Electric Dipole Moments and Neutrino Mass Models

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EW18

C. Smith, S.T., Nucl.Phys. B924 (2017) 417 [arXiv:1707.06805]

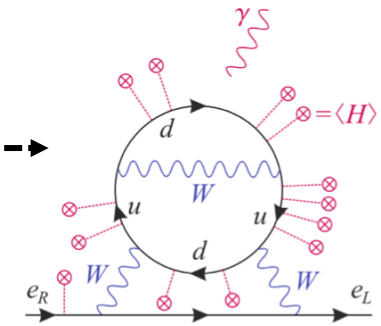
What do we do ?

- <u>Usually:</u>

CP-violation is measured by the **Jarlskog invariant**

(Non-vanishing J_{CP} is a necessary condition for CP-violation)

Adequate for estimating CP-violation from **closed fermion loops**



CKM-induced lepton EDM

$$\propto \det[\mathbf{Y}_u^\dagger \mathbf{Y}_u, \mathbf{Y}_d^\dagger \mathbf{Y}_d]$$

$$\propto \mathbf{Im}(\mathbf{V_{us}} \mathbf{V_{cb}} \mathbf{V_{ub}^*} \mathbf{V_{cs}^*})$$

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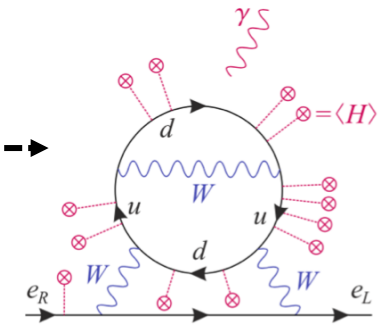

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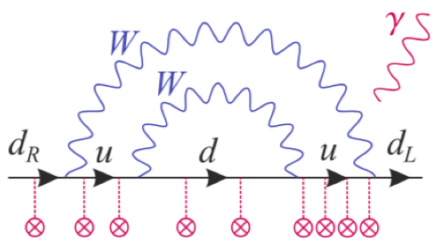
- **But …**

Non-invariants structures arise from **rainbow-like processes**.



$$\propto Im[\mathbf{Y}_u^\dagger \mathbf{Y}_u \ , \ \mathbf{Y}_u^\dagger \mathbf{Y}_u \mathbf{Y}_d^\dagger \mathbf{Y}_d \mathbf{Y}_u^\dagger \mathbf{Y}_u]^{dd}$$

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CKM-induced quark EDM

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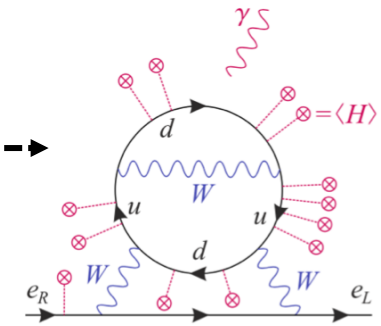

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10 orders of magnitude larger

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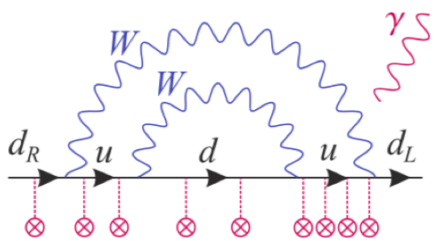

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Let us check this behavior in various scenarios for generating neutrino masses

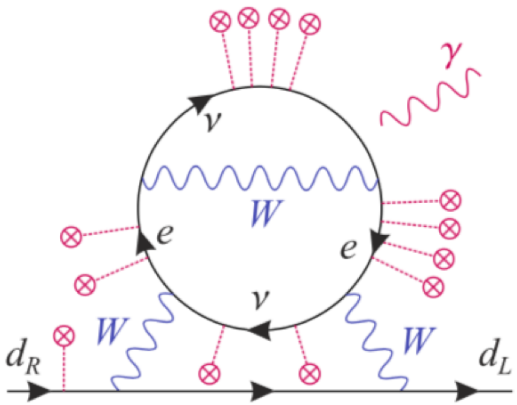
Dirac neutrino masses

- Addition of 3 right-handed (RH) fully neutral neutrinos: $N = \nu_R^\dagger \sim (1,1)_0$
- Additional Yukawa interaction: $\mathcal{L}_{Yukawa} = \mathcal{L}_{Yukawa}^{SM} - N^I Y_\nu^{IJ} L^J H^{\dagger C} + h.c$

