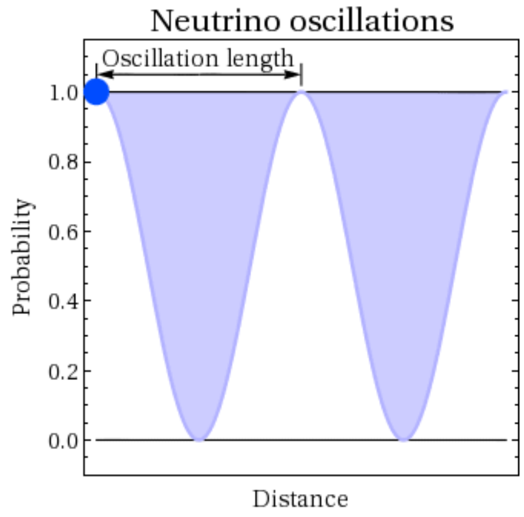
Perspectives for neutrino oscillations.



Walter Winter

DESY, 10./11.06.2014

HELMHOLTZ ASSOCIATION

DESY

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> Introduction to neutrino oscillations

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> The future:

- Measurement of δ_{CP}
- Determination of the neutrino mass ordering

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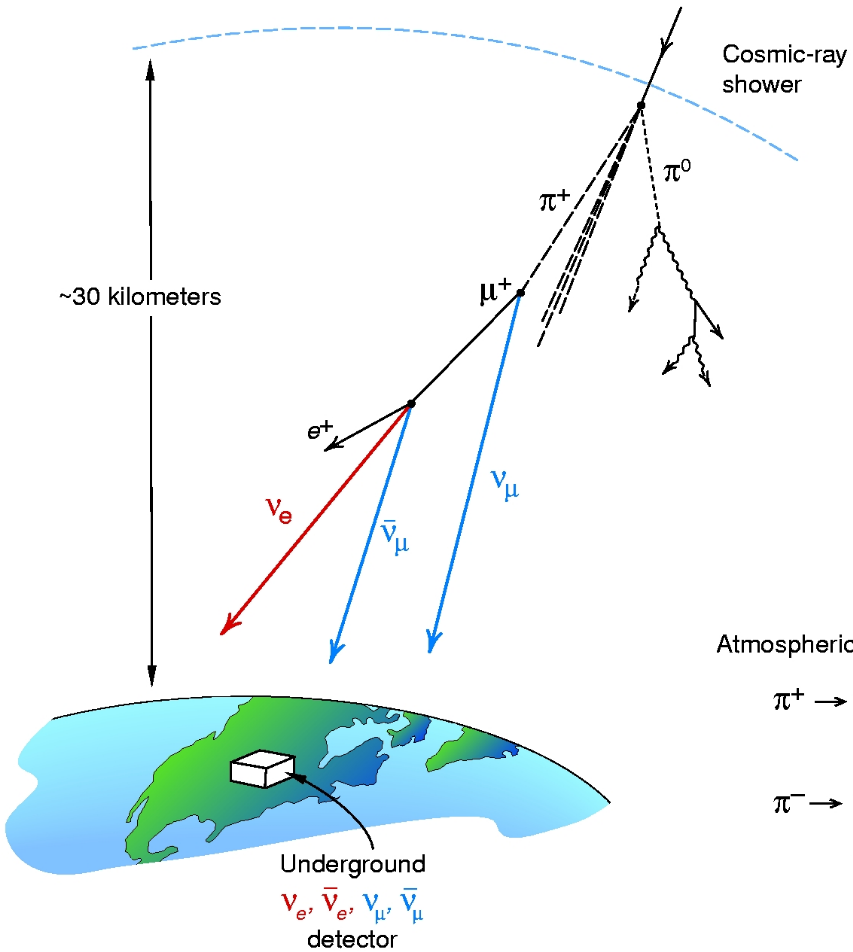
Introduction to neutrino oscillations

Neutrinos from the atmosphere

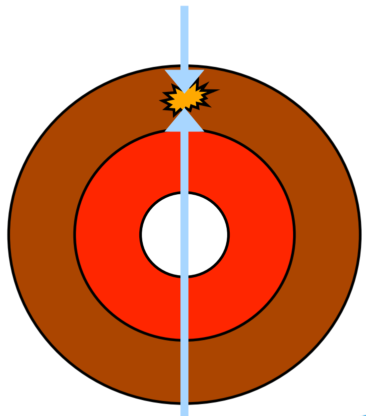


- The rate of neutrinos should be the same from below and above
- But: About 50% missing from below
- Neutrino change their flavor on the path from production to detection: Neutrino oscillations
- Neutrinos are massive!

(Super-Kamiokande: "Evidence for oscillations of atmospheric neutrinos", 1998)

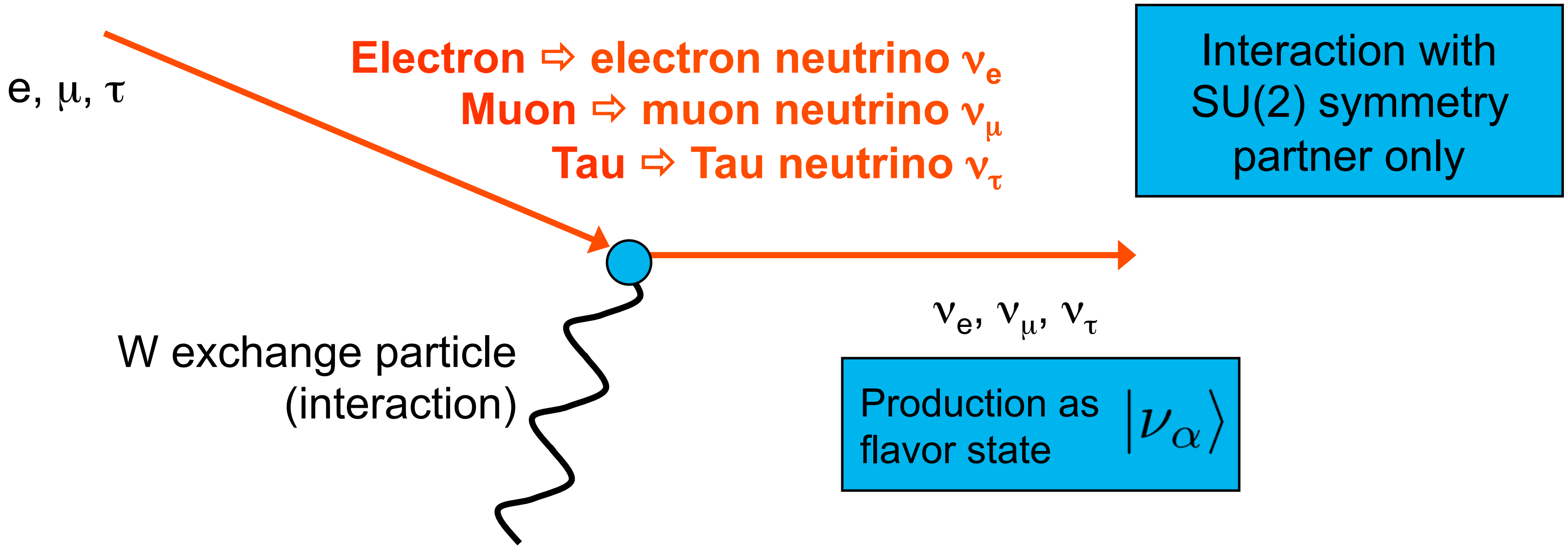
Atmospheric neutrino source

$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$
$$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$$
$$\pi^- \rightarrow \mu^- + \bar{\nu}_\mu$$
$$\mu^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu$$



Neutrino production/detection

- Neutrinos are only produced and detected by the weak interaction:



- The dilemma: One cannot assign a mass to the flavor states ν_e, ν_μ, ν_τ!

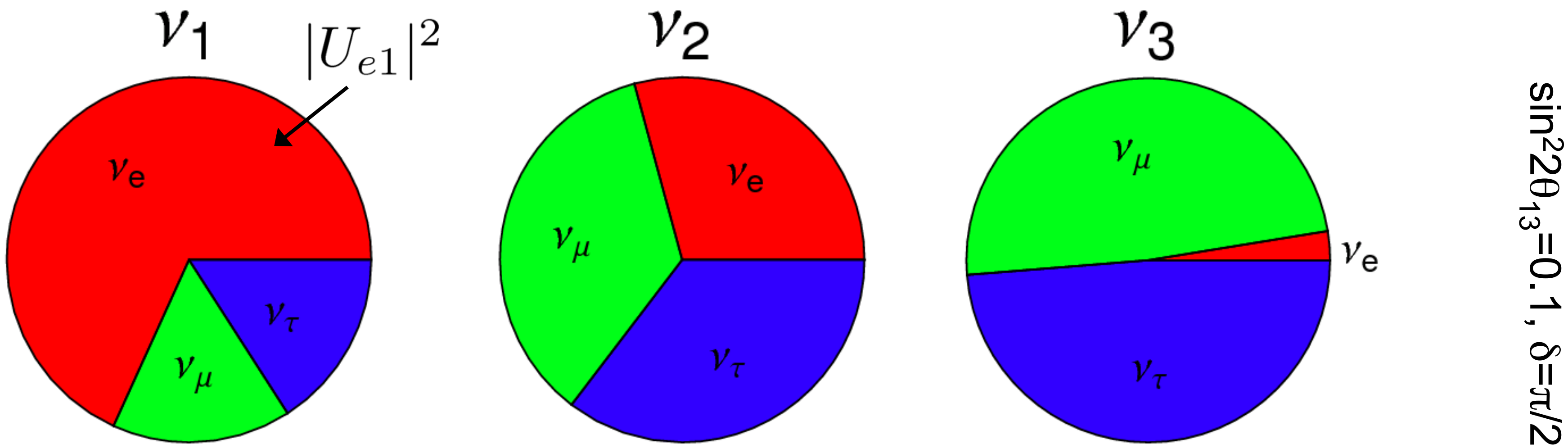
Which mass do the neutrinos have?

- There is a set of neutrinos ν_1, ν_2, ν_3, for which a mass can be assigned.

$$|\nu_i\rangle$$

- Mixture of flavor states:

$$|\nu_\alpha\rangle = \sum_{k=1}^{3} U^*_{\alpha k} \, |\nu_k\rangle$$



- Not unusual, know from the Standard Model for quarks
- However, the mixings of the neutrinos are much larger!

Neutrino oscillation probability

Standard derivation N active, S sterile (not weakly interacting) flavors

- Mixing of flavor states

$$|\nu_\alpha\rangle = \sum_{k=1}^{N+S} U_{\alpha k}^* |\nu_k\rangle$$

- Time evolution of mass state

$$|\nu_k(t)\rangle = \exp(-iE_k t)\,|\nu_k\rangle$$

- Transition amplitude

$$A_{\nu_\alpha\to\nu_\beta} \equiv A_{\alpha\beta} = \langle\nu_\beta|\nu_\alpha(t)\rangle = \sum_{k=1}^{N+S} U_{\alpha k}^* U_{\beta k}\, \exp(-iE_k t)$$

- Transition probability

$$P_{\alpha\beta} = A_{\alpha\beta}^* A_{\alpha\beta} = \sum_{k,j=1}^{N+S} \underbrace{U_{\alpha k}^* U_{\beta k} U_{\alpha j} U_{\beta j}^*}_{\equiv J_{kj}^{\alpha\beta}} \exp\left(-i(E_k - E_j)t\right)$$

“quartic re-phasing invariant“

Further simplifications

- Ultrarelativistic approximations:

$$E_k = \sqrt{\vec{p}^2 + m_k^2} \simeq E + \frac{m_k^2}{2E}\,, \qquad t \simeq L$$

L: baseline (distance source-detector)

- Plus some manipulations: “Master formula“

$$P_{\alpha\beta} = \delta_{\alpha\beta} - 4 \underbrace{\sum_{k>j} \mathrm{Re} J_{kj}^{\alpha\beta} \, \sin^2\left(\frac{\Delta m_{kj}^2 L}{4\,E}\right)}_{\text{CP conserving}} + 2 \underbrace{\sum_{k>j} \mathrm{Im} J_{kj}^{\alpha\beta} \, \sin\left(\frac{\Delta m_{kj}^2 L}{2\,E}\right)}_{\text{CP violating}}$$

$\Delta m_{kj}^2 \equiv m_k^2 - m_j^2$ “mass squared difference“

F(L,E)=L/E “spectral dependence“

- For antineutrinos: U ⇨ U*

Two flavor limit: N=2, S=0

- Only two parameters:

$$U = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix}$$

Lower limit for neutrino mass!

