LNV AND LFV SEMILEPTONIC DECAYS FROM INTERFERING MAJORANA NEUTRINOS

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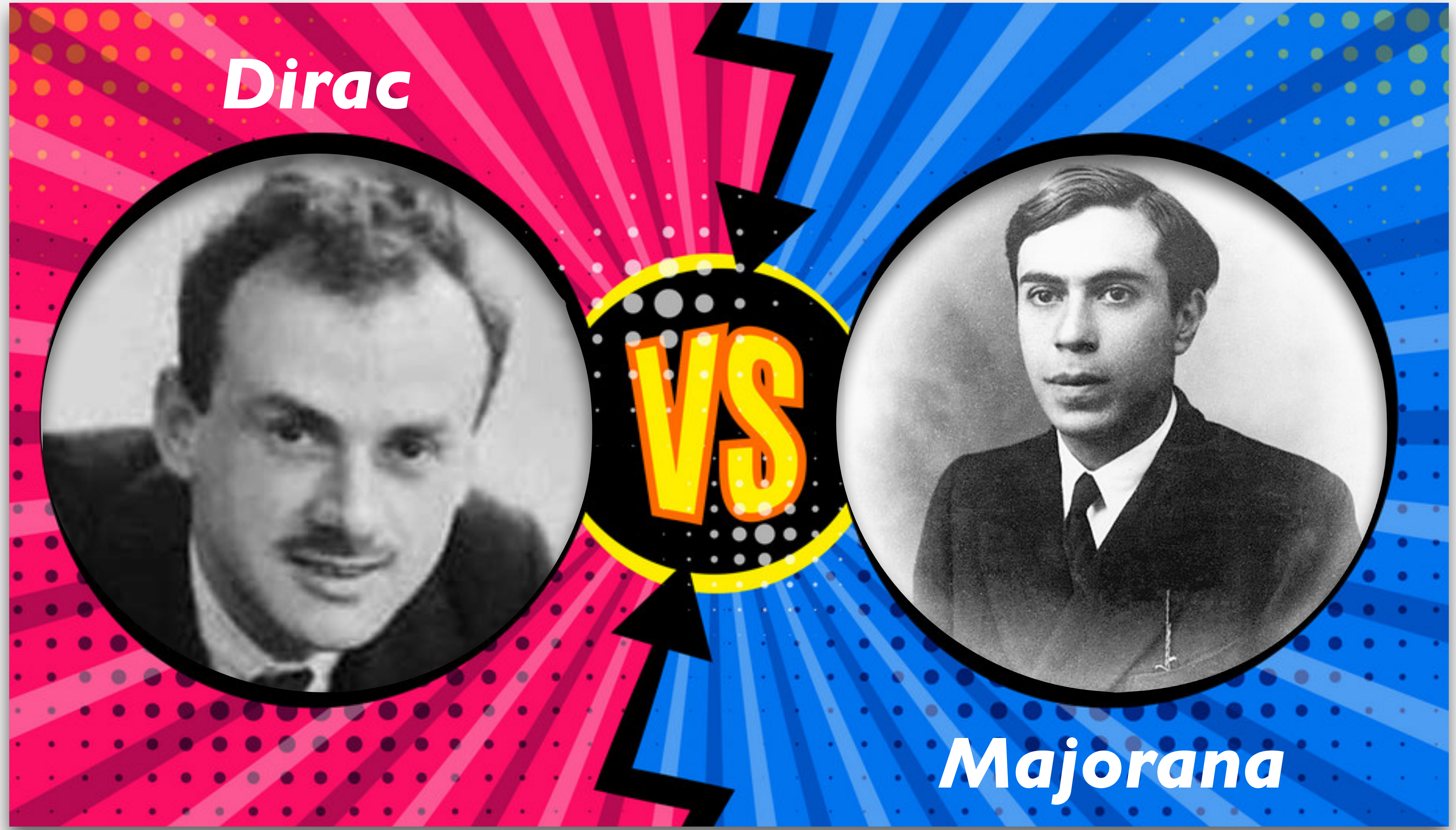
Why neutrinos?

Present knowns&unknown

$\theta_{12}, \theta_{23}, \theta_{13}$	✔	[34°, 50°, 8°]
Δm^2_{21}	✔	$\left[10^{-5}\ \mathrm{eV}^2\right]$
Δm^2_{31}	$\pm$ ✔	$\left[10^{-3}\ \mathrm{eV}^2\right]$
δ_{CP}	✘	
ϕ_1, ϕ_2	✘	
Mass ordering	✘	
Absolute mass scale	✘	
Neutrino nature	✘	

Neutrino Nature

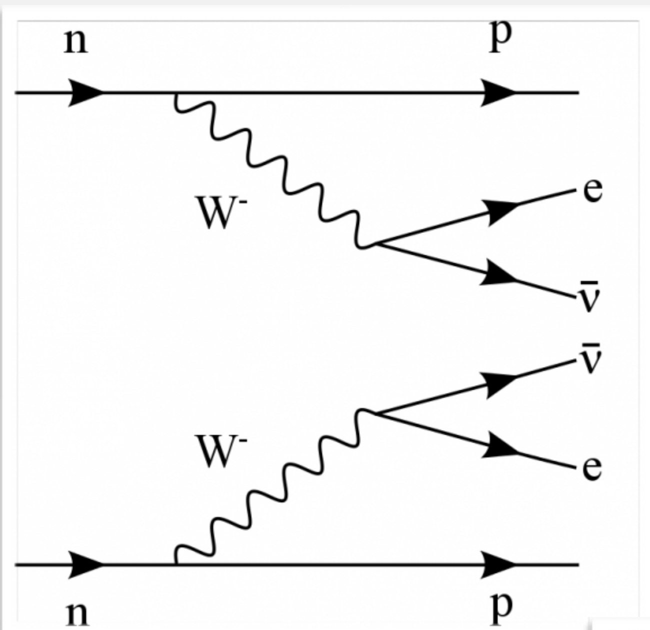


$$\nu^c \neq \nu \qquad\qquad \nu^c = \nu$$

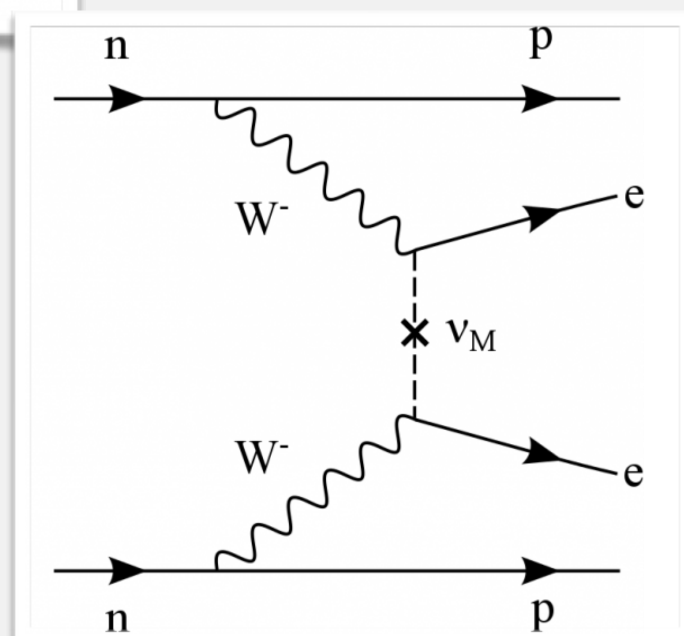
Neutrinoless Double Beta Decays

- Learn about **neutrinos** looking for **no neutrinos**

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



$2\nu\beta\beta$



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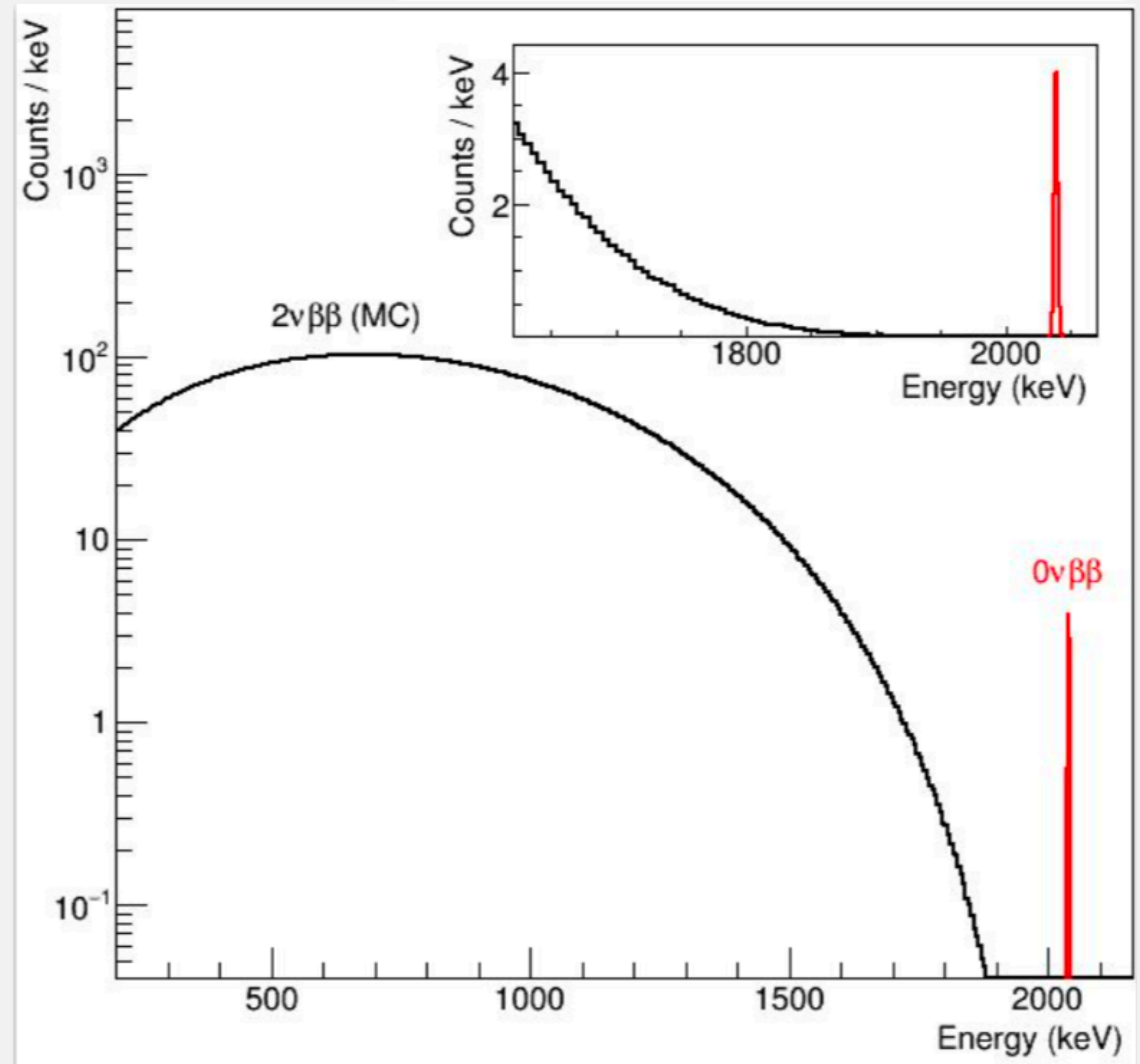
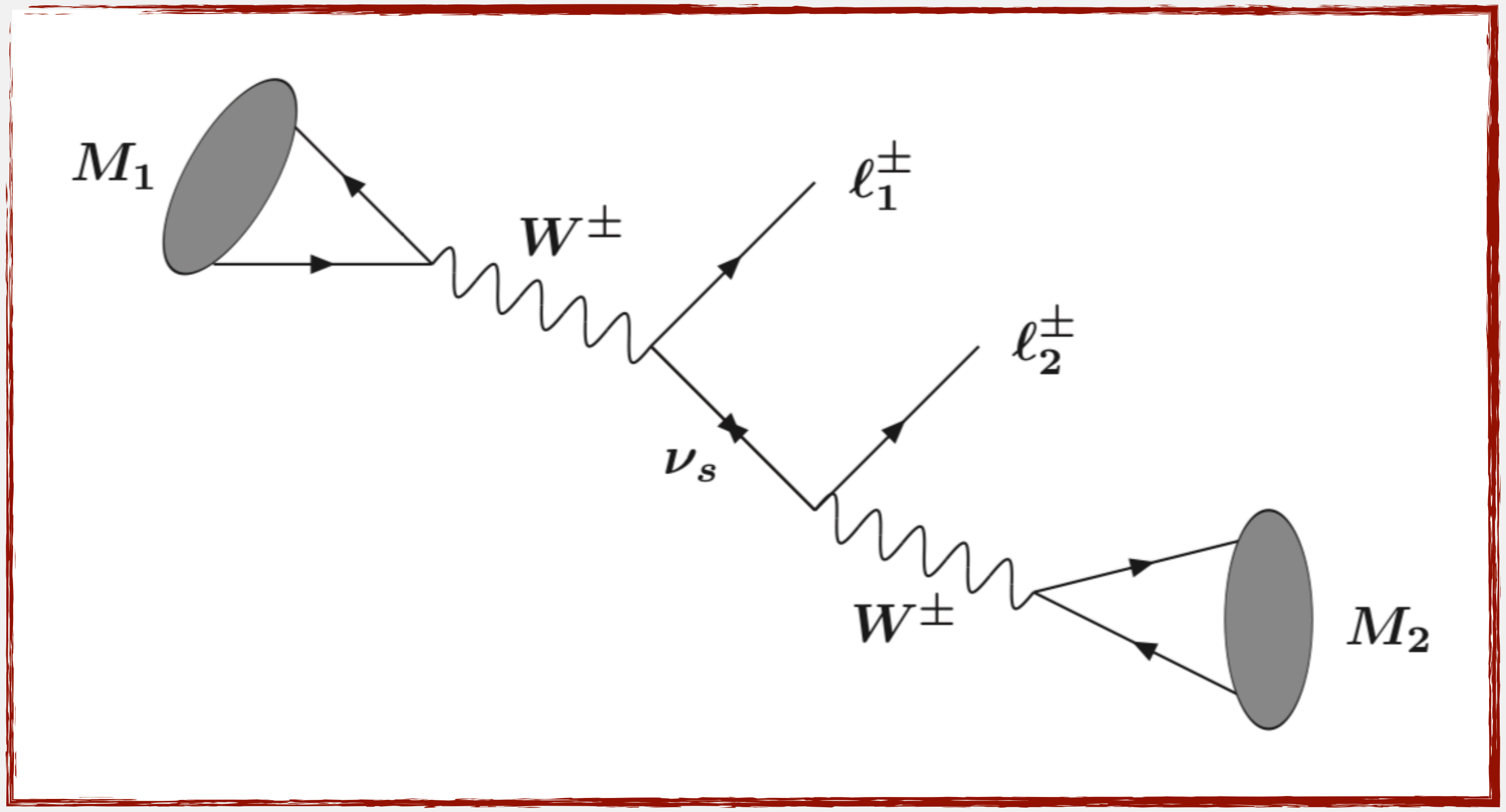


