Low-energy non unitary leptonic mixing

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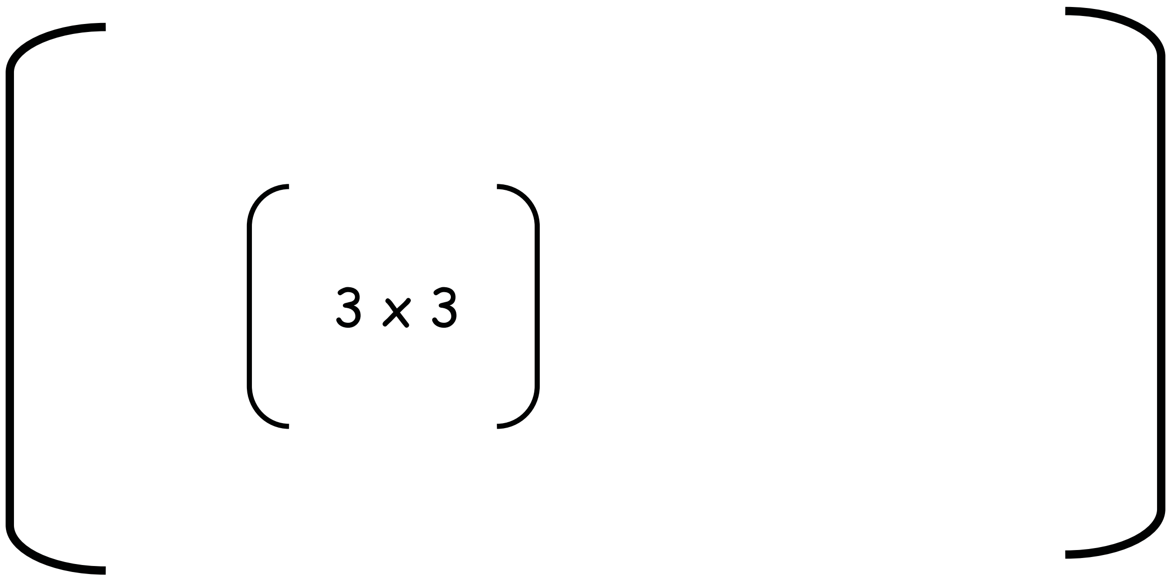
i.e, a neutrino mass matrix larger than 3x3



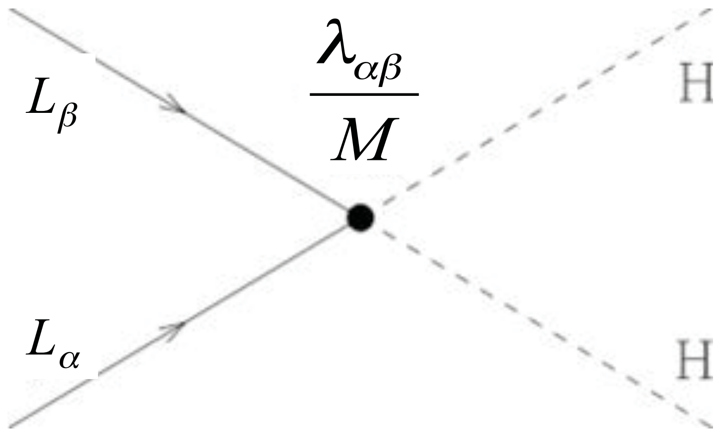
ν masses beyond the SM

Favorite options: BSM theory at higher scale M

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

Dimension 5 operator:

$$\lambda/M\ (L\ L\ H\ H) \rightarrow \lambda v^2/M\ (\nu\nu)$$

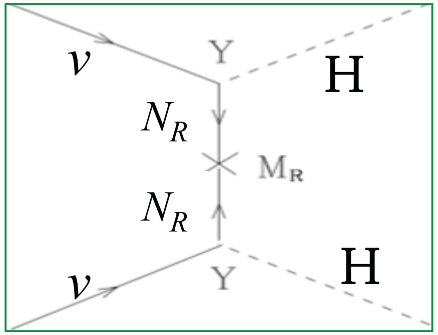


It's unique → very special role of ν masses: lowest-order effect of higher energy physics

This mass term violates lepton number
→ Majorana neutrinos

ν masses beyond the SM

★ Tree-level realizations



Heavy fermion singlet N_R

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

ν masses beyond the SM

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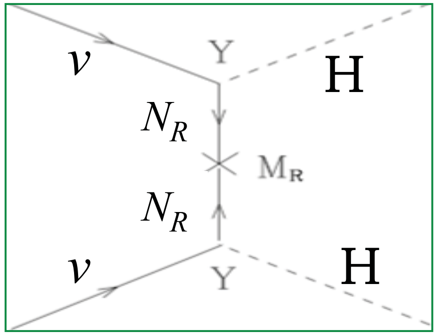

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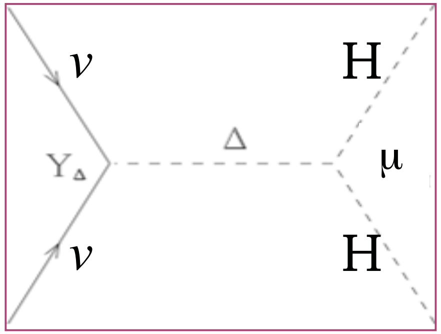

Heavy scalar triplet Δ

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

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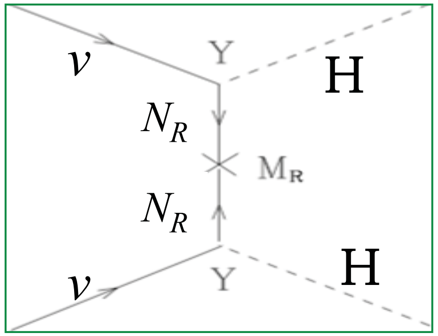

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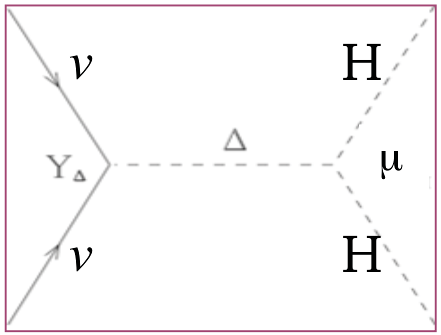

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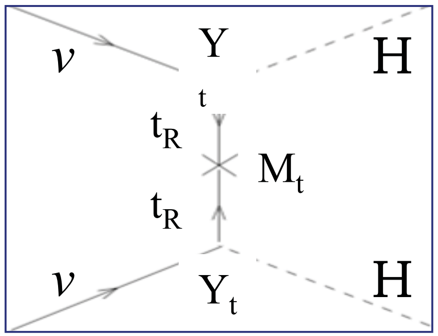

Heavy fermion triplet t_R

Ma, Roy, Senjanovic, Hambye et al., …

A general statement…

We have unitarity violation whenever we integrate out heavy fermions:

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

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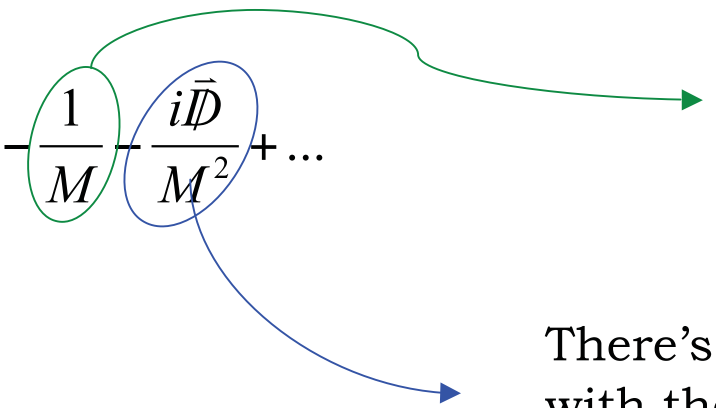

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The propagator of a scalar field does not contain γ^μ →
if it generates neutrino mass, it cannot correct the kinetic term

Low-energy theory

After EWSB, in the flavour basis:

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

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

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

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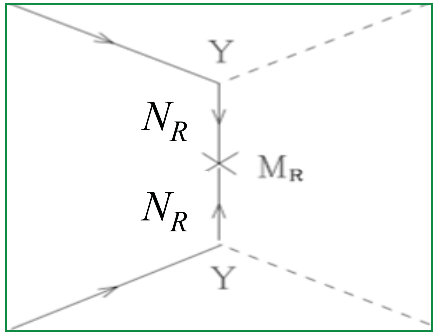
N non-unitary

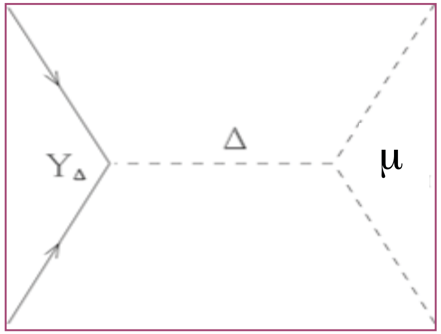
ν masses beyond the SM

★ Tree-level realizations



Heavy fermion singlet N_R (Seesaw I)

