Subdominant Oscillation Effects in Atmospheric Neutrinos

Concha Gonzalez-Garcia

(Stony Brook, IFIC-Valencia)

OUTLINE

Introduction: 2ν Oscillation Analysis

3ν Oscillations: Effect of θ_{13}

3ν Oscillations: Effect of Δm^2_{21}

Measuring Deviations from Maximal θ_{23} Mixing

Some New Physics Effects in Atmospheric Neutrinos

Comment on Uncertainties and Summary

In collaboration with M. Maltoni and A. Smirnov

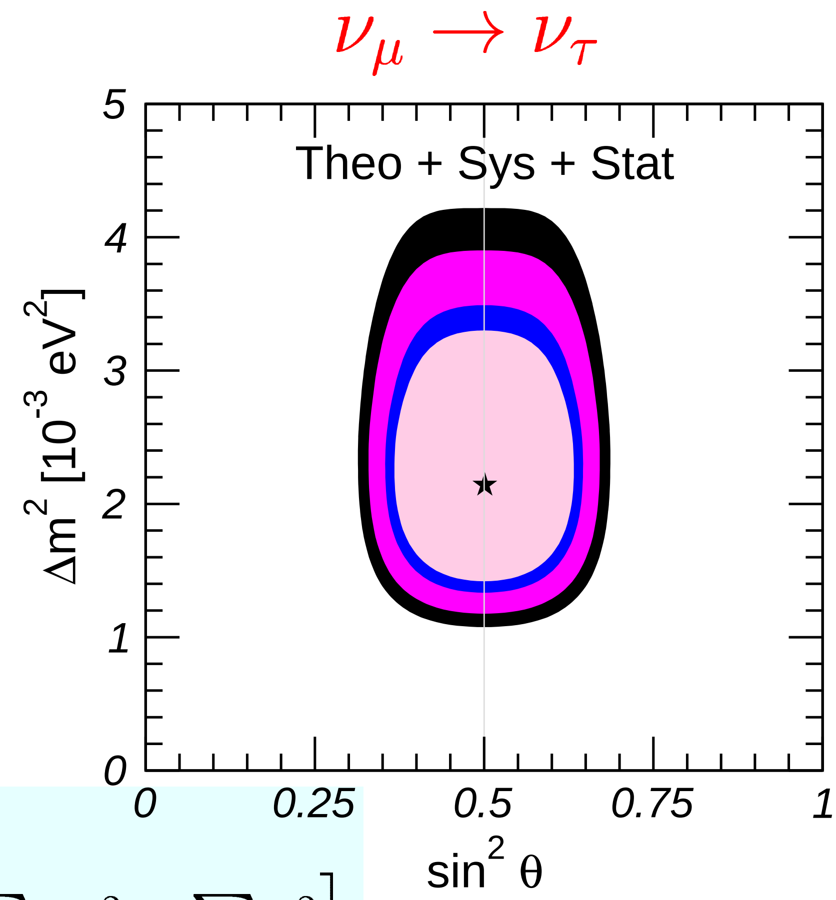
Introduction: Our 2–ν Atmospheric Data Analysis

Including 55 data points SKI data:

- Sub-GeV e-like and μ-like: 10+10 points
- Multi-GeV e-like and μ-like: 10+10 points
- Stopping and Thrugoing μ's: 5+10 points

Using 3-dim atmospheric fluxes from Honda

Use "pull" approach for theoretical and systematic errors Fogli, Lisi *etal* 02



$$\chi^2 = \min_{\xi_i}\left[\sum_{n=1}^{55}\left(\frac{R_n^{\rm theo} - \sum_i \xi_i \sigma_n^i - R_n^{\rm exp}}{\sigma_n^{\rm stat}}\right)^2 + \sum_{i,theory}\xi_i^2 + \sum_{i,syt}\xi_i^2\right]$$

Include 18 sources of theoretical and systematic uncertainties

- Flux Uncertainties:

(1) Total normalization: $\sigma_{\rm norm} = 20\%$

(2) "Tilt" error
$\Phi_\delta(E) = \Phi_0(E)\left(\frac{E}{E_0}\right)^\delta$
$\sigma_\delta = 5\%$ $E_0 = 2$ GeV

(3) ν_μ/ν_e ratio: $\sigma_{\mu/e} = 5\%$
E independent for contained events

(4) Zenith angle dependence:
$\sigma_{\rm zen,i} = 5\%\langle\cos\theta\rangle_i$

- Cross Section Uncertainties:

(5) $\sigma^{\sigma_{\rm QE}}_{\rm norm} = 15\%$

(6) $\sigma^{\sigma_{1\pi}}_{\rm norm} = 15\%$,

(7) $\sigma^{\sigma_{\rm DIS}}_{\rm norm} = 15\%$ for contained
$\sigma^{\sigma_{\rm DIS}}_{\rm norm} = 10\%$ for upward-going μ

(8)–(10) $\sigma^{\rm QE,1\pi,DIS}_{i,\nu_\mu}/\sigma^{\rm QE,1\pi,DIS}_{i,\nu_e} = 0.1$–$1\%$

- Systematic uncert (from SK pub):

(11) Simulation of had int (contained):
$\sigma^{\rm sys}_{\rm hadron} = -0.25$–$1.1$ %

(12) Particle identification (contained):
$\sigma^{\rm sys}_{\mu/e} = -1.1$–$1.6\%$

(13) Ring Counting:
$\sigma^{\rm sys}_{\rm ring} = -0.75$–$5.5\%$

(14) Fiducial Volume:
$\sigma^{\rm sys}_{\rm f-vol} = -0.3$–$1.4\%$

(15) Energy Calibration:
$\sigma^{\rm sys}_{\rm E-cal} = -0.4$–$2\%$

(16) PC/FC norm: (multi-GeV μ)
$\sigma^{\rm sys}_{\rm PC-nrm} = 2.85\%$

(17) Up-μ track reconstruction:
$\sigma^{\rm sys}_{\rm track} = 1.4$–$6.4\%$

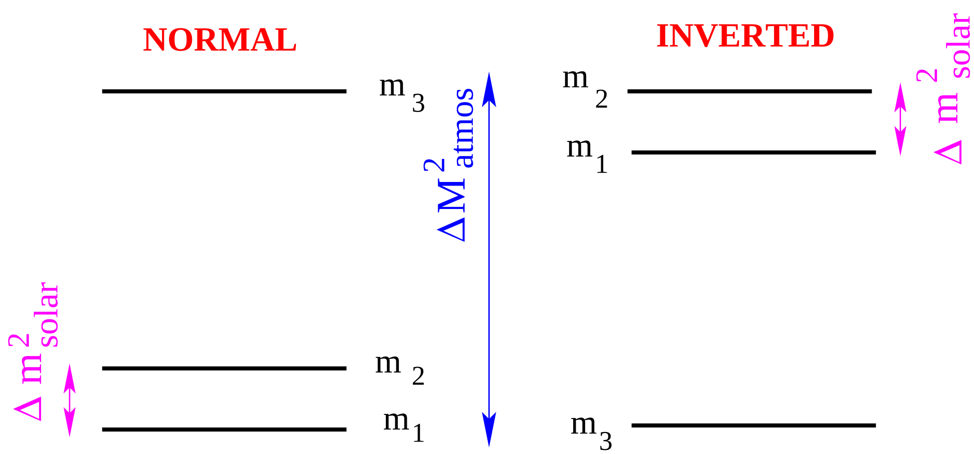
(18) Up Effi and Stop/Thru separation:
$\sigma^{\rm sys}_{\rm up-eff} = 1$–$1.4\%$

Solar+Atmospheric+Reactor+LBL 3ν Oscillations

U: 3 angles, 1 CP-phase
+ (2 Majorana phases)

$$\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{21} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Two mass schemes



2ν oscillation analysis $\Rightarrow \Delta m^2_{21} = \Delta m^2_{\odot} \ll \Delta M^2_{atm} \simeq \pm\Delta m^2_{32} \simeq \pm\Delta m^2_{31}$

Generic 3ν mixing effects:

- Effects due to θ_{13}
- Difference between Inverted and Normal
- Interference of two wavelength oscillations
- CP violation due to phase δ

3–ν Atmospheric Neutrino Oscillation: Effect of θ_{13}

- In general one has to solve: $i\frac{d\vec{\nu}}{dt} = H\,\vec{\nu}$ $\quad H = U \cdot H_0^d \cdot U^\dagger + V$

$$H_0^d = \frac{1}{2E_\nu}\text{diag}\left(-\Delta m^2_{21}, 0, \Delta m^2_{32}\right) \qquad V = \text{diag}\left(\pm\sqrt{2}G_F N_e, 0, 0\right)$$

- Hierarchical approximation: $\Delta m^2_{21} \ll \Delta m^2_{31} \sim \Delta m^2_{32}$ $\Rightarrow$ neglect Δm^2_{21} in ATM

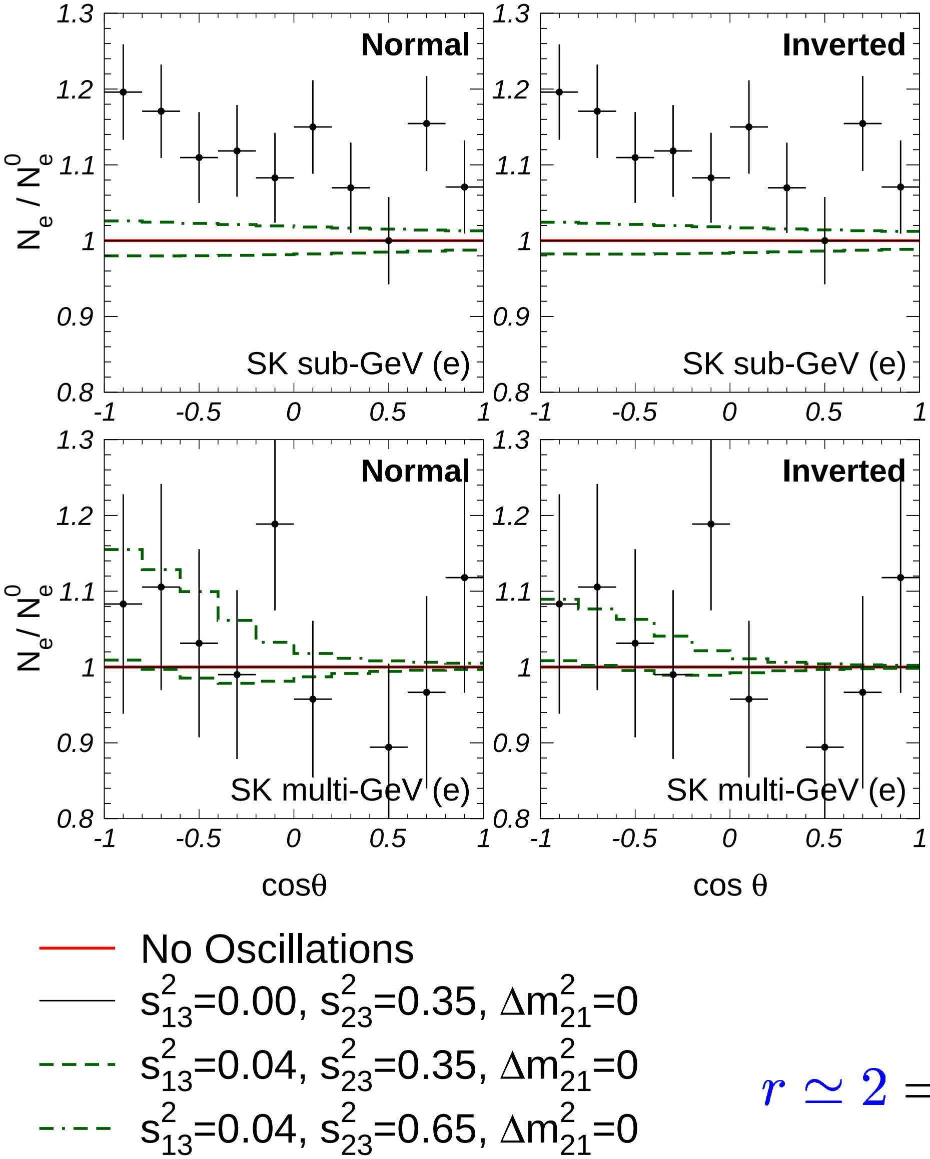
$$
\begin{aligned}
P_{ee} &= 1 - 4 s^2_{13,m} c^2_{13,m}\, S_{31} \\
P_{\mu\mu} &= 1 - 4 s^2_{13,m} c^2_{13,m} s^4_{23}\, S_{31} - 4 s^2_{13,m} s^2_{23} c^2_{23}\, S_{21} - 4 c^2_{13,m} s^2_{23} c^2_{23}\, S_{32} \\
P_{e\mu} &= 4 s^2_{13,m} c^2_{13,m} s^2_{23}\, S_{31} \\
S_{ij} &= \sin^2\left(\frac{\Delta\mu^2_{ij}}{4E_\nu} L\right) \\
\Delta\mu^2_{21} &= \frac{\Delta m^2_{32}}{2}\left(\frac{\sin 2\theta_{13}}{\sin 2\theta_{13,m}} - 1\right) - E_\nu V_e \\
\Delta\mu^2_{32} &= \frac{\Delta m^2_{32}}{2}\left(\frac{\sin 2\theta_{13}}{\sin 2\theta_{13,m}} + 1\right) + E_\nu V_e \\
\Delta\mu^2_{31} &= \Delta m^2_{32}\frac{\sin 2\theta_{13}}{\sin 2\theta_{13,m}} \\
\sin 2\theta_{13,m} &= \frac{\sin 2\theta_{13}}{\sqrt{(\cos 2\theta_{13} \mp \frac{2E_\nu V_e}{\Delta m^2_{31}})^2 + \sin^2 2\theta_{13}}}
\end{aligned}
$$

Pantaleone 94; Used by many ...