$$\Delta m^2 \equiv m_2^2 - m_1^2$$

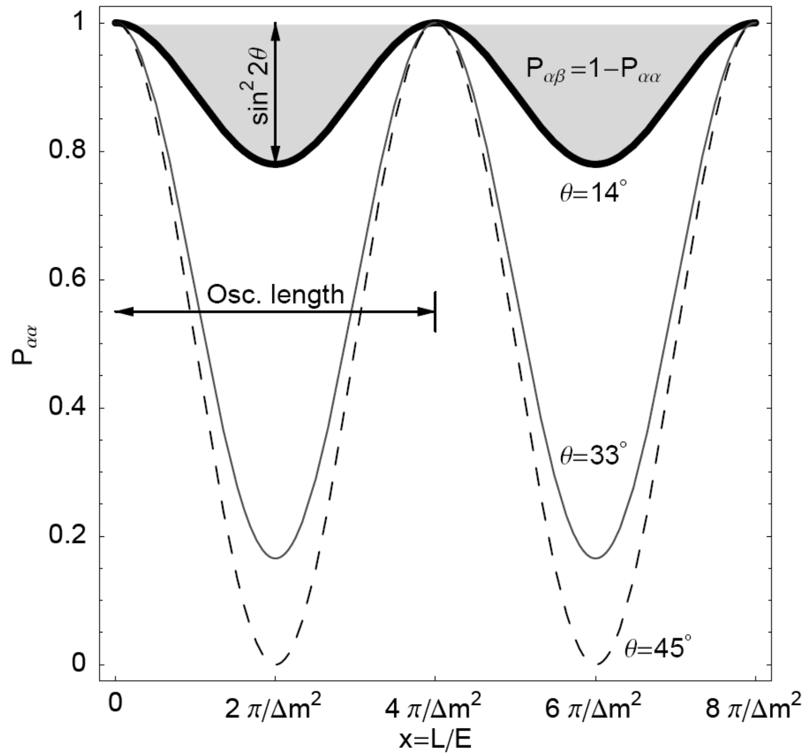
- From the master formula:

Disappearance or
survival probability

$$P_{\alpha\alpha} = 1 - \sin^2 2\theta \, \sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

Appearance probability

$$P_{\alpha\beta} = \sin^2 2\theta \, \sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$



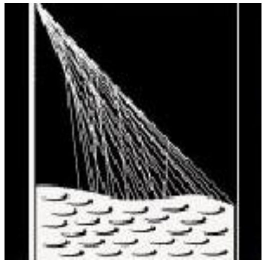
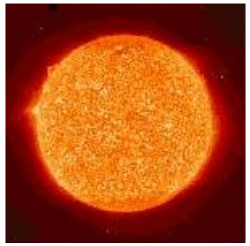
Three flavors: Mixings

- Use same parameterization as for CKM matrix

Potential CP violation ~ θ_{13}

$$U_{\mathrm{PMNS}} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}\, e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}\, e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} .$$

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

= () x () x ()

Pontecorvo-Maki-Nakagawa-Sakata matrix

- Neutrinos ⇨ Anti-neutrinos: **U ⇨ U*** (neutrino oscillations)
- If neutrinos are their own anti-particles (Majorana neutrinos):
  U ⇨ U diag(1,$e^{i\alpha}$,$e^{i\beta}$) - do enter $0\nu\beta\beta$, but not neutrino oscillations

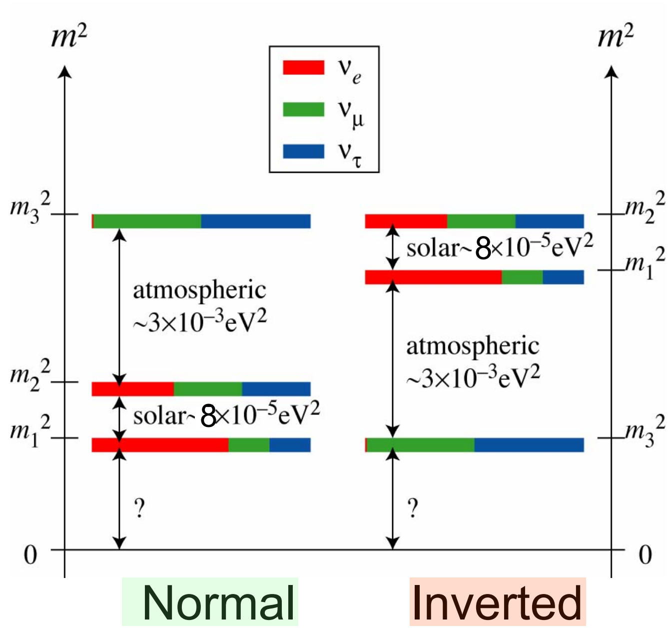
Three active flavors: Masses

- Two independent mass squared splittings, typically
  Δm^2_{21} (solar) Δm^2_{31} (atmospheric)

  Will be relevant for neutrino oscillations!

- The third is given by
  $\Delta m^2_{32} = \Delta m^2_{31} - \Delta m^2_{21}$

- The (atmospheric) mass **ordering** (hierarchy) is unknown (normal or inverted) →



- The absolute neutrino mass scale is unknown (< eV)

Current knowledge of neutrino oscillations

Three flavors: Simplified

- What we know (qualitatively):
  - Hierarchy of mass splittings $$\Delta m^2_{21} \ll |\Delta m^2_{31}| \simeq |\Delta m^2_{32}|$$
  - Two mixing angles large, one (θ_{13}) small ~ 0?

$$U_{\text{PMNS}}^{\theta_{13}\to 0} = \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12}\, c_{23} & c_{12}\, c_{23} & s_{23} \\ s_{12}\, s_{23} & -c_{12}\, s_{23} & c_{23} \end{pmatrix}$$

- From the “master formula“, we have

$$P_{\alpha\beta} = \delta_{\alpha\beta} - 4\, \left(J_{31}^{\alpha\beta} + J_{32}^{\alpha\beta} \right) \sin^2 \Delta_{31} - 4\, J_{21}^{\alpha\beta} \sin^2 \Delta_{21}$$

$$J_{kj}^{\alpha\beta} = U_{\alpha k}^* U_{\beta k} U_{\alpha j} U_{\beta j}^* \qquad \Delta_{ij} \equiv \Delta m^2_{ij}\, L/(4E)$$

Two flavor limits

$$P_{\alpha\beta} = \delta_{\alpha\beta} - 4\,\left(J_{31}^{\alpha\beta} + J_{32}^{\alpha\beta}\right) \sin^2 \Delta_{31} - 4\,J_{21}^{\alpha\beta} \sin^2 \Delta_{21}$$

$$\Delta_{ij} \equiv \Delta m_{ij}^2\, L/(4E)$$

Two flavor limits by selection of frequency:

- Atmospheric frequency: $\Delta_{31} \sim \pi/2$ ⇨ $\Delta_{21} << 1$

$$P_{\alpha\beta} = \delta_{\alpha\beta} - 4\,\left(J_{31}^{\alpha\beta} + J_{32}^{\alpha\beta}\right) \sin^2 \Delta_{31} - 4\,J_{21}^{\alpha\beta} \sin^2 \Delta_{21}$$

- Solar frequency: $\Delta_{21} \sim \pi/2$ ⇨ $\Delta_{31} >> 1$

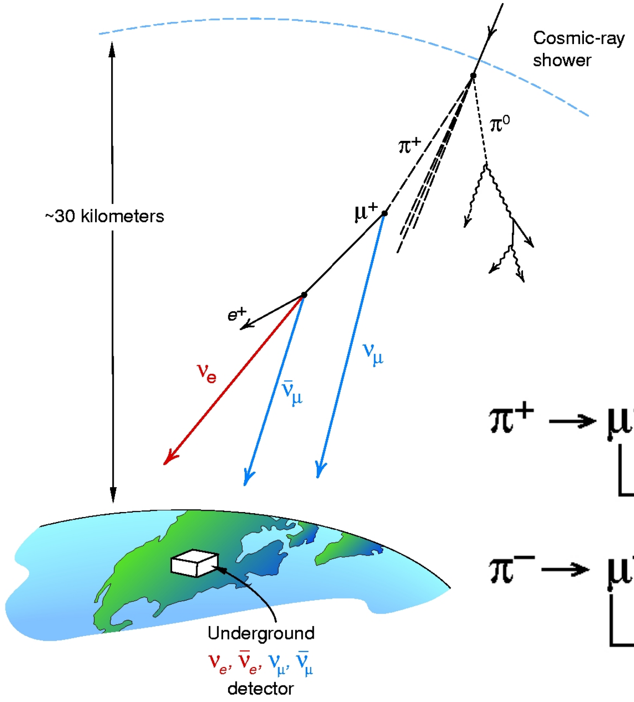
$$P_{\alpha\beta} = \delta_{\alpha\beta} - 4\,\left(J_{31}^{\alpha\beta} + J_{32}^{\alpha\beta}\right) \sin^2 \Delta_{31} - 4\,J_{21}^{\alpha\beta} \sin^2 \Delta_{21}$$

averages out

0.5

Select sensitive term by choice of L/E!

Atmospheric neutrinos



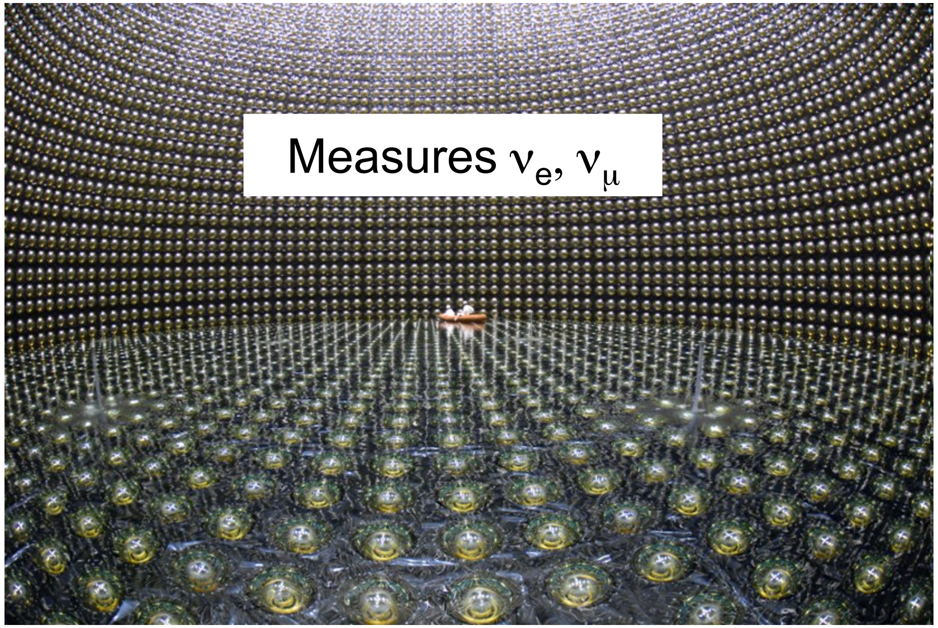
$\pi^+ \rightarrow \mu^+ + \nu_\mu$

$\quad \hookrightarrow e^+ + \nu_e + \bar{\nu}_\mu$

$\pi^- \rightarrow \mu^- + \bar{\nu}_\mu$

$\quad \hookrightarrow e^- + \bar{\nu}_e + \nu_\mu$

Super-Kamiokande



From $P_{\alpha\beta} = \delta_{\alpha\beta} - 4 \left(J_{31}^{\alpha\beta} + J_{32}^{\alpha\beta} \right) \sin^2 \Delta_{31}$ and θ_{13} small

we have: $P_{ee} \sim 1$, $P_{e\mu} \sim P_{\mu e} \sim 0$ and

$$P_{\mu\mu} \simeq 1 - \sin^2(2\theta_{23}) \sin^2 \Delta_{31}$$

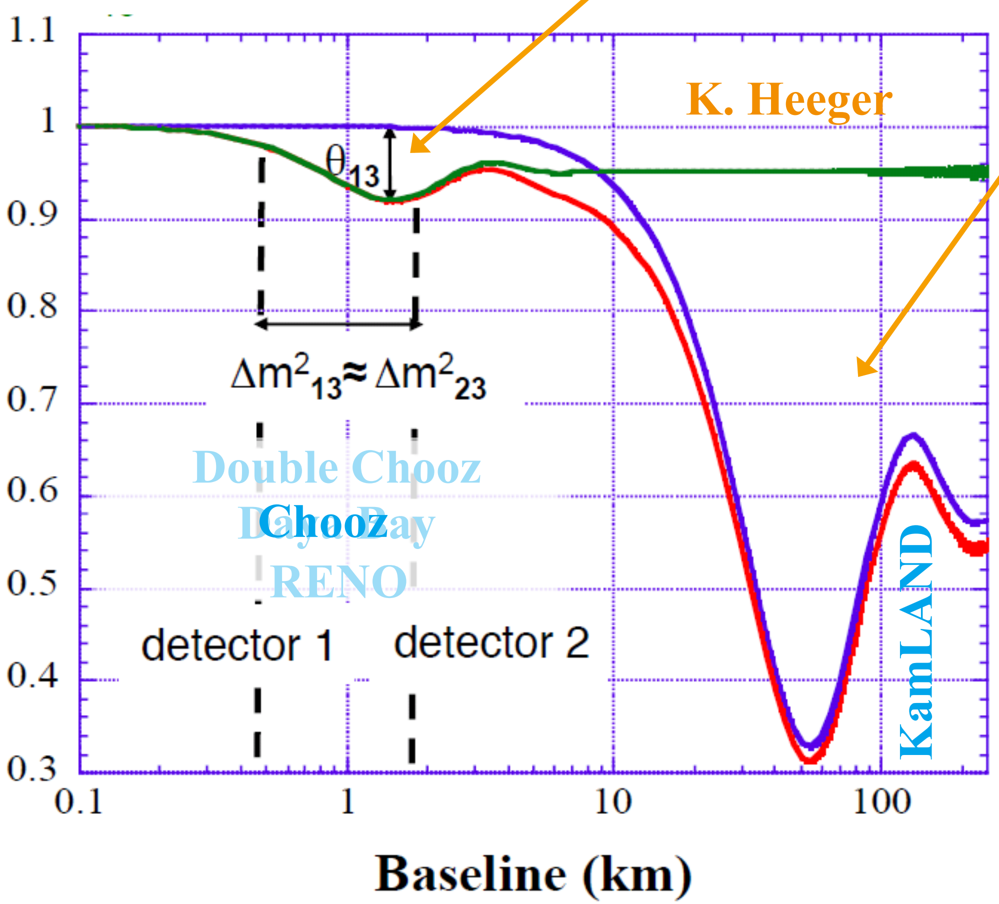
⇨ Two flavor limit with particular parameters θ_{23}, Δm_{31}^2

