Fall, 2002

Summer, 2011

H. P. Nilles

# The $\mu$ problem

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Planck 2011
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12. **Completing natural inflation.**
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Published in **JCAP 0501 (2005) 005**
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My collaboration with Peter always questioned physics at the fundamental level.  He is a good friend of mine and a teacher to most young Korean elementary particle physicists. He visited Korea first in the summer of 1984 when (except me) most old Koreans here were students, or babies.

At that beginning period of Korean particle physics, he came and taught his idea on SUGRA effect to electroweak physics and on the SUSY question about SUSY QCD.

Now Korea has taken a giant step toward basic science and we hope to have good particle physics Institutions soon.

1. The weak CP Violation

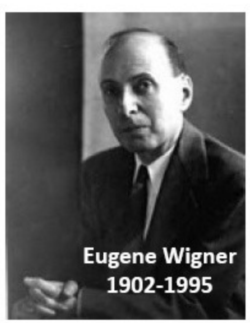
2. The μ problem

3. Is there U(1)' ?

# 1. The weak CP problem

The charge conjugation C and parity P have been known as exact symmetries in atomic physics, i.e. in electromagnetic interactions.


1924: Atomic wave functions are either symmetric or antisymmetric:
Laporte rule




1927: Nature is parity symmetric, Wigner:
Laporte rule = parity symmetric

Quantum mechanics was developed after the atomic rule of Laporte was known. It is based on the

SYMMETRY PRINCIPLE !!!!

In QM, these symmetry operations are represented by unitary operators. For continuous symmetries, we represent them by generators

$$U = e^{i\theta\cdot F}$$

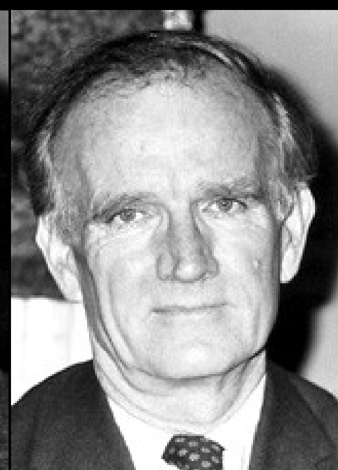
where F is a set of generators.

For discrete symmetries, we use U directly like
P, C, CP, etc.

For the chiral SM, we must mention one most important breakthrough on the road : the “V-A” theory of Marshak-Sudarshan(1957); Feynman-Gell-Mann(1958).

In the SM, the P violation in weak interactions is ultimately given at low energy perspective by the Glashow-Salam-Weinberg chiral model of weak interactions.

CP violation observed in the neutral K-meson system (and now from B-meson system) needed to introduce a CP violation in the SM. It was given by the Kobayashi-Maskawa model.

Since I am in the flavor world now here in Lisboa, let us start with the CKM matrix. It has been written by many since the KM paper,

Kobayashi-Maskawa, Prog. Theor. Phys. 49 (1973) 652
using N. Cabibbo, PRL10 (1963) 531;
Maiani, PLB 62 (1976) 183; Chau-Keung, PRL 53 (1984) 1802

Wolfenstein, PRL 51 (1983) 1945 : Approximate form
Qin-Ma, PLB 695 (2011) 194 : Approximate form
Branco-Lavoura, Phys. Rev. D 38, 2295 (1988);
Buras-Lautenbacher-Ostermaier, Phys. Rev. D 50, 3433 (1994) ;
Xing, PRD 51, 3958 (1995)

Recently, Seo and I wrote an exact CKM matrix replacing the Wolfenstein form. Another complification in lit.? or reaching to the end of the road of writing the CKM matrix?

CP violation books contain basics:

G. C. Branco, L. Lavoura and J. P. Silva,
CP Violation, Int. Ser. Monogr. Phys 103 (1999).

I. I. Bigi and A. I. Sanda, CP violation, Cambridge
Monographs on Particle Phys. and Cosmology (2009)

Still, I would like to repeat the (probably) knowns about the CKM matrix V(CKM):

1. Det. V(CKM) is better to be real !
2. 3x3 V(CKM) is complex to describe CP violation
3. If any among 9 elements is zero, then there is no weak CP violation.
4. $\lambda$ is a good expansion parameter (Wolfenstein) .
5. (31)·(22)·(13) is the barometer of weak CP violation.
6. Eventually, V(CKM) is derivable from the Yukawa texture.

1. Det. V(CKM) is better to be real !

If not, then Arg. Det. $M_q$ is not zero. Usually, we remove this to define a good quark basis. The PQ symmetry? Or calculable models?

KM model has a phase. MCK do not have a phase.

4. $\lambda$ is a good expansion parameter (Wolfenstein) .

$$V_{\rm Wolf} = \begin{pmatrix} 1-\lambda^2/2, & \lambda, & A\lambda^3(\rho - i\eta) \\ -\lambda, & 1-\lambda^2/2, & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta), & -A\lambda^2, & 1 \end{pmatrix} + \mathcal{O}(\lambda^4).$$

We expand in terms of $\theta_1$ since $\theta_2$ and $\theta_3$ are of order $\theta_1^2$.

Satisfying all the requirements, we write an exact CKM matrix,

$$V_{\rm KS} = \begin{pmatrix} c_1 & s_1 c_3 & s_1 s_3 \\ -c_2 s_1 & e^{-i\delta} s_2 s_3 + c_1 c_2 c_3 & -e^{-i\delta} s_2 c_3 + c_1 c_2 s_3 \\ -e^{i\delta} s_1 s_2 & -c_2 s_3 + c_1 s_2 c_3 e^{i\delta} & c_2 c_3 + c_1 s_2 s_3 e^{i\delta} \end{pmatrix}$$

$$\theta_1 = 13.0305^\circ \pm 0.0123^\circ = 0.227426 \pm 2.14 \times 10^{-4},$$
$$\theta_2 = 2.42338^\circ \pm 0.1705^\circ = 0.042296 \pm 2.976 \times 10^{-3},$$
$$\theta_3 = 1.54295^\circ \pm 0.1327^\circ = 0.027567 \pm 2.315 \times 10^{-3},$$
$$\delta = 89.0^\circ \pm 4.4^\circ.$$

