WHAT WE CAN LEARN FROM ATMOSPHERIC NEUTRINOS

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Goals for the Future / Plan of Talk
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- Confirmation of oscillations of atmospheric neutrinos
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- Confirmation of oscillations of atmospheric neutrinos
- Precision measurement of $\Delta m^2_{31}$ and $\theta_{23}$

Measuring the deviation of $\theta_{23}$ from its maximal value
Determining the octant of $\theta_{23}$
Determining the sign of $m^2_{23}$

Compare and contrast the capabilities of large water Cerenkov (SK50) and magnetized iron detectors (INO-ICAL) for all of the above. (See hep-ph/0604182 for discussion on Liquid Argon.)

Using atmospheric neutrinos to constrain new physics
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Confirmation of Oscillations of Atmospheric Neutrinos
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Smoking Gun Signal for $\nu_\mu - \nu_\tau$ Oscillations

It’s important to observe the characteristic “dip” in $L/E$
Confirmation of Oscillations of Atmospheric Neutrinos

\[ \Delta m^2 = 2 \times 10^{-3} \text{ eV}^2 \]

\[ \Delta m^2 = 3 \times 10^{-3} \text{ eV}^2 \]

\[ \log_{10}(L/E \text{ (km/GeV))} \]

INO collaboration
Confirmation of Oscillations of Atmospheric Neutrinos

The first oscillation dip should be clearly observable

INO collaboration

\[ \log_{10}(L/E \text{ (km/GeV)}) \]

\( \Delta m^2 = 2 \times 10^{-3} \text{ eV}^2 \)  
\( \Delta m^2 = 3 \times 10^{-3} \text{ eV}^2 \)

SANDHYA CHOUBEY

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Precision Measurement of $\Delta m^2_{31}$ and $\theta_{23}$
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| Experiment | $|\Delta m_{31}^2|$ | $\sin^2 \theta_{23}$ |
|------------|-----------------|---------------------|
| Current    | 30%             | 34%                 |
Precision Measurement of $\Delta m_{31}^2$ and $\theta_{23}$

| Experiment    | $|\Delta m_{31}^2|$ | $\sin^2 \theta_{23}$ |
|---------------|---------------------|-----------------------|
| Current       | 30%                 | 34%                   |
| MINOS+CNGS    | 13%                 | 38%                   |
| T2K (5 yrs)   | 6%                  | 22%                   |
| NO$\nu$A (5 yrs) | 13%               | 42%                   |
| Combination   | 4.5%                | 20%                   |

Huber et al. hep-ph/0403068
### Precision Measurement of $\Delta m_{31}^2$ and $\theta_{23}$

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| SK20 (1.84 MTy)      | 17%                 | 24%                   |

Huber et al hep-ph/0403068
Gonzalez-Garcia et al, hep-ph/0408170
Precision Measurement of $\Delta m_{31}^2$ and $\theta_{23}$

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| Combination        | 4.5%                | 20%                   |
| SK20 (1.84 MTy)    | 17%                 | 24%                   |
| INO (250 kTy)      | 10%                 | 30%                   |

Huber et al hep-ph/0403068
Gonzalez-Garcia et al, hep-ph/0408170
INO Collaboration
Three Generation Oscillation Probabilities
Muon Neutrino Survival Probability

\[
\lim_{\Delta m_{21}^2 \to 0} P_{\mu\mu}(L, E) = 1 - P_{\mu\mu}^1(L, E) - P_{\mu\mu}^2(L, E) - P_{\mu\mu}^3(L, E)
\]

\[
P_{\mu\mu}^1(L, E) = \sin^2 \theta_{13}^M \sin^2 2\theta_{23} \sin^2 \frac{(A + \Delta m_{31}^2) - (\Delta m_{31}^2)^M}{8E} L
\]

\[
P_{\mu\mu}^2(L, E) = \cos^2 \theta_{13}^M \sin^2 2\theta_{23} \sin^2 \frac{(A + \Delta m_{31}^2) + (\Delta m_{31}^2)^M}{8E} L
\]

\[
P_{\mu\mu}^3(L, E) = \sin^2 2\theta_{13}^M \sin^4 \theta_{23} \sin^2 \frac{(\Delta m_{31}^2)^M}{4E} L
\]
Muon Neutrino Survival Probability

