PHYSICS WITH ATMOSPHERIC NEUTRINOS

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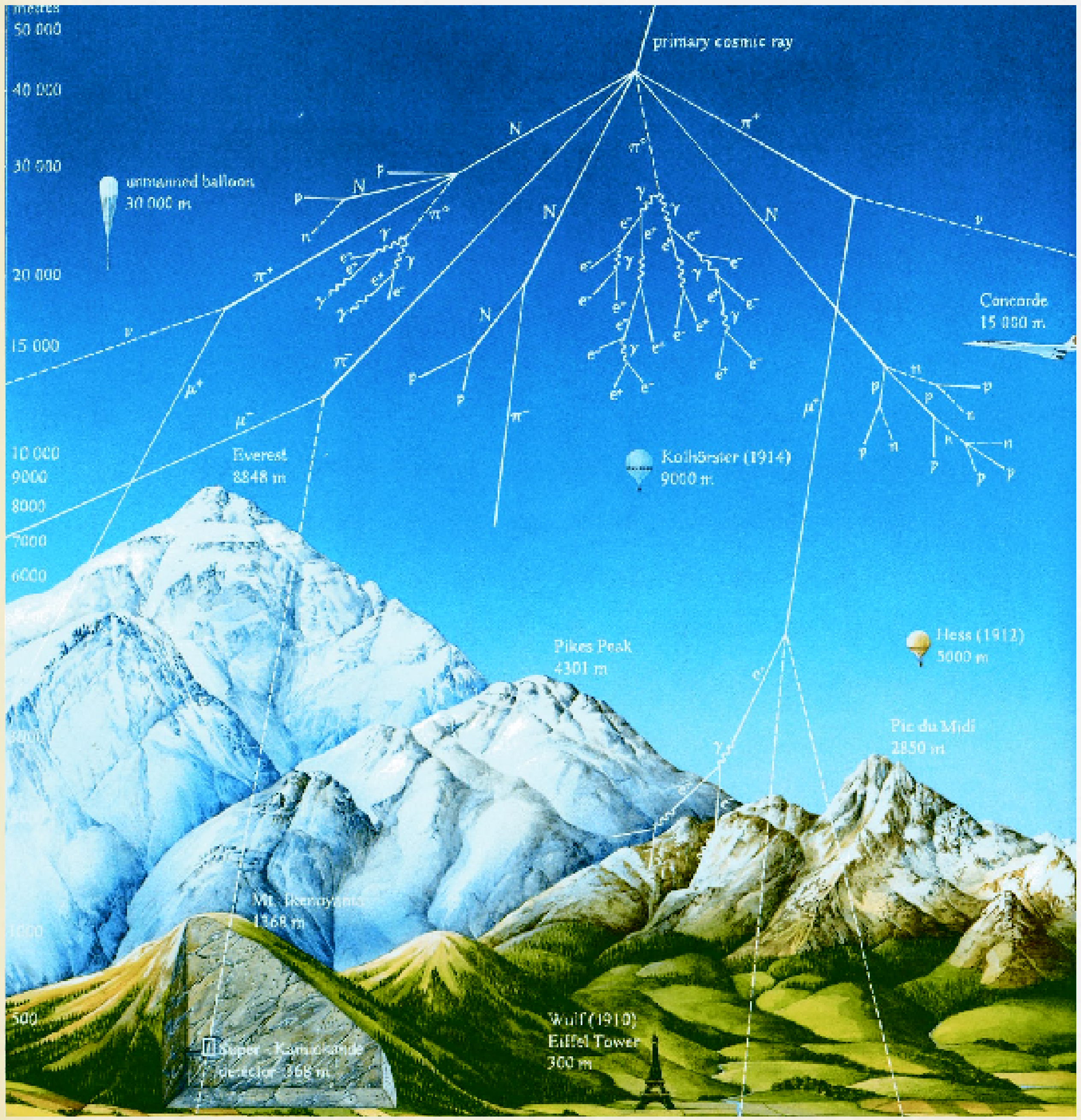
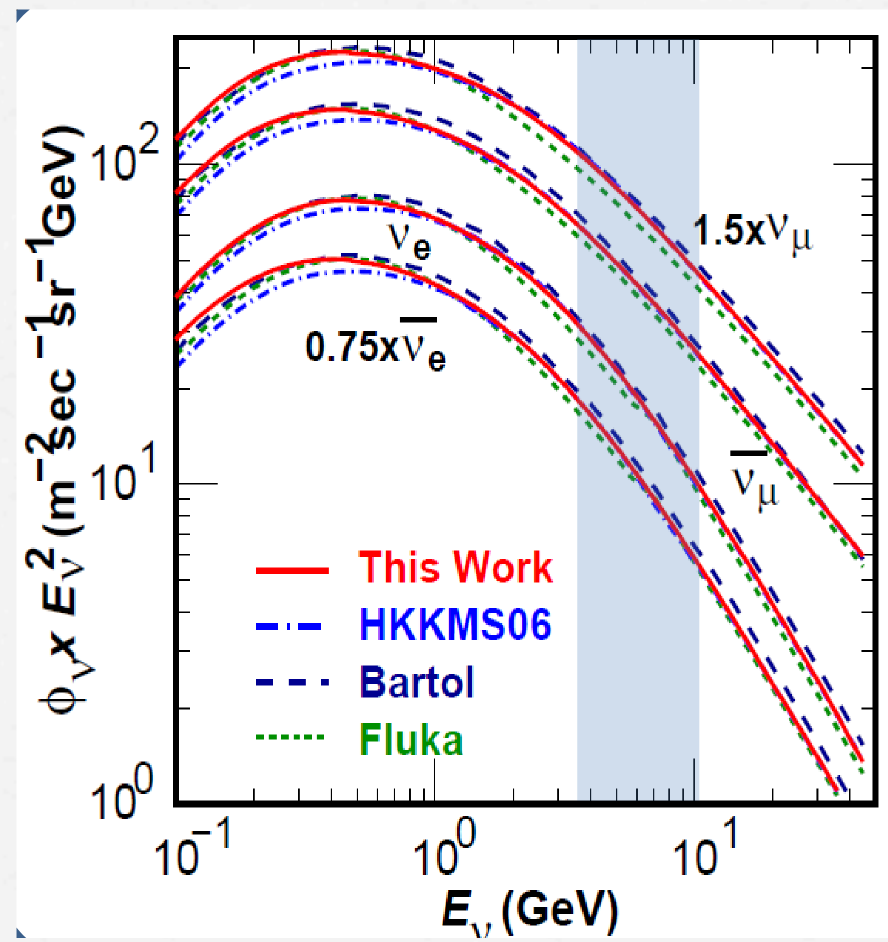
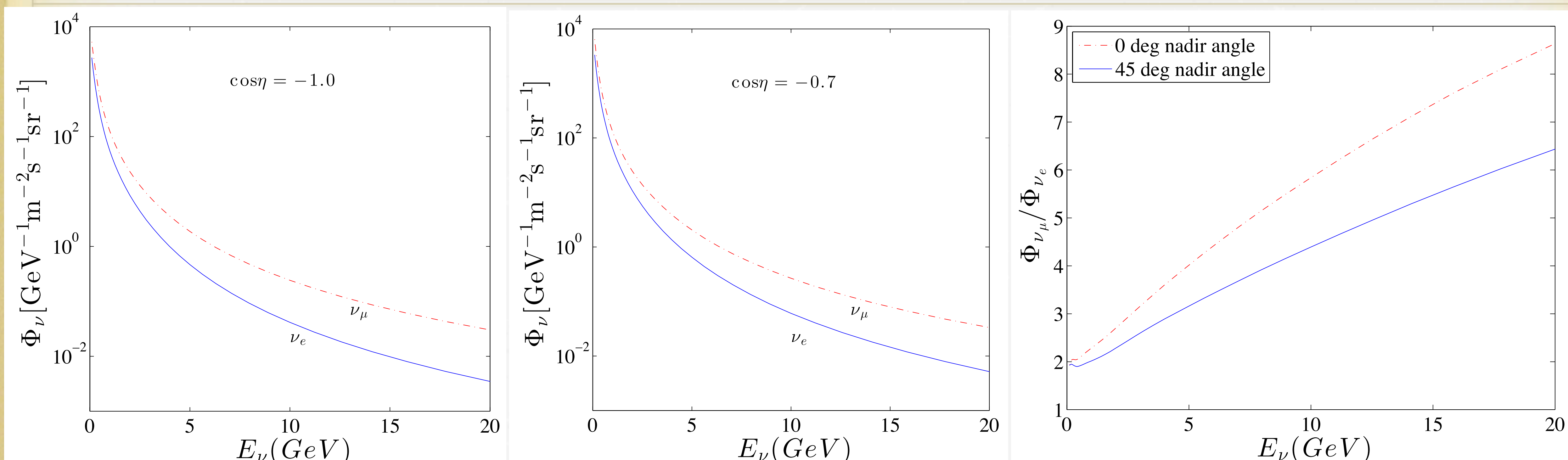
ATMOSPHERIC NEUTRINOS





$$p + X \to \pi^+ + Hadrons$$
$$\hookrightarrow \mu^+ + \nu_\mu$$
$$\hookrightarrow e^+ + \nu_e + \bar{\nu}_\mu$$

ATMOSPHERIC NEUTRINO FLUXES

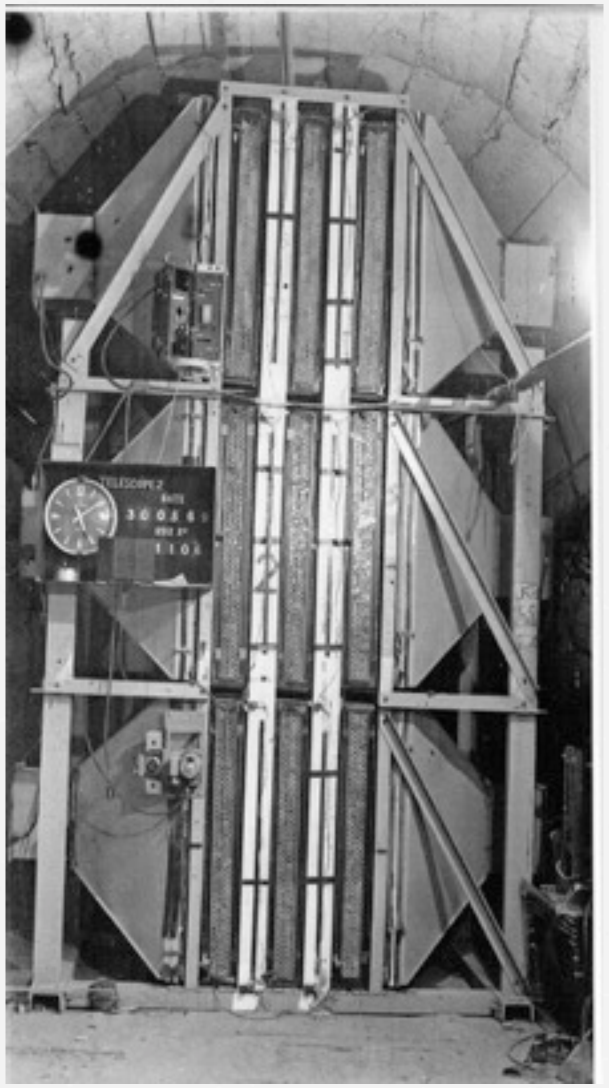


- *The flux ratio starts at 2, but then quickly rises*
- *The rate of this rise is more for vertical bins*
- *At E~7 GeV, the flux ratio for center-crossing bin is close to 5*

ATMOSPHERIC NEUTRINO EXPERIMENTS

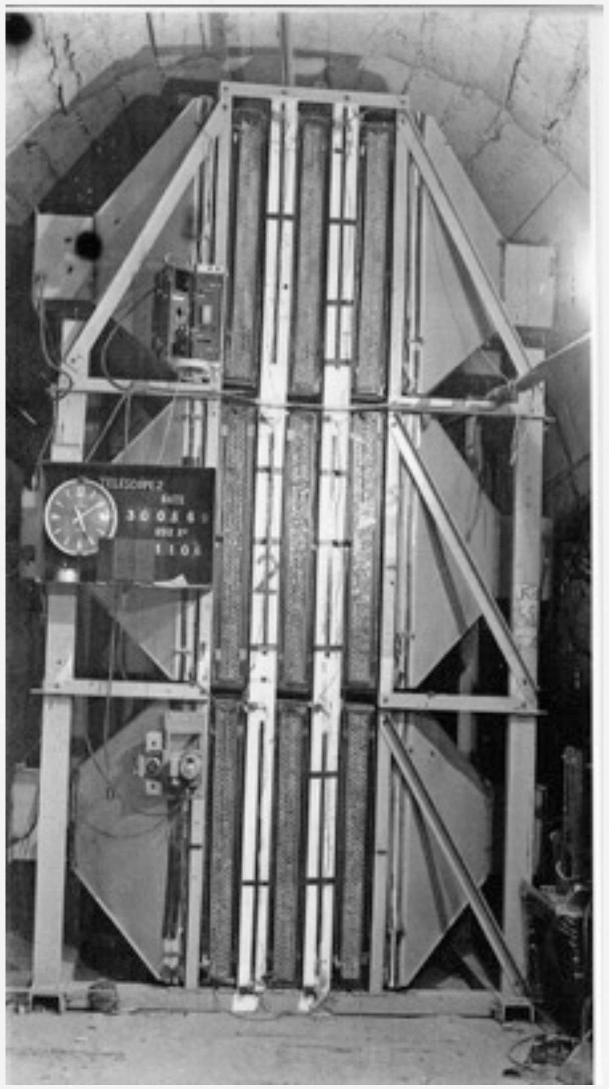
Slide courtesy N.K. Mondal

ATMOSPHERIC NEUTRINO EXPERIMENTS

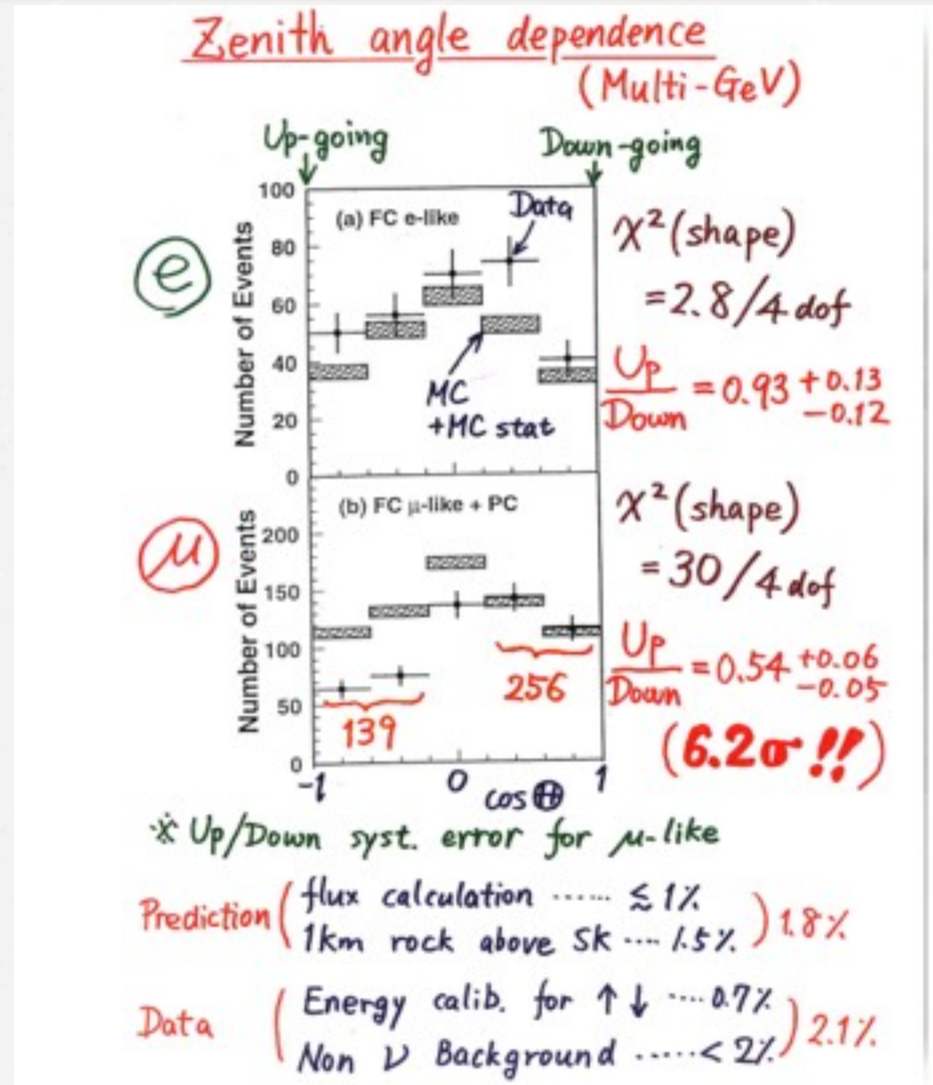


Slide courtesy N.K. Mondal

ATMOSPHERIC NEUTRINO EXPERIMENTS



Detection of atmospheric neutrino at Kolar Gold Field in 1965



The announcement of the discovery of neutrino oscillation at Neutrino 98 by T. Kajita

Slide courtesy N.K. Mondal

NEUTRINO OSCILLATIONS

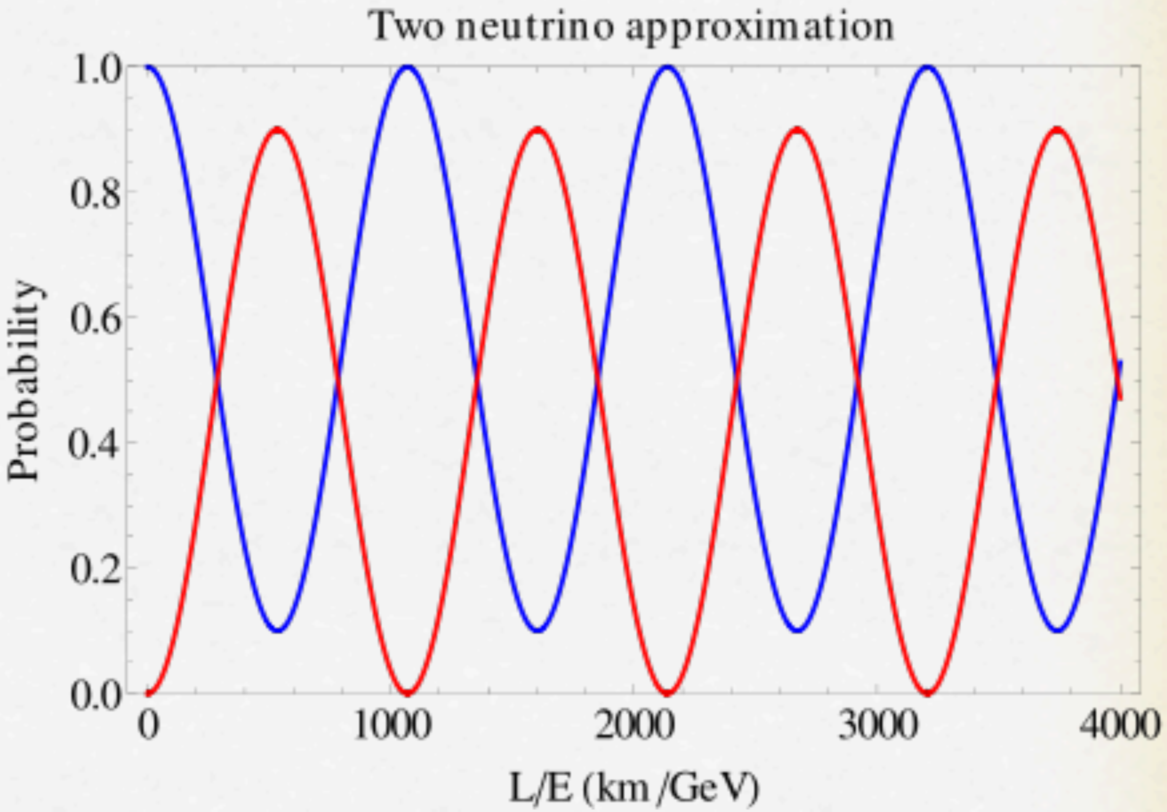
Neutrino Oscillations in Two Generations

- Flavor Eigenstates $\neq$ Mass Eigenstates

$$\nu_\mu = \cos\theta\,\nu_2 + \sin\theta\,\nu_3$$

$$\nu_\mu(t) = \cos\theta\,e^{-iE_2}\,\nu_2 + \sin\theta\,e^{-iE_3}\,\nu_3$$

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



- *No dependence on the sign of* Δm^2
- *No dependence on the octant of theta23*
- *No possibility of any CP violation*

The third generation!

NEUTRINO OSCILLATIONS

Three Flavor Oscillations in Vacuum

- Flavor Eigenstates $\neq$ Mass Eigenstates
- $|\nu_\alpha\rangle = \sum_i U_{\alpha i}|\nu_i\rangle$

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

$$\begin{aligned} P_{\beta\gamma}(L) = \quad \delta_{\beta\gamma} \quad & -4\sum_{j>1} Re\left(U_{\beta i}U^\star_{\gamma i}U^\star_{\beta j}U_{\gamma j}\right)\frac{\sin^2 \Delta m^2_{ij}L}{4E} \\ & \pm 2\sum_{j>1} Im\left(U_{\beta i}U^\star_{\gamma i}U^\star_{\beta j}U_{\gamma j}\right)\frac{\sin \Delta m^2_{ij}L}{2E}. \end{aligned}$$

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$$\pm 2\sum_{j>1} Im\left(U_{\beta i}U^\star_{\gamma i}U^\star_{\beta j}U_{\gamma j}\right)\frac{\sin \Delta m^2_{ij} L}{2E}.$$

CP dependent

sign of Δm^2 ***dependent***

NEUTRINO OSCILLATIONS

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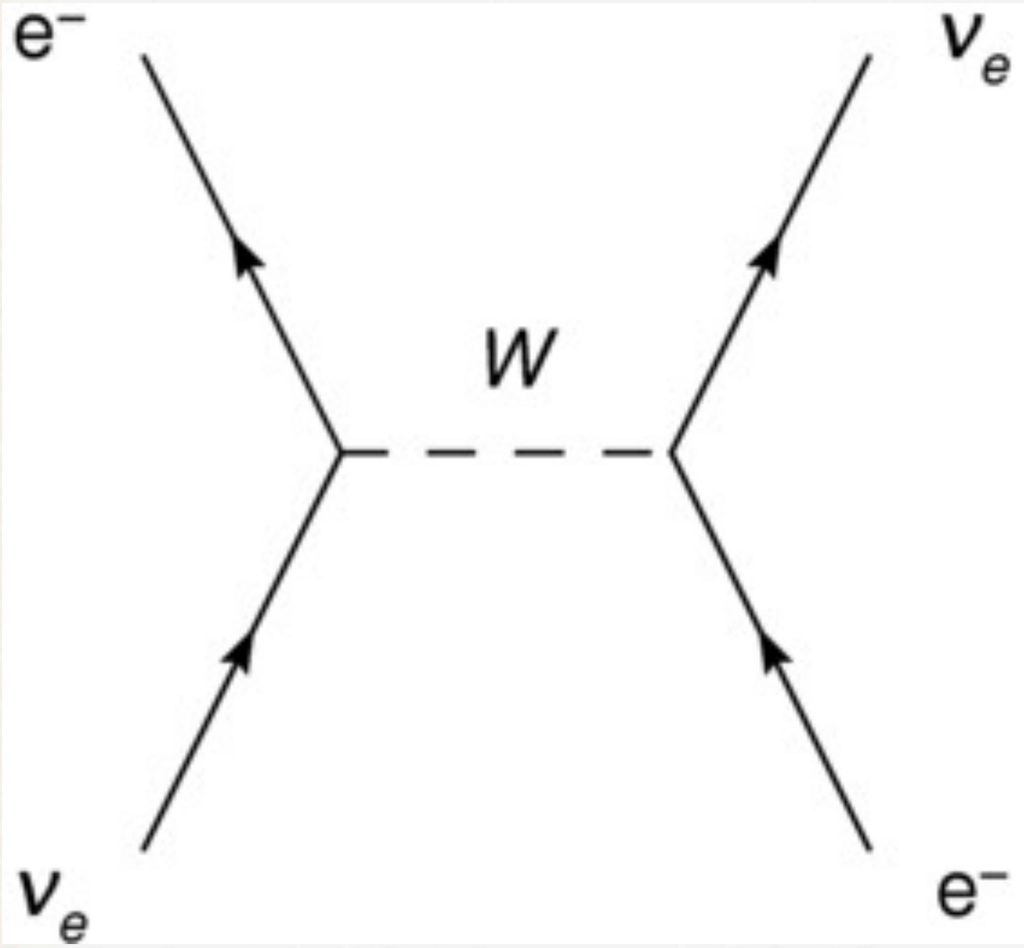
$$\pm 2\sum_{j>1} Im\left(U_{\beta i}U^\star_{\gamma i}U^\star_{\beta j}U_{\gamma j}\right)\frac{\sin \Delta m^2_{ij}L}{2E}.$$