Concha Gonzalez-Garcia

3–ν Atmospheric Neutrino Oscillation: Effect of θ_{13}

Ahkmedov,Dighe,Lipari,Smirnov 99; Petcov, Maris 98; Palomares, Petcov, 03



$$\frac{N_e}{N_{e0}} - 1 = \overline{P_{e3}}\,\bar{r}\left(s^2_{23} - \frac{1}{\bar{r}}\right)$$

$$\bar{r} = \frac{N_{\mu 0}}{N_{e0}}$$

$$P_{e3} = \sin^2 2\theta_{13,m} \sin^2\left(\frac{\Delta m^2_{31}\, L}{4E_\nu}\,\frac{\sin 2\theta_{13}}{\sin 2\theta_{13,m}}\right)$$

$$\sin 2\theta_{13,m} = \frac{\sin 2\theta_{13}}{\sqrt{(\cos 2\theta_{13} \mp \frac{2E_\nu V_e}{\Delta m^2_{31}})^2 + \sin^2 2\theta_{13}}}$$

- Multi-GeV : Enhancement due to Matter

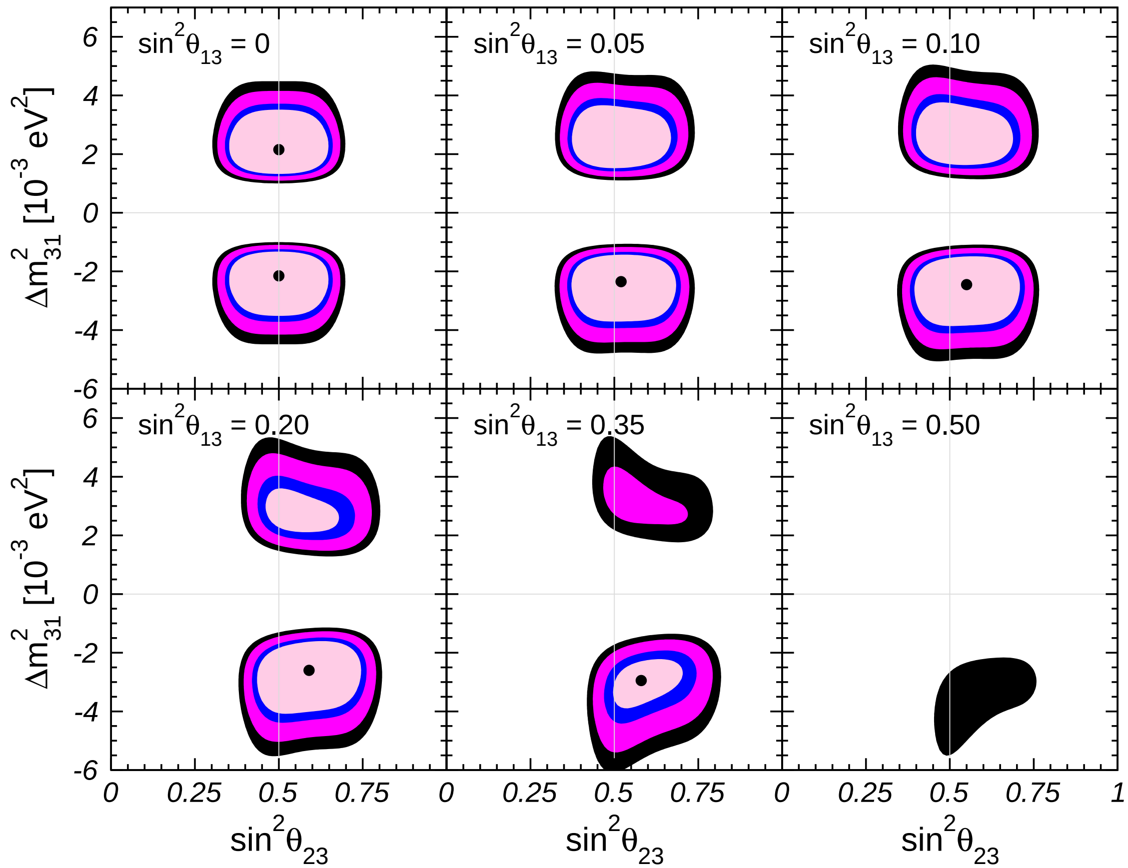
  Larger Effect in Normal

  Possible Sensitivity to Mass Ordering

- Sub-GeV: Vacuum Osc: Smaller Effect

$$r \simeq 2 \Rightarrow \begin{array}{l} \theta_{23} < \frac{\pi}{4} \Rightarrow s^2_{23} < \frac{1}{2} \Rightarrow N_e(\theta_{13}) < N_{e0} \\ \theta_{23} > \frac{\pi}{4} \Rightarrow s^2_{23} > \frac{1}{2} \Rightarrow N_e(\theta_{13}) > N_{e0} \end{array}$$

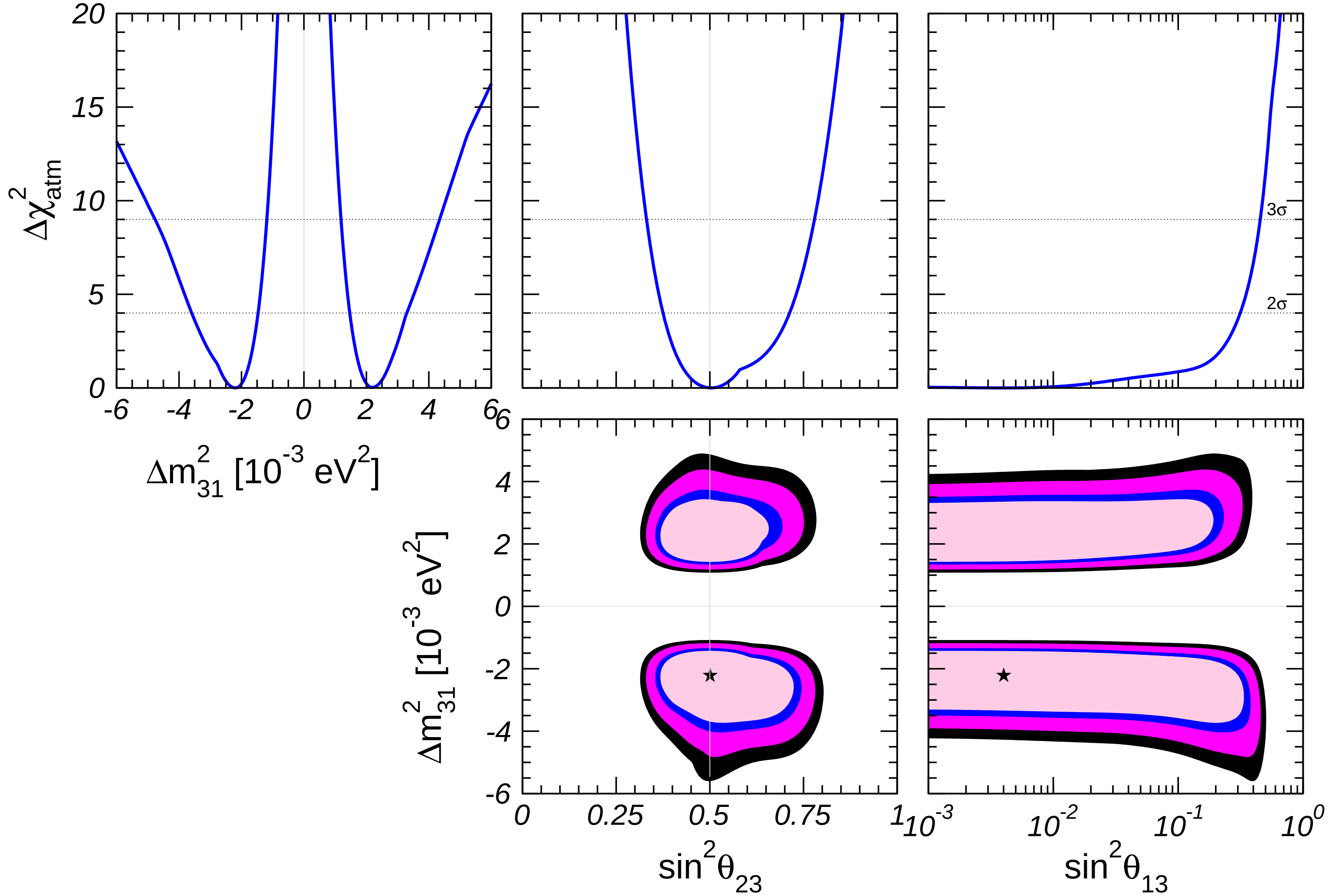
Effect of θ_{13} in Present Data



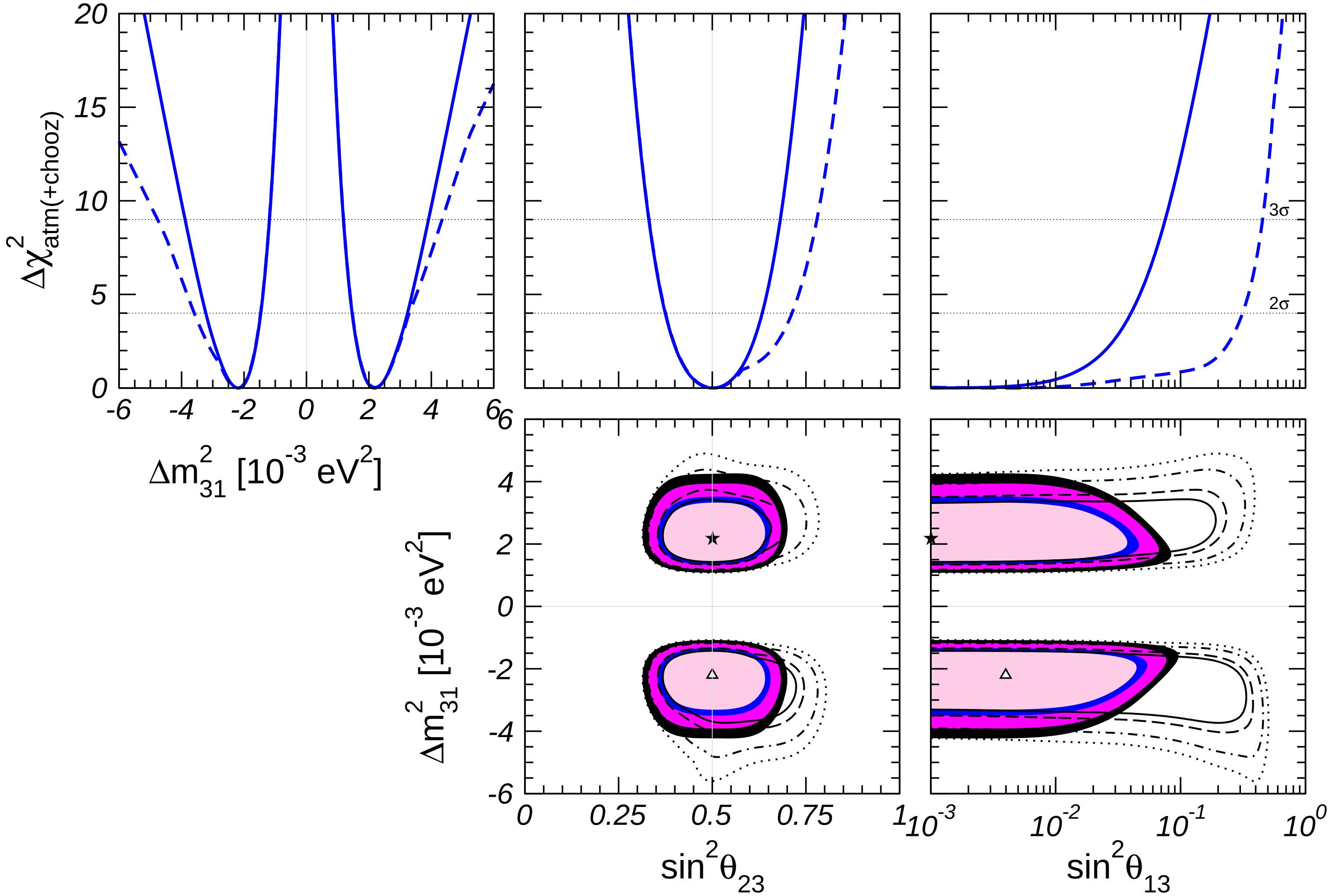
– So far no evidence of $\theta_{13} \neq 0$

