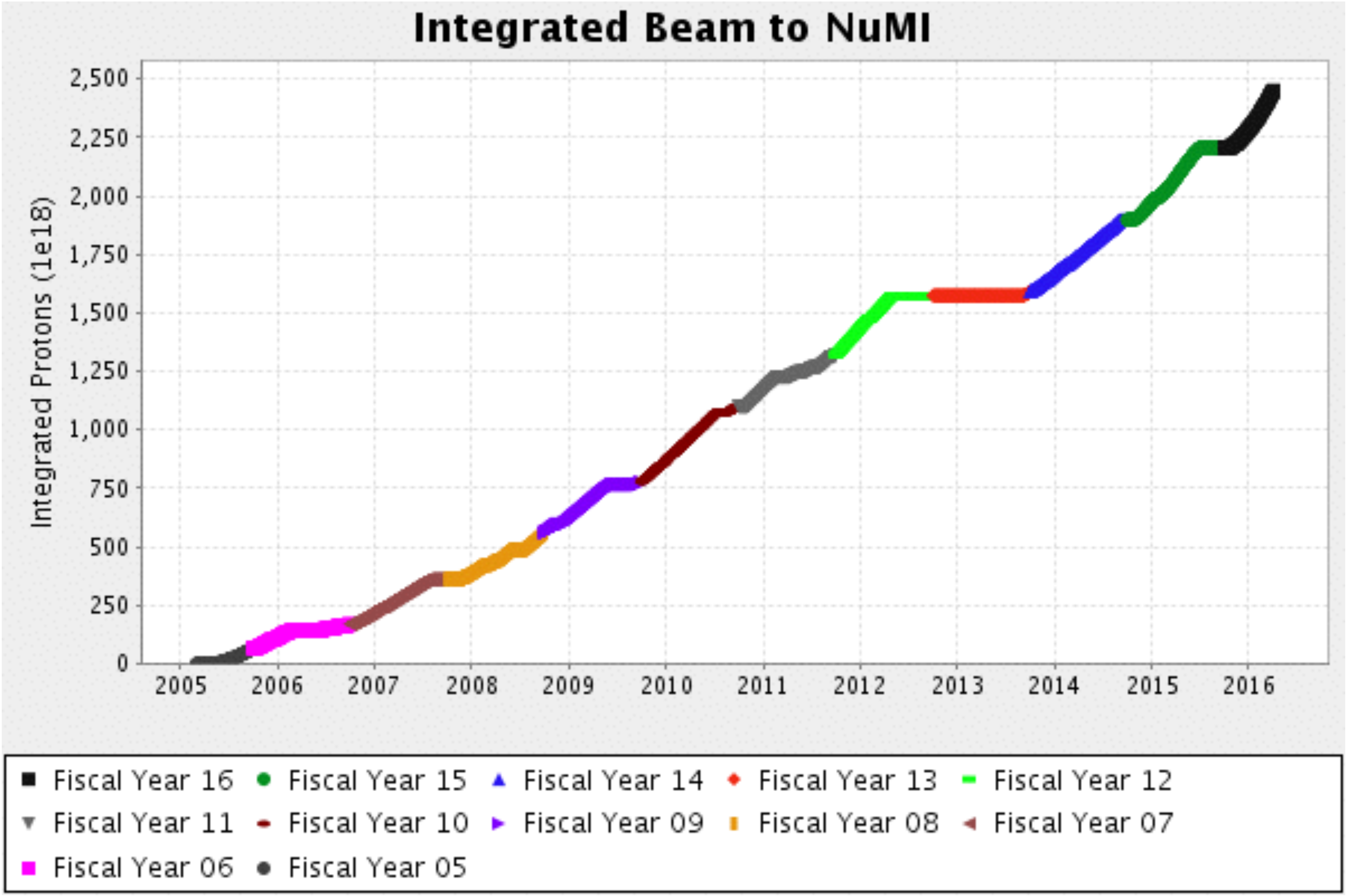
- Measurement campaigns of low energy cross-section on Argon needed to exploit statistical power of SN event burst.