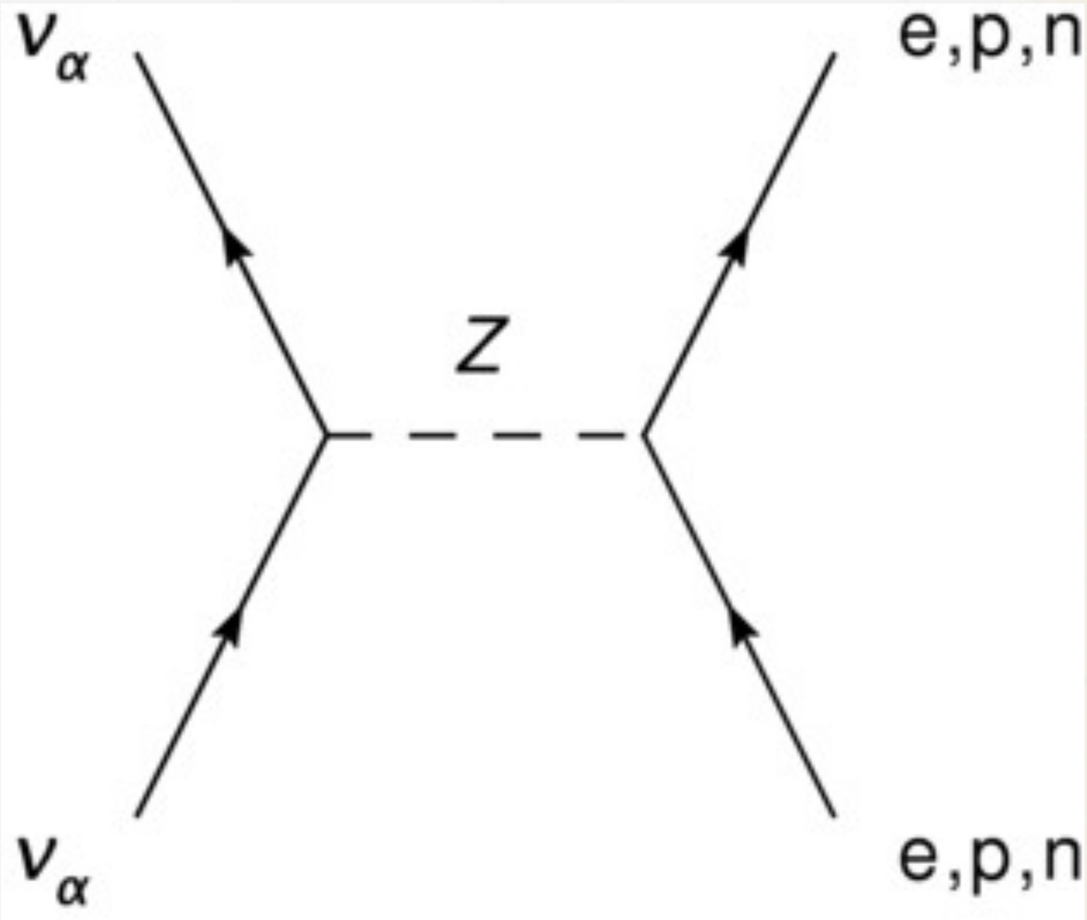
Octant of th23 dependence in both terms

CP dependent

sign of Δm^2 ***dependent***

NEUTRINO SCATTERING IN MATTER





NEUTRINO OSCILLATIONS

Three Flavor Oscillations in Matter

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- $|\nu_\alpha\rangle = \sum_i U^m_{\alpha i}|\nu^m_i\rangle$

$$U^m = \begin{pmatrix} c^m_{12}c^m_{13} & s^m_{12}c^m_{13} & s^m_{13}e^{-i\delta^m} \\ -s^m_{12}c^m_{23} - c^m_{12}s^m_{23}s^m_{13}e^{i\delta^m} & c^m_{12}c^m_{23} - s^m_{12}s^m_{23}s^m_{13}e^{i\delta^m} & s^m_{23}c^m_{13} \\ s^m_{12}s^m_{23} - c^m_{12}c^m_{23}s^m_{13}e^{i\delta^m} & -c^m_{12}s^m_{23} - s^m_{12}c^m_{23}s^m_{13}e^{i\delta^m} & c^m_{23}c^m_{13} \end{pmatrix}$$

$$P^m_{\beta\gamma}(L) = \delta_{\beta\gamma} \quad -4\sum_{j>1} Re\left(U^m_{\beta i}U^{m\star}_{\gamma i}U^{m\star}_{\beta j}U^m_{\gamma j}\right)\frac{\sin^2(\Delta m^2_{ij})^m L}{4E}$$

$$\pm 2\sum_{j>1} Im\left(U^m_{\beta i}U^{m\star}_{\gamma i}U^{m\star}_{\beta j}U^m_{\gamma j}\right)\frac{\sin(\Delta m^2_{ij})^m L}{2E}.$$

NEUTRINO OSCILLATIONS

Three Flavor Oscillations in Matter

- Mass squared difference in matter changes to:

$$(\Delta m^2_{31})^m = \sqrt{(\Delta m^2_{31}\cos 2\theta_{13} - A)^2 + (\Delta m^2_{31}\sin 2\theta_{13})^2}$$

- Mixing angle in matter changes to:

$$\sin 2\theta^m_{13} = \sin 2\theta_{13}\,\frac{\Delta m^2_{31}}{(\Delta m^2_{31})^m}$$

- Both of these depend on the sign of Δm^2_{31}
- Effect is opposite for neutrinos and antineutrinos
- When

$$A = \Delta m^2_{31}\cos 2\theta_{13}$$

$$\sin 2\theta^m_{13} = 1$$

Matter Enhanced (MSW) Resonance

Wolfenstein 1978, Mikheyev and Smirnov 1985-6

ATMOSPHERIC NEUTRINO OSCILLATIONS

- *Atm neutrinos cover a wide energy band (100 MeV to 100 TeV)*
- *Atmospheric neutrinos cover long distances in matter*
- *For* $\Delta m^2_{31} = 2.5 \times 10^{-3} eV^2$ and $\rho = 4$ gm/cc, $E_{res} = 7.5$ GeV

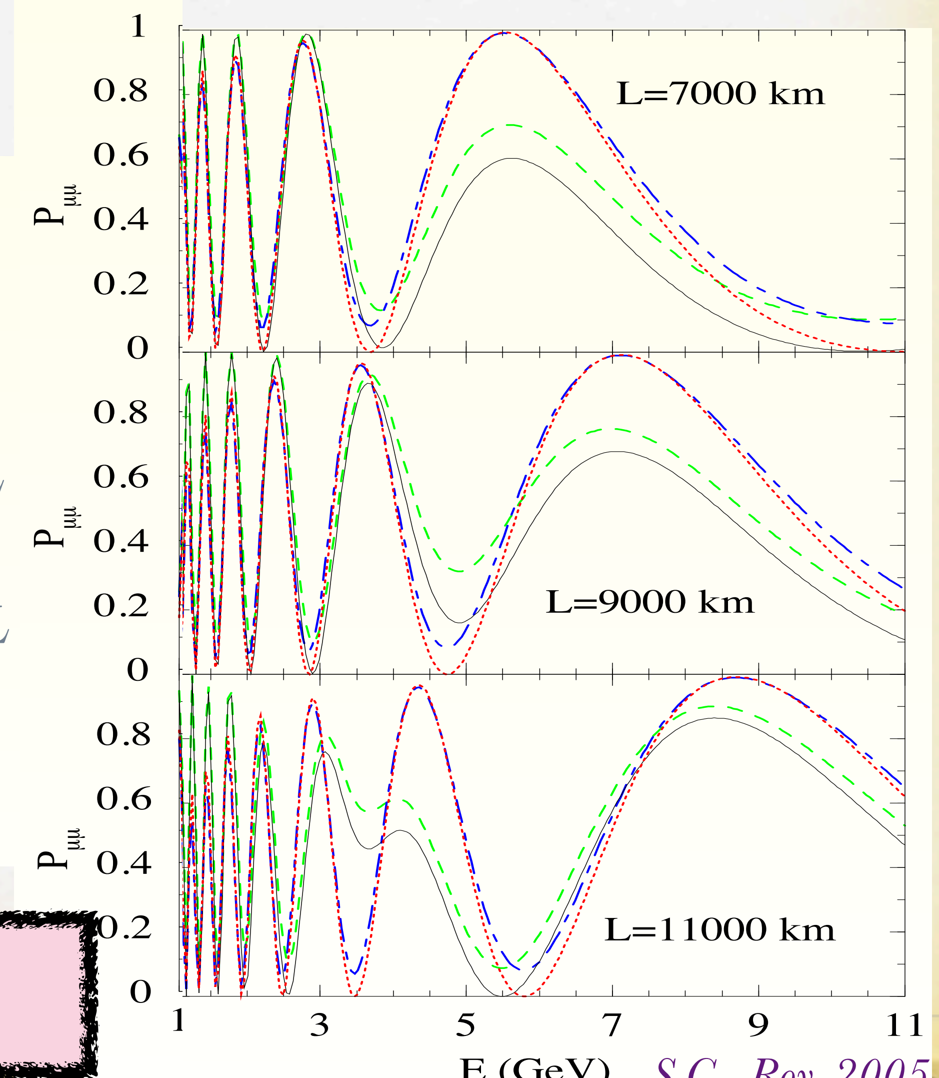
MUONS

$$\lim_{\Delta m^2_{21} \to 0} P_{\mu\mu}(L,E) = 1 - P^1_{\mu\mu}(L,E) - P^2_{\mu\mu}(L,E) - P^3_{\mu\mu}(L,E)$$

$$P^1_{\mu\mu}(L,E) = \sin^2\theta^m_{13} \sin^2 2\theta_{23} \sin^2 \frac{(A+\Delta m^2_{31}) - (\Delta m^2_{31})^m}{8E} L$$

$$P^2_{\mu\mu}(L,E) = \cos^2\theta^m_{13} \sin^2 2\theta_{23} \sin^2 \frac{(A+\Delta m^2_{31}) + (\Delta m^2_{31})^m}{8E} L$$

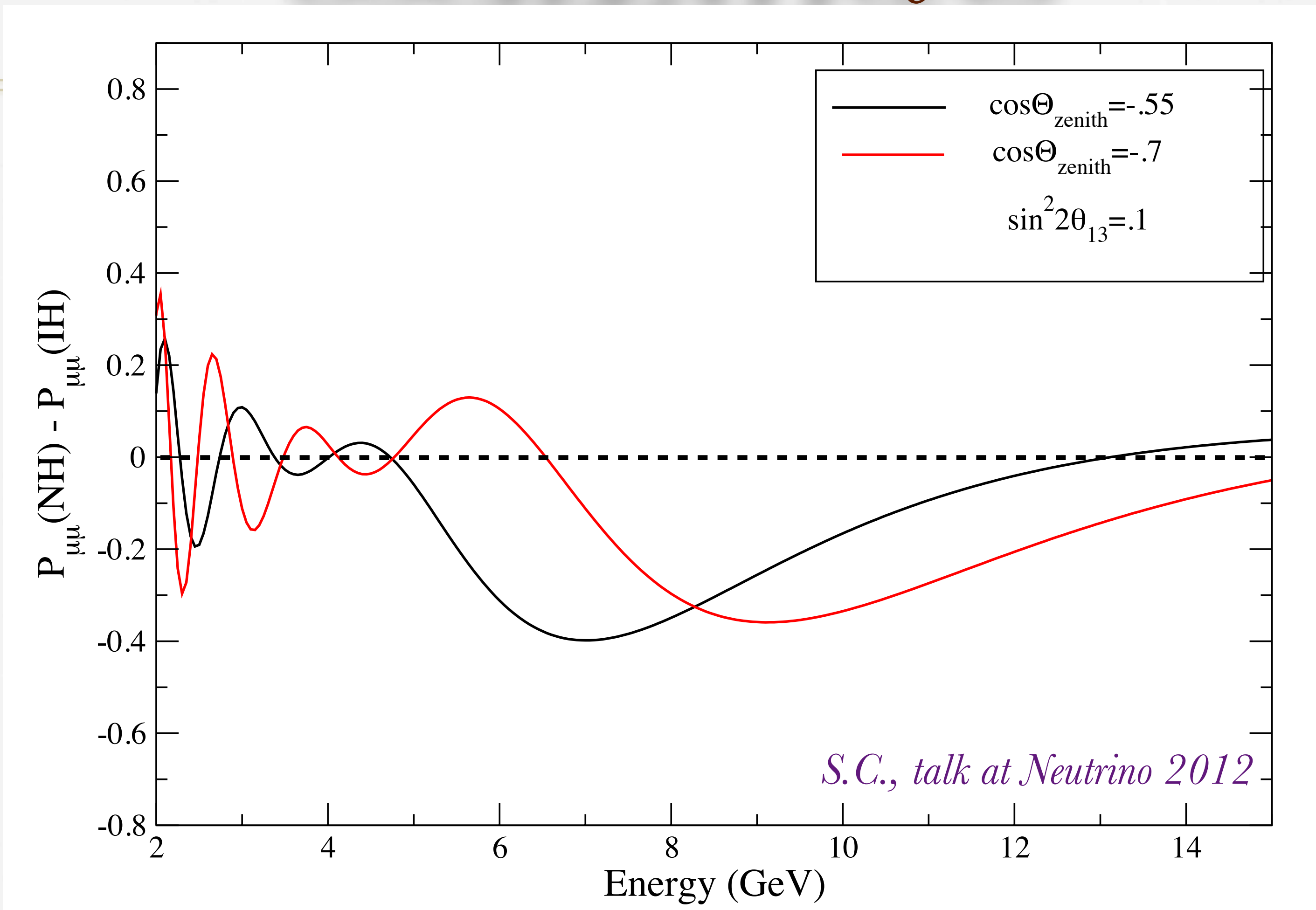
$$P^3_{\mu\mu}(L,E) = \sin^2 2\theta^m_{13} \sin^4 \theta_{23} \sin^2 \frac{(\Delta m^2_{31})^m}{4E} L$$



S.C., Roy, 2005

Effect of matter is large at the osc max and min

ATMOSPHERIC MUON NEUTRINO OSCILLATIONS



- *Matter effects fluctuate rapidly with E and $\cos\theta_{zenith}$*
- *Good E and $\cos\theta_{zenith}$ resolution helps*
- *Effect opposite for nu and anti-nu ---- charge discrimination helps*
- *Larger detector and hence larger statistics helps*

ATMOSPHERIC MUON NEUTRINO OSCILLATIONS

$$\lim_{\Delta m^2_{21} \to 0} P_{\mu\mu}(L,E) = 1 - P^1_{\mu\mu}(L,E) - P^2_{\mu\mu}(L,E) - P^3_{\mu\mu}(L,E)$$

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Contribution from the muon nu flux

$$\lim_{\Delta m^2_{21} \to 0} P_{\mu e}(L,E) = \sin^2\theta_{23}\sin^2 2\theta^m_{13}\sin^2\frac{(\Delta m^2_{31})^m L}{4E}$$

Contribution from the e nu flux

$$\Phi_\mu(detector) = \Phi^0_\mu(P_{\mu\mu} + (\Phi^0_e/\Phi^0_\mu)P_{e\mu}) = \Phi^0_\mu(1 - P^1_{\mu\mu} - P^2_{\mu\mu} - (\underbrace{\sin^2\theta_{23}}_{1/2} - \underbrace{\Phi^0_e/\Phi^0_\mu}_{1/2})P_{e\mu})$$

Earth matter effects in the two terms partially cancel each other

ATMOSPHERIC ELECTRON NEUTRINO OSCILLATIONS

$$P_{ee} \underset{\Delta m^2_{21} \to 0}{=} 1 - \sin^2 2\theta^m_{13} \sin^2 \left[1.27(\Delta m^2_{31})^m L/E\right]$$

Contribution from the e nu flux

$$\lim_{\Delta m^2_{21} \to 0} P_{\mu e}(L, E) = \sin^2 \theta_{23} \sin^2 2\theta^m_{13} \sin^2 \frac{(\Delta m^2_{31})^m L}{4E}$$

Contribution from the muon nu flux

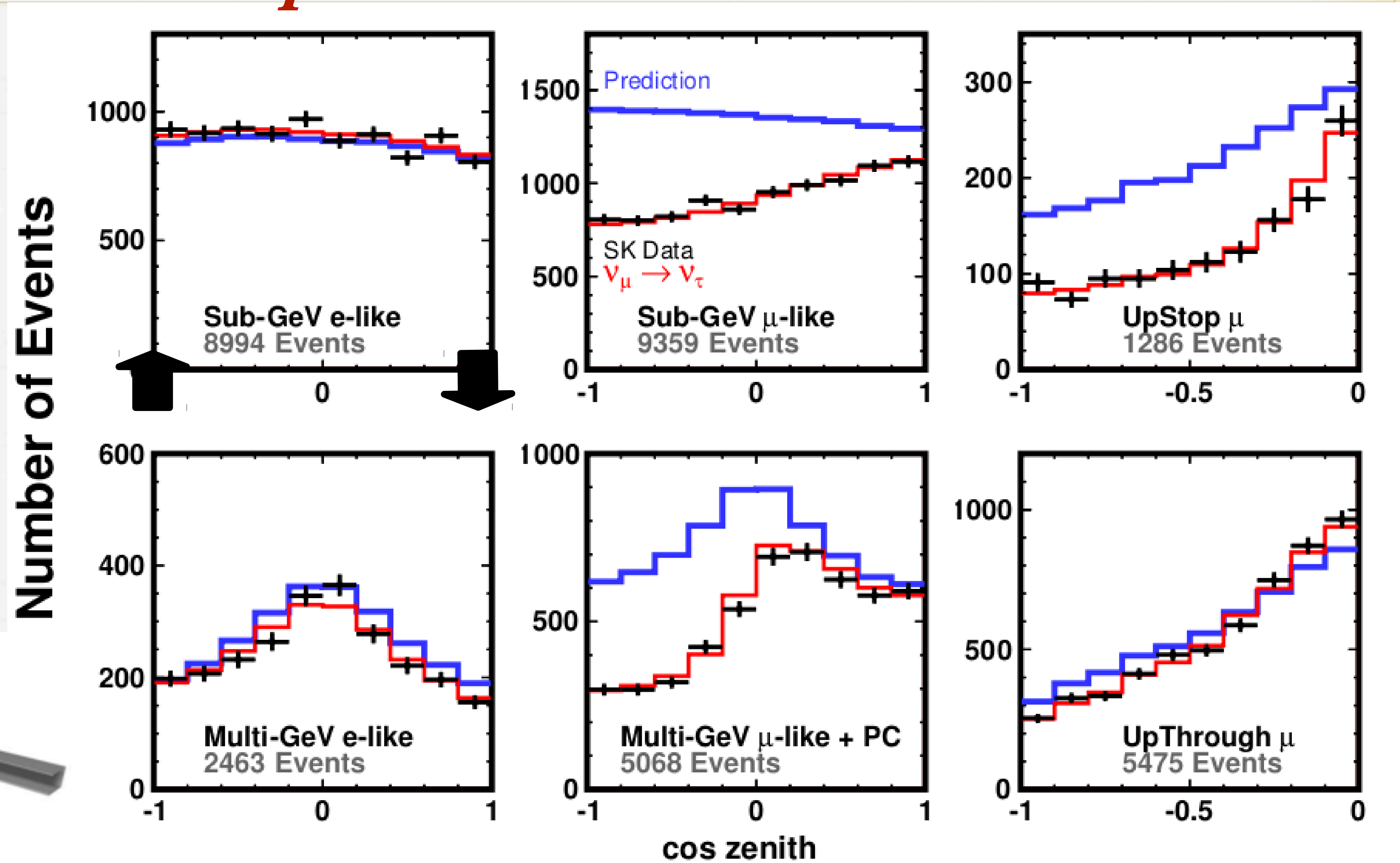
$$\Phi_e(detector) = \Phi^0_e(P_{ee} + (\Phi^0_\mu/\Phi^0_e)P_{\mu e} = \Phi^0_e(1 - (\frac{1}{\sin^2 \theta_{23}} - \Phi^0_\mu/\Phi^0_e)P_{e\mu})$$

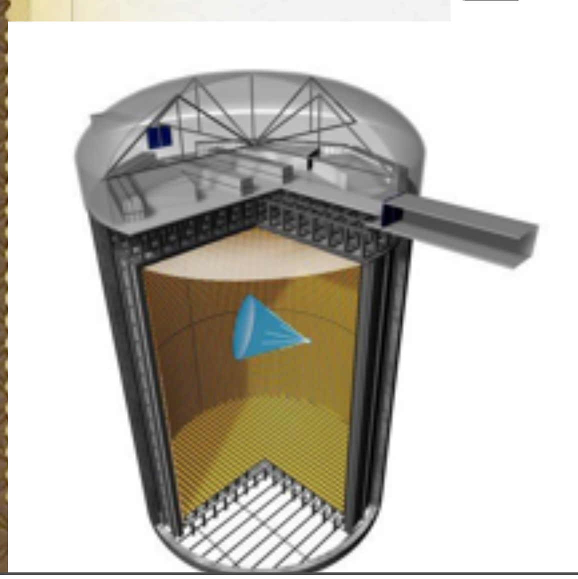
2 2

Earth matter effects in the two terms partially cancel each other

CURRENT STATUS

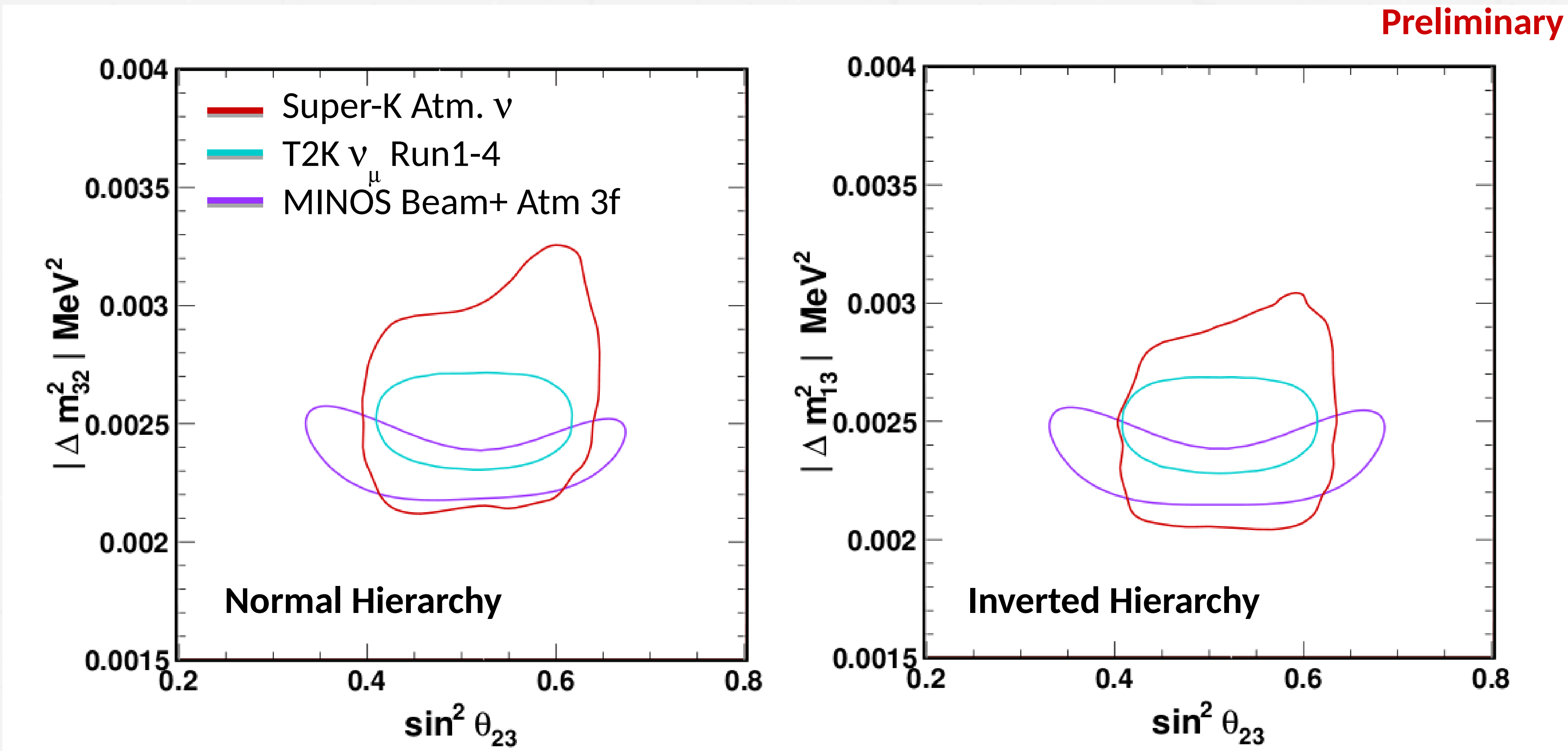
Super-Kamiokande Data





R. Wendell, Talk at Neutrino 2014

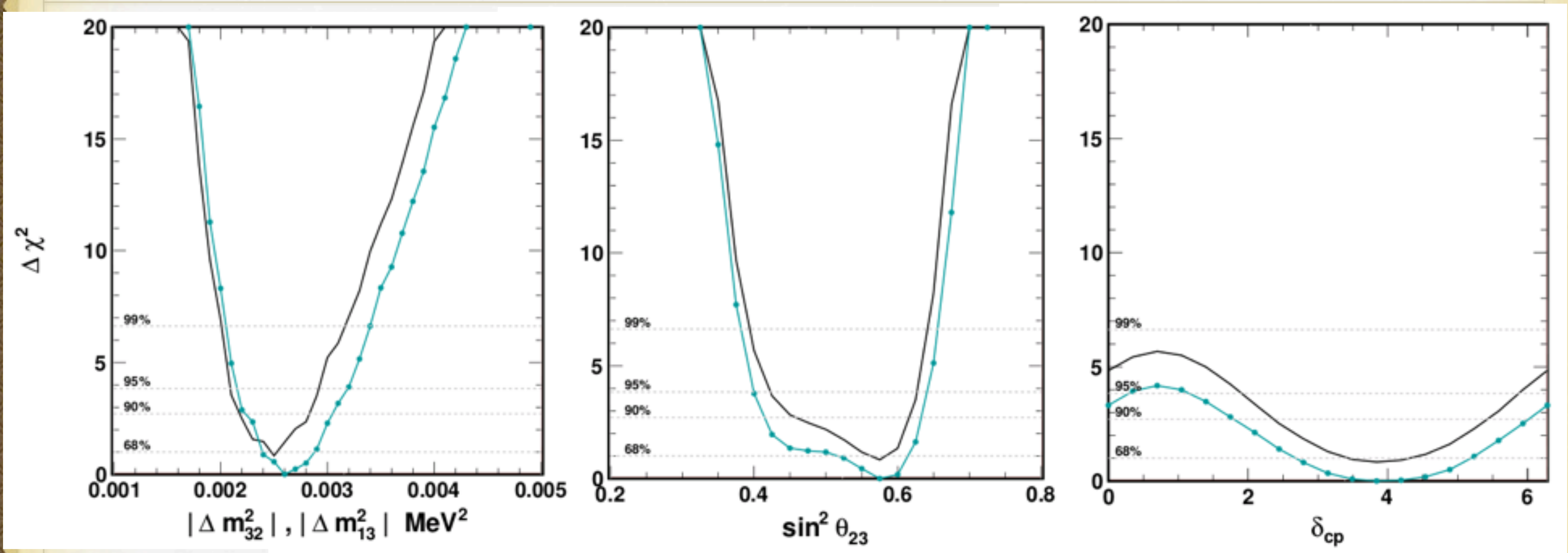
WHAT WE HAVE LEARNED



- *Experiments are mutually consistent*

R. Wendell, Talk at Neutrino 2014

WHAT WE HAVE LEARNED



Fit (517 dof)	χ^2	θ_{13}	δ_{cp}	θ_{23}	Δm_{23} (x10^{-3})
SK (NH)	559.8	0.025	3.84	0.57	2.6
SK (IH)	560.7	0.025	3.84	0.57	2.5

- *Statistically insignificant....can they be regarded as hints?*

R. Wendell, Talk at Neutrino 2014

WHAT WE STILL HAVE TO LEARN

- The neutrino mass ordering (MH)…
- CP violation in the lepton sector…
- Octant of the mixing angle θ_{23} …
- Beyond 3-flavor oscillation physics..