– Further Constrained by CHOOZ

Effect of θ_{13} in Present ATM Data



Effect of θ_{13} in Present ATM + CHOOZ



Δm^2_{21} effects in ATM Data

Concha Gonzalez-Garcia

Smirnov, Peres 99,01; Fogli, Lisi, Marrone 01; MC G-G, Maltoni 02; MCG-G, Maltoni, Smirnov hep-ph/0408170

- In general one has to solve: $i\frac{d\vec{\nu}}{dt} = H\,\vec{\nu}$ $\quad H = U\cdot H_0^d \cdot U^\dagger + V$

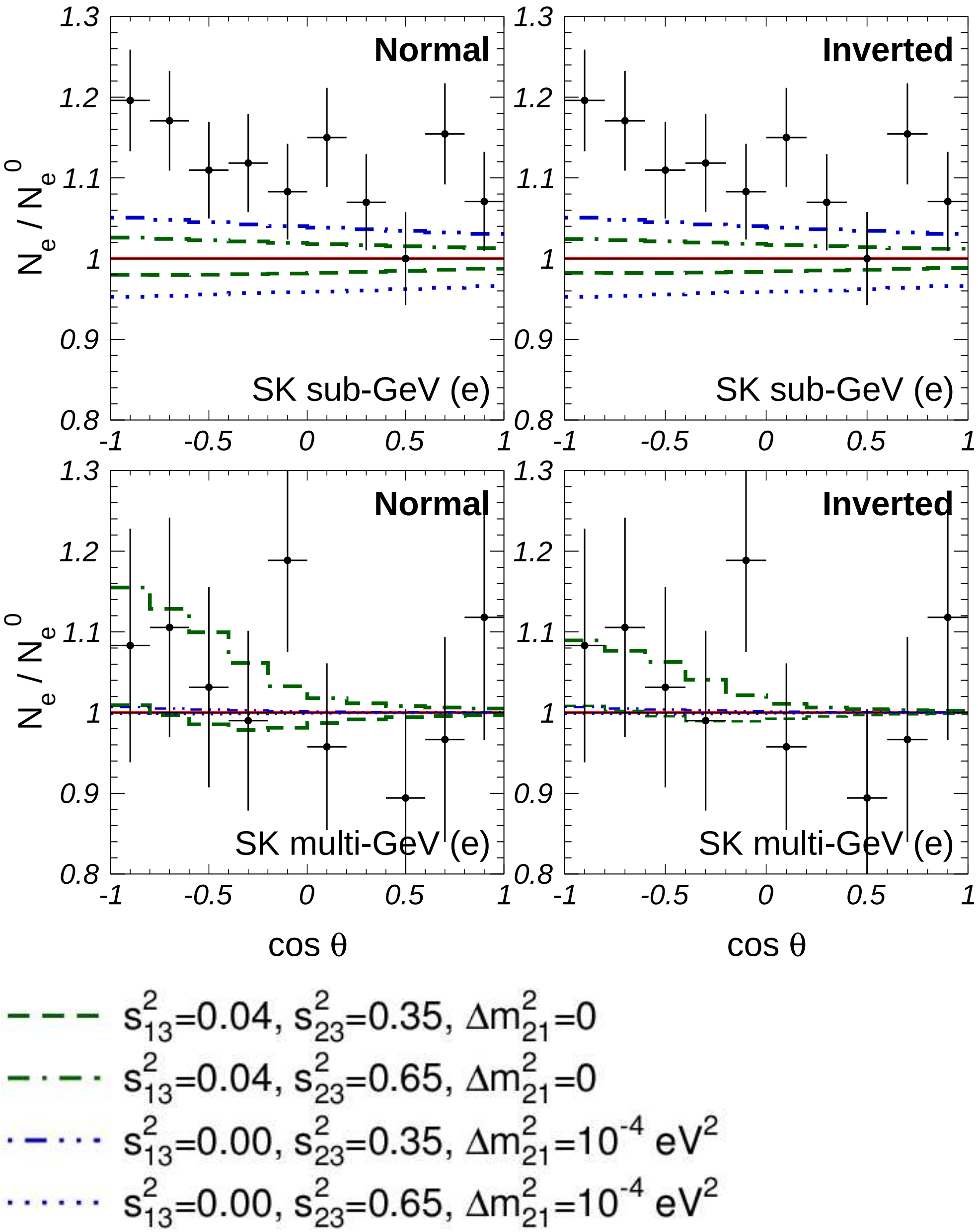
$$H_0^d = \frac{1}{2E_\nu}\text{diag}\left(-\Delta m^2_{21}, 0, \Delta m^2_{32}\right) \qquad V = \text{diag}\left(\pm\sqrt{2}G_F N_e, 0, 0\right)$$

- Neglecting θ_{13}:

$$\begin{aligned}
P_{ee} &= 1 - P_{e2} \\
P_{e\mu} &= c^2_{23} P_{e2} \\
P_{\mu\mu} &= 1 - c^4_{23} P_{e2} - 2 s^2_{23} c^2_{23}\ \left[1 - \sqrt{1 - P_{e2}}\cos\phi\right] \\
P_{e2} &= \sin^2 2\theta_{12,m} \sin^2\left(\frac{\Delta m^2_{21}\,L}{4E_\nu}\,\frac{\sin 2\theta_{12}}{\sin 2\theta_{12,m}}\right) \\
\sin 2\theta_{12,m} &= \frac{\sin 2\theta_{12}}{\sqrt{(\cos 2\theta_{12} \mp \frac{2E_\nu V_e}{\Delta m^2_{21}})^2 + \sin^2 2\theta_{12}}} \\
\phi &\approx (\Delta m^2_{31} + s^2_{12}\,\Delta m^2_{21})\frac{L}{2E_\nu}
\end{aligned}$$

Concha Gonzalez-Garcia

Δm^2_{21} effects in ATM Data



$$\frac{N_e}{N_{e0}} - 1 = \overline{P_{e2}}\,\bar{r}\left(c^2_{23} - \frac{1}{\bar{r}}\right)$$

$$P_{e2} = \sin^2 2\theta_{12,m} \sin^2\left(\frac{\Delta m^2_{21} L}{4E_\nu}\,\frac{\sin 2\theta_{12}}{\sin 2\theta_{12,m}}\right)$$

$$\sin 2\theta_{12,m} = \frac{\sin^2 2\theta_{12}}{\sqrt{(\cos 2\theta_{12} \mp \frac{2EV_e}{\Delta m^2_{21}})^2 + \sin^2 2\theta_{12}}}$$

For Sub-GeV:

$$P_{e2} = \frac{(\Delta m^2_{21})^2}{(2EV_e)^2} \sin^2 2\theta_{12} \sin^2 \frac{V_e L}{2}$$

$$\theta_{23} < \frac{\pi}{4} \Rightarrow c^2_{23} > \frac{1}{2} \Rightarrow N_e(\theta_{13}) > N_{e0}$$

$$\theta_{23} > \frac{\pi}{4} \Rightarrow c^2_{23} < \frac{1}{2} \Rightarrow N_e(\theta_{13}) < N_{e0}$$

$\Rightarrow$ Sensitiv to Deviations from Maximal θ_{23}

$\Rightarrow$ Sensitivity to Octant of θ_{23}

(even for vanishing θ_{13})

$\Rightarrow$ Effect proportional to $(\Delta m^2_{21})^2$

Concha Gonzalez-Garcia

Effect of θ_{13} and Δm^2_{21}

Smirnov, Peres 01,03
MC G-G, Maltoni 02

For sub-GeV energies

$$\frac{N_e}{N_e^0} - 1 \simeq \overline{P_{e2}}\,\overline{r}\left(c_{23}^2 - \frac{1}{\overline{r}}\right) + 2\tilde{s}_{13}^2\overline{r}\left(s_{23}^2 - \frac{1}{\overline{r}}\right) - \overline{r}\tilde{s}_{13}\tilde{c}_{13}^2 \sin 2\theta_{23}\left(\cos\delta_{CP}\,\overline{R_2} - \sin\delta_{CP}\,\overline{I_2}\right)$$

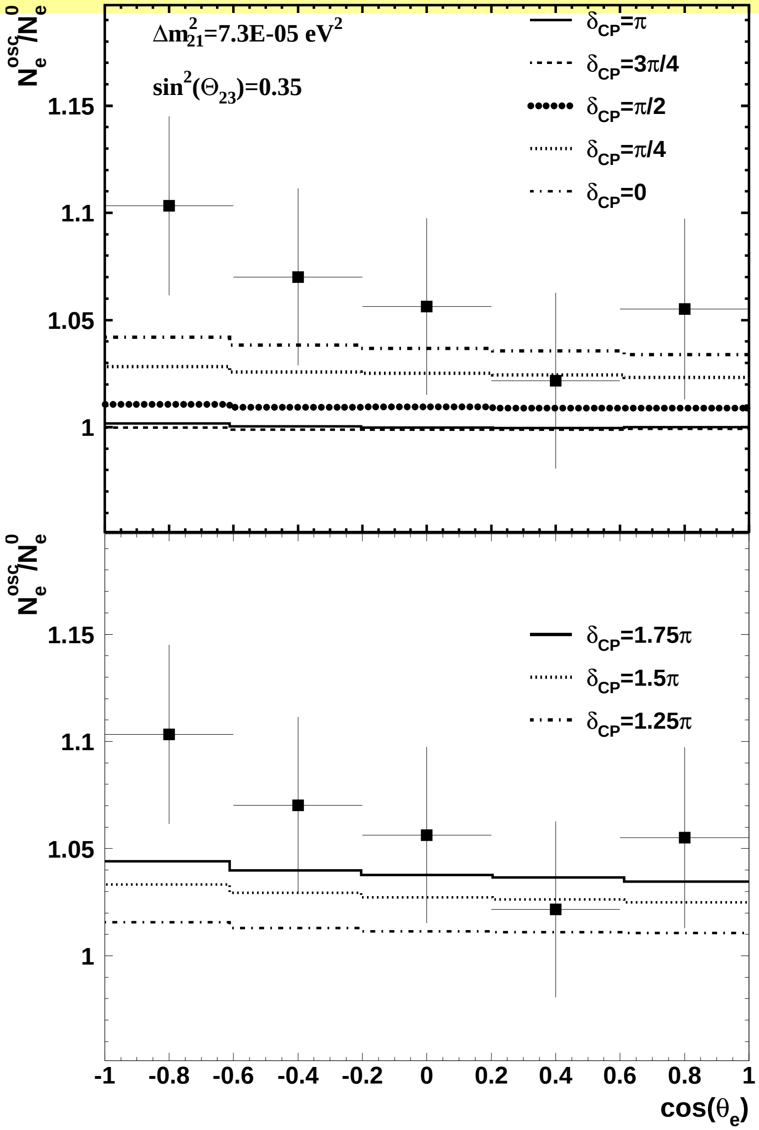
$$P_{e2} = \sin^2 2\theta_{12,m}\, \sin^2\frac{\phi_m}{2}$$

$$R_2 = -\sin 2\theta_{12,m}\cos 2\theta_{12,m}\, \sin^2\frac{\phi_m}{2}$$

$$I_2 = -\frac{1}{2}\sin 2\theta_{12,m}\, \sin\phi_m$$

$$\sin 2\theta_{12,m} = \frac{\sin 2\theta_{12}}{\sqrt{(\cos 2\theta_{12} \mp \frac{2E_\nu V_e}{\Delta m^2_{21}})^2 + \sin^2 2\theta_{12}}}$$

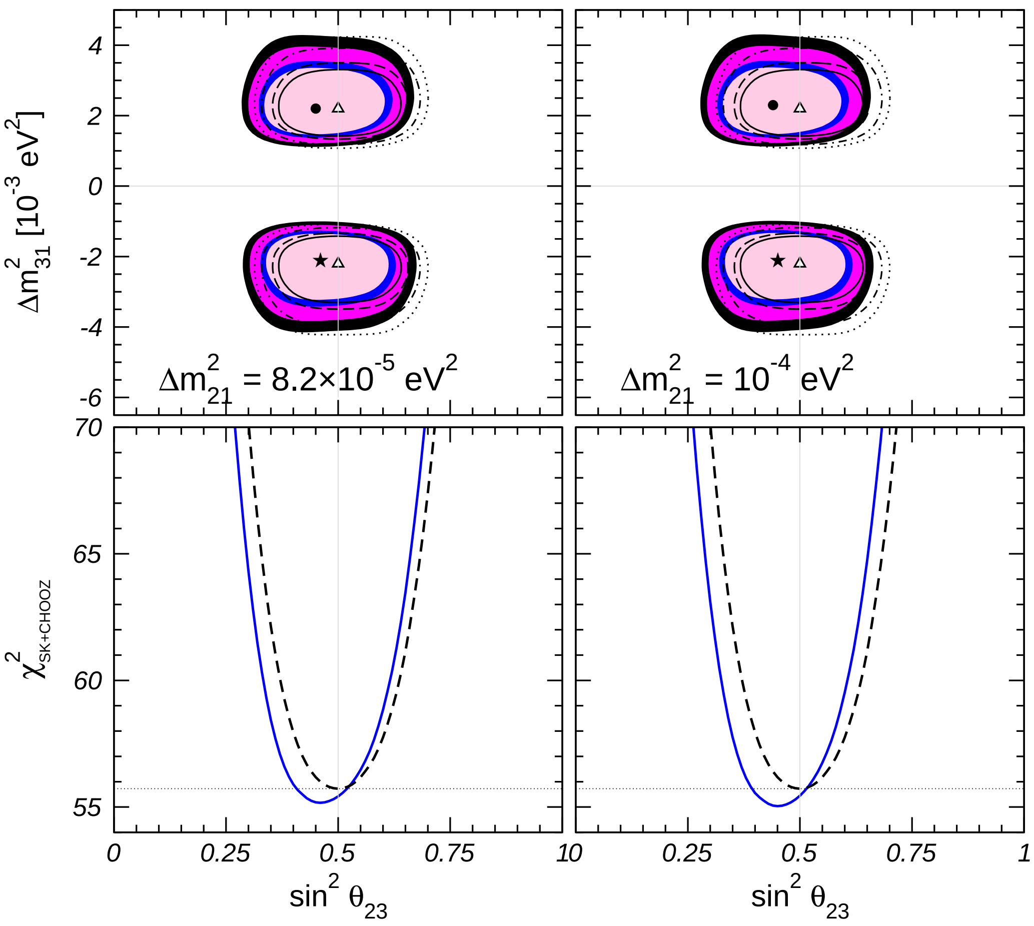
$$\tilde{\theta}_{13} \approx \theta_{13}\left(1 + \frac{2E_\nu V_e}{\Delta m^2_{31}}\right)$$

