Plan of Lectures

I. Standard Neutrino Properties and Mass Terms (Beyond Standard)

II. Effects of ν Mass: Neutrino Oscillations (Vacuum)

III. Neutrino Oscillations in Matter

IV. The Emerging Picture and Some Lessons

Summary I

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  - Accidental global symmetry: $B \times L_e \times L_\mu \times L_\tau \leftrightarrow m_\nu \equiv 0$
  - neutrinos are left-handed ($\equiv$ helicity -1): $m_\nu = 0 \Rightarrow$ chirality $\equiv$ helicity
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  $\rightarrow$ different ways of adding m_ν to the SM
  - *breaking* total lepton number ($L = L_e + L_\mu + L_\tau$) $\rightarrow$ Majorana ν: $\nu = \nu^C$
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- Question: How to search for m_ν?

  Answer: Today

Plan of Lecture II

Effects of ν Mass: Neutrino Oscillations (Vacuum)

Lepton Mixing

Direct Probes of Neutrino Mass Scale
Weak decays, ν-less $\beta\beta$ decay, Cosmology

Neutrino Oscillations in Vacuum

Vacuum Neutrino Oscillations Searches and Findings

Alternative Mechanisms for Neutrino Oscillations

Lepton Mixing

- Charged current and mass for 3 charged leptons ℓ_i and N neutrinos ν_j in weak basis

$$\mathcal{L}_{CC}+\mathcal{L}_M = -\frac{g}{\sqrt{2}}\sum_{i=1}^{3}\overline{\ell^W_{L,i}}\gamma^\mu\nu^W_i W^+_\mu - \sum_{i,j=1}^{3}\overline{\ell^W_{L,i}}M_{\ell\,ij}\ell^W_{R,j} - \frac{1}{2}\sum_{i,j=1}^{N}\overline{\nu^{c\,W}_i}M_{\nu\,ij}\nu^W_j + \text{h.c.}$$

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- Changing to mass basis by rotations

$$\ell^W_{L,i} = V^\ell_{L\,ij}\ell_{L,j} \qquad \ell^W_{R,i} = V^\ell_{R\,ij}\ell_{R,j} \qquad \nu_i^W = V^\nu_{ij}\nu_j$$

$$V_L^{\ell\,\dagger} M_\ell V_R^\ell = \text{diag}(m_e, m_\mu, m_\tau) \qquad V^{\nu\,T} M_\nu V^\nu = \text{diag}(m_1^2, m_2^2, m_3^2, \ldots, m_N^2)$$

$V^\ell_{L,R} \equiv$ Unitary 3×3 matrices

$V^\nu \equiv$ Unitary $N\times N$ matrix.

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- For 3 Majorana ν's : 3 Mixing angles + 1 Dirac Phase + 2 Majorana Phases

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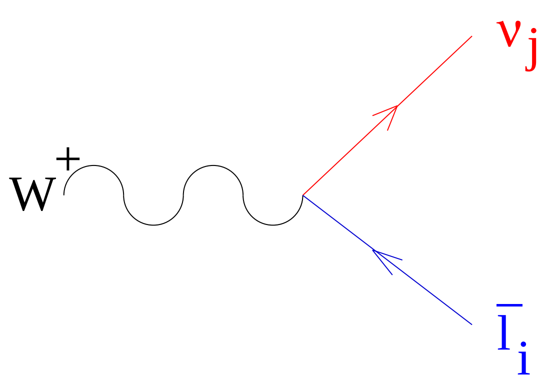

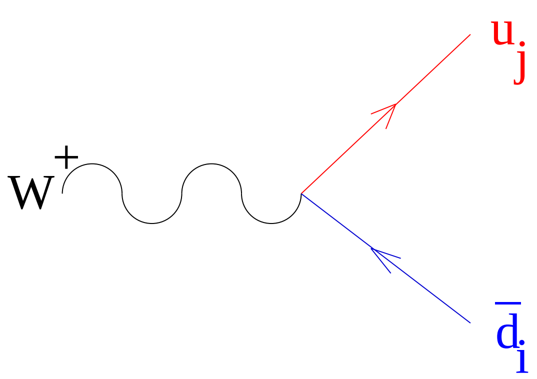

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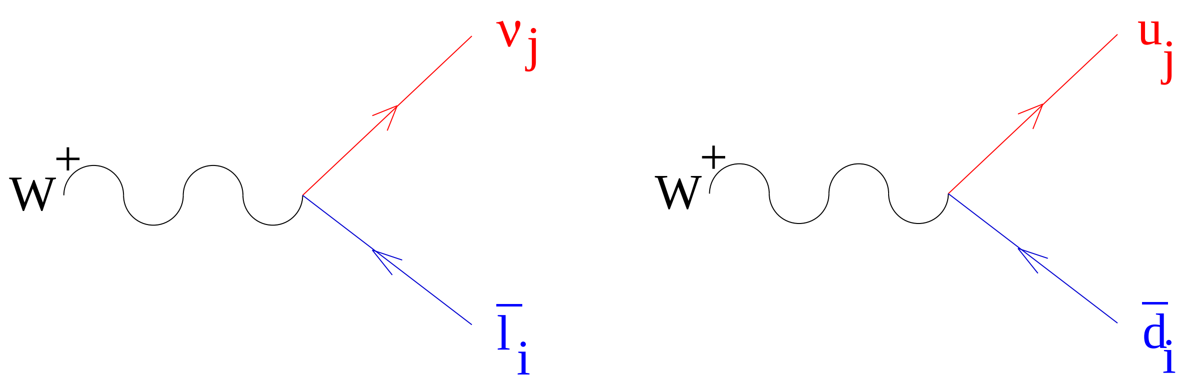

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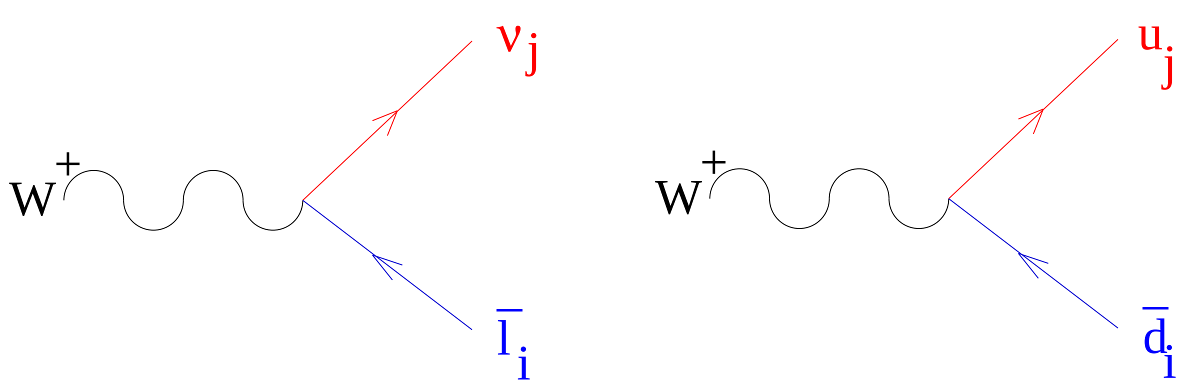

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• Total lepton number $U(1)_L = U(1)_{Le+L_\mu+L_\tau}$ can be or cannot be still a symmetry depending on whether neutrinos are Dirac or Majorana

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- To fully determine the lepton flavour sector we want to know:

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  * Their CP properties:

    Dirac: $\nu^C \neq \nu$ $\quad \#\text{ phases} = \begin{cases} 0 \text{ for } N=2 \\ 1 \text{ for } N=3 \\ 3 \text{ for } N=4 \end{cases}$

    Majorana: $\nu^C = \nu$ $\quad \#\text{ phases} = \begin{cases} 1 \text{ for } N=2 \\ 3 \text{ for } N=3 \\ 6 \text{ for } N=4 \end{cases}$

    $U_{\alpha j}^{\text{Maj}} = U_{\alpha j}^{\text{Dir}} \times \mathrm{e}^{-i\eta_j}$

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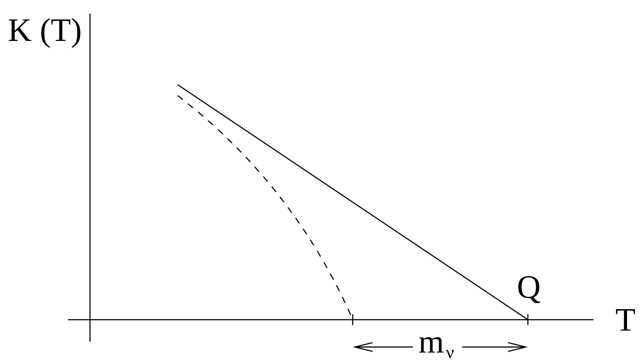

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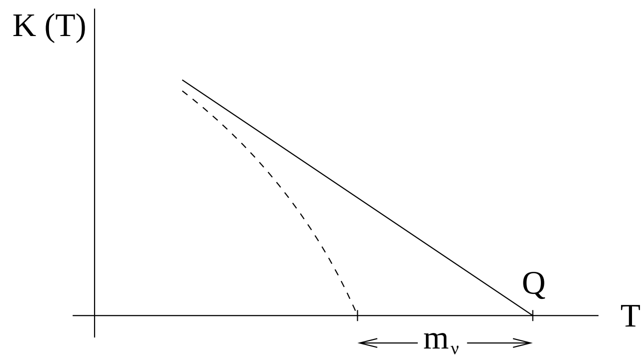

– At present only a bound: $m_{\nu_e}^{eff} \equiv \sqrt{\sum m_j^2 |U_{ej}|^2} < 2.2$ eV (at 95 % CL)
(Mainz & Troisk experiments)

– Katrin proposed to improve present sensitivity to $m_{eff}^{\beta} \sim 0.3\,\text{eV}$

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Muon neutrino mass

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- Measurement of p_μ plus the precise knowledge of m_π and $m_\mu \Rightarrow m_\nu$
- The present experimental result bound:

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- The τ is much heavier $m_\tau = 1.776$ GeV

$\Rightarrow$ Large phase space $\Rightarrow$ difficult precision for m_ν

- The best precision is obtained from hadronic final states

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$\Rightarrow$ If mixing angles U_{ej} are not negligible

Best kinematic limit on Neutrino Mass Scale comes from Tritium Beta Decay

Neutrino Mass Scale: ν-less Double-β Decay

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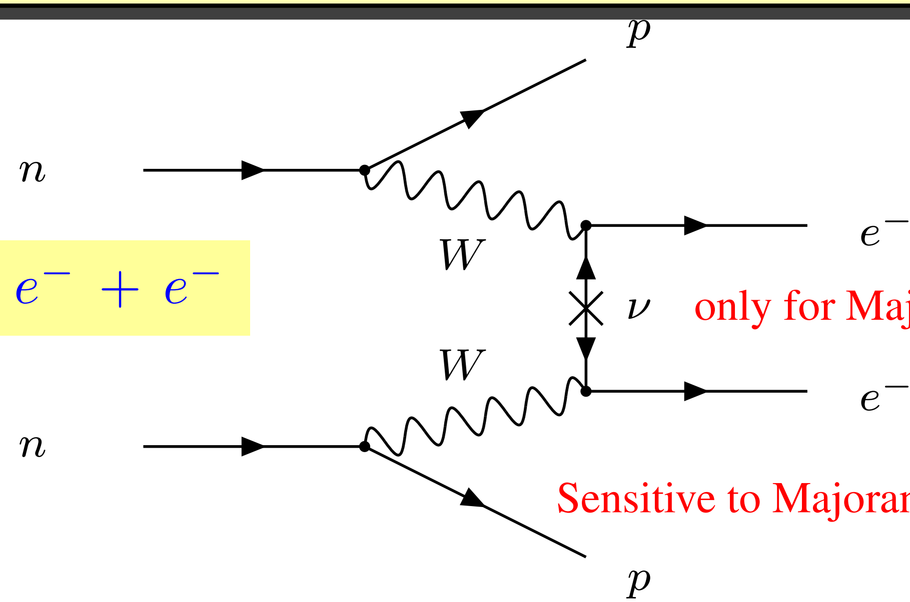
$$(A, Z) \rightarrow (A, Z+2) + e^- + e^-$$



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Sensitive to Majorana CP phases

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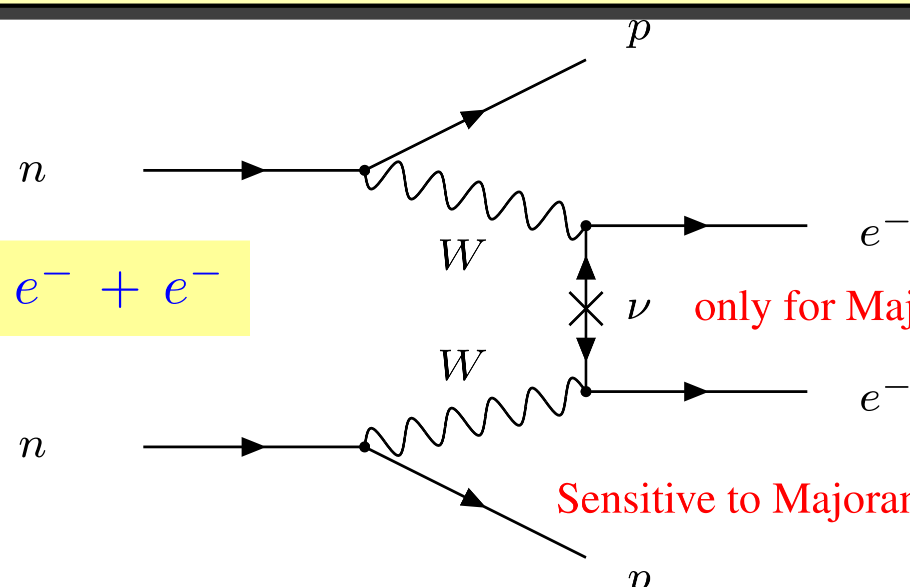

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- Amplitude involves the product of two leptonic currents: $\left[\overline{e}\gamma^\mu L\nu\right]\left[\overline{e}\gamma^\mu L\nu\right]$
  - If ν Dirac $\Rightarrow$ ν *annihilates* a *neutrino* and *creates* an *antineutrino*
    $\Rightarrow$ no same state $\Rightarrow$ Amplitude = 0
  - If ν Majorana $\Rightarrow$ $\nu = \nu^c$ *annihilates and creates* a *neutrino=antineutrino*
    $\Rightarrow$ same state $\Rightarrow$ Amplitude $\propto \overbracket{\nu\ (\nu^c})^T \neq 0$
- Amplitude of ν-less-$\beta\beta$ decay is proportional to $|\langle m_{ee}\rangle| = |\sum U_{ej}^2 m_j|$

