INTERFERENCE EFFECTS IN SEMILEPTONIC DECAYS FROM HEAVY MAJORANA NEUTRINOS

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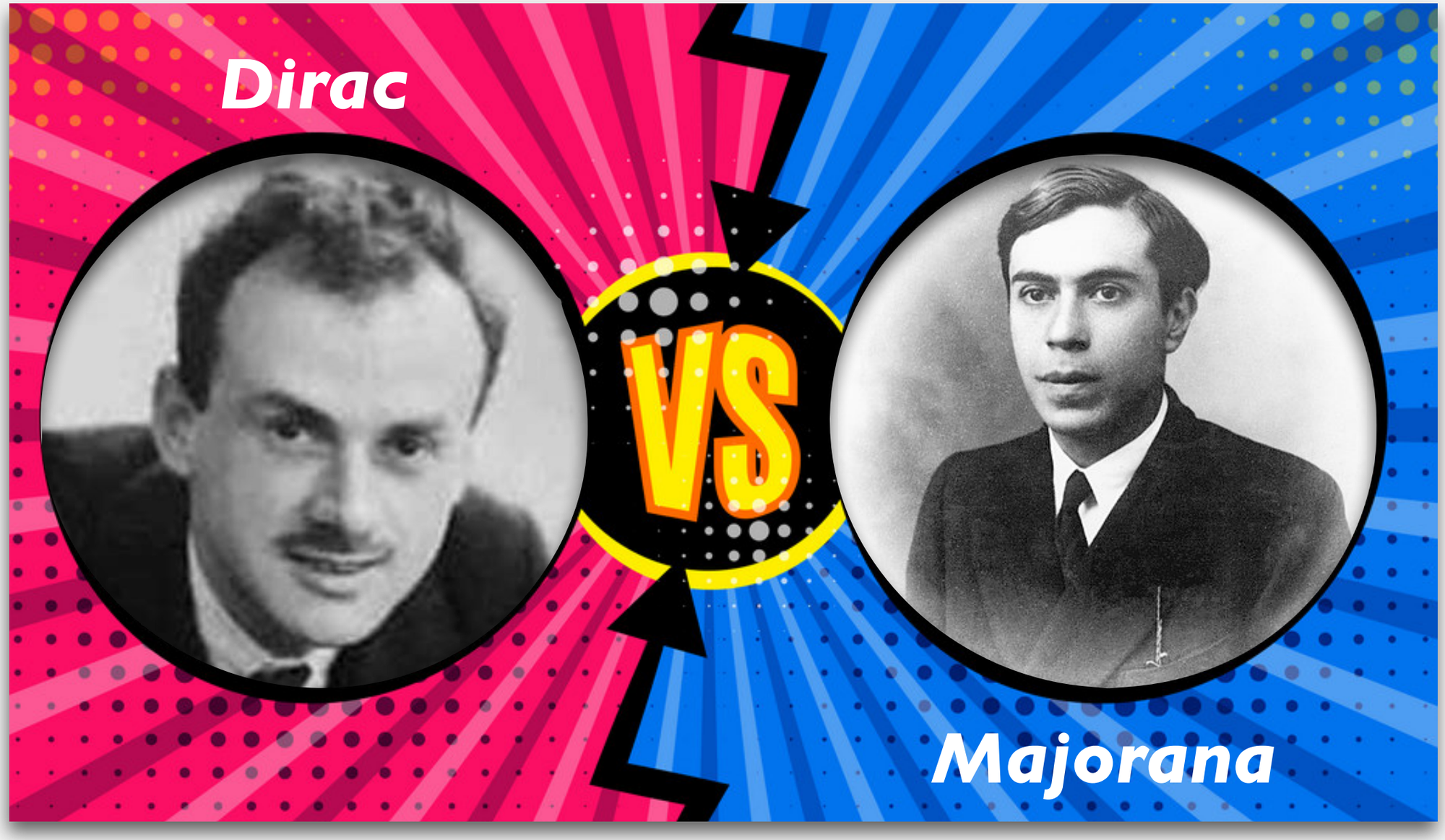
arXiv:1904.05367

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

July 13th 2019, Ghent

Why neutrinos?

Neutrino Nature



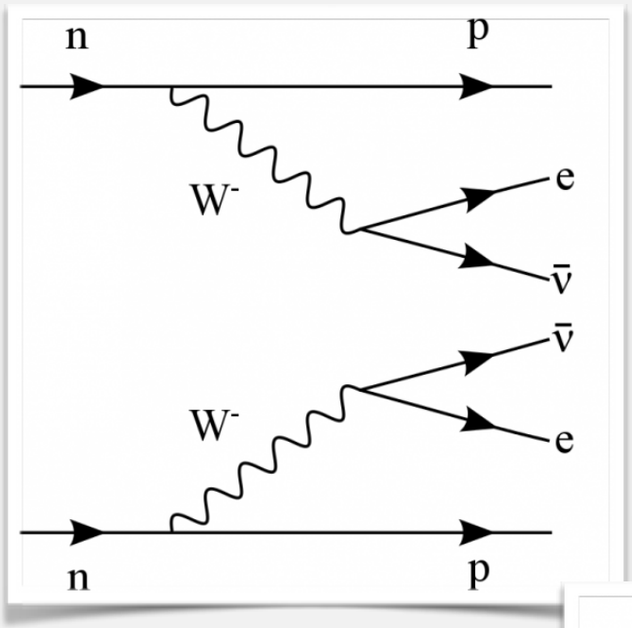
$\nu^c \neq \nu$

$\nu^c = \nu$

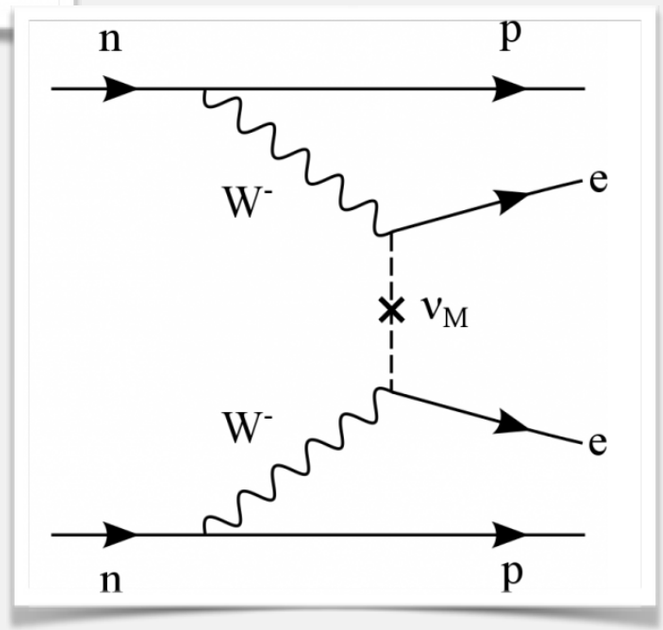
Neutrinoless Double Beta Decays

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

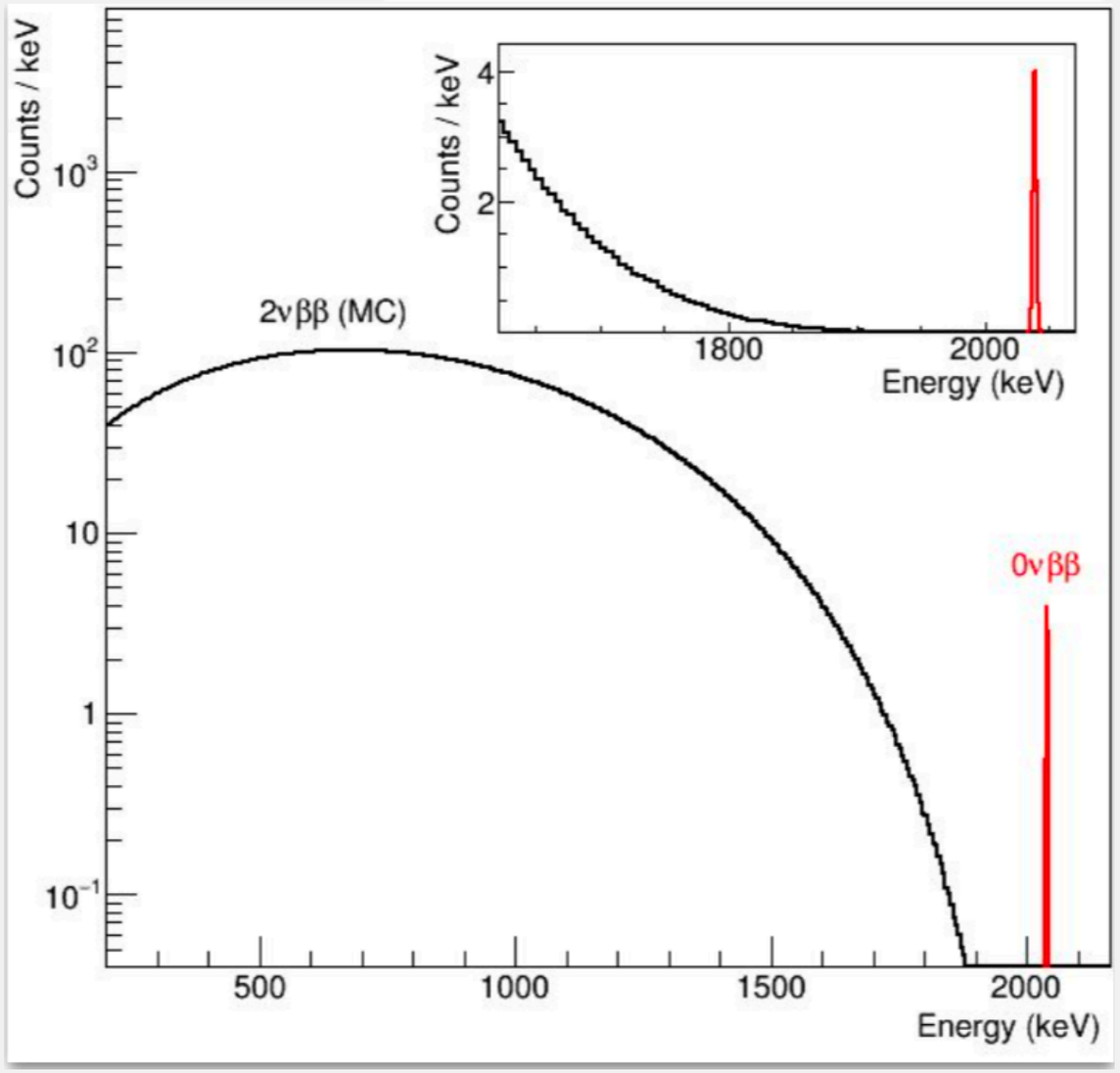
$$m_{ee} = \left| \sum_i m_i U_{ei} \right|^2$$



