Neutrino mass hierarchy with atmospheric neutrinos:

Exploiting the interaction inelasticity for partial discrimination of ν_μ - $\bar{\nu}_\mu$ fluxes in Megaton-scale detectors (ORCA, PINGU)

M. Ribordy
LPHE - EPFL - CH

Paris, April, 2013

Content

Brief reminder on NMH discrimination

Interaction inelasticity and 3D-oscillograms

Significance (upper bound and experimental)

Parameter degeneracy

References:

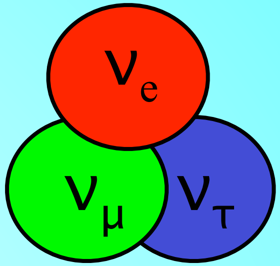
- E. Akhmedov, S. Razzaque, A. Y. Smirnov.**JHEP 1302 (2013) 082** [arXiv: 1205.7071]

- M. R., A.Y.Smirnov, arXiv:1303.0758

- M.R. arXiv:1205.4965

credit: some slides from A. Smirnov's talk given in Heraeus seminar, Bad Honnef, Jan. 2013

Reminder

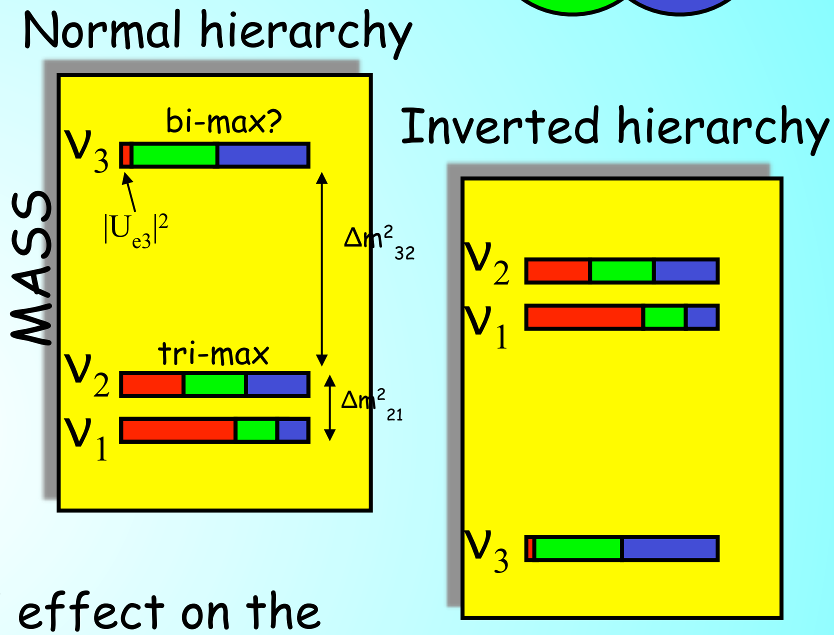


Matter effect enables in principle neutrino mass hierarchy discrimination

- distinct $P_{\alpha\beta}$ for ν_α and $\bar{\nu}_\alpha$ in the electronic matter potential

- NH $\leftrightarrow$ IH $\equiv$ $\nu \leftrightarrow \bar{\nu}$ but $\sigma\Phi_\nu \neq \bar{\sigma}\Phi_{\bar{\nu}}$
(2ν system)

(note that $p(\bar{\nu})_{NH} \approx p(\bar{\nu})_{vac}$, $p(\nu)_{IH} \approx p(\nu)_{vac}$)

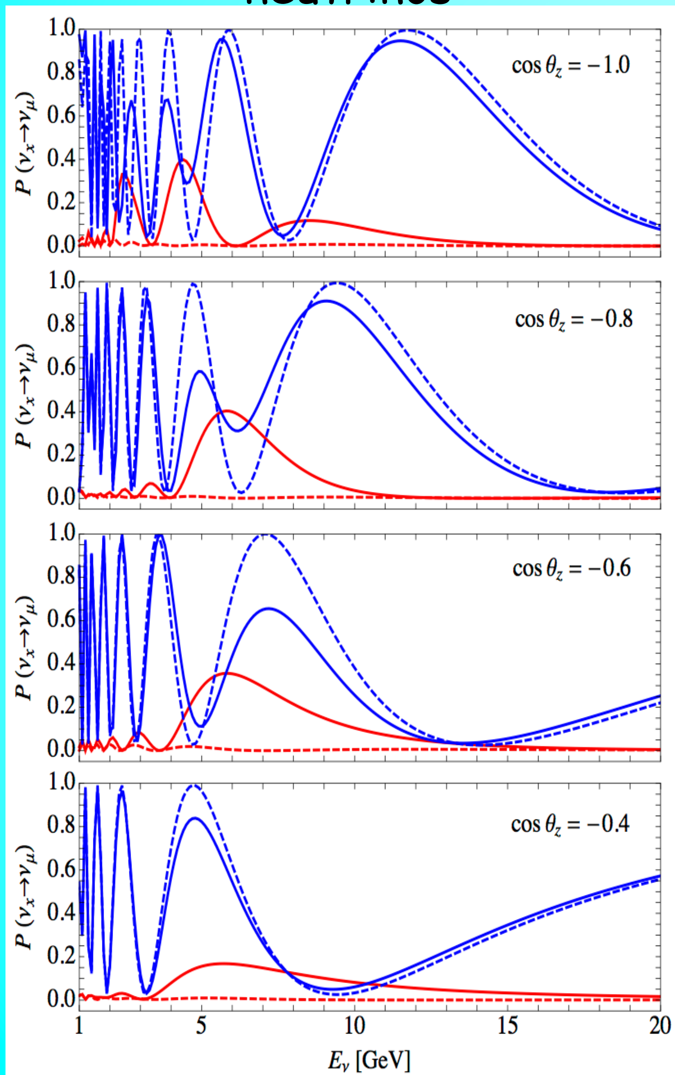


- Current value of $\theta_{13} \cong 10^o$ ➞ sizable MH effect on the atm. ν beam between {few GeV, ≈20 GeV}, i.e. energies, which can be probed with affordable (?) Megaton-scale detectors

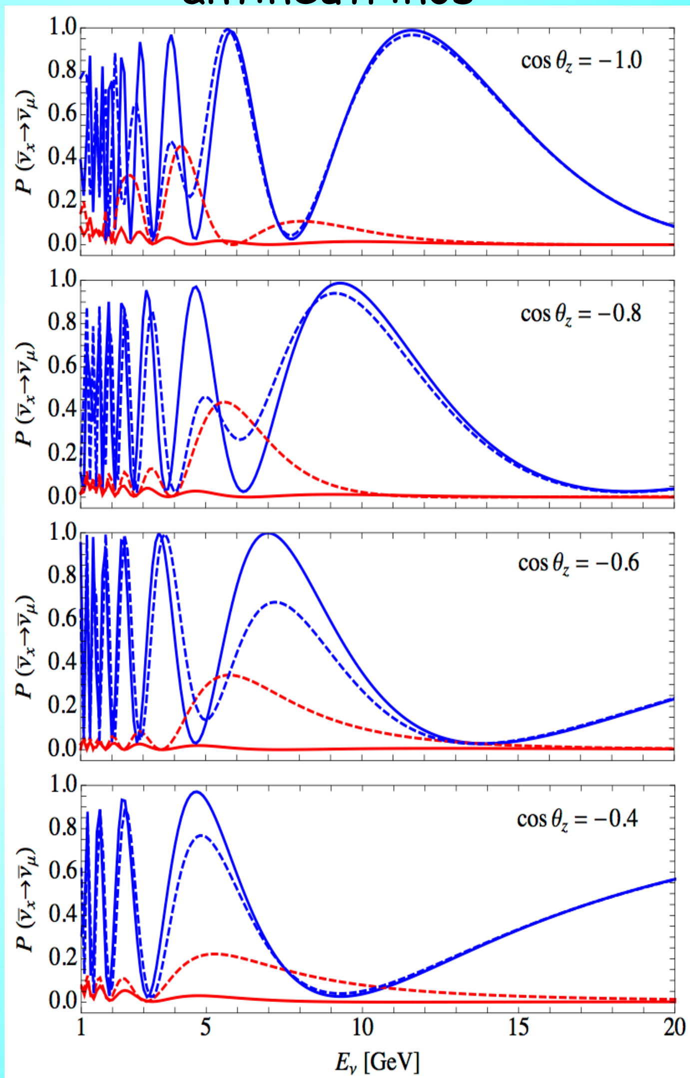
- Muon neutrinos are particularly good candidates, because
  - induced muons keep ≈ track of the original neutrino incoming direction with an angle $\theta_{\mu\nu} \equiv \beta \sim \sqrt{\frac{GeV}{E_\nu}}$
  - CC interaction ➞ composite events, $E_\mu \approx (1-y)E_\nu$ $E_h \approx yE_\nu$ ➞ constraint $\beta(y)$

