NSI with High-Energy Atmospheric ν's at IceCube

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Outline

- Introduction
- NSI: theory
- Phenomenology of NSI
- NSI with HE atmospheric neutrinos at IceCube
- Summary

1. Introduction

- Neutrino oscillations robustly established (Physics Nobel Prize 2015)
- Mass eigenstates (ν_i) are not the same as flavour eigenstates ($\nu_\alpha;\alpha$=e,μ,τ), produced in $\ell_\alpha + N \to \nu_\alpha + N'$:

$$\nu_\alpha = \sum_{i=1}^{n} U_{\alpha i}\, \nu_i \qquad U(\theta_{12}, \theta_{23}, \theta_{13}, \delta_{CP})$$

- After a distance L, the probability of detecting a neutrino of flavour β is

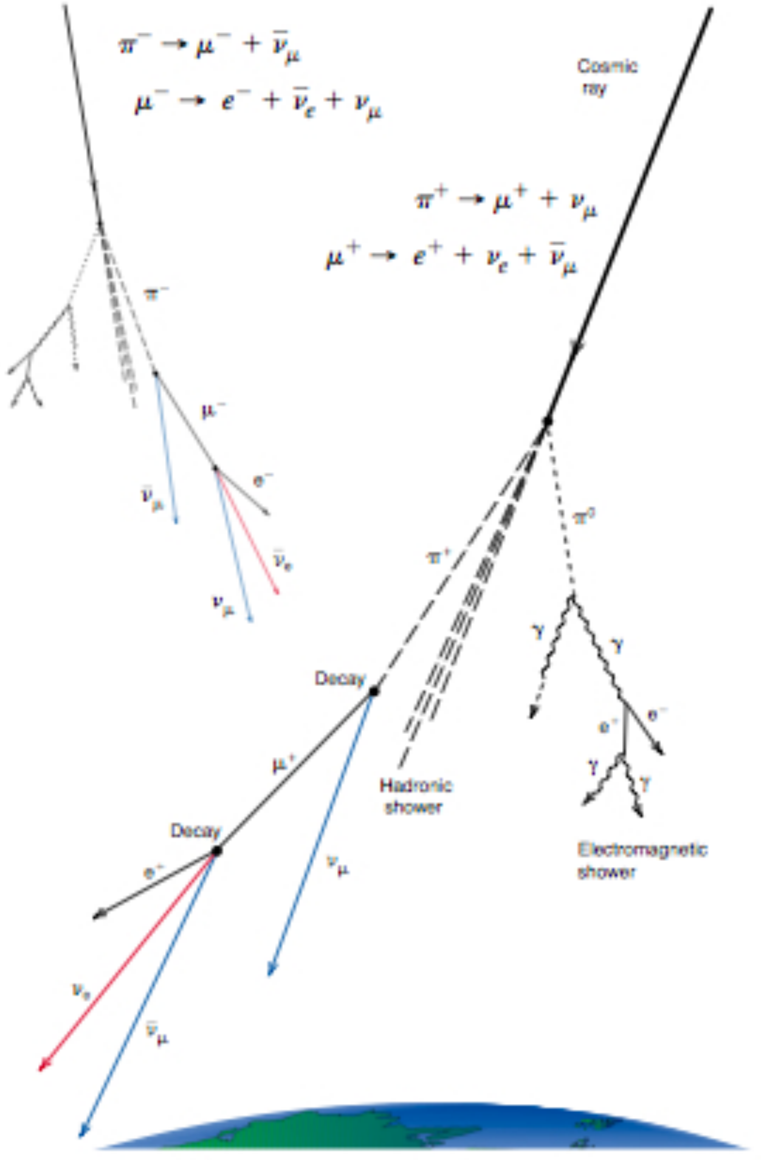
$$P(\nu_\alpha \to \nu_\beta) = \delta_{\alpha\beta} - 4\sum_{i\neq j} \mathrm{Re}\left[U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j}\right] \sin^2\left(\frac{\Delta_{ij}}{2}\right) + 2\sum_{i\neq j} \mathrm{Im}\left[U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j}\right] \sin(\Delta_{ij})$$

$$\Delta_{ij} \equiv (E_i - E_j)L$$

- **Neutrino masses** ⟹ new physics
- **Scale ?**
  - **Type I seesaw:** RH neutrino
    a) Accesible in meson decay ⟹ sterile neutrino oscillations
    b) Heavier RH neutrinos **(Inverse seesaw)** ⟹ non-unitary PMNS matrix
  - **Radiative neutrino masses:** new particles at TeV scale ⟹ neutrino's NSI

⟹ **Impact on (atmospheric) neutrino oscillations**

Atmospheric neutrinos



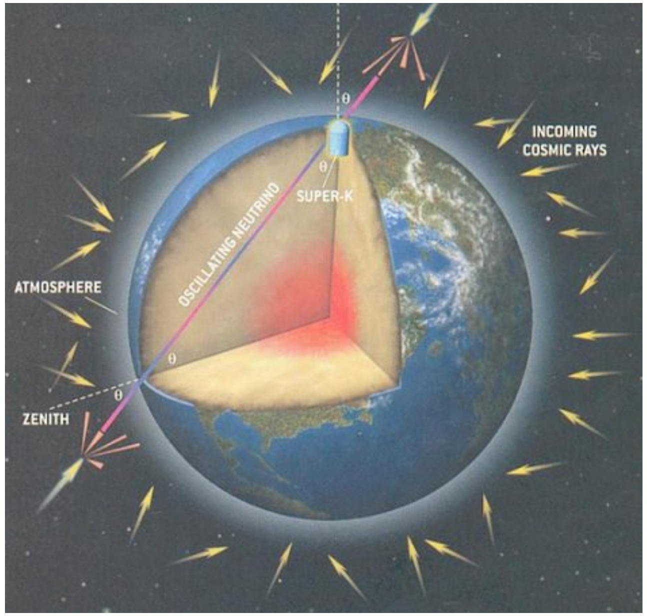
- Produced when cosmic ray primaries hit Earth's atmosphere

- From pion and kaon decays

- Prompt atmospheric neutrinos produced in decay of charmed mesons, relevant above ~ 100 TeV

Matter effects

- Atmospheric neutrinos come from different zenith angles (θ_z), crossing different Earth layers



- Effective potential in matter:

$$H(E_\nu) = \frac{1}{2E_\nu} U M^2 U^\dagger + \text{diag}(V_e, 0, 0)$$

$$M^2 = \text{diag}(0, \Delta m^2_{21}, \Delta m^2_{31}) \ , \qquad V_e = \sqrt{2}\, G_F\, n_e$$

n_e: electron number density

- Antineutrinos: $\overline{V}_e = -V_e$

- Modification of mixing angle and oscillation frequency: Mikheyev-Smirnov-Wolfenstein, MSW

$$\Delta m_m^2 = \sqrt{(\Delta m^2 \cos 2\theta - 2E_\nu V_e)^2 + (\Delta m^2 \sin 2\theta)^2}$$

$$\sin(2\theta_m) = \frac{\Delta m^2 \sin 2\theta}{\Delta m_m^2}$$

- Resonant flavour transition if

$$E_\nu^{res} \simeq -\cos 2\theta \, \frac{\Delta m^2}{2V_e}$$

2. NSI: theory

- Recent reviews: Ohlsson 2013, Miranda & Nunokawa 2015

Standard parametrization of NSI's :

$$\mathcal{L}_{NSI}^{NC} = -\varepsilon_{\alpha\beta}^{fP} 2\sqrt{2} G_F (\bar{\nu}_\alpha \gamma_\rho P_L \nu_\beta)(\bar{f} \gamma^\rho P f)$$

Matter NSI $P = P_L, P_R$, f is any SM fermion

$$\mathcal{L}_{\rm NSI}^{{\rm CC}\ell} = -\, 2\sqrt{2}\, G_F\, \varepsilon_{\alpha\beta}^{\delta\sigma P}\, (\bar{\nu}_\alpha \gamma_\rho P_L \nu_\beta)(\bar{\ell}_\delta \gamma^\rho P \ell_\sigma)$$

$$\mathcal{L}_{\rm NSI}^{{\rm CC}q} = -\, 2\sqrt{2}\, G_F\, \varepsilon_{\alpha\beta}^{qq'P}\, (\bar{\nu}_\alpha \gamma_\rho P_L \ell_\beta)(\bar{q} \gamma^\rho P q') + h.c.$$

Production (source) and detection NSI

NSI from D=6 operators ➜ gauge invariance implies

e.g.

$$\frac{1}{\Lambda^2}(\bar{\nu}_\alpha \gamma_\rho P_L \nu_\beta)(\bar{\ell}_\gamma \gamma^\rho P_L \ell_\delta) \Longrightarrow \frac{1}{\Lambda^2}(\bar{L}_\alpha \gamma_\rho L_\beta)(\bar{L}_\gamma \gamma^\rho L_\delta)$$

Involves 4-charged leptons, severe exp. constraints from $\ell_\alpha^- \to \ell_\beta^- \ell_\gamma^+ \ell_\delta^-$

$$\mathrm{BR}(\mu \longrightarrow 3e) < 10^{-12} \Longrightarrow \epsilon_{e\mu}^{e} < 10^{-6}$$