→ deviations from unitarity



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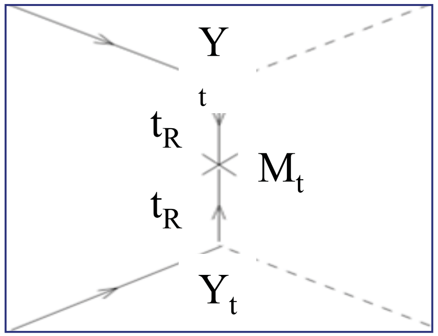

Heavy fermion triplet t_R

→ deviations from unitarity

Non-unitarity from see-saw

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

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

$YY^T/M\ (L\ L\ H\ H)$

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

d=5 operator
it gives mass to ν

d=6 operator
it renormalises kinetic energy

Broncano, Gavela, Jenkins 02

ν masses beyond the SM

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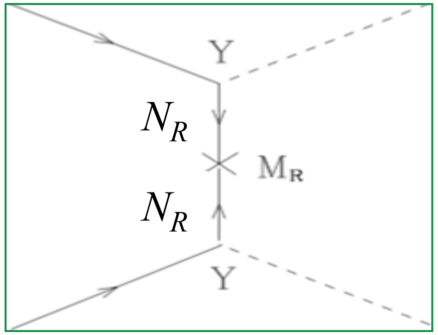

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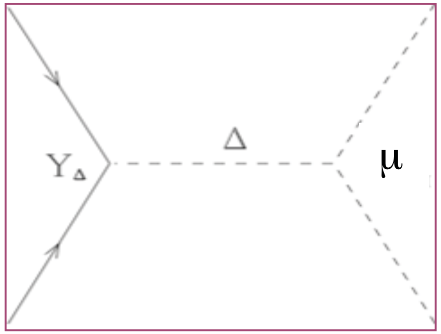

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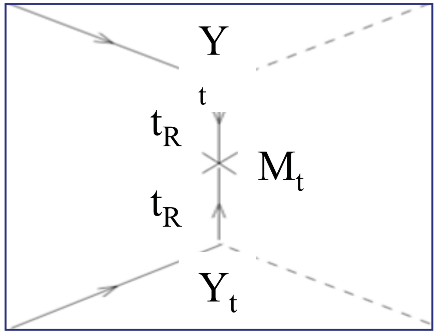

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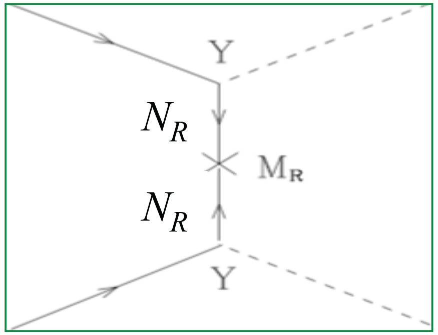

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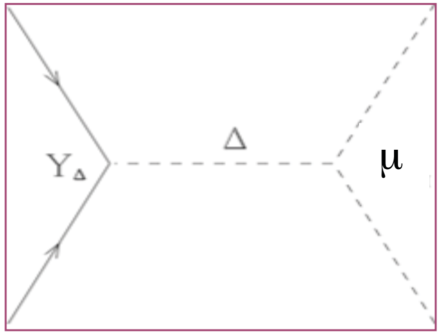
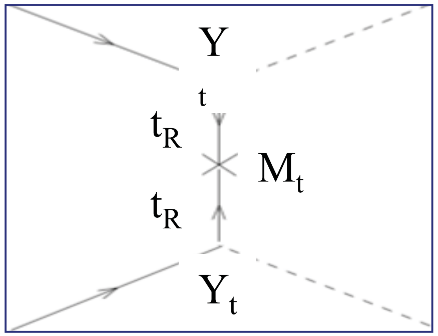


Abada,
Antusch,
Biggio,
Bonnet,
Hambye,
M.B.G.



In short

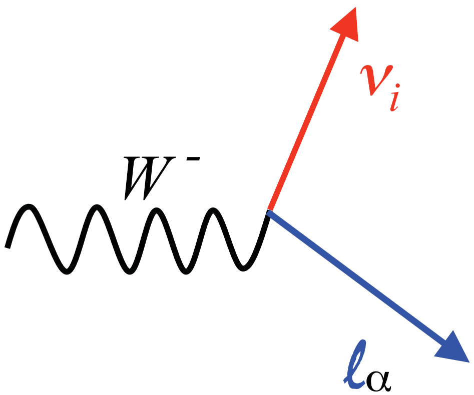
- Unitarity violations arise in models for ν masses with heavy fermions

→ *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………

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



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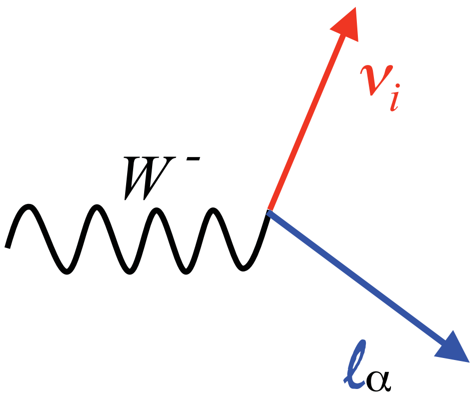


$$\approx N_{\alpha i}$$

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

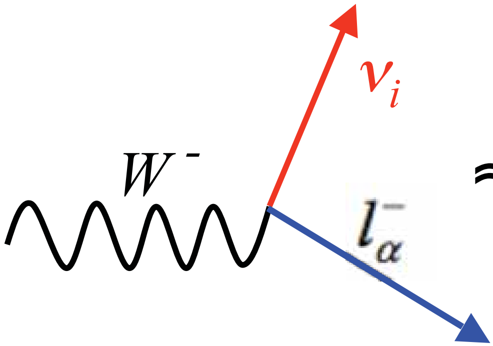
M(inimal) U(nitarity) V(iolation) :

$$L = i\bar{\nu}_i \partial\!\!\!/ \nu_i + \bar{\nu}_i m_{ii} \nu_i - \frac{g}{\sqrt{2}}\left(W_\mu^+ \bar{l}_\alpha \gamma^\mu P_L N_{\alpha i} \nu_i + h.c. \right) - \frac{g}{\cos\theta_W}\left(Z_\mu \bar{\nu}_i \gamma^\mu P_L (N^+ N)_{ij} \nu_j + h.c. \right) + \dots$$

with only 3 light ν

The effects of non-unitarity…

… appear in the interactions



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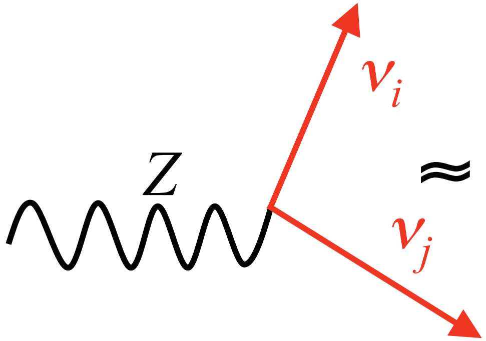

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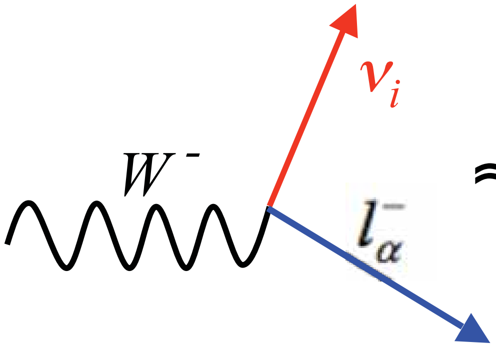

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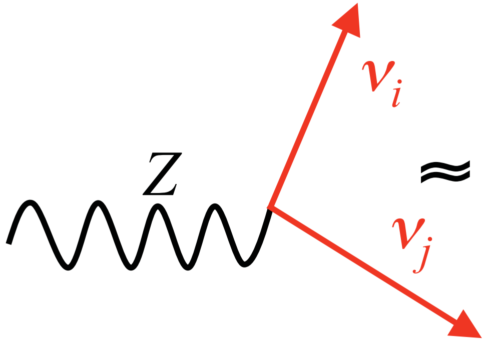

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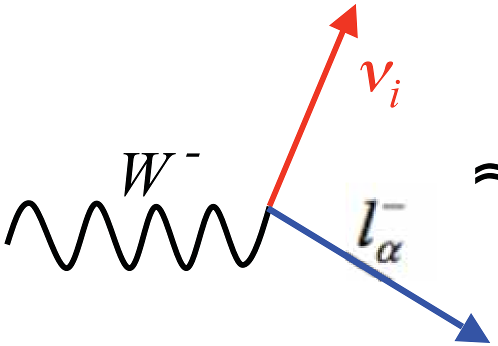

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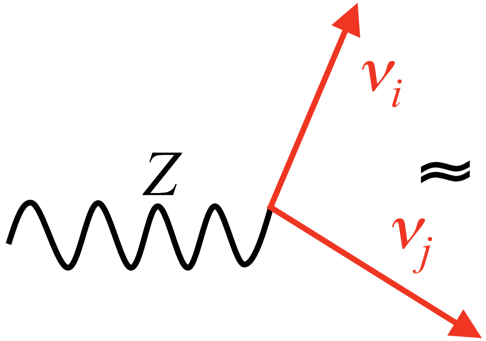

