

Present and Future Constraints on TeV Scale Left-Right Symmetry

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Contents

- From Standard Model to Left-Right symmetry.
- Constraints from meson oscillations and epsilon-prime.
- Nucleon (atomic) Electric Dipole Moment in minimal Left-Right Symmetric Model.
- Hints on future constraints vs direct detection.
- Outlook.

Why a Left-Right (LR) symmetry?

Starting from **Standard Model** (SM):

1. **Massless neutrino** in contrast with neutrino oscillation phenomenology.
2. Total asymmetry from left and right-handed sector, reflecting the chiral structure of weak interactions. [Wu, Garwin, Lederman, Weinrich]

Taking these issues separately, they can be dealt, for instance by

1. SM + a singlet right-handed neutrino
2. A first attempt: mirror universe [Lee and Yang 1956]

These points can be related to an unique issue



LR Symmetric Model.

(More economical than a mirror universe)

[Pati-Salam '74, Mohapatra-Senjanovic '75]

Coming to SM

In the SM the neutrino mass can be built by the non-renormalizable operator (dimension 5):

$$L = y_{\nu_L} \frac{(\Psi_L^t i \sigma_2 \Phi) C (\Phi^t i \sigma_2 \Psi_L)}{M}$$

This term violates lepton number

$$M_{\nu_L} \nu_L^t C \nu_L$$

“**M**” is any **NP** scale

[Weinberg '79]

Standard Higgs

$$\langle \Phi \rangle = \begin{pmatrix} 0 \\ v \end{pmatrix}$$



$$M_{\nu_L} = y_{\nu_L} \frac{v^2}{M}$$

Another picture for SM neutrino mass

Adding a **right-handed neutrino** $\left\{ \begin{array}{ll} \text{Dirac} & m \bar{\nu}_L \nu_R \\ \text{Majorana} & M \bar{\nu}_R \nu_R^C \end{array} \right.$

$$\begin{pmatrix} 0 & m \\ m^t & M \end{pmatrix}$$

But “**M**” is not dynamically generated by the theory. It is not related with any spontaneous symmetry breaking into the model .



That is like the effective Weinberg picture .

Left-Right Symmetric Model

Gauge group:

[Pati-Salam '74, Mohapatra-Senjanovic '75]

$$SU(3)_c \otimes SU(2)_L \otimes SU(2)_R \otimes U(1)_{B-L} \Rightarrow SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$$

We consider low scale minimal model

$$g_L = g_R$$

The theory has a further symmetry, or a generalized **Parity** between left and right sectors

$$L \leftrightarrow R$$

Fermionic representations:

$$Q_L = \begin{pmatrix} u \\ d \end{pmatrix}_L$$

$$Q_R = \begin{pmatrix} u \\ d \end{pmatrix}_R$$

$$\Psi_L = \begin{pmatrix} \nu_l \\ l \end{pmatrix}_L$$

$$\Psi_R = \begin{pmatrix} \nu_l \\ l \end{pmatrix}_R$$

Electric charge:

$$Q_{el} = T_{3L} + T_{3R} + \frac{B-L}{2}$$

Quantum numbers:

$$Q_L \in (3, 2, 1, 1/3)$$

$$Q_R \in (3, 1, 2, 1/3)$$

$$\Psi_L \in (1, 2, 1, -1)$$

$$\Psi_R \in (1, 1, 2, -1)$$

The difference between **Barionic** and **Leptonic** number is a gauge generator.

The *gauge bosons* are:

—	γ	Photon
	$Z_L, W_L^\pm$	Standard weak bosons
	$Z_R, W_R^\pm$	Right-handed twins bosons

Gauge Interactions

$$L_{c.c.} = \frac{g}{2\sqrt{2}} [\bar{\nu} \gamma^\mu (1 - \gamma^5) e] W_{\mu L}^+ + \frac{g}{2\sqrt{2}} [\bar{\nu} \gamma^\mu (1 + \gamma^5) e] W_{\mu R}^+ + h.c.$$

$$L_{n.c.}^{SM} = \frac{g}{c_W} Z_L (J_{3L} - \frac{s_W^2}{e} J^0) \quad L_{n.c.}^{N.P.} = \frac{g \sqrt{c_W^2 - s_W^2}}{c_W} Z_R (J_{3R} - J_Y \frac{s_W^2}{c_W^2 - s_W^2})$$

$J^0, J_{3L}, J_{3R}, J_Y =$ Electric, left, right and Hyper-charge currents with normalization:

$$\frac{1}{e} J^0 = J_{3L} + J_{3R} + J_Y$$

Higgs Sector

A bi-doublet

$$\Phi \in (2_L, 2_R, 0)$$

↓
Vevs

$$\begin{pmatrix} v_1 & 0 \\ 0 & v_2 e^{i\alpha} \end{pmatrix}$$

$$v_L \ll v_{1,2} \ll v_R$$

$$v_L \propto 1/v_R$$

[Senjanovic '79]

Two triplets

$$\Delta_L \in (3_L, 1_R, 2)$$

$$\Delta_R \in (1_L, 3_R, 2)$$

↓
Vevs

$$\begin{pmatrix} 0 & 0 \\ v_{L,R} & 0 \end{pmatrix}$$

A superposition of these field gives the physical (dynamical) ones, the spectrum contains:

Standard Higgs $h \Rightarrow m_h^2 \propto v_1^2 + v_2^2$ Flavor Changing Heavy Higgs $H \Rightarrow m_H^2 \propto v_R^2$

- Yukawa Lagrangian:

$$L_Y^{lep.} = [\bar{\Psi}_{Li}(F_{ij}\Phi + \tilde{F}_{ij}\tilde{\Phi})\Psi_{Rj}] + [\bar{\Psi}_{Li}\Gamma_{1ij}\Delta_L^\dagger\sigma_2\Psi_{Lj}^c + \bar{\Psi}_{Ri}\Gamma_{2ij}\Delta_R^\dagger\sigma_2\Psi_{Rj}^c] + h.c.$$

$$\tilde{\Phi} = \sigma_2\Phi\sigma_2$$

Neutrino masses in LR

$$\begin{pmatrix} \bar{\nu}_L & \bar{\nu}_R^c \end{pmatrix} \begin{pmatrix} M_L & m_\nu \\ m_\nu^T & M_R \end{pmatrix} \begin{pmatrix} \nu_L^c \\ \nu_R \end{pmatrix}$$

diagonalization

$$\mathcal{M}_d \simeq \begin{pmatrix} M_L - m M_R^{-1} m^T & 0 \\ 0 & M_R \end{pmatrix} = \begin{pmatrix} M_\nu & 0 \\ 0 & M_N \end{pmatrix}$$