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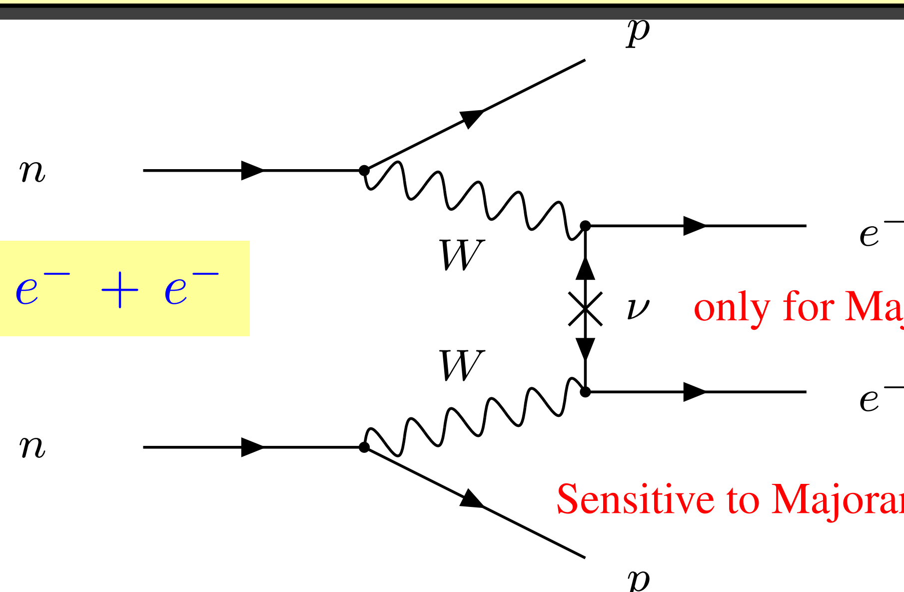

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    $\Rightarrow$ same state $\Rightarrow$ Amplitude $\propto$ $\overbrace{\nu\ (\nu^c})^T \neq 0$
- Amplitude of ν-less-$\beta\beta$ decay is proportional to $|\langle m_{ee}\rangle| = |\sum U_{ej}^2 m_j|$
  - Present bound: $|\langle m_{ee}\rangle| < 0.35$ eV +theor. uncert. < 1.05 eV (90% CL)
  - Several proposed experiments to reach $|\langle m_{ee}\rangle| \sim 10^{-2}$ eV

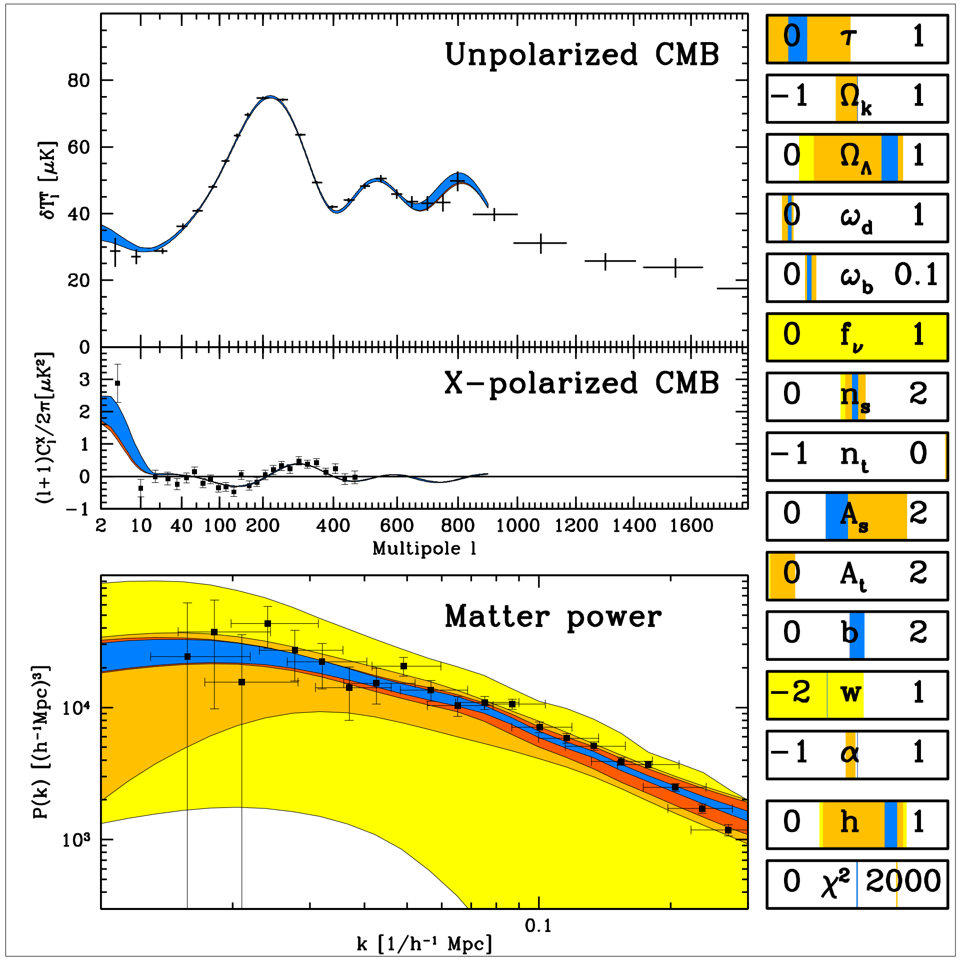
Neutrino Mass Scale in Cosmology

$\sum m_{\nu_i}$ has effects on:

Cosmic Microwave Background Temperature Fluctuations

Most recent from WMAP

Large scale structure:
– 2° Field Galaxy Redshift Survey (2dFGRS)
–Sloan Digital Sky Survey (SDSS)



Tegmark *et. al* astro-ph/0310723

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Large scale structure:
– 2° Field Galaxy Redshift Survey (2dFGRS)
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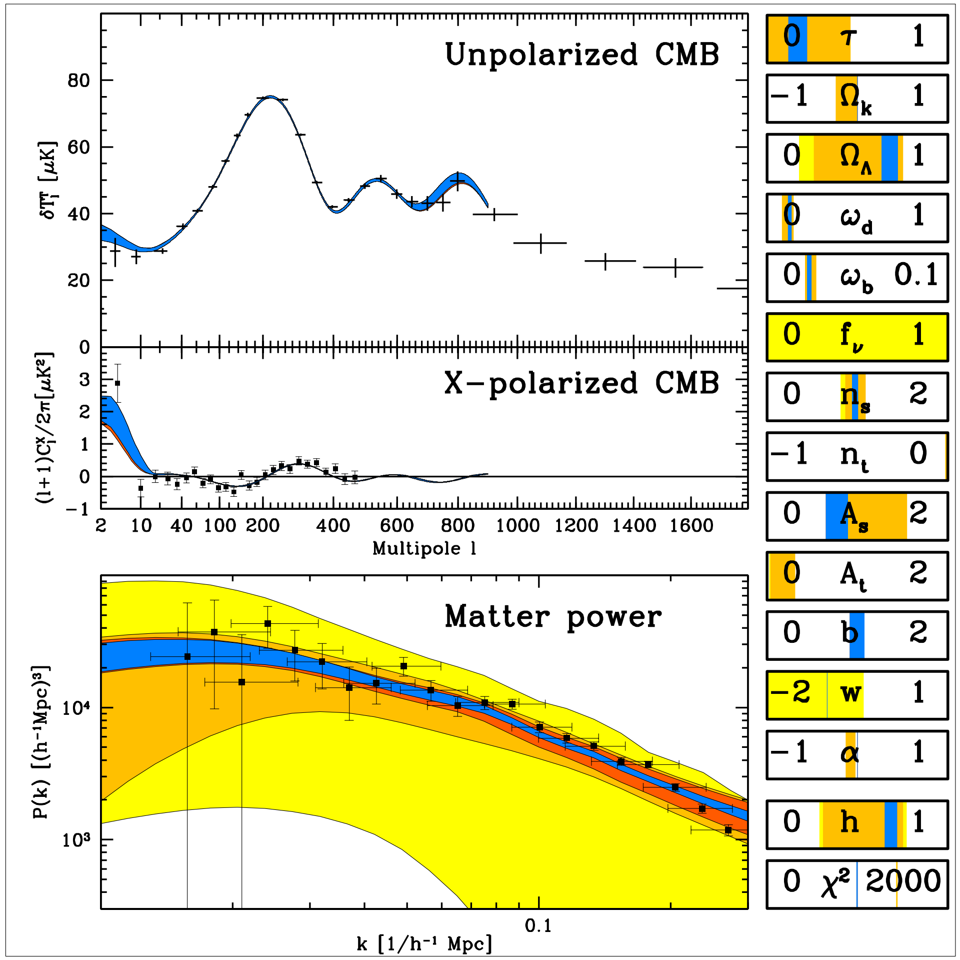

Tegmark *et. al* astro-ph/0310723

Problem: 13 parameters to be determined!!

Neutrino Mass Scale in Cosmology

$\sum m_{\nu_i}$ has effects on:

Cosmic Microwave Background Temperature Fluctuations

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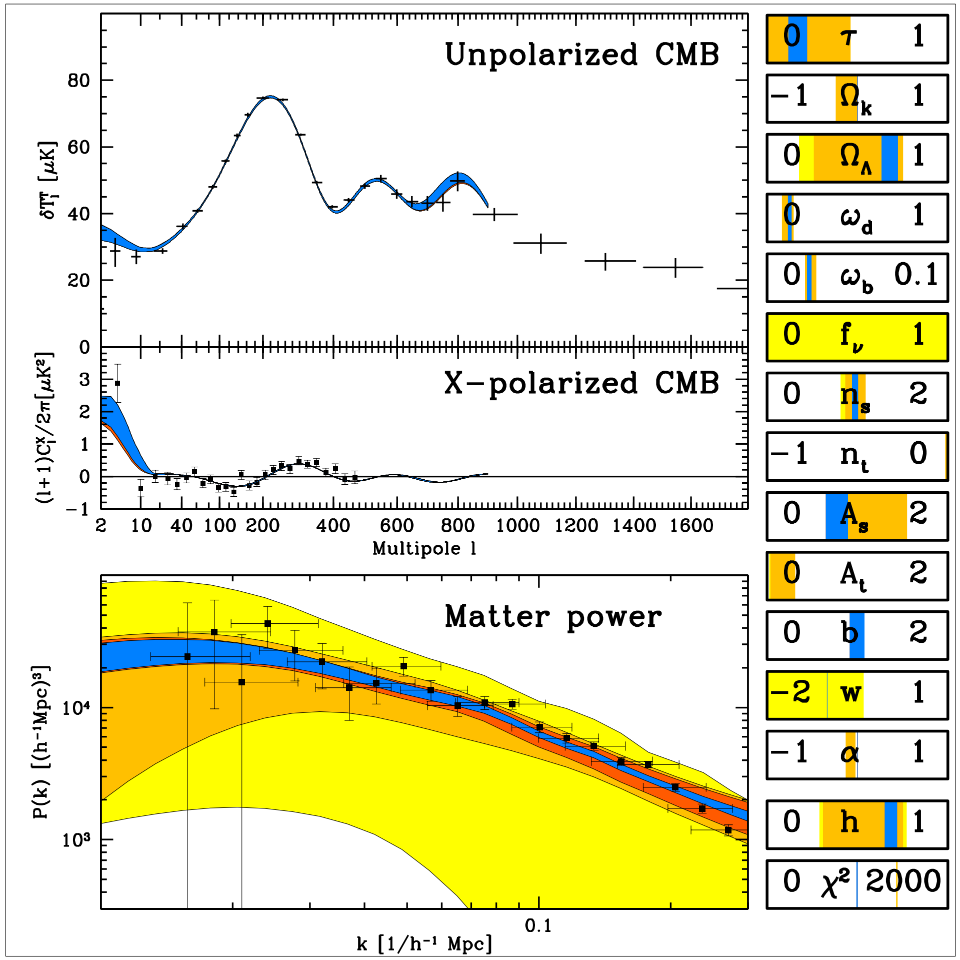

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Problem: 13 parameters to be determined!!

⇒ limit on $\sum m_{\nu_i}$ depends on prior and data used to constraint other 12 parameters

$\sum m_{\nu_i} \leq 0.7 \; - \; 2.1$ eV at 95 % CL

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Vacuum Oscillations

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  $(\mathbf{3})$ Assuming $p_i \simeq p_j = p \simeq E$

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  - $\Delta m^2_{ij} = m_i^2 - m_j^2$ The mass differences
  - $U_{\alpha j}$ The mixing angles (and Dirac phases)

and on Two *Experimental* Parameters:

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- No information on mass scale nor Majorana phases

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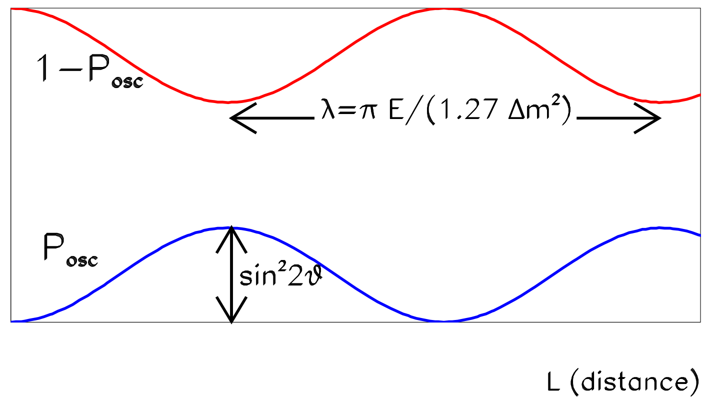
$P_{\alpha\alpha} = 1 - P_{osc}$ Disappear



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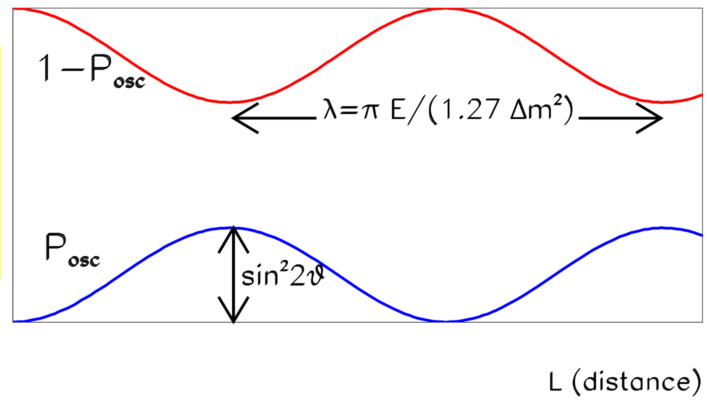

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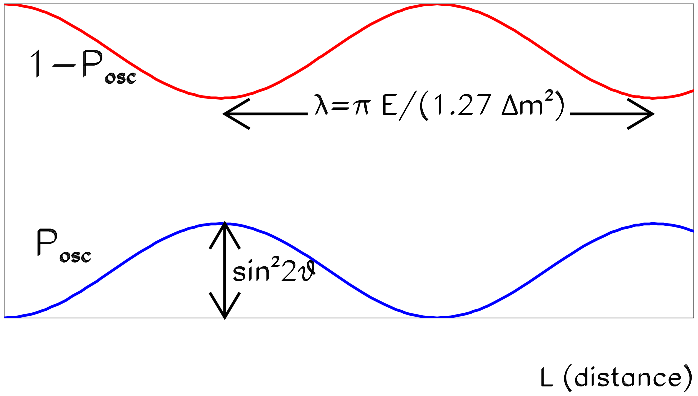

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- Moreover P_{osc} is symmetric under $\Delta m^2 \to -\Delta m^2$ *or* $\theta \to -\theta + \frac{\pi}{2}$

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  This only happens for 2ν vacuum oscillations

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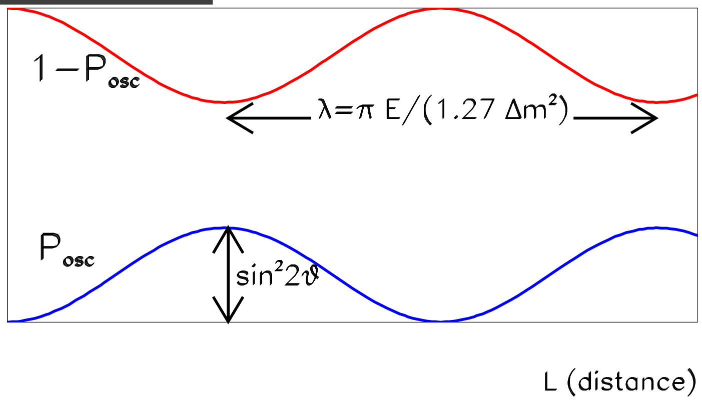

