The neutrino mass hierarchy

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Interplay between Particle and Astroparticle Physics
LAL-Orsay
5/9/2016

NB mass hierarchy/mass ordering
are used interchangeably in this talk

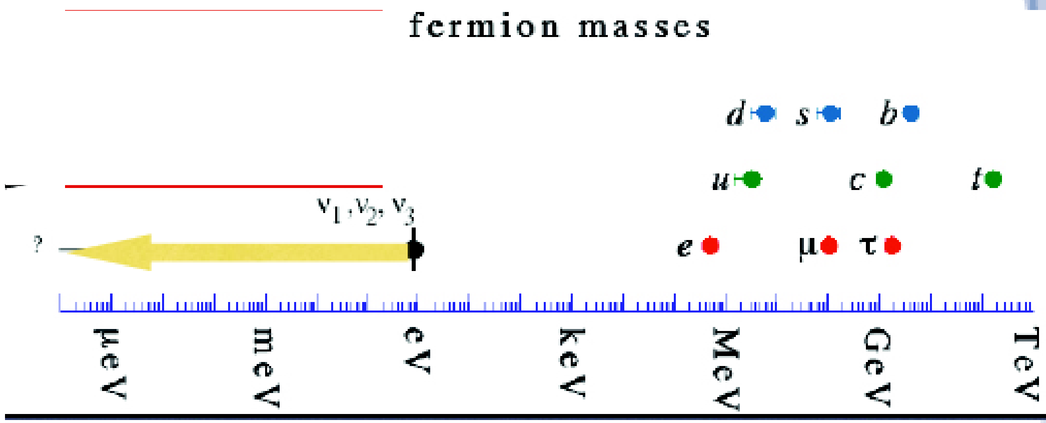
DE LA RECHERCHE À L'INDUSTRIE

Outline

- Introduction- neutrino and neutrino oscillations
- Matter-CP effects
- Ongoing measurements: T2K, NOVA
- Middle term: INO, PINGU, ORCA, JUNO
- Long term: DUNE, HyperKamiokande
- Implications for cosmology, double beta
- Warning, not covered in this talk: theory and mass models, octant-MH dependency, cosmological measurements, SN, statistics issues in MH determination

Neutrino physics: surprising results

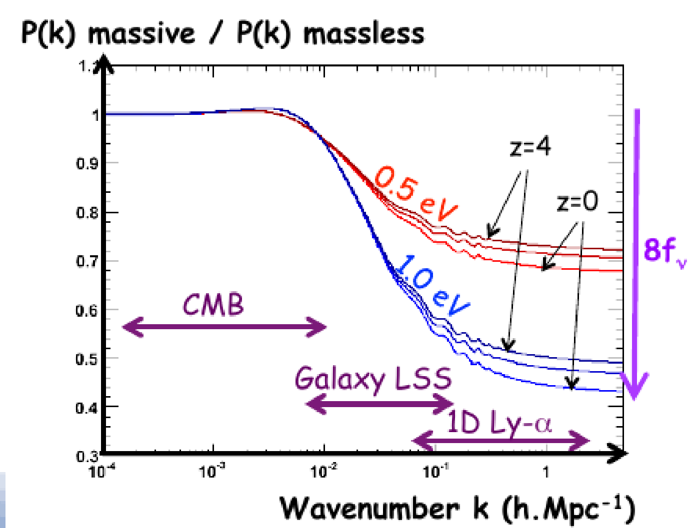
- The extreme lightness of neutrino masses begs a compelling explanation



- The neutrino mixing angles are large, at variance with the quark mixing angles: large CP violation effects are allowed

$$V_{PMNS} = \begin{pmatrix} 0.8 & 0.5 & 0.2 \\ 0.4 & 0.6 & 0.7 \\ 0.4 & 0.6 & 0.7 \end{pmatrix} \qquad V_{CKM} = \begin{pmatrix} 1 & 0.2 & 0.001 \\ 0.2 & 1 & 0.01 \\ 0.001 & 0.01 & 1 \end{pmatrix}$$

- Neutrinos play an important role in the evolution of the Universe. Can they explain matter-antimatter asymmetry ?



Neutrino oscillations

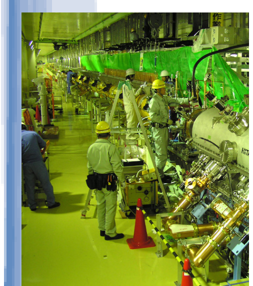
$$\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

If neutrino flavor eigenstates are different from mass eigenstates, propagation induces a phase shift with the appearance of a new flavor

$\nu_\mu = -\sin\theta\, \nu_1 + \cos\theta\, \nu_2$

Propagation

Source



W ν_μ μ

$\nu_1 \rightarrow \exp(-ip_1 x)\, \nu_1$

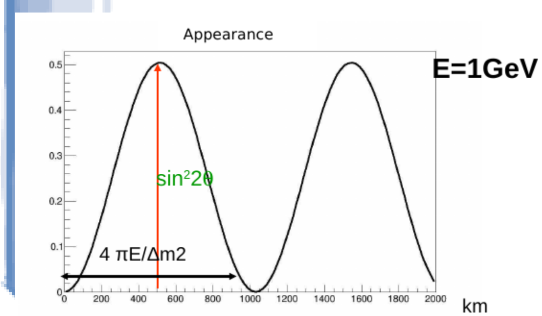
$\nu_2 \rightarrow \exp(-ip_2 x)\, \nu_2$

$\Delta\varphi = \Delta m^2 L/(4E)$

ν_e e

Detector

L

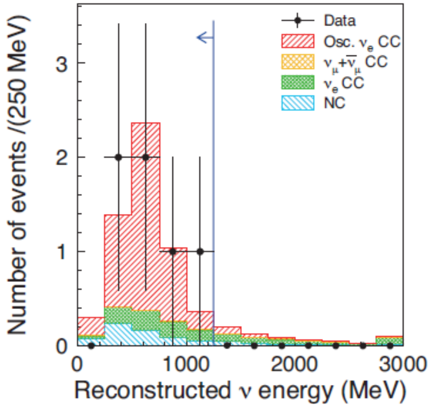


$\text{Prob}(\nu_\mu \rightarrow \nu_e) = \sin^2(2\theta)\, \sin^2(\Delta m^2 L/4E)$

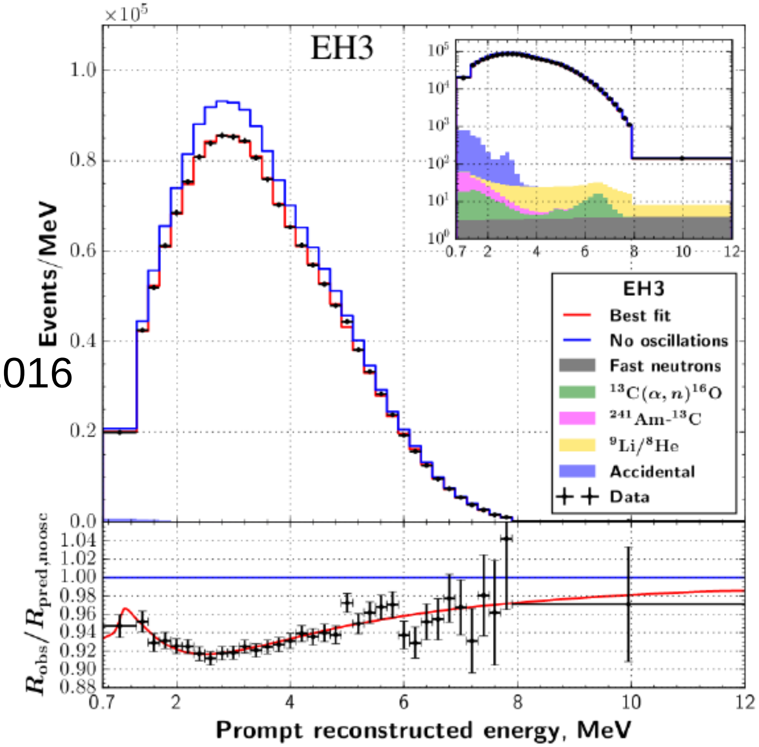
This is a simplified two neutrino scenario

Notice that the expression is invariant replacing Deltam**2 → -Deltam**2

The measurement of the last mixing angle θ_{13}



- 2011: early indication by T2K (appearance mode, 2.5 σ)
- 2011-2016 Precise measurement by the Daya Bay experiment (and Reno, Double Chooz)
- Over 2 10^6 antineutrinos detected
- Shape distortion agrees with the oscillation prediction



Z. Yu@Neutrino2016

$\sin^2 2\theta_{13} = [8.41 \pm 0.27(\text{stat.}) \pm 0.19(\text{syst.})] \times 10^{-2}$

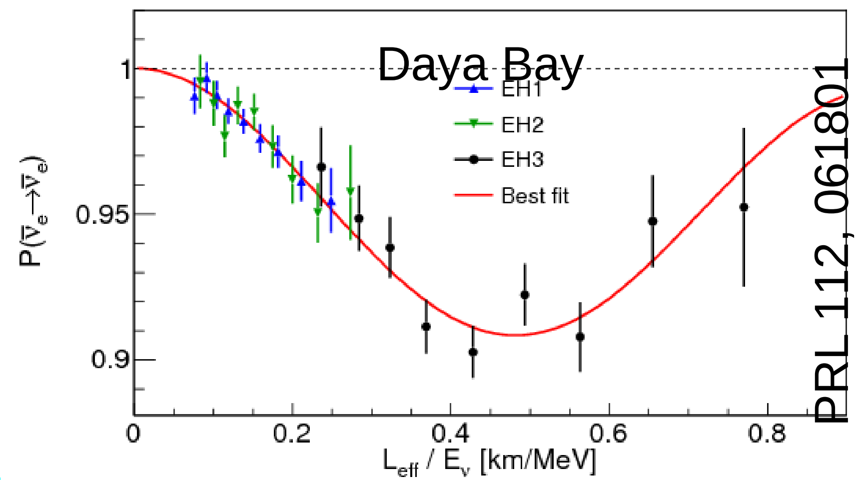
$|\Delta m^2_{ee}| = [2.50 \pm 0.06(\text{stat.}) \pm 0.06(\text{syst.})] \times 10^{-3} \text{eV}^2$

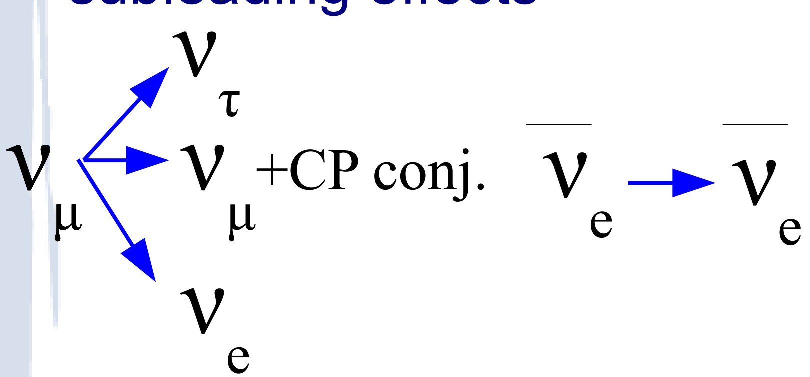
The Pontecorvo-Maki-Nakagawa-Sakata (PMNS) mixing matrix

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

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \begin{pmatrix}U_{e1}&U_{e2}&U_{e3}\\U_{\mu 1}&U_{\mu 2}&U_{\mu 3}\\U_{\tau 1}&U_{\tau 2}&U_{\tau 3}\end{pmatrix} = \begin{pmatrix}1&0&0\\0&c_{23}&s_{23}\\0&-s_{23}&c_{23}\end{pmatrix}\begin{pmatrix}c_{13}&0&s_{13}e^{-i\delta}\\0&1&0\\-s_{13}e^{i\delta}&0&c_{13}\end{pmatrix}\begin{pmatrix}c_{12}&s_{12}&0\\-s_{12}&c_{12}&0\\0&0&0\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

- The oscillation phenomena have been convincingly observed using solar, atmospheric (Nobel prize 2015), reactor and accelerator neutrinos, establishing the three neutrino SM paradigm
- Currently unveiling three-neutrino subleading effects





Parameter	Value	Precision (%)
Δm^2_{21}	$7.5\ 10^{-5}$ eV^2	2.6
θ_{12}	34°	5.4
Δm^2_{32}	$2.4\ 10^{-3}$ eV^2	2.6
θ_{23}	42°	~10
θ_{13}	8.4°	4 (Daya Bay 2016)

Capozzi et al. ArXiv:1312.2878

Outstanding questions in neutrino physics

1) Is θ_{23} =45°? which octant ?
2) Determine the mass ordering
3) Measure the CP violation parameter δ
4) Precision tests of the PMNS paradigm (ideally at the % level, as for the CKM matrix)
5) Are there any new neutrino states ?
6) Dirac or Majorana ?