Oscillation probabilities

neutrinos



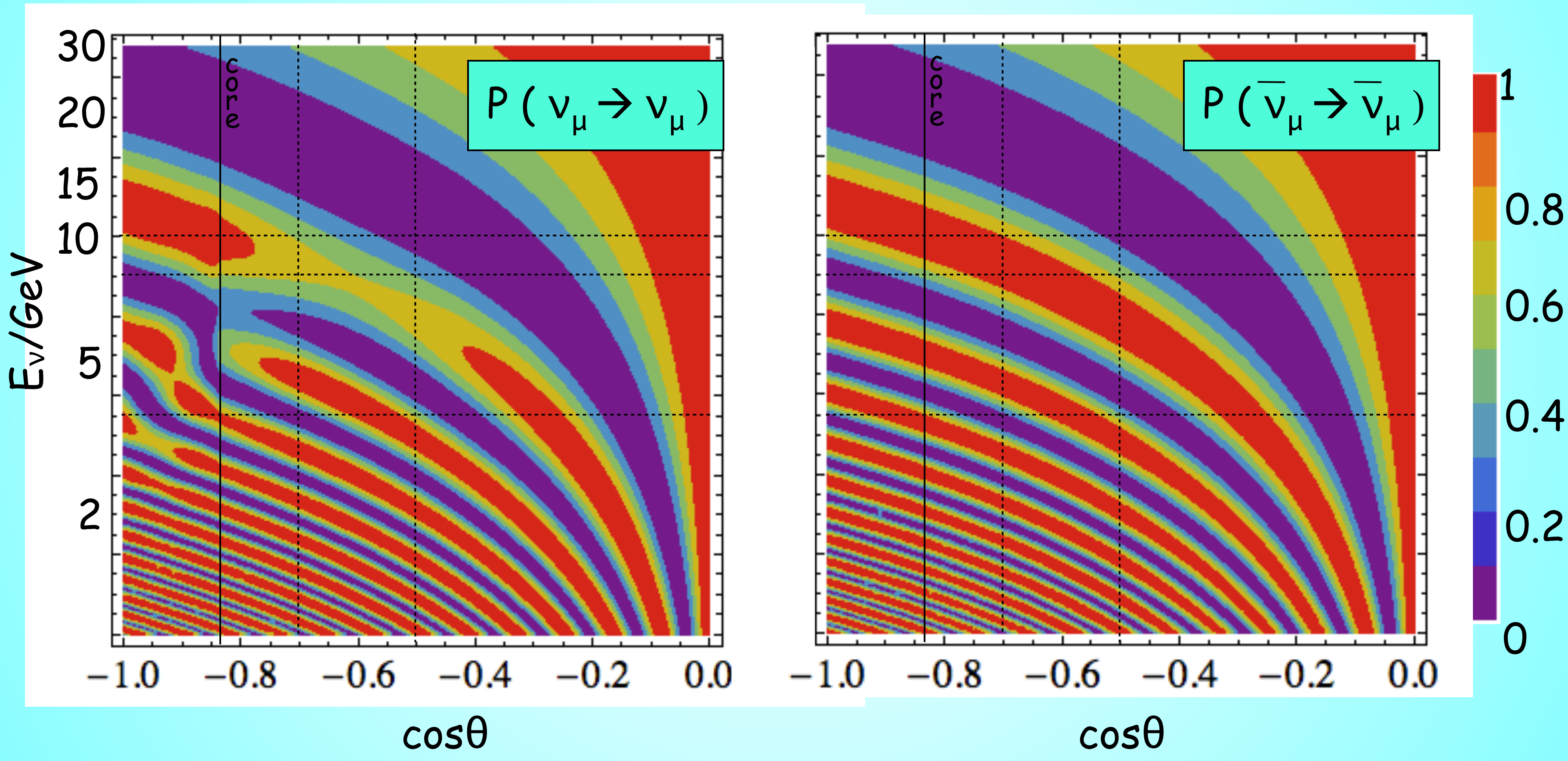
antineutrinos



NH - solid
IH - dashed
x = μ - blue
x = e - red

$$\mathrm{NH} \leftrightarrow \mathrm{IH} \equiv \nu \leftrightarrow \bar{\nu}$$

Neutrino oscillograms



Contours of constant oscillation probability in {energy , zenith angle} plane

Atmospheric neutrinos

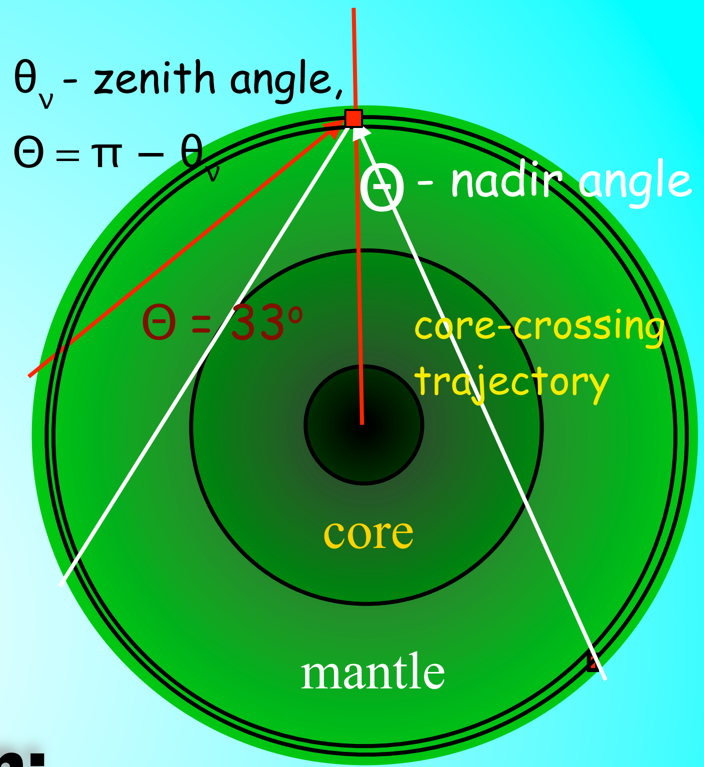
Energy range: E_ν = 0.01 – 10^5 GeV

Baselines: L = 0 – 13000 km

→ Matter effects: ρ = 2.5 – 13 g/cm^3

⊕ energy and zenith dependence of

- $\{ \Phi_\nu \}_\alpha$ (flavor content)
- $\{ \Phi_\nu / \Phi_{\bar{\nu}} \}_\alpha$ (lepton number)



Limitations to NMH identification:

Flavor identification

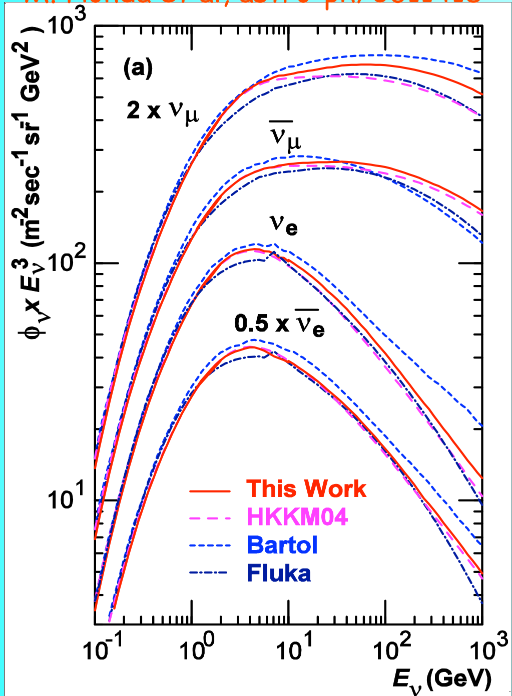
- Partial cancellation of the NMH effect from the presence of ν and $\bar{\nu}$ in the atm. neutrino beam
- Presence of other flavors:
  - ν_e, which accentuates the cancellation
  - ν_τ, from oscillations: τ decay into μ with BR~18%

and Uncertainties of original fluxes → high statistics

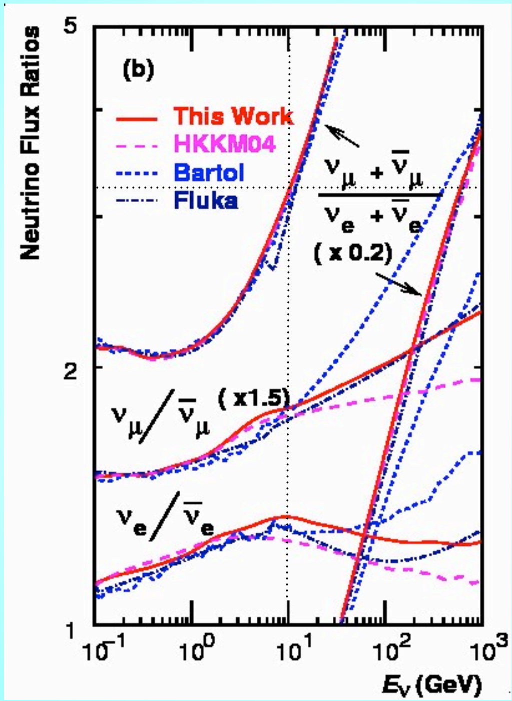
mardi, 16 avril 2013

Energy spectra

M. Honda et al, astro-ph/0611418



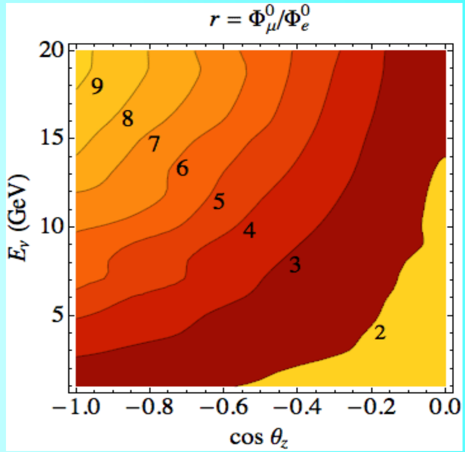
Neutrino fluxes averaged over all directions

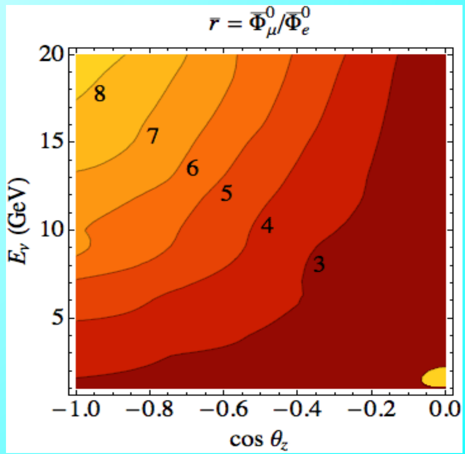


Flavor ratios

Charge asymmetries

Flux ratios





Further challenge to NMH identification

- Kinematic of the interaction dilutes the NH - IH asymmetry (θ_ν)

- Detector:

  - resolution accuracy in $\{E_\mu , \theta_\mu , E_h\} \rightarrow \{E_\nu , \theta_\nu\}$ (θ_h not measurable)

  - response, etc.

