25th International Workshop on Weak Interactions and Neutrinos (WIN2015)

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Super-PINGU for measuring leptonic CP phase with atmospheric neutrinos

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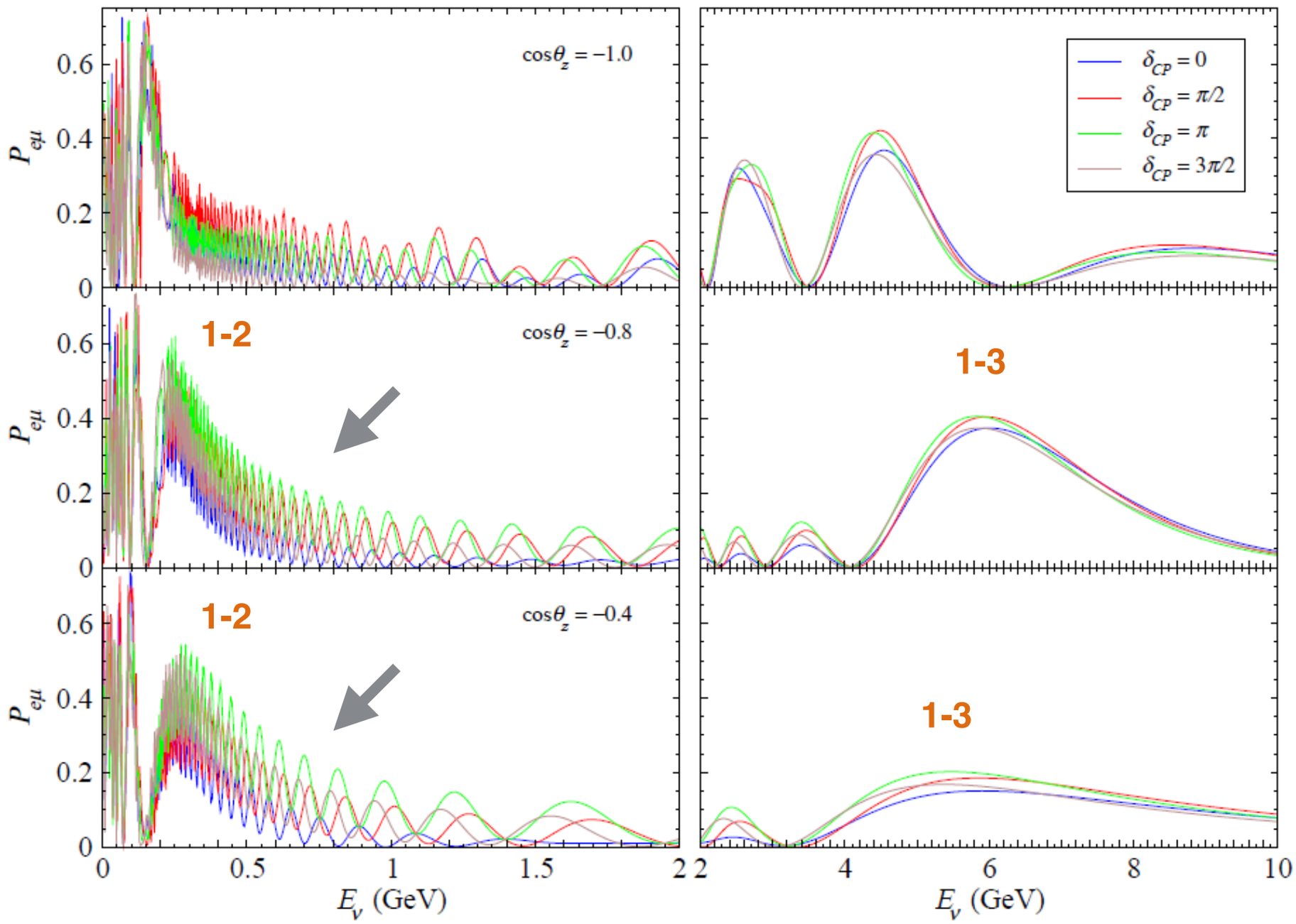
JHEP 05 (2015) 139 [arXiv:1406.1407 [hep-ph]]

Outline of talk

- Explore a possibility to measure CP with atmospheric neutrinos - **small effect (few percent)**
  - Identify CP sensitive energy and zenith angle range
  - Earlier estimates (*E.Kh. Akhmedov, S.R., A.Yu. Smirnov, arXiv: 1205.7071; PINGU LoI, arXiv:1401.2046*) showed **PINGU** (~3 GeV threshold) **will have limited sensitivity to CP**
- Estimate of CP sensitivity using a toy detector **- Super-PINGU**
  - Characteristics extrapolated from PINGU
  - Explore effects of systematic uncertainties

Transition Probability $\nu_e \rightarrow \nu_\mu$

Systematic shift of probability with CP phase in **~0.3-2 GeV** range, below 1-3 resonances, over a wide zenith angle range - mantle



PREM

Core

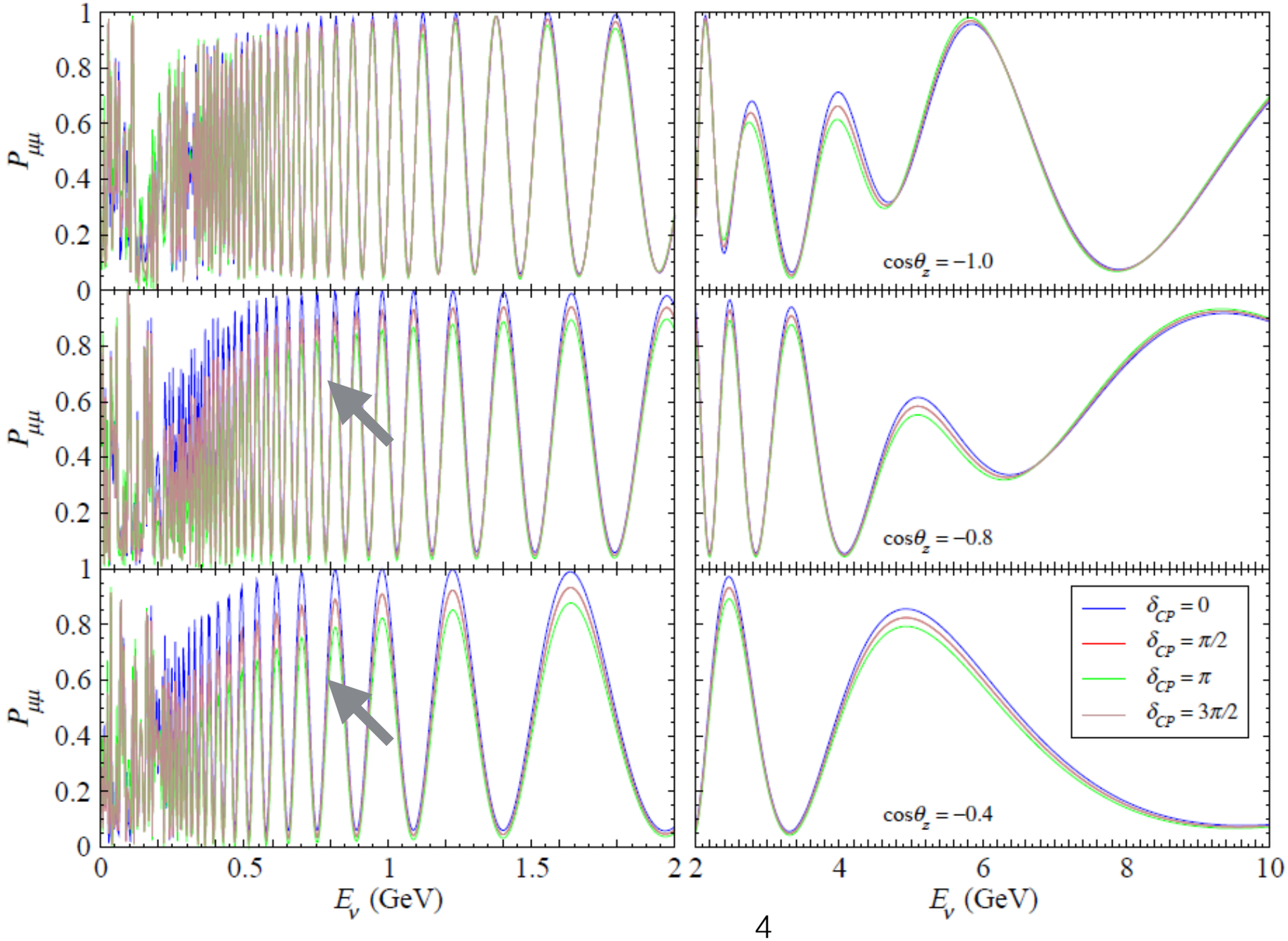
Parametric

Mantle

MSW

Survival Probability $\nu_\mu \rightarrow \nu_\mu$

Systematic shift of probability with CP phase in **~0.3-2 GeV** range, below 1-3 resonances, over a wide zenith angle range - mantle



PREM

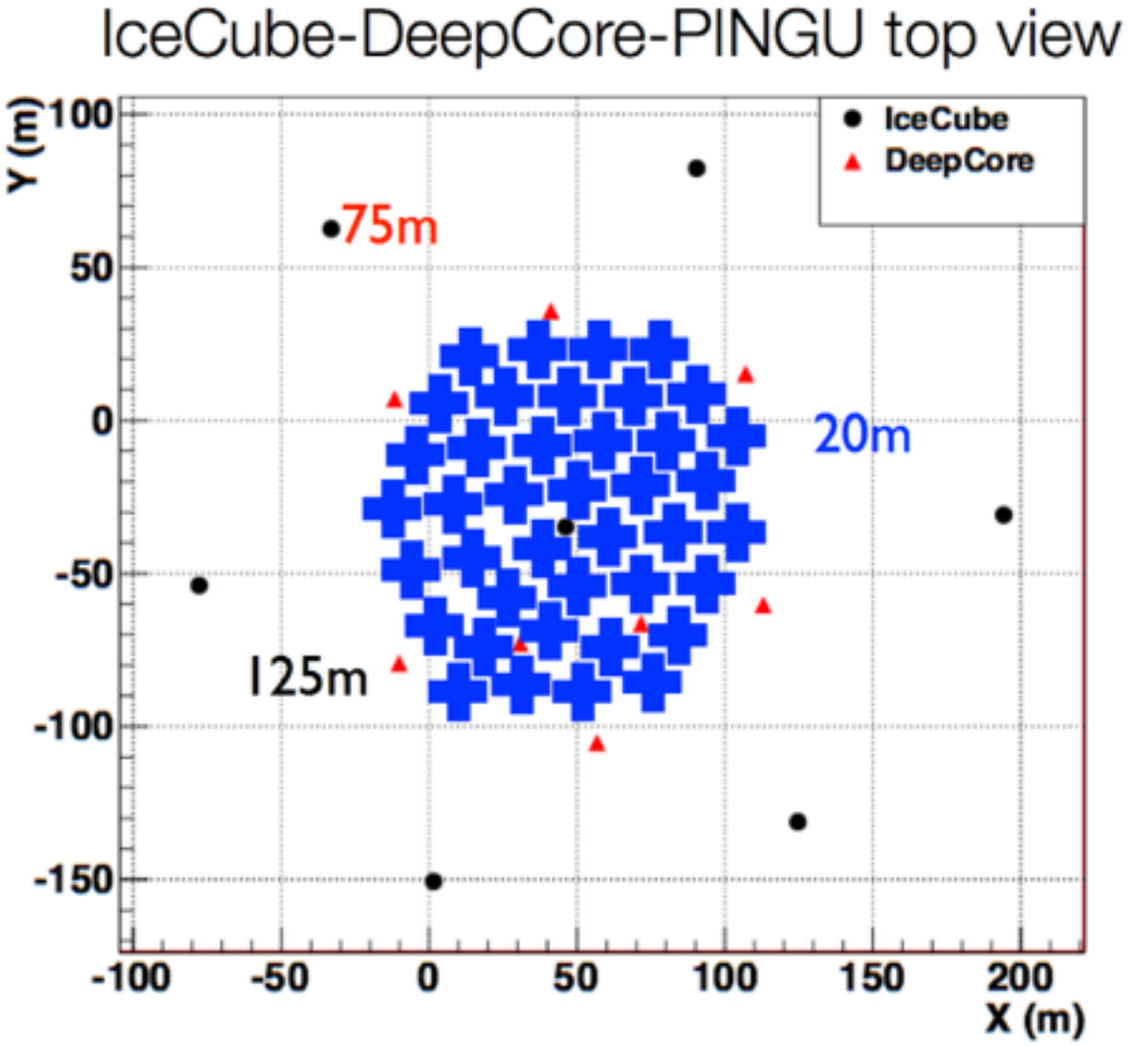
Core

Mantle

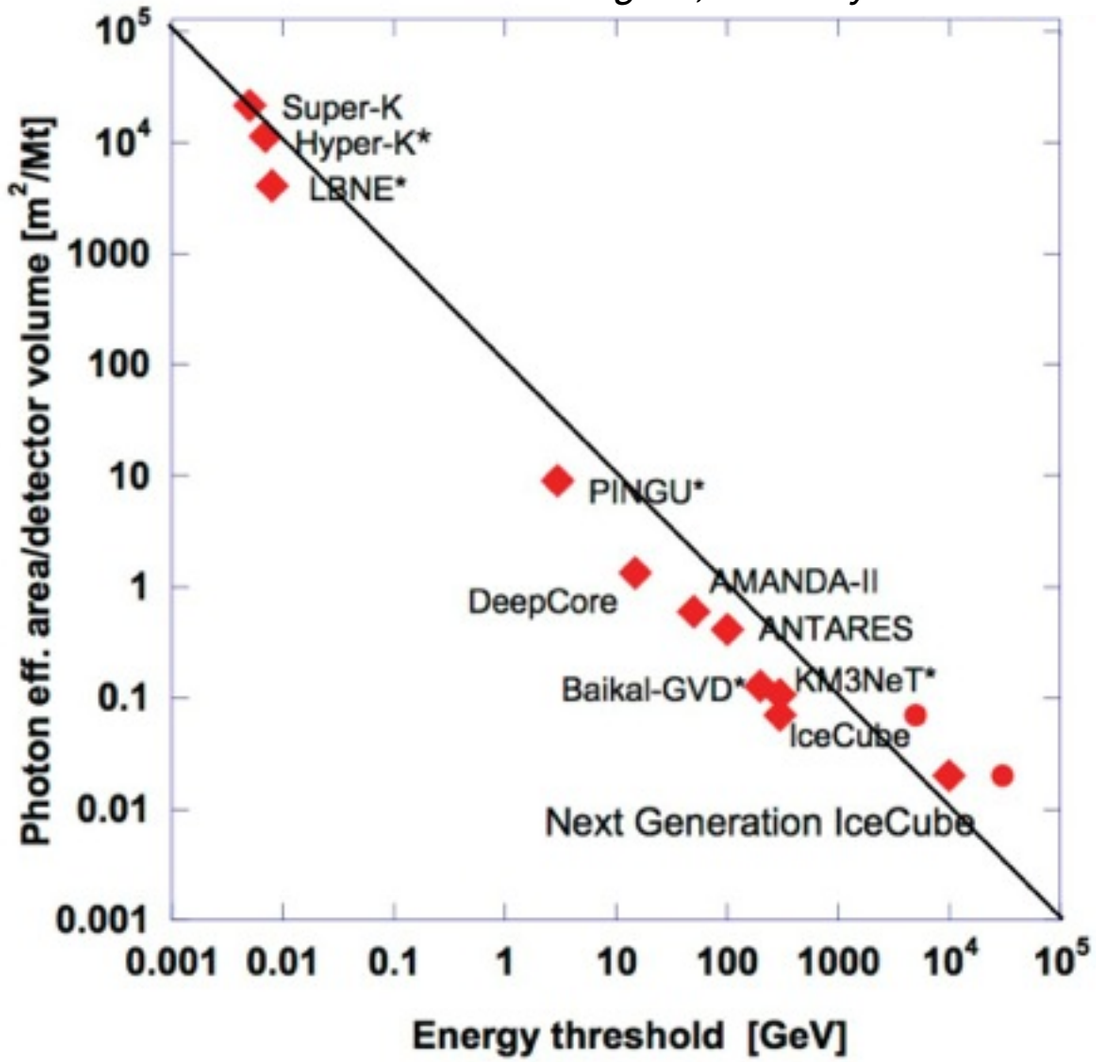
No shift of oscillation phase

A march to lower energy

- **IceCube:** 78 strings, 125 m separation, 17 m DOM spacing
- **Deep Core:** 8 additional strings, 75 m separation, 7 m DOM spacing
- **PINGU:** 40 additional strings, 20 m separation, 3-5 m DOM spacing



Figure, courtesy of A. Karle



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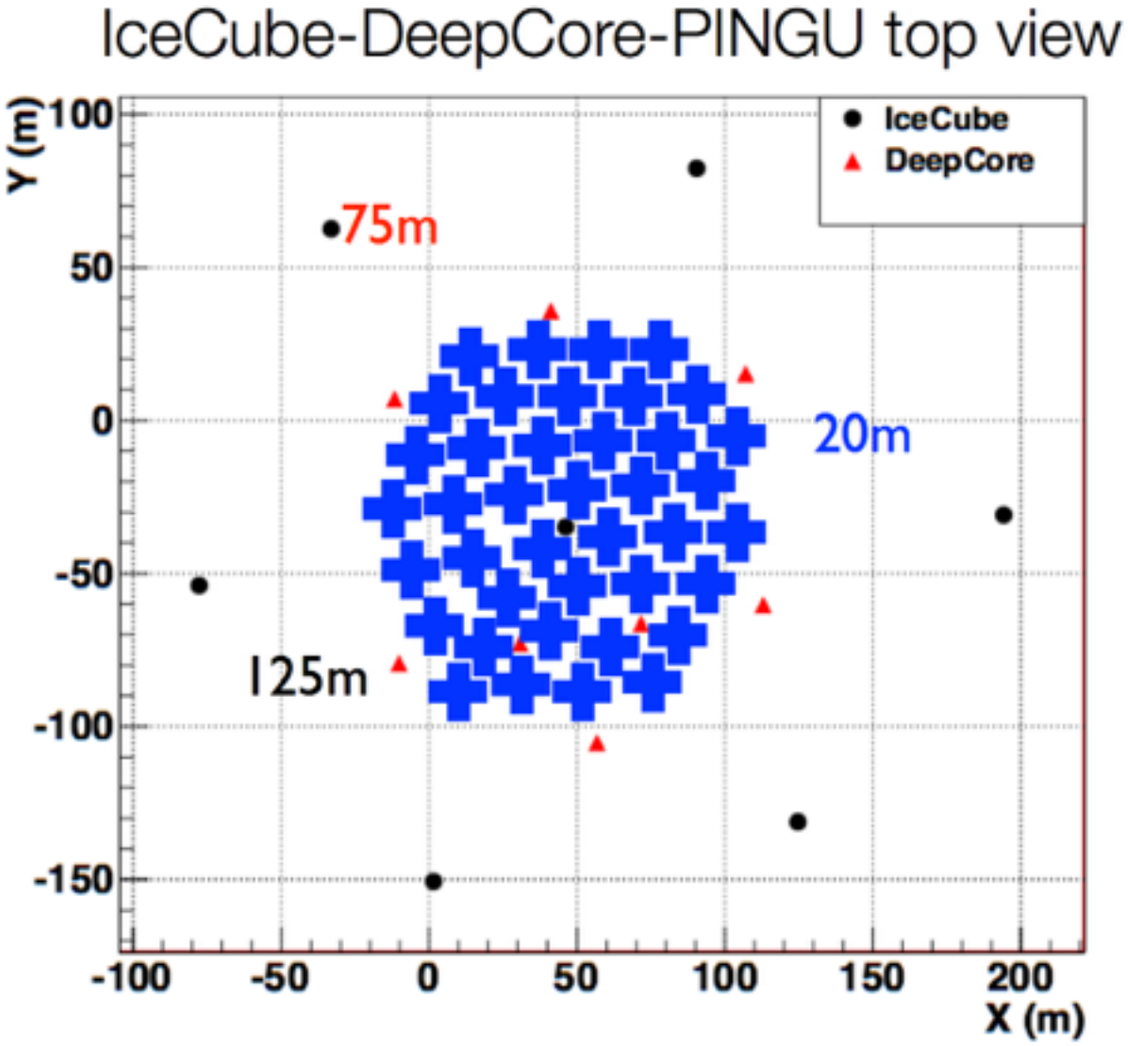

