RPP – Clermont-Ferrand

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CP-violation in and beyond the SM

LPSC Grenoble

Christopher Smith

Université Grenoble Alpes

CNRS IN2P3 Les deux infinis

Grenoble INP

- Outline

I. CP-violation in the SM

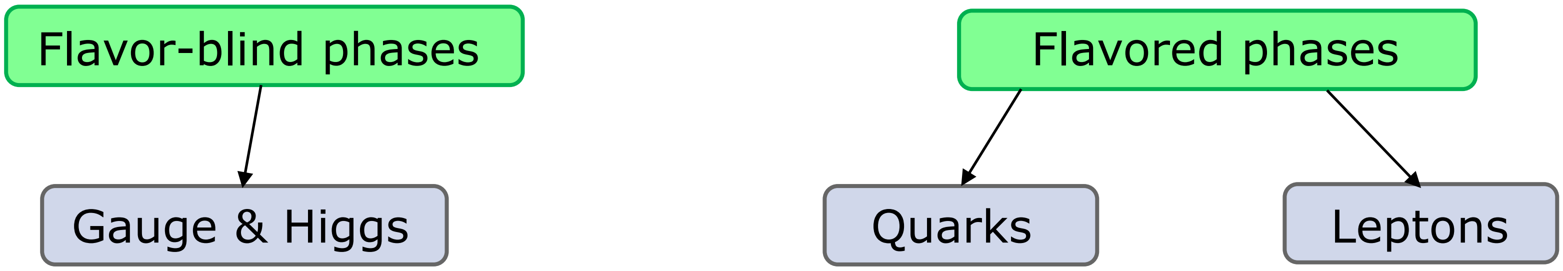
II. CP-violation beyond the SM

III. Perspective and Conclusion

I. CP-violation in the SM

A. CP-violating sources in the SM

In the SM, two types of phases survive to all field redefinitions:



B. Flavor-blind phases in the SM

Three CPV terms are present in the SM gauge Lagrangian:

$$\mathcal{L}_{\not{CP}} = \theta_C \frac{\alpha_S}{8\pi} G_{\mu\nu}\tilde{G}^{\mu\nu} + \theta_L \frac{g^2}{16\pi^2} W_{\mu\nu}\tilde{W}^{\mu\nu} + \theta_Y \frac{g'^2}{16\pi^2} B_{\mu\nu}\tilde{B}^{\mu\nu}$$

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When massless, the quarks/leptons have identical gauge interactions

→ flavor symmetry: $G_F = U(3)^5 = U(3)_Q \times U(3)_U \times U(3)_D \times U(3)_L \times U(3)_E$

Example:

$$U_R^I = \begin{pmatrix} u_R \\ c_R \\ t_R \end{pmatrix} \rightarrow U_R'^I = \begin{pmatrix} u'_R \\ c'_R \\ t'_R \end{pmatrix} = (g_U)^{IJ} U_R^J \ , \ g_U^\dagger g_U = 1 :$$

$$\mathcal{L}_{Kin} = \sum_{I=1,2,3} \bar{U}_R^I i\not{D} U_R^I \rightarrow \sum_{k,I,J,K} \bar{U}_R^J (g_U^\dagger)^{JI} i\not{D} (g_U)^{IK} U_R^K = \mathcal{L}_{Kin}$$

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These U(1)s are chiral hence anomalous:

$$\begin{pmatrix} \partial_\mu J_Q^\mu \\ \partial_\mu J_U^\mu \\ \partial_\mu J_D^\mu \\ \partial_\mu J_L^\mu \\ \partial_\mu J_E^\mu \end{pmatrix} = -\frac{N_f}{16\pi^2} \begin{pmatrix} 1 & 3/2 & 1/6 \\ 1/2 & 0 & 4/3 \\ 1/2 & 0 & 1/3 \\ 0 & 1/2 & 1/2 \\ 0 & 0 & 1 \end{pmatrix} \cdot \begin{pmatrix} g_s^2 G_{\mu\nu}\tilde{G}^{\mu\nu} \\ g^2 W_{\mu\nu}\tilde{W}^{\mu\nu} \\ g'^2 B_{\mu\nu}\tilde{B}^{\mu\nu} \end{pmatrix}$$

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$$\begin{pmatrix} \partial_\mu J_Y^\mu \\ \partial_\mu J_B^\mu \\ \partial_\mu J_L^\mu \\ \partial_\mu J_{PQ}^\mu \\ \partial_\mu J_E^\mu \end{pmatrix} = -\frac{N_f}{16\pi^2} \begin{pmatrix} 0 & 0 & 0 \\ 0 & 1/2 & -1/2 \\ 0 & 1/2 & -1/2 \\ 1 & 0 & 8/3 \\ 0 & 0 & 1 \end{pmatrix} \cdot \begin{pmatrix} g_s^2 G_{\mu\nu}\tilde{G}^{\mu\nu} \\ g^2 W_{\mu\nu}\tilde{W}^{\mu\nu} \\ g'^2 B_{\mu\nu}\tilde{B}^{\mu\nu} \end{pmatrix}$$

$U(1)_{B-L}$ and $U(1)_Y$ are anomaly-free.

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These U(1)s are chiral hence anomalous.

With the appropriate rotations, all three CPV terms are eliminated:

$$\theta_C \to \theta_C - N_f(2\alpha_Q + \alpha_U + \alpha_D)$$

$$\theta_L \to \theta_L - N_f(3\alpha_Q + \alpha_L)$$

$$\theta_Y \to \theta_Y - N_f(1/3\alpha_Q + 8/3\alpha_U + 2/3\alpha_D + \alpha_L + 2\alpha_E)$$

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When massive, the $U(3)^5$ symmetry is broken by the Yukawa couplings.

We must require the quark/lepton masses to be real!

= Three $U(1)$ are fixed to get to $v\mathrm{Y}_u = m_u V_{CKM}$, $v\mathrm{Y}_{d,e} = m_{d,e}$.

Not enough freedom remains to get rid of all three CPV interactions:

$$\theta_C \to \theta_C - \arg\det \mathrm{Y}_u - \arg\det \mathrm{Y}_d$$

$$\theta_L \to \theta_L - N_f (3\alpha_Q + \alpha_L)$$

$$\theta_Y \to \theta_Y + N_f (3\alpha_Q + \alpha_L) - \tfrac{8}{3}\arg\det \mathrm{Y}_u - \tfrac{2}{3}\arg\det \mathrm{Y}_d - 2\arg\det \mathrm{Y}_e$$

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Cannot be removed: Strong CP puzzle.

Removed thanks to $U(1)_{B+L}$ (choice for $3\alpha_Q + \alpha_L$)

Removed by partial integration.

Not enough freedom remains to get rid of all three CPV interactions:

$$\theta_C \to \theta_C - \arg\det \mathbf{Y}_u - \arg\det \mathbf{Y}_d$$

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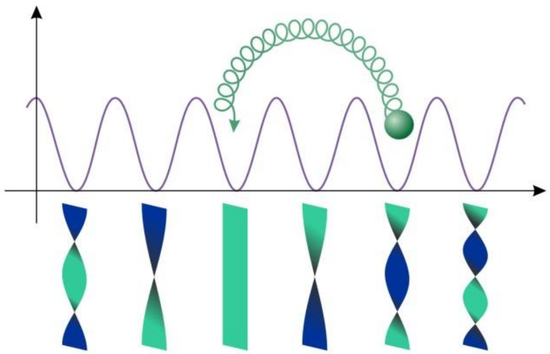
B. Flavor-blind phases in the SM

Why is this strong CP-violation term so puzzling?

$$\mathcal{L}_{\not{CP}} = (\theta_C - \arg\det Y_u - \arg\det Y_d)\frac{\alpha_S}{8\pi} G_{\mu\nu}\tilde{G}^{\mu\nu}$$

QCD has a non-trivial topology:

Explains the large η' mass ←



Violates time-reversal

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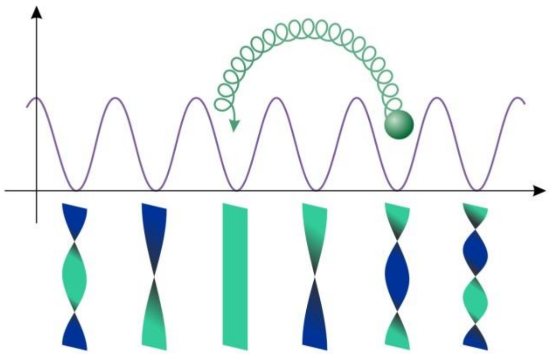

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Yukawa couplings to the Higgs:

We know they are complex.

$$\delta_{CKM} \neq 0$$

from K and B physics

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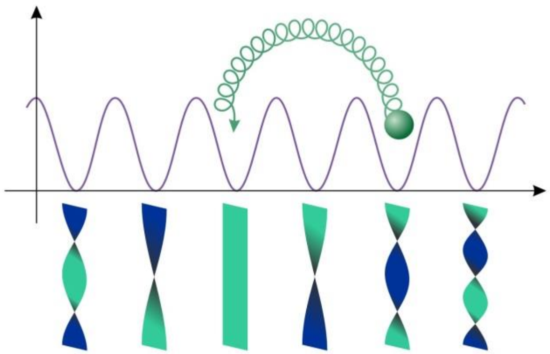