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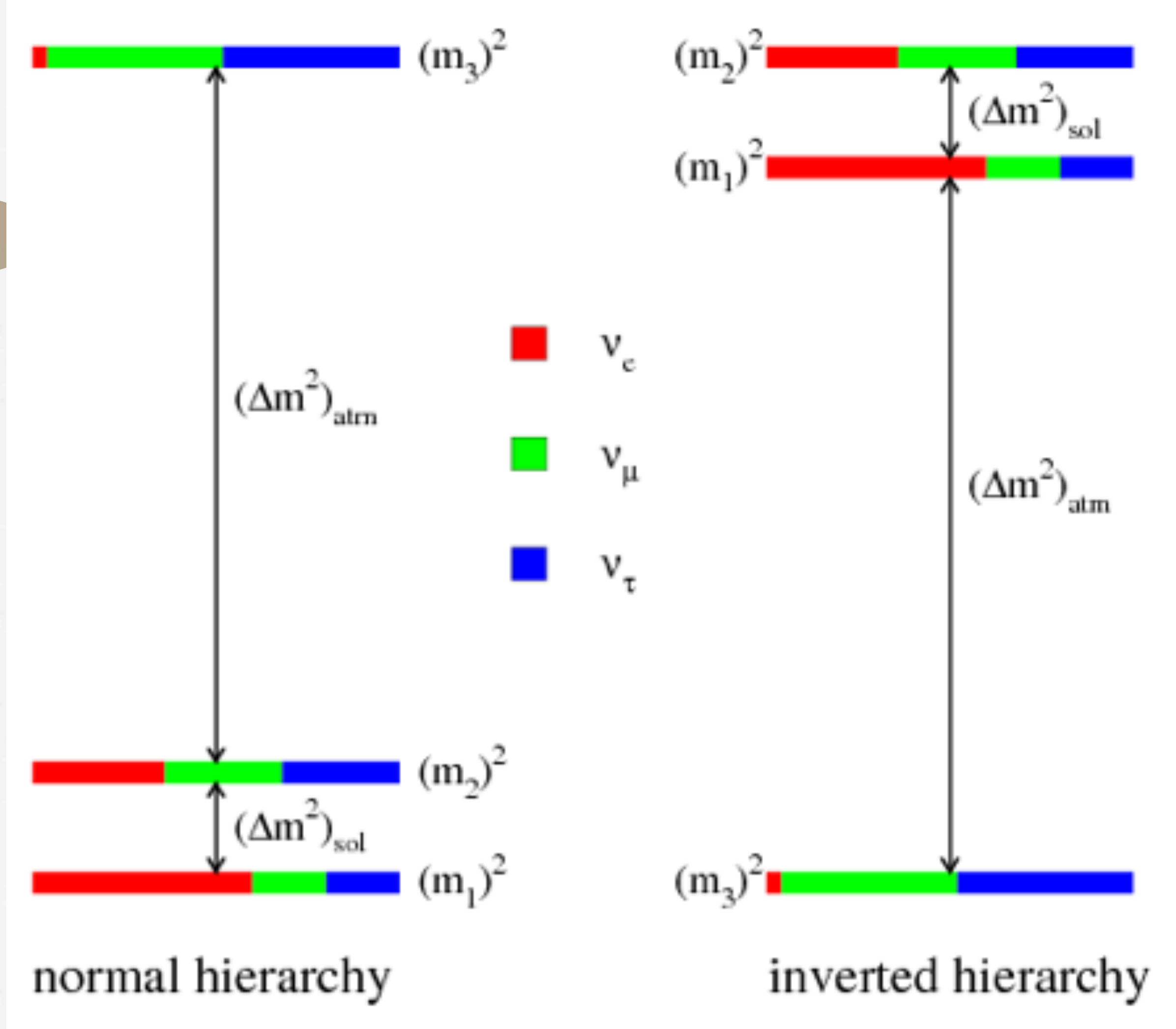
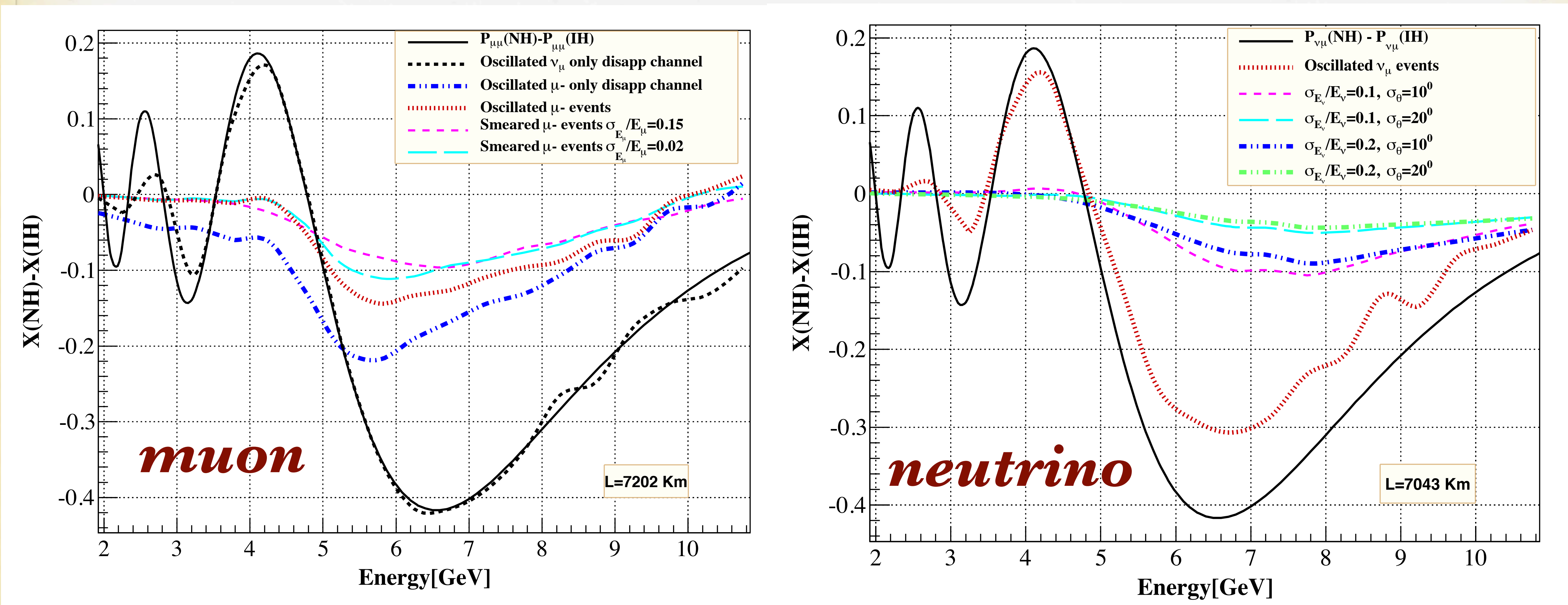


NEUTRINO MASS HIERARCHY

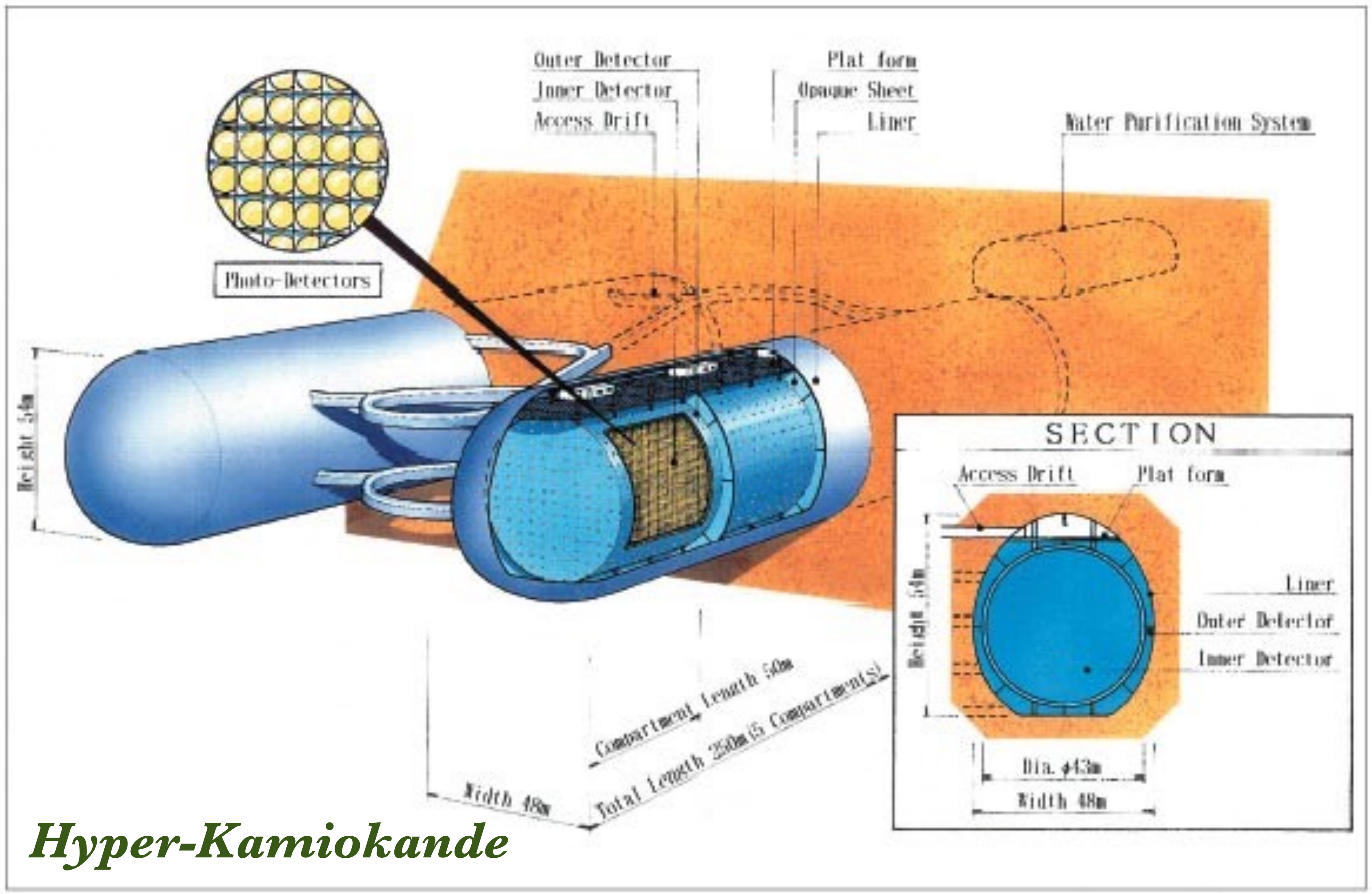


S.C.,Ghosh, 1306.1423

- *Smearing due to the ν-n cross-section*
- *Smearing due to presence of both ν_μ and ν_e in the atm flux*
- *Smearing due to finite detector resolution*

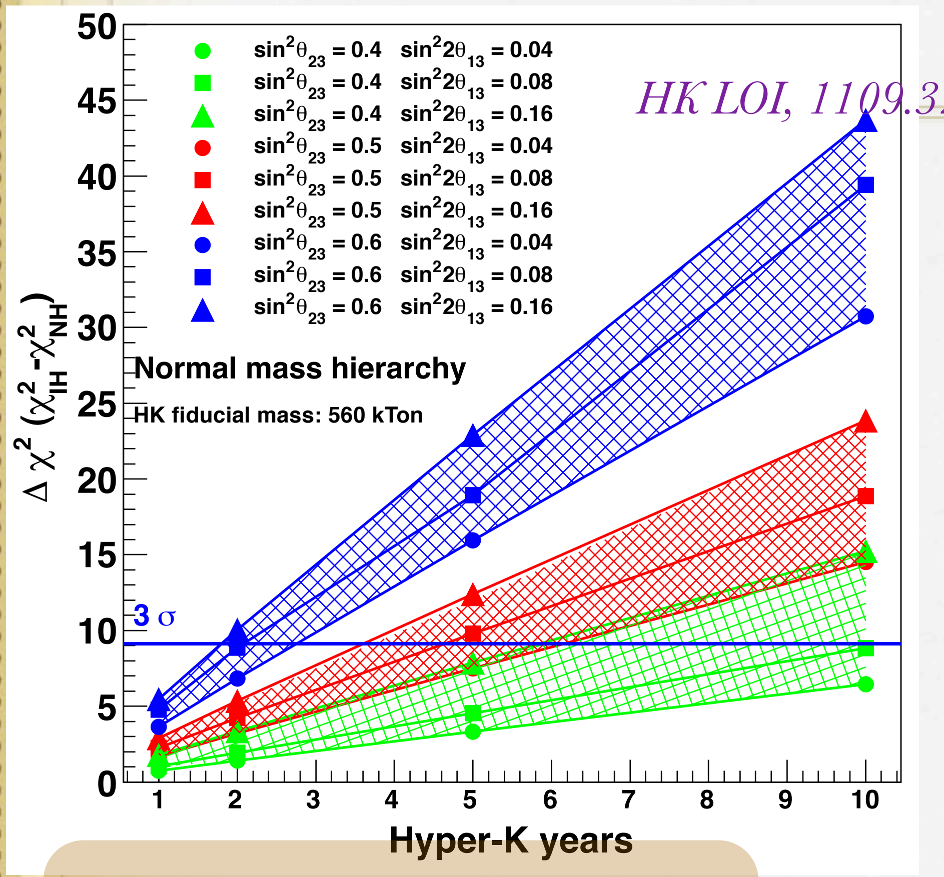
FUTURE ATMOSPHERIC NEUTRINO EXPERIMENTS

Megaton-class Water Cerenkov Detectors



- Good zenith angle resoln
- e vs mu discrimination
- low E threshold
- statistical separation of nue vs anti-nue
- large statistics