Ana Julia Zsigmond (GERDA), Neutrino 2018

LNV & LFV semileptonic meson decays



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

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

$\mathrm{BR}(K^+ \to \pi^- e^+ \mu^+) \leq 5.0 \times 10^{-10}$

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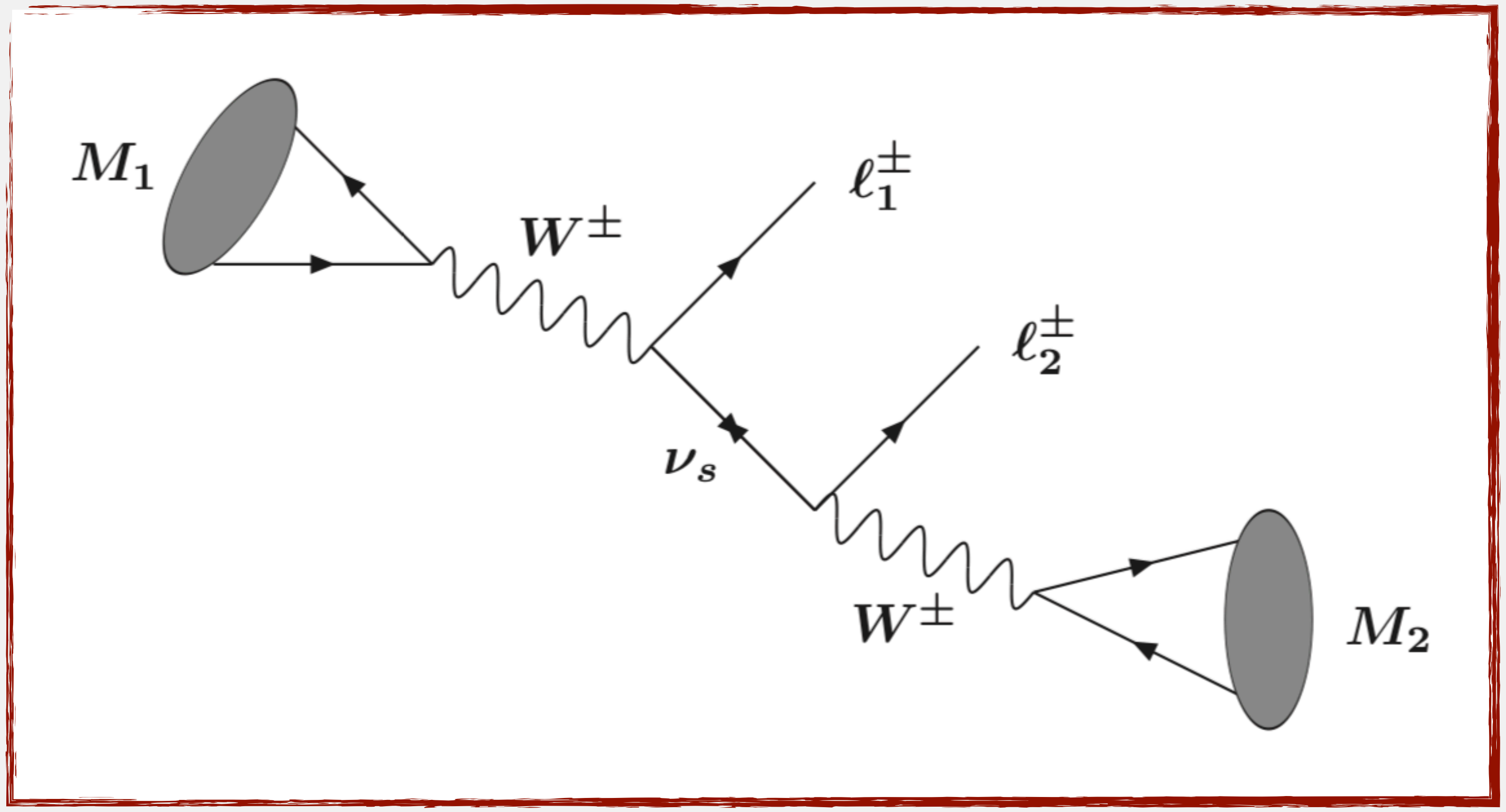

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NEW!!!
NA62 (2019)

Outline

Neutrino mass models

type-I, inverse, 'model independent' seesaws

Semileptonic LNV&LNC decays (I)

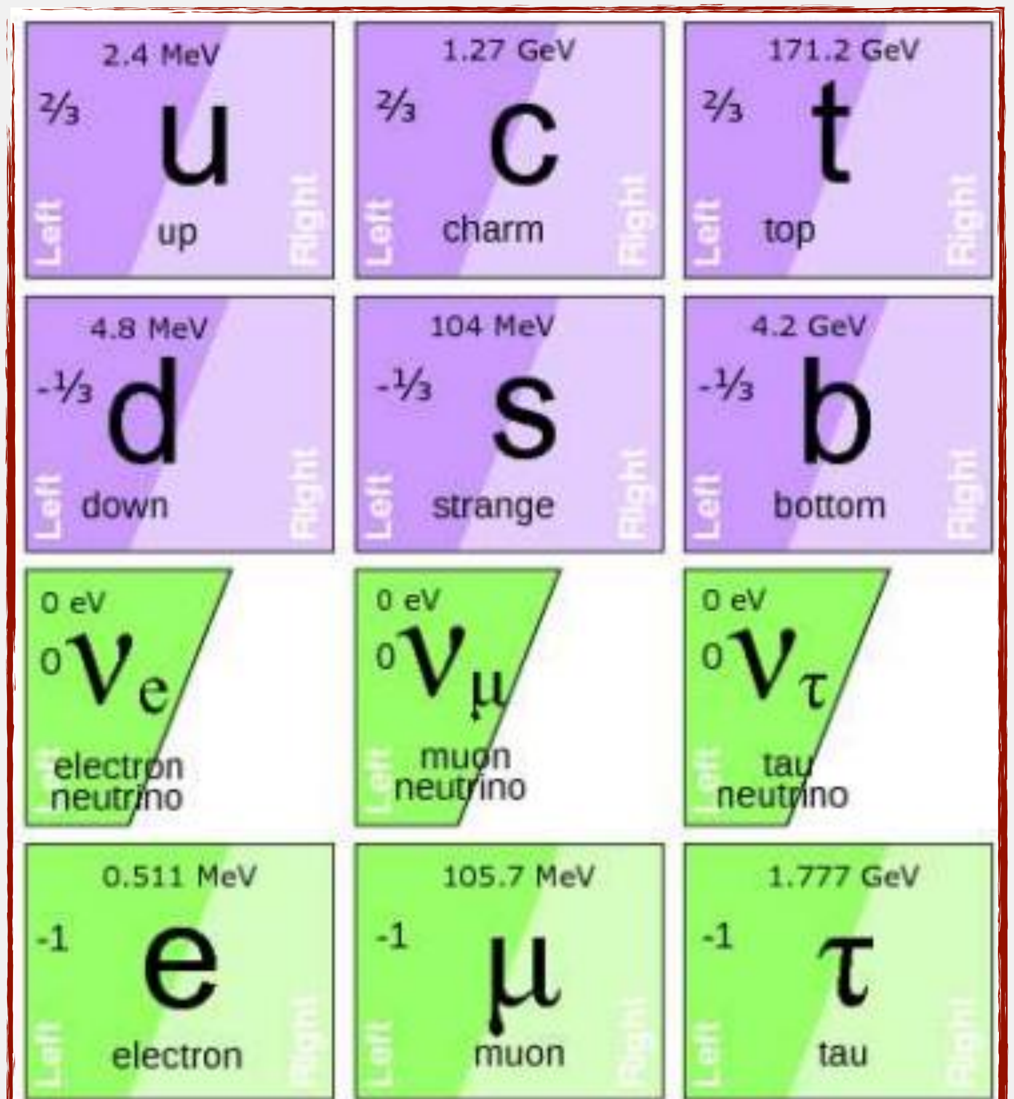
in presence of one heavy Majorana neutrino

Semileptonic LNV&LNC decays (II)

in presence of two heavy Majorana neutrinos

interference

Why massless in the SM?