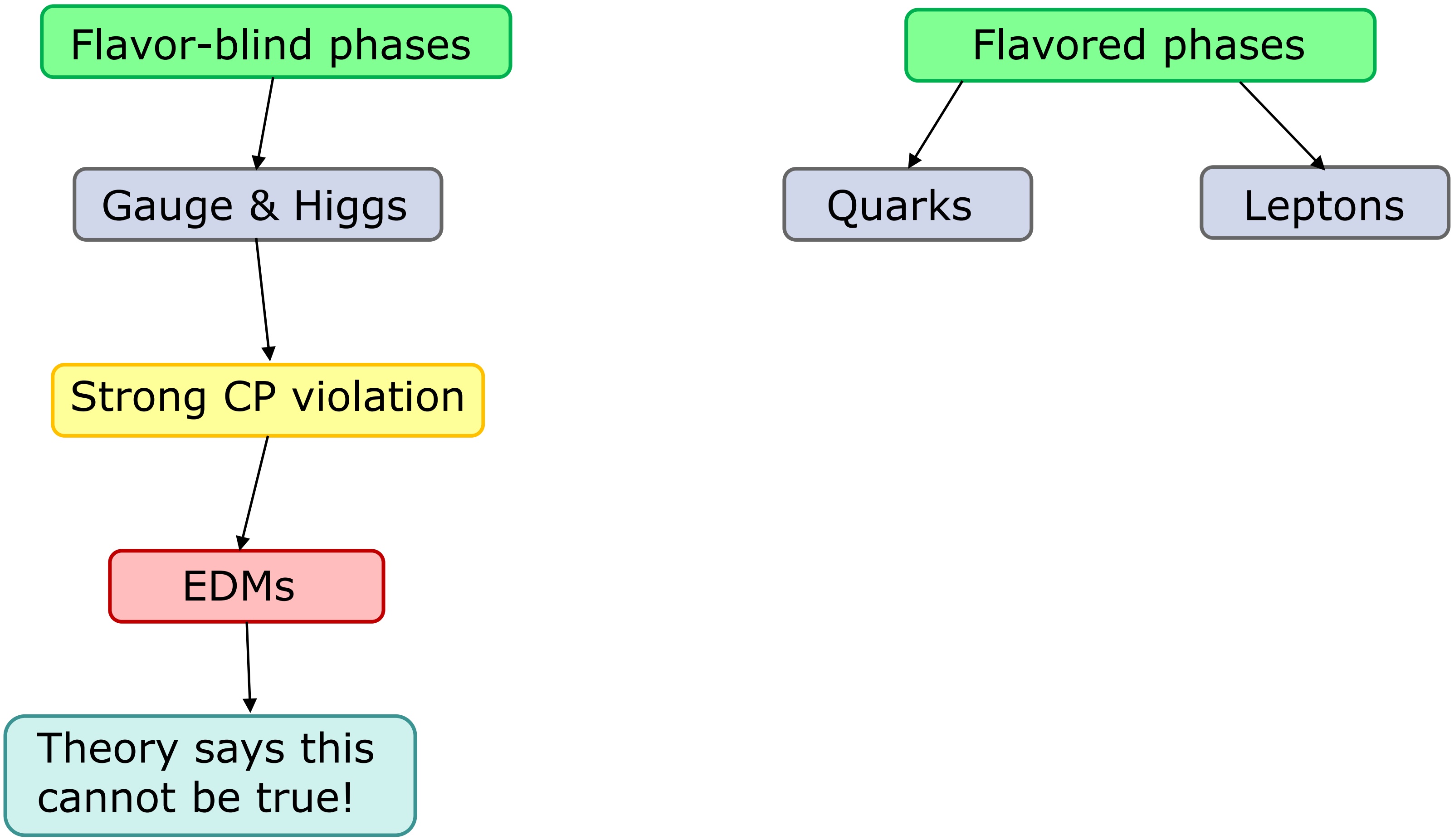
Violates time-reversal

Strong CP puzzle

Neutron EDM implies $\theta_{eff} \equiv \theta_C - \arg\det Y_u - \arg\det Y_d < 10^{-10}$!!!

B. Flavor-blind phases in the SM

The unique flavor-blind phase of the SM is very problematic!

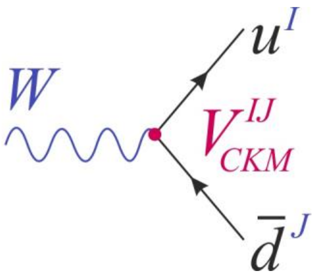


C. Flavored phases in the SM

The U(3) symmetry of the gauge sector permits to rotate to:

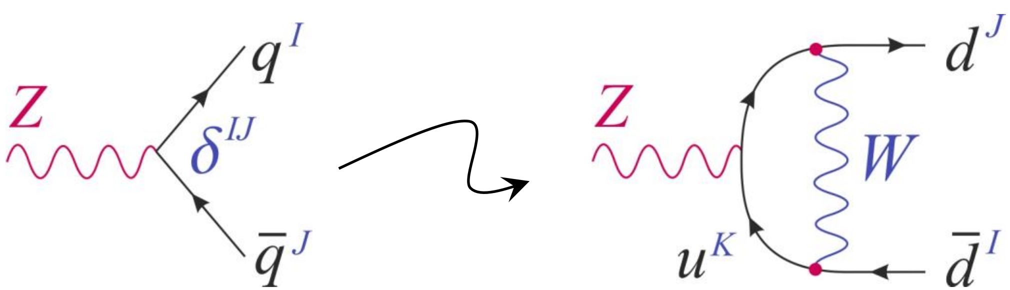
$$\mathcal{L} = -U\mathrm{Y}_u QH - D\mathrm{Y}_d QH^C - E\mathrm{Y}_e LH^C \quad \text{with} \quad v\mathrm{Y}_u = m_u V_{CKM}\,,\ v\mathrm{Y}_{d,e} = m_{d,e}\,.$$

CP-violation hidden in the CKM matrix → Flavor transitions



$$= \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \approx \begin{pmatrix} 1 & 10^{-1} & 10^{-3} \\ 10^{-1} & 1 & 10^{-2} \\ 10^{-3} & 10^{-2} & 1 \end{pmatrix} + \mathcal{O}(10^{-4})$$

Interplay with FCNC, both CPV and CPC

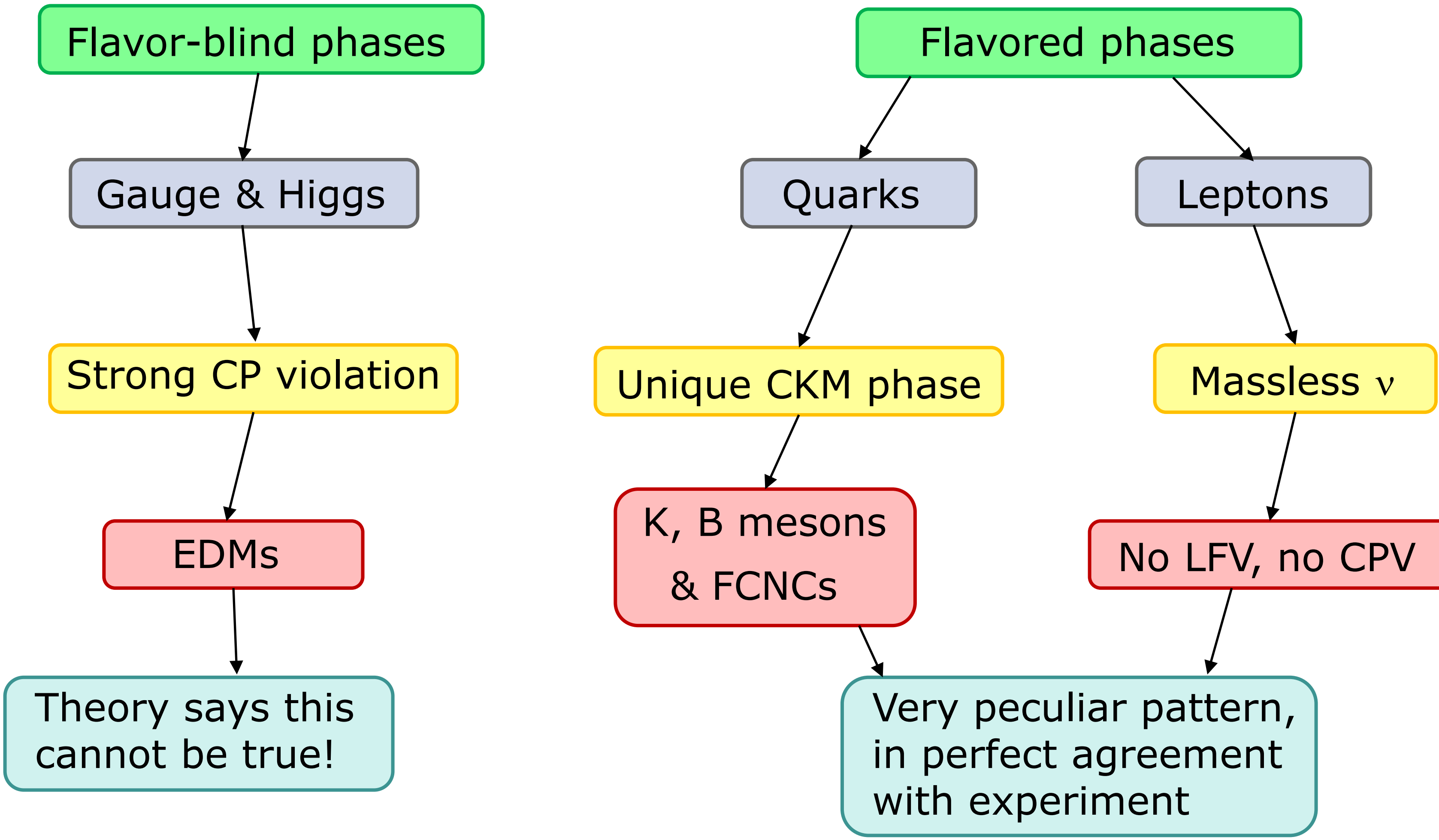


Loop-level only

GIM suppressed

C. Flavored phases in the SM

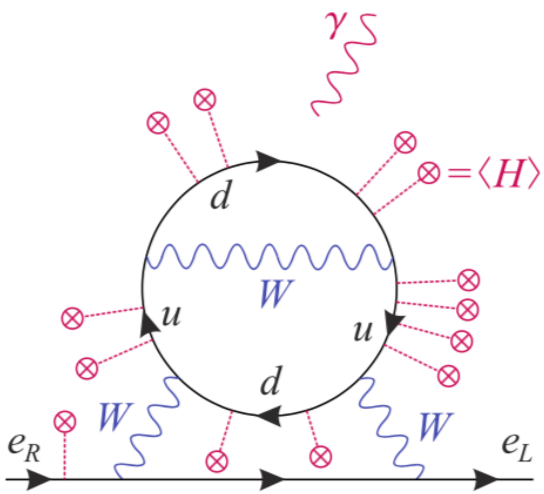
In the SM, flavored phases are rather peculiar, but experiment agrees!