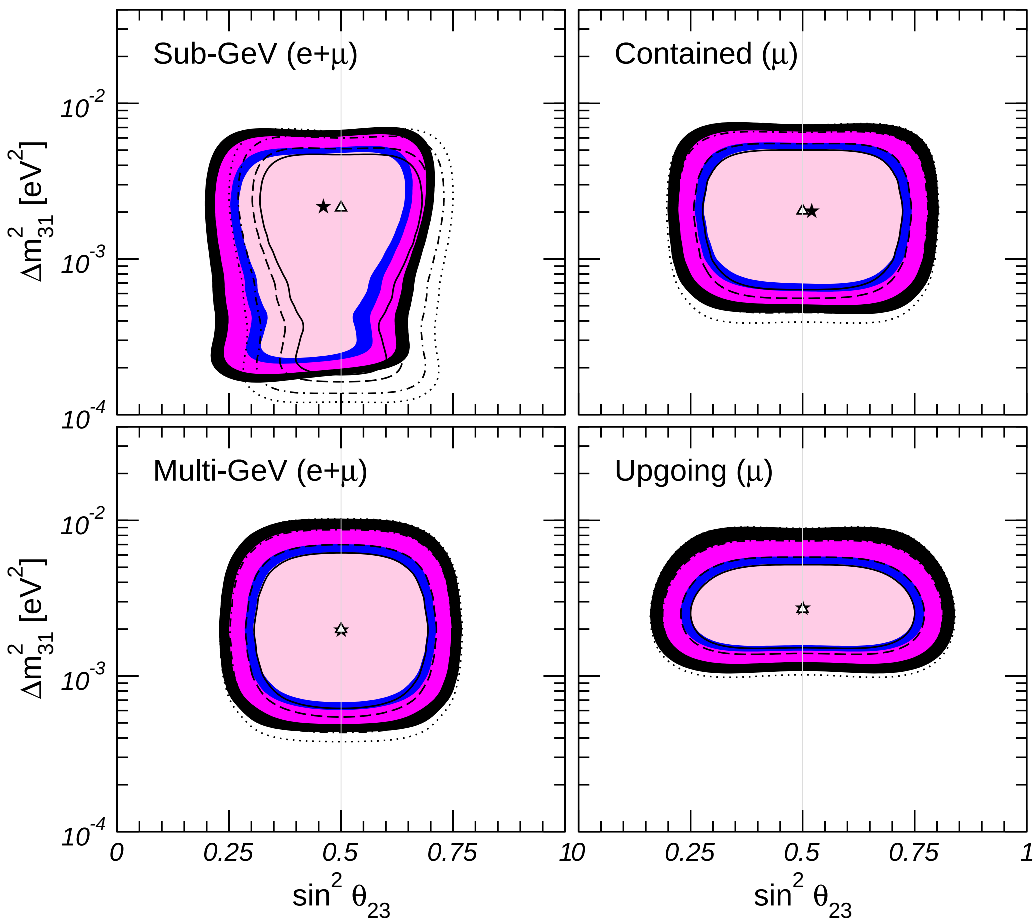


Smirnov, Peres hep-ph/0309312

Δm^2_{21} effects in ATM Data: Present

MC G-G, Maltoni, Smirnov hep-ph/0408170





From present analysis:

$$D_{23} = \frac{1}{2} - \sin^2\theta_{23} = 0.04 \pm 0.07$$

Sensitivity at Future ATM Experiment

MC G-G, Maltoni, Smirnov hep-ph/0408170

1) Simulate SK-like observables according to expectations from "true" parameters

$$\overline{\omega} \equiv (\Delta\overline{m}^2_{21},\, \Delta\overline{m}^2_{31},\, \overline{\theta}_{12},\, \overline{\theta}_{13},\, \overline{\theta}_{23})\,,$$

2) Construct

$$\chi^2_{\rm SK}(\Delta m^2_{21},\, \Delta m^2_{31},\, \theta_{12},\, \theta_{13},\, \theta_{23}\,|\,\overline{\omega})$$

For 20 or 50 times present SK statistics and

(A) same theoretical and systematic errors as in present SK;

(B) same systematic errors as in present SK, but no theoretical uncertainties;

(C) neither theoretical nor systematic uncertainties (perfect experiment).

3) Add present information from reactors

$$\chi^2_{\rm ATM+REAC}(\Delta m^2_{31},\, \theta_{23}\,|\,\overline{\omega}) \equiv \min_{\Delta m^2_{21},\theta_{13}} \Bigg[\chi^2_{\rm SK}(\Delta m^2_{21},\, \Delta m^2_{31},\, \theta_{12}=\overline{\theta}_{12},\, \theta_{13},\, \theta_{23}\,|\,\overline{\omega}) + \chi^2_{\rm CHOOZ}(\Delta m^2_{21},\, \Delta m^2_{31},\, \theta_{12}=\overline{\theta}_{12},\, \theta_{13}\,|\,\overline{\omega}) + \left(\frac{\Delta m^2_{21}-\Delta\overline{m}^2_{21}}{\sigma_{\Delta m^2_{21}}}\right)^2\Bigg]$$

Sensitivity at Future ATM Experiment

4) Add expected future information from reactors and LBL

$$\chi^2_{\rm ATM+REAC+LBL}(\Delta m^2_{31},\,\theta_{23}\,|\,\overline{\omega}) \equiv \min_{\Delta m^2_{21},\theta_{13}} \Big[\chi^2_{\rm SK}(\Delta m^2_{21},\,\Delta m^2_{31},\,\theta_{12}=\overline{\theta}_{12},\,\theta_{13},\,\theta_{23}\,|\,\overline{\omega}) + \chi^2_{\rm CHOOZ}(\Delta m^2_{21},\,\Delta m^2_{31},\,\theta_{12}=\overline{\theta}_{12},\,\theta_{13}\,|\,\overline{\omega}) + \left(\frac{\Delta m^2_{21}-\Delta\overline{m}^2_{21}}{\sigma_{\Delta m^2_{21}}}\right)^2 + \left(\frac{\Delta m^2_{31}-\Delta\overline{m}^2_{31}}{\sigma_{\Delta m^2_{31}}}\right)^2 + \left(\frac{\sin^2 2\theta_{23}-\sin^2 2\overline{\theta}_{23}}{\sigma_{\sin^2 2\theta_{23}}}\right)^2 + \left(\frac{\sin^2 2\theta_{13}-\sin^2 2\overline{\theta}_{13}}{\sigma_{\sin^2 2\theta_{13}}}\right)^2 \Big]$$

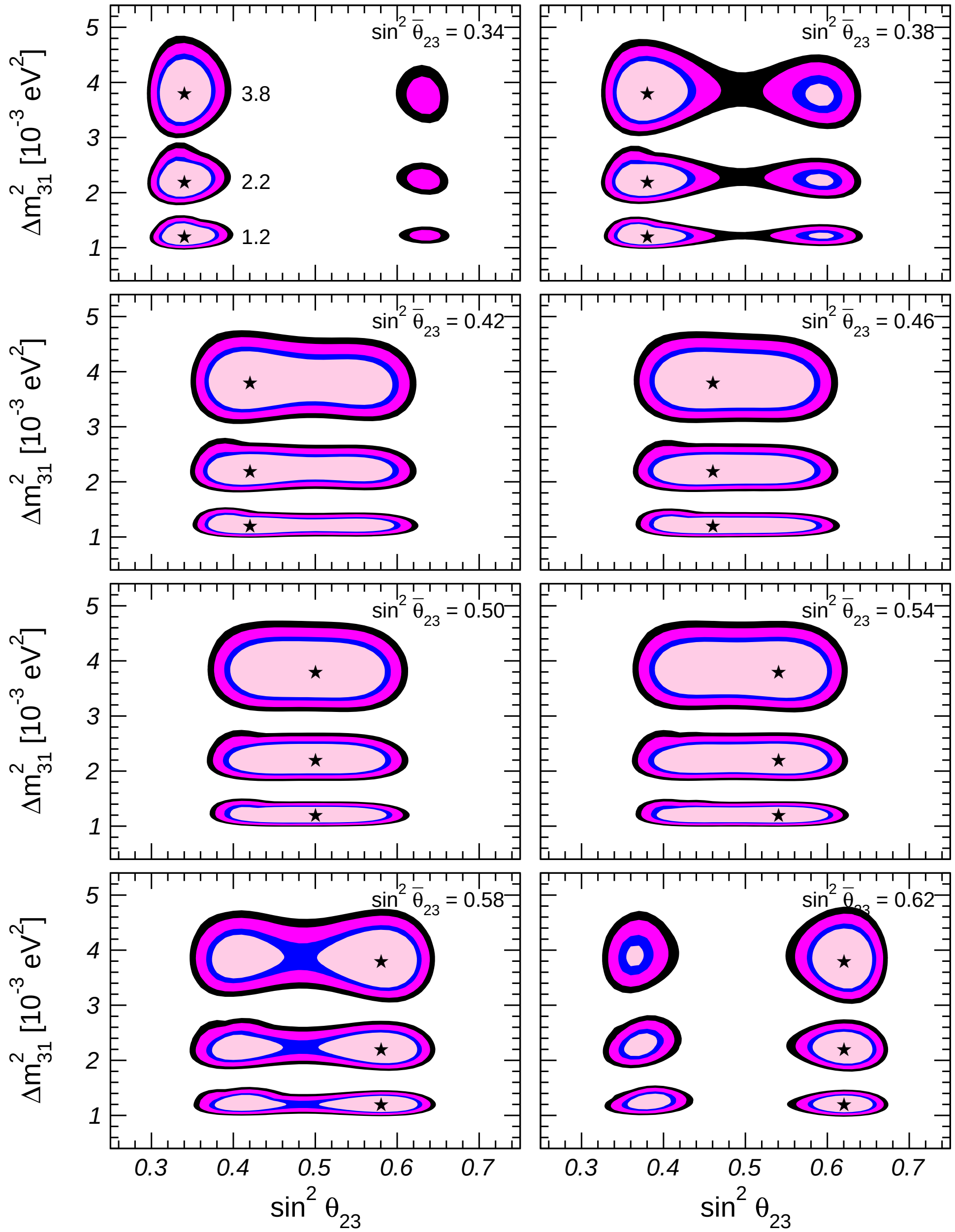
Assumed:

$$\sigma_{\Delta m^2_{21}} = 3\%$$
$$\sigma_{\sin^2\theta_{13}} = 0.01$$
$$\sigma_{\sin^2 2\theta_{23}} = 0.015$$
$$\sigma_{\Delta m^2_{31}} = 1.5\%$$

No evidence of $\theta_{13}\neq 0 \Rightarrow$ LBL (NUMI, T2K) sensitive only to $\sin^2 2\theta_{23}$

Sensitivity at Future ATM Experiment

Reconstructed regions for SK× 20 case (A):



MC G-G, Maltoni, Smirnov hep-ph/0408170

$\overline{\theta}_{13} = 0$

$\tan^2 \overline{\theta}_{12} = 0.42$, $\Delta \overline{m}^2_{21} = 8.2 \times 10^{-5}$ eV^2

Future ATM experiment can :