- Higgs* mechanism

$$\mathcal{L}_{\text{Yukawa}} \sim \bar{L} H R\,, \qquad H = \begin{pmatrix} \omega^+ \\ v + \frac{h + i\omega^0}{\sqrt{2}} \end{pmatrix}$$

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

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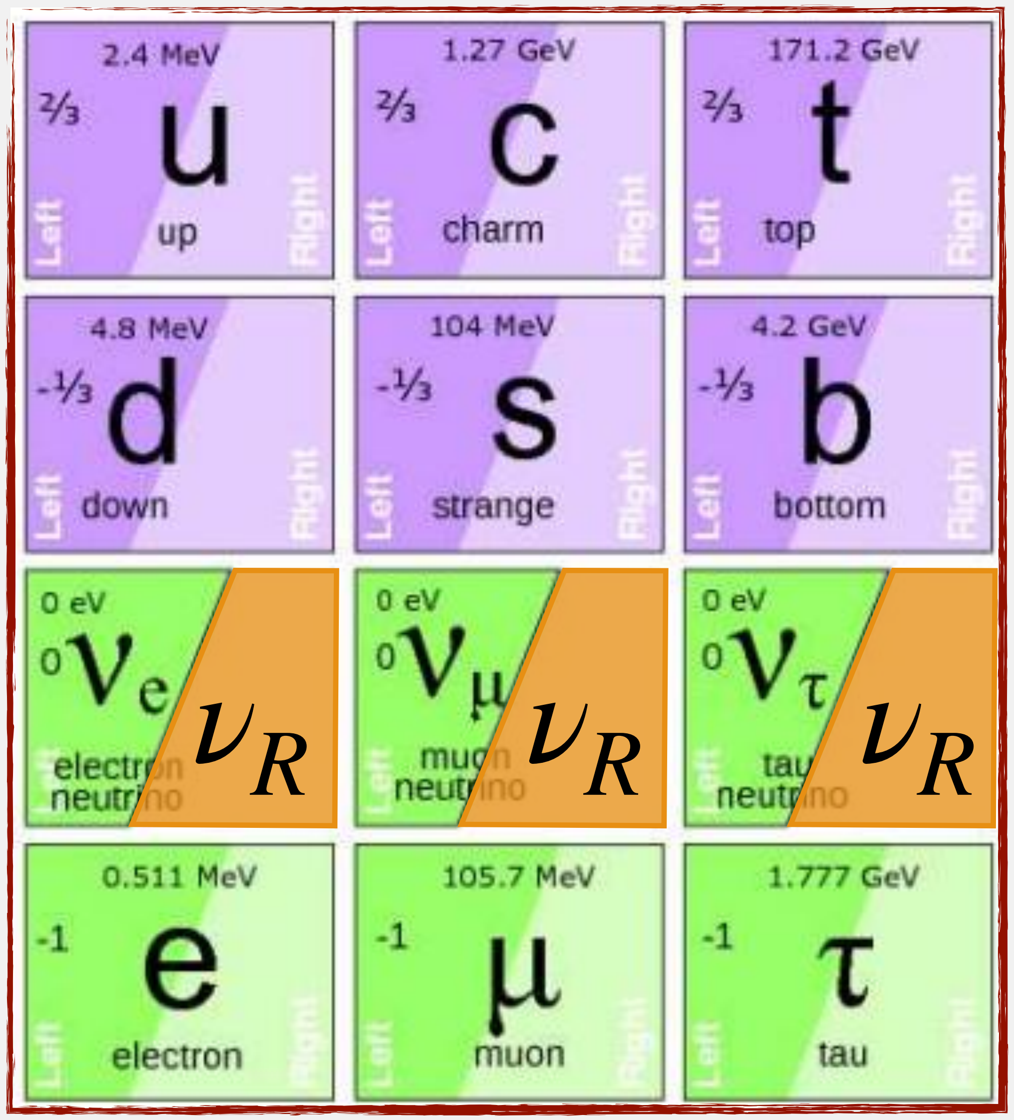

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- Add RH neutrinos

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

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

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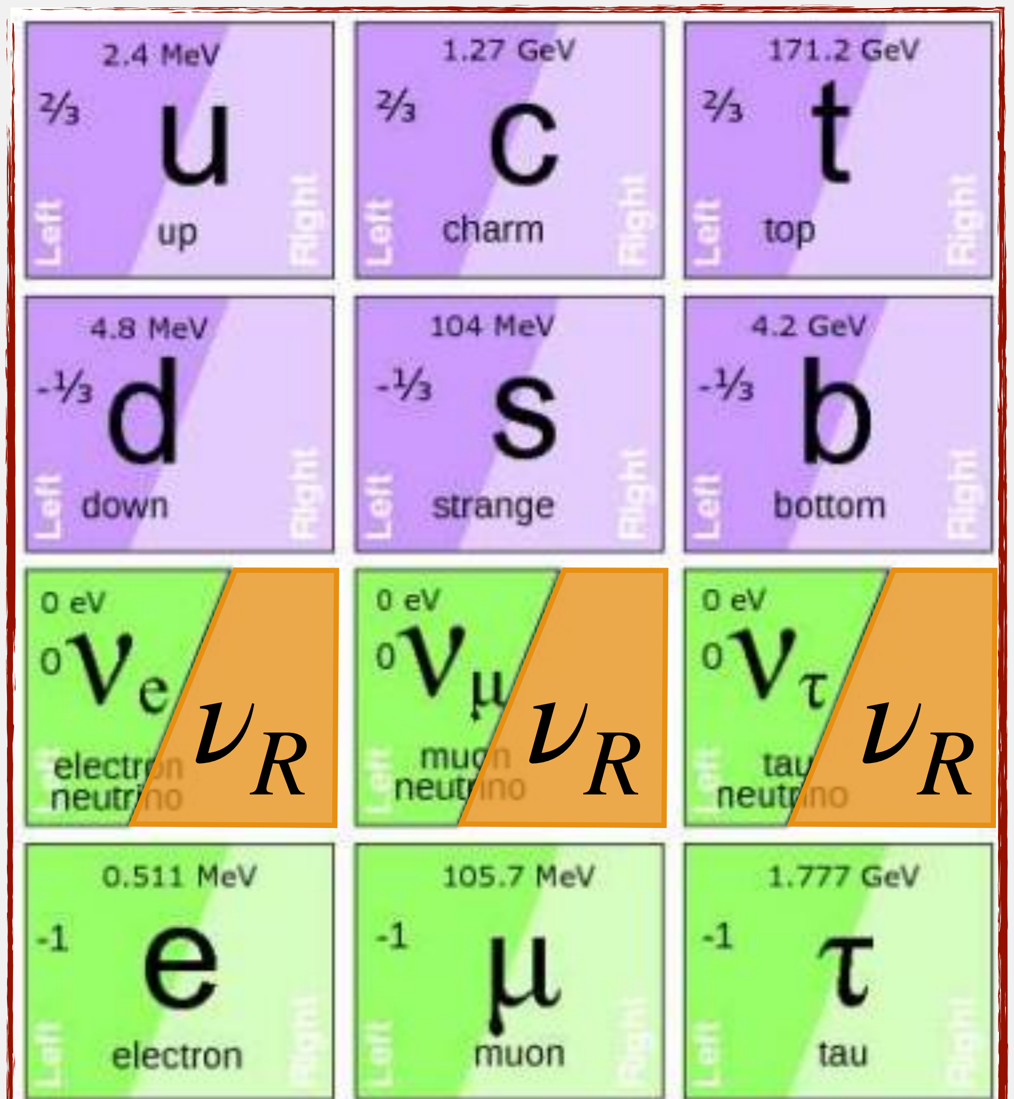

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- RH neutrinos are SM singlets

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

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

Seesaw mechanism (type-I)

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

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

- After the EW symmetry breaking

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

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

Inverse seesaw model

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

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

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

$$M^\nu_{\rm ISS} = \begin{pmatrix} 0 & m_D & 0 \\ m_D^T & 0 & M \\ 0 & M & \mu \end{pmatrix}$$

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

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

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 → $\mathrm{SM}_{m_\nu} + N$

- 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

$$U_\nu = \left(\begin{array}{c|cc} & U_{e4} & U_{e5} \\ \tilde{U}_{\rm PMNS} & U_{\mu 4} & U_{\mu 5} \\ & U_{\tau 4} & U_{\tau 5} \\ \hline & & \end{array}\right)$$

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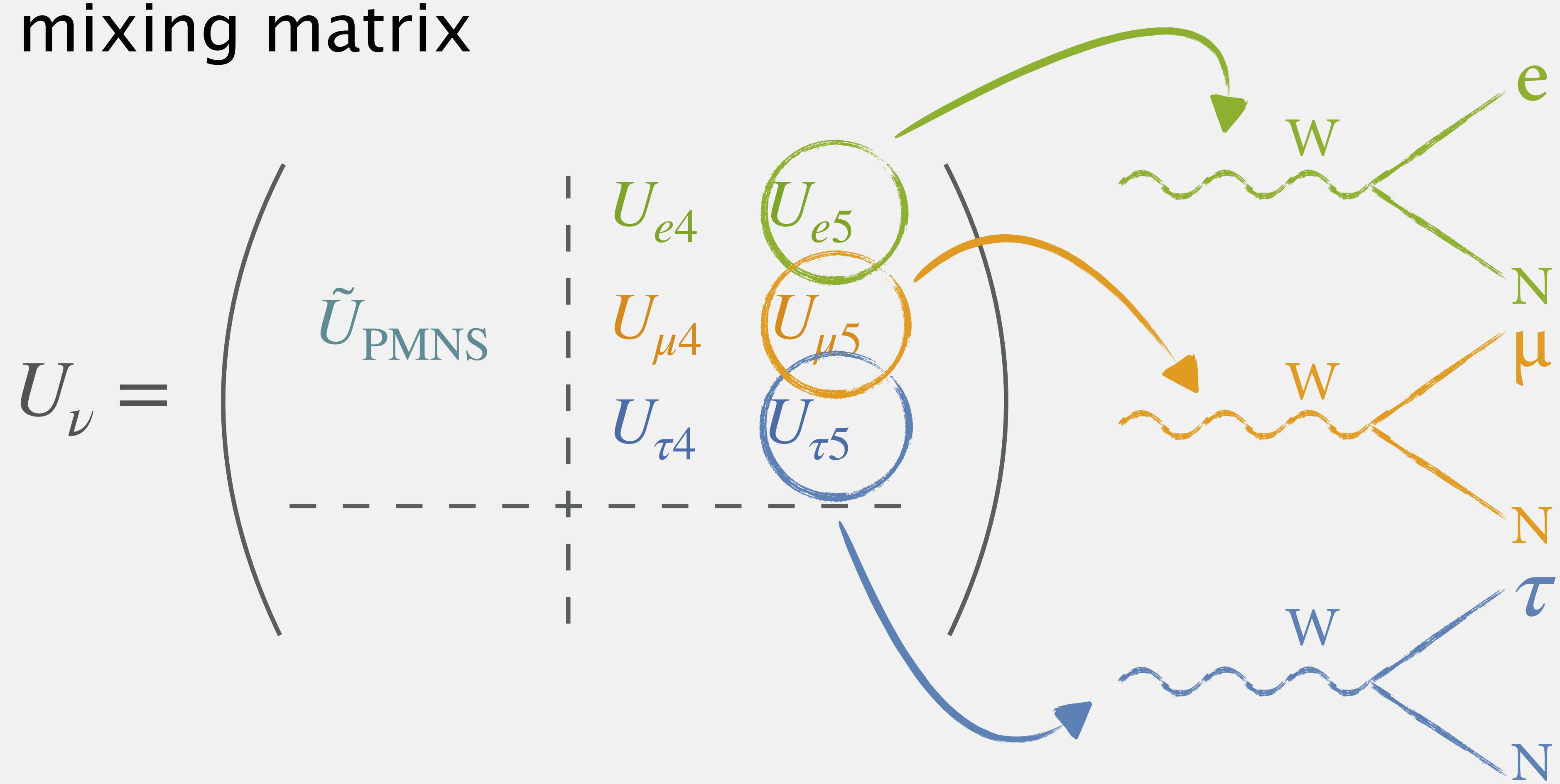

