NEUTRINO MASS AND THE LHC

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1. Neutrino oscillations and mass
2. Experimental discovery of neutrino oscillations
3. The see-saw mechanisms
4. Radiative neutrino mass generation
5. Final remarks

1. NEUTRINO OSCILLATIONS AND MASS

The neutrino flavour or interaction eigenstates are not Hamiltonian eigenstates in general:

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

unitary mixing matrix

mass estates
m_1, m_2, m_3

Two flavour case for clarity:

$$\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

Say at t=0 a ν_e is produced by some weak interaction process:

$$|t=0\rangle = |\nu_e\rangle = \cos\theta\,|\nu_1\rangle + \sin\theta\,|\nu_2\rangle$$

After time evolution:

$$|t\rangle = \cos\theta \exp(-iE_1 t)\,|\nu_1\rangle + \sin\theta \exp(-iE_2 t)\,|\nu_2\rangle \neq |\nu_e\rangle$$

$$(\hbar = c = 1)$$

Suppose they are ultrarelativistic 3-momentum eigenstates:

$$E_i = \sqrt{p^2 + m_i^2} \approx p + \frac{m_i^2}{2p}$$

Probability that the state is ν_μ is:

$$P(\nu_e \to \nu_\mu) = 1 - \left| \langle t \,|\, t=0 \rangle \right|^2 = \sin^2 2\theta \sin^2\left(\frac{\Delta m^2 t}{4p}\right)$$

$$\approx \sin^2 2\theta \sin^2\left(1.27\, \Delta m^2 / eV^2 \, \frac{L/km}{E/GeV}\right)$$

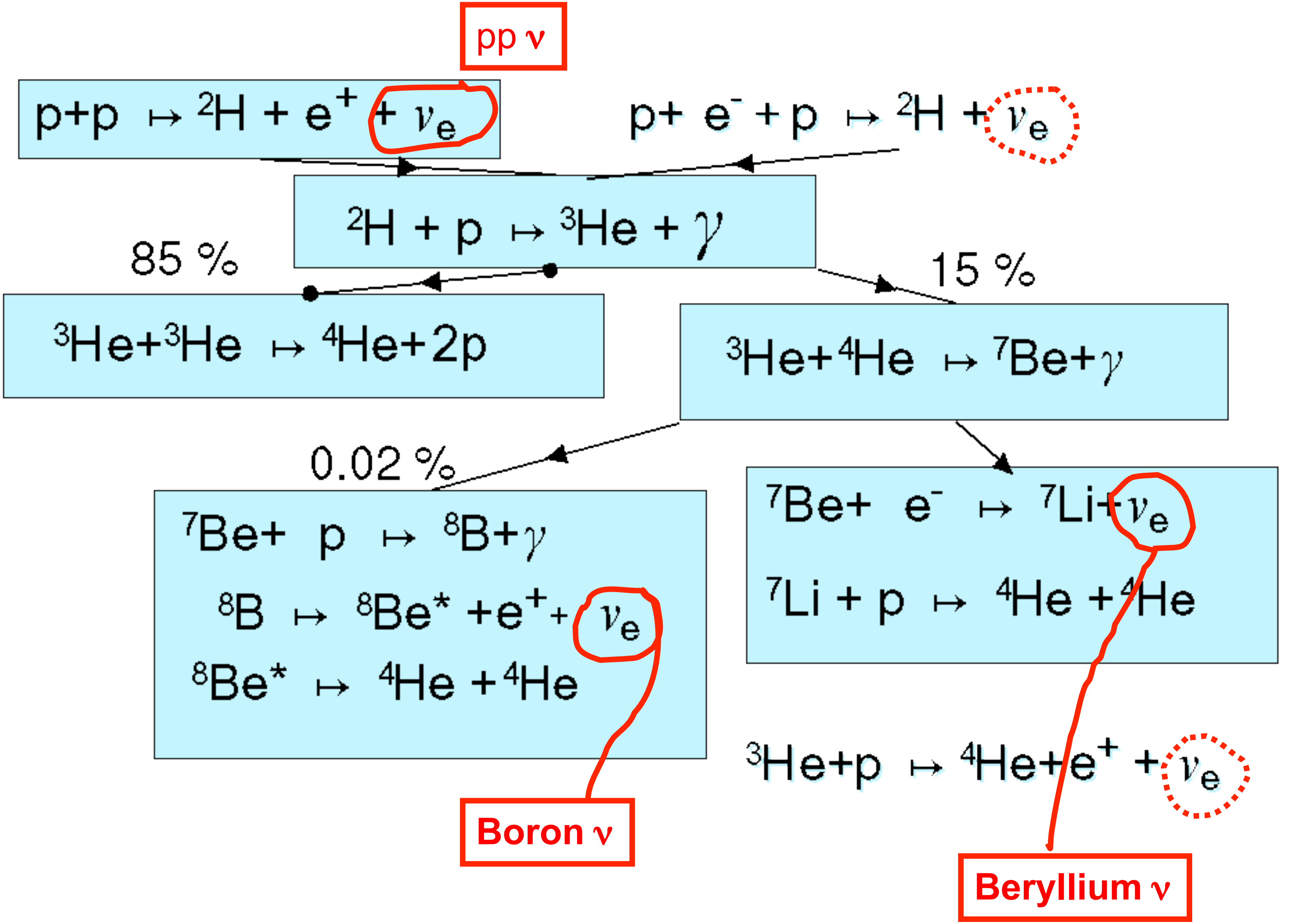
Amplitude set by mixing angle

Oscillation length set by $\Delta m^2/E = (m_2^2 - m_1^2)/E$

For solar neutrinos, this formula is invalidated by the "matter effect" -- a refractive index effect for neutrinos.

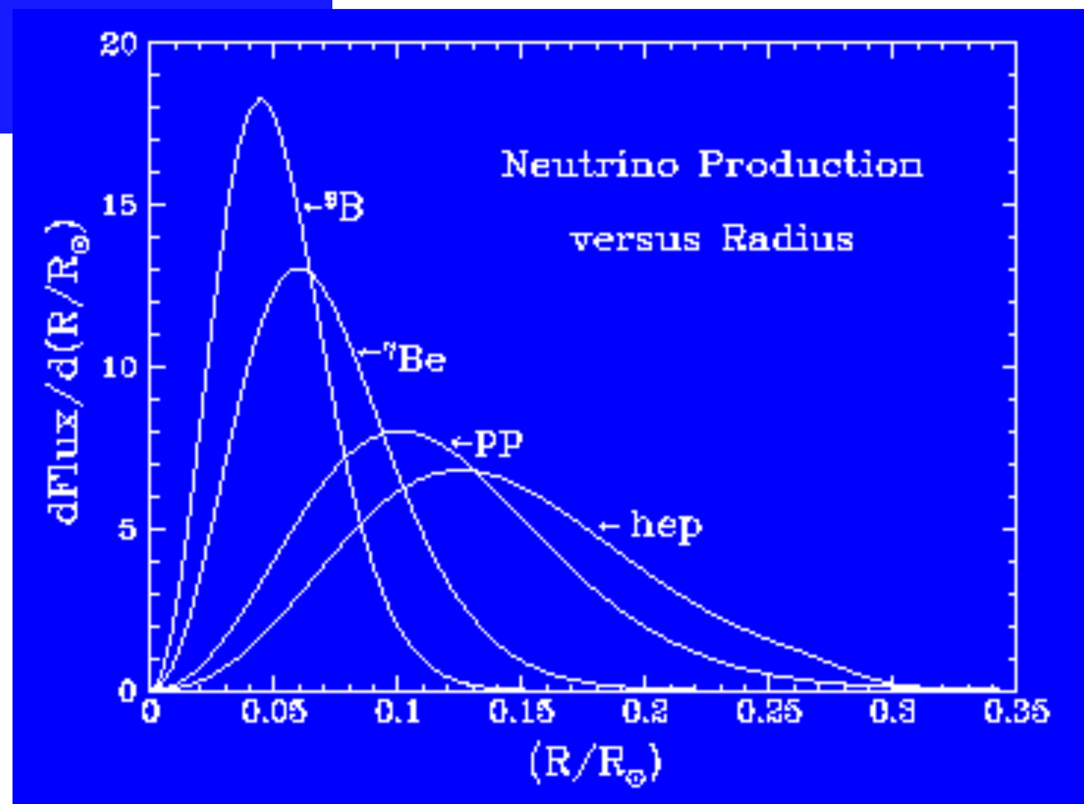
2. EXPERIMENTAL DISCOVERY OF NEUTRINO OSCILLATIONS

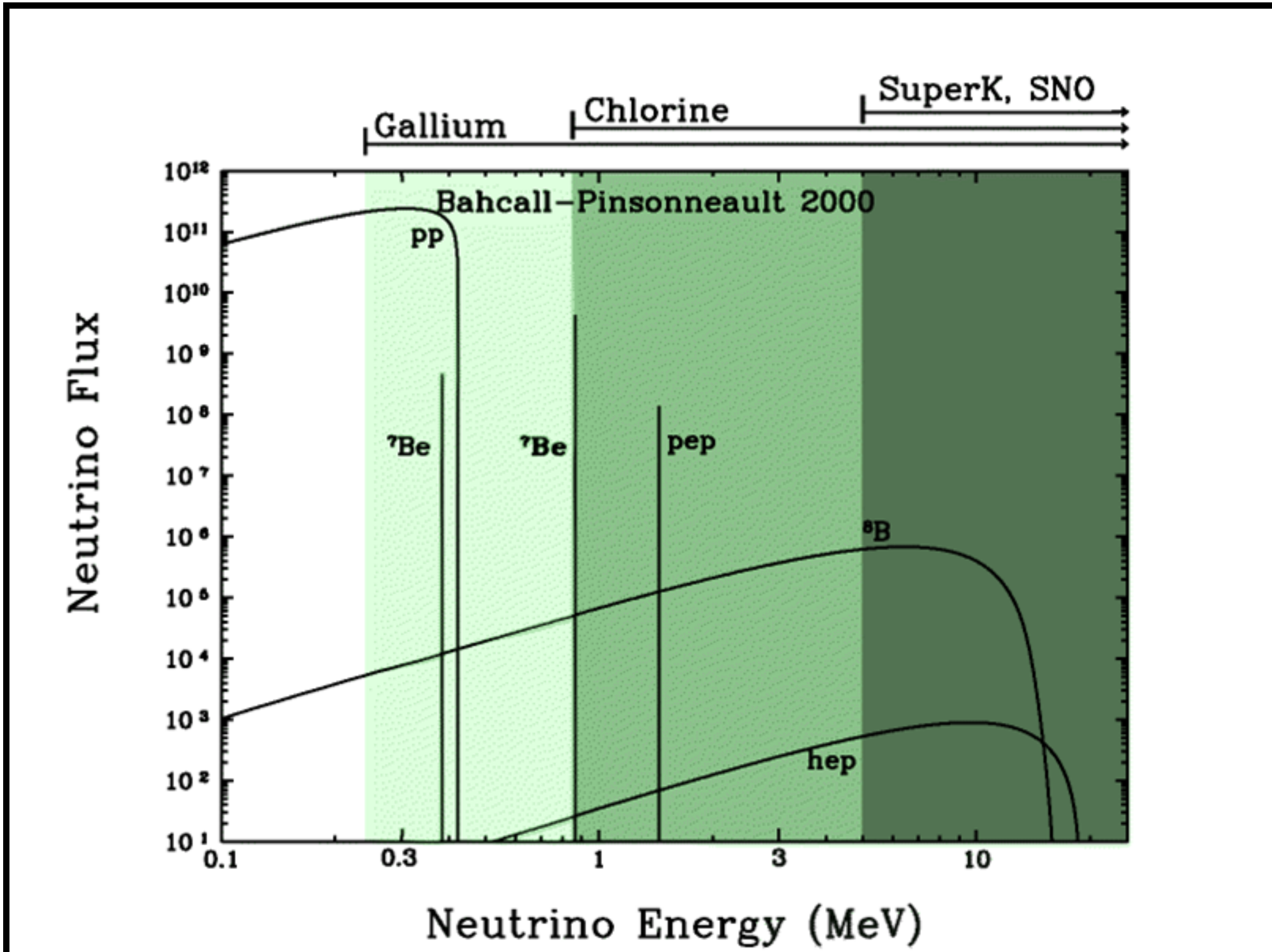
Solar neutrinos


pp ν
p+p ↦ ²H + e⁺ + ν_e
p+ e⁻ + p ↦ ²H + ν_e
²H + p ↦ ³He + γ
85 %
15 %
³He+³He ↦ ⁴He+2p
³He+⁴He ↦ ⁷Be+γ
0.02 %
⁷Be+ p ↦ ⁸B+γ
⁸B ↦ ⁸Be* +e⁺+ ν_e
⁸Be* ↦ ⁴He + ⁴He
⁷Be+ e⁻ ↦ ⁷Li+ν_e
⁷Li + p ↦ ⁴He + ⁴He
³He+p ↦ ⁴He+e⁺ + ν_e
Boron ν
Beryllium ν

