Spontaneous Parity Violation and Induced Electroweak Symmetry Breaking

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All experiments so far prove the perfect conservation of parity symmetry (P) in both electromagnetic and strong gauge interactions, except that weak force which maximally violates P. A striking fact is that the weak gauge group itself has to be spontaneously broken while both the electromagnetic and color gauge symmetries are exact. We conjecture that there is a deep, intrinsic connection between the P violation in the weak interaction and the electroweak symmetry breaking (EWSB) which gives the observed masses of weak gauge bosons ($W^{\pm}$, Z^0). We construct a generic minimal left-right symmetric model for the spontaneous P violation (SPV) and CP violation (SCPV) where we demonstrate that the SPV must induce the EWSB at the right scale of $O(100)$ GeV as uniquely fixed by the top-quark mass $m_t \simeq 174$ GeV. We realize the natural SPV and SCPV by performing a global minimization of Higgs potential, which generically predicts: (i) a vacuum expectation value v_R, characterizing the scale of SPV and SCPV, is tied to the EWSB scale [$O(100)$ GeV] within one order of magnitude due to the naturalness of Higgs potential; (ii) there are always light Higgs bosons in the mass-range of $O(120-300)$ GeV as enforced by the SPV and SCPV, giving rise to discovery signatures at the LHC and ILC via their gauge interactions with light ($W^{\pm}$, Z^0) as well as their Yukawa interactions with (t, b) quarks.

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Outline

- P Violation and Fermion Mass Generation
- Spontaneous P Violation (SPV) and Induced EWSB
- Incorporating Spontaneous CP Violation (SCPV)
- SPV+SCPV from Global Minimization of Higgs Potential
- FCNC Bounds associated with Light Fermions
- Light Higgs Spectrum Probes SPV+SCPV

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▶ P Violation vs Fermion Mass Generation

- Our Real World turns out to perfectly Conserve Parity (P) in Electromagnetic & Strong Gauge Interactions.

- Vafa-Witten Theorem (1984) asserts:
  NO Spontaneous P Violation (SPV) in Gauge Theories with only Vector Fermions.

- But the Real World Maximally Violates P in Weak Interaction which, however, can only be Consistently described by
  a Spontaneously Broken Gauge Theory.

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- **We observe:** **If there were no Weak Force in nature, All known Fermions could not acquire their Observed Masses.**

- Because E.M. & Strong Forces are exactly Vector-like Gauge Theories, they allow Fermions to have Arbitrarily Large & Gauge-Invariant Dirac Masses, So Large that they should be essentially of the order of nature's Fundamental UV Scale for a Massless Gauge Theory, ie, the Planck Scale $M_{\rm Pl}$.

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▶ P Violation as Protection of Light Fermions

- **Hence, these fermions, if exist at all, must have Decoupled from the Particle Spectrum Long Before we could write down the SM Lagrangian as a Low Energy Effective Theory of the Real World.**
- Conclusion: Without Weak Interaction, the Real World could not contain All the Known Light Fermions (Leptons and Quarks), causing a disaster of no quarks, no nucleons and no electrons, thus no atoms, no molecules, and no life.
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- **Nature seems kind enough in her original making to include the Weak Gauge Force as a fundamental building block, under which All Quarks & Leptons (including Neutrinos) are Protected from having Planck-Scale Masses, because Weak Force discriminates Fermions' Handedness (Chirality) and thus violates P symmetry.**

- **Parity becomes a truly Nontrivial Ingredient of a Fundamental QFT only in the Presence of Fermions.**

- **Lorentz Group** $SO(3,1) \Longrightarrow$ **isomorphic to** $SU(2) \otimes SU(2)$
  Generators: $A_i = \frac{1}{2}(J_i + iK_i)$ **and** $B_i = \frac{1}{2}(J_i - iK_i)$
  Under P transf $\vec{x} \to -\vec{x}$
  $\Longrightarrow \quad J_i \to J_i \quad$ **and** $\quad K_i \to -K_i$,
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- **Under P transformation $\vec{x} \to -\vec{x}$,**

$$\left(\frac{1}{2}, 0\right) \leftrightarrow \left(0, \frac{1}{2}\right) \qquad \Longrightarrow \qquad \psi_R \leftrightarrow \psi_L \,.$$

- **Weak Interaction plays a Key Role to keep all SM Fermions Light and Prevent them from having Huge Planck-Scale Mass-Term, $M_{\rm Pl}\overline{\psi}\psi = M_{\rm Pl}\left(\overline{\psi_L}\psi_R + \overline{\psi_R}\psi_L\right)$, by assigning Left- and Right-handed Fermions under Different Representations of $SU(2)_L$.**
- **However, if Weak Gauge Symmetry $SU(2)_L$ could serve as an Exact (Unbroken) Symmetry of Nature, then All SM Fermions would have to be a bit too light, as they have to Remain Massless.**

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▶ SPV, Fermion Mass & Induced EWSB

- The fact that **All SM Fermions do have Small Masses** requires **EW Gauge Symmetry** be broken – actually be **Spontaneously Broken** for the Consistency with the Renormalizability of a Fundamental Gauge Theory.

