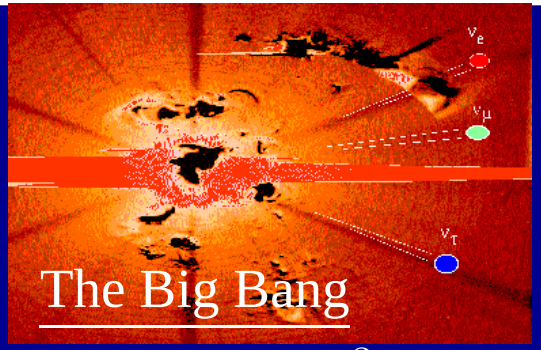
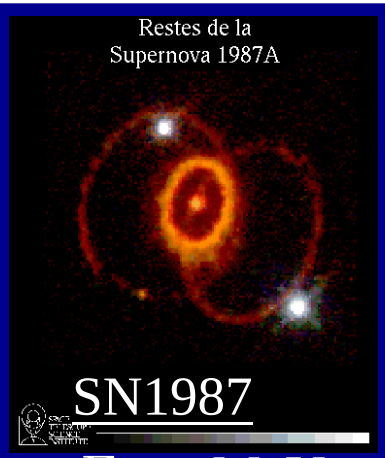
Sources of ν's



The Big Bang

$n_\nu = 330/\text{cm}^3$

E_ν =0.0004 eV



SN1987

$E_\nu \sim$ MeV

The Sun

ν_e

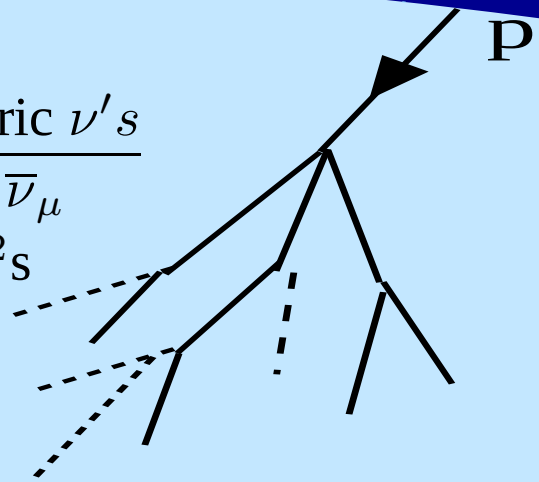
$\Phi_\nu^{Earth} = 6 \times 10^{10} \nu/\text{cm}^2\text{s}$

$E_\nu \sim 0.1$–20 MeV

Atmospheric $\nu's$

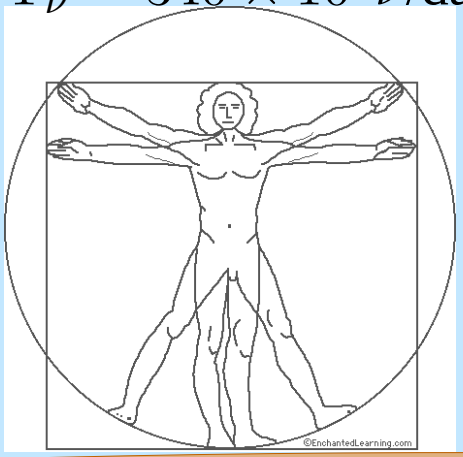
$\nu_e, \nu_\mu, \overline{\nu}_e, \overline{\nu}_\mu$

$\Phi_\nu \sim 1\nu/\text{cm}^2\text{s}$



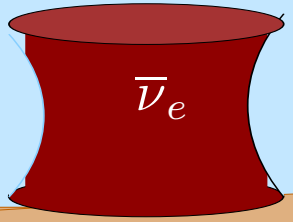
Human Body

$\Phi_\nu = 340 \times 10^6 \nu/\text{day}$



Nuclear Reactors

$E_\nu \sim$ few MeV



Earth's radioactivity

$\Phi_\nu \sim 6 \times 10^6 \nu/\text{cm}^2\text{s}$

Accelerators

$E_\nu \simeq 0.3$–30 GeV

Fermilab

Discovering the Nature of Nature

CERN

~宇宙と物質の起源と構造を探る~

KEK

ν Interactions

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$$\sigma^{\nu p} \sim 10^{-38}\mathrm{cm}^2 \frac{E_\nu}{\mathrm{GeV}}$$