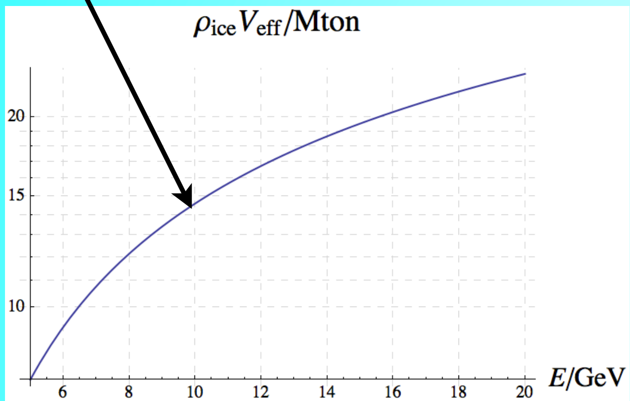
    → smoothing the NH - IH asymmetry

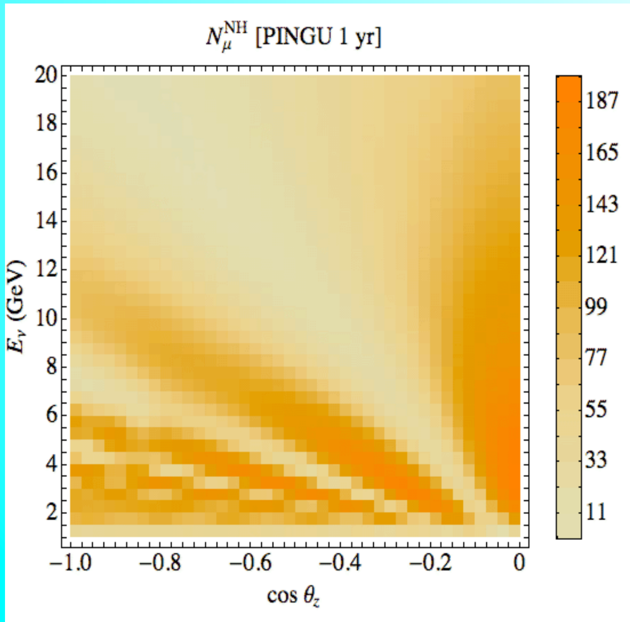
- Partial degeneracy of parameters, mimicking a MH inversion
(given current uncertainties in Δm^2_{31} , θ_{23} , δ)

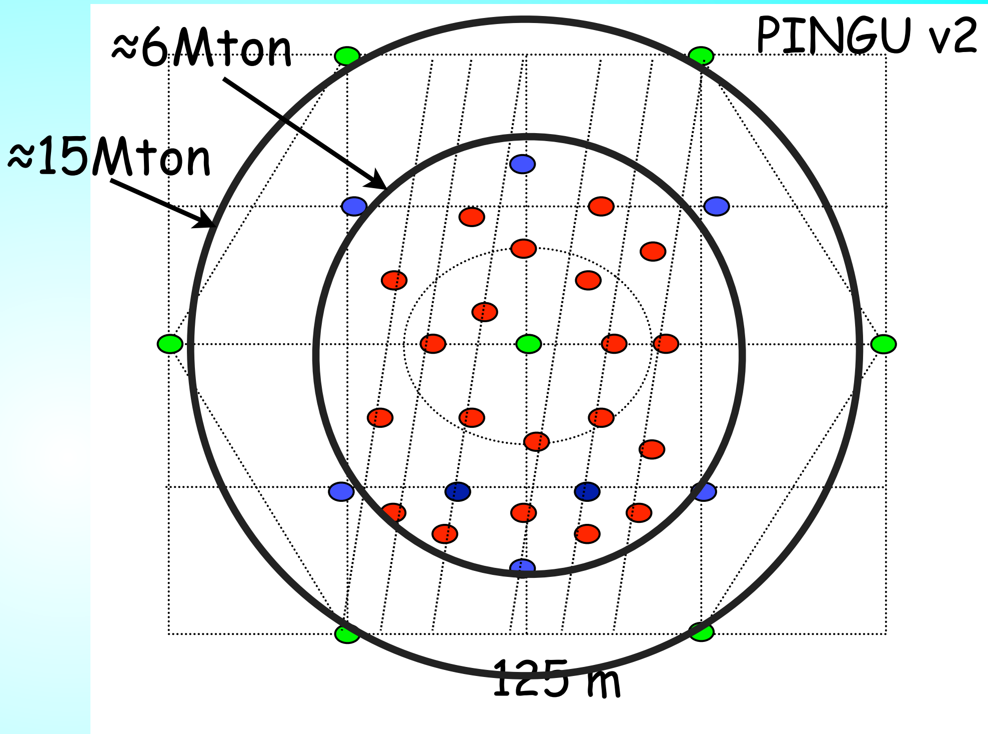
Some of these difficulties can be alleviated if we can measure the neutrino interaction inelasticity y

Experimental setup

$\rho_{ice} V_{eff} \cong 15$ Mt
@ 10 GeV







~ 10^5 events/year

PINGU: probably necessary to add at least 2-3000 OM instrumentation in a extended dense core

Expectations on NMH identification significance

Numbers of ν_μ events and asymmetry

2-ν system estimate (zero 1-2 splitting)

Notation: $\bar{p}_{\alpha\beta} \equiv \bar{p}_{\alpha\beta}^{NH} \cong p_{\alpha\beta}^{IH}$,

$\kappa_\alpha \equiv (\bar{\sigma}\bar{\Phi}_\alpha)/(\sigma\,\Phi_\alpha)$,

$\bar{\Phi} \equiv \Phi_{\bar{\nu}}$,

$r = \Phi_\mu/\Phi_e$,

etc.

$$N_\nu^{NH} = 2\pi\, T \int V_{eff}\, \sigma\, (\Phi_\mu\, p_{\mu\mu} + \Phi_e\, p_{e\mu})\; dc_\nu\, dE_\nu$$

$$N_\nu^{IH} = \ldots$$

$$N_{\bar{\nu}}^{NH} = \ldots$$

Asymmetry:

$$N_\nu^{IH} - N_\nu^{NH} \sim \Phi_\mu\,(\bar{p}_{\mu\mu} - p_{\mu\mu}) + \Phi_e\,(\bar{p}_{e\mu} - p_{e\mu})$$

$$N_{\bar{\nu}}^{IH} - N_{\bar{\nu}}^{NH} \sim -[\,\bar{\Phi}_\mu\,(\bar{p}_{\mu\mu} - p_{\mu\mu}) + \bar{\Phi}_e\,(\bar{p}_{e\mu} - p_{e\mu})\,]$$

$$N_{\nu+\bar{\nu}}^{IH} - N_{\nu+\bar{\nu}}^{NH} \sim (1-\kappa_\mu)(\bar{p}_{\mu\mu} - p_{\mu\mu}) + r^{-1}(1-\kappa_e)(\bar{p}_{e\mu} - p_{e\mu})$$

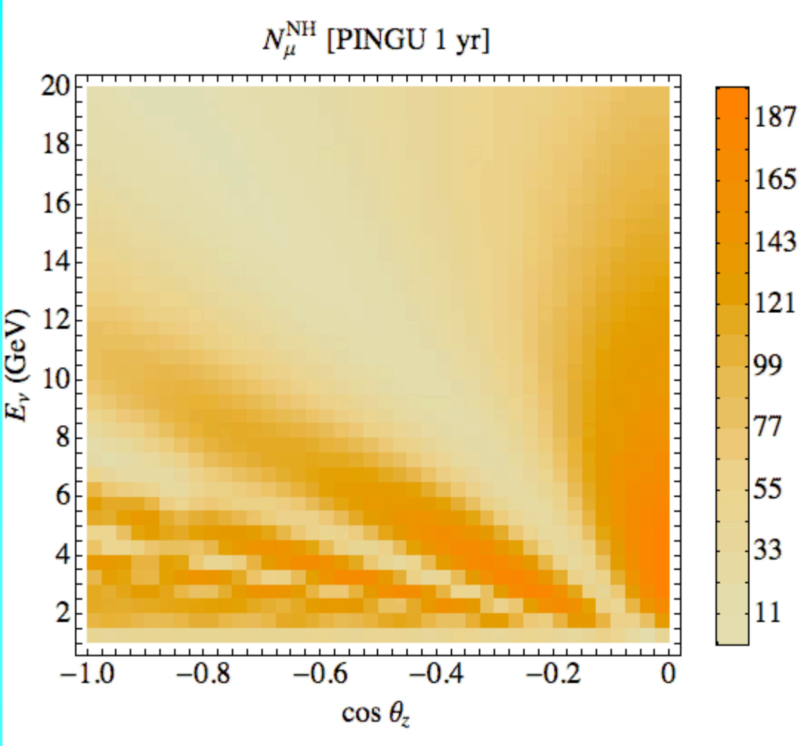
$\nu - \bar{\nu}$ CP asymmetry suppression