M_L	}	Majorana masses
M_R		
m_ν		Dirac mass

[Minkowski '77, Mohapatra
Senjanovic '79,
Glashow '79; Yanagida '79]

Recalling SM+ ν_R , for a match

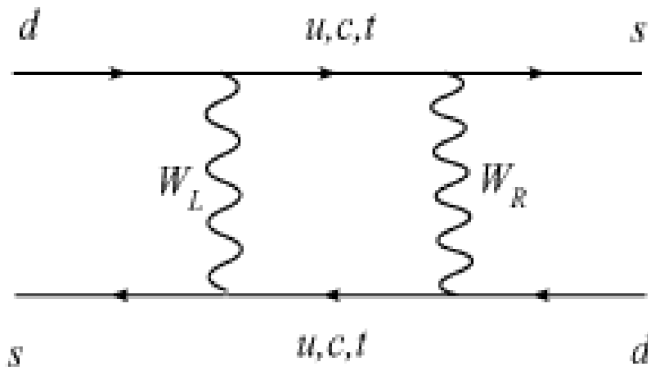
$$\begin{pmatrix} 0 & m \\ m^t & M \end{pmatrix}$$

Now, for LR, M_R is dynamically generated.

Limits and bounds on the LR model from Flavor Physics

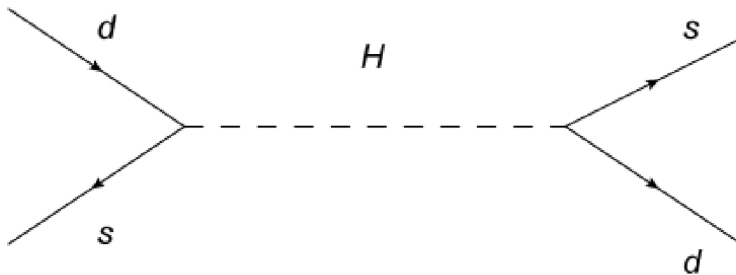
- $\Delta F = 2$ both CP-preserving and CP-violating processes in neutral **K** and **B_d**, **B_s**.
- $\Delta F = 1$ CP-violating parameter **epsilon-prime**.
- Nucleon Electric Dipole Moment (EDM)

Well known Left-Right contributions for meson oscillations



New **Box diagram** from charged gauge interactions. V_L and V_R entering.

[Beall, Bander, Soni '82, Ecker, Grimus '85]



Neutral Heavy Higgs
flavor Changing at
tree level.

Same V_L and V_R
structure.

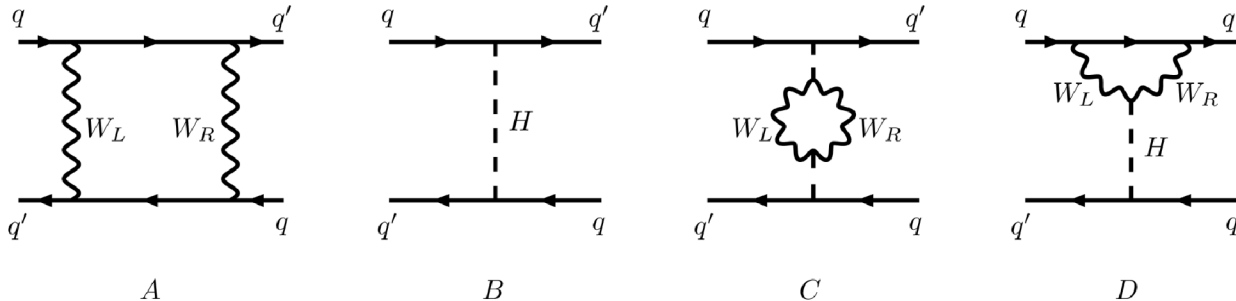
$$L \propto \bar{d}_L V_L^+ m_u V_R d_R H$$

[G. Senjanovic, P. Senjanovic '80]

The issue of gauge independence

More diagrams are necessary for a gauge independent result: also the self-energy and vertex renormalization of tree-level

[Basecq, Li, Pal '85]



$$\mathcal{H}_A = \frac{2G_F^2\beta}{\pi^2} \sum_{i,j} m_i m_j \lambda_i^{LR} \lambda_j^{RL} \eta_{ij}^A F_A(x_i, x_j, \beta) O_S$$

[AM, Bertolini, Nesti, 2014]

$$\mathcal{H}_B = -\frac{2\sqrt{2}G_F}{M_H^2} \sum_{i,j} m_i m_j \lambda_i^{LR} \lambda_j^{RL} \eta_{ij}^B O_S$$

$$\mathcal{H}_C = -\frac{G_F^2\beta}{2\pi^2 M_H^2} \sum_{i,j} m_i m_j \lambda_i^{LR} \lambda_j^{RL} \eta_{ij}^C F_C(M_{W_L}, M_{W_R}, M_H) O_S \leftarrow \begin{cases} \bar{s}Ld \bar{s}Rd \\ \bar{b}Ld \bar{b}Rd \\ \bar{b}Ls \bar{b}Rs \end{cases}$$

$$\mathcal{H}_D = -\frac{4G_F^2\beta}{\pi^2 M_H^2} \sum_{i,j} m_i m_j \lambda_i^{LR} \lambda_j^{RL} \eta_{ij}^D F_D(m_i, m_j, M_{W_L}, M_{W_R}, M_H) O_S$$

All diagrams have the same CKM structure.

