# OSCILLATION PHYSICS WITH ATMOSPHERIC NEUTRINOS

Soebur Razzaque
*George Mason University, Fairfax, Virginia*

NNN 2012, FNAL, 4-6 October

# NNN 2006, Seattle

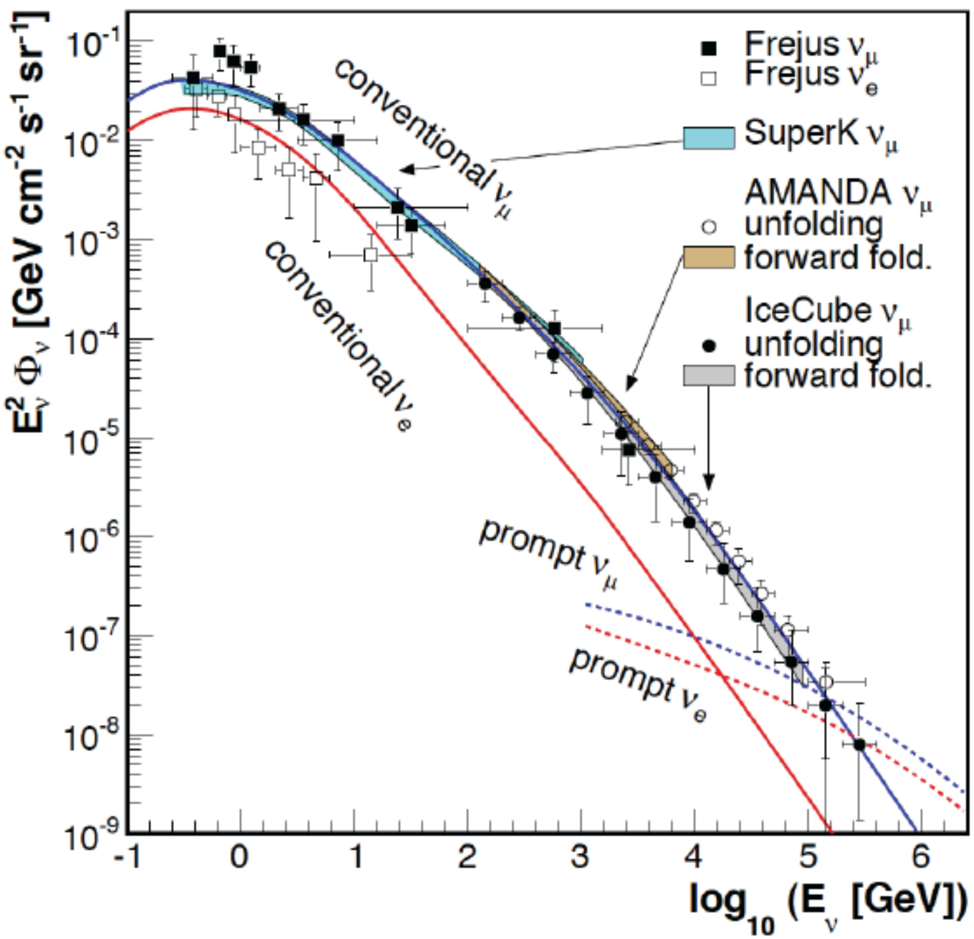
# Talk Outline

- Atmospheric neutrino flux
- IceCube-DeepCore-PINGU
- Three-flavor neutrino mixing parameters
- Neutrino mass hierarchy determination with huge atmospheric neutrino detectors
- Sensitivity to 2-3 mixing and CP phase
- Search for light sterile neutrinos

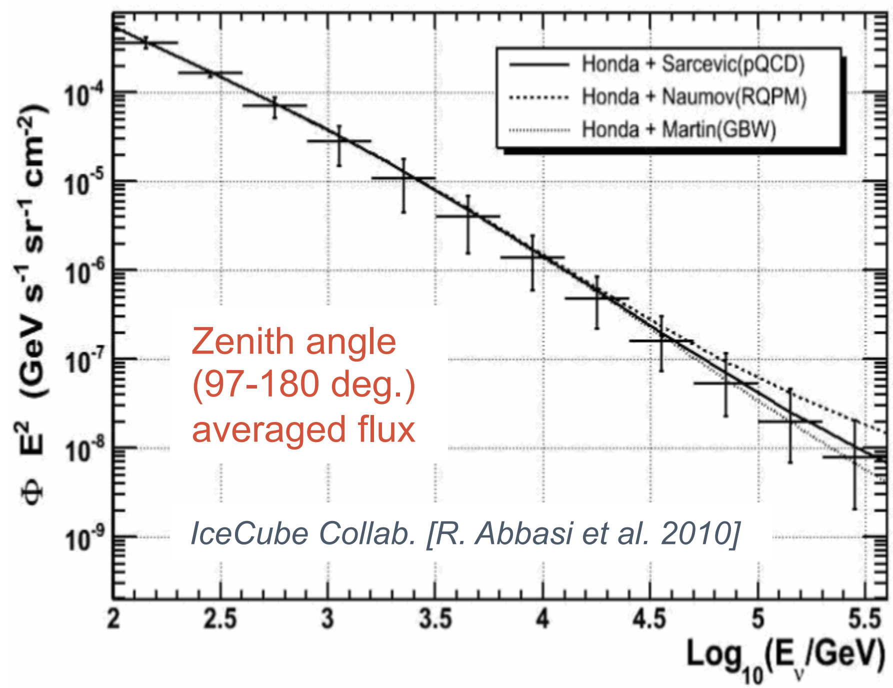
*E. Kh. Akhmedov, S. Razzaque and A. Yu. Smirnov, arXiv:1205.7071*
*O. Mena, I. Mocioiu and S. Razzaque, arXiv:0803.3044*
*S. Razzaque and A. Yu. Smirnov, arXiv:1104.1390*
*S. Razzaque and A. Yu. Smirnov, arXiv:1203.5406*

# Atmospheric neutrino flux

Nature's neutrino beam

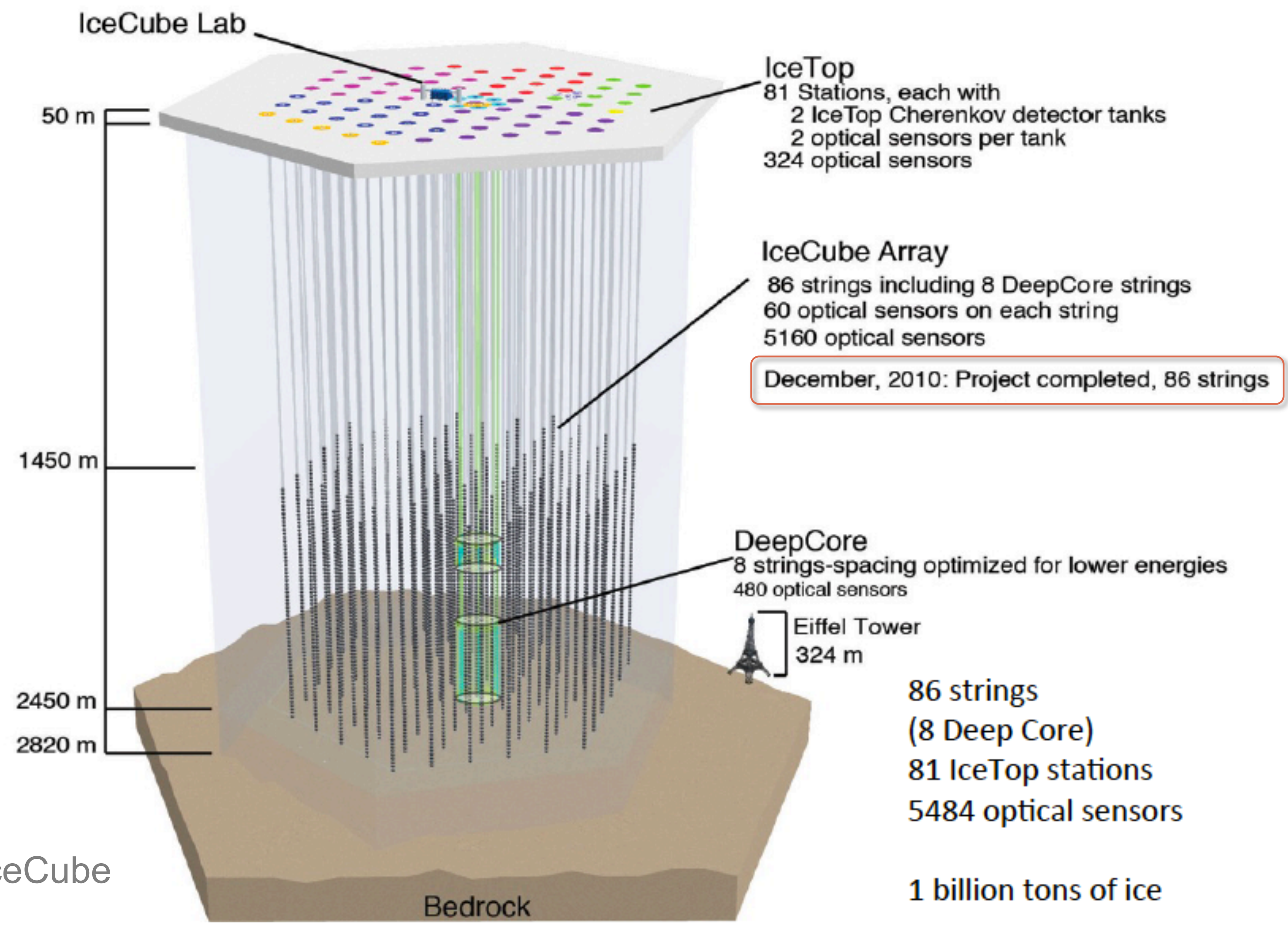



- Measurements of muon neutrino flux from ~200 MeV to ~400 TeV
- Uncertainties are getting smaller to constrain models at > 100 GeV
- DeepCore/PINGU will reduce uncertainties at < 100 GeV



# IceCube $\nu$ Observatory at the South Pole

Sensitive to >10 GeV $\nu$'s with its Deep Core sub-array



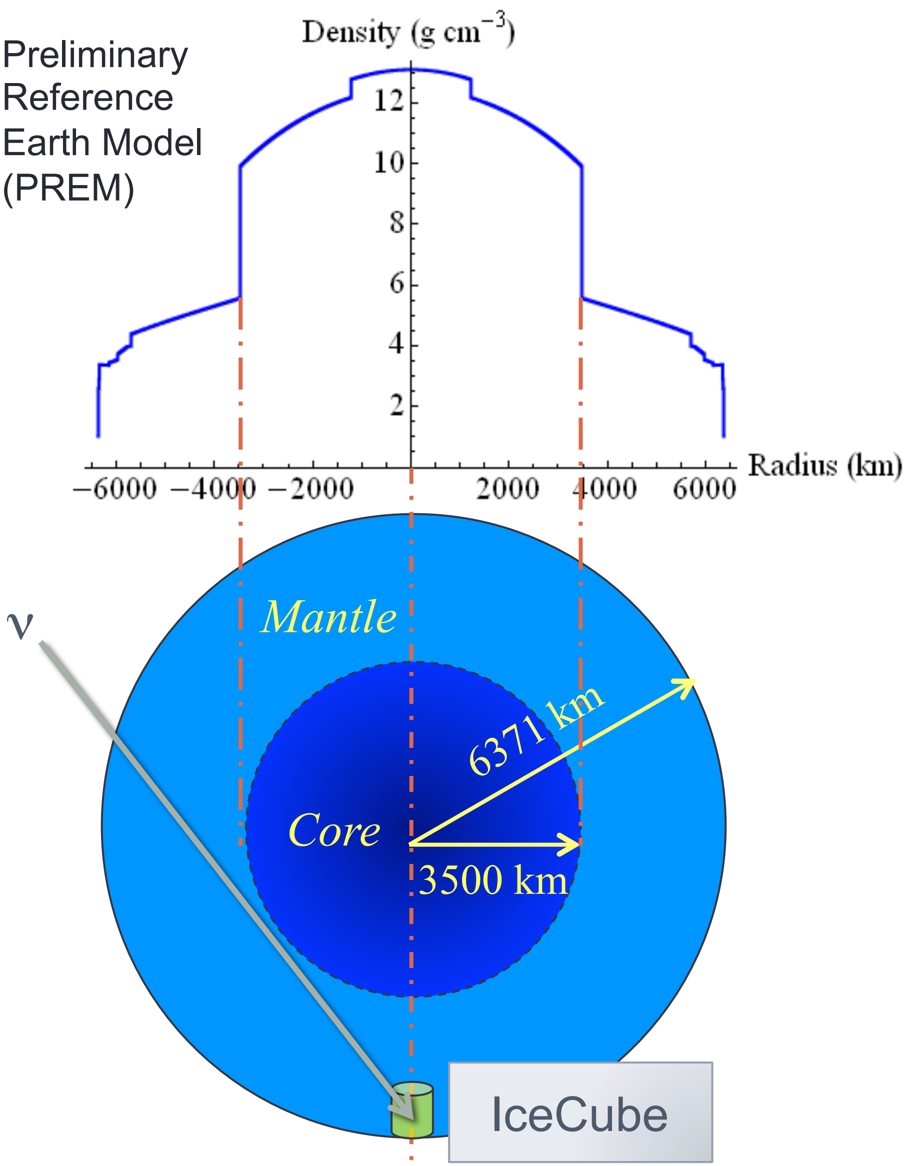

86 strings
(8 Deep Core)
81 IceTop stations
5484 optical sensors

1 billion tons of ice

Credit: IceCube

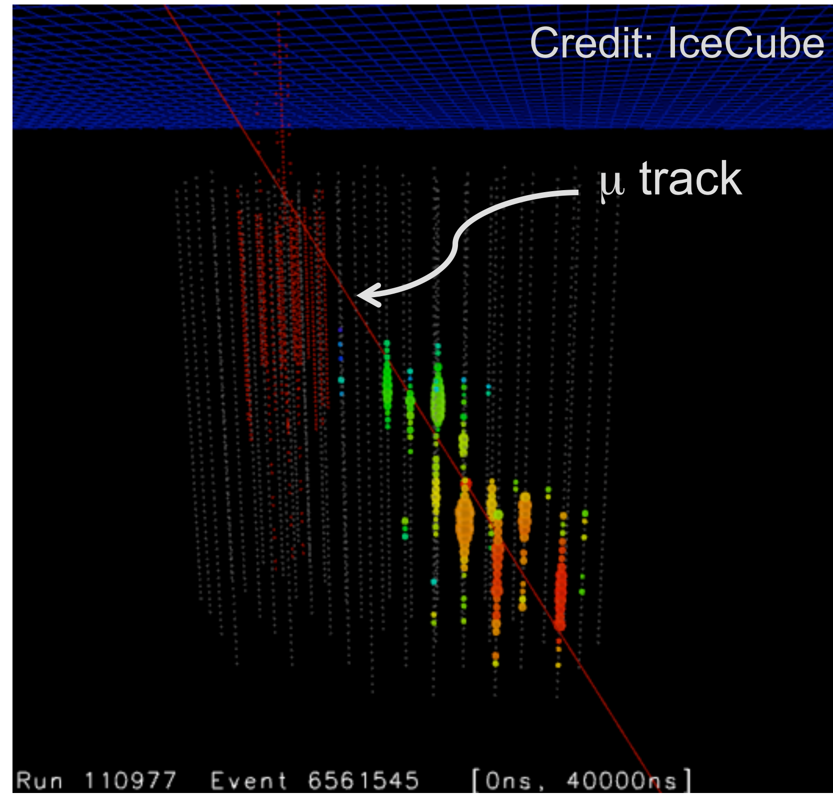
# $\nu$ detection techniques

Preliminary Reference Earth Model (PREM)