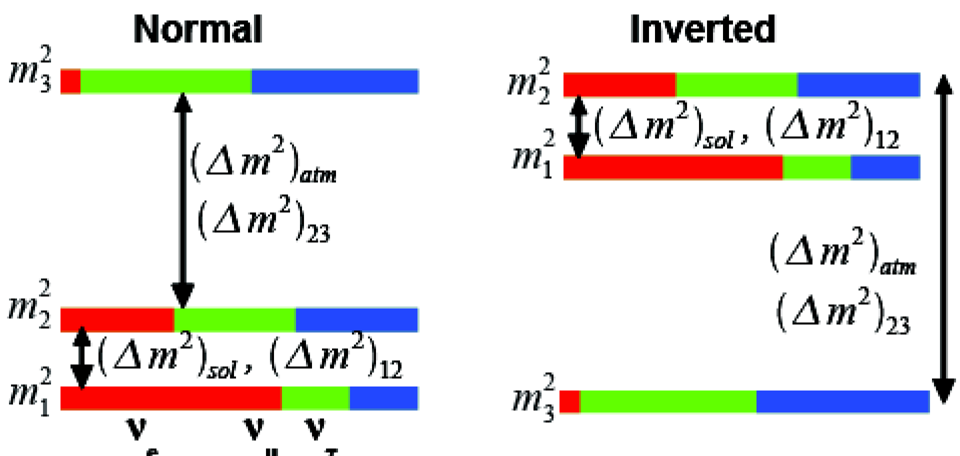
→

1) Is there a symmetry between ν_μ and ν_τ ?
2) Help model builders. Impact on cosmology.
3) Link with leptogenesis. Are we born out of (heavy) neutrinos ?
4) How different are neutrinos ?
5) New states are expected btw 1eV and 10**16 GeV
6) Majorana mass term: major discovery

Neutrino masses and ordering

- Neutrinos have a tiny mass : m < 2 eV from measurement of the beta spectrum (Katrin will push this limit to 0.2 eV)
- Since they oscillate, neutrino have masses (NB clear sign of phenomena BSM)
- Oscillations have measured two mass splitting: $|\Delta m^2_{atm}| = 2.4\ 10^{-3}\ eV^2$ and $\Delta m^2_{sol} = 7.5\ 10^{-5}\ eV^2$ and vacuum leading order measurements are not sensitive to the absolute mass scale

The lightest solution is: m1~0, m2~7 meV and m3~50 meV

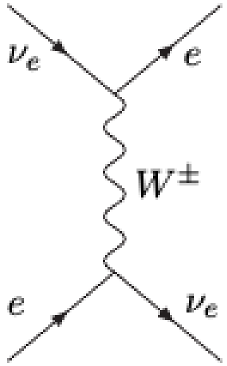


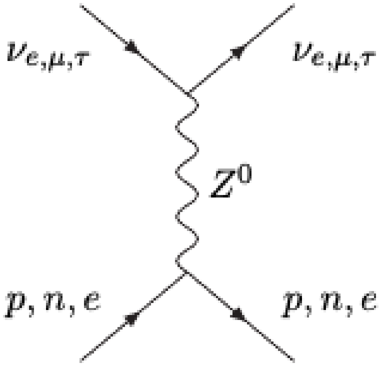
The lightest solution is: m3~0, m1~m2~50 meV

- The measurement of the sign of Δm^2_{atm} has implications for the theoretical understanding of the nu mass mechanism, long baseline CP violation measurements, 0-nu double beta decay, and cosmology

Neutrino oscillation in matter

- Neutrino forward scattering on electrons, equivalent to light refraction index, leads to an additional phase for electron neutrinos proportional to $G_F N_e$
- The sign of the phase depends on neutrino vs antineutrino and normal/inverted ordering
- NC diagrams do not contribute to the phase shift (same for ν_e, ν_μ and ν_τ)





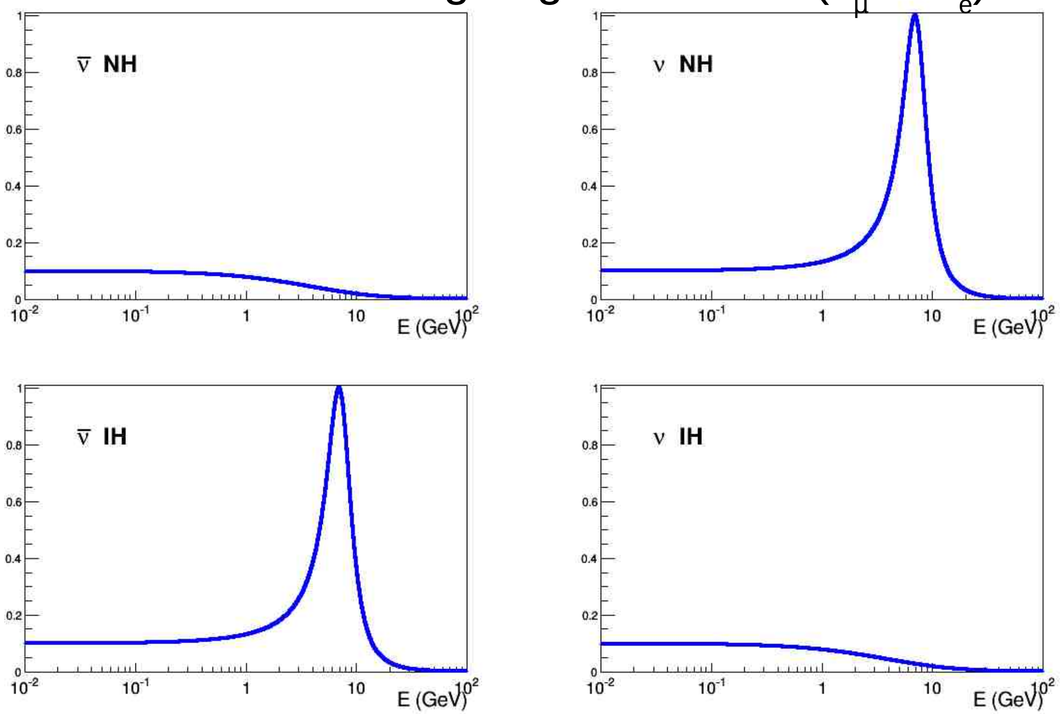
Neutrino oscillation in matter

In the constant density case, the effective mixing angle reads

$$\sin^2(2\theta_m) = \frac{(\Delta m^2/2E)^2 \sin^2(2\theta_0)}{((\Delta m^2/2E)\cos(2\theta_0) - 2\sqrt{2} G_F N_e)^2 + (\Delta m^2/2E)^2 \sin^2(2\theta_0)}$$

This expression has a resonant behavior, the effective mixing angle can be maximal even if the vacuum mixing is tiny (MSW effect)

Effective mixing angle in matter ($\nu_\mu \to \nu_e$)



Eres = 7 GeV for atm mass splitting and 4.5 g/cm**3 density

For the three neutrino case, for Normal Ordering matter effect enhance Prob ($\nu_\mu \to \nu_e$) and suppress it for antineutrinos. Viceversa for Inverted Ordering.

CP violation effects

$\nu_\mu \to \nu_e$: beyond the leading term in vacuum

$$P(\nu_\mu \to \nu_e) \approx 4 C^2_{13} S^2_{13} S^2_{23} \sin^2 \Phi_{31}$$ "Atmospheric" term

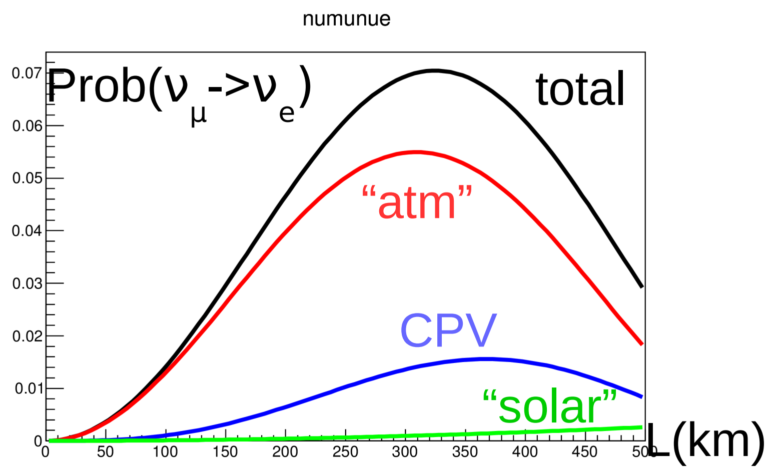
$$\pm 8 C^2_{13} C_{12} C_{23} S_{12} S_{13} S_{23} \sin\delta \sin\Phi_{32} \sin\Phi_{31} \sin\Phi_{21}$$ CP violating term

$$+4 S^2_{12} C^2_{13} (C^2_{12} C^2_{23} + S^2_{12} S^2_{23} S^2_{13} - 2 C_{12} C_{23} S_{12} S_{23} S_{13} \cos\delta) \sin^2 \Phi_{21}$$ "Solar" term

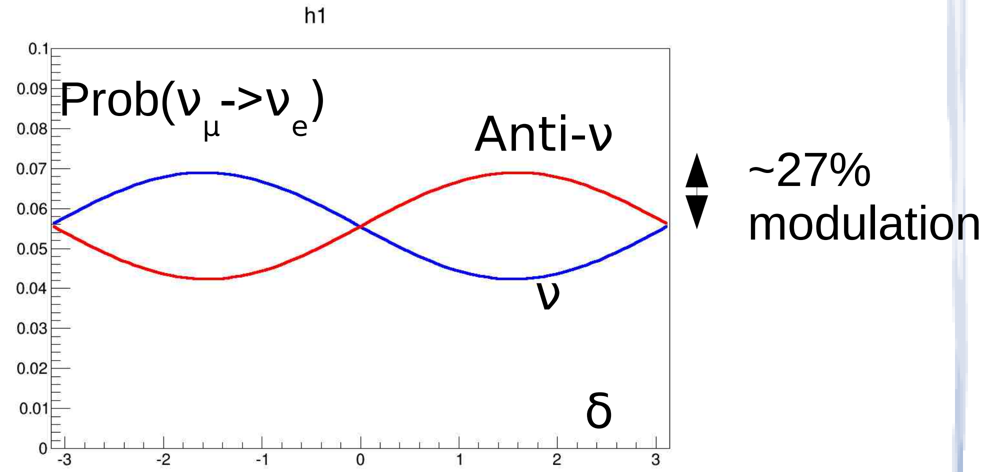
$$C_{ij} = \cos(\theta_{ij})$$

$$\Phi_{ij} = \Delta m^2_{ij} L / 4E$$

Change sign from nu to anti-nu! An accelerator based neutrino beam is ideal to study this, as either neutrinos or antineutrinos can be produced

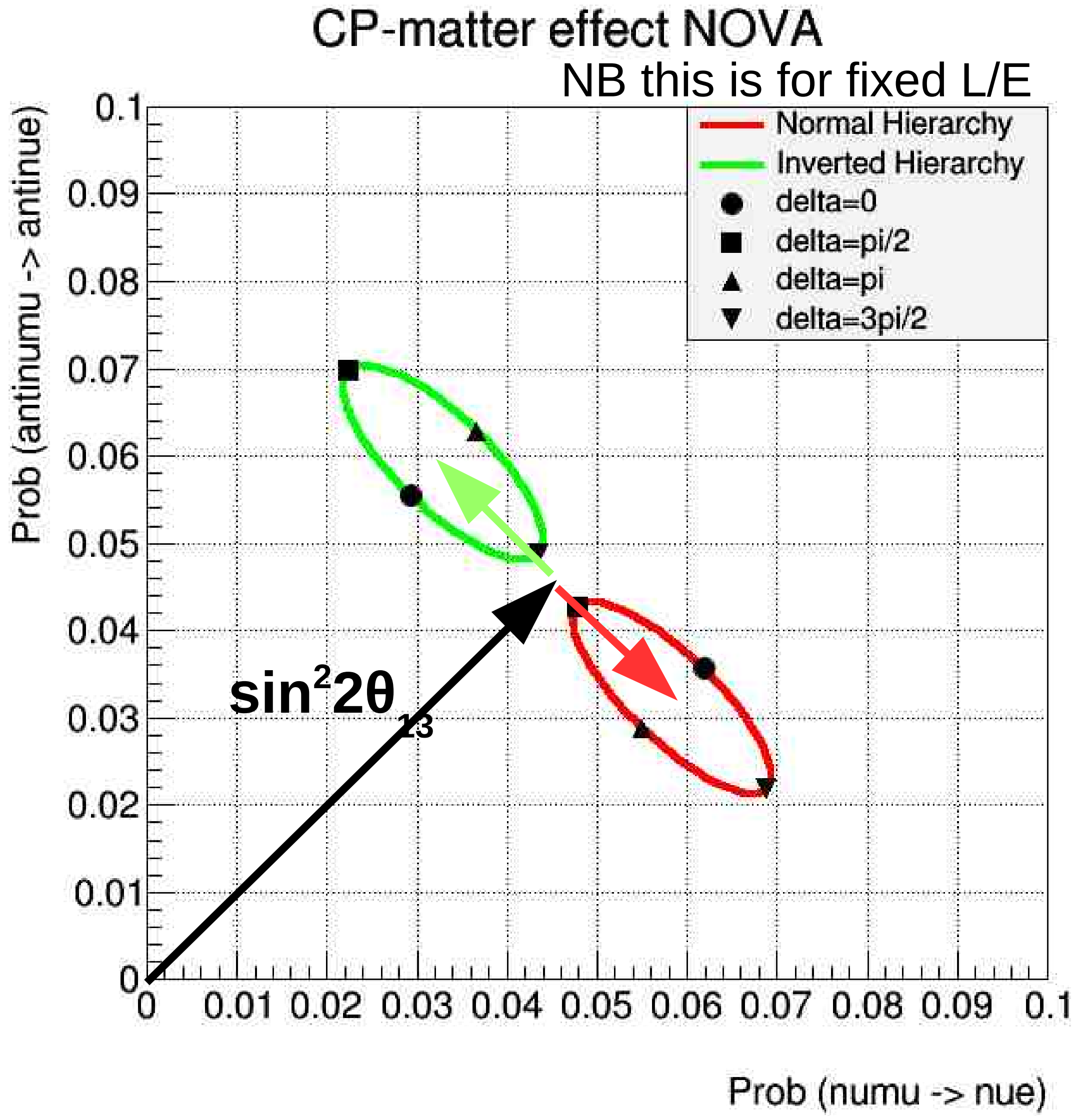


E=0.6 GeV



Caution: indicative plots !!