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\lim_{\Delta m_{21}^2 \to 0} P_{\mu\mu}(L, E) = 1 - P_{\mu\mu}^1(L, E) - P_{\mu\mu}^2(L, E) - P_{\mu\mu}^3(L, E)
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P_{\mu\mu}^1(L, E) = \sin^2 \theta_{13}^M \sin^2 2\theta_{23} \sin^2 \left(\frac{A + \Delta m_{31}^2}{8E}\right) L
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\[
P_{\mu\mu}^3(L, E) = \sin^2 2\theta_{13}^M \sin^4 \theta_{23} \sin^2 \left(\frac{\Delta m_{31}^2}{4E}\right) L
\]

- Dependence on \(\theta_{23}\) in the form \(\sin^4 \theta_{23}\)
- Octant sensitivity is expected to be good
Large Matter Effects in $\nu_\mu$ Survival Probability

$\sin^2 \theta_{23} = 0.50$ (matter)
$\sin^2 \theta_{23} = 0.50$ (vacuum)
$\sin^2 \theta_{23} = 0.36$ (matter)
$\sin^2 \theta_{23} = 0.36$ (vacuum)

L = 1000 km
L = 3000 km
L = 5000 km
L = 7000 km
L = 9000 km
L = 11000 km

Large Matter Effects in $\nu_\mu$ Survival Probability

$$\sin^2 \theta_{23} = 0.50 \text{ (matter)}$$
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$L=1000 \text{ km}$
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$L=11000 \text{ km}$

Large Matter Effects in $\nu_\mu$ Survival Probability

Max effect for $L \approx 7000$ km and $E \approx 5$ GeV $\Rightarrow (E_{\text{SPMAX}} \approx E_{\text{res}})$
Large Matter Effects in $\nu_\mu$ Survival Probability

- Max effect for $L \simeq 7000$ km and $E \simeq 5$ GeV $\Rightarrow (E_{\text{SPMAX}} \simeq E_{\text{res}})$

- $P_{\mu\mu}$ decreases (increases) at SP-MAX (SPMIN) due to matter effects

$\sin^2 \theta_{23} = 0.50$ (matter) $\sin^2 \theta_{23} = 0.50$ (vacuum) $\sin^2 \theta_{23} = 0.36$ (matter) $\sin^2 \theta_{23} = 0.36$ (vacuum)
Large Matter Effects in $\nu_{\mu}$ Survival Probability

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- Sign of the earth matter effects depends on both $E$ and $L$
Large Matter Effects in $\nu_\mu$ Survival Probability

- Max effect for $L \simeq 7000$ km and $E \simeq 5$ GeV $\Rightarrow (E_{\text{SPMAX}} \simeq E_{\text{res}})$
- $P_{\mu\mu}$ decreases (increases) at SP-MAX (SPMIN) due to matter effects
- Sign of the earth matter effects depends on both $E$ and $L$
- Matter effects depend on the value of $\sin^2 \theta_{23}$
Large Matter Effects in $\nu_\mu$ Survival Probability

- Max effect for $L \simeq 7000$ km and $E \simeq 5$ GeV $\Rightarrow (E_{SP\text{MAX}} \simeq E_{\text{res}})$

- $P_{\mu\mu}$ decreases (increases) at $SP\text{-MAX}$ ($SP\text{MIN}$) due to matter effects

- Sign of the earth matter effects depends on both $E$ and $L$

- Matter effects depend on the value of $\sin^2 \theta_{23}$

- Most important to choose the bins properly in both $E$ and $L$
Very Large Matter Effects in $\nu_\mu \leftrightarrow \nu_e$ Probability
Very Large Matter Effects in $\nu_\mu \leftrightarrow \nu_e$ Probabilities

$$\lim_{\Delta m_{21}^2 \to 0} P_{\mu e}(L, E) = \sin^2 \theta_{23} \sin^2 2\theta_{13}^M \sin^2 \frac{(\Delta m_{31}^2)^M L}{4E}$$
Very Large Matter Effects in $\nu_\mu \leftrightarrow \nu_e$ Probabilities

\[
\lim_{\Delta m_{21}^2 \to 0} P_{\mu e}(L, E) = \sin^2 \theta_{23} \sin^2 2\theta_{13}^M \sin^2 \left(\frac{\Delta m_{31}^2}{4E}\right)^M L
\]

![Graph showing the dependence of $P_{\mu e}$ on energy $E$ for two different values of $L$ (7000 km and 9000 km).]

