SUSY'16
Melbourne, 7/07/2016

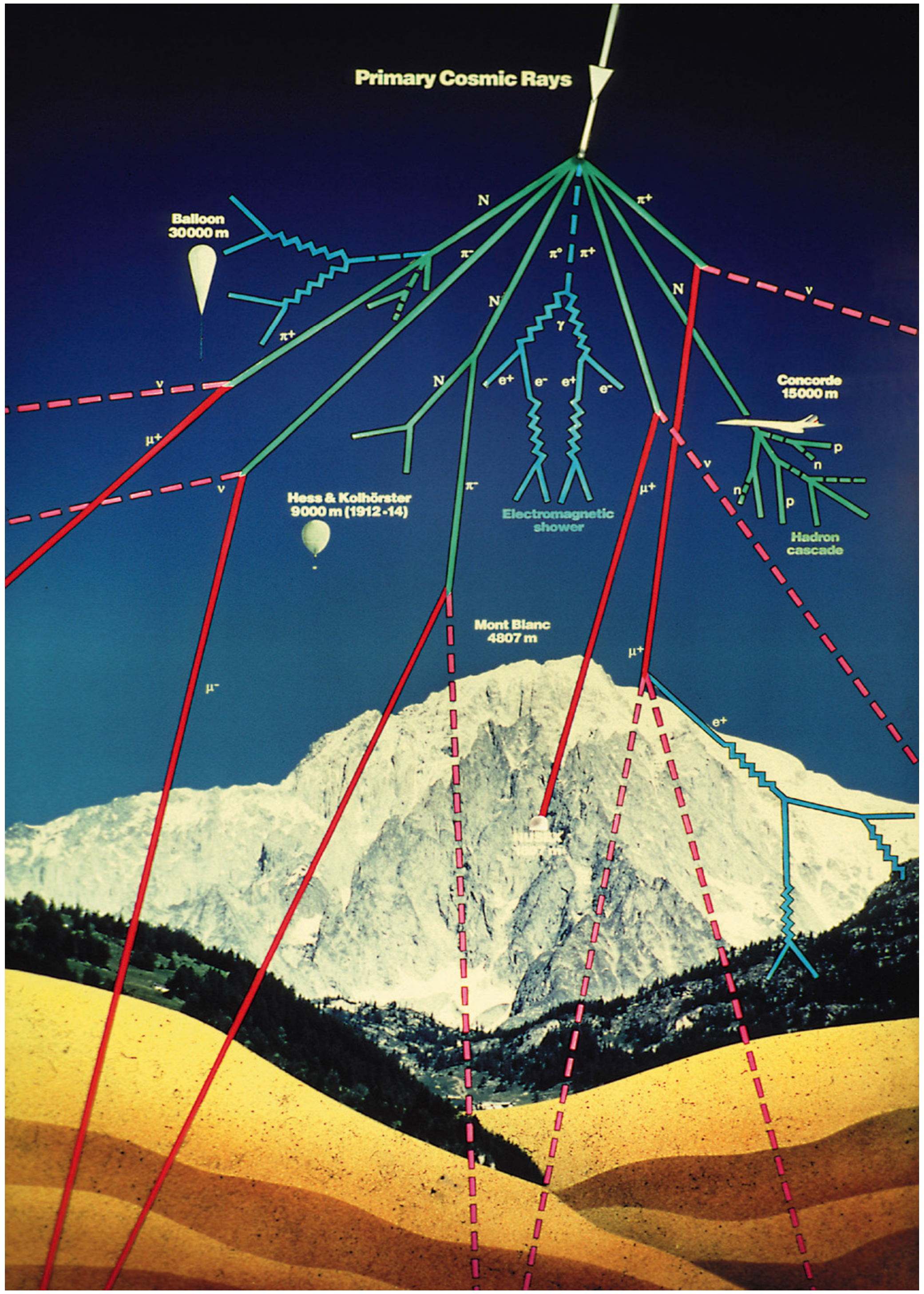
Latest Results from Neutrino Oscillation Experiments

Anselmo Cervera Villanueva
IFIC (UV-CSIC)
Valencia

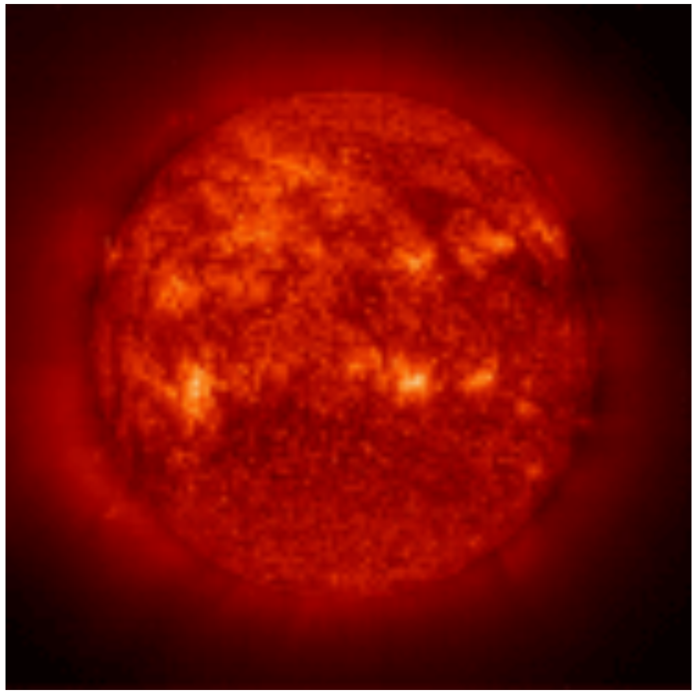
On behalf of the T2K Collaboration

Neutrino sources

Atmosphere



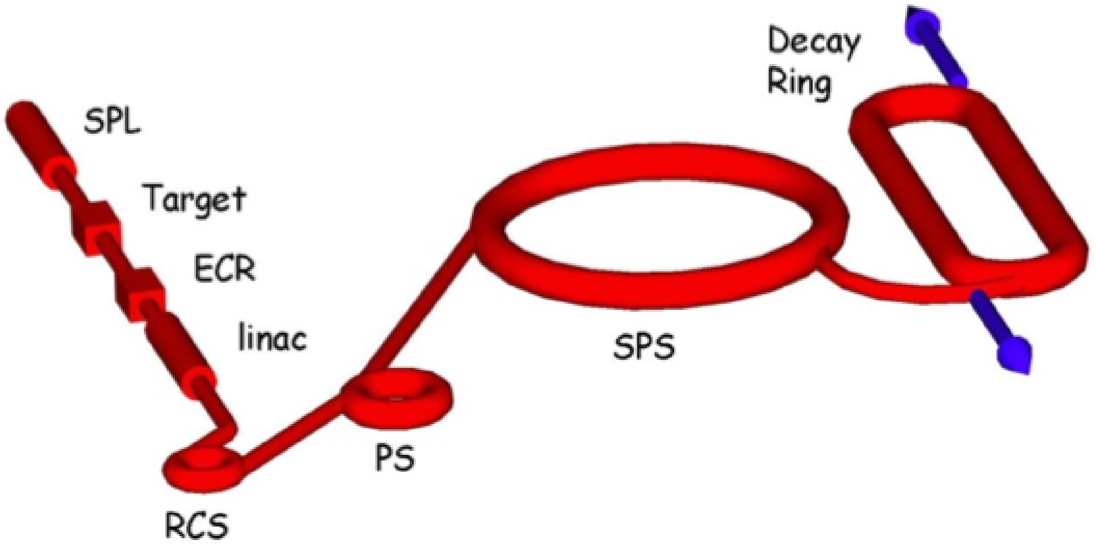
Sun



Supernovae

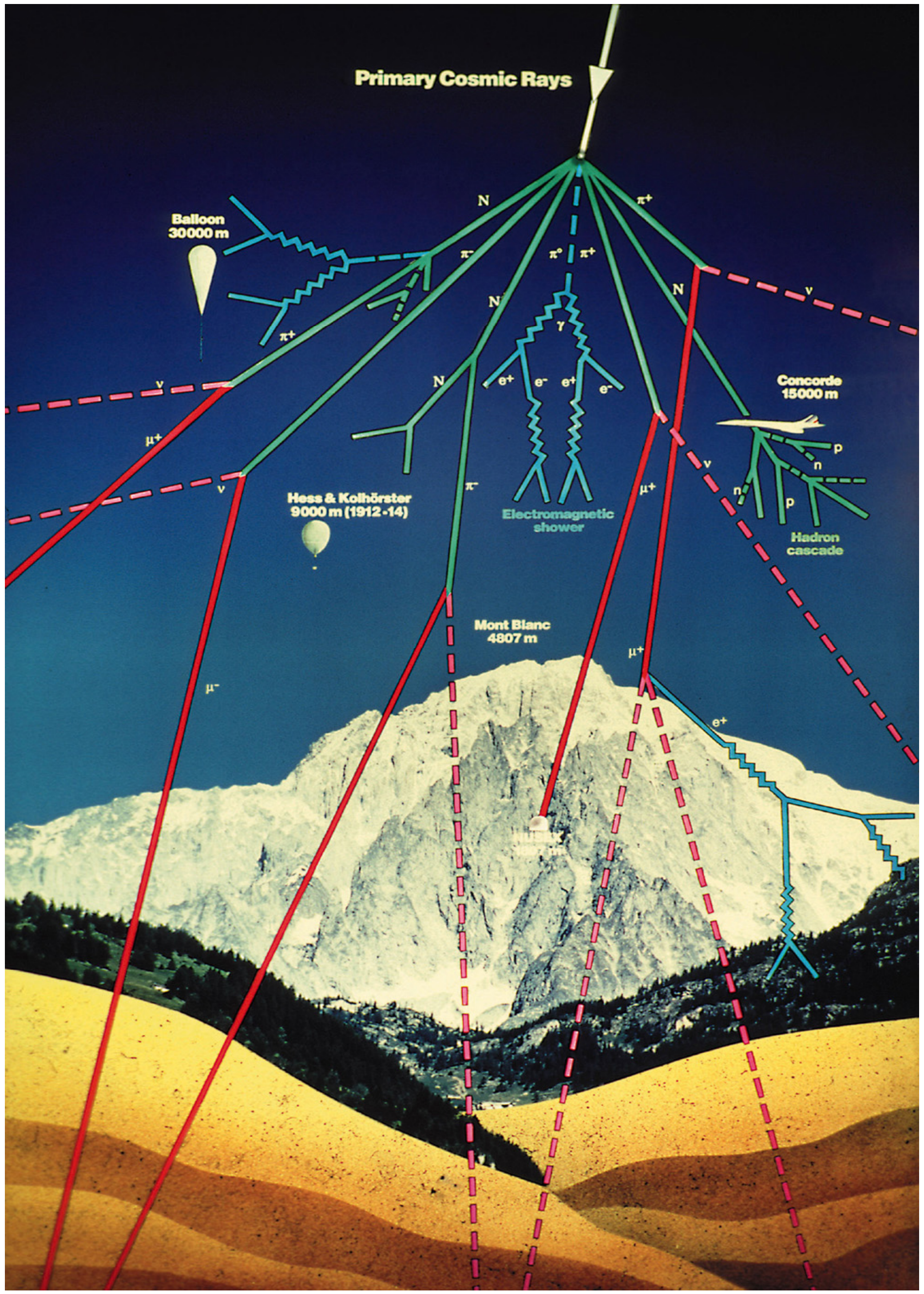
Reactors

Accelerators

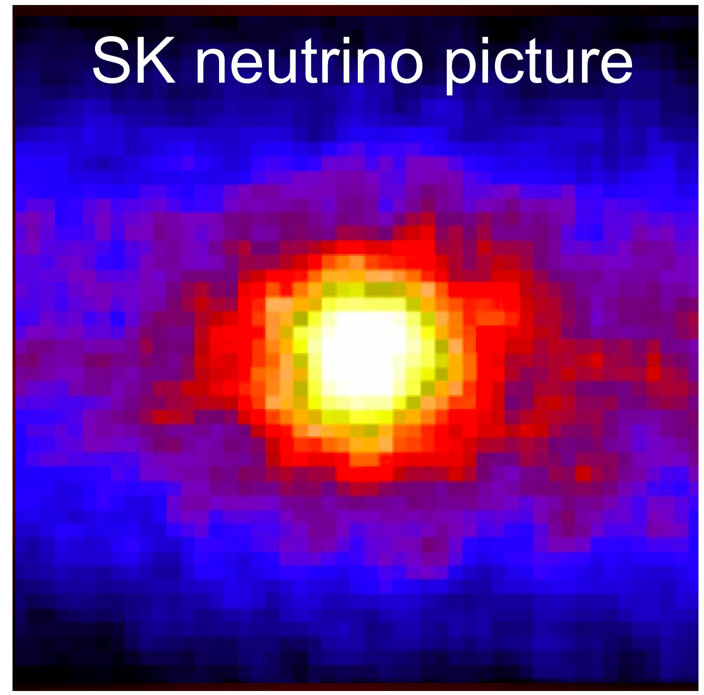


Neutrino sources

Atmosphere



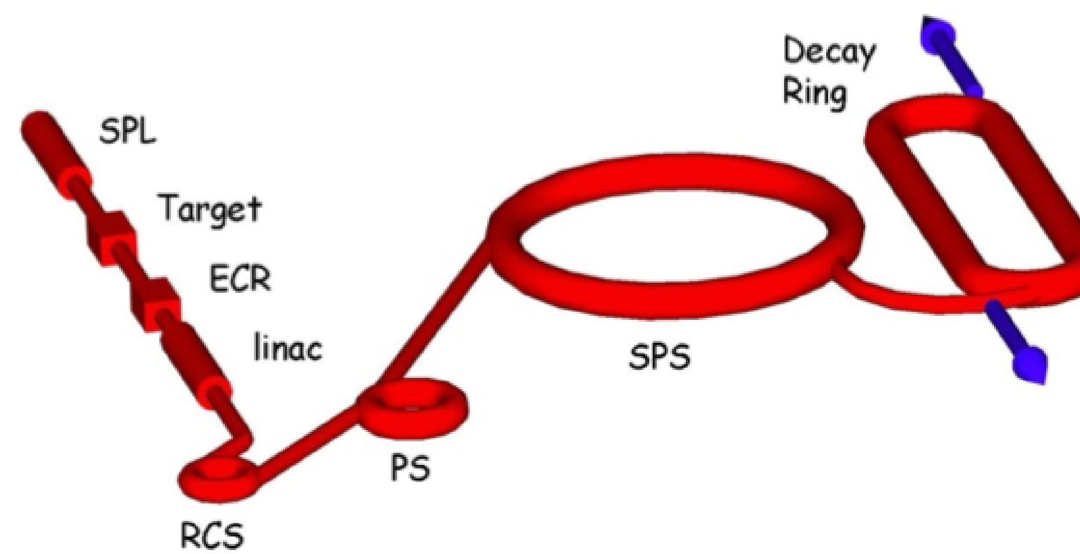
Sun



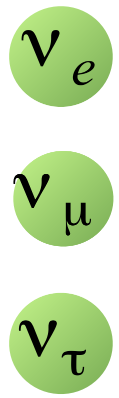
Supernovae

Reactors

Accelerators



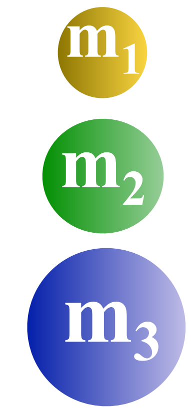
Flavour mixing



weak
eigenstates

$$\nu_{\alpha L} = \sum_{k=1}^{n} U_{\alpha k} \nu_{kL}$$

(arbitrary sizes)



mass
eigenstates

Flavour mixing

ν_e

ν_μ

ν_τ

weak eigenstates

$$\nu_{\alpha L} = \sum_{k=1}^{n} U_{\alpha k} \nu_{kL}$$

(arbitrary sizes)

m_1

m_2

m_3

mass eigenstates

PMNS mixing matrix

Pontecorvo–Maki–Nakagawa–Sakata

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{21} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

atmospheric sector — connection between solar and atmospheric — solar sector

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

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

Dirac

Flavour mixing

(arbitrary sizes)

ν_e

ν_μ

ν_τ

weak eigenstates

$$\nu_{\alpha L} = \sum_{k=1}^{n} U_{\alpha k} \nu_{kL}$$

m_1

m_2

m_3

mass eigenstates

θ_{23} | θ_{13}, δ_{CP} | θ_{12}

PMNS mixing matrix

Pontecorvo–Maki–Nakagawa–Sakata

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{21} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

atmospheric sector | connection between solar and atmospheric | solar sector

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

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

Dirac

Flavour mixing

ν_e

ν_μ

ν_τ

weak eigenstates

$$\nu_{\alpha L} = \sum_{k=1}^{n} U_{\alpha k} \nu_{kL}$$

(arbitrary sizes)

m_1

m_2

m_3

mass eigenstates

Δm^2_{12}

Δm^2_{23}

$\Delta m^2_{ij} = m^2_i - m^2_j$

θ_{23} θ_{13}, δ_{CP} θ_{12}

PMNS mixing matrix

Pontecorvo–Maki–Nakagawa–Sakata

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{21} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

atmospheric sector — connection between solar and atmospheric — solar sector

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

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

Dirac

Flavour mixing

ν_e

ν_μ

ν_τ

weak eigenstates

$$\nu_{\alpha L} = \sum_{k=1}^{n} U_{\alpha k} \nu_{kL}$$

(arbitrary sizes)

m_1

m_2

m_3

mass eigenstates

Δm^2_{12}

Δm^2_{23}

$\Delta m^2_{ij} = m^2_i - m^2_j$

θ_{23} | θ_{13}, δ_{CP} | θ_{12} | α_1, α_2

PMNS mixing matrix

Pontecorvo–Maki–Nakagawa–Sakata

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{21} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} e^{i\alpha_1} & 0 & 0 \\ 0 & e^{i\alpha_2} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

atmospheric sector | connection between solar and atmospheric | solar sector

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

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

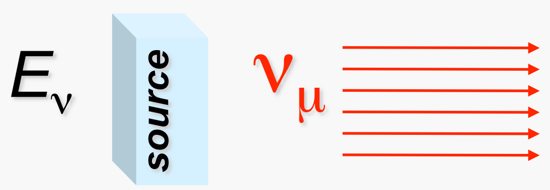
Majorana

Dirac

Neutrino oscillations

Requirements: Massive neutrinos & different masses

weak Hamiltonian

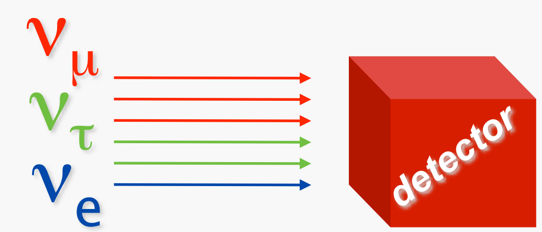


free Hamiltonian
(mass eigenstates)

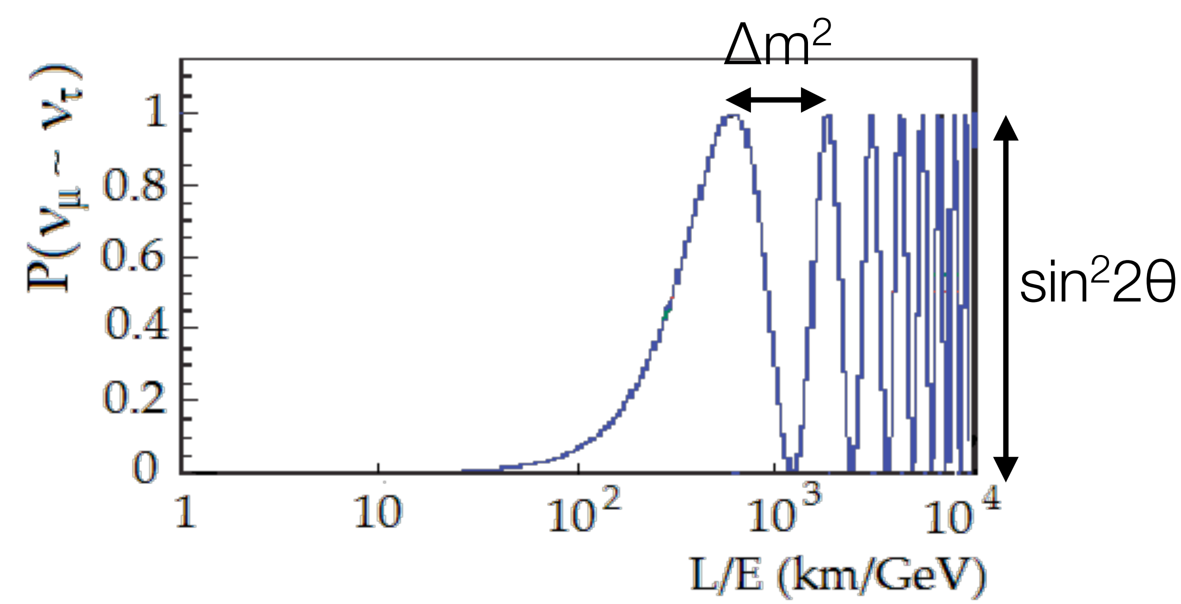
$$P_{\nu_\mu \nu} \sim \sin^2 2\theta \cdot \sin^2\left(\frac{\Delta m^2 \cdot L}{4E_\nu}\right)$$

2-family approx. for illustration purposes

weak Hamiltonian



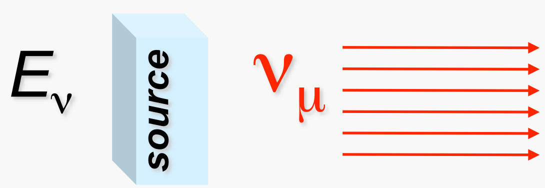
L



Neutrino oscillations

Requirements: Massive neutrinos & different masses

weak Hamiltonian

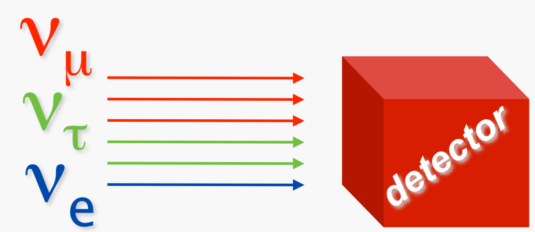


free Hamiltonian
(mass eigenstates)

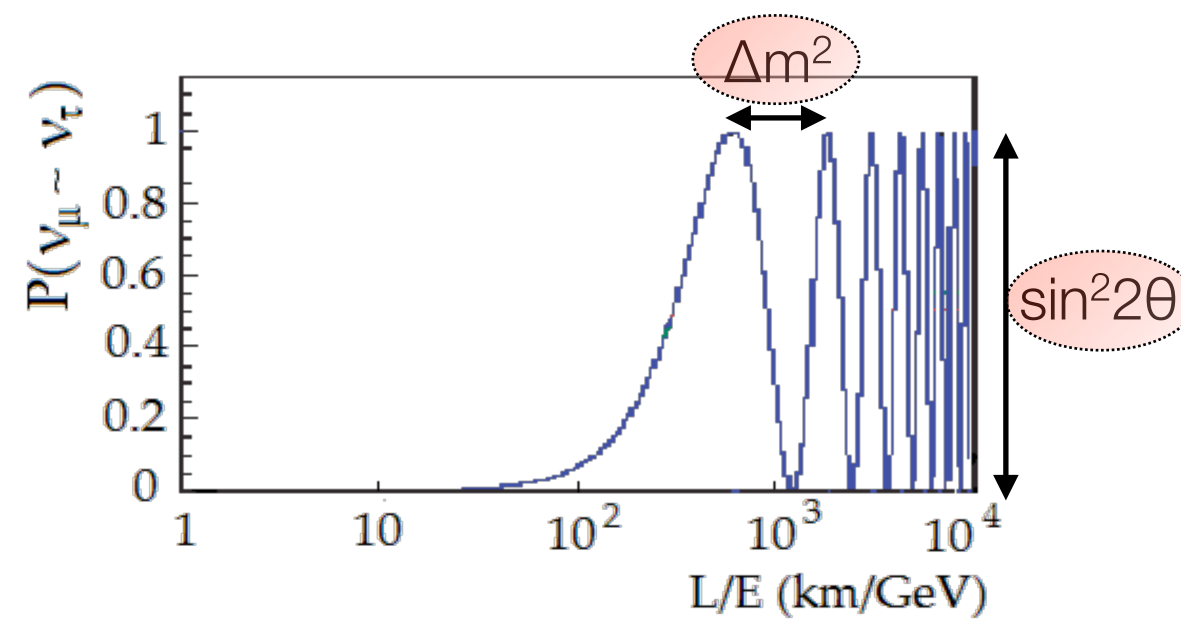
$$P_{\nu_\mu \nu} \sim \sin^2 2\theta \cdot \sin^2\left(\frac{\Delta m^2 \cdot L}{4E_\nu}\right)$$

