The charged Lepton Flavor Violation with trilinear R-parity Violating SUSY

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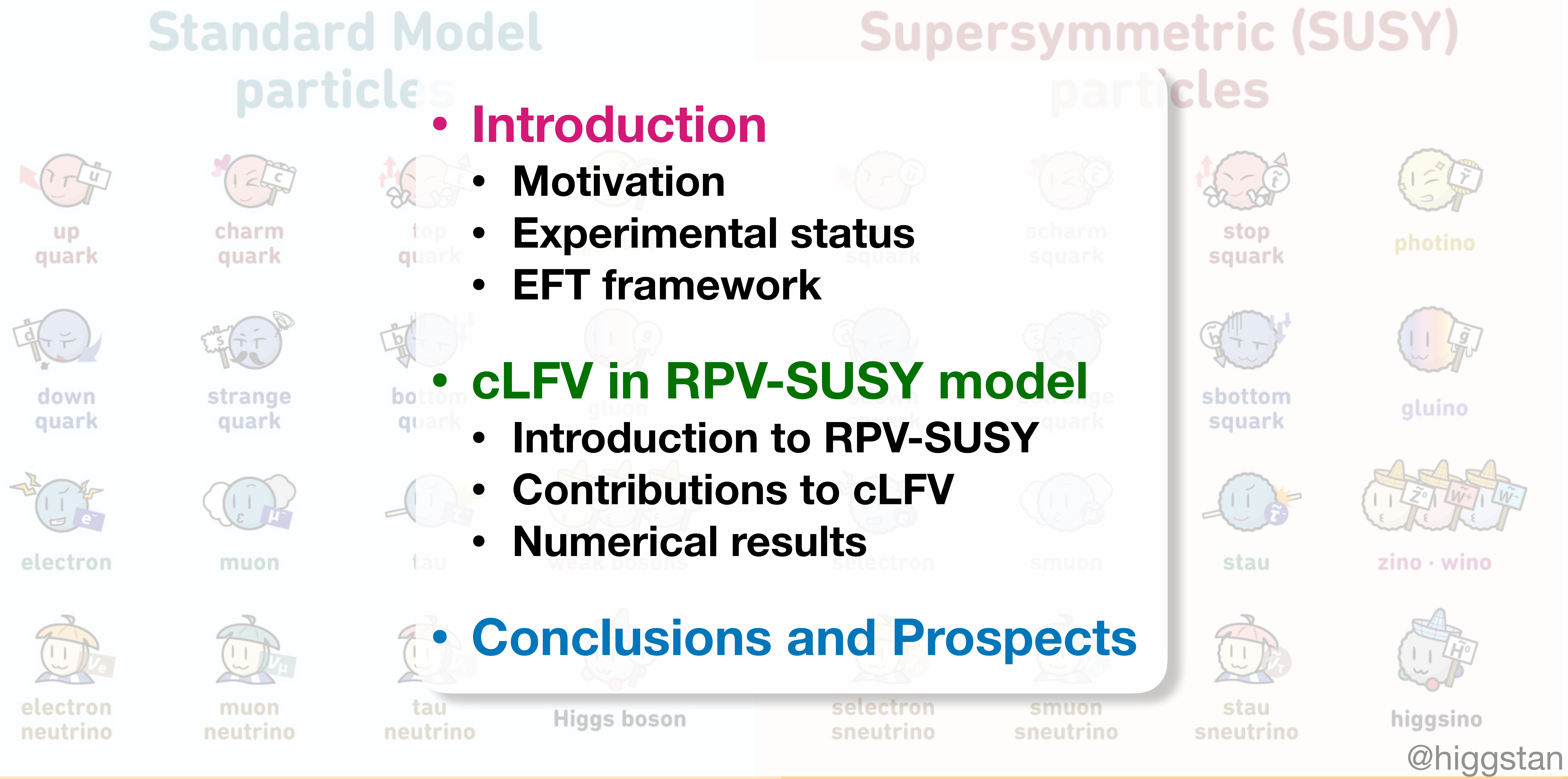

- **Introduction**
  - **Motivation**
  - **Experimental status**
  - **EFT framework**
- **cLFV in RPV-SUSY model**
  - **Introduction to RPV-SUSY**
  - **Contributions to cLFV**
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- **Conclusions and Prospects**

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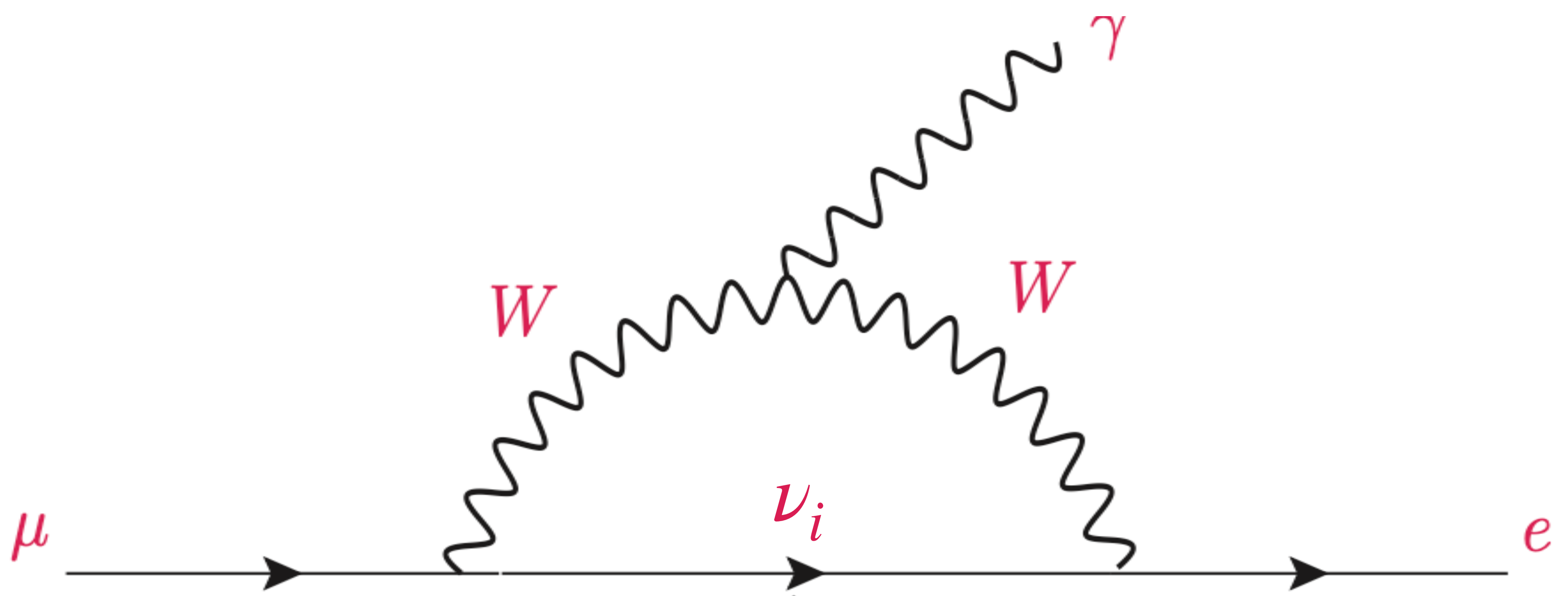
- **SM contribution on cLFV:**

$$B_{\rm SM}(\mu \to e\gamma) \sim O(10^{-52})$$



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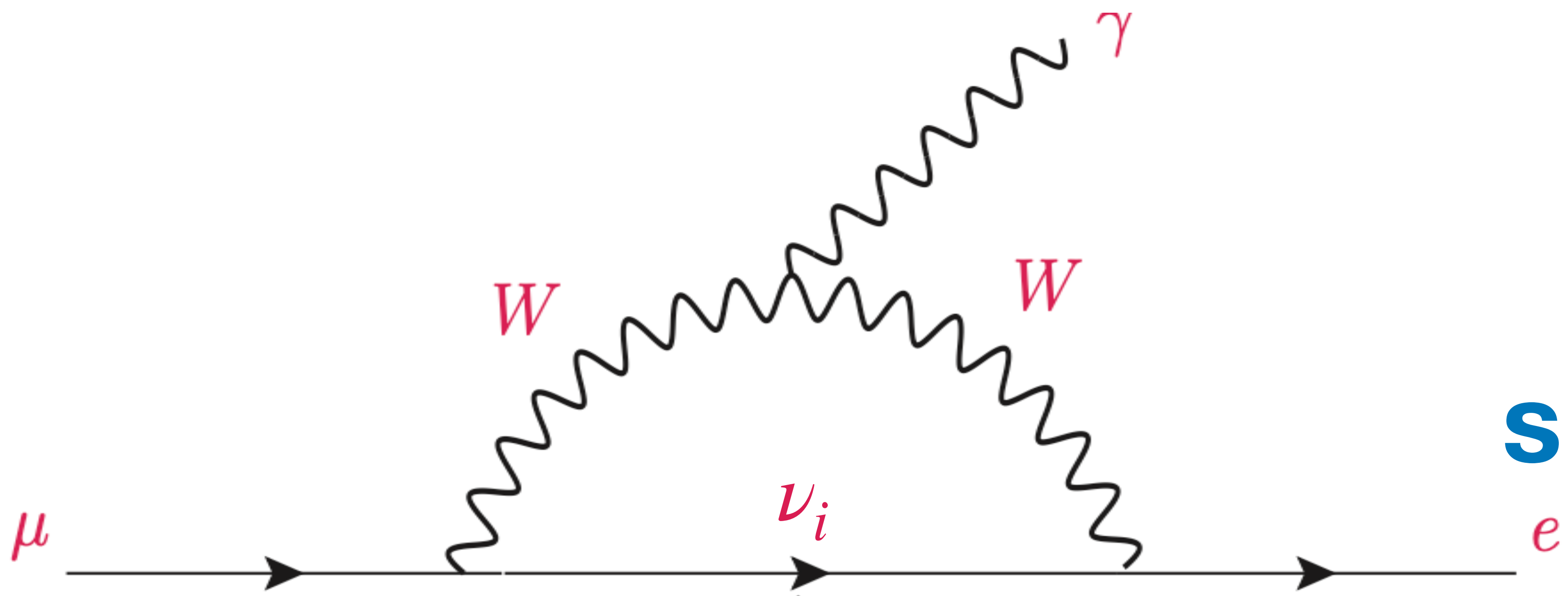

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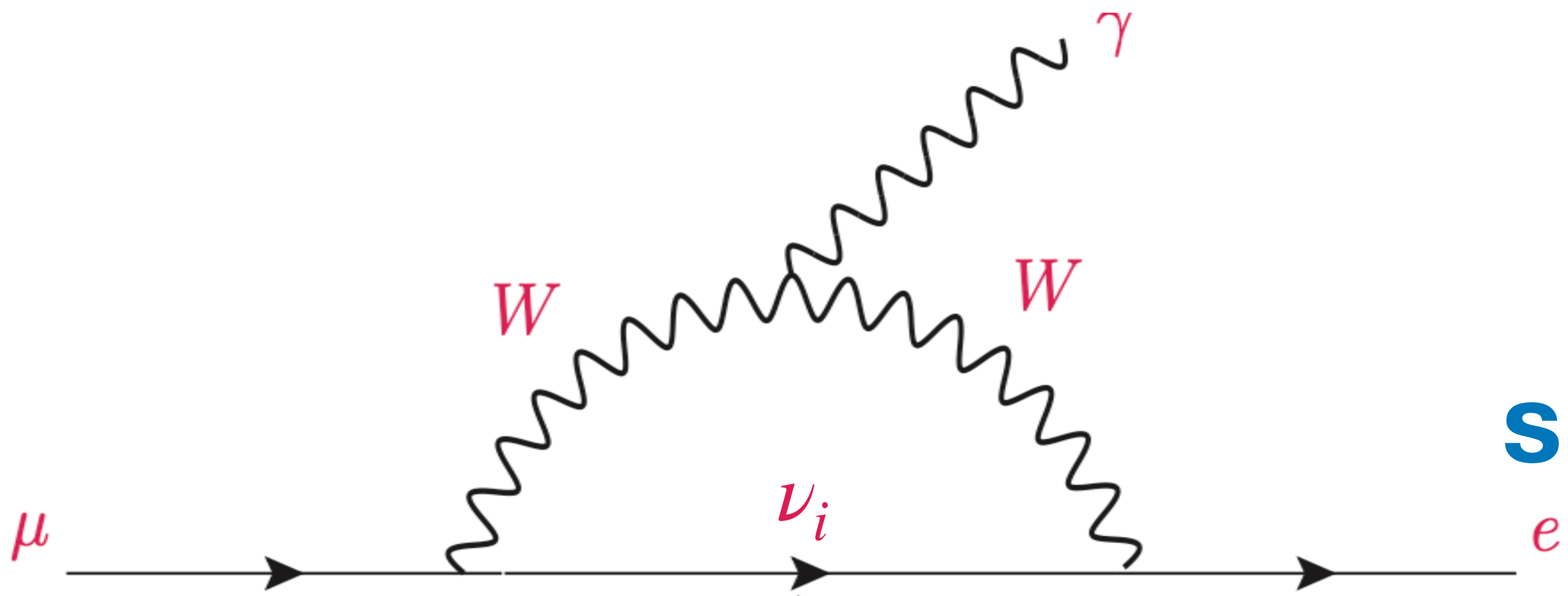

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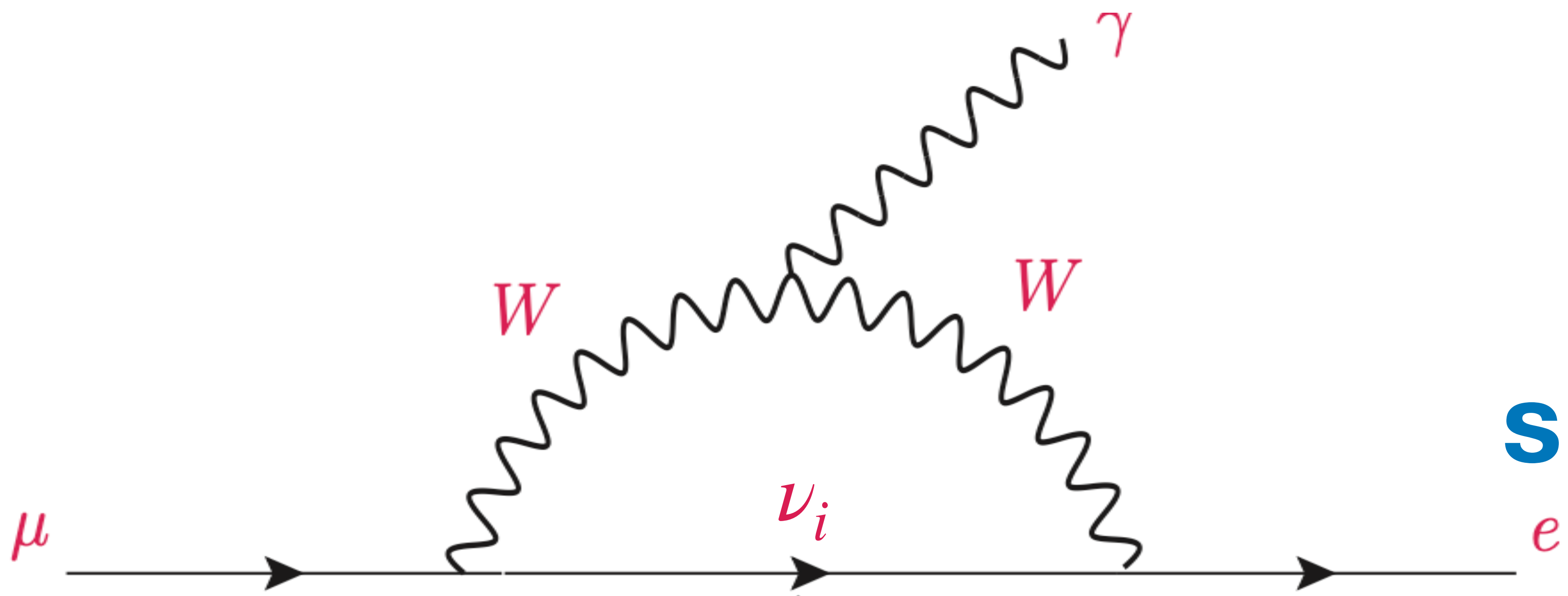

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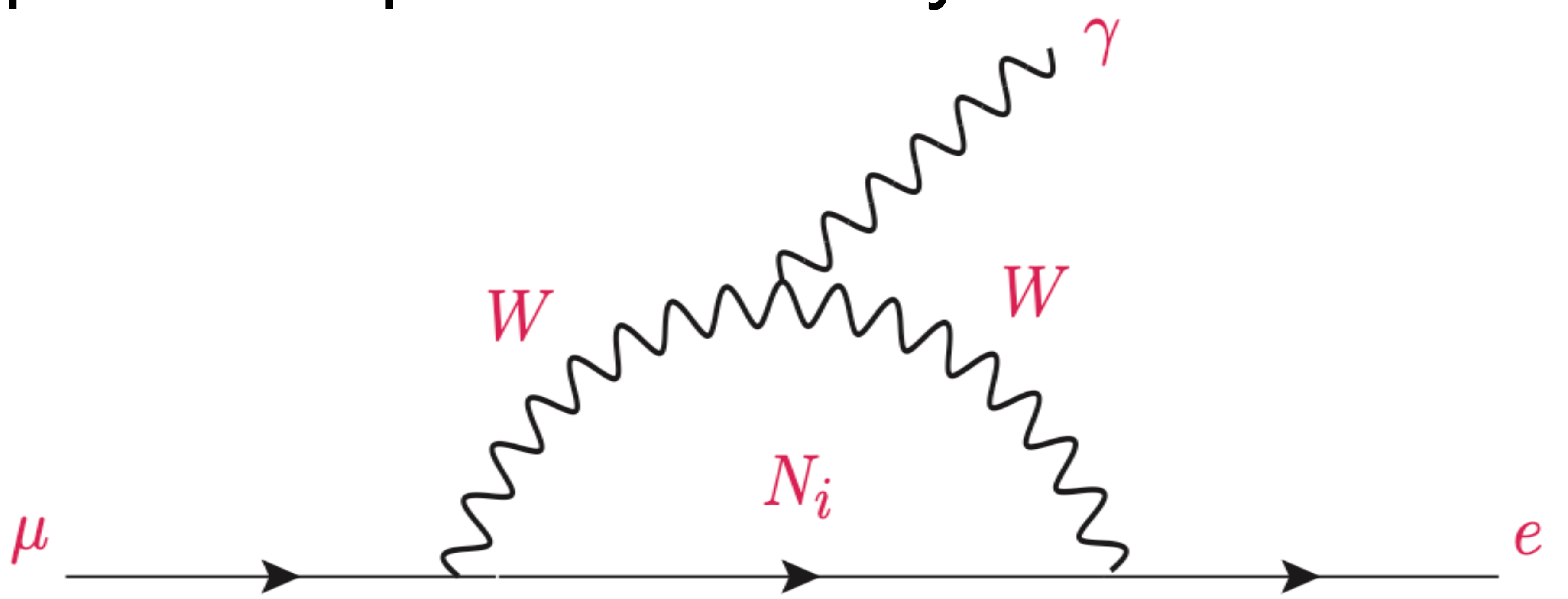

