Lepton flavour violation

(and neutrinos)

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Outline

$\mathcal{I}$. Introduction: ν's

$\mathcal{II}$. Charged Lepton Flavour violation

$\mathcal{III}$. SUSY, neutrino masses and LFV

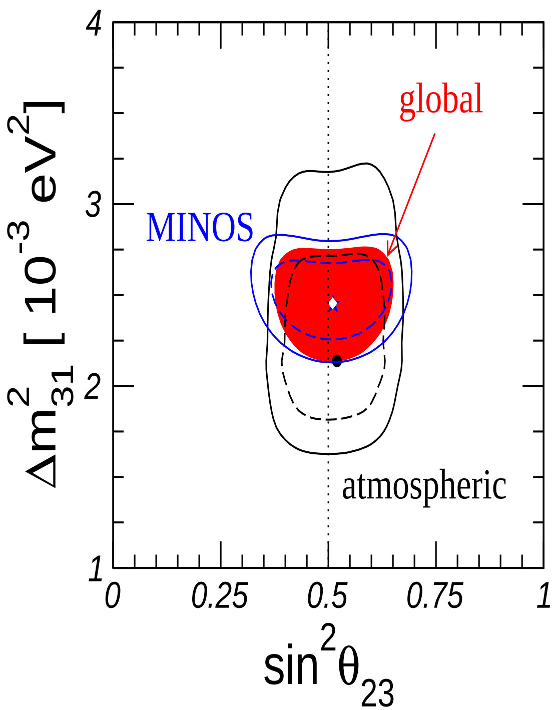
$\mathcal{IV}$. Discrete symmetries and LFV

$\mathcal{I}.$

Introduction

Lepton flavour is violated!

Status ν's

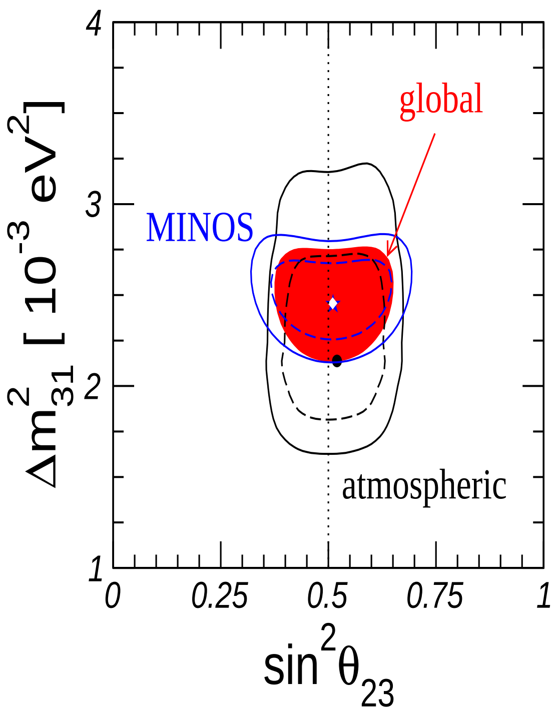


Super-K
fixes $\theta_{\rm Atm}$

MINOS
fixes $\Delta m^2_{\rm Atm}$

Schwetz, Tortola & Valle; arXiv:1103.0734 and arXiv:1108.1376

Status ν's



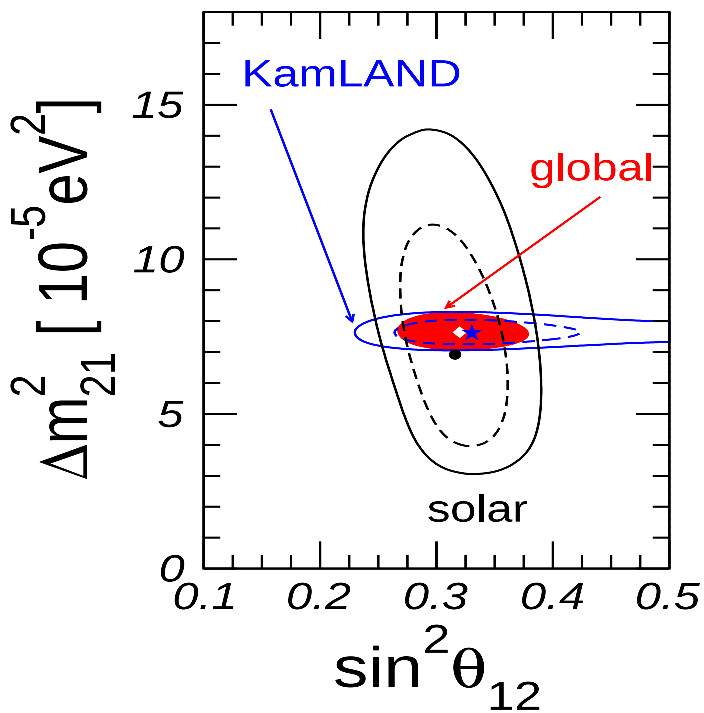
Super-K fixes $\theta_{\rm Atm}$

MINOS fixes $\Delta m^2_{\rm Atm}$

Schwetz, Tortola & Valle; arXiv:1103.0734 and arXiv:1108.1376

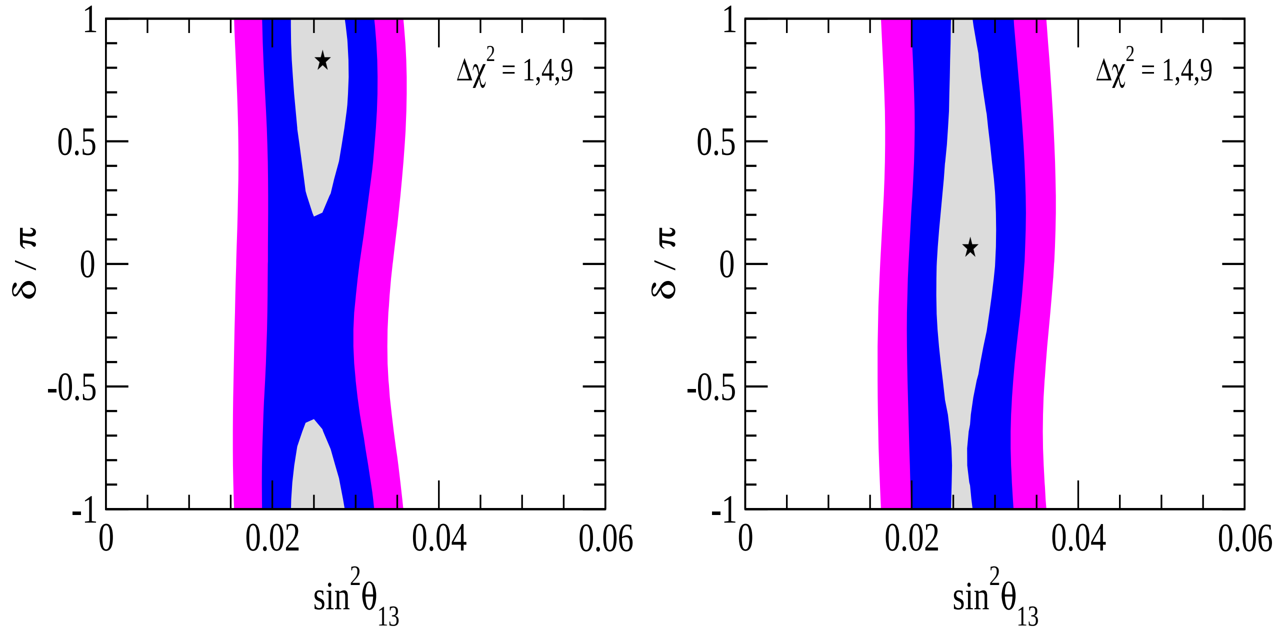
Solar data fixes $\theta_{\odot}$

KamLAND fixes $\Delta m^2_{\odot}$



Latest ν's

Normal hierarchy: Inverted hierarchy:



M. Tortola et al.
arXiv:1205.4018

Last mixing angle has finally been measured: θ_{13}

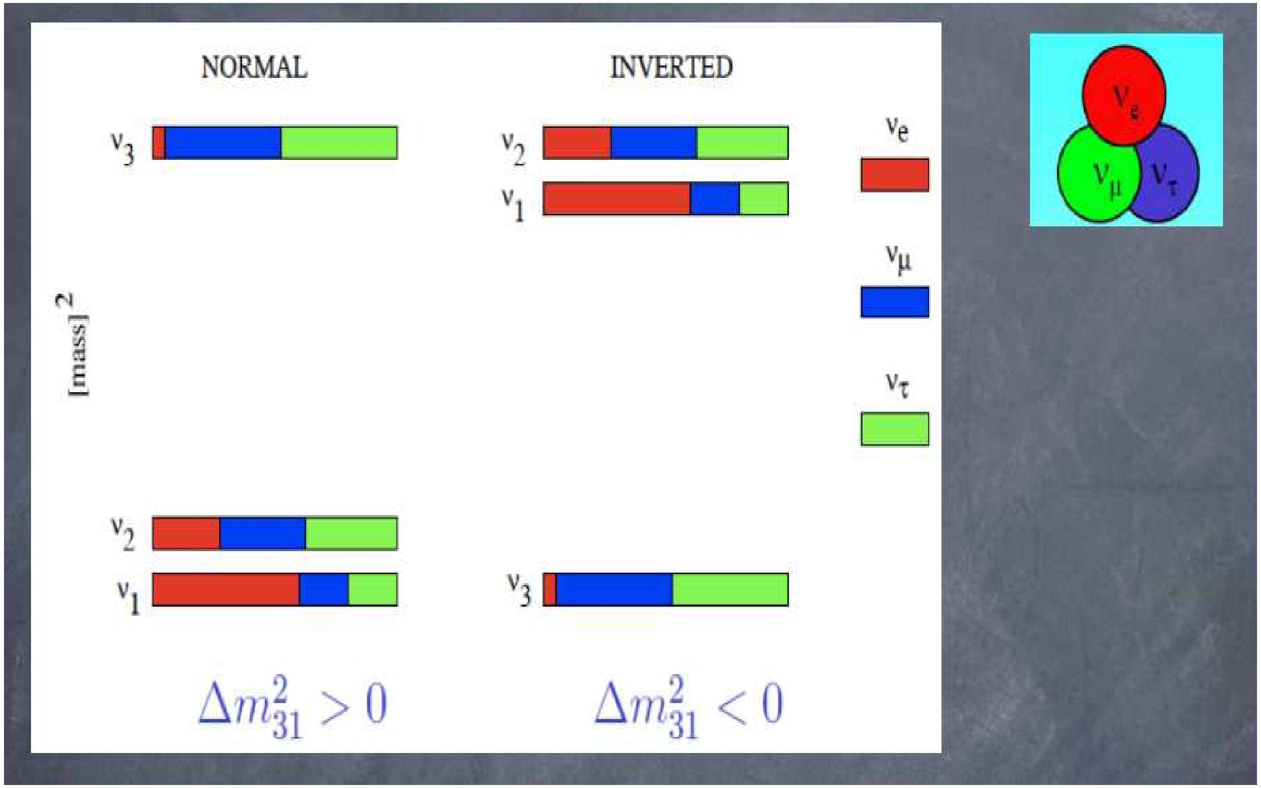
T2K (arXiv:1106.2822):
0.03(0.04)$< \sin^2 2\theta_{13} <$ 0.28(0.34)

Double Chooz (arXiv:1112.6353):
$\sin^2(2\theta_{13}) = 0.086 \pm 0.041(stat) \pm 0.030(syst)$

Daya Bay (arXiv:1203.1669):
$\sin^2(2\theta_{13}) = 0.092 \pm 0.016(\mathrm{stat}) \pm 0.005(\mathrm{syst})$

RENO (arXiv:1204.0626):
$\sin^2(2\theta_{13}) = 0.113 \pm 0.013(\mathrm{stat.}) \pm 0.019(\mathrm{syst.})$