- Observe and measure deviations of θ_{23} from maximal mixing

  Complementary to T2K/NUMI

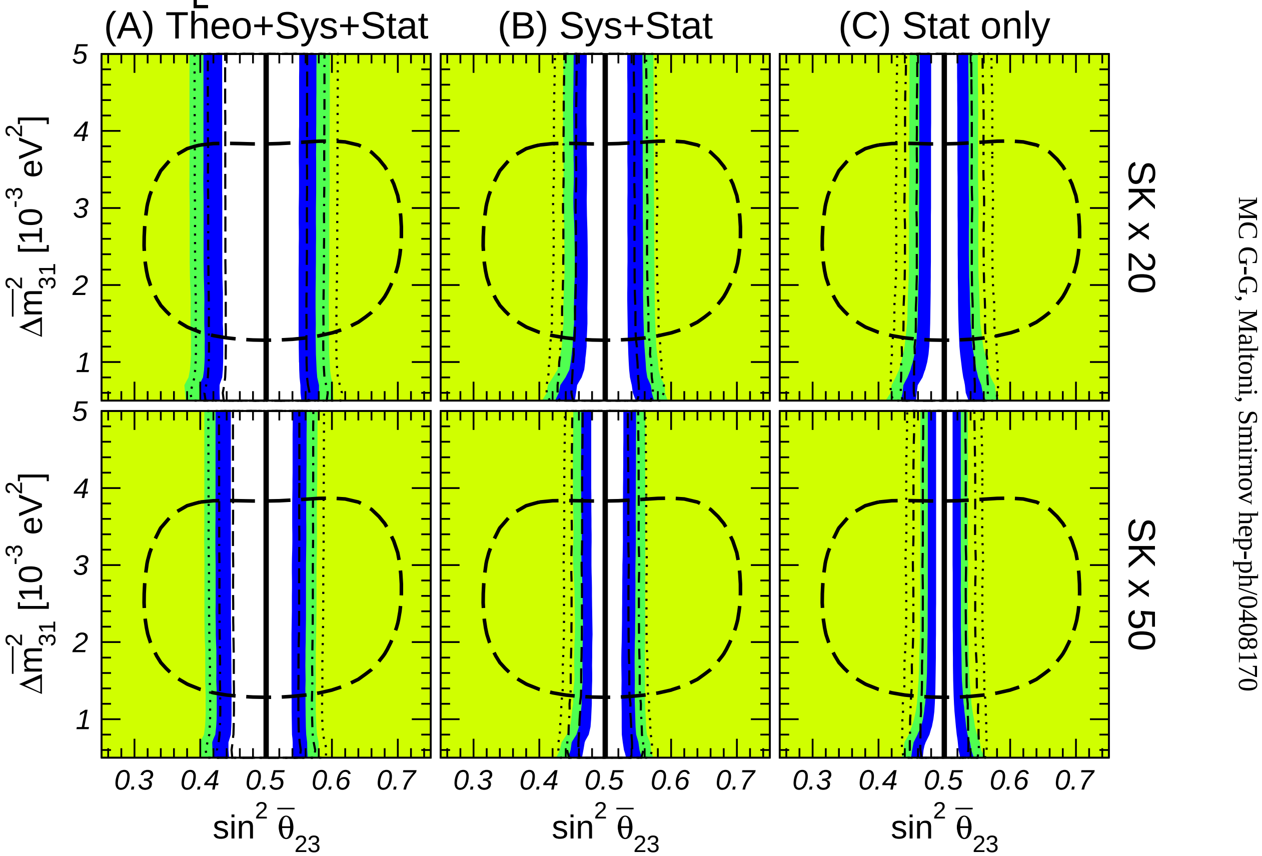
- Discriminate between the "light-side" and "dark-side" for θ_{23}

  Unique to ATM if θ_{13} very small

Future: Deviations from Maximal θ_{23}

a Gonzalez-Garcia

$$\Delta\chi^2_{\rm no-max}(\overline{\omega}) \equiv \min_{\Delta m^2_{31},\theta_{23}} \left[\chi^2_{\rm ATM+REAC}(\Delta m^2_{31},\ \theta_{23}=45^\circ\,|\,\overline{\omega}) - \chi^2_{\rm ATM+REAC}(\Delta m^2_{31},\ \theta_{23}\,|\,\overline{\omega}) \right]$$



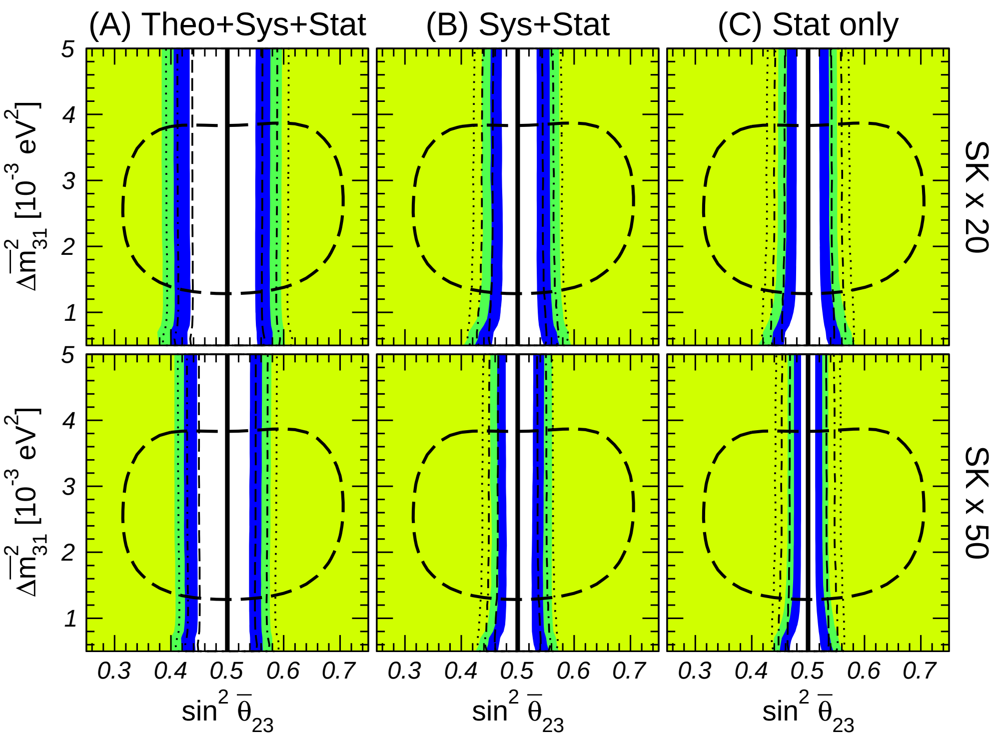
$|0.5 - \sin^2\overline{\theta}_{23}|$

	$\Delta\overline{m}^2_{21} = 8.2\times10^{-5}$ 90% C.L.	3σ	$\Delta\overline{m}^2_{21} = 0$ 90% C.L.	3σ
SK×50 (A)	[-0.070, 0.053]	[-0.094, 0.077]	[-0.064, 0.064]	[-0.087, 0.087]
SK×50 (B)	[-0.030, 0.040]	[-0.046, 0.061]	[-0.046, 0.046]	[-0.063, 0.063]
SK×50 (C)	[-0.021, 0.021]	[-0.037, 0.036]	[-0.042, 0.042]	[-0.058, 0.058]

