Probing the Neutrino Mass Hierarchy in Future Detectors using the Atmospheric ν_μ Survival Rate

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Outline . . .

- Introduction

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- Importance of the Mass Hierarchy and future prospects of its detection

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- Results:Detecting the Mass Hierarchy in atmospheric ν_μ events
- Conclusions

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- Goals for Neutrino Physics experiments have become sharply defined over the last few years, after strong evidence for neutrino oscillations and mass from solar, atmospheric, reactor and accelerator experiments.
- About a decade ago, the goals were understanding the origin of the solar and atmospheric anomalies and deficits, and whether these were due to oscillations or were related to our incomplete understanding of the sources.

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- Precision allows us to identify or exclude special valued mixing angles like $\theta_{13} = 0^o, \theta_{23} = 45^o$, and special relations between the quark and lepton sectors like $\theta_{12} + \theta_C = 45^o$, check for unitarity of 3 generations, non-standard interactions, decoherence scenarios.......

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- A multi-pronged effort to acheive these goals is underway via various operating, planned and proposed experiments, *e.g.* long-baseline, reactor, atmospheric, solar, beta-decay, ν-less double beta decay, large-mass water cerenkov detectors

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- The 3×3 neutrino mixing matrix U in the MNS parametrization is:

$$\begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix}$$

where $c_{ij} = \cos\theta_{ij}$, $s_{ij} = \sin\theta_{ij}$ ($\theta_{ij} =$ mixing angle between i^{th} & j^{th} mass states). $\delta =$ CP phase.

Introduction . . .

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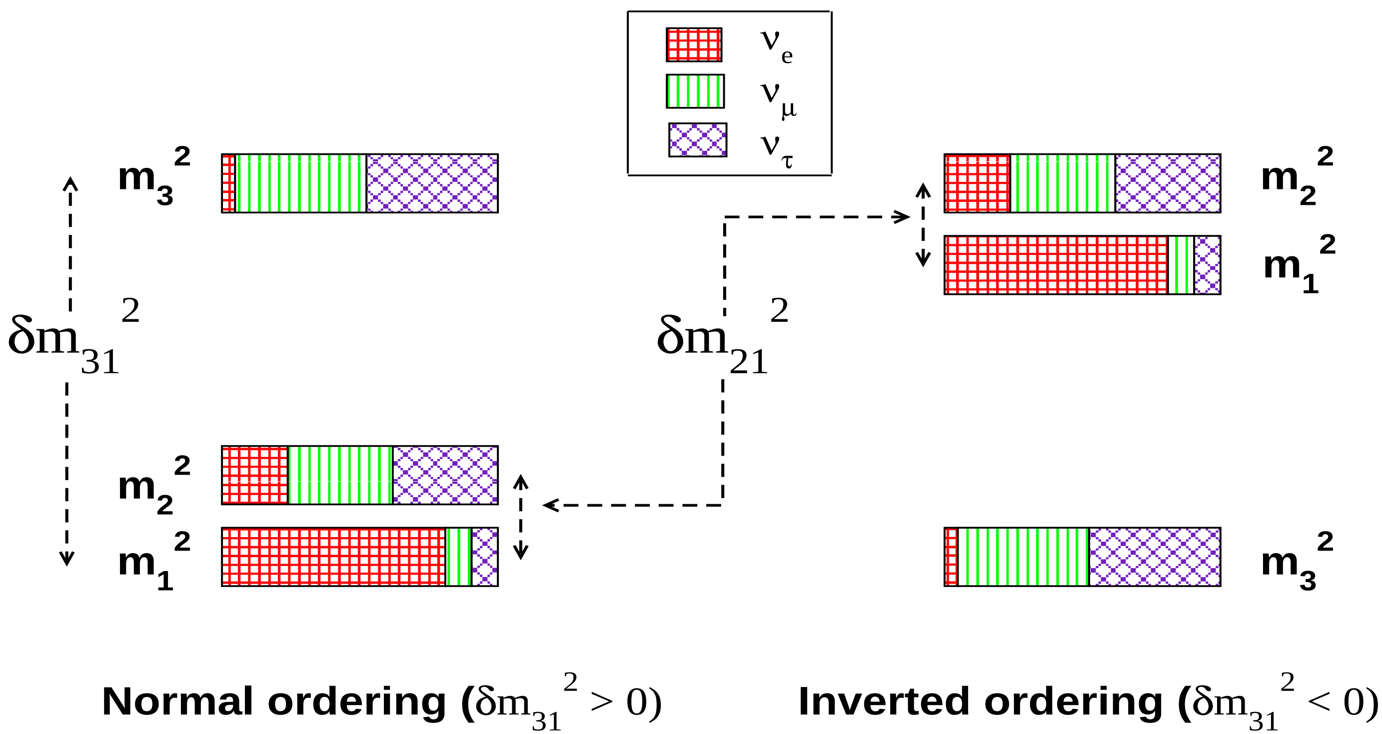
  - $\tan^2\theta_{12} = 0.39^{+0.05}_{-0.04}$ solar,reactor
  - $\tan^2\theta_{23} = 1.0^{+0.3}_{-0.3}$ atmospheric, K2K
  - $\theta_{13} < 12^o @ 3\sigma$ reactor, atmospheric
  - $\delta m^2_{21} = 8.2^{+0.3}_{-0.3} \times 10^{-5} eV^2$ solar,reactor
  - $|\delta m^2_{31}| = 2.2^{+0.6}_{-0.4} \times 10^{-3} eV^2$ atmospheric, K2K
  - $m_\beta < 2.2$ eV beta decay
  - $m_{\beta\beta 0\nu} < 0.3$ eV ν less double beta decay
  - $\Sigma m_i < 1.6 - 0.7$ eV Precision Cosmology
  - δ_{CP} is unknown

ν *The Mass Hierarchy, its Significance and Detection*

So far we only know $|\Delta m^2_{31}|$ and not its Sign



The Mass Hierarchy . . .