Don't know ν's



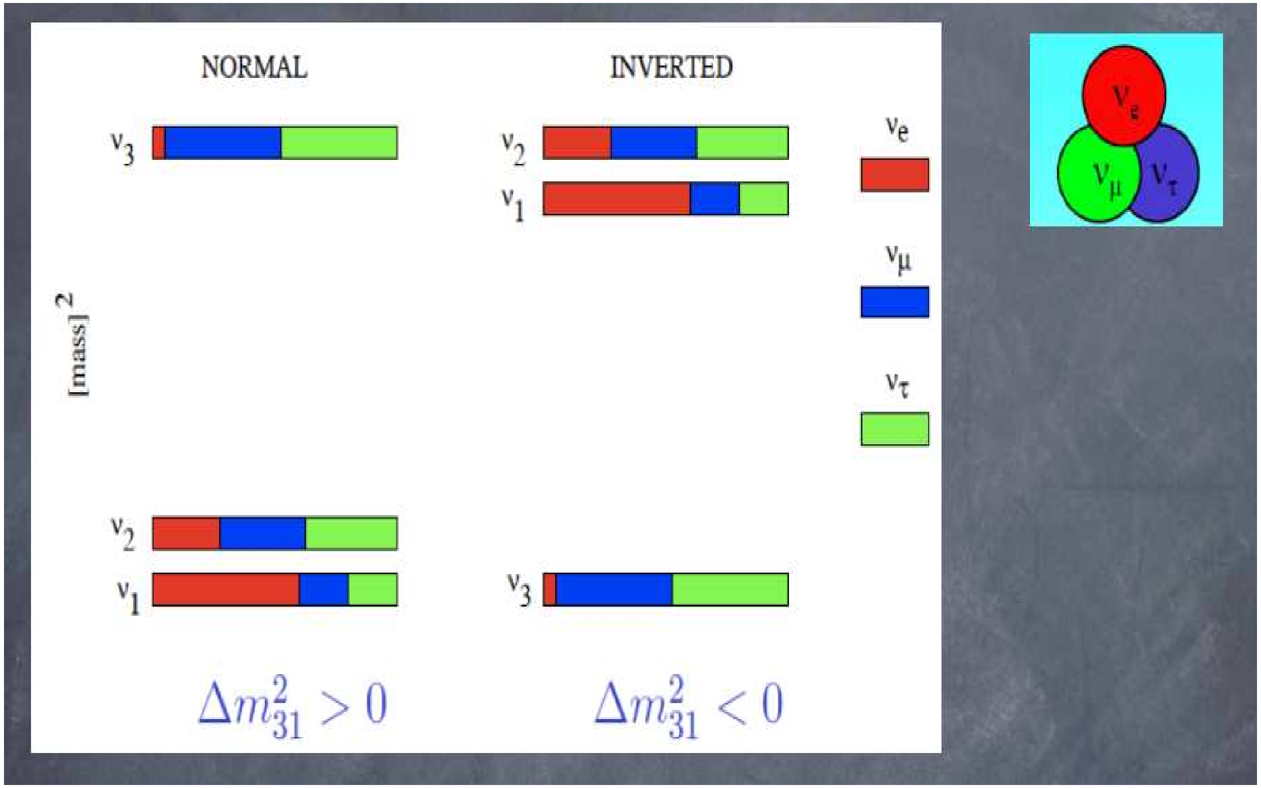
Open questions:

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:

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

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

Double beta decay:

Majorana neutrino!

$$m_\nu^{\beta\beta} = \sum_i U_{ei}^2 m_i \leq (0.5 - 1.0) \text{ eV}$$

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

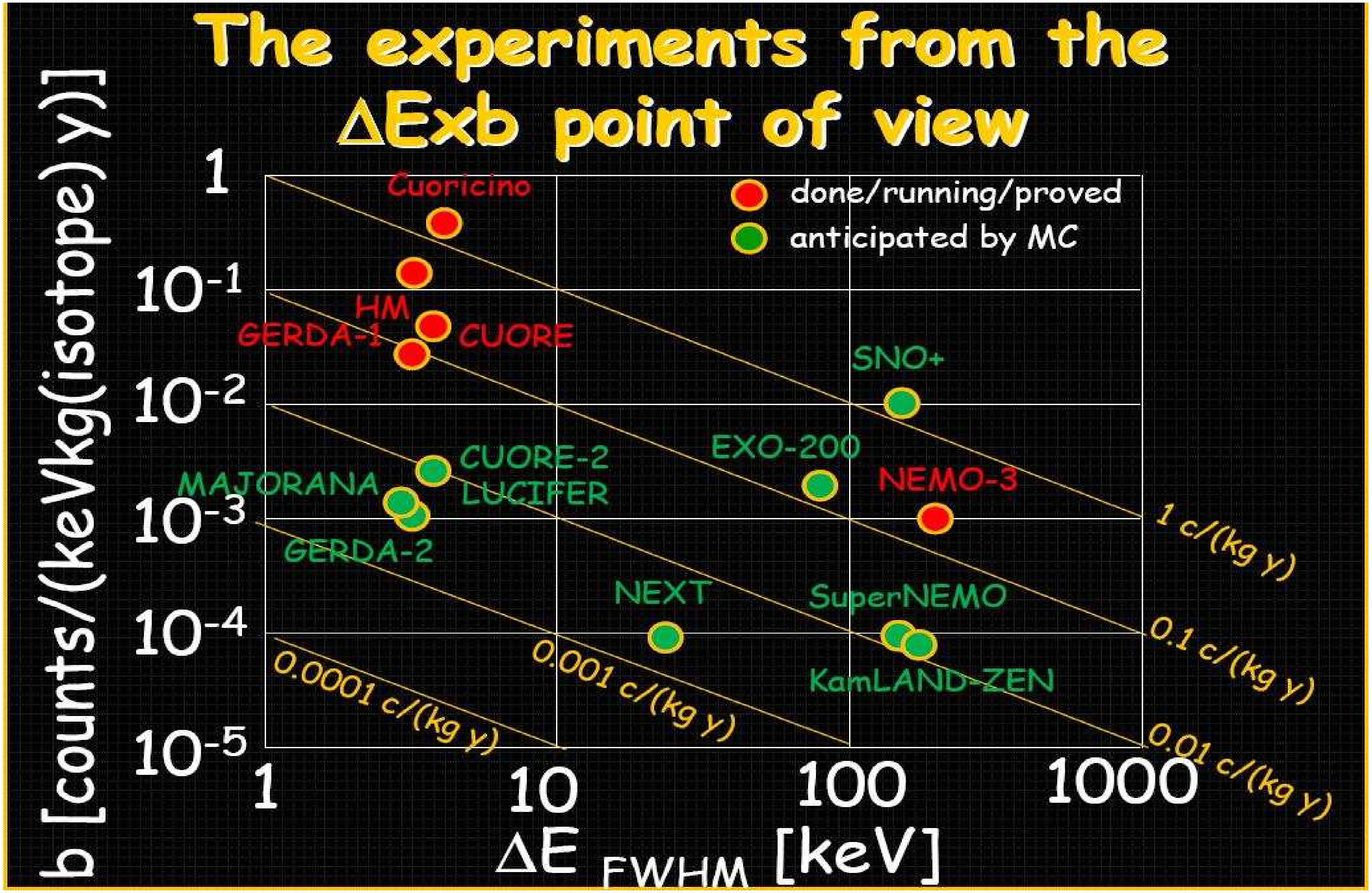
$$\sum_i m_{\nu_i} \leq (0.4 - 1.0) \text{ eV}$$

$\Rightarrow$ Recall for hierarchical neutrinos:

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

$0\nu\beta\beta$ experiments

From: A. Giuliani



Experimental sensitivity: $$T_{1/2} \geq \; c \; a \sqrt{\frac{Mt}{B\Delta E}}$$

Future experiments

Currently 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 **

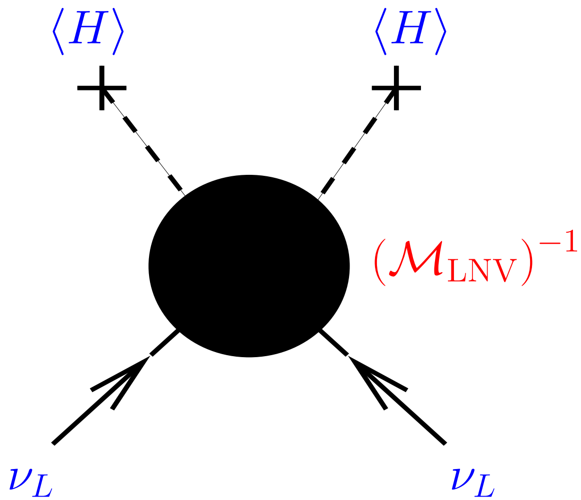
Assumptions:

* - 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

Majorana $\mathcal{M}_\nu$

If Lepton Number is Violated:



Weinberg, 1979

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

Many possible models:

(i) Seesaw mechanism: Type-I, Type-II, Type-III, Inverse seesaw, etc ...

(ii) Radiative models: Zee, Babu, LQs ...

(iii) SUSY neutrino masses: $R\!\!\!/_p$

(iv) $\cdots$

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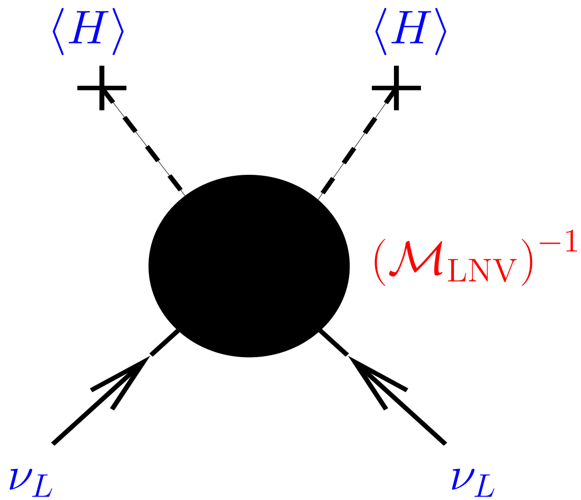

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(iv) $\cdots$

Experimental tests?

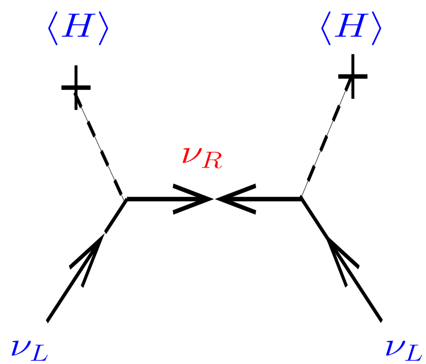
$0\nu\beta\beta$ decay!

LHC (???)

Seesaw mechanism

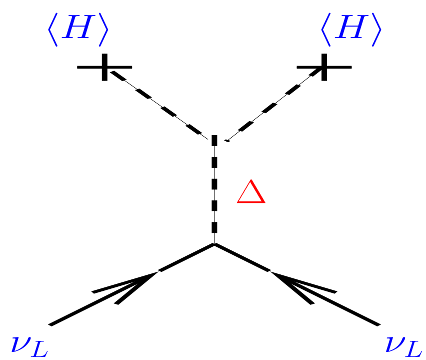
Seesaw type-I, right-handed neutrinos:

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



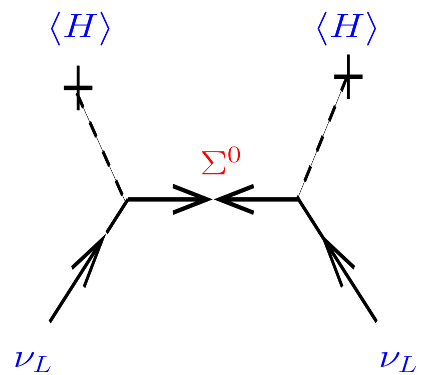
Seesaw type-II, scalar triplet:

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



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

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



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:

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

$\mathcal{II}.$

Charged Lepton Flavour violation

Experimental status: CLFV

All values from:
Particle Data Group
http://pdg.lbl.gov/

Decay	Current Limit
$\tau \to \mu\gamma$	$4.4 \cdot 10^{-8}$
$\tau \to e\gamma$	$3.3 \cdot 10^{-8}$
$\mu \to e\gamma$	$1.2 \cdot 10^{-11}$
$\tau \to 3\mu$	$2.1 \cdot 10^{-8}$
$\tau^- \to e^-\mu^+\mu^-$	$2.7 \cdot 10^{-8}$
$\tau^- \to e^+\mu^-\mu^-$	$1.7 \cdot 10^{-8}$
$\tau^- \to \mu^-e^+e^-$	$1.8 \cdot 10^{-8}$
$\tau^- \to \mu^+e^-e^-$	$1.5 \cdot 10^{-8}$
$\tau \to 3e$	$2.7 \cdot 10^{-8}$
$\mu \to 3e$	$1 \cdot 10^{-12}$

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MEG 2011,
PRL107, 171801:
Br($\mu \to e\gamma$)$\leq 2.4 \times 10^{-12}$

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MEG 2011,

PRL107, 171801:

Br($\mu \to e\gamma$)$\leq 2.4 \times 10^{-12}$

Limit on $\mu \to 3e$ from:

SINDRUM 1988

New experiment could reach:

Br($\mu \to 3e$) $\simeq 10^{-16}$ (?)