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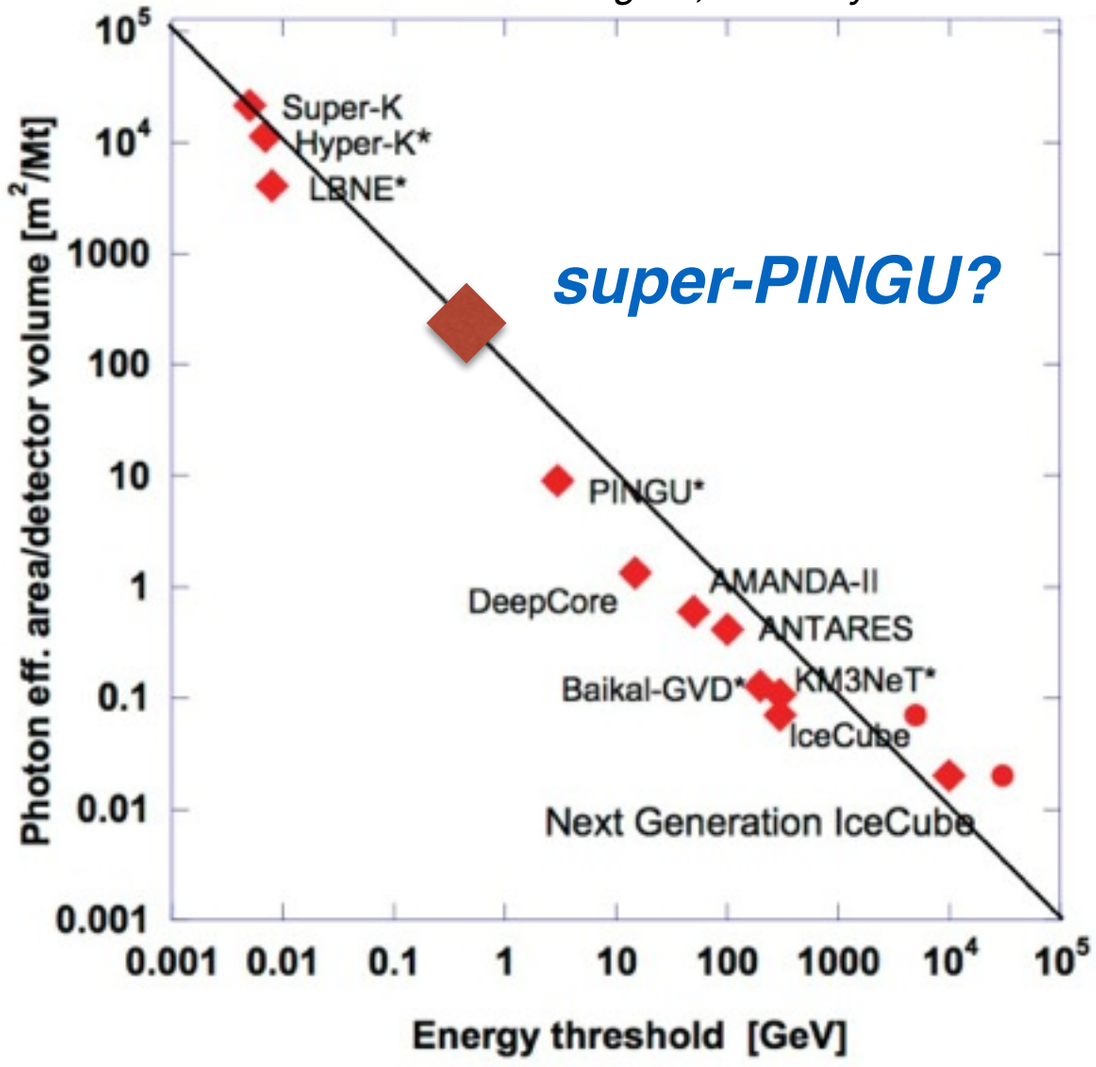
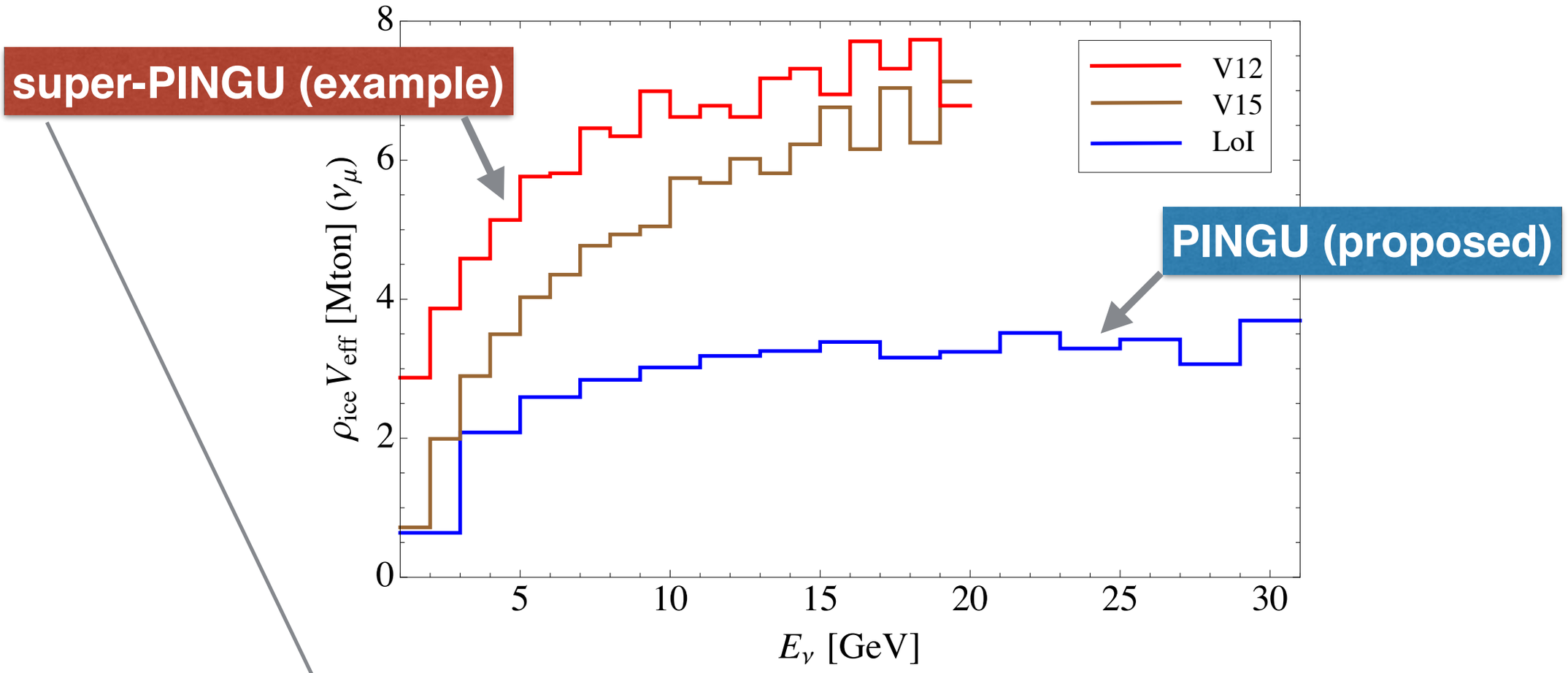


Super-PINGU: An example

- 126 strings within Deep Core volume (60 DOM per string)
- Geometrical volume remains the same as PINGU
- Sensitivity at low energy increases (~3x DOM density)



Parametrization: $\rho V_{\rm eff}(E_\nu) = 2.6[\log(E_\nu/{\rm GeV}) + 1]^{1.32}\,{\rm Mt}$

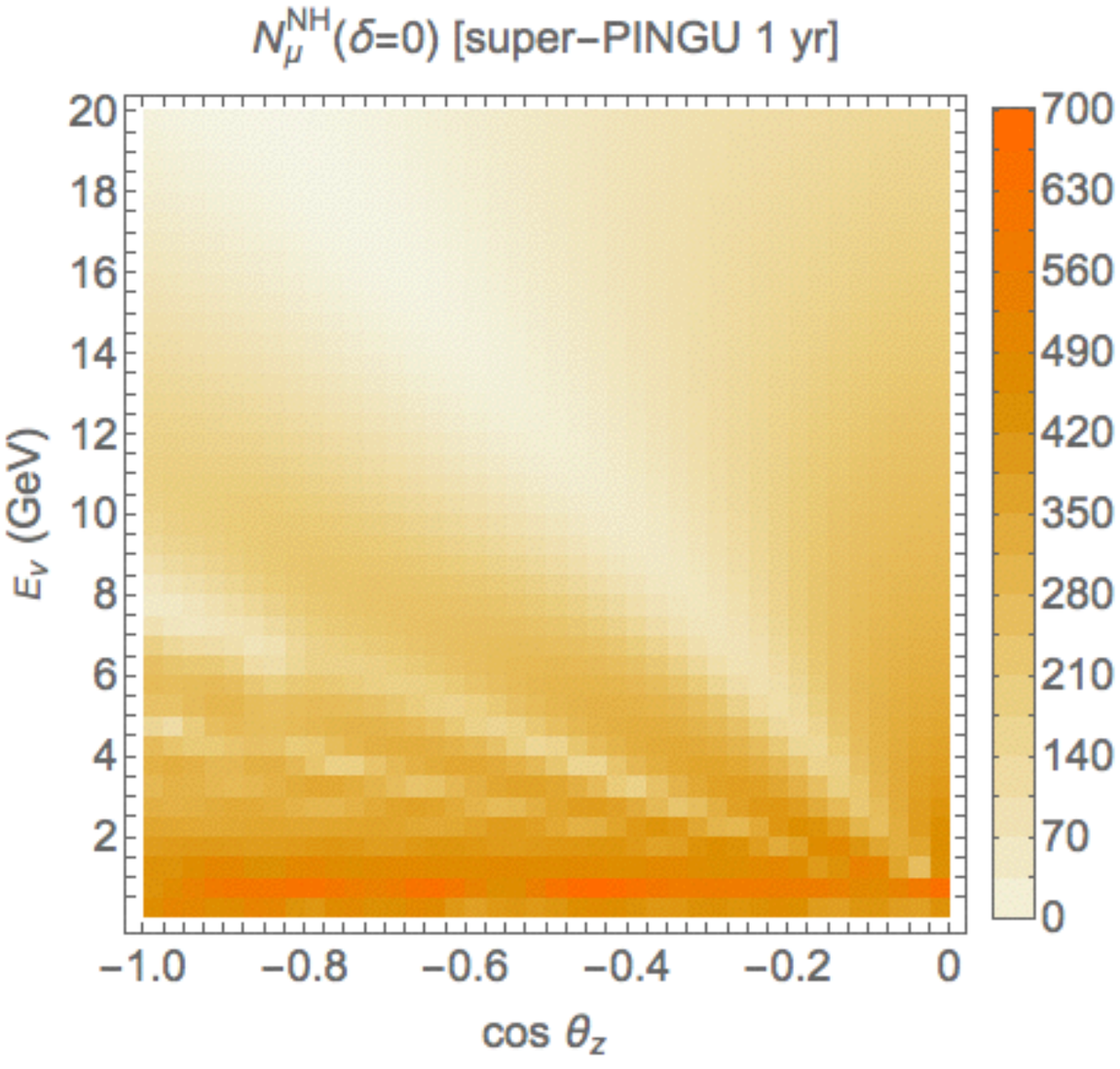
~2.2 Mt @ <1 GeV

Ideal distribution of events

Huge statistics!

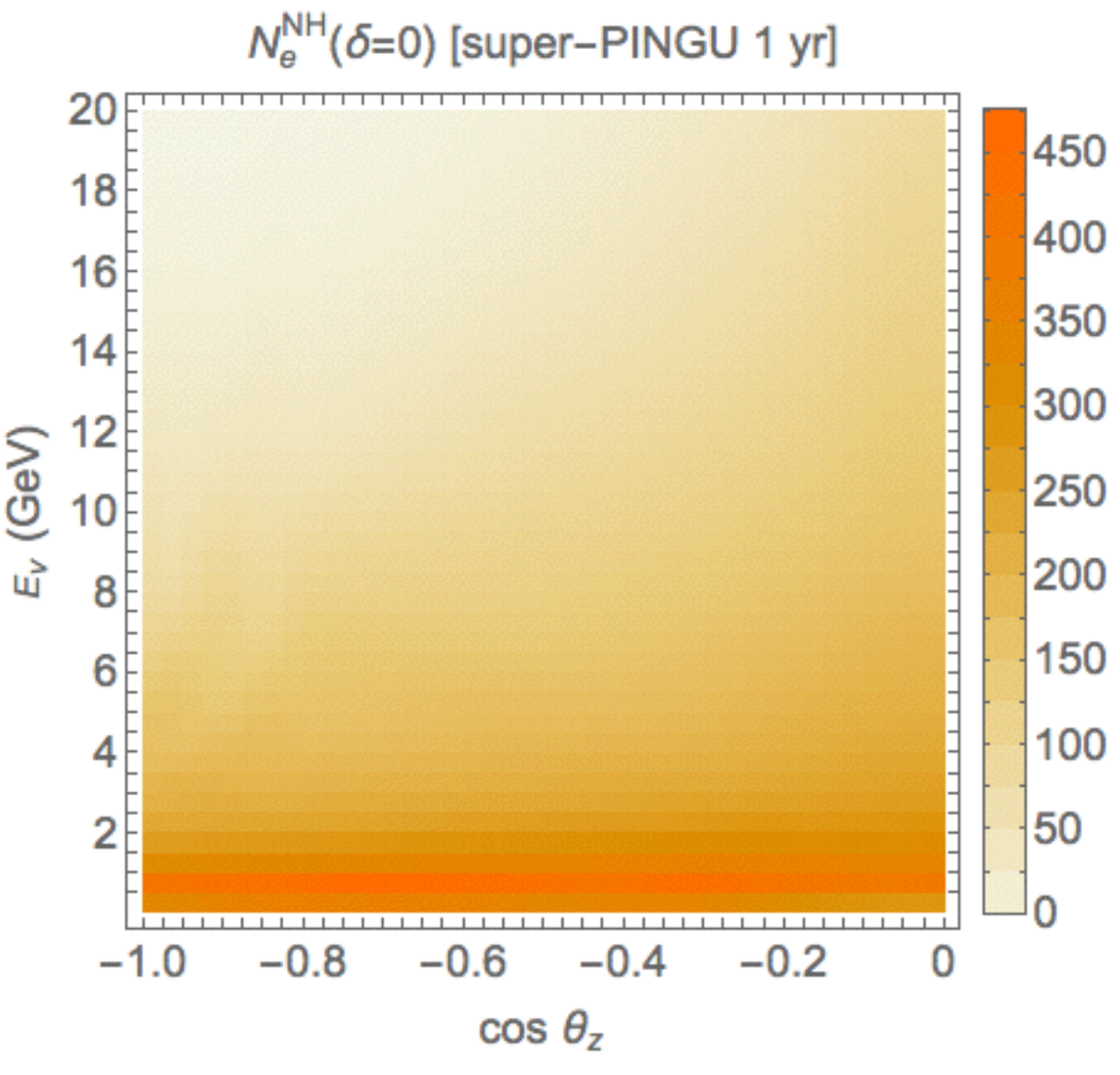
$\nu_\mu + \bar{\nu}_\mu$

Total events ~90,000/yr



$\nu_e + \bar{\nu}_e$

Total events ~75,000/yr



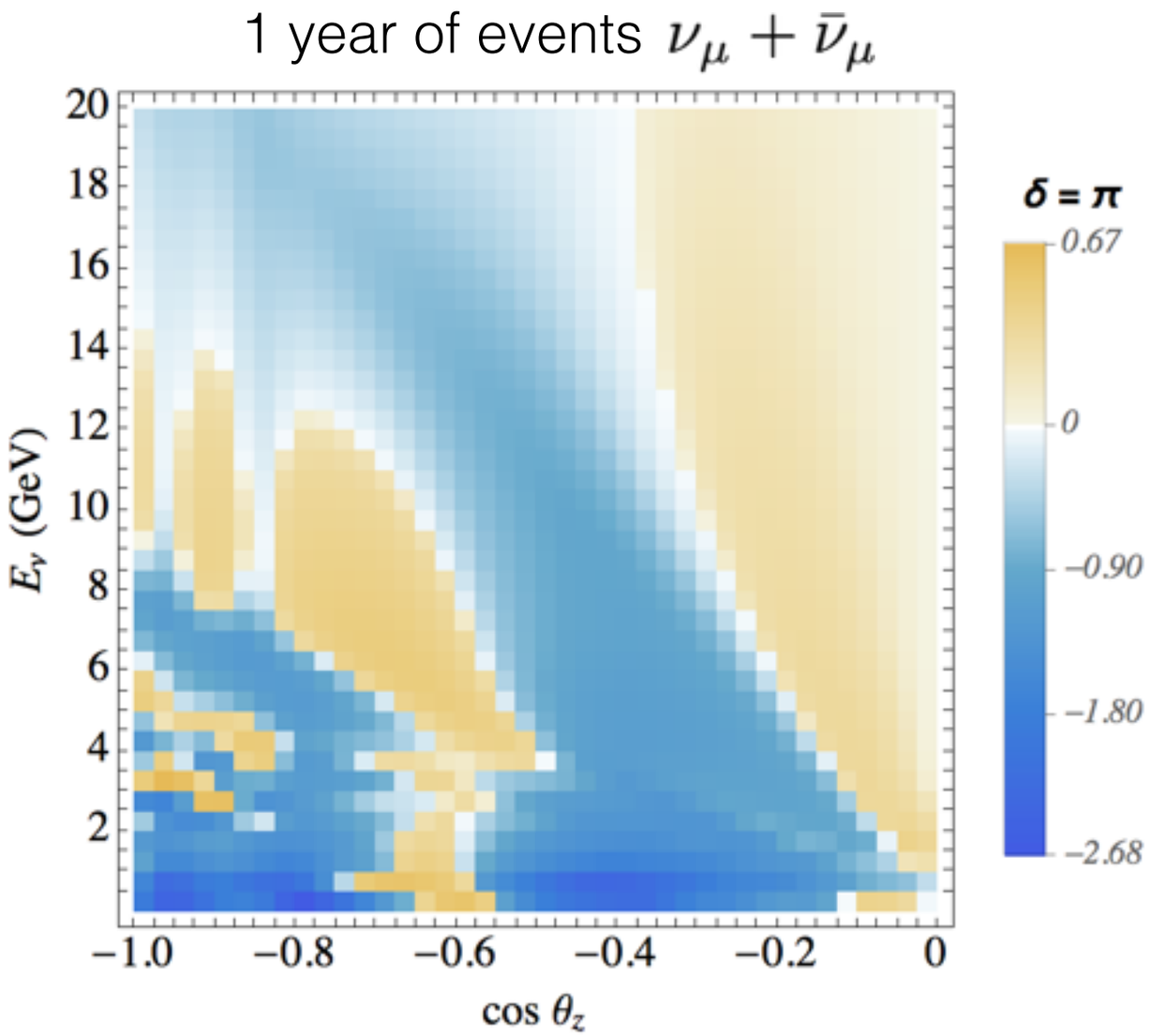
Distinguishability of CP phase

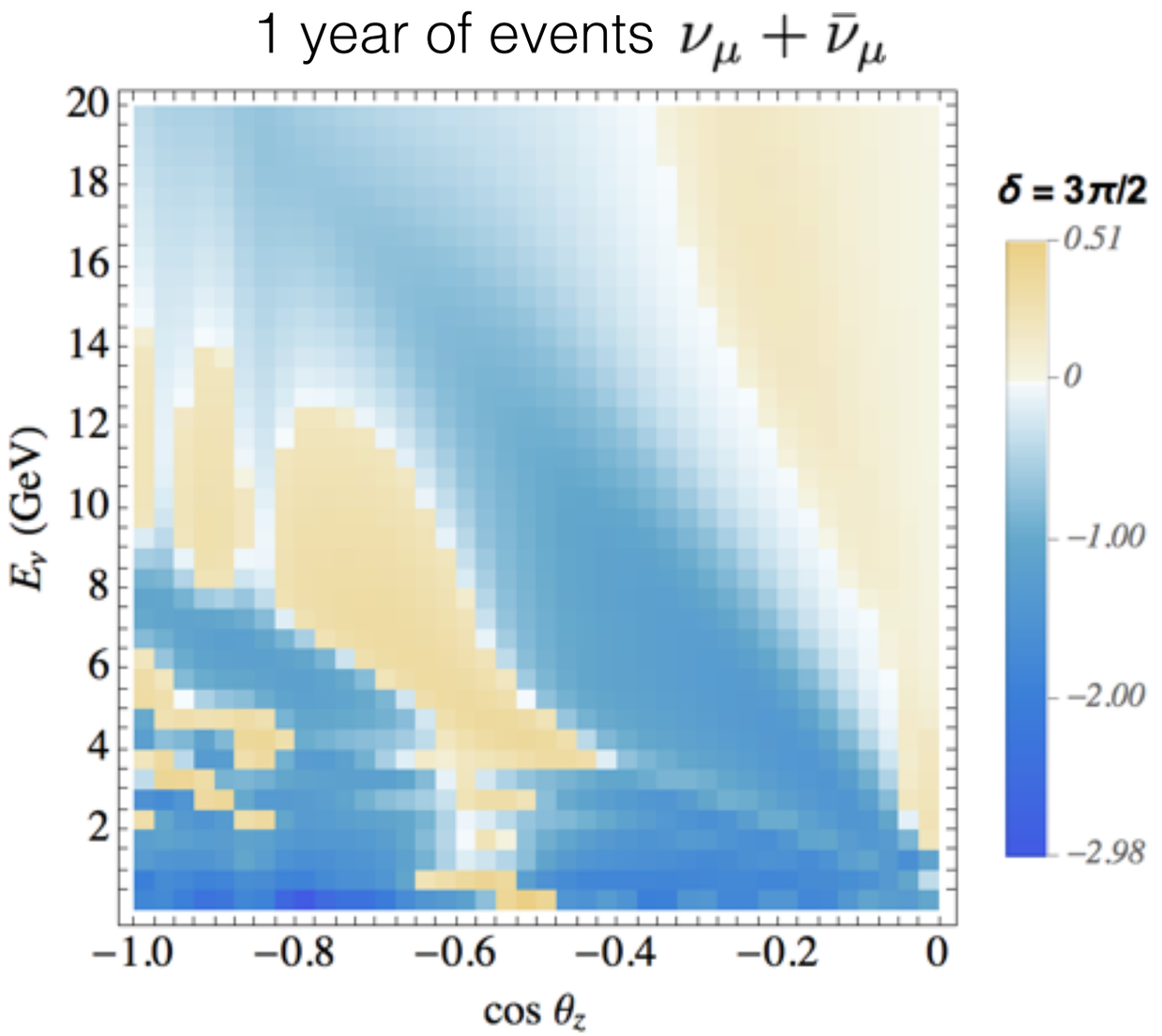
Distinguishability parameter

$$S_{ij} = \frac{N_{ij}^{\delta} - N_{ij}^{\delta=0}}{\sqrt{N_{ij}^{\delta=0}}}$$