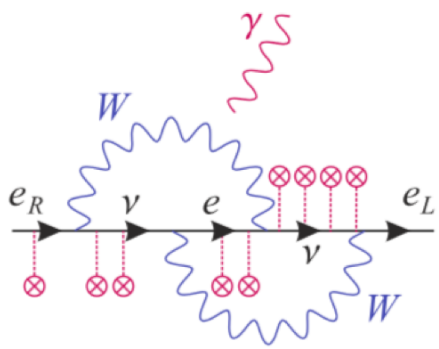
CP-violating flavor structures

Jarlskog-like $J_{\mathcal{CP}}^{Dirac} \equiv \frac{1}{2i} \det\left[Y_\nu^\dagger Y_\nu, Y_e^\dagger Y_e\right]$

Weak rainbow process $\mathbf{X}_{Dirac} = \left[Y_\nu^\dagger Y_\nu, Y_\nu^\dagger Y_\nu Y_e^\dagger Y_e Y_\nu^\dagger Y_\nu\right]$



PMNS-induced quark EDM



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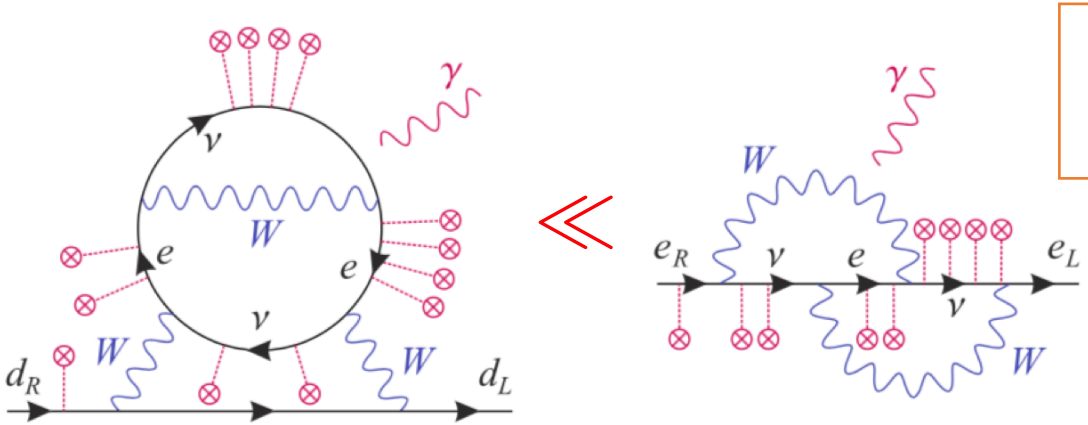
11 orders of magnitude **larger** than J_{CP} and **correlated**



PMNS-induced quark EDM

PMNS-induced lepton EDM

Majorana neutrino masses

- No additional RH neutrinos → directly a mass term for the LH neutrinos

$$\mathcal{L}_{Yukawa} = \mathcal{L}^{SM}_{Yukawa} - \frac{1}{2v}(L^I H)(\Upsilon_\nu)^{IJ}(L^J H) + h.c$$

- After spontaneous symmetry breaking, the dimension-five **Weinberg operator** collapses to a **Majorana mass term**

$$\frac{1}{2v}(L^I H)(\Upsilon_\nu)^{IJ}(L^J H) \xrightarrow{SSB} \frac{1}{2}(\Upsilon_\nu)^{IJ}\nu_L^I \nu_L^J$$