V_R plays an important role in determining the LR contribution to flavor violations. If right CKM matrix were free no bound or prediction emerges. [Langacker, Sankar '89]

Left and right quark mixing matrices

$$L_Y^{had.} = [\bar{Q}_{Li}(Y_{ij}\Phi + \tilde{Y}_{ij}\tilde{\Phi})Q_{Rj}] + h.c.$$

$$M_u = Yv_1 + \tilde{Y}v_2e^{-i\alpha}$$

$$M_d = Yv_2e^{i\alpha} + \tilde{Y}v_1.$$



Bi-diagonalization

$$L_{cc} = \frac{g}{2\sqrt{2}} \{ [\bar{u}V_L\gamma^\mu(1 - \gamma_5)d]W_{L\mu} + [\bar{u}V_R\gamma^\mu(1 + \gamma_5)d]W_{R\mu} \} + h.c.$$

with

$$\left\{ \begin{array}{l} V_L = U_{uL}^\dagger U_{dL} \\ V_R = U_{uR}^\dagger U_{dR} \end{array} \right.$$

Left and Right **CKM** mixing matrices

The choice of Left-Right symmetry is not univocal

$$\mathcal{P} : \begin{cases} Q_L \leftrightarrow Q_R \\ \Phi \rightarrow \Phi^\dagger \end{cases} \quad \mathcal{C} : \begin{cases} Q_L \leftrightarrow (Q_R)^c \\ \Phi \rightarrow \Phi^T \end{cases}$$

Which lead respectively to

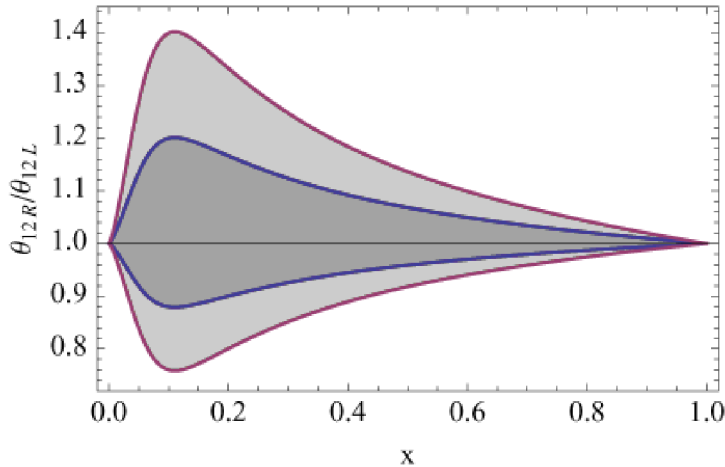
$$\mathcal{P} : Y = Y^\dagger, \quad \mathcal{C} : Y = Y^T \quad [\text{AM, Nemevsek, Nesti, Senjanovic, 2010}]$$

- The case of “**P**” is the original one, hence it is the most known in literature. It can be interesting for nEDM.
- The case of “**C**” should be considered equally. It is also interesting in SO(10) GUT scenario, where charge conjugation enters automatically in the algebra. (For instance the fermions and their charge conjugated in the same important representation **16_F**).

Effects of the “parity” on V_R

$\mathcal{P}$

$$V_R \cong S_u V_L S_d$$



x is the VEVs ratio v_2/v_1 .

The phases S are not free parameters. They are non-trivially related to the VEVs structure, i.e. x and α (the intrinsic phases of LR mixing).

[AM, Nemevsek, Nesti, Senjanovic, 2010]

$$\mathcal{C} \\ V_R = S_u V_L^* S_d$$

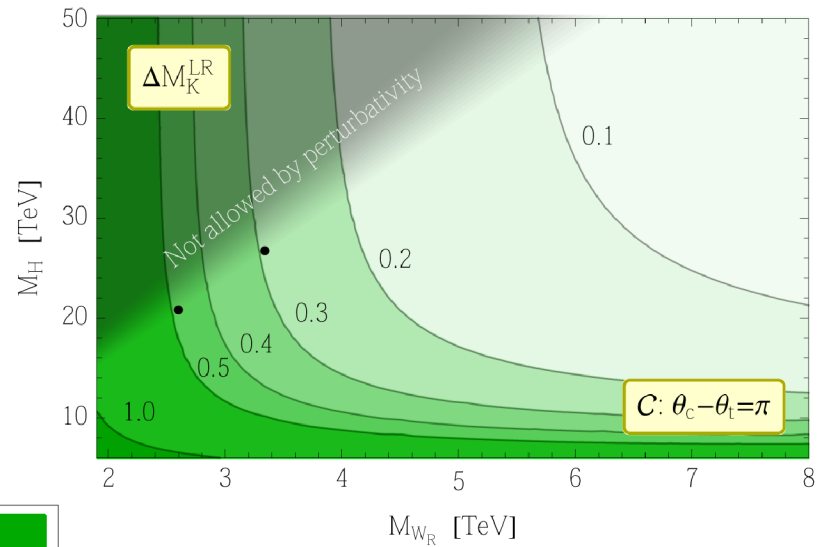
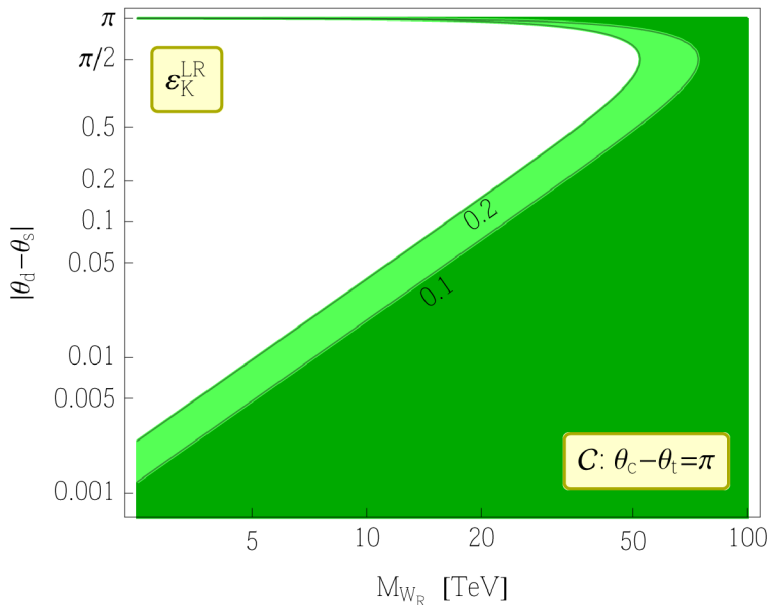
The external phases are completely free parameters. They can be fixed from the phenomenology and can be exploited whenever a “tension” of CPV data with SM emerges.

