Sterile Neutrinos in IceCube

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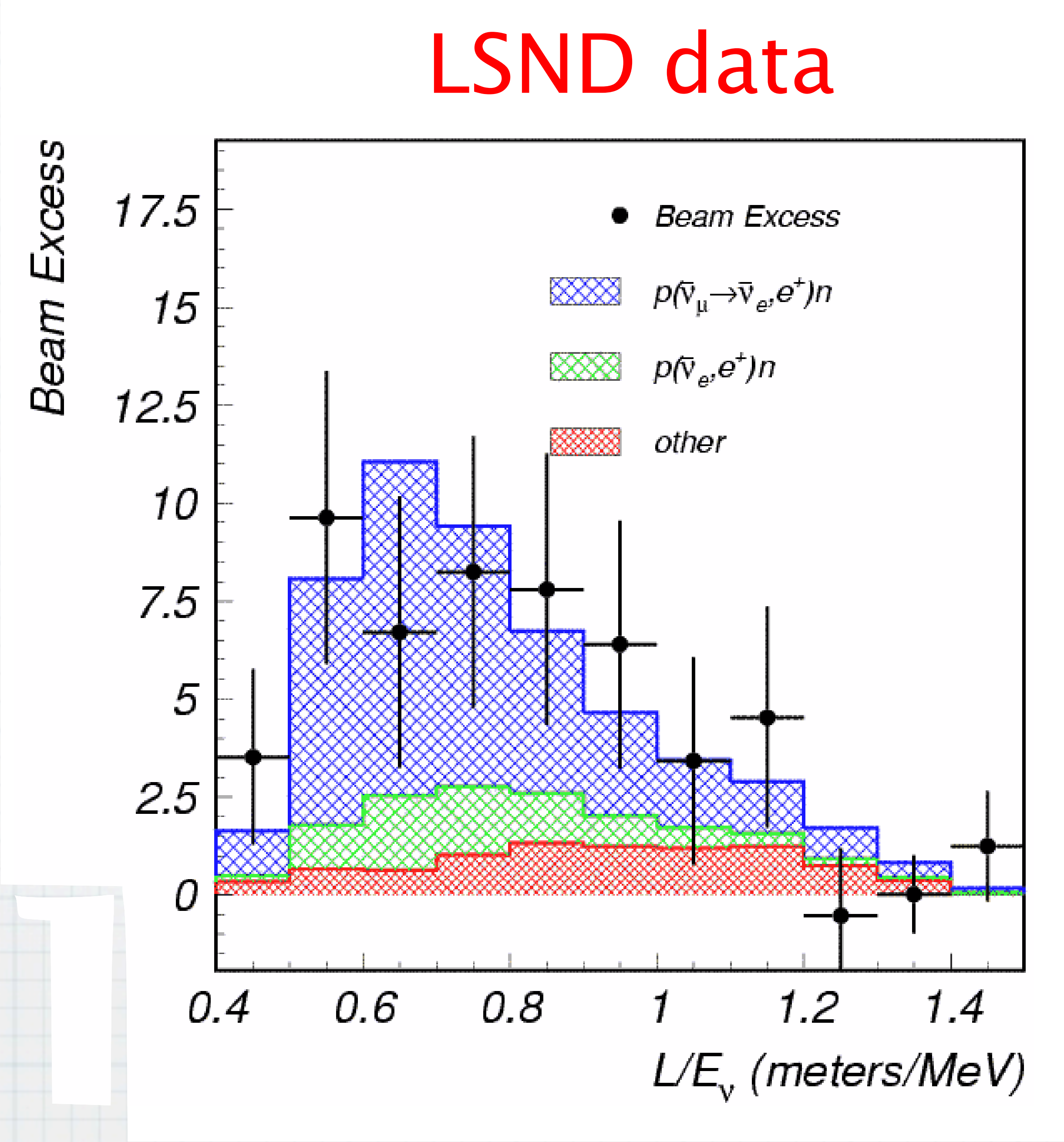
What is nu? Invisibles 12 & Alexei Smirnov Fest
GGI Firenze, June 25 - 29, 2012

First there was LSND...

* 3.8σ excess in antineutrinos at L/E ≈ 0.4-1.2 m/MeV

* requires presence of sterile neutrino states with $\Delta m^2 = 1$ eV^2



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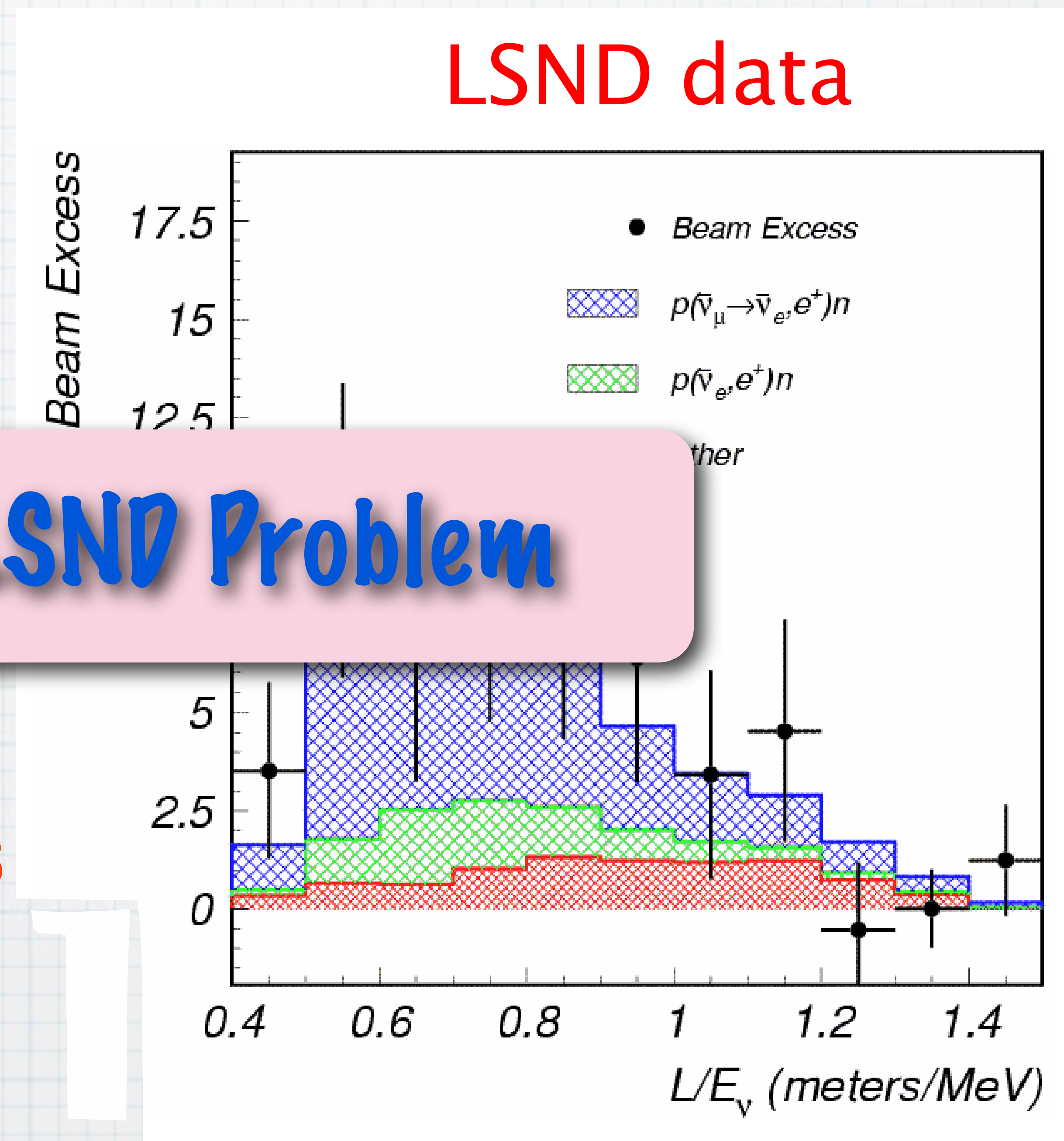


The LSND Problem

and then MiniBooNE...

* The idea was to specifically test the LSND signal

* Since oscillations depend on L/E......

* The L/E was chosen to be the same as LSND

* Expectation was that if there is no excess at this same L/E, then LSND would be refuted

