Neutrino Physics

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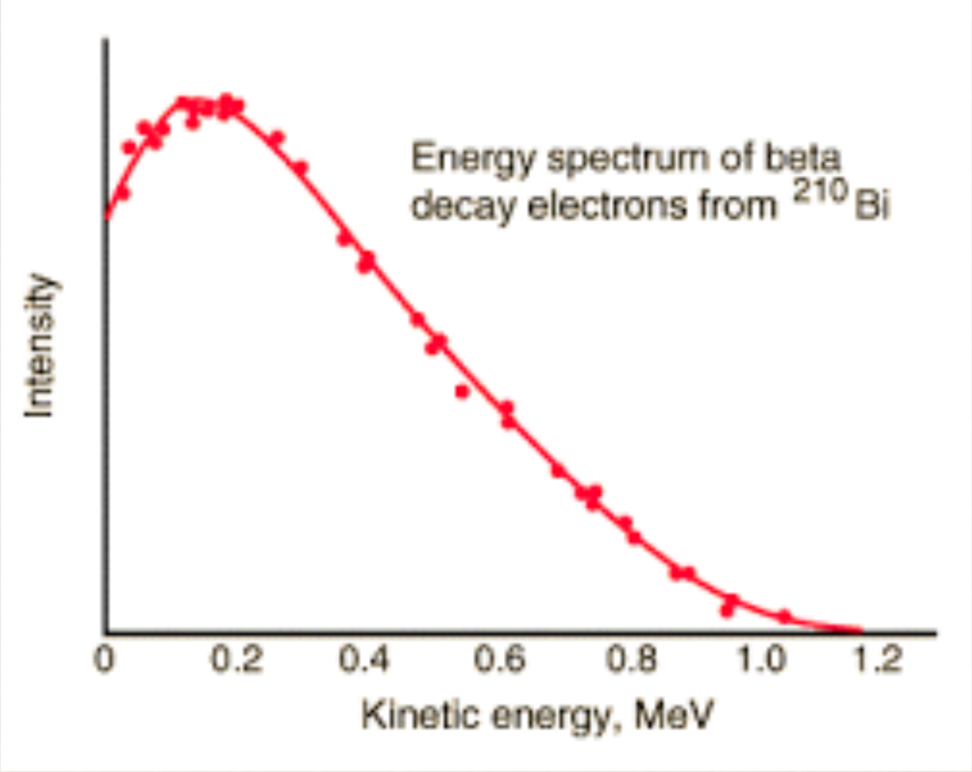
Discovery of neutrino

Beta Decay $(A, Z) \rightarrow (A, Z+1) + e^-$

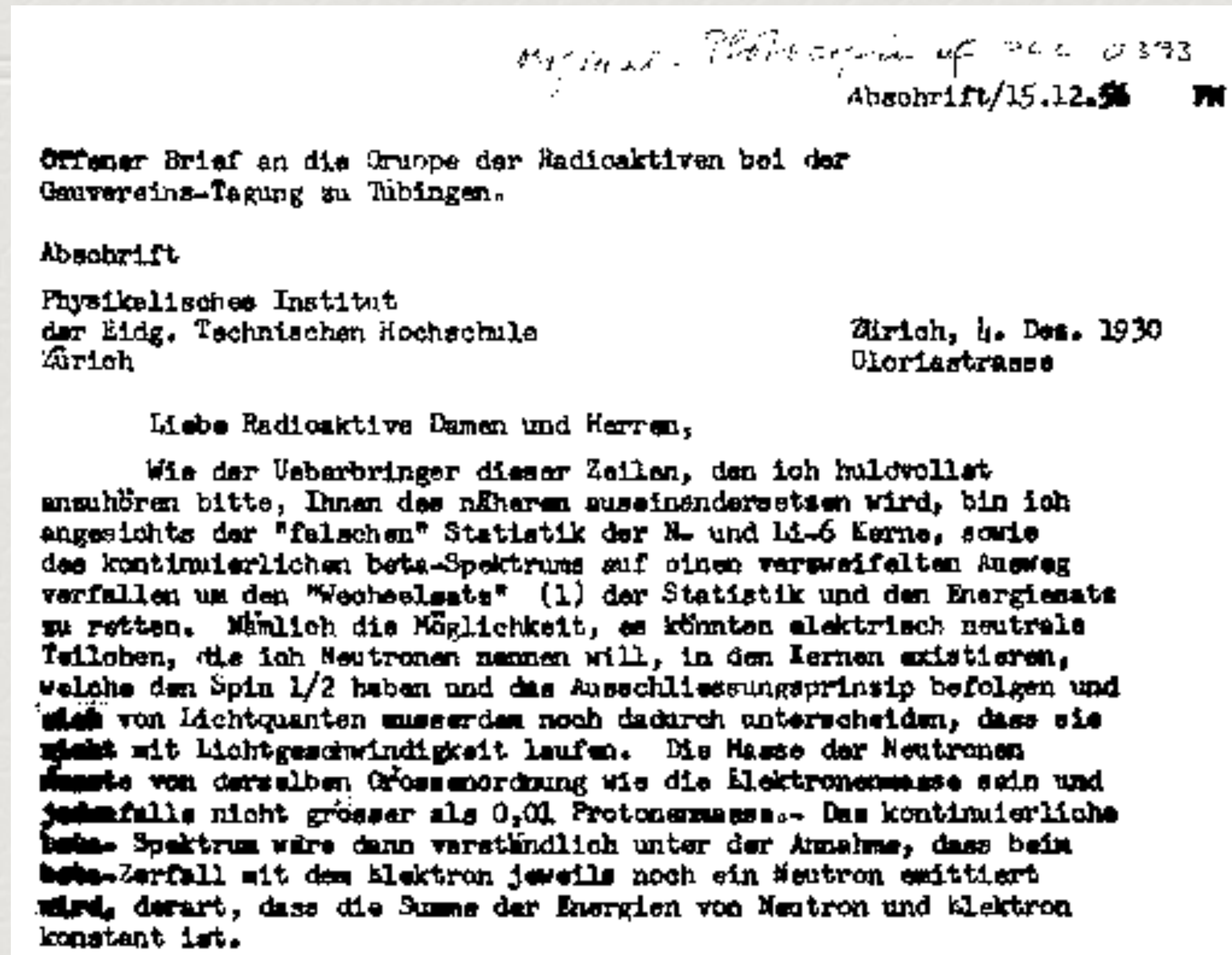
Beta energy $E_e = M(A, Z) - M(A, Z+1)$



But the beta decay spectrum is seen to be continuous

Do we give up energy conservation?

Discovery of neutrino



Abschrift/15.12.56

Offener Brief an die Gruppe der Radioaktiven bei der Gauvereins-Tagung zu Tübingen.

Abschrift

Physikalisches Institut
der Eidg. Technischen Hochschule
Zürich

Zürich, 4. Dez. 1930
Gloriastrasse

Liebe Radioaktive Damen und Herren,

Wie der Ueberbringer dieser Zeilen, den ich huldvollst anzuhören bitte, Ihnen des näheren auseinandersetzen wird, bin ich angesichts der "falschen" Statistik der N- und Li-6 Kerne, sowie des kontinuierlichen beta-Spektrums auf einen verzweifelten Ausweg verfallen um den "Wechselsatz" (1) der Statistik und den Energiesatz zu retten. Nämlich die Möglichkeit, es könnten elektrisch neutrale Teilchen, die ich Neutronen nennen will, in den Kernen existieren, welche den Spin 1/2 haben und das Ausschliessungsprinzip befolgen und sich von Lichtquanten ausserdem noch dadurch unterscheiden, dass sie nicht mit Lichtgeschwindigkeit laufen. Die Masse der Neutronen müsste von derselben Grössenordnung wie die Elektronenmasse sein und jedenfalls nicht grösser als 0,01 Protonenmasse.- Das kontinuierliche beta- Spektrum wäre dann verständlich unter der Annahme, dass beim beta-Zerfall mit dem Elektron jeweils noch ein Neutron emittiert wird, derart, dass die Summe der Energien von Neutron und Elektron konstant ist.

In 1930 Pauli proposed the neutrino to save the principle of energy conservation

Discovery of neutrino

$$(A, Z) \to (A, Z+1) + e^- + \bar{\nu}_e$$

In 1930 Pauli proposed the neutrino to save the principle of energy conservation

Discovery of neutrino

This new particle was postulated to be light with spin 1/2 and no charge in order to conserve energy momentum in nuclear beta decay and was called neutron

In 1932 the neutron was discovered and it was clear that this was different from Pauli's proposed particle

Fermi proposed the name neutrino for the new particle

Being chargeless, neutrinos have only weak interactions, making their detection difficult

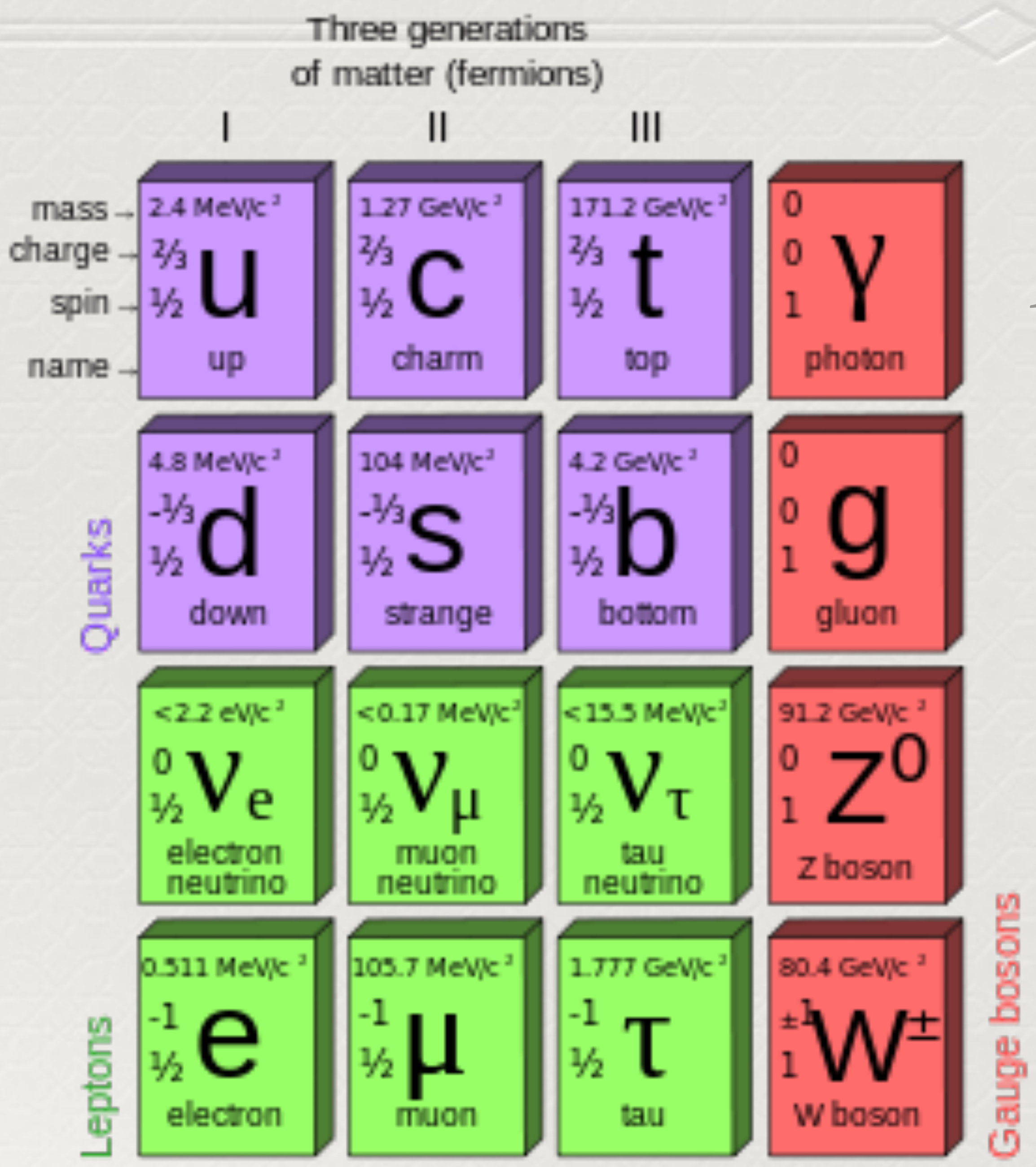
Discovery of neutrino

$$\bar{\nu}_e + p \to e^+ + n$$

26 years later the neutrinos were finally detected in 1956 by the inverse beta decay process by Reines and Cowan

Reines received the Nobel Prize for their discovery in 1995

The Standard Model



No right-handed neutrinos

$B \times L_e \times L_\mu \times L_\tau$ *symmetry*

Neutrinos were postulated to be massless in the SM

Neutrino Mass

Dirac Mass Term

Add to the SM ν_R *which can give a Yukawa term*

$$\mathcal{L}_Y^\nu = -Y\bar{\psi}_L \nu_R \tilde{\phi} + h.c. \qquad (\tilde{\phi} = i\tau_2\phi^*)$$

After spontaneous symmetry breaking we get a Dirac mass term for the neutrinos

$$-\mathcal{L}_{Mass}^\nu = \bar{\nu}_L M_D \nu_R + h.c.$$

Neutrino Mass

Majorana Mass Term

- A natural way to obtain small Majorana masses is to write down a 5-dimensional operator

Weinberg'79

$$-\mathcal{L}_\nu^Y = C_\nu^5 \frac{1}{\Lambda} LLHH + h.c.$$

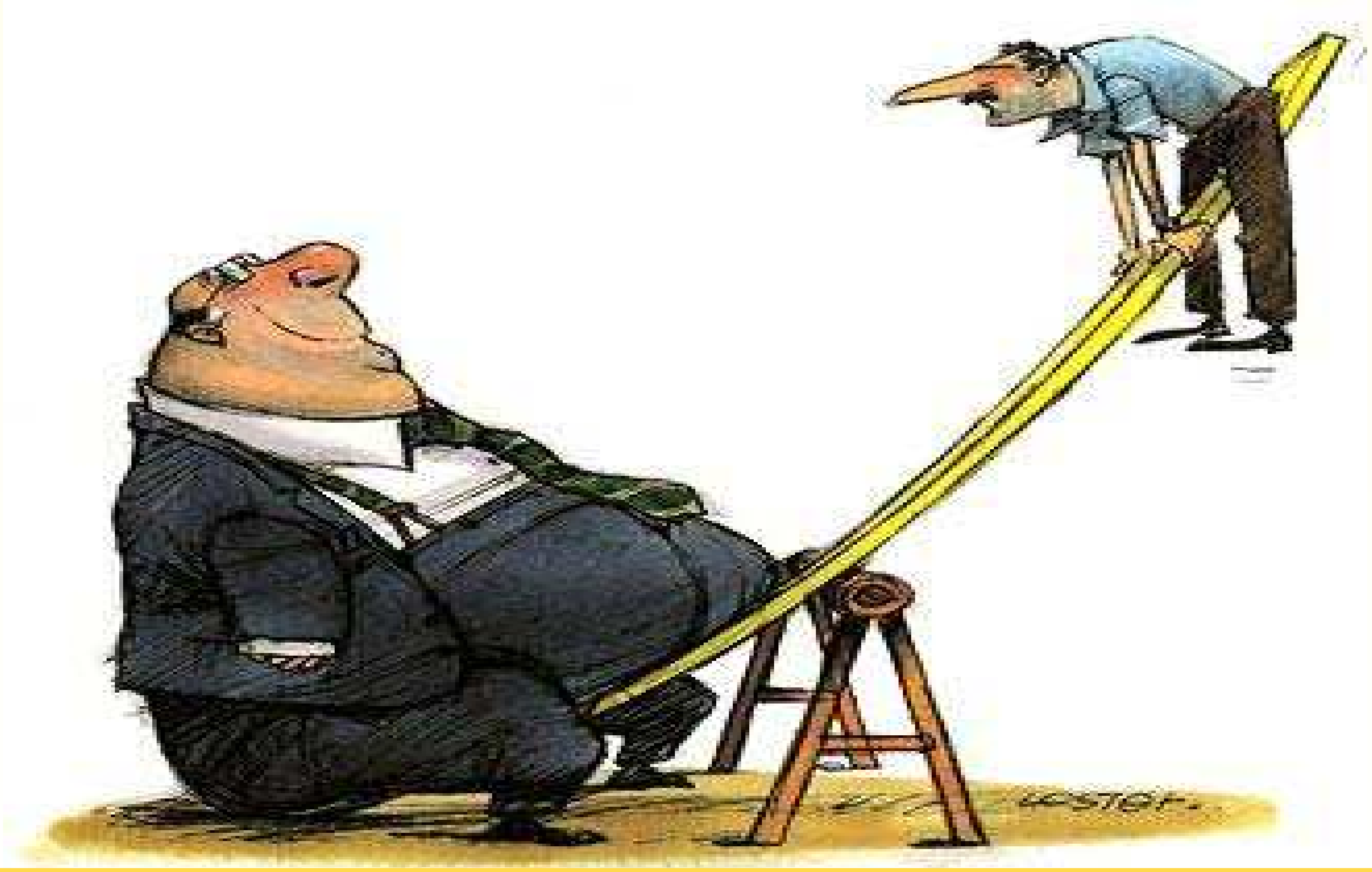
$$\Rightarrow m_\nu = \frac{C_\nu^5 \, v^2}{\Lambda}$$

- For $C_\nu^5 \sim 1$, one gets $m_\nu \sim 0.1$ eV when $\Lambda \sim 10^{15}$ GeV
- Is this an indication of new physics at a higher scale?

(SMALL) Neutrino Mass

The Seesaw Mechanism

- High scale corresponds to a heavy particle which gets integrated out $\Rightarrow$ 5-dim effective operator suppressed by the mass of the heavy particle



Neutrino Mass

The Seesaw Mechanism

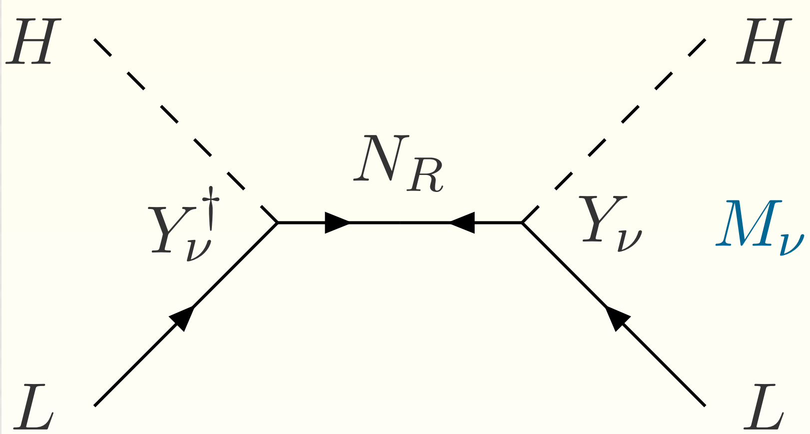
- Ways to generate a gauge invariant term from the SM doublets L and H: $2 \otimes 2 = 3 \oplus 1$
- Type I: L and H form a SU(2) singlet
  - Mediated by a heavy SU(2) singlet fermion with Y=0
- Type II: L and L form a SU(2) triplet
  - Mediated by a heavy SU(2) triplet scalar with Y=1
- Type III: L and H form a SU(2) triplet
  - Mediated by a heavy SU(2) triplet fermion with Y=0

Neutrino Mass

Type I Seesaw

- Introduce heavy right handed neutrinos $N_R \sim (1,1,0)$

$$-\mathcal{L}_Y = Y_\nu \bar{L}\tilde{H} N_R + \frac{1}{2} M_N \overline{N_R^c} N_R + h.c.$$



$$M_\nu = \begin{pmatrix} 0 & vY_\nu \\ vY_\nu & M_R \end{pmatrix}$$

$$m_\nu = -v^2 Y_\nu M_N^{-1} Y_\nu^T$$

Minkowski'77

Yanagida'79, Gelmann, Ramond, Slansky'79

Glashow'80, Mohapatra, Senjanovic'80

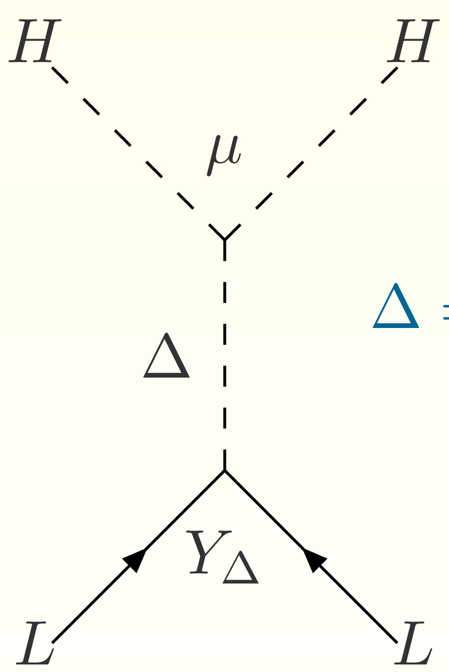
- Fits naturally in 16 of SO(10) GUTS
- Scale of $M_N \sim 10^{15}$ GeV very naturally
- At least 2 RH neutrino required

Neutrino Mass

Type II Seesaw

- Introduce heavy scalar triplet $\Delta \sim (1,3,1)$

$$-\mathcal{L}_{II} = Y_\Delta L^T C^{-1} i\sigma_2 \Delta L + M_\Delta^2 Tr(\Delta^\dagger \Delta) + \mu H^T i\sigma_2 \Delta^\dagger H + ...$$



$$\Delta = \begin{pmatrix} \delta^+/\sqrt{2} & \delta^{++} \\ \delta^0 & -\delta^+/\sqrt{2} \end{pmatrix}$$

$$m_\nu = Y_\Delta \frac{\mu\, v^2}{M_\Delta^2}$$

Konetschny,Kummer '77, Chen,Li '80, Magg, Wetterich '80
Schecter,Valle '80, Lazarides,Shafi,Wetterich '81,
Mohapatra,Senjanovic '81

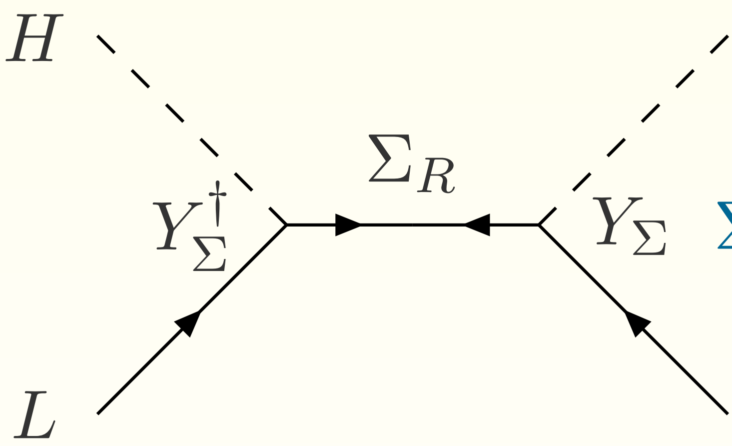
- Basically Seesaw of the Δ VEV v_Δ
- Fits naturally in L-R symmetric models

Neutrino Mass

Type III Seesaw

- Introduce heavy fermion triplets $\Sigma_R \sim (1,3,0)$

$$-\mathcal{L}_Y = Y_\Sigma \bar{L} \tilde{H} \Sigma_R + \frac{1}{2} M_\Sigma Tr(\overline{\Sigma_R^c} \Sigma_R) + h.c.$$

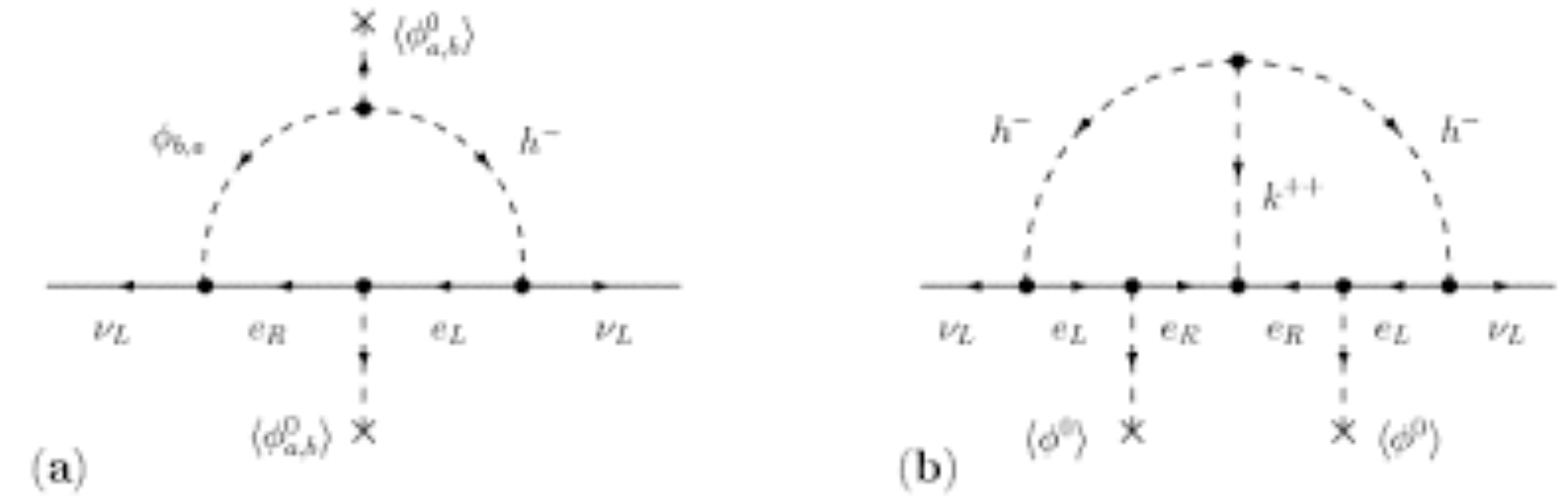


$$\Sigma = \begin{pmatrix} \Sigma^0/\sqrt{2} & \Sigma^+ \\ \Sigma^- & -\Sigma^0/\sqrt{2} \end{pmatrix}$$

$$m_\nu = -v^2 Y_\Sigma M_\Sigma^{-1} Y_\Sigma^T$$

Neutrino Mass

The dim 5 Majorana mass term can be generated by loops, in extensions of the SM. The loop suppression explains the smallness of neutrino masses