2-family approx. for illustration purposes

weak Hamiltonian



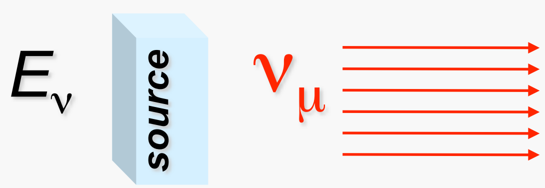
L



Neutrino oscillations

Requirements: Massive neutrinos & different masses

weak Hamiltonian

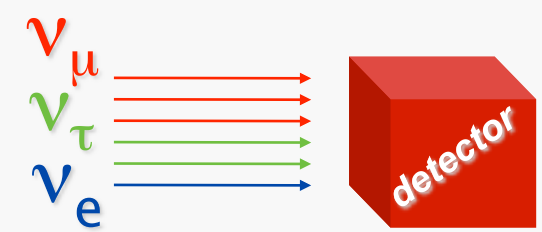


free Hamiltonian
(mass eigenstates)

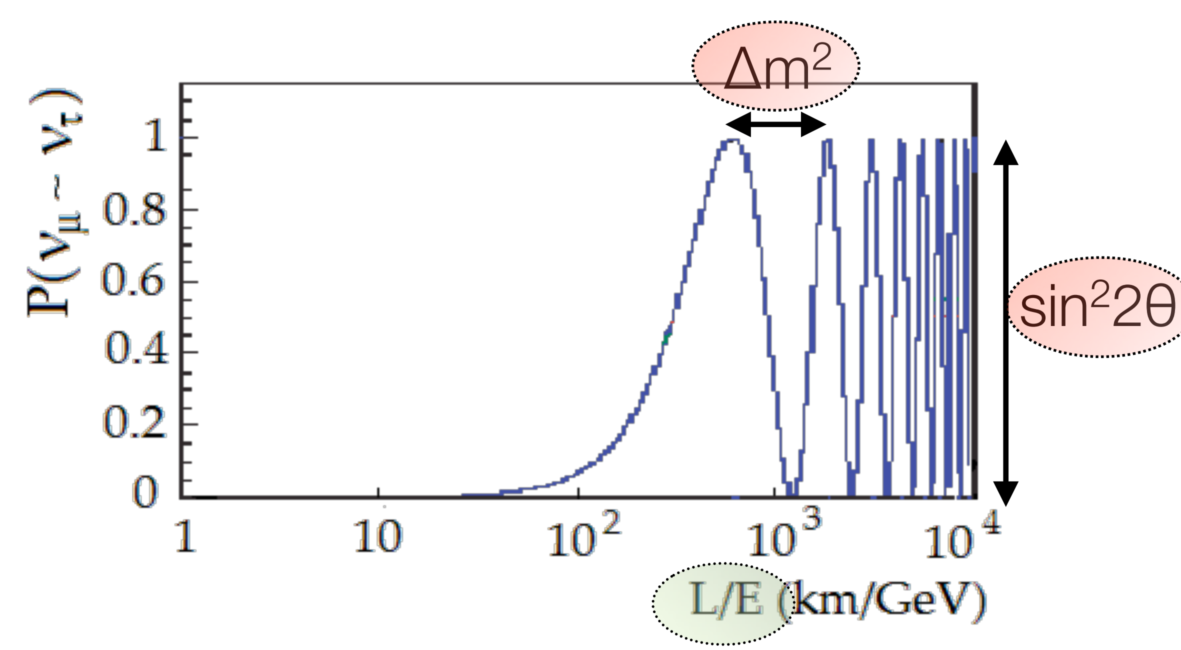
$$P_{\nu_\mu \nu} \sim \sin^2 2\theta \cdot \sin^2\left(\frac{\Delta m^2 \cdot L}{4E_\nu}\right)$$

2-family approx. for illustration purposes

weak Hamiltonian

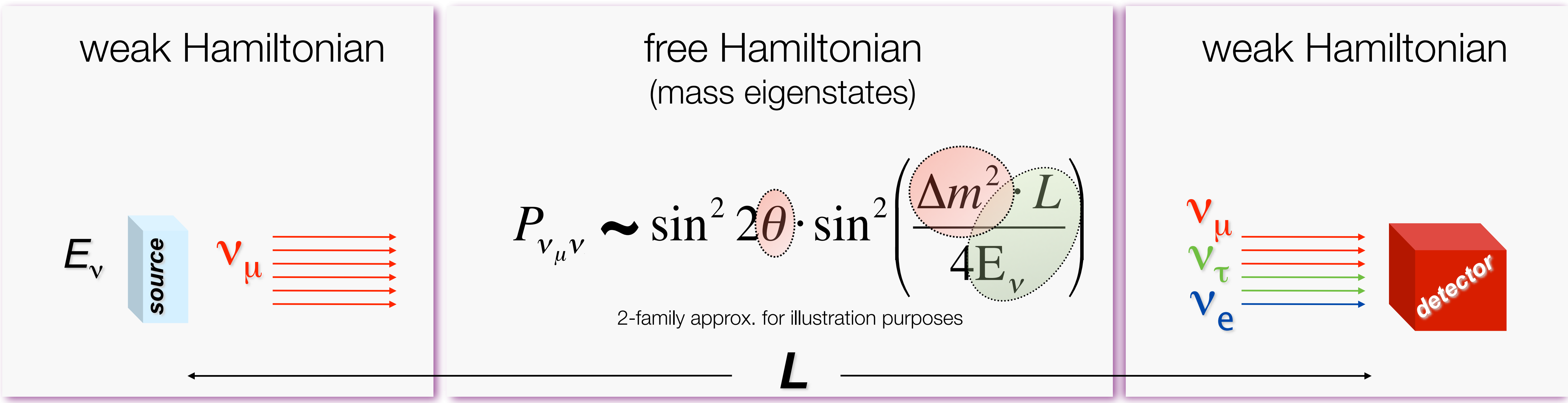


L

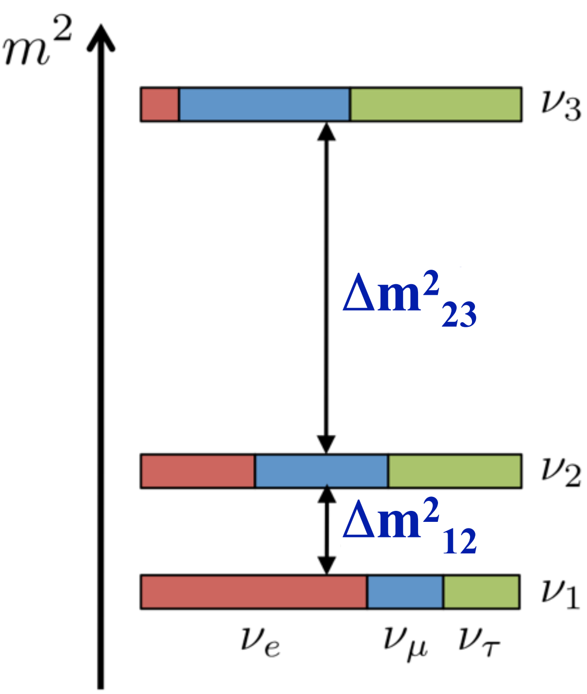


Neutrino oscillations

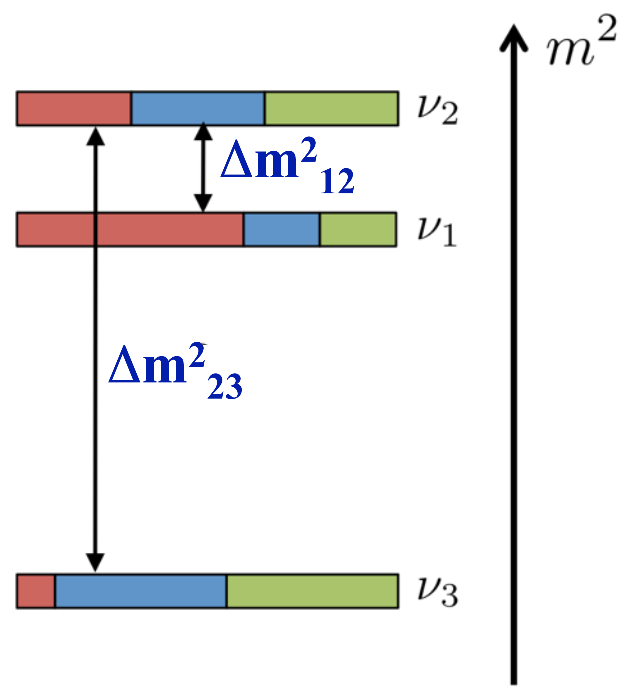
Requirements: Massive neutrinos & different masses

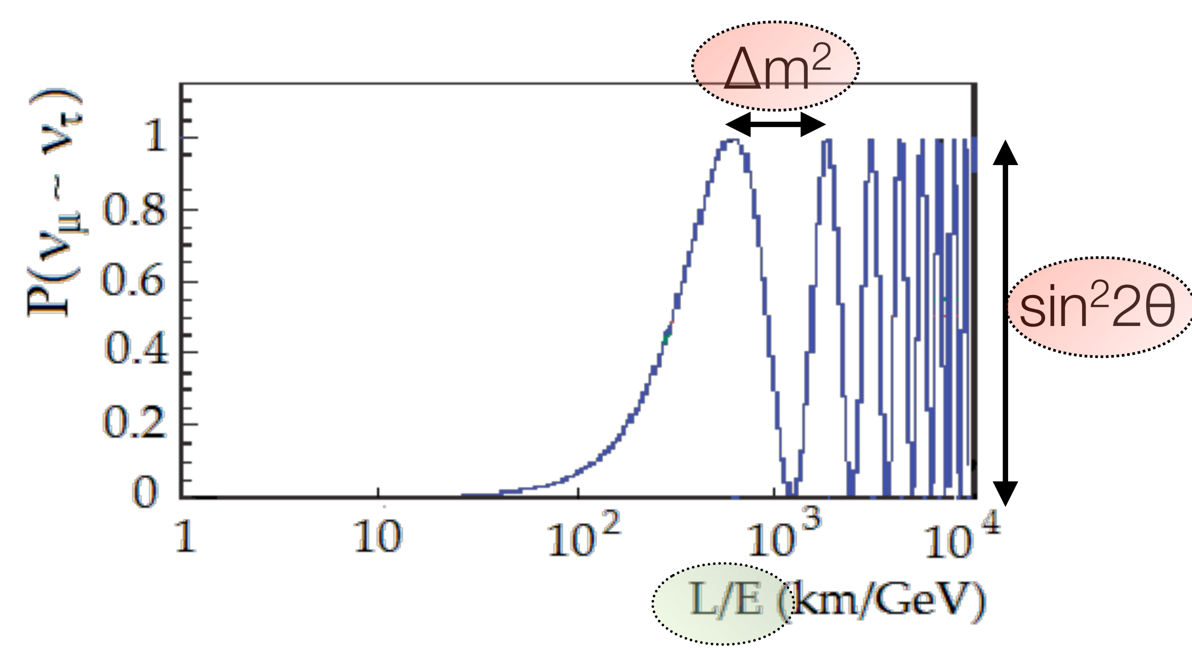


normal hierarchy (NH)



inverted hierarchy (IH)





A bit of recent history

1998: Super-Kamiokande discovered neutrino oscillations ($\boldsymbol{\nu_\mu \rightarrow \nu_x}$)

1999: K2K (Japan) is the first Long-Baseline (LBL) ν-osc experiment

2001: SNO discovered the solar transition ($\boldsymbol{\nu_e \rightarrow \nu_x}$)

2002: Kamland (Japan) reactor experiment confirms solar transition ($\boldsymbol{\bar{\nu}_e \rightarrow \bar{\nu}_x}$)

2002: **Nobel Prize** for Koshiba and Davis

2011: T2K (Japan, LBL) has 2.5σ indication of $\boldsymbol{\nu_\mu \rightarrow \nu_e}$ (and $\boldsymbol{\theta_{13} \neq 0}$)

2012: Daya-Bay (China) reactor experiment measured $\boldsymbol{\theta_{13} \neq 0}$ **(~8.4º)**

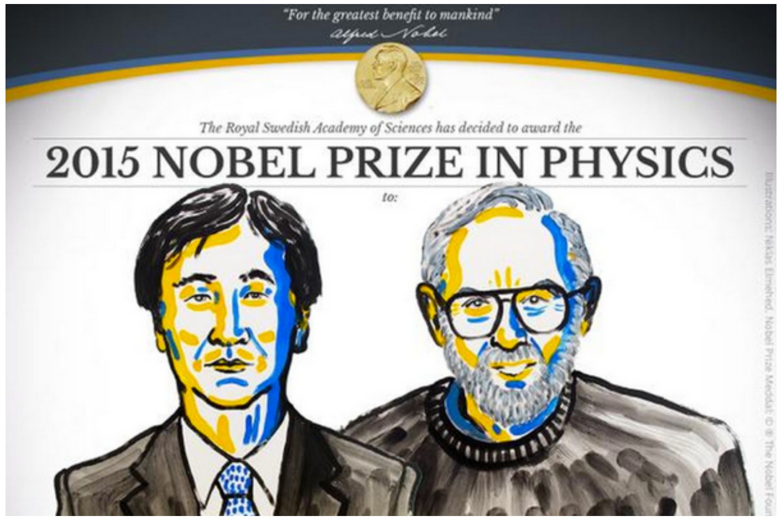
2013: T2K discovers (> 7σ) the $\boldsymbol{\nu_\mu \rightarrow \nu_e}$ transition

2014: NOvA (US) LBL experiment began data-taking

2015: OPERA (Italy, LBL) discovers $\boldsymbol{\nu_\mu \rightarrow \nu_\tau}$ oscillation

2015: US and EU LBL programs collapse into DUNE

2015: **Nobel Prize** for Kajita and McDonald



A bit of recent history

1998: Chooz (France) puts a limit on $\boldsymbol{\theta_{13}}$ **(<12º)**

1998: Super-Kamiokande discovered neutrino oscillations ($\boldsymbol{\nu_\mu \to \nu_x}$)

1999: K2K (Japan) is the first Long-Baseline (LBL) ν-osc experiment

2001: SNO discovered the solar transition ($\boldsymbol{\nu_e \to \nu_x}$)

2002: Kamland (Japan) reactor experiment confirms solar transition ($\boldsymbol{\bar{\nu}_e \to \bar{\nu}_x}$)

2002: **Nobel Prize** for Koshiba and Davis

2011: T2K (Japan, LBL) has 2.5σ indication of $\boldsymbol{\nu_\mu \to \nu_e}$ (and $\boldsymbol{\theta_{13} \neq 0}$)

2012: Daya-Bay (China) reactor experiment measured $\boldsymbol{\theta_{13} \neq 0}$ **(~8.4º)**

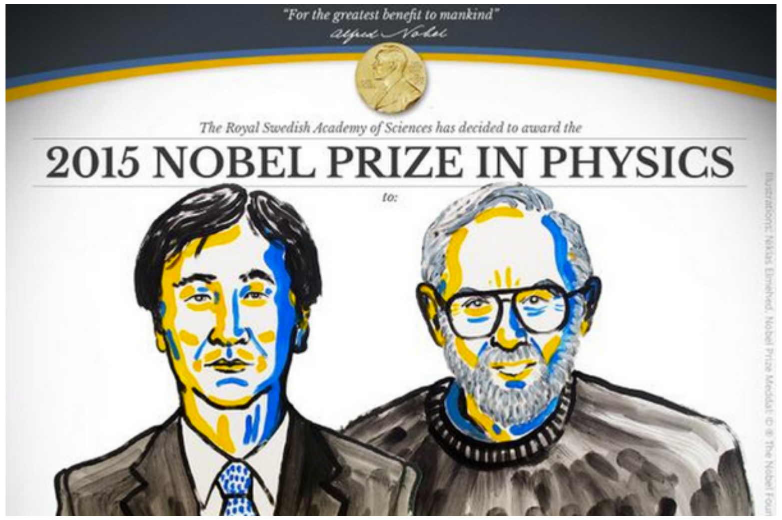
2013: T2K discovers (> 7σ) the $\boldsymbol{\nu_\mu \to \nu_e}$ transition

2014: NOvA (US) LBL experiment began data-taking

2015: OPERA (Italy, LBL) discovers $\boldsymbol{\nu_\mu \to \nu_\tau}$ oscillation

2015: US and EU LBL programs collapse into DUNE

2015: **Nobel Prize** for Kajita and McDonald



Experimental strategies

θ_{23}~42º (8.4%), **octant ?** **θ_{13}~8.9º** (2%), **δ_{CP} ?** **θ_{12} ~34º** (4.5%)

$$\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{21} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

2015

Δm^2_{12} ~ 7.5x10^{-5} eV^2 (3.4%)

$|\Delta m^2_{23}|$ ~ 2.4x10^{-3} eV^2 (2.4%)

sign(Δm^2_{23}) unknown

Experimental strategies

θ_{23}~42º (8.4%), **octant ?** **θ_{13}~8.9º** (2%), **δ_{CP} ?** **θ_{12} ~34º** (4.5%)

$$\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{21} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

PDG particle data group **2015**

Δm^2_{12} ~ 7.5x10^{-5} eV^2 (3.4%)
$|\Delta m^2_{23}|$ ~ 2.4x10^{-3} eV^2 (2.4%)
sign(Δm^2_{23}) unknown

Experimental strategies

θ_{23}~42º (8.4%), **octant ?** **θ_{13}~8.9º** (2%), **δ_{CP} ?** **θ_{12} ~34º** (4.5%)

$$\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{21} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

PDG particle data group **2015**

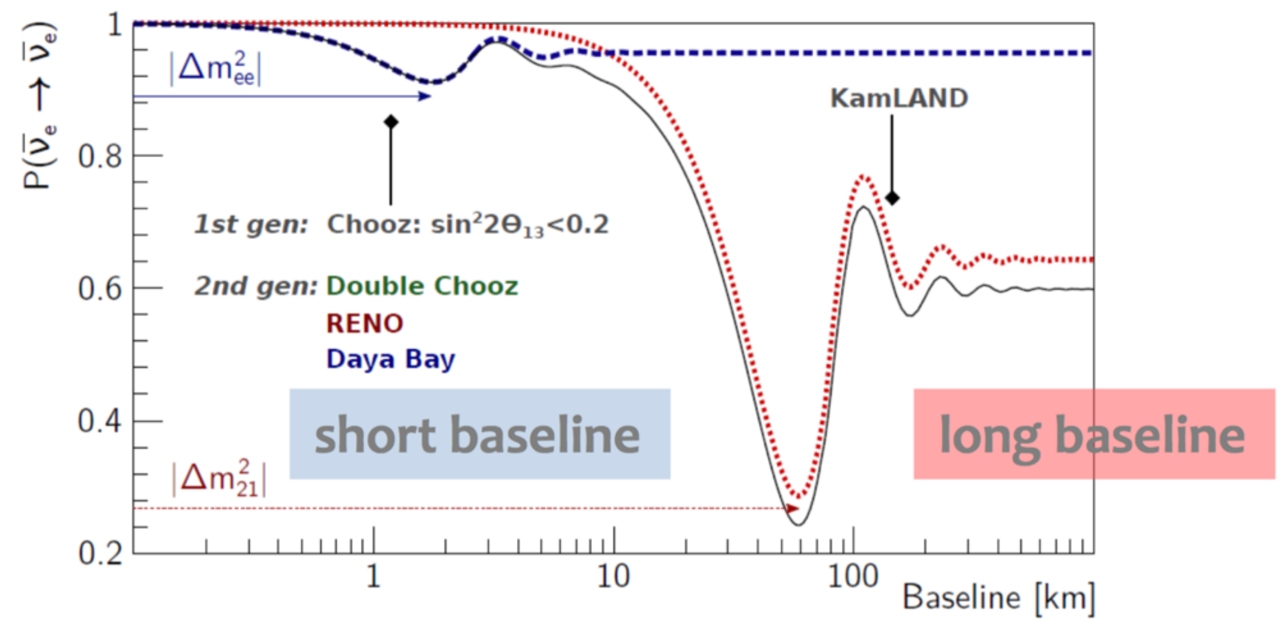
Δm^2_{12} ~ 7.5x10^{-5} eV^2 (3.4%)
$|\Delta m^2_{23}|$ ~ 2.4x10^{-3} eV^2 (2.4%)
sign(Δm^2_{23}) unknown

- Independent θ_{13} measurement at reactor experiments

short baseline **long baseline**

$$P_{\bar{\nu}_e\to\bar{\nu}_e} = 1 - \sin^2 2\theta_{13}\sin^2(\Delta m^2_{ee}\frac{L}{4E}) - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2(\Delta m^2_{21}\frac{L}{4E})$$

$$\sin^2(\Delta m^2_{ee}\frac{L}{4E}) \equiv \cos^2\theta_{12}\sin^2(\Delta m^2_{31}\frac{L}{4E}) + \sin^2\theta_{12}\sin^2(\Delta m^2_{32}\frac{L}{4E})$$



Experimental strategies

θ_{23}~42º (8.4%), **octant ?** θ_{13}~8.9º (2%), **δ_{CP} ?** θ_{12} ~34º (4.5%)

$$\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{21} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

PDG particle data group 2015

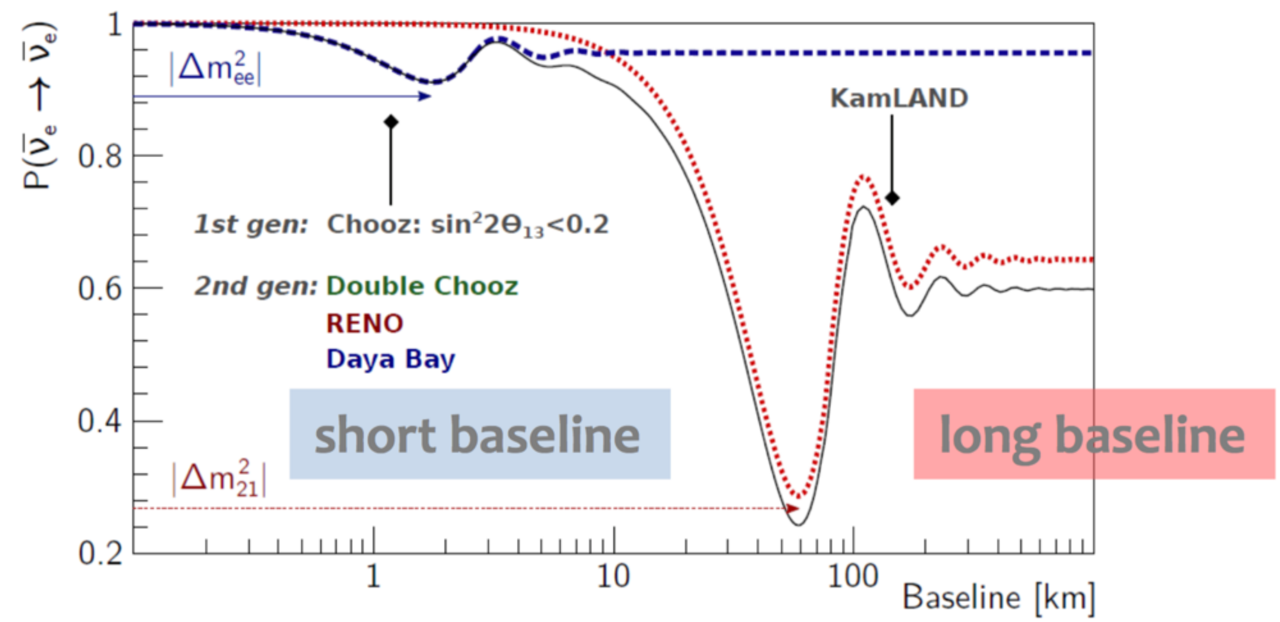
Δm^2_{12} ~ 7.5x10^{-5} eV^2 (3.4%)
$|\Delta m^2_{23}|$ ~ 2.4x10^{-3} eV^2 (2.4%)
sign(Δm^2_{23}) unknown