- SM does NOT explain Origin of P violation, but merely accepts it as a Low Energy Experimental Fact.
- A Higgs Doublet breaking EW Gauge Symmetry is NOT forced to couple to Fermions at all !!!

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- **We apply the Concept of Spontaneous Symmetry Breaking (SSB) to P Violation, ie, Observed P violation at Low Energies originates from Spontaneous Parity Violation (SPV) at a higher scale, where Weak Force is described by a Fundamental Lagrangian under Minimal P-symmetric Gauge Group $SU(2)_L \otimes SU(2)_R$**

- **For reproduction of unbroken $U(1)_{\rm em}$ at Low Energy, we need an Abelian $U(1)_{B-L}$ as well.**
  $\Longrightarrow$ Full EW Gauge Group before SPV is:

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  (Pati & Salam 1974, Mohapatra & Pati 1974)

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- **A Crucial Observation:**
  (i) Exact P symmetry of original Lagrangian enforces left- and right-handed fermions be embedded into fundamental representations of $SU(2)_L$ and $SU(2)_R$.
  (ii) Exact P symmetry forbids us to make use of any Higgs Doublet to construct Renormalizable Mass-Terms for All SM Fermions.
  $\Longrightarrow$ Essential to introduce at least one Higgs Bidoublet Φ transforming as $(2,\, 2,\, 0)$,

$$\Phi \;=\; \begin{pmatrix} \frac{\phi_1^0}{\sqrt{2}} & \phi_1^\dagger \\ \phi_2^- & \frac{\phi_2^0}{\sqrt{2}} \end{pmatrix}$$

Under P transformation it requires,

$$\Phi \;\to\; \Phi^\dagger\,, \qquad\qquad \widetilde{\Phi} \to \widetilde{\Phi}^\dagger\,.$$

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- **Bidoublet Φ is KEY to form L-R Gauge-Invariant Fermion Mass Terms via Yukawa Interactions**

$$\left(y\,\overline{\psi_L}\Phi\psi_R + \widetilde{y}\,\overline{\psi_L}\widetilde{\Phi}\psi_R\right) + \text{h.c.}$$

Given the Vacuum Expectation Values (VEVs),

$$\langle\Phi\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix} u_1 & 0 \\ 0 & u_2 \end{pmatrix},$$

SM Fermion Acquires a Dirac Mass,

$$\begin{pmatrix} m_{fu} \\ m_{fd} \end{pmatrix} = \frac{1}{\sqrt{2}}\begin{pmatrix} yu_1 + \widetilde{y}u_2 \\ yu_2 + \widetilde{y}u_1 \end{pmatrix}.$$

- **Heaviest SM Fermion is t-Quark with Observed Mass**

$$m_t = \frac{1}{\sqrt{2}}(y_3 u_1 + \widetilde{y}_3 u_2) \simeq 174\,\text{GeV}$$

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We must at least Ensure t-Mass Generation be Natural: Yukawa coupling which gives the major part of t-Mass should be naturally of $O(1)$, Neither Too Large (to Keep Well-defined Perturbative Expansion), Nor Too Small (to Avoid Excessive Fine-Tuning).

- **With EXP Value of m_t as a Unique Input & Requiring the Largest t Yukawa Coupling $\max(y_3, \widetilde{y}_3)$ to be Naturally of $O(1)$, we reach the Unique Conclusion on VEVs of Bidoublet Higgs Φ,**

$$\max(u_1, u_2) = O(m_t) = O(100)\,\mathrm{GeV}.$$

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- Note-1: Any Nonzero VEV of such a Bidoublet Φ must Spontaneously Break EW Gauge Symmetry & thus Generate Certain Nonzero Masses for Light $(W^{\pm},\, Z^0)$ Bosons, because Bidoublt Φ carries $SU(2)_L$ Quantum Number.

- Note-2: Most strikingly, it generates EWSB just at the Right Scale, of $O(m_t) = O(100)$ GeV, as Uniquely Fixed by the Top Mass, the heaviest SM fermion !!!