Combined effect of CP and matter

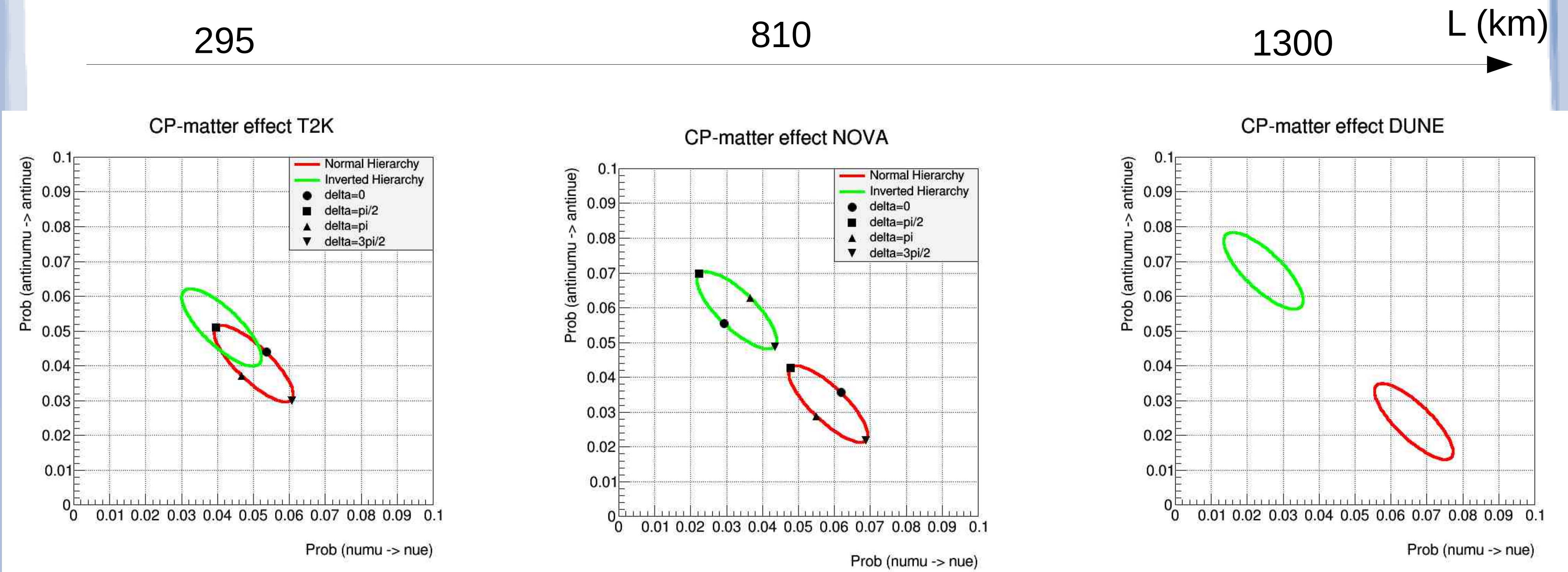


Effect of **inverse** or **direct** mass ordering

CP violation

NB A precise measurement in this plane can determine theta13, MH, delta, octant

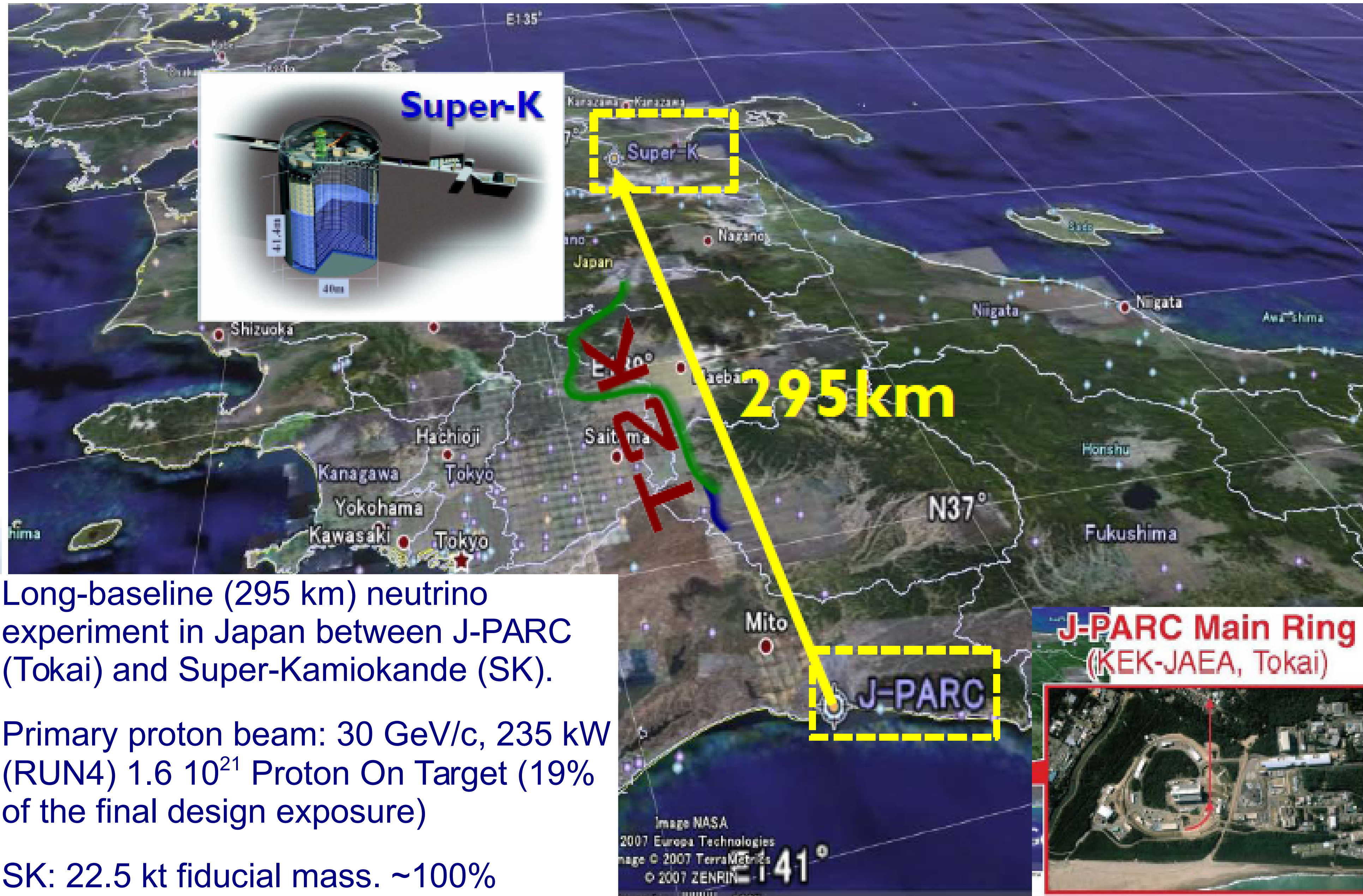
Combined effect of CP and matter



The relative increase of matter effect versus CP effect is due to the fact that these experiments are tuned to the L/E of the first oscillation maximum. The increasing L and E are such that Prob (numu->nue) climbs the slope of the MSW resonance.

For T2K, CP modulation +-27%, Matter effect ~10%

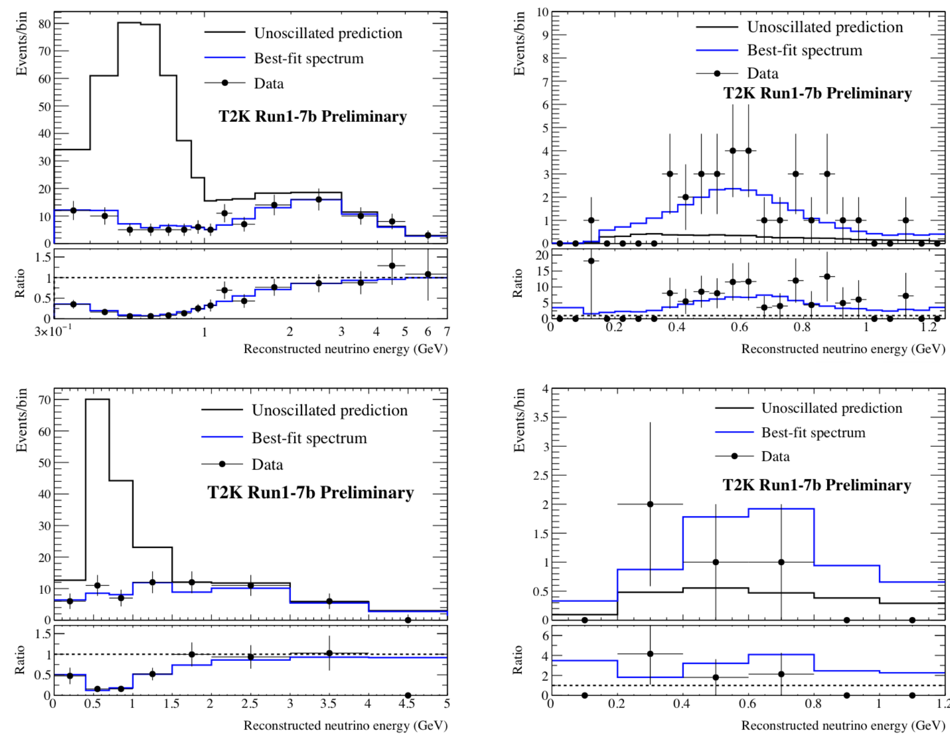
The Tokai to Kamioka (T2K) experiment

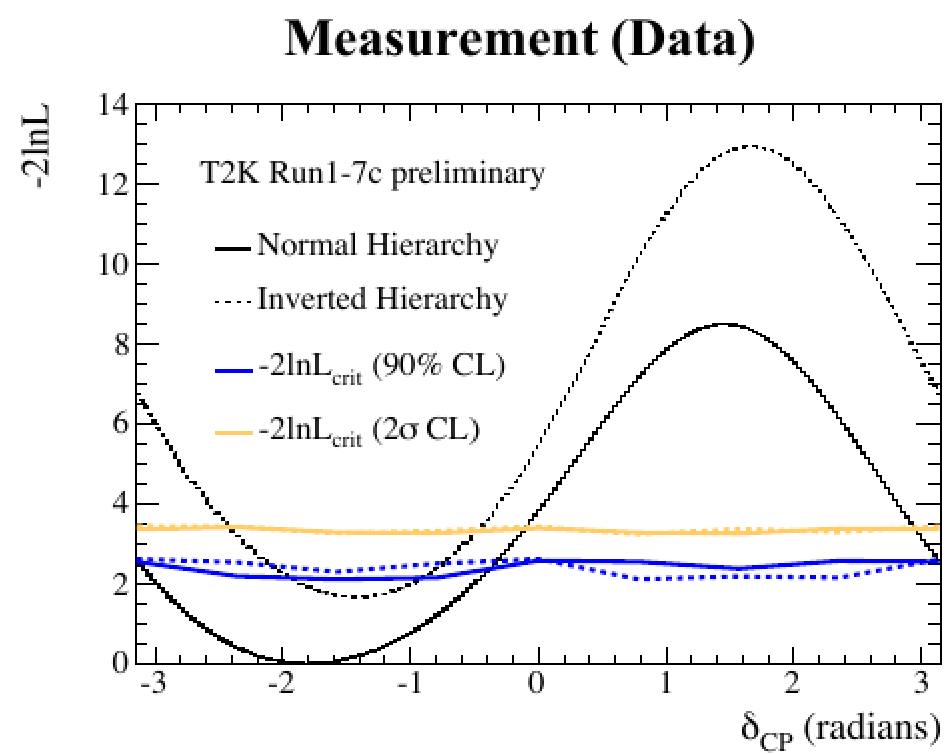


- Long-baseline (295 km) neutrino experiment in Japan between J-PARC (Tokai) and Super-Kamiokande (SK).
- Primary proton beam: 30 GeV/c, 235 kW (RUN4) 1.6 10^{21} Proton On Target (19% of the final design exposure)
- SK: 22.5 kt fiducial mass. ~100% livetime