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- A large class of GUTS use the Type I seesaw mechanism to unify quarks and leptons. Several positive features are lost if in such models the neutrino hierarchy is *inverted* rather than *normal*
  C. Albright, Phys. Lett. **B599**, 285 (2004)

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- It would also favour theories utilising *the Type II seesaw mechanism* with additional *Higgs triplets*.
- The type of hierarchy impacts the effectiveness of *leptogenesis* in most theoretical models.

The Mass Hierarchy . . . Future Measurements

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  ➢ Nu Factories substantial improvement in bounds

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- Overcoming this in superbeam experiments would require using either *multiple oscillation channels, 2 baselines, different energies, the magic baseline, 2 off-axis locations* or a combination of these stategies.

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- These degeneracies are absent in methods which utilise the muon survival probability.

Matter effects in $P_{\mu e}$

- Vacuum 1-MSD limit ($\Delta m^2_{21} = 0$) :

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- and $\Delta^m_{31} = \Delta_{31}\sqrt{(\frac{A}{\delta m^2_{31}} - \cos 2\theta_{13})^2 + \sin^2 2\theta_{13}}$

Matter effects in $P_{\mu e}$

- We note that: $\mathcal{P}^m_{\mu e}$ is maximized not just at resonance but when the combination $\sin^2(2\theta^m_{13}) \sin^2[\Delta^m_{31} L/E]$ is maximal, *i.e*i.e. when $E = E_{res} = E^m_{peak}$.

Matter effects in $P_{\mu e}$

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- For Earth baselines, this translates to:

$$[\rho L]_{\mu e}^{max} = \frac{(2p+1)\pi \times 5.18 \times 10^3}{\tan 2\theta_{13}} \;\; km\ gm/cc$$

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- *Co-relations and degeneracies play an important role and reduce sensitivity when* $\mathcal{P}^m_{\mu e}$ *is used to determine the hierarchy*

Matter effects in $P_{\mu\tau}$ and $P_{\mu\mu}$

- Vacuum 1-MSD limit ($\Delta m^2_{21} = 0$) :

$$\mathcal{P}_{\mu e} = \sin^2\theta_{23}\sin^2(2\theta_{13})\sin^2\left[1.27\Delta m^2_{31}L/E\right]$$

$$\mathcal{P}_{\mu\tau} = \cos^4\theta_{13}\sin^2(2\theta_{23})\sin^2\left[1.27\Delta m^2_{31}L/E\right]$$

$\Rightarrow$

$$\mathcal{P}_{\mu\mu} = 1 - \mathcal{P}_{\mu e} - \mathcal{P}_{\mu\tau}$$

Matter effect on $P(\nu_\mu \to \nu_\tau)$

- The 1-MSD vacuum expression is:

$$\mathcal{P}^{v}_{\nu_\mu \to \nu_\tau} = \cos^2\theta_{13}\sin^2 2\theta_{23}\sin^2(\Delta_{31})$$
$$- \cos^2\theta_{23} P^{vac}_{\nu_\mu \to \nu_e}$$

- The 1-MSD analytic expression in matter is:

$$\mathcal{P}^{m}_{\nu_\mu \to \nu_\tau} = \cos^2\theta^m_{13}\sin^2 2\theta_{23}\sin^2[(\Delta_{31} + A + \Delta^m_{31})/2]$$
$$+ \sin^2\theta^m_{13}\sin^2 2\theta_{23}\sin^2[(\Delta_{31} + A - \Delta^m_{31})/2]$$
$$- \cos^2\theta_{23} P^{mat}_{\nu_\mu \to \nu_e}$$

Maximizing the matter effect in $\mathcal{P}_{\mu\tau}$

- $E = E_{res} = E^{v}_{peak}$ leads to:

$$\Delta\mathcal{P}_{\mu\tau} \simeq \cos^4[\sin 2\theta_{13}(2p+1)\pi/4] - 1$$

(with $\sin^2 2\theta_{23} = 1$, $\cos^2\theta_{13}, \cos 2\theta_{13} \simeq 1$).

- The maximum matter effect condition for L is:

$$[\rho L]^{max}_{\mu\tau} = (2p+1)\pi \times 5.18 \times 10^3 \times \cos 2\theta_{13} \ \ km\ gm/cc$$

The maximum matter effect occurs for $L = 9700$ km for p=1 & $\sin^2 2\theta_{13} = 0.1$ (9300 km, 9900 km for 0.2, 0.05).