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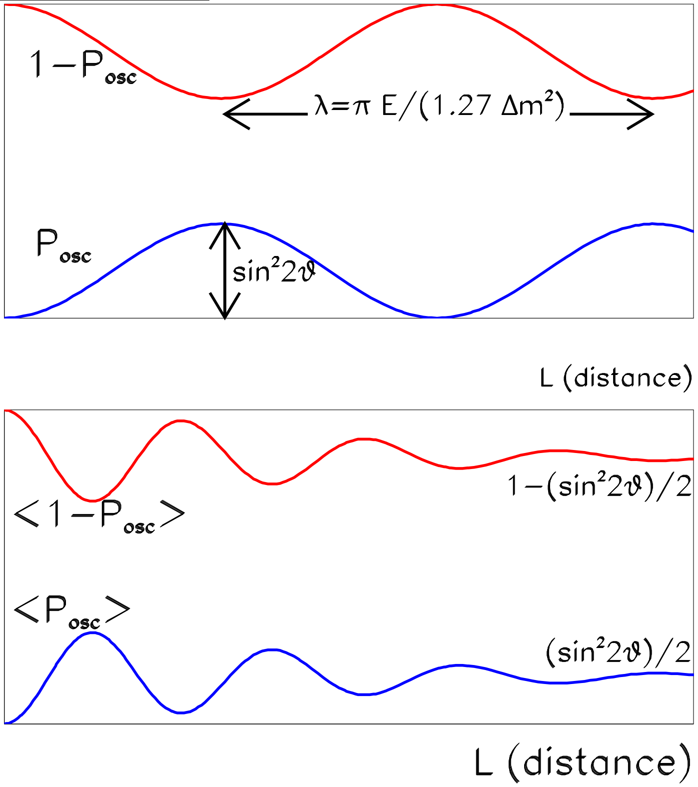

- In real experiments
  neutrinos are not monochromatic

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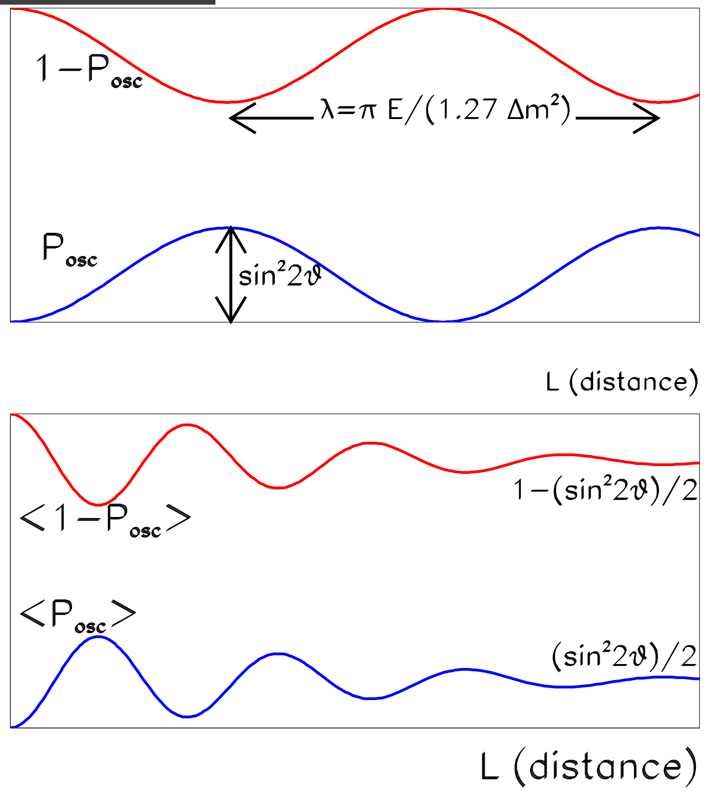

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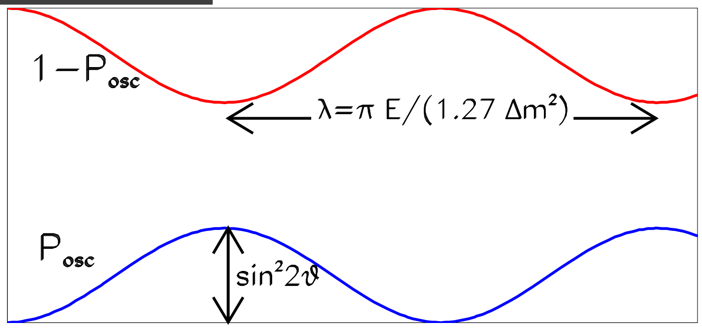

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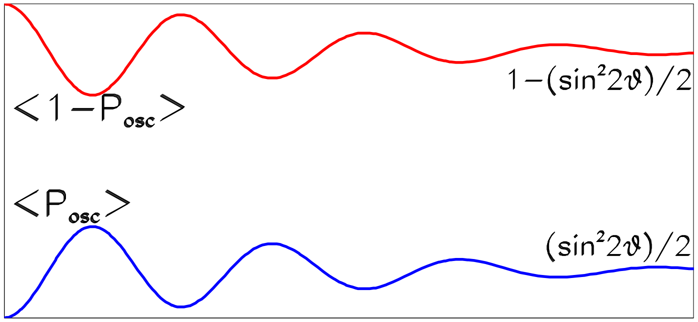

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  $\Rightarrow \langle\sin^2(1.27\Delta m^2 L/E)\rangle \simeq 0 \rightarrow \langle P_{osc}\rangle \simeq 0$

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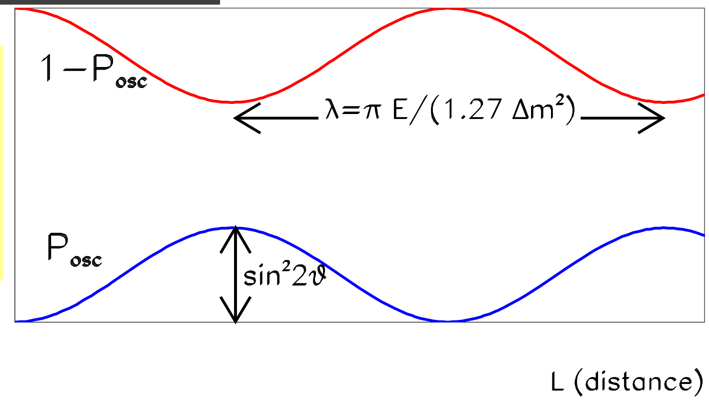

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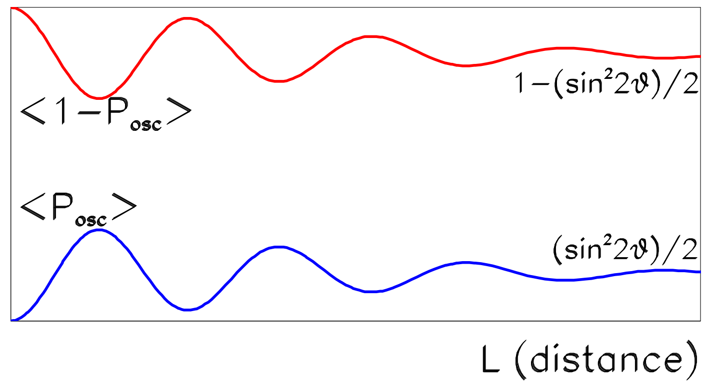

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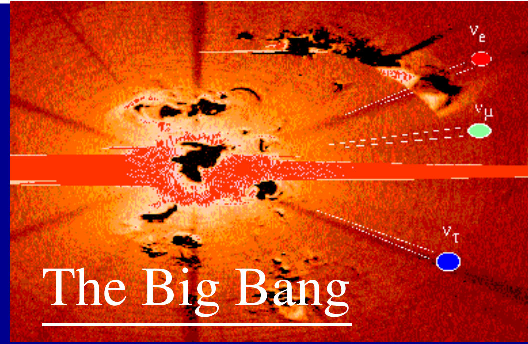
  – $\Delta m^2 \gg E/L \;\Rightarrow$ Averaged oscillations

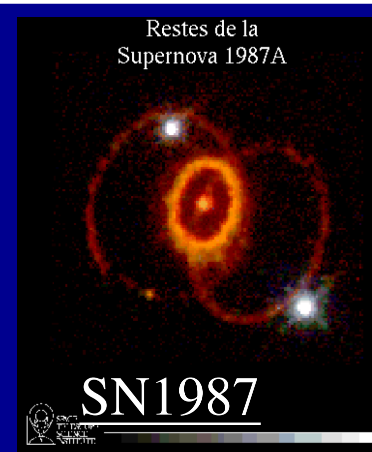
  $$\Rightarrow \langle \sin^2(1.27\Delta m^2 L/E)\rangle \simeq \frac{1}{2} \rightarrow \langle P_{osc}\rangle \simeq \frac{1}{2}\sin^2(2\theta)$$

Sources of ν's



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

E_ν =0.0004 eV



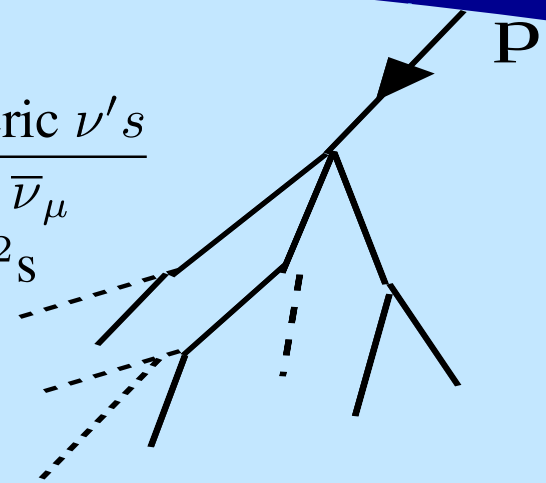
$E_\nu \sim$ MeV

The Sun

ν_e

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

$E_\nu \sim$ 0.1–20 MeV



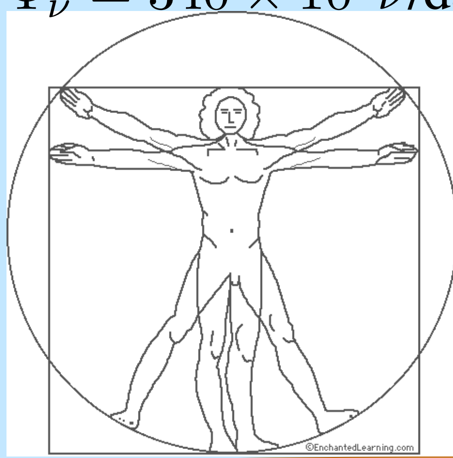
Atmospheric $\nu' s$

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

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

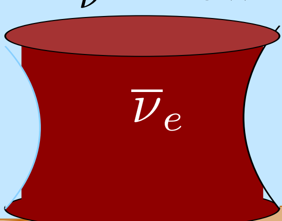
Human Body

$\Phi_\nu = 340 \times 10^6 \nu$/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

KEK

Concha Gonzalez-Garcia

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

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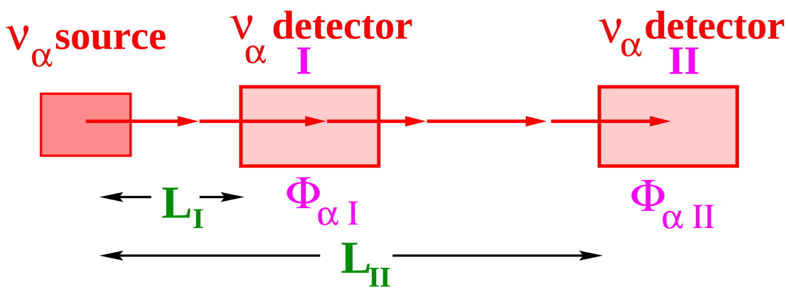

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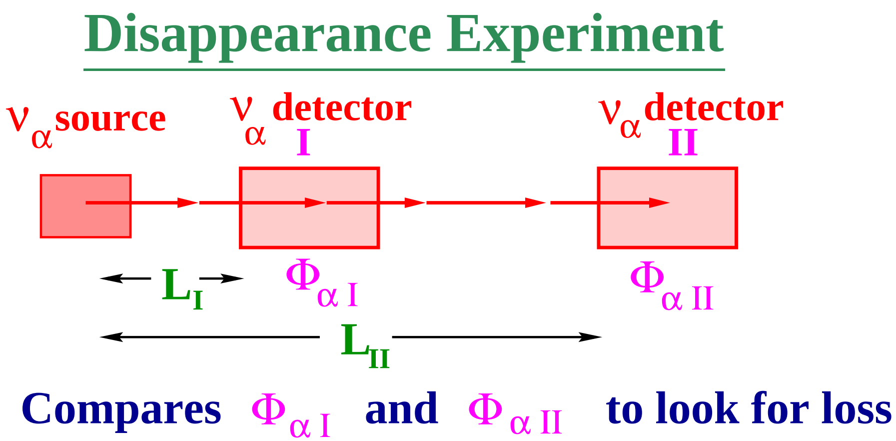
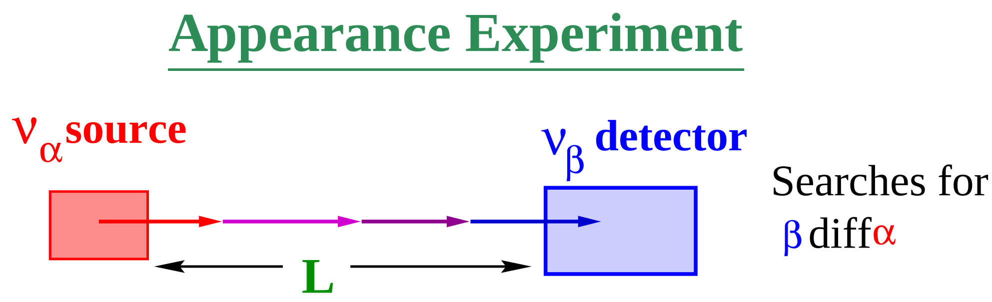
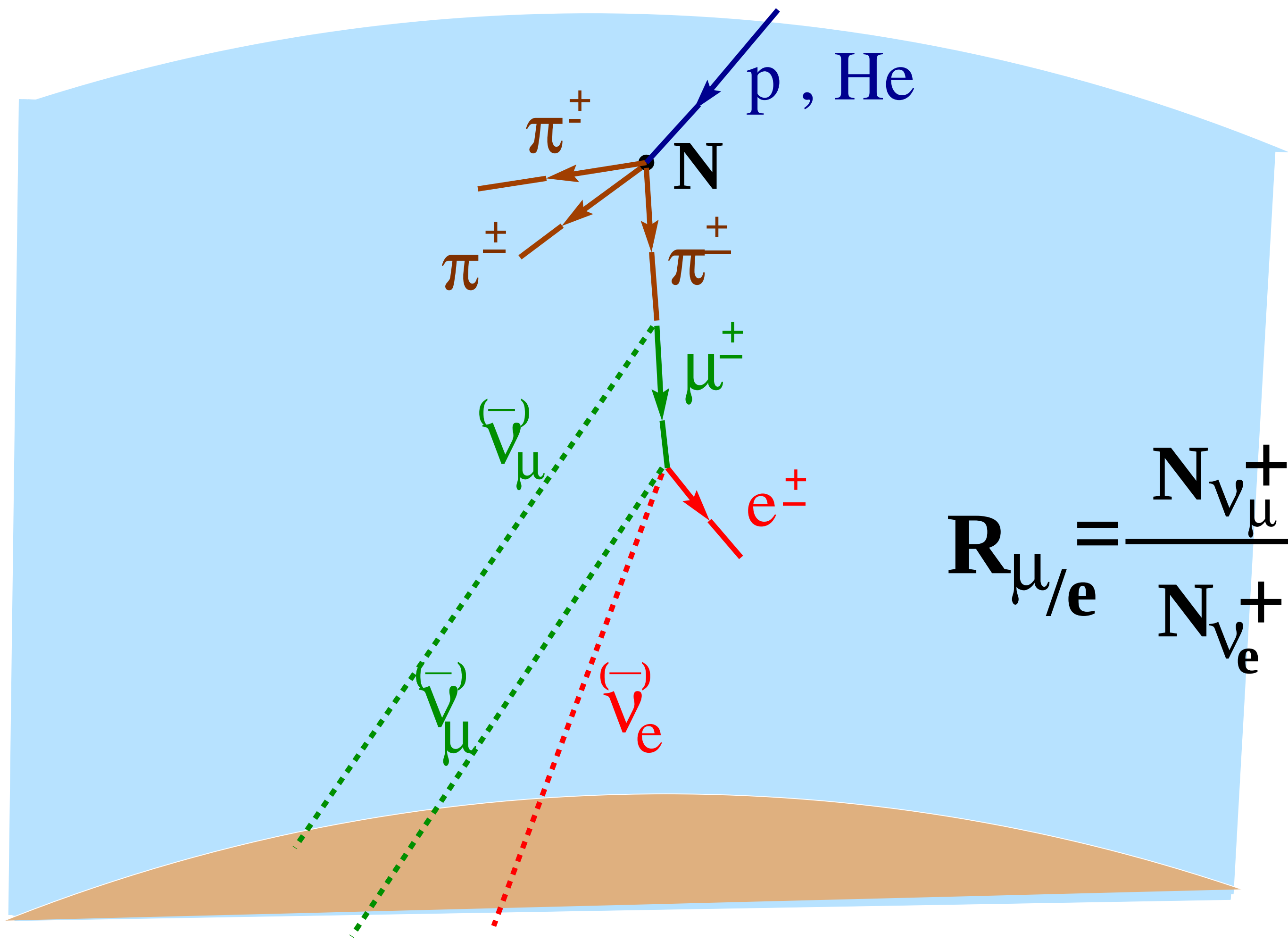