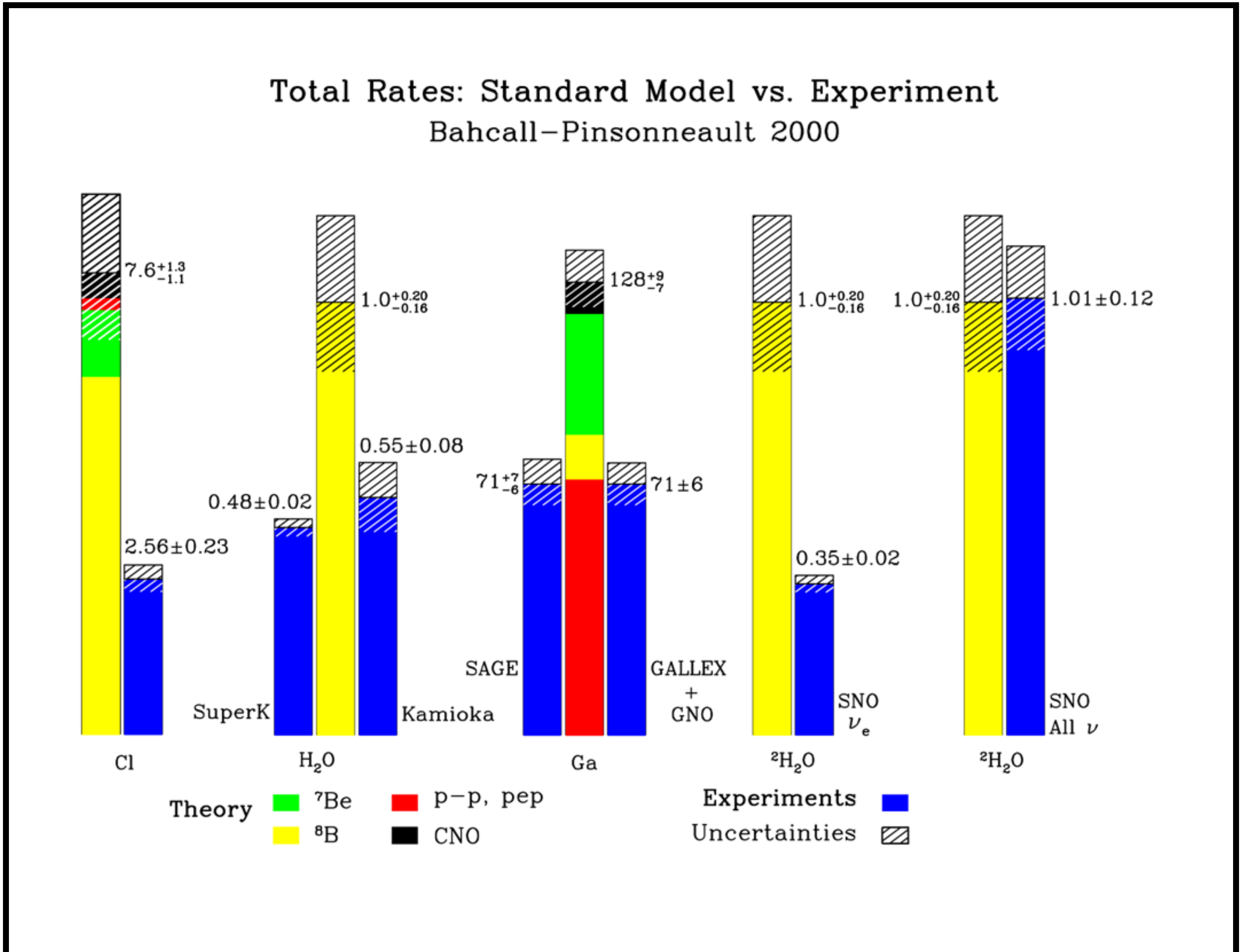
NUCLEAR BURNING

$$4\,p \;\rightarrow\; {}^{4}\mathrm{He} + 2e^{+} + 2\nu_e + 25\ \mathrm{MeV}$$



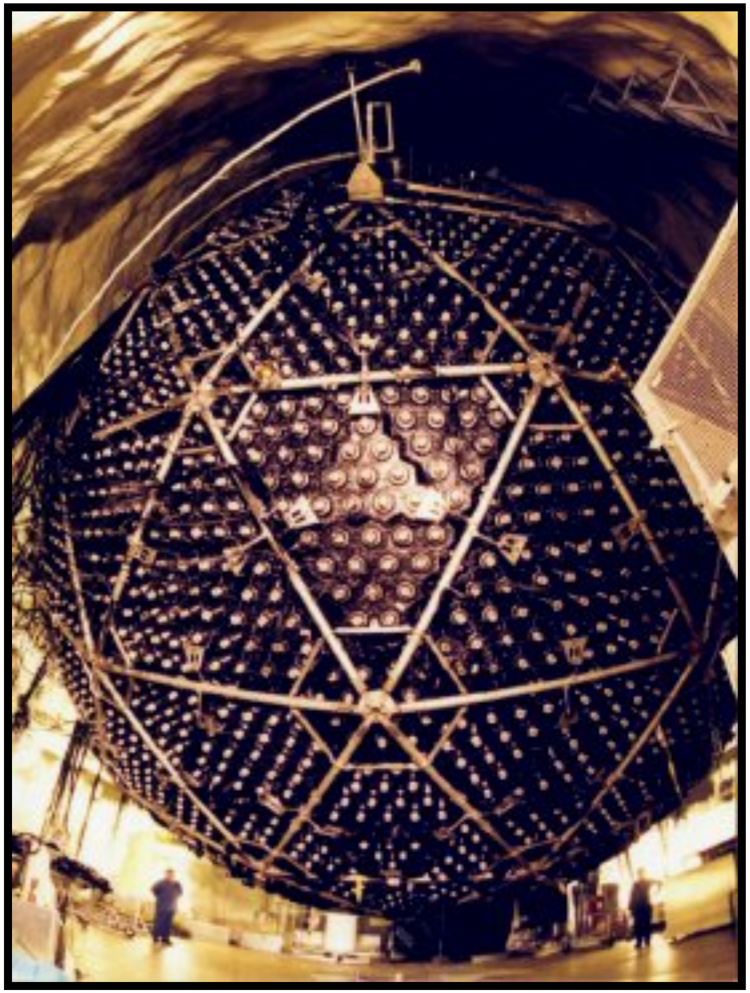


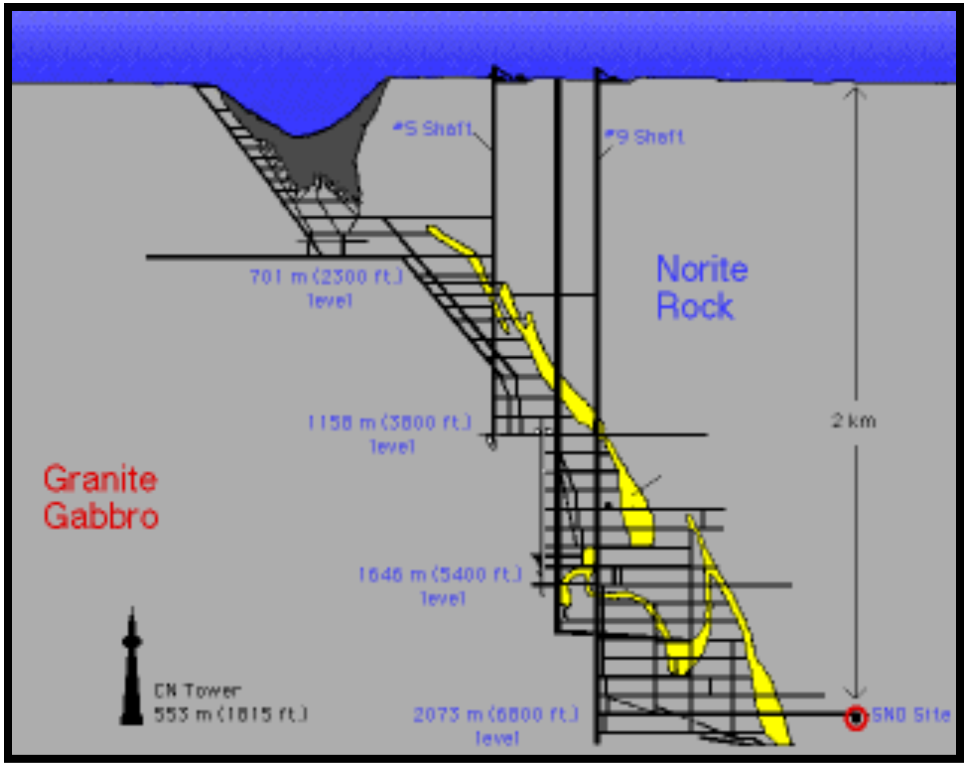
Gallium
Chlorine
SuperK, SNO
Bahcall–Pinsonneault 2000
pp
^{7}Be
^{7}Be
pep
^{8}B
hep
Neutrino Flux
10^{12}
10^{11}
10^{10}
10^9
10^8
10^7
10^6
10^5
10^4
10^3
10^2
10^1
0.1
0.3
1
3
10
Neutrino Energy (MeV)



Total Rates: Standard Model vs. Experiment
Bahcall–Pinsonneault 2000
7.6 +1.3 −1.1
2.56±0.23
Cl
0.48±0.02
1.0 +0.20 −0.16
0.55±0.08
SuperK
Kamioka
H2O
128 +9 −7
71 +7 −6
71±6
SAGE
GALLEX + GNO
Ga
1.0 +0.20 −0.16
0.35±0.02
SNO νe
2H2O
1.0 +0.20 −0.16
1.01±0.12
SNO All ν
2H2O
Theory
7Be
8B
p−p, pep
CNO
Experiments
Uncertainties

Sudbury Neutrino Observatory (SNO) proves flavour conversion:

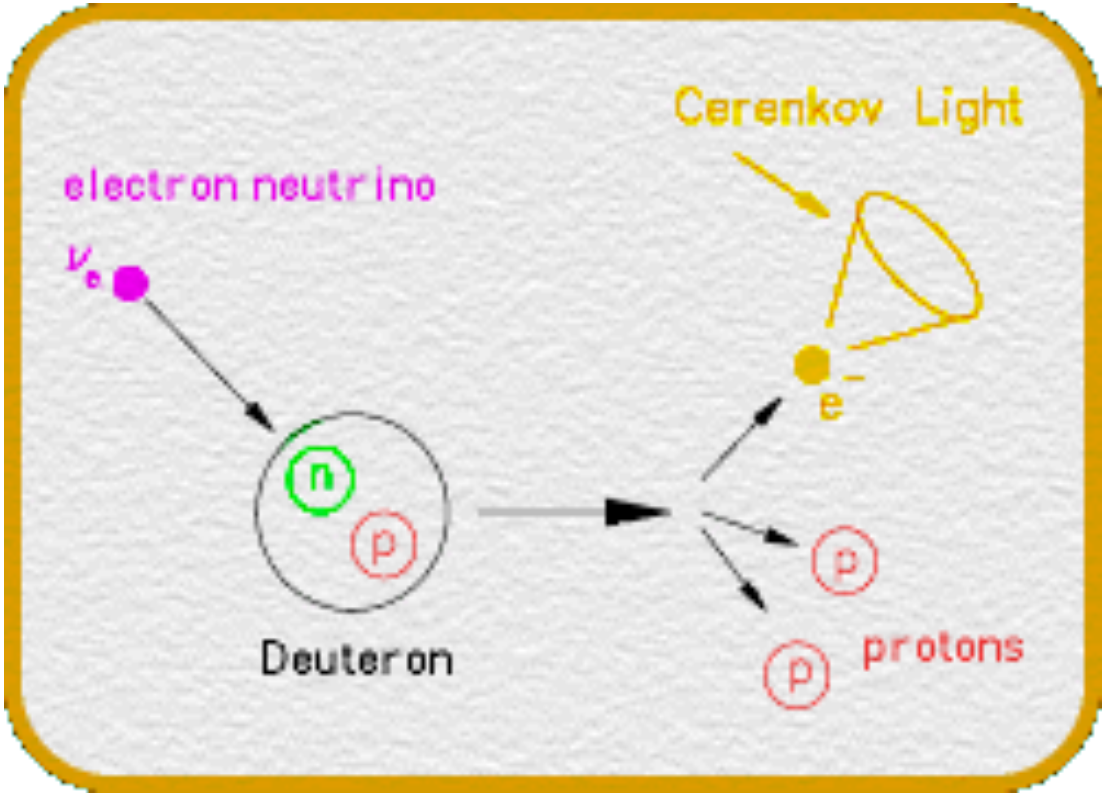


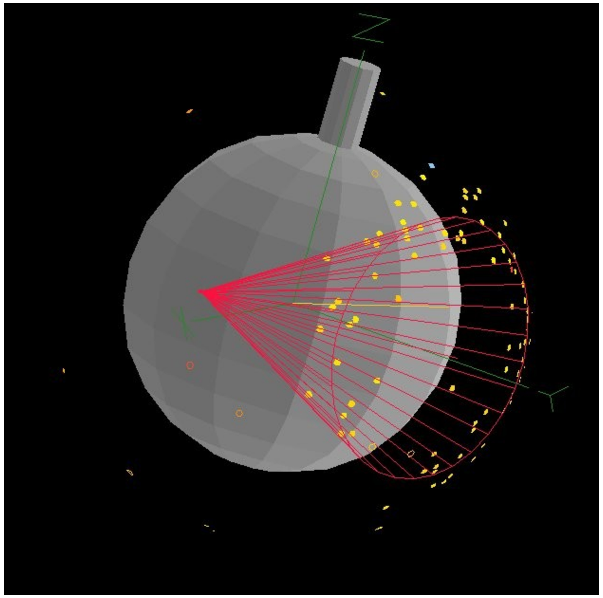


Courtesy of SNO Collaboration

SNO was a heavy water detector.

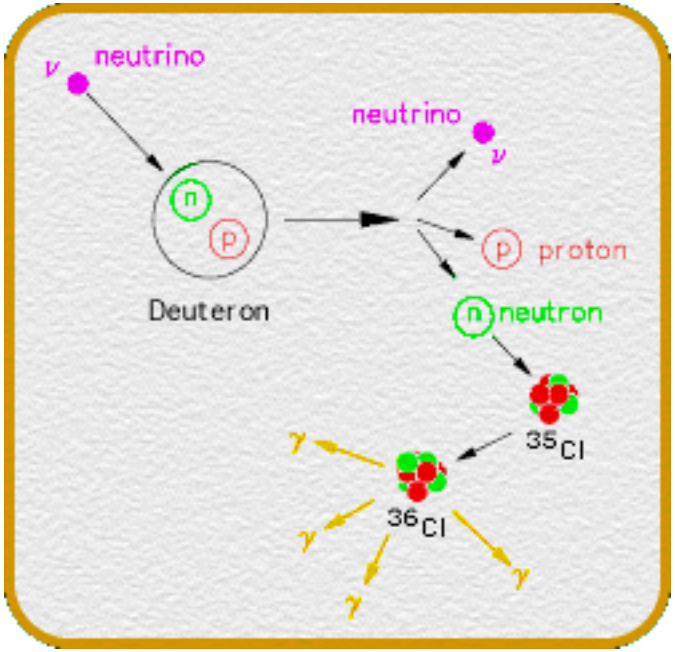
It was sensitive to ν_e's through charge-exchange deuteron dissociation:

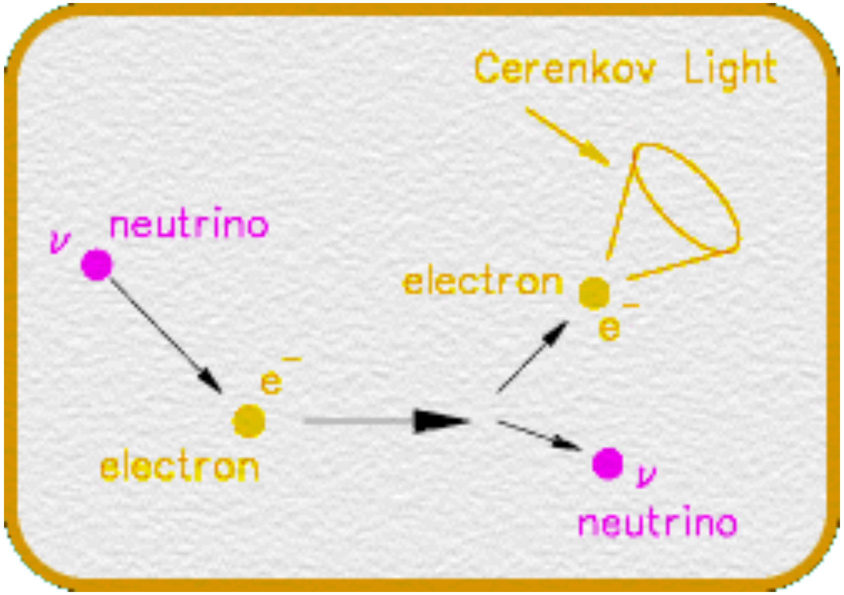




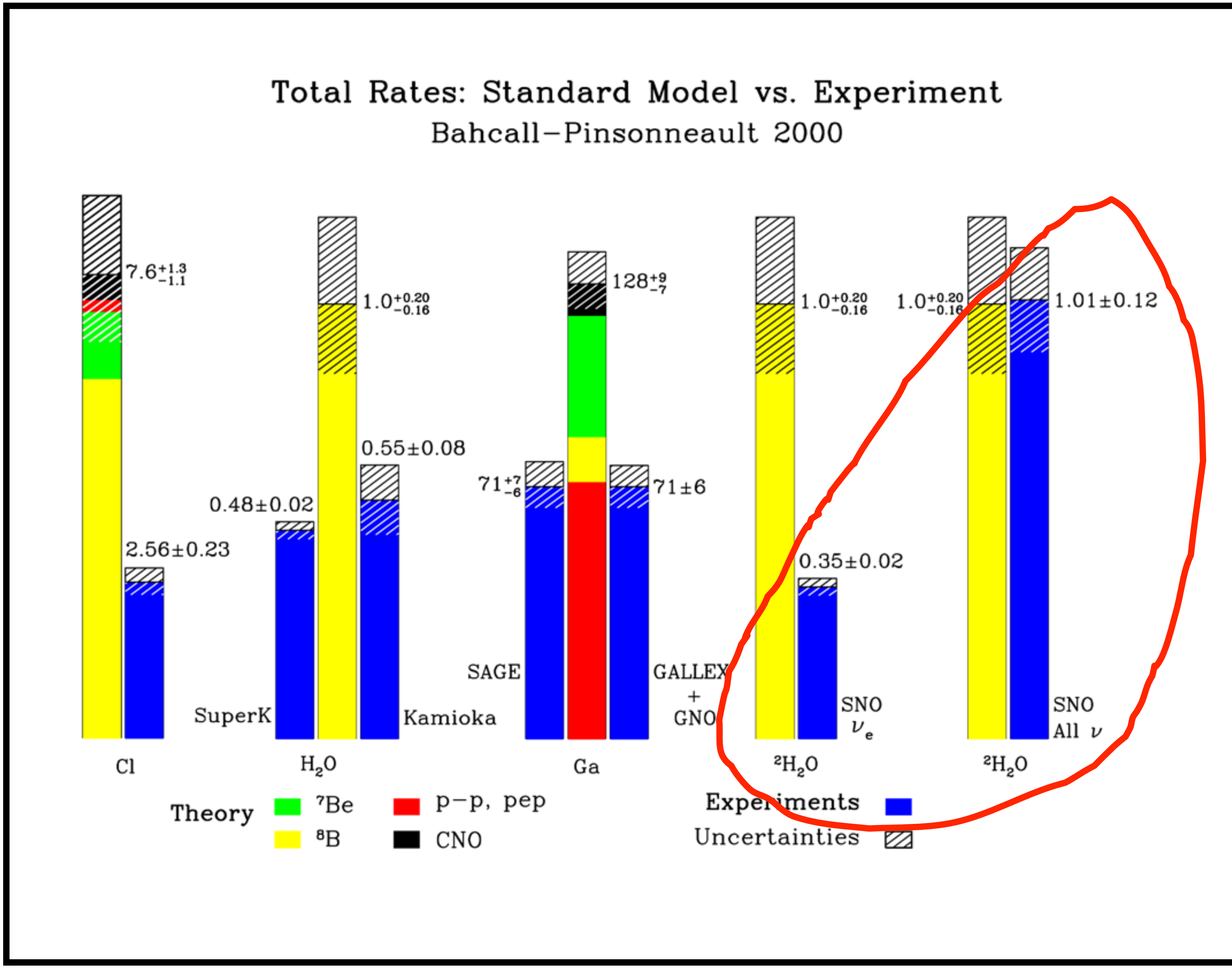
diagrams courtesy of SNO collaboration

But, through Z-boson exchange, it was also sensitive to the TOTAL neutrino flux $\nu_e + \nu_\mu + \nu_\tau$:





Diagrams courtesy of SNO Collaboration



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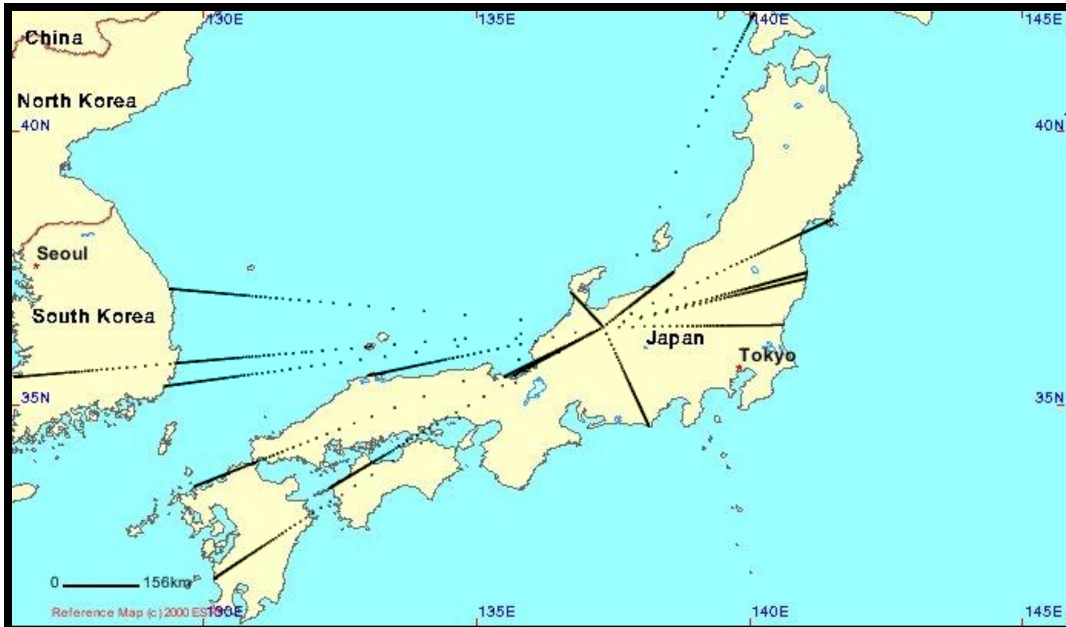
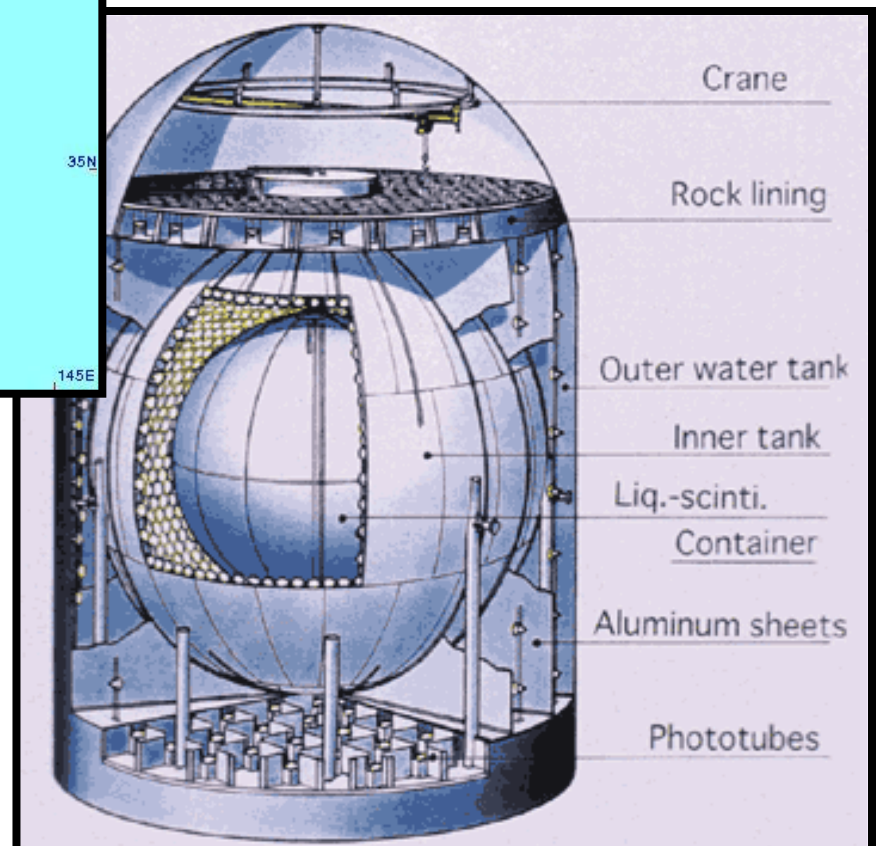
1.01±0.12
SNO
All ν
^2H_2O
Theory
^{7}Be
^{8}B
p−p, pep
CNO
Experiments
Uncertainties

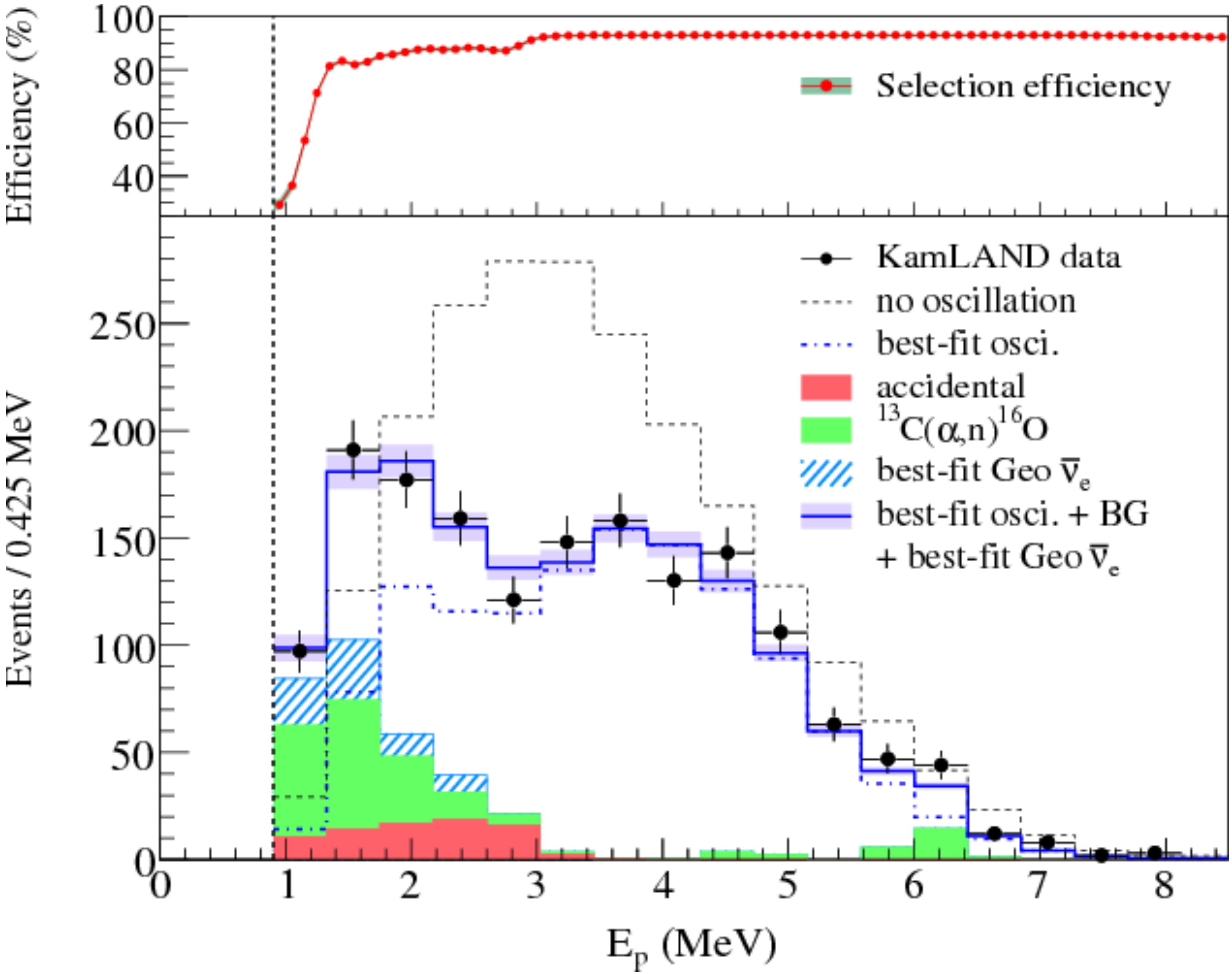
Terrestrial confirmation from KAMLAND

Integrated flux of anti-ν_e from Japanese (and Korean!) reactors

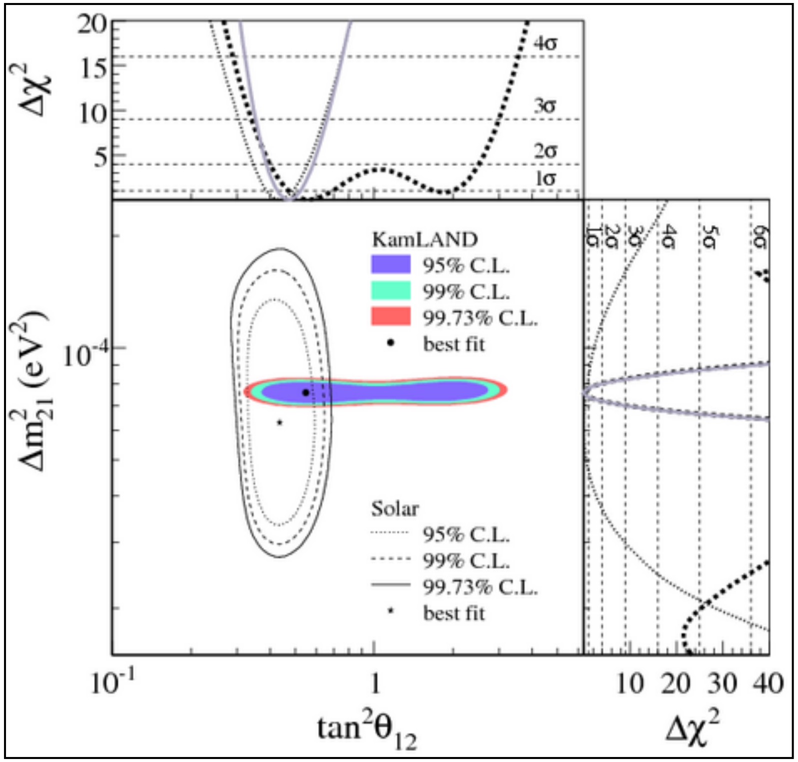




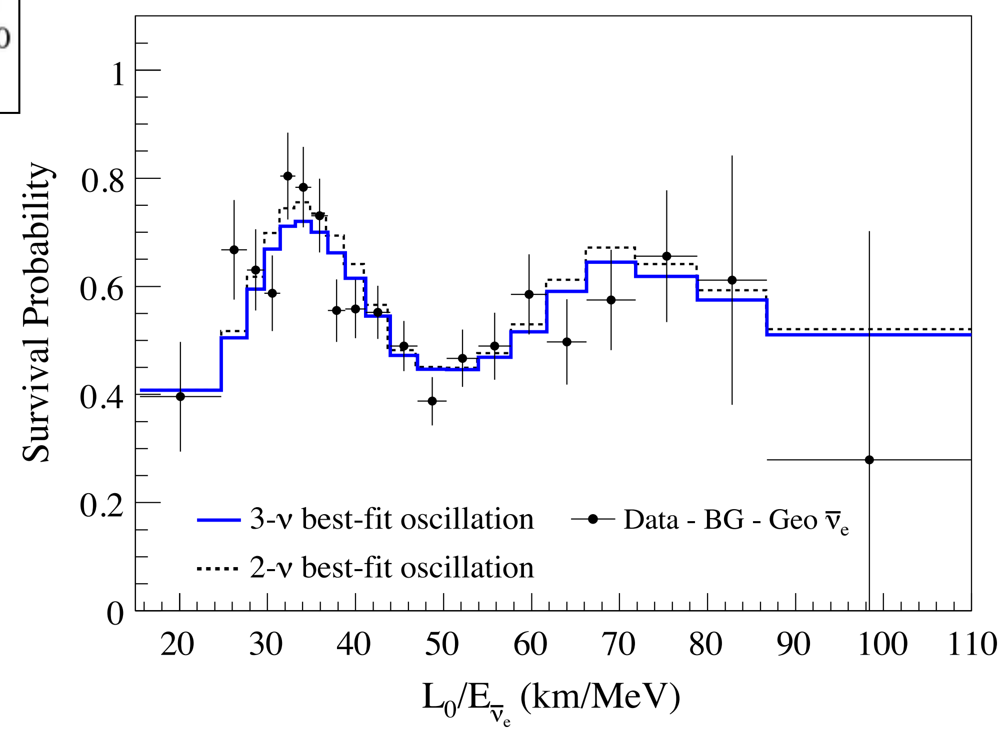
Diagrams courtesy of KAMLAND collab.



Efficiency (%)
100
80
60
40
Selection efficiency
KamLAND data
no oscillation
best-fit osci.
accidental
$^{13}C(\alpha,n)^{16}O$
best-fit Geo $\bar{\nu}_e$
best-fit osci. + BG
+ best-fit Geo $\bar{\nu}_e$
Events / 0.425 MeV
250
200
150
100
50
0
0
1
2
3
4
5
6
7
8
E_p (MeV)



$\Delta\chi^2$
4σ
3σ
2σ
1σ
KamLAND
95% C.L.
99% C.L.
99.73% C.L.
best fit
Solar
95% C.L.
99% C.L.
99.73% C.L.
best fit
Δm^2_{21} (eV^2)
10^{-4}
10^{-1}
1
10 20 30 40
$\tan^2\theta_{12}$
$\Delta\chi^2$
5σ
6σ



Survival Probability
3-ν best-fit oscillation
2-ν best-fit oscillation
Data - BG - Geo $\bar{\nu}_e$
$L_0/E_{\bar{\nu}_e}$ (km/MeV)

Atmospheric neutrinos

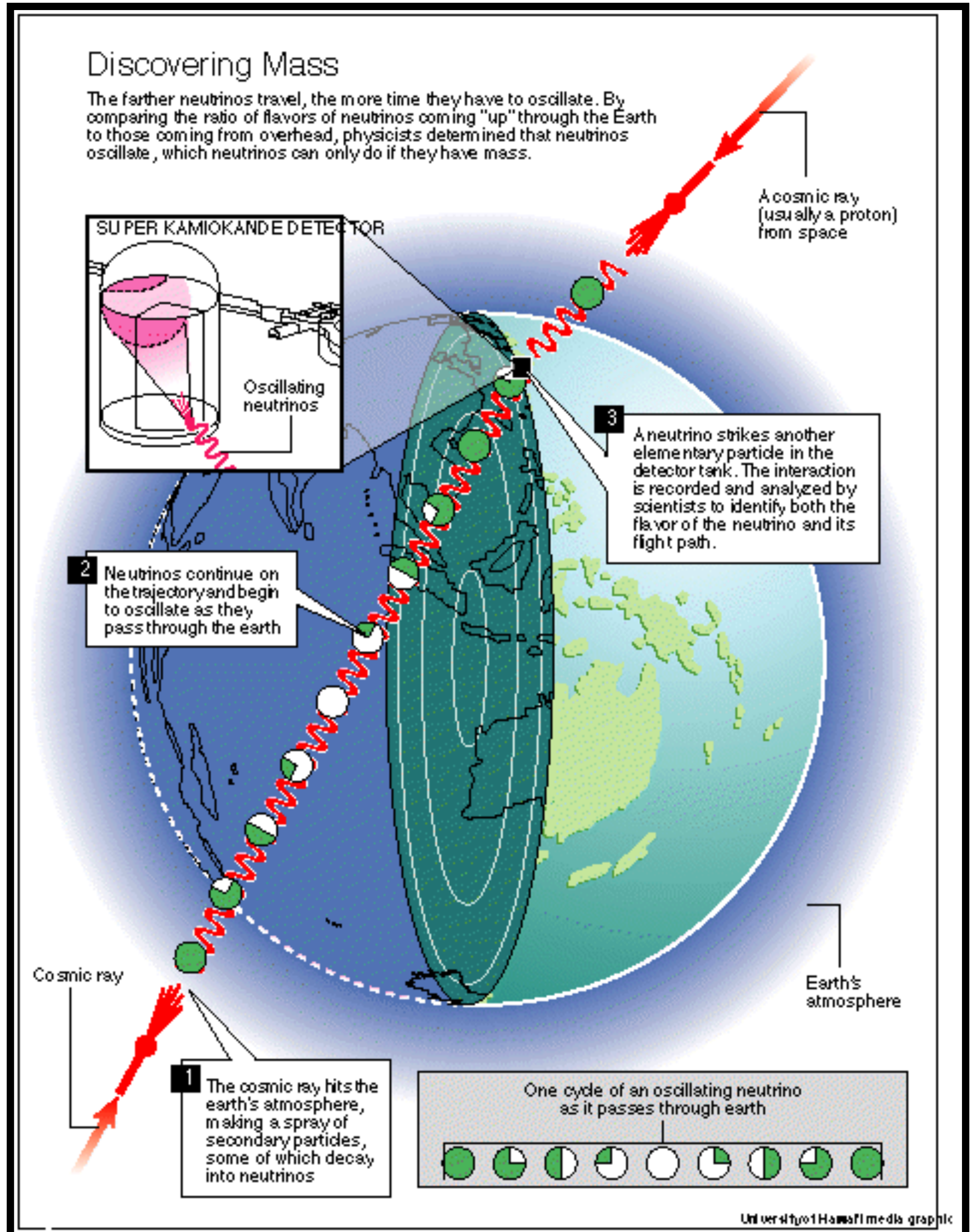
Cosmic rays hit upper atmosphere, produce pions and kaons.

They decay to give neutrinos.

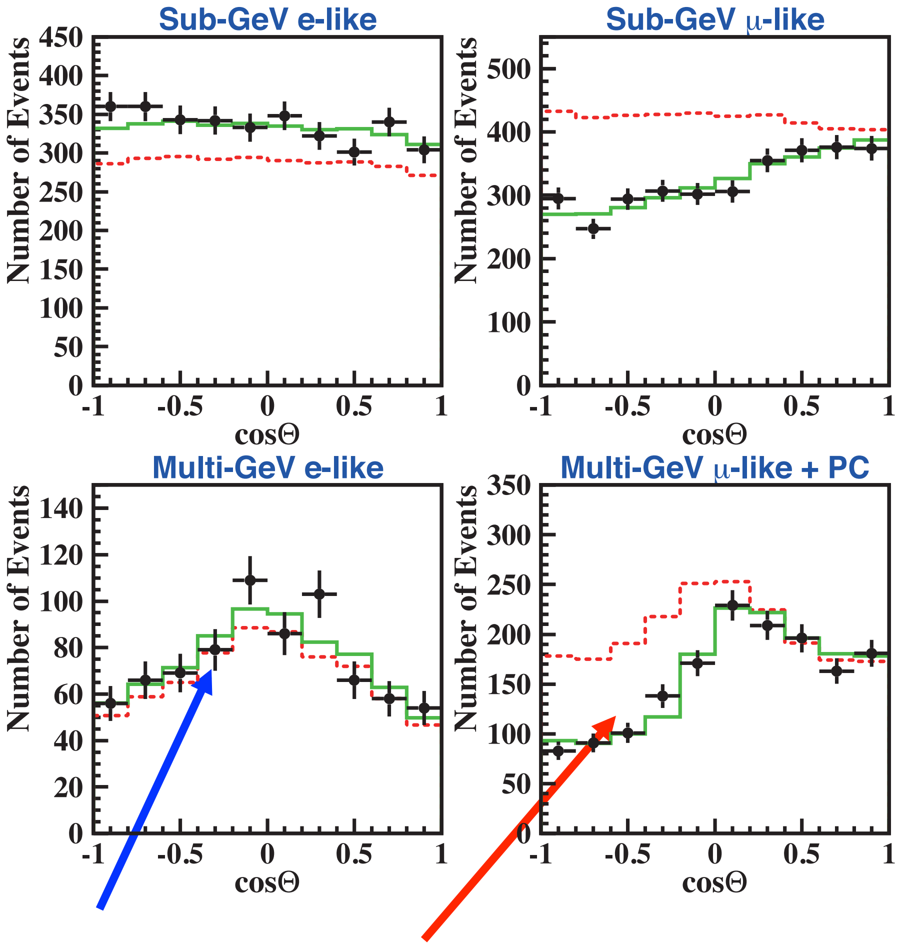
$$\pi \rightarrow \mu \nu_{\mu}$$

$$\hookrightarrow e \nu_{e} \nu_{\mu}$$

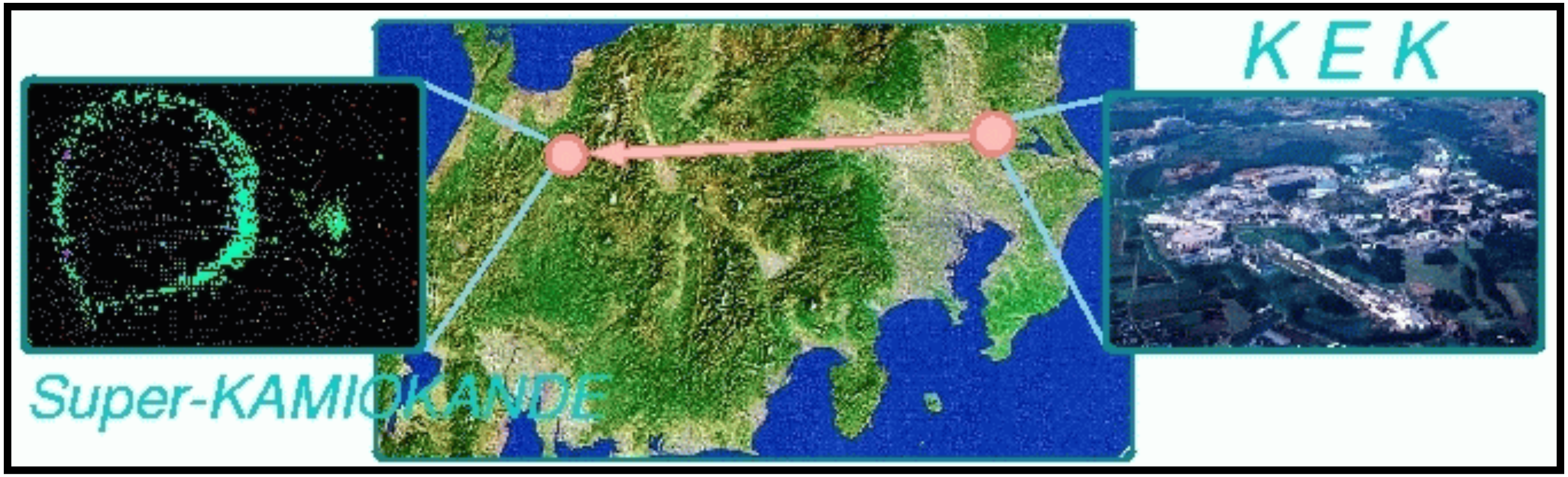
Provided muons decay in time, you get 2:1 ratio of μ to e type neutrinos.

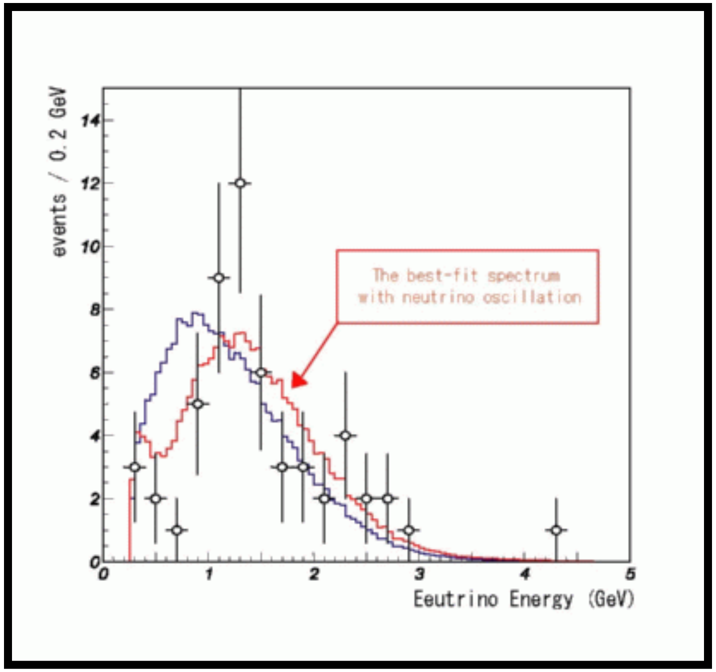


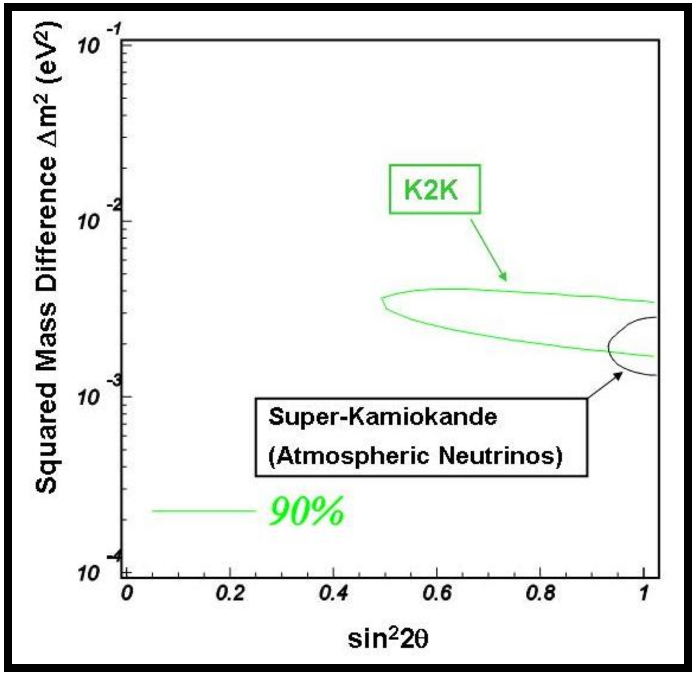
Super-K results



Terrestrial confirmation: K2K

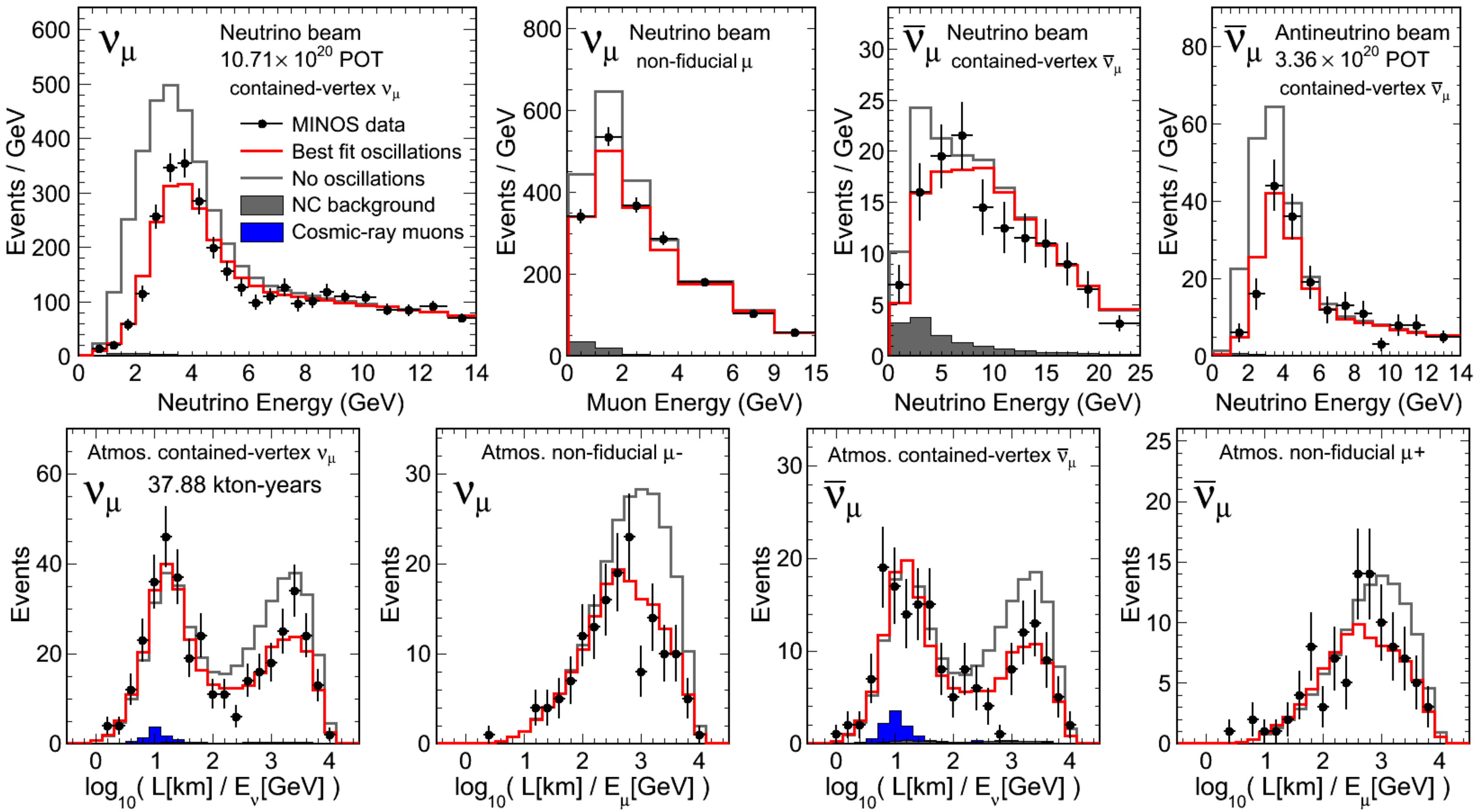


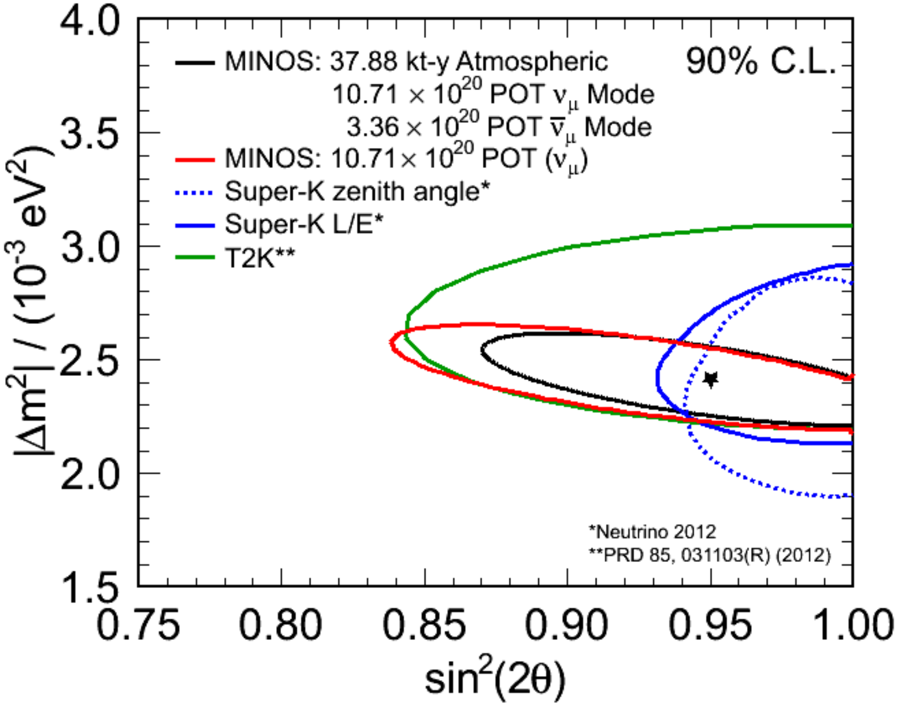




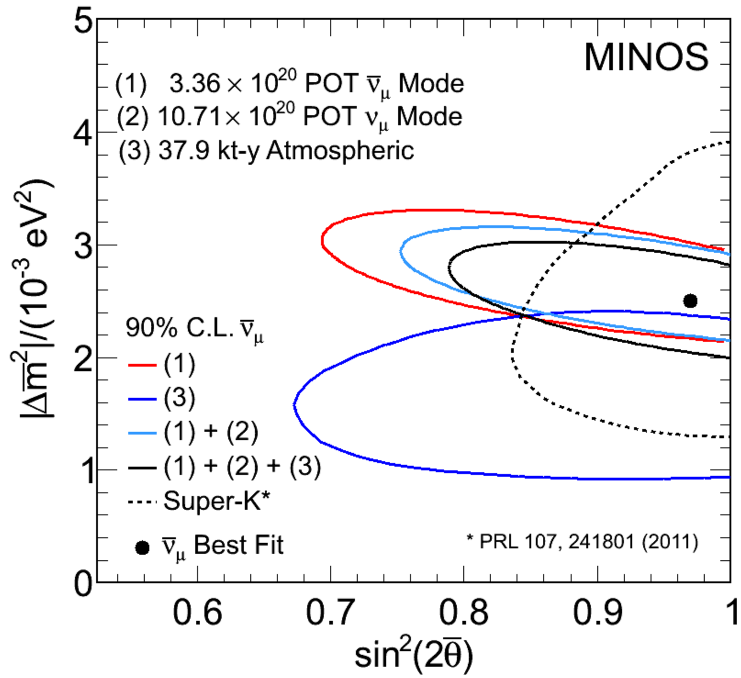
Terrestrial confirmation: MINOS

Long baseline experiment from Fermilab to the Soudan mine in northern Minnesota



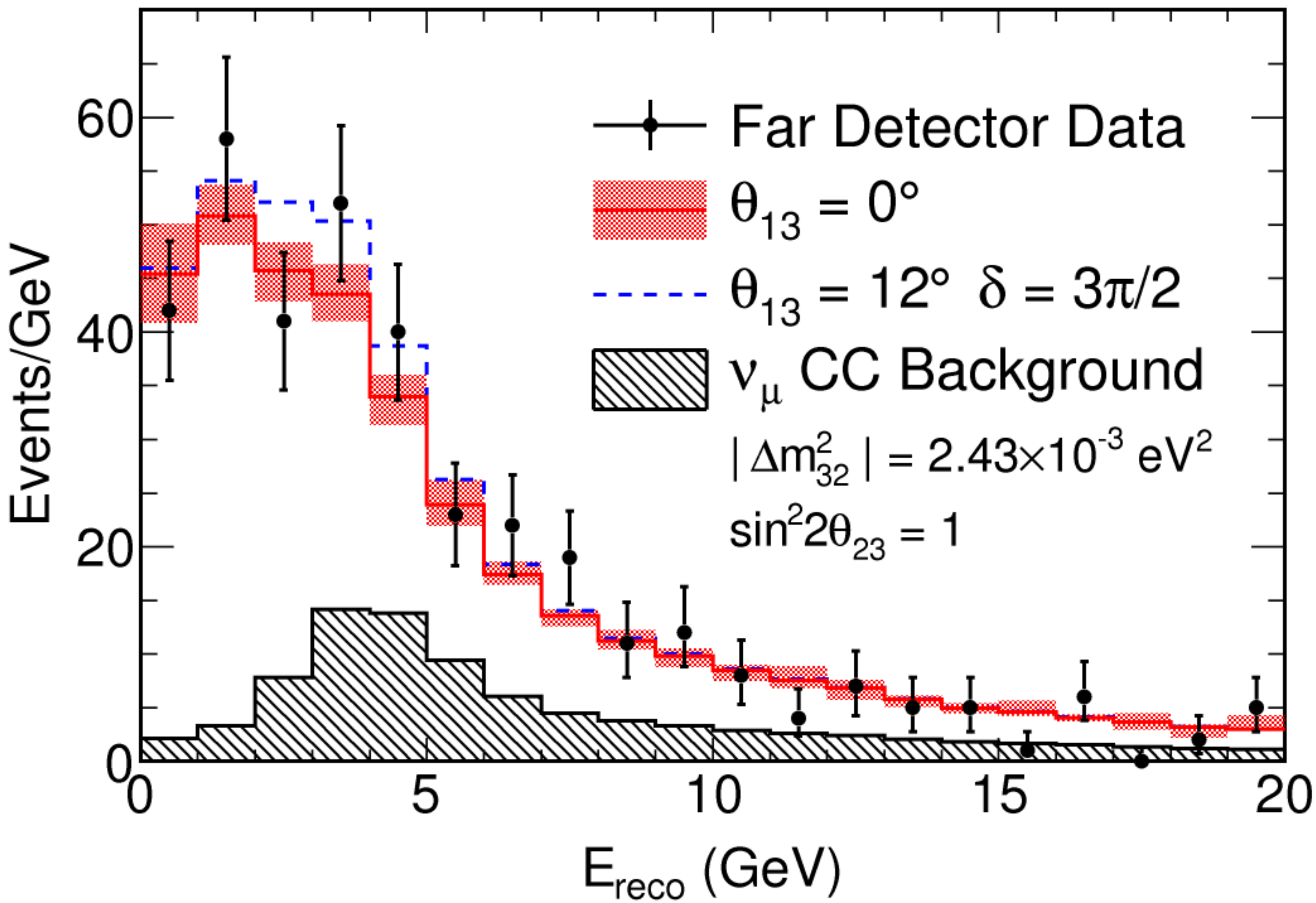


neutrinos



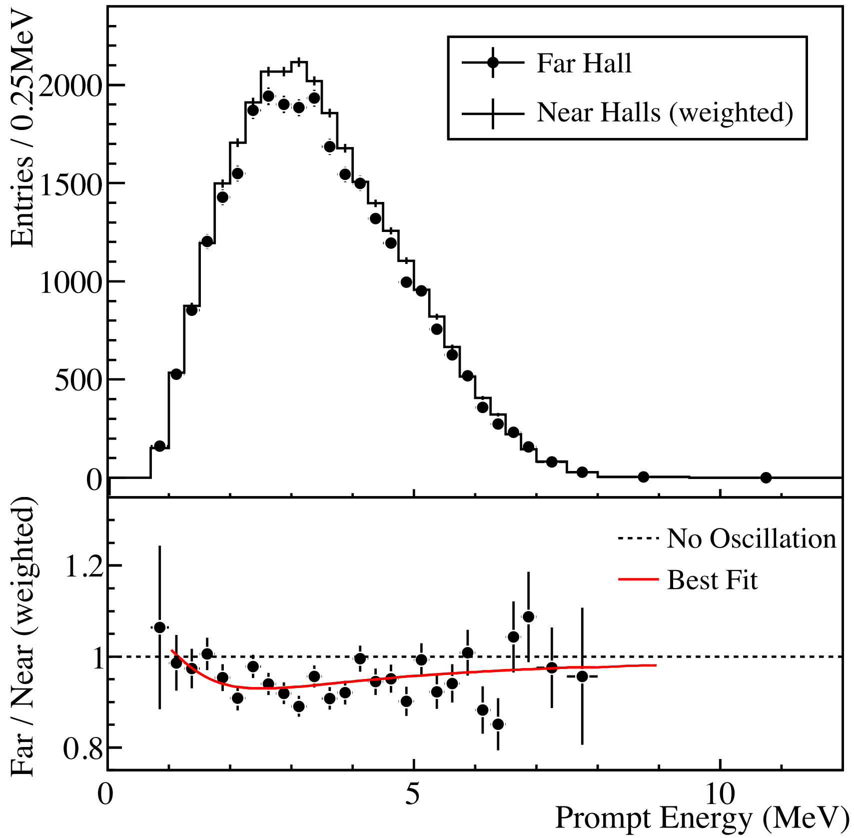
antineutrinos

MINOS has also provided strong evidence that ν_μ's oscillate into ν_τ's



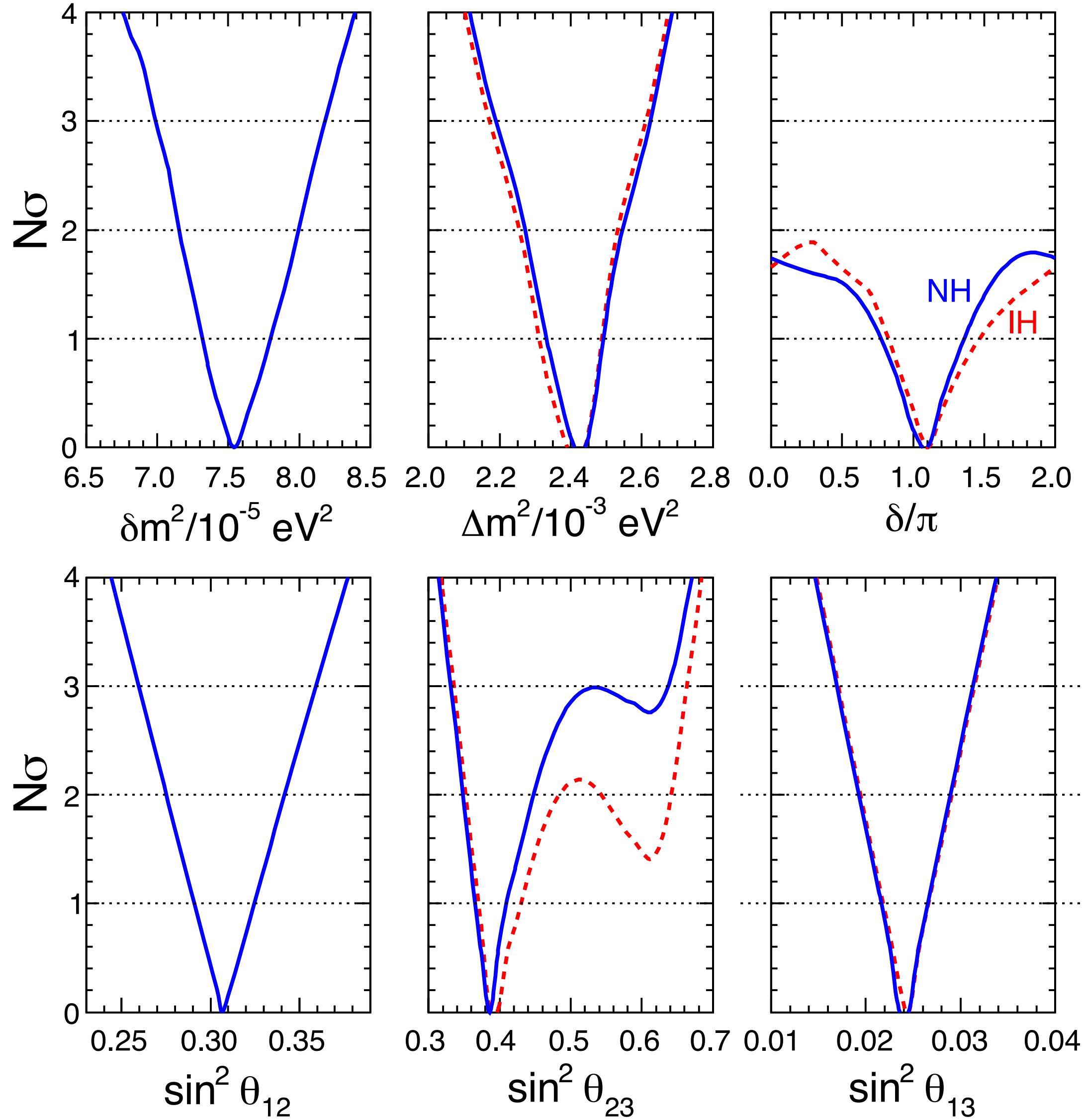
Neutral current measurement

Reactor anti-ν_e disappearance and θ_{13}



Daya Bay collaboration
Also: Reno, Double-CHOOZ, T2K, MINOS

Synopsis of global 3ν oscillation analysis



Fogli et al: PRD86 (2012) 013012

3. THE SEE-SAW MECHANISMS

Minimal standard model:

$$SU(3)_c \times SU(2)_L \times U(1)_Y \to SU(3)_c \times U(1)_Q \qquad Q = I_3 + \frac{Y}{2}$$

$$q_L \sim (3,2)(1/3) \quad d_R \sim (3,1)(-2/3) \quad u_R \sim (3,1)(4/3)$$
$$\ell_L \sim (1,2)(-1) \quad e_R \sim (1,1)(-2)$$

$$H \sim (1,2)(1) \qquad \tilde{H} \equiv i\tau_2 H^*$$

$$\mathcal{L}_{\text{Yuk}} = \lambda_{dij}\bar{q}_{iL} H d_{jR} + \lambda_{uij}\bar{q}_{iL}\tilde{H} u_{jR} + \lambda_{eij}\bar{\ell}_{iL} H e_{jR} + H.c.$$

$$\langle H \rangle = \begin{pmatrix} 0 \\ v/\sqrt{2} \end{pmatrix} \qquad m_f = \lambda_f \frac{v}{\sqrt{2}}$$

No RH neutrinos means zero neutrino masses

Dirac neutrinos:

simply add $\nu_R \sim (1,1)(0)$

$$\mathcal{L}_{\rm Yuk} \to \mathcal{L}_{\rm Yuk} + \lambda_{\nu ij} \bar{\ell}_{iL} \tilde{H} \nu_{jR} + H.c.$$

$$m_\nu^D = \lambda_\nu \frac{v}{\sqrt{2}}$$ **like all the other fermions**

Possible, but (1) no explanation for why $m_\nu \ll m_{u,d,e}$

(2) RH neutrino Majorana mass terms are gauge invariant and thus can be in the Lagrangian

Minkowski; Gell-Mann, Ramond, Slansky; Yanagida; Mohapatra and Senjanovic

Type 1 see-saw:

$$\mathcal{L} \supset \lambda_{\nu ij}\bar{\ell}_{iL}\tilde{H}\,\nu_{jR} + \frac{1}{2}M_{ij}\overline{(\nu_{iR})^c}\nu_{jR} + H.c.$$

Dirac mass $m \equiv m_\nu^D = \lambda_\nu \frac{v}{\sqrt{2}}$

RH Majorana mass

Neutrino mass matrix:

$$\frac{1}{2}\begin{pmatrix} \bar{\nu}_L & \overline{(\nu_R)^c} \end{pmatrix}\begin{pmatrix} 0 & m \\ m^T & M \end{pmatrix}\begin{pmatrix} (\nu_L)^c \\ \nu_R \end{pmatrix}$$

For M >> m: 3 small evalues of magnitude $m_\nu = m^2/M$

3 large evalues of order M

see-saw

Majorana estates:

$$\hat{\nu}_L \simeq \nu_L - \frac{m}{M}(\nu_R)^c$$

$$N_R \simeq \nu_R + \frac{m}{M}(\nu_L)^c$$

Notoriously hard to test because N is mostly sterile to SM gauge interactions and also expected to be very massive

Magg; Wetterich; Schechter; Valle; Lazarides; Shafi; Mohapatra; Senjanovic; Cheng; Li.

Type 2 see-saw:

Add Higgs triplet instead of RH neutrinos:

$$\Delta \sim (1,3)(2)$$

$$\mathcal{L} \supset \frac{h}{2}\overline{(\ell_L)^c}\ell_L \Delta + H.c. \qquad m_\nu = h\langle\Delta\rangle$$

Why small <Δ>? $$V = +\mu_\Delta^2 \Delta^\dagger \Delta + 2A\Delta^\dagger H^2 + \lambda_\Delta (\Delta^\dagger \Delta)^2 + \ldots$$

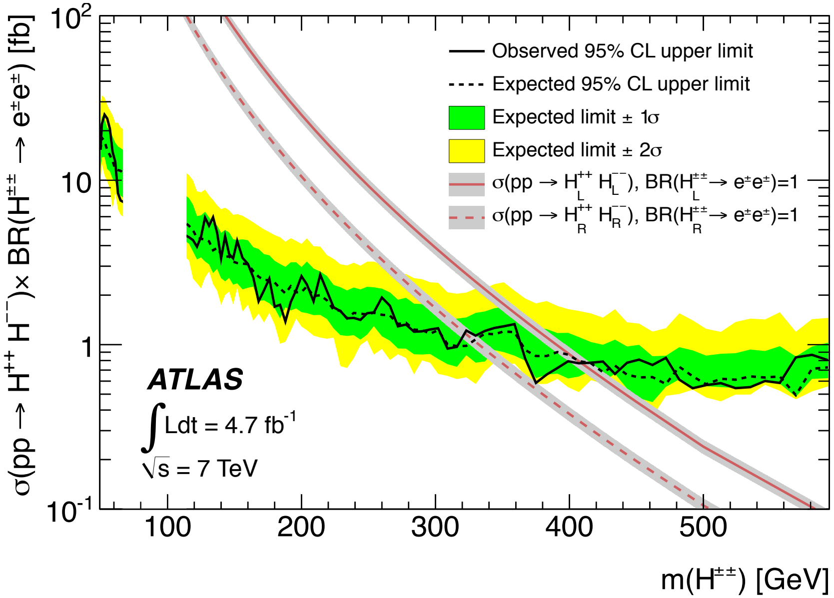
positive

<H> induces linear term in Δ

$$\langle\Delta\rangle \simeq -\frac{Av^2}{\mu_\Delta^2} \qquad \mu_\Delta \gg v,\ A$$

$$\Delta = \begin{pmatrix} \Delta^{++} \\ \Delta^{+} \\ \Delta^{0} \end{pmatrix}$$

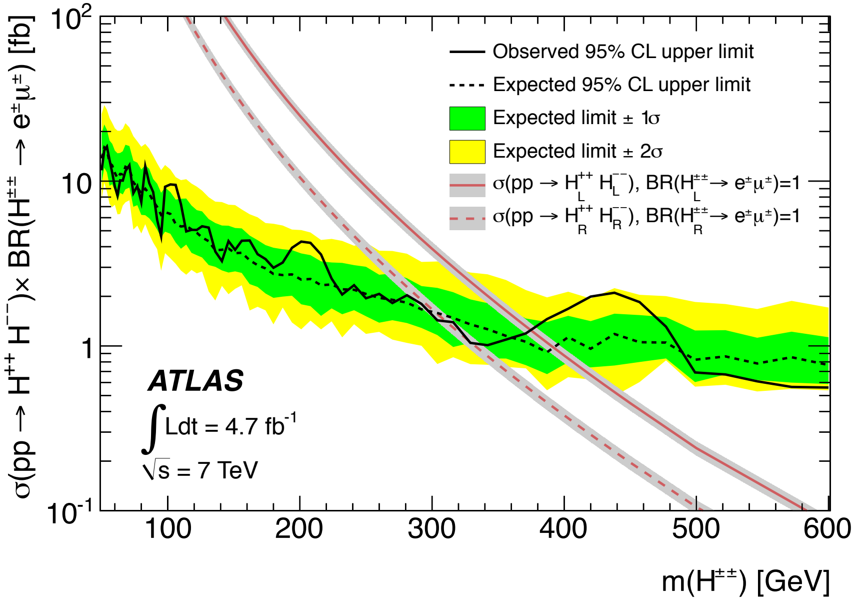
Weak and EM interactions: more testable

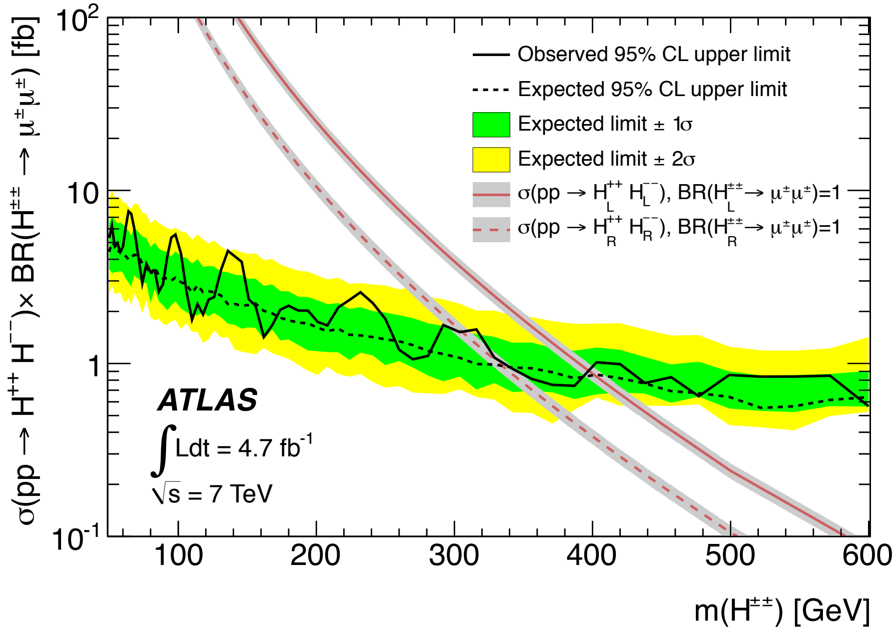


Mass limits on charge-2 scalar. Depends on BR assumption.

Eur.Phys.J. C72 (2012) 2244

Barberio, Hamano, Rodd



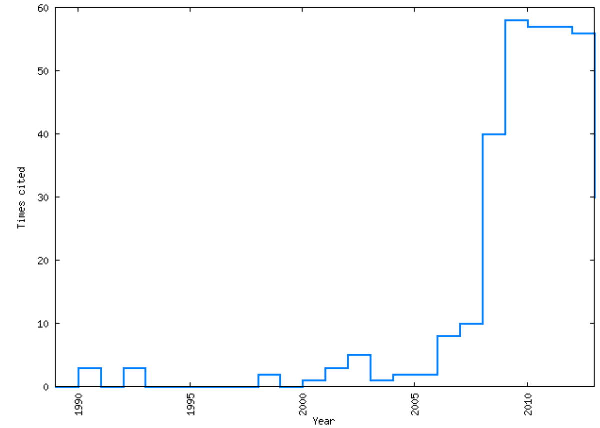


Type 3 see-saw:

Foot, Lew, He, Joshi

$$\mathcal{L} \supset \lambda_{\nu ij} \bar{\ell}_{iL} \tilde{H}\, \Psi_R + \frac{1}{2} M_{ij} \overline{(\Psi_R)^c} \Psi_R + H.c.$$

$$\Psi_R \sim (1,3)(0) = \begin{pmatrix} N_R^+ \\ N_R^0 \\ (N_L^+)^c \end{pmatrix}$$



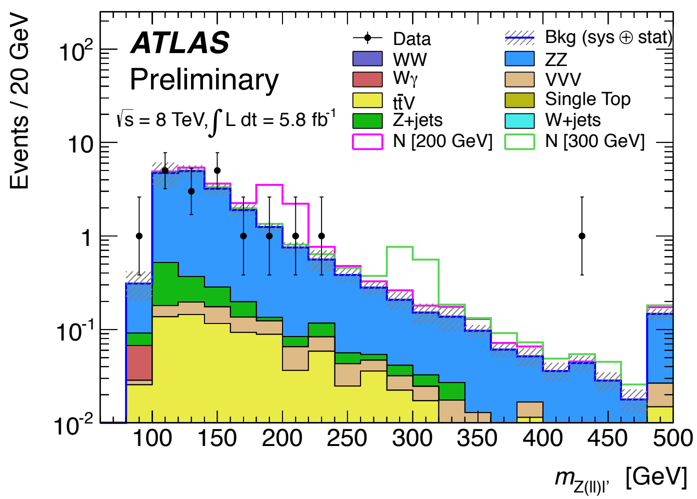
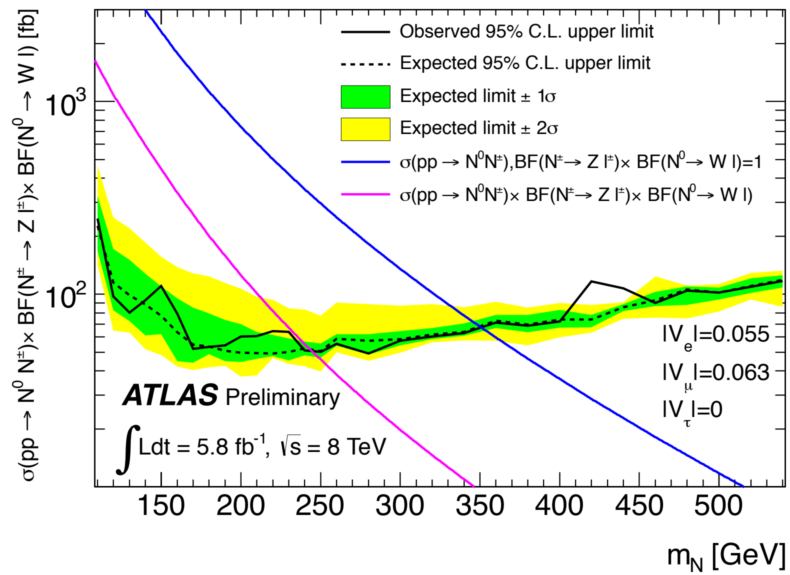


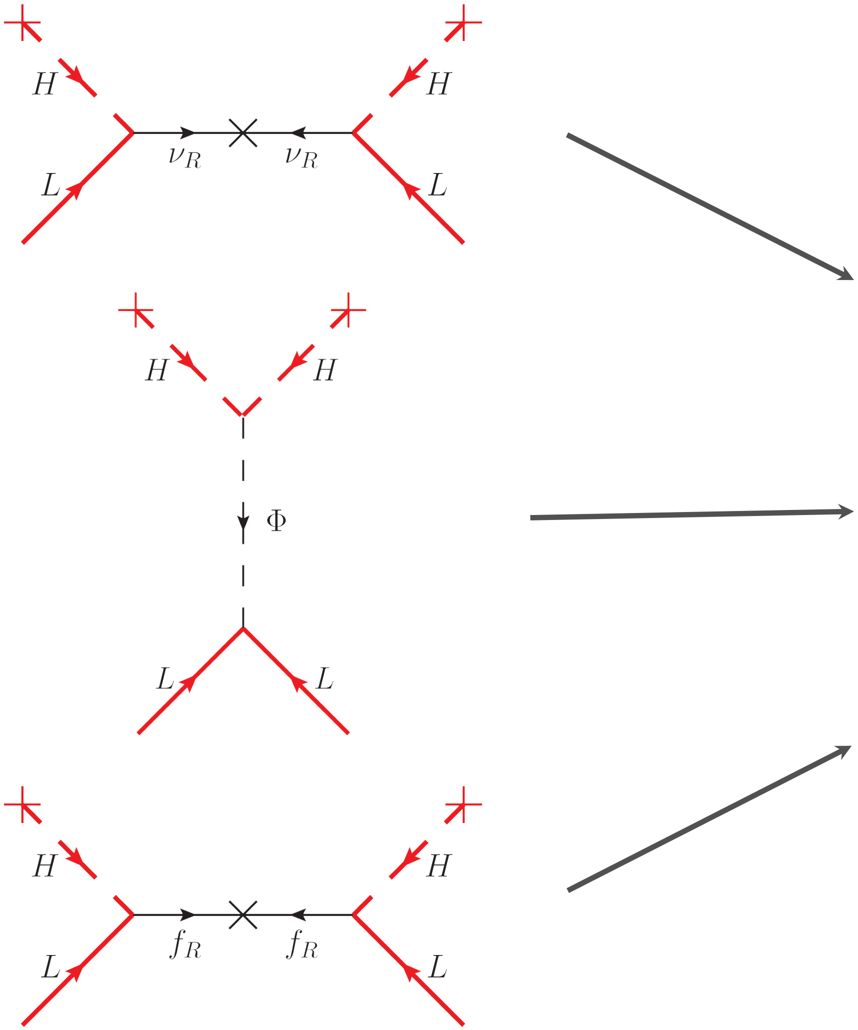
Figure 2: Invariant mass distribution of the $N^{\pm}$ candidates, $Z(\ell\ell)\ell'$, in the signal region, for data (black points), and the expected total background (solid histograms). The rightmost bins in the histograms include overflow events.

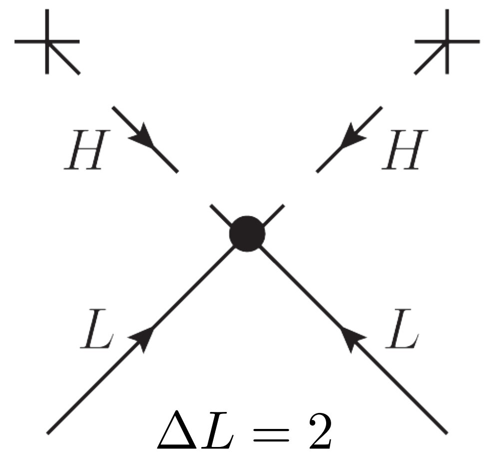


ATLAS-CONF-2013-19

Barberio, Hamano, Ong

Seesaw Models - a common thread:





Dimension-5 Weinberg effective operator (1/M)LLHH (shorthand).

$$\left(\overline{(\ell_L)^c} H\right)_1 (\ell_L H)_1$$

4. RADIATIVE NEUTRINO MASS GENERATION

Start with the Weinberg operator and "open it up" – derive it in the low-energy limit of a renormalisable model – in all possible minimal ways.

You will then systematically construct the three see-saw models.

This procedure can be used for higher mass-dimension ΔL=2 effective operators.

In principle, one can construct all possible minimal* models of Majorana neutrinos.

All d>5 operators [except those of the form LLHH(H Hbar)^n] produce neutrino mass only at loop-level. For success need 1-loop, 2-loop and maybe 3-loop scenarios.

*** Have to define "minimal" – there are always assumptions.**

B=Babu J=Julio L=Leung Z=Zee

d=detailed, b=brief

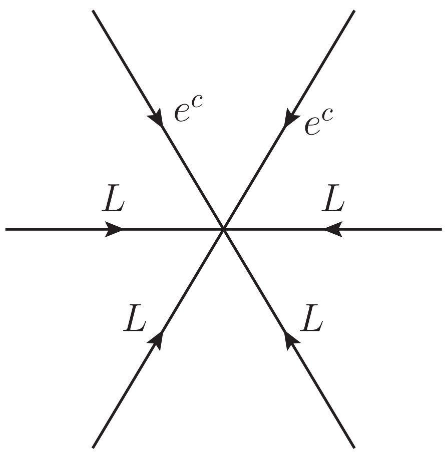
d	f	operator(s)	scale from m_ν (TeV)	model(s)?	comments
7	4	$O_2 = LLLe^cH$	10^7	Z (1980,d)	pure-leptonic,1-loop, ruled out
		$O_3 = LLQd^cH(2)$	$10^{5,8}$	BJ (2012,d) BL (2001,b)	2012 = 2-loop 2001 = 1-loop
		$O_4 = LL\bar{Q}\bar{u}^cH(2)$	$10^{7,9}$	BL (2001,b)	1-loop vector leptoquarks
		$O_8 = L\bar{e}^c\bar{u}^cd^cH$	10^4	BJ (2010,d)	2-loop
9	4	$O_5 = LLQd^cHH\bar{H}$	10^6	BL (2001,b)	1-loop
		$O_6 = LL\bar{Q}\bar{u}^cHH\bar{H}$	10^7		
		$O_7 = LQ\bar{e}^c\bar{Q}HHH$	10^2		
		$O_{61} = (LLHH)(Le^c\bar{H})$	10^5		purely leptonic
		$O_{66} = (LLHH)(Qd^c\bar{H})$	10^6		
		$O_{71} = (LLHH)(Qu^cH)$	10^7	BL (2001,b)	1-loop

A=Angel   dGJ=deGouvêa+Jenkins

d	f	operator(s)	scale from mν (TeV)	model(s)?	comments
9	6	$O_9 = LLLe^cLe^c$	10^3	BZ (1988,d)	2-loop, purely leptonic
		$O_{10} = LLLe^cQd^c$	10^4	BL (2001,b)	two 2-loop models
		$O_{11} = LLQd^cQd^c(2)$	30, 10^4	BL (2001,b) A (2011,d)	three 2-loop models one 2-loop model
		$O_{12} = LL\bar{Q}\bar{u}^c\bar{Q}\bar{u}^c(2)$	$10^{4,7}$	BL (2001,b)	2-loop
		$O_{13} = LL\bar{Q}\bar{u}^cLe^c$	10^4		
		$O_{14} = LL\bar{Q}\bar{u}^cQd^c(2)$	$10^{3,6}$		
		$O_{15} = LLLd^c\bar{L}\bar{u}^c$	10^3		at least 3-loop
		$O_{16} = LL\bar{e}^cd^c\bar{e}^c\bar{u}^c$	2		at least 3-loop
		$O_{17} = LLd^cd^c\bar{d}^c\bar{u}^c$	2		at least 3-loop
		$O_{18} = LLd^cu^c\bar{u}^c\bar{u}^c$	2		at least 3-loop
		$O_{19} = LQd^cd^c\bar{e}^c\bar{u}^c$	1	dGJ (2008,b)	at least 3-loop
		$O_{20} = Ld^c\bar{Q}\bar{u}^c\bar{e}^c\bar{u}^c$	40		at least 3-loop

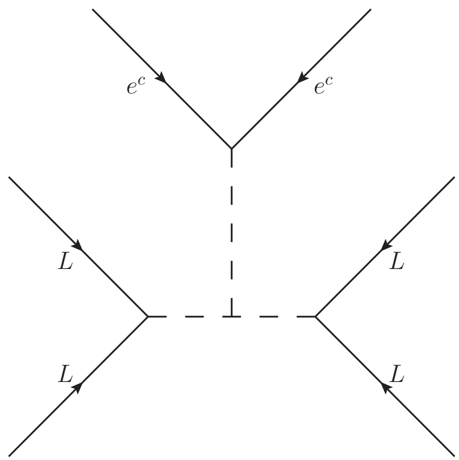
Zee-Babu model

Doubly-charged scalar k

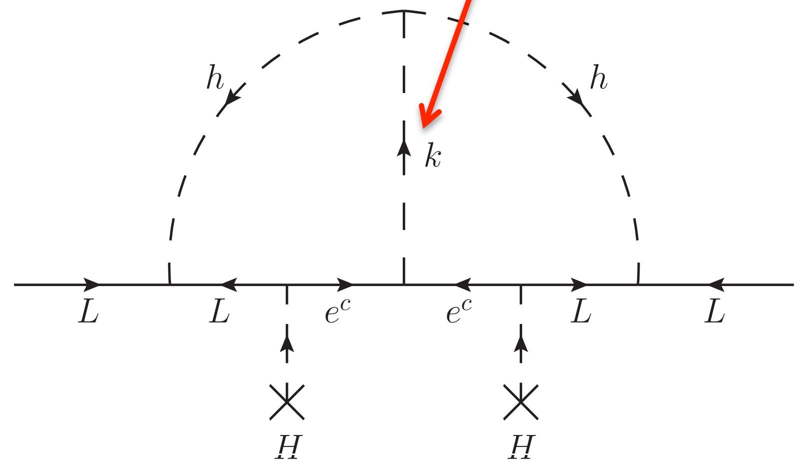


$$O_9 = LLLe^cLe^c$$

Effective op



Opening it up



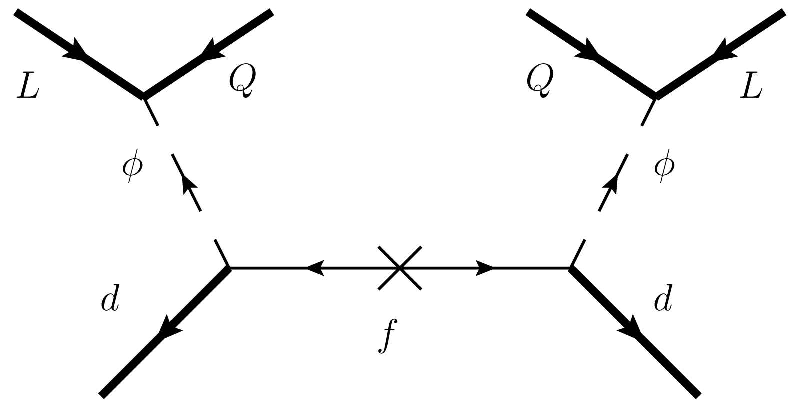
2-loop nu mass diagram

The previously shown ATLAS bounds on doubly-charged scalars coupling to RH charged leptons apply to this model as well.

Angelic O_{11} model

$$O_{11} = LLQd^cQd^c(2)$$

(Angel, Cai, Rodd, Schmidt, RV, nearly finished!)

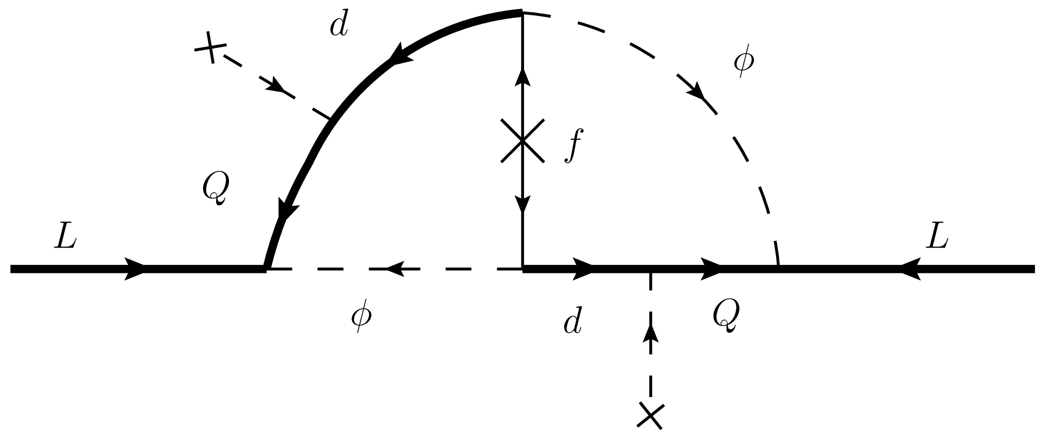


$$\phi \sim (3^*, 1, 2/3) \qquad f \sim (8, 1, 0)$$

leptoquark scalar **colour octet fermion**

$$\mathcal{L} = \lambda_{ab}^{LQ} \overline{L}_a^c Q_b \phi + \lambda_a^f \overline{d}_a f \phi^* + \frac{1}{2} m_f \overline{f}^c f + H.c.$$

ΔL=2 term



Neutrino mass and mixing angles can be fitted with m_f, m_φ ~ TeV and couplings 0.01-0.1.

Need two generations of φ to get rank-2 neutrino mass matrix.

Flavour violation bounds can be satisfied.

5. FINAL REMARKS

- Neutrinos have mass. We don’t know Dirac or Majorana, or the mechanism.
- Conspicuously light: different mechanism?
- The answer “probably” lies beyond the LHC, but at the very least we should understand what the LHC excludes.