$2\nu\beta\beta$

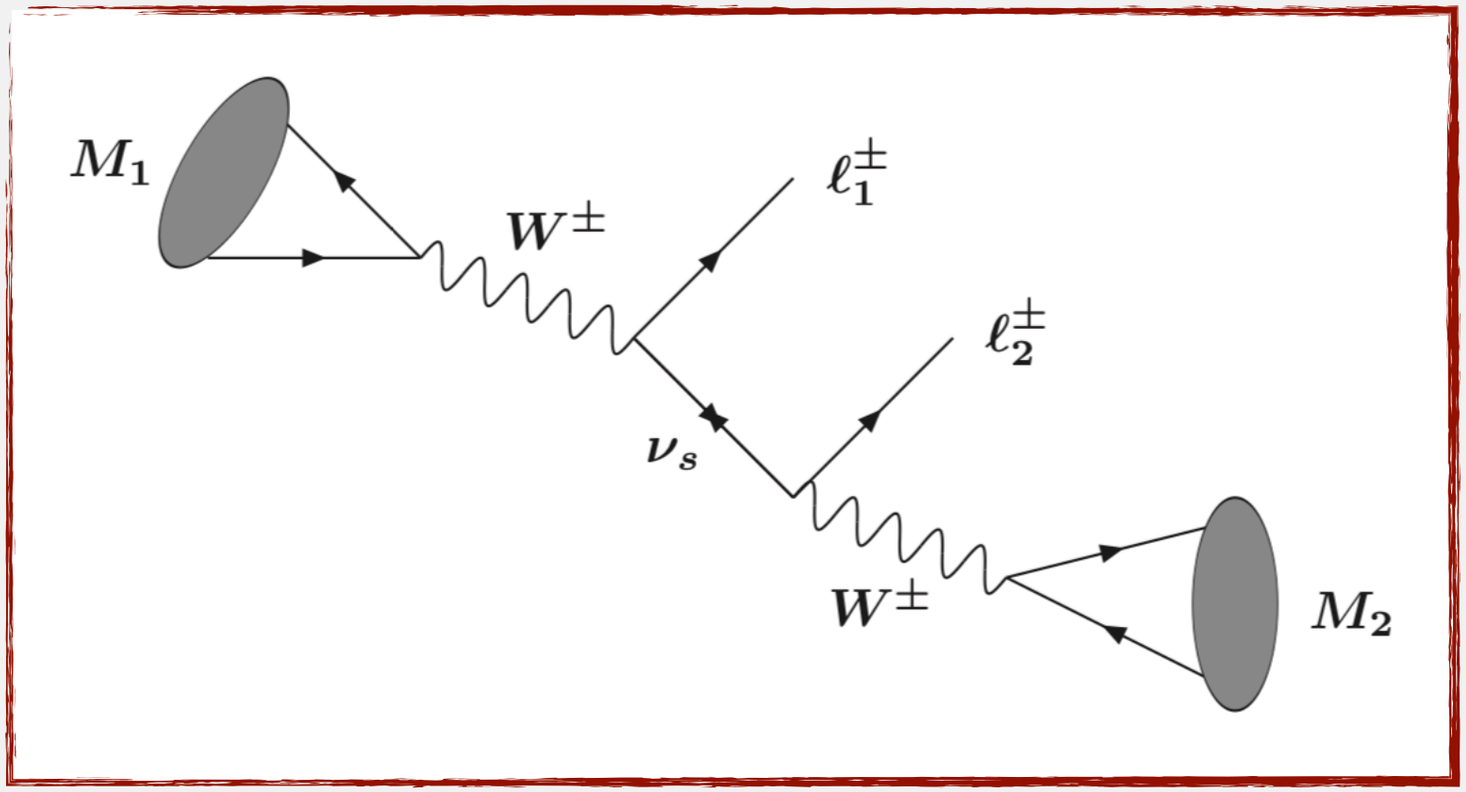


$0\nu\beta\beta$



Ana Julia Zsigmond (GERDA), Neutrino 2018

LNV & LFV semileptonic meson decays



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

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

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

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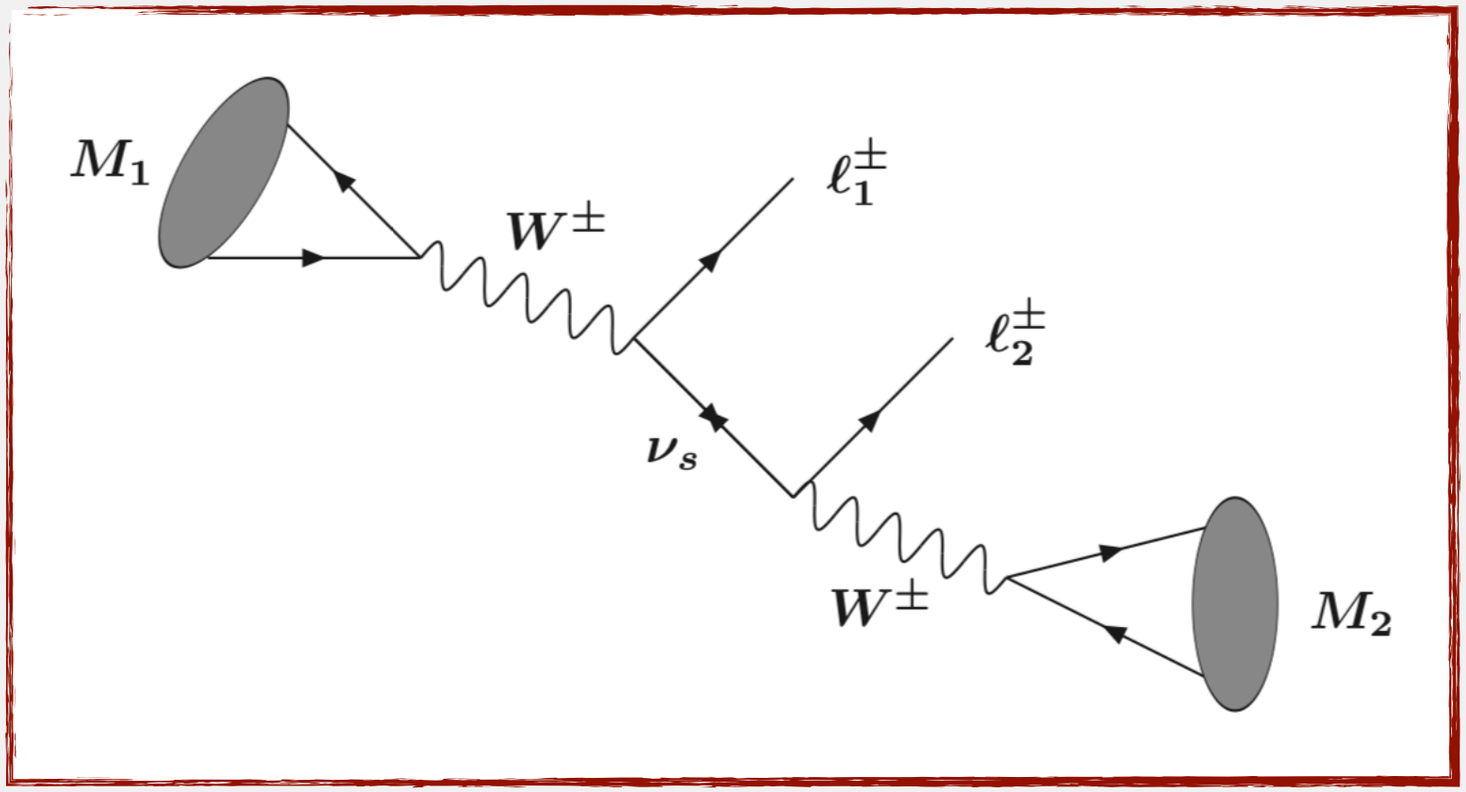

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NEW!!!
NA62 (2019)
(see Angela Romano's talk)