[AM, Nemevsek, Nesti, Senjanovic, 2010]

Results from kaon oscillations: C symmetry

Dominated by **charm-charm**
quark exchange

[AM, Bertolini, Nesti, 2014]



The rule of “**ct**” contribution is fundamental,
for a cancellation between “**cc**” and “**ct**”

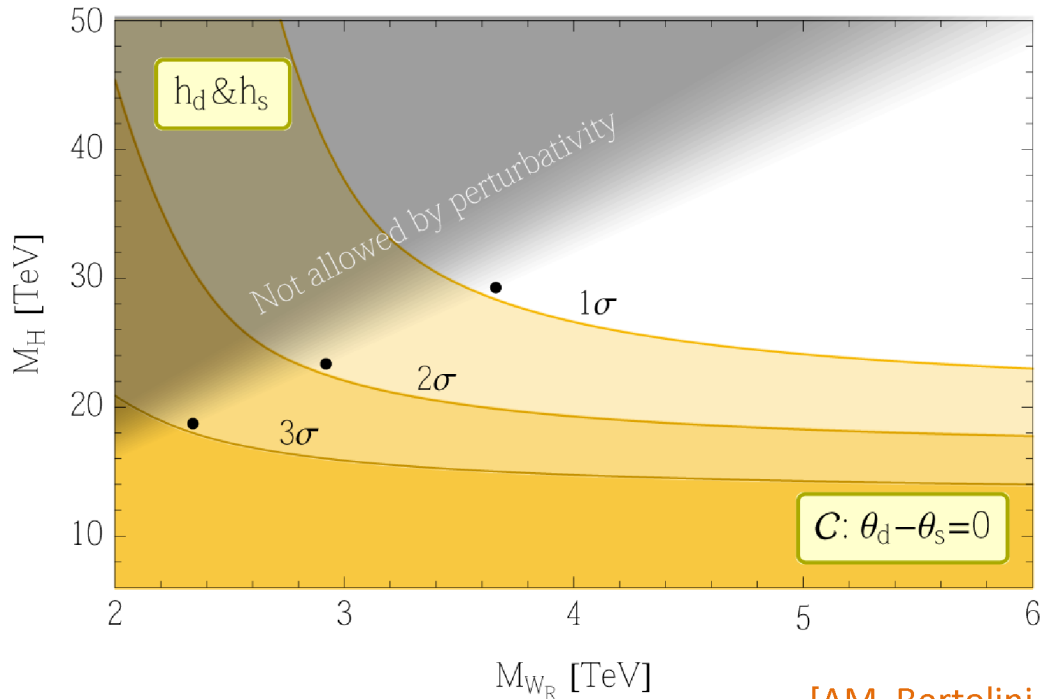
$$\simeq \text{Im} \left[e^{i(\theta_d - \theta_s)} (A_{cc} + A_{ct} \cos(\theta_c - \theta_t + \phi)) \right]$$

$$\phi = \arg(V_{Ltd}) \simeq -22^\circ$$

Results from $B_{d,s}$ oscillations: C symmetry

Following CKM-fitter and their constraints from data, we use the parameters $h_{d,s}$ for the matching with phenomenology

$$h_q = \frac{\langle B_q | H_{LR} | \bar{B}_q \rangle}{\langle B_q | H_{SM} | \bar{B}_q \rangle}$$

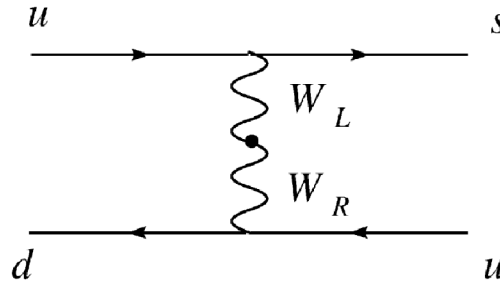


The relevant operators for epsilon'

Current-Current

$$Q_1^{RL} = (\bar{s}_\alpha u_\beta)_R (\bar{u}_\beta d_\alpha)_L \quad Q_1^{LR} = (\bar{s}_\alpha u_\beta)_L (\bar{u}_\beta d_\alpha)_R$$

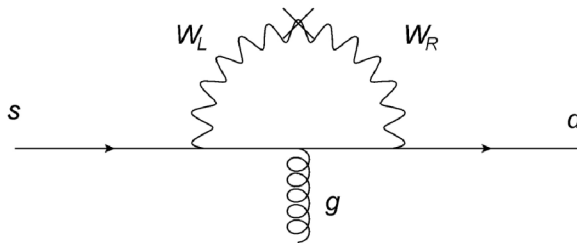
$$Q_2^{RL} = (\bar{s}u)_R (\bar{u}d)_L \quad Q_2^{LR} = (\bar{s}u)_L (\bar{u}d)_R$$



[AM, Nesti, Bertolini, Eeg, 2013]

Dipole operators

$$Q_g^L = \frac{g_s m_s}{8\pi^2} \bar{s} \sigma_{\mu\nu} t^a G_a^{\mu\nu} L d \quad Q_g^R = \frac{g_s m_s}{8\pi^2} \bar{s} \sigma_{\mu\nu} t^a G_a^{\mu\nu} R d$$



Enhanced by internal quark mass.
However It is not sufficient to compensate the gap with the current-current ones.

Chiral Quark Model approach

-By means of a **quark-meson interaction**

$$L = -m(\bar{q}_R \Sigma q_L + \bar{q}_L \Sigma^\dagger q_R)$$

[Manohar, Georgi, '84,
Gasser, Leutwyler, '84,
Weinberg, 2010]

any kaon to pion amplitude is evaluated through **quark loops**.

-By matching the loop result with the transition resulting from chiral Lagrangian expansion, one determines the unknown parameters

-Finally, with the completely determined chiral Lagrangian, one can compute the **chiral loop corrections** to the transitions.

