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Left-right symmetry scale from CP-violating observables

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Outline

- A minimal left-right symmetric model
- Solving for the right-handed quark mixing
- K_L-K_S mixing
- K-decay ε and neutron EDM
- CP-violating in B-decay
- Outlook

Left-right symmetric model (LRSM)

- Based on gauge group $SU_L(2)XSU_R(2)XU_{B-L}(1)$ with parity symmetry at high-energy
- New gauge bosons: W_R & Z'
- Explain the SM hypercharge
  - $Q = I_{3L} + I_{3R} + (B – L)/2$
- Right-handed neutrino ν
  - ν_R (massive neutrinos!)
- Manifest and spontaneous CP violations

A choice of the Higgs sector

- Left and right-handed triplets, Δ_L, Δ_R, breaking the symmetry to the standard model
  - $\langle \Delta_R \rangle = (0, 0, v_R)$ v_R is at least TeV scale
- One Higgs bi-doublet, Φ, generating standard electroweak symmetry breaking

$$\langle \phi \rangle = \begin{pmatrix} \kappa & 0 \\ 0 & \kappa' e^{i\alpha} \end{pmatrix}.$$

  - α is a CP violating phase
  - κ and κ' are electroweak scale vevs

Charged gauge bosons

- The mass of the W_L is close to the SM gauge boson (80 GeV)
- The mass of the W_R is unknown (Tevatron bound > 800 GeV): $M_{W_R} = gv_R$
- They mix

$$W_1 = W_L \cos\zeta + W_R \sin\zeta$$

  - The mixing angle depends on the vevs

$$\tan\zeta = \kappa\kappa'/v_R^2 = M_{W_L}^2/M_{W_R}^2\,\xi, \quad \xi = \kappa'/\kappa$$

Quark currents

- Both *left* and *right-handed* quark currents participate in weak interactions.
- The left-handed quark mixing follows the standard model CKM matrix.
- The right-handed coupling is a new unitary matrix in flavor space (quark-mass eigenstates)
  - 6 CP violating phases
  - 3 rotational angles.
  - $2^5 = 32$ discrete sectors (quark mass signs)

Quark mass matrices

- Quarks obtain masses through Yukawa coupling with Higgs bi-doublet

$$M_u = \kappa h + \kappa' e^{-i\alpha} \tilde{h}$$
$$M_d = \kappa' e^{i\alpha} h + \kappa \tilde{h} \ .$$

  - where *h* and *h*-tilde are hermitian matrices.
- M_u and M_d are general complex matrices and each must be diagonalized with two unitary matrices: Right-handed quark mixing is independent of that of the left-handed quarks.

Special limits

- There are two sources of CP violations
  - Explicit CP violation in quark Yukawa coupling.
  - Spontaneous CP violation (SCPV) in Higgs vev.
- When there is no SCPV, we have the limit of *manifest left-right symmetry*.
- When there is no explicit CPV, we have *pseudo-manifest left right symmetry*.
- In both cases, the right-handed quark mixings are related to the CKM matrix.

Manifest left-right symmetry

- When α=0, there is no SCPV, and the quark mass matrices are hermitian

$$\begin{aligned} M_u &= \kappa h + \kappa' \tilde{h} \\ M_d &= \kappa' h + \kappa \tilde{h} \; . \end{aligned}$$

- Both can be diagonalized by single unitary matrices.
- The right-handed quark mixing is the same as the CKM matrix, except for signs.

Pseudo-manifest LR symmetry

- All CP violation is generated by SCPV.
  - The CP phase in the CKM is also generated from the phase of the vev.
  - Very beautiful idea!
- The quark mass matrices are now complex but symmetric, can be diagonalized by single unitary matrices
- The right-handed quark mixing elements have the same modules as these of the CKM matrix.