Reactor neutrinos

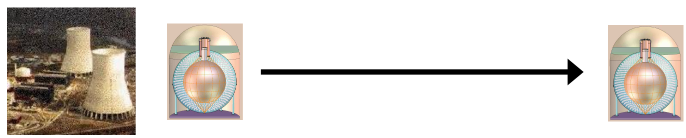
- In the presence of θ_{13}:

$$P_{\bar{e}\bar{e}} \simeq 1 - \sin^2(2\theta_{13}) \sin^2 \Delta_{31} - \cos^4 \theta_{13} \sin^2(2\theta_{12}) \sin^2 \Delta_{21}$$

atmospheric solar



New idea:



Identical detectors, L ~ 1-2 km
to control systematics

(Minakata, Sugiyama, Yasuda, Inoue, Suekane, 2003; Huber, Lindner, Schwetz, Winter, 2003)

Observation of Mixing Angle θ_{13}

in the Daya Bay Reactor Antineutrino Experiment

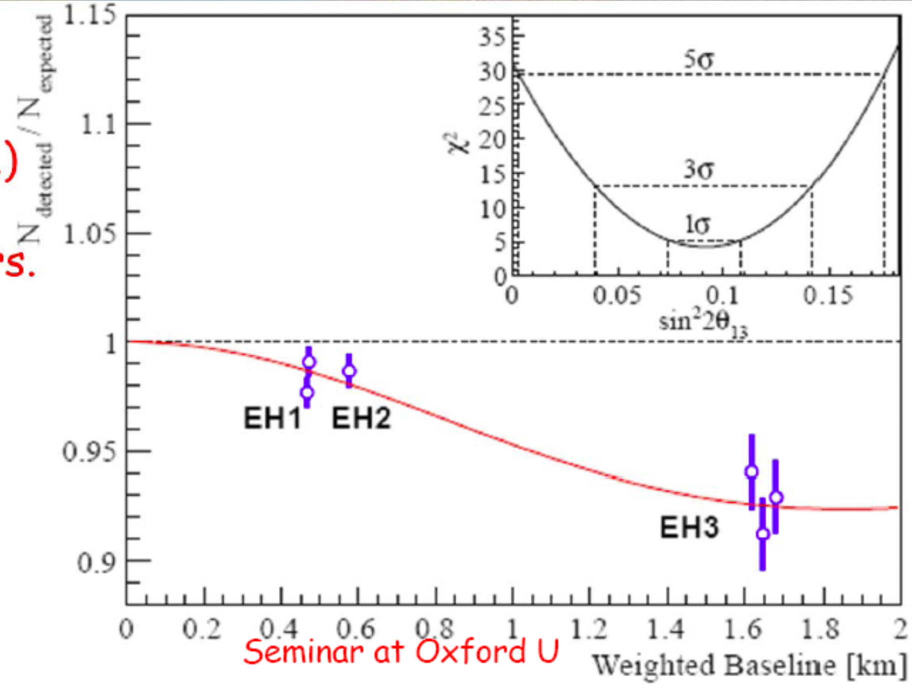
Kirk T McDonald
Princeton U
(April 24, 2012)
on behalf of the Daya Bay Collaboration

$$P_{\bar{e}\bar{e}} \simeq 1 - \sin^2(2\theta_{13}) \sin^2 \Delta_{31}$$

(short distance)

We observe that
$\sin^2 2\theta_{13}$ = 0.092 ± 0.016 (stat.) ± 0.005 (syst.)
after 55 days of operation with 6 detectors
at 3 sites close to 3 pairs of ~ 3 GW reactors.

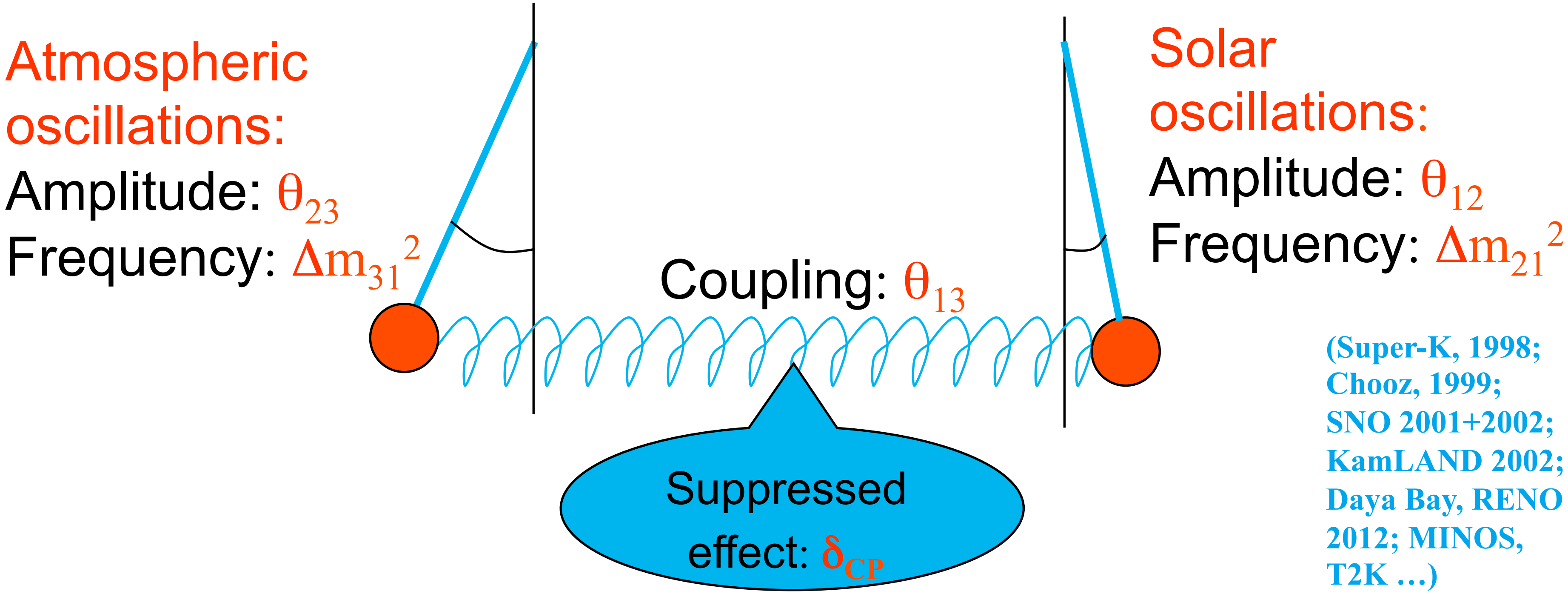
F.P. Ahn *et al.*
Phys. Rev. Lett. **108**, 171803 (2012).



(also: T2K, Double Chooz, RENO)

Three flavors: Summary

- Three flavors: 6 params (3 angles, one phase; 2 x Δm^2)



(Super-K, 1998; Chooz, 1999; SNO 2001+2002; KamLAND 2002; Daya Bay, RENO 2012; MINOS, T2K …)

- Describes solar and atmospheric neutrino anomalies, as well as reactor antineutrino disappearance!

Precision of parameters?

NuFIT 1.2 (2013)

	bfp $\pm 1\sigma$	3σ range
$\sin^2\theta_{12}$	$0.306^{+0.012}_{-0.012}$	$0.271 \to 0.346$
$\theta_{12}/^\circ$	$33.57^{+0.77}_{-0.75}$	$31.38 \to 36.01$
$\sin^2\theta_{23}$	$0.446^{+0.007}_{-0.007} \oplus 0.587^{+0.032}_{-0.037}$	$0.366 \to 0.663$
$\theta_{23}/^\circ$	$41.9^{+0.4}_{-0.4} \oplus 50.0^{+1.9}_{-2.2}$	$37.2 \to 54.5$
$\sin^2\theta_{13}$	$0.0229^{+0.0020}_{-0.0019}$	$0.0170 \to 0.0288$
$\theta_{13}/^\circ$	$8.71^{+0.37}_{-0.38}$	$7.50 \to 9.78$
$\delta_{\rm CP}/^\circ$	265^{+56}_{-61}	$0 \to 360$
$\frac{\Delta m^2_{21}}{10^{-5}\ {\rm eV}^2}$	$7.45^{+0.19}_{-0.16}$	$6.98 \to 8.05$
$\frac{\Delta m^2_{31}}{10^{-3}\ {\rm eV}^2}$ (N)	$+2.417^{+0.013}_{-0.013}$	$+2.247 \to +2.623$
$\frac{\Delta m^2_{32}}{10^{-3}\ {\rm eV}^2}$ (I)	$-2.410^{+0.062}_{-0.062}$	$-2.602 \to -2.226$

- θ_{12}: ± 2%
- θ_{23}: ± 4% (or better)
- θ_{13}: ± 4%
- Δm^2_{21}: ± 3%
- Δm^2_{31} / Δm^2_{32}: ± 3%

Age of the **precision flavor physics of the lepton sector**

Open issues:

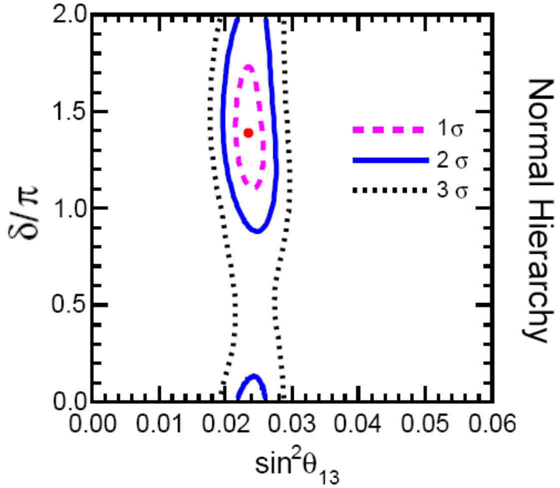
- Degeneracies (mass ordering, octant)

- CP phase

Gonzalez-Garcia, Maltoni, Salvado, Schwetz, JHEP 1212 (2012) 123

Current status and perspectives for existing equipment

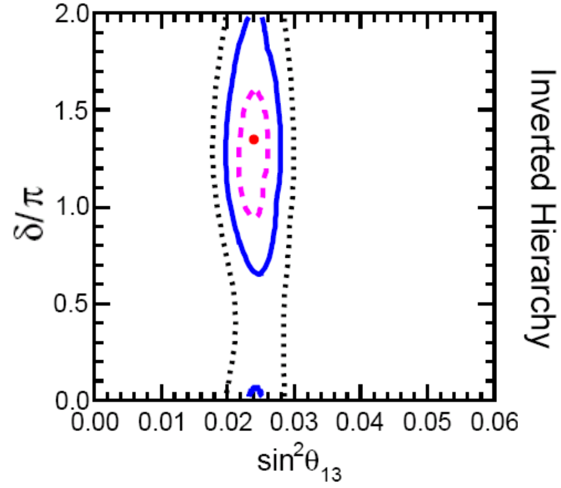
- Indication for δ_{CP}, no evidence for mass hierarchy



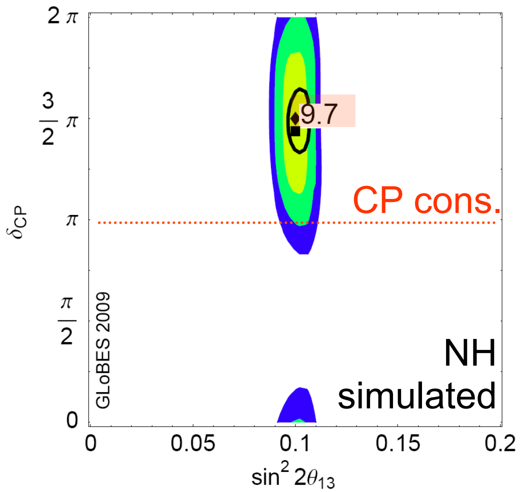
LBL Acc + Solar + KL
+ SBL Reactors
+ SK Atm

Capozzi, Fogli, Lisi, Marrone, Montanino, Palazzo, arXiv:1312.2878

Main difference: NOvA data!