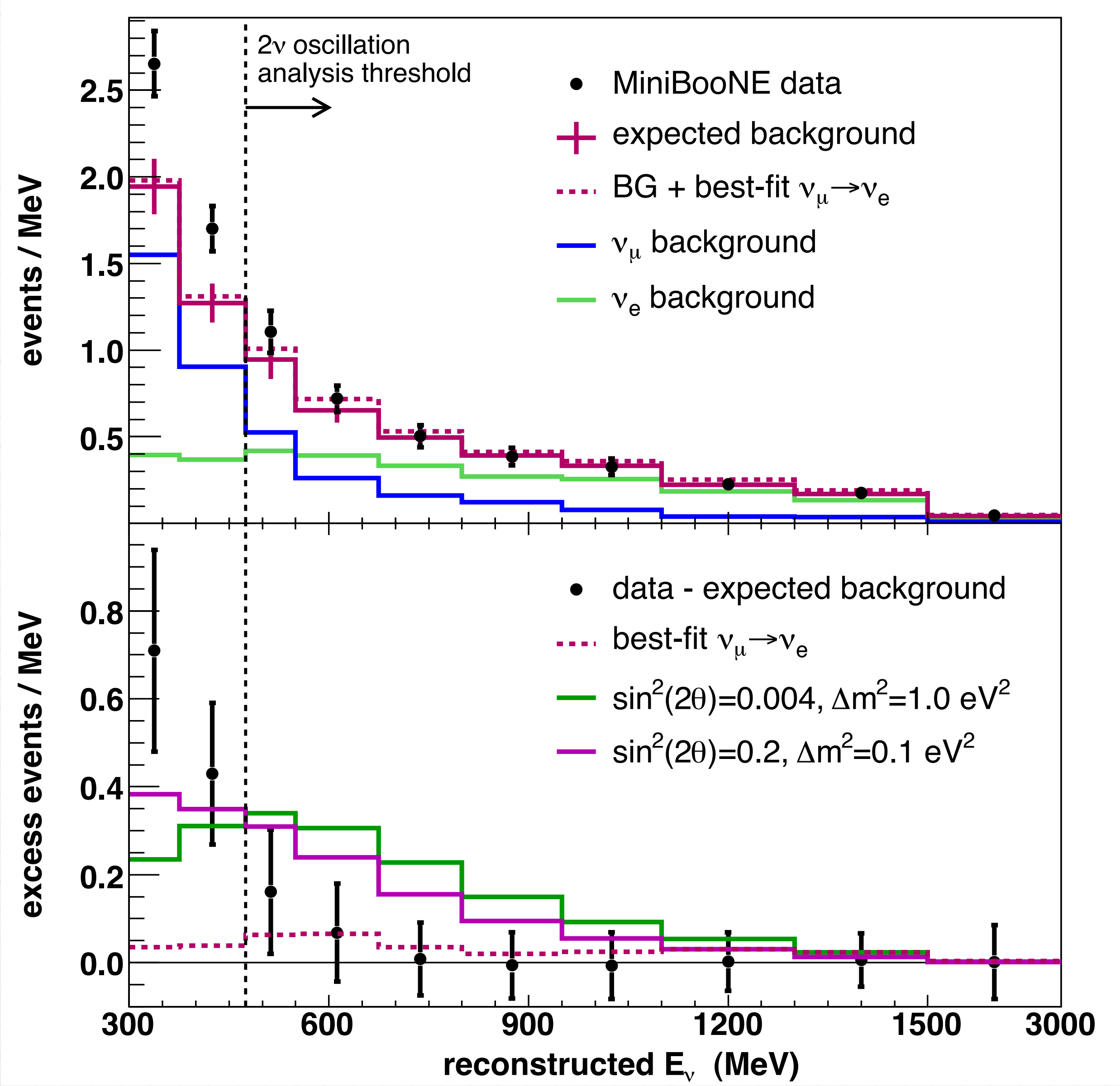
MiniBooNE (2007)

April 7, 2007
Press Release

"The MiniBooNE results **resolve** questions raised by observations of the LSND.....

MiniBooNE researchers showed **conclusively** that the **LSND results could not be due to simple neutrino oscillation,....** "

arxiv:0704.1500



MiniBooNE (2007)

April 7, 2007 Press Release

* "It was very important to verify or refute the surprising LSND result," said Robin Staffin, DOE Associate Director of Science for High Energy Physics. "The MiniBooNE experiment was an important one to do and is to be complimented for a job well done."

* "We are delighted to see that the work of the MiniBooNE team has led to the resolution of this puzzle," said Marv Goldberg, Program Director for Elementary Particle Physics at the National Science Foundation. "

* As in many particle physics experiments, we have a result that answers some questions and raises others," said MiniBooNE co-spokesperson William Louis, Los Alamos National Laboratory, who also worked on the original LSND experiment. "We live in interesting times."

* "It is great to get the MiniBooNE results out," said Fermilab Director Pier Oddone. "It clears one mystery but it leaves us with a puzzle that is important to understand."

MiniBooNE (2007)

But wait...LSND saw oscillations in anti-neutrinos

MiniBooNE 2007 data was for neutrinos....

↓

CPT violation?

No...only CP violation is enough...
add 2 sterile neutrinos .....
(3+2) mass spectrum

Sorel, Conrad, Shaevitz 0305255

Maltoni, Schwetz, 0705.0107

Karagiorgi et al, 0906.1997

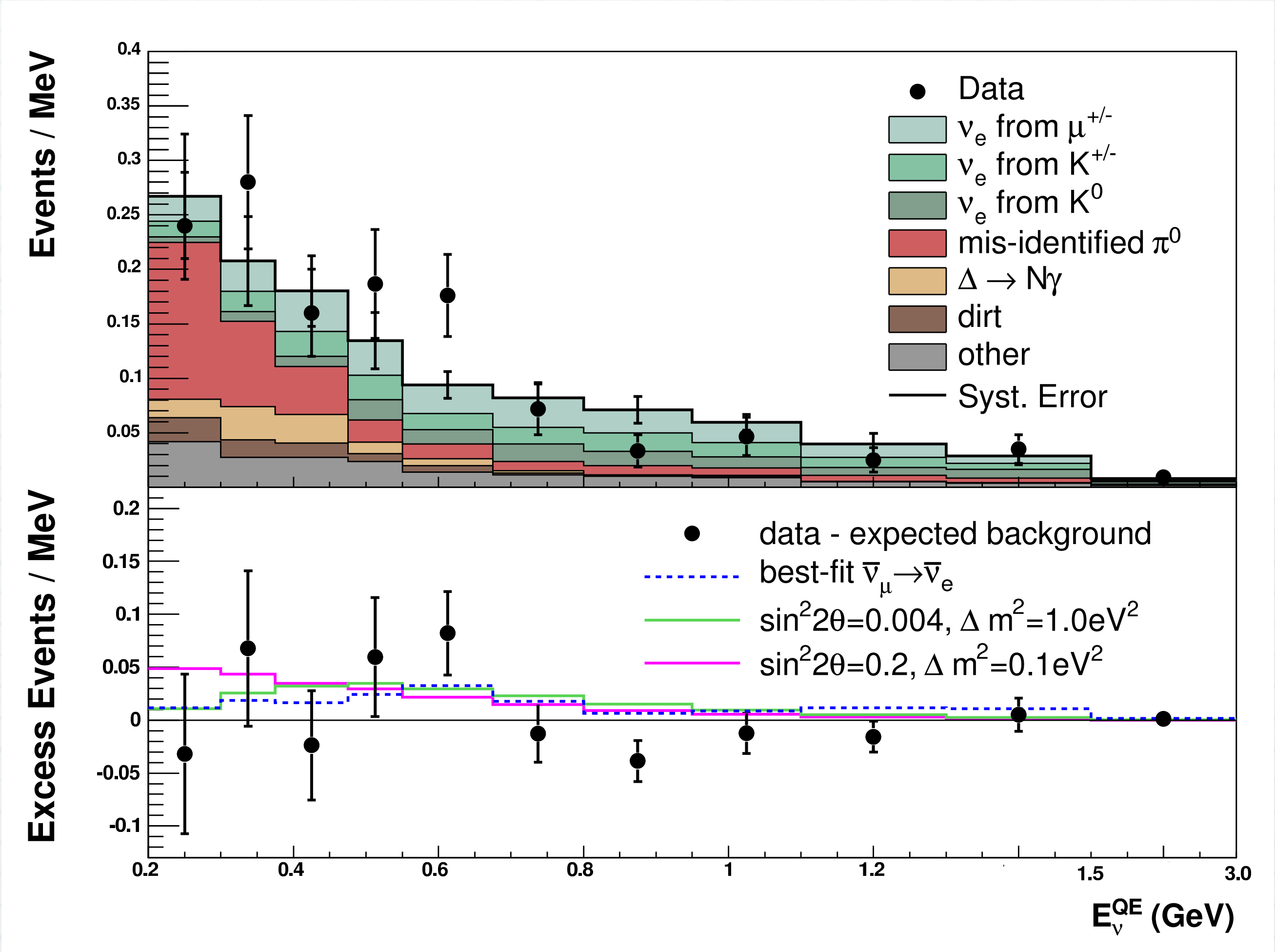
MiniBooNE (2009)

From the abstract

arxiv:0907.1958

antineutrino data sample corresponding to 3.39×10^{20} protons on target

"No significant excess of events has been observed......
The data are **inconclusive** with respect to antineutrino oscillations suggested by data from the **Liquid Scintillator Neutrino Detector** at Los Alamos National Laboratory."



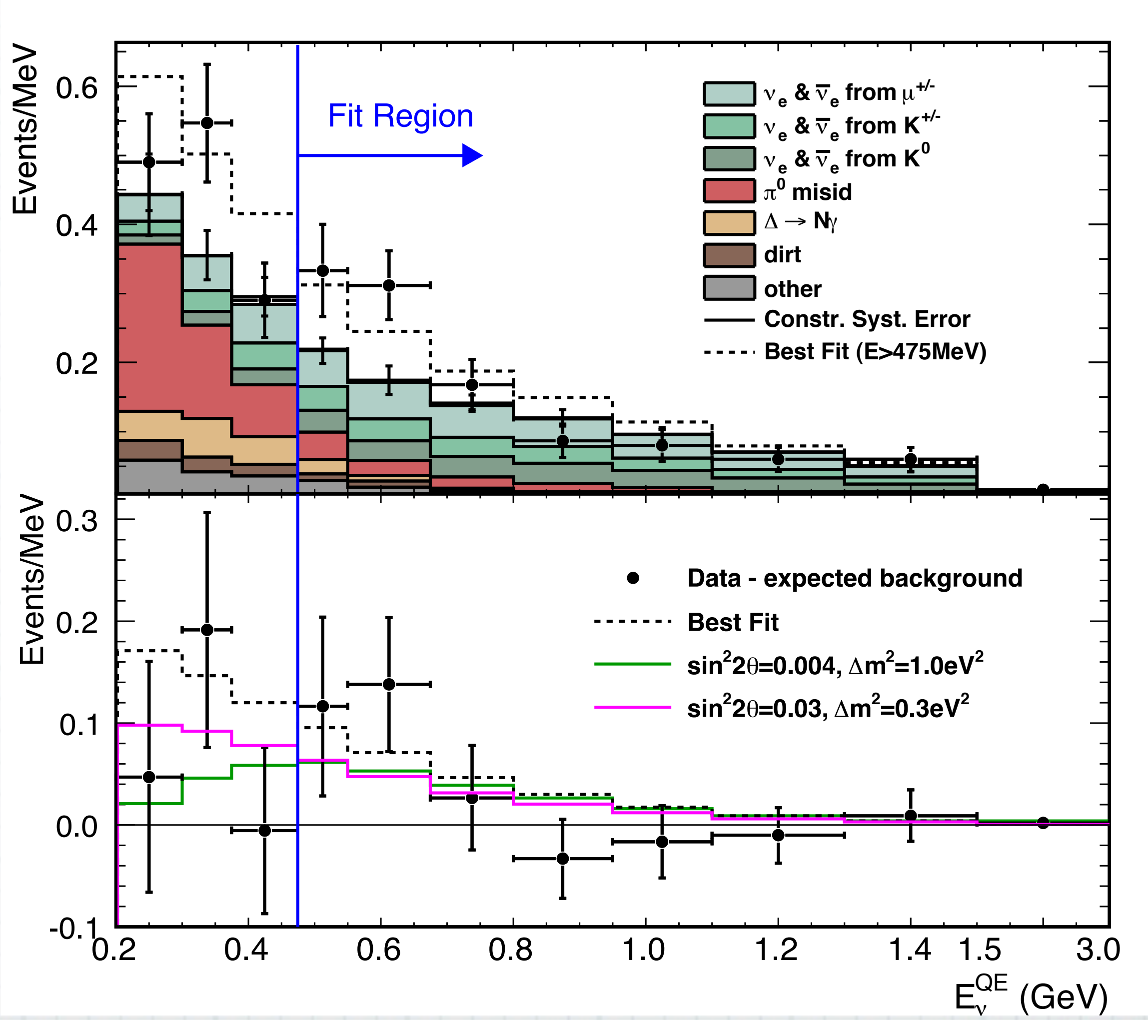
MiniBooNE (2010)