A metric to quickly estimate effect of different CP values

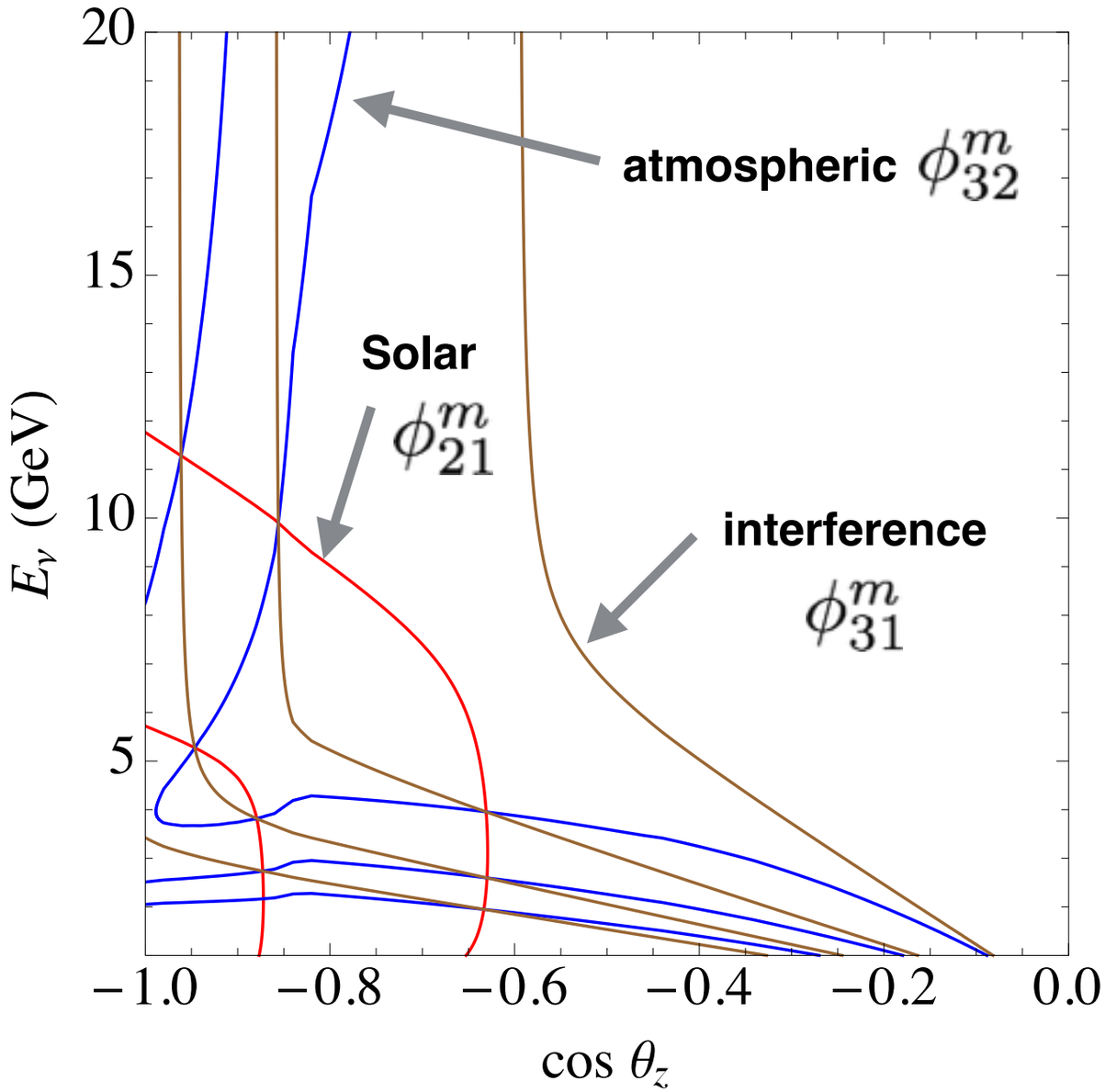
E.Kh. Akhmedov, SR, A.Yu. Smirnov, arXiv: 1205.7071





CP asymmetric domains

Determined by the solar, atmospheric and interference magic lines



Probability is roughly independent of CP along the magic lines

$\phi^m_{21}, \phi^m_{32}, \phi^m_{31}$

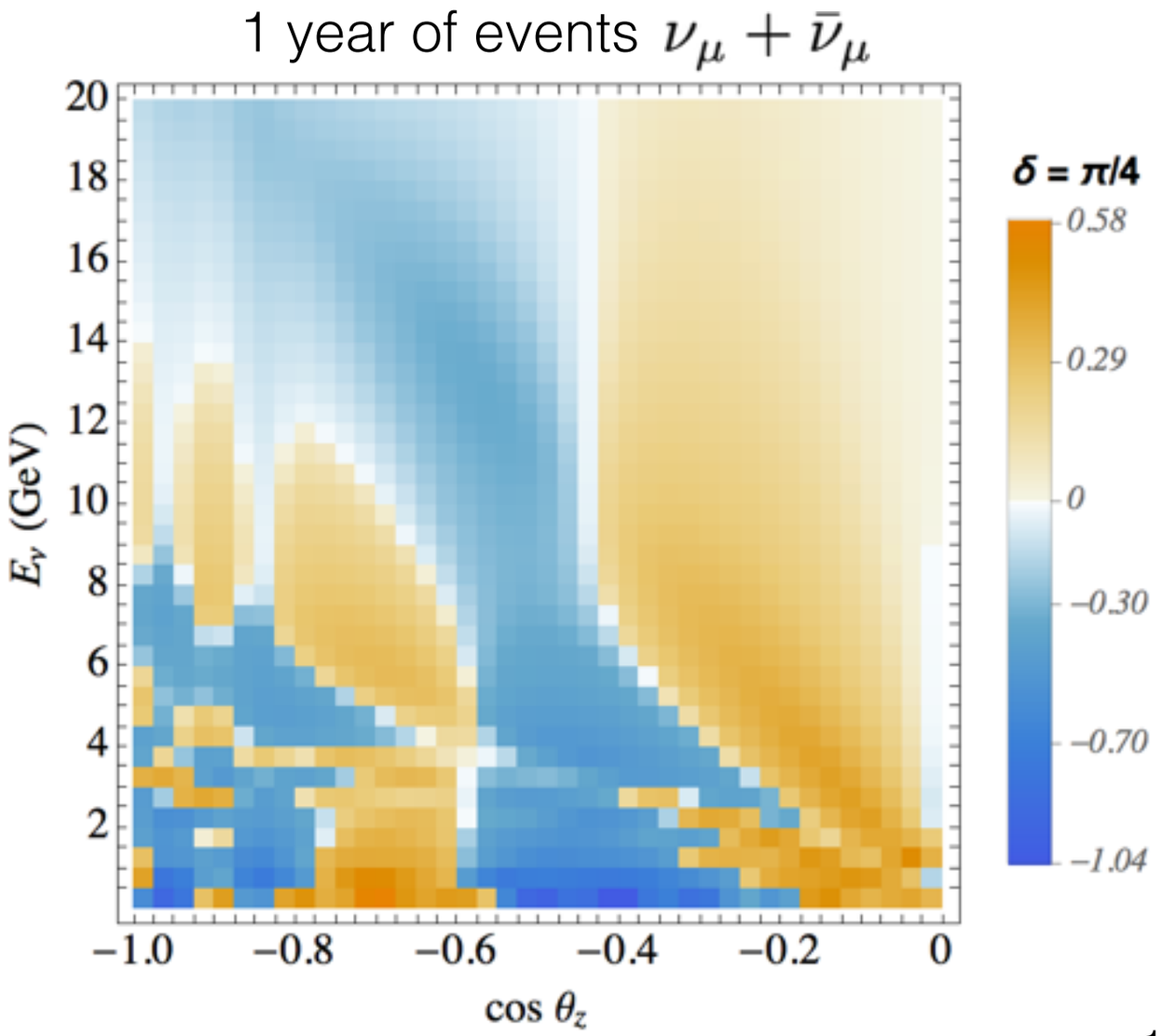
proportional to the oscillation phases for corresponding mass-splitting-square

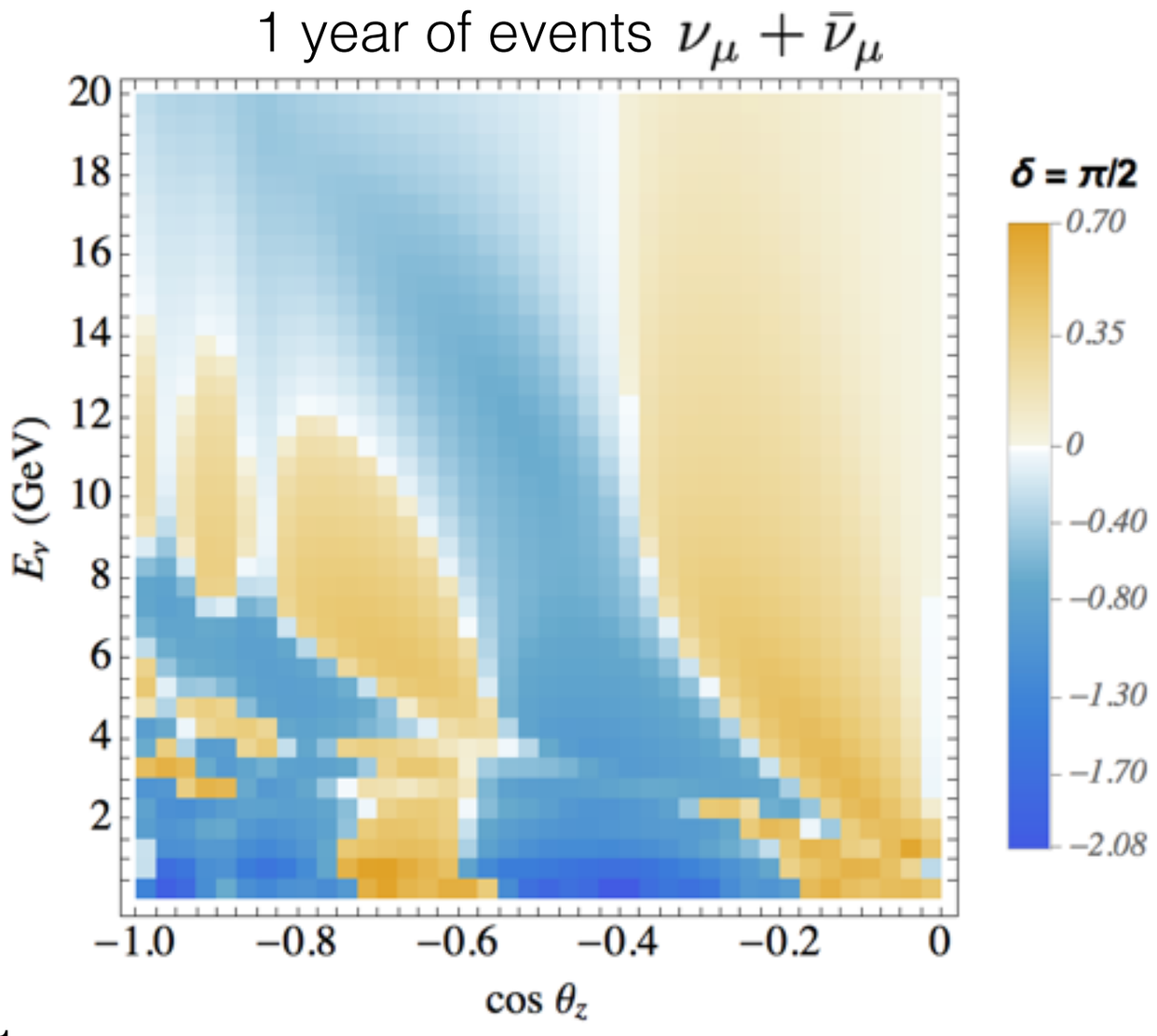
Using average density profile

Distinguishability of CP phase

Presence of both ν_μ and ν_e fluxes reduces CP asymmetry - Flavor suppression

Presence of both ν and $\bar{\nu}$ fluxes reduces CP asymmetry - Charge suppression

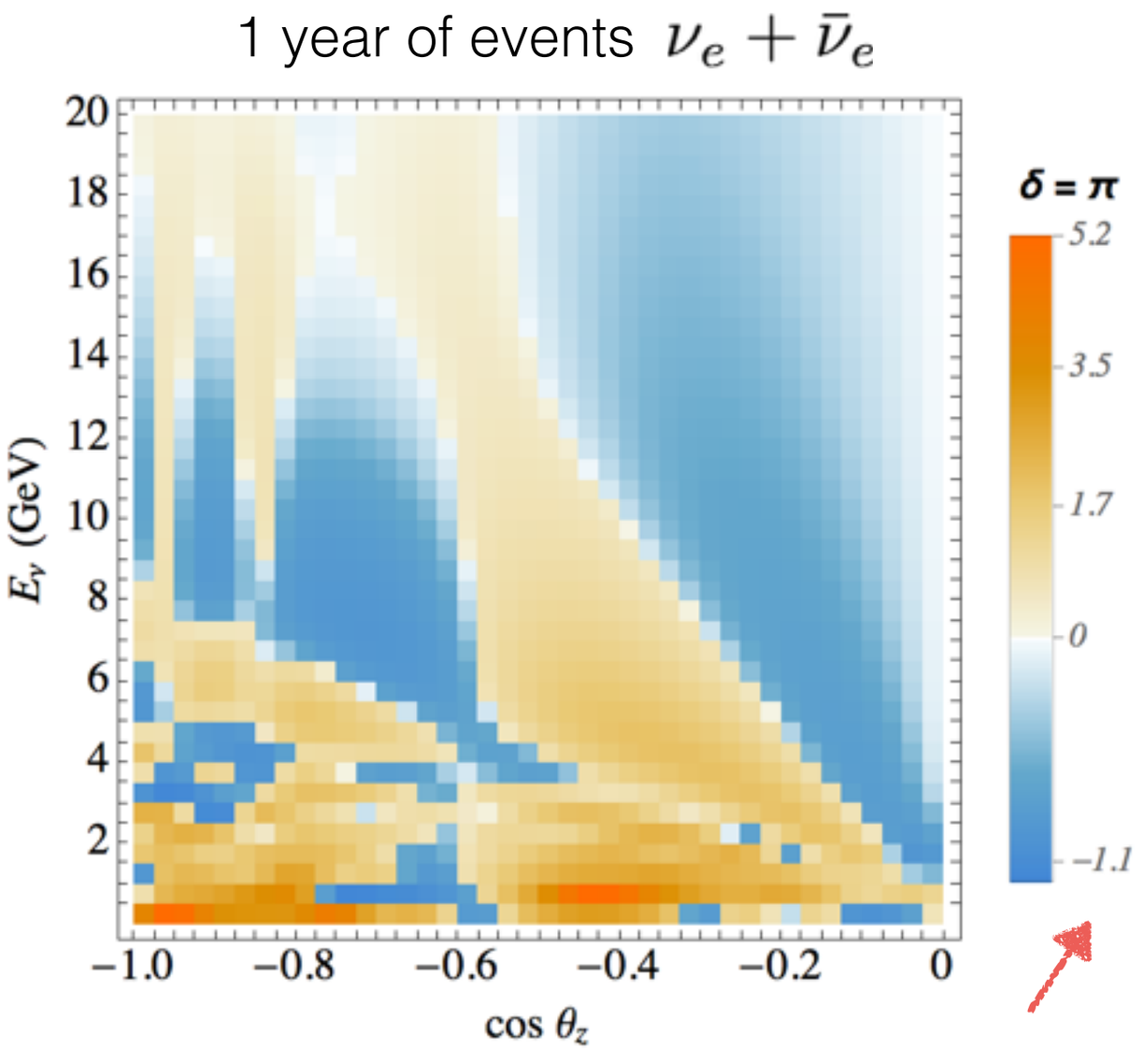


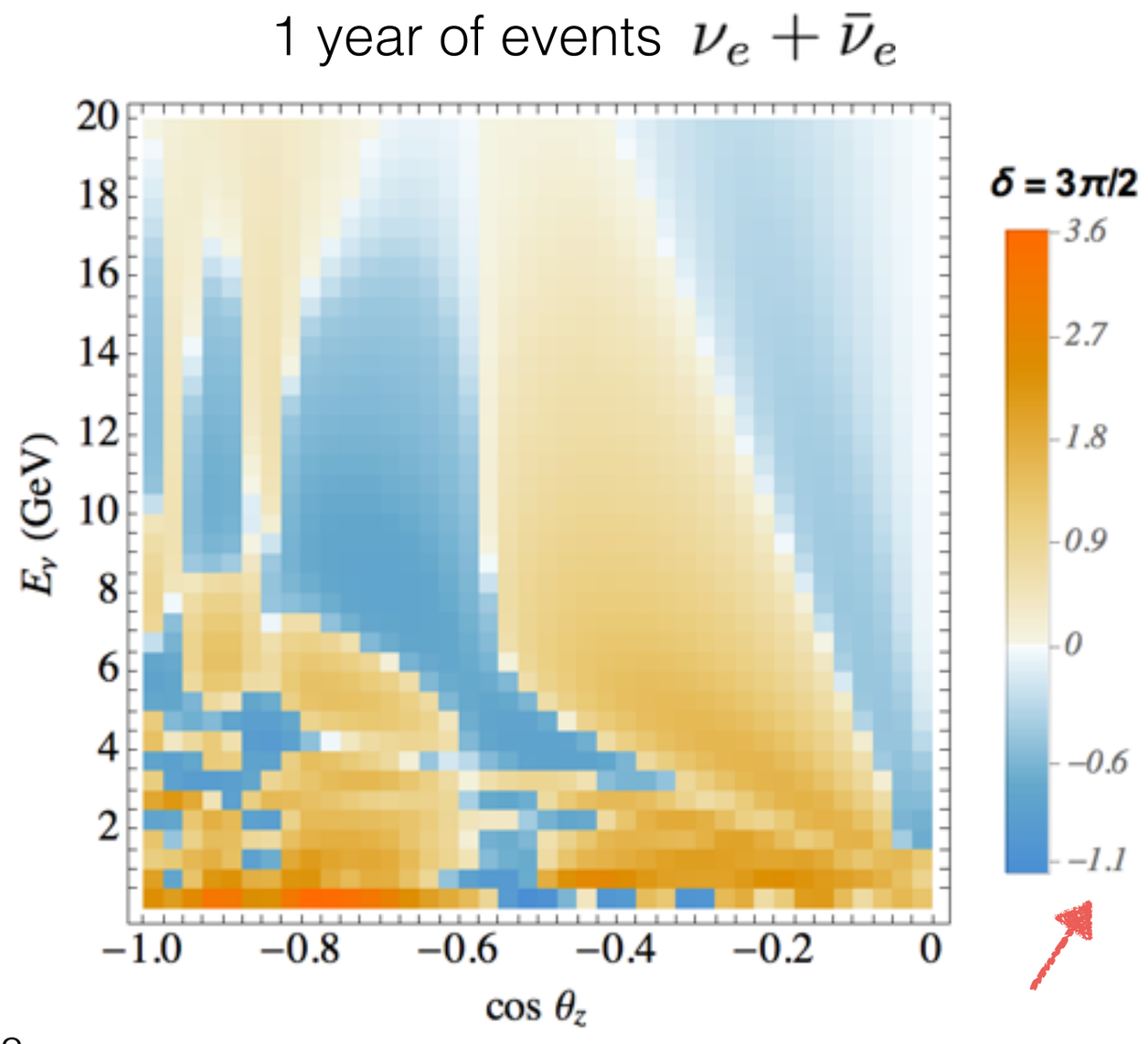


Distinguishability of CP phase

Cascade (ν_e) channel gives sharper distinguishability

No flavor suppression: contribution from $P_{\mu e}$ only, P_{ee} is independent of CP

