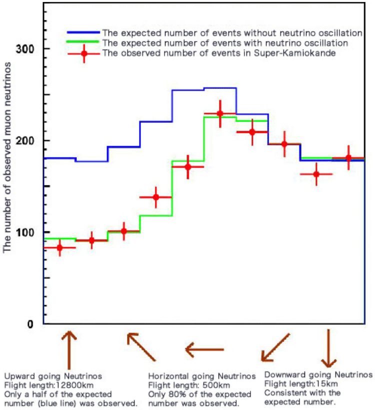
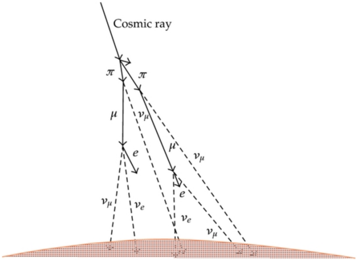
Searching eV-scale sterile neutrino in Atmospheric Neutrino Experiments

Jordi Salvado

Advanced Workshop on Physics of Atmospheric Neutrinos - PANE

Atmospheric neutrinos where crucial (announced 1998)



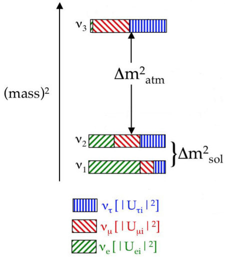


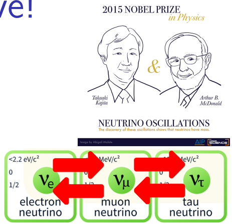
- Proton decay experiments see neutrinos missing in some zenith directions:

  Takaaki Kajita

- Oscillation with small matter effect was the answer!
  $|\Delta m^2_{\mathrm{atm}}| = 2.534 \times 10^{-3}\mathrm{eV}^2$

Neutrinos are massive!



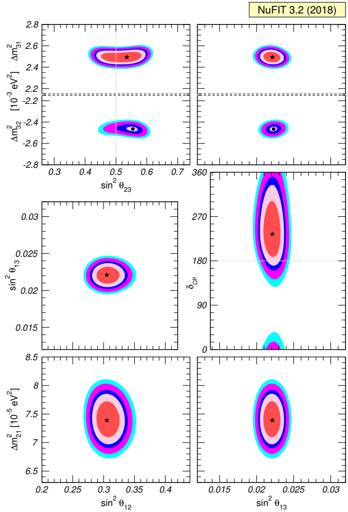


$$\Delta m^2_{\rm sol} = 7.50 \times 10^{-5}\,{\rm eV}^2$$

$$|\Delta m^2_{\rm atm}| = 2.534 \times 10^{-3}\,{\rm eV}^2$$

NuFIT 3.2 (2018)

$$|U|_{3\sigma} = \begin{pmatrix} 0.799 \to 0.844 & 0.516 \to 0.582 & 0.141 \to 0.156 \\ 0.242 \to 0.494 & 0.467 \to 0.678 & 0.639 \to 0.774 \\ 0.284 \to 0.521 & 0.490 \to 0.695 & 0.615 \to 0.754 \end{pmatrix}$$



[B. Kayser, hep-ph/0506165 (2004)]

[Fig. from: Ivan Esteban et. al. JHEP 01 (2017) 087 www.nu-fit.org]

[F.Capozzi et al. Arxiv:1804.09678]