D. From flavored to flavorless phases in the SM

Smith, Touati, '17

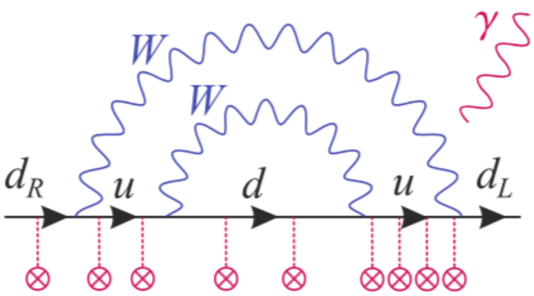
CKM-induced lepton EDM



$$\propto \det\left[Y_u^\dagger Y_u, Y_d^\dagger Y_d\right] \sim 10^{-22}$$

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

CKM-induced quark EDM



$$\propto \mathrm{Im}\left[Y_u^\dagger Y_u,\ Y_u^\dagger Y_u Y_d^\dagger Y_d Y_u^\dagger Y_u\right]^{dd} \sim 10^{-12}$$

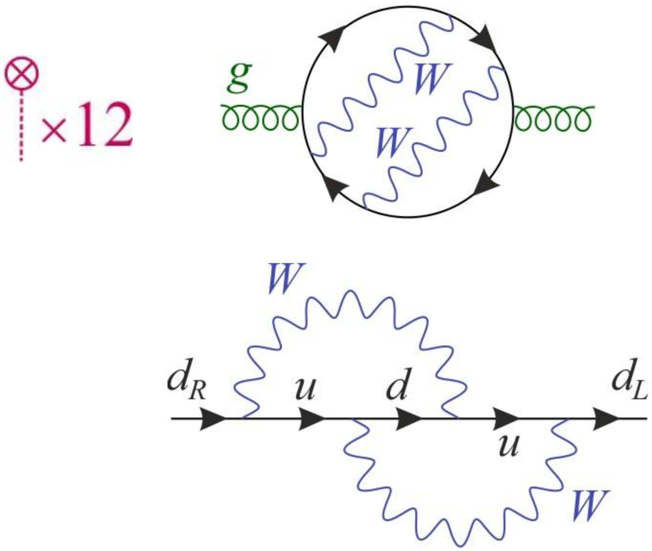
$$\propto \mathrm{Im}(V_{us}V_{cb}V_{ub}^*V_{cs}^*)$$

The induced EDMs are way beyond experimental reach.

The SM dynamics effectively shields strong CPV from weak CPV.

D. From flavored to flavorless phases in the SM

CKM-induced strong phase:



Imaginary part of the vacuum polarization

(shifts $G_{\mu\nu}\tilde{G}^{\mu\nu}$)

Imaginary contributions to quark masses

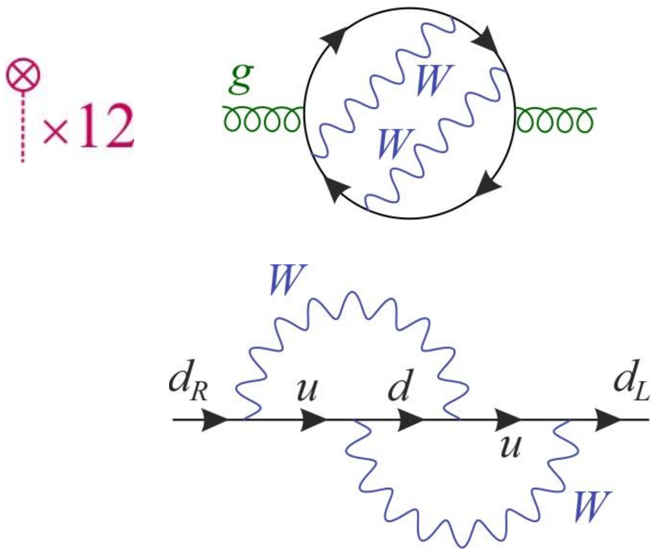
(shifts $\arg\det Y_{u,d}$)

$$\Delta\theta_{eff} \approx O(10^{-16})$$

D. From flavored to flavorless phases in the SM

Wilczek, '78
Ellis, Gaillard, '79
Khriplovich, Vainshtein, '93

CKM-induced strong phase:



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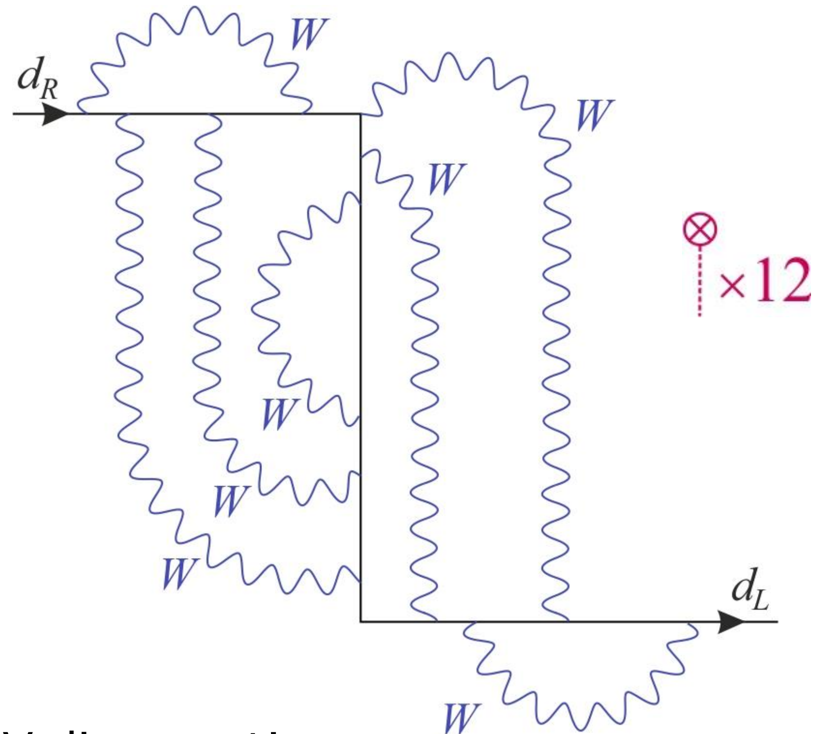
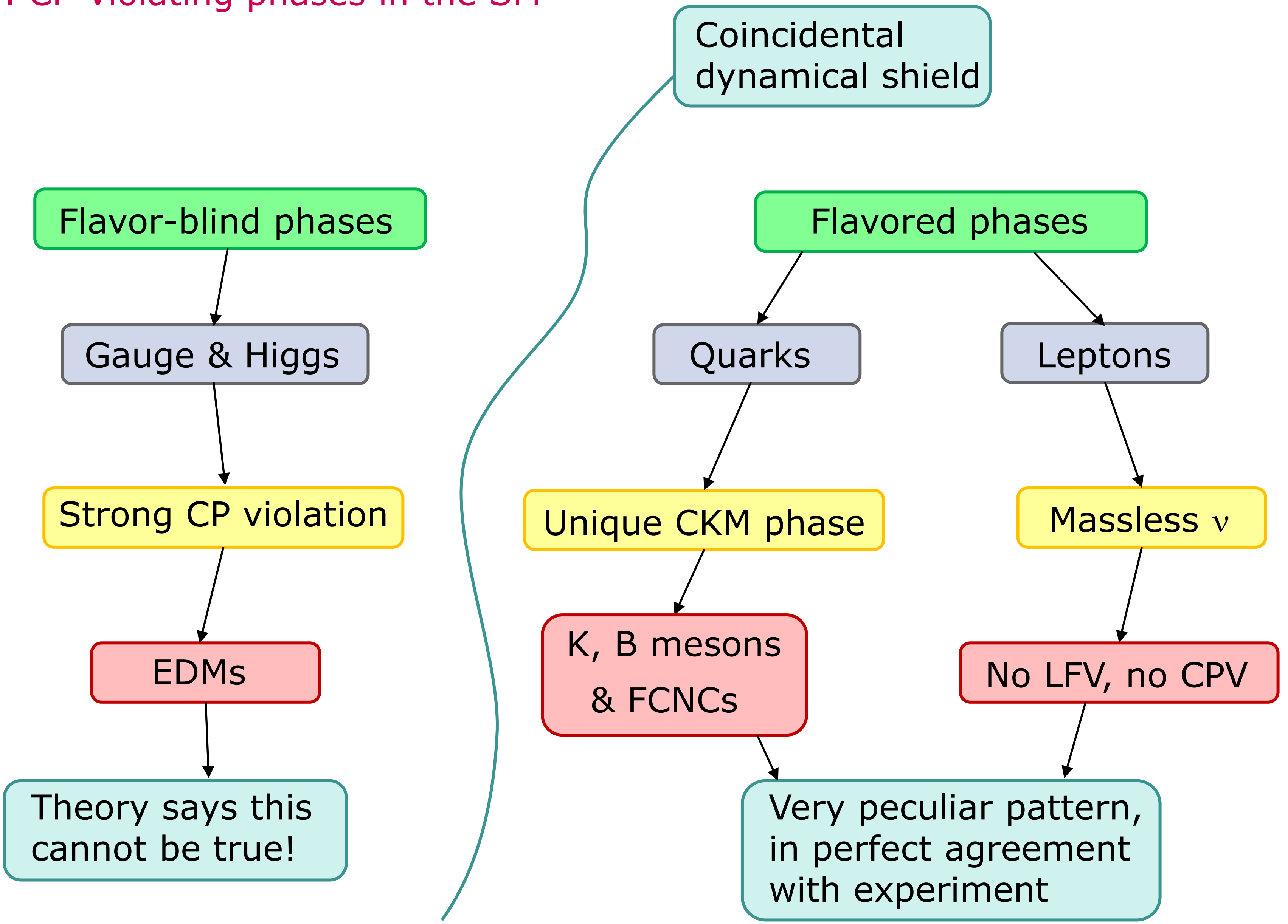


UV divergent!