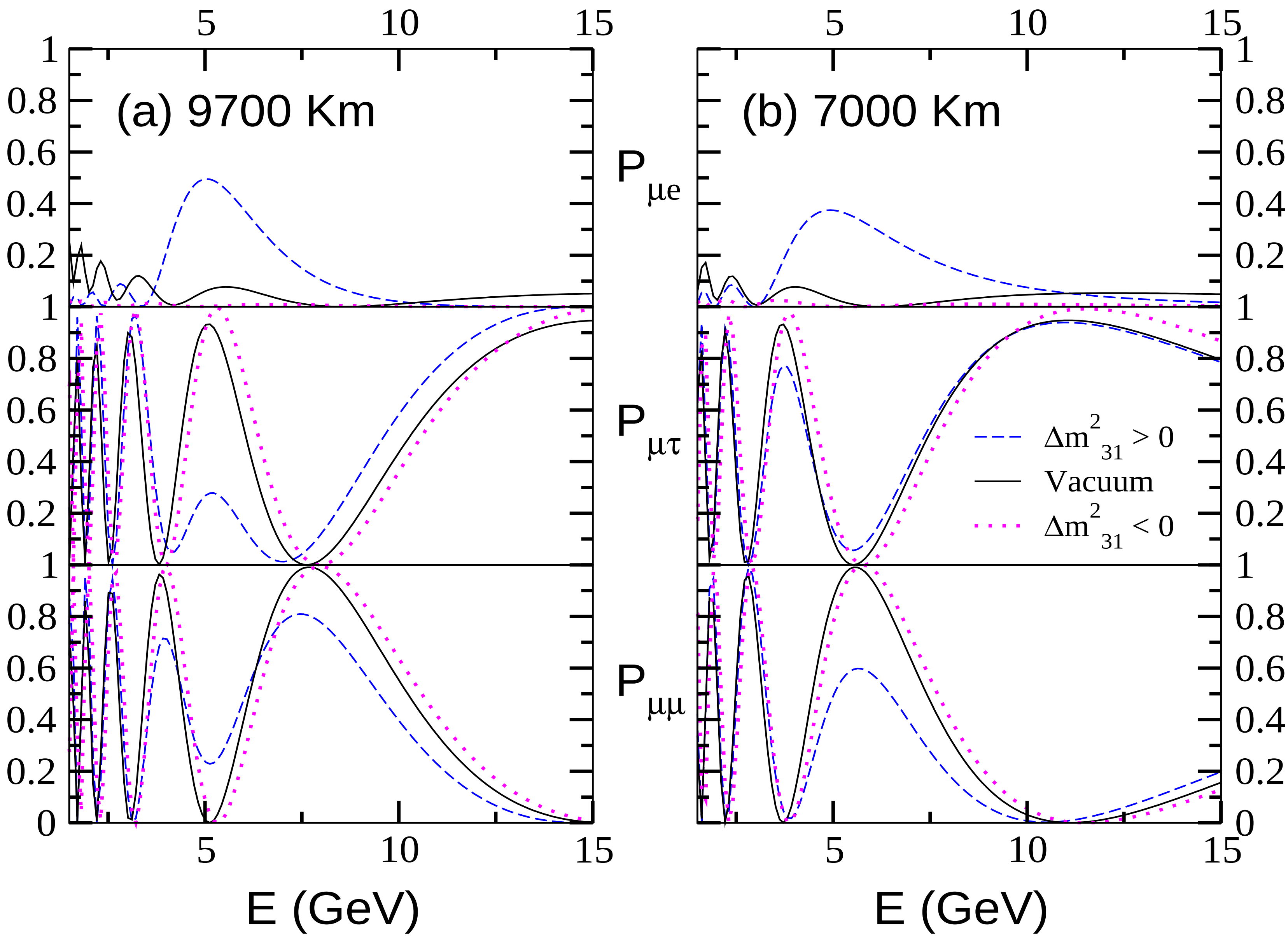
Summary of Conditions for Large Matter effects . . .

Thus, conditions for maximizing the matter effects at very long baselines are:

- $[\rho L]^{\max}_{\mu e} = \frac{(2p+1)\pi 5.18\times 10^3}{\tan 2\theta_{13}}$ Km gm/cc.
- $[\rho L]^{\max}_{\mu \tau} = (2p+1)\pi 5.18 \times 10^3 \cos 2\theta_{13}$ Km gm/cc.
- $[\rho L]^{\max}_{\mu \mu} = p\pi \times 10^4 \cos 2\theta_{13}$ Km gm/cc.

Plot of Probabilities . . .