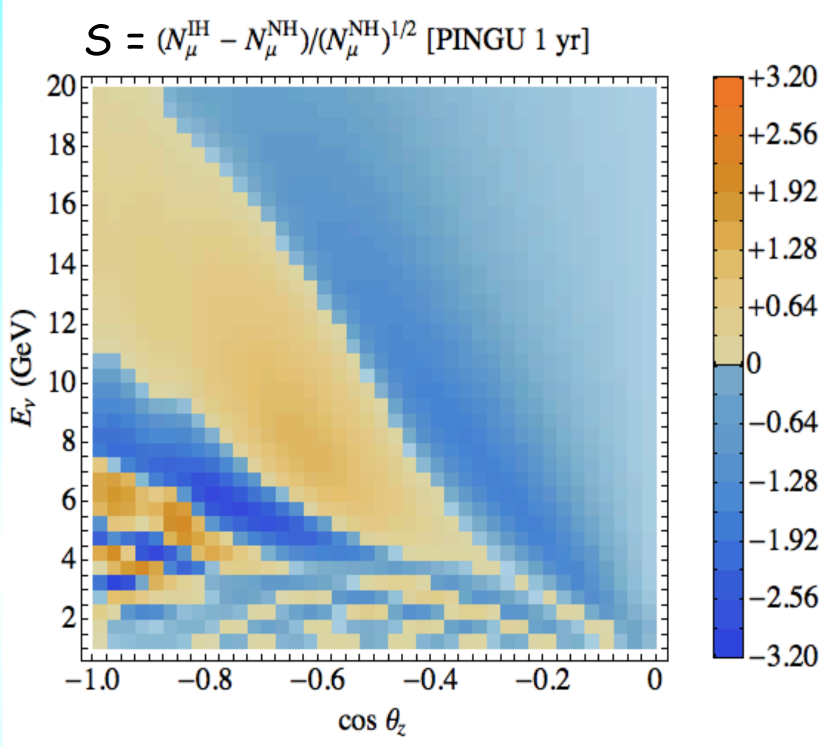
can be avoided

Flavor suppression
(screening factors)

unavoidable

Hierarchy asymmetry





Estimator of significance:

$$S = \frac{(N_{\bar\nu} + N_\nu)^{IH} - (N_{\bar\nu} + N_\nu)^{NH}}{\sqrt{(N_{\bar\nu} + N_\nu)^{NH}}}$$

S – asymmetry

|S| - significance

$$S_{tot}^{\nu+\bar\nu} = \sqrt{\sum S(E_i,\theta_j)^2} \approx 23$$

sum in quadrature of S from different regions (c_μ , E_ν)

$$\sqrt{(S_{tot}^{\nu})^2+(S_{tot}^{\bar\nu})^2} \approx 60$$

N_ν and $N_{\bar\nu}$ measured independently

R = 2.6

Smeared asymmetries

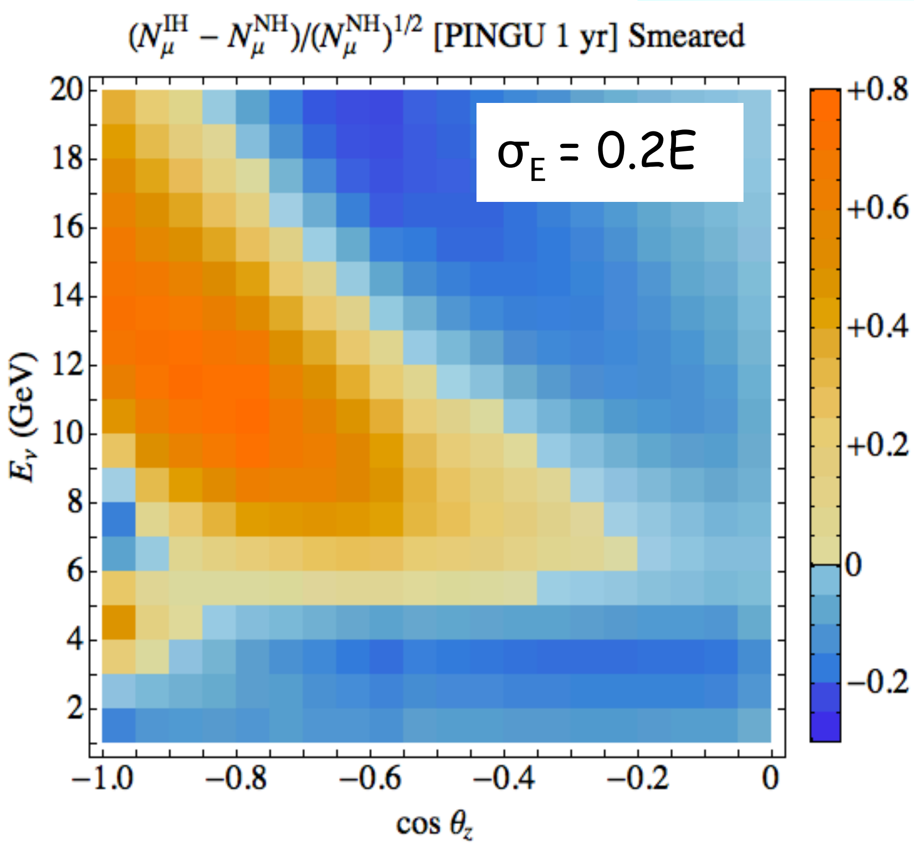
E. Akhmedov, S. Razzaque, A. Y. Smirnov

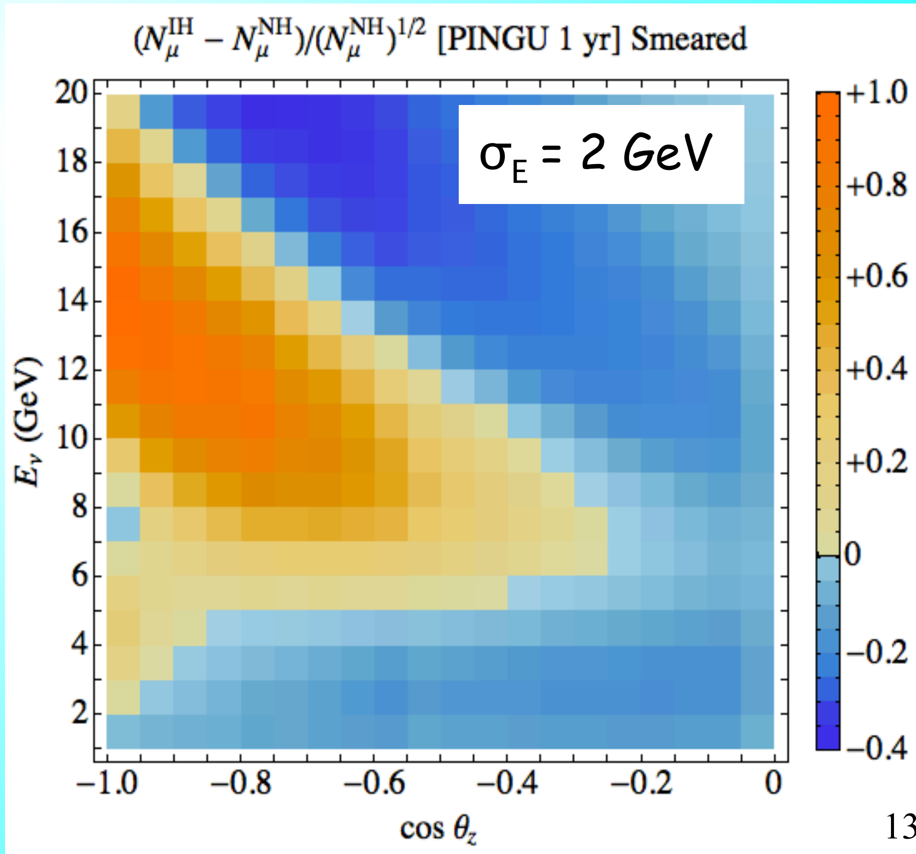
JHEP 02 (2013) 082, JHEP 1302 (2013) 082, arXiv: 1205.7071

Experimental smearing functions characterized by

$$\begin{cases} \sigma_E \propto E_\nu, \ \text{cte} \\ \sigma_\theta \propto (m_p / E_\nu)^{1/2} \end{cases}$$