- $\sin^2 \theta_{23} = 0.5$ (matter)
- $\sin^2 \theta_{23} = 0.5$ (vacuum)
Very Large Matter Effects in $\nu_\mu \leftrightarrow \nu_e$ Probabilities

$$\lim_{\Delta m_{21}^2 \to 0} P_{\mu e}(L, E) = \sin^2 \theta_{23} \sin^2 2\theta_{13} \sin^2 \frac{(\Delta m_{31}^2)^M L}{4E}$$

Above $\sim 3$ GeV, matter effects increase $P_{\mu e}$ for all $E$ and $L$
Very Large Matter Effects in $\nu_\mu \leftrightarrow \nu_e$ Probabilities

$$\lim_{\Delta m_{21}^2 \to 0} P_{\mu e}(L, E) = \sin^2 \theta_{23} \sin^2 2\theta_{13} \sin^2 M \frac{(\Delta m_{31}^2)^M L}{4E}$$

Sub-dominant $\Delta m_{21}^2$ oscillations in $P_{\mu e}$ is also crucial
Atmospheric Neutrino Events
Atmospheric Neutrino Events

Change in number of muon events:

\[ N_\mu = N_\mu^0 P_{\mu\mu} + N_e^0 P_{e\mu} \]

\[ = N_\mu^0 \left[ P_{\mu\mu} + \frac{1}{r} P_{e\mu} \right] ; \quad \text{(where } r = \frac{N_\mu^0}{N_e^0} \text{)} \]

\[ 1 - \frac{N_\mu}{N_\mu^0} \approx (P_{\mu\mu}^1 + P_{\mu\mu}^2) + (P_{\mu\mu}^3)' s_{23}^2 (s_{23}^2 - \frac{1}{r}) \]

\[ (P_{\mu\mu}^3)' = \sin^2 2\theta_{13} \sin^2 \left( \frac{\Delta m_{31}^2}{4E} \right) L \]

- Can be used to study maximality and octant of \( \theta_{23} \)
- Can be used to study the neutrino mass hierarchy
- \( \Delta m_{21}^2 \) and \( \delta_{CP} \) bring in small effects
Atmospheric Neutrino Events

Change in number of electron events:

\[
\frac{N_{e}}{N_{e}^{0}} - 1 \approx \sin^{2} 2\theta_{12}^{M} \sin^{2} \left( \frac{(\Delta m_{21}^{2})^{M} L}{4E} \right) \times (r \cos^{2} \theta_{23} - 1) \\
+ \sin^{2} 2\theta_{13}^{M} \sin^{2} \left( \frac{(\Delta m_{31}^{2})^{M} L}{4E} \right) \times (r \sin^{2} \theta_{23} - 1) \\
+ \sin \theta_{23} \cos \theta_{23} \ r \ \text{Re} \left[ A_{13}^{*} A_{12} \exp(-i\delta_{CP}) \right]
\]
Atmospheric Neutrino Events

Change in number of electron events:

\[
\frac{N_e}{N_e^0} - 1 \simeq \sin^2 2\theta_{12} \sin^2 \left( \frac{\Delta m_{21}^2 M L}{4E} \right) \times (r \cos^2 \theta_{23} - 1) \\
+ \sin^2 2\theta_{13} \sin^2 \left( \frac{\Delta m_{31}^2 M L}{4E} \right) \times (r \sin^2 \theta_{23} - 1) \\
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\(\Delta m_{21}^{2}\)-driven oscillation effect
Atmospheric Neutrino Events

Change in number of electron events:

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\frac{N_e}{N^0_e} - 1 \simeq \sin^2 2\theta_{12} \sin^2 \left( \frac{\Delta m^2_{21} M L}{4E} \right) \times (r \cos^2 \theta_{23} - 1) \\
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\(\Delta m^2_{21}\)-driven oscillation effect

Brings an excess (depletion) in the sub-GeV electron event sample for \(\sin^2 \theta_{23} < 0.5(>0.5)\)
Atmospheric Neutrino Events

Change in number of electron events:

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\frac{N_e}{N_{e}^{0}} - 1 \simeq \sin^2 2\theta_{12} \sin^2 \left( \frac{(\Delta m_{21}^2)^{M} L}{4E} \right) \times (r \cos^2 \theta_{23} - 1) \\
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- \(\Delta m_{21}^2\)-driven oscillation effect

- Brings an excess (depletion) in the sub-GeV electron event sample for \(\sin^2 \theta_{23} < 0.5(>0.5)\)

- Can be used for studying maximality and octant of \(\theta_{23}\)
Atmospheric Neutrino Events

Change in number of electron events:

\[ \frac{N_e}{N_{e0}} - 1 \simeq \sin^2 2\theta_{12} \sin^2 \left( \frac{\Delta m_{21}^2 M L}{4E} \right) \times (r \cos^2 \theta_{23} - 1) \]

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\[ + \sin \theta_{23} \cos \theta_{23} \ r \ Re \left[ A_{13}^* A_{12} \exp(-i\delta_{CP}) \right] \]
Atmospheric Neutrino Events

Change in number of electron events:

\[
\frac{N_e}{N_{e0}} - 1 \simeq \sin^2 2\theta_{12}^M \sin^2 \left( \frac{(\Delta m_{21}^2)^M L}{4E} \right) \times (r \cos^2 \theta_{23} - 1) \\
+ \sin^2 2\theta_{13}^M \sin^2 \left( \frac{(\Delta m_{31}^2)^M L}{4E} \right) \times (r \sin^2 \theta_{23} - 1) \\
+ \sin \theta_{23} \cos \theta_{23} \ r \ \text{Re} \left[ A_{13}^* A_{12} \exp(-i\delta_{CP}) \right]
\]

\(\theta_{13}\)-driven oscillation effect
Atmospheric Neutrino Events

Change in number of electron events:

$$\frac{N_e}{N^0_e} - 1 \approx \sin^2 2\theta^M_{12} \sin^2 \left( \frac{(\Delta m^2_{21})^M L}{4E} \right) \times (r \cos^2 \theta_{23} - 1)$$

$$+ \sin^2 2\theta^M_{13} \sin^2 \left( \frac{(\Delta m^2_{31})^M L}{4E} \right) \times (r \sin^2 \theta_{23} - 1)$$

$$+ \sin \theta_{23} \cos \theta_{23} \ r \ \text{Re} \left[ A^*_{13} A_{12} \exp(-i\delta_{CP}) \right]$$

- \(\theta_{13}\)-driven oscillation effect
- Reduces the excess (depletion) in the sub-GeV electron event sample for \(\sin^2 \theta_{23} < 0.5(> 0.5)\) – thats the bad part!!
Atmospheric Neutrino Events

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+ \sin \theta_{23} \cos \theta_{23} \ r \ Re \left[ A^*_{13} A_{12} \exp(-i\delta_{CP}) \right]
\]

- \(\theta_{13}\)-driven oscillation effect
- Reduces the excess (depletion) in the sub-GeV electron event sample for \(\sin^2 \theta_{23} < 0.5 (> 0.5)\) – thats the bad part!!
- Contains big earth matter effects resulting in sizable change in multi-GeV electron event sample, with the change being \(\sin^2 \theta_{23}\) dependent – thats the excellent part!!
Atmospheric Neutrino Events

Change in number of electron events:

\[
\frac{N_{e}}{N_{e}^{0}} - 1 \simeq \sin^{2} 2\theta_{12} \sin^{2} \left(\frac{(\Delta m_{21}^{2})^{M} L}{4E}\right) \times (r \cos^{2} \theta_{23} - 1)
\]

\[+ \sin^{2} 2\theta_{13} \sin^{2} \left(\frac{(\Delta m_{31}^{2})^{M} L}{4E}\right) \times (r \sin^{2} \theta_{23} - 1)\]

\[+ \sin \theta_{23} \cos \theta_{23} \ r \ Re \left[A_{13}^{*} A_{12} \exp(-i\delta_{CP})\right]\]