From the abstract

arxiv:1007.1150

antineutrino data sample corresponding to 5.66×10^{20} protons on target

"The data are **consistent** with $\bar{\nu}_\mu$ to $\bar{\nu}_e$ in the 0.1 to 1.0 eV^2 Δm^2 range and with the **evidence for** antineutrino oscillations from the **Liquid Scintillator Neutrino Detector** at Los Alamos National Laboratory."



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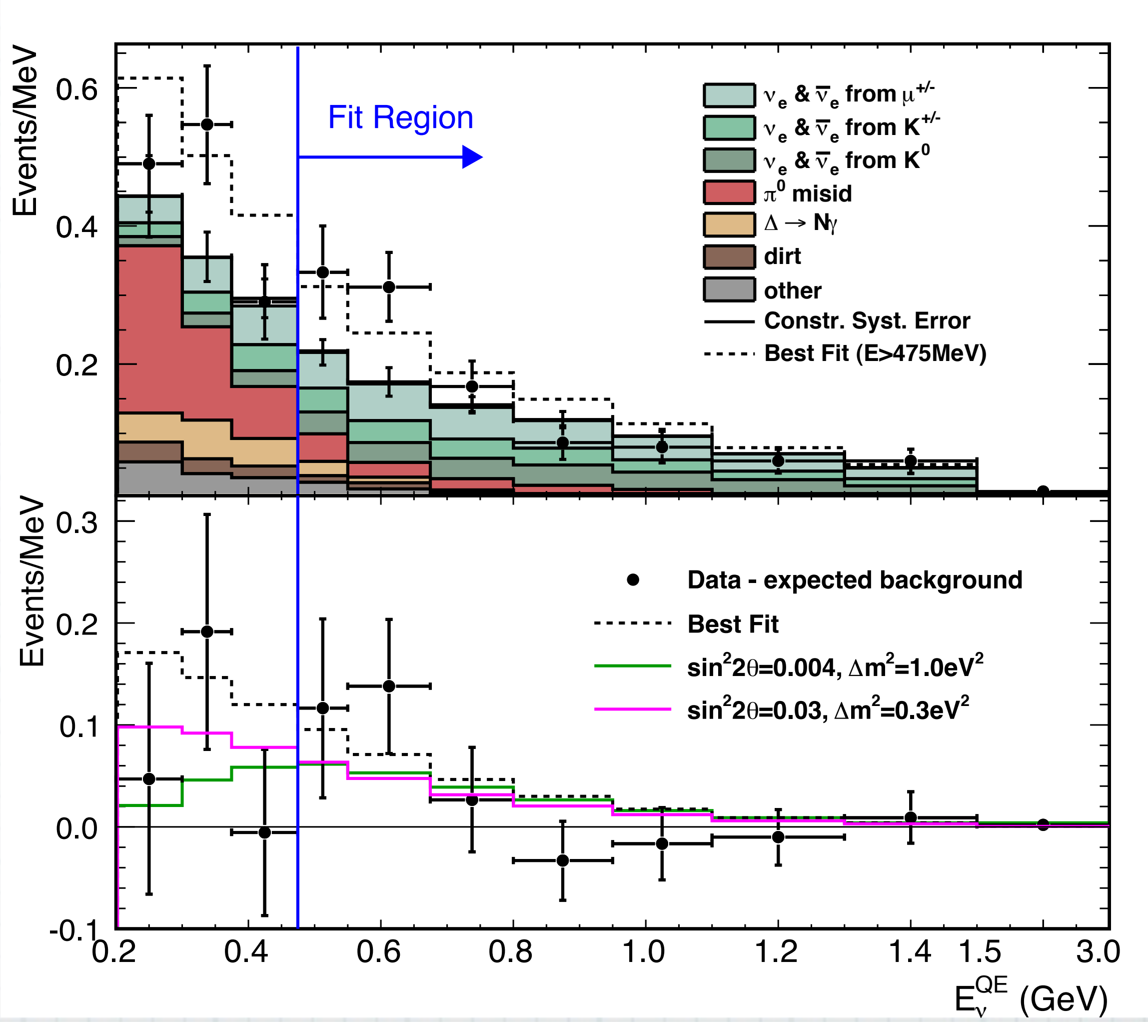

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Does that mean that it is inconsistent with their ν data?

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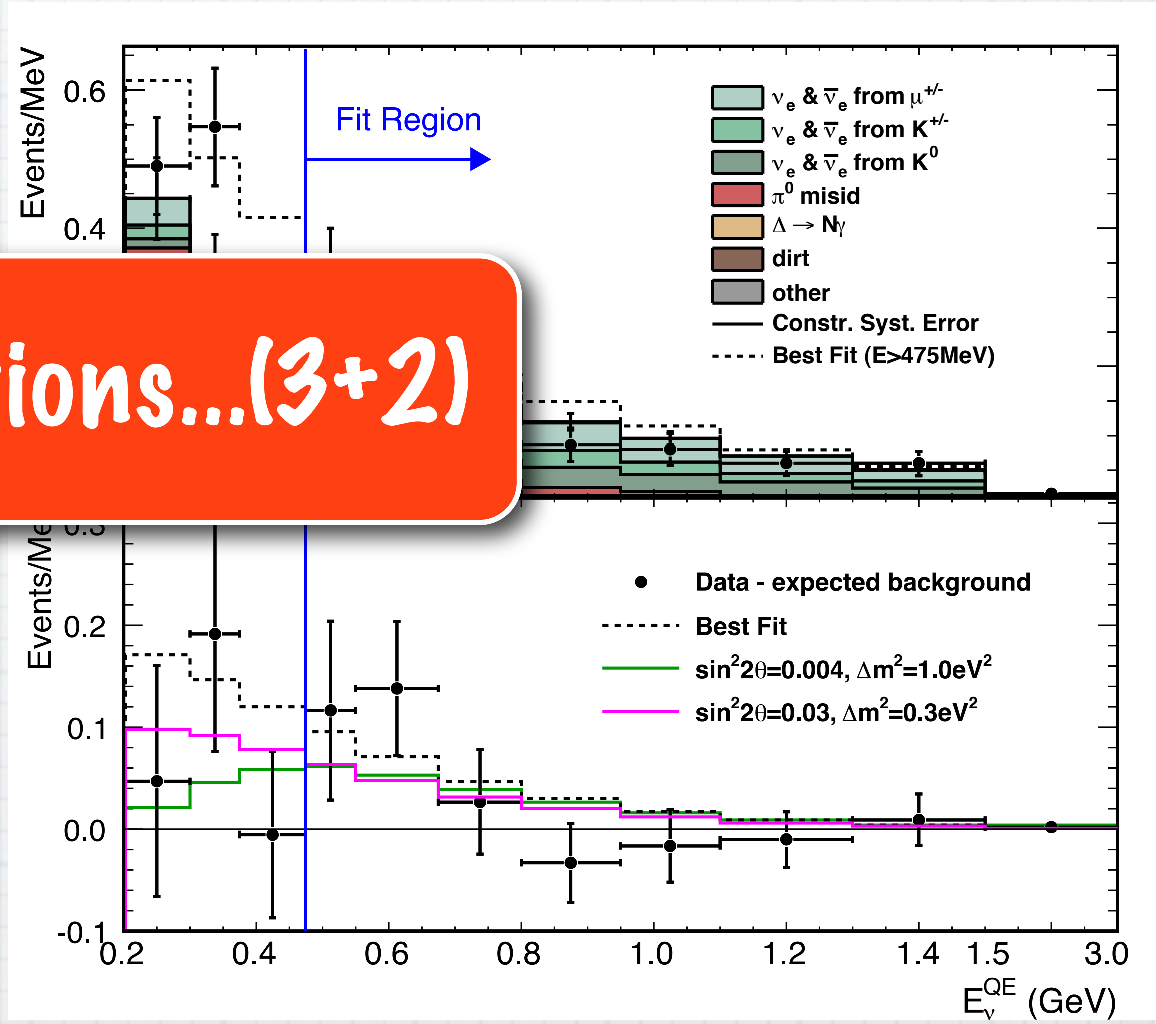

CPT violation? CP violations...(3+2)

