The Abdus Salam International Centre for Theoretical Physics

Physics of Atmospheric Neutrinos (PANE) 2018

28 May - 1 June 2018, Trieste, Italy

CP Violation Searches in Atmospheric Neutrinos

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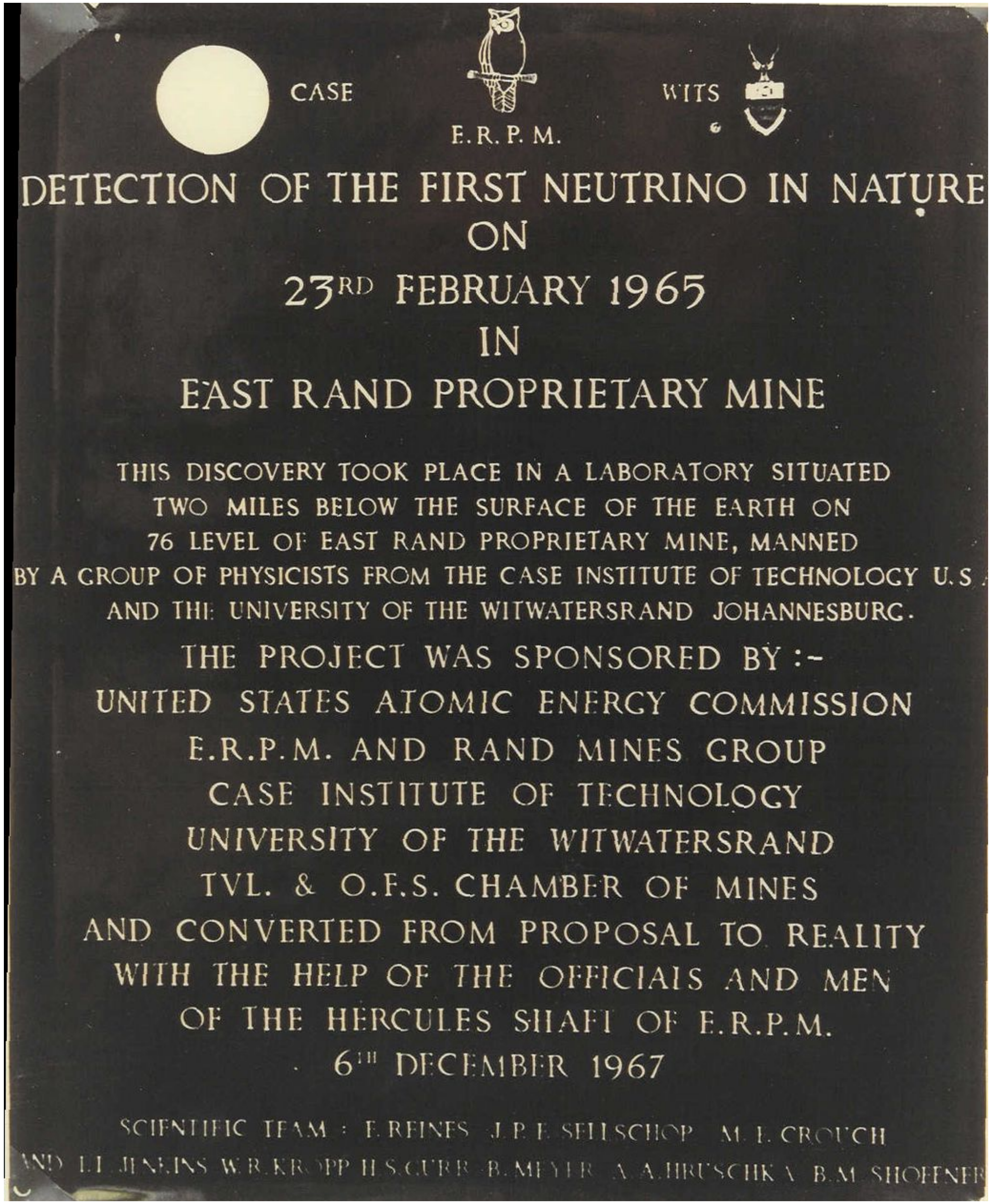
Discovery of Atmospheric Neutrinos



South Africa

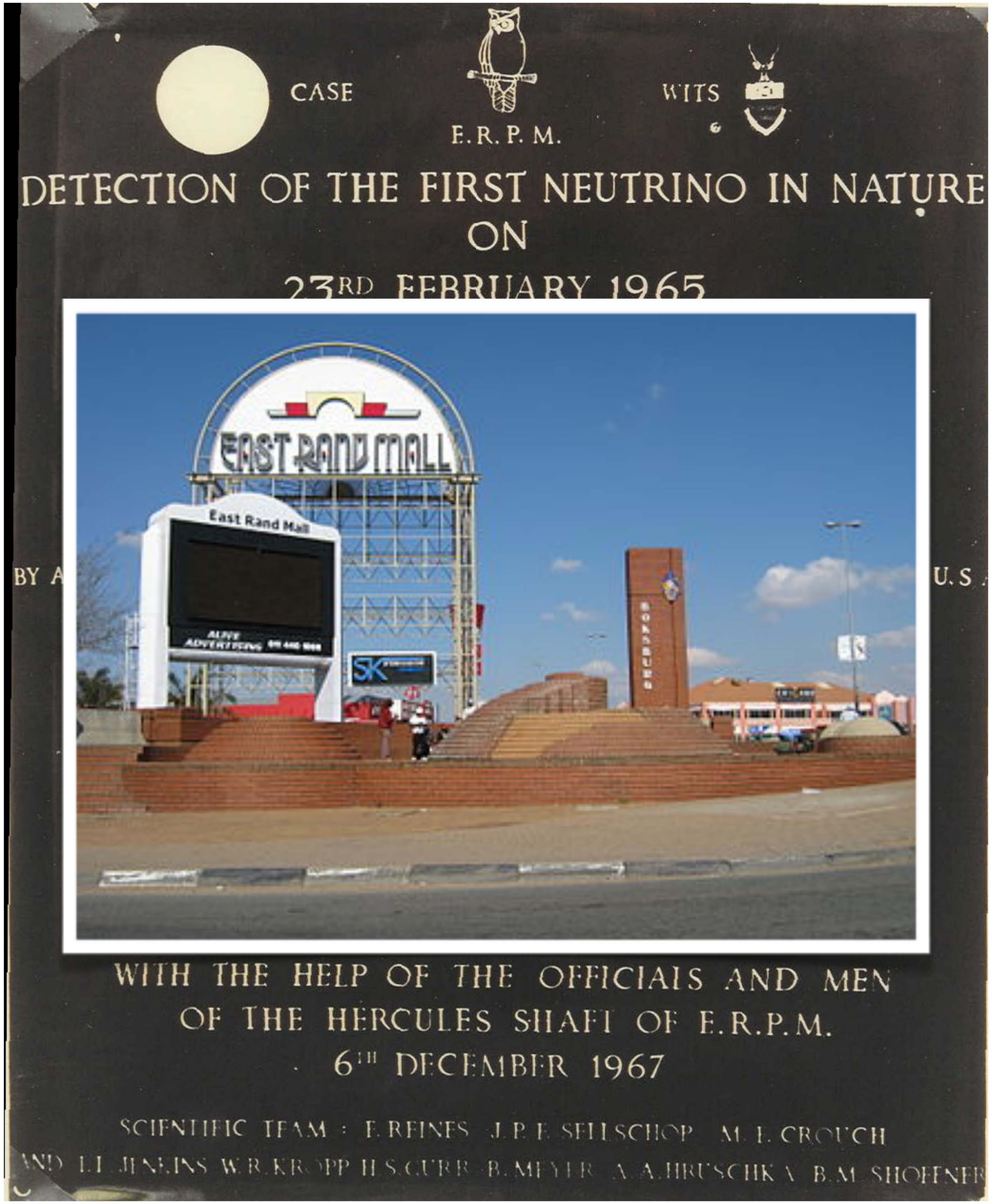
Case Institute of Technology - University of the Witwatersrand

F. Reines et al. 1965

Gold mine in Johannesburg, South Africa
8800 mwe

Liquid scintillator detectors

Discovery of Atmospheric Neutrinos



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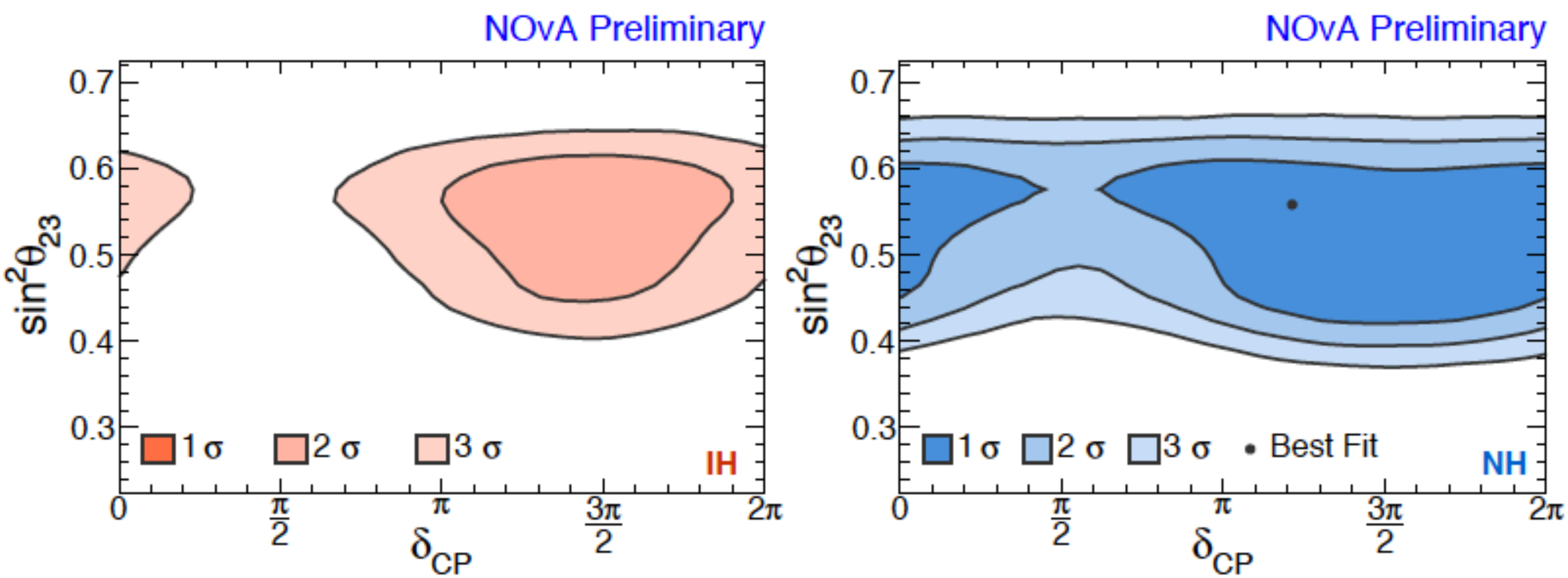
Current Status of CPV Search - NOvA

Slide from Liudmila Kolupaeva at Nu HoRIzons 2018

$\nu_e + \nu_\mu$ fit results



- Best Fit: $\delta_{CP} = 1.21\pi$, Upper Octant, Normal Hierarchy.
- Upper octant is prefered at 0.2σ.
- Exclude $\delta_{CP} = \pi/2$ region in the IH at $> 3\sigma$.
- Approaching IH rejection at 2σ.

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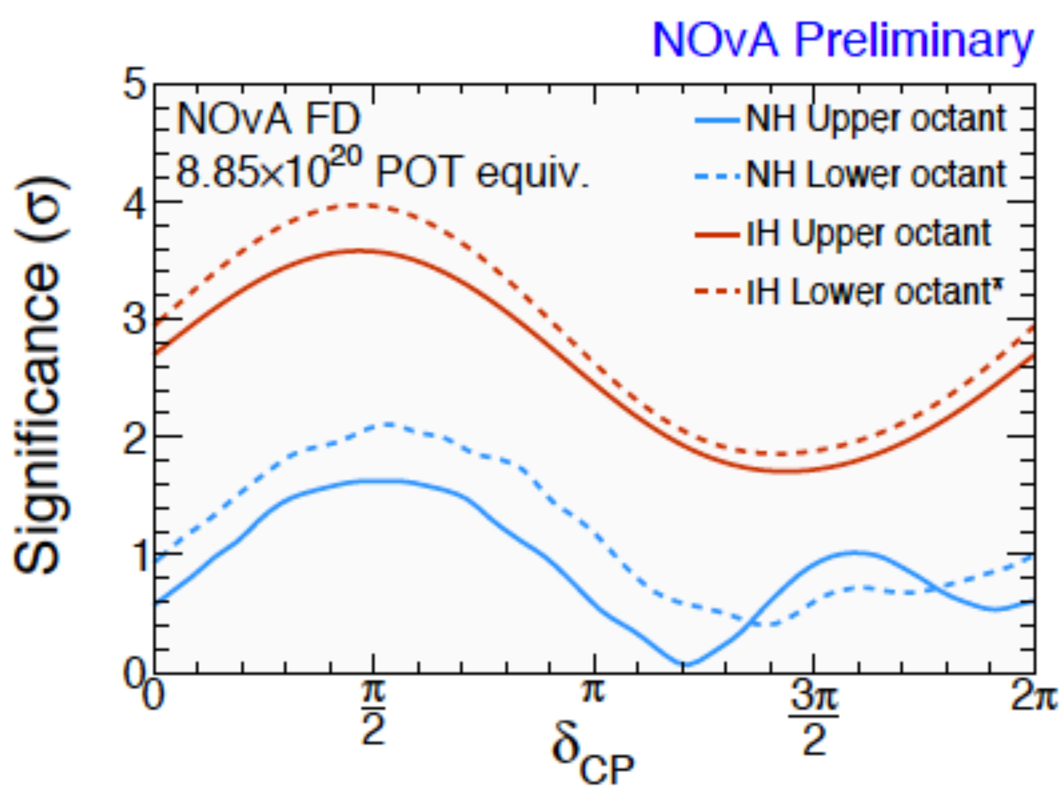

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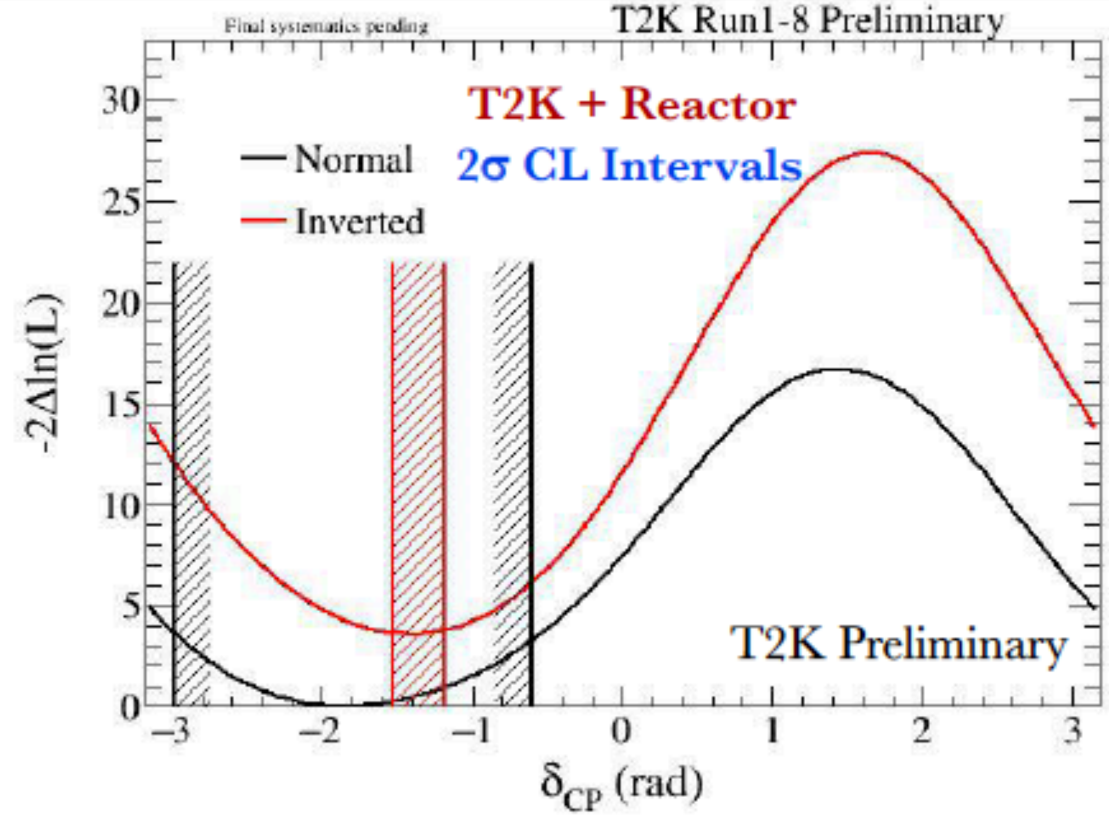
Current Status of CPV Search - T2K

Slide from Zoya Vallari at Nu HoRIzons 2018

T2K Oscillation Result : δ_{CP} Measurement



Best-fit: $\delta_{CP} = -1.833^{+0.604}_{-0.658}$ radians

2σ confidence interval:

Normal hierarchy $[-2.98, -0.60]$

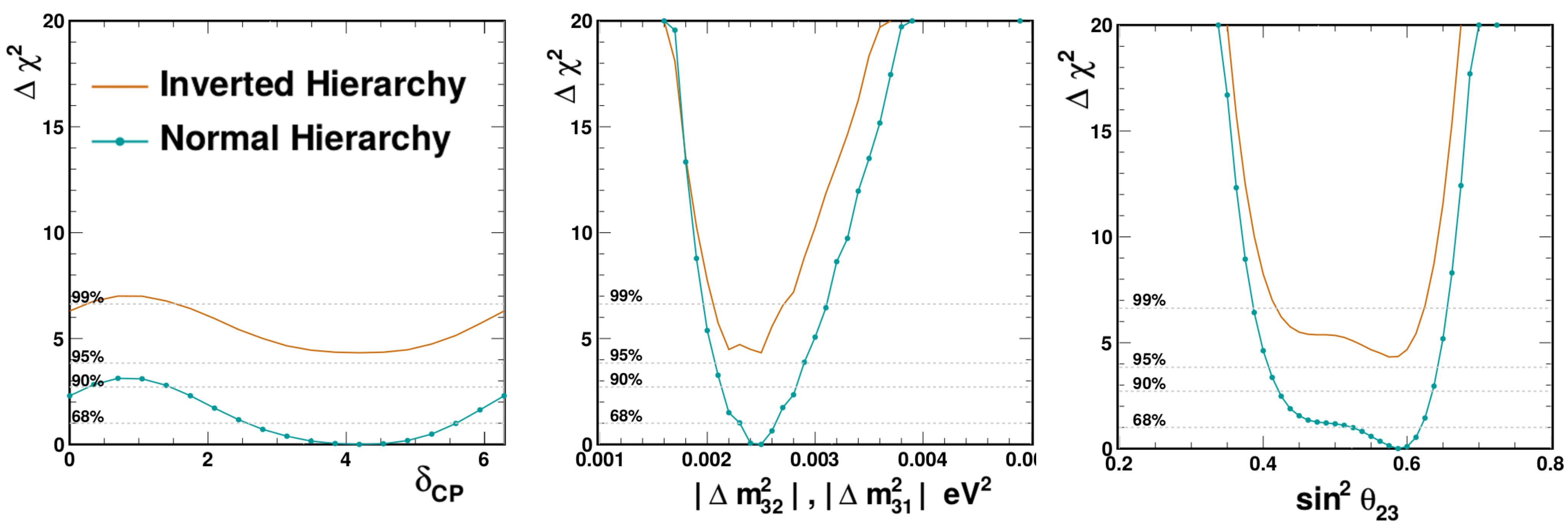
Inverted hierarchy $[-1.53, -1.18]$

T2K disfavors CP conserving values $(0, \pi)$ by 2σ.

Current Status of CPV Search - SK

Slide from Christophe Bronner at PANE 2018

Atmospheric neutrino results



	χ^2	$\lvert\Delta m^2_{32/31}\rvert$	$\sin^2(\theta_{23})$	δ_{CP}
Normal hierarchy	571.33	2.5×10^{-3}	0.5875	4.18
Inverted hierarchy	575.66	2.5×10^{-3}	0.575	4.18

- **χ^2(NH)-χ^2(IH)=-4.33**
- P-value for this $\Delta\chi^2$ (true values of the parameters corresponding to the NH best fit point) is 0.027 for true IH
  → **Preference for the normal hierarchy hypothesis**

CPV Search with Atmospheric Neutrinos

- Another (less expensive) way to search for CP violation and measure the CP phase
  - Wider energy range and many baselines compared to accelerator experiments
  - No significant degeneracy between CP and theta23
  - Available and well-understood technology
    - PINGU, ORCA —> Super-PINGU, Super-ORCA
- Outline of this talk
  - Estimates of sensitivity (Assuming normal hierarchy, known osc. param.)
  - Identify CP sensitive energy and zenith angle ranges
  - Current challenges and future improvements
    - Flux, cross-section, particle identification, oscillation parameters, systematics

See next talk: <u>Super ORCA by Jannik Hofestaedt</u>

Oscillation Probabilities - CP part

Quasi-constant density approximations above 1-2 resonance and averaged over 1-3 oscillation

$$\langle P^{\delta}_{e\mu}\rangle = \frac{J_\theta}{2}\left[-\cos\delta\sin^2\phi^m_{21} + \frac{1}{2}\sin\delta\sin 2\phi^m_{21}\right] \qquad \langle \bar{P}^{\delta}_{e\mu}\rangle = \frac{\bar{J}_\theta}{2}\left[\cos\delta\sin^2\bar{\phi}^m_{21} - \frac{1}{2}\sin\delta\sin 2\bar{\phi}^m_{21}\right]$$

$$\langle P^{\delta}_{\mu\mu}\rangle = -\frac{J_\theta}{2}\cos\delta\sin^2\phi^m_{21} \qquad \langle \bar{P}^{\delta}_{\mu\mu}\rangle = -\frac{\bar{J}_\theta}{2}\cos\delta\sin^2\bar{\phi}^m_{21}$$

CP asymmetry

$$\langle P^{\delta}_{e\mu}\rangle - \langle P^{0}_{e\mu}\rangle = \frac{J_\theta}{2}\left[(1-\cos\delta)\sin^2\phi^m_{21} + \frac{1}{2}\sin\delta\sin 2\phi^m_{21}\right] \qquad \langle P^{\delta}_{\mu\mu}\rangle - \langle P^{0}_{\mu\mu}\rangle = -\frac{J_\theta}{2}(1-\cos\delta)\sin^2\phi^m_{21}.$$

$$\langle \bar{P}^{\delta}_{e\mu}\rangle - \langle \bar{P}^{0}_{e\mu}\rangle = -\frac{\bar{J}_\theta}{2}\left[(1-\cos\delta)\sin^2\bar{\phi}^m_{21} + \frac{1}{2}\sin\delta\sin 2\bar{\phi}^m_{21}\right] \qquad \langle \bar{P}^{\delta}_{\mu\mu}\rangle - \langle \bar{P}^{0}_{\mu\mu}\rangle = \frac{\bar{J}_\theta}{2}(1-\cos\delta)\sin^2\bar{\phi}^m_{21}.$$

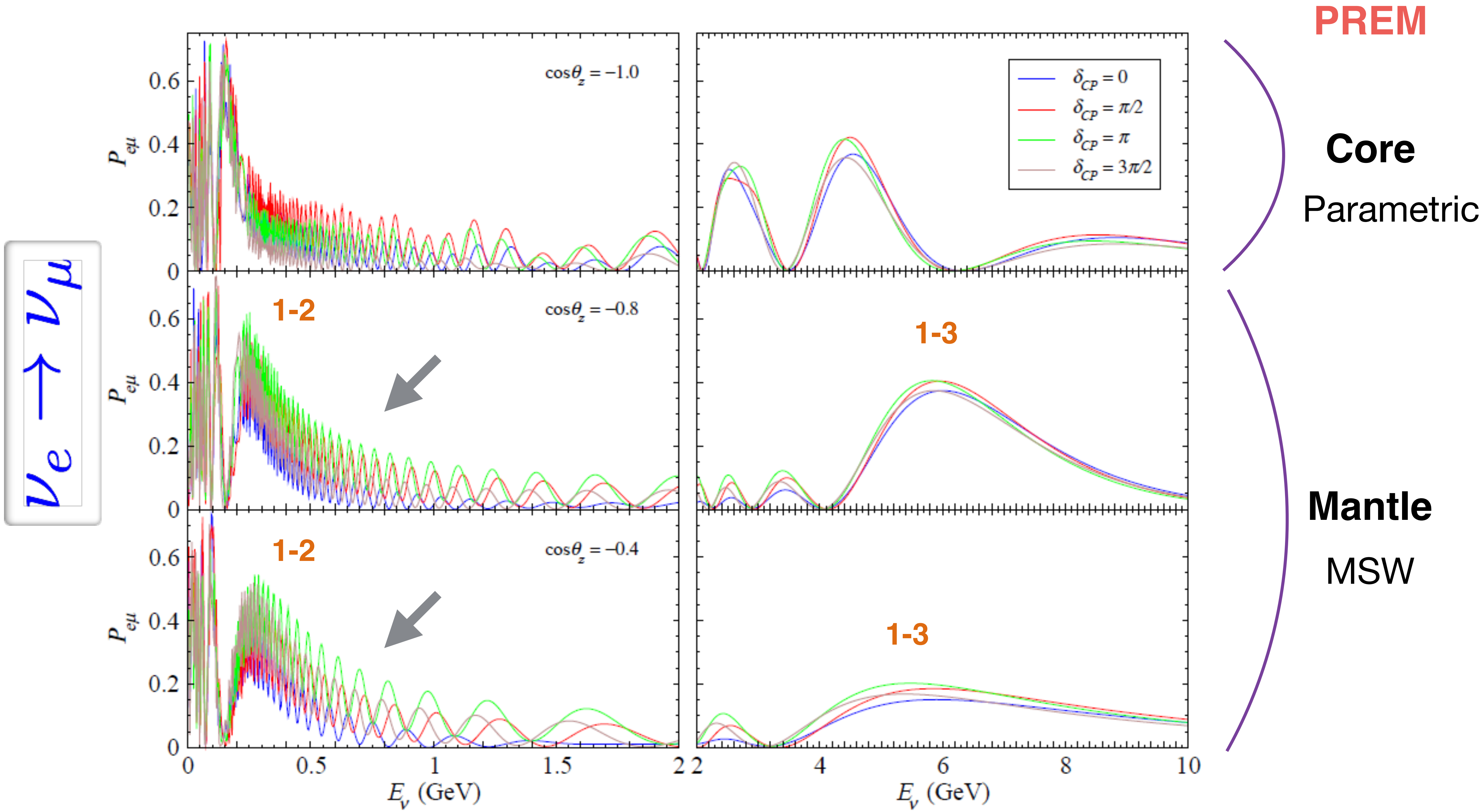
$$J_\theta \equiv \sin 2\theta_{23}\sin 2\theta^m_{12}\sin 2\theta^m_{13}\cos\theta^m_{13}$$