θ_{eff} is a physical free parameter

If $\theta_{eff}(M_{GUT}) \equiv 0 \Rightarrow \theta_{eff}(M_W) \approx O(10^{-18})$

D. CP-violating phases in the SM



E. The axionic solution

$$\mathcal{L}_{axion} = -\frac{1}{4} G_{\mu\nu} G^{\mu\nu} - \frac{3g^2}{32\pi^2} \theta_S G_{\mu\nu} \tilde{G}^{\mu\nu} + \bar{\psi}_{L,R} i \not{D} \psi_{L,R} + y_i \bar{\psi}_L \psi_R H_i + V(H_i)$$

Step 1: Invariant under some global U(1) symmetry.

Spontaneously broken by the Higgses VEVs.

One massless goldstone boson, $\langle 0 | J^\mu | a(p) \rangle = i v p^\mu$.

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This makes the symmetry anomalous: $\partial_\mu J^\mu \sim G_{\mu\nu} \tilde{G}^{\mu\nu}$

Net effect: $\mathcal{L}_{axion} = \mathcal{L}_{QCD} + \frac{1}{v} a G_{\mu\nu} \tilde{G}^{\mu\nu} + \ldots$

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Step 3: Non-perturbative QCD effects induce

$$\mathcal{L}_{axion} \to \mathcal{L}_{ChPT}(\partial_\mu a, \pi, \eta, \eta', \ldots) + V_{eff}(\theta_S + a/v, \pi, \eta, \ldots)$$

Miminum at $\theta_S + \langle a \rangle / v = 0$: Strong CP relaxes to zero!

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Cannot be EW-scale!

Step 3: Non-perturbative QCD effects induce

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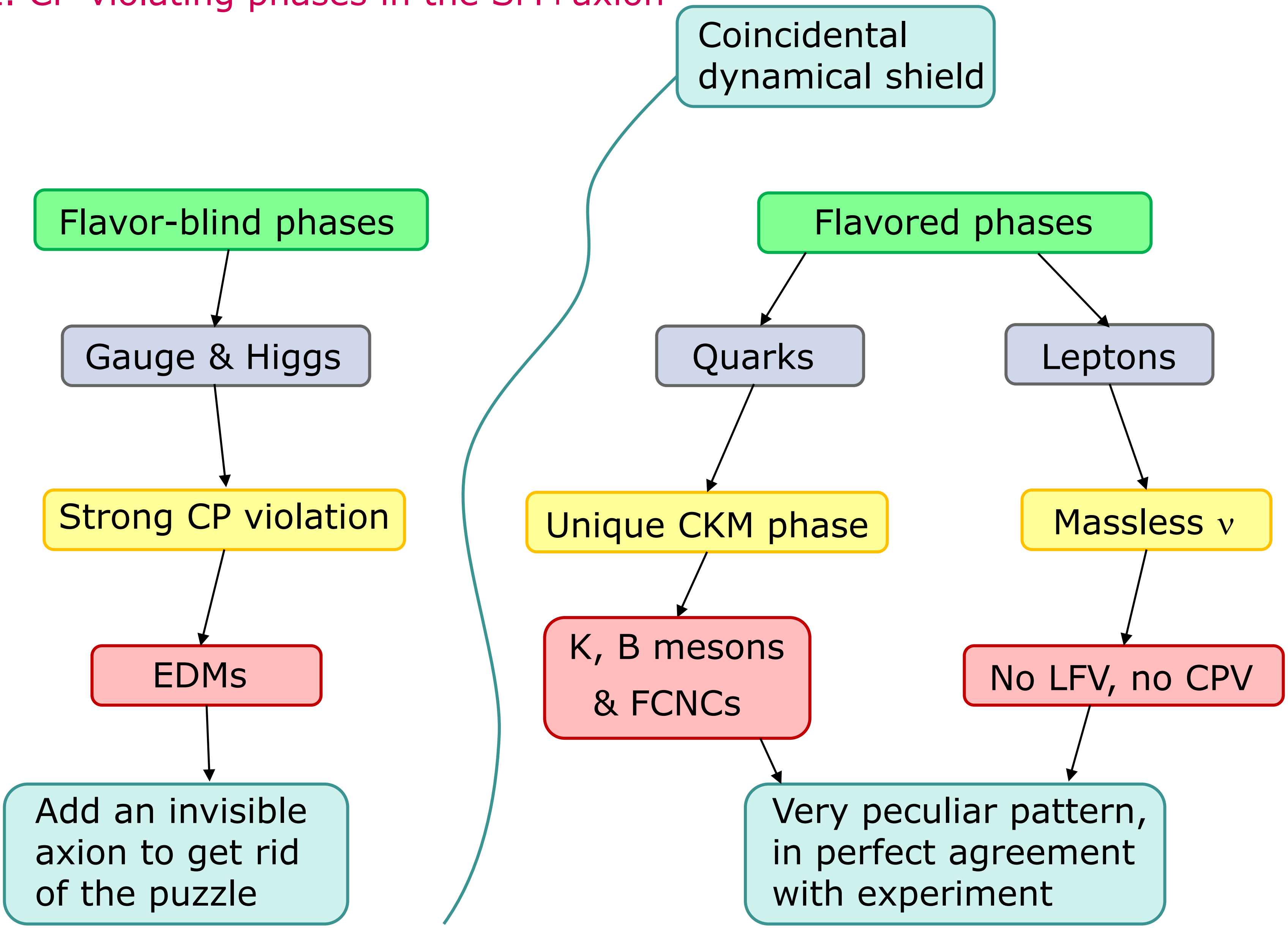
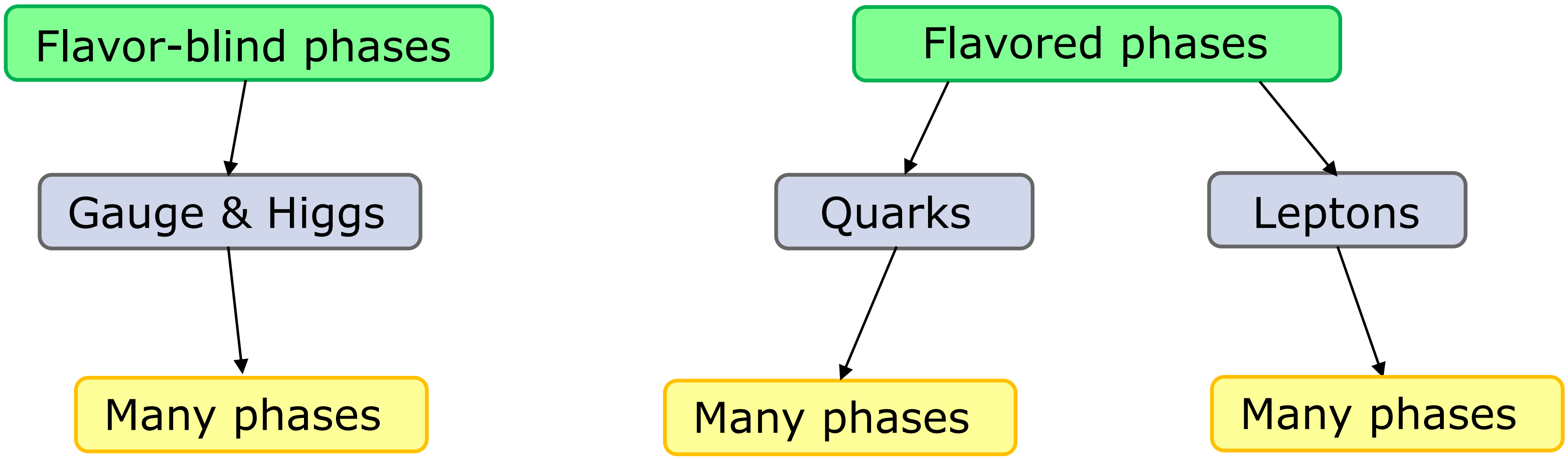
E. CP-violating phases in the SM+axion



II. CP-violation beyond the SM

A. CP-violating phases beyond the SM

Still two types of phases, but a lot of each of them!