➢ No observable effects in neutrino interactions

D=8 operators

Berezhiani, Rossi 2002

$$\frac{1}{\Lambda^4}(\bar{L}H)\gamma_\rho(H^\dagger L)(\bar{e}_R \gamma^\rho e_R) \Longrightarrow \frac{\langle H \rangle^2}{\Lambda^4}(\bar{\nu}\gamma_\rho P_L \nu)(\bar{e}\gamma^\rho P_R e)$$

➢ UV realizations: fine-tuning to avoid D=6 operators

Gavela et al. 2009

- SU(2) singlet scalar S with Y=1 $\Longrightarrow$ only gauge invariant d=6 operator which does not generate charged lepton NSIs

Bilenky, Santamaría 1994, Antusch et al. 2009

- Zee-Babu model of neutrino masses: extra scalars h^+ k^{++}

$$\mathcal{L}_{int} = -f_{\alpha\beta}\overline{L^c_\alpha} i\sigma_2 L_\beta h^+ + h.c. \Longrightarrow \mathcal{L}^{d=6}_{\rm NSI} = 4\frac{f_{\alpha\beta}f^*_{\delta\gamma}}{m_h^2}(\overline{\ell^c_\alpha}P_L\nu_\beta)(\bar{\nu}_\gamma P_R \ell^c_\delta)$$

- $\varepsilon^{eL}_{\alpha\beta} = \frac{f_{e\beta}f^*_{e\alpha}}{\sqrt{2}G_F\, m_h^2} \sim \mathcal{O}(10^{-3})$, too small

to be observable now

Ohlsson, Schwetz, Zhang 2009

- Type II seesaw model (triplet scalar) $\varepsilon^{eL}_{\alpha\beta} \propto \frac{m_W^2}{m_\Delta^2}$

Sizeable $\varepsilon^{e\mu}_{e\mu}$, ε^{e}_{ee} for degenerate spectrum ($\gtrsim$ 3 10^{-3})

Malinsky et al. 2009

- Mixing with sterile neutrinos ⟹ generates NSI via non-unitarity effetcs:

$$N = T\ U = (I - \alpha)U \rightarrow \text{unitary}$$

lower triangular ↲ Xing 2008, Escrihuela et al. 2015

$$\varepsilon_{\delta\beta}^{fP} \propto \alpha_{\beta\delta} \sim \mathcal{O}(s_{ij}^2) \qquad i \leq 3, j > 3$$

- Heavy sterile neutrinos ⟹ non-unitarity of PMNS matrix induces changes in W,Z couplings ⟹ strong bounds from charged lepton LFV electroweak precision data $\alpha \lesssim 10^{-3}$ Antusch et al. 2009

- Light sterile neutrinos (below keV) ⟹ kinematically accessible, unitarity restored $\alpha \lesssim$ few 10^{-2}

Blennow et al. 2017

- Very light vector boson, $m_{Z'} \sim$ 10 – 100 MeV
- Matter effects in oscillations: $\epsilon \propto (g'/m_{Z'})^2/G_F^{-1}$, but neutrino scattering suppressed by $(m_{Z'}^2/q^2)^2$

- Diagonal NSI: Solar LMA – Dark solution $\varepsilon_{ee}^{qV} \sim -1$

$\Longrightarrow$ Z´ with $m_{Z'} \sim$ 10 MeV coupled to 1st generation quarks and 2nd,3rd generation of leptons

Farzan, 2015

- LFV NSI: Z´ with much smaller ($\zeta \sim 10^{-5}$) coupling to leptons than to quarks

$$\varepsilon_{\mu\tau}^{qP} \sim 5 \times 10^{-3},\ \varepsilon_{\mu\mu}^{qP} - \varepsilon_{\tau\tau}^{qP} \sim 0.05 \qquad \varepsilon_{\alpha\beta}^{qP} \sim \frac{\zeta}{G_F} \frac{g'^2}{m_{Z'}^2}$$

- Charged lepton FV amplitude $\propto \zeta^2$
- $\Gamma(\tau \to \mu q \bar{q})$ suppressed by $(m_{Z'}/m_\tau)^4$

Farzan, Shoemaker 2016

3. Phenomenology of NSI

- In general, CC NSI bounds are one order of magnitude stronger than NC ones, $10^{-2} - 10^{-1}$

  (affect ν's production and detection)

  Grossman 95, González-García et al. 2001, Biggio et al. 2009

- NC NSI in oscillations:

$$H_{\rm mat} = V_e \begin{pmatrix} 1+\varepsilon_{ee} & \varepsilon_{e\mu} & \varepsilon_{e\mu} \\ \varepsilon^*_{e\mu} & \varepsilon_{\mu\mu} & \varepsilon_{\mu\tau} \\ \varepsilon^*_{e\tau} & \varepsilon^*_{\mu\tau} & \varepsilon_{\tau\tau} \end{pmatrix} \qquad V_e = \sqrt{2} G_F n_e$$

$$\varepsilon_{\alpha\beta} \equiv \sum_f \frac{n_f}{n_e} \varepsilon^{fV}_{\alpha\beta} \ , \ \varepsilon^{fV}_{\alpha\beta} = \varepsilon^{fR}_{\alpha\beta} + \varepsilon^{fL}_{\alpha\beta}$$

- Only sensitive to differences of diagonal NSI, e.g.

$$\varepsilon'_{\alpha\alpha} \equiv \varepsilon_{\alpha\alpha} - \varepsilon_{\mu\mu}$$