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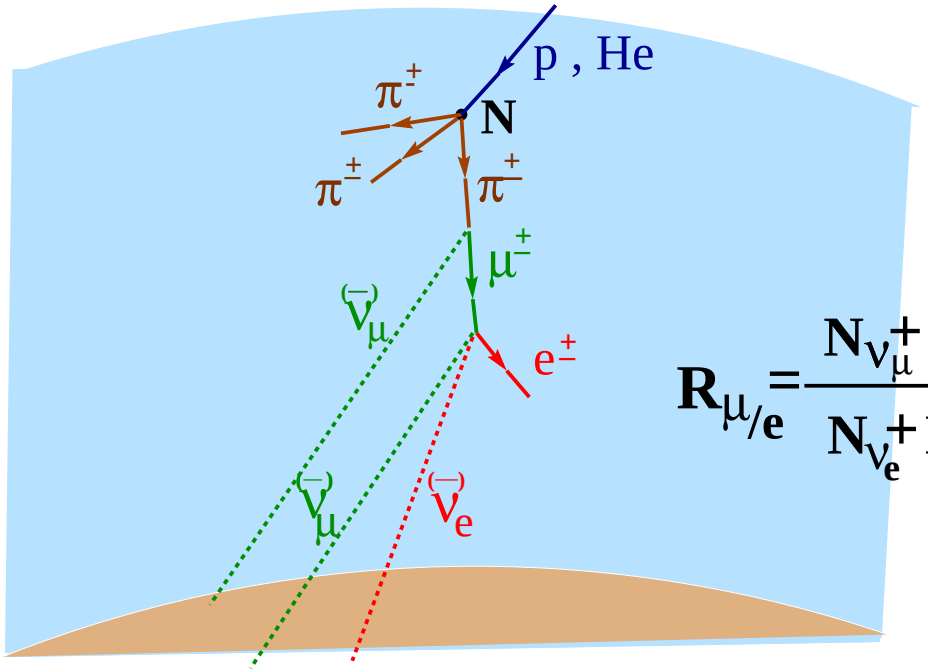
$\Rightarrow$ Need huge detectors with Exposure $\sim$ KTon $\times$ year