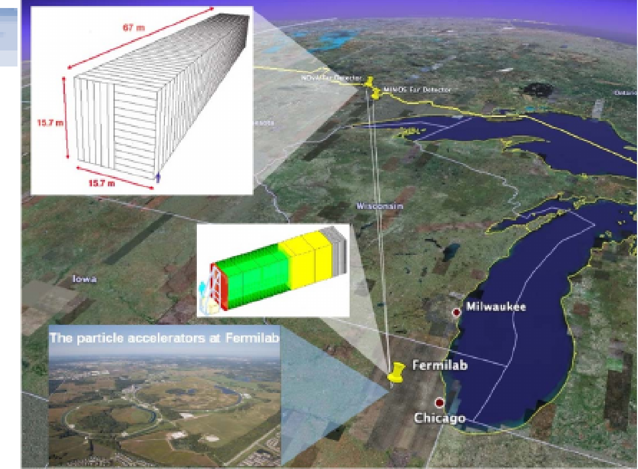
19% of full data set: nu/antinu=1

T2K combined ν_e, ν_μ, $\bar{\nu}_e$, $\bar{\nu}_\mu$ analysis





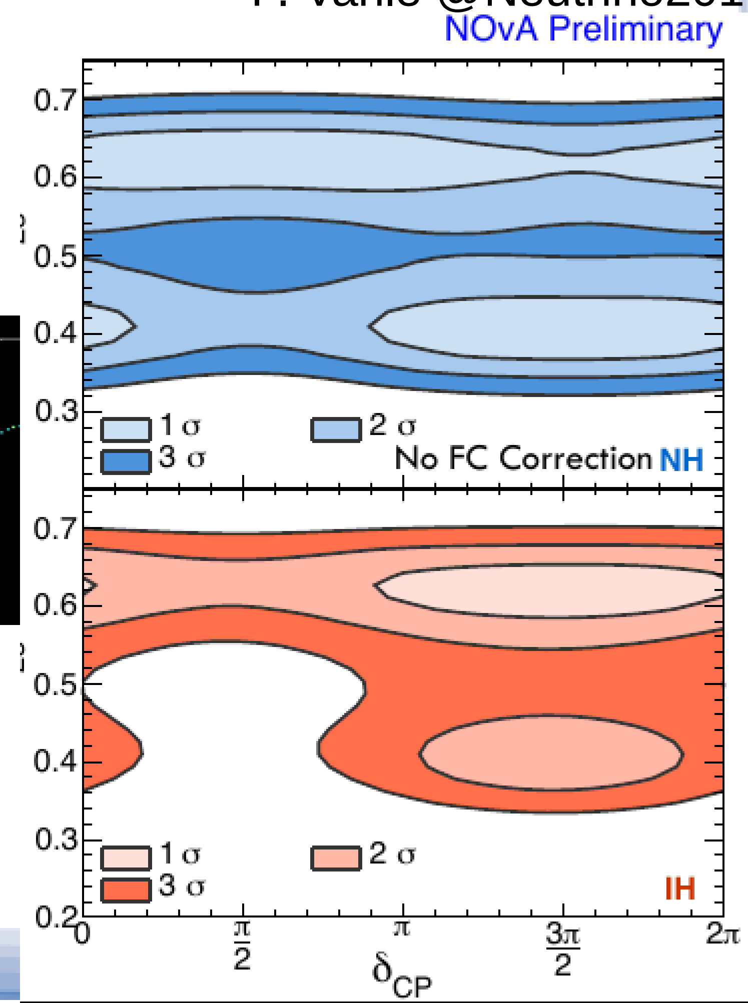
	$\delta_{cp} = -\pi/2$ (NH)	$\delta_{cp} = 0$ (NH)	$\delta_{cp} = +\pi/2$ (NH)	$\delta_{cp} = \pi$ (NH)	Observed
ν_e	28.7	24.2	19.6	24.1	32
$\bar{\nu}_e$	6.0	6.9	7.7	6.8	4

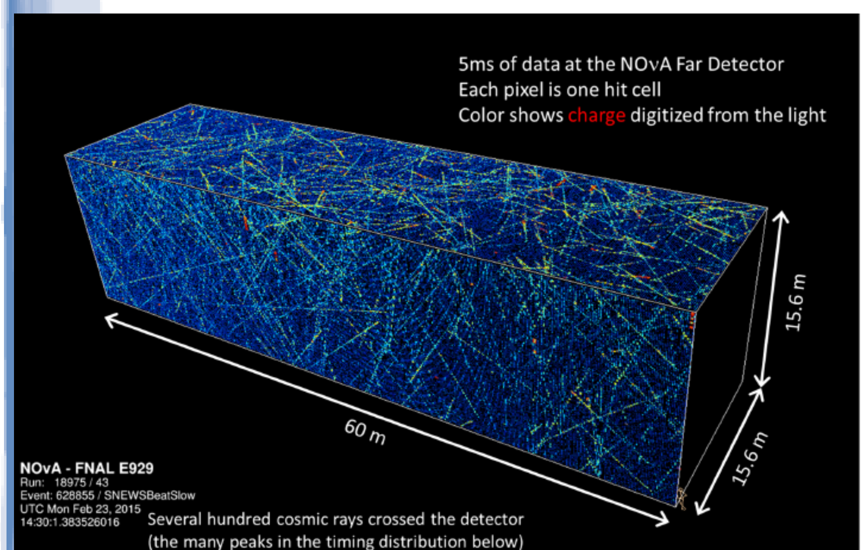


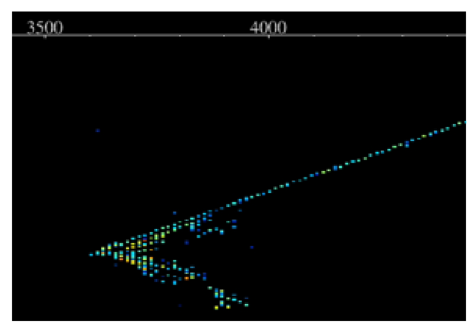
NOvA

- L=810 km from FNAL to Ash River (Minnesota)
- Off-axis NUMI beam (2 GeV) with 500->700 kW
- 14kt surface liquid scintillator segmented detector
- Weak preference for NH
- Region around delta=π/2 IH excluded

P. Vahle @Neutrino2016



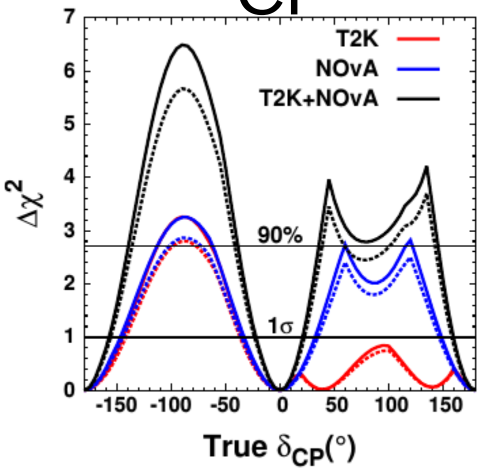




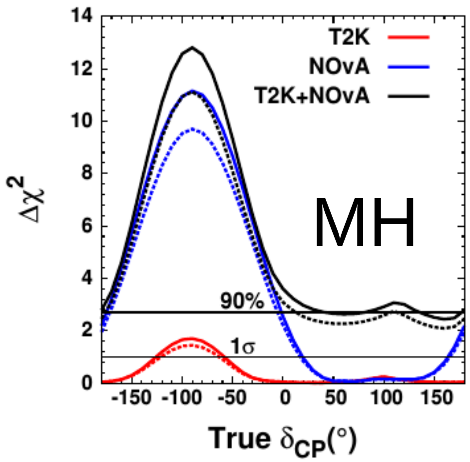
Final reach of T2K and NOvA

- Presently weak indications favoring NH
- Similar sensitivity to CP for T2K and NovA, better sensitivity to MH for NOvA (larger baseline)
- Best sensitivity for δ=-π/2 and NH
- T2K proposes an extension (T2K-II) up to 2026 to increase by ~3 the effective data set
- Might reach 3σ on CP violation around 2021 for a sizable fraction of the parameter space

CP



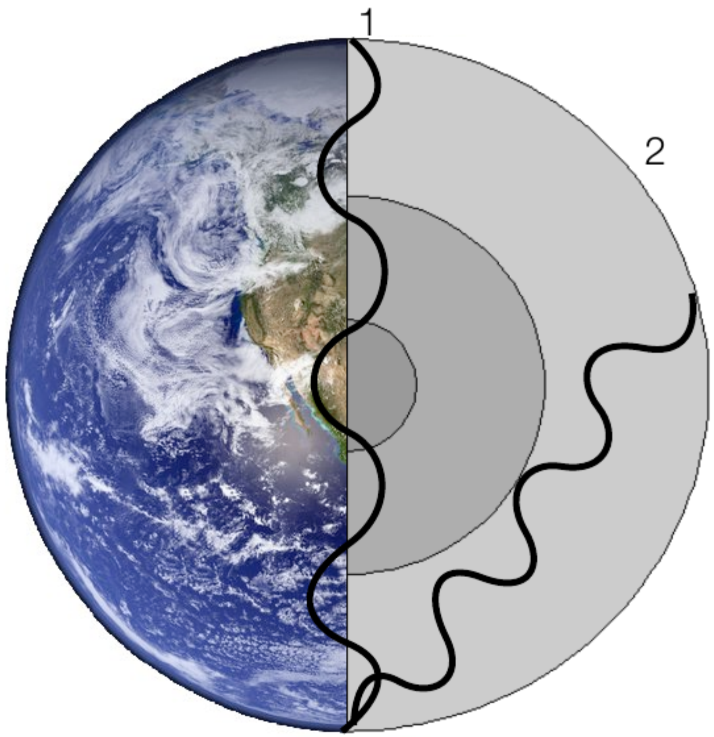
(b) 1:1 T2K, 1:1 NOνA ν:ν̄, NH

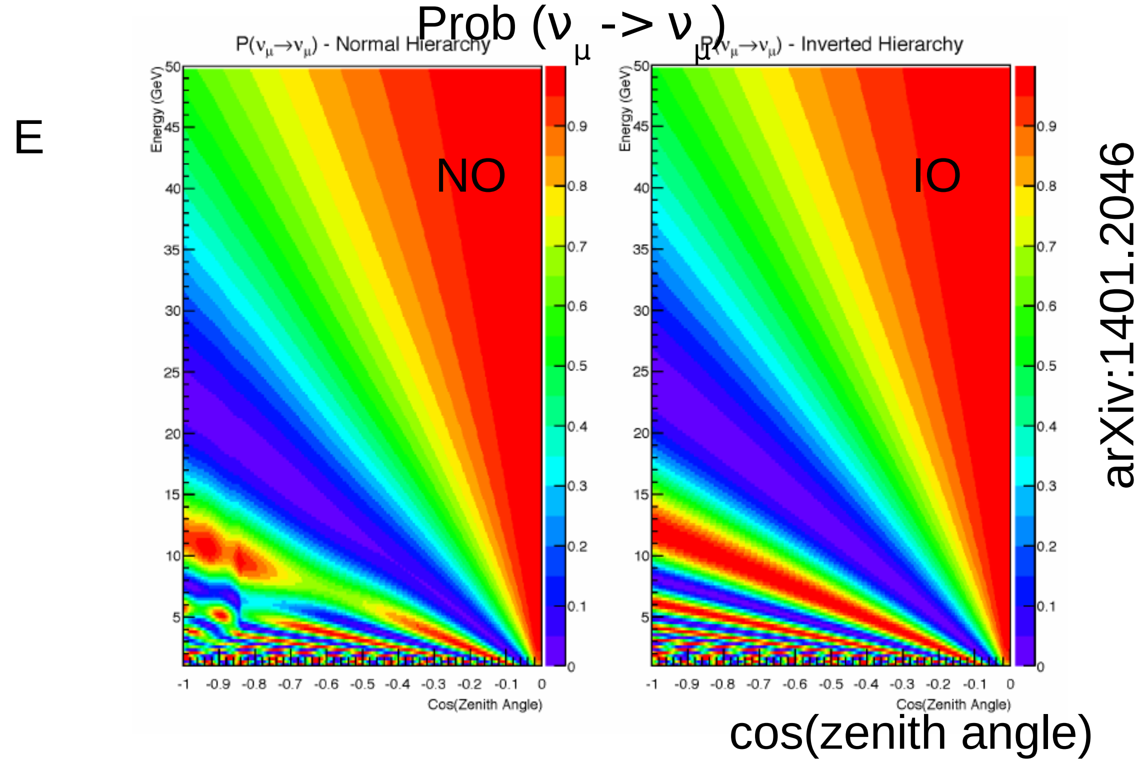


(b) 1:1 T2K, 1:1 NOνA ν:ν̄, NH

Future projects

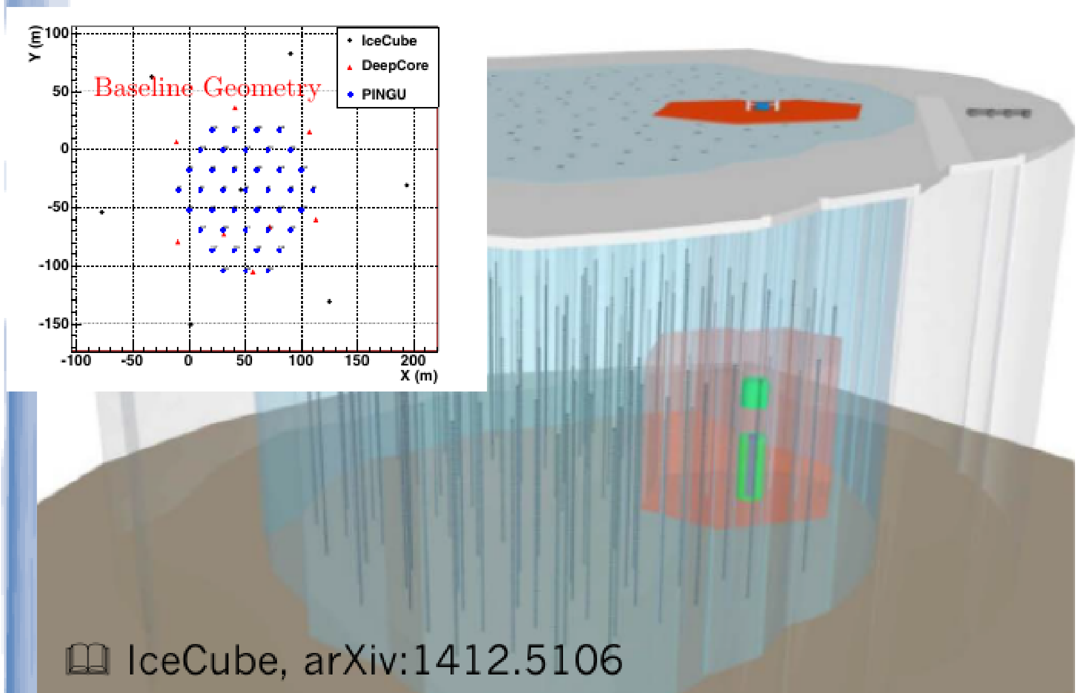
Matter effects for atmospheric neutrinos





- The matter effect can be studied with atmospheric neutrinos traveling in the mantle or the core (cos theta)<-0.8. Two channels are available: Prob (ν_μ -> ν_e) and Prob (ν_μ -> ν_μ). Max sensitivity below 20 GeV.
- These plots get smeared by angular and energy resolutions.
- Some detectors do not separate neutrinos from antineutrinos and rely on the difference in neutrino and antineutrino cross-sections (additional smearing).