Consequence of neutrino mass and mixing

Neutrino Oscillations

Neutrinos are produced by weak charged current interaction

For example: $\pi^+ \rightarrow \mu^+ + \nu_\mu$ *as flavor eigenstates*

Their propagation is defined in terms of mass eigenstates

The flavor eigenstates can be written as a linear combination of the mass eigenstates

$$|\nu_\alpha\rangle = \sum_{i=1}^{n} U_{\alpha i} |\nu_i\rangle$$

Neutrino Oscillations

After time t or distance L, the state evolves to

$$|\nu(t)\rangle = \sum_{i=1}^{n} U_{\alpha i} e^{-iE_i t} |\nu_i\rangle$$

Neutrinos are detected by weak charged current interaction

For example: $\nu_\mu + N \to \mu^- + N'$ as flavor eigenstates

Probability that the detected flavor is ν_β

$$P_{\alpha\beta} = |\langle \nu_\beta | \nu(t) \rangle|^2$$

Neutrino Oscillations

Assume that there are two generations of massive neutrinos

$$U = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \qquad 0 \le \theta \le \frac{\pi}{2}$$

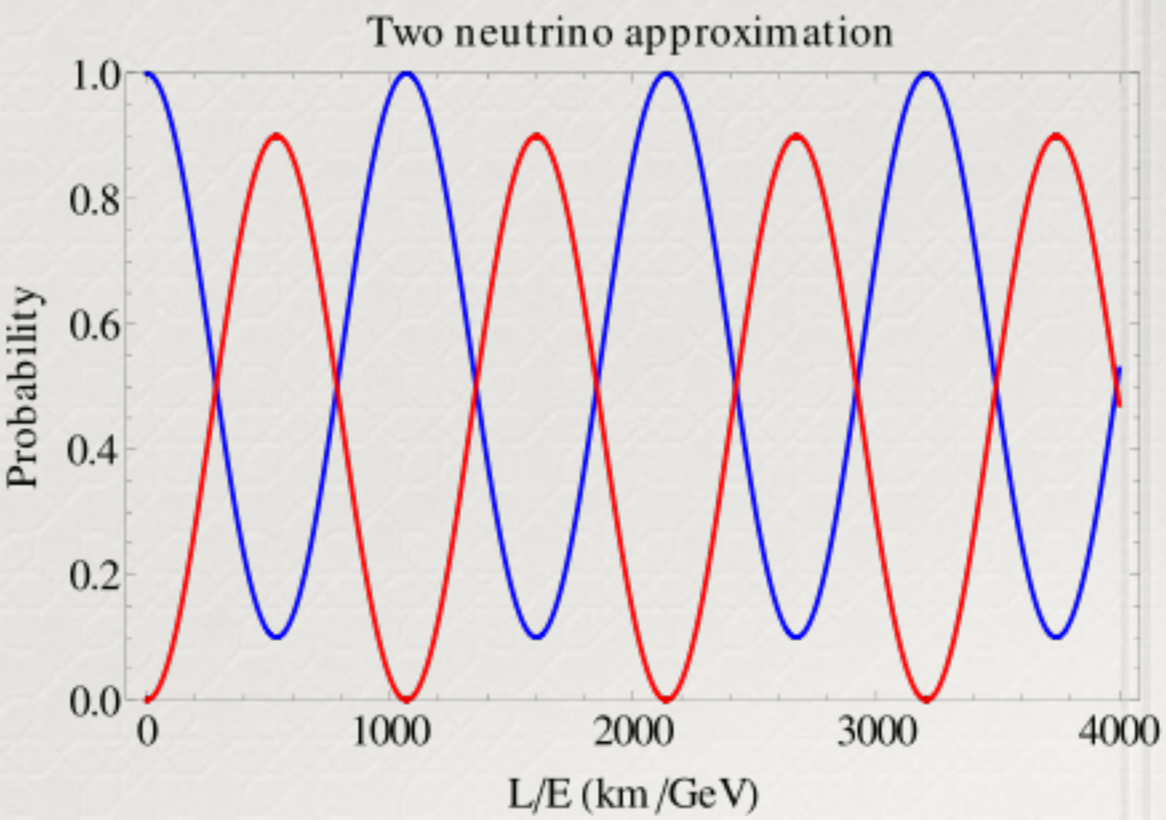
Neutrino Oscillations in Two Generations

- Flavor Eigenstates $\neq$ Mass Eigenstates

$$\nu_\mu = \cos\theta\,\nu_2 + \sin\theta\,\nu_3$$

$$\nu_\mu(t) = \cos\theta\, e^{-iE_2}\,\nu_2 + \sin\theta\, e^{-iE_3}\,\nu_3$$

$$P_{\mu\mu} = 1 - \sin^2 2\theta \sin^2\left(\frac{\Delta m^2\, L}{4E}\right)$$



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$$\nu_\mu = \cos\theta\, \nu_2 + \sin\theta\, \nu_3$$

$$\nu_\mu(t) = \cos\theta\, e^{-iE_2}\, \nu_2 + \sin\theta\, e^{-iE_3}\, \nu_3$$

$$P_{\mu\mu} = 1 - \sin^2 2\theta \sin^2 \left(\frac{\Delta m^2\, L}{4E} \right)$$

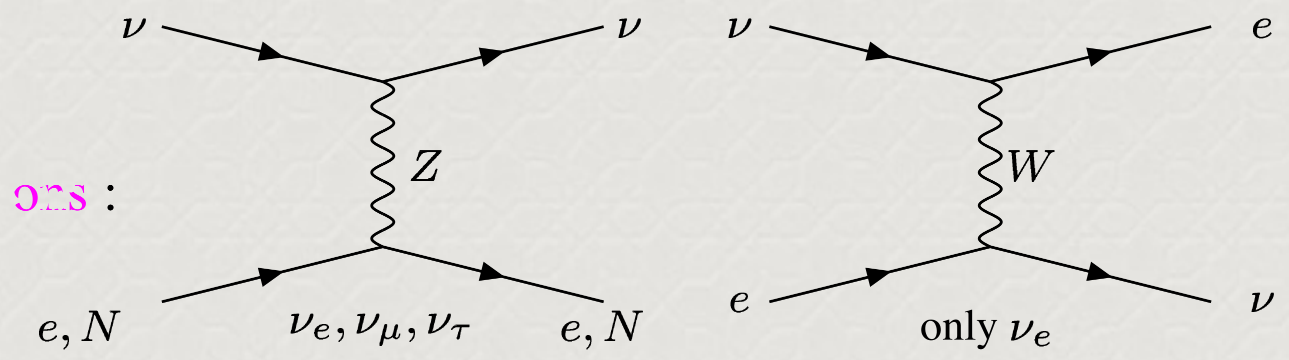
No dependence on the sign of Δm^2

No dependence on the octant of theta

No possibility of any CP violation

Matter Effects in nu osc

Assume that there are two generations of massive neutrinos



Modifies the mass matrix of the neutrinos

$$\begin{pmatrix} V_e + \frac{\Delta m^2}{2E}\cos 2\theta & -\frac{\Delta m^2}{2E}\sin 2\theta \\ -\frac{\Delta m^2}{2E}\sin 2\theta & V_X - \frac{\Delta m^2}{2E}\cos 2\theta \end{pmatrix}$$

$$V_e = \sqrt{2}G_F(N_e - \frac{1}{2}N_n)$$

$$V_X = -\sqrt{2}G_F\frac{1}{2}N_n$$

Matter Effects in nu osc

Assume that there are two generations of massive neutrinos

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$$V_e = \sqrt{2}G_F(N_e - \frac{1}{2}N_n)$$

$$V_X = -\sqrt{2}G_F\frac{1}{2}N_n$$

$$\sin^2 2\theta_m = \frac{\Delta m^2 \sin 2\theta}{\sqrt{(\Delta m^2 \cos 2\theta - 2\sqrt{2}G_F N_e E)^2 + (\Delta m^2 \sin 2\theta)^2}}$$

$$\Delta m^2 \cos 2\theta = 2\sqrt{2}G_F N_e E \Rightarrow \theta_m = \pi/4$$

sign   *octant*

MSW Resonance

Matter Effects in nu osc

Assume that there are two generations of massive neutrinos

Modifies the mass matrix of the neutrinos

$$\begin{pmatrix} V_e + \frac{\Delta m^2}{2E}\cos 2\theta & -\frac{\Delta m^2}{2E}\sin 2\theta \\ -\frac{\Delta m^2}{2E}\sin 2\theta & V_X - \frac{\Delta m^2}{2E}\cos 2\theta \end{pmatrix}$$

$$V_e = \sqrt{2} G_F (N_e - \frac{1}{2} N_n)$$

$$V_X = -\sqrt{2} G_F \frac{1}{2} N_n$$

$$\sin^2 2\theta_m = \frac{\Delta m^2 \sin 2\theta}{\sqrt{(\Delta m^2 \cos 2\theta - 2\sqrt{2} G_F N_e E)^2 + (\Delta m^2 \sin 2\theta)^2}}$$

We need more than 2 gen for CP violation, and we do have 3 gen of neutrinos at least

$$\Delta m^2 \cos 2\theta = 2\sqrt{2} G_F N_e E \quad \Rightarrow \quad \theta_m = \pi/4$$

sign *octant*

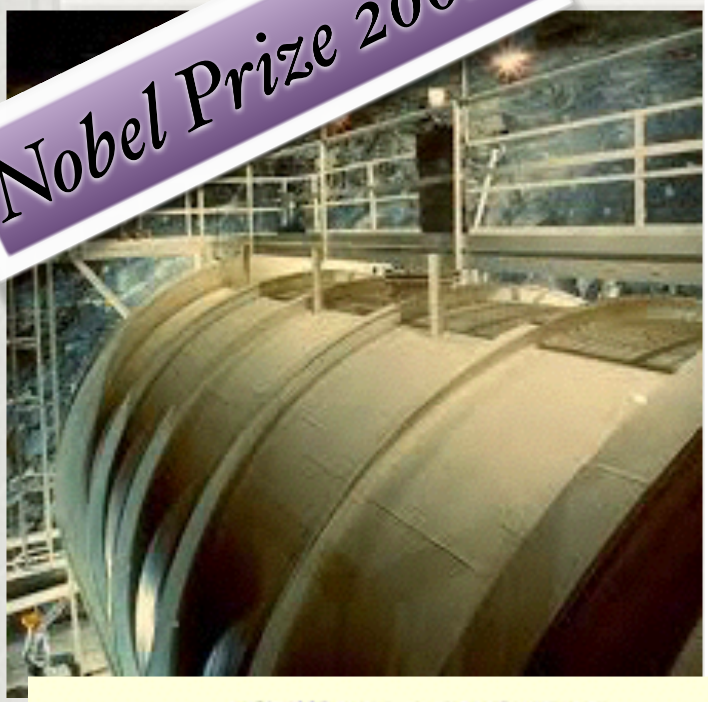
MSW Resonance

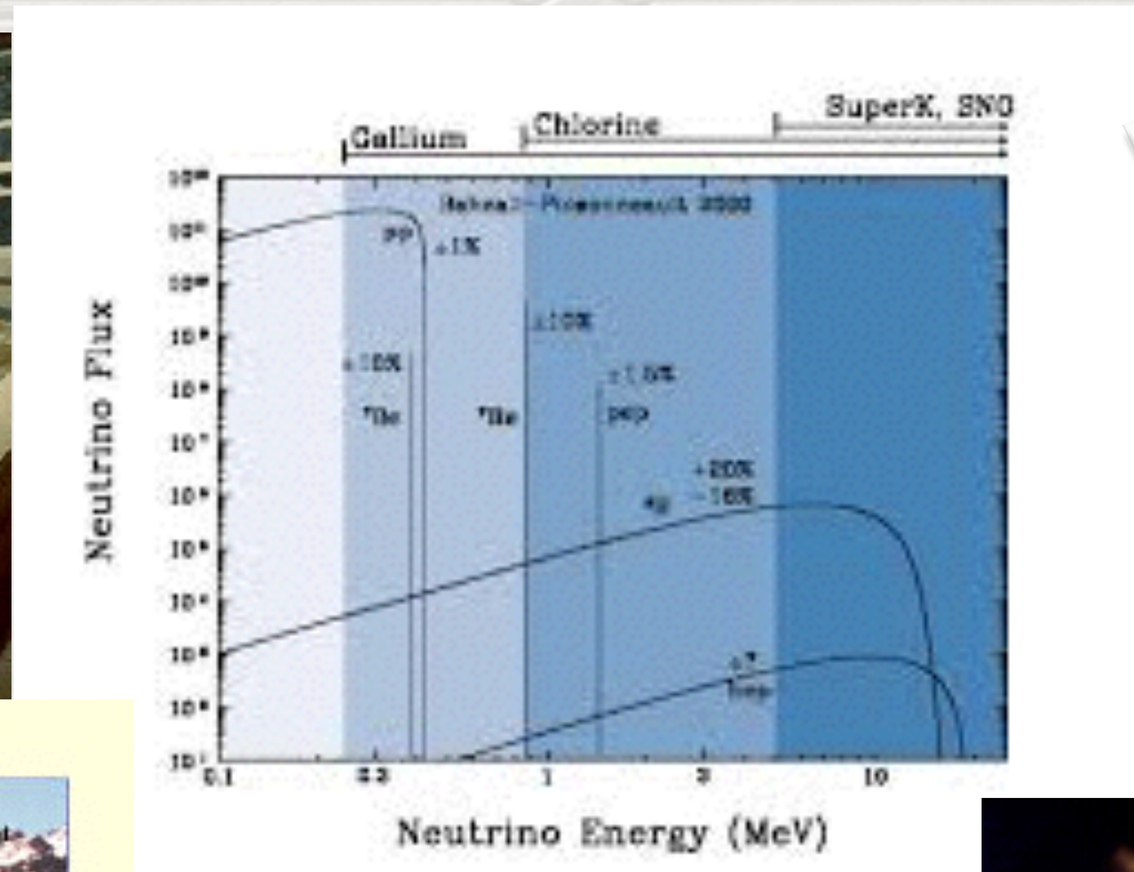
Neutrino Experiments

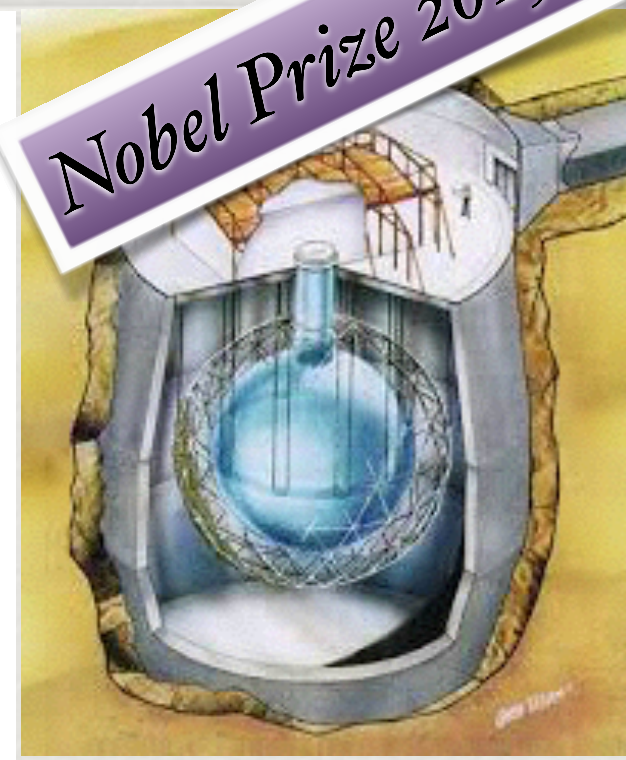
Solar Nu Experiments

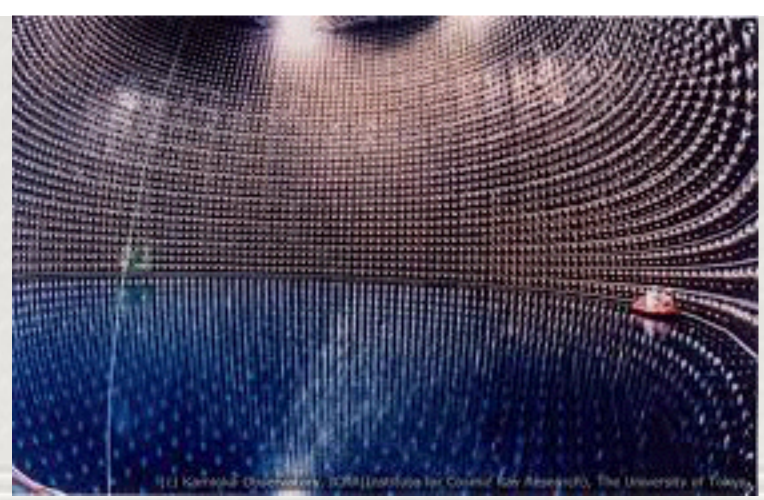
Nobel Prize 2002

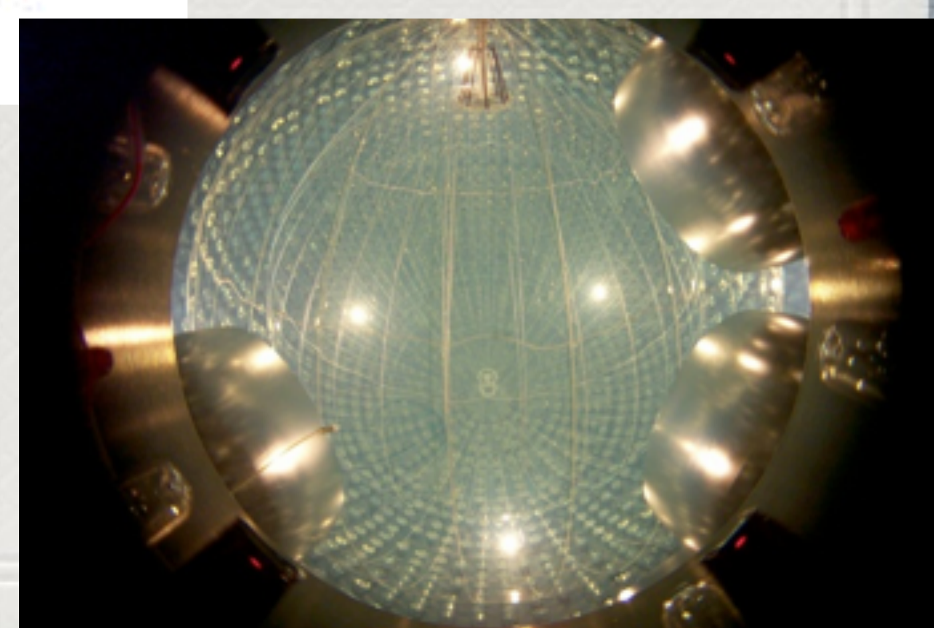
Nobel Prize 2015



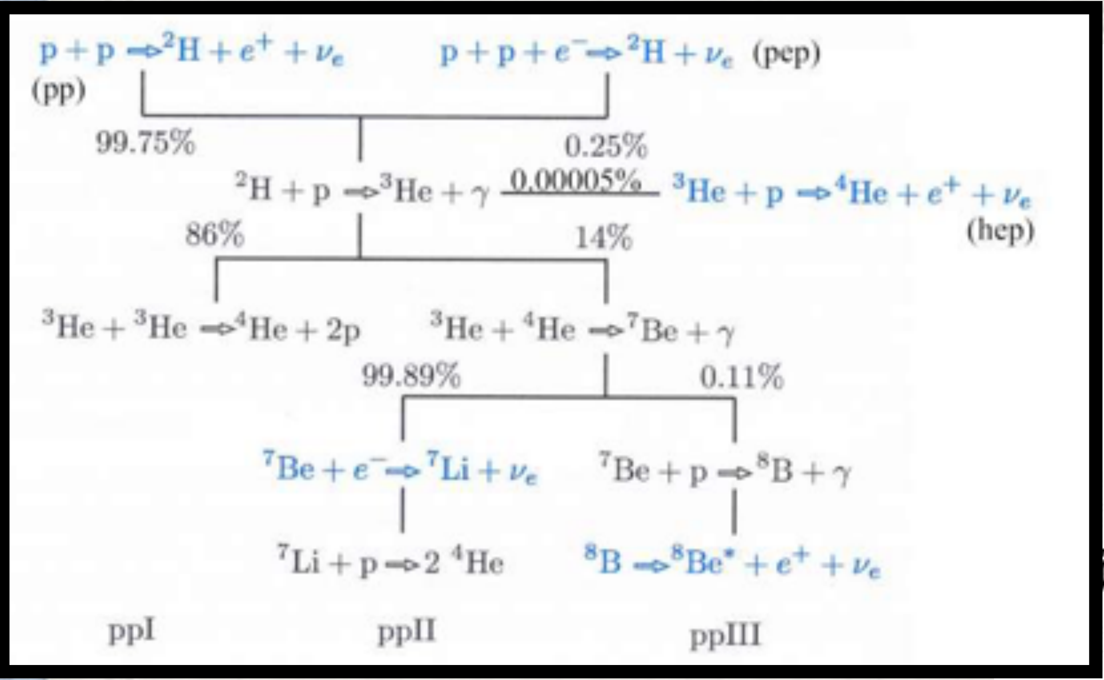




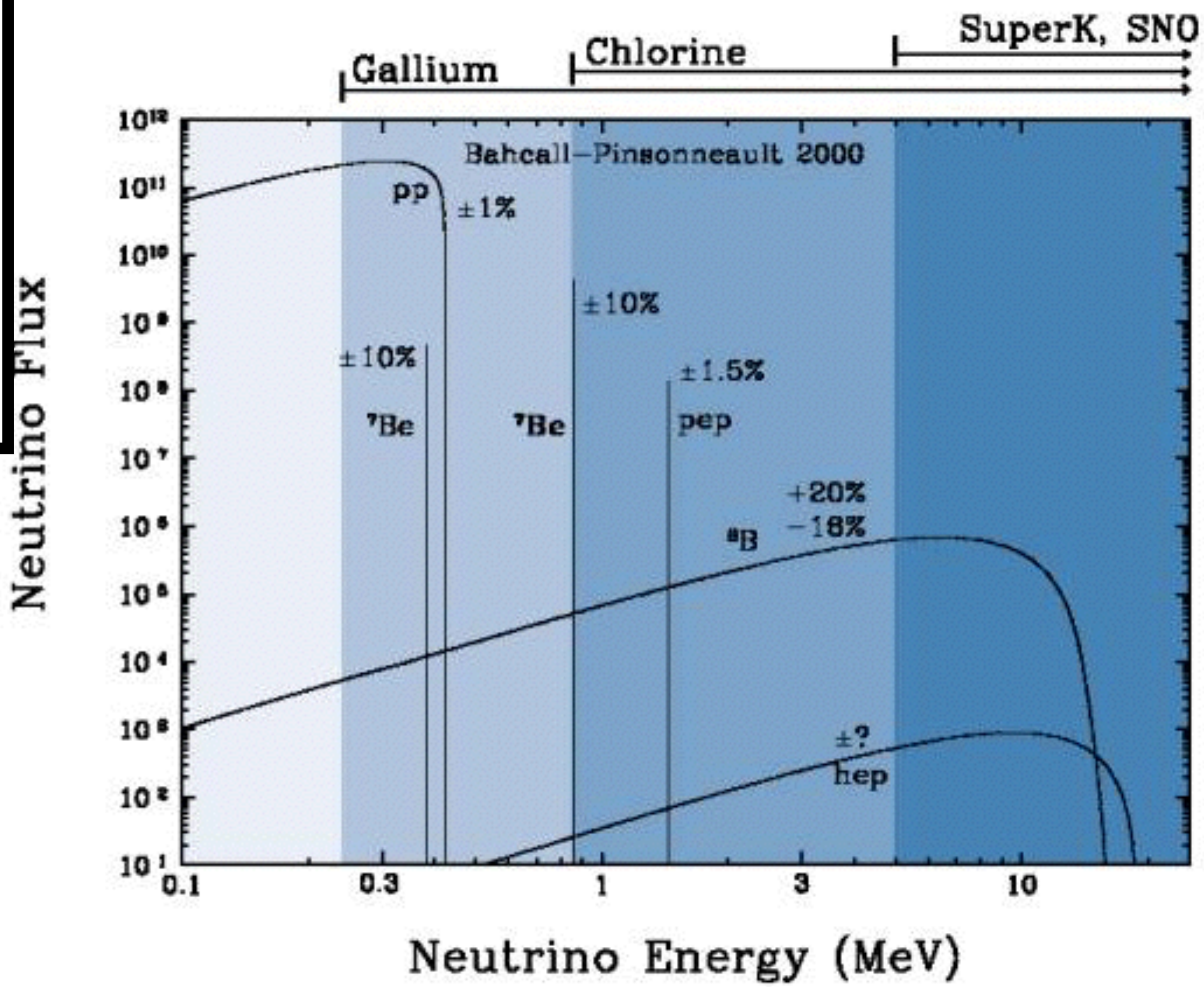




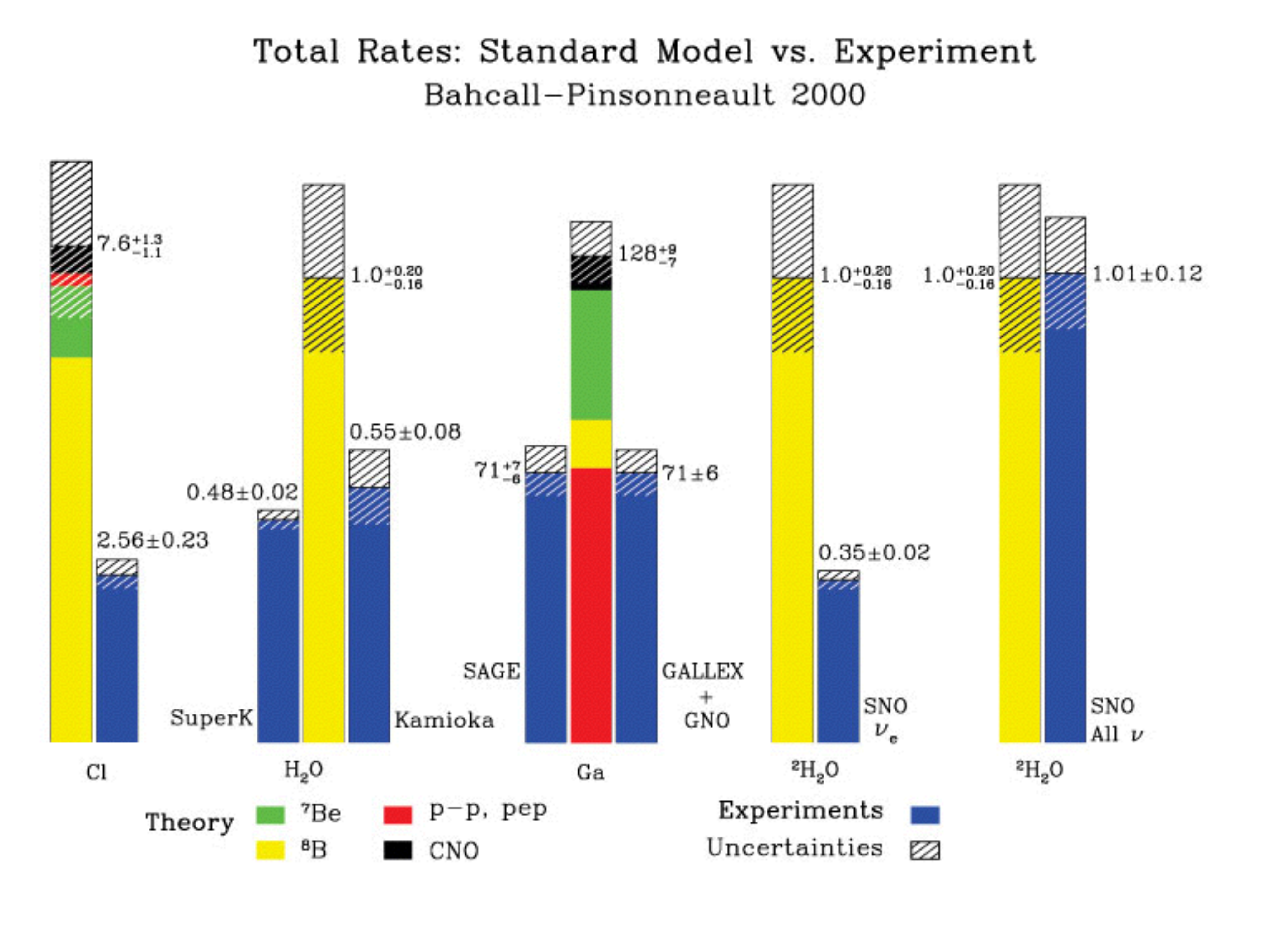
Solar Neutrinos



$$
\begin{aligned}
{}^{12}C + {}^{1}H &\rightarrow {}^{13}N + \gamma \\
{}^{13}N &\rightarrow {}^{13}C + e^{+} + \nu_e \\
{}^{13}C + {}^{1}H &\rightarrow {}^{14}N + \gamma \\
{}^{14}N + {}^{1}H &\rightarrow {}^{15}O + \gamma \\
{}^{15}O &\rightarrow {}^{15}N + e^{+} + \nu_e \\
{}^{15}N + {}^{1}H &\rightarrow {}^{12}C + {}^{4}He
\end{aligned}
$$