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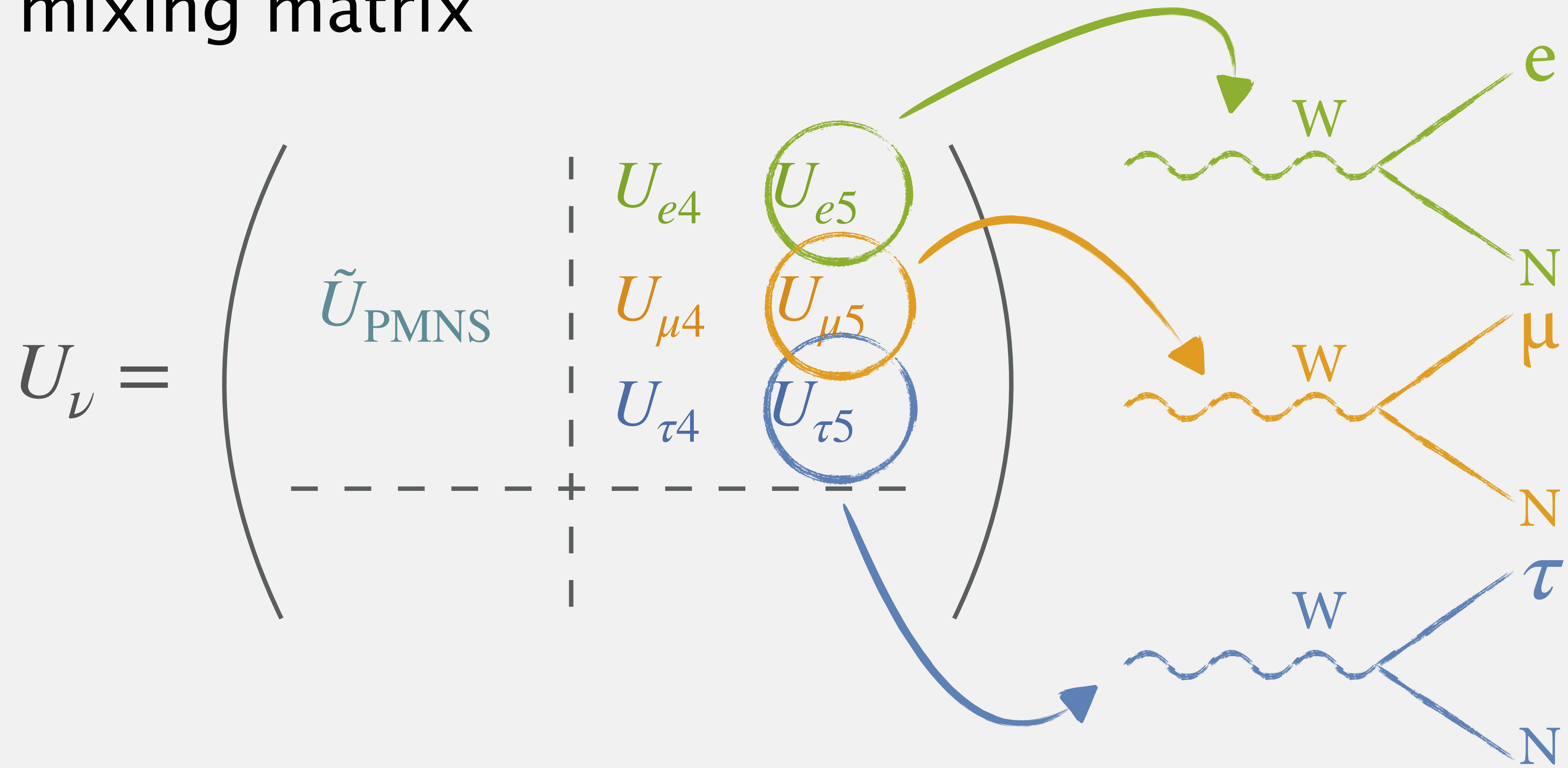
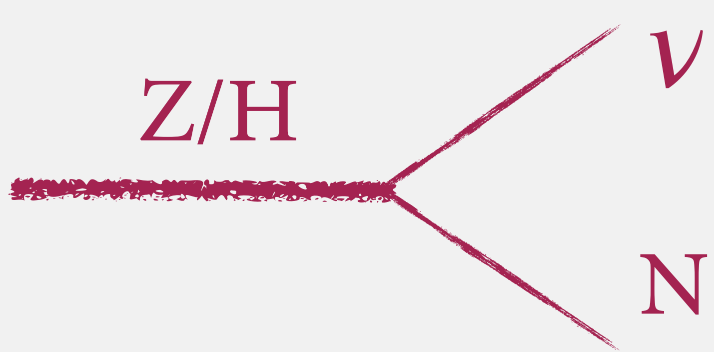


⊕Neutral currents



$\Gamma_4, \Gamma_5, \dots$

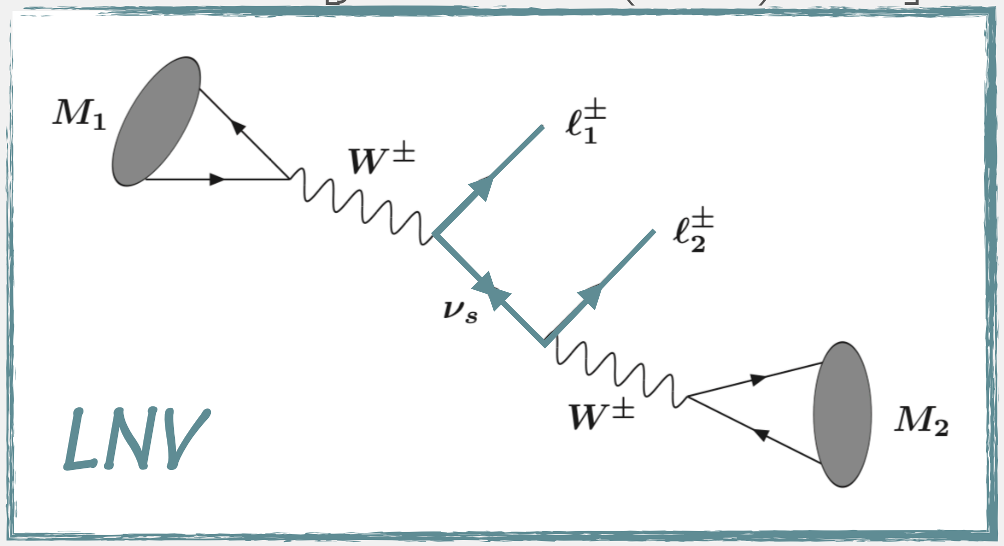
[0901.3589, 1712.03984, 1805.08567]

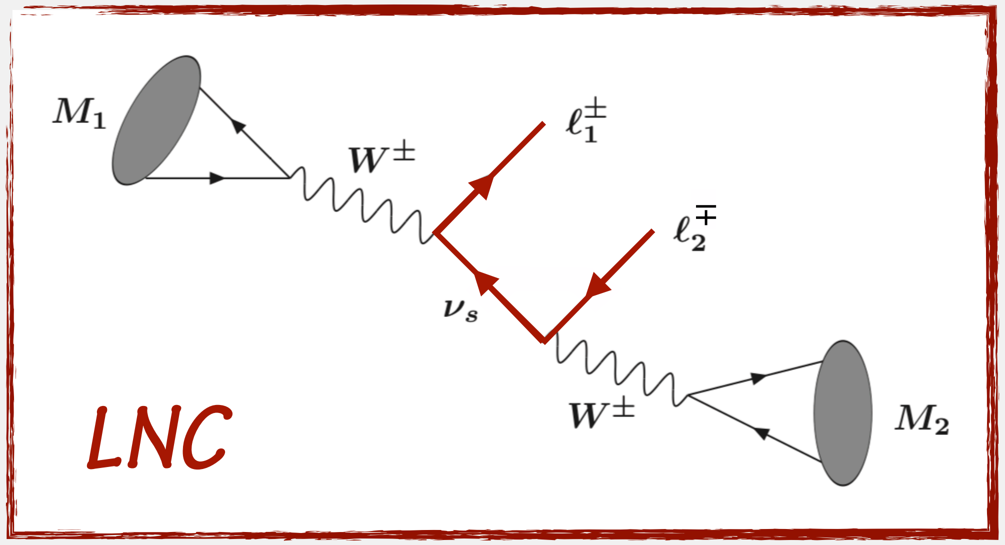
Semileptonic LNV&LNC decays (I)

in presence of one heavy Majorana neutrino

LNV&LNC from on-shell neutrinos

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





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

$$\mathcal{A}_{\rm LNC}\Big| \sim U_{\ell 4} \frac{\not{q}}{q^2 - m_4^2 - m_4\Gamma_4} U^*_{\ell' 4}$$

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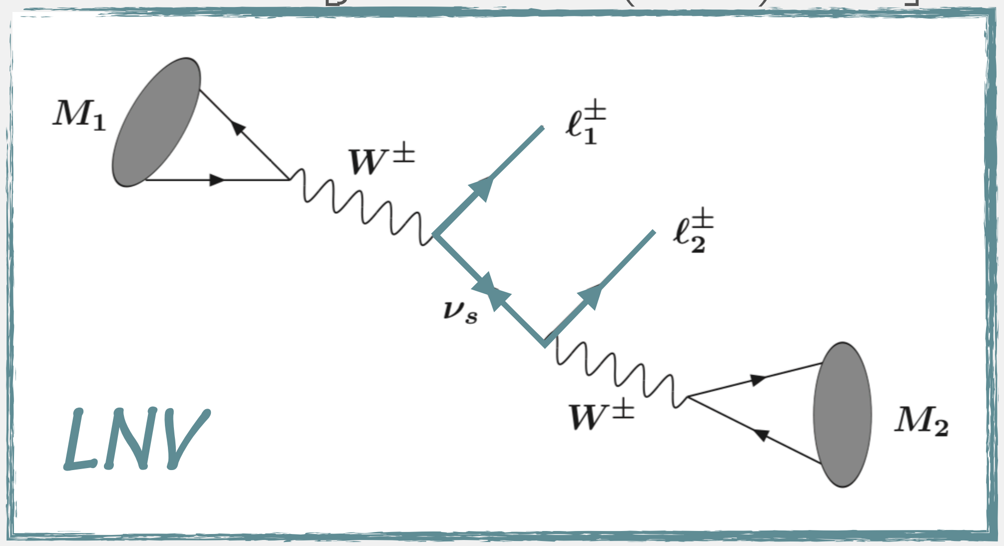

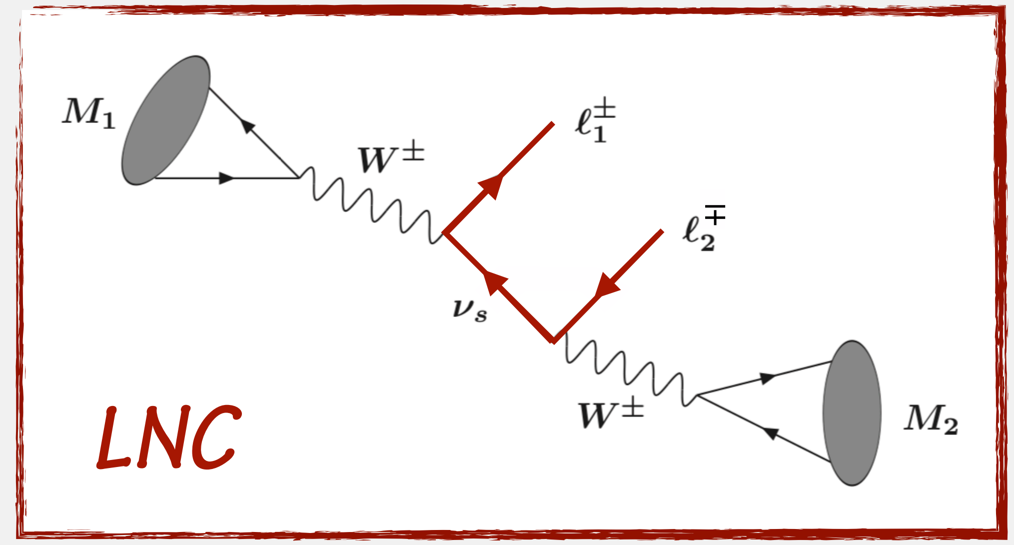

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on-shell neutrino $\qquad \not{q}^2 = m_4^2$

narrow width approx. $\qquad \frac{1}{(q^2 - m_4^2)^2 + m_4^2\Gamma_4^2} \sim \frac{\pi}{m_4\Gamma_4}\delta(q^2 - m_4^2)$