Events vs distance

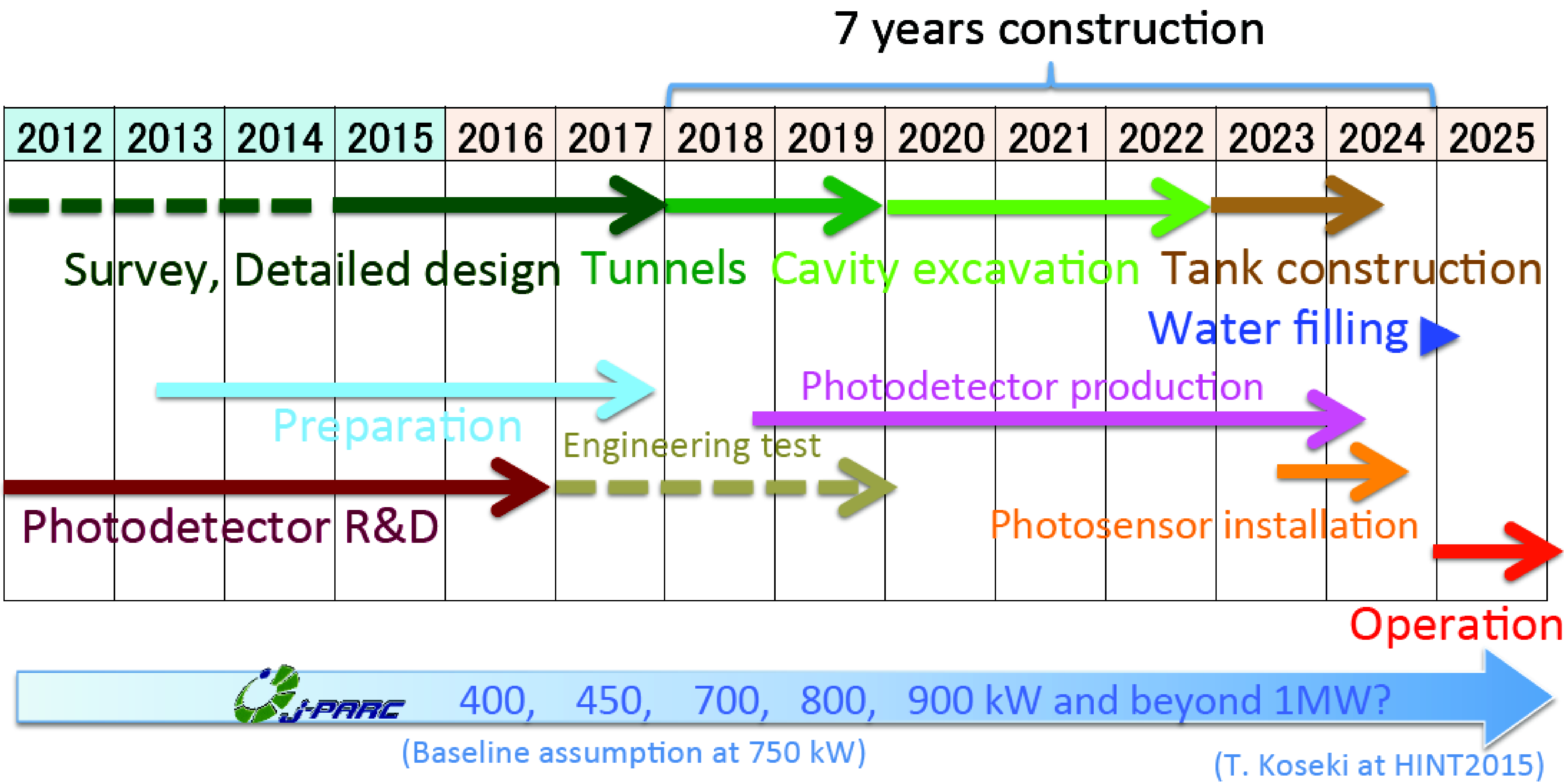


- Band represents range of models (factor of ~10 in rate)
- Solid line: "Garching" model (Raffelt et al., PRL104, p. 251101, 2010)