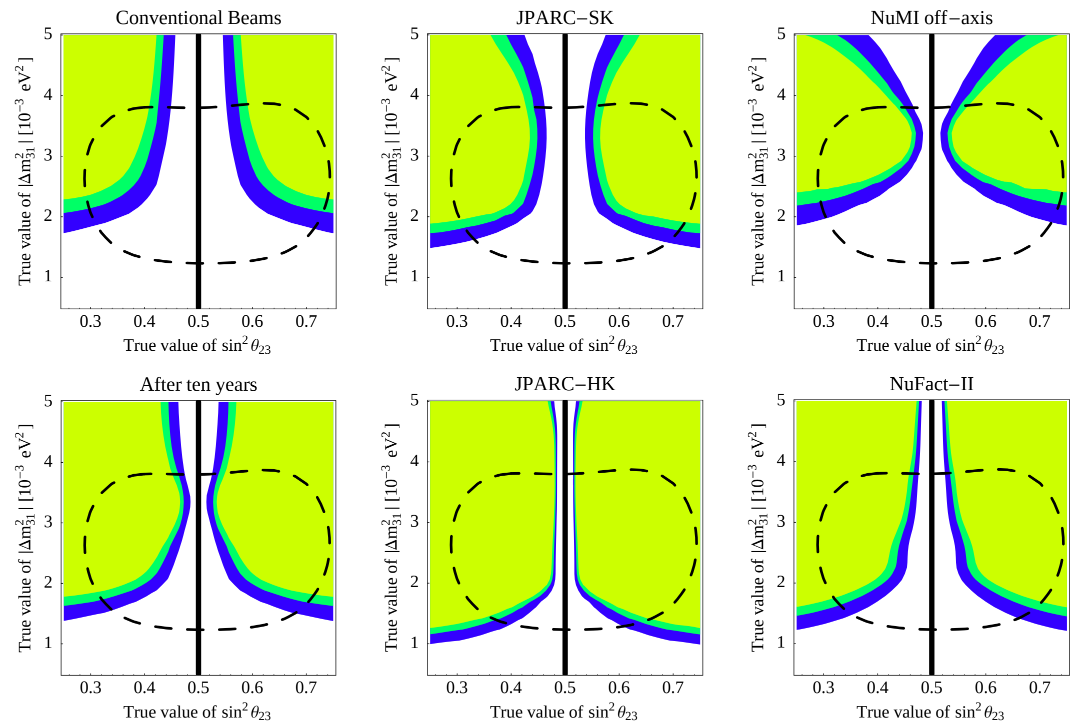
Concha Gonzalez-Garcia

Deviations from Maximal θ_{23}: Comparison to LBL

Atmospheric Neutrinos



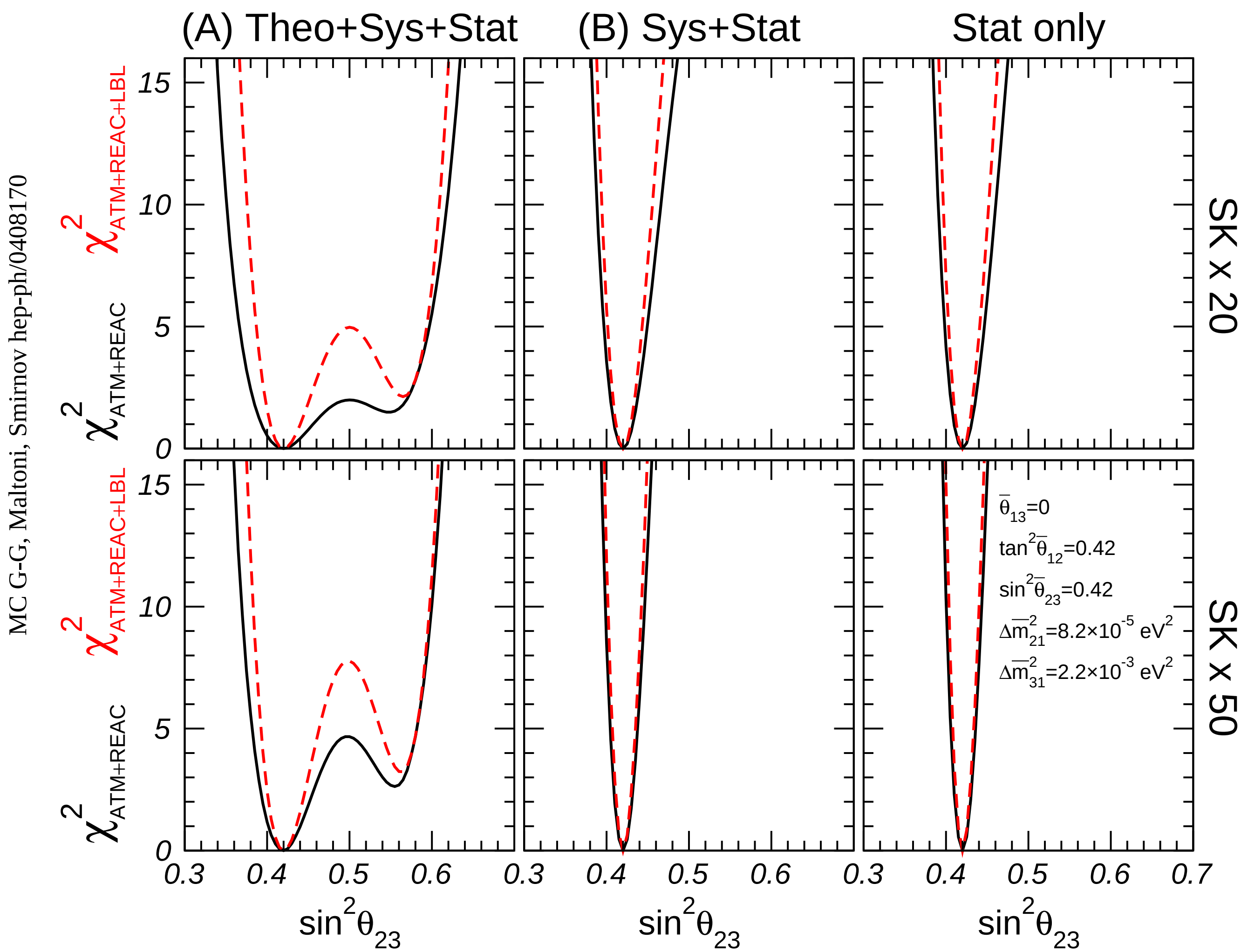
Long Baseline Experiments



Antusch, Huber, Kersten, Schwetz, Winter
hep-ph/0404268

Concha Gonzalez-Garcia

Future: Octant of θ_{23}



$\sin^2\overline{\theta}_{23} = 0.42$

$\overline{\theta}_{13} = 0$

$\tan^2\overline{\theta}_{12} = 0.42$

$\Delta\overline{m}^2_{21} = 8.2\times 10^{-5}\ \mathrm{eV}^2$

$\Delta\overline{m}^2_{31} = 2.2\times 10^{-3}\ \mathrm{eV}^2$

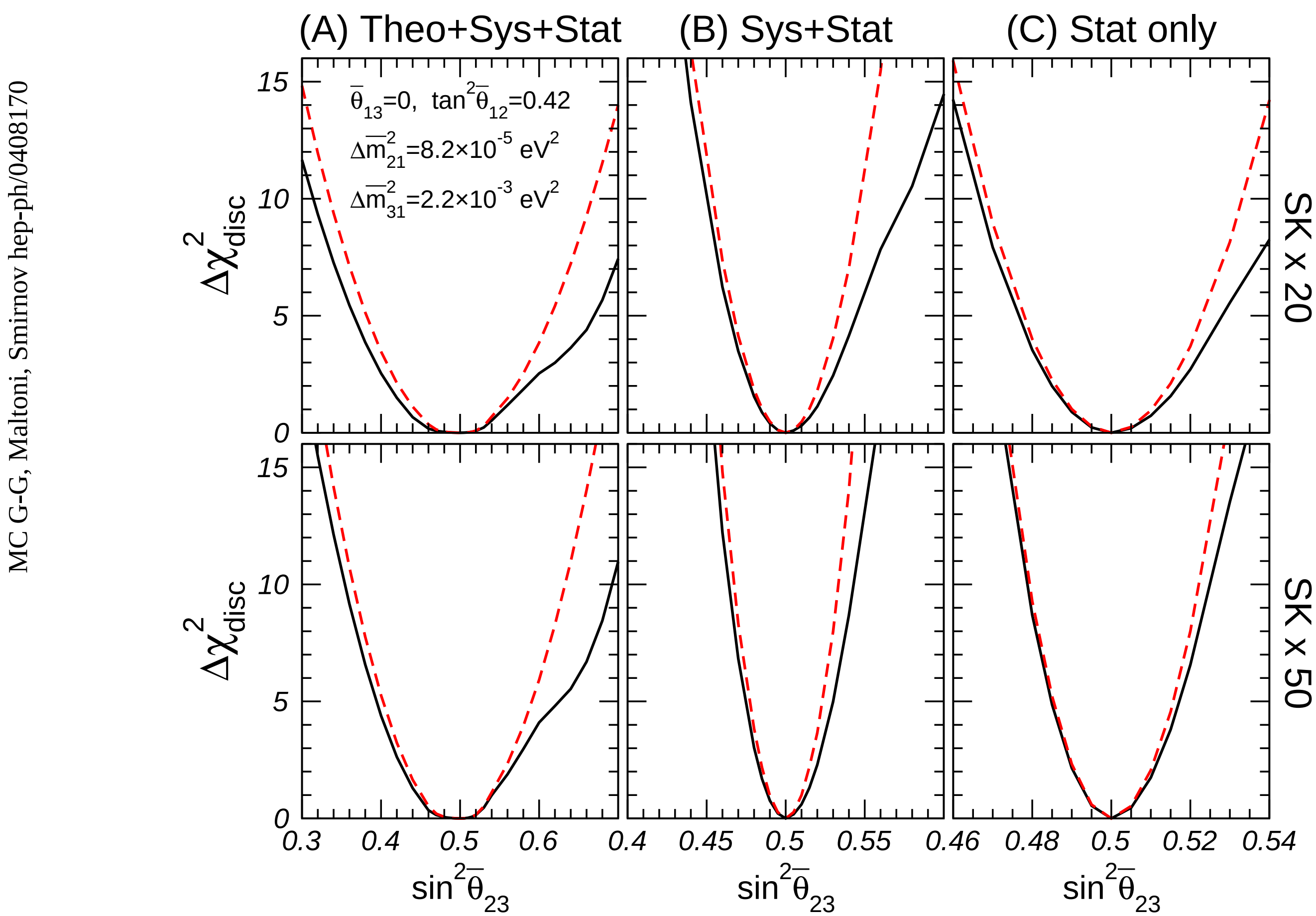
To quantify the octant discrimination we define:

$$\Delta\chi^2_{\rm disc}(\overline{\omega}) \equiv \min_{\Delta m^2_{31}}\left[\chi^2_{\rm atm+reac(+lbl)}(\Delta m^2_{31},\theta_{23}^{\rm false}\,|\,\overline{\omega})\right] - \min_{\Delta m^2_{31}}\left[\chi^2_{\rm atm+reac(+lbl)}(\Delta m^2_{31},\theta_{23}^{\rm true}\,|\,\overline{\omega})\right]$$

Concha Gonzalez-Garcia

Future: Octant of θ_{23}

$$\Delta\chi^2_{\rm disc}(\overline{\omega}) \equiv \min_{\Delta m^2_{31}} \left[\chi^2_{\rm atm+reac(+lbl)}(\Delta m^2_{31}, \theta_{23}^{\rm false}\,|\,\overline{\omega})\right] - \min_{\Delta m^2_{31}} \left[\chi^2_{\rm atm+reac(+lbl)}(\Delta m^2_{31}, \theta_{23}^{\rm true}\,|\,\overline{\omega})\right]$$



$\bar\theta_{13} = 0$

$\tan^2\bar\theta_{12} = 0.42$

$\Delta\overline{m}^2_{21} = 8.2\times10^{-5}\ {\rm eV}^2$

$\Delta\overline{m}^2_{31} = 2.2\times10^{-3}\ {\rm eV}^2$

For SK $\times$50 octant of θ_{23} can be determined at 90% CL if

$\sin^2\bar\theta_{23}$	$\leq 0.42\ [\bar\theta_{23} \leq 40°]$	or	$\sin^2\bar\theta_{23}$	$\geq 0.57\ [\bar\theta_{23} \geq 49°]$	(A)
$\sin^2\bar\theta_{23}$	$\leq 0.48\ [\bar\theta_{23} \leq 43°]$	or	$\sin^2\bar\theta_{23}$	$\geq 0.52\ [\bar\theta_{23} \leq 46°]$	(B)
$\sin^2\bar\theta_{23}$	$\leq 0.49\ [\bar\theta_{23} \leq 44.4°]$	or	$\sin^2\bar\theta_{23}$	$\geq 0.51\ [\bar\theta_{23} \leq 45.6°]$	(C)

Some New Physics in ATM ν -Oscillations

- 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 $\lambda = \frac{4\pi E}{\Delta m^2}$

- 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: $\bar{\nu}_L^{\alpha} b_{\mu}^{\alpha\beta} \gamma_\mu \nu_L^{\beta} \Rightarrow E_i = \frac{m_i^2}{2p} \pm b_i$

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

Non-standard ν interactions in matter: Wolfenstein 78

$$G_F \varepsilon_{\alpha\beta} (\overline{\nu_\alpha} \gamma^\mu \nu_\beta)(\overline{f} \gamma_\mu f)$$

$$\lambda = \frac{2\pi}{2\sqrt{2} G_f \; N_f \; \sqrt{\varepsilon_{\alpha\beta}^2 + (\varepsilon_{\alpha\alpha} - \varepsilon_{\beta\beta})^2/4}}$$

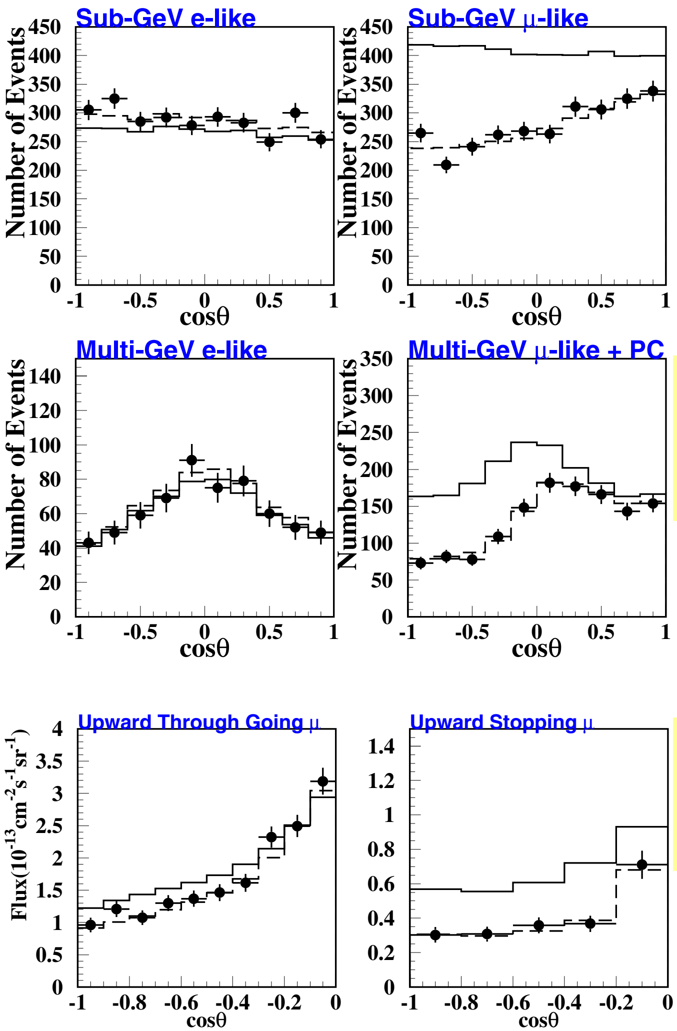
In general $\lambda = \beta E^{-n}$

$n = -1$ oscillations

$n = 1$ Viol Equiv. Principle

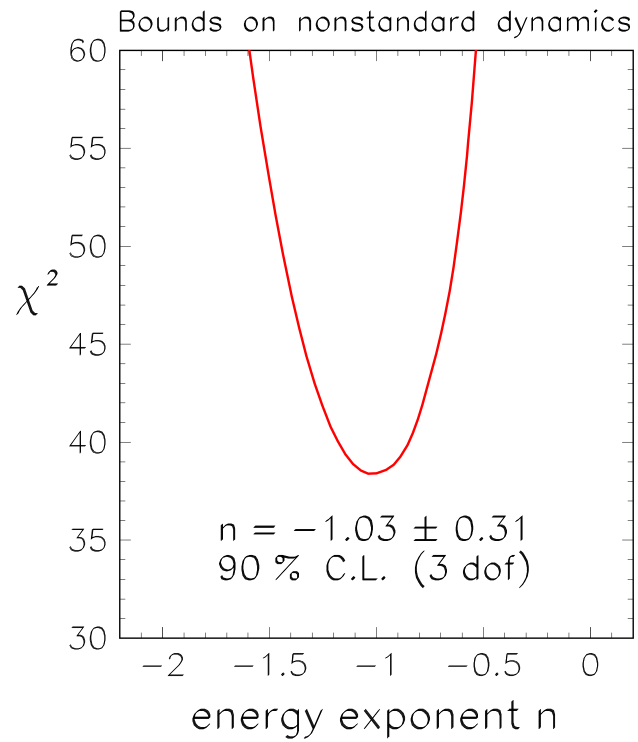
$n = 1$ Viol Lorentz invariance

Fit : $n = -1.03 \pm 0.31$ 90%CL



$\rightarrow$ Deficit grows with L

$\rightarrow$ Decreases with E



Fogli, Lisi and Marrone hep-ph/0105139

ATM ν's: Subdominant NP Effects

Fogli, Lisi and Marrone 01; MCG-G, M. Maltoni hep-ph/0404085

$$\mathbf{H}_\pm \equiv \frac{\Delta m^2}{4E} \mathbf{U}_\theta \begin{pmatrix} -1 & 0 \\ 0 & 1 \end{pmatrix} \mathbf{U}_\theta^\dagger + \sigma_n^\pm \frac{\Delta\delta_n \, E^n}{2} \mathbf{U}_{\xi_n} \begin{pmatrix} -1 & 0 \\ 0 & 1 \end{pmatrix} \mathbf{U}_{\xi_n}^\dagger \,,$$

For Violation of Equivalence Principle

$$\Delta\delta_1 = 2|\phi|(\gamma_1 - \gamma_2) \equiv 2|\phi|\Delta\gamma \,, \qquad \sigma_1^+ = \sigma_1^- \,.$$

For Violation of Lorentz Invariance:

$$\Delta\delta_1 = (c_1 - c_2) \equiv \Delta v \,, \qquad \sigma_1^+ = \sigma_1^- \,.$$

For Coupling to a space-time torsion field

$$\Delta\delta_0 = Q(k_1 - k_2) \equiv Q\,\Delta k \,, \qquad \sigma_0^+ = \sigma_0^- \,.$$

For Violation of Lorentz Invariance via CPT violation

$$\Delta\delta_0 = b_1 - b_2 \equiv \Delta b \,, \qquad \sigma_0^+ = -\sigma_0^-$$