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

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

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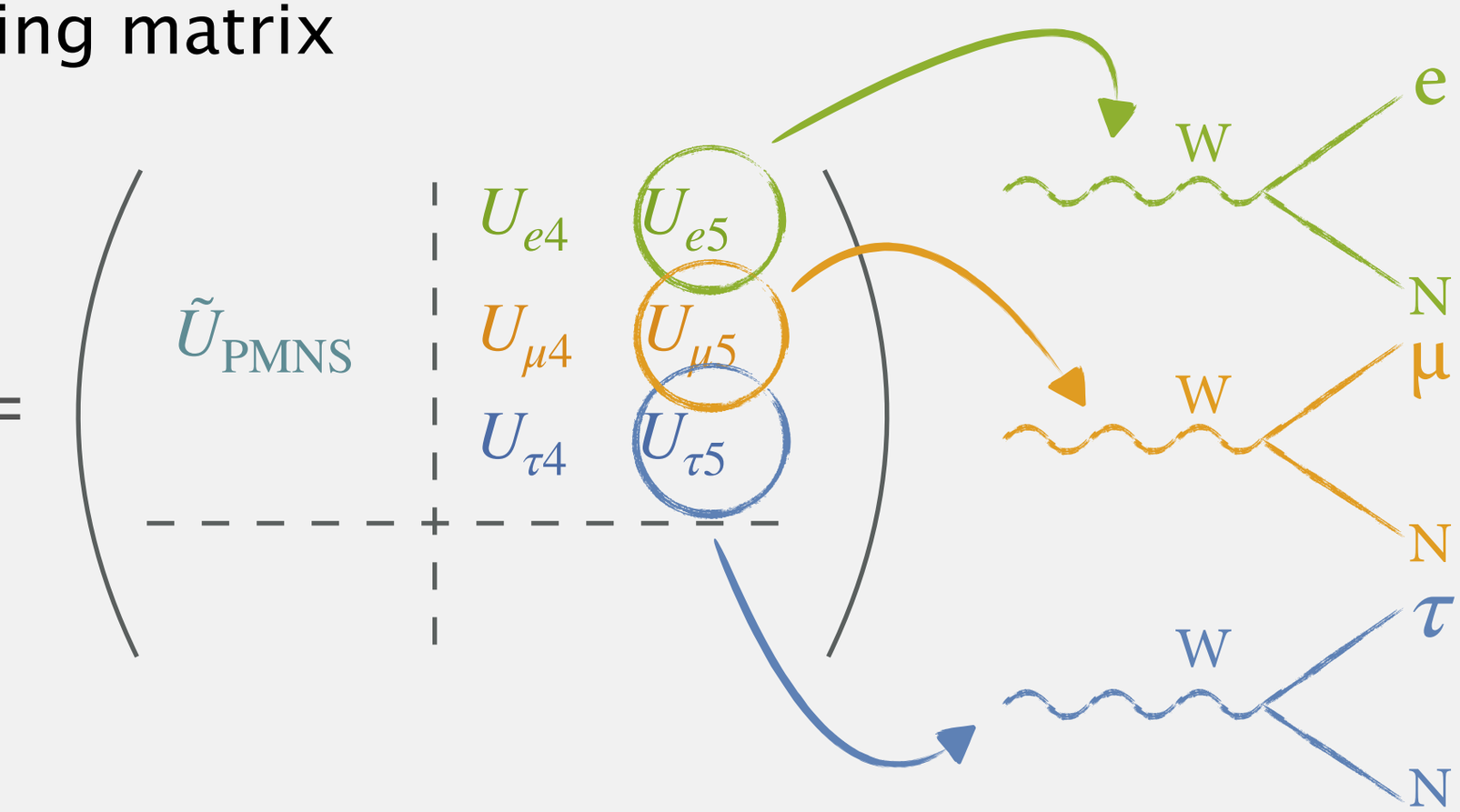

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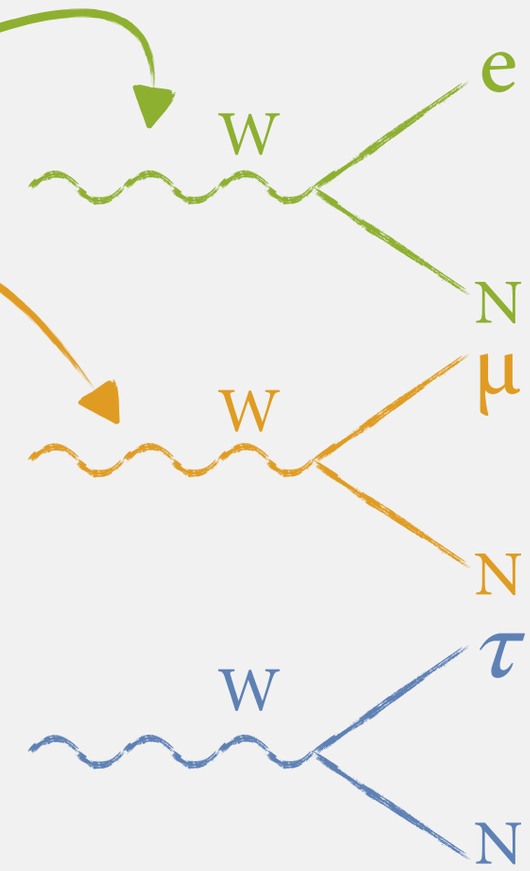
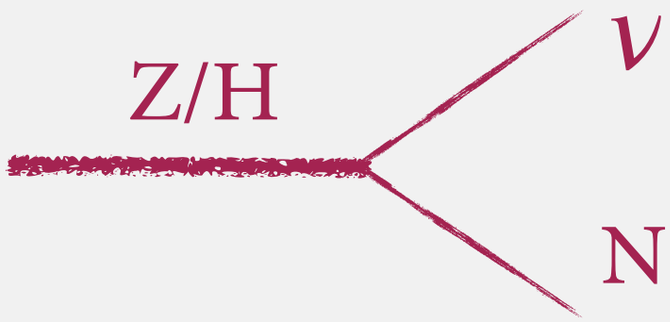


⊕ Neutral currents



$\Gamma_4, \Gamma_5, \dots$

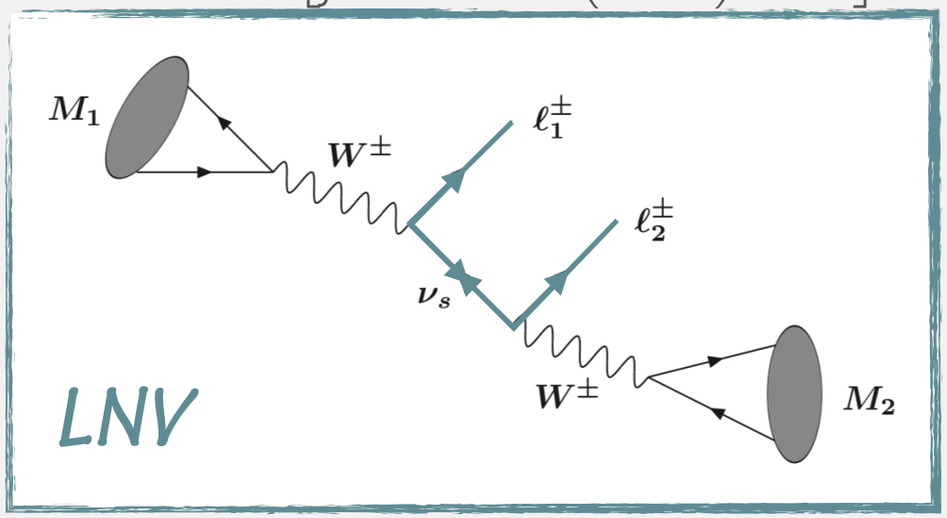
[0901.3589, 1712.03984, 1805.08567]

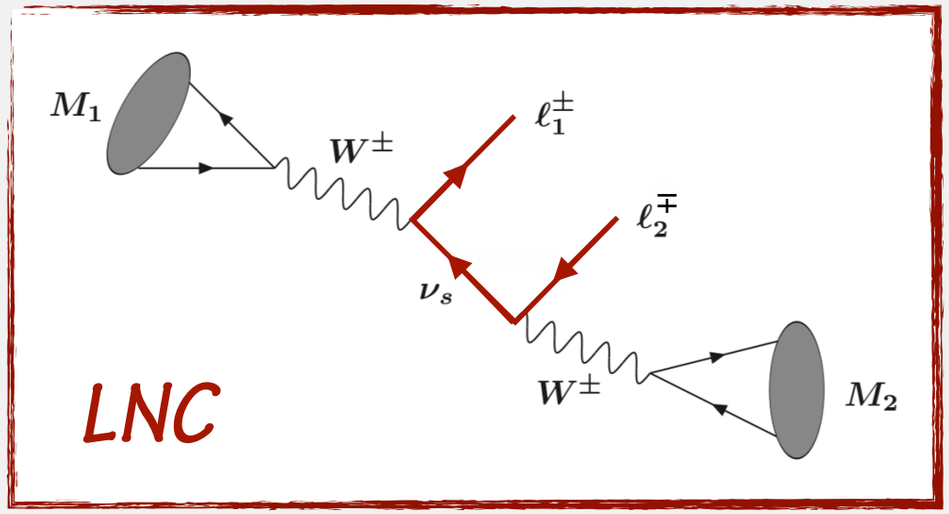
Semileptonic LNV&LNC decays (I)

in presence of ***one*** heavy Majorana neutrino

LNV&LNC from on-shell neutrinos

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





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

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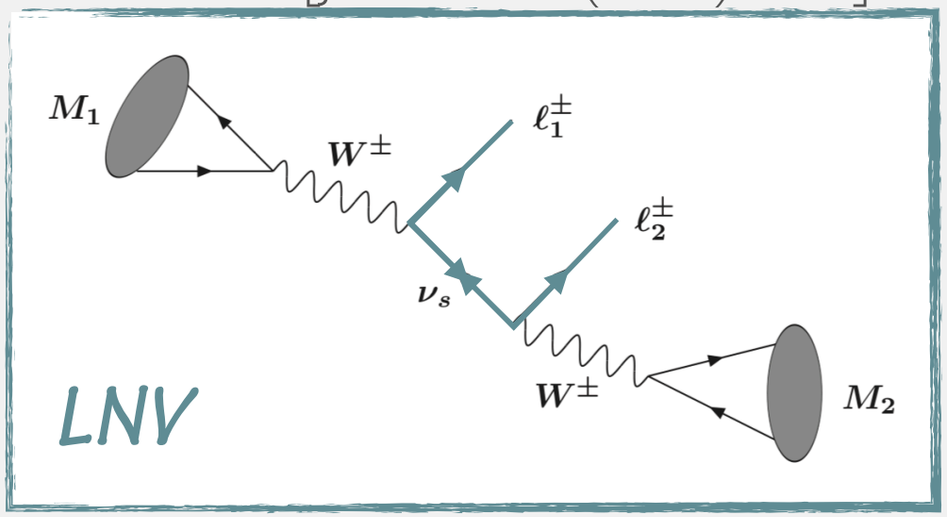