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This affects weak decays…

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

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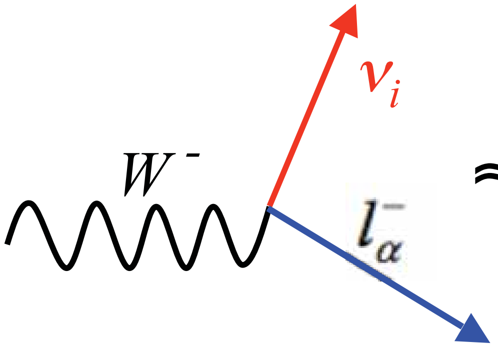

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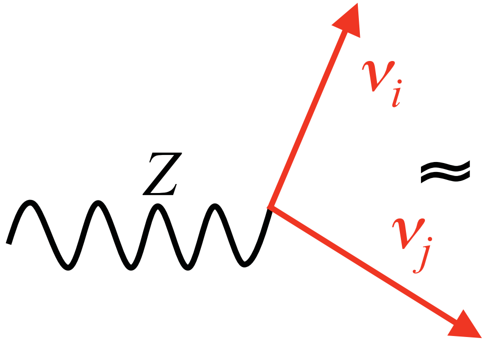

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… and oscillation probabilities…

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

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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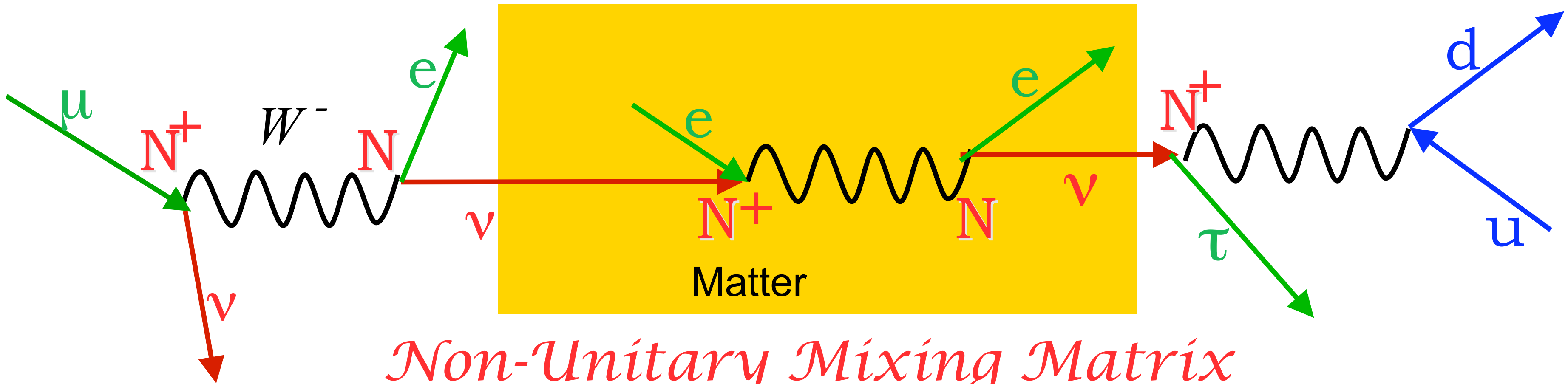

Non-Unitary Mixing Matrix

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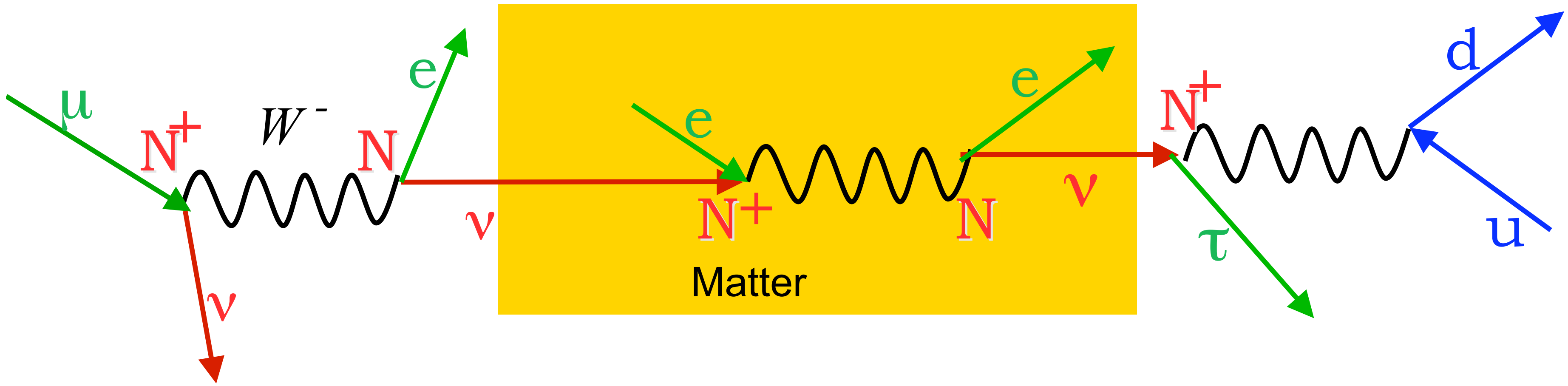


In matter

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

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

N elements from oscillations: *e*-row

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

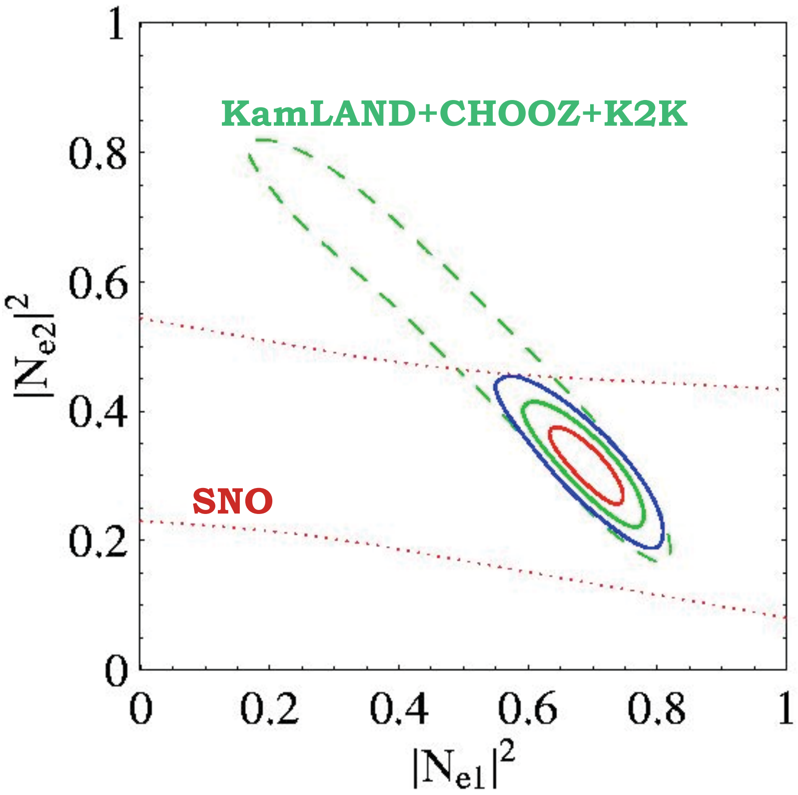
KamLAND: $\hat{P}(\bar{\nu}_e \to \bar{\nu}_e) \cong |N_{e1}|^4 + |N_{e2}|^4 + |N_{e3}|^4 + 2|N_{e1}|^2|N_{e2}|^2 \cos(\Delta_{12})$

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

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: μ-row

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

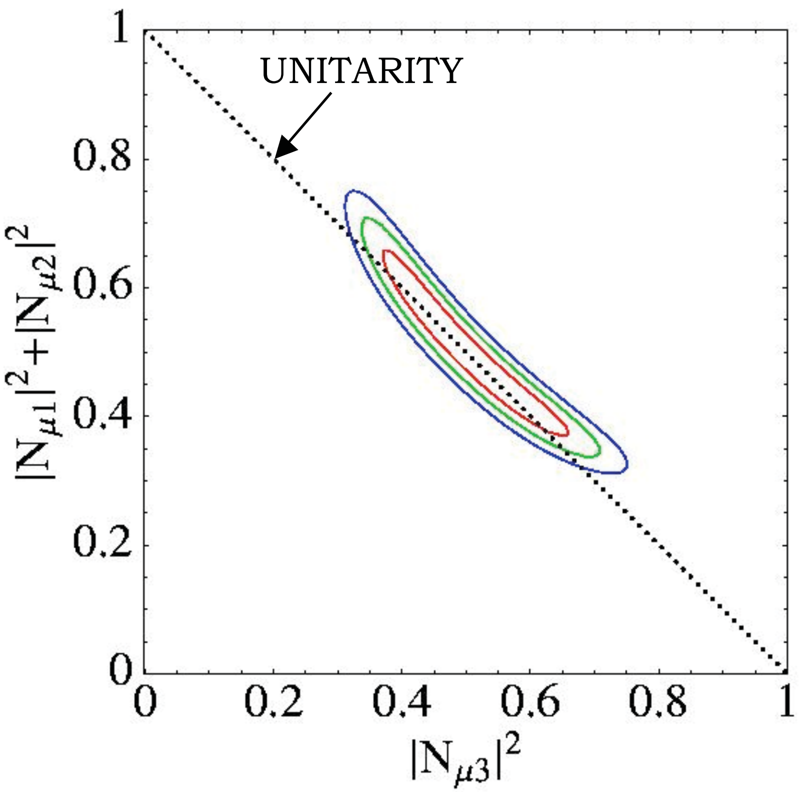
$$\hat{P}(\nu_\mu \to \nu_\mu) \cong \left(|N_{\mu 1}|^2 + |N_{\mu 2}|^2\right)^2 + |N_{\mu 3}|^4 + 2\left(|N_{\mu 1}|^2 + |N_{\mu 2}|^2\right)|N_{\mu 3}|^2 \cos(\Delta_{23})$$