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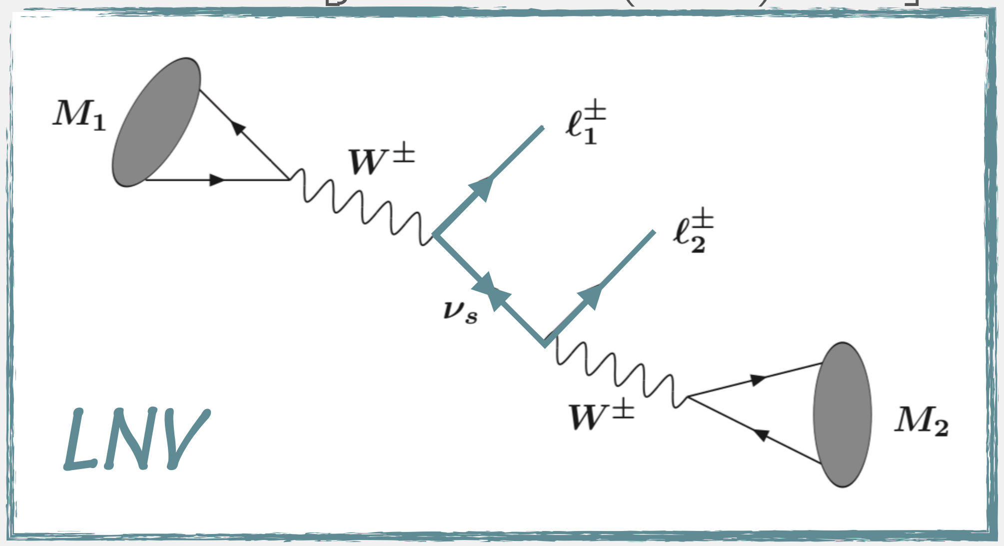

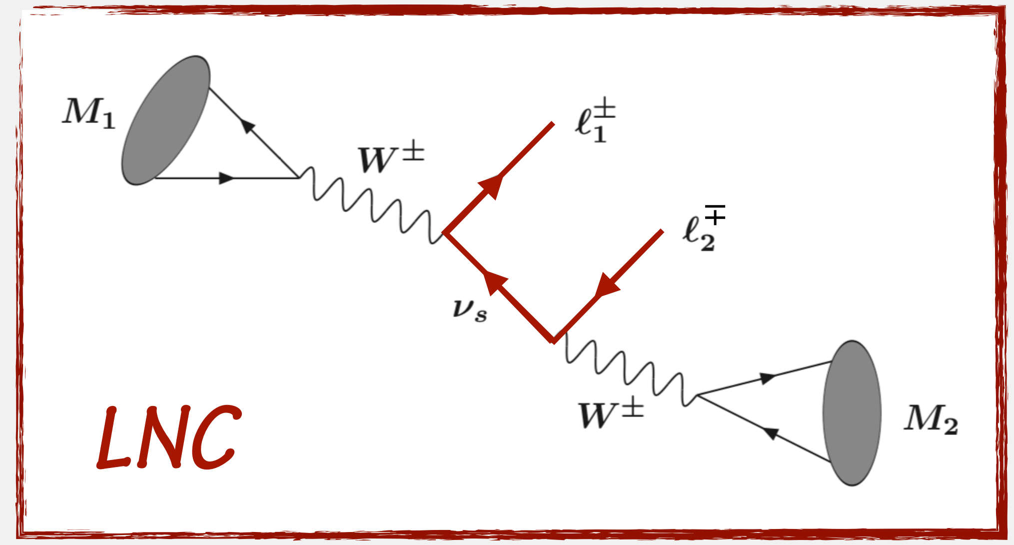

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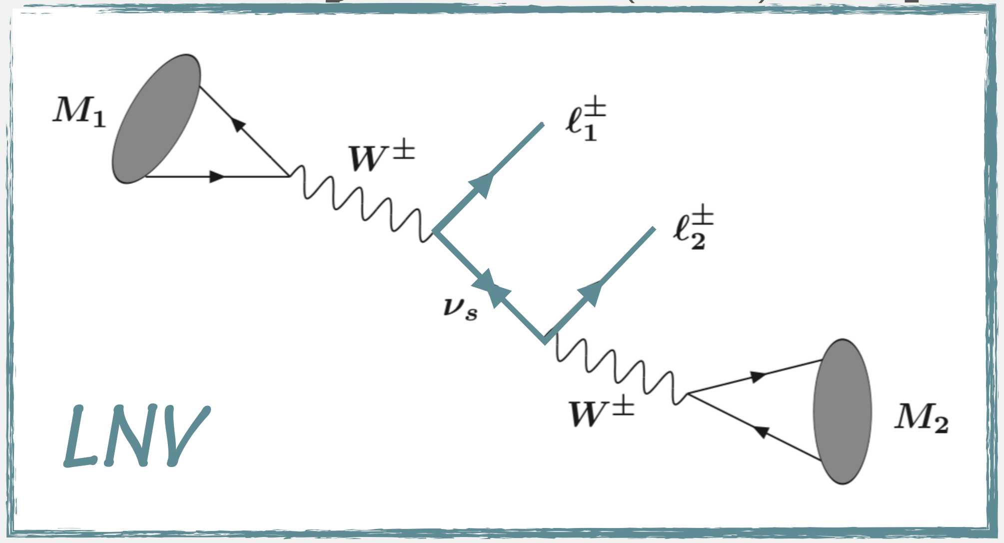

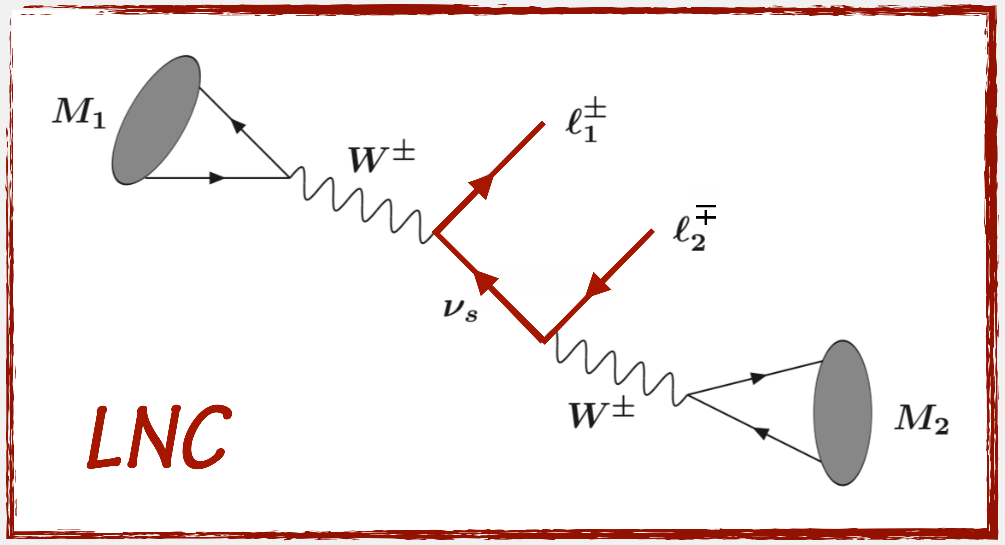

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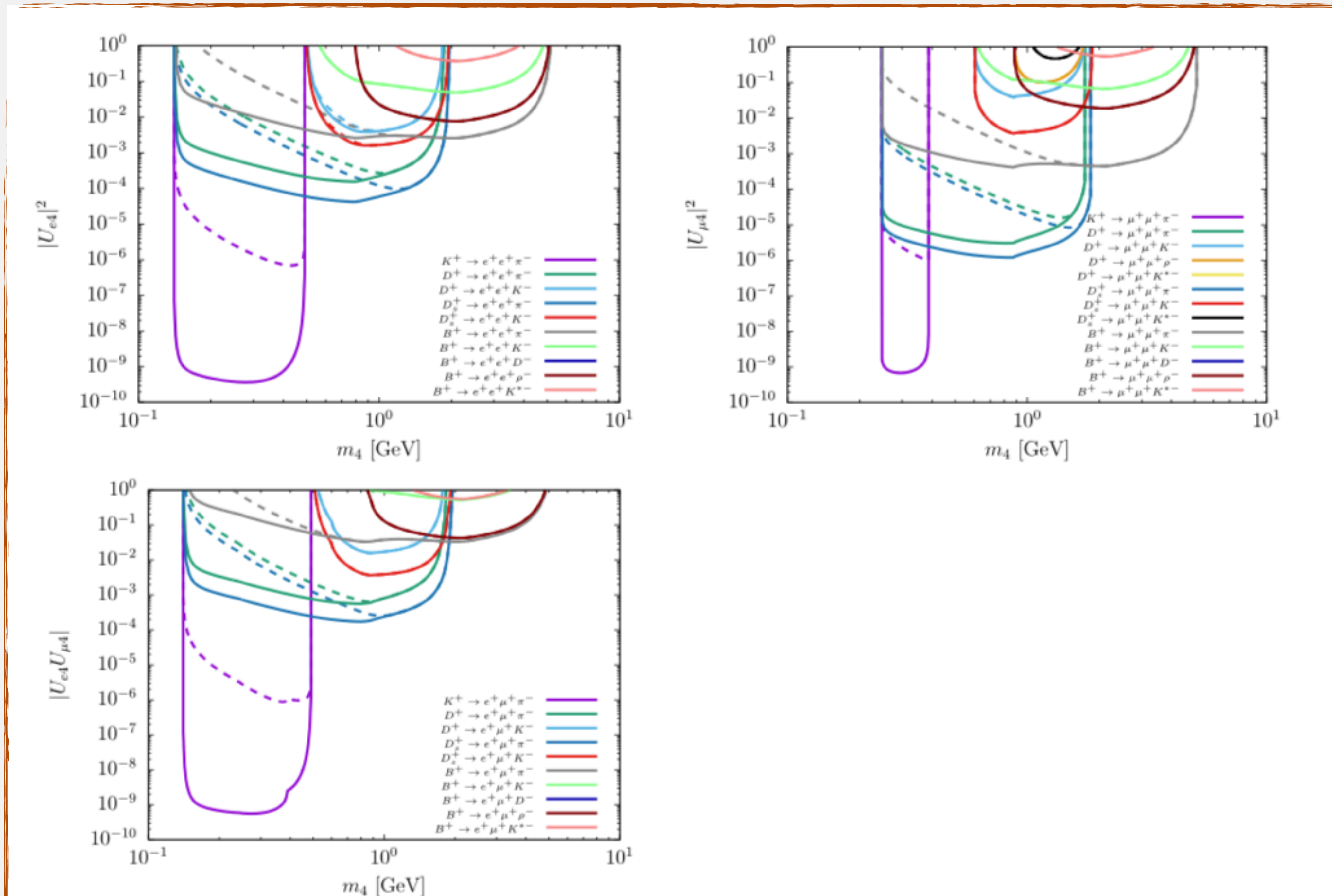
$$|\mathcal{A}_{\rm LNV}|^2 \sim |U_{\ell 4}|^2 \, |U_{\ell' 4}|^2 \, \frac{m_4}{\Gamma_4}$$

$$|\mathcal{A}_{\rm LNC}|^2 \sim |U_{\ell 4}|^2 \, |U_{\ell' 4}|^2 \, \frac{m_4}{\Gamma_4}$$

$$\Gamma^{\rm LNV}_{M_1 \to M_2 \ell^\pm \ell'^\pm} = \Gamma^{\rm LNC}_{M_1 \to M_2 \ell^\pm \ell'^\mp}$$