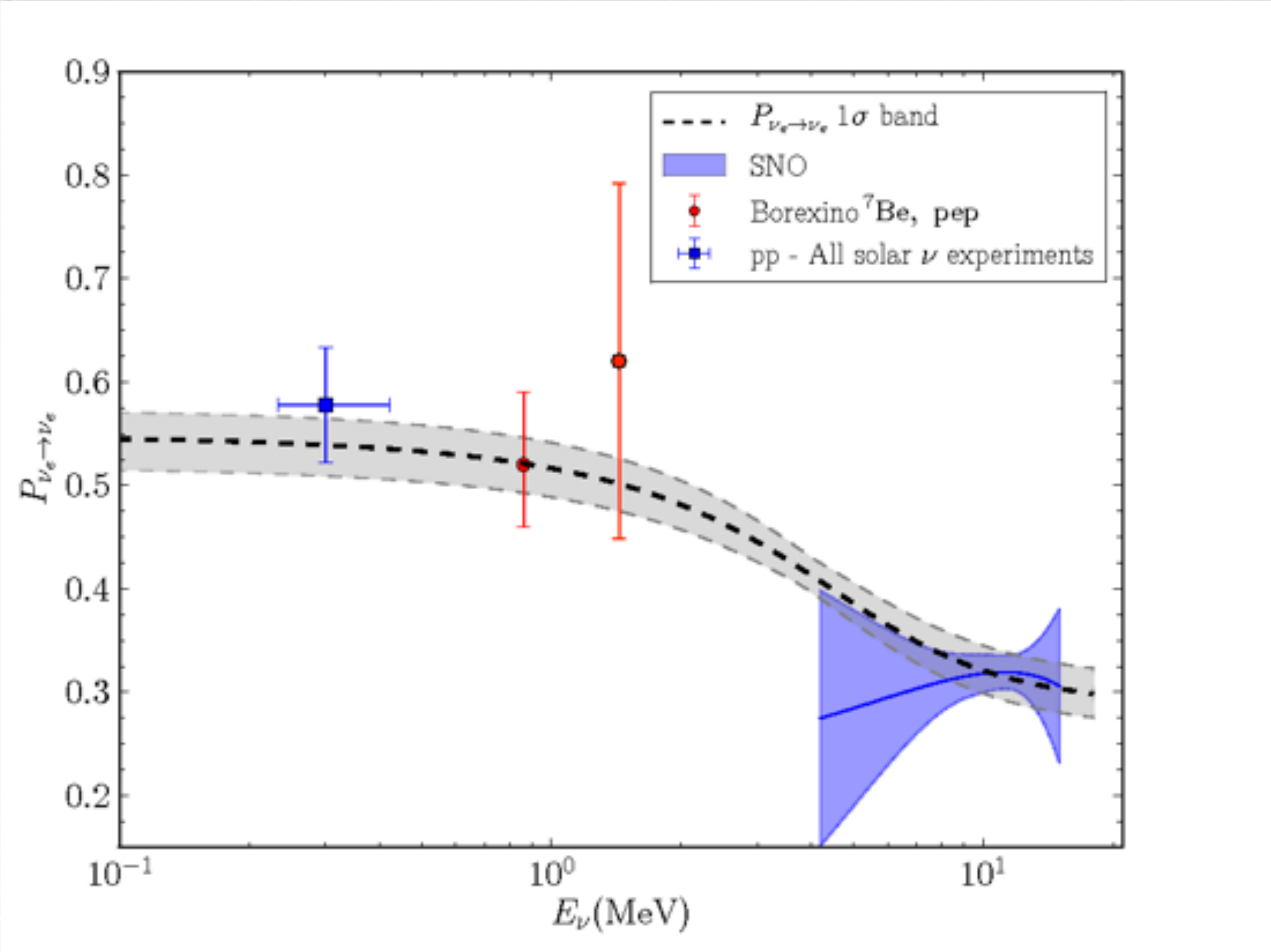
Solar Neutrino Problem

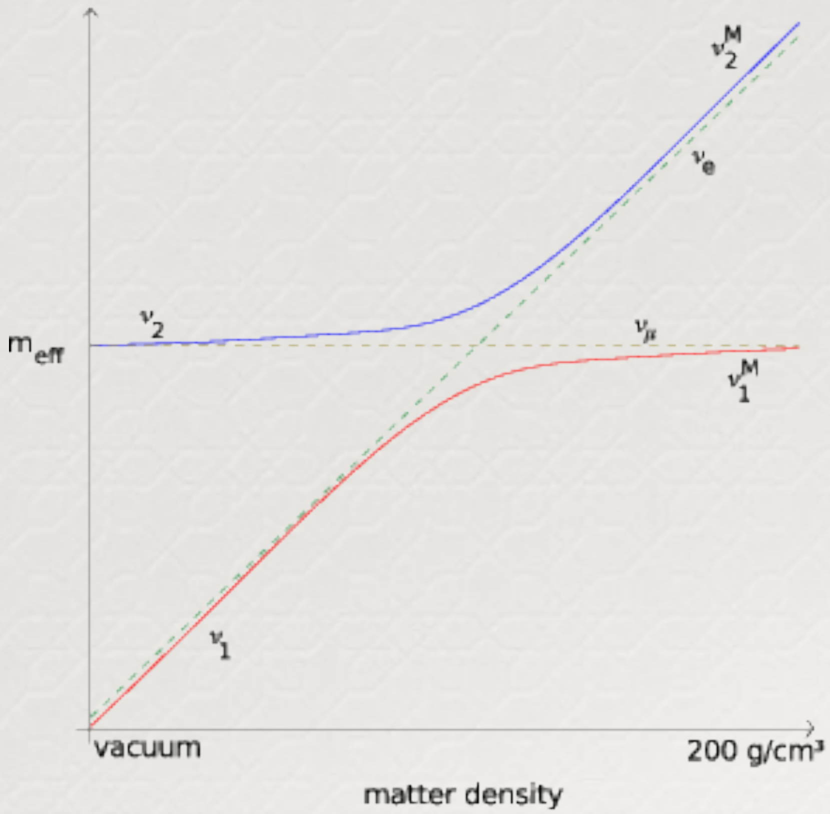


Solution to the Solar Neutrino Problem

$$P_{ee}^{2\nu,\mathrm{sun}} \simeq 1 - \frac{1}{2}\sin^2(2\theta_{12}) \qquad \text{for } E_\nu \lesssim \text{few} \times 100 \text{ KeV}$$

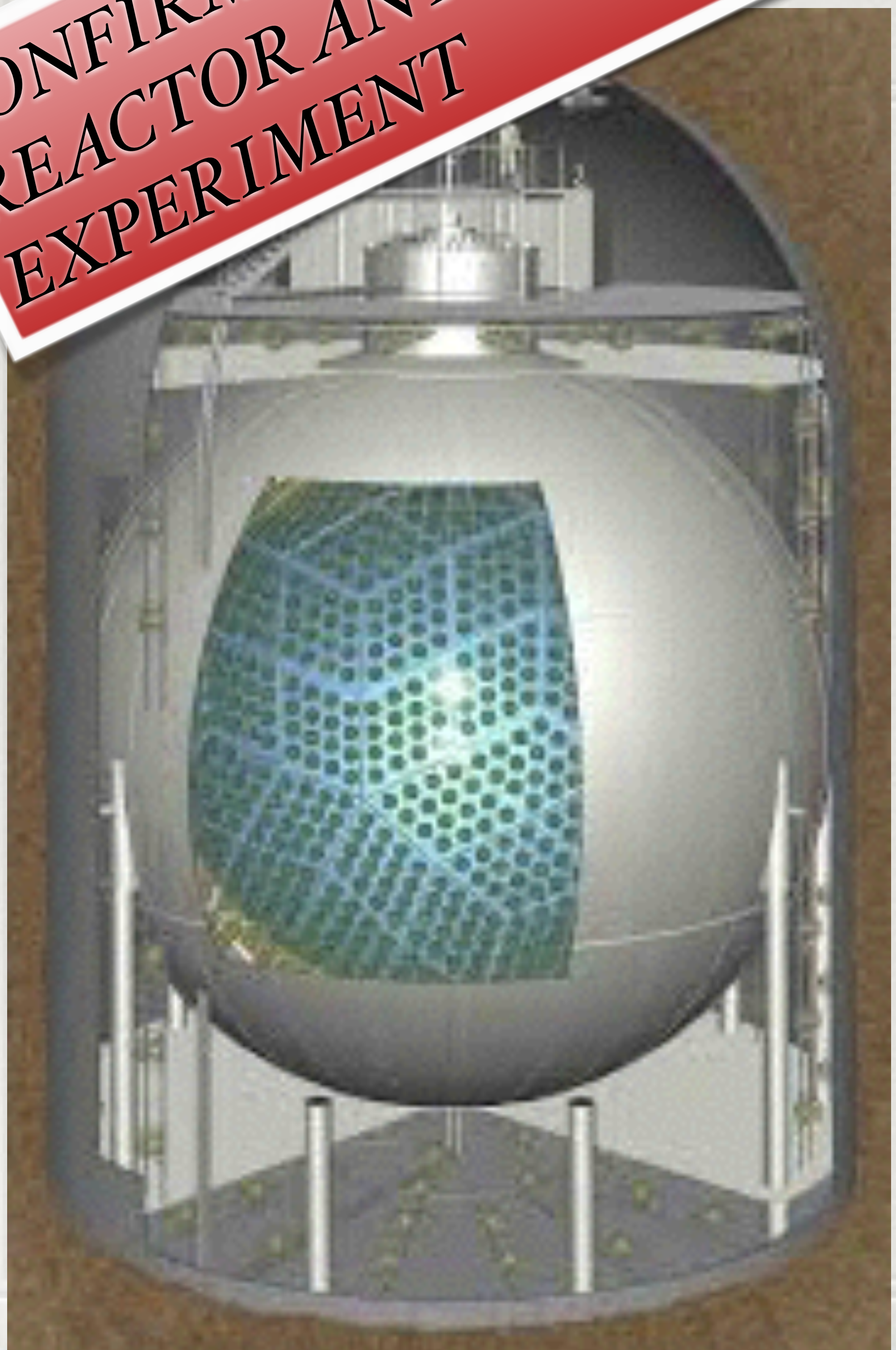
$$P_{ee}^{2\nu,\mathrm{sun}} \simeq \sin^2(\theta_{12}) \qquad \text{for } E_\nu \gtrsim \text{few} \times 1 \text{ MeV}$$

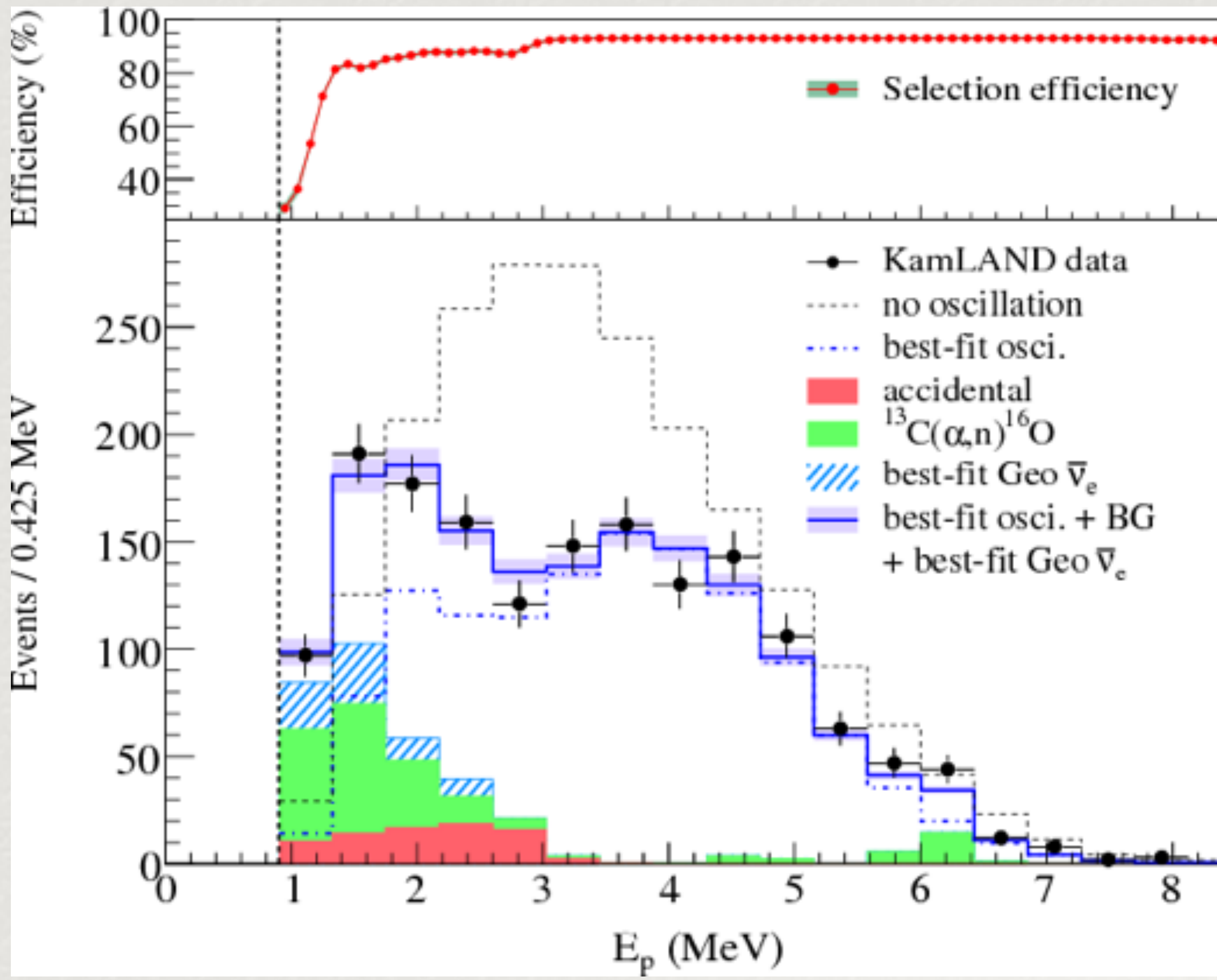




CONFIRMED BY KAMLAND REACTOR ANTI-NEUTRINO EXPERIMENT

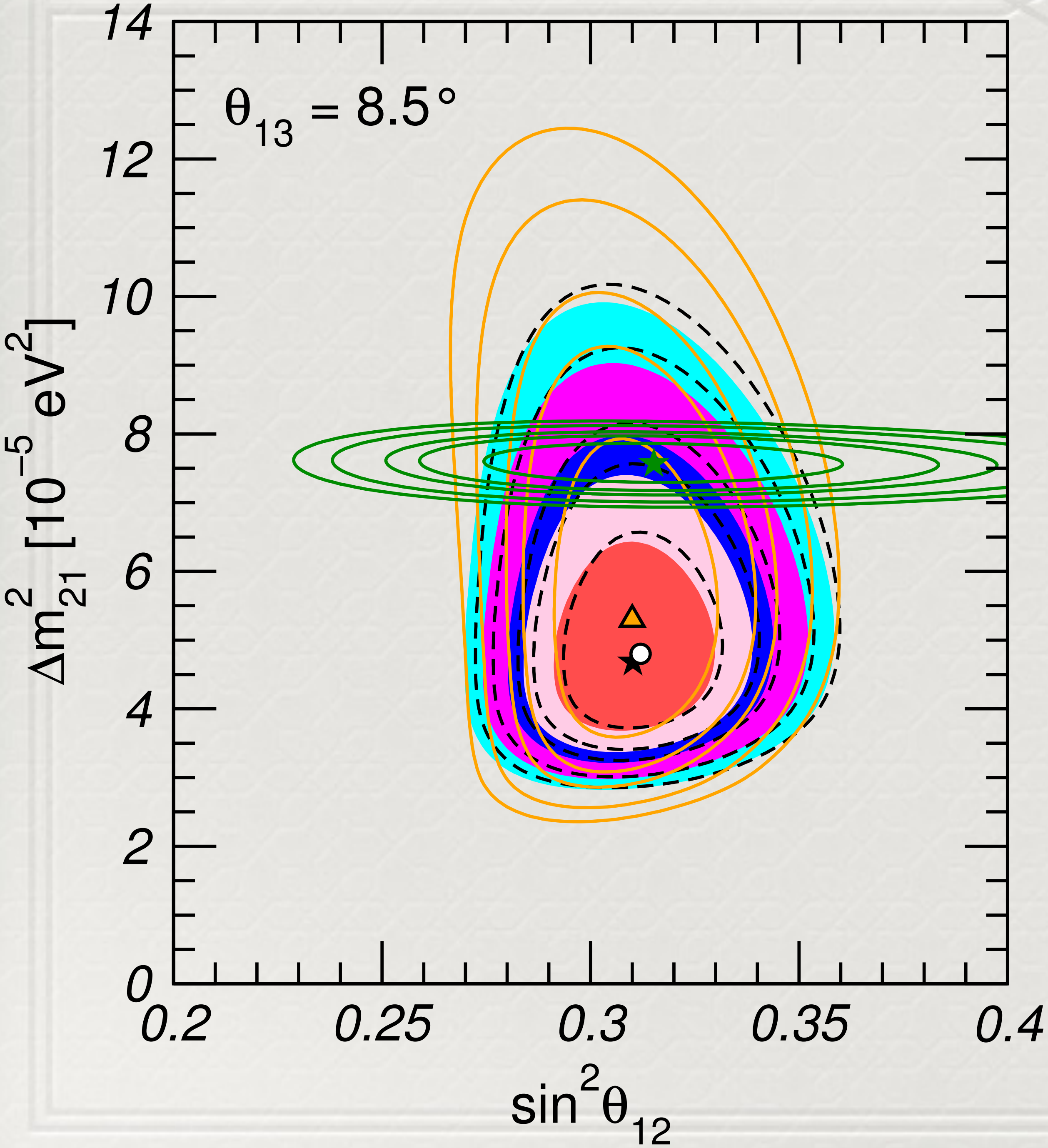
Experiments

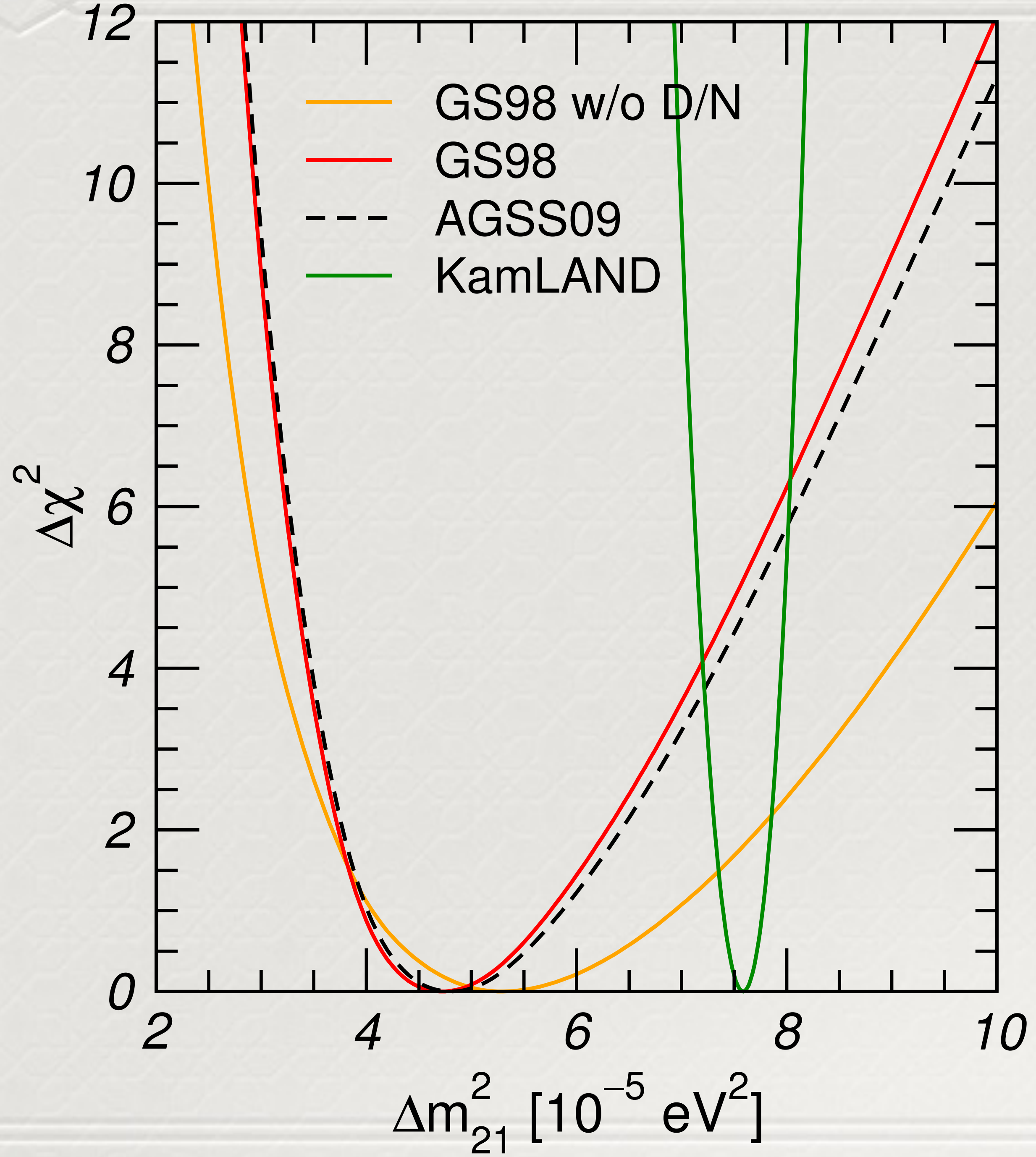




Soln to Solar nu Problem

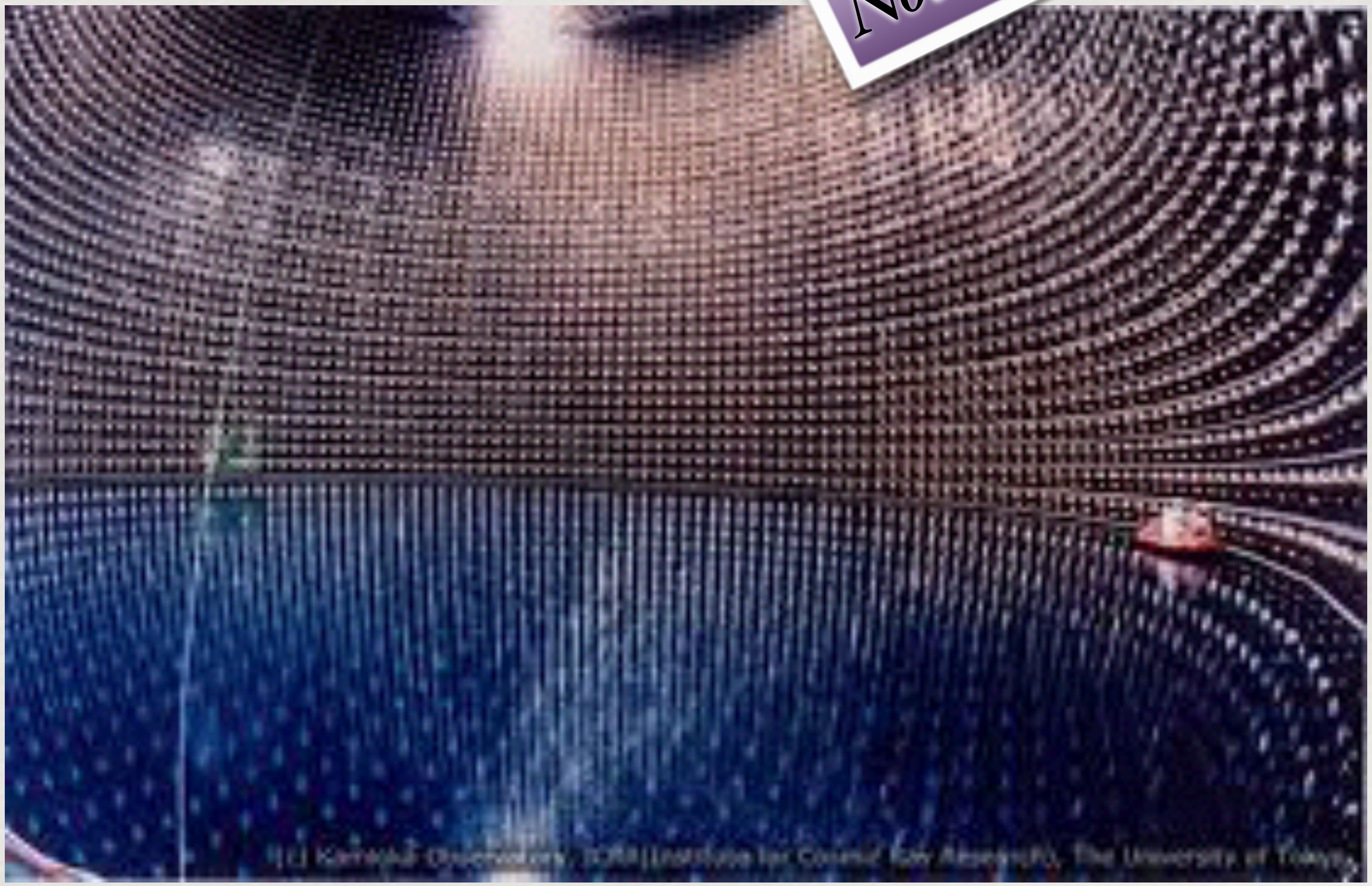
NuFIT 2.0 (2014)