← Maximal CP violation

(31)(22)(13) is $-e^{i\delta} s_1^2 s_2 s_3 c_1 c_2 c_3 - s_1^2 s_2^2 s_3^2$

The approximate form is,

$$\begin{pmatrix} 1-\frac{\lambda^2}{2}-\frac{\lambda^4}{8}-\frac{\lambda^6}{16}(1+8\kappa_b^2), & \lambda, & \lambda^3\kappa_b\left(1+\frac{\lambda^2}{3}\right) \\ -\lambda+\frac{\lambda^5}{2}(\kappa_t^2-\kappa_b^2), & \begin{array}{l} 1-\frac{\lambda^2}{2}-\frac{\lambda^4}{8}-\frac{\lambda^6}{16} \\ -\frac{\lambda^4}{2}(\kappa_t^2+\kappa_b^2-2\kappa_b\kappa_t e^{-i\delta}) \\ -\frac{\lambda^6}{12}\left(7\kappa_b^2+\kappa_t^2-8\kappa_t\kappa_b e^{-i\delta}\right) \end{array}, & \begin{array}{l} \lambda^2\left(\kappa_b-\kappa_t e^{-i\delta}\right) \\ -\frac{\lambda^4}{6}(2\kappa_t e^{-i\delta}+\kappa_b) \end{array} \\ -\lambda^3\kappa_t e^{i\delta}\left(1+\frac{\lambda^2}{3}\right), & \begin{array}{l} -\lambda^2\left(\kappa_b-\kappa_t e^{i\delta}\right) \\ -\frac{\lambda^4}{6}(2\kappa_b+\kappa_t e^{i\delta}) \end{array}, & \begin{array}{l} 1-\frac{\lambda^4}{2}(\kappa_t^2+\kappa_b^2-2\kappa_b\kappa_t e^{i\delta}) \\ -\frac{\lambda^6}{6}\left(2[\kappa_b^2+\kappa_t^2]-\kappa_t\kappa_b e^{i\delta}\right) \end{array} \end{pmatrix}$$

$$\lambda = 0.22527 \pm 0.00092,$$
$$\kappa_t = 0.7349 \pm 0.0141, \quad \kappa_b = 0.3833 \pm 0.0388,$$
$$\delta = 89.0^\circ \pm 4.4^\circ$$

$\kappa_b$, or $\kappa_t$ , or $\delta$ being zero washes out the CP violation, in the exact or in the approximate form.

The elements of Det. V(CKM) is,

$$
\begin{aligned}
V_{11}V_{22}V_{33} &= c_1^2c_2^2c_3^2 + c_1^2s_2^2s_3^2 + 2c_1c_2c_3s_2s_3\cos\delta \\
&\qquad - c_1c_2c_3s_1^2s_2s_3e^{i\delta} \\
-V_{11}V_{23}V_{32} &= c_1^2c_2^2s_3^2 + c_1^2s_2^2c_3^2 - 2c_1c_2c_3s_2s_3\cos\delta \\
&\qquad + c_1c_2c_3s_1^2s_2s_3e^{i\delta} \\
V_{12}V_{23}V_{31} &= s_1^2s_2^2c_3^2 - c_1c_2c_3s_1^2s_2s_3e^{i\delta} \\
-V_{12}V_{21}V_{33} &= s_1^2c_2^2c_3^2 + c_1c_2c_3s_1^2s_2s_3e^{i\delta} \\
V_{13}V_{21}V_{32} &= s_1^2c_2^2s_3^2 - c_1c_2c_3s_1^2s_2s_3e^{i\delta} \\
-V_{13}V_{22}V_{31} &= s_1^2s_2^2s_3^2 + c_1c_2c_3s_1^2s_2s_3e^{i\delta}\,.
\end{aligned}
$$

All elements have the same imaginary part, due to our good choice of Det. being real. But, the individual part describes CP violating processes.

# The Jarlskog triangles are

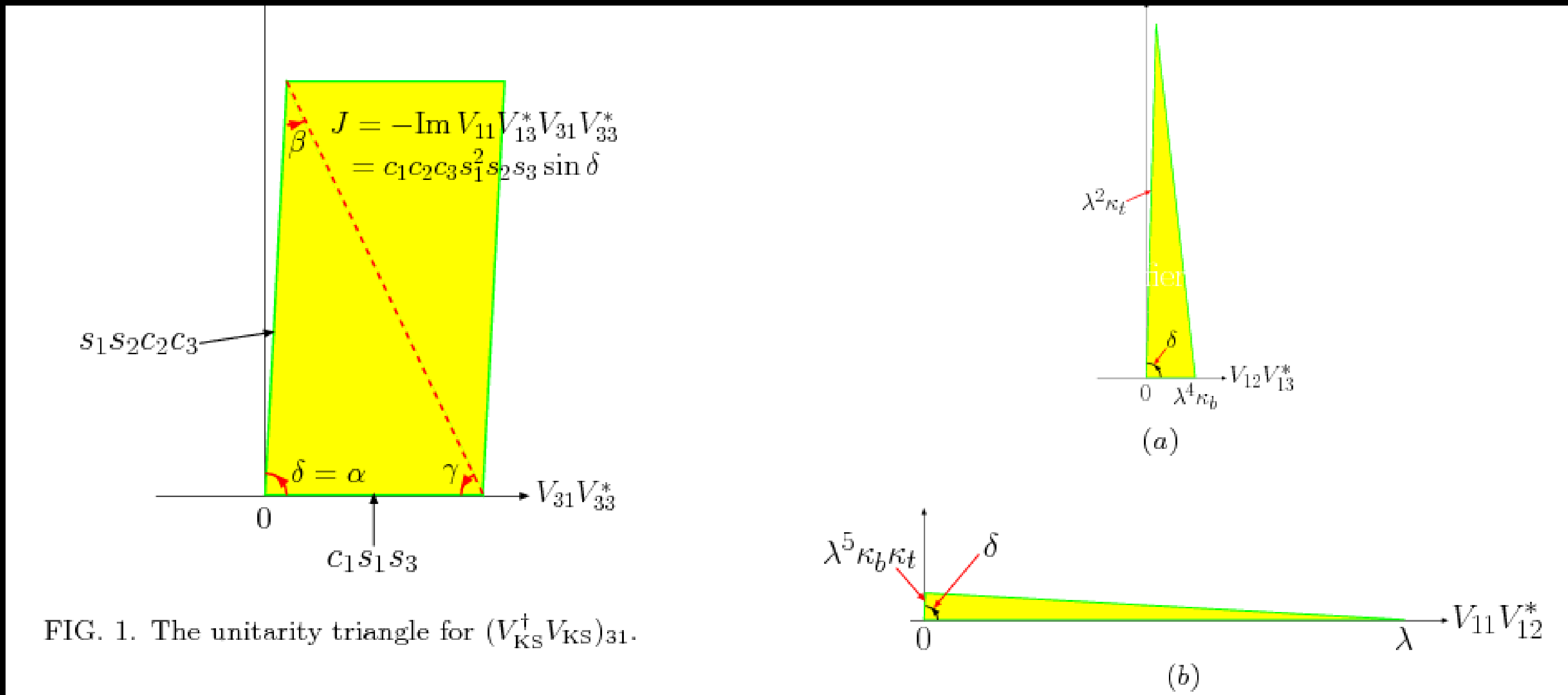



FIG. 1. The unitarity triangle for $(V_{\rm KS}^\dagger V_{\rm KS})_{31}$.