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 only

without unitarity
OSCILLATIONS
MUV

$$|N| = \begin{pmatrix} .76 - .89 & .45 - .66 & < .36 \\ [(|N_{\mu 1}|^2+|N_{\mu 2}|^2)^{1/2} = 0.57\text{-}0.85] & & .57 - .85 \\ ? & ? & ? \end{pmatrix}$$

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 $\rightarrow \dfrac{\left|(NN^{+})_{\beta\alpha}\right|^2}{(NN^{+})_{\alpha\alpha}(NN^{+})_{\beta\beta}}$

→ Limits on NN^+

Global fit

$$90\%\ \mathrm{cl}\quad |NN^{+}| \approx \begin{pmatrix} 1.002 \pm 0.005 & < 7.2\cdot 10^{-5} & < 1.6\cdot 10^{-2} \\ < 7.2\cdot 10^{-5} & 1.003 \pm 0.005 & < 1.3\cdot 10^{-2} \\ < 1.6\cdot 10^{-2} & < 1.3\cdot 10^{-2} & 1.003 \pm 0.005 \end{pmatrix}$$

→ N is unitary at the % level

N elements from oscillations & decays

MUV

without unitarity
OSCILLATIONS
+DECAYS

$$|N| = \begin{pmatrix} .75 - .89 & .46 - .66 & < .20 \\ .19 - .55 & .41 - .73 & .57 - .82 \\ .10 - .57 & .32 - .76 & .54 - .84 \end{pmatrix}$$

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

In the future...

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

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

In the future…

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OPERA like

Can we measure the phases of N ?

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

If we parametrize $N = (1+\varepsilon)\cdot U$ with $U \approx U_{PMNS}$

and

$$\varepsilon = \begin{pmatrix} \varepsilon_{ee} & \varepsilon_{e\mu} & \varepsilon_{e\tau} \\ \varepsilon^*_{e\mu} & \varepsilon_{\mu\mu} & \varepsilon_{\mu\tau} \\ \varepsilon^*_{e\tau} & \varepsilon^*_{\mu\tau} & \varepsilon_{\tau\tau} \end{pmatrix}$$

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

If L/E small

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If L/E small

$$P_{\alpha\beta} = \sin^2(2\theta)\sin^2\left(\frac{\Delta m^2 L}{4E}\right) - 2\,\mathrm{Im}(\varepsilon_{\alpha\beta})\sin(2\theta)\sin\left(\frac{\Delta m^2 L}{2E}\right) + 4\left|\varepsilon_{\alpha\beta}\right|^2$$

SM

CP violating interference

Zero dist. effect

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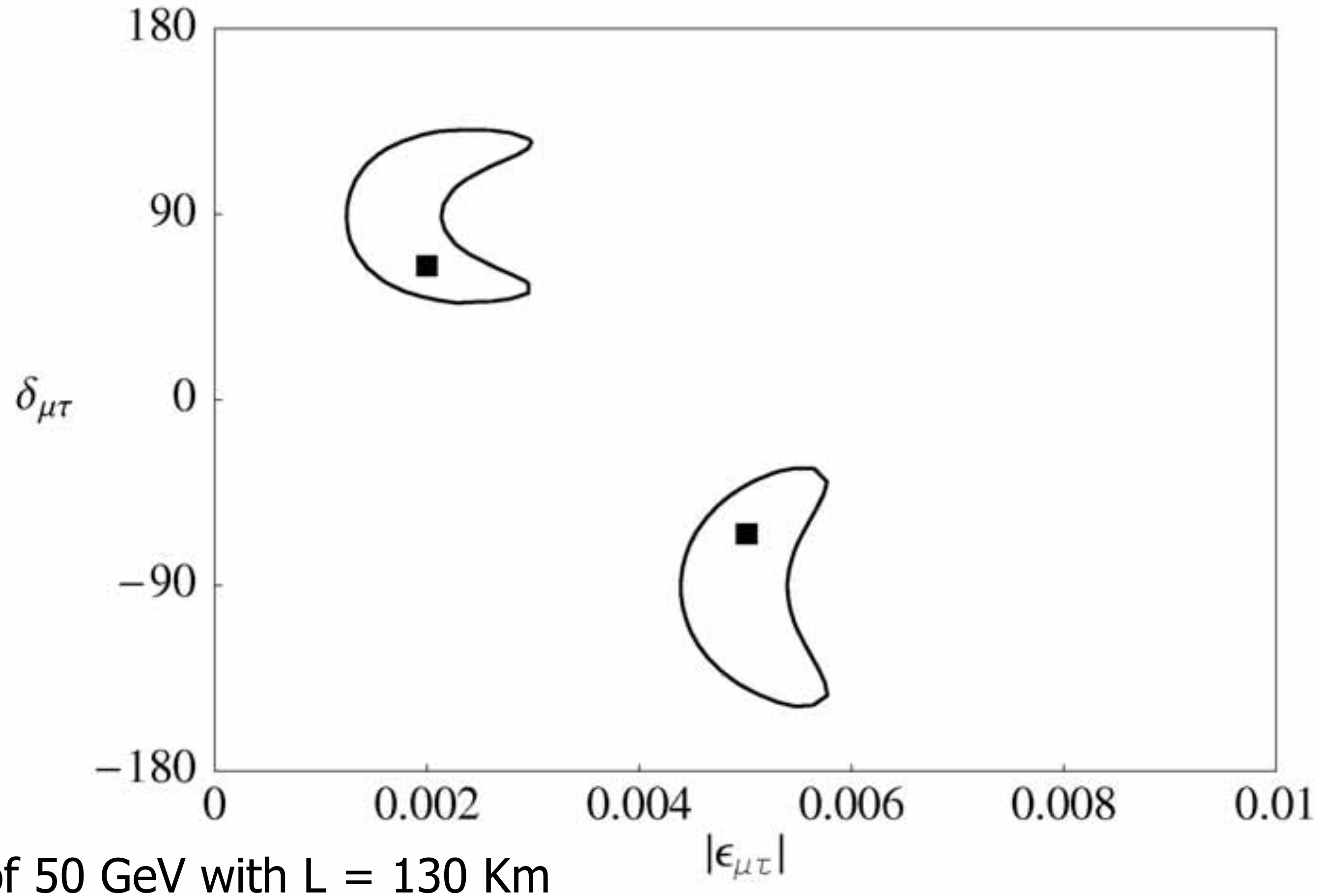
i.e. $P(\nu_\mu \dashrightarrow \nu_\tau) \neq P(\overline{\nu_\mu} \dashrightarrow \overline{\nu_\tau})$