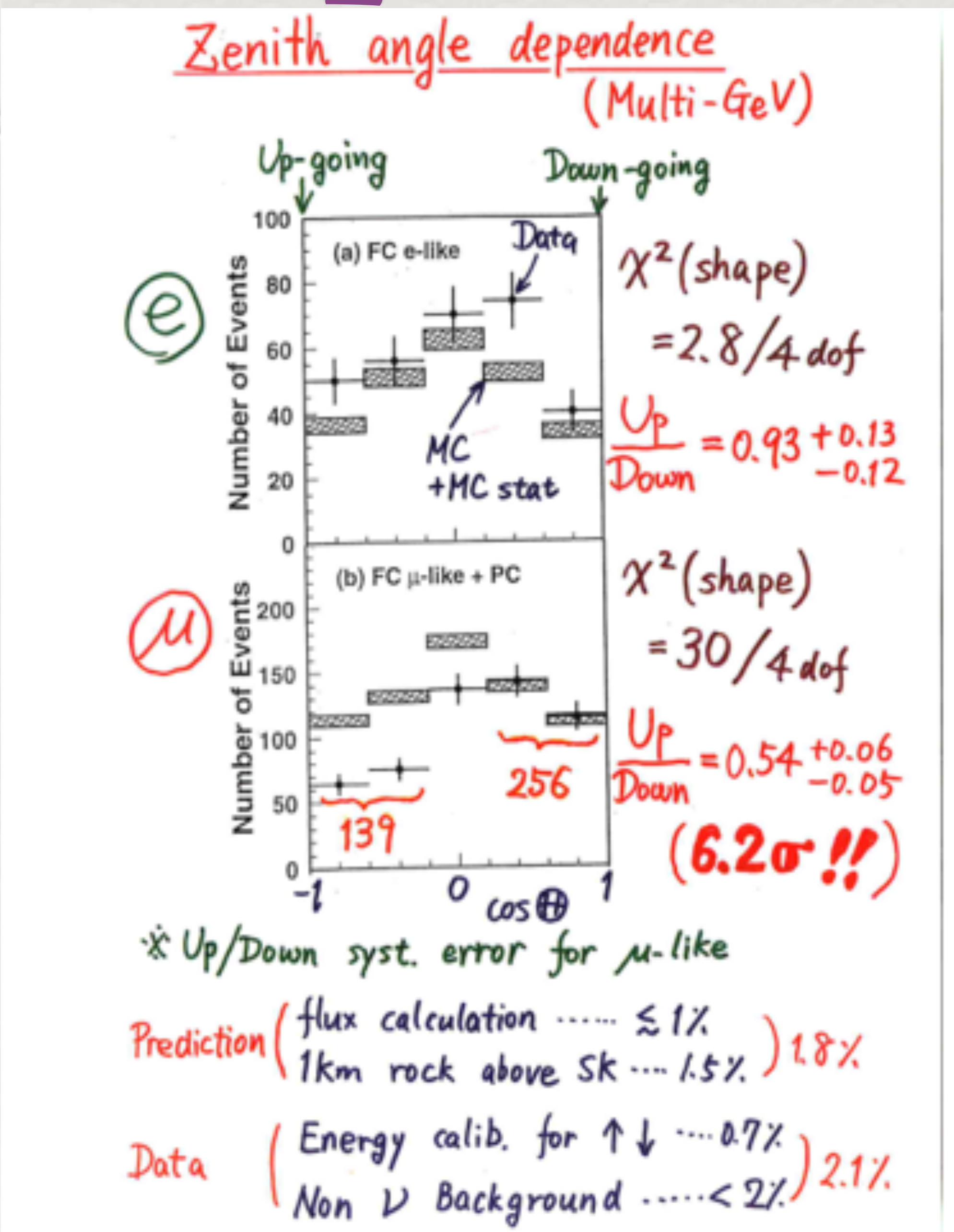


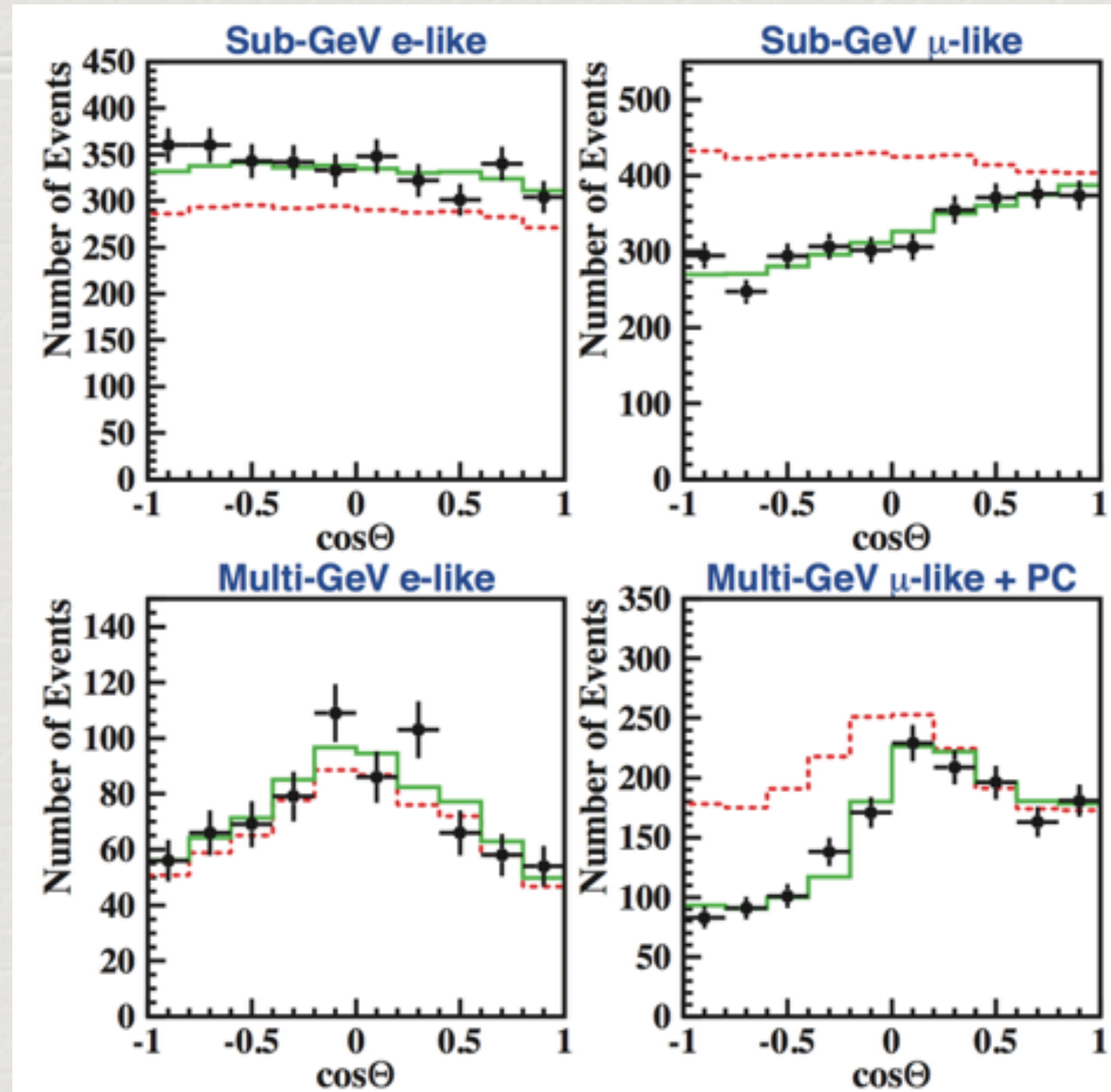
Atmospheric Nu Experiments

Nobel Prize 2015



Super-Kamiokande Data



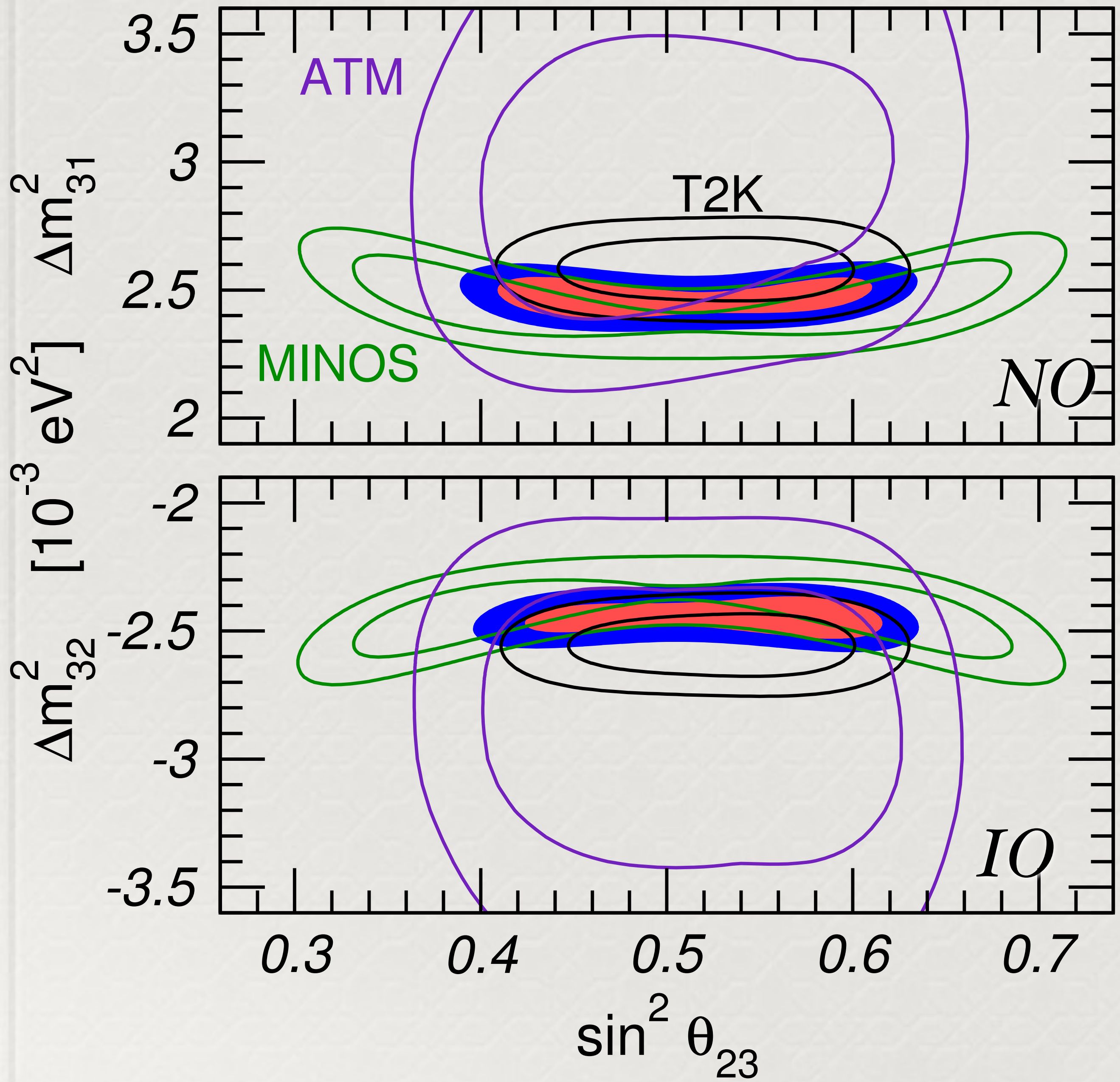


The announcement of the discovery of neutrino oscillation at Neutrino 98 by T. Kajita

CONFIRMED BY K2K, MINOS, T2K AND NOνA EXPERIMENTS

Atmospheric Nu Parameters

Gonzalez-Garcia, Maltoni, Schwetz, 1409.5439



Using only disappearance data from atmospheric and LBL Expts

Bound on $|\Delta m^2_{3l}|$ comes also from Daya Bay

Reactor Experiments

degrees of freedom). All best estimates of pull parameters are within its 1 standard deviation based on the correspond-

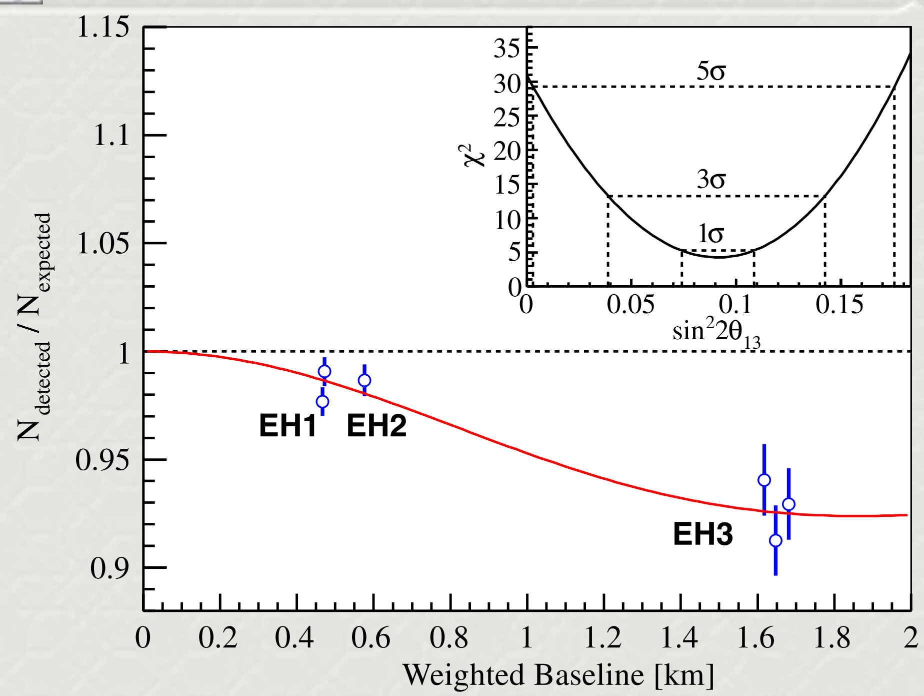
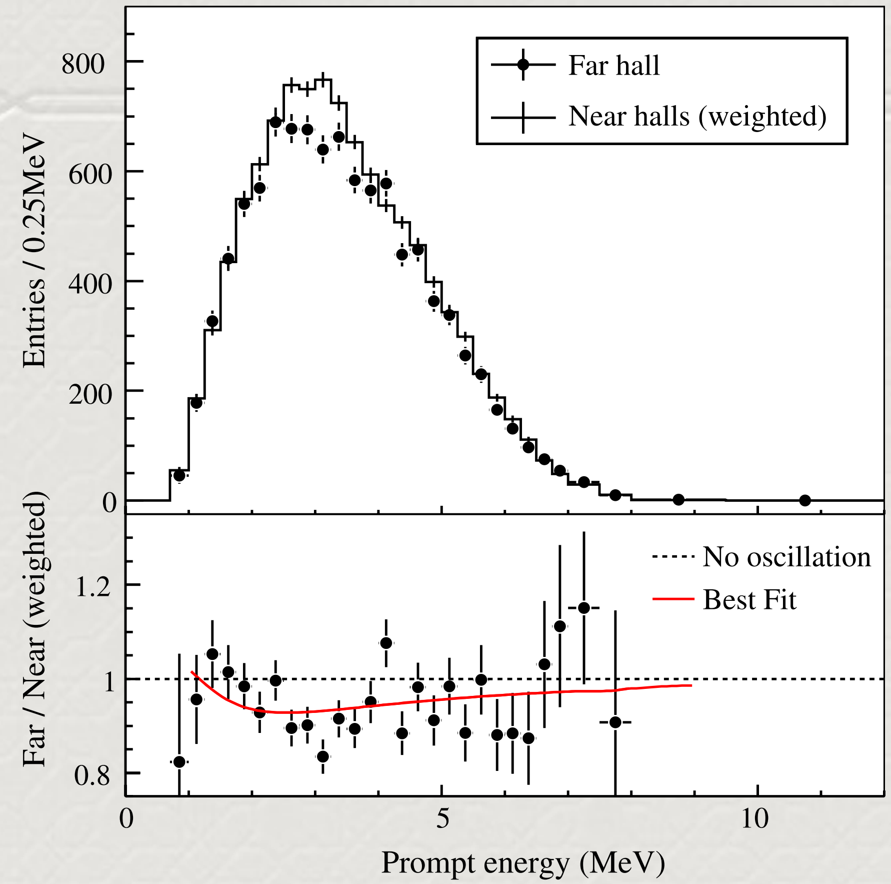
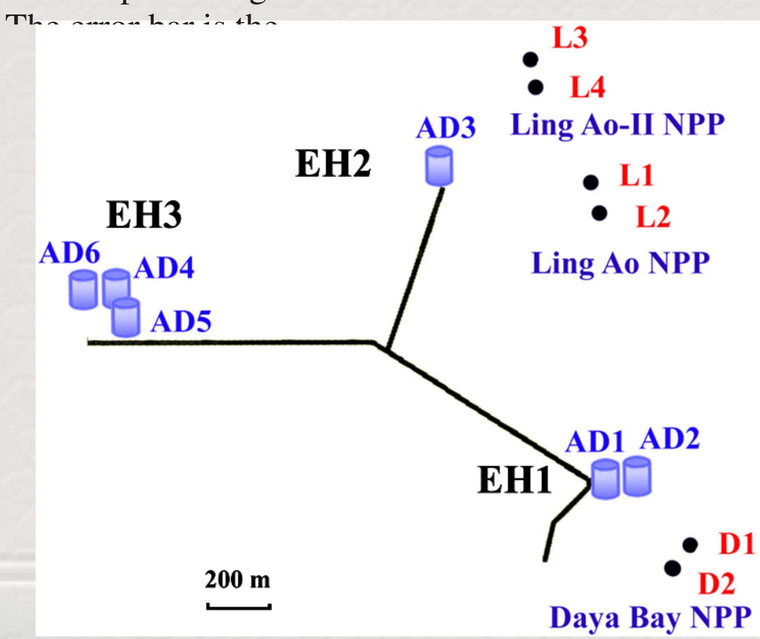
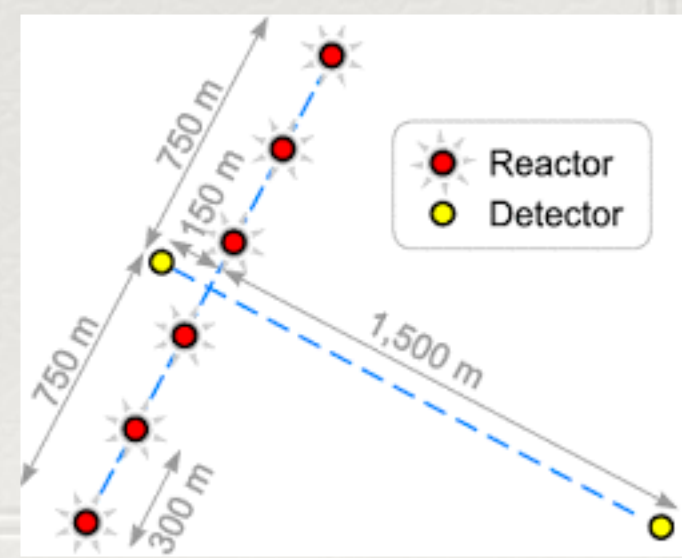


FIG. 4 (color online). Ratio of measured versus expected sig-

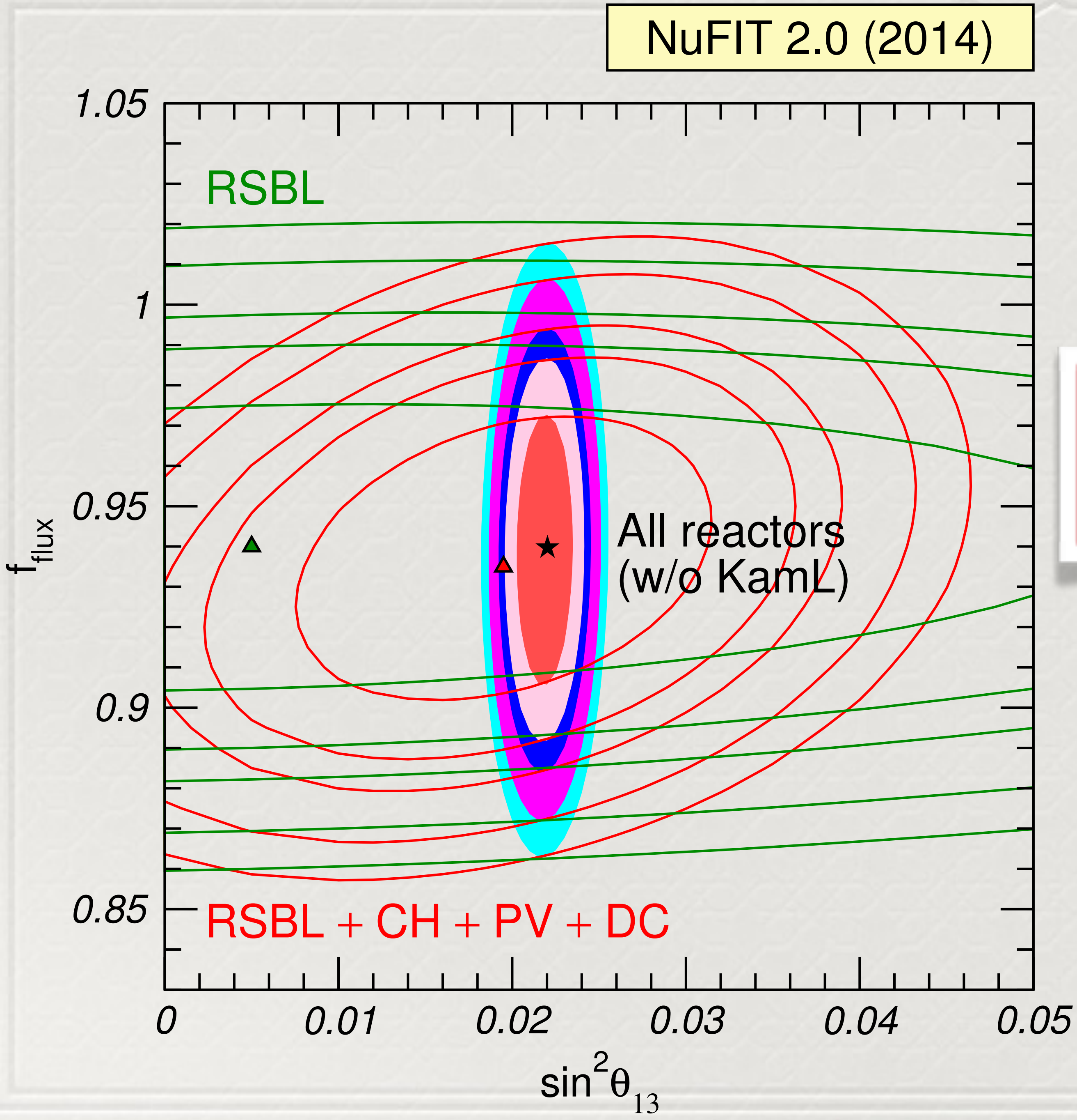






Issue with the reactor fluxes

Gonzalez-Garcia, Maltoni, Schwetz, 1409.5439



Not a problem for oscillation analysis once near detector is added

Three Flavor Oscillations

$$|\nu_f\rangle = \sum_{i=1}^{3} U^*_{fi} |\nu_i\rangle$$

Flavor Eigenstate

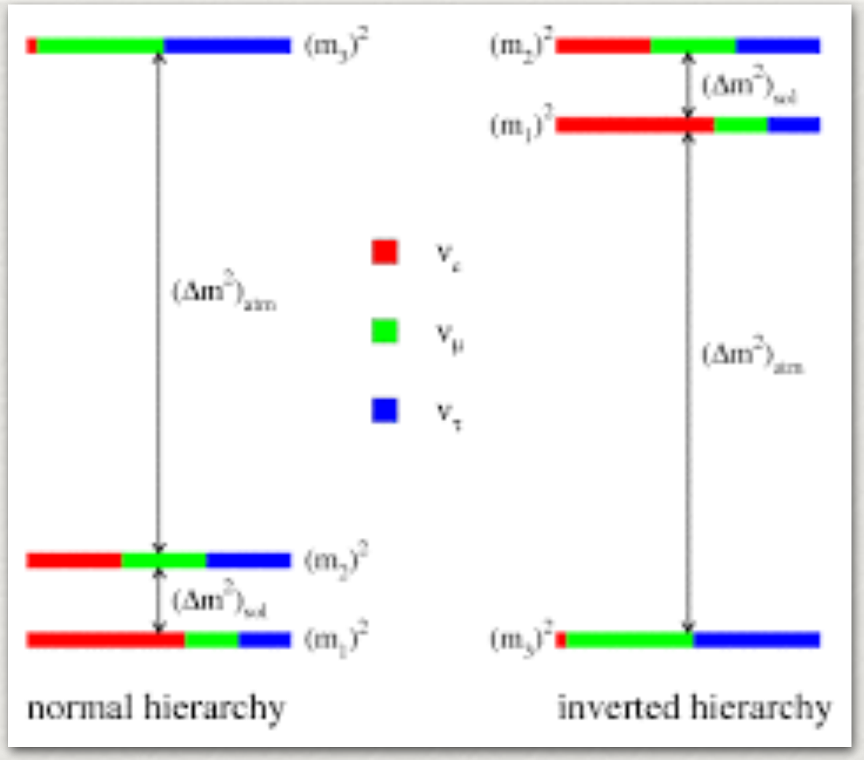
PMNS Mixing Matrix

Mass Eigenstate

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} e^{i\alpha_1/2} & 0 & 0 \\ 0 & e^{i\alpha_2/2} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$$P_{\alpha\beta} = \delta_{\alpha\beta} - 4 \sum_{i>j} \mathcal{R}(U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j}) \sin^2(\Delta m^2_{ij} L/4E)$$
$$\pm 2 \sum_{i>j} \mathcal{I}(U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j}) \sin(\Delta m^2_{ij} L/2E)$$