Integrated beam to NUMI



Hyper-Kamiokande Notional Timeline



- If the budget proposal is approved, **construction** can start in **2018**
- **Physics** running would then start in **2025**
- J-PARC has already achieved 360 kW operation and is expected 750 kW by 2019
  - Opens the possibility for >= MW operation after 2020

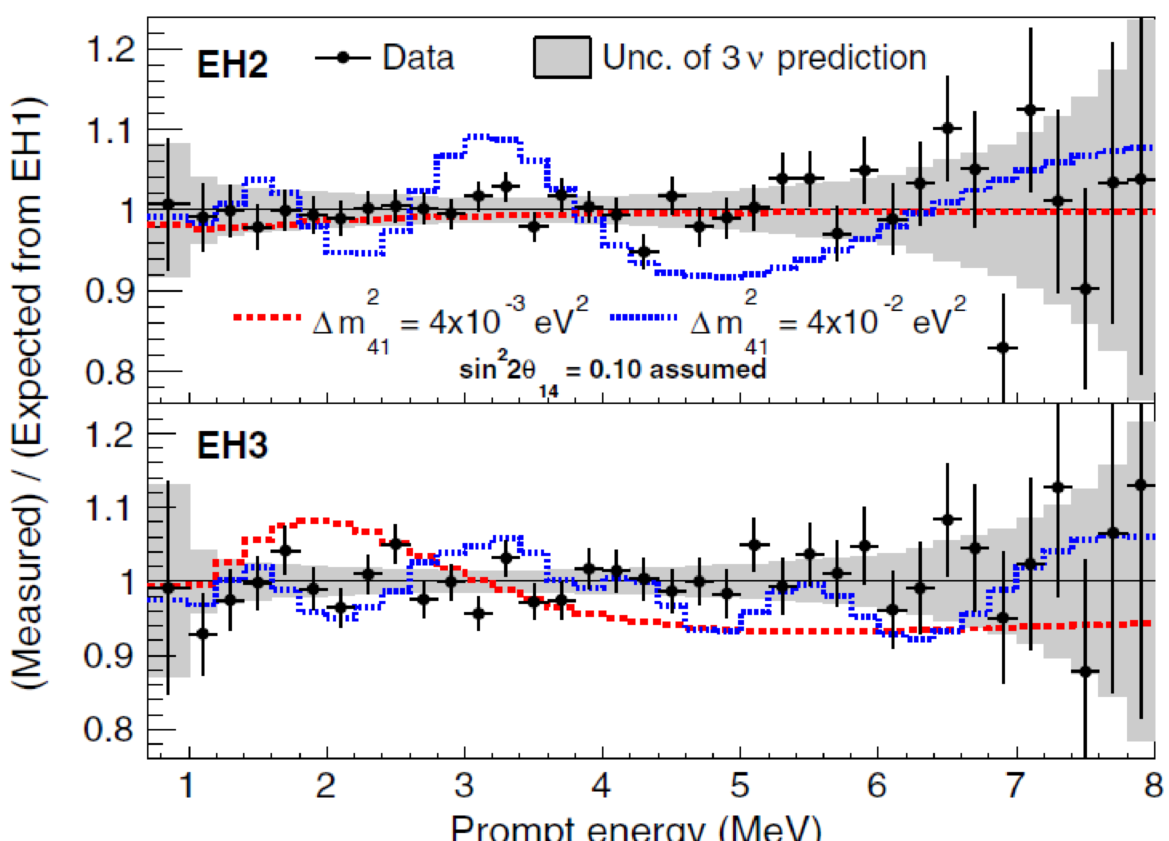
Search for light sterile neutrinos

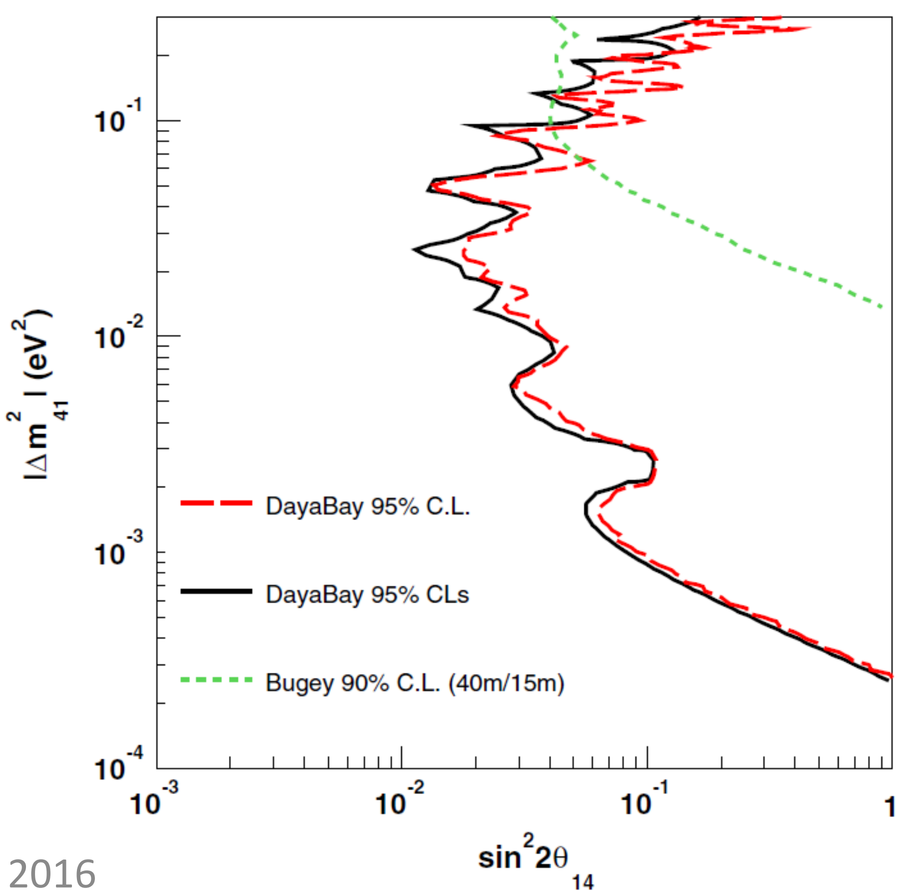
PRL 113, 141802 (2014)

- **An unique opportunity for sterile neutrino searches**
  - Sterile neutrino would introduce additional oscillation mode.
  - Relative measurement at multiple baselines: EH1 (~350m), EH2 (~500m), EH3 (~1600m)

$$P_{\bar{\nu}_e \to \bar{\nu}_e} \approx 1 - \sin^2 2\theta_{14} \sin^2(\Delta m^2_{41} \frac{L}{4E}) - \cos^4\theta_{14} \sin^2 2\theta_{13} \sin^2(\Delta m^2_{ee} \frac{L}{4E})$$

- **Oscillation analysis**
  - No significant signal observed, consistent with 3-flavor neutrino oscillation.
  - Set most stringent limit at $10^{-3}\mathrm{eV}^2 < \left|\Delta m^2_{41}\right| < 0.1\mathrm{eV}^2$