For NSNI

$$\Delta\delta_0 = 2\sqrt{2}\, G_F\, N_f(\vec{r}) \sqrt{\varepsilon_{\mu\tau}^2 + \frac{(\varepsilon_{\mu\mu} - \varepsilon_{\tau\tau})^2}{4}} \qquad \sin^2 2\xi = \frac{\varepsilon_{\mu\tau}}{\sqrt{\varepsilon_{\mu\tau}^2 + \frac{(\varepsilon_{\mu\mu} - \varepsilon_{\tau\tau})^2}{4}}} \qquad \sigma_0^+ = -\sigma_0^-$$

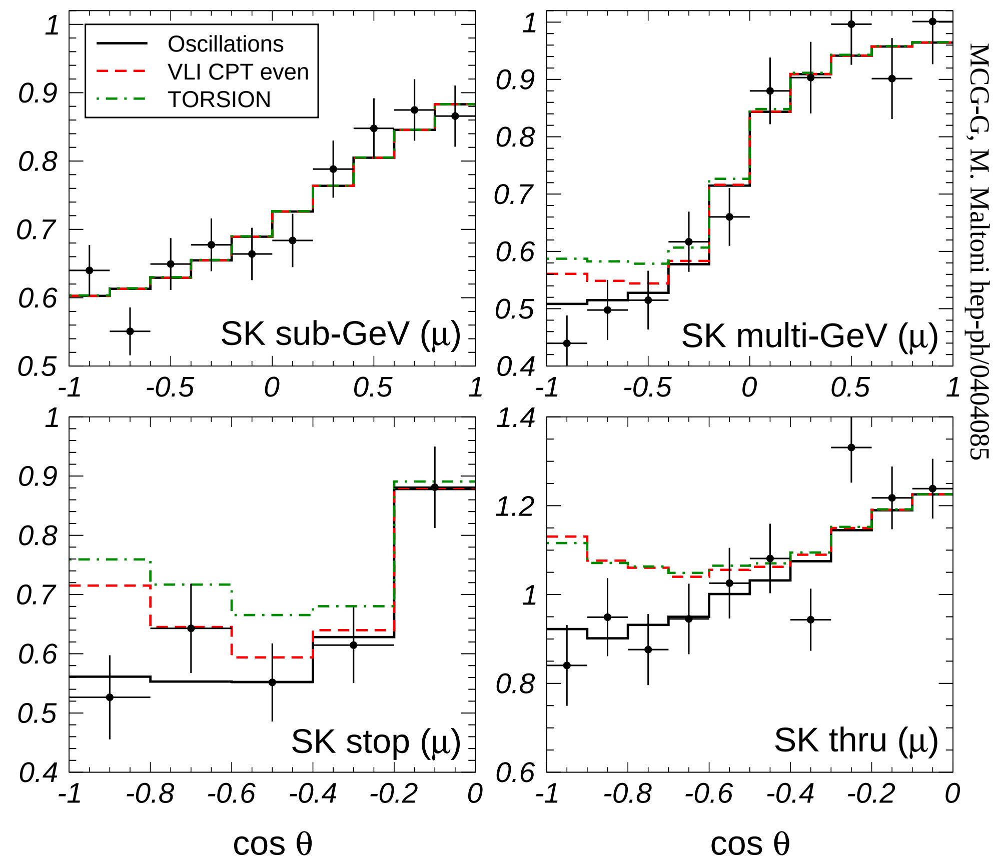
ATM ν's: Subdominant NP Effects

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

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

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

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

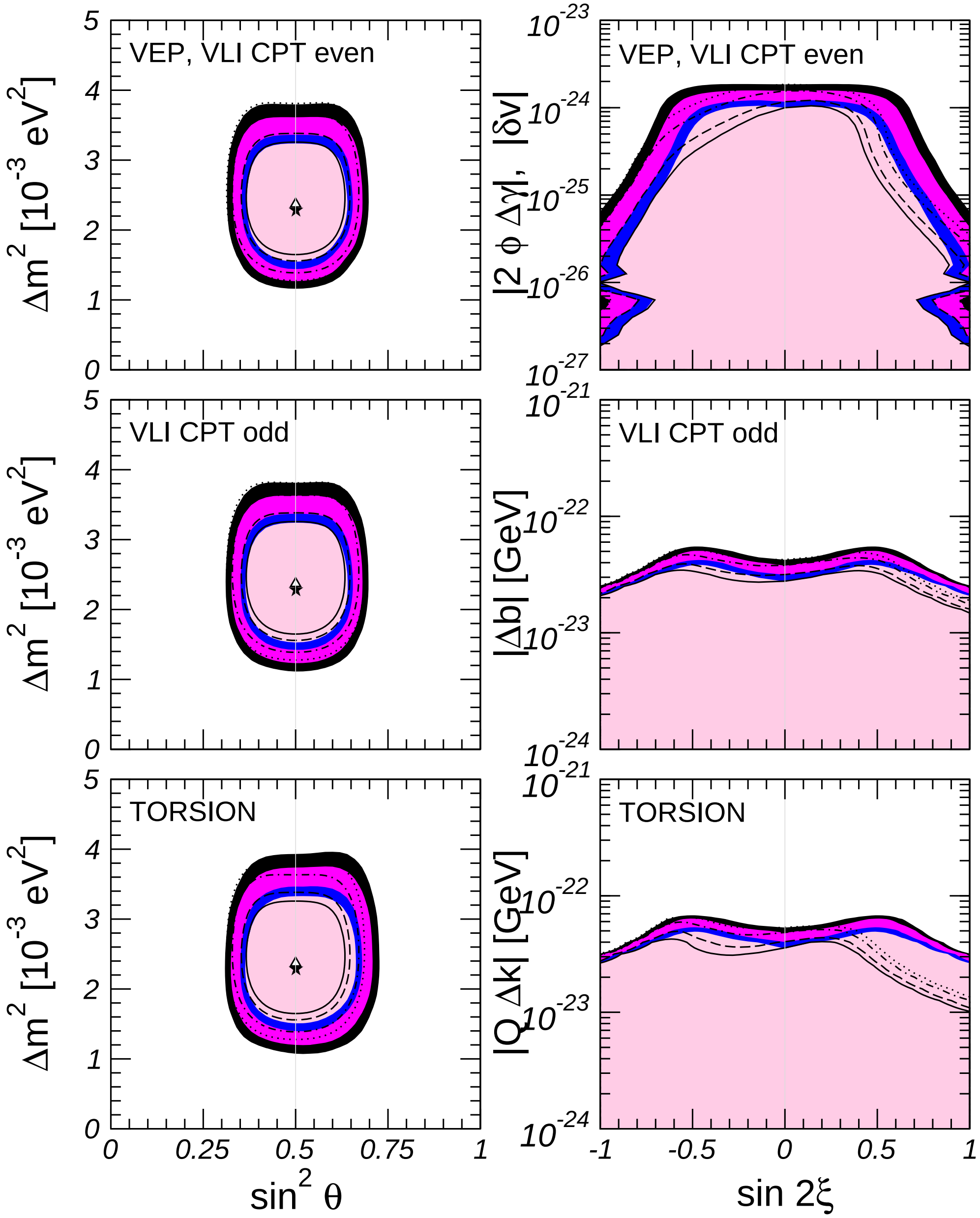


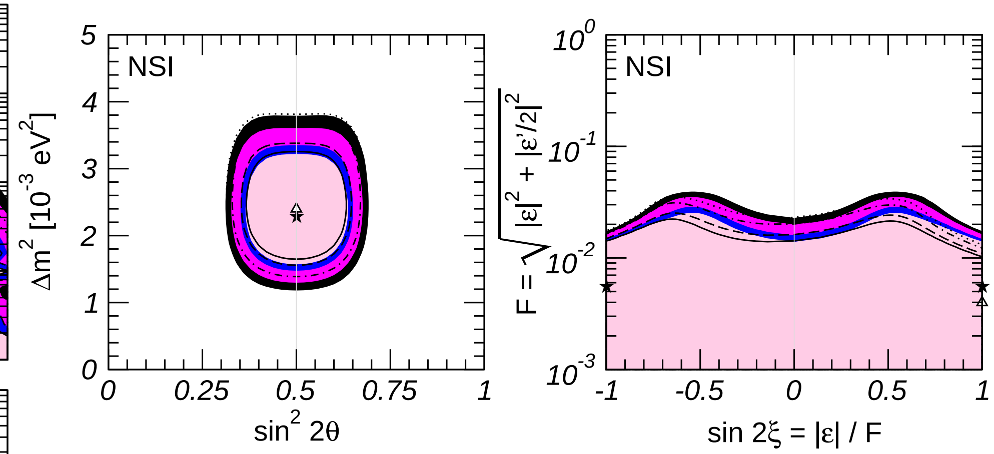
- Questions:
  - Do these effects affect our determination of oscillation parameters?
  - Can we limit these effects?

Concha Gonzalez-Garcia

ATM ν's: Subdominant NP Effects

MCG-G, M. Maltoni hep-ph/0404085





At 90% CL:

$$\frac{|\Delta c|}{c} \leq 8.1 \times 10^{-25}$$

$$|\phi\,\Delta\gamma| \leq 4.0 \times 10^{-25}$$

$$|\Delta b| \leq 3.2 \times 10^{-23}\ \text{GeV}$$

$$|Q\,\Delta k| \leq 4.0 \times 10^{-23}\ \text{GeV}$$

$$|\varepsilon_{\mu\mu} - \varepsilon_{\tau\tau}| \leq 0.013$$

$$|\varepsilon_{\mu\tau}| \leq 0.034$$

Comment on Theoretical Uncertainties

- Flux Uncertainties:

(1) Total normalization: $\sigma_{\rm norm} = 20\%$

(2) "Tilt" error

$\Phi_\delta(E) = \Phi_0(E)\left(\frac{E}{E_0}\right)^\delta$

$\sigma_\delta = 5\%$ $E_0 = 2$ GeV

(3) ν_μ/ν_e ratio: $\sigma_{\mu/e} = 5\%$

E independent for contained events

(4) Zenith angle dependence:

$\sigma_{\rm zen,i} = 5\%\langle\cos\theta\rangle_i$

- Cross Section Uncertainties:

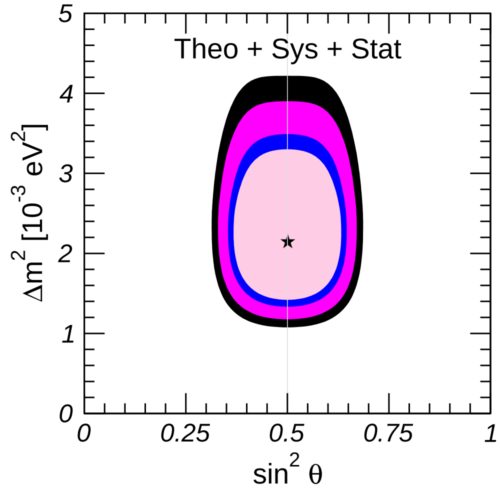
(5) $\sigma_{\rm norm}^{\sigma{\rm QE}} = 15\%$

(6) $\sigma_{\rm norm}^{\sigma 1\pi} = 15\%$,

(7) $\sigma_{\rm norm}^{\sigma{\rm DIS}} = 15\%$ for contained

$\sigma_{\rm norm}^{\sigma{\rm DIS}} = 10\%$ for upward-going μ

(8)–(10) $\sigma_{i,\nu_\mu}^{{\rm QE},1\pi,{\rm DIS}}/\sigma_{i,\nu_e}^{{\rm QE},1\pi,{\rm DIS}} = 0.1$–$1\%$



Comment on Theoretical Uncertainties

- Flux Uncertainties:

(1) Total normalization: $\sigma_{\rm norm} = 20\%$

(2) "Tilt" error

$\Phi_\delta(E) = \Phi_0(E)\left(\frac{E}{E_0}\right)^\delta$

$\sigma_\delta = 5\%$ $E_0 = 2$ GeV

(3) ν_μ/ν_e ratio: $\sigma_{\mu/e} = 5\%$

E independent for contained events

(4) Zenith angle dependence:

$\sigma_{\rm zen,i} = 5\% \langle \cos\theta \rangle_i$

- Cross Section Uncertainties:

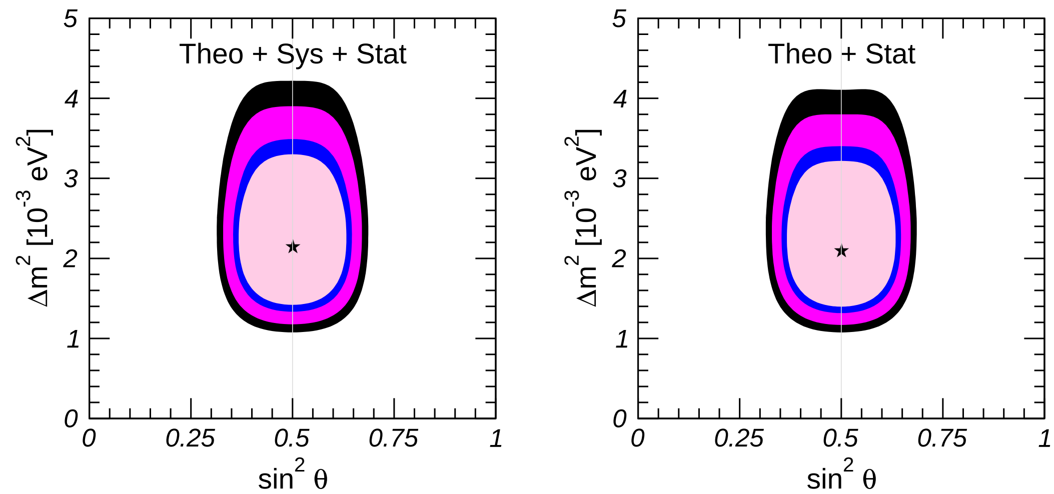
(5) $\sigma_{\rm norm}^{\sigma_{\rm QE}} = 15\%$