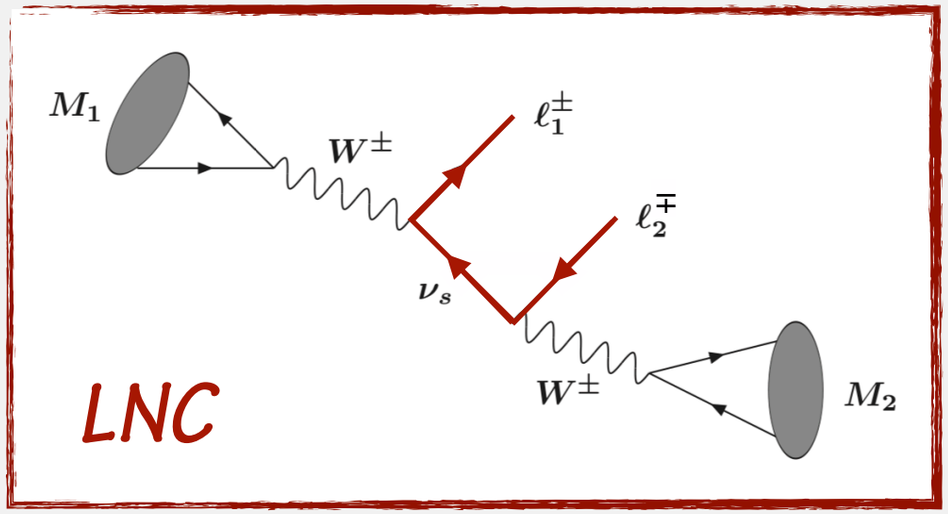

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on-shell neutrino $\not{q}^2 = m_4^2$

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

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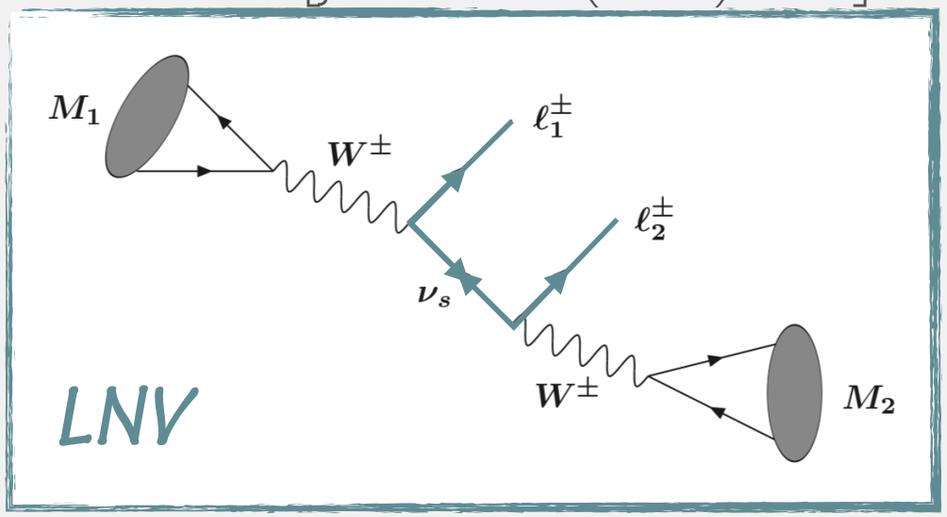

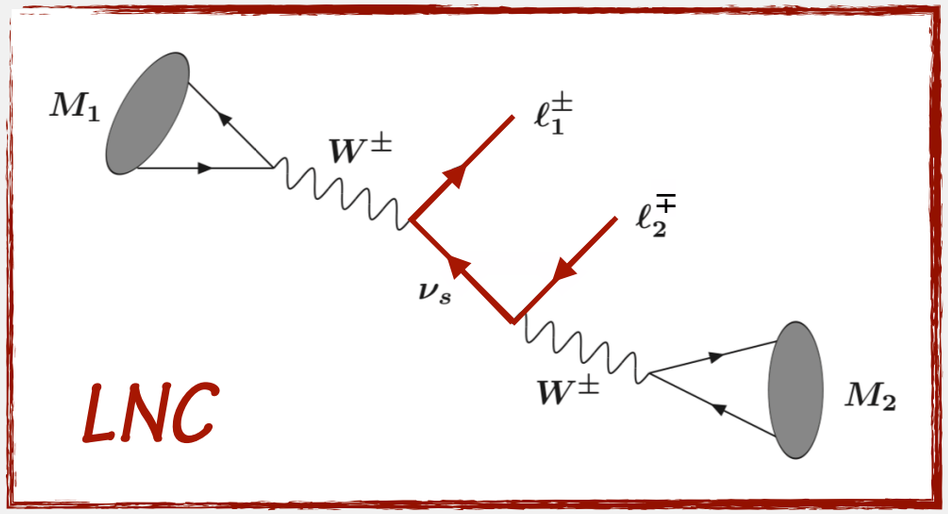

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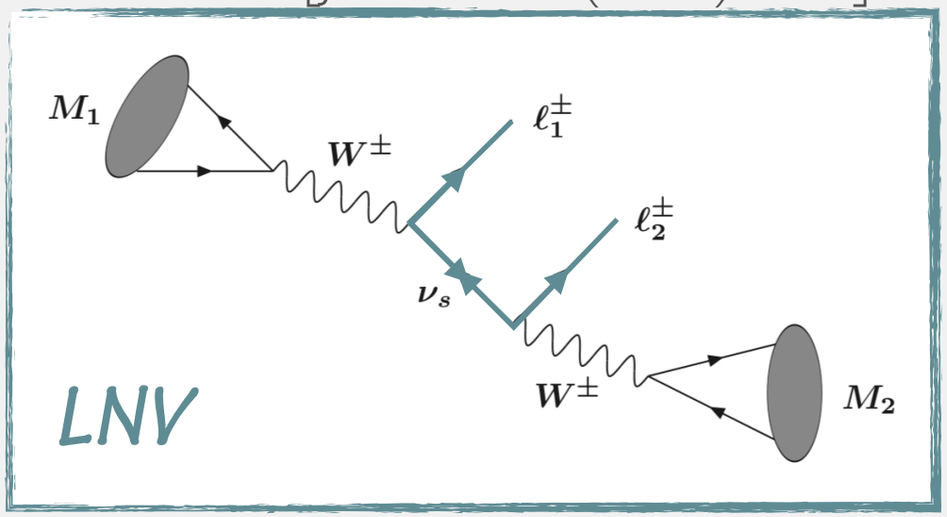