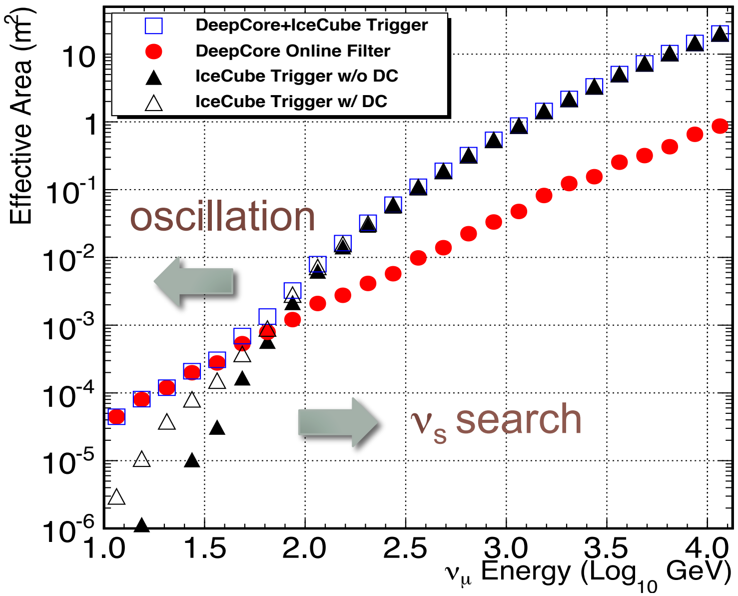

Charge-Current interactions

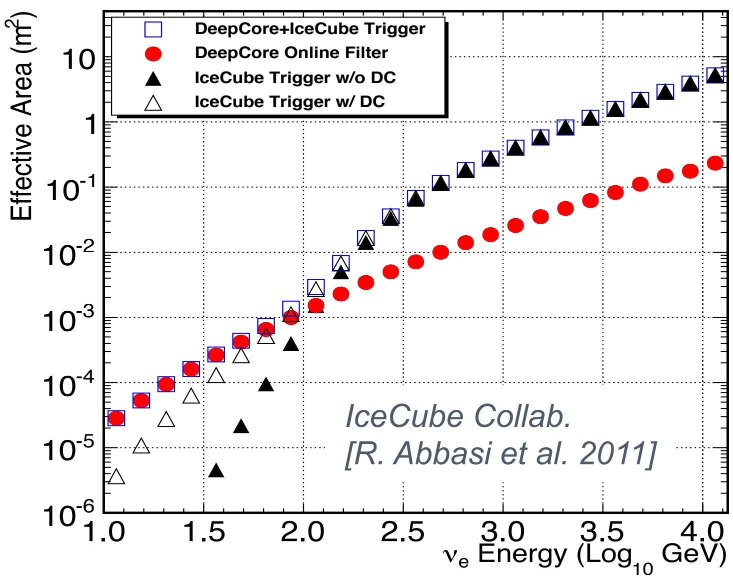
$\nu_{e/\mu/\tau}$ + N → e/μ/τ + X




Good angular resolution (<1° @ 1 TeV) for $\nu_\mu$ –induced CC events

# IceCube and Deep Core sensitivities

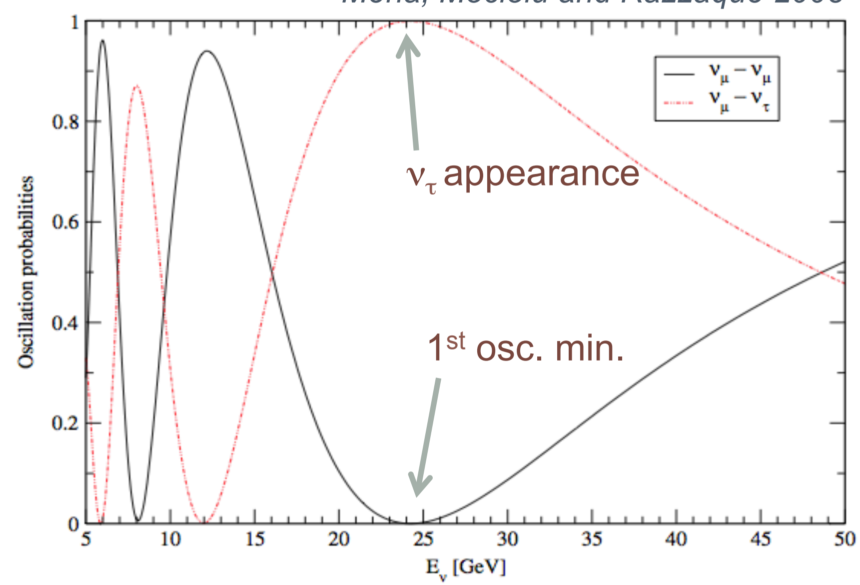


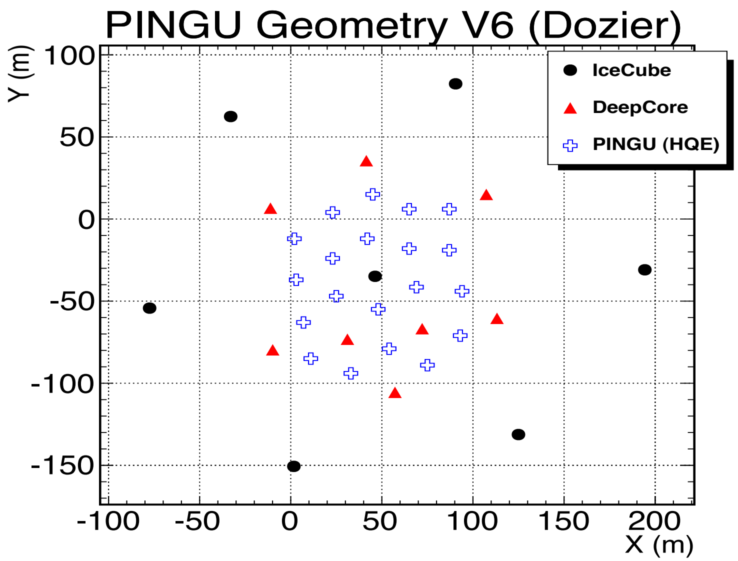

Oscillation physics requires good sensitivity below ~50 GeV which Deep Core provides

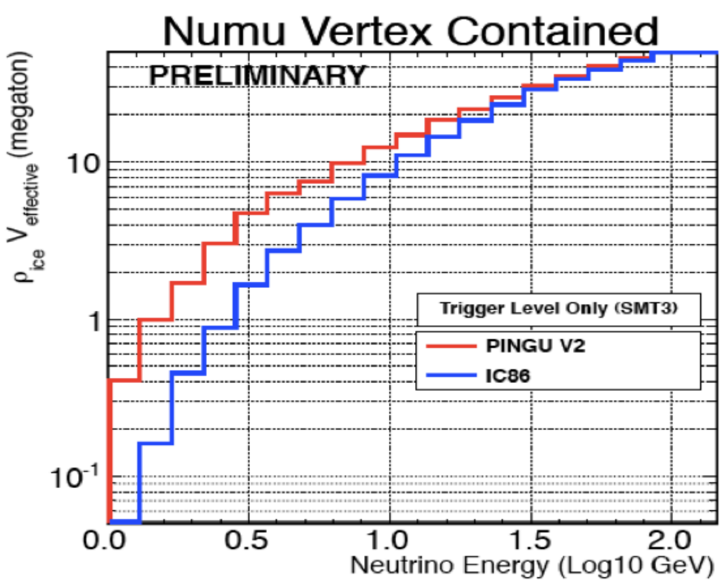
- Oscillation confirmation over large L/E
- Atmospheric mixing angle $\theta_{23}$
- Mass-square difference $|\Delta m_{32}|^2$
- Appearance of $\nu_\tau$
- Search for light sterile species

*Mena, Mocioiu and Razzaque 2008*



# Next generation: PINGU sensitivities

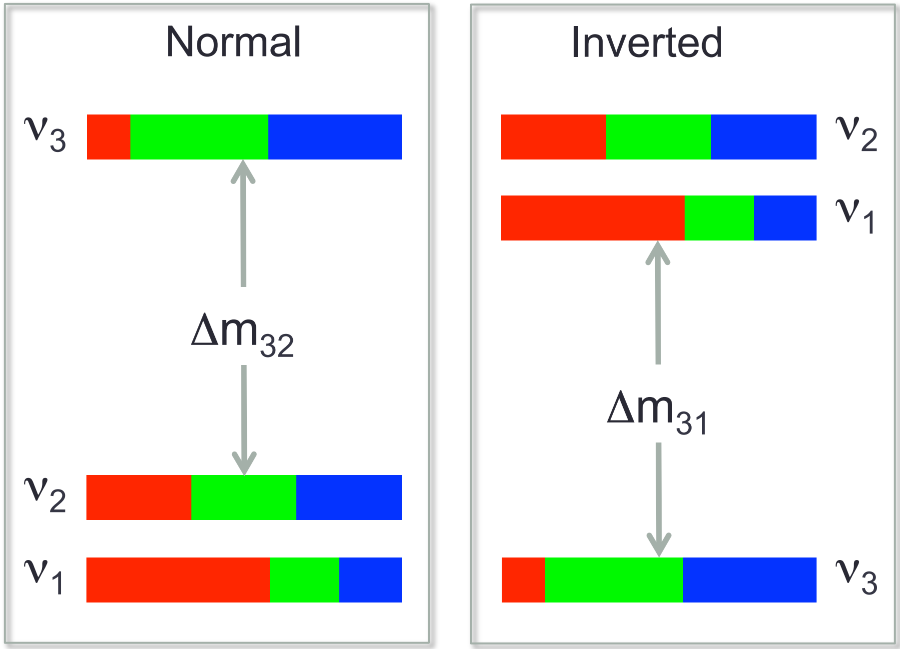



Additional strings ~20, denser array within IC/DC, threshold down to ~1 GeV

*Talk by J. Koskinen*

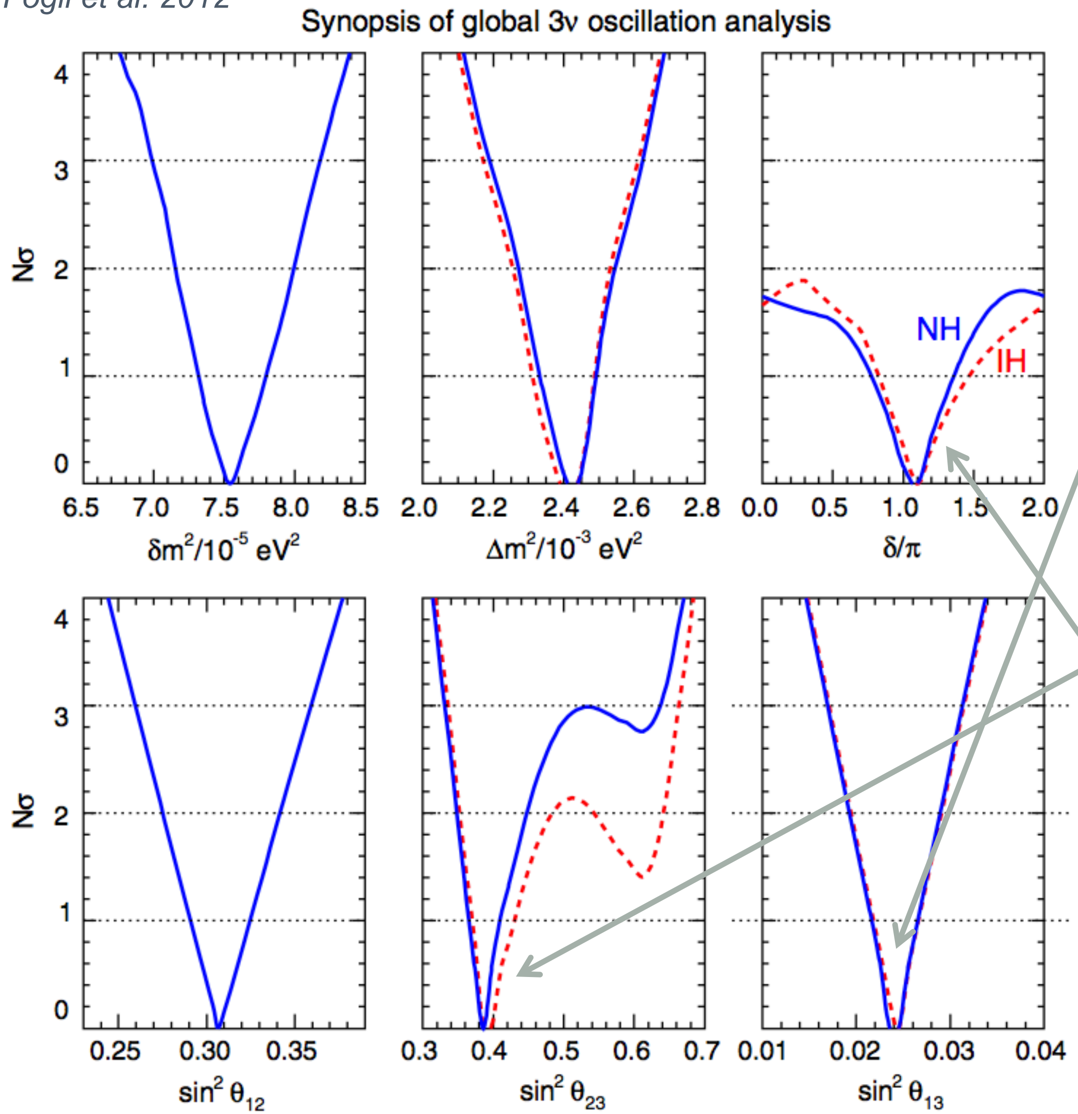
Main oscillation physics: neutrino mass hierarchy




Credit: D. Cowen, J. Koskinen, D. Grant, K. Clark, …

# Three-flavor neutrino mixing parameters

*Fogli et al. 2012*




All mixing parameters are known!

