Recent developments in neutrino physics

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What are the main physics goals in ν physics?

- To determine the absolute scale of masses

- To determine whether they are Dirac or Majorana

* To discover Leptonic CP-violation

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Can leptogenesis be "proved"?

The short, and rather accurate answer

NO

Nevertheless, a positive discovery of *both*
2 last points

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in favour of leptogenesis

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Go for those discoveries!

What are the main physics goals in ν physics?

- To determine the absolute scale of masses
- To determine whether they are Dirac or Majorana

  (neutrinoless $\beta\beta$ decay,degenerate or inverse hierarchy)
- To discover Leptonic CP-violation

  (in ν_μ-ν_e oscillations at superbeams, betabeams....

  neutrino factory)

Where are we today?

- Absolute mass scale:

---- Cosmo: $\sim \Sigma m < 1\text{eV}$

---- Tritium

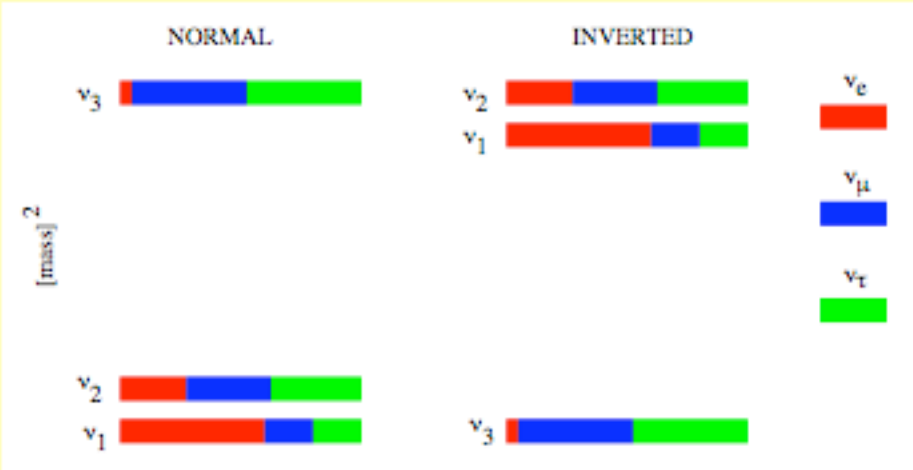
- Majorana character:

---- $0\nu\beta\beta$ decay $\sim m_{\beta} < 2.3$ eV

3-flavour oscillation parameters

$$\Delta m^2_{31} \qquad\qquad\qquad\qquad \Delta m^2_{21}$$

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



3-flavour oscillation parameters

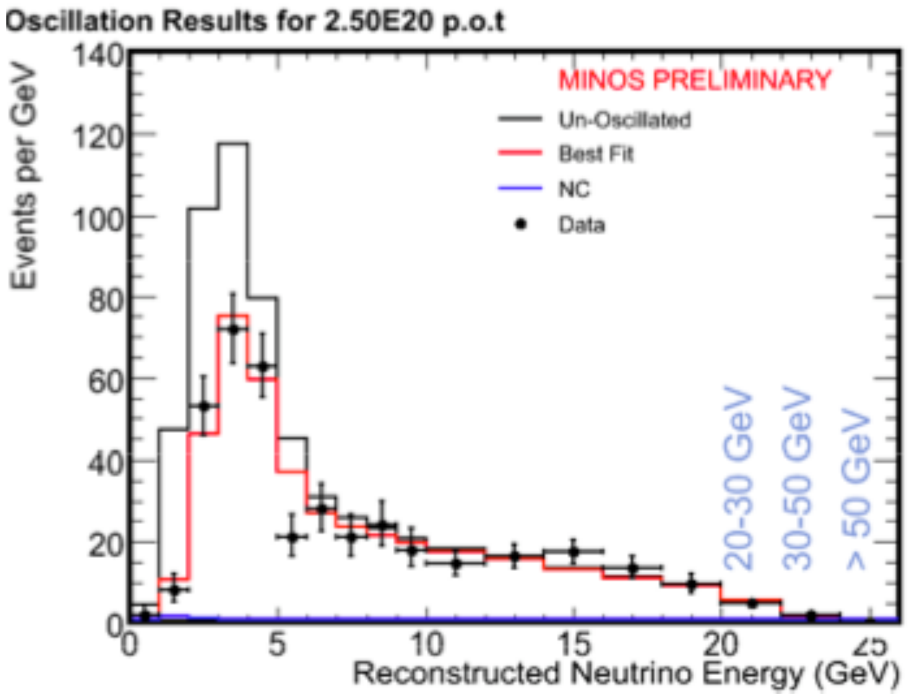
	bf $\pm 1\sigma$	acc. @ 3σ	
Δm^2_{21}	$(7.9 \pm 0.3)\, 10^{-5}\,\mathrm{eV}^2$	(11%)	KamLAND
$\sin^2\theta_{12}$	$0.3^{+0.02}_{-0.03}$	(27%)	SNO CC/NC
$\lvert\Delta m^2_{31}\rvert$	$(2.4^{+0.20}_{-0.16})\, 10^{-3}\,\mathrm{eV}^2$	(24%)	MINOS*
$\sin^2\theta_{23}$	$0.50^{+0.08}_{-0.07}$	(34%)	SK atm

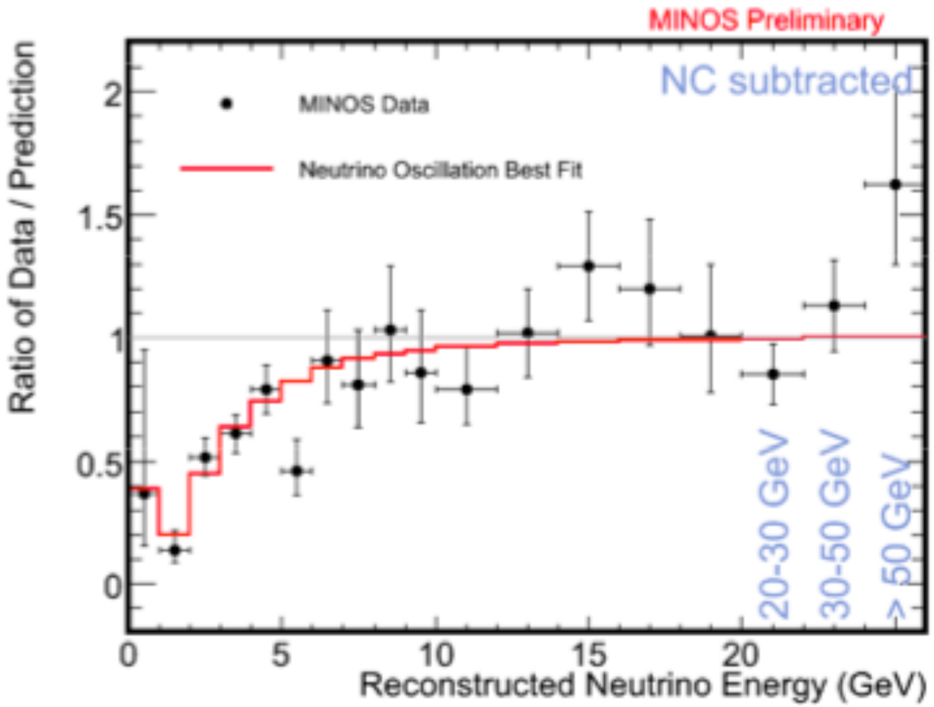
$\sin^2\theta_{13} < 0.04$ $(\sin^2 2\theta_{13} < 0.15)$ @ 3σ CHOOZ

* numbers from recent MINOS update

(T. Schwetz at Nufact07)

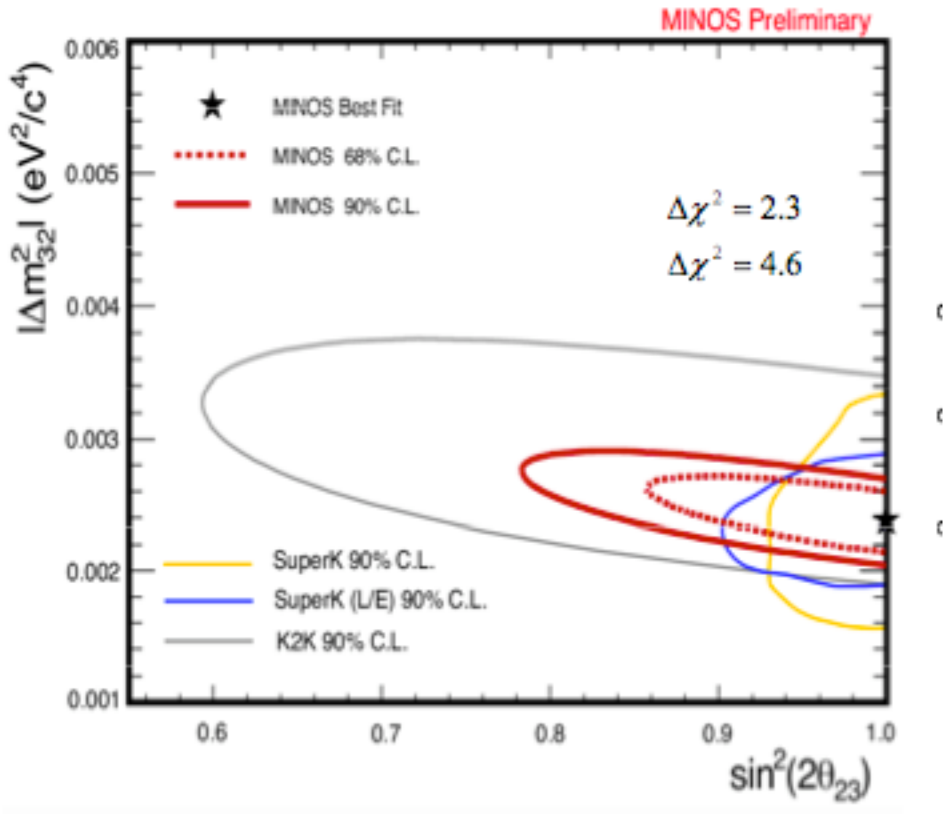
MINOS update





Kajita Nufact07

MINOS update



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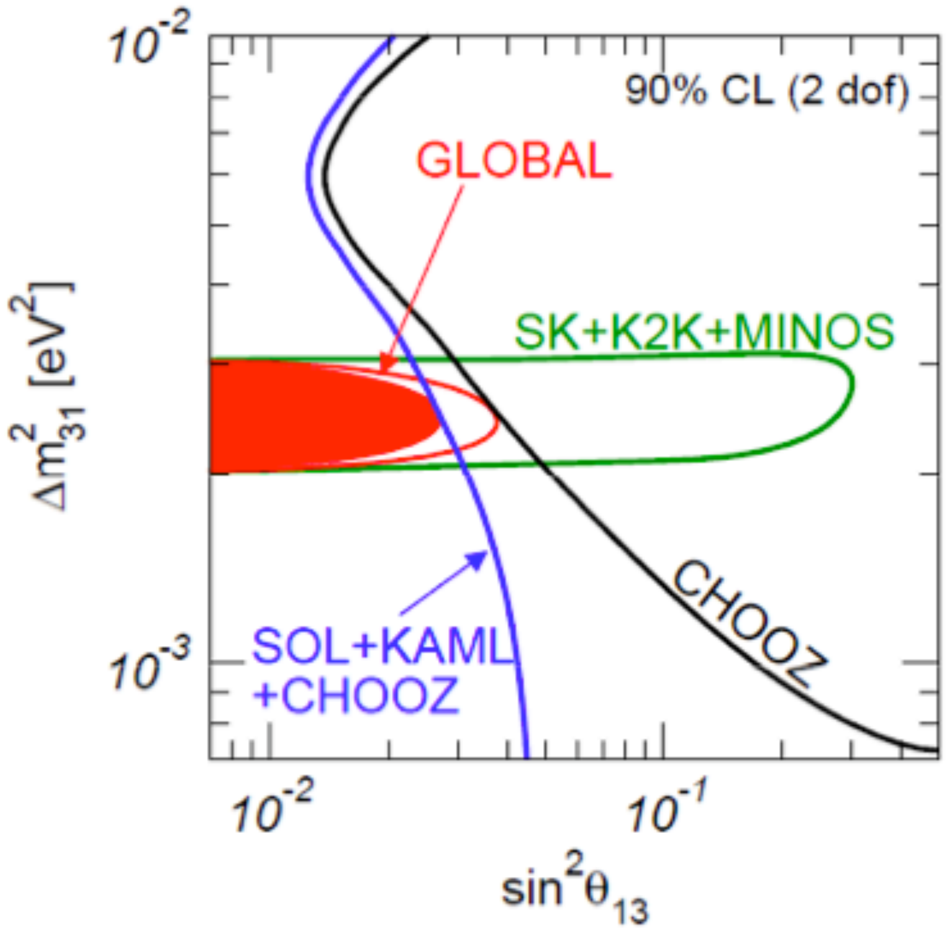
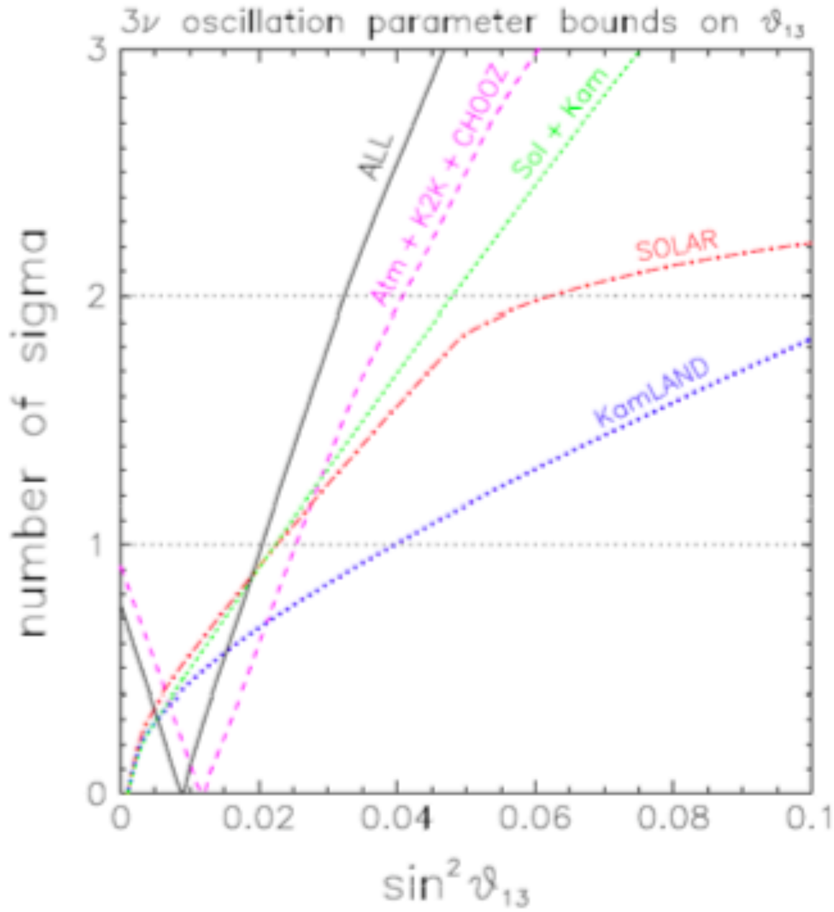
(T. Schwetz at Nufact07)

θ_{13} is the key to CP-violation

T. Schwetz, hep-ph/0606060

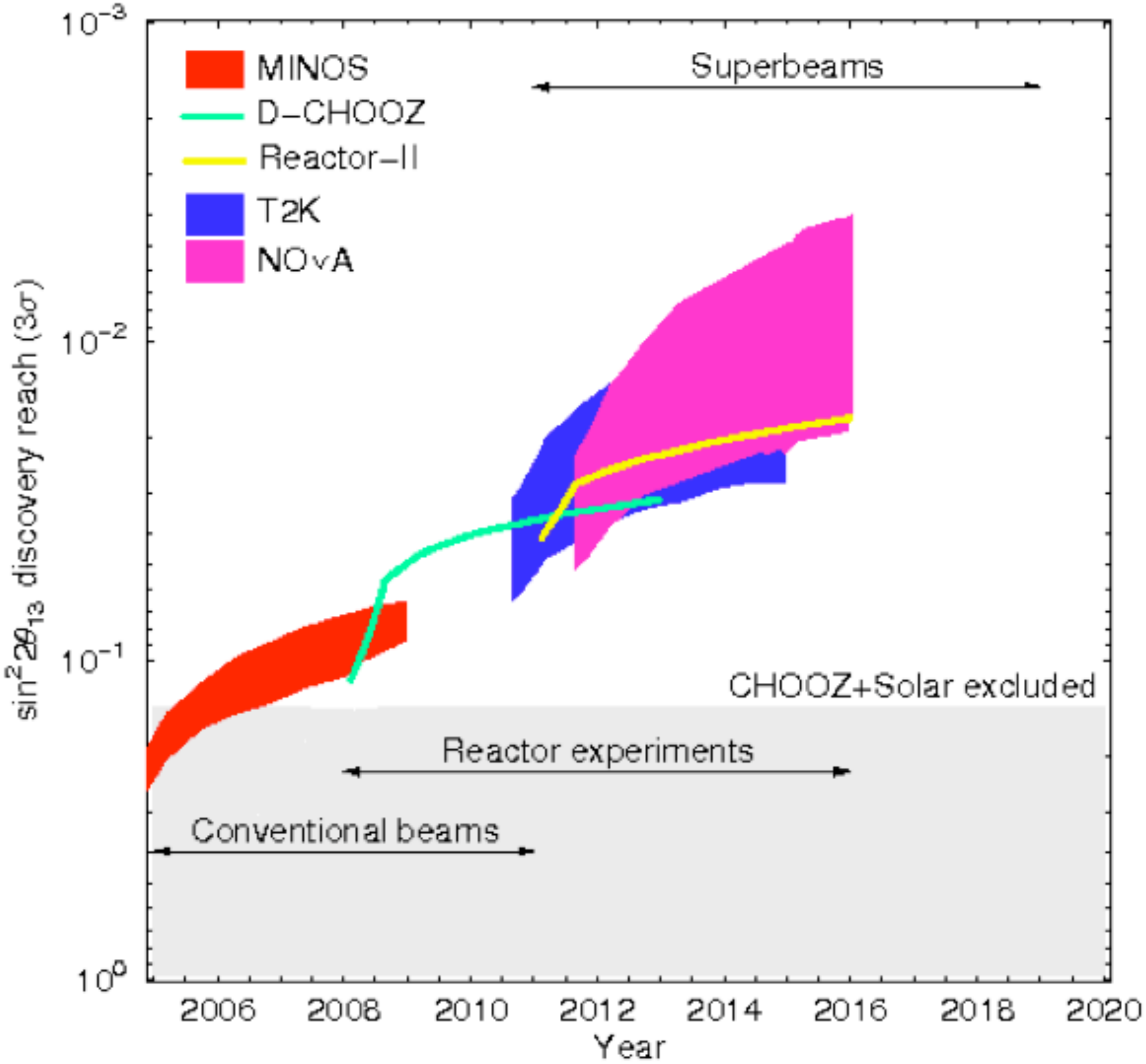


G.L.Fogli et al., hep-ph/0506083



$\sin^2\theta_{13} < 0.02$ (0.041) at 90%CL (3σ) (1dof) (hep-ph/0606060)

θ_{13} future sensitivities



Example with
fixed atmosph.
parameters
(Albrow et al.)

Going towards the era of precision neutrino physics

~ % level

What are the main physics goals in ν physics?

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only three ν ????

MiniBoone shows, for the first time, that only 3 νs is OK ?