- Independent θ_{13} measurement at reactor experiments

short baseline / long baseline

$$P_{\bar{\nu}_e\to\bar{\nu}_e} = 1 - \sin^2 2\theta_{13}\sin^2(\Delta m^2_{ee}\frac{L}{4E}) - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2(\Delta m^2_{21}\frac{L}{4E})$$

$$\sin^2(\Delta m^2_{ee}\frac{L}{4E}) \equiv \cos^2\theta_{12}\sin^2(\Delta m^2_{31}\frac{L}{4E}) + \sin^2\theta_{12}\sin^2(\Delta m^2_{32}\frac{L}{4E})$$



- θ_{13}-δ_{CP} measurement at LBL experiments: ν_e appearance

$$\begin{aligned} P(\nu_\mu \to \nu_e) \sim\; & \sin^2 2\theta_{13} \times \sin^2\theta_{23} \times \frac{\sin^2[(1-x)\Delta]}{(1-x)^2} \\ & -\alpha\sin\delta \times \sin 2\theta_{12}\sin 2\theta_{13}\sin 2\theta_{23} \times \sin\Delta\frac{\sin[x\Delta]}{x}\frac{\sin[(1-x)\Delta]}{(1-x)} \\ & +\alpha\cos\delta \times \sin 2\theta_{12}\sin 2\theta_{13}\sin 2\theta_{23} \times \cos\Delta\frac{\sin[x\Delta]}{x}\frac{\sin[(1-x)\Delta]}{(1-x)} \\ & +\mathcal{O}(\alpha^2) \end{aligned}$$

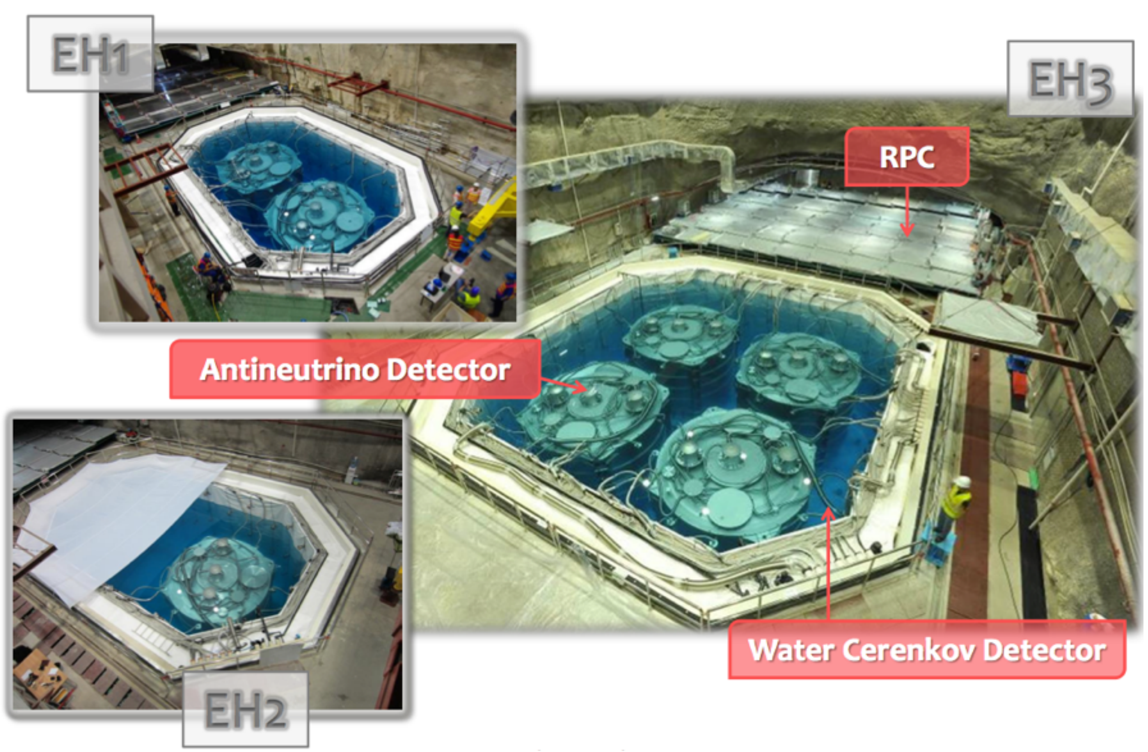
$$\alpha = \left|\frac{\Delta m^2_{21}}{\Delta m^2_{31}}\right| \sim \frac{1}{30} \qquad \Delta \equiv \frac{\Delta m^2_{31}L}{4E} \qquad x \equiv \frac{2\sqrt{2}G_F N_e E}{\Delta m^2_{31}}$$

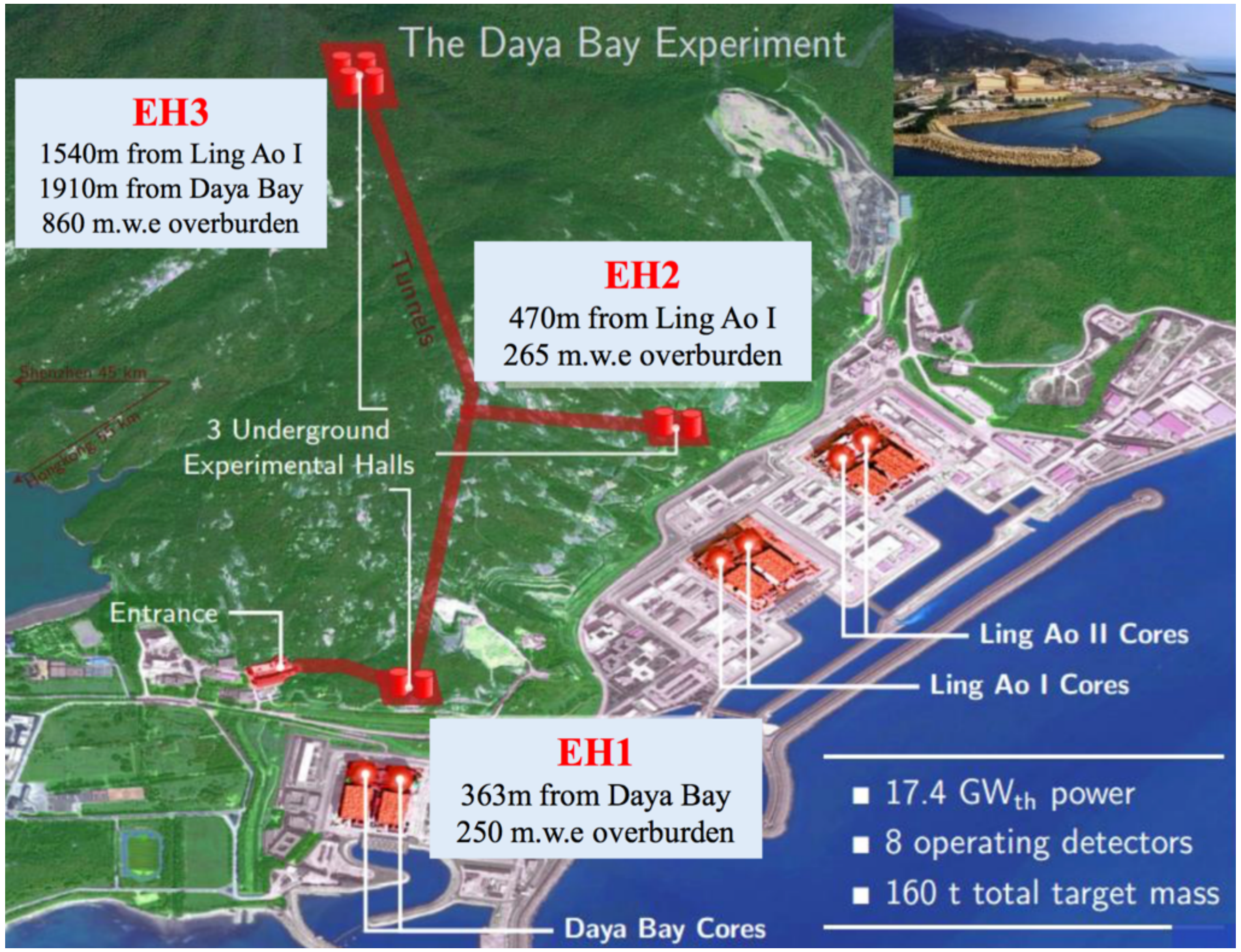
M. Freund, Phys.Rev. D64 (2001) 053003

- $\sin^2 2\theta_{13}$ dependence of leading term
- θ_{23} dependence of leading term: "octant" dependence (θ_{23}=/>/<45º?)
- CP odd phase δ: asymmetry of probabilities $P(\nu_\mu\to\nu_e) \neq P(\bar{\nu}_\mu\to\bar{\nu}_e)$ if sin δ ≠ 0
- Matter effect through x: $\nu_e(\bar{\nu}_e)$ enhanced in normal (inverted) hierarchy

Daya Bay reactor experiment

- $\overline{\nu}_e$ detection by Inverse Beta Decay (search for $\overline{\nu}_e$ disappearance)
- High statistics with 6 powerful reactors: 4th largest in the world
- Small reactor flux uncertainty by relative measurement: 2 near sites, 1 far site
- Small detector uncertainty with multiple identical detectors

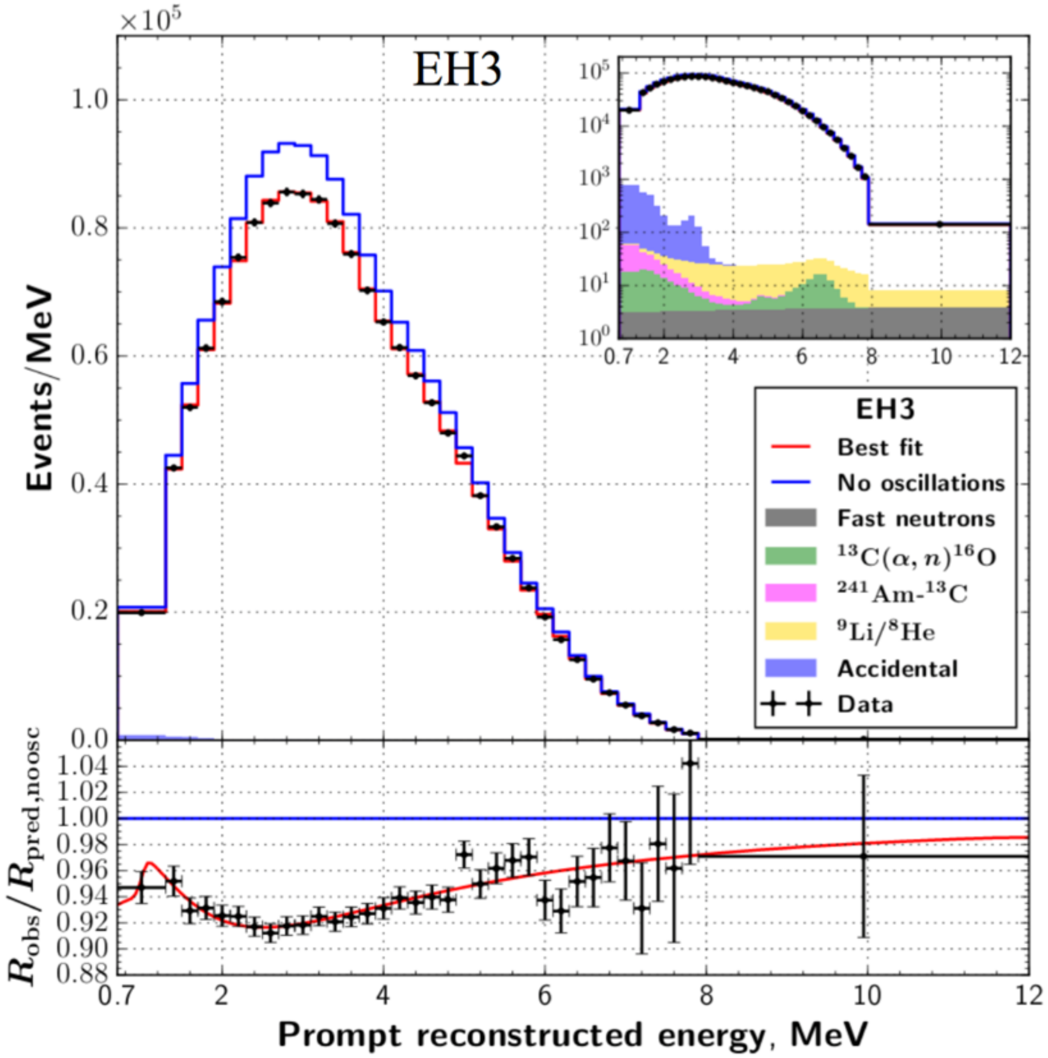


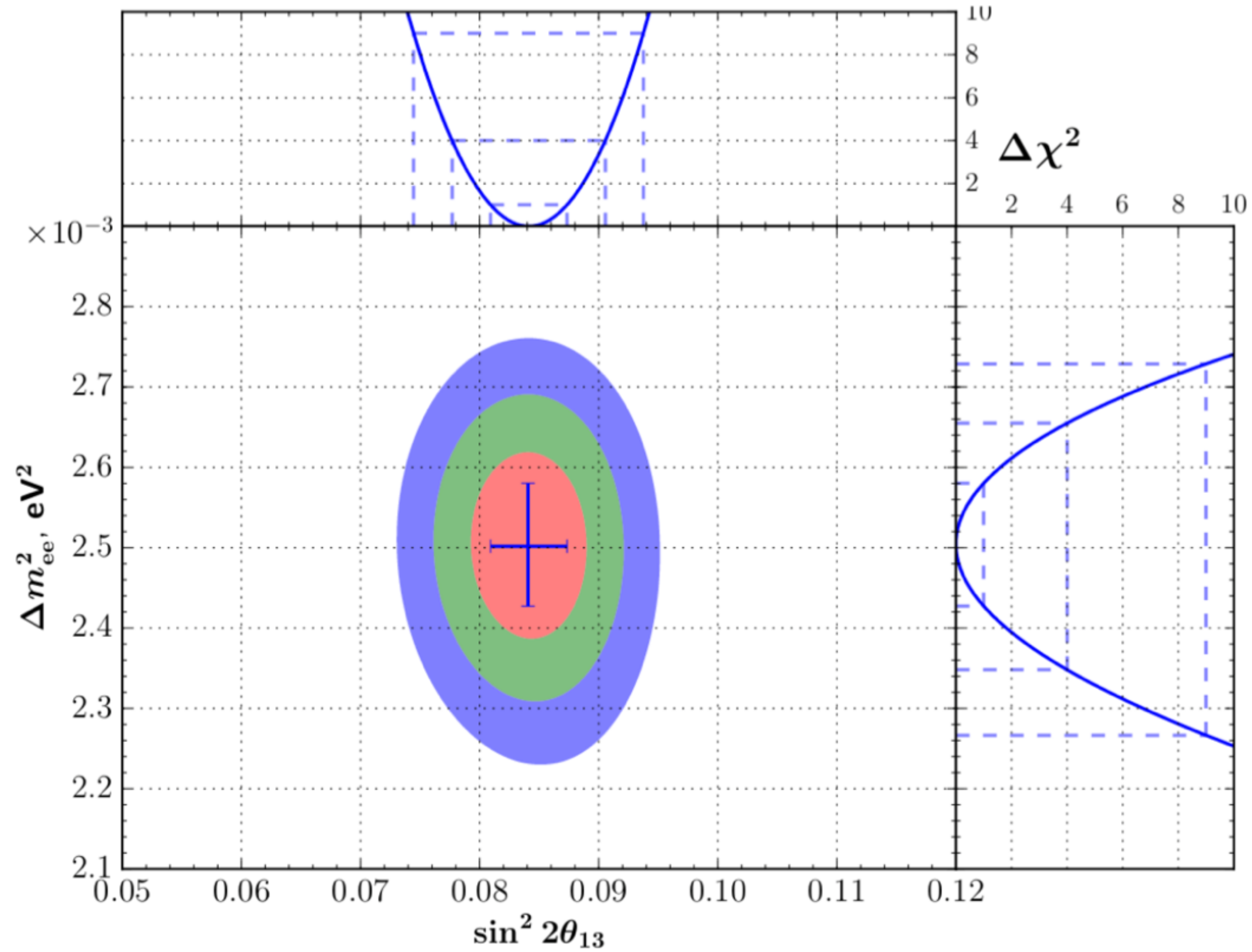


Latest results

See talk by B. ROSKOVEC, at 14:00 in flavour physics WG

1230 days data





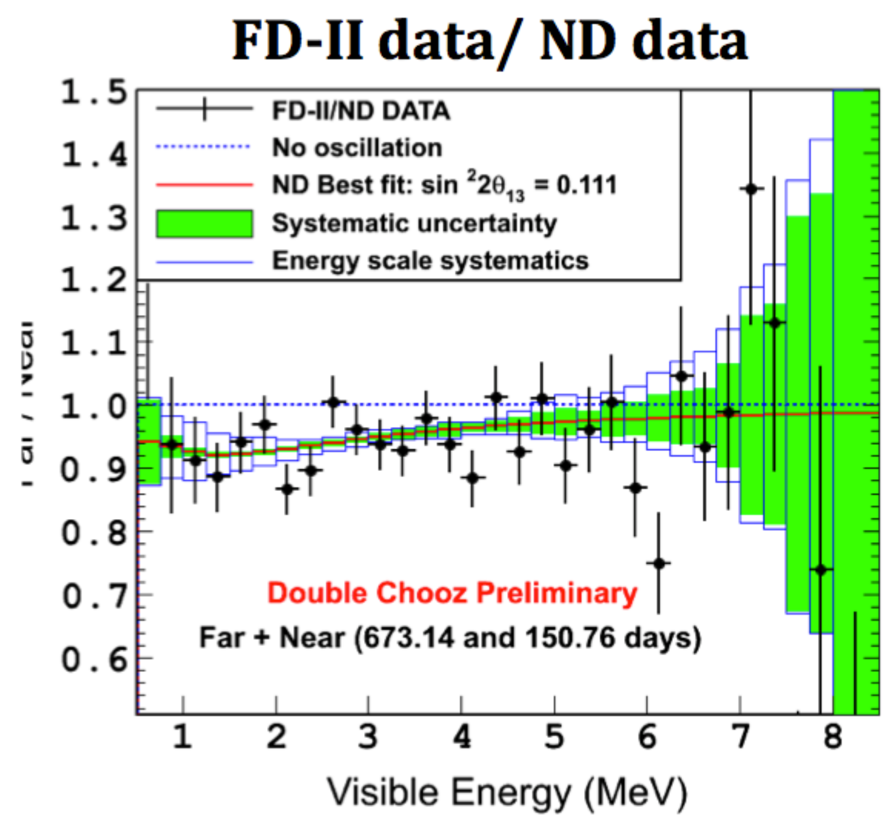
Best (by far) measurement of θ_{13} $\sin^2 2\theta_{13} = [8.41 \pm 0.33] \times 10^{-2}$ 4%

$|\Delta m^2_{ee}| = [2.50 \pm 0.08] \times 10^{-3} eV^2$

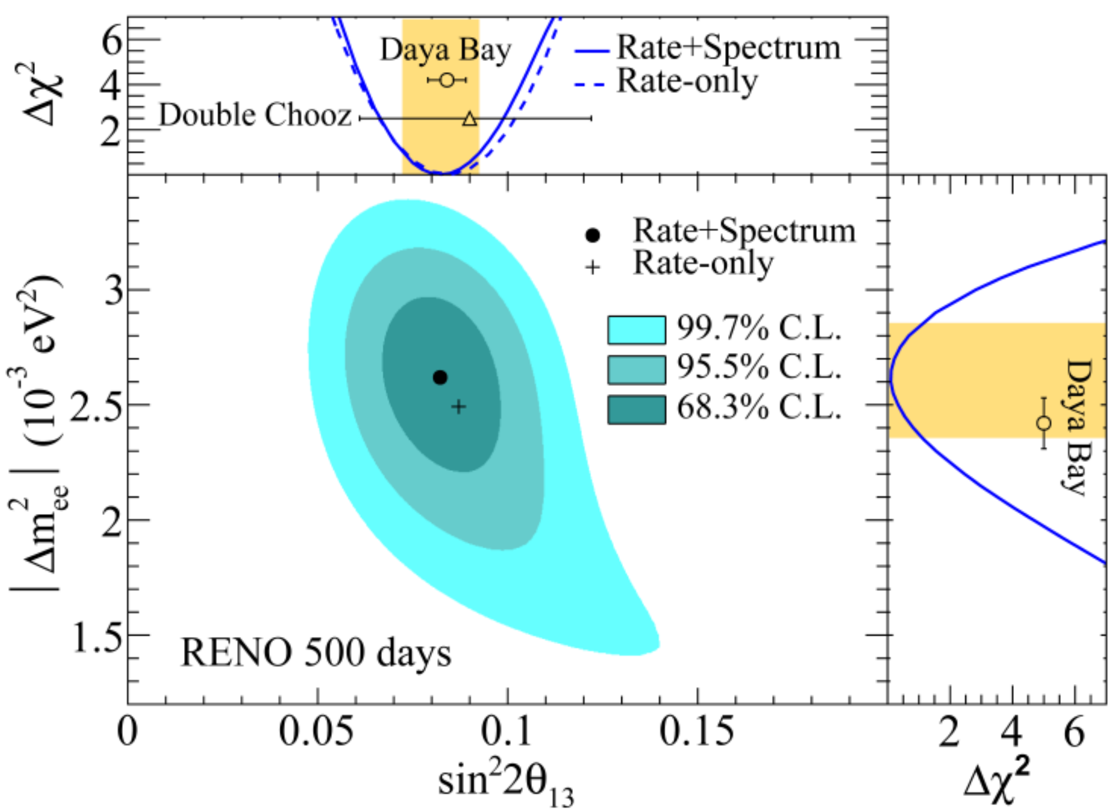
Significant precision on Δm^2_{23} $\Delta m^2_{32}(NH) = [2.45 \pm 0.08] \times 10^{-3} eV^2$ 3.3%

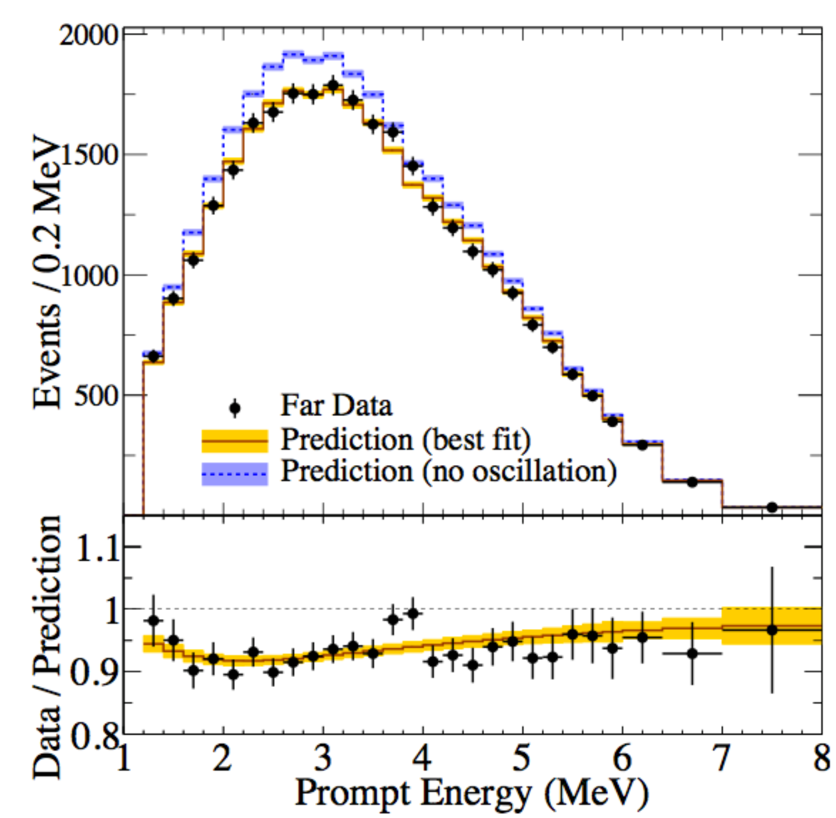
Other reactor experiments

- **Double-Chooz (France):** first results including near detector data
  - Lots of improvements in calibration and systematics but not new results since Moriond'16