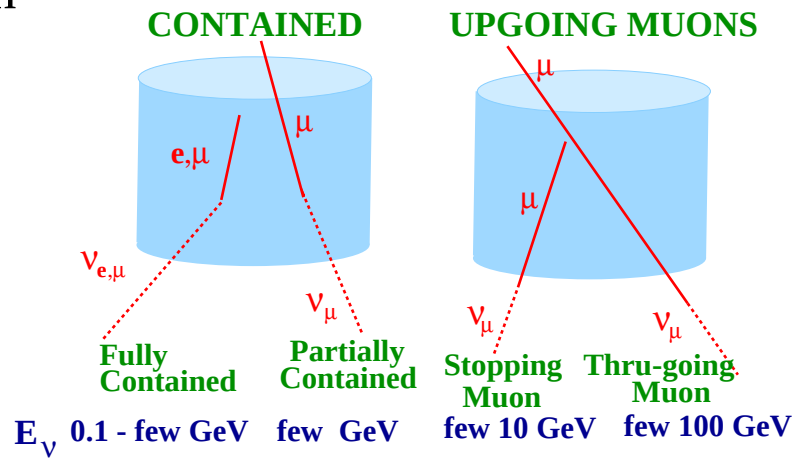
Atmospheric Neutrinos

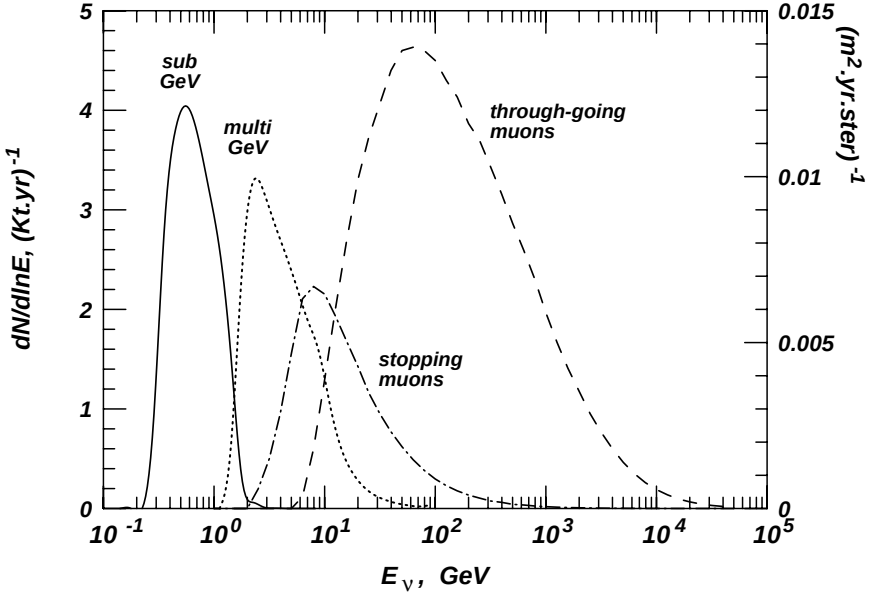
Atmospheric $\nu_{e,\mu}$ are produced by the interaction of cosmic rays (p, He . . .) with the atmosphere



$$R_{\mu/e} = \frac{N_{\nu_\mu} + N_{\bar{\nu}_\mu}}{N_{\nu_e} + N_{\bar{\nu}_e}} \sim 2$$