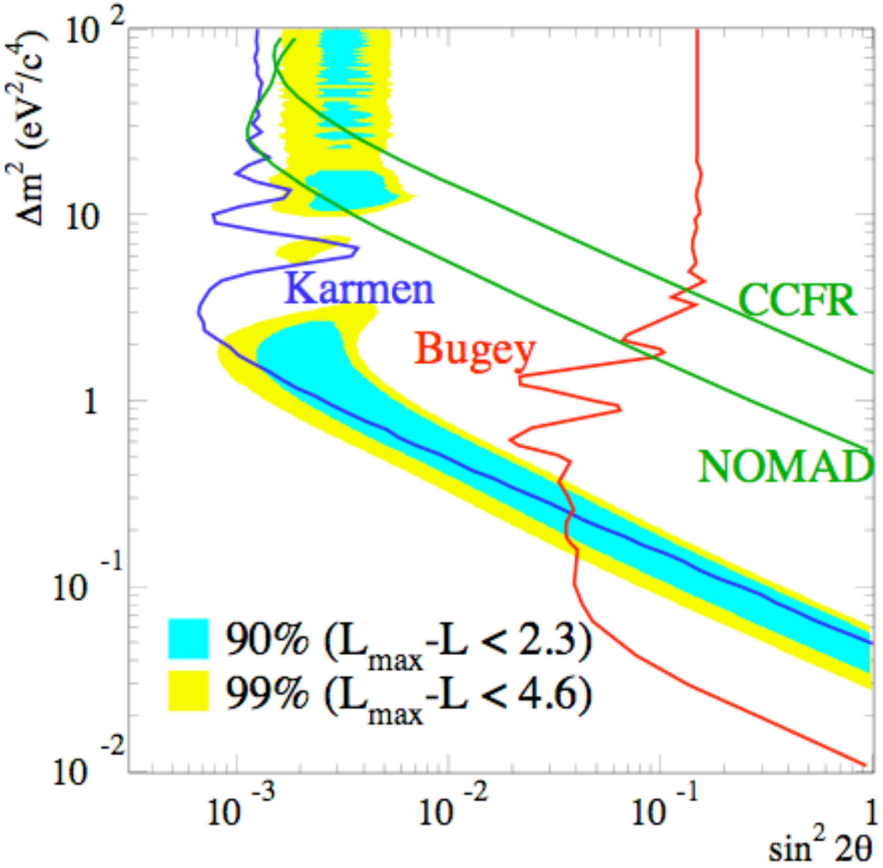
Designed to check LSND signal of > 3 νs

LSND: observed $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$, $E_\nu \sim 30$ MeV, L= 35 m

MiniBoone: explored $\nu_\mu \rightarrow \nu_e$, $E_\nu \sim 750$ MeV, L= 541 m

and did not find it

The LSND problem: $\Delta m^2 \gtrsim 0.1\ \mathrm{eV}^2$



while

$$\Delta m^2_{\mathrm{SOL}} = 7.67\,^{+0.67}_{-0.61} \times 10^{-5}\ \mathrm{eV}^2\,,$$

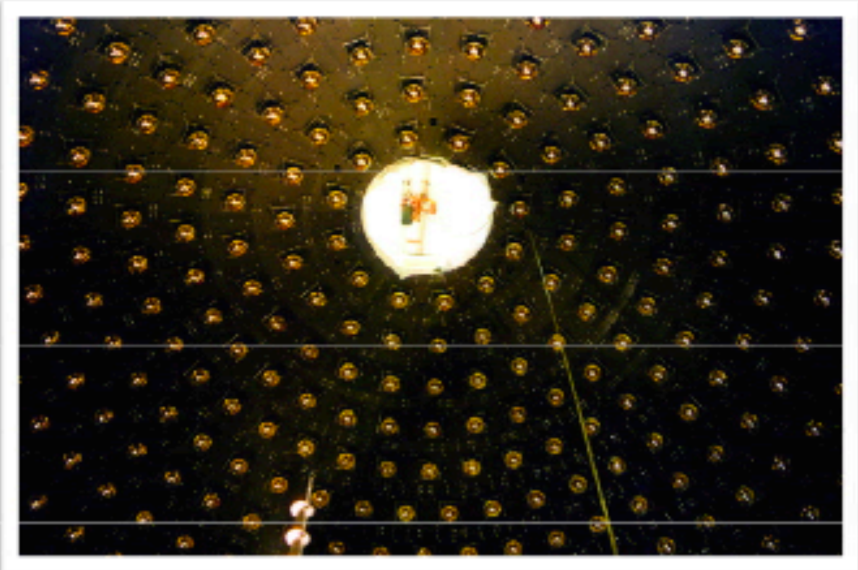
$$\Delta m^2_{\mathrm{ATM}} = \begin{cases} -2.37\,^{+0.43}_{-0.46} \times 10^{-3}\ \mathrm{eV}^2 & (\mathrm{IH})\,, \\ +2.46\,^{+0.47}_{-0.42} \times 10^{-3}\ \mathrm{eV}^2 & (\mathrm{NH})\,; \end{cases}$$

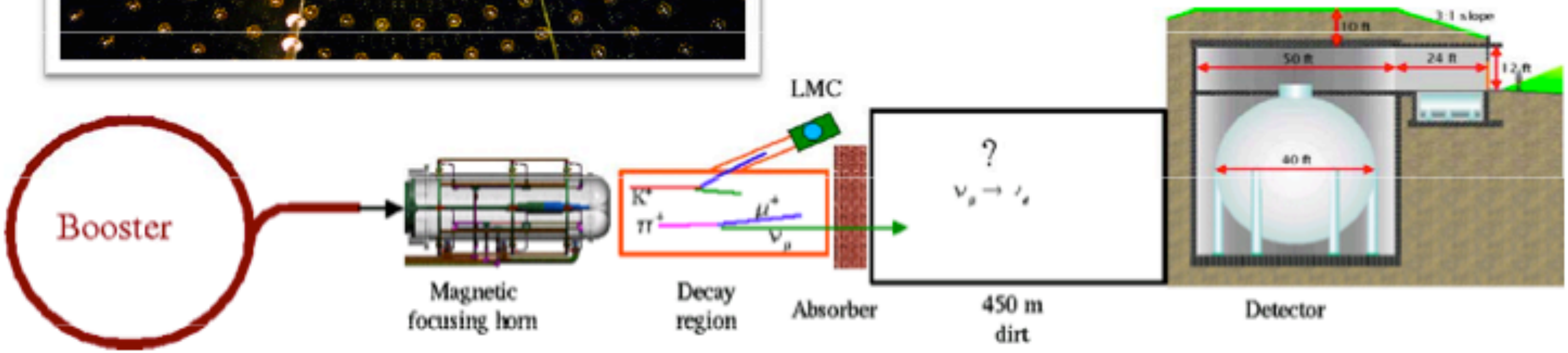
(Gzlez-Garcia+Maltoni07))

-> more than 3 ν generations

MiniBoone

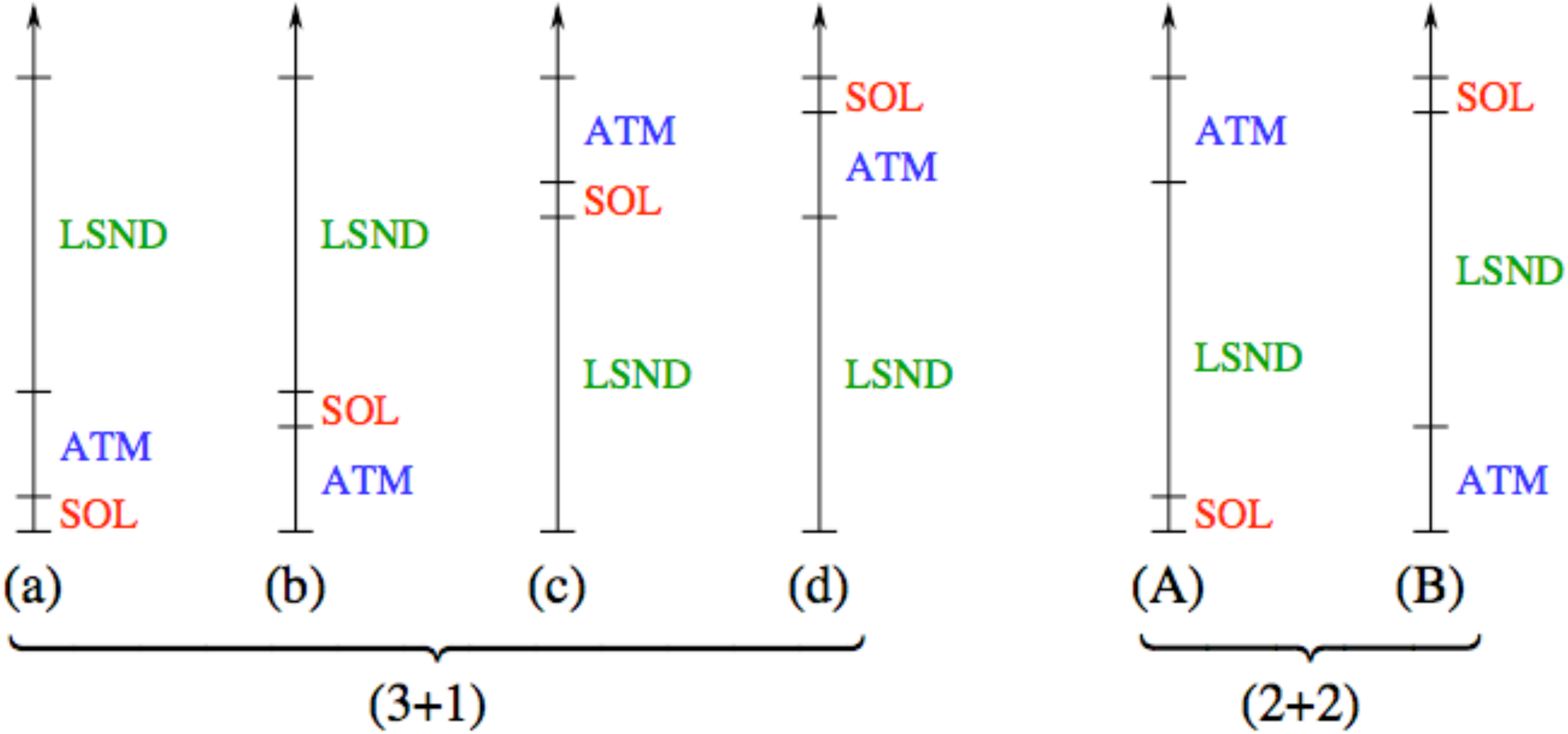
arXiv:0704.1500 and C. Polly in this meeting





	L	E_ν	L/E
LSND	30m	30MeV	1
MiniBooNE	500m	500MeV	1

(Slide from Kajita Nufact07)



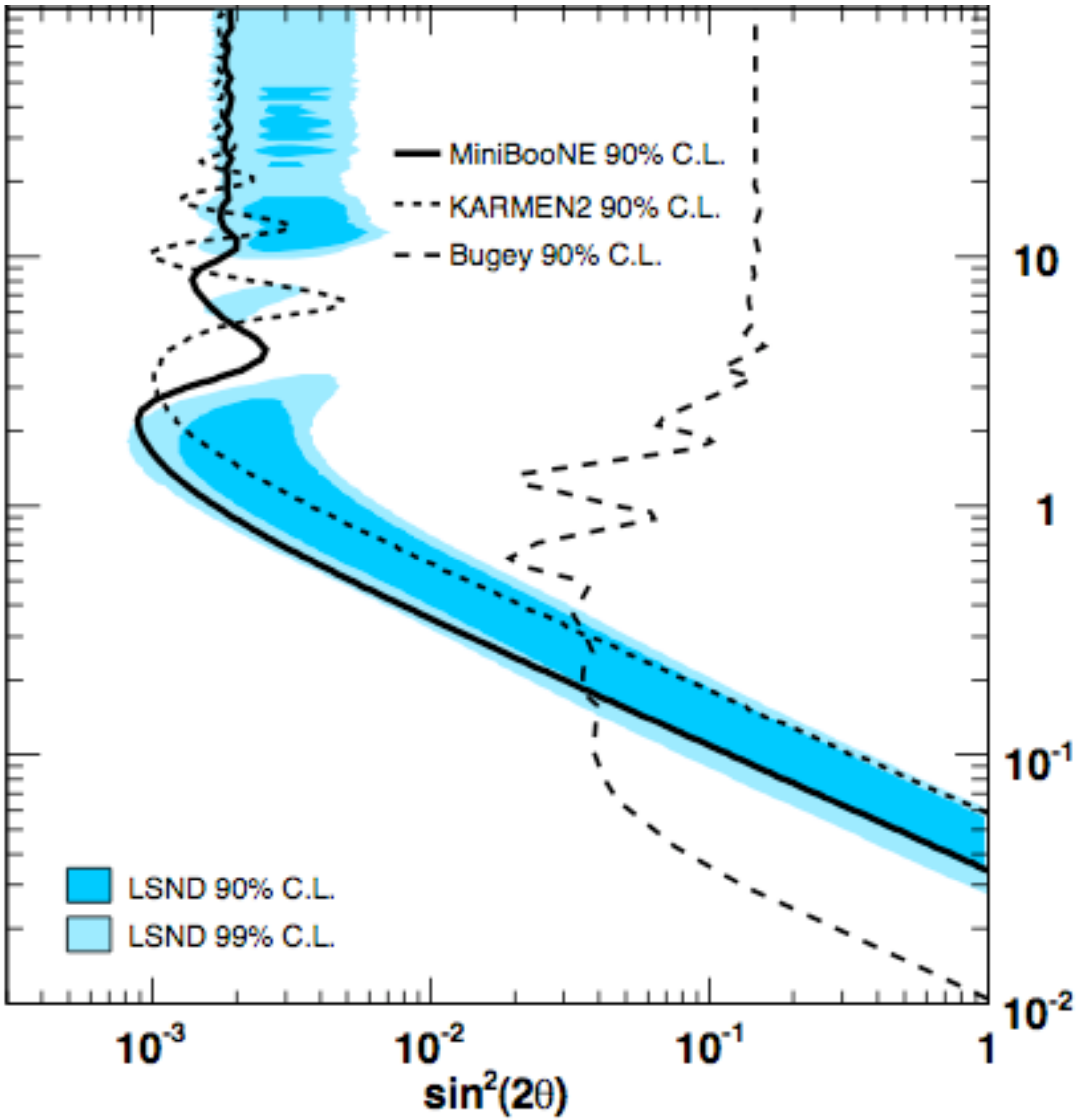
Tension with disappearance data, and ruled out by MiniBoone

(Maltoni+Schwetz07)

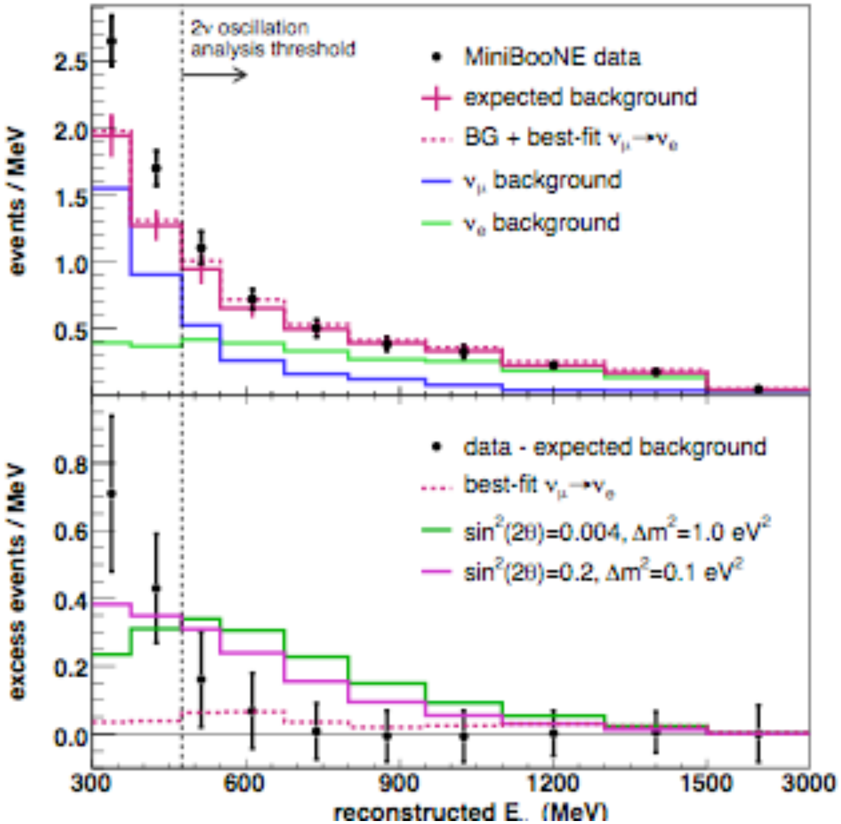
Ruled out by solar+atmosph.

All short base line vs. LSND

(3+1analysis alike to 2-flavour analysis)

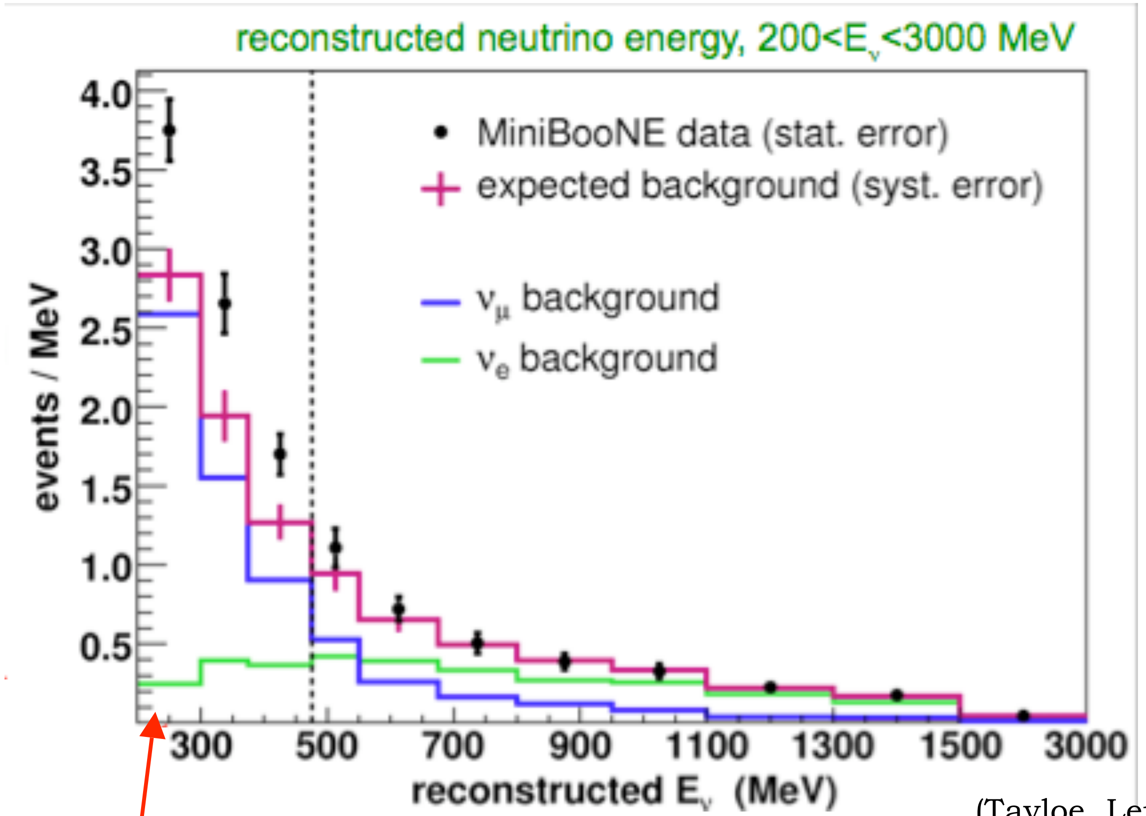


The MiniBoone excess



Excess of ~ 100 ν_e events below 475 MeV

Excess reinforced during summer



(Tayloe, Lepton-Photon07)

+ this bin

What if there was something in there + LSND ?

After all, νs are favorite probes of “dark” sectors:

they can mix with sterile fermions of BSM theories

MiniBoone shows, for the first time, that only 3 νs is OK

?

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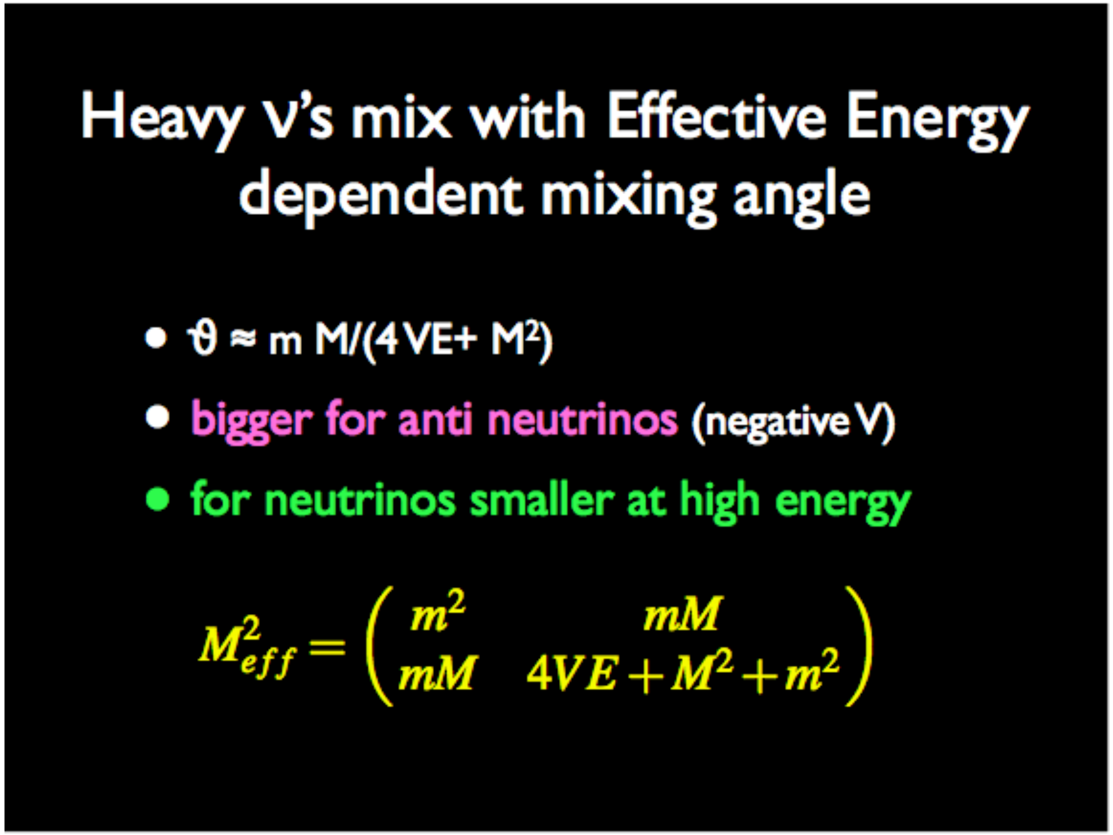
i.e. A new gauged B-L force

LSND, MiniBoone go through matter: MSW-like effect ?

- Spontaneous B-L violation
- Gauge boson mass at keV
- Sterile neutrinos at eV with miniseesaw

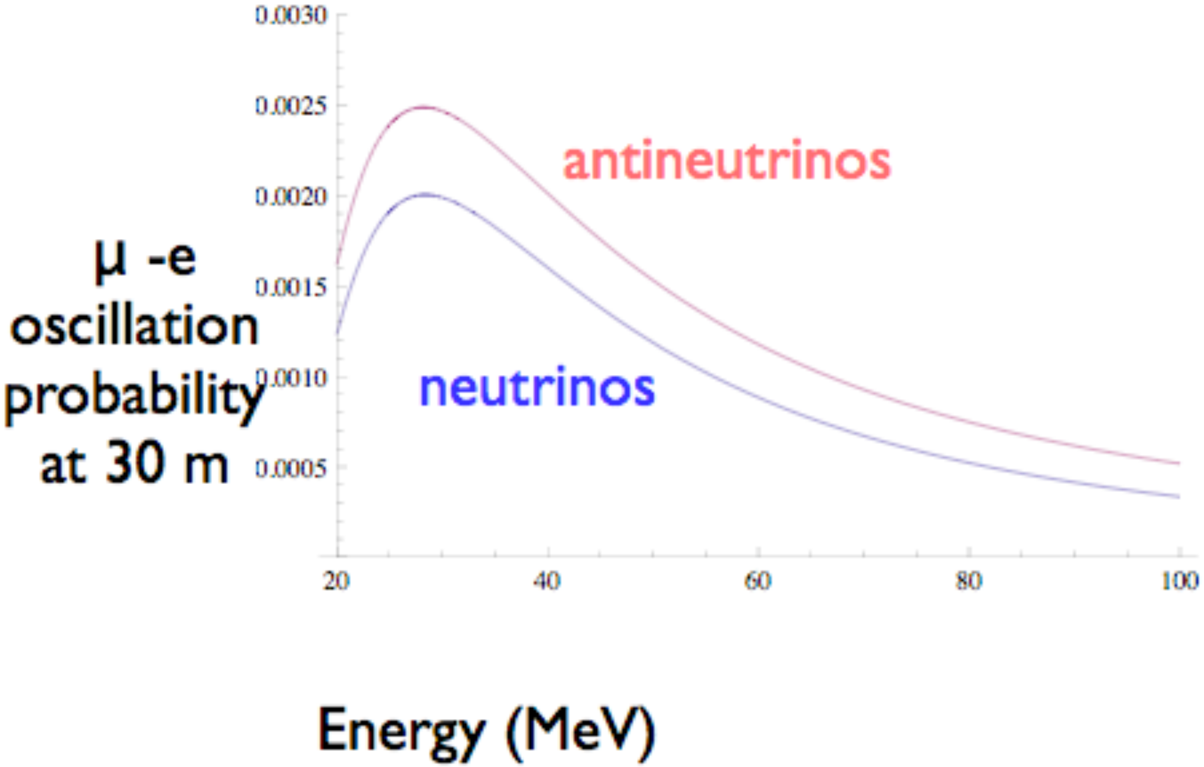
(Ann Nelson and collab.)