A solution in general case (Zhang,An,Ji, Mohapatra, PRD, Nov. 2007, NPB,2008)

- Observation:
  - Because m_t is much large m_b, it is quite possible that there is a strong hierarchy between different vevs, κ and κ' barring fine tuning.
- If so M_u is nearly hermitian, and one can neglect the small κh-tilde term.

$$M_u = U_u \hat{M}_u S U_u^\dagger = \kappa h$$

- Now the equation diagonlizing M_d is

$$e^{i\alpha}\xi \hat{M}_u + \kappa U_u \tilde{h} U_u^\dagger S = V_L \hat{M}_d V_R^\dagger$$

Equation for V_R

- Using the hermiticity condition for *h*-tilde, one has,

$$\hat{M}_d \hat{V}_R^\dagger - \hat{V}_R \hat{M}_d = 2i\xi \sin\alpha \; V_L^\dagger \hat{M}_u S V_L$$

  - Since it is a hermitian matrix eq., it has 9 independent equations, which are sufficient for solving for 9 parameters in V_R
  - Let $\xi = r\, m_b/m_t$, the solution exists only for $r\sin\alpha < 1$

The leading-order solution

- The solution

$$V_R = P_U V P_D$$

$$P_U = \text{diag}(s_u, s_d \exp(2i\theta_2), s_t \exp(2i\theta_3))$$

$$P_D = \text{diag}(s_d \exp(i\theta_1, s_s \exp(-i\theta_2), s_b \exp(-i\theta_3))$$

$$V = \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 e^{-i2\theta_2} \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 e^{2i\theta_2} & 1 \end{pmatrix}$$

CP phases

$$\theta_i = \tilde{s}_i \sin^{-1} \mathrm{Im}\hat{V}_{Rii}.$$

$$\begin{aligned}
\mathrm{Im}\hat{V}_{R11} &= -r\sin\alpha \frac{m_b m_c}{m_d m_t}\lambda^2 \\
&\times \left(s_c + s_t \frac{m_t}{m_c} A^2\lambda^4((1-\rho)^2+\eta^2) \right) \\
\mathrm{Im}\hat{V}_{R22} &= -r\sin\alpha \frac{m_b m_c}{m_s m_t} \left(s_c + s_t \frac{m_t}{m_c} A^2\lambda^4 \right) \\
\mathrm{Im}\hat{V}_{R33} &= -r\sin\alpha\ s_t
\end{aligned}$$

Main features

- The hierarchical structure of the mixing is similar to that of CKM.
- Every element has a significant CP phase (first two families, order λ; third family order 1), all related to the SCPV phase α.
- 32 discrete solutions are manifest.
- From the above solution, one can construct the unknown *h*-tilde and solve M_u more accurately.

Δm_K

K_L-K_S mixing

- The mass difference between K_L-K_S due to weak interaction.
  - $\Delta m_K = 3.5 \text{ X } 10^{-12}$ MeV
- SM contribution
  - Long distance contribution,
    - hard to calculate exactly, order 50%, right sign
  - Short distance contribution
    - from intermediate charm quark. about 1/3 of the contribution, right sign.

LRSM contribution

$$H_{12} = \frac{G_F}{2}\frac{\alpha_{\rm em}}{4\pi\sin^2\theta_W}2\eta\lambda_c^{LR}\lambda_c^{RL}m_c^2 \quad (1$$
$$\times\ [4(1+\ln x_c)+\ln\eta]\ [(\bar{d}s)^2-(\bar{d}\gamma_5 s)^2]+\text{h.c.}$$

- Large!
  - QCD correction, running from W_R scale to 2 GeV, yielding a factor of ~ 1.4
  - Large logarithms $\ln(m_{W_R}{}^2/m_c{}^2)$
  - Large QCD matrix elements

    $\sim (m_K/(m_s+m_d))^2$ $m_s \sim 100$ MeV

The B-factor

- It was calculated in Wilson fermion formulation by UK QCD collaboration (Allton et al. PLB453,30)

  $B_4 = 1.03$

- Recently it has also been calculated in domain-wall fermion formulation by Babich et al

  $B_4 = 0.8$ (hep-lat/0605016)

  and CP-PACS (hep-lat/0610075)

  $B_4 = 0.70$

Constraint on M_{W_R}

- Because of the large hadronic matrix element, the bound on M_{W_R} is very strong.
- The new contribution has an opposite sign.
- The standard criteria is that the new contribution shall be less than the experimental value. This demands the SM contribution is $2\Delta M^{exp}$
- Using this criteria, one finds,

$$M_{W_R} > 2.5 \text{ TeV!}$$

Comparison with previous bounds

- Smaller strange quark mass
- QCD running effects
- In the most general CP-violation scenario.
- If one uses less conservative criteria (new contribution less than ½ of data), one finds 4 TeV

Is there a way to make the constraint relaxed?