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▶ SPV vs Induced EWSB: Summary-1

- **In our SPV construction, EWSB is NOT input, but a Derived Output, coming out as an Unavoidable Byproduct of Realizing Top-Mass Generation via P Symmetric Yukawa Interaction.**
- **Scale of SPV, as characterized by VEV $v_R \gtrsim O(\mathrm{TeV})$, is Higher Than EWSB Scale $v = O(100)$ GeV. For P being a Nontrivial Symmetry of a QFT, we must invoke Fermions into Proper Representations of Gauge Group so that Fermion Lagrangian itself has Manifest P Symmetry; this Naturally Protects SM Fermions from getting Dangerous Planck Scale Mass so that they are Generically Light and Non-decoupled from the Low Energy SM Particle Spectrum.**

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- **Fermions can acquire Light Masses only through L-R Symmetric Yukawa Interaction via introduction of Bidoublet Higgs Φ, and EXP Input m_t & Naturalness of t-Yukawa Coupling Uniquely fixed Scale of the Bidoublet VEV, $\langle\Phi\rangle = O(m_t) = O(100)$ GeV.**

- **This fact leads to 2 Striking Outcomes:**

  (i) Any Nonzero VEV of Bidoublet Φ must Spontaneously Break EWSB;

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  The Higgs Sector, Related to Bi-Doublet Φ and Induced EWSB, holds a Best Hope to Test SPV !!

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▶ Generation of Light Fermion Masses

- **We define our model by Coupling Bidoublet Φ only to 3rd Family Quarks for generating Large (t, b) Masses.**

- We introduce a 2nd Heavy Bidoublet Φ' with a Small VEV, $\langle\Phi'\rangle = O(1)$ GeV, generated at a much Higher Scale, at $O(100)$ TeV. Also, Φ' Couples to All 3 Family Fermions to generate All Light Fermion Masses & CKM Mixings. Heavy Φ' decouples at Low Energy.

- Purpose of our Construction is Twofold:
  (i) To Avoid Huge Fine-Tuning of Light Fermion Yukawa Couplings occured in SM.
  (ii) To Avoid Severe Tree-level FCNC Bounds with Light Fermions on the Φ-Sector which must Naturally Stay at $O(100)$GeV Scale for Top-Mass & Induced EWSB.

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▶ Incorporating Spontaneous CP Violation

Consider Higgs Potential $V(\Phi, H_L, H_R)$ or $V(\Phi, \Delta_L, \Delta_R) \Longrightarrow$ Only 2 Independent CP Phases, which can be parametrized into Bidoublet Φ,

$$\langle\Phi\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix} u_1 e^{i\varphi_1} & 0 \\ 0 & u_2 e^{i\varphi_2} \end{pmatrix},$$

$\widetilde{\Phi}$ is charge-conjugate of Φ. Define C-eigenstates fields, $\Phi_\pm = \frac{1}{\sqrt{2}}(\Phi \pm \widetilde{\Phi})$, where Φ_+ (Φ_-) is even (odd) under C.

$$\langle\Phi_\pm\rangle \equiv \frac{1}{2}\begin{pmatrix} u_\pm e^{i\varphi_\pm} & 0 \\ 0 & \pm u_\pm e^{-i\varphi_\pm} \end{pmatrix}$$

where $u_\pm e^{i\varphi_\pm} \equiv u_1 e^{i\varphi_1} \pm u_2 e^{-i\phi_2}$.

▶ SPV & SCPV from Global Minimization

Consider Higgs Potential $V(\Phi, H_L, H_R)$ for example,

$$V(\Phi, H_L, H_R) =$$
$$-\mu_{LR}^2(H_L^\dagger H_L + H_R^\dagger H_R) + \lambda_{LR}\left[(H_L^\dagger H_L)^2 + (H_R^\dagger H_R)^2\right] + \xi_{LR}(H_L^\dagger H_L)(H_R^\dagger H_R)$$
$$-\mu_{ij}^2 Tr(\Phi_i^\dagger \Phi_j) + \alpha_{ijmn} Tr(\Phi_i^\dagger \Phi_j) Tr(\Phi_m^\dagger \Phi_n) + \beta_{ijmn} Tr(\Phi_i^\dagger \Phi_j \Phi_m^\dagger \Phi_n)$$
$$+\lambda_{ij}^a(H_L^\dagger \Phi_i \Phi_j^\dagger H_L + H_R^\dagger \Phi_i^\dagger \Phi_j H_R) + \lambda_{ij}^b(H_L^\dagger H_L + H_R^\dagger H_R) Tr(\Phi_i^\dagger \Phi_j)$$
$$+\sqrt{2}\lambda_i^c(H_L^\dagger \Phi_i H_R + H_R^\dagger \Phi_i^\dagger H_L)$$