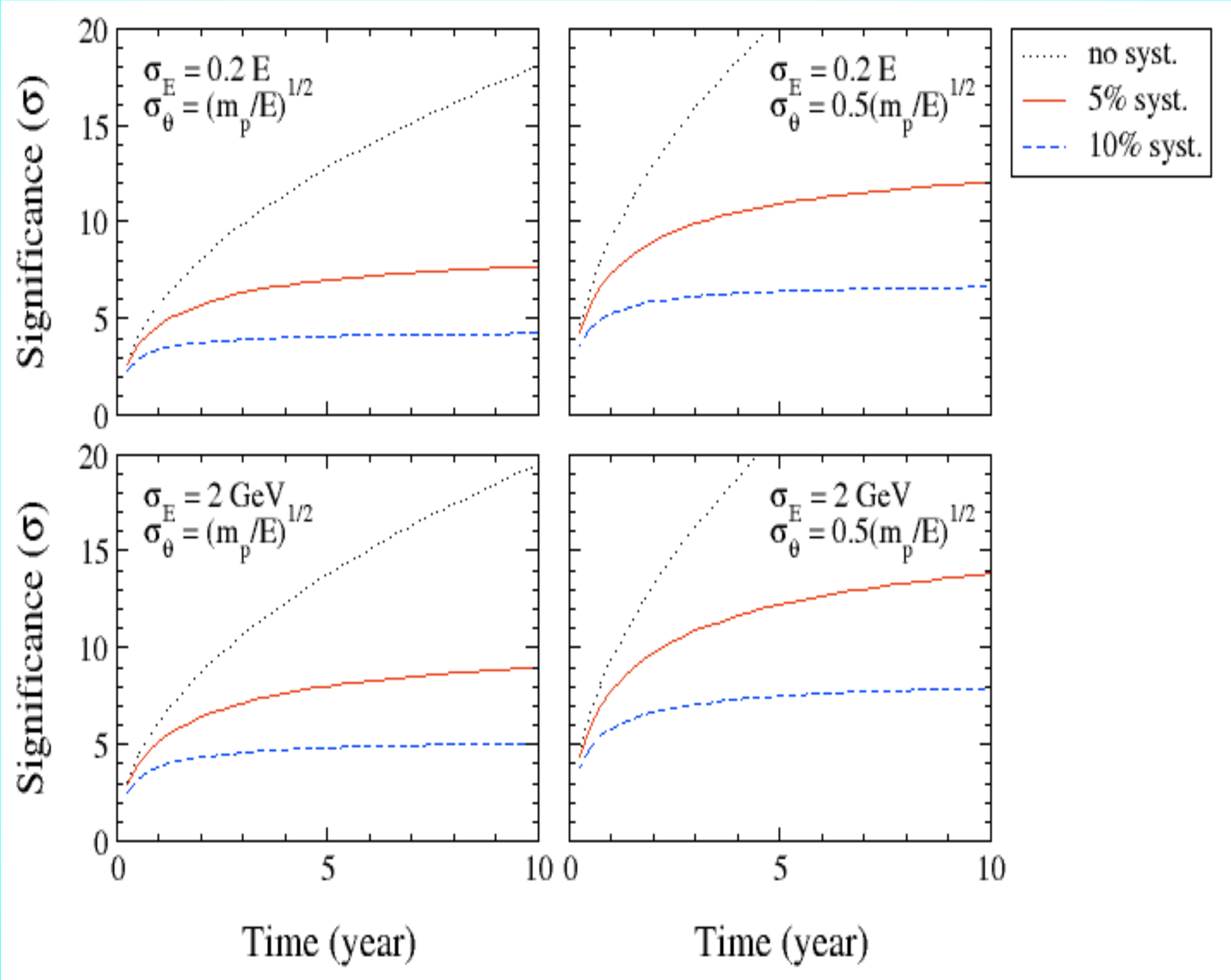
$\sigma_\theta \sim \sqrt{m_n/E} \qquad (E \equiv E_\nu)$





Total significance

$S_{tot} \propto \sqrt{T}$



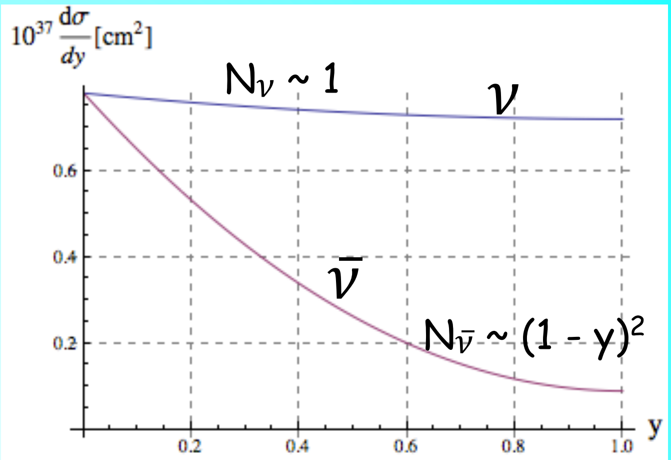
Improvements of reconstruction of the neutrino angle leads to substantial increase of significance

Inelasticity

Inelasticity y - Basic idea

1) Differential cross-sections for neutrino and anti-neutrinos behave distinctly with $y \approx 1 - E_\mu / E_\nu$

2) Significance increases by a factor about R ≈ 2.5 if ν and $\bar{\nu}$ contributions can be measured separately (reduction of cancellation effects)



Then we should:

➡ measure E_μ and $E_\nu \approx E_h + E_\mu$ for each event,

➡ obtain y-distribution

➡ extract the $\nu - \bar{\nu}$ admixture $\alpha = \frac{N_{\bar{\nu}}}{N_{\bar{\nu}} + N_\nu}$

Precision on the admixture determination δα for a given number of events N in the distribution can be estimated analytically (calculating the moments of the y distribution).

δα {
1) weakly depend on the admixture itself
2) and can be expressed simply by $\delta\alpha = \frac{\gamma}{\sqrt{N_{\bar{\nu}} + N_\nu}}$, where $\gamma \approx 5/3$

(a max. likelihood determination of δα is slightly better)

R - absolute $\nu - \bar{\nu}$ event tagging

$$R = \frac{\text{significances from independent measurement of } \nu \text{ and } \bar{\nu}}{\text{significance without } \nu - \bar{\nu} \text{ separation}}$$

i.e.:

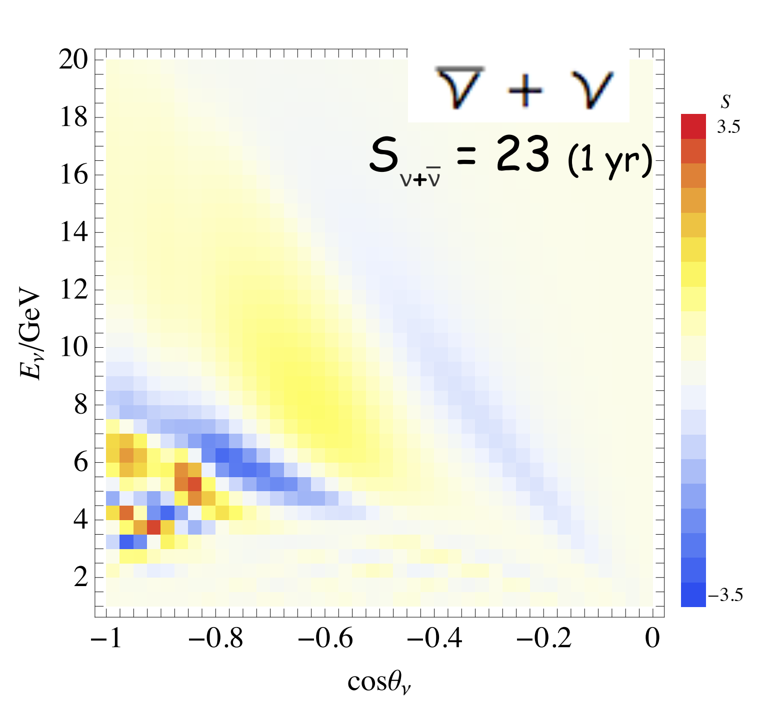
$$R = \frac{1}{1 - \kappa_\mu f_P} \frac{1}{\sqrt{\alpha}} \sqrt{\frac{\alpha}{1-\alpha} + (\kappa_\mu f_P)^2}$$

where $$\kappa_\mu f_P = -\frac{N_{\bar{\nu}}^{IH} - N_{\bar{\nu}}^{NH}}{N_{\nu}^{IH} - N_{\nu}^{NH}}$$

with

$$\kappa_\mu \equiv \frac{\bar{\sigma}^{CC}\bar{\Phi}_\mu^0}{\sigma^{CC}\Phi_\mu^0} \propto N^0_{\bar{\nu}} / N^0_{\nu}$$

$$f_P \equiv \frac{\bar{P}_{\mu\mu}^{NH} - \bar{P}_{\mu\mu}^{IH} + \frac{1}{\bar{r}}\left(\bar{P}_{e\mu}^{NH} - \bar{P}_{e\mu}^{IH}\right)}{P_{\mu\mu}^{IH} - P_{\mu\mu}^{NH} + \frac{1}{r}\left(P_{e\mu}^{IH} - P_{e\mu}^{NH}\right)} \overset{2\nu\text{-system}}{\underset{\bar{r} = r}{=}} 1$$



$S_\nu = 45$, $S_{\bar{\nu}} = 41 \Rightarrow R = 2.6$

R - $\nu - \bar{\nu}$ **separation** with precision $\delta\,\alpha$

$$S_\nu = \frac{N_\nu^{IH} - N_\nu^{NH}}{\sigma_\nu}, \qquad S_{\bar\nu} = \frac{N_{\bar\nu}^{IH} - N_{\bar\nu}^{NH}}{\sigma_{\bar\nu}}$$

where $\frac{\sigma_\nu}{\sqrt{N^{NH}}} = \sqrt{(1-\alpha)^2 + \gamma^2}, \qquad \frac{\sigma_{\bar\nu}}{\sqrt{N^{NH}}} = \sqrt{\alpha^2 + \gamma^2}$

→ R = $\dfrac{\text{significances from measurement of } \alpha \text{ with error } \delta\alpha}{\text{significance without } \nu - \bar\nu \text{ separation}}$

$$= \frac{1}{1-\kappa_\mu f_P} \frac{1}{\sqrt{\alpha^2+\gamma^2}} \sqrt{\frac{\alpha^2+\gamma^2}{(1-\alpha)^2+\gamma^2} + (\kappa_\mu f_P)^2}$$