A. Schöning et al.,
Physics Procedia 17 (2011) 181

Experimental status: CLFV

All values from:
Particle Data Group
http://pdg.lbl.gov/

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

Experimental status: CLFV

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Future experiments:

Sensitivities of $\mathcal{O}(10^{-16})$ (?)

COMET:
Letter of interest @:
http://j-parc.jp/

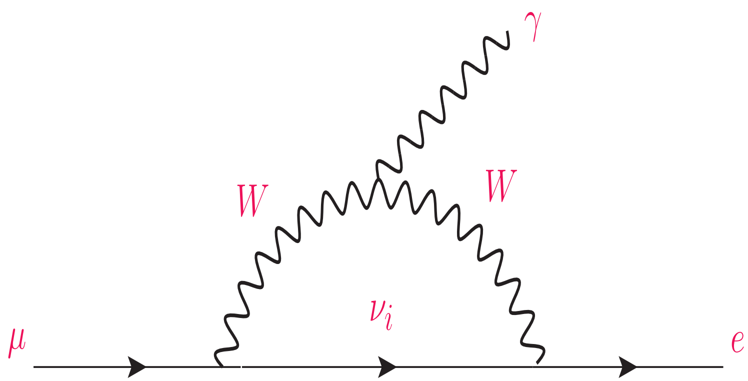
Mu2E:

Proposal @:
http://mu2e.fnal.gov/

Timeline: 2016 (?)

Guaranteed CLFV

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



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

$\Rightarrow$ GIM suppressed by small neutrino masses

Guaranteed CLFV

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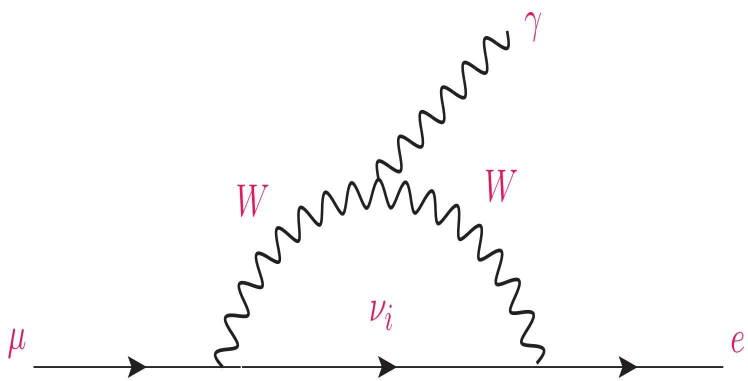

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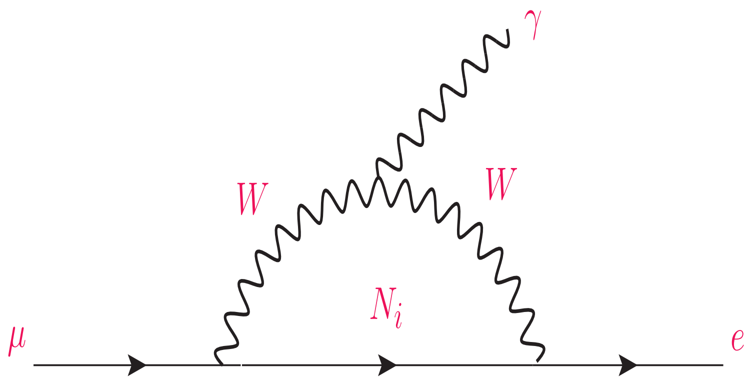
Any observation of charged LFV
points to physics beyond neutrino masses

CLFV beyond m_ν

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



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

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

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

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

CLFV beyond m_ν

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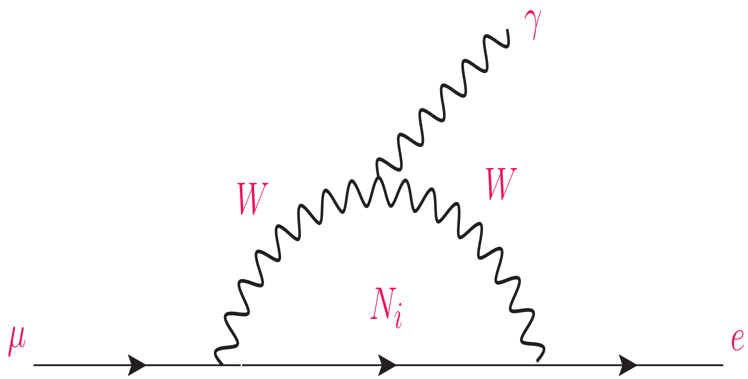

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– K_{ik} heavy neutrino - lepton mixing
– G(x) loop function, $G(1) = 1/8$

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

(C)LFV - Models

⇒ Example models that produce sizeable CLFV:

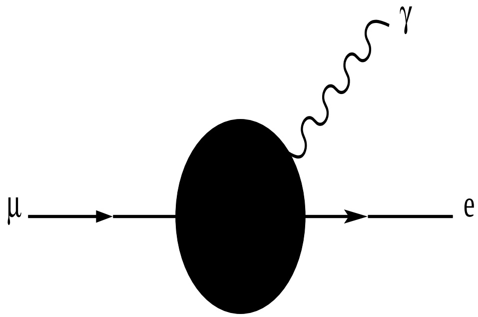
- TeV scale seesaw: Inverse seesaw, linear seesaw, etc.
- Radiative neutrino mass models: Zee-, Babu-Zee model, etc.

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

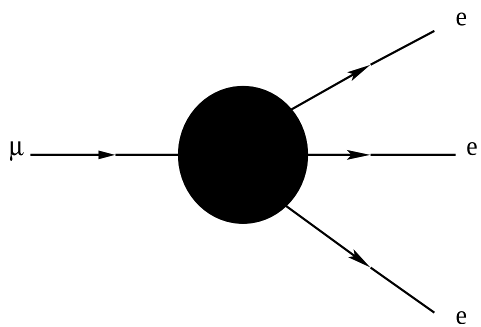
⇒ In fact, many models generate way to much CLFV:
"Flavour problem" of BSM

Schematically:

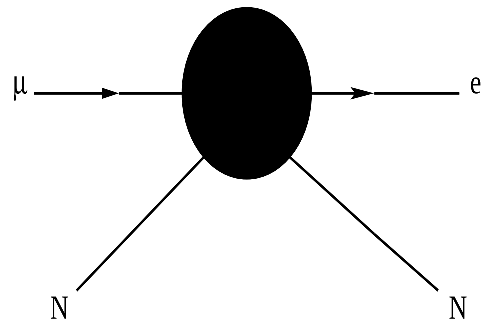
$\mu \to e\gamma$:



$\mu \to 3e$



μ-capture:

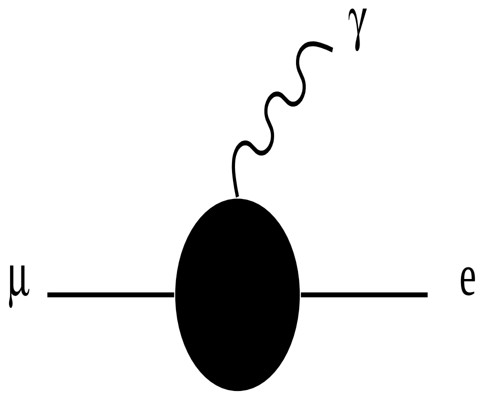


Can we learn about
different BSM models
from different LFV processes?

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

Consider $\mu \to e\gamma$:

Some physics beyond SM generates blob:



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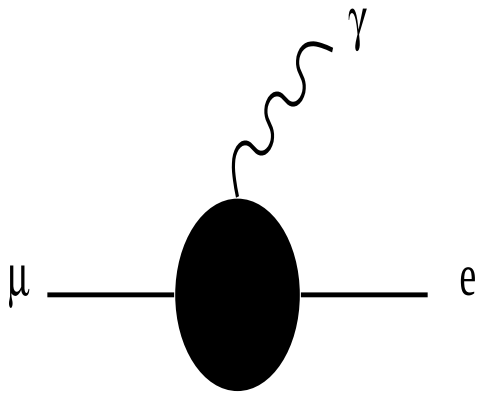
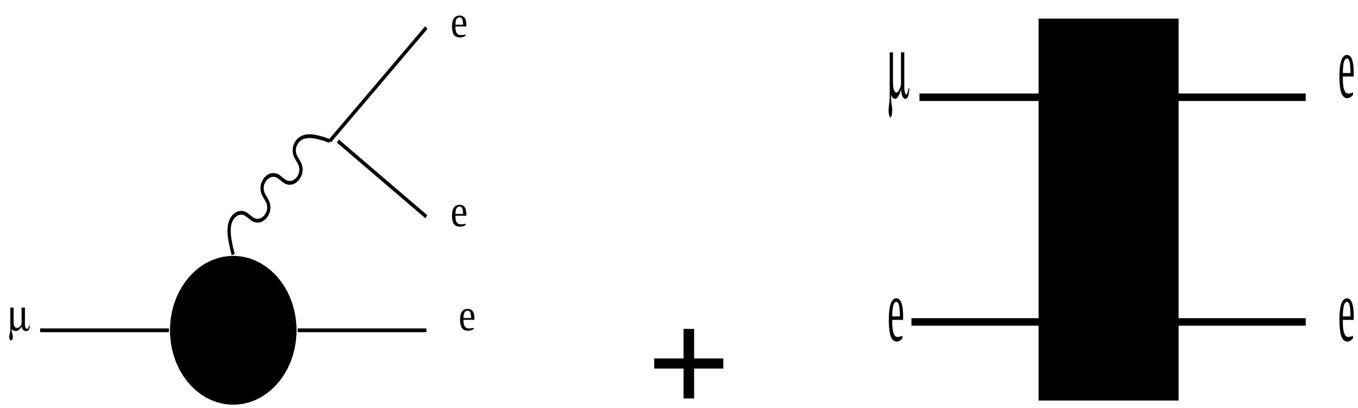


Compare $\mu \to 3e$:

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



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

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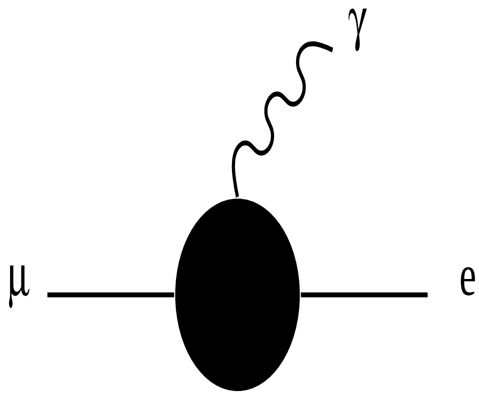
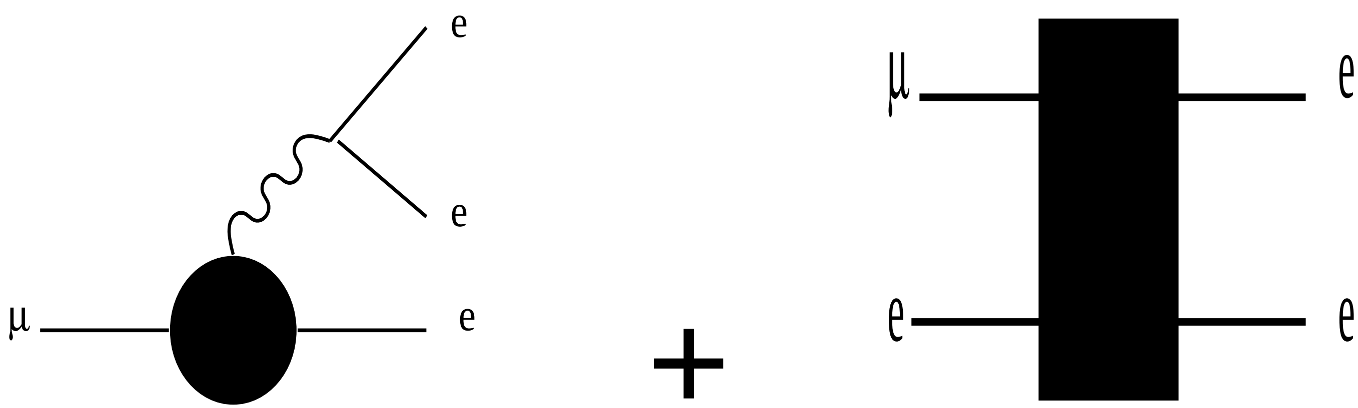


If photon diagram dominates:

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

Compare $\mu \to 3e$:

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

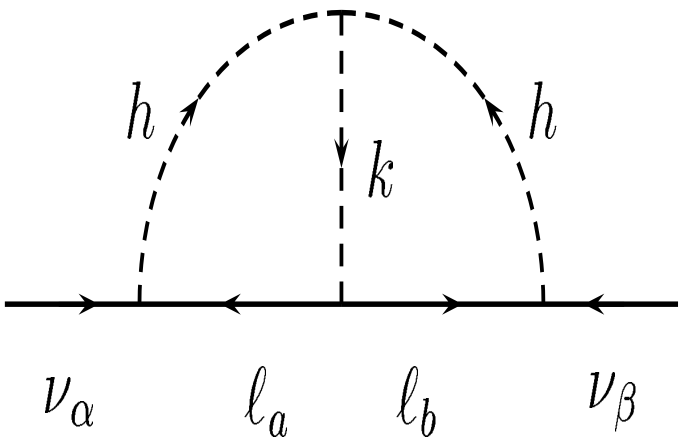


Simple example

Babu-Zee model for neutrino mass:

Cheng & Li, 1980
Zee, 1985
Babu, 1988

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



Neutrino mass is
2-loop suppressed!

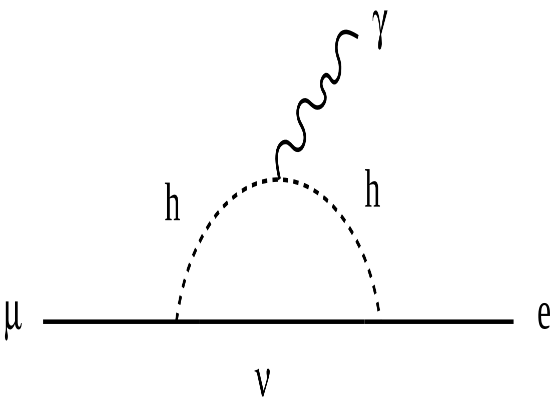
Babu & Macesanu, 2003
Aristizabal & Hirsch, 2006

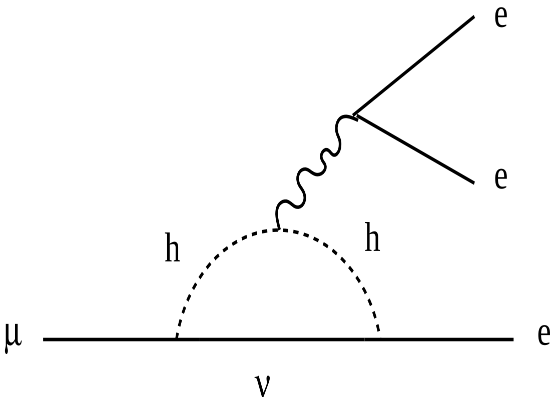
$$\mathcal{M}^\nu_{\alpha\beta} = \frac{8\mu}{(16\pi^2)^2 m_h^2} f_{\alpha a} m_a g_{xy} m_b f_{b\beta} \mathcal{I}\left(\frac{m_k^2}{m_h^2}\right),$$

Large neutrino mixing angles
require large CLFV

CLFV in Babu-Zee model

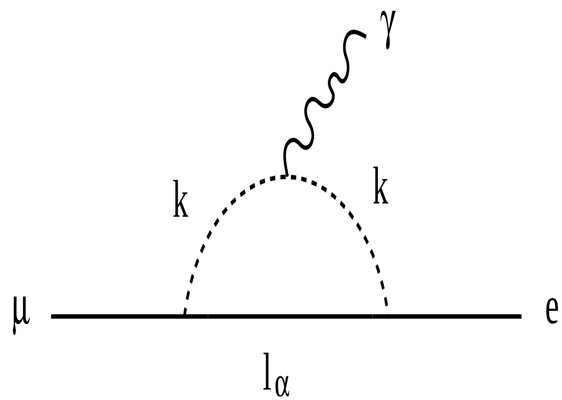
If $\frac{g^2}{m_k^2} \ll \frac{f^2}{m_h^2}$:

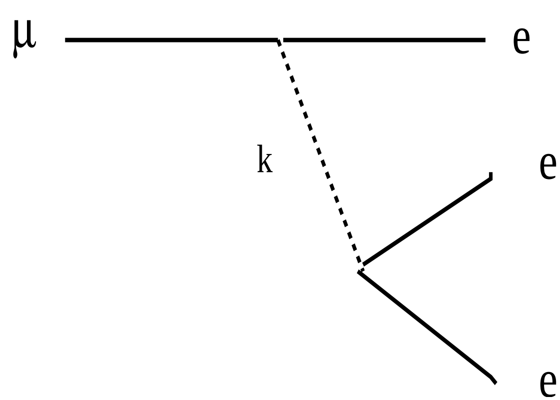




Photon dominance!

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



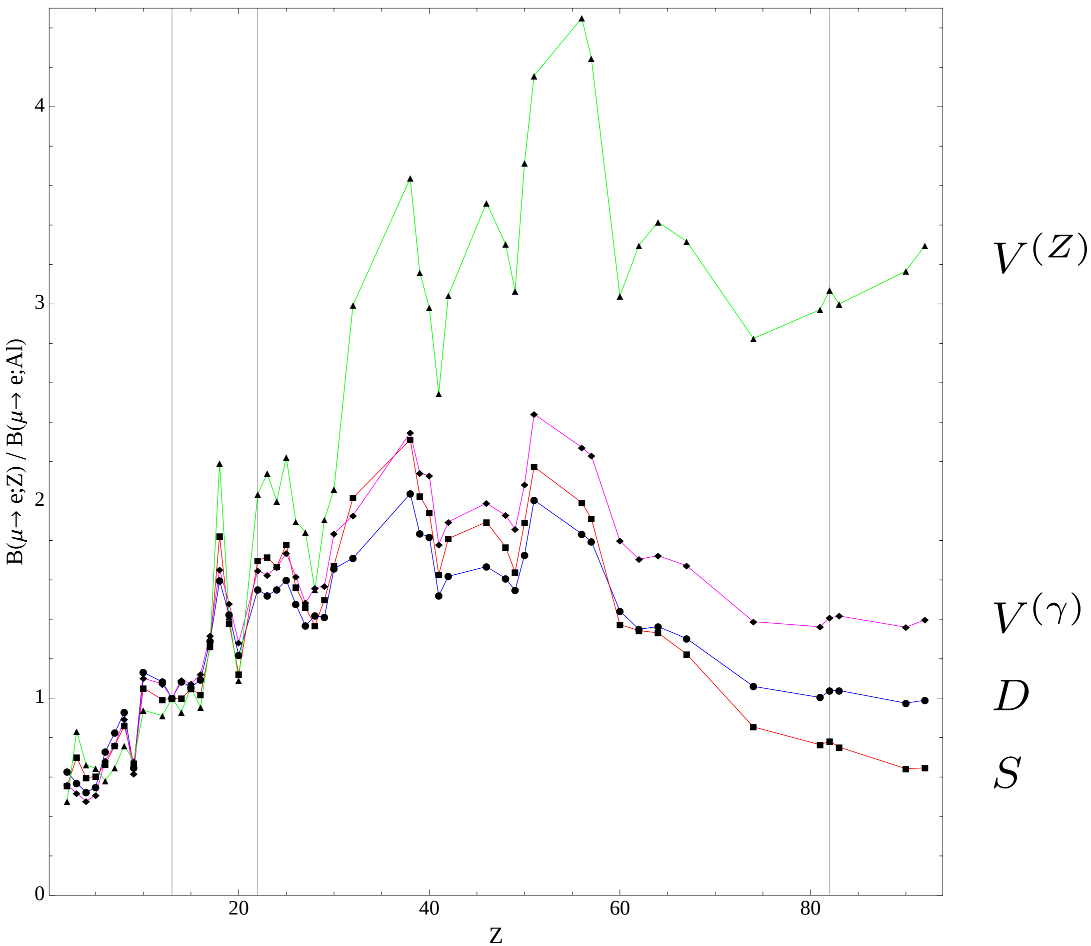


$\mu \to 3e$ tree-level!

μ-capture: Different targets

Fig. from Cirigliano et al., 2009

Kitano et al., 2002



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

$\Rightarrow$ use different nuclear targets to distinguish different operators

$\mathcal{III}.$

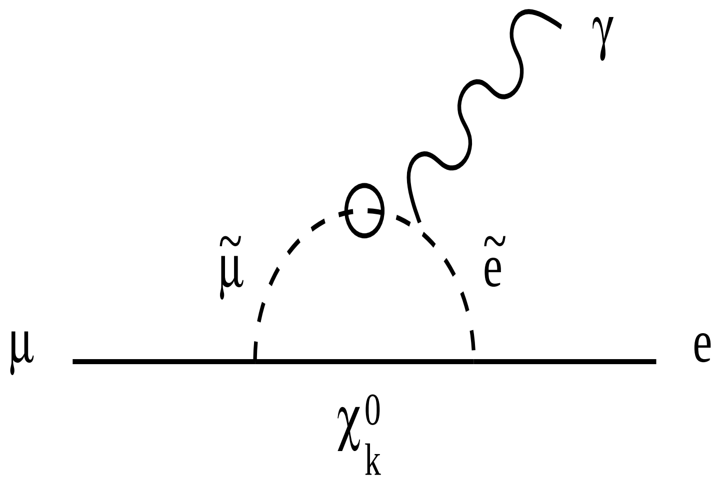
SUSY, neutrino masses and LFV

SUSY flavour problem

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!

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

SUSY flavour problem

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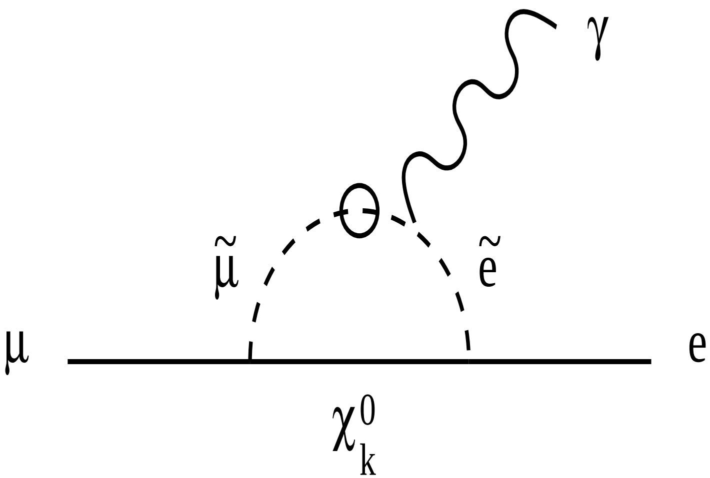
$$V = (m^2_{\tilde{L}})_{ij} \tilde{L}_i^* \tilde{L}_j + \cdots$$

Off-diagonal elements induce decays, such as:



Example only!

