Detecting tau Neutrinos at Ultahigh Energies

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Two interesting topics

- The discovery of ultra-high energy cosmic neutrinos opens a unique window to test neutrino properties and mixings at high energies. In these experiments the lepton flavor composition of the flux is essential.
- The presence or not of new sterile neutrino states (Majorana !) at a mass of 1.0 eV from the reactor experiments

Summary

- Why search for tau neutrinos
- Results so far
- Expected distributions

$$\nu_\mu + N \to \mu + X,$$

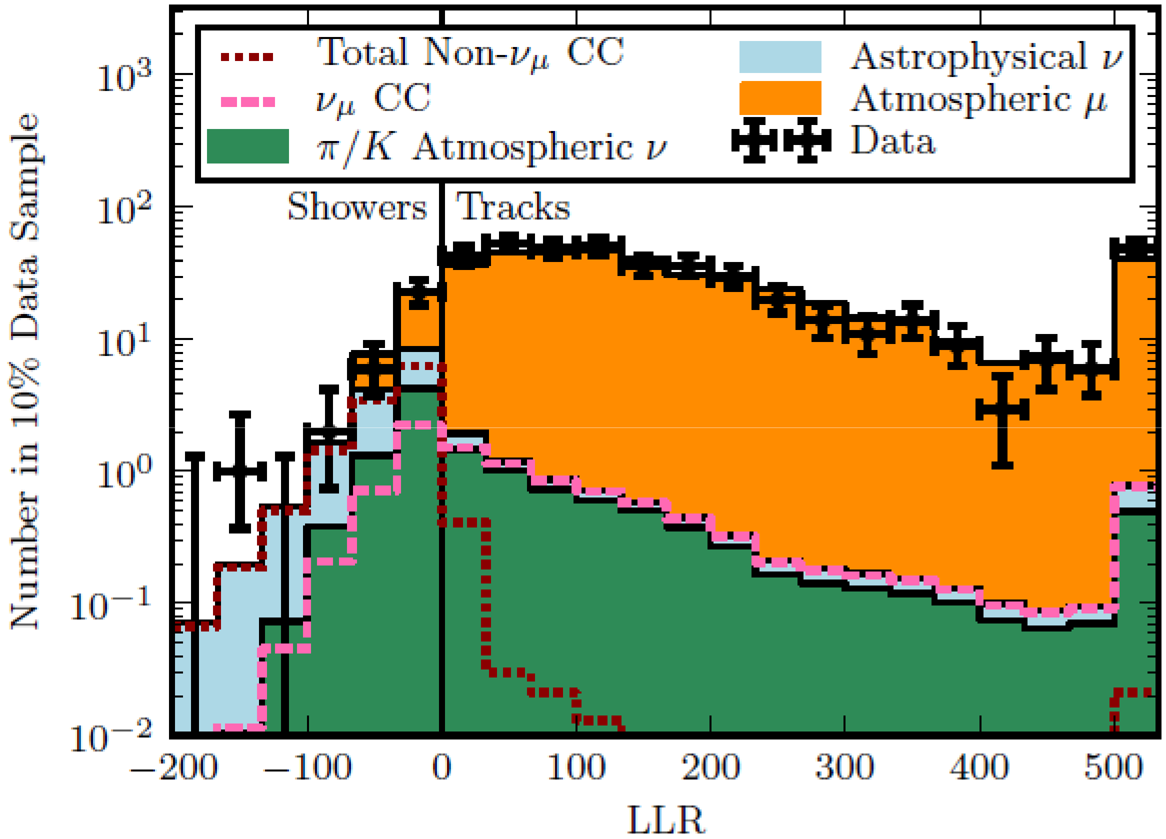
$$\nu_\tau + N \to \tau + X$$

$$\mu + \nu_\tau + \bar{\nu}_\mu,$$

- $\nu(e):\nu(\mu):\nu(\tau) = 1:2:0$ from pion decays
- $\nu(e):\nu(\mu):\nu(\tau) = 0:1:0$ when in interstellar medium the energy of particles is decreased
- Mixing brings the fluxes on earth to