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

$$\left|\mathcal{A}^{\rm LNV}_{M\to M'\ell^+_\alpha\ell^+_\beta}\right|^2 \propto \left|U_{\alpha4}U_{\beta4}\, f(m_4) + U_{\alpha5}U_{\beta5}\, f(m_5)\right|^2 = \left|U_{\alpha4}\right|^2\left|U_{\beta4}\right|^2 |f(M)|^2 \left|1+\kappa\, e^{\mp i(\psi_\alpha+\psi_\beta)}\right|^2$$

$$\left|\mathcal{A}^{\rm LNC}_{M\to M'\ell^+_\alpha\ell^-_\beta}\right|^2 \propto \left|U_{\alpha4}U^*_{\beta4}\, g(m_4) + U_{\alpha5}U^*_{\beta5}\, g(m_5)\right|^2 = \left|U_{\alpha4}\right|^2\left|U_{\beta4}\right|^2 |g(M)|^2 \left|1+\kappa'\, e^{\mp i(\psi_\alpha-\psi_\beta)}\right|^2$$

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- Notation:

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

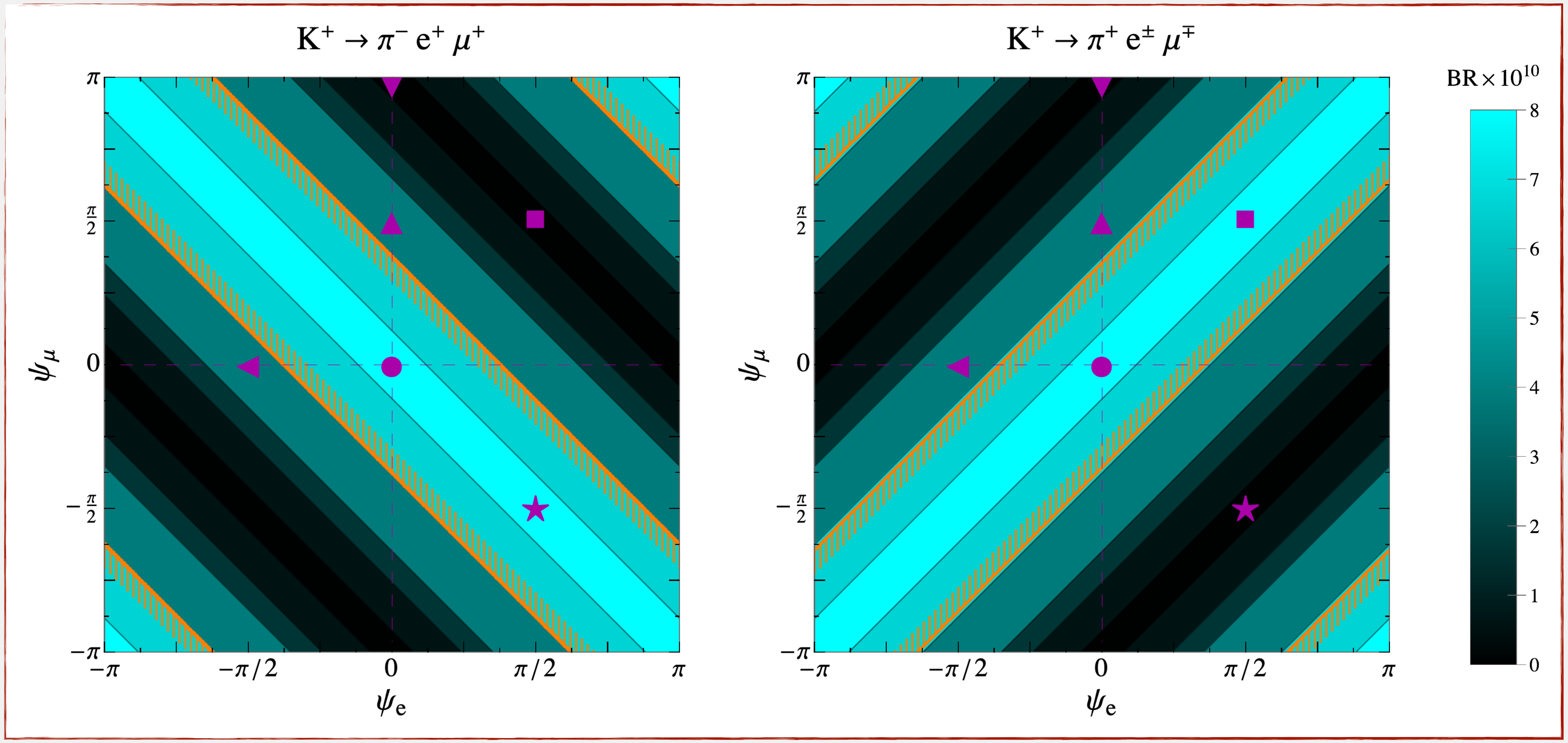
$$\kappa \equiv \frac{|U_{\alpha 5}U_{\beta 5}|}{|U_{\alpha 4}U_{\beta 4}|}\frac{f(m_5)}{f(m_4)}, \quad \kappa' \equiv \frac{|U_{\alpha 5}U^*_{\beta 5}|}{|U_{\alpha 4}U^*_{\beta 4}|}\frac{g(m_5)}{g(m_4)}$$

$$\psi_\alpha \equiv \phi_{\alpha_5}-\phi_{\alpha 4} \text{ where } U_{\alpha i}=e^{-i\phi_{\alpha i}}|U_{\alpha i}|$$

→ ***relative phases for each flavor***

Relative phases in LNV and LFV

$$\mathrm{LNV} \sim (\psi_\alpha + \psi_\beta) \qquad \mathrm{LNC} \sim (\psi_\alpha - \psi_\beta)$$



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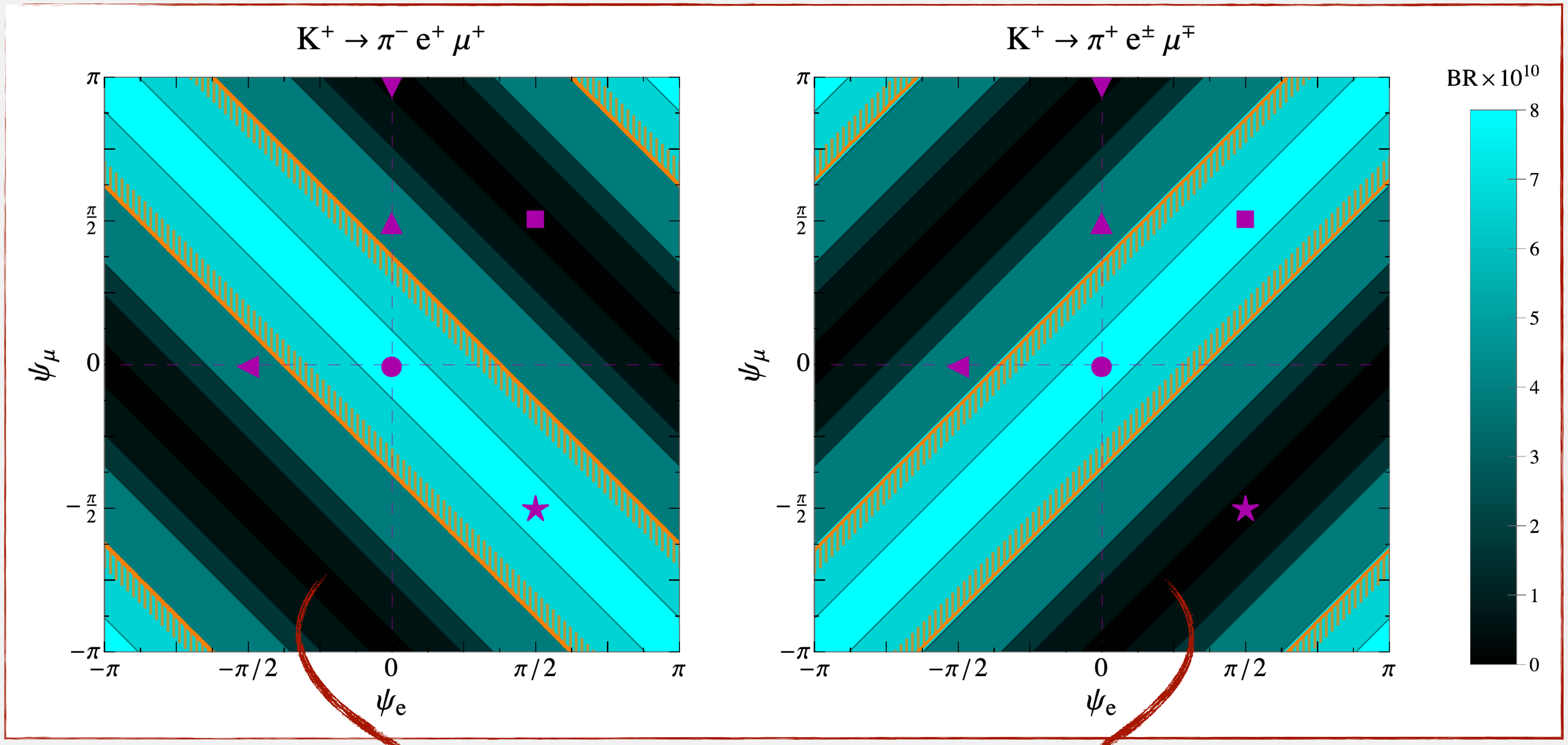

destructive interferences

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:

$$R_{\ell_\alpha \ell_\beta} \equiv \frac{\Gamma^{\text{LNV}}_{M \to M' \ell^\pm_\alpha \ell^\pm_\beta}}{\Gamma^{\text{LNC}}_{M \to M' \ell^\pm_\alpha \ell^\mp_\beta}}$$

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$R_{\ell_\alpha \ell_\beta}$: 0 → Dirac, 1 → Majorana

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$R_{\ell_\alpha \ell_\beta}$:

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

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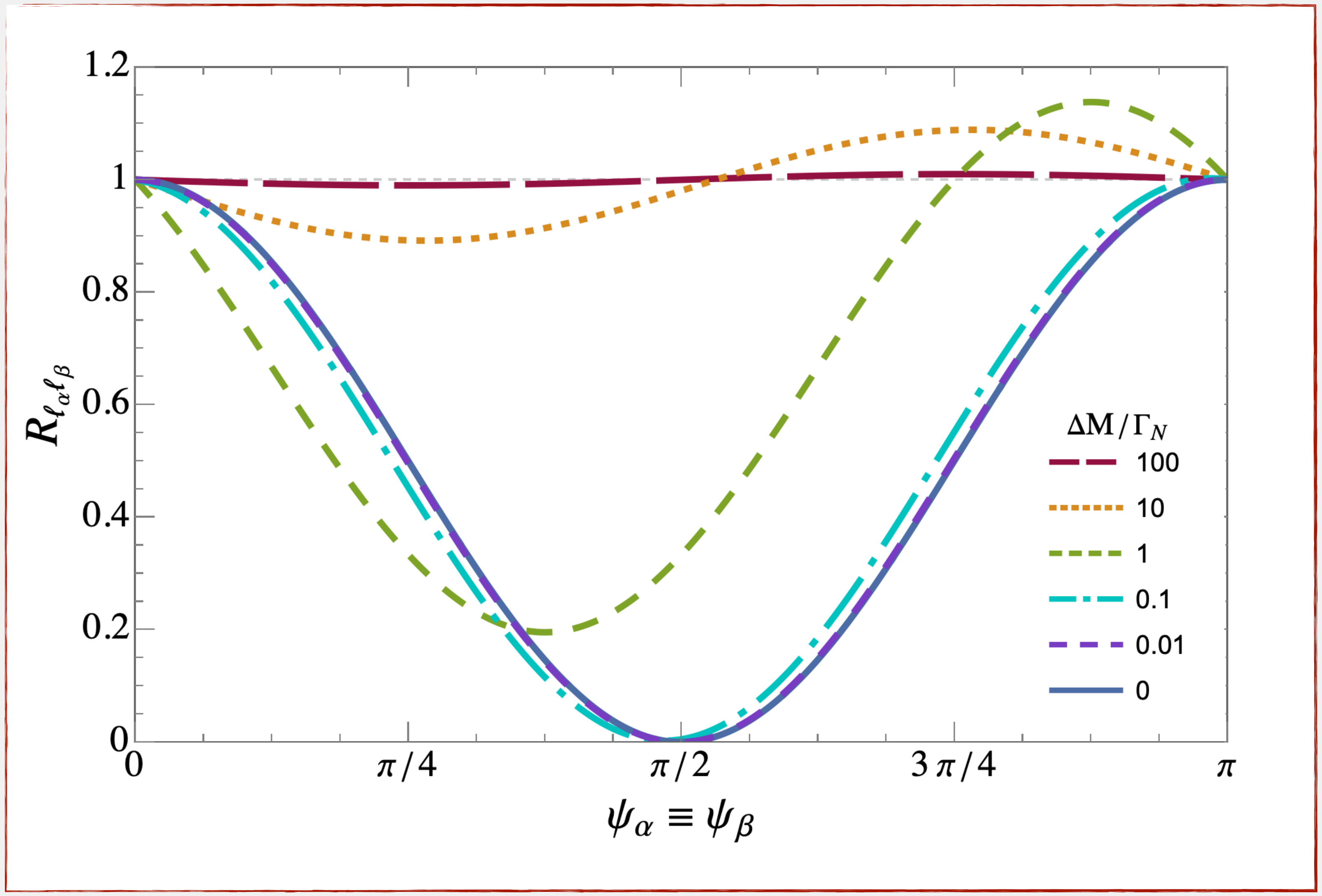