Left-Right Symmetry imposes the relations,

$$\mu_{ij}^2 = \mu_{ji}^2\,, \qquad \lambda_{ij}^a = \lambda_{ji}^a\,, \qquad \lambda_{ij}^b = \lambda_{ji}^b\,,$$
$$\alpha_{ijmn} = \alpha_{mnij} = \alpha_{jimn} = \alpha_{ijnm}\,, \qquad \beta_{ijmn} = \beta_{jmni} = \beta_{mnij} = \beta_{nijm}\,,$$

▶ SPV & SCPV from Global Minimization

Impose Extreme Conditions:

$$0 = \frac{\partial V}{\partial v_L} = \frac{\partial V}{\partial v_R} = \frac{\partial V}{\partial u_+} = \frac{\partial V}{\partial u_-} = \frac{\partial V}{\partial \phi_+} = \frac{\partial V}{\partial \phi_-} ,$$

and Require Jacobian being positive-definite
$\Longrightarrow$ **Global Minimum (Physical Vacuum).**

Derive One Important Relation,

$$\lambda^a_{-+} = \frac{16\sin 2(\varphi_- - \varphi_p)u_-^2 u_+^2 \alpha_{-+-+} + \csc(\varphi_- - \varphi_+)\sin\varphi_- \sin\varphi_+ v_L^2 v_R^2(\xi_{LR} - 2\lambda_{LR})}{2\sin(\varphi_- - \varphi_+)u_- u_+(v_L^2 + v_R^2)}$$

For $v_L < O(1)$GeV, it reduces to

$$\lambda^a_{-+} = 16\cos(\varphi_- - \varphi_+)\alpha_{-+-+}\frac{u_- u_+}{v_R^2} \; = \; O\left(\frac{v^2}{v_R^2}\right)$$

▶ Non-Decoupling of SPV Scale v_R

For $v_L < O(1)$GeV, it reduces to

$$\lambda^a_{-+} = 16\cos(\varphi_- - \varphi_+)\alpha_{-+-+}\frac{u_- u_+}{v_R^2} = O\left(\frac{v^2}{v_R^2}\right)$$

▶ **Requiring Fine-Tuning of λ^a_{-+} less than 1% puts Upper Bound on v_R ,**

$$v_R \;<\; O(10)v \;<\; 10\,\mathrm{TeV}$$

★ **Hence, SPV Scale v_R does NOT decouple and leads to**

Generic Light Higgs Spectrum as Manifestion of SPV !

▶ Two Sample Solutions of Minimization

Output-A:

$u_+ = 222\,\mathrm{GeV}, \quad u_- = 126\,\mathrm{GeV}, \quad v_L = .186\,\mathrm{GeV}, \quad v_R = 5.42\,\mathrm{TeV},$

$\varphi_- = 84.7^o, \quad \varphi_+ = 16.4^o;$

$M_{h_0^0} = 148\,\mathrm{GeV}, \quad M_{h_1^0} = 219\,\mathrm{GeV}, \quad M_{h_2^0} = 324\,\mathrm{GeV},$

$M_{h_3^0} = 4.1\,\mathrm{TeV}, \quad M_{h_4^0} = 4.1\,\mathrm{TeV}, \quad M_{h_5^0} = 9.9\,\mathrm{TeV},$

$M_{h^\pm} = 204\,\mathrm{GeV}, \quad M_{H^\pm} = 4.1\,\mathrm{TeV},$

$M_{W0} = 80.4\,\mathrm{GeV}, \; M_{Z0} = 91.8\,\mathrm{GeV}, \; M_{W1} = 1.71\,\mathrm{TeV}, \; M_{Z1} = 2.04\,\mathrm{TeV}.$

and parameter $\rho = \dfrac{M_{W0}^2}{c_W^2 M_{Z0}^2} = 1.0009\,,$

▶ Two Sample Solutions of Minimization

Output-B:

$$u_+ = 222\,\mathrm{GeV}, \quad u_- = 125\,\mathrm{GeV}, \quad v_L = .275\,\mathrm{GeV}, \quad v_R = 3.87\,\mathrm{TeV},$$

$$\varphi_- = 95.5^o, \quad \varphi_+ = 16.4^o;$$

$$M_{h_0^0} = 164\,\mathrm{GeV}, \quad M_{h_1^0} = 210\,\mathrm{GeV}, \quad M_{h_2^0} = 322\,\mathrm{GeV},$$