(6) $\sigma_{\rm norm}^{\sigma_{1\pi}} = 15\%$,

(7) $\sigma_{\rm norm}^{\sigma_{\rm DIS}} = 15\%$ for contained

$\sigma_{\rm norm}^{\sigma_{\rm DIS}} = 10\%$ for upward-going μ

(8)–(10) $\sigma_{i,\nu_\mu}^{\rm QE,1\pi,DIS}/\sigma_{i,\nu_e}^{\rm QE,1\pi,DIS} = 0.1$–$1\%$



Comment on Theoretical Uncertainties

- Flux Uncertainties:

(1) Total normalization: $\sigma_{\rm norm} = 20\%$

(2) "Tilt" error

$\Phi_\delta(E) = \Phi_0(E)\left(\frac{E}{E_0}\right)^\delta$

$\sigma_\delta = 5\%\ E_0 = 2$ GeV

(3) ν_μ/ν_e ratio: $\sigma_{\mu/e} = 5\%$

E independent for contained events

(4) Zenith angle dependence:

$\sigma_{\rm zen,i} = 5\% \langle \cos\theta \rangle_i$

- Cross Section Uncertainties:

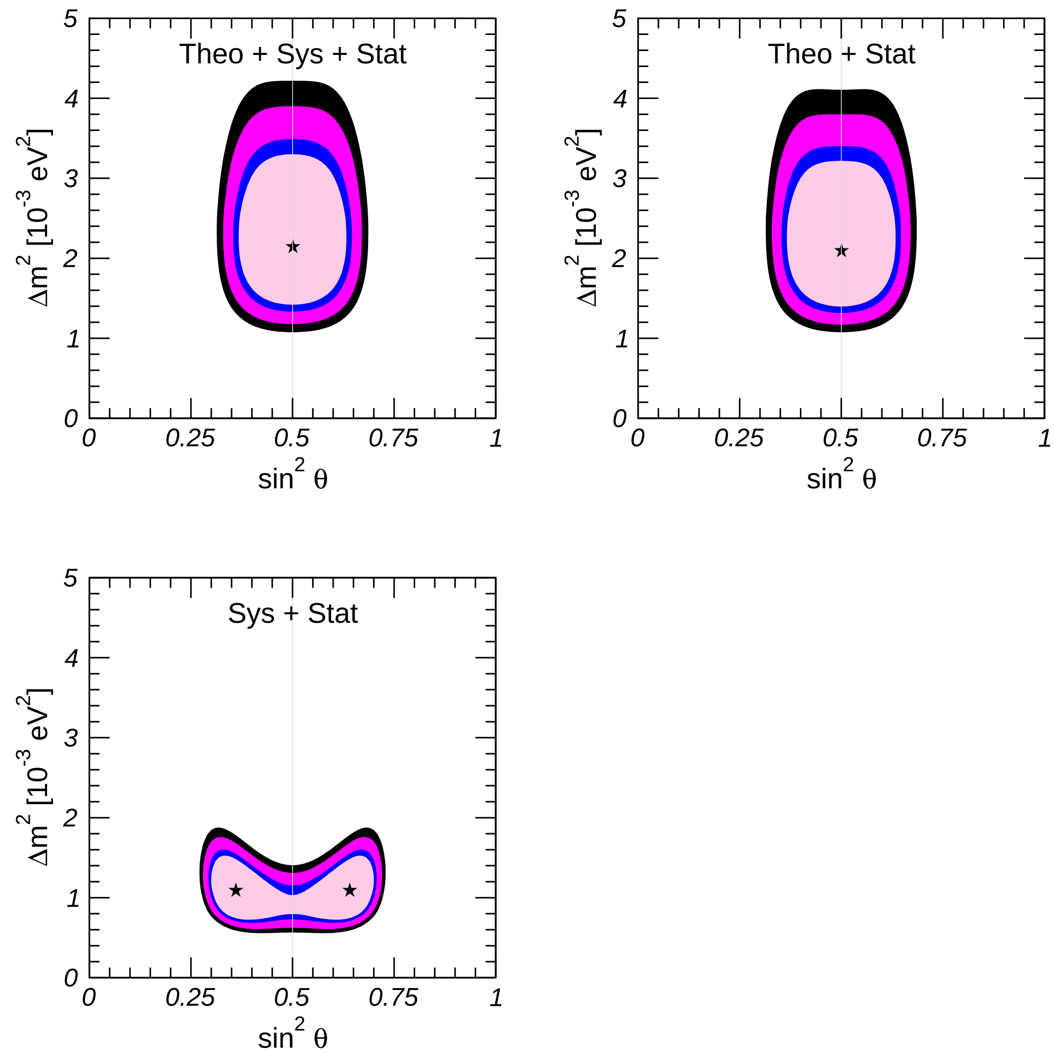
(5) $\sigma_{\rm norm}^{\sigma{\rm QE}} = 15\%$

(6) $\sigma_{\rm norm}^{\sigma 1\pi} = 15\%$,

(7) $\sigma_{\rm norm}^{\sigma{\rm DIS}} = 15\%$ for contained

$\sigma_{\rm norm}^{\sigma{\rm DIS}} = 10\%$ for upward-going μ

(8)–(10) $\sigma_{i,\nu_\mu}^{\rm QE,1\pi,DIS}/\sigma_{i,\nu_e}^{\rm QE,1\pi,DIS} = 0.1$–$1\%$



Concha Gonzalez-Garcia

Comment on Theoretical Uncertainties

- <u>Flux Uncertainties:</u>

(1) Total normalization: $\sigma_{\rm norm} = 20\%$

(2) "Tilt" error

$\Phi_\delta(E) = \Phi_0(E)\left(\frac{E}{E_0}\right)^\delta$

$\sigma_\delta = 5\%\ E_0 = 2$ GeV

(3) ν_μ/ν_e ratio: $\sigma_{\mu/e} = 5\%$

E independent for contained events

(4) Zenith angle dependence:

$\sigma_{\rm zen,i} = 5\%\langle\cos\theta\rangle_i$

- <u>Cross Section Uncertainties:</u>

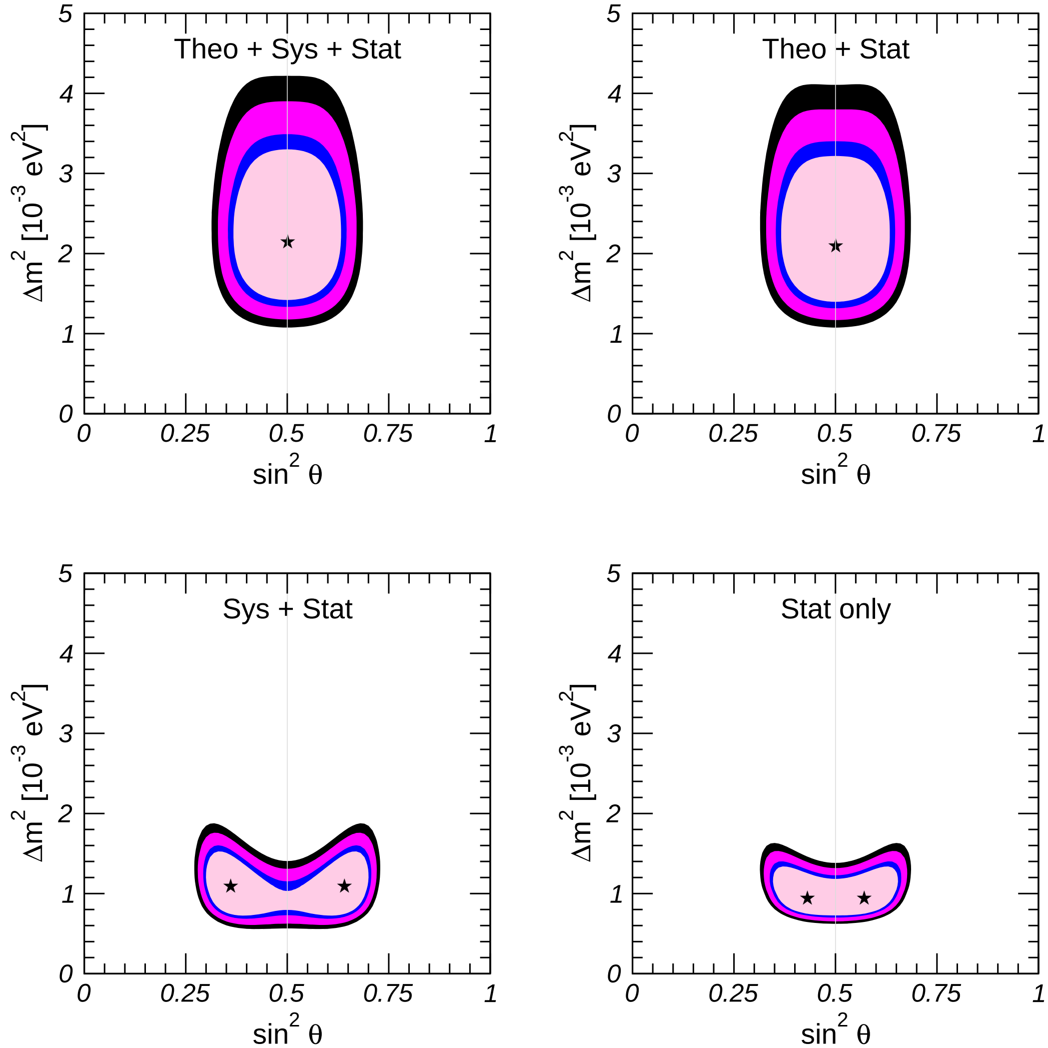
(5) $\sigma^{\sigma{\rm QE}}_{\rm norm} = 15\%$

(6) $\sigma^{\sigma 1\pi}_{\rm norm} = 15\%$,

(7) $\sigma^{\sigma{\rm DIS}}_{\rm norm} = 15\%$ for contained

$\sigma^{\sigma{\rm DIS}}_{\rm norm} = 10\%$ for upward-going μ

(8)–(10) $\sigma^{{\rm QE},1\pi,{\rm DIS}}_{i,\nu_\mu}/\sigma^{{\rm QE},1\pi,{\rm DIS}}_{i,\nu_e} = 0.1$–$1\%$



Comment on Theoretical Uncertainties

- Flux Uncertainties:
  - Total normalization:
  - "Tilt" error
  - ν_μ/ν_e ratio
  - Zenith angle dependence

- Cross Section Uncertainties:
  - $\sigma_{\rm norm}^{\sigma_{\rm QE}}$
  - $\sigma_{\rm norm}^{\sigma_{1\pi}}$,
  - $\sigma_{\rm norm}^{\sigma_{\rm DIS}}$
  - $\sigma_{i,\nu_\mu}^{\rm QE,1\pi,DIS}/\sigma_{i,\nu_e}^{\rm QE,1\pi,DIS}$

- Question/"plea" to flux/cross-section experts:

(1) Is this the most general characterization of uncertainties?

(2) Is it possible to obtain the uncertainties as follows?

– Characterize flux (cross-section) *independent input parameters* $X_i^{\rm flux,cs}$ and their uncertainties $\Delta X_i^{\rm flux,cs}$

– Modify input parameter $X_i \to X_i + \Delta X_i$

– Give $\frac{d\Phi(E_\nu)}{d\Delta X_i^{\rm flux}}$ or $\frac{d\sigma(E_\nu)}{d\Delta X_i^{\rm cs}}$

Summary

- High Statistics Atmospheric Neutrino Experiment can give important information on:
  - Deviation of θ_{23} from Maximal Mixing

    From dominant and subdominan Δm^2_{21} and θ_{13} effects
  - Octant of θ_{23}

    From subdominant Δm^2_{21} Effects
  - Mass Ordering

    From subdominant θ_{13} effects if large
  - New Physics effects in neutrino propagation
  - In principle also CP violation

    From interference of subdominat Δm^2_{21} and θ_{13} effects

Summary

- High Statistics Atmospheric Neutrino Experiment can give important information on:
  - Deviation of θ_{23} from Maximal Mixing

    From dominant and subdominan Δm^2_{21} and θ_{13} effects
  - Octant of θ_{23}

    From subdominant Δm^2_{21} Effects
  - Mass Ordering

    From subdominant θ_{13} effects if large
  - New Physics effects in neutrino propagation
  - In principle also CP violation

    From interference of subdominat Δm^2_{21} and θ_{13} effects
- Lots of work still to be done in the characterization of the uncertainties

That's what we are here for!