  $1/3:1/3:1/3$

Arxiv:1502.03376 IceCube



Arxiv:1507.03991 IceCube

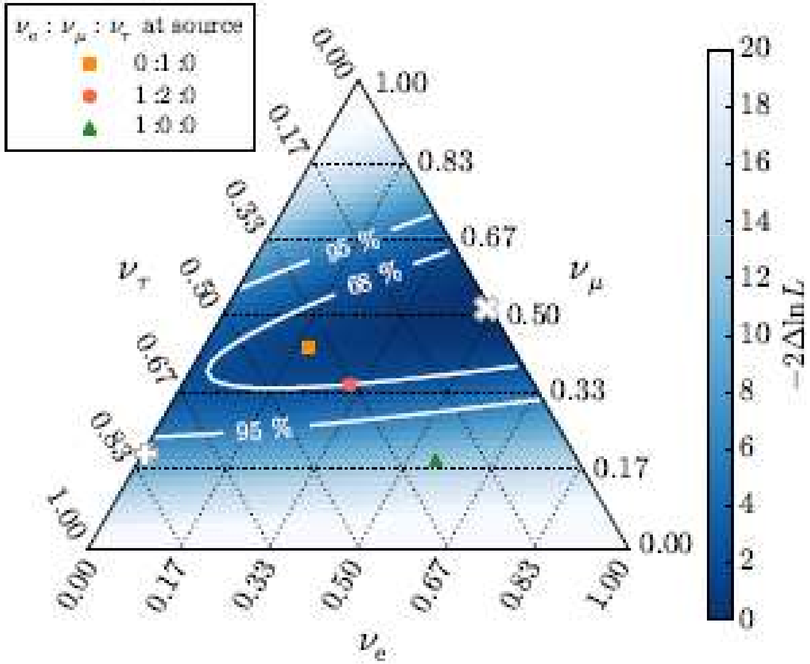


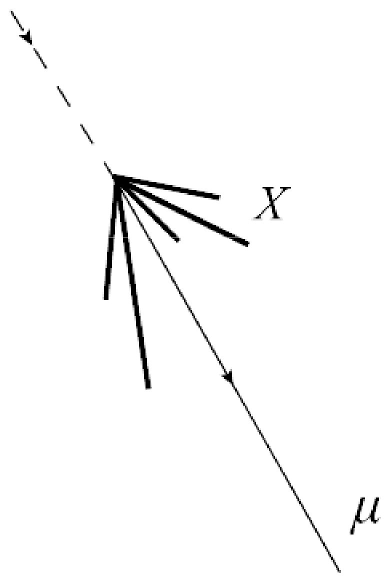
Figure 8. Profile likelihood scan of the flavor composition at Earth. Each point in the triangle corresponds to a ratio