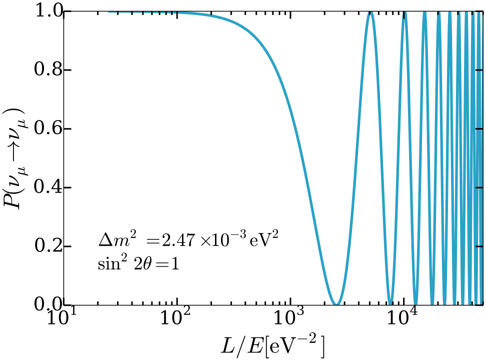
Neutrino Oscillations

$$H = \frac{1}{2E} U M^2 U^\dagger + V_m$$

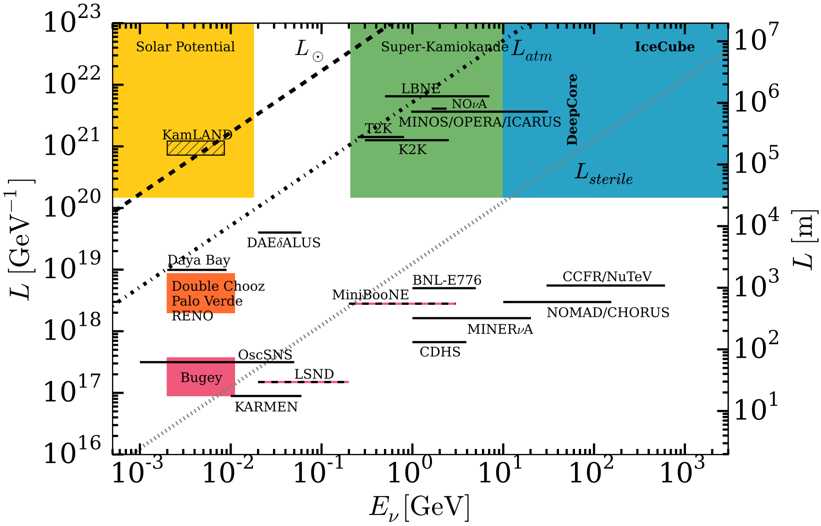
M, V and U are 3×3 matrices. In two generations the oscillation probability at a given distance L and energy E in vacuum

$$P_{\nu_\alpha \to \nu_\alpha}\left(\frac{L}{E}\right) = 1 - \sin^2 2\theta \sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

- $\sin^2 2\theta$: oscillation amplitude
- Δm^2: oscillation frequency
  - $L/E \ll 1/\Delta m^2$ → no oscillations
  - $L/E \sim 1/\Delta m^2$ → oscillations
  - $L/E \gg 1/\Delta m^2$ → fast oscillations ("averaged")



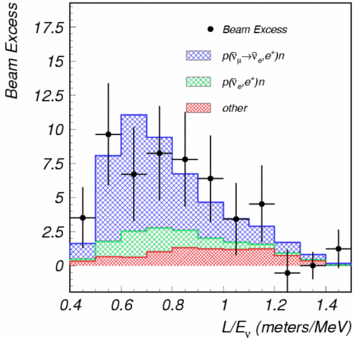
Experiments: $L_{\rm osc} = 2\pi \frac{E}{\Delta m^2} \mid \Delta m^2_{\rm LSND} = 1 eV^2$

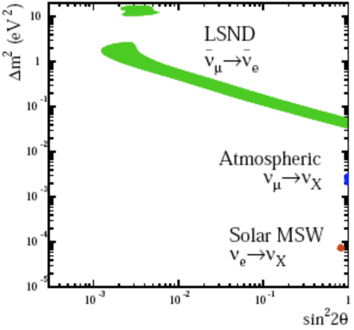


[modified from J.S. Diaz and V.A. Kostelecky, Phys.Lett. B700, 25 (2011)]

Why eV? The LSND experiment (90's)

- The LSND experiment saw an excess of $\bar{\nu}_e$ over background.
- 3.8σ signal.





More motivation: short baseline anomalies

- **LSND** found $\bar{\nu}_\mu \to \bar{\nu}_e$ **oscillation** with $\Delta m^2 \sim 1eV^2$ and $\sin^2 2\theta \sim 0.003$

- MiniBoone $\nu_\mu \to \nu_e$ and $\bar{\nu}_\mu \to \bar{\nu}_e$ appearance
  - No significant excess at high energies (E $>$ 475 MeV)
  - Unexplained events at low energies, interpretation as oscillations similar to LSND: $\Delta m^2 \sim 1eV^2$
  - New result today! arxiv:1805.12028 4.5σ 6.1σ with LSND

- Gallium Anomaly, SAGE and GALLEX event rates lower than expected, can be explained by ν_e disappearance with $\Delta m^2 \geq 1eV^2$

For a current global status:

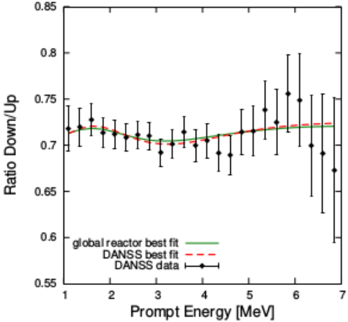
Mona Dentler et al. arXiv:1803.10661

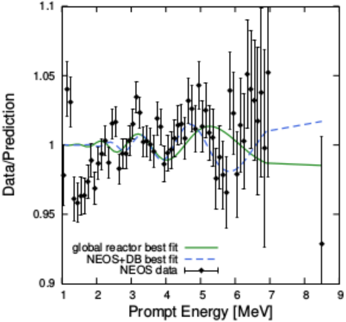
S. Gariazzo, et.al., JHEP 06 (2017) 135

G. H. Collin, et al., Phys. Rev. Lett. 117, 221801 (2016)

More motivation: New data in reactors

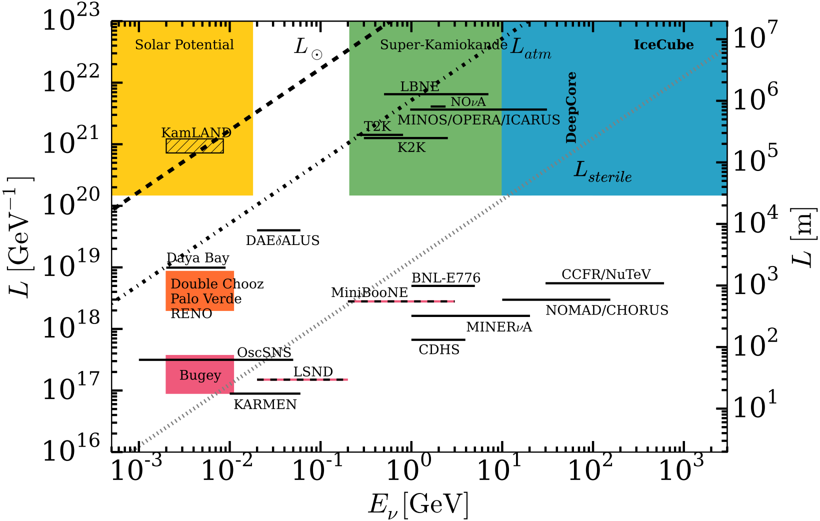
- New reactor flux calculation (Mueller et al., 1101.2663, P. Huber, 1106.0687) 3% higher, tension in short-baseline ($L \leq 100m$) experiments.
- After the 5MeV bump we have new DANSS and NEOS results more independent of the flux calculation!





Y. Ko et al., Phys. Rev. Lett. 118 (2017)
M. Danilov, Moriond EW 2017
Mona Dentler et al. JHEP 1711 (2017) 099
C.Giunti, et al. JHEP 10 (2017) 143.

Experiments: $L_{\text{osc}} = 2\pi \frac{E}{\Delta m^2} \mid \Delta m^2_{\text{LSND}} = 1eV^2$



[modified from J.S. Diaz and V.A. Kostelecky, Phys.Lett. B700, 25 (2011)]

Averaged ATM neutrinos

$$|\nu_\alpha\rangle = \sum_i U^*_{\alpha i} |\nu_i\rangle$$

The mixing matrix for n neutrino flavours can be decomposed as the product of $n(n-1)/2$ rotations.

$$U = V_{3n} V_{2n} V_{1n} V_{3(n-1)} V_{2(n-1)} V_{1(n-1)} \cdots V_{34} V_{24} V_{14} \underbrace{V_{23} V_{13} V_{12}}_{=U_0}$$

with

$$(V_{ij})_{ab} = \begin{cases} \cos(\theta_{ij}), & a = b \in \{i,j\} \\ \sin(\theta_{ij}) e^{i\delta_{ij}}, & a = i,\ b = j \\ -\sin(\theta_{ij}) e^{-i\delta_{ij}}, & a = j,\ b = i \\ 1, & a = b \notin \{i,j\} \\ 0, & \text{otherwise} \end{cases}$$