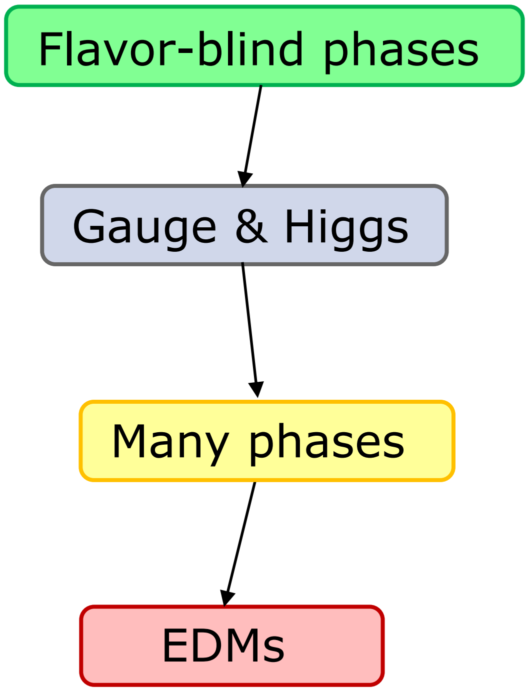


Lagrangian contains new particles & couplings

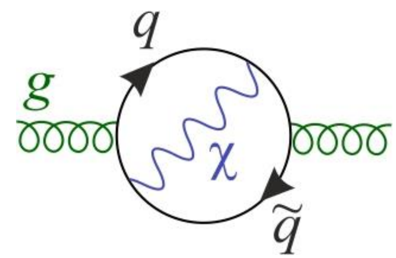
In general, number of couplings increases a lot!
Many of them are physically complex.

B. Flavor-blind CP-violating phases beyond the SM

Flavor-blind CP-violation much more problematic than in the SM:

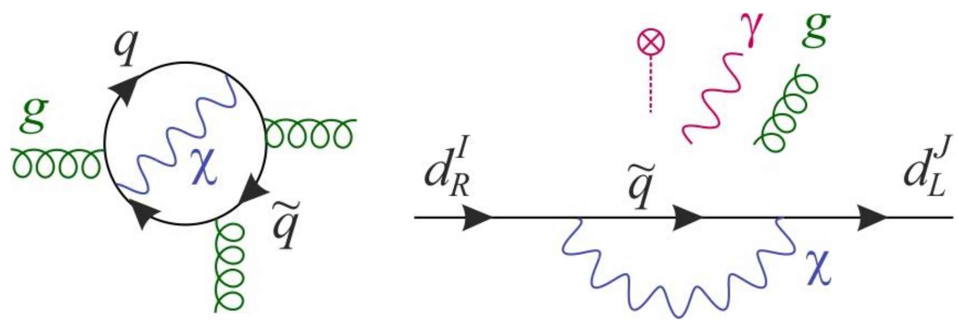


Effect 1: Large contributions to $\Delta\theta^{SUSY}_{eff}$



... but the usual axion is sufficient.

Effect 2: (In)direct contributions to EDMs

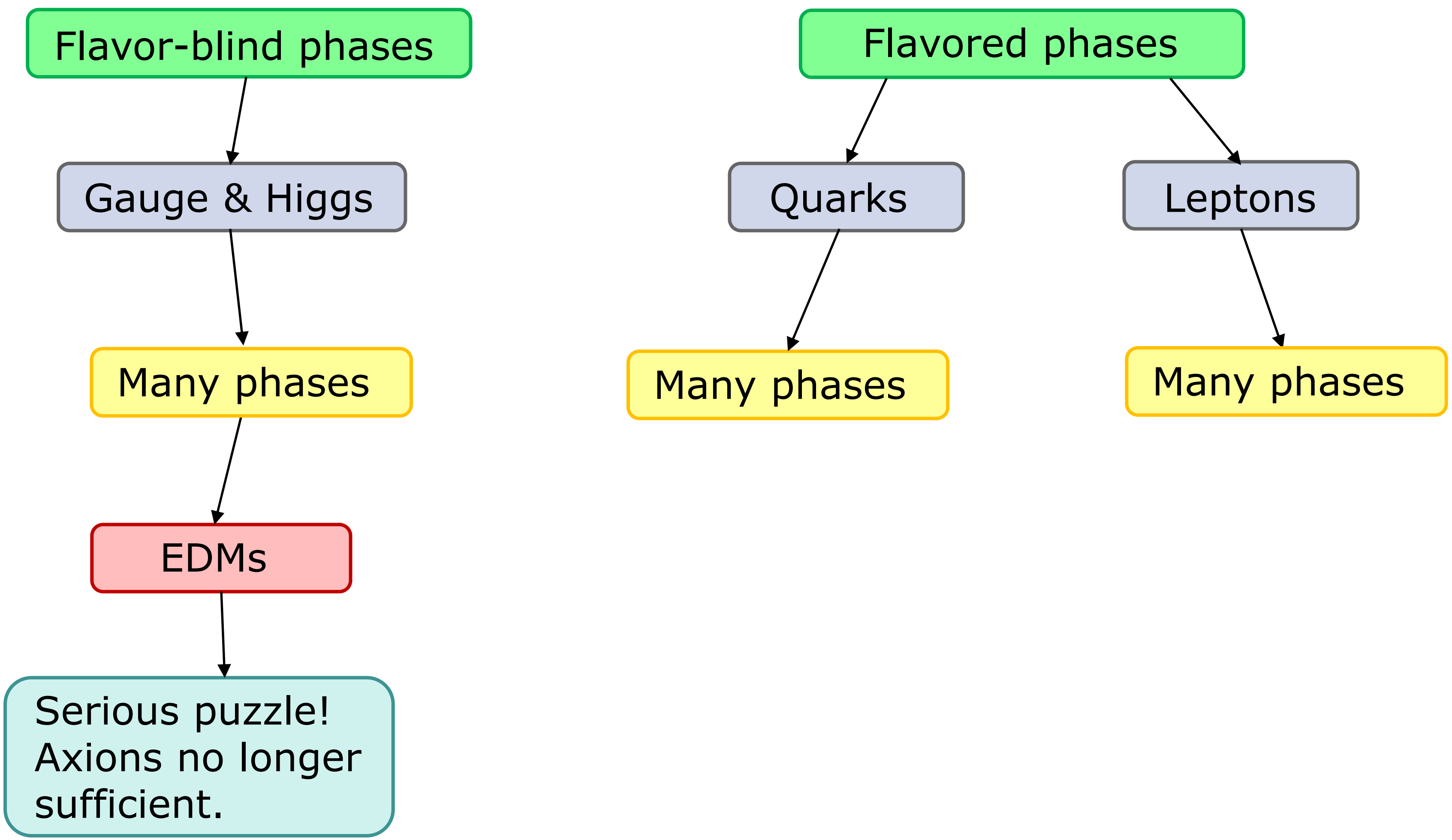


Some fine-tuning unavoidable!

E.g., SUSY CP puzzle from $Arg(\mu,...) \ll 1^\circ$.

B. Flavor-blind CP-violating phases beyond the SM

Flavor-blind CP-violation must be controlled, but axions not enough.



C. Flavored CP-violating phases beyond the SM

Hierarchy puzzle = Stability of the EW scale:

→ New physics must be light.

Flavor puzzles = non-observation of new effects at low energy:

→ New physics must be very heavy.

OR

→ New physics must have tiny, fine-tuned couplings.

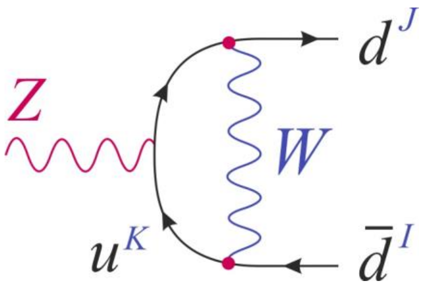
The SM flavor sector is full of «tiny» parameters.

New Physics just needs to be approximately aligned with the SM.

To do this consistently: Use the tools of Minimal Flavor Violation.

C. Flavored CP-violating phases beyond the SM

Example : The Z penguin in the SM: $\mathcal{O}_Z^{SM} \sim \frac{1}{M_W^2} \times \mathcal{C}^{IJ} \times \bar{Q}^I \gamma^\mu Q^J H^\dagger D_\mu H$

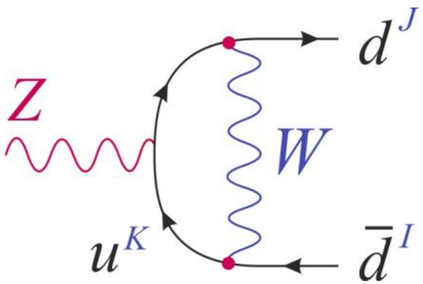


$$\mathcal{C}_{SM}^{IJ} \sim (\mathrm{Y}_u^\dagger \mathrm{Y}_u)^{IJ} \sim \frac{m_t^2}{v^2} V_{tI}^\dagger V_{tJ}$$

$b \to s$	$b \to d$	$s \to d$
0.04	0.008	0.0003

C. Flavored CP-violating phases beyond the SM

Example : The Z penguin with NP: $\mathcal{O}_Z^{NP} \sim \frac{1}{\Lambda^2} \times \mathcal{C}^{IJ} \times \bar{Q}^I \gamma^\mu Q^J H^\dagger D_\mu H$



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$b \to s$	$b \to d$	$s \to d$
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Current bounds on Λ (in TeV):

$\mathcal{C}^{IJ}$	1	$g^2/4\pi$
$B_s \to \mu^+\mu^-$	12	2.2
$B_d \to \mu^+\mu^-$	17	3
$K \to \pi\nu\bar{\nu}$	100	18

C. Flavored CP-violating phases beyond the SM

Example : The Z penguin with MFV: $\mathcal{O}_Z^{NP} \sim \frac{1}{\Lambda^2} \times \mathcal{C}^{IJ} \times \bar{Q}^I \gamma^\mu Q^J H^\dagger D_\mu H$

$$\mathcal{C} = a_0 1 + a_1 Y_u^\dagger Y_u + a_2 Y_d^\dagger Y_d + \ldots \sim \begin{pmatrix} 1 & 10^{-4} & 10^{-3} \\ 10^{-4} & 1 & 10^{-2} \\ 10^{-3} & 10^{-2} & 1 \end{pmatrix} + i \begin{pmatrix} 0 & 10^{-4} & 10^{-3} \\ 10^{-4} & 0 & 10^{-4} \\ 10^{-3} & 10^{-4} & 0 \end{pmatrix}$$

The pattern of CPC and CPV is similar as in the SM.