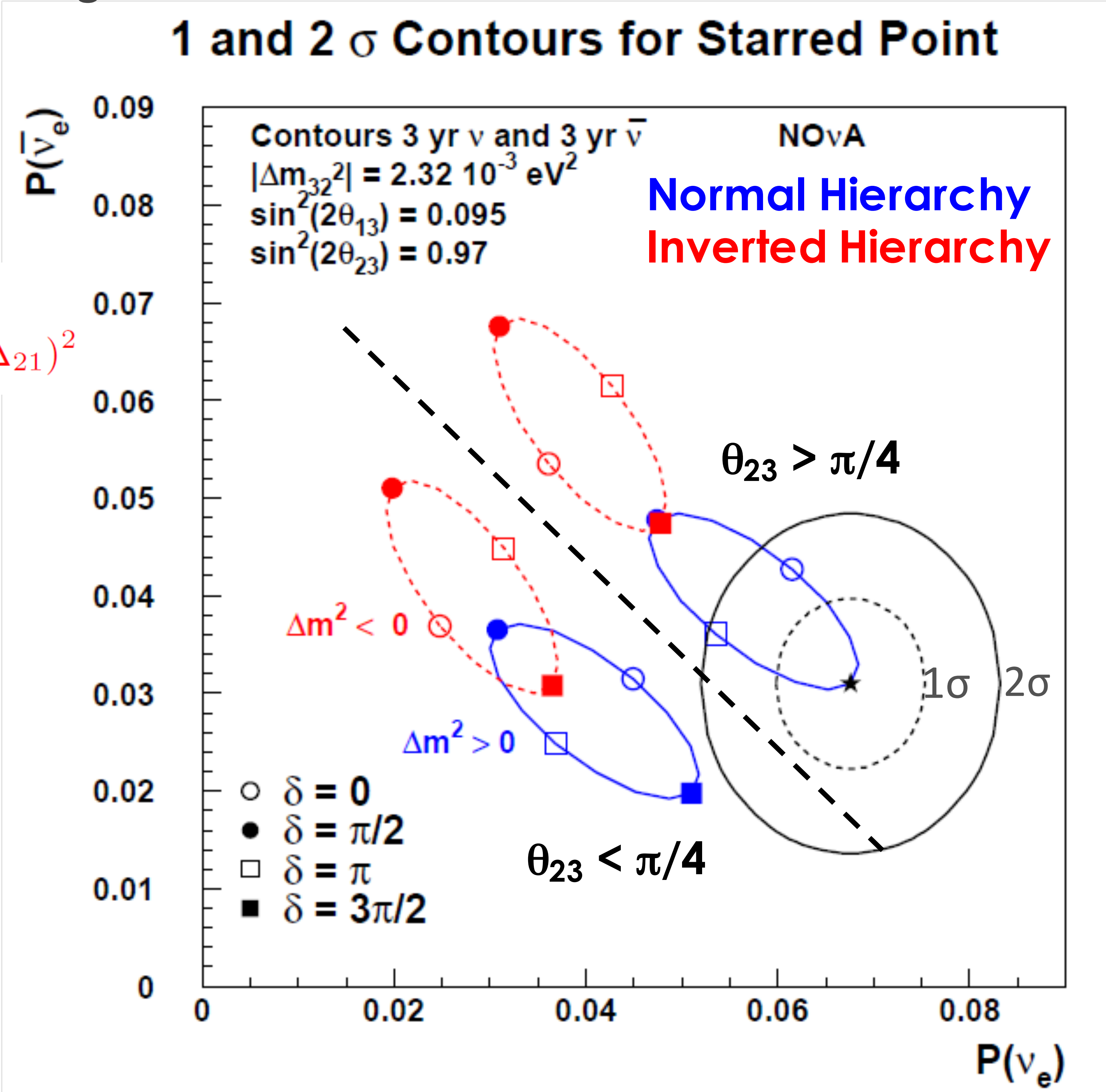
Measuring mixing parameters with NOvA

- Measuring ν_e and $\overline{\nu}_e$ appearance in the ν_μ and $\overline{\nu}_\mu$ beam is key
- Showing expected 1σ and 2σ allowed regions around most favorable case for NOvA

$$P(\nu_\mu \to \nu_e) \approx \sin^2\theta_{23}\sin^2(2\theta_{13})\sin^2\Delta_{\mu e} \pm \boxed{\tilde{J}\sin\delta\sin\Delta_{21}\sin^2\Delta_{\mu e}} + \mathcal{O}(\Delta_{21})^2$$