Three Flavor Oscillations



# of parameters involved

3 masses => 2 mass sq diff Δm^2_{21} *and* Δm^2_{31}
and the absolute mass scale
3 mixing angles $\theta_{12}, \theta_{13}, \theta_{23}$
1 "Dirac" CP phase δ
2 "Majorana" CP phases α_1 α_2

Since $|\Delta m^2_{31}| >> |\Delta m^2_{21}|$ → Oscillations decouple and we can work with 2-flavor approx

Three Flavor Oscillations

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} e^{i\alpha_1/2} & 0 & 0 \\ 0 & e^{i\alpha_2/2} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Atmospheric
Accelerator

Reactor
Accelerator

Solar
Reactor

Neutrinoless
double beta dk

The Knowns

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} e^{i\alpha_1/2} & 0 & 0 \\ 0 & e^{i\alpha_2/2} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Atmospheric Accelerator	Reactor Accelerator	Solar Reactor	Neutrinoless double beta dk
$\lvert\Delta m^2_{31}\rvert, \sin^2 2\theta_{23}$	$\sin^2\theta_{13}$	Δm^2_{21} , $\sin^2\theta_{12}$	

The Unknowns

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} e^{i\alpha_1/2} & 0 & 0 \\ 0 & e^{i\alpha_2/2} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Atmospheric
Accelerator

Reactor
Accelerator

Solar
Reactor

Neutrinoless
double beta dk

sgn(Δm^2_{31}),*octant of* θ_{23}

δ_{CP}

Issues with solar
and KamLAND

As well as the absolute neutrino mass scale - 0vbb, beta dk, cosmology

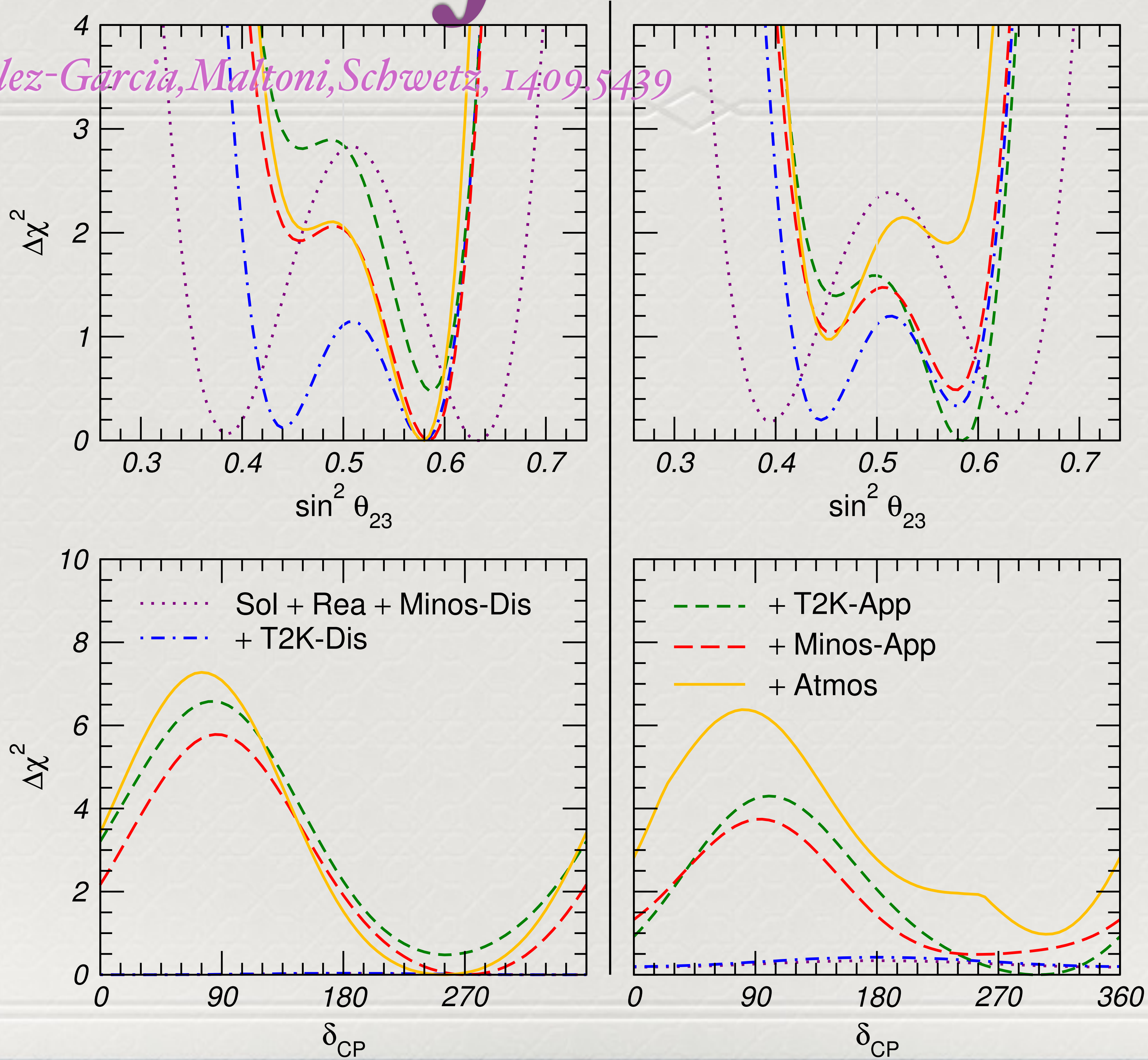
Results of Global Analyses

Gonzalez-Garcia, Maltoni, Schwetz, 1409.5439

	Normal Ordering ($\Delta\chi^2 = 0.97$)		Inverted Ordering (best fit)		Any Ordering
	bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range	3σ range
$\sin^2\theta_{12}$	$0.304^{+0.013}_{-0.012}$	$0.270 \to 0.344$	$0.304^{+0.013}_{-0.012}$	$0.270 \to 0.344$	$0.270 \to 0.344$
$\theta_{12}/^\circ$	$33.48^{+0.78}_{-0.75}$	$31.29 \to 35.91$	$33.48^{+0.78}_{-0.75}$	$31.29 \to 35.91$	$31.29 \to 35.91$
$\sin^2\theta_{23}$	$0.452^{+0.052}_{-0.028}$	$0.382 \to 0.643$	$0.579^{+0.025}_{-0.037}$	$0.389 \to 0.644$	$0.385 \to 0.644$
$\theta_{23}/^\circ$	$42.3^{+3.0}_{-1.6}$	$38.2 \to 53.3$	$49.5^{+1.5}_{-2.2}$	$38.6 \to 53.3$	$38.3 \to 53.3$
$\sin^2\theta_{13}$	$0.0218^{+0.0010}_{-0.0010}$	$0.0186 \to 0.0250$	$0.0219^{+0.0011}_{-0.0010}$	$0.0188 \to 0.0251$	$0.0188 \to 0.0251$
$\theta_{13}/^\circ$	$8.50^{+0.20}_{-0.21}$	$7.85 \to 9.10$	$8.51^{+0.20}_{-0.21}$	$7.87 \to 9.11$	$7.87 \to 9.11$
$\delta_{CP}/^\circ$	306^{+39}_{-70}	$0 \to 360$	254^{+63}_{-62}	$0 \to 360$	$0 \to 360$
$\frac{\Delta m^2_{21}}{10^{-5}\ \text{eV}^2}$	$7.50^{+0.19}_{-0.17}$	$7.02 \to 8.09$	$7.50^{+0.19}_{-0.17}$	$7.02 \to 8.09$	$7.02 \to 8.09$
$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \text{eV}^2}$	$+2.457^{+0.047}_{-0.047}$	$+2.317 \to +2.607$	$-2.449^{+0.048}_{-0.047}$	$-2.590 \to -2.307$	$\begin{bmatrix} +2.325 \to +2.599 \\ -2.590 \to -2.307 \end{bmatrix}$

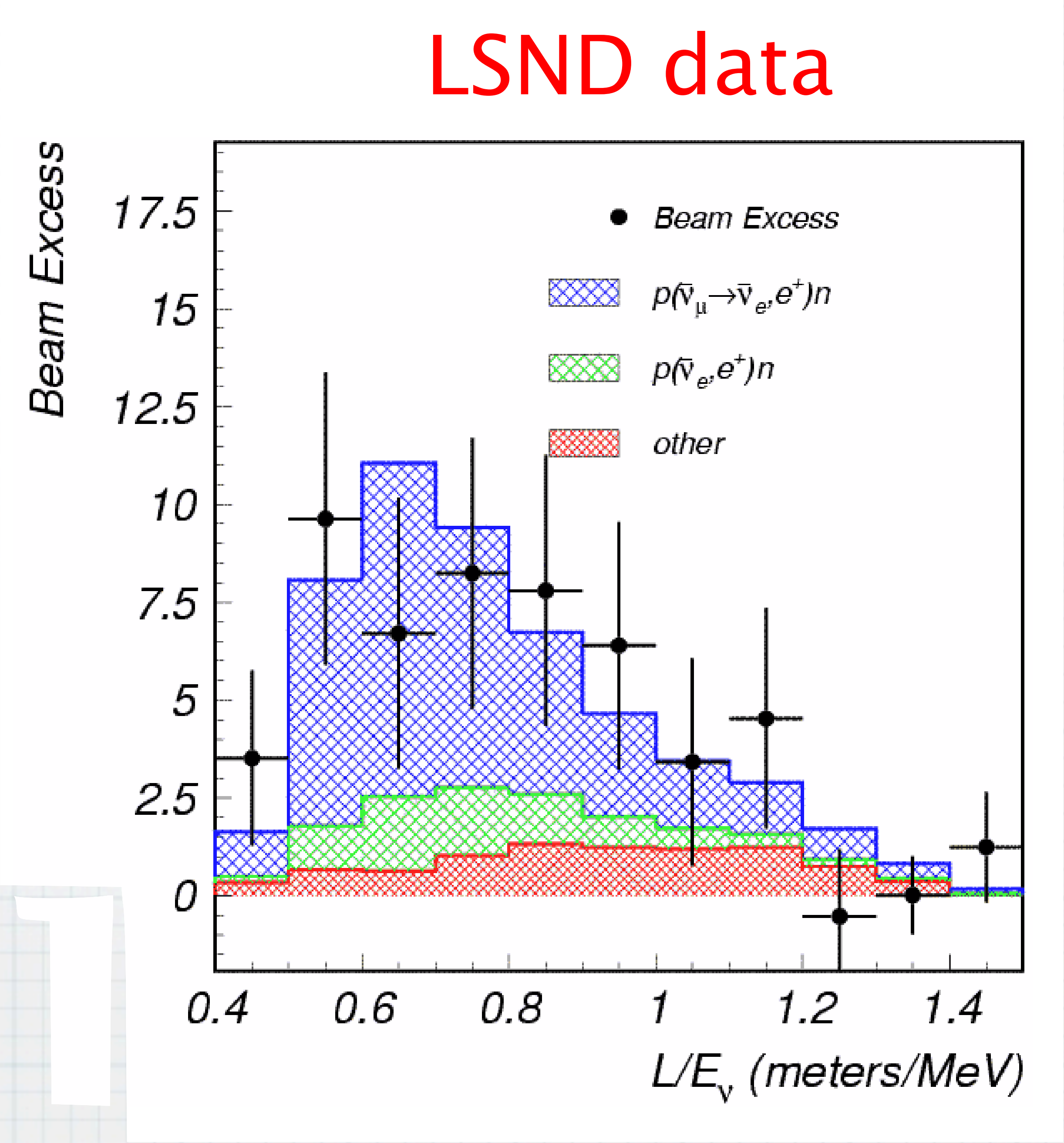
Results of Global Analyses

Gonzalez-Garcia, Maltoni, Schwetz, 1409.5439



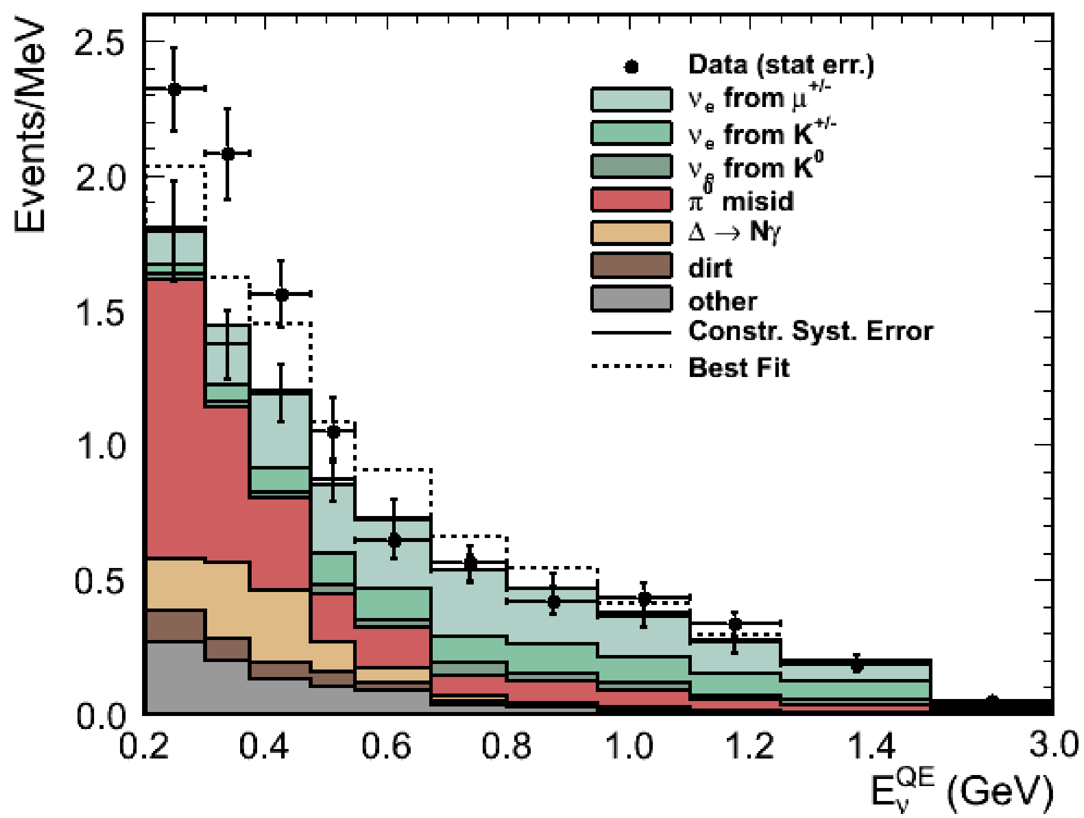
LSND

* 3.8σ excess in antineutrinos at L/E ≈ 0.4-1.2 m/MeV
* requires presence of sterile neutrino states with $\Delta m^2 = 1\ eV^2$

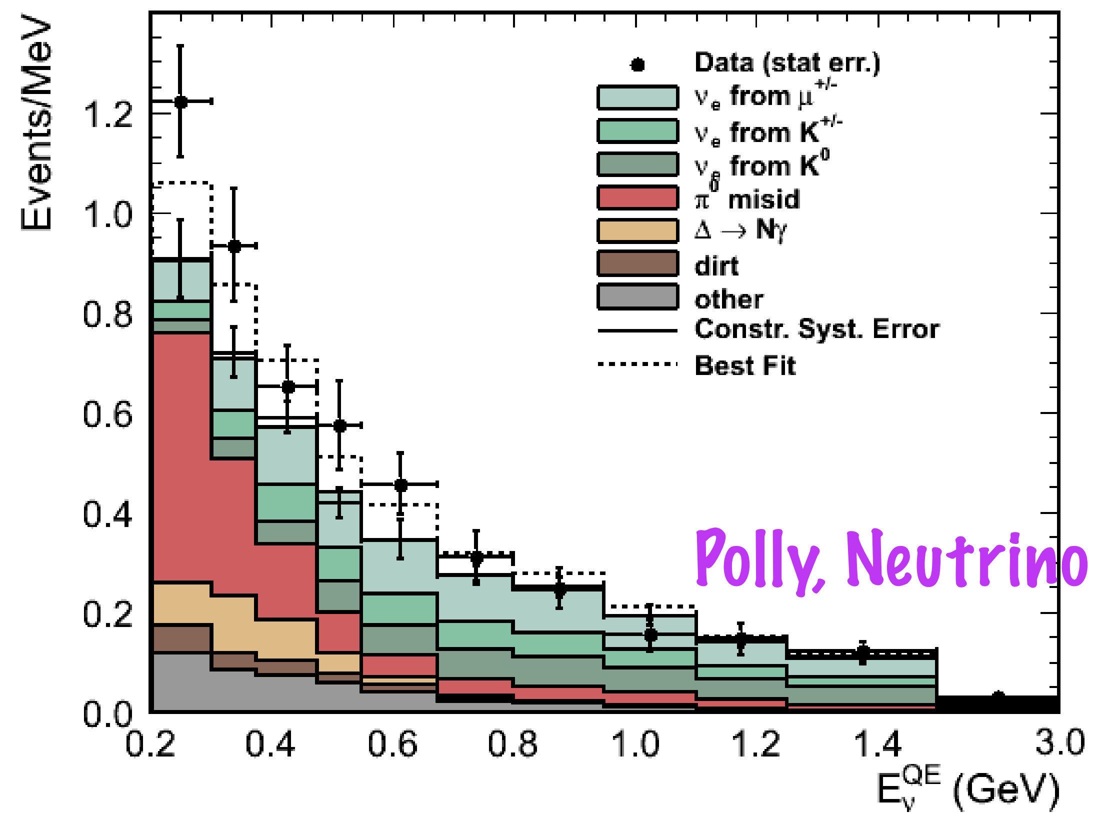


MiniBooNE

6.5e20 POT neutrino mode w/ 3+1 fit



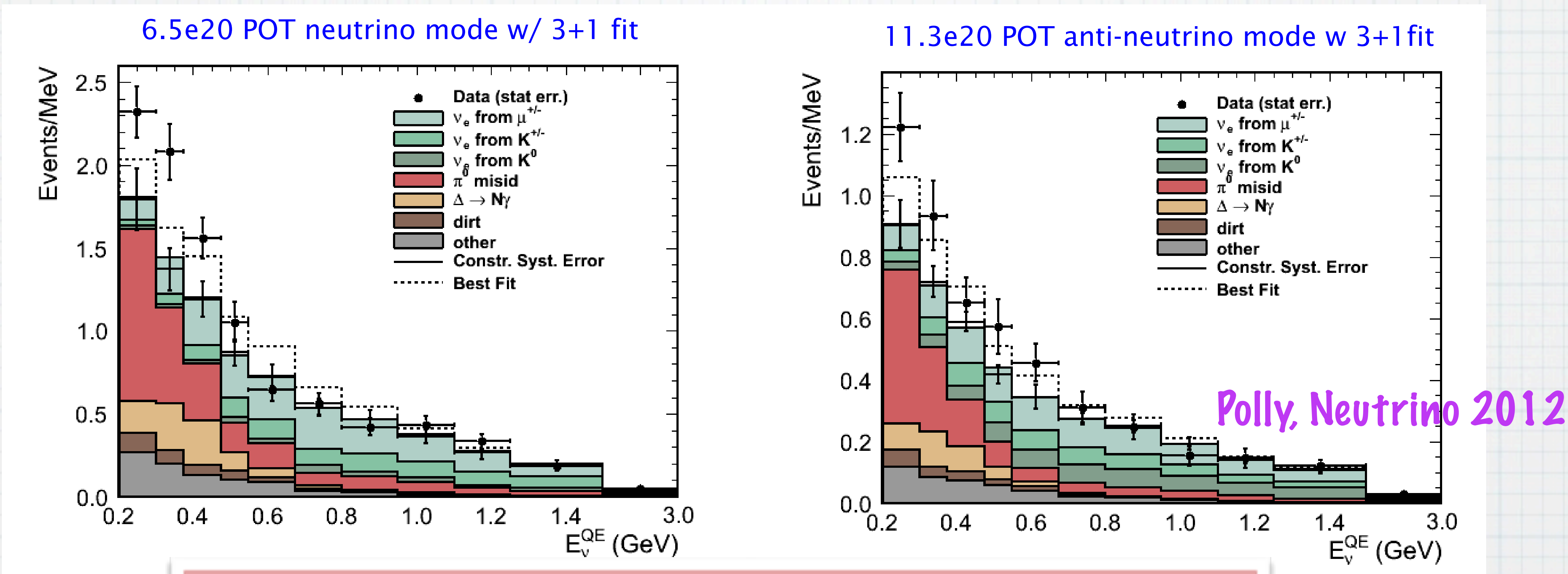
11.3e20 POT anti-neutrino mode w 3+1fit



Polly, Neutrino 2012

- Neutrino and anti-neutrino data now consistent
- Together they see a 3.8σ excess....LSND??

MiniBooNE

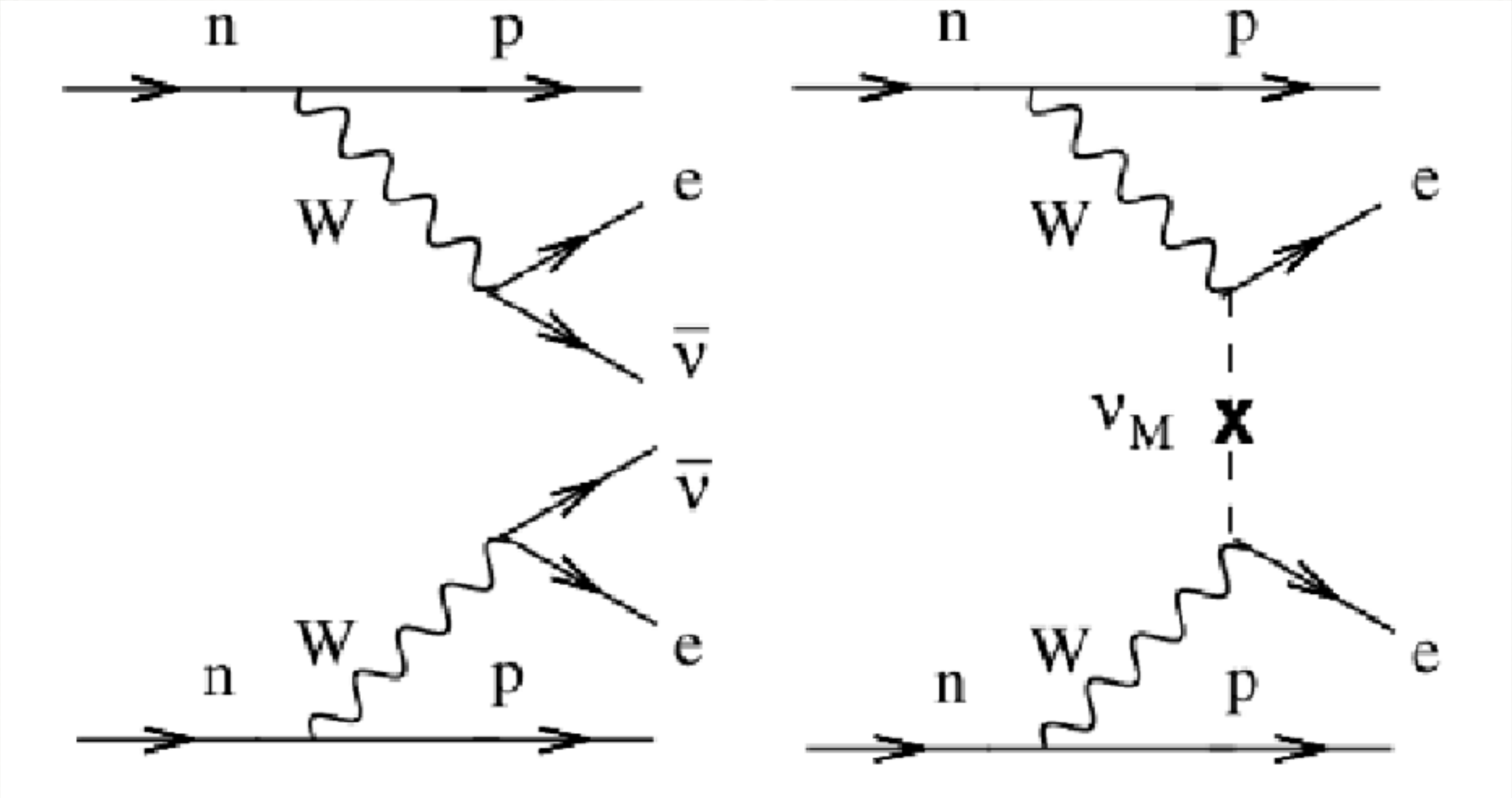


* Neutr … tent

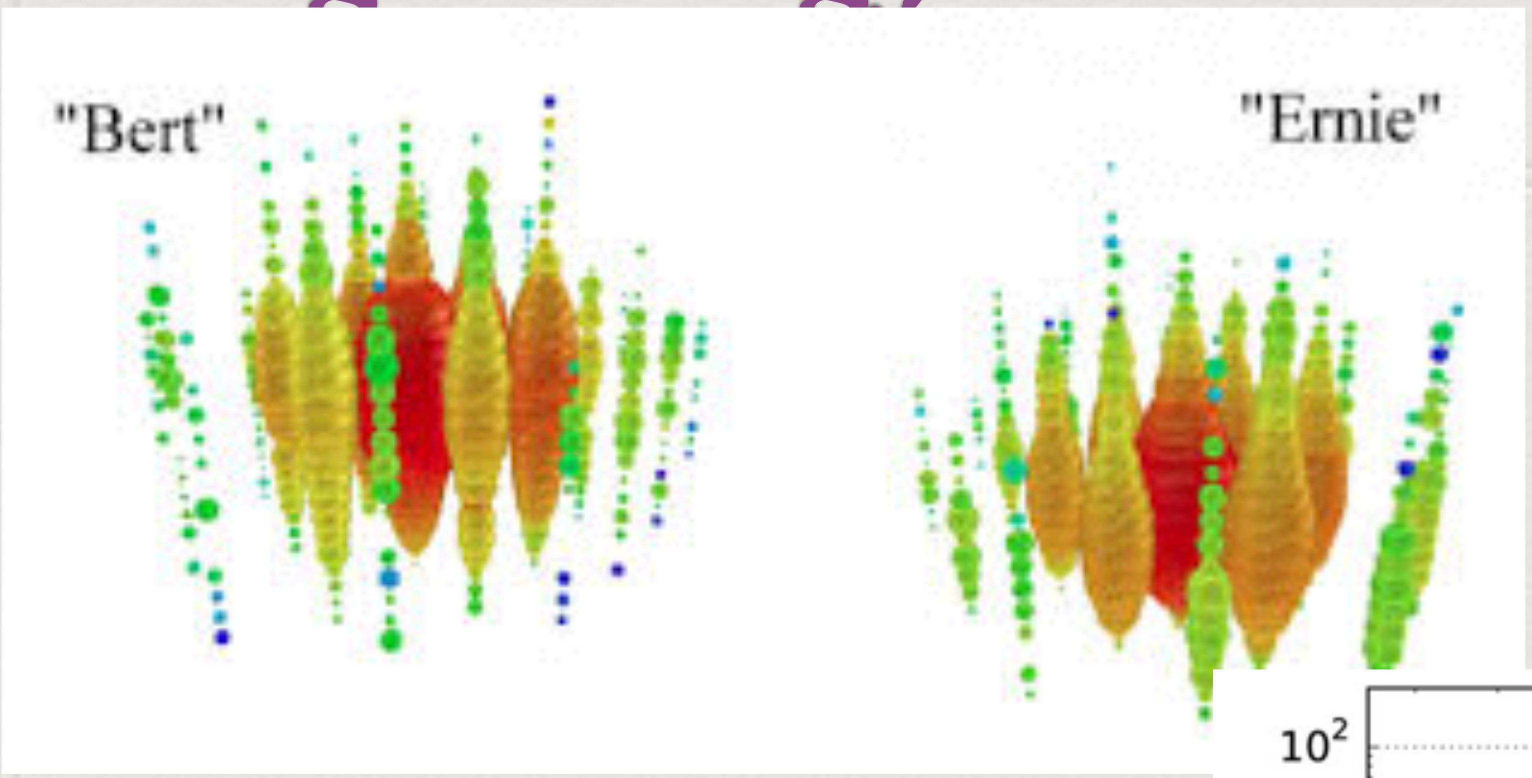
Conflict with neutrino mass bounds from cosmological data