R. Gandhi *et al.*, Phys. Rev. Lett. **94**, 051801 (2005); hep-ph/0411252



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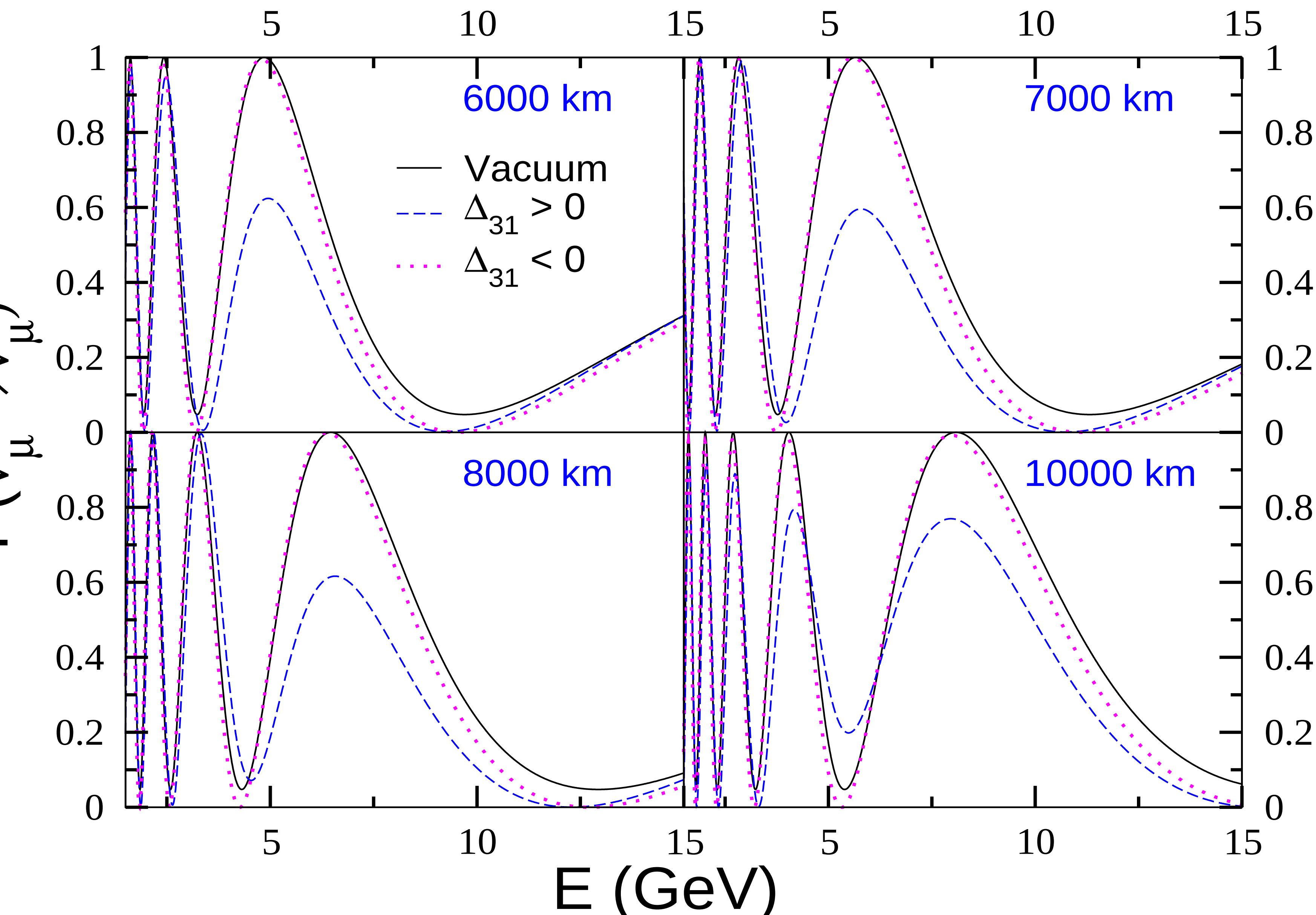
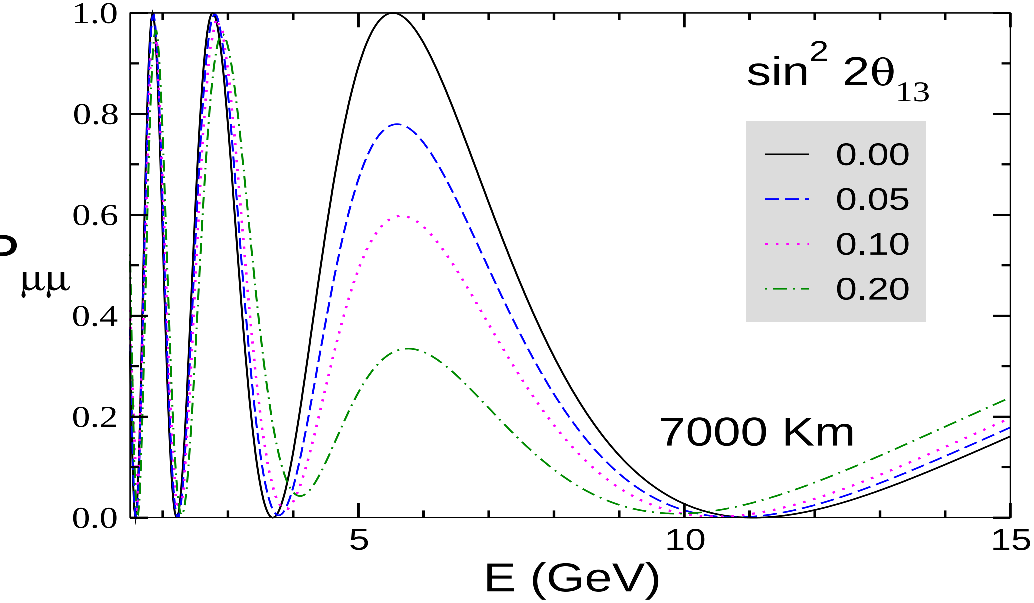


Survival Probability : θ_{13} sensitivity . . .



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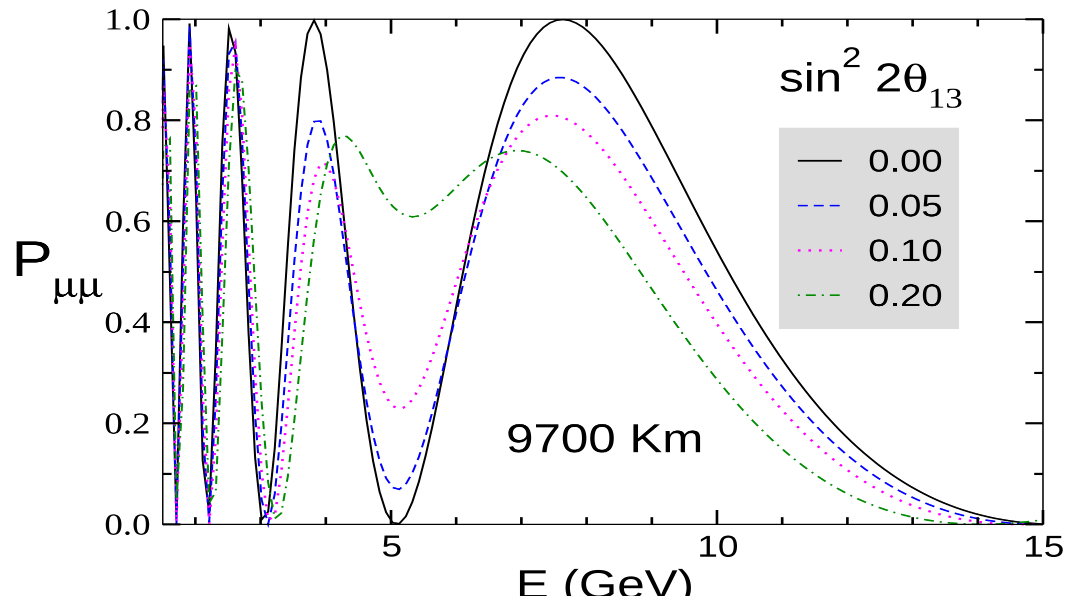
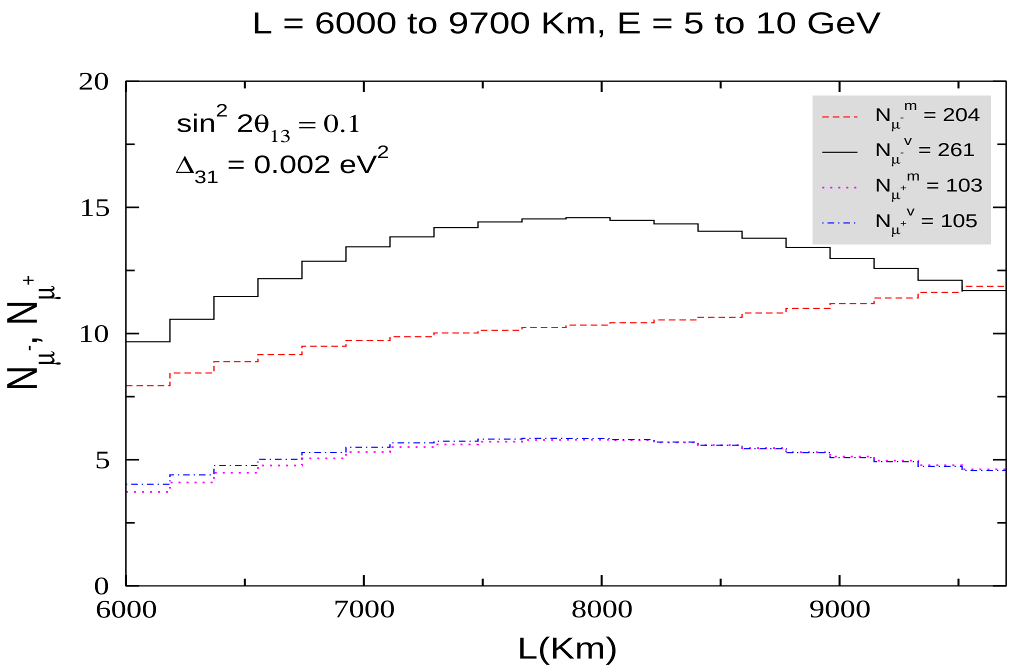