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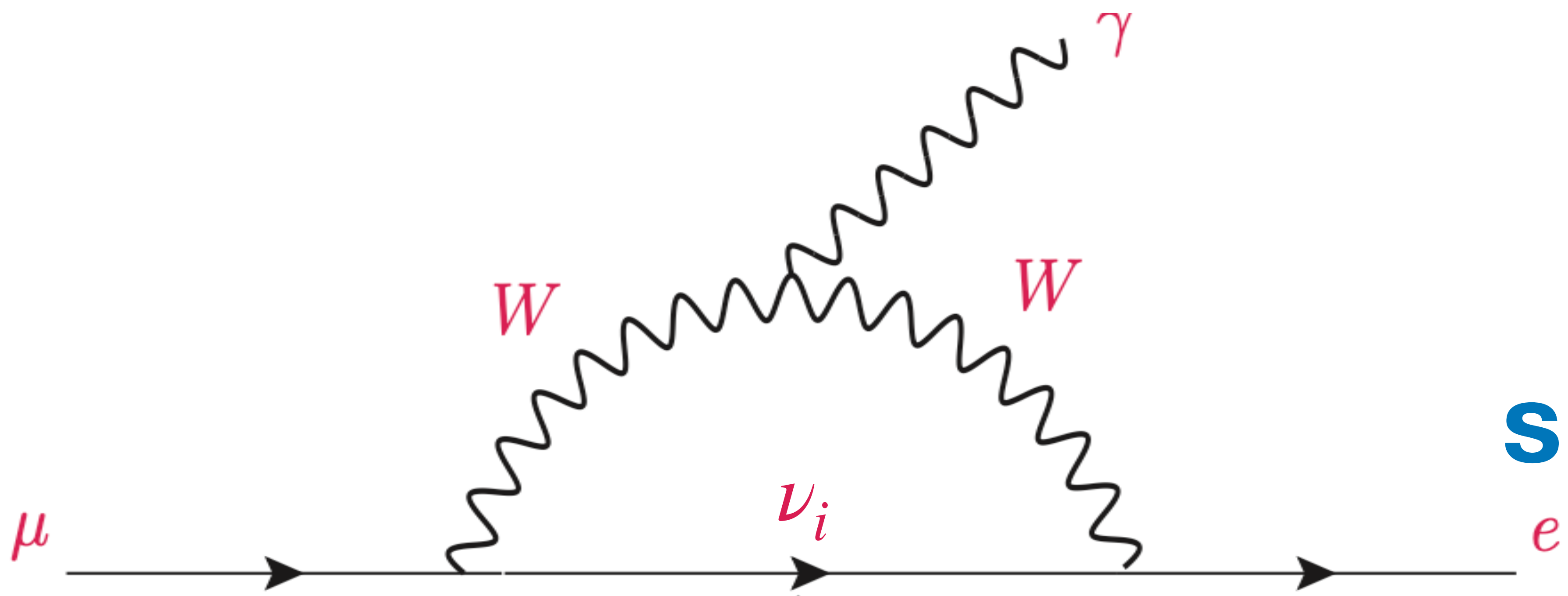

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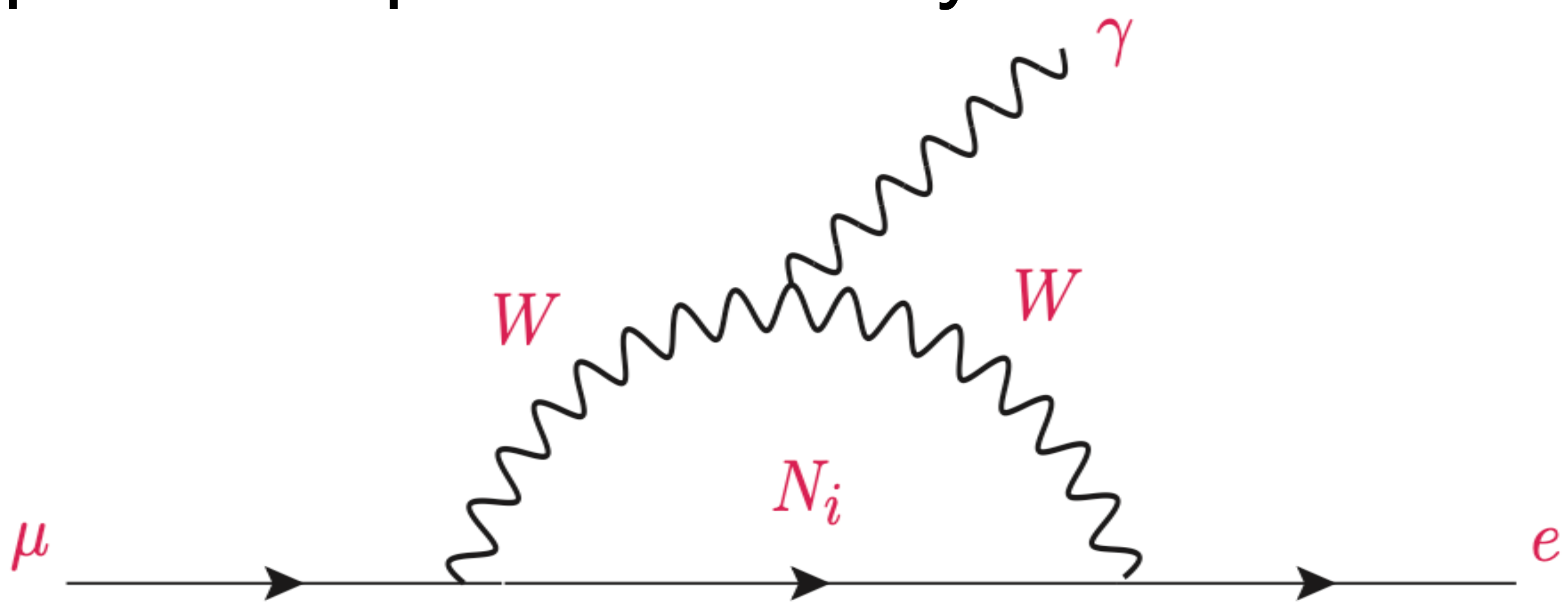

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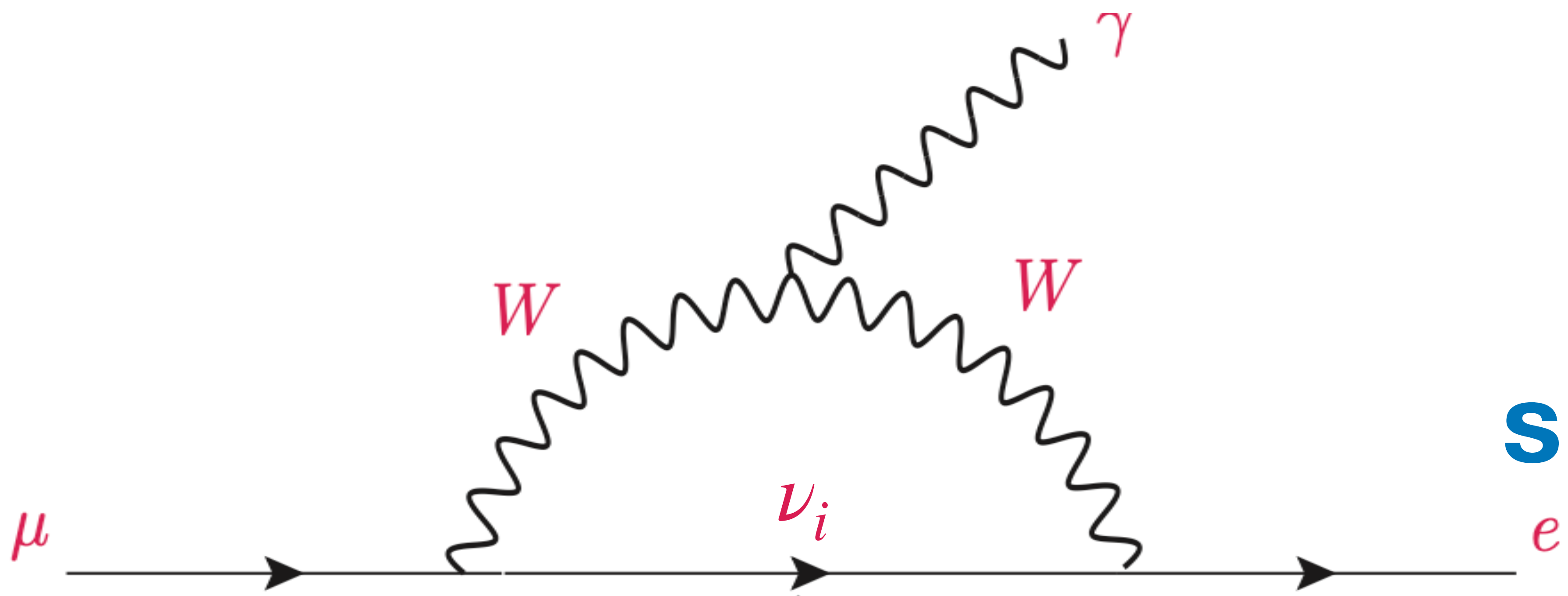

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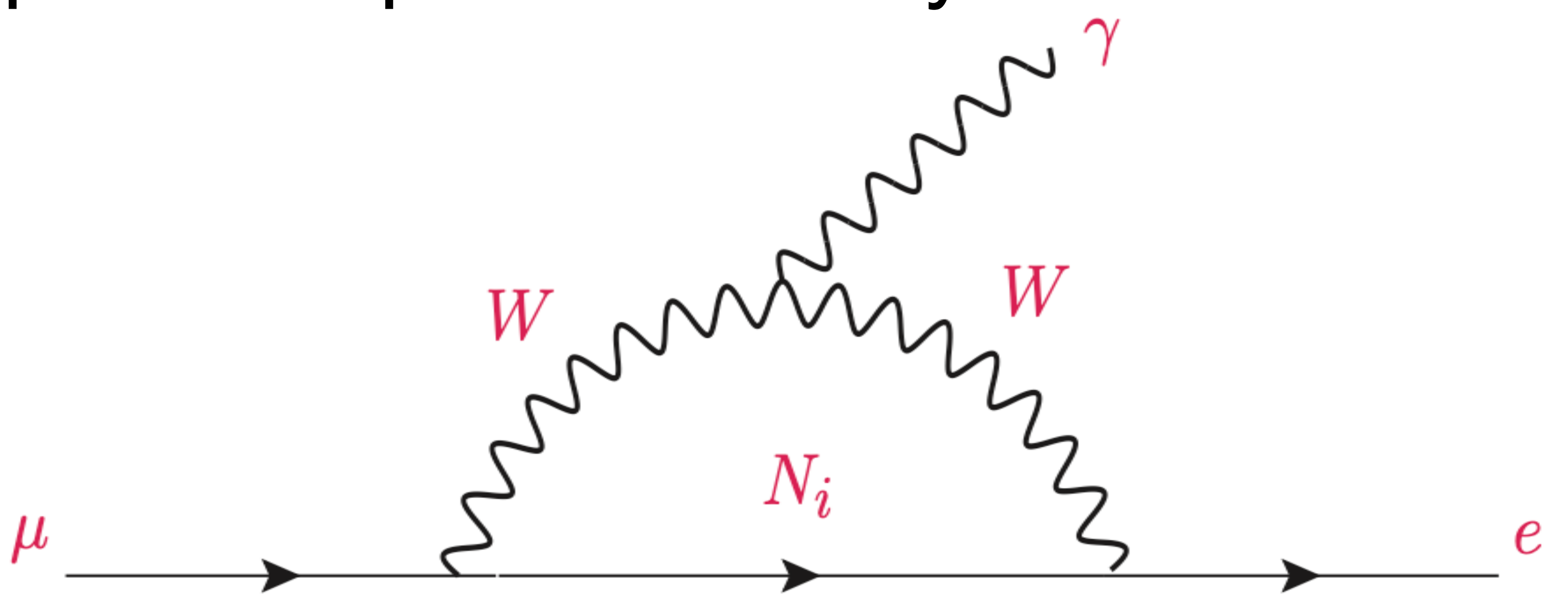

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Observation of cLFV would indicate a clear signal of New physics

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$\mu + \mathrm{Au} \to e + \mathrm{Au}$	$< 7 \times 10^{-13}$	2006	SINDRUM II
$\mu^+ \to e^+ \gamma$	$< 1.5 \times 10^{-13}$	2025	MEG-II
$\mu^+ \to e^+ e^+ e^-$	$< 1.0 \times 10^{-12}$	1987	SINDRUM
$\mu + \mathrm{Al} \to e + \mathrm{Al}$	$\sim 3 \times 10^{-15}$	2027	COMET (Phase I)
$\mu + \mathrm{Al} \to e + \mathrm{Al}$	$\sim 3 \times 10^{-17}$		COMET (Phase II)
$\mu + \mathrm{Al} \to e + \mathrm{Al}$	$\sim 6.2 \times 10^{-16}$	2027	Mu2e (Run I)
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- **New progress on $\mu \to e\gamma$ in 2025**
- **Best limits from Exp. Searches on $\mu N \to eN$ and $\mu \to 3e$ are given by 20~40 years ago**
- **Near future plans for $\mu N \to eN$ and $\mu \to 3e$**

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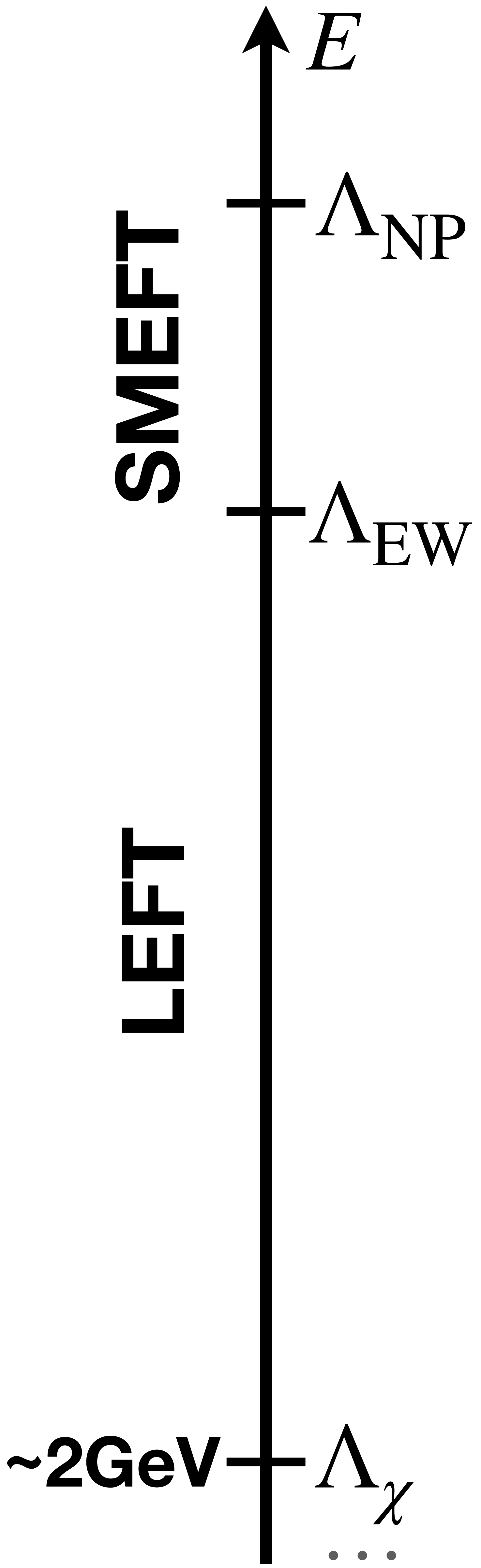

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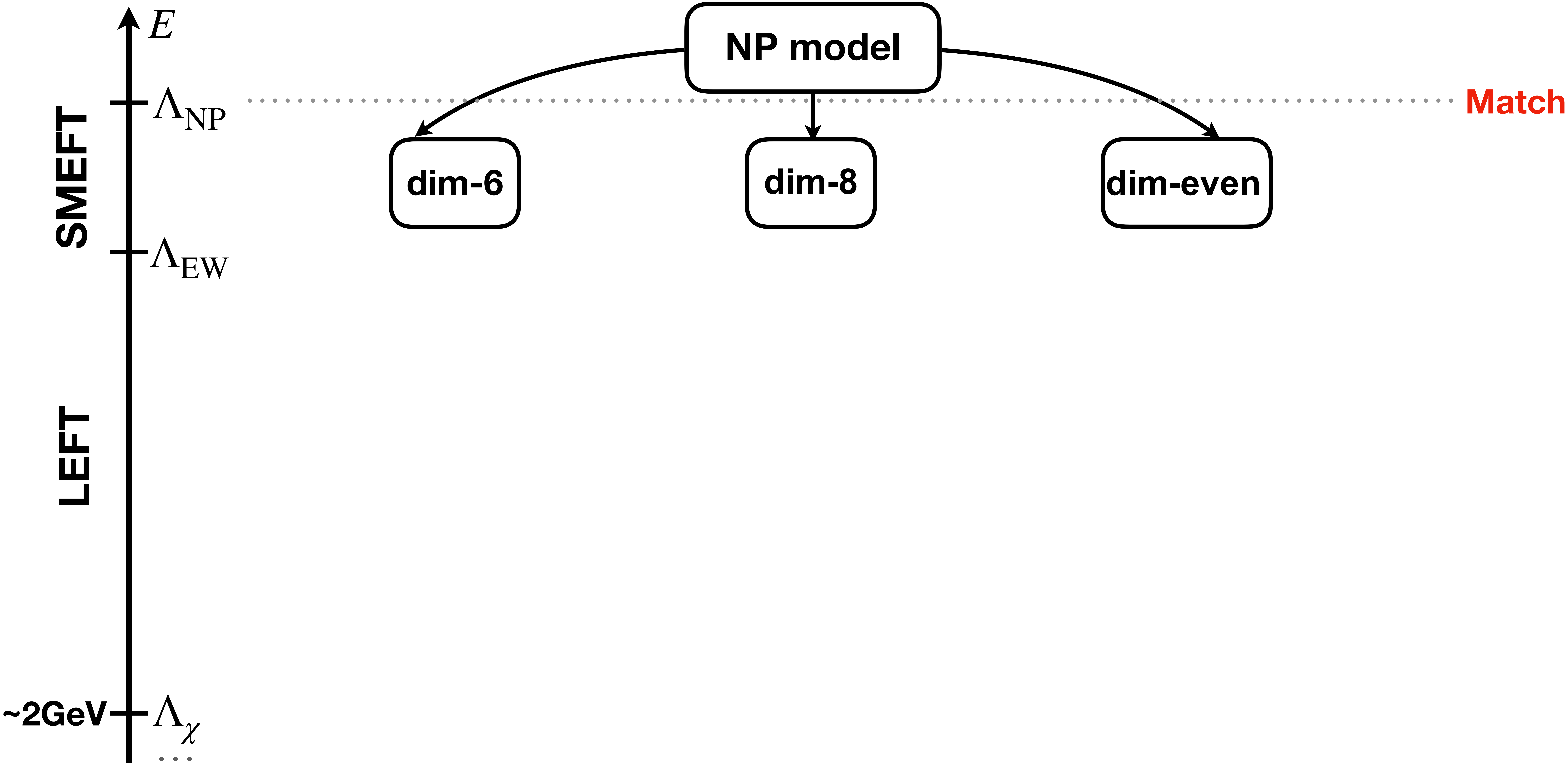