Akhmedov, Dighe, Lipari and Smirnov 1999
Akhmedov, Maltoni and Smirnov 2008
Akhmedov, S.R. and Smirnov 2013
S.R. and Smirnov 2015

$$\phi^m_{21} \approx \frac{\Delta m^2_{21} L}{4E_\nu}\sqrt{\left(\cos 2\theta_{12} \mp \frac{2VE_\nu}{\Delta m^2_{21}}\right)^2 + \sin^2 2\theta_{12}}.$$

CP Sensitive Energy Range

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



S.R., Smirnov 2015

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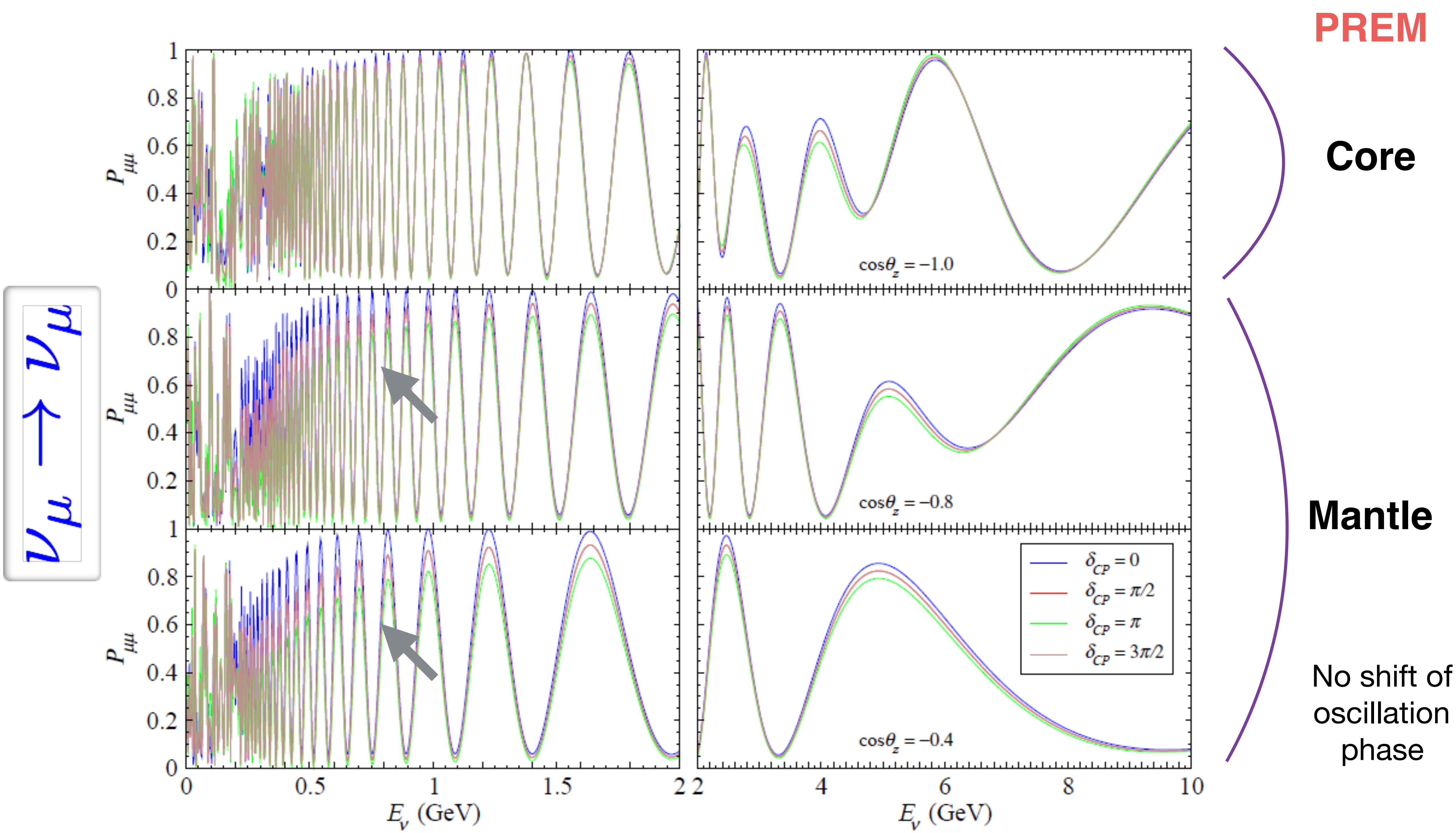

S.R., Smirnov 2015

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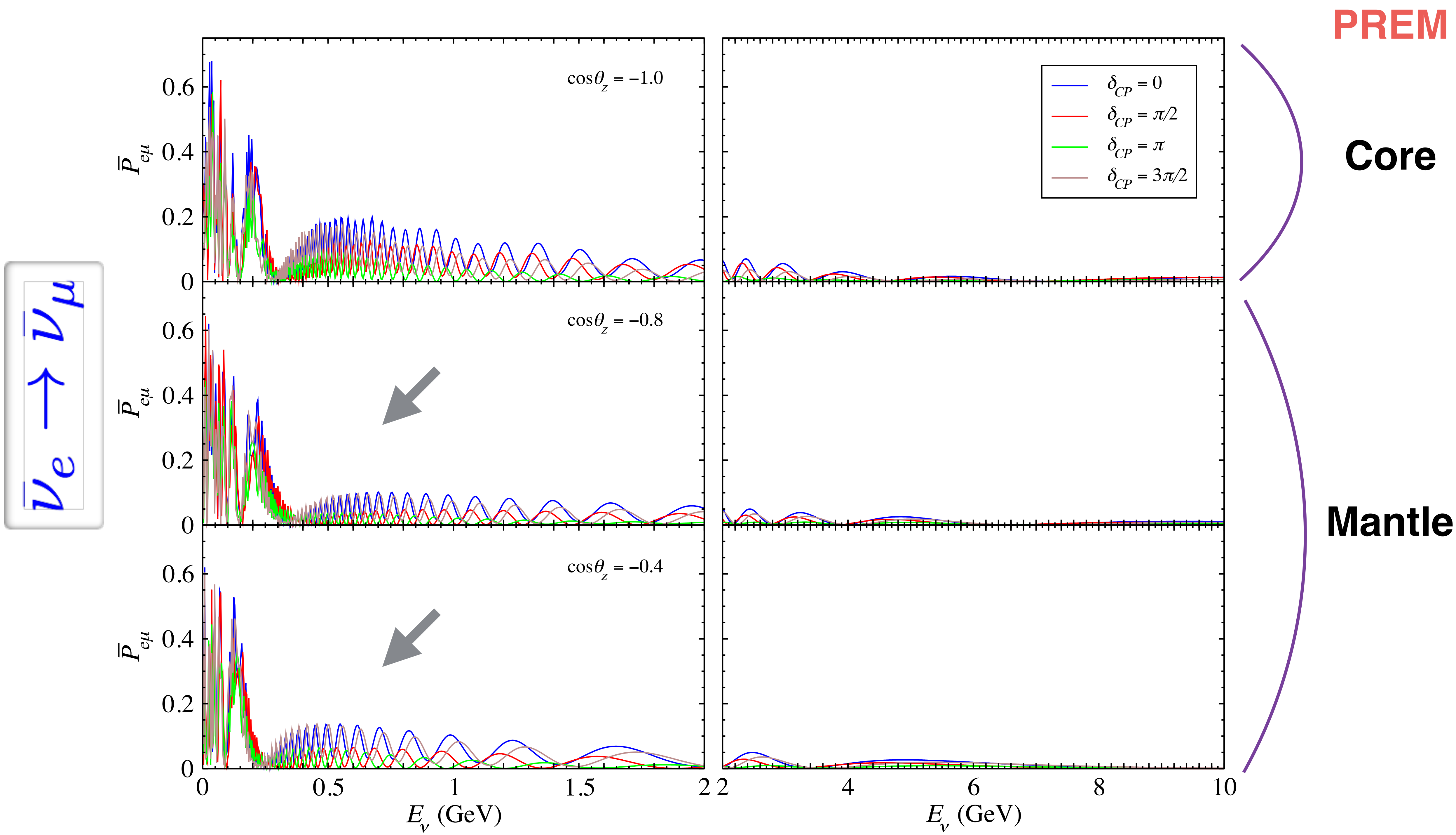

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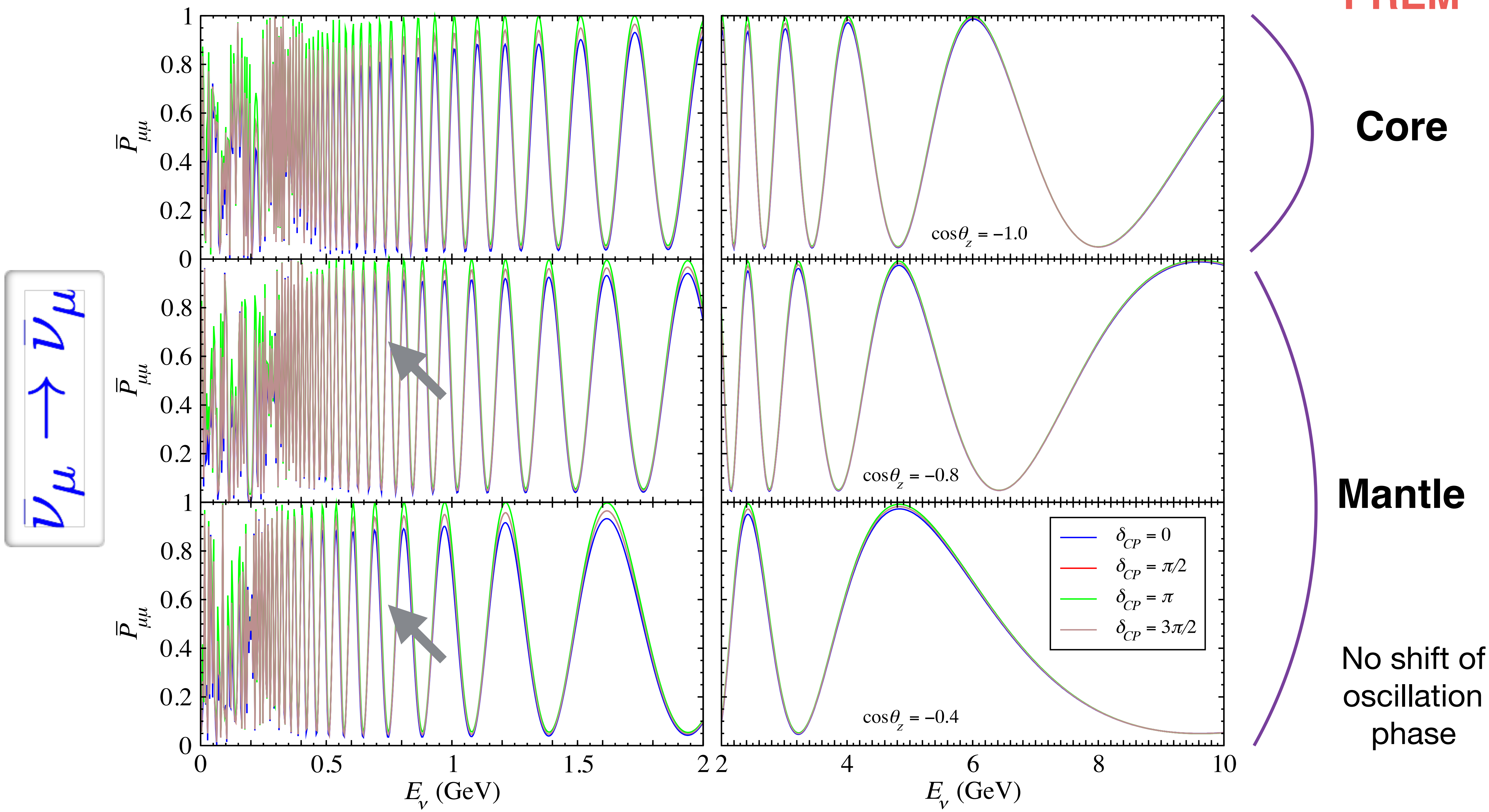
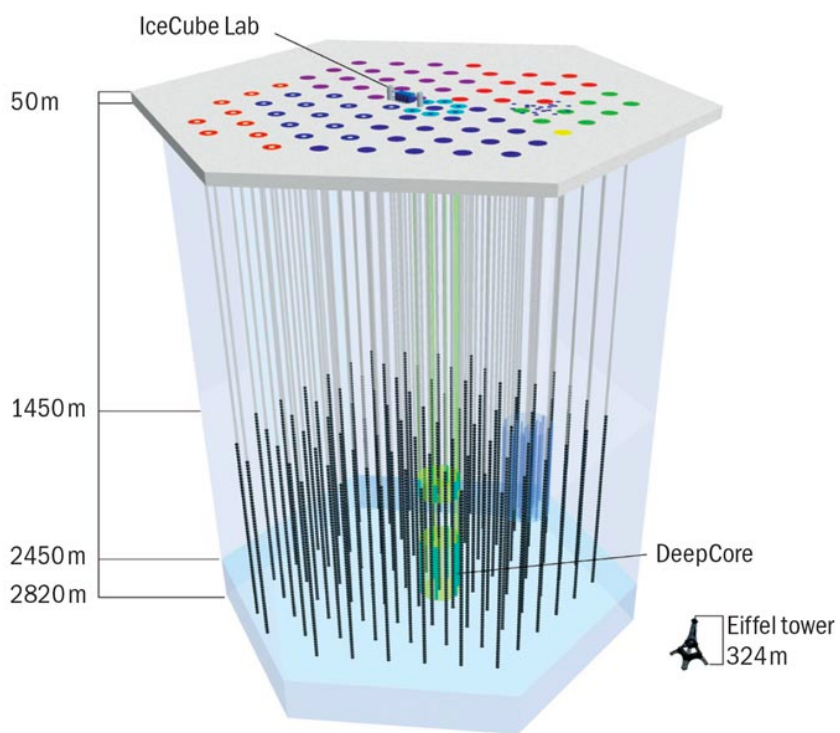
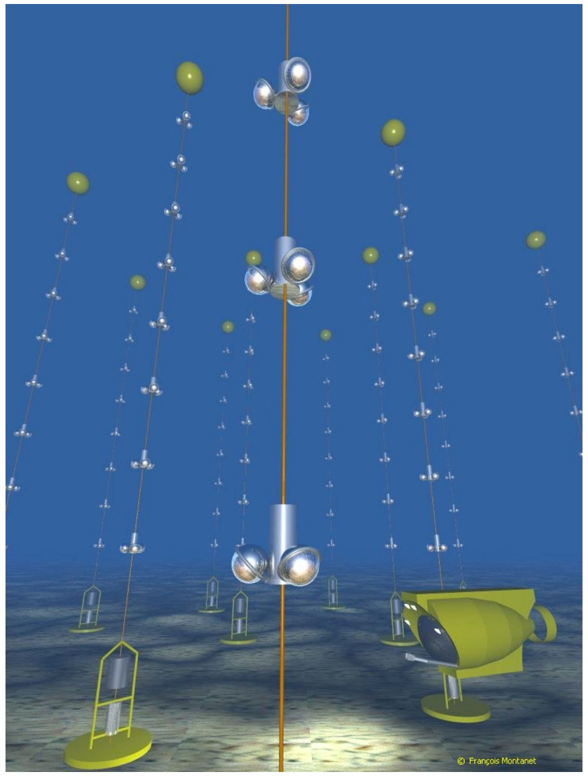


S.R., Smirnov 2015

Huge Ice/Water Cherenkov Detectors

IceCube



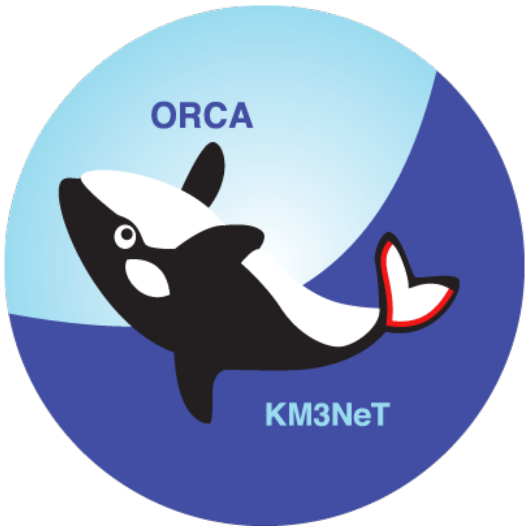


ANTARES

PINGU

PRECISION ICECUBE NEXT GENERATION UPGRADE

- **Denser array**
- **Low energy threshold**
  ~ 1-3 GeV



Oscillation Research with Cosmics in the Abyss

KM3NeT-ORCA

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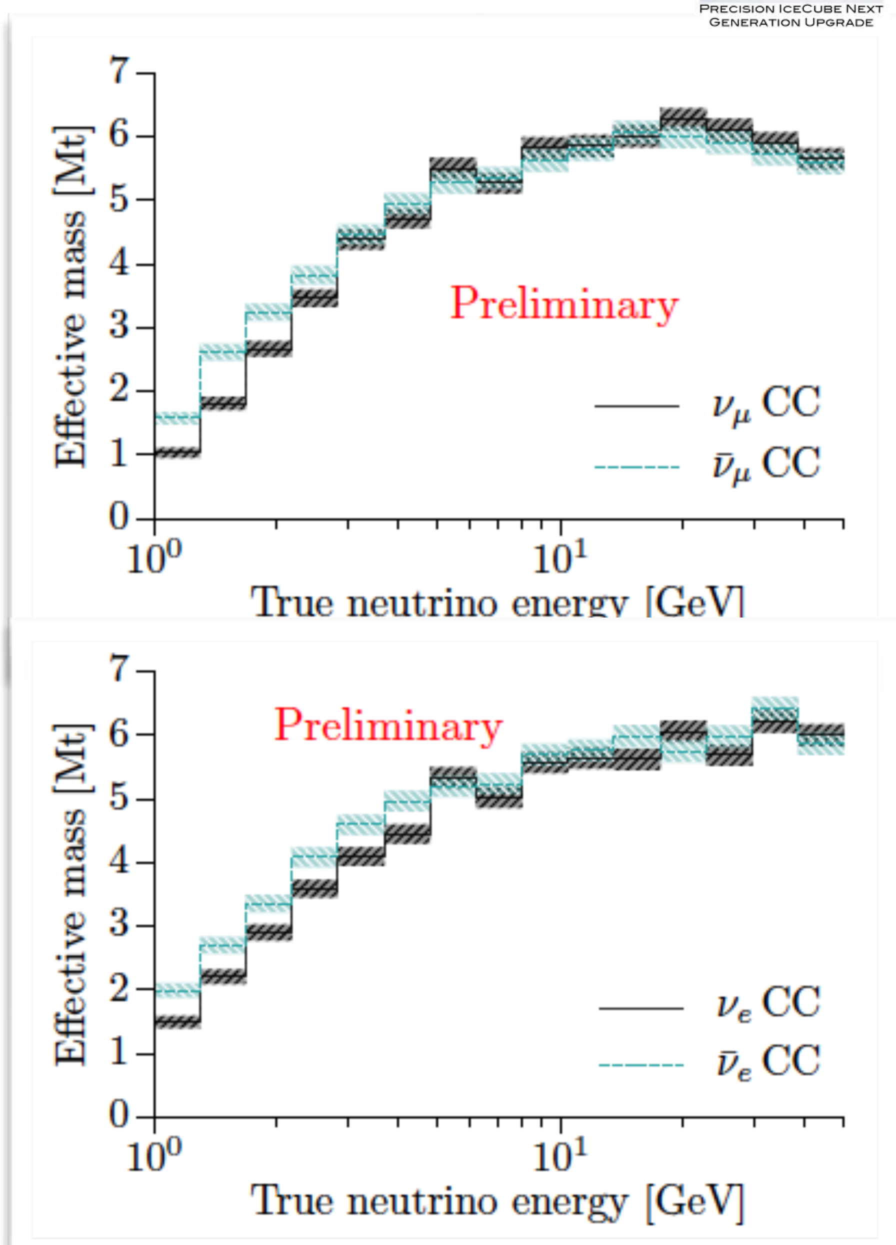
PINGU and ORCA Proposals

Aartsen et al. 2017

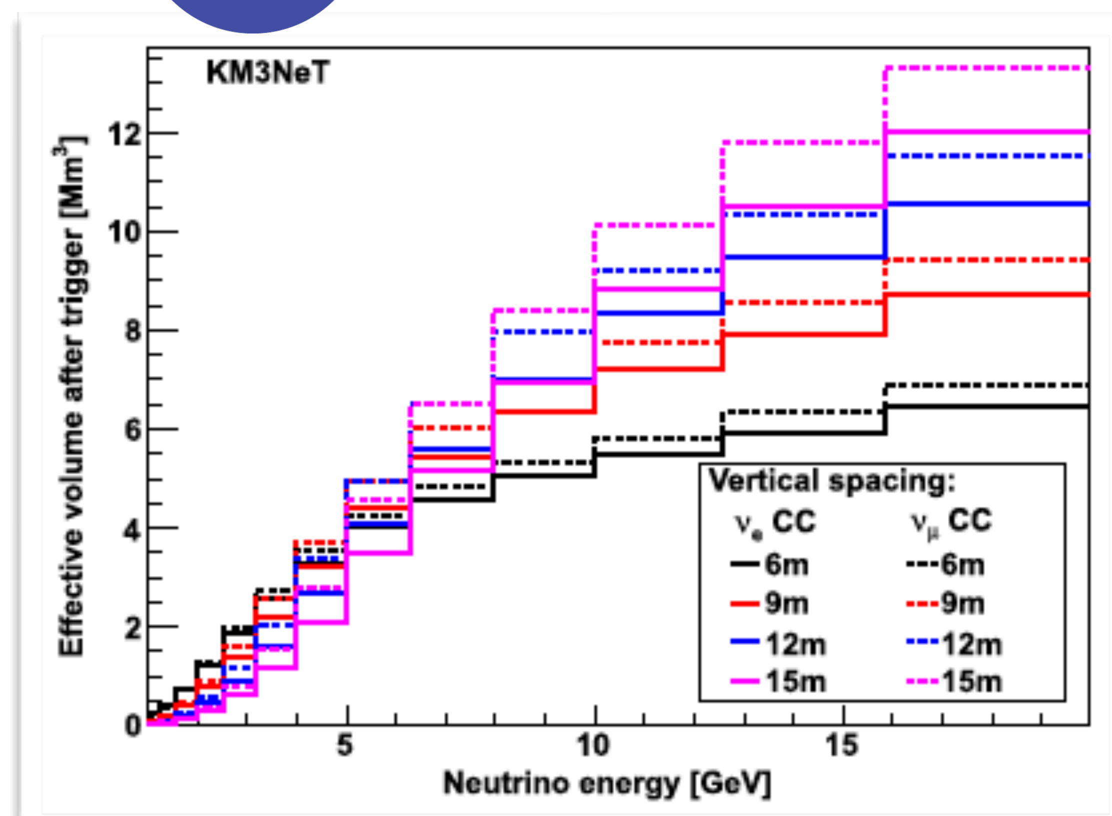
PRECISION ICECUBE NEXT GENERATION UPGRADE



