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Neutrino mass Hierarchy determination with PINGU

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(based on a work in collaboration with F. Capozzi and E. Lisi, to appear soon)

Outline

Status of mixing and masses

Mass Hierarchy and Experiments

PINGU features and expected rates

Sensitivity to the Hierarchy

Conclusions

Neutrino Mixing

$$\nu_\alpha = U_{\alpha i}\nu_i$$

$\alpha = e, \nu, \tau$ — flavor eigenstates

$i = 1, 2, 3$ — mass eigenstates

Mixing Matrix (PNMS)

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

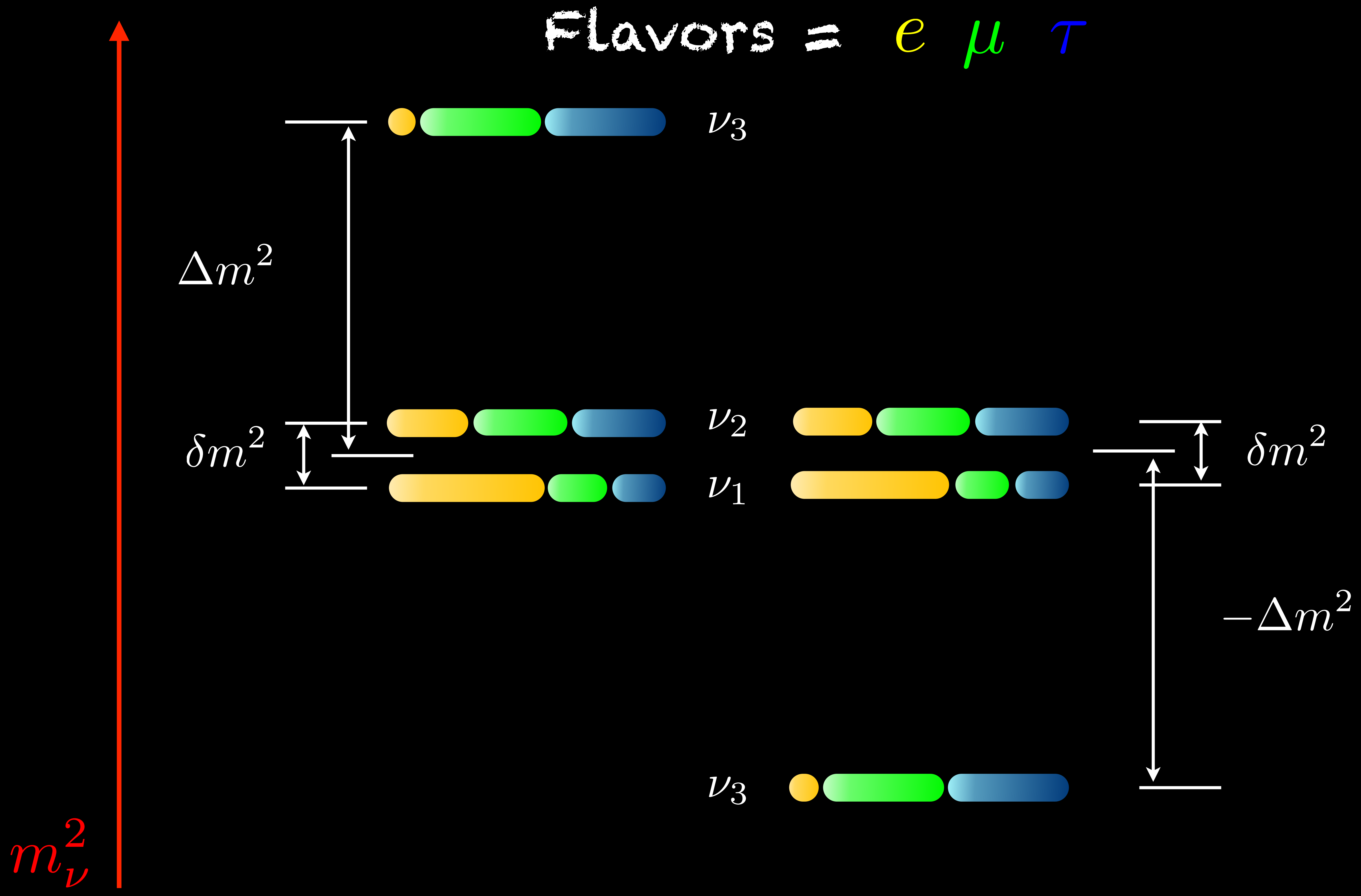
$$U_{\alpha i} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha/2} & 0 \\ 0 & 0 & e^{i\beta/2} \end{pmatrix}$$

$(\theta_{12}, \theta_{13}, \theta_{23})$ — 3 mixing angles

$\delta \in [0, 2\pi]$ — "CP" phase

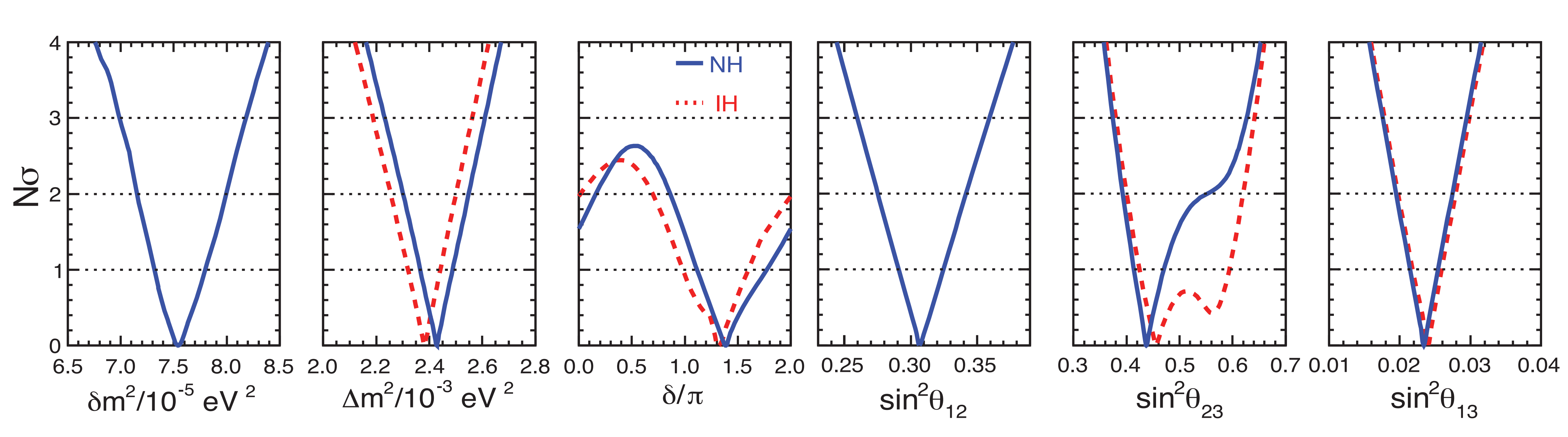
(α, β) — Two Majorana phases (unobservable with oscillations)

Neutrino Mass Spectrum



$$\Delta m^2 = (\Delta m^2_{31} + \Delta m^2_{32})/2 \qquad \delta m^2 = \Delta m^2_{12}$$

Summarizing our present knowledge



Parameter	Best fit	1σ error (%)
$\delta m^2/10^{-5}$ eV^2 (NH or IH)	7.54	2.6 %
$\sin^2\theta_{12}/10^{-1}$ (NH or IH)	3.08	5.4 %
$\Delta m^2/10^{-3}$ eV^2 (NH)	2.43	3.0 %
$\Delta m^2/10^{-3}$ eV^2 (IH)	2.38	
$\sin^2\theta_{13}/10^{-2}$ (NH)	2.34	8.5 %
$\sin^2\theta_{13}/10^{-2}$ (IH)	2.40	
$\sin^2\theta_{23}/10^{-1}$ (NH)	4.37	11 % + octant indet.
$\sin^2\theta_{23}/10^{-1}$ (IH)	4.55	
δ/π (NH)	1.39	$\sin\delta < 0$ (at 90% CL)
δ/π (IH)	1.31	

Still no information about the hierarchy

Neutrino mass hierarchy can be probed by oscillation experiments through

Interference between oscillation driven by $\pm\Delta m^2$

and oscillations driven by

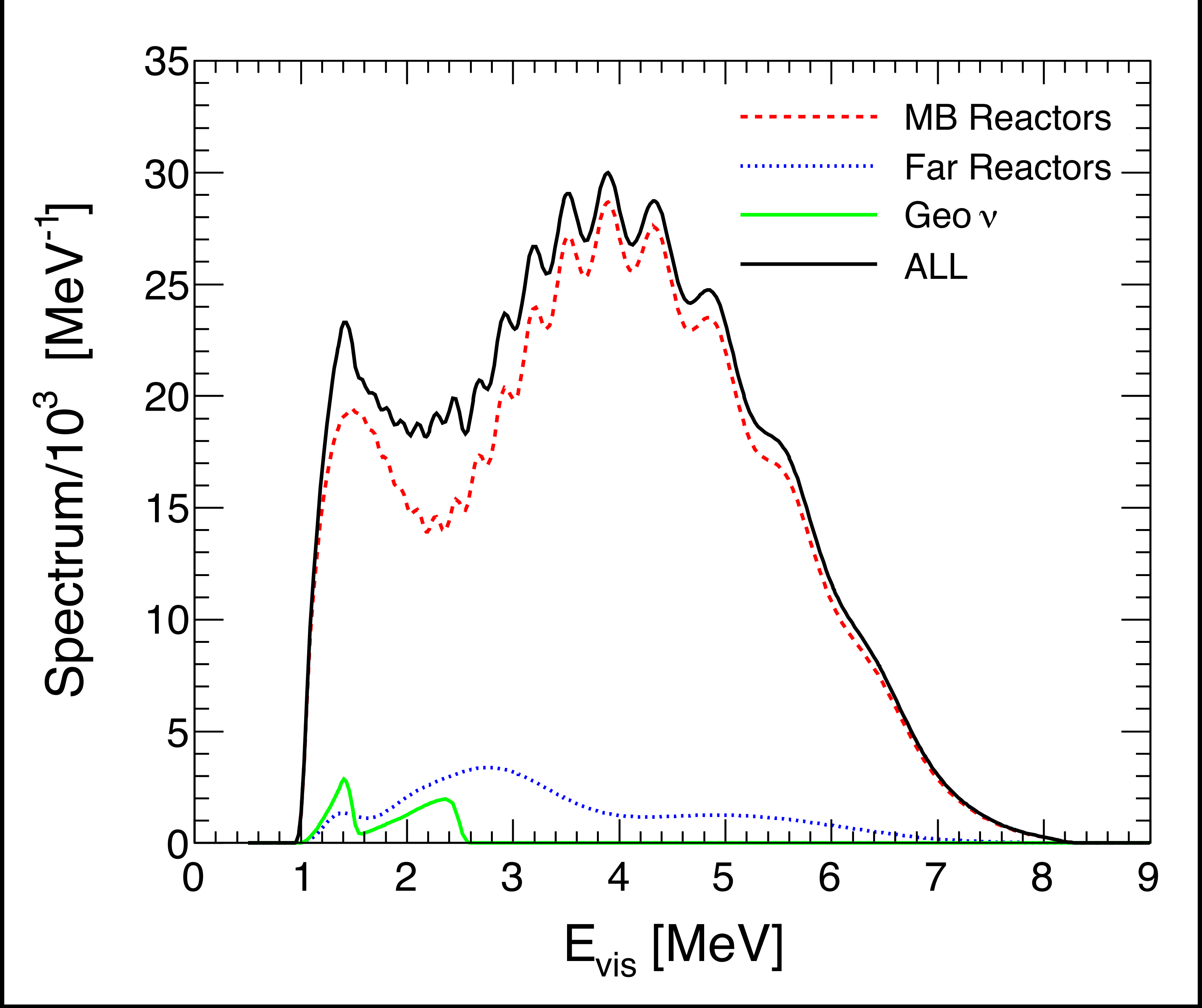
- "solar" δm^2 (medium baseline reactors)
- MSW effective neutrino mass (matter effects) (atmospheric neutrinos/LBL)
- self-interaction induced collective oscillations + MSW matter effects of Supernova neutrinos

JUNO-like experiment ($\sim 10^5$ events in about 5 years)

(F. Capozzi, E. Lisi and A.M.Phys.Rev. D89 (2014) 013001)