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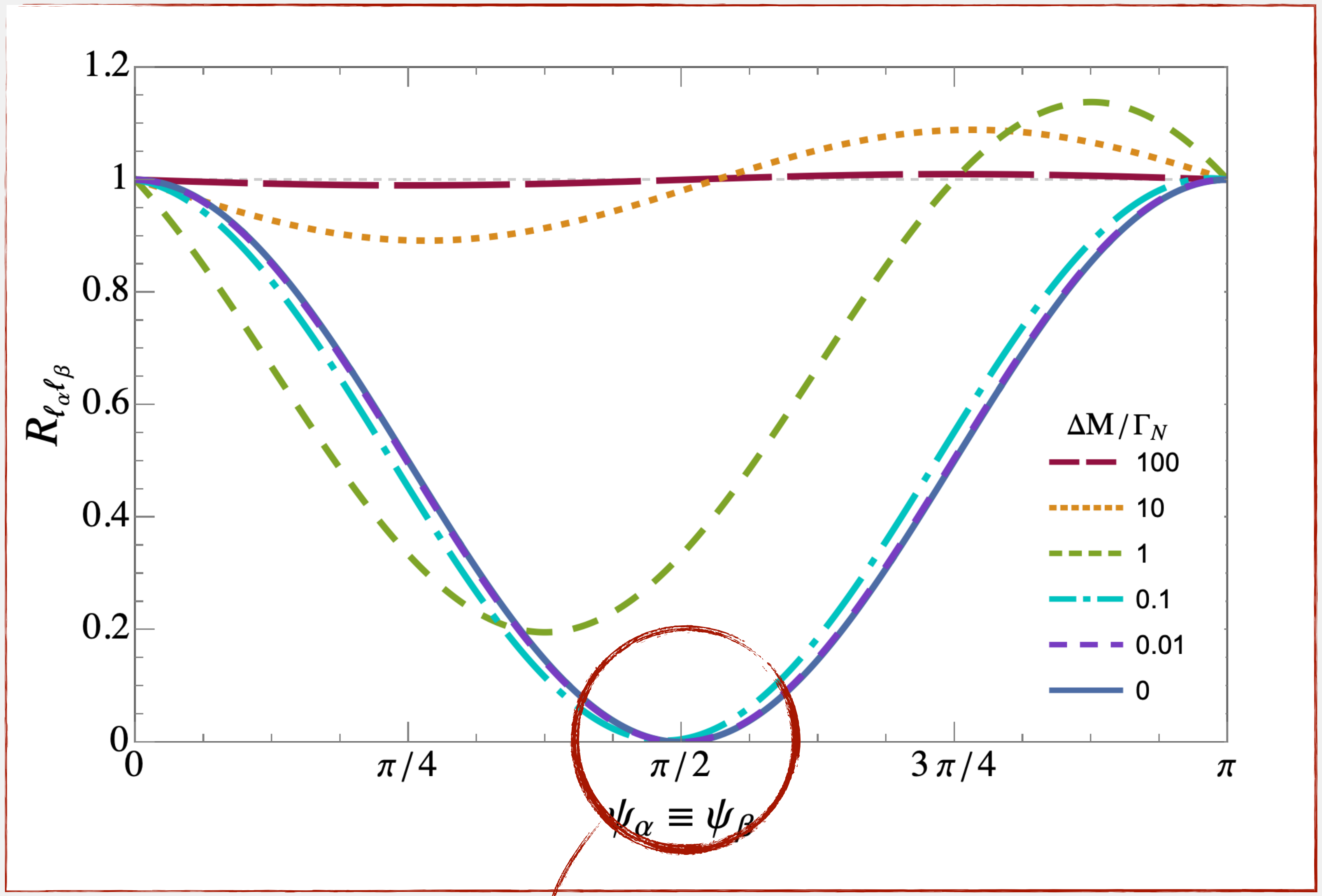

inverse seesaw (et al) models live over here

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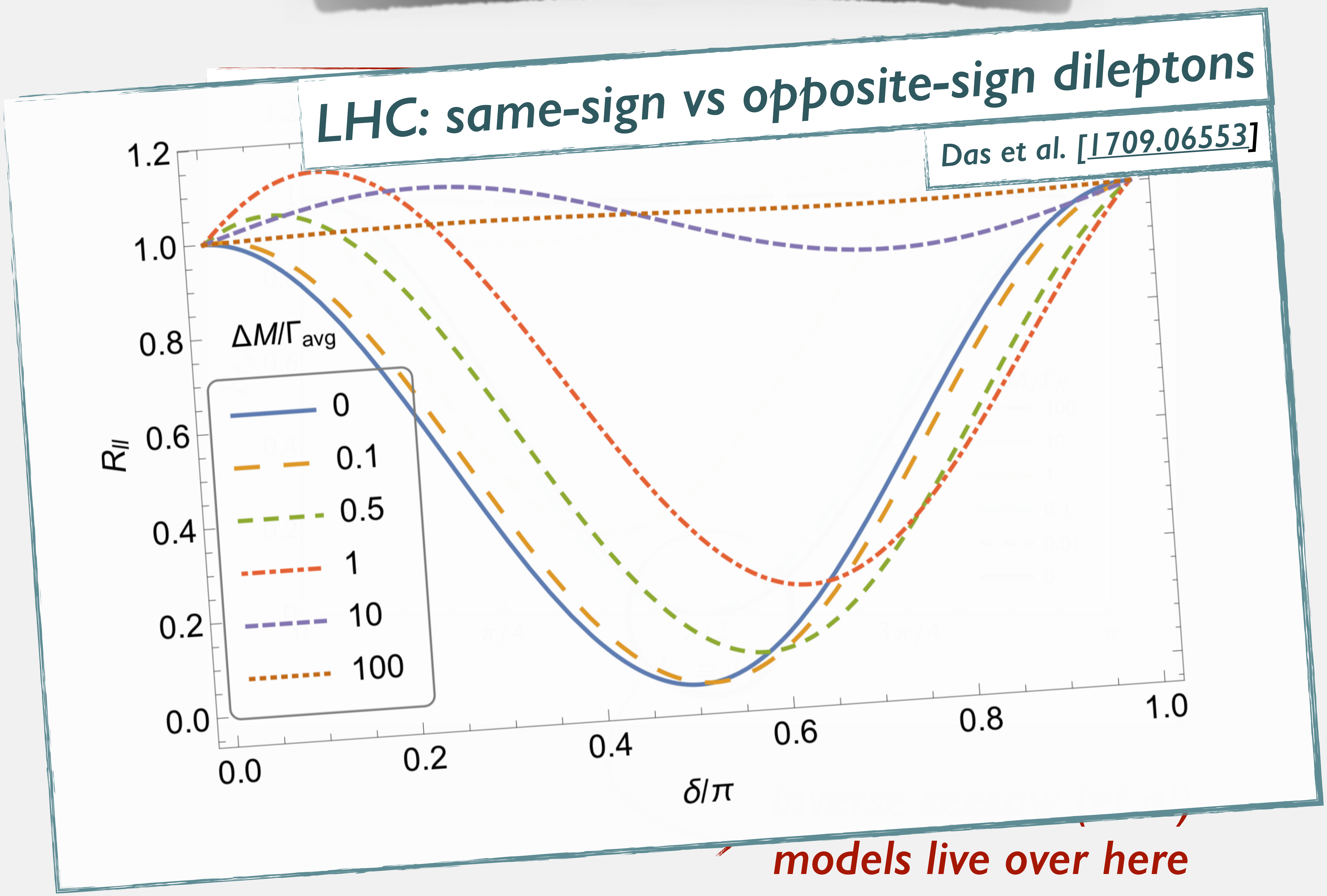
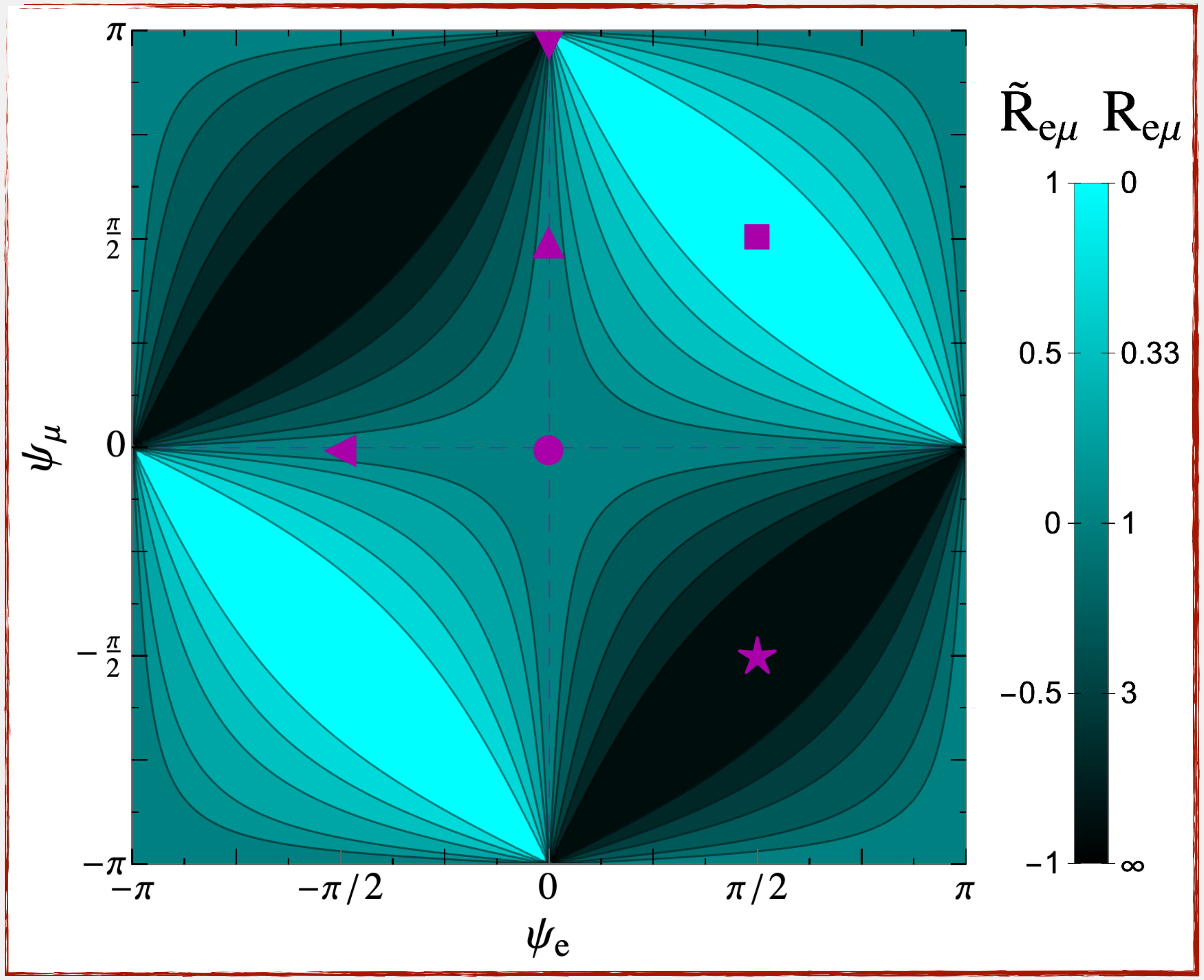