Global fit from neutrino oscillation data including NSI

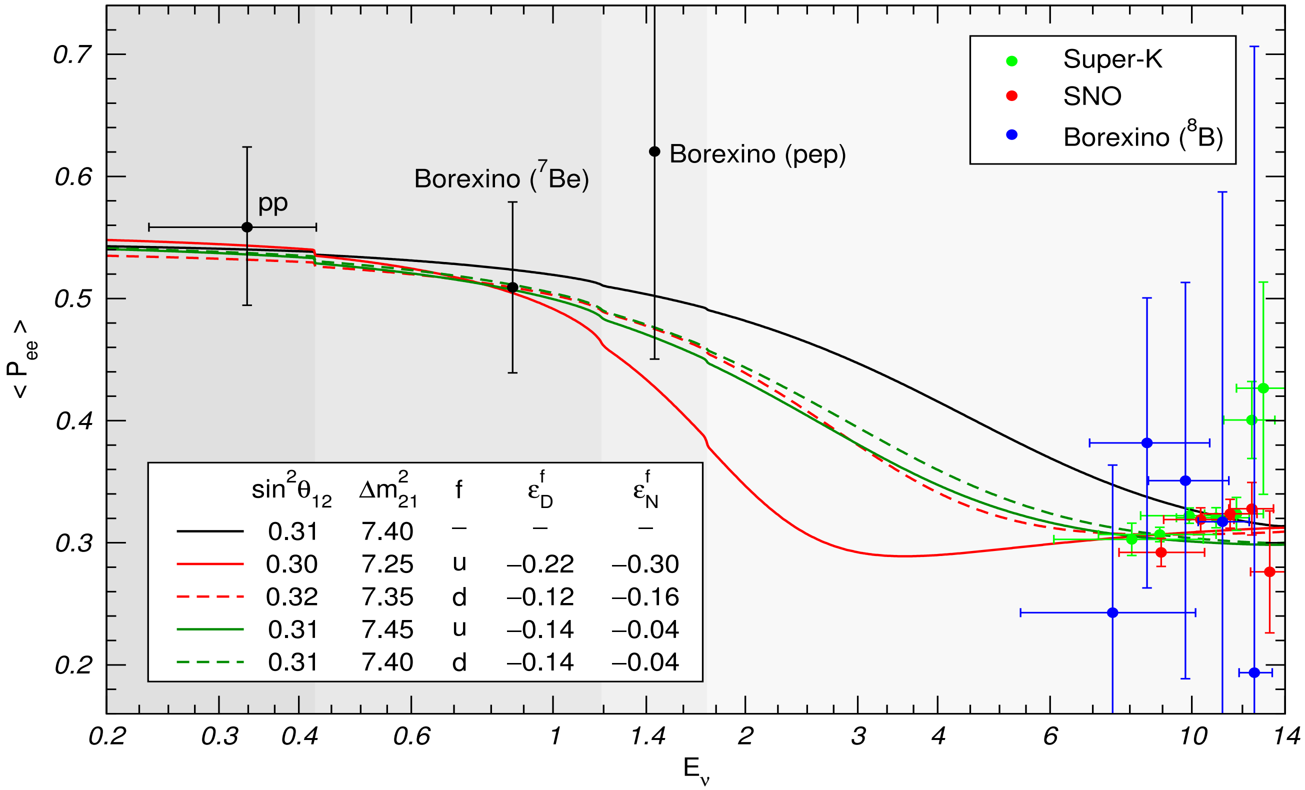
González-García and Maltoni, 2013

		90% CL	
Param.	best-fit	LMA	LMA $\oplus$ LMA-D
$\varepsilon^u_{ee} - \varepsilon^u_{\mu\mu}$	+0.298	[+0.00, +0.51]	$\oplus$ [−1.19, −0.81]
$\varepsilon^u_{\tau\tau} - \varepsilon^u_{\mu\mu}$	+0.001	[−0.01, +0.03]	[−0.03, +0.03]
$\varepsilon^u_{e\mu}$	−0.021	[−0.09, +0.04]	[−0.09, +0.10]
$\varepsilon^u_{e\tau}$	+0.021	[−0.14, +0.14]	[−0.15, +0.14]
$\varepsilon^u_{\mu\tau}$	−0.001	[−0.01, +0.01]	[−0.01, +0.01]
ε^u_D	−0.140	[−0.24, −0.01]	$\oplus$ [+0.40, +0.58]
ε^u_N	−0.030	[−0.14, +0.13]	[−0.15, +0.13]
$\varepsilon^d_{ee} - \varepsilon^d_{\mu\mu}$	+0.310	[+0.02, +0.51]	$\oplus$ [−1.17, −1.03]
$\varepsilon^d_{\tau\tau} - \varepsilon^d_{\mu\mu}$	+0.001	[−0.01, +0.03]	[−0.01, +0.03]
$\varepsilon^d_{e\mu}$	−0.023	[−0.09, +0.04]	[−0.09, +0.08]
$\varepsilon^d_{e\tau}$	+0.023	[−0.13, +0.14]	[−0.13, +0.14]
$\varepsilon^d_{\mu\tau}$	−0.001	[−0.01, +0.01]	[−0.01, +0.01]
ε^d_D	−0.145	[−0.25, −0.02]	$\oplus$ [+0.49, +0.57]
ε^d_N	−0.036	[−0.14, +0.12]	[−0.14, +0.12]

LMA – Dark solution ($\theta_{12} > \pi/4$)

Miranda et al. 2004

Due to no evidence of low energy turn-up in the solar neutrino spectrum



González-García and Maltoni, 2013

ε^f_N, ε^f_D ⟹ linear combinations of mixing angles and NSI NC $\varepsilon^f_{\alpha\beta}$

Such $\varepsilon^q_{e\tau}$ can be tested by atmospheric neutrinos at Hyper-Kamiokande and T2HKK Fukasawa et al. 2017 (Yasuda's talk)

LMA – Dark solution can be ruled out at DUNE Coloma 2016, Blennow et al. 2016

- Relative size of NSI and standard oscillations depends on neutrino energy:
  - $E_\nu < 1$ GeV $\Longrightarrow$ vacuum oscillations dominate
  - 1 GeV $< E_\nu <$ 10 GeV $\Longrightarrow$ intereference NSI – vacuum osc.
  - $E_\nu >$ 10 GeV $\Longrightarrow$ NSI may dominate
- NSI affect ν's propagation in a medium
- Atmospheric ν's span a huge range of neutrino energies, $10^{-1} - 10^{5}$ GeV and of neutrino baselines crossing the Earth, 10 – few 10^3 km $\Longrightarrow$ disentangling NSI and standard oscillations

$\Longrightarrow$ **ideal tool to test and constrain NSI !!!**

- Many atmospheric neutrino's NSI analysis restrict to the $\nu_\mu - \nu_\tau$ sector.
- Sensitivity of atmospheric neutrinos to $\nu_e - \nu_\tau$ NSI:

Friedland, Lunardini, Maltoni 2004

- One by one $\varepsilon_{\alpha\beta}$ leads to e.g. $\varepsilon_{\tau\tau} \lesssim 0.2$
- All non-vanishing $\varepsilon_{\alpha\beta}$ in $\nu_e - \nu_\tau$ sector leads to a H_{mat} which can be diagonalized as

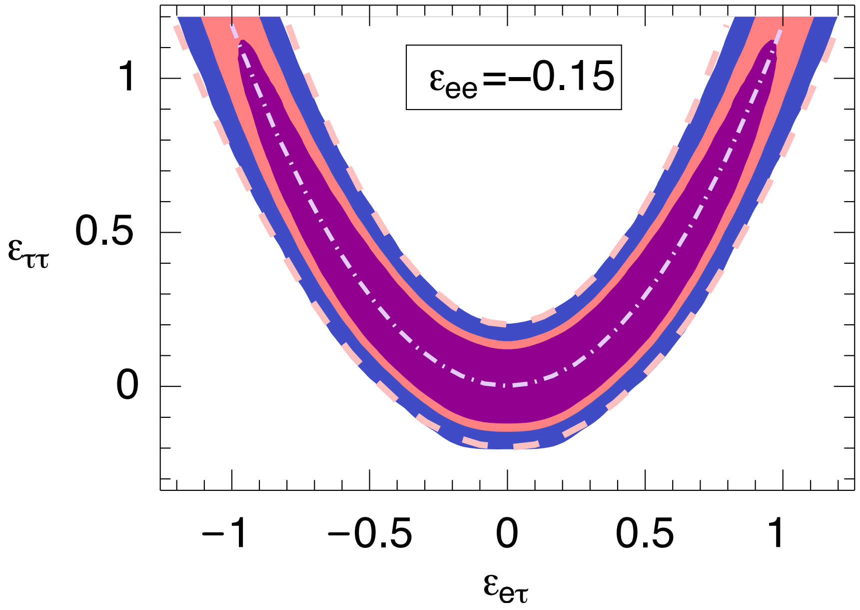
$$H_{\rm mat} = {\rm diag}(\lambda_{e'}, 0, \lambda_{\tau'})$$

- If $\lambda_{\tau'} \lesssim \Delta m^2/(2E_\nu) \sim 0.4$, for $E_\nu \gtrsim 10$ GeV, oscillations $\nu_\mu \to \nu_{\tau'}$ mimic vacuum oscillations with the same E_ν dependence and effective

$$\Delta m_m^2 > \Delta m^2 \qquad \sin(2\theta_m) < \sin(2\theta)$$

Along the parabola $\lambda_{\tau'} = 0 \Longrightarrow \varepsilon_{\tau\tau} = |\varepsilon_{e\tau}|^2/(1+\varepsilon_{ee})$