These can be read directly from V(CKM).

Jarlskog removed the real parts by considering a commutator of the weak basis mass matrices.

$$C = -i\left[L^{(u)+} M^{(u)} L^{(u)}, L^{(d)+} M^{(d)} L^{(d)}\right],$$

$$Det.C = i(e^{i\delta} - e^{-i\delta})cs\,\kappa_t \kappa_b \lambda^{12}$$

$$J_{Jkg} = \frac{-Det.C}{2F_c F_s} = \kappa_t \kappa_b \sin\delta$$

$$\frac{M_u}{m_t} = \begin{pmatrix} \lambda^7 u & 0 & 0 \\ 0 & \lambda^4 c & 0 \\ 0 & 0 & 1 \end{pmatrix}, \qquad \frac{M_d}{m_b} = \begin{pmatrix} \lambda^4 d & 0 & 0 \\ 0 & \lambda^2 s & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

# With our exact V(CKM), R=1 and R=L give

$R = \mathbf{1}$,

$$\tilde{M}^{(u)} = \begin{pmatrix} u\lambda^7, & 0, & 0 \\ -c\lambda^5, & c\lambda^4(1+\frac{1}{6}\lambda^2), & c\kappa_t\lambda^6 \\ -\kappa_t e^{i\delta}\lambda^3(1+\frac{1}{3}\lambda^2), & \kappa_t e^{i\delta}\lambda^2(1-\frac{\lambda^2}{6}+[\kappa_b^2-\frac{41}{360}]\lambda^4), & -e^{i\delta}(1-\kappa_t\frac{\lambda^4}{2}-\kappa_t^2\frac{\lambda^6}{3}) \end{pmatrix}$$

$$\tilde{M}^{(d)} = \begin{pmatrix} d\lambda^4(1+\frac{2}{3}\lambda^2), & 0, & 0 \\ 0, & s\lambda^2(1+\frac{\lambda^2}{3}+[\frac{8}{45}+\frac{\kappa_b^2}{2}]\lambda^4), & s\kappa_b e^{i\delta}\lambda^4(1+\frac{2}{3}\lambda^2) \\ 0, & \kappa_b\lambda^2(1+\frac{\lambda^2}{3}+[\frac{8}{45}+\kappa_b^2]\lambda^4), & -e^{i\delta}(1-\kappa_b^2\frac{\lambda^4}{2}-\kappa_b^2\frac{\lambda^6}{3}) \end{pmatrix}.$$

$R = L$,

$$\tilde{M}^{(u)} = \begin{pmatrix} (c+\kappa_t^2\lambda)\lambda^6, & -(c+\kappa_t^2)\lambda^5, & \kappa_t\lambda^3(1+\frac{1}{3}\lambda^2) \\ -(c+\kappa_t^2)\lambda^5, & c\lambda^4(1-\frac{1}{3}\lambda^2), & -\kappa_t\lambda^2+\frac{\kappa_t}{6}\lambda^4+O(\lambda^6) \\ \kappa_t\lambda^3(1+\frac{1}{3}\lambda^2), & -\kappa_t\lambda^2+\frac{\kappa_t}{6}\lambda^4+O(\lambda^6), & 1-\kappa_t^2\frac{\lambda^4}{2}-\kappa_t^2\frac{\lambda^6}{3} \end{pmatrix}$$

$$\tilde{M}^{(d)} = \begin{pmatrix} d\lambda^4(1+\frac{2}{3}\lambda^2), & 0, & 0 \\ 0, & s\lambda^2+(\kappa_b+\frac{s}{3})\lambda^4+(\frac{8}{45}s+\frac{2\kappa_b^2}{3})\lambda^6, & \kappa_b e^{i\delta}(-\lambda^2+(s-\frac{1}{3})\lambda^4)+O(\lambda^6) \\ 0, & \kappa_b e^{-i\delta}(-\lambda^2+[s-\frac{1}{3}]\lambda^4)+O(\lambda^6), & 1-\kappa_b^2\lambda^4+\kappa_b^2(s-\frac{2}{3})\lambda^6 \end{pmatrix}$$

Useful textures to find symmetries behind Yukawa couplings at the fundamental scale.

# For the PMNS, we show one around dodeca,

$$\begin{pmatrix} \frac{1}{2}(\sqrt{3}-\beta-\frac{\sqrt{3}}{2}(1+B^2)\beta^2), & \frac{1}{2}(1+\sqrt{3}\beta-\frac{1}{2}(1+B^2)\beta^2), & B\beta, \\ -\frac{1}{2\sqrt{2}}\begin{matrix}(1+\sqrt{3}(1+Be^{-i\delta})\beta \\ -(A+\frac{1}{2}+Be^{-i\delta})\beta^2)\end{matrix}, & \frac{1}{2\sqrt{2}}\left(\begin{matrix}\sqrt{3}-(1+Be^{-i\delta})\beta \\ -\sqrt{3}(A+\frac{1}{2}+Be^{-i\delta})\beta^2\end{matrix}\right), & \frac{1}{\sqrt{2}}(1+(A-\frac{B^2}{2})\beta^2)e^{-i\delta} \\ \frac{1}{2\sqrt{2}}\left(\begin{matrix}e^{i\delta}+\sqrt{3}(e^{i\delta}-B)\beta \\ +([A-\frac{1}{2}]e^{i\delta}+B)\beta^2\end{matrix}\right), & -\frac{1}{2\sqrt{2}}\left(\begin{matrix}\sqrt{3}e^{i\delta}-[e^{i\delta}-B]\beta \\ +\sqrt{3}([A-\frac{1}{2}]e^{i\delta}+B)\beta^2\end{matrix}\right), & \frac{1}{\sqrt{2}}\left(1-(A+\frac{B^2}{2})\beta^2\right) \end{pmatrix}$$

$$V_{11}V_{22}V_{33} = \frac{1}{8}\left((3-2\sqrt{3}\beta-(2+6A+3B^2)\beta^2)-(\sqrt{3}+2\beta)B\beta\cos\delta-i(\sqrt{3}+2\beta)B\beta\sin\delta\right)$$

$$-V_{11}V_{23}V_{32} = \frac{1}{8}\left((3-2\sqrt{3}\beta-(2-6A+3B^2)\beta^2)+(\sqrt{3}+2\beta)B\beta\cos\delta+i(\sqrt{3}+2\beta)B\beta\sin\delta\right)$$