Measuring the neutrino mass ordering with atmospheric ν: PINGU and ORCA



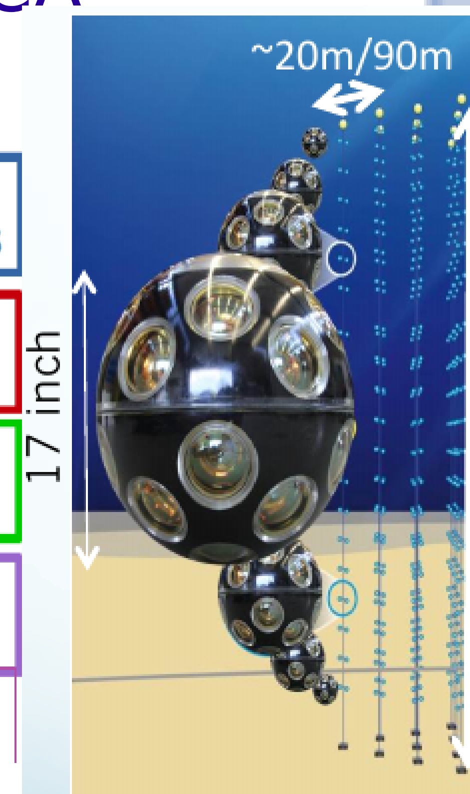
IceCube Gen2
→ +120 strings, 7,200 DOMs

IceCube
→ 86 strings, 5,160 DOMs

DeepCore
→ 8+7 strings, 500 DOMs

PINGU
→ +40 strings, 3,600 DOMs

10” R7081-02 High-QE
+ electronics upgrade

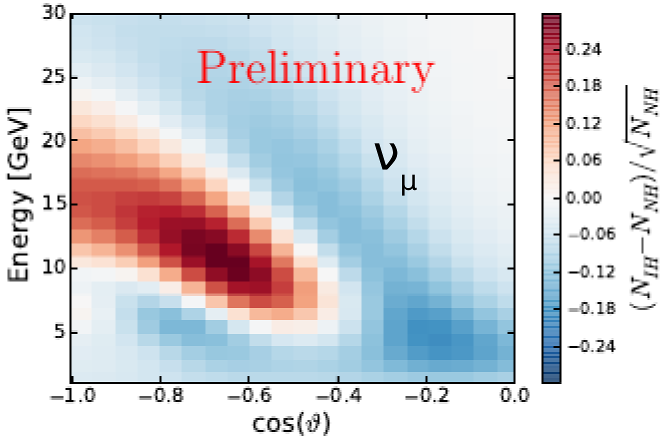


PINGU is a proposed low energy extension of the ICECUBE South Pole neutrino observatory. A much denser optical module array will provide a threshold at the few GeV level.

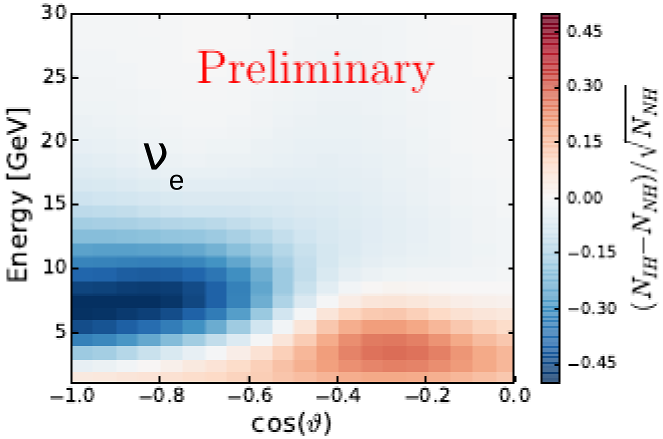
ORCA (based on Antares, KM3NET technology) is a similar project in the Mediterranean sea (Toulon site) with new optical modules (115 lines, 20m btw lines, 6m spaced OM, 2070 OM in total)

Multi Mt instrumented mass in both cases.

Measuring the neutrino mass ordering with atmospheric ν: PINGU and ORCA

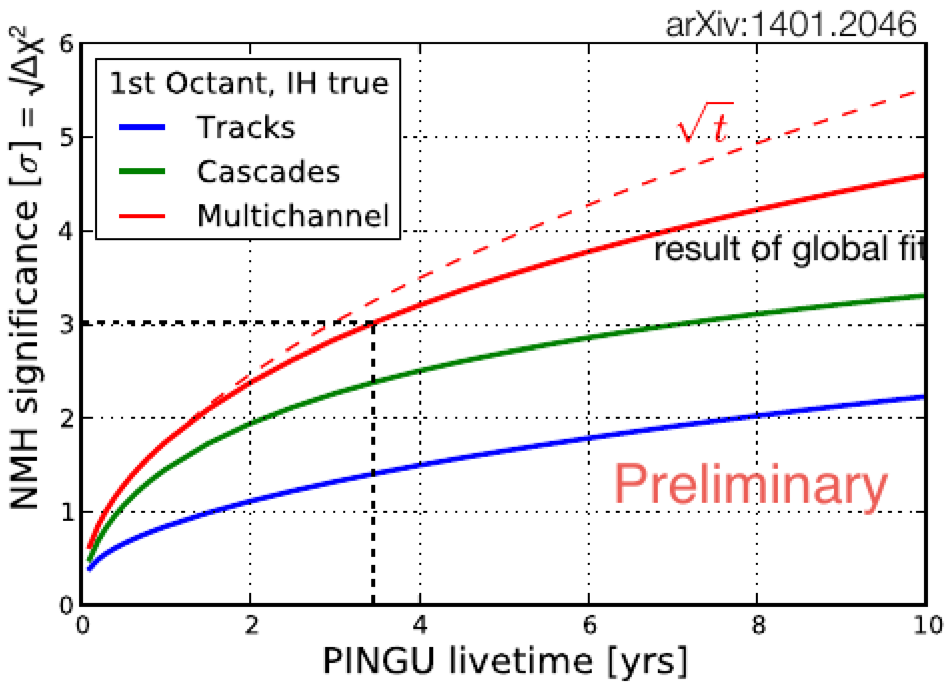


(a) ν_μ CC events.



(b) ν_e CC events.

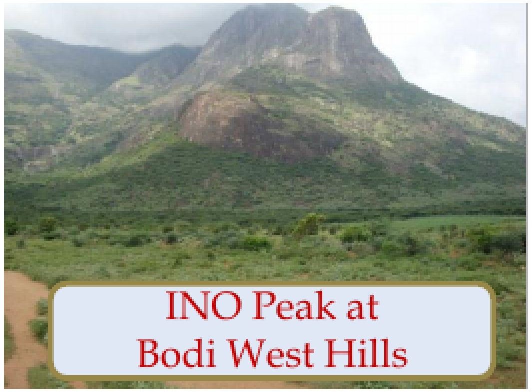
Sensitive regions in the energy-zenith angle plane



PINGU LOI (arXiv:1401.2046)
Main sensitivity from the ν_e channel
Normal and inverted mass ordering distinguished at 3 σ in 3.5 years.
Similar sensitivity for ORCA

The India-based Neutrino observatory

INO: located in Tamil Nadu (Southern India) 1289m (~3800mwe) vertical rock coverage



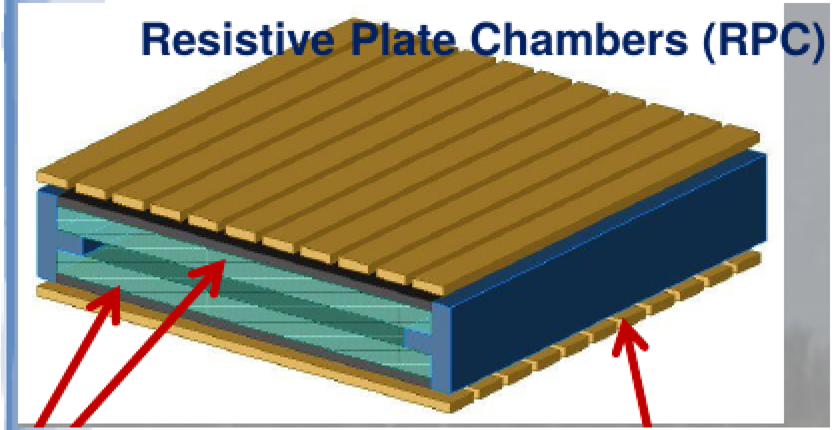
50 kton magnetized iron detector

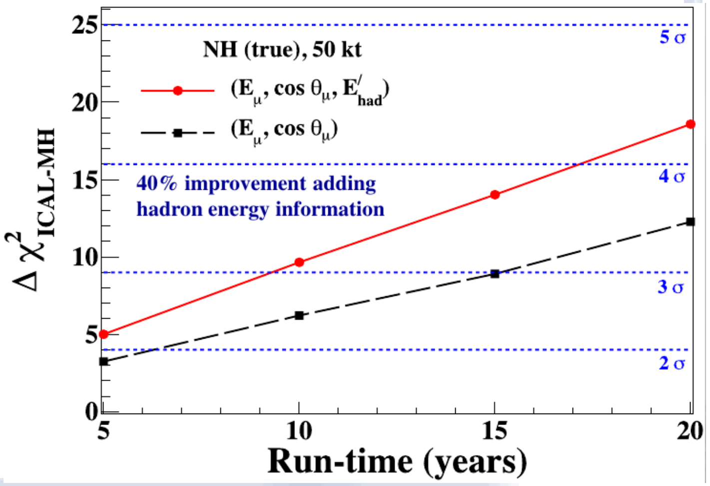
1.4 T magnetic field

Resistive plate chambers with 5.6 cm iron plates

Differentiate neutrinos from antineutrinos based on curvature

arXiv:1406.3689

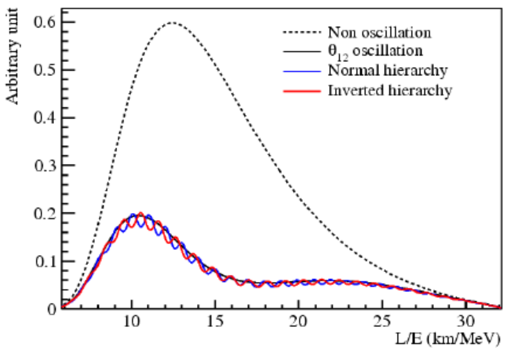




Measuring the neutrino mass ordering: JUNO

- A different method, not related to matter effect has been proposed looking at reactor anti nu_e disappearance around the solar maximum (~50 km)

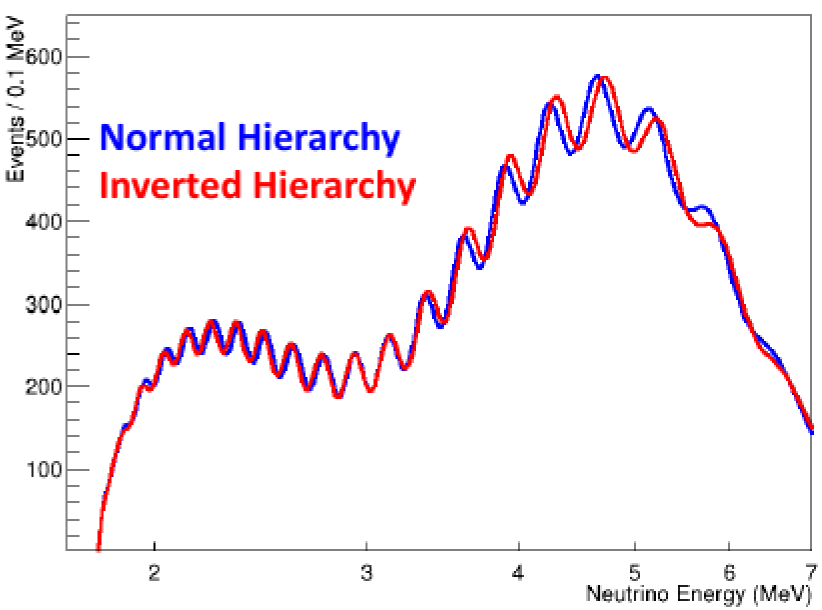
Petcov and Piai,
Phys Lett B 553, 94 (2002)

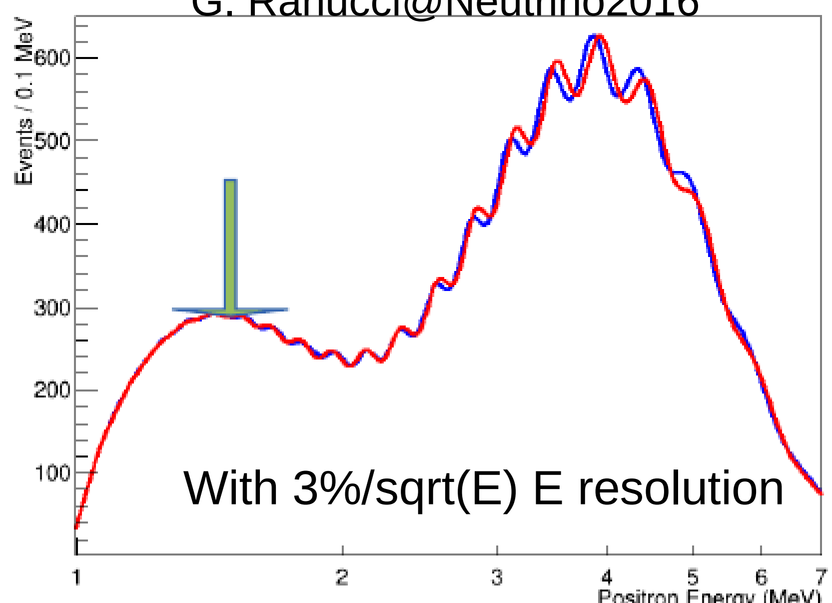


$$P_{ee} = 1 - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2(\Delta_{21}) - \sin^2 2\theta_{13}\sin^2(|\Delta_{31}|) - \sin^2\theta_{12}\sin^2 2\theta_{13}\sin^2(\Delta_{21})\cos(2|\Delta_{31}|) \pm \frac{\sin^2\theta_{12}}{2}\sin^2 2\theta_{13}\sin(2\Delta_{21})\sin(2|\Delta_{31}|)$$