Similar framework in Hisakazu Minakata talk

Averaged ATM neutrinos

$$U = \mathcal{U} U_0 = \begin{pmatrix} 1-\alpha & \Theta \\ X & Y \end{pmatrix} \begin{pmatrix} U_\nu & 0 \\ 0 & 1 \end{pmatrix} = \begin{pmatrix} (1-\alpha) U_\nu & \Theta \\ X U_\nu & Y \end{pmatrix}$$

$$\alpha = \begin{pmatrix} \alpha_{ee} & 0 & 0 \\ \alpha_{\mu e} & \alpha_{\mu\mu} & 0 \\ \alpha_{\tau e} & \alpha_{\tau\mu} & \alpha_{\tau\tau} \end{pmatrix}$$

whose components to leading order in the active-heavy mixing elements are given by

$$\alpha_{\beta\gamma} \simeq \begin{cases} \frac{1}{2}\sum_{i=4}^{n} |U_{\beta i}|^2, & \beta = \gamma \\ \sum_{i=4}^{n} U_{\beta i} U_{\gamma_i}^*, & \beta > \gamma \\ 0, & \gamma > \beta \end{cases}$$

Averaged ATM neutrinos

$$\tilde{H} = \begin{pmatrix} H_0 & 0 \\ 0 & H_1 \end{pmatrix} + V_{\rm NC} \mathcal{U}^\dagger \begin{pmatrix} 1 & 0 \\ 0 & 0 \end{pmatrix} \mathcal{U}$$

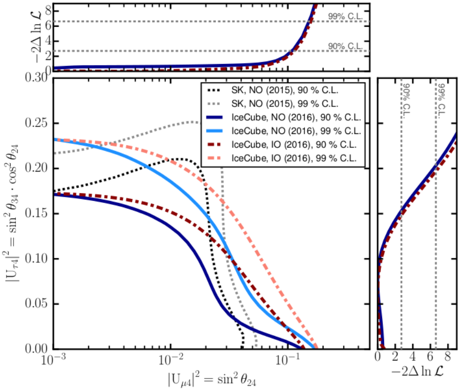
$$\tilde{H}_0 = H_0 + V_{\rm NC}(1 - \alpha^\dagger)(1 - \alpha) \simeq H_0 - V_{\rm NC}(\alpha + \alpha^\dagger)$$

$$\tilde{H}_0 = \frac{\Delta m^2_{31}}{4E} \begin{pmatrix} -\cos(2\theta_{23}) & \sin(2\theta_{23}) \\ \sin(2\theta_{23}) & \cos(2\theta_{23}) \end{pmatrix} - V_{\rm NC} \begin{pmatrix} 2\alpha_{\mu\mu} & \alpha^*_{\tau\mu} \\ \alpha_{\tau\mu} & 2\alpha_{\tau\tau} \end{pmatrix}$$

- The averaged effect of sterile neutrinos is esencially a modification of the matter potential (NSI Arman Esmaili Talk)

eV steriles by SuperKamiokande and deepcore

- SuperKamikande and DC they both measure atmospheric neutrino oscillations and give a bound due to matter effects.
- eV is too heavy for this data samples to see oscillaitons, esencially a reparameterizaiton of the NSI result.



K. Abe et al. (Super-Kamiokande Collaboration), Phys. Rev. D91, 052019 (2015).
IceCube Collaboration, Phys. Rev. Lett.117 no. 7, (2016) 071801

Matter effects with the Sterile Neutrino at Earth

$$P_{\nu_\alpha \to \nu_\alpha} = 1 - \sin^2 2\theta_M \sin^2\left(\frac{\Delta {m_M}^2 L}{4E_\nu}\right)$$

where θ_M and Δm_M^2 satisfy

$$\Delta {m_M}^2 = \sqrt{(\Delta m^2 \cos 2\theta - A)^2 + (\Delta m^2 \sin 2\theta)^2}$$

$$\tan 2\theta_M = \frac{\tan 2\theta}{1 - \frac{A}{\Delta m^2 \cos 2\theta}}$$

and $A = \pm 2\sqrt{2} E G_F N$, N number density. Resonant flavor transition can happen if