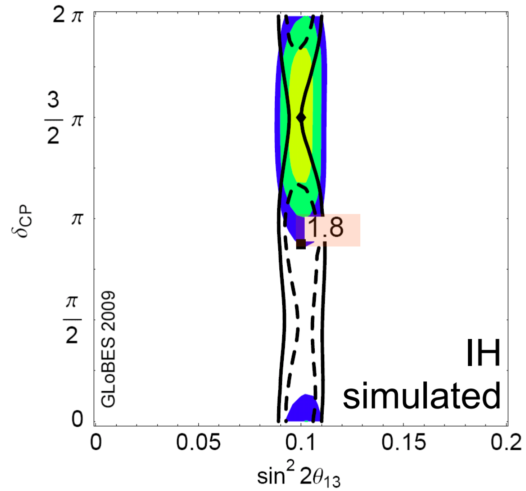
- Potential of existing equipment



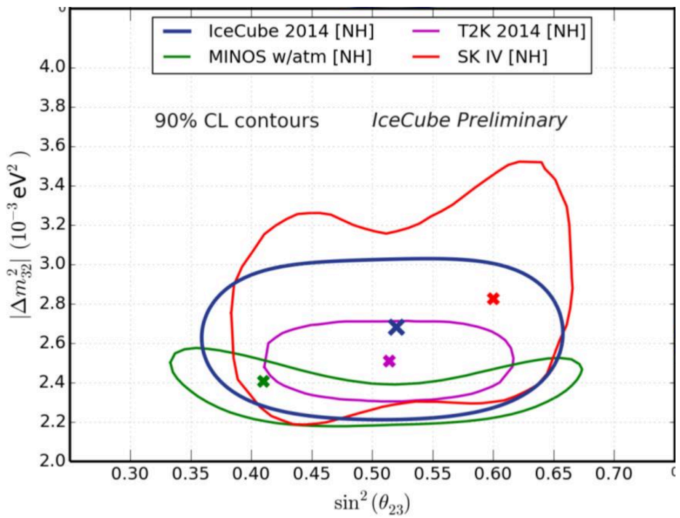
T2K, NOvA,
Double Chooz, Daya Bay;
5 years each

High CL determination requires new equipment

Huber, Lindner, Schwetz, Winter, JHEP 0911 (2009) 044



- Largest, bi-annual conference of the neutrino community, 550 participants
- Highlights:
  - Discovery of cosmic neutrinos, by IceCube
  - First direct high-CL evidence for ν_μ to ν_e flavor transitions, by T2K
  - First atmospheric measurement of leading atmospheric parameters comparable with long-baseline experiments, by IceCube-DeepCore **(analysis done by DESY-Zeuthen group)** →



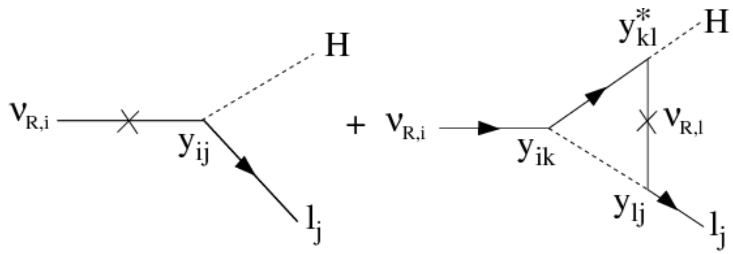
Juan-Pablo Yanez @ Neutrino 2014

  - θ_{13} central value shifts down (Daya Bay), tension with T2K increased; may strengthen hint for maximal leptonic CP violation δ_{CP}~$-\pi/2$
  - P5 prioritisation of Long Baseline Neutrino Oscillation Experiment at Fermilab
  - DESY with three plenary talks one of the strongest represented institutions in the program (after INFN, before Fermilab)

The future: measurement of δ_{CP}

Why is δ_{CP} interesting?

- **CP violation** **$\sin\delta$**
  Necessary condition for successful baryogenesis
  (dynamical mechanism to create matter-antimatter asymmetry of the universe)
  ⇨ thermal leptogenesis by decay of heavy see-saw partner?



- **Model building** **$\cos\delta$**

$$U_{\rm PMNS} = U_\ell^\dagger U_\nu$$

CKM-like correction leading to non-zero θ_{13}?	Symmetry e.g. TBM, BM, …?

e.g. TBM sum rule: $\theta_{12} = 35° + \theta_{13}$ **$\cos\delta$** (Antusch, King; Masina …)

➢ Need performance which is equally good for all δ_{CP}

Necessary conditions for the observation of CP violation

$$P_{\alpha\beta}^{\text{CPV}} \simeq$$

~ Jarlskog invariant

$$\underbrace{\cdot\, 2 \sum_{k>j} \text{Im} J_{kj}^{\alpha\beta} \sin\left(\frac{\Delta m_{kj}^2 L}{2\,E}\right)}_{\text{CP violating}}$$

$$J_{kj}^{\alpha\beta} = U_{\alpha k}^* U_{\beta k} U_{\alpha j} U_{\beta j}^*$$

- Since $\left\langle \sin\left(\frac{\Delta m_{kj}^2 L}{2E}\right)\right\rangle_{L/E} = 0$

  ⇨ need spectral info!

- Since for $\alpha=\beta$

  $$J_{kj}^{\alpha\alpha} = |U_{\alpha k}|^2 \, |U_{\alpha j}|^2$$

  ⇨ need to observe flavor transitions

- Need (at least) three flavors
  (actually conclusion in quark sector by
  Kobayashi, Maskawa, Nobel Prize 2008)
  ⇨ No CP violation in two flavor subspaces!
  ⇨ Need to be sensitive to (at least) two mass squared splittings at the same time!

Electron-muon neutrino flavor transitions

$$P_{e\mu} \simeq \sin^2 2\theta_{13} \begin{matrix}\cos^2\theta_{23} \\ \sin^2\theta_{23}\end{matrix} \frac{\sin^2[(1 \pm \hat{A})\Delta]}{(1 \pm \hat{A})^2}$$

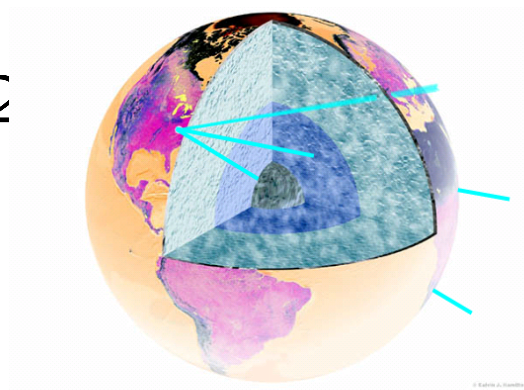
$$\alpha \equiv \frac{\Delta m_{21}^2}{\Delta m_{31}^2},\ \Delta \equiv \frac{\Delta m_{31}^2 L}{4E},\ \hat{A} \equiv \frac{2\sqrt{2} G_F n_e E}{\Delta m_{31}^2}$$

$$+ \alpha \sin 2\theta_{13} \sin 2\theta_{12} \sin 2\theta_{23} \sin\delta_{CP} \sin(\Delta) \frac{\sin(\hat{A}\Delta)}{\hat{A}} \frac{\sin[(1 \pm \hat{A})\Delta]}{(1 \pm \hat{A})}$$

$$\mp \alpha \sin 2\theta_{13} \sin 2\theta_{12} \sin 2\theta_{23} \cos\delta_{CP} \cos(\Delta) \frac{\sin(\hat{A}\Delta)}{\hat{A}} \frac{\sin[(1 \pm \hat{A})\Delta]}{(1 \pm \hat{A})}$$

$$+ \alpha^2 \begin{matrix}\sin^2\theta_{23} \\ \cos^2\theta_{23}\end{matrix} \sin^2 2\theta_{12} \frac{\sin^2(\hat{A}\Delta)}{\hat{A}^2}$$

- Antineutrinos: $P_{\bar{e}\bar{\mu}} = P_{e\mu}(\delta_{CP}, \rightarrow -\delta_{CP}, \hat{A} \rightarrow -\hat{A})$
- Silver: $P_{e\tau} = P_{e\mu}(s_{23}^2 \leftrightarrow c_{23}^2, \sin 2$ … $_{23})$
- Platinum, T-inv.: $P_{\mu e} = P_{e\mu}(\delta_{CP}, \rightarrow$



(Cervera et al. 2000; Freund, Huber, Lindner, 2000; Akhmedov et al, 2004)

Possible experimental setups (future)

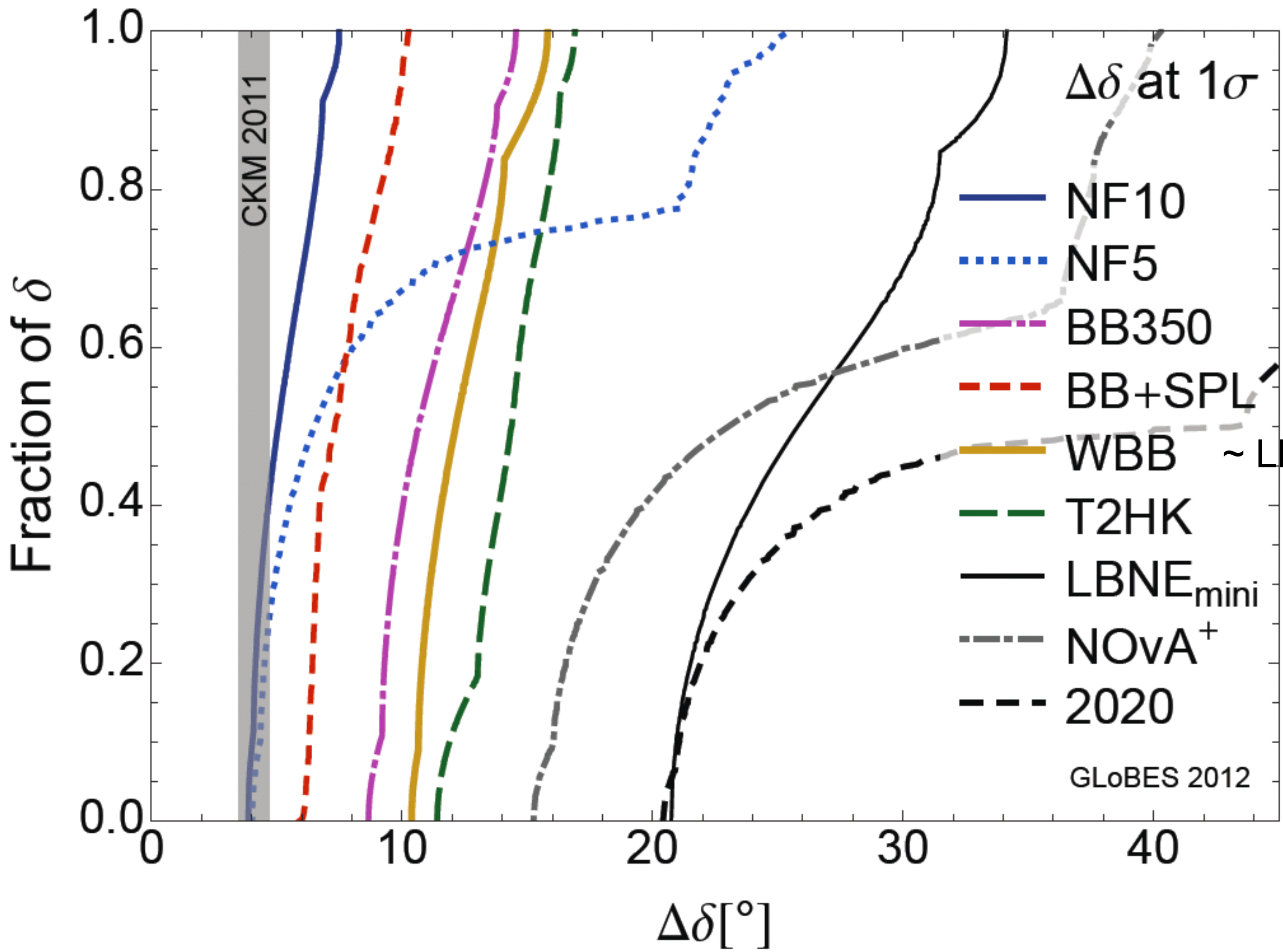
	Setup	E_ν^{peak}	L	OA	Detector	kt	MW	Decays/yr	$(t_\nu, t_{\bar{\nu}})$
Benchmark	BB350	1.2	650	–	WC	500	–	$1.1(2.8)\times10^{18}$	(5,5)
Benchmark	NF10	5.0	2 000	–	MIND	100	–	7×10^{20}	(10,10)
Benchmark →	WBB	4.5	2 300	–	LAr	100	0.8	–	(5,5)
Benchmark →	T2HK	0.6	295	2.5°	WC	560	1.66	–	(1.5,3.5)
Alternative	BB100	0.3	130	–	WC	500	–	$1.1(2.8)\times10^{18}$	(5,5)
Alternative	+ SPL			–			4	–	(2,8)
Alternative	NF5	2.5	1 290	–	MIND	100	–	7×10^{20}	(10,10)
Alternative →	$\mathrm{LBNE}_{\mathrm{mini}}$	4.0	1 290	–	LAr	10	0.7	–	(5,5)
Alternative	$\mathrm{NO}\nu\mathrm{A}^+$	2.0	810	0.8°	LAr	30	0.7	–	(5,5)
2020	T2K	0.6	295	2.5°	WC	22.5	0.75	–	(5,5)
2020	$\mathrm{NO}\nu\mathrm{A}$	2.0	810	0.8°	TASD	15	0.7	–	(4,4)