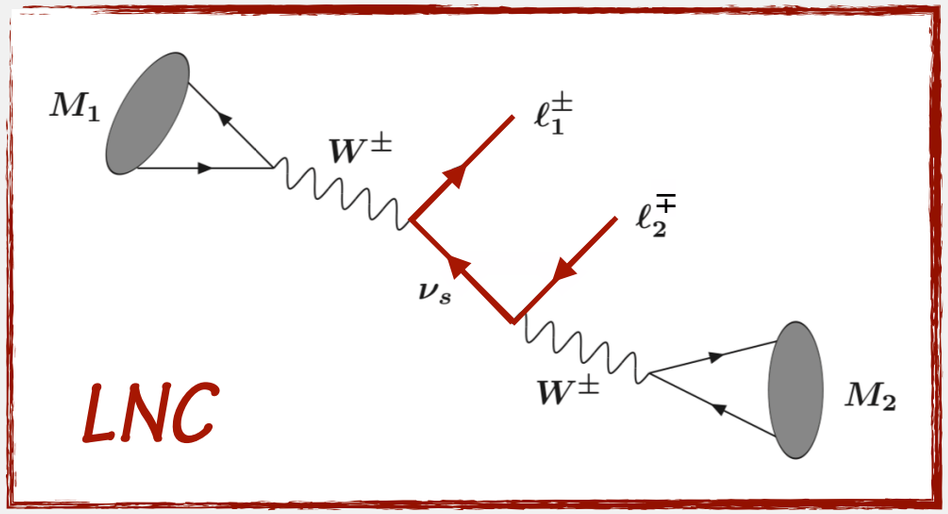

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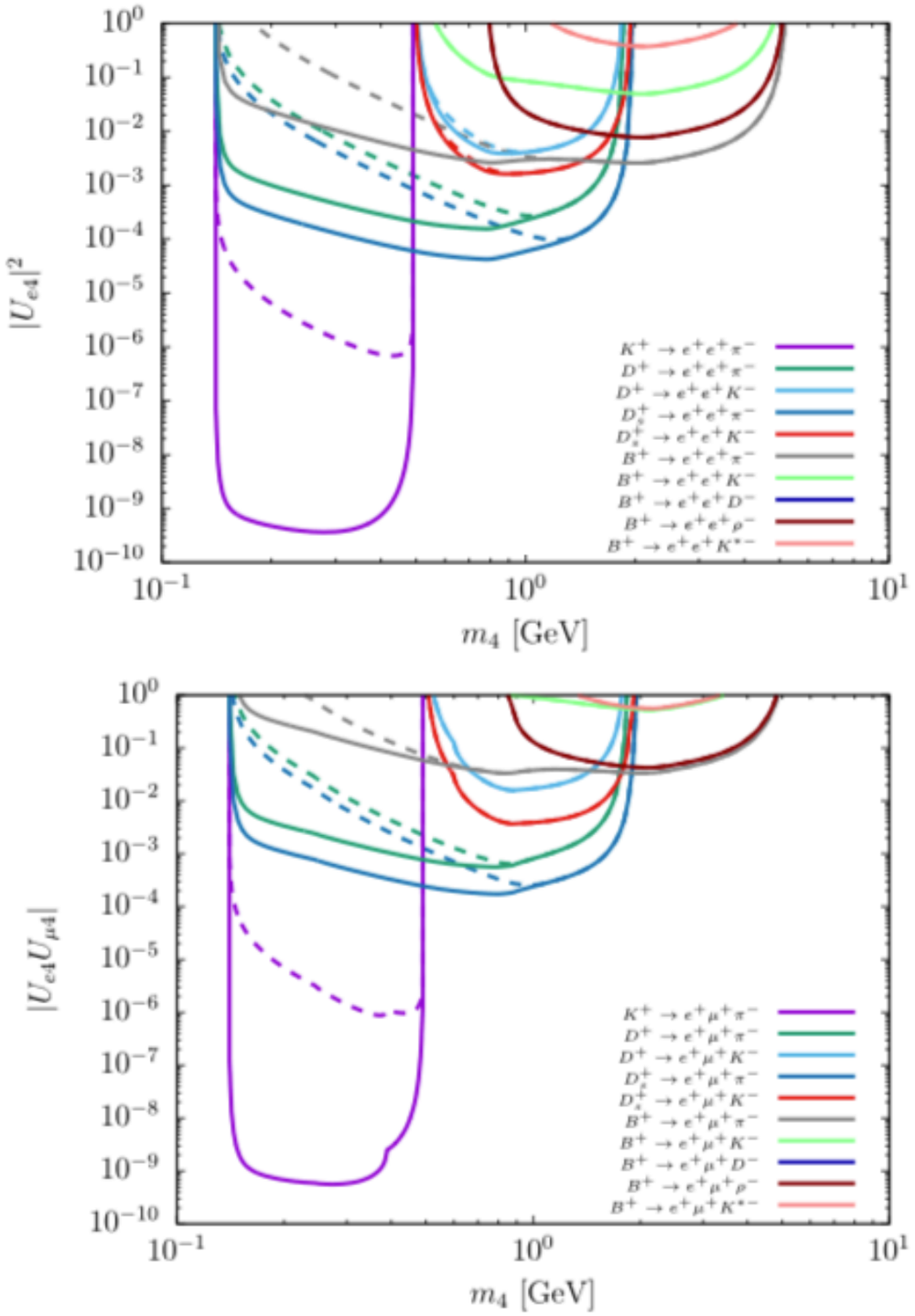
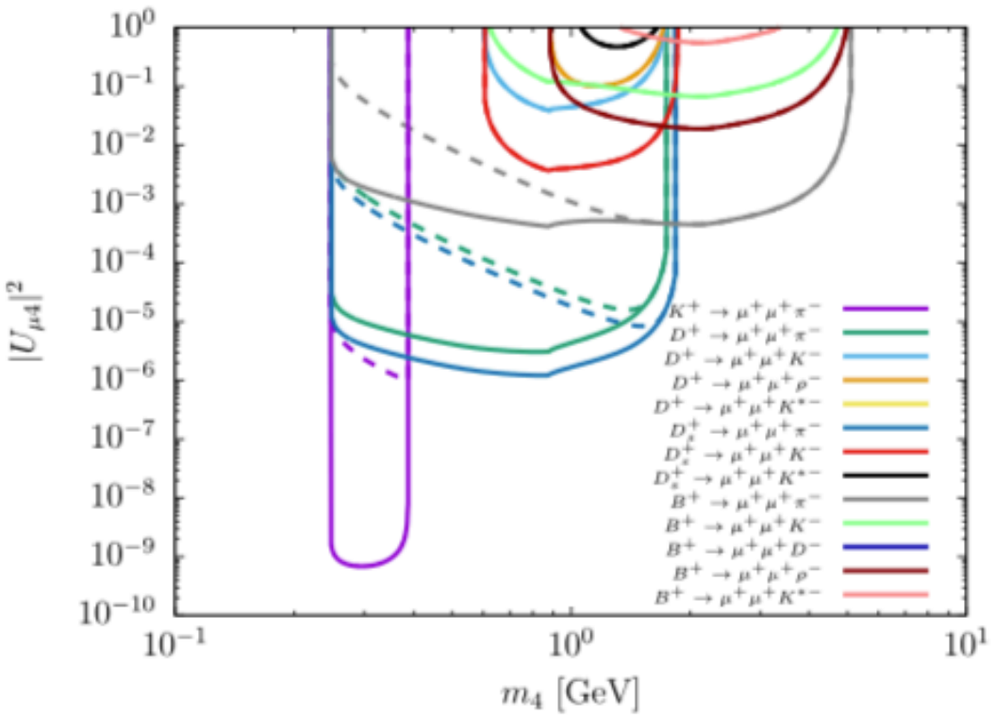
$$\Gamma^{\rm LNV}_{M_1 \to M_2 \ell^\pm \ell'^\pm} = \Gamma^{\rm LNC}_{M_1 \to M_2 \ell^\pm \ell'^\mp}$$

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

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

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

- Notation: $f(m), g(m)$ ⟶ full integrands [JHEP 1802 (2018) 169]

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

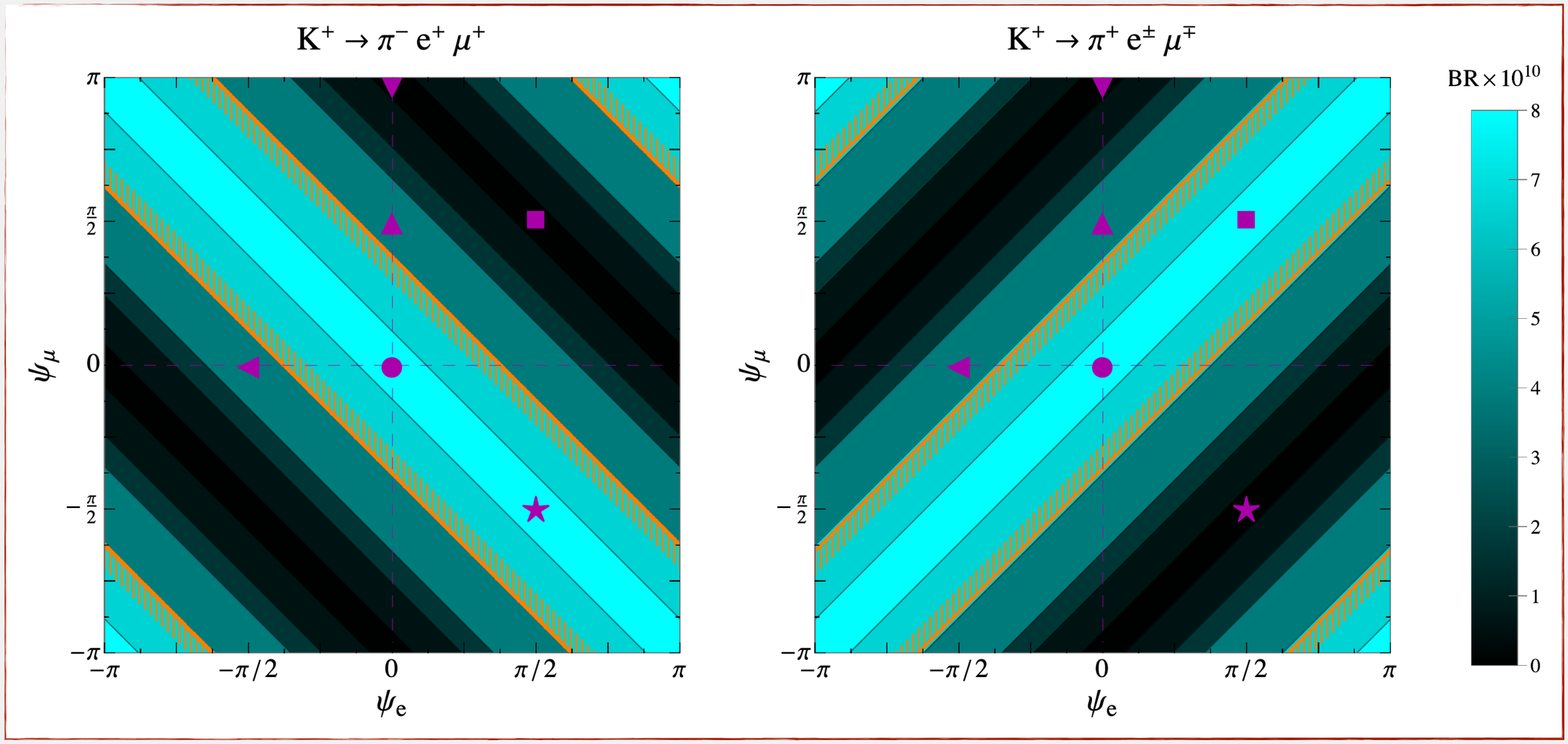
$$\kappa\equiv\frac{|U_{\alpha5}U_{\beta5}|}{|U_{\alpha4}U_{\beta4}|}\frac{f(m_5)}{f(m_4)},\quad \kappa'\equiv\frac{|U_{\alpha5}U^*_{\beta5}|}{|U_{\alpha4}U^*_{\beta4}|}\frac{g(m_5)}{g(m_4)}$$

$$\psi_\alpha\equiv\phi_{\alpha_5}-\phi_{\alpha4}\ \text{where}\ U_{\alpha i}=e^{-i\phi_{\alpha i}}|U_{\alpha i}|$$