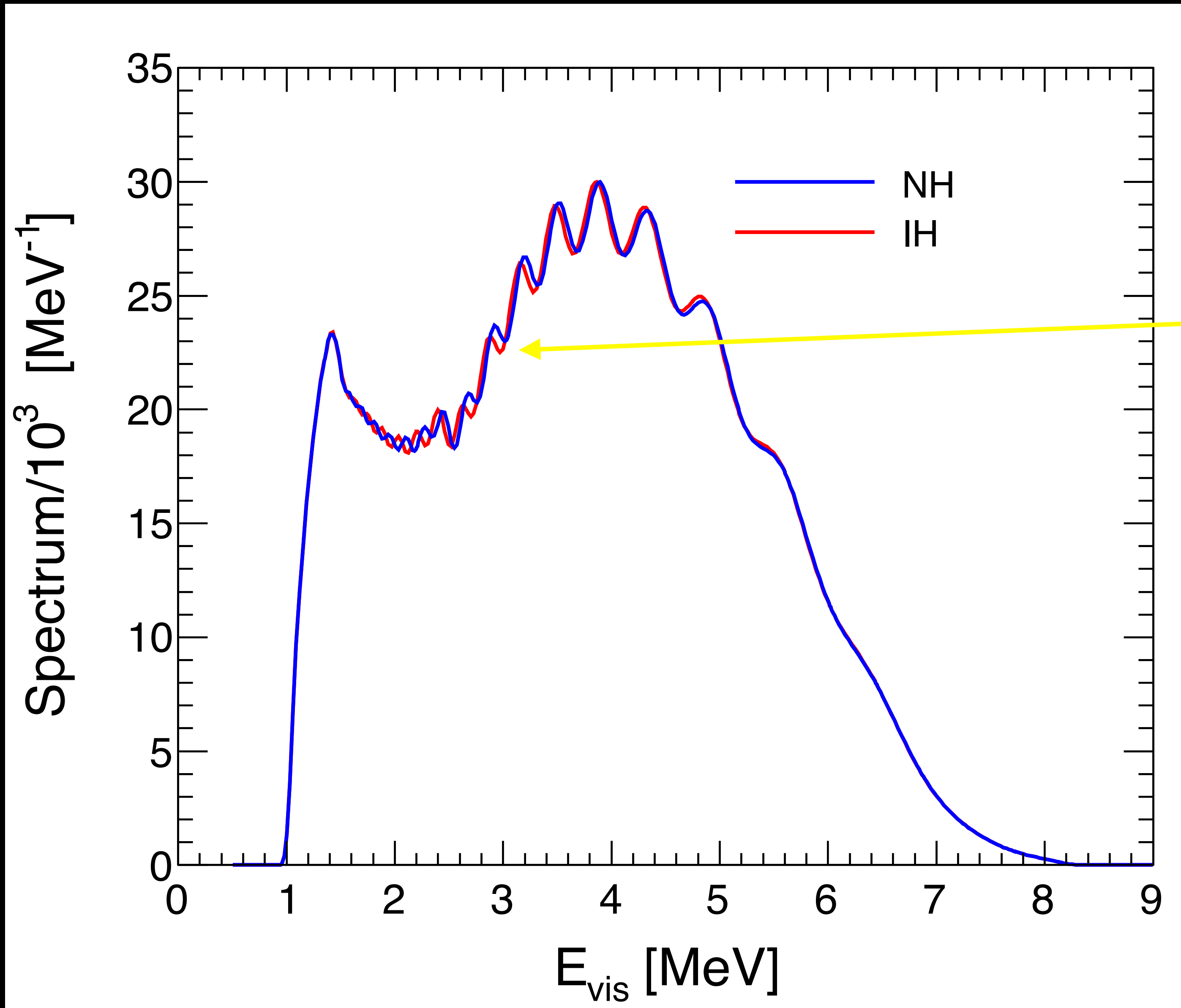
One order of magnitude reduction on the errors on some oscillation parameter

	1σ (%)	now
Δm^2	0.26	(3.0)
δm^2	0.22	(2.6)
$\sin^2\theta_{12}$	0.49	(5.4)

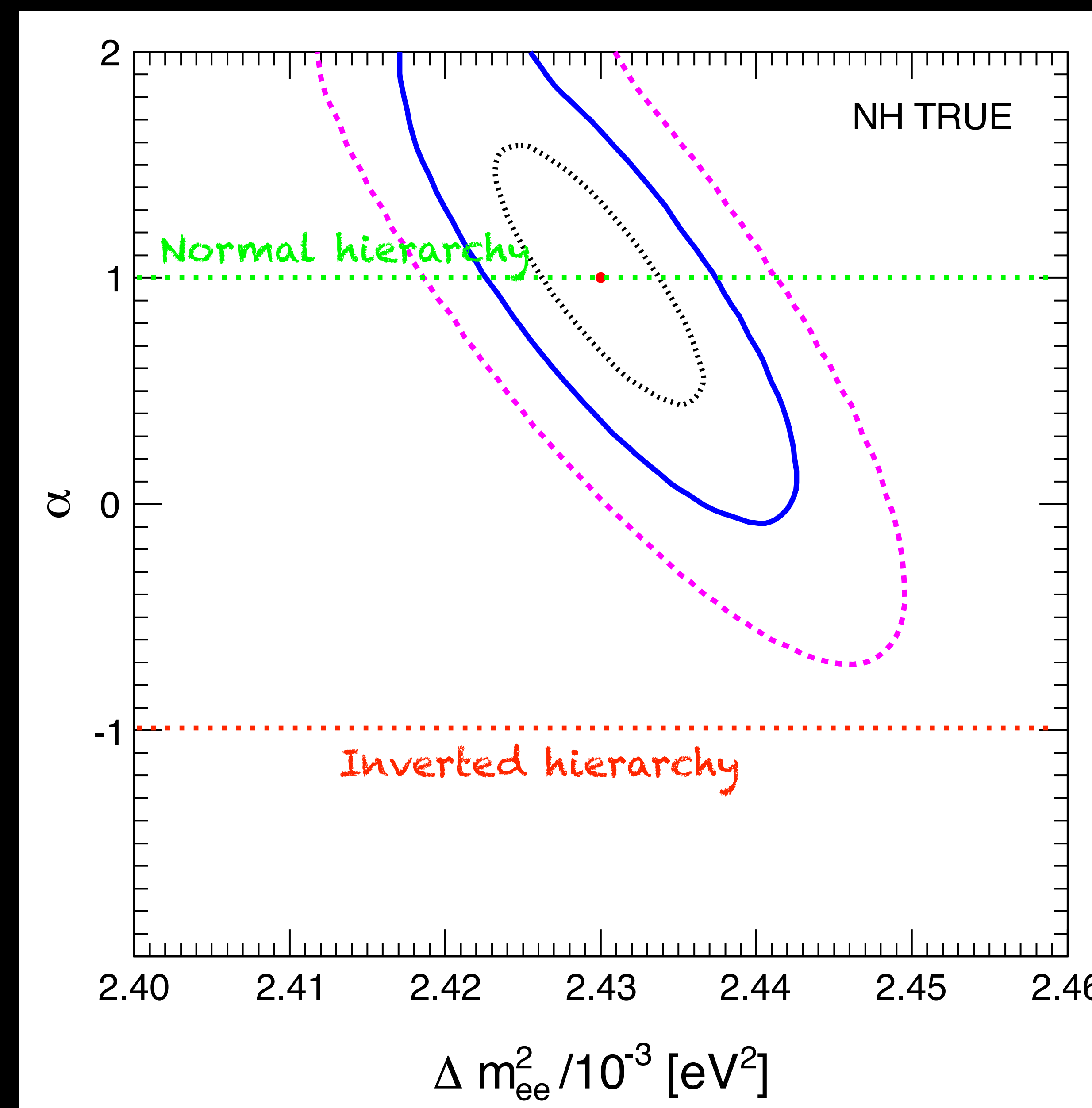


Baseline ~ 50 km

Typical event spectrum and its components



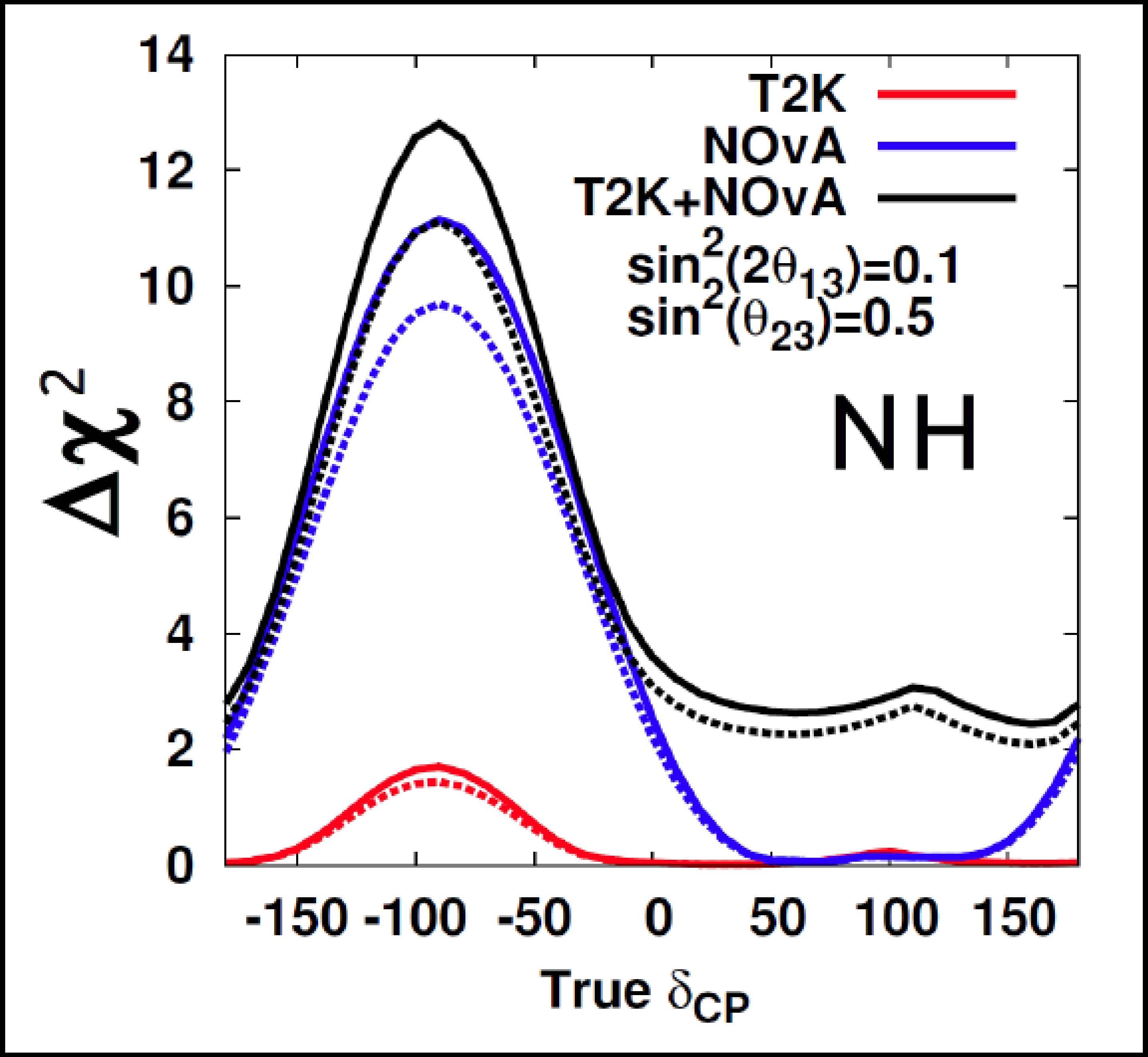
Possible hierarchy discrimination through interference effects in the oscillation probability



Hierarchy discrimination at about 3.4 sigma (distance between $\alpha = 1$ and $\alpha = -1$)

But crucial to reduce as much as possible systematics and to achieve energy resolution at 2-3% level