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

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

A very old problem indeed!

Ellis and Nanopoulos, 1981
Donoghue et al., 1983
Gerard et al., 1984
Hall et al., 1985
Romao et al., 1985
Borzumati, Masiero, 1986
$\cdots$ many

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

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

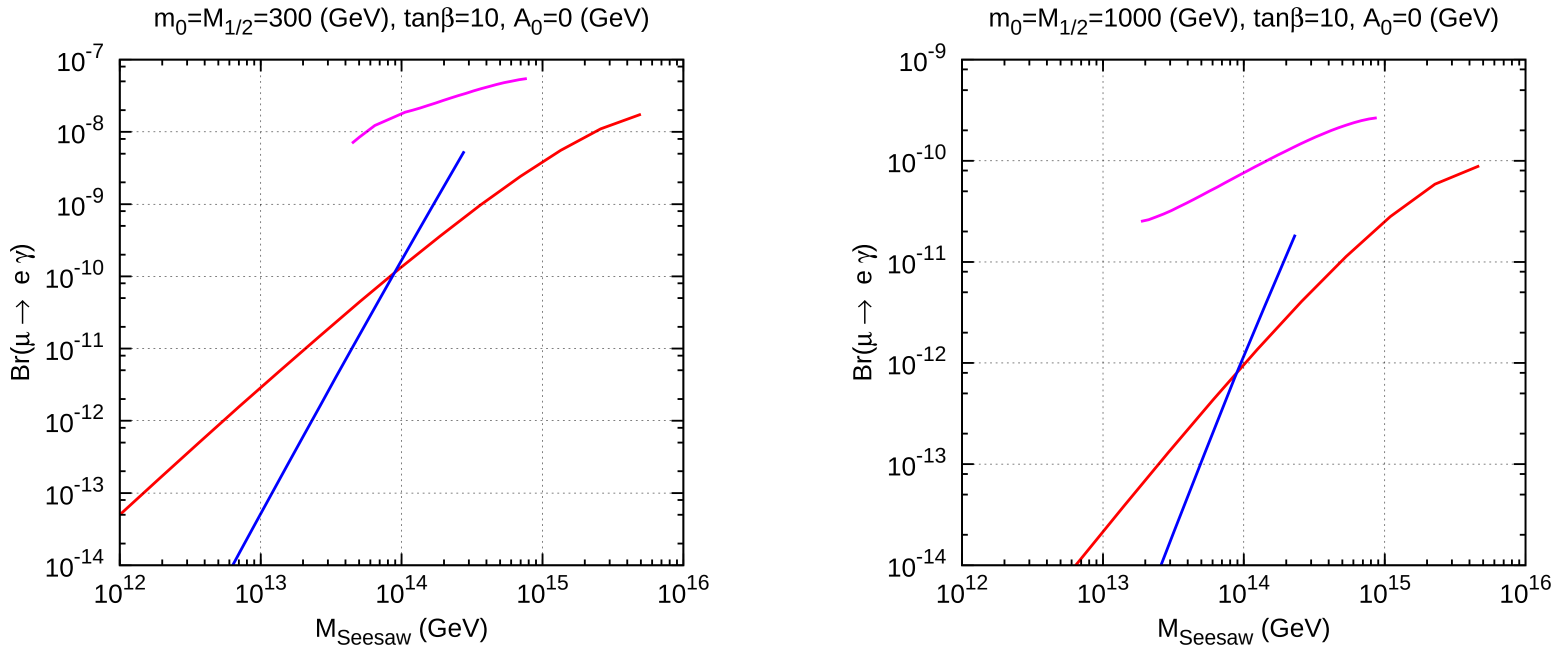
$\Rightarrow$ 9 entries, but proportional to Y_T^2

$\Rightarrow$ 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

Esteves et al., 2011



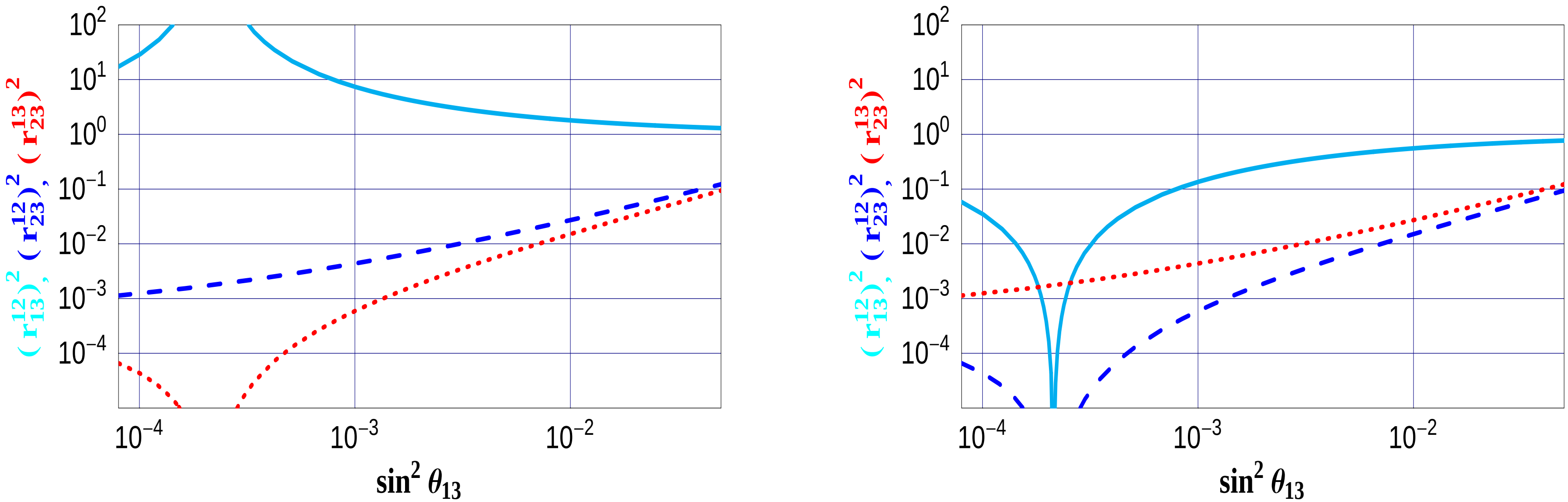
⇒ The three different seesaws are: type-III, type-II and type-I

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

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

Only for Type-II

Neutrino angles fix relative size of entries in Y_T: Hirsch et al., 2008



Here: $(r^{13}_{23})^2 =$ Br($\tau \to e\gamma$)/Br($\tau \to \mu\gamma$) etc.

Ratios of BR's "predicted" as function of neutrino parameters

SUSY LR model

Consider gauge group:

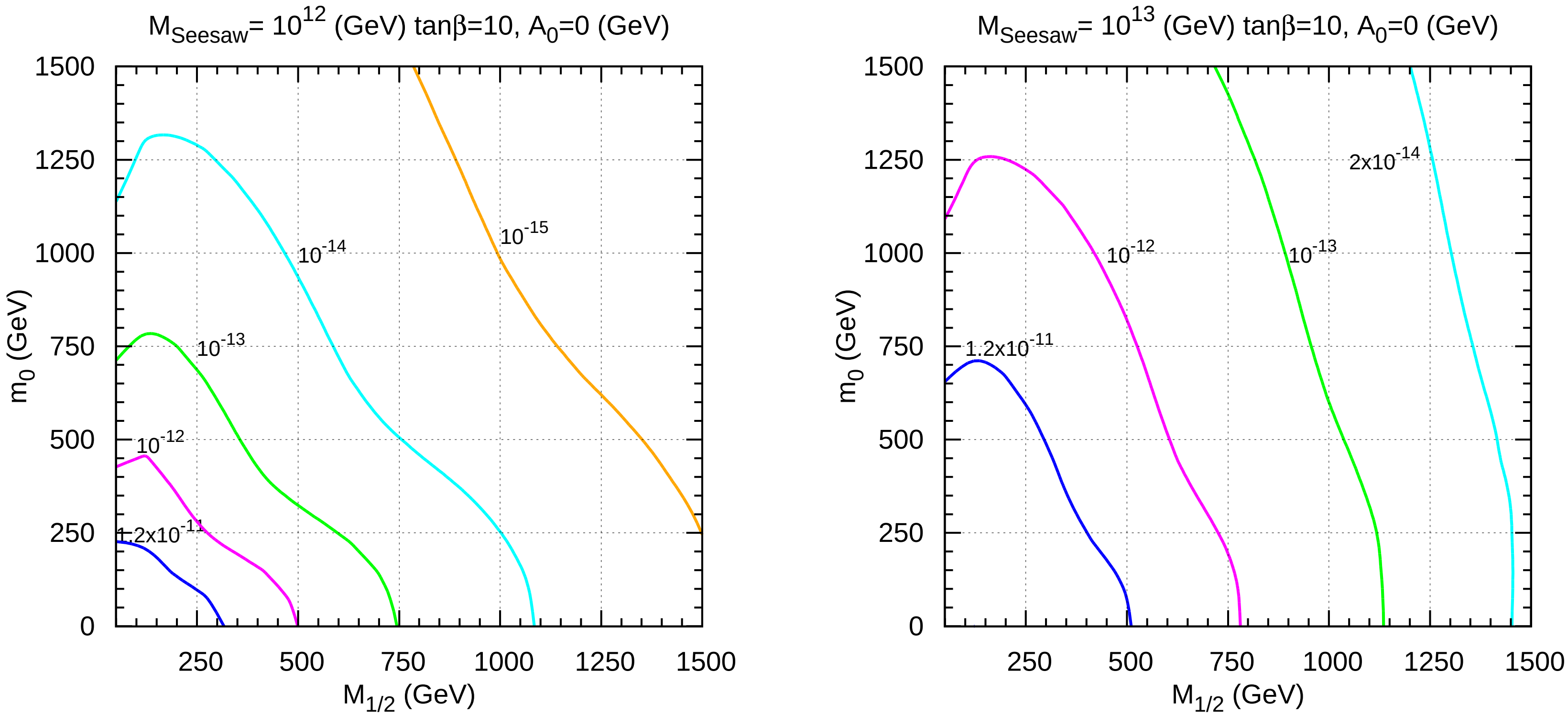
$$SU(3)_c \times SU(2)_L \times SU(2)_R \times U(1)_{B-L}$$

Advantages:

- . Restoration of parity at high energy
- . Generates seesaw: N^c is part of theory
- . Provides (potentially) solution to CP problems
- . Can be embedded in SO(10)
- . R-parity conservation can be automatic