- Cancellation from the top quark contribution?
  - Top CKM mixing is too small
- Cancellation from the flavor-changing neutral Higgs contribution
  - They come with the same sign. (mass>15 TeV)
- Smaller right-handed CKM?
  - Already fixed by the model, cannot be adjusted!
- Two bi-doublets? SUSY

K-decay parameter ε

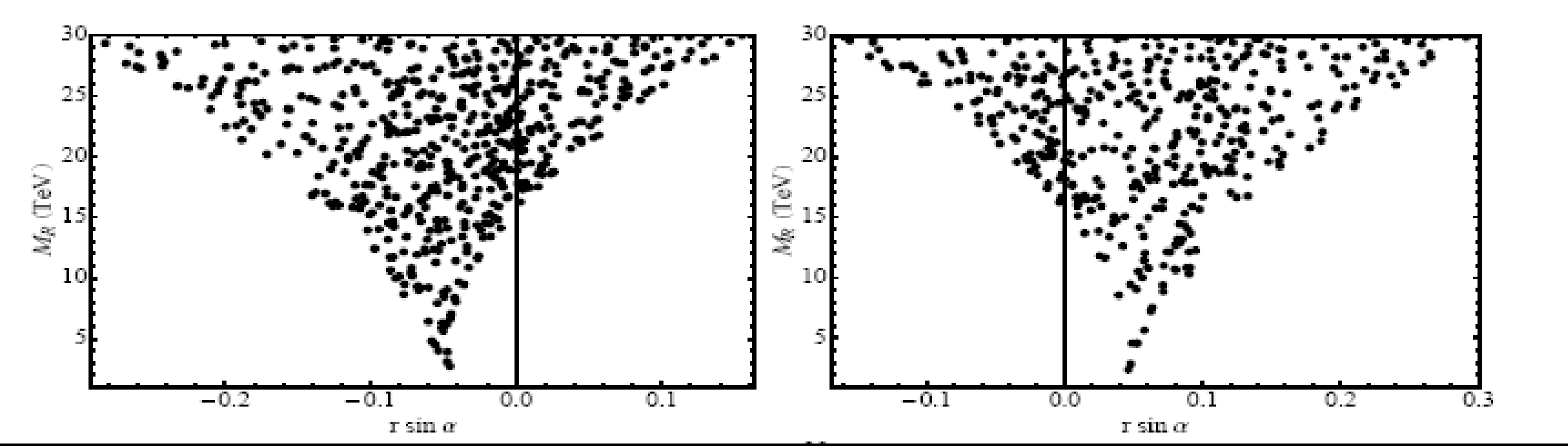
ε: Indirect CP violating in K-decay

- K_L (predominantly CP-odd state) can decay into ππ state (CP-even)
- The decay rate is proportional to $\varepsilon = 3x10^{-3}$
- In SM, ε arises from the box diagram with top-quark intermediate states.
- In LRSM, $W_L W_R$ box diagram provides the additional contribution.

Box contribution

- Dirac phase contribution
  - Large contribution due to enhanced hadronic matrix element
- New SCPV phase contribution
  - Comes from c-quark intermediate state.
- Two contribution must cancel to generate reasonable size: this large fixes the parameter $r\sin\alpha$