O(1) values of $\varepsilon_{\tau\tau}$, $\varepsilon_{e\tau}$ are allowed

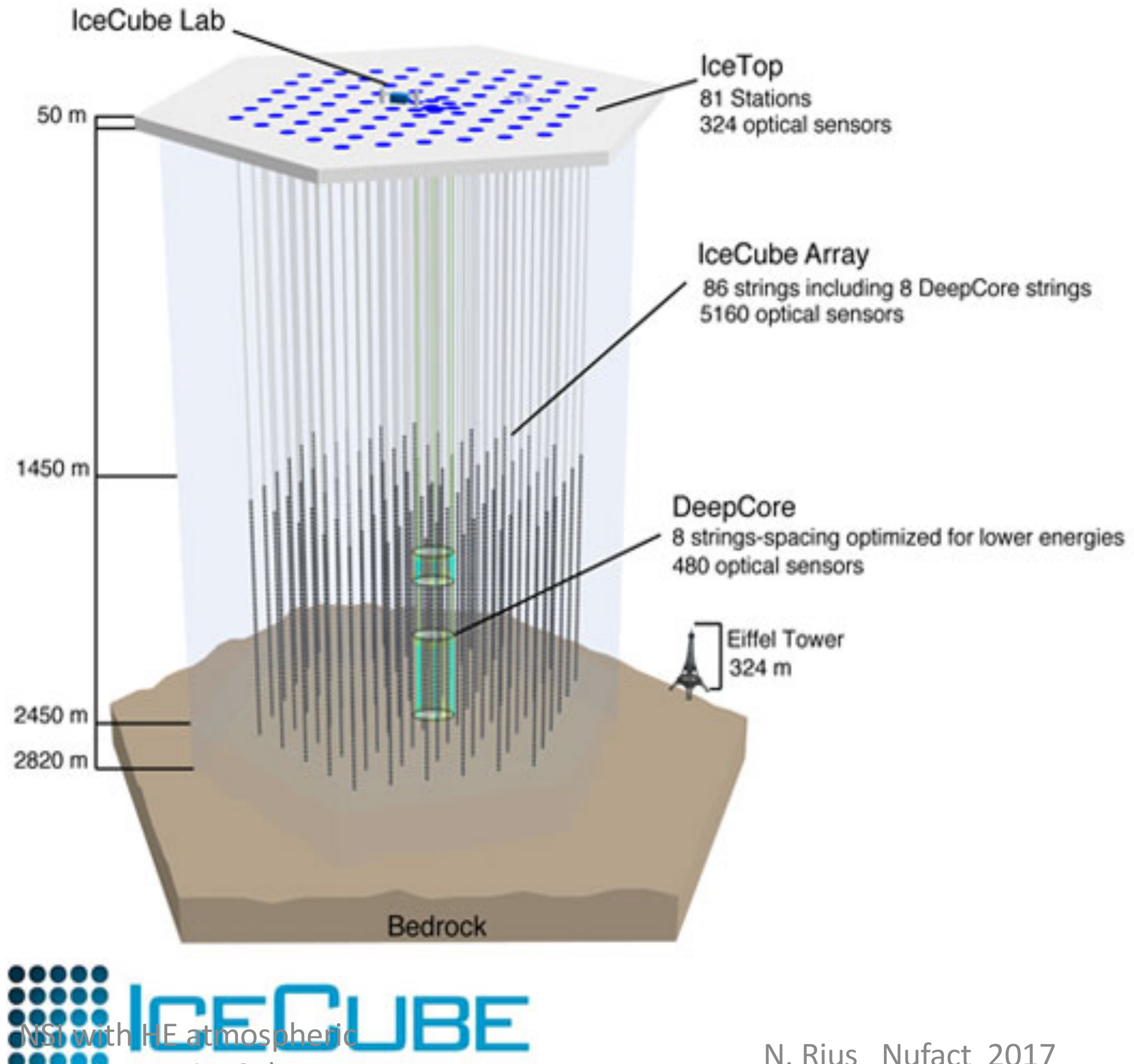


SK atmospheric data

From Friedland et al. 2004

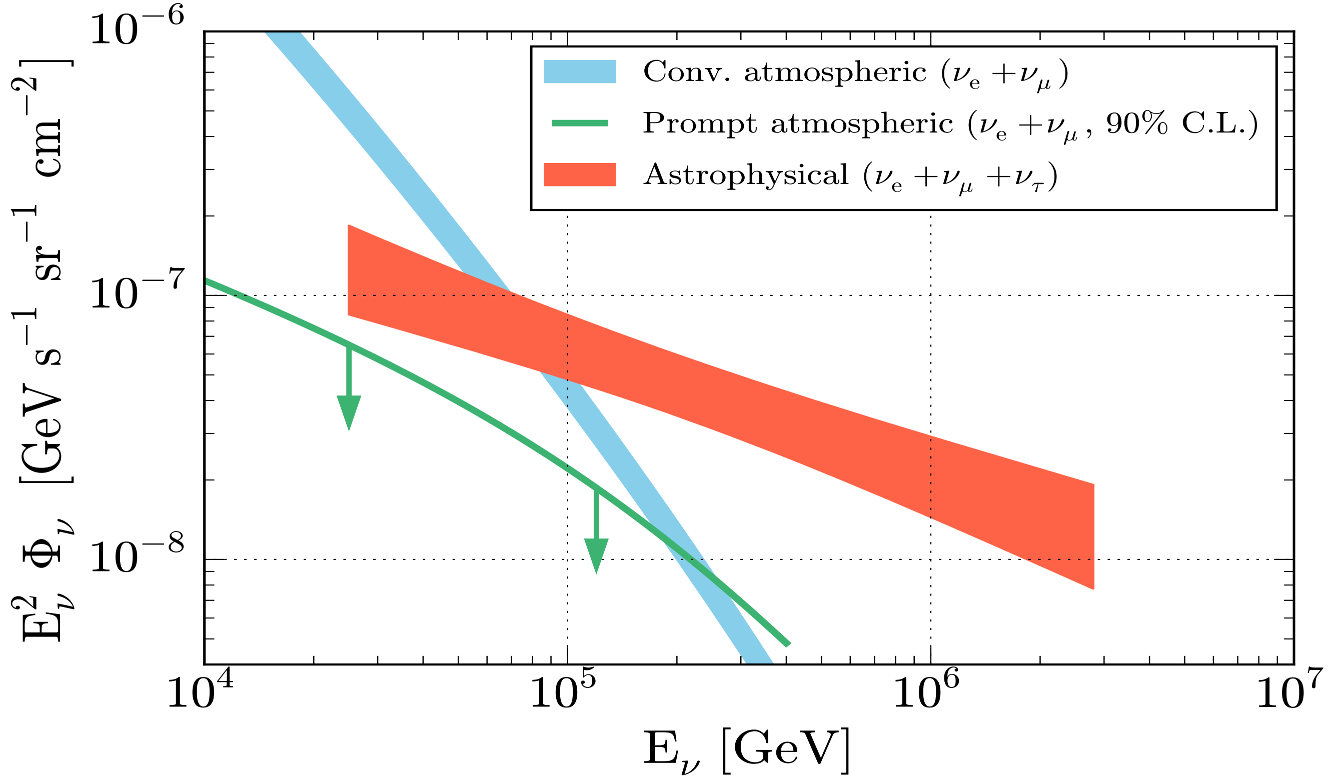
- This scenario can be tested by comparing Δm^2_{31} , θ_{23} from MINOS (almost no matter effects) and future experiments with longer baselines (few 10^3 km) and $E_\nu \gtrsim 10$ GeV

4. NSI with HE atmospheric ν's at IceCube



IceCube, at the South Pole

- Neutrino flux at IceCube:



IceCube Collaboration 2015

- Search data set: one year of up-going IceCube-86 high energy data (400 GeV to 20 TeV)

- At energies above ~ TeV, attenuation of the neutrino flux due to inelastic scattering becomes important
- Effects of ν_τ regeneration very small
- Density matrix formalism:

$$\frac{d\rho(E_\nu,x)}{dx} = -i[H(E_\nu,x),\rho(E_\nu,x)]$$

$$-\sum_\alpha \frac{1}{2\,\lambda_\alpha(E_\nu,x)}\{\Pi_\alpha(E_\nu),\rho(E_\nu,x)\}$$

$$+\int_{E_\nu}^{\infty}\rho(E'_\nu,x)\frac{1}{n_N(x)}\frac{d\sigma_{\rm NC}(E'_\nu,E_\nu)}{dE_\nu}dE'_\nu$$

oscillation

NC+CC absorption

NC redistribution

González-García, Halzen and Maltoni 2005

- Note different normalization: $\varepsilon_{\alpha\beta} \equiv \sum_f \frac{n_f}{n_d} \varepsilon^{fV}_{\alpha\beta} \simeq \frac{1}{3}\bar{\varepsilon}_{\alpha\beta}$

- We consider $\varepsilon_{\mu\tau}$ and $\varepsilon' = \varepsilon_{\tau\tau} - \varepsilon_{\mu\mu}$
- Diagonal NSI change the effective matter density, while off-diagonal NSI shifts the effective mixing angle.
- Analytic approximation:

$$\phi_\alpha(E_\nu, \theta_z) = \phi^0_\mu(E_\nu, \theta_z)\, P\,(\nu_\mu \to \nu_\alpha; E_\nu, L(\theta_z))\ \exp\{-\int_0^{L(\theta_z)} dx/\lambda_\alpha(E_\nu, x)\}$$

$L(\theta_z)$ is the baseline across the Earth

- Two neutrino oscillation probability at a distance L:

$$P(\nu_\mu \to \nu_\tau) = \sin^2 2\theta_{\rm mat}\ \sin^2\left(\frac{\Delta m^2_{31}\, L}{4\, E_\nu}\, R\right)$$

$$\sin^2 2\theta_{\rm mat} = \frac{(\sin 2\theta_{23} + R_0\ \sin 2\xi)^2}{R^2}$$

$$R_0 = \frac{\phi_{\rm mat}}{\phi_{\rm vac}} = \frac{V_{\rm NSI}\, L/2}{\Delta m^2_{31}\, L/4E_\nu}$$

$$R^2 = 1 + R_0^2 + 2\, R_0\ \cos 2(\theta_{23} - \xi)$$

$$V_{\rm NSI} = V_d \sqrt{4\, \varepsilon^2_{\mu\tau} + \varepsilon'^2}$$

$$\sin 2\xi = \frac{2\, \varepsilon_{\mu\tau}}{\sqrt{4\, \varepsilon^2_{\mu\tau} + \varepsilon'^2}}$$

Coleman, Glashow 1999

- For E_ν > 100 GeV, $\phi_{\rm vac} = \Delta m^2_{31}\, L/4E_\nu \ll 1$ and if R_0 = O(1)

$$\phi_{\rm mat} \sim \phi_{\rm vac}$$

$$P(\nu_\mu \to \nu_\tau) \simeq \left(\sin 2\theta_{23}\, \frac{\Delta m^2_{31}}{2\, E_\nu} + 2\, V_d\, \varepsilon_{\mu\tau}\right)^2 \left(\frac{L}{2}\right)^2$$

- Independent of **ε'**

- for antineutrinos

- More sensitivity to ε' at $E_\nu < 100$ GeV
- At higher E_ν , $\phi_{\rm mat} \gg \phi_{\rm vac}$, $R_0 \gg 1$

$$P(\nu_\mu \to \nu_\tau) \simeq \sin^2 2\xi \, \sin^2 \phi_{\rm mat}$$

where $\phi_{\rm mat} = \frac{V_d L}{2}\sqrt{4\,\varepsilon_{\mu\tau}^2 + \varepsilon'^2} \simeq 30 \left(\frac{\rho}{8\,{\rm g/cm^3}}\right)\left(\frac{L}{2\,R_\oplus}\right)\sqrt{4\,\varepsilon_{\mu\tau}^2 + \varepsilon'^2}$