Non-zero and somewhat large $\theta_{13}$

- Indicated by global fits
- measured by Daya Bay

$\sin^2 2\theta_{13} = 0.092 \pm 0.016$ (stat.) $\pm 0.005$ (syst.)

Interestingly non-maximal $\theta_{23}$

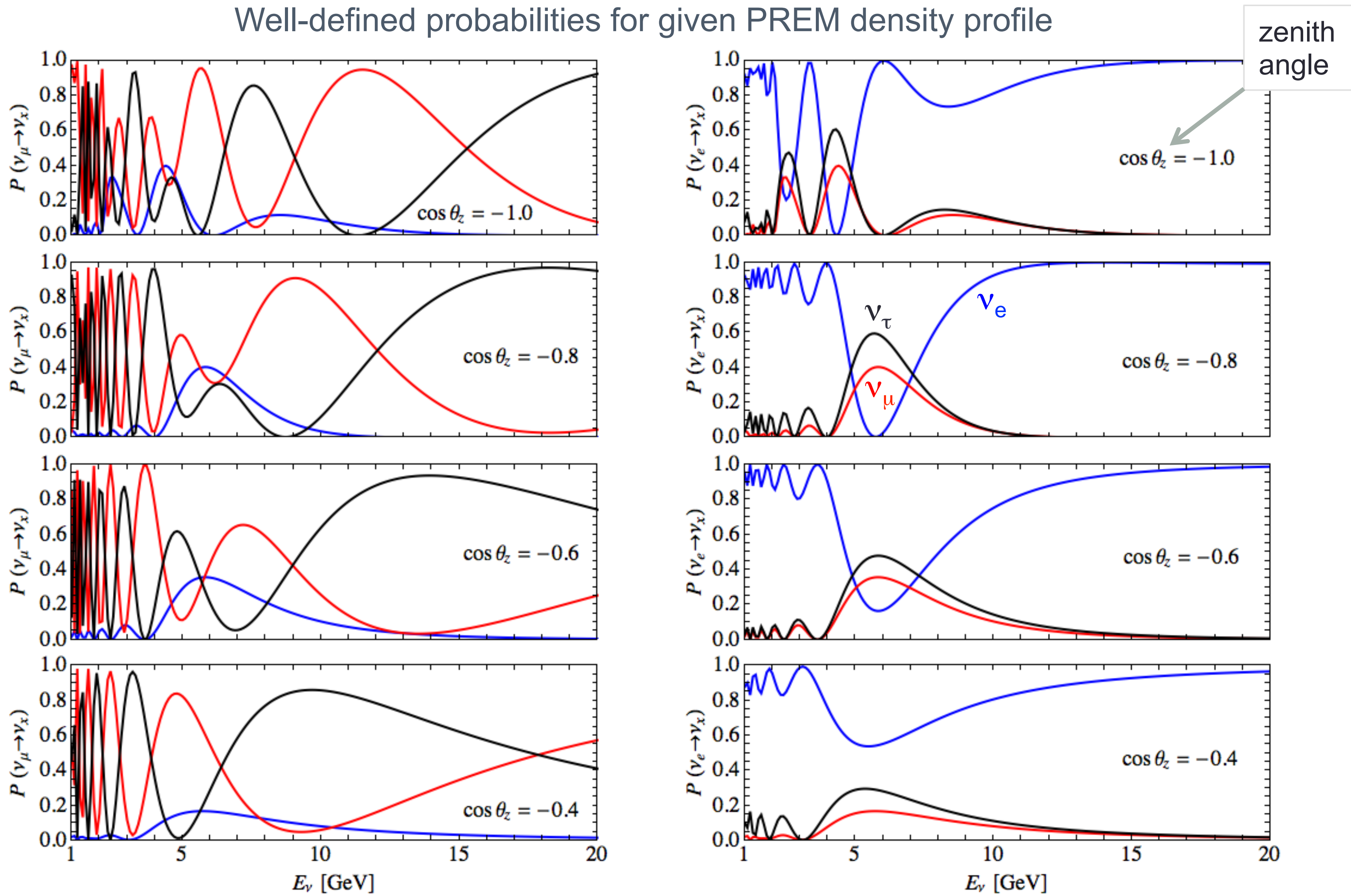
CP phase is weakly constrained

Mass hierarchy is unknown

Great opportunity to determine with huge atmospheric $\nu$ detectors!

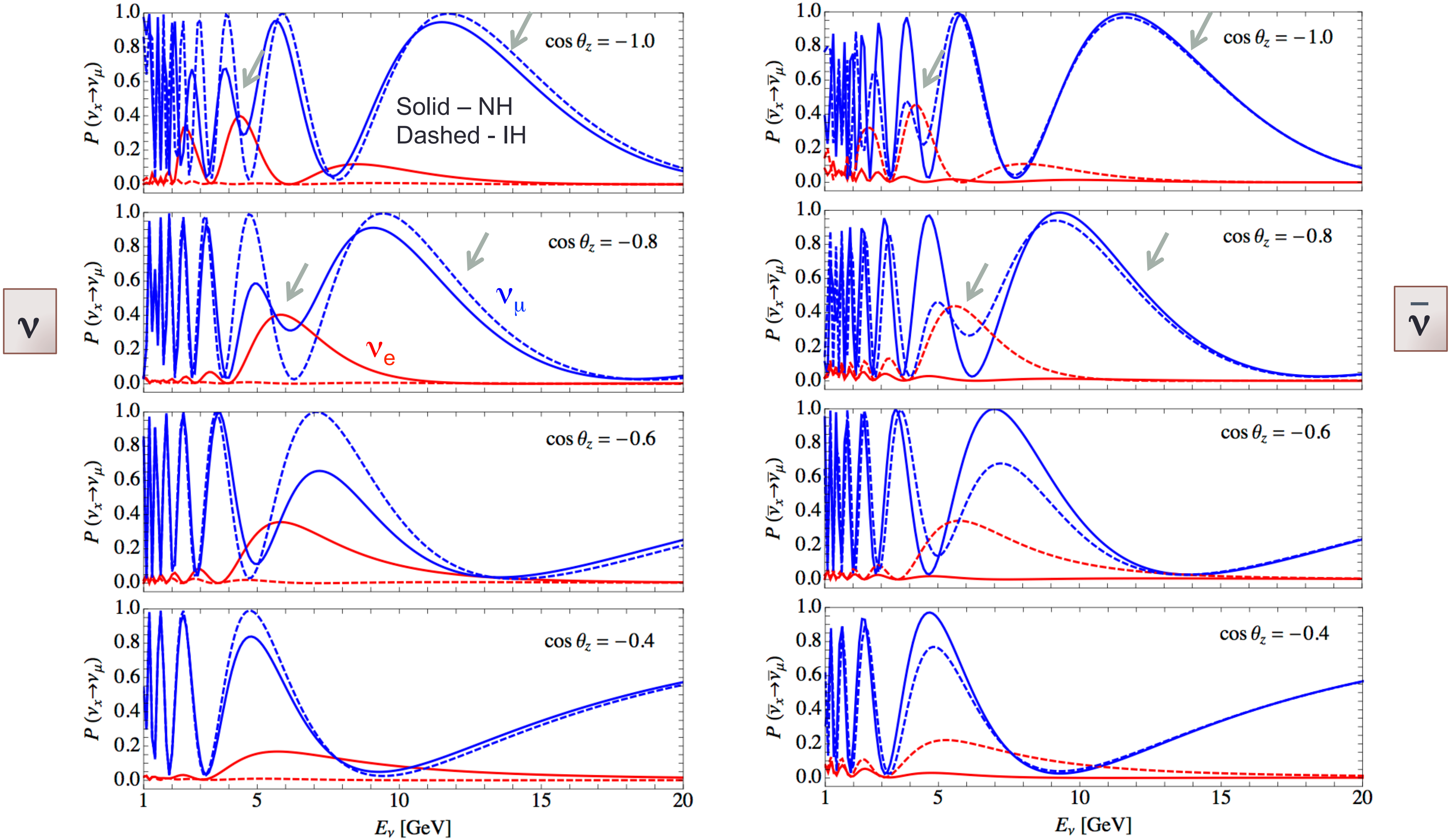
# Atmospheric ν oscillation probabilities

Well-defined probabilities for given PREM density profile



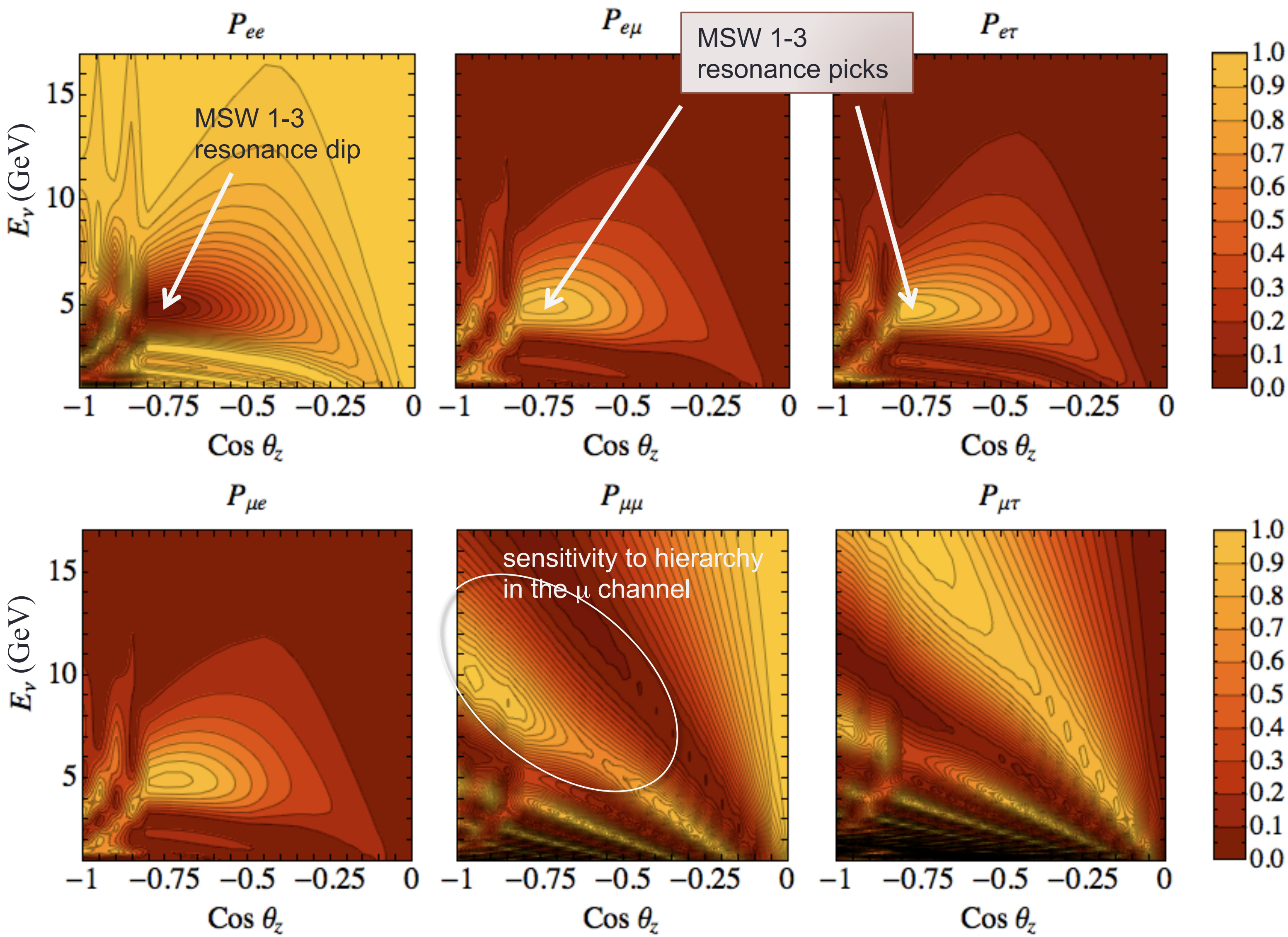
# Atmospheric ν oscillation probabilities

Subtle differences between ν and $\bar{\nu}$ probabilities when mass ordering is exchanged