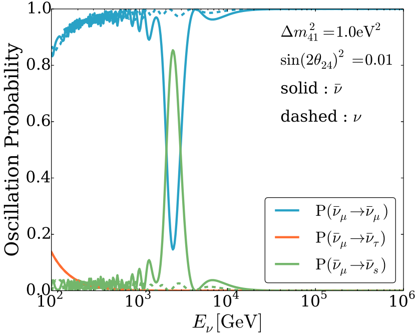
$$E_\nu^{res} = \mp \cos 2\theta \frac{\Delta m^2}{2N} \frac{1}{\sqrt{2} G_F}$$

this resonance can enhance the transition between active and sterile neutrinos. Talk by Alexei Smirnov

Matter effects with the Sterile Neutrino at Earth

In the **Earth**, sterile neutrino with small mixing and $\Delta m^2 = O(1eV^2)$ the resonance happens when

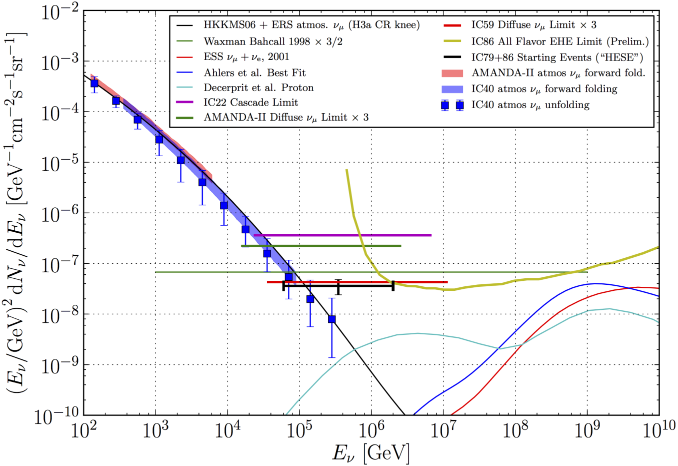
$$E_\nu^{res} = \frac{\Delta m^2 \cos 2\theta}{2\sqrt{2} G_F N} \sim O(TeV)$$



M.V. Chizhov, S.T. Petcov. Phys.Rev. D63 (2001) 073003
H. Nunokawa et al. Phys.Lett. B562 (2003) 279-290
Sandhya Choubey JHEP 0712 (2007) 014
Barger et al.,Phys.Rev.D85:011302,(2012)
Arman Esmaili et al. JCAP 1211 (2012) 041

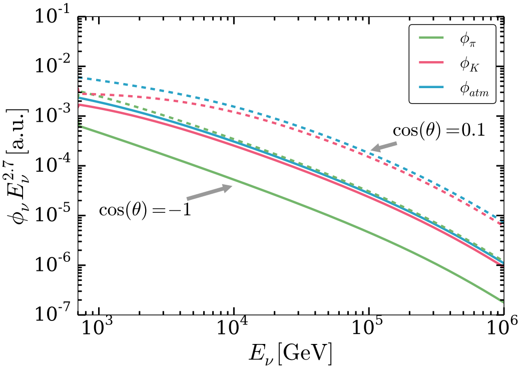
Matter effects with the Sterile Neutrino at Earth

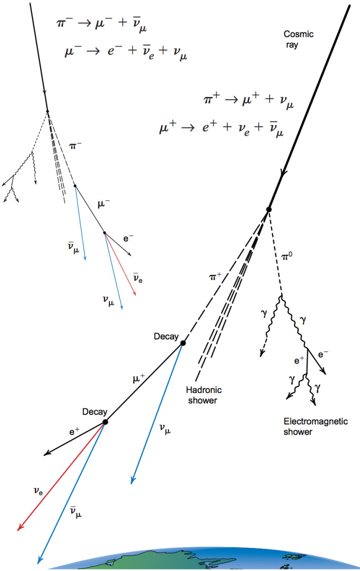
- TeV is in the center of the atmospheric data in IceCube.
- Other experiments are not sensitive at this energies.



The **initial** atmospheric neutrino flux

The conventional atmospheric neutrino (muon) flux originates from the decay of $\pi^{\pm}$ and $K^{\pm}$ in the atmosphere.