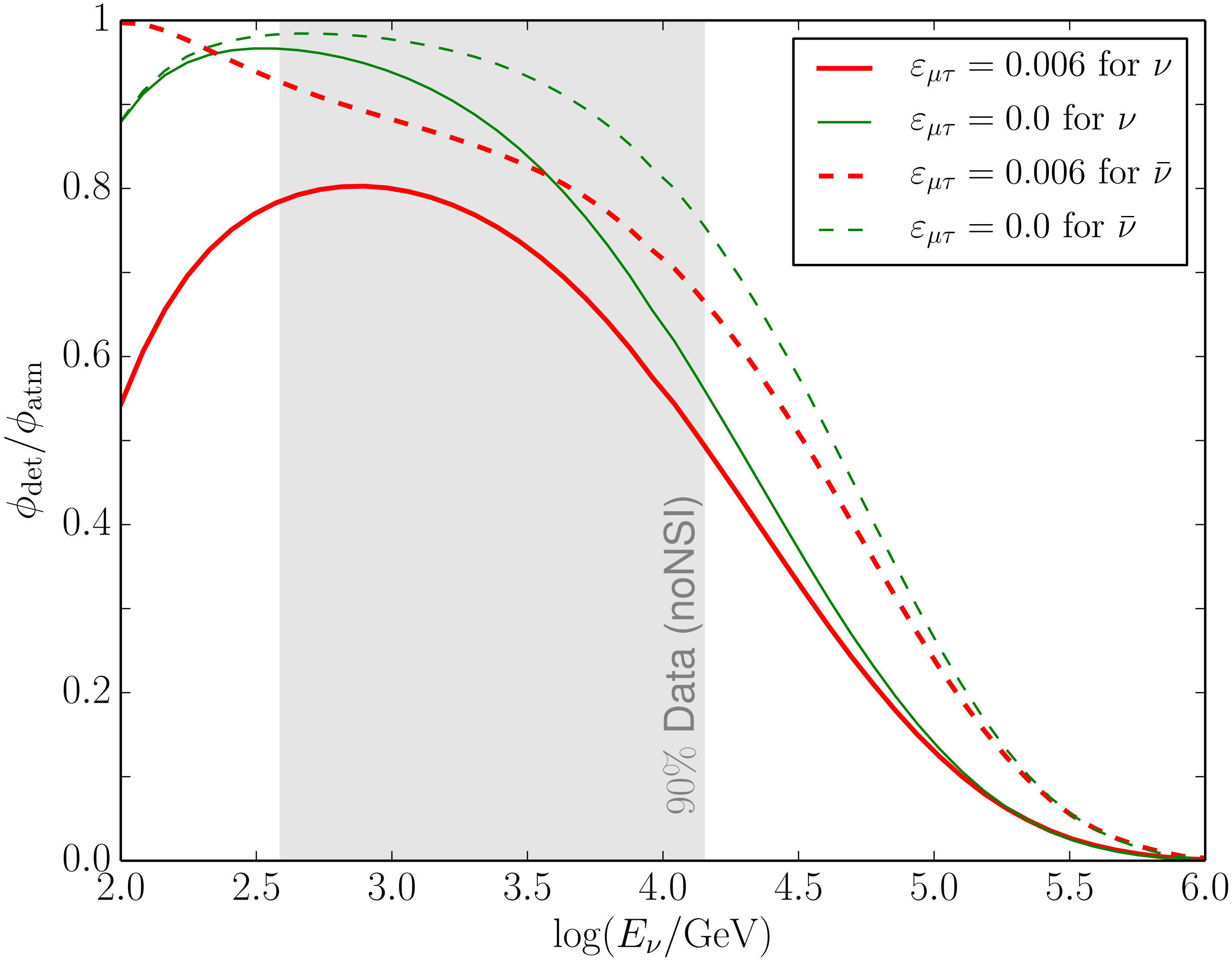
for $\phi_{\rm mat} \ll 1$ $\quad P(\nu_\mu \to \nu_\tau) \simeq \left(\sin^2 2\xi\right)\, \phi_{\rm mat}^2 = \left(\varepsilon_{\mu\tau}\, V_d\, L\right)^2$

and the same for antineutrinos

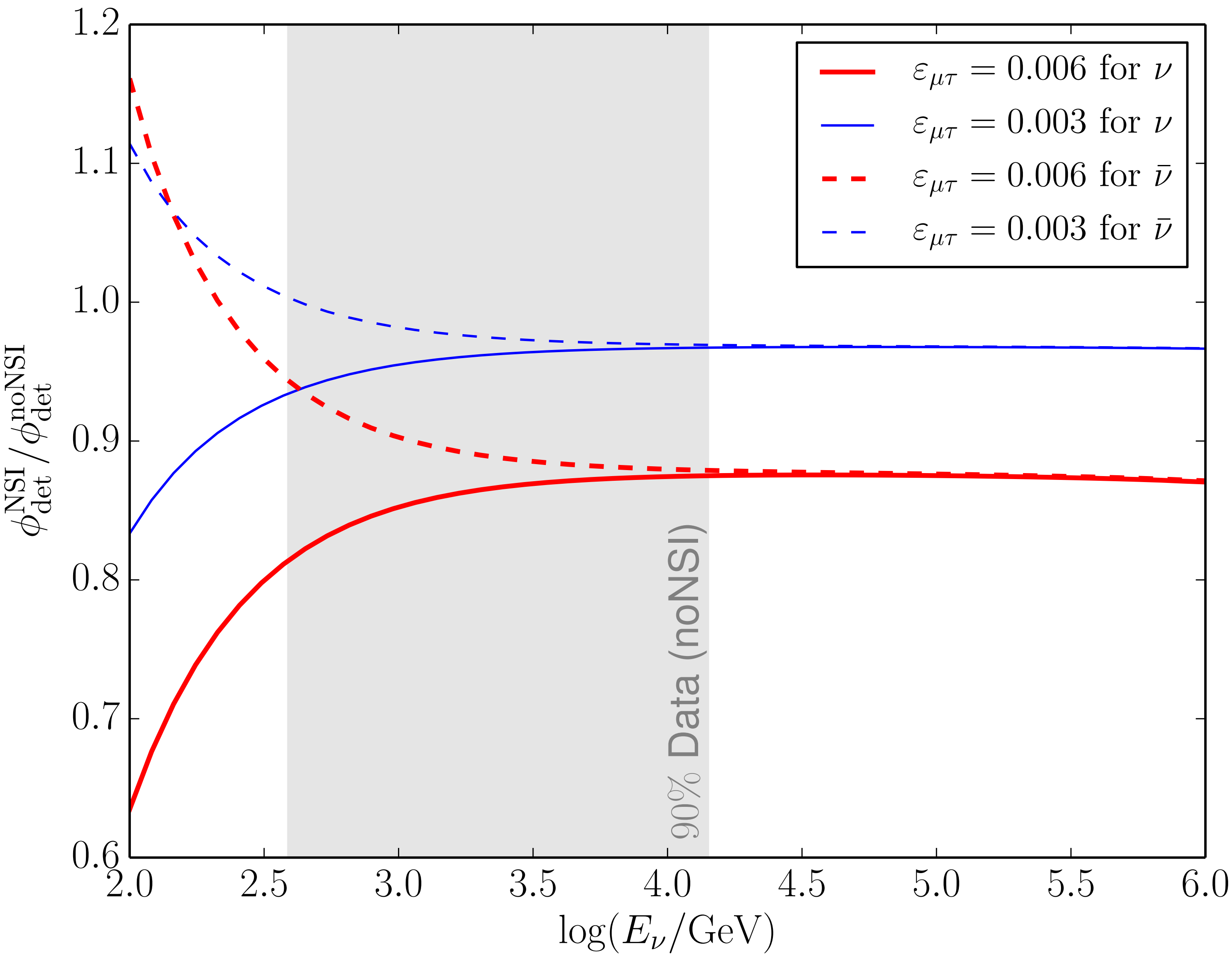
- Numerical solution of the full 3ν propagation equations: publicly available libraries SQuIDS and ν-SQuIDS

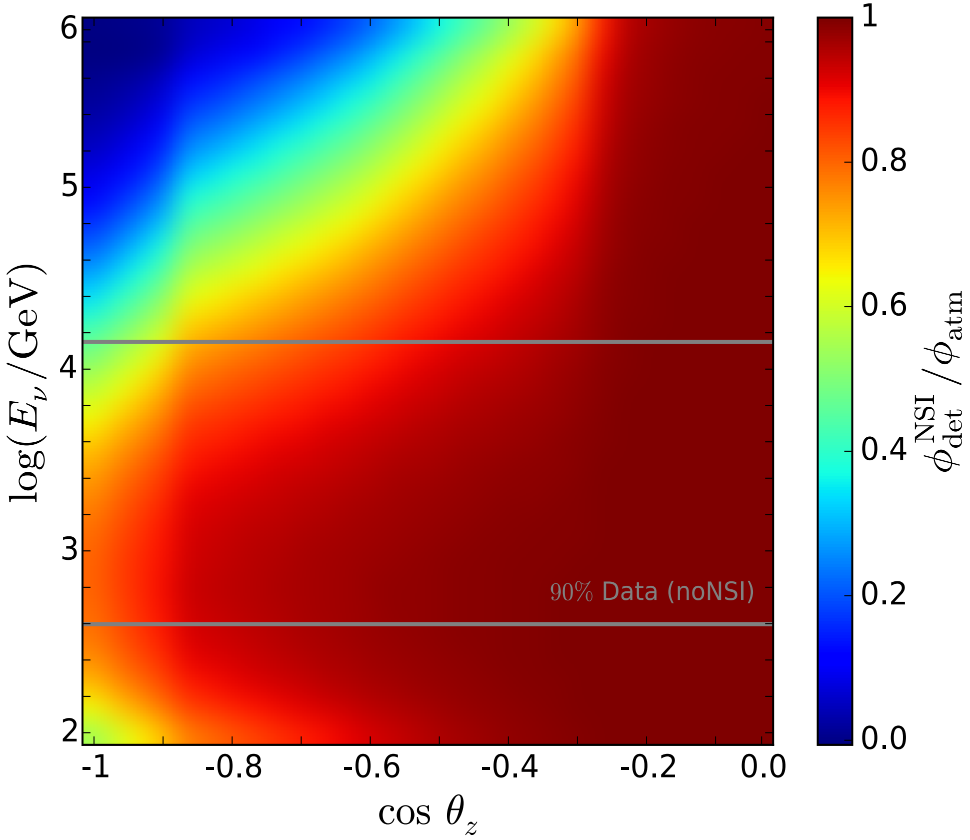
Arguelles Delgado, Salvado, Weaver, 2016