Current bounds on Λ (in TeV):

$\mathcal{C}^{IJ}$	1	$g^2/4\pi$	$V_{tI}^\dagger V_{tJ}$	$V_{tI}^\dagger V_{tJ}\, g^2/4\pi$
$B_s \to \mu^+\mu^-$	12	2.2	2.5	0.45
$B_d \to \mu^+\mu^-$	17	3	1.5	0.27
$K \to \pi\nu\bar{\nu}$	100	18	1.8	0.33

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The pattern of CPC and CPV is similar as in the SM.

EDMs: The γ penguin with MFV: $\mathcal{O}_\gamma^{NP} \sim \frac{1}{\Lambda^2} C_\gamma^{IJ} (\bar{D}^I \sigma_{\mu\nu} Q^J) H F^{\mu\nu}$

$$\mathrm{Im}\,\mathcal{C}_\gamma^{II} = Y_d\, \mathrm{Im}\,\mathcal{C}^{II} = Y_d (\mathrm{Im}\, a_0 1 + \underbrace{\mathrm{Im}\, a_1 (Y_u^\dagger Y_u)^{II} + \mathrm{Im}\, a_2 (Y_d^\dagger Y_d)^{II} + \ldots}_{})$$

$$\mathrm{Im}\, a_0 + a_0' \det\left[Y_u^\dagger Y_u, Y_d^\dagger Y_d \right]$$

Flavored: suppressed

Flavor blind: unconstrained

MFV shields EDMs from flavored phases.

C. Flavored CP-violating phases beyond the SM

Neutrino masses require some new flavor structures.

Cirigliano,Grinstein Isidori,Wise '05

For example, with a seesaw mechanism:

$$\mathrm{Y}_e\,,\quad \mathrm{Y}_\nu^\dagger \mathrm{Y}_\nu\,,\quad \mathrm{Y}_\nu^T \mathrm{M}^{-1} \mathrm{Y}_\nu\,,\quad \mathrm{Y}_\nu^\dagger \mathrm{M}^{-1*} \mathrm{M}^{-1} \mathrm{Y}_\nu\,,\quad \ldots$$

Lepton masses:

$$v_d \mathrm{Y}_e = \mathrm{m}_e$$

Neutrino masses:

$$v_u^2 \mathrm{Y}_\nu^T \mathrm{M}^{-1} \mathrm{Y}_\nu = U^* \mathrm{m}_\nu U^\dagger$$

Not completely fixed (we take $\mathrm{M} = M_R \mathbf{1}$):

$$v_u^2 \mathrm{Y}_\nu^\dagger \mathrm{Y}_\nu = M_R U^* \mathrm{m}_\nu^{1/2} e^{2i\Phi} \mathrm{m}_\nu^{1/2} U^\dagger\,,\quad \Phi^{IJ} = \varepsilon^{IJK} \phi_K$$

Casas,Ibarra '01, Pascoli,Petcov, Yaguna '03,...

Main constraint then comes from $\mu \to e\gamma$:

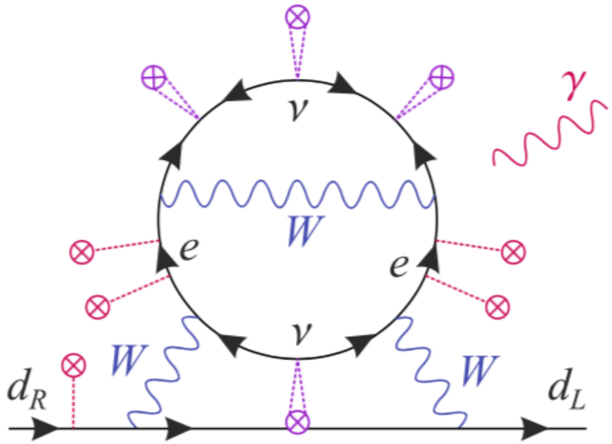
Once satisfied, difficult to have visible effects elsewhere.

C. Flavored CP-violating phases beyond the SM

Smith, Touati, '17

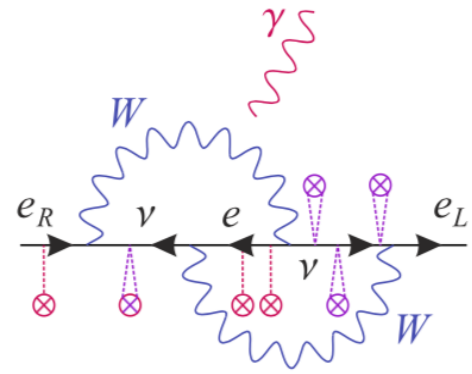
EDM : What happens with new Majorana structures?

Majorana-induced quark EDM



$$\propto \mathrm{Im}\left[\Upsilon_\nu^\dagger Y_e^\dagger Y_e \Upsilon_\nu \cdot Y_e^\dagger Y_e \cdot \Upsilon_\nu^\dagger \Upsilon_\nu\right]$$

Majorana-induced lepton EDM



$$\propto \mathrm{Im}\left[\Upsilon_\nu^\dagger \Upsilon_\nu,\ \Upsilon_\nu^\dagger (Y_e^\dagger Y_e)^T \Upsilon_\nu\right]^{ee}$$

Both could lead to visible effects in a seesaw Type II scenario.

Flavor-blind CPV not always well-protected against leptonic phases.

Smith, Touati, '17

C. Flavored CP-violating phases beyond the SM

EDM : The simplest invariant in terms of Majorana phases?

$$\mathcal{L}_{majorana} \supset \frac{1}{\Lambda}(LH)^T \Upsilon_\nu (LH)$$

In analogy with $\det\left[\mathrm{Y}_u^\dagger \mathrm{Y}_u, \mathrm{Y}_d^\dagger \mathrm{Y}_d\right]$, why not construct:

$$\mathrm{Im}\det \Upsilon_\nu \sim \frac{\Lambda^3}{v_{EW}^6} m_{\nu 1} m_{\nu 2} m_{\nu 3} \sin(\alpha_M + \beta_M) \leq O(1)$$

Smith, Touati, '17

C. Flavored CP-violating phases beyond the SM

EDM : The simplest invariant in terms of Majorana masses?

$$\mathcal{L}_{majorana} \supset \frac{1}{\Lambda}(LH)^T \Upsilon_\nu (LH)$$

In analogy with $\det\left[Y_u^\dagger Y_u, Y_d^\dagger Y_d\right]$, why not construct:

$$\operatorname{Im}\det \Upsilon_\nu \sim \frac{\Lambda^3}{v_{EW}^6} m_{\nu 1} m_{\nu 2} m_{\nu 3} \sin(\alpha_M + \beta_M + \gamma_M - \alpha_L) \equiv 0$$

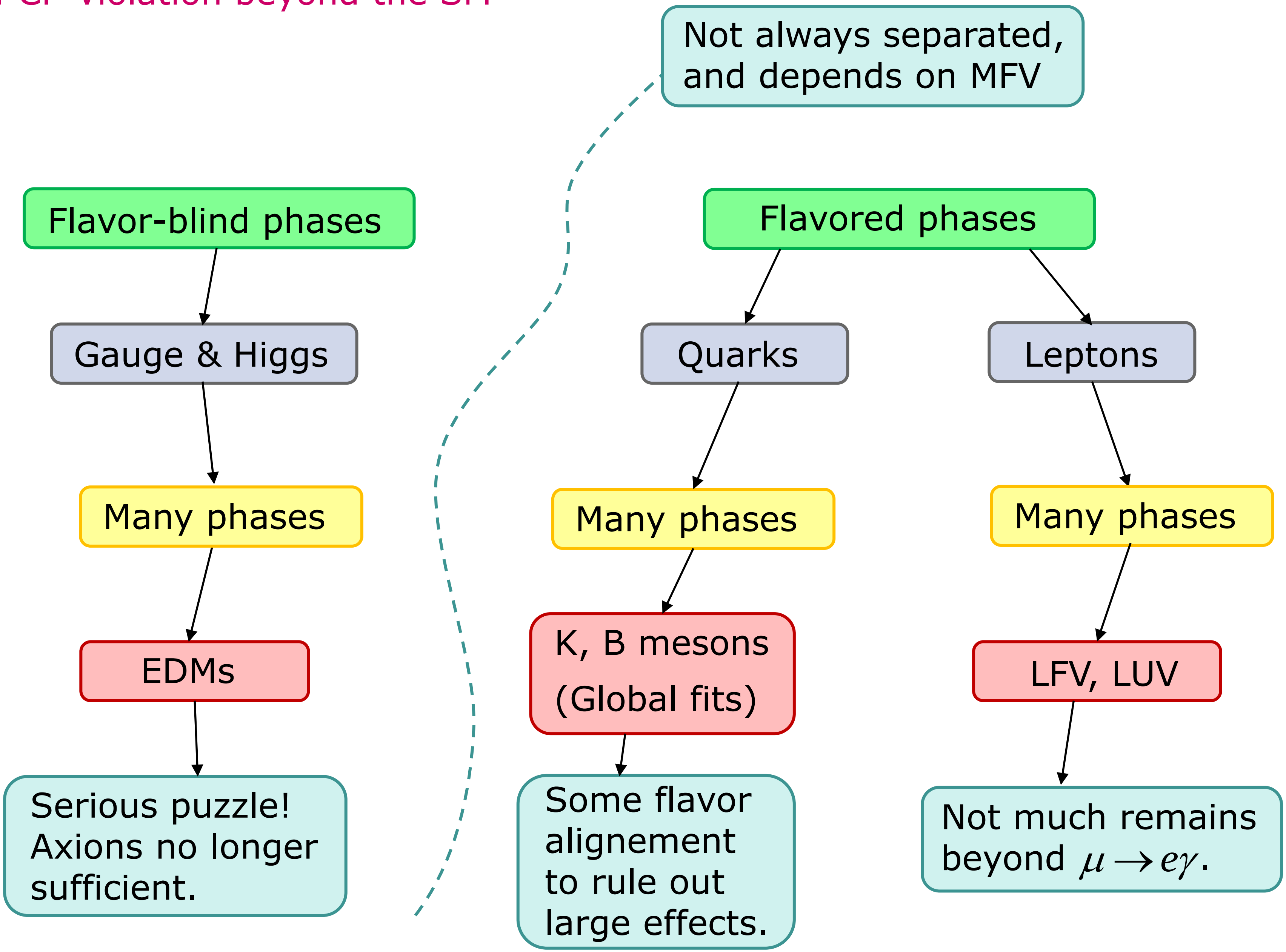
Spurious! Bad choice of phase conventions:

$$(\theta_L - 3\alpha_Q - \alpha_L)\frac{g^2}{16\pi^2} W_{\mu\nu}\tilde{W}^{\mu\nu}$$

Beware though: No freedom remain for α_Q !