(Nelson Retenu07)

Effects of B-L potential

- eg m=.3 eV, M_1 =1 eV, M_2 heavy, V= .3 10^{-9}



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Effects of B-L potential

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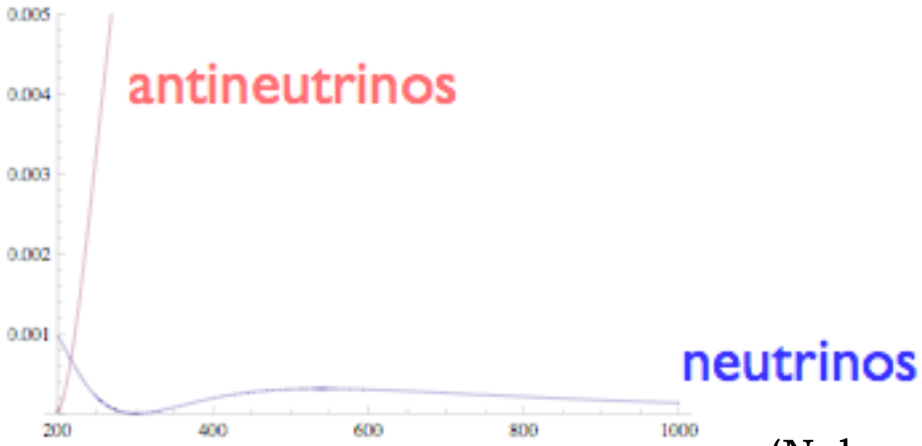
μ -e oscillation probability at 500 m



(Nelson Retenu07)

Energy (MeV)

Falsifiable: they predict large signal in on-going antineutrino run at MiniBoone

Assume 3 light νs for the rest of the talk

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.....The rest of the talk deals much with the Majorana character

ν masses ---->

Beyond SM scale M

* What is the prize for M~TeV without unnatural fine-tunings?

* What observable observable effects could we then expect?

No ν **masses** in the SM

because the SM *accidentally* preserves B-L

……only left-handed neutrinos

and

……only scalar doublets (Higgs)

ν masses beyond the SM

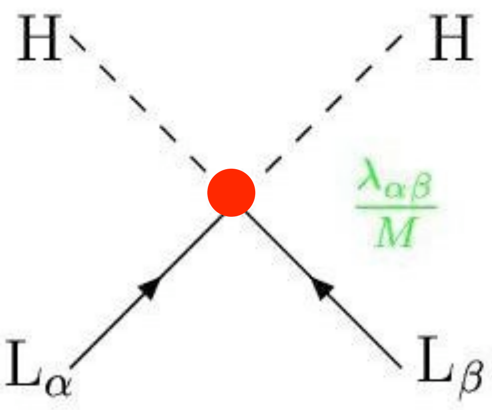
Favorite options: new physics at higher scale M

Heavy fields manifest in the low energy effective theory (SM) via higher dimensional operators

$$\delta L = c^i \, O^i$$

Dimension 5 operator:

$$\lambda/M \, \underbrace{(L\,L\,H\,H)}_{O^{d=5}} \rightarrow \lambda v^2/M \, (\nu\nu)$$



It’s unique → very special role of ν masses: lowest-order effect of higher energy physics

ν masses beyond the SM

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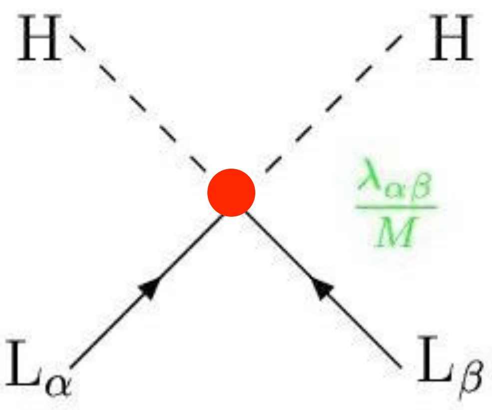

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This mass term violates lepton number (B-L)
→ Majorana neutrinos

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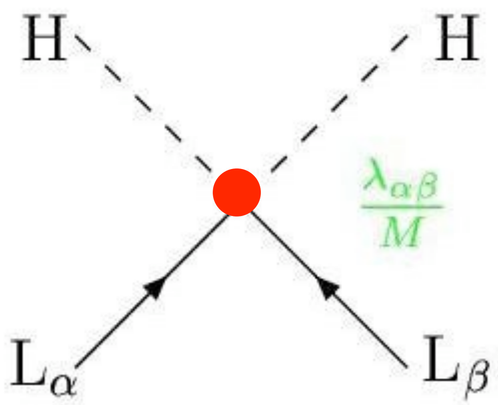

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$O^{d=5}$ *is common to all models of Majorana* ν*s*

Dimension 6 operators,

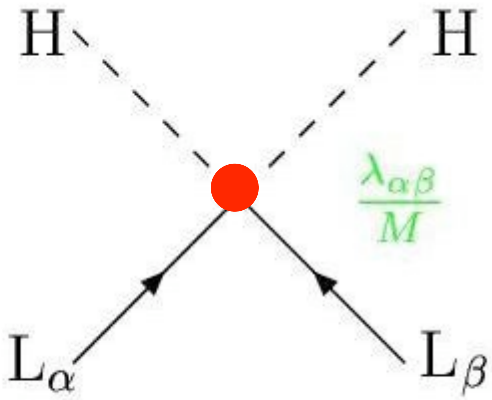
$$O^{d=6}$$

discriminate among models.

Which are the d=6 operators characteristic of Seesaw models?

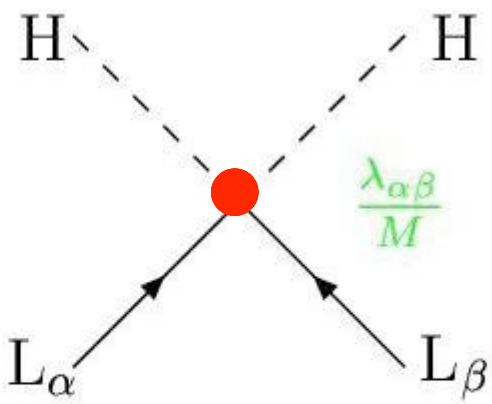
(A. Abada, C. Biggio, F.Bonnet, T. Hambye +MBG)

ν masses beyond the SM : tree level



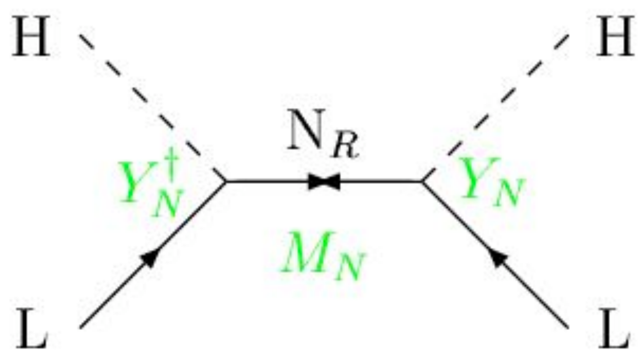
3 generic types (Ma)

ν masses beyond the SM : tree level



2 x 2 = 1 + 3

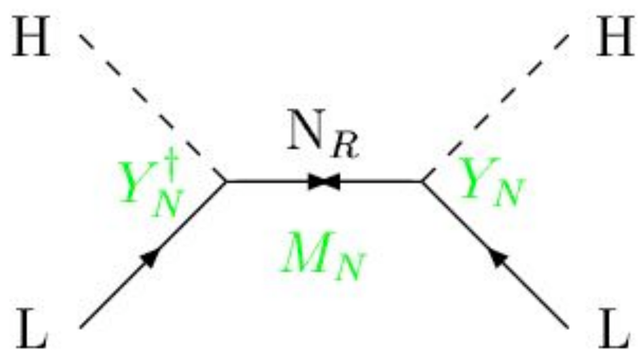
ν masses beyond the SM : tree level



Fermionic Singlet
Seesaw (or type I)

2 x 2 = 1 + 3

ν masses beyond the SM : tree level



Fermionic Singlet
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$$m_\nu \sim v^2\, c^{d=5} = v^2\, Y_N^T Y_N / M_N$$

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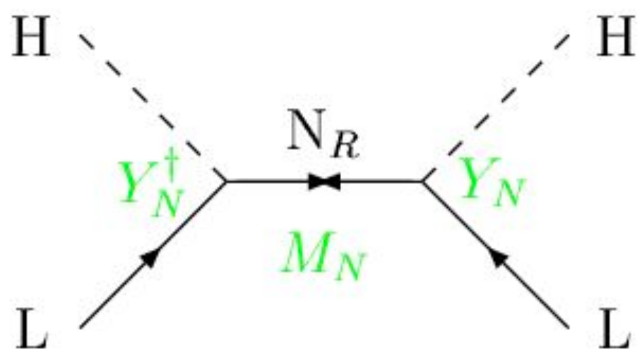

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Which allows $Y_N \sim 1$ --> $M \sim M_{Gut}$

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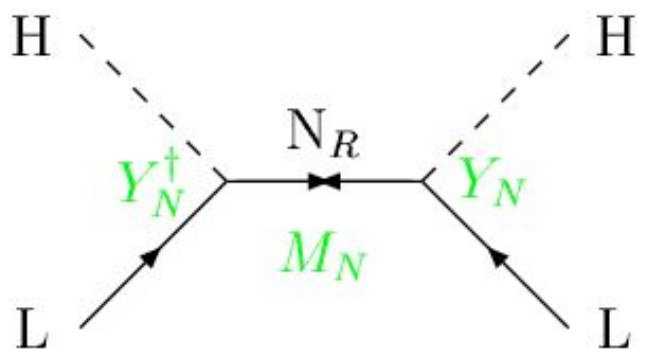

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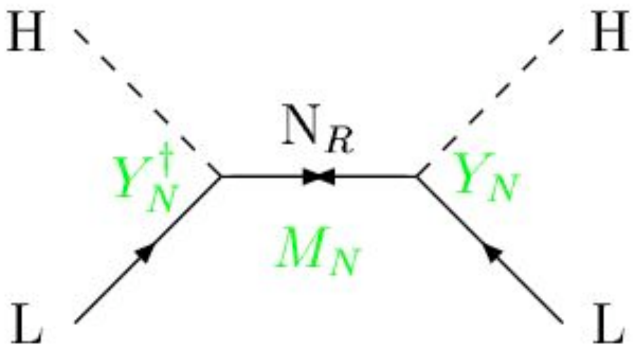
Which allows $Y_N \sim 1$ --> $M \sim M_{Gut}$

$Y_N \sim 10^{-6}$ --> $M \sim TeV$

ν masses beyond the SM : tree level



Fermionic Singlet
Seesaw (or type I)

(Fukugita, Yanagida)

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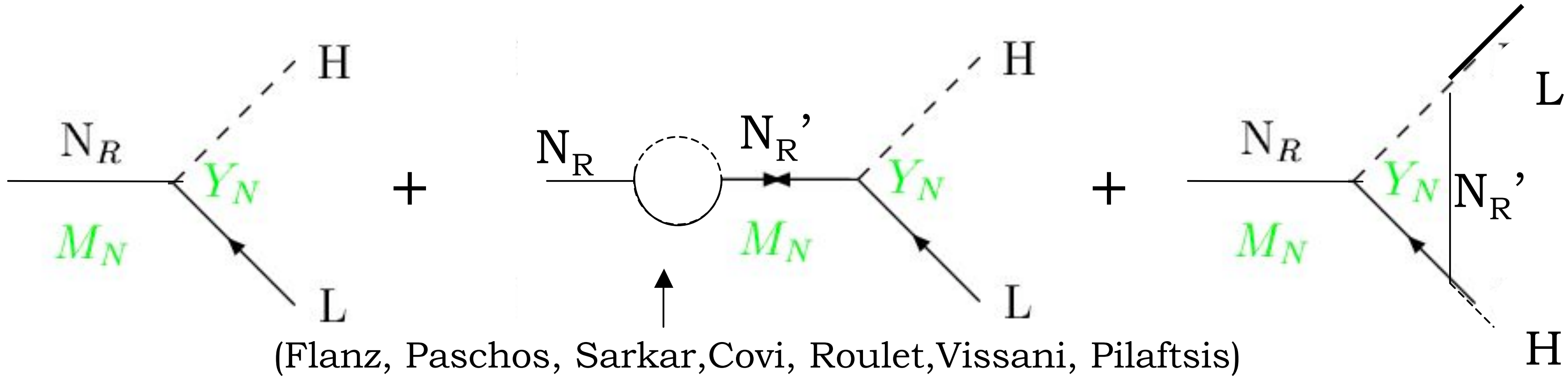
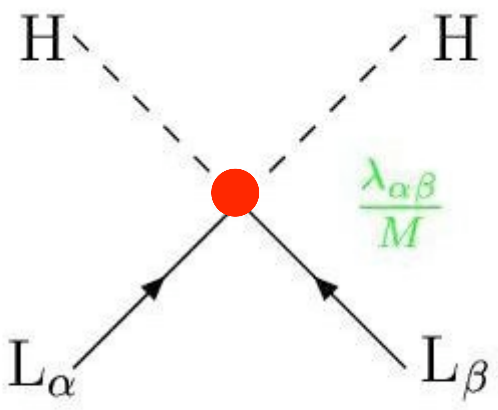
LEPTOGENESIS:



(Flanz, Paschos, Sarkar,Covi, Roulet,Vissani, Pilaftsis)

ν masses beyond the SM : tree level



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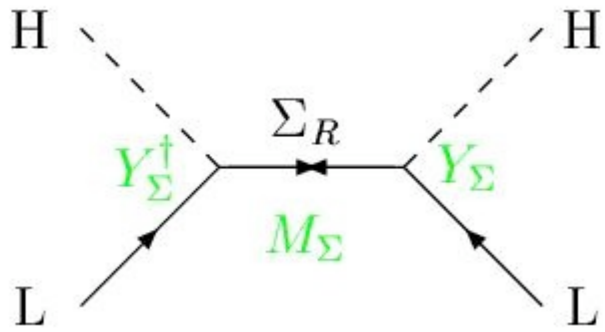

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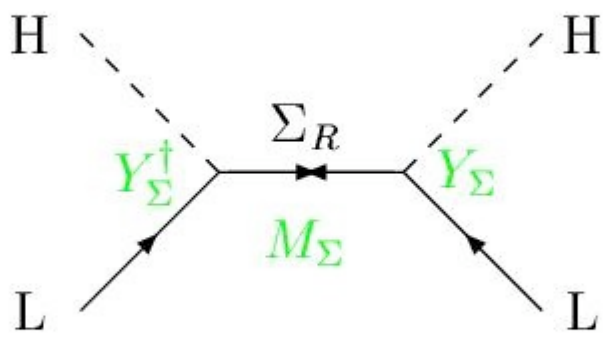
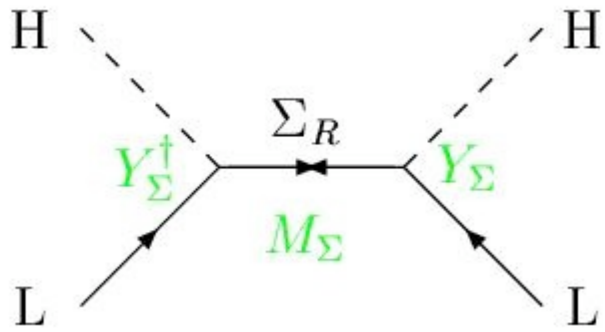


Fermionic Triplet
Seesaw (or type III)

2 x 2 = 1 + 3

ν masses beyond the SM : tree level



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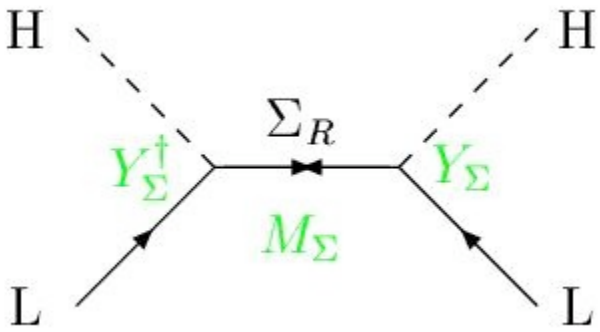

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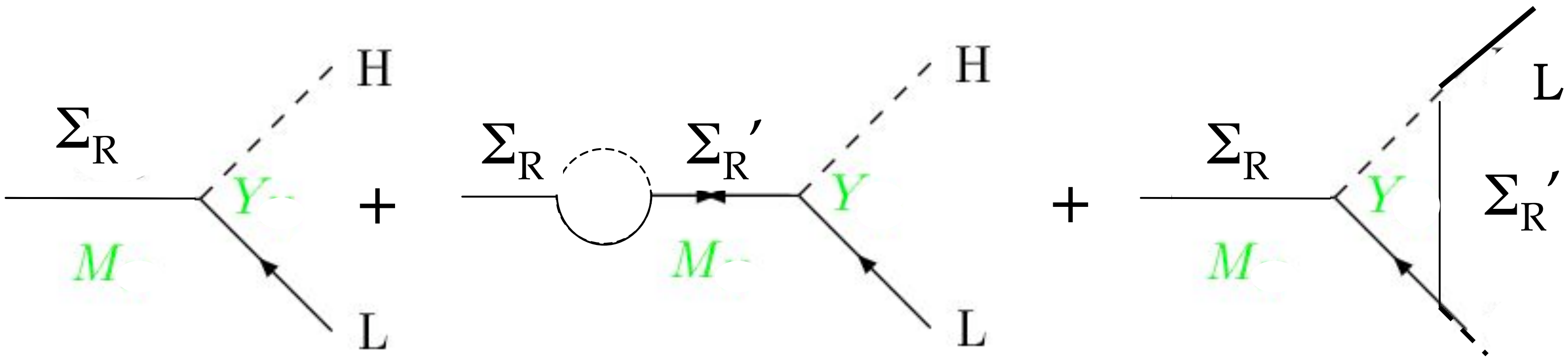
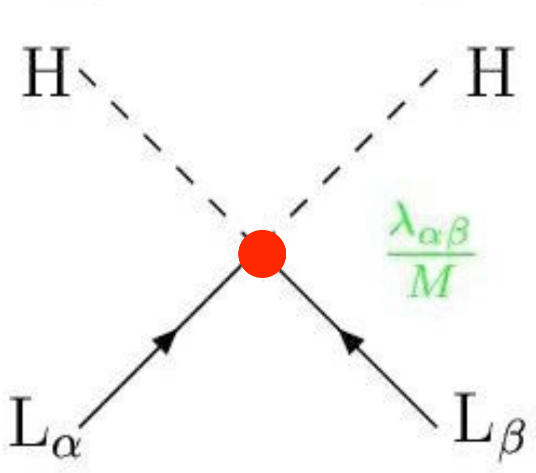


(Hambye, Li, Papucci, Notari, Strumia))

ν masses beyond the SM : tree level



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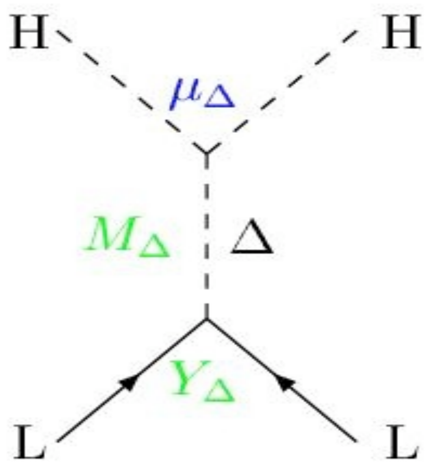
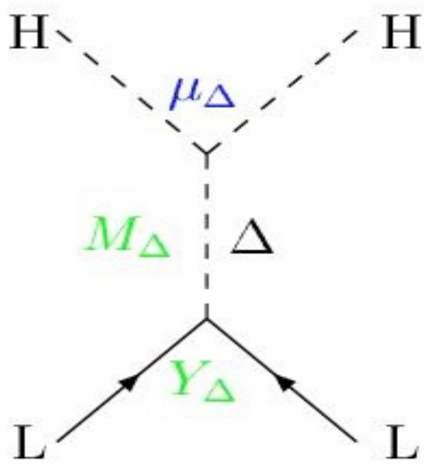


Scalar Triplet
Seesaw (or type II)

2 x 2 = 1 + 3

ν masses beyond the SM : tree level



Scalar Triplet
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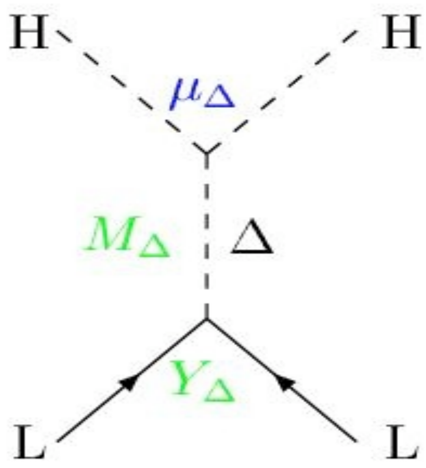
ν masses beyond the SM : tree level



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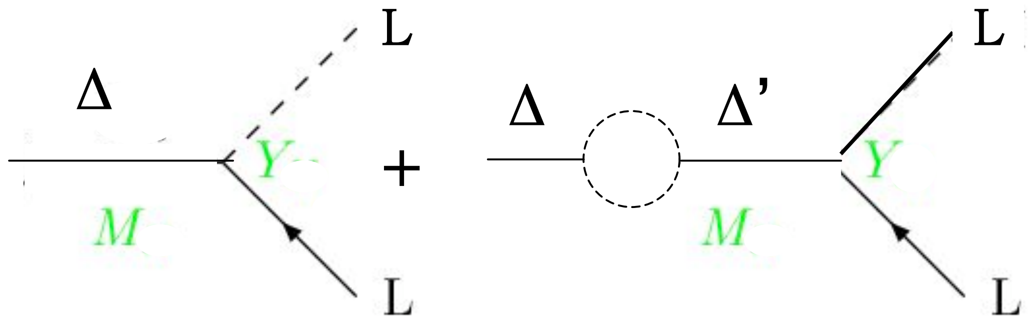
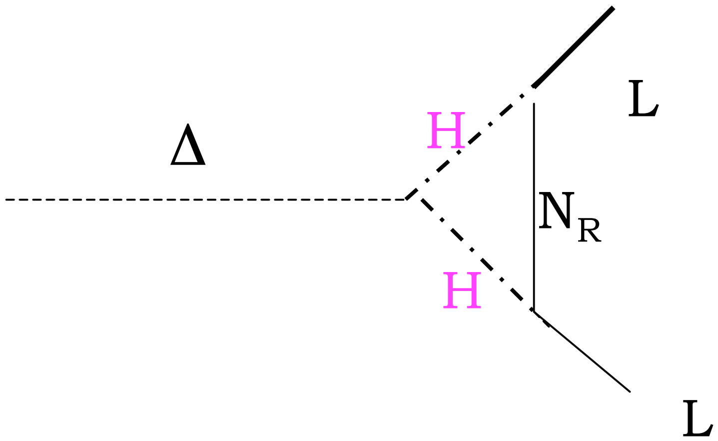