+ Daya Bay

(Coloma, Huber, Kopp, Winter, arXiv:1209.5973)

Performance

- Comparison at default systematics:



~ LBNE/LBNO

(Coloma, Huber, Kopp, Winter, arXiv:1209.5973)

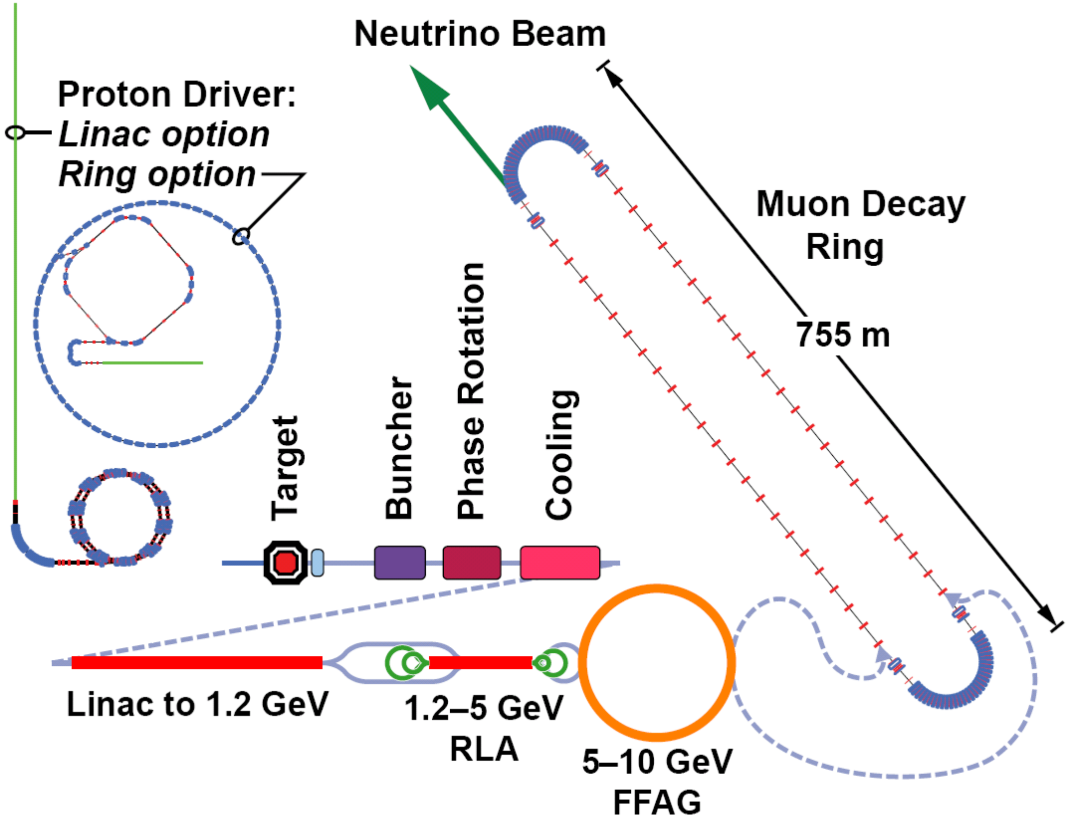
The International Design Study for the Neutrino Factory

$$\mu^- \to e^- + \bar{\nu}_e \to \bar{\nu}_\mu$$
$$+ \nu_\mu \to \nu_\mu$$

(Geer, 1997; de Rujula, Gavela, Hernandez, 1998; Cervera et al, 2000)

- Signal prop. $\sin^2 2\theta_{13}$
- Contamination ⇨ magnetized detector!

Muons decay in straight sections of a storage ring

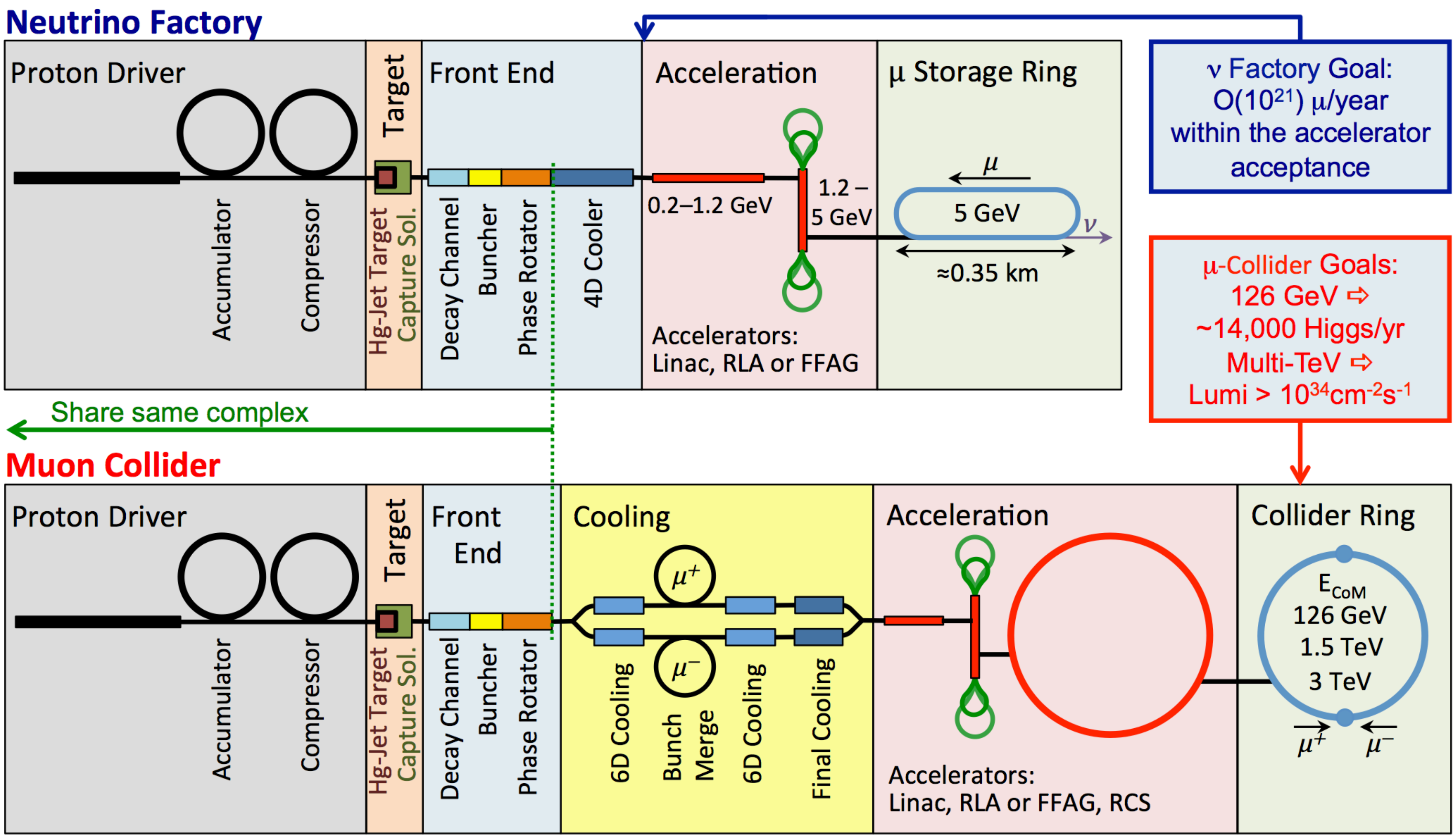


> IDS-NF: Initiative from ~ 2007-2014 to present a design report, schedule, cost estimate, risk assessment for a neutrino factory

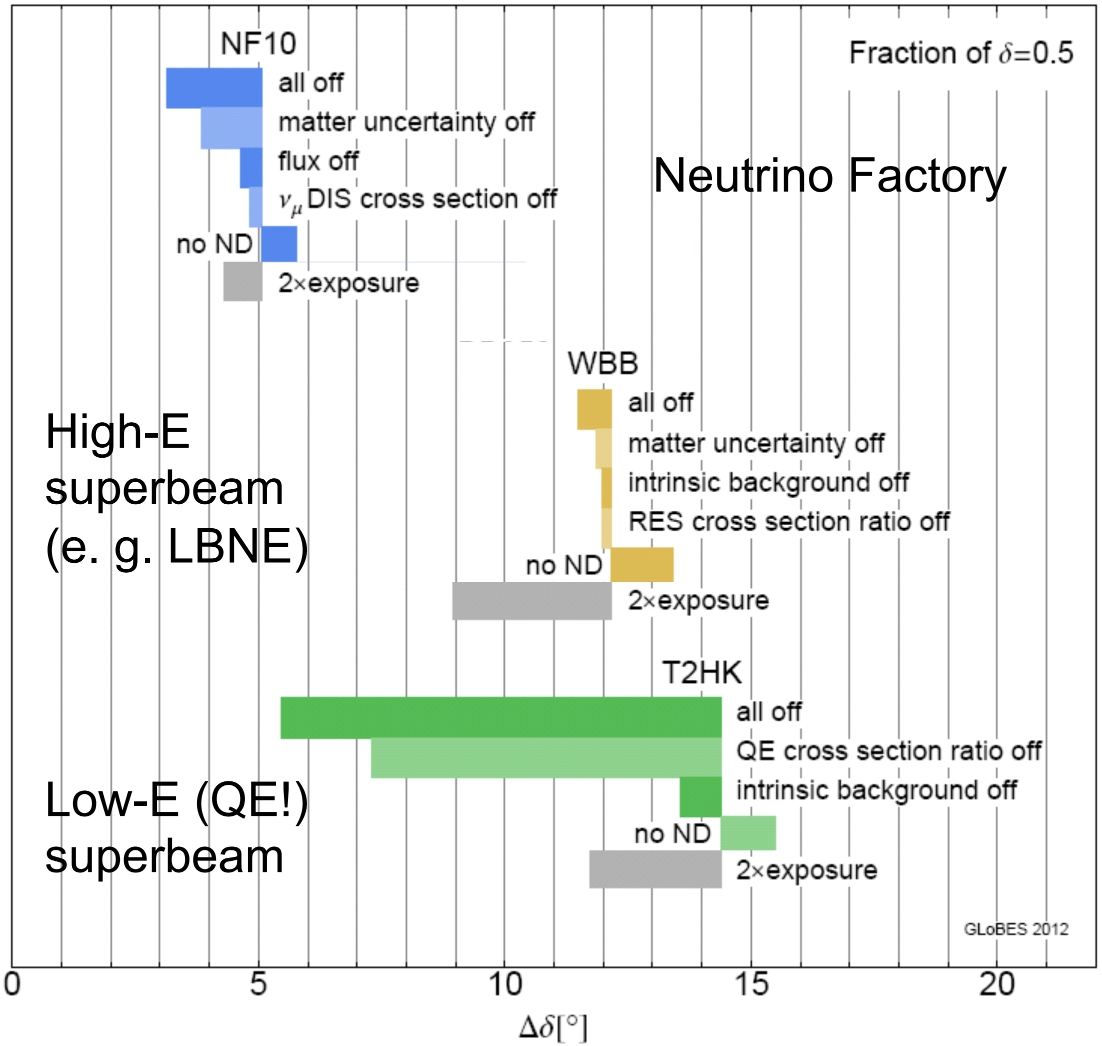
Muon Accelerator Staging Programme

Synergies between NuMAX and Muon Collider components

Muon Accelerator Staging Study (MASS)



Systematics: Main challenges for δ_{CP}



(Coloma, Huber, Kopp, Winter, arXiv:1209.5973)

Robust wrt systematics

Main impact:
Matter density uncertainty

Operate in statistics-limited regime

Exposure more important than near detector

QE ν_e X-sec critical: cannot be measured in near detector

Theory: ν_e/ν_μ ratio?
Experiment: νSTORM

$$\mu^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu$$

Mass hierarchy determination

Why would one like to measure the mass ordering?

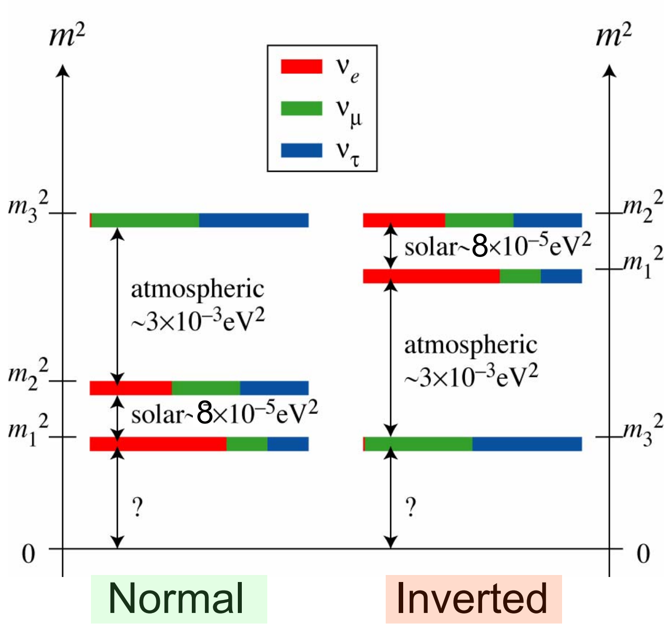


TABLE I: Mixing Angles for Models with Lepton Flavor Symmetry.

