
LNV AND LFV SEMILEPTONIC DECAYS FROM INTERFERING MAJORANA NEUTRINOS

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with **Asmaa Abada, Chandan Hati and Ana M. Teixeira**

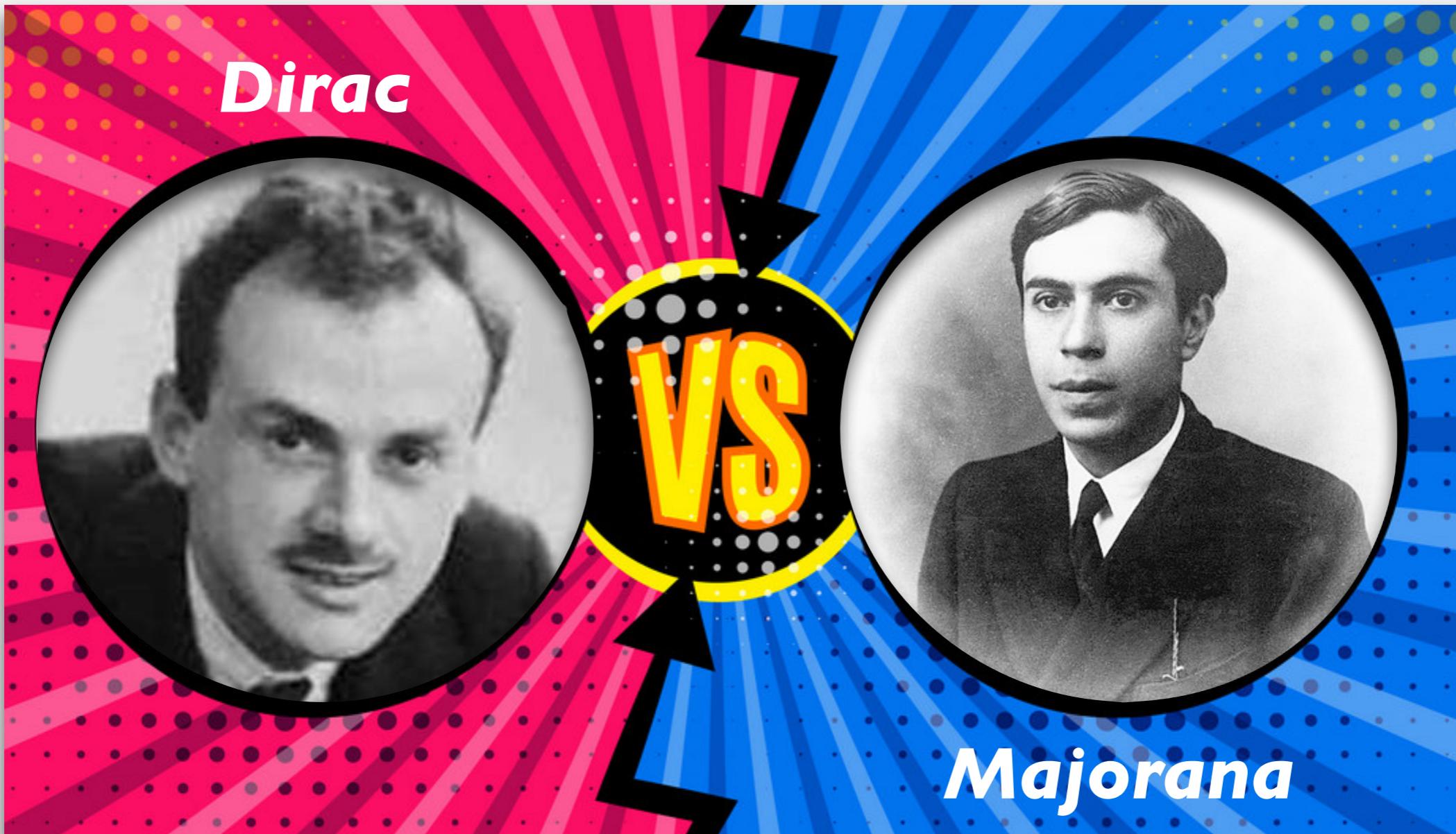
Why neutrinos?



Present knowns&unknown

$\theta_{12}, \theta_{23}, \theta_{13}$	✓	[$34^\circ, 50^\circ, 8^\circ$]
Δm_{21}^2	✓	[10^{-5} eV^2]
Δm_{31}^2	± ✓	[10^{-3} eV^2]
δ_{CP}	✗	
ϕ_1, ϕ_2	✗	
Mass ordering	✗	
Absolute mass scale	✗	
Neutrino nature	✗	

Neutrino Nature



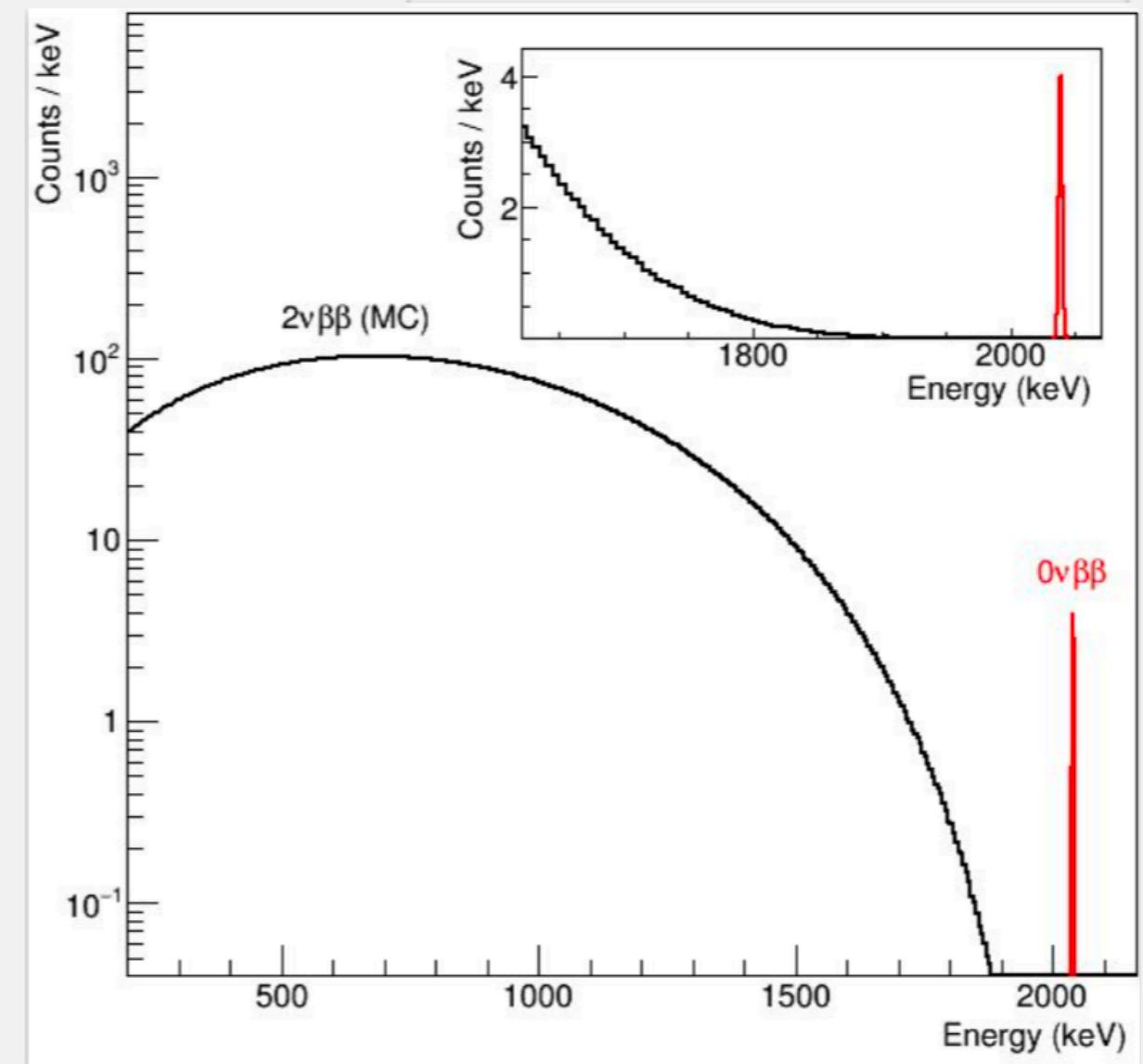
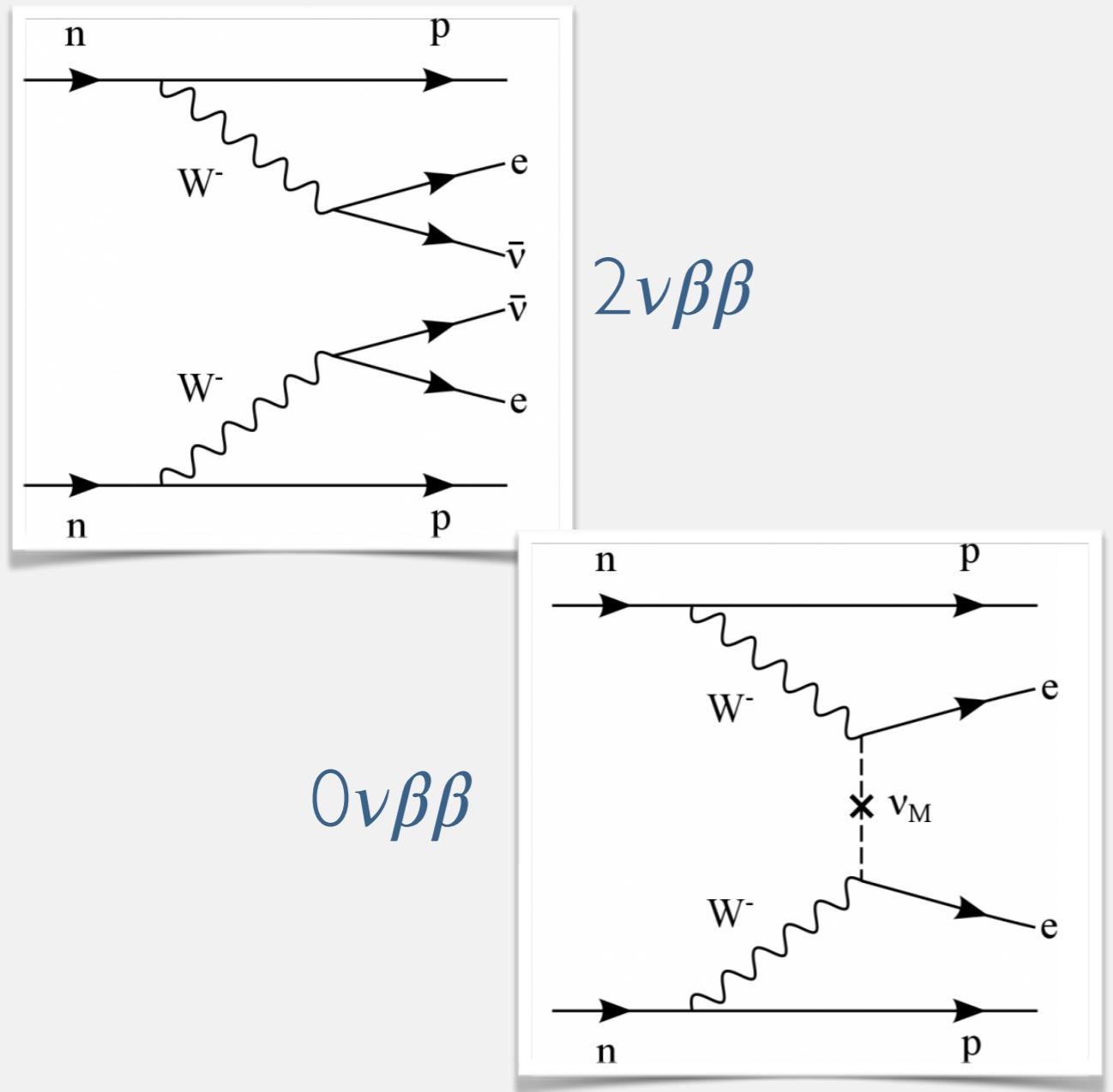
$$\nu^c \neq \nu$$