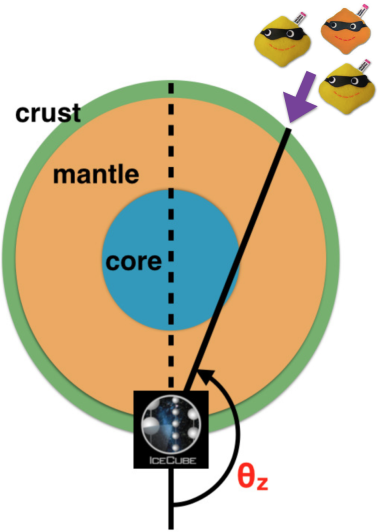
[Honda et al., Phys.Rev.D75:043006 (2007)]

[Louis et al., Los Alamos Science Number 25 (1997)]

we are improving, talks by Thomas K. Gaisser, Anatoli Fedynitch, Morihiro Honda

Neutrinos through the Earth

The muon neutrinos come from different zenith angles (θ_z) crossing different Earth layers



core :

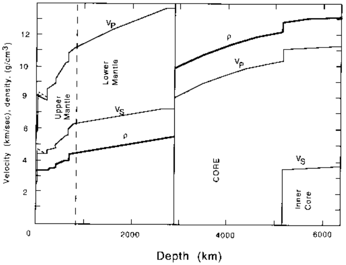
$\cos\theta_z \sim [-1, -0.8]$

mantle :

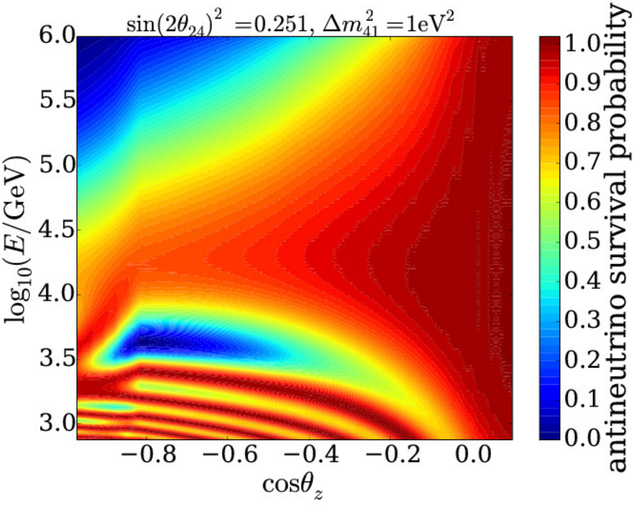
$\cos\theta_z \sim [-0.8, -0.1]$

crust :

$\cos\theta_z > -0.1$



3+1 Oscillogram



[Carlos Argüelles, J.S., C. Weaver. *SQuIDS*, CPC 2015.06.022.]

https://github.com/jsalvado/SQuIDS

https://github.com/arguelles/nuSQuIDS

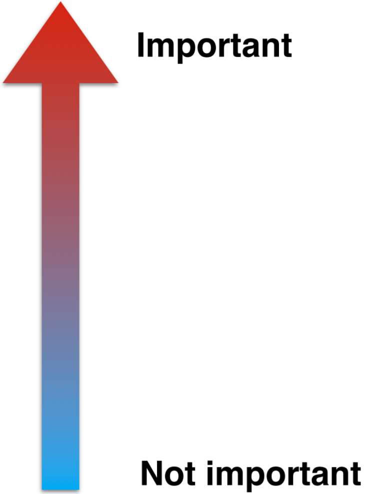
SQuIDS
Simple Quantum Integro Differential Solver

Systematic errors

Systematics are very important; *some more than others*. This are the systematics we considered:

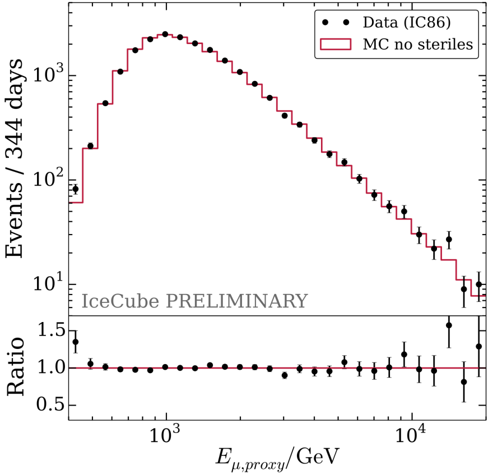
- *DOM efficiency*
- *Flux continuous parameters*
  - *spectral index*
  - π/K *ratio*
  - $\nu/\bar{\nu}$ *ratio*
- Air shower hadronic models
- Primary cosmic ray fluxes
- Hole Ice
- Neutrino cross sections
- Bulk ice scattering/absorption
- Earth model