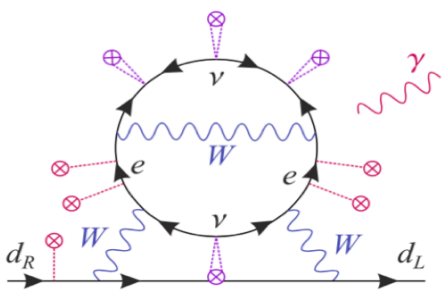
<u>CP-violating flavor structures</u>

Jarlskog-like

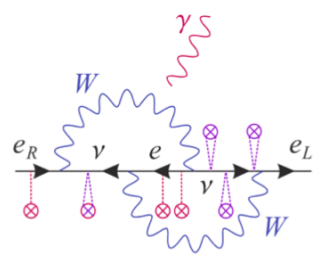
$$J^{\text{Majo}}_{\mathcal{CP}} = \frac{1}{2i} Tr[\boldsymbol{\Upsilon}_\nu^\dagger \boldsymbol{\Upsilon}_\nu \cdot \mathbf{Y}_e^\dagger \mathbf{Y}_e \cdot \boldsymbol{\Upsilon}_\nu^\dagger (\mathbf{Y}_e^\dagger \mathbf{Y}_e)^T \boldsymbol{\Upsilon}_\nu \quad (*)$$
$$- \boldsymbol{\Upsilon}_\nu^\dagger (\mathbf{Y}_e^\dagger \mathbf{Y}_e)^T \boldsymbol{\Upsilon}_\nu \cdot \mathbf{Y}_e^\dagger \mathbf{Y}_e \cdot \boldsymbol{\Upsilon}_\nu^\dagger \boldsymbol{\Upsilon}_\nu]$$

Weak rainbow process

$$\mathbf{X}_e^{\text{Majo}} = [\boldsymbol{\Upsilon}_\nu^\dagger \boldsymbol{\Upsilon}_\nu \,,\; \boldsymbol{\Upsilon}_\nu^\dagger (\mathbf{Y}_e^\dagger \mathbf{Y}_e)^T \boldsymbol{\Upsilon}_\nu]$$



PMNS-induced quark EDM



PMNS-induced lepton EDM

(*) *Branco et al.(2012)*

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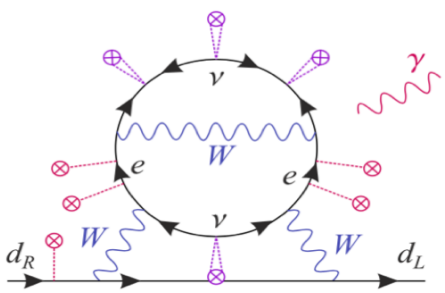
$$- \boldsymbol{\Upsilon}_\nu^\dagger (\mathbf{Y}_e^\dagger \mathbf{Y}_e)^T \boldsymbol{\Upsilon}_\nu \cdot \mathbf{Y}_e^\dagger \mathbf{Y}_e \cdot \boldsymbol{\Upsilon}_\nu^\dagger \boldsymbol{\Upsilon}_\nu]$$

Weak rainbow process

$$\mathbf{X}_e^{\text{Majo}} = [\boldsymbol{\Upsilon}_\nu^\dagger \boldsymbol{\Upsilon}_\nu \,,\; \boldsymbol{\Upsilon}_\nu^\dagger (\mathbf{Y}_e^\dagger \mathbf{Y}_e)^T \boldsymbol{\Upsilon}_\nu]$$

4 orders of magnitude **larger** than J_{CP} and **not correlated**



PMNS-induced quark EDM

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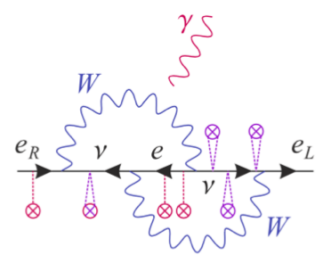