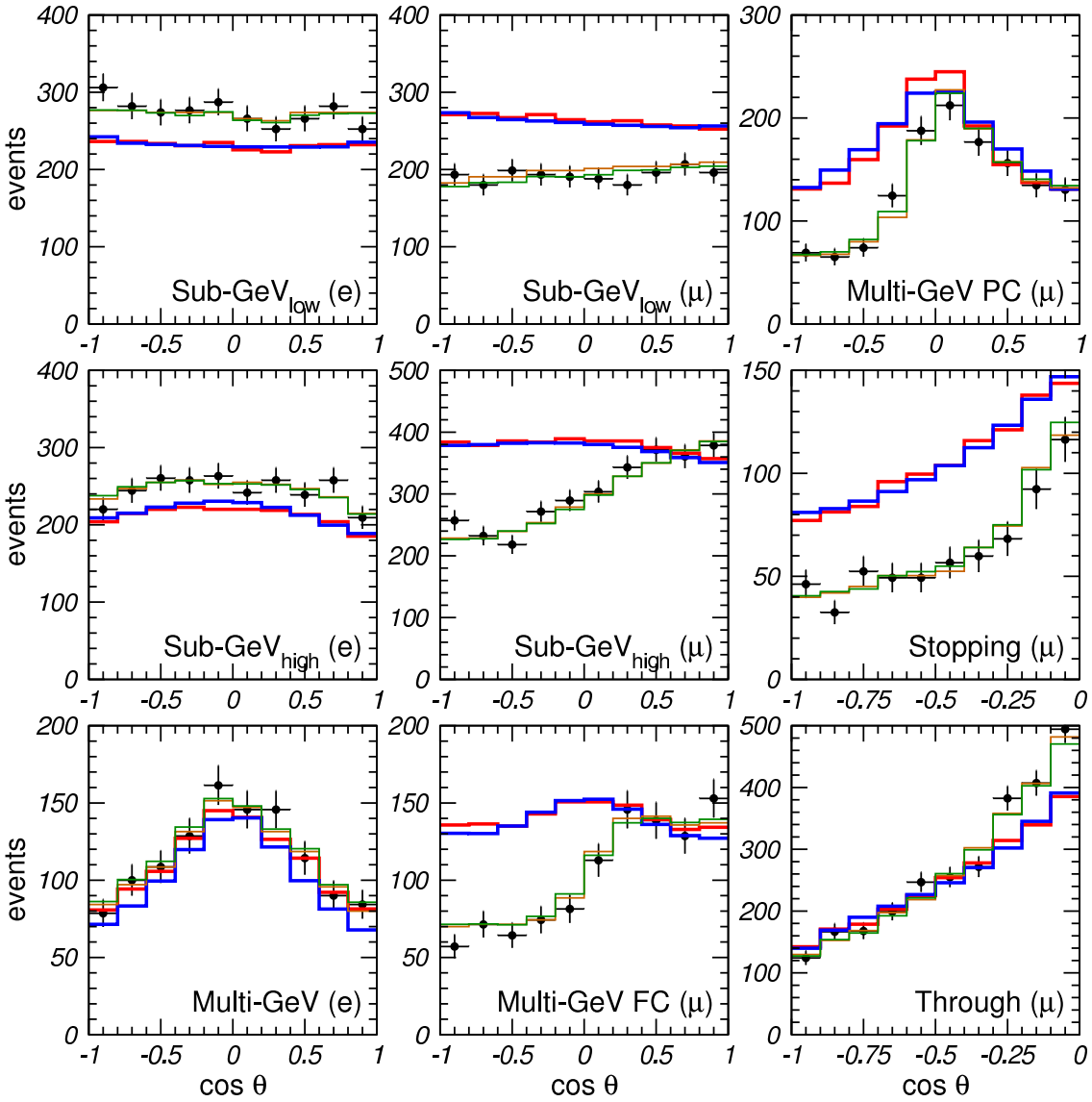
EVENT CLASSIFICATION

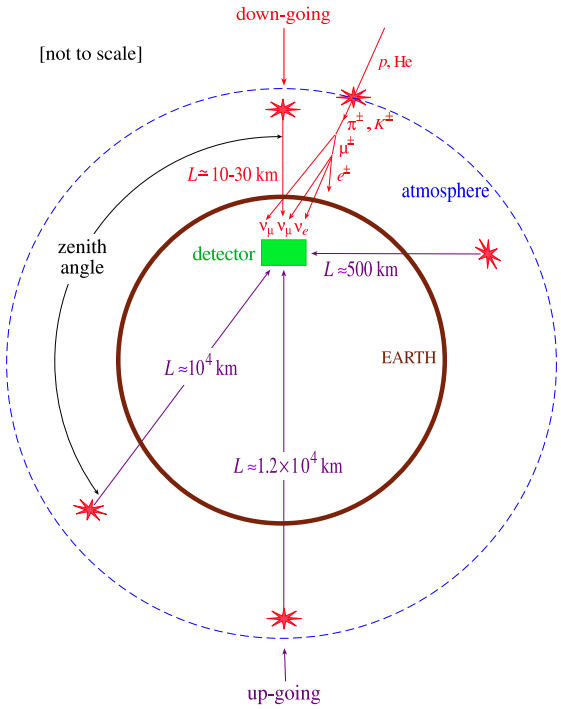




Atmospheric Neutrinos: Data

- Complete SKI+II data:





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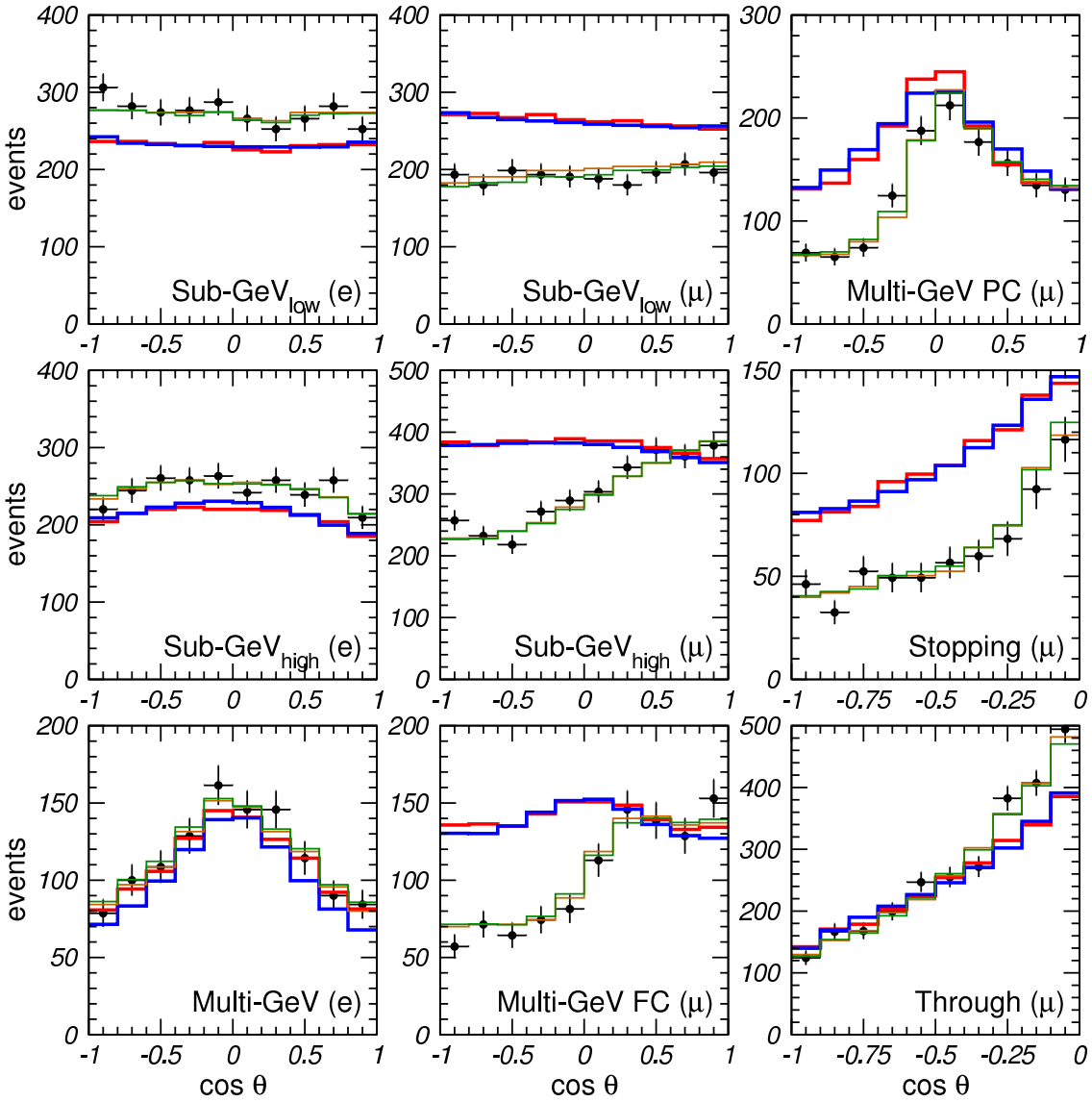
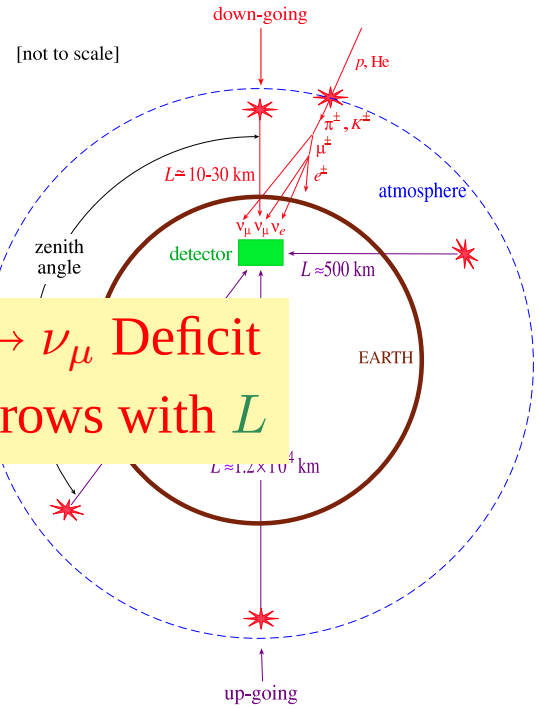