$$\nu^c = \nu$$

Neutrinoless Double Beta Decays

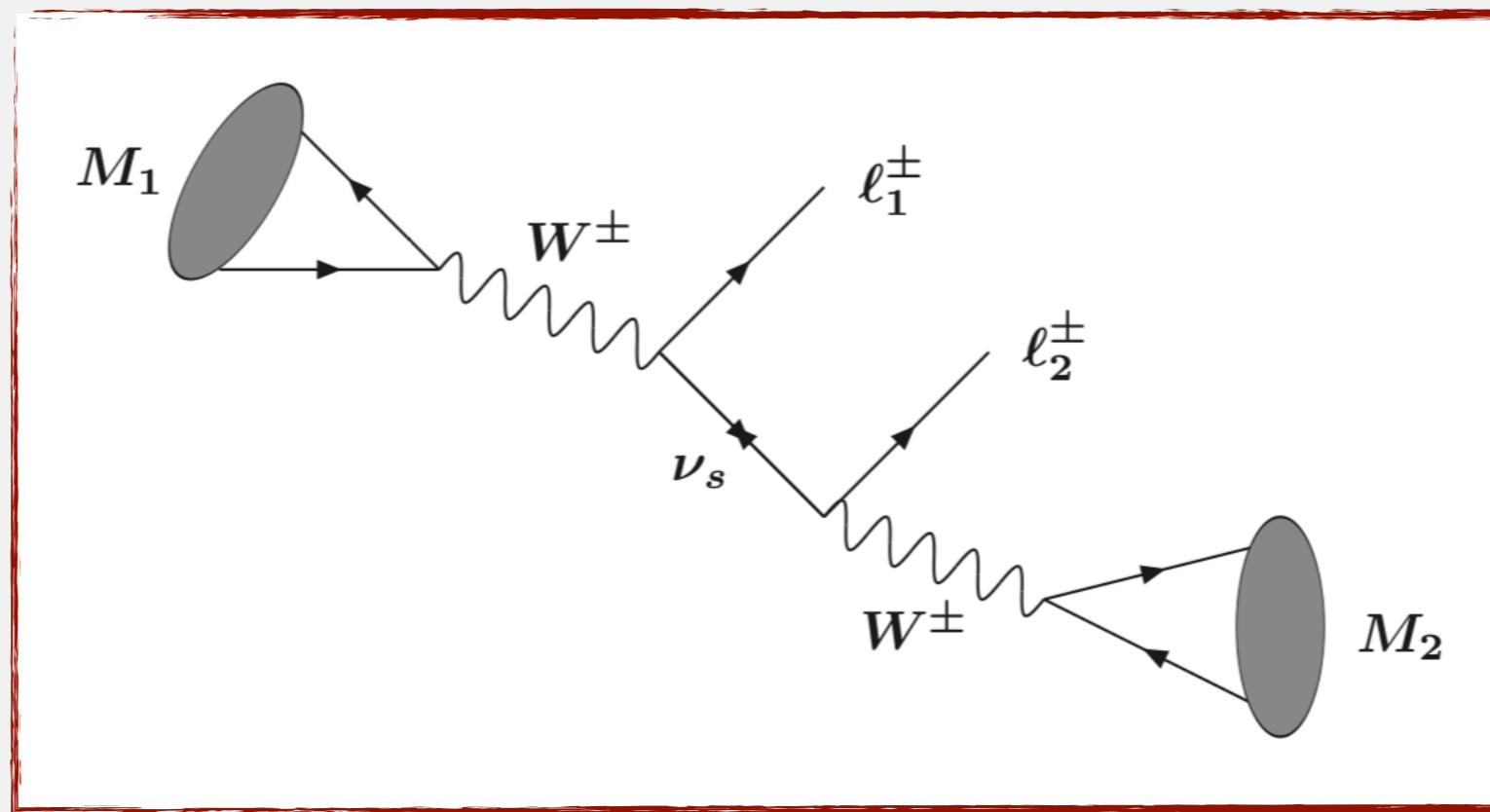
► Learn about **neutrinos** looking for **no neutrinos**

$$m_{ee} = \left| \sum_i m_i U_{ei} \right|^2$$



Ana Julia Zsigmond (GERDA), Neutrino 2018

LNV & LFV semileptonic meson decays

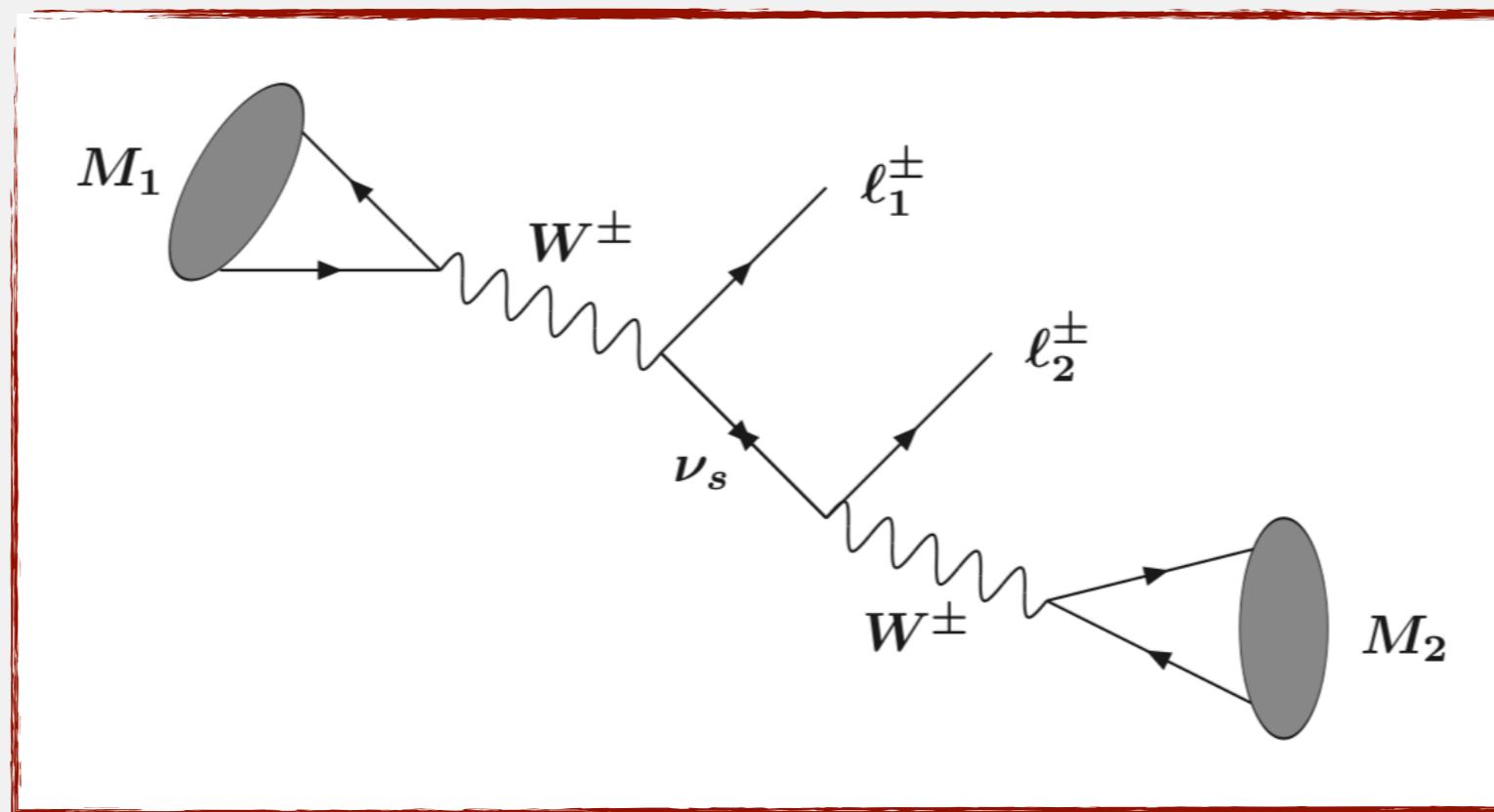


$$\text{BR}(K^+ \rightarrow \pi^+ e^- \mu^+) \leq 1.3 \times 10^{-11}, \quad \text{BR}(K^+ \rightarrow \pi^+ e^+ \mu^-) \leq 5.2 \times 10^{-10}$$

$$\text{BR}(K^+ \rightarrow \pi^- e^+ e^+) \leq 2.2 \times 10^{-10}, \quad \text{BR}(K^+ \rightarrow \pi^- \mu^+ \mu^+) \leq 4.2 \times 10^{-11}$$

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LNV & LFV semileptonic meson decays



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NEW!!!
NA62 (2019)

Outline

Neutrino mass models

type-I, inverse, ‘model independent’ seesaws

Semileptonic LNV&LNC decays (I)

in presence of one heavy Majorana neutrino

Semileptonic LNV&LNC decays (II)

in presence of two heavy Majorana neutrinos
interference

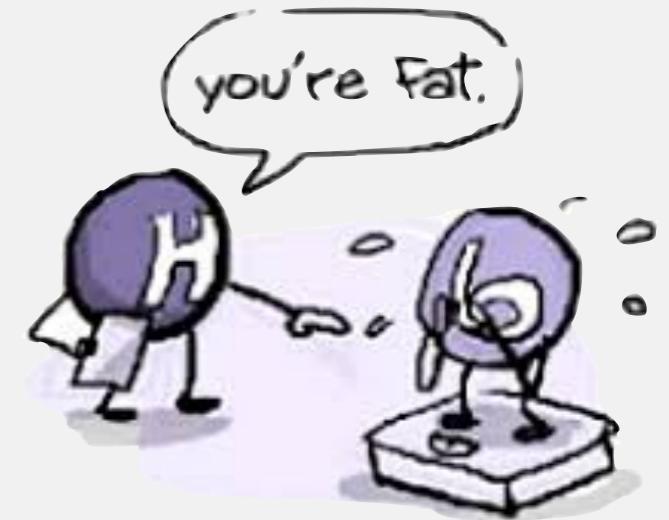
Why massless in the SM?

$\frac{2}{3}$ Left u up Flight	$\frac{2}{3}$ Left c charm Flight	$\frac{2}{3}$ Left t top Right
$\frac{-1}{3}$ Left d down Flight	$\frac{-1}{3}$ Left s strange Flight	$\frac{-1}{3}$ Left b bottom Right
0 eV $0 \nu_e$ electron neutrino	0 eV $0 \nu_\mu$ muon neutrino	0 eV $0 \nu_\tau$ tau neutrino
-1 Left e electron Right	-1 Left μ muon Right	-1 Left τ tau Right

► Higgs* mechanism

$$\mathcal{L}_{\text{Yukawa}} \sim \bar{L} H R,$$

$$H = \begin{pmatrix} \omega^+ \\ v + \frac{h+i\omega^0}{\sqrt{2}} \end{pmatrix}$$



*Brout-Englert-Higgs-Guralnik-Hagen-Kibble mechanism

Why massless in the SM?