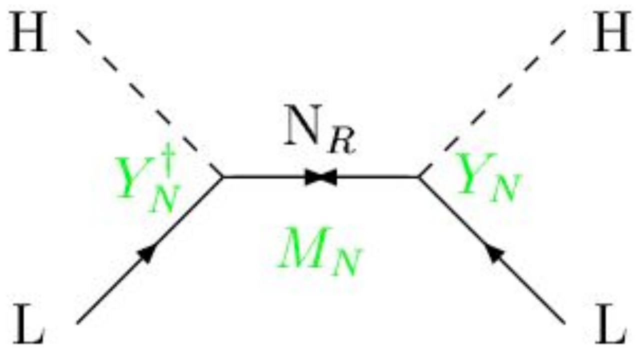
(Ma, Sarkar, Hambye)

Or hybrid models, i.e Fermionic Singlet + Scalar Triplet



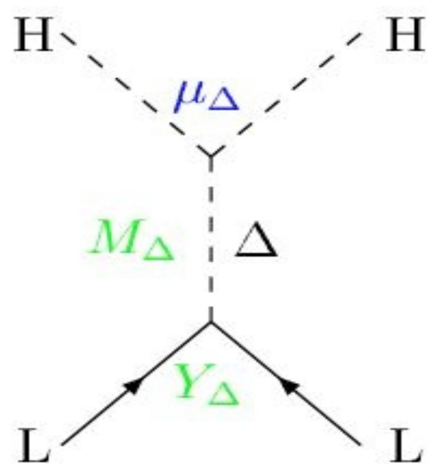
(O'Donnell, Sarkar, Hambye, Senjanovic;
Antusch, King)

ν masses beyond the SM : tree level



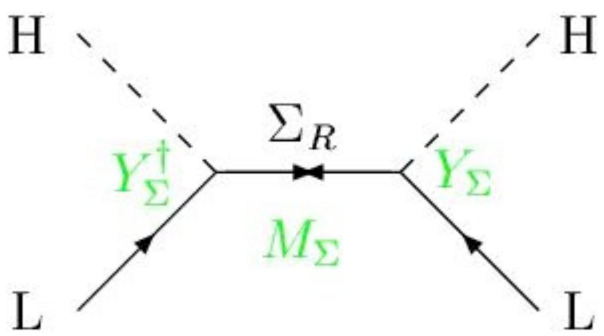
Heavy fermion singlet N_R

(Type I See-Saw) Minkowski, Gell-Mann, Ramond, Slansky, Yanagida, Glashow, Mohapatra, Senjanovic



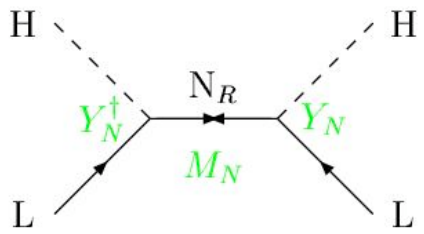
Heavy scalar triplet Δ

Magg, Wetterich, Lazarides, Shafi, Mohapatra, Senjanovic, Schecter, Valle



Heavy fermion triplet Σ_R

Ma, Roy, Senjanovic, Hambye et al., ...



Minimal see-saw (fermionic singlet)

$$\mathcal{L} = \mathcal{L}_{SM} + i\, \overline{N_R} \not\partial N_R - Y_N\, \overline{L}\, H\, N_R - M\, N_R\, N_R$$

Integrate out N_R $\quad \mathcal{L}^{eff} = \mathcal{L}_{SM} + \frac{1}{M}\mathcal{L}^{d=5} + \frac{1}{M^2}\mathcal{L}^{d=6} + \ldots$

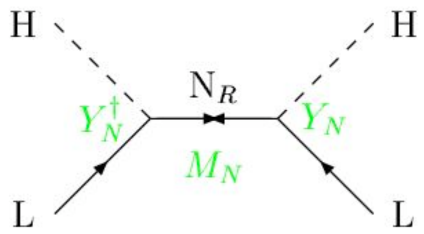
$$Y_N^T Y_N / M \; (L\, L\, H\, H)$$

d=5 operator
it gives mass to ν

$$Y_N^+ Y_N / M^2 \; (\overline{L}\, H) \not\partial (H\, L)$$

d=6 operator
it renormalises kinetic energy

Broncano, Gavela, Jenkins 02



Minimal see-saw (fermionic singlet)

$$L = L_{SM} + i\, \overline{N_R} \not\partial N_R - Y_N \overline{L} H N_R - M N_R N_R$$

Integrate out N_R

$$L^{eff} = L_{SM} + \frac{1}{M} L^{d=5} + \frac{1}{M^2} L^{d=6} + \ldots$$

$$Y_N^T Y_N / M \; (L\, L\, H\, H)$$

$$Y_N^+ Y_N / M^2 \; (\overline{L}\, H) \not\partial (H\, L)$$

d=5 operator
it gives mass to ν

d=6 operator
it renormalises kinetic energy

Kaluza-Klein model: De Gouvea, Giudice, Strumia, Tobe with

$$m_\nu \sim v^2\, c^{d=5} = v^2\, Y_N^T Y_N / M_N$$

while

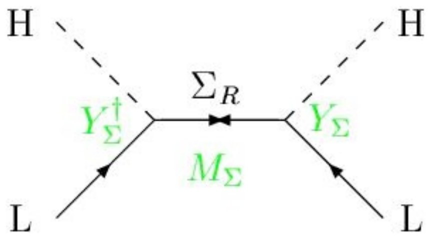
$$c^{d=6} = Y_\Sigma^+ Y_\Sigma / M^2$$

For Y´s ~ O(1),

$$c^{d=6} \sim (c^{d=5})^2$$

and the smallness of neutrino masses would preclude in practice observable effects from $c^{d=6}$

How to evade this without ad-hoc cancelations of Yukawas?



Fermionic triplet seesaw

$$\mathcal{L} = \mathcal{L}_{SM} + i\,\overline{\Sigma_R}\,\not{D}\,\Sigma_R - Y_\Sigma\,\overline{L}\,\tau . H\,\Sigma_R - M\,\Sigma_R\,\Sigma_R$$

Integrate out N_R $\quad L^{eff} = L_{SM} + \frac{1}{M} L^{d=5} + \frac{1}{M^2} L^{d=6} + \ldots$

$$Y_\Sigma^T Y_\Sigma / M \; (L\,L\,H\,H)$$

$$Y_\Sigma^+ Y_\Sigma / M^2 \; (\overline{L}\,\tau\,H)\,\not{D}\,(H\,\tau\,L)$$

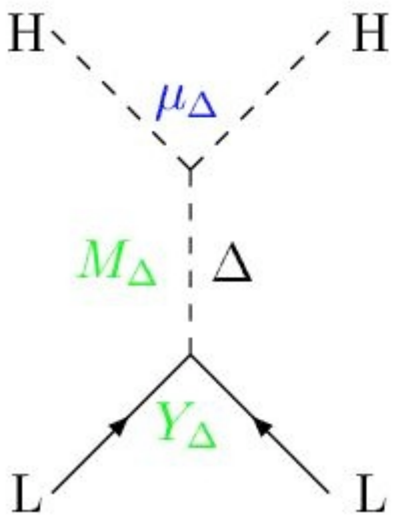
d=5 operator
it gives mass to ν

d=6 operator
it renormalises kinetic energy+…

Scalar triplet see-saw

$$L = L_{SM} + D_\mu D^\mu \Delta - \Delta^+ M^2 \Delta +$$

$$Y_\Delta\, L\, \tau.\Delta\, L + \mu_\Delta\, H\, \tau.\Delta\, H + V(H,\Delta,\lambda_i)$$



d=5 $Y_\Delta\, \mu_\Delta / M^2\ (L\, L\, H\, H)$

d=6

$Y^+_\Delta Y_\Delta / M^2\ (\bar{L}\, L)\ (\bar{L}\, L)$

$\mu^2_\Delta / M^4\ (H^+ H)^3$

$\lambda_i \mu^2_\Delta / M^4 (H\tau H) D_\mu D^\mu (H\tau H)$

Model	Effective Lagrangian $\mathcal{L}_{eff} = c_i \mathcal{O}_i$		
	$c^{d=5}$	$c_i^{d=6}$	$\mathcal{O}_i^{d=6}$
Fermionic Singlet	$Y_N^T \frac{1}{M_N} Y_N$	$Y_N^\dagger \frac{1}{\lvert M_N \rvert^2} Y_N$	$\left(\overline{L}\widetilde{H}\right) i\partial\!\!\!/ \left(\widetilde{H}^\dagger L\right)$
Fermionic Triplet	$Y_\Sigma^T \frac{1}{M_\Sigma} Y_\Sigma$	$Y_\Sigma^\dagger \frac{1}{\lvert M_\Sigma \rvert^2} Y_\Sigma$	$\left(\overline{L}\vec{\tau}\widetilde{H}\right) iD\!\!\!\!/ \left(\widetilde{H}^\dagger \vec{\tau} L\right)$
Scalar Triplet	$4Y_\Delta \frac{\mu_\Delta}{\lvert M_\Delta \rvert^2}$	$Y_\Delta^\dagger \frac{1}{2\lvert M_\Delta \rvert^2} Y_\Delta$	$\left(\overline{\widetilde{L}}\vec{\tau}L\right)\left(\overline{L}\vec{\tau}\widetilde{L}\right)$
		$\frac{\lvert \mu_\Delta \rvert^2}{\lvert M_\Delta \rvert^4}$	$\left(H^\dagger \vec{\tau} \widetilde{H}\right)\left(\overleftarrow{D_\mu} \overrightarrow{D^\mu}\right)\left(\widetilde{H}^\dagger \vec{\tau} H\right)$
		$-2\left(\lambda_3 + \lambda_5\right) \frac{\lvert \mu_\Delta \rvert^2}{\lvert M_\Delta \rvert^4}$	$\left(H^\dagger H\right)^3$

Model	Effective Lagrangian $\mathcal{L}_{eff} = c_i \mathcal{O}_i$		
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Fermionic Triplet	$Y_\Sigma^T \frac{1}{M_\Sigma} Y_\Sigma$	$Y_\Sigma^\dagger \frac{1}{\lvert M_\Sigma\rvert^2} Y_\Sigma$	$\left(\overline{L}\vec{\tau}\widetilde{H}\right) i\not{D} \left(\widetilde{H}^\dagger \vec{\tau} L\right)$
Scalar Triplet	$4Y_\Delta \frac{\mu_\Delta}{\lvert M_\Delta\rvert^2}$	$Y_\Delta^\dagger \frac{1}{2\lvert M_\Delta\rvert^2} Y_\Delta$	$\left(\overline{\widetilde{L}}\vec{\tau}L\right)\left(\overline{L}\vec{\tau}\widetilde{L}\right)$
		$\frac{\lvert\mu_\Delta\rvert^2}{\lvert M_\Delta\rvert^4}$	$\left(H^\dagger\vec{\tau}\widetilde{H}\right)\left(\overleftarrow{D}_\mu \overrightarrow{D^\mu}\right)\left(\widetilde{H}^\dagger\vec{\tau}H\right)$
		$-2\left(\lambda_3+\lambda_5\right)\frac{\lvert\mu_\Delta\rvert^2}{\lvert M_\Delta\rvert^4}$	$\left(H^\dagger H\right)^3$

$$\downarrow$$

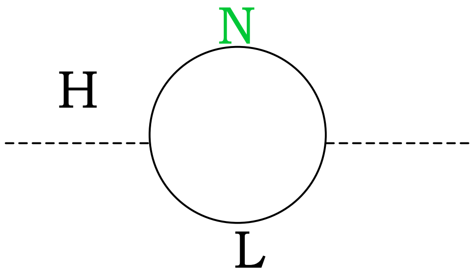
$$\frac{Y^+ Y}{M^2}$$

Model	Effective Lagrangian $\mathcal{L}_{eff} = c_i \mathcal{O}_i$		
	$c^{d=5}$	$c_i^{d=6}$	$\mathcal{O}_i^{d=6}$
Fermionic Singlet	$Y_N^T \frac{1}{M_N} Y_N$	$Y_N^\dagger \frac{1}{\lvert M_N \rvert^2} Y_N$	$\left(\overline{L}\widetilde{H}\right) i\partial\!\!\!/ \left(\widetilde{H}^\dagger L\right)$
Fermionic Triplet	$Y_\Sigma^T \frac{1}{M_\Sigma} Y_\Sigma$	$Y_\Sigma^\dagger \frac{1}{\lvert M_\Sigma \rvert^2} Y_\Sigma$	$\left(\overline{L}\vec{\tau}\widetilde{H}\right) iD\!\!\!\!/ \left(\widetilde{H}^\dagger \vec{\tau} L\right)$
Scalar Triplet	$4Y_\Delta \frac{\mu_\Delta}{\lvert M_\Delta \rvert^2}$	$Y_\Delta^\dagger \frac{1}{2\lvert M_\Delta \rvert^2} Y_\Delta$	$\left(\overline{\widetilde{L}}\vec{\tau}L\right)\left(\overline{L}\vec{\tau}\widetilde{L}\right)$
		$\frac{\lvert \mu_\Delta \rvert^2}{\lvert M_\Delta \rvert^4}$	$\left(H^\dagger \vec{\tau}\widetilde{H}\right)\left(\overleftarrow{D}_\mu \overrightarrow{D^\mu}\right)\left(\widetilde{H}^\dagger \vec{\tau} H\right)$
		$-2\left(\lambda_3 + \lambda_5\right)\frac{\lvert \mu_\Delta \rvert^2}{\lvert M_\Delta \rvert^4}$	$\left(H^\dagger H\right)^3$

$$\frac{Y^+ Y}{M^2}$$

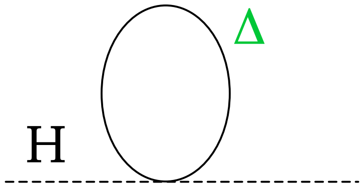
Can M *be close to EW scale, say ~ TeV?*

M~1 TeV is suggested by electroweak hierarchy problem

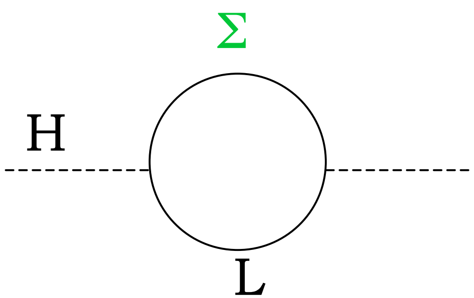


$$\delta m_H^2 = -\frac{Y_N^\dagger Y_N}{16\pi^2}\left[2\Lambda^2 + 2M_N^2 \log\frac{M_N^2}{\Lambda^2}\right]$$

(Vissani, Casas et al., Schmaltz)



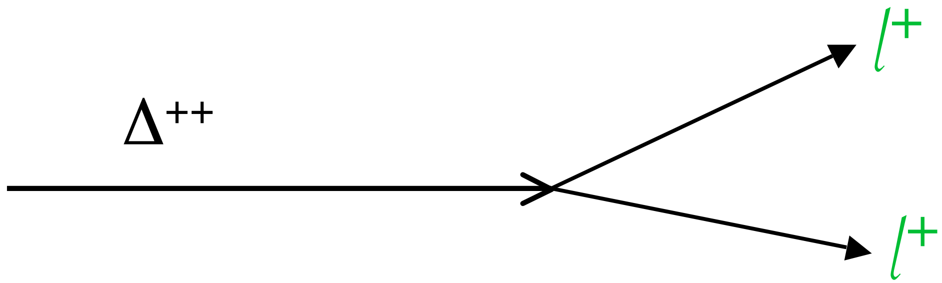
$$\delta m_H^2 = -3\frac{\lambda_3}{16\pi^2}\left[\Lambda^2 + M_\Delta^2\left(\log\frac{M_\Delta^2}{\Lambda^2} - 1\right)\right] - \frac{\mu_\Delta^2}{2\pi^2}\log\left(\left|\frac{M_\Delta^2 - \Lambda^2}{M_\Delta^2}\right|\right)$$



$$\delta m_H{}^2 = -3\frac{Y_\Sigma^\dagger Y_\Sigma}{16\pi^2}\left[2\Lambda^2 + 2M_\Sigma^2 \log\frac{M_\Sigma^2}{\Lambda^2}\right]$$

M~1 TeV actively searched for in colliders

i.e. Scalar Triplet $\Delta = (\Delta^{++}, \Delta^{+}, \Delta^{0})$



Same sign dileptons….~ no SM background

-> $m_\Delta > 136$ GeV by CDF

Atlas groups studying searches of Triplet Seesaws
(scalar and fermionic)

(Foot-Volkas……………….Bajc, Senjanovic))

Is it possible to have

M ~ 1 TeV

with large Yukawas (even O(1)) ?

It requires to decouple the coefficient $\mathbf{c}^{d=5}$ of $\mathbf{O}^{d=5}$

from $\mathbf{c}^{d=6}$ of $\mathbf{O}^{d=6}$

Notice that all d=6 *operators preserve* B-L,
in contrast to the d=5 *operator.*

This suggests that,
from the point of view of symmetries,
it may be natural to have large $\mathbf{c^{d=6}}$, *while*
having small $\mathbf{c^{d=5}}$.

Light Majorana m_ν *should vanish:*

- *inversely proportional to a Majorana scale*

  ($c^{d=5}$ ~ 1/M)

- *or directly proportional to it*

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Ansatz:

When the breaking of L is proportional to a small scale $\mu << M$, while M ~ O(TeV), $c^{d=5}$ is suppressed while $c^{d=6}$ is large:

$$c^{d=5} \sim \frac{\mu}{M^2} \qquad\qquad c^{d=6} \sim \frac{1}{M^2}$$

Light Majorana m_ν should vanish:

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Ansatz:

When the breaking of L is proportional to a small scale $\mu << M$, while $M \sim O(\text{TeV})$, $c^{d=5}$ is suppressed while $c^{d=6}$ is large:

$$c^{d=5} \sim f(Y)\frac{\mu}{M^2} \qquad\qquad c^{d=6} \sim \frac{Y^+ Y}{M^2}$$

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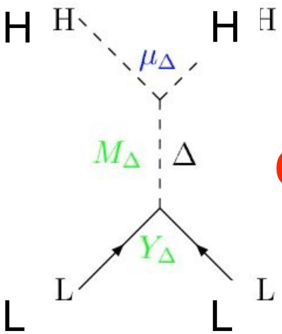
		$\frac{\vert\mu_\Delta\vert^2}{\vert M_\Delta\vert^4}$	$\left(H^\dagger \vec{\tau} \widetilde{H}\right)\left(\overleftarrow{D}_\mu \overrightarrow{D}^\mu\right)\left(\widetilde{H}^\dagger \vec{\tau} H\right)$
		$-2\left(\lambda_3 + \lambda_5\right) \frac{\vert\mu_\Delta\vert^2}{\vert M_\Delta\vert^4}$	$\left(H^\dagger H\right)^3$

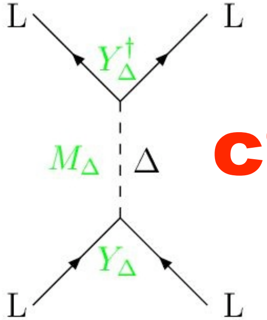
$$Y \frac{\mu}{M^2}$$

$$\frac{Y^+ Y}{M^2}$$

* The minimal scalar triplet model obeys that ansatz:



$$c^{d=5} \sim Y \frac{\mu}{M^2}$$



$$c^{d=6} \sim \frac{Y^+ Y}{M^2}$$

In fact, any Scalar mediated Seesaw will give

$$1/(D^2-M^2) \sim -1/M^2 - D^2/M^4 + \ldots\ldots$$

$$\Rightarrow \quad m_\nu \sim v^2 c^{d=5} \sim 1/M^2$$

What about fermionic-mediated Seesaws?

* Singlet fermion seesaws with M~1 TeV also obey it !!! :

i.e. **INVERSE SEESAW**

INVERSE SEESAW texture

* Toy: 1 light ν

$$
\begin{array}{c|ccc}
 & \nu_L & N_1 & N_2 \\
\hline
\nu_L & 0 & Y_N \frac{v}{\sqrt{2}} & 0 \\
N_1 & Y_N \frac{v}{\sqrt{2}} & 0 & M_N \\
N_2 & 0 & M_N & \mu
\end{array}
$$

$$
m_\nu \xrightarrow{\quad} (vY_N \ll M_N) \xrightarrow{\quad} \frac{v^2}{2} Y_N^2 \frac{\mu}{M_N^2}
$$

Mohapatra, Valle, Glez- Garcia

INVERSE SEESAW texture

* Toy: 1 light ν

$$
\begin{array}{c|ccc}
 & \nu_L & N_1 & N_2 \\
\hline
\nu_L & 0 & Y_N \frac{v}{\sqrt{2}} & 0 \\
N_1 & Y_N \frac{v}{\sqrt{2}} & M'_N & M_N \\
N_2 & 0 & M_N & \mu
\end{array}
$$

$$
m_\nu \xrightarrow{(vY_N \ll M_N)} \frac{v^2}{2} Y_N^2 \frac{\mu}{M_N^2}
$$

INVERSE SEESAW texture

* Toy: 1 light ν

$$\begin{array}{c|ccc} & \nu_L & N_1 & N_2 \\ \nu_L & 0 & Y_N \frac{v}{\sqrt{2}} & 0 \\ N_1 & Y_N \frac{v}{\sqrt{2}} & 0 & M_N \\ N_2 & 0 & M_N & \mu \end{array}$$

$$m_\nu \xrightarrow{} (vY_N \ll M_N) \longrightarrow \frac{v^2}{2} Y_N^2 \frac{\mu}{M_N^2}$$

* 3 generation Inverse Seesaw: $\nu_e, \nu_\mu, \nu_\tau, N_1, N_2, N_3$

Abada et al., Kersten+Smirnov

Experimental information on

$$c^{d=6} \sim \frac{Y^{+}Y}{M^{2}}$$

from:

--- 4 fermion operators (Scalar triplet seesaw)
M_W, W decays...