$\varepsilon' = 0$ $\cos\theta_z = -1$



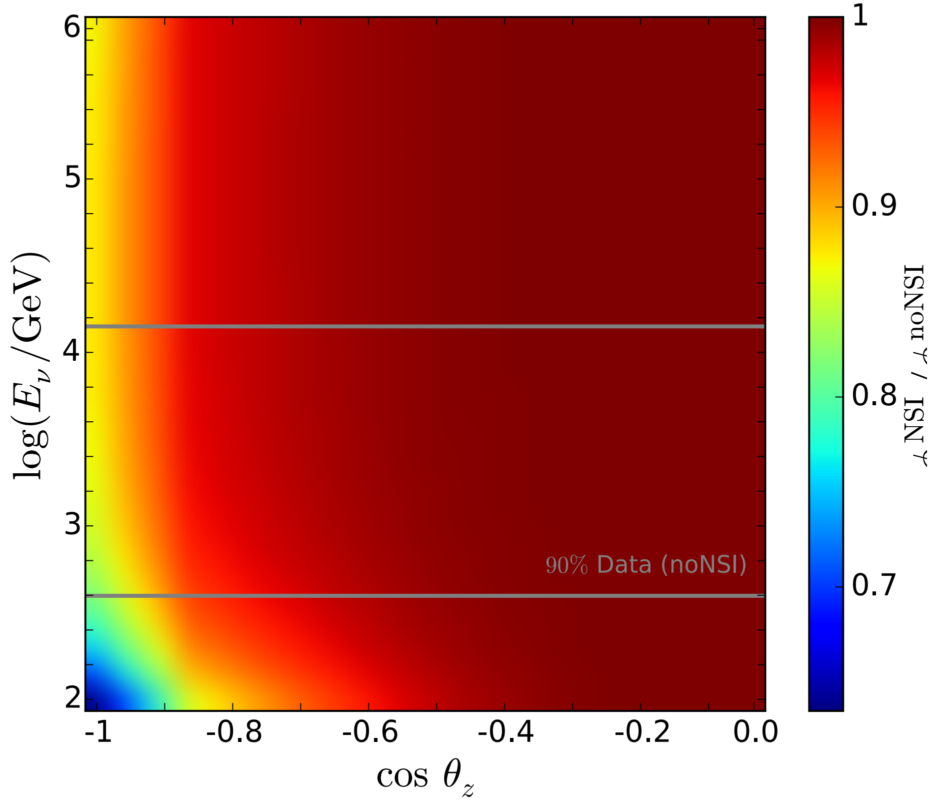
$\varepsilon' = 0 \qquad \cos\theta_z = -1$





$$\varepsilon_{\mu\tau} = 0.006$$

$$\varepsilon' = 0$$



- Data: 2011-2012 IceCube 86-string configuration, through-going muon tracks
- Two primary cosmic-ray flux (HG-GH-H3a, ZS) and two hadronic models (QGSJET-II-4 and SIBYLL2.3)
- Systematics:
  - flux normalization, N
  - π/K ratio
  - spectral index $\Delta\gamma$ (tilt in the energy spectrum)
  - DOM_{eff}: uncertainty in the optical efficiency
- Prior on ε' from SK limits

$$|\varepsilon'| = |\varepsilon_{\tau\tau} - \varepsilon_{\mu\mu}| < 0.049 \, , \qquad 90\% \text{ CL}$$

SK Collaboration 2011

- Current uncertainties in Δm^2_{31} , θ_{23}

Summary of parameter's ranges and priors:

Parameter	Default value	Range	Prior	Description
$\varepsilon_{\mu\tau}$	**0.006**	$[-1, 1]$	Flat	NSI flavor off-diagonal term
ε'	**0**	$[-1, 1]$	Gaussian: $\sigma = 0.04$	NSI flavor diagonal term
N	**1**	$[0.5, 2.0]$	Flat	Normalization of the energy spectrum
π/K	**1**	$[0.7, 1.5]$	Gaussian: $\sigma = 0.10$	Pion-to-kaon ratio contribution
$\Delta\gamma$	**0**	$[-0.2, 0.2]$	Gaussian: $\sigma = 0.05$	Tilt of the energy spectrum
$\mathrm{DOM_{eff}}$	**0.99**	$[0.90, 1.19]$	Flat	Optical efficiency
$\Delta m^2_{31}/10^{-3}$ [eV^2]	**2.484**	$[2.3, 2.7]$	Gaussian: $\sigma = 0.048$	Atmospheric mass square difference
θ_{23} [°]	**49.3**	$[43.0, 54.4]$	Gaussian: $\sigma = 1.7$	Atmospheric mixing angle

- Likelihood:

$$\ln \mathcal{L}(\varepsilon_{\mu\tau}, \varepsilon'; \boldsymbol{\eta}) = \sum_{i \in \text{bins}} \left(N_i^{\text{data}} \ln N_i^{\text{th}}(\varepsilon_{\mu\tau}, \varepsilon'; \boldsymbol{\eta}) - N_i^{\text{th}}(\varepsilon_{\mu\tau}, \varepsilon'; \boldsymbol{\eta}) \right) - \frac{\varepsilon'^2}{2\,\sigma_{\varepsilon'}^2} - \sum_j \frac{(\eta_j - \eta_j^0)^2}{2\,\sigma_j^2}$$

- N_i^{th} , N_i^{data} are the expected number of events (number of data events) in bin i
- Public IceCube Monte Carlo: $(E_\nu, \boldsymbol{\theta}_z) \Longrightarrow (E_\mu^{rec}, \boldsymbol{\theta}_z^{rec})$

  https://icecube.wisc.edu/science/data/IC86-sterille-neutrino
- Nuissance parameters:

$$\boldsymbol{\eta} \equiv \{N, \pi/K, \Delta\gamma, \mathrm{DOM}_{\mathrm{eff}}, \Delta m_{31}^2, \theta_{23}\}$$

- Bayesian analysis with MultiNest nested sampling algorithm

Current bounds:

- SK limit: SK Collab. 2011

$$|\varepsilon_{\mu\tau}| < 1.1 \times 10^{-2} \qquad 90\% \text{ C.L.}$$

- 79-string IceCube configuration + DeepCore data:

$$-6.1 \times 10^{-3} < \varepsilon_{\mu\tau} < 5.6 \times 10^{-3} \,, \qquad 90\% \text{ C.L.}$$

Esmaili, Smirnov 2013

- Analysis of 3-year IceCube-DeepCore data:

$$-6.7 \times 10^{-3} < \varepsilon_{\mu\tau} < 8.1 \times 10^{-3} \qquad 90\% \text{ C.L.} \qquad \varepsilon' = 0$$