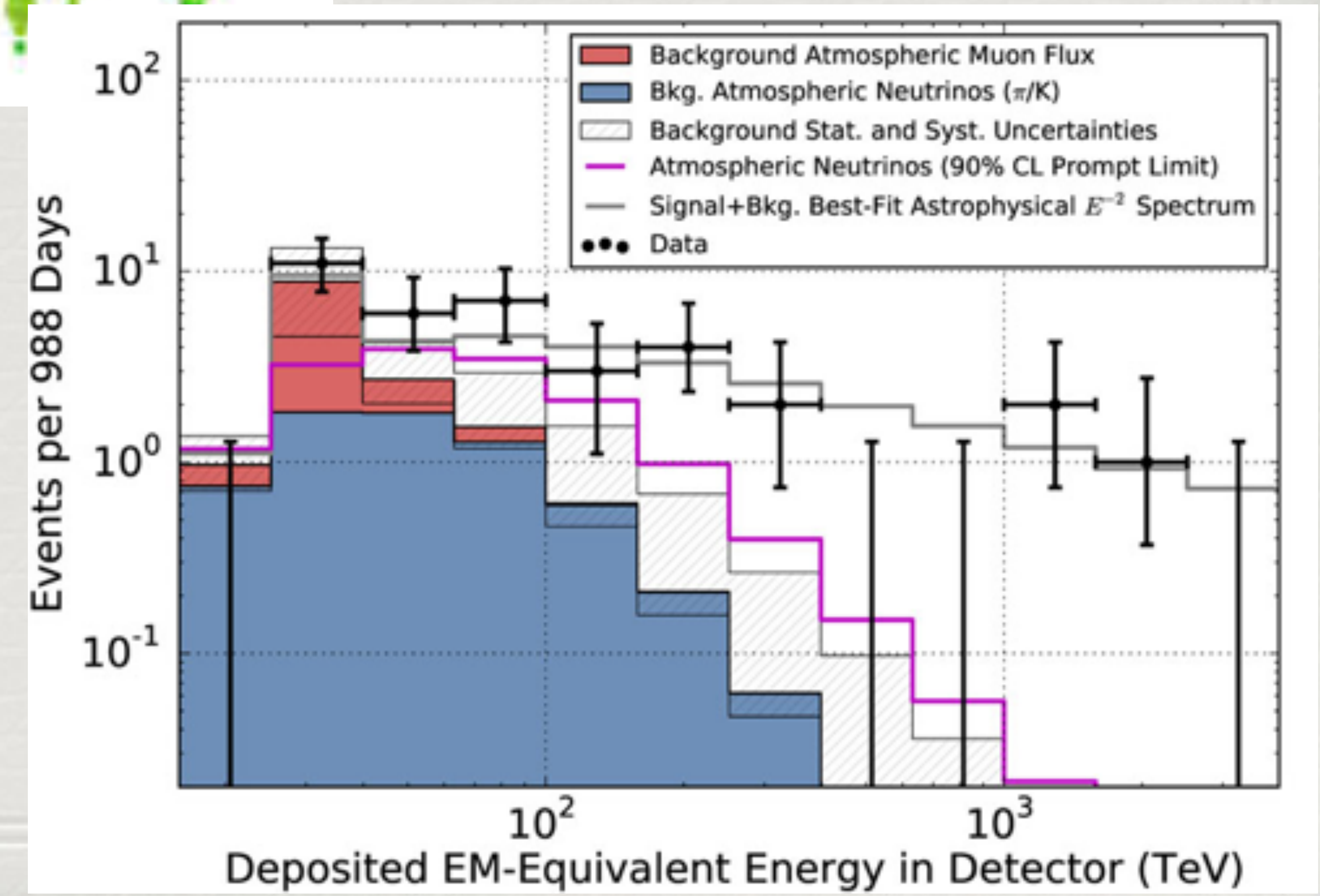
* Together they see a 3.8σ excess....LSND??

Neutrinoless Double Beta Decay

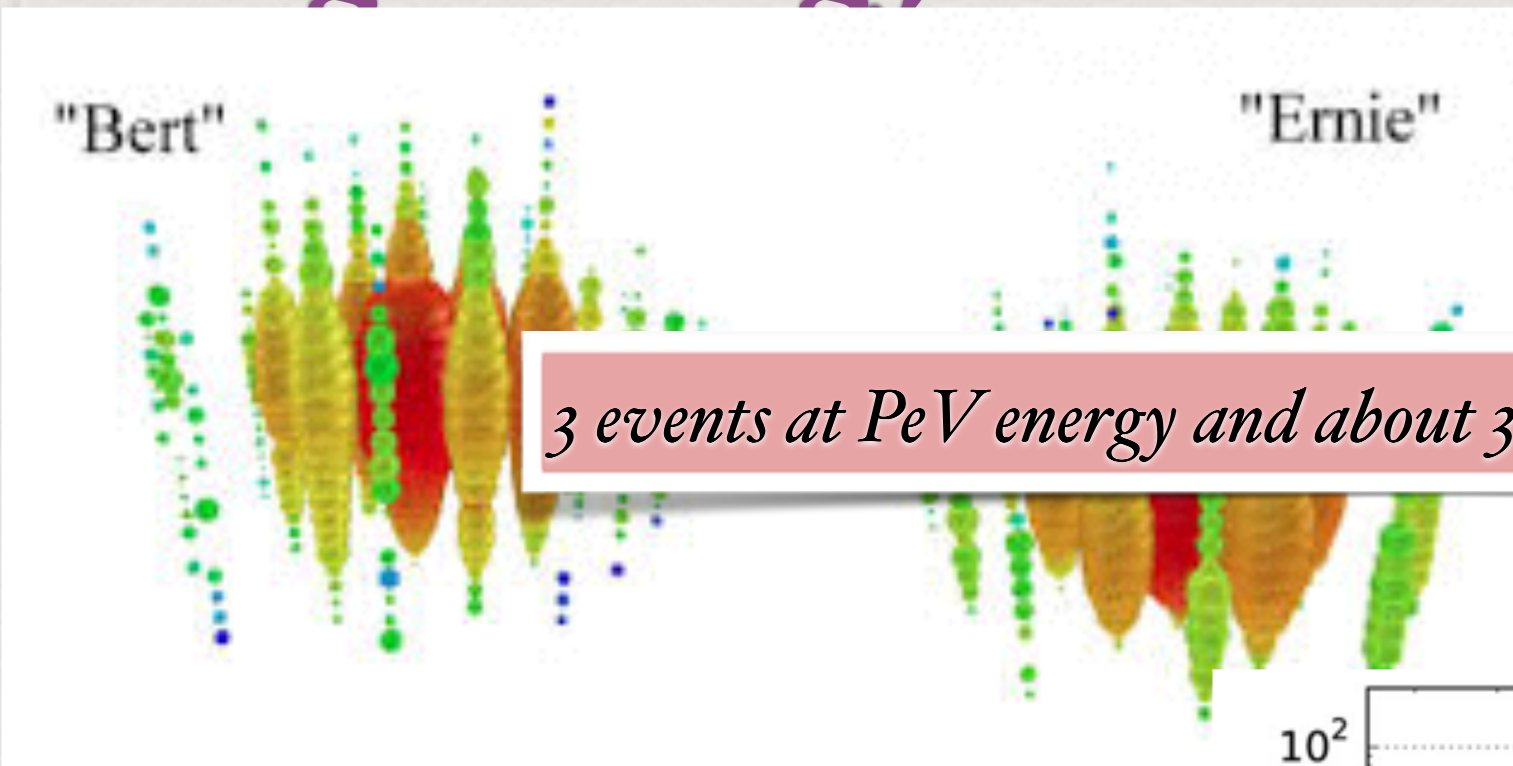


High Energy Neutrinos at IceCube

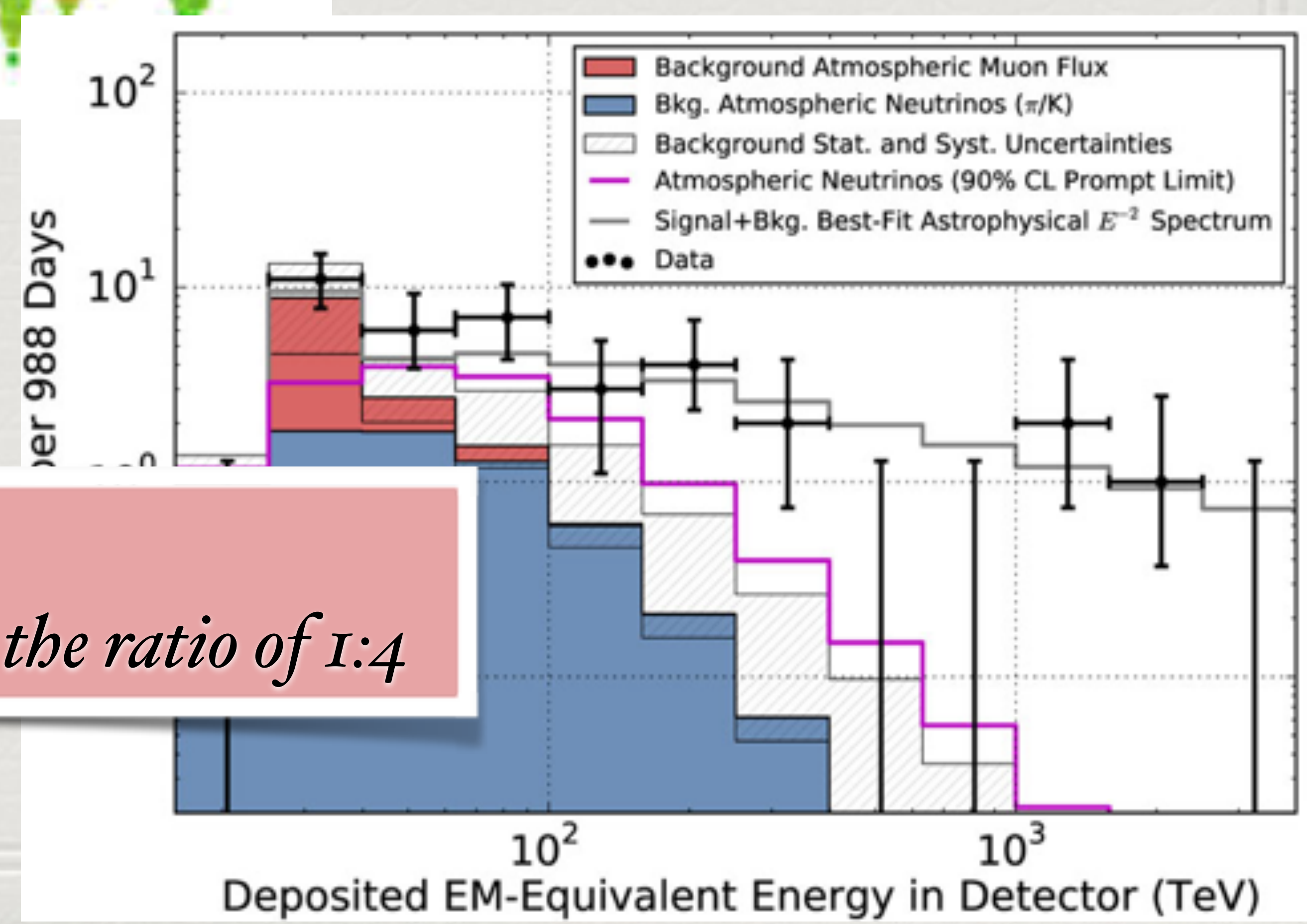




High Energy Neutrinos at IceCube



3 events at PeV energy and about 30 odd events in the TeV range



The 3 PeV events are shower events
The TeV events have tracks to shower in the ratio of 1:4

Future

- Many on-going and proposed projects

- Main physics goals to be probed are the **neutrino mass ordering** and **CP violation** and measurement of the CP phase

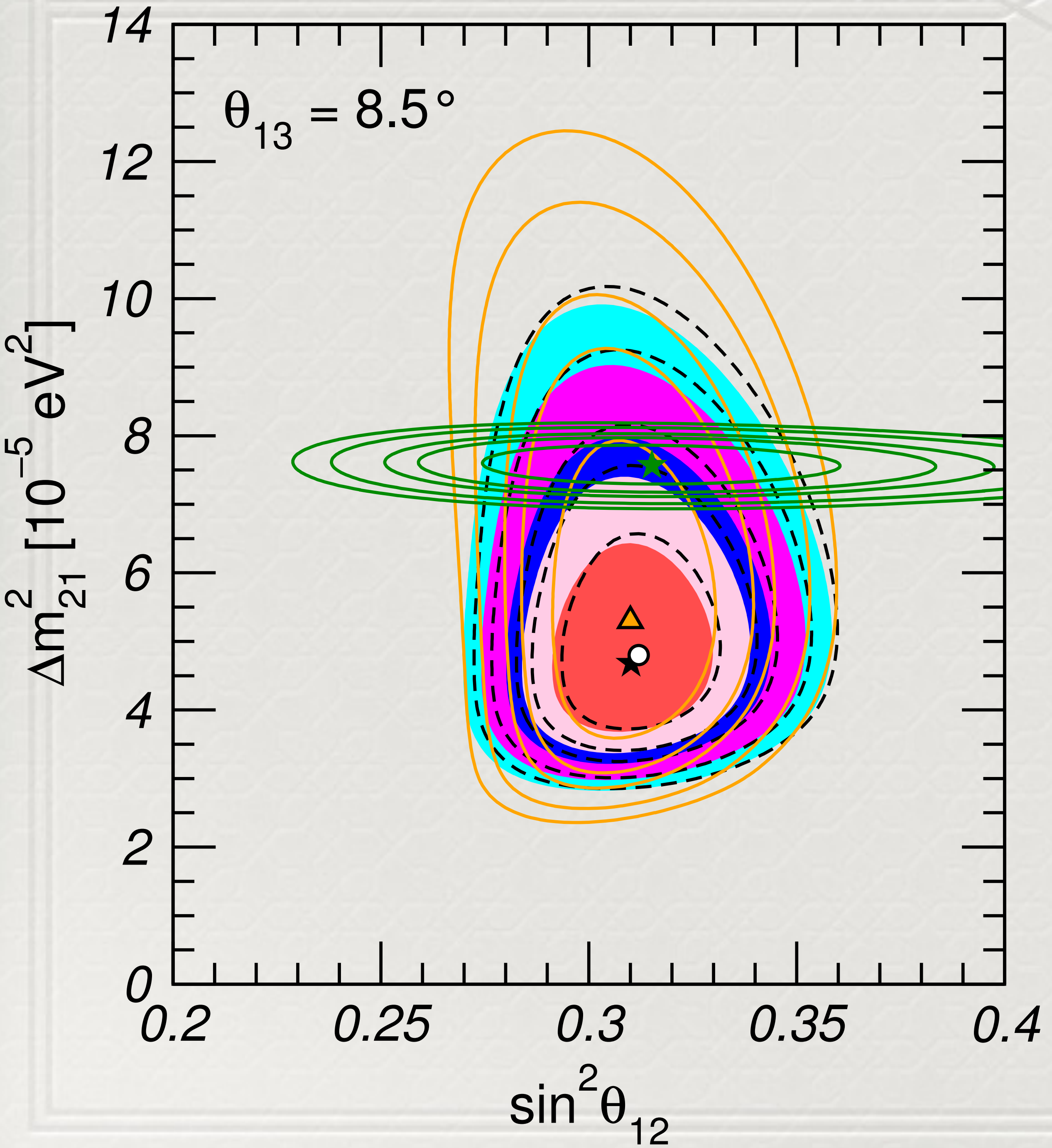
- There could be **new physics** hiding behind the dominant the mass-driven dominant flavor oscillations

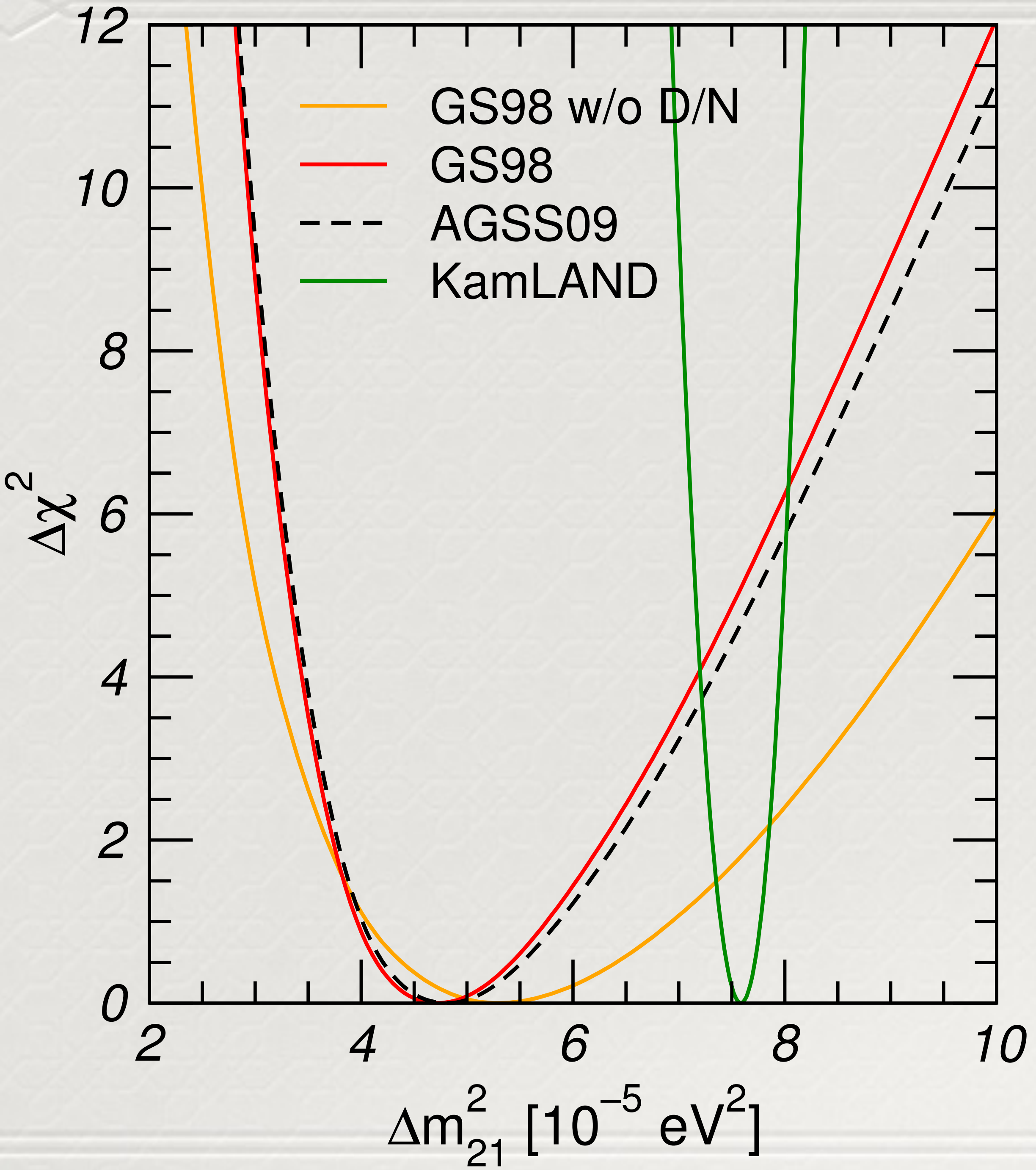
- There could be **degeneracies between new physics and standard oscillations**

Solar Nu Parameters

NuFIT 2.0 (2014)

Gonzalez-Garcia, Maltoni, Schwetz, 1409.5439





Solar Nu Parameters

$$P_{ee}^{2\nu,\text{sun}} \simeq 1 - \frac{1}{2}\sin^2(2\theta_{12}) \qquad \text{for } E_\nu \lesssim \text{few} \times 100 \text{ KeV}$$

$$P_{ee}^{2\nu,\text{sun}} \simeq \sin^2(\theta_{12}) \qquad \text{for } E_\nu \gtrsim \text{few} \times 1 \text{ MeV}$$

$$P_{ee}^{2\nu,\text{kam}} = 1 - \frac{1}{2}\sin^2(2\theta_{12})\sin^2\frac{\Delta m_{21}^2 L}{2E_\nu}\,.$$

Solar Mixing Angle

This determines the mixing angle theta12

$$P_{ee}^{2\nu,\text{sun}} \simeq 1 - \frac{1}{2}\sin^2(2\theta_{12}) \qquad \text{for } E_\nu \lesssim \text{few} \times 100\text{ KeV}$$

$$P_{ee}^{2\nu,\text{sun}} \simeq \sin^2(\theta_{12}) \qquad \text{for } E_\nu \gtrsim \text{few} \times 1\text{ MeV}$$

$$P_{ee}^{2\nu,\text{kam}} = 1 - \frac{1}{2}\sin^2(2\theta_{12})\sin^2\frac{\Delta m_{21}^2 L}{2E_\nu}\,.$$

weaker dependence

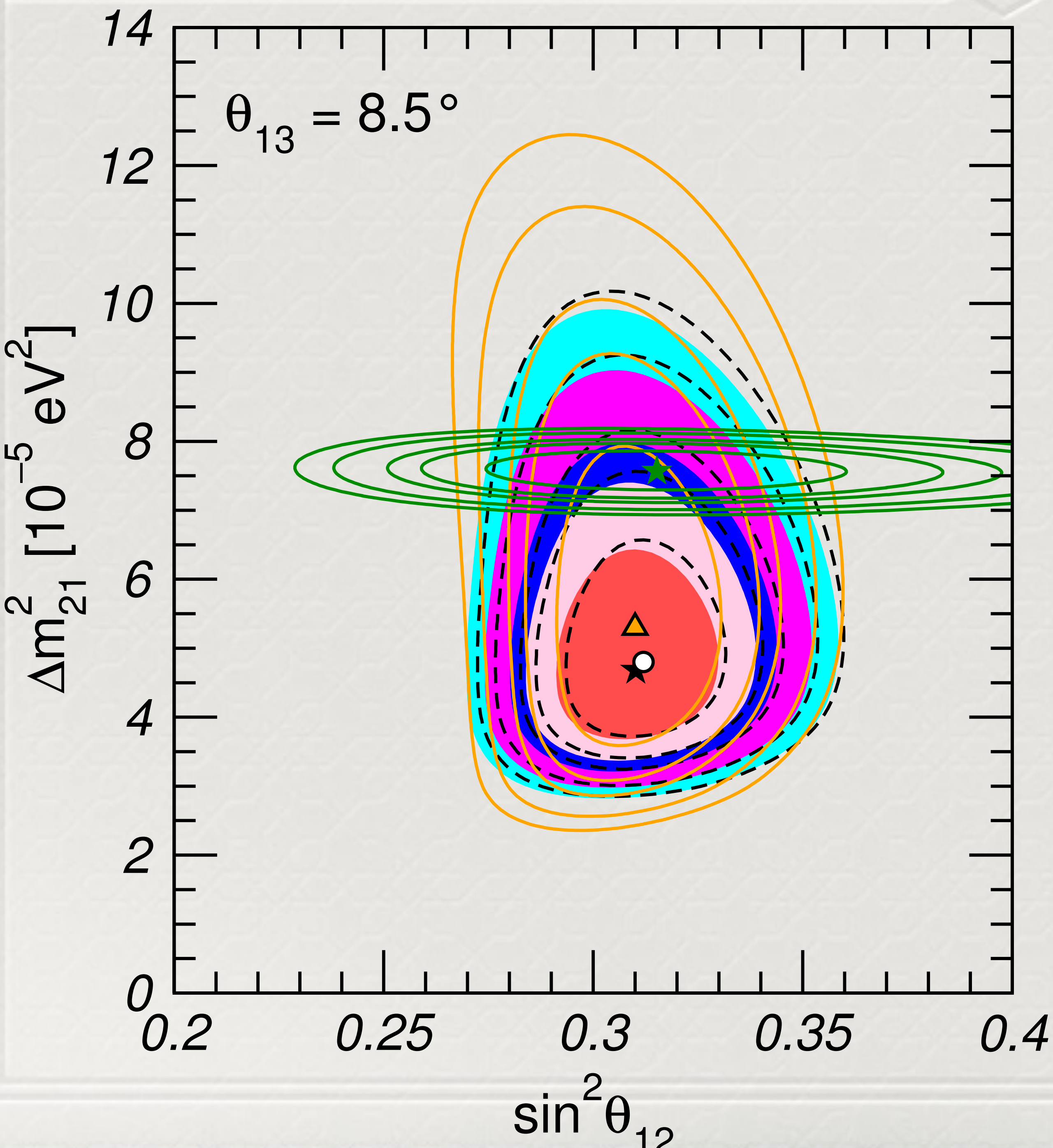
$$P_{ee}^{3\nu} = \sin^4\theta_{13} + \cos^4\theta_{13} P_{ee}^{2\nu}(\Delta m_{21}^2, \theta_{12})\,,$$