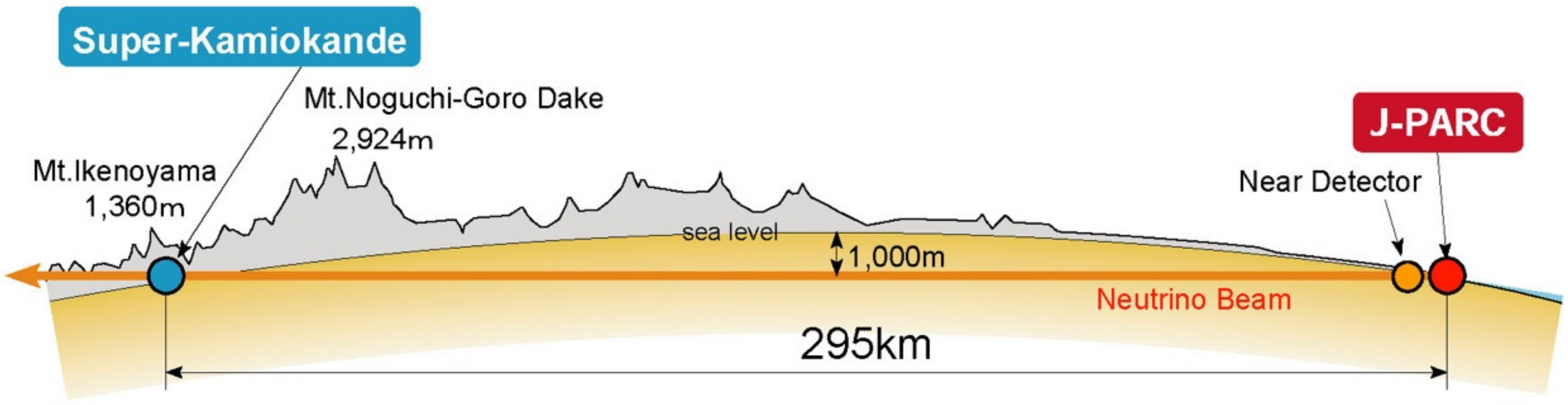
- **RENO (Korea):** Phys. Rev. Lett. 116, 211801 (May 2016)





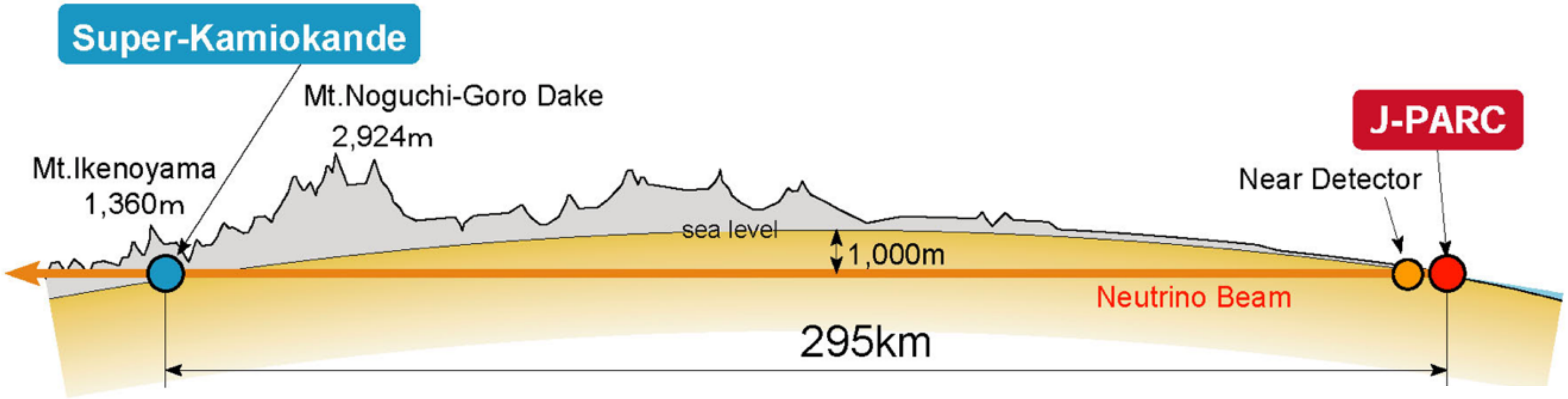
The T2K experiment

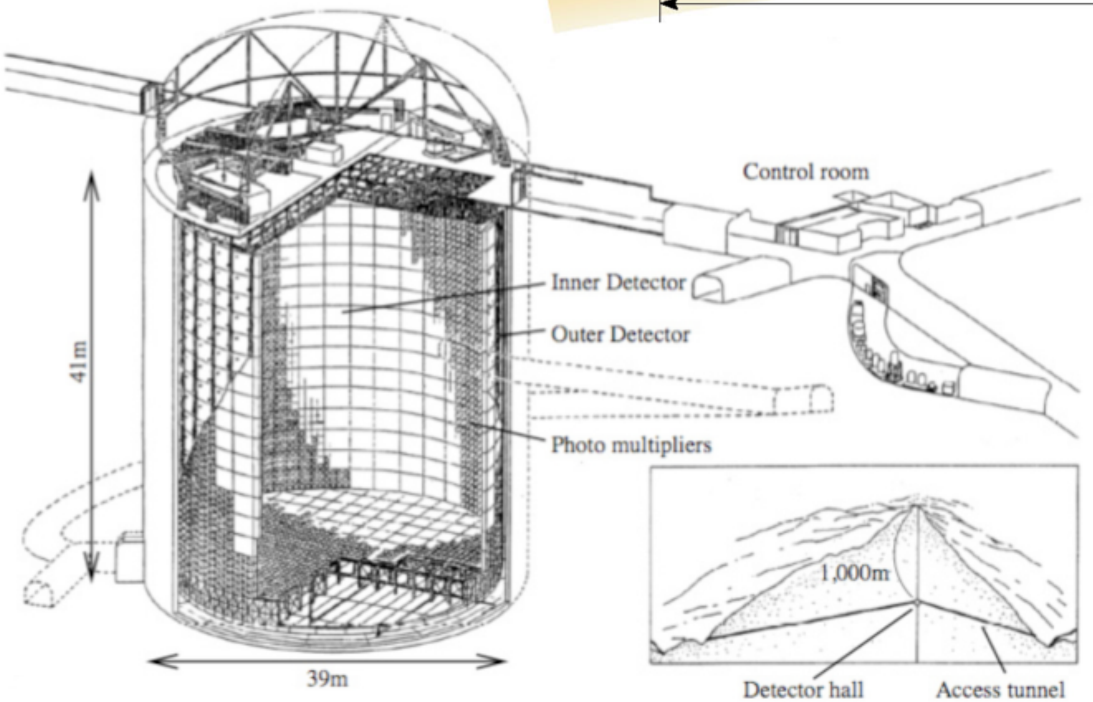
- **T2K** (Japan) was the first **off-axis** neutrino oscillation experiment, started taking data early 2010 and in 2011 published the first indication of **electron neutrino appearance** (and non-zero θ_{13}), which was later discovered (> 5σ) in 2013

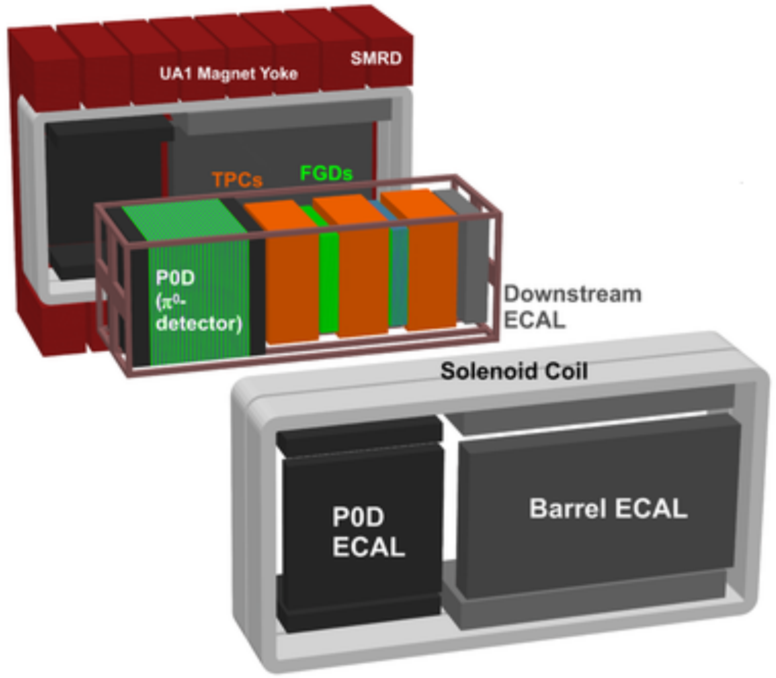


- Taking data in anti-neutrino mode since 2014
- Next goals:
  - Discover $\bar{\nu}_e$ appearance
  - Search for strong indication of CP violation