2.4 MeV $\frac{2}{3}$ u up Left Right	1.27 GeV $\frac{2}{3}$ c charm Left Right	171.2 GeV $\frac{2}{3}$ t top Left Right
4.8 MeV $-\frac{1}{3}$ d down Left Right	104 MeV $-\frac{1}{3}$ s strange Left Right	4.2 GeV $-\frac{1}{3}$ b bottom Left Right
0 eV 0 ν_e electron neutrino Left Right	0 eV 0 ν_μ muon neutrino Left Right	0 eV 0 ν_τ tau neutrino Left Right
0.511 MeV -1 e electron Left Right	105.7 MeV -1 μ muon Left Right	1.777 GeV -1 τ tau Left Right

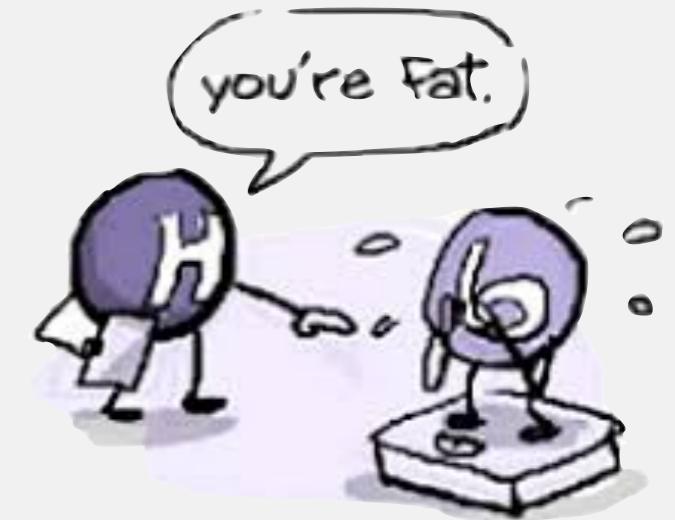
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► Add RH neutrinos

$$\mathcal{L}_{\text{Yukawa}} = -Y_\nu \bar{L} \tilde{H} \nu_R + h.c.$$

$$\langle H \rangle \neq 0 \rightarrow m_\nu^{\text{Dirac}} = v Y_\nu$$



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► RH neutrinos are SM singlets

$$\mathcal{L}_{\text{Majorana}} = -M \overline{\nu_R^c} \nu_R$$



*Brout-Englert-Higgs-Guralnik-Hagen-Kibble mechanism

Seesaw mechanism (type-I)

- ▶ Add right-handed neutrinos with **Dirac** and **Majorana** terms

$$\mathcal{L}_{\text{type-I}} = \mathcal{L}_{\text{SM}} + i\overline{\nu_R}\partial\nu_R - \left(Y_\nu \overline{L} \tilde{H} \nu_R + \frac{1}{2} M \overline{\nu_R^c} \nu_R + h.c. \right)$$

- ▶ After the EW symmetry breaking

$$M_{\text{type I}} = \begin{pmatrix} 0 & m_D \\ m_D^T & M \end{pmatrix}$$



$$m_\nu \simeq \frac{m_D^2}{M} \quad m_N \simeq M$$



Inverse seesaw model

- ▶ Add two type of neutrinos with almost conserved Lepton number symmetry

$$\mathcal{L}_{\text{ISS}} = -Y_D \bar{L} \tilde{H} \nu_R - M \overline{\nu_R^c} \nu_s - \frac{1}{2} \mu \overline{\nu_s^c} \nu_s + h.c.$$

- ▶ Different spectrum: **quasi-degenerate** heavy neutrinos with **opposite CP**

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



$$m_\nu \simeq \frac{m_D}{M} \mu$$

$$m_{N_1, N_2} \simeq \pm M + \mathcal{O}(\mu)$$



Effective 3+N neutrino model

- ▶ In each kind of seesaw model, different relations between the parameters to explain light neutrino masses
In the physical basis translates to related masses and mixings

Bottom-up approach  $\text{SM}_{m_\nu} + N$

- ▶ Seesaw particle content, but no seesaw assumptions

Take the mass as a free parameter

Take the mixings as free parameters



Effective 3+N neutrino model

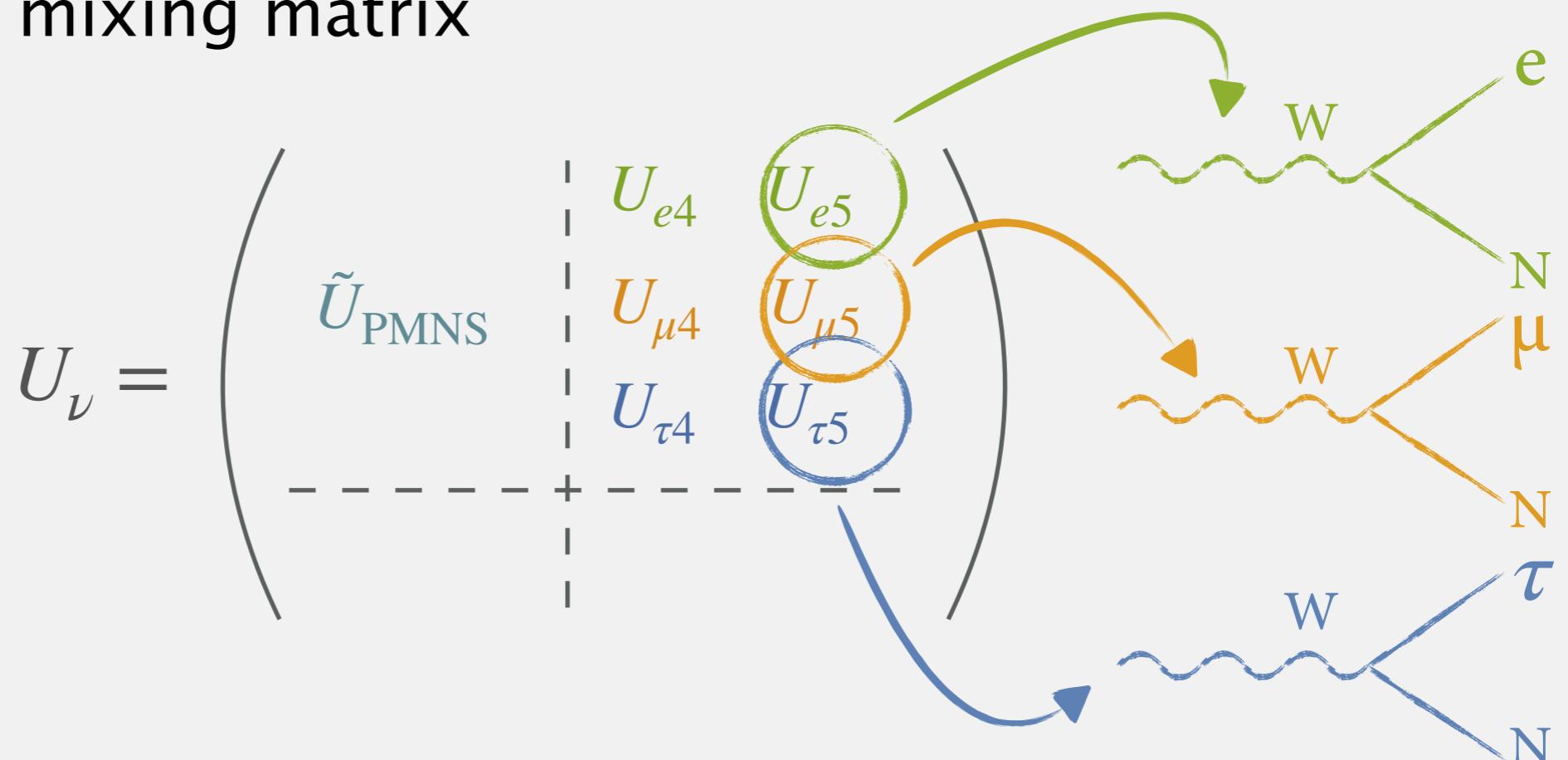
- ▶ 3+N masses $m_\nu = (m_{\nu_1}, m_{\nu_2}, m_{\nu_3}, m_4, m_5, \dots)$
- ▶ 3+N unitary mixing matrix

$$U_\nu = \begin{pmatrix} \tilde{U}_{\text{PMNS}} & | & U_{e4} & U_{e5} \\ & | & U_{\mu 4} & U_{\mu 5} \\ & | & U_{\tau 4} & U_{\tau 5} \\ \hline - & - & - & - + & - & - & - & - \\ & | & & & | & & & | \end{pmatrix}$$

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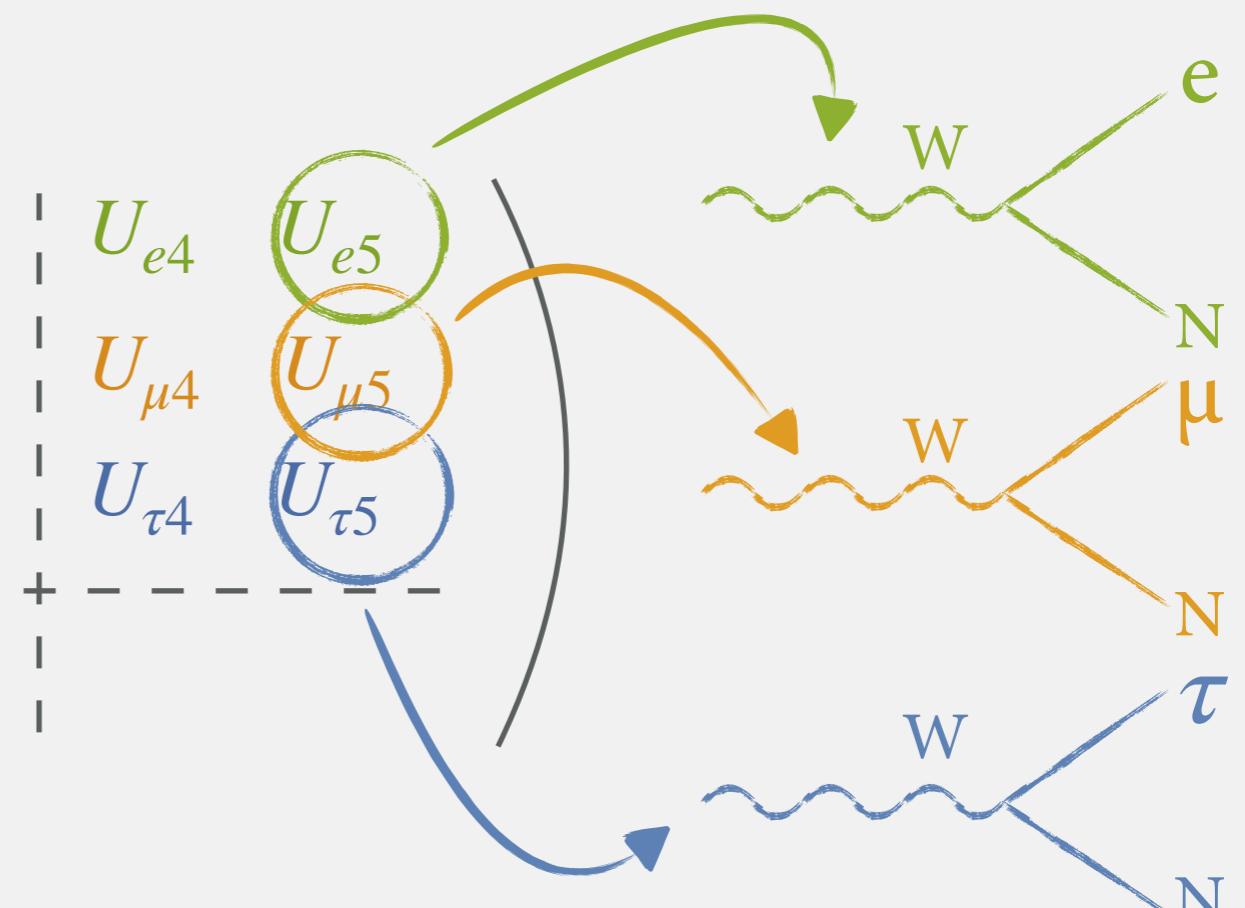


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$$U_\nu = \begin{pmatrix} & & U_{e4} \\ & & U_{\mu 4} \\ & & U_{\tau 4} \\ \tilde{U}_{\text{PMNS}} & + & \cdots \\ & & U_{e5} \\ & & U_{\mu 5} \\ & & U_{\tau 5} \end{pmatrix}$$