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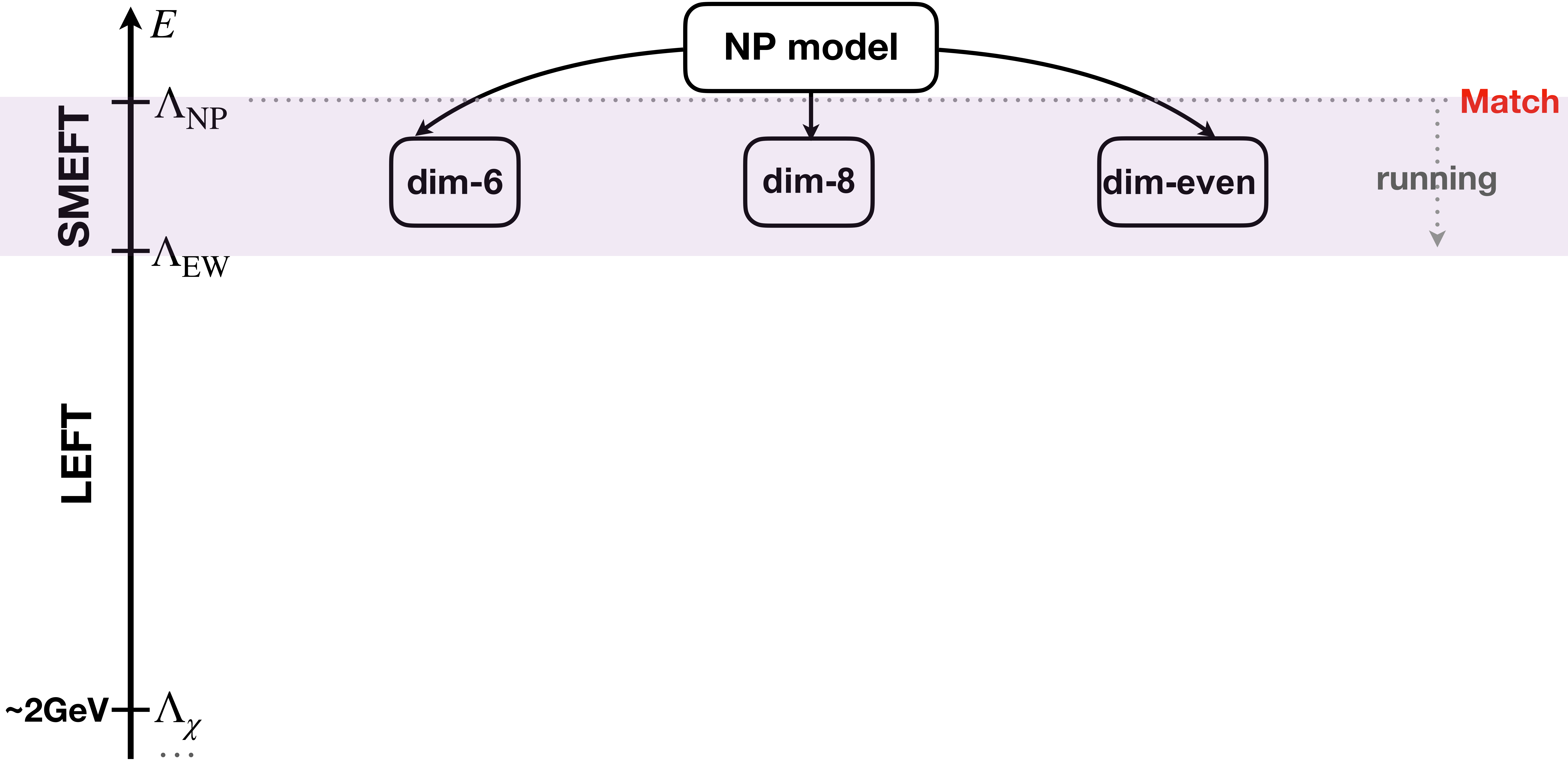

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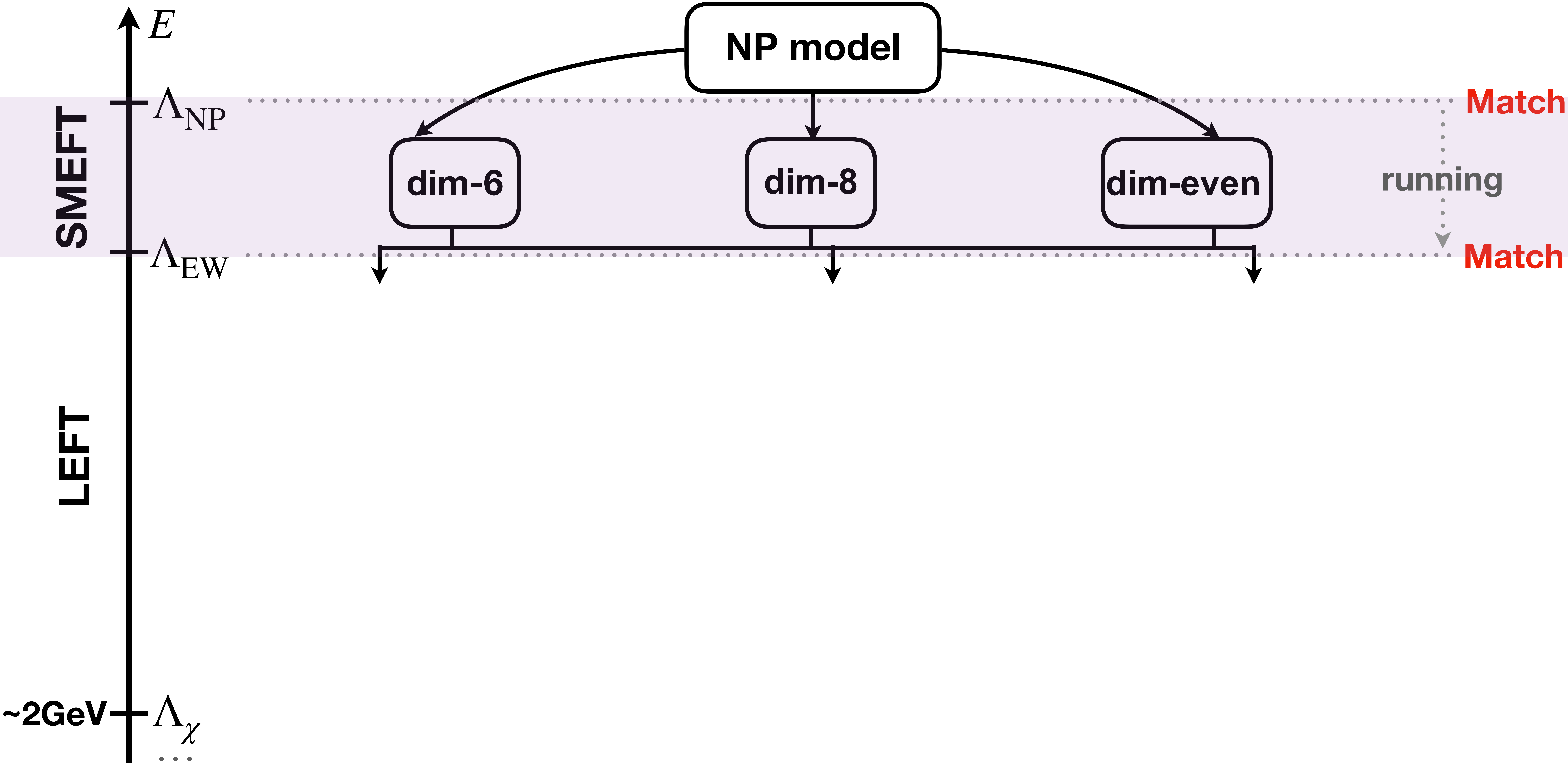

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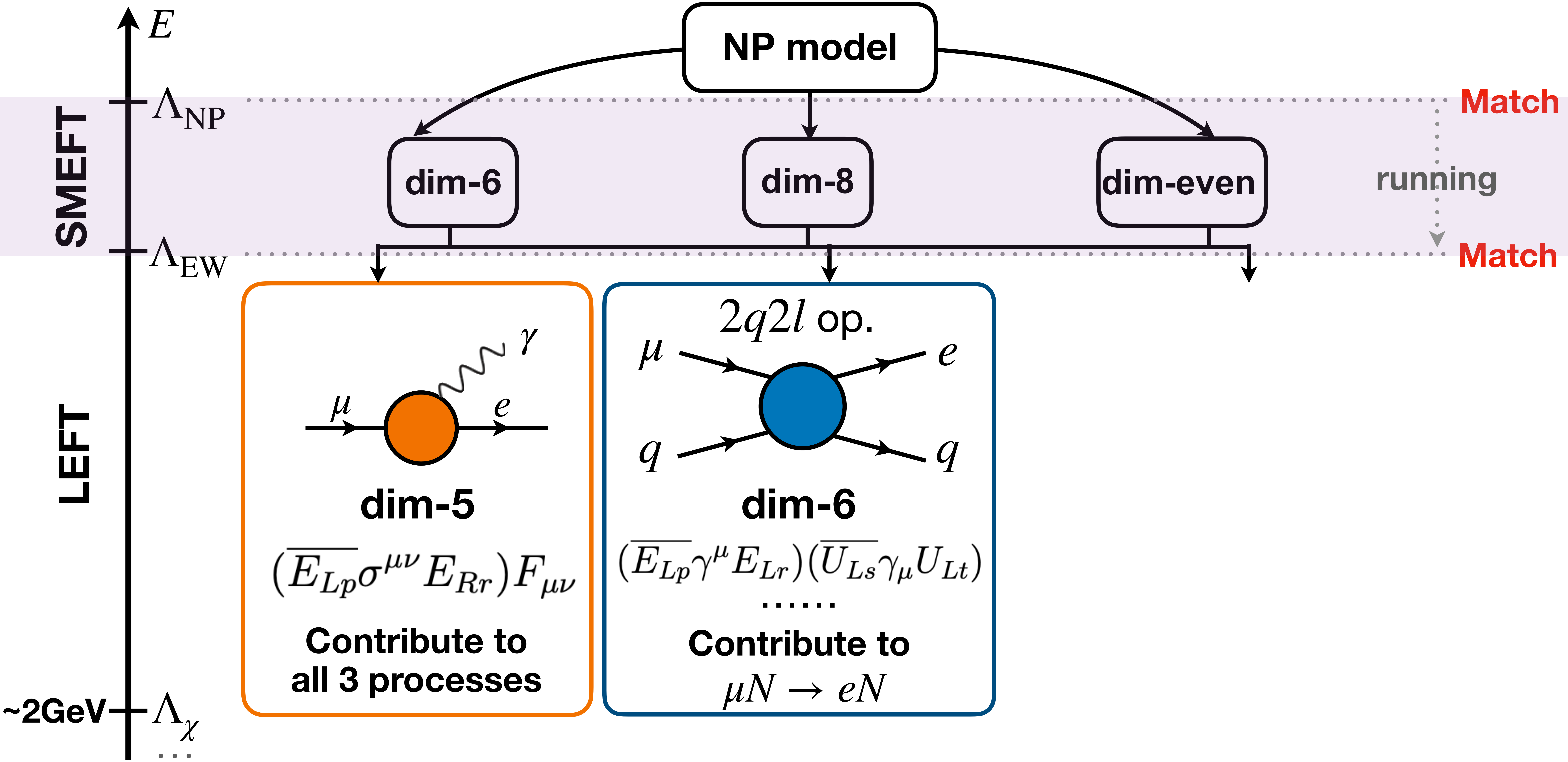

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LNV

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$$W_{\rm MSSM} = y_u \overline{u} Q H_u - y_d \overline{d} Q H_d - y_e \overline{e} L H_d + \mu H_u H_d$$

- ***R*-parity violating (RPV) superpotential:**

LNV   BNV

$$W \supset \frac{1}{2}\lambda_{ijk} L_i L_j E_k^c + \lambda'_{ijk} L_i Q_j D_k^c + \frac{1}{2}\lambda''_{ijk} U_i^c D_j^c D_k^c$$

cLFV in RPV-SUSY: Model

Name		spin-0	spin-1/2	$SU(3)_C \times SU(2)_L \times U(1)_Y$
sqaurk, quark	Q	$(\tilde{U}_L, \tilde{D}_L)$	(U_L, D_L)	$(3, 2, 1/6)$
	U	$\tilde{U}_R$	U_R	$(3, 1, 2/3)$
	D	$\tilde{D}_R$	D_R	$(3, 1, -1/3)$
slepton, lepton	L	$(\tilde{\nu}, \tilde{E}_L)$	(ν, E_L)	$(1, 2, -1/2)$
	E	$\tilde{E}_R$	E_R	$(1, 1, -1)$
Higgs, higgsino	H_u	(H_u^+, H_u^0)	$(\tilde{H}_u^+, \tilde{H}_u^0)$	$(1, 2, 1/2)$
	H_d	(H_d^0, H_d^-)	$(\tilde{H}_u^0, \tilde{H}_u^-)$	$(1, 2, -1/2)$

Name	spin-1	spin-1/2	$SU(3)_C \times SU(2)_L \times U(1)_Y$
gluon, gluino	g	$\tilde{g}$	$(8, 1, 0)$
W bosons, winos	$W^\pm, W^0$	$\tilde{W}^\pm, \tilde{W}^0$	$(1, 3, 0)$
B boson,bino	B^0	$\tilde{B}^0$	$(1, 1, 0)$

Each particle has a SUSY partner

Same QNs but different spin

- ***R*-parity: conserve the baryon number and lepton number**
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$$W_{\text{MSSM}} = y_u \overline{u} Q H_u - y_d \overline{d} Q H_d - y_e \overline{e} L H_d + \mu H_u H_d$$

- ***R*-parity violating (RPV) superpotential:**

LNV BNV

$$W \supset \frac{1}{2}\lambda_{ijk} L_i L_j E_k^c + \lambda'_{ijk} L_i Q_j D_k^c + \frac{1}{2}\lambda''_{ijk} U_i^c D_j^c D_k^c$$

contribute to $\mu N \to eN$ and $\mu \to 3e$ at tree level

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slepton, lepton	L	$(\tilde{\nu}, \tilde{E}_L)$	(ν, E_L)	$(1, 2, -1/2)$
	E	$\tilde{E}_R$	E_R	$(1, 1, -1)$
Higgs, higgsino	H_u	(H_u^+, H_u^0)	$(\tilde{H}_u^+, \tilde{H}_u^0)$	$(1, 2, 1/2)$
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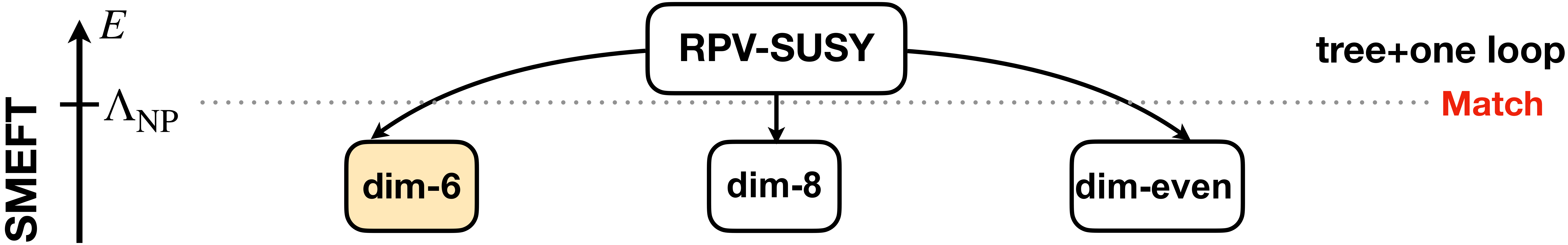
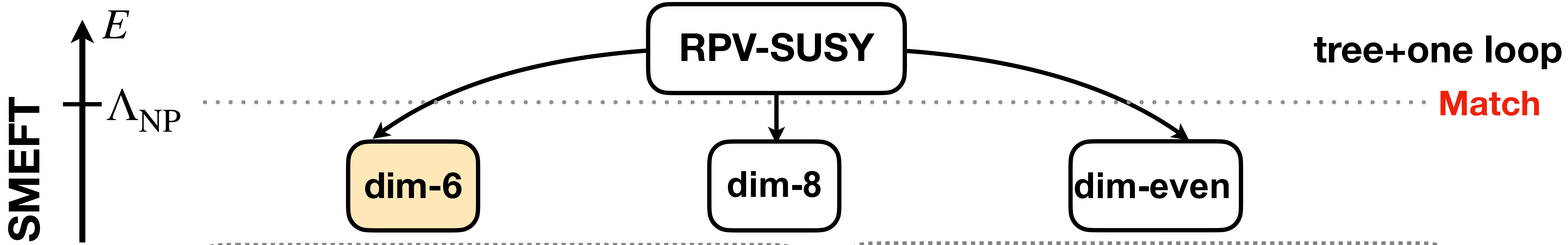
contribute to $\mu N \to eN$ and $\mu \to 3e$ at tree level

$$\mathcal{L}_{\lambda'} = -\lambda'_{ijk}\Big(\overline{\nu_{Li}^c} D_{Lj} \tilde{D}_{Rk}^* + \overline{\nu_{Li}^c} \tilde{D}_{Lj} D_{Rk}^c + \tilde{\nu}_{Li} \overline{D_{Lj}^c} D_{Rk}^c - \overline{E_{Li}^c} U_{Lj} \tilde{D}_{Rk}^* - \overline{E_{Li}^c} \tilde{U}_{Lj} D_{Rk}^c - \tilde{E}_{Li} \overline{U_{Lj}^c} D_{Rk}^c\Big) + \text{h.c.}$$

cLFV in RPV-SUSY: Matching Conditions (UV to SMEFT)



cLFV in RPV-SUSY: Matching Conditions (UV to SMEFT)



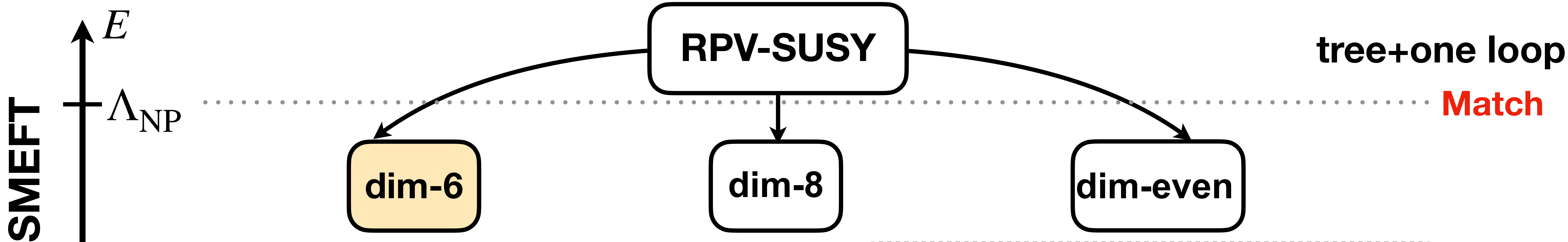
e.g.

$\mathcal{O}_{\ell q}^{(1)}$ $\quad (\overline{L_{Lp}}\gamma_\mu L_{Lr})(\overline{Q_{Ls}}\gamma^\mu Q_{Lt})$

$\mathcal{O}_{\ell q}^{(3)}$ $\quad (\overline{L_{Lp}}\gamma_\mu \tau^I L_{Lr})(\overline{Q_{Ls}}\gamma^\mu \tau^I Q_{Lt})$

$\mathcal{O}_{\ell d}$ $\quad (\overline{L_{Lp}}\gamma_\mu L_{Lr})(\overline{D_{Rs}}\gamma^\mu D_{Rt})$

cLFV in RPV-SUSY: Matching Conditions (UV to SMEFT)



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Tree-level matching

$$[\mathcal{C}_{\ell q}^{(1)}]_{prst} = -[\mathcal{C}_{\ell q}^{(3)}]_{prst} = \frac{1}{4}\frac{\lambda'_{rtk}\lambda'^{*}_{psk}}{m^2_{\tilde{d}_{Rk}}}$$

$$[\mathcal{C}_{\ell d}]_{prst} = -\frac{1}{2}\frac{\lambda'_{rjs}\lambda'^{*}_{pjt}}{m^2_{\tilde{u}_{Lj}}}$$

cLFV in RPV-SUSY: Matching Conditions (UV to SMEFT)

E

SMEFT

Λ_{NP}

RPV-SUSY

tree+one loop

Match

dim-6 | **dim-8** | **dim-even**

e.g.