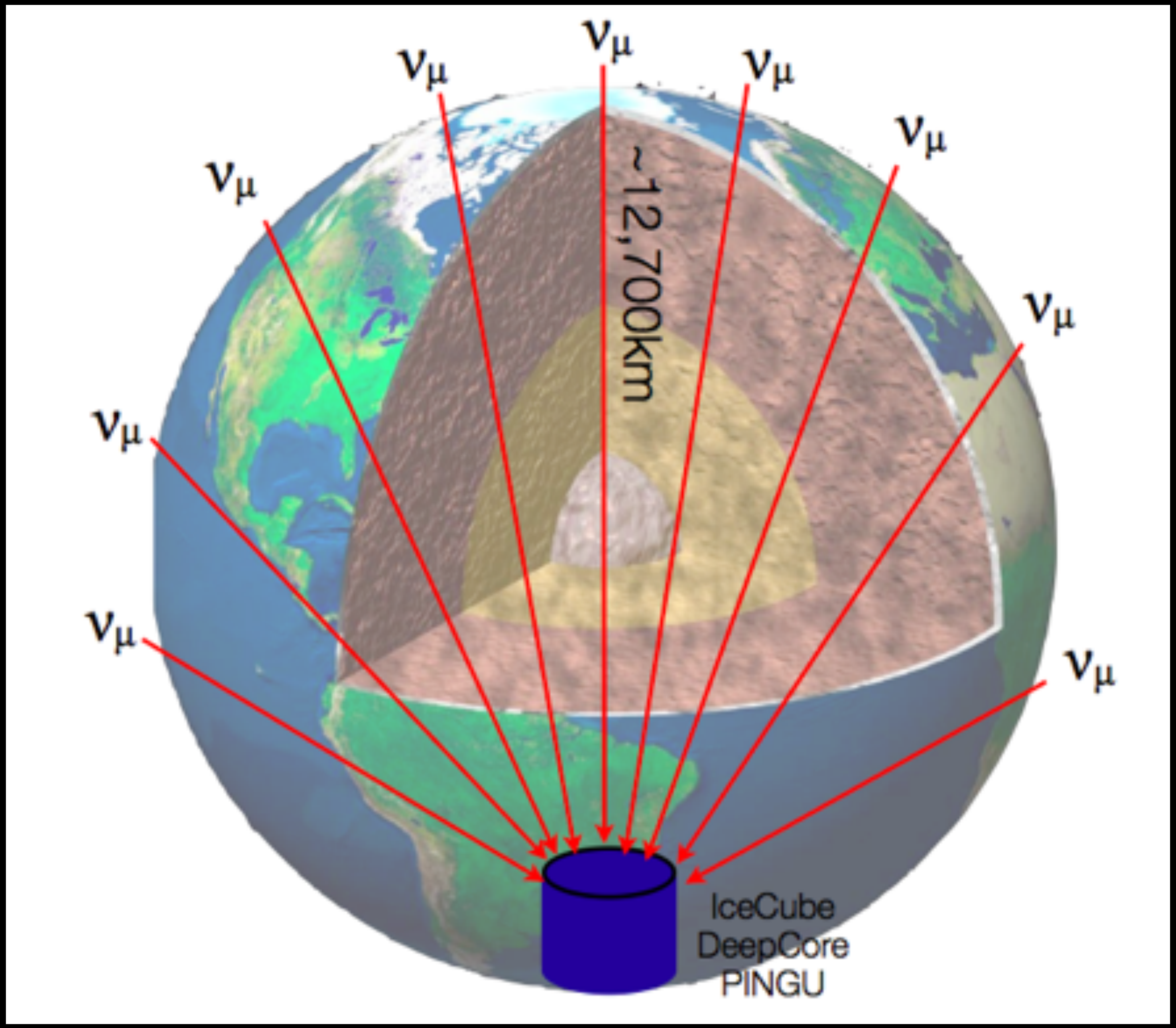
Mass hierarchy discrimination with LBL



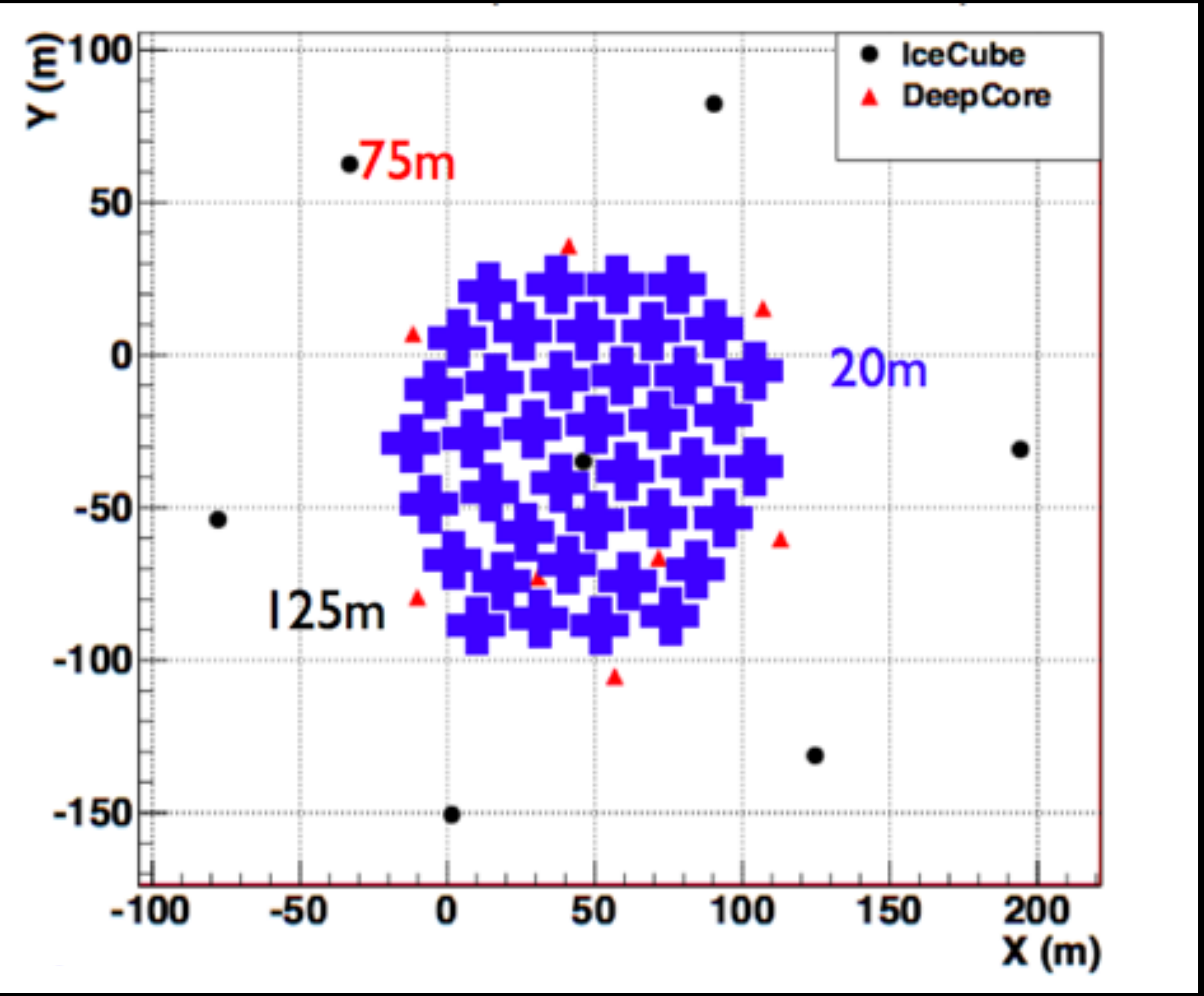
up to $\sim 3\sigma$
depending on δ_{CP}

C.K Yung at ICFA Seminar October 26, 2014 (Beijing)

Neutrino Mass Hierarchy discrimination with PINGU (Precision IceCube Next Generation Upgrade)

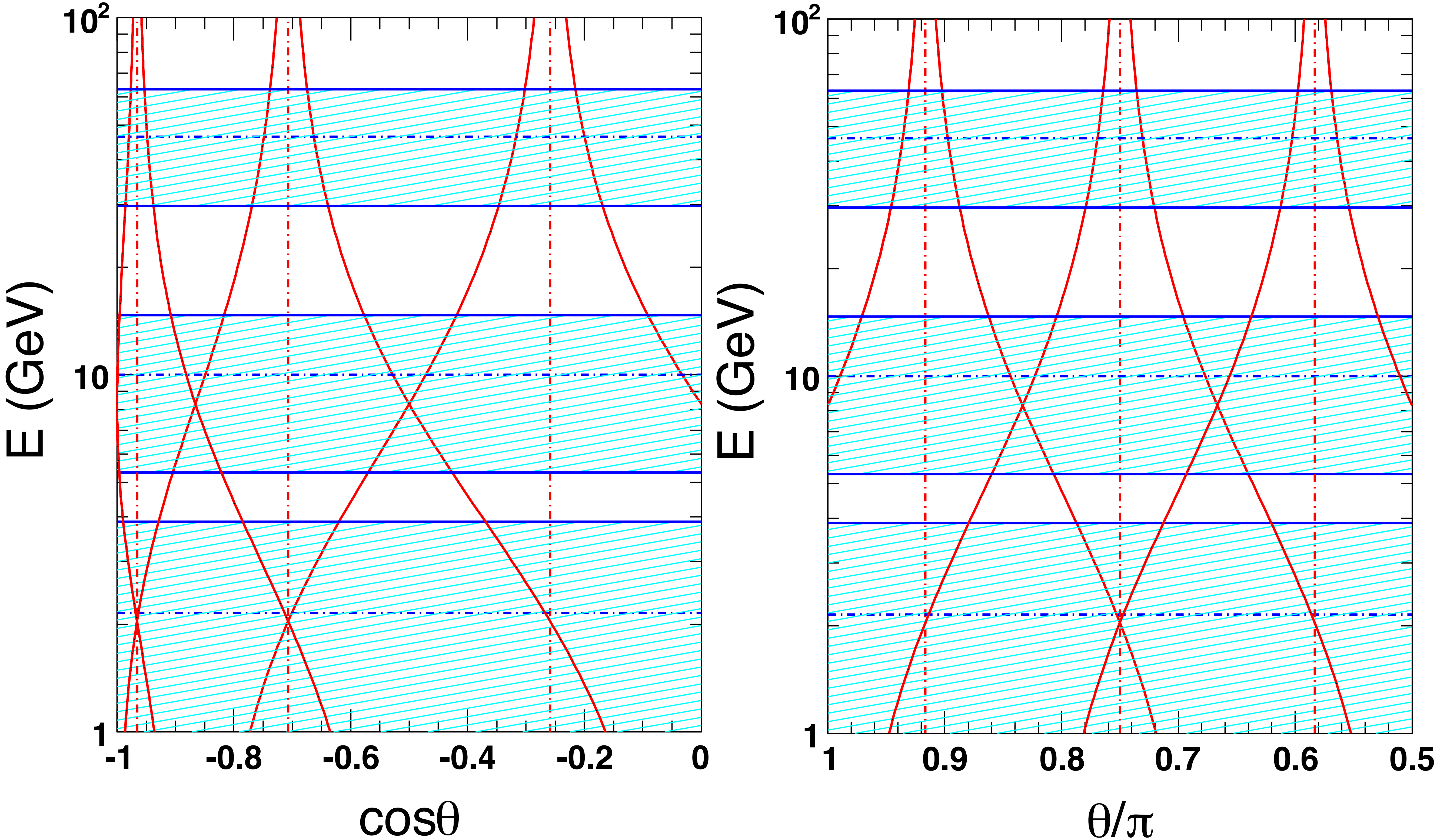


In-fill array for IceCube to determine neutrino hierarchy using atmospheric neutrinos (energy threshold of few GeV)



40 new strings (60 optical module each) deployed in the Deep Core region of the IceCube array

Energy and Zenith Angle Resolution



PINGU rate from the convolution of different ingredients

$$\mathcal{N}(E_\nu,\theta) \sim V(E_\nu) \otimes \sigma(E_\nu) \otimes \phi(E_\nu,\theta) \otimes P(E_\nu,\theta) \otimes \mathcal{R}(E_\nu,\theta)$$

Effective volume — Cross section — Atm. neutrino flux — Oscillation probability — Resolution

Schematically (ideal case of perfect resolution)

$$\mathcal{N}_\alpha \sim [V \times \sigma \times \phi]_\alpha \otimes P_\alpha$$

$$\alpha = \mu\ , e$$

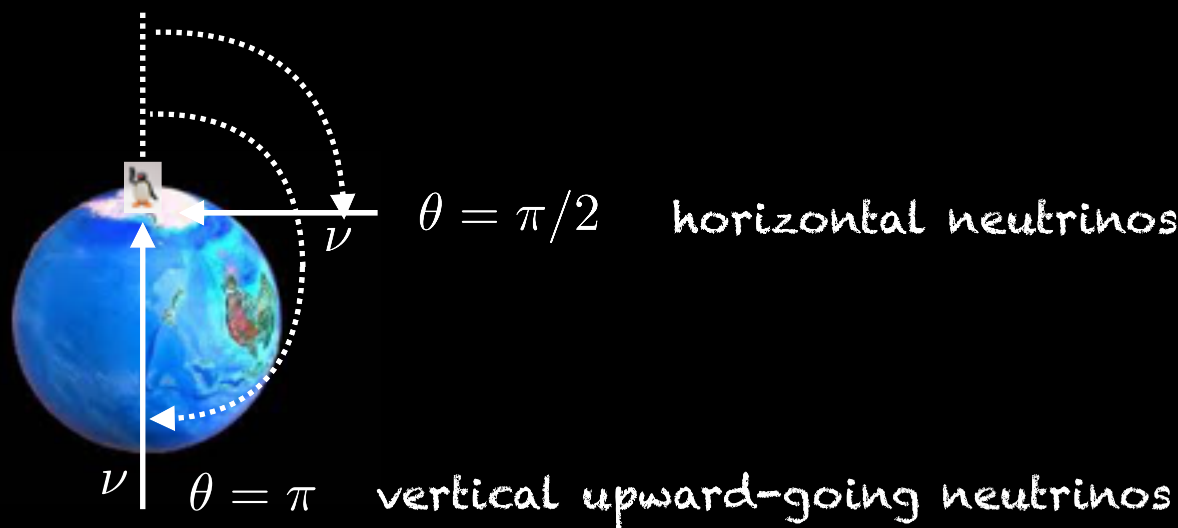
Factorise terms not depending on the mass hierarchy