--- Unitarity corrections (Fermionic seesaws)

Scalar triplet seesaw

Bounds on $c^{d=6}$

Process	Constraint on	Bound $(\times (\frac{M_\Delta}{1\,\text{TeV}})^2)$
M_W	$\lvert Y_{\Delta_{\mu e}}\rvert^2$	$< 7.3 \times 10^{-2}$
$\mu^- \to e^+ e^- e^-$	$\lvert Y_{\Delta_{\mu e}}\rvert \lvert Y_{\Delta_{ee}}\rvert$	$< 1.2 \times 10^{-5}$
$\tau^- \to e^+ e^- e^-$	$\lvert Y_{\Delta_{\tau e}}\rvert \lvert Y_{\Delta_{ee}}\rvert$	$< 1.3 \times 10^{-2}$
$\tau^- \to \mu^+ \mu^- \mu^-$	$\lvert Y_{\Delta_{\tau\mu}}\rvert \lvert Y_{\Delta_{\mu\mu}}\rvert$	$< 1.2 \times 10^{-2}$
$\tau^- \to \mu^+ e^- e^-$	$\lvert Y_{\Delta_{\tau\mu}}\rvert \lvert Y_{\Delta_{ee}}\rvert$	$< 9.3 \times 10^{-3}$
$\tau^- \to e^+ \mu^- \mu^-$	$\lvert Y_{\Delta_{\tau e}}\rvert \lvert Y_{\Delta_{\mu\mu}}\rvert$	$< 1.0 \times 10^{-2}$
$\tau^- \to \mu^+ \mu^- e^-$	$\lvert Y_{\Delta_{\tau\mu}}\rvert \lvert Y_{\Delta_{\mu e}}\rvert$	$< 1.8 \times 10^{-2}$
$\tau^- \to e^+ e^- \mu^-$	$\lvert Y_{\Delta_{\tau e}}\rvert \lvert Y_{\Delta_{\mu e}}\rvert$	$< 1.7 \times 10^{-2}$
$\mu \to e\gamma$	$\lvert \Sigma_{l=e,\mu,\tau} Y_{\Delta}{}^{\dagger}_{l\mu} Y_{\Delta_{el}}\rvert$	$< 4.7 \times 10^{-3}$
$\tau \to e\gamma$	$\lvert \Sigma_{l=e,\mu,\tau} Y_{\Delta}{}^{\dagger}_{l\tau} Y_{\Delta_{el}}\rvert$	< 1.05
$\tau \to \mu\gamma$	$\lvert \Sigma_{l=e,\mu,\tau} Y_{\Delta}{}^{\dagger}_{l\tau} Y_{\Delta_{\mu l}}\rvert$	$< 8.4 \times 10^{-1}$

Scalar triplet seesaw

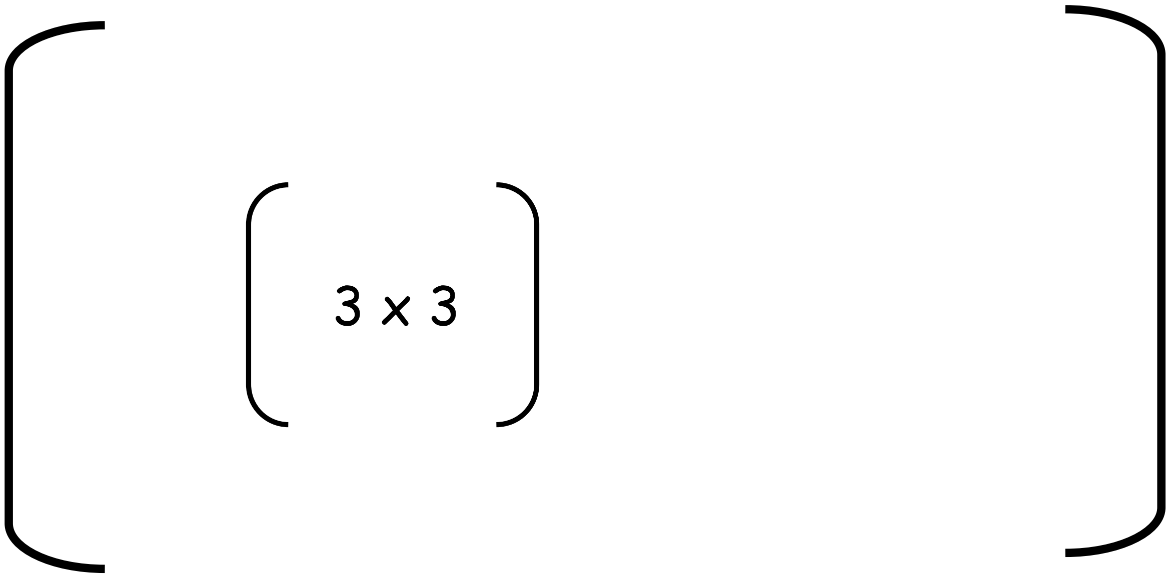
Combined bounds on $c^{d=6}$

Combined bounds		
Process	Yukawa	Bound $\left(\times \left(\frac{M_\Delta}{1\,\mathrm{TeV}}\right)^4\right)$
$\mu \to e\gamma$	$\left|{Y_\Delta}^\dagger_{\mu\mu} {Y_\Delta}_{\mu e} + {Y_\Delta}^\dagger_{\tau\mu} {Y_\Delta}_{\tau e}\right|$	$< 4.7 \times 10^{-3}$
$\tau \to e\gamma$	$\left|{Y_\Delta}^\dagger_{\tau\tau} {Y_\Delta}_{\tau e}\right|$	< 1.05
$\tau \to \mu\gamma$	$\left|{Y_\Delta}^\dagger_{\tau\tau} {Y_\Delta}_{\tau\mu}\right|$	$< 8.4 \times 10^{-1}$

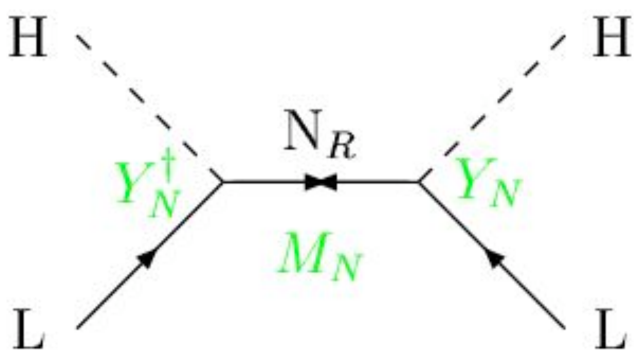
Fermionic seesaws ---> Non unitarity

The complete theory of ν masses is unitary.

i.e, a neutrino mass matrix larger than 3x3



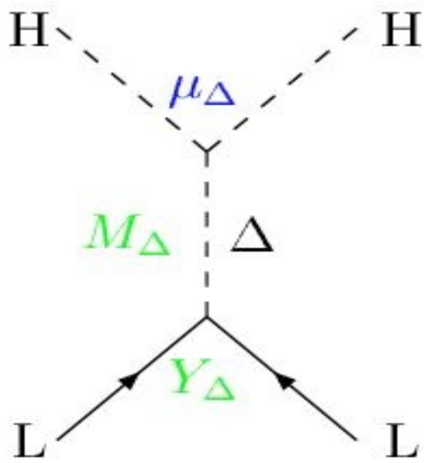
- Unitarity violations arise in models for ν masses with heavy fermions



Fermion singlet N_R (Type I See-Saw)

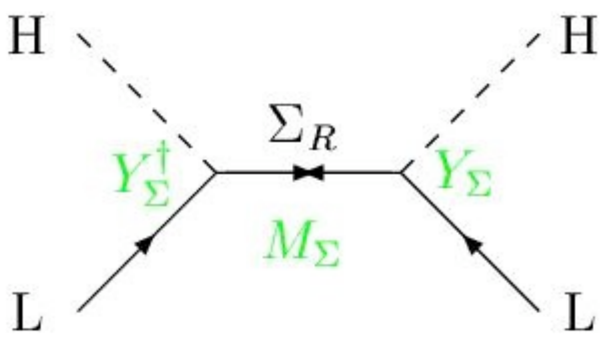
→ YES deviations from unitarity

Broncano, Gavela, Jenkins 02



Scalar triplet Δ

→ NO deviations from unitarity



Fermion triplet Σ_R

→ YES deviations from unitarity

A general statement…

We have unitarity violation whenever we integrate out heavy fermions:

$$\frac{1}{i\not{D} - M} = -\frac{1}{M} - \frac{i\not{D}}{M^2} + \ldots$$

It connects fermions with opposite chirality → mass term

There's a γ^μ: it connects fermions with the same chirality → correction to the kinetic terms

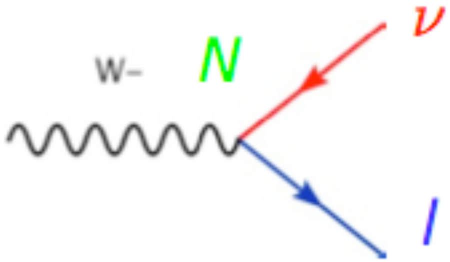
Fermionic seesaws:

I $\quad Y_N Y_N / M^2 \, (\bar{L}\, H)\ \not{\partial} (H\ L)$

II $\quad Y_\Sigma Y_\Sigma / M^2 \, (\bar{L}\, \tau\, H)\ \not{D} (H\, \tau\, L)$

A flavour dependent rescaling is needed, which is NOT a unitary transformation

U_{PMNS} --------> N (non-unitary)



$$N \propto \left(1 + \frac{Y^\dagger Y}{M^2} v^2 + \mathcal{O}\left(\frac{1}{M^4}\right)\right) U_{PMNS}$$

$$(|NN^\dagger| - 1)_{\alpha\beta} = \frac{v^2}{2} |c^{d=6}|_{\alpha\beta} = \frac{v^2}{2} |Y^\dagger \frac{1}{|M|^2} Y|_{\alpha\beta}$$

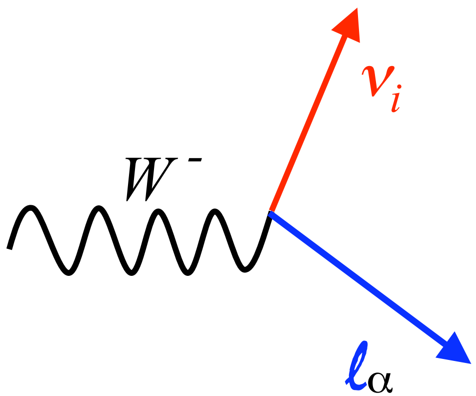
In all fermionic Seesaws, the departures from unitarity give directly $|c^{d=6}|$

→ *Worthwhile to analyze neutrino data relaxing the hypothesis of unitarity of the mixing matrix*

Antusch, Biggio, Fernández-Martínez, López-Pavón, M.B.G. 06

The general idea………

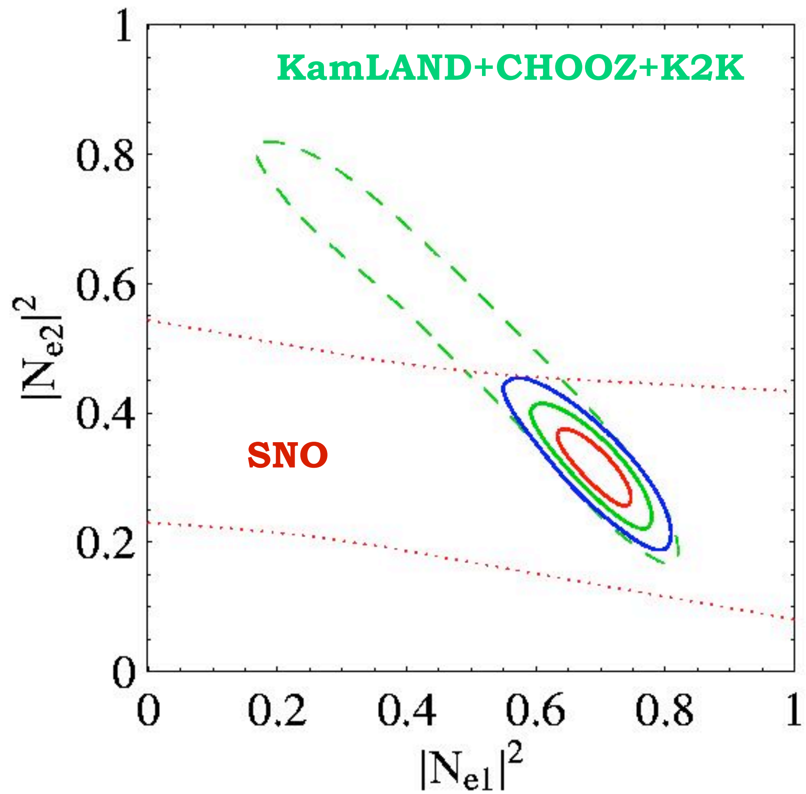
$$U=\begin{pmatrix} c_{13}c_{12} & s_{12}c_{13} & s_{13}e^{i\delta} \\ -s_{12}c_{23}-s_{23}s_{13}c_{12}e^{-i\delta} & c_{12}c_{23}-s_{23}s_{13}s_{12}e^{-i\delta} & s_{23}c_{13} \\ s_{23}s_{12}-c_{23}s_{13}c_{12}e^{-i\delta} & -s_{23}c_{12}-c_{23}s_{13}s_{12}e^{-i\delta} & c_{23}c_{13} \end{pmatrix} \begin{pmatrix} e^{i\alpha} & & \\ & e^{i\beta} & \\ & & 1 \end{pmatrix}$$

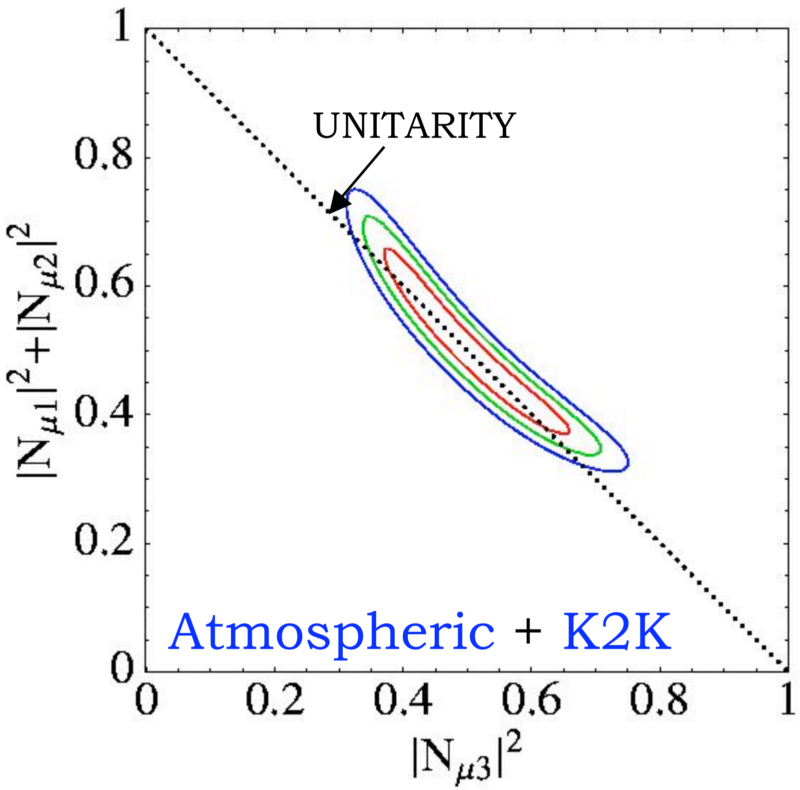


$$\approx N_{\alpha i}$$

$$N=\begin{pmatrix} N_{e1} & N_{e2} & N_{e3} \\ N_{\mu 1} & N_{\mu 2} & N_{\mu 3} \\ N_{\tau 1} & N_{\tau 2} & N_{\tau 3} \end{pmatrix}$$

This affects ν oscillation probabilities …





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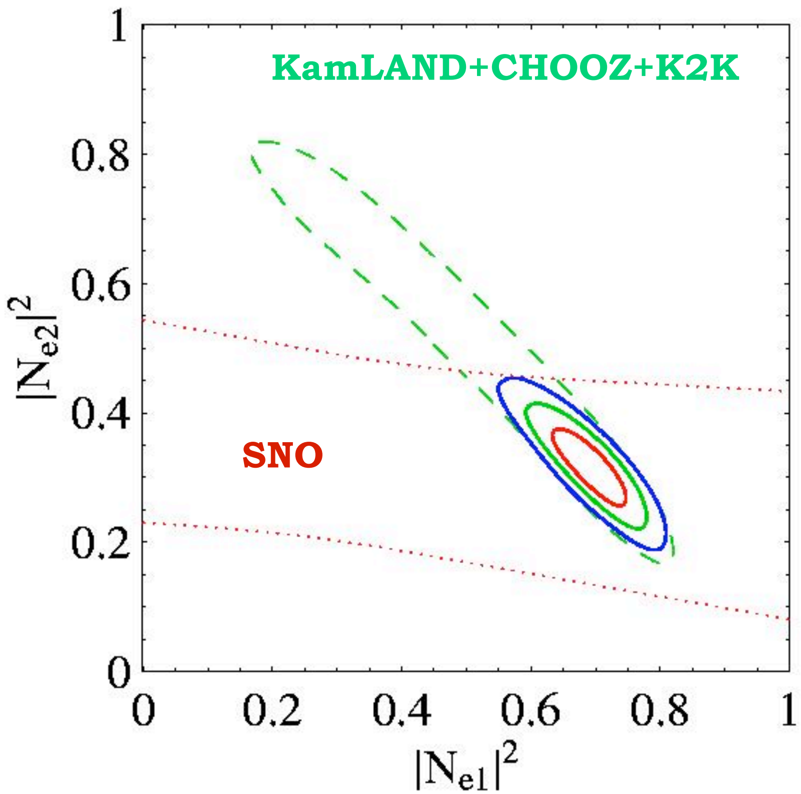

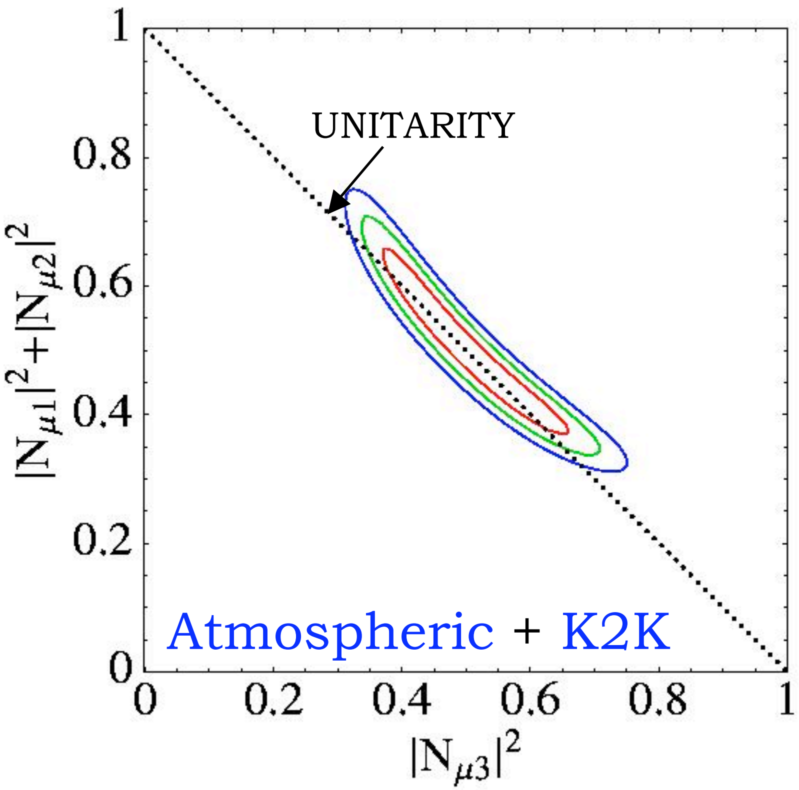

.... τ raw of N remains unconstrained

Unitarity constraints on (NN^+) from:

* Near detectors...

- MINOS, NOMAD, BUGEY, KARMEN

* Weak decays...

* W decays

* Invisible Z width

* Universality tests

* Rare lepton decays

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➡ $|N|$ is unitary at the % level

All in all, as of today,

for the Singlet-fermion Seesaws:

$$(NN^{+}-1)_{\alpha\beta}= \frac{v^2}{2}\,|c^{d=6}|_{\alpha\beta} = \frac{v^2}{2}\,|Y_N^{\dagger}\frac{1}{|M_N|^2}Y_N|_{\alpha\beta} \lesssim \begin{pmatrix} 10^{-2} & 7.2\cdot10^{-5} & 1.6\cdot10^{-2} \\ 7.2\cdot10^{-5} & 10^{-2} & 1.1\cdot10^{-2} \\ 1.6\cdot10^{-2} & 1.1\cdot10^{-2} & 10^{-2} \end{pmatrix}$$

➡ New CP-violation signals
even in the two-family approximation

E. Fdez-Martinez, J.Lopez, O. Yasuda, M.B.G.

i.e. $P\,(\nu_\mu \dashrightarrow \nu_\tau) \neq P\,(\overline{\nu_\mu} \dashrightarrow \overline{\nu_\tau})$

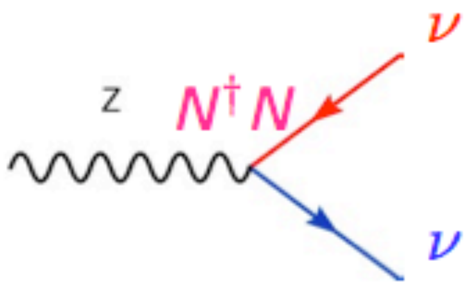
➡ Increased sensitivity to the moduli |N|
in future Neutrino Factories

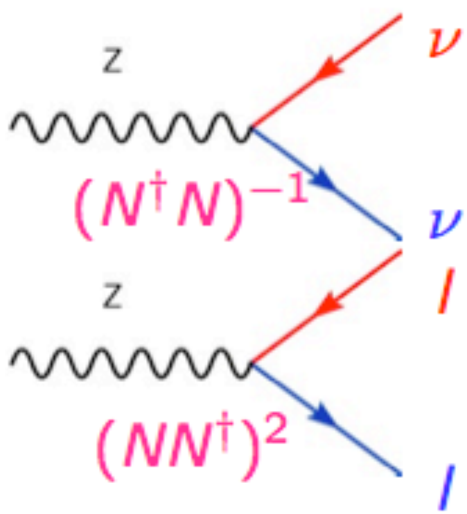
Fermion-triplet seesaws:

similar - although richer! - analysis

Singlet and triplet Seesaws differ in the the pattern of the Z *couplings*

Singlet	Triplet
$J_\mu^{-\,CC} \equiv \overline{l_L}\,\gamma_\mu\, N\, \nu$	$J_\mu^{-\,CC} \equiv \overline{l_L}\,\gamma_\mu\, N\, \nu$
$J_\mu^{NC} \equiv \frac{1}{2}\overline{\nu}\,\gamma_\mu (N^\dagger\, N)\, \nu$	$J_\mu^{Z}(\text{neutrinos}) \equiv \frac{1}{2}\overline{\nu}\,\gamma_\mu (N^\dagger\, N)^{-1}\, \nu$
	$J_\mu^{3}(\text{leptons}) \equiv \frac{1}{2}\overline{l}\,\gamma_\mu (N N^\dagger)^2\, l$





Bounds on Yukawas type III

$\mu \to eee$
$\tau \to eee$
$\tau \to \mu ee$
$\tau \to \mu\mu e$
$\tau \to \mu\mu\mu$

$Z \to \mu e$
$Z \to \tau e$
$Z \to \tau\mu$

@ tree level
in Type III
(not in Type I)

+
W decays
Invisible Z width
Universality tests

$\mu \to e\gamma$
$\tau \to e\gamma$
$\tau \to \mu\gamma$

For $M \approx TeV \to |Y| < 10^{-2}$

Production @ colliders

Ma, Roy 02
Bajc, Nemevsek, Senjanovic 07

➡ For the Triplet-fermion Seesaws (type III):

$$(NN^{+}-1)_{\alpha\beta} = \frac{v^2}{2}|c^{d=6}|_{\alpha\beta} = \frac{v^2}{2}|Y_\Sigma^\dagger \frac{1}{M_\Sigma^\dagger}\frac{1}{M_\Sigma} Y_\Sigma|_{\alpha\beta} \lesssim \begin{pmatrix} 3\cdot 10^{-3} & < 1.1\cdot 10^{-6} & < 1.2\cdot 10^{-3} \\ < 1.1\cdot 10^{-6} & 4\cdot 10^{-3} & < 1.2\cdot 10^{-3} \\ < 1.2\cdot 10^{-3} & < 1.2\cdot 10^{-3} & 4\cdot 10^{-3} \end{pmatrix}$$

In summary, for all scalar and fermionic Seesaw models, present bounds:

$$\frac{v^2}{2}|c^{d=6}|_{\alpha\beta} = \frac{v^2}{2}|Y^\dagger \frac{1}{M^2} Y|_{\alpha\beta} \lesssim 10^{-2}$$

$$\Rightarrow \boxed{|Y| \lesssim 10^{-1} \frac{M}{1TeV}}$$

or stronger

Conclusions (exp.)