- 6 Mt Fiducial mass
- 1.5m DOM spacing
- 26 PINGU strings

ORCA KM3NeT

Adrian-Martinez et al. 2016



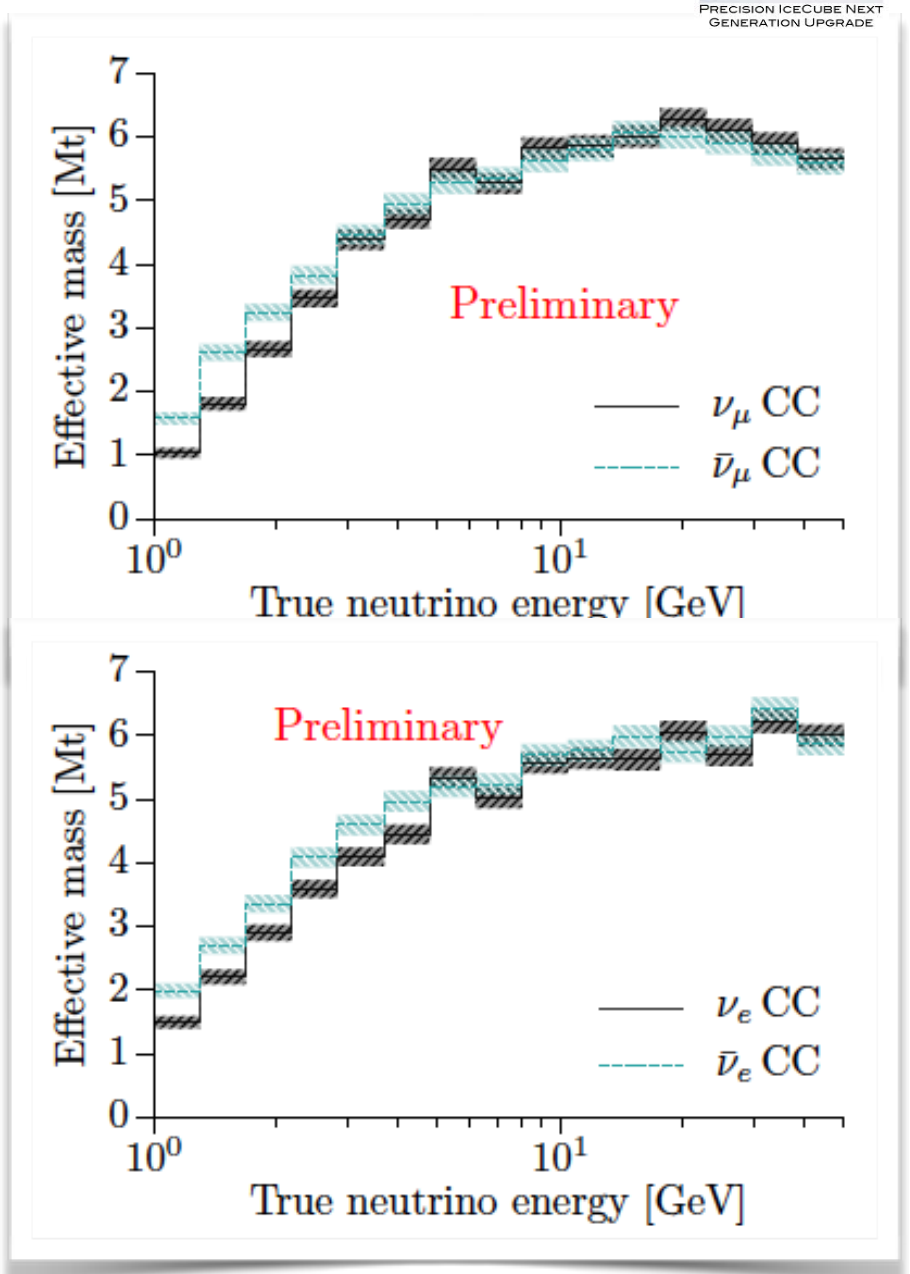
- 3.7 Mt Fiducial mass
- 115 Detection units
- 2070 optical modules

PINGU and ORCA Proposals

Aartsen et al. 2017

Precision IceCube Next Generation Upgrade

Adrian-Martinez et al. 2016



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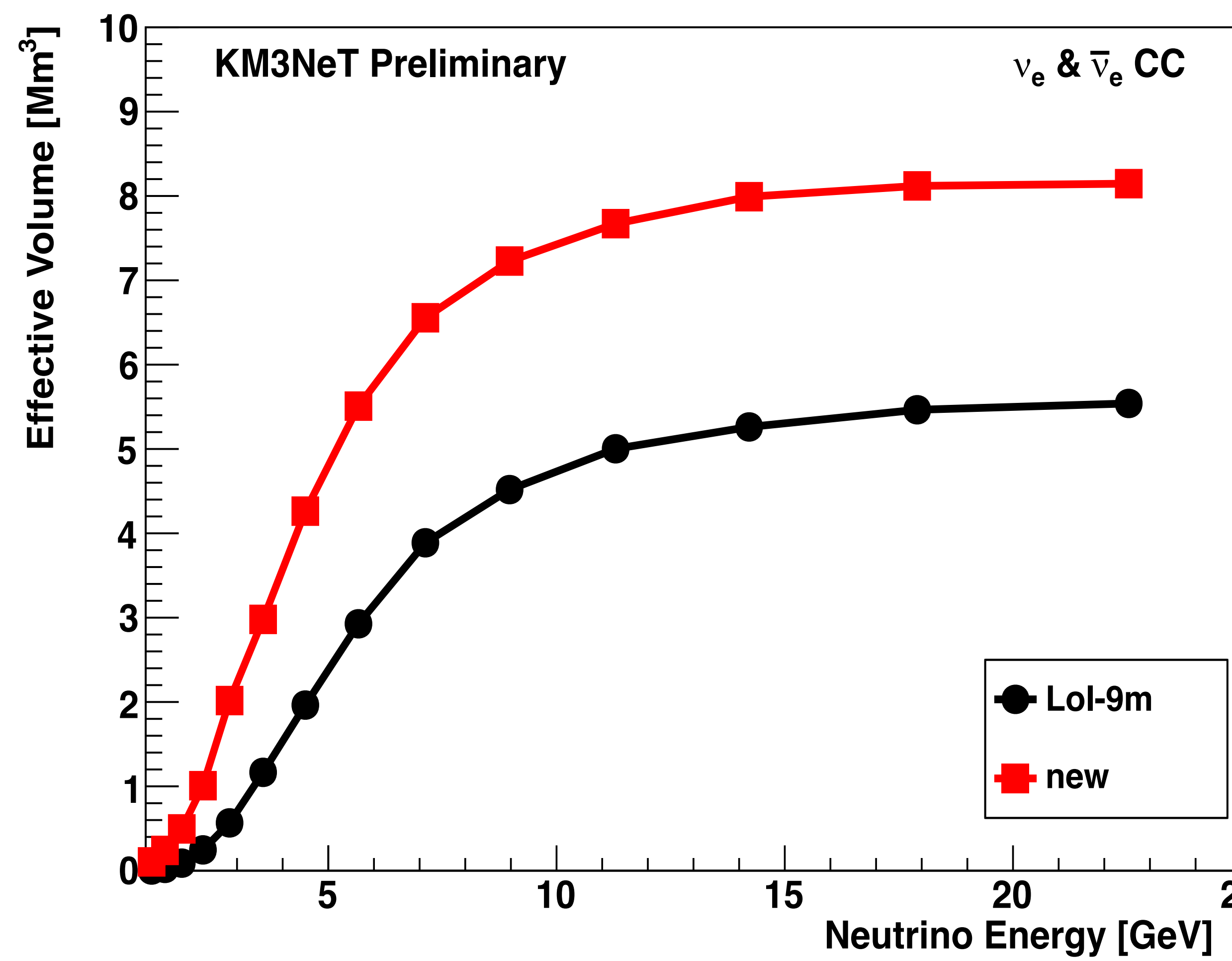
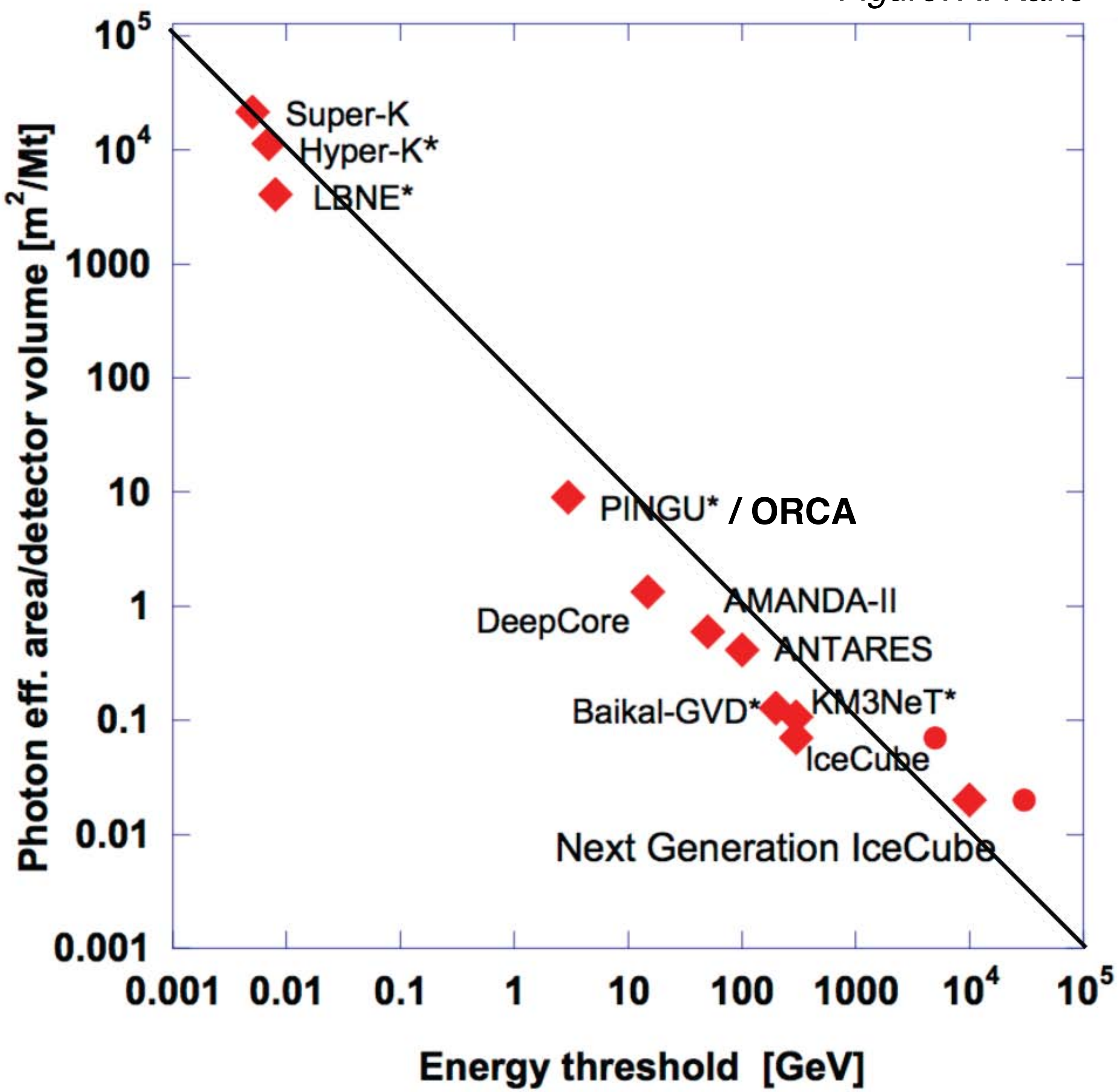


Search for CP violation requires sizable effective mass in the ~0.3-2 GeV range

Reaching sub-GeV Energies

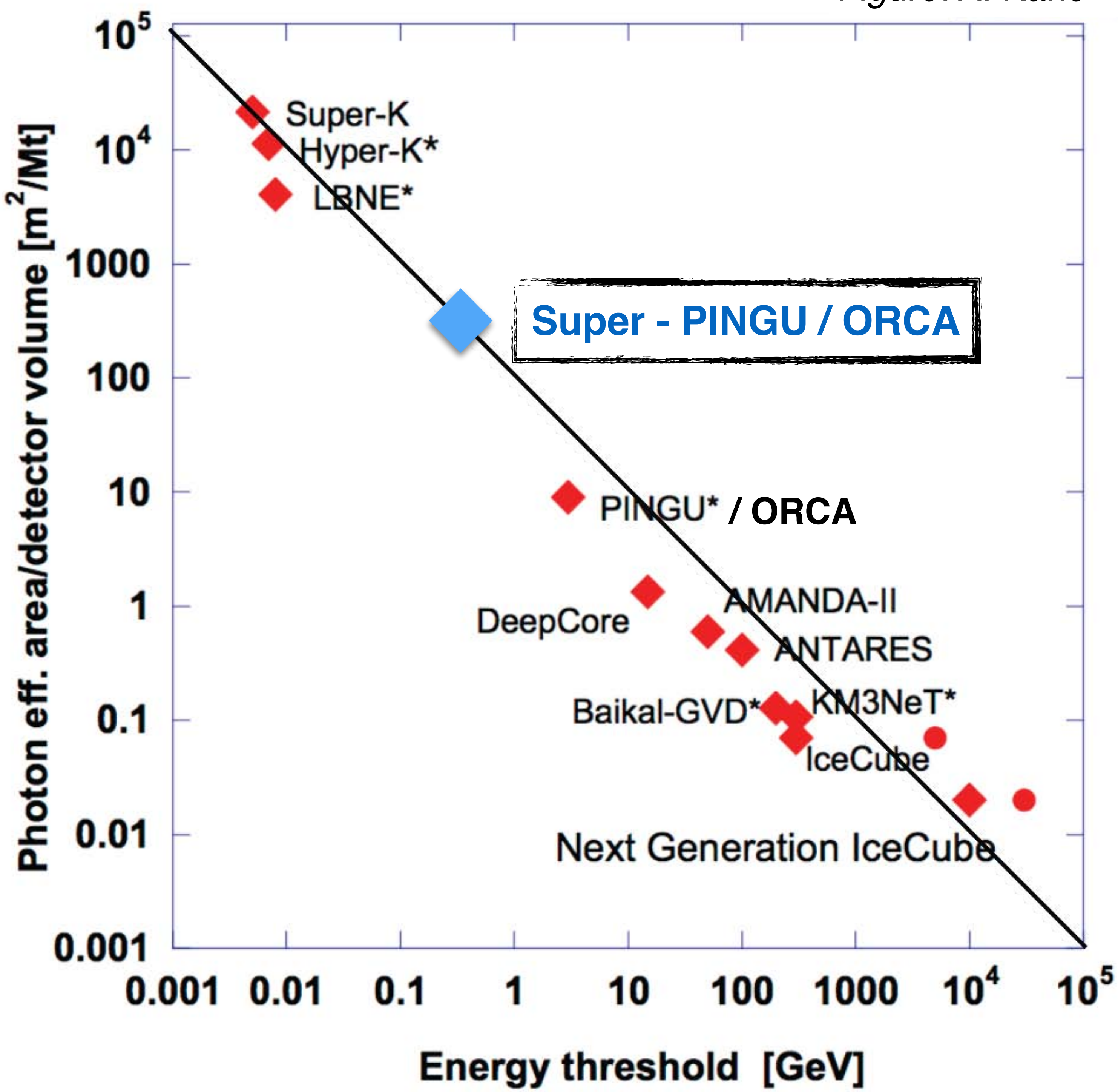
Figure: A. Karle



Reaching sub-GeV Energies

Requires ~10x denser detector than PINGU/ORCA

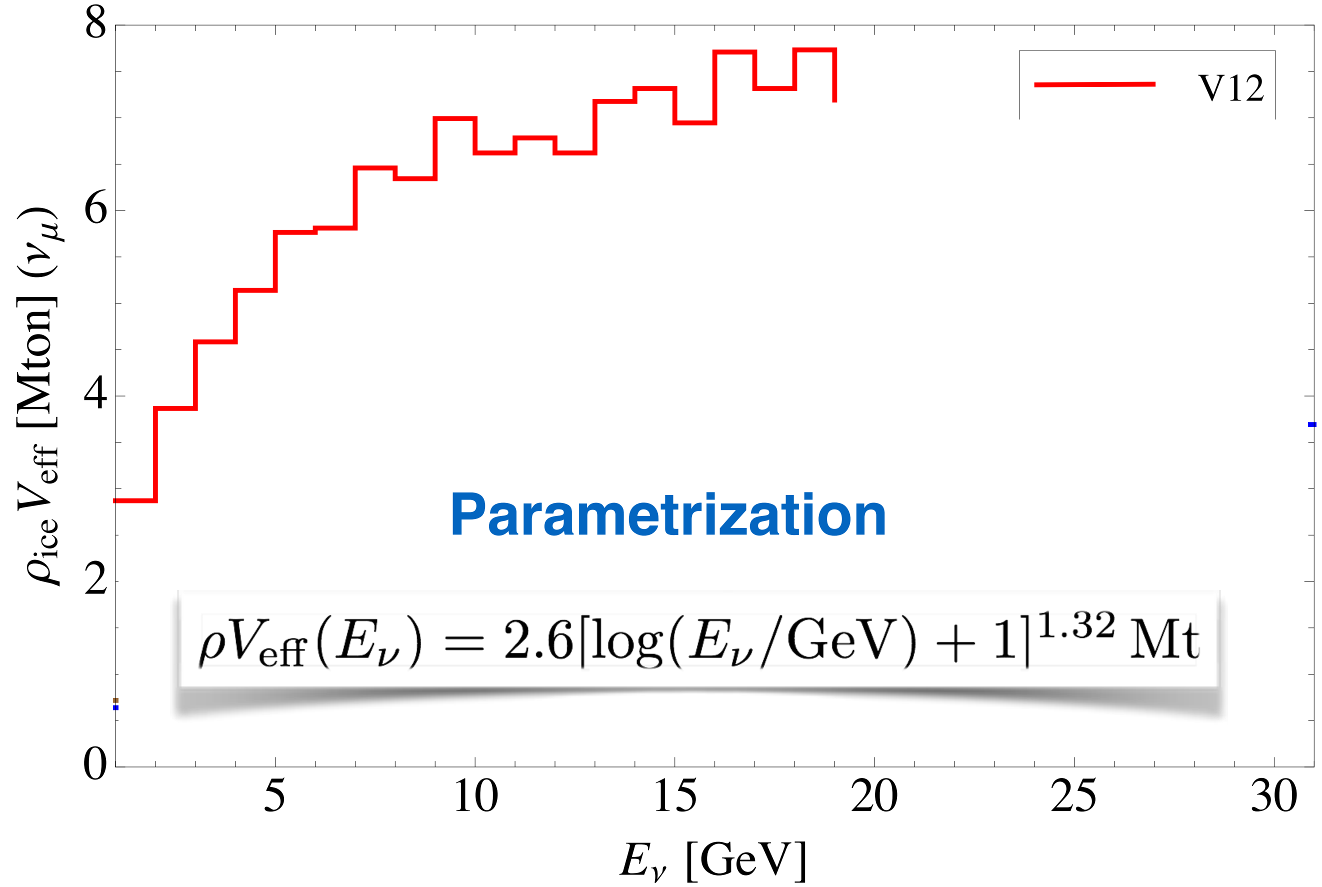
Figure: A. Karle



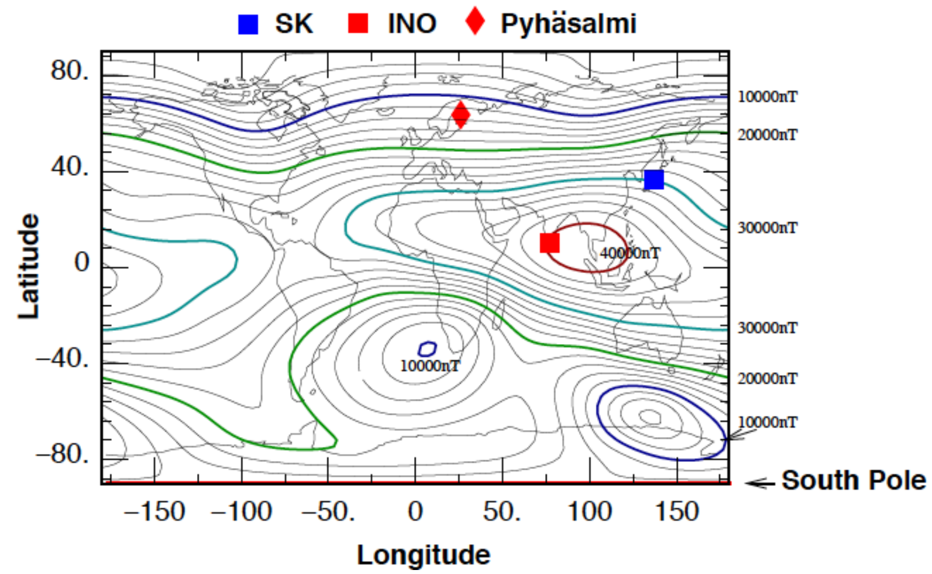
Super-PINGU / Super-ORCA

Preliminary sensitivity studies

- **Goals:**
  - Identification of the relevant CP signatures and uncertainties
  - Estimation of rough significance
- **Use some realistic detector characteristics:**
  - Energy-dependence of the effective mass
  - Angular and energy resolutions, systematic uncertainties