$$\nu_\mu + N \to \mu + X,$$

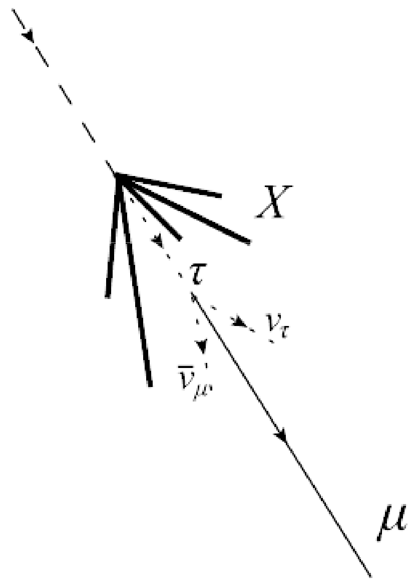
$$\nu_\tau + N \to \tau + X$$

$$\mu + \nu_\tau + \bar{\nu}_\mu,$$

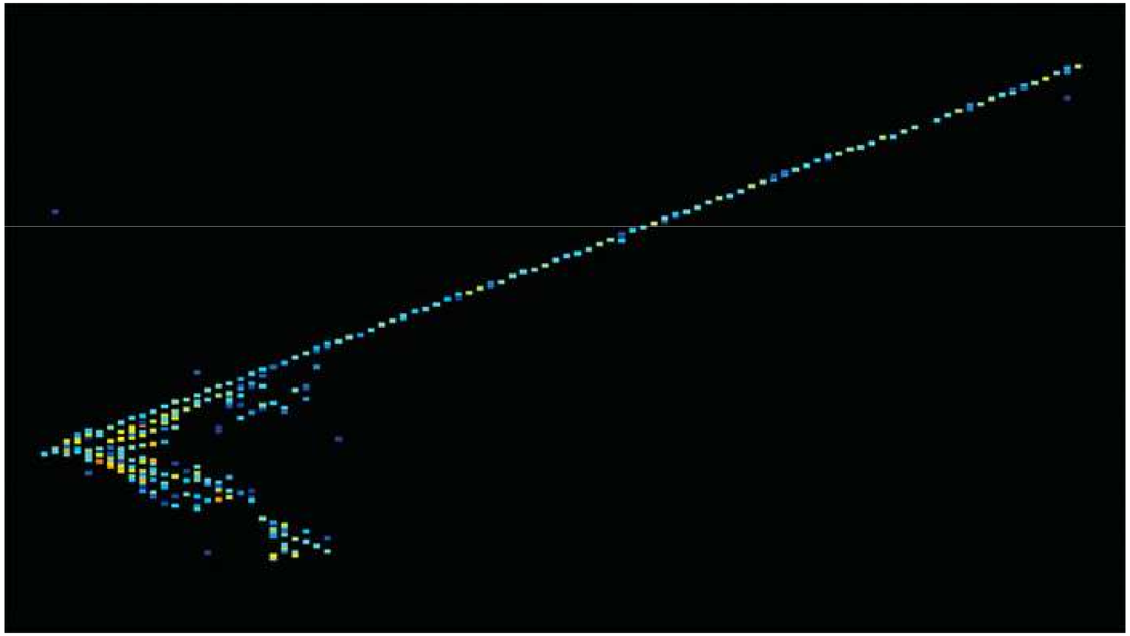
Schematic picture of neutrinos events



(a)



(b)



Branching ratio 17%

$$r_l = \frac{E_X}{E_l} \quad (0 \leq r_l \leq \infty)$$

$$y' = \frac{E_X}{E_\mu + E_X} = \frac{r_\mu}{1 + r_\mu}.$$

$x = Q^2/2Mv$, $y = v/E$

$$\frac{d^2\sigma}{dxdy} = \frac{2G_F^2 M E_\nu}{\pi}\left(\frac{M_W^2}{Q^2 + M_W^2}\right)^2 \left[xq(x, Q^2) + x\bar{q}(x, Q^2)(1-y)^2\right]$$

$$\frac{d^2\sigma}{dxdy} = \frac{2G_F^2 M E_\nu}{\pi} \left[xq(x) + x\bar{q}(x)(1-y)^2 \right] .$$

For cross sections use point interactions with known pdf

$$\frac{d\sigma}{dy} = \frac{2G_F^2 M E_\nu}{\pi}\left[Q + \bar{Q}(1-y)^2\right]$$

$$\frac{d\bar{\sigma}}{dy} = \frac{2G_F^2 M E_\nu}{\pi}\left[\bar{Q} + Q(1-y)^2\right]$$

$$\overset{(-)}{Q} = \int_0^1 x \overset{(-)}{q}(x)\,dx.$$

I. Alikhanov and EAP arxiv:1605.04864

$$\nu_\mu + N \to \mu + X,$$

$$\nu_\tau + N \to \tau + X$$

$$\mu + \nu_\tau + \bar{\nu}_\mu,$$

$$\frac{d\sigma^{(\tau)}}{dE_\mu} = \int\limits_{E_\mu}^{E_\nu} \frac{d\sigma}{dE_\tau} \frac{1}{\Gamma_{\tau\to\mathrm{all}}} \frac{d\Gamma_{\tau\to\mu+\nu_\tau+\bar{\nu}_\mu}}{dE_\mu} dE_\tau ,$$