⊕ Neutral currents



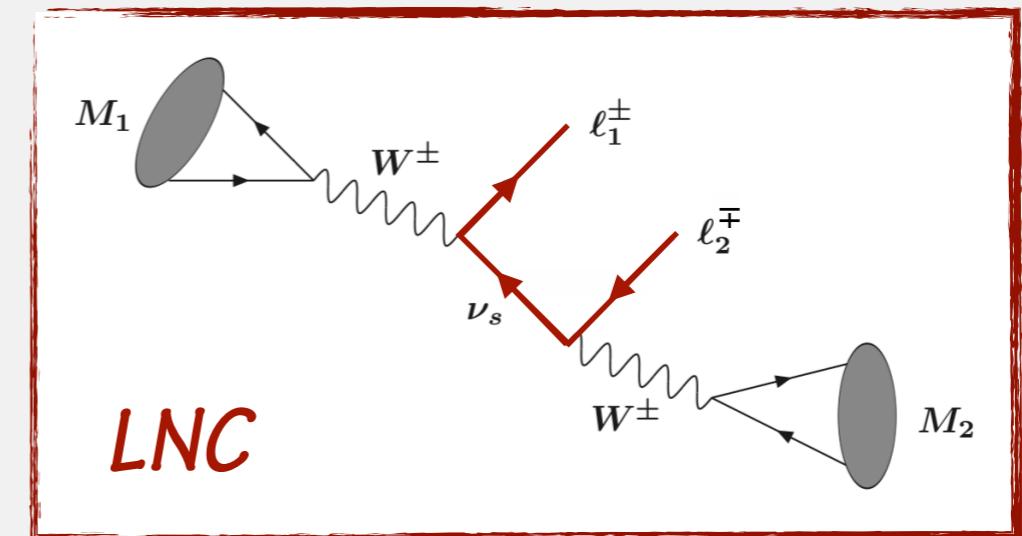
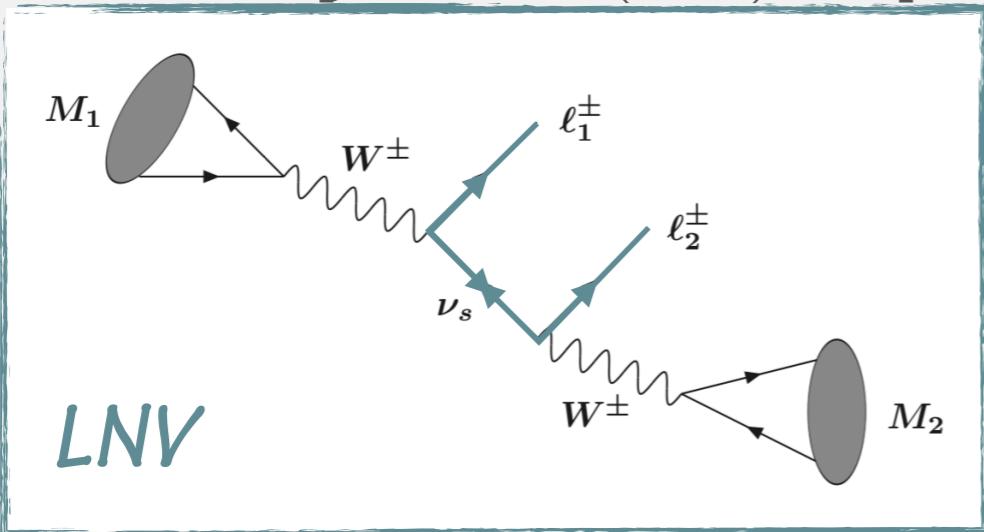
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Semileptonic LNV&LNC decays (I)

in presence of one heavy Majorana neutrino

LNV&LNC from on-shell neutrinos

Abada et al. [JHEP 1802 (2018) 169]

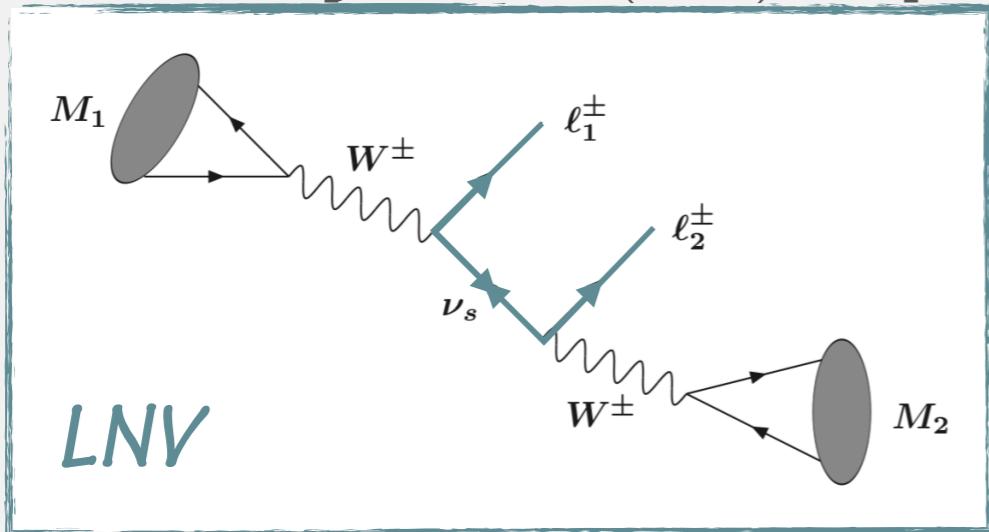


$$\mathcal{A}_{\text{LNV}} \sim U_{\ell 4} \frac{m_4}{q^2 - m_4^2 - m_4 \Gamma_4} U_{\ell' 4}$$

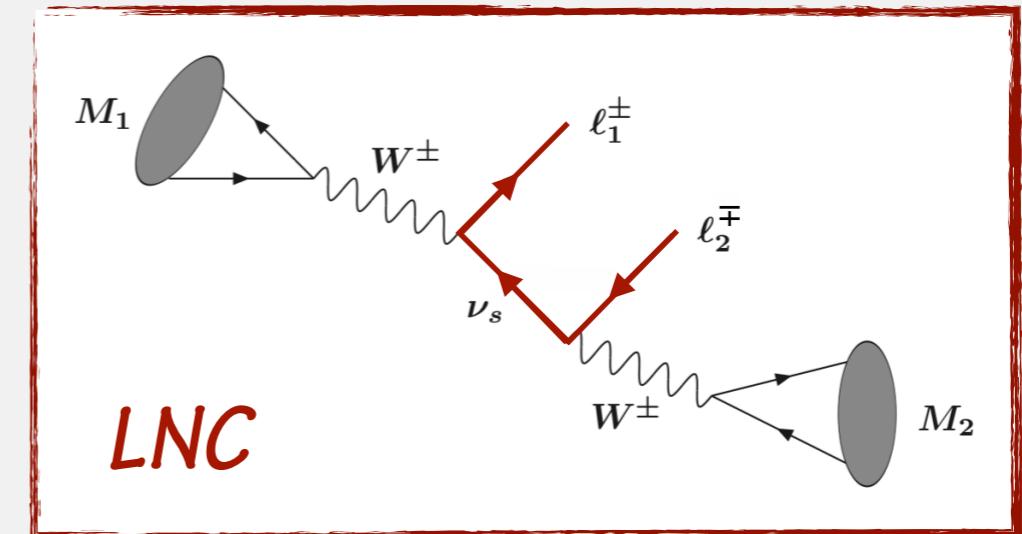
$$|\mathcal{A}_{\text{LNC}}| \sim U_{\ell 4} \frac{q}{q^2 - m_4^2 - m_4 \Gamma_4} U_{\ell' 4}^*$$

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LNV



LNC

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on-shell neutrino

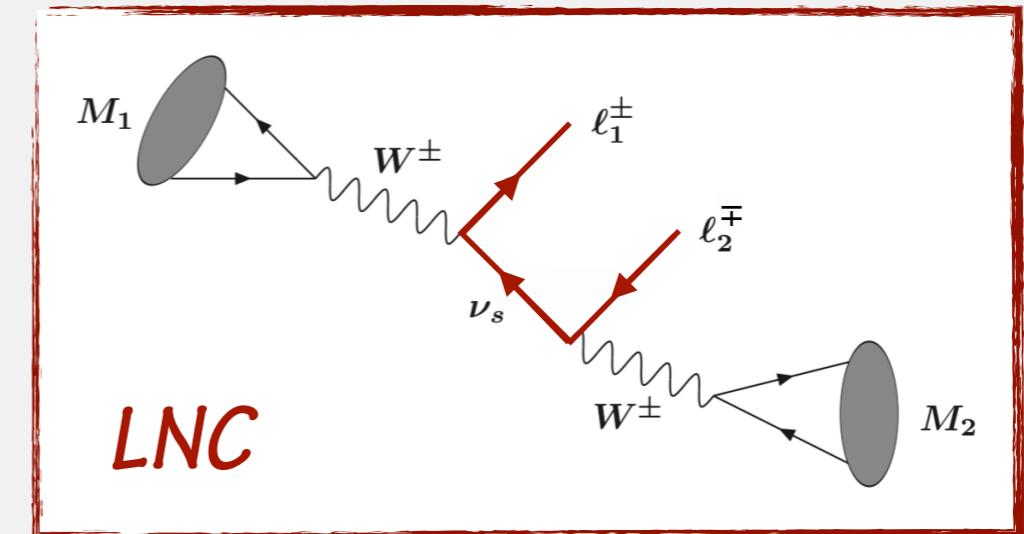
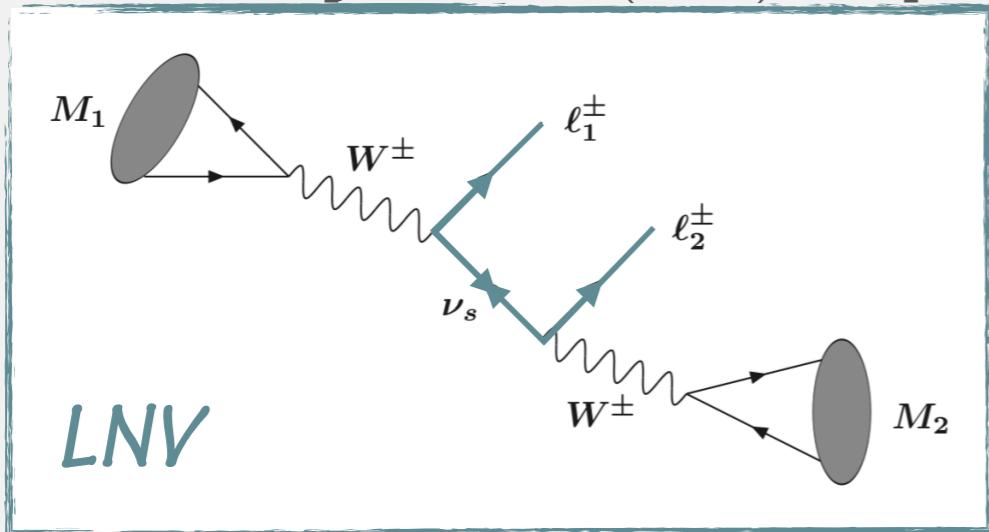
$$q^2 = m_4^2$$

narrow width approx.

$$\frac{1}{(q^2 - m_4^2)^2 + m_4^2 \Gamma_4^2} \sim \frac{\pi}{m_4 \Gamma_4} \delta(q^2 - m_4^2)$$