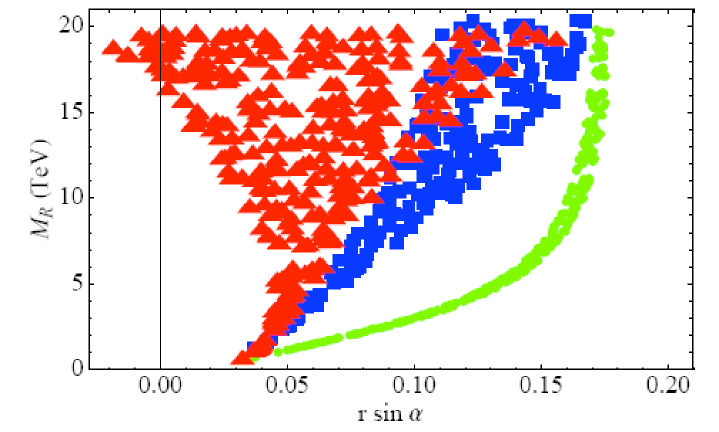
Fixing SCVP angle α



- Effects of flavor changing-neutral Higgs

Blue: M_h = 75 TeV

Red: M_h = 20 TeV



Neutron EDM d_n

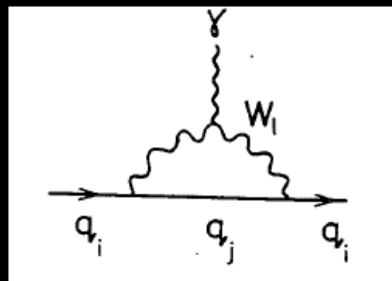
Neutron EDM

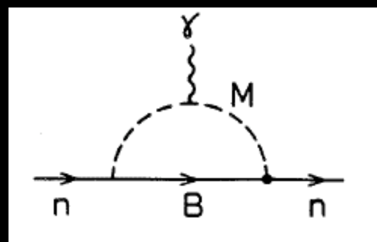
- Current best exp. bound
  $d_n < 3.0 \times 10^{-26}$ e-cm
- A new EDM exp. at LANL
  $d_n < 6.0 \times 10^{-29}$ e-cm, improvement by ~ 500
- Standard Model prediction
  - Second-order weak effect (hadron level 10^{-7})
  - CP phase in s->d channel (10^{-4})
  - $d_n \sim 10^{-32}$ ecm

EMD in LRSM

- First-order effect from
  - W_L & W_R mixing: $W_1 = W_L \sin\zeta + W_R \cos\zeta$
  - Flavor-conserving, CP-odd weak current

- Hadronic uncertainty
  - Single quark EDM
  - Hadron-loop calculation

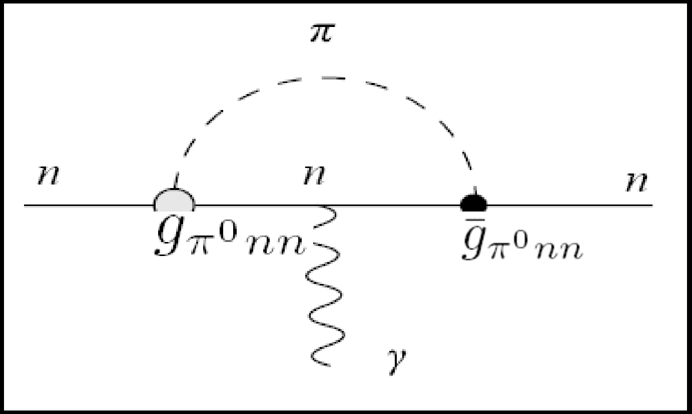




Neutron EDM from the CP-odd 4-quark operators

$$\bar{g}_{\pi^0 nn} = \langle \pi^0 n | \mathscr{L} | n \rangle \propto \langle \pi^0 n | (\bar{u}\gamma_5 u \bar{d} d - \bar{u} u \bar{d} \gamma_5 d) | n \rangle$$

$$\bar{g}_{\pi^0 nn} \simeq 4 \times 10^{-5} \sin\zeta \mathrm{Im}(e^{-i\alpha} V^L_{ud} V^{R*}_{ud})$$