relative phases for each flavor

Relative phases in LNV and LFV

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



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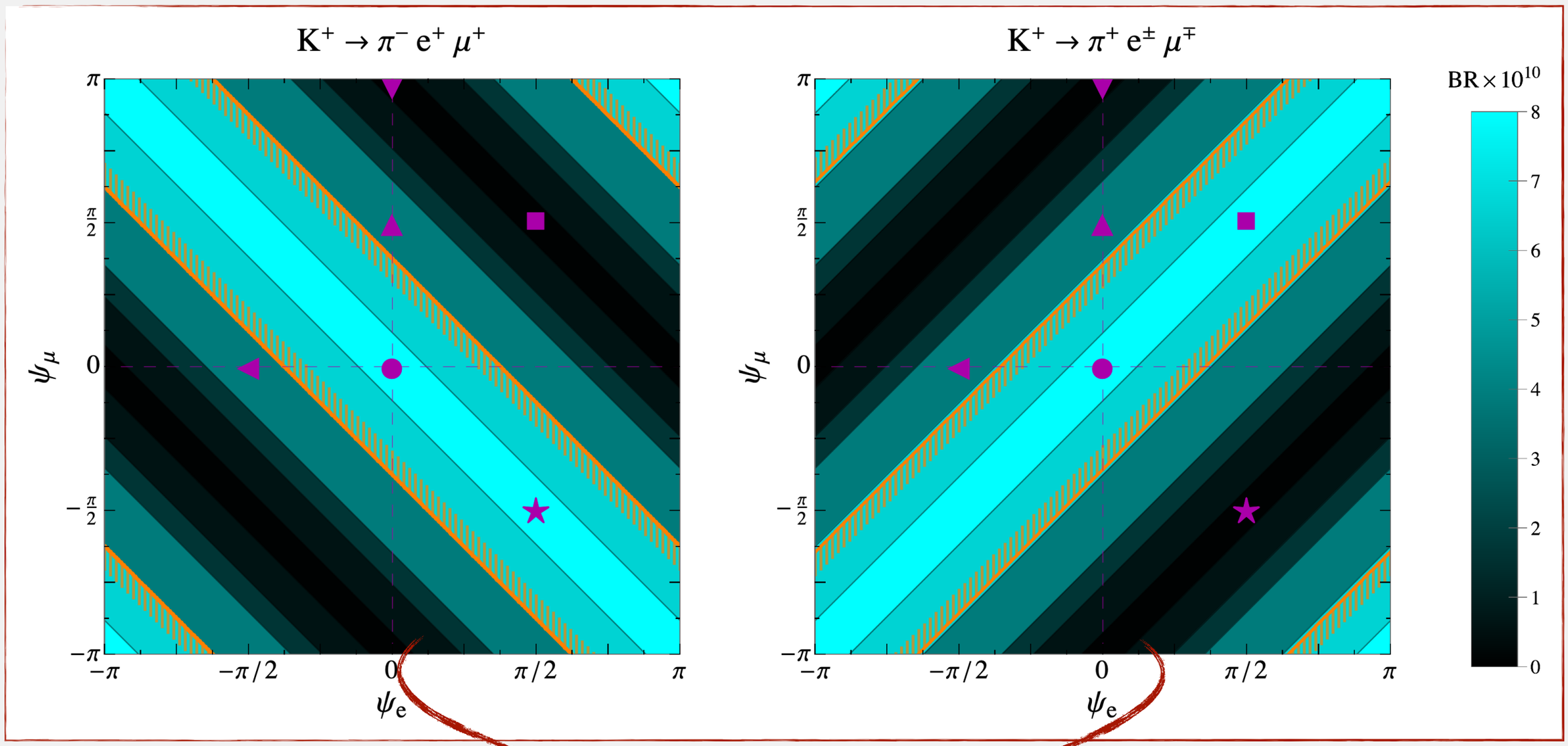

destructive interferences

Exploring the interference

- Conditions to have relevant interference effects if

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

- Resonant enhancement: on-shell and narrow-width

- Maximal interference effects when: $\kappa' \sim \kappa \equiv \dfrac{|U_{\alpha 5} U_{\beta 5}|}{|U_{\alpha 4} U_{\beta 4}|} \dfrac{f(m_5)}{f(m_4)} \sim 1$

- Define LNV/LNC ratio:

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

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

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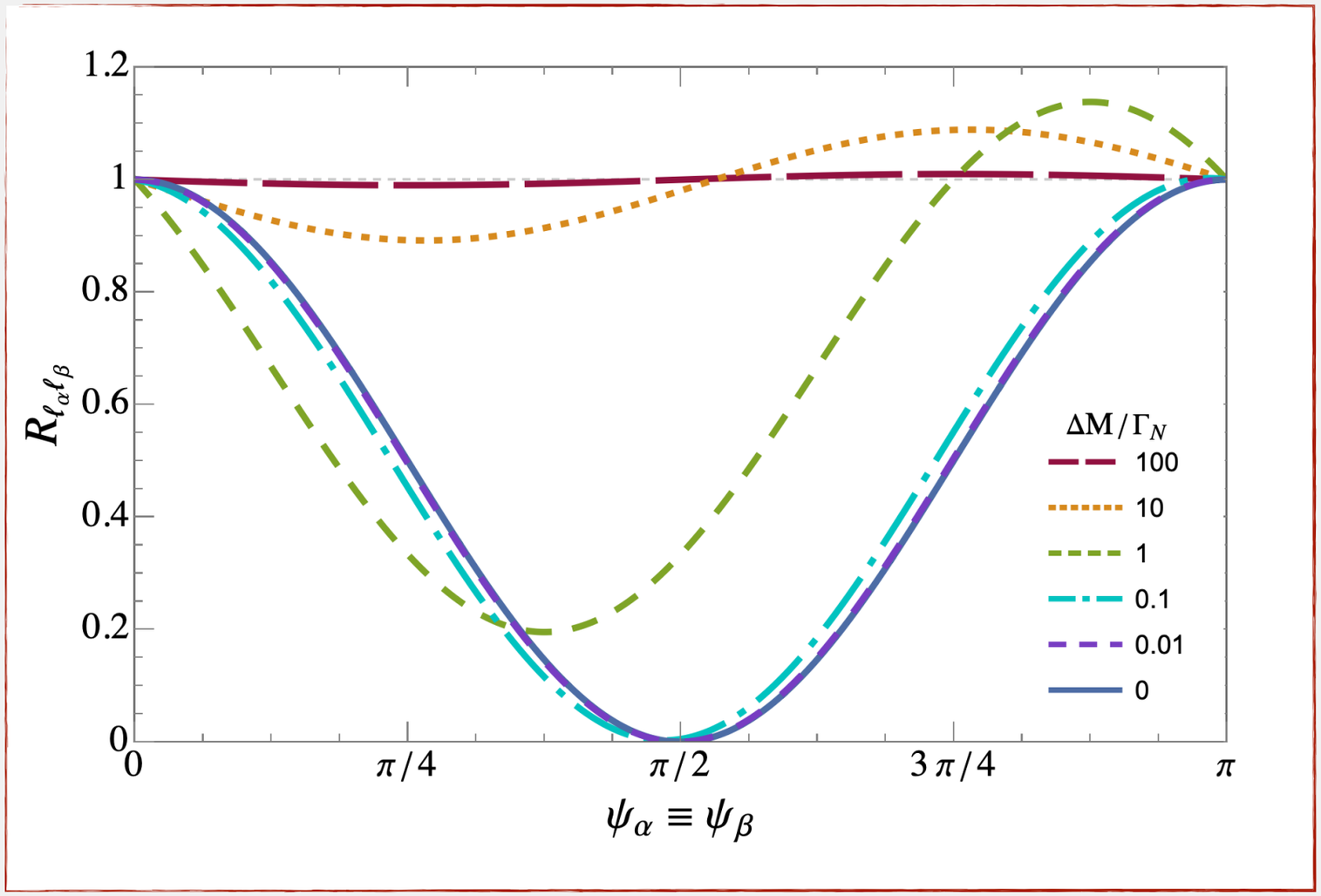
Interference: simple case $\psi_\alpha \equiv \psi_\beta$

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



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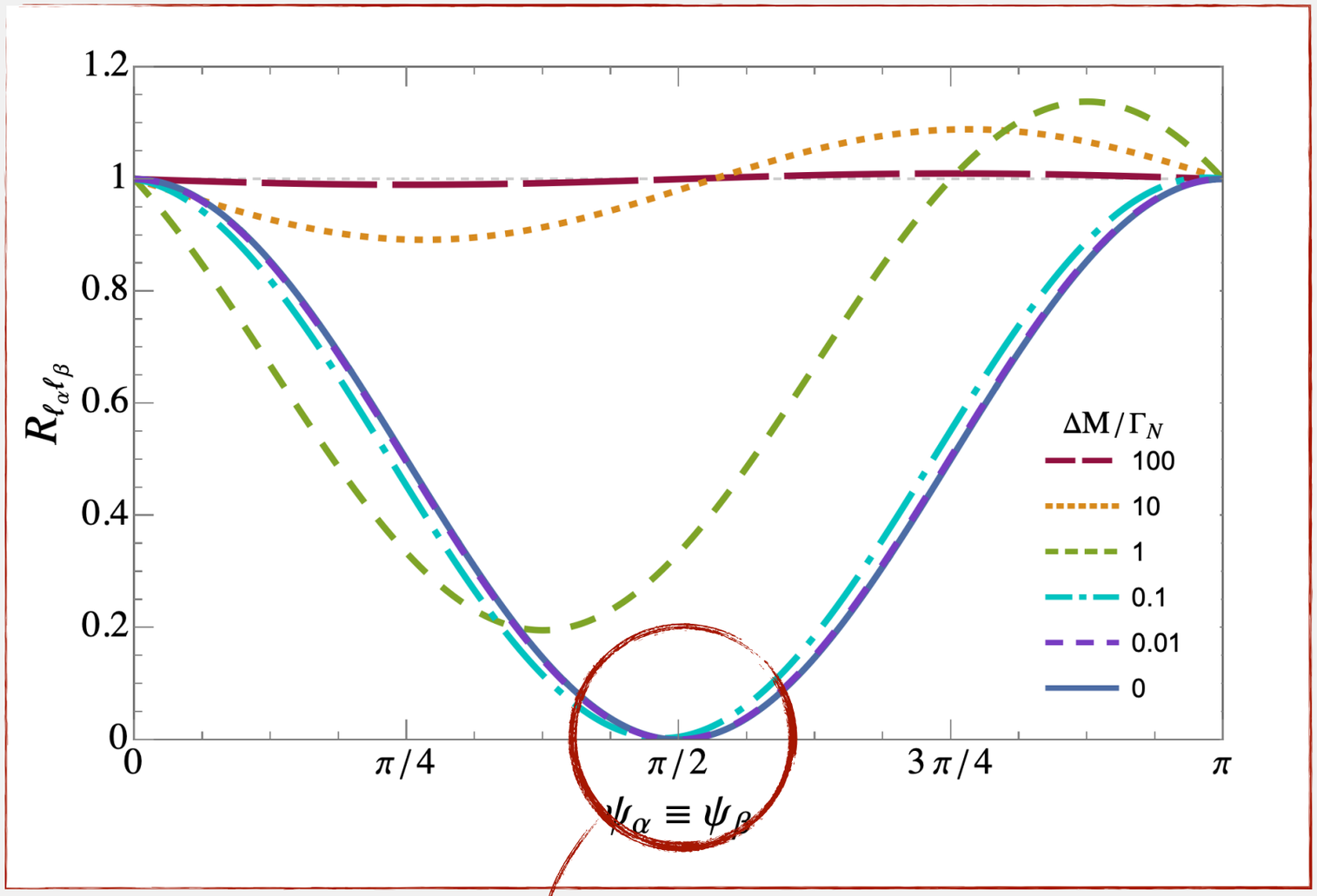