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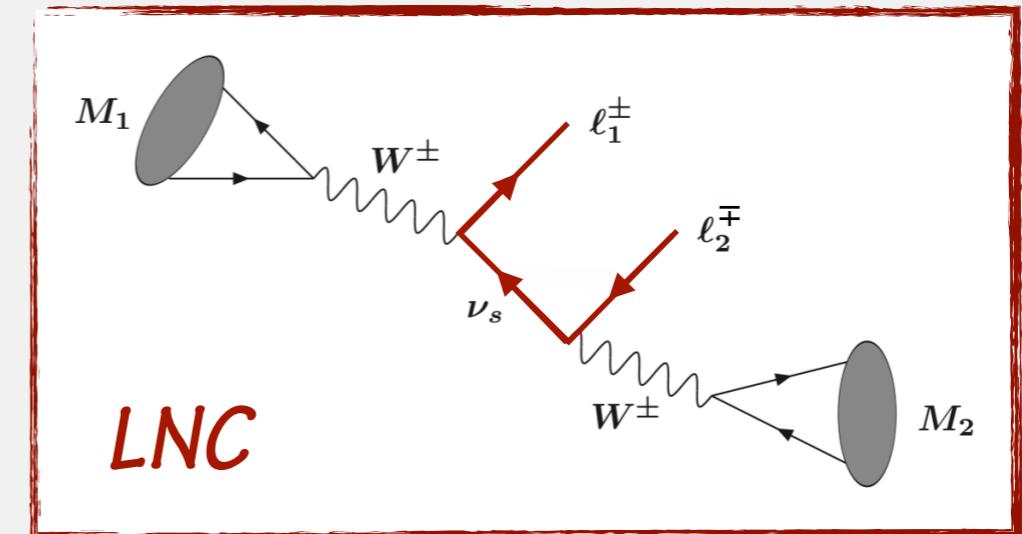
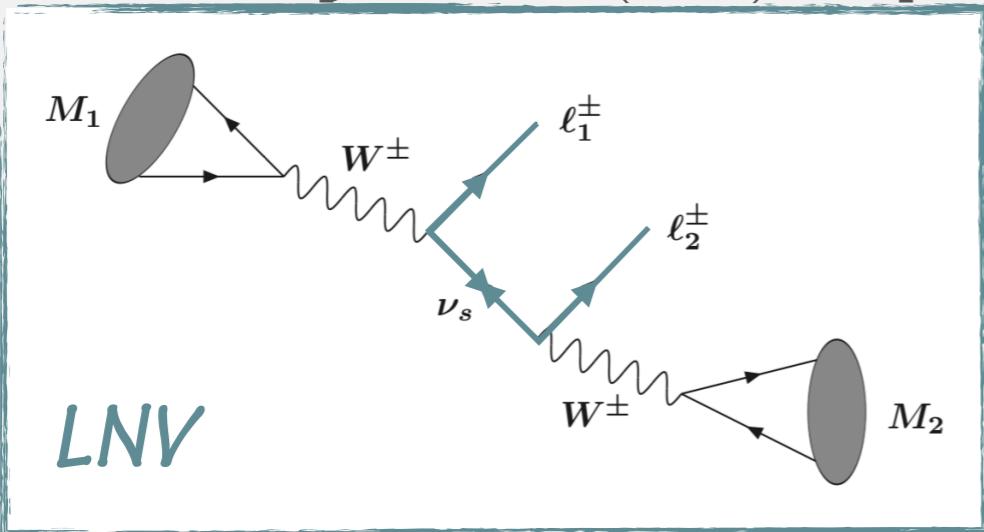
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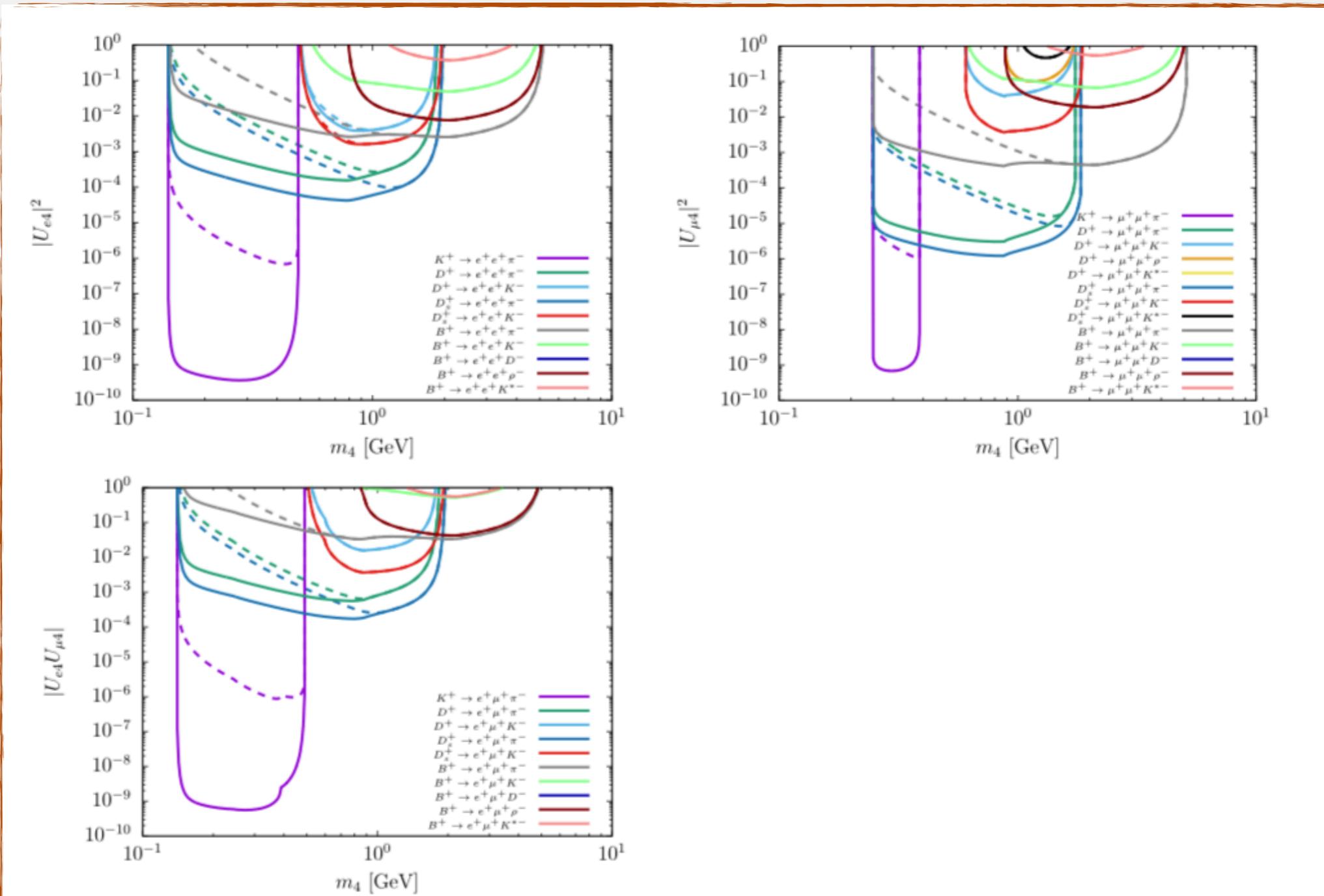
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$$\Gamma_{M_1 \rightarrow M_2 \ell^\pm \ell'^\pm}^{\text{LNV}} = \Gamma_{M_1 \rightarrow M_2 \ell^\pm \ell'^\mp}^{\text{LNC}}$$

Bounds on the one Neutrino case

Abada et al. [JHEP 1802 (2018) 169]



Semileptonic LNV&LNC decays (II)

in presence of two heavy Majorana neutrinos
interference

Computations with 2 neutrinos

- ▶ Similar to the one N case, but two contributions

$$\begin{aligned} \left| \mathcal{A}_{M \rightarrow M' \ell_\alpha^+ \ell_\beta^+}^{\text{LNV}} \right|^2 &\propto \left| U_{\alpha 4} U_{\beta 4} f(m_4) + U_{\alpha 5} U_{\beta 5} f(m_5) \right|^2 = \left| U_{\alpha 4} \right|^2 \left| U_{\beta 4} \right|^2 |f(M)|^2 \left| 1 + \kappa e^{\mp i(\psi_\alpha + \psi_\beta)} \right|^2 \\ \left| \mathcal{A}_{M \rightarrow M' \ell_\alpha^+ \ell_\beta^-}^{\text{LNC}} \right|^2 &\propto \left| U_{\alpha 4} U_{\beta 4}^* g(m_4) + U_{\alpha 5} U_{\beta 5}^* g(m_5) \right|^2 = \left| U_{\alpha 4} \right|^2 \left| U_{\beta 4} \right|^2 |g(M)|^2 \left| 1 + \kappa' e^{\mp i(\psi_\alpha - \psi_\beta)} \right|^2 \end{aligned}$$

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- ▶ Notation:

$$M = \frac{1}{2}(m_5 + m_4), \quad \Delta M = \frac{1}{2}(m_5 - m_4)$$

$$\kappa \equiv \frac{|U_{\alpha 5} U_{\beta 5}|}{|U_{\alpha 4} U_{\beta 4}|} \frac{f(m_5)}{f(m_4)}, \quad \kappa' \equiv \frac{|U_{\alpha 5} U_{\beta 5}^*|}{|U_{\alpha 4} U_{\beta 4}^*|} \frac{g(m_5)}{g(m_4)}$$

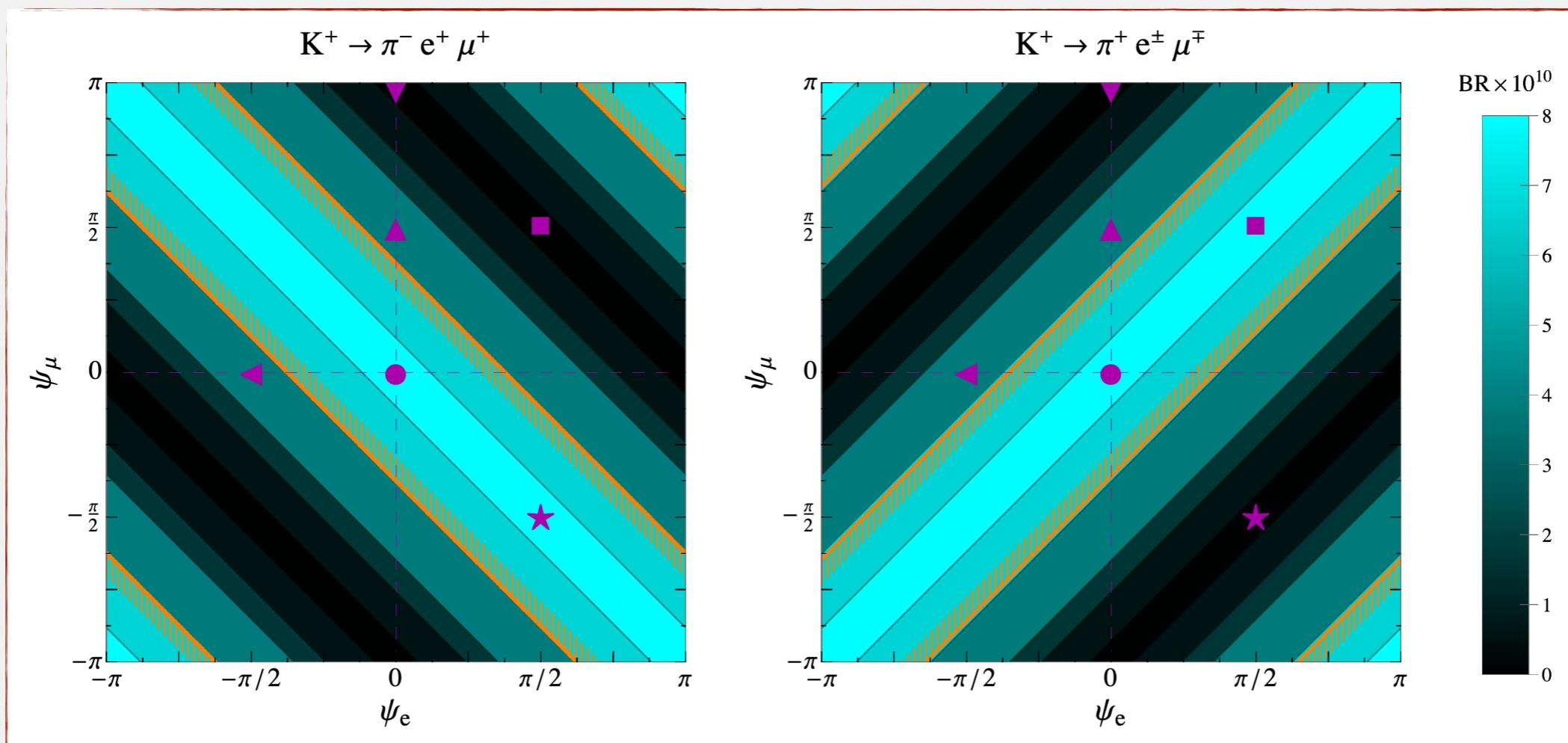
$$\psi_\alpha \equiv \phi_{\alpha 5} - \phi_{\alpha 4} \text{ where } U_{\alpha i} = e^{-i\phi_{\alpha i}} |U_{\alpha i}|$$