Results for an Iron Calorimeter type detector

Results : Iron Calorimeter, 1000 kt-yr . . .



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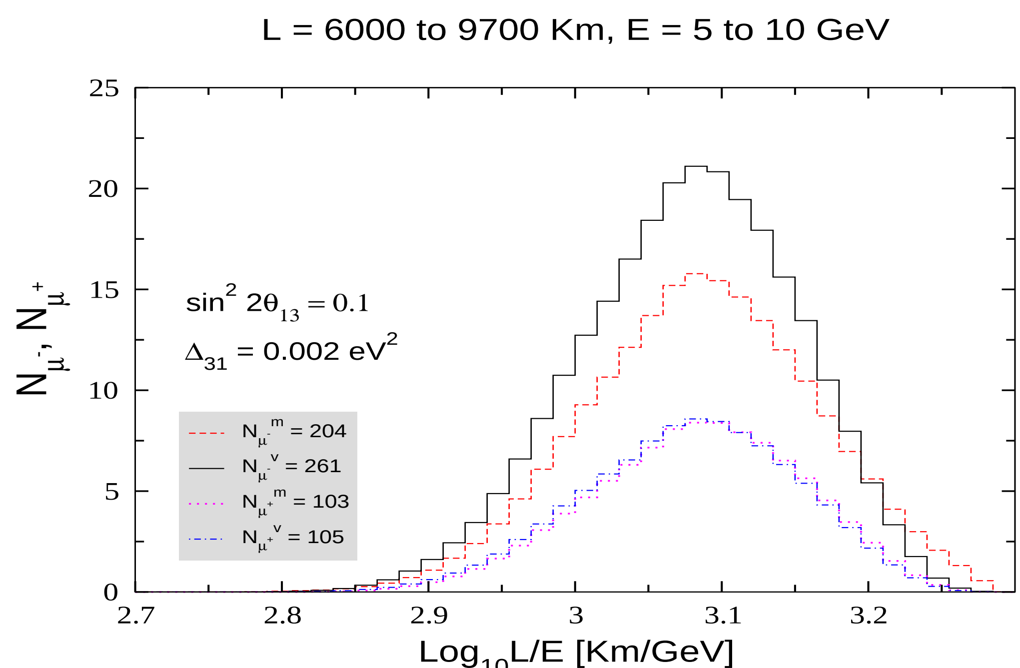

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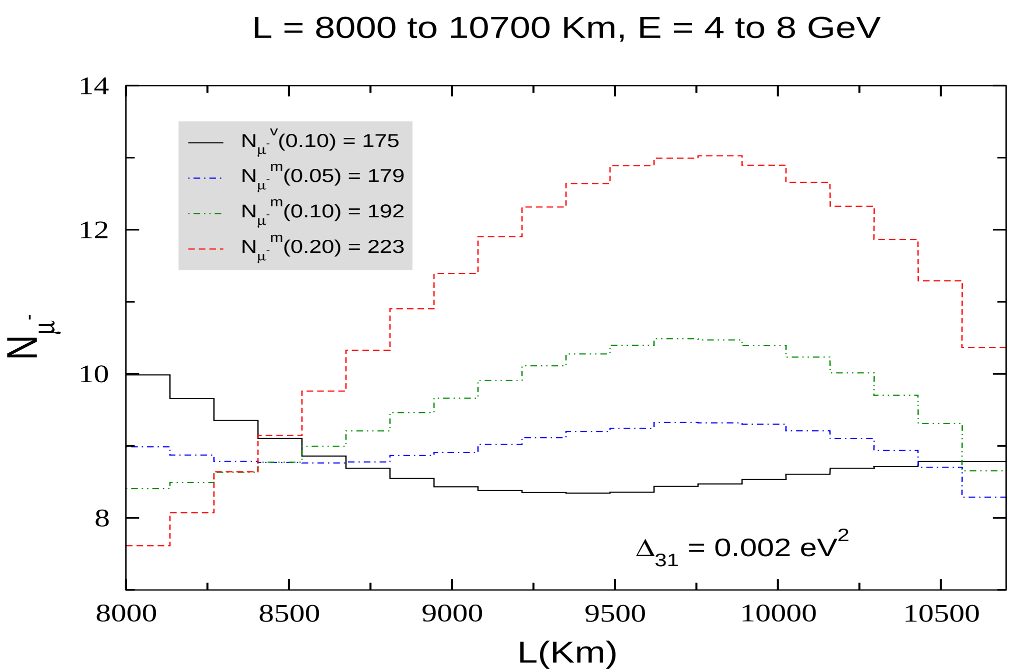