$\mathcal{O}_{\ell q}^{(1)}$	$(\overline{L_{Lp}}\gamma_\mu L_{Lr})(\overline{Q_{Ls}}\gamma^\mu Q_{Lt})$	$\mathcal{O}_{\ell d}$	$(\overline{L_{Lp}}\gamma_\mu L_{Lr})(\overline{D_{Rs}}\gamma^\mu D_{Rt})$
$\mathcal{O}_{\ell q}^{(3)}$	$(\overline{L_{Lp}}\gamma_\mu \tau^I L_{Lr})(\overline{Q_{Ls}}\gamma^\mu \tau^I Q_{Lt})$		

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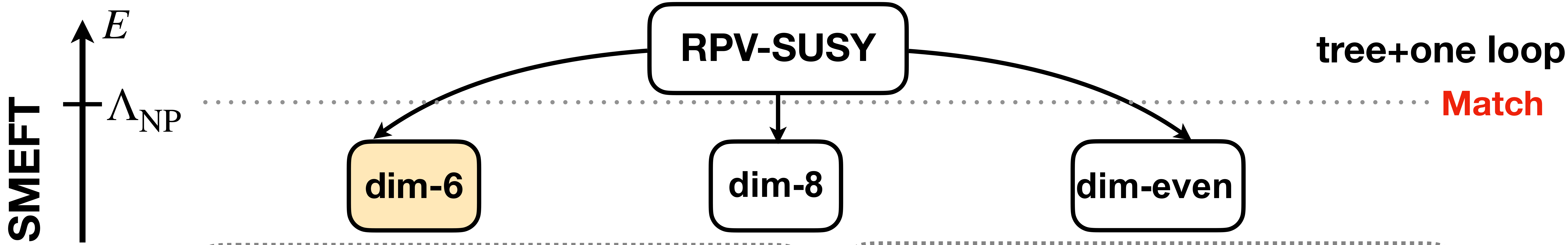
$$[\mathcal{C}_{\ell d}]_{prst} = -\frac{1}{2}\frac{\lambda'_{rjs}\lambda'^{*}_{pjt}}{m^2_{\tilde{u}_{Lj}}}$$

$\mathcal{O}_{eW}$	$(\overline{L_{Lp}}\sigma^{\mu\nu}E_{Rr})\tau^I\varphi W^I_{\mu\nu}$
$\mathcal{O}_{eB}$	$(\bar{\ell}_p\sigma^{\mu\nu}E_{Rr})\varphi B_{\mu\nu}$

cLFV in RPV-SUSY: Matching Conditions (UV to SMEFT)



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$\mathcal{O}_{\ell q}^{(1)}$ $(\overline{L_{Lp}}\gamma_\mu L_{Lr})(\overline{Q_{Ls}}\gamma^\mu Q_{Lt})$

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$$[\mathcal{C}_{\ell q}^{(1)}]_{prst} = -[\mathcal{C}_{\ell q}^{(3)}]_{prst} = \frac{1}{4}\frac{\lambda'_{rtk}\lambda'^{*}_{psk}}{m^2_{\tilde{d}_{Rk}}}$$

$$[\mathcal{C}_{\ell d}]_{prst} = -\frac{1}{2}\frac{\lambda'_{rjs}\lambda'^{*}_{pjt}}{m^2_{\tilde{u}_{Lj}}}$$

One-loop matching

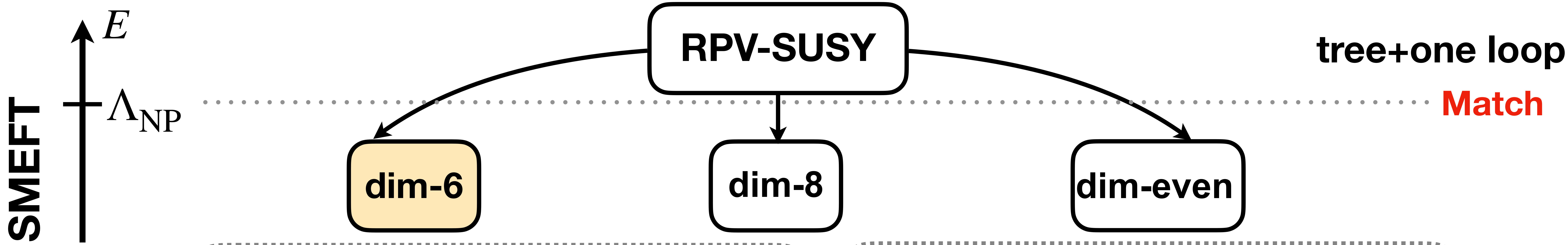
$\mathcal{O}_{eW}$ $(\overline{L_{Lp}}\sigma^{\mu\nu}E_{Rr})\tau^I\varphi W^I_{\mu\nu}$

$\mathcal{O}_{eB}$ $(\bar{\ell}_p\sigma^{\mu\nu}E_{Rr})\varphi B_{\mu\nu}$

$$\mathcal{C}^{12}_{eW} = \frac{-3g_2 Y_e^{s2}}{128\pi^2 m^2_{\tilde{q}}}\lambda'_{spr}\lambda'^{*}_{1pr}\left(\frac{1}{3}F_2^{(1)} + \frac{2}{3}F_2^{(1)} - \frac{2}{3}F_5^{(1)} - \frac{1}{3}F_5^{(1)}\right)$$

$$\mathcal{C}^{12}_{eB} = \frac{3g_1 Y_e^{s2}}{128\pi^2 m^2_{\tilde{q}}}\lambda'_{spr}\lambda'^{*}_{1pr}\left(\frac{1}{3}F_2^{(1)} + \frac{2}{3}F_2^{(1)} - \frac{2}{3}F_5^{(1)} - \frac{1}{3}F_5^{(1)}\right)$$

cLFV in RPV-SUSY: Matching Conditions (UV to SMEFT)



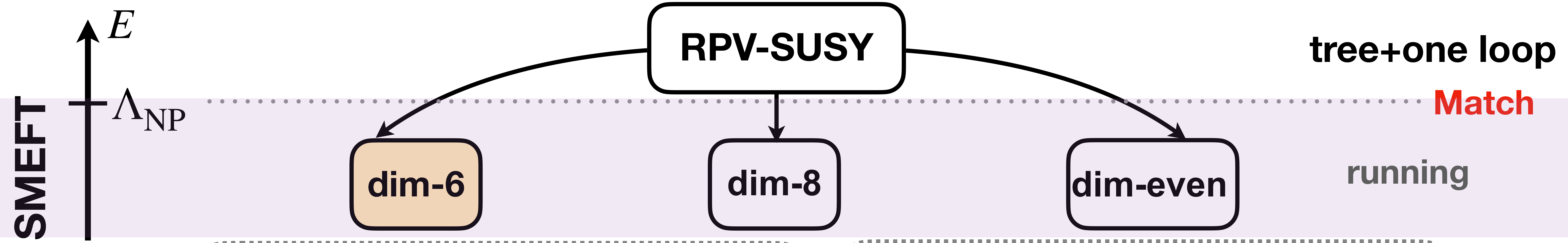
e.g.

	dim-6	
e.g.	$\mathcal{O}_{\ell q}^{(1)}$ $\quad (\overline{L_{Lp}}\gamma_\mu L_{Lr})(\overline{Q_{Ls}}\gamma^\mu Q_{Lt})$ $\mathcal{O}_{\ell q}^{(3)}$ $\quad (\overline{L_{Lp}}\gamma_\mu \tau^I L_{Lr})(\overline{Q_{Ls}}\gamma^\mu \tau^I Q_{Lt})$	$\mathcal{O}_{\ell d}$ $\quad (\overline{L_{Lp}}\gamma_\mu L_{Lr})(\overline{D_{Rs}}\gamma^\mu D_{Rt})$
Tree-level matching	$[\mathcal{C}_{\ell q}^{(1)}]_{prst} = -[\mathcal{C}_{\ell q}^{(3)}]_{prst} = \frac{1}{4}\frac{\lambda'_{rtk}\lambda'^{*}_{psk}}{m^2_{\tilde{d}_{Rk}}}$	$[\mathcal{C}_{\ell d}]_{prst} = -\frac{1}{2}\frac{\lambda'_{rjs}\lambda'^{*}_{pjt}}{m^2_{\tilde{u}_{Lj}}}$

One-loop matching

$\mathcal{O}_{eW}$	$(\overline{L_{Lp}}\sigma^{\mu\nu}E_{Rr})\tau^I\varphi W^I_{\mu\nu}$	$\mathcal{C}^{12}_{eW} = \frac{-3g_2 Y_e^{s2}}{128\pi^2 m^2_{\tilde{q}}}\lambda'_{spr}\lambda'^{*}_{1pr}\left(\frac{1}{3}F_2^{(1)} + \frac{2}{3}F_2^{(1)} - \frac{2}{3}F_5^{(1)} - \frac{1}{3}F_5^{(1)}\right)$
$\mathcal{O}_{eB}$	$(\bar{\ell}_p\sigma^{\mu\nu}E_{Rr})\varphi B_{\mu\nu}$	$\mathcal{C}^{12}_{eB} = \frac{3g_1 Y_e^{s2}}{128\pi^2 m^2_{\tilde{q}}}\lambda'_{spr}\lambda'^{*}_{1pr}\left(\frac{1}{3}F_2^{(1)} + \frac{2}{3}F_2^{(1)} - \frac{2}{3}F_5^{(1)} - \frac{1}{3}F_5^{(1)}\right)$

cLFV in RPV-SUSY: Matching Conditions (UV to SMEFT)



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$$\mathcal{C}^{12}_{eB} = \frac{3g_1 Y_e^{s2}}{128\pi^2 m^2_{\tilde{q}}}\lambda'_{spr}\lambda'^{*}_{1pr}\left(\frac{1}{3}F_2^{(1)} + \frac{2}{3}F_2^{(1)} - \frac{2}{3}F_5^{(1)} - \frac{1}{3}F_5^{(1)}\right)$$

cLFV in RPV-SUSY: Matching Conditions (SMEFT to LEFT)

cLFV in RPV-SUSY: Matching Conditions (SMEFT to LEFT)

1709.04486

cLFV in RPV-SUSY: Matching Conditions (SMEFT to LEFT)

Deriving the WCs around 2 GeV

1709.04486

cLFV in RPV-SUSY: Pheno.

For $\mu N \to e N$:

cLFV in RPV-SUSY: Pheno.

For $\mu N \to eN$:

$$\begin{aligned}\Gamma_{\rm conv} = \Big| & \left(\mathcal{C}^{S,RR}_{eu,1211} + \mathcal{C}^{S,RL}_{eu,1211}\right)\left(G^{p,u}_S S^{(p)} + G^{n,u}_S S^{(n)}\right) \\ & + \left(\mathcal{C}^{S,RR}_{ed,1211} + \mathcal{C}^{S,RL}_{ed,1211}\right)\left(G^{p,d}_S S^{(p)} + G^{n,d}_S S^{(n)}\right) \\ & + \left(\mathcal{C}^{S,RR}_{ed,1222} + \mathcal{C}^{S,RL}_{ed,1222}\right)\left(G^{p,s}_S S^{(p)} + G^{n,s}_S S^{(n)}\right) \\ & + \left(\mathcal{C}^{V,LL}_{eu,1211} + \mathcal{C}^{V,LR}_{eu,1211}\right)\left(G^{p,u}_V V^{(p)} + G^{n,u}_V V^{(n)}\right) \\ & + \left(\mathcal{C}^{V,LL}_{ed,1211} + \mathcal{C}^{V,LR}_{ed,1211}\right)\left(G^{p,d}_V V^{(p)} + G^{n,d}_V V^{(n)}\right) \\ & + \left(\mathcal{C}^{V,LL}_{ed,1222} + \mathcal{C}^{V,LR}_{ed,1222}\right)\left(G^{p,s}_V V^{(p)} + G^{n,s}_V V^{(n)}\right) \\ & + D C^{*}_{e\gamma,12} / \left(2 m_\mu\right) \Big|^2 + \ldots\end{aligned}$$

$D, S^{(p,n)}, V^{(p,n)}$: overlap integrals

2203.00702

Different values in Ti, Au, Al

The integral uncertainties: 2%~5% for Al, Ti

8%~10% for Au

cLFV in RPV-SUSY: Pheno.

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For $\mu \to e\gamma$:

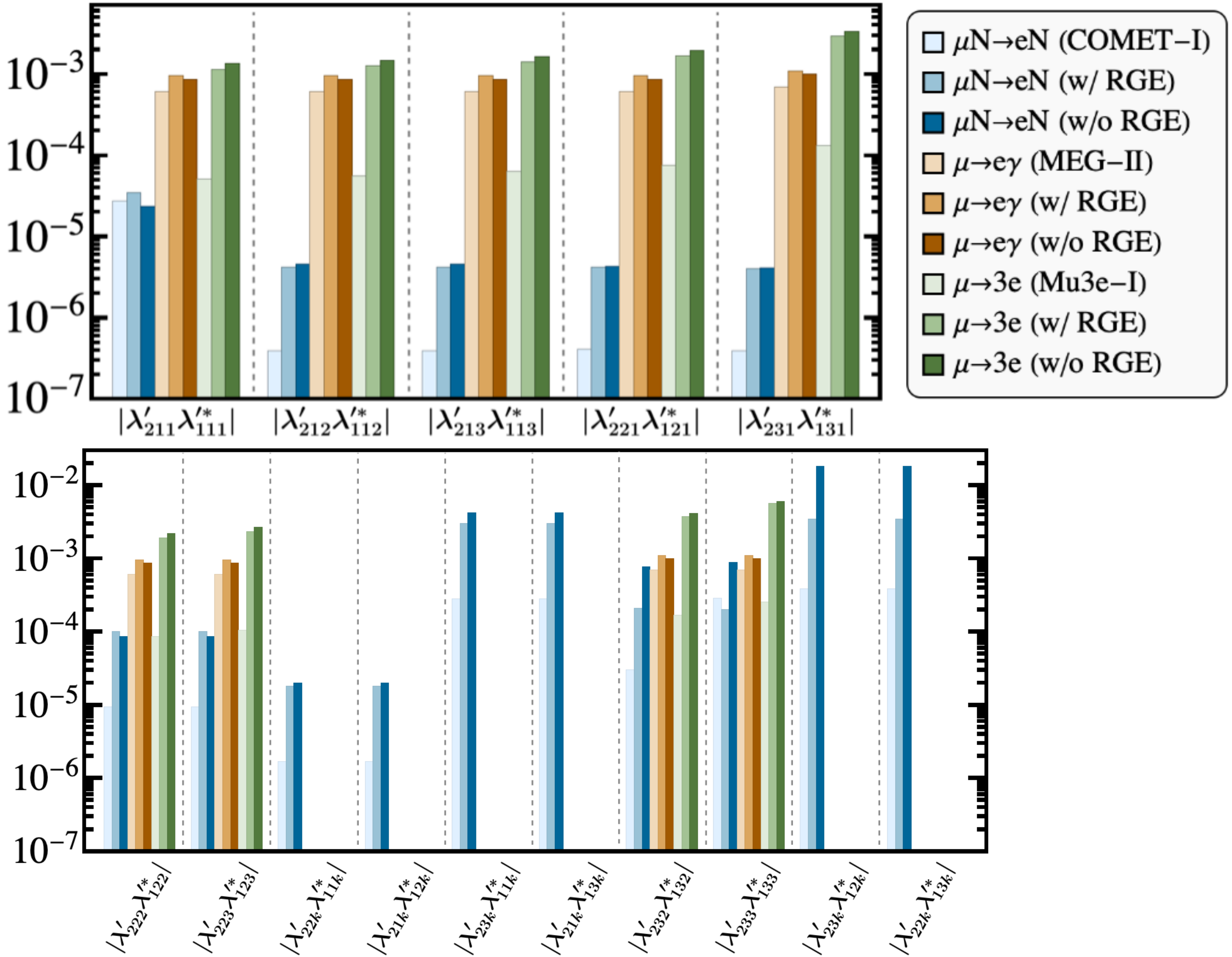
$$\mathrm{Br}(\mu \to e\gamma) = \tau_\mu \times \frac{(m_\mu^2 - m_e^2)^3}{4\pi m_\mu^3}\left(|\mathcal{C}_{e\gamma,12}|^2 + |\mathcal{C}_{e\gamma,21}|^2\right) ,$$

For $\mu \to eee$:

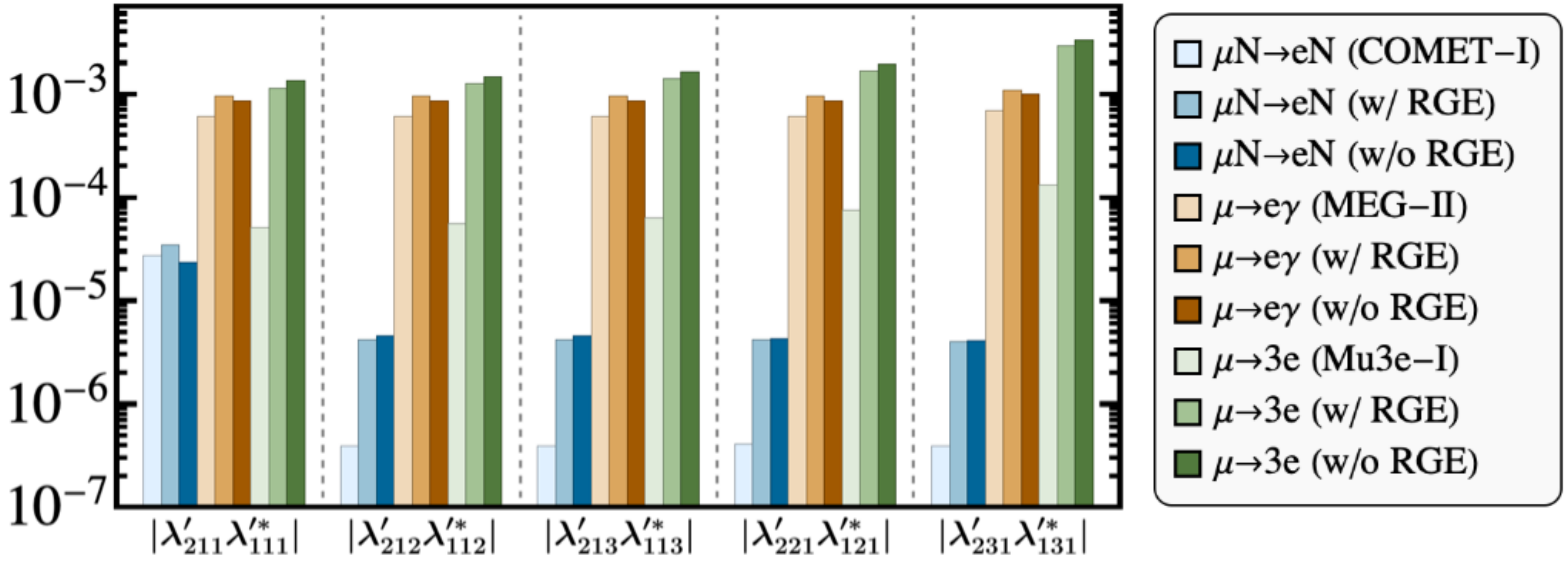
$$\begin{aligned}\mathrm{Br}(\mu \to 3e) = & \frac{1}{64G_F^2}\left(\left|\mathcal{C}^{S,RR}_{ee,1121}\right|^2 + \left|\mathcal{C}^{S,RR}_{ee,1112}\right|^2\right) \\ & + \frac{\alpha_{\rm em}}{\pi G_F^2 m_\mu^2}\left(\ln\frac{m_\mu^2}{m_e^2} - \frac{17}{4}\right)\left(|\mathcal{C}_{e\gamma,12}|^2 + |\mathcal{C}_{e\gamma,21}|^2\right) \\ & + \frac{1}{8G_F^2}\left(2\left|\mathcal{C}^{V,RR}_{ee,1112} + \frac{4e}{m_\mu}\mathcal{C}^{*}_{e\gamma,12}\right|^2 + 2\left|\mathcal{C}^{V,LL}_{ee,1112} + \frac{4e}{m_\mu}\mathcal{C}_{e\gamma,21}\right|^2\right. \\ & \left. + \left|\mathcal{C}^{V,LR}_{ee,1112} + \frac{4e}{m_\mu}\mathcal{C}^{*}_{e\gamma,12}\right|^2 + \left|\mathcal{C}^{V,LR}_{ee,1211} + \frac{4e}{m_\mu}\mathcal{C}_{e\gamma,21}\right|^2\right)\end{aligned}$$