$$V_{12}V_{23}V_{31} = \frac{1}{8}\left((1+2\sqrt{3}\beta+(2+2A-B^2)\beta^2)-(\sqrt{3}+2\beta)B\beta\cos\delta-i(\sqrt{3}+2\beta)B\beta\sin\delta\right)$$

$$-V_{12}V_{21}V_{33} = \frac{1}{8}[(1+2\sqrt{3}\beta+(2-2A-B^2)\beta^2)+(\sqrt{3}+2\beta)B\beta\cos\delta+i(\sqrt{3}+2\beta)B\beta\sin\delta]$$

$$V_{13}V_{21}V_{32} = \frac{1}{8}\left(4B^2\beta^2-i(\sqrt{3}+2\beta)B\beta\sin\delta\right)$$

$$-V_{13}V_{22}V_{31} = \frac{1}{8}\left(4B^2\beta^2+i(\sqrt{3}+2\beta)B\beta\sin\delta\right)$$

# 2. The μ problem

The good choice of the phases such that Det. V(CKM)=real is related to the PQ symmetry.

The PQ symmetry needs two Higgs doublets or heavy quarks. SUSY, probably most of us here study, needs two Higgs doublets.

With two Higgs doublets, $H_u$ and $H_d$, the PQ does not like to write the following term in W,

In tree superpotential W, no $H_u$ $H_d$

K-Nilles (1984)

This is a serious problem in the MSSM.
Did it serve as the guideline to the MSSM? As Marshak-Sudarshan and Feynman-Gell-Mann to the SM?

The μ problem can be stated in several disguises:

1. The doublet-triplet splitting problem in SUSY GUTs,
2. Is there PQ symmetry?
3. How large is the μ term?
4. The $B_\mu$ problem in the GMSB.
5. Why only 1 pair of Higgs doublets?

To forbid at the GUT scale, PQ or R symmetries are used.

$$W = \mu H_u H_d , \quad \text{forbidden}$$

$$\text{if} \quad X(H_u) = 1, X(H_d) = 1$$

To generate a TeV scale μ is another problem. There are some ways such as,

Nonrenormalizable superpotential helps,

Kim-Nilles (in W)

SUSY breaking scale is used

Giudice-Masiro (Kaehler potential)

In any case, a symmetry in particular the PQ symmetry might be behind this story.

Since the PQ symmetry is good, one can use this

$$W = \frac{S_1 S_2}{M_P} H_u H_d$$

$$\text{if} \quad \begin{array}{l} X(S_1) = -1, X(S_2) = -1, X(H_u) = 1, X(H_d) = 1 \\ \langle S_1 \rangle = \langle S_1 \rangle \approx 10^{10-12}\ \text{GeV} \end{array}$$

Also, an axion solution of the strong CP problem

# Orbifold compactification of heterotic string:

Dixon-Harvey-Vafa-Witten (1986)
Ibanez-Nilles-Quevedo (1987)

1. We used the orbifold idea toward the composite invisible axion solving mu:

   Chun, Kim, Nilles, NPB 370, 105 (1992)

2. Approximate symmetry from orbifold compactification was used to obtain a PQ symmetry:

   K.-S. Choi, I.-W. Kim, Kim, JHEP 0703, 116 (2007) [hep-ph/0612107].

3. Approximate R-symmetry from orbifold compactification was used to obtain a power-law generated mu:

   R. Kappl, H. P. Nilles, S. Ramos-Sanches, M. Ratz, K. Schmidt-Hoberg, P. K.S. Vaudrevange, PRL 102 (2009) 121602 arXiv:0812.2120 [hep-th]

# One pair of Higgs doubets with $SU(3)_W$

Z(12-I) orbifold: [JEK, plb 656, 207 (2007) [arXiv:0707.3292]

The shift vector and Wilson line is taken as

$V = (1/12)(6\ 6\ 6\ 2\ 2\ 2\ 3\ 3)(3\ 3\ 3\ 3\ 3\ 1\ 1\ 1)'$

$a_3 = (1/12)(1\ 1\ 2\ 0\ 0\ 0\ 0\ 0)(0\ 0\ 0\ 0\ 0\ 1\ 1\ -2)'$

Gauge group is

$SU(3)_c \times SU(3)_W \times SU(5)' \times SU(3)' \times U(1)s$

Lee-Weinberg electroweak model and no exotics

| $P+[kV+ka]$ | No.$\times$(Repts.)$_{Y[Q_1,Q_2,Q_3,Q_4,Q_5]}$ | $\Gamma$ | Label |
|---|---|---|---|
| $(\underline{\tfrac{-1}{3}\ \tfrac{-1}{3}\ \tfrac{-2}{3}}\ \underline{\tfrac{2}{3}\ \tfrac{-1}{3}}\ \tfrac{-1}{3}\ 0\ 0)(0^8)'_{T_{4_-}}$ | $3\cdot(\mathbf{3},\mathbf{2})^L_{1/6\ [0,0,0;0,0]}$ | 1 | $q_1,\ q_2,\ q_3$ |
| $(\underline{\tfrac{1}{6}\ \tfrac{1}{6}\ \tfrac{5}{6}}\ \tfrac{1}{6}\ \tfrac{1}{6}\ \tfrac{1}{6}\ \tfrac{1}{2}\ \tfrac{1}{2})(0^8)'_{T_{4_-}}$ | $2\cdot(\overline{\mathbf{3}},\mathbf{1})^L_{-2/3\ [-3,3,2;0,0]}$ | 3 | $u^c,\ c^c$ |
| $(\underline{\tfrac{-1}{3}\ \tfrac{-1}{3}\ \tfrac{-2}{3}}\ \tfrac{1}{3}\ \tfrac{1}{3}\ \tfrac{1}{3}\ \tfrac{-1}{4}\ \tfrac{-1}{4})(\tfrac{1}{4}^5\ \tfrac{1}{12}\ \tfrac{1}{12}\ \tfrac{1}{12})'_{T_{7_+}}$ | $(\overline{\mathbf{3}},\mathbf{1})^L_{-2/3\ [0,6,-1;5,1]}$ | 1 | $t^c$ |
| $(\underline{\tfrac{1}{2}\ \tfrac{1}{2}\ \tfrac{1}{2}}\ \tfrac{-1}{6}\ \tfrac{-1}{6}\ \tfrac{-1}{6}\ 0\ 0)(0^5\ \tfrac{-1}{3}\ \tfrac{-1}{3}\ \tfrac{-1}{3})'_{T_{2_0}}$ | $(\overline{\mathbf{3}},\mathbf{1})^L_{1/3\ [3,-3,0;0,-4]}$ | $-1$ | $d^c$ |
| $(\underline{\tfrac{1}{6}\ \tfrac{1}{6}\ \tfrac{5}{6}}\ \tfrac{1}{6}\ \tfrac{1}{6}\ \tfrac{1}{6}\ \tfrac{-1}{2}\ \tfrac{-1}{2})(0^8)'_{T_{4_-}}$ | $2\cdot(\overline{\mathbf{3}},\mathbf{1})^L_{1/3\ [-3,3,-2;0,0]}$ | 1 | $s^c,\ b^c$ |
| $(\tfrac{-1}{3}\ \tfrac{-1}{3}\ \tfrac{1}{3}\ \underline{\tfrac{2}{3}\ \tfrac{-1}{3}}\ \tfrac{2}{3}\ 0\ 0)(0^8)'_{T_{4_-}}$ | $(\mathbf{1},\mathbf{2})^L_{-1/2\ [-6,6,0;0,0]}$ | 1 | $l_1,l_2,l_3$ |
| $(0\ 0\ 0\ \underline{\tfrac{2}{3}\ \tfrac{-1}{3}}\ \tfrac{2}{3}\ \tfrac{-1}{4}\ \tfrac{-1}{4})(\tfrac{1}{4}^5\ \tfrac{1}{12}\ \tfrac{1}{12}\ \tfrac{1}{12})'_{T_{1_0}}$ | $(\mathbf{1},\mathbf{2})^L_{1/2\ [0,6,-1;5,1]}$ | 0 | $H_u$ |
| $(\tfrac{-1}{3}\ \tfrac{-1}{3}\ \tfrac{1}{3}\ \underline{\tfrac{1}{3}\ \tfrac{-2}{3}}\ \tfrac{1}{3}\ \tfrac{-1}{4}\ \tfrac{-1}{4})(\tfrac{1}{4}^5\ \tfrac{1}{12}\ \tfrac{1}{12}\ \tfrac{1}{12})'_{T_{7_+}}$ | $(\mathbf{1},\mathbf{2})^L_{-1/2\ [-6,0,-1;5,1]}$ | $-2$ | $H_d$ |