NEUTRINO MASS HIERARCHY

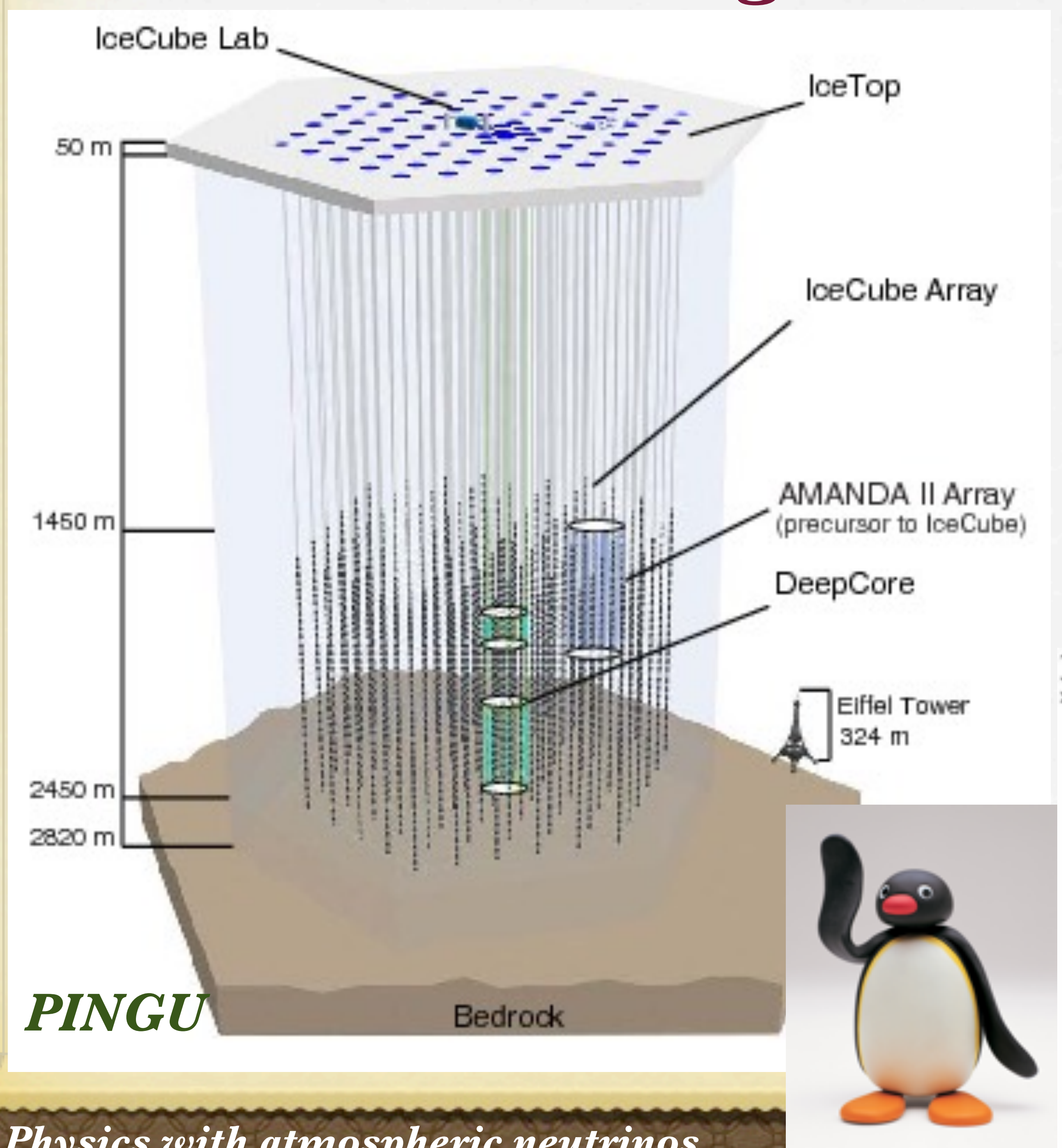


HK LOI, 1109.3262

3σ sensitivity in less than 5 yrs

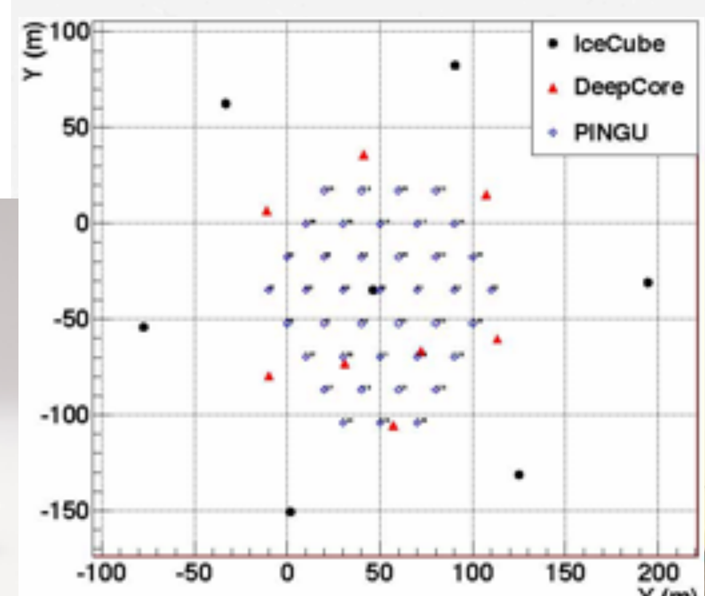
FUTURE ATMOSPHERIC NEUTRINO EXPERIMENTS

Multi-megaton Ice/Water Detectors

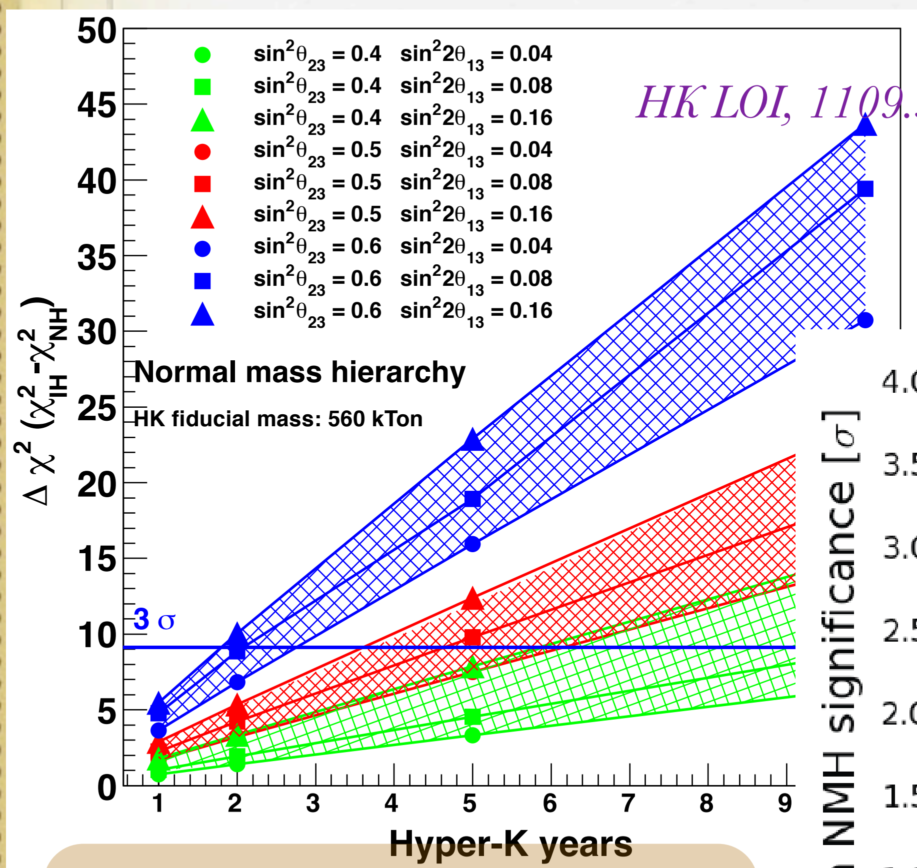


PINGU

- *e vs mu discrimination*
- *very large statistics*



NEUTRINO MASS HIERARCHY



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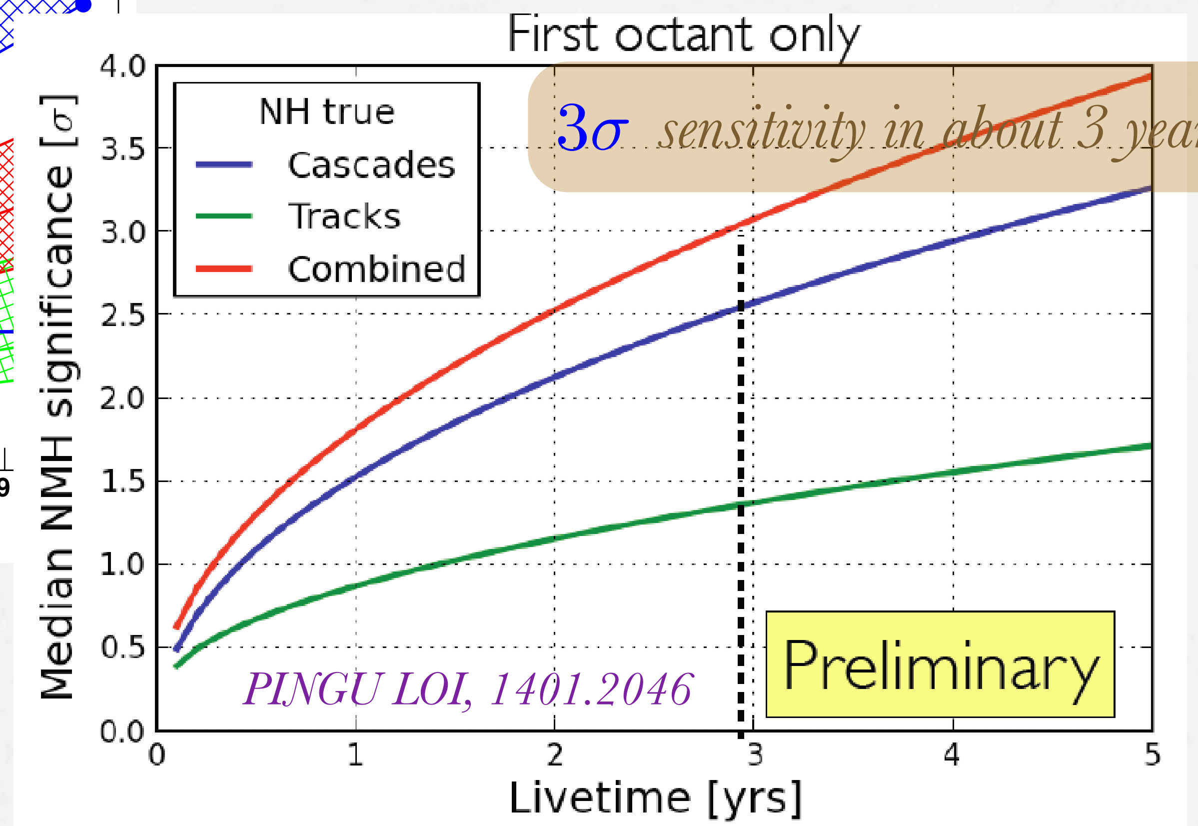
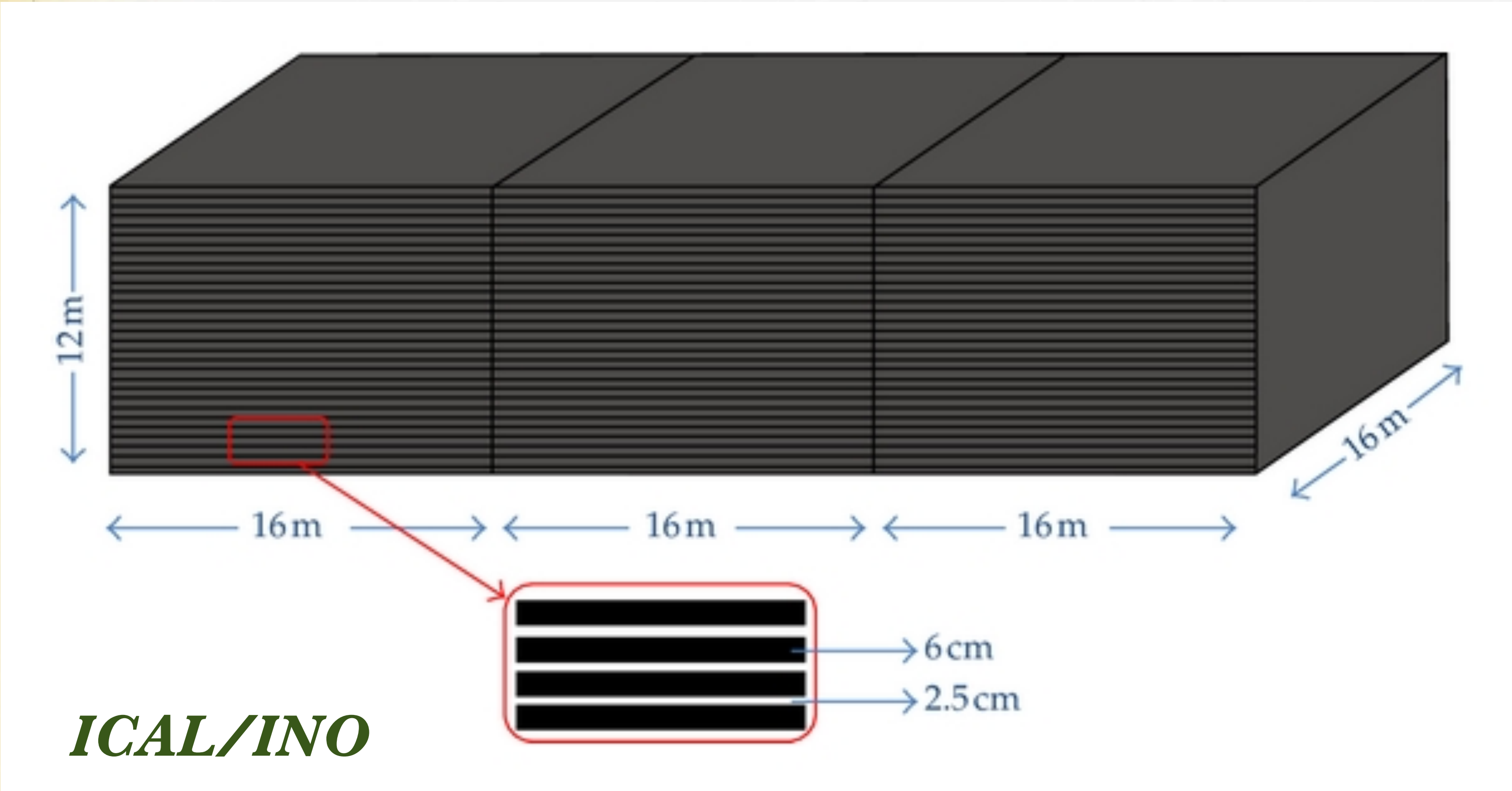


PINGU LOI, 1401.2046

3σ sensitivity in about 3 years

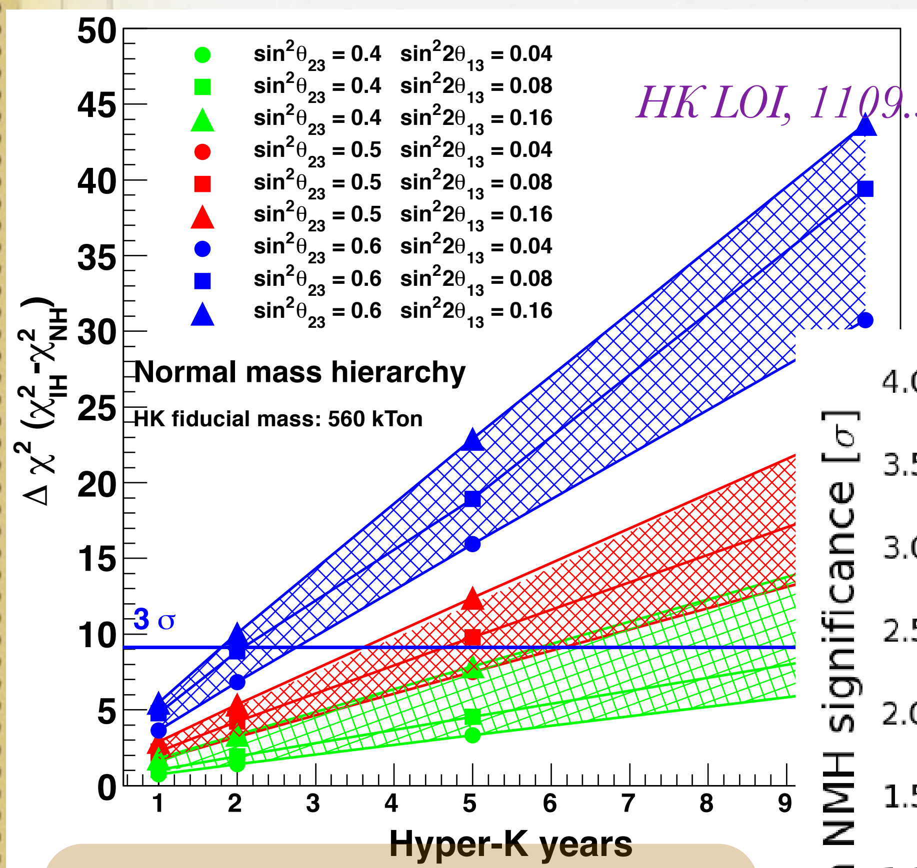
FUTURE ATMOSPHERIC NEUTRINO EXPERIMENTS

Large Magnetized Iron Detectors



- Good E and θ resoln
- 99% charge-id
- good statistics

NEUTRINO MASS HIERARCHY



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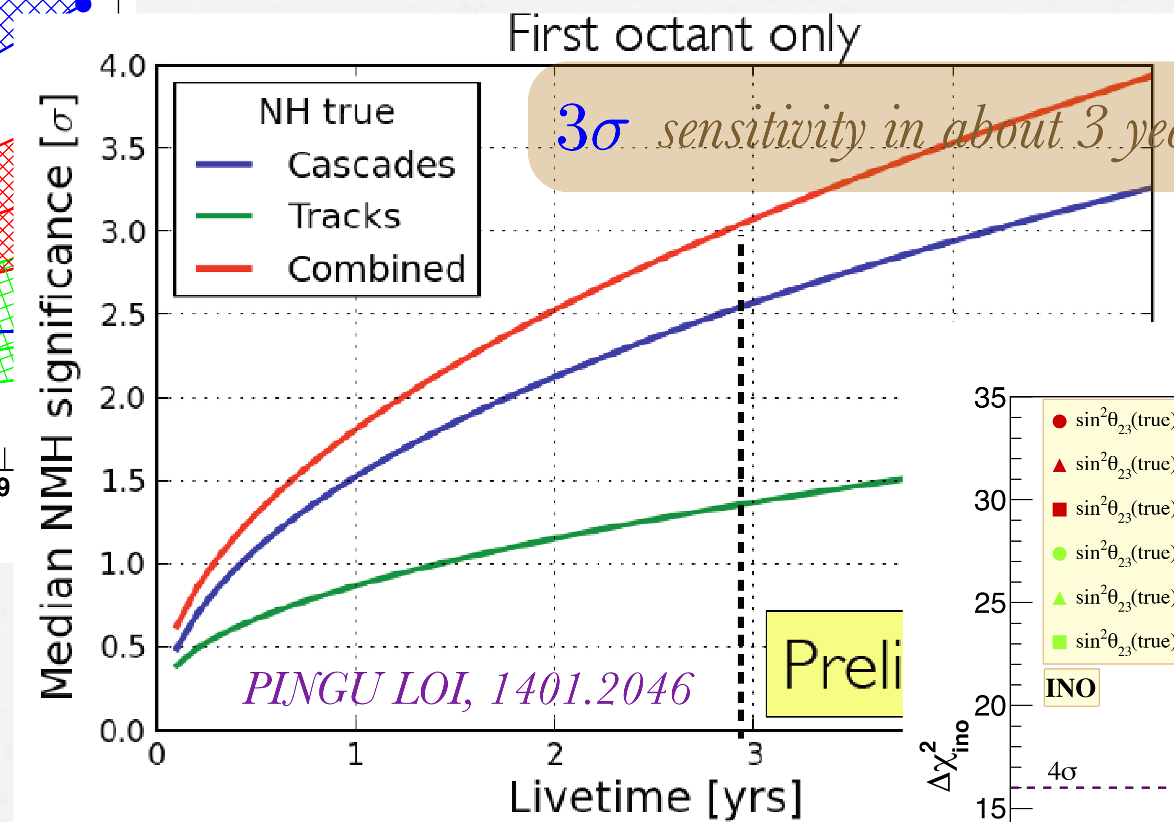

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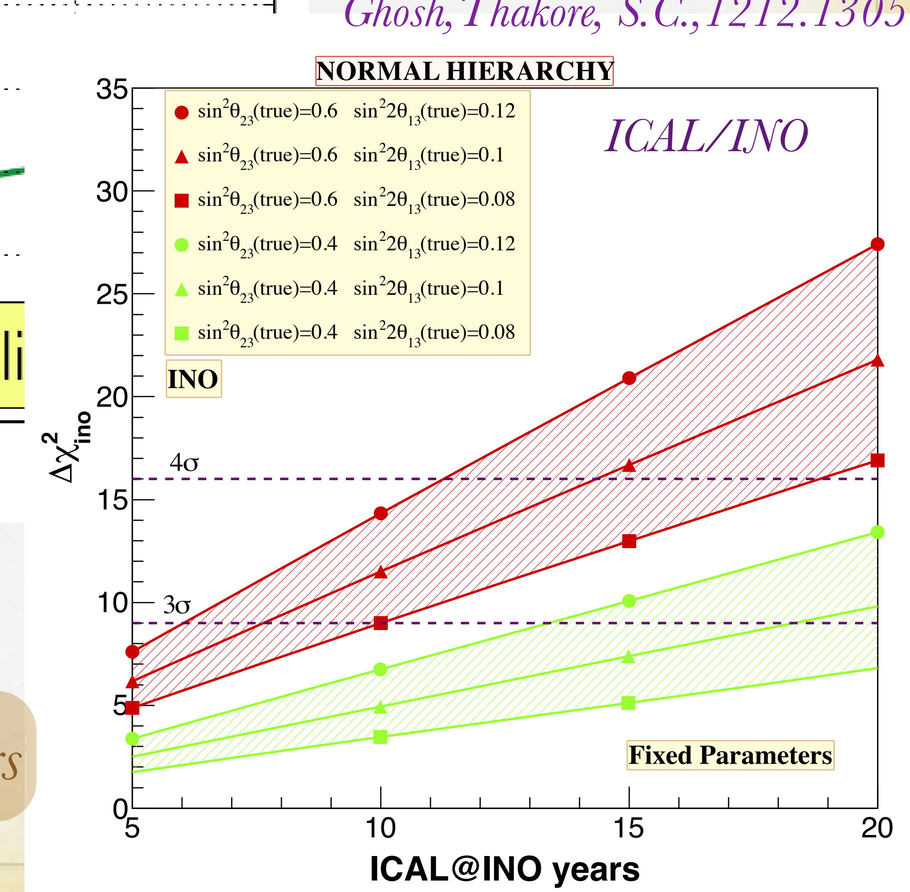
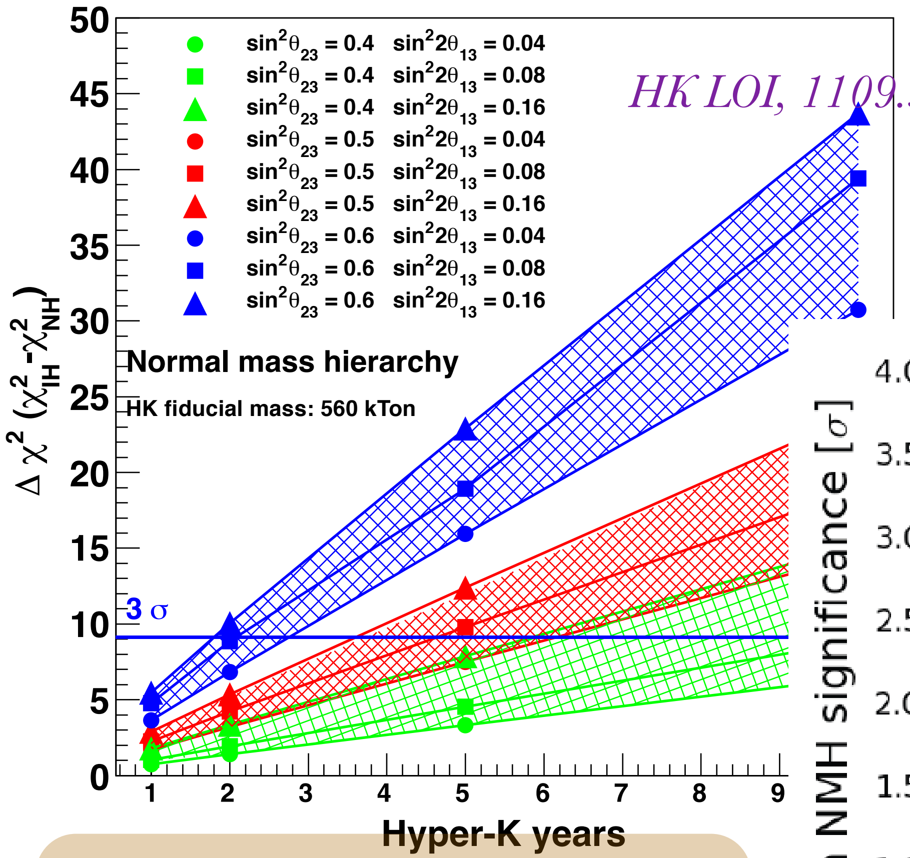
PINGU LOI, 1401.2046