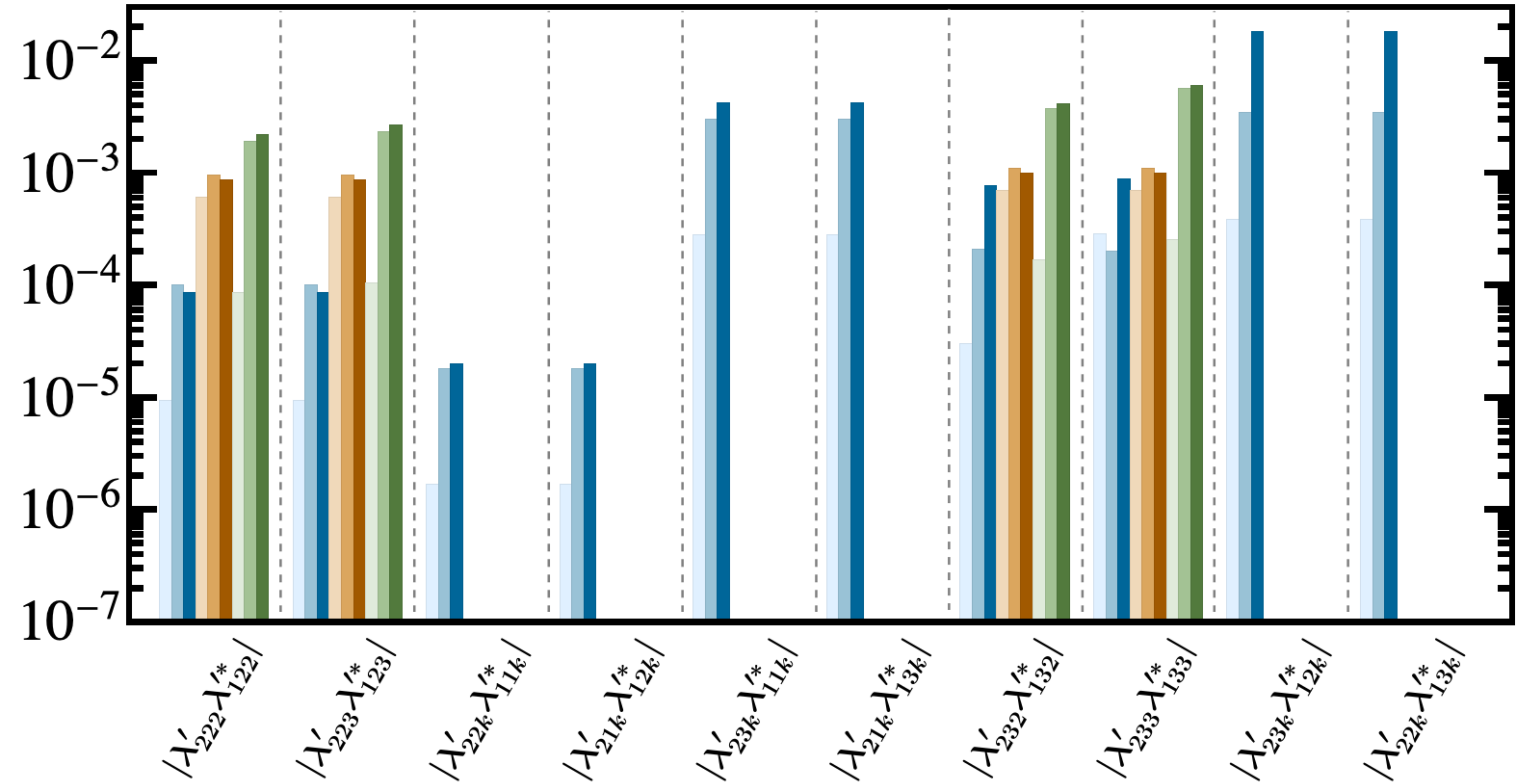
Numerical Results

Keep one combination nonzero at a time



Numerical Results

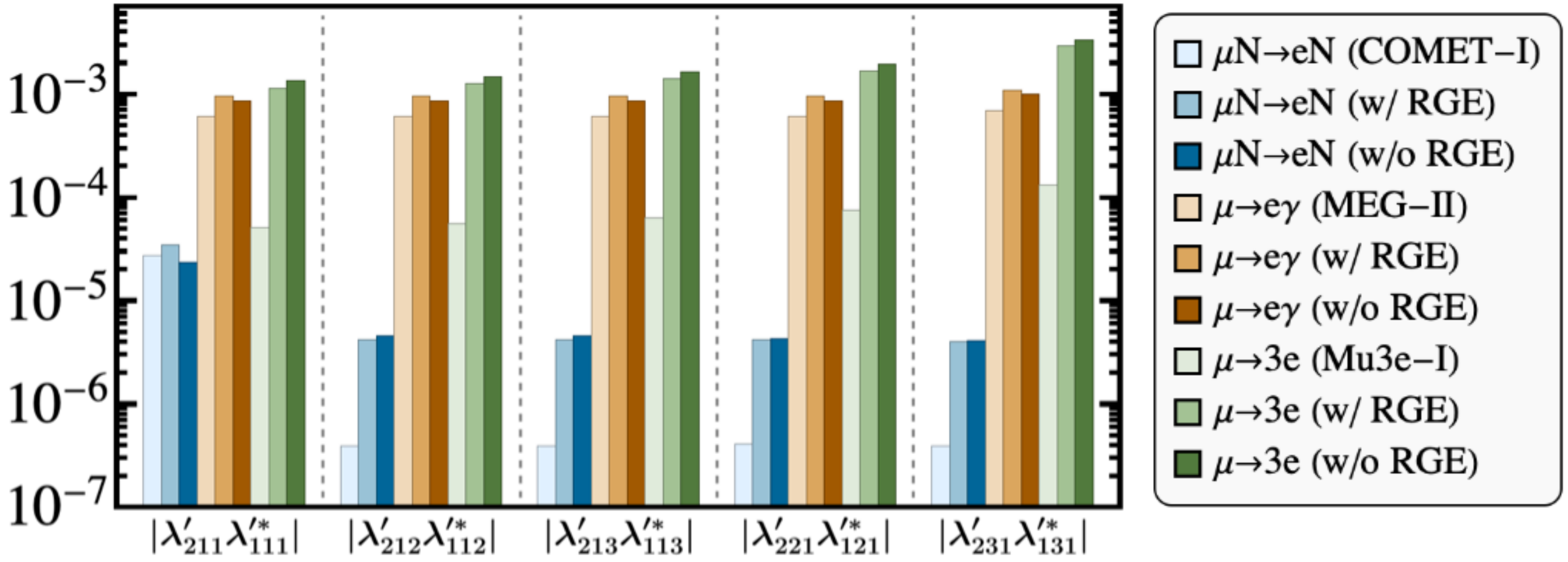


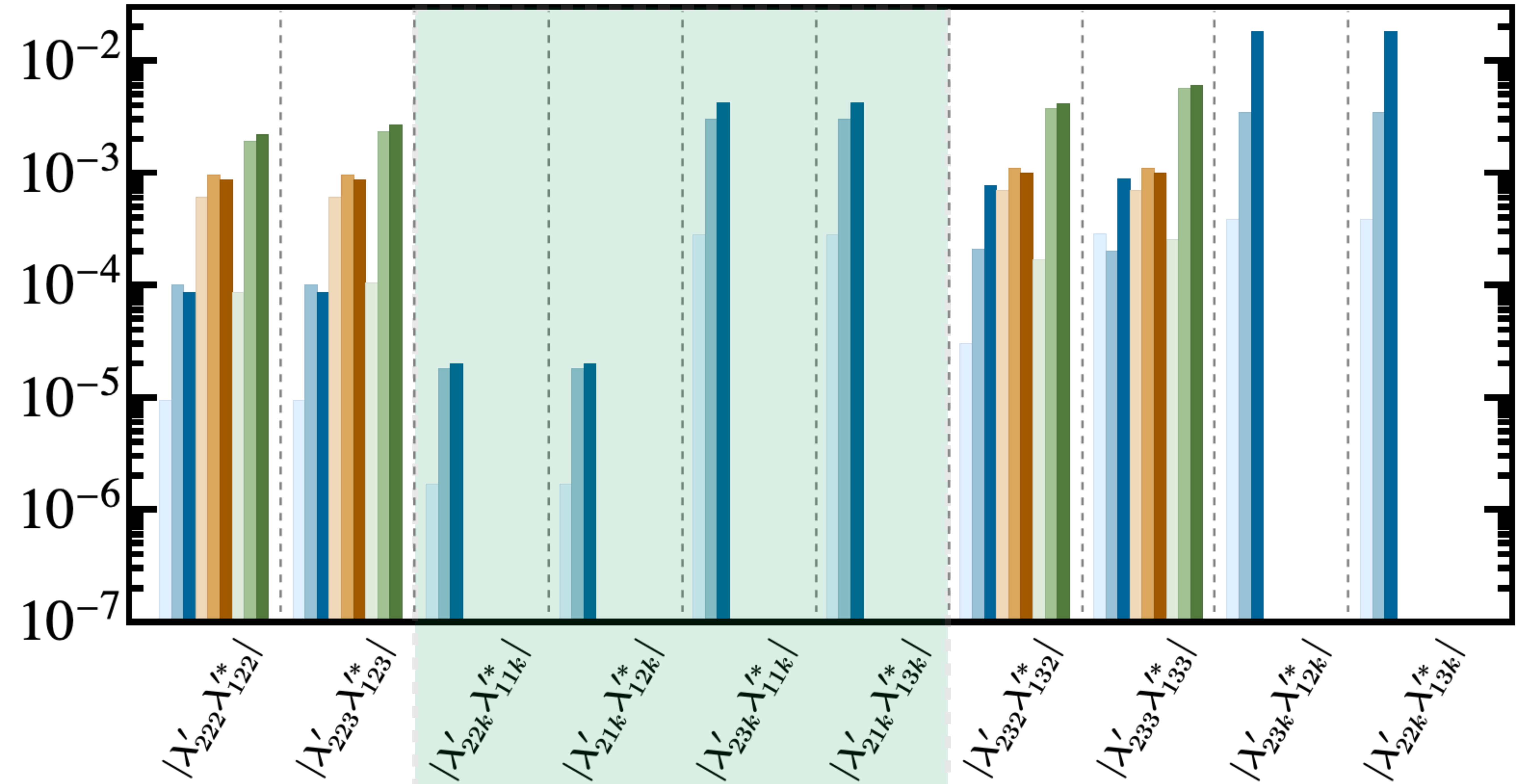


- For $\mu N \to eN$ in most of cases, tree level contributions dominate.
- For $\mu \to e\gamma$ and $\mu \to 3e$, only loop-level can contribute
- future $\mu N \to eN$ exp. can give the stronger limits.

Numerical Results

Keep one combination nonzero at a time





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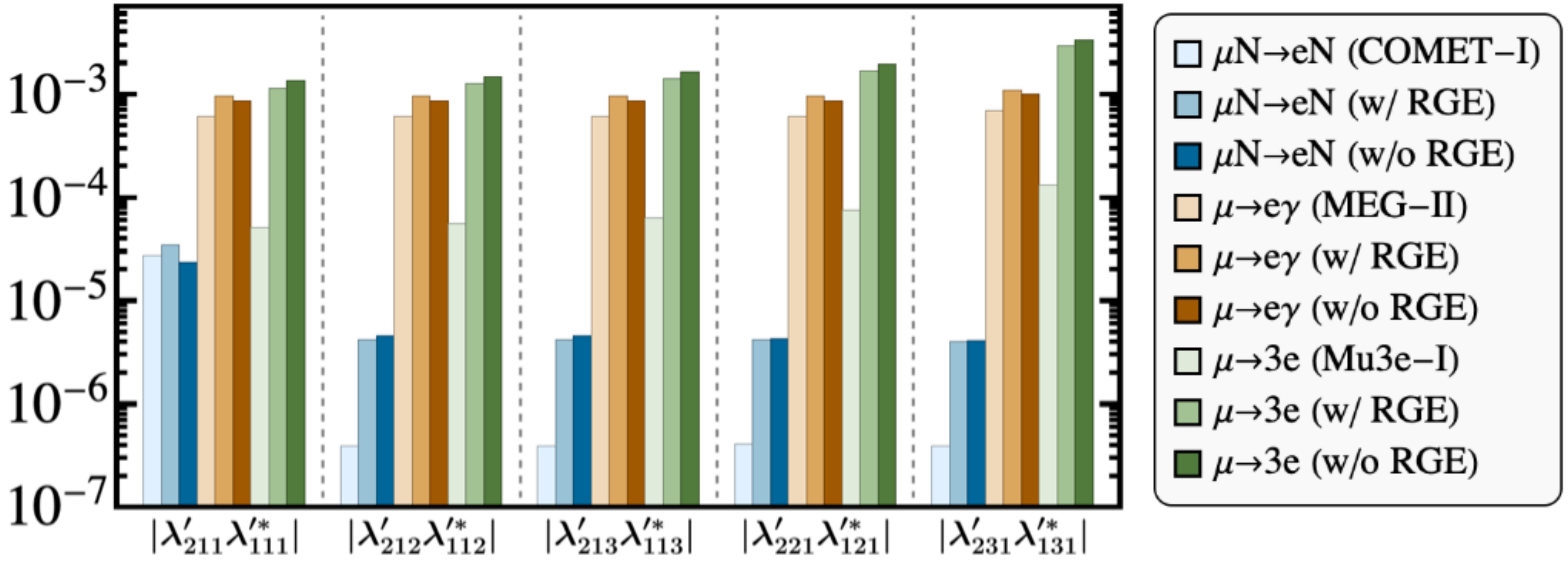

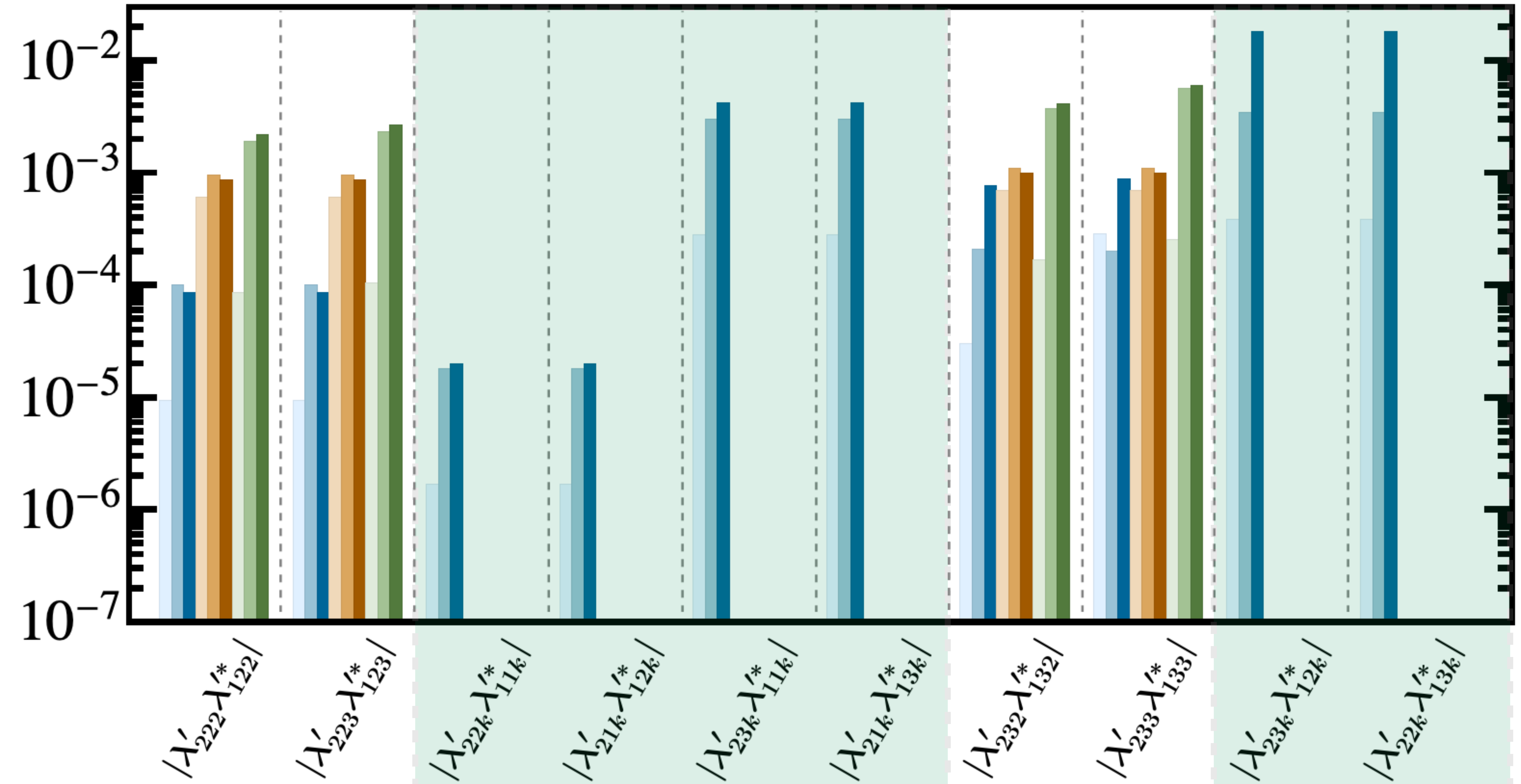

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Numerical Results

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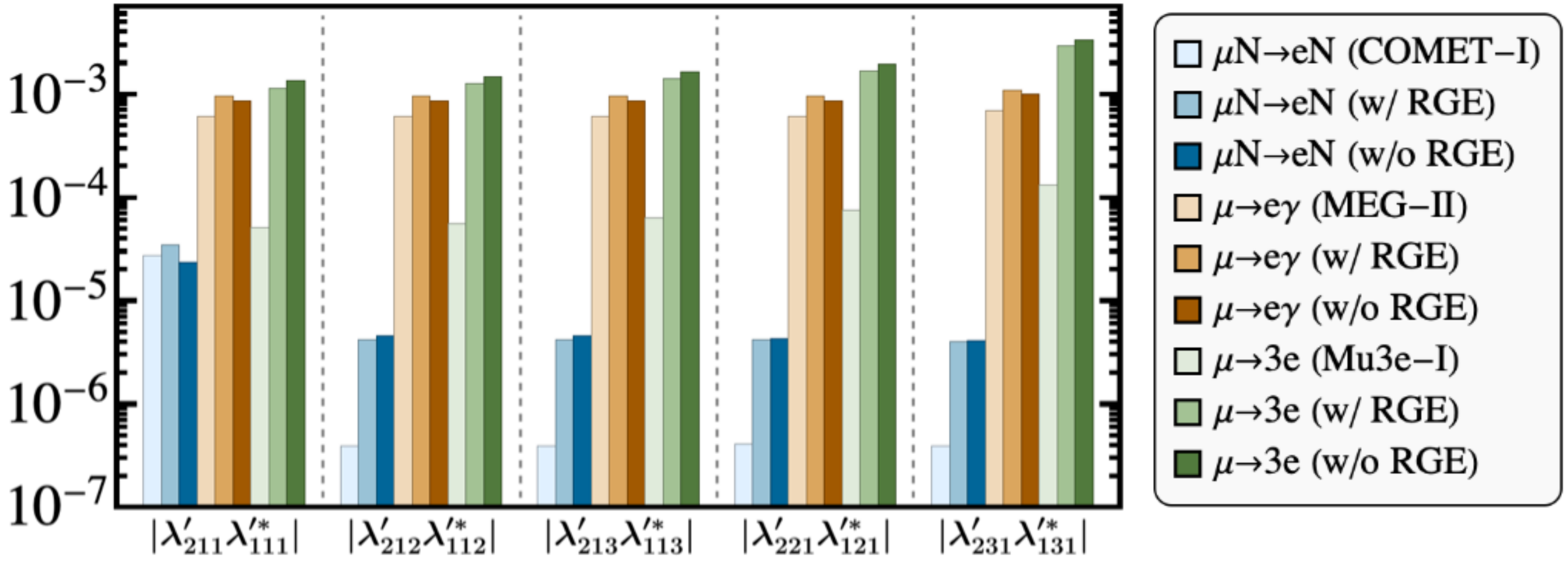