* MiniBoone shows, for the first time, that only 3 νs is OK

………. Is the low-energy excess hiding physics?

* Minos update of atmospheric data

…….walking towards θ_{13}

….. and % precision era

Conclusions (th)

* d= 6 operators discriminate among models of Majorana νs.
    - we have determined them for the 3 families of Seesaw models.

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•d=6 operator crucial: if observed at low energies, only resonant leptogenesis is possible

* $c^{d=6} \sim Y^{+}Y/M^2$ bounded from 4-Ψ interactions + unitarity deviations

$\nu_\mu - \nu_\tau$ CP-asymmetry may be a clean probe of the new phases of seesaw scenarios.

-> Keep tracking these deviations in the future.
They are excellent signals of new physics.

Back-up slides

Low-energy effective theory

After EWSB, in the flavour basis:

$$L = \frac{1}{2}\left(i\overline{\nu}_\alpha \partial\!\!\!/ K_{\alpha\beta}\nu_\beta - \overline{\nu}^c_\alpha M_{\alpha\beta}\nu_\beta + h.c.\right) +$$

$$- \frac{g}{\sqrt{2}}\left(W^+_\mu \overline{l}_\alpha \gamma^\mu P_L \nu_\alpha + h.c.\right)$$

$M_{\alpha\beta}$ → diagonalized → unitary transformation

$K_{\alpha\beta}$ → diagonalized and normalized → unitary transf. + rescaling

In the mass basis:

$$L = \frac{1}{2}\left(i\overline{\nu}_i \partial\!\!\!/ \nu_i - \overline{\nu}^c{}_i m_{ii}\nu_i\right)$$

N non-unitary

A general statement…

We have unitarity violation whenever we integrate out heavy fermions:

$$\frac{1}{i\vec{\not{D}} - M} = -\frac{1}{M} - \frac{i\vec{\not{D}}}{M^2} + \ldots$$

It connects fermions with opposite chirality → mass term

There's a γ^μ: it connects fermions with the same chirality → correction to the kinetic terms

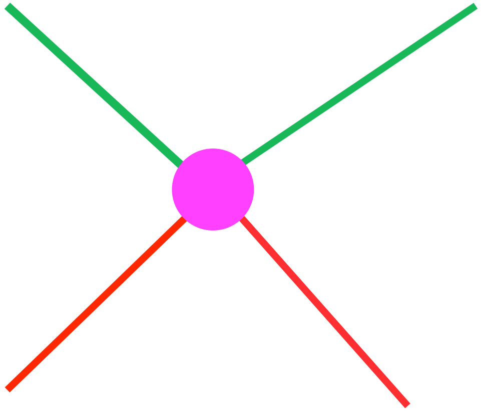
The propagator of a scalar field does not contain γ^μ →
if it generates neutrino mass, it cannot correct the kinetic term

$$1/(D^2-M^2) \sim -1/M^2 - D^2/M^4 + \ldots\ldots$$

Our analysis will also apply to ``non-standard" or ``exotic" neutrino interactions.

Grossman, Gonzalez-Garcia et al., Huber et al., Kitazawa et al., Davidson et al. Blennow et al...)

They add 4-fermion exotic operators to production
or detection
or propagation in matter



$$\bar{\Psi}\,\Psi\,\bar{\Psi}\,\Psi$$

3 generation Inverse Seesaw

$$\nu_e, \nu_\mu, \nu_\tau, N_1, N_2, N_3$$

$$\begin{pmatrix} 0 & 0 & 0 & c & 0 & 0 \\ 0 & 0 & 0 & d & 0 & 0 \\ 0 & 0 & 0 & e & 0 & 0 \\ c & d & e & f & g & a \\ 0 & 0 & 0 & g & b & 0 \\ 0 & 0 & 0 & a & 0 & 0 \end{pmatrix},$$

$$\begin{pmatrix} 0 & 0 & 0 & c & \varepsilon_1 & \varepsilon_2 \\ 0 & 0 & 0 & d & \varepsilon_3 & \varepsilon_4 \\ 0 & 0 & 0 & e & \varepsilon_5 & \varepsilon_6 \\ c & d & e & f & g & a \\ \varepsilon_1 & \varepsilon_3 & \varepsilon_5 & g & b & \varepsilon_7 \\ \varepsilon_2 & \varepsilon_4 & \varepsilon_6 & a & \varepsilon_7 & \varepsilon_8 \end{pmatrix}$$

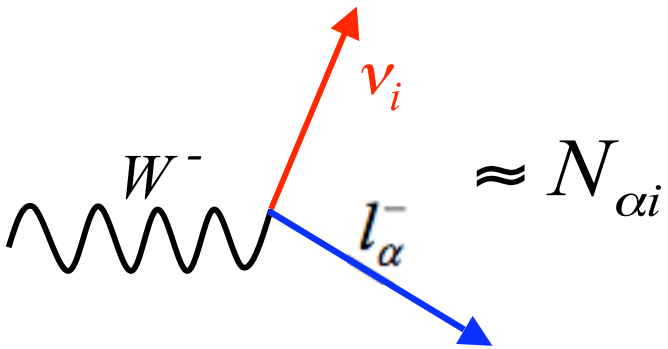
Abada et al.
Kersten+Smirnov

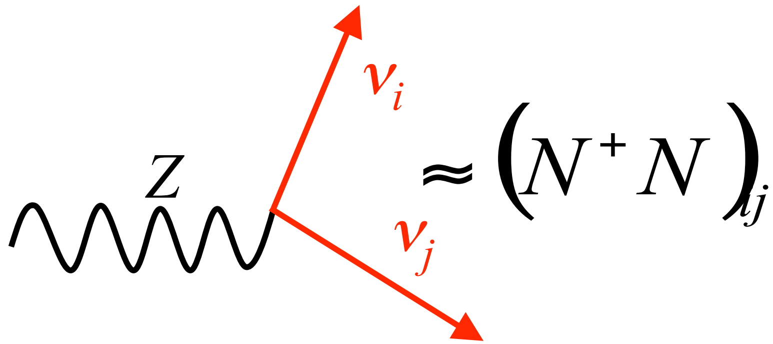
and also similar extensions of the fermionic triplet Seesaw

M(inimal) U(nitarity) V(iolation) :

$$L = i\bar{\nu}_i \not{\partial} \nu_i + \bar{\nu}_i m_{ii} \nu_i - \frac{g}{\sqrt{2}}\left(W_\mu^+ \bar{l}_\alpha \gamma^\mu P_L N_{\alpha i} \nu_i + h.c.\right) - \frac{g}{\cos\theta_W}\left(Z_\mu \bar{\nu}_i \gamma^\mu P_L (N^+ N)_{ij} \nu_j + h.c.\right) + \ldots$$

with only 3 light ν





N elements from oscillations & decays

MUV

without unitarity
OSCILLATIONS
+DECAYS

$$|N| = \begin{pmatrix} .75 - .89 & .45 - .65 & < .20 \\ .19 - .55 & .42 - .74 & .57 - .82 \\ .13 - .56 & .36 - .75 & .54 - .82 \end{pmatrix}$$

Antusch, Biggio, Fernández-Martínez, López-Pavón, M.B.G. 06

3σ

with unitarity
OSCILLATIONS

$$|U| = \begin{pmatrix} .79 - .88 & .47 - .61 & < .20 \\ .19 - .52 & .42 - .73 & .58 - .82 \\ .20 - .53 & .44 - .74 & .56 - .81 \end{pmatrix}$$

M. C. Gonzalez Garcia hep-ph/0410030

Can we measure the phases of N ?

E. Fdez-Martinez, J.Lopez, O. Yasuda, M.B.G.

If we parametrize $N \approx (1 + \varepsilon)\, U_{PMNS}$ with $\varepsilon = -\frac{v^2}{4}\, c^{d=6}$

$$P_{\alpha\beta} \approx \left| 2\varepsilon_{\alpha\beta} - i \sin(2\theta) \sin\left(\frac{\Delta m^2 L}{4E}\right) \right|^2$$

If L/E small

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SM

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Zero dist. effect

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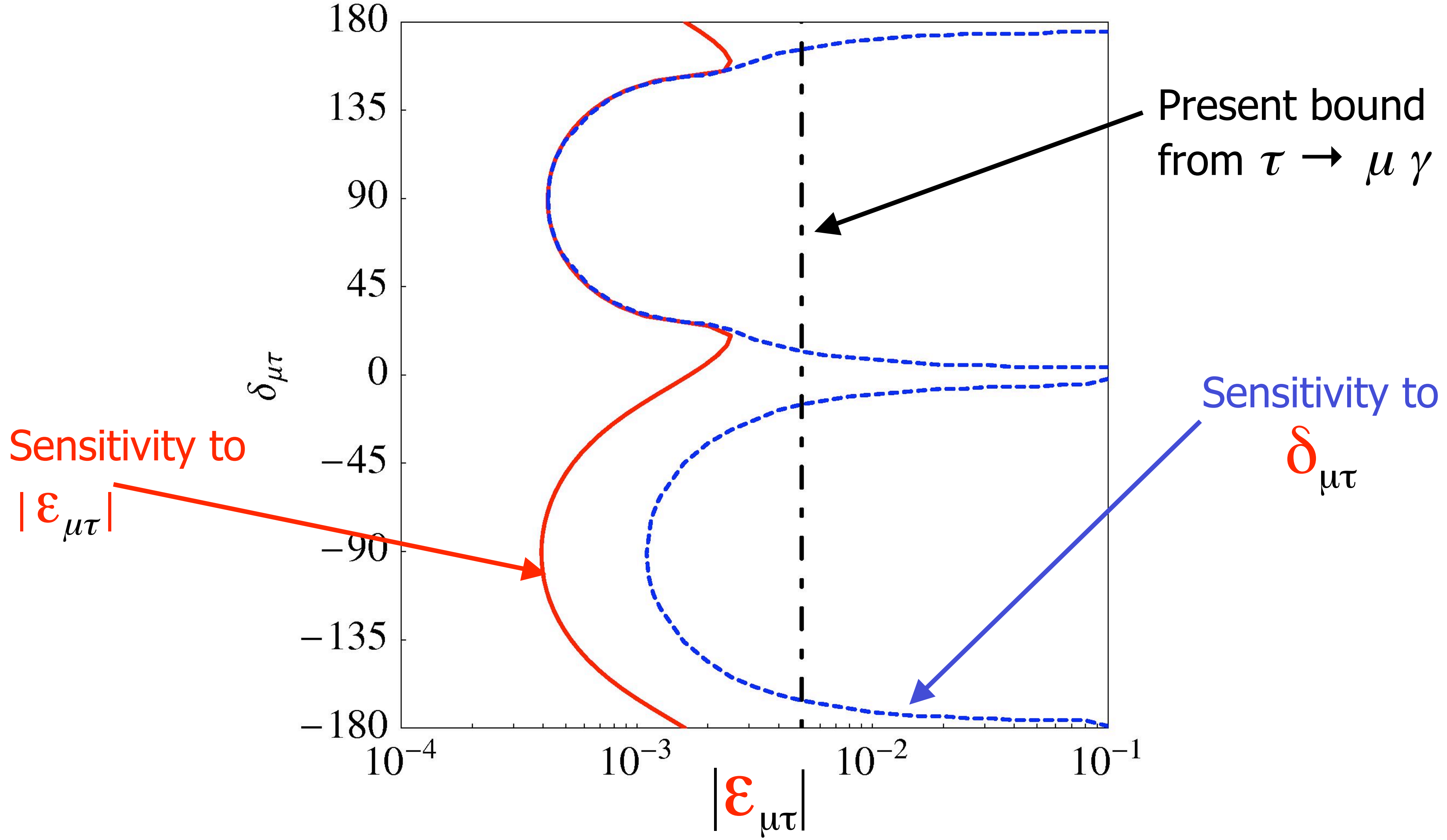
SM

CP violating interference

Zero dist. effect

Measuring non-unitary phases

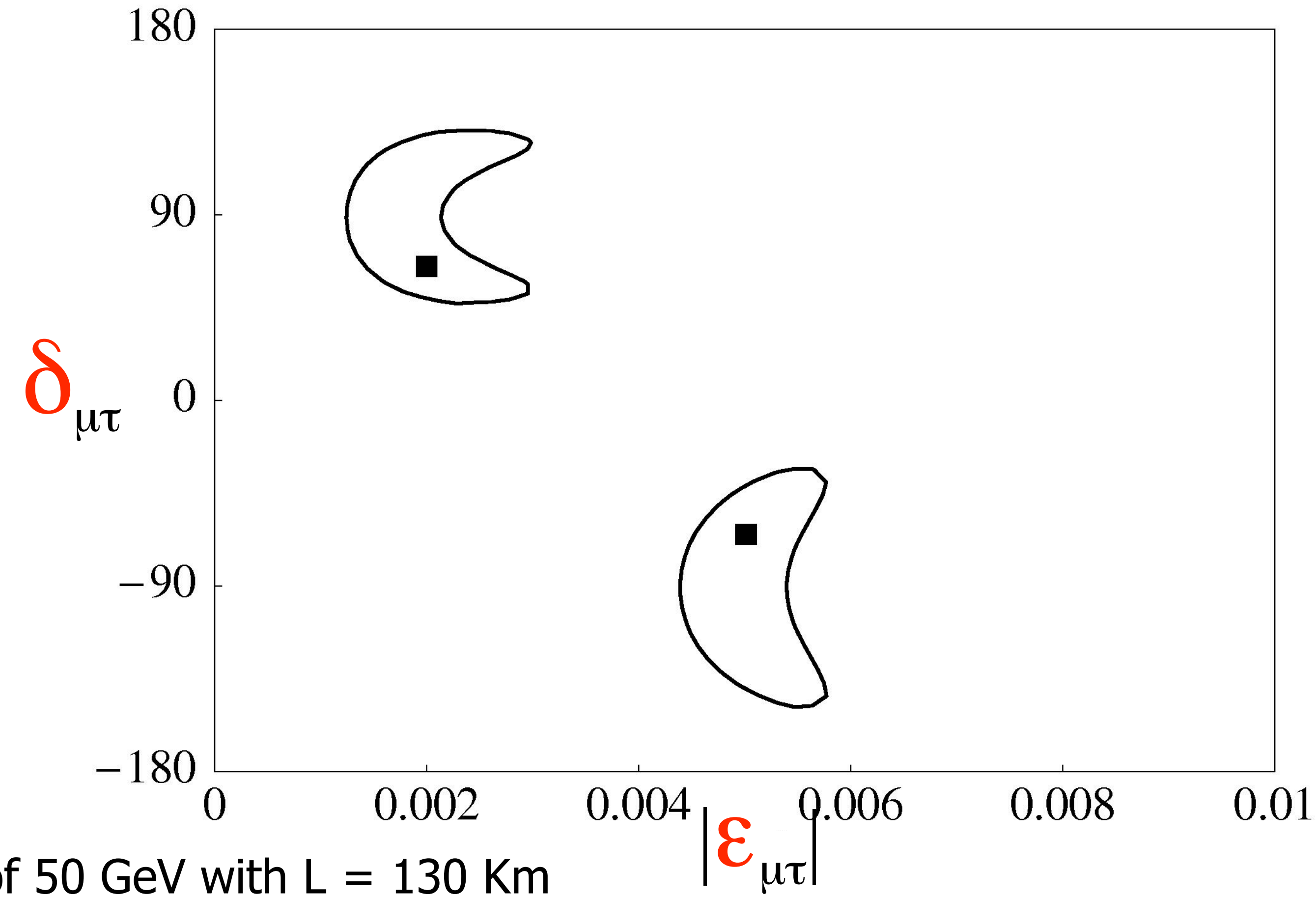


For non-trivial $\delta_{\mu\tau}$, one order of magnitude improvement for |N|

In $P_{\mu\tau}$ there is no $\sin\theta_{13}$ or Δ_{12} suppression:

$$P_{\mu\tau} - P_{\bar{\mu}\bar{\tau}} = -4\,\mathrm{Im}(\varepsilon_{\mu\tau})\sin(2\theta_{23})\sin\left(\frac{\Delta m_{23}^2 L}{2E}\right)$$

The CP phase $\delta_{\mu\tau}$ can be measured



At a Neutrino Factory of 50 GeV with L = 130 Km

➡ New CP-violation signals
even in the two-family approximation

i.e. $P(\nu_\mu \dashrightarrow \nu_\tau) \neq P(\overline{\nu_\mu} \dashrightarrow \overline{\nu_\tau})$

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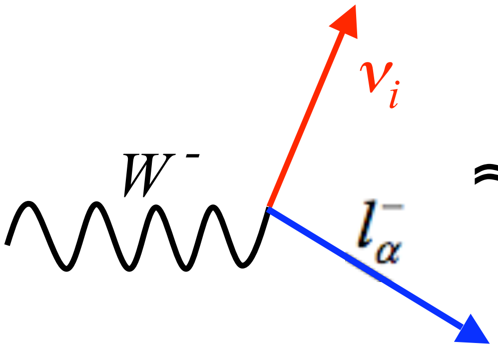
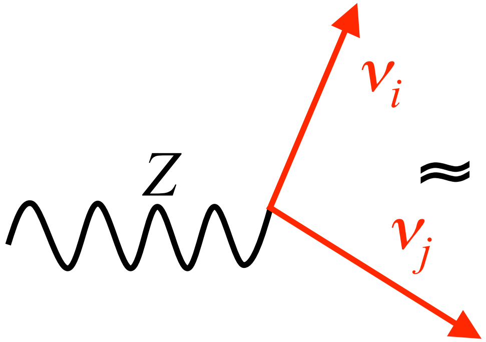
The effects of non-unitarity…

… appear in the interactions



$$\approx N_{\alpha i}$$



$$\approx \left(N^{+} N\right)_{ij}$$

$$\langle \nu_\beta | \nu_\alpha \rangle \sim \left(\mathrm{NN}^{+}\right)_{\alpha\beta} \neq \delta_{\alpha\beta}$$

This affects weak decays…

$$\Gamma = \Gamma_{SM} \sum_i |N_{\alpha i}|^2 = \Gamma_{SM} \left(NN^{+}\right)_{\alpha\alpha} \qquad \Gamma = \Gamma_{SM} \sum_{ij} \left|\left(N^{+} N\right)_{ij}\right|^2$$

… and oscillation probabilities…

This affects weak decays...

$$\Gamma = \Gamma_{SM} \sum_i \left| N_{\alpha i} \right|^2 = \Gamma_{SM} \left(N N^+ \right)_{\alpha\alpha}$$

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$$\Gamma = \Gamma_{SM} \sum_{ij} \left|(N^+ N)_{ij}\right|^2$$

... and oscillation probabilities...

$$P_{\alpha\beta}(E,L) = \frac{\left|\sum_i N^*_{\alpha i} e^{iP_i L} N_{\beta i}\right|^2}{(NN^\dagger)_{\alpha\alpha} (NN^\dagger)_{\beta\beta}}$$

Zero-distance effect at near detectors:

$$P(\nu_\alpha \to \nu_\beta; 0) \propto \left|\sum_i N^*_{\alpha i} N_{\beta i}\right|^2 \neq \delta_{\alpha\beta}$$