 **relative phases for each flavor**

Relative phases in LNV and LFC

$$\text{LNV} \sim (\psi_\alpha + \psi_\beta)$$

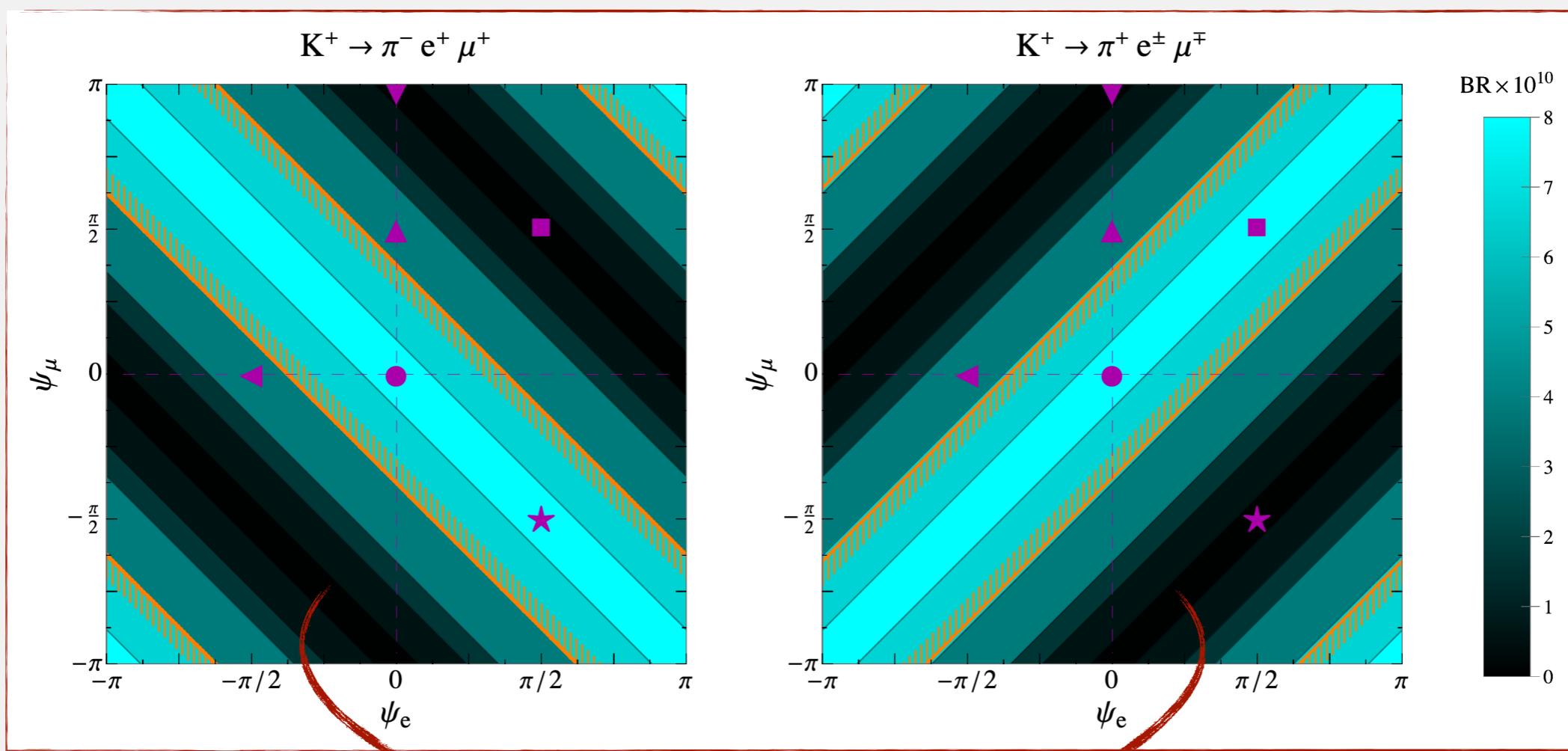
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Relative phases in LNV and LNV

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destructive interferences

Exploring the interference

- ▶ Conditions to have relevant interference effects if

$$\Delta M \ll M \text{ and } \Delta M < \Gamma_N$$

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- ▶ Define LNV/LNC ratio:

$$R_{\ell_\alpha \ell_\beta} \equiv \frac{\Gamma_{M \rightarrow M' \ell_\alpha^\pm \ell_\beta^\mp}^{\text{LNV}}}{\Gamma_{M \rightarrow M' \ell_\alpha^\pm \ell_\beta^\mp}^{\text{LNC}}}$$

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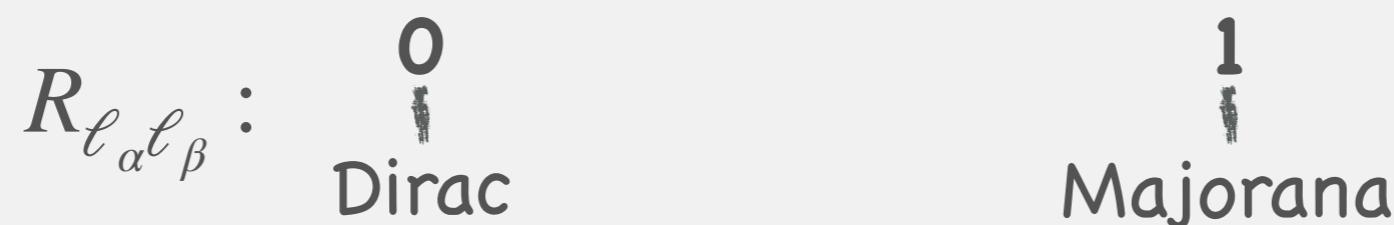
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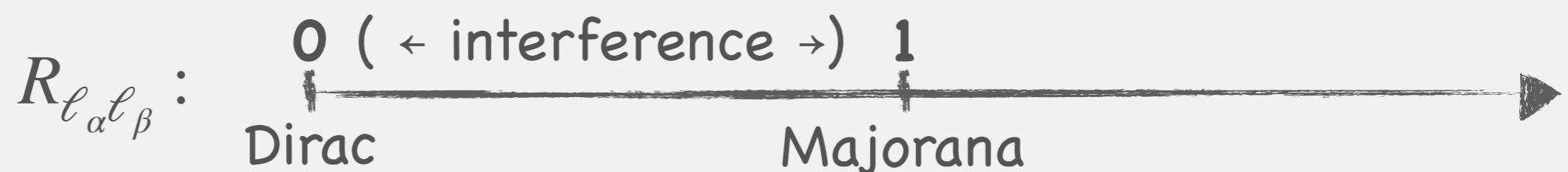
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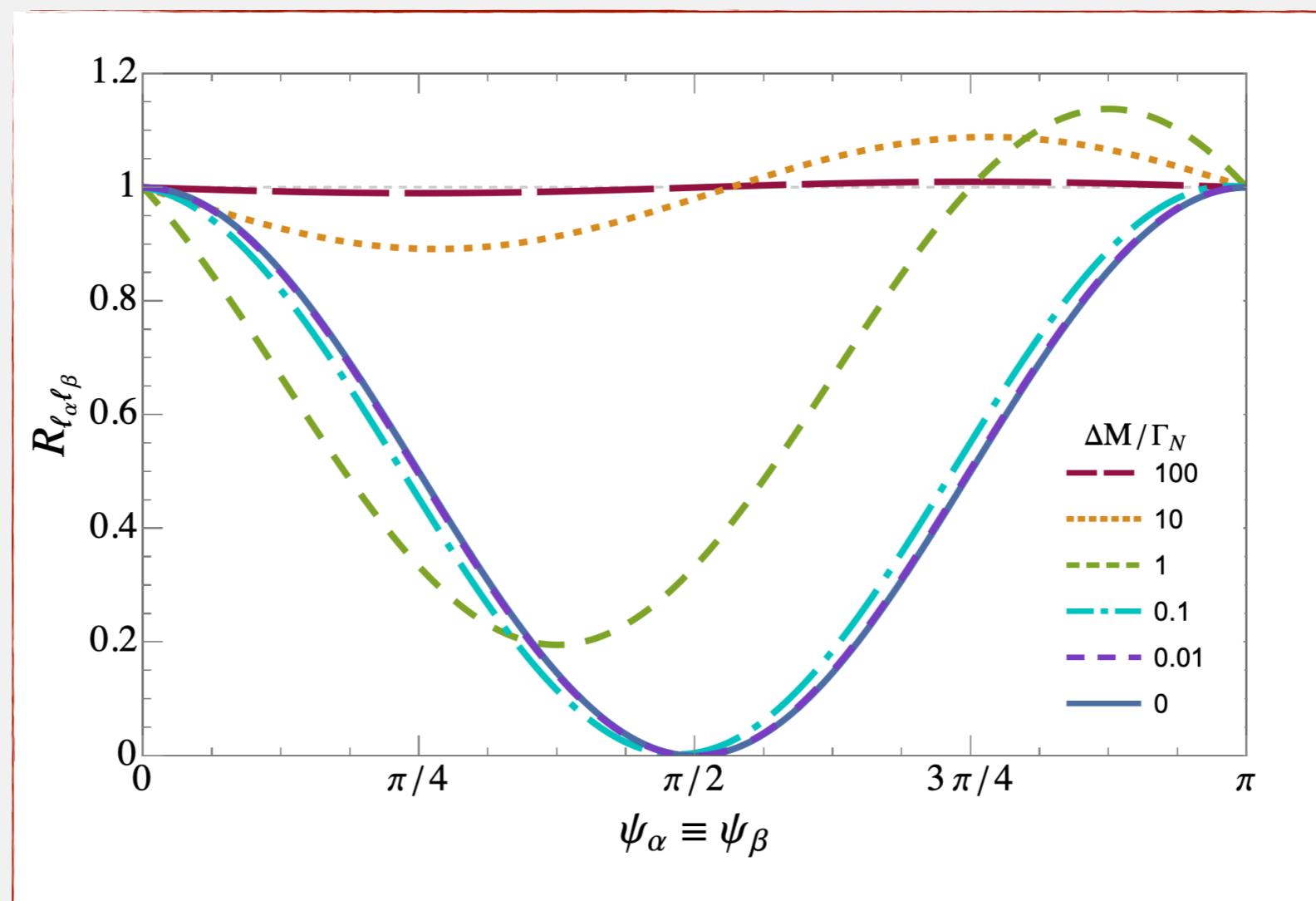
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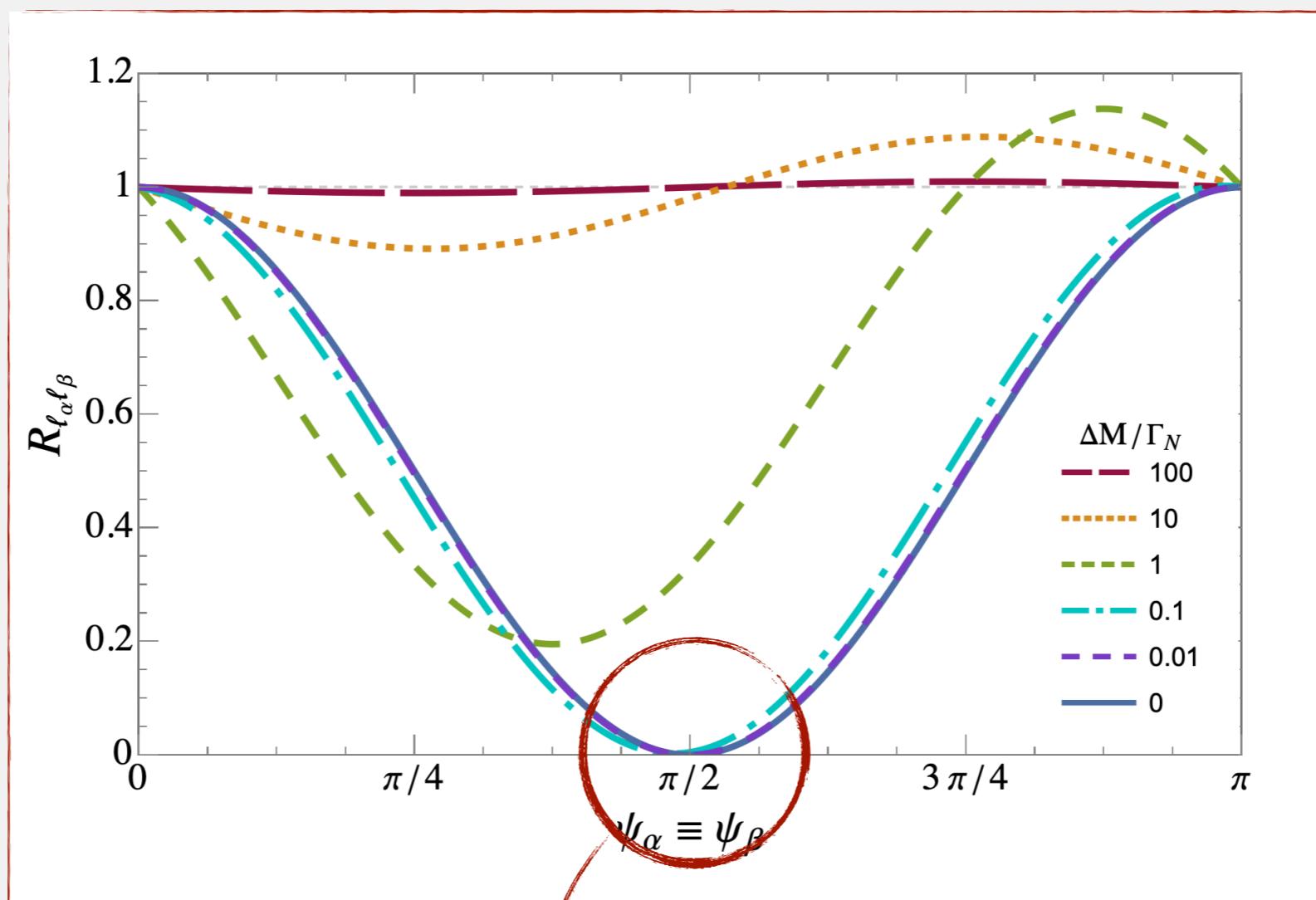
Interference: simple case $\psi_\alpha \equiv \psi_\beta$