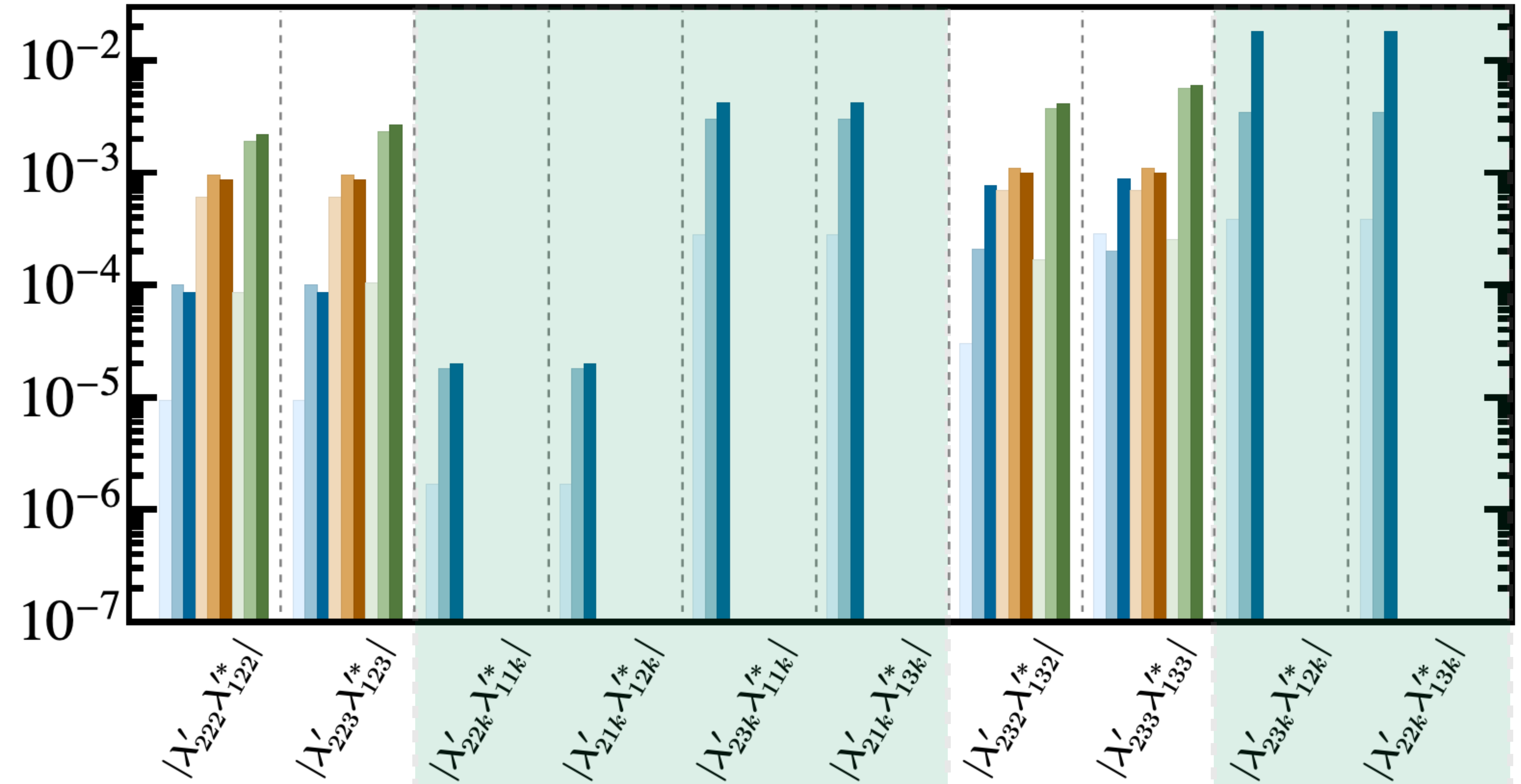

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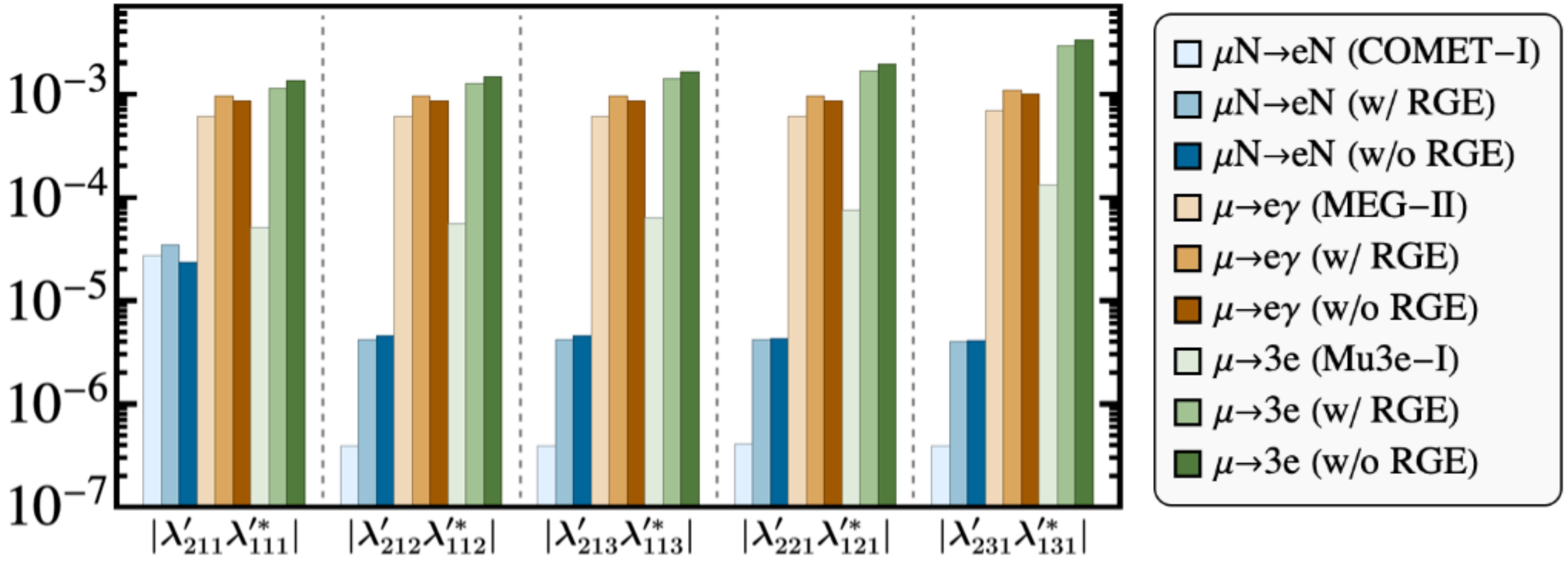
For $\mu \to e\gamma$, $\mu \to 3e$, contributions are **GIM suppressed**

Numerical Results

Keep one combination nonzero at a time



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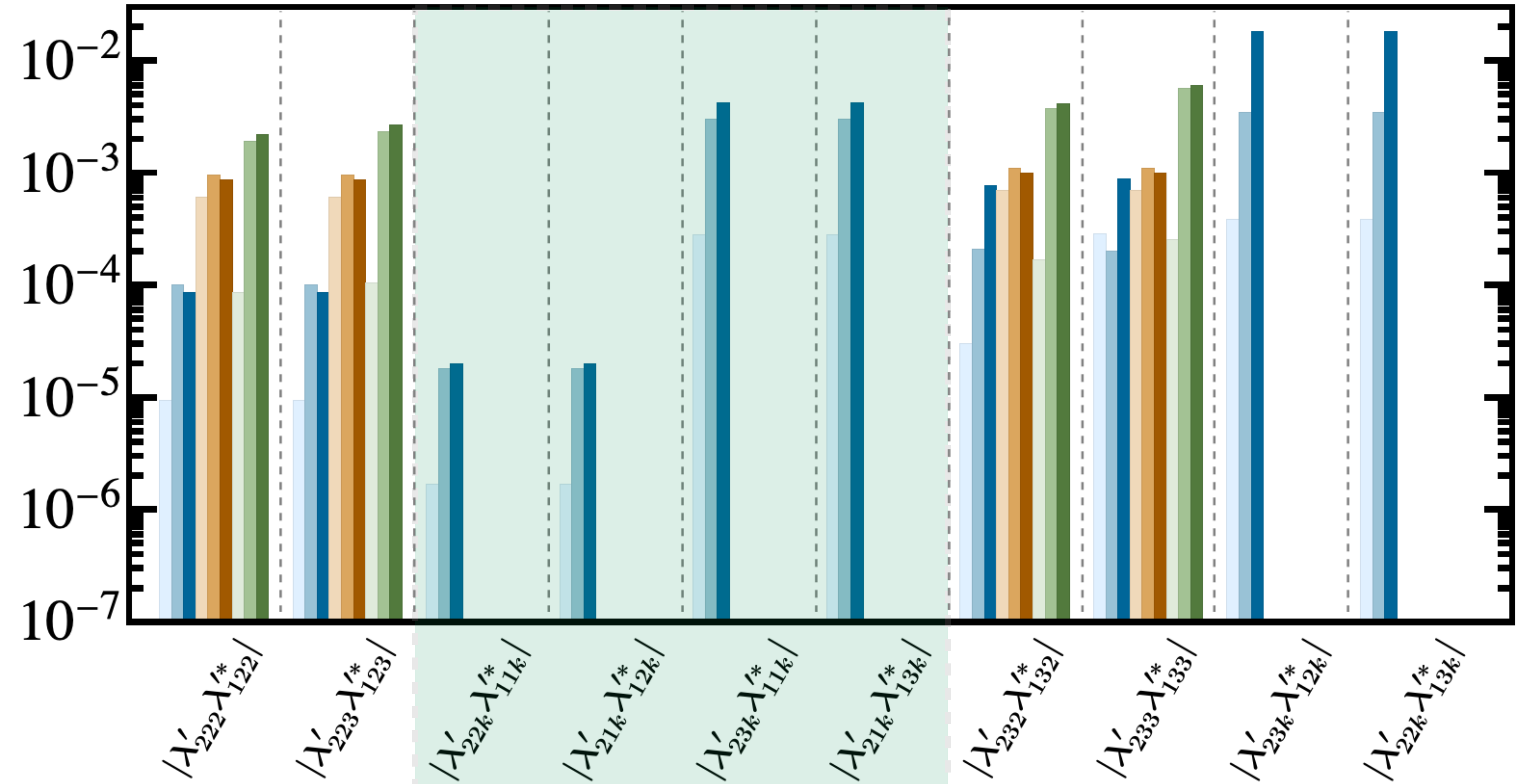
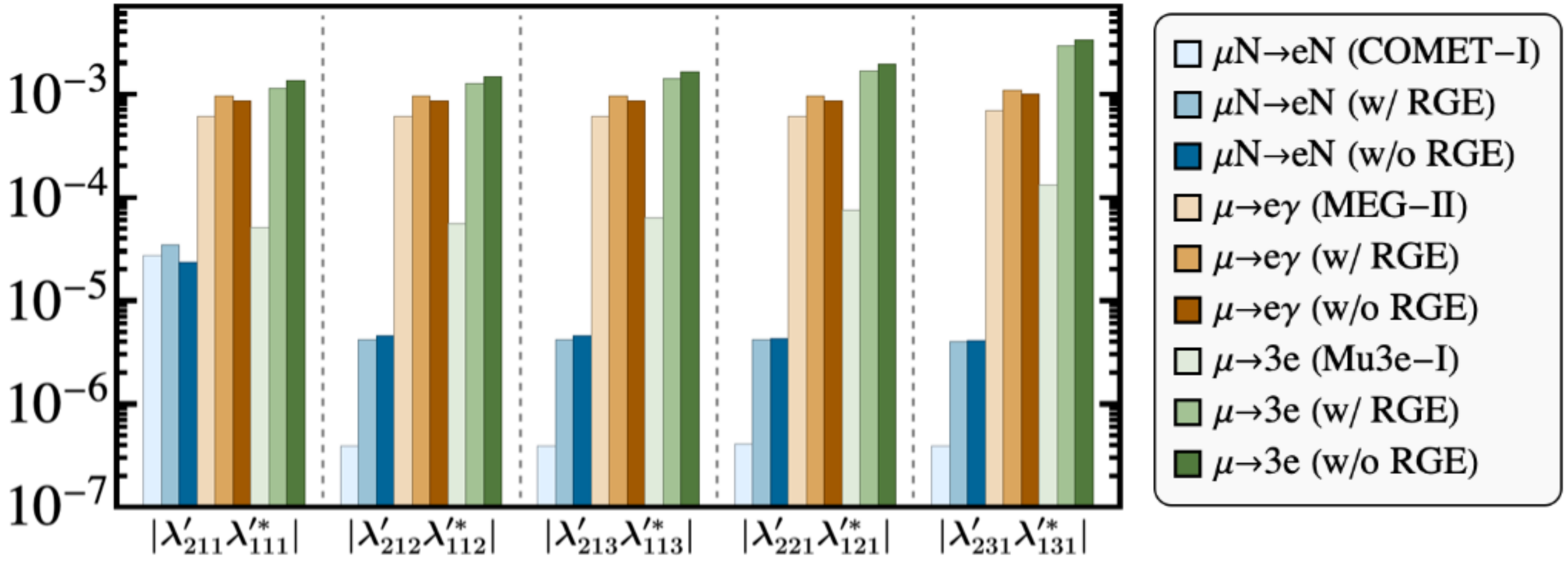


For $\mu \to e\gamma$, $\mu \to 3e$, contributions are **GIM suppressed**

Numerical Results

Keep one combination nonzero at a time



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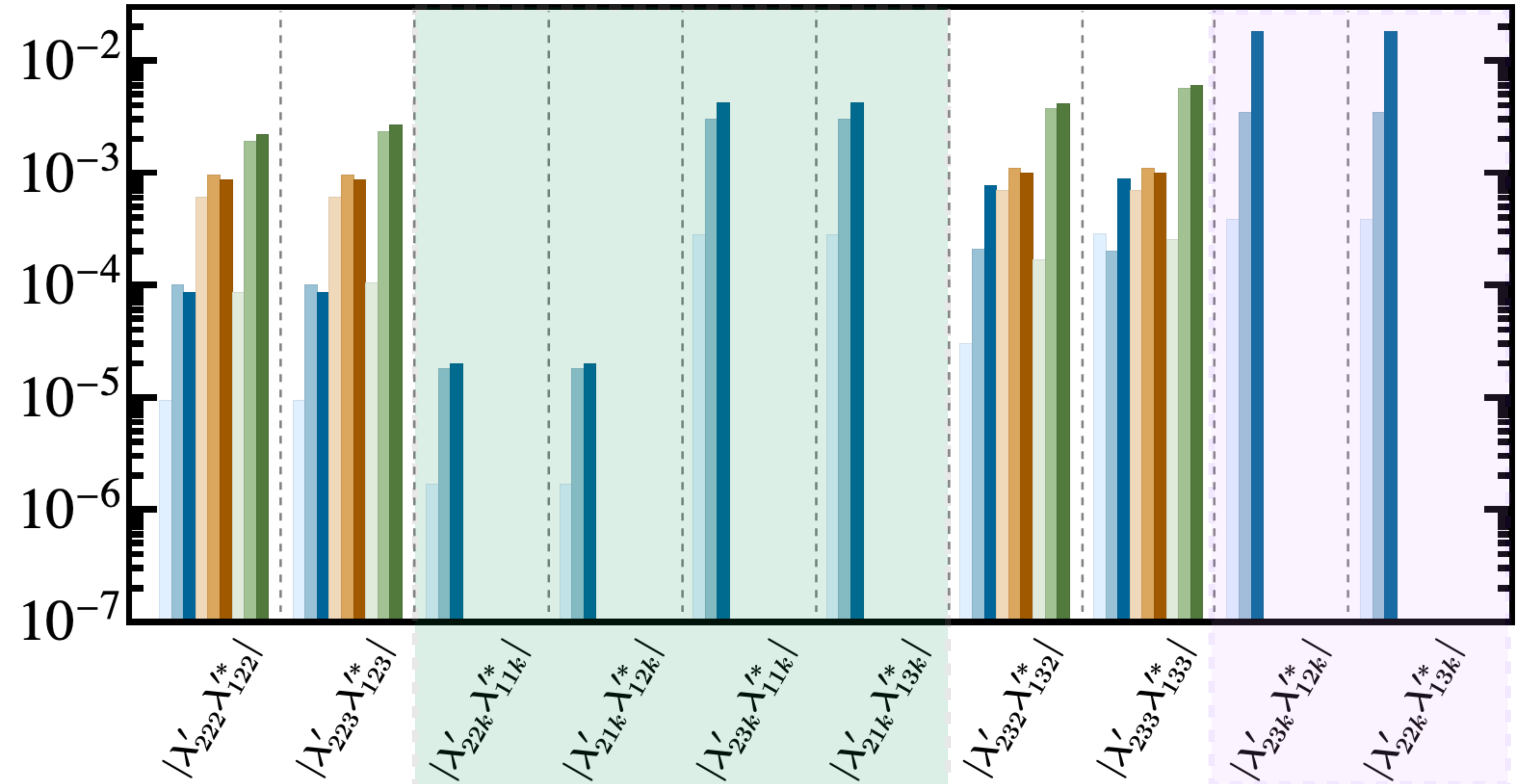