Reference	Hierarchy	$\sin^2 2\theta_{23}$	$\tan^2\theta_{12}$	$\sin^2\theta_{13}$
Anarchy Model:				
dGM [18]	Either			≥ 0.011 @ 2σ
$L_e - L_\mu - L_\tau$ Models:				
BM [35]	Inverted			0.00029
BCM [36]	Inverted			0.00063
GMN1 [37]	Inverted		≥ 0.52	≤ 0.01
GL [38]	Inverted			0
PR [39]	Inverted		≤ 0.58	≥ 0.007
S_3 and S_4 Models:				
CFM [40]	Normal			0.00006 - 0.001
HLM [41]	Normal	1.0	0.43	0.0044
	Normal	1.0	0.44	0.0034
KMM [42]	Inverted	1.0		0.000012
MN [43]	Normal			0.0024
MNY [44]	Normal			0.000004 - 0.000036
MPR [45]	Normal			0.006 - 0.01
RS [46]	Inverted	$\theta_{23} \geq 45°$		≤ 0.02
	Normal	$\theta_{23} \leq 45°$		0
TY [47]	Inverted	0.93	0.43	0.0025
T [48]	Normal			0.0016 - 0.0036
A_4 Tetrahedral Models:				
ABGMP [49]	Normal	0.997 - 1.0	0.365 - 0.438	0.00069 - 0.0037
AKKL [50]	Normal			0.006 - 0.04
Ma [51]	Normal	1.0	0.45	0
SO(3) Models:				
M [52]	Normal	0.87 - 1.0	0.46	0.00005
Texture Zero Models:				
CPP [53]	Normal			0.007 - 0.008
	Inverted			≥ 0.00005
	Inverted			≥ 0.032
WY [54]	Either			0.0006 - 0.003
	Either			0.002 - 0.02
	Either			0.02 - 0.15

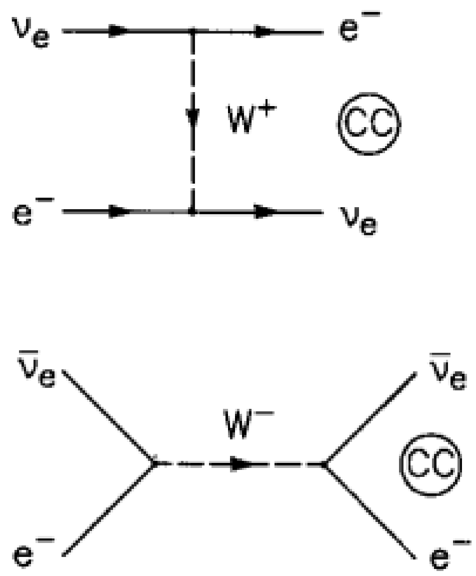
- Specific models typically come together with specific MH prediction (e.g. textures are very different)
- Good model discriminator →

(Albright, Chen, hep-ph/0608137)

Method 1: Matter effects in neutrino oscillations

- Ordinary matter: electrons, but no μ, τ
- Coherent forward scattering in matter: Net effect on electron flavor
- Hamiltonian in matter (matrix form, flavor space):

(Wolfenstein, 1978; Mikheyev, Smirnov, 1985)



$$\mathcal{H}(n_e) = U \begin{pmatrix} 0 & 0 & 0 \\ 0 & \frac{\Delta m_{21}^2}{2E} & 0 \\ 0 & 0 & \frac{\Delta m_{31}^2}{2E} \end{pmatrix} U^\dagger + \begin{pmatrix} V(n_e) & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

$$V_\nu = +\sqrt{2} G_F n_e, \; V_{\bar{\nu}} = -\sqrt{2} G_F n_e, \; n_e = Y \rho_j / m_N$$

Y: electron fraction ~ 0.5

(electrons per nucleon)

Parameter mapping … for two flavors, constant matter density

Oscillation probabilities in

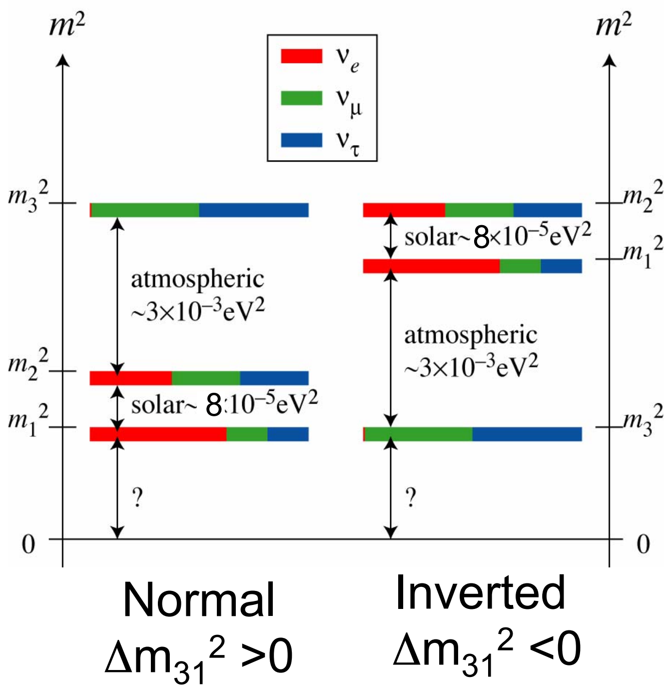
vacuum: $P_{\alpha\alpha} = 1 - \sin^2 2\theta \, \sin^2 \frac{\Delta m^2 L}{4E}$

matter: $P_{\alpha\alpha} = 1 - \sin^2 2\tilde{\theta} \, \sin^2 \frac{\Delta \tilde{m}^2 L}{4E}$

$$\Delta\tilde{m}^2 = \xi \cdot \Delta m^2, \qquad \sin 2\tilde{\theta} = \frac{\sin 2\theta}{\xi},$$

$$\xi \equiv \sqrt{\sin^2 2\theta + \left(\cos 2\theta - \hat{A}\right)^2},$$

$$\hat{A} = \frac{2EV}{\Delta m^2} = \frac{\pm 2\sqrt{2} E \, G_F \, n_e}{\Delta m^2}$$

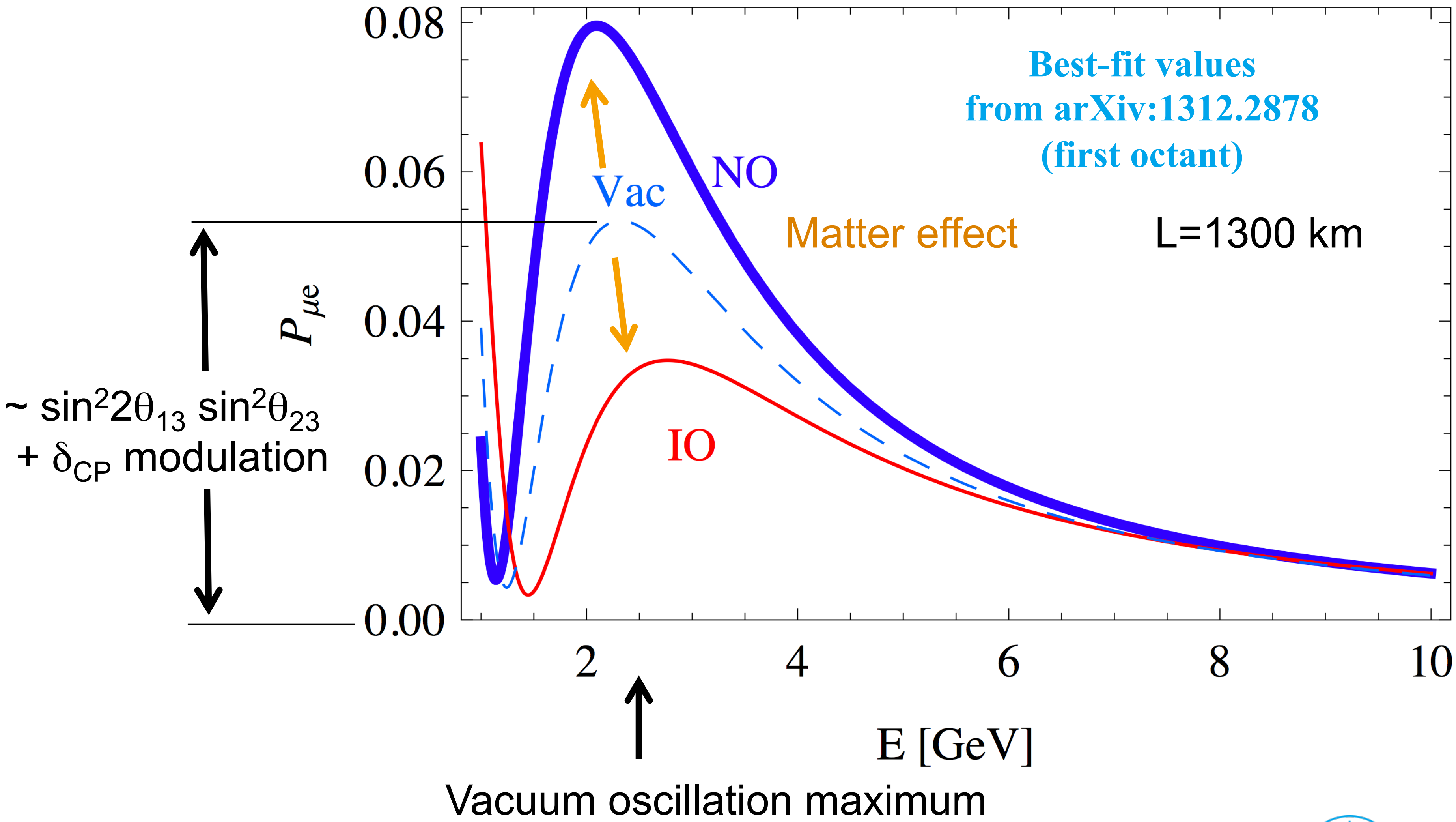


Enhancement condition

$$\cos 2\theta \to \hat{A}$$

	Normal	**Inverted**
Neutrinos	Resonance	Suppression
Antineutrinos	Suppression	Resonance

Long baseline experiments (up to first vacuum osc. maximum)



Long-Baseline Neutrino Oscillation Experiment (LBNE)

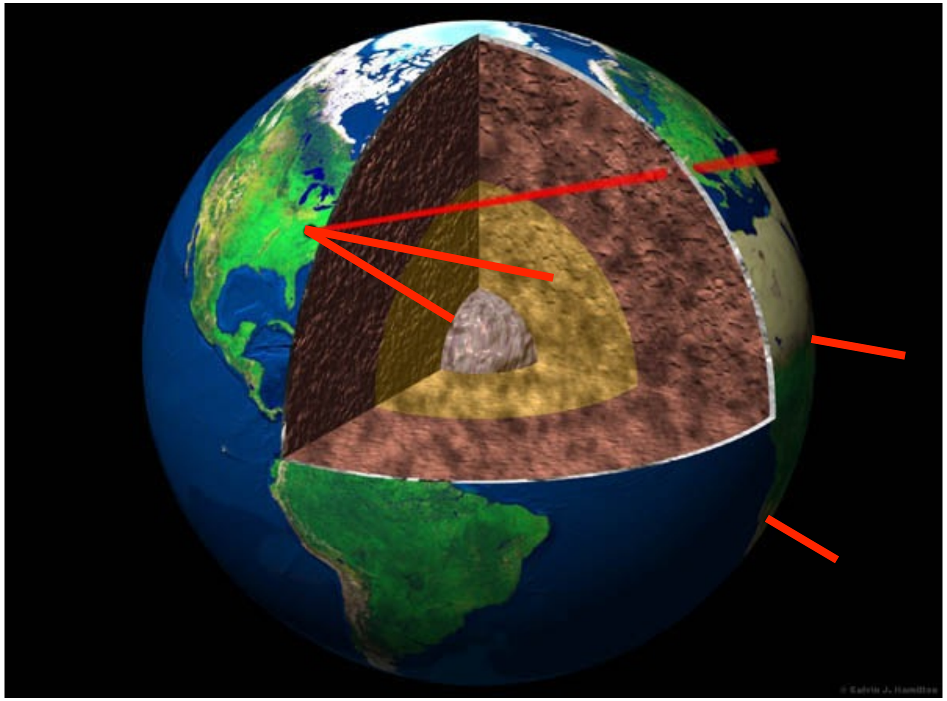
Bob Wilson @ Neutrino 2014

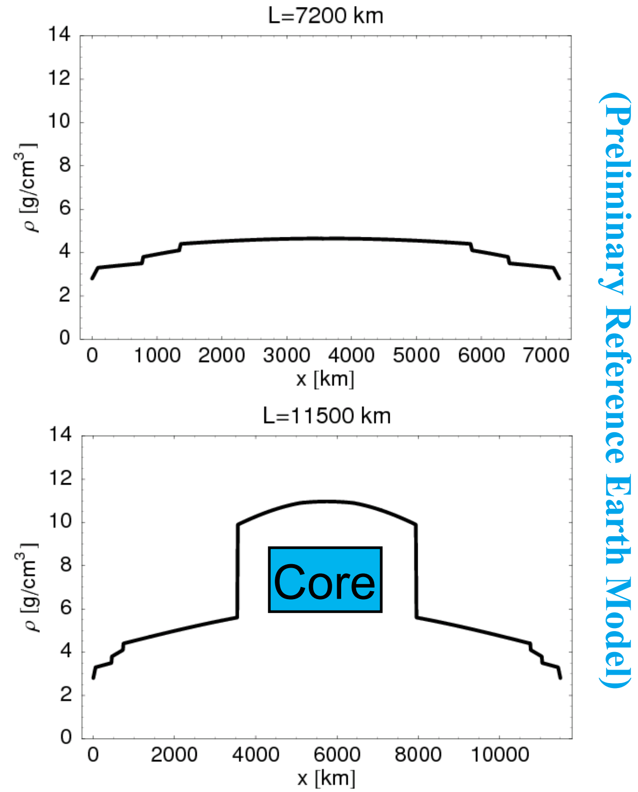
> Particle Physics Project Prioritization Panel (P5) in the US; Report May '14

- The Science Drivers:
  - Use the Higgs boson as a new tool for discovery
  - **Pursue the physics associated with neutrino mass**
  - Identify the new physics of dark matter
  - Understand cosmic acceleration: dark energy and inflation
  - Explore the unknown: new particles, interactions, and physical principles

Recommendation 13: 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.