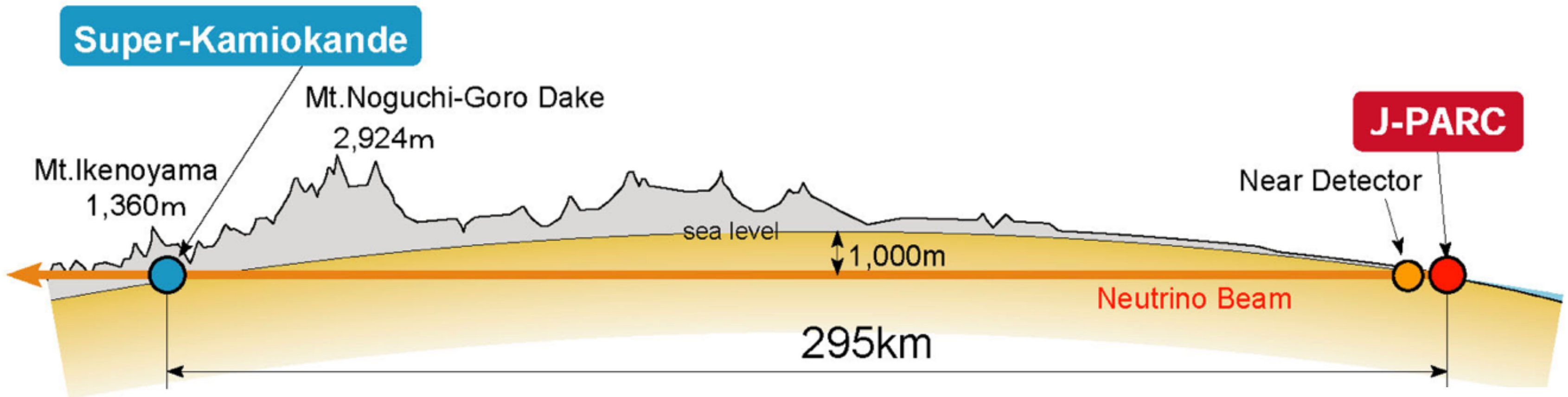
T2K detectors

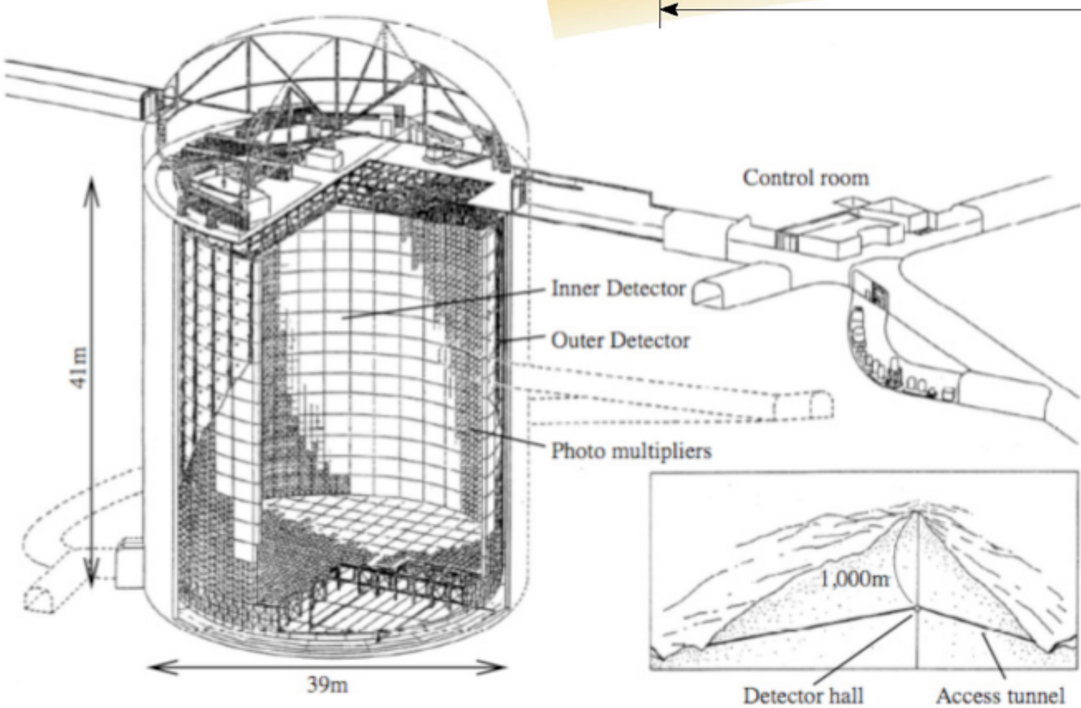


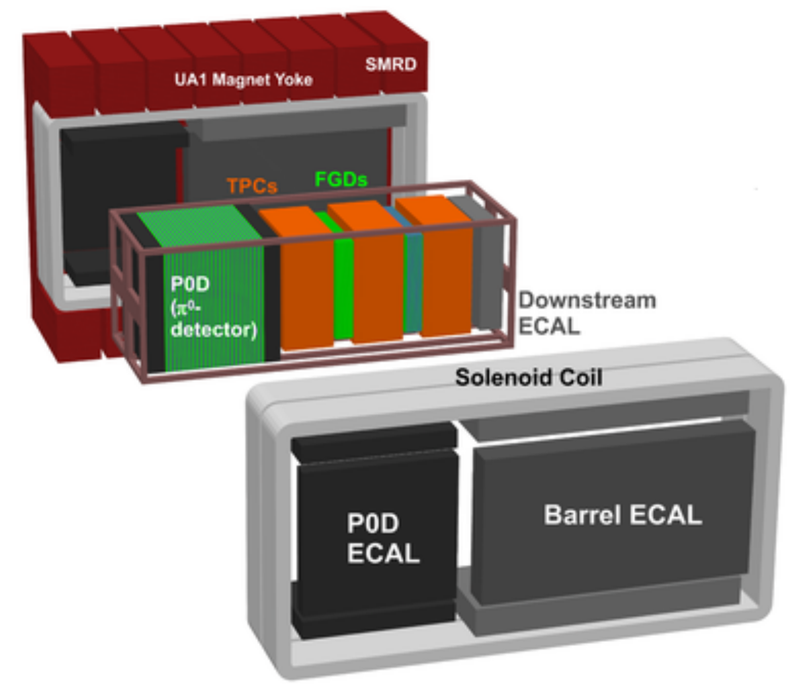


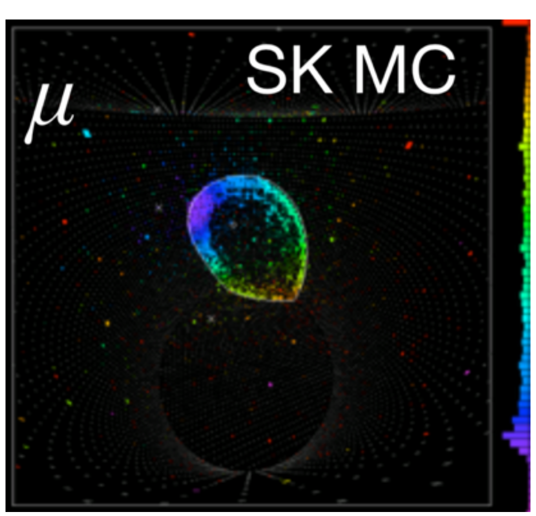


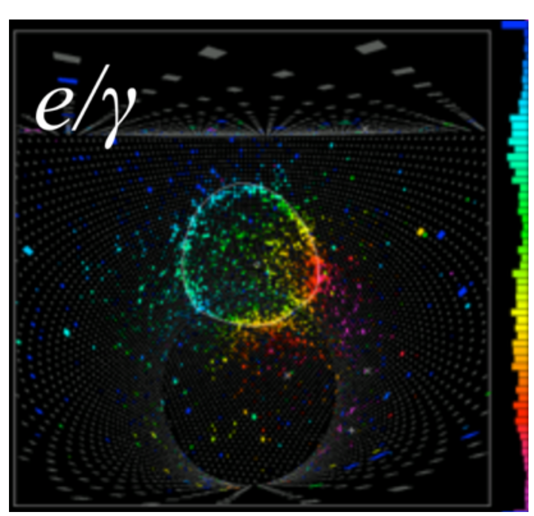
T2K detectors



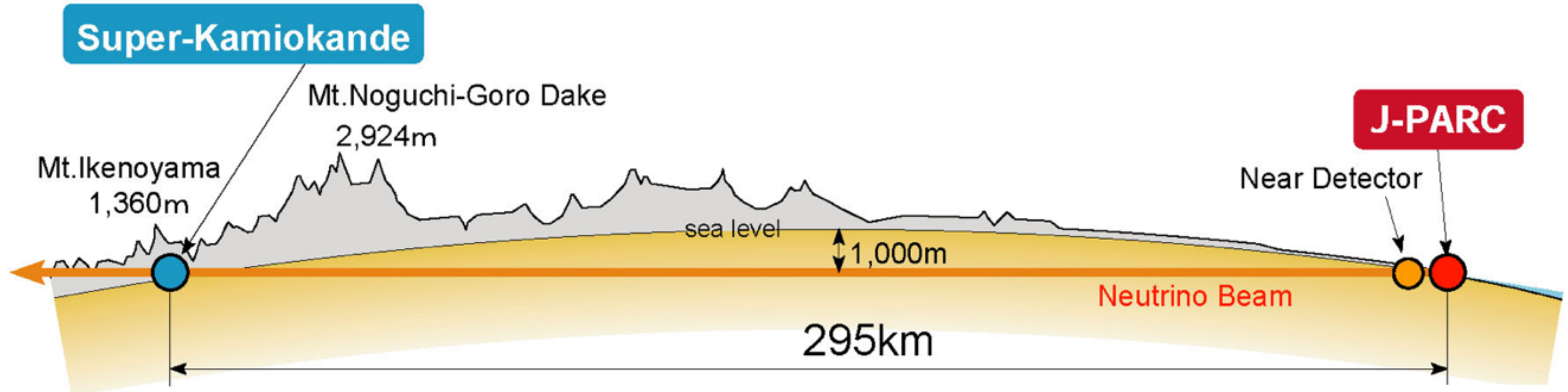


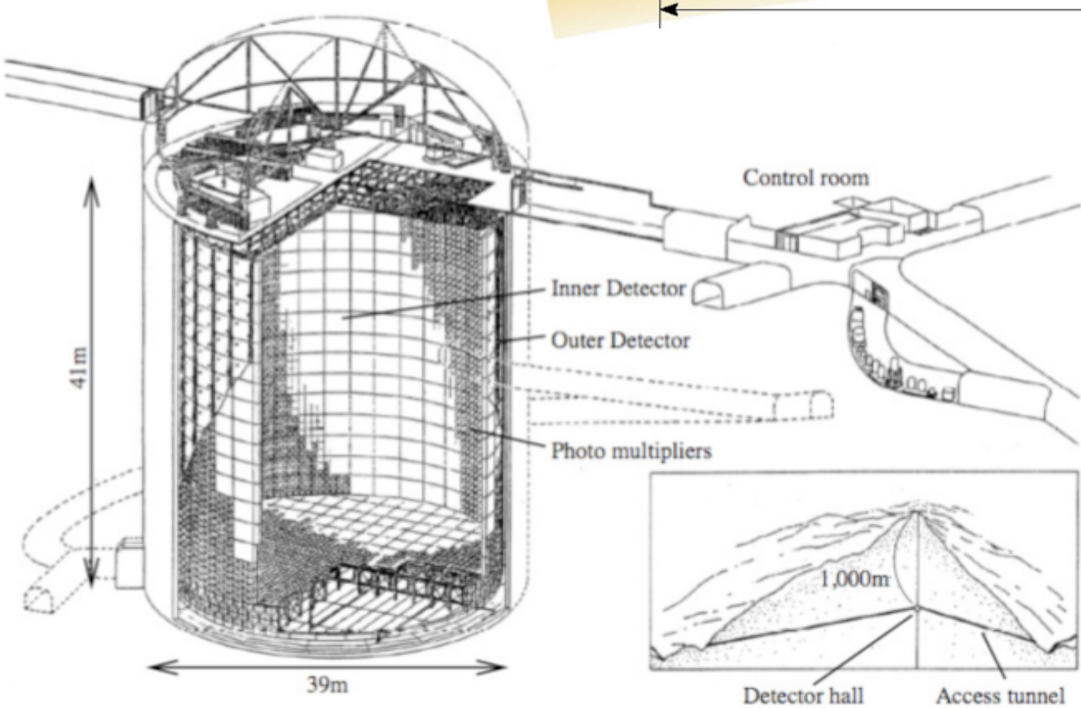


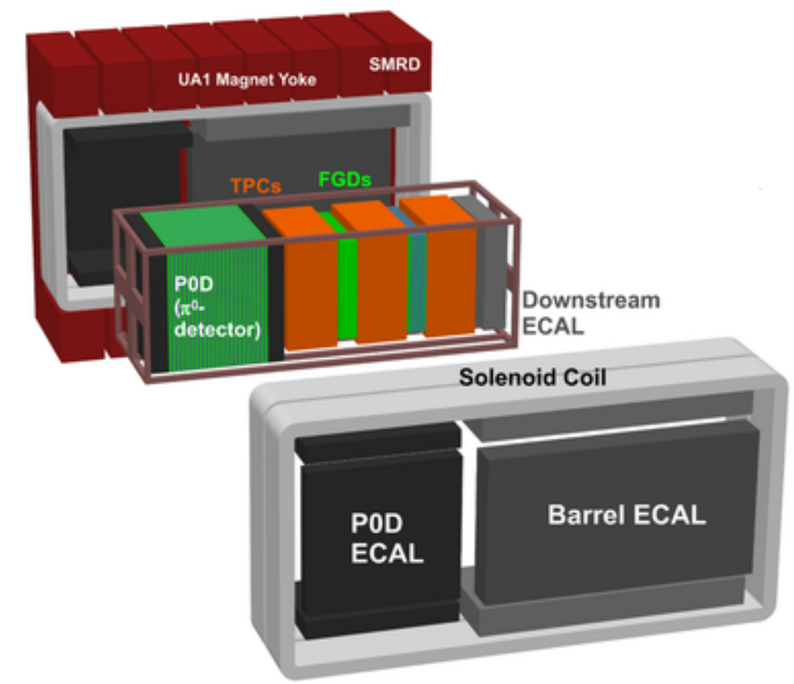


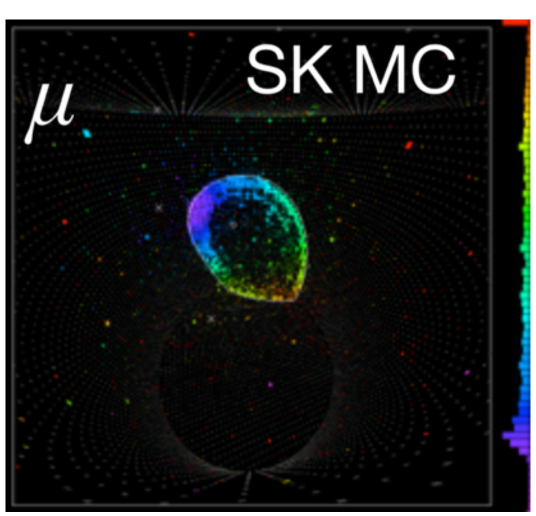


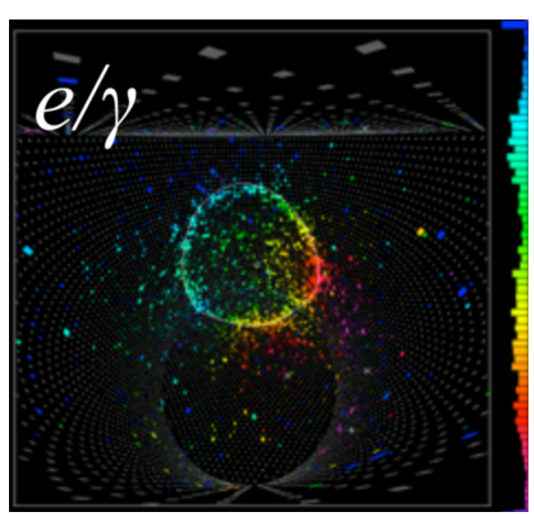
T2K detectors

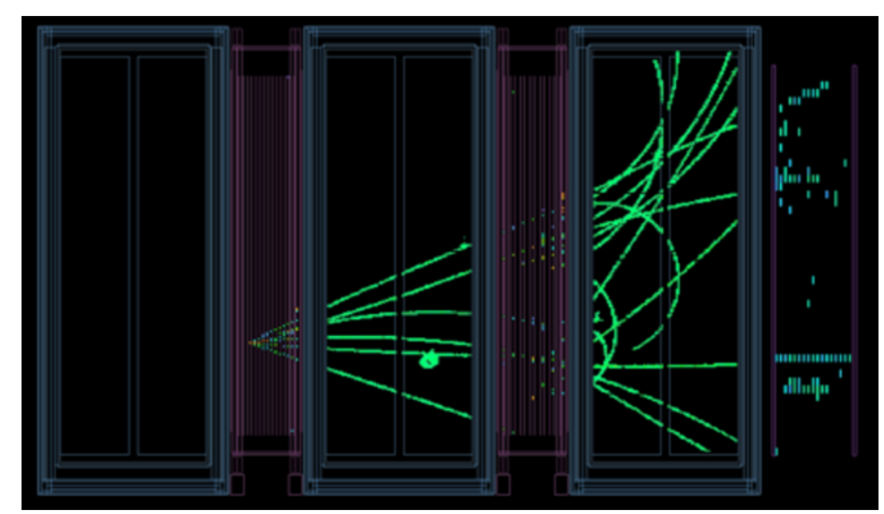




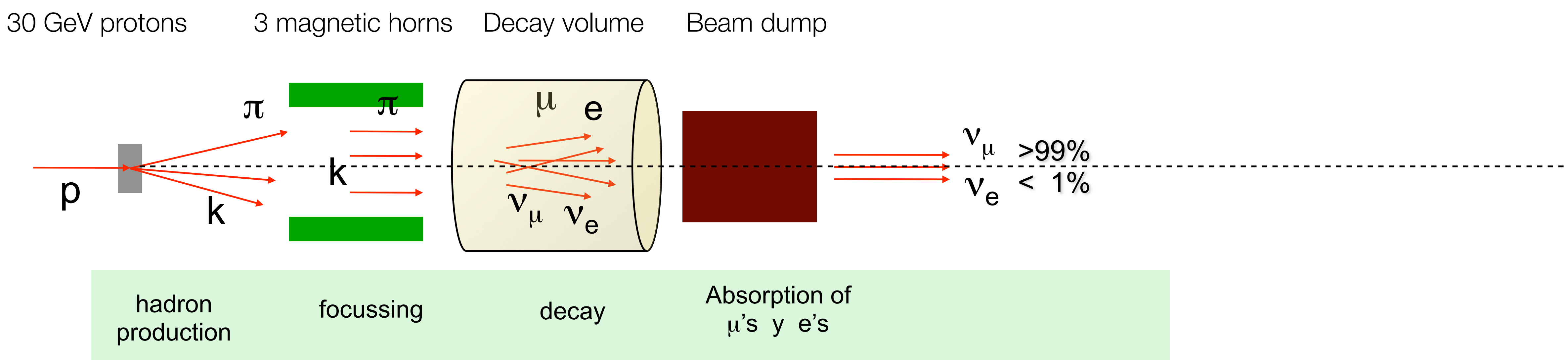




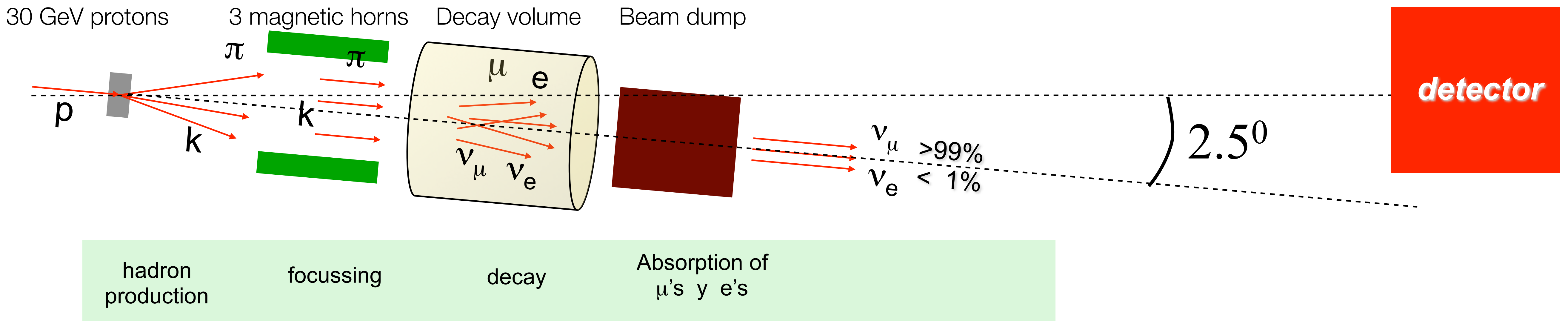




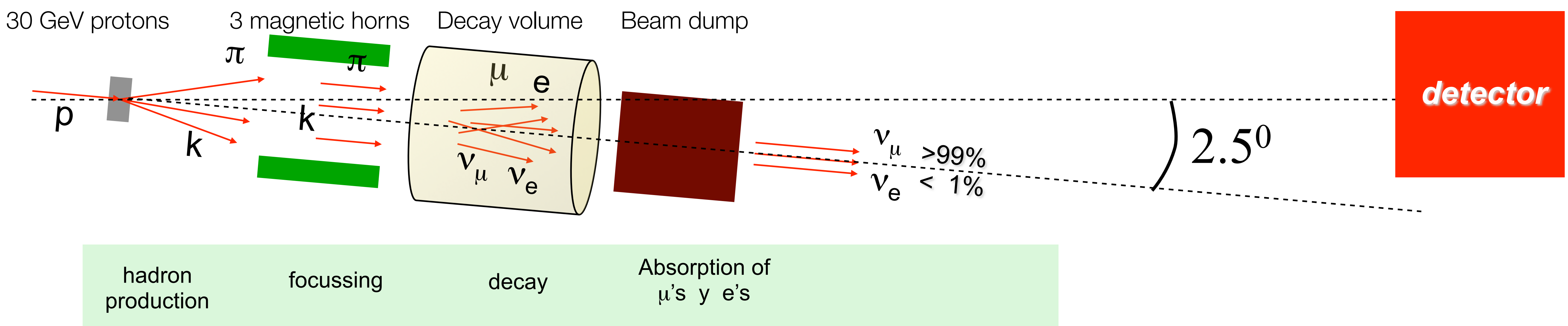
Off-axis concept

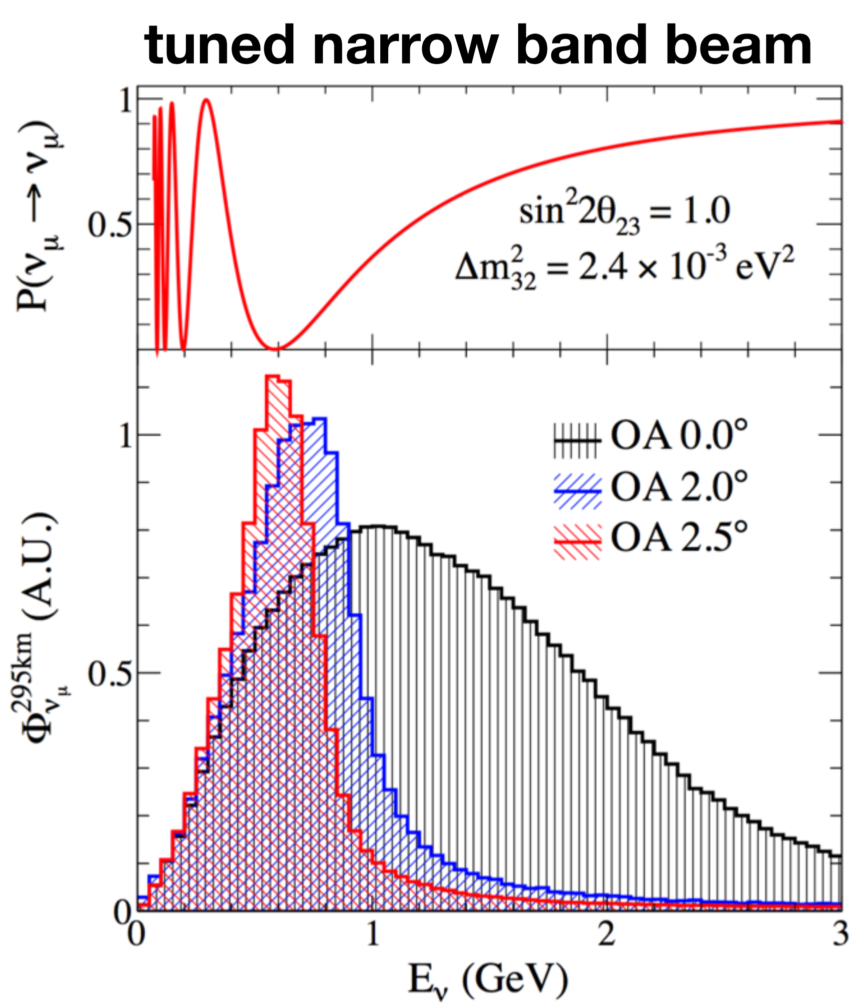


Off-axis concept

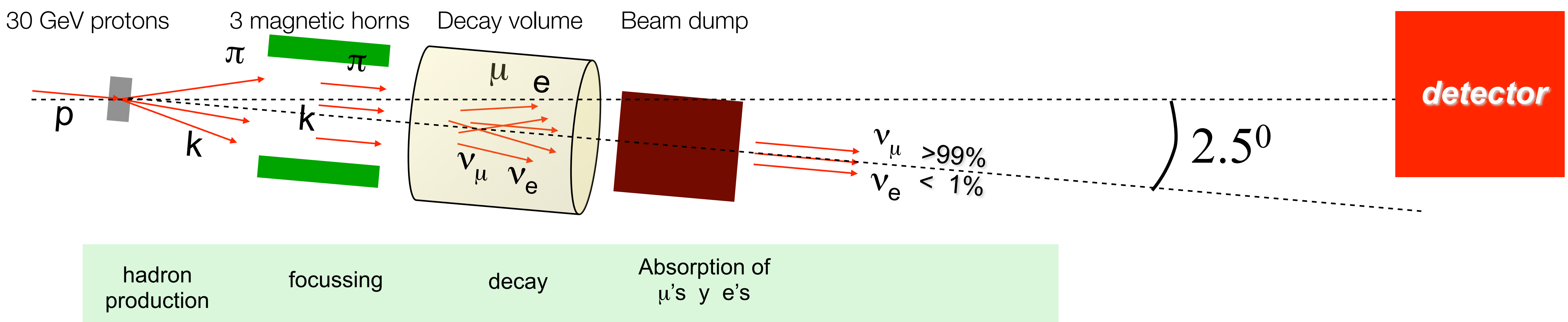


Off-axis concept

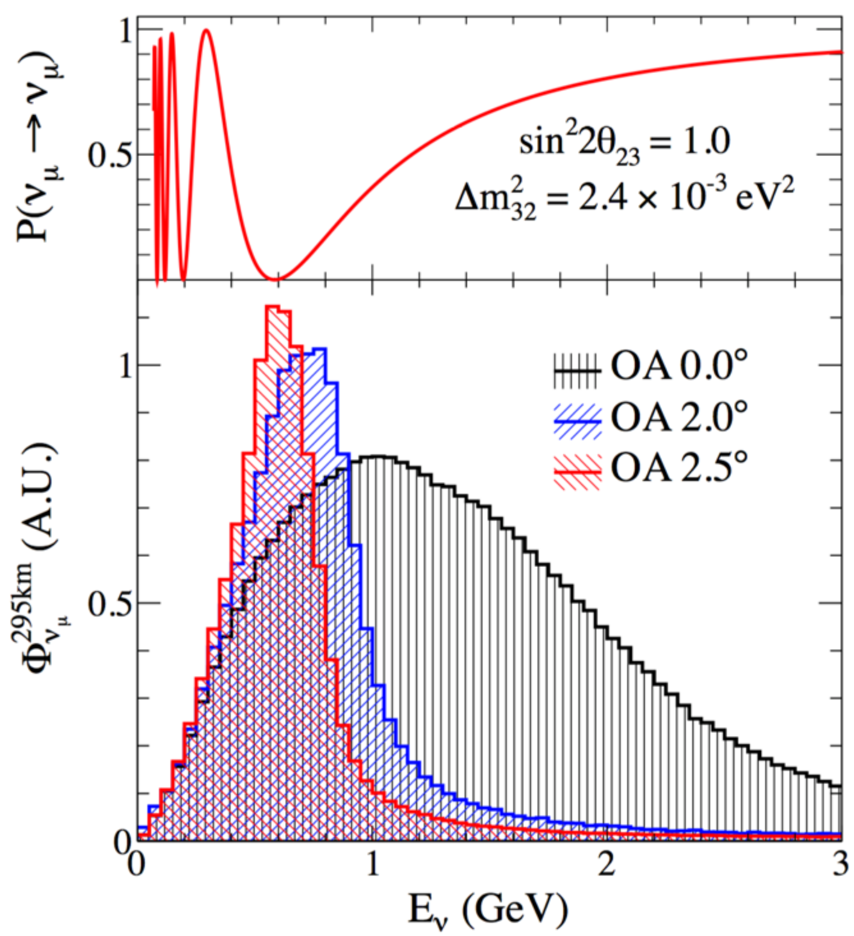




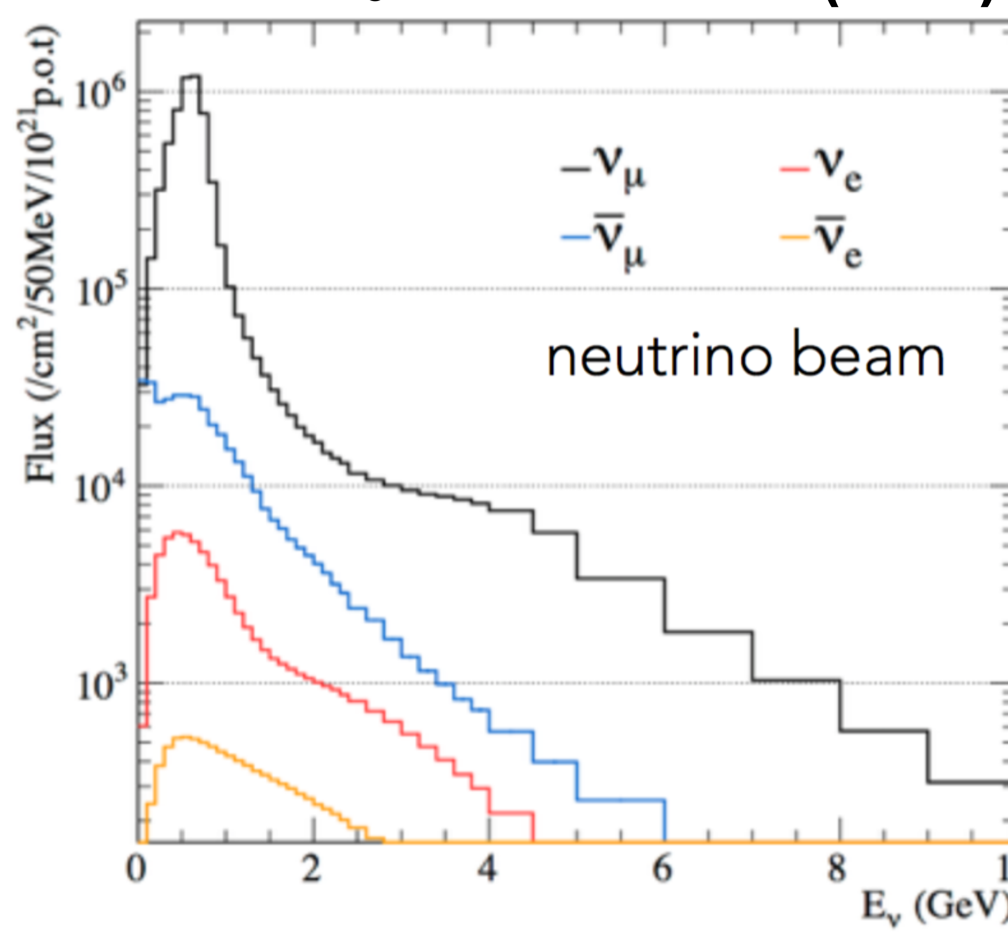
Off-axis concept



tuned narrow band beam

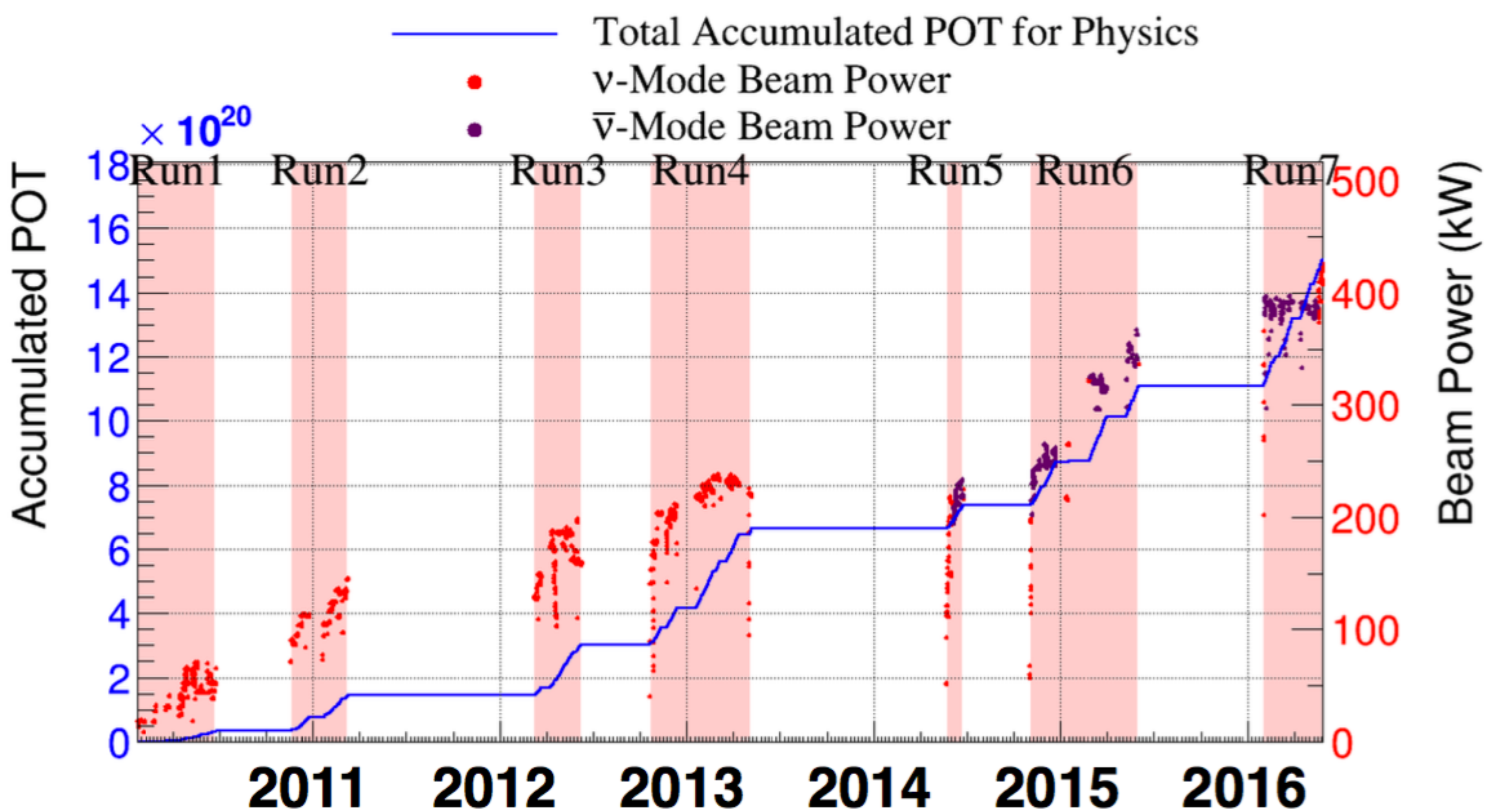


lower ν_e contamination (<1 %)



Data taking summary

- Started data taking with anti-neutrinos in 2014
- Continuous rise in power from ~225 kW (2014) to 420 kW (2016)



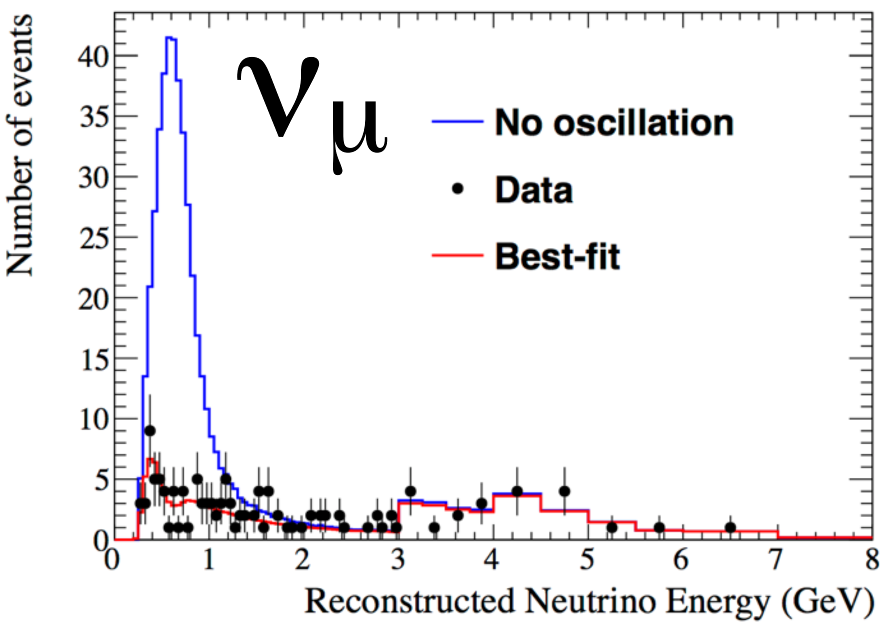
27 May 2016
POT total: 1.510×10^{21}

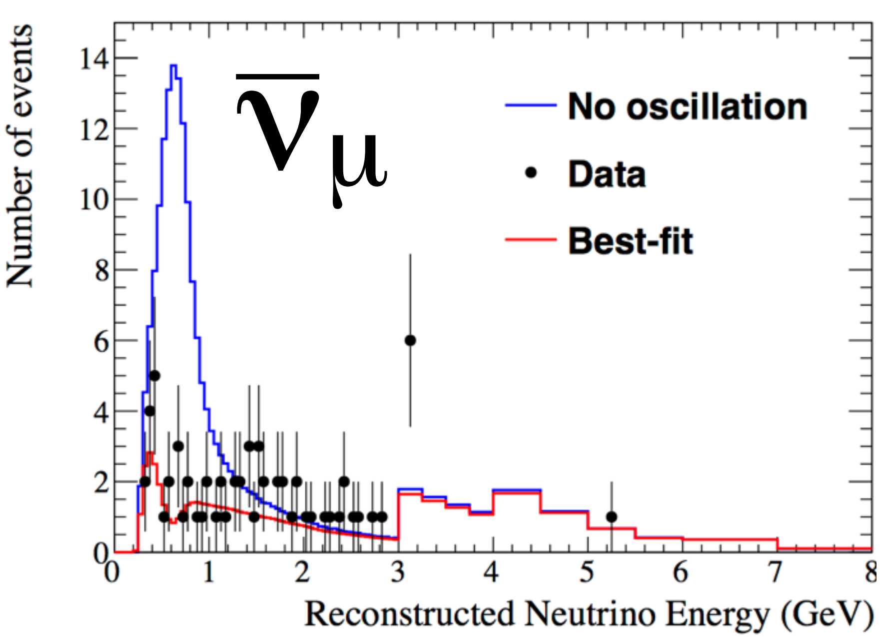
ν-mode POT: 7.57×10^{20} (50.14%) ⇢ 6.9×10^{20} analysed
ν̄-mode POT: 7.53×10^{20} (49.86%)