$d\Gamma$

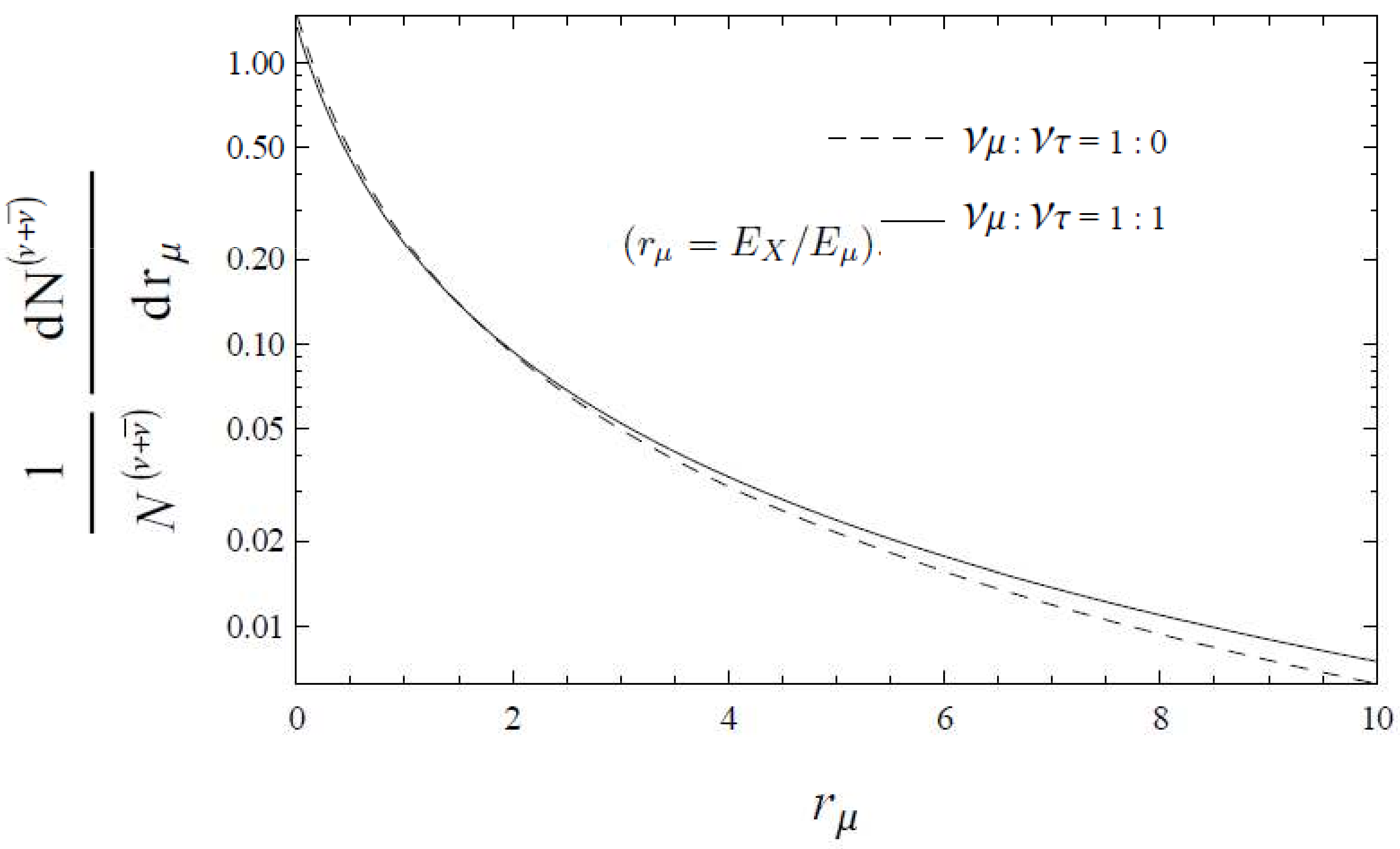
$$\frac{d\sigma^{(\tau)}}{dr_\mu} = \frac{1}{r_\mu^2}\int\limits_0^{r_\mu} \frac{r_\tau}{1+r_\tau}\frac{d\sigma}{dr_\tau} f\left(\frac{1}{1+r_\tau}, \zeta\right) dr_\tau,$$

$$\frac{d\sigma^{(\tau)}}{dr_\mu} = \frac{G^2 M E_\nu}{9\pi} \frac{\mathrm{Br}}{r_\mu^5 (1+r_\mu)^2} \Big\{ 96\left(Q+\bar{Q}\right) r_\mu + \left(306\,Q + 198\,\bar{Q}\right) r_\mu^2 + \left(275\,Q + 113\,\bar{Q}\right) r_\mu^3 + \left(16\,Q + 10\,\bar{Q}\right) r_\mu^4 - \left(49\,Q - 5\,\bar{Q}\right) r_\mu^5 - 6\,(1+r_\mu)^2 \left[16(Q+\bar{Q}) + 9(3\,Q+\bar{Q})\, r_\mu - 5\,Q\, r_\mu^3\right] \ln(1+r_\mu) \Big\}\,.$$