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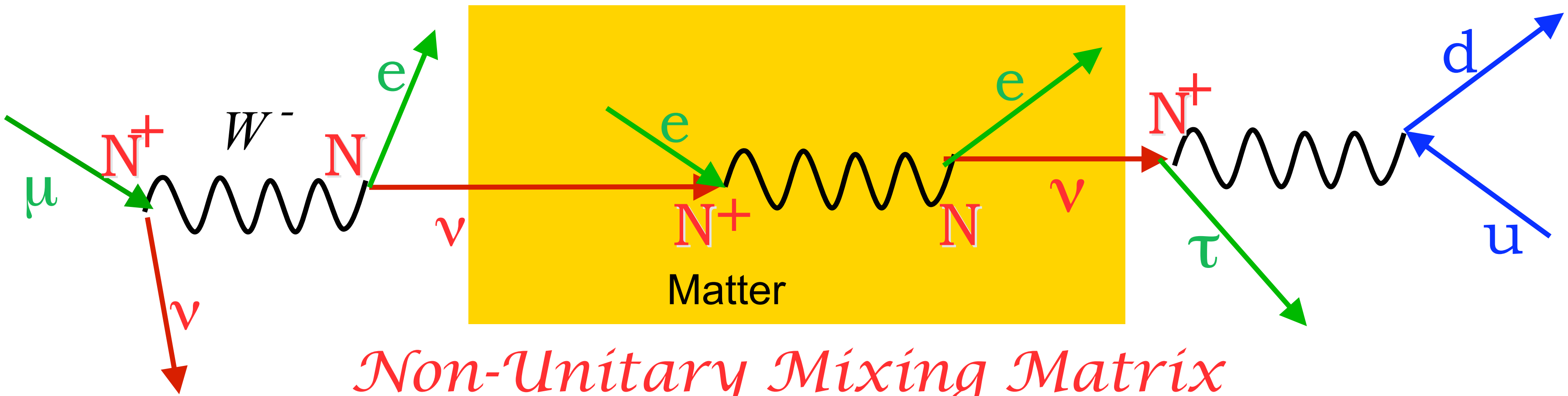
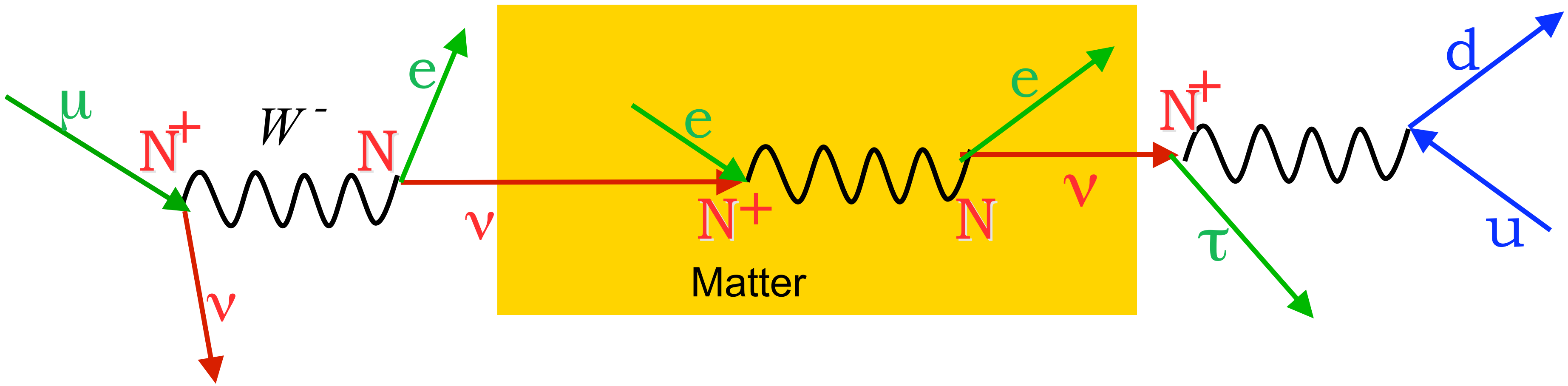


Non-Unitary Mixing Matrix

$$P_{\alpha\beta}(E,L)=\frac{\left|\sum_i N^*_{\alpha i} e^{iP_iL} N_{\beta i}\right|^2}{(NN^\dagger)_{\alpha\alpha}(NN^\dagger)_{\beta\beta}}$$

Zero-distance effect at near detectors:

$$P(\nu_\alpha\to\nu_\beta;0)\propto\left|\sum_i N^*_{\alpha i}N_{\beta i}\right|^2\neq\delta_{\alpha\beta}$$



In matter

$$i\frac{d}{dt}\begin{pmatrix}\nu_e\\ \nu_\mu\end{pmatrix}=\left[N^*\begin{pmatrix}E_1 & 0\\ 0 & E_2\end{pmatrix}(N^*)^{-1}+\begin{pmatrix}(V_{CC}-V_{NC})\sum_i|N_{ei}|^2 & -V_{NC}\sqrt{\frac{\sum_i|N_{\mu i}|^2}{\sum_i|N_{ei}|^2}}\sum_i N^*_{ei}N_{\mu i}\\ (V_{CC}-V_{NC})\sqrt{\frac{\sum_i|N_{ei}|^2}{\sum_i|N_{\mu i}|^2}}\sum_i N^*_{ei}N_{\mu i} & -V_{NC}\sum_i|N_{\mu i}|^2\end{pmatrix}\right]\begin{pmatrix}\nu_e\\ \nu_\mu\end{pmatrix}$$

Number of events

$$n_{ev} \sim \int dE \frac{d\Phi_\alpha(E)}{dE} P_{\alpha\beta}(E,L)\sigma_\beta(E)\varepsilon(E)$$

ν produced and detected in CC

$$\begin{cases} \dfrac{d\Phi_\alpha}{dE} \sim \dfrac{d\Phi_\alpha^{SM}}{dE}\left(NN^+\right)_{\alpha\alpha} \\ \sigma_\beta \sim \sigma_\beta^{SM}\left(NN^+\right)_{\beta\beta} \end{cases}$$

$$n_{ev} \sim \int dE \frac{d\Phi_\alpha^{SM}(E)}{dE} \underbrace{\left(NN^+\right)_{\alpha\alpha} P_{\alpha\beta}(E,L)\left(NN^+\right)_{\beta\beta}} \sigma_\beta^{SM}(E)\varepsilon(E)$$

$$\hat{P}_{\alpha\beta}(E,L) = \left|\sum_i N_{\alpha i}^* e^{iP_i L} N_{\beta i}\right|^2$$

Exceptions:

- measured flux
- leptonic production mechanism
- detection via NC

N elements from oscillations: μ-row

Atmospheric + K2K: $\Delta_{12} \approx 0$

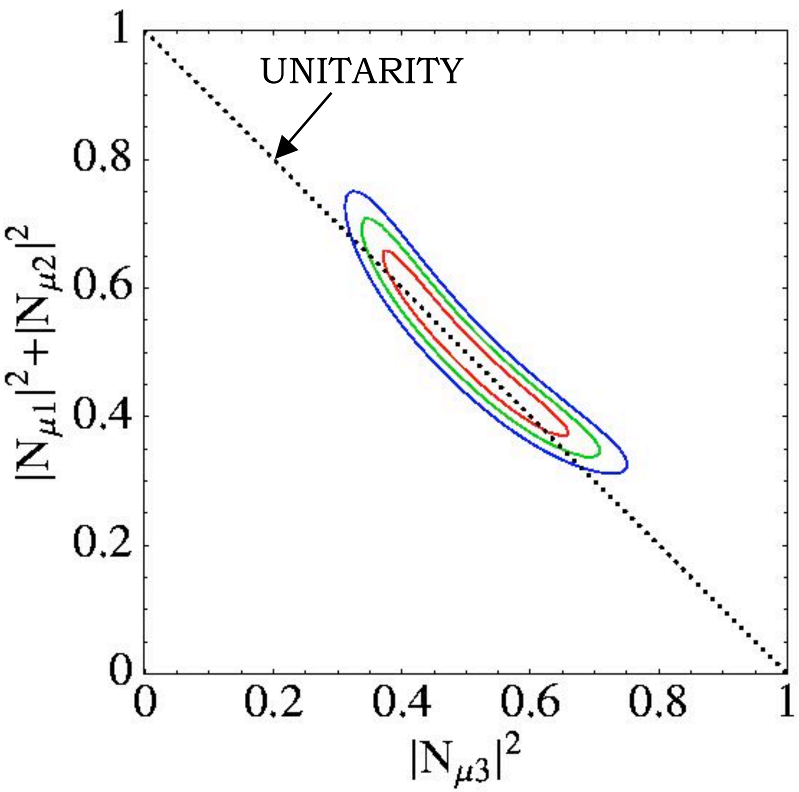
$$\hat{P}(\nu_\mu \to \nu_\mu) \cong \left(|N_{\mu 1}|^2 + |N_{\mu 2}|^2\right)^2 + |N_{\mu 3}|^4 + 2\left(|N_{\mu 1}|^2 + |N_{\mu 2}|^2\right)|N_{\mu 3}|^2 \cos(\Delta_{23})$$

1. Degeneracy

   $|N_{\mu 1}|^2 + |N_{\mu 2}|^2 \leftrightarrow |N_{\mu 3}|^2$

2. $|N_{\mu 1}|^2$, $|N_{\mu 2}|^2$

   cannot be disentangled



N elements from oscillations: e-row

CHOOZ $$P(\bar{\nu}_e \to \bar{\nu}_e) \cong \left(|N_{e1}|^2 + |N_{e2}|^2\right)^2 + |N_{e3}|^4 + 2\left(|N_{e1}|^2 + |N_{e2}|^2\right)|N_{e3}|^2 \cos(\Delta_{23})$$

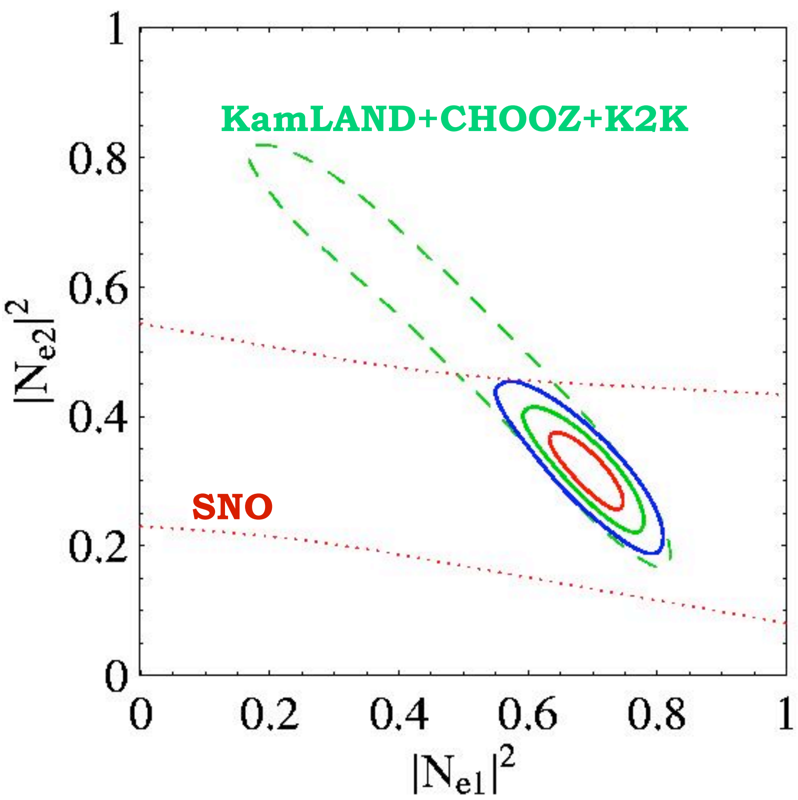
KamLAND: $$\hat{P}(\bar{\nu}_e \to \bar{\nu}_e) \cong |N_{e1}|^4 + |N_{e2}|^4 + |N_{e3}|^4 + 2|N_{e1}|^2|N_{e2}|^2 \cos(\Delta_{12})$$

$$\Delta_{ij} = \Delta m_{ij}^2 L / 2E$$

SNO:

$$\hat{P}(\nu_e \to \nu_e) \cong 0.1|N_{e1}|^2 + 0.9|N_{e2}|^2$$

→ all $|N_{ei}|^2$ determined



N elements from oscillations only

without unitarity
OSCILLATIONS
MUV

$$|N| = \begin{pmatrix} .75 - .89 & .45 - .66 & < .34 \\ [(|N_{\mu 1}|^2+|N_{\mu 2}|^2)^{1/2} = 0.57\text{-}0.86] & & .57 - .86 \\ ? & ? & ? \end{pmatrix}$$

3σ

with unitarity
OSCILLATIONS

$$|U| = \begin{pmatrix} .79 - .89 & .47 - .61 & < .20 \\ .19 - .52 & .42 - .73 & .58 - .82 \\ .20 - .53 & .44 - .74 & .56 - .81 \end{pmatrix}$$

M. C. Gonzalez Garcia hep-ph/0410030

Unitarity constraints on (NN^{+}) from:

* Near detectors…

- MINOS: $(NN^{\dagger})_{\mu\mu} = 1 \pm 0.05$
- BUGEY: $(NN^{\dagger})_{ee} = 1 \pm 0.04$
- NOMAD: $(NN^{\dagger})_{\mu\tau} < 0.09$ $(NN^{\dagger})_{e\tau} < 0.013$
- KARMEN: $(NN^{\dagger})_{\mu e} < 0.05$

* Weak decays…

- W decays $\rightarrow \dfrac{(NN^{+})_{\alpha\alpha}}{\sqrt{(NN^{+})_{ee}}\sqrt{(NN^{+})_{\mu\mu}}}$
- Universality tests $\rightarrow \dfrac{(NN^{+})_{\alpha\alpha}}{(NN^{+})_{\beta\beta}}$
- Invisible Z $\rightarrow \dfrac{\sum_{ij}(N^{+}N)_{ij}}{\sqrt{(NN^{+})_{ee}}\sqrt{(NN^{+})_{\mu\mu}}}$
- Rare leptons decays $\rightarrow \dfrac{\left|(NN^{+})_{\beta\alpha}\right|^{2}}{(NN^{+})_{\alpha\alpha}(NN^{+})_{\beta\beta}}$

$$|NN^\dagger| \approx \begin{pmatrix} 0.994 \pm 0.005 & < 7.2 \cdot 10^{-5} & < 1.6 \cdot 10^{-2} \\ < 7.2 \cdot 10^{-5} & 0.995 \pm 0.005 & < 1.1 \cdot 10^{-2} \\ < 1.6 \cdot 10^{-2} & < 1.1 \cdot 10^{-2} & 0.995 \pm 0.005 \end{pmatrix}$$

At 90% CL

→ |N| is unitary at the % level

In the future…

TESTS OF UNITARITY (90%CL)

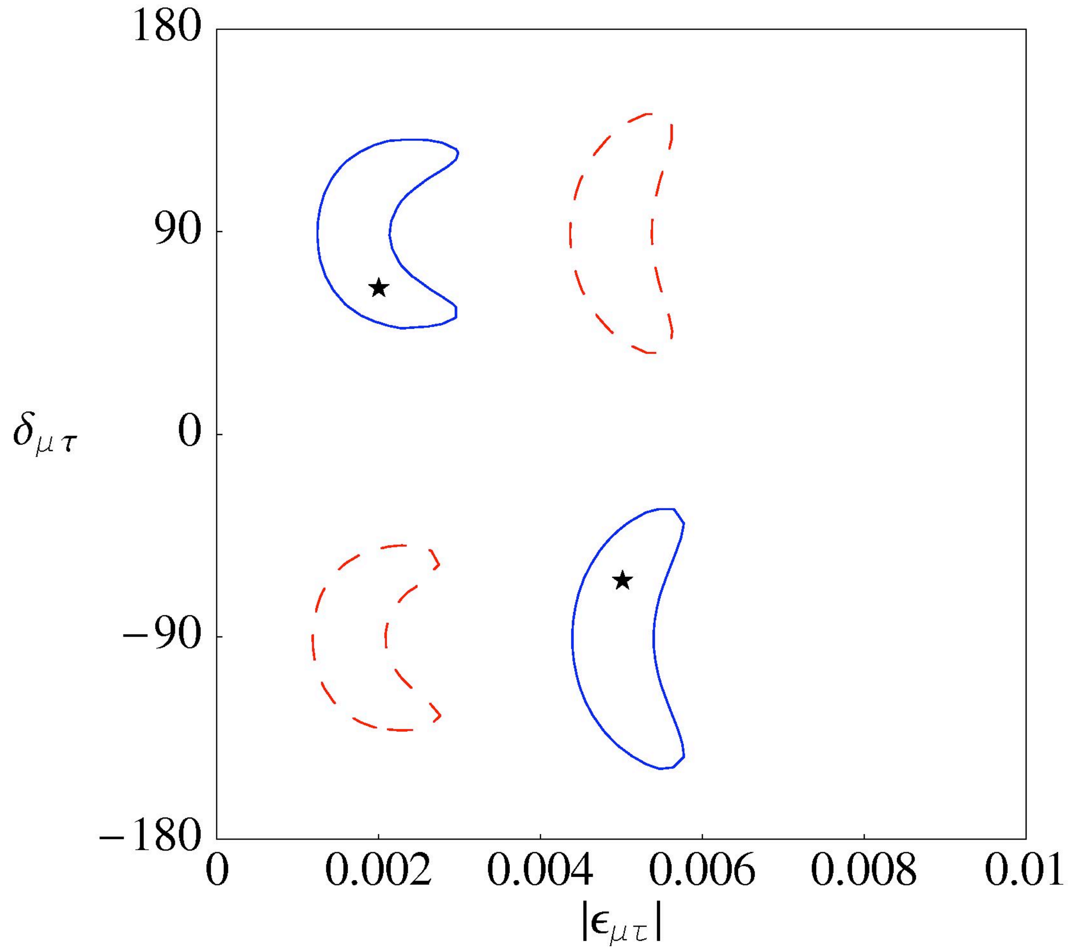
Rare leptons decays (present)

- $\mu \to e\gamma$ $\quad |\sum_i N_{ei} N^*_{\mu i}|^2 < 7.2 \cdot 10^{-5}$
- $\tau \to e\gamma$ $\quad |\sum_i N_{ei} N^*_{\tau i}|^2 < 0.016$
- $\tau \to \mu\gamma$ $\quad |\sum_i N_{\mu i} N^*_{\tau i}|^2 < 0.013$

ZERO-DISTANCE EFFECT
Near detector at a ν factory

- $\nu_e \to \nu_\mu$ $\quad |\sum_i N_{ei} N^*_{\mu i}|^2 < 2.3 \cdot 10^{-4}$
- $\nu_e \to \nu_\tau$ $\quad |\sum_i N_{ei} N^*_{\tau i}|^2 < 2.9 \cdot 10^{-3}$
- $\nu_\mu \to \nu_\tau$ $\quad |\sum_i N_{\mu i} N^*_{\tau i}|^2 < 2.6 \cdot 10^{-3}$

OPERA like



180
90
0
−90
−180
$\delta_{\mu\tau}$
0
0.002
0.004
0.006
0.008
0.01
$|\epsilon_{\mu\tau}|$

Measuring unitarity deviations

The bounds on

$$\left|NN^{\dagger}\right| = \left|(1+\varepsilon)^2\right| \approx \left|1+2\varepsilon\right|$$

Also apply to ε

$$|\varepsilon| \approx \begin{pmatrix} < 2.5\cdot10^{-3} & < 3.6\cdot10^{-5} & < 8.0\cdot10^{-3} \\ < 3.6\cdot10^{-5} & < 2.5\cdot10^{-3} & < 5.0\cdot10^{-3} \\ < 8.0\cdot10^{-3} & < 5.0\cdot10^{-3} & < 2.5\cdot10^{-3} \end{pmatrix}$$

The constraints on $\varepsilon_{e\mu}$ from $\mu \to e\,\gamma$ are very strong

We will study the sensitivity to the CP violating terms
$\varepsilon_{e\tau}$ and $\varepsilon_{\mu\tau}$ in $P_{e\tau}$ and $P_{\mu\tau}$

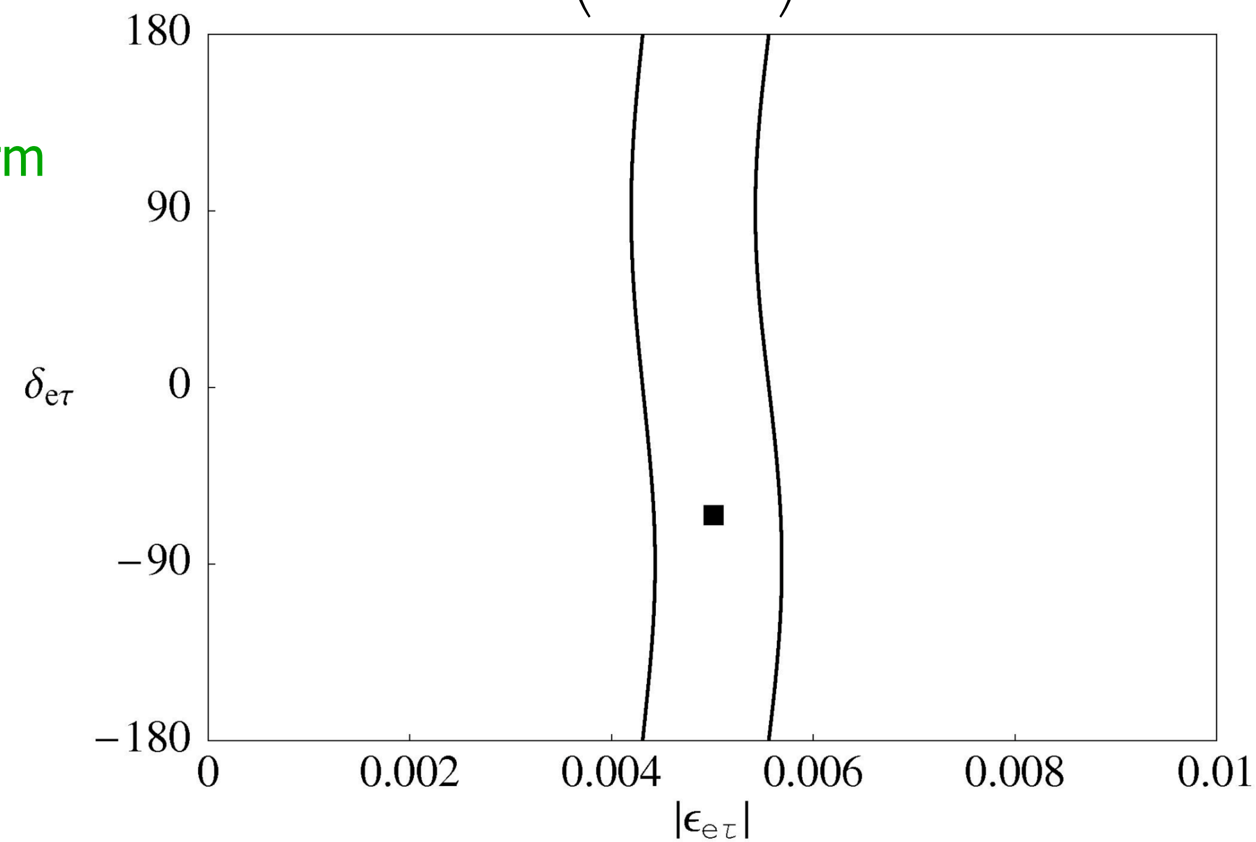
Measuring unitarity deviations

In $P_{e\tau}$ the CP violating term is supressed by

$\sin\theta_{13}$ or Δ_{12} appart from $|\varepsilon_{e\tau}|\sin\left(\frac{\Delta m^2_{23} L}{2E}\right)$

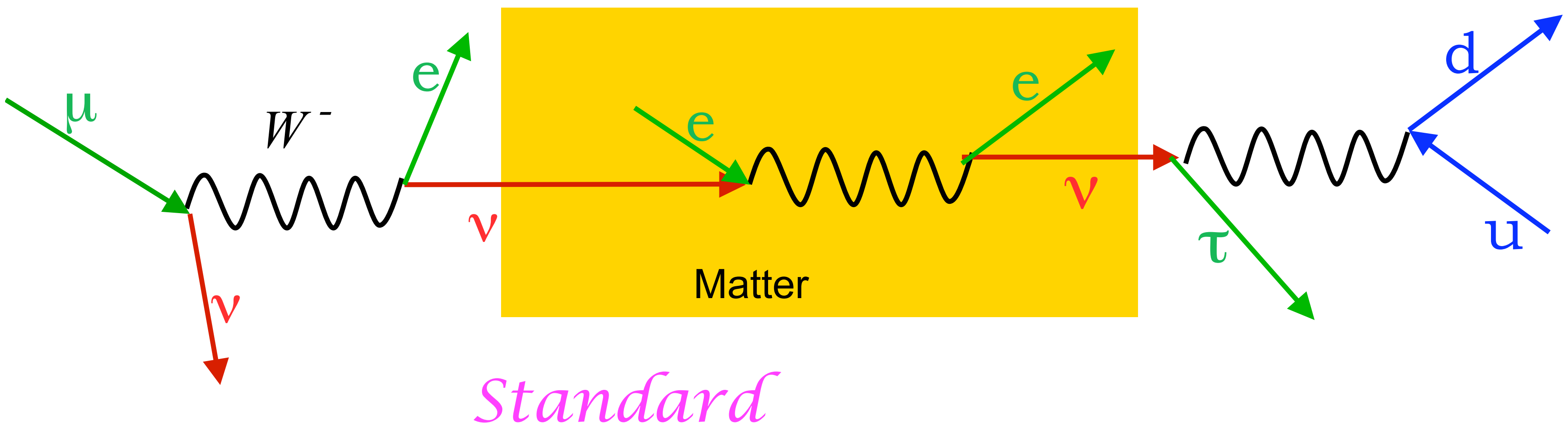
The zero distance term in $|\varepsilon_{e\tau}|^2$ dominates

No sensitivity to the CP phase $\delta_{e\tau}$



Our analysis will also apply to ``non-standard" or ``exotic" neutrino interactions.