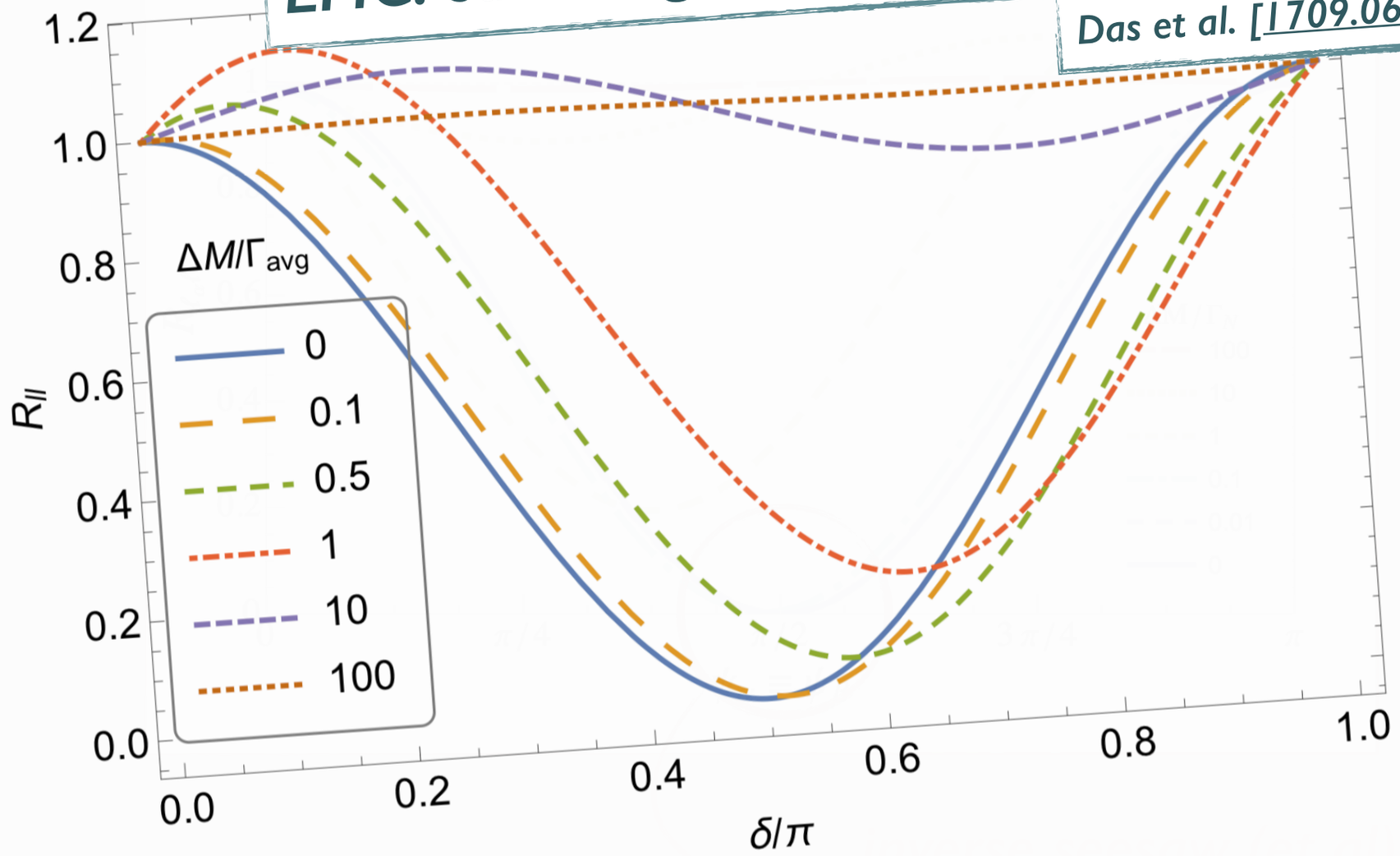
inverse seesaw (et al) models live over here

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

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

LHC: same-sign vs opposite-sign dileptons

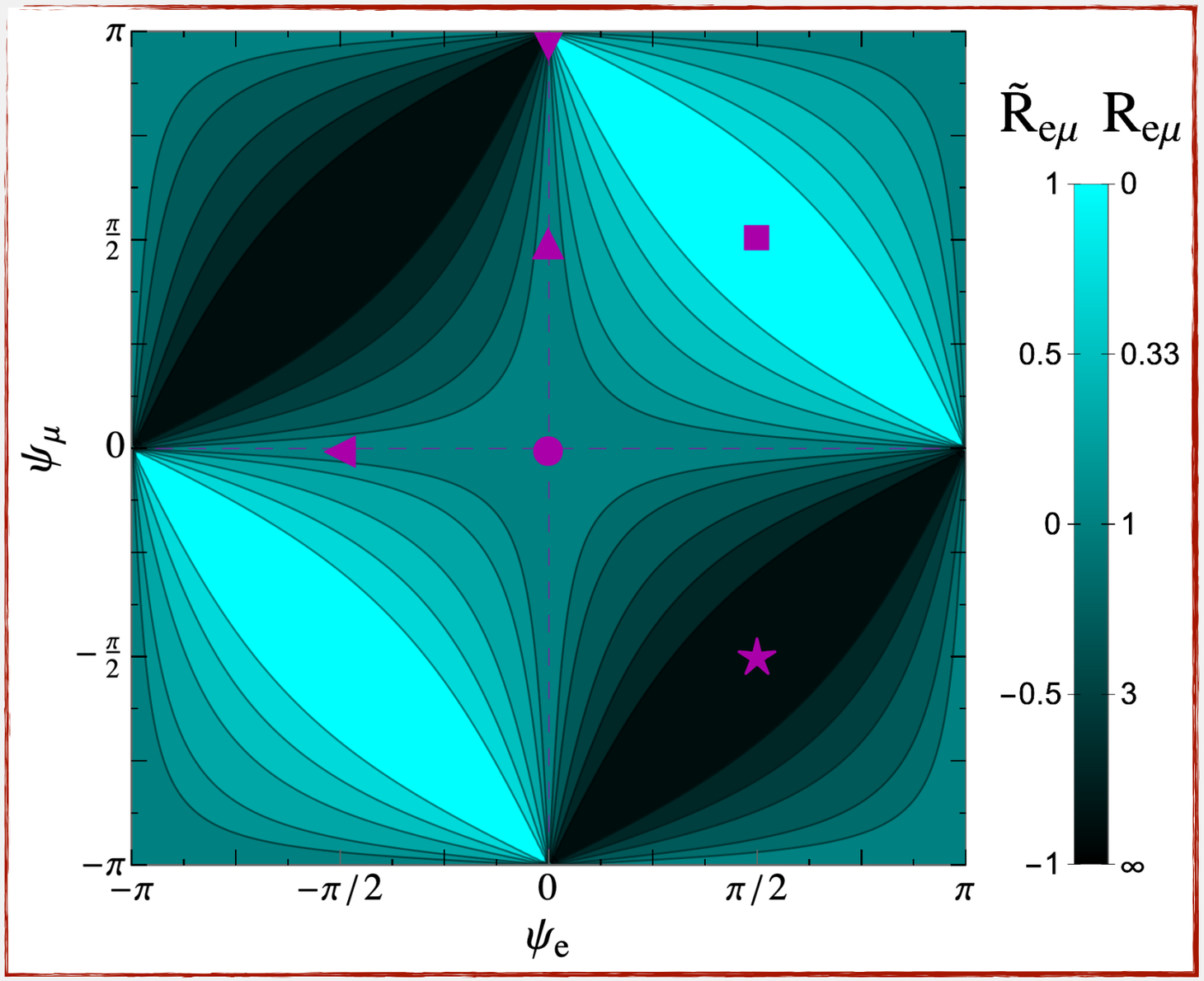
Das et al. [1709.06553]