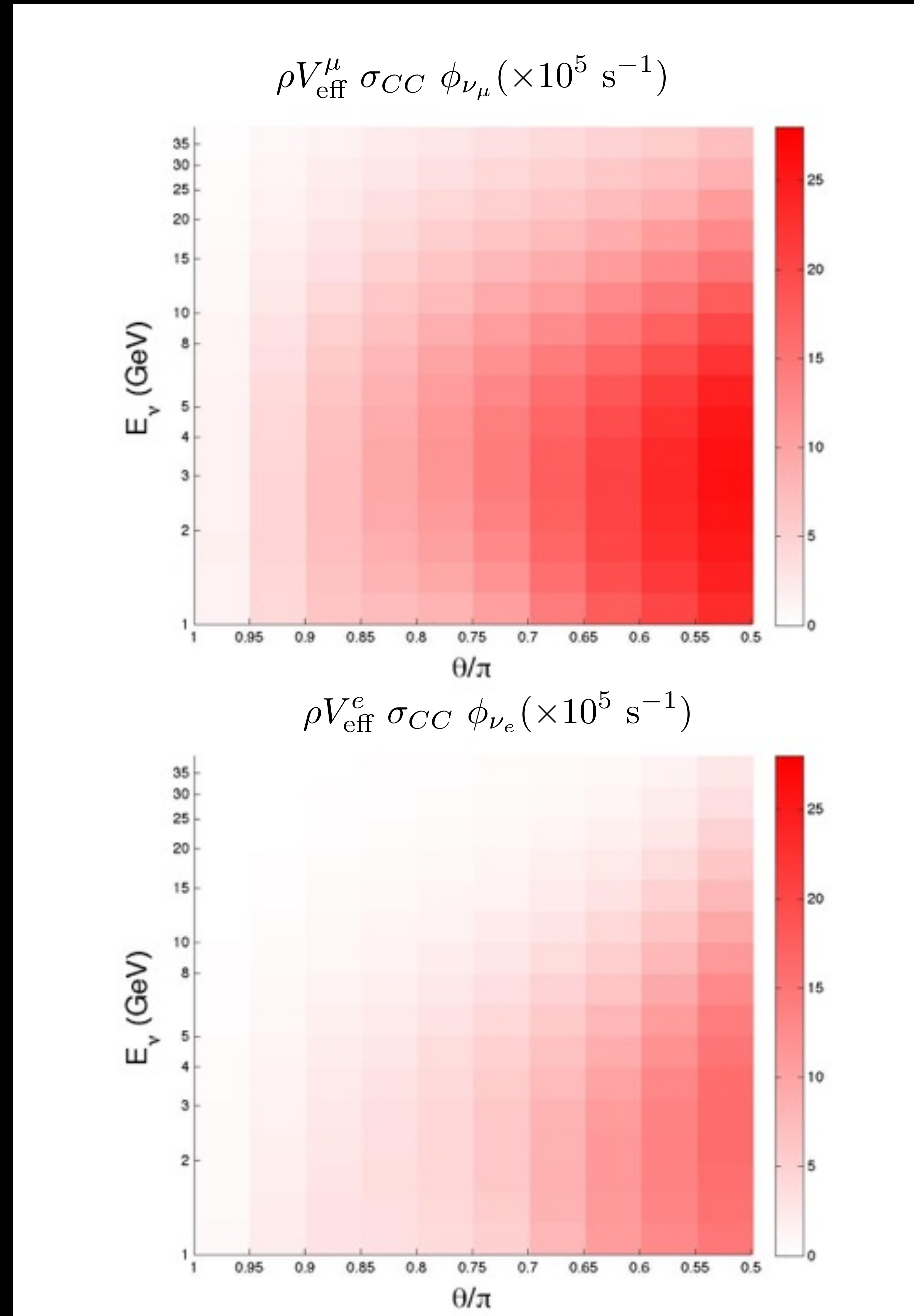
Combination of probabilities depending on the hierarchy

$$P_\mu = P_{\mu\mu} + \frac{\phi_{\nu_e}}{\phi_{\nu_\mu}} P_{e\mu} + \frac{\overline{\sigma}_{CC}\ \phi_{\overline{\nu}_\mu}}{\sigma_{CC}\ \phi_{\nu_\mu}} \overline{P}_{\mu\mu} + \frac{\overline{\sigma}_{CC}\ \phi_{\overline{\nu}_e}}{\sigma_{CC}\ \phi_{\nu_\mu}} \overline{P}_{e\mu}$$

$$P_e = P_{ee} + \frac{\phi_{\nu_\mu}}{\phi_{\nu_e}} P_{\mu e} + \frac{\overline{\sigma}_{CC}\ \phi_{\overline{\nu}_e}}{\sigma_{CC}\ \phi_{\nu_e}} \overline{P}_{ee} + \frac{\overline{\sigma}_{CC}\ \phi_{\overline{\nu}_\mu}}{\sigma_{CC}\ \phi_{\nu_e}} \overline{P}_{\mu e}$$

Note: to get the actual rate $\longrightarrow \int dE\ d\cos\theta\ \mathcal{N}_\alpha$





- 16 energy bins $E_\nu \in [1, 10^{1.6}]$ GeV
  10 bins in $\theta_{\rm zenith} \in [\pi/2, \pi]$

  (choice motivated by the resolution in angle and energy)

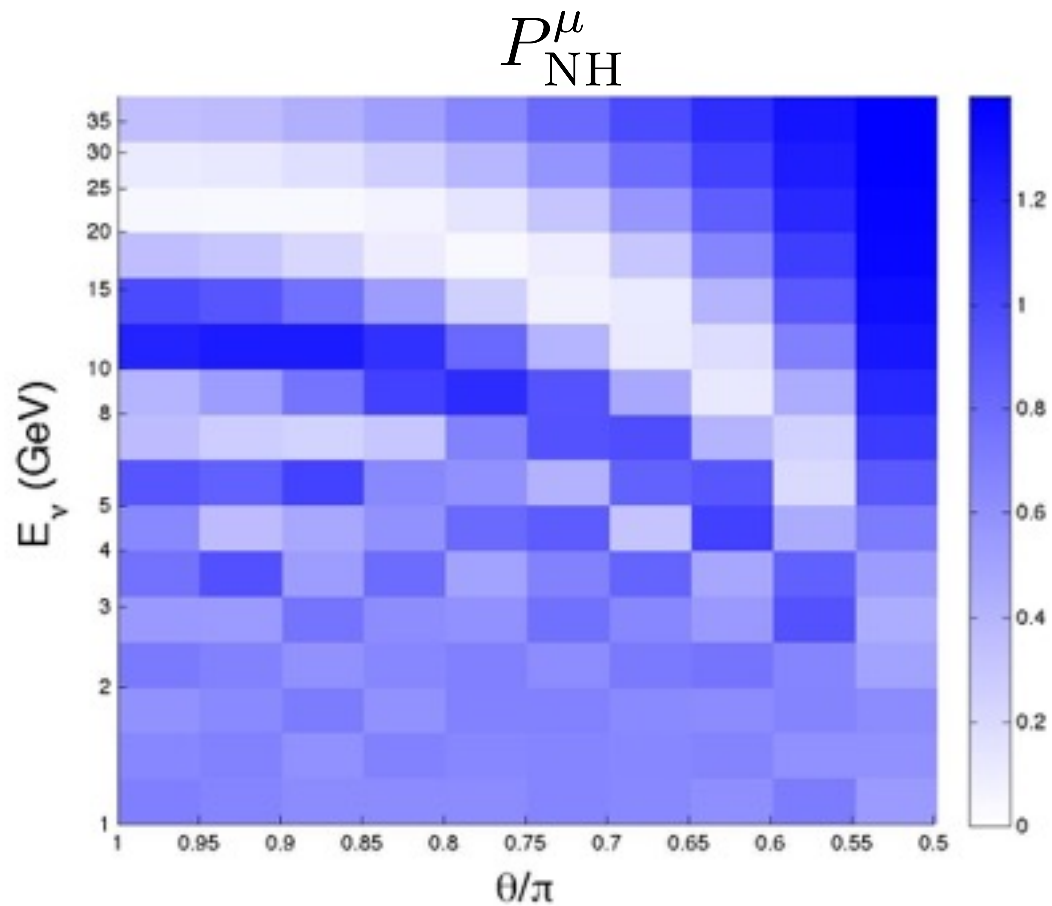
- Neutrino fluxes peaked at the horizon $(\theta \to \pi/2)$

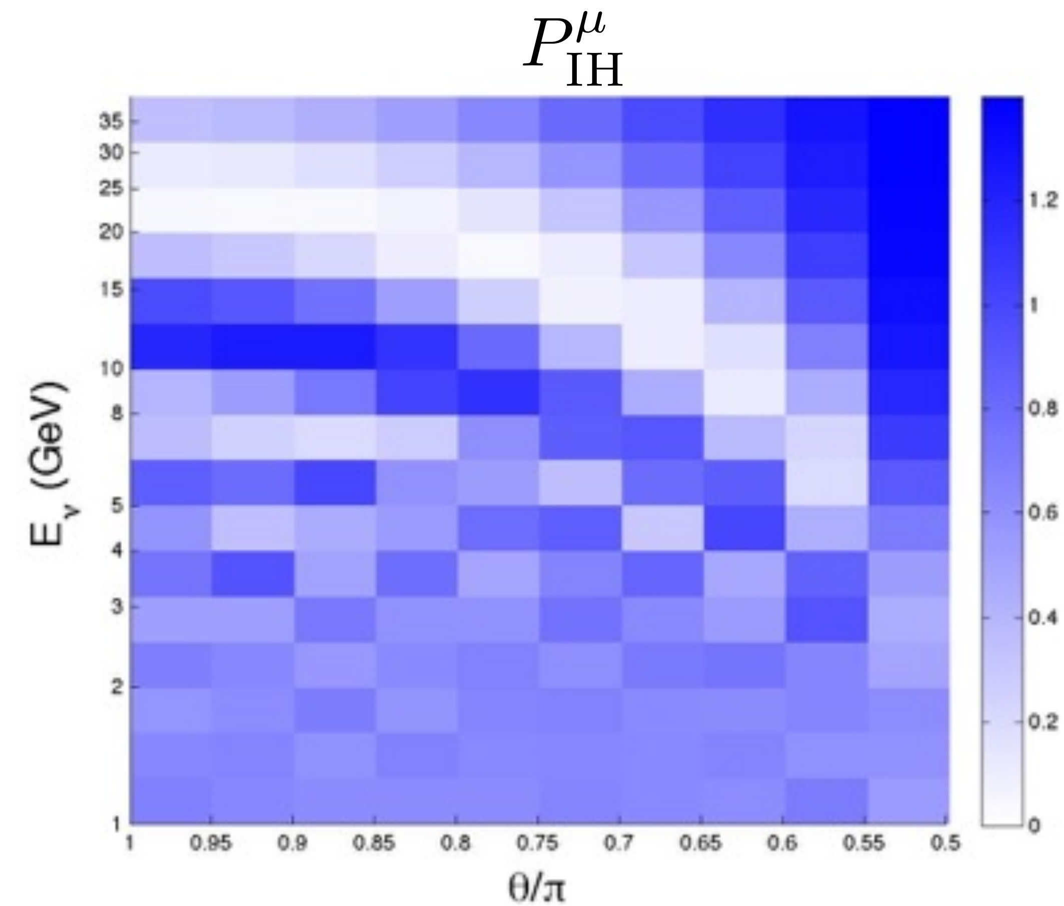
- As a function of energy maximum for few GeV since