ν_e in agreement with SM

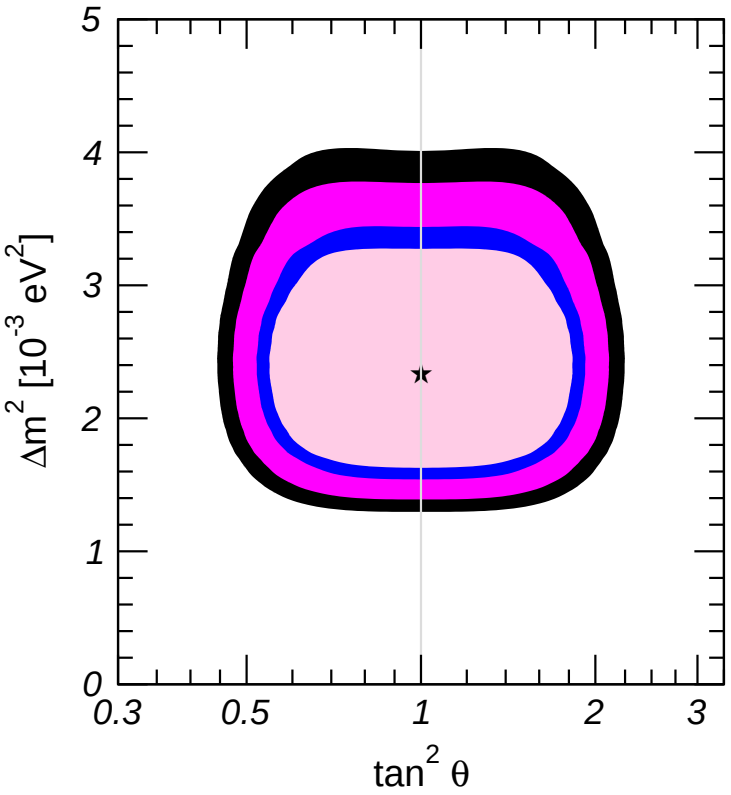


$\rightarrow \nu_\mu$ Deficit grows with L

$\rightarrow \nu_\mu$ Deficit decreases with E

Atmospheric Neutrinos: Oscillation Solutions

- $\nu_\mu \to \nu_\tau$: best channel



Best fit

$\Delta m^2 = 2.35 \times 10^{-3}$ eV^2

$\tan^2\theta = 1$

ATM Test at Long Baseline Experiments

K2K	ν_μ at KEK	SK	L=250 km
MINOS	ν_μ at Fermilab	Soundan	L=735 km
Opera	ν_μ at CERN	Gran Sasso	L=740 km

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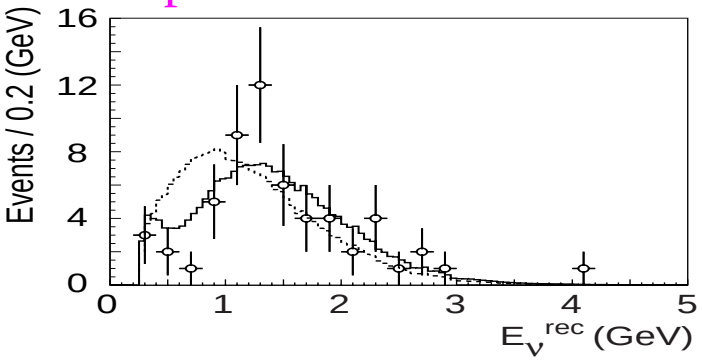
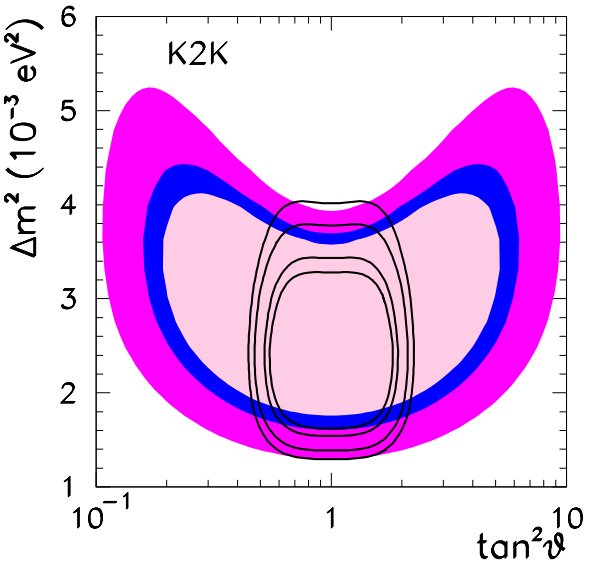
K2K 2004: spectral distortion