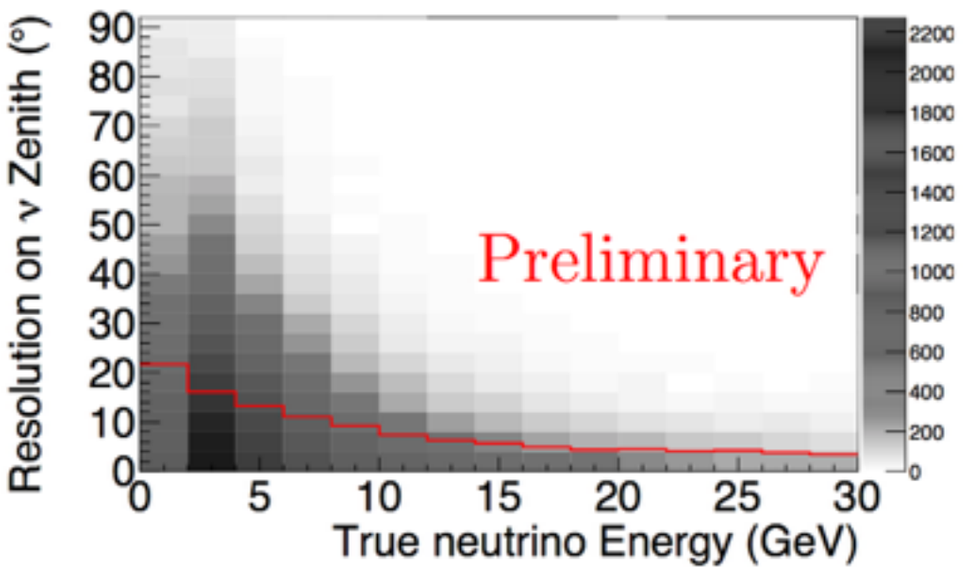




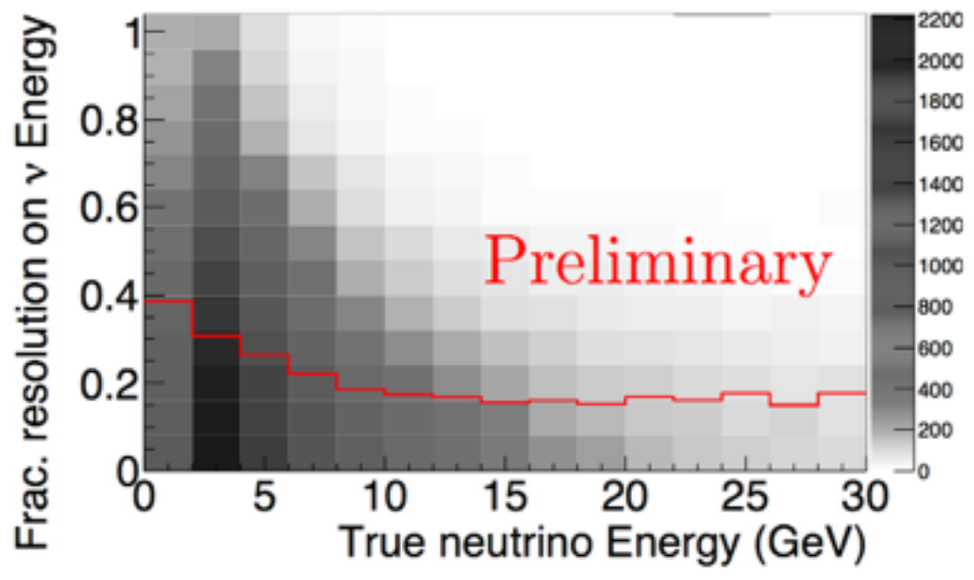
Energy, angular resolutions - PINGU

PINGU Letter of Intention, arXiv:1401.2046

ν_μ

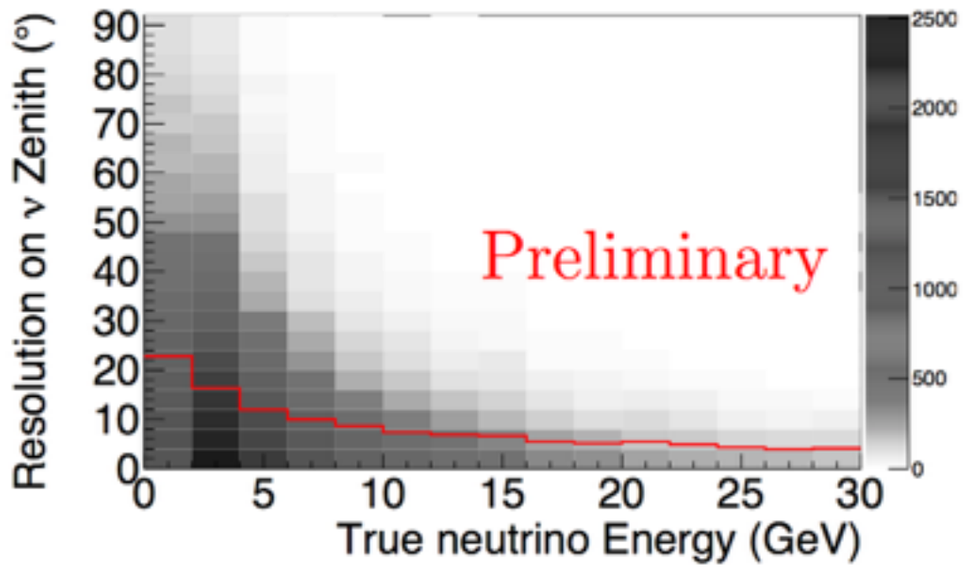


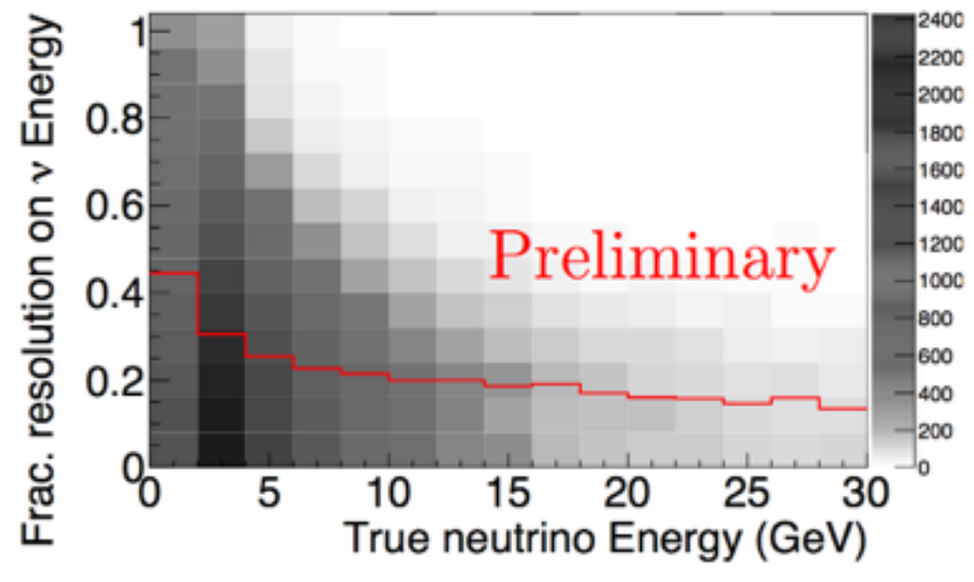
(b) $|\theta_{\nu,\text{true}} - \theta_{\nu,\text{reco}}|$ vs. $E_{\nu,\text{true}}$.



(c) $|E_{\nu,\text{reco}} - E_{\nu,\text{true}}|/E_{\nu,\text{true}}$ vs. $E_{\nu,\text{true}}$.

ν_e



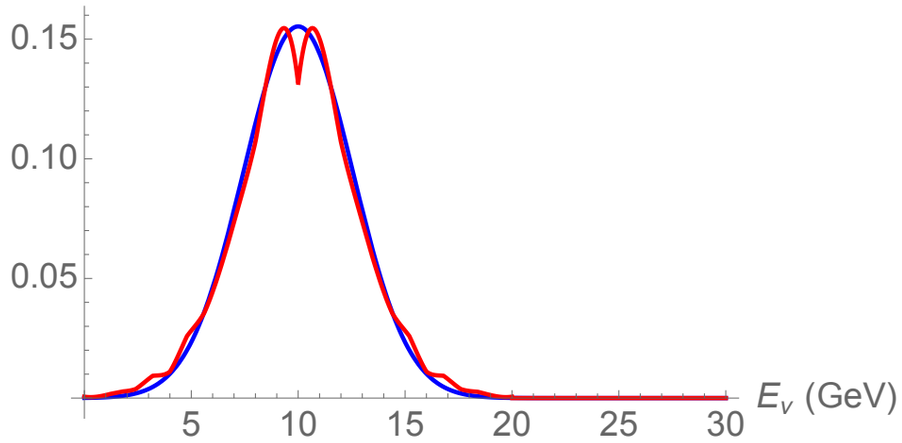


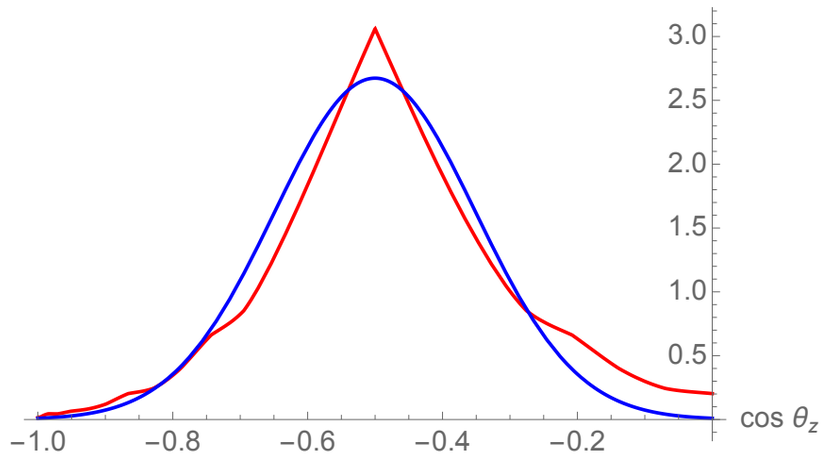
Energy, angular resolutions - PINGU

Model 2-D energy and angular resolutions with Gaussian functions of varying width

ν_μ

10 GeV

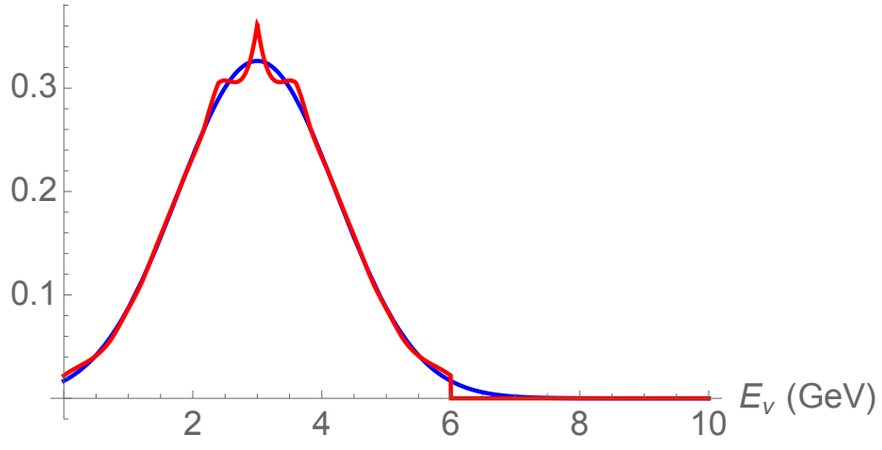


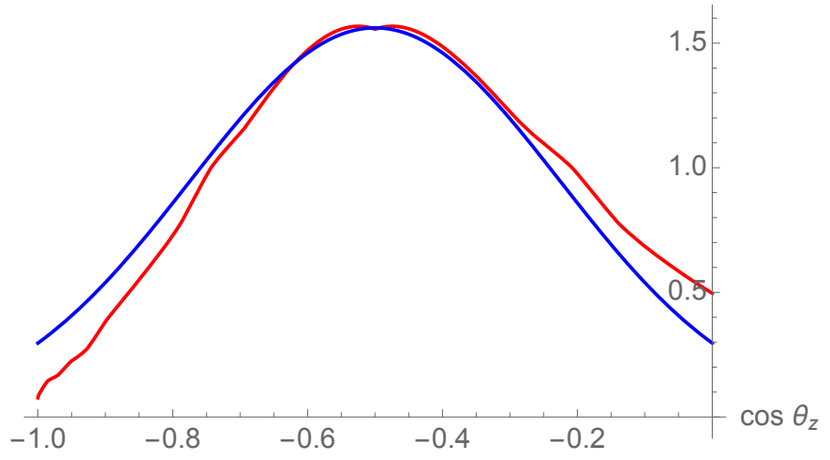


Energy resolution

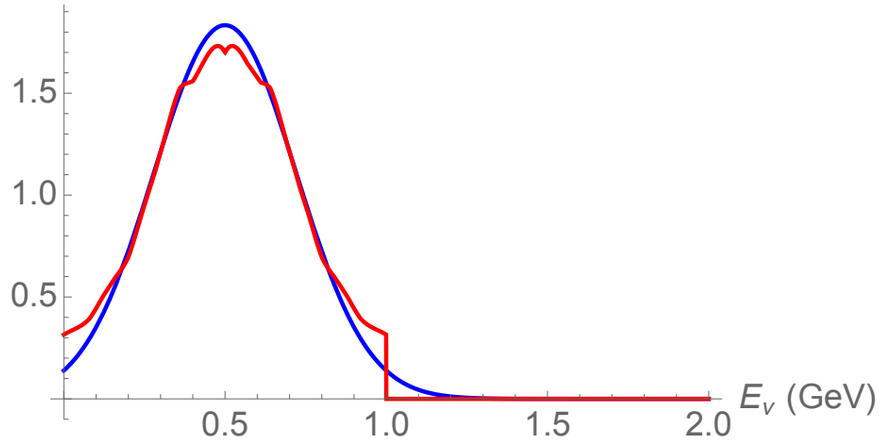
Angular resolution

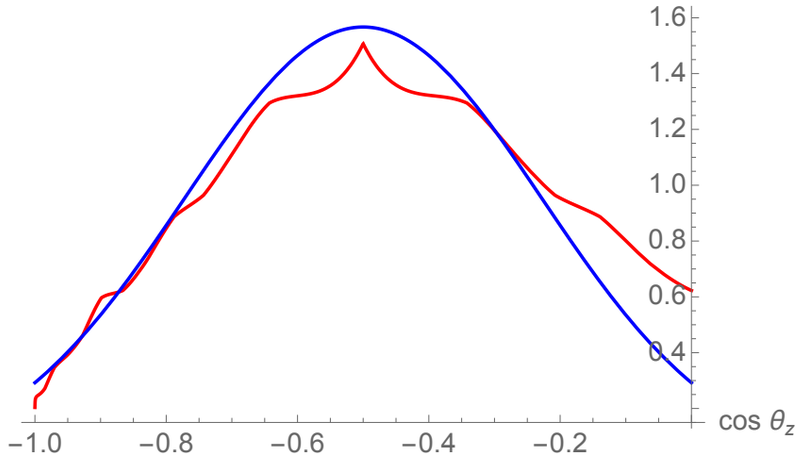
3 GeV





0.5 GeV





Energy, angular resolutions - Super-PINGU

Reconstruction in Super-PINGU is expected to be better than PINGU

Number photons collected from an event ~ density of DOM

or for a fixed volume $\propto N_{\mathrm{DOM}}$

Statistical error $\propto 1/\sqrt{N_{\mathrm{DOM}}}$

Width of the Gaussian reconstruction functions scales as

$$\sigma_\theta \propto 1/\sqrt{N_{\mathrm{DOM}}} \qquad \sigma_E \propto 1/\sqrt{N_{\mathrm{DOM}}}$$

Deep Core and PINGU $N_{\mathrm{DOM}}^{\mathrm{PINGU}}/N_{\mathrm{DOM}}^{\mathrm{DC}} = 2400/530 = 4.5$

(median errors) $\sigma_\theta^{\mathrm{PINGU}}/\sigma_\theta^{\mathrm{DC}} \approx 0.5 \quad \sigma_E^{\mathrm{PINGU}}/\sigma_E^{\mathrm{DC}} \approx 0.6$

Darren Grant in NEUTRINO 2014

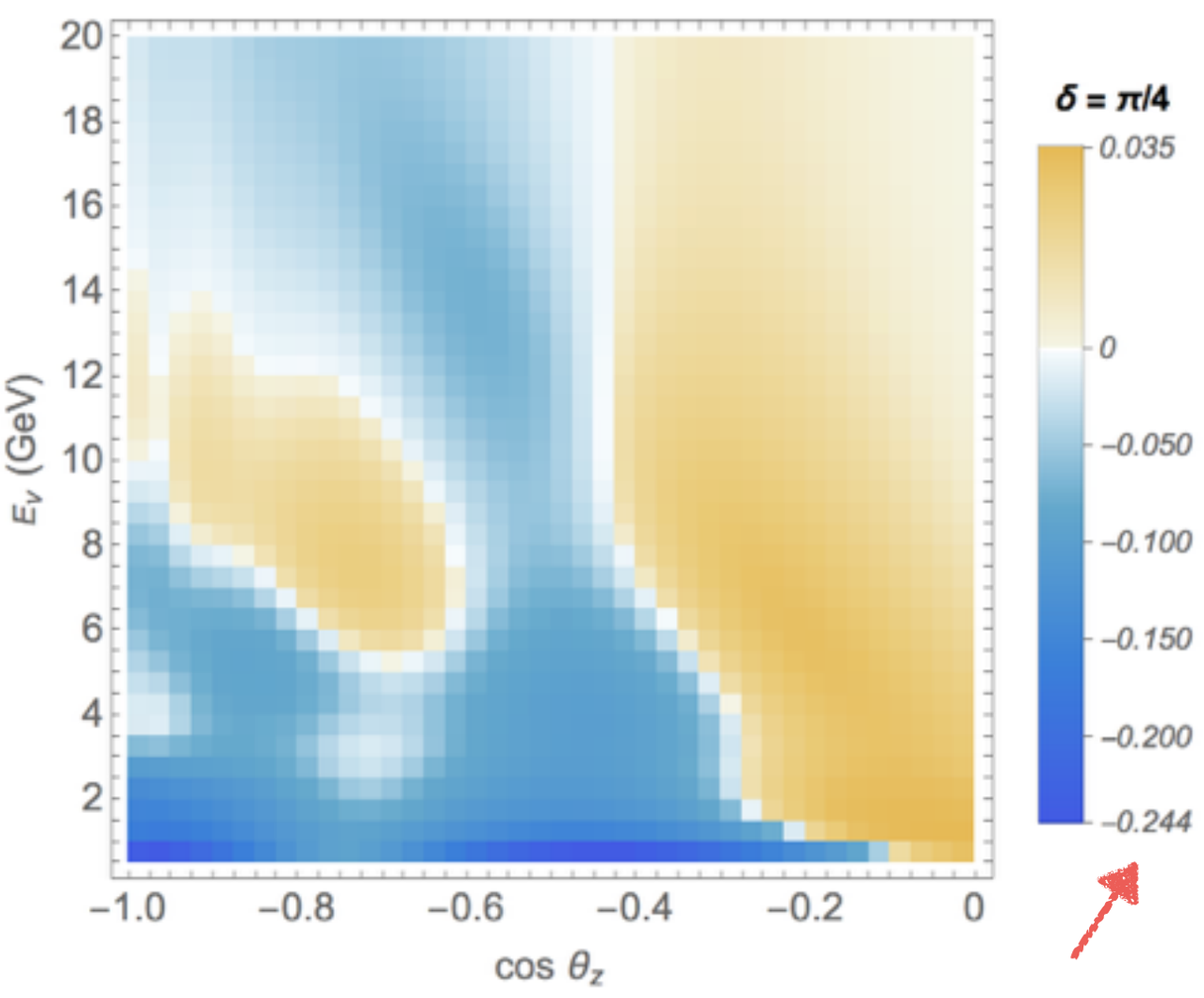
PINGU and Super-PINGU $N_{\mathrm{DOM}}^{\mathrm{Super-PINGU}}/N_{\mathrm{DOM}}^{\mathrm{PINGU}} = 3$

$$\sigma_{\theta/E}^{\mathrm{Super-PINGU}} \approx \sigma_{\theta/E}^{\mathrm{PINGU}}/\sqrt{3}$$

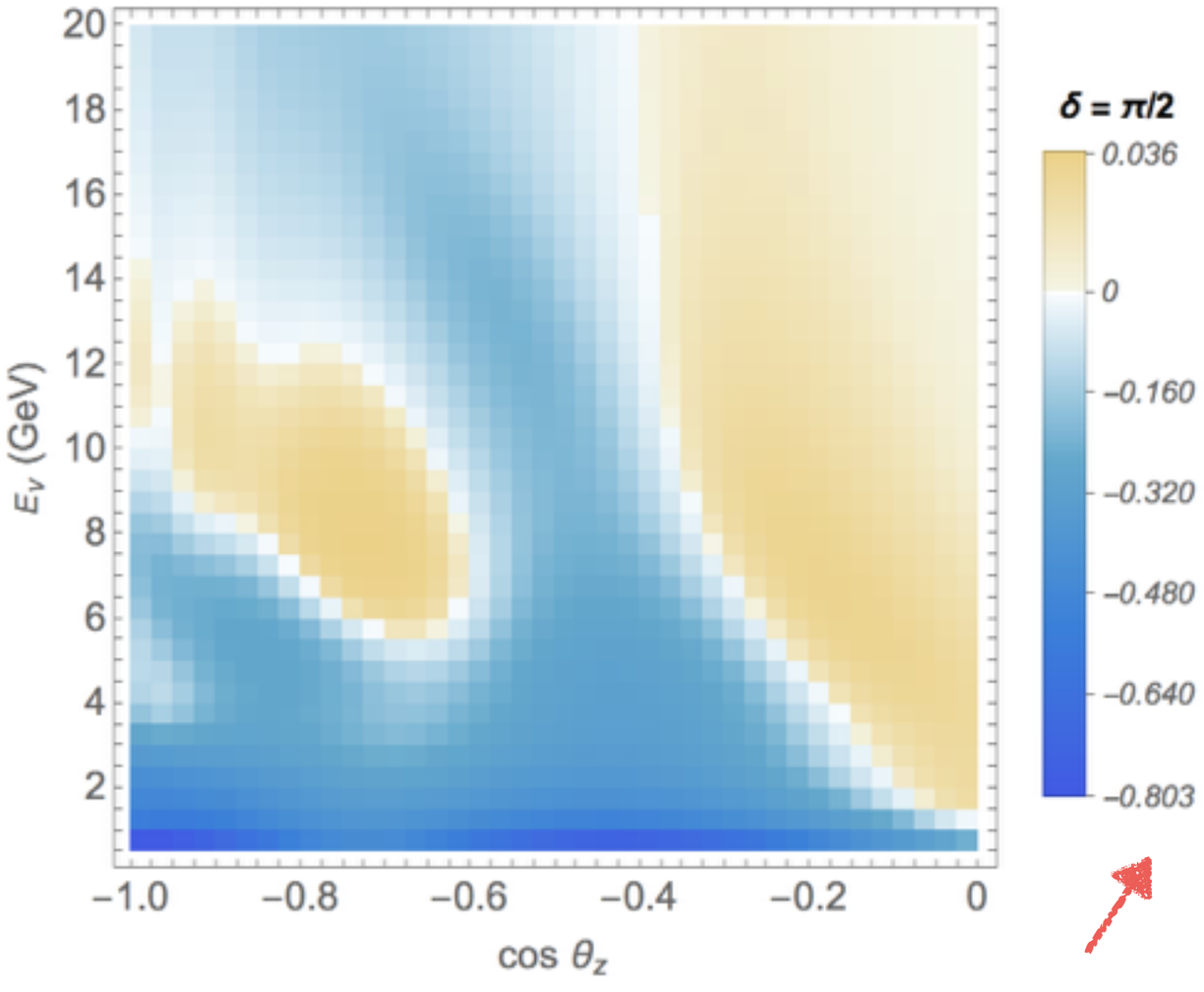
Smeared distribution of events

- Substantial reduction of CP distinguishability - merging of small regions
- Systematic broadening of negative CP asymmetric region
- Large zenith angle range of same sign distinguishability at low energies