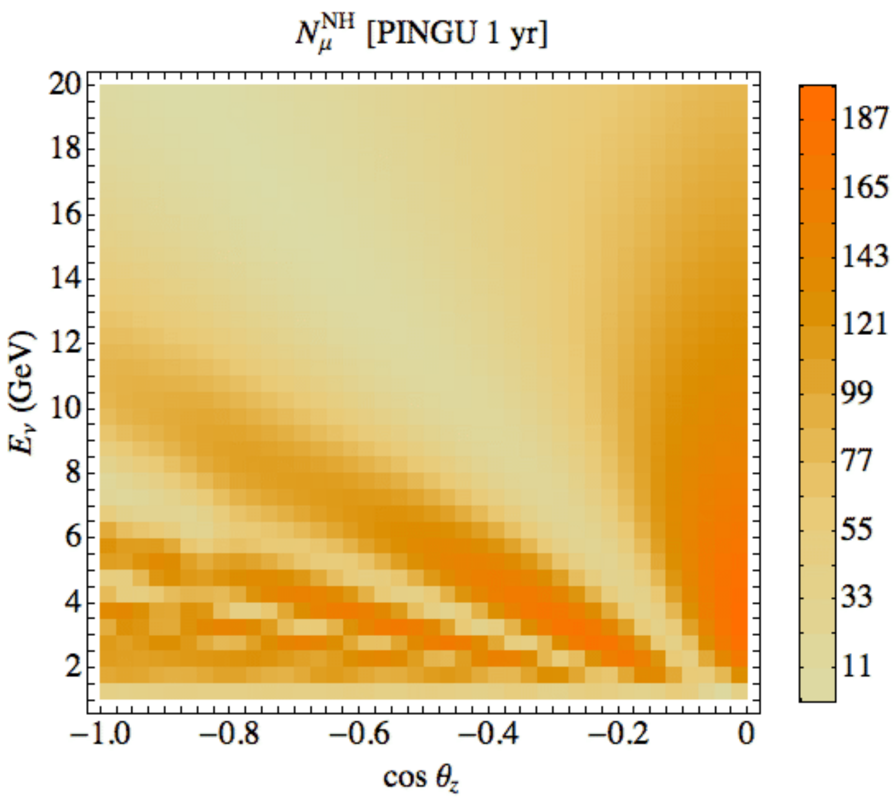
# Neutrino oscillograms

Equal probability contours in the energy-angle plane



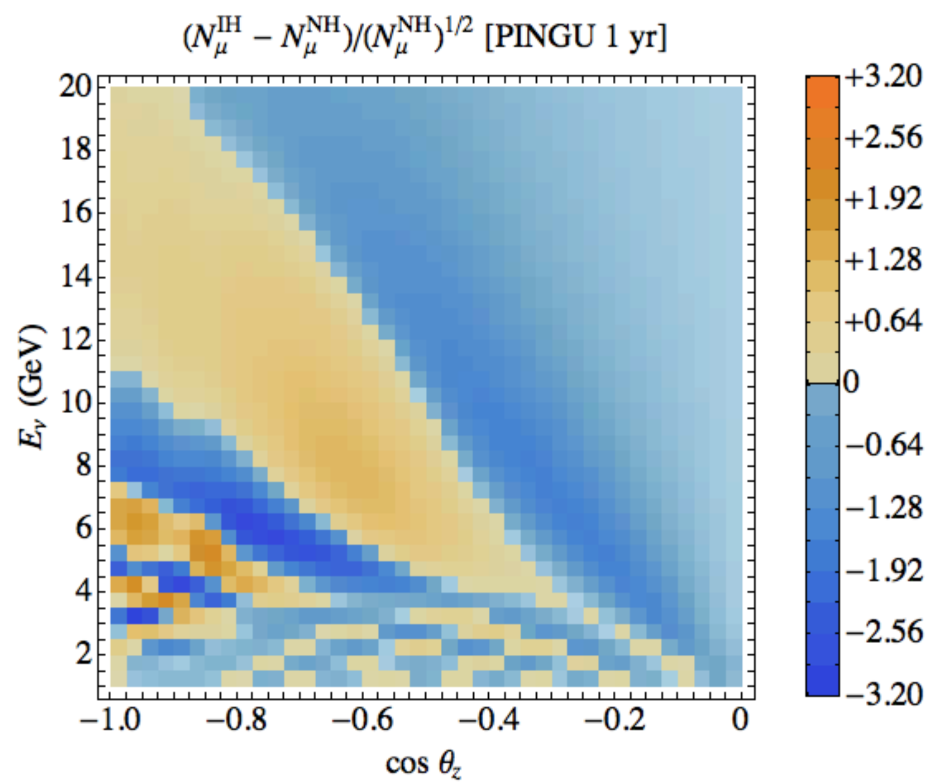
# Atmospheric $\nu_\mu$ track events in PINGU

$\nu_\mu$ CC-induced racking events follow the oscillation pattern




A metric to determine hierarchy from asymmetry in events in NH and IH

*Significance*




The asymmetry of events arises mostly due to $\sigma(\nu) \sim 2\,\sigma(\bar{\nu})$

# Asymmetry in $\nu_\mu$ track events in PINGU

$$N^{\rm IH}_{ij,\mu} - N^{\rm NH}_{ij,\mu} = 2\pi N_A \rho T \int_{\Delta_i \cos\theta_z} d\cos\theta_z \int_{\Delta_j E_\nu} dE_\nu V_{\rm eff} (D^{\rm IH}_\mu - D^{\rm NH}_\mu),$$

$\nu_\mu$ events

$$D^{\rm IH}_\mu - D^{\rm NH}_\mu = \sigma^{CC}\Phi^0_\mu \left[ (1-\kappa_\mu)\left(\bar{P}_{\mu\mu} - P_{\mu\mu}\right) + \frac{1}{r}(1-\kappa_e)\left(\bar{P}_{e\mu} - P_{e\mu}\right)\right]$$

$$r \equiv \frac{\Phi^0_\mu}{\Phi^0_e} \sim 5\text{–}10 \qquad \bar{r} \equiv \frac{\bar{\Phi}^0_\mu}{\bar{\Phi}^0_e} \sim 5\text{–}10$$

$$\kappa_\mu \equiv \frac{\bar{\sigma}^{CC}\bar{\Phi}^0_\mu}{\sigma^{CC}\Phi^0_\mu} \sim (1/2)\times(1/1.25) \sim 1/2.5$$

$$\kappa_e \equiv \frac{\bar{\sigma}^{CC}\bar{\Phi}^0_e}{\sigma^{CC}\Phi^0_e} = \kappa_\mu \frac{r}{\bar{r}} \sim 1/2.5$$

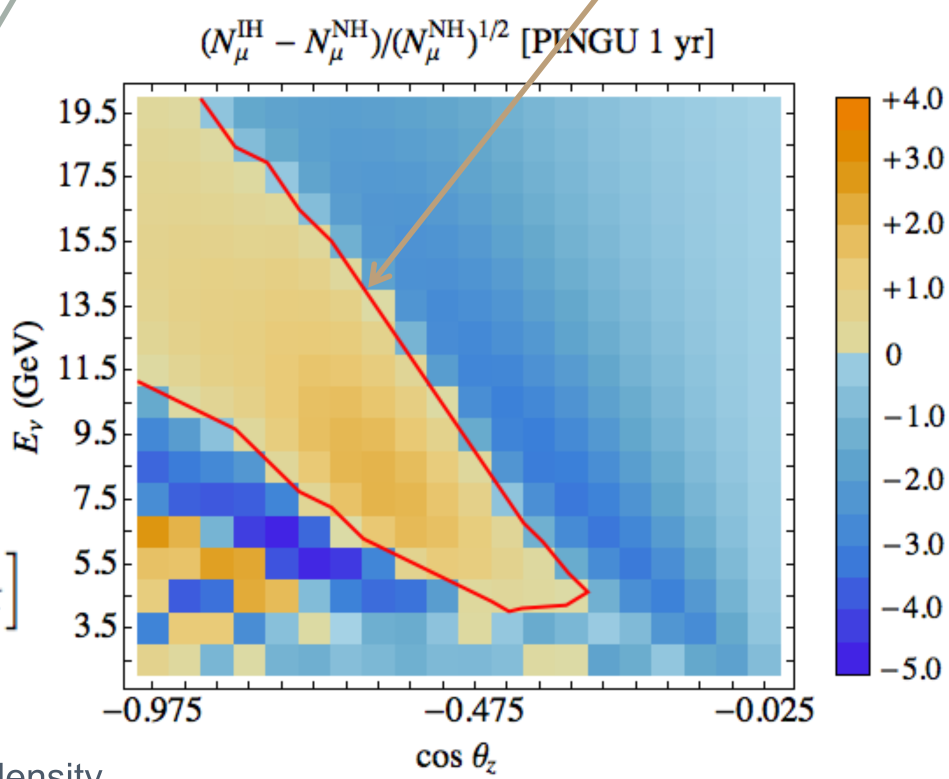
Original $\nu_e$ contribution is suppressed by a factor ~ $(1/r)(1-k_e) > (1/5)(1-1/2.5) \sim 3/25$!

$$\bar{P}_{\mu\mu} - P_{\mu\mu} \approx \frac{1}{2}\sin^2 2\theta_{23}\left[\cos\phi_{32} - \sqrt{1-P_A}\cos\phi_X\right] + s^4_{23} P_A$$

$$P_A = 1 - P_{ee} = \boxed{\sin^2 2\theta^m_{13} \sin^2 \phi^m_{31}/2}$$

Const. density

Analytic curve

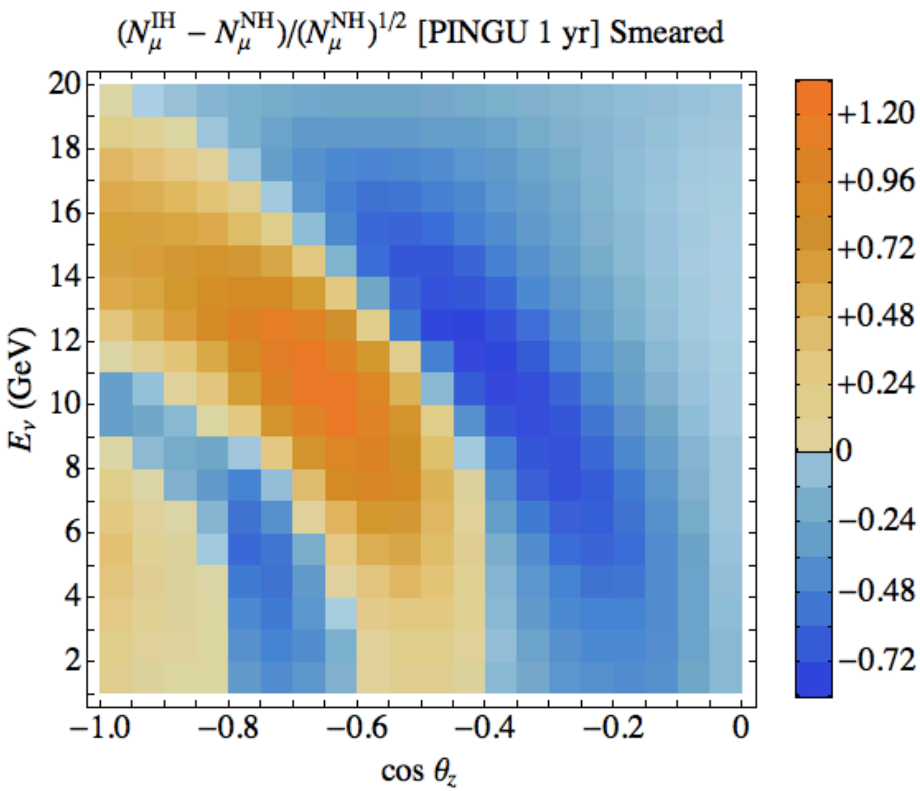


# Energy and angle reconstruction errors

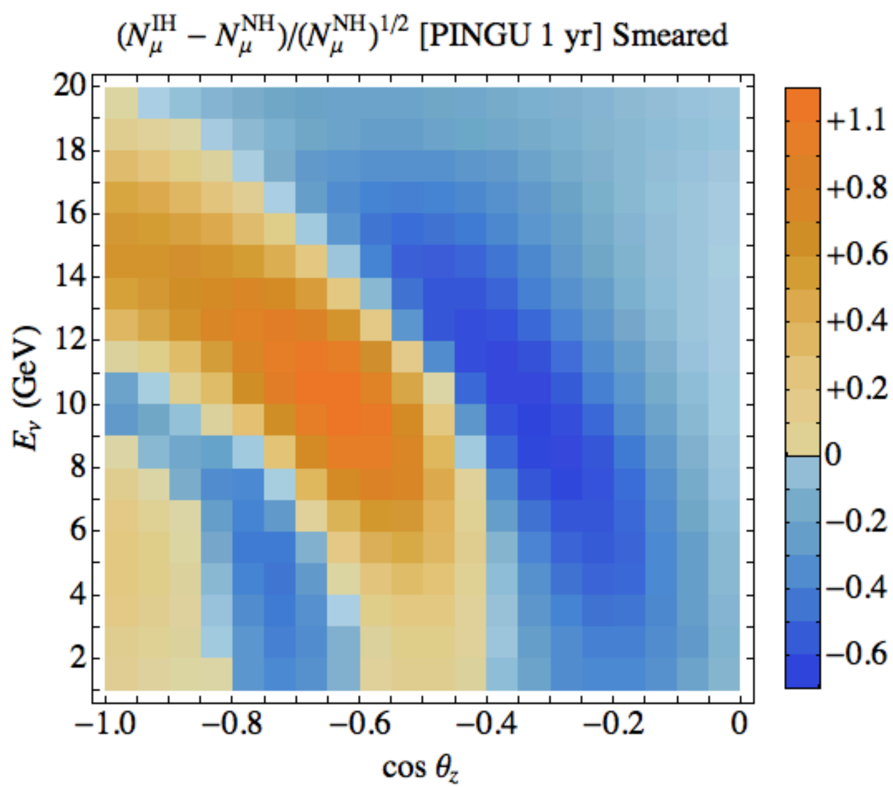
Energy and angular reconstruction errors are expected to be sizeable

Assume Gaussian smearing of true neutrino energy and angle with errors ($\sigma_E$, $\sigma_\theta$)