Same approach in the past for SM

[Antonelli, Bertolini, Eeg, Fabbrichesi, Lashin, '96-2001]

B parameters for LR current-current operators

We give the results in the standard form, i.e. parameterizing the amplitude as

$$B_i^{(0,2)} \equiv \frac{\text{Re}\langle Q_i \rangle_{0,2}^{\text{model}}}{\langle Q_i \rangle_{0,2}^{\text{VSA}}} \quad \langle Q_i \rangle_{0,2} \equiv \langle (\pi\pi)_{(I=0,2)} | Q_i | K^0 \rangle$$

where VSA is the Vacuum Saturation Approximation.

B parameters (HV scheme)

$$\begin{aligned} B_0(Q_1^{LR}) &= 2.26_{-0.46}^{+0.79} \\ B_2(Q_1^{LR}) &= 1.01_{-0.29}^{+0.25} \\ B_0(Q_2^{LR}) &= 2.20_{-0.44}^{+0.75} \\ B_2(Q_2^{LR}) &= 1.01_{-0.32}^{+0.30} \end{aligned}$$

[AM, Nesti,
Bertolini, 2013]

-Very small dependence on the scheme.

-The errors are evaluated varying all input parameters. We use the fitted values, see: [Bertolini, Eeg, Fabbrichesi, Lashin, '98]

Note that the RL **B** are equal to the LR ones.

Constraint form epsilon': C symmetry

The above analysis leads to:

$$|\varepsilon'| \cong |\zeta| \times |5.4 \sin(\alpha - \theta_u - \theta_d) + 0.016 \sin(\alpha - \theta_c - \theta_d)|$$

with $\zeta \approx 10^{-3}$ the LR mixing parameter.

The **first** term is due to **LR current-current** operators and the latter to the dipole operators.

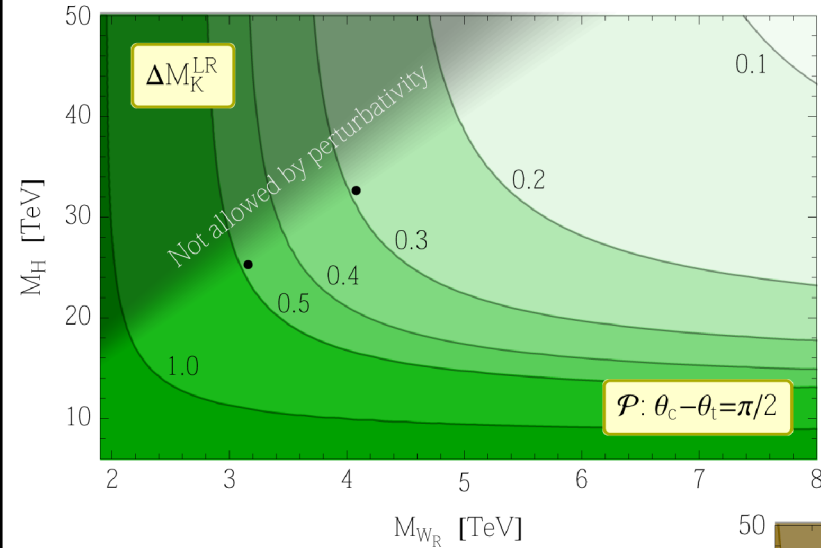
We can fix

$$\sin(\alpha - \theta_u - \theta_d) < 0.5 \times 10^{-3}$$

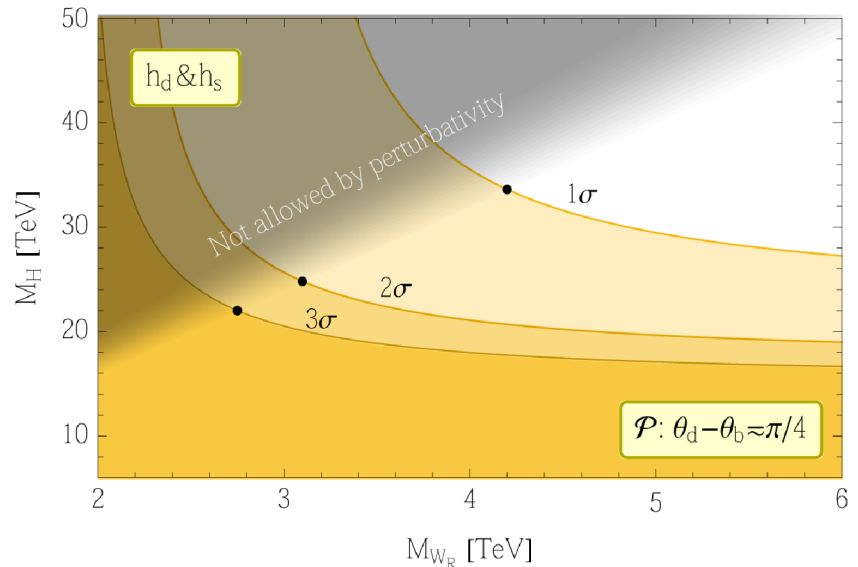
[AM, Nesti, Bertolini, Eeg, 2013
AM, Nesti, Bertolini, 2014]

Combined constraints on LR with P symmetry

In the case of **P** the combined constraints have to be computed all together, while **fitting the quark mass spectrum**, since all the phases depend only on the VEVs parameters α and V_2/V_1 .