➡ Increased sensitivity to the moduli $|N|$

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

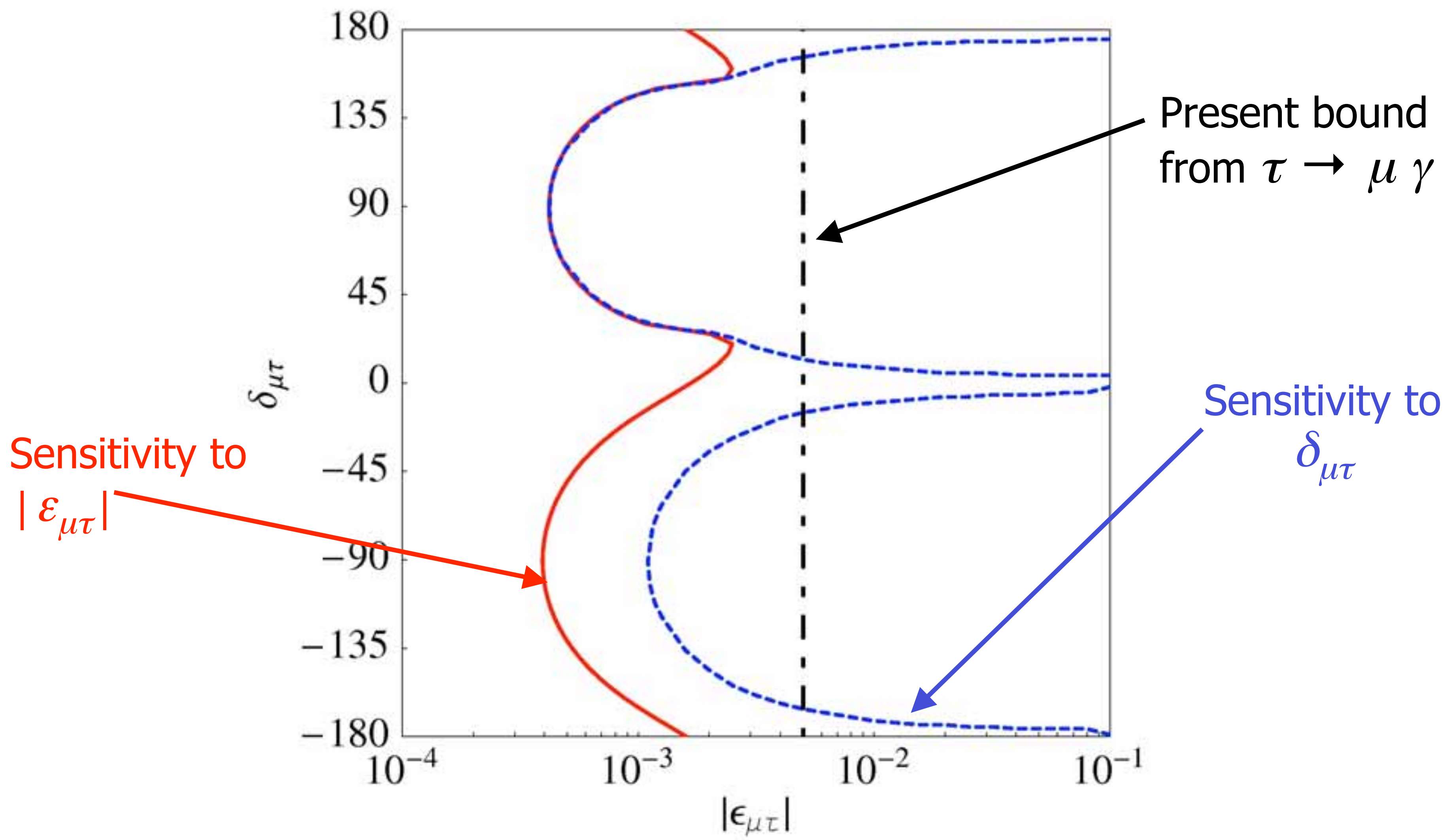
$$P_{\mu\tau} - P_{\bar{\mu}\bar{\tau}} = -4\,\mathrm{Im}(\varepsilon_{\mu\tau})\sin(2\theta_{23})\sin\left(\frac{\Delta m_{23}^2 L}{2E}\right)$$

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



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

Measuring non-unitary phases

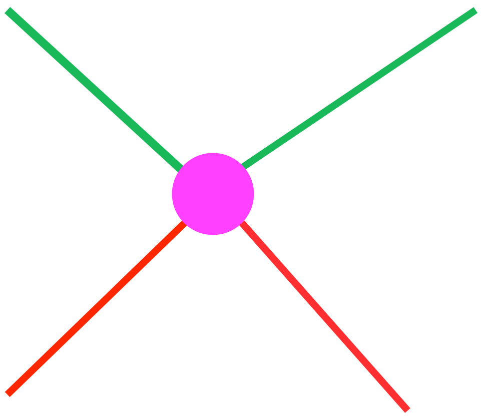


For non-trivial $\delta_{\mu\tau}$, one order of magnitude improvement for $|N|$

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



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

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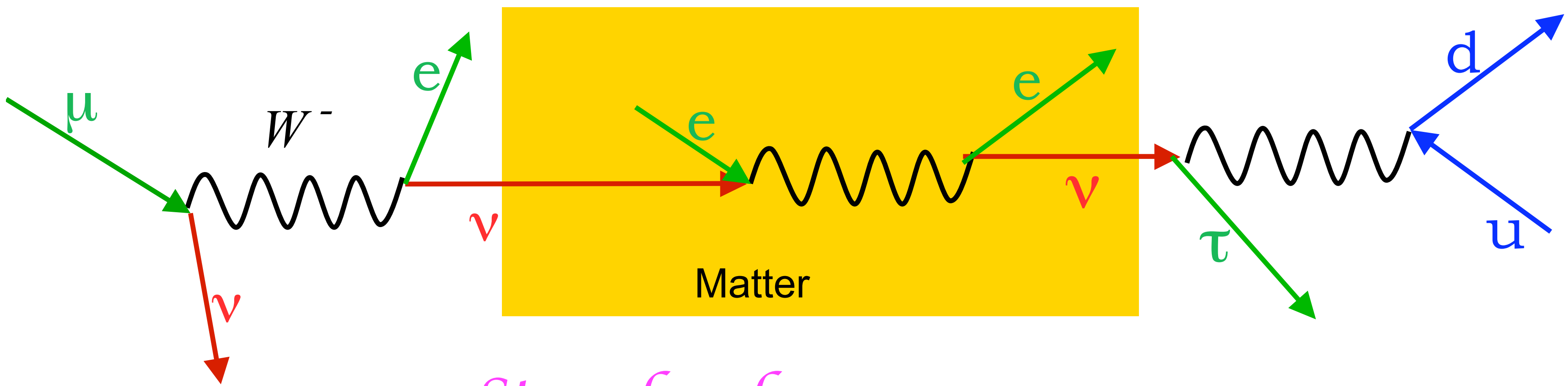

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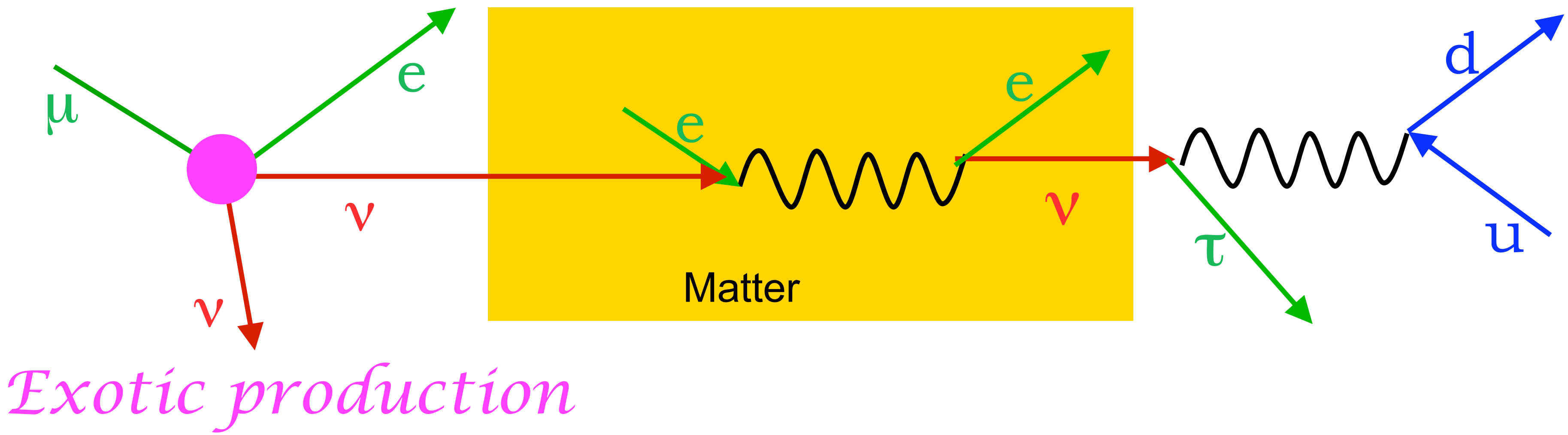

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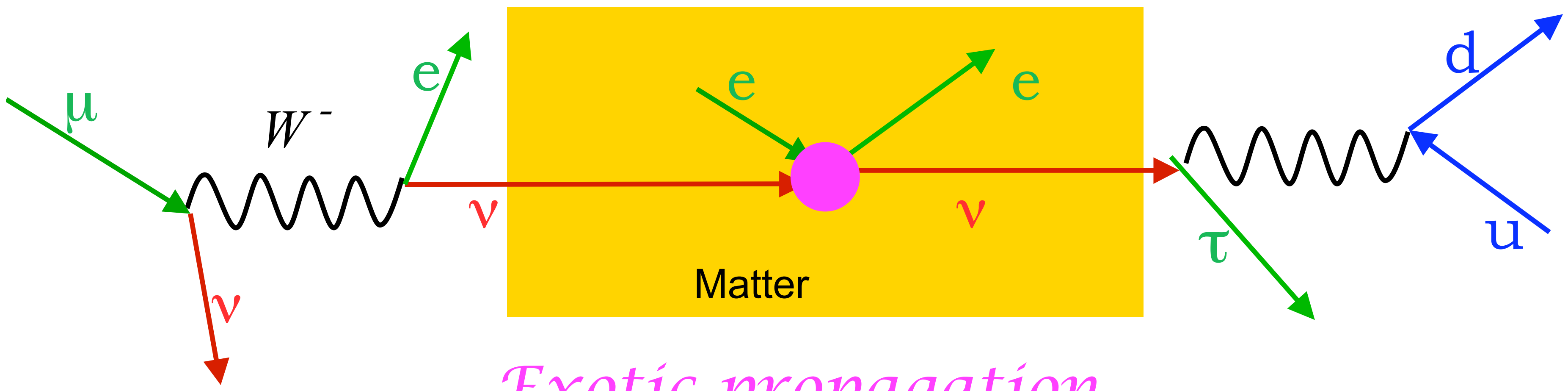