Atmospheric Neutrinos

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



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

Atmospheric Neutrinos: Data

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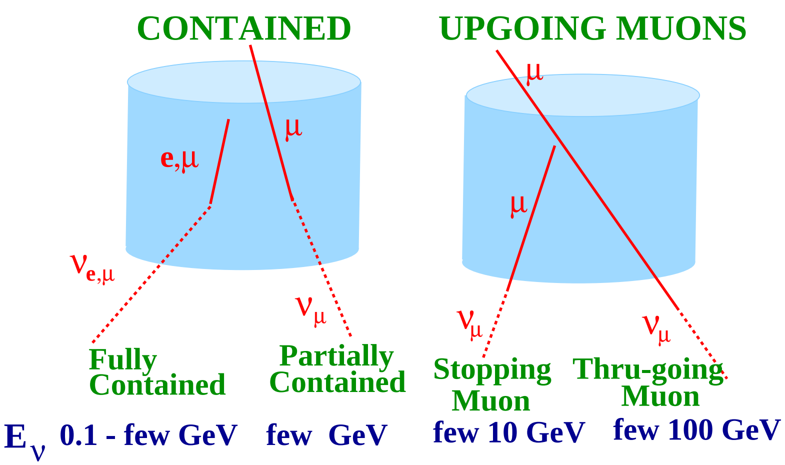
EVENT CLASSIFICATION



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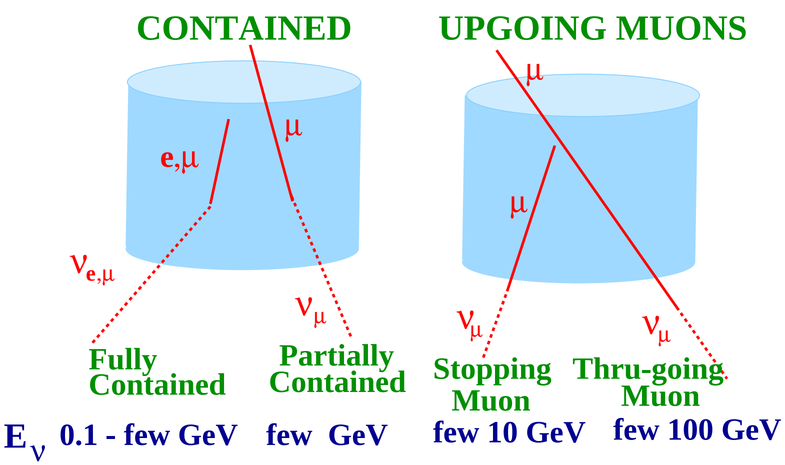
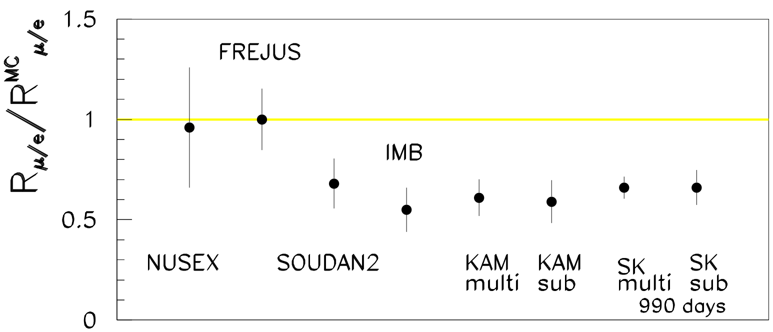


- Total Rates for Contained Events



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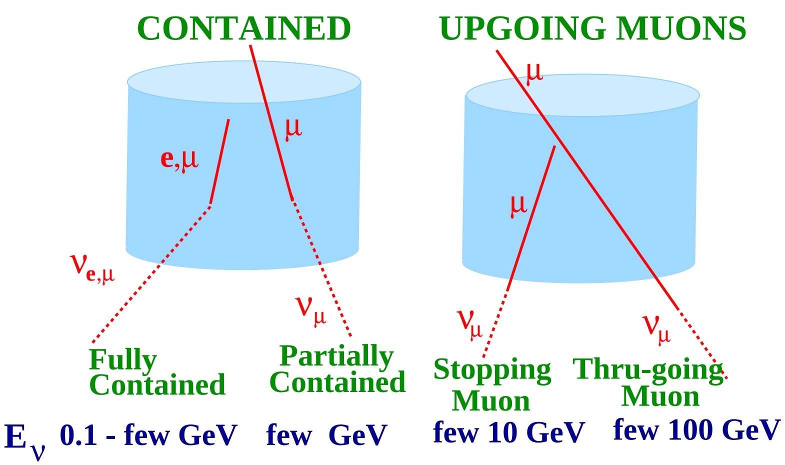

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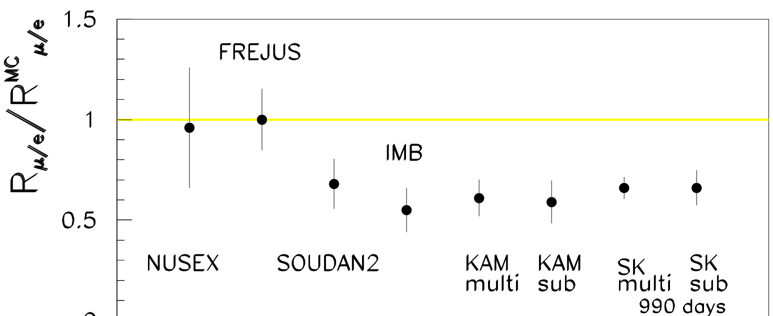
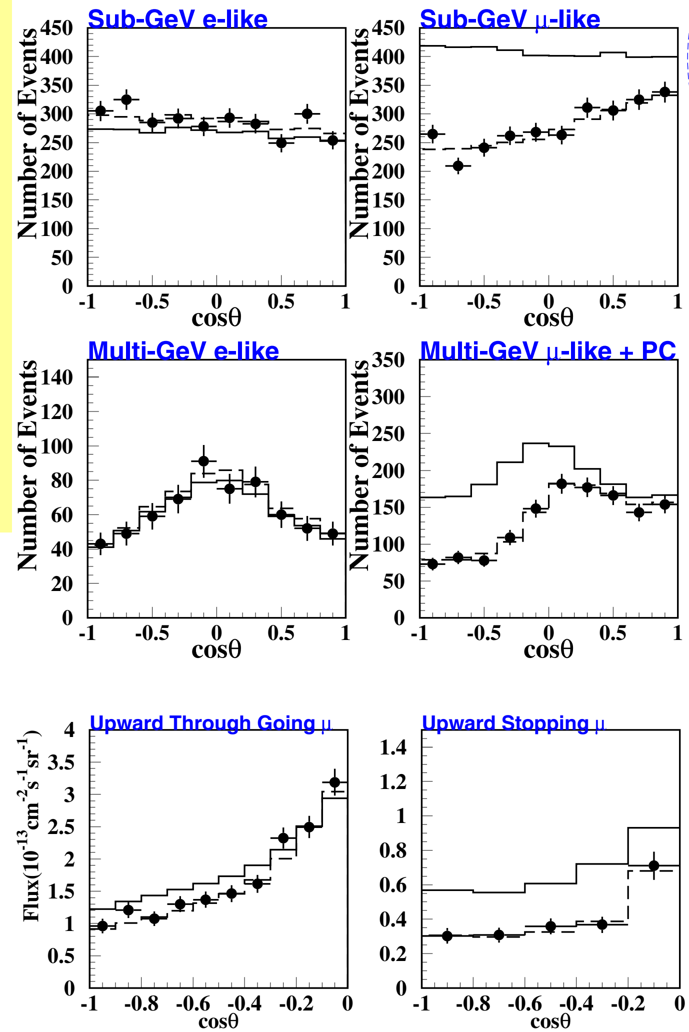
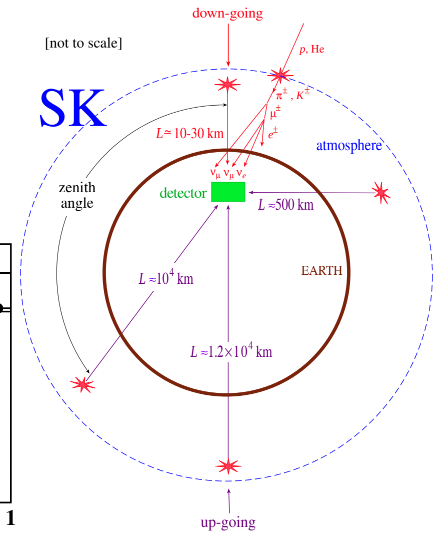


- Angular Distribution at SK

ν_e in agreement with SM





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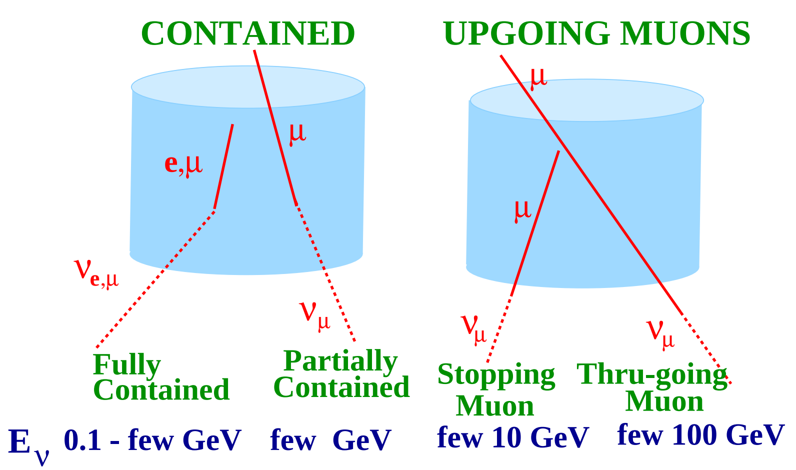

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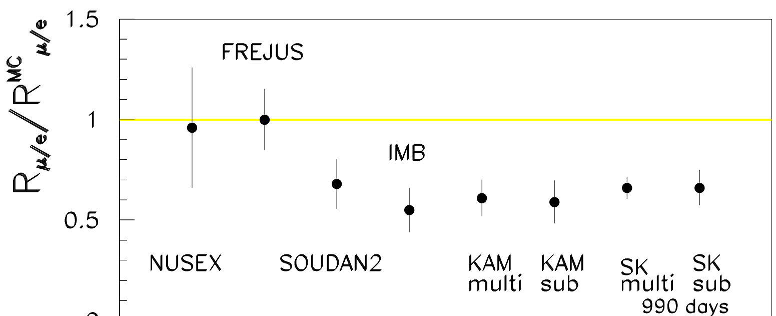

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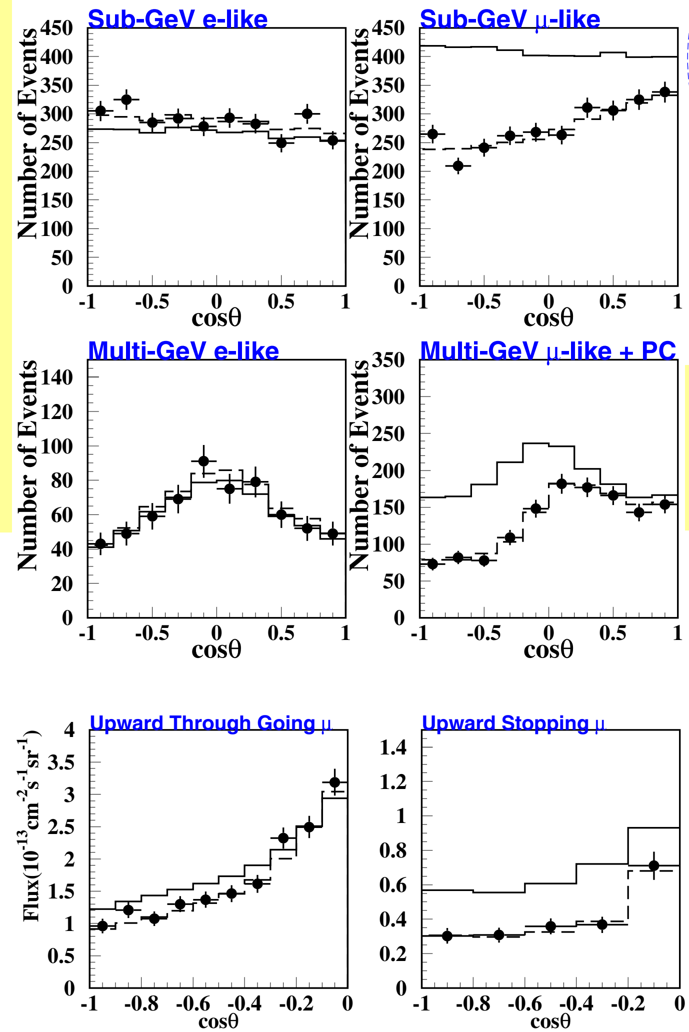