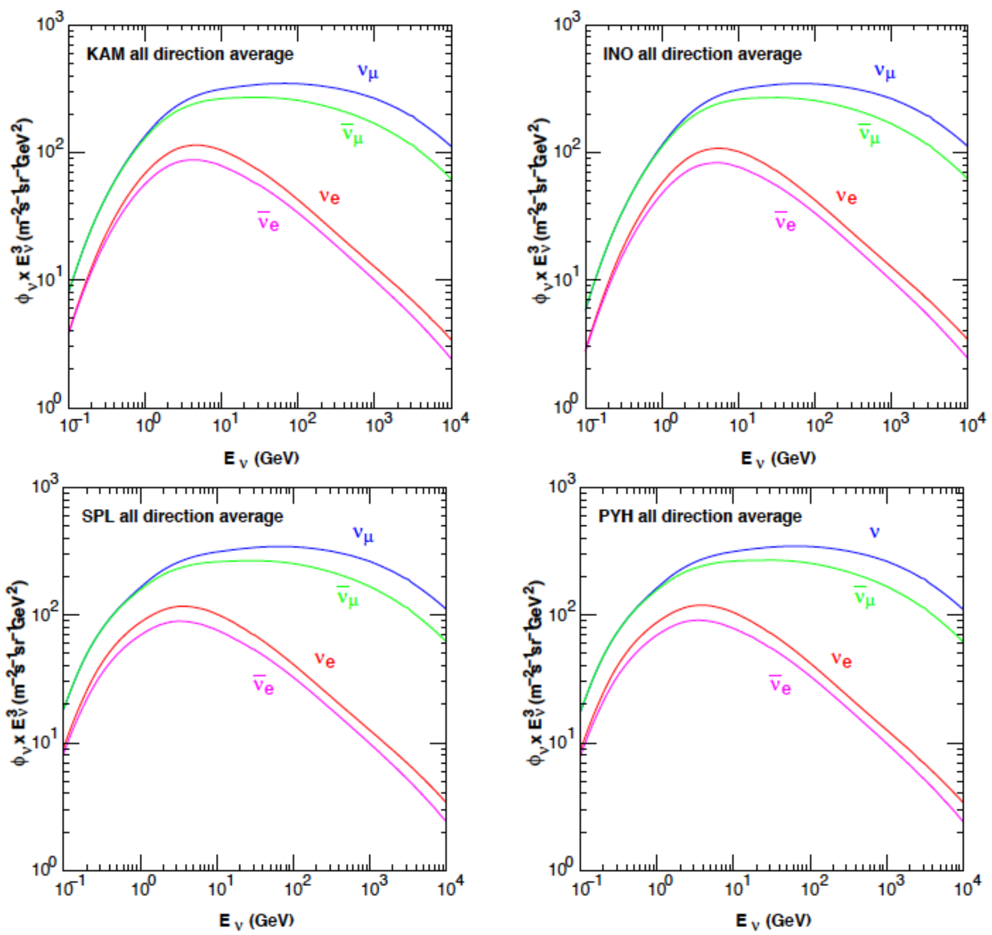


Atmospheric Fluxes

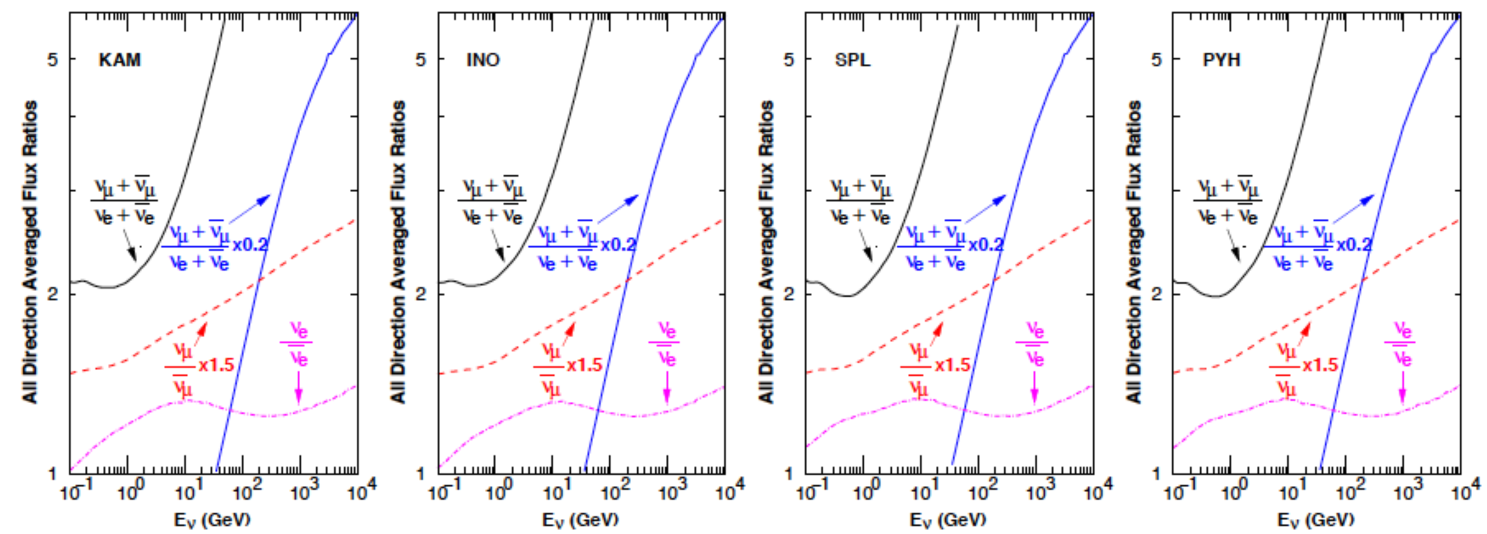


Honda, Athar, Kajita, Kasahara and Midorikawa 2015

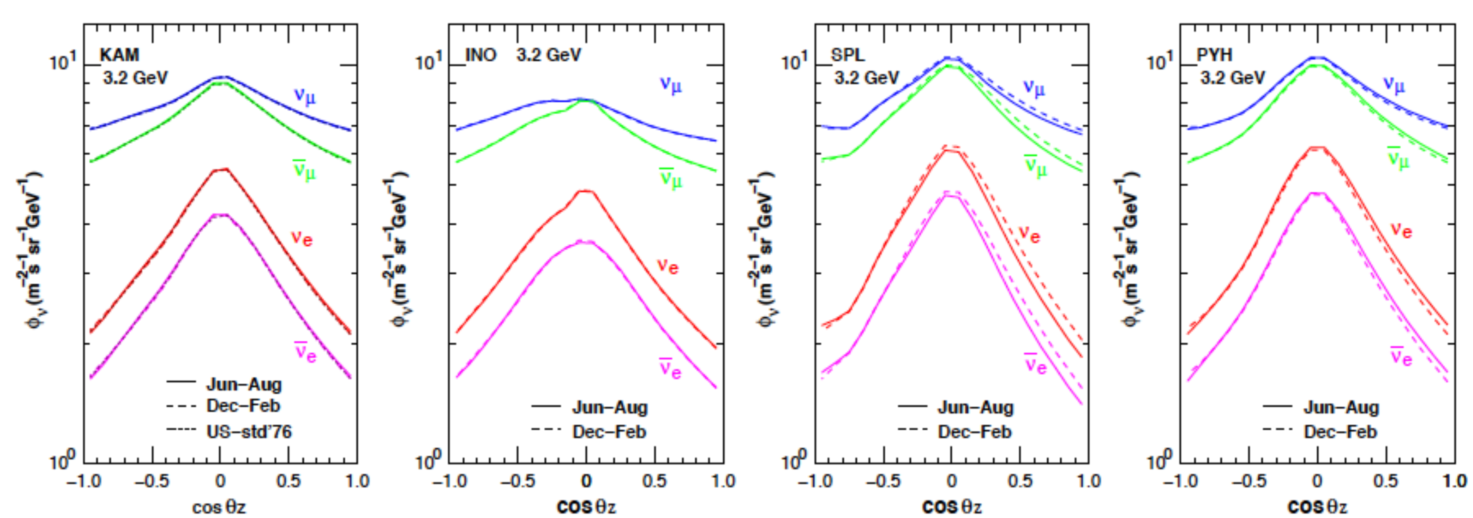
Averaged Flux from all directions



Flavor ratios



Zenith dependence



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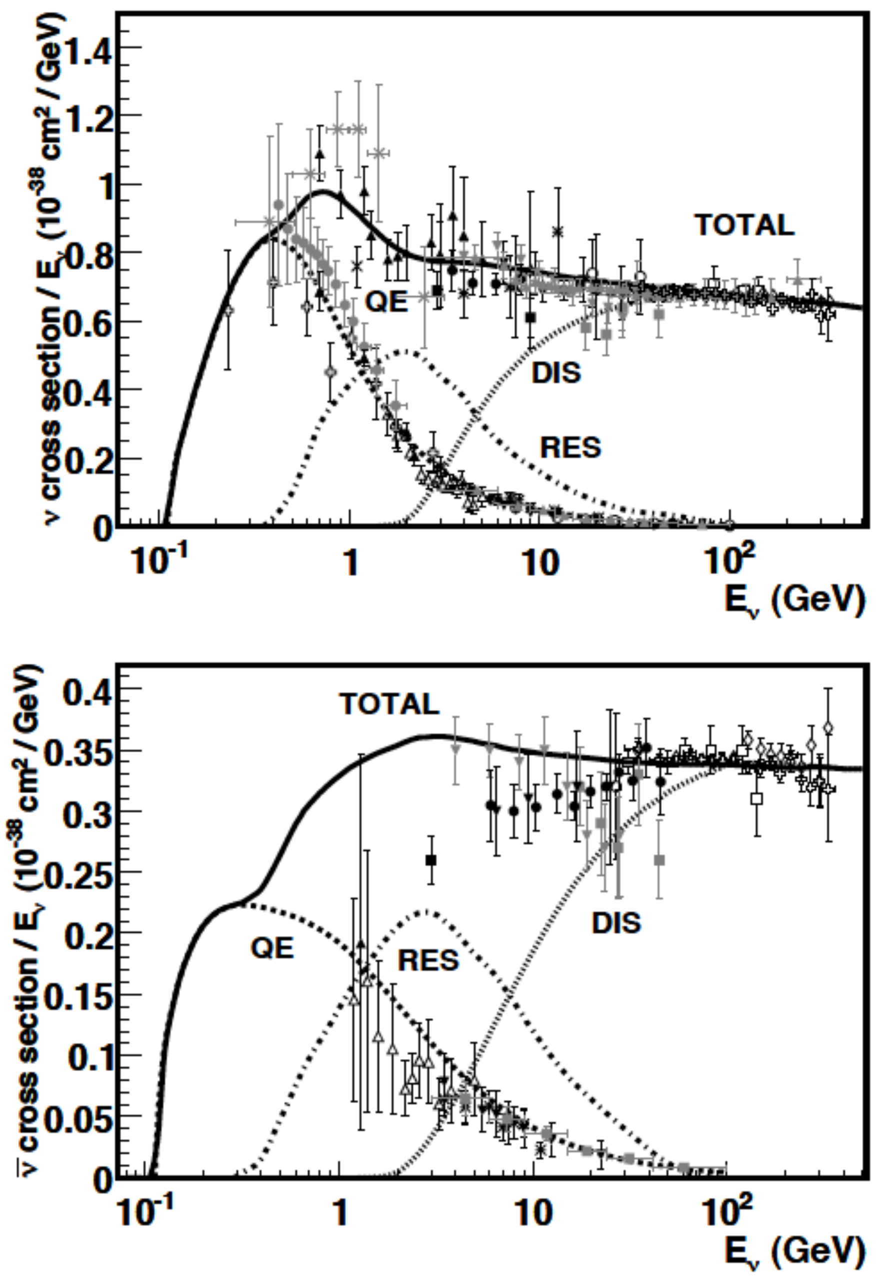
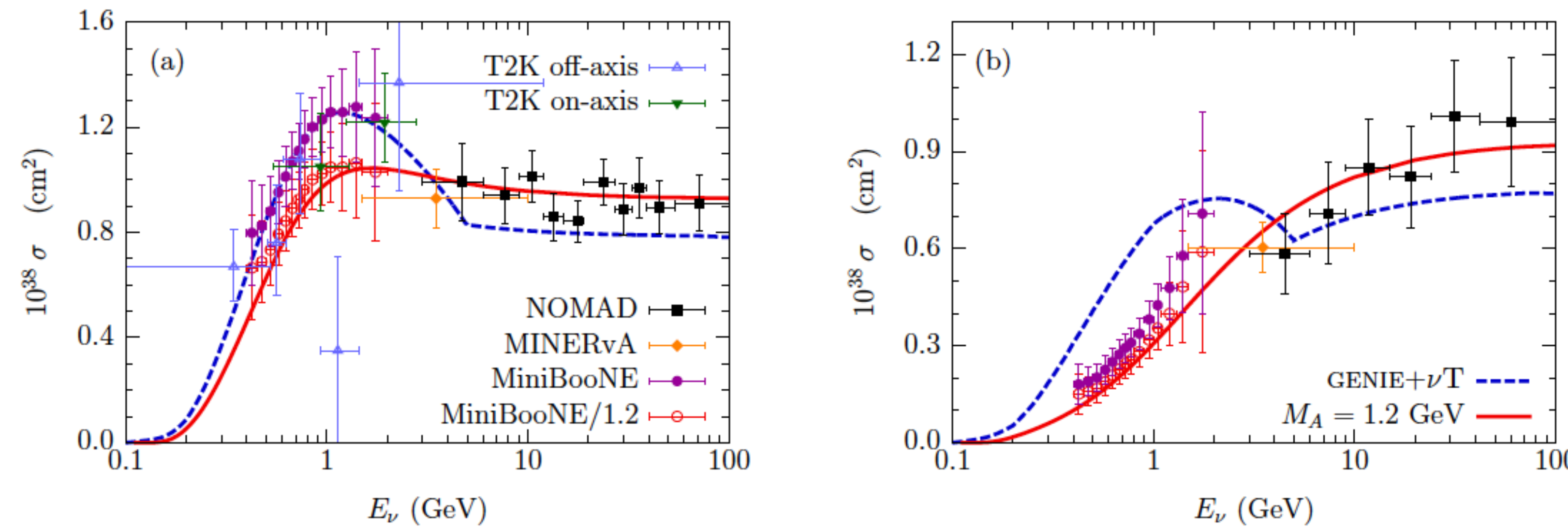
Cross sections

Formaggio and Zeller 2013

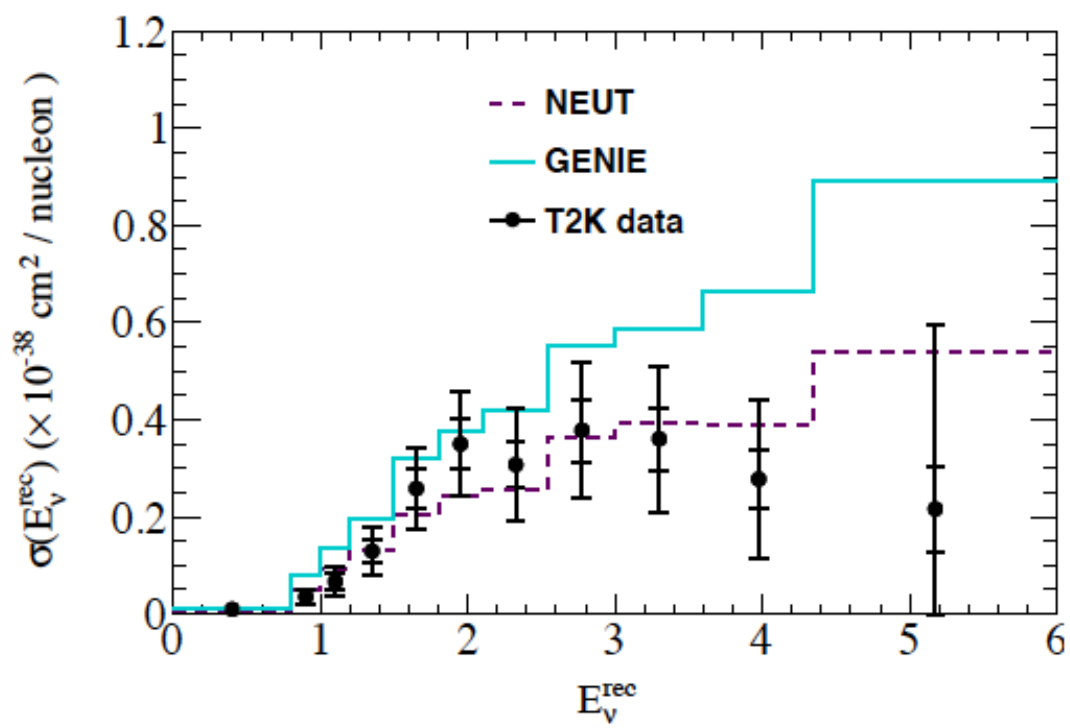
Total



Ankowski et al. 2016 **CC QE**



Abe et al. 2016 **single pion**



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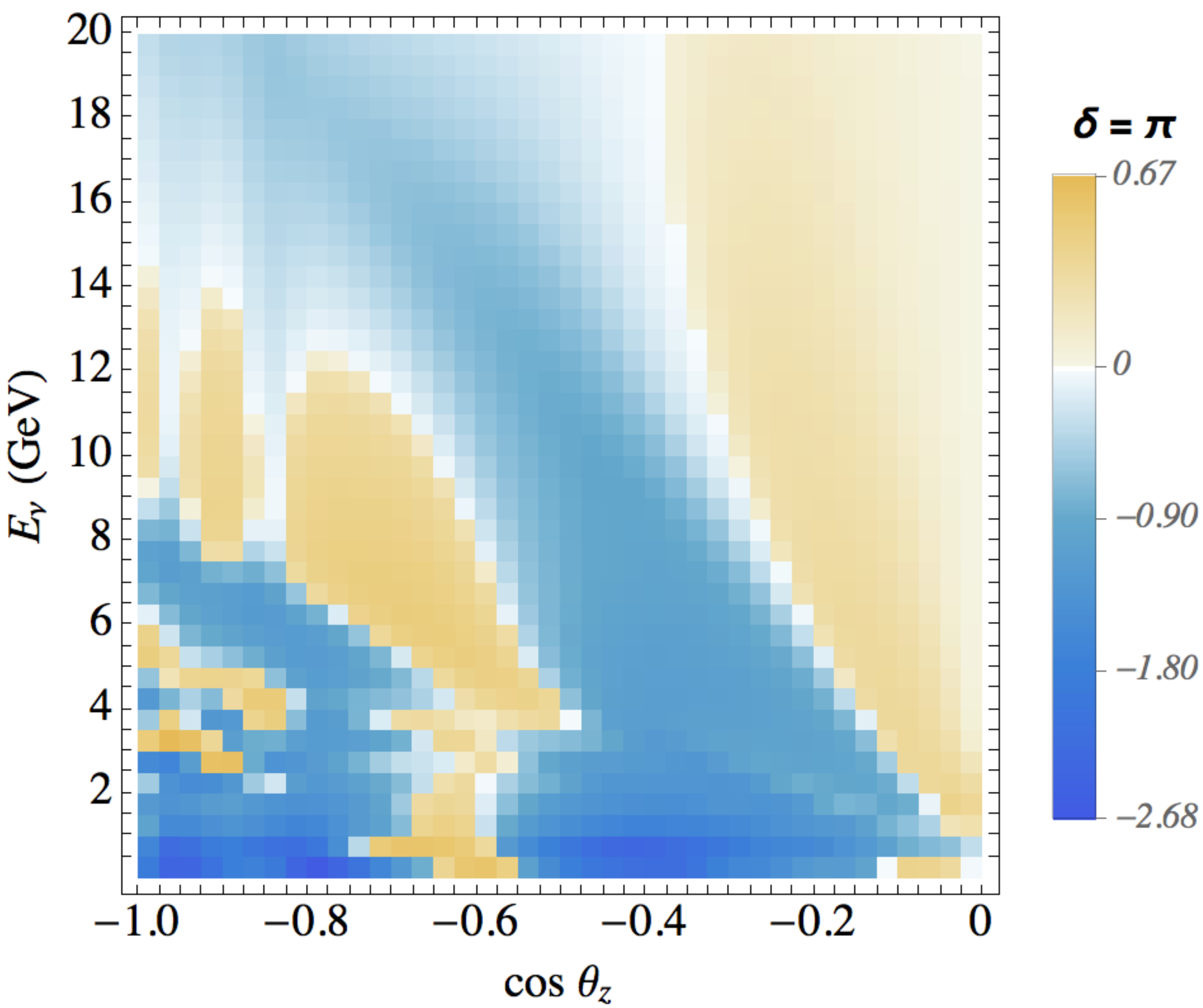
Distinguishability of the CP phase

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

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



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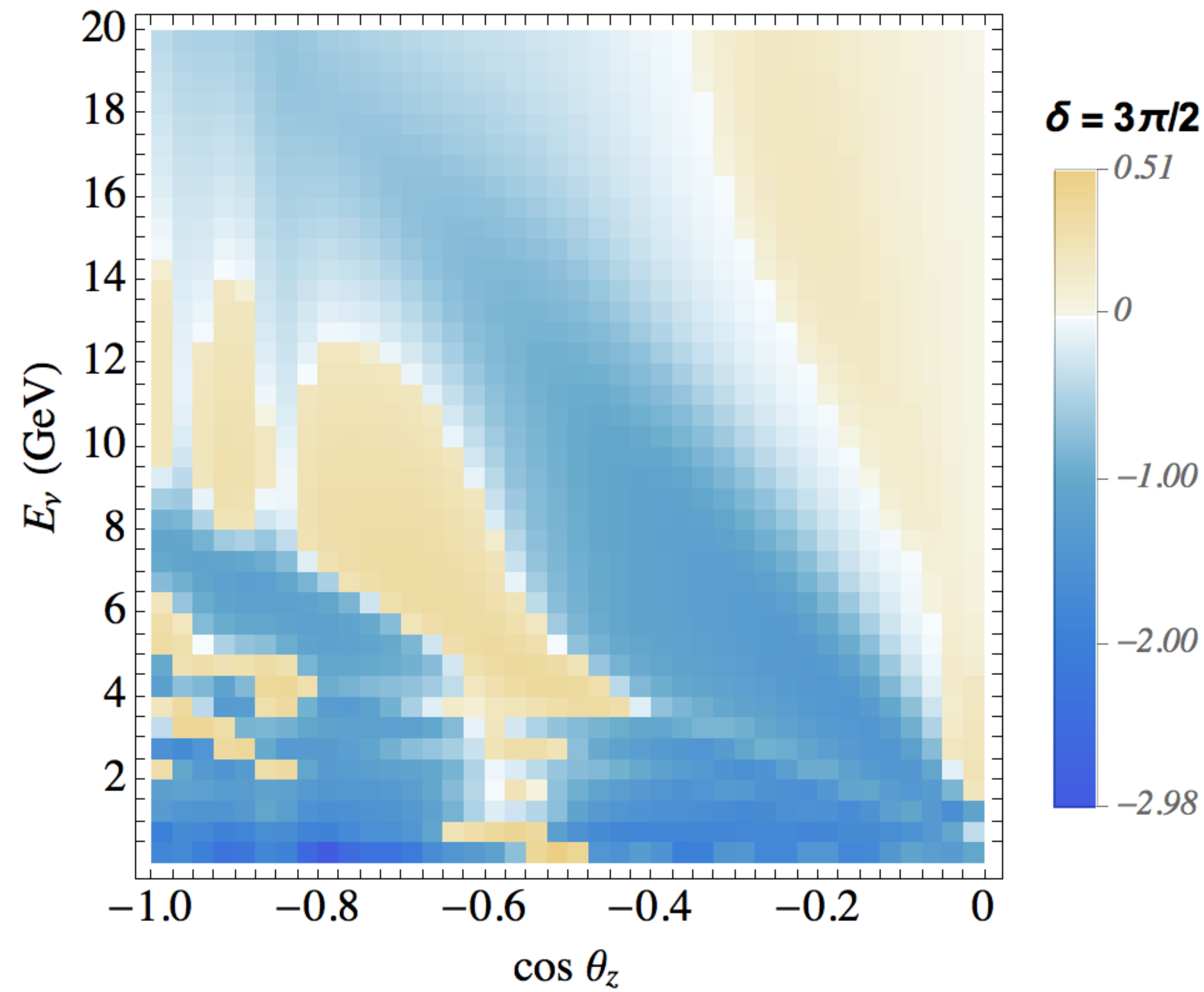

S.R., Smirnov 2015

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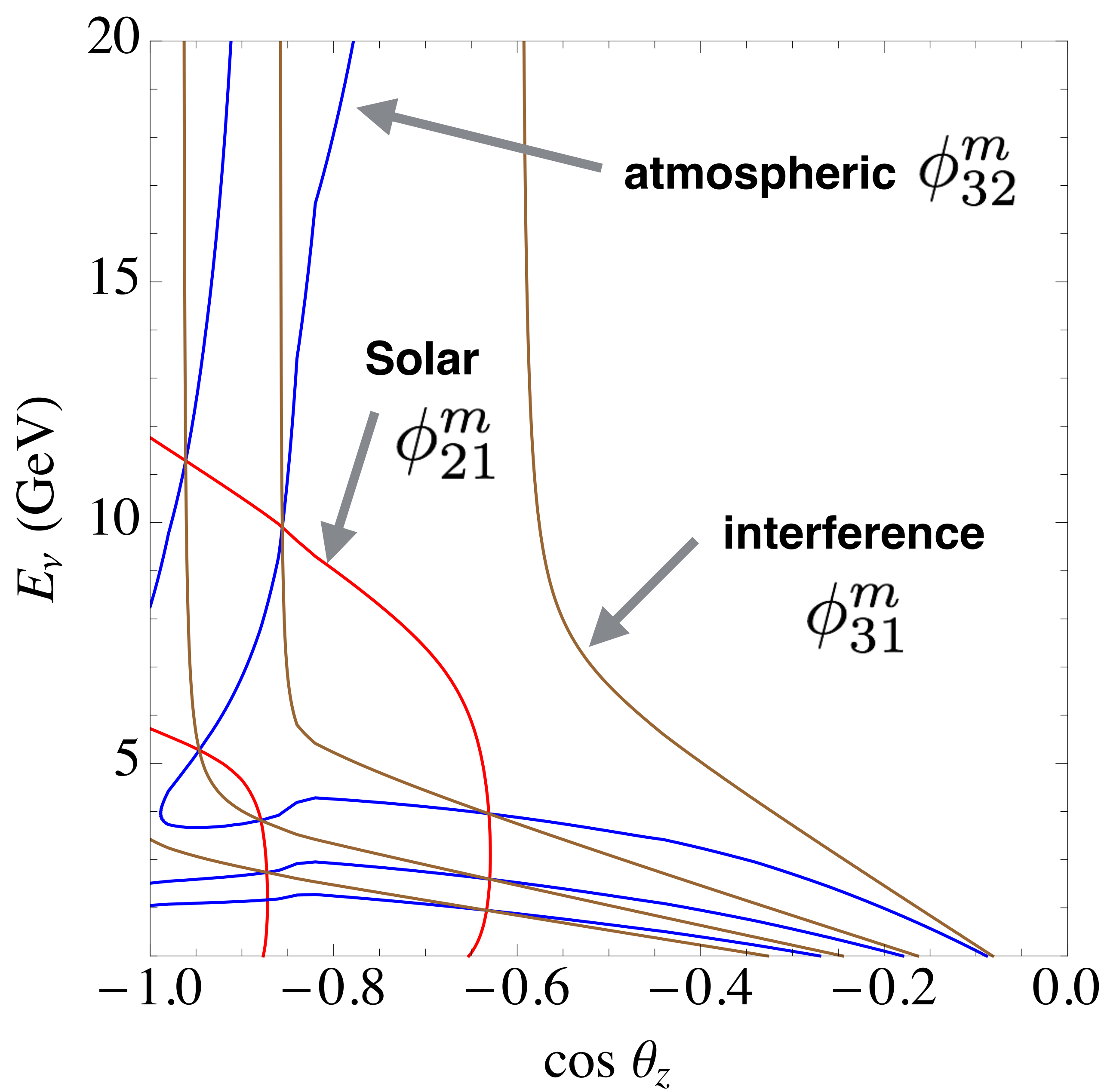
CP-asymmetric Domains

Determined by the solar, atmospheric and interference magic lines



Probability is roughly independent of CP along the magic lines

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

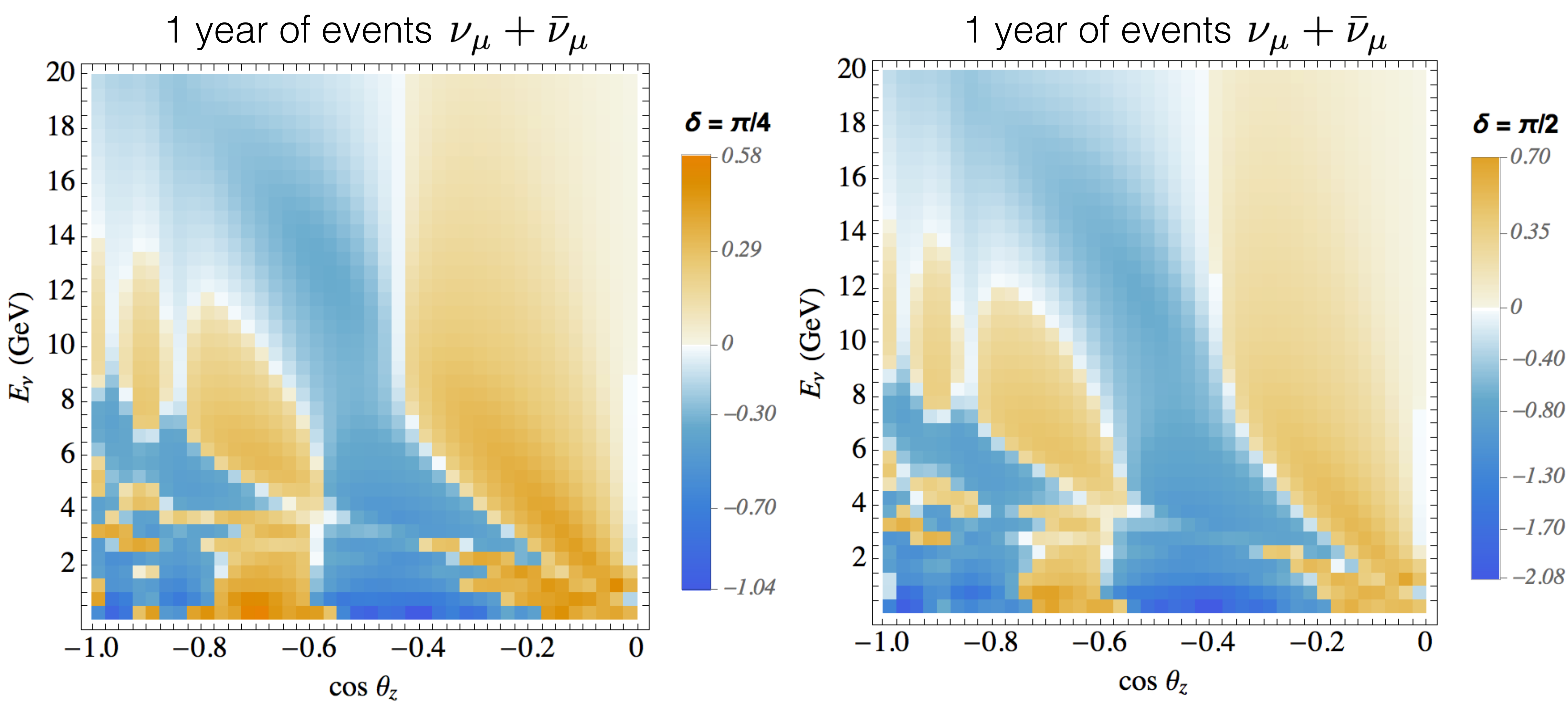
proportional to the oscillation phases for corresponding mass-splitting-square