  $\phi_\nu \sim E_\nu^{-3} \quad \sigma \sim E_\nu$

  $V \sim {\rm const}$ above 10-15 GeV

- $[V \times \sigma \times \phi]_\mu > [V \times \sigma \times \phi]_e$



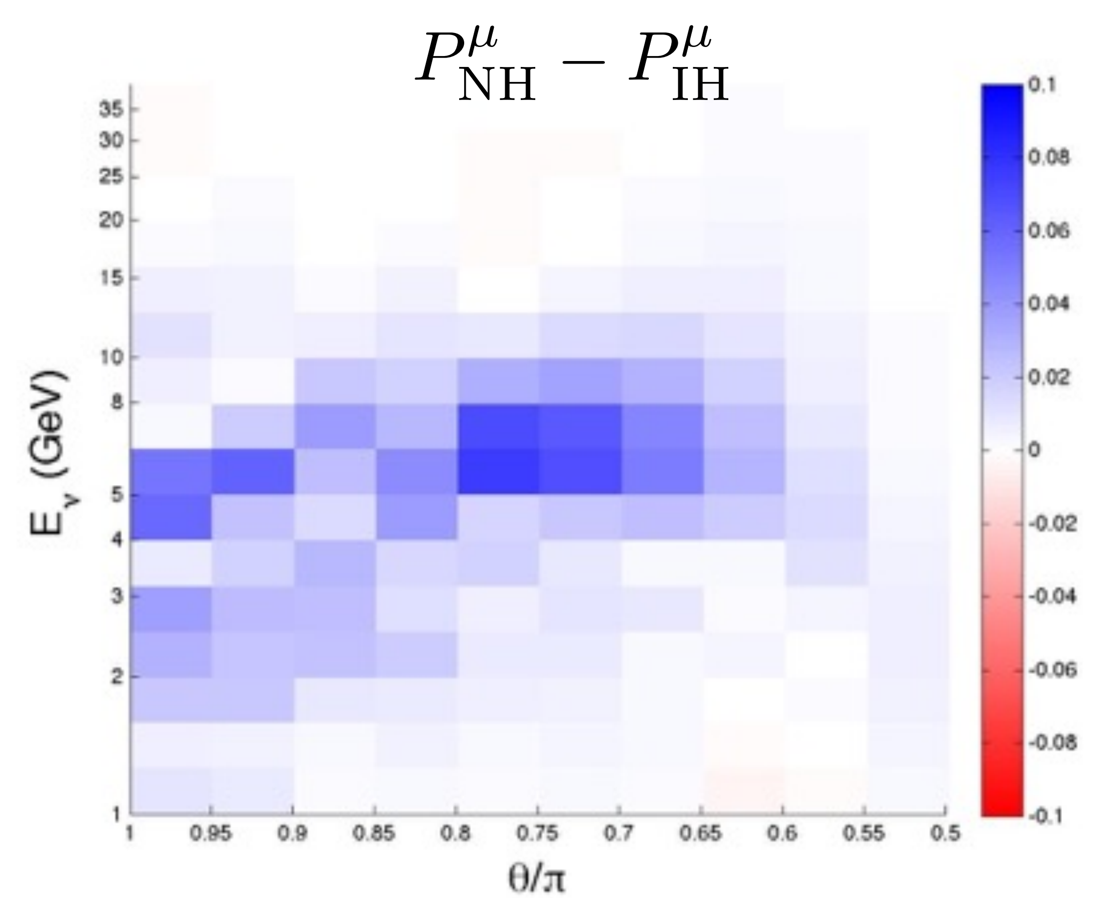


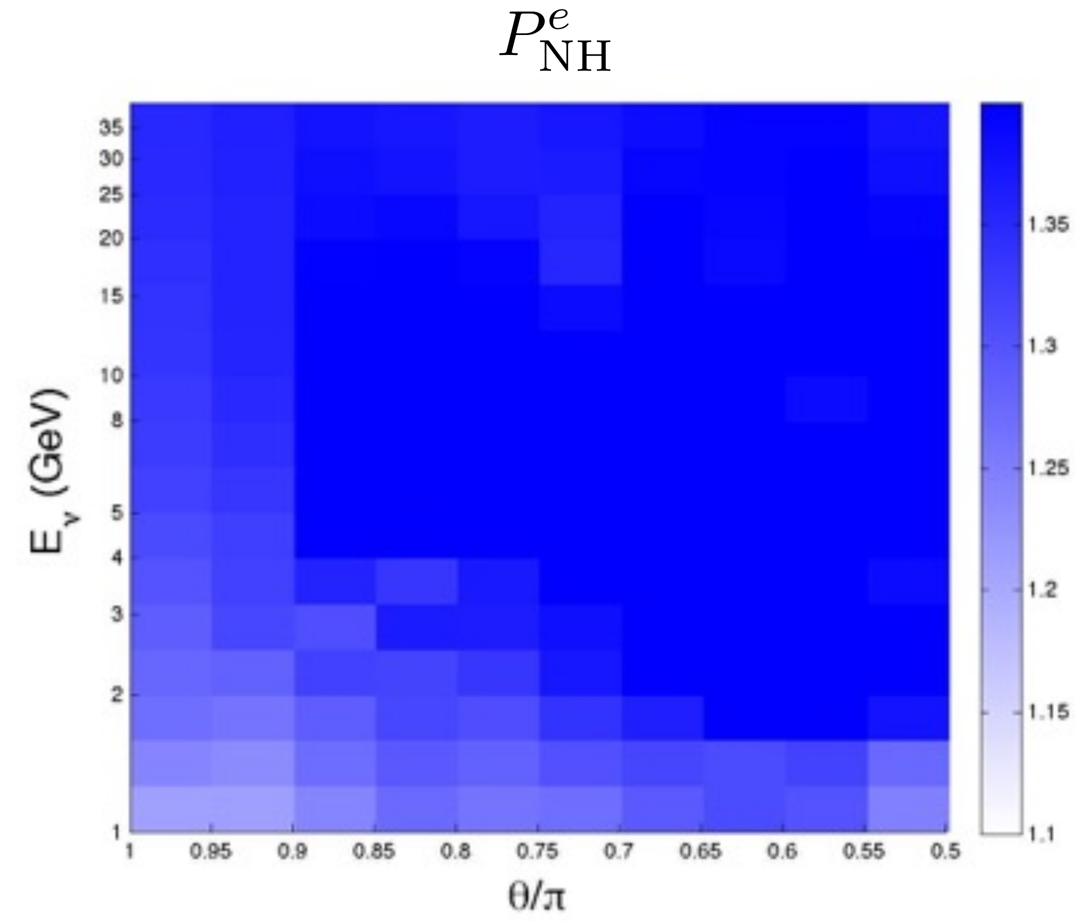
NH and IH probability very similar

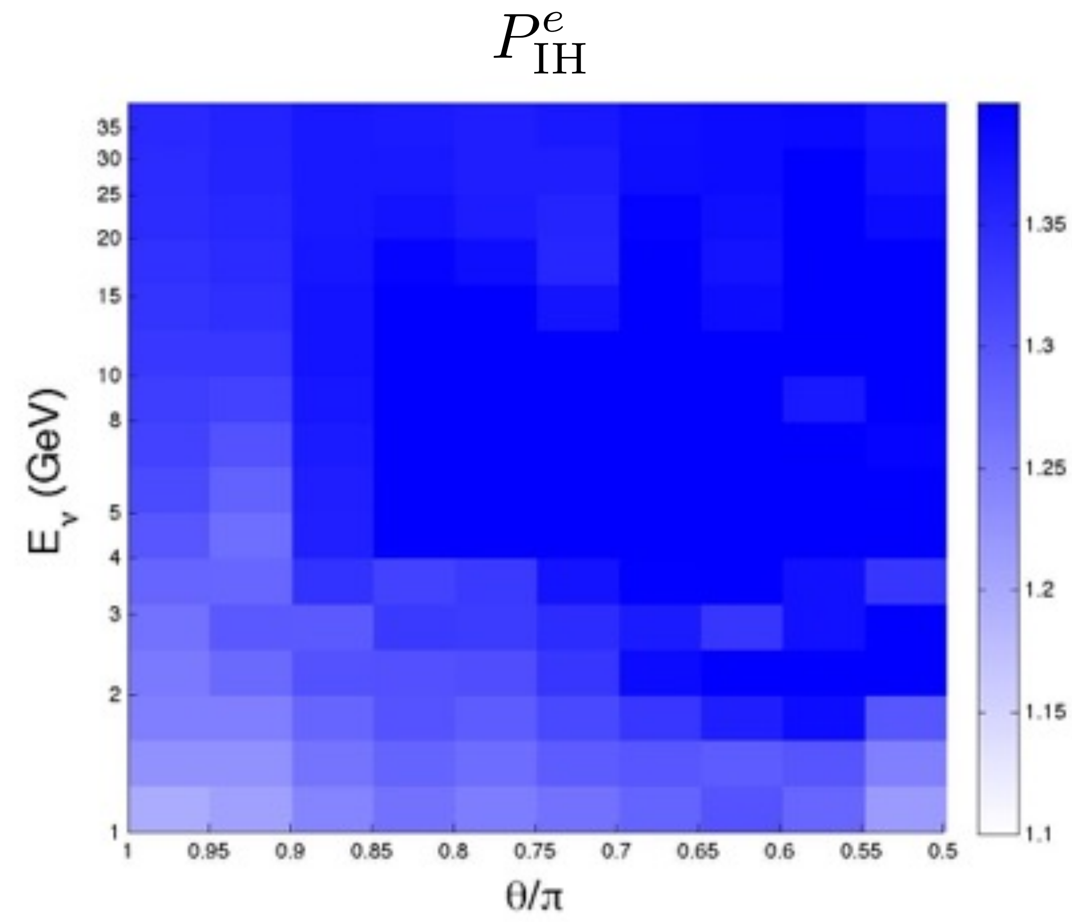
Differences mostly located at the mantle-core interface, at the MSW resonances in the core and in the mantle and for energies < 10 GeV

$$\theta_{\rm core}/\pi \sim 0.82$$

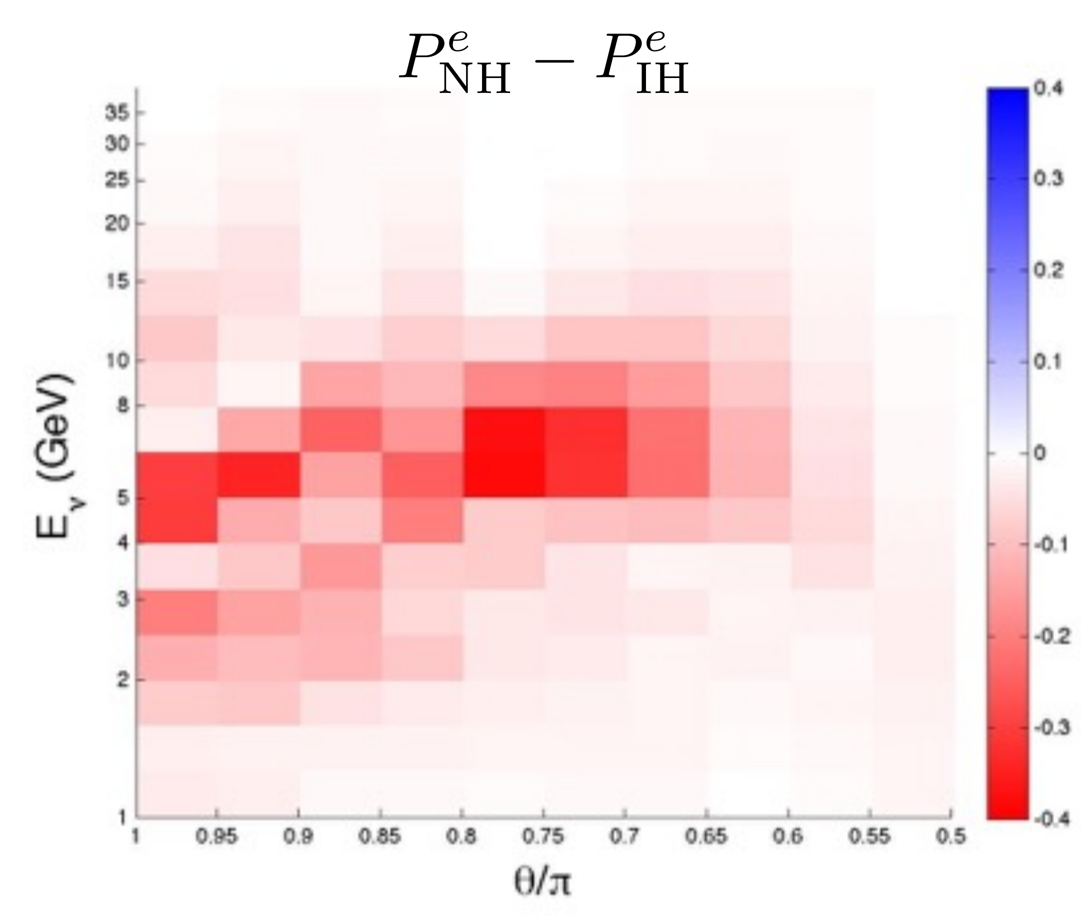
Oscillation parameters fixed at they best fit (1 octant of θ_{23})



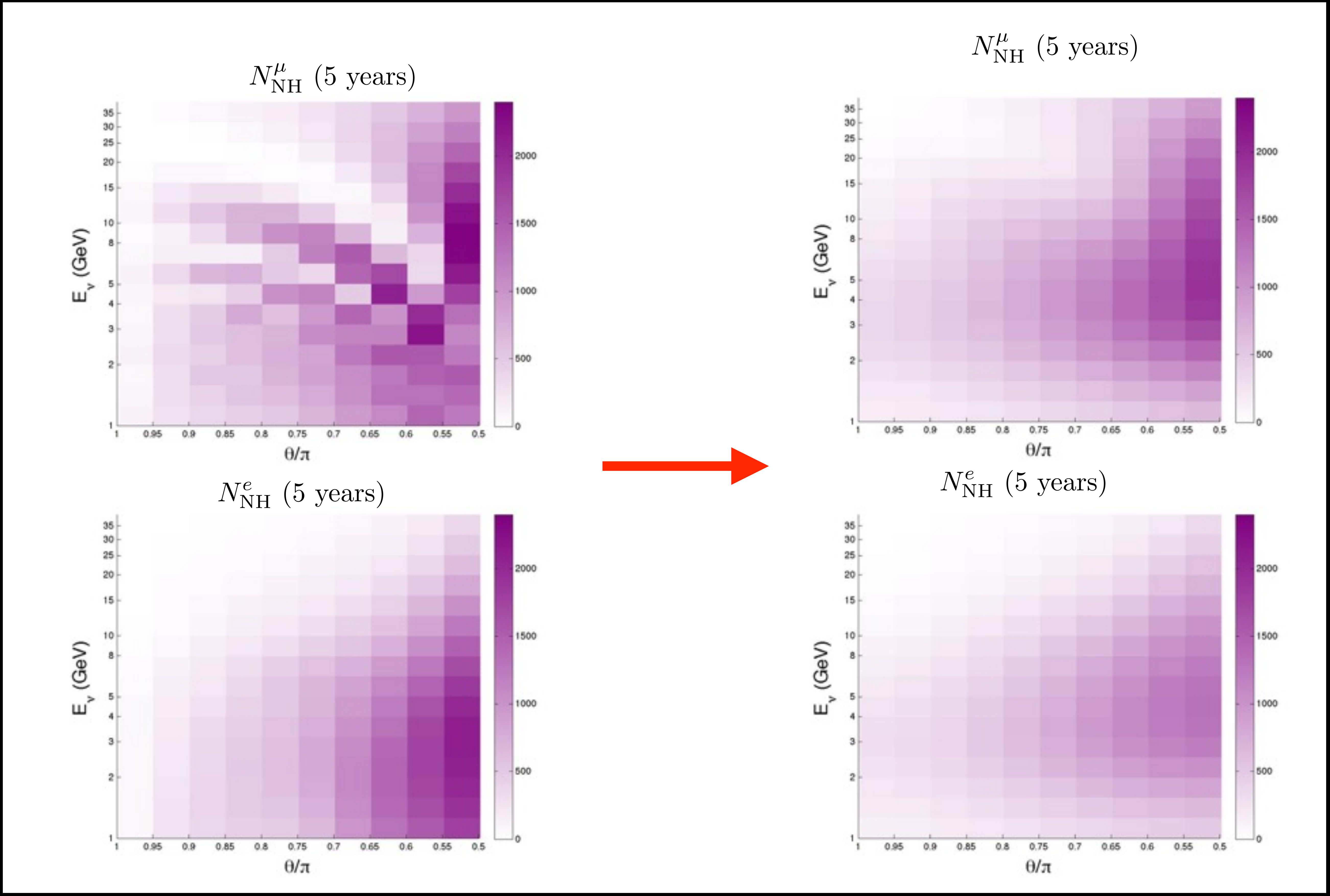




Probabilities with less structure but more pronounced dependence on th hierarchy (note the different color map scale)