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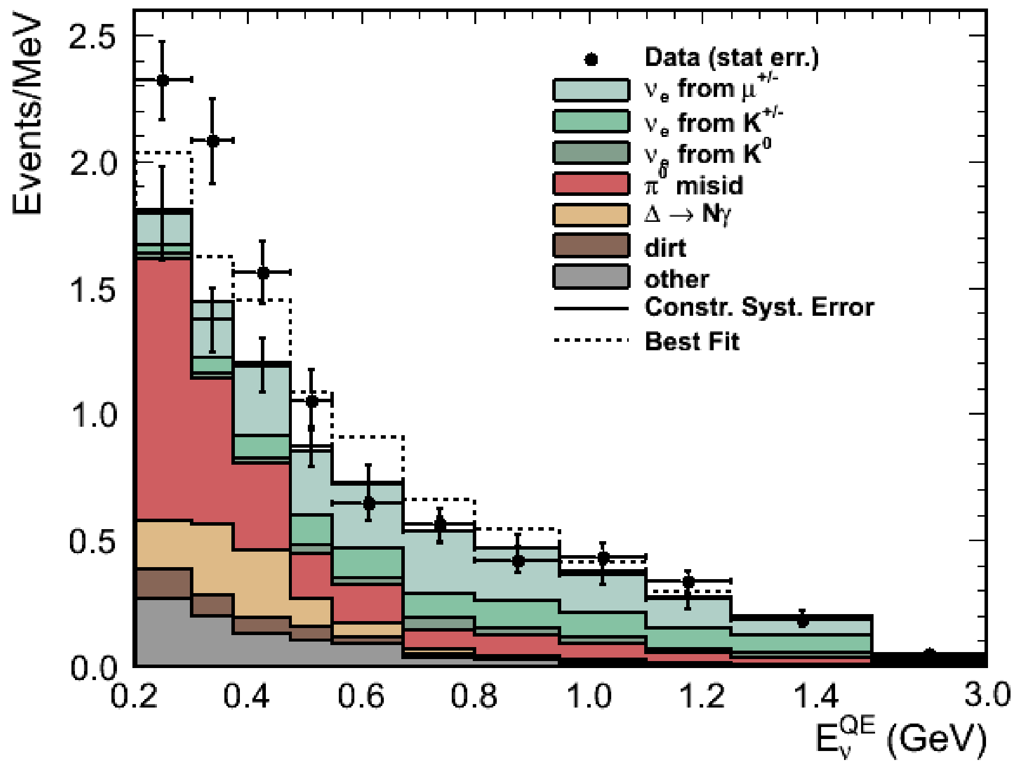
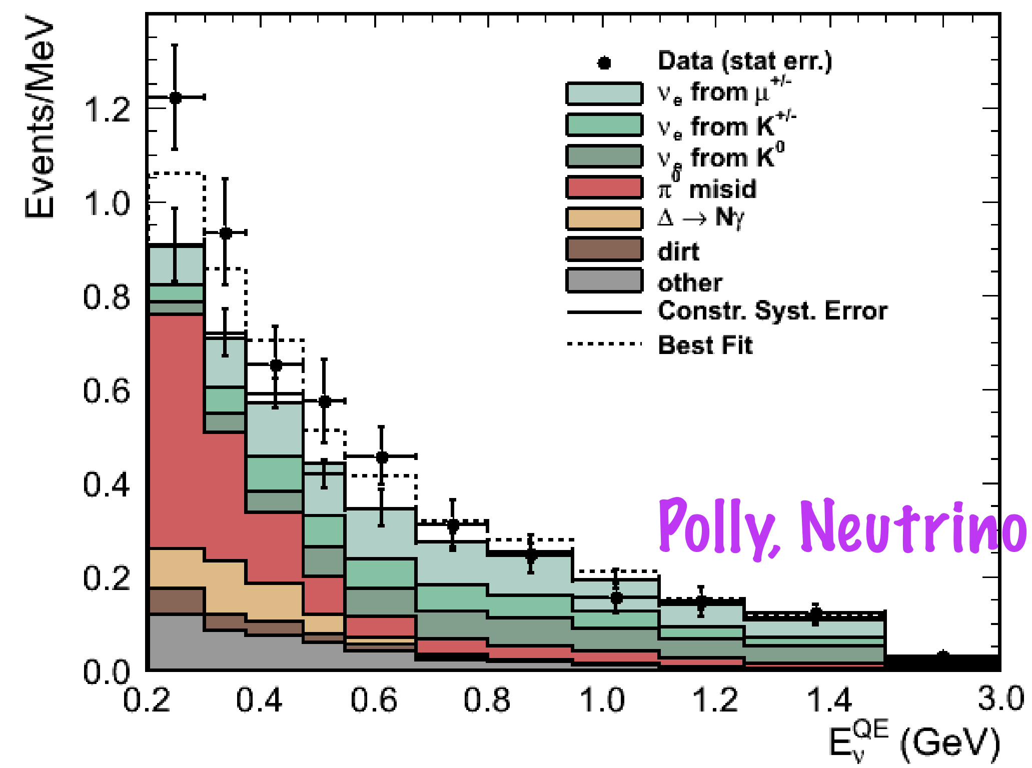
MiniBooNE (2012)



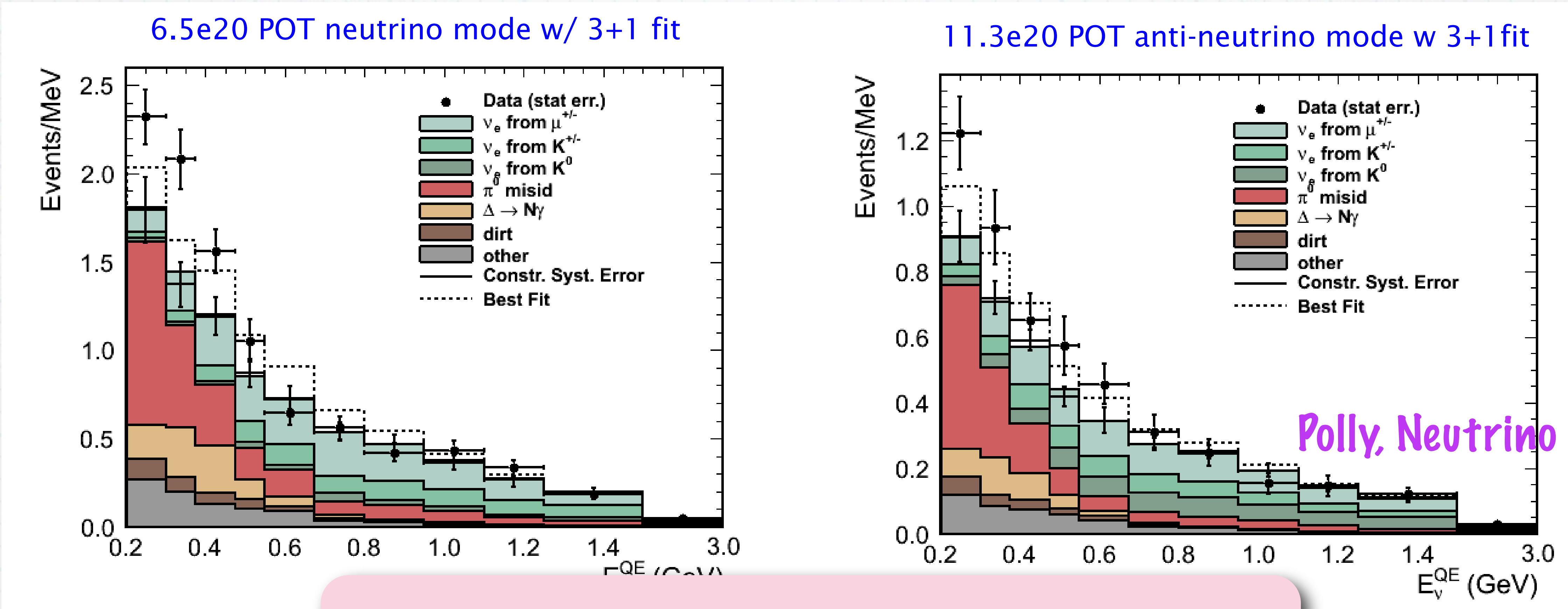


Polly, Neutrino 2012

* Neutrino and anti-neutrino data now consistent
* Together they see a 3.8σ excess....LSND??
* If neutrino and anti-neutrino data are consistent then do we need CP violation anymore?
* What is then the role of 3+2?

M. Maltoni talk

MiniBooNE (2012)



Polly, Neutrino 2012

The MiniBooNE Problem??

- Neutrino a … istent
- Together t… excess....LSND??
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M. Maltoni talk