Ghosh, Thakore, S.C., 1212.1305



2.7σ sensitivity in about 10 yrs

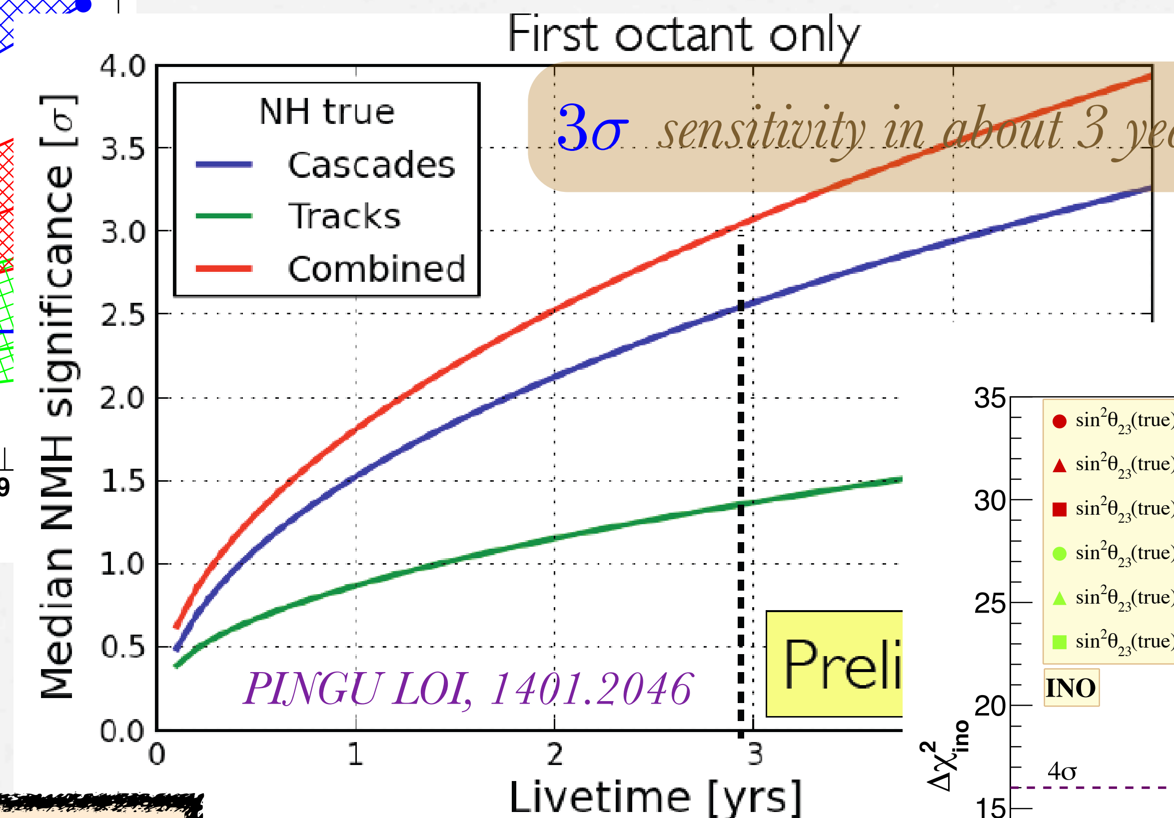
NEUTRINO MASS HIERARCHY



HK LOI, 1109.3262

Little dependence on deltacp

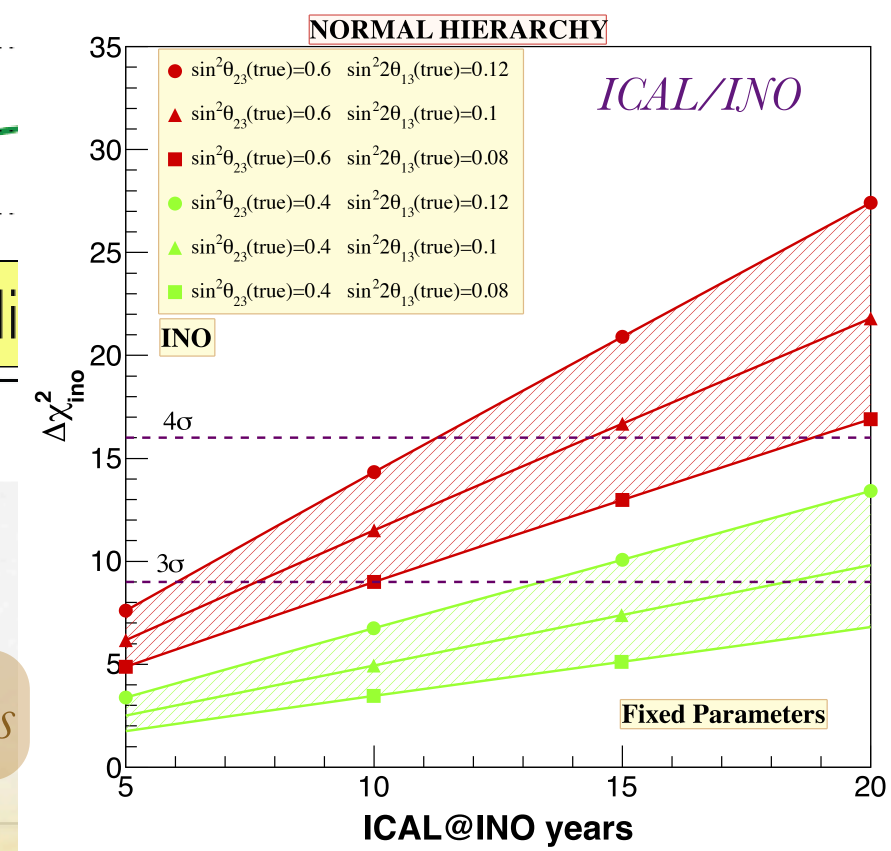
3σ *sensitivity in less than 5 yrs*



3σ *sensitivity in about 3 years*

PINGU LOI, 1401.2046

Ghosh, Thakore, S.C., 1212.1305

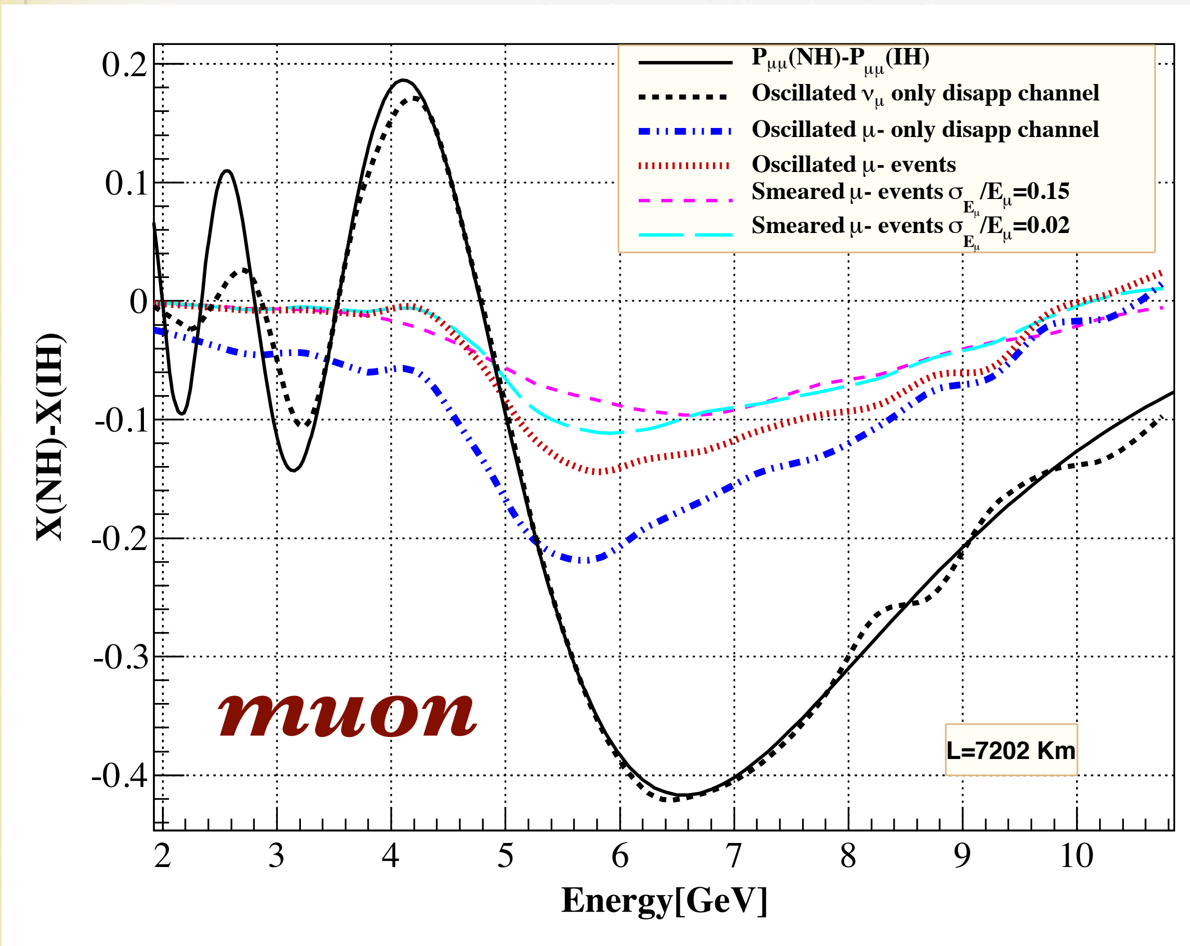


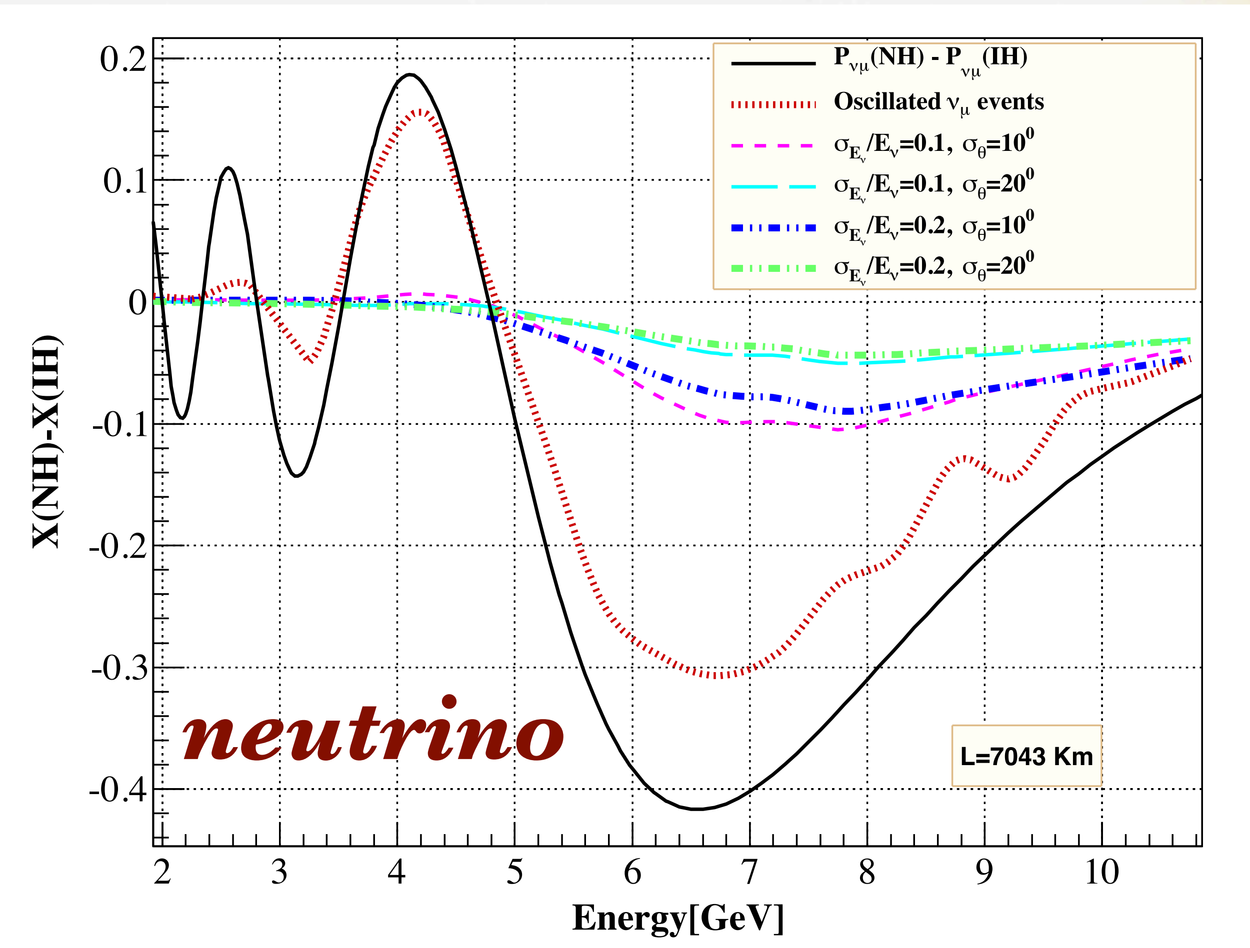
Results for IH for both HK and Pingu are worse...
But for INO, its still good

2.7σ *sensitivity in about 10 yrs*

Monday, 10 November 14

NEUTRINO MASS HIERARCHY





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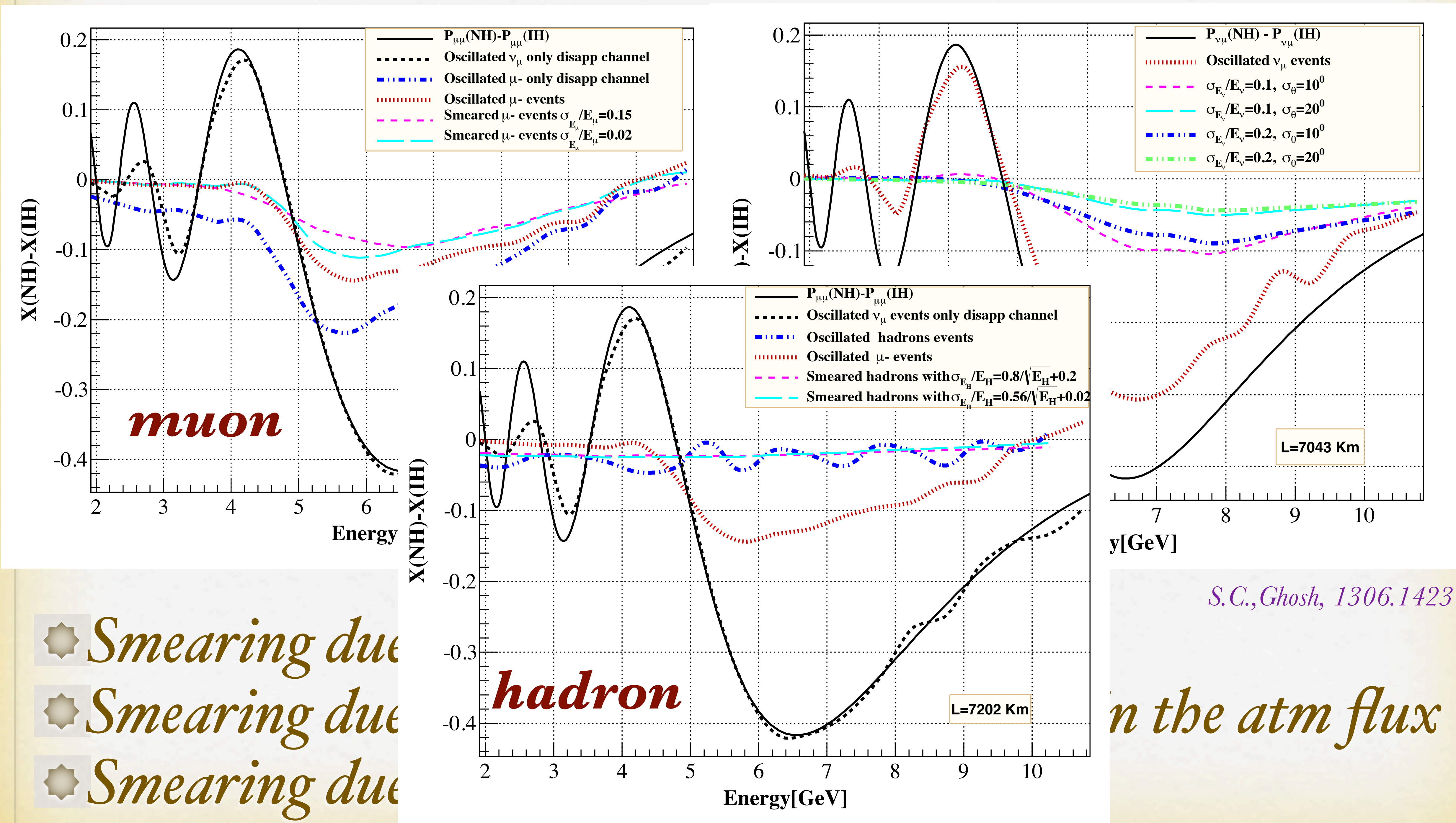
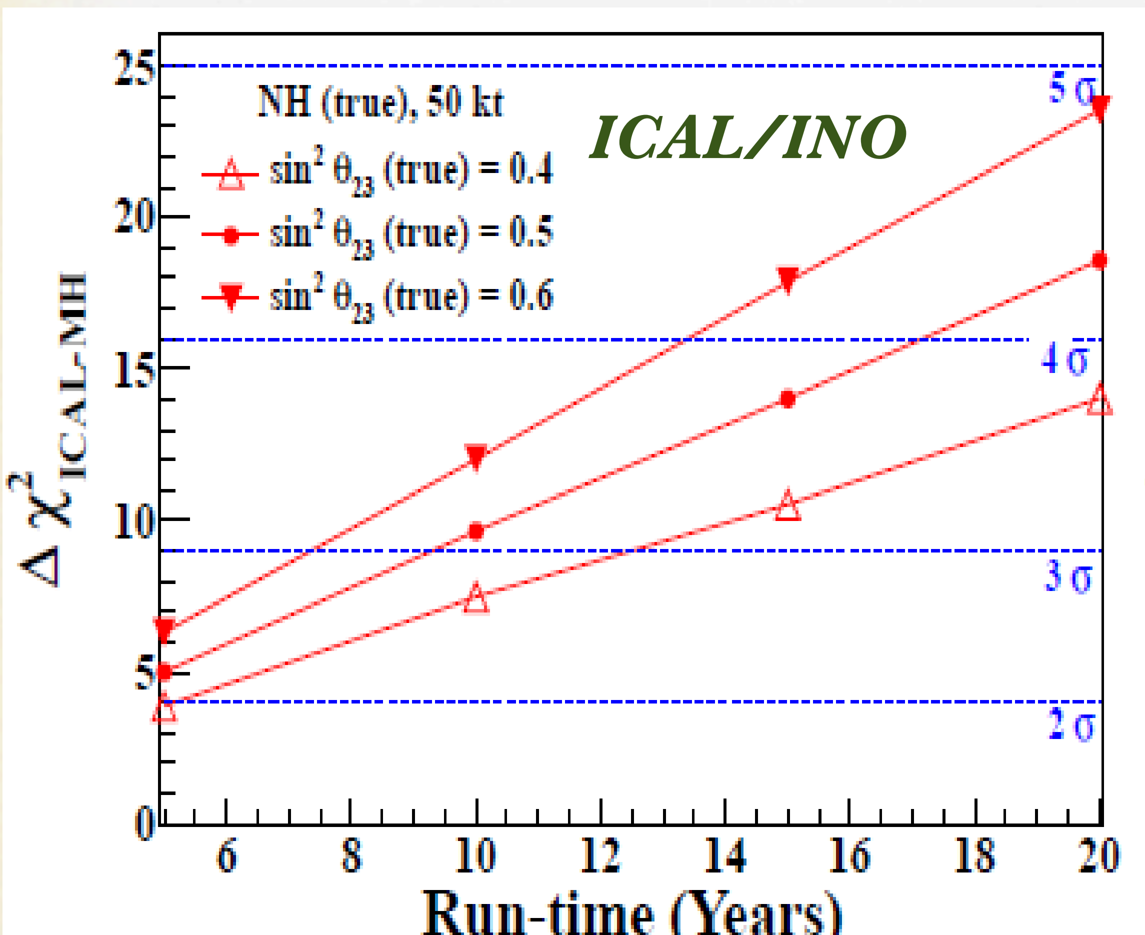


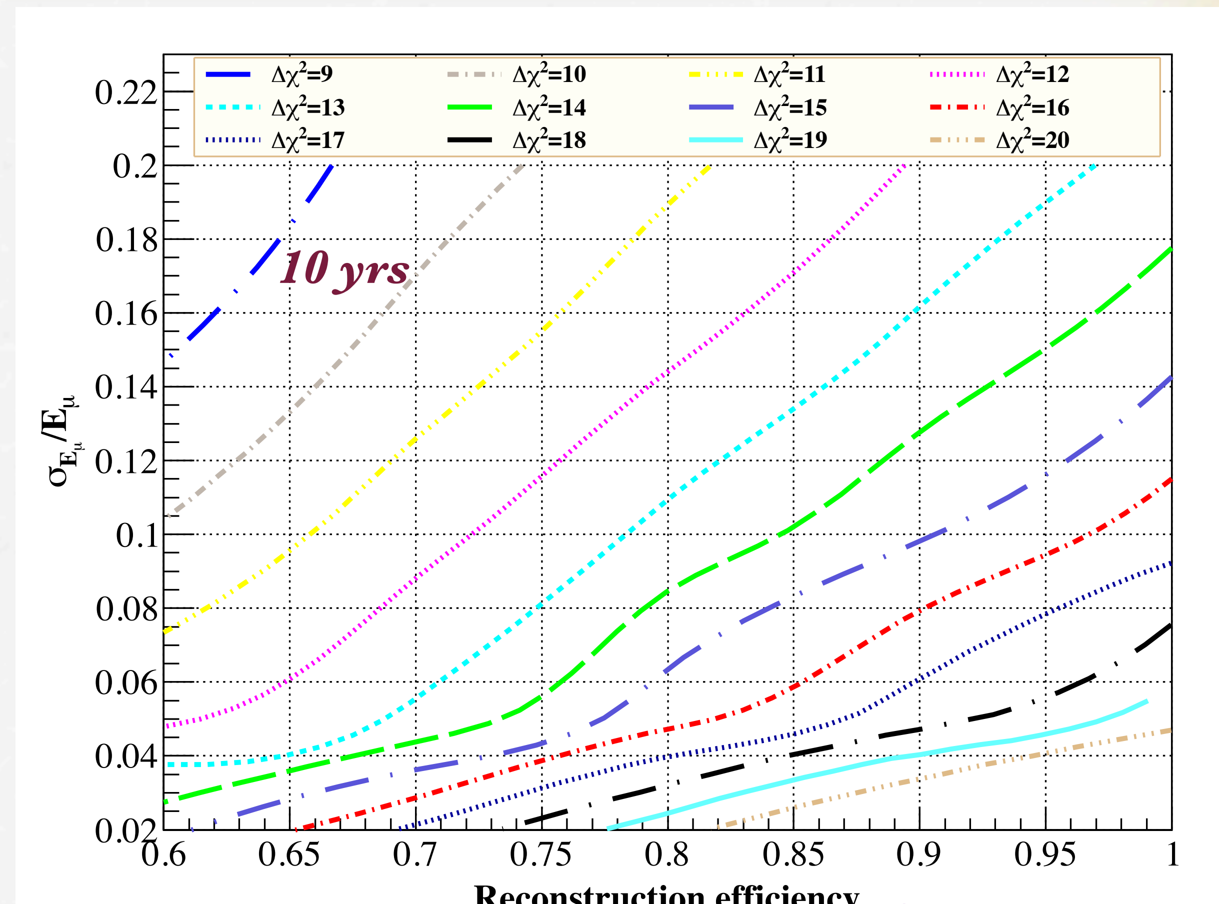
S.C.,Ghosh, 1306.1423

- Smearing due
- Smearing due ... n the atm flux
- Smearing due

NEUTRINO MASS HIERARCHY



Devi,Thakore,Agarwalla,Dighe,1406.3689



S.C.,Ghosh, 1306.1423

3σ *sensitivity in about 10 yrs*

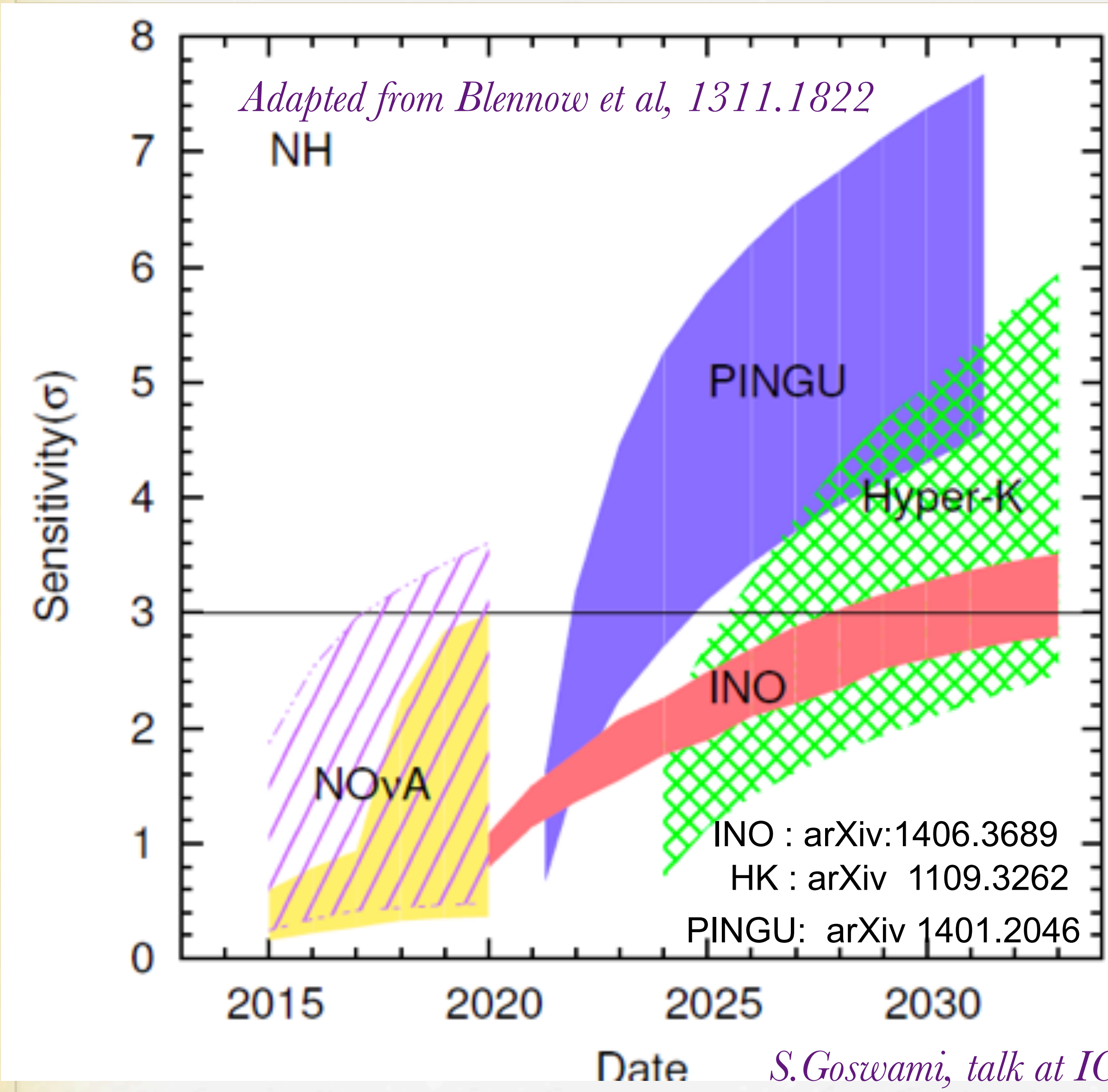
Sensitivity can increase if the muon energy resolution can be improved