LFV in SUSY LR model

Esteves et al., 2010

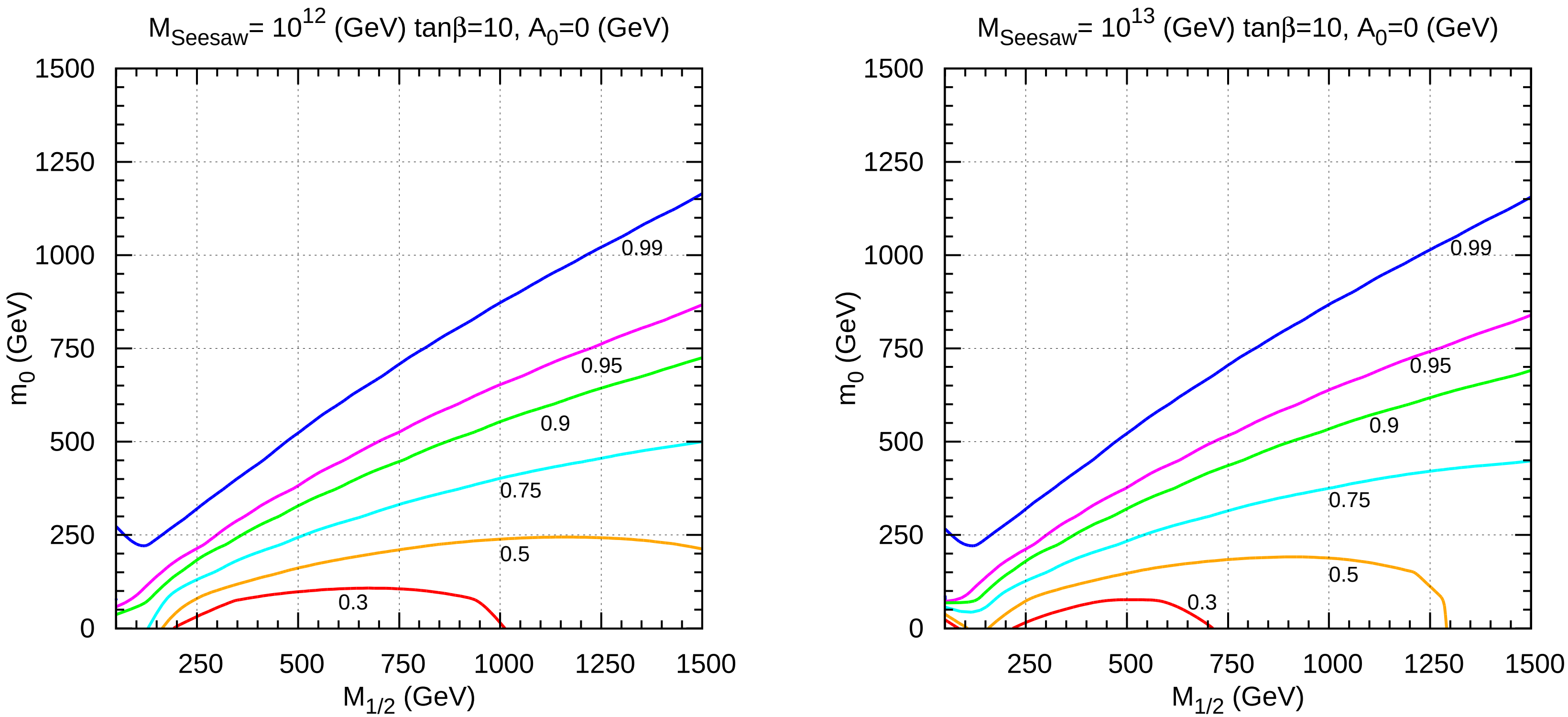


$\Rightarrow$ As in seesaw Br($\mu^+ \to e^+\gamma$) strong function of M_{Seesaw}

... but ...

LFV in SUSY LR model

Esteves et al., 2010

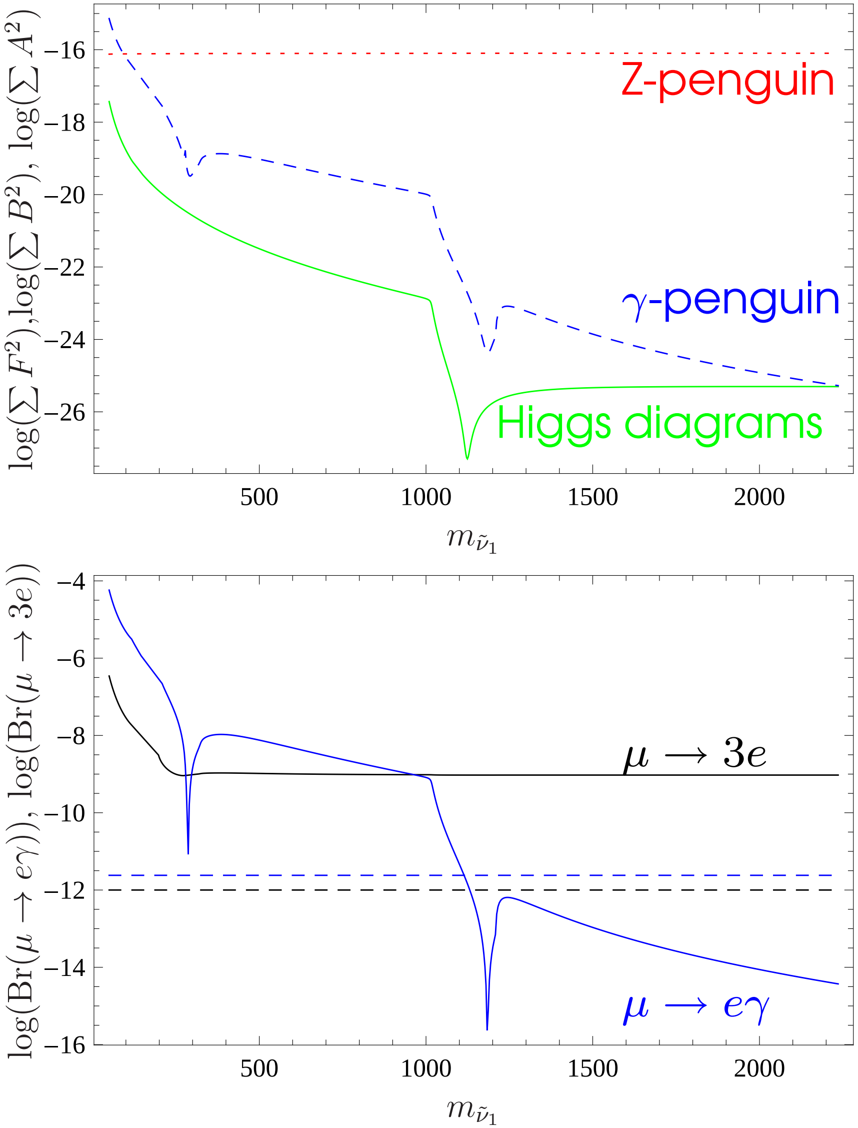


Asymmetry:

$$\mathcal{A}(\mu^+ \to e^+\gamma) = \frac{|A_L|^2 - |A_R|^2}{|A_L|^2 + |A_R|^2},$$

$\Rightarrow$ Note: In mSugra seesaw $\mathcal{A} = 1$ always

SUSY Inverse seesaw



Hirsch, Staub
& Vicente, 2012

Z-penguin dominates
when MSSM extended:

(i) particle content ($\hat{\nu}^c$)
(ii) new Yukawa-like interactions
(example also: RPV)

See talk by:
A. Vicente

$\mathcal{IV}$.

Discrete symmetries and LFV

Discrete flavour symmetries

Group	d	Irr. Repr.'s	Presentation
$D_3 \sim S_3$	6	$1, 1', 2$	$A^3 = B^2 = (AB)^2 = 1$
D_4	8	$1_1, \ldots 1_4, 2$	$A^4 = B^2 = (AB)^2 = 1$
D_5	10	$1, 1', 2, 2'$	$A^5 = B^2 = (AB)^2 = 1$
D_6	12	$1_1, \ldots 1_4, 2, 2'$	$A^6 = B^2 = (AB)^2 = 1$
D_7	14	$1, 1', 2, 2', 2''$	$A^7 = B^2 = (AB)^2 = 1$
A_4	12	$1, 1', 1'', 3$	$A^3 = B^2 = (AB)^3 = 1$
$A_5 \sim PSL_2(5)$	60	$1, 3, 3', 4, 5$	$A^3 = B^2 = (BA)^5 = 1$
T'	24	$1, 1', 1'', 2, 2', 2'', 3$	$A^3 = (AB)^3 = R^2 = 1,\ B^2 = R$
S_4	24	$1, 1', 2, 3, 3'$	$BM : A^4 = B^2 = (AB)^3 = 1$ $TB : A^3 = B^4 = (BA^2)^2 = 1$
$\Delta(27) \sim Z_3 \rtimes Z_3$	27	$1_1, \ldots 1_9, 3, \bar{3}$	
$PSL_2(7)$	168	$1, 3, \bar{3}, 6, 7, 8$	$A^3 = B^2 = (BA)^7 = (B^{-1}A^{-1}BA)^4 = 1$
$T_7 \sim Z_7 \rtimes Z_3$	21	$1, 1', \overline{1'}, 3, \bar{3}$	$A^7 = B^3 = 1,\ AB = BA^4$

Many Refs in Reviews by:

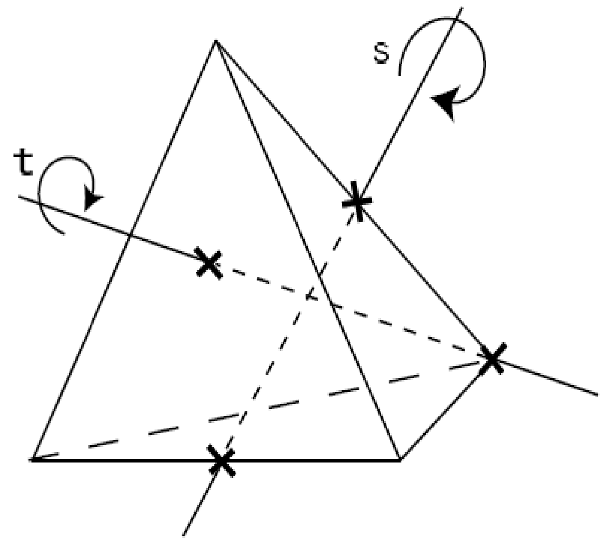
Altarelli & Feruglio arXiv:1002.0211

Ishimori et al. arXiv:1003.3552

Summary: A_4

- 12 elements: rotations
- 4 irreps: 1, $1'$, $1''$ and 3
- smallest group with 3

$\Rightarrow$ Symmetry of the tetrahedron:



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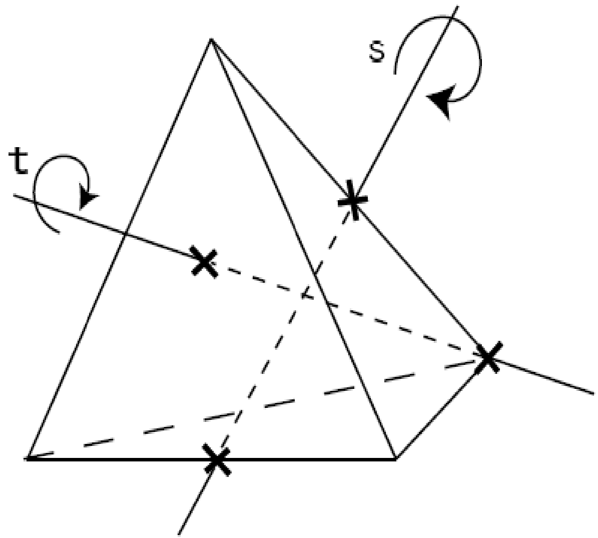