More Anomalies

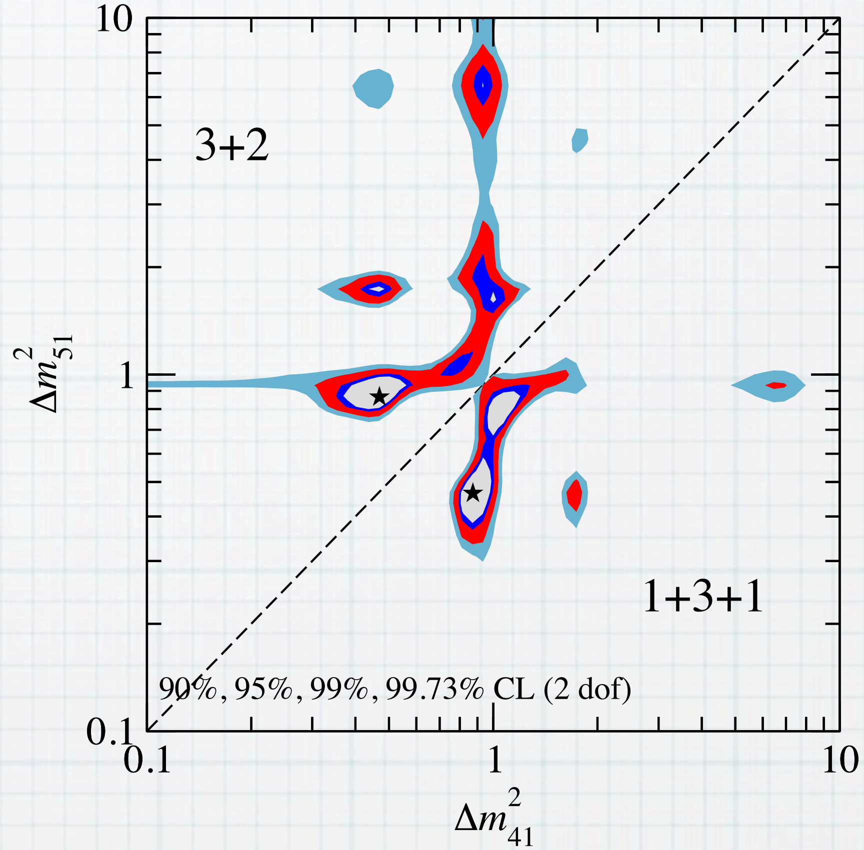
Talks by M. Maltoni and S. Brice

* The reactor anomaly..... 2.9σ

* The Gallium anomaly..... 3.3σ

Best-fit Parameters

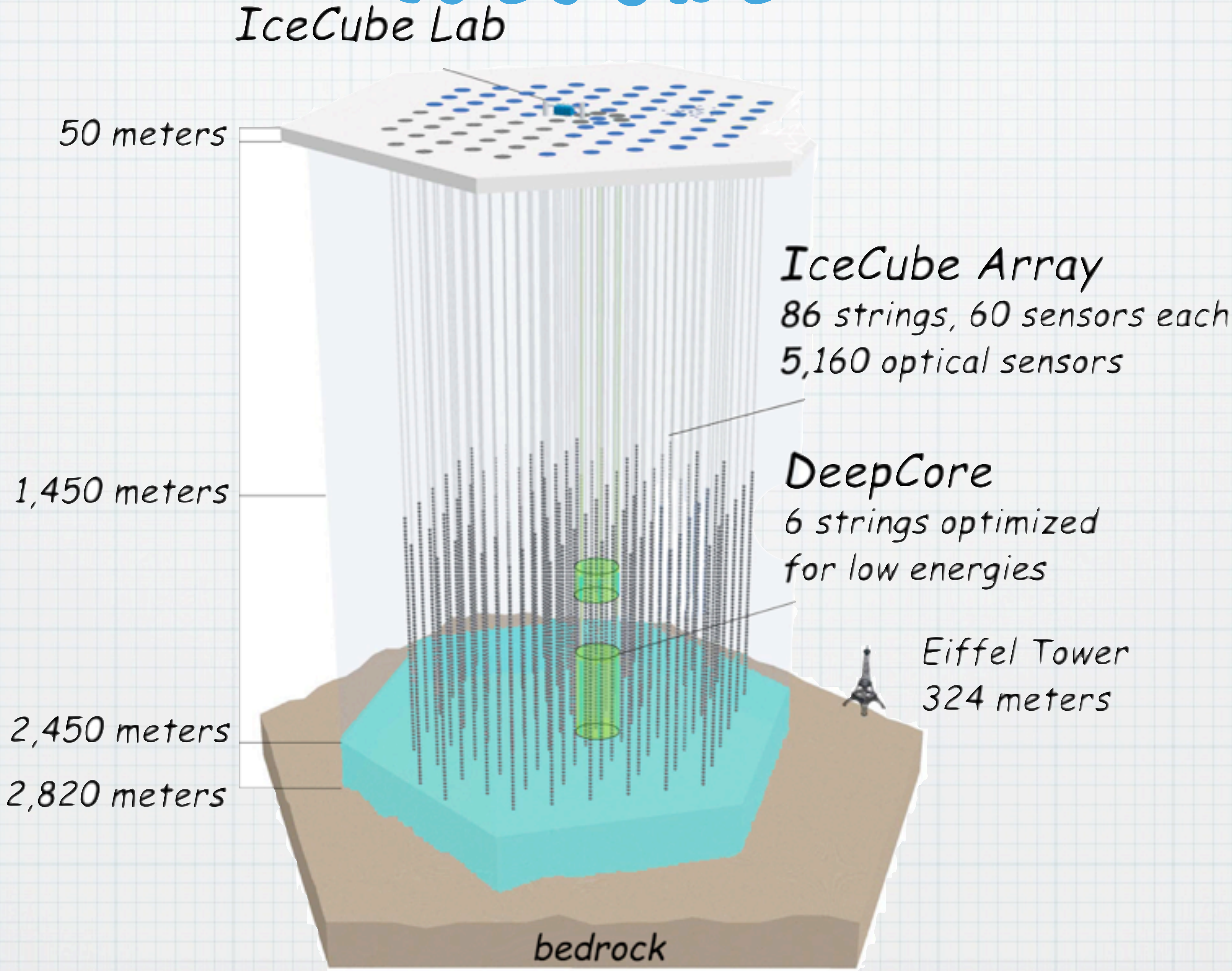
From a Global Fit with data before Neutrino 2012



	Δm^2_{41}	$\lvert U_{e4}\rvert$	$\lvert U_{\mu4}\rvert$	Δm^2_{51}	$\lvert U_{e5}\rvert$	$\lvert U_{\mu5}\rvert$	δ/π	χ^2/dof
3+2	0.47	0.128	0.165	0.87	0.138	0.148	1.64	110.1/130
1+3+1	0.47	0.129	0.154	0.87	0.142	0.163	0.35	106.1/130

Schwetz, Maltoni, 11034570

IceCube


IceCube Lab
50 meters
1,450 meters
2,450 meters
2,820 meters
IceCube Array
86 strings, 60 sensors each
5,160 optical sensors
DeepCore
6 strings optimized
for low energies
Eiffel Tower
324 meters
bedrock

Oscillations driven by Sterile Neutrinos

* oscillation maximum: $\sin^2\left(\frac{\Delta m^2 L}{4E}\right) = 1$
* $E(TeV) = 8.1 \times (\frac{\Delta m^2}{1eV^2}) \times (\frac{L}{10,000km})$
* Atmospheric neutrinos travel 10,000 km to IceCube
* Atmospheric neutrinos can have energies in 1-10 TeV
* In the 3+1 mass scheme:

$$P_{\nu_\mu\nu_\mu} \approx 1 - 4|U_{\mu 4}^2(1 - |U_{\mu 4}|^2)\sin^2\left(\frac{\Delta m_{42}^2 L}{4E}\right)$$

$$\approx 1 - \sin^2 2\theta_{24} \sin^2\left(\frac{\Delta m_{42}^2 L}{4E}\right)$$

Matter Effects at TeV

(-A_{NC} is the matter induced NC pot)

* $A_{NC} = \pm\sqrt{2} G_F \rho N_A (1 - Y_e) E$

* $(\Delta m^2_{42})^M = \sqrt{(\Delta m^2_{42} \cos 2\theta_{24} - A_{NC})^2 + (\Delta m^2_{42} \sin 2\theta_{24})^2}$

* $\tan 2\theta^M_{24} = \dfrac{\Delta m^2_{42} \sin 2\theta_{24}}{\Delta m^2_{42} \cos 2\theta_{24} - A_{NC}}$

Nunokawa, Peres, Zukanovich Funchal, 0302039

* $E^{\nu_\alpha \to \nu_s}_{res}(TeV) = \dfrac{\Delta m^2_{4i} \cos 2\theta_{4i}}{0.038 \times \rho(gm/cc)}$

* For Δm^2_{42}=1 eV^2, ρ = 8 gm/cc, E_{res}=3 TeV

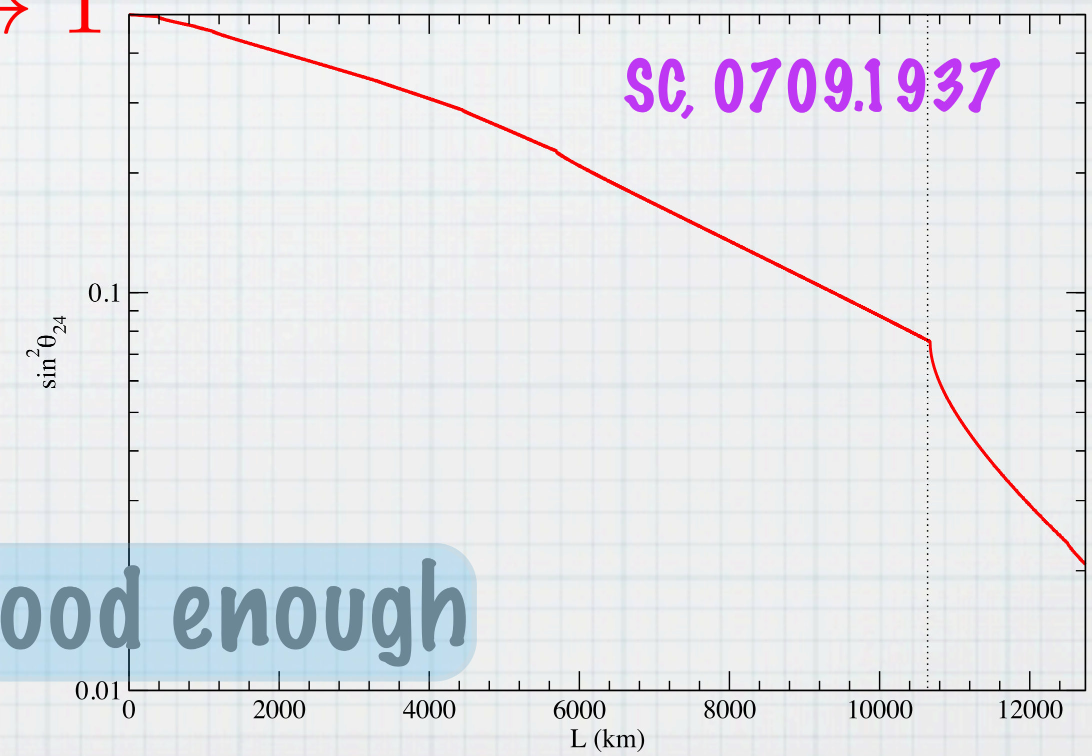
Conditions for Maximal Oscillations

$$P_{\nu_\mu\nu_\mu} \approx 1 - \sin^2 2\theta_{24}^M \sin^2\left(\frac{(\Delta m^2_{42})^M L}{4E}\right)$$