PMNS-induced lepton EDM

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Conclusion

- **Developpement of a systematic method** to study the flavor structure behind the quark and lepton EDMs
  - Can be extended easily to other models (Sterile neutrinos, SUSY, …)
- **Different behavior** for Dirac and Majorana neutrinos
  - Quark and lepton EDM proportional in the former case but independant in the latter case
- Different dependences on Majorana phases for lepton and quark EDM
- **Sum rules**:

	CKM-induced EDM	PMNS-induced EDM
Quarks:	$\frac{d_d}{m_d} + \frac{d_s}{m_s} + \frac{d_b}{m_b} = 0$	$\frac{d_d}{m_d} = \frac{d_s}{m_s} = \frac{d_b}{m_b}$
Leptons:	$\frac{d_e}{m_e} = \frac{d_\mu}{m_\mu} = \frac{d_\tau}{m_\tau}$	$\frac{d_e}{m_e} + \frac{d_\mu}{m_\mu} + \frac{d_\tau}{m_\tau} = 0$

Backup slides

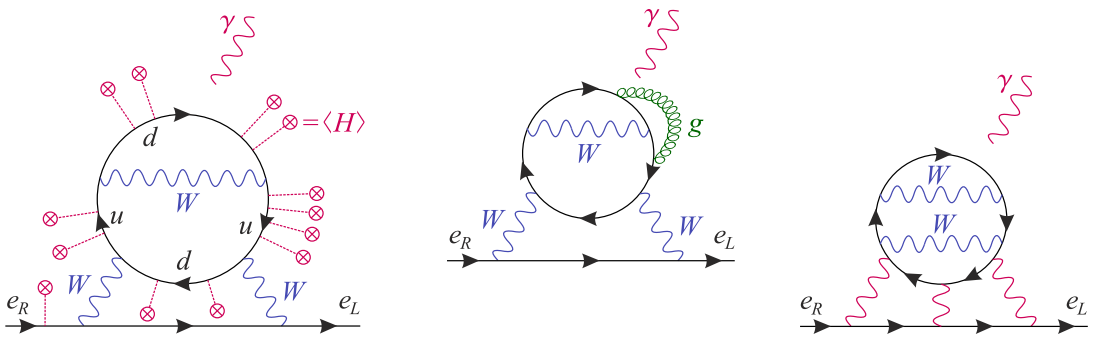
How to predict the EDM generated by the CKM phase?

$$\mathcal{H}_{eff} = e\frac{a}{4m}\bar{\psi}\sigma^{\mu\nu}\psi F_{\mu\nu} + i\frac{\mathbf{d}}{2}\bar{\psi}\sigma^{\mu\nu}\gamma_5\psi F_{\mu\nu}$$

d: particle ψ EDM

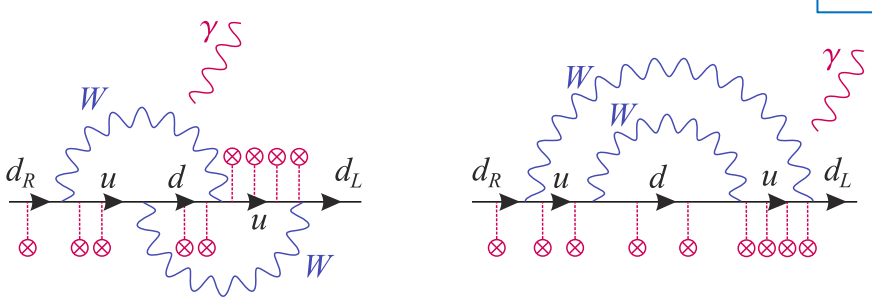
❖ Leptons:

$$\mathcal{L}_{eff} = \frac{c}{M_W^2}(EY_e\mathbf{X}\sigma_{\mu\nu}L)H^\dagger F^{\mu\nu} \Rightarrow \mathbf{X} = \det[Y_u^\dagger Y_u, Y_d^\dagger Y_d] \equiv 2iJ_{\mathcal{CP}} \Rightarrow \boxed{\frac{d_e}{e} \approx \frac{m_e}{M_W^2}\left(\frac{g^2}{16\pi^2}\right)^3 \frac{\alpha_S}{4\pi} J_{\mathcal{CP}}}$$