Impact of the resolution



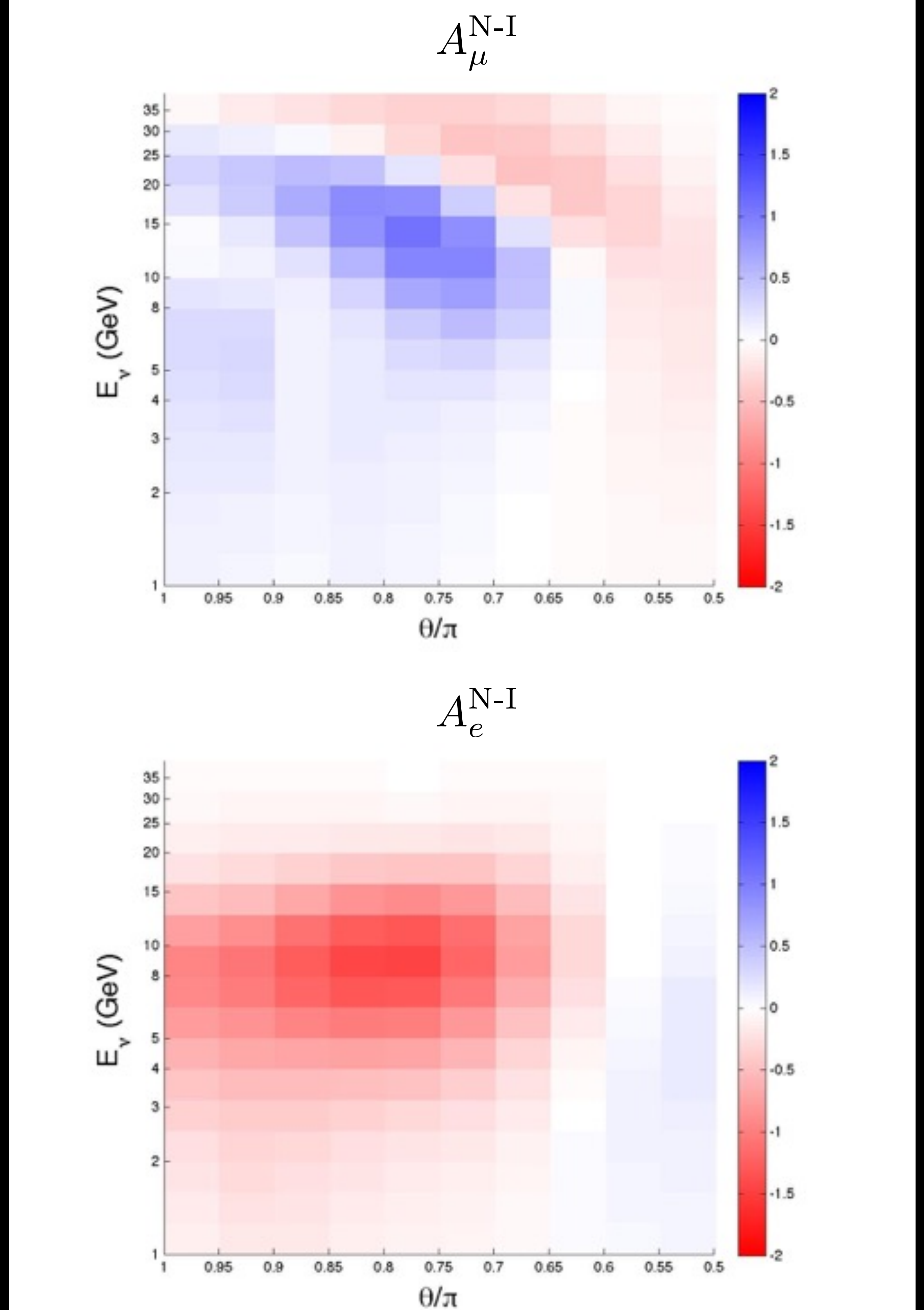
Define the Hierarchy Asymmetry as

$$A_\alpha^{\text{N-I}} = \frac{N_\alpha^{\text{NH}} - N_\alpha^{\text{IH}}}{\sqrt{\frac{1}{2}(N_\alpha^{\text{NH}} + N_\alpha^{\text{IH}})}}$$

Much of the asymmetry in the region where the rate tends to decrease (left upper part of the plots)

Rate of electron-like event gives an important contribution to the hierarchy discrimination

Size of bins large enough to resolve structures of the asymmetry in the angle-energy plane



Analysis strategy

Identify all parameters on which the expected rate depends linearly and treat them as pulls

Treat nonlinear parameters as free parameters

Check the results of the fit against possible unknown shape errors that could worsen the sensitivity to the hierarchy

For instance consider shape errors that can be parametrised as polynomial in the energy-angle plane (up to the fourth degree)

STATISTICAL ANALYSIS

Pull method as in Fogli et al., Phys.Rev.D66:053010,2002

$$\chi^2_{\rm cov} = \sum_{ij} (R_i^{\rm expt} - R_i^{\rm theor}) \sigma_{ij}^{-2} (R_j^{\rm expt} - R_j^{\rm theor})$$

$$\sigma_{ij}^2 = u_i u_j \delta_{ij} + \sum_k c_i^k c_j^k$$

Uncorrelated and correlated errors

$$\chi^2_{\rm pull} = \min_{\{\xi_k\}} \left[\sum_i \left(\frac{R_i^{\rm expt} - R_i^{\rm theor} - \sum_k \xi_k c_i^k}{u_i} \right)^2 + \sum_k \xi_k^2 \right]$$

$$\chi^2_{\rm cov} = \chi^2_{\rm pull} = \chi^2_{\rm obs} + \chi^2_{\rm sys}$$

Advantages of the pull method:

It allows

- a faster calculation when number of systematic errors increases
- to check the consistency of the fit
- to extract lots of informations on systematic errors

Inputs of the Analysis

320 Observables

(16x10)x(16x10) bins

11-39 Systematic Errors

Oscillation parameters

$(\delta m^2, \sin^2\theta_{12}) = (7.54 \times 10^{-5}\ \mathrm{eV}^2, 0.308)$	fixed
$(\Delta m^2, \sin^2\theta_{13})$	"parametric" linear errors
$(\delta, \sin^2\theta_{23})$	free

Systematics

"No-shape" errors

α	Earth density	3%
ν_μ/ν_e	flavor ratio	8%
$\nu/\bar{\nu}$	ratio	6%
f_N	Normalisation	15%

"Shape" errors

$(\sigma_E^\mu, \sigma_E^e)$	Energy resolution	10%
$(\sigma_\theta^\mu, \sigma_\theta^e)$	Angular resolution	10%
α_E	Energy scale	5%