The SM spectrum.

Note that $U(1)_\Gamma$ charges of SM fermions are odd and Higgs doublets are even. By breaking by VEVs of even $\Gamma$ singlets, we break $U(1)_\Gamma$ to a discrete matter parity P or Dreiner's matter parity Z6 is realized; dim. 5 operator qqql [Sakai-Yanagida, Hall-Weinberg] is not allowed.

After removing vectorlike representations by $\Gamma$ = even integer singlets, the starred representations remain

| $P+n[V\pm a]$ | $\Gamma$ | $\text{No.}\times(\text{Repts.})_{Y[Q_1,Q_2,Q_3,Q_4,Q_5]}$ |
|---|---|---|
| $(\frac{1}{6}\,\frac{1}{6}\,\frac{-1}{6}\,\frac{1}{6}\,\frac{1}{6}\,\frac{1}{6}\,\frac{1}{4}\,\frac{1}{4})(\underline{\frac{-3}{4}\,\frac{1}{4}\,\frac{1}{4}\,\frac{1}{4}\,\frac{1}{4}}\,\frac{-1}{4}\,\frac{-1}{4}\,\frac{-1}{4})'_{T1_-}$ | 2 | $(1;\bar{5}',1)^L_{0[3,3,1;1,-1]}$ |
| $(\frac{1}{6}\,\frac{1}{6}\,\frac{-1}{6}\,\frac{-1}{6}\,\frac{-1}{6}\,\frac{-1}{6}\,00)(\underline{\frac{1}{2}\,\frac{1}{2}\,\frac{-1}{2}\,\frac{-1}{2}\,\frac{-1}{2}}\,\frac{-1}{6}\,\frac{-1}{6}\,\frac{-1}{6})'_{T2_+}$ | −1 | $\star(1;\mathbf{10}',1)^L_{0[3,-3,0;-2,-2]}$ |
| $(0^6\,\underline{\frac{1}{4}\,\frac{-3}{4}})(\underline{\frac{3}{4}\,\frac{-1}{4}\,\frac{-1}{4}\,\frac{-1}{4}\,\frac{-1}{4}}\,\frac{1}{4}\,\frac{1}{4}\,\frac{1}{4})'_{T3}$ | −1 | $(2_n;5',1)^L_{0[0,0,-1;-1,3]}$ |
| $(0^6\,\underline{\frac{3}{4}\,\frac{-1}{4}})(\underline{\frac{-3}{4}\,\frac{1}{4}\,\frac{1}{4}\,\frac{1}{4}\,\frac{1}{4}}\,\frac{-1}{4}\,\frac{-1}{4}\,\frac{-1}{4})'_{T9}$ | 1 | $(2_n;\bar{5}',1)^L_{0[0,0,1;1,-3]}$ |
| $(0^3\,\frac{-1}{3}\,\frac{-1}{3}\,\frac{-1}{3}\,\frac{1}{4}\,\frac{1}{4})(\underline{\frac{-3}{4}\,\frac{1}{4}\,\frac{1}{4}\,\frac{1}{4}\,\frac{1}{4}}\,\frac{1}{12}\,\frac{1}{12}\,\frac{1}{12})'_{T7_0}$ | −1 | $\star(1;\bar{5}',1)^L_{0[0,-6,1;1,1]}$ |
| $(\frac{1}{6}\,\frac{1}{6}\,\frac{-1}{6}\,\frac{1}{6}\,\frac{1}{6}\,\frac{1}{6}\,\frac{-1}{4}\,\frac{-1}{4})(\underline{\frac{3}{4}\,\frac{-1}{4}\,\frac{-1}{4}\,\frac{-1}{4}\,\frac{-1}{4}}\,\frac{1}{4}\,\frac{1}{4}\,\frac{1}{4})'_{T7_-}$ | 0 | $(1;5',1)^L_{0[3,3,-1;-1,3]}$ |
| $(0^6\,\frac{-1}{2}\,\frac{-1}{2})(\underline{-10000}000)'_{T6}$ | −2 | $3\cdot(1;\bar{5}',1)^L_{0[0,0,-2;-4,0]}$ |
| $(0^6\,\frac{-1}{2}\,\frac{-1}{2})(\underline{10000}000)'_{T6}$ | −2 | $2\cdot(1;5',1)^L_{1[0,0,-2;4,0]}$ |
| $(0^6\,\frac{1}{2}\,\frac{1}{2})(\underline{-10000}000)'_{T6}$ | 2 | $2\cdot(1;\bar{5}',1)^L_{-1[0,0,2;-4,0]}$ |
| $(0^6\,\frac{1}{2}\,\frac{1}{2})(\underline{10000}000)'_{T6}$ | 2 | $3\cdot(1;5,1)^L_{0[0,0,2;4,0]}$ |

The hidden SU(5)’ spectrum.