1 year of events $\nu_\mu + \bar{\nu}_\mu$



1 year of events $\nu_\mu + \bar{\nu}_\mu$



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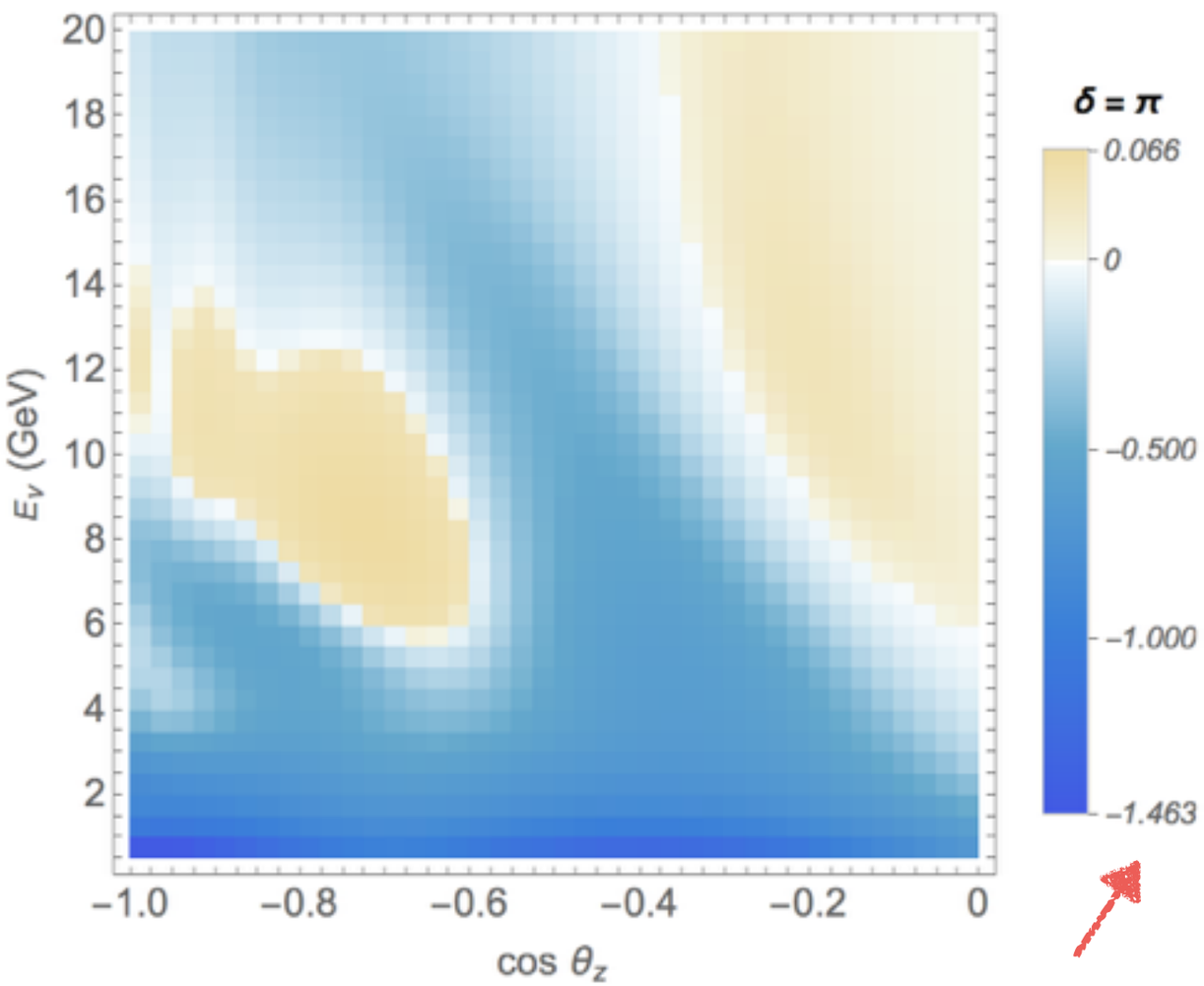

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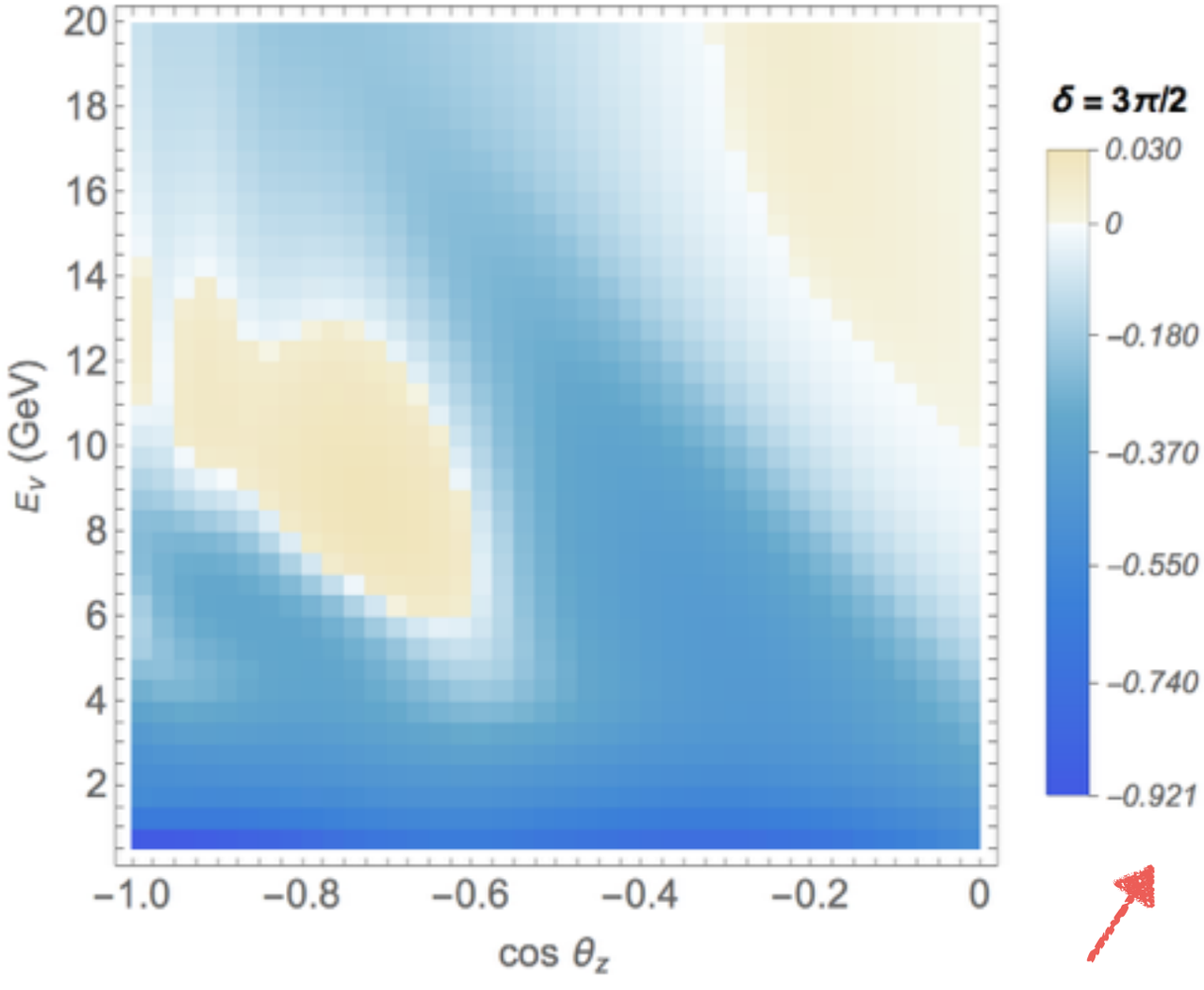

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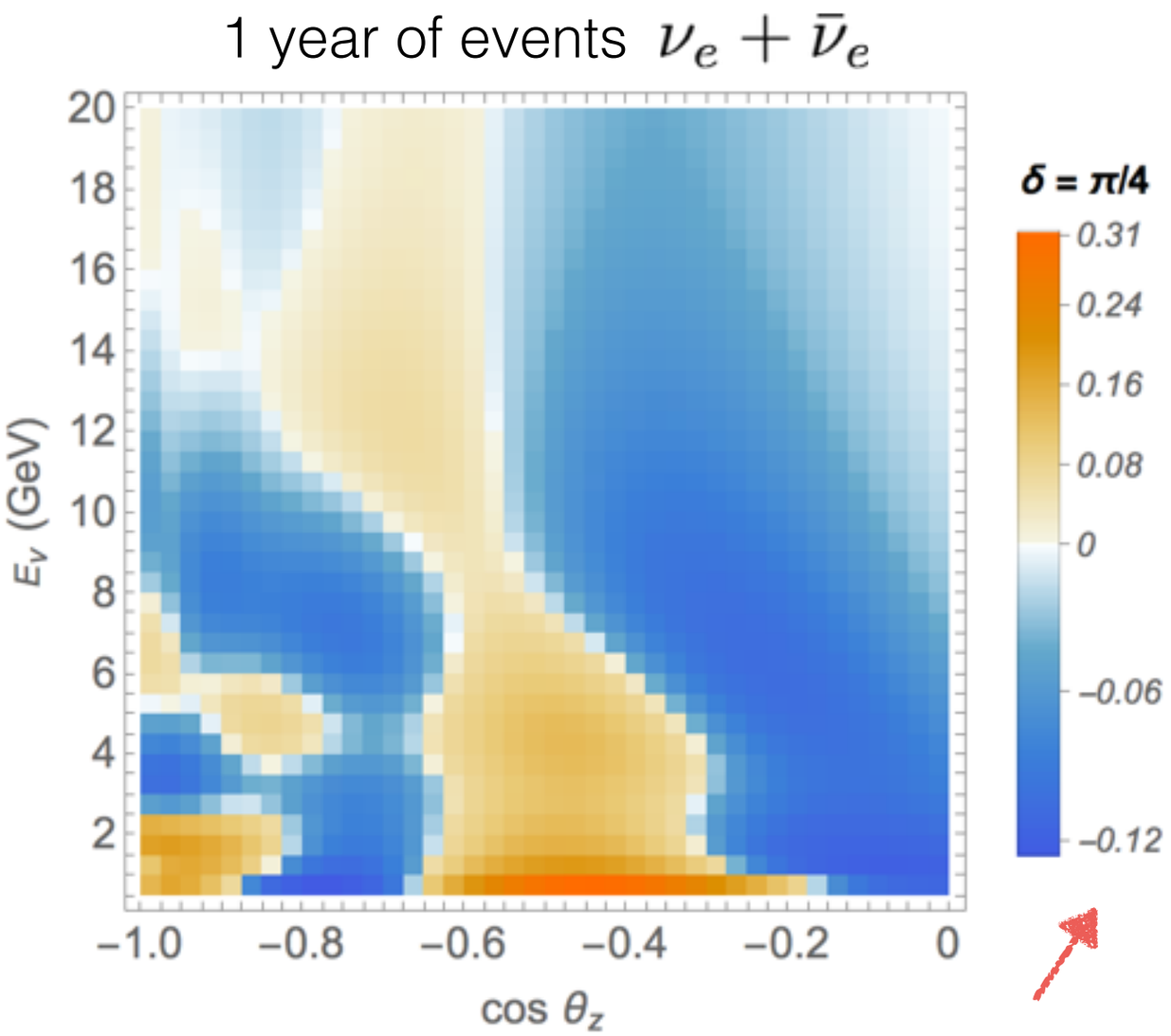

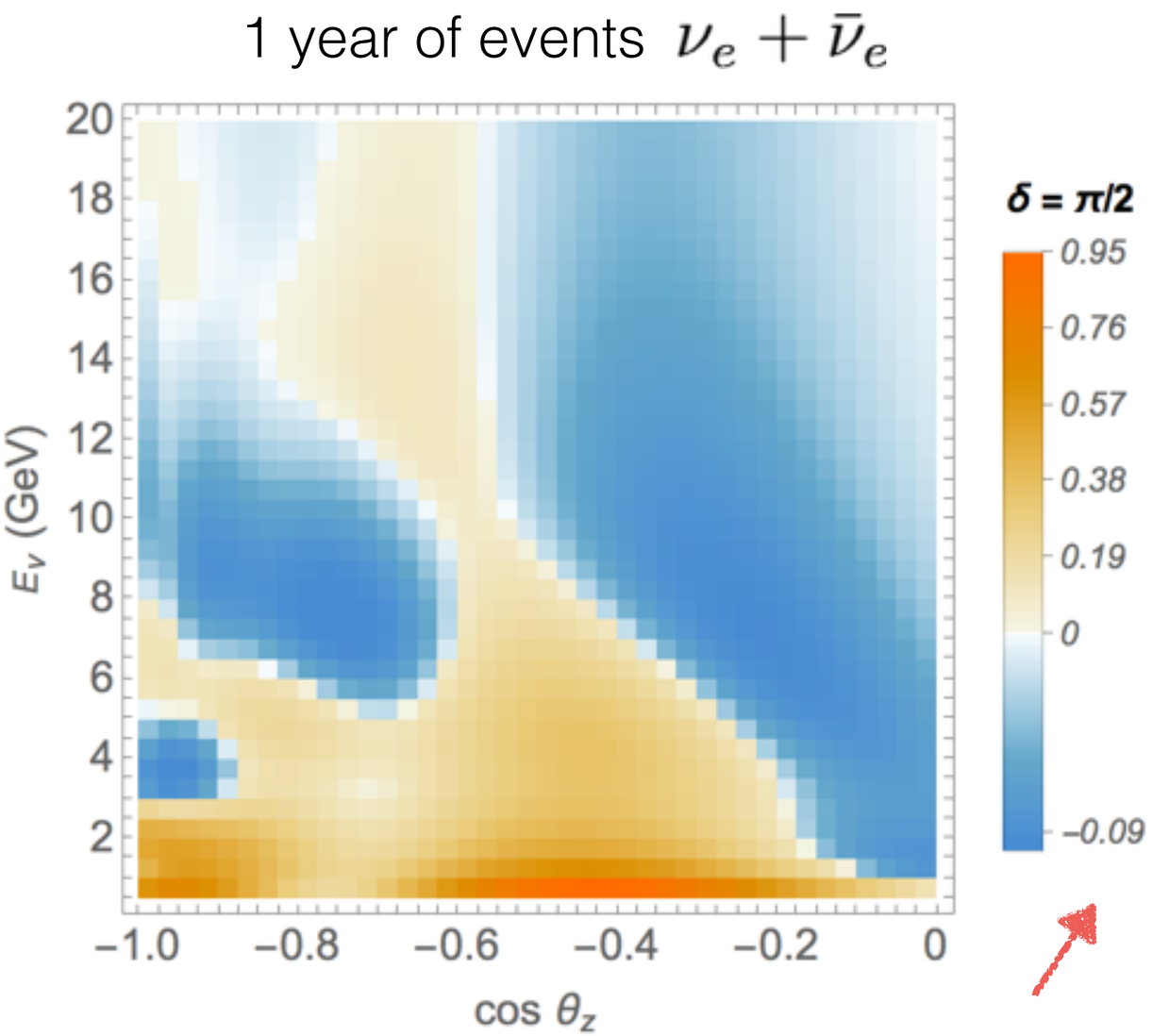

Smeared distribution of events

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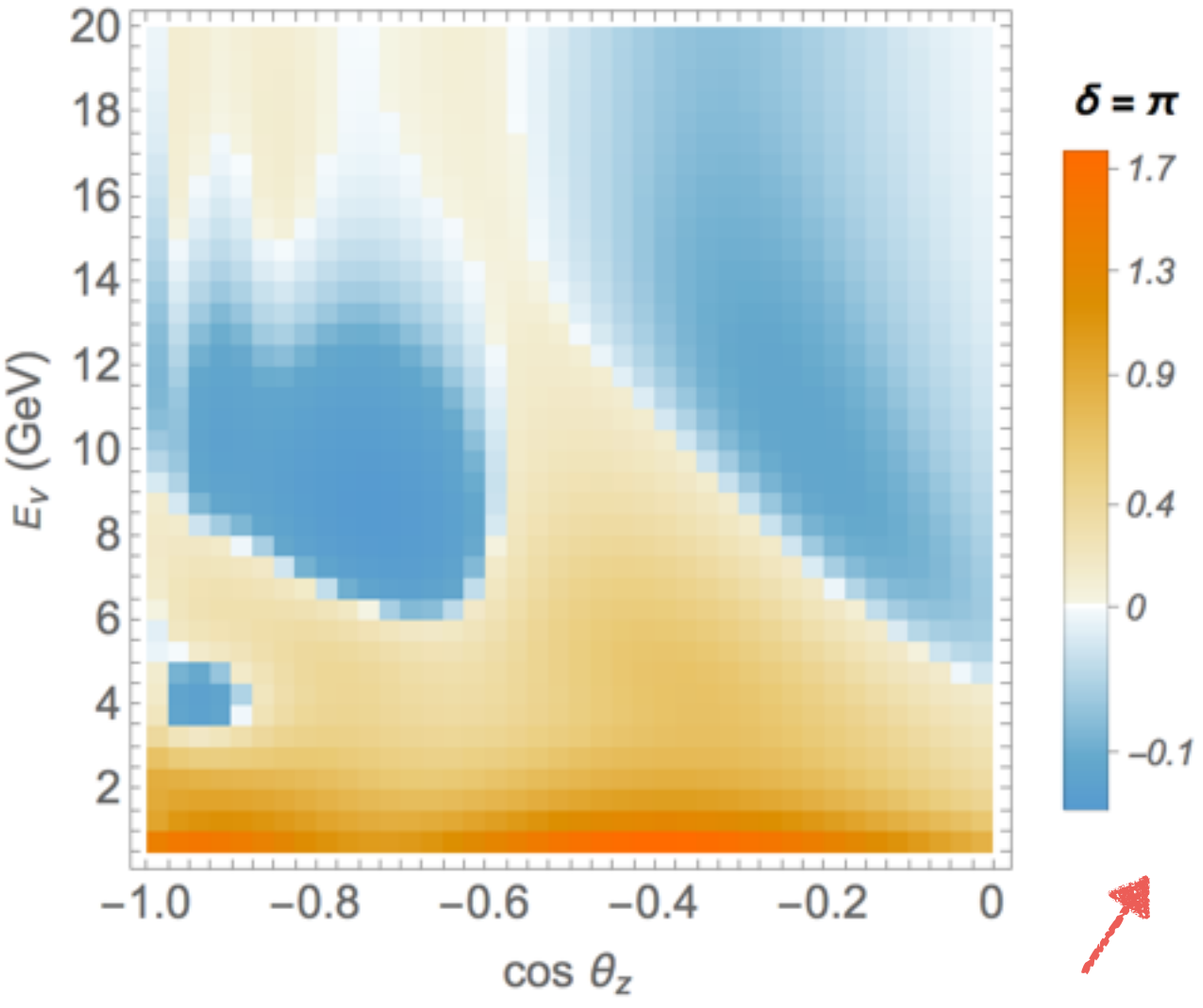
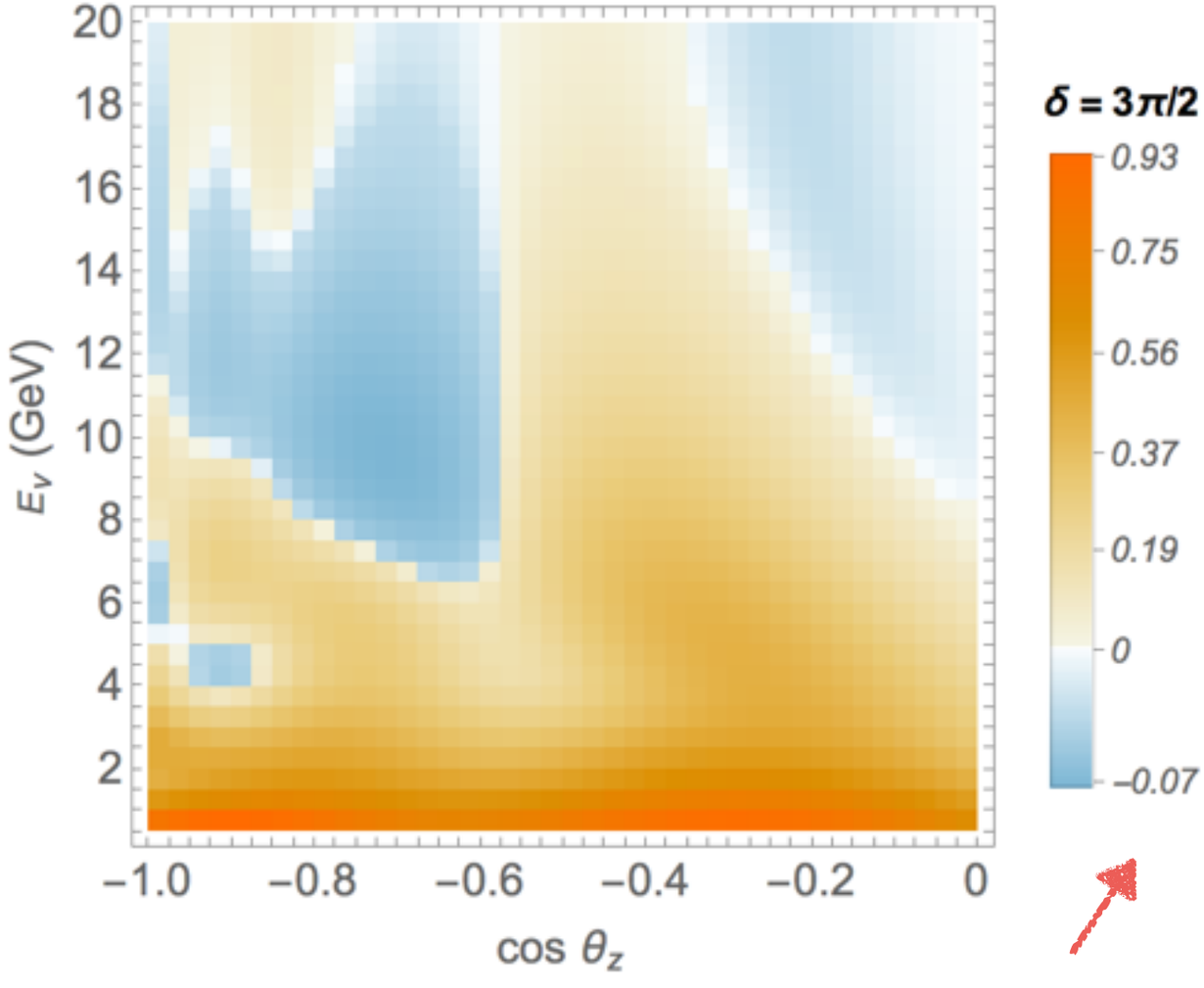
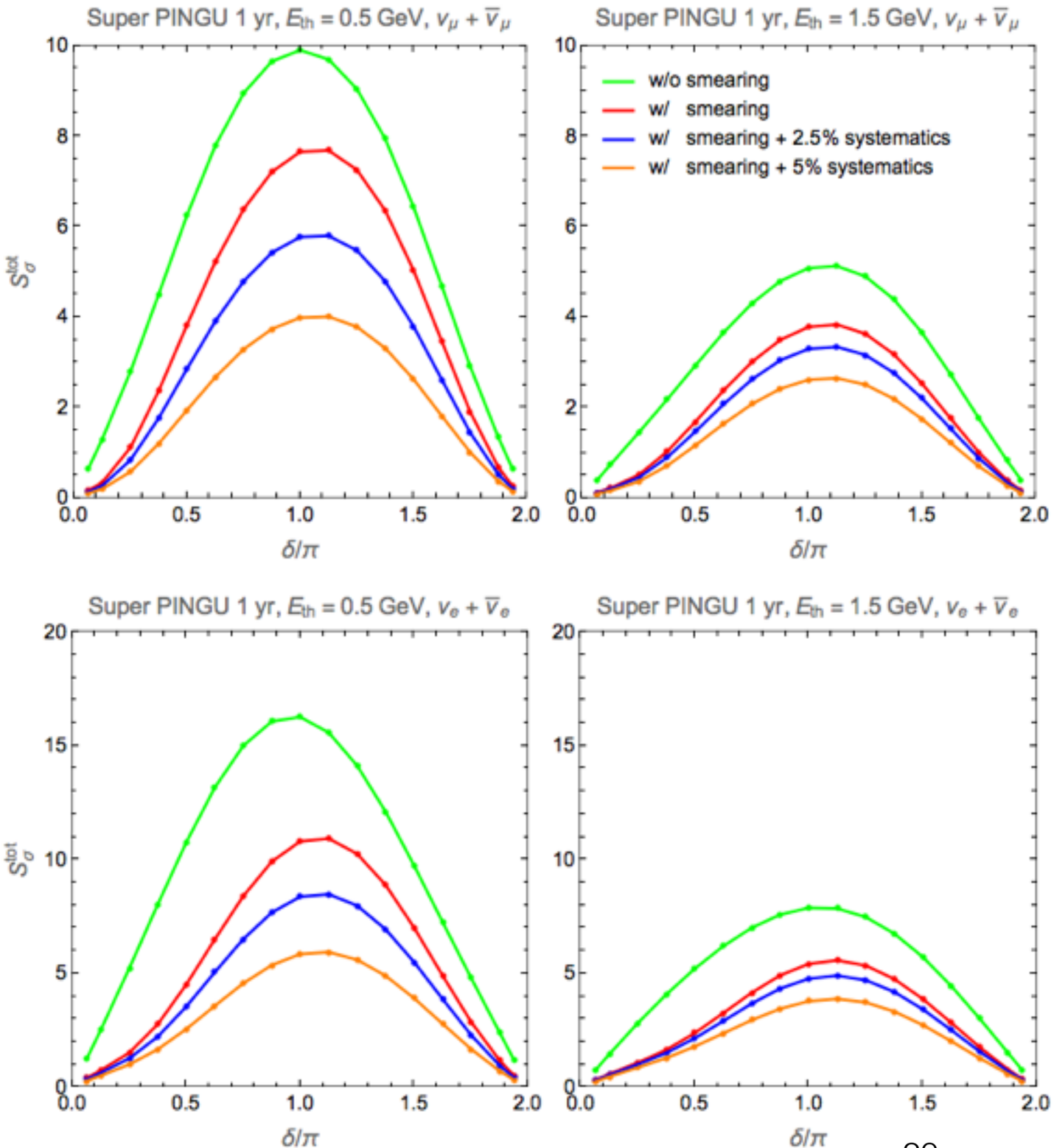
1 year of events $\nu_e + \bar{\nu}_e$