Polynomial shape errors

linear, quadratic, cubic or quartic polynomial

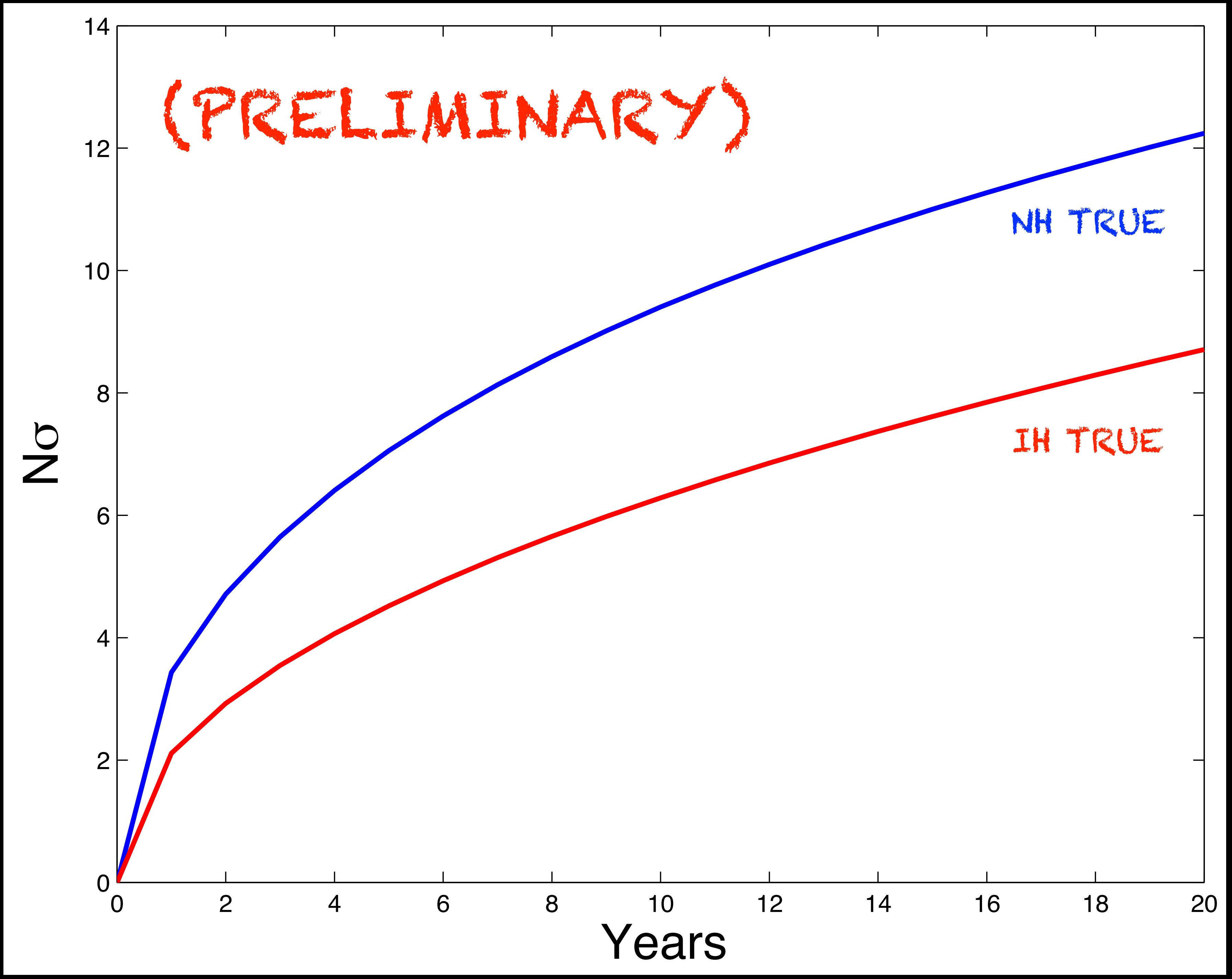
$(2, 5, 9, 14)$ coefficients

Shape distortion < 3%

Maximal Mixing case $(\sin^2\theta_{23} = 0.5)$

Different cases with increasing number of systematics

"no-shape" errors

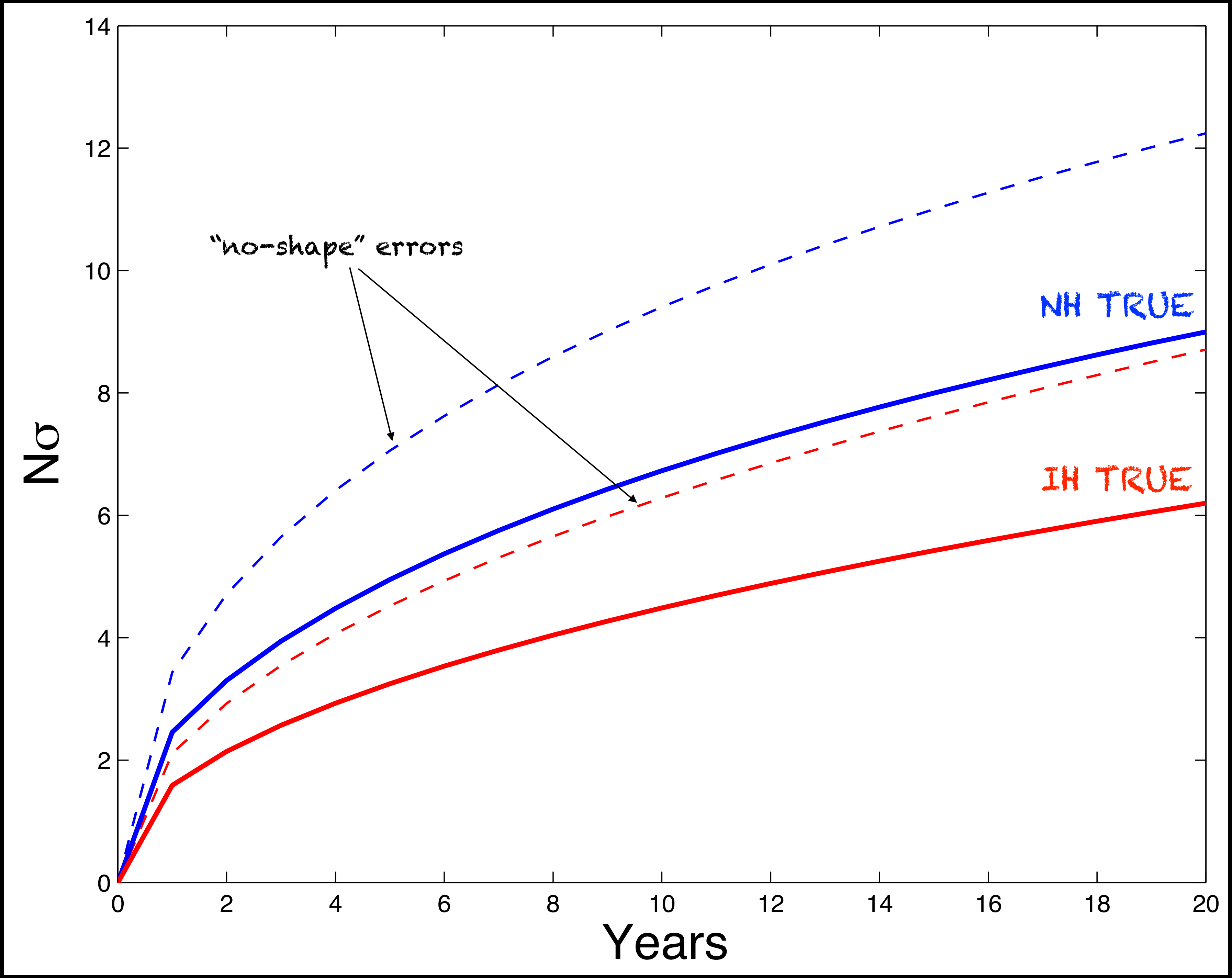


Maximal Mixing case $(\sin^2\theta_{23} = 0.5)$

Different cases with increasing number of systematics

"no-shape" errors

+"shape" errors
(energy/angle resolution, energy scale)



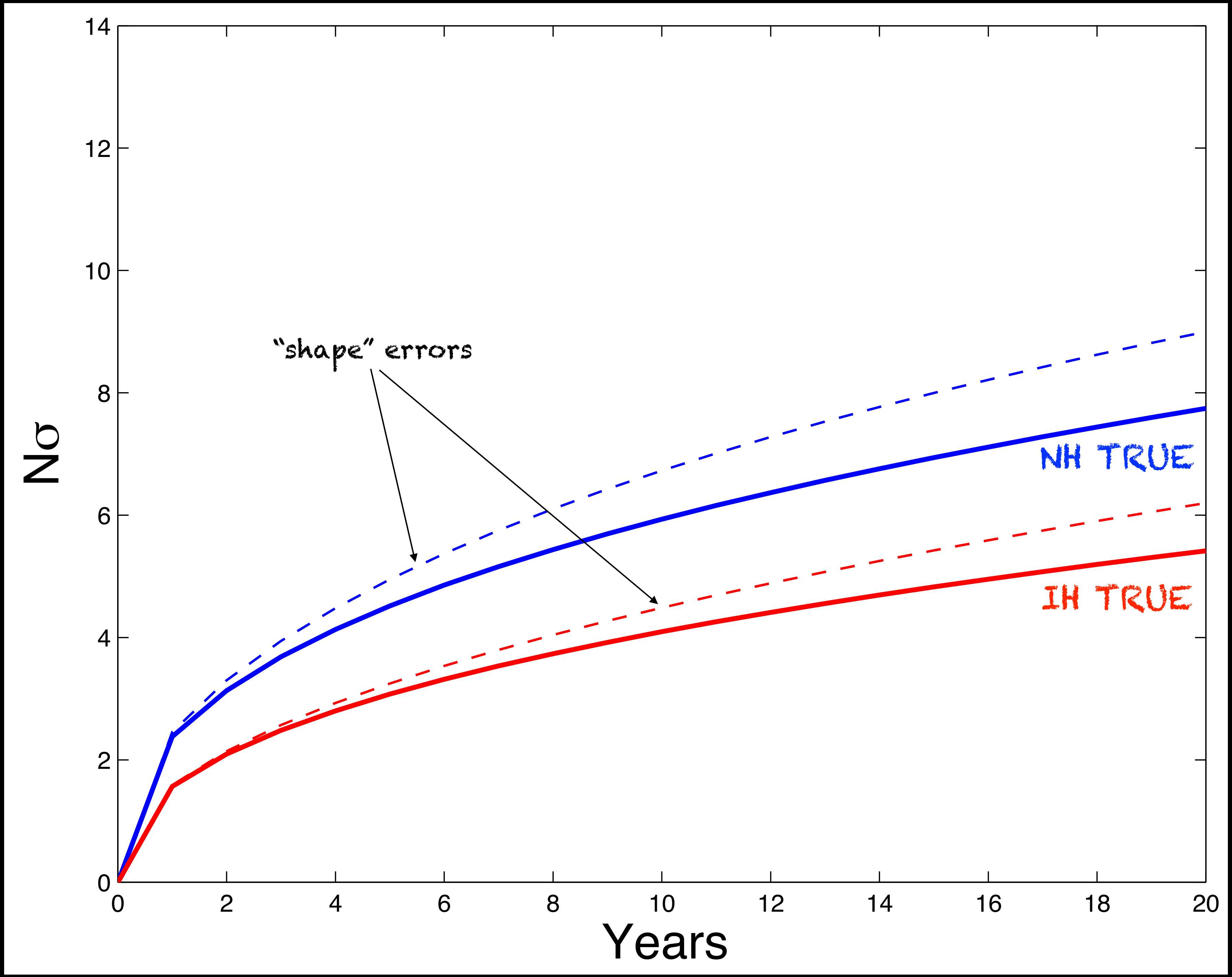
Maximal Mixing case $(\sin^2\theta_{23} = 0.5)$

Different cases with increasing number of systematics

"no-shape" errors

+"shape" errors
(energy/angle resolution, energy scale)

+ polynomial shape errors (linear)



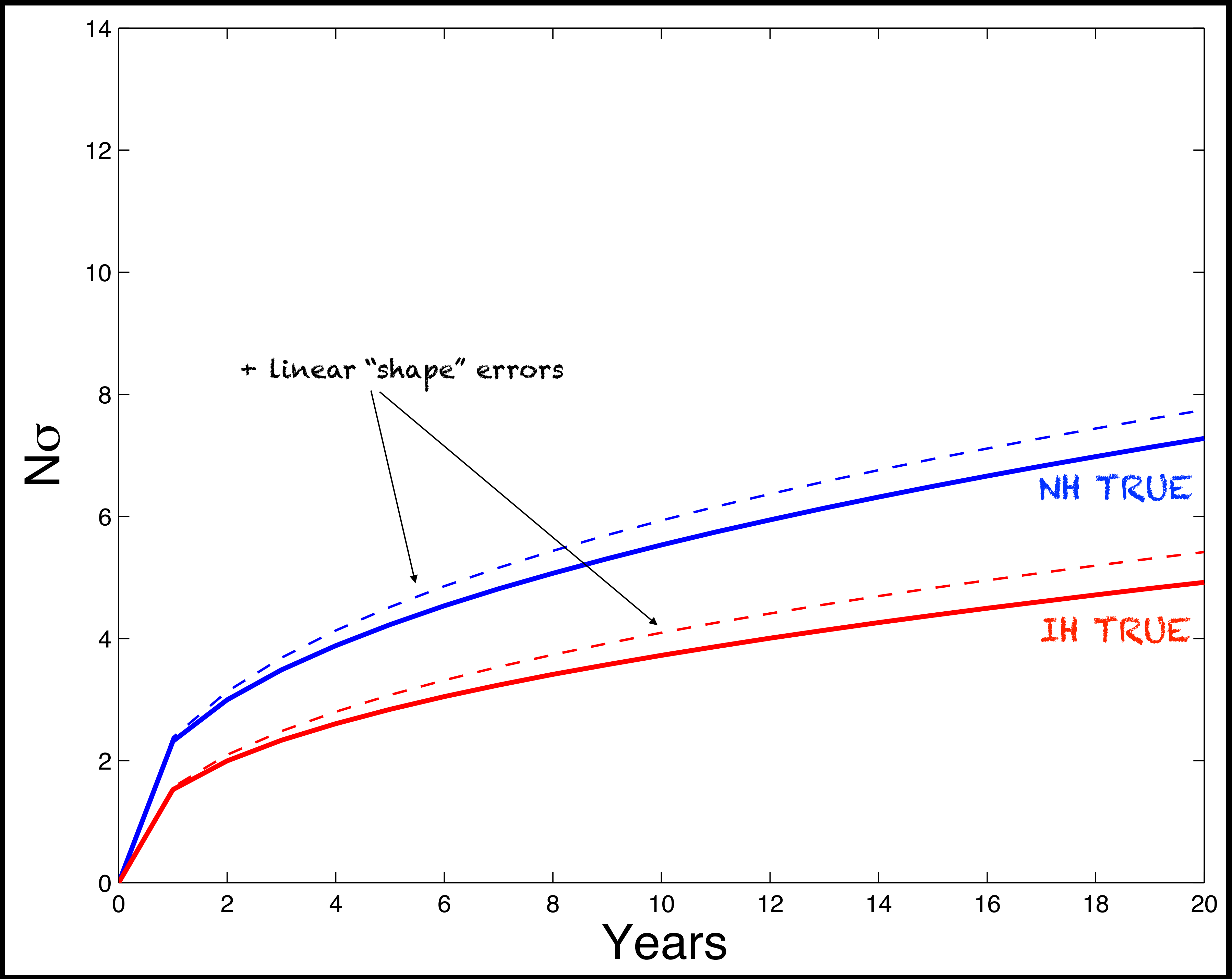
Maximal Mixing case $(\sin^2\theta_{23} = 0.5)$

Different cases with increasing number of systematics

"no-shape" errors

+"shape" errors
(energy/angle resolution, energy scale)

+ polynomial shape errors (quadratic)



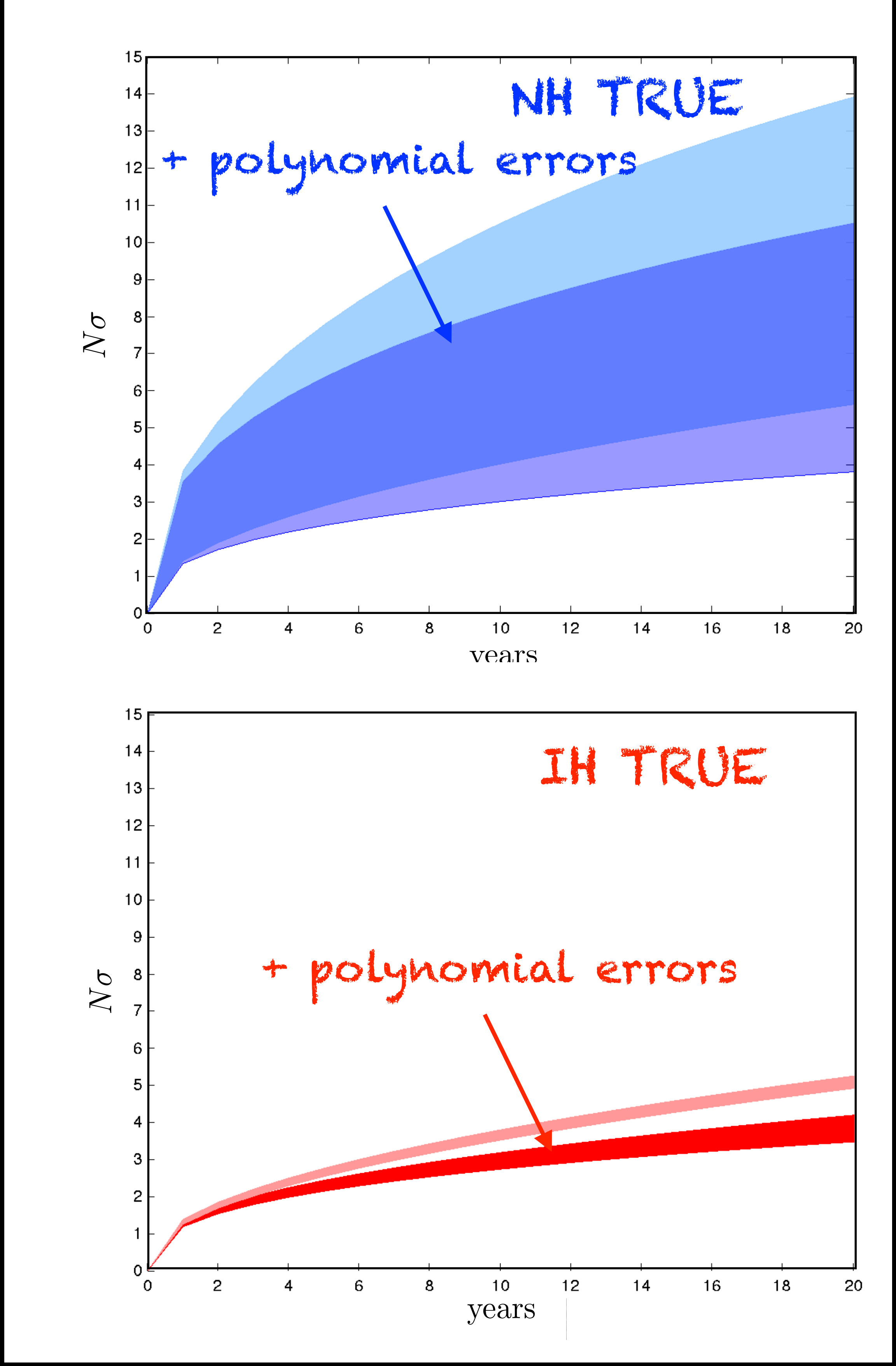
Non-Maximal Mixing case $(\sin^2\theta_{23} = 0.4, 0.6)$