$\sigma_E = 0.2E_\nu$, $\sigma_\theta = (m_p/E_\nu)^{1/2}$



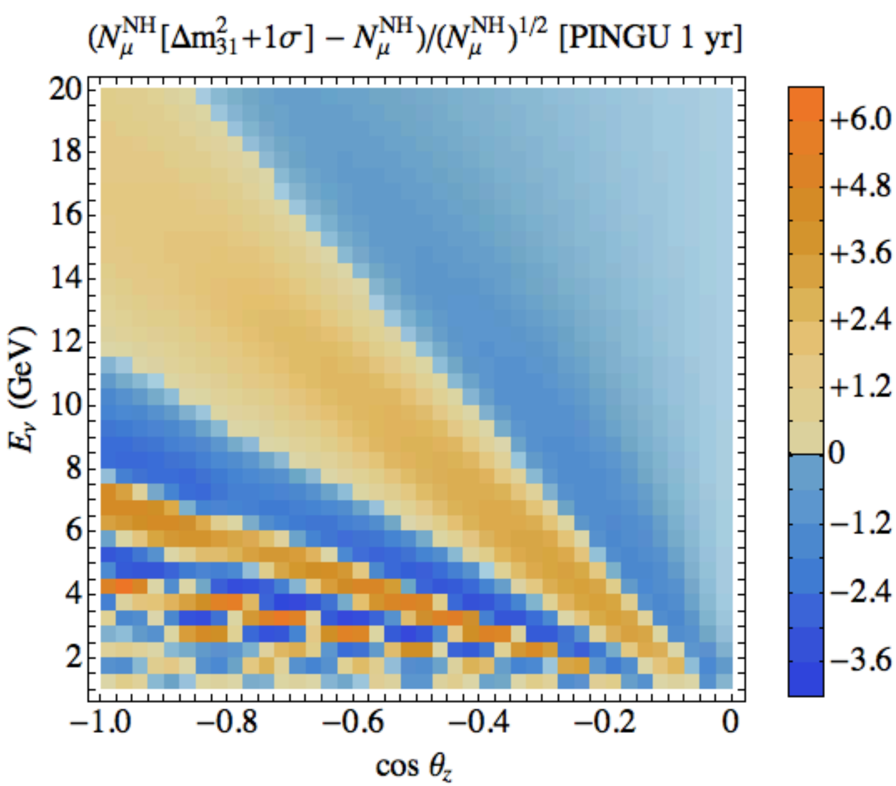

$\sigma_E = 0.2E_\nu$, $\sigma_\theta = 1.2(m_p/E_\nu)^{1/2}$



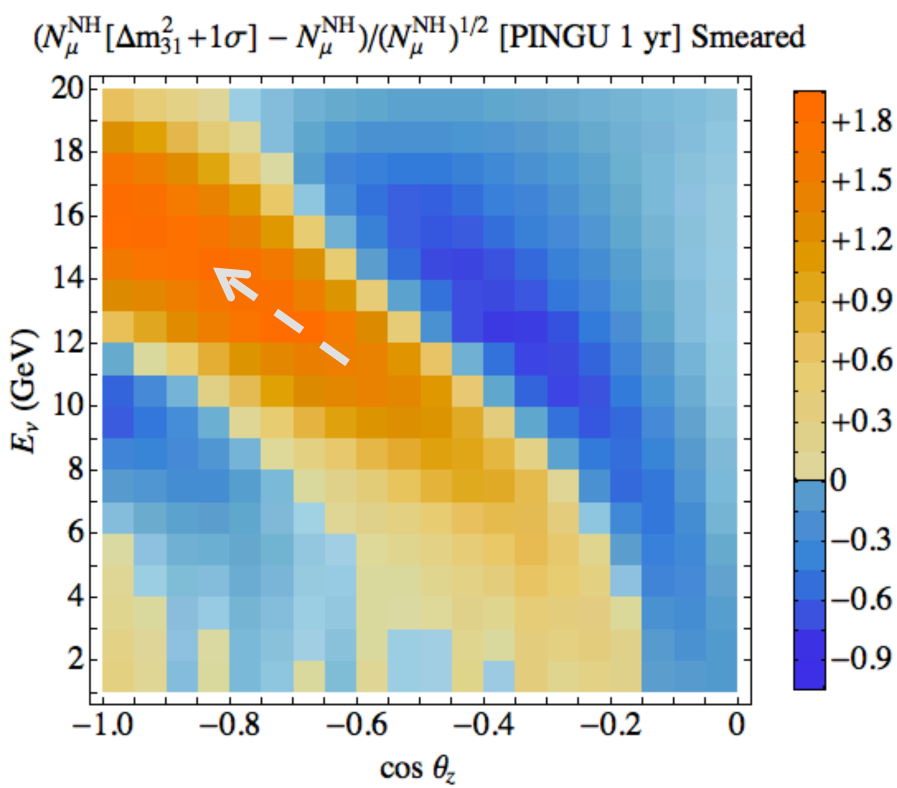
# Effect of uncertain value of $|\Delta m_{31}|^2$

Degeneracy in 3-2 mass-squared difference can mimic hierarchy determination significance distribution in the $E_\nu$ - $\theta_z$ plane

If E and θ could be accurately reconstructed




After Gaussian smearing (Most sensitive region for hierarchy and $|\Delta m_{31}|^2$ are separate)



# Hierarchy determination significance

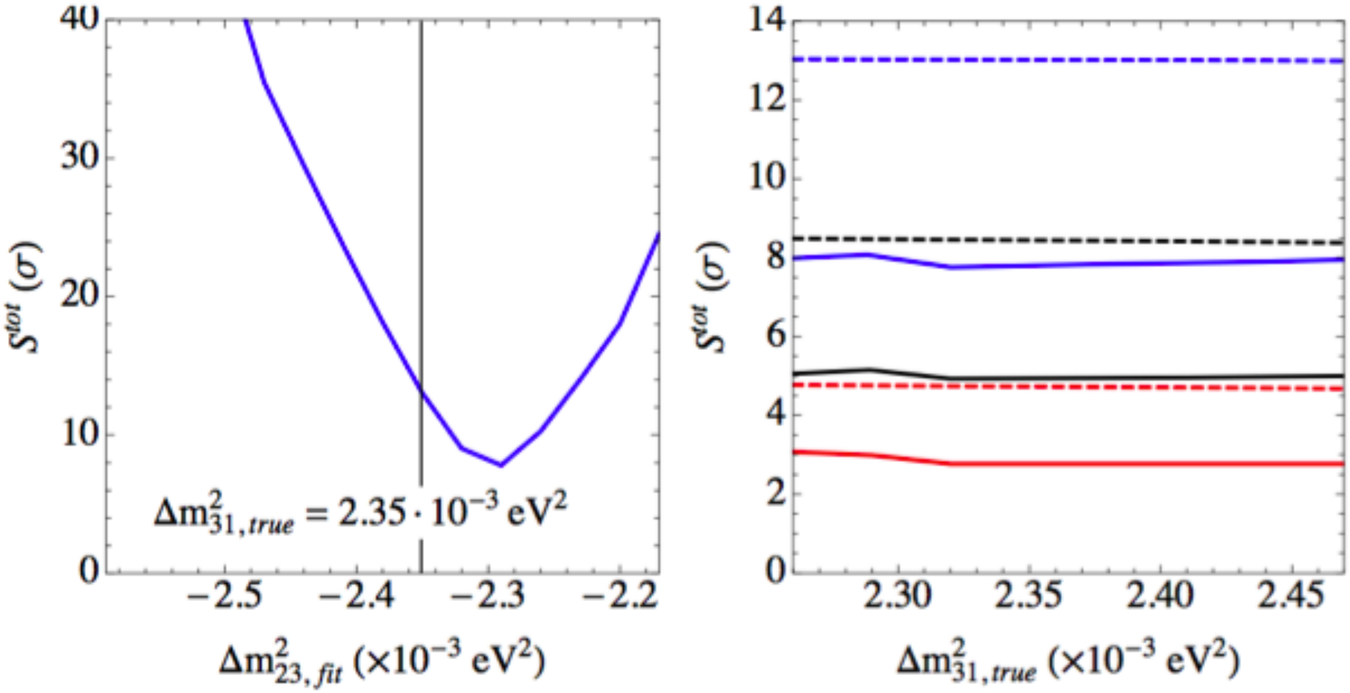
Calculate total significance from binned data, after accounting for reconstruction errors

$$S^{tot} = \sqrt{\sum_{ij} S_{ij}^2} = \sqrt{\sum_{ij} \frac{(N_{ij}^{IH} - N_{ij}^{NH})^2}{\sigma_{ij}^2}}, \ \sigma_{ij}^2 = N_{ij}^{NH} + (f N_{ij}^{NH})^2$$

Minimize over $\Delta m_{23}^2$ fit values to the true unknown $\Delta m_{31}^2$ value

5 years of PINGU data

If true $\Delta m_{31}^2$ is known (dashed) or uncertain within $\pm 1\sigma$ (solid)



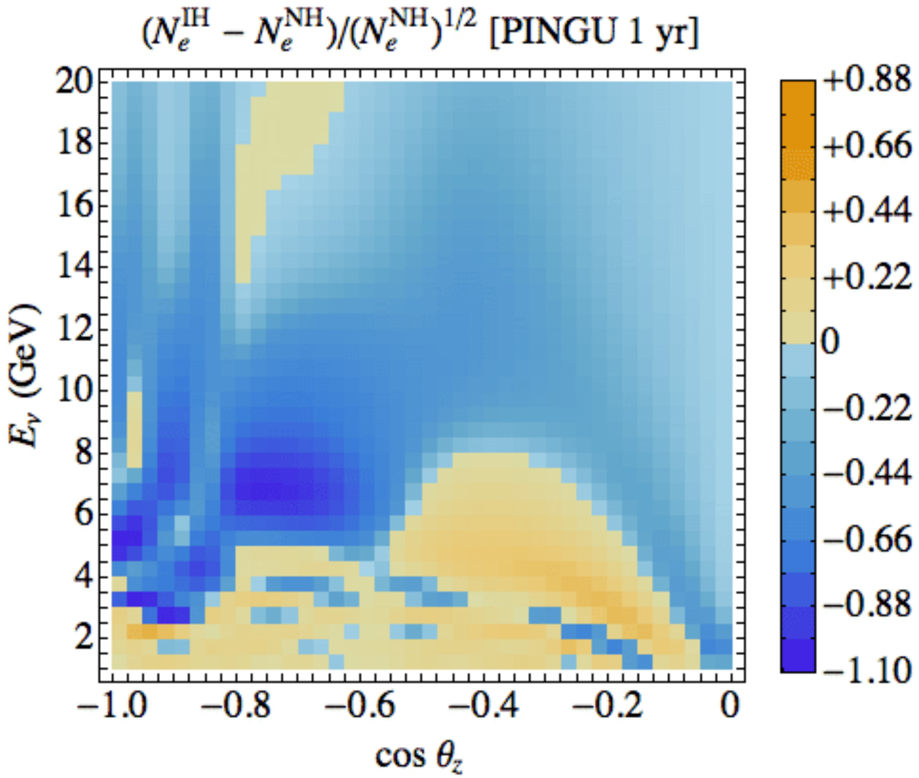
# Cascade events in PINGU

Asymmetry for NH and IH for $\nu_e$ events arises from

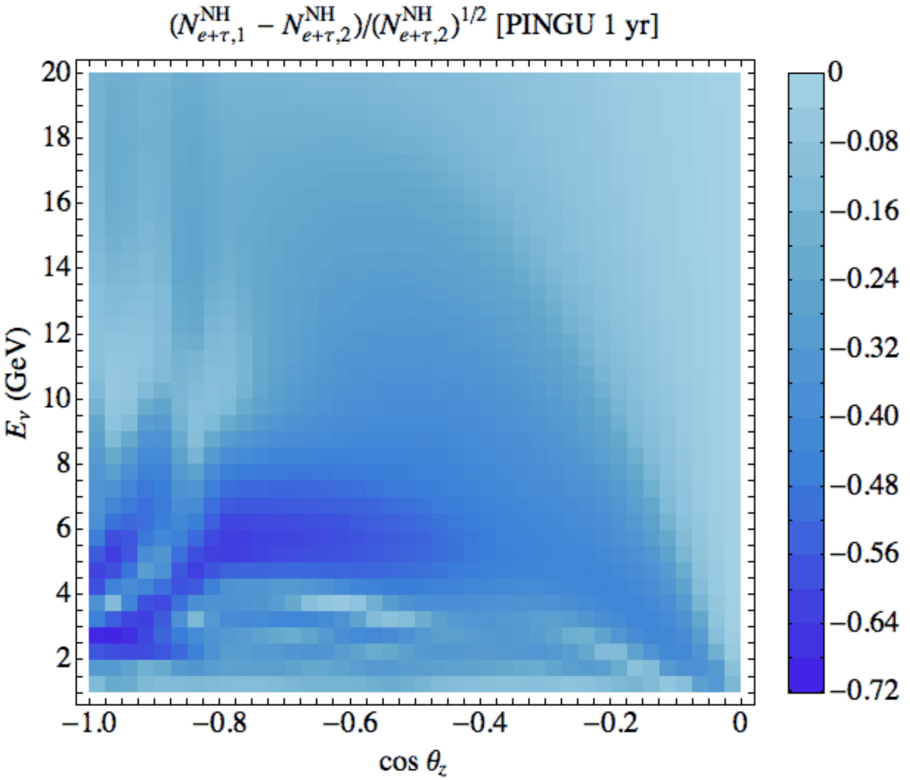
$$D_e^{\rm IH} - D_e^{\rm NH} = \sigma^{CC}\Phi_e^0\,(\bar{P}_A - P_A)\left[(rs_{23}^2 - 1) - \kappa_e(\bar{r}s_{23}^2 - 1)\right]$$

Cascade events from $\nu_\mu$ - $\nu_\tau$ oscillation reduce significance

Electron ν only




Electron + tau ν



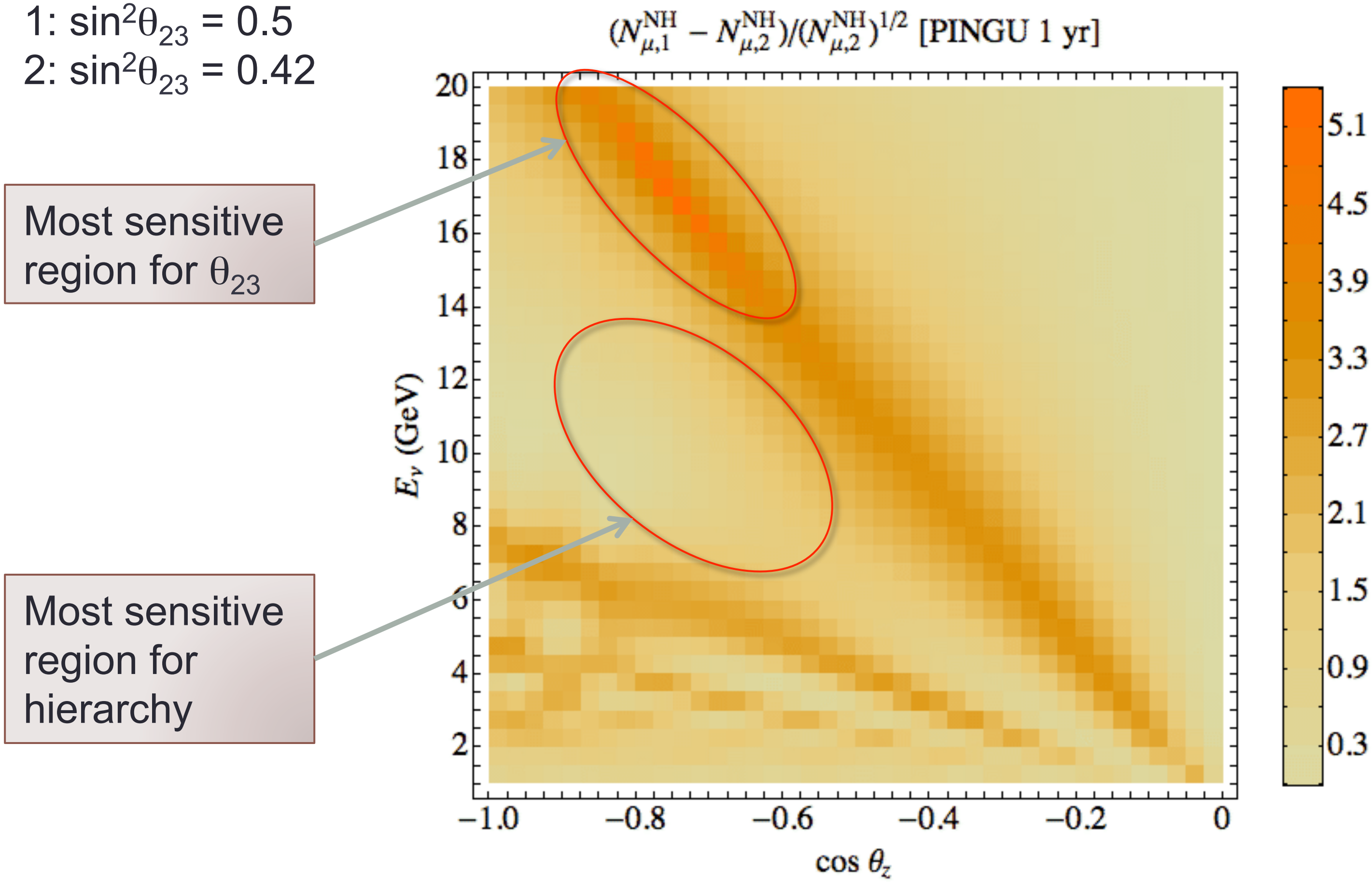
# Sensitivity to $\theta_{23}$

Asymmetry in events for 2 different $\theta_{23}$ arises from

$$D_\mu^{NH}(\theta_{23}) - D_\mu^{NH}(\pi/4) \approx \sigma^{CC}\Phi_\mu^0 \left\{2d_{23}^2\left[1-\sqrt{1-P_A}\cos\phi_X\kappa_\mu(1-\cos\phi_{32})\right] + d_{23}\left(1-\frac{1}{r}-d_{23}\right)P_A\right\}$$