$\gamma = 3/2 ... 5/3$, □α=0.32...0.5, κ_μ=0.4...0.5 : R = 1 ... 1.4

→ 1) accuracy factor γ strongly limits R

2) need to study in more detail as α and κ_μ depends on (E_ν, c_ν)

(and introduce detailed kinematic of the interaction)

Other obvious benefits of y

1) y **constrains the angle** between the muon and the neutrino:

$$\sin^2 \beta/2 = \frac{x\, y\, m_N (E_\nu + m_N)}{2 E_\nu E_\mu}$$

$$\langle \beta \rangle \approx \frac{0.75}{\sqrt{E_\nu/\mathrm{GeV}}} \sqrt{\frac{y}{1-y}}$$ ($\langle x \rangle \sim 0.3$)

(with $\bar{y}_\nu$=0.5 and $\bar{y}_{\bar{\nu}}$=0.3, we get $\approx 10^o$ for 10 GeV muon)

Not too large y → select an event sample, which preserves NMH features

2) Not too large y → **filter out** ν_e and ν_τ events

(3-body τ decay: $\tau \to \mu\nu\nu$ with BR=18%)

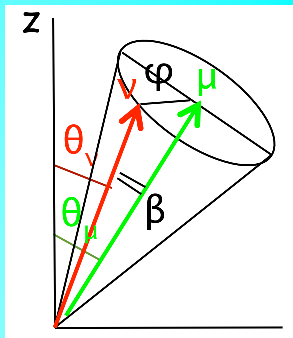
3) **Analysis control:** event y-distribution **must** be a linear superposition of ν and $\bar{\nu}$ y-distributions

3D - oscillograms

Neutrino event density (NH) in (E_ν, c_μ, y):

$$n_\nu(E_\nu, c_\mu, y) = \int dc_\beta \, d\varphi \, \frac{d^2\sigma}{dc_\beta \, dy} \{F \, P \, (E_\nu, c_\nu)\}$$

with $c_\nu = c_\nu (\beta, c_\mu, \varphi)$



Variable change: $(c_\beta, \varphi) \Rightarrow (c_\nu, x)$:

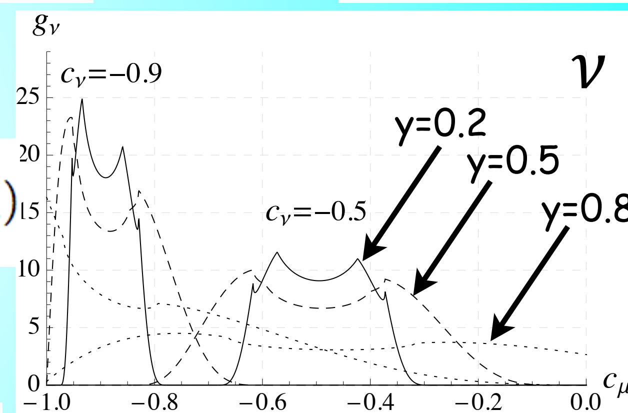
$$n_\nu^{\mathrm{NH}}(E_\nu, c_\mu, y) = \frac{1}{\pi} \int_{|\theta_\mu - \theta_\nu| \leq \beta_0} \mathrm{d}c_\nu \rho_\nu^{\mathrm{NH}}(E_\nu, c_\nu) g_\nu(E_\nu, y, c_\nu, c_\mu)$$

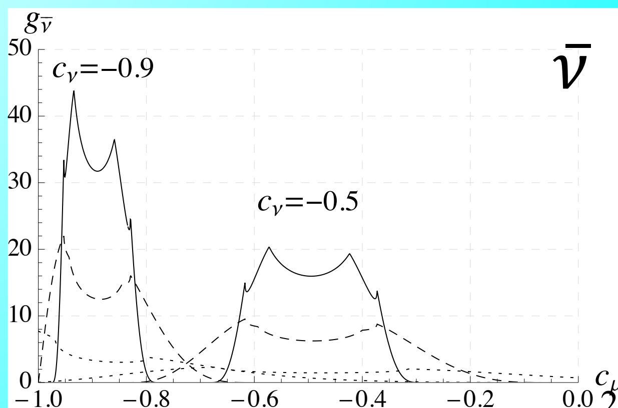
where

$$g_\nu(E_\nu, y, c_\nu, c_\mu) \equiv \frac{1}{\sigma_\nu^{\mathrm{CC}}(E_\nu)} \int_{x^-}^{x^+} \mathrm{d}x \, \frac{\mathrm{d}^2\sigma_\nu^{\mathrm{CC}}(E_\nu, x, y)}{\mathrm{d}x \mathrm{d}y} \times \frac{1}{\sqrt{s_\beta^2 s_\mu^2 - (c_\nu - c_\beta c_\mu)^2}}$$

is the "kinematical smearing function"

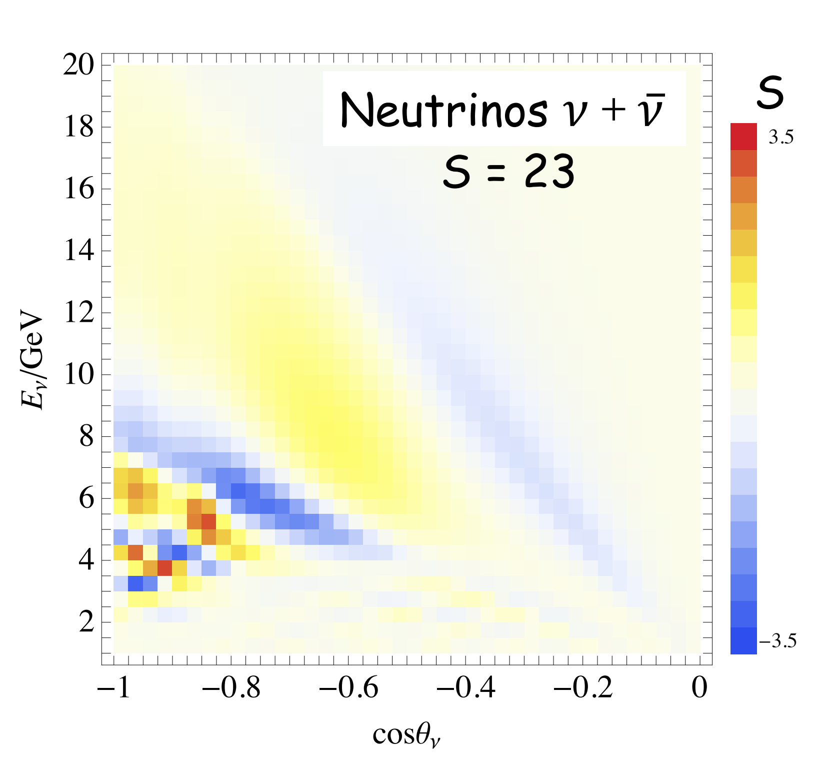
$$\left(x = x(c_\beta, E_\nu, y) \sim \frac{E_\nu (E_\mu - c_\beta |p_\mu|)}{m_N (E_\nu - E_\mu)} \right)$$