40% improvement compared to only muon analysis

PINGU → *Ribordy, Smirnov, 1303.0758*

Include inelasticity y, increase sensitivity by 20-50%

NEUTRINO MASS HIERARCHY



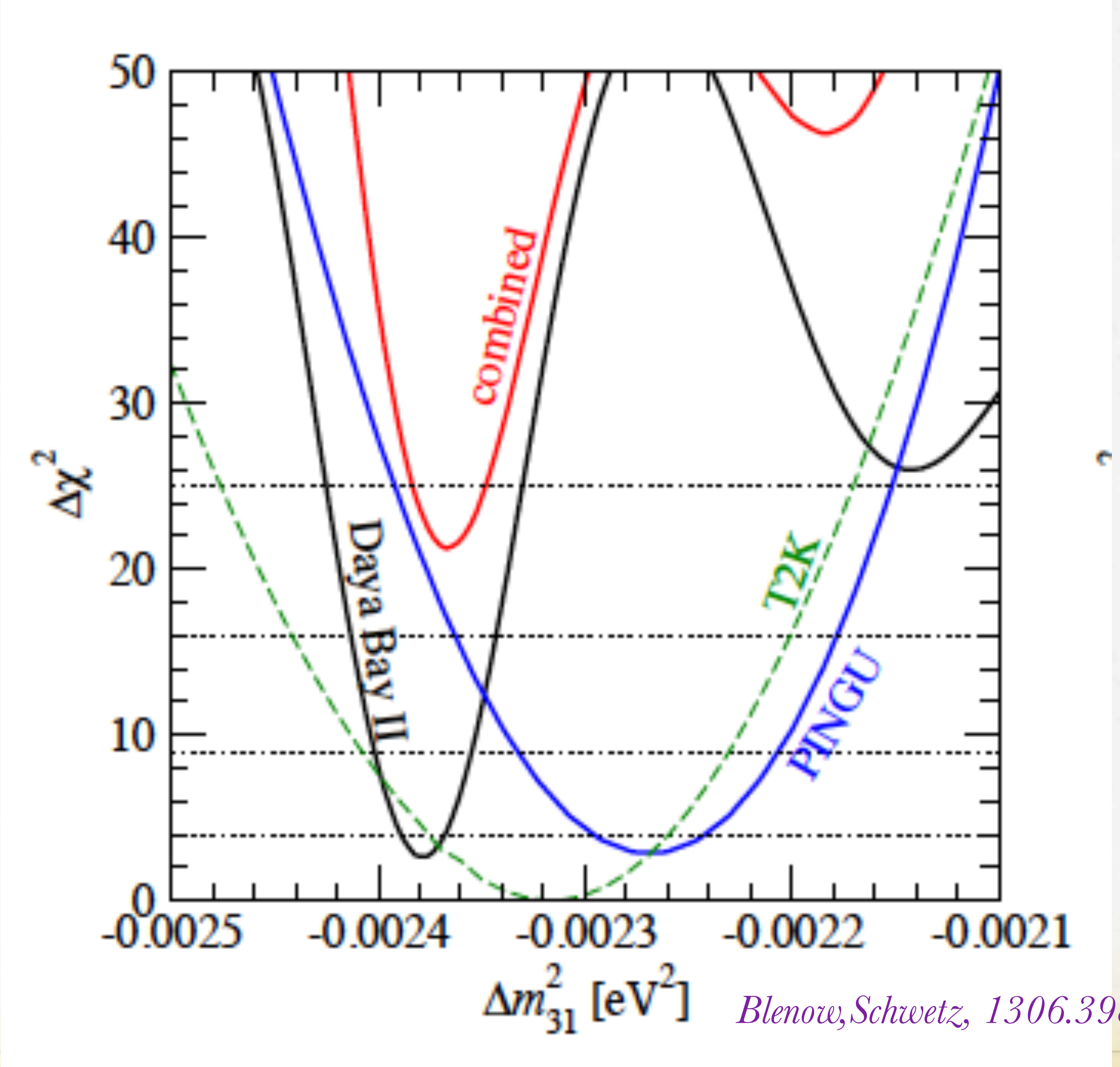
S.Goswami, talk at ICHEP 2014

For favorable δ_{CP} values, early hints expected from NOvA

For unfavorable δ_{CP} values, early hints expected from atmospheric expts

MH: SYNERGY WITH OTHER EXPTS

Synergy between PINGU and JUNO

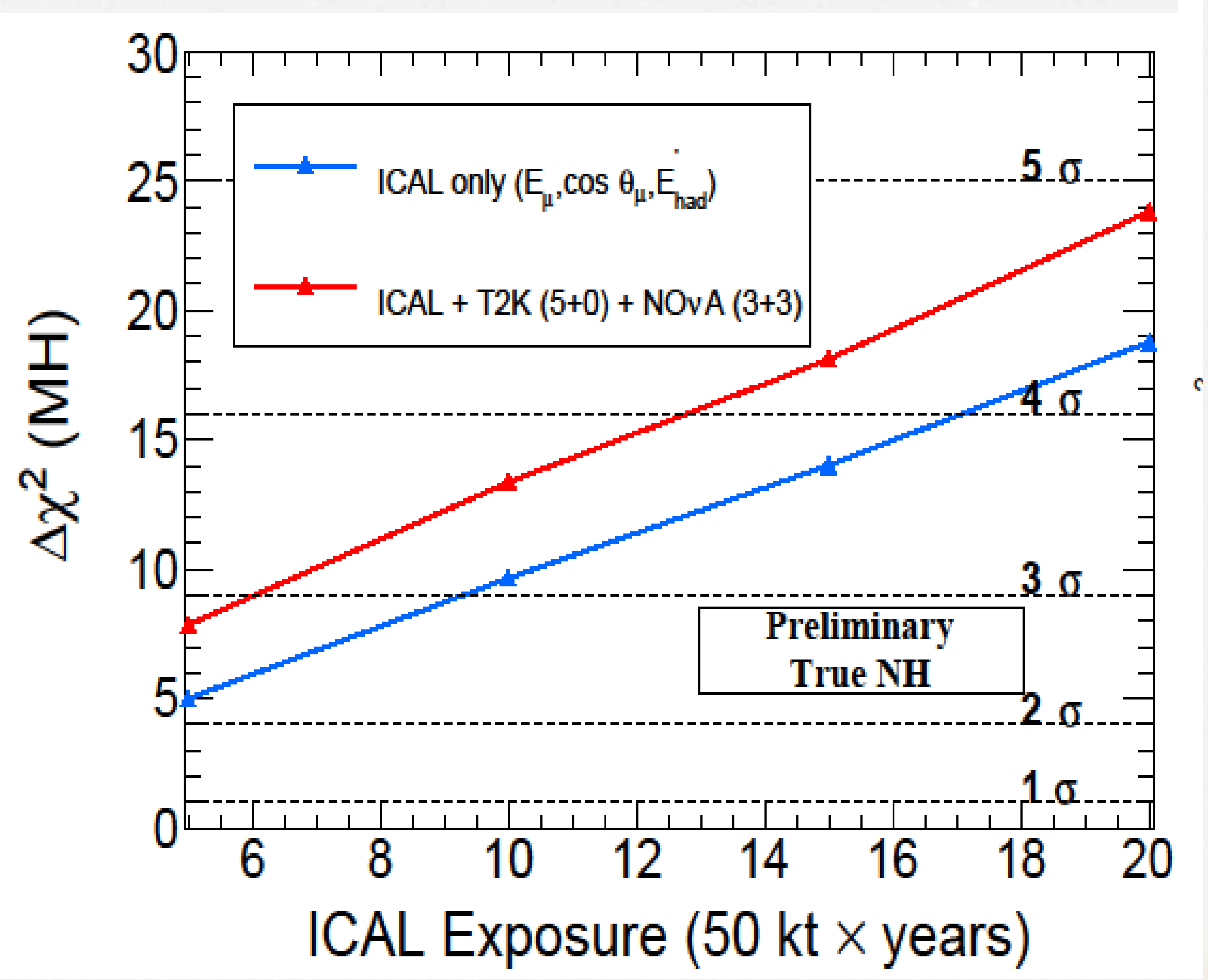


Blenow,Schwetz, 1306.3988

Monday, 10 November 14

MH: SYNERGY WITH OTHER EXPTS

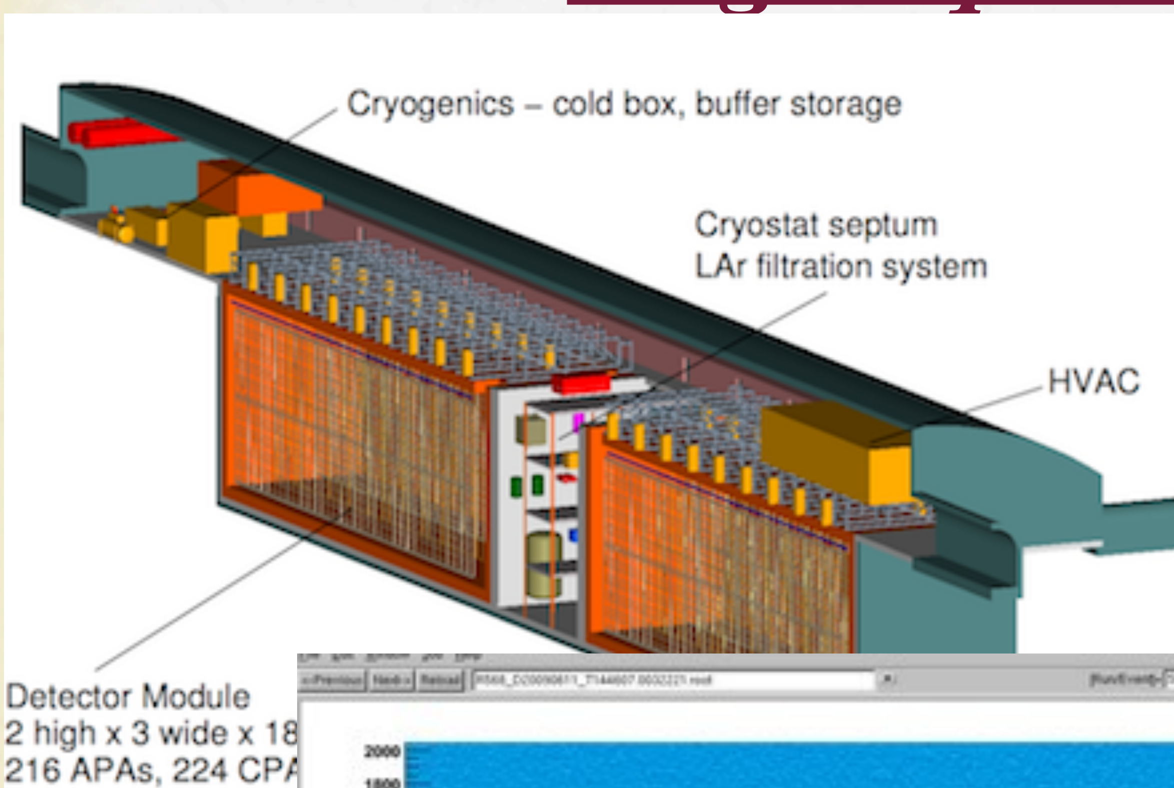
Combined sensitivity of INO with T2K and NOvA

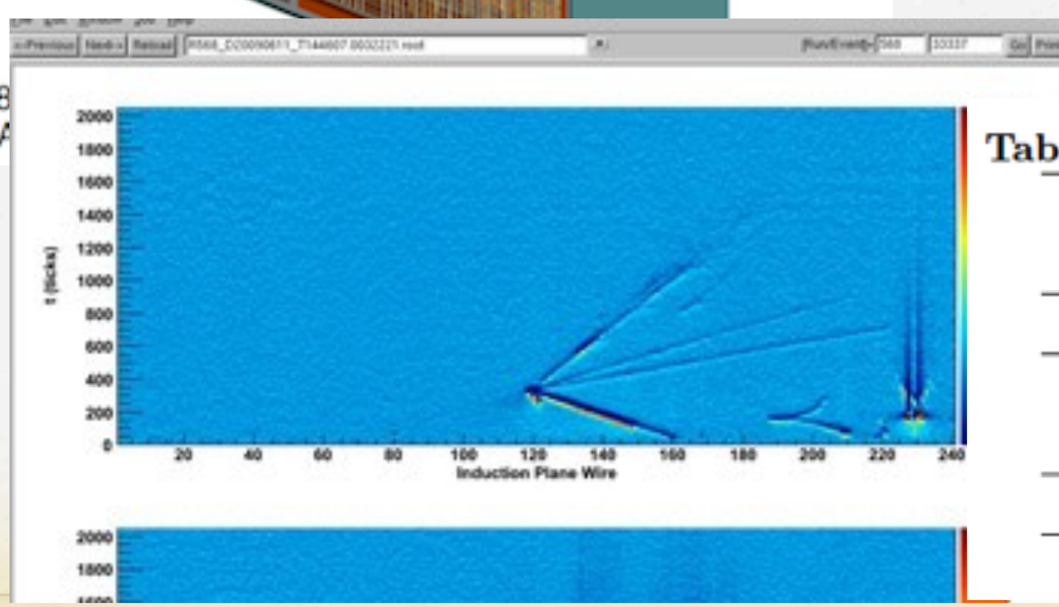


Devi, Thakore, Agarwalla, Dighe, in preparation

FUTURE ATMOSPHERIC NEUTRINO EXPERIMENTS

Large Liquid Argon Detectors



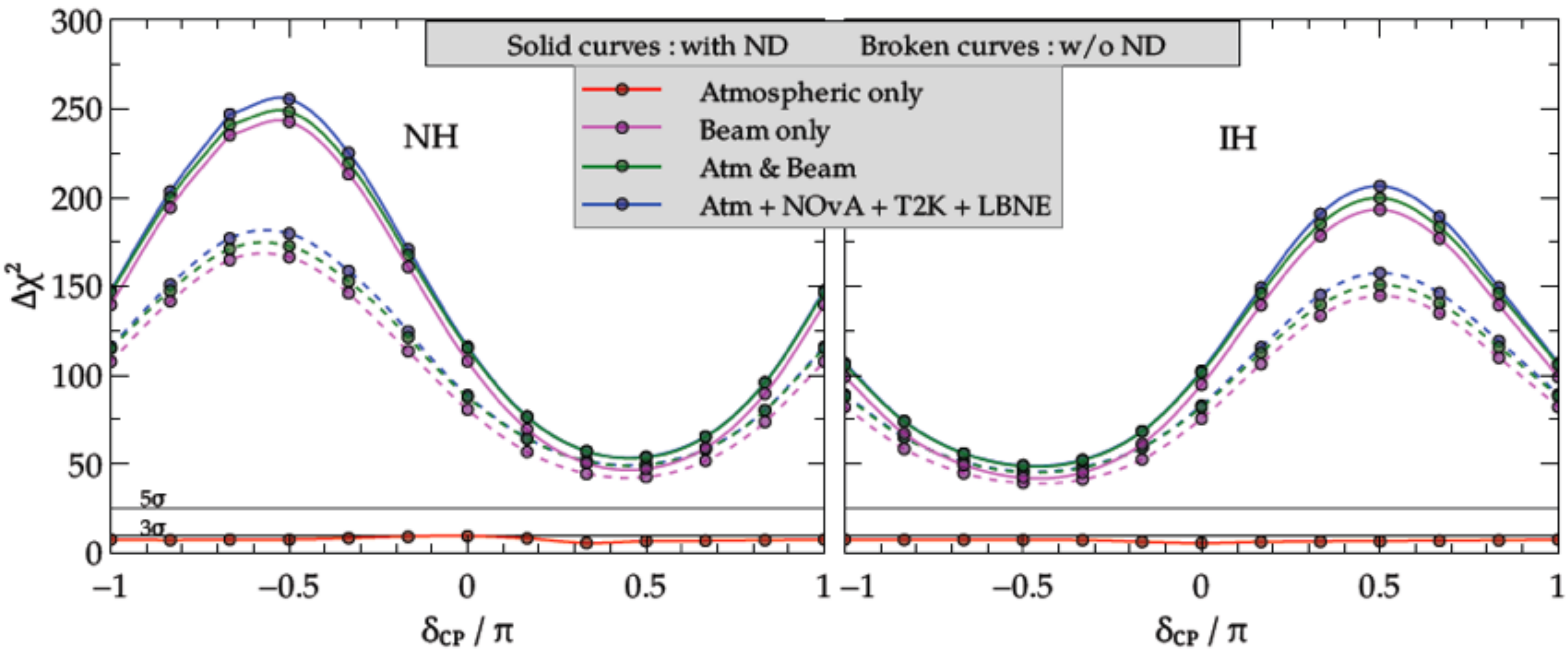


- *Very good E and θ resoln*
- *e vs mu discrimination*
- *low E threshold*

Table 4. Detector parameters used for the analysis of atmospheric neutrino

Rapidity (y)	0.45 for ν 0.30 for $\bar{\nu}$
Energy Resolution (ΔE)	$\sqrt{(0.01)^2 + (0.15)^2/(yE_\nu) + (0.03)^2}$
Angular Resolution ($\Delta\theta$)	3.2° for ν_μ 2.8° for ν_e
Detector efficiency ($\mathcal{E}$)	85%

MH: SYNERGY WITH OTHER EXPTS



Barger et al, 1405.1054

Figure 1. Sensitivity to the mass hierarchy as a function of true δ_{CP} for a true normal hierarchy (NH) and a true inverted hierarchy (IH) with an 350 kt-yr exposure at the unmagnetized far detector configured with and without a near detector (ND). A run-time of 5 years each (3×10^{21} protons on target) with a ν and $\bar{\nu}$ beam is assumed. The combined sensitivity with NOνA (15 kt TASD, 3 yrs. ν + 3 yrs. $\bar{\nu}$) and T2K (22.5 kt water cerenkov, 5 yrs. ν) data is also shown.

ATMOSPHERIC NEUTRINO OSCILLATIONS

$$\lim_{\Delta m^2_{21} \to 0} P_{\mu\mu}(L,E) = 1 - P^1_{\mu\mu}(L,E) - P^2_{\mu\mu}(L,E) - P^3_{\mu\mu}(L,E)$$

$$P^1_{\mu\mu}(L,E) = \sin^2\theta^m_{13}\sin^2 2\theta_{23}\sin^2\frac{(A+\Delta m^2_{31}) - (\Delta m^2_{31})^m}{8E}L$$

$$P^2_{\mu\mu}(L,E) = \cos^2\theta^m_{13}\sin^2 2\theta_{23}\sin^2\frac{(A+\Delta m^2_{31}) + (\Delta m^2_{31})^m}{8E}L$$

$$P^3_{\mu\mu}(L,E) = \sin^2 2\theta^m_{13}\sin^4\theta_{23}\sin^2\frac{(\Delta m^2_{31})^m}{4E}L$$

octant sensitivity

S.C., Roy, 2005

ATMOSPHERIC MUON NEUTRINO OSCILLATIONS

$$\lim_{\Delta m^2_{21} \to 0} P_{\mu\mu}(L,E) = 1 - P^1_{\mu\mu}(L,E) - P^2_{\mu\mu}(L,E) - P^3_{\mu\mu}(L,E)$$

$$P^1_{\mu\mu}(L,E) = \sin^2\theta^m_{13}\sin^2 2\theta_{23}\sin^2\frac{(A+\Delta m^2_{31}) - (\Delta m^2_{31})^m}{8E}L$$

$$P^2_{\mu\mu}(L,E) = \cos^2\theta^m_{13}\sin^2 2\theta_{23}\sin^2\frac{(A+\Delta m^2_{31}) + (\Delta m^2_{31})^m}{8E}L$$

$$P^3_{\mu\mu}(L,E) = \sin^2 2\theta^m_{13}\sin^4\theta_{23}\sin^2\frac{(\Delta m^2_{31})^m}{4E}L$$

Contribution from the muon nu flux

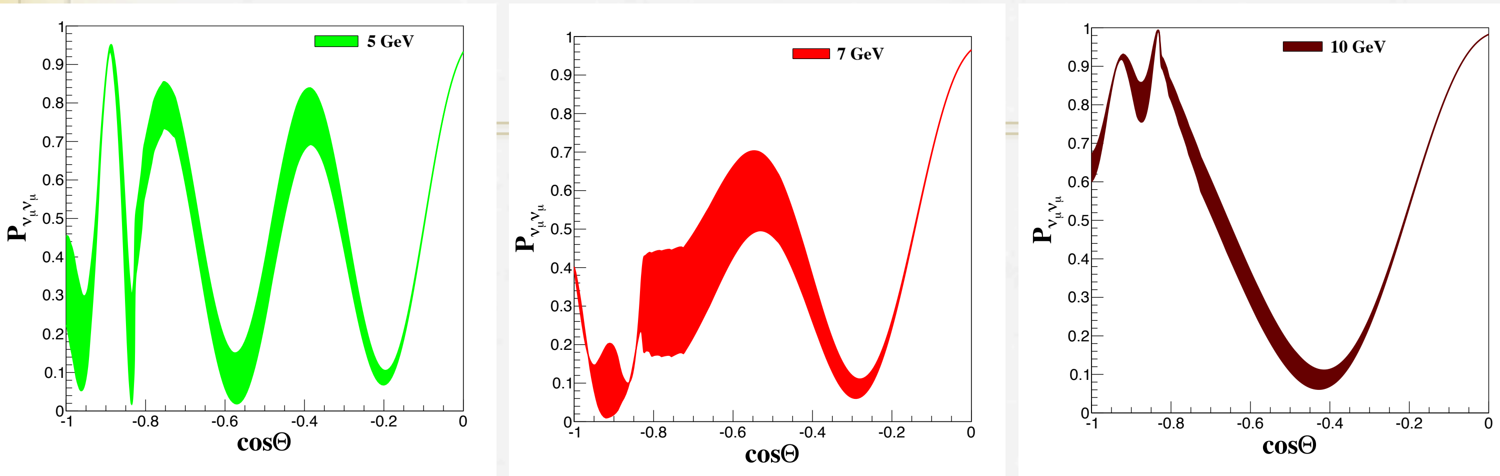
$$\lim_{\Delta m^2_{21} \to 0} P_{\mu e}(L,E) = \sin^2\theta_{23}\sin^2 2\theta^m_{13}\sin^2\frac{(\Delta m^2_{31})^m L}{4E}$$

Contribution from the e nu flux

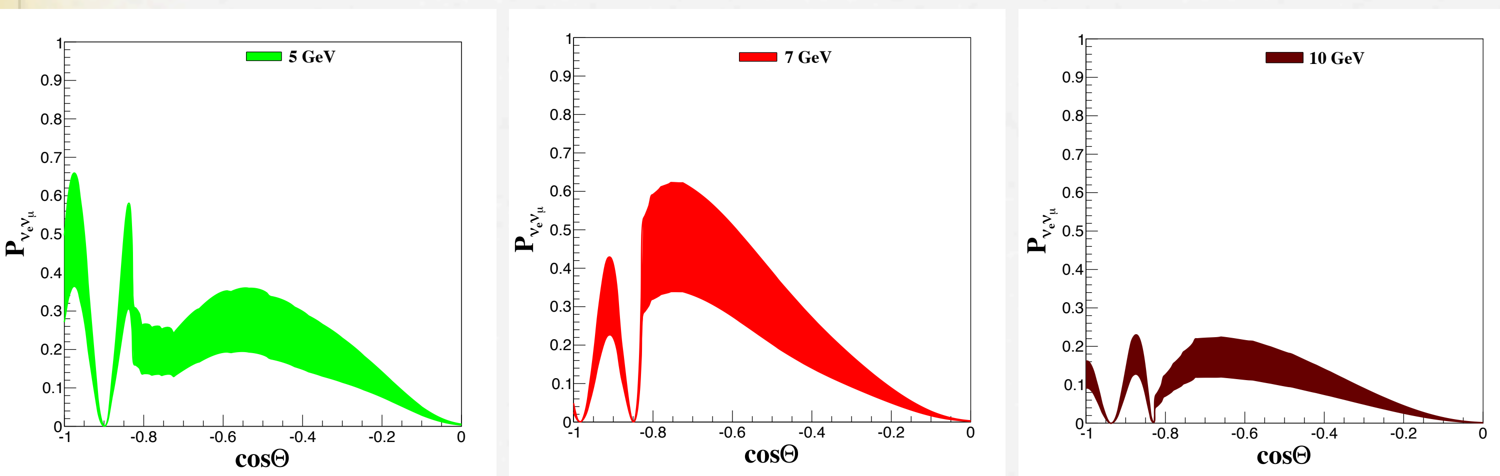
$$\Phi_\mu(detector) = \Phi^0_\mu(P_{\mu\mu} + (\Phi^0_e/\Phi^0_\mu)P_{e\mu}) = \Phi^0_\mu(1 - P^1_{\mu\mu} - P^2_{\mu\mu} - (\underbrace{\sin^2\theta_{23}}_{1/2} - \underbrace{\Phi^0_e/\Phi^0_\mu}_{1/2})P_{e\mu})$$

Earth matter effects in the two terms partially cancel each other

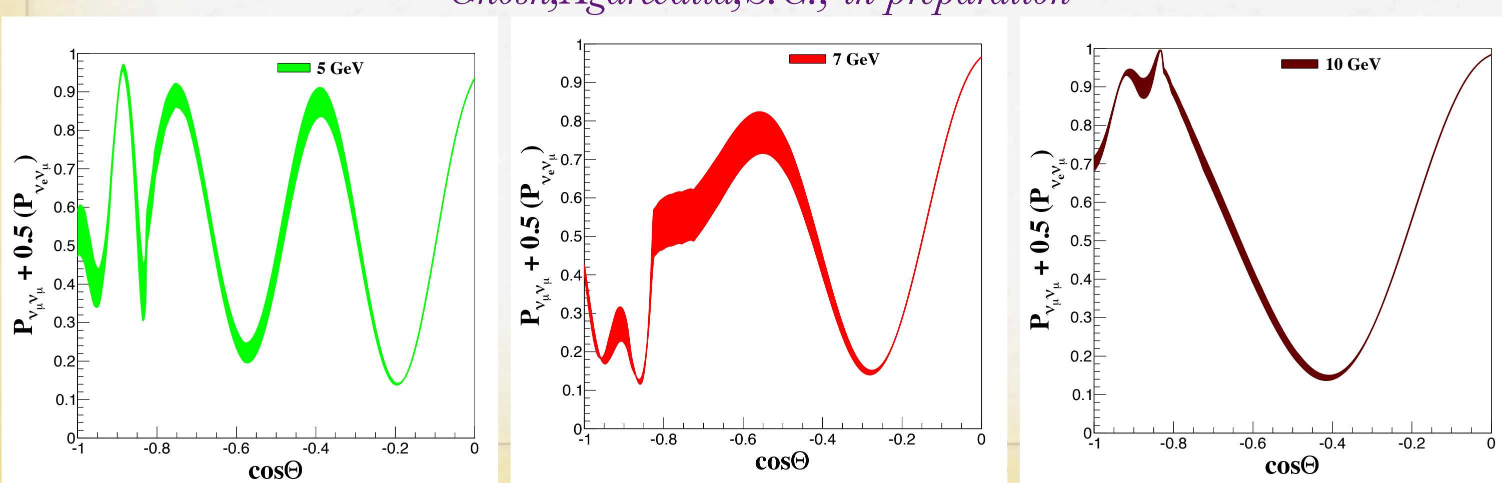
OCTANT OF THETA23

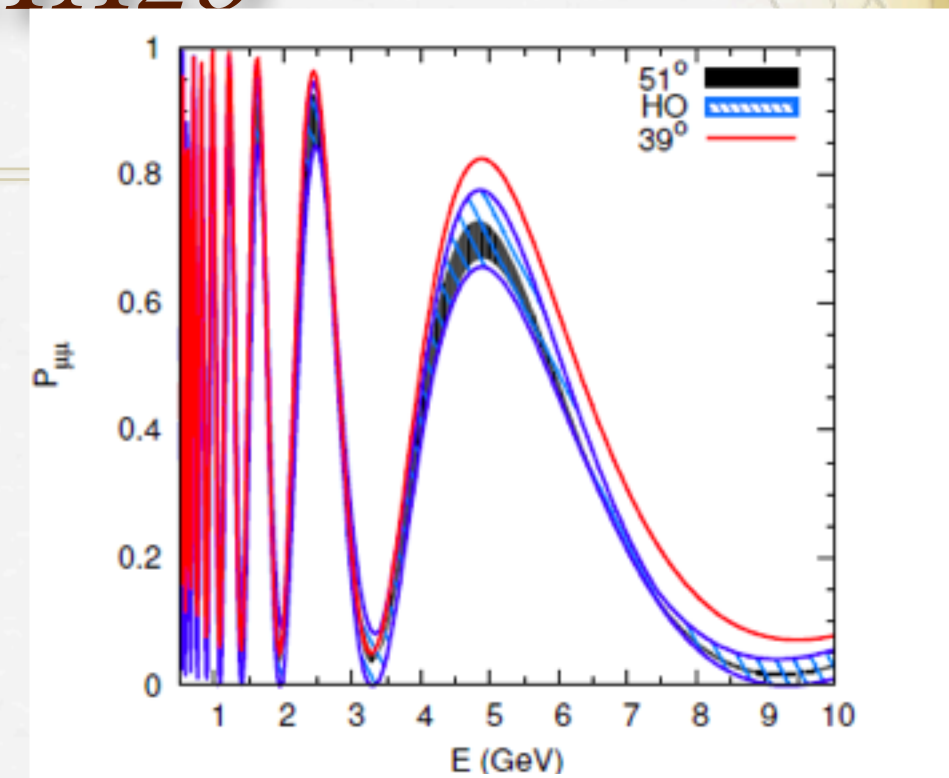


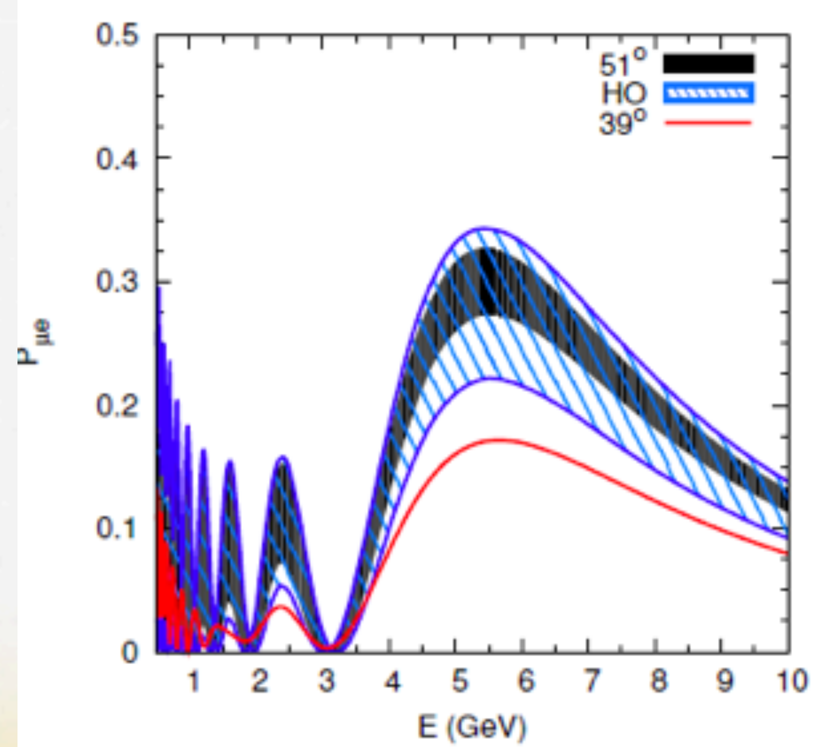
Varying $\sin^2\theta_{23}$ in the range [0.36-0.67]