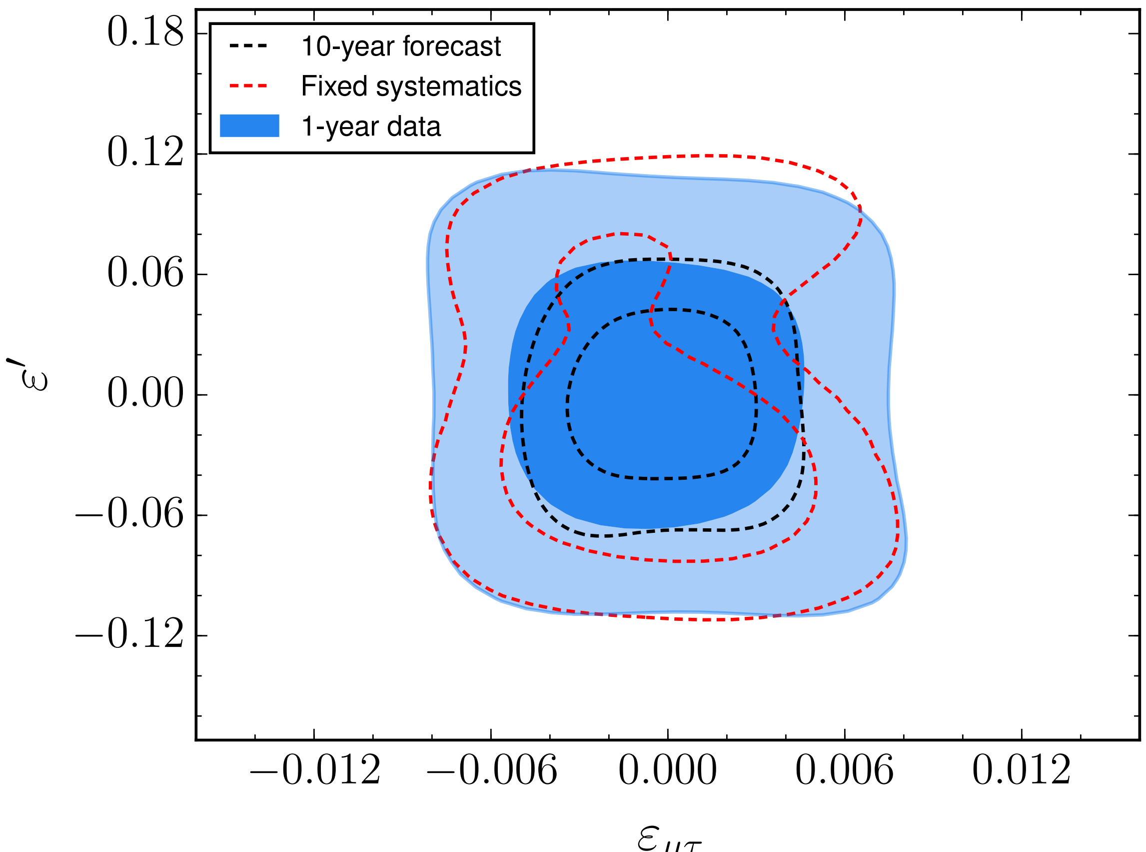
IceCube collaboration, arXiv:1709.07079

- Our limit (HG-GH-H3a + QGSJET-II-49):

$$-6.0 \times 10^{-3} < \varepsilon_{\mu\tau} < 5.4 \times 10^{-3} \,, \qquad 90\% \text{ credible interval (C.I.).}$$

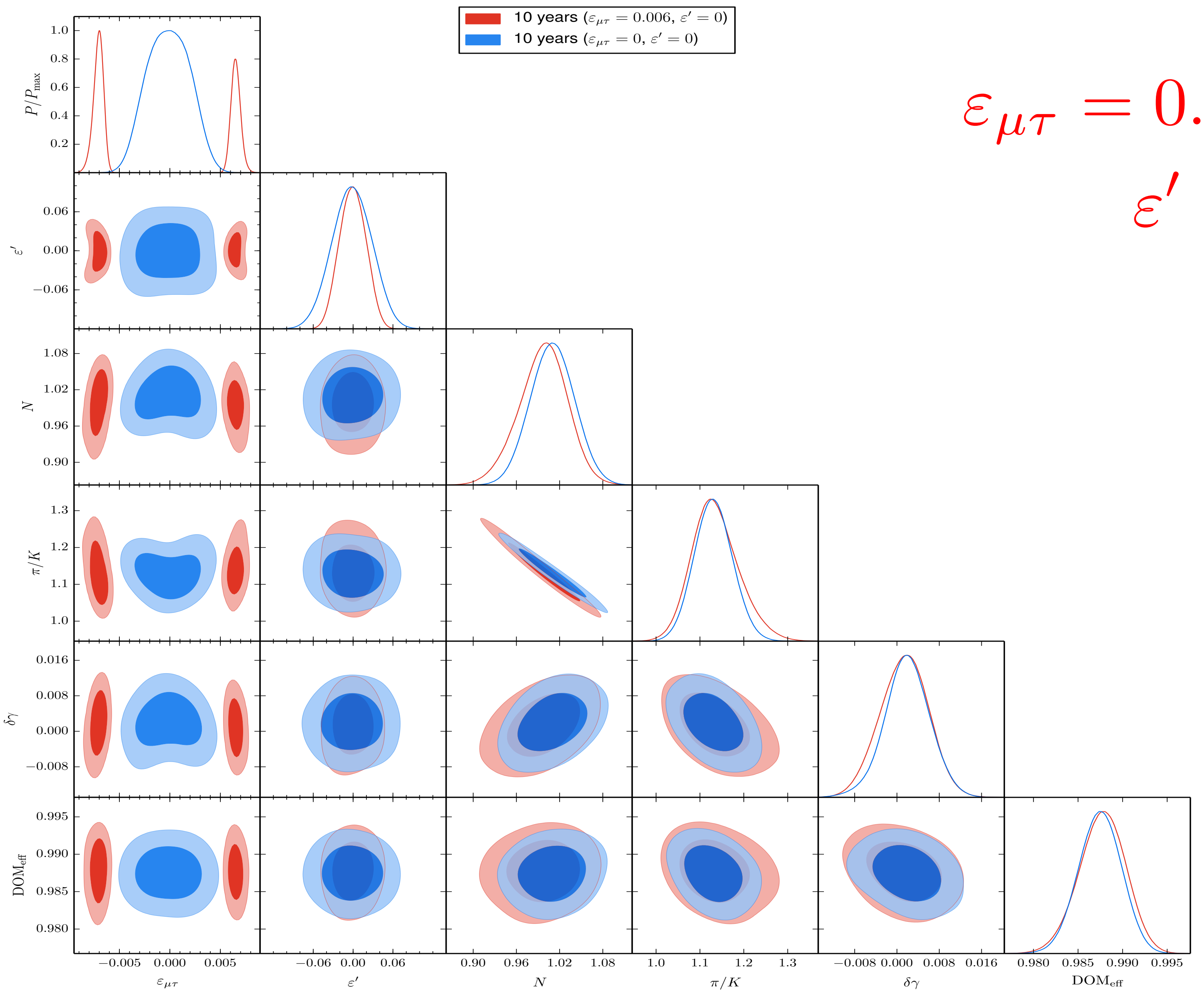
Salvado et al. 2016

Ten year forecast, assuming no NSI



HG-GH-H3a + QGSJET-II-49, fixed Δm^2_{31} , θ_{23}

$$-3.3 \times 10^{-3} < \varepsilon_{\mu\tau} < 3.0 \times 10^{-3} \qquad 90\% \text{ C.I.}$$



$$\varepsilon_{\mu\tau} = 0.006$$

$$\varepsilon' = 0$$

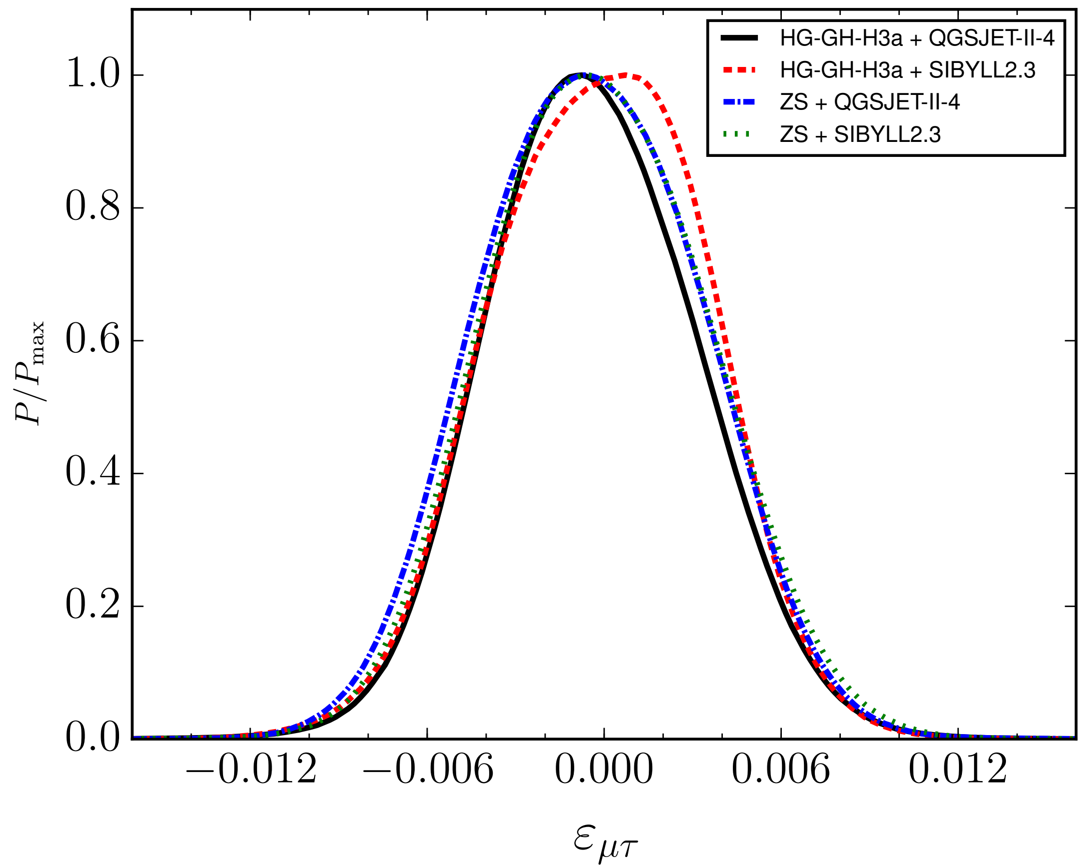
4. SUMMARY

- High energy atmospheric neutrinos at IceCube are a powerful tool to constrain new physics: NSI