models live over here

Interference: more general case

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



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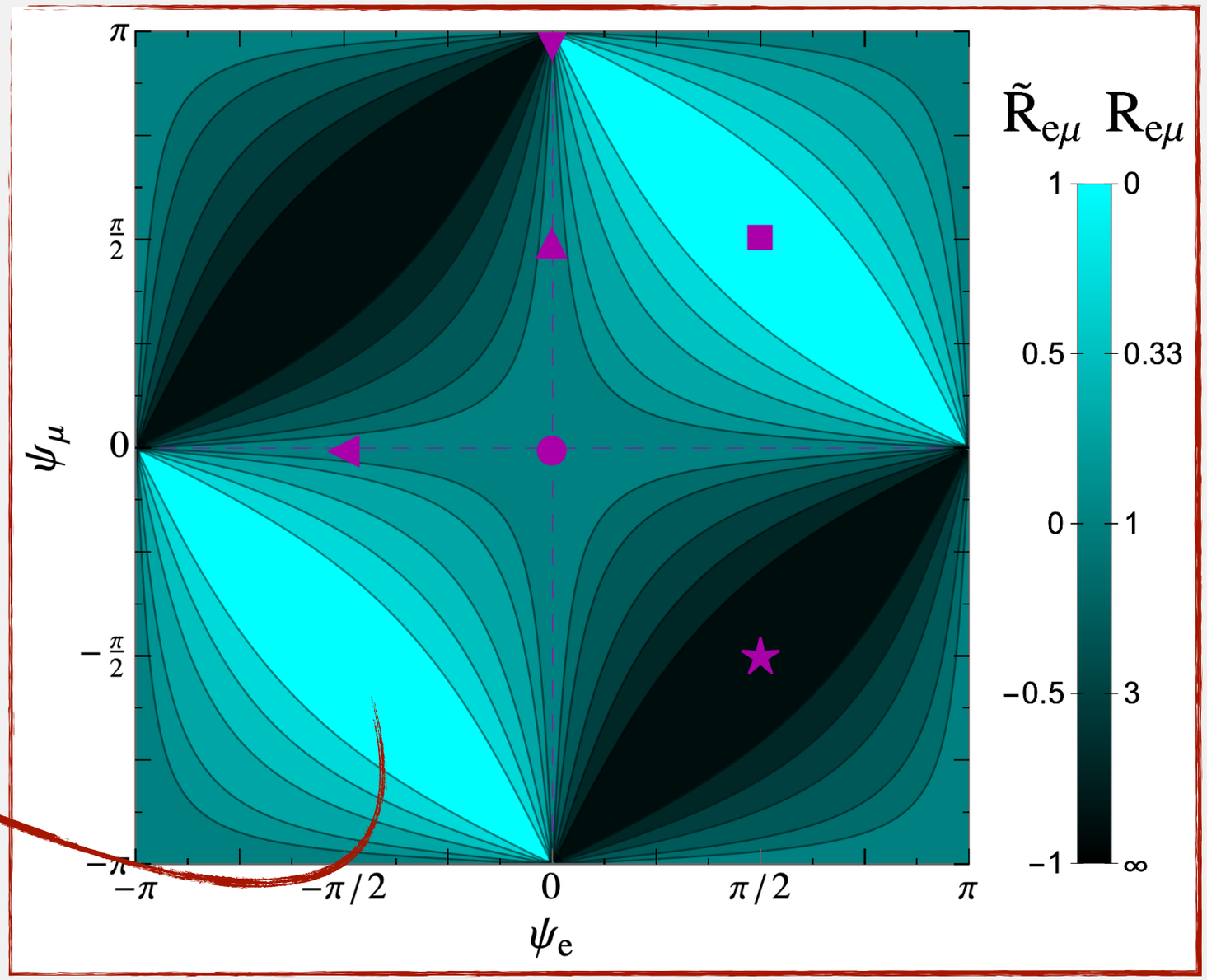


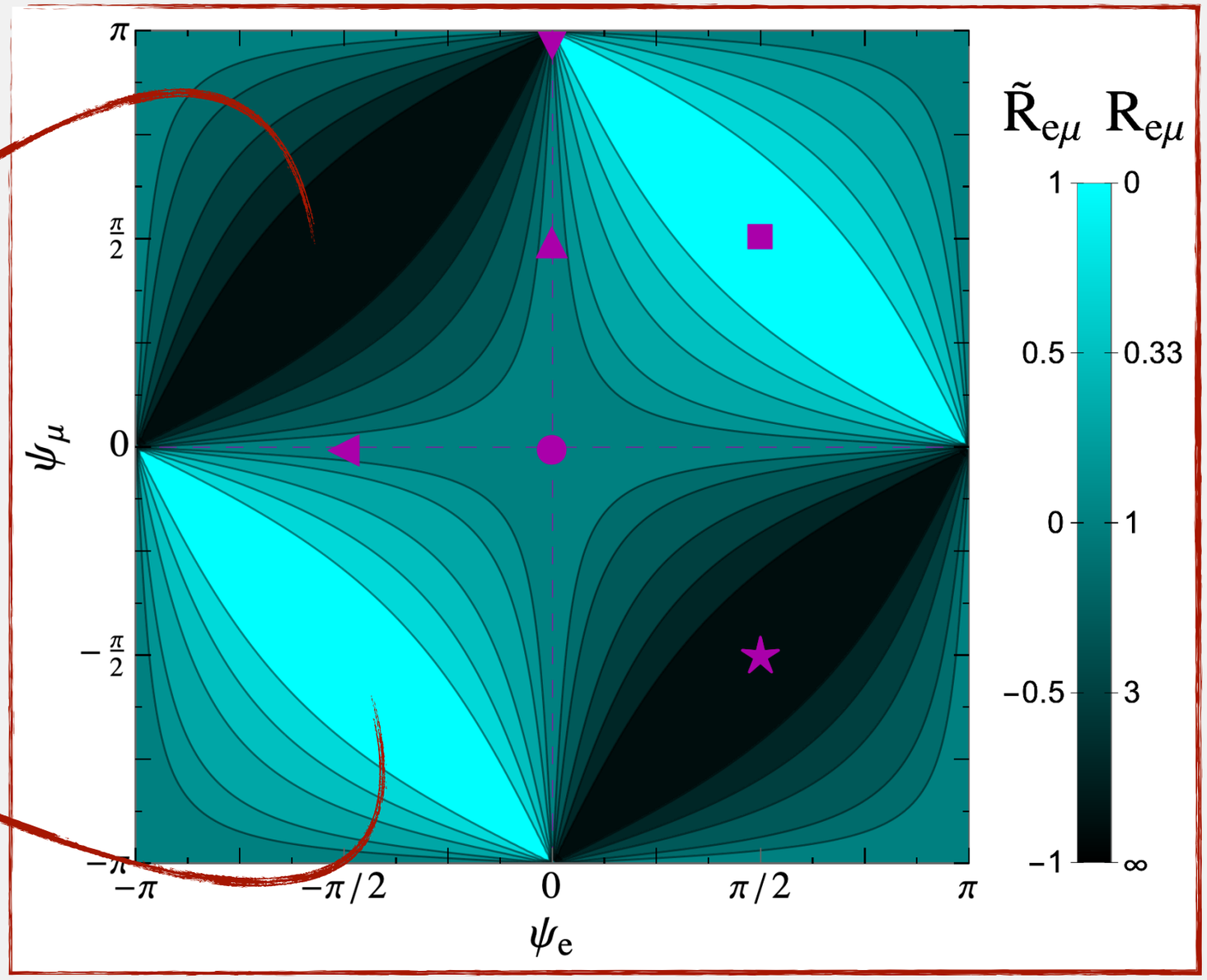
LNV suppressed

Interference: more general case

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

LNC suppressed

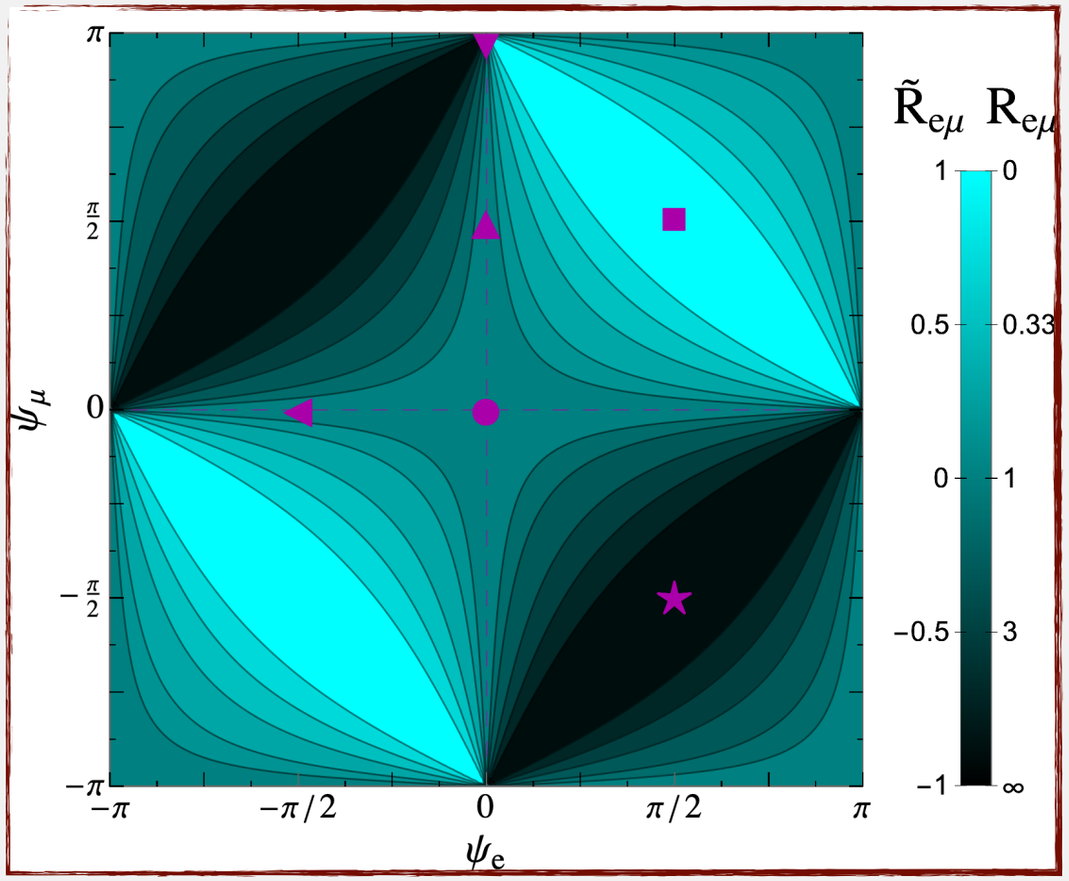
LNV suppressed



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

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

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

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