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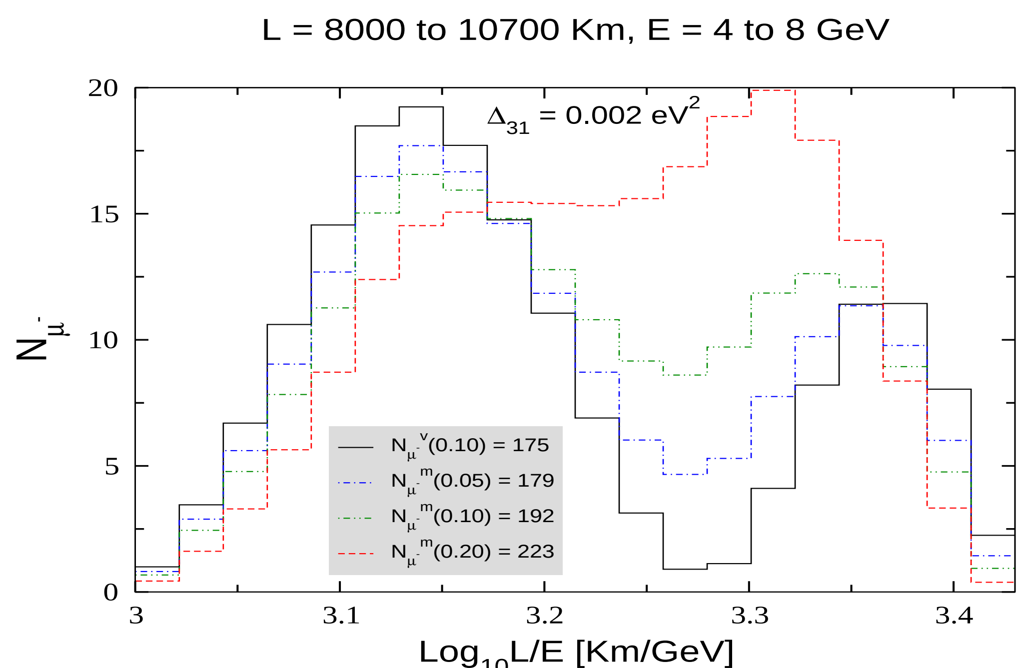

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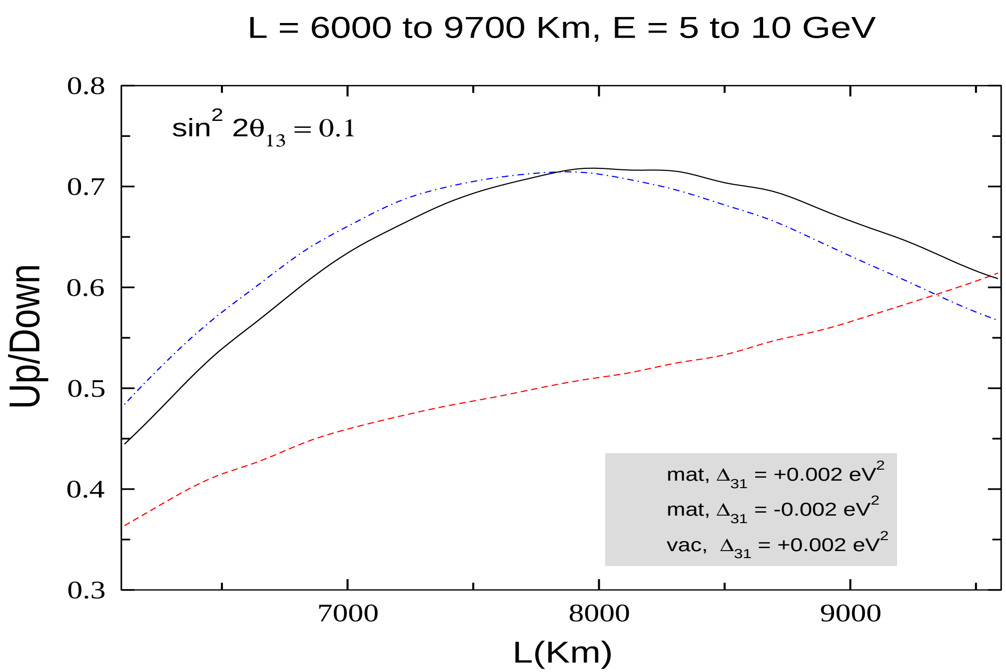