- $\theta_{13}$-driven oscillation effect
- Reduces the excess (depletion) in the sub-GeV electron event sample for $\sin^{2} \theta_{23} < 0.5 (> 0.5)$ – thats the bad part!!
- Contains big earth matter effects resulting in sizable change in multi-GeV electron event sample, with the change being $\sin^{2} \theta_{23}$ dependent – thats the excellent part!!
- Can be used for studying maximality and octant of $\theta_{23}$
Atmospheric Neutrino Events

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\frac{N_e}{N^0_e} - 1 \approx \sin^2 2\theta_{12} \sin^2 \left( \frac{(\Delta m^2_{21})^M L}{4E} \right) \times (r \cos^2 \theta_{23} - 1) \\
+ \sin^2 2\theta_{13} \sin^2 \left( \frac{(\Delta m^2_{31})^M L}{4E} \right) \times (r \sin^2 \theta_{23} - 1) \\
+ \sin \theta_{23} \cos \theta_{23} \ r \ \text{Re} \left[ A^*_{13} A_{12} \exp(-i\delta_{CP}) \right]
\]

- $\theta_{13}$-driven oscillation effect
- Reduces the excess (depletion) in the sub-GeV electron event sample for $\sin^2 \theta_{23} < 0.5 (> 0.5)$ – that’s the bad part!!
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- Can be used for studying maximality and octant of $\theta_{23}$
- Can be used for studying the neutrino mass hierarchy
Atmospheric Neutrino Events

Change in number of electron events:

\[
\frac{N_e}{N_e^0} - 1 \approx \sin^2 2\theta_{12} \sin^2 \left( \frac{(\Delta m_{21}^2) M L}{4E} \right) \times (r \cos^2 \theta_{23} - 1) \\
+ \sin^2 2\theta_{13} \sin^2 \left( \frac{(\Delta m_{31}^2) M L}{4E} \right) \times (r \sin^2 \theta_{23} - 1) \\
+ \sin \theta_{23} \cos \theta_{23} \ r \ \text{Re} \left[ A_{13}^* A_{12} \exp(-i\delta_{CP}) \right]
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Atmospheric Neutrino Events

Change in number of electron events:

\[
\frac{N_e}{N_e^0} - 1 \approx \sin^2 2\theta_{12} \sin^2 \left( \frac{(\Delta m^2_{21})^{M L}}{4E} \right) \times (r \cos^2 \theta_{23} - 1)
\]

\[
+ \sin^2 2\theta_{13} \sin^2 \left( \frac{(\Delta m^2_{31})^{M L}}{4E} \right) \times (r \sin^2 \theta_{23} - 1)
\]

\[
+ \sin \theta_{23} \cos \theta_{23} \ r \ Re \left[ A^*_1 A_2 \ exp(-i\delta_{CP}) \right]
\]

“interference” term which depends on $\delta_{CP}$
Atmospheric Neutrino Events

Change in number of electron events:

\[
\frac{N_e}{N^0_e} - 1 \approx \sin^2 2\theta_{12} \sin^2 \left( \frac{(\Delta m^2_{21})^{1/2} L}{4E} \right) \times (r \cos^2 \theta_{23} - 1)
\]

\[+ \sin^2 2\theta_{13} \sin^2 \left( \frac{(\Delta m^2_{31})^{1/2} L}{4E} \right) \times (r \sin^2 \theta_{23} - 1)
\]

\[+ \sin \theta_{23} \cos \theta_{23} r \, \text{Re} \left[ A^*_{13} A_{12} \exp(-i\delta_{CP}) \right]
\]

- “interference” term which depends on $\delta_{CP}$

- It might cancel the effect of the $\Delta m^2_{21}$ and $\theta_{13}$ terms depending on the value of $\delta_{CP}$ – bad bad bad...
Atmospheric Neutrino Events