$P_{\nu_\mu\nu_\mu} \approx 0$ **when** $\sin^2\left(\frac{(\Delta m^2_{42})^M L}{4E}\right) \to 1$

AND $\sin^2 2\theta_{24}^M \to 1$

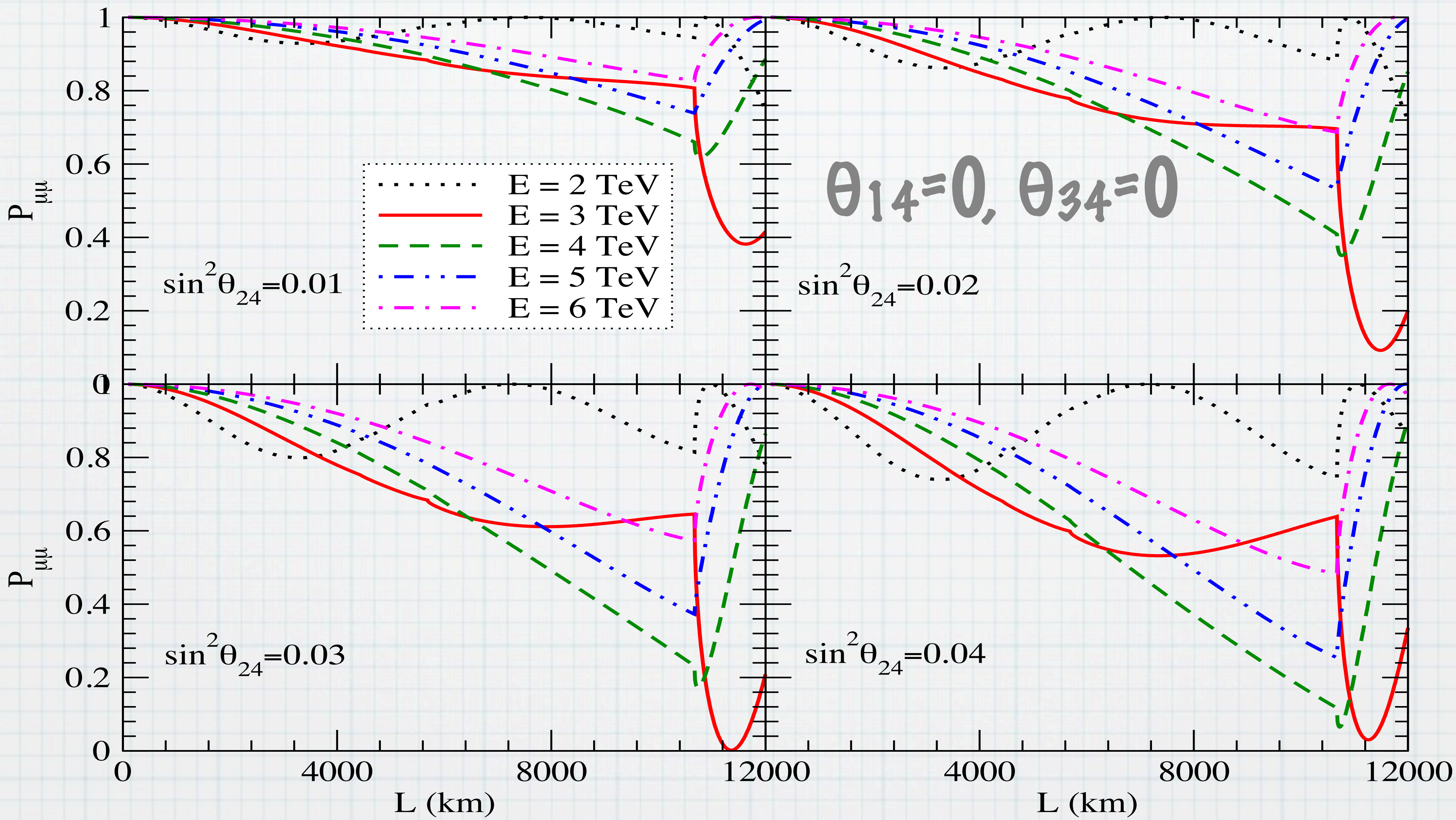
$$\tan\theta_{24} = \frac{32.55 \times 10^3}{\rho L(km\ gm/cc)}$$



Values of $\sin^2\theta_{24}$ >0.02 should be good enough

Oscillations at TeV

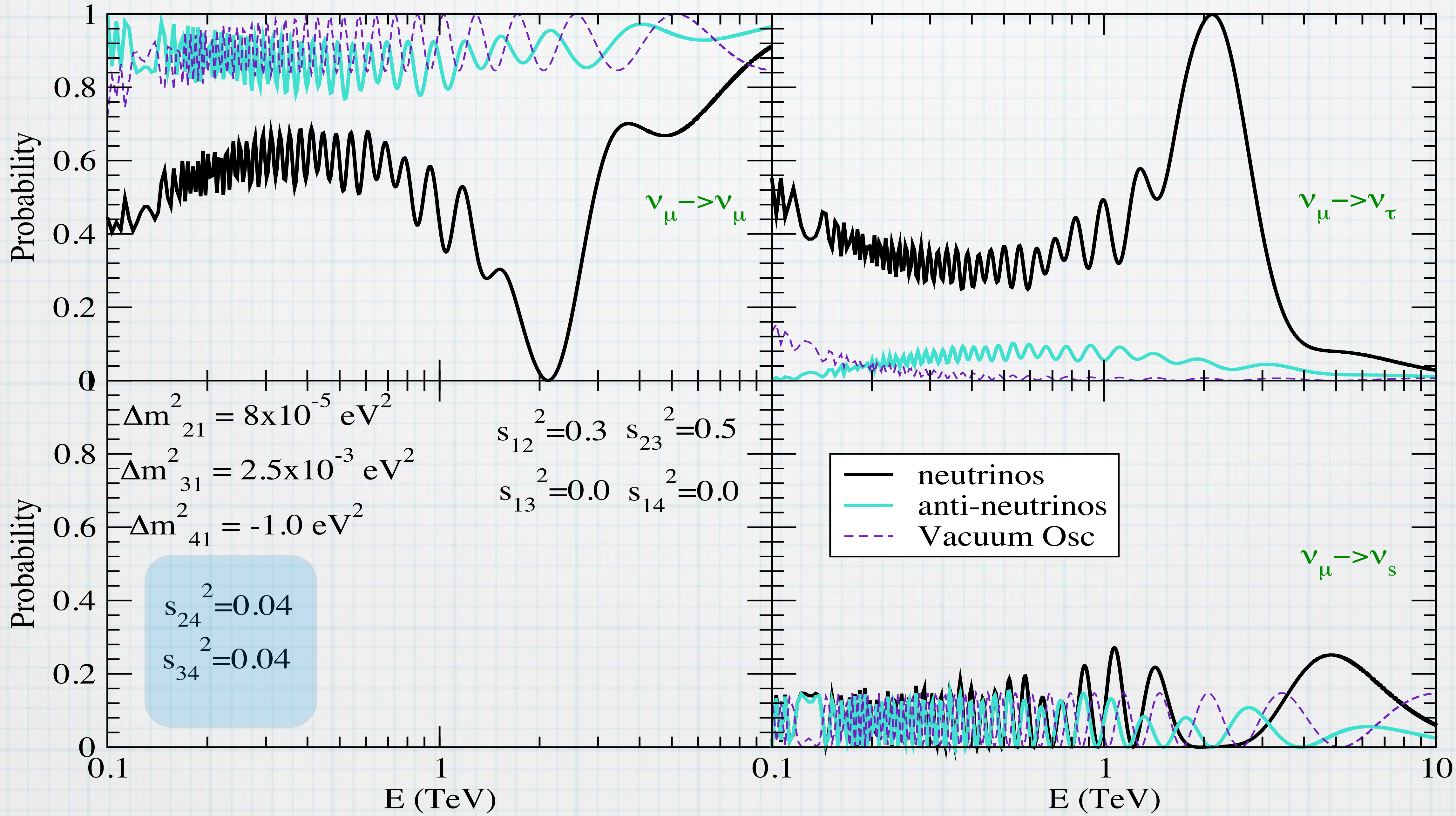
SC, 0709.1937



- Very large oscillations for E ≈3-4 TeV
- Effectively these are 2-gen $\nu_\mu \rightarrow \nu_s$ at LSND scale