Reconciles solar with KamLAND

Fogli,Lisi,Marrone,Palazzo,Rotunno, 0806.2649

Solar Mixing Angle

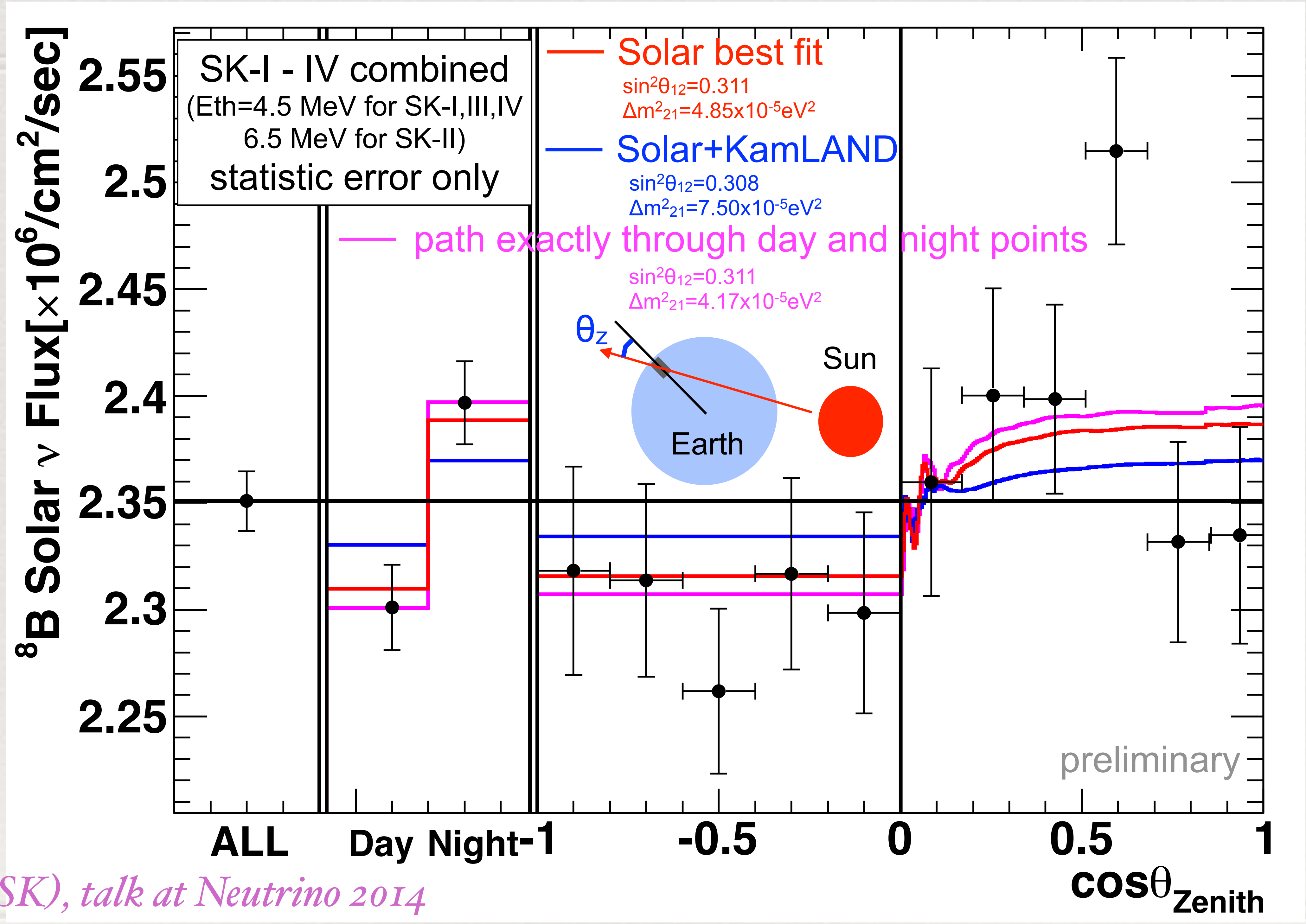
Gonzalez-Garcia, Maltoni, Schwetz, 1409.5439



Good agreement between Solar and KamLAND consistent with reactor theta13 measurement

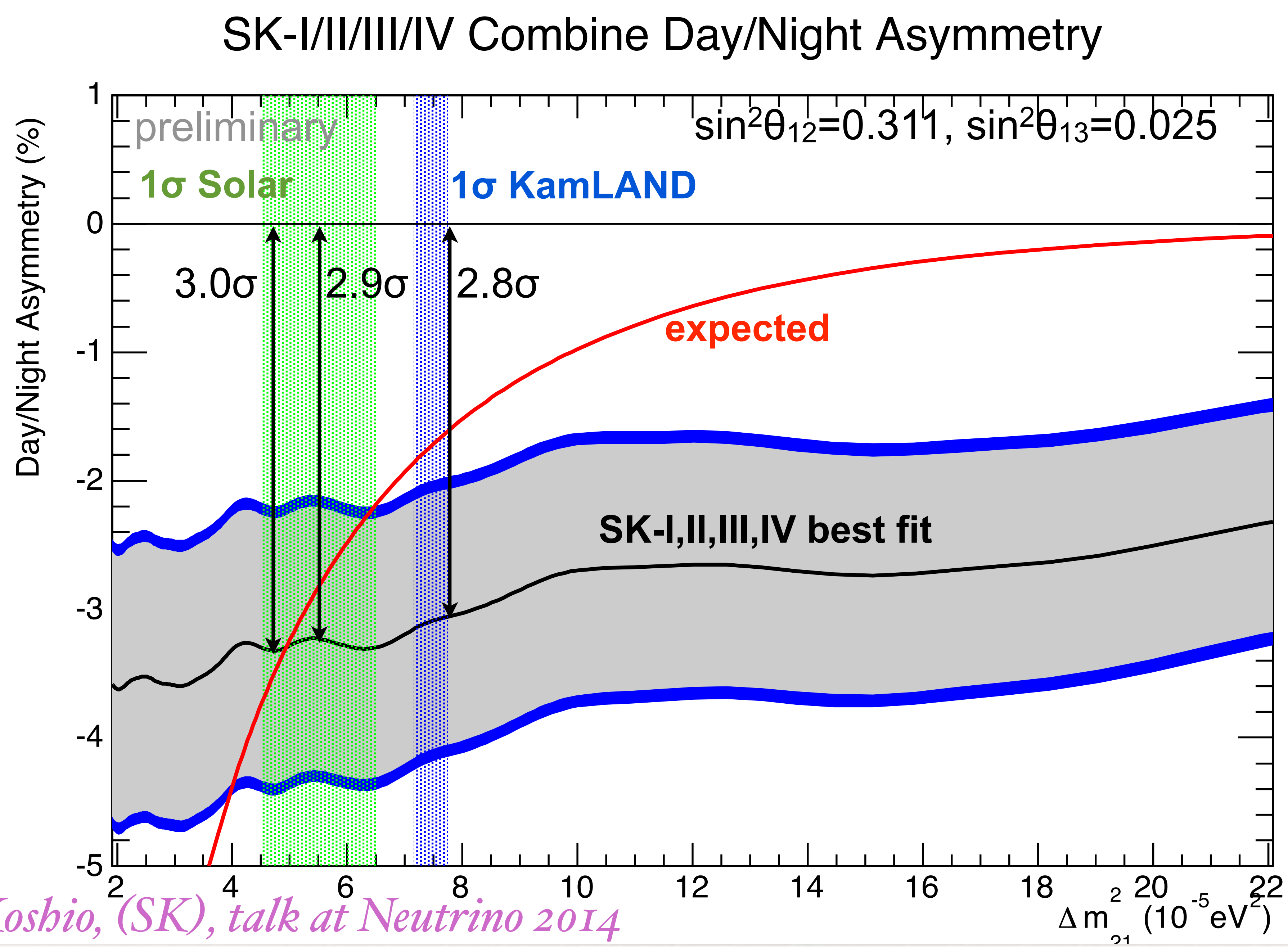
Situation with delmsq_21 is not so consistent

Solar D/N effect at SK



Koshio, (SK), talk at Neutrino 2014

Solar D/N effect at SK



Solar region

- ✓ differ from zero by 2.9~3.0σ
- ✓ agree with expect by 1.0σ

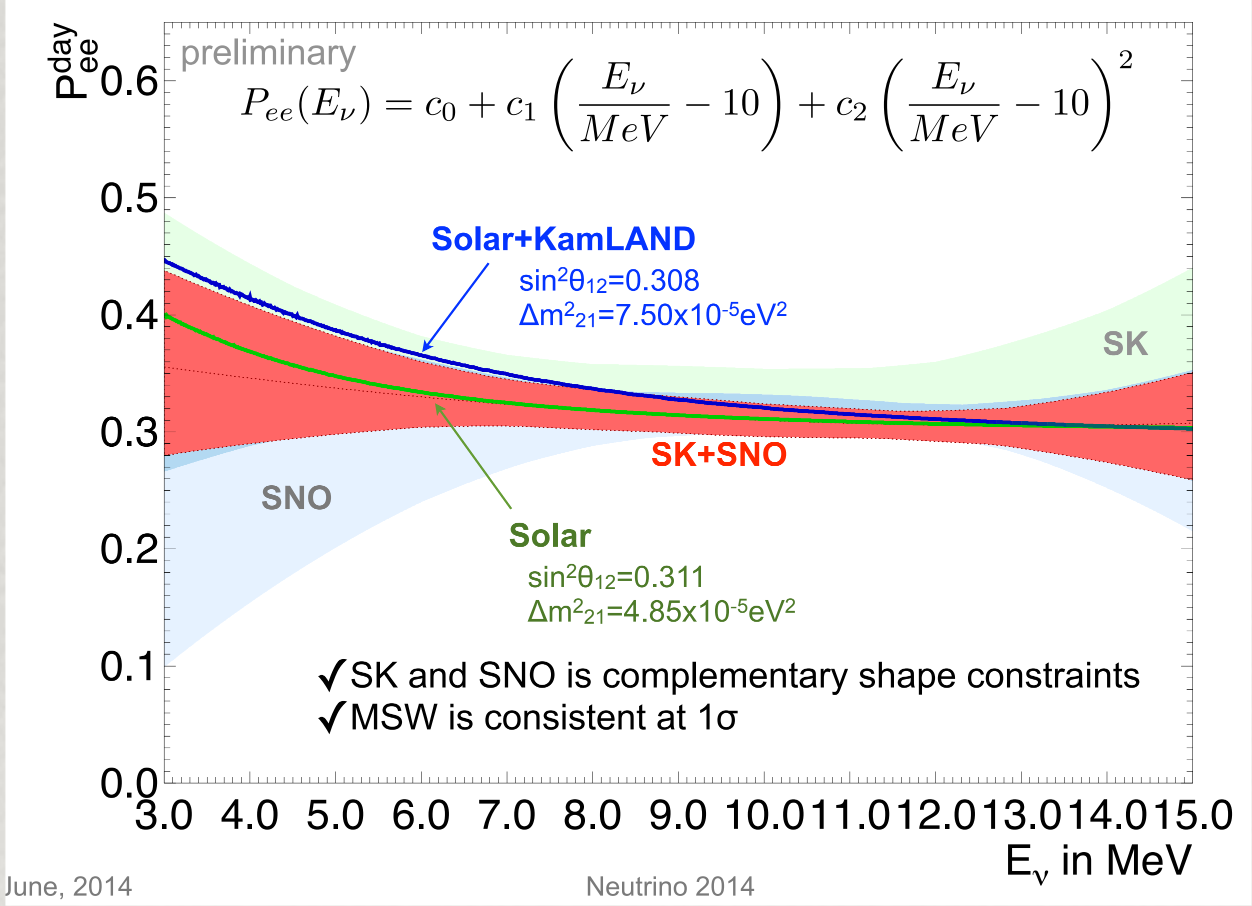
KamLAND region

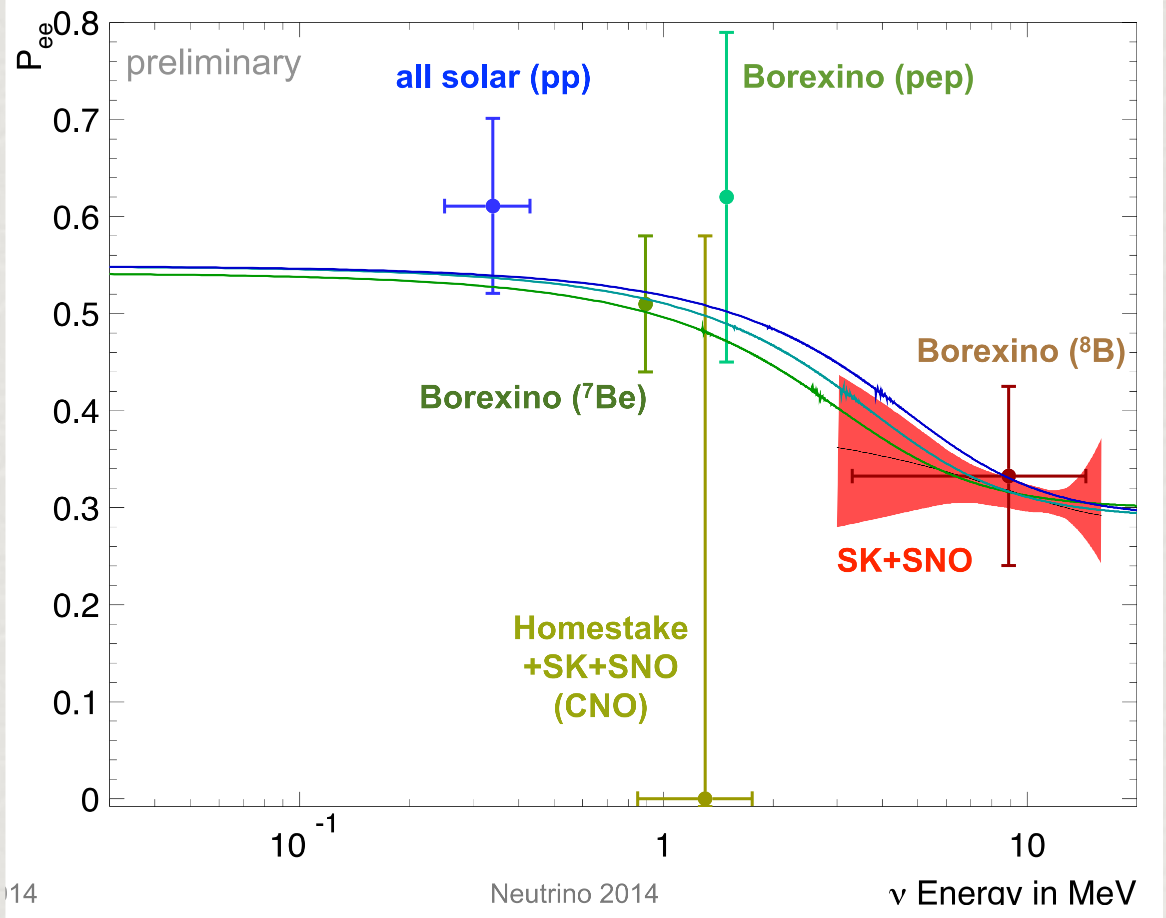
- ✓ differ from zero by more than 2.8σ
- ✓ agree with expect by 1.3σ

Koshio, (SK), talk at Neutrino 2014

Solar Neutrino Spectrum

Koshio, (SK), talk at Neutrino 2014

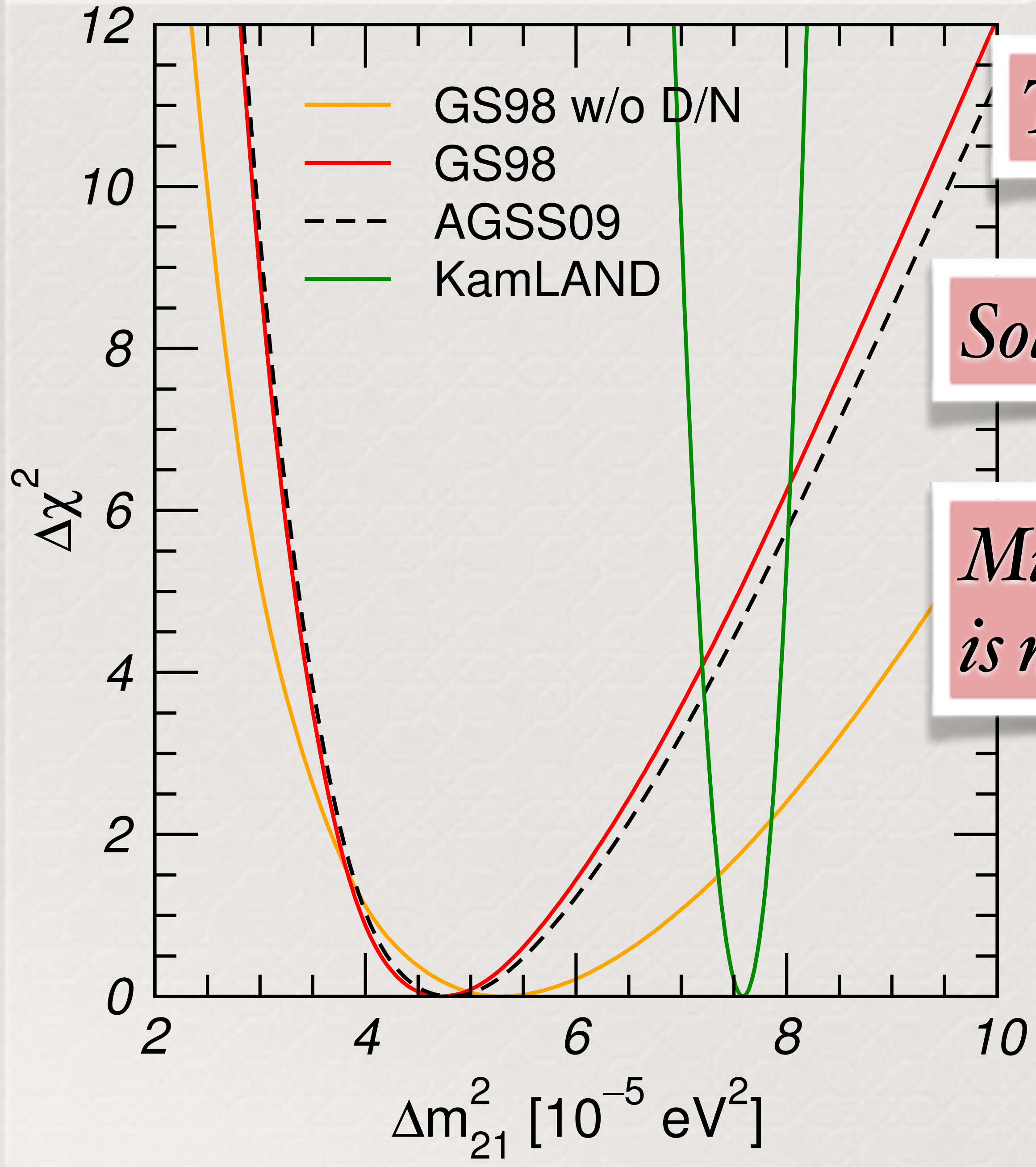




The upturn predicted by KL is missing in solar nu data - mild effect

Solar Mass Sq. Diff

Gonzalez-Garcia,Maltoni,Schwetz, 1409.5439



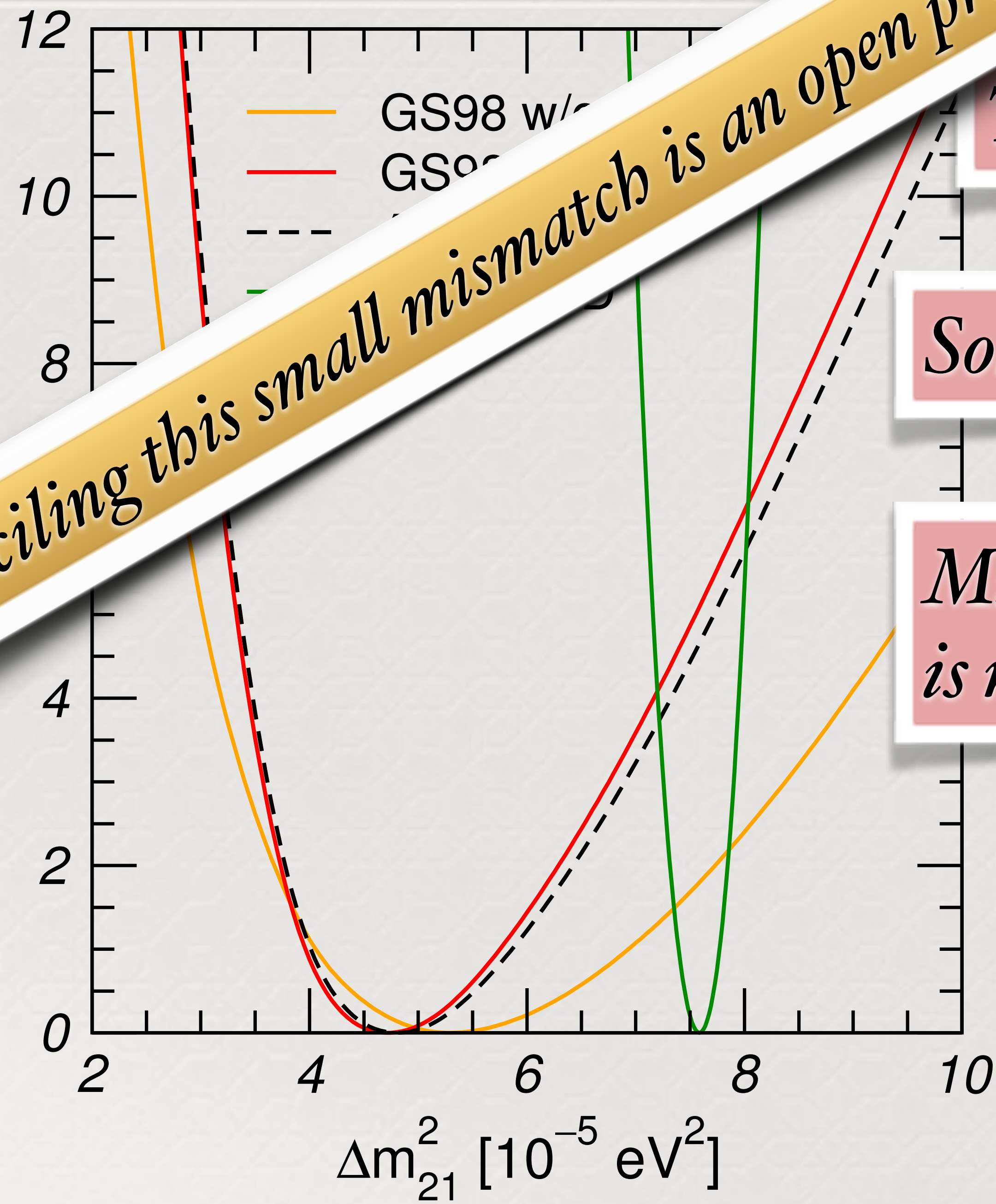
The diff SSM models are fairly consistent

Solar and KL bf Δm^2_{21} inconsistent at 2σ

Mismatch reduces to 1.4σ is SK D/N data is not included in the analysis

Solar Mass Sq. Diff

Gonzalez-Garcia,Maltoni,Schwetz, 14...