Confirmation of ATM oscillations



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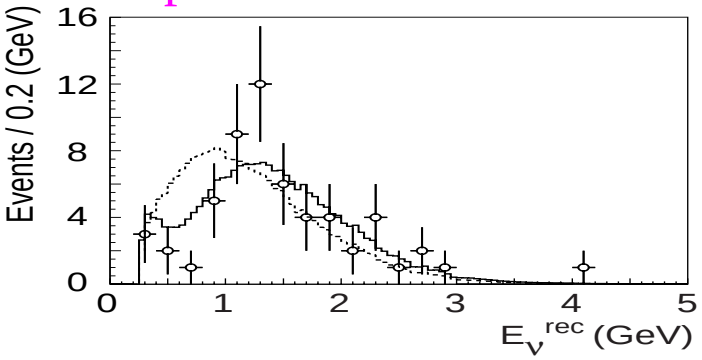
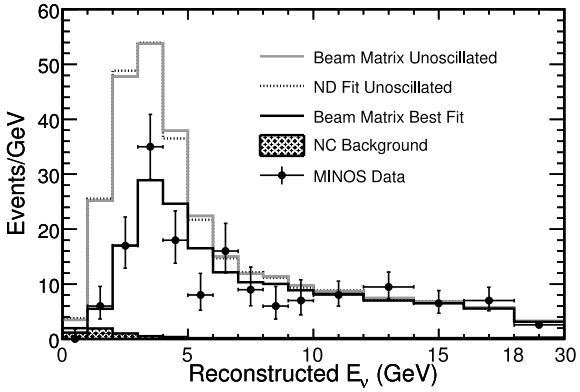


MINOS 2006-2008: spectral distortion



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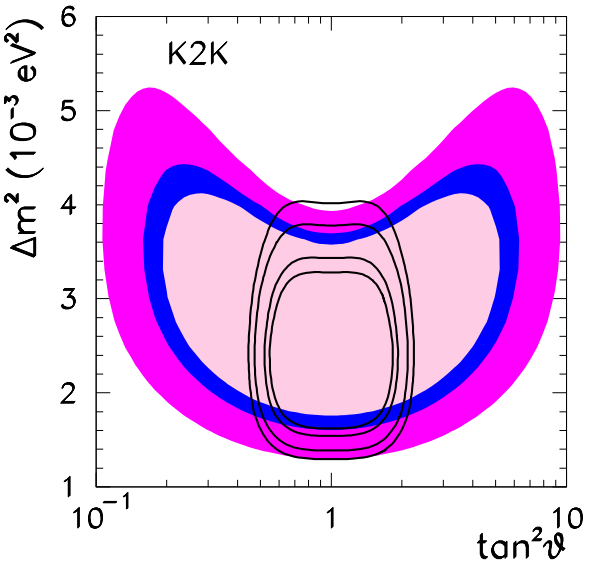
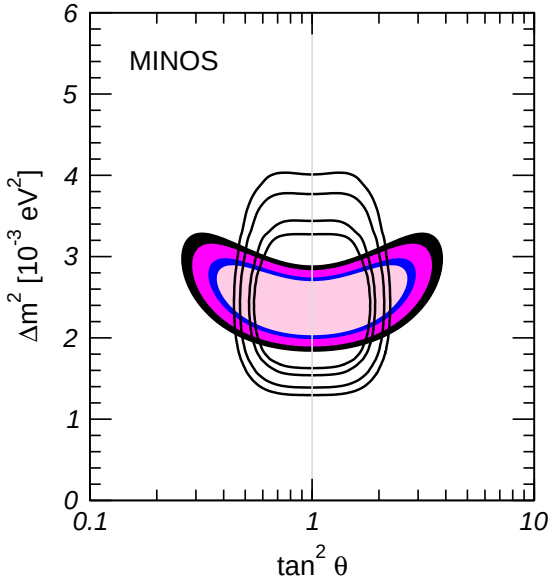