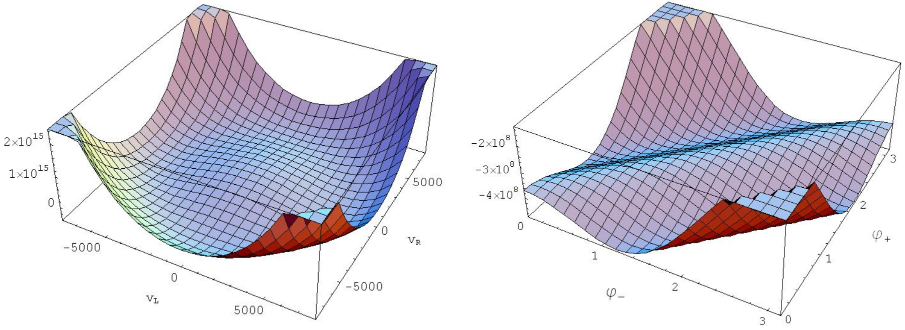
$$M_{h_3^0} = 2.9\,\mathrm{TeV}, \quad M_{h_4^0} = 2.9\,\mathrm{TeV}, \quad M_{h_5^0} = 7.07\,\mathrm{TeV},$$

$$M_{h^\pm} = 204\,\mathrm{GeV}, \quad M_{H^\pm} = 2.9\,\mathrm{TeV},$$

$$M_{W0} = 80.4\,\mathrm{GeV}, \; M_{Z0} = 91.7\,\mathrm{GeV}, \; M_{W1} = 1.2\,\mathrm{TeV}, \; M_{Z1} = 1.5\,\mathrm{TeV}.$$

and the parameter $\rho = \dfrac{M_{W0}^2}{c_W^2 M_{Z0}^2} = 1.00211,$.

▶ Higgs Potential around Global Minimum



FCNC Bounds associated with Light Fermions

- **Tree-Level Higgs induced $\Delta S = 2$ FCNC contribution to $K - \overline{K}$ Mixing on Neutral Higgs Mass in usual One bidoublet LR Model: $M_H < O(10)$ TeV.**
- **Our Φ couples to $(t,\ b)$ only, contribution to ΔM_K is proportional to $V_u^\dagger I_3 V_u$ and $V_d^\dagger I_3 V_d$, with $I_3 = \mathrm{diag}(0,0,1)$.**
- **For $K\bar{K}$, $B\bar{B}$ and $D\bar{D}$ mixing, we have**

$$\begin{aligned}
\sqrt{\Delta M_K(\Phi)} &\propto V_{31}^d V_{32}^d = \theta_{d,31}\theta_{d,23} \\
\sqrt{\Delta M_B(\Phi)} &\propto V_{33}^d V_{31}^d = \theta_{d,31} \\
\sqrt{\Delta M_D(\Phi)} &\propto V_{32}^u V_{31}^u = \theta_{u,23}\theta_{u,31}
\end{aligned}$$

- **Choosing $\theta_{u,23} = \theta_{d,31} = 0$, Φ will NOT contribute to $K\bar{K}$, $B\bar{B}$, $D\bar{D}$ mixing $\Longrightarrow$ There will be No bound on Φ mass!**

Light LR Higgs Sector Probes SPV

★ **Our Higgs boson spectrum always contains:**
(i) One Pair of light $h^{\pm}$ with mass $\sim 200-250$ GeV;
(ii) 3 Light Neutral Higgs with masses $\sim 120-350$ GeV.

These Light Higgs are Manifestation of SPV !!!
Very distinct from SM and MSSM !!!

★ **Discovery Signatures at LHC and ILC:**

▶ **Precision Tests of Light Higgs couplings with $(t,\ b)$ and $(W_0,\ Z_0)$ can Probe Manifestations of SPV at Weak Scale.**

▶ **Typical Collider Processes at LHC & ILC:**

$pp \to W_0^{+*} \to h^+ Z_0^0 \to W_0^+ Z_0^0 Z_0^0, \quad pp \to H^{+*}jj \to W_0^+ Z_0^0 jj$

$e^+e^- \to Z_0^{0*} \to h^+ W_0^- \to W_0^+ Z_0^0 W_0^-$

$e^+e^- \to Z_0^0 h_j^0$ ....

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- Incorporating Spontaneous CP Violation (SCPV)
- SPV+SCPV from Global Minimization of Higgs Potential
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