A4 is spontaneously broken in

Z3 in the charged sector

Z2 in the neutrino sector

TBM

Assign:
L_i, l_j^c, H_k $(\nu_m^c, \cdots)$
to different irreps of A_4

$\Rightarrow \cdots$

A_4: models

Type	L_i	ℓ_i^c	ν_i^c	Δ	References
A1				-	[1–14] [15]$^\#$
A2	$\underline{3}$	$\underline{1}, \underline{1}', \underline{1}''$	-	$\underline{1}, \underline{1}', \underline{1}'', \underline{3}$	[16–18]
A3				$\underline{1}, \underline{3}$	[19]
B1	$\underline{3}$	$\underline{1}, \underline{1}', \underline{1}''$	$\underline{3}$	-	[4, 20–27]$^\#$ [28–30]* [31–48]
B2				$\underline{1}, \underline{3}$	[49]$^\#$
C1				-	[2, 50, 51] [52]$^\#$
C2	$\underline{3}$	$\underline{3}$	-	$\underline{1}$	[53, 54] [55]$^\#$
C3				$\underline{1}, \underline{3}$	[56]
C4				$\underline{1}, \underline{1}', \underline{1}'', \underline{3}$	[57]
D1				-	[58, 59]$^\#$ [60, 61]* [62]
D2	$\underline{3}$	$\underline{3}$	$\underline{3}$	$\underline{1}$	[63] [64]*
D3				$\underline{1}'$	[65]*
D4				$\underline{1}', \underline{3}$	[66]*
E1	$\underline{3}$	$\underline{3}$	$\underline{1}, \underline{1}', \underline{1}''$	-	[67, 68]
E2				$\underline{1}$	[69]
F	$\underline{1}, \underline{1}', \underline{1}''$	$\underline{3}$	$\underline{3}$	$\underline{1}$ or $\underline{1}'$	[70]
G	$\underline{3}$	$\underline{1}, \underline{1}', \underline{1}''$	$\underline{1}, \underline{1}', \underline{1}''$	-	[71]
H	$\underline{3}$	$\underline{1}, \underline{1}, \underline{1}$	-	-	[72]
I	$\underline{3}$	$\underline{1}, \underline{1}, \underline{1}$	$\underline{1}$	-	[73]*
J	$\underline{3}$	$\underline{1}, \underline{1}, \underline{1}$	$\underline{1}, \underline{1}$	-	[74]* [75]
K	$\underline{3}$	$\underline{1}, \underline{1}, \underline{1}$	$\underline{1}, \underline{1}, \underline{1}$	-	[76]*
L	$\underline{3}$	$\underline{1}, \underline{1}, \underline{1}$	$\underline{1}, \underline{1}', \underline{1}''$	-	[77]
M	$\underline{3}$	$\underline{1}, \underline{1}, \underline{1}$	$\underline{3}$	-	[12, 39, 78, 79]
N	$\underline{3}$	$\underline{1}, \underline{1}, \underline{1}$	$\underline{1}, \underline{1}$	$\underline{1}$	[80]*
O	$\underline{1}, \underline{1}', \underline{1}''$	$\underline{1}, \underline{1}', \underline{1}''$	$\underline{3}$	-	[81]
P	$\underline{1}, \underline{1}', \underline{1}''$	$\underline{1}, \underline{1}'', \underline{1}'$	$\underline{3}, \underline{1}$	-	[82, 83]
Q	$\underline{1}, \underline{1}', \underline{1}''$	$\underline{1}, \underline{1}'', \underline{1}'$	$\underline{3}, \underline{1}', \underline{1}''$	-	[84]

Barry & Rodejohann, PRD81 093002 (2010)

Many - but not all! - can give TBM

A_4: *models*

Type	L_i	ℓ_i^c	ν_i^c	Δ	References
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C4				$\underline{1}, \underline{1}', \underline{1}'', \underline{3}$	[57]
D1				-	[58, 59]$^\#$ [60, 61]* [62]
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I	$\underline{3}$	$\underline{1}, \underline{1}, \underline{1}$	$\underline{1}$	-	[73]*
J	$\underline{3}$	$\underline{1}, \underline{1}, \underline{1}$	$\underline{1}, \underline{1}$	-	[74]* [75]
K	$\underline{3}$	$\underline{1}, \underline{1}, \underline{1}$	$\underline{1}, \underline{1}, \underline{1}$	-	[76]*
L	$\underline{3}$	$\underline{1}, \underline{1}, \underline{1}$	$\underline{1}, \underline{1}', \underline{1}''$	-	[77]
M	$\underline{3}$	$\underline{1}, \underline{1}, \underline{1}$	$\underline{3}$	-	[12, 39, 78, 79]
N	$\underline{3}$	$\underline{1}, \underline{1}, \underline{1}$	$\underline{1}, \underline{1}$	$\underline{1}$	[80]*
O	$\underline{1}, \underline{1}', \underline{1}''$	$\underline{1}, \underline{1}', \underline{1}''$	$\underline{3}$	-	[81]
P	$\underline{1}, \underline{1}', \underline{1}''$	$\underline{1}, \underline{1}'', \underline{1}'$	$\underline{3}, \underline{1}$	-	[82, 83]
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Barry & Rodejohann, PRD81 093002 (2010)

Many - but not all! - can give TBM

Predictions?

(a) High-scale models

$\rightarrow 0\nu\beta\beta$ decay?

$\rightarrow \theta_{13}$?

Others?

A_4: models

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(a) High-scale models

$\rightarrow$ $0\nu\beta\beta$ decay?

$\rightarrow$ θ_{13} ?

Others?

(b) EW-scale models

$\rightarrow$ $0\nu\beta\beta$ decay?

$\rightarrow$ θ_{13} ?

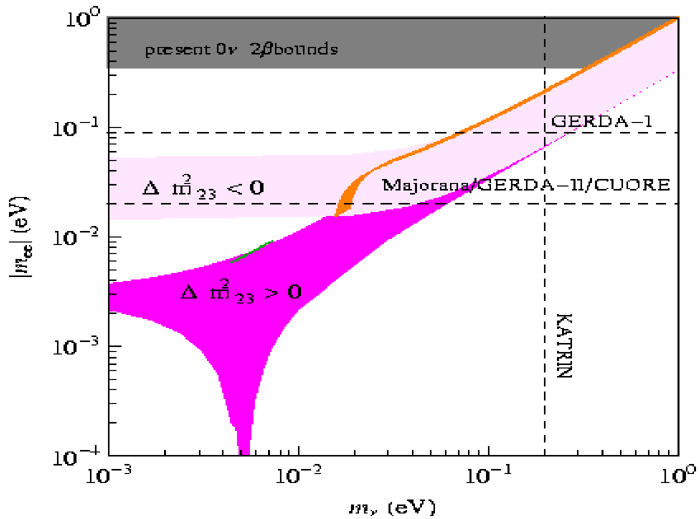
$\rightarrow$ Lepton flavour violation ?

$\rightarrow$ New states at LHC?

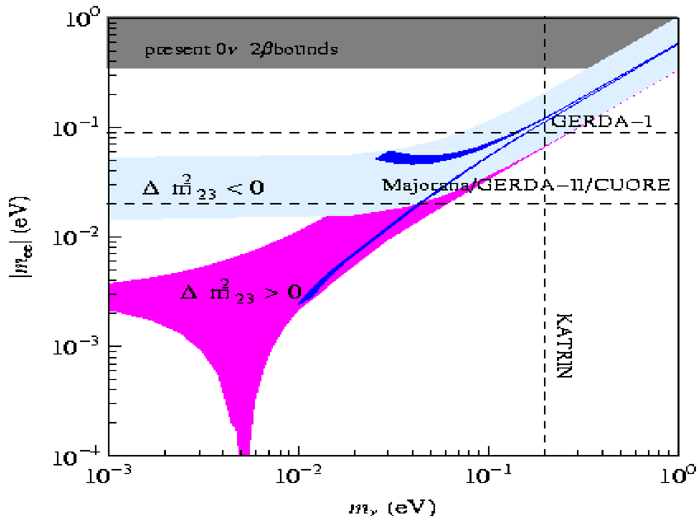
Others?

Discrete sym's and $0\nu\beta\beta$

Altarelli & Feruglio

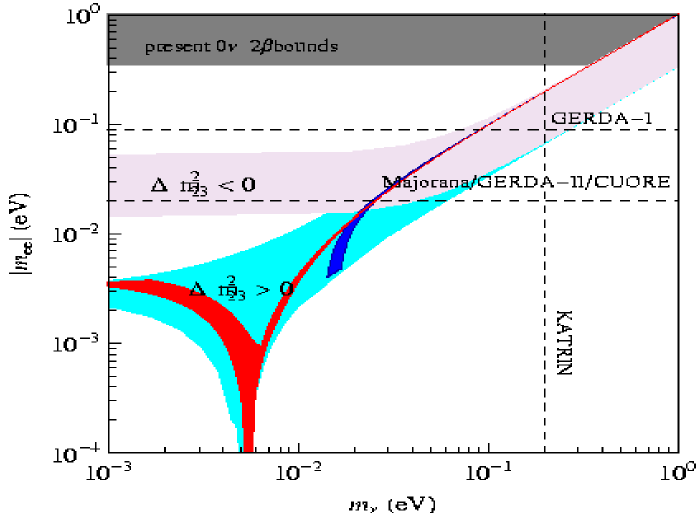


Bazzocchi, Merlo & Morisi



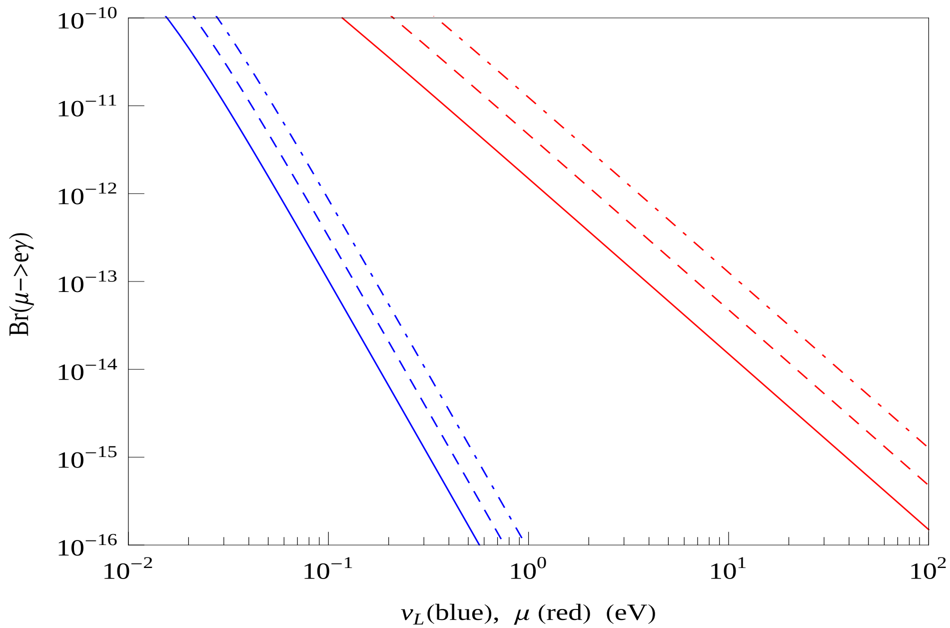
A_4

S_4



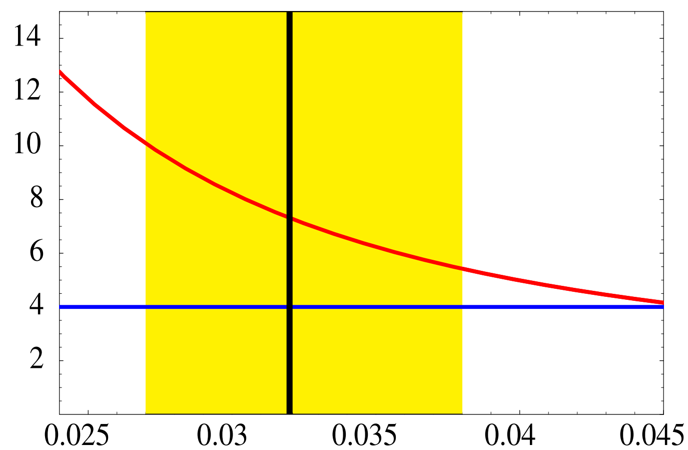
Hirsch, Morisi & Valle

Linear and inverse SS in A_4



$\mathrm{Br}(\mu \to e\gamma)$ for 3 different values of m_N for inverse and linear seesaw

Ratio:
$\mathrm{Br}(\tau \to \mu\gamma)/\mathrm{Br}(\tau \to e\gamma)$ for inverse and linear seesaw assuming exact TBM mixing as function of
$\alpha = \frac{\Delta m^2_{\odot}}{\Delta m^2_{\mathrm{Atm}}}$



Discrete Dark Matter

A4 is spontaneously broken in

Z3 in the charged sector X   Z2 in the neutrino sector

stabilize the DM

TBM X

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A4 is spontaneously broken in