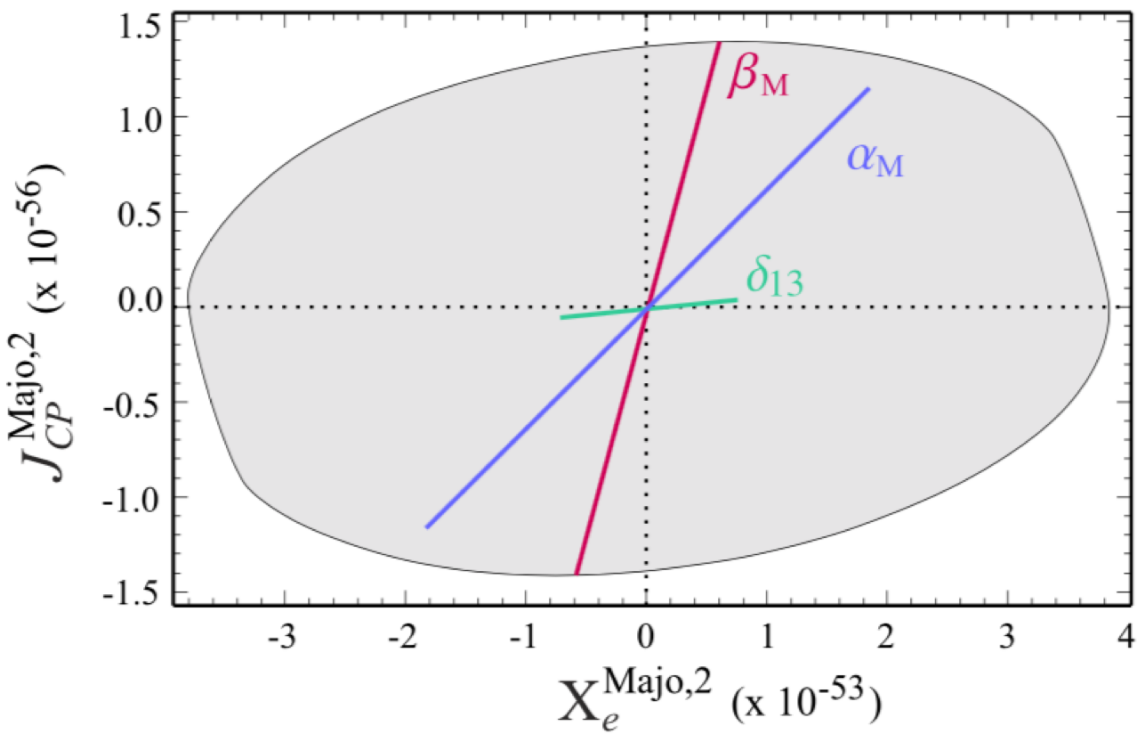
❖ Quarks:

$$\mathcal{L}_{eff} = \frac{c}{M_W^2}(DY_d\mathbf{X}\sigma_{\mu\nu}Q)H^\dagger F^{\mu\nu} \Rightarrow \mathbf{X} = \left[Y_u^\dagger Y_u, Y_u^\dagger Y_u Y_d^\dagger Y_d Y_u^\dagger Y_u\right] \Rightarrow \boxed{d_d \approx e\frac{m_d}{M_W^2}\left(\frac{g^2}{16\pi^2}\right)^2 \frac{\alpha_S}{4\pi} Im(\mathbf{X}^{11})}$$



Correlations

- $m_{\nu 1}$ = 1 eV
- PMNS phase δ_{13} and the Majorana phases α_M, β_M are allowed to take on any values.



→ The lines show the strict correlation occurring when only one phase is non-zero