Typically, baryon-number violating operators must violate CP.

D. CP-violation beyond the SM



E. Is MFV ruled out by Flavor Universality violation?

Quark and lepton universality appear quite automatic with MFV:

$$\mathcal{C}^{IJ} \times Q^I \gamma^\mu Q^J \times (\ldots) \;\rightarrow\; \mathcal{C} = a_0 \mathbf{1} + \underbrace{a_1 \mathbf{Y}_u^\dagger \mathbf{Y}_u + a_2 \mathbf{Y}_d^\dagger \mathbf{Y}_d + \ldots}_{<1}$$

But actually, there is a peculiar point:

Brümmer, Kraml, Kulkarni, CS, ‘14

$$\mathcal{C}^{IJ} \times Q^I \gamma^\mu Q^J \times (\ldots) \;\rightarrow\; \mathcal{C} \sim \mathbf{1} + \frac{-1}{\langle \mathbf{Y}_u^\dagger \mathbf{Y}_u \rangle} \mathbf{Y}_u^\dagger \mathbf{Y}_u \approx \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

Maximal violation of flavor universality!

Natural thanks to the large top Yukawa,

Respects MFV: no problem with FCNC

But is intrinsically fine-tuned!

E. Is MFV ruled out by Flavor Universality violation?

CS, ‘16

Consider Geometric MFV expansions:

$$\mathcal{C} = 1 + \eta \mathrm{Y}_u^\dagger \mathrm{Y}_u + \eta^2 (\mathrm{Y}_u^\dagger \mathrm{Y}_u)^2 + \eta^3 (\mathrm{Y}_u^\dagger \mathrm{Y}_u)^3 + \ldots = \frac{1}{1 - \eta \mathrm{Y}_u^\dagger \mathrm{Y}_u}$$

No need to fine-tune η, it just needs to be large enough:

$$\mathcal{C} = \begin{pmatrix} \frac{1}{1-\eta y_u^2} \approx 1 & & \\ & \frac{1}{1-\eta y_c^2} \approx 1 & \\ & & \frac{1}{1-\eta y_t^2} \approx 0 \end{pmatrix}$$

But $1 + x + x^2 + x^3 + \ldots \to 0$ if $x \gg 1$???

E. Is MFV ruled out by Flavor Universality violation?

CS, '16

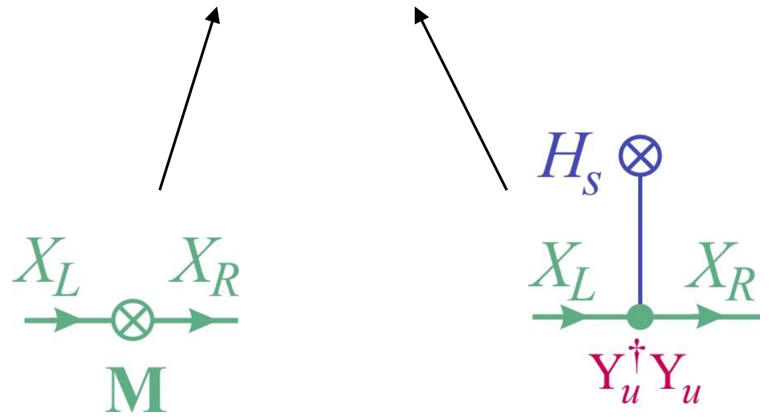
Consider Geometric MFV expansions:

$$\mathcal{C}^{IJ} \times Q^I \gamma^\mu Q^J \times (\ldots) \to \mathcal{C} = \frac{1}{1-\eta \mathbf{Y}_u^\dagger \mathbf{Y}_u} \approx \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

Dynamical toy model to resum the series:

1. Add heavy vector-like flavored fermions + Higgs singlet:

$$M_X^2 = M_0^2 - M_{SSB}^2 = M_0^2 \mathbf{1} - v_s^2 \mathbf{Y}_u^\dagger \mathbf{Y}_u$$



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CS, ‘16

Consider Geometric MFV expansions:

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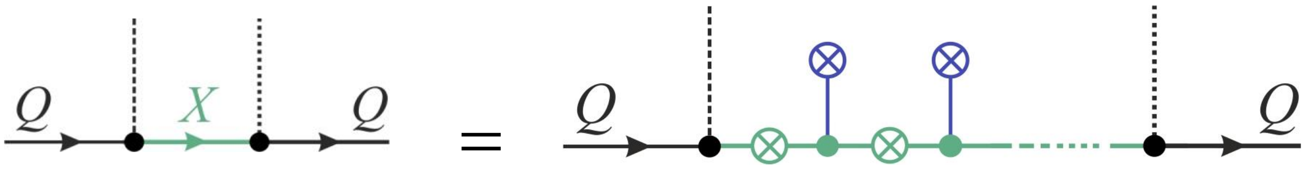
Dynamical toy model to resum the series:

1. Add heavy vector-like flavored fermions + Higgs singlet:

$$M_X^2 = M_0^2 - M_{SSB}^2 = M_0^2 1 - v_s^2 \mathrm{Y}_u^\dagger \mathrm{Y}_u$$

2. Ensure $\mathcal{C}$ is induced by a Fermi-like interaction:



The large parameter is dynamical: $\eta = v_s^2 / M_0^2$

E. Is MFV ruled out by Flavor Universality violation?

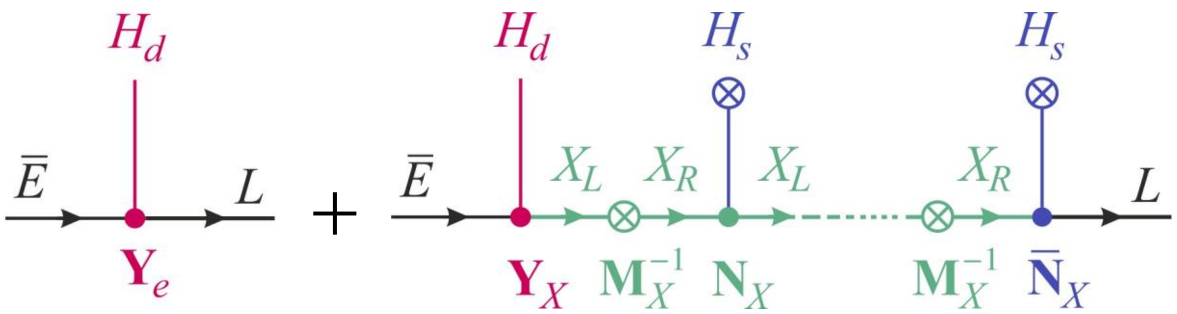
CS, ‘16

Why could this concern leptons?

Because it is the ONLY way to naturally express $\mathbf{Y}_e$ in terms of $\mathbf{Y}_{u,d}$:

$$\mathbf{Y}_e = c_0 \mathbf{Y}_d \cdot \mathcal{C} \quad \Rightarrow \quad \mathcal{C} \approx \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

Can be induced dynamically:



Dressed lepton Yukawa, with $\mathbf{Y}_e, \mathbf{Y}_X, \mathbf{M}_X, \mathbf{N}_X = poly(\mathbf{Y}_u, \mathbf{Y}_d)$:

$$\mathbf{Y}_e^{eff} = c_0 \mathbf{Y}_d \frac{1}{1 + (v_s / M_X)(c_1 \mathbf{Y}_u^\dagger \mathbf{Y}_u + c_2 \mathbf{Y}_d^\dagger \mathbf{Y}_d)}$$

E. Is MFV ruled out by Flavor Universality violation?

CS, '16

What about lepton flavor universality then?

Consider the leptonic part of a semi-leptonic operator:

$$\mathcal{Q}^{NP} = \frac{1}{\Lambda^n}\mathcal{C}^{IJ} \times L^I \gamma^\mu L^J \times (\ldots) \rightarrow \mathcal{C} \approx \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

Very suppressed for the 3rd generation gauge state:

$$\mathrm{Y}_e = c_0 \mathrm{Y}_d \cdot \mathcal{C} \quad \Rightarrow \begin{pmatrix} e_L \\ \mu_L \\ \tau_L \end{pmatrix}^{gauge} \approx \begin{pmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ 1 & 0 & 0 \end{pmatrix} \cdot \begin{pmatrix} e_L \\ \mu_L \\ \tau_L \end{pmatrix}^{phys}$$

So we actually expect $\mathcal{Q}^{NP}(\mu) \approx \mathcal{Q}^{NP}(\tau) \gg \mathcal{Q}^{NP}(e)$!

Overall: Accounting for LFUV requires quite some work!