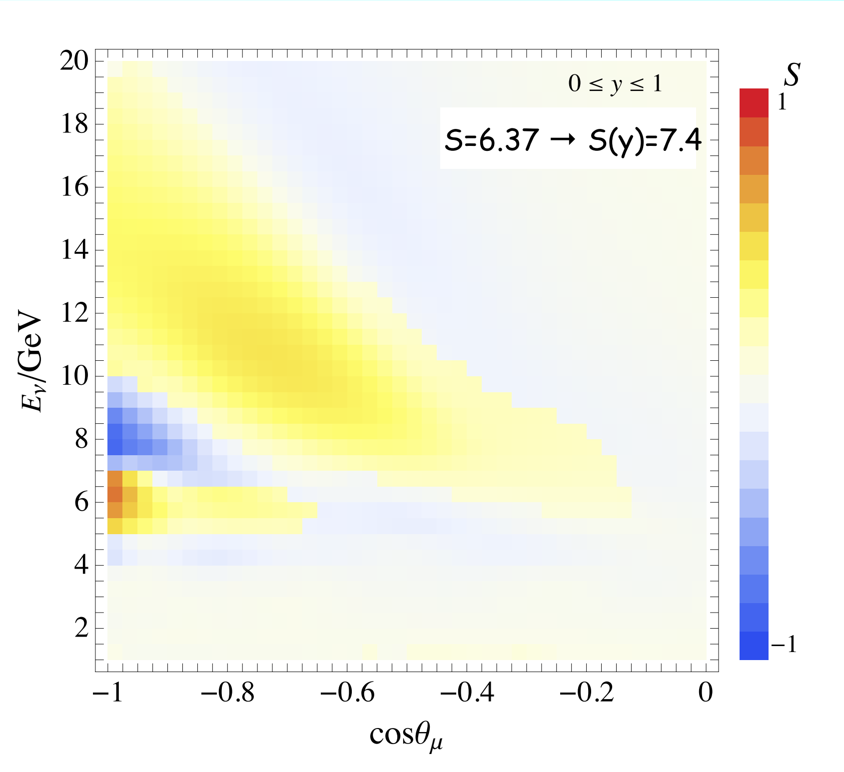




Inelasticity - Significance upper bound

kinematic smearing only



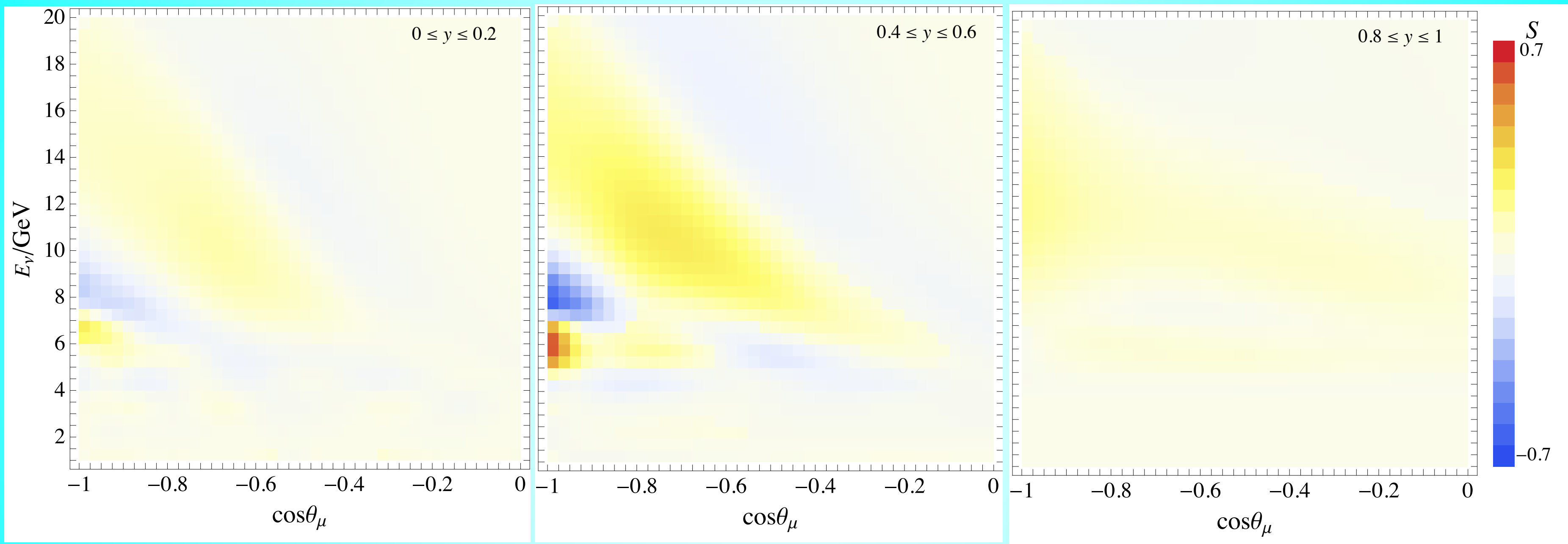


$S_{\nu+\bar{\nu}} = 23$ —kinematic smearing→ $S = 6.37$ —using y-distribution→ $S(y) = 7.4$

16% increase
(35% on lifetime)

y - dependence of asymmetries

kinematic smearing only



Small y: small angle between mu and nu, but same cross-section (NMH features only from difference in fluxes)

Intermediate y region: largest contribution to the significance

Large y: while pure neutrino beam, β is large, diluting NMH discrimination significance

Smearing the 3D oscillograms

Experimental resolution functions:

- **Energy**: for cascade and muon track, we consider normal energy resolution $dE \propto E$ and with $dE \propto \sqrt{E} \propto \sqrt{N_{hit}}$ (see M. Salathe and M.R., Astropart.Phys. 35 (2012) 485 [arXiv:1106.1937 [astro-ph.IM]])

We consider "$\propto$" cte for an average $d(\nu \to \mu, OM) \cong 10$ m

$$\rightarrow \quad \sigma_{E_{h,\mu}} = \sqrt{a_E E_{h,\mu}} \qquad a_E \in \{0.35,\ 0.7\}$$

- **Angular**: $\sigma_{\tilde{\mu}-\mu}(E_\mu)$ between 2^o - 5^o for N_{hit}=60 $\oplus$ $\sigma_{\tilde{\mu}-\mu} \propto \sqrt{N_{hit}}$

$$\rightarrow \quad \sigma_{\psi 0} = \psi_0 \sqrt{m_N / E_\mu} \qquad \psi_0 \in \{10^o,\ 40^o\}$$

angular resolution function NOT gaussian

- **Inelasticity**: σ_y follows from $\sigma_{E_{h,\mu}}$ and is well approximated with a normal distribution:

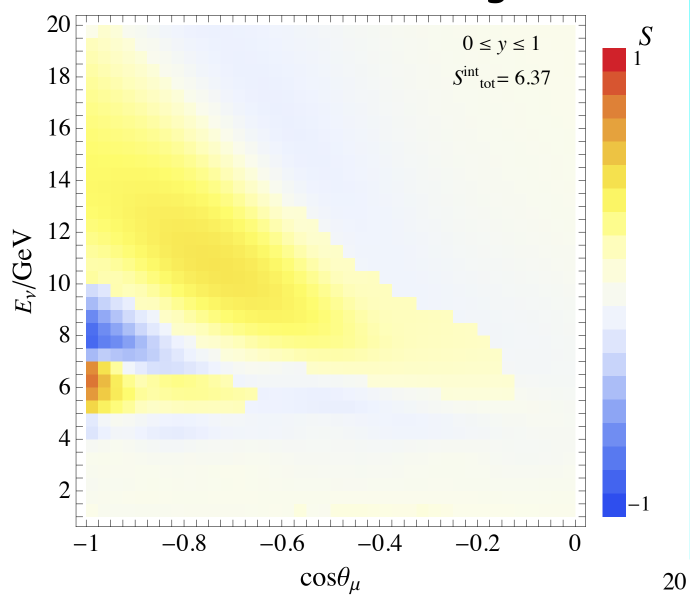
$y \sim E_h / (E_h + E_\mu)$ (distribution ~ ratio of normal random variables)