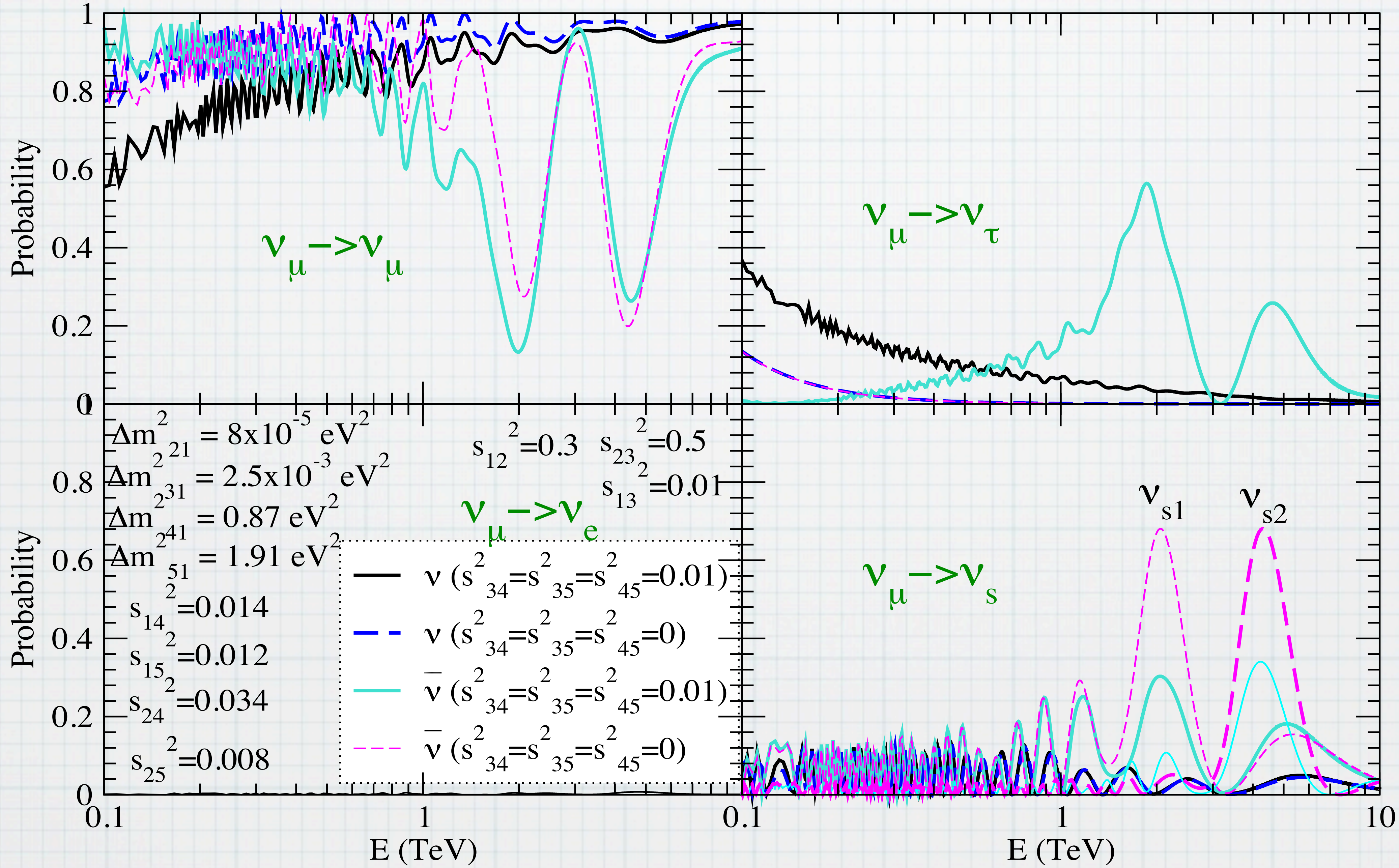
Impact of θ_{34} on matter effects

SC, 0709.1937



TeV Oscillations in the (3+2) Scheme

SC, 0709.1937

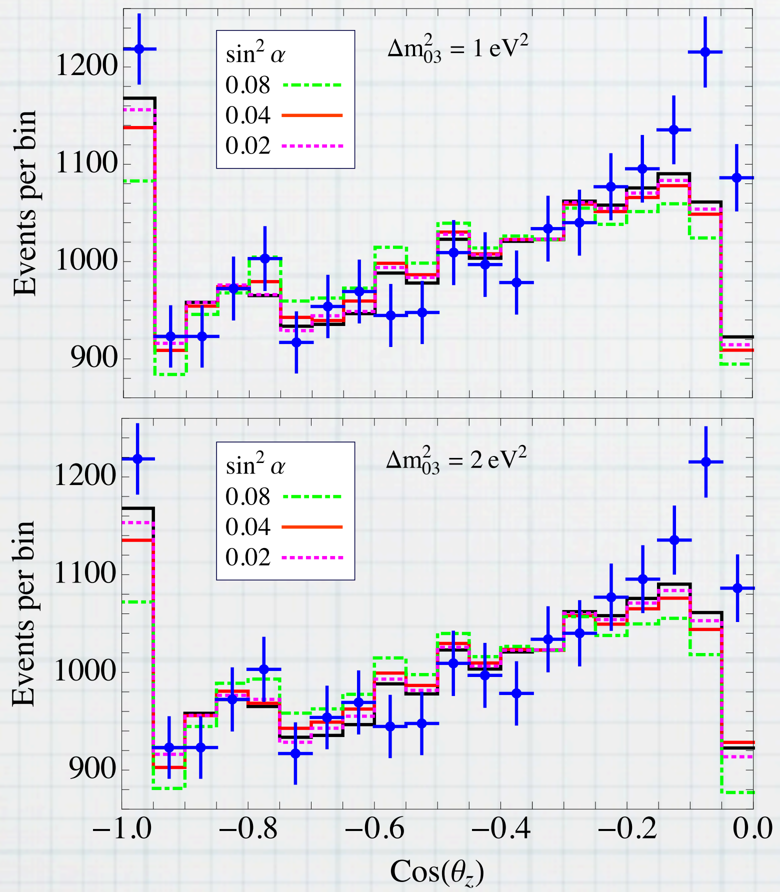


Fluxes and Events

$$\Phi_\mu = \Phi^0_\mu P_{\mu\mu} + \Phi^0_e P_{e\mu} \approx \Phi^0_\mu P_{\mu\mu},$$

effective area

$$N_j = 2\pi \int_{\Delta_j \cos\theta_z} d\cos\theta_z \int_{E_{th}} dE\ \Phi^0_\nu(E,\theta_z) A_{\rm eff}(E,\theta_z) P_{\mu\mu}(E,\theta_z) + \text{antineutrinos}.$$