POT ≡ Protons on Target

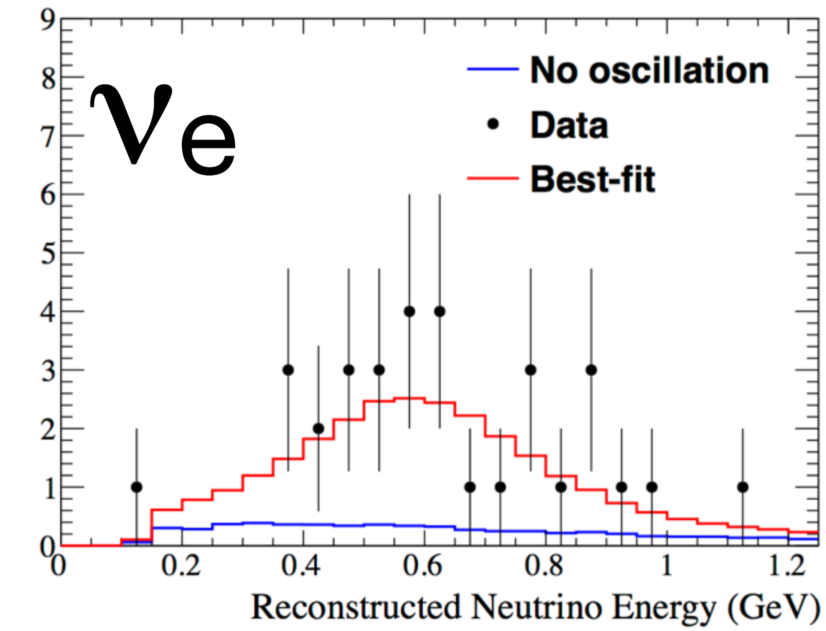
4 neutrino samples

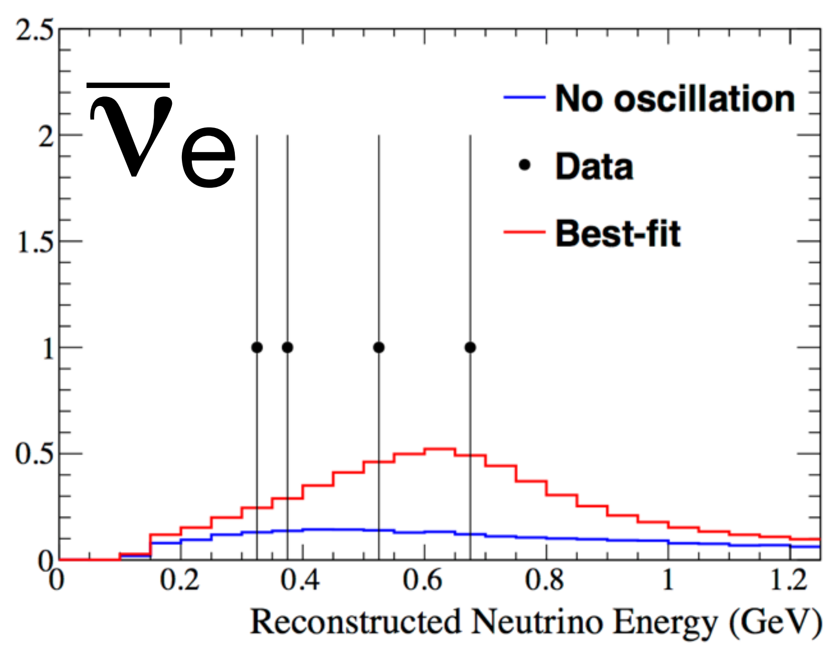
$\overset{(-)}{\nu}_\mu$ disappearance





$\overset{(-)}{\nu}_e$ appearance





sample	obs.	Exp. not osc.	δ_{CP}= 0	δ_{CP}= -1.6
ν_μ	125	489.9	127.2	127.5
ν_e	32	5.8	22.7	26.9
$\bar{\nu}_\mu$	66	184.8	64.1	64.2
$\bar{\nu}_e$	4	2.3	6.9	6.0

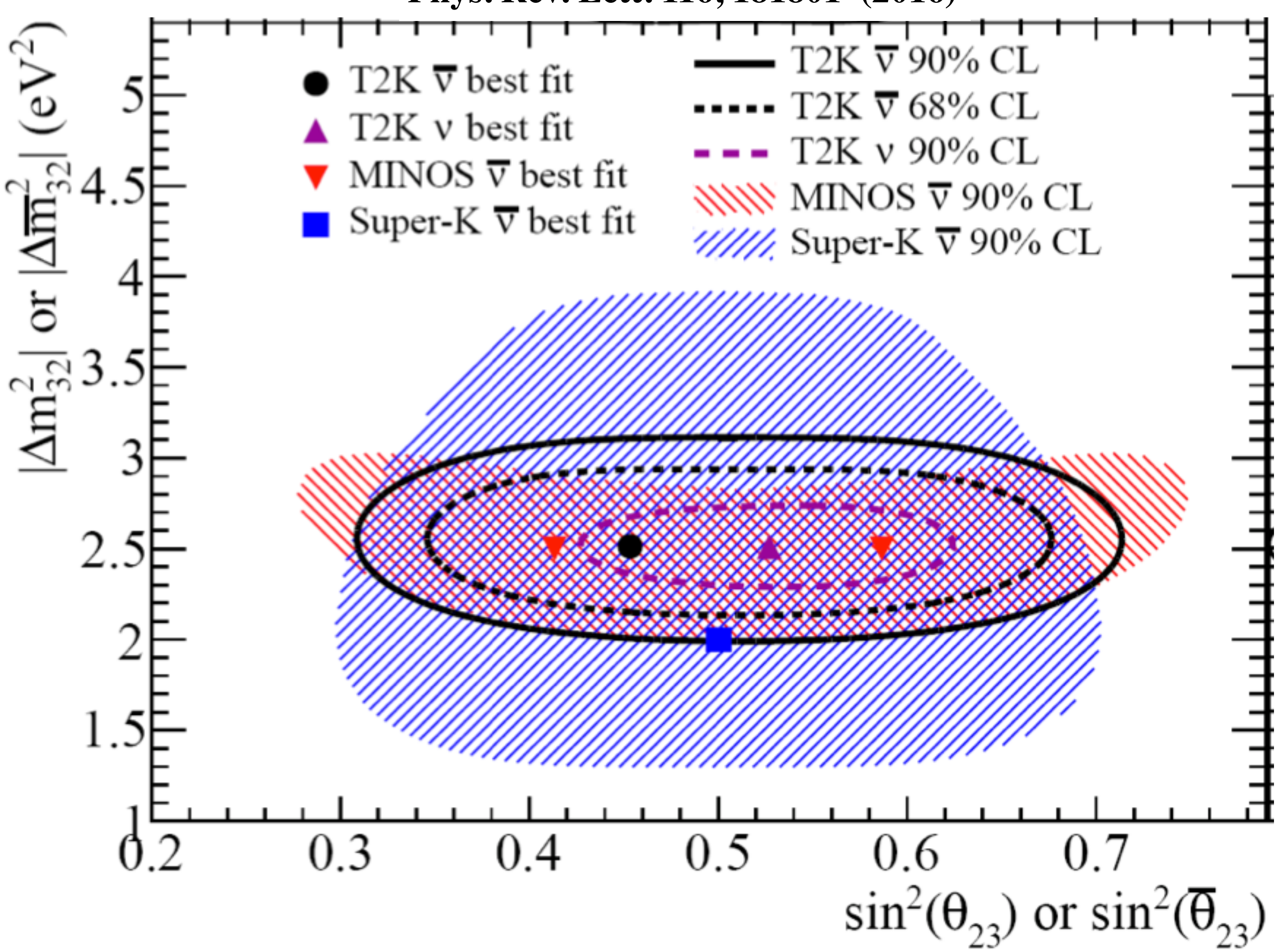
next goal:
probe (5σ) of $\bar{\nu}_e$ appearance

E_{rec} distribution assuming 2-body quasi-elastic kinematics

Antineutrino analysis

- This is the 2015 analysis. Results to be updated at ICHEP
- Best results for $\overline{\nu}_\mu$ disappearance with one year of data
- Allow test of CPT symmetry. For the moment consistent with neutrino results

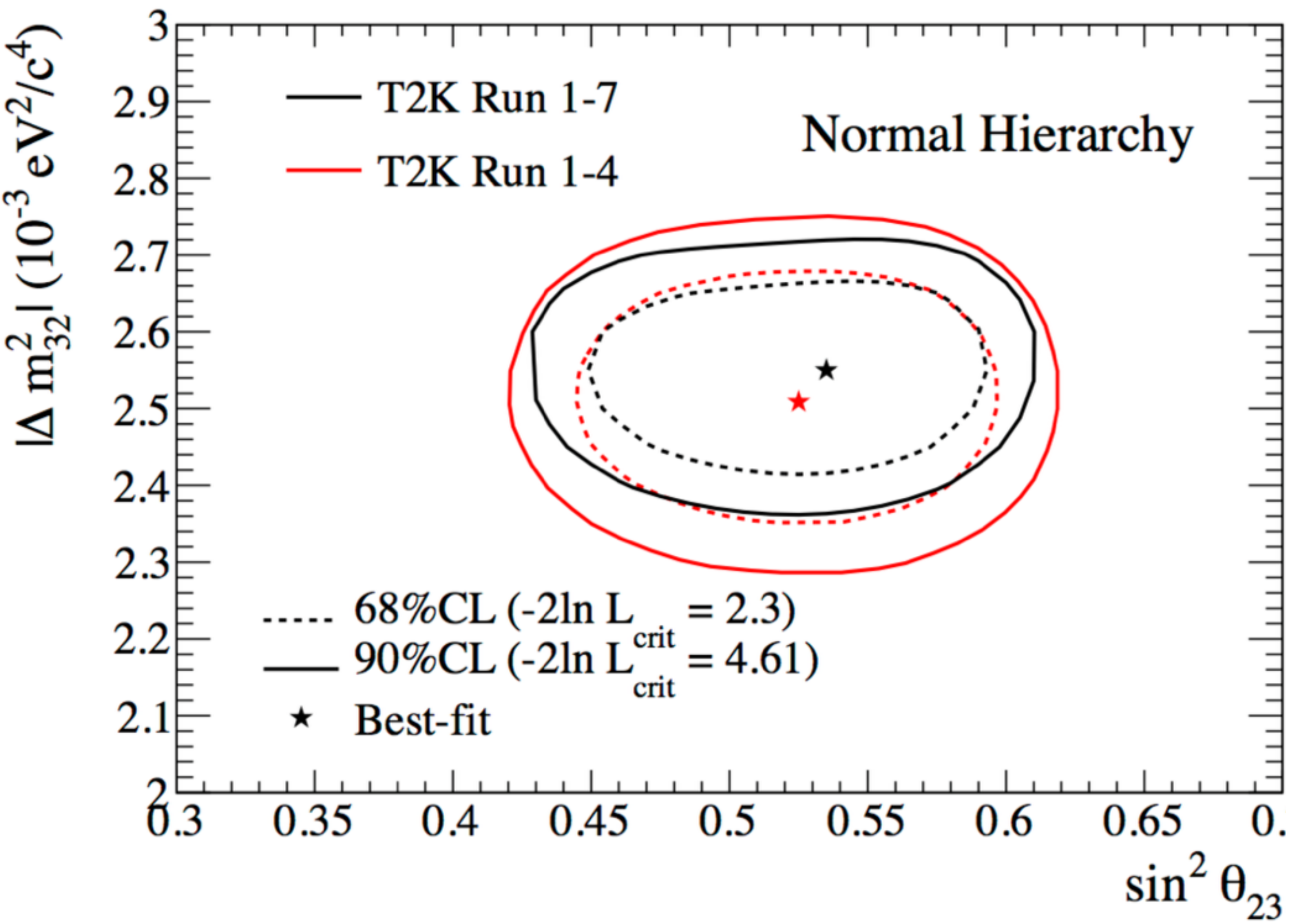
Phys. Rev. Lett. 116, 181801 (2016)



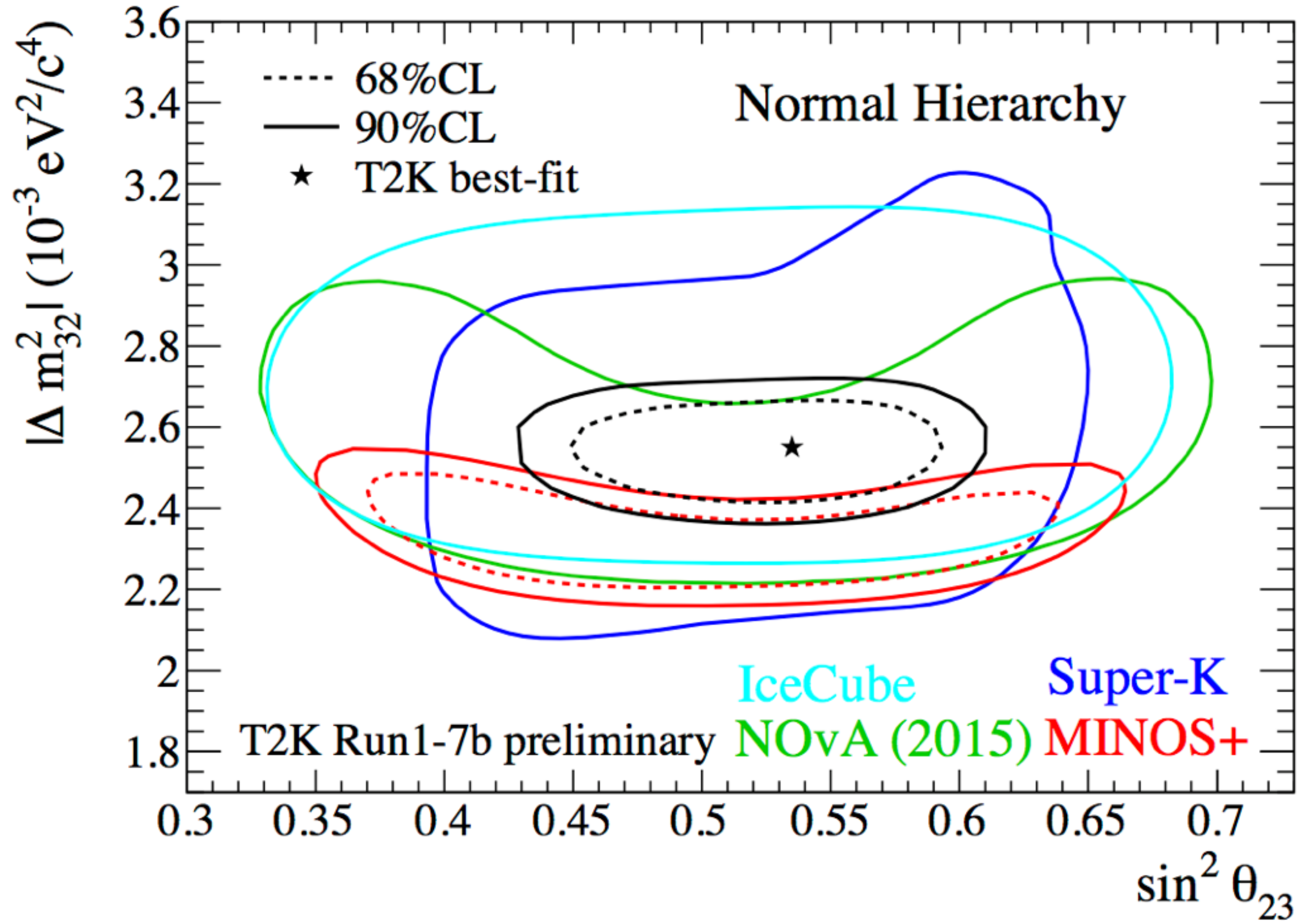
First fully joint analysis

- First fully joint analysis across all modes of oscillation

$\nu_\mu \rightarrow \nu_e$ $\nu_\mu \rightarrow \nu_\mu$ $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ $\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu$

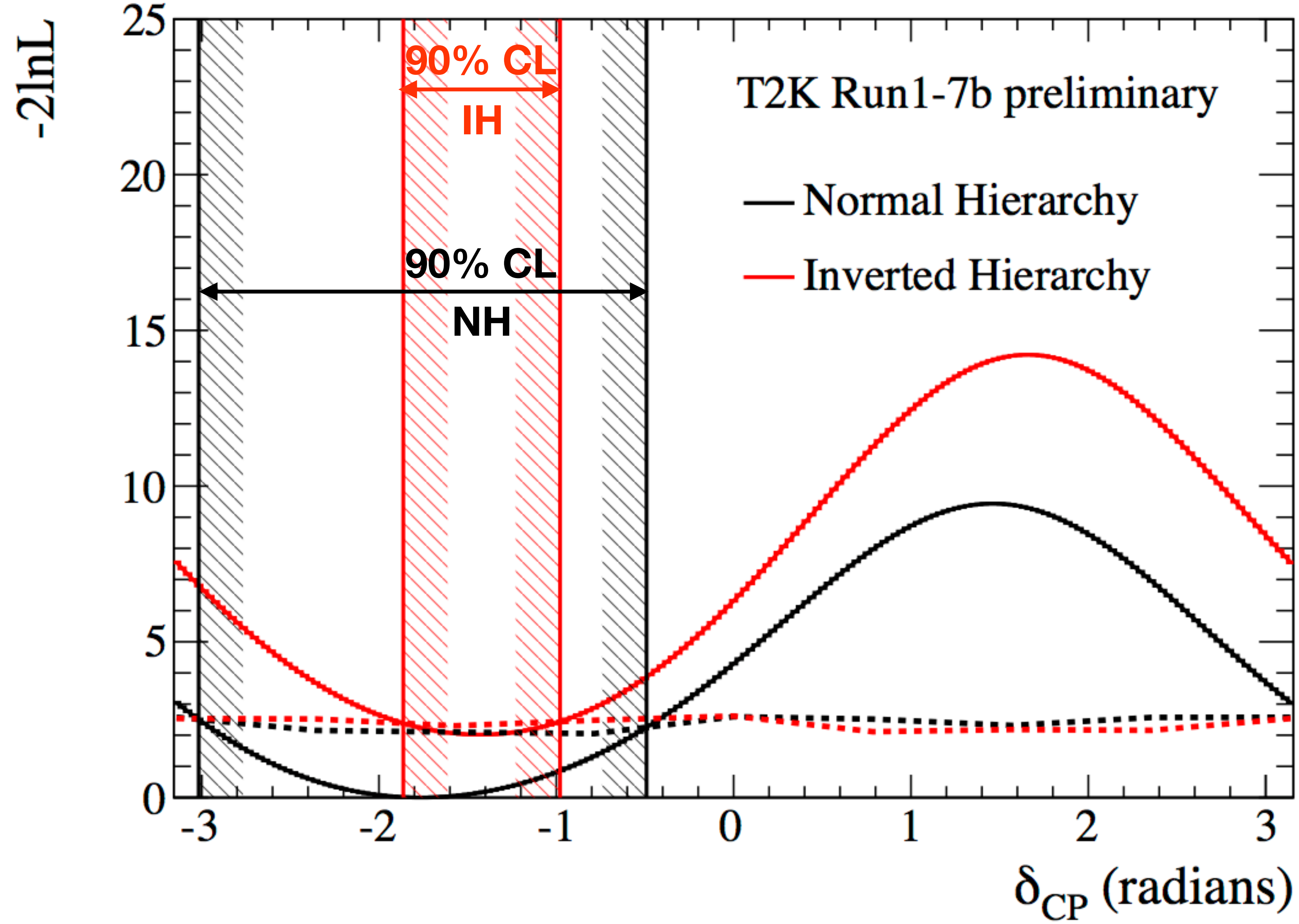


T2K has the most precise measurement of θ_{23}



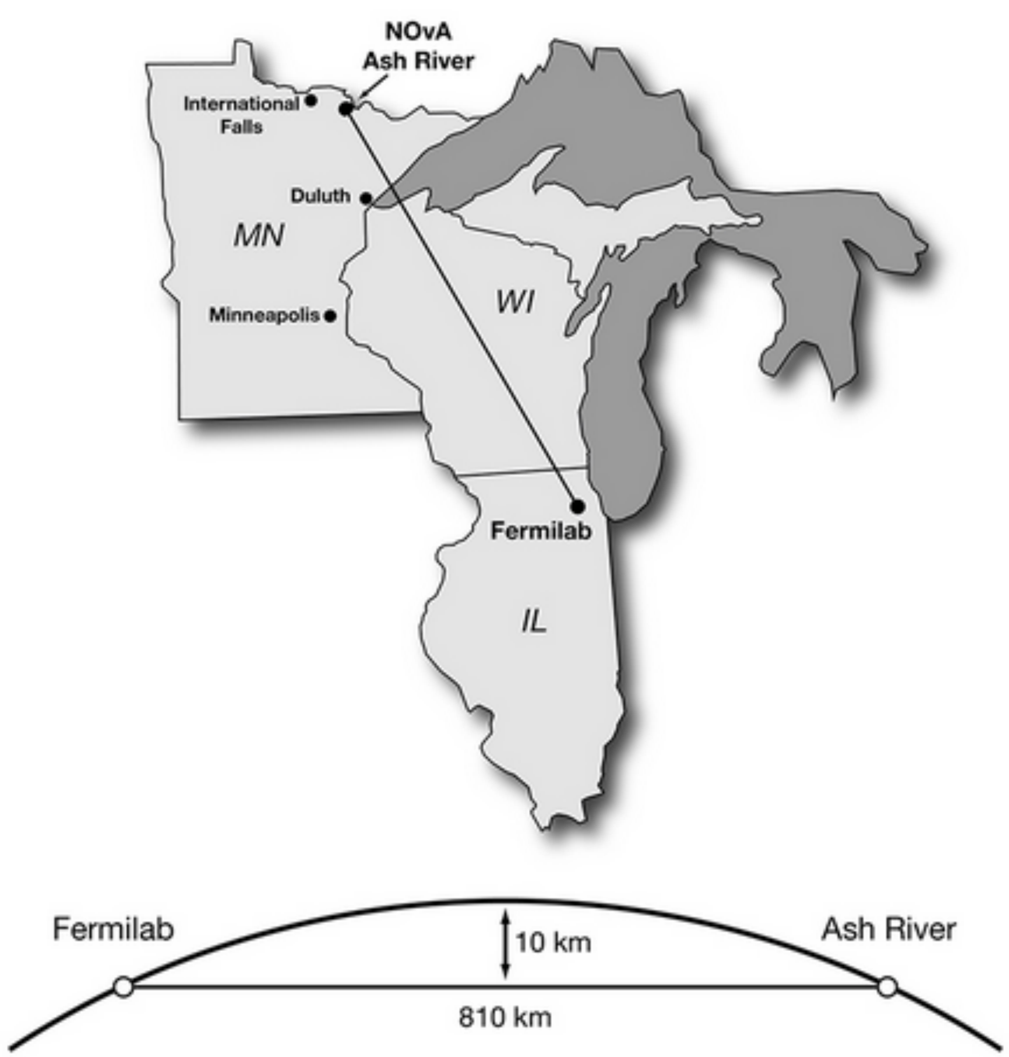
Hints of CP violation

- no CP-violation (δ_{CP}=0) excluded at 90% CL. Best fit δ_{CP} ~ -π/2
- Almost a 2σ effect



The NOvA experiment

- NOvA, in the US, started data taking in 2014
- A similar concept to T2K but different detector type (scintillator), and much **longer baseline** (810 km): it has **better sensitivity to mass hierarchy** (the sign of Δm^2_{23})