Ghosh, Agarwalla, S.C., in preparation

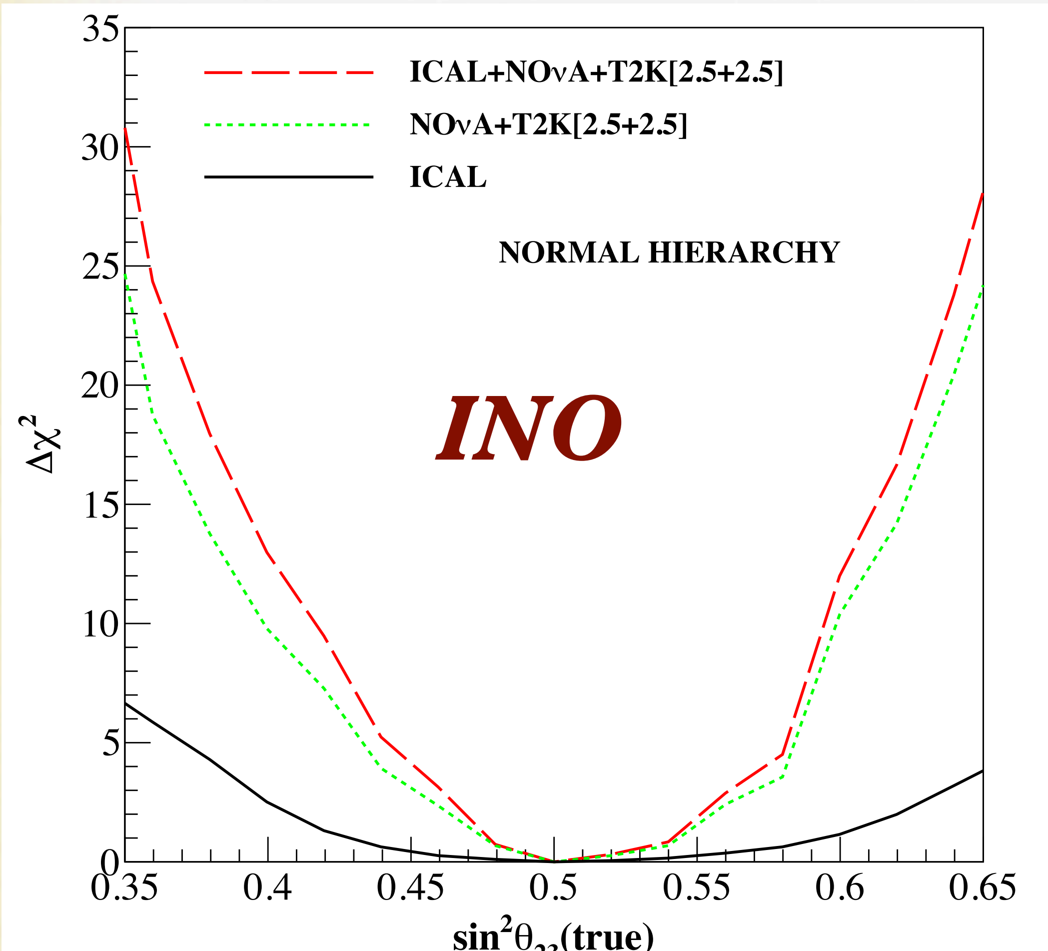




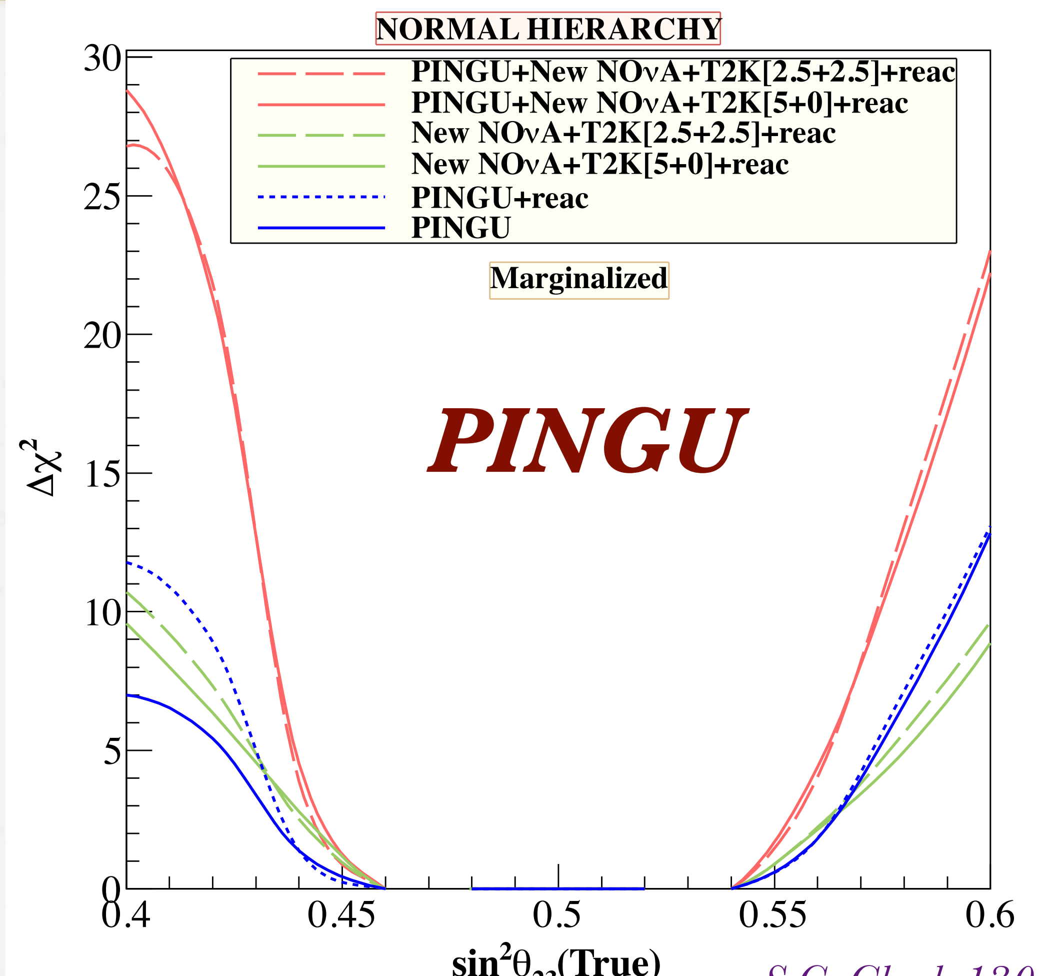


Chatterjee, Ghoshal, Goswami, Raut, 2013

OCTANT OF THETA23



Ghosh,Agarwalla,S.C., in preparation



S.C.,Ghosh,1309.5760

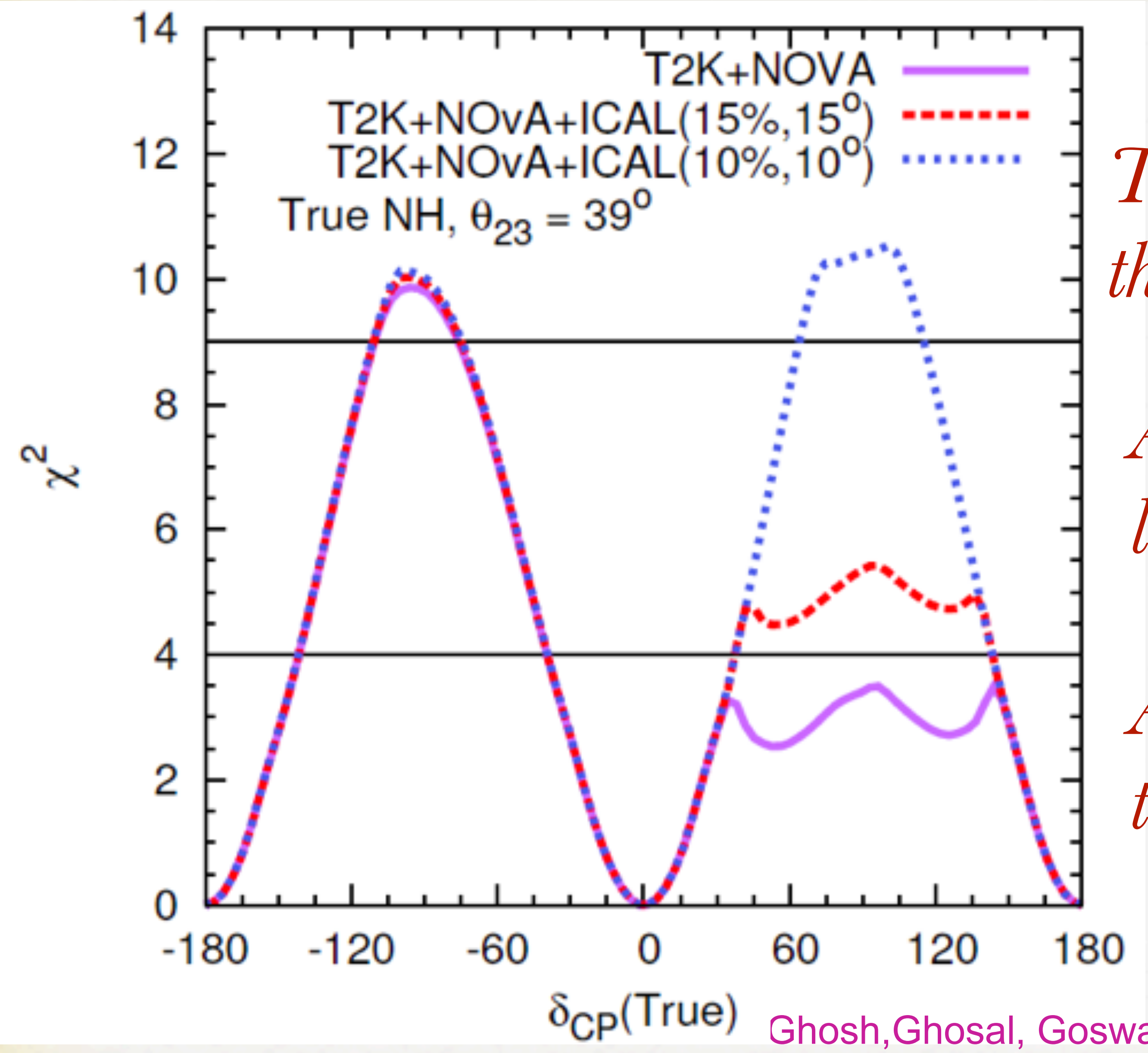
Mild sensitivity expected from INO over T2K and NOvA

Synergy

Pingu+T2K+NOvA can find the octant at 5sig for $\sin^2 th_{23}=0.4$

Synergy

ROLE IN CPV DISCOVERY



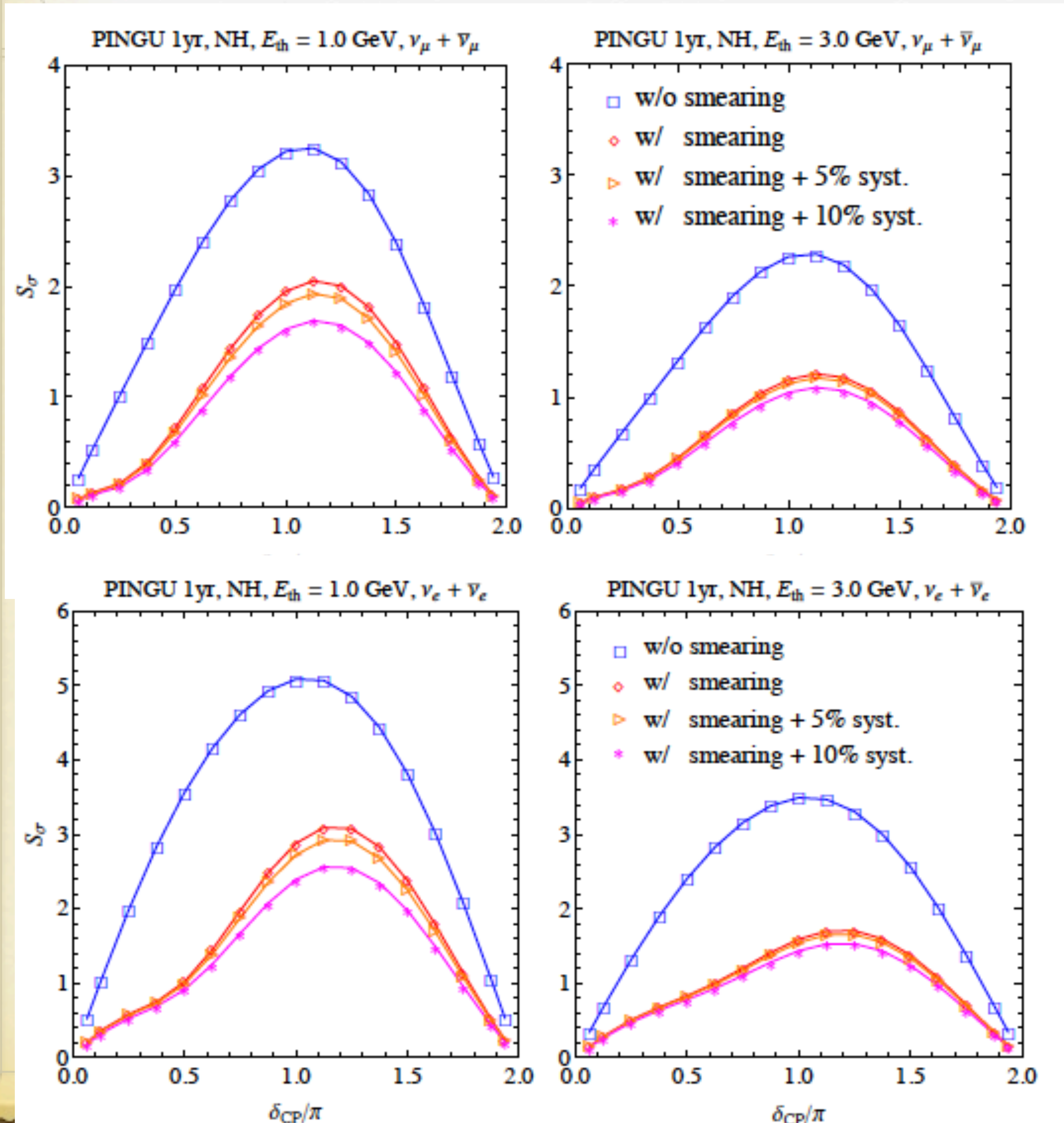
Ghosh,Ghosal, Goswami, Raut (2013)

The T2K+NOvA data suffer from the MH uncertainty

Adding the atm nu data helps in lifting this degeneracy

Adding the INO data can improve the CP coverage by up to 50%

ROLE IN CP DISCOVERY



$$S_{ij}(f) = \frac{N_{ij}^{\delta} - N_{ij}^{0}}{\sigma_{ij}},$$

$$\sigma_{ij}^2 = N_{ij}^0 + (f N_{ij}^0)^2,$$

Razzaque, Smirnov, 1406.1407

NON-STANDARD NEUTRINO INTERACTIONS

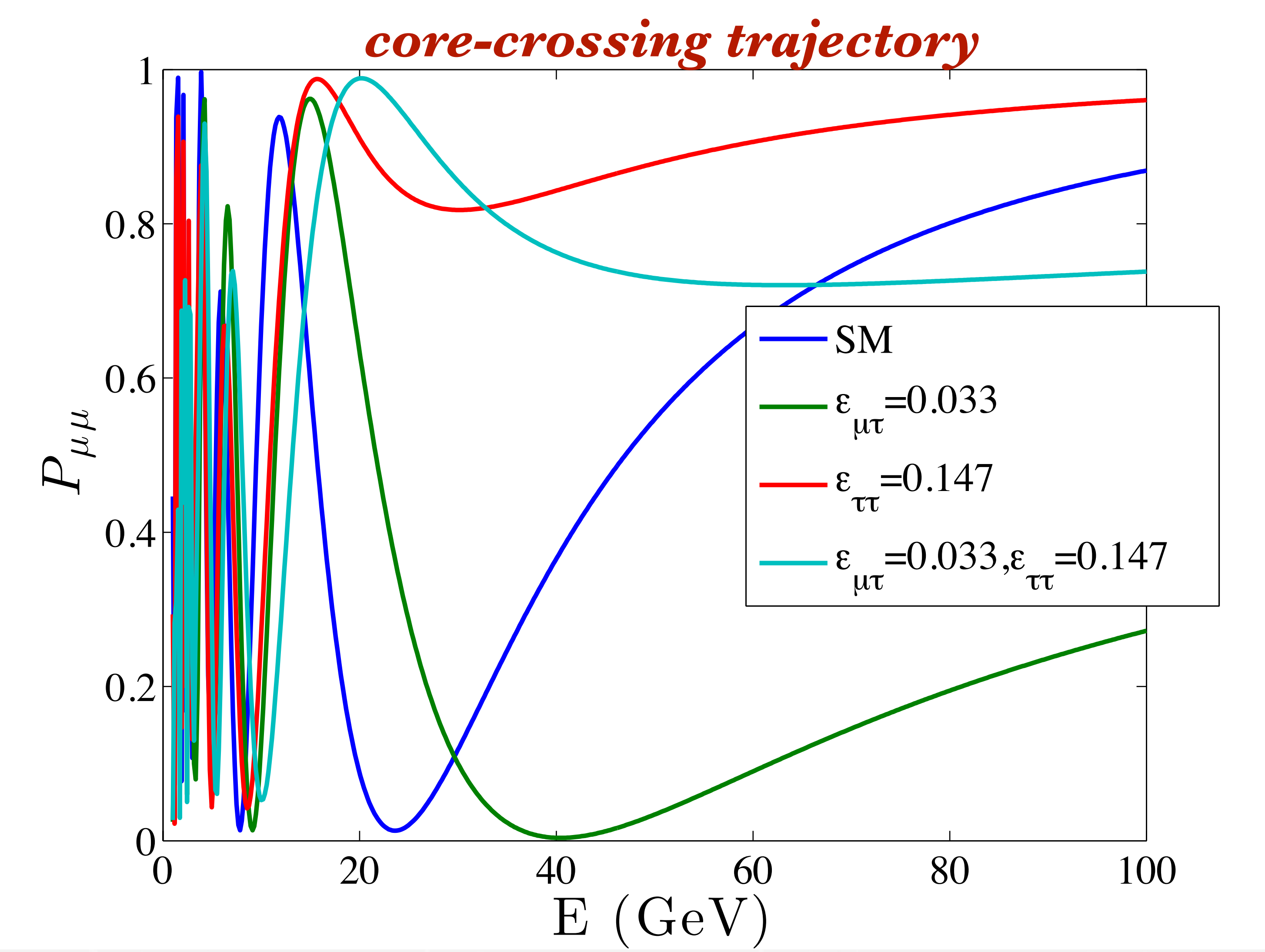
If there exist effective operators of the form

$$\mathcal{L}_{\rm NSI} = -2\sqrt{2}G_F\varepsilon^{ff'C}_{\alpha\beta}\left(\overline{\nu_\alpha}\gamma^\mu P_L\nu_\beta\right)\left(\bar{f}\gamma_\mu P_C f'\right)$$

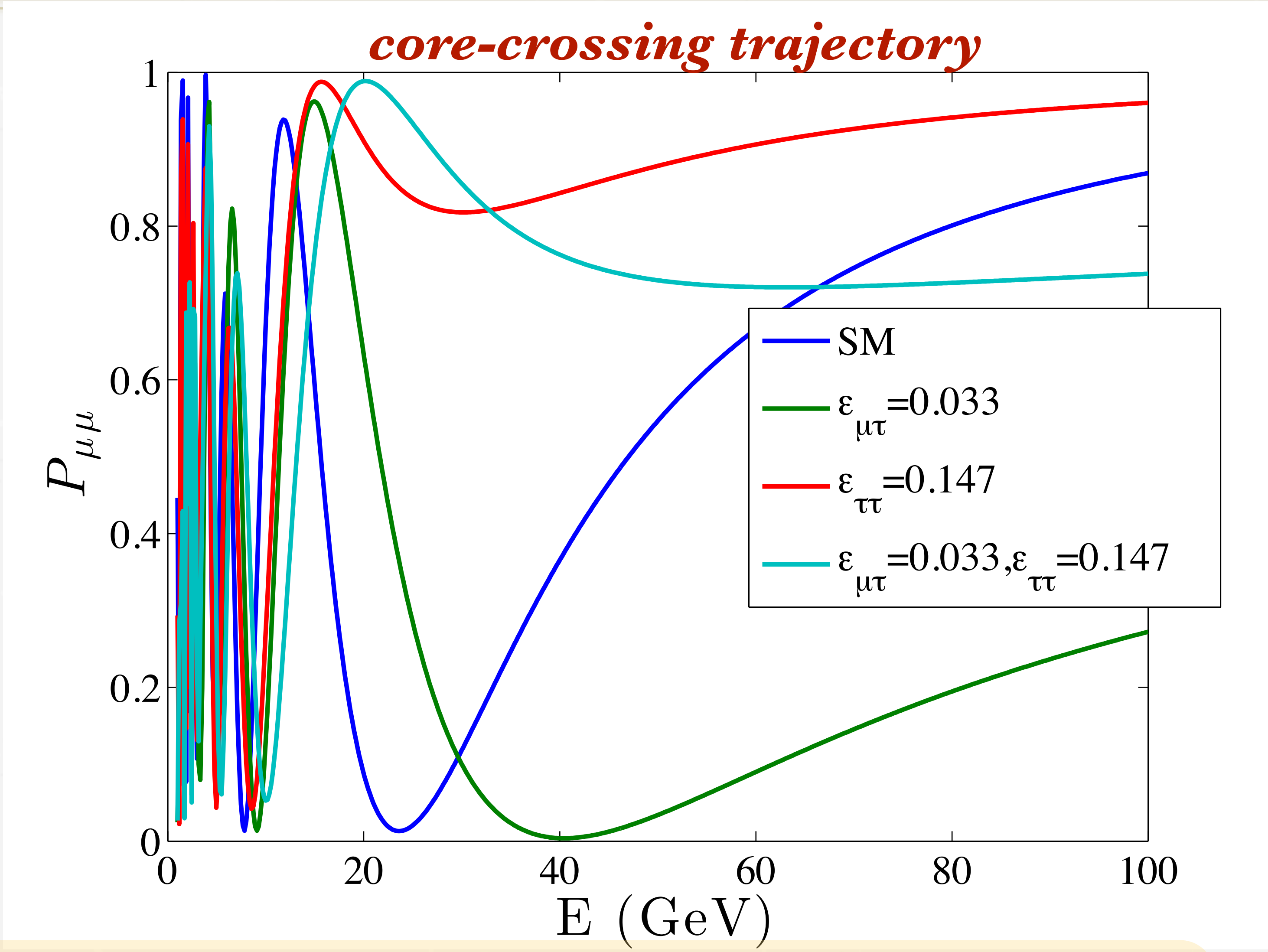
then they will modify neutrino evolution inside matter

$$\hat{H} = \frac{1}{2E}\left[U{\rm diag}(m_1^2, m_2^2, m_3^2)U^\dagger + {\rm diag}(A,0,0) + A\varepsilon^m\right]$$

NON-STANDARD NEUTRINO INTERACTIONS



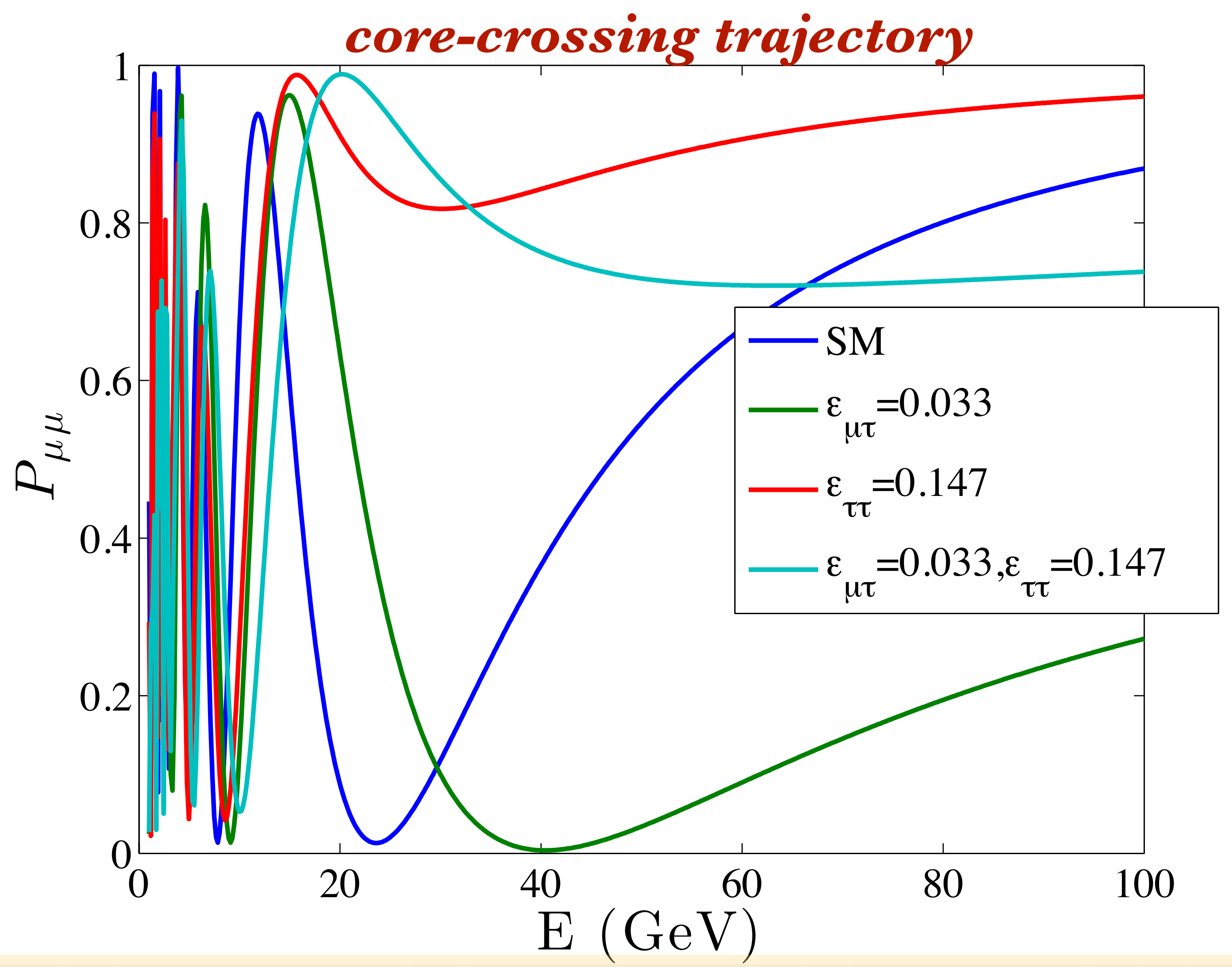
NON-STANDARD NEUTRINO INTERACTIONS



90% C.L. bound from Super-kamiokande:

$$|\varepsilon_{\mu\tau}| < 0.033 \quad \text{and} \quad |\varepsilon_{\tau\tau} - \varepsilon_{\mu\mu}| < 0.147$$