Grossman, Gonzalez-Garcia et al., Huber et al., Kitazawa et al., Davidson et al. Blennow et al...)



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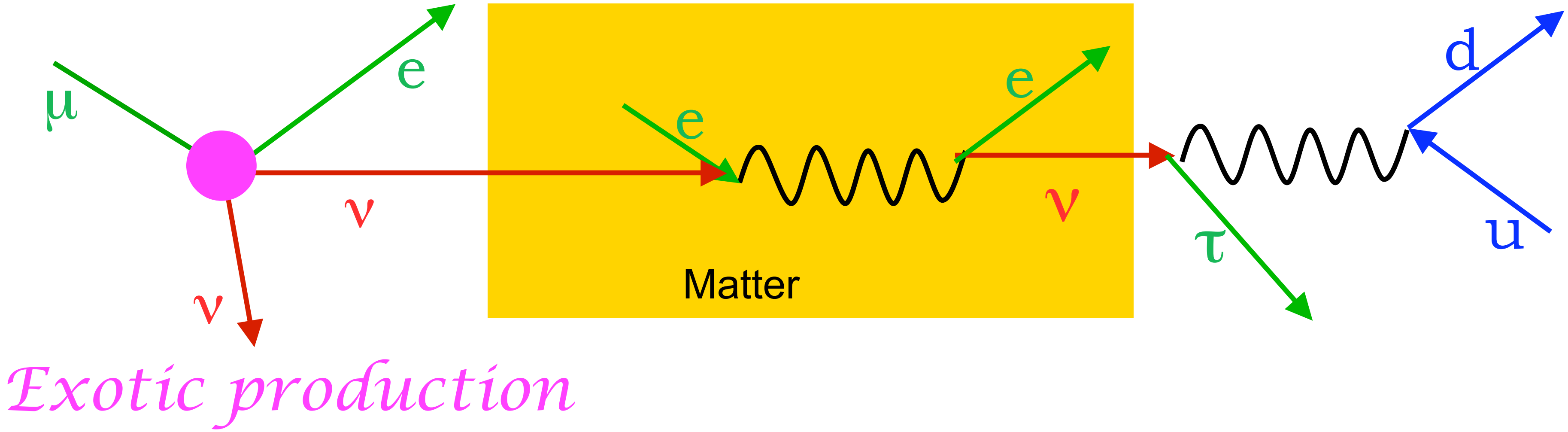

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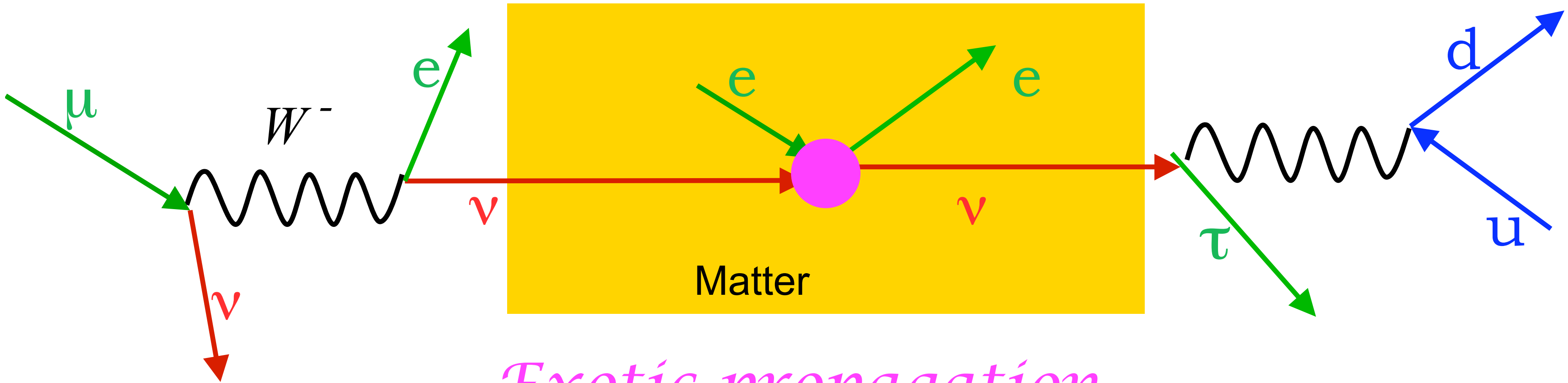

Exotic propagation

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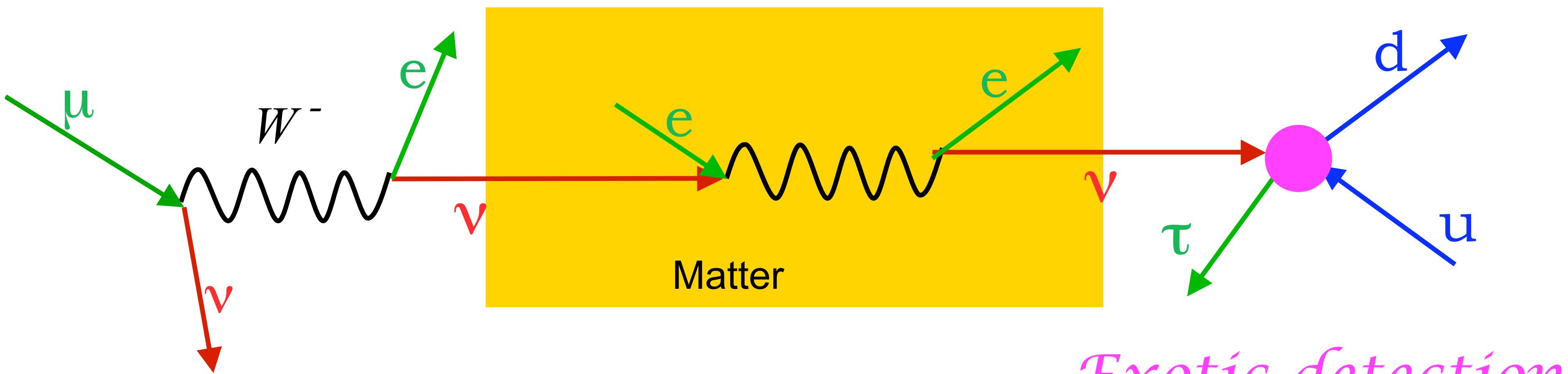

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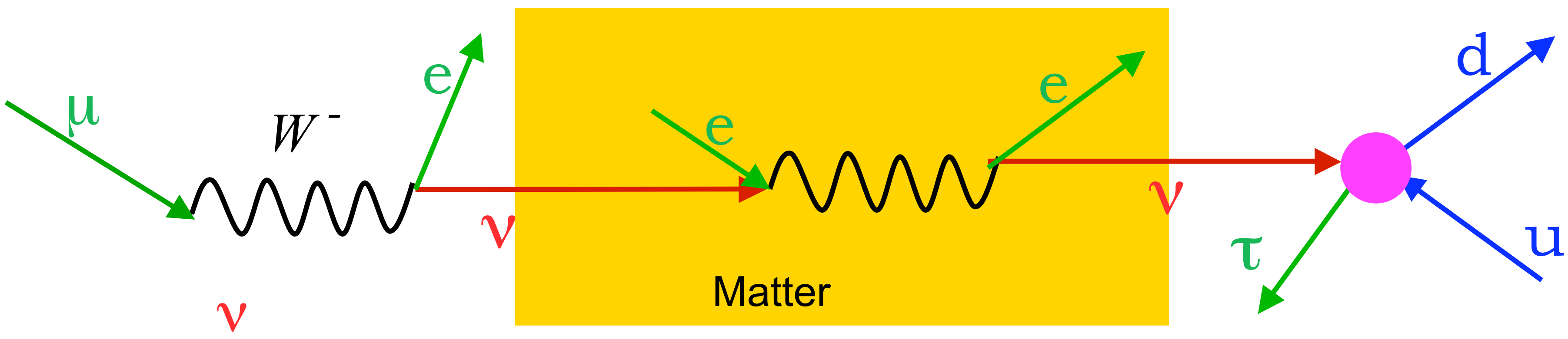

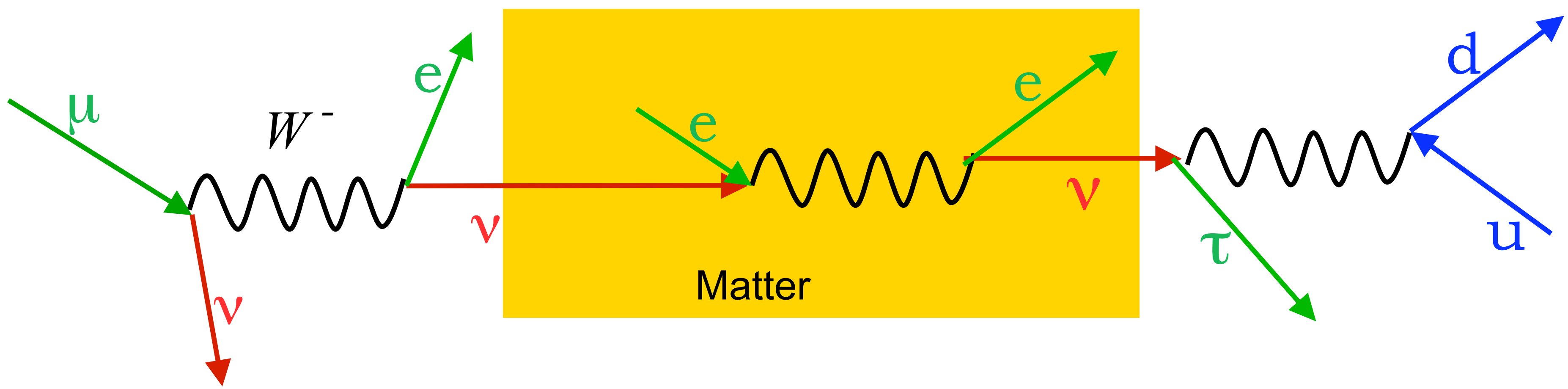

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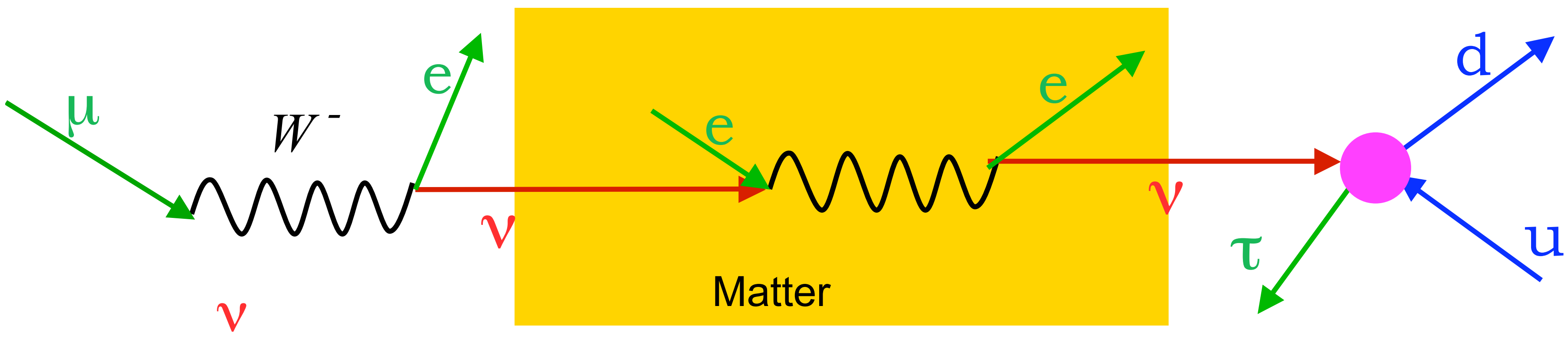

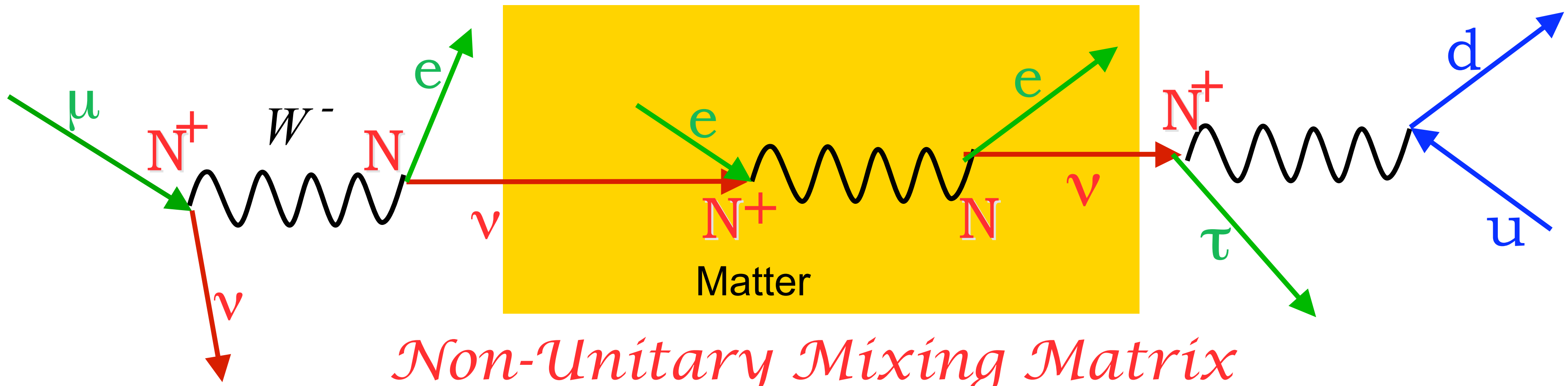

Non-Unitary Mixing Matrix

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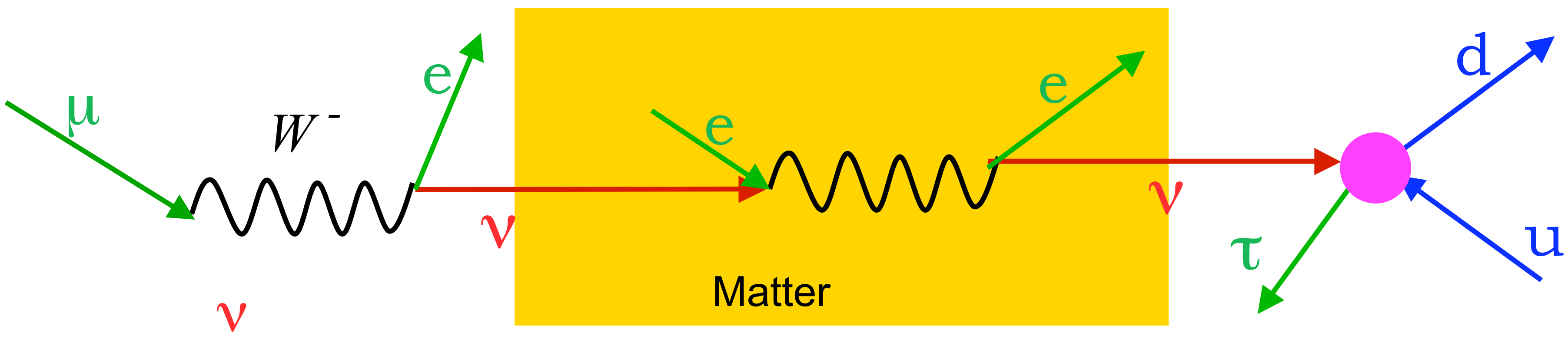
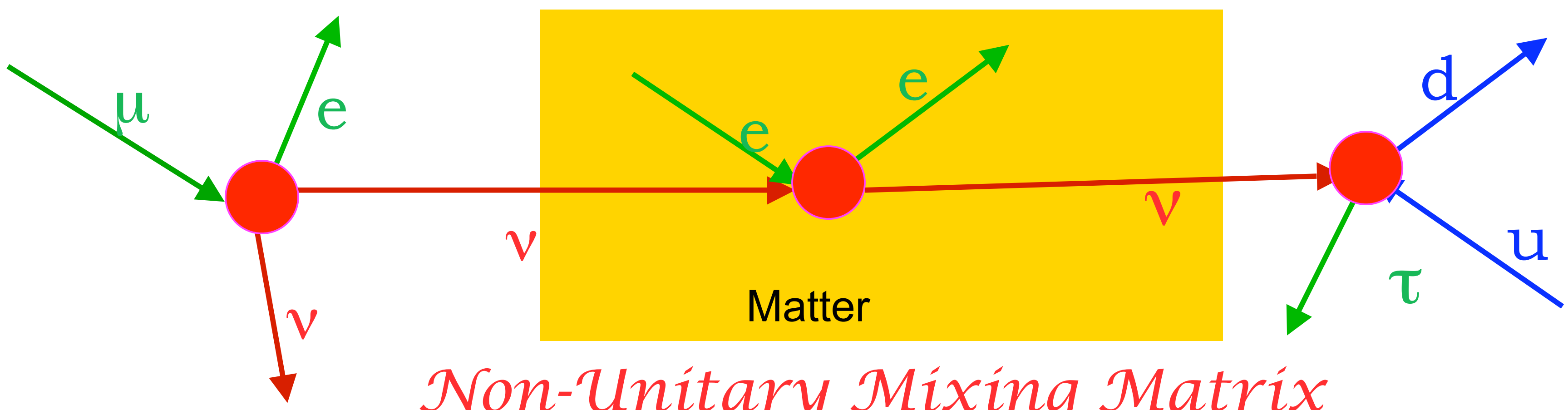


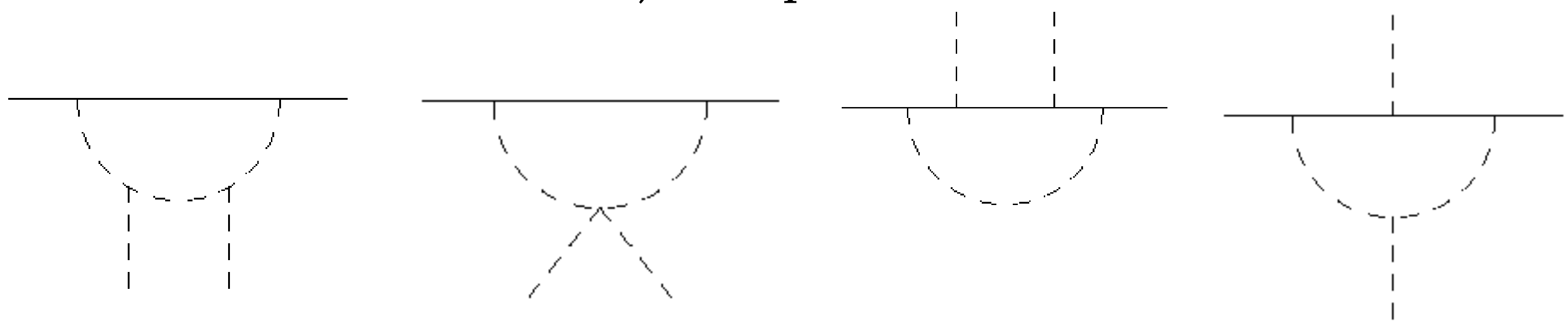


Non-Unitary Mixing Matrix

ν masses beyond the SM

★ Other realizations

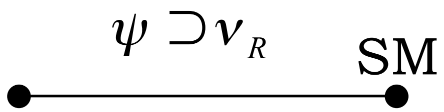
- radiative mechanisms: ex.) 1 loop:



Frigerio

- SUSY models with R-parity violation

- Models with large extra dimensions: i.e., ν_R are Kaluza-Klein replicas



Dirac mass suppressed by $(2\pi R)^{d/2}$

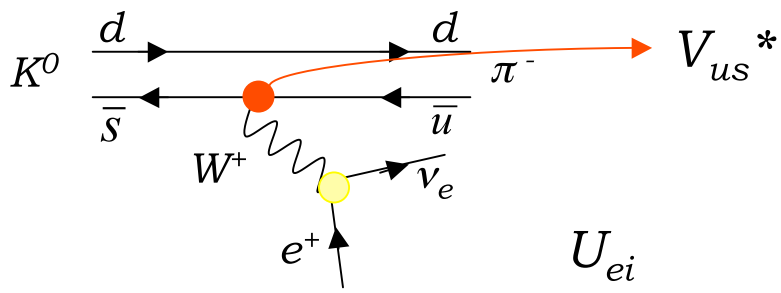
- …

Unitarity in the quark sector

Quarks are detected in the final state

→ we can directly measure $|V_{ab}|$

ex: $|V_{us}|$ from $K^0 \rightarrow \pi^- e^+ \nu_e$



→ $\sum_i |U_{ei}|^2 = 1$ if U unitary

With V_{ab} we check unitarity conditions:

ex: $|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 - 1 = -0.0008 \pm 0.0011$

→ *Measurements of V_{CKM} elements relies on U_{PMNS} unitarity*

With leptons:

- decays → only $(NN^\dagger)$ and $(N^\dagger N)$
- N elements → we need oscillations
- to study the unitarity of N: no assumptions on V_{CKM}