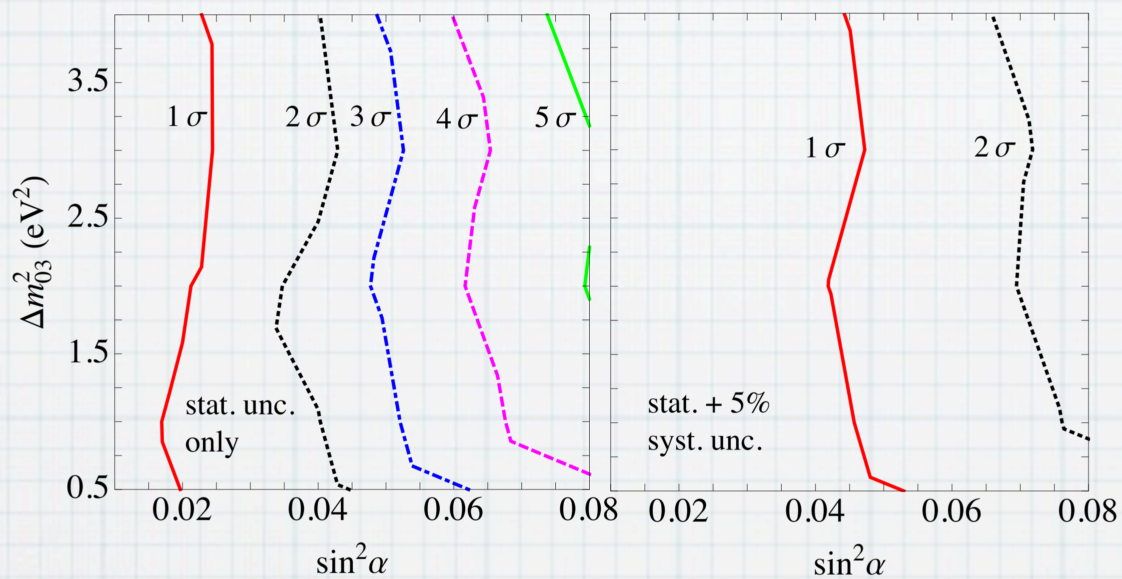
$$S_j = \frac{N_j}{N_j^0},$$

Smirnov, Razzaque, 1104.1390

$$N_j = N_j^{MC} S_j,$$

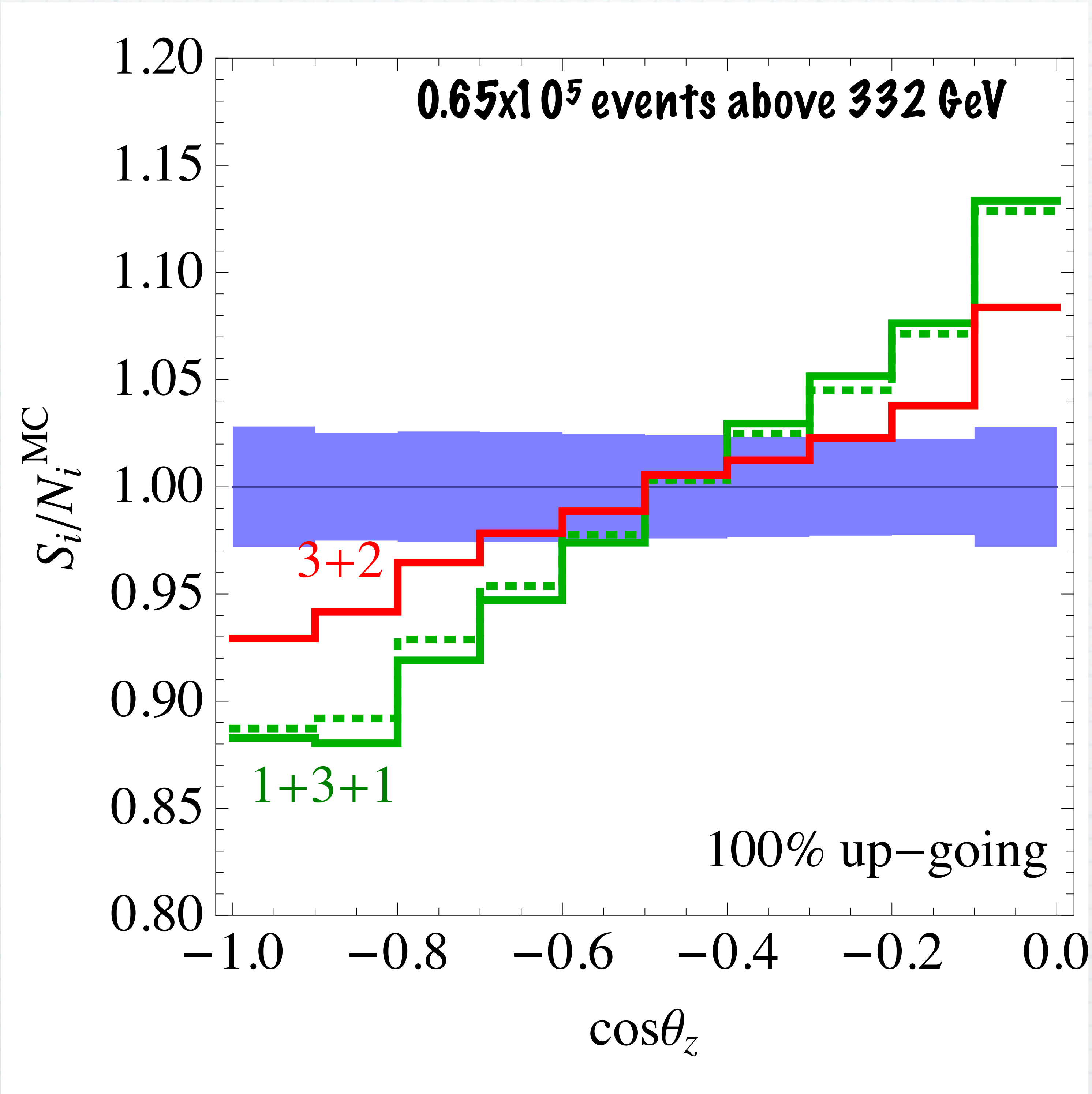
Limits from IC40

Smirnov, Razzaque, 1104.1390



* $|U_{\mu 4}|^2 > 0.025$ is ruled out at 3σ
* $|U_{\mu 4}|^2 \cong 0.03$ is the global best-fit from the 3+2 fit

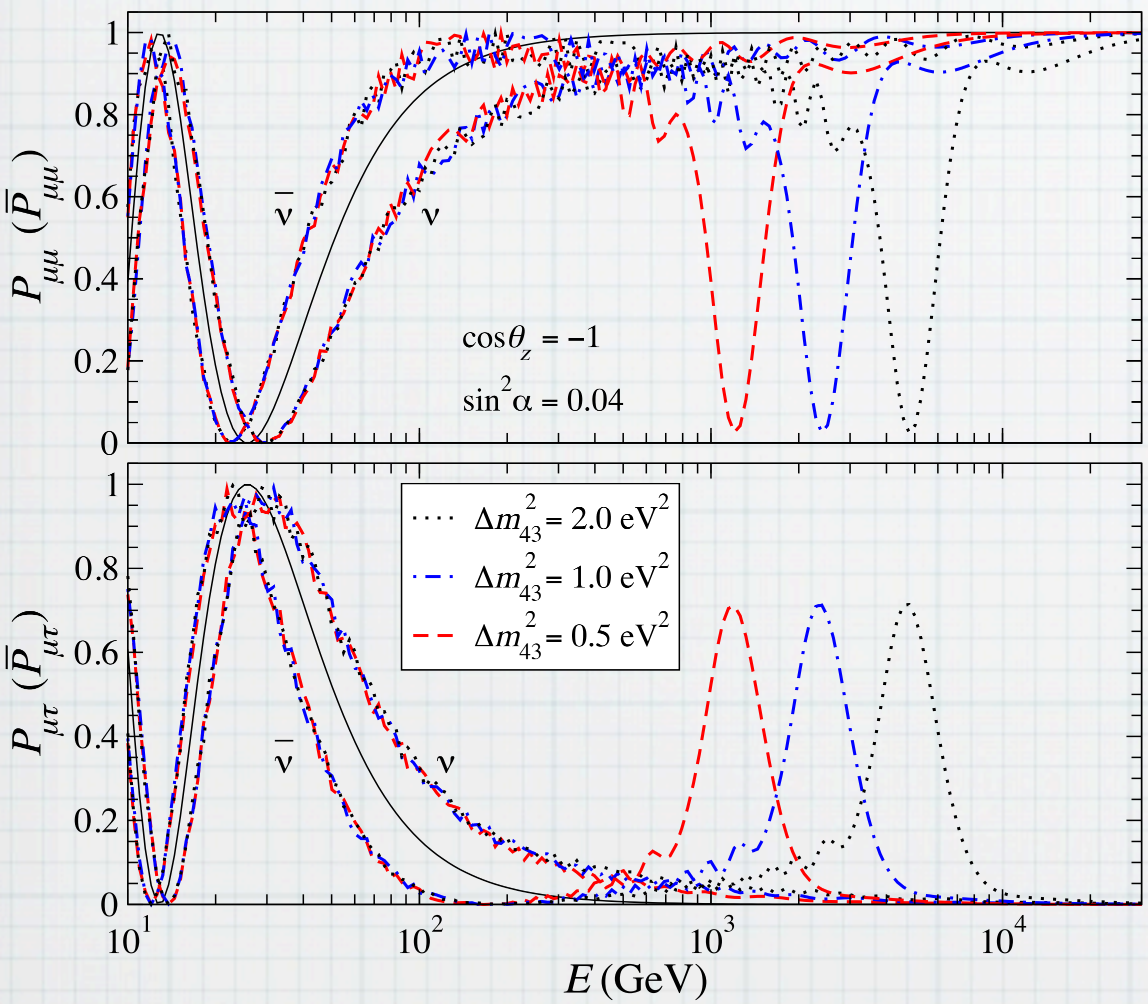
Future Prospects at IC

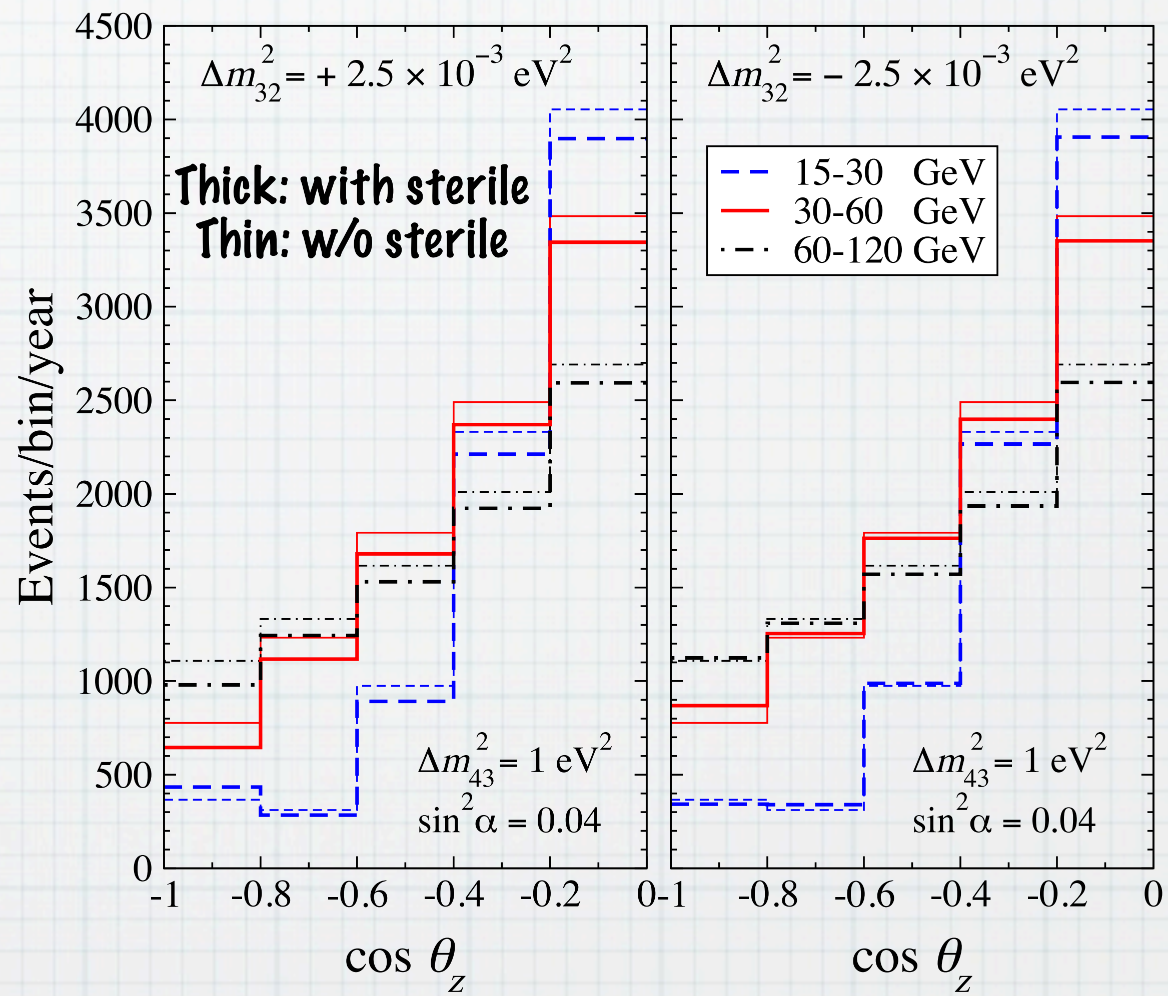


Barger, Gao, Marfatia, 1109.5748

Sterile Neutrinos in Deep Core

Smirnov, Razzaque, 1203.5406





- Deep Core could probe $|U_{\mu 4}|^2$ down to 0.01 or 0.02

Conclusions

* Many (experimental) reasons to believe that sterile neutrinos with 1 eV mass scale exist
* A large variety of experiments being planned to test sterile neutrino osc
* Makes sense to look for their signatures in currently running experiments

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* One should see sterile-driven MSW conversions of TeV range atmospheric neutrinos in IceCube
* IceCube could confirm or refute the 3+2 scheme
* One could see oscillation effects of sterile nus in the 10-100 GeV range
* ICDC could put stringent bounds...

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Thank You