Reconciling this small mismatch is an open problem

The diff SSM models are fairly consistent

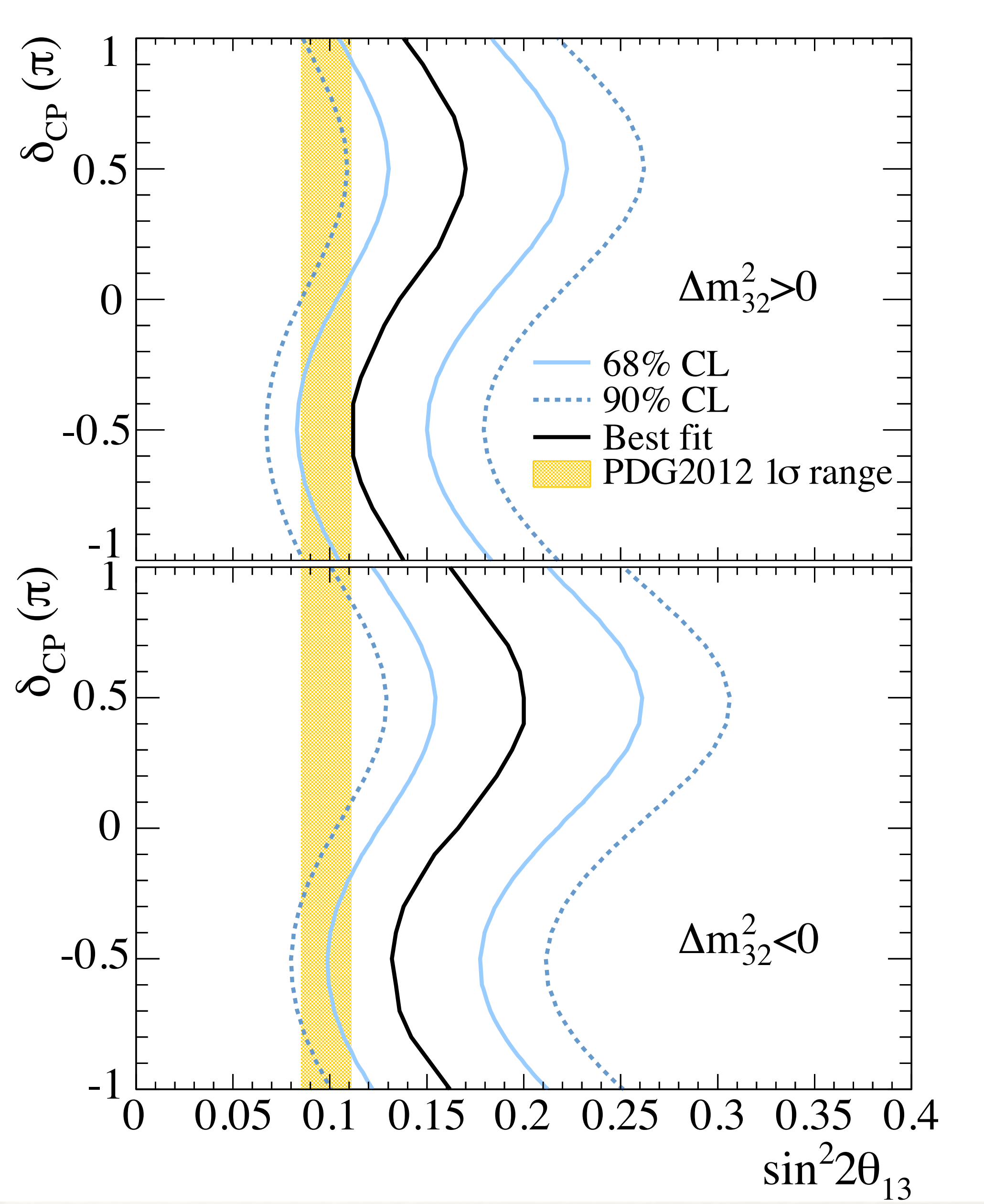
Solar and KL bf Δm^2_{21} inconsistent at 2σ

Mismatch reduces to 1.4σ is SK D/N data is not included in the analysis

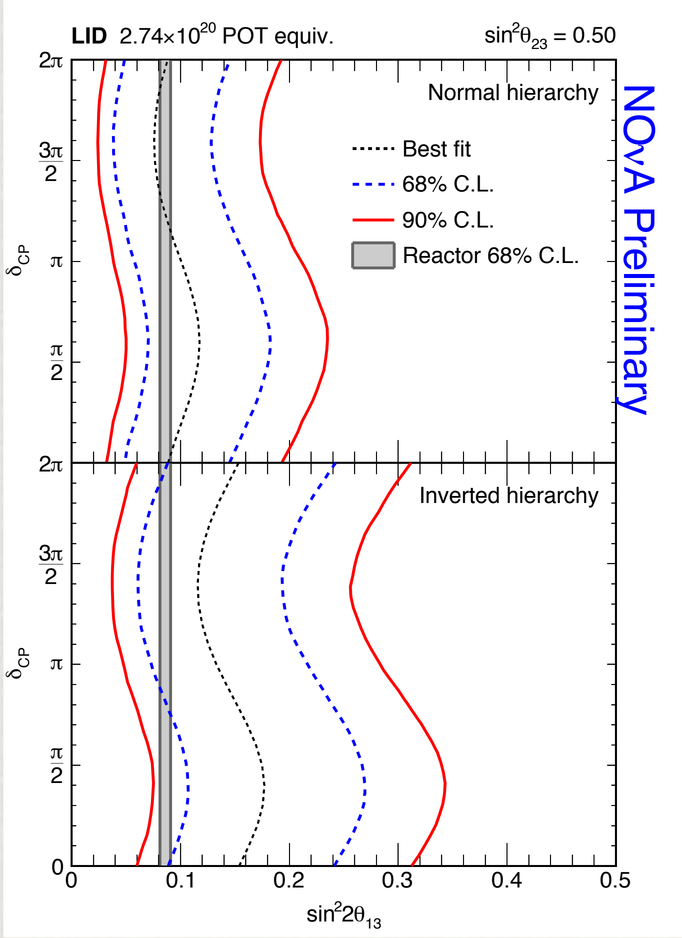
One needs new physics to explain it ?

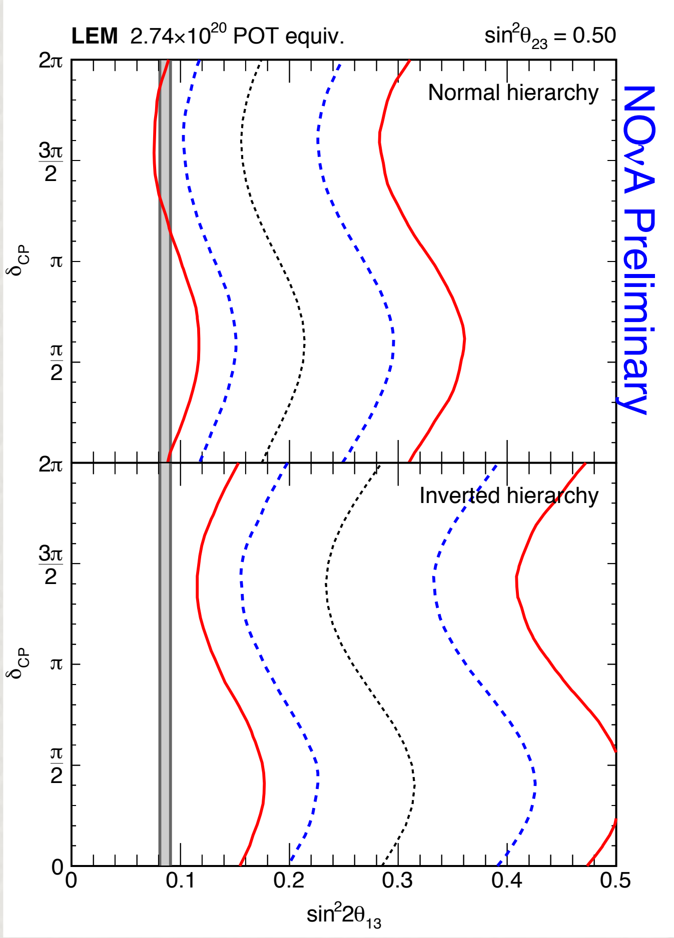
Accelerator Vs Reactor

T2K



NOvA

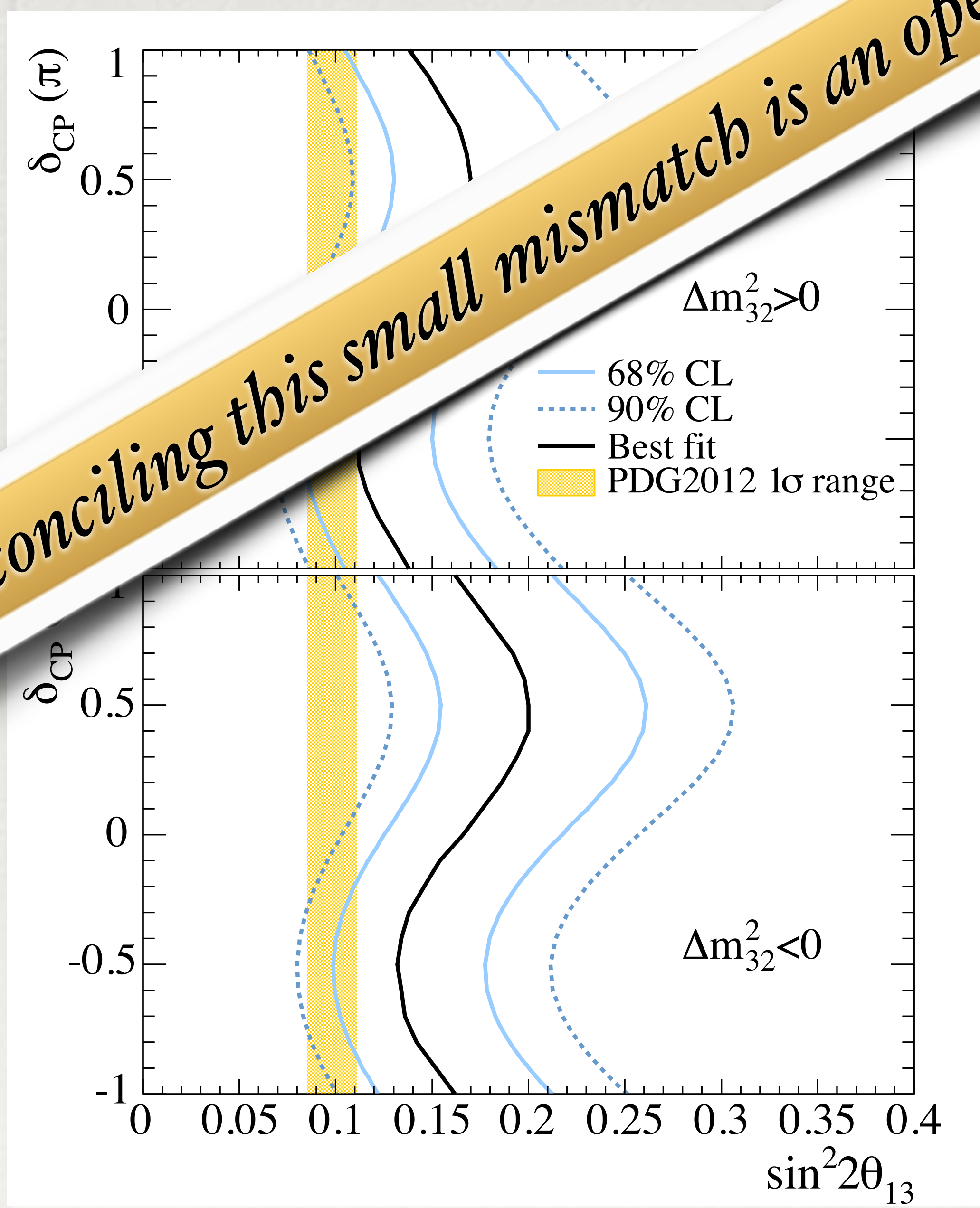




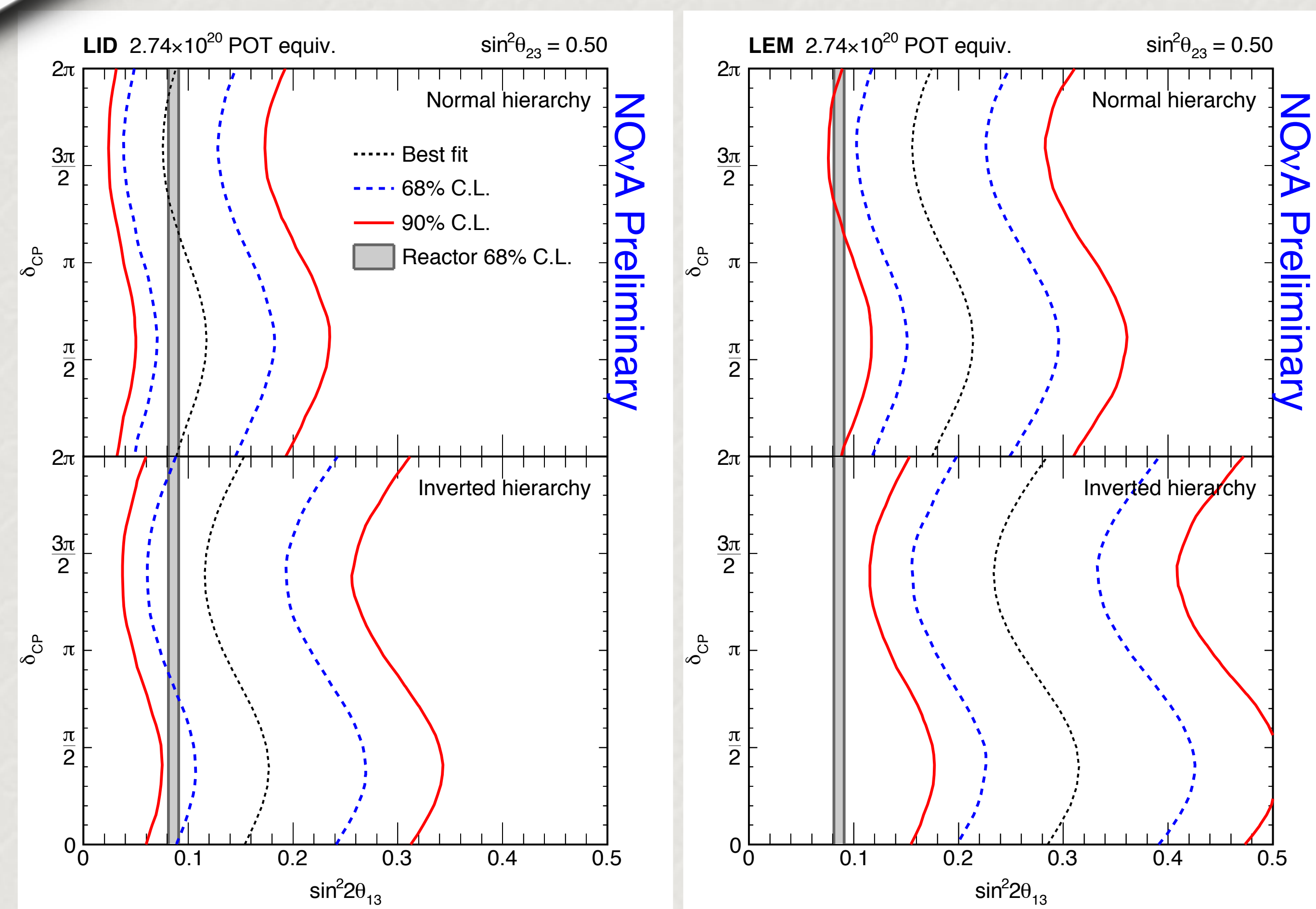
Accelerator Vs Reactor

Reconciling this small mismatch is an open problem

T2K

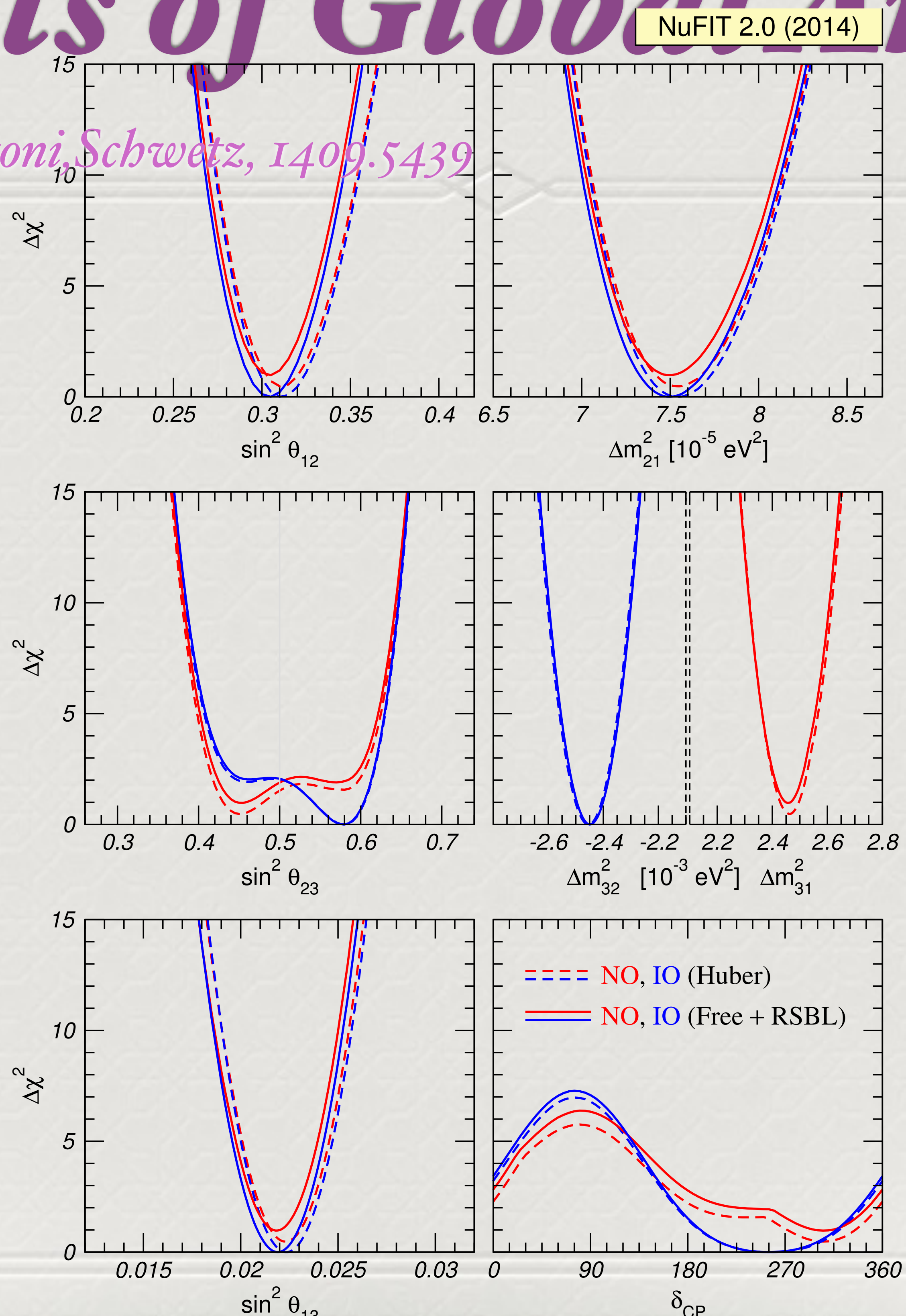


NOvA



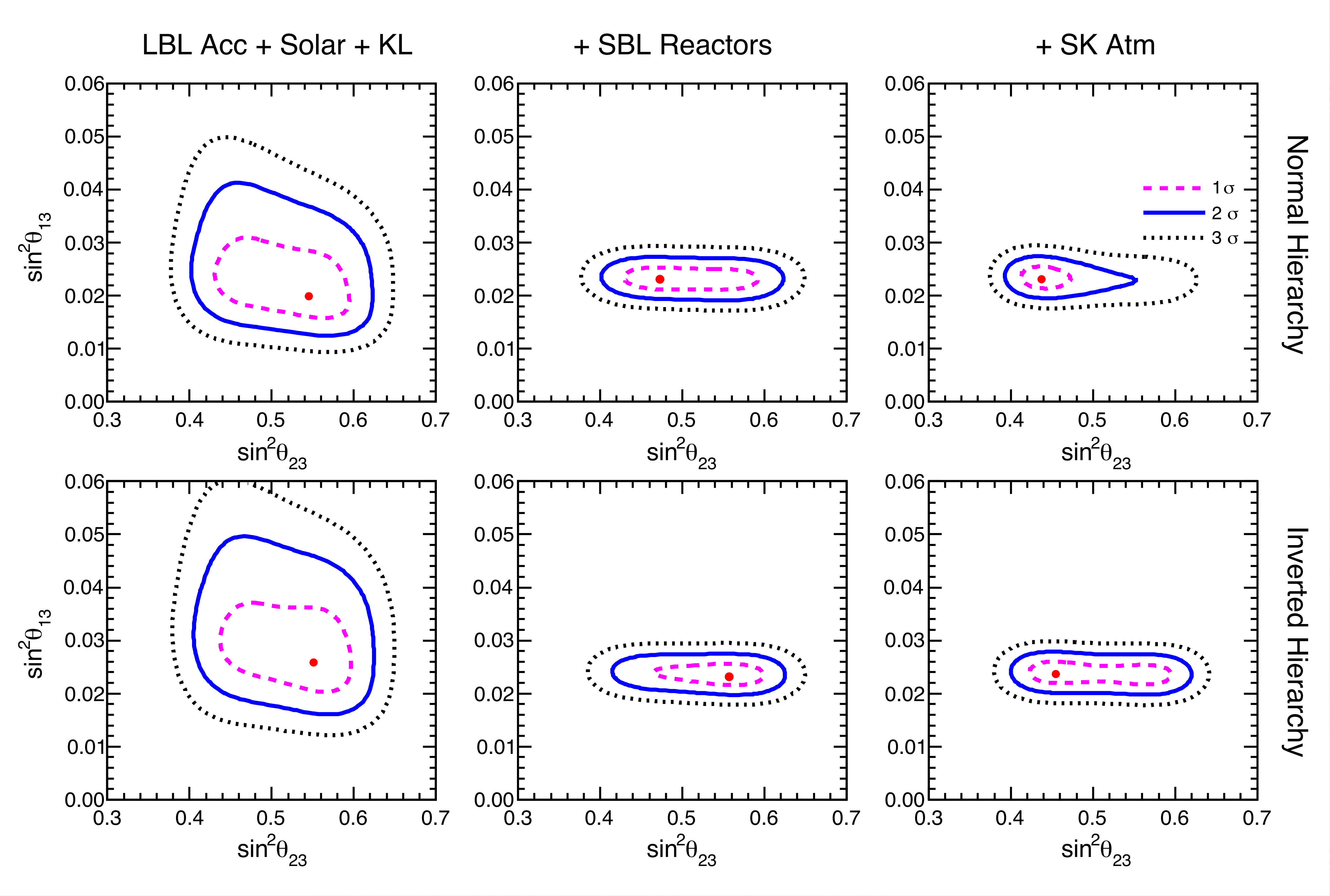
Results of Global Analyses

Gonzalez-Garcia,Maltoni,Schwetz, 1409.5439



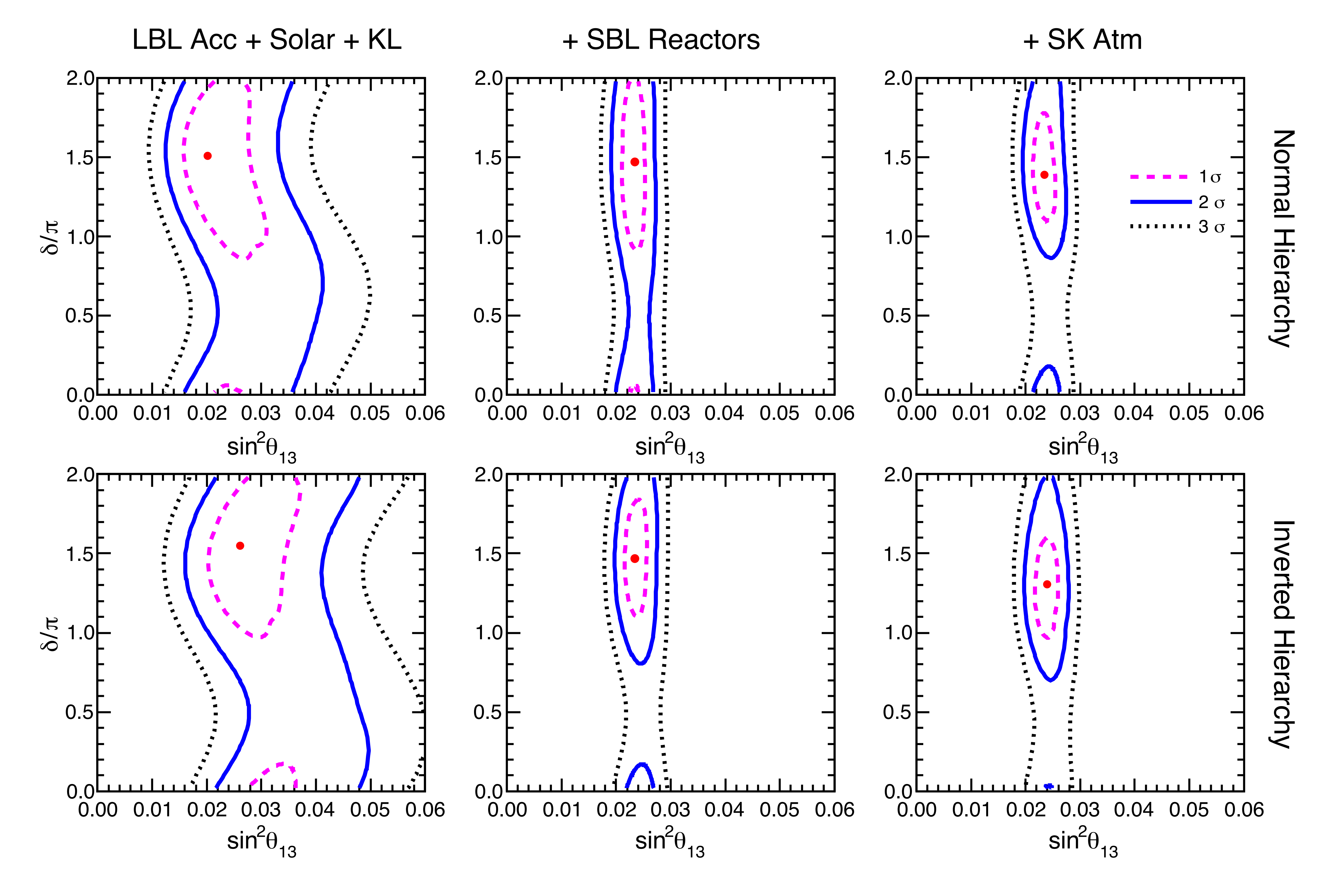
Capozzi,Fogli,Lisi,Marrone,Montanino,Palazzo, 1312.2878

Results of Global Analyses



Capozzi,Fogli,Lisi,Marrone,Montanino,Palazzo, 1312.2878

Results of Global Analyses



Capozzi,Fogli,Lisi,Marrone,Montanino,Palazzo, 1312.2878

Results of Global Analyses