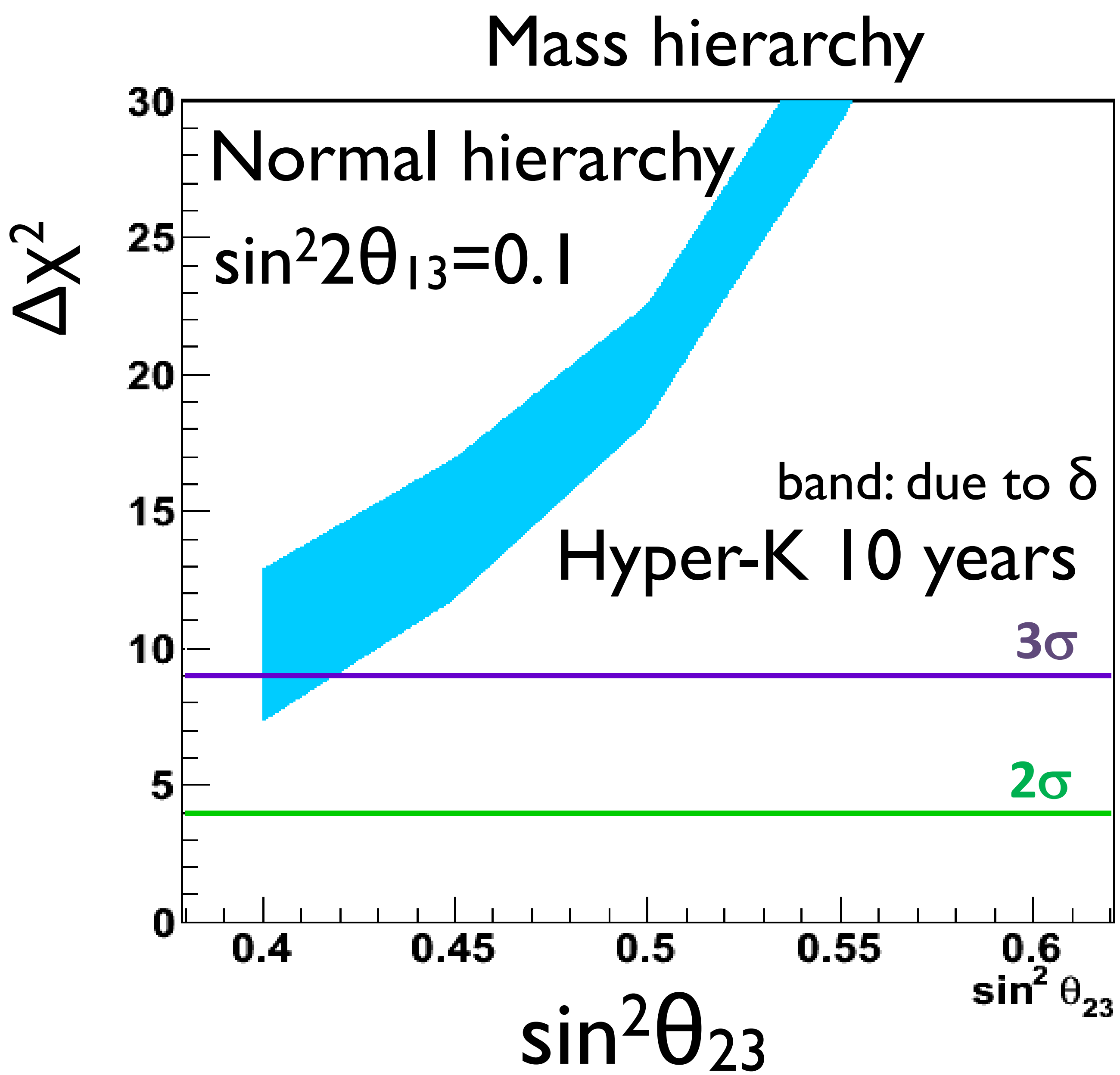
$$\boxed{A \equiv \frac{\sqrt{2}G_F n_e}{\Delta m^2_{32}/2E} \sim \frac{E}{11.5\text{ GeV}}}$$