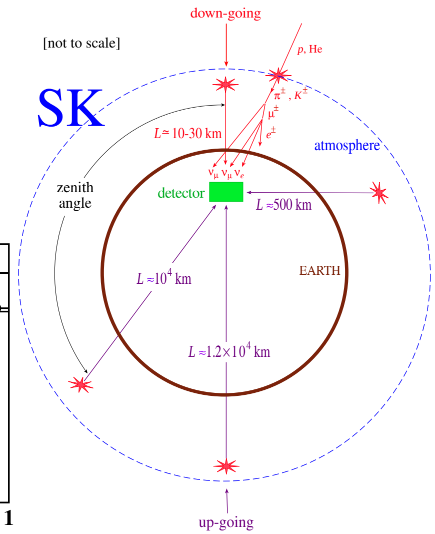

→ Deficit grows with L

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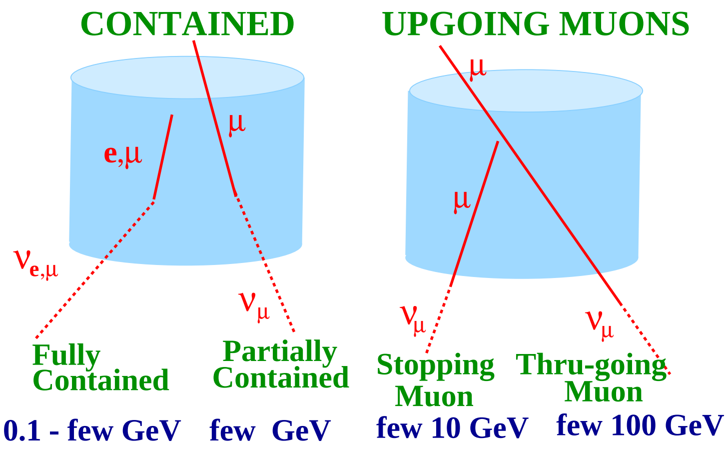

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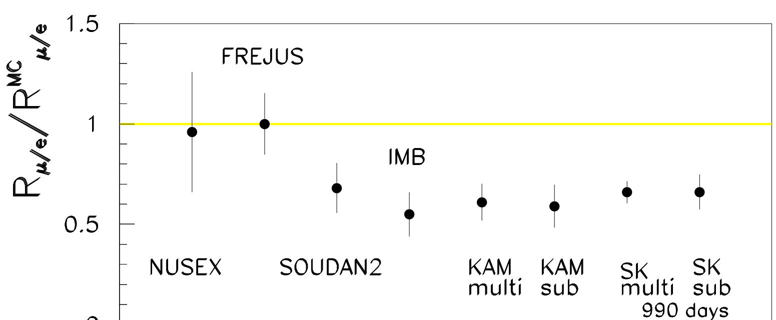

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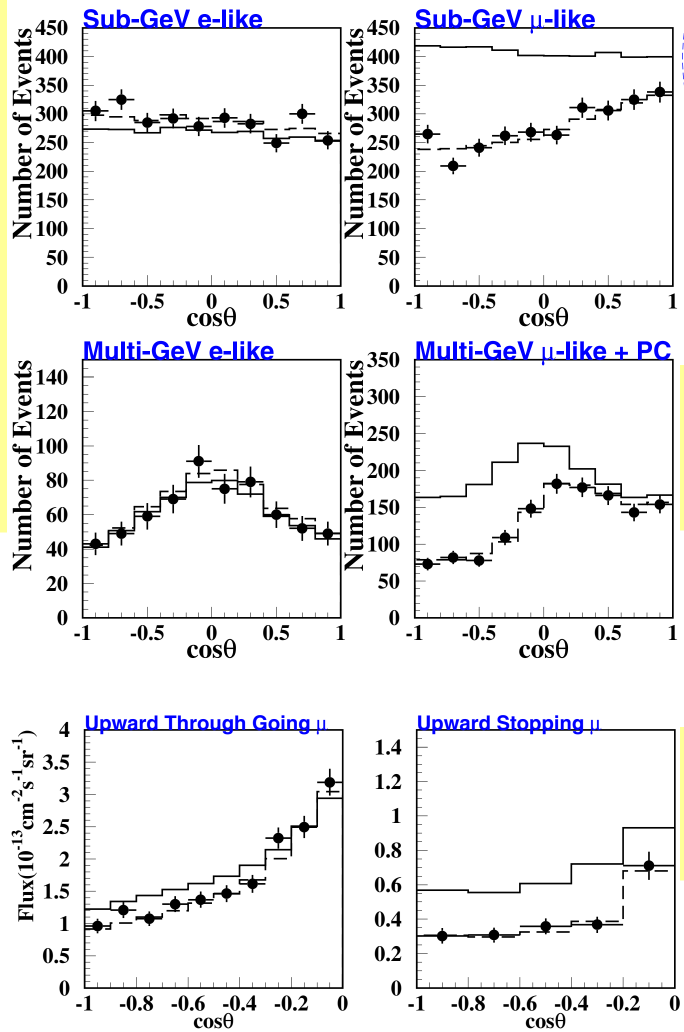

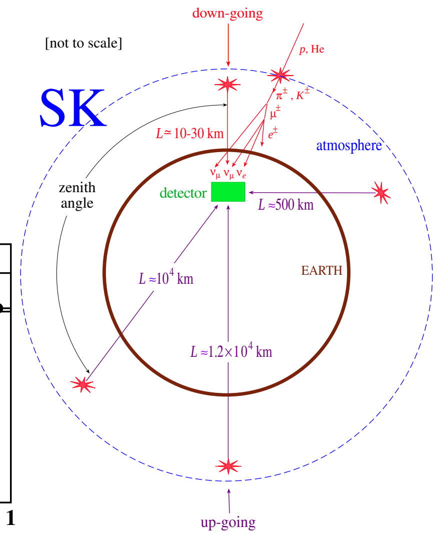

→ Deficit grows with L

→ Decreases with E

Atmospheric ν Oscillations: Parameter Estimate

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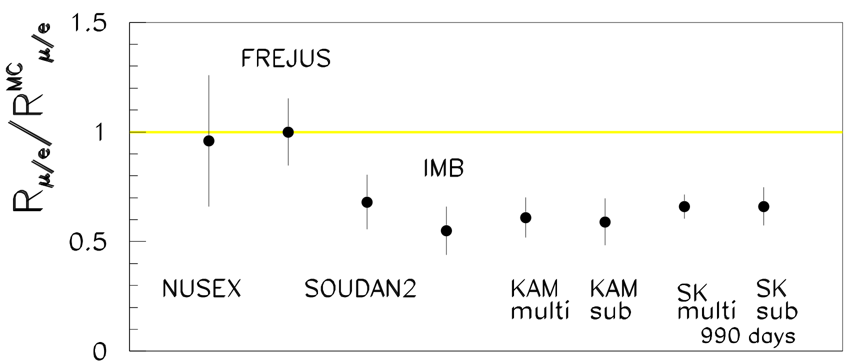
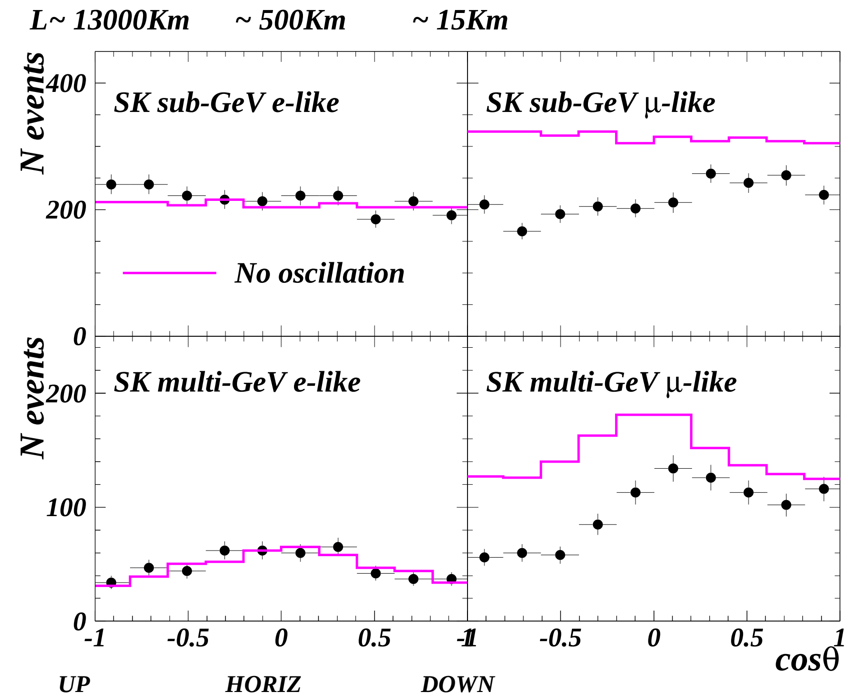
- From Total Contained Event Rates:



$$\langle P_{\mu\mu}\rangle = 1 - \sin^2 2\theta \sin^2 \frac{\Delta m^2 L}{2E}$$
$$\sim 0.5 - 0.7$$

$$\Rightarrow \sin^2 2\theta \gtrsim 0.6$$

- From Angular Distribution:

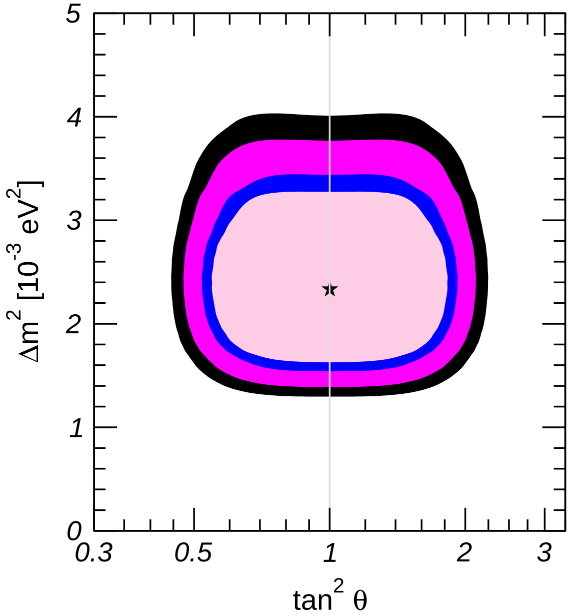


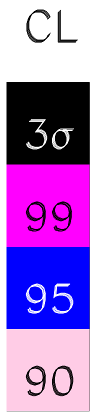
For $E \sim 1$ GeV deficit at $L \sim 10^2$– 10^4 Km

$$\frac{\Delta m^2(\mathrm{eV}^2) L(\mathrm{km})}{2E(\mathrm{GeV})} \sim 1$$

$$\Rightarrow \Delta m^2 \sim 10^{-4} - 10^{-2} \mathrm{eV}^2$$

Atmospheric ν Oscillation Solution: $\nu_\mu \to \nu_\tau$





Best fit:

$\Delta m^2 = 2.2 \times 10^{-3}$ eV^2

$\tan^2\theta = 1$

ν Oscillations: Lab Searches at Short Distance

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- In laboratory experiments ν source: Accelerator or Nuclear Reactor

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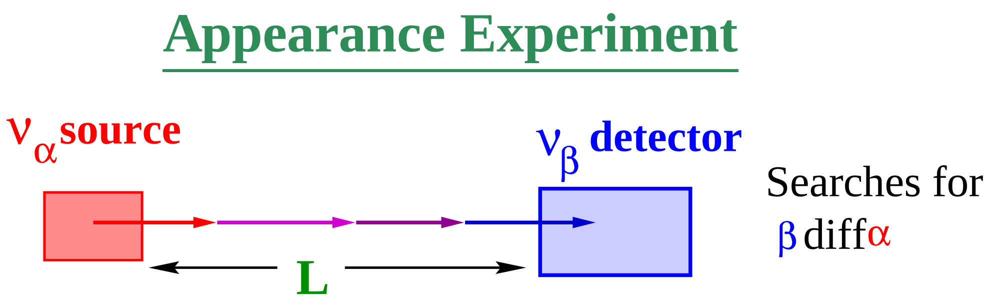

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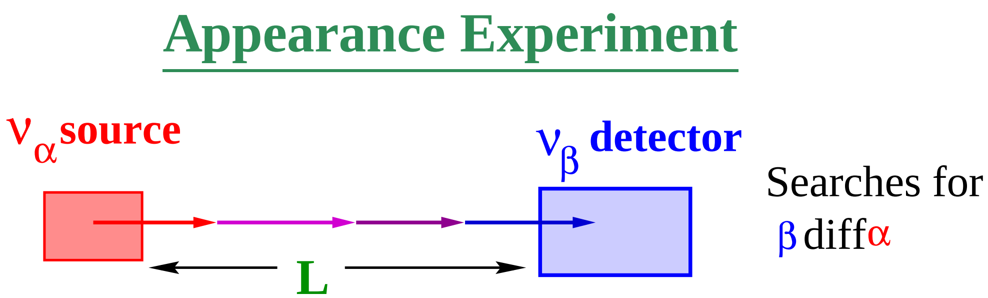

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E531	25	FNAL	ν_μ, ν_e	ν_τ
Nomad	13	CERN	ν_μ, ν_e	ν_τ
Chorus	13	CERN	ν_μ, ν_e	ν_τ
E776	2.5	BNL	ν_μ	ν_e
Karmen2	2.5	Rutherford	$\bar{\nu}_\mu$	$\bar{\nu}_e$
LSND	3	Los Alamos	$\bar{\nu}_\mu$	$\bar{\nu}_e$
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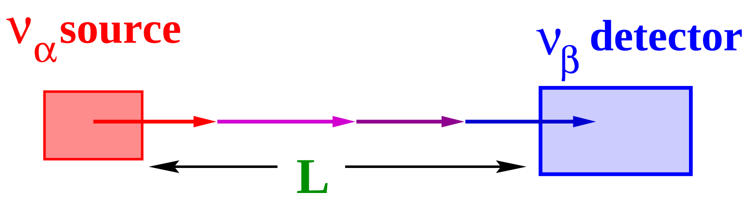

Searches for β diff α

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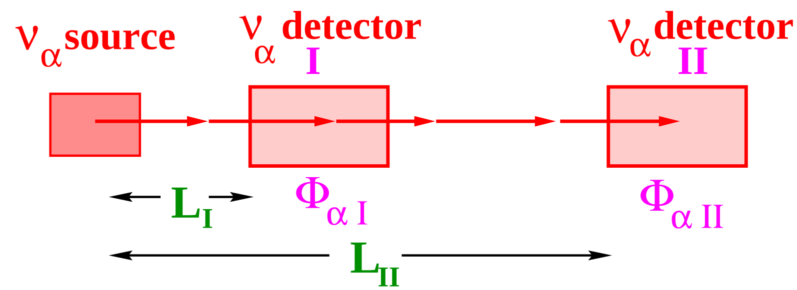
Disappearance Experiment



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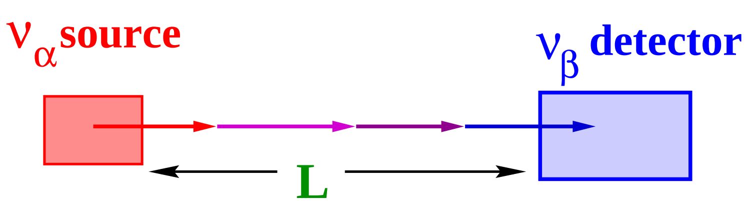