1: $\sin^2\theta_{23} = 0.5$
2: $\sin^2\theta_{23} = 0.42$

$$d_{23} \equiv \frac{1}{2} - s_{23}^2$$

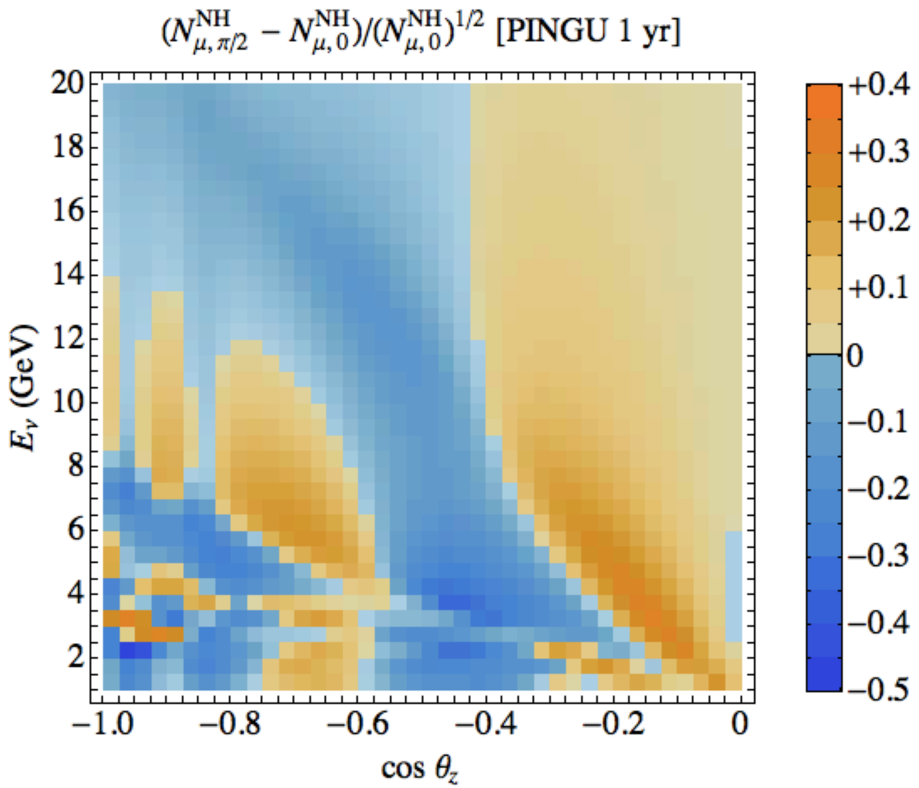


# Sensitivity to CP phase

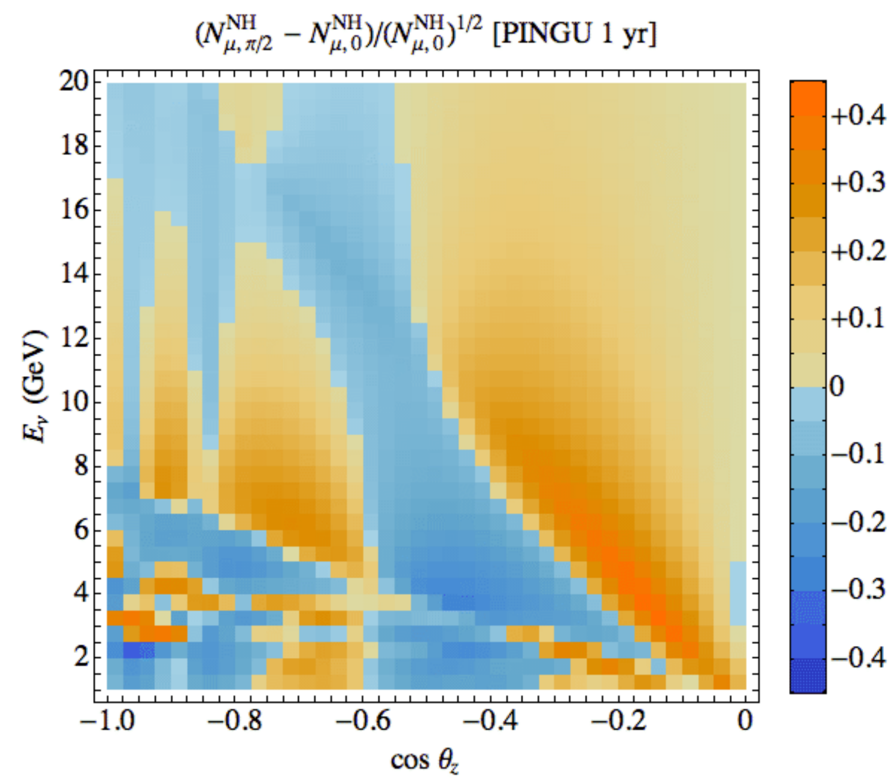
Asymmetry in events for 2 different CP phases arises from

$$D_\mu^\delta - D_\mu^{\delta=0} = \sigma^{CC}\Phi_\mu^0 \sin 2\theta_{23}\sqrt{P_A P_S}\left[\frac{r-1}{r}\cos\phi(1-\cos\delta) - \frac{1}{r}\sin\phi\sin\delta\right]$$

$\delta = \pi/2$ and 0, $\sin^2\theta_{23} = 0.42$




$\delta = \pi/2$ and 0, $\sin^2\theta_{23} = 0.5$



# IceCube's sensitivity to sterile neutrinos

Mixing of sterile $\nu$ with active $\nu$ affect probabilities of active-to-active $\nu$ flavor conversions

MSW resonance condition
$$\frac{\Delta m_{03}^2}{2E}\cos 2\alpha = -\frac{1}{\sqrt{2}} G_F n_n$$

$\alpha$ mixes $\nu_4$ and $\nu_3$ states

Resonance energy for typical earth-crossing density: $E \sim (2-5)\ \mathrm{TeV}\ (\Delta m_{03}^2/1\mathrm{eV}^2)$

- MSW resonance effect appears in the antineutrino channel ( '-' potential)
- Effects of 2-3 mixing and mass-splitting becomes dominant below ~0.5 TeV
  - affect both neutrinos and anti-neutrinos

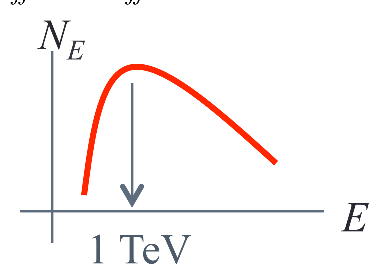
IceCube energy range is well-suited to explore sterile $\nu$ signature using atmospheric $\nu$ flux

*Nunokawa, Peres & Zukanovich Funchal 2003*
*Coubey 2007*
*Razzaque & Smirnov 2011*
*Barger, Gao & Marfatia 2011*

Roughly the number of $\nu_\mu$ events scales as

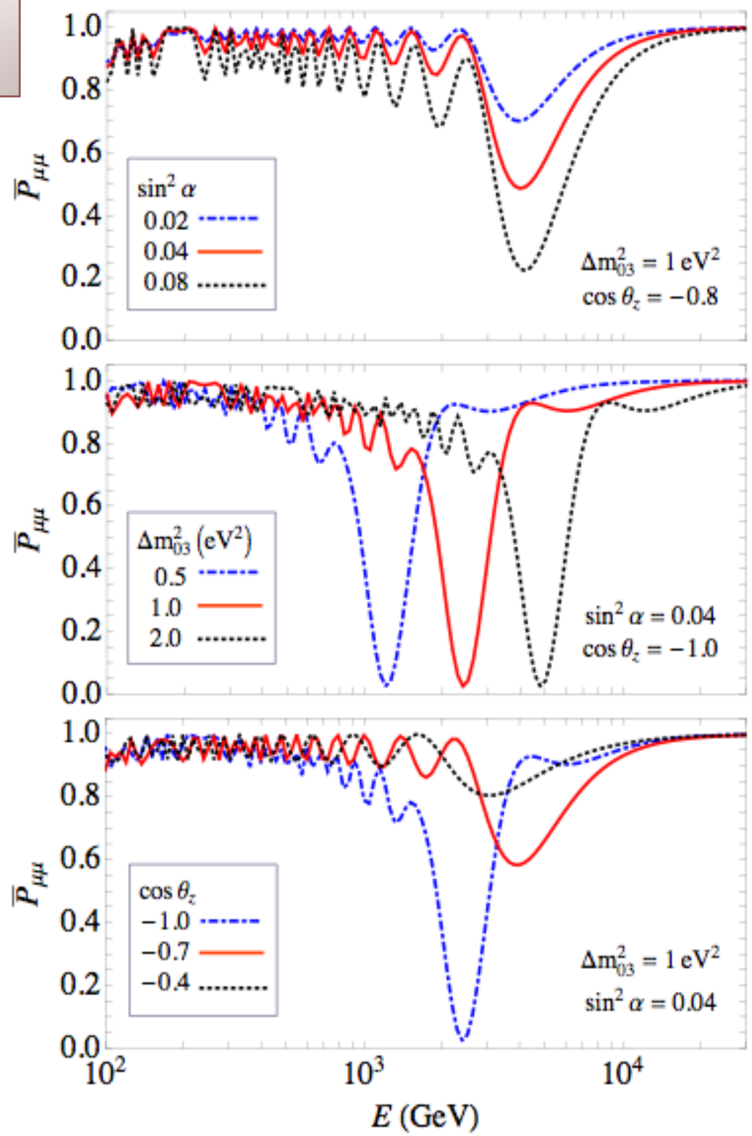
$$N_E \sim A_{eff}\, E\, \Phi_\nu\ ; \Phi_\nu \propto E^{-3.7}\ ; A_{eff} \sim V_{eff}\, n_N\, \sigma_{nN}\, \varepsilon_{\mathrm{det}}$$

$$V_{eff} \propto R_\mu^3 \propto \begin{cases} E^3 ; < 1\,\mathrm{TeV} \\ (\ln E)^3 ; > 1\,\mathrm{TeV} \end{cases}$$