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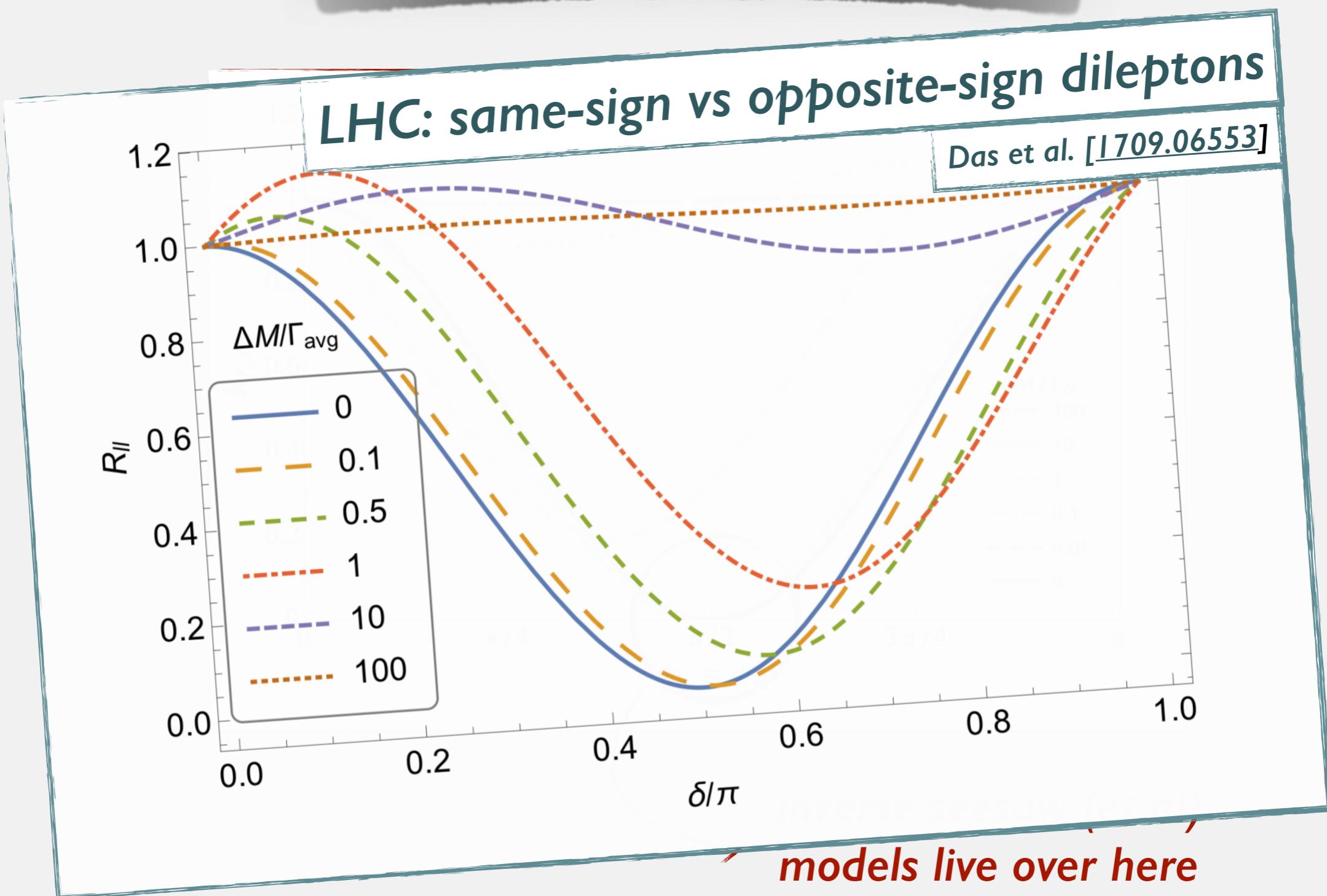
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inverse seesaw (et al)
models live over here

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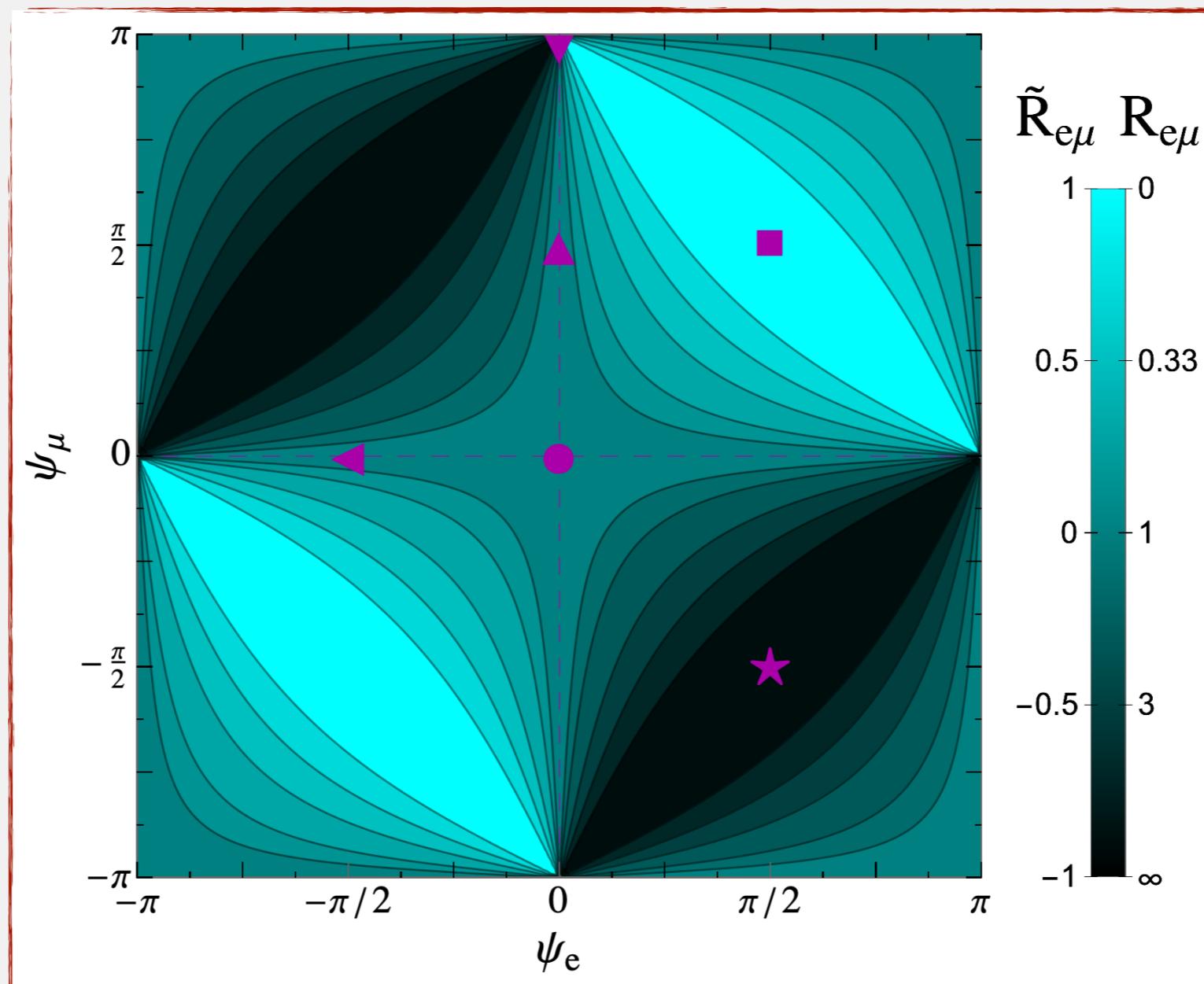