Change in number of electron events:

\[
\frac{N_e}{N^0_e} - 1 \approx \sin^2 2\theta_{12} \sin^2 \left( \frac{(\Delta m^2_{21})^{M/L}}{4E} \right) \times (r \cos^2 \theta_{23} - 1)
\]

\[
+ \sin^2 2\theta_{13} \sin^2 \left( \frac{(\Delta m^2_{31})^{M/L}}{4E} \right) \times (r \sin^2 \theta_{23} - 1)
\]

\[
+ \sin \theta_{23} \cos \theta_{23} \ r \ Re \left[ A_{13}^* A_{12} \exp(-i\delta_{CP}) \right]
\]

• “interference” term which depends on $\delta_{CP}$

• It might cancel the effect of the $\Delta m^2_{21}$ and $\theta_{13}$ terms depending on the value of $\delta_{CP}$ – bad bad bad...

• But it might tell us if $\delta_{CP} = 0$ or $\pi$ \hspace{1cm} (Fogli et al. hep-ph/0506083)
Atmospheric Neutrino Events in MTon Water Detector
Atmospheric Neutrino Events in MTon Water Detector

These are just 2-gen $\nu_\mu \rightarrow \nu_\tau$ oscillations.
Atmospheric Neutrino Events in MTon Water Detector

\[ \Delta m^2_{21} = 8 \times 10^{-5} \text{ eV}^2 \]
\[ \sin^2 \theta_{23} = 0.91 \]
\[ \sin^2 \theta_{13} = 0.00 \]

- **$S_{\mu}$**
- **$S_{e}$**
- **$M_{\mu}$**
- **$M_{e}$**

$\Delta m^2_{21}$-driven oscillations bring in octant sensitivity in SGe events
Atmospheric Neutrino Events in MTon Water Detector

\[ \Delta m_{21}^2 = 8 \times 10^{-5} \text{ eV}^2 \]
\[ \Delta m_{31}^2 = 2.5 \times 10^{-3} \text{ eV}^2 \]
\[ \sin^2 \theta_{23} = 0.91 \]
\[ \sin^2 \theta_{13} = 0.04 \]

\( \theta_{13} \) brings in more octant sensitivity through matter effects
Atmospheric Neutrino Events in INO-ICAL
Atmospheric Neutrino Events in INO-ICAL

S.C and P. Roy hep-ph/0509197
Testing Maximality of $\theta_{23}$
Testing maximality of $\theta_{23}$

$|D|$ within 14%

LBL combined

Antusch, et al,

hep-ph/0404268
Testing maximality of $\theta_{23}$

| $|D|$ within 14% |
|---|
| LBL combined |
| Antusch, et al, |
| hep-ph/0404268 |

| $|D|$ within 19% |
|---|
| SK50 |
| Gonzalez-Garcia, et al, |
| hep-ph/0408170 |
Testing maximality of $\theta_{23}$

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LBL combined
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$|D|$ within 19%
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$|D|$ within 25%
INO-ICAL 500 kTy
S.C. and P. Roy, 
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Sensitivity to $|D| \equiv |(\sin^2 \theta_{23} - 0.5)|$ comparable to LBL expts
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$|D|$ within 20%
SK50
preliminary

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INO-ICAL 500 kTy
S.C. and P. Roy,
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Antusch, et al,
hep-ph/0404268

$|D|$ within 20%
SK50
preliminary

$|D|$ within 23%
INO-ICAL 500 kTy
S.C. and P. Roy,
hep-ph/0509197

Sensitivity to $|D|$ in INO-ICAL improves marginally with $\theta_{13}$
Testing Maximality of $\theta_{23}$

$|D|$ within 14%  
LBL combined  
Antusch, et al,  
hep-ph/0404268

$|D|$ within 11%  
SK50  
preliminary  
S.C. and P. Roy,  
hep-ph/0509197

Sensitivity to $|D|$ in INO-ICAL improves marginally with $\theta_{13}$  
Sensitivity to $|D|$ in SK50 improves remarkably with $\theta_{13}$
Resolving the $\theta_{23}$ Octant Ambiguity
Resolving the $\theta_{23}$ Octant Ambiguity with INO-ICAL