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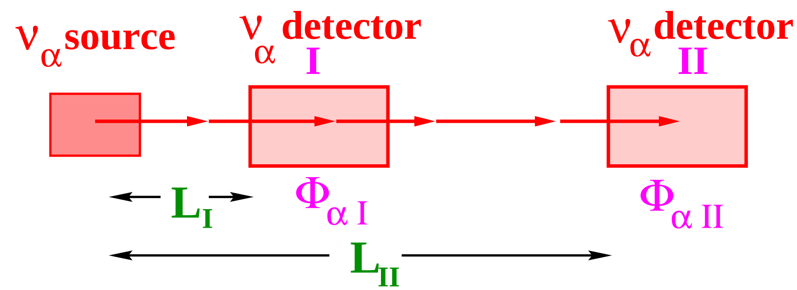

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Experiment	$\langle \frac{E/MeV}{L/m} \rangle$		α
CDHSW	1.4	CERN	ν_μ
BugeyIII	0.05	Reactor	$\bar\nu_e$
Chooz	0.005	Reactor	$\bar\nu_e$

LSND

LSND

- The only short distance signal for oscillation: $L = 30$ m with $\langle E_\nu \rangle \sim 30$ MeV
- Used the proton beam of Los Alamos $p + Target \rightarrow \pi^+ + X$

$$\pi^+ \rightarrow \nu_\mu \, \mu^+$$

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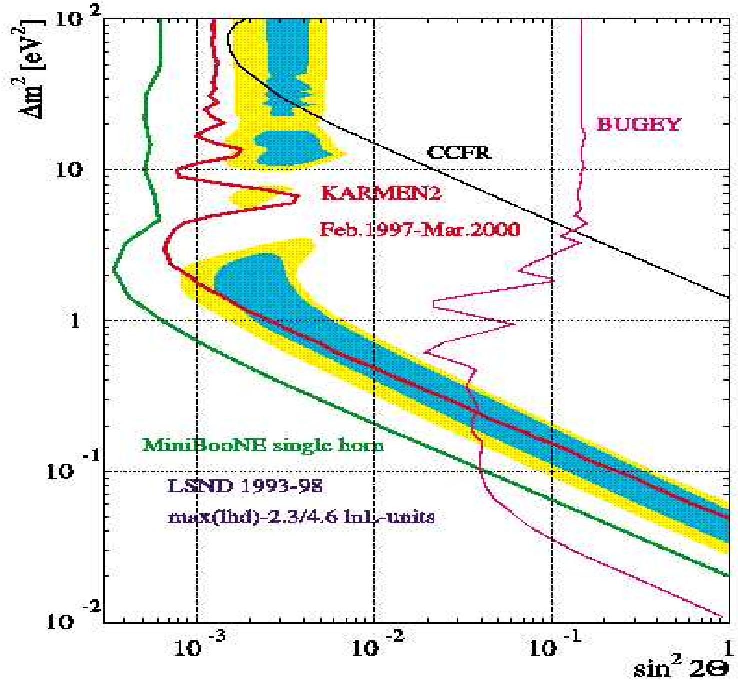

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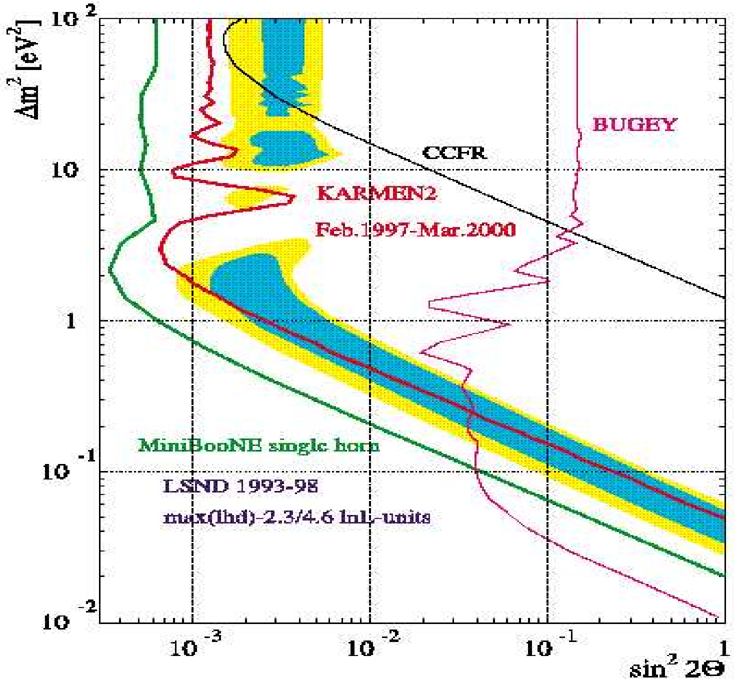

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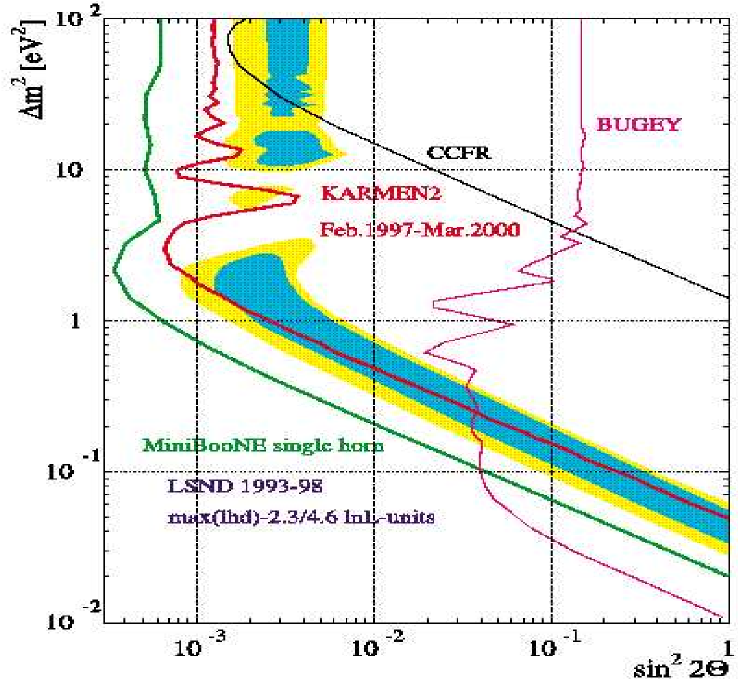

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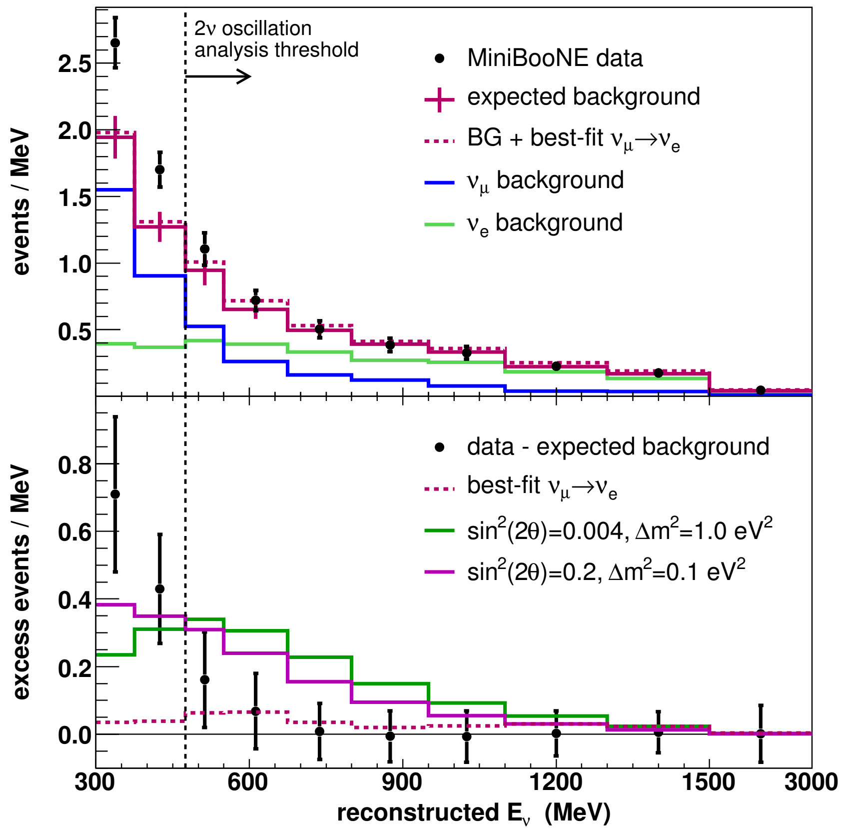
- $MiniBoone$ in Fermilab is/has been running to solve this.

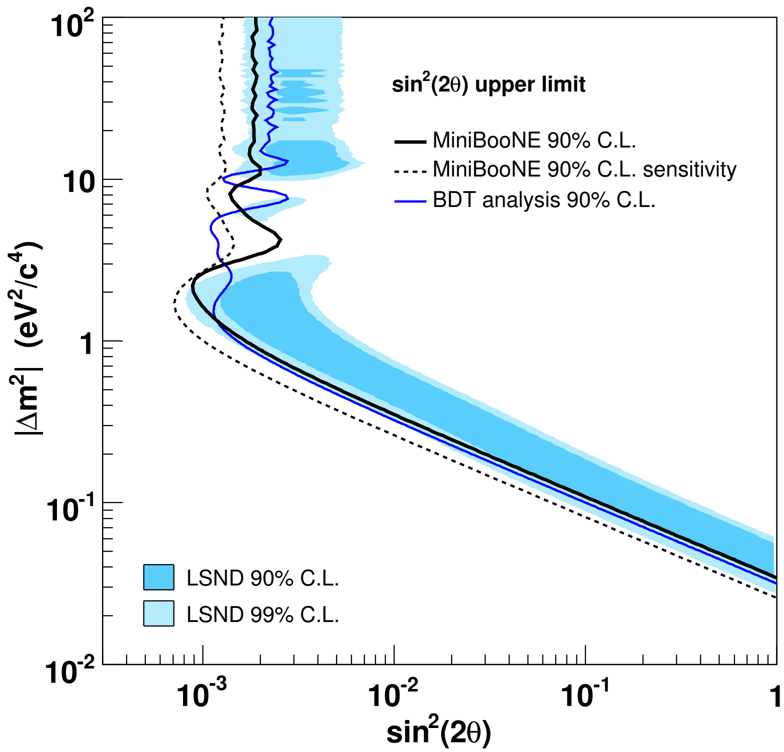
MiniBooNE

- Search for $\nu_\mu \to \nu_e$ with $E_\nu = 0.3 - 2$ GeV and $L = 540$ m

Observed spectrum of ν_e

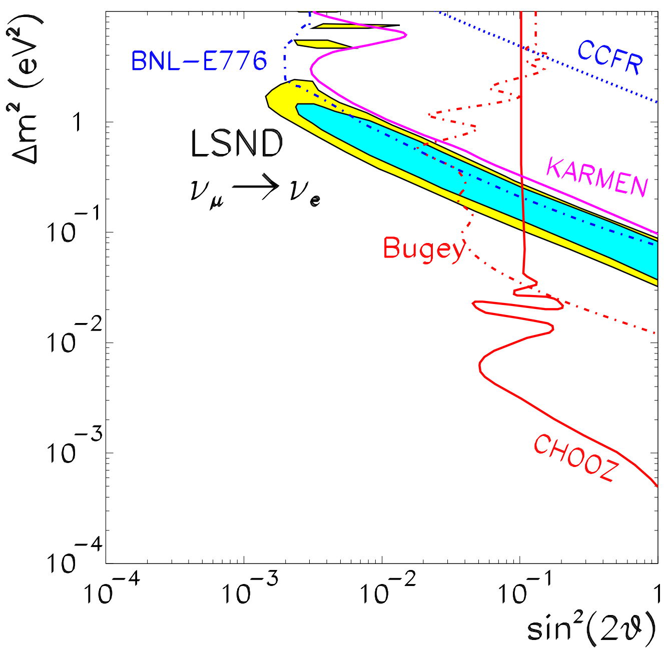


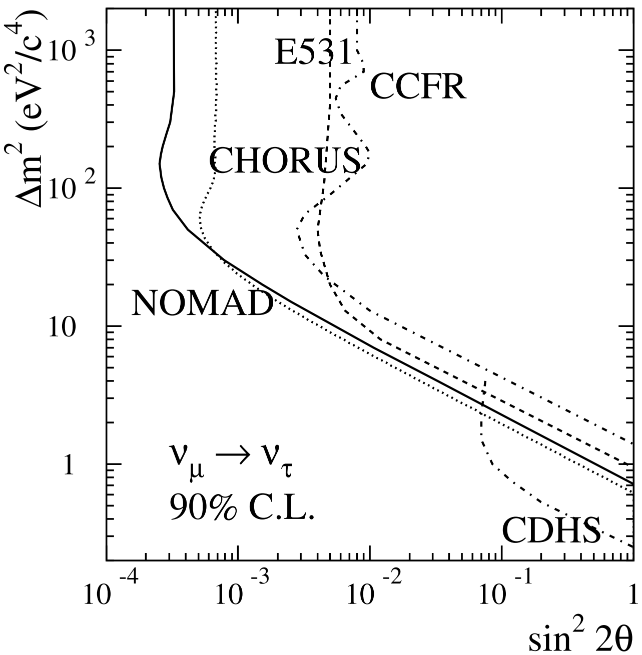
Excluded region

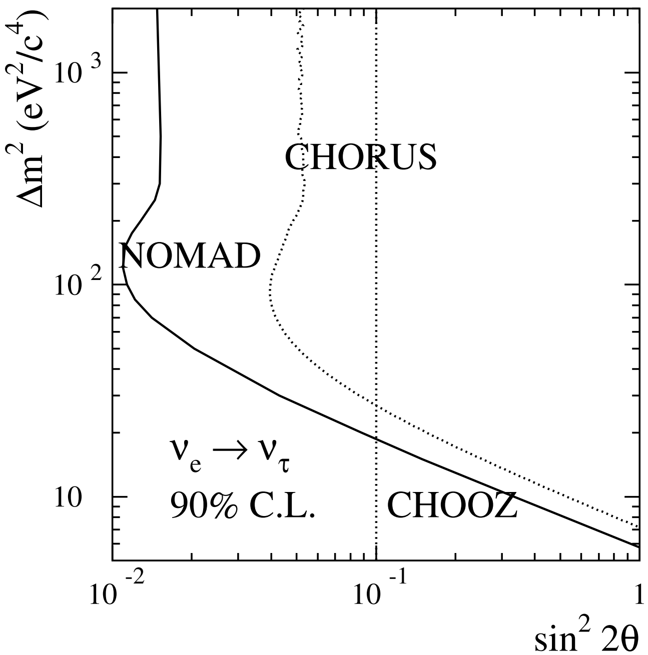


Based on this analysis LSND Excluded at 90-98% CL by MiniBooNE.