Matter profile of the Earth … as seen by a neutrino





Resonance energy (from $\hat{A} \to \cos 2\theta$):

$$E_{\mathrm{res}}\,[\mathrm{GeV}] \sim 13\,200\ \cos 2\theta\, \frac{\Delta m^2\,[\mathrm{eV}^2]}{\rho\,[\mathrm{g/cm}^3]}$$

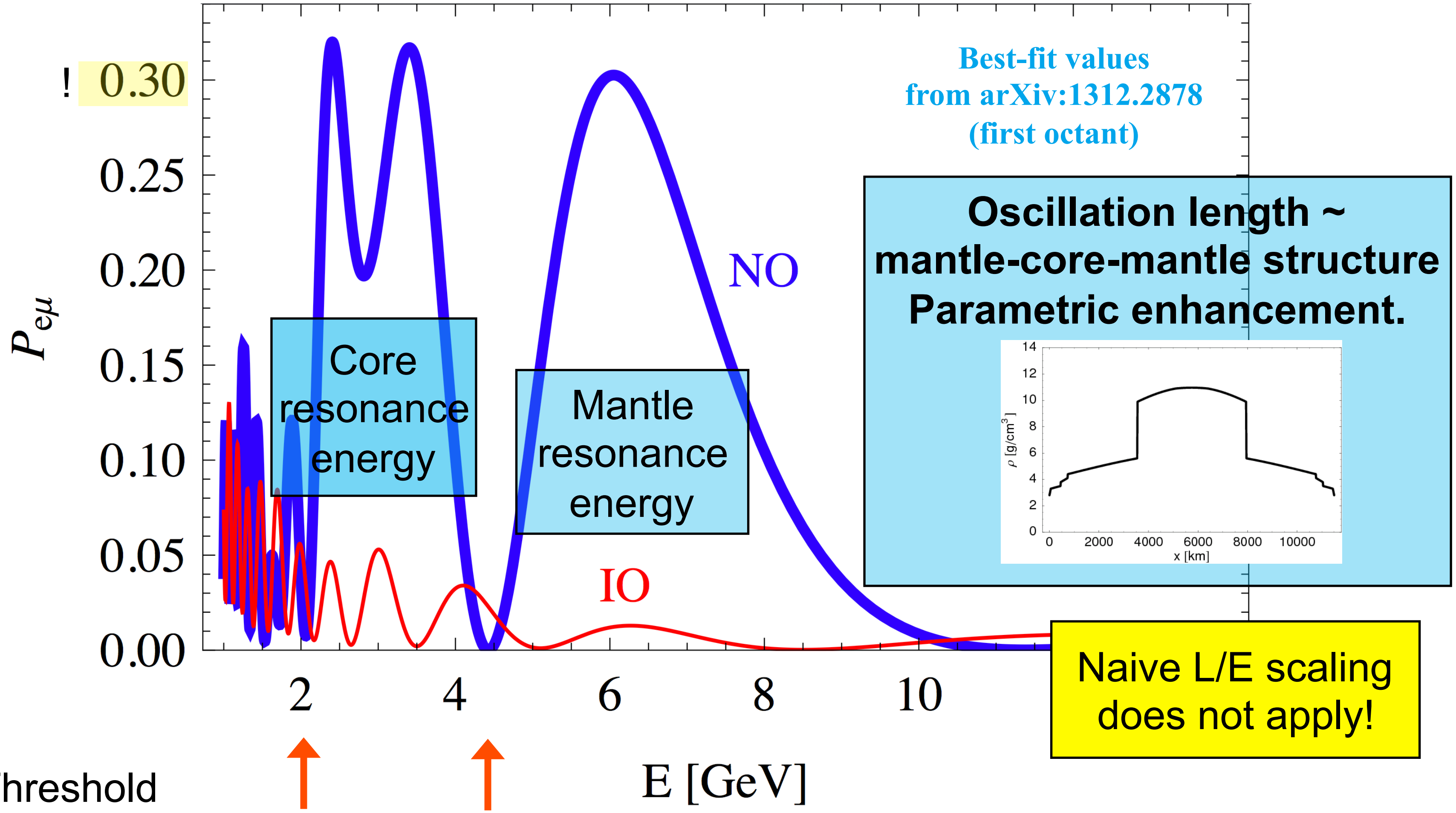
For ν_μ appearance, Δm_{31}^2:

- $\rho \sim 4.7$ g/cm³ (Earth's mantle): **$E_{res} \sim 6.4$ GeV**
- $\rho \sim 10.8$ g/cm³ (Earth's outer core): **$E_{res} \sim 2.8$ GeV**

Mantle-core-mantle profile

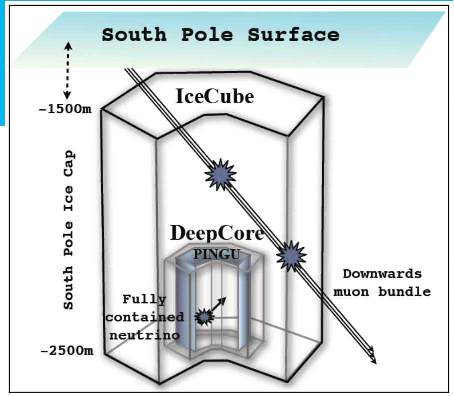
(Parametric enhancement: Akhmedov, 1998; Akhmedov, Lipari, Smirnov, 1998; Petcov, 1998)

- Probability for L=11810 km

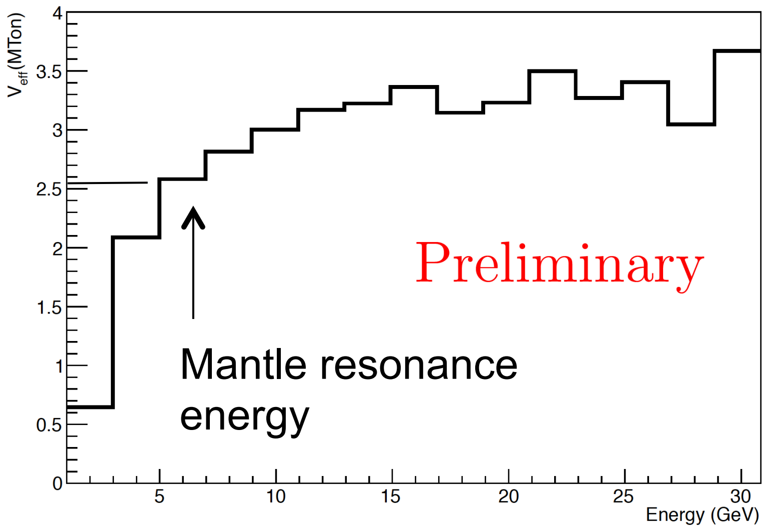


Threshold effects expected at: 2 GeV 4-5 GeV

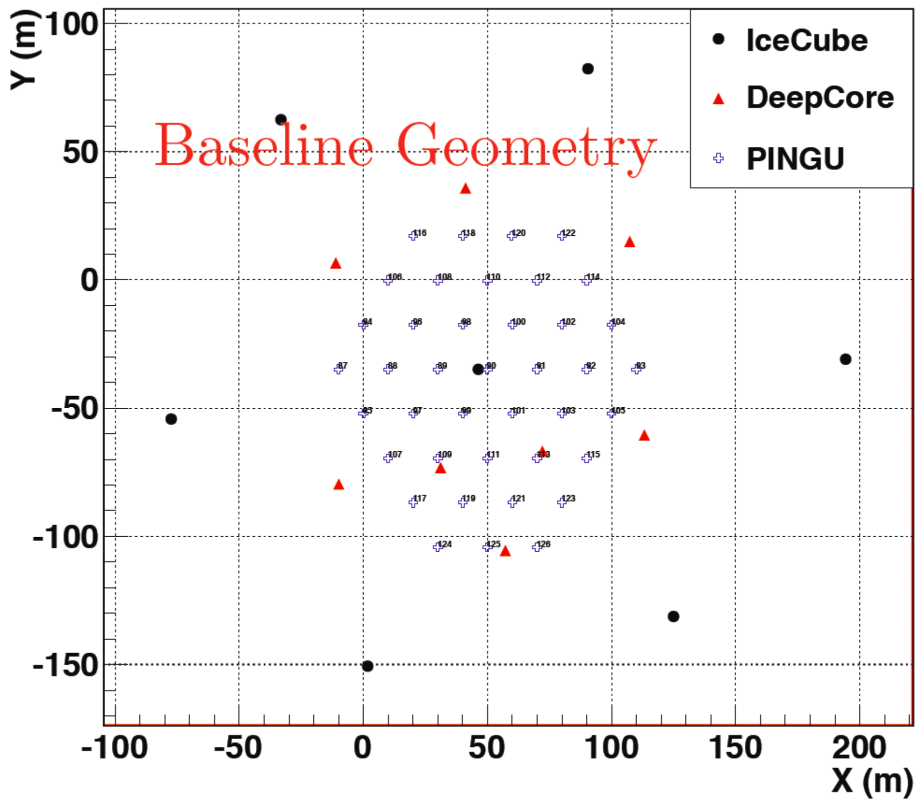
Emerging technologies: Atmospheric νs



- Example: PINGU
  ("Precision IceCube Next Generation Upgrade")
- 40 additional strings, 60 optical modules each
- Lower threshold, few Mtons at a few GeV
- ORCA, INO: similar methods



(a) $V_{\text{eff}}(\nu_\mu)$



(PINGU LOI, arXiv:1401.2046)

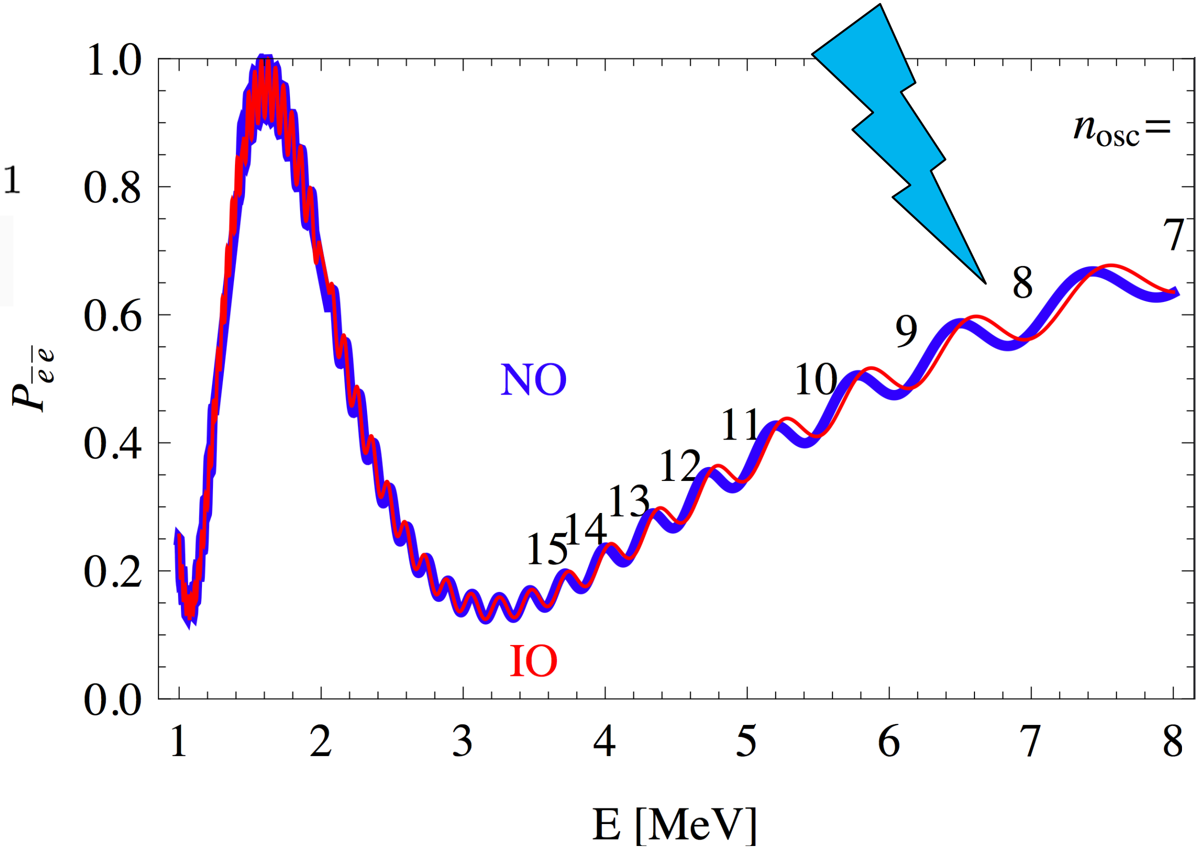
Method 2: Disappearance probabilities

- Works in vacuum, and even for $\theta_{13}=0$
- Just flipping the sign of Δm^2 is not sufficient
- Example: Reactor experiment, L=53 km

$$\Delta m^2_{31} \to -\Delta m^2_{31}$$

$$\Delta m^2_{ij} = m_i^2 - m_j^2$$

Probabilities apparently different (unphysical effect!)