Exotic propagation

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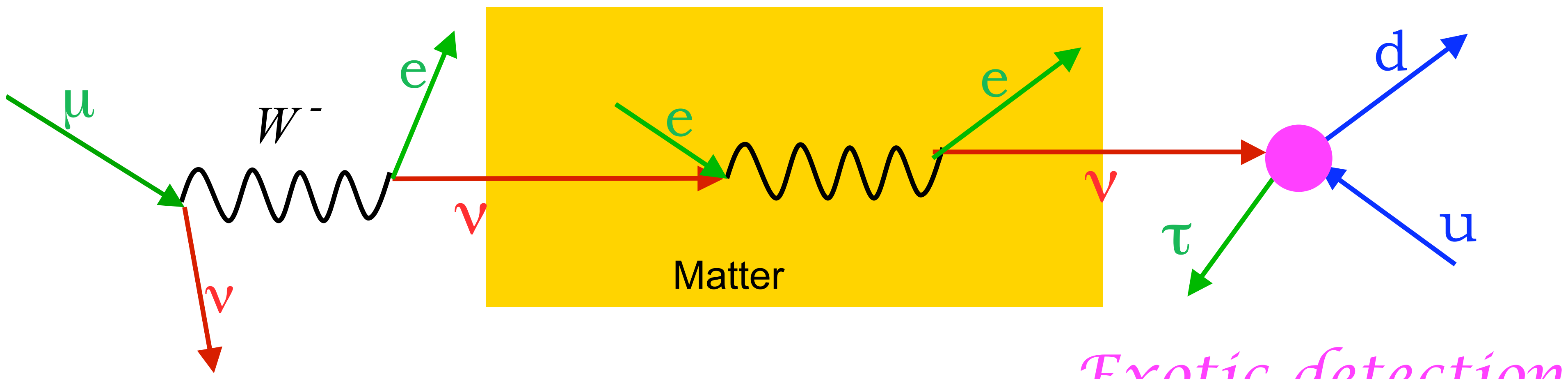

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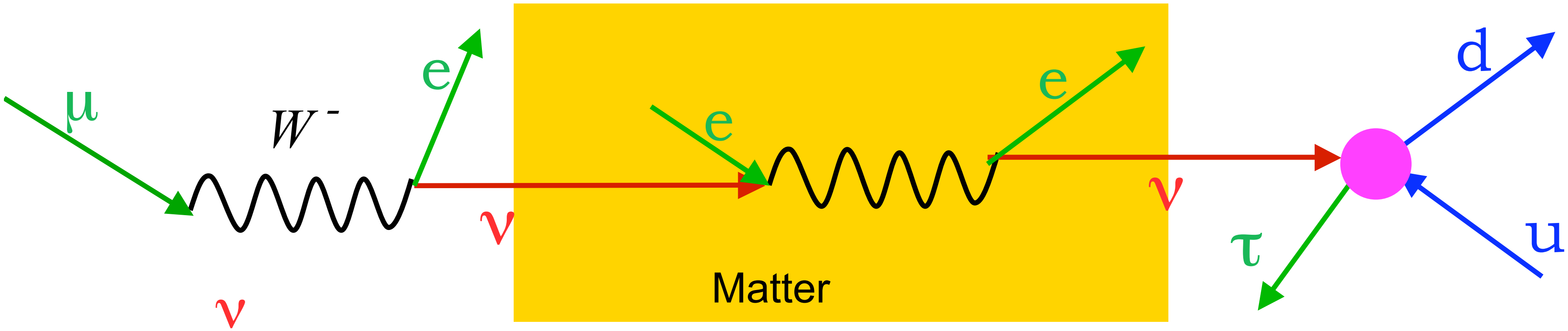

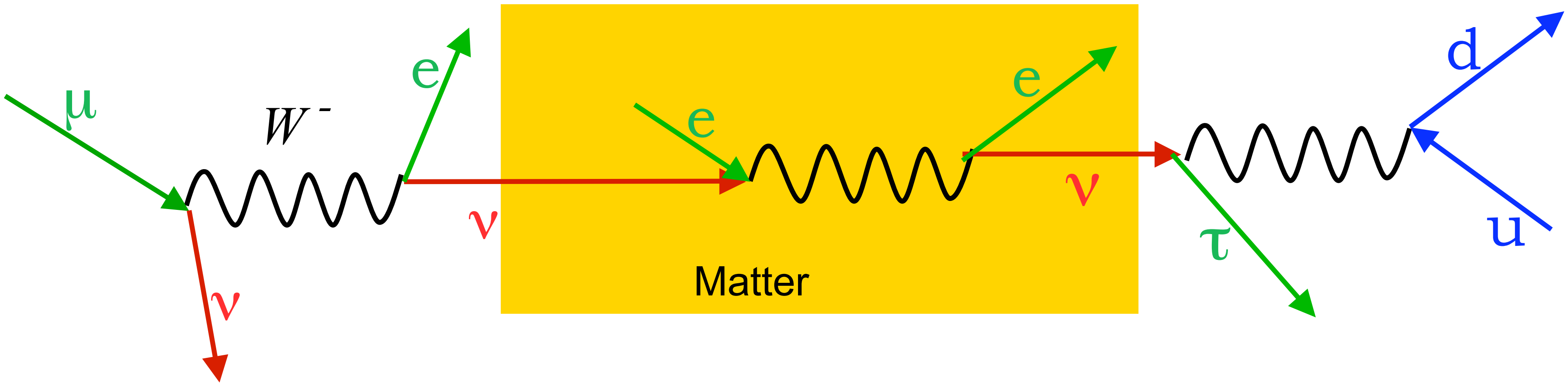

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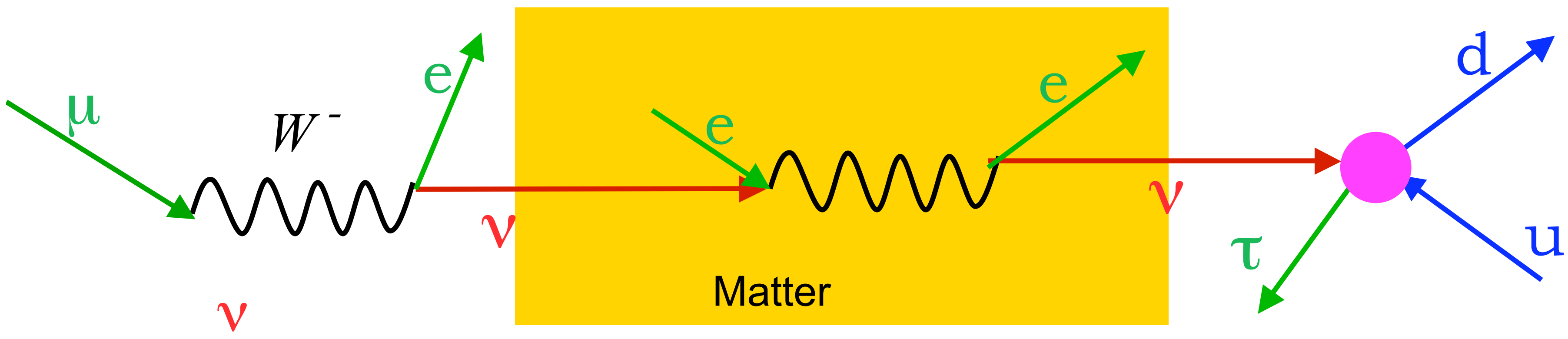