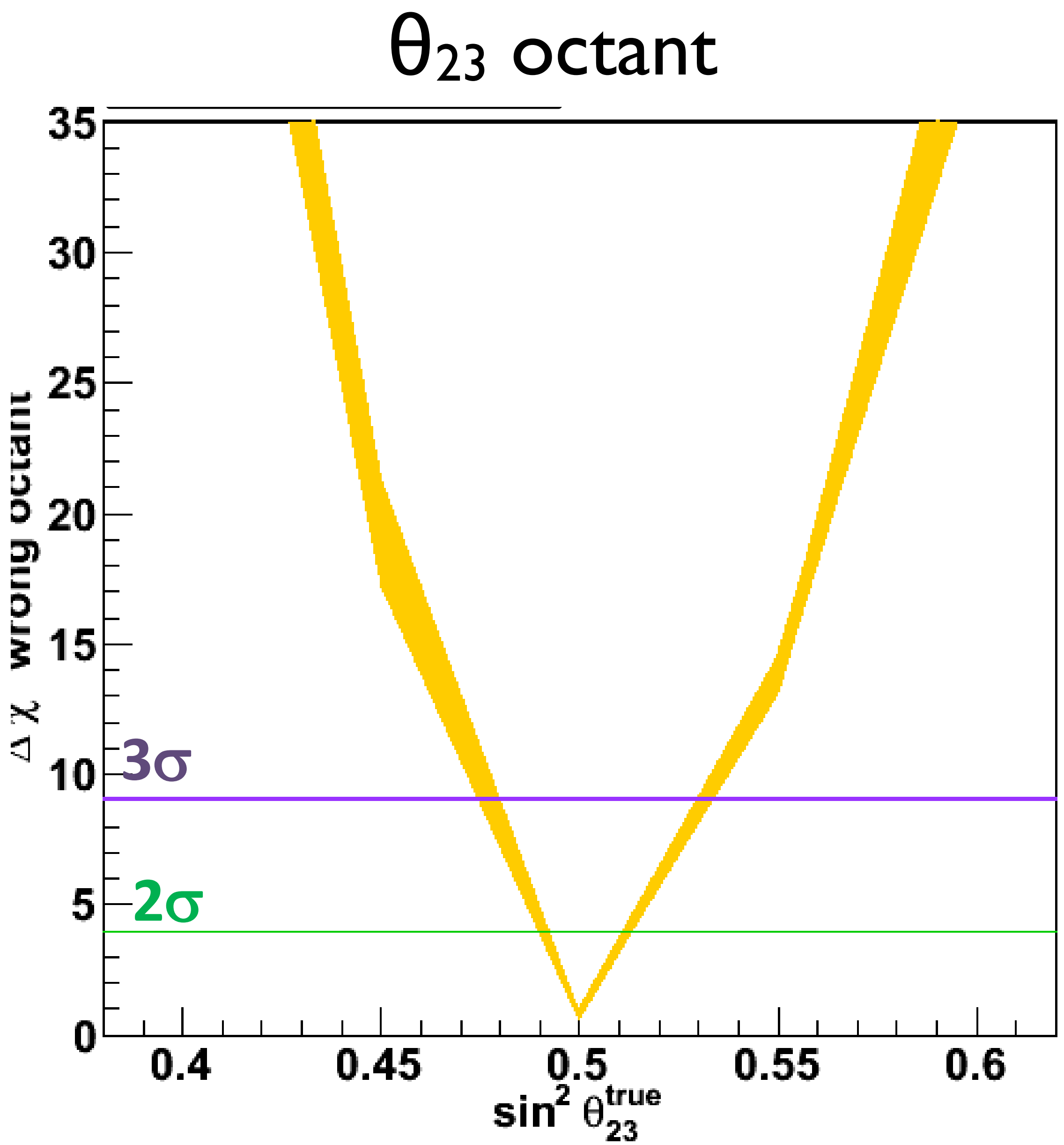
$$\tan(2\tilde{\theta}_{13}) \equiv \frac{\sin(2\theta_{13})}{\cos(2\theta_{13})-A}$$



- Matter effects change osc. prob. by 30% for NOvA (810 km), 11% for T2K (295 km)

Atmospheric ν





Complementary measurements to accelerator ν
Combined analysis of acc + atm ν will enhance capability