Note that 10’+5*’ remain.
It leads to a dynamical SUSY breaking.

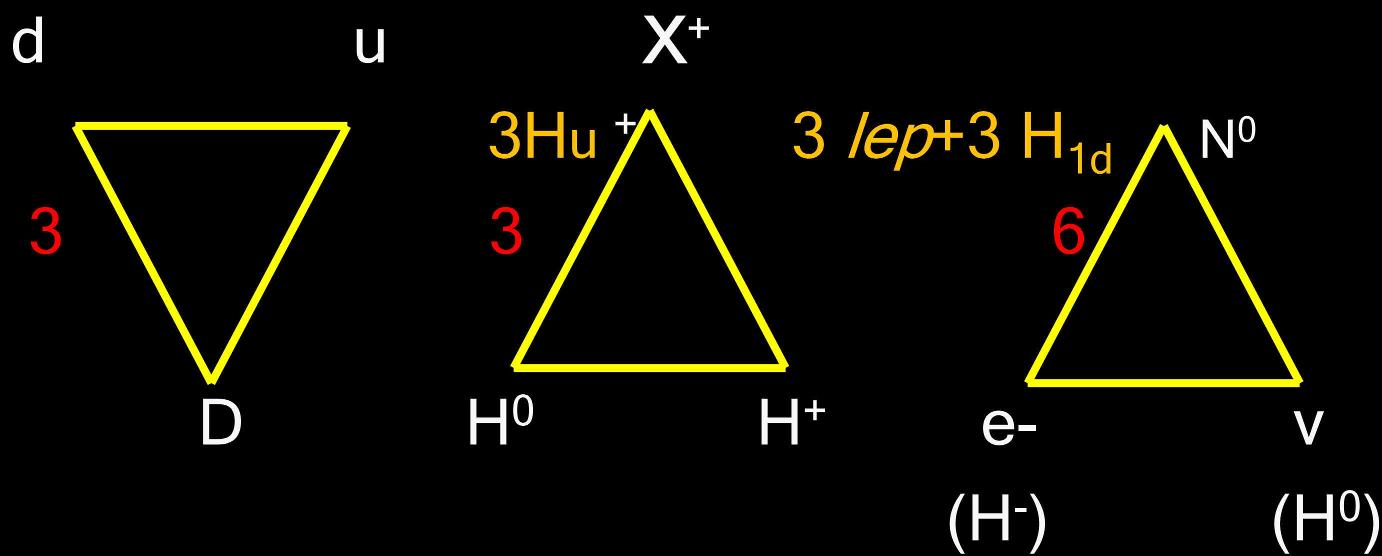
$$SU(3)_c\times SU(3)_W\times SU(2)_N$$
$$\times\, SU(5)'\times SU(3)'$$

Three quark families appear as

$3\,(3_c, 3_W)$

At low energy, we must have nine $3^*_W$ to cancel $SU(3)_W$ anomaly.

Both $H_u$ and $H_d$ appear from $3^*$. It is in contrast to the other cases such as in SU(5) or SO(10). Now, the $H_u$ and $H_d$ coupling must come from $3^*_W\, 3^*_W\, 3^*_W$ coupling.




There remain three pairs of $3^*_W(H^+)$ and $3^*_W(H^-)$ plus three families of $3_W$(quark) and $3^*_W$(lepton)

Thus, there appears the Levi-Civita symbol and two epsilons are appearing, in $SU(3)_W$ space, a, b, c and in flavor space, I, J, ….

Therefore, in the flavor space the $H_u$-$H_d$ mass matrix is antisymmetric and hence its determinant is zero.

It is interesting to compare an old QCD idea and the this SU(3) model:

Introduction of color:

56 of old SU(6) in 1960s = completely symm: $\Omega^-$ = s□s□s□

But spin-half quarks are fermions →

introduce antisymmetric index= SU(3) color [Han-Nambu]

## Introduction of flavor in the Higgs sector:

Lee-Weinberg SU(3)-weak gives

3*-3*-3* SU(3)-weak singlet = antisymmetric gives

antisymmetric bosonic flavor symmetry (SUSY)!

and one pair of Higgs doublets is massless.

We had this in the orbifold compactification.
I never thought of it as a GUT model.

With F-theory, we can talk about GUTs.

# GUT gauge group : SU(6)$_{GUT}$

Flavor unification: JEK, PLB107 (1982) 69

$$
\mathbf{15}_L = \begin{pmatrix} 0 & u^c & -u^c & u & d & D \\ -u^c & 0 & u^c & u & d & D \\ u^c & -u^c & 0 & u & d & D \\ -u & -u & -u & 0 & e^c & H_u^+ \\ -d & -d & -d & -e^c & 0 & H_u^0 \\ -D & -D & -D & -H_u^+ & -H_u^0 & 0 \end{pmatrix},
$$

$$
\overline{\mathbf{6}}_L = \begin{pmatrix} d^c \\ d^c \\ d^c \\ N \\ \nu_e \\ -e \end{pmatrix}, \quad \overline{\mathbf{6}}'_L = \begin{pmatrix} D^c \\ D^c \\ D^c \\ N' \\ H_d^0 \\ -H_d^- \end{pmatrix}.
$$

This GUT contains the previous SU(3)$_W$. So, if we succed in unification with SU(3)$_c$, then the needed flavor symmetry will result. In F-theory, we succeeded.

Note that:

R-parity (or some matter parity) in the MSSM is basically put in by hand:

quarks and leptons are odd, Higgses are even

SO(10) GUT advocates that it has a natural R-parity

matter16 odd, Higgs10 even

But it is nothing but the disparity between spinor-vector difference : Spinor(not in the sense of fermion) and Vector representations:

SSV coupling allowed, but SSS coupling not allowed

$u^c d^c d^c$ : it is the first step

In the KKK Z(12-I) paper, it is stated in generality. $U(1)_X$

Let us see how it works in F-theory.