Impact on Δm^2 Determination

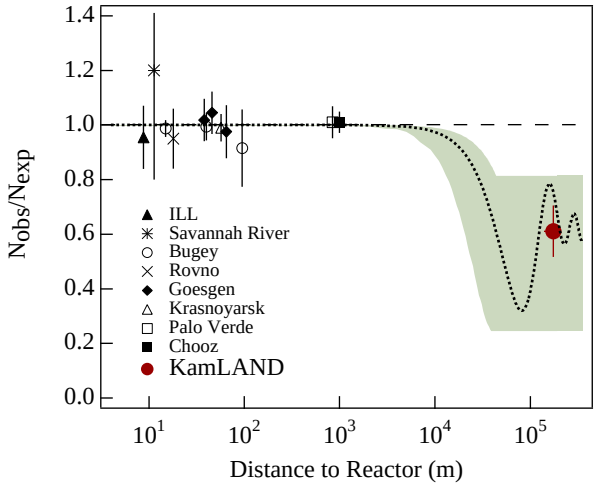


Reactor Experiments: KamLAND

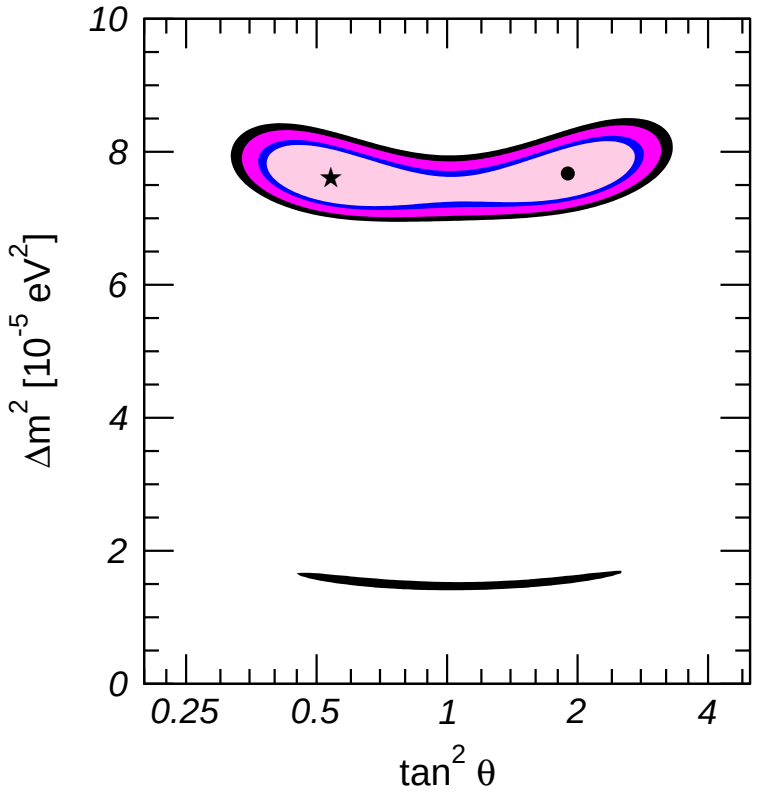
Gonzalez-Garcia

- Search on $\overline{\nu_e}$ at L$\sim$ 180 km reactors, $E_{\overline{\nu}} \sim$ few MeV: $\bar{\nu}_e + p \rightarrow n + e^+$

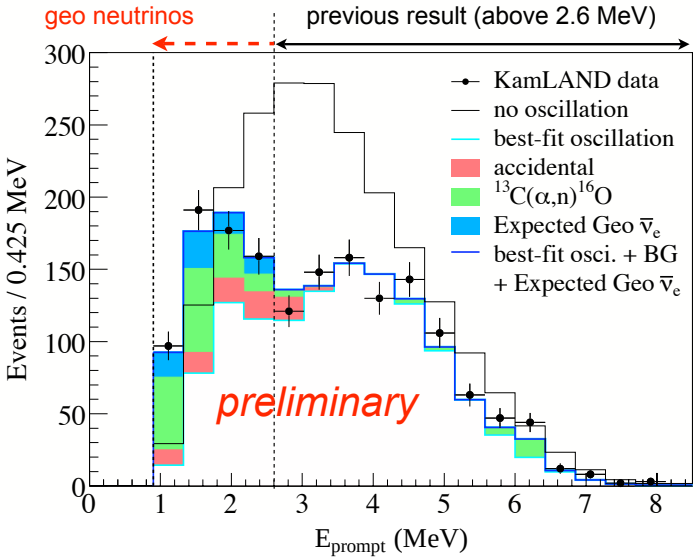
2002: Deficit $R_{\rm KLAND} = 0.611 \pm 0.094$



Oscillation Analysis



2004-2008: Significant Energy Distortion



Best Fit

$\Delta m^2 = 7.7 \times 10^{-5}$ eV^2

$\tan^2\theta = 0.5 \quad (2.)$