+ NH
- IH

G. Ranucci@Neutrino2016

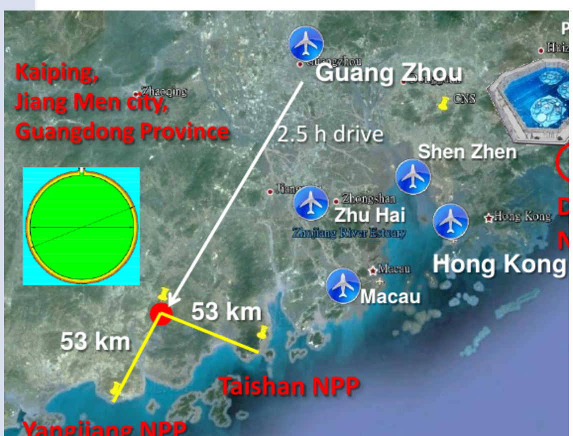


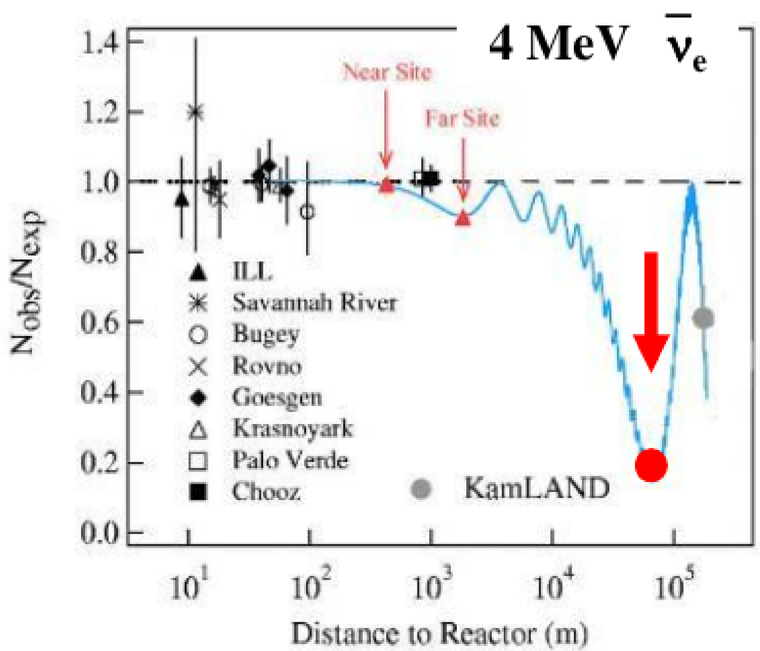


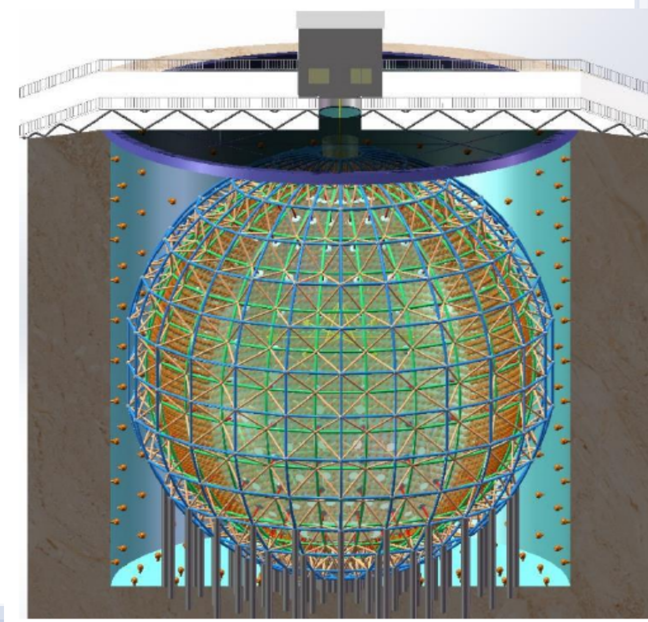
PRD78:111103, 2008; PRD79:073007,2009

Measuring the neutrino mass ordering: JUNO

- 20kton Liquid Scintillator detector in southern China, 700m underground
- At 50 km from two nuclear reactors complexes
- Several other measurements: precision solar ν parameters Δm^2_{21}, θ_{12}, SN,
- Stringent requirements on energy (3% resolution) for MO
- Project approved, under construction, data taking 2020

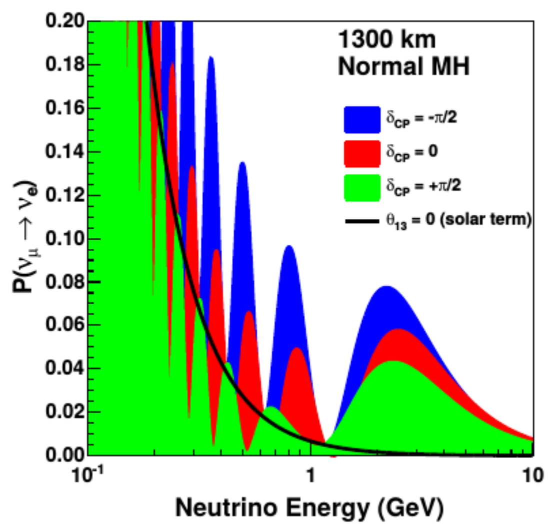


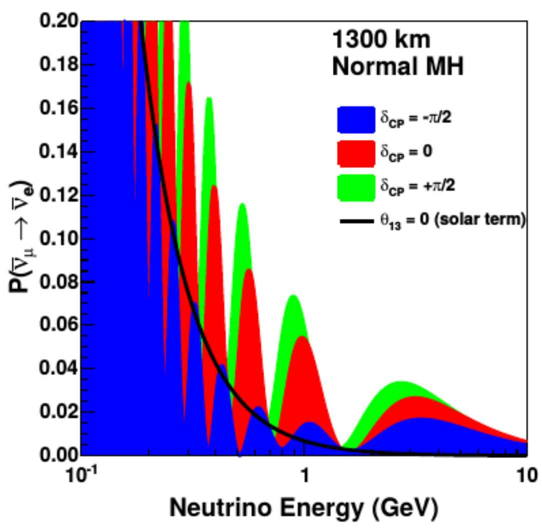


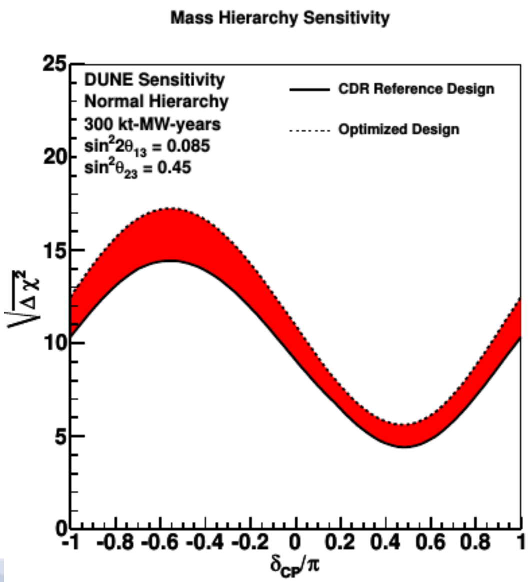


The LBNF/DUNE project

- LBNF DUNE: flagship particle physics project in the US
- 1300 km baseline from FNAL to SURF (South Dakota)
- Based on PIP-II upgrade to FNAL accelerator complex: 1.2 MW at 120 GeV (ultimate beam power 2.4 MW)
- SURF: 4 caverns with 4x10 kt fiducial mass far detector
- >5 "σ" for Mass Ordering with 300 kt-MW-years = 3.5 (nu)+3.5 antinu) with 40kt and 1.07 MW beam (80 GeV)



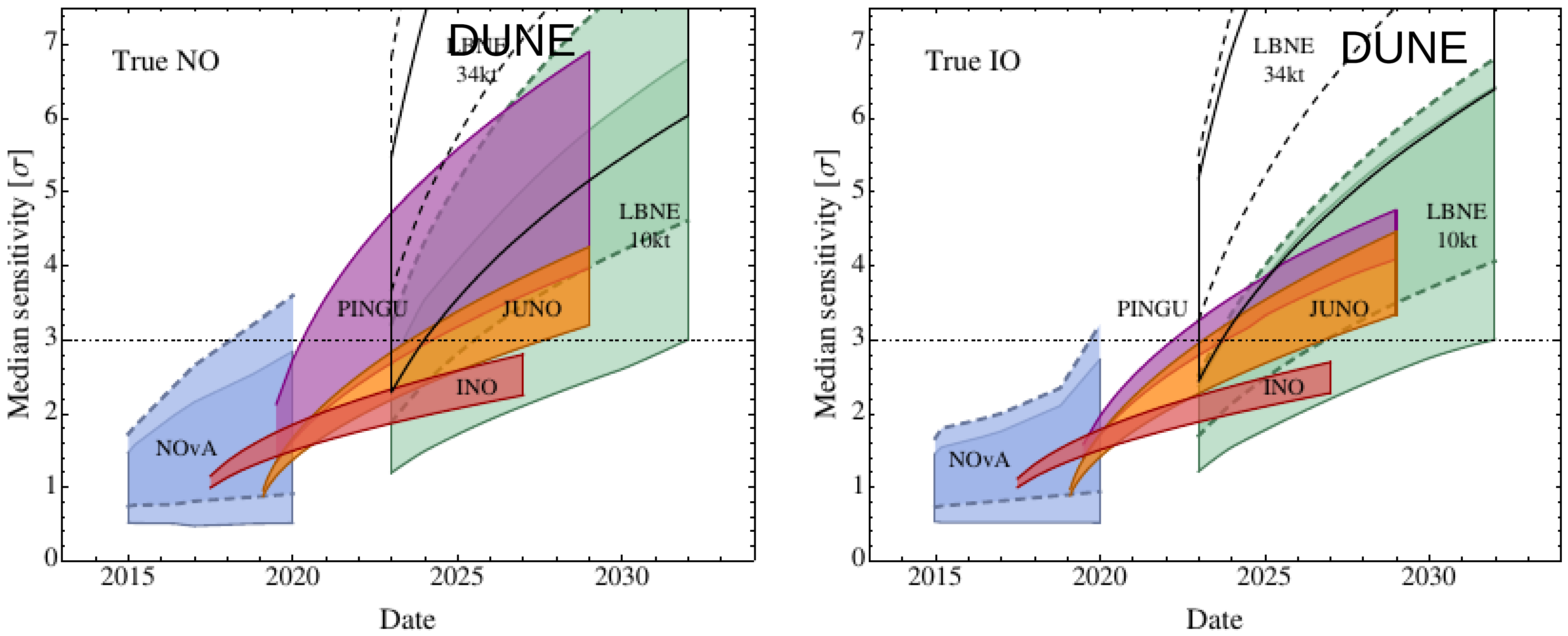




ArXiv:1512.06148

Blennow JHEP 1403 2014 028

Mass ordering timeline



Caution: median sensitivity, starting dates indicative.

Fogli et al 1205.5254

Impact of neutrino mass ordering

- Mass ordering has an impact on neutrinoless double beta decay and cosmology
- It has no impact on the design of future long baseline experiments

β **decay**, sensitive to the "effective electron neutrino mass":

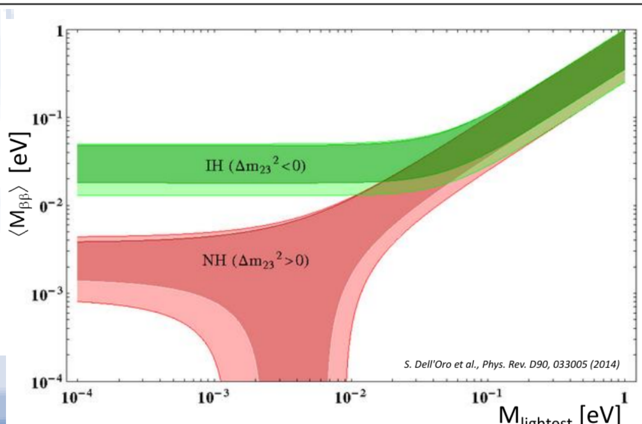
$$m_\beta = \left[c_{13}^2 c_{12}^2 m_1^2 + c_{13}^2 s_{12}^2 m_2^2 + s_{13}^2 m_3^2\right]^{\frac{1}{2}}$$