Using average density profile

Distinguishability in Muon Channels

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**



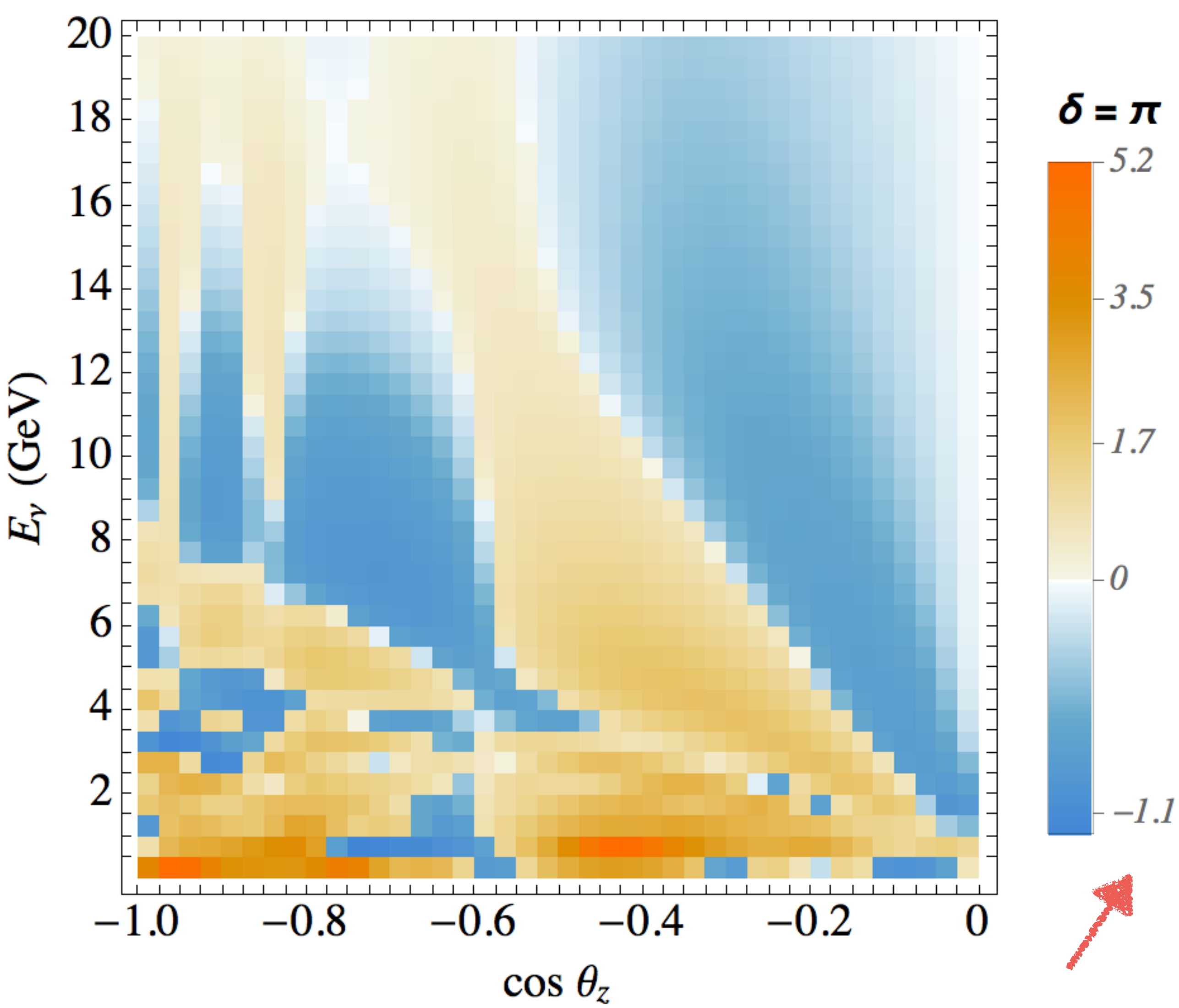
S.R., Smirnov 2015

Distinguishability in Electron Channels

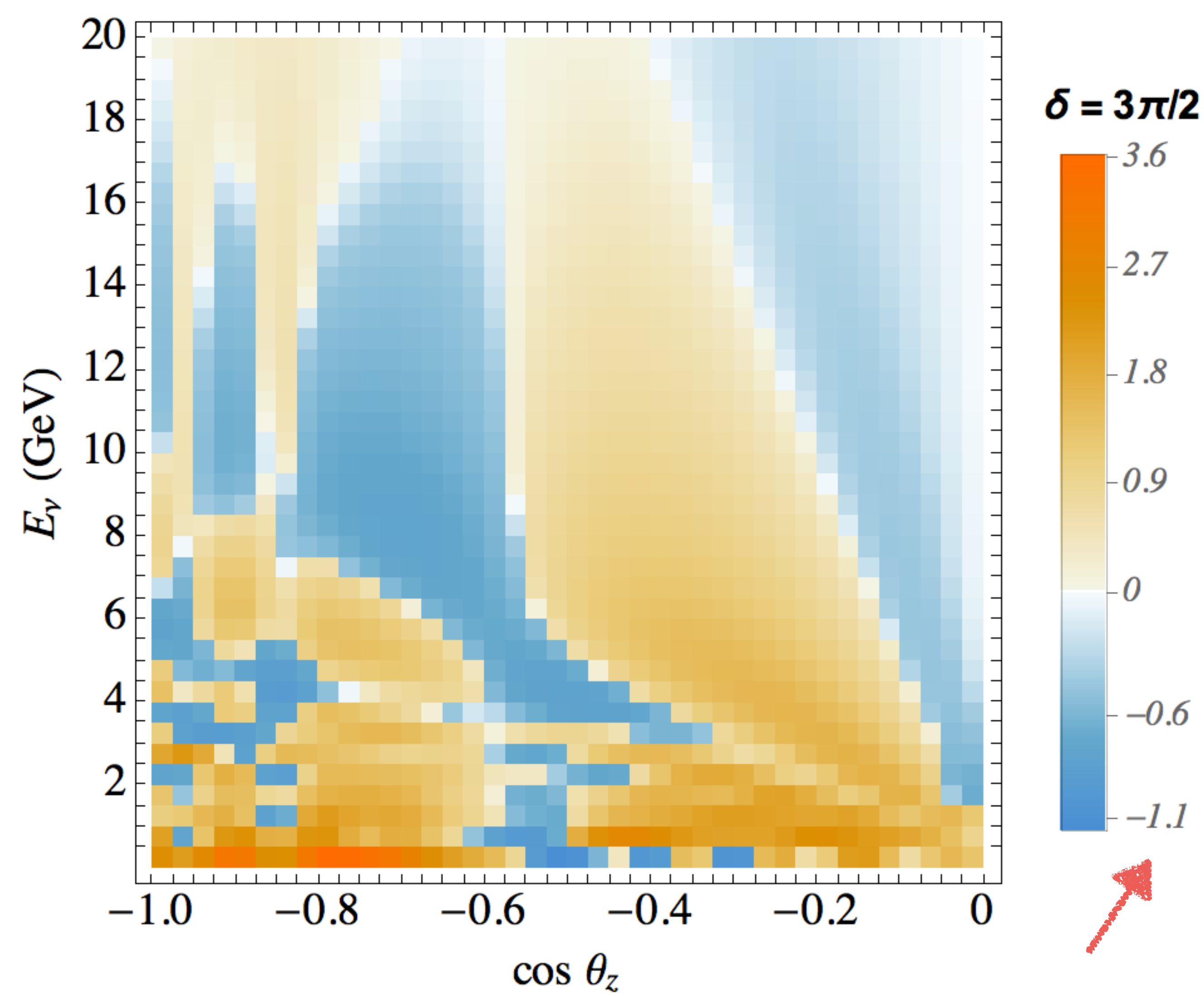
Electron (ν_e) channel gives sharper distinguishability

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

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



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

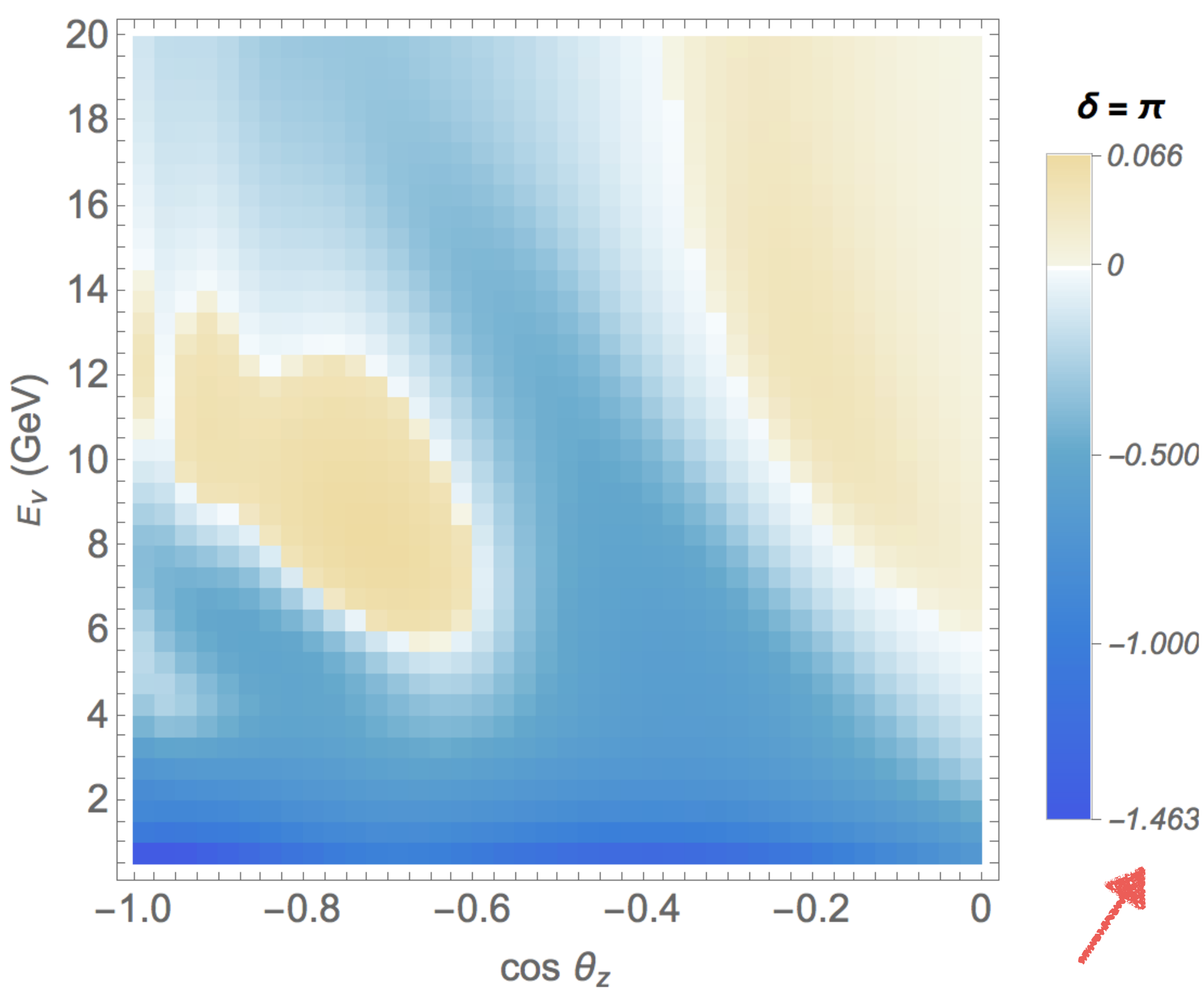


S.R., Smirnov 2015

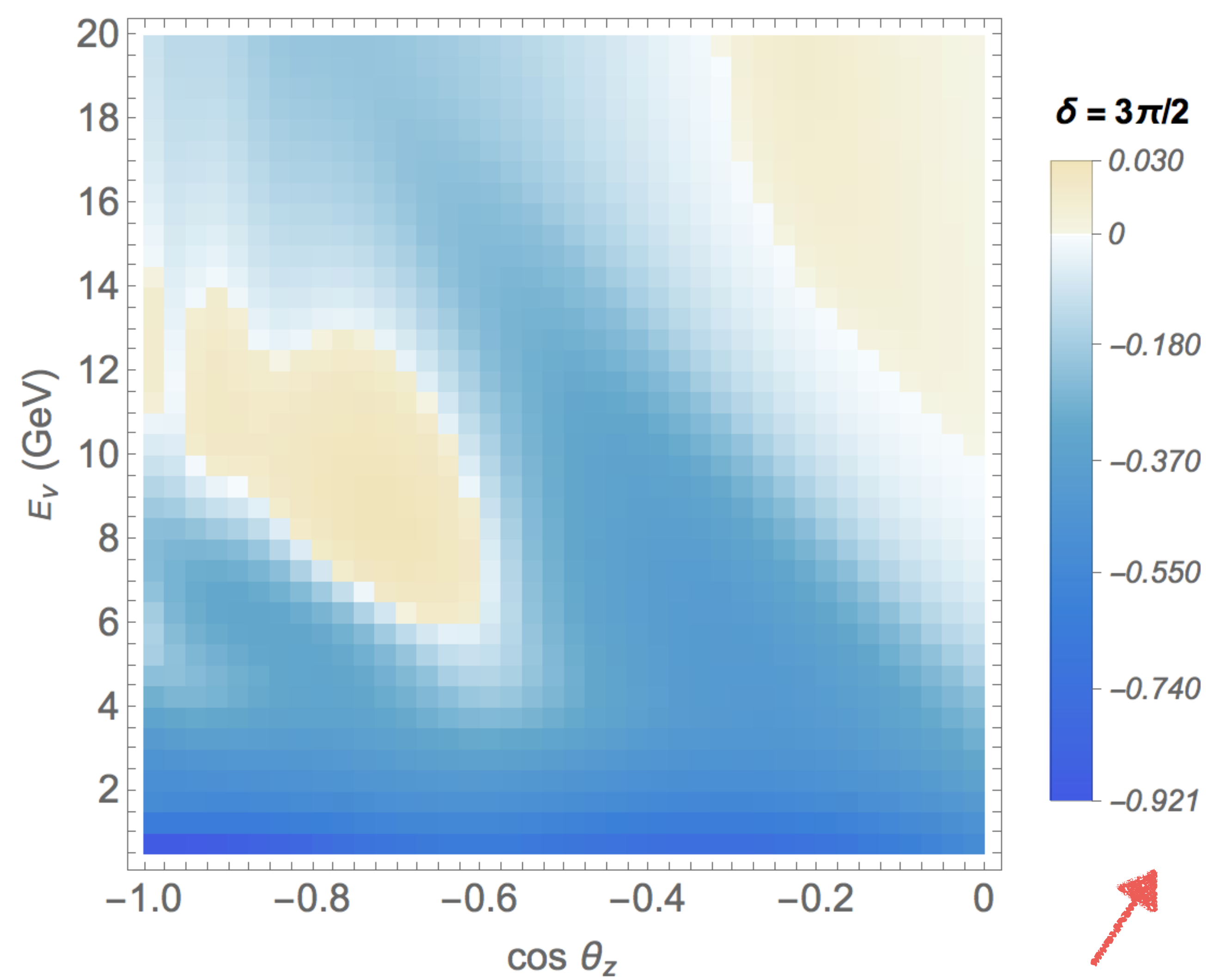
Smeared with Energy and Angular Resolutions

- 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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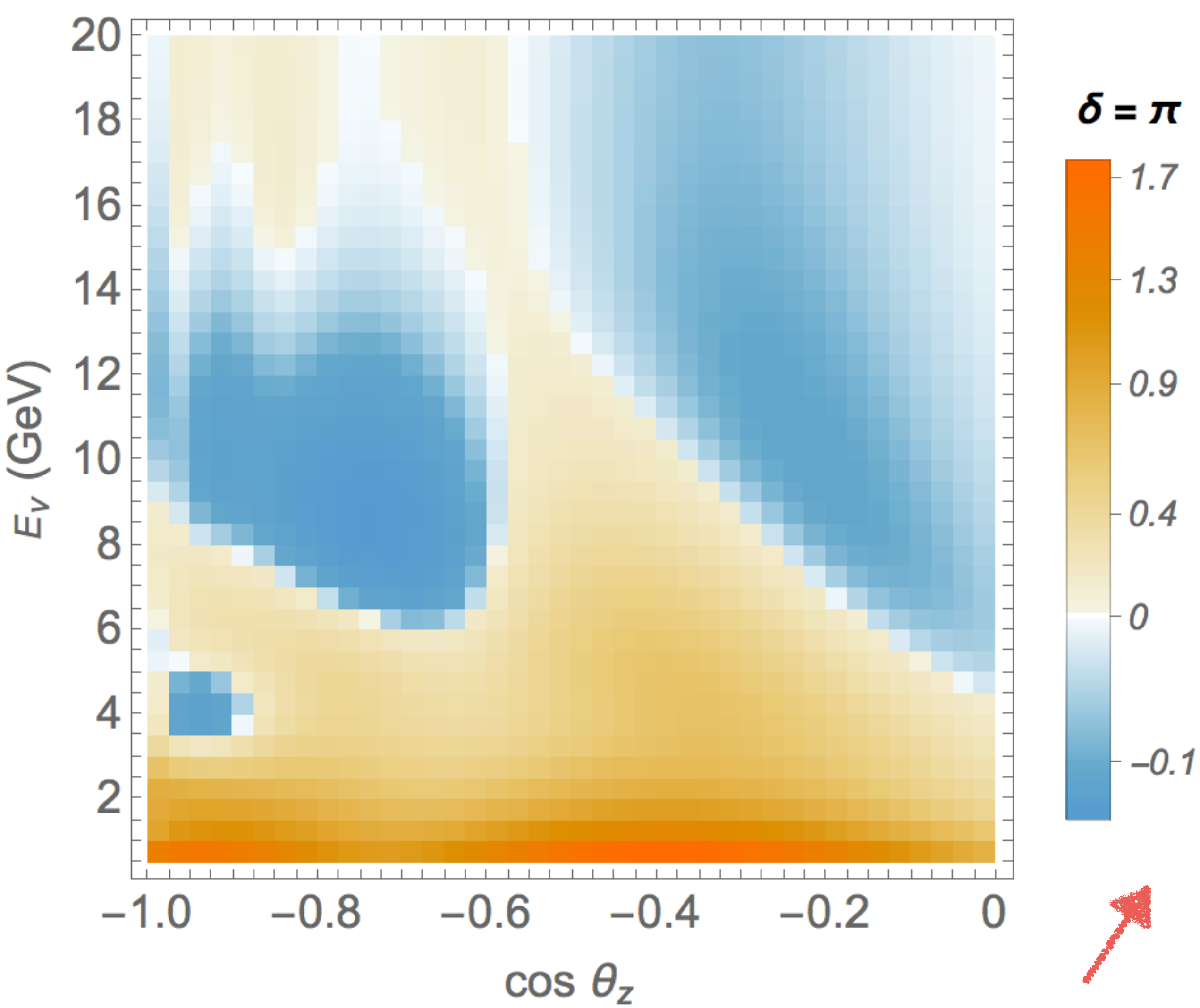
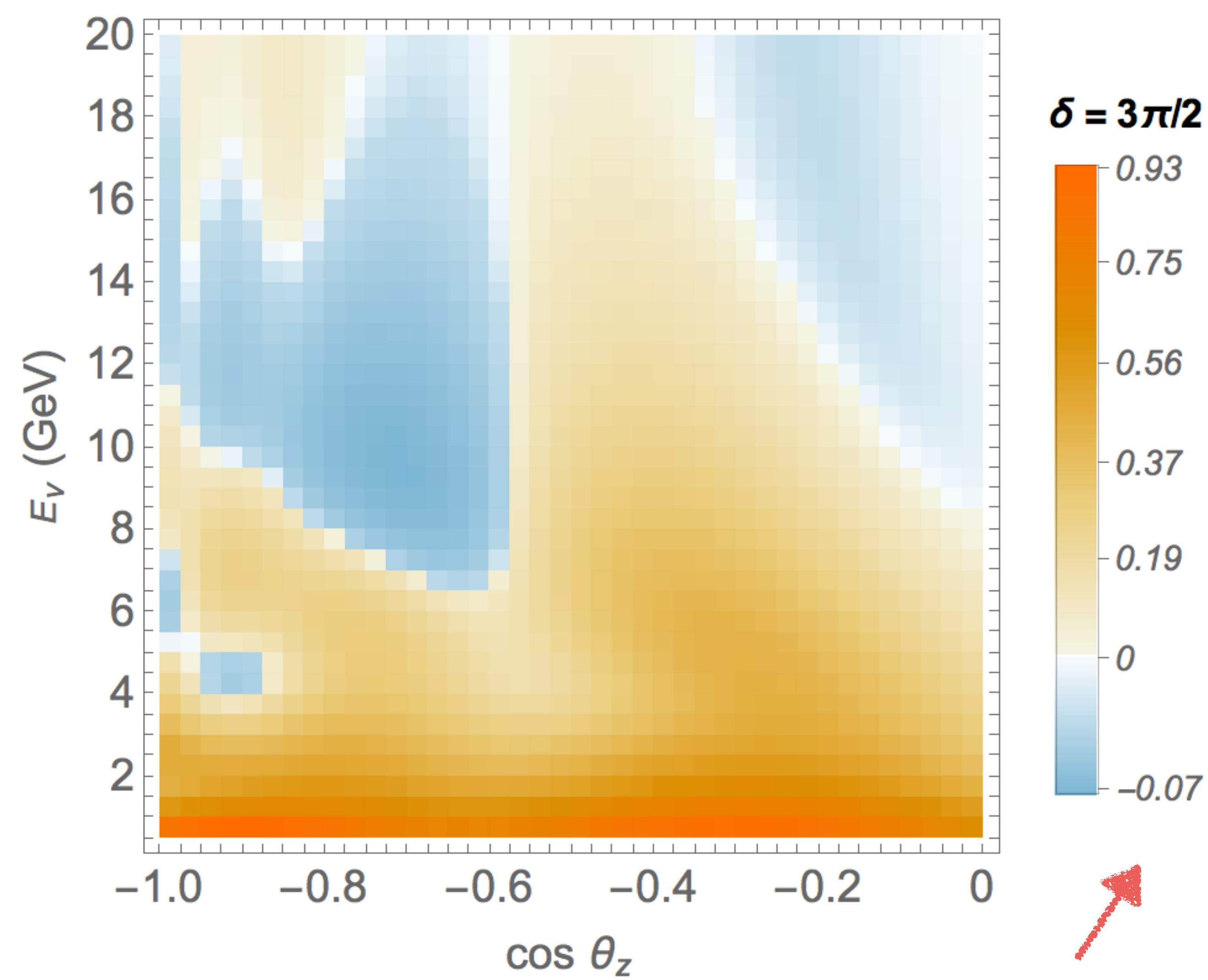


1 year of events $\nu_e + \bar{\nu}_e$



S.R., Smirnov 2015

Correlated systematic uncertainties

- Flux times cross-section normalization: 10% (σ_α)
- Flux tilt factor (spectral index): 0.1 (σ_η)
- Muon to electron neutrino 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