Z3 in the charged sector X

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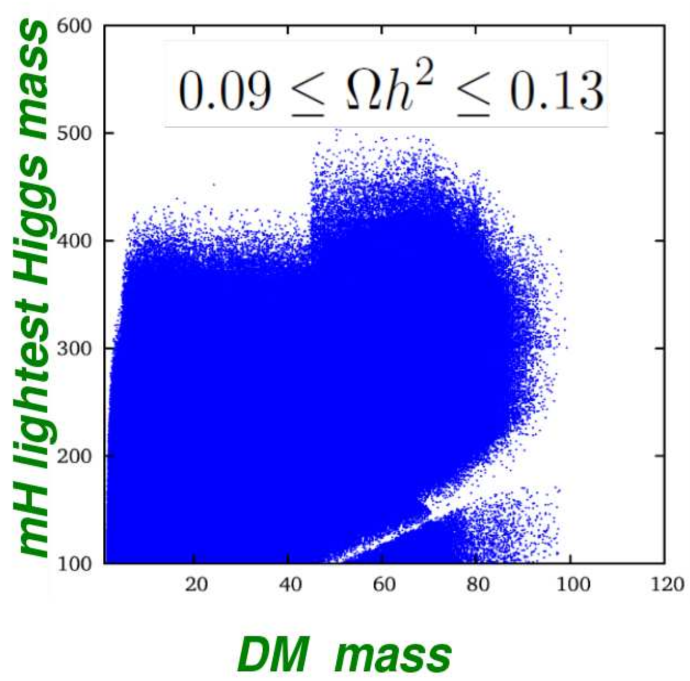


Hirsch, Morisi, Peinado & Valle
arXiv:1007.0871

Boucenna et al.
arXiv:1101.2874

Summary

$\Rightarrow$ Neutrino oscillations show LF is violated

$\Rightarrow$ last neutrino angle θ_{13} has been measured

$\Rightarrow$ CLVF interesting model discriminator

$\Rightarrow$ Discrete symmetries may help, but $\cdots$

Summary

$\Rightarrow$ Neutrino oscillations show LF is violated

$\Rightarrow$ last neutrino angle θ_{13} has been measured

$\Rightarrow$ CLVF interesting model discriminator

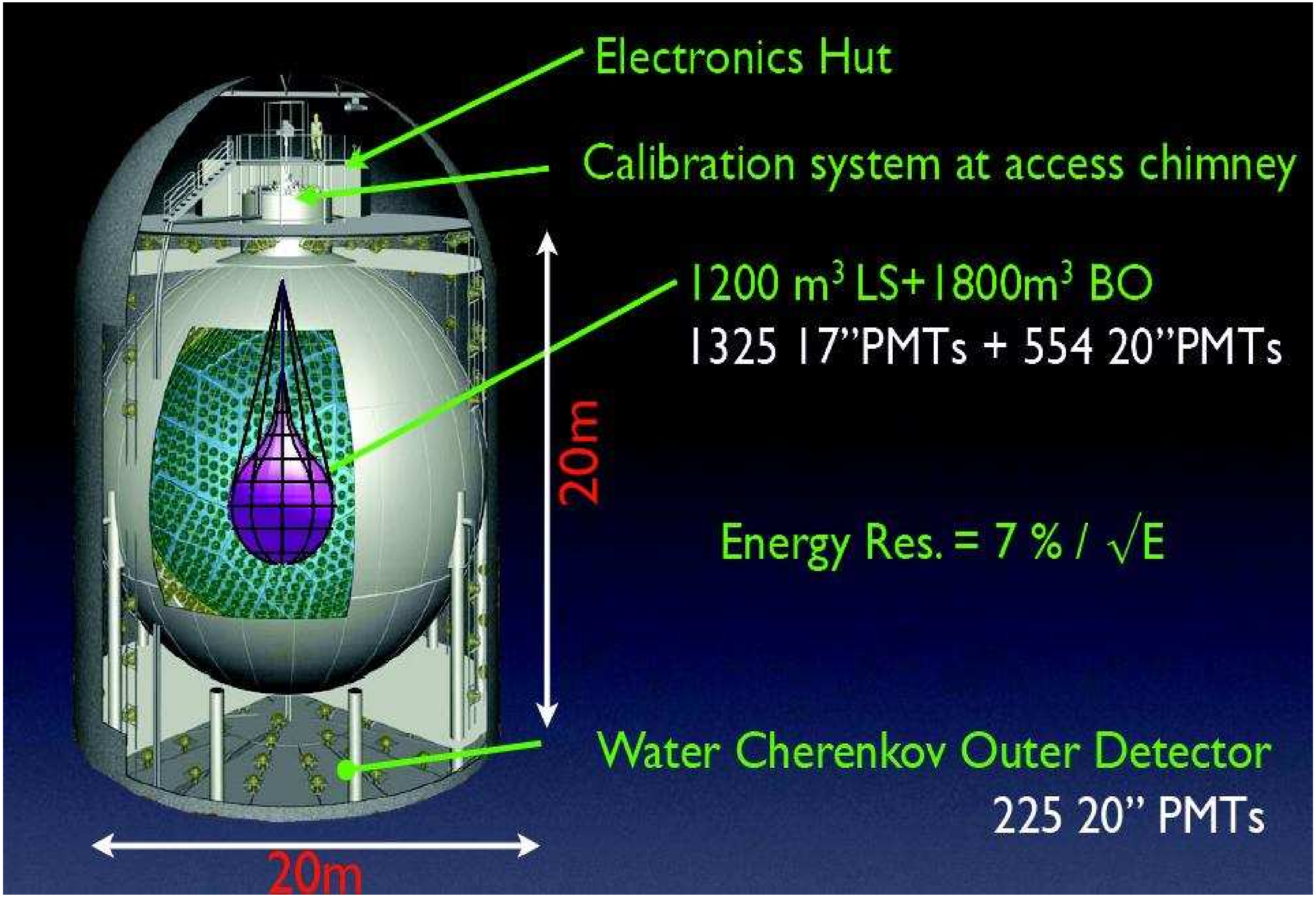
$\Rightarrow$ Discrete symmetries may help, but $\cdots$

$\Rightarrow$ Flavour problem not understood!

$\Rightarrow$ New ideas needed!

Backup slides

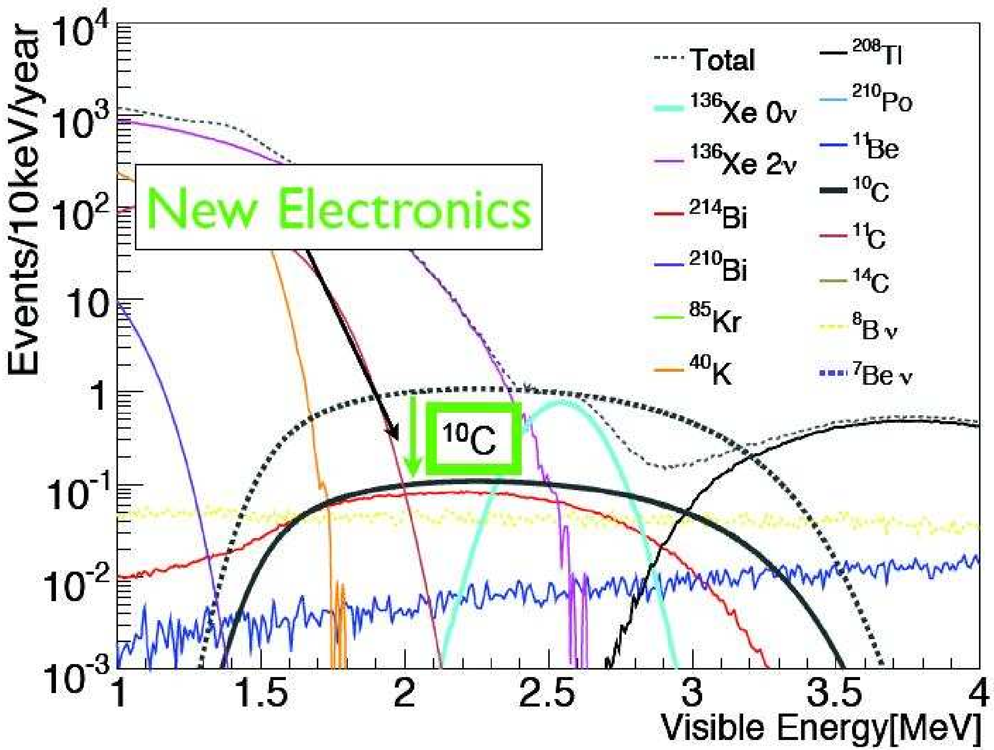
KamLAND-Zen



Electronics Hut
Calibration system at access chimney
1200 m³ LS+1800m³ BO
1325 17"PMTs + 554 20"PMTs
20m
Energy Res. = 7 % / √E
Water Cherenkov Outer Detector
225 20" PMTs
20m

KamLAND-Zen

With ^{136}Xe 400 kg loaded liquid scintillator in mini-ballon:



MC background simulation

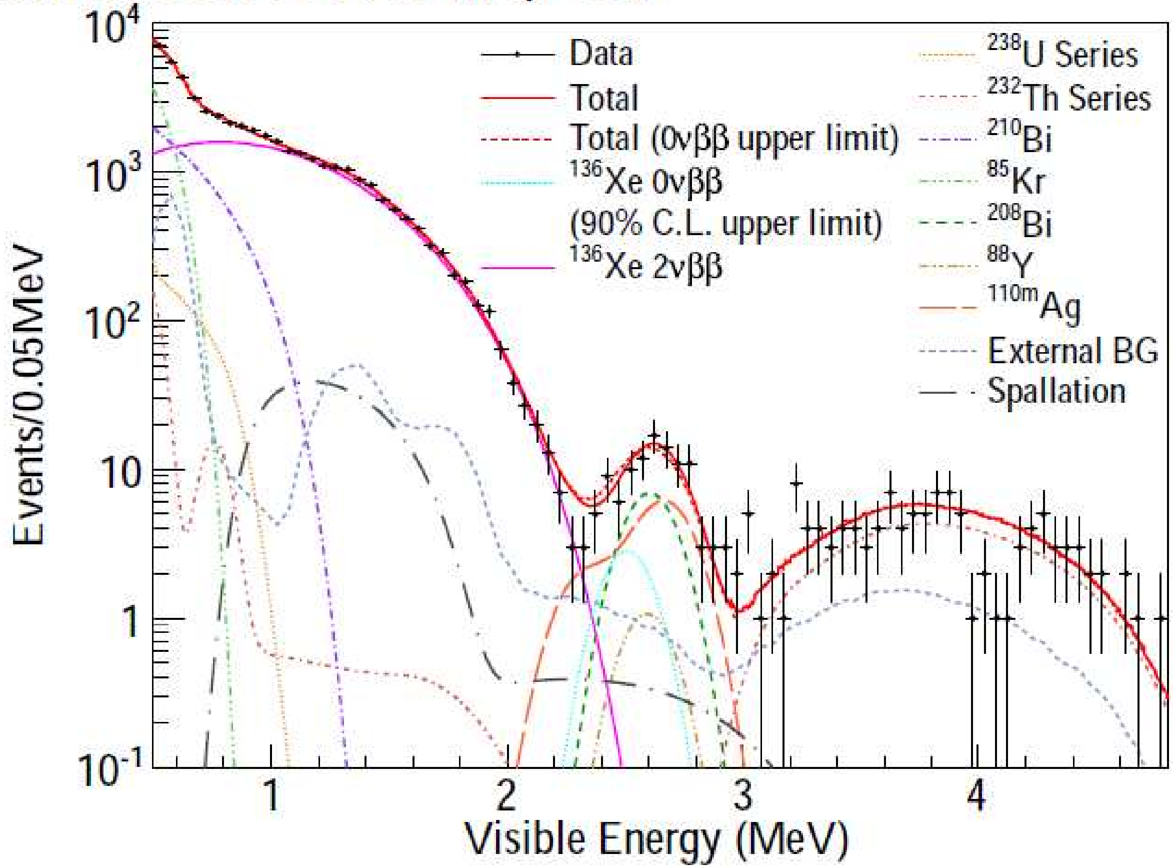
Experiment has started!

$\Rightarrow$ 2 year sensitivity limit: $\langle m_\nu \rangle \leq 60$ meV

$\Rightarrow$ 1 ton ^{136}Xe & 5 years: $\langle m_\nu \rangle \leq 20$ meV

KamLAND-ZEN: Reality

arXiv:1201.4664v1 [hep-ex]



- $2\nu\beta\beta$ decay measured: $T_{1/2} = (2.38 \pm 0.14) \times 10^{21}$ ys
- but: unexpected background in $0\nu\beta\beta$ decay region