continuous systematics
discrete systematic



How the fit looks

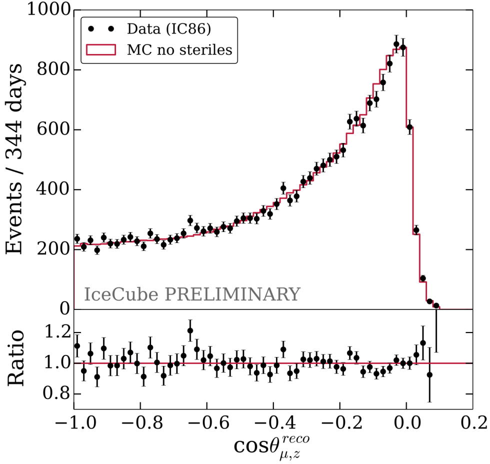
- We fitted the null hypothesis (no steriles) using the central sets (no variants) on the full 2D sample space.
- We recover a good fit and sensible nuisance parameters.



Parameter	Value	Prior
Normalization	1.02	No Prior
$\Delta\gamma$	0.05	G(0.,0.05)
DOMeff	0.985	No Prior
π/K	1.10	G(1.,0.1)
$\nu/\bar{\nu}$	1.0	G(1.,0.05)
δ	0.001	G(0.,0.05)

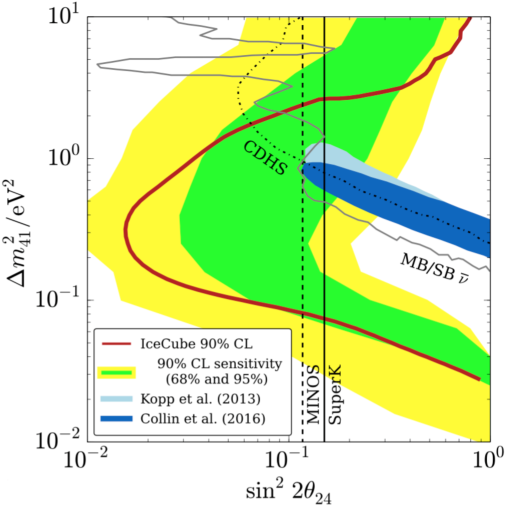
How the fit looks

- We fitted the null hypothesis (no steriles) using the central sets (no variants) on the full 2D sample space.
- We recover a good fit and sensible nuisance parameters.



Parameter	Value	Prior
Normalization	1.02	No Prior
$\Delta\gamma$	0.05	G(0.,0.05)
DOMeff	0.985	No Prior
π/K	1.10	G(1.,0.1)
$\nu/\bar{\nu}$	1.0	G(1.,0.05)
δ	0.001	G(0.,0.05)

Main result!

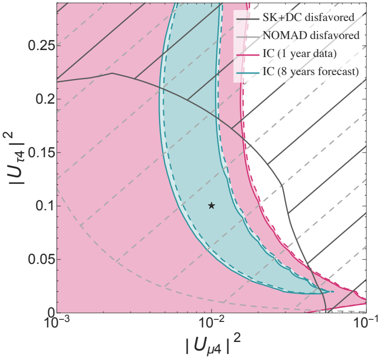


Phys.Rev.Lett. 117 (2016) no.7, 071801 [arXiv:1605.01990]

And if they are heavier? $> 10eV$

- Effectively a re-definition of the matter potential, a la NSI.