Adding polynomial shape errors reduces the Hierarchy sensitivity

After 10 years (in the worst case) the reduction of the sensitivity is of about 1 sigma

NH $4\sigma \rightarrow 3\sigma$

IH $3.8\sigma \rightarrow 2.7\sigma$



Detailed studies of the detector needed to exclude such shape distortions

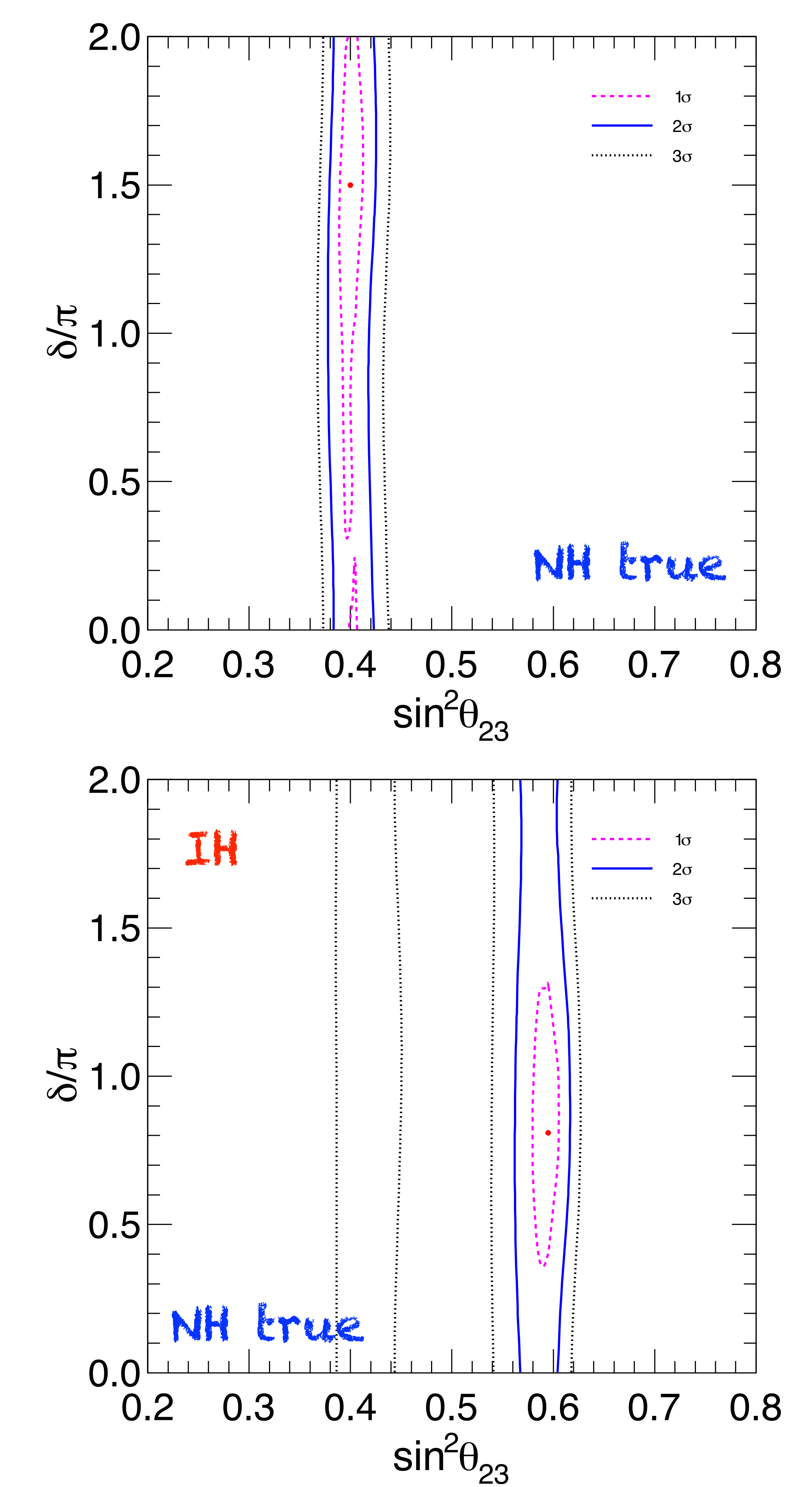
Octant of θ_{23}

If the hierarchy is known, precision on θ_{23} of few %

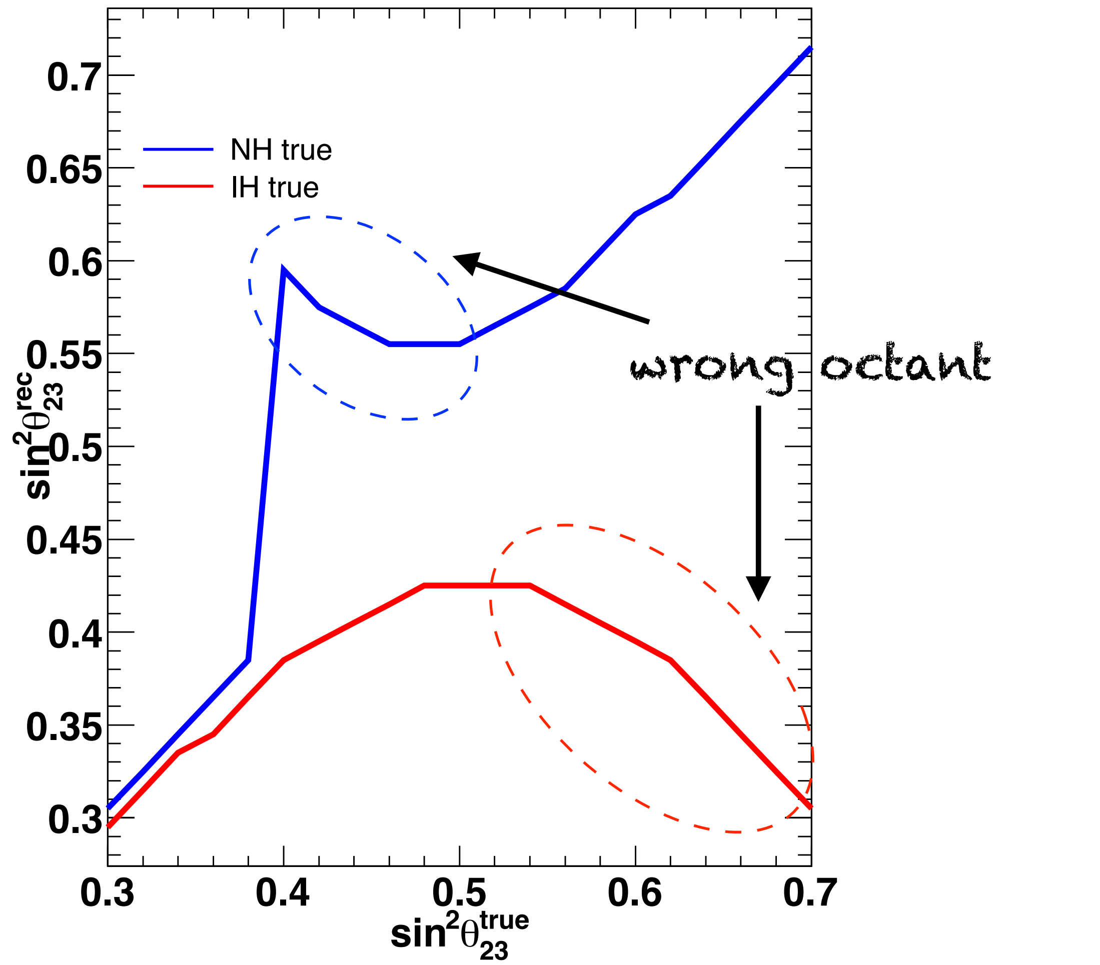
No information on CP phase
All values allowed even at 1σ

But if hierarchy is not known, in the IH one gets the wrong octant of θ_{23}

Also wrong value of δ

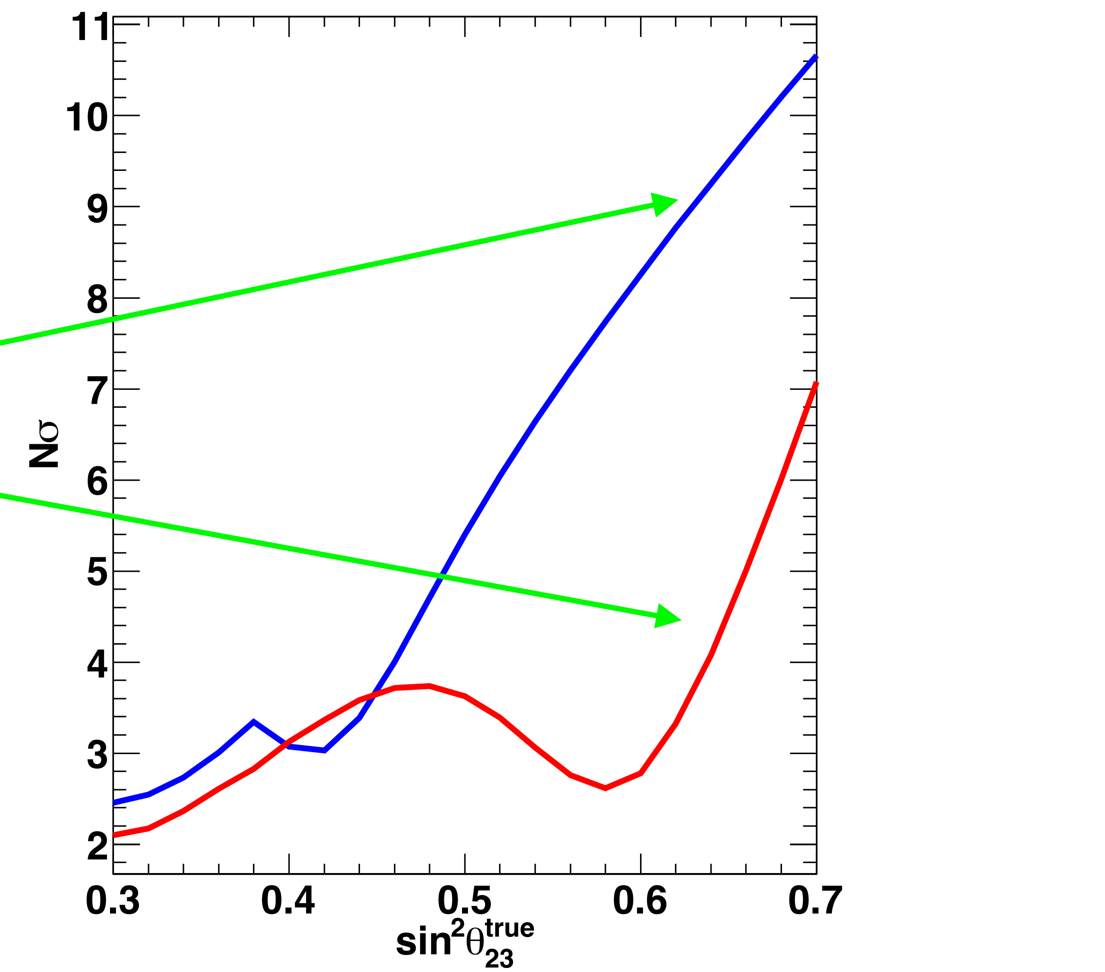


The reconstructed value of depends on the true θ_{23} value and on the hierarchy and it can be in the wrong octant



Hierarchy sensitivity and the true value of θ_{23}

Easy to discriminate hierarchy when θ_{23} is large and in the second octant



(10 years of Data taking)

Conclusions

PINGU exploits matter effects in the propagation of atmospheric neutrinos

PINGU is one of the most promising experiment to determine the neutrino mass hierarchy

Possible hierarchy discrimination at a level $\gtrsim 3\sigma$ in a reasonable time