1 year of events $\nu_e + \bar{\nu}_e$



Sensitivity to CP - Super-PINGU



$\nu_\mu + \bar{\nu}_\mu$ **channel - 1yr**

Threshold - 0.5 GeV, 1.5 GeV

Total distinguishability (~ sensitivity)

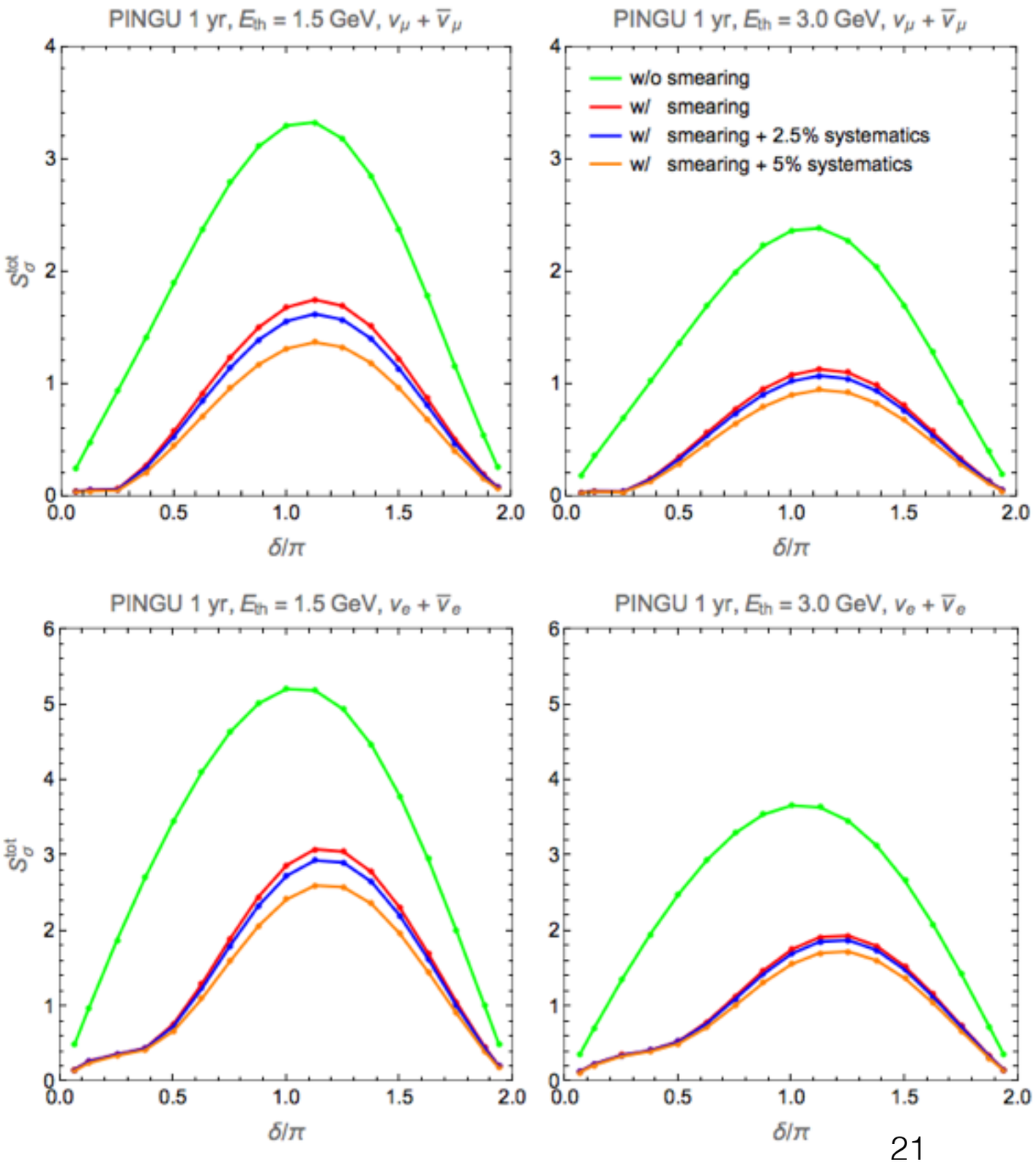
$$S_\sigma = \sqrt{\sum_{ij} \frac{\left(N_{ij}^{\delta} - N_{ij}^{\delta=0}\right)^2}{N_{ij}^{\delta=0} + \left(f N_{ij}^{\delta=0}\right)^2}}$$

f = uncorrelated systematics (~2.5-5%)

$\nu_e + \bar{\nu}_e$ **channel - 1yr**

Threshold - 0.5 GeV, 1.5 GeV

Sensitivity to CP - PINGU



$\nu_\mu + \bar{\nu}_\mu$ **channel - 1yr**

Threshold - 1.5 GeV, 3 GeV

At the same 1.5 GeV threshold

PINGU is a factor ~2-5 times less sensitive than Super-PINGU

$\nu_e + \bar{\nu}_e$ **channel - 1yr**

Threshold - 1.5 GeV, 3 GeV

Correlated systematic uncertainties

- Flux times cross-section normalization: 10% (σ_α)
- Flux tilt factor (spectral index): 0.1 (σ_η)
- Muon to electron flux ratio: 5% (σ_{z_l})

Vary parameters from standard values and calculate event distributions in the energy-angle (ij) bins

Similar to method of pull in chi^2

$$N^{\delta}_{ij,l}(\delta,\xi_k) = \alpha z_l \left(\frac{E}{2\ \mathrm{GeV}}\right)^{\eta} [1+\beta(0.5+\cos\theta_z)] N^{\delta}_{ij,l}(\xi^{st}_k), \qquad l=e,\mu.$$

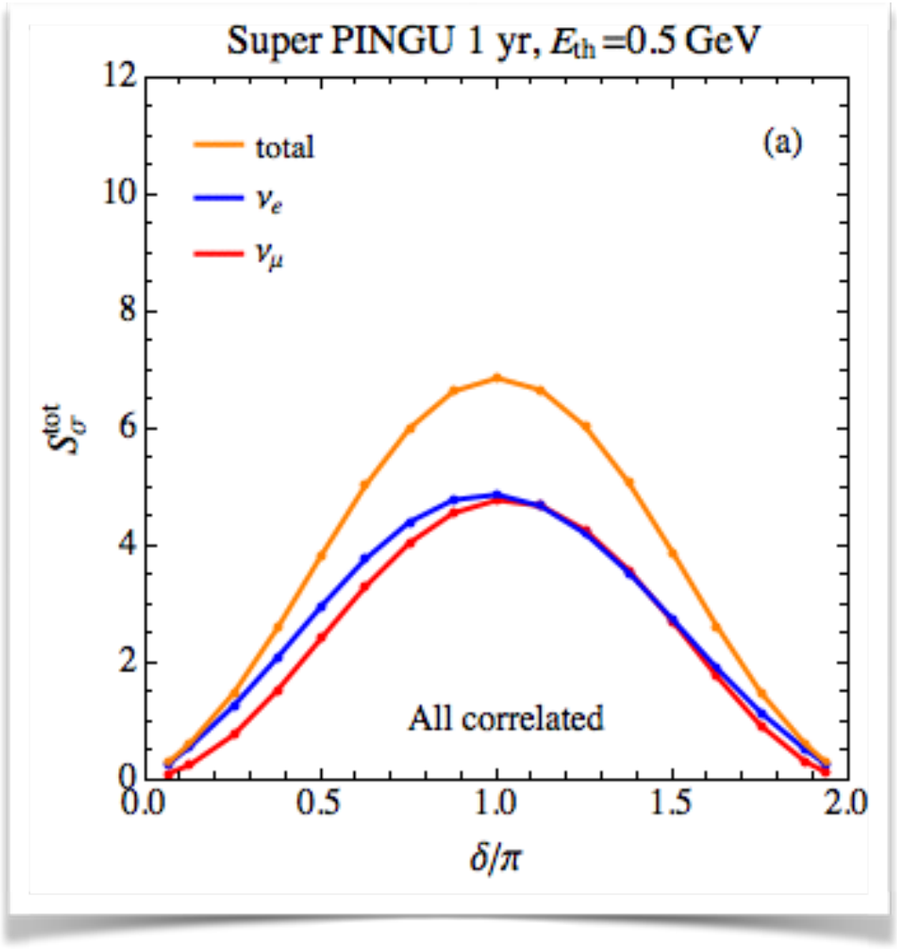
pull variables: $\xi_k \equiv (\alpha,\beta,\eta,z_l)$ standard values: $\xi^{st}_k \equiv (1,0,0,1)$

$$S^{tot}_{\sigma}(\xi_k) = \sqrt{\sum_{l=e,\mu}\sum_{ij} \frac{[N_{ij,l}(\delta,\xi_k) - N_{ij}(\delta=0,\xi^{st}_k)]^2}{\sigma^2_{ij,l}} + \sum_k \frac{(\xi_k-\xi^{st}_k)^2}{\sigma^2_k}}.$$

Minimize with respect to the pull variables

Towards realistic sensitivity to CP

All correlated (4) and 2.5% additional uncorrelated uncertainties



Assumed true CP = 0

- Systematics dominate
- Comparable sensitivity muon and electron neutrino channels
- Flavor misidentification at 20% level can reduce the sensitivity by a factor ~ 2-3

4 year sensitivity - Super-PINGU

$$S_\sigma^{tot}(\pi/2) = (3-8)$$
$$S_\sigma^{tot}(\pi) = (6-14)$$
$$S_\sigma^{tot}(3\pi/2) = (3-8)$$

Summary and Outlook

- The effect of CP phase dominates below 1-3 resonance - A systematic shift of probabilities in the ~0.3-2.0 GeV range and in wide zenith angle range (mantle region)
  - **CP measurement requires lowering threshold to < 0.5-1GeV range**
  - **Averaging over fast 1-3 oscillation does not wash out signal**
  - **Integration over zenith angle does not decrease CP sensitivity**
- Water/ice Cherenkov detectors with few Mt volume and sub-GeV threshold may be able to measure CP with competitive significance
  - **Naive estimates with Super-PINGU, a factor ~ 3 denser array than PINGU**
- Many improvements are expected to enhance sensitivity
  - **Atmospheric flux uncertainties -** Direct measurement may improve
  - **Cross section uncertainties at <3 GeV -** Recent new activity in measurement
  - **Event reconstruction, flavor identification -** Expected improvements for super-PINGU

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Estimates are encouraging - motivates further detailed study

Back up slides

Calculation

- Assume neutrino mass hierarchy is already established (likely by PINGU/ORCA)
  - **Normal mass hierarchy for calculation**
- Standard 3-neutrino flavor oscillation scheme
  - **Parameters from global fit, except CP**
- Preliminary Reference Earth Model (PREM)
- Standard Honda Atmospheric flux model, cross-sections

Oscillation parameters

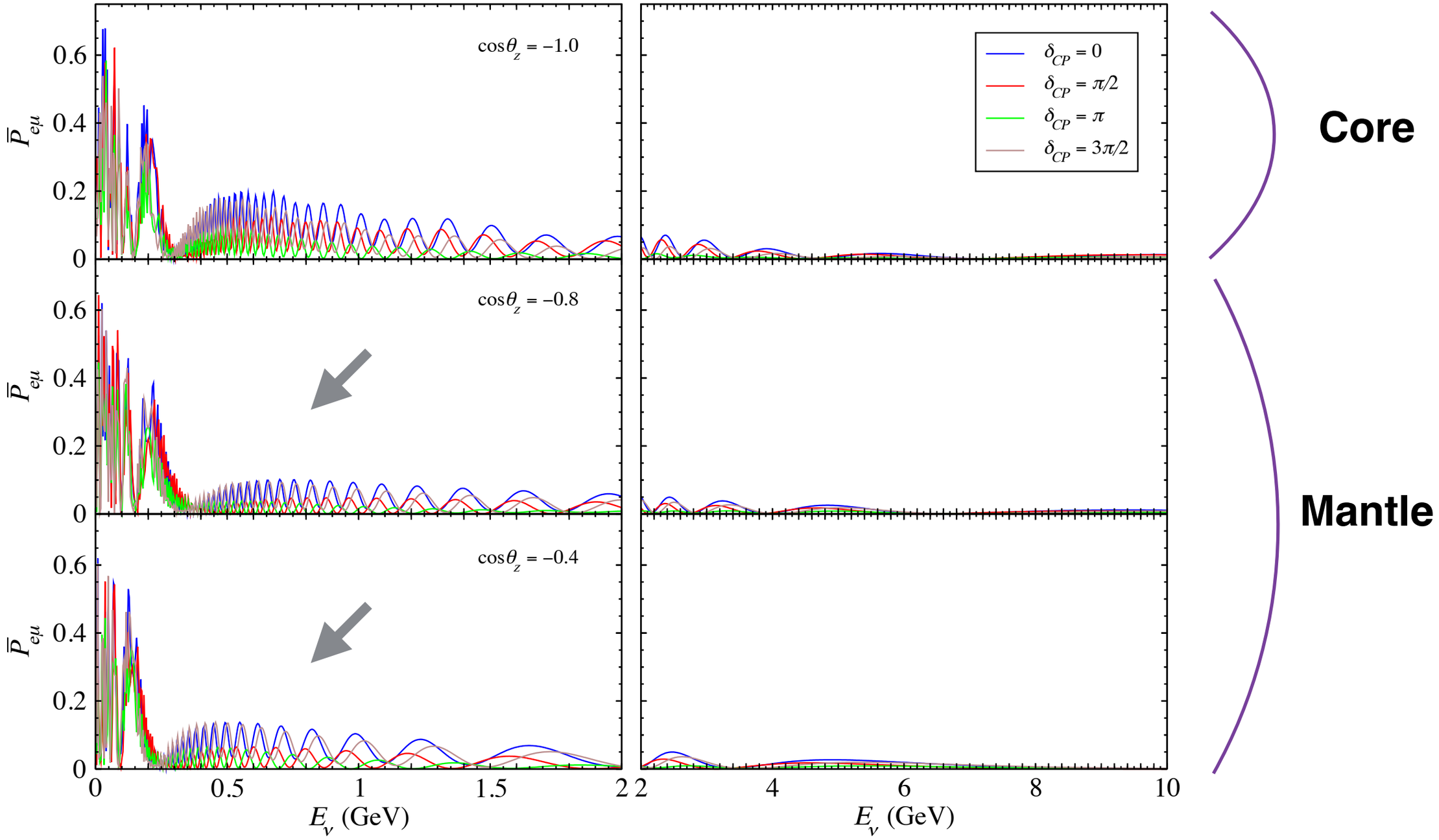
TABLE I. Results of the global 3ν oscillation analysis, in terms of best-fit values and allowed 1, 2 and 3σ ranges for the 3ν mass-mixing parameters. We remind that Δm^2 is defined herein as $m_3^2 - (m_1^2 + m_2^2)/2$, with $+\Delta m^2$ for NH and $-\Delta m^2$ for IH.

Parameter	Best fit	1σ range	2σ range	3σ range
$\delta m^2/10^{-5}$ eV^2 (NH or IH)	7.54	7.32–7.80	7.15–8.00	6.99–8.18
$\sin^2\theta_{12}/10^{-1}$ (NH or IH)	3.07	2.91–3.25	2.75–3.42	2.59–3.59
$\Delta m^2/10^{-3}$ eV^2 (NH)	2.43	2.33–2.49	2.27–2.55	2.19–2.62
$\Delta m^2/10^{-3}$ eV^2 (IH)	2.42	2.31–2.49	2.26–2.53	2.17–2.61
$\sin^2\theta_{13}/10^{-2}$ (NH)	2.41	2.16–2.66	1.93–2.90	1.69–3.13
$\sin^2\theta_{13}/10^{-2}$ (IH)	2.44	2.19–2.67	1.94–2.91	1.71–3.15
$\sin^2\theta_{23}/10^{-1}$ (NH)	3.86	3.65–4.10	3.48–4.48	3.31–6.37
$\sin^2\theta_{23}/10^{-1}$ (IH)	3.92	3.70–4.31	3.53–4.84 $\oplus$ 5.43–6.41	3.35–6.63
δ/π (NH)	1.08	0.77–1.36	...	...
δ/π (IH)	1.09	0.83–1.47	...	...

G.L.Fogli, E.Lisi, A.Marrone, D.Montanino, A.Palazzo, et al. "Global analysis of neutrino masses, mixings and phases : entering the era of leptonic CP violation searches." Phys.Rev. D86, 013012 (2012) [arXiv:1205.5254]

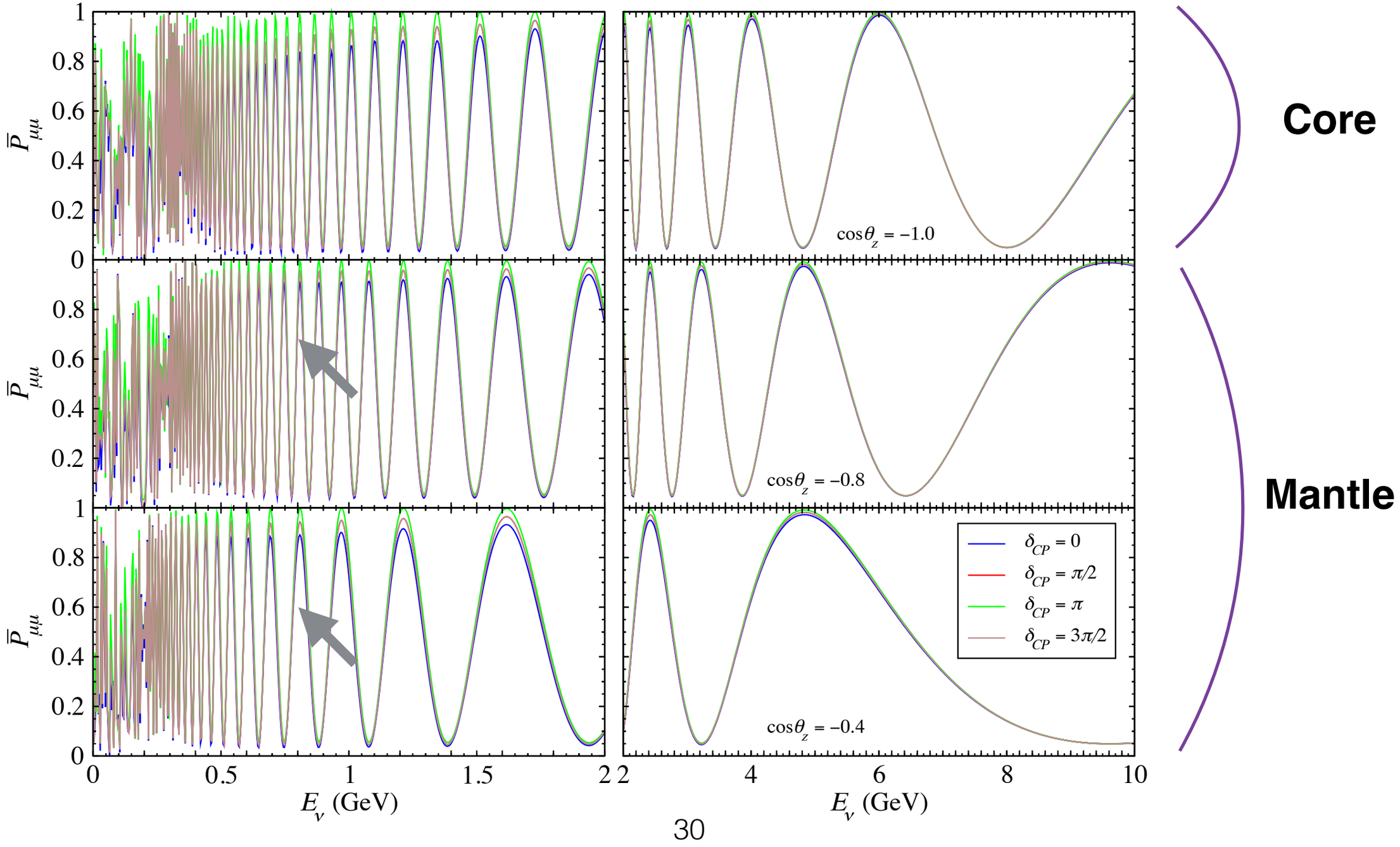
Transition Probability $\bar{\nu}_e \rightarrow \bar{\nu}_\mu$