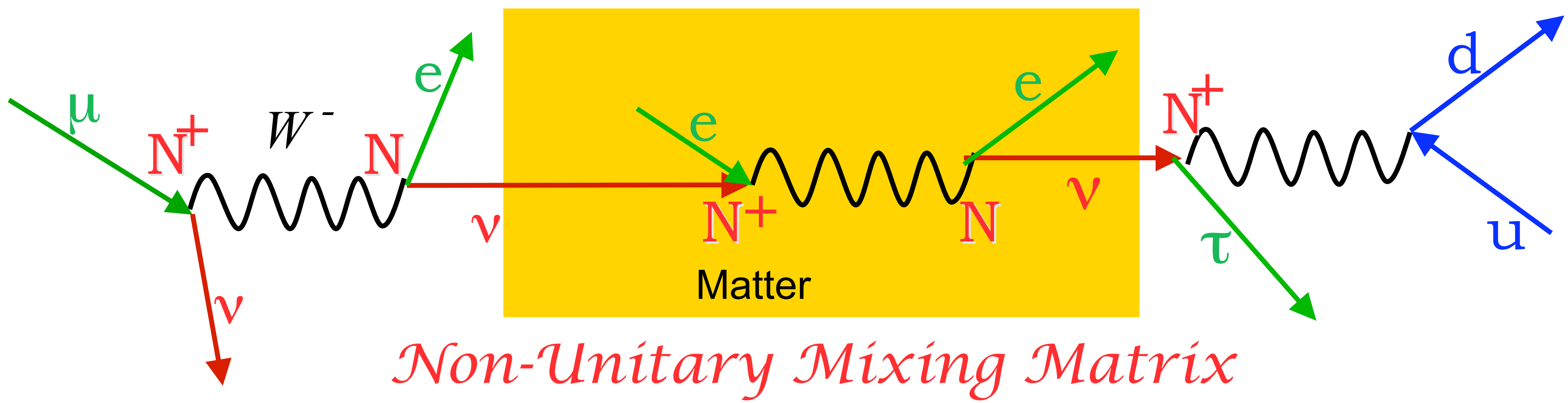

Non-Unitary Mixing Matrix

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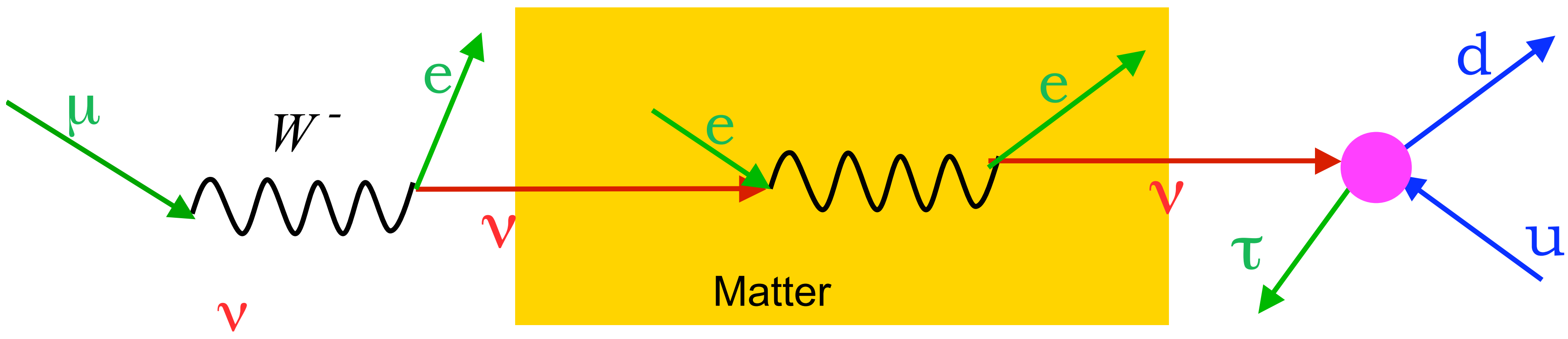
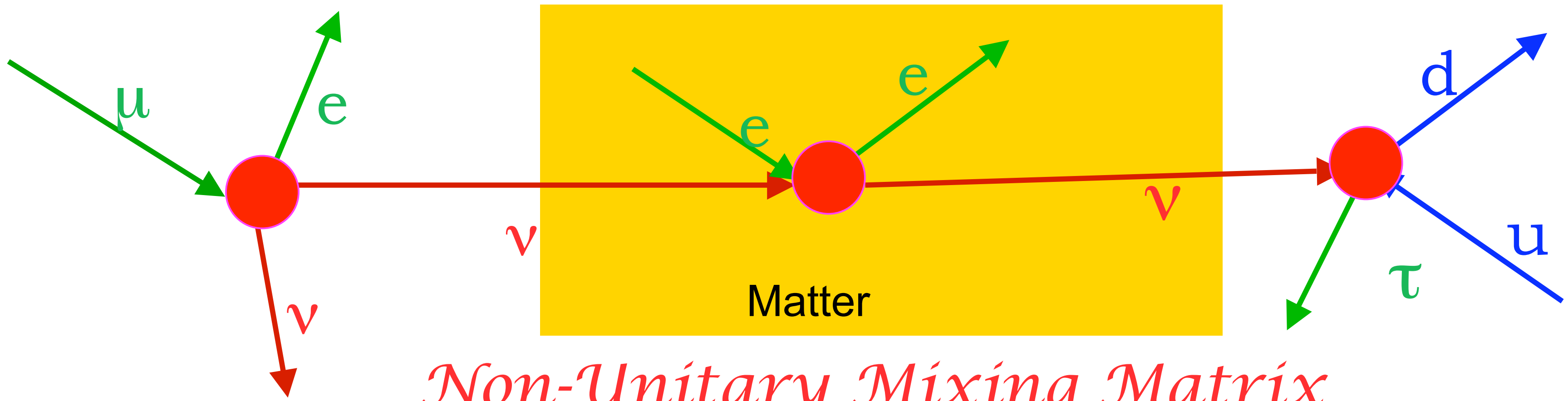




Non-Unitary Mixing Matrix

Conclusions

- A non-unitary mixing matrix is characteristic of models of ν mass involving heavy fermions.

- Analyze neutrino data without assuming unitarity.
  We developed a formalism for it and started the first analyses.

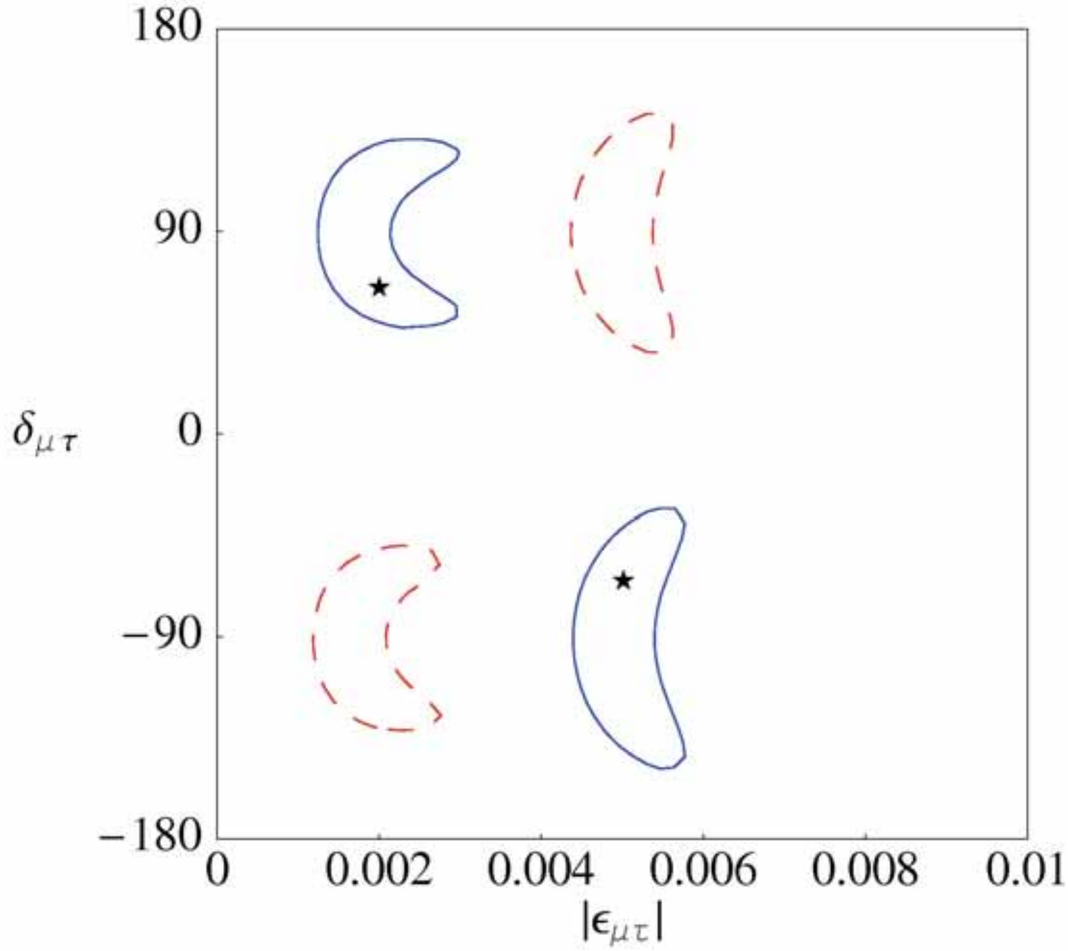
- $\nu_\mu - \nu_\tau$ CP-asymmetry is a clean probe of the new phases.

- Our results also apply to *non-standard* or *exotic* ν interactions.

- Non-unitary effects in simplest models are too small for nowadays detection, but not in extensions/others: i.e., models with M~ TeV.

-> keep tracking them in the future.
They are excellent signals of new physics.

Back-up slides


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

$$|\varepsilon| \approx \begin{pmatrix} < 2.5\cdot 10^{-3} & < 3.6\cdot 10^{-5} & < 8.0\cdot 10^{-3} \\ < 3.6\cdot 10^{-5} & < 2.5\cdot 10^{-3} & < 5.0\cdot 10^{-3} \\ < 8.0\cdot 10^{-3} & < 5.0\cdot 10^{-3} & < 2.5\cdot 10^{-3} \end{pmatrix}$$