Summary of Searches at Short Baseline







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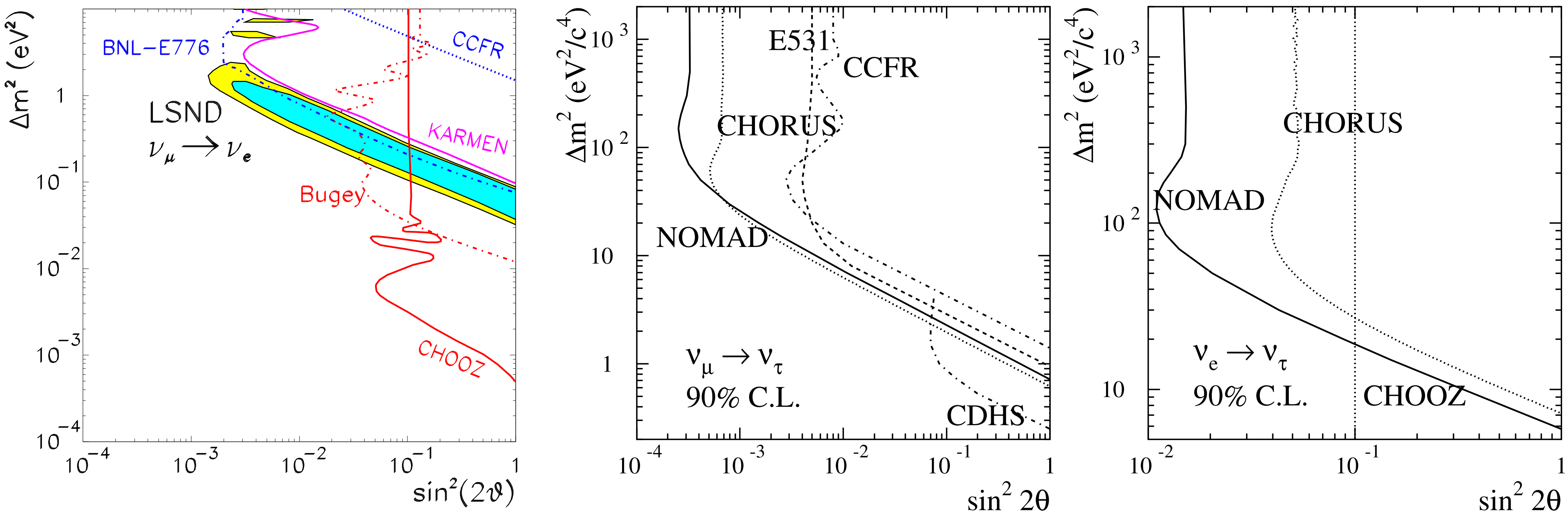

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  ⇒ Lower E and longer L

  ⇒ are more sensitive to lower Δm^2

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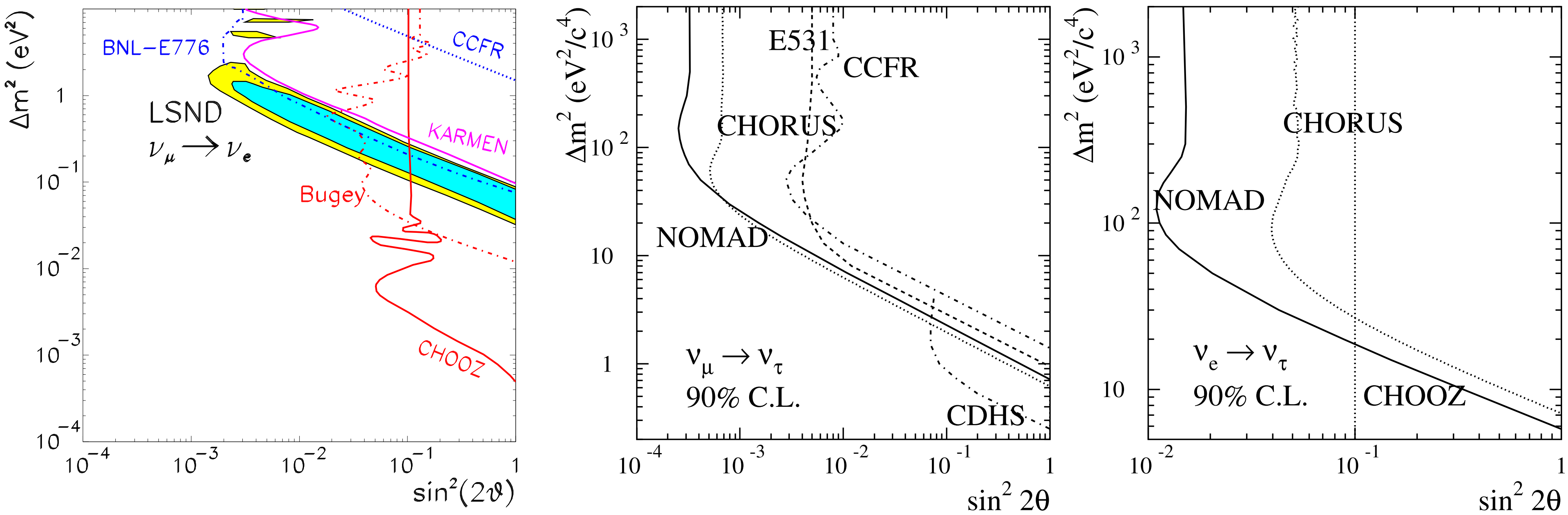

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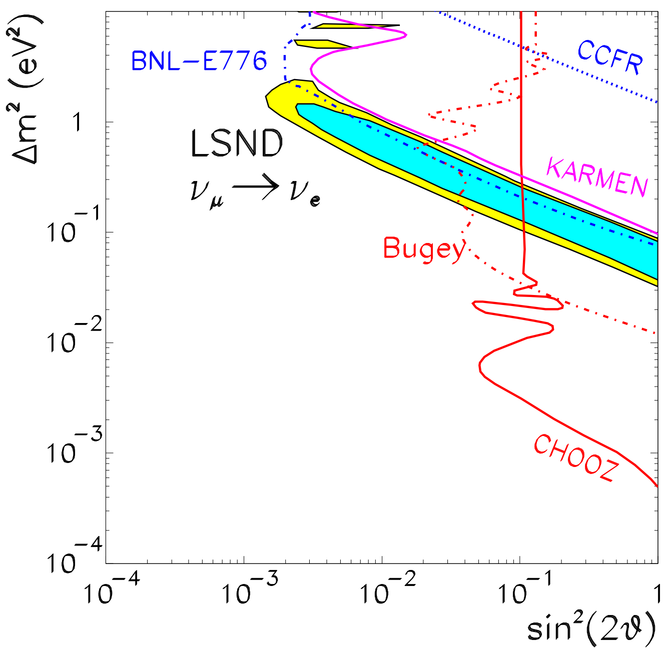

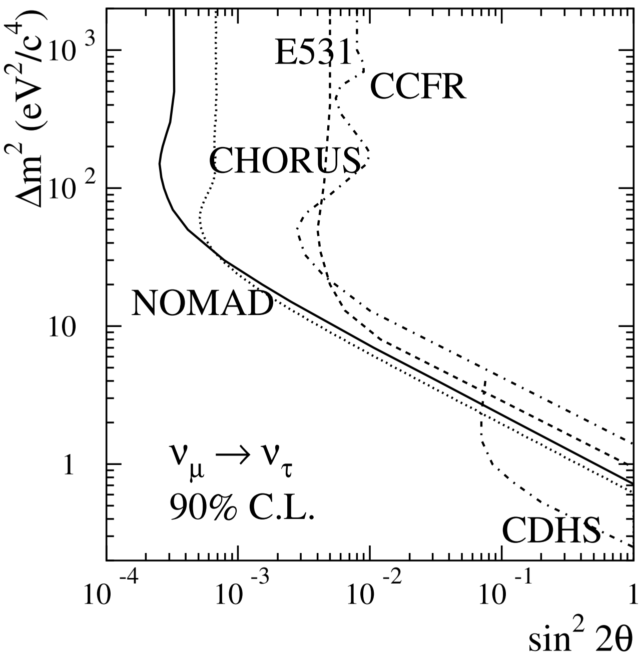

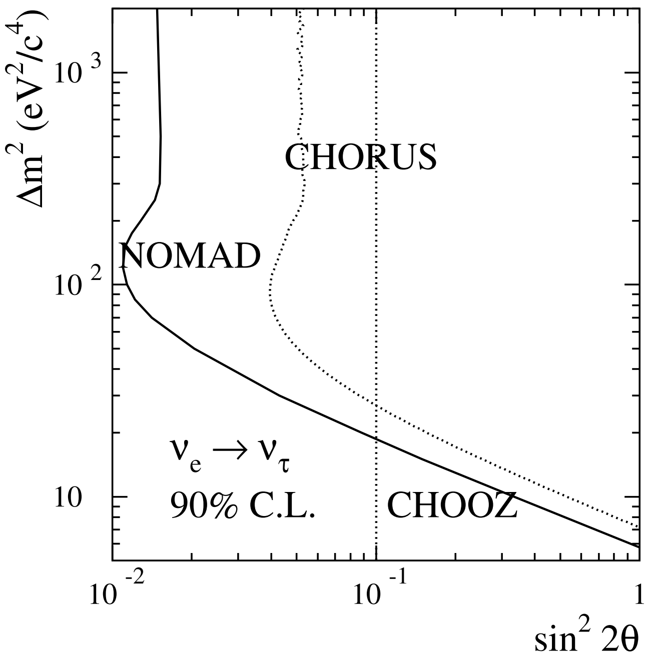

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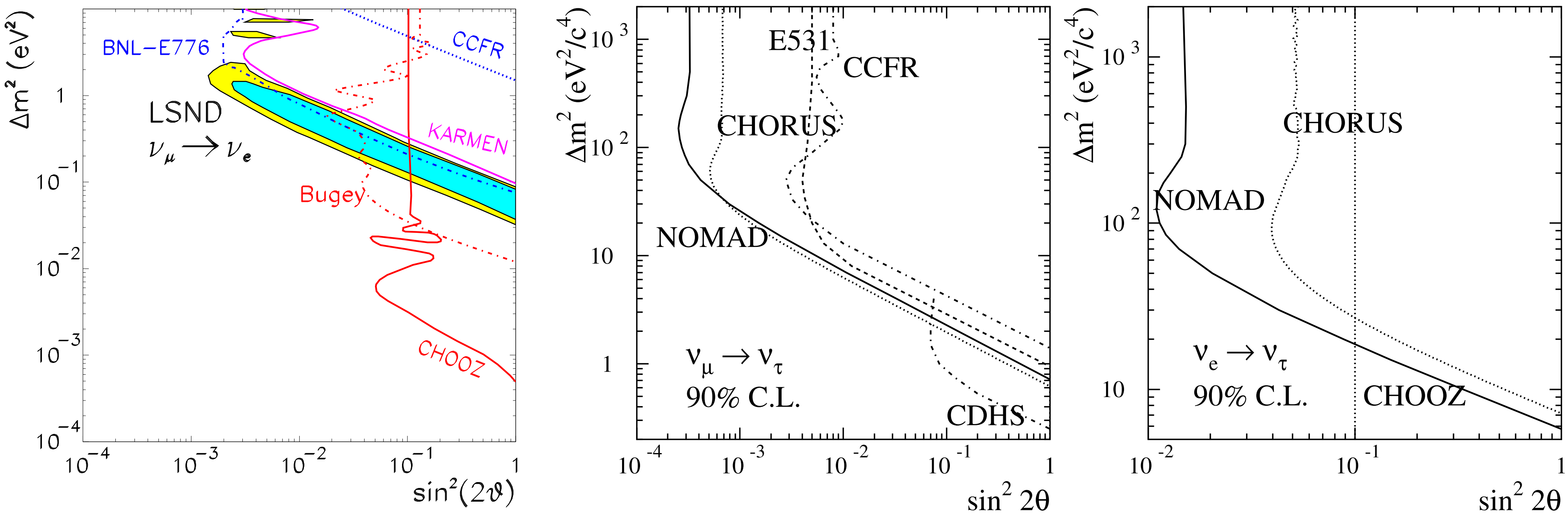

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ATM Test at Long Baseline Experiments

K2K	ν_μ at KEK	SK	L=250 km
MINOS	ν_μ at Fermilab	Soundan	L=735 km
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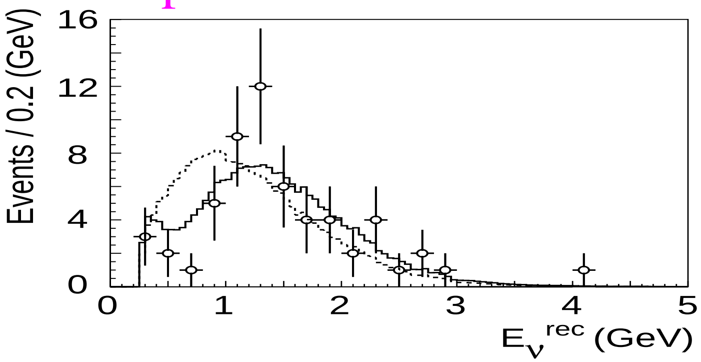
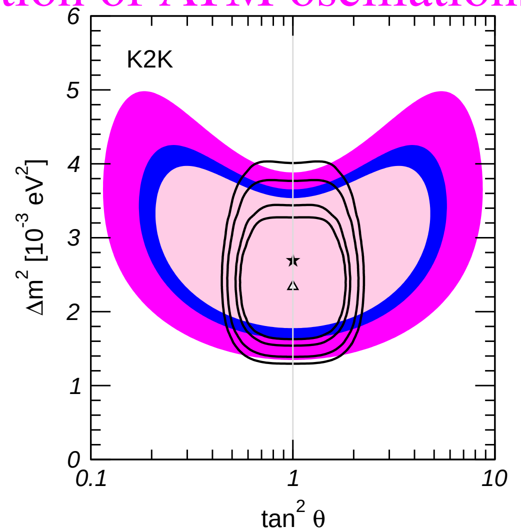
K2K 2004: spectral distortion



Confirmation of ATM oscillations



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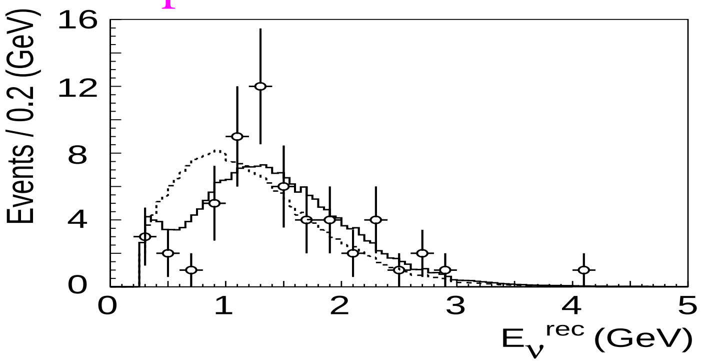
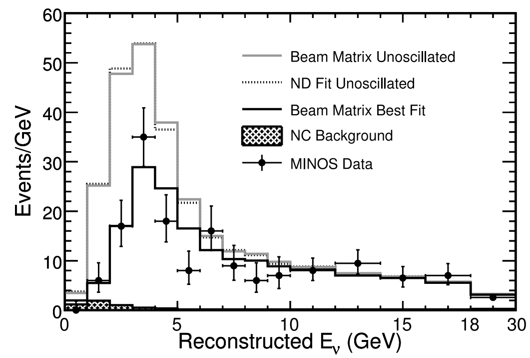