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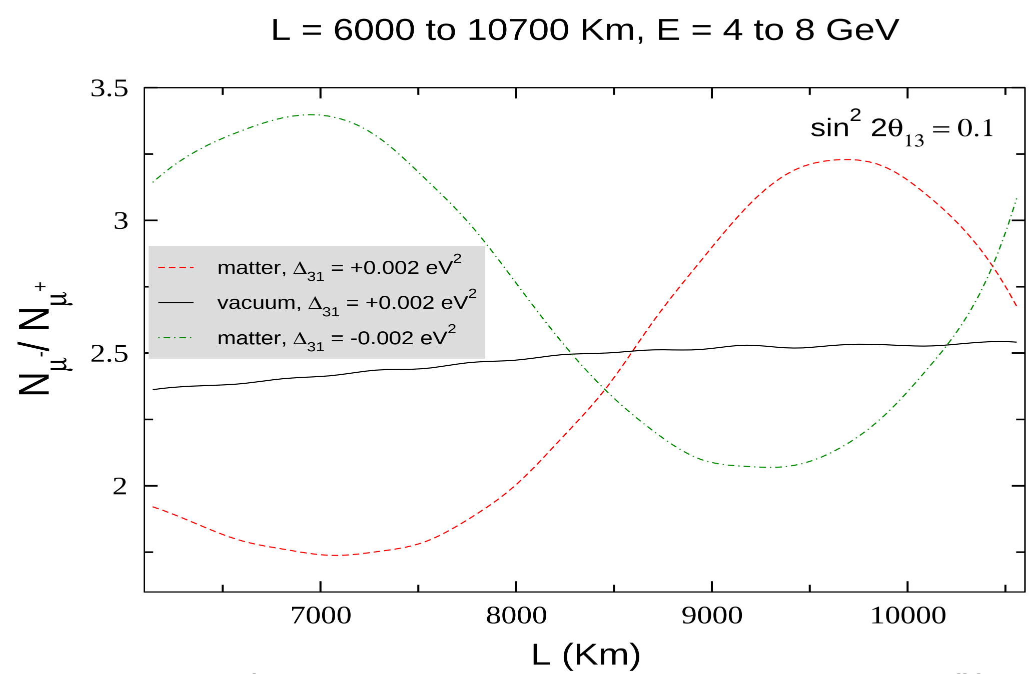


Fe Calorimeter, 1000kt-yr, $\Delta\chi^2$ and σ sensitivity . . .

Choice of the optimal ranges for μ^- events for 1000 kiloton-yr:

Range 1 : E = 5 - 10 GeV and L = 6000 - 9700 Km (4 selected bins)

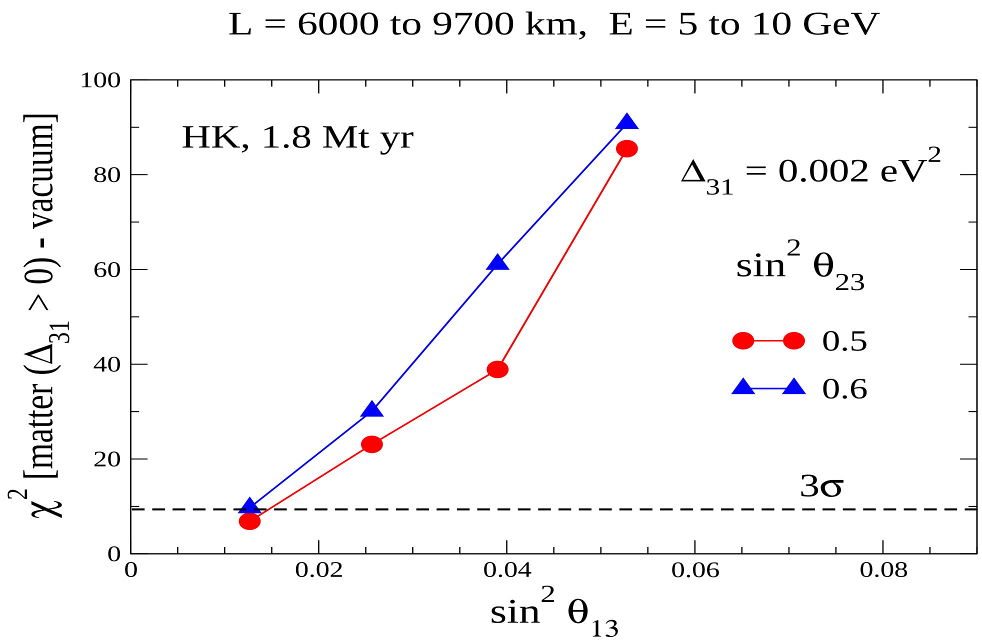
$\sin^2 2\theta_{13}$	$\mathrm{N_{vac}}$	$\mathrm{N_{mat}}(\Delta m^2_{31} > 0)$	$\Delta\chi^2$	sensitivity
0.05	260	227	5.35	1.14σ
0.1	261	204	19.76	3.44σ
0.2	263	163	86.40	8.6σ

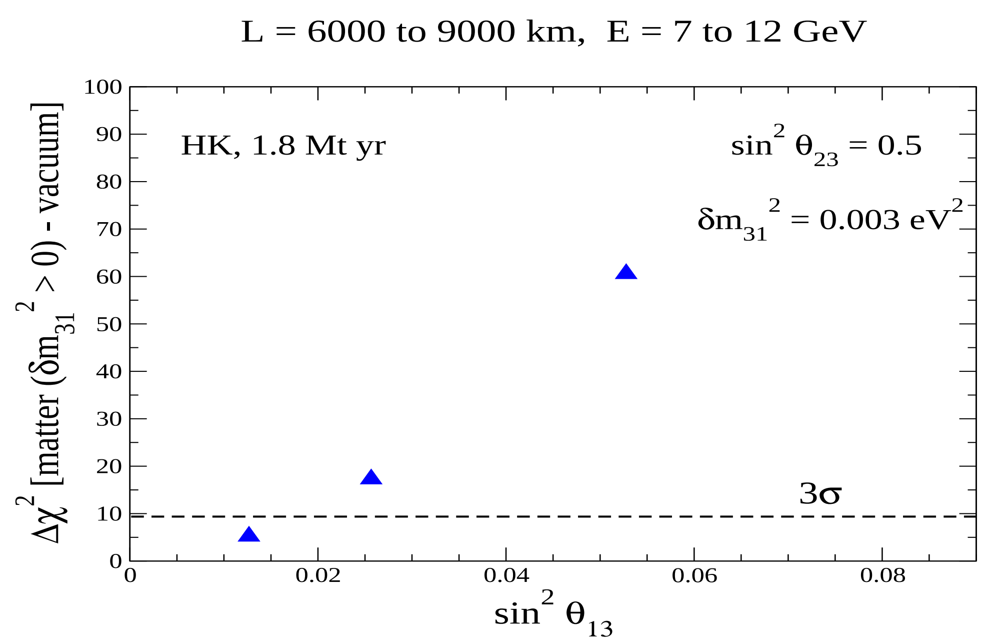
Range 2 : E = 4 - 8 GeV and L = 8000 - 10700 Km ($Log_{10}(L/E)$=3.21-3.44)