Systematic shift of probability with CP phase (~0.3-2 GeV)



Survival Probability $\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu$

Systematic opposite shift of probability with CP phase (~0.3-2 GeV)

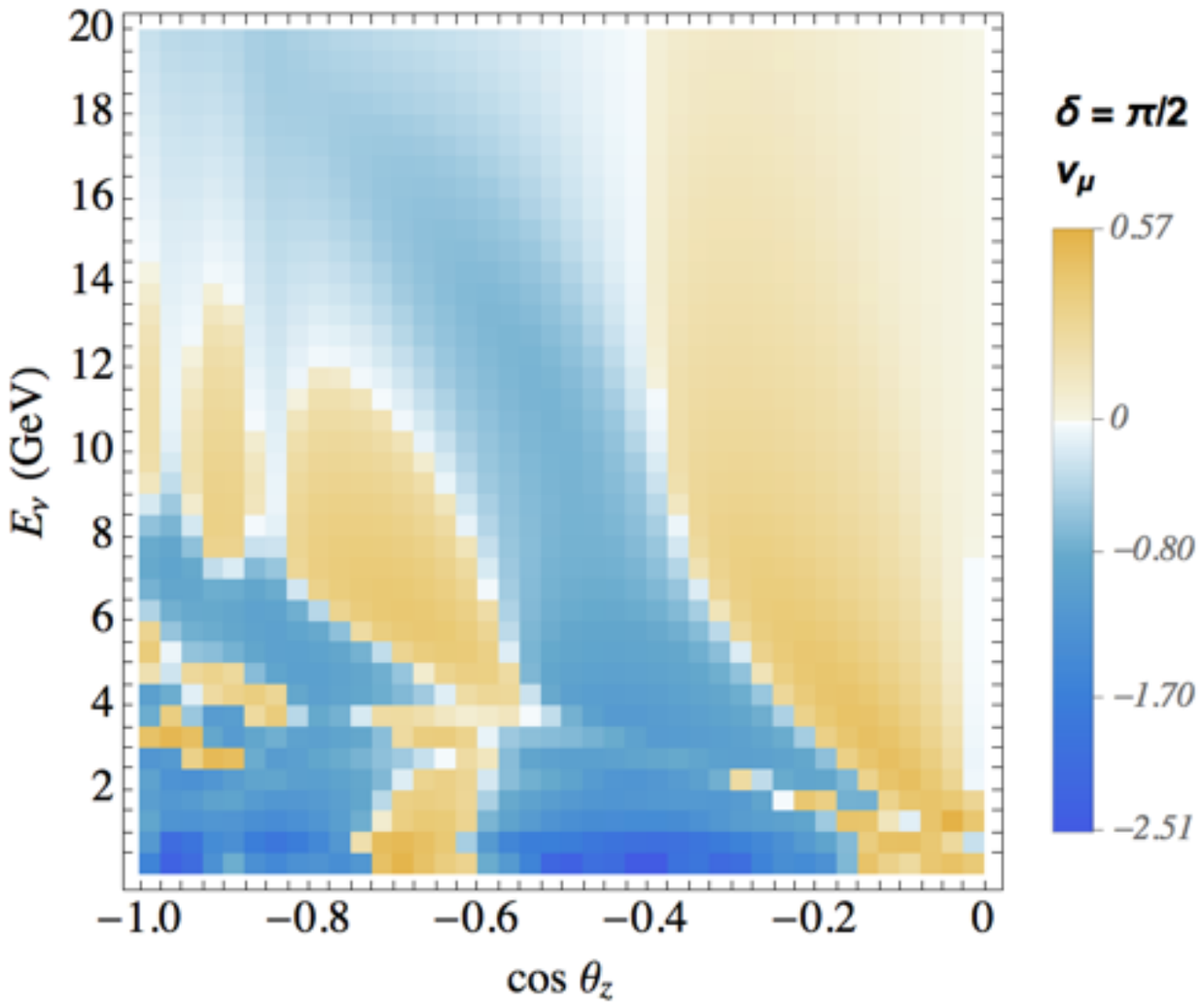


Separation of nu and anitnu

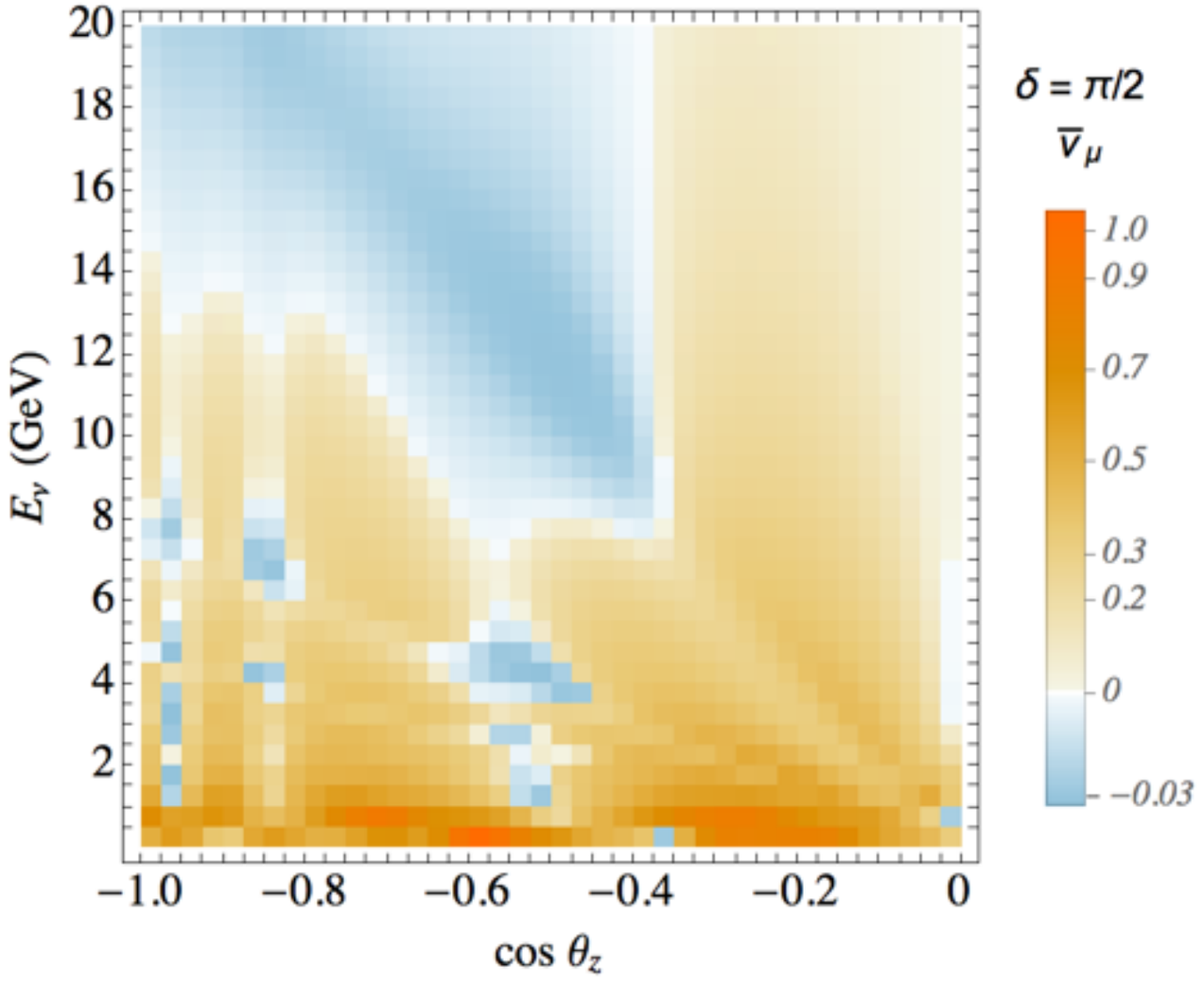
Increases sensitivity by ~30% - 40%

Due to reduction of cancellation for opposite signs for probabilities

1 year of events



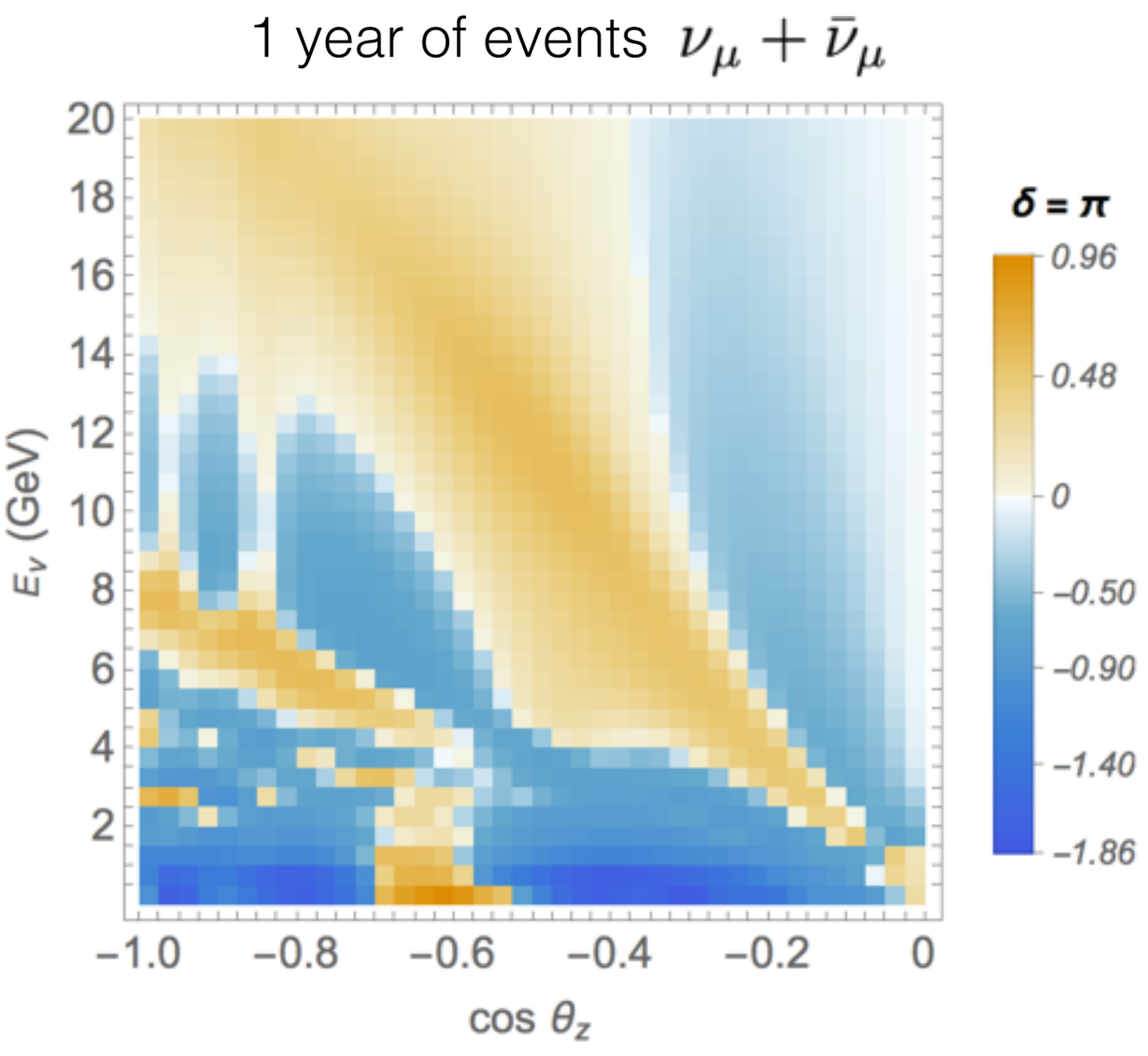
1 year of events

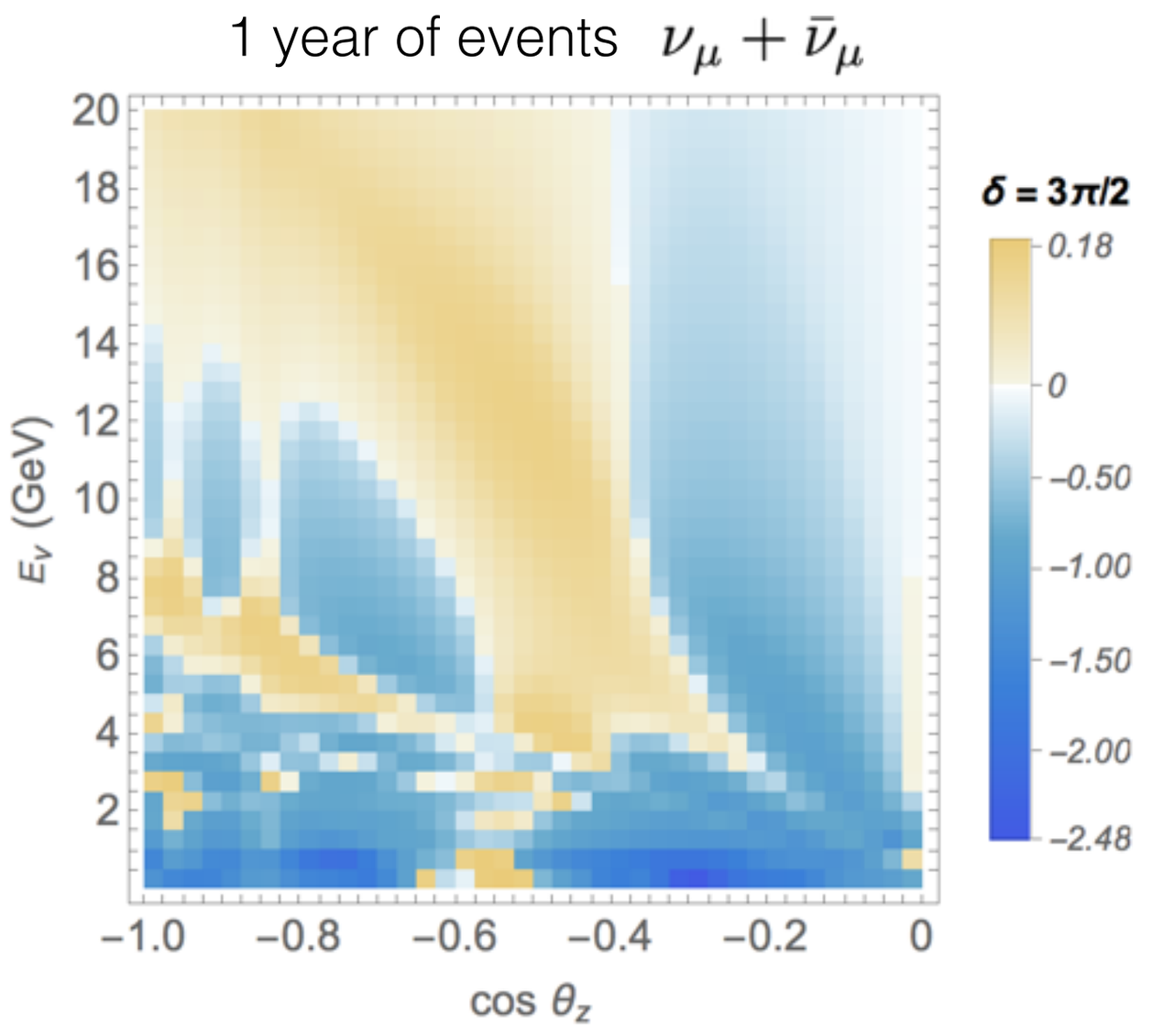


Inverted mass hierarchy

Decreases sensitivity by ~25% - 30%

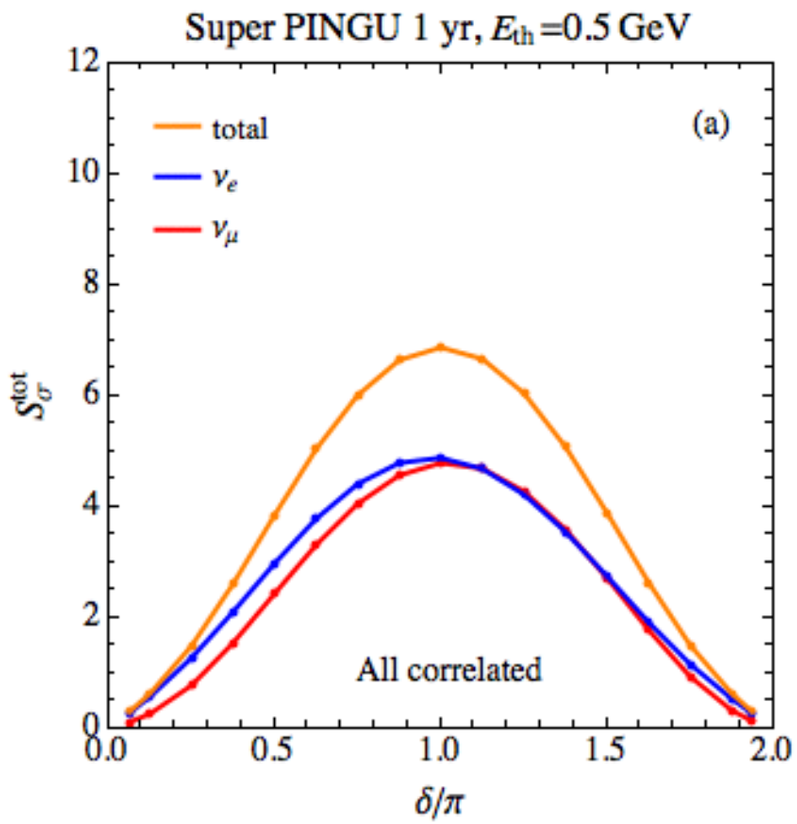
Mostly due to absence of 1-3 resonance in antinu channel