[AM, Nesti, Bertolini, 2014]



C

$ h_{d,s}^B $	$ h_m^K $	$\theta_c - \theta_t$	$\theta_d - \theta_s$	$\theta_d - \theta_b$	$M_{W_R}^{min} [\text{TeV}]$
$< 2\sigma$	< 0.5	0	$\simeq 0$	$-0.8 \div 2.4$	3.7
			$\simeq \pi$	$-1.3 \div 1.8$	3.7
		π	$\simeq 0$	$\simeq 1.7$	2.9
			$\simeq \pi$	$\simeq -0.9$	2.9
$< 1\sigma$	< 0.3	0	$\simeq 0$	$-0.2 \div 1.5$	4.9
			$\simeq \pi$	$-0.5 \div 0.8$	4.9
		π	$\simeq 0$	$\simeq 0.5$	3.7
			$\simeq \pi$	$\simeq -0.7$	3.3

P

$ h_{d,s}^B $	$ h_m^K $	$ \theta_c - \theta_t $	$ \theta_d - \theta_s $	$\theta_d - \theta_b$	$M_{W_R}^{min} [\text{TeV}]$
$< 2\sigma$	< 0.5	$\simeq \pi/2$	$\simeq \pi$	$\simeq \pi/4$	3.1 (3.2)
$< 1\sigma$	< 0.3				4.2 (4.1)

Nucleon Electric Dipole Moment: chiral loop

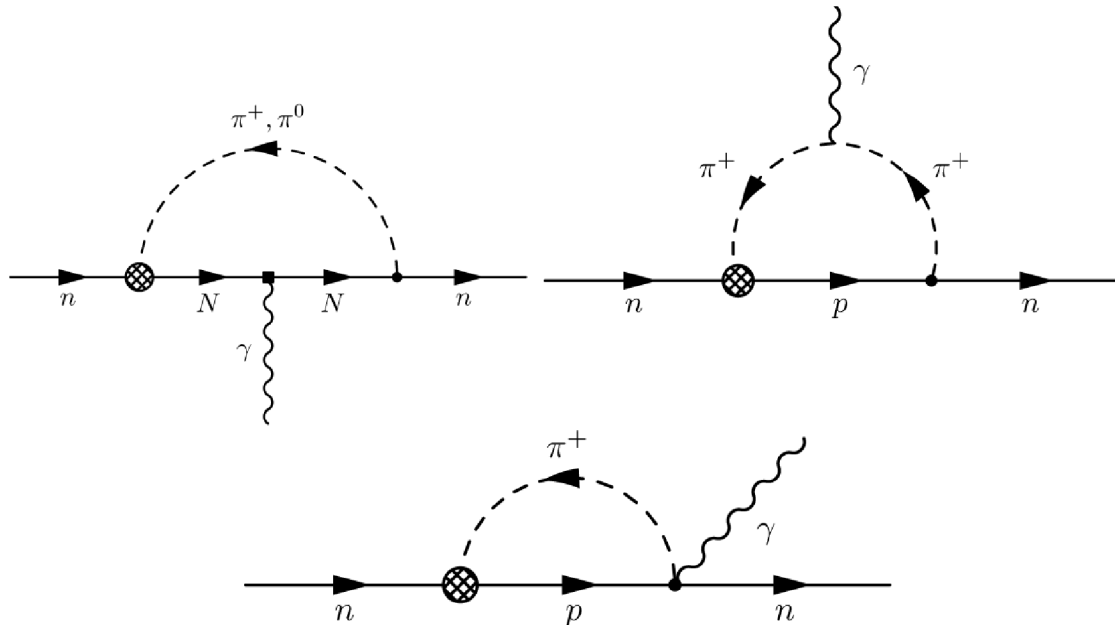
Power-counting

$$D = d - N_N - 2N_\pi + 2kV_\pi^{(k)} + kV_{\pi N}^{(k)}$$

$$D = 1(2)$$

For the nEDM
form factor:
LO(NLO)

[Weinberg, '91]



[AM, Nemevsek, in preparation]

We can get automatically the right power counting in relativistic approach, via **EOMS** (extended-on-mass-shell) renormalization scheme.

Of course this confirms the well known result on theta-bar from nEDM, where there is no problem of power-counting.

[Pich, de Rafael, '91]

Nucleon Electric Dipole Moment: weak source

In addition to $\bar{\theta}$ there are other sources of CP violation, the four-quark operators

$$\begin{aligned} Q_1^{LR} &= (\bar{u}_\alpha d_\beta)_{V-A} (\bar{d}^\beta u^\alpha)_{V+A} \\ Q_2^{LR} &= (\bar{u}d)_{V-A} (\bar{d}u)_{V+A} \end{aligned} \quad + \text{RL ones}$$

$$\mathcal{L}_{B\chi pt}^{C/P} = \bar{g}_+ (\bar{n}\pi^- p + \bar{p}\pi^+ n) + (\bar{g}_n \bar{n}n + \bar{g}_p \bar{p}p) \pi^0$$

$$\bar{g}_+ \ll \bar{g}_n$$

For instance in VSA.

The Wilson coefficients are included.

Usual CP-conserving strong lagrangian

[AM, Nemevsek, in preparation]

$$\mathcal{L}_{B\chi pt}^{(1)} = \bar{N} \left(i\not{D} - m_N + \frac{g_A}{2} \not{p} \gamma_5 \right) N,$$

$$\mathcal{L}_{B\chi pt}^{(2)} = -\frac{e}{4m_N} [\kappa_p \bar{p} \sigma^{\mu\nu} p + \kappa_n \bar{n} \sigma^{\mu\nu} n] F_{\mu\nu}$$

Nucleon Electric Dipole Moment: $\bar{\theta}$

For this issue the choice of **discrete symmetry** is more fundamental and the difference goes beyond the parameterization of the right-handed CKM matrix!

Starting with **P** symmetry.

A restored “**P**” at high scale can be an alternative to PQ symmetry to solve the strong CP problem: it rules out automatically the strong CP-odd term

$G\tilde{G}$

[Berezhiani, Mohapatra, Senjanovic, '93]

$$\bar{\theta} = \arg \det M_u M_d$$

It becomes computable and **depends by the same parameters of the weak contributions** (i.e. α and VEVs ratio.)

[AM, Nemevsek, in preparation]

This contribution in chiral loop is dominant over the weak induced one.
Imposing the stringent constraint from nEDM, while fitting together the quark mass spectrum:

$$\alpha=0 \quad \text{and/or} \quad v_2/v_1=0$$

Leading to the so called “**manifest LR symmetry**” with **$V_L=V_R$** .

Again P vs C

The condition $\mathbf{V}_L=\mathbf{V}_R$ does not match with the previously analysis on **epsilon**.

The absence of external quark phases avoids any useful cancellation between the charm-top and charm-charm contribution.

The bound becomes

$$M_{W_R} > 25 TeV \quad [AM, Nemevsek, in preparation]$$

Leaving “C” as the only LR symmetry available at LHC.

Passing to C symmetry.