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

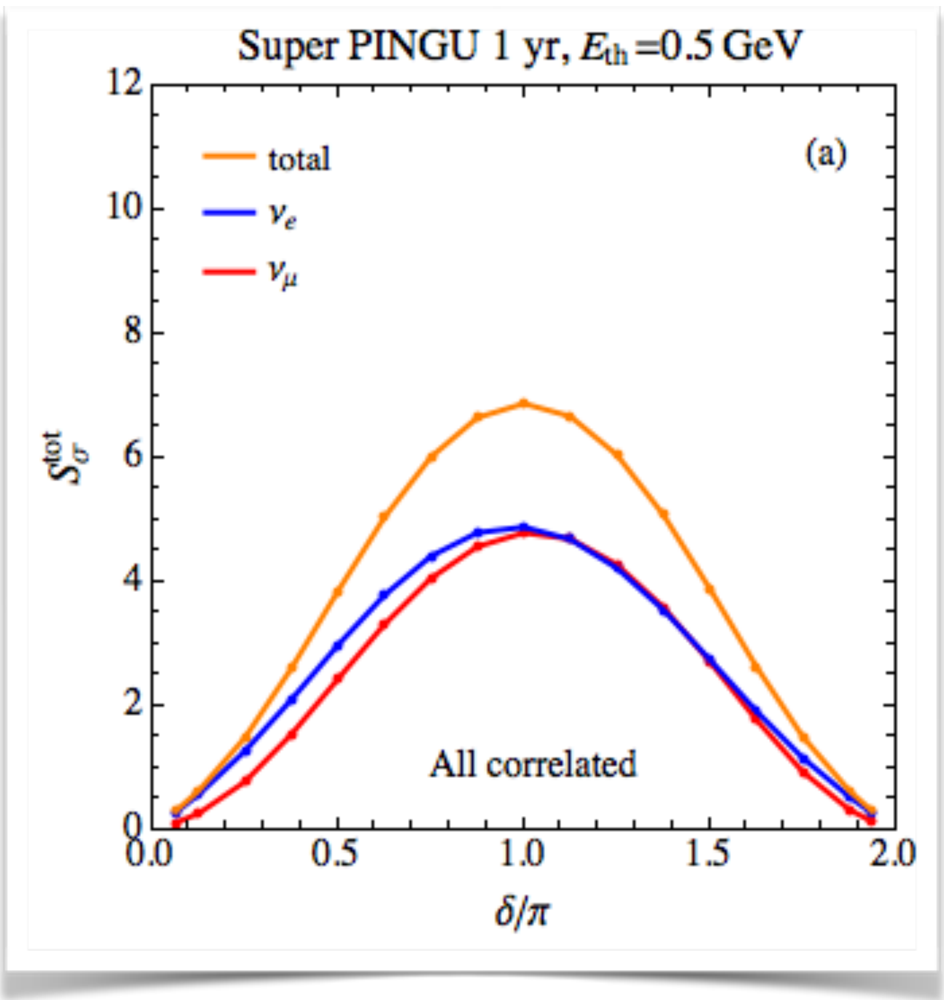
pull variables: $\xi_k \equiv (\alpha, \beta, \eta, z_l)$ standard values: $\xi^{st}_k \equiv (1, 0, 0, 1)$

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

Minimize with respect to the pull variables

Estimated Sensitivity to CP

All correlated (4) and 2.5% additional uncorrelated uncertainties



Assumed true CP = 0

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

4 year sensitivity - Super-PINGU/ORCA

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

Lower values are for 20% misidentification

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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 < 0.5-1 GeV 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 can measure CP with competitive significance**
    - **Crude, first estimates with Super-PINGU/ORCA**
- 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 -** Expect improvements with dedicated simulations

Back up slides

Estimated Sensitivity to CP

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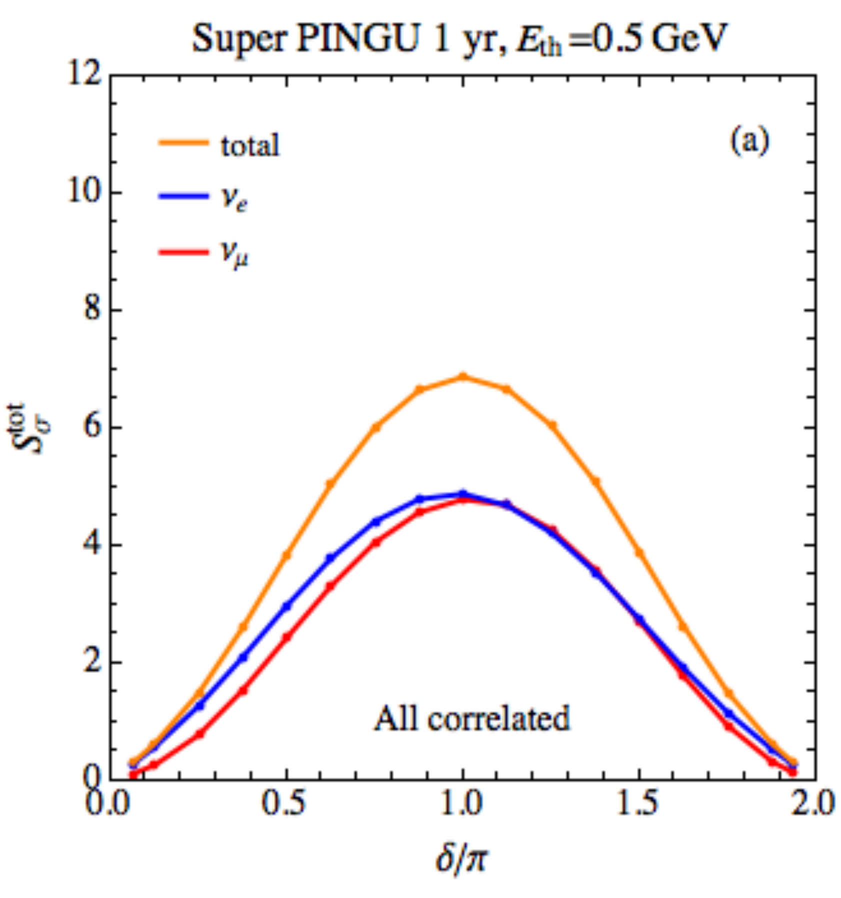
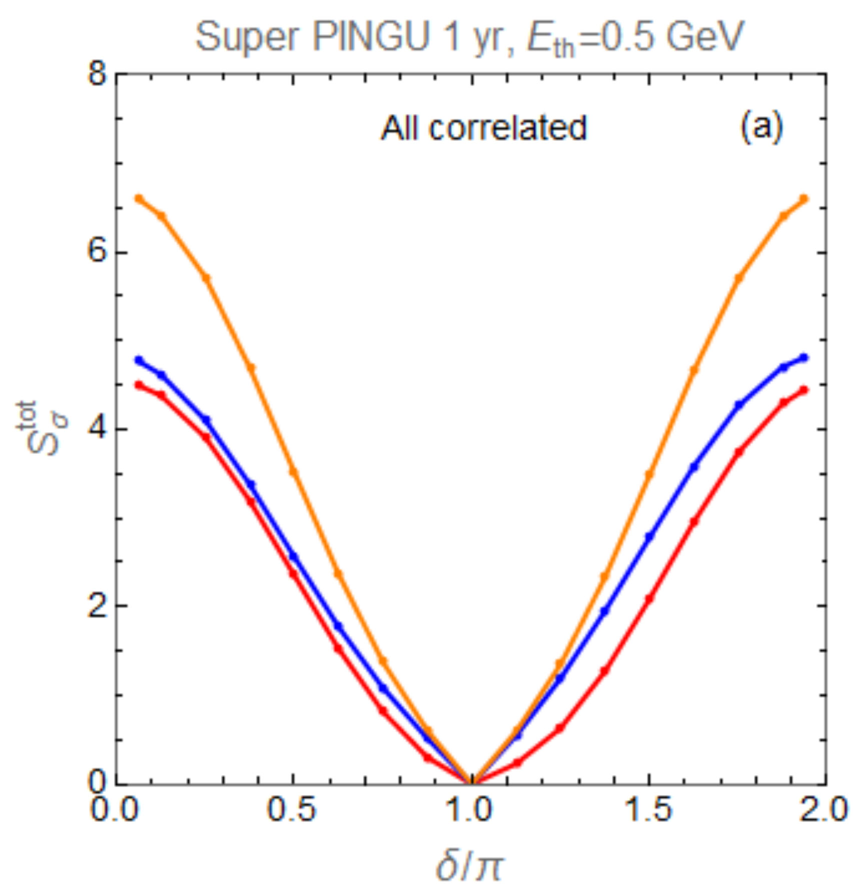
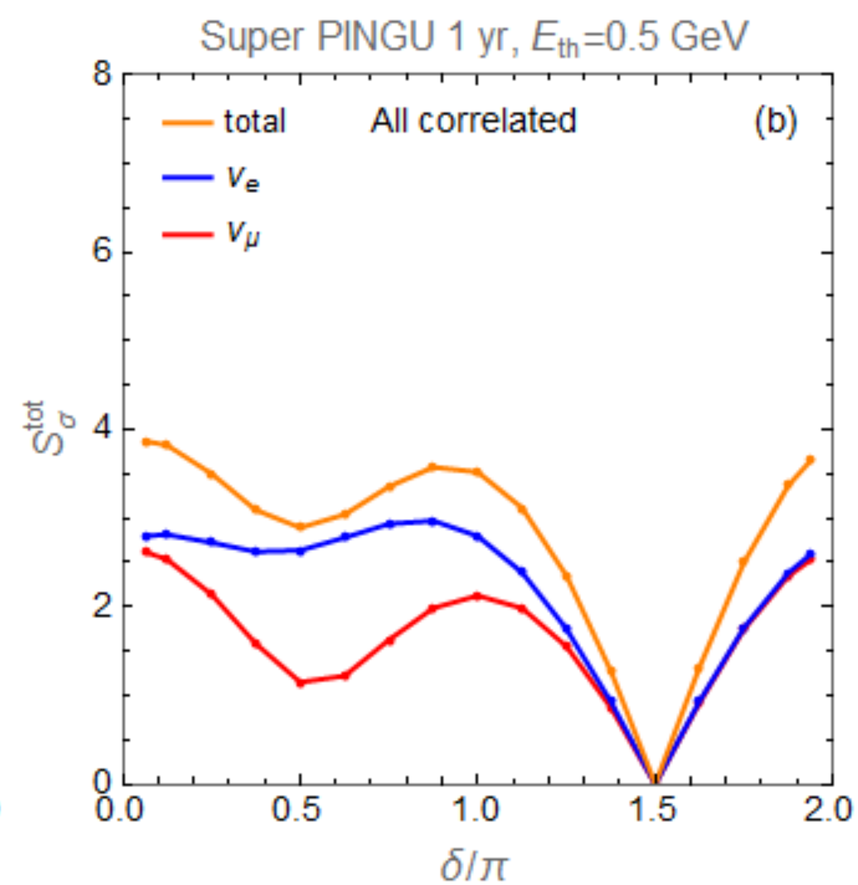


True CP = 0



True CP = pi



True CP = 3pi/2

Oscillation Parameters

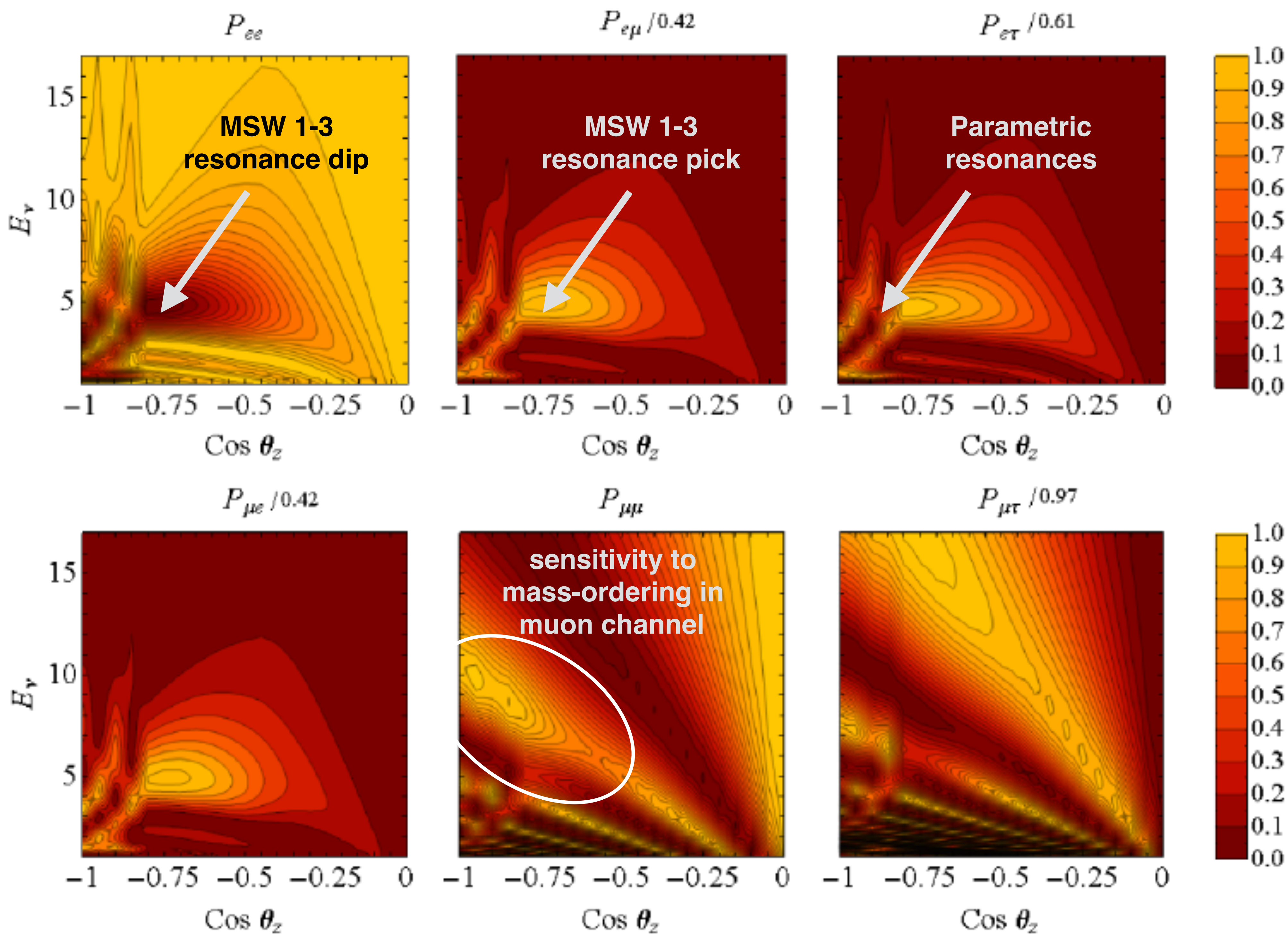
TABLE I. Results of the global 3ν oscillation analysis, in terms of best-fit values and allowed 1, 2 and 3σ ranges for the 3ν mass-mixing parameters. We remind that Δm^2 is defined herein as $m_3^2 - (m_1^2 + m_2^2)/2$, with $+\Delta m^2$ for NH and $-\Delta m^2$ for IH.

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 ⊕ 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]

Neutrino Oscillograms of the Earth

Equal probability contours in the energy-zenith angle plane **PREM**

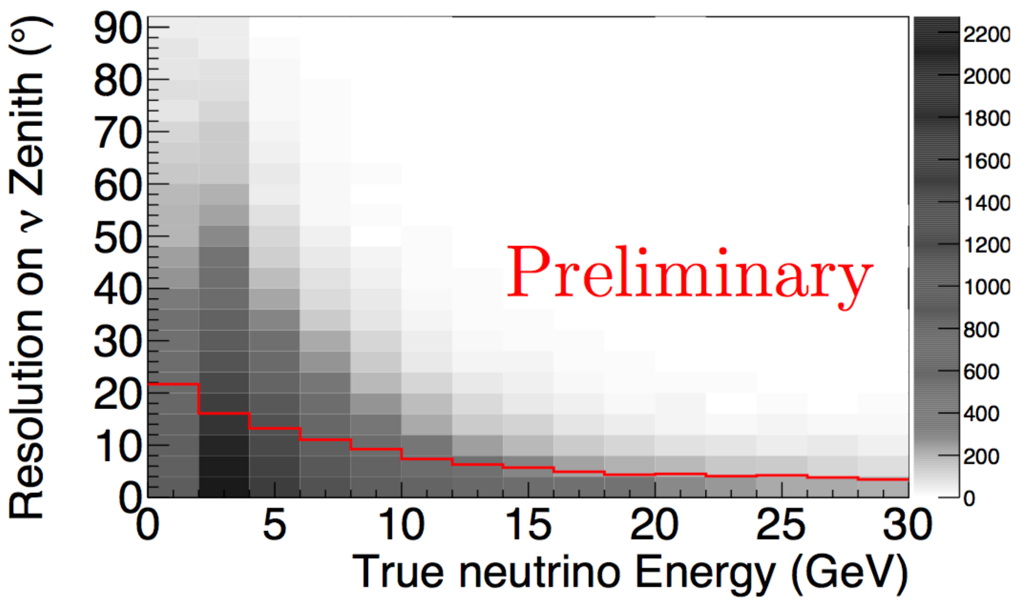


Akhmedov, S.R., Smirnov 2013

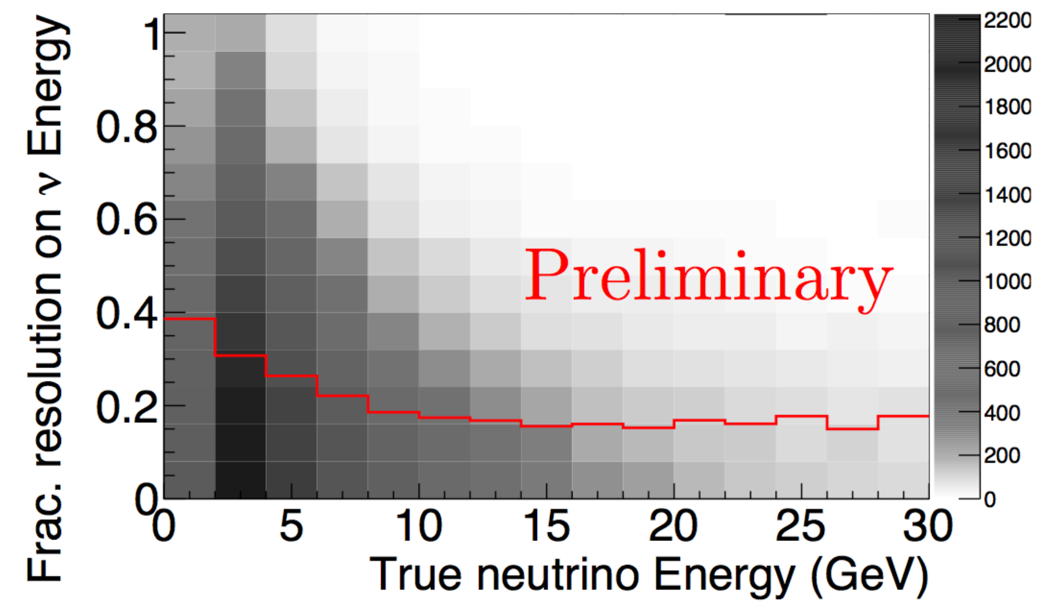
Energy, angular resolutions

PINGU Letter of Intention, arXiv:1401.2046

ν_μ

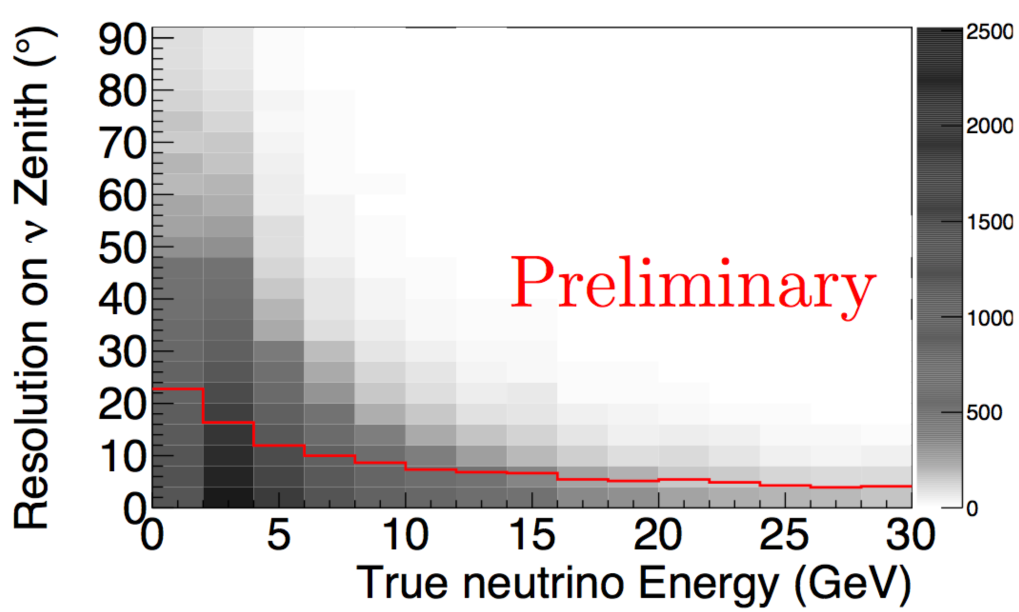


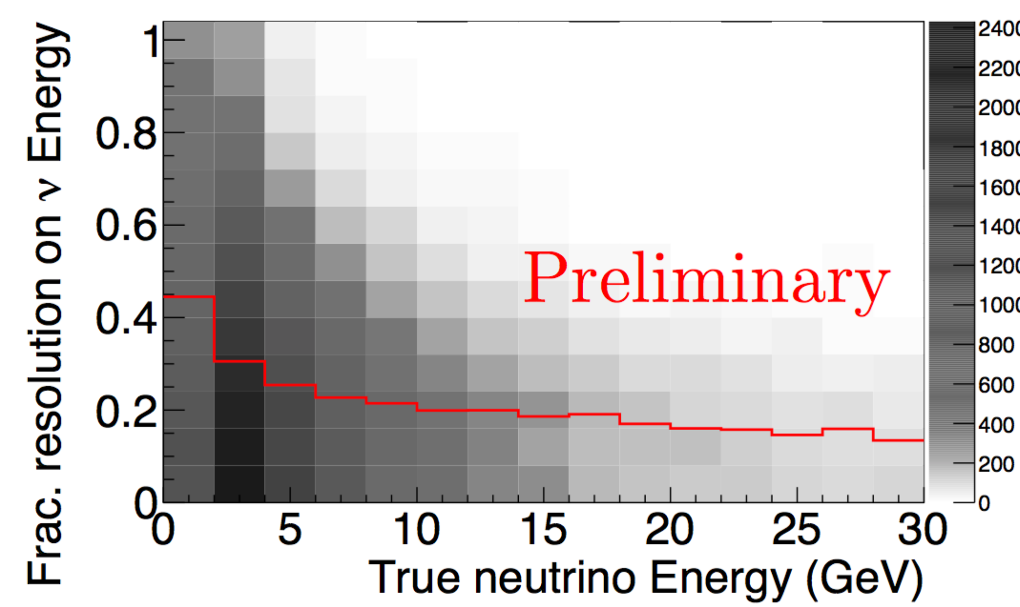
(b) $|\theta_{\nu,\mathrm{true}} - \theta_{\nu,\mathrm{reco}}|$ vs. $E_{\nu,\mathrm{true}}$.