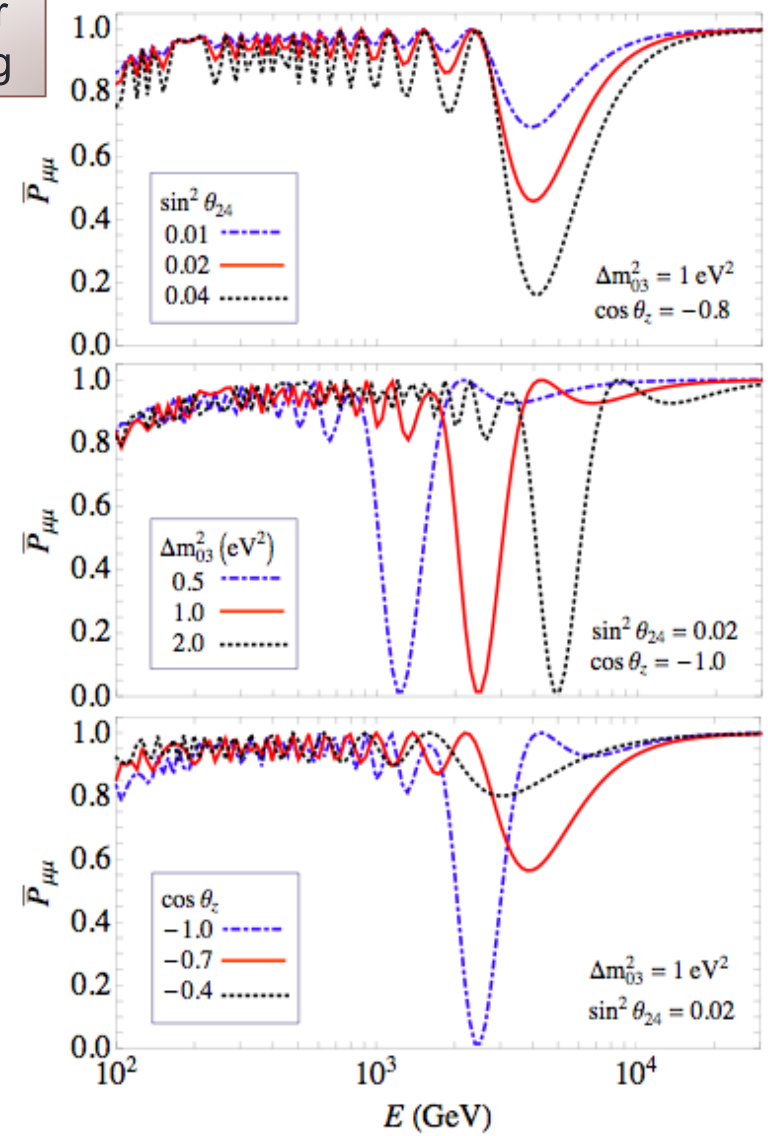


# Atmospheric $\bar{\nu}_\mu$ - $\bar{\nu}_\mu$ oscillation with sterile

Mass mixing

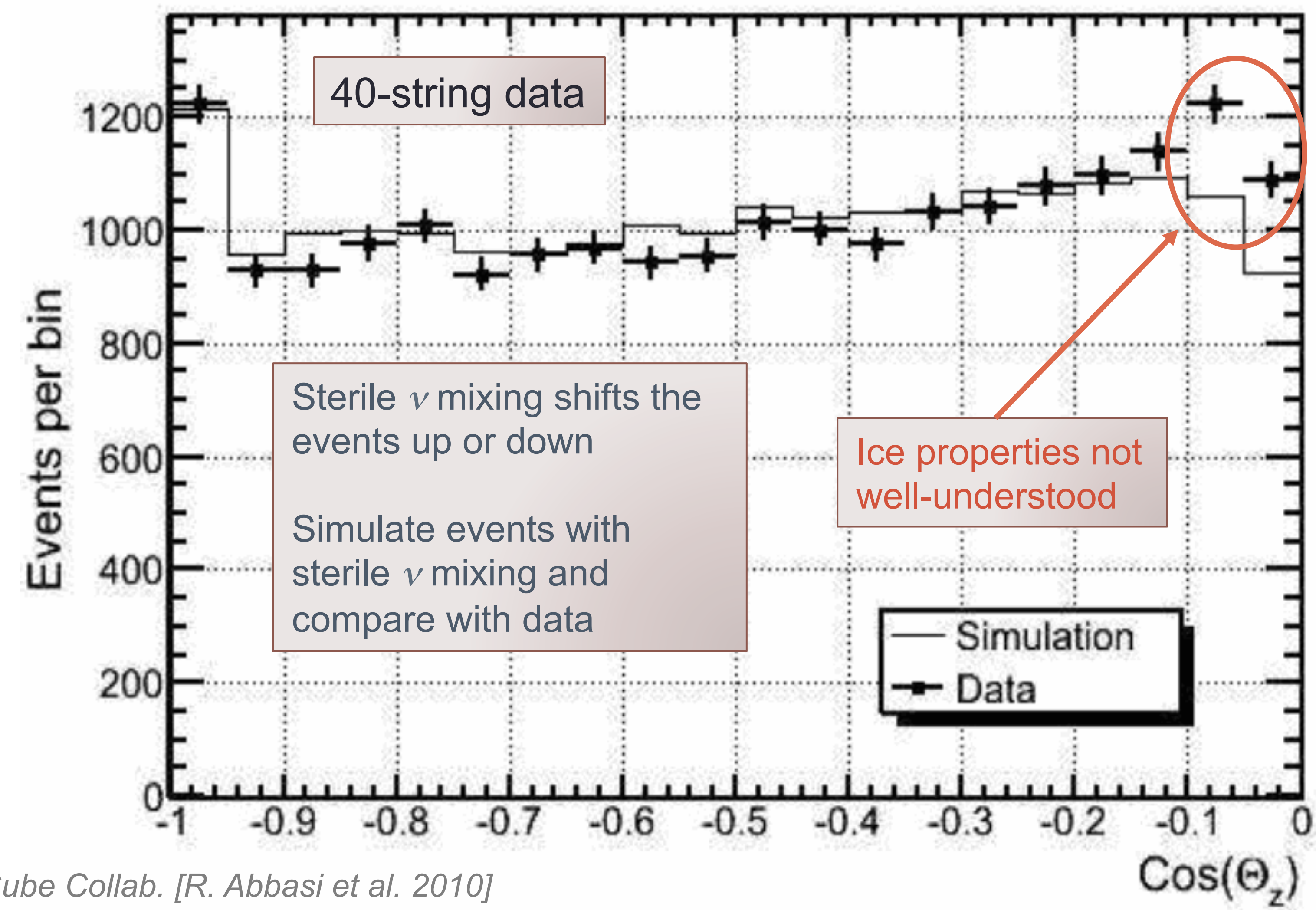



Flavor mixing



# Zenith angle distribution of $\nu_\mu$ events in IC

Integrated over $E$ > 100 GeV in each bin

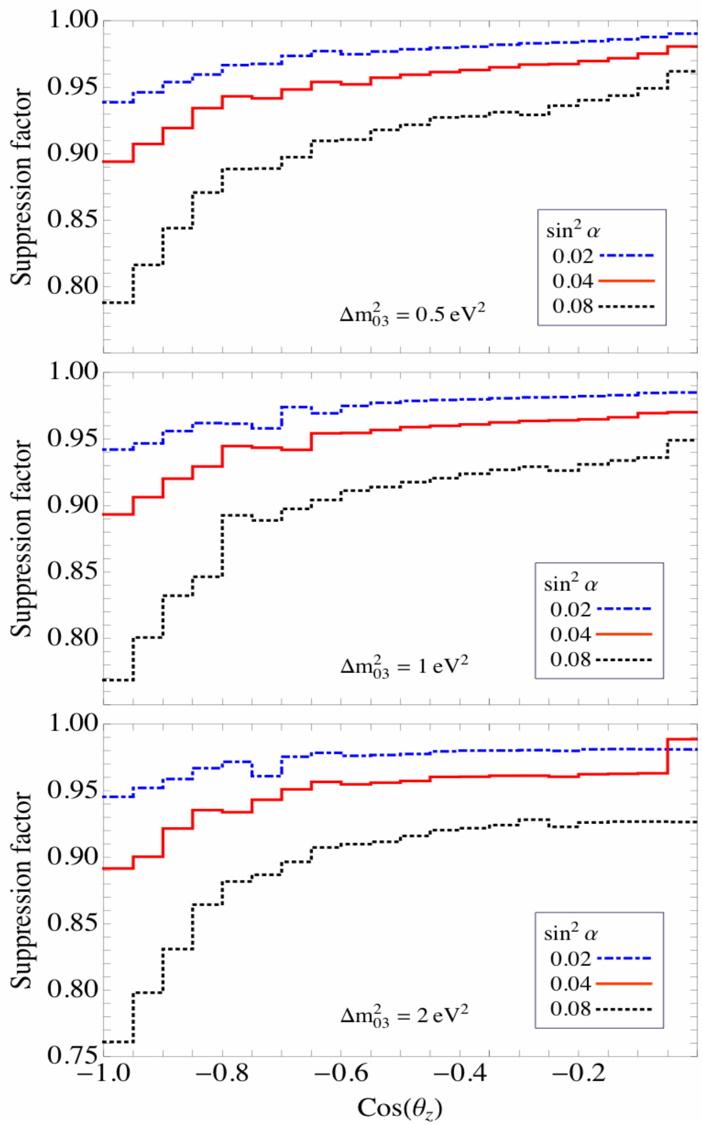



*IceCube Collab. [R. Abbasi et al. 2010]*

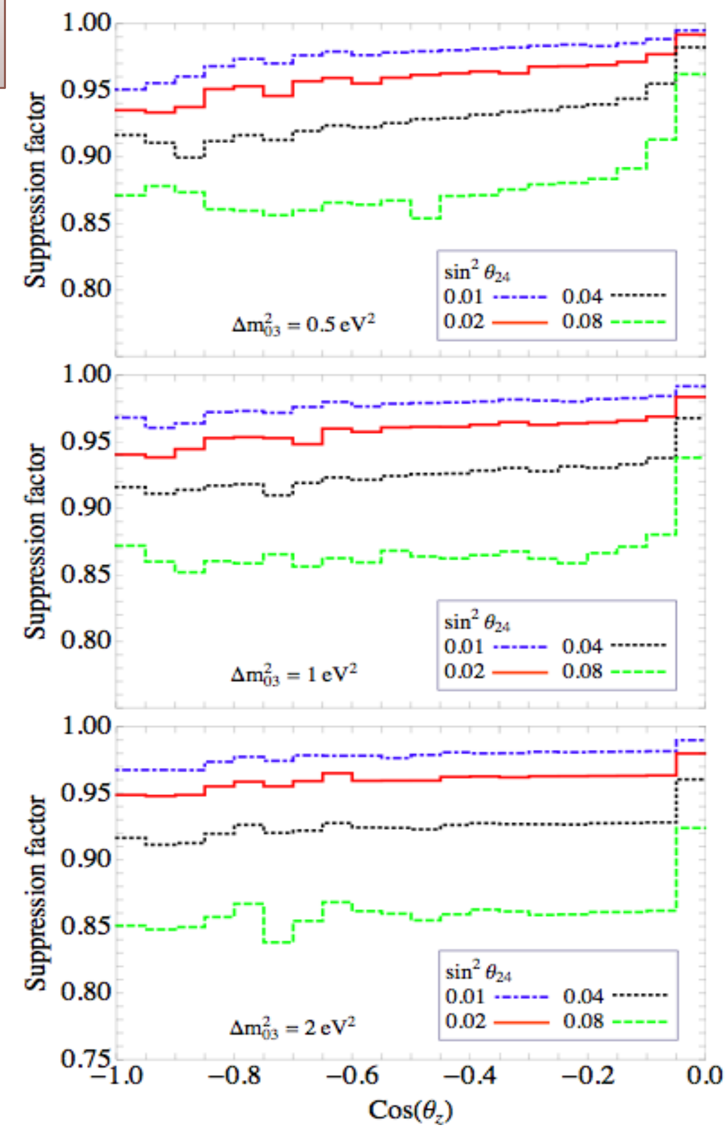
# Suppression of $\nu_\mu$ events in IC

Ratio between events with and without $\nu_s$

Mass mixing

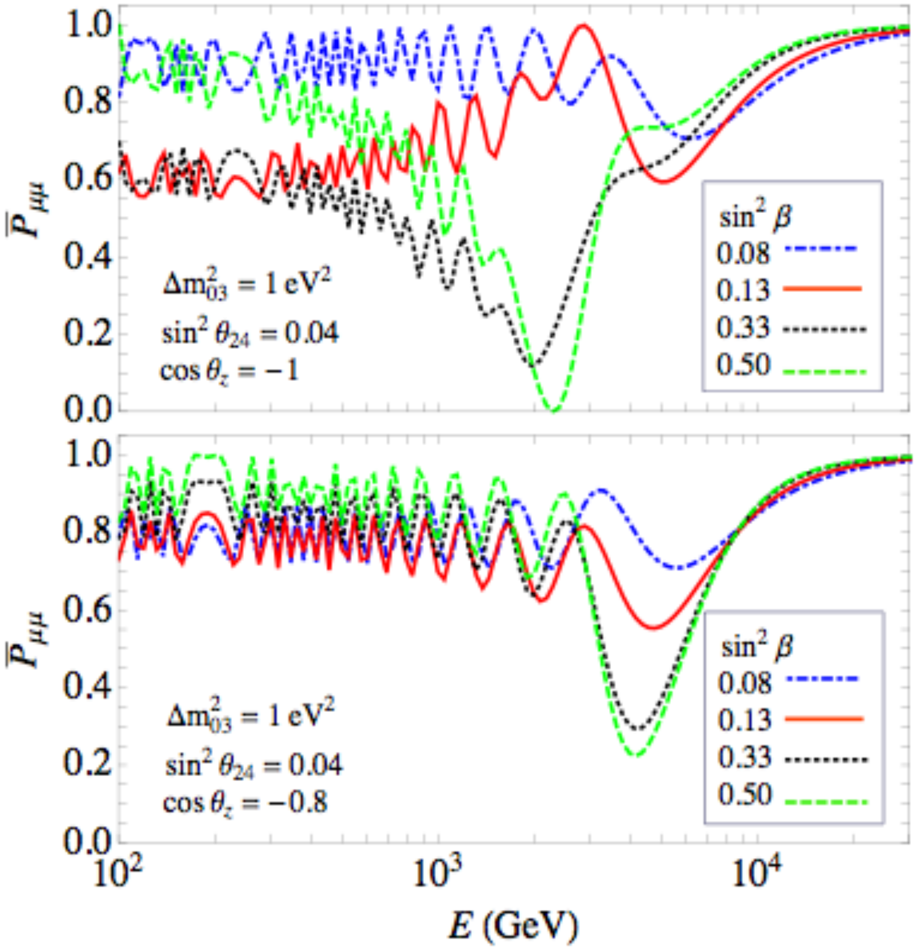



Flavor mixing



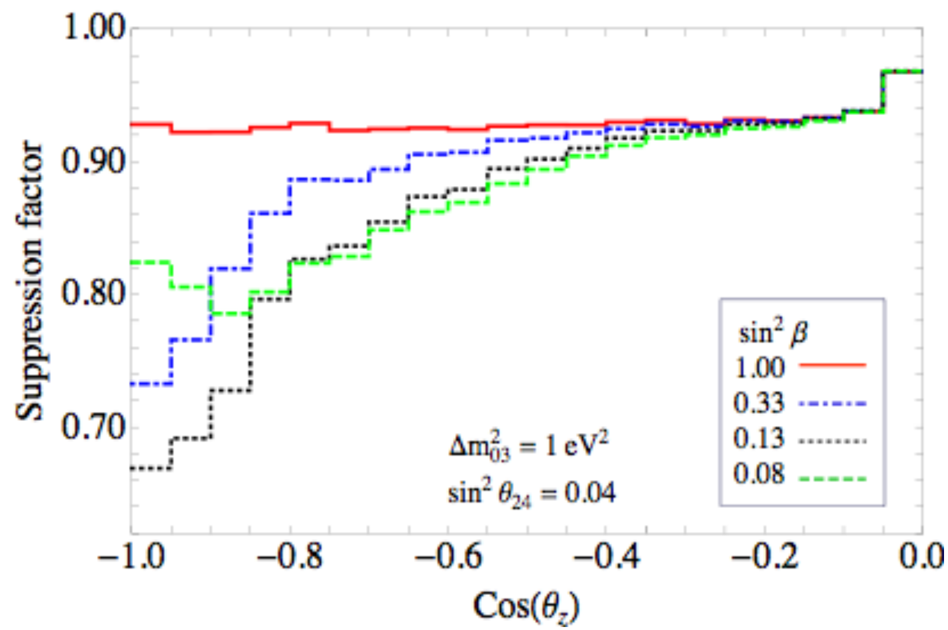
# Different sterile mixing schemes

Mixing angles between $\nu_4$ and $\nu_2$ , $\nu_4$ and $\nu_3$ can be different




Effects of different mixing angles

$$\sin^2\beta = \frac{s_{24}^2}{s_{24}^2 + s_{34}^2 - s_{34}^2 s_{24}^2} \approx \frac{s_{24}^2}{s_{24}^2 + s_{34}^2}$$