models live over here

Interference: more general case

only **LFV**

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



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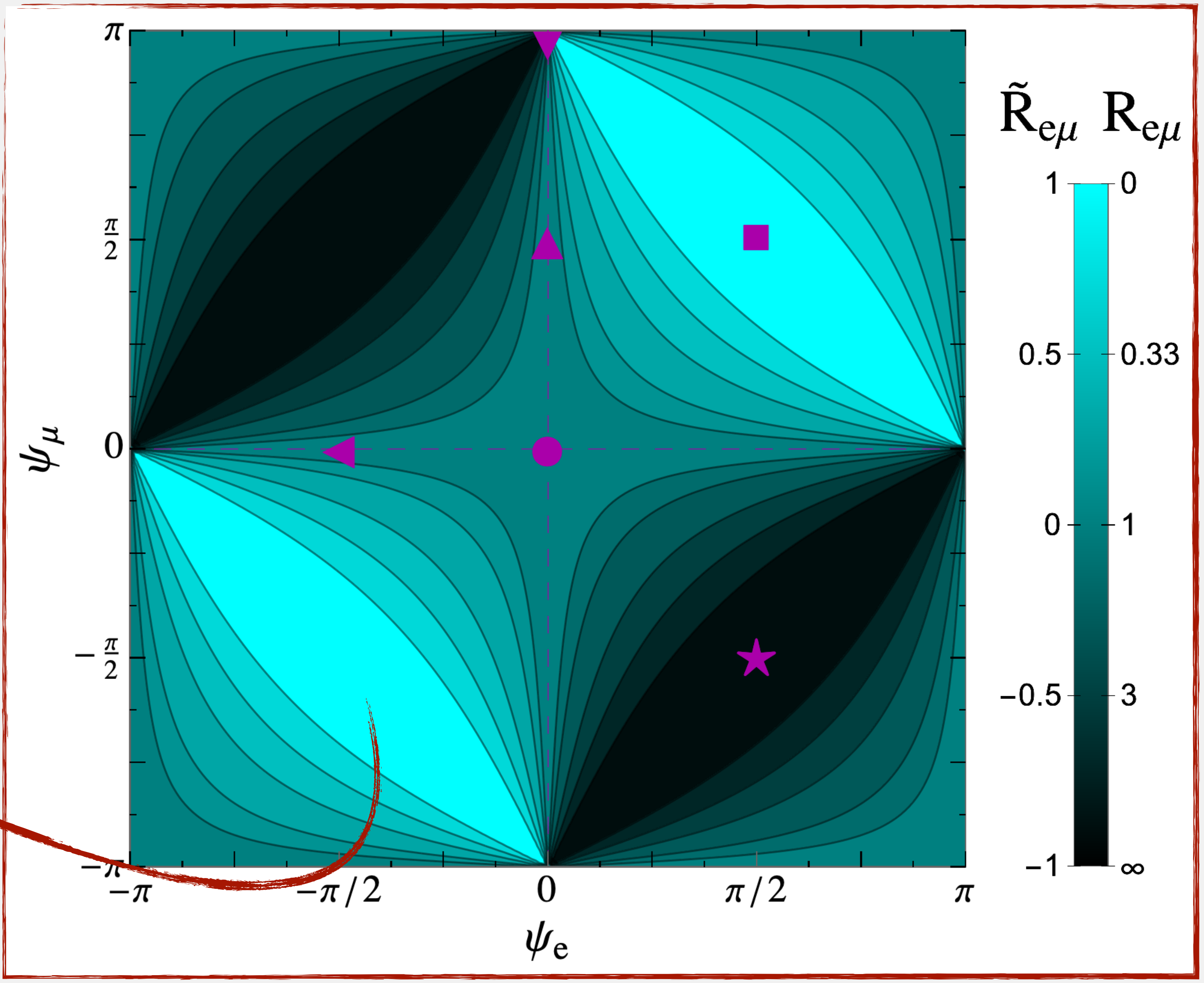

LNV suppressed

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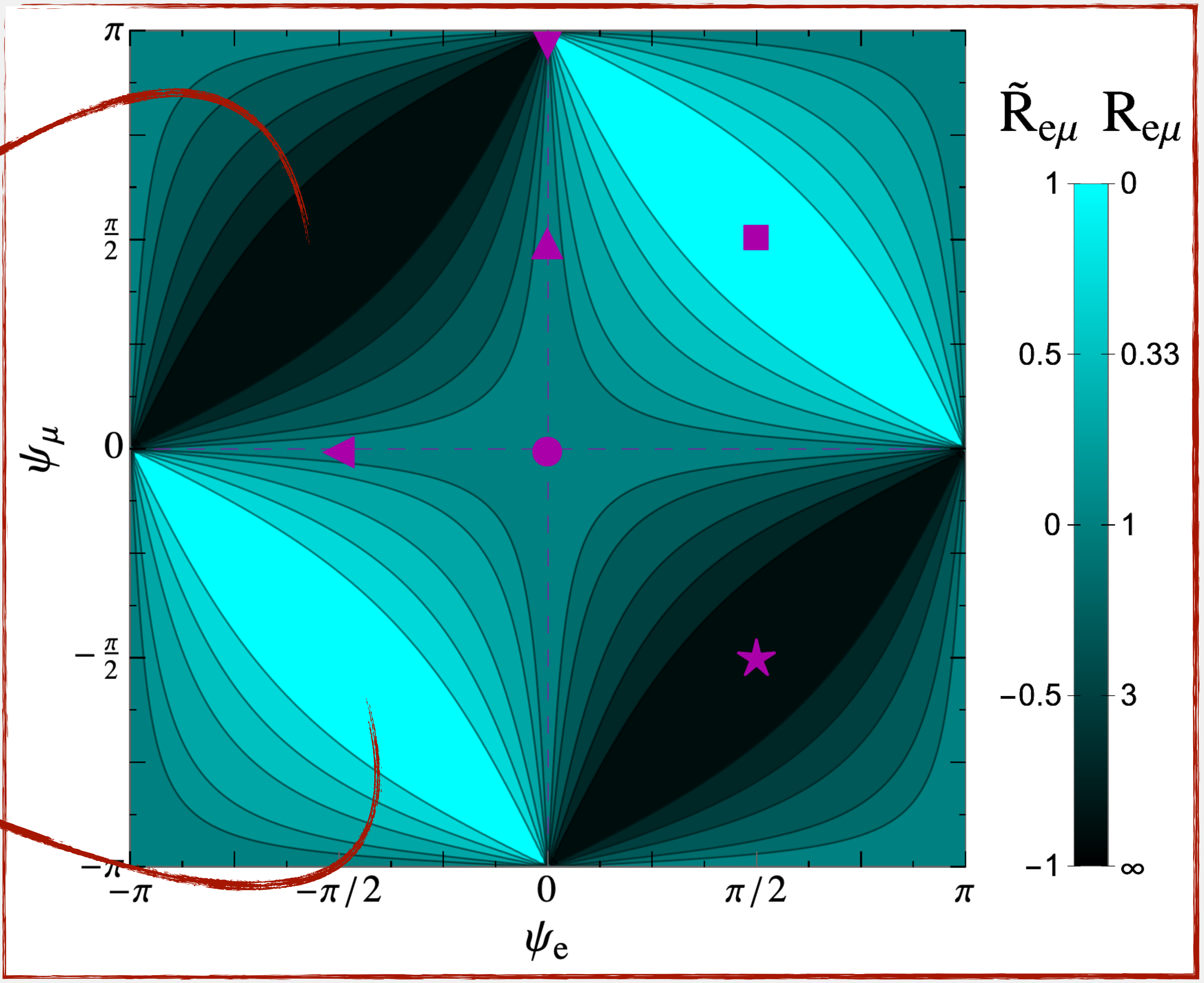
LNC suppressed

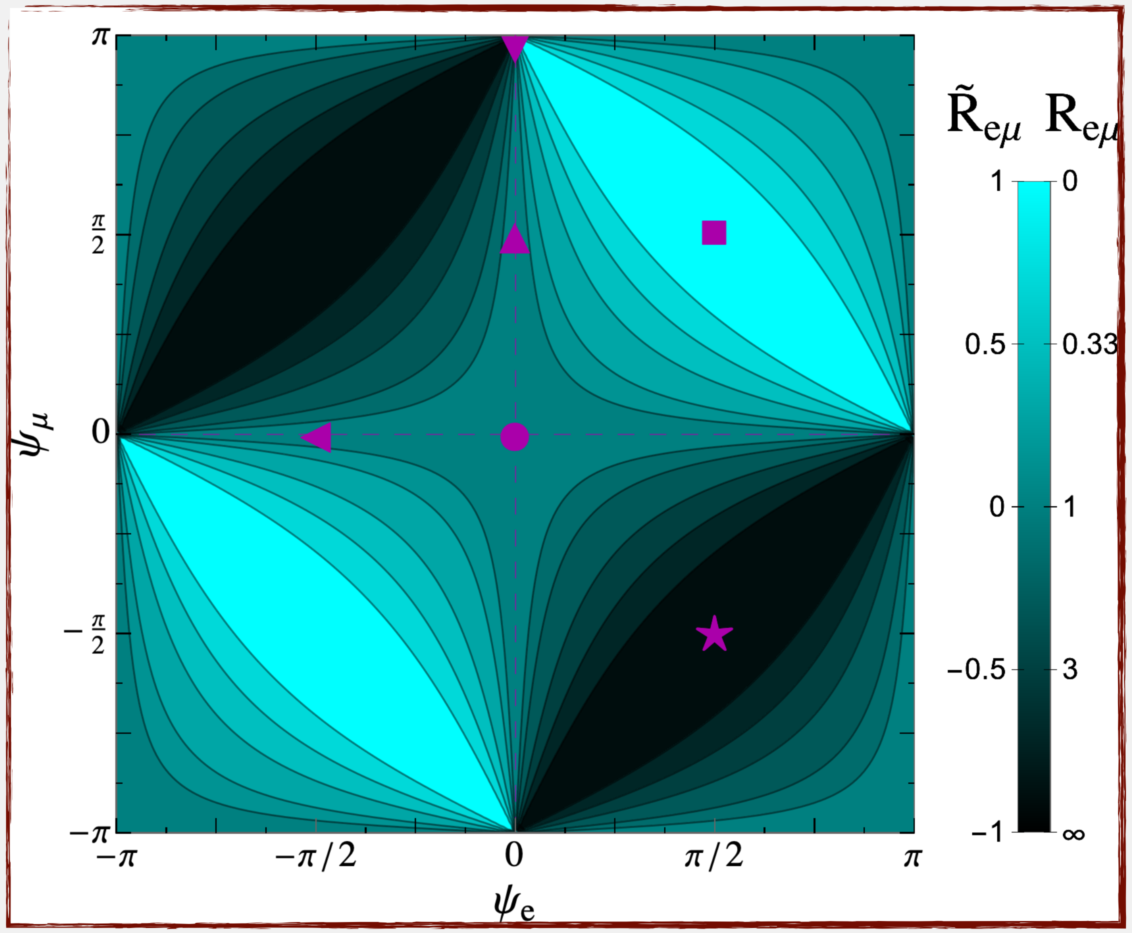
LNV suppressed



Learning about phases

- Combine LNV and LFV searches:

$$K^+ \to \pi^- e^+ e^+$$
$$K^+ \to \pi^- \mu^+ \mu^+$$
$$K^+ \to \pi^- e^+ \mu^+$$
$$K^+ \to \pi^+ e^\pm \mu^\mp$$



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

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