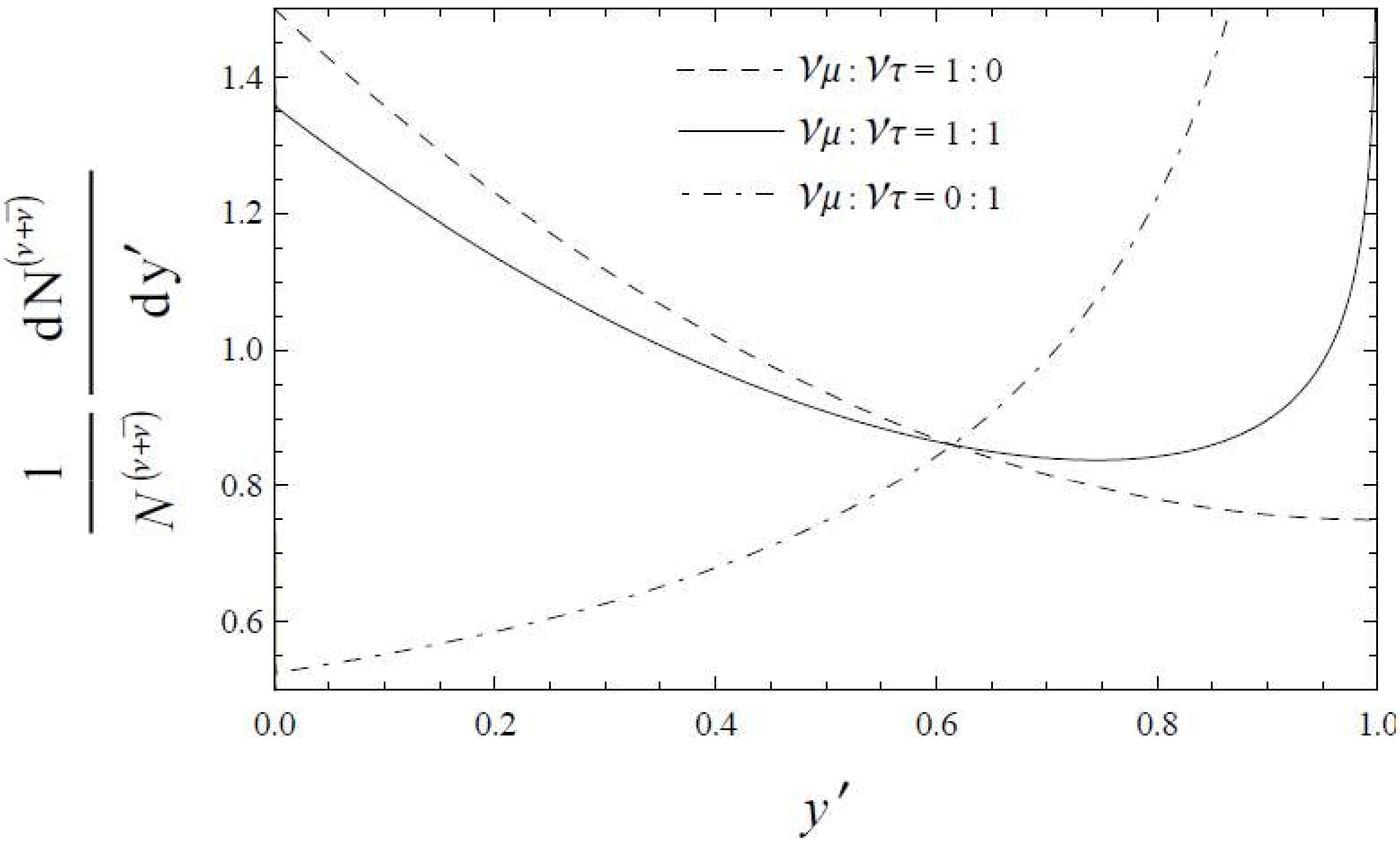
$$
\begin{aligned}
\frac{1}{N^{(\nu+\bar{\nu})}}\frac{dN^{(\nu+\bar{\nu})}}{dr_\mu} &= \frac{1}{12(1+\mathrm{Br})r_\mu^5(1+r_\mu)^4} \\
&\times \left[3\mathrm{Br}\left(5r_\mu^3-36r_\mu-32\right)(1+r_\mu)^4\log(1+r_\mu)\right. \\
\mathrm{Br}\left(22r_\mu^5-13r_\mu^4-194r_\mu^3-252r_\mu^2-96r_\mu\right)&(1+r_\mu)^2+9r_\mu^5\left(r_\mu^2+2r_\mu+2\right)\left.\right].
\end{aligned}
$$