$\sin^2 2\theta_{13}$	$\mathrm{N_{vac}}$	$\mathrm{N_{mat}}(\Delta m^2_{31} > 0)$	$\Delta\chi^2$	sensitivity
0.05	23.3	42.6	8.7	2.94σ
0.1	23.3	62.7	24.79	4.97σ
0.2	24.5	104.5	61.24	7.82σ

Results for a Megaton water cerenkov detector

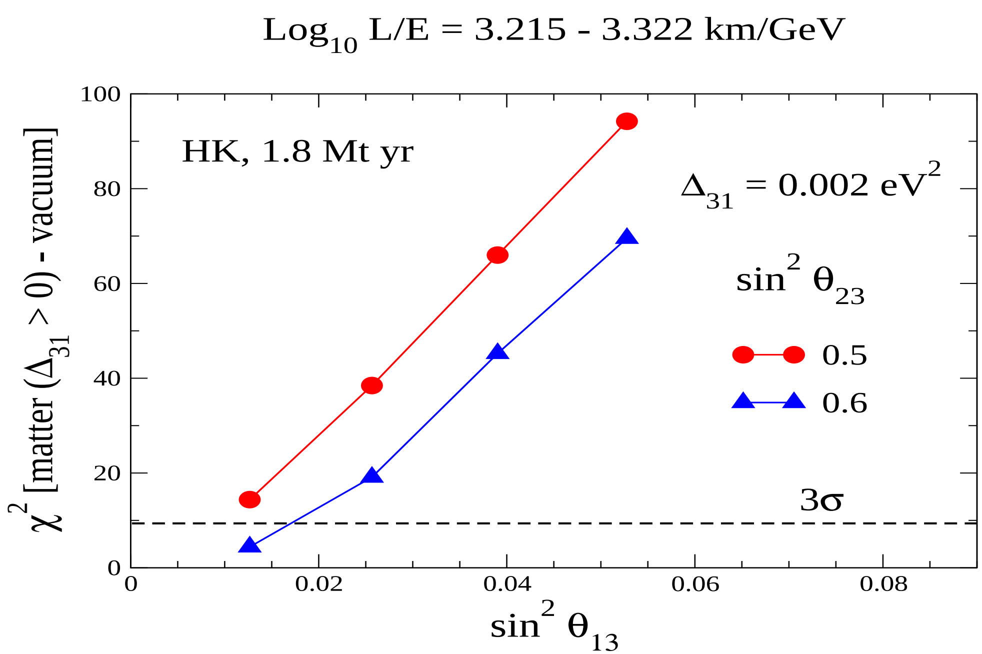
Megaton Water Cerenkov, 1.8 Mt-yr exposure . . .





In Preparation

Megaton Water Cerenkov, 1.8 Mt-yr exposure . . .



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Range 1 : E = 5 - 10 GeV and L = 6000 - 9700 Km

$\sin^2 2\theta_{13}$	$\mathrm{N_{vac}}$	$\mathrm{N_{mat}}(\Delta m^2_{31} > 0)$	$\Delta\chi^2$	sensitivity
0.05	731.8	664.4	6.86	2.62σ
0.1	735.3	616.0	23.09	4.8 σ
0.2	743.0	530.1	85.50	9.25σ

Range 2 : E = 4 - 8 GeV and L = 8000 - 10700 Km

$Log_{10}(L/E) = 3.215 - 3.322 \mathrm{Km/GeV}$

$\sin^2 2\theta_{13}$	$\mathrm{N_{vac}}$	$\mathrm{N_{mat}}(\Delta m^2_{31} > 0)$	$\Delta\chi^2$	sensitivity
0.05	40.9	73.5	14.38	3.79σ
0.1	42.9	107.2	38.45	6.2 σ
0.2	48.7	178.3	94.22	9.71σ

To Sum Up . . .

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- The *mass hierarchy* is a *powerful discriminator* between various classes of unification theories and its determination is a key goal for the future.
- Future superbeam experiments using the $\nu_\mu \longrightarrow \nu_e$ channel for hierarchy determination will find it difficult to acheive the required sensitivities due to degeneracies
- It is worthwhile to explore the $\nu_\mu \longrightarrow \nu_\mu$ channel for this purpose since it is largely free of degeneracies.

To Sum Up . . .

- Large matter effects are not only confined to $P_{\mu e}$ but also arise in $P_{\mu\tau}$ at GeV energies at very long Earth baselines. Both must be properly considered when evaluating the event-rates for experiments measuring muon survival.
- The effects discussed above are significantly sensitive to θ_{13} and Sign of Δm^2_{31}, determination of which are outstanding problems of neutrino physics.
- We have tried to show that there is a good possibility that one can determine the Sign of Δm^2_{31} using atmospheric neutrinos in a large mass iron calorimeter with charge id as well as using a Megaton water Cerenkov detector

Matter effect in $\nu_\mu \rightarrow \nu_\tau$

♠ Click here for $P_{\mu\tau}$ $\rightsquigarrow$

- ◇ The animation shows the matter effects building up in $P_{\mu\tau}$ for L = 6000 to 10500 km.
- ◇ Maximum matter effects seen at 9700 km.
- ◇ The term wise break up of probability is also depicted in the animation.

$\rightarrow$

To Summary page

Matter effect in $\nu_\mu \rightarrow \nu_\mu$

♠ Click here for $P_{\mu\mu} \rightsquigarrow$

◇ The animation shows the matter effects building up in $P_{\mu\tau}$ for L = 6000 to 10500 km.
◇ Maximum matter effects seen at 9700 km.
◇ The term wise break up of probability is also depicted in the animation.