Here the PQ symmetry or another mechanism is needed.

The right-handed scale remains in the reach of LHC and some constraint on CP-phases can be fixed from the Wilson coefficients of current-current operators

$$Q_1^{LR} = (\bar{u}_\alpha d_\beta)_{V-A} (\bar{d}^\beta u^\alpha)_{V+A}$$
$$Q_2^{LR} = (\bar{u}d)_{V-A} (\bar{d}u)_{V+A}$$

through nEDM chiral loops.

Again P vs C

It is worth noting that the involved CP-phases are the same of the ones appearing in **epsilon'** .

By using the correct power-counting loop functions for nEDM, the bound on the Wilson coefficients are quite weaker than the ones in previously literature!

A preliminary analysis shows that it does not improve the constraint from epsilon'

$$\sin(\alpha - \theta_u - \theta_d) < 0.5 \times 10^{-3}$$

However an improvement could come from **HgEDM**.
From the **Schiff moment** induced by the current-current operators, it is possible to fix

Following for instance
[Engel,
Ramsey, Musolf, Kolck,
2013]

$$\sin(\alpha - \theta_u - \theta_d) < 8 \times 10^{-5}$$

[AM, Nemevsek, work in progress]

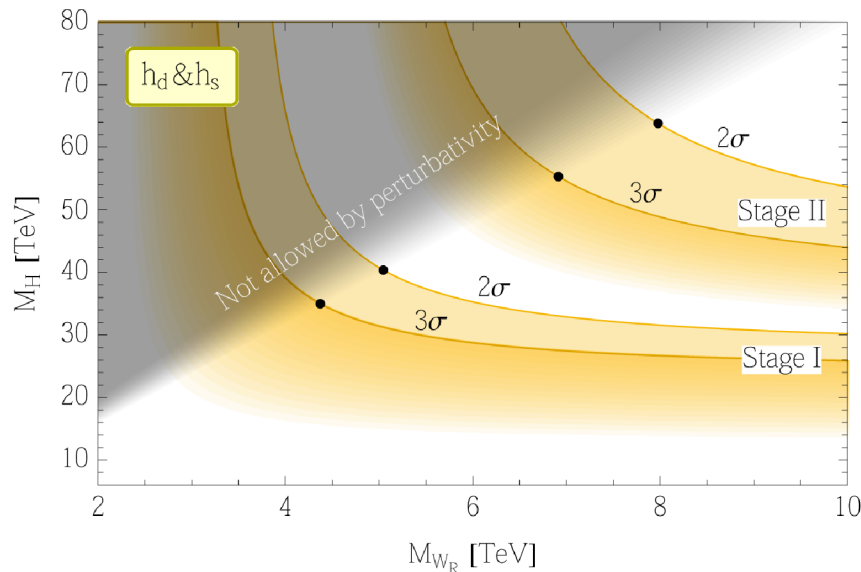
... a look at the future

Pessimistic scenario...

The foreseen data accumulation of LHCb and Belle II in the coming years shall improve on the present sensitivity by a factor of two within the decade and up to a factor of five by mid 2020s.

Assuming that the future data on B_d and B_s mixings will be centered on the SM values. ➡ **No NP**

[Charles, Descotes, Genon, Ligeti, Monteil, Papucci, Trabelsi]



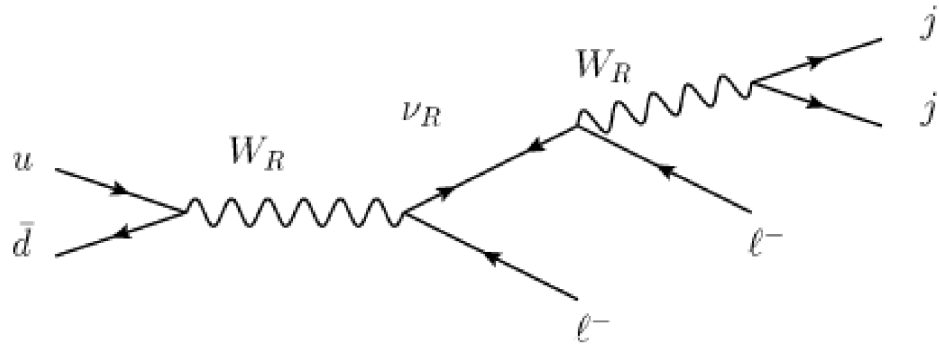
[AM, Bertolini, Nesti, 2014]

...a look at the future

Optimistic...detection at LHC

For instance via this clear signature

Drell-Yan process,
producing *same sign leptons* via a right-handed gauge boson. It is the high energy analogous of neutrinoless double beta decay.



[Keung-Senjanovic '83]

Current direct bound 2-2.9 TeV

[ATLAS]

Sensitivity to W_R is expected to approach the **6 TeV** mass threshold

[Ferrari et al. , 2000]

Gninenko, Kirsanov, Krasnikov, Matveev, 2007]

Outlook

- We had a look at the constraints from both CP-conserving and CP-violating processes, in kaon, B-physics as well as in nucleon (and atomic) dynamics.
- We revisited **P**-symmetry as an alternative to PQ solution of strong CP problem. The combined analysis of epsilon and nEDM rules out the **P** from the current direct search.
- The **C**-symmetry remains as the only choice available at LHC. Thus the right-handed scale is again in the full experimental reach.
- Several constraints were fixed on the free parameters of the model, i.e. on the quark CP-phases.

Thank you!