But note: adding vector fermions + Higgs singlet is precisely the DFSZ receipt to make the axion invisible!

Perspective & Conclusion

Flavor-blind
CP violation
& axions

Axions can solve the SM CP-puzzle, but this looks very coincidental

Conclusion 1/4

Flavor-blind CP violation & axions ⟷ Bayon & lepton Number Violation

Instrinsically similar!

Axions can solve the SM CP-puzzle, but this looks very coincidental

Baryon/lepton number conservation is also very coincidental in the SM

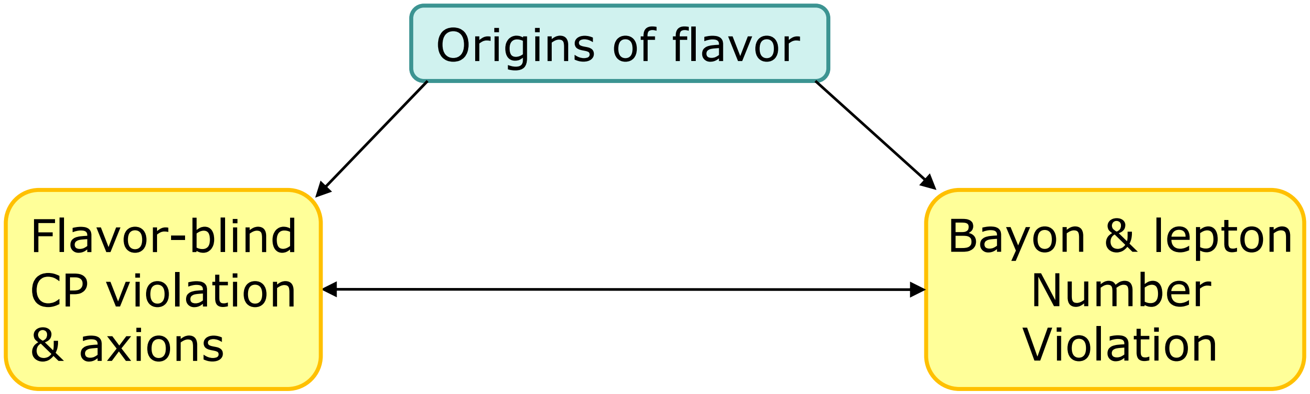
$U(1)_{PQ}, U(1)_B, U(1)_L$ = anomalous combinations of flavored U(1)s.

Note: flavor-blind ≠ unflavored!!!

Not trivial to make axion models compatible with BNV / LNV.

Watamura & Yoshimura, ‘82

Conclusion 2/4

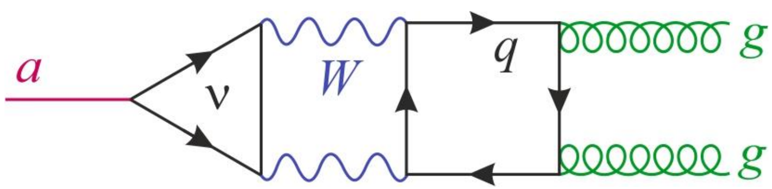


Axions should have more than one role:

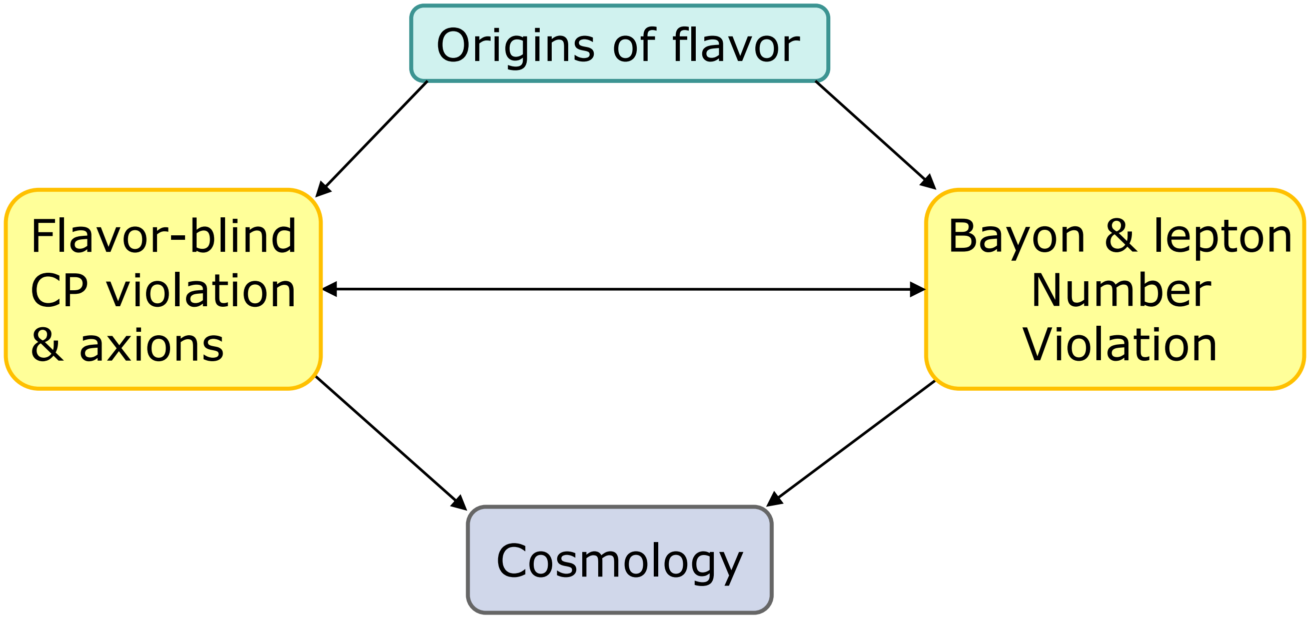
- Flavored/MFV axions?

Ema, Hamaguchi, Moroi, Nakayama, 1612.05492
Calibbi, Goertz, Redigolo, Ziegler, Zupan, 1612.08040
Arias-Aragon, Merlo, 1709.07039
Choi, Im, Park, Yun, 1708.00021
Ema, Hagihara, Hamaguchi, Moroi, Nakayama, 1802.07739
Reig, Valle, Wilczek, 1805.08048
Björkeroth, Chun, King, 1806.00660
Bonnefoy, Dudas, 1809.08256
Björkeroth, Di Luzio, Mescia, Nardi, 1811.09637
…………

- Majoron = axion? A la DFSZ or through multiloop processes



Latosinski, Meissner, Nicolai, '12
Ballesteros, Redondo, Ringwald, Tamarit, '16
Ma, Ohata, Tsumura, '17



Axions may play a big role in the Universe:

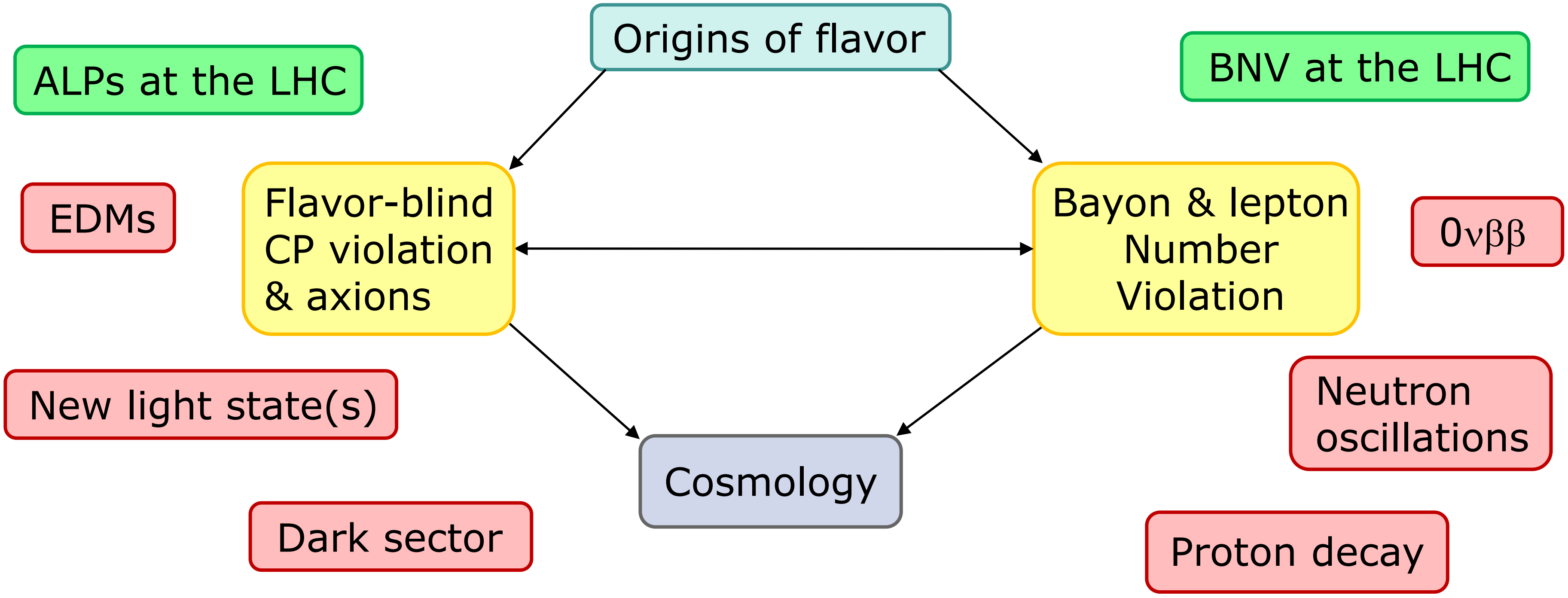
Dark Matter candidate

+

Baryon/lepton number violation

+

CP violation



Rich non-standard phenomenology to explore!

Plenty of exotic signals to look for!