$\Delta \chi^2 [\sin^2 \theta_{23}^{(true)} - \sin^2 \theta_{23}^{(false)}]$ can be excluded at $3\sigma$ if:

$$\sin^2 \theta_{23}^{(true)} < 0.402 \text{ or } > 0.592 \text{ for } \sin^2 \theta_{13}^{(true)} = 0.02,$$

$$\sin^2 \theta_{23}^{(true)} < 0.421 \text{ or } > 0.573 \text{ for } \sin^2 \theta_{13}^{(true)} = 0.04.$$
Resolving the $\theta_{23}$ Octant Ambiguity with SK50

$\sin^2 \theta_{23}$ (false) can be excluded at 3$\sigma$ if:

$\sin^2 \theta_{23}$ (true) $< 0.36$ or $> 0.62$ for $\sin^2 \theta_{13}$ (true) $= 0.00$. 

Gonzalez-Garcia et al, hep-ph/0408170
Resolving the $\theta_{23}$ Octant Ambiguity with SK50

- Solid Lines: no priors; Dashed Lines: external priors
- Blue Lines: $\sin^2 \theta_{13} (\text{true}) = 0.00$
- Red Lines: $\sin^2 \theta_{13} (\text{true}) = 0.02$

$\sin^2 \theta_{23} (\text{false})$ can be excluded at $3\sigma$ if:

- $\sin^2 \theta_{23} (\text{true}) < 0.384$ or $> 0.601$ for $\sin^2 \theta_{13} (\text{true}) = 0.00$.
- $\sin^2 \theta_{23} (\text{true}) < 0.438$ or $> 0.574$ for $\sin^2 \theta_{13} (\text{true}) = 0.02$. 
Resolving the $\theta_{23}$ Octant Ambiguity with SK50

$\sin^2 \theta_{23}(true)$ can be excluded at $3\sigma$ if:

- $\sin^2 \theta_{23}(true) < 0.384$ or $> 0.601$ for $\sin^2 \theta_{13}(true) = 0.00$.
- $\sin^2 \theta_{23}(true) < 0.438$ or $> 0.574$ for $\sin^2 \theta_{13}(true) = 0.02$.

Sensitivity to octant of $\theta_{23}$ improves remarkably as $\theta_{13}$ increases from zero.
Resolving the $\text{sgn}(\Delta m_{31}^2)$ Ambiguity
Resolving the $\text{sgn}(\Delta m_{31}^2)$ Ambiguity with INO-ICAL

osc. params. fixed, external prior information, osc. params. free
**solid:** true hierarchy normal, **dashed:** true hierarchy inverted

4000 upward going events

true value of $\sin^2 2\theta_{13}$

(Thomas Schwetz)

Petcov and Schwetz, hep-ph/0511277
Resolving the $sgn(\Delta m_{31}^2)$ Ambiguity with INO-ICAL

The wrong hierarchy can be ruled out at $2\sigma$ with 4000 upward going events for $\sin^2 2\theta_{13} = 0.1(\sin^2 \theta_{13} = 0.026)$ and $\sin^2 \theta_{23} = 0.5$
Resolving the $sgn(\Delta m^2_{31})$ Ambiguity with INO-ICAL

The wrong hierarchy can be ruled out at $2\sigma$ with 4000 upward going events for $\sin^2 2\theta_{13} = 0.1 (\sin^2 \theta_{13} = 0.026)$ and $\sin^2 \theta_{23} = 0.5$

- Indumathi, Murthy (2004)
- Ghoshal, Gandhi, Goswami, Mehta, UmaSankar (2004)

(Thomas Schwetz) Petcov and Schwetz, hep-ph/0511277
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Sensitivity increases with $E$ and $L$ resolution.
Resolving the $\text{sgn}(\Delta m^2_{31})$ Ambiguity with INO-ICAL

4000 upward going events

The wrong hierarchy can be ruled out at $2\sigma$ with 4000 upward going events for $\sin^2 2\theta_{13} = 0.1 (\sin^2 \theta_{13} = 0.026)$ and $\sin^2 \theta_{23} = 0.5$