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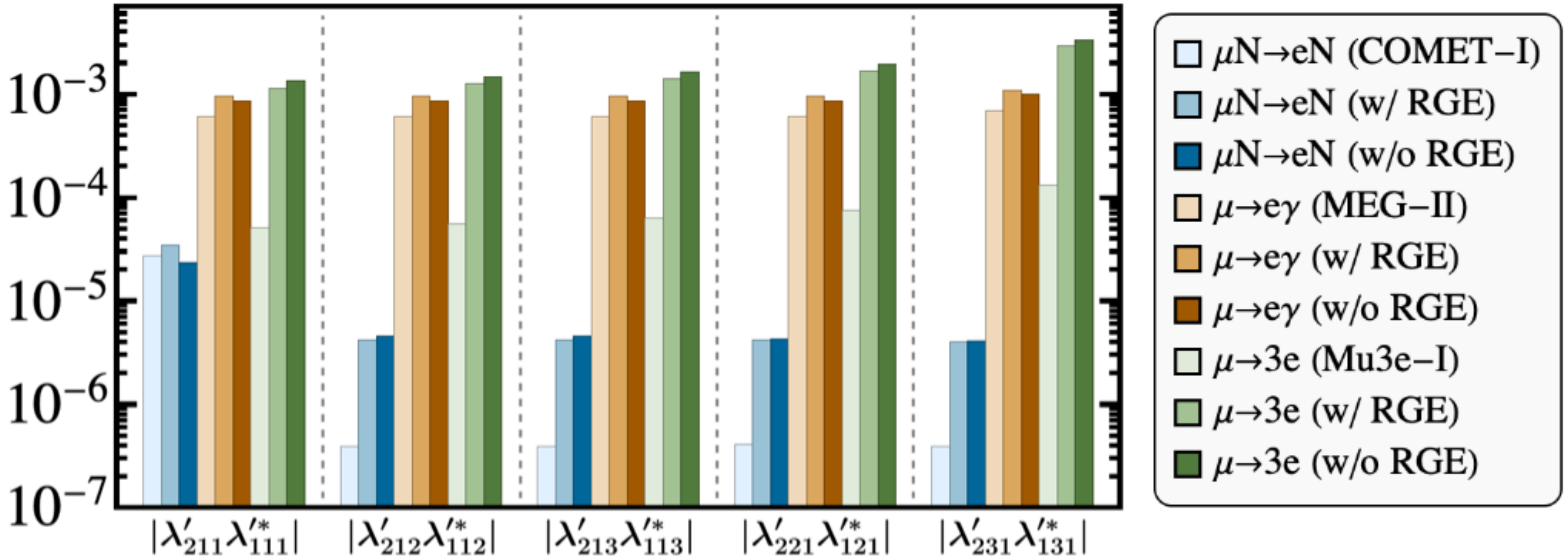

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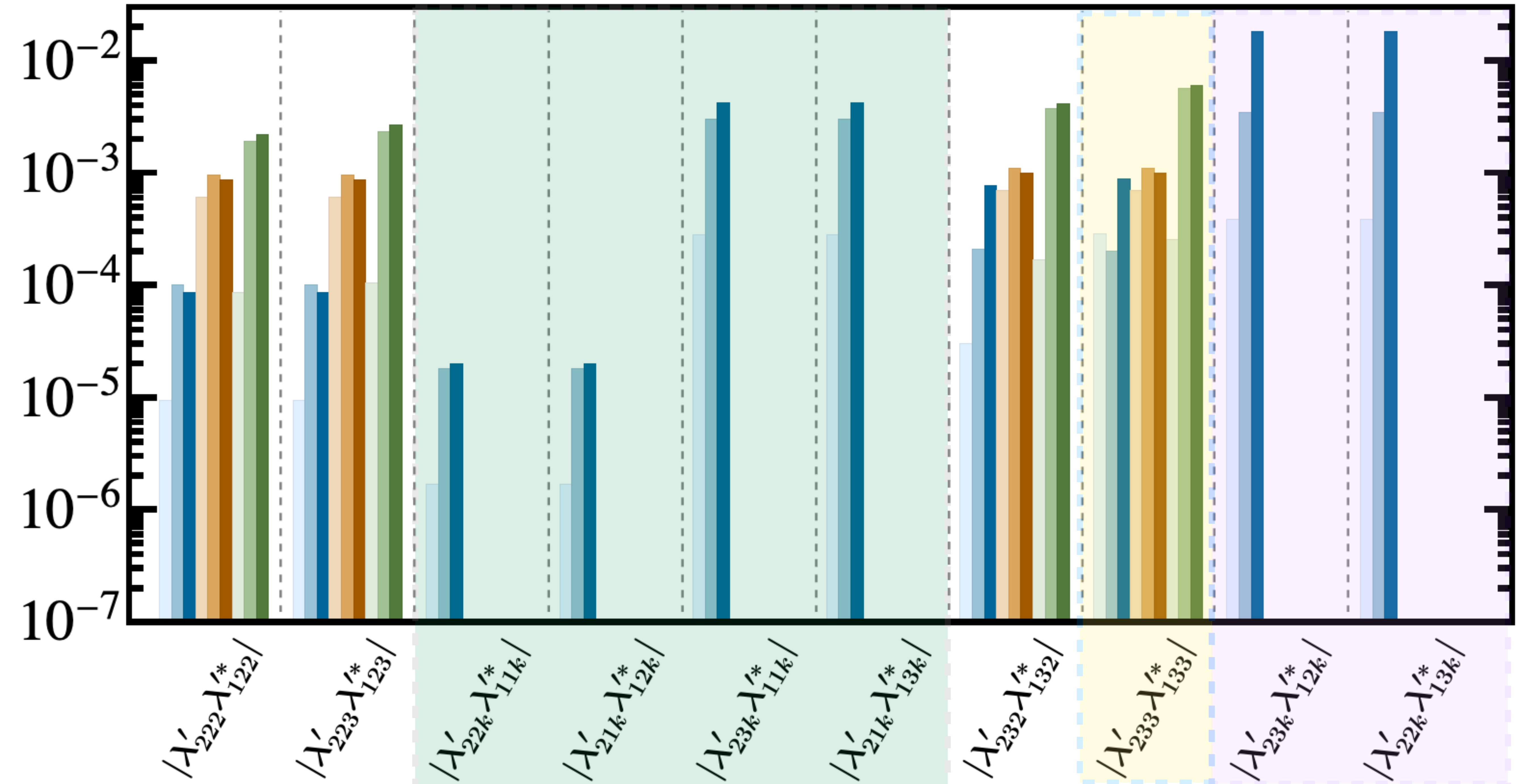

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Neutrino mass will give much stronger limits than cLFV NPB 231 (1984) 194

$$|\lambda'_{133}\lambda'_{233}| < \mathcal{O}(10^{-7} \sim 10^{-8}) \times (\tilde{m}\ \mathrm{TeV}^{-1})$$

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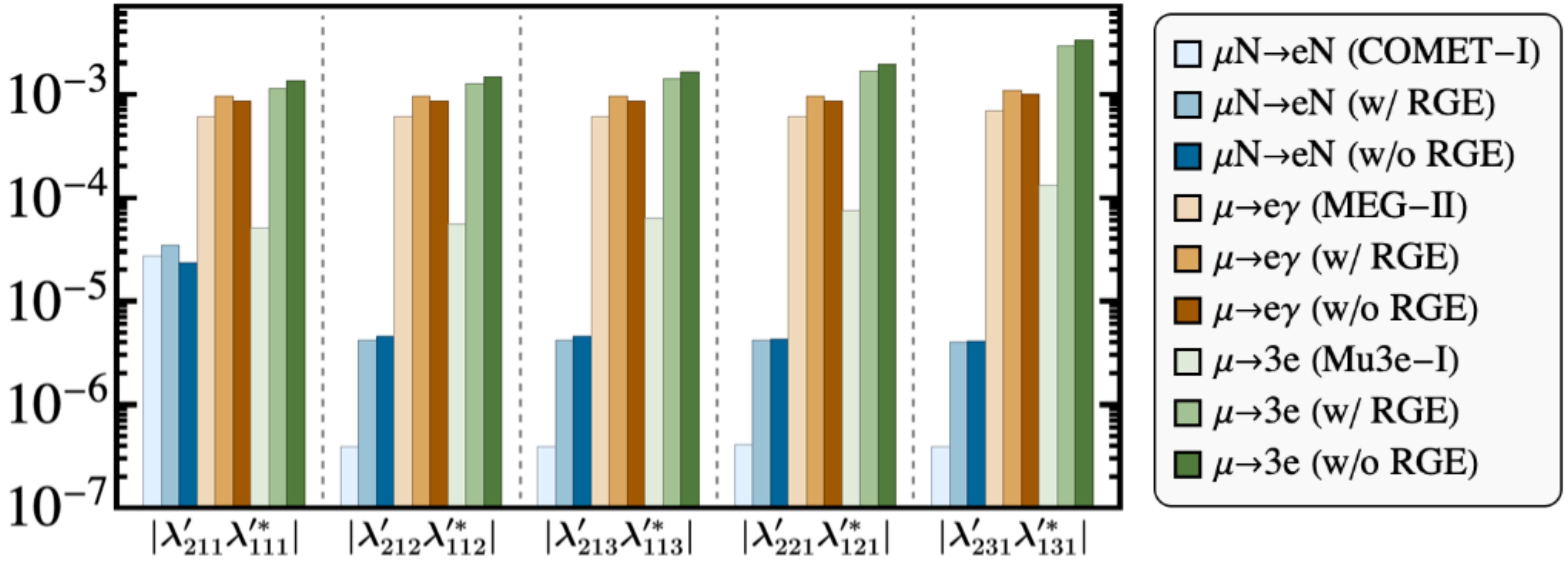

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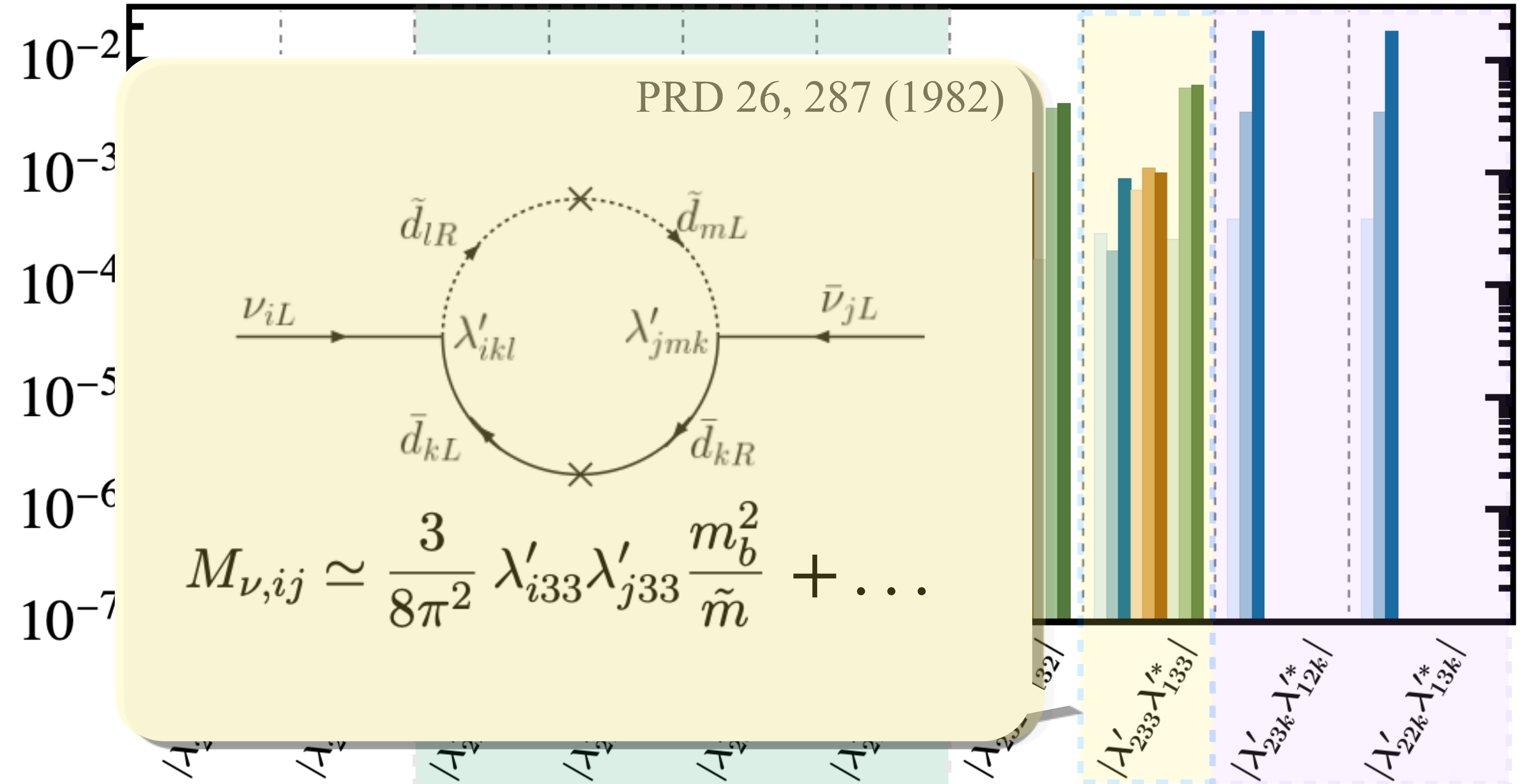

$$M_{\nu,ij} \simeq \frac{3}{8\pi^2}\lambda'_{i33}\lambda'_{j33}\frac{m_b^2}{\tilde{m}} + \ldots$$

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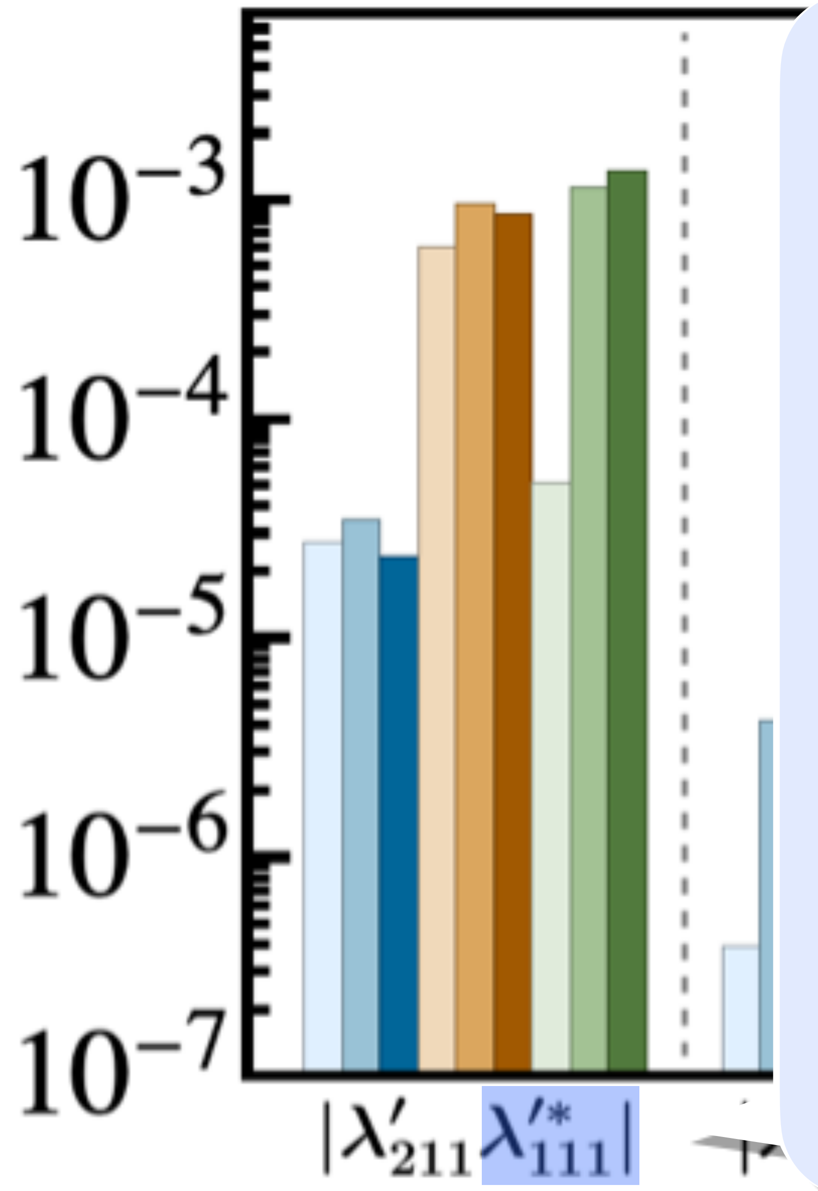
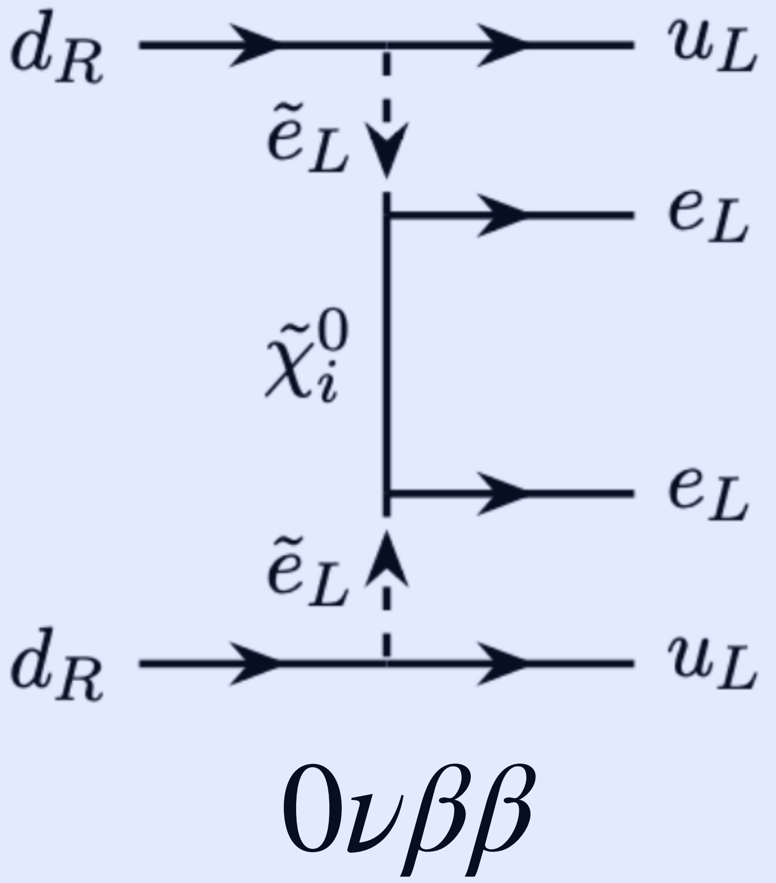


hep-ph/0406199



KamLAND-Zen / GERDA give limit

$$\lambda'^2_{111}/m^4_{\tilde{q}} m_{\tilde{g}} < 4 \times 10^{-4}\ \mathrm{TeV}^{-5}$$

$\Rightarrow \lambda'_{111} < 10^{-2}$ If TeV scale $m_{\tilde{q},\tilde{g}}$

$m_{\tilde{\chi}^0}$ below the GeV scale leads to $|\lambda'_{111}| < 10^{-4}$ 2112.12658