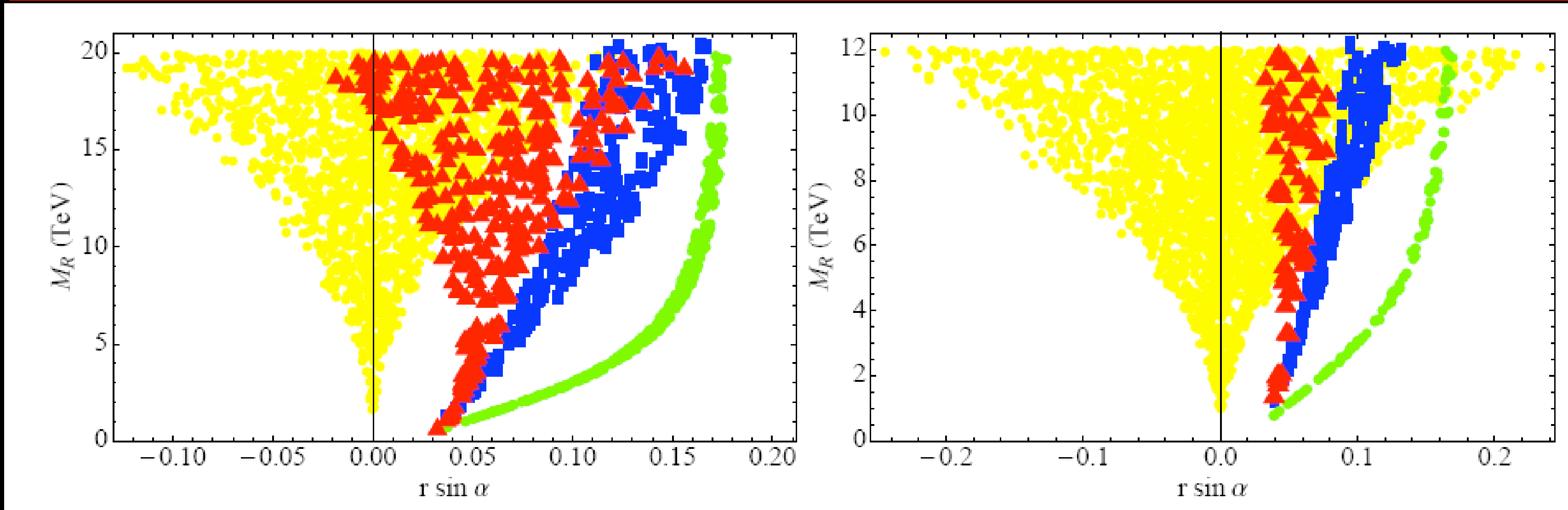


$$d_n = \frac{e\, g_{\pi nn}\, \bar{g}_{\pi nn}}{8\pi^2} \frac{\mu_N}{2m_N} F\left(\frac{m_\pi^2}{m_N^2}\right)$$

$$|d_n^e| \simeq 3 \times 10^{-19} \sin\zeta\ \mathrm{Im}\left(e^{-i\alpha} V^L_{ud} V^{R*}_{ud}\right)\ \ e\mathrm{cm}$$

$$\sin\zeta \approx \frac{\kappa\kappa'}{v_R^2} \approx \frac{M_L^2}{2M_R^2} \frac{m_b}{m_t} r \qquad r \equiv \frac{\kappa'}{\kappa} \frac{m_t}{m_b}$$

Bound on M_{W_R} from EDM



- The bounds from 4-quark operators is about 8 TeV
- If we decrease the hadronic calculation by a factor of 5, the bound becomes 4 TeV.

Additional CP observables

- ε-prime: New four-quark operator contributions to decay
  - Calculation of matrix elements is again difficult
  - Use factorization approximation, one finds a bound of order 4TeV
- B-mixing and B-decay (J/ψ-Ks)
  - Less stringent bound, no chiral enhancement in matrix elements.

Outlook and conclusion

- With the standard Higgs choice, the conservative bound on M_{W_R} on is about 4 TeV.
- Possible lower bound?
  - Add supersymmetry (Zhange et al. **arXiv:0710.1454)**
  - Different Higgs structure
    - Two Higgs doublet
    - Hard to generate fermion mass
- LHC? ILC?

LHC & ILC

- At LHC, RH-W can be searched through 2 lepton+2 jet signals.

  A year running -> bound 3.5 TeV
- At ILC, impossible in direct production

  Asymmetries through virtual production