Equal fluxes on Earth of neutrinos and antineutrinos

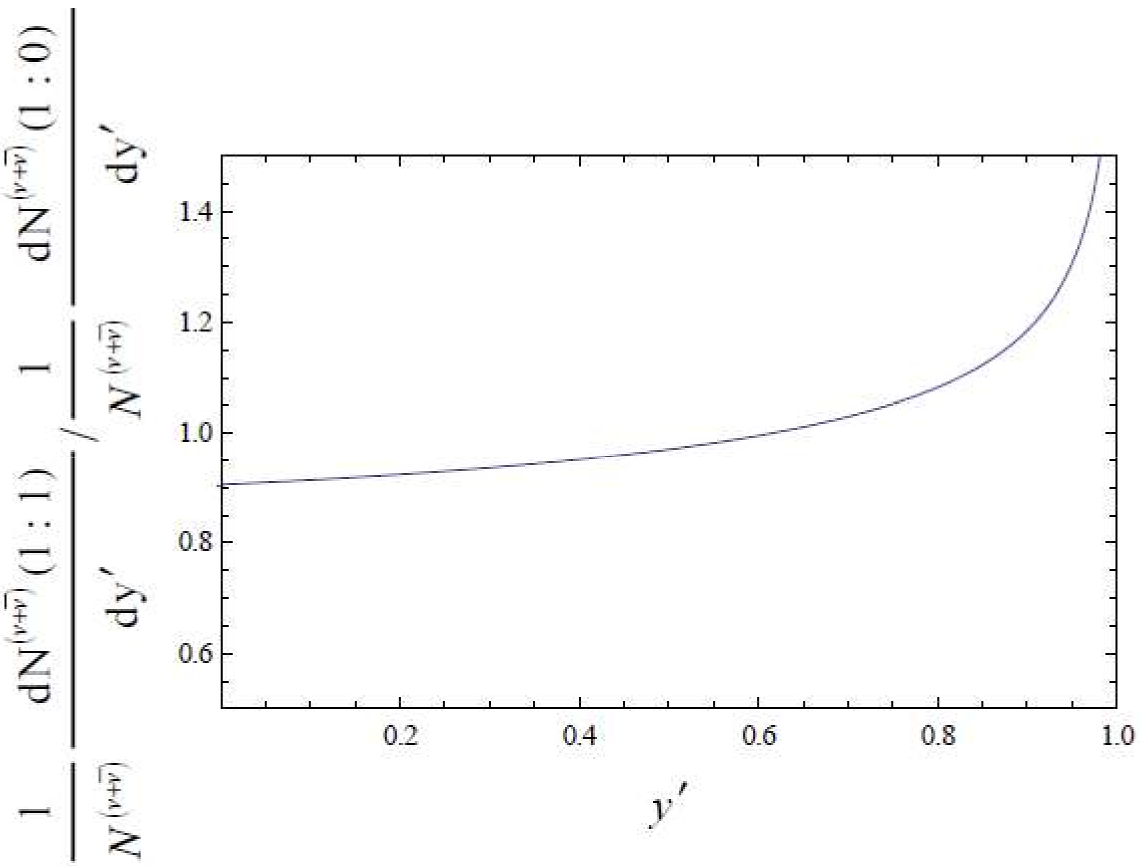
$$
\begin{aligned}
\frac{1}{N^{(\nu+\bar{\nu})}}\frac{dN^{(\nu+\bar{\nu})}}{dy'} &= \frac{1}{12(1+\mathrm{Br})y'^5} \\
&\times \left[\mathrm{Br}\left(3y'^5 - 3y'^4 + 14y'^3 - 132y'^2 + 96y'\right)\right. \\
&\left. -3\mathrm{Br}\left(y'^3 - 24y'^2 + 60y' - 32\right)\log\left(1-y'\right) + 9y'^5\left(y'^2 - 2y' + 2\right)\right].
\end{aligned}
$$



1.00
0.50
0.20
0.10
0.05
0.02
0.01
0
2
4
6
8
10
$\nu_\mu : \nu_\tau = 1:0$
$\nu_\mu : \nu_\tau = 1:1$
$(r_\mu = E_X/E_\mu)$
$\frac{1}{N^{(\nu+\bar{\nu})}} \frac{dN^{(\nu+\bar{\nu})}}{dr_\mu}$
r_μ



Production spectra as a function of the visible inelasticity ($y' = E_X/(E_\mu + E_X)$).