Sensitivity increases if it were possible to detect electrons
Resolving the $\text{sgn}(\Delta m^2_{31})$ Ambiguity with INO-ICAL

- **osc. params. fixed, external prior information, osc. params. free**
  - **solid:** true hierarchy normal, **dashed:** true hierarchy inverted

![Graphs showing sensitivity and hierarchy resolution](image)

4000 upward going events

- The wrong hierarchy can be ruled out at $2\sigma$ with 4000 upward going events for $\sin^2 2\theta_{13} = 0.1 (\sin^2 \theta_{13} = 0.026)$ and $\sin^2 \theta_{23} = 0.5$

- Sensitivity increases with $\sin^2 \theta_{23}$

(Thomas Schwetz)

Petcov and Schwetz, hep-ph/0511277

SANDHYA CHOUBEY

WHAT CAN WE LEARN FROM ATMOSPHERIC NEUTRINOS

Neutrino 2006, 16.06.06 – p.33/41
Resolving the $sgn(\Delta m_{31}^2)$ Ambiguity with SK50

True Hierarchy is Normal

solid: $\delta_{CP}=0$

$s_{23}^2(\text{true})=0.4$  
$s_{23}^2(\text{true})=0.5$  
$s_{23}^2(\text{true})=0.6$
Resolving the $\text{sgn}(\Delta m_{31}^2)$ Ambiguity with SK50

**True Hierarchy is Normal**

- Solid: $\delta_{CP}=0$
- Dashed: $\delta_{CP}=\text{free}$

$s_{23}^2(\text{true})=0.4$
$s_{23}^2(\text{true})=0.5$
$s_{23}^2(\text{true})=0.6$

Sensitivity drops appreciably due to $\delta_{CP}$
Resolving the $sgn(\Delta m^2_{31})$ Ambiguity with SK50

Resolving param degen:

- T2K+ATM: hep-ph/0501037
- $\beta$beams+ATM: hep-ph/0603172

Sensitivity drops appreciably due to $\delta_{CP}$
Searching for New Physics
Searching for New Physics

- Non-Standard neutrino-matter Interaction
- Violation of Equivalence Principle
- Lorentz Invariance Violation
- Violation of CPT Symmetry
- Neutrino Decay
- Quantum Decoherence

(This list is not exhaustive.)
Searching for New Physics in INO-ICAL/SK50 like Expts

- Non-Standard neutrino-matter Interaction
- Violation of Equivalence Principle
- Lorentz Invariance Violation
- Violation of CPT Symmetry
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- Quantum Decoherence

Each one has a distinctive $L/E$ behavior
- Oscillations go linearly as $L/E$
- Atmospheric neutrinos have a very wide range of $L/E$
- This $L/E$ data can be used to probe new physics – INO-ICAL
- Comparison of contained events and upward going muons in water Cerenkov detectors can also be used
Searching for New Physics with Neutrino Telescopes

- Neutrino Telescopes have atmospheric \( \nu \)'s as background
Searching for New Physics with Neutrino Telescopes

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- The atm $\nu$’s seen will be of highest energies: $\left(10^{-1}-10^{4}\right)$ TeV
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\[ p_i = \frac{N_i}{N_i^{\text{osc}}} \quad \text{vert=[-1.0, -0.6]} \quad \text{horiz=[-0.6, -0.2]} \]

$\delta c/c = \text{vary}, \xi = 45$

**ICECUBE**

Gonzalez-Garcia et al, hep-ph/0502223
Searching for New Physics with Neutrino Telescopes

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- The atm $\nu$'s seen will be of highest energies: $(10^{-1} - 10^4)$ TeV
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- Octant of $\theta_{23}$ can be determined with SK50 if $\sin^2\theta_{23}(\text{true}) < 0.38$ or $> 0.60$ for $\sin^2\theta_{13}(\text{true}) = 0$.
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New Physics might be discovered/constrained using atmospheric neutrinos
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I thank the organizers of Neutrino 2006, Harish-Chandra Research Institute, University of Oxford, INO collaboration, Srubabati Goswami, Michele Maltoni, Probir Roy and Thomas Schwetz.

Thank You!!