# Sterile mixing effect in Deep Core

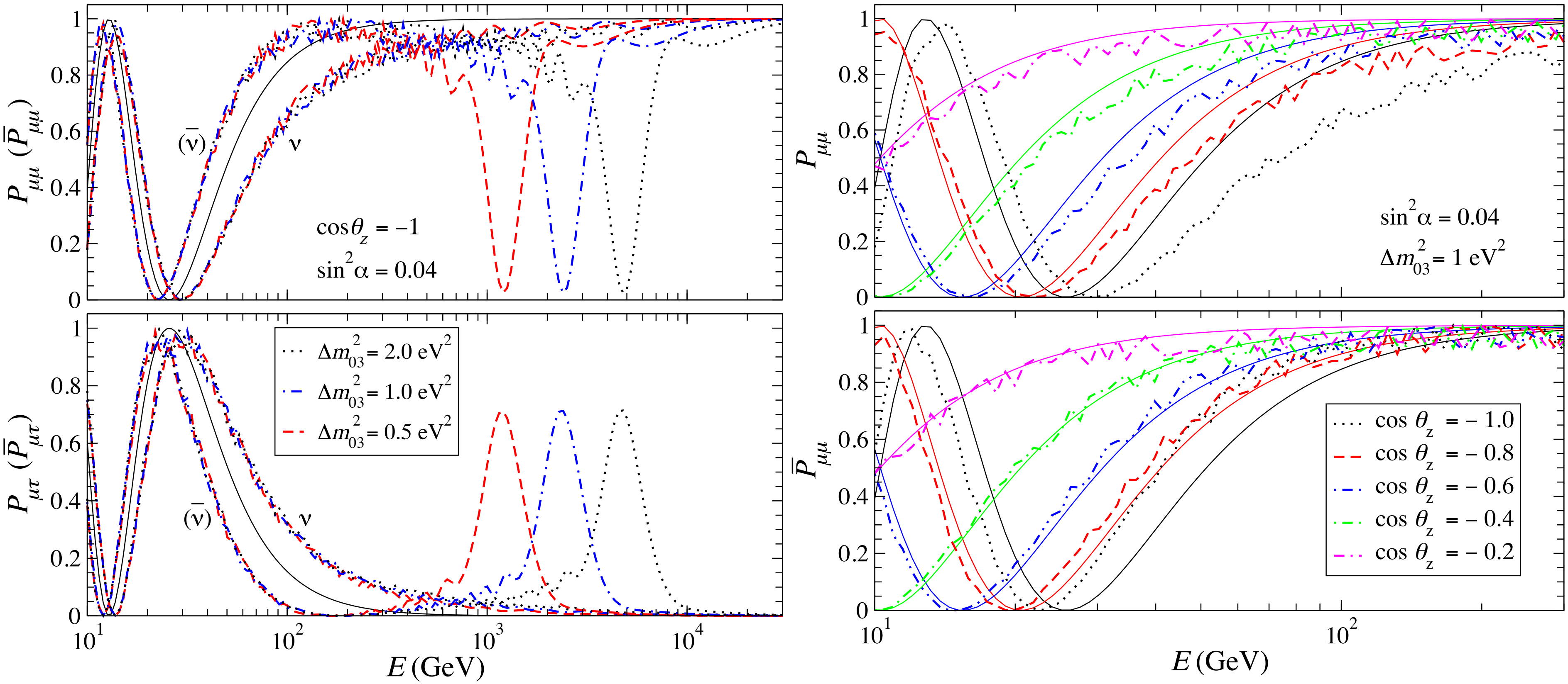
Mass-mixing scheme

First oscillation minimum for $\nu_\mu - \nu_\mu$

$$E^0_{\rm min} = \frac{1}{\pi}\Delta m^2_{32} R_\oplus \cos\theta_z \quad \sim 25.7 \text{ GeV } (\theta_z = \pi)$$

- Matter-induced shift due to $\nu_s$ mixing
- Implications for mass hierarchy

$$E_{\rm min} \approx \frac{|\Delta m^2_{32}|}{\frac{\pi}{R_\oplus \cos\theta_z} \mp 2|V_\mu(\cos\theta_z)|\sin^2\alpha} = \frac{E^0_{min}}{1 \mp \frac{2}{\pi}|V_\mu(\cos\theta_z)|R_\oplus \sin^2\alpha\cos\theta_z}$$



# Summary

- Huge Atmospheric neutrino detector such as PINGU can determine mass hierarchy with high significance
  - Sensitivity to CP phase is rather low
- IceCube and Deep Core can be very effective to search for light sterile neutrinos
  - 10’s of thousands of events/year!

# Summary

- Huge Atmospheric neutrino detector such as PINGU can determine mass hierarchy with high significance
  - Sensitivity to CP phase is rather low
- IceCube and Deep Core can be very effective to search for light sterile neutrinos
  - 10's of thousands of events/year!

Go PINGU!!!

# Fermilab Today

Friday, July 22, 2005

## Calendar

**Friday, July 22**
**3:30 p.m.** DIRECTOR'S COFFEE BREAK - 2nd Flr X-Over
**4:00 p.m.** Joint Experimental Theoretical Physics Seminar - 1 West
Speaker: R. Demina, University of Rochester
Title: Top Quark Mass Measurement from DZero

**Monday, July 25**
PARTICLE ASTROPHYSICS SEMINARS WILL RESUME IN THE FALL
**3:30 p.m.** DIRECTOR'S COFFEE BREAK - 2nd Flr X-Over
**4:00 p.m.** All Experimenters' Meeting - Curia II

## Weather

Mostly Sunny 93º/66º

Extended Forecast

Weather at Fermilab

## Current Security Status

Secon Level 3

## TeV Particle Astrophysics: The Workshop in Review

Chris Quigg presents Soebur Razzaque of Penn State University with first prize at Thursday's poster session.

Last Wednesday, Fermilab Director Pier Oddone welcomed attendees of the TeV Particle Astrophysics Workshop with a little known fact about himself. "I have had a soft-spot for particle astrophysics all along," he said. "I think this connection is very deep…it enhances our field." Following Oddone, theoretical astrophysicist and workshop organizer Gianfranco Bertone outlined the main topics of the three-day conference. Covering everything from neutrino detection, to dark matter research, to discussion of a unified theory, the workshop would be a full three days.

## Drug Sniffing Dogs Perform At Users' Center Tonight

One of the many incarnations of Drug Sniffing Dogs, the CDF band, will perform at the Users' Center tonight at 7:30.

Drug Sniffing Dogs, the CDF band, will play at the Users' Center on Friday, July 22. The show will begin at 7:30 p.m. and will include renditions of approximately 35 songs spanning the last 40 years of rock 'n' roll.

"The band has been playing in one form or another since 1985," said Steve Hahn, who leads the band, playing guitar and keyboards. "We've been around longer than most CDF collaborators!" Currently, the band includes Hahn, guitarists Randy Thurman and Greg Field (who doubles as a vocalist), bassists Larry Nodulman and Aron Soha, Andy Hocker and Ulrich Husemann on saxophone, vocalist Ben Kilminster, and drummer Todd Keaffaber.

# Back up slides

# Evolution of $\nu$ states

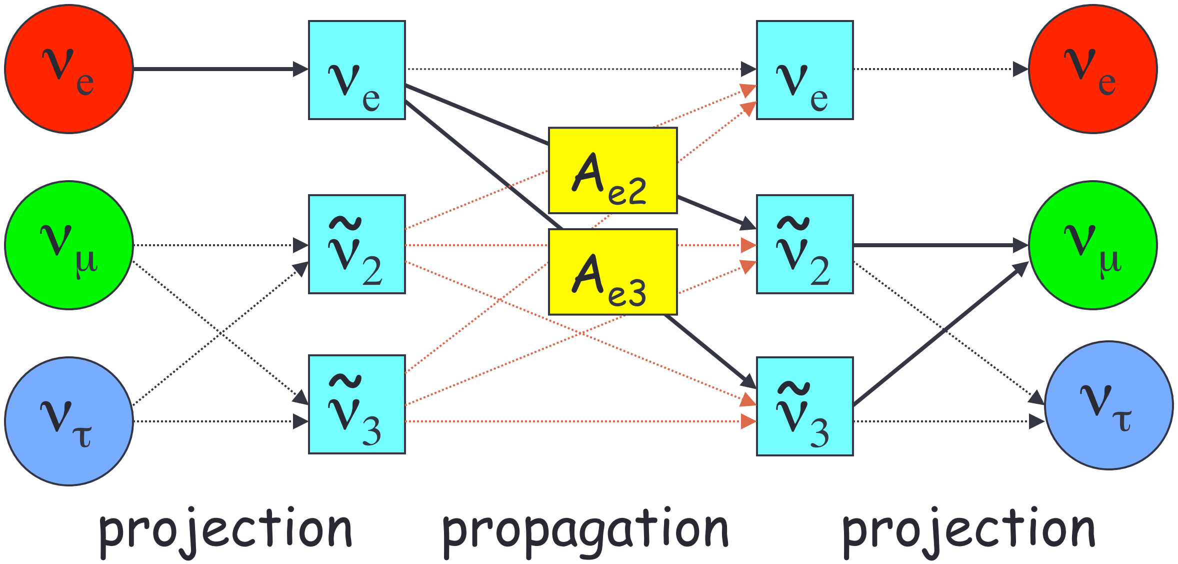
For E > 0.1 GeV

**Propagation basis**

$\nu_f = U_{23} I_\delta \tilde{\nu}$

$I_\delta = \mathrm{diag}\,(1, 1, e^{i\delta})$

CP-violation and 2-3 mixing are excluded from dynamics of propagation




CP appears in projection only

$A_{22}$ $A_{33}$ $A_{23}$

For instance: $A(\nu_e \to \nu_\mu) = \cos\theta_{23} A_{e2} e^{i\delta} + \sin\theta_{23} A_{e3}$

# Oscillation probabilities

for hierarchy determination

$$P(\nu_e \to \nu_\mu) = s_{23}^2 |A_{e3}|^2$$

$$P(\nu_\mu \to \nu_\mu) = 1 - \tfrac{1}{2} \sin^2 2\theta_{23} - s_{23}^4 |A_{e3}|^2 + \tfrac{1}{2} \sin^2 2\theta_{23} (1 - |A_{e3}|^2)^{\frac{1}{2}} \cos\phi$$

Reduces the average probability

Reduces the depth of oscillations interference

Modifies phase

$$\phi = \arg (A_{22} A_{33}^*)$$

$$P(\nu_\mu \to \nu_\tau) = \tfrac{1}{2} \sin^2 2\theta_{23} - s_{23}^2 c_{23}^2 |A_{e3}|^2 - \tfrac{1}{2} \sin^2 2\theta_{23} (1 - |A_{e3}|^2)^{\frac{1}{2}} \cos\phi$$

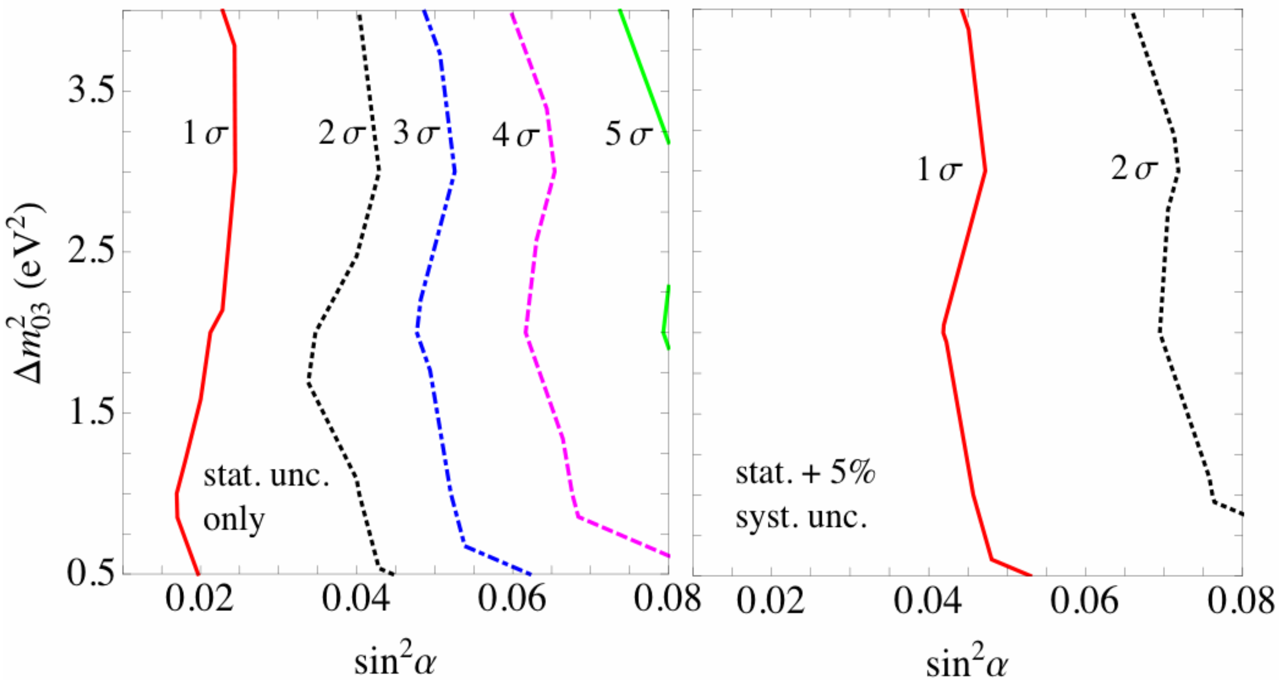
# Bound on sterile ν parameter

Null hypothesis (without sterile $\nu$ mixing) fits data rater well

$$\chi^2_{\rm min,null} = 14.16\ (20\ {\rm dof});\ C = 0.98,\ \tau = 0.04$$

Null (MC)

Reject sterile $\nu$ mixing models: $\Delta\chi^2 = \chi^2_{\rm min,model} - \chi^2_{\rm min,null}$




Models with large mixing of sterile $\nu$ with active $\nu$'s can be constrained

$$|U_{\mu 0}|^2 = \sin^2\theta_{23}\sin^2\alpha \approx \tfrac{1}{2}\sin^2\alpha$$

$$|U_{\mu 0}|^2 \sim 0.02 - 0.04$$