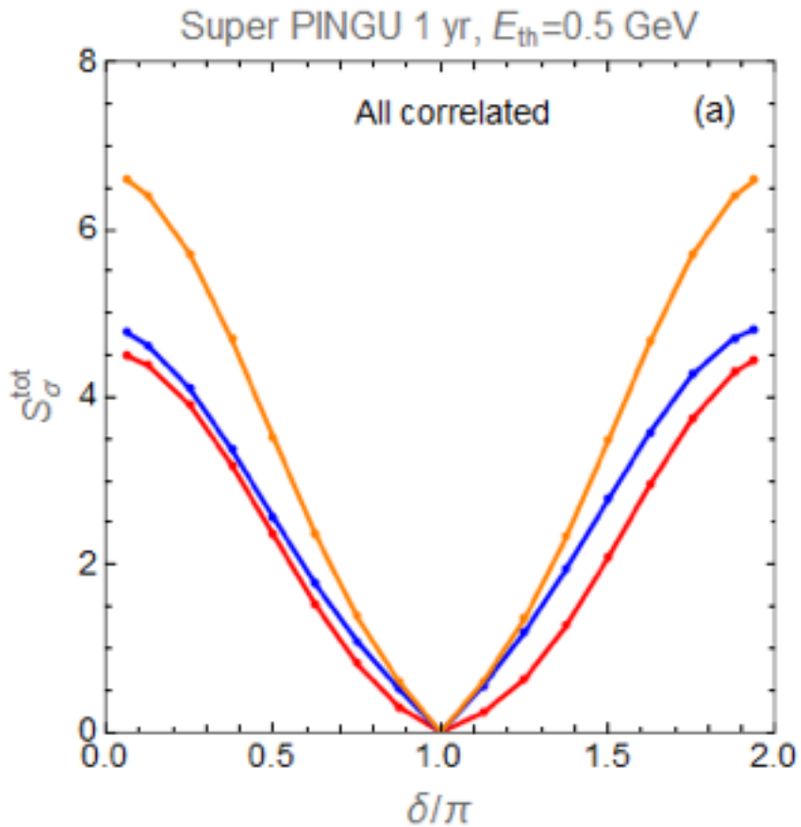


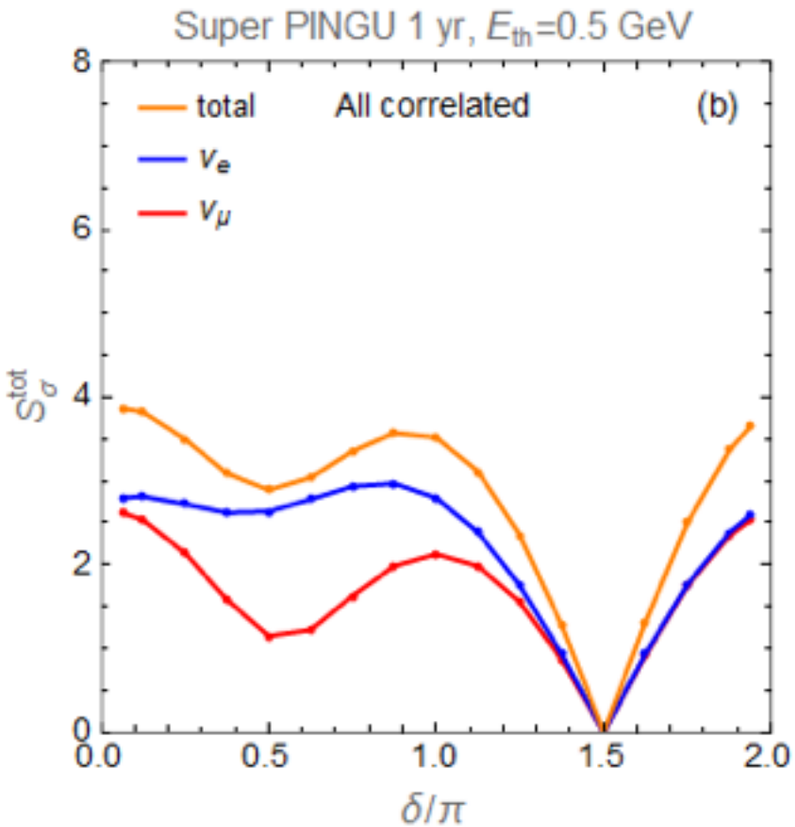


Towards realistic sensitivity to CP

All correlated (4) and 2.5% additional uncorrelated uncertainties





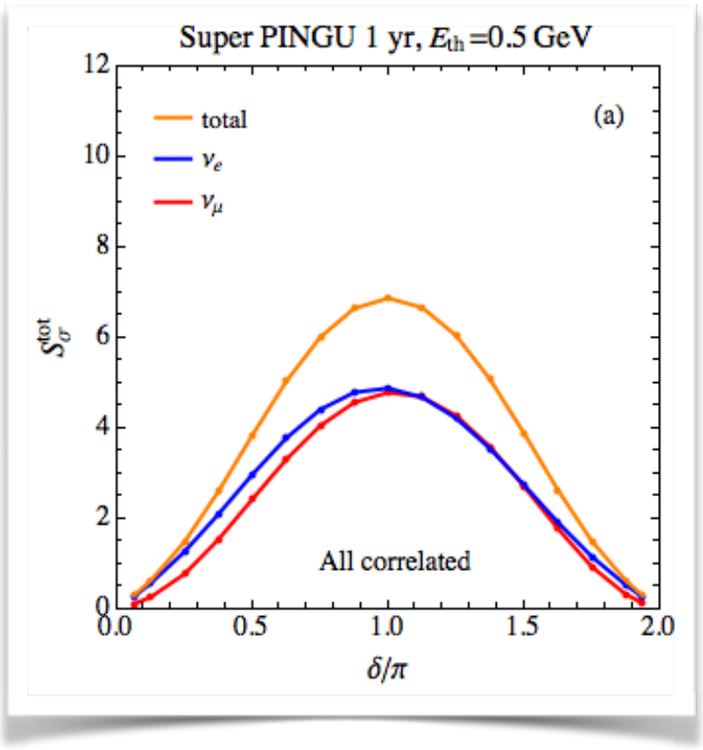


True CP = 0

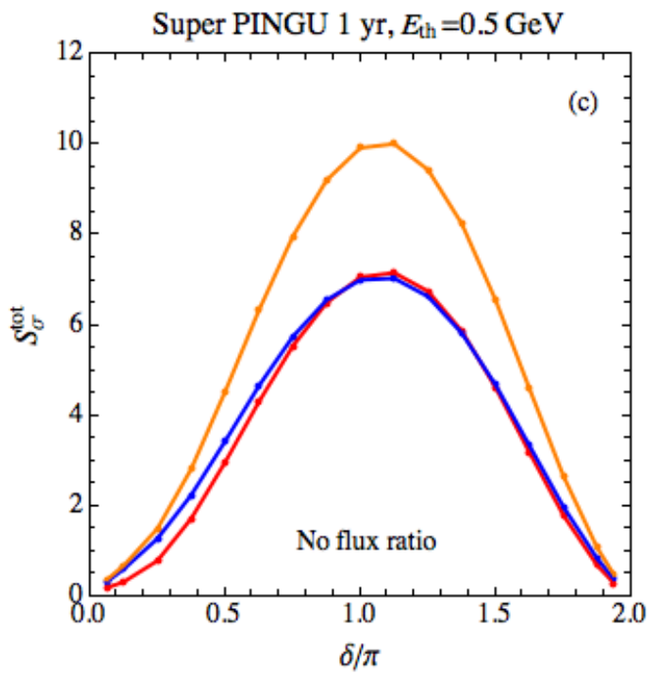
True CP = pi

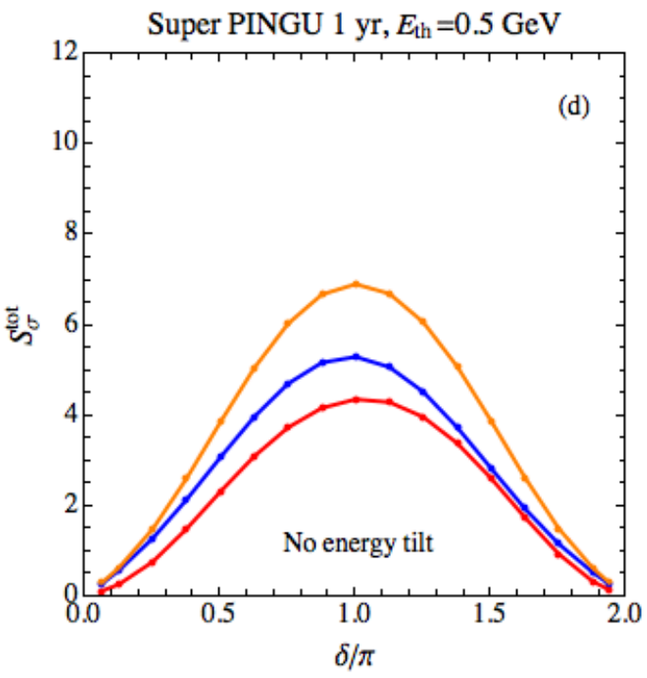
True CP = 3pi/2

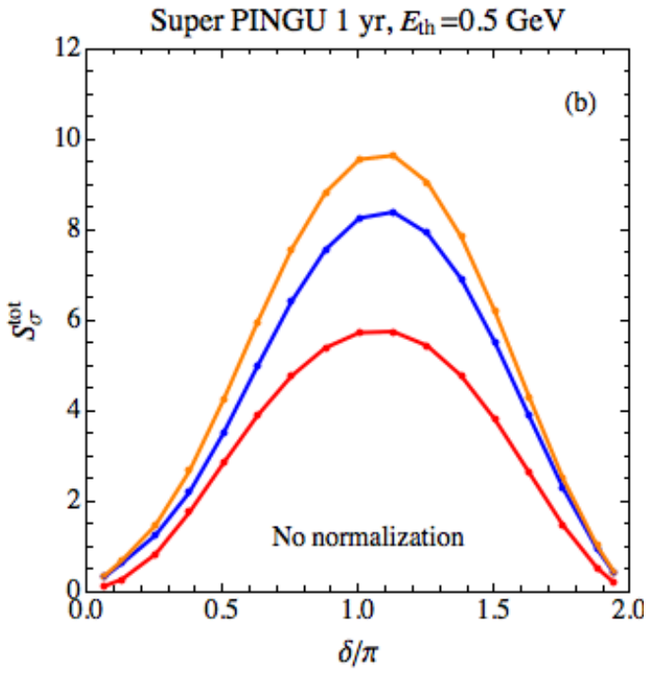
Towards realistic sensitivity to CP

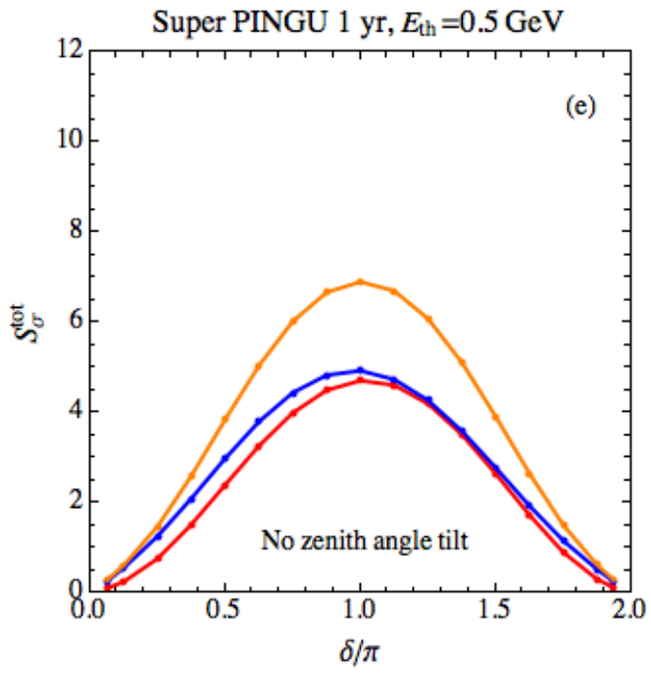


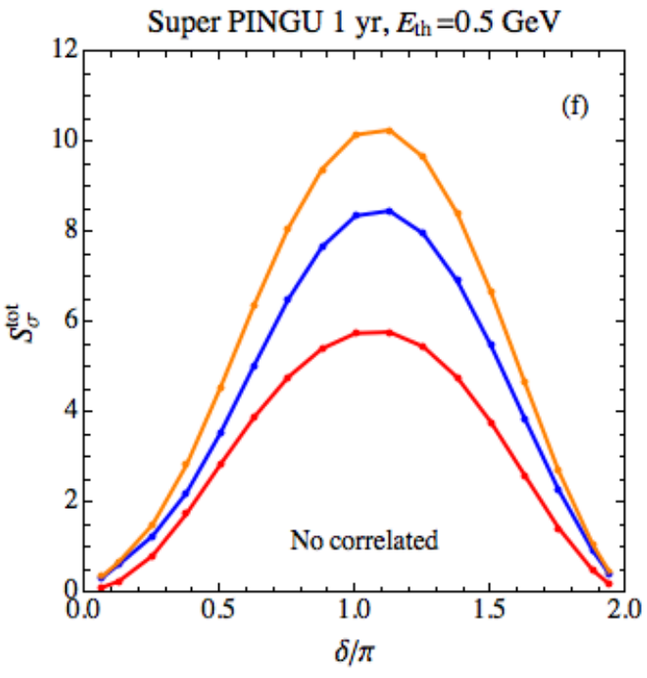
Effects of removing individual systematics



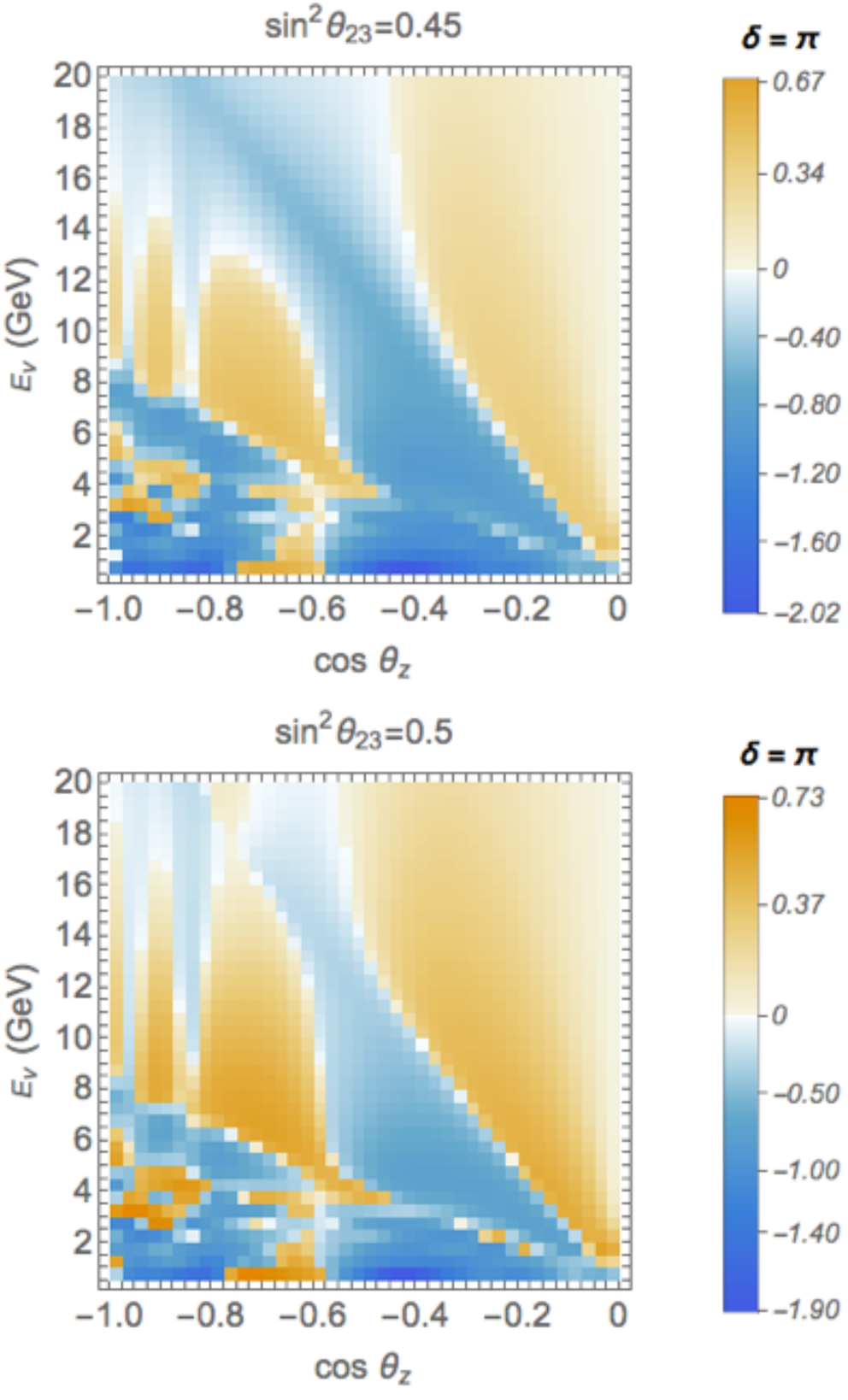








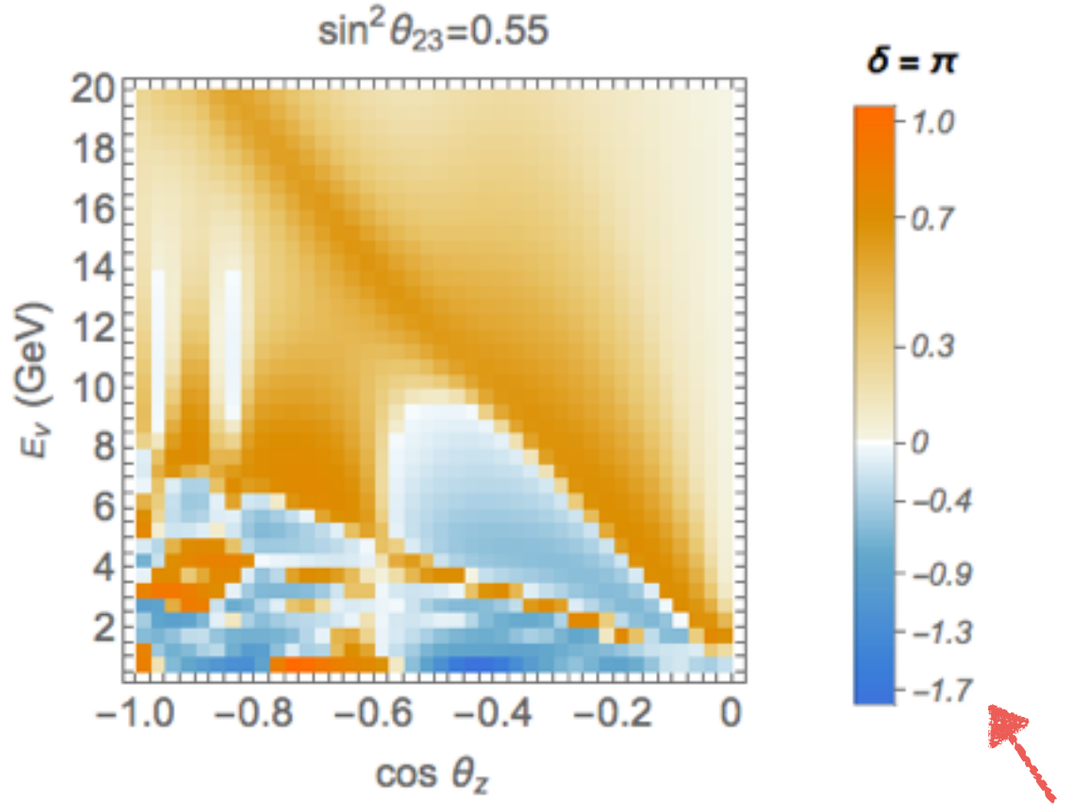
Dependence on theta_{23}



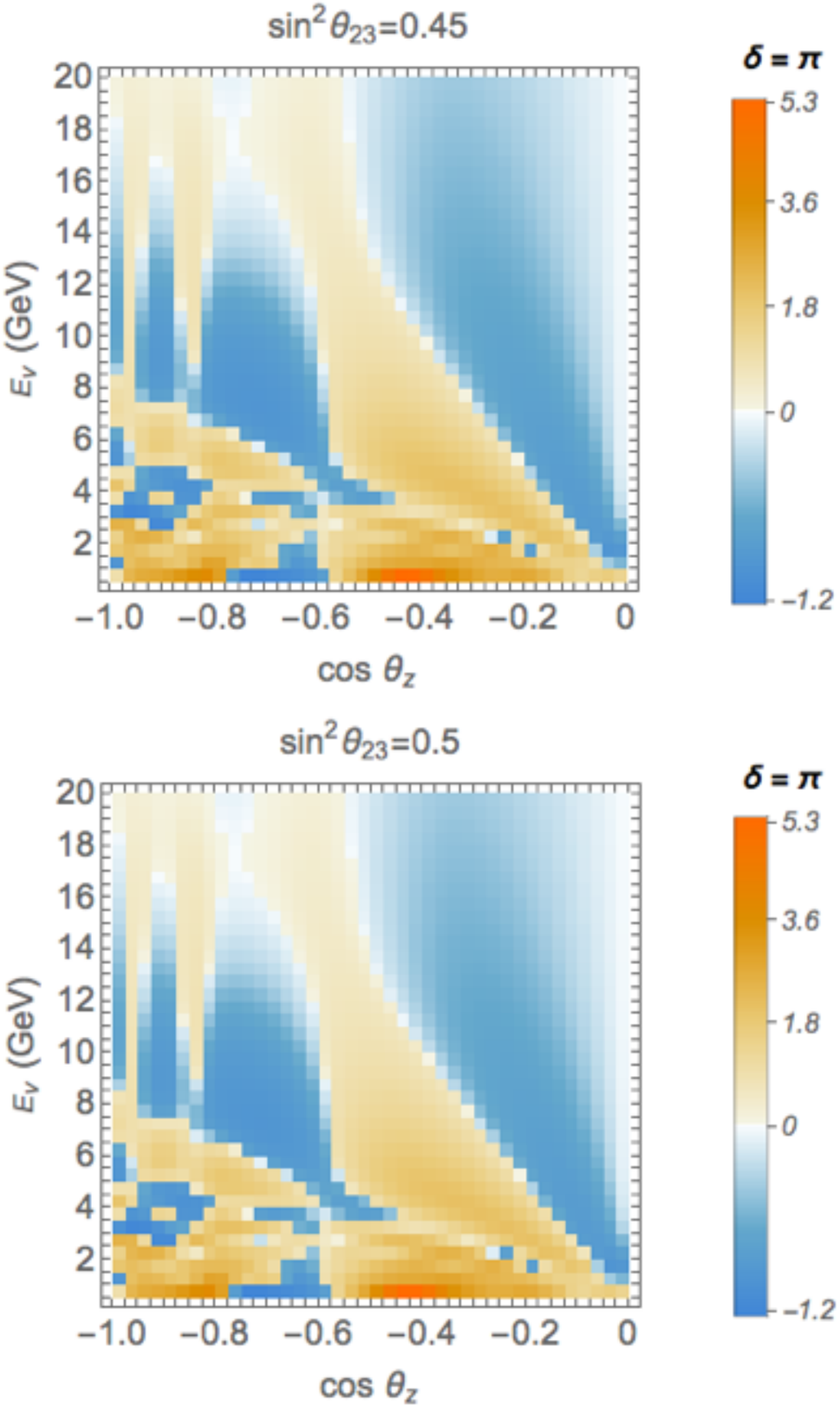
Mild dependence on theta_{23} in the

$\nu_\mu + \bar{\nu}_\mu$ **channel**

1 year of events



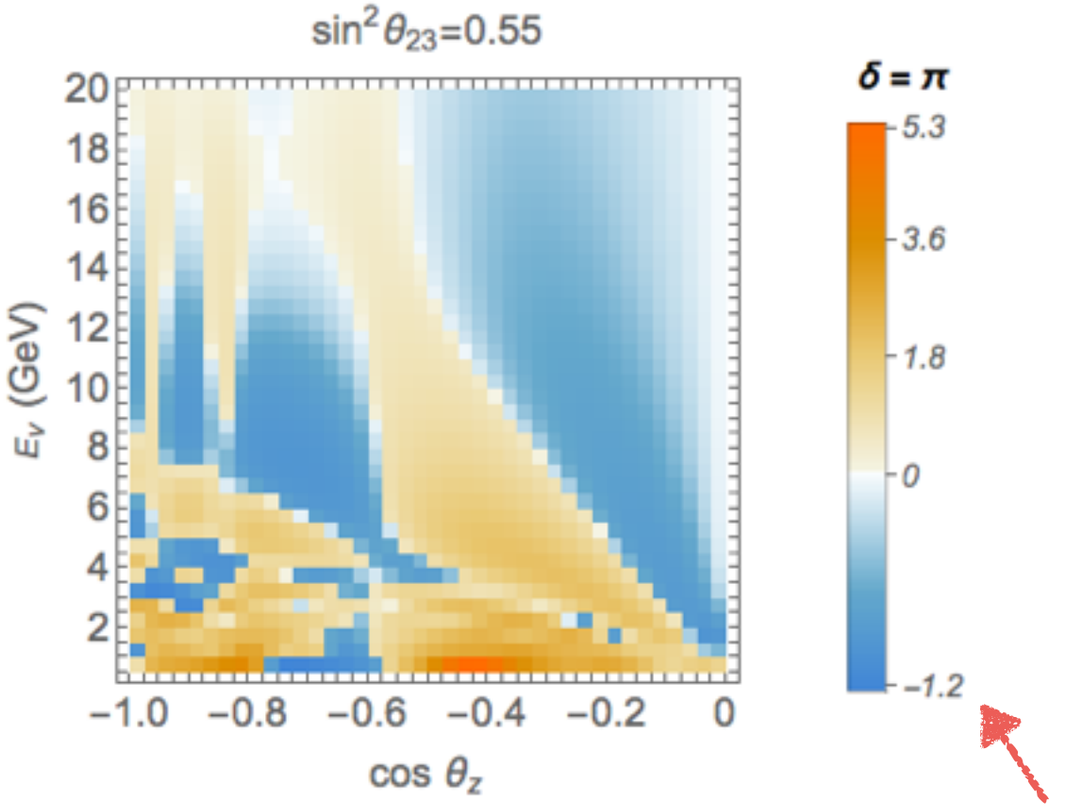
Dependence on theta_{23}



Almost no dependence on theta_{23} in the

$\nu_e + \bar{\nu}_e$ **channel**

1 year of events



Dependence on theta_{23}