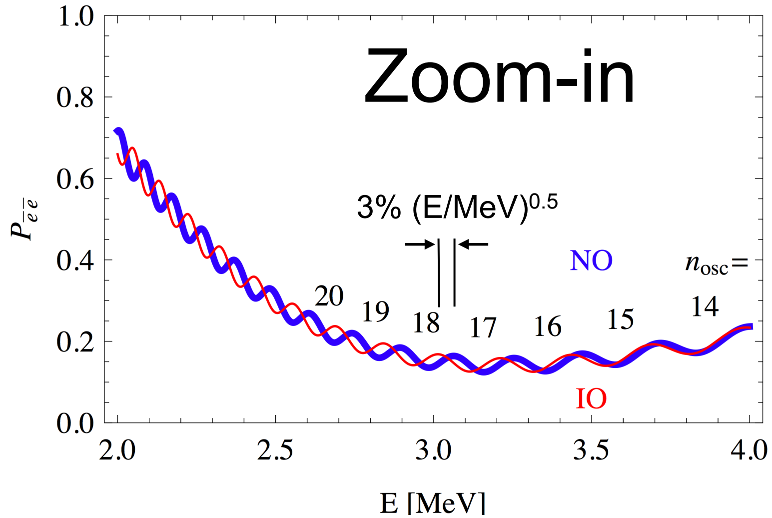
Method 2: Disappearance probabilities

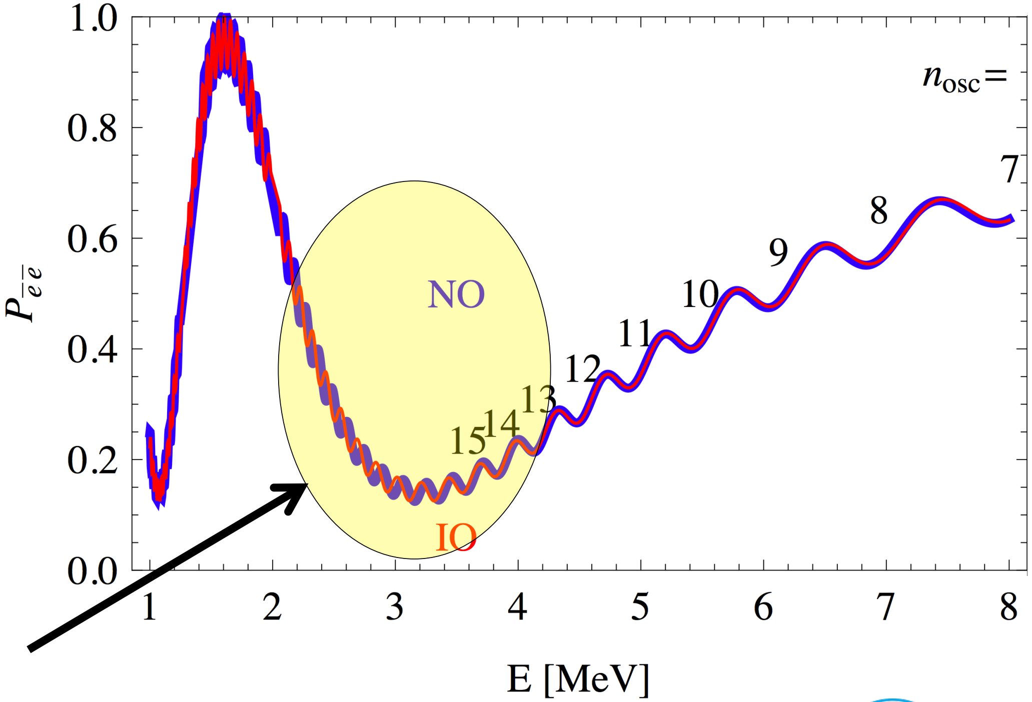
- The disappearance Δm^2 depends on the channel. Consequence e. g.

$$|\delta m^2_{\text{eff}}|_e - |\delta m^2_{\text{eff}}|_\mu = \pm \delta m^2_{21} (\cos 2\theta_{12} - \cos\delta \sin\theta_{13} \sin 2\theta_{12} \tan\theta_{23})$$

de Gouvea, Jenkins, Kayser, hep-ph/0503079;
Nunokawa, Parke, Zukanovich, hep-ph/0503283

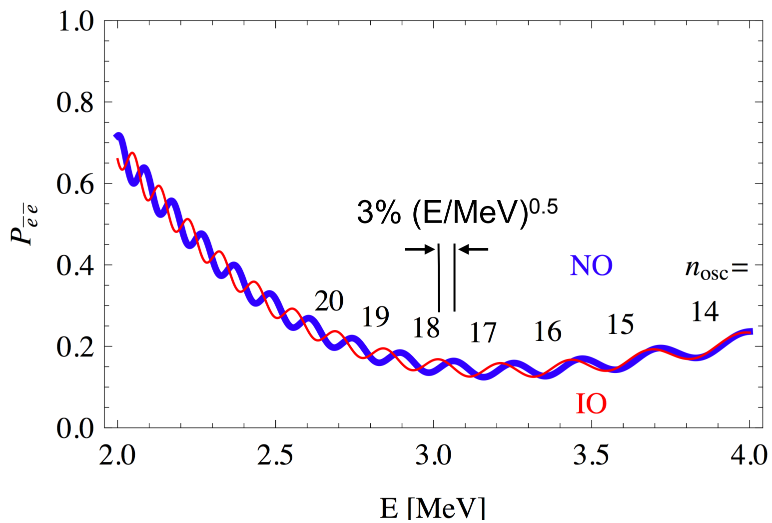
- Now first oscillation maxima match. Discrimination by higher osc. Maxima. Need energy resolution!

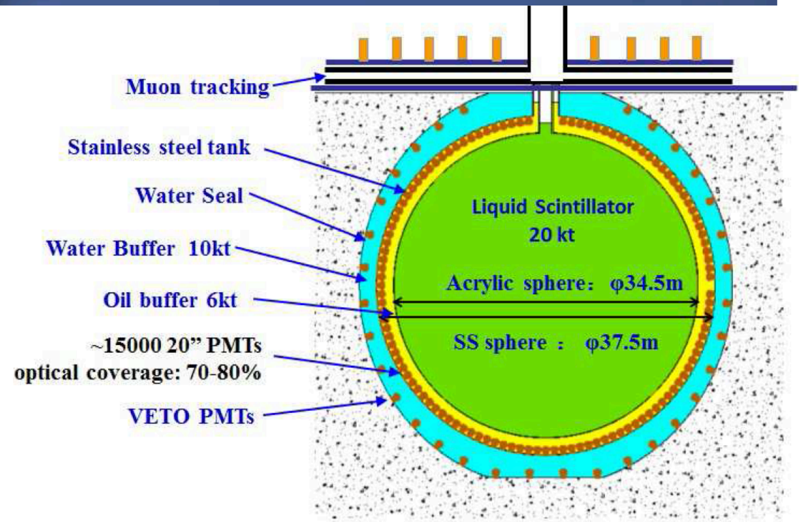




Emerging technologies: Reactor experiments

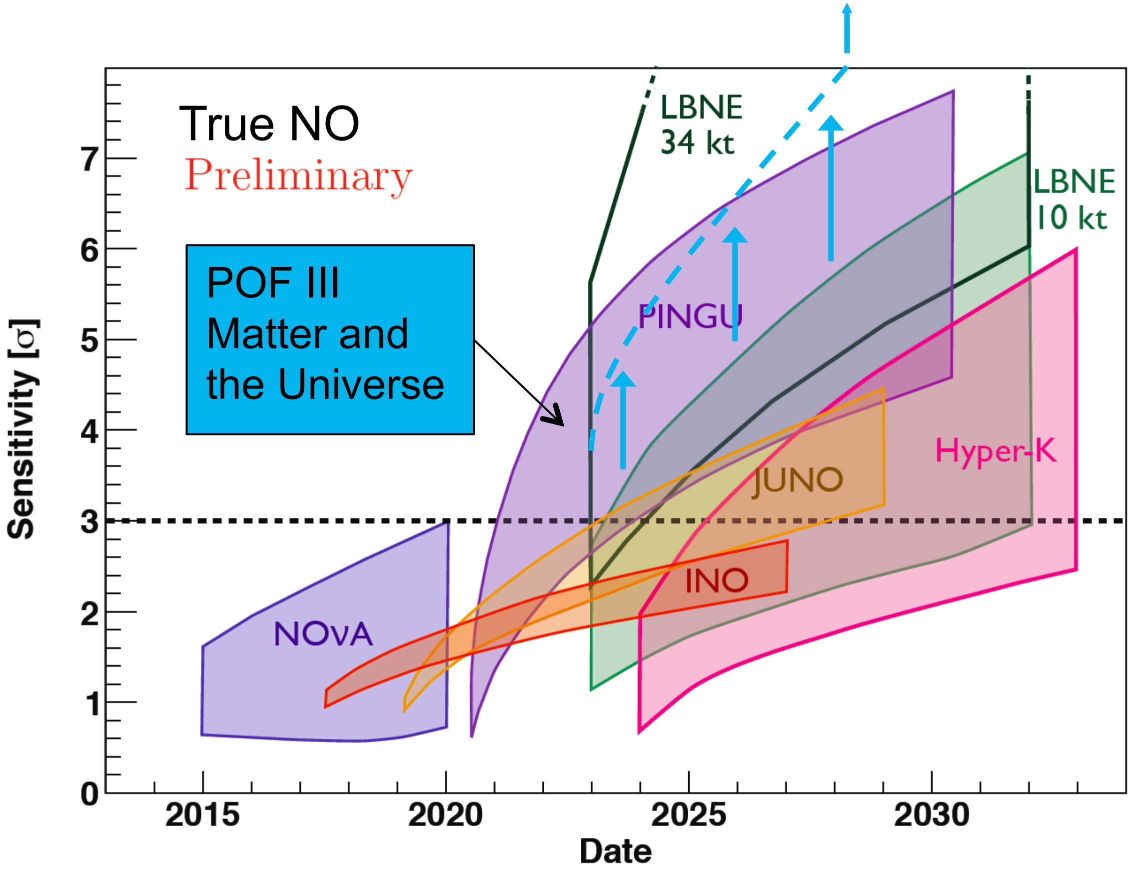
- Jiangmen Underground Neutrino Observatory (JUNO) [formerly Daya Bay-II]
- L=53 km
- Excellent energy resoluton (3% $(E/MeV)^{0.5}$) requires O(100%) PMT coverage





Global context

LBNE 10kt if θ_{23} varied as well
⇨ Fig. 9 in arXiv:1305.5539; see also arXiv:1311.1822v2



- Bands: risk wrt θ_{23} (PINGU, INO), δ_{CP} (NOvA, LBNE), energy resolution (JUNO)
- LBNE and sensitivity also scales with θ_{23}!

(version from PINGU LOI, arXiv:1401.2046, based on Blennow, Coloma, Huber, Schwetz, arXiv:1311.1822)

Summary and conclusions

- Mass hierarchy: may be tested in beginning of 2020s by "emerging technologies", such as PINGU or JUNO

  PINGU has a good chance to be the first experiment to measure the mass hierarchy if timely; DESY involved

- CP violation: requires a new long-baseline experiment, such as LBNE, T2HK, NuFact;
  P5 recognition milestone towards such a program at Fermilab

- Other issues: θ_{23} maximal? Octant?
  Sun and Earth tomography? New physics?

- Light sterile neutrinos - best candidate for physics BνSM? Test short-baseline anomalies, measure neutrino X-secs, …

- Perspectives for neutrino oscillations? Fantastic!