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

ν_e





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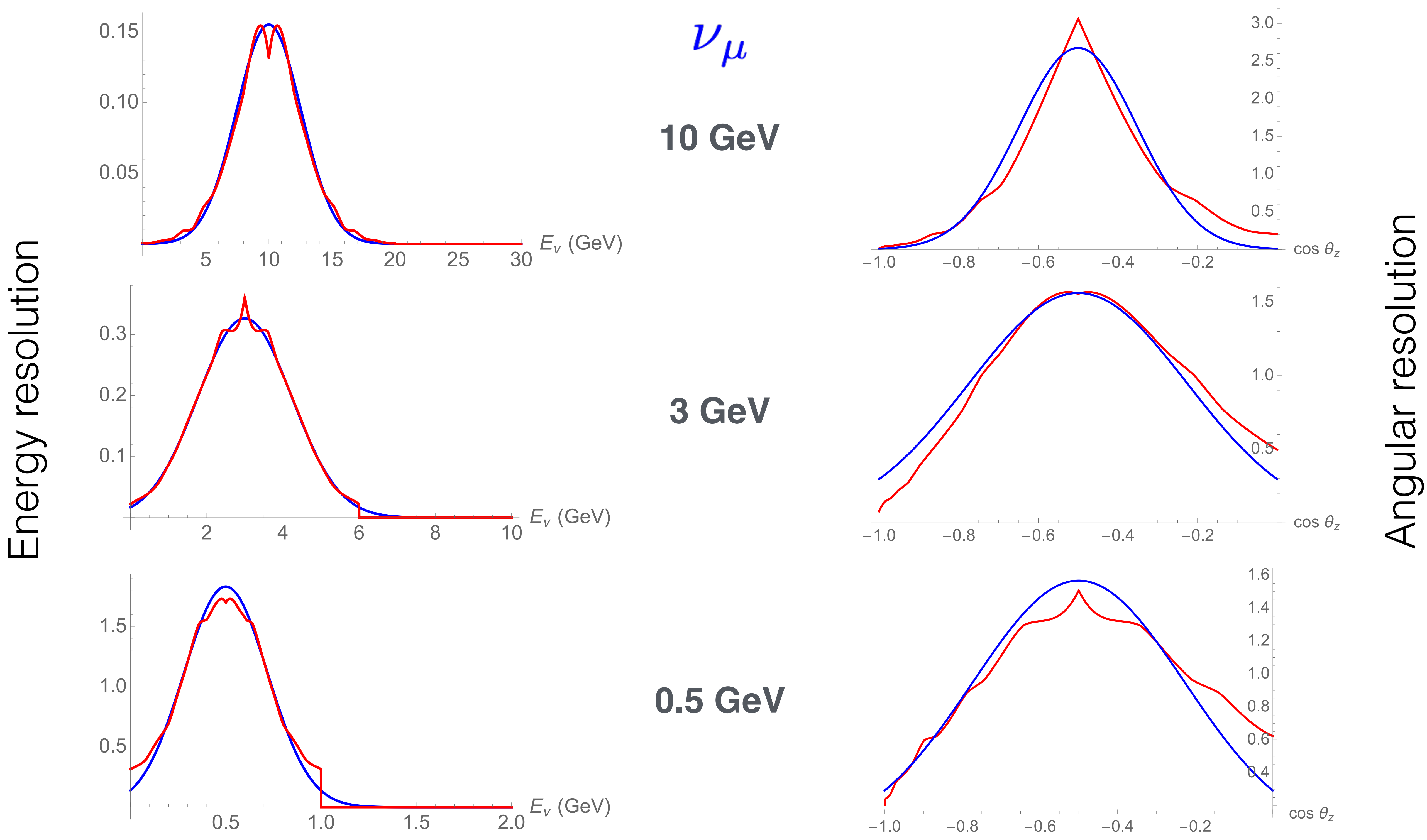
Energy, angular resolutions

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



Energy and angular resolutions

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

Width of the Gaussian reconstruction functions scales as

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

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

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

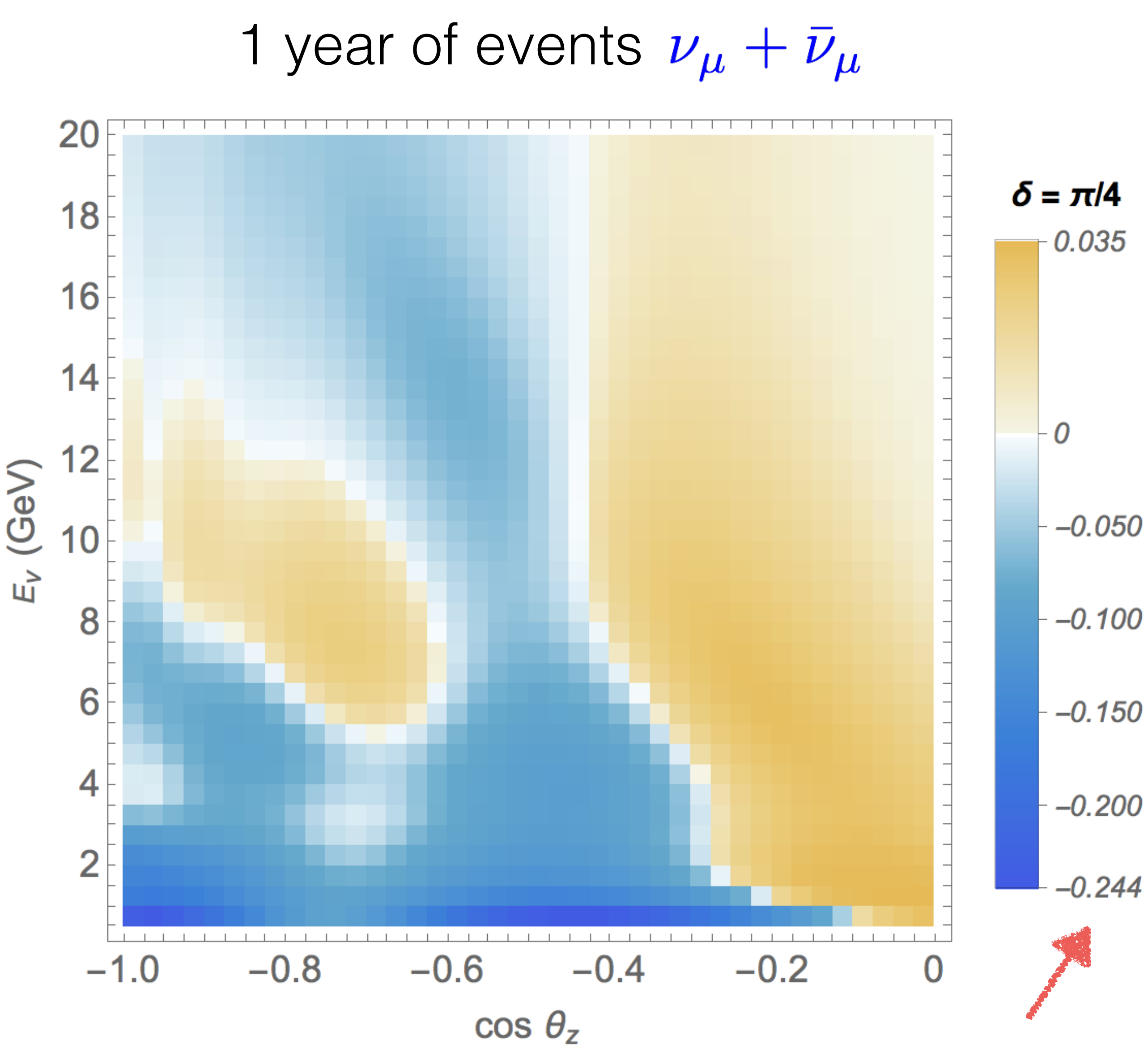
Darren Grant in NEUTRINO 2014

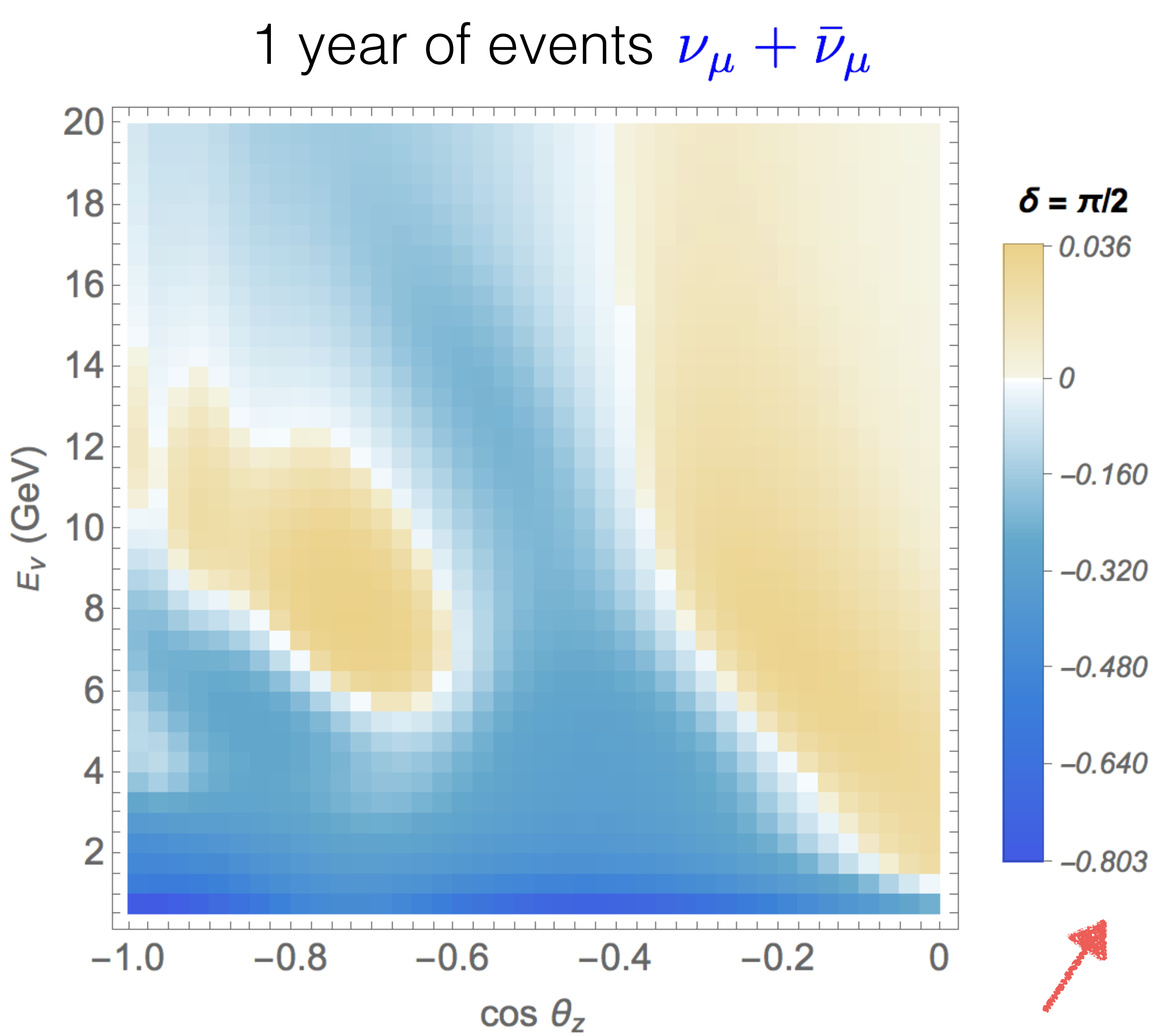
PINGU and Super-PINGU $N_{\rm DOM}^{\rm Super-PINGU}/N_{\rm DOM}^{\rm PINGU} = 3$

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

Smeared with Energy and Angular Resolutions

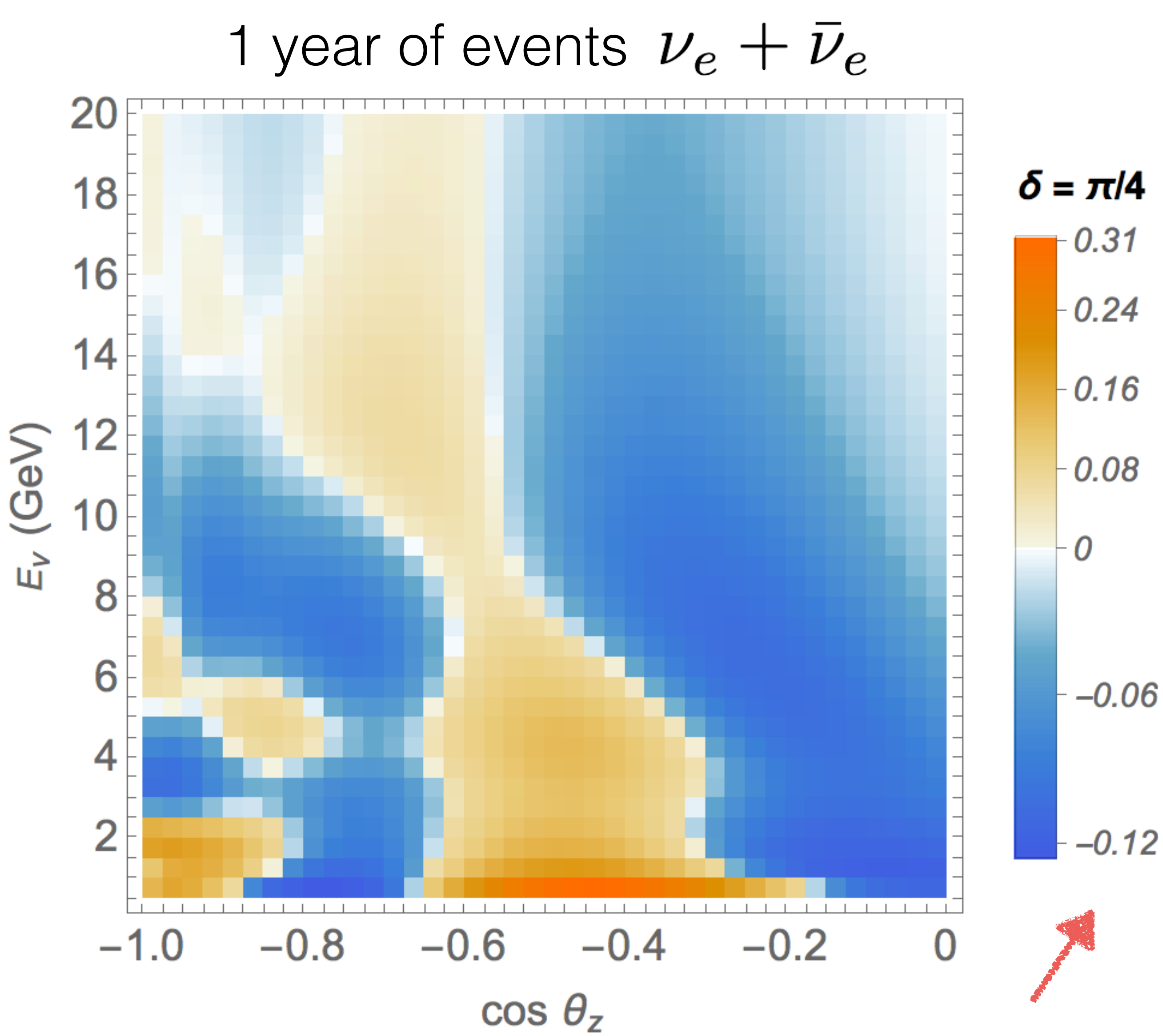
- Substantial reduction of CP distinguishability - merging of small regions
- Systematic broadening of negative CP asymmetric region
- Large zenith angle range of same sign distinguishability at low energies

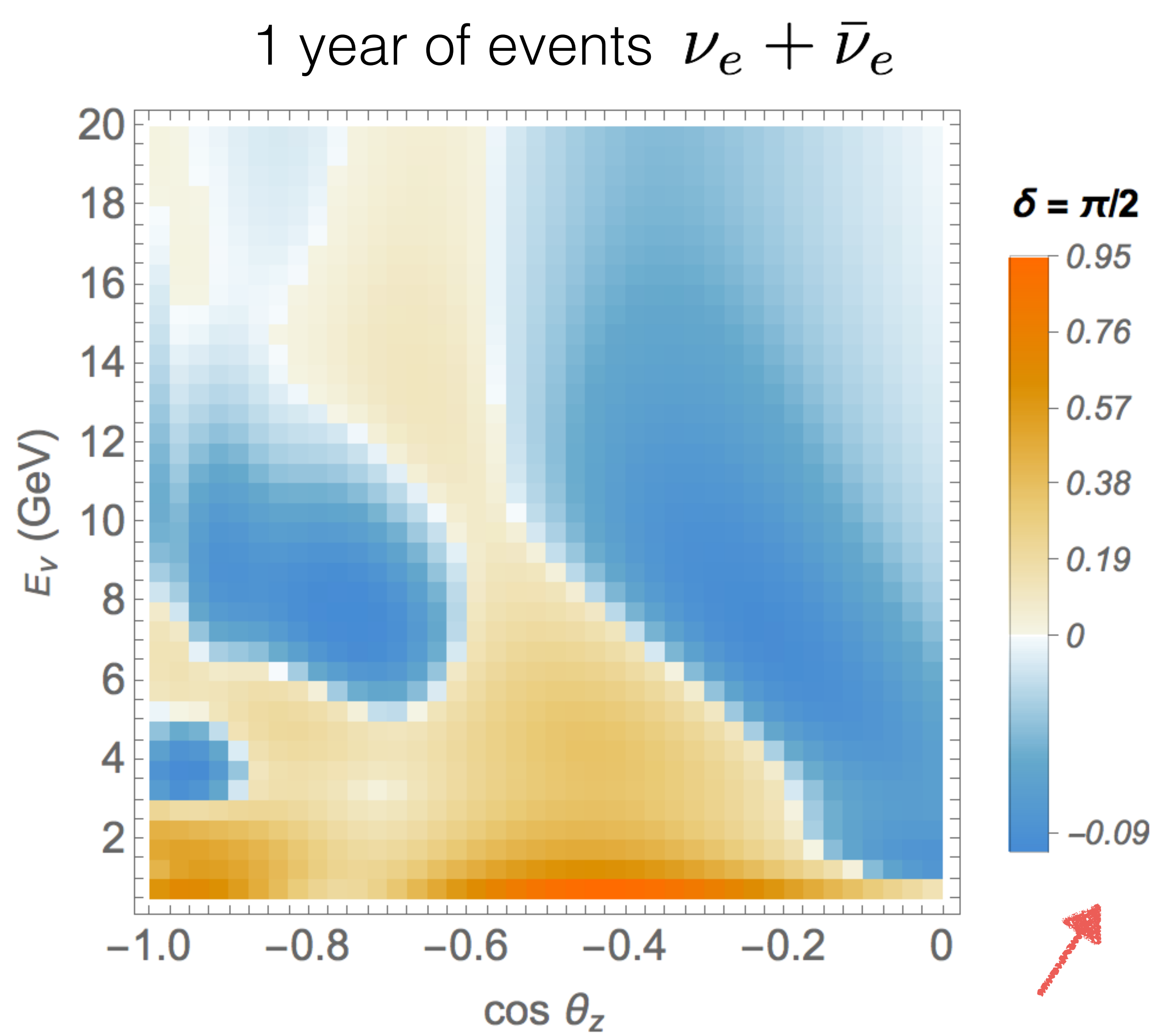




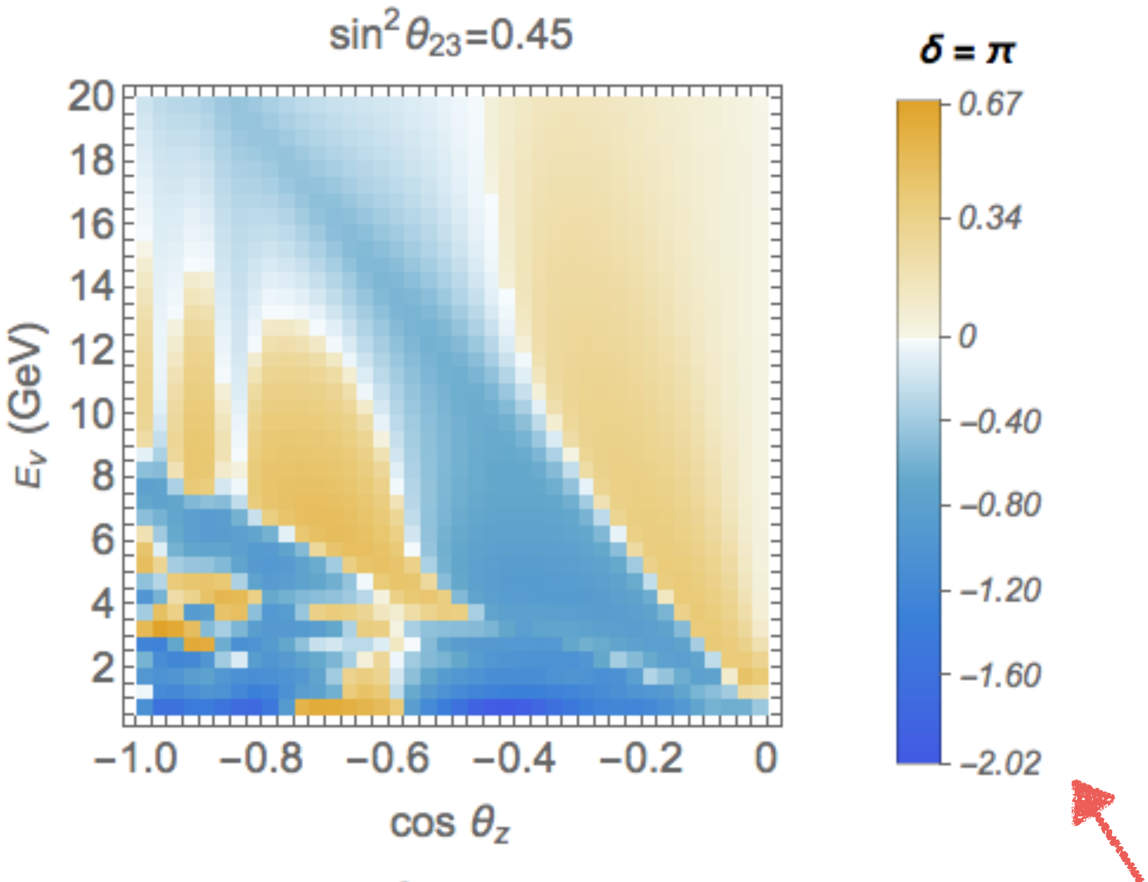
Smeared with Energy and Angular Resolutions