MINOS 2006: spectral distortion



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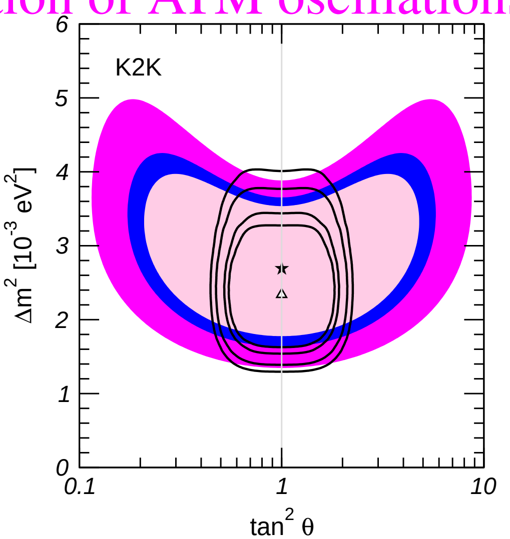
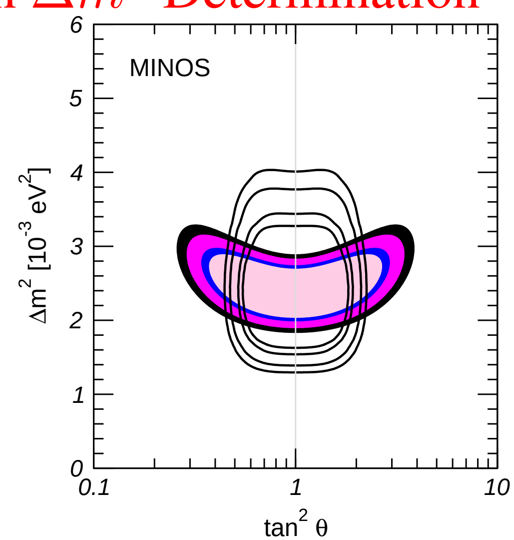


Impact on Δm^2 Determination



Altenative Oscillation Mechanisms

- Oscillations are due to:
  - Misalignment between CC-int and propagation states: Mixing $\Rightarrow$ Amplitude
  - Difference phases of propagation states $\Rightarrow$ Wavelength. For Δm^2-OSC $\lambda = \dfrac{4\pi E}{\Delta m^2}$

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- ν masses are not the only mechanism for oscillations

Violation of Equivalence Principle (VEP): Gasperini 88, Halprin,Leung 01

Non universal coupling of neutrinos $\gamma_1 \neq \gamma_2$ *to graviational potential* ϕ

$$\lambda = \frac{\pi}{E|\phi|\delta\gamma}$$

Violation of Lorentz Invariance (VLI): Coleman, Glashow 97

Non universal asymptotic velocity of neutrinos $c_1 \neq c_2 \Rightarrow E_i = \frac{m_i^2}{2p} + c_i p$

$$\lambda = \frac{2\pi}{E\Delta c}$$

Interactions with space-time torsion: Sabbata, Gasperini 81

Non universal couplings of neutrinos $k_1 \neq k_2$ *to torsion strength* Q

$$\lambda = \frac{2\pi}{Q\Delta k}$$

Violation of Lorentz Invariance (VLI) Colladay, Kostelecky 97; Coleman, Glashow 99

due to CPT violating terms: $\bar\nu_L^\alpha b_\mu^{\alpha\beta}\gamma_\mu \nu_L^\beta \Rightarrow E_i = \frac{m_i^2}{2p} \pm b_i$

$$\lambda = \pm\frac{2\pi}{\Delta b}$$

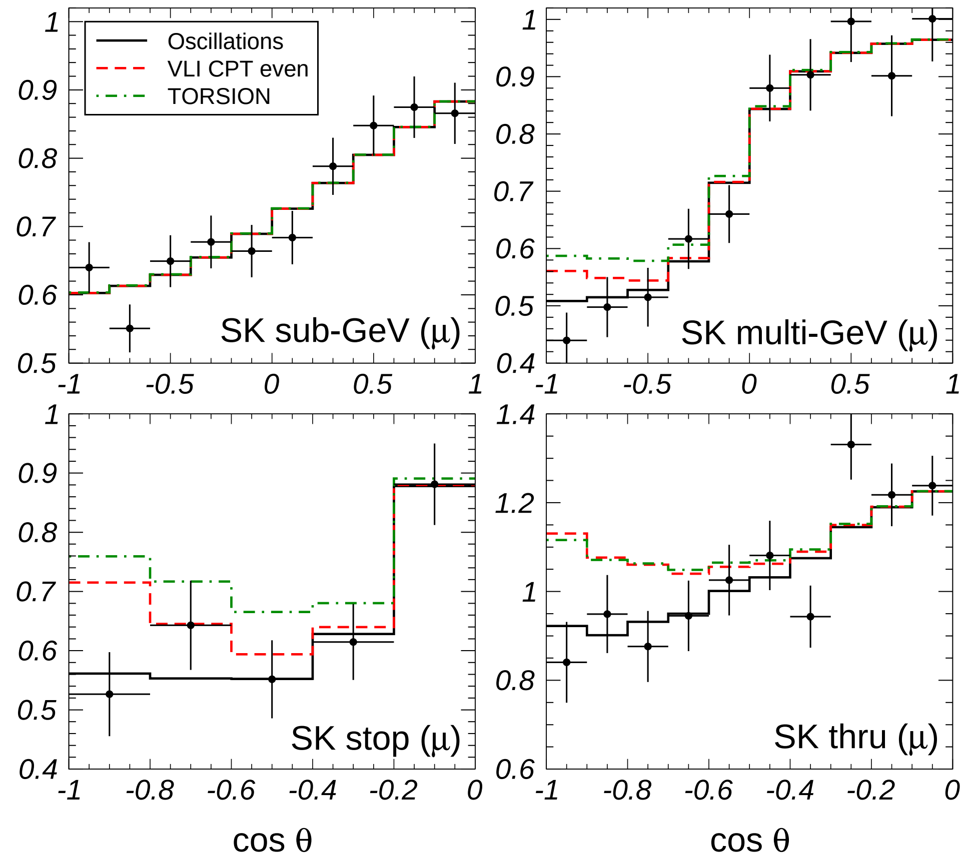
ATM ν's: Subdominant NP Effects

$$P_{\nu_\mu\to\nu_\mu} = 1 - \sin^2 2\Theta \, \sin^2\left(\frac{\Delta m^2 L}{4E}\mathcal{R}\right)$$

$$\mathcal{R}\cos 2\Theta = \cos 2\theta + \sum_n R_n \cos 2\xi_n$$

$$\mathcal{R}\sin 2\Theta = \sin 2\theta + \sum_n R_n \sin 2\xi_n \, e^{i\eta_n}$$

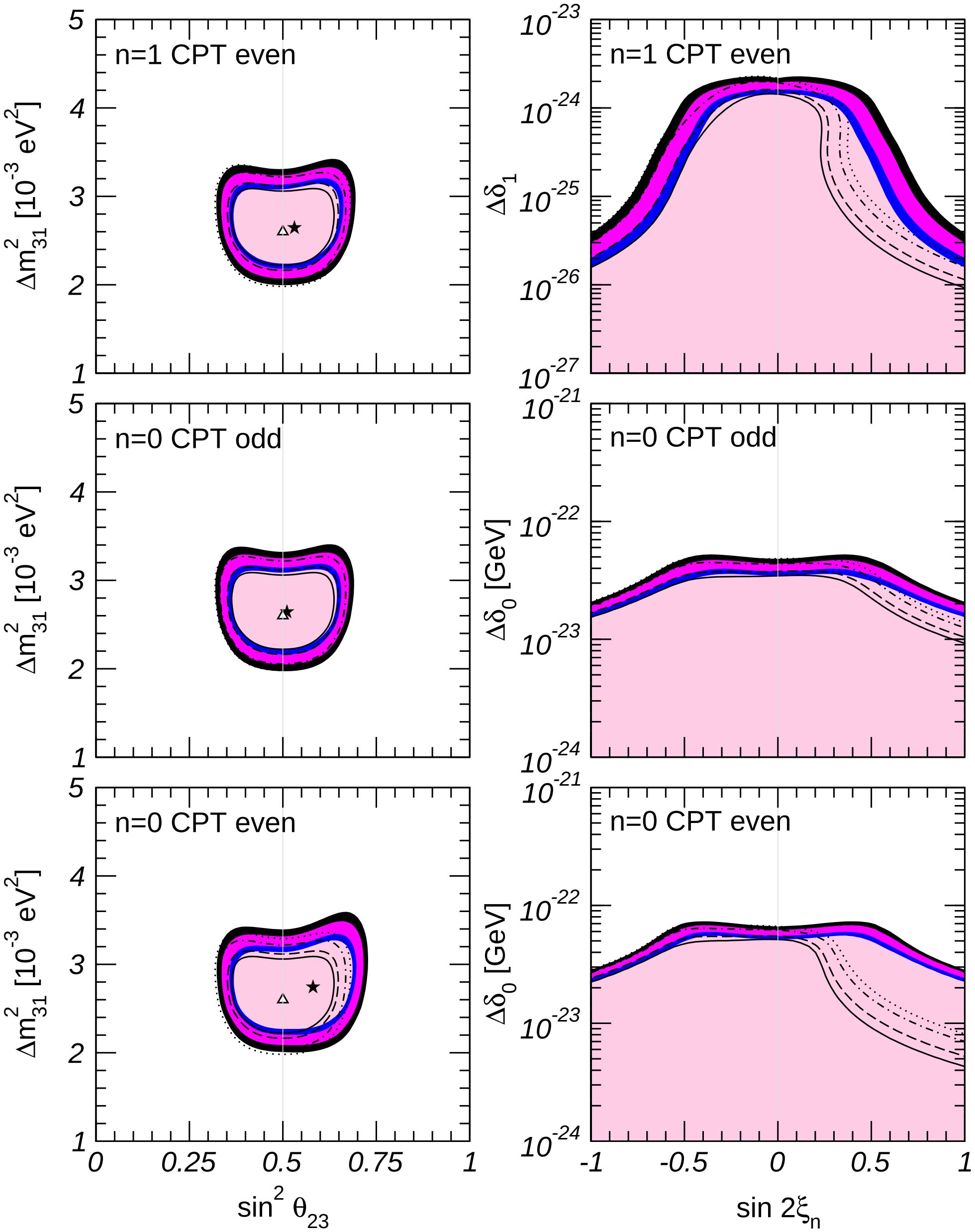
$$R_n = \sigma_n^+ \frac{\Delta\delta_n E^n}{2}\,\frac{4E}{\Delta m^2}$$



- Questions:
  - Do these effects affect our determination of oscillation parameters?
  - Can we limit these effects?

ATM ν's: Subdominant NP Effects

MCG-G, M. Maltoni 04,07



At 90% CL:

$$\frac{|\Delta c|}{c} \leq 1.2 \times 10^{-24}$$

$$|\phi\,\Delta\gamma| \leq 5.9 \times 10^{-25}$$

$$|\Delta b| \leq 3.0 \times 10^{-23}\ \text{GeV}$$

$$|Q\,\Delta k| \leq 4.8 \times 10^{-23}\ \text{GeV}$$

$$|\varepsilon^d_{\mu\mu} - \varepsilon^d_{\tau\tau}| \leq 0.012$$

$$|\varepsilon^d_{\mu\tau}| \leq 0.038$$

Future Bounds on New Physics: ν Telescopes

At ν Telescopes (Amanda, Antares, IceCube)

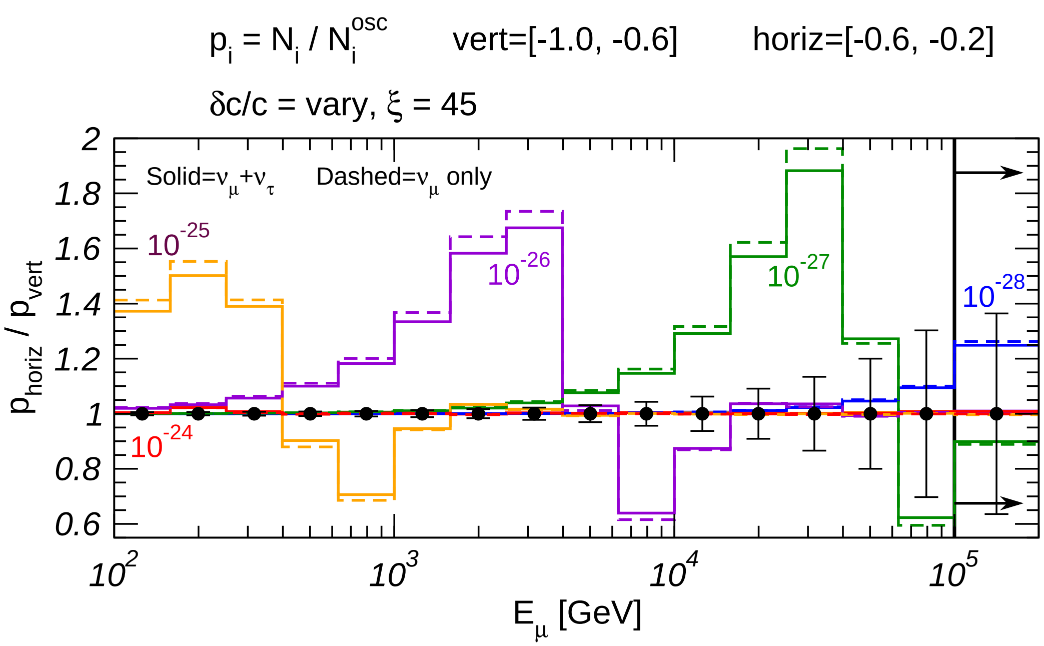
$E_{\nu,thres} \gtrsim$ 100 GeV

Large # ATM $\nu's$

($\sim 10^5 \nu_\mu$ events/yr at ICECUBE)

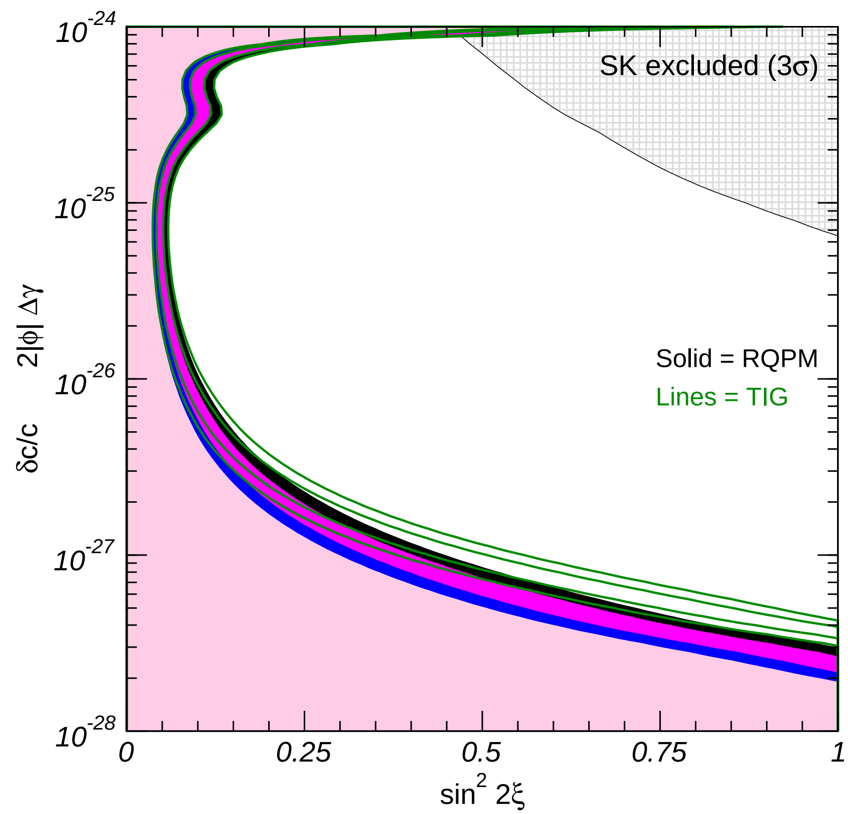
$\Rightarrow$ Standard oscillations suppressed

$\Rightarrow$ Better sensitivity to Oscillations due to NP



MCG-G, Halzen,Maltoni, 05

Expected Sensitivity at IceCube



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- Possible alternative oscillation scenarios due to *non-universal* VLI, VWEP, etc...
  But Strongly Constrained from Existing Oscillation Data