$\frac{1}{N^{(\nu+\bar{\nu})}}\frac{dN^{(\nu+\bar{\nu})}(1:1)}{dy'} \Big/ \frac{1}{N^{(\nu+\bar{\nu})}}\frac{dN^{(\nu+\bar{\nu})}(1:0)}{dy'}$
1.4
1.2
1.0
0.8
0.6
0.2
0.4
0.6
0.8
1.0
y'

Summary

- In this analysis one selects events which contain both showers and tracks. Then the analytic estimates show an excess of tau events at high $y' = Ex/(Ex+E\mu)$ or $Ex/E\mu$ large.
- At the moment there are few events to make the comparison, but several experiments will be operating soon (IceCube, Antares,Baikal Lake ...).

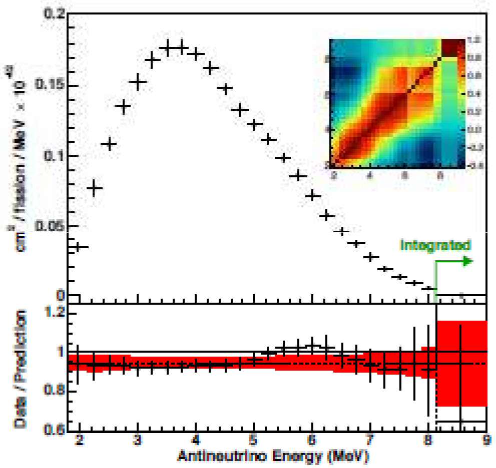
Deficit of antineutrinos in reactor experiments

$$\mathcal{L}_Y^{(\nu)} = \frac{1}{2} \begin{pmatrix} \bar{\nu}_L & \bar{N}_R^C \end{pmatrix} \begin{pmatrix} 0 & m_D \\ m_D^T & M \end{pmatrix} \begin{pmatrix} \nu_L^C \\ N_R \end{pmatrix} + h.\ c.$$

$$U = \begin{pmatrix} (1-\frac{1}{2}JJ^\dagger) & J \\ -J^\dagger & (1-\frac{1}{2}J^\dagger J) \end{pmatrix} \begin{pmatrix} U_\theta & 0 \\ 0 & U_\chi \end{pmatrix}$$
$$= \begin{pmatrix} (1-\frac{1}{2}JJ^\dagger)U_\theta & JU_\chi \\ -J^\dagger U_\theta & (1-\frac{1}{2}J^\dagger J)U_\chi \end{pmatrix}$$

with $J = m_D \dfrac{1}{M}$ and U_θ, U_χ diagonalizing the submatrices $m_D \dfrac{1}{M} m_D^T$ and

$$
\begin{aligned}
U_{e1} &= [1 - \frac{1}{2}(JJ^\dagger)_{11}]c_\theta + \frac{1}{2}(JJ^\dagger)_{12}s_\theta \\
U_{e2} &= [1 - \frac{1}{2}(JJ^\dagger)_{11}]s_\theta - \frac{1}{2}(JJ^\dagger)_{12}c_\theta \\
U_{e3} &= J_{11}c_\chi - J_{12}s_\chi \\
U_{e4} &= J_{11}s_\chi + J_{12}c_\chi,
\end{aligned}
$$



cm^2 / fission / MeV × 10^{-42}
Integrated
Data / Prediction
Antineutrino Energy (MeV)

$$P_{\nu_e \to \nu_e} = 1 - \left[1 - 2(JJ^\dagger)_{11} - \frac{2}{\sin 2\theta} Re(JJ^\dagger)_{12}\right] \sin^2 2\theta \sin^2 \frac{\Delta m_{12}^2 t}{4E}$$
$$-2\left(|J_{11}|^2 + |J_{12}|^2\right) - 4|U_{e3}|^2 |U_{e4}|^2 \sin^2\left(\frac{E_3 - E_4}{2} t\right).$$

$$0.06 = 2\,(|J_{11}|^2 + |J_{22}|^2)\,\sin^2(\Delta_{41} L/4E)$$