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





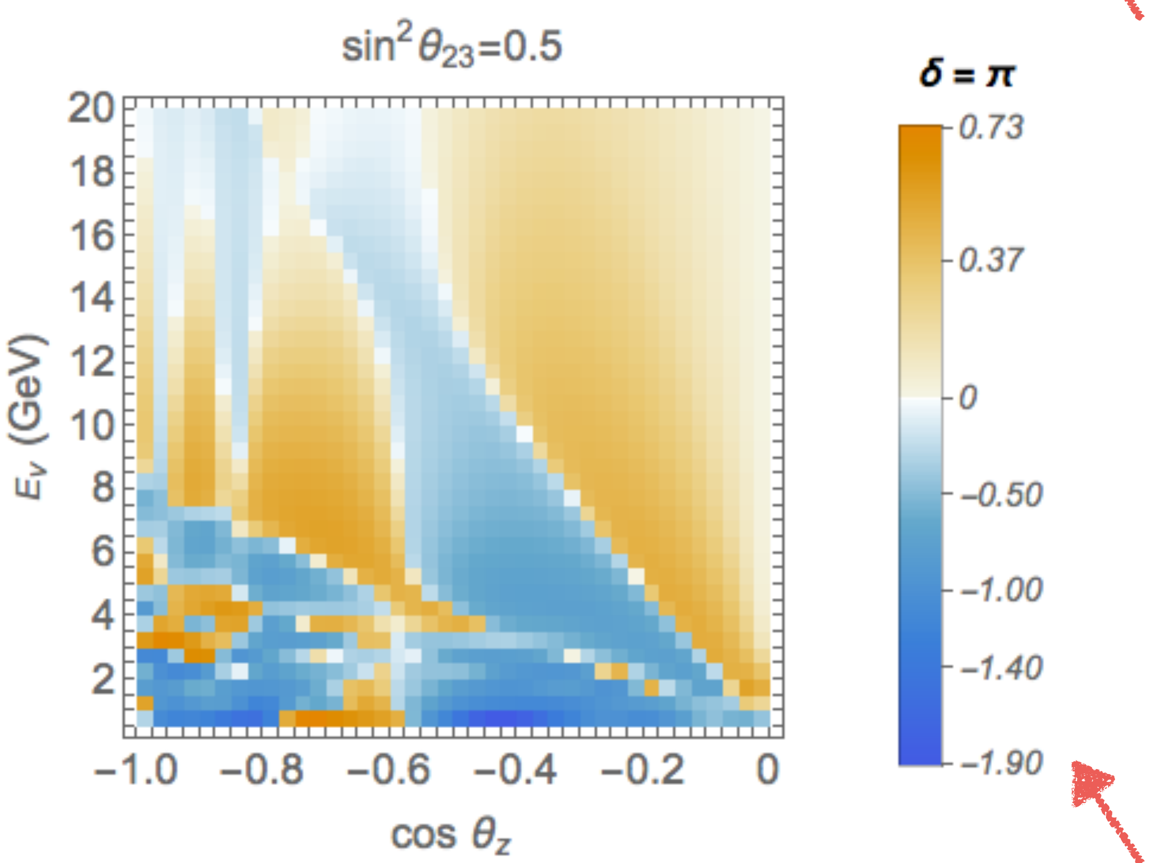
Dependence on theta_{23}

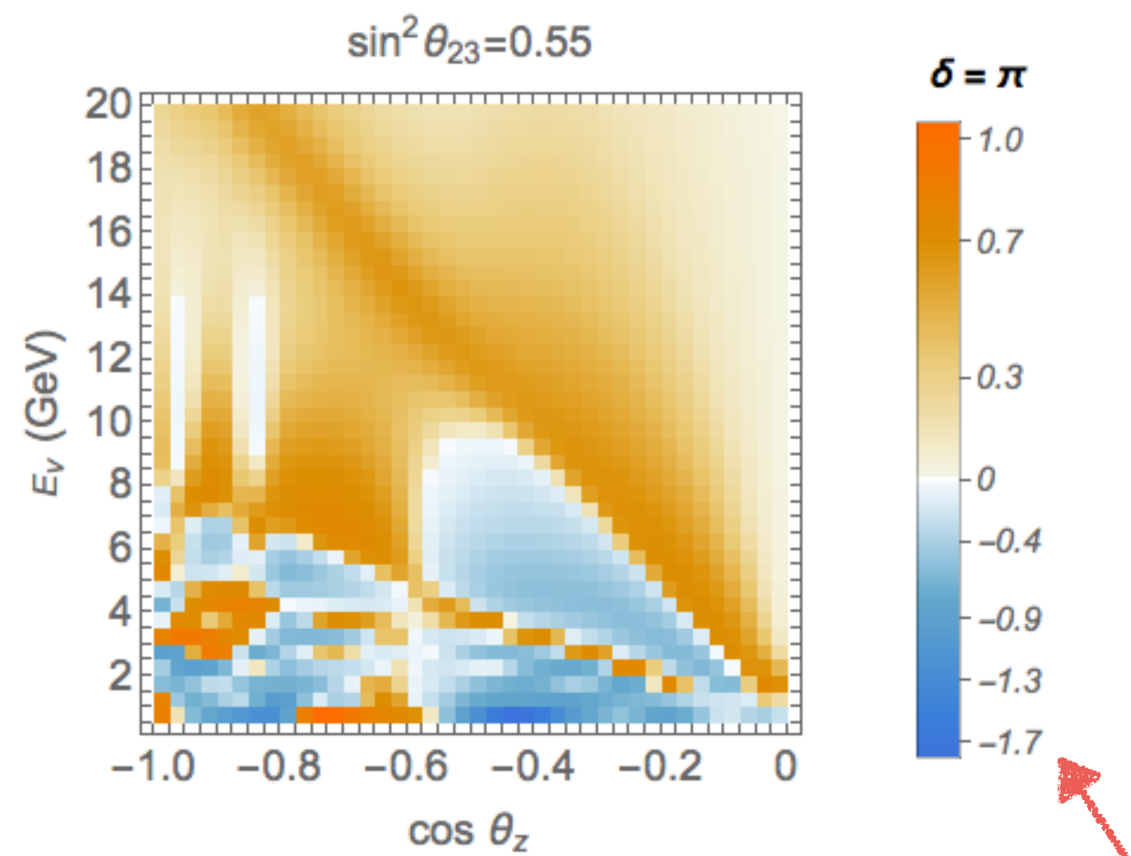


Mild dependence on theta_{23} in the

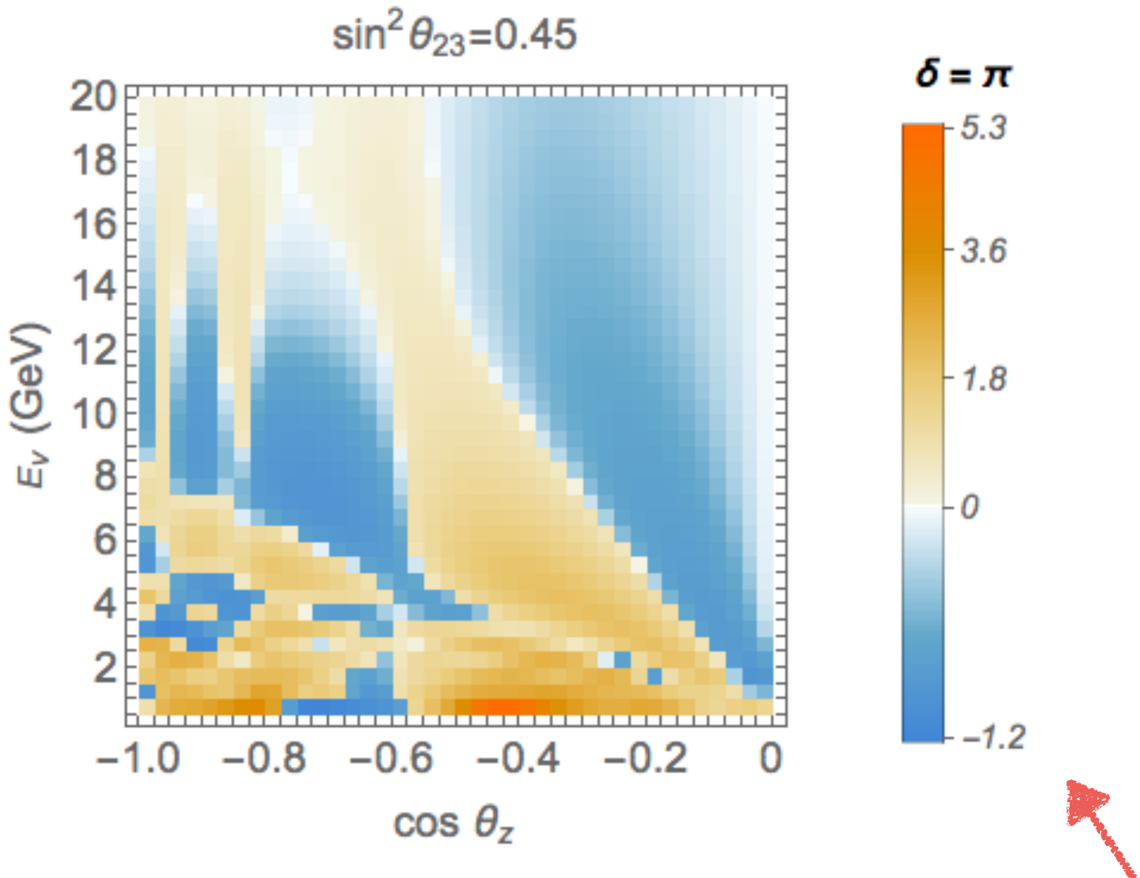
$\nu_\mu + \bar{\nu}_\mu$ **channel**

1 year of events





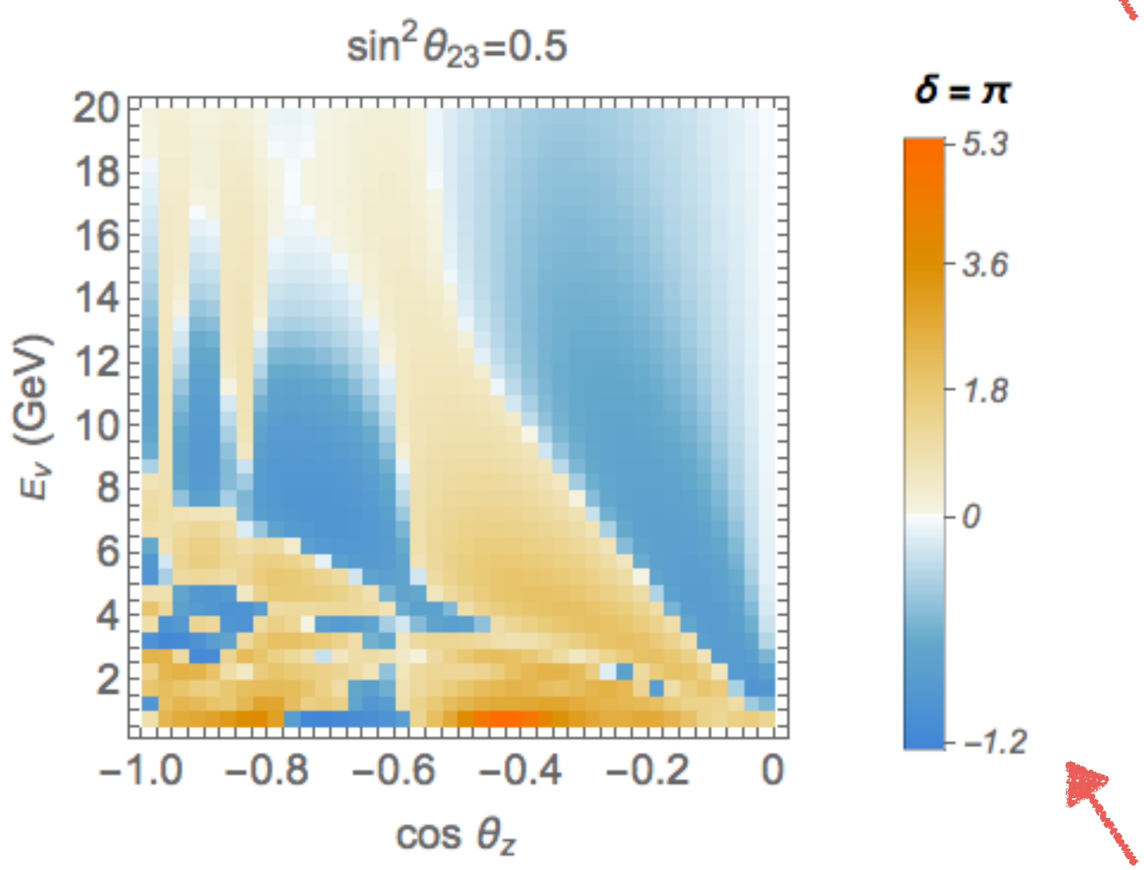
Dependence on theta_{23}

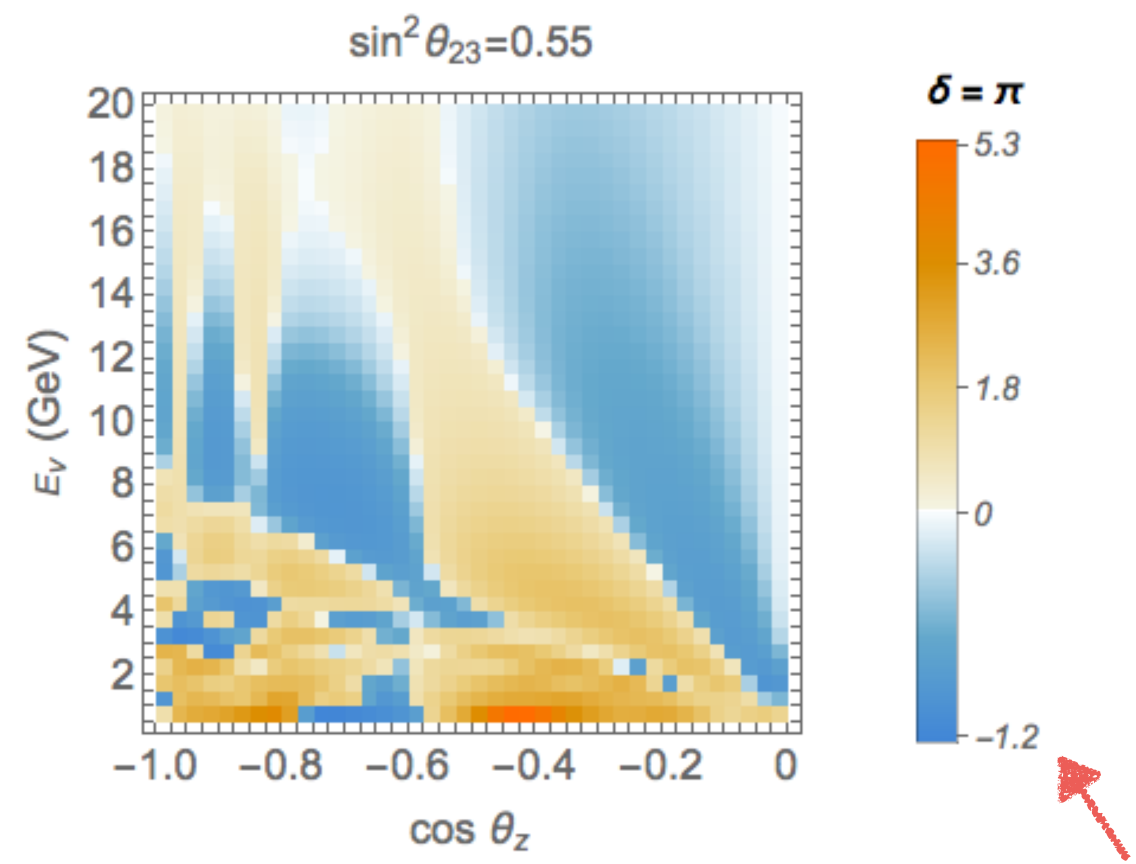


Almost no dependence on theta_{23} in the

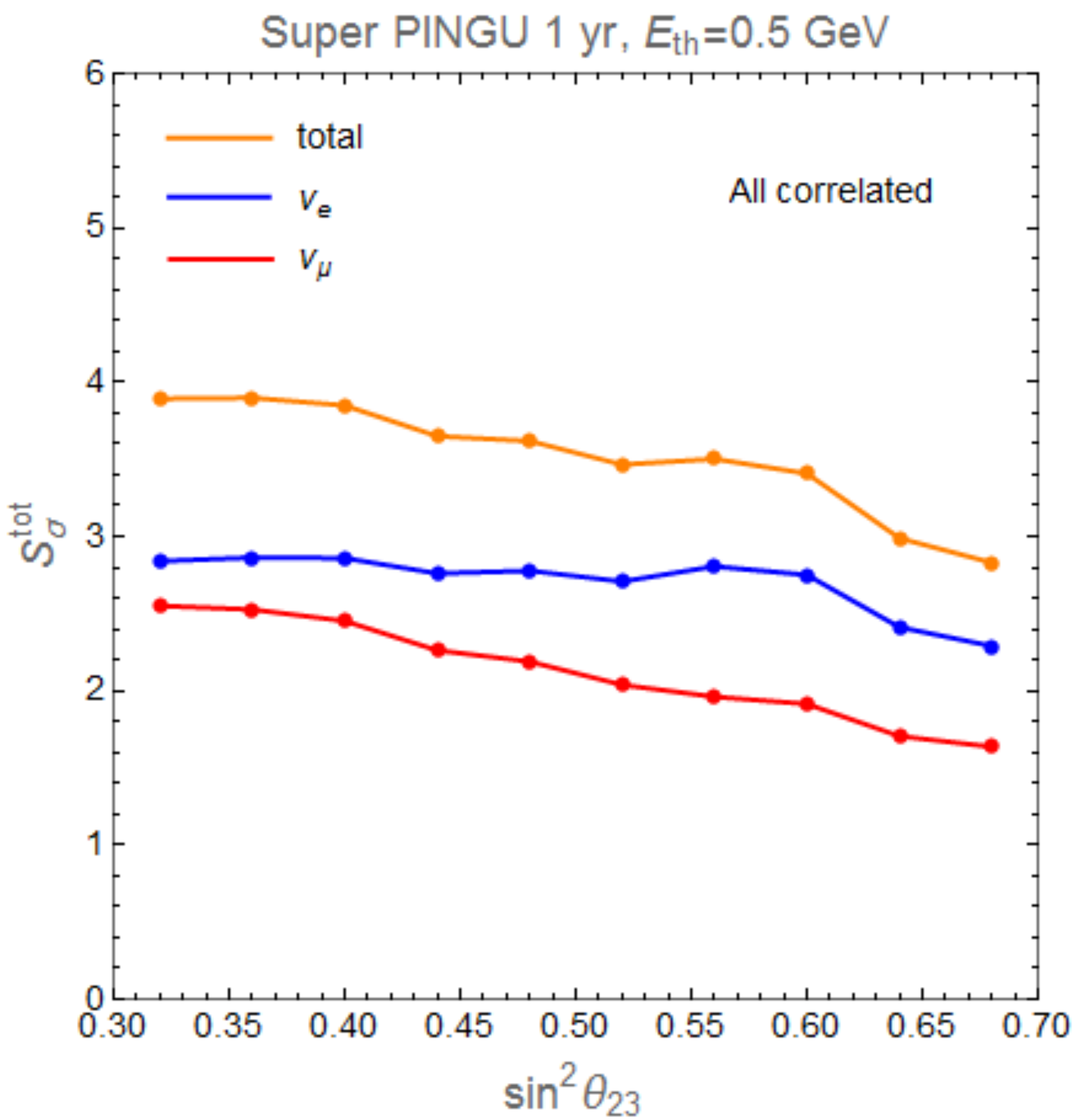
$\nu_e + \bar{\nu}_e$ **channel**

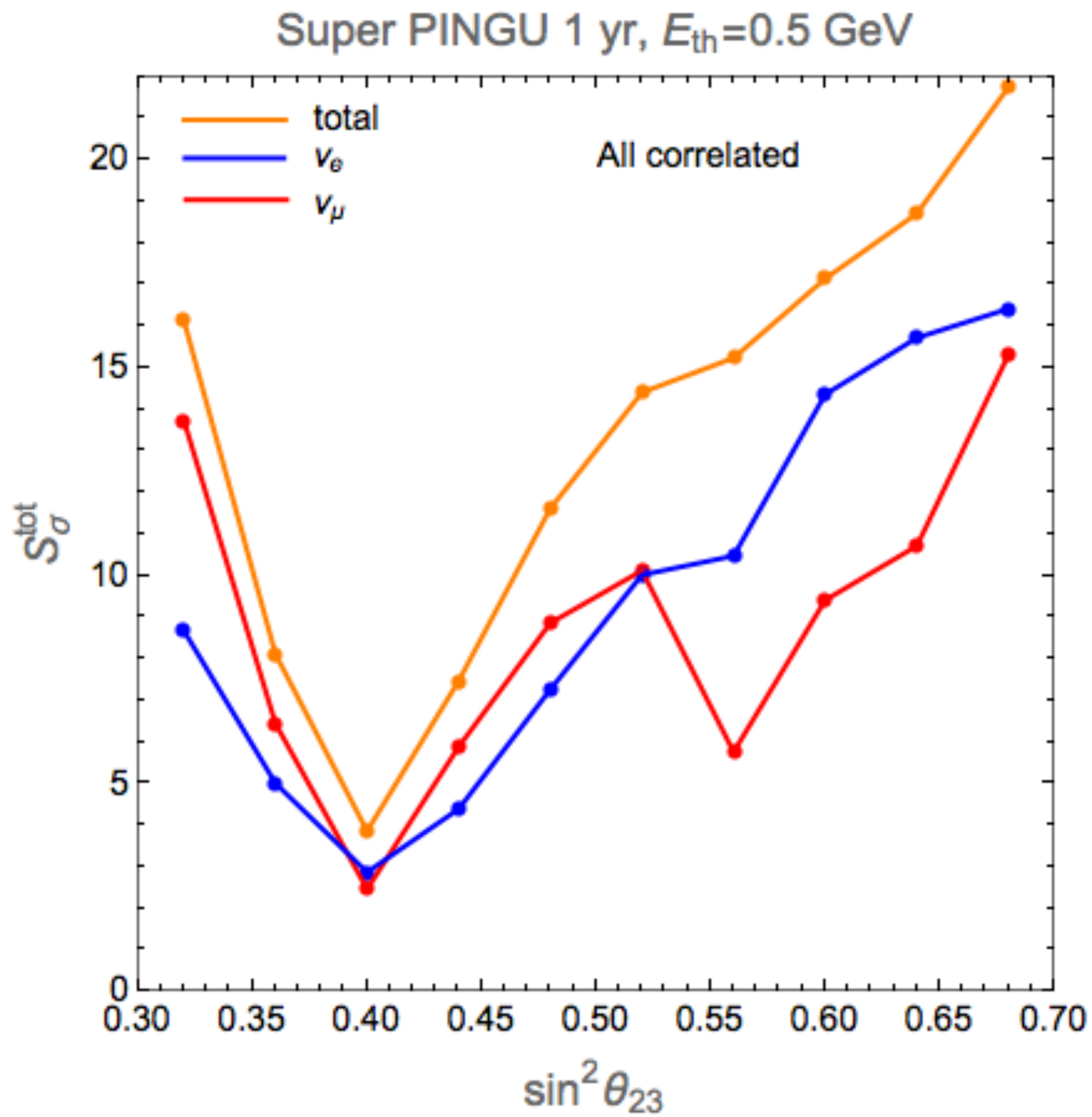
1 year of events



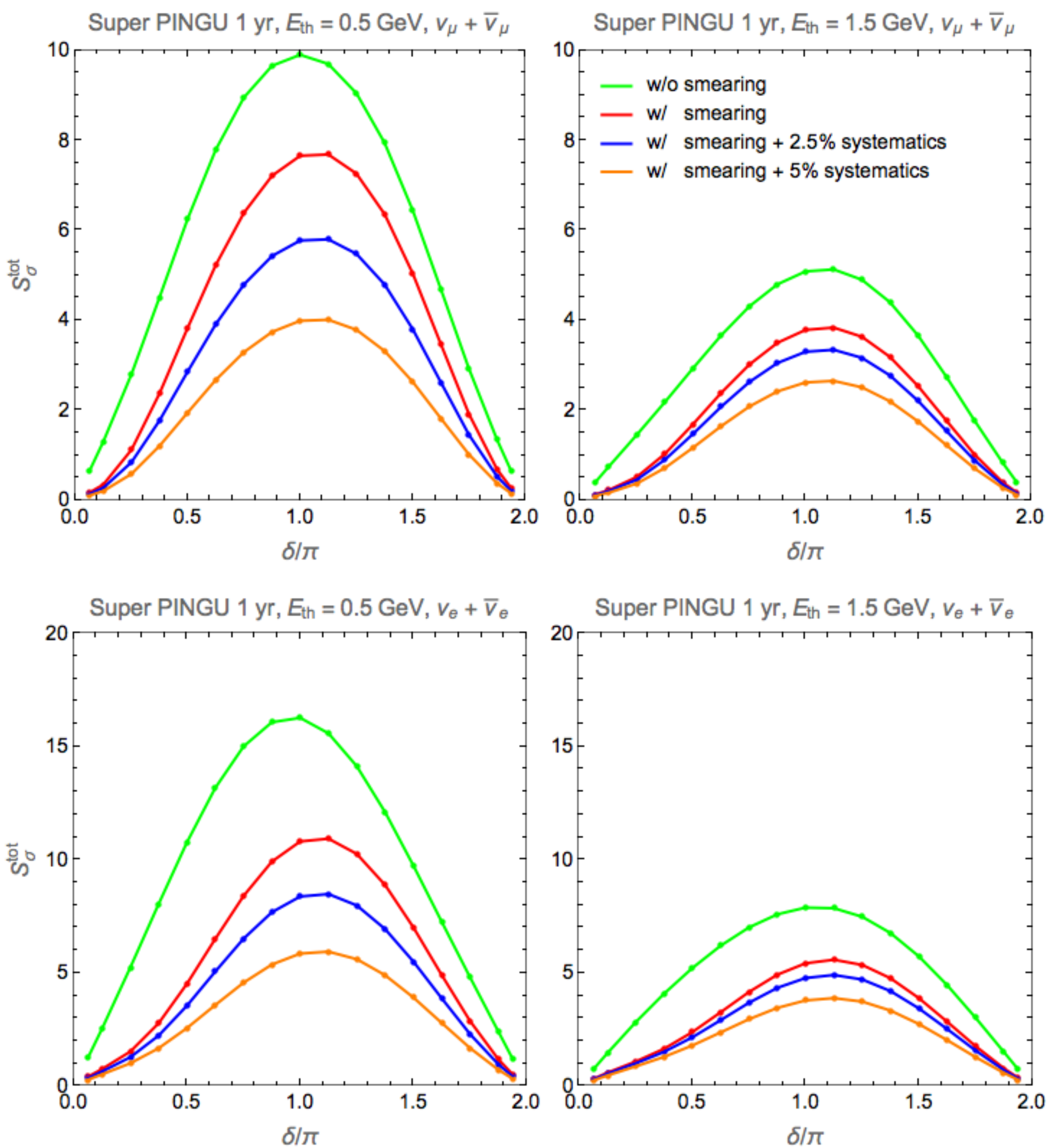


Dependence on theta_{23}





Sensitivity to CP - Super-PINGU/ORCA



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

Threshold - 0.5 GeV, 1.5 GeV

Total distinguishability (~ sensitivity)

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

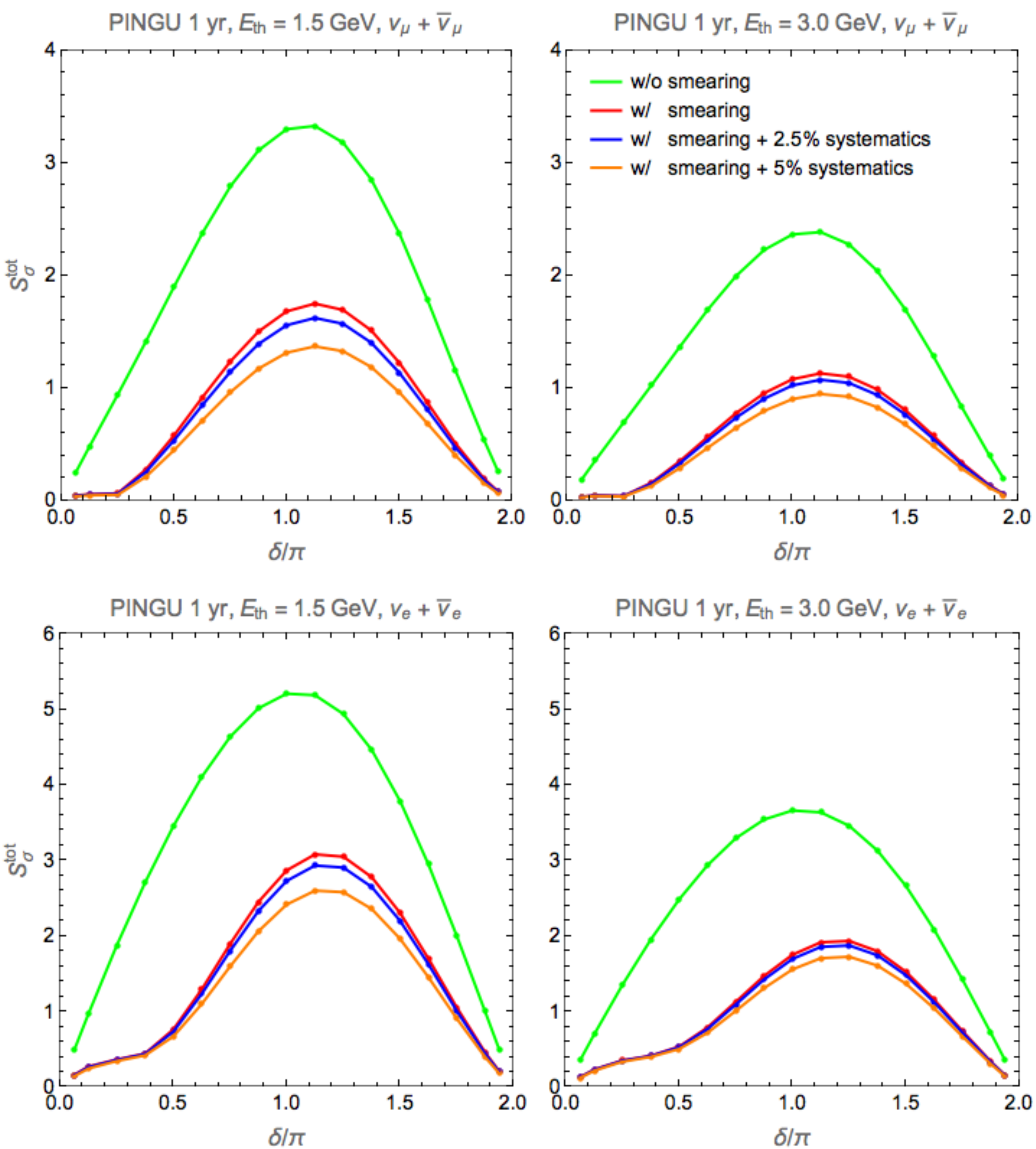
f = uncorrelated systematics (~2.5-5%)

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

Threshold - 0.5 GeV, 1.5 GeV

S.R., Smirnov 2015

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

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Details of Systematic Effects

Effects of removing individual systematics