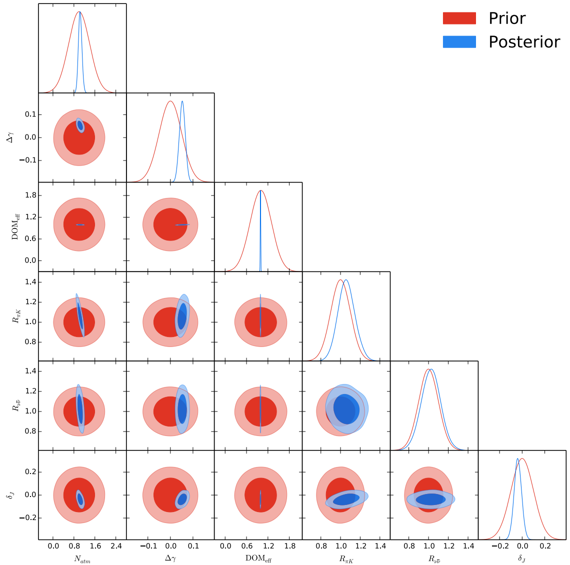
$$H = \frac{1}{2E_\nu} U M^2 U^\dagger + V_m$$



arXiv:1803.02362: Mattias Blennow, Enrique Fernandez-Martinez, Julia Gehrlein, Josu Hernandez-Garcia, J.S.

Continuous Systematics

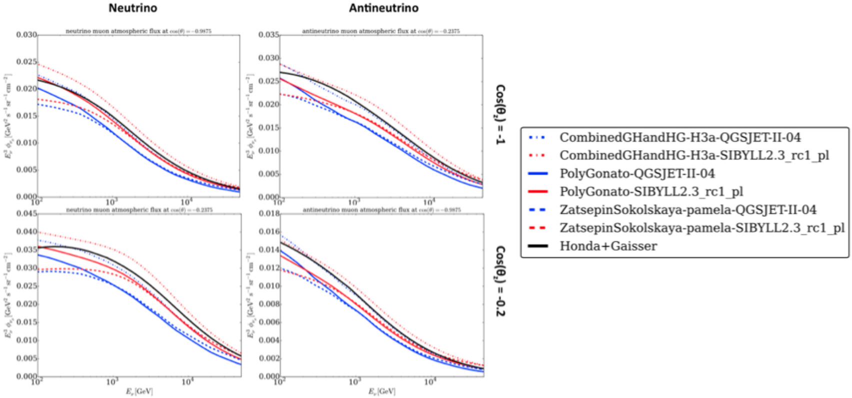
- Some of them like the DOMeff are well measured by the data.



From C.A.

More on Flux Systematics!

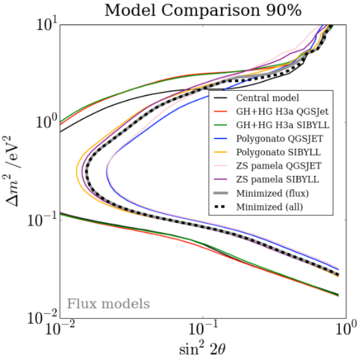
Main uncertainties in the neutrino flux are capture by the *continuous* parameters.
CR flux uncertainties and Hadronic models are discrete systematics

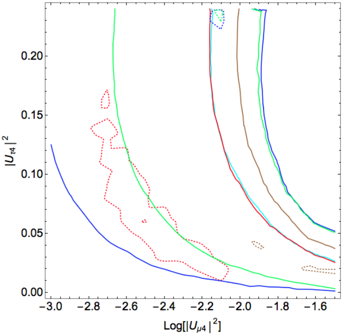


[Fedynitch et al. arXiv:1504.06639]
[Collins et al. URL: http://dspace.mit.edu/handle/1721.1/98078]

More on Flux Systematics!

- Discrete flux systematics have a big impact.
- Still OK treatment for 1year but an improvement is needed for future analysis.





More in C.Arguelles and B.J.P.Jones thesis

Conclusions

- Atm neutrinos are great! They constrain eV and heavier sterile neutrinos, specially in the high energy region due to the parametric resonance.
- Matter effect are essential in both cases(lowE and highE) therefore any modification of the matter effects change this bounds.(Yasaman Farzan and Danny Marfatia Talks)
- In the next updates O(10yrs) systematic errors are becoming important.
- Our knowledge of the flux is going to be limiting all the BSM searches in the future, better knowledge or treatment is very important (talks by Thomas K. Gaisser, Anatoli Fedynitch, Morihiro Honda)

¡Thanks!