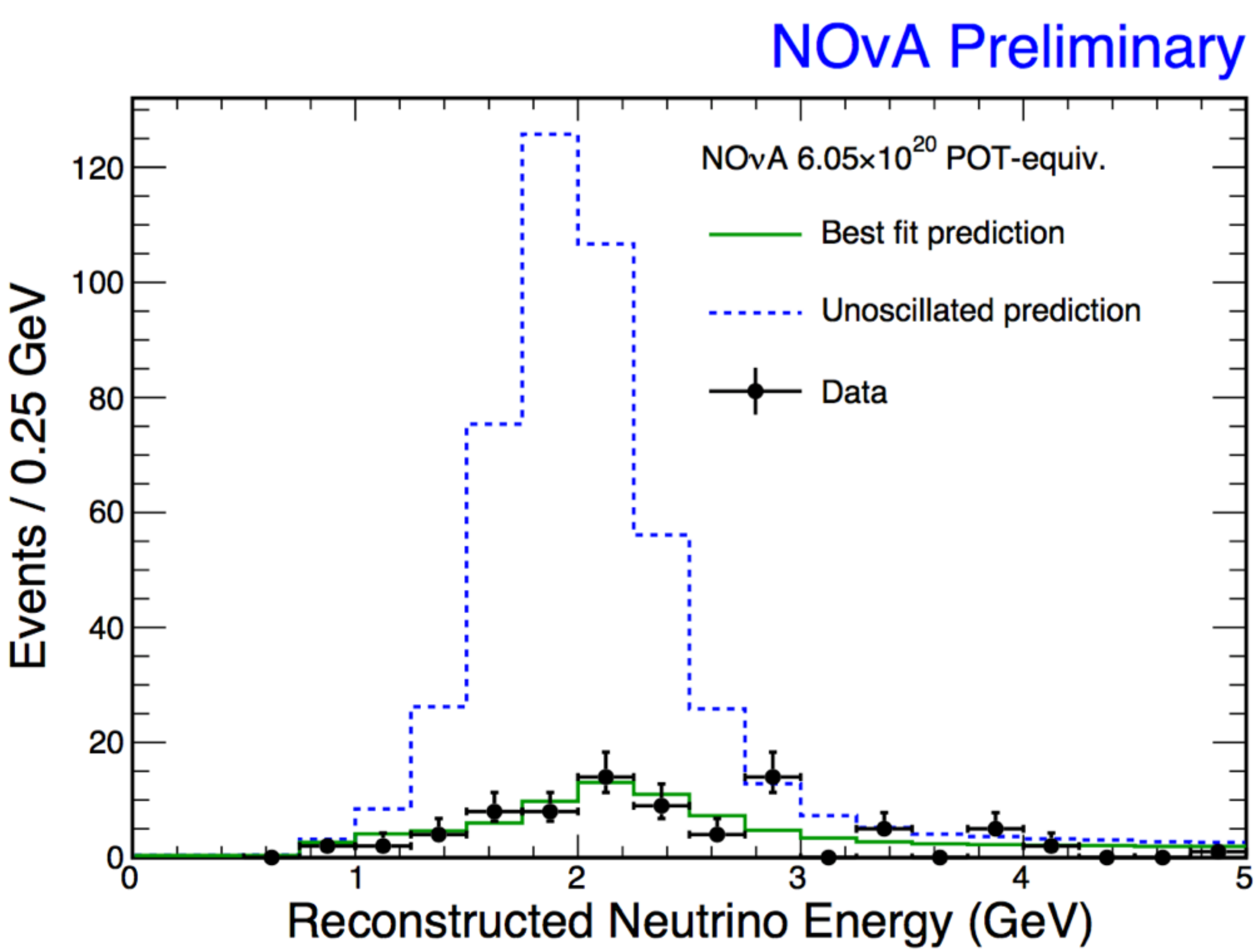
Latest results

NEUTRINO 2016
SOUTH KENSINGTON, LONDON
XXVII INTERNATIONAL CONFERENCE ON NEUTRINO PHYSICS AND ASTROPHYSICS
4–9 JULY 2016

~20% of planned exposure (6.05×10^{20} POT)

ν_μ disappearance

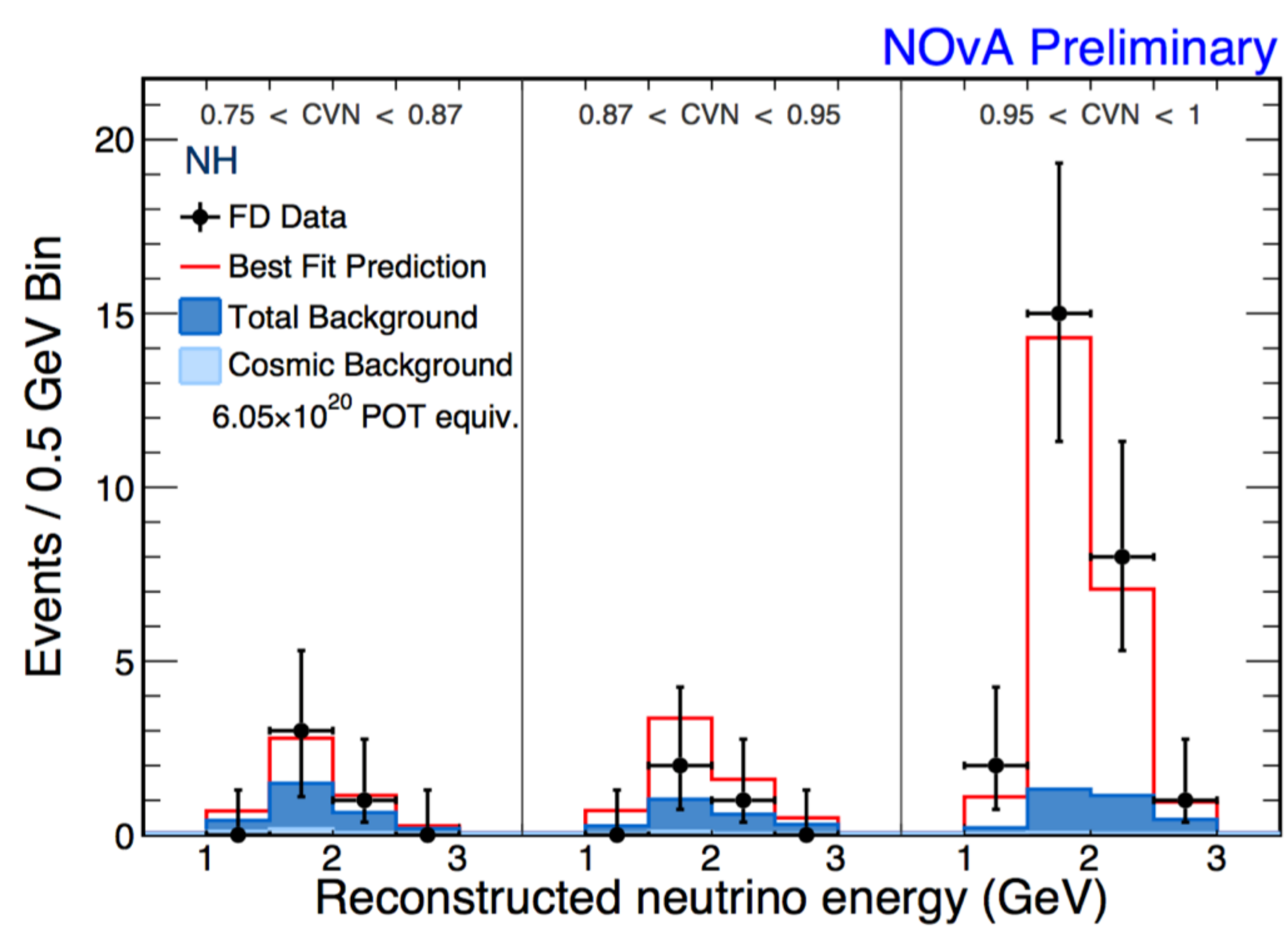
- 78 events observed in FD
  - 473±30 with No Oscillation
  - 82 at best oscillation fit
  - 3.7 beam BG + 2.9 cosmic



ν_e appearance

- Observe 33 events in FD
  - background 8.2±0.8

>8σ signal



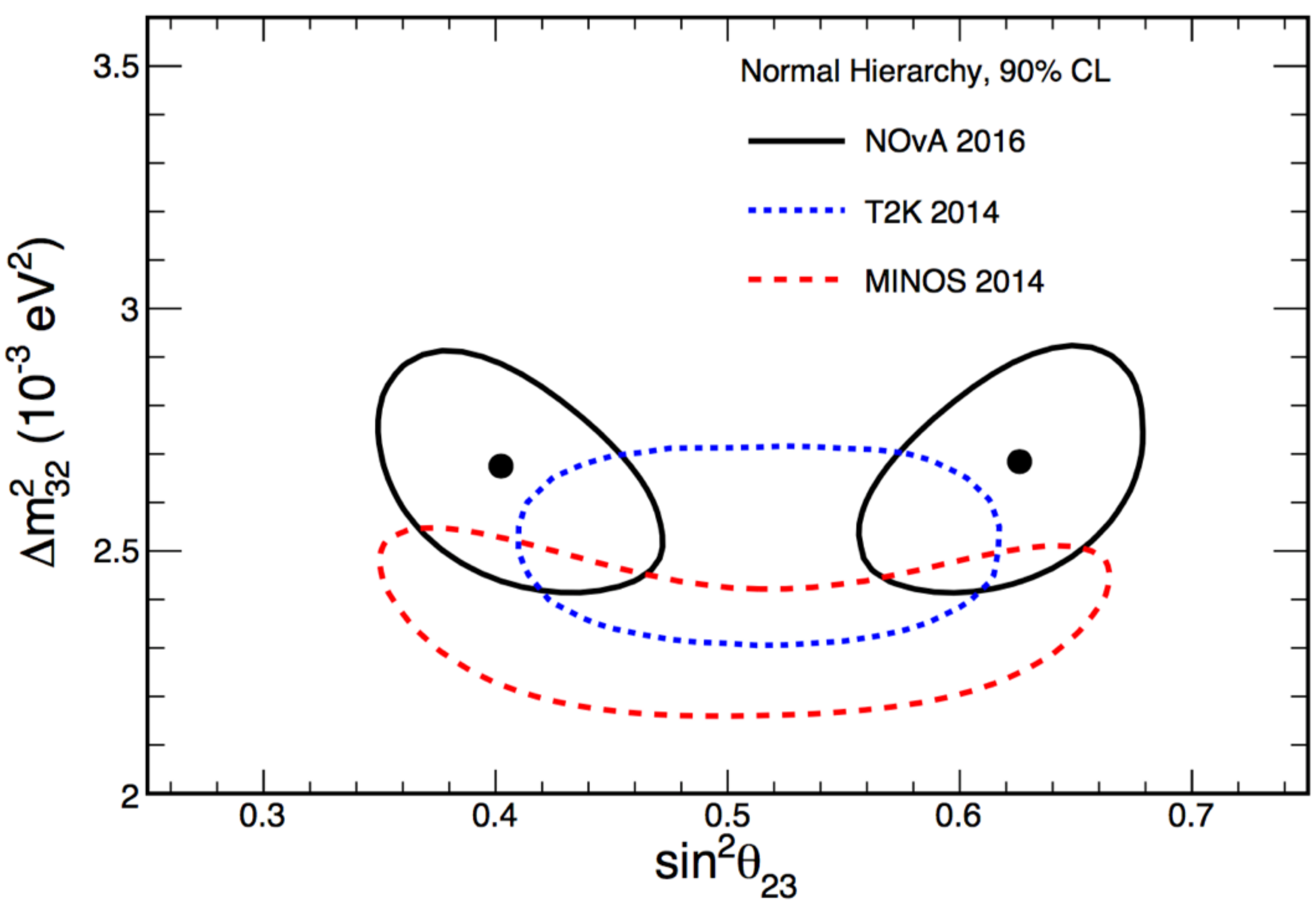
Hints of non maximal mixing

- Weakly prefer normal mass hierarchy and $\delta_{CP} \sim 3\pi/2$ $(-\pi/2)$
- $\delta_{CP} \sim \pi/2$ excluded at 3σ for IH

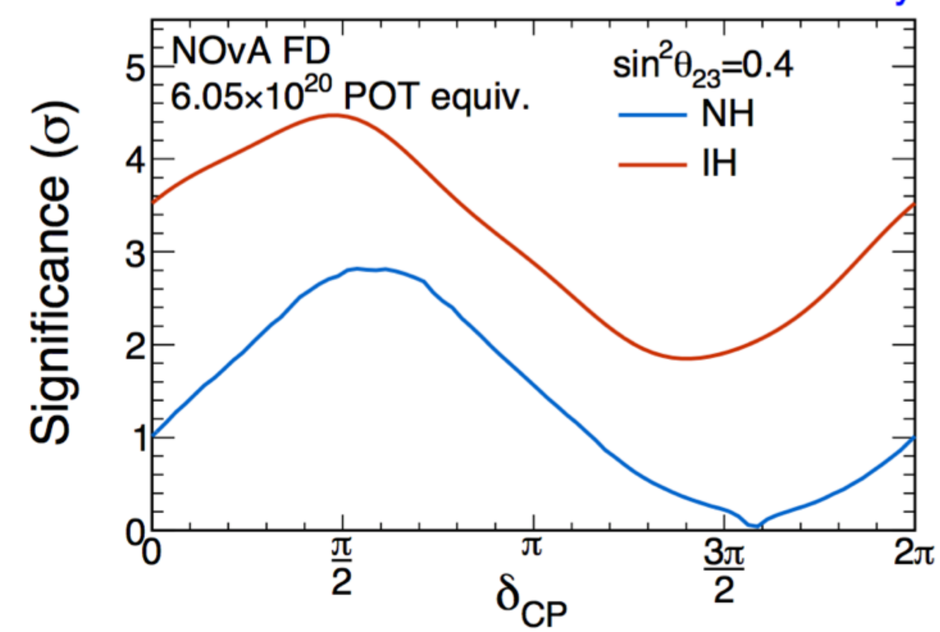
- Maximal mixing ($\theta_{23} = 45^\circ$) excluded at 2.5σ

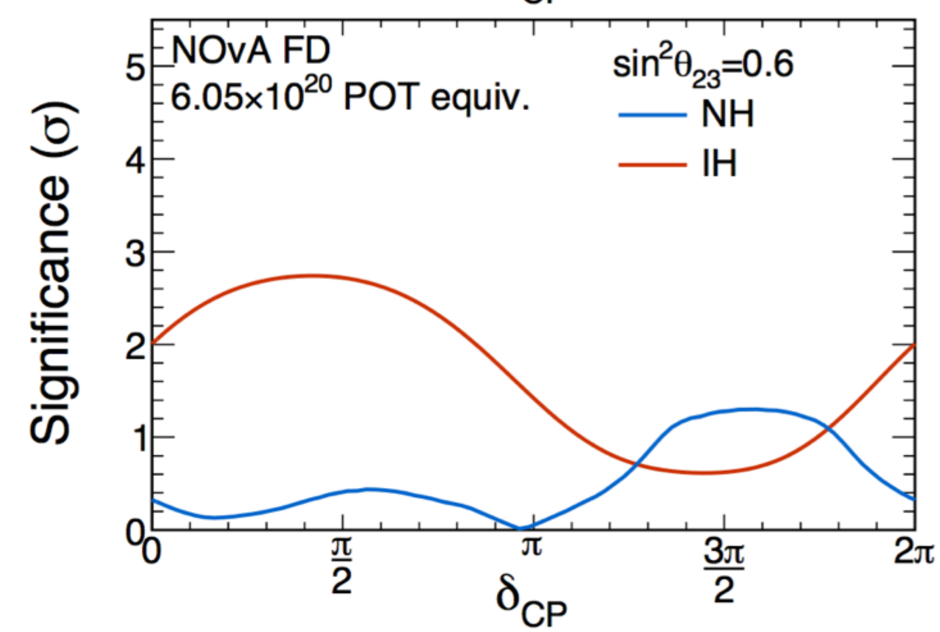
$$\sin^2\theta_{23} = 0.40^{+0.03}_{-0.02} \left(0.63^{+0.02}_{-0.03}\right)$$

NOvA Preliminary



NOvA Preliminary





Summary of current results

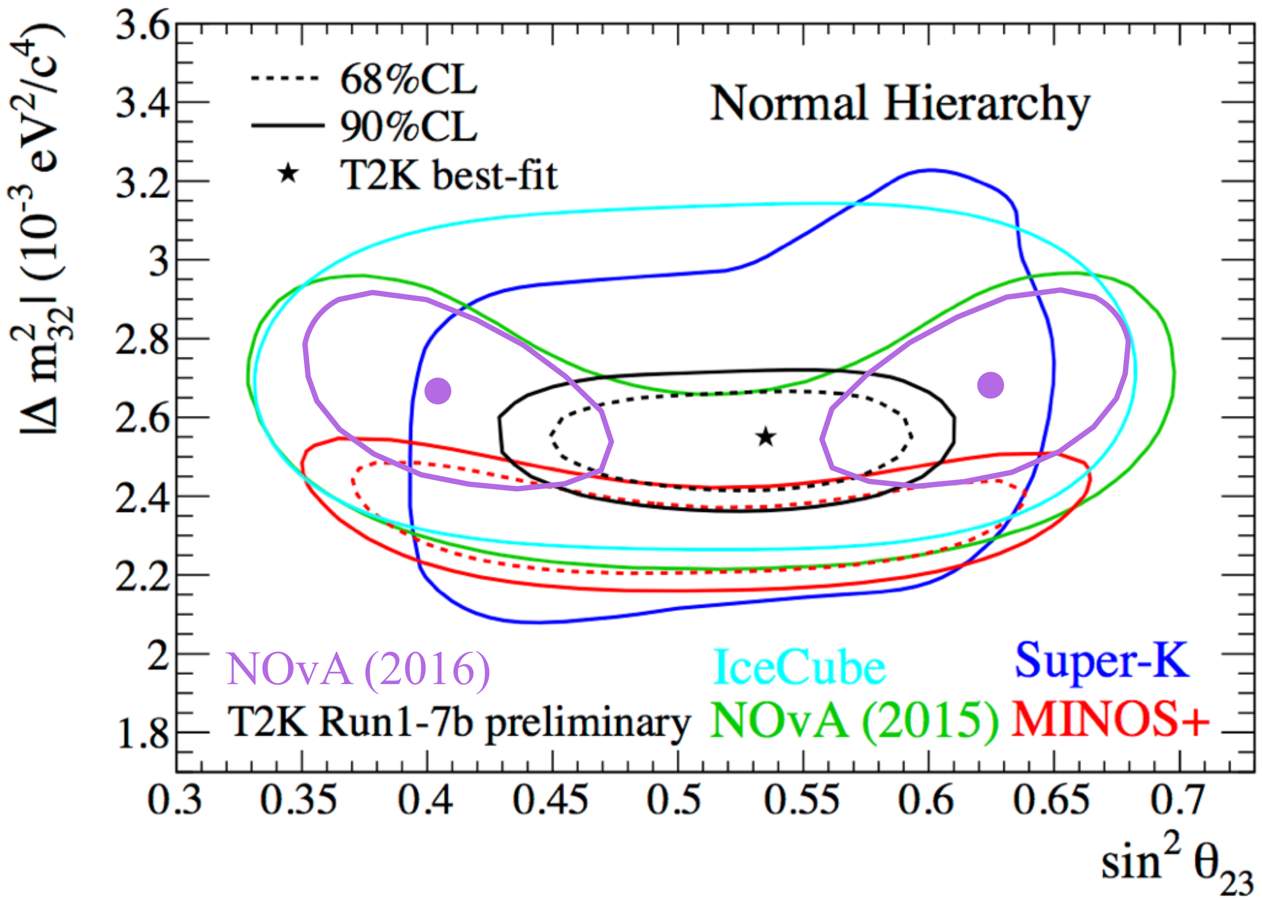
...

Summary of current results

…

θ_{23}-Δm^2_{23}

- compatible for all experiments also between ν & $\bar{\nu}$ (no CPT)
- **Maximal mixing (θ_{23}=45º) excluded at 2.5σ by NOvA**

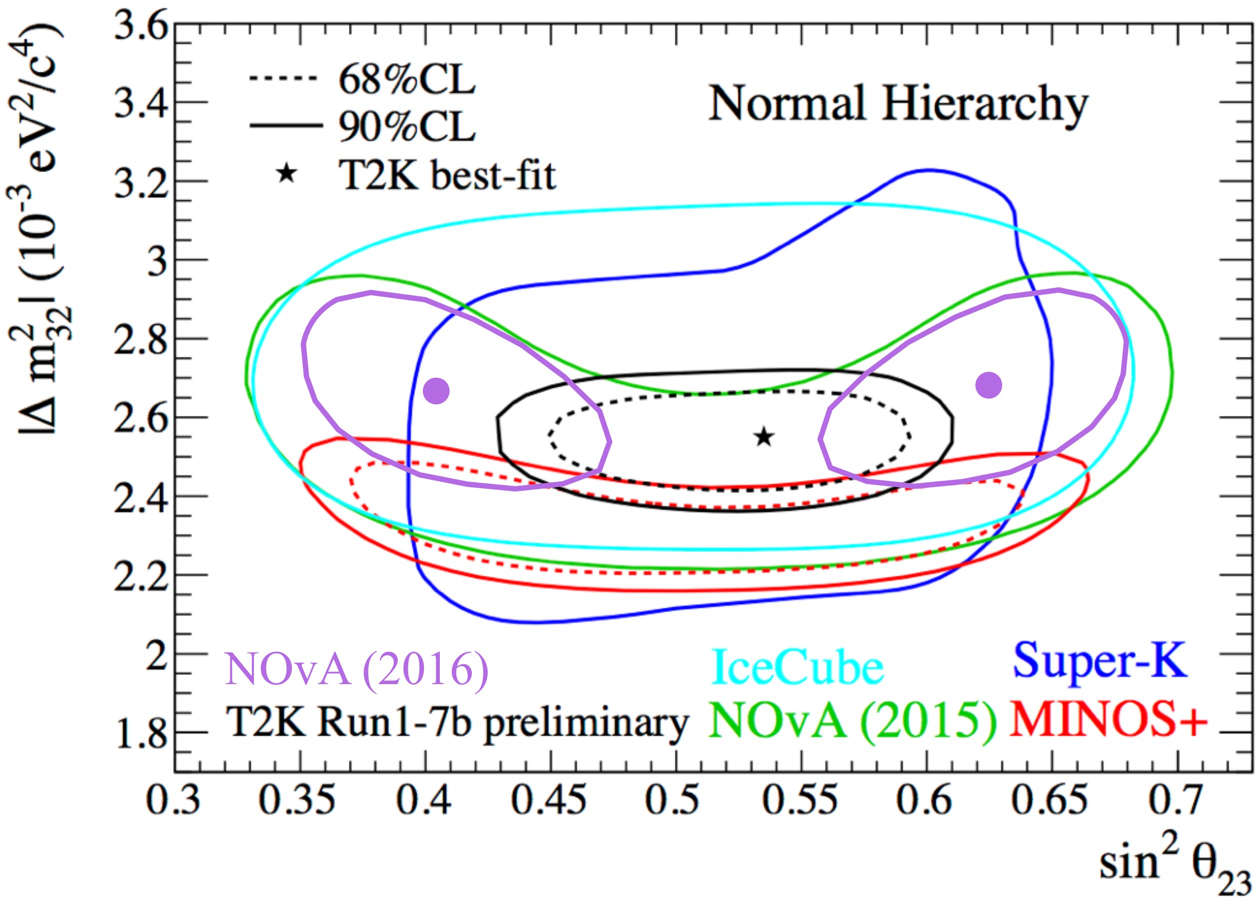


Summary of current results

…

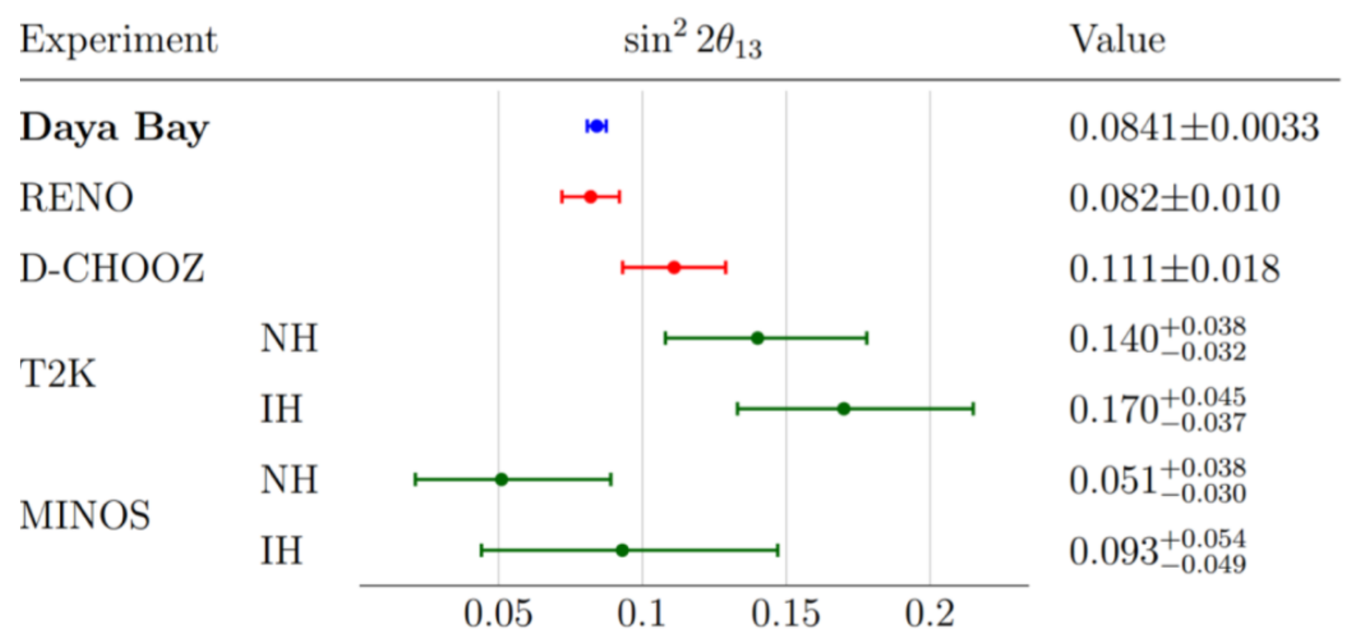
θ_{23}-Δm^2_{23}

- compatible for all experiments also between ν & $\bar{\nu}$ (no CPT)
- **Maximal mixing (θ_{23}=45º) excluded at 2.5σ by NOvA**