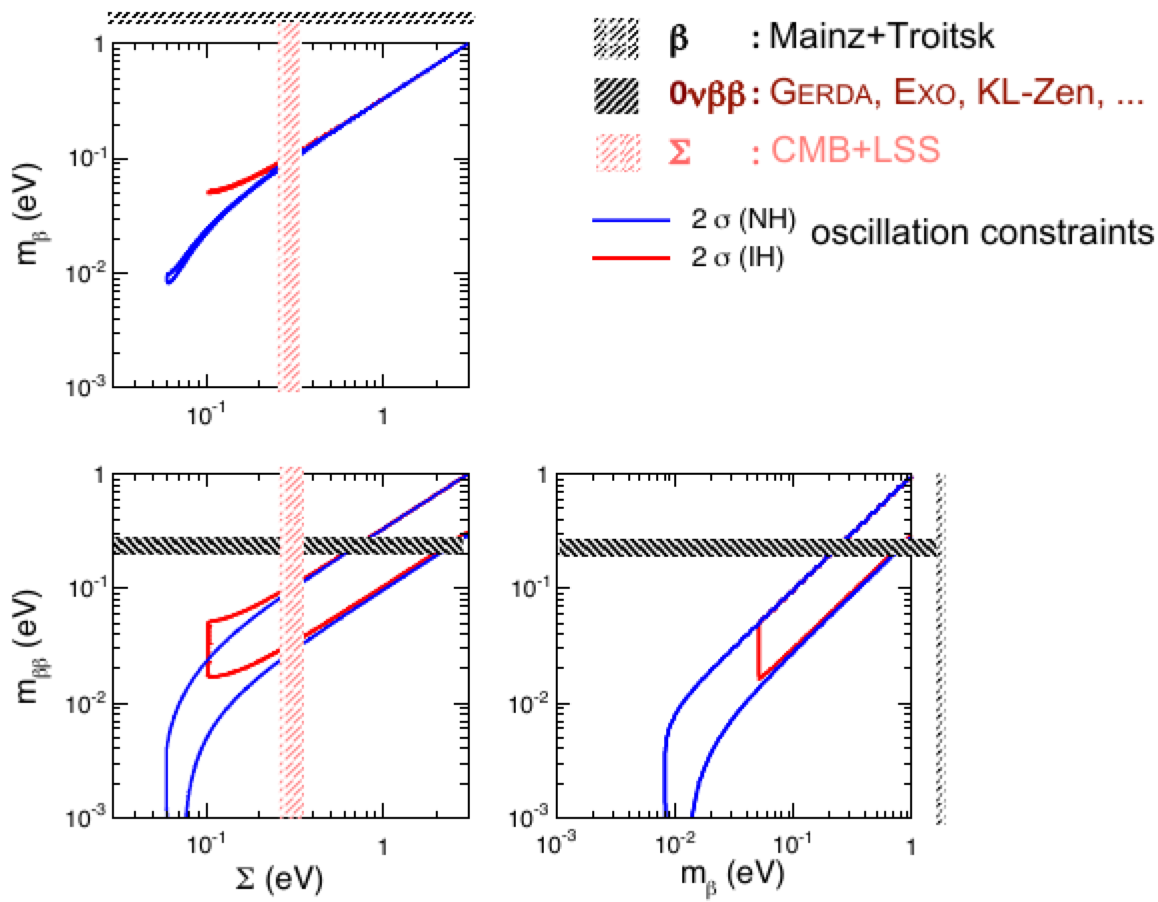
0νββ decay: only if Majorana. "Effective Majorana mass":

$$m_{\beta\beta} = \left|c_{13}^2 c_{12}^2 m_1 + c_{13}^2 s_{12}^2 m_2 e^{i\phi_2} + s_{13}^2 m_3 e^{i\phi_3}\right|$$

Cosmology: Dominantly sensitive to sum of neutrino masses:

$$\Sigma = m_1 + m_2 + m_3$$



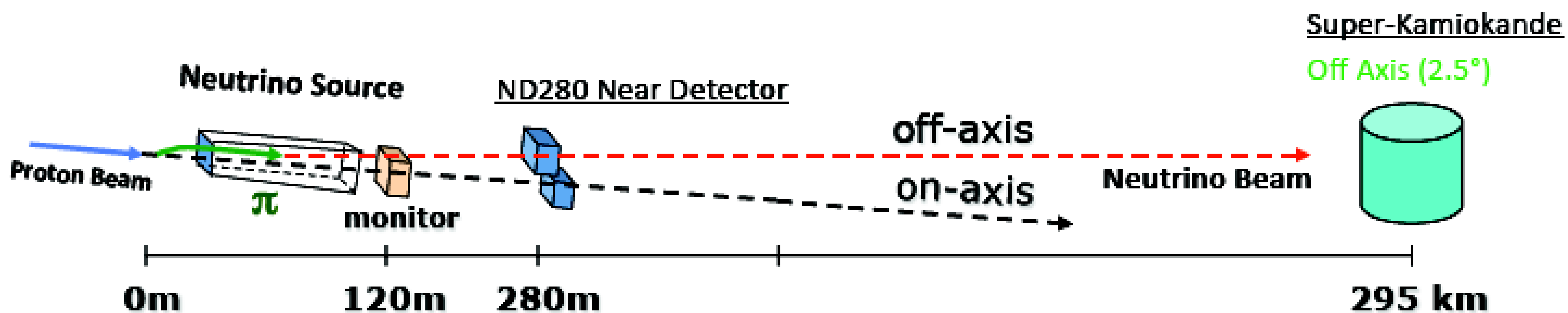


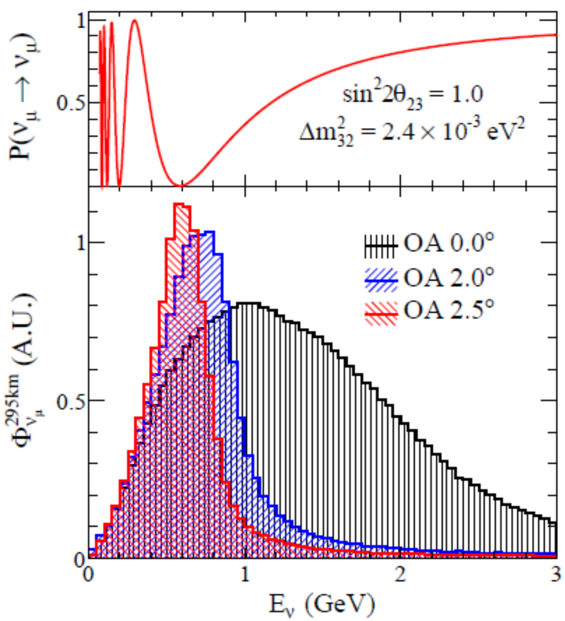
Conclusions

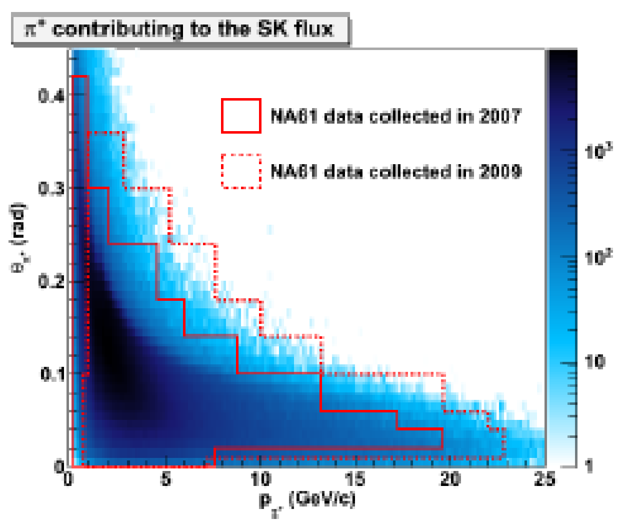
- The neutrino mass hierarchy has far reaching consequences for the study of neutrino oscillations and CP violation, double beta decay, cosmology and above all to give additional information on the neutrino mass mechanism
- For instance most of the neutrino mass models surveyed by Albright and Chen in 2006 (arXiv:hep-ph/0608137) and practically all the SO(10)-inspired predict normal hierarchy
- The current generation of long baseline experiments (NOvA,T2K) is taking data and can reach ~2σ sensitivity for a portion of the phase space
- In the middle term, several experiments are in preparation for the 2020 horizon
- If not already done, the questions will be closed with high sensitivity by DUNE after 2026

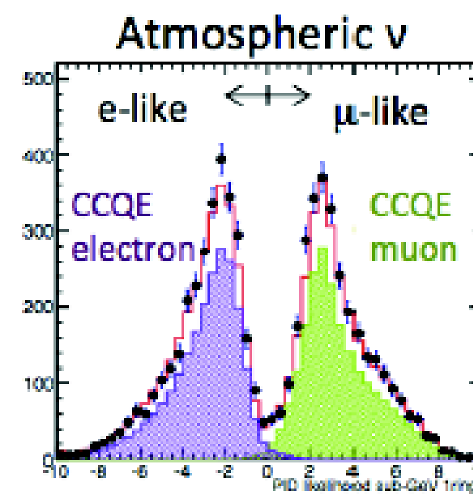
Backup

T2K: Main Experimental Features







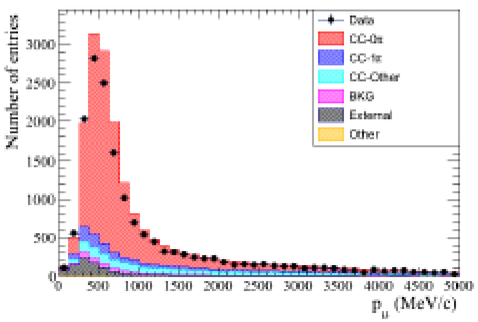


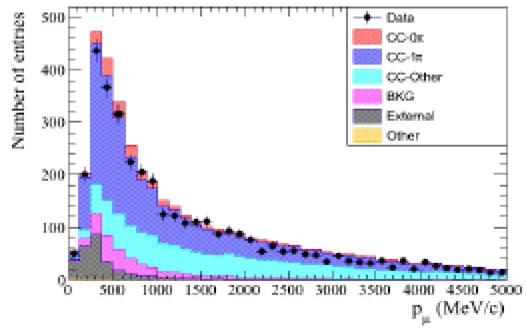
Off-axis beam.
Flux has a narrow peak tuned for the first oscillation maximum

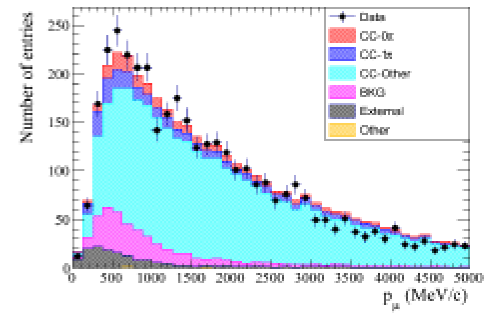
Pion and kaon production measured by the NA61 exp. at CERN

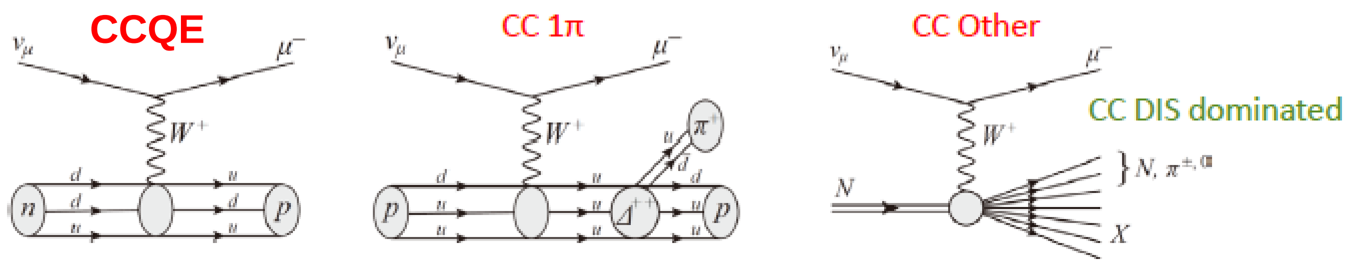
Excellent particle identification capabilities in SK (misid <1%)

T2K Near detector constraint

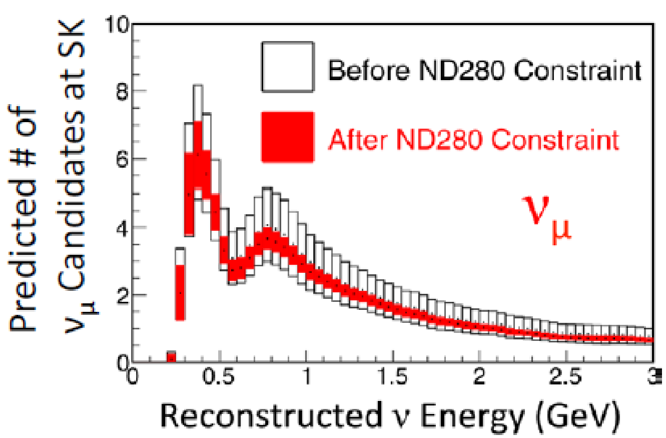


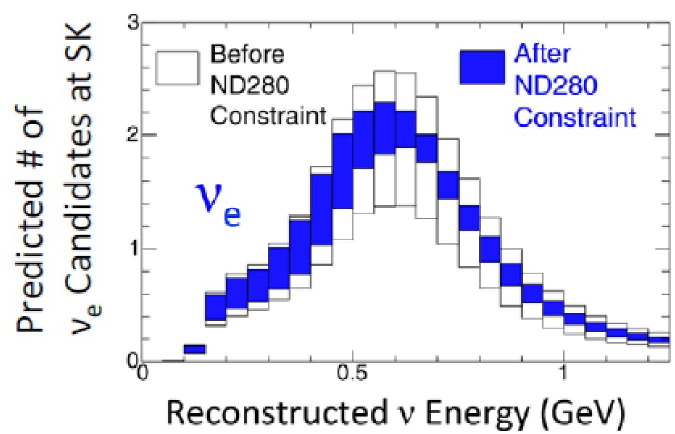






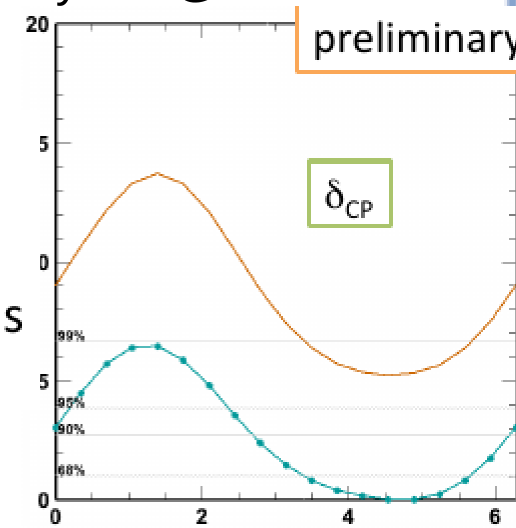
Flux and cross-section systematic uncertainty on N_{SK} significantly reduced to ~7%





