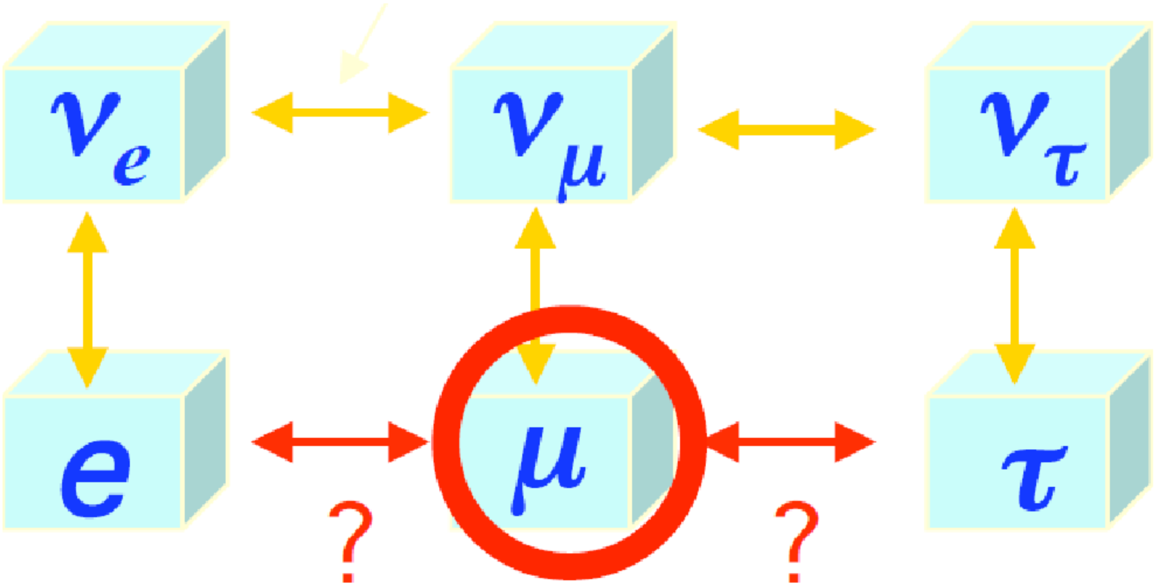
Lepton Flavour Violation

M. Hirsch

mahirsch@ific.uv.es

Astroparticle and High Energy Physics Group
Instituto de Fisica Corpuscular - CSIC
Universidad de Valencia
Valencia - Spain

Motivation



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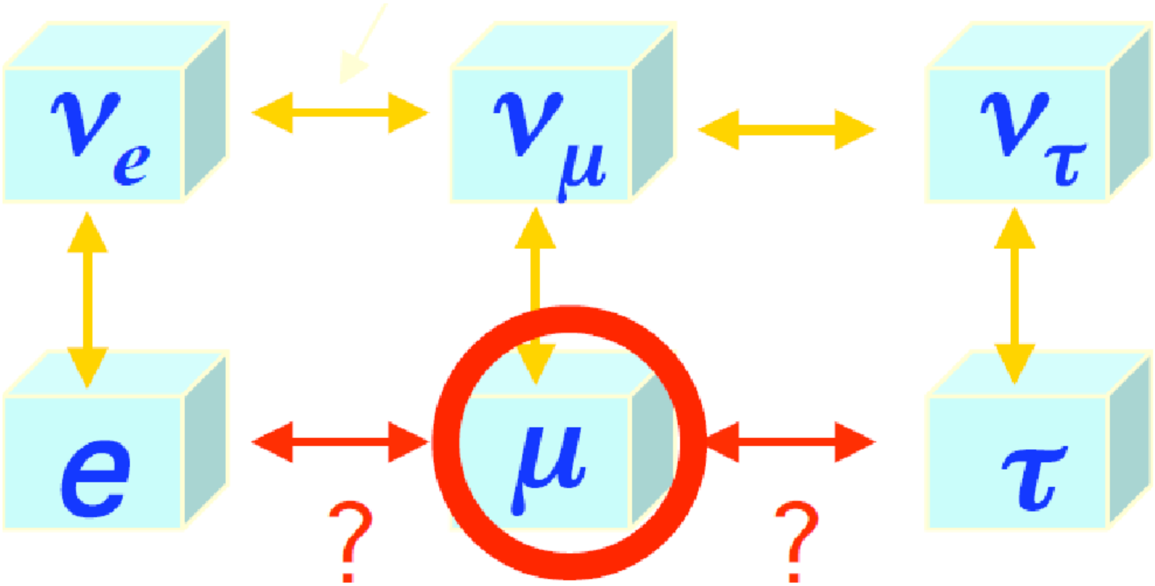

Neutrinos oscillate!

Confirmed by
many experiments:
SuperK, SNO, KamLAND,
T2K, MINOS ...

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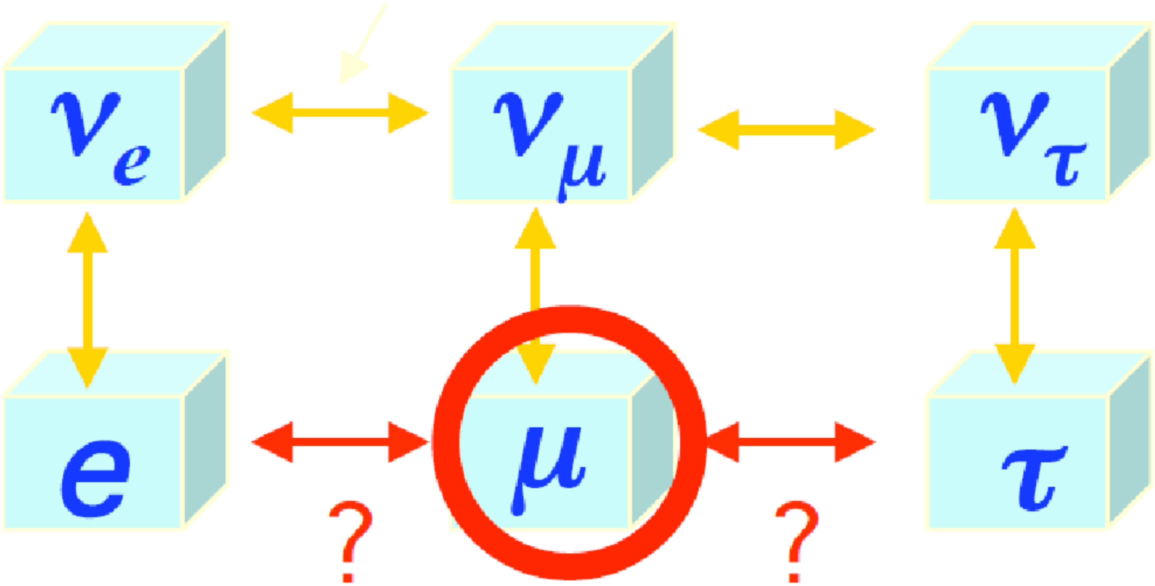

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Charged leptons?

... only
upper limits!

Outline

$\mathcal{I}$. Neutrinos - experiment

$\mathcal{II}$. Short aside on neutrino masss

$\mathcal{III}$. Charged lepton flavour violation

$\mathcal{IV}$. Conclusions

$\mathcal{I}.$

Neutrinos - experiment

Neutrino oscillations

Consider simplified two generation example:

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

A neutrino created as $|\nu_e>$ at $x = (t, \vec{x}) = (0, \vec{0})$ with energy E will evolve as:

$$|\nu_e(x)> = e^{ip_1 x}|\nu_1> + e^{ip_2 x}|\nu_2>$$

The probability of ν_μ *appearance* at a distance $\vec{x} = (0, 0, L)$ is

$$P(\nu_e \to \nu_\mu) = |<\nu_\mu|\nu(L)>|^2 \simeq \sin^2(2\theta)\sin^2(\frac{\Delta m_{12}^2 L}{4E})$$

$\Rightarrow$ oscillations in vacuum

3-generation mixing

For 3 generations of leptons, 2 independent Δm^2_{ij}, mixing has 3 θ_{ij}:

$$U = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix} \cdot P$$

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

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atmospheric and long-baseline experiments	reactor & long-baseline experiments	solar & reactor experiments

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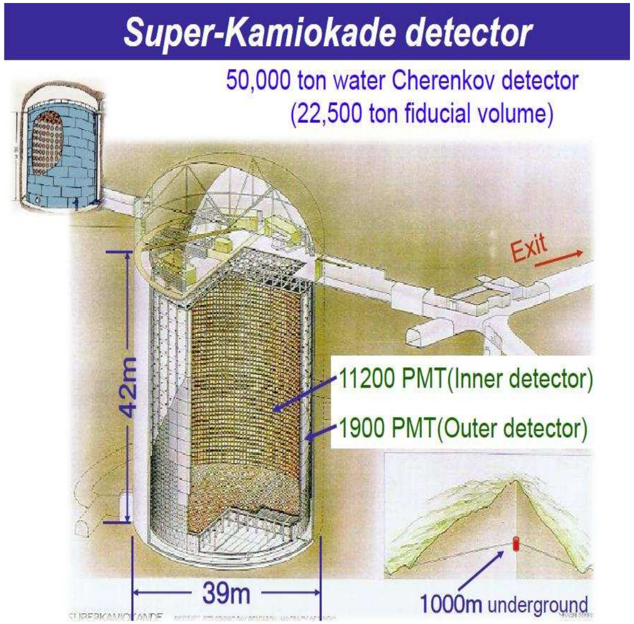
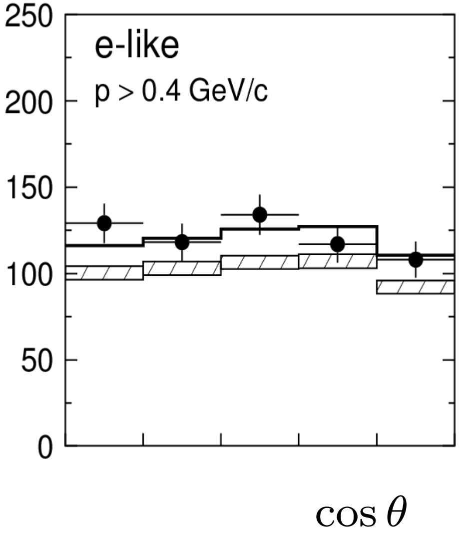
atmospheric and long-baseline experiments	reactor & long-baseline experiments	solar & reactor experiments

⇒ P - diagonal matrix of Majorana phases

observable only in $\Delta L = 2$ processes

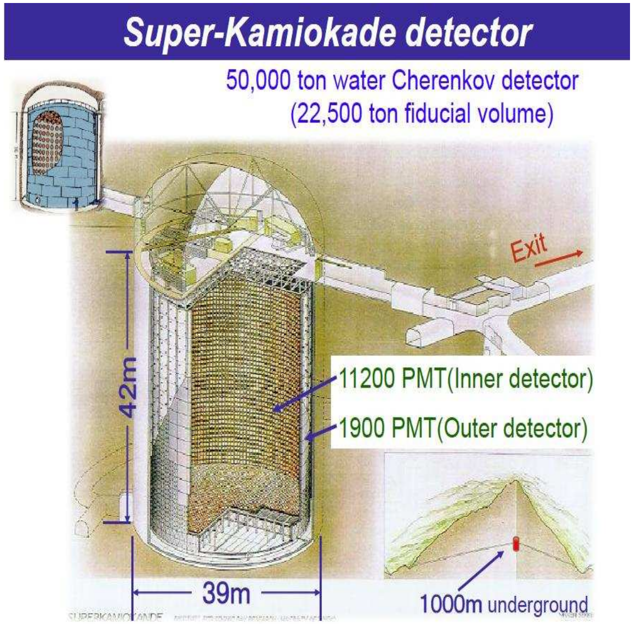
Atmospheric oscillations

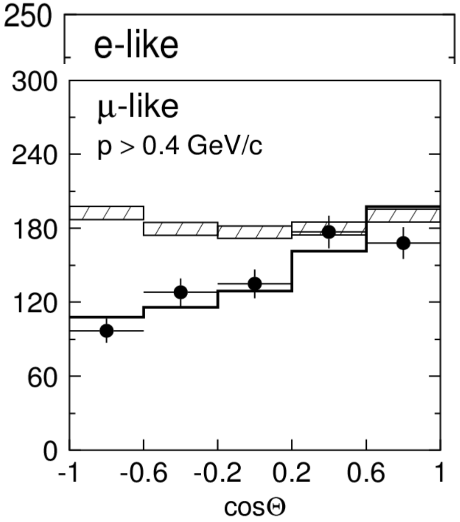




SuperK, 1998:

Atmospheric oscillations



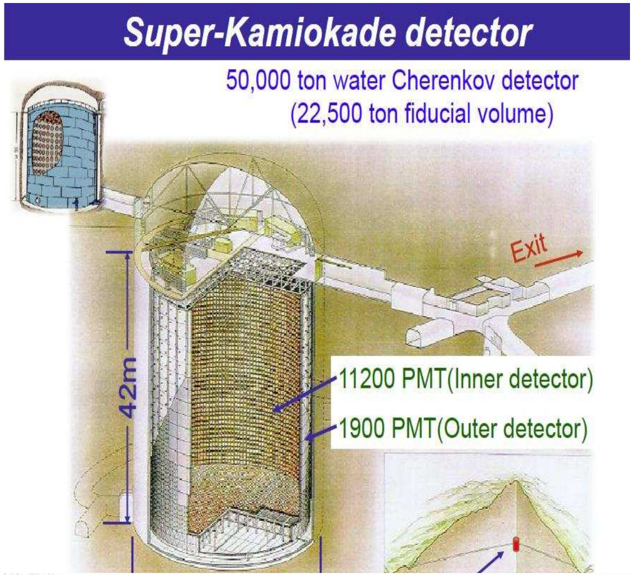


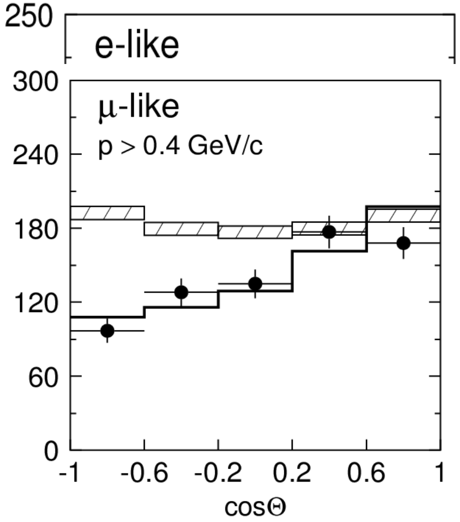
SuperK, 1998:

angular dependent deficit of ν_μ

$\Rightarrow$ ν_μ oscillate!

Atmospheric oscillations





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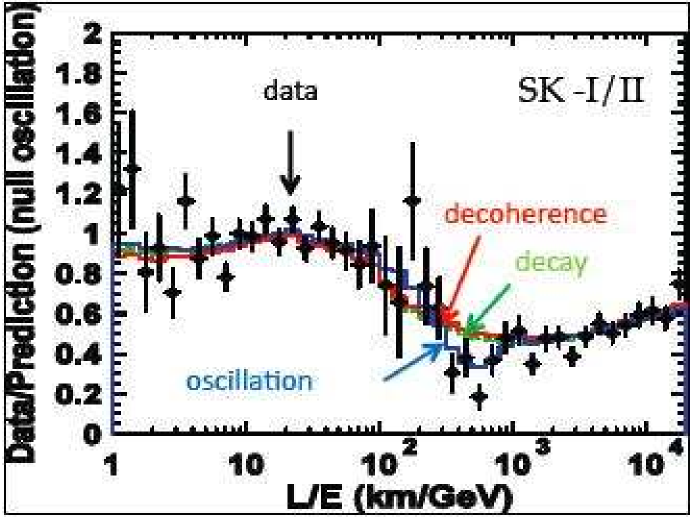


Super-K, 2004:

L/E dependence favours oscillation solution!

Atmospheric oscillations

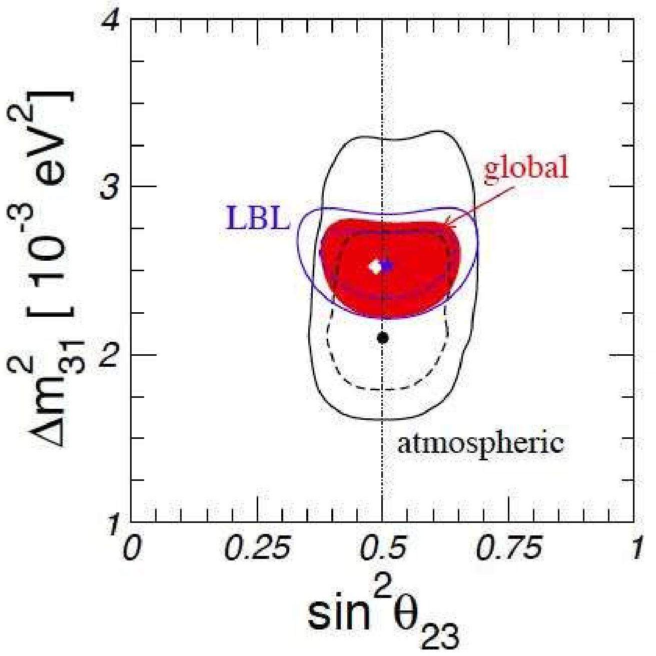
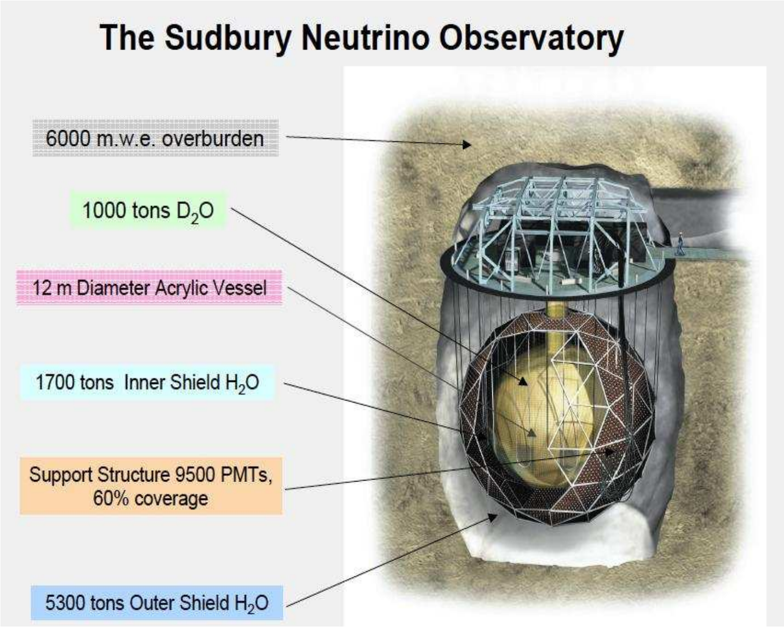


Fig from:
Forero, Tortola
& Valle, 2012

LBL - long baseline experiments (mostly MINOS)
ATM - atmospheric neutrino data, Super-Kamiokande

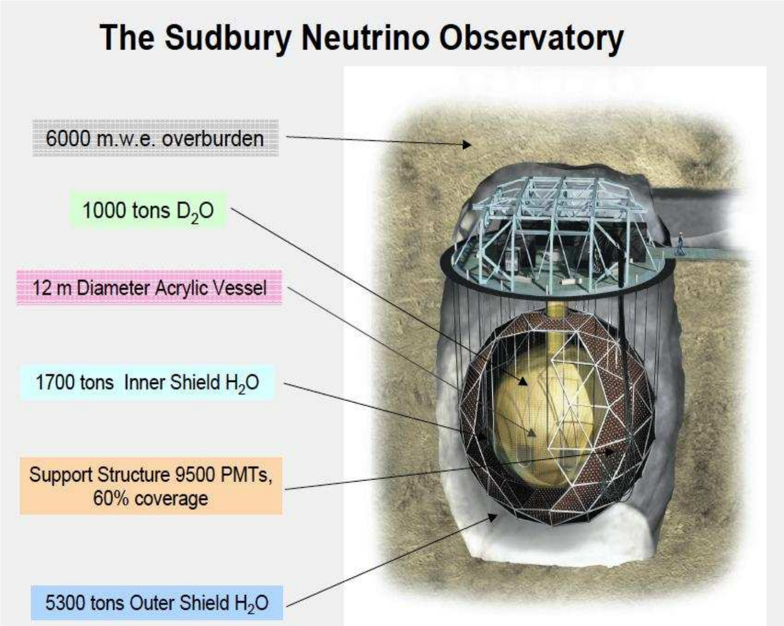
$\Delta m^2_{\rm Atm} = (2.2 - 2.74) \times 10^{-3}$ eV^2
$\sin^2\theta_{\rm Atm} = (0.36 - 0.68)$ - consistent with maximal mixing

Solar oscillations



SNO, 2000 & 2002:

Solar oscillations



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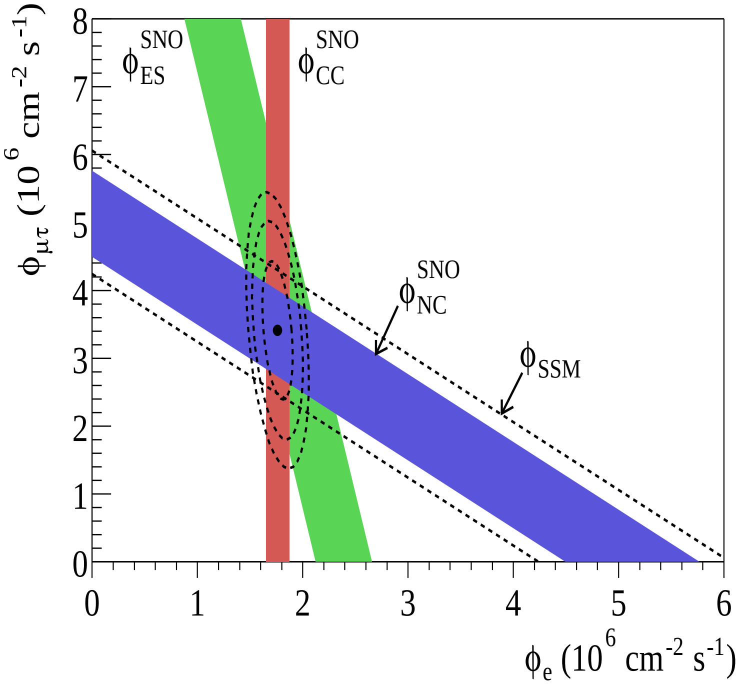
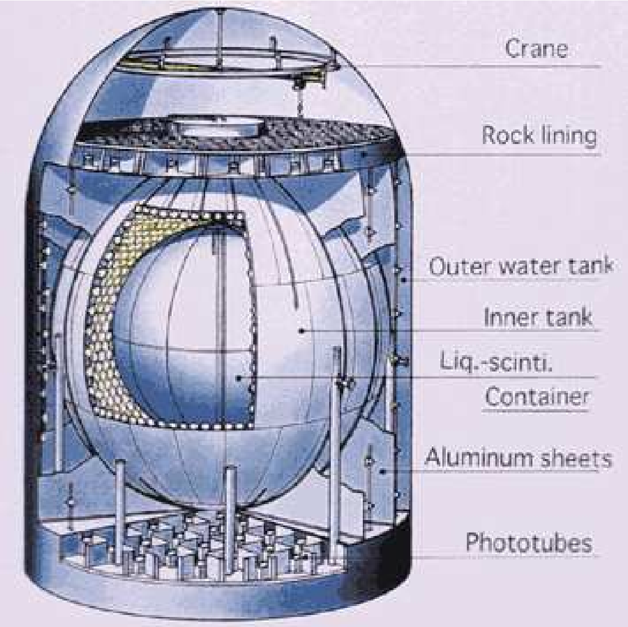


⇒ Measurement of NC confirms flavour conversion of $\nu_\odot$

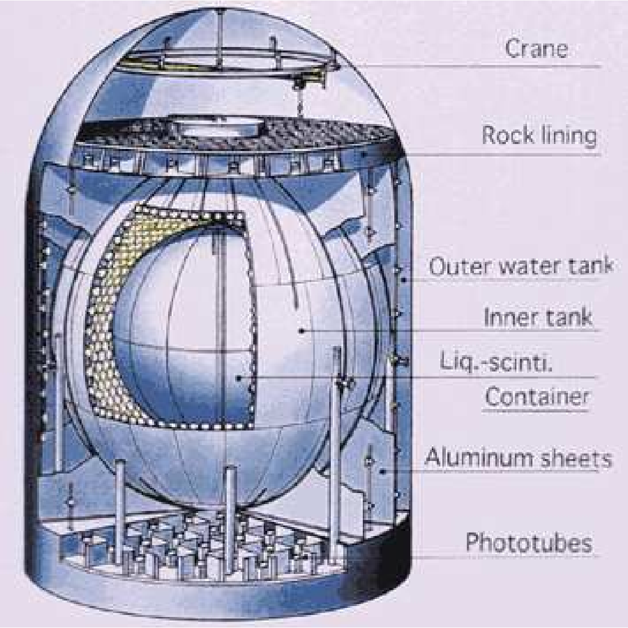
⇒ Oscillations as explanation likely, but not proven

Solar oscillations

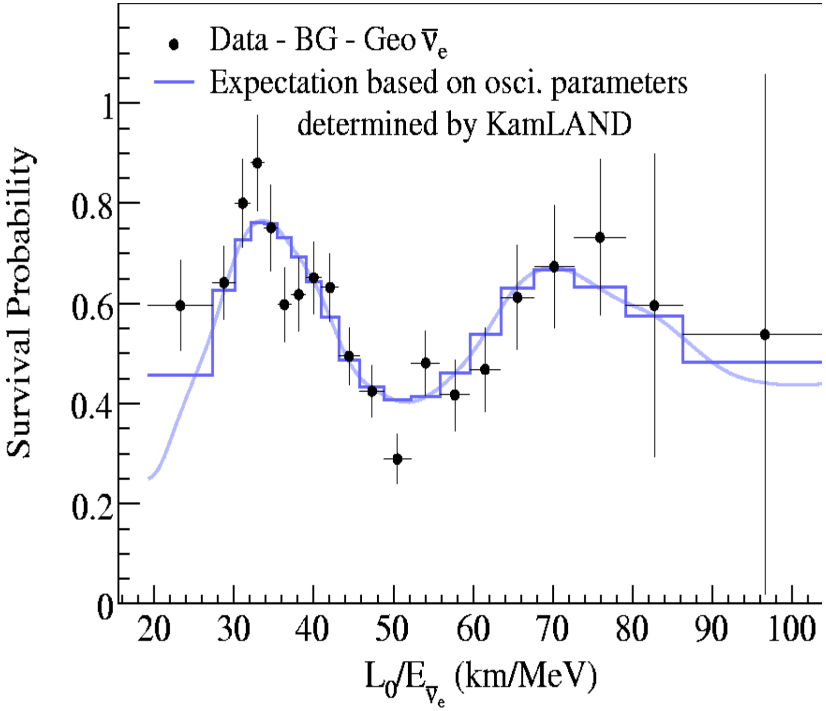


KamLAND 2002, & 2008:

Solar oscillations



KamLAND 2002, & 2008:



⇒ Measurement of LE proves neutrino oscillations

⇒ LA-MSW Oscillations as only explanation for $\nu_\odot$

Solar neutrinos - fit

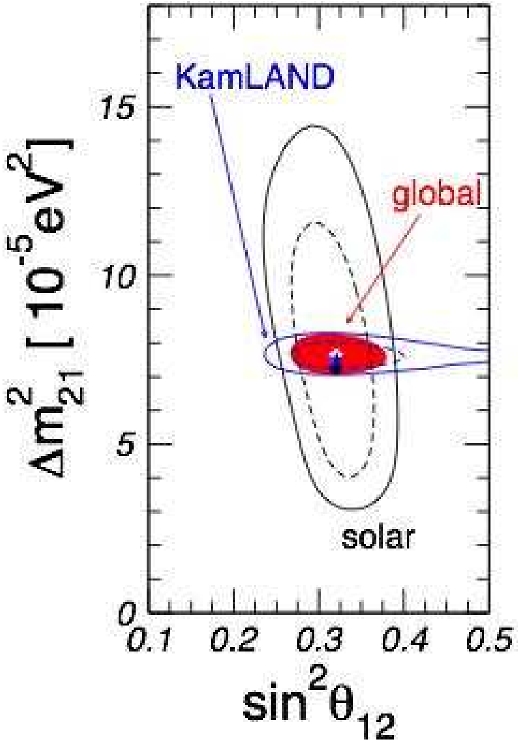
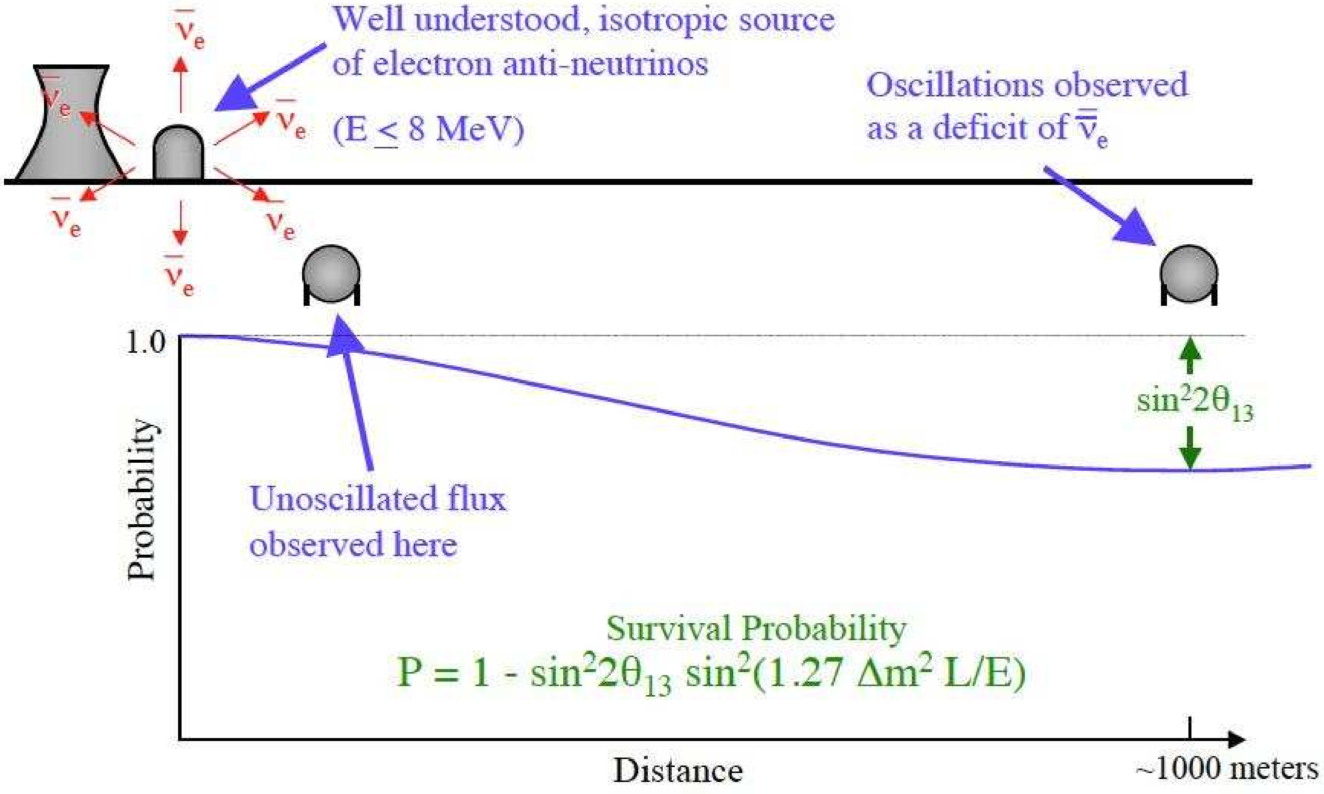


Fig from:
Forero, Tortola
& Valle, 2012

KamLAND - reactor data
solar - SNO, SuperK, GALLEX, CL, etc ...
global - combination of all data

$\Delta m^2_\odot = (7.27 - 8.01) \times 10^{-5}$ eV^2
$\sin^2\theta_\odot = (0.27 - 0.37)$ - consistent with 1/3.

Reactor neutrinos



Well understood, isotropic source of electron anti-neutrinos

($E \le 8$ MeV)

Oscillations observed as a deficit of $\bar{\nu}_e$

Unoscillated flux observed here

Survival Probability

$$P = 1 - \sin^2 2\theta_{13} \sin^2(1.27\, \Delta m^2\, L/E)$$

Reactor neutrinos

PRL 108 (2012) (arXiv:1112.6353)

$\sin^2(2\theta_{13}) = 0.086 \pm 0.041(stat) \pm (0.030)(syst)$

Non-zero @ 2 σ c.l.

PRL 108 (2012) (arXiv:1203.1669)

$\sin^2(2\theta_{13}) = 0.092 \pm 0.016(stat) \pm (0.005)(syst)$

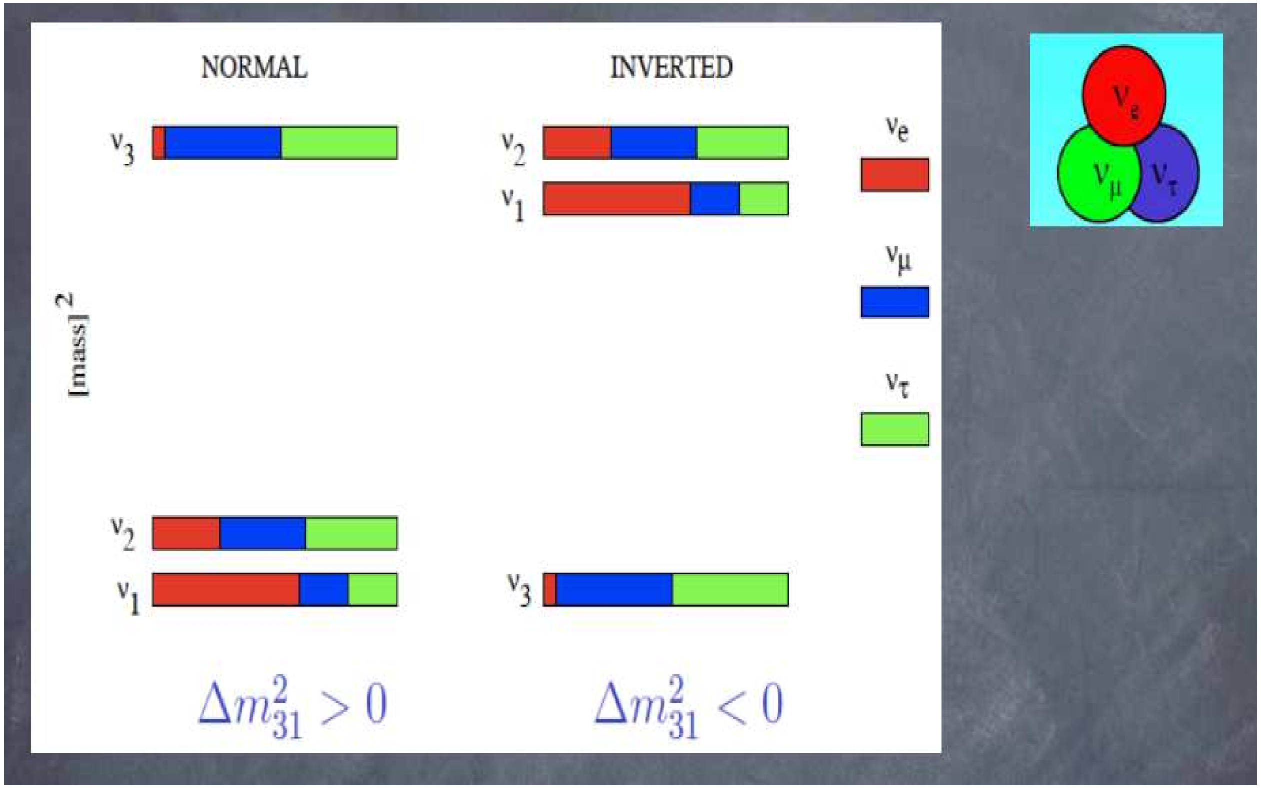
Non-zero @ 5.2 σ c.l.

PRL 108 (2012) (arXiv:1204.0626)

$\sin^2(2\theta_{13}) = 0.113 \pm 0.013(stat) \pm (0.019)(syst)$

Non-zero @ 4.9 σ c.l.

Don't know ν's



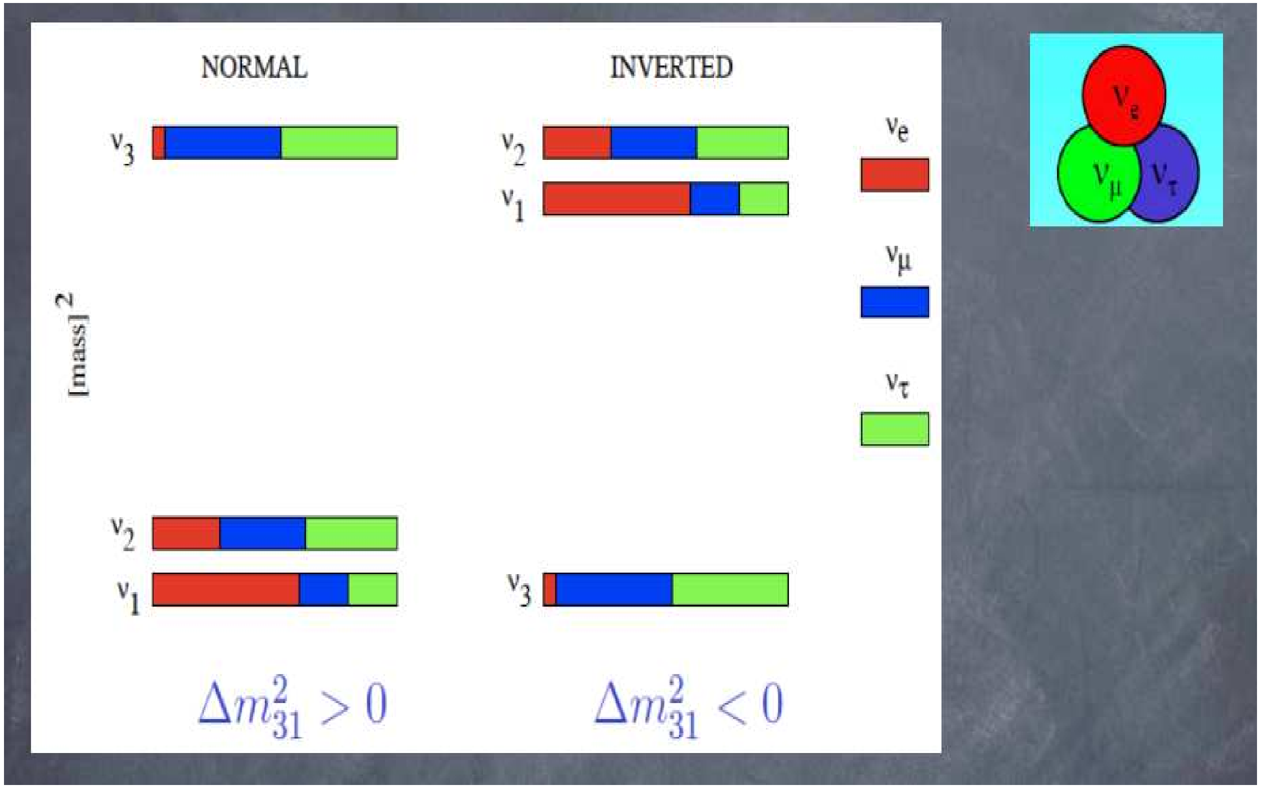
Open questions:

Which hierarchy: Normal or inverted?

What is the absolute neutrino mass scale?

Is there CP violation in the lepton sector?

Don‘t know ν‘s



Open questions:

Which hierarchy: Normal or inverted?

What is the absolute neutrino mass scale?

Is there CP violation in the lepton sector?

Is lepton number violated???

Absolute mass scale

Tritium decay end point searches:

$$m_\nu^\beta = \sqrt{\sum_i |U_{ei}|^2 m_i^2} \leq 2.2 \text{ eV}$$

KATRIN:
$m_\nu^\beta \leq 0.2$ eV
2017 (??)

Double beta decay:

Majorana neutrino!

$$m_\nu^{\beta\beta} = \sum_i U_{ei}^2 m_i \leq (0.25 - 0.5) \text{ eV}$$

KamLAND-Zen
& EXO-200

Cosmology (CMB Planck + LSS + $\cdots$):

depending on data set!
Planck only:
$\sum_i m_{\nu_i} \leq 1.0$ eV
Planck+BAO:
$\sum_i m_{\nu_i} \leq 0.3$ eV

$$\sum_i m_{\nu_i} \leq (0.3 - 1.0) \text{ eV} \quad \Leftarrow$$

$\Rightarrow$ Recall for hierarchical neutrinos:

$$\sqrt{\Delta m^2_{\text{Atm}}} \sim 50 \text{ meV} \qquad \text{and} \qquad \sqrt{\Delta m^2_\odot} \sim 9 \text{ meV}$$

Future experiments

Currently running / under construction / comissioning:

	EXO-200	GERDA-I/II	CUORE	KamLAND-Zen
A^Z	^{136}Xe	^{76}Ge	^{130}Te	^{136}Xe
Mass	160 kg	35 kg	200 kg	400 kg
Method	liquid TPC	ionization	bolometer	scint.
Location	WIPP	LNGS	LNGS	Kamioka
Starts (?)	2010	2010	2012	2011
$T_{1/2}^{0\nu\beta\beta}$ (est.)	6.4 $\times 10^{25}$	3$\times 10^{25}$ - 1.5 $\times 10^{26}$ *	(2-6.5) $\times 10^{26}$	6 $\times 10^{26}$
$\langle m_\nu \rangle^{(est.)}$ eV	0.19	0.28-0.12	0.03-0.05 *	0.02-0.06 **

Assumptions:

* - Background level 10^{-2} - 10^{-3} $e/(\mathrm{y} \cdot \mathrm{kg} \cdot \mathrm{keV})$, i.e. improvement $\simeq 20 - 200$

** - Phase II with 1 ton: 0.020 @ 5 years, BG with MC simulation

$\mathcal{II}.$

Short aside on neutrino masss

or

Why is m_ν so small?

Dirac $\mathcal{M}_\nu$

If Lepton Number is Conserved:

$$\mathcal{L} = \mathcal{L}^{SM} + Y^{\nu}_{ij} L_i H \nu_{R,j}$$

Experimental data requires: $|Y_\nu| \simeq 10^{-12}$

Fit to all oscillation data possible and simple, but ...

$\Rightarrow$ Any “predictions” of this scenario???

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Fit to all oscillation data possible and simple, but ...

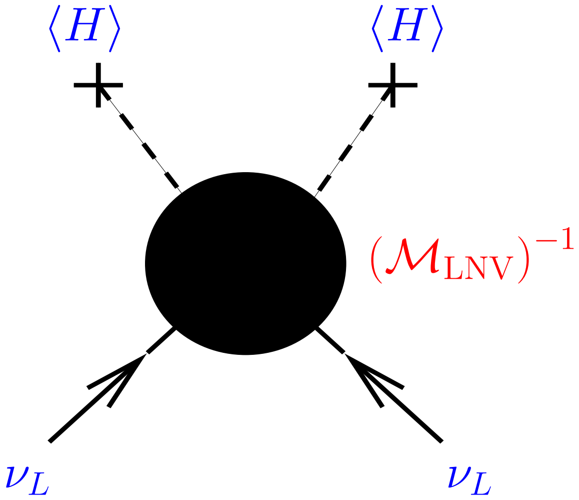
$\Rightarrow$ Any "predictions" of this scenario???

(i) No double beta decay

(ii) No charged lepton flavour violation

Majorana $\mathcal{M}_\nu$

If Lepton Number is Violated:



Weinberg, 1979

$$m_\nu = \frac{1}{\mathcal{M}_{LNV}}(LH)(LH)$$

Many realizations:

(i) Seesaw mechanism: Type-I, Type-II,
Type-III, Inverse seesaw, etc ...
(ii) Radiative models: Zee, Babu, LQs ...
(iii) SUSY neutrino masses: $\not{R}_p$
(iv) $\cdots$

Which scale?

$$\mathcal{M}_{LNV} \simeq M_{GUT}$$

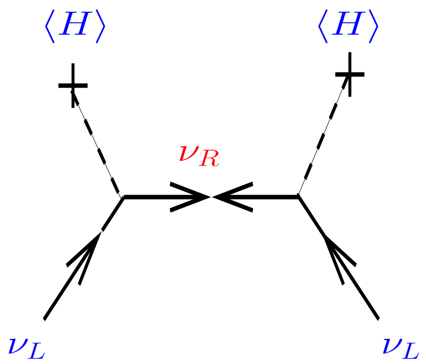
or

$$\mathcal{M}_{LNV} \simeq M_{EW}$$

Seesaw mechanism

Seesaw type-I, right-handed neutrinos:

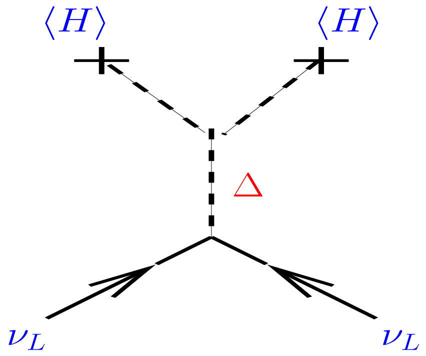
$$m_{1/2} \simeq \left(-\frac{Y_\nu^2 v^2}{M_M}, M_M\right)$$



$\Rightarrow$ For $M_M \sim 10^{15}$ GeV $h_\nu \sim 1$

Seesaw type-II, scalar triplet:

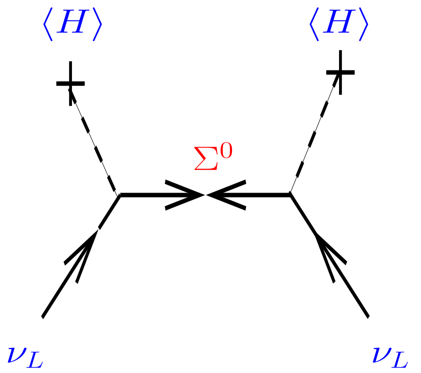
$$m_\nu \simeq Y_T \langle \Delta_L^0 \rangle \simeq Y_T \frac{v^2}{m_\Delta}$$



$\Rightarrow$ For $M_T \sim 10^{15}$ GeV $Y_T \sim 1$

Type-III: Replace ν_R by $\mathbf{\Sigma} = (\Sigma^+, \Sigma^0, \Sigma^-)$:

$$m_{1/2} \simeq \left(-\frac{Y_\Sigma^2 v^2}{M_\Sigma}, M_\Sigma\right)$$



$\Rightarrow$ Similar to type-I, but $\mathbf{\Sigma} = (\Sigma^+, \Sigma^0, \Sigma^-)$

Linear & inverse seesaw

Inverse seesaw, basis (ν, ν^c, S):

Mohapatra & Valle, 1986

$$M_\nu = \begin{pmatrix} 0 & m_D & 0 \\ m_D^T & 0 & M \\ 0 & M^T & \mu \end{pmatrix},$$

After EWSB the effective light neutrino mass matrix is given by

$$M_\nu = m_D {M^T}^{-1} \mu M^{-1} m_D^T.$$

Linear seesaw:

Akhmedov et al., 1995

$$M_\nu = \begin{pmatrix} 0 & m_D & M_L \\ m_D^T & 0 & M \\ M_L^T & M^T & 0 \end{pmatrix}.$$

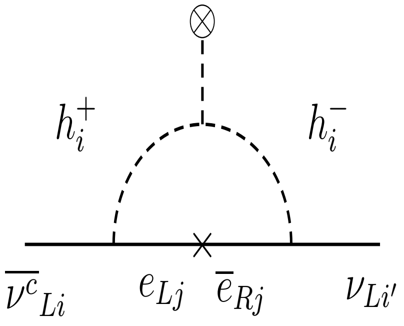
Light neutrino mass:

$$M_\nu = m_D (M_L M^{-1})^T + (M_L M^{-1}) {m_D}^T$$

Radiative models

Zee, 1981:

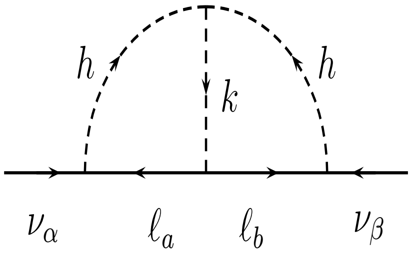
2 Higgs doublets
+ 1 charged singlet:



$$m_\nu \propto \frac{1}{16\pi^2} Y^2 \cdots$$

Cheng & Li, 1980;
Zee, 1985; Babu, 1988:

1 singly charged singlet
+ 1 doubly charged singlet:



$$m_\nu \propto \left(\frac{1}{16\pi^2}\right)^2 Y^3 \mu \cdots$$

+ many others $\cdots \Rightarrow M_{LNV} \simeq M_{EW}$

III.

Charged lepton flavour violation

or

At which scale is the new physics?

Experimental status: LFV

Decay	Current Limit
$\tau \to \mu\gamma$	$4.4 \cdot 10^{-8}$
$\tau \to e\gamma$	$3.3 \cdot 10^{-8}$
$\mu \to e\gamma$	$2.4 \cdot 10^{-12}$
$\tau \to 3\mu$	$2.1 \cdot 10^{-8}$
$\tau^- \to e^-\mu^+\mu^-$	$2.7 \cdot 10^{-8}$
$\tau^- \to e^+\mu^-\mu^-$	$1.7 \cdot 10^{-8}$
$\tau^- \to \mu^-e^+e^-$	$1.8 \cdot 10^{-8}$
$\tau^- \to \mu^+e^-e^-$	$1.5 \cdot 10^{-8}$
$\tau \to 3e$	$2.7 \cdot 10^{-8}$
$\mu \to 3e$	$1 \cdot 10^{-12}$

Particle Data Group
2012

Updated MEG, 2013:
Br($\mu \to e\gamma$)$\lesssim 5.7 \cdot 10^{-13}$

Proposed MEG upgrade:
Br($\mu \to e\gamma$)$\lesssim 6 \cdot 10^{-14}$

Mu3E and MUSIC:
Br($\mu \to eee$)$\lesssim 10^{-16}$

Experimental status: LFV

Capture	Current Limit
$\mu^- \, {}^{32}S \to e^- \, {}^{32}S$	$7 \cdot 10^{-11}$
$\mu^- \, {}^{32}S \to e^+ \, {}^{32}Si$	$9 \cdot 10^{-10}$
$\mu^- Ti \to e^- Ti$	$4.3 \cdot 10^{-12}$
$\mu^- Ti \to e^+ Ca$	$3.6 \cdot 10^{-11}$
$\mu^- Pb \to e^- Pb$	$4.6 \cdot 10^{-11}$
$\mu^- Au \to e^- Au$	$7 \cdot 10^{-13}$

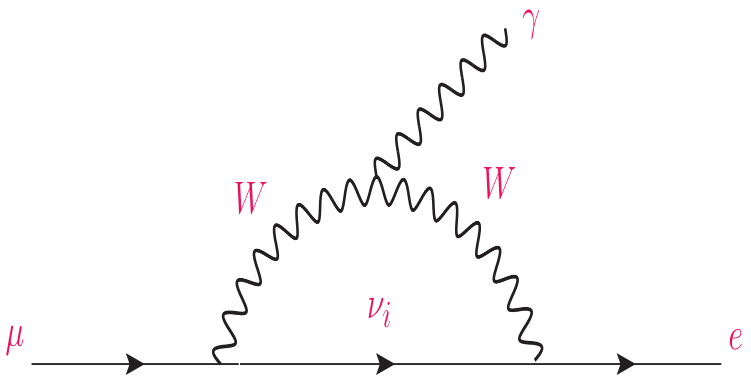
Particle Data Group
2012

Future sensitivity:
Mu2E (FermiLab)
& COMET (Japan):
$\sim 10^{-16}$

2020+?
Prisme/Prime (J-Parc):
$\sim 10^{-18}$

Guaranteed CLFV

Oscillations experiments have shown that $m_\nu \neq 0$:



$$\mathrm{Br}(\mu \to e\gamma) \sim \frac{3\alpha}{32\pi}\left(\sum_{i=2,3} U^*_{\mu i} U_{ei} \frac{\Delta m^2_{i1}}{m^2_W}\right)^2 \leq 10^{-53}$$

⇒ GIM suppressed by small neutrino masses

Guaranteed CLFV

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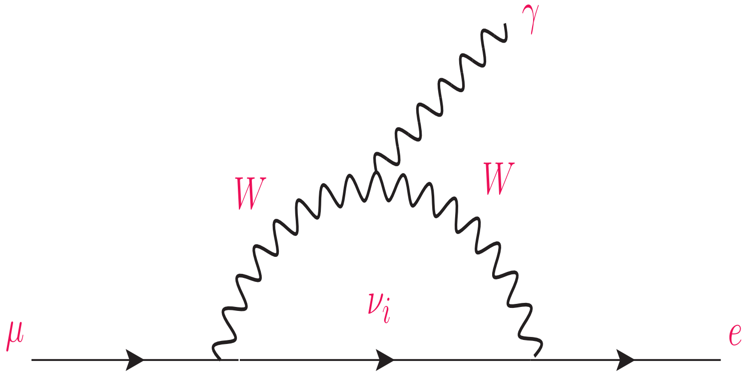

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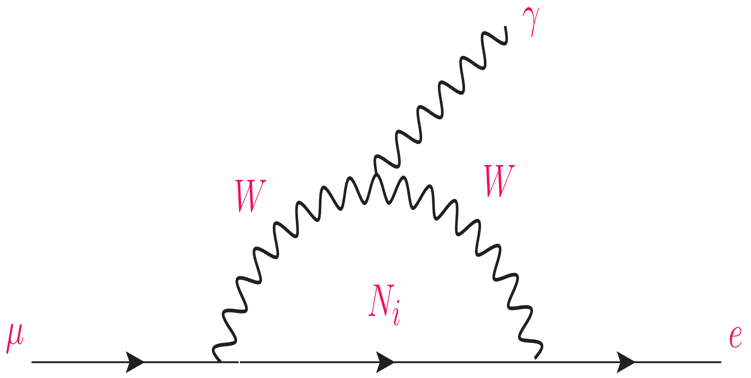
$\Rightarrow$ GIM suppressed by small neutrino masses

Any observation of charged LFV
points to physics beyond neutrino masses

CLFV beyond m_ν

Simple example: Heavy neutrinos (N) with m_N $\mathcal{O}(TeV)$:



$$\mathrm{Br}(\mu \to e\gamma) \sim$$

$$\frac{\alpha^3 s_W^2}{256\pi^2}\frac{m_\mu^5}{m_W^4\Gamma_\mu}\left(\sum_i K_{\mu i}^* K_{ei} G(\frac{m_{N_k}^2}{m_W^2})\right)^2$$

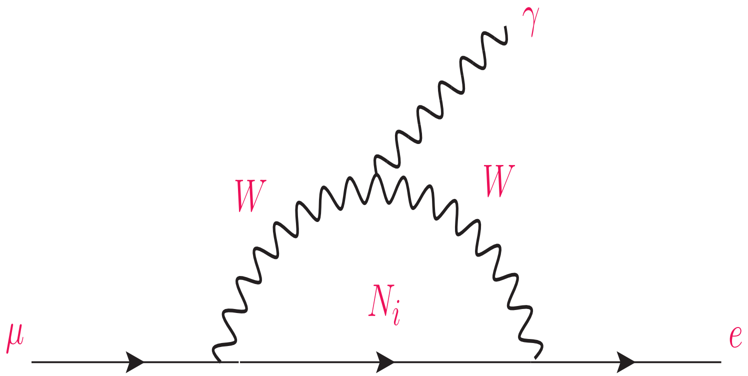
$$\leq 9 \times 10^{-6}\left(\sum_i K_{\mu i}^* K_{ei} G(\frac{m_{N_k}^2}{m_W^2})\right)^2$$

– K_{ik} heavy neutrino - lepton mixing

– G(x) loop function, $G(1) = 1/8$

CLFV beyond m_ν

Simple example: Heavy neutrinos (N) with m_N $\mathcal{O}(TeV)$:



$$\mathrm{Br}(\mu \to e\gamma) \sim$$
$$\frac{\alpha^3 s_W^2}{256\pi^2}\frac{m_\mu^5}{m_W^4\Gamma_\mu}\Big(\sum_i K^*_{\mu i}K_{ei}G(\frac{m^2_{N_k}}{m^2_W})\Big)^2$$
$$\leq 9 \times 10^{-6}\Big(\sum_i K^*_{\mu i}K_{ei}G(\frac{m^2_{N_k}}{m^2_W})\Big)^2$$

– K_{ik} heavy neutrino - lepton mixing
– G(x) loop function, $G(1) = 1/8$

Practically any extension of SM
with new states at TeV scale
generates large charged LFV!

(C)LFV - Models

$\Rightarrow$ Example models that produce sizeable CLFV:

- TeV scale seesaw: Inverse seesaw, linear seesaw, etc.
- Radiative neutrino mass models: Zee-, Babu-Zee model, etc.

- RPC Supersymmetry
- RPV Supersymmetry
- Practically any extended Higgs sector:
  Little Higgs models, additional Higgs doublets, triplets, etc...
- Extra (large) dimensions
- etc ...

$\Rightarrow$ In fact, many models generate way to much CLFV:
"Flavour problem" of BSM

The MSSM: Superpartners

Superfield	Bosons	Fermions	SU(3)$_C$	SU(2)$_L$	U(1)$_Y$
Gauge Multiplets					
$\widehat{G}$	g	$\tilde{g}$	8	0	0
$\widehat{V}$	W^a	$\widetilde{W}^a$	1	3	0
$\widehat{V}'$	B	$\widetilde{B}$	1	1	0
Matter Multiplets					
$\widehat{L}$	$(\tilde{\nu}, \tilde{e}^-_L)$	(ν, e^-_L)	1	2	-1
$\widehat{E}^C$	$\tilde{e}^+_R$	e^c_L	1	1	2
$\widehat{Q}$	$(\tilde{u}_L, \tilde{d}_L)$	(u_L, d_L)	3	2	1/3
$\widehat{U}^C$	$\tilde{u}^*_R$	u^c_L	3^*	1	-4/3
$\widehat{D}^C$	$\tilde{d}^*_R$	d^c_L	3^*	1	2/3
Higgs Multiplets					
$\widehat{H}_d$	(H^0_d, H^-_d)	$(\tilde{H}^0_d, \tilde{H}^-_d)$	1	2	-1
$\widehat{H}_u$	(H^+_u, H^0_u)	$(\tilde{H}^+_u, \tilde{H}^0_u)$	1	2	1

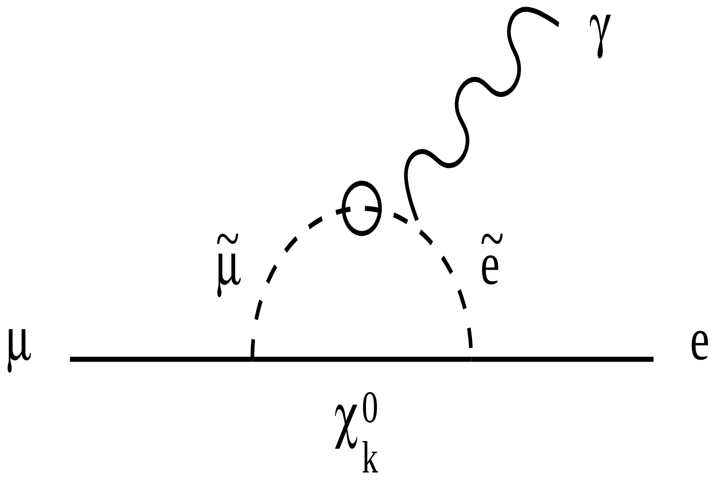
Slepton mixing

Soft SUSY breaking:

$$V = (m^2_{\tilde{L}})_{ij} \tilde{L}^*_i \tilde{L}_j + \cdots$$

Off-diagonal elements induce decays, such as:

Example only!



$$\delta_{12} = \frac{(m^2_{\tilde{L}})_{21}}{m^2_{SUSY}} \lesssim 10^{-4}$$

$$\sim (m^2_{\tilde{L}})_{21}$$

mSugra

Boundary conditions: mSUGRA ("minimal Supergravity") :

$$M_1 = M_2 = M_3 = M_{1/2},$$
$$m^2_{H_u} = m^2_{H_d} = m^2_0,$$
$$M^2_{\tilde{Q}} = M^2_{\tilde{U}} = M^2_{\tilde{D}} = M^2_{\tilde{L}} = M^2_{\tilde{E}} = m^2_0 1_3,$$
$$A_d = A_0 Y_d,\ A_u = A_0 Y_u,\ A_e = A_0 Y_e.$$

$\Leftarrow$ Flavour blind SUSY breaking!

$\Rightarrow$ # of parameters: $4\frac{1}{2}$ ($m_0, M_{1/2}, A_0, \tan\beta, sgn(\mu)$)

$\Rightarrow$ Sometimes also called the CMSSM (C = constrained)

$\Rightarrow$ All low energy masses can then be calculated by RGE ("renormalization group equations")

$\Rightarrow$ No neutrino masses and no LFV

mSugra and RGEs

Seesaw type-I: Borzumati & Masiero, 1986

$$(\Delta M^2_{\tilde{L}})_{ij} \sim -\frac{1}{8\pi^2} f(m_0, A_0, M_{1/2}, ...)(Y_\nu^\dagger L Y_\nu)_{ij}$$

Hisano et al. 1996, 1999
Arganda & Herrero, 2006
. . .

Note: $L_i = \log[M_G/M_i]$.

$\Rightarrow$ 9 new independent parameters

Seesaw type-II: Rossi, 2002

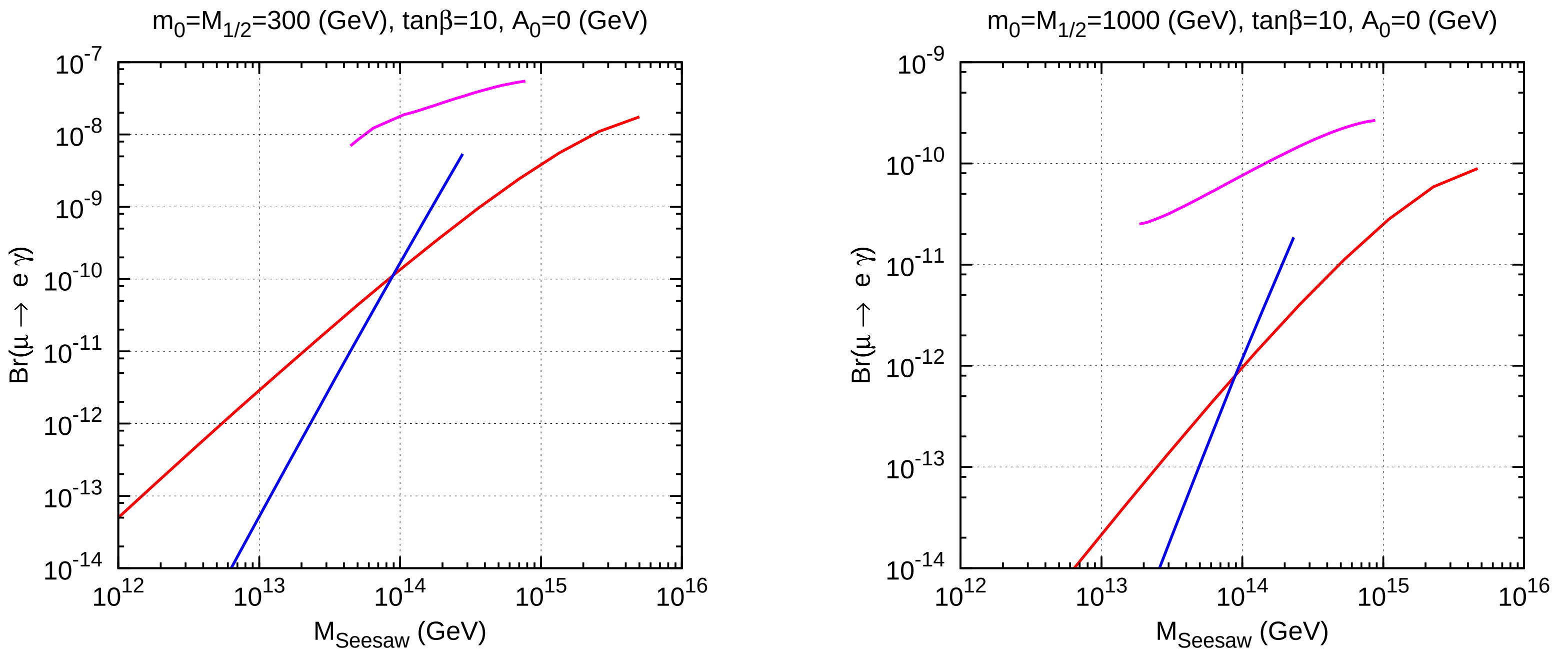
$$(\Delta M^2_{\tilde{L}})_{ij} \sim -\frac{1}{8\pi^2} g(m_0, A_0, M_{1/2}, ...)(Y_T^\dagger Y_T)_{ij} \log(M_G/M_T)$$

$\Rightarrow$ 9 entries, but proportional to Y_T^2

$\Rightarrow$ Measuring all entries in $(\Delta M^2_{\tilde{L}})_{ij}$ "over-constrains" type-II seesaw!

Note: type-III equation as type-I, but larger LFV ... see below

$\mu \to e\gamma$ in mSugra sessaw



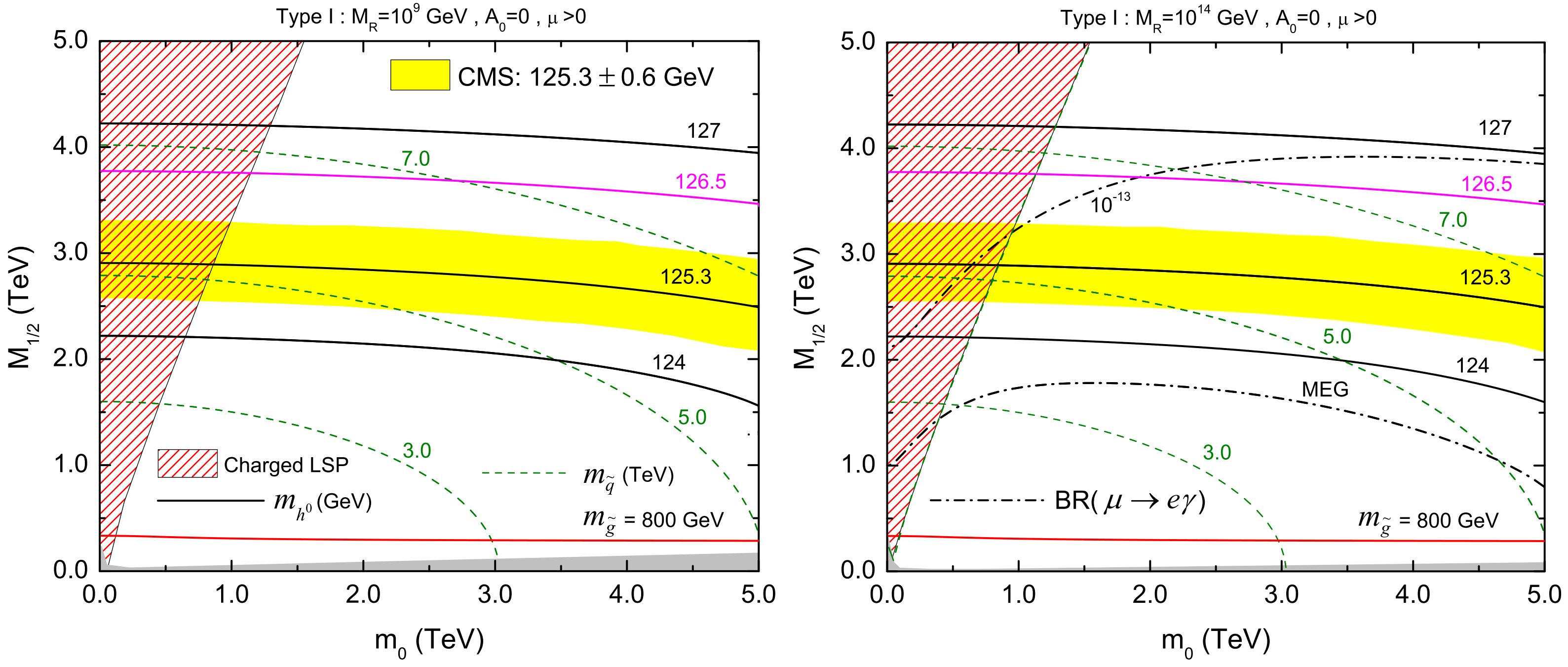
⇒ The three different seesaws are: type-III, type-II and type-I

⇒ General expectation: “Large” LFV for “large” M_{Seesaw}

⇒ General expectation LFV in type-III $\gg$ type-I

m_{h^0} and LFV in SUSY seesaw

Seesaw type-I:



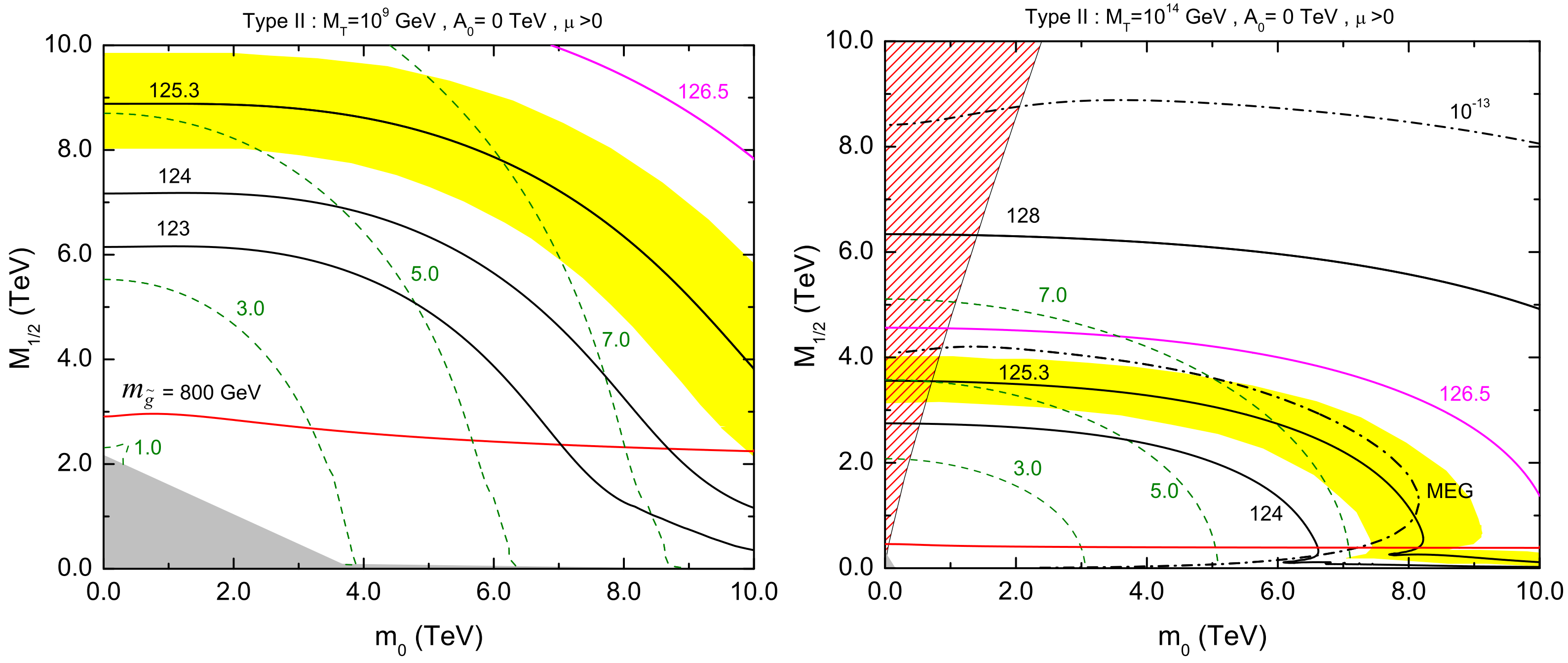
$\Rightarrow$ $M_{\nu_R} = 10^9$ GeV (left) and $M_{\nu_R} = 10^{14}$ GeV (right)

$\Rightarrow$ Yellow: Allowed band from $m_{h^0} = 125.3 \pm 0.6$ GeV

$\Rightarrow$ CLFV constrains large M_{ν_R}

m_{h^0} and LFV in SUSY seesaw

Seesaw type-II:



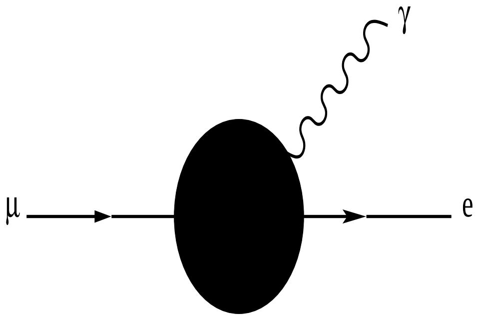
⇒ $M_T = 10^9$ GeV (left) and $M_T = 10^{14}$ GeV (right)

⇒ Yellow: Allowed band from $m_{h^0} = 125.3 \pm 0.6$ GeV

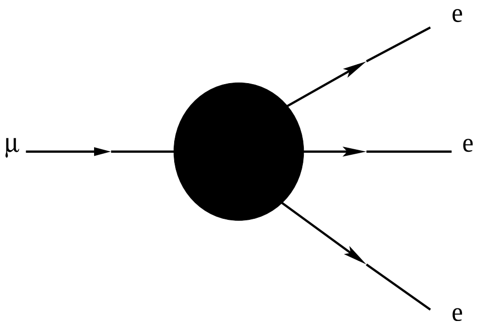
⇒ CLFV and m_{h^0} constrain large M_T

Schematically:

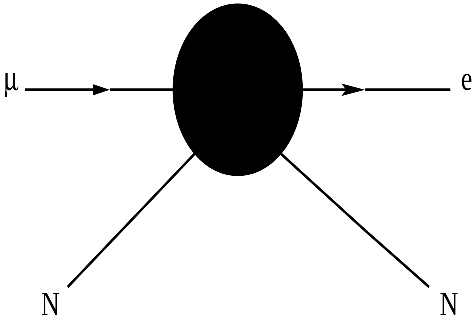
$\mu \to e\gamma$:



$\mu \to 3e$



μ-capture:

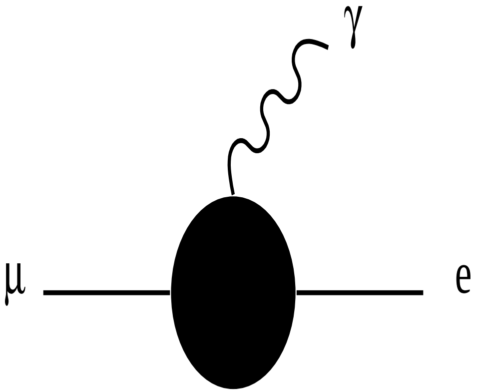


Can we learn about
different BSM models
from different LFV processes?

$\mu \to e\gamma$ versus $\mu \to 3e$

Consider $\mu \to e\gamma$:

Some physics
beyond SM
generates blob:



$\mu \to e\gamma$ versus $\mu \to 3e$

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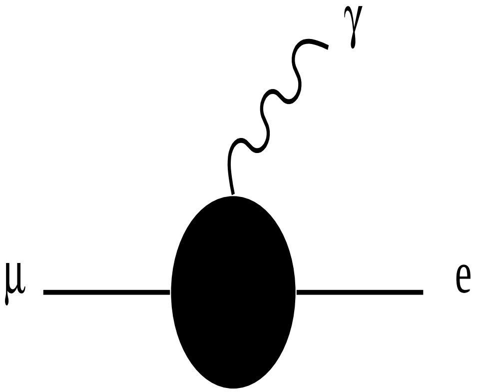
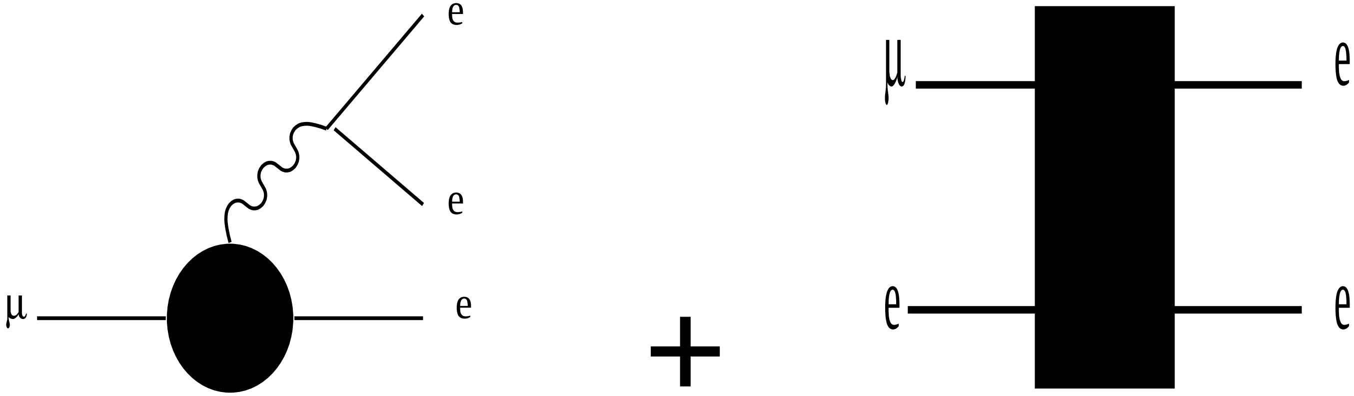


Compare $\mu \to 3e$:

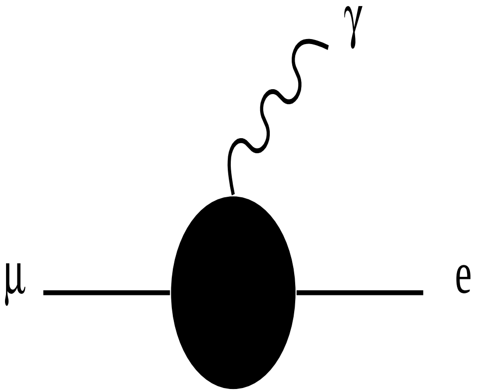
Same blob
appears in
$\mu \to 3e$



$\mu \to e\gamma$ versus $\mu \to 3e$

Consider $\mu \to e\gamma$:

Some physics beyond SM generates blob:

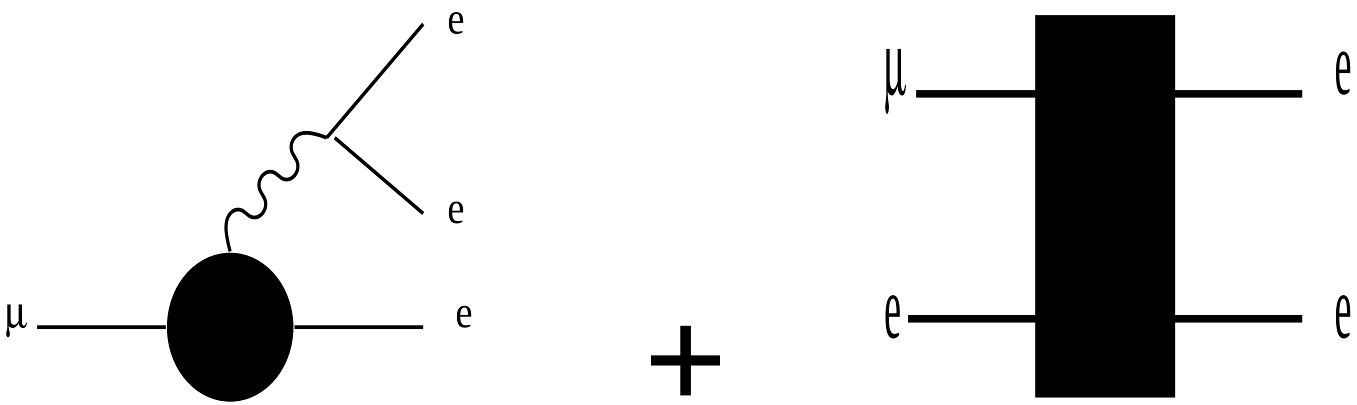


If photon diagram dominates:

$$Br(l_i \to l_j l_k l_k) \sim \alpha \times Br(e \to l_j + \gamma)$$

Compare $\mu \to 3e$:

Same blob appears in $\mu \to 3e$

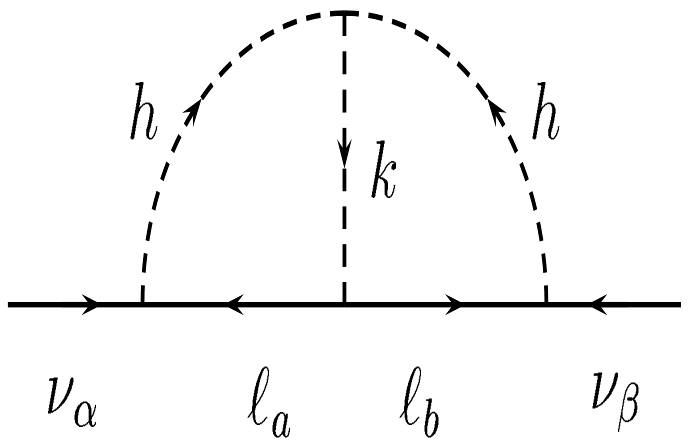


Simple example

Babu-Zee model for neutrino mass:

$$\mathcal{L} = f(L^T L)h^+ + g(e_R^T e_R)k^{++} - \mu h^+ h^+ k^{--}$$

Cheng & Li, 1980
Zee, 1985
Babu, 1988



Neutrino mass is
2-loop suppressed!

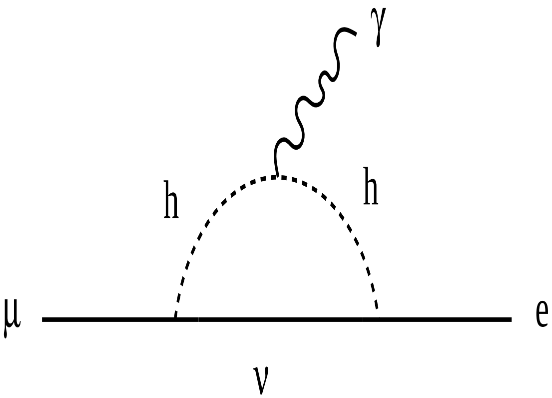
Babu & Macesanu, 2003
Aristizabal & Hirsch, 2006

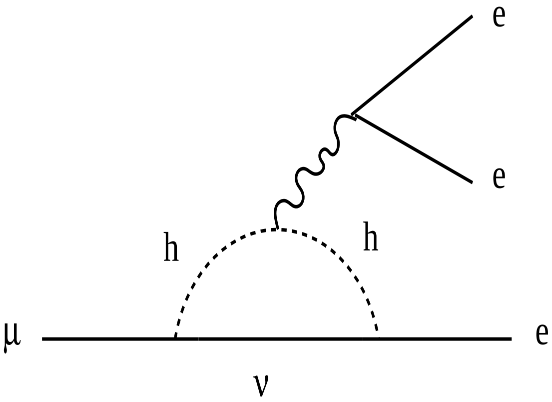
$$\mathcal{M}^\nu_{\alpha\beta} = \frac{8\mu}{(16\pi^2)^2 m_h^2} f_{\alpha a} m_a g_{xy} m_b f_{b\beta} \mathcal{I}\left(\frac{m_k^2}{m_h^2}\right),$$

Large neutrino mixing angles
require large CLFV

CLFV in Babu-Zee model

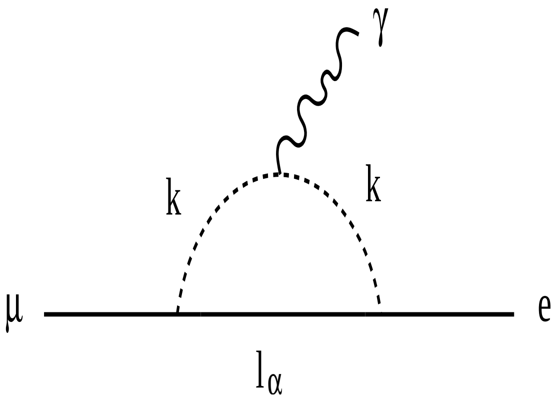
If $\frac{g^2}{m_k^2} \ll \frac{f^2}{m_h^2}$:

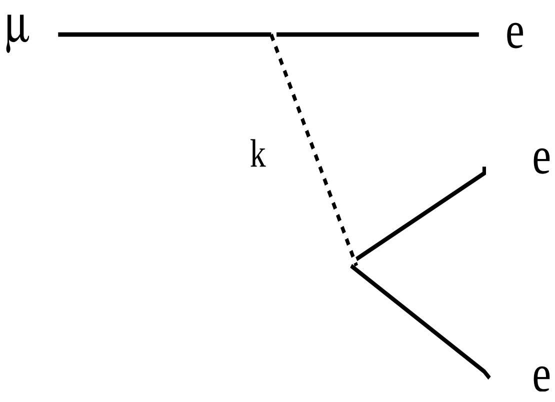




Photon dominance!

if $\frac{f^2}{m_h^2} \ll \frac{g^2}{m_k^2}$:





$\mu \to 3e$ tree-level!

Photon dominance?

From Buras et al., 2010: Different particle models predict different ratios for ...

ratio	LHT	MSSM (dipole)	MSSM (Higgs)	SM4
$\frac{\mathrm{Br}(\mu^- \to e^- e^+ e^-)}{\mathrm{Br}(\mu \to e\gamma)}$	0.02. . . 1	$\sim 6 \cdot 10^{-3}$	$\sim 6 \cdot 10^{-3}$	$0.06 \ldots 2.2$
$\frac{\mathrm{Br}(\tau^- \to e^- e^+ e^-)}{\mathrm{Br}(\tau \to e\gamma)}$	0.04. . . 0.4	$\sim 1 \cdot 10^{-2}$	$\sim 1 \cdot 10^{-2}$	$0.07 \ldots 2.2$
$\frac{\mathrm{Br}(\tau^- \to \mu^- \mu^+ \mu^-)}{\mathrm{Br}(\tau \to \mu\gamma)}$	0.04. . . 0.4	$\sim 2 \cdot 10^{-3}$	$0.06 \ldots 0.1$	$0.06 \ldots 2.2$
$\frac{\mathrm{Br}(\tau^- \to e^- \mu^+ \mu^-)}{\mathrm{Br}(\tau \to e\gamma)}$	0.04. . . 0.3	$\sim 2 \cdot 10^{-3}$	$0.02 \ldots 0.04$	$0.03 \ldots 1.3$
$\frac{\mathrm{Br}(\tau^- \to \mu^- e^+ e^-)}{\mathrm{Br}(\tau \to \mu\gamma)}$	0.04. . . 0.3	$\sim 1 \cdot 10^{-2}$	$\sim 1 \cdot 10^{-2}$	$0.04 \ldots 1.4$
$\frac{\mathrm{Br}(\tau^- \to e^- e^+ e^-)}{\mathrm{Br}(\tau^- \to e^- \mu^+ \mu^-)}$	0.8. . . 2	~ 5	0.3. . . 0.5	$1.5 \ldots 2.3$
$\frac{\mathrm{Br}(\tau^- \to \mu^- \mu^+ \mu^-)}{\mathrm{Br}(\tau^- \to \mu^- e^+ e^-)}$	0.7. . . 1.6	~ 0.2	5. . . 10	$1.4 \ldots 1.7$
$\frac{\mathrm{R}(\mu\mathrm{Ti} \to e\mathrm{Ti})}{\mathrm{Br}(\mu \to e\gamma)}$	$10^{-3} \ldots 10^{2}$	$\sim 5 \cdot 10^{-3}$	$0.08 \ldots 0.15$	$10^{-12} \ldots 26$

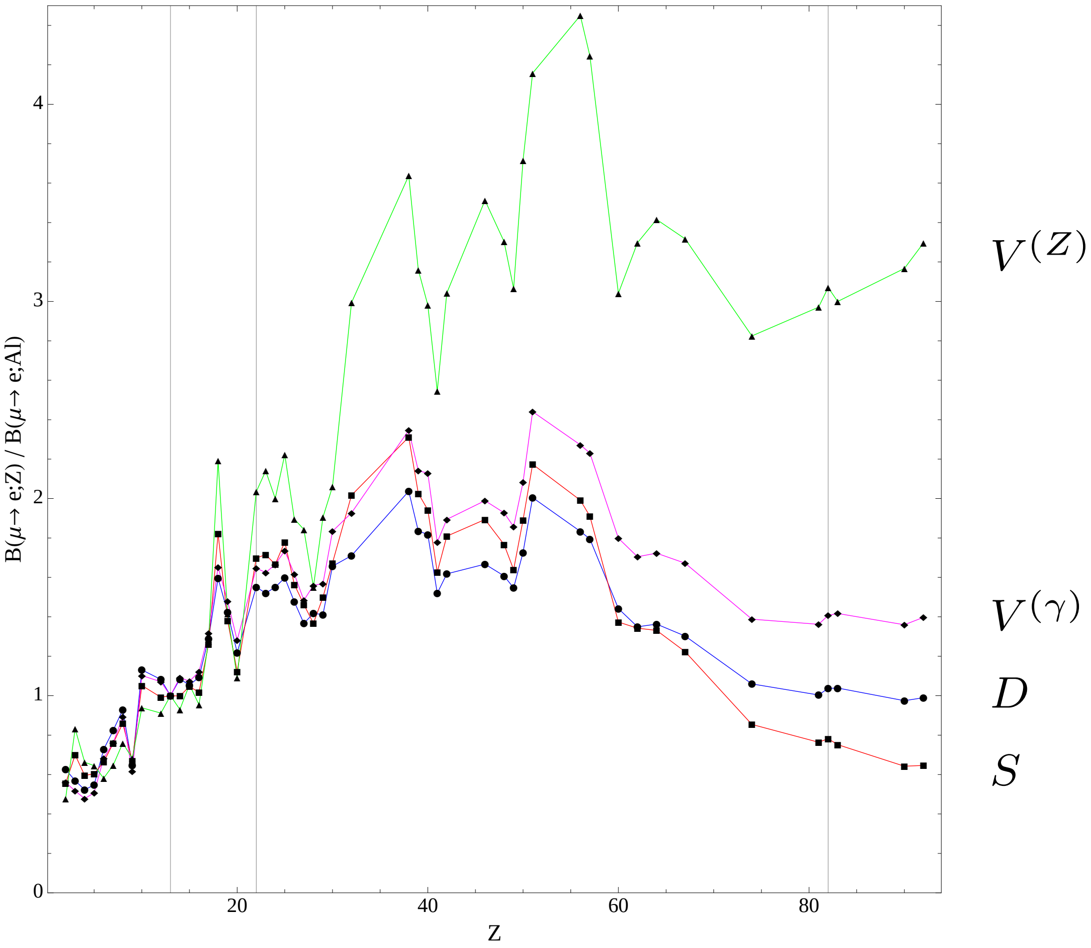
LHT: Little Higgs model with T-parity

MSSM: Minimal supersymmetric model (with R_P)

SM4: Standard model with 4th generation

μ-capture: Different targets

Fig. from Cirigliano et al., 2009



Kitano et al., 2002

μ-capture
on different
nuclei
normalized
to ^{26}Al

⇒ use different nuclear targets to distinguish different operators

Conclusions

$\Rightarrow$ lepton flavour is violated - neutrino oscillations

$\Rightarrow$ all (active) neutrino angles have been measured

$\Rightarrow$ Δm^2_{ij} known with precission

$\Rightarrow$ Since 2012 all active neutrino angles measured

$\Rightarrow$ CP-violation not yet proven experimentally

$\Rightarrow$ lepton number violation? - neutrinless double beta decay

Conclusions

⇒ lepton flavour is violated - neutrino oscillations

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⇒ Δm^2_{ij} known with precission

⇒ Since 2012 all active neutrino angles measured

⇒ CP-violation not yet proven experimentally

⇒ lepton number violation? - neutrinless double beta decay

⇒ charged lepton flavour not observed

⇒ several orders of magnitude improvments expected
Room for discovery!