NON-STANDARD NEUTRINO INTERACTIONS



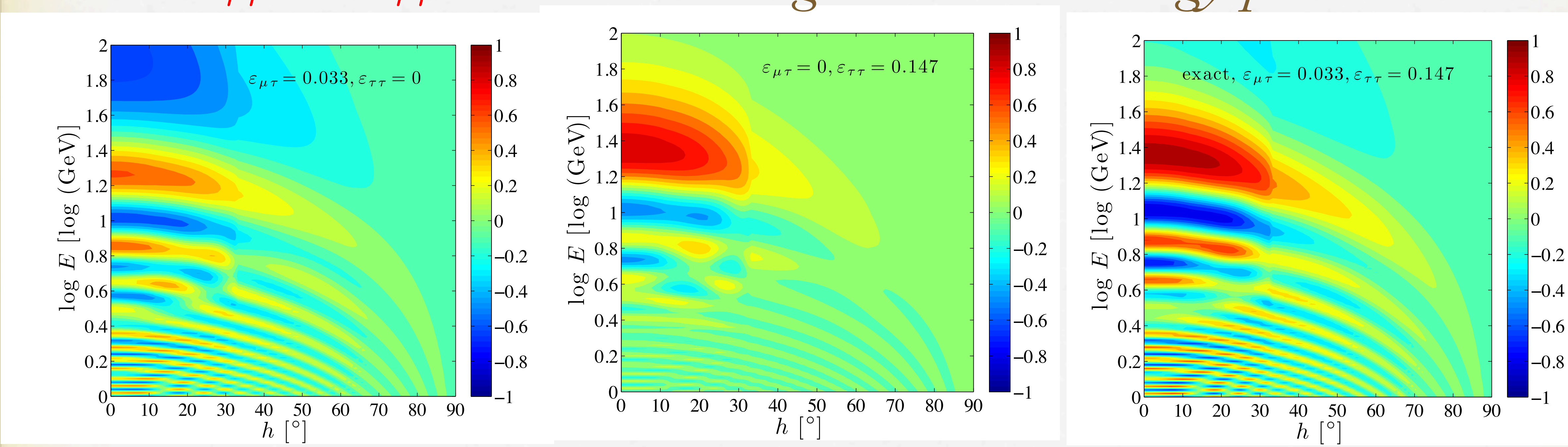
90% C.L. bound from IceCube:

$|\varepsilon_{\mu\tau}| < 6\times10^{-3}$ and $|\varepsilon_{\mu\mu}-\varepsilon_{\tau\tau}|<3\times10^{-2}$

Esmaili, Smirnov, 1304.1042

NON-STANDARD NEUTRINO INTERACTIONS

$\Delta P = P_{\mu\mu}^{NSI} - P_{\mu\mu}^{SM}$ *in the nadir angle - neutrino energy plane*



S.C., Ohlsson, 1410.0410

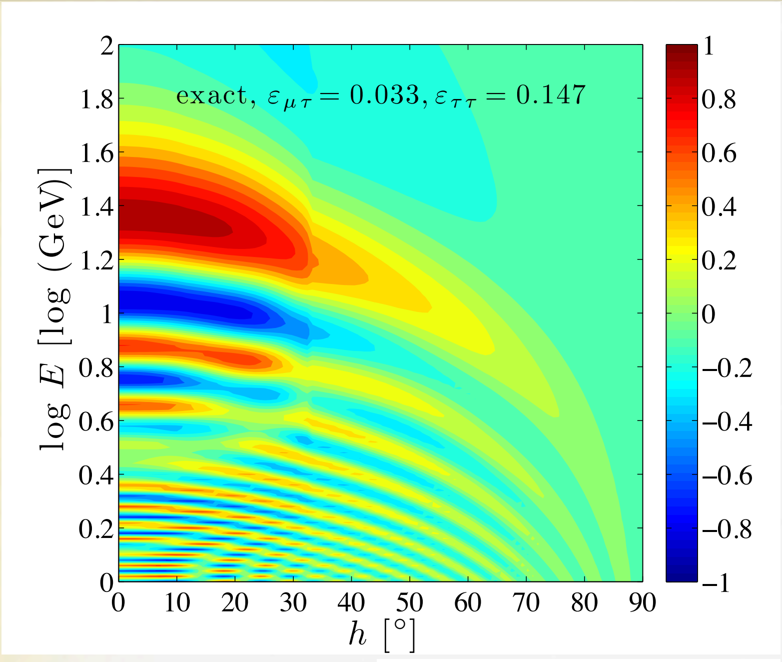
- *NSI effects large for neutrinos crossing the earth core*
- *NSI effects large at E~25 GeV*

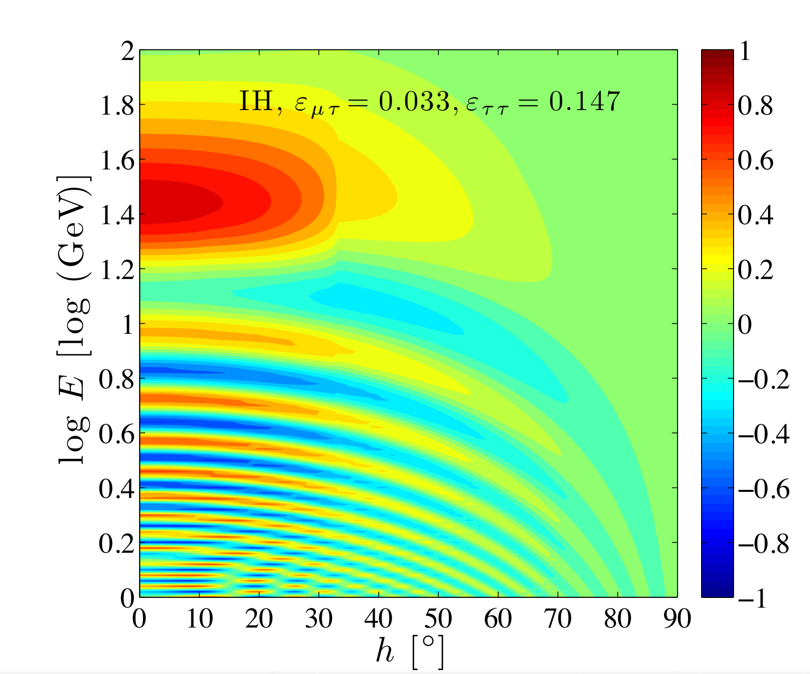
$$E_{\max,n} \sim \frac{\Delta m^2 L}{2n\pi}, \quad \text{where } n = 1, 2, 3, \ldots$$

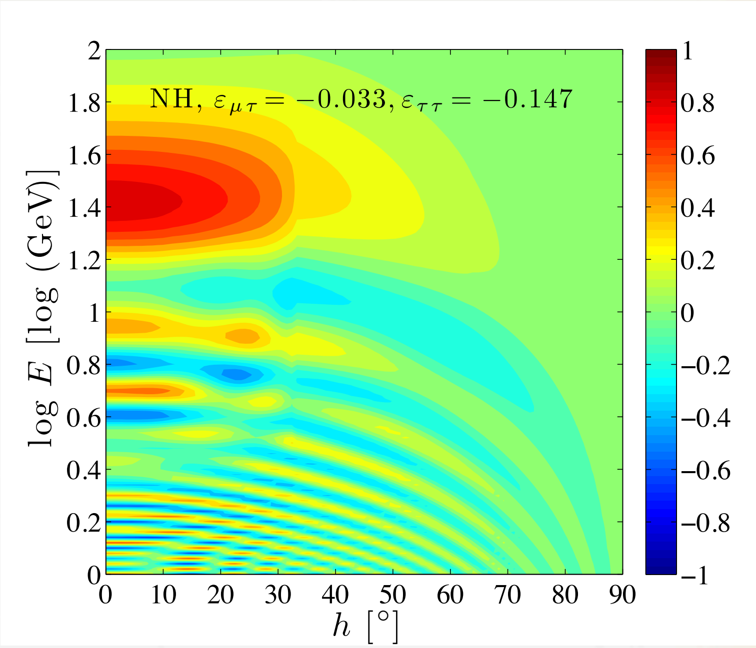
$$E_{\max,1} \simeq 24.8\,\text{GeV}$$

- $\epsilon_{\mu\tau}$ *driven NSI effects bring a big difference at E~100 GeV*
- *The effect can be large ....*

NON-STANDARD NEUTRINO INTERACTIONS







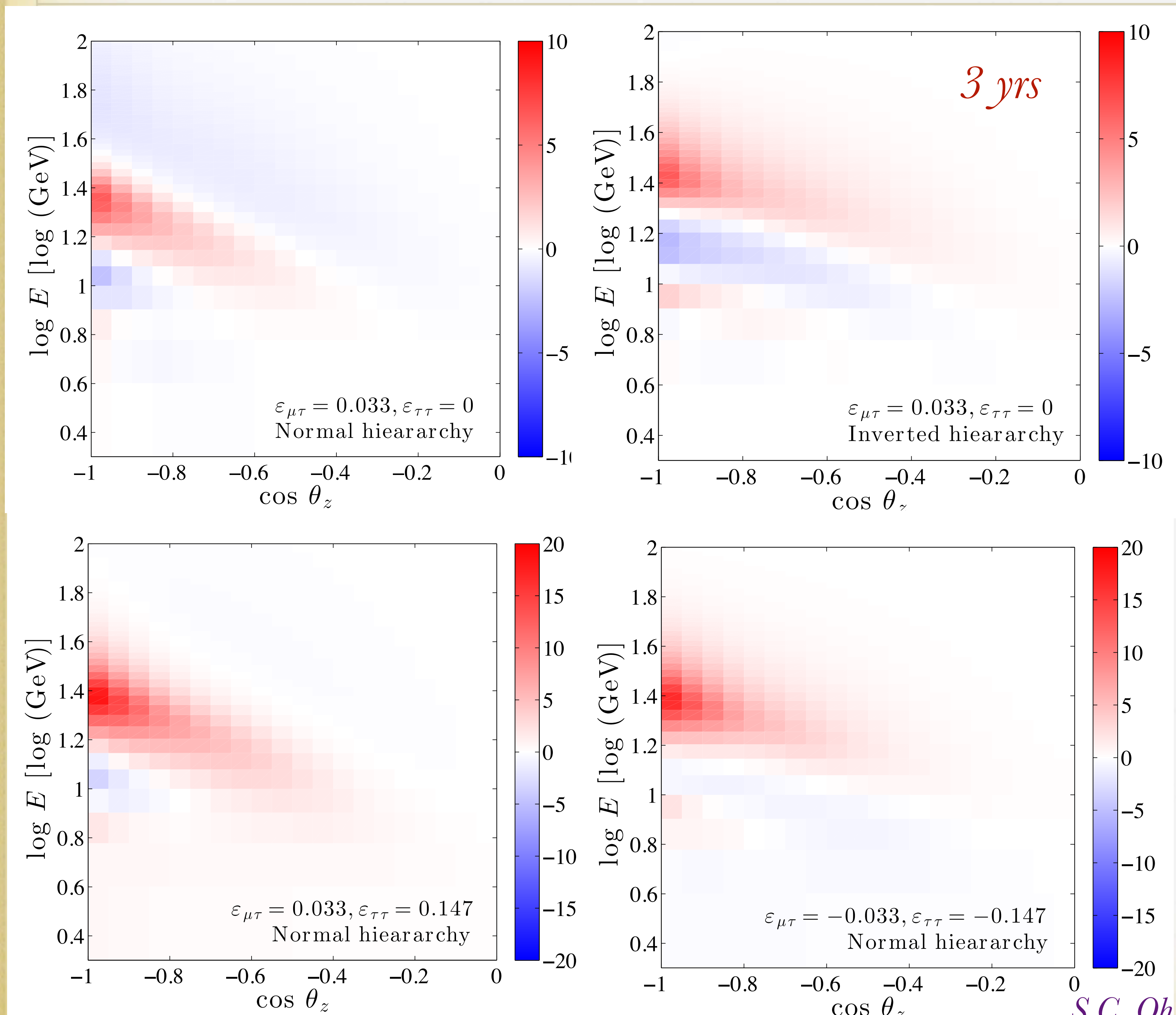
S.C., Ohlsson, 1410.0410

- *Qualitative as well as quantitative changes when hierarchy is flipped*
- *When the sign of the NSI parameters are flipped as well, we almost get back the same feature*

Mocioiu, Wright, 1410.6193

Chatterjee, Mehta, Choudhury, Gandhi, 1410.6193

NON-STANDARD NEUTRINO INTERACTIONS



Shown is $(N_{NSI} - N_{SM})/\sqrt{N_{SM}}$

Fast oscillatory NSI effects are erased due to detector resolutions

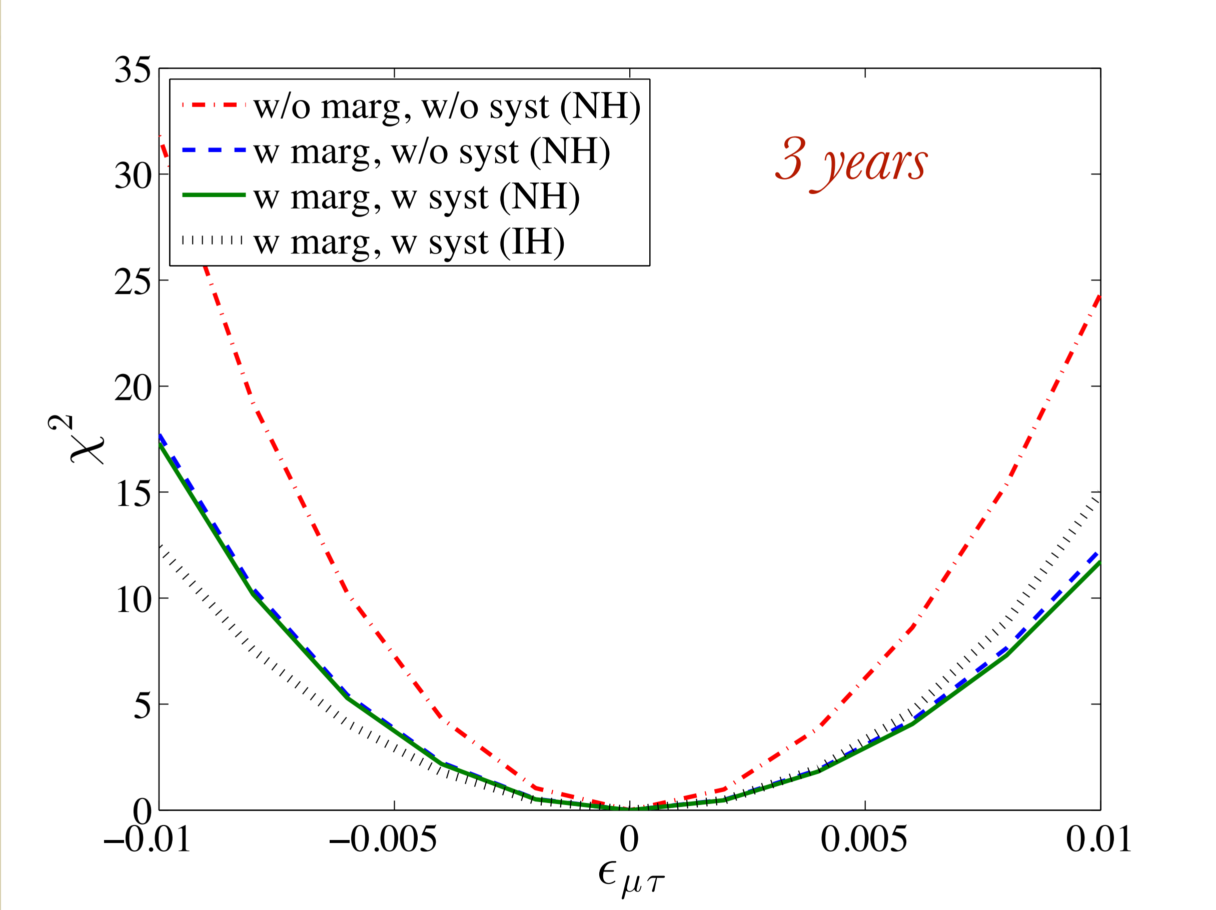
NSI effects between E~10-100 GeV survive

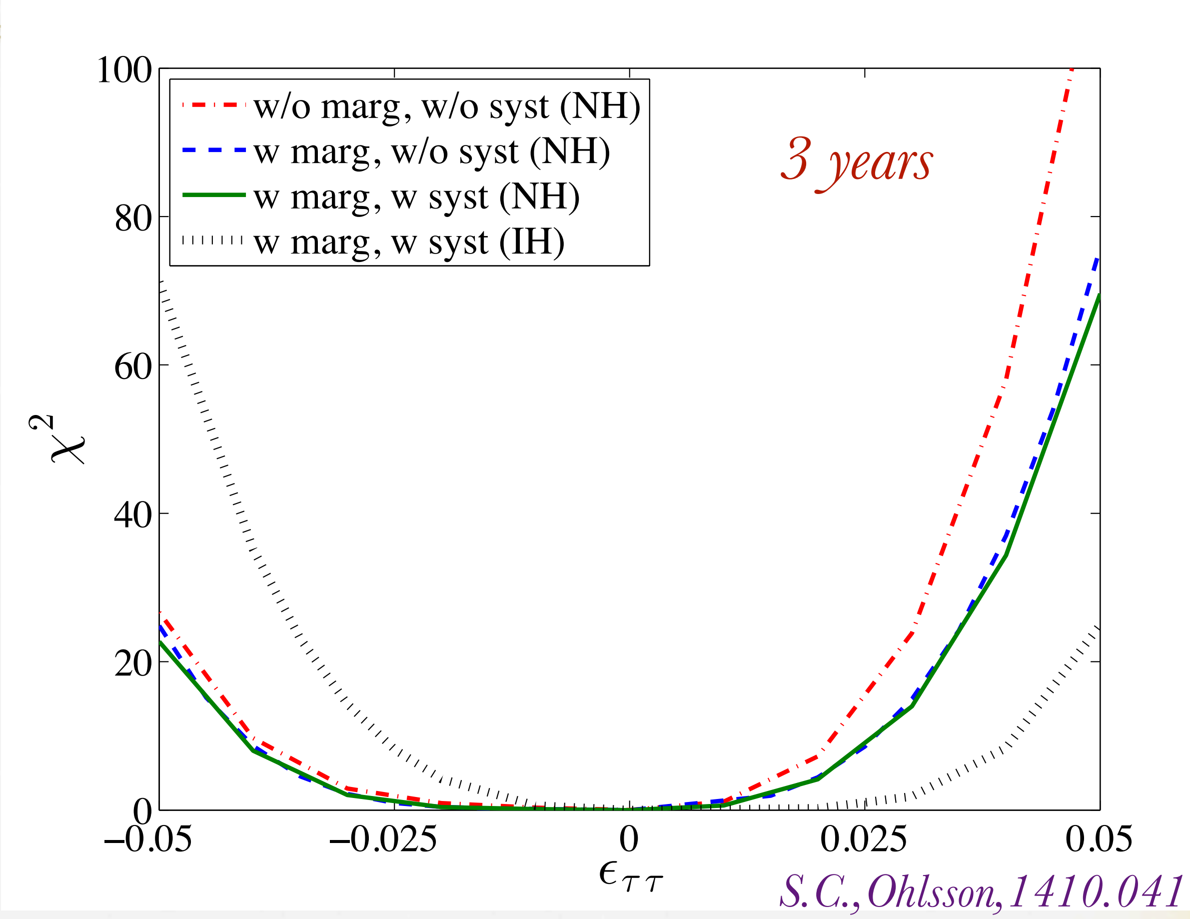
NSI effects can be probed better at higher neutrino energies

Marked difference between NH & IH

S.C.,Ohlsson,1410.0410

NON-STANDARD NEUTRINO INTERACTIONS





S.C., Ohlsson, 1410.0410

90% C.L. bound expected from PINGU:

$$-0.0043\ (-0.0048) < \varepsilon_{\mu\tau} < 0.0047\ (0.0046)\,,$$

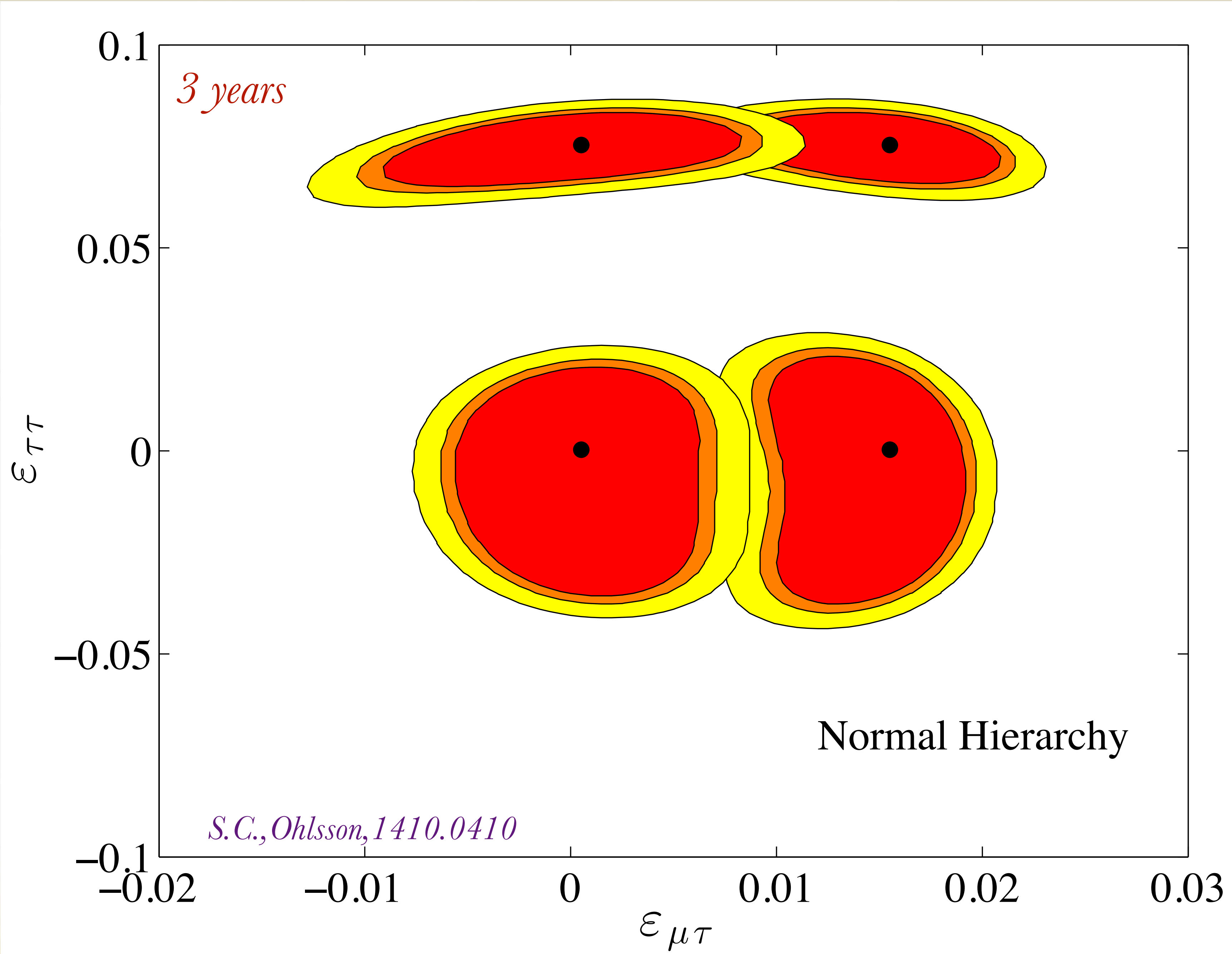
$$-0.03\ (-0.016) < \varepsilon_{\tau\tau} < 0.017\ (0.032)$$

NH (IH)

90% C.L. bound from Super-kamiokande:

$$|\varepsilon_{\mu\tau}| < 0.033 \quad \text{and} \quad |\varepsilon_{\tau\tau} - \varepsilon_{\mu\mu}| < 0.147$$

NON-STANDARD NEUTRINO INTERACTIONS



CONCLUSIONS

- *The first unambiguous signal of neutrino mass and mixing came from observation of atmospheric neutrinos at Super-Kamiokande*
- *The atmospheric neutrino oscillation parameters now well established.*
- *First hints for MH, octant of theta23 and deltacp are emerging.*
- *With theta13 measured 'large' in the reactor experiments, atmospheric nu expts have a good chance at MH determination.*
- *One could measure the octant of theta23 - synergy with LBL expts*
- *High neutrino energies open the possibility of further probing NSI and other new physics at atmospheric neutrino experiments.*

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Thank You!