Smeared asymmetries

$$\sigma_{E_{h,\mu}} = \sqrt{a_E\, E_{h,\mu}}$$

$$\sigma_{\psi 0} = \psi_0 \sqrt{m_N / E_\mu}$$

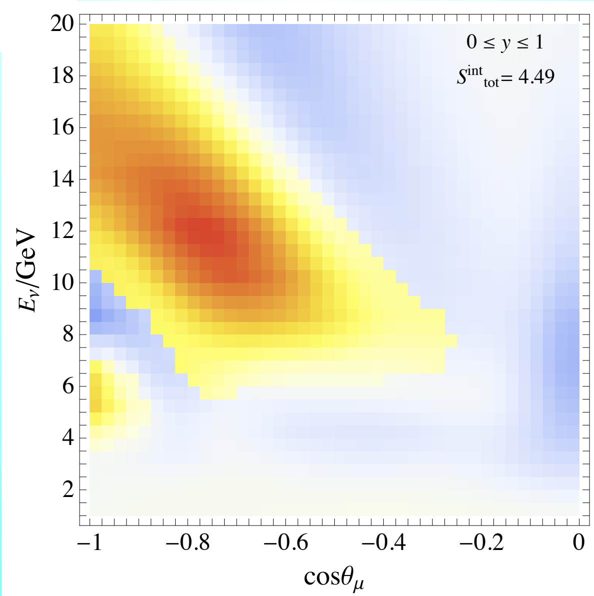
kinematic smearing



S(y)=7.4

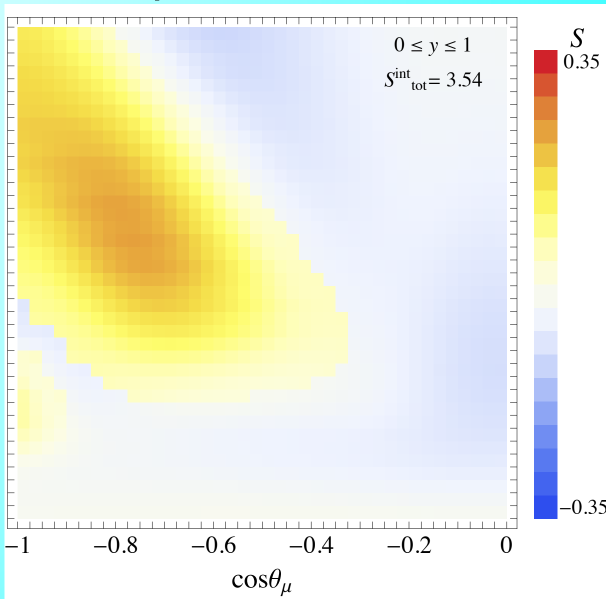
0<y<1

$\psi_0=10^o,\ a_E=0.35$



S (y) =4.9

$\psi_0=20^o,\ a_E=0.7$



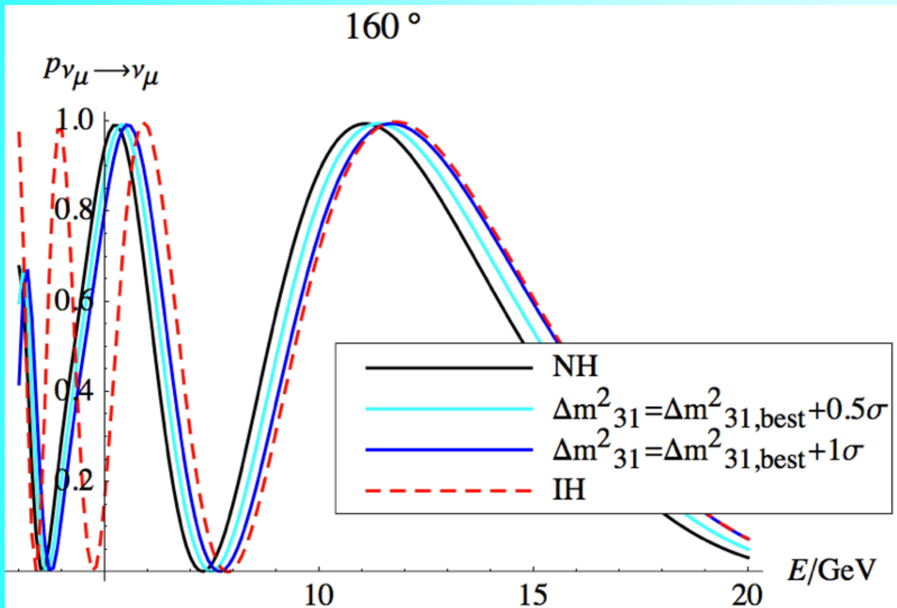
S(y) =3.8

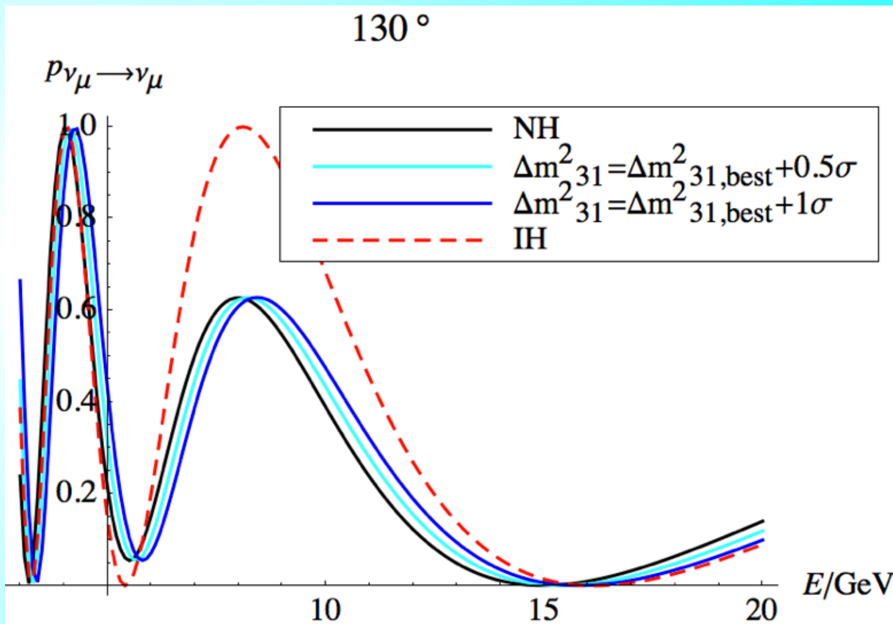
Parameter degeneracy

Parameter degeneracy

Illustration

IH can be mimicked with a positive change of Δm^2_{31} within current and future errors



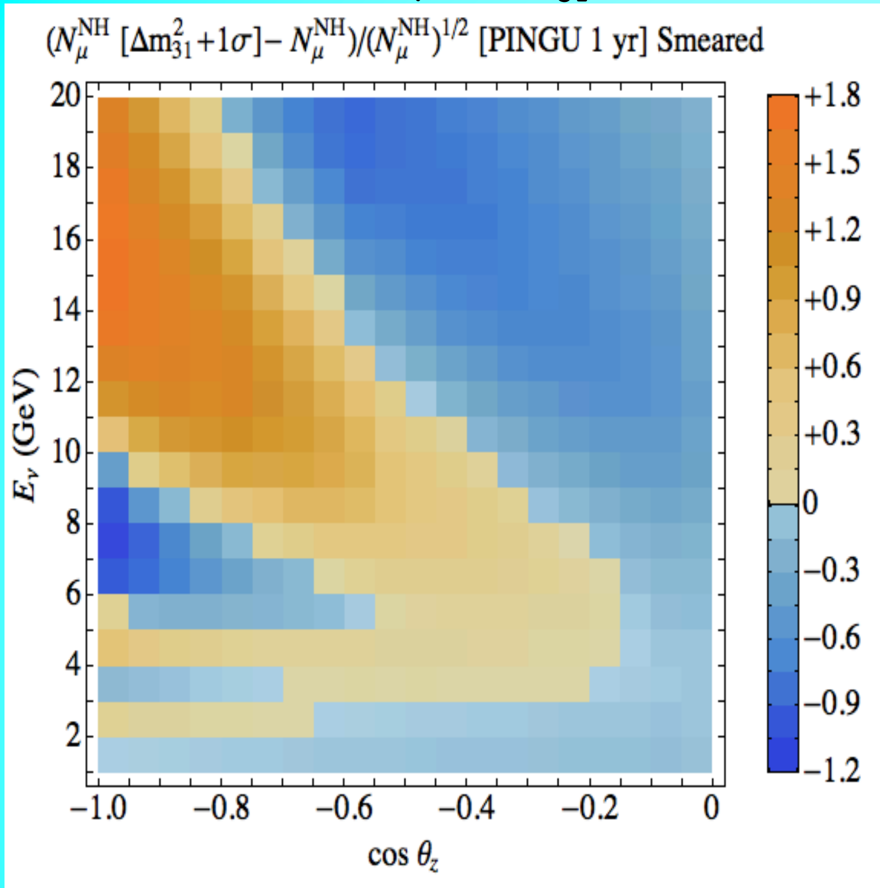


For instance: very strong degeneracy at 160° for

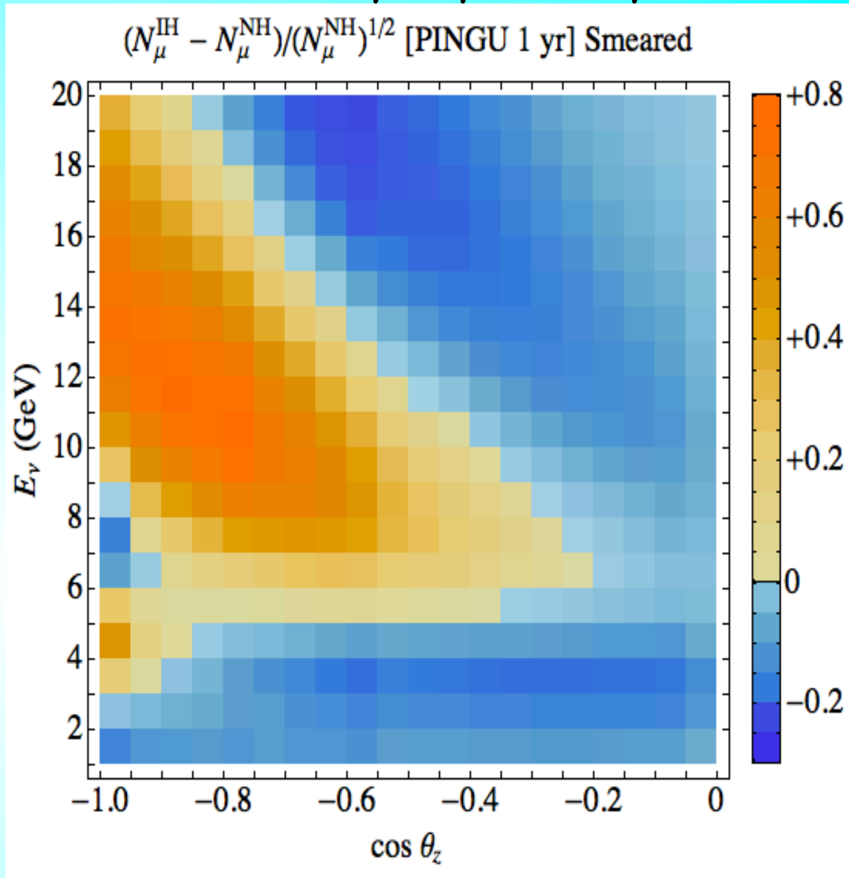
$\Delta m^2_{31} = \Delta m^2_{31,best} + \sigma(\Delta m^2_{31})$

Legend: NH - IH - Δm^2_{31} modified

Uncertainty Δm^2_{31}



Hierarchy asymmetry



smeared

Minimize S over $\Delta m^2_{31,\, fit}$

in minimum $[\Delta m^2_{31,\, true} - \Delta m^2_{31,\, fit}] \sim 5\ 10^{-5}\ eV^2 \sim \frac{1}{2}\sigma$

$S^{tot} = 6 \rightarrow 3.8\ \sigma$

(reduction factor of 1.6)

y and parameter degeneracy

1 year exposure

y-measurement → reduced impact of degeneracy:
- distinct $\nu - \bar{\nu}$ y - distributions
- similar effect of a change of Δm^2_{32} to ν and $\bar{\nu}$

Kin. smearing only:

S ≈ 6.4 → 3.6 (no y) → S(y) = 7.4 → 4.8

→ y improves significance by >30% (while upper bound improves by 16%)

(or >70% increased lifetime to reach the same significance in an ideal detector without y)

Including exp. smearing: $\psi_0 = 20^o, a_E = 0.7$:

S ≈ 3.5 → 1.9 (no y) → S(y) ≈ 3.8 → 2.2

Results are for worst Δm^2_{32} degeneracy case: S reduced by factor 1.5 - 1.7

for $\Delta m^2_{31,\,true} = \Delta m^2_{31,\,best} + \frac{1}{2}\sigma(\Delta m^2_{31,best})$

→ Future measurements (NOvA, T2K) will not improve the situation

y improves S by 15 - 35%

Conclusions

Mass hierarchy can be identified at **5**-10 σ C.L. after ~2 yr with **considered** multi-Mton **atmospheric neutrino** detector

Experimental challenges:
large effective detection volume with low E threshold, flavor ID (identify ν_μ), energies and direction resolutions

Degeneracy of parameters could be problematic (up to **≈3 times longer exposure** necessary in worst case)

Inelasticity measurement help analysis control and increases significance (especially in the case of worst parameter degeneracy)