θ_{13}-δ_{CP}

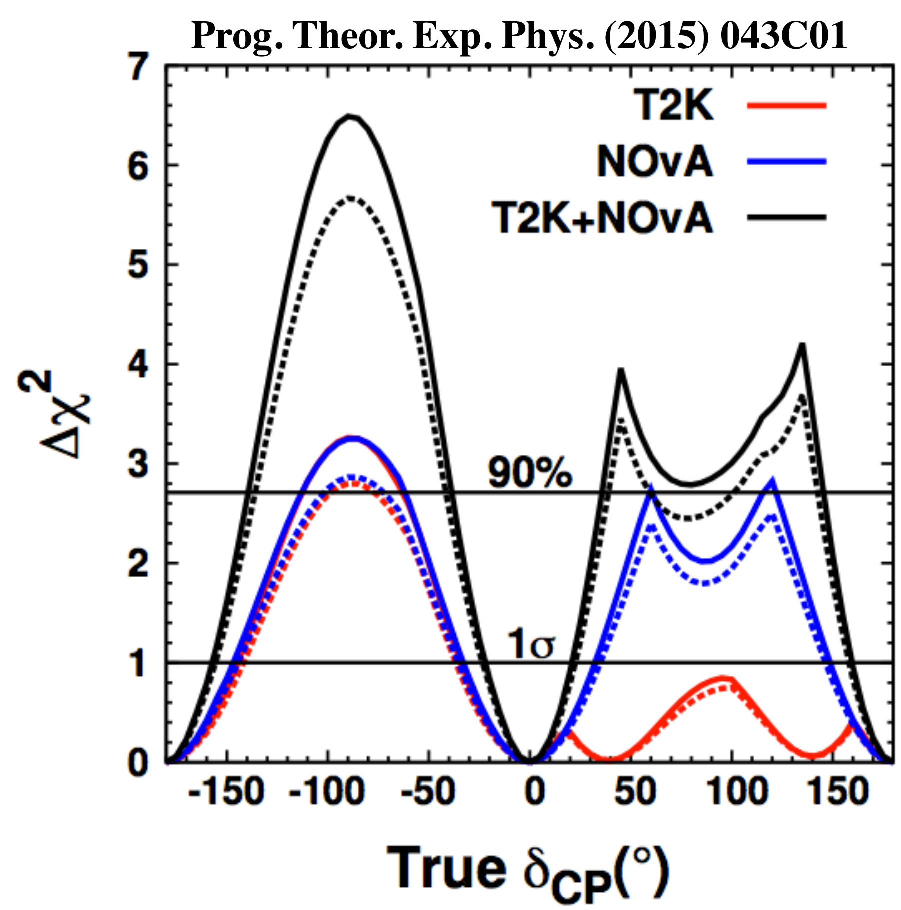
- small preference for **δ_{CP}≈-π/2** and normal mass hierarchy (Δm^2_{23}>0) from T2K and NOvA
- **θ_{13}**, dominated by Daya Bay, also compatible



2015 values except for Daya Bay

What's next ?

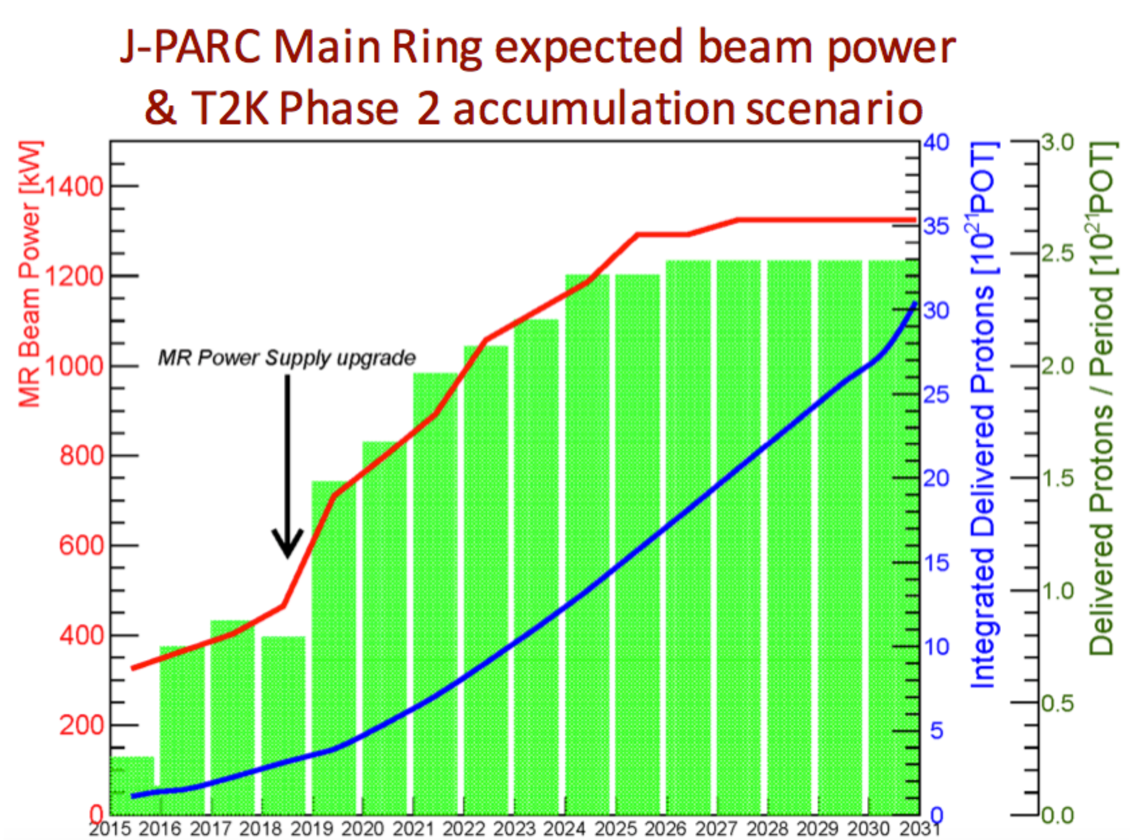
- The combination of all current experiments will probably result in a measurement of the mass hierarchy and an indication of non-zero δ_{CP} (2-3 sigma)

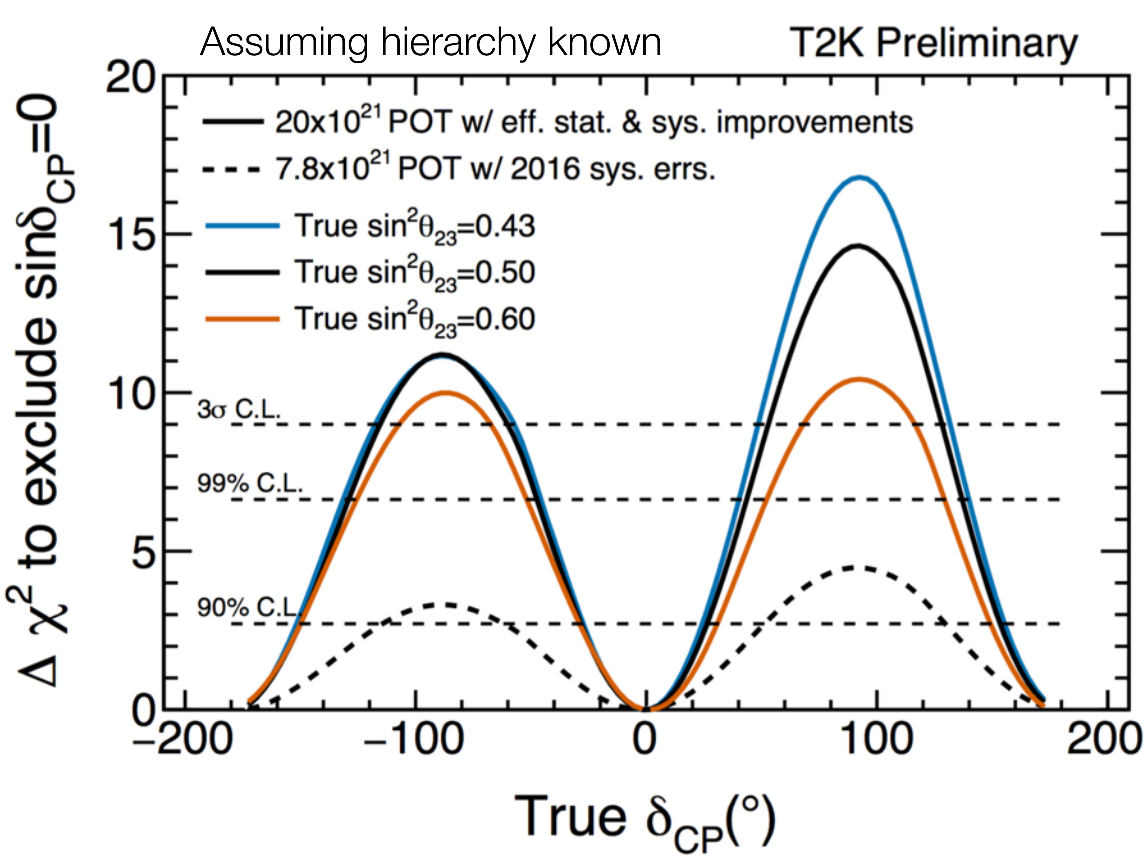


- A new generation is needed to measure CP: larger or more precise detectors, more powerful beams

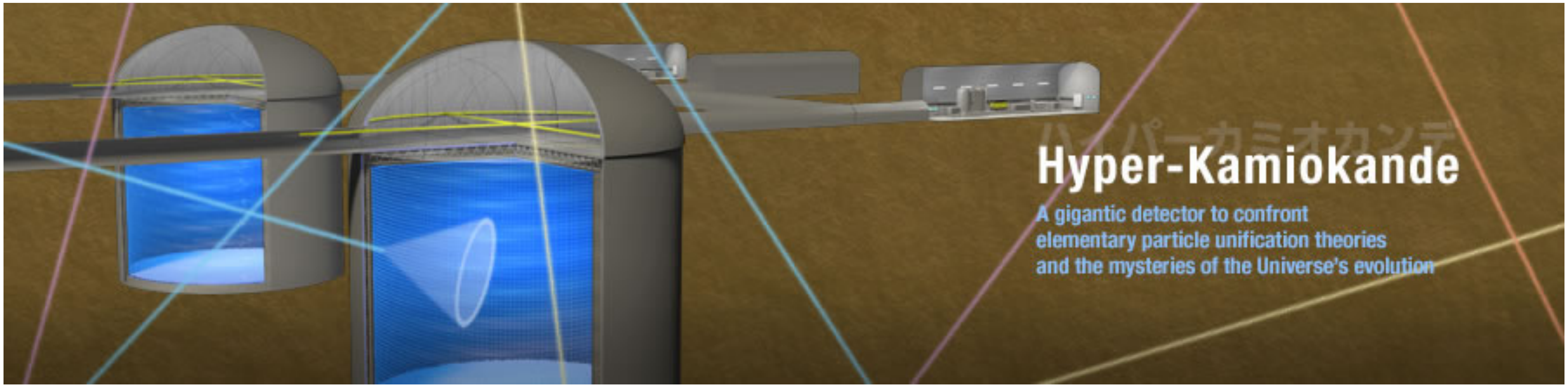
T2K phase II

- Proposed to cover the gap between T2K/NOvA and the next generation of experiments: HK/DUNE (from 2020 to 2026)
- Same far detector (SK) + beam upgrade: collect $20x10^{21}$ p.o.t. **30 x T2K**
- New improved near detector complex and reduced systematics
- Could achieve >3σ sensitivity on CP violation



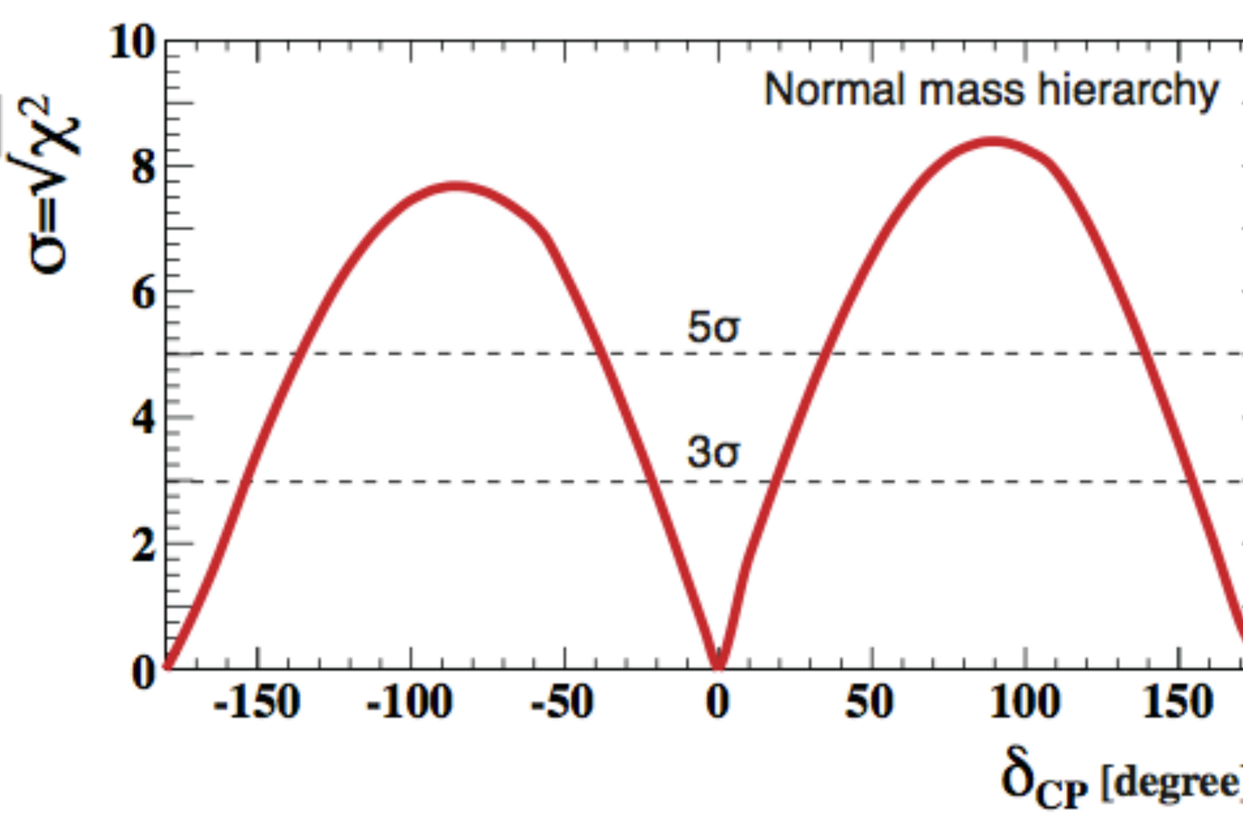


Hyper-Kamiokande (HK)



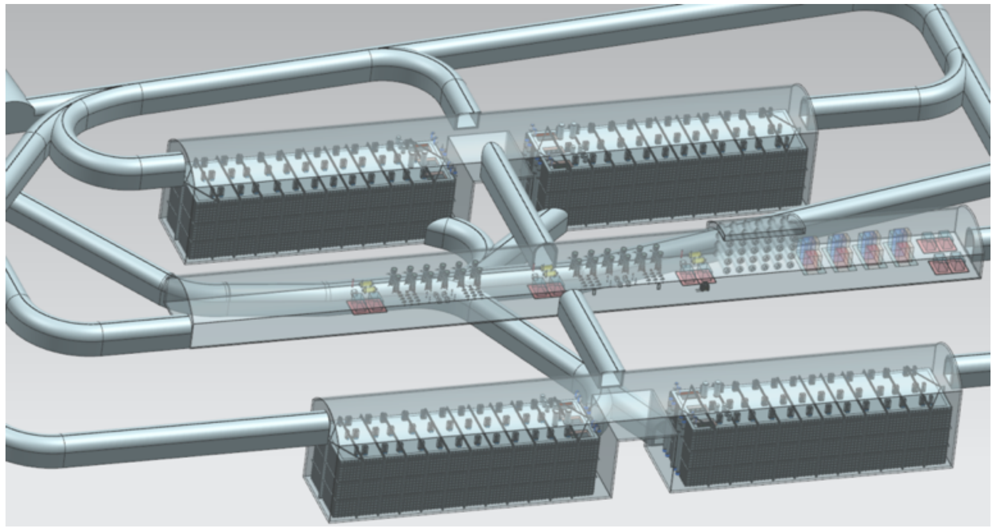
http://www.hyper-k.org/en/

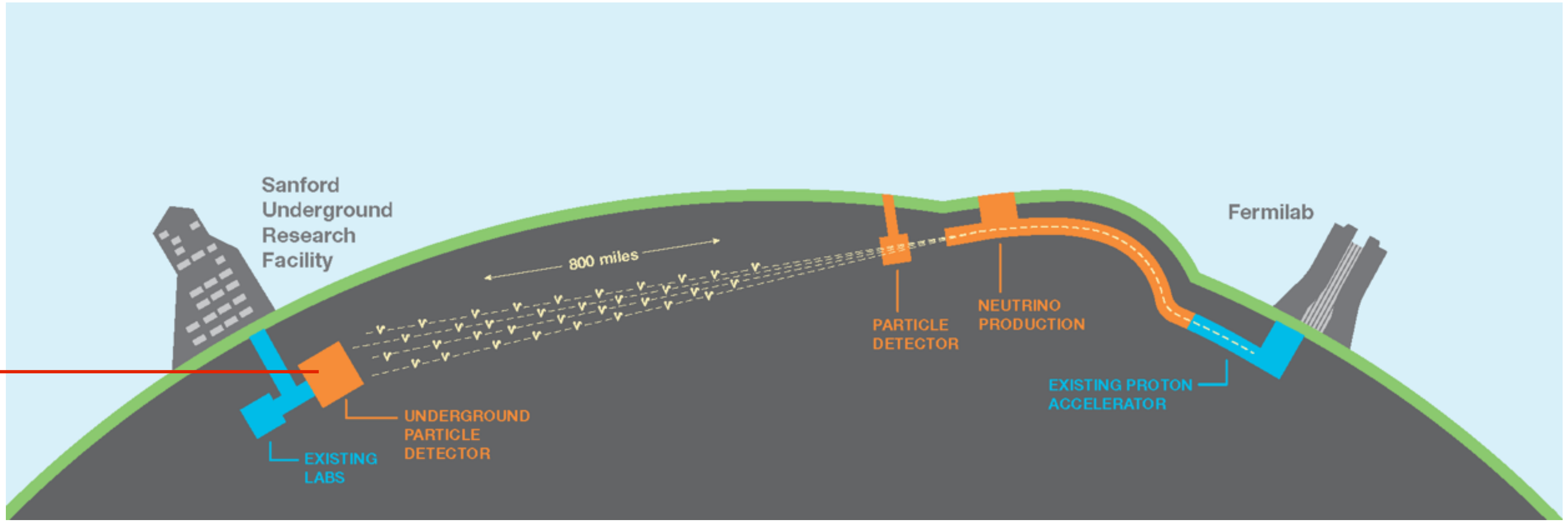
- 560 kiloton (fiducial) water-Cherenkov detector with high intensity beam from J-PARC
- Multipurpose machine with all of the physics topics of Super-K and T2K, plus a few more

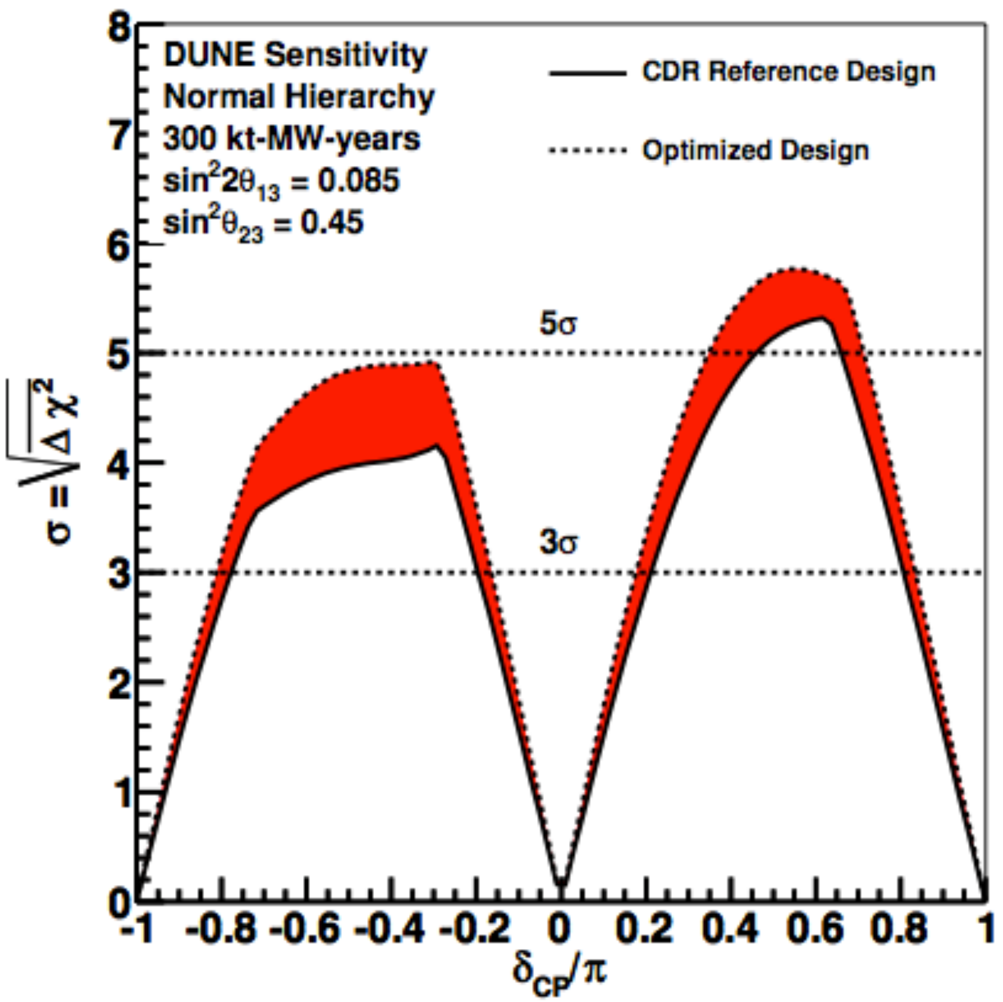


Physics in 2026

Deep Underground Neutrino Experiment







- High Intensity Wide Band beam from Fermilab to SURF (Homestake mine)
- **40 kton**: 4 Liquid Argon TPC detectors of 10 ktons each
    - Lower mass compensated by much larger efficiency
- Oscillation physics in **2026**

Outlook

- **Neutrino oscillations** have been a very vibrant field for the last two decades, crucial for the understanding of neutrino properties, as mixing angles and mass-square splittings, which were measured with **precisions better than 4%, except θ_{23} (~8%)**
- Three unknowns remain: **δ_{CP}**, **sign(Δm^2_{23})** and **θ_{23} octant**
- With hints on these three unknowns, the current generation of experiments, **T2K**, **NOvA**, **Daya Bay**, etc, should be able to achieve 3σ sensitivity on δ_{CP} and sign(Δm^2_{23}), even more in **T2K-II**
- A new generation of experiments as **DUNE** and **HK** will cover a larger phase space of δ_{CP} with sensitivities **beyond 5σ**
- Is that the full story ? What about sterile neutrinos ? Let's be opened to surprises …