Some general and interesting references

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from non-minimal LR
model

Some general and interesting references

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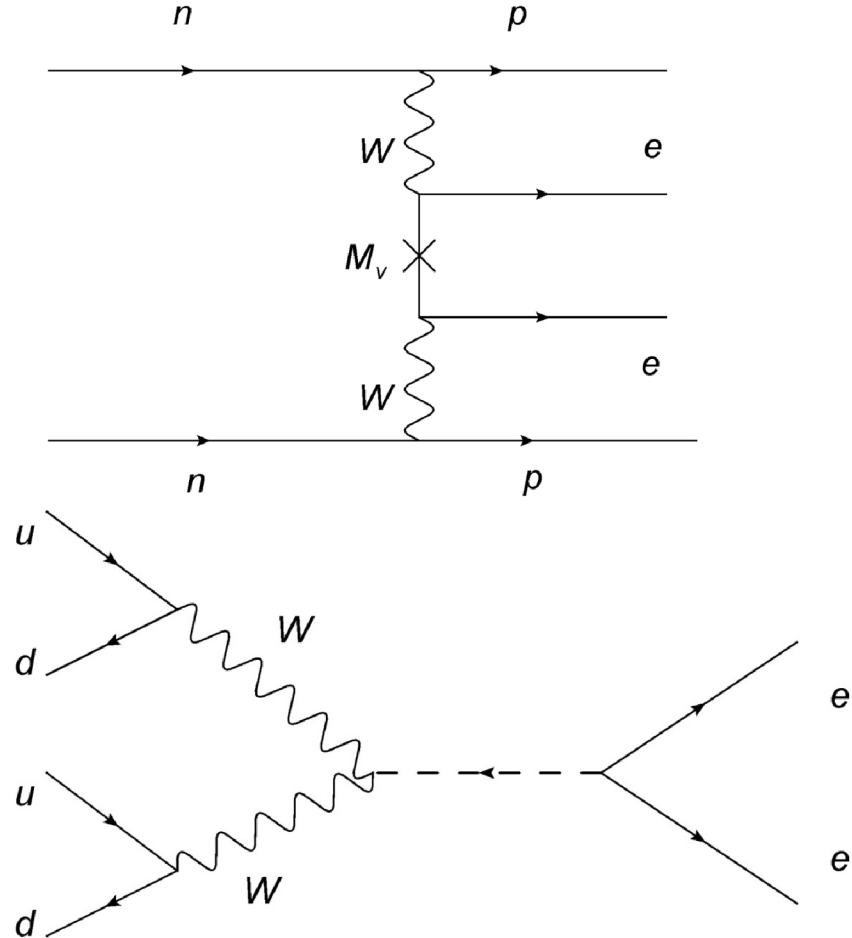
EOMS (extended on mass shell) subtraction

Scalar potential

$$\mathcal{V}(\phi, \Delta_L, \Delta_R)$$

$$\begin{aligned} &= -\mu_1^2 \text{Tr}(\phi^\dagger \phi) - \mu_2^2 [\text{Tr}(\tilde{\phi} \phi^\dagger) + \text{Tr}(\tilde{\phi}^\dagger \phi)] - \mu_3^2 [\text{Tr}(\Delta_L \Delta_L^\dagger) + \text{Tr}(\Delta_R \Delta_R^\dagger)] \\ &\quad + \lambda_1 [\text{Tr}(\phi^\dagger \phi)]^2 + \lambda_2 \{ [\text{Tr}(\tilde{\phi} \phi^\dagger)]^2 + [\text{Tr}(\tilde{\phi}^\dagger \phi)]^2 \} + \lambda_3 \text{Tr}(\tilde{\phi} \phi^\dagger) \text{Tr}(\tilde{\phi}^\dagger \phi) \\ &\quad + \lambda_4 \text{Tr}(\phi^\dagger \phi) [\text{Tr}(\tilde{\phi} \phi^\dagger) + \text{Tr}(\tilde{\phi}^\dagger \phi)] + \rho_1 \{ [\text{Tr}(\Delta_L \Delta_L^\dagger)]^2 + [\text{Tr}(\Delta_R \Delta_R^\dagger)]^2 \} \\ &\quad + \rho_2 [\text{Tr}(\Delta_L \Delta_L) \text{Tr}(\Delta_L^\dagger \Delta_L^\dagger) + \text{Tr}(\Delta_R \Delta_R) \text{Tr}(\Delta_R^\dagger \Delta_R^\dagger)] \\ &\quad + \rho_3 \text{Tr}(\Delta_L \Delta_L^\dagger) \text{Tr}(\Delta_R \Delta_R^\dagger) + \rho_4 [\text{Tr}(\Delta_L \Delta_L) \text{Tr}(\Delta_R^\dagger \Delta_R^\dagger) + \text{Tr}(\Delta_L^\dagger \Delta_L^\dagger) \text{Tr}(\Delta_R \Delta_R)] \\ &\quad + \alpha_1 \text{Tr}(\phi^\dagger \phi) [\text{Tr}(\Delta_L \Delta_L^\dagger) + \text{Tr}(\Delta_R \Delta_R^\dagger)] \\ &\quad + \{ \alpha_2 e^{i\delta_2} [\text{Tr}(\tilde{\phi} \phi^\dagger) \text{Tr}(\Delta_L \Delta_L^\dagger) + \text{Tr}(\tilde{\phi}^\dagger \phi) \text{Tr}(\Delta_R \Delta_R^\dagger)] + \text{h.c.} \} \\ &\quad + \alpha_3 [\text{Tr}(\phi \phi^\dagger \Delta_L \Delta_L^\dagger) + \text{Tr}(\phi^\dagger \phi \Delta_R \Delta_R^\dagger)] + \beta_1 [\text{Tr}(\phi \Delta_R \phi^\dagger \Delta_L^\dagger) + \text{Tr}(\phi^\dagger \Delta_L \phi \Delta_R^\dagger)] \\ &\quad + \beta_2 [\text{Tr}(\tilde{\phi} \Delta_R \phi^\dagger \Delta_L^\dagger) + \text{Tr}(\tilde{\phi}^\dagger \Delta_L \phi \Delta_R^\dagger)] + \beta_3 [\text{Tr}(\phi \Delta_R \tilde{\phi}^\dagger \Delta_L^\dagger) + \text{Tr}(\phi^\dagger \Delta_L \tilde{\phi} \Delta_R^\dagger)] \end{aligned}$$

Neutrinoless double beta decay



Epsilon-prime definition

$$\epsilon' = \frac{i}{\sqrt{2}} \omega \left(\frac{\text{Im}A_2}{\text{Re}A_2} - \frac{\text{Im}A_0}{\text{Re}A_0} \right) \frac{q}{p} e^{i(\delta_2 - \delta_0)}$$

$$0,2 = \textit{Isospin}$$

$$\omega = A_2 / A_0 \cong 22$$

$$q / p \cong 1$$