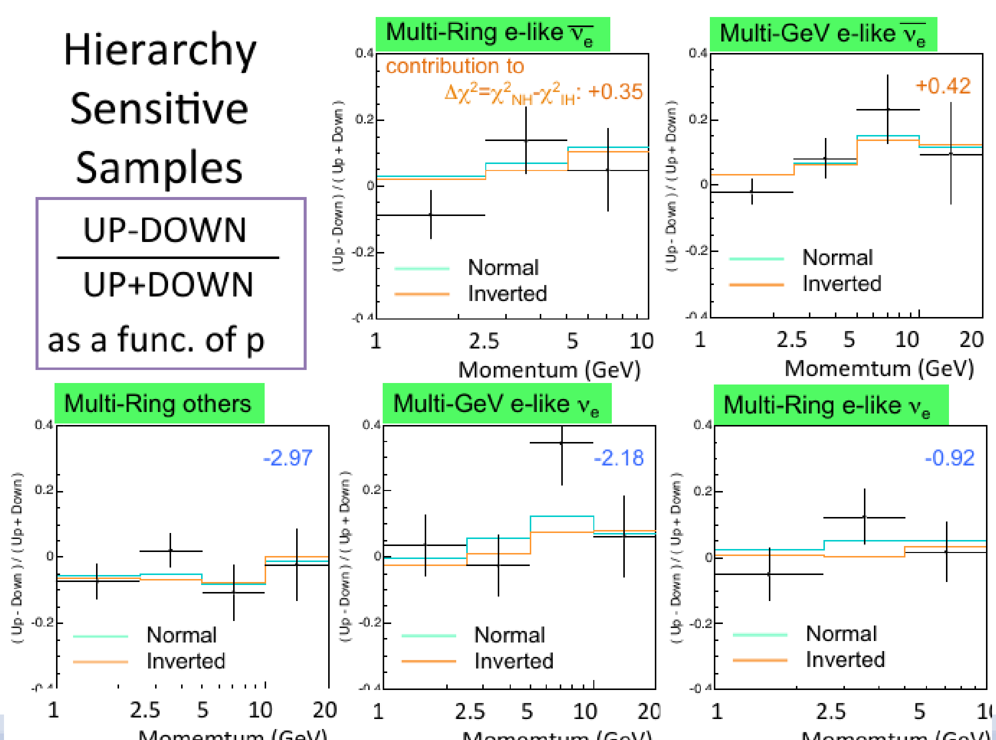
T2K+SuperKamiokande

S. Moriyama@Neutrino2016

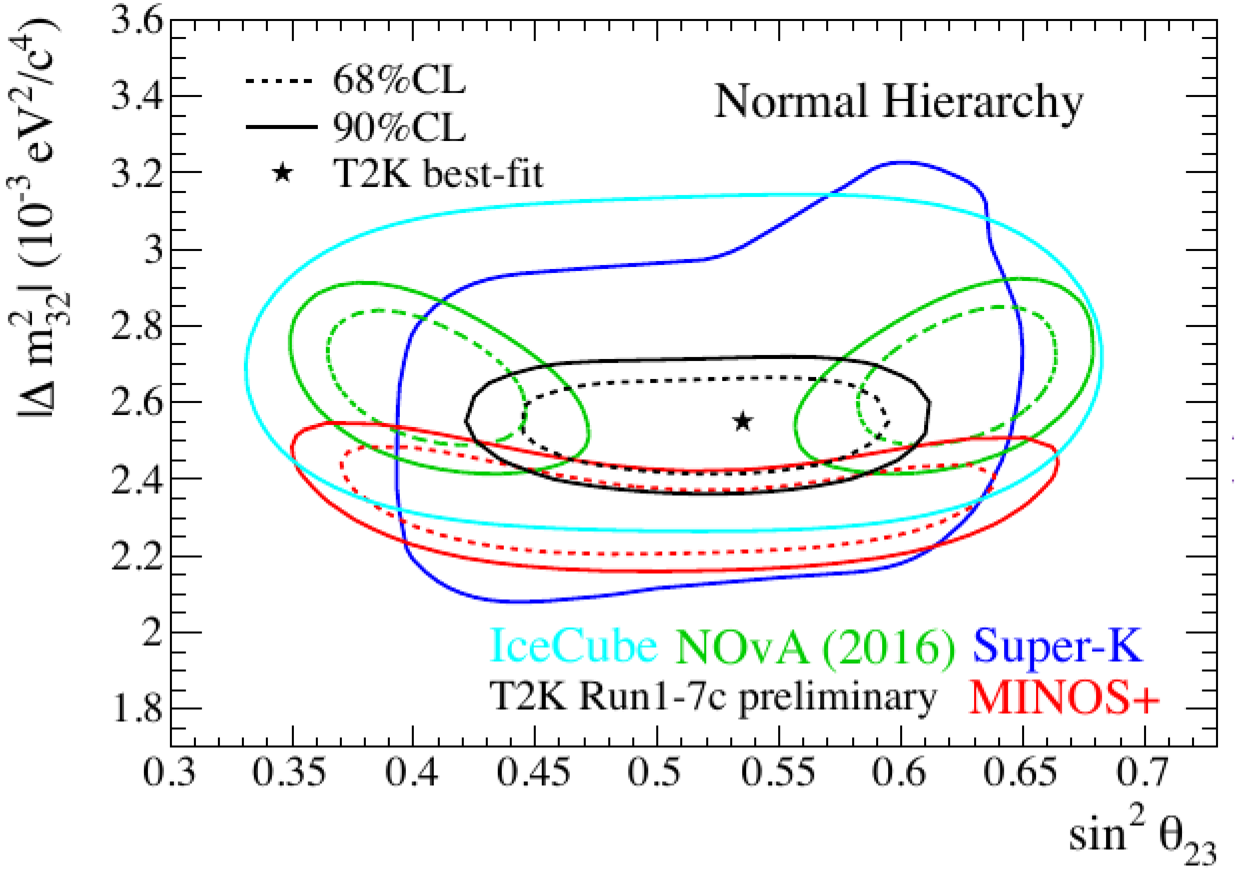


The SK atmosperic nu sample has some sensitivity to MH

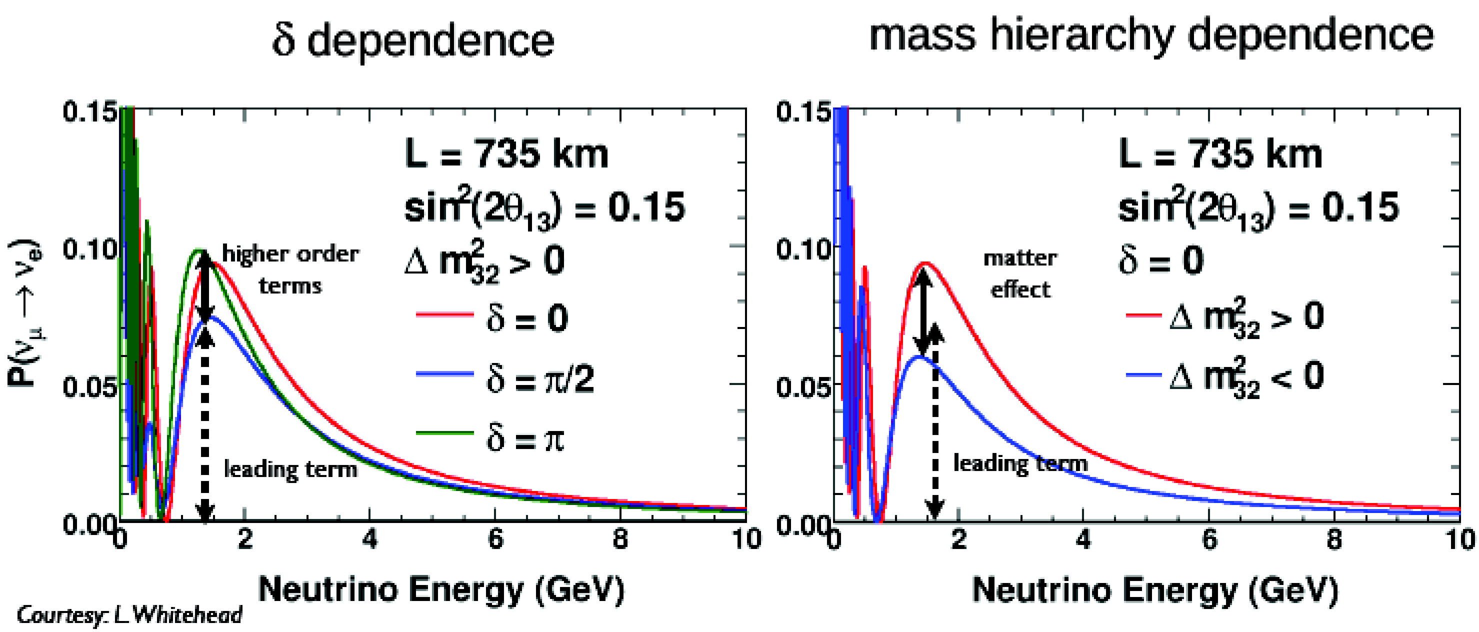
- SK+T2K (θ_{13} fixed): $\Delta\chi^2 = \chi^2_{NH}-\chi^2_{IH} = -5.2$
  (-3.8 exp. for SK best, -3.1 for combined best)
- Under IH hypothesis, the probability to obtain $\Delta\chi^2$ of -5.2 or less is 0.024 ($\sin^2\theta_{23}$=0.6) and 0.001 ($\sin^2\theta_{23}$=0.4). NH: 0.43 ($\sin^2\theta_{23}$=0.6)



T2K-numu disappearance



The matter with CP

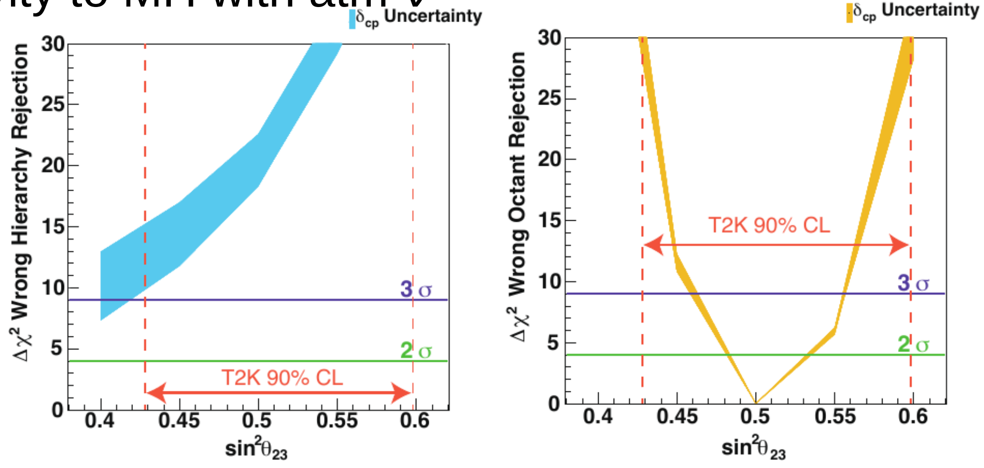


- The study of the CP asymmetry is obscured (or enriched) by matter effects (interaction of ν with e in the traversed matter) that mimic a CP effect
- This complication can be seen as a challenge or an opportunity : clean measurement of mass hierarchy
- Solutions: go to a shorter baseline (~100km, little matter effects) or to a very long baseline (~1000km, decoupling of the two effects)
- The study of CP violation gets coupled to the determination of the neutrino mass ordering (MO)

MH-octant

- The leading $\nu_\mu \to \nu_e$ appearance term depends on $\sin^2(\theta_{23}) \sin^2(2\theta_{13})$
- This leads to a dependency of MH sensitivity on the octant ($\theta_{23} < \pi/4$ or $\theta_{23} > \pi/4$) as ν_μ disappearance measures only $\sin^2(2\theta_{23})$ with worse sensitivity in the first octant

Example: HK sensitivity to MH with atm ν



1412.4673

See Qian et al PRD 86, 113011 (2012)

Statistics issues

- Wilks theorem states that the likelihood ratio between the null and alternate hypothesis approaches a Delta Chi**2 distribution for nested hypothesis
- This is not the case for Normal versus Inverted MH (non nested, discrete hypothesis)
- Qian et al have showed that PDF($\Delta\chi^2$) ~ Gaus ($<\Delta\chi^2>, 2<\Delta\chi^2>$)
- The p-value will need to be determined with toys

Nunokawa et al 0503283 (2005)

Another (difficult) method

- The disappearance measurement for electron and muon neutrinos do not measure the same physical quantity
- Delta m**2 ee and Delta m**2 mu mu contain a dependency on Delta m**2 31 and Delta m**2 32 sensitive to the mass ordering
- It is practically very challenging as the measurement of Delta m**2 is related to the absolute energy scale of the experiment and a precision much better than 1% is needed!

$$\delta m^2_{\rm eff}|_e = \cos^2\theta_{12}\delta m^2_{31} + \sin^2\theta_{12}\delta m^2_{32}$$

$$\delta m^2_{\rm eff}|_\mu = \sin^2\theta_{12}\delta m^2_{31} + \cos^2\theta_{12}\delta m^2_{32} + \cos\delta\sin\theta_{13}\sin 2\theta_{12}\tan\theta_{23}\delta m^2_{21}$$