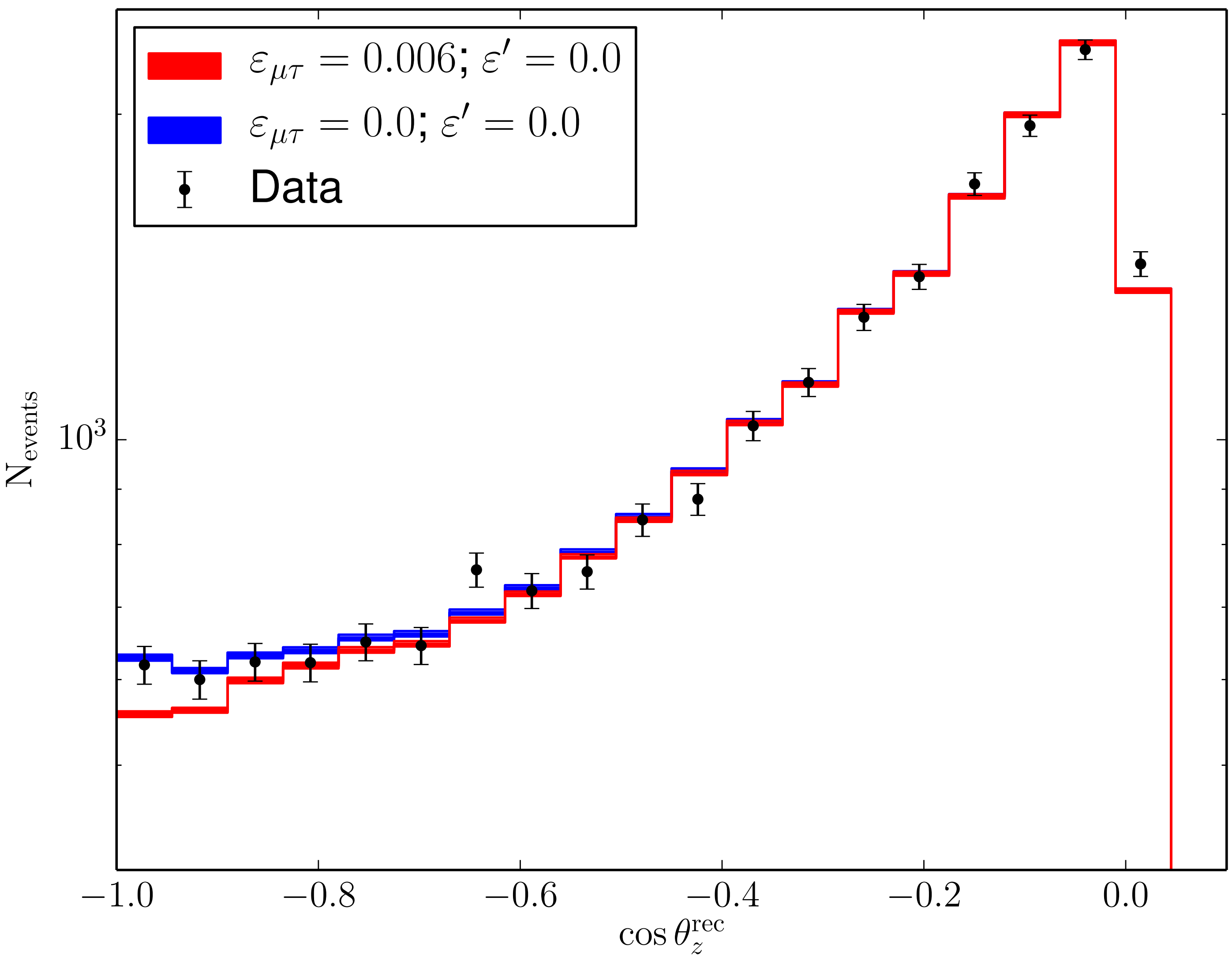
- One year data analysis: $-6.0 \times 10^{-3} < \varepsilon_{\mu\tau} < 5.4 \times 10^{-3}$ including systematic uncertainties **(90% C.I.)**

- Ten year data: sensitive to $\varepsilon_{\mu\tau}$ close to current bound, or improve to $-3.3 \times 10^{-3} < \varepsilon_{\mu\tau} < 3.0 \times 10^{-3}$

THANK YOU !



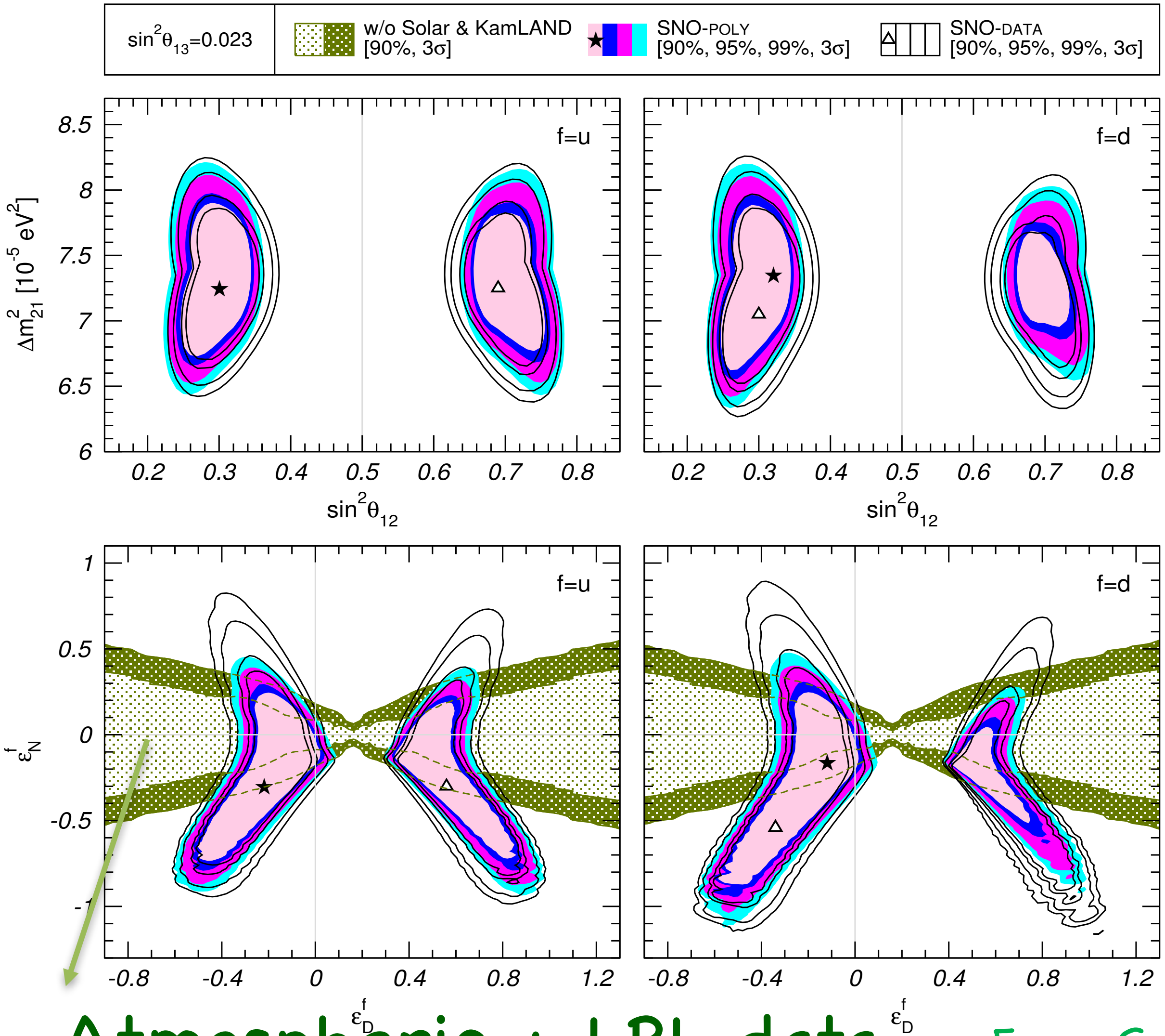
Posterior $\epsilon_{\mu\tau}$ probabilities for the different primary cosmic-rays and hadronic models, marginalizing wrt other parameters.



$\varepsilon_{\mu\tau} = 0.006;\ \varepsilon' = 0.0$
$\varepsilon_{\mu\tau} = 0.0;\ \varepsilon' = 0.0$
Data
N_{events}
10^3
-1.0
-0.8
-0.6
-0.4
-0.2
0.0
$\cos\theta_z^{\text{rec}}$

Solar & KamLAND fit: LMA – Dark solution ($\theta_{12} > \pi/4$)

Miranda, Tortola, Valle 2004



ε^f_N, ε^f_D are linear combinations of mixing angles and NSI NC $\varepsilon^f_{\alpha\beta}$

Two neutrino oscillations in the $\Delta m^2_{31} \to \infty$ limit

Atmospheric + LBL data

From González-García and Maltoni, 2013