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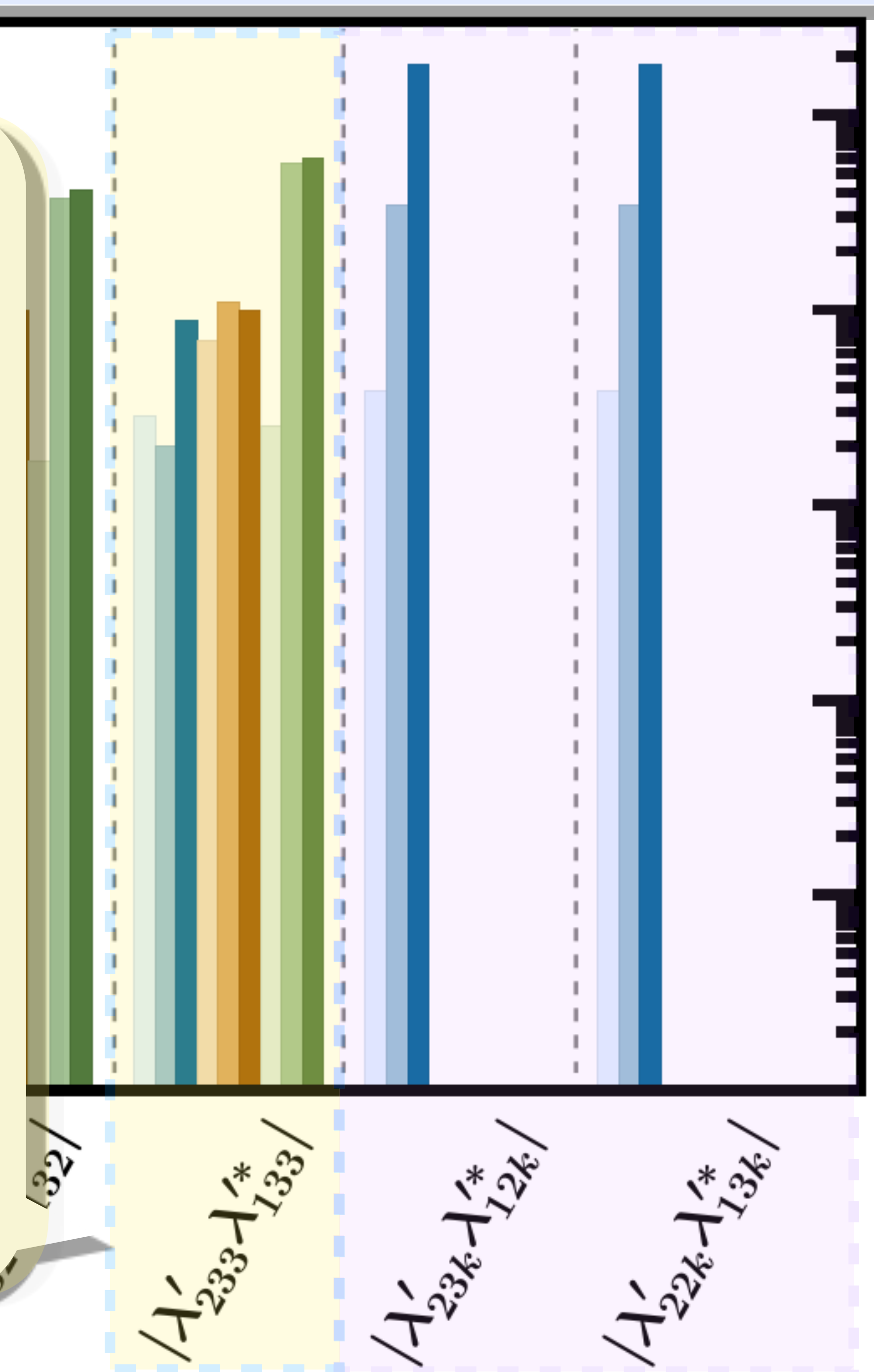
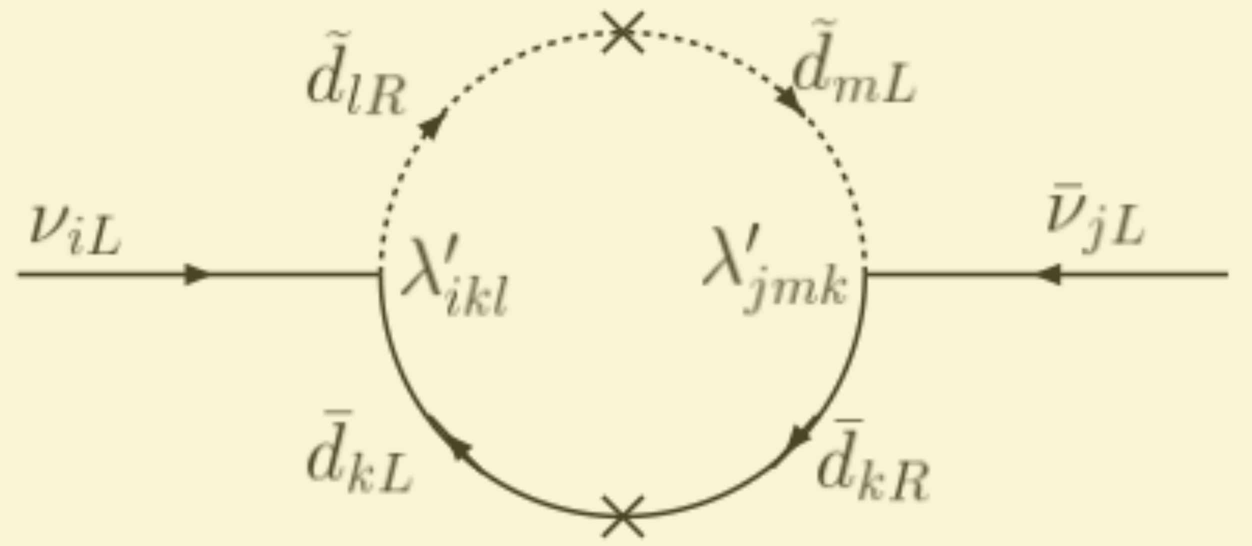


PRD 26, 287 (1982)



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Numerical Results

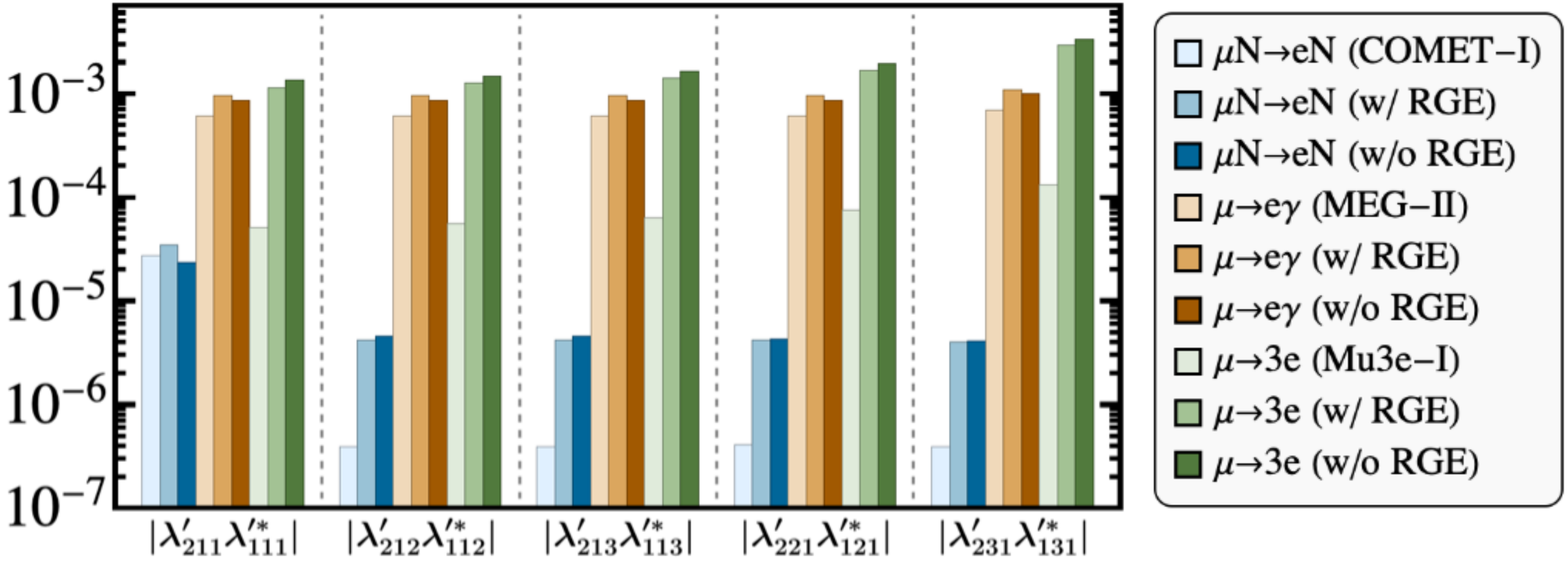
- **If no signals in these exp.:**

para. space can be constrained by the exp. limits

- **If signals have been found in $\mu \to e\gamma, \mu \to 3e$, but no signals in $\mu N \to eN$ in near future exp. with similar sensitivities:**

Most of these combinations can be ruled out

Things maybe different when keep more than one nonzero at a time



Numerical Results

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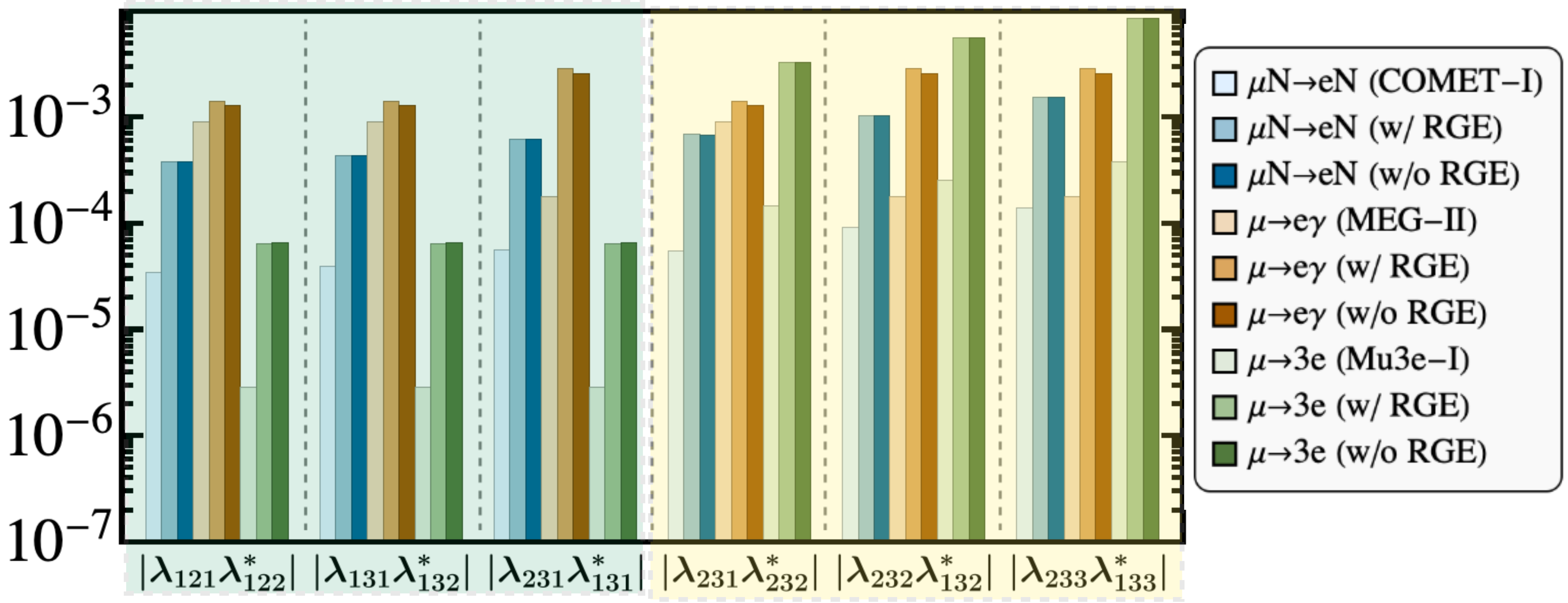

For the **first three cases**:

- Tree-level contribution to $\mu \to 3e$
- Future $\mu \to 3e$ exp. , e.g., Mu3e Phase-I, will **give the most stringent limits** on the para.

For the **last three cases**:

- **No tree-level** contribution to $\mu \to 3e$
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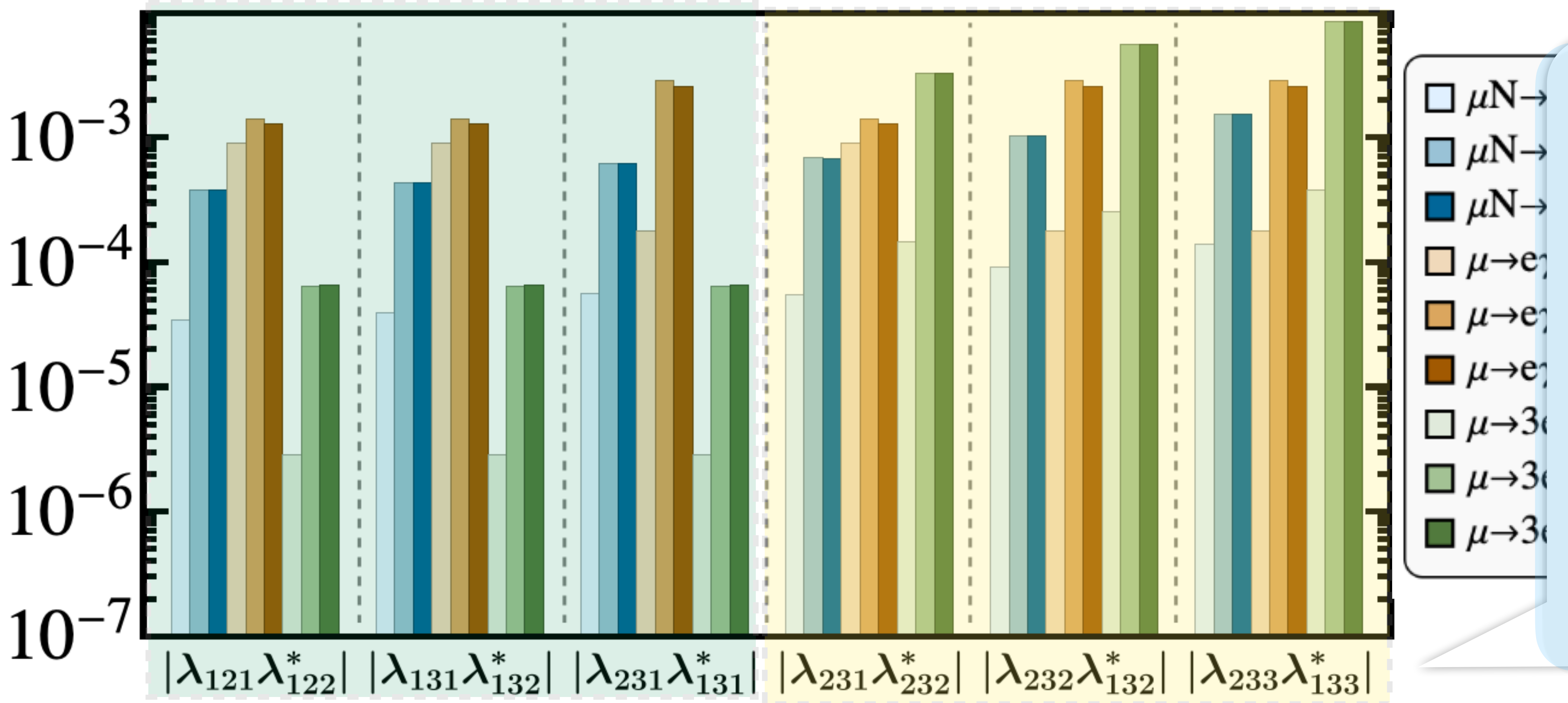

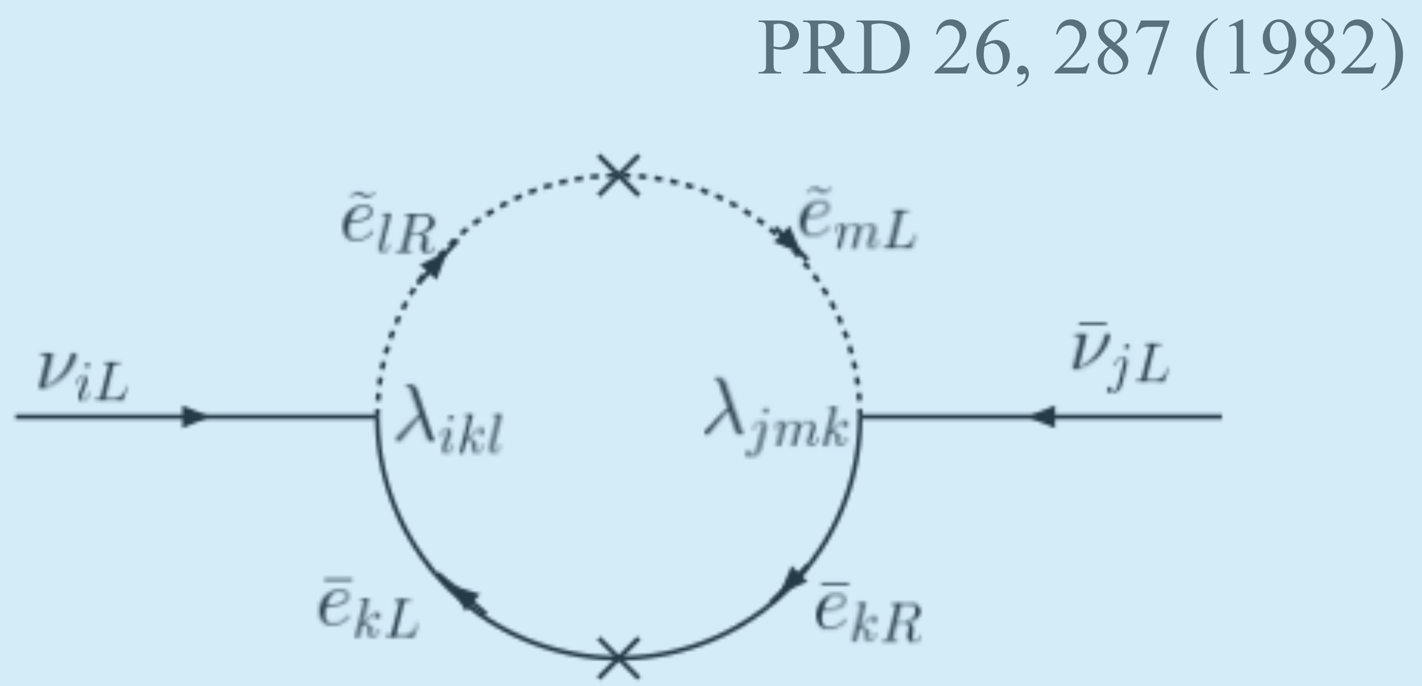

$$M_{\nu,ij} \simeq \frac{1}{8\pi^2}\lambda_{i33}\lambda_{j33}\frac{m_\tau^2}{\tilde{m}} + \ldots$$

$$|\lambda_{233}\lambda_{133}| < 3\times 10^{-6}$$

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- We follow the **EFT framework**, **matching** the RPV-SUSY model to SMEFT at **tree and one-loop** level, and accounting for **RG running effects**.
- We find that **the $\mu N \to eN$ can give much stronger limits** than $\mu \to e\gamma, \mu \to 3e$ in most cases for λ' terms, also the same for specific cases of λ terms. In certain cases, $\mu N \to eN$ **conversion is the only process that can provide constraints**.
- The **RGE running effects** **can play an important role** and **cannot be neglected** in certain cases.
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Thank you !