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 $P_{\mu\tau}$

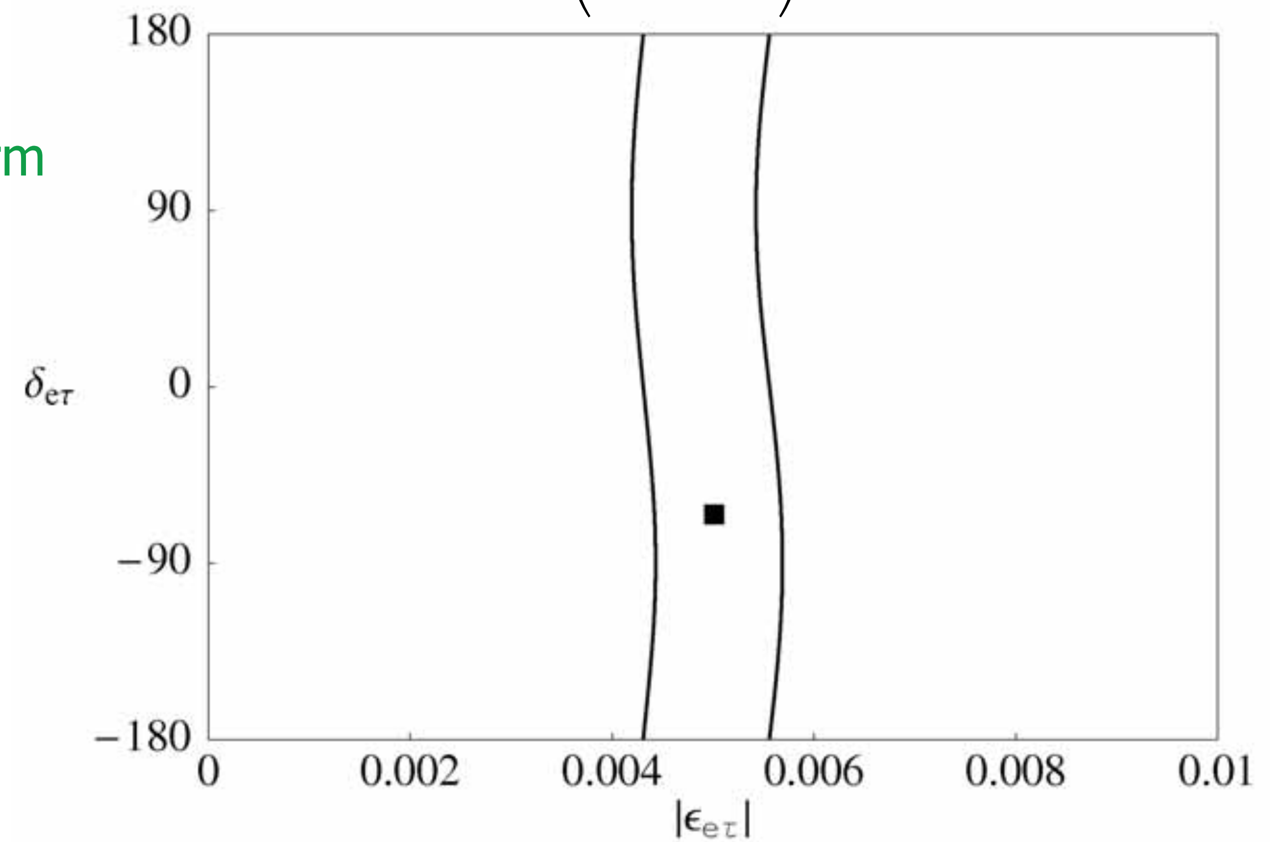
Measuring unitarity deviations

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

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

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

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



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

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

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

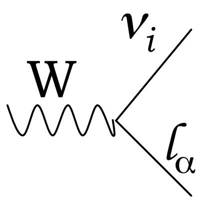
$$\hat{P}_{\alpha\beta}(E,L) = \left|\sum_i N_{\alpha i}^* e^{iP_i L} N_{\beta i}\right|^2$$

Exceptions:

- measured flux
- leptonic production mechanism
- detection via NC

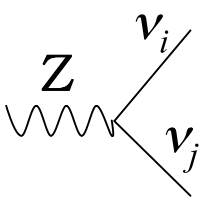
$(NN^\dagger)$ from decays: G_F

- W decays



[redacted]

- Invisible Z



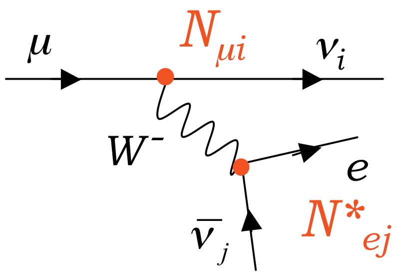
[redacted]

- Universality tests

[redacted]

Info on $(NN^\dagger)_{aa}$

G_F is measured in μ-decay

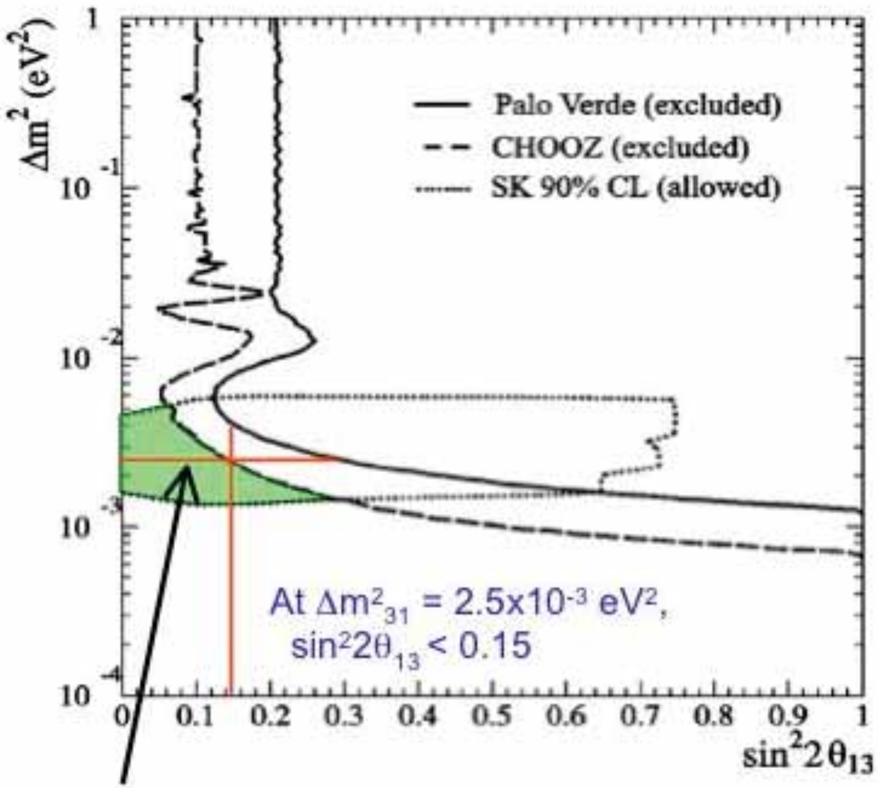


$$\Gamma = \frac{G_F^2 m_\mu^5}{192\pi^3} \sum_i \left|N_{\mu i}\right|^2 \sum_j \left|N_{ej}\right|^2$$

[redacted]

CHOOZ

Direct search

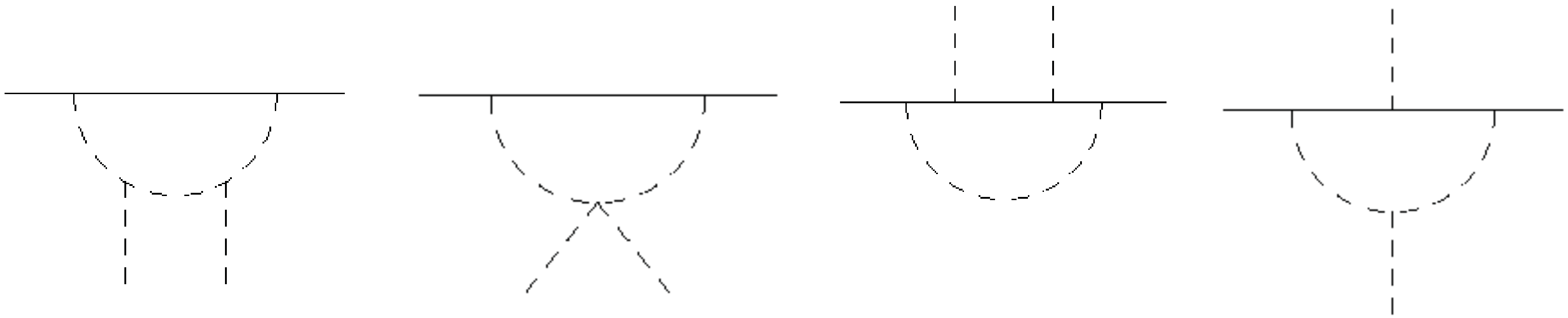


allowed region

ν masses beyond the SM

★ Other realizations

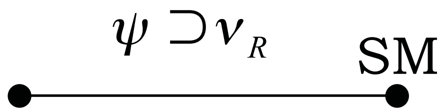
- radiative mechanisms: ex.) 1 loop:



Frigerio

- SUSY models with R-parity violation

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



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

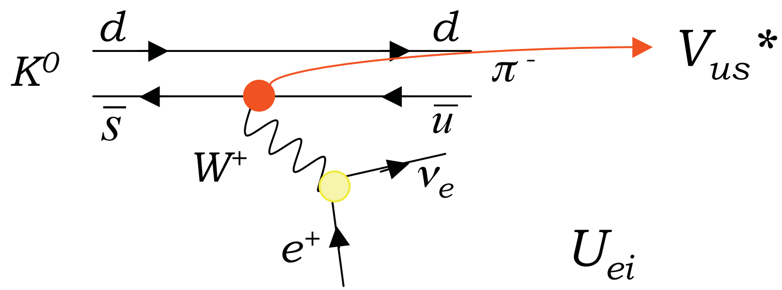
- …

Unitarity in the quark sector

Quarks are detected in the final state

→ we can directly measure $|V_{ab}|$

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



→ $\sum_i |U_{ei}|^2 = 1$ 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}