Heterotic dual F-theory gauge group is expected from breaking $E_8$. $E_8 \to SU(6)\times SU(2)\times SU(3)$ is geometrically written to obtain SU(6): K.-S. Choi+JEK, PRD83, 065016 (2011) [arXiv:1012.0847]

$$y^2 = x^3 + b_{-1}z^6 + b_2 z^3 x + b_2' z^3 y + b_4 z x^2 + b_5 xy$$

$$\begin{aligned} 248 = &(35,1,1) + (1,3,1) + (1,1,8) \\ &+ [\, (15,1,3) + (6^*,2,3) + \text{c.c.} \,] \\ &+ (20,2,1) \end{aligned}$$

The error in the Patera-Sankoff Tables, corrected here.
Slansky is correct

It is equivalent to describe in terms of visible sector group or in the broken perp group. F-theorists prefer the latter, and I prefer the former.

$$SU(6): (\underline{1 \quad -1 \quad 0 \quad 0 \quad 0 \quad 0} \quad 0 \quad 0)$$

$$SU(2): (0 \quad 0 \quad 0 \quad 0 \quad 0 \quad 0 \quad \underline{1 \quad -1})$$

$$\begin{aligned} SU(3): I_\pm &= \pm(0 \quad 0 \quad 0 \quad 0 \quad 0 \quad 0 \quad 1 \quad 1) \\ V_+ &= (- \quad - \quad - \quad - \quad - \quad - \quad + \quad +), \quad \pm \to \pm\frac{1}{2} \\ V_- &= (+ \quad + \quad + \quad + \quad + \quad + \quad - \quad -), \quad \pm \to \pm\frac{1}{2} \\ U_+ &= (- \quad - \quad - \quad - \quad - \quad - \quad - \quad -), \quad \pm \to \pm\frac{1}{2} \\ U_- &= (+ \quad + \quad + \quad + \quad + \quad + \quad + \quad +), \quad \pm \to \pm\frac{1}{2} \end{aligned}$$

# The adjoint 248 of E8 branches under SU(6)xSU(2)xSU(3) as

$248 \to$ (35,1,1) + (1,3,1) + (1,1,8) +(20,2,1)
+ (15,1,3) + (6*,2,3) +c.c. [Corrected PS table]

Adjoints are

$$\mathrm{SU}(6) : (\underline{1\ \bar{1}\ 0\ 0\ 0\ 0}\ 0\ 0);$$
$$\mathrm{SU}(2) : T_{\pm} = (0\ 0\ 0\ 0\ 0\ 0\ \underline{1\ \bar{1}});$$
$$\mathrm{SU}(3)_{\perp} : I_{\pm} = \pm(0\ 0\ 0\ 0\ 0\ 0\ 1\ 1),$$
$$V_{+} = (-^{6} + +),\ V_{-} = (+^{6} - -),$$
$$U_{+} = (-^{6} - -),\ U_{-} = (+^{6} + +),$$

We represented in terms of physicists' matrices.

Matters are

$$(\mathbf{15}, \mathbf{1}, \mathbf{3}) = \begin{cases} (\underline{+ + - - - -}\ - -), (\underline{+ + - - - -}\ + +) \\ (\underline{1\,1\,0\,0\,0\,0}\ 0\,0) \end{cases}$$
$$(\bar{\mathbf{6}}, \mathbf{2}, \mathbf{3}) = \begin{cases} (\underline{\bar{1}\,0\,0\,0\,0\,0}\ \underline{\bar{1}\,0}), (\underline{\bar{1}\,0\,0\,0\,0\,0}\ \underline{1\,0}) \\ (\underline{+ + + + + -}\ \underline{+ -}) \end{cases}$$
$$(\mathbf{20}, \mathbf{2}, \mathbf{1}) = (\underline{+ + + - - -}\ \underline{+ -}). \quad (7)$$

## SU(6)xSU(2)xSU(3): Z6 is the center of SU(6) and hexality is there

$$SU(6): \text{diag. generator}: Y_6$$
$$SU(2): \text{diag. generator}: X_3$$
$$SU(3): \text{diag. generators}: F_3, F_8$$

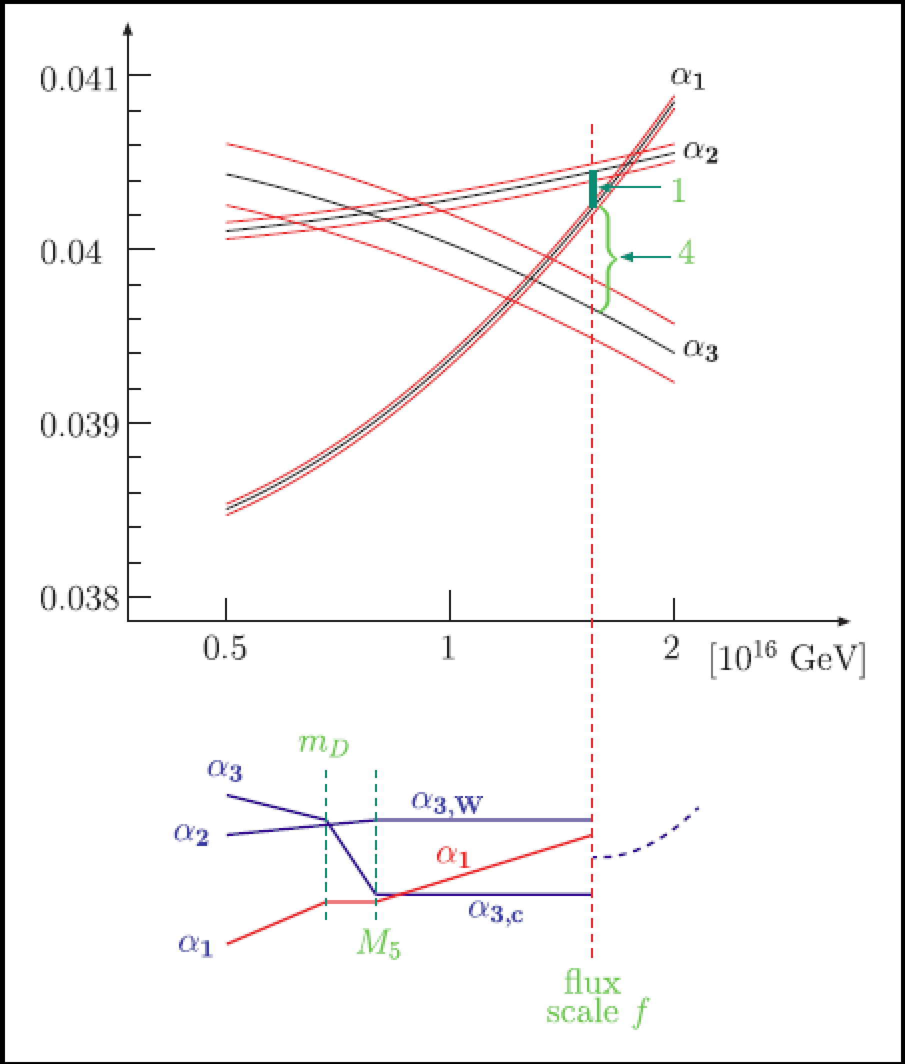
$$F_3 = (0\quad 0\quad 0\quad 0\quad 0\quad 0\quad 1\quad 1)$$
$$F_8 = (-1\quad -1\quad -1\quad -1\quad -1\quad -1\quad 0\quad 0)$$

$$X_3 = (0\quad 0\quad 0\quad 0\quad 0\quad 0\quad -1\quad 1)$$

$$X = -F_8 + X_3$$
$$= (1\quad 1\quad 1\quad 1\quad 1\quad 1\quad -1\quad 1)$$

$\Lambda_8$ touches the 6th component of SU(6). The same SU(6) representation contains two values of X. But SU(5) rep. has the same X.

It is so similar to the Z(12-I) heterotic, I suspect a global model exists for this.




Two-loop running of couplings in F-theory. At low energy, it is almost the same as the standard one, but Z6 is there in the beginning.

# 3. Is there U(1)'?

Kim-Shin, arXiv:1104.5500

"Z' from $SU(6)xSU(2)_h$ GUT, Wjj anomaly and Higgs boson mass bound"

To have Z', it is the one to study. cf,. PS SU(4)xSU(4)

Rank 6 to rank 5. So, one to house Z'. Rank 6 to rank 5.

1. No-go theorem for $U(1)_B$ from $E_6$.

2. If Z' found below 10 TeV, our understanding of the SM from subgroups of $E_6$ is not realized.

   GUTs, SU(5), SO(10), SU(3)xSU(3)xSU(3), SU(6)xSU(2), flipped SU(5) are all out.
   This is independent of SUSY.

# SU(6)xSU(2) model:

JEK and S. Shin, arXiv:1104.5500.

Here we can see directly the gauge quantum numbers

$$\mathbf{15}_L \equiv (\mathbf{15},\mathbf{1}) = \begin{pmatrix} 0 & u^c & -u^c & u & d & D \\ -u^c & 0 & u^c & u & d & D \\ u^c & -u^c & 0 & u & d & D \\ -u & -u & -u & 0 & e^c & H_u^+ \\ -d & -d & -d & -e^c & 0 & H_u^0 \\ -D & -D & -D & -H_u^+ & -H_u^0 & 0 \end{pmatrix},$$

$$\overline{\mathbf{6}}_{\mathbf{2},1} \equiv (\overline{\mathbf{6}},\mathbf{2}^{\uparrow}) = \begin{pmatrix} d^c \\ d^c \\ d^c \\ -\nu_e \\ e \\ N \end{pmatrix}, \quad \overline{\mathbf{6}}_{\mathbf{2},2} \equiv (\overline{\mathbf{6}},\mathbf{2}^{\downarrow}) = \begin{pmatrix} D^c \\ D^c \\ D^c \\ -H_d^0 \\ H_d^- \\ N' \end{pmatrix}. \tag{1}$$

27=
(15,1)
+(6*,2)

For diagonal subgroups of $E_6$, any U(1) generator can be a linear combination of Cartan subgroup of $E_6$. So is in terms of the Cartan subgroup of SU(6)xSU(2). So, we prove in terms of the Cartan subgroup of SU(6)xSU(2).

$$F_3,\ F_8,\ T_3,\ Y,\ Y_6,\ X_3$$

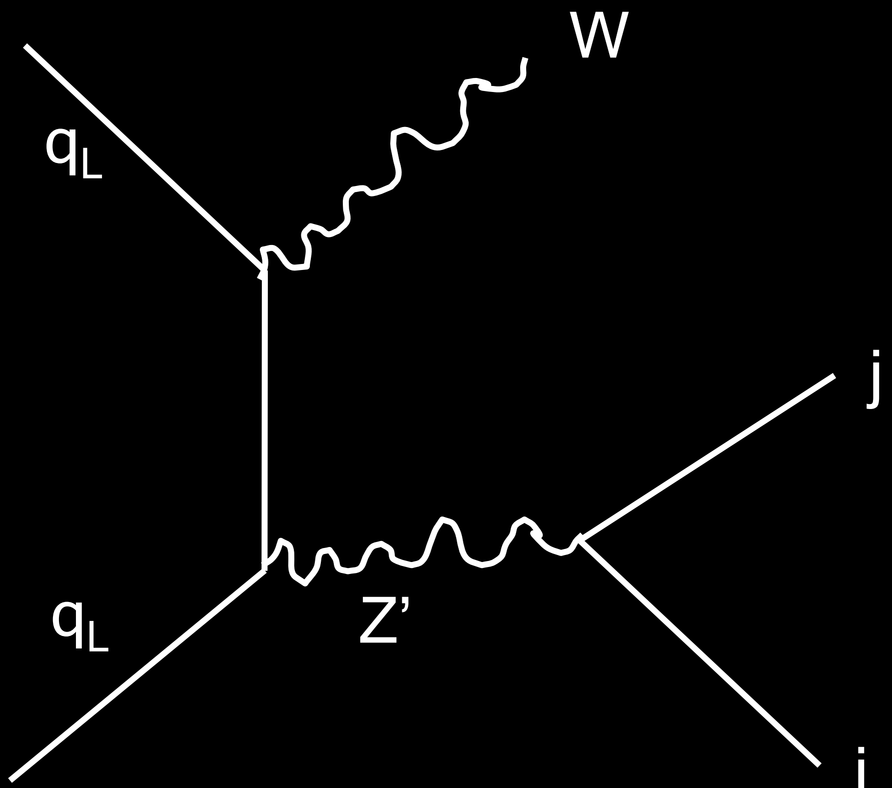
Leptons and Higgs doublets do not carry the baryon number.

$$B = aY + bY_6 + cX_3 + dR$$

$$\begin{aligned}
e^c :&\quad a - \frac{1}{3}b \qquad + (R_{\mathbf{15}} - 1)\, d = 0 \\
(\nu, e) :&\quad -\frac{1}{2}a + \frac{1}{6}b + \frac{1}{2}c + (R_{\overline{\mathbf{6}}} - 1)\, d = 0 \\
H_d :&\quad -\frac{1}{2}a + \frac{1}{6}b - \frac{1}{2}c + R_{\overline{\mathbf{6}}}\, d = 0 \\
H_u :&\quad +\frac{1}{2}a + \frac{2}{3}b \qquad + R_{\mathbf{15}}\, d = 0
\end{aligned}$$

No solution.

The Wjj anomaly may arise from



Still, we studied the Z-Z’ mass in the SU(6)xSU(2) model with fined tuned coupling constants.

So, we consider SU(6)xSU(2)

In this study, we assume of course the lepton coupling to Z’. Then, the LEP2 precision experiment bound on the rho parameter is crucial to constrain the model.