Interference: more general case



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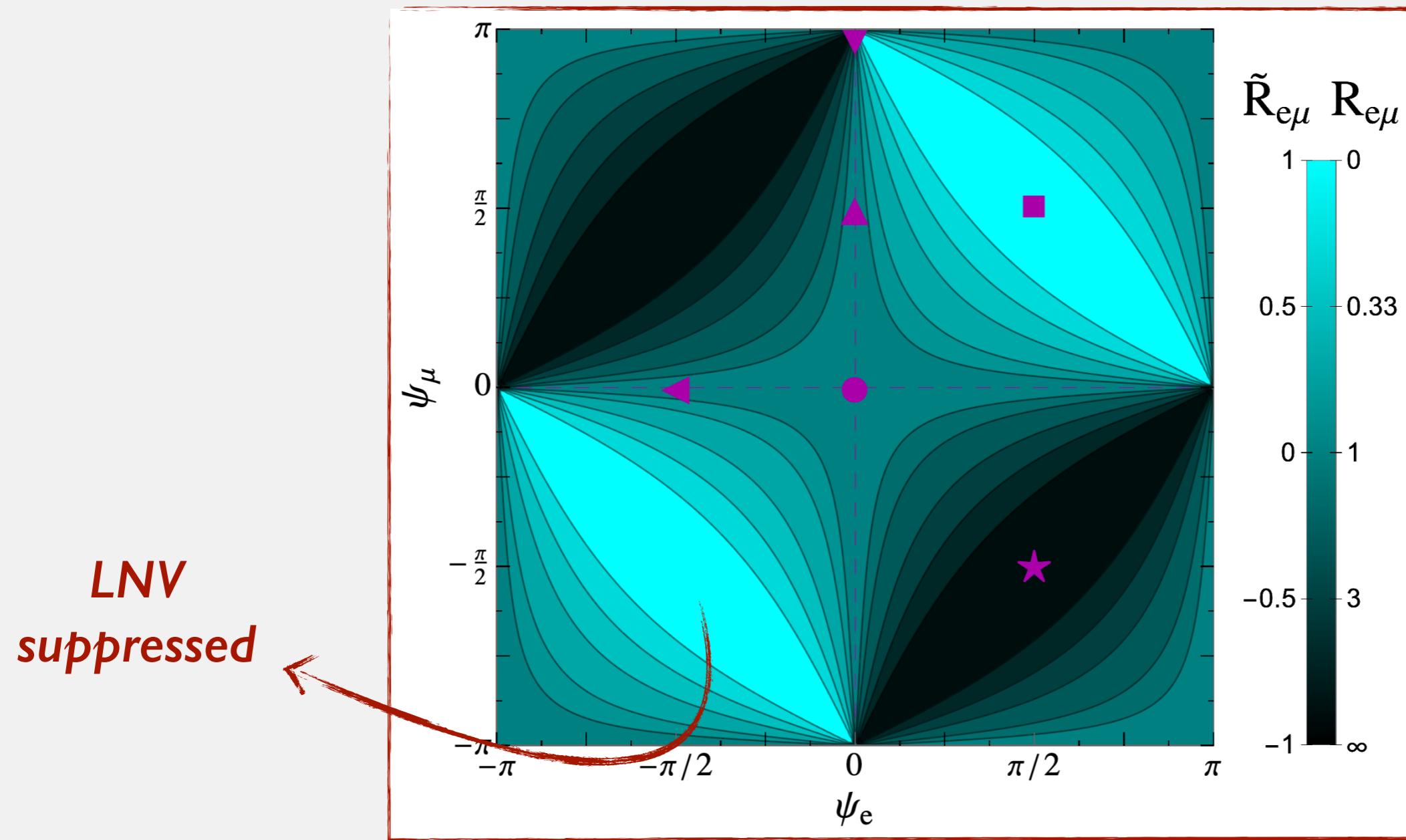
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Interference: more general case



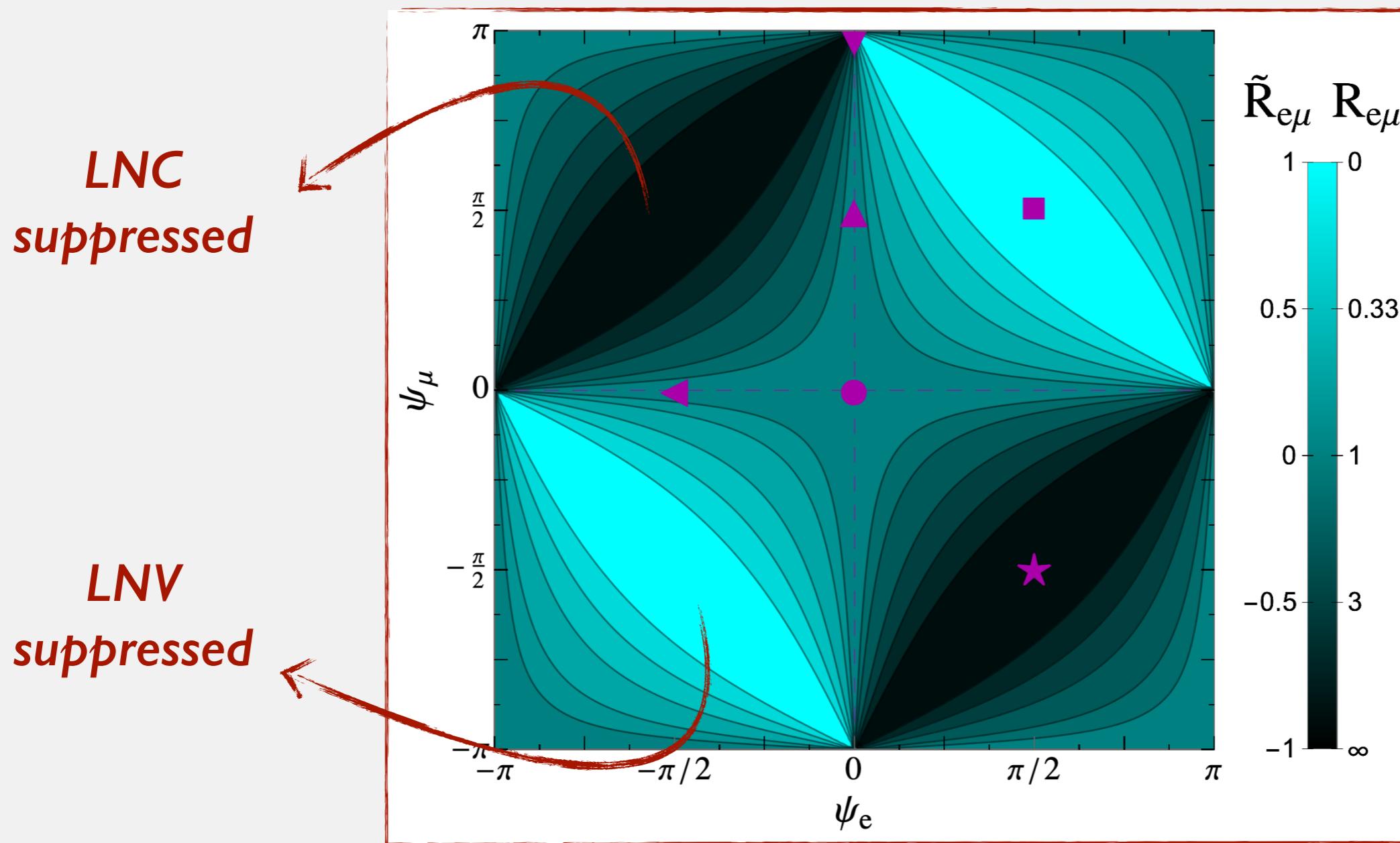
$$\text{LNV} \sim (\psi_\alpha + \psi_\beta) \quad \text{LNC} \sim (\psi_\alpha - \psi_\beta)$$



Interference: more general case



$$\text{LNV} \sim (\psi_\alpha + \psi_\beta) \quad \text{LNC} \sim (\psi_\alpha - \psi_\beta)$$



Learning about phases

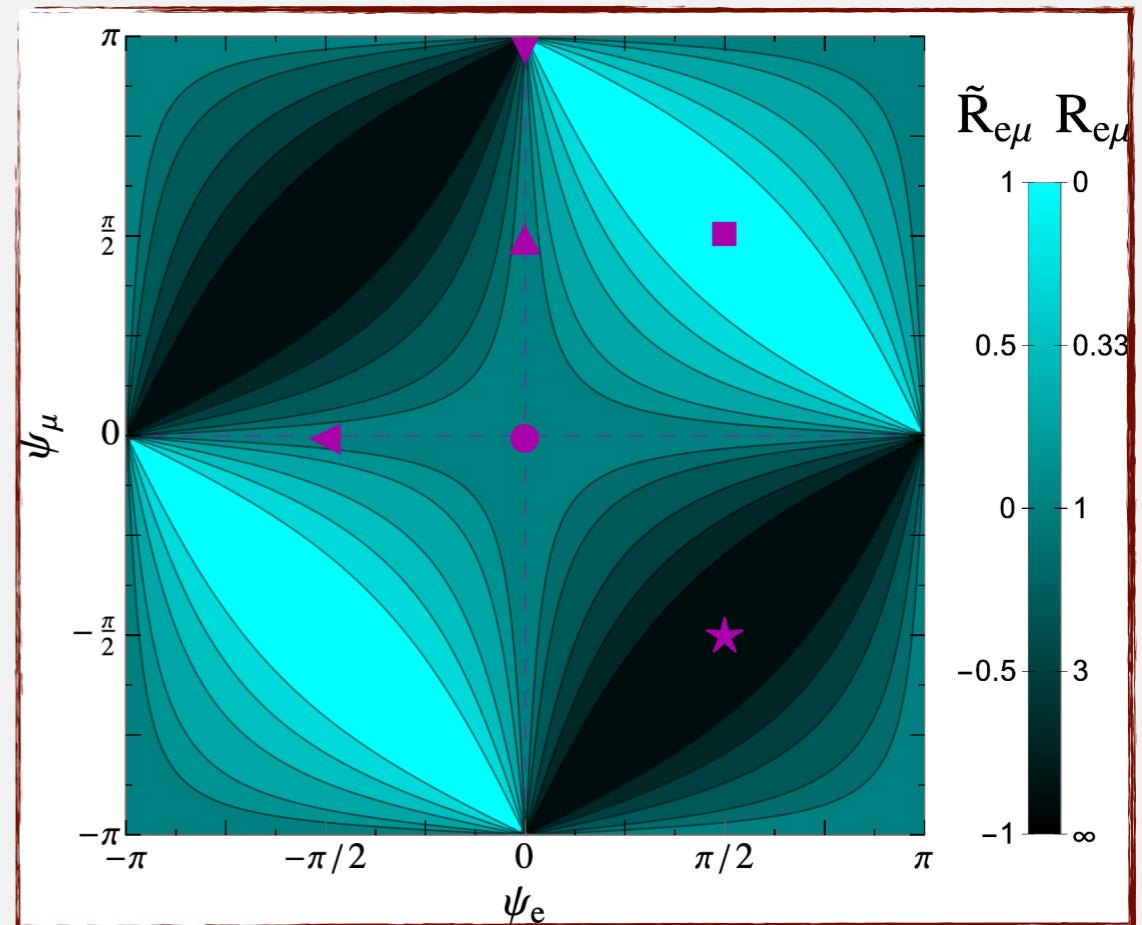
► Combine LNV and LFV searches:

$$K^+ \rightarrow \pi^- e^+ e^+$$

$$K^+ \rightarrow \pi^- \mu^+ \mu^+$$

$$K^+ \rightarrow \pi^- e^+ \mu^+$$

$$K^+ \rightarrow \pi^+ e^\pm \mu^\mp$$



(ψ_e, ψ_μ)	$e^\pm e^\pm$	$\mu^\pm \mu^\pm$	$e^\pm \mu^\pm$	$e^\mp \mu^\pm$
● (0, 0)	👍	👍	👍	👍
■ ($\pi/2, \pi/2$)	👎	👎	👎	👍
★ ($\pi/2, -\pi/2$)	👎	👎	👍	👎
▼ (0, π)	👍	👍	👎	👎
▲ (0, $\pi/2$)	👍	👎	1/2	1/2
◀ ($-\pi/2, 0$)	👎	👍	1/2	1/2

Conclusions

Neutrino mass generation is a mystery
are there new neutrinos? are they Majorana?

Semileptonic meson decays
good place to search for MeV-GeV heavy neutrinos

Comparing LNV and LNC ratios
learn about the Majorana/Dirac nature of heavy neutrinos

$$R = \begin{cases} 1 & \Rightarrow \text{one Majorana neutrino} \\ 0 & \Rightarrow \text{Dirac neutrinos or interfering Majorana neutrinos} \\ \text{else} & \Rightarrow \text{interfering Majorana neutrinos} \end{cases}$$

Interference effect may also impact the bounds derived
assuming only one Majorana neutrino
to be continued...

A large, colorful word cloud centered around the words "thank" and "you" in various languages. The words are rendered in different colors and sizes, creating a dense and visually appealing composition. The languages represented include English, German, French, Spanish, Italian, Portuguese, Dutch, Swedish, Polish, Czech, Russian, Chinese, Japanese, Korean, Vietnamese, Thai, Indonesian, Malay, and many others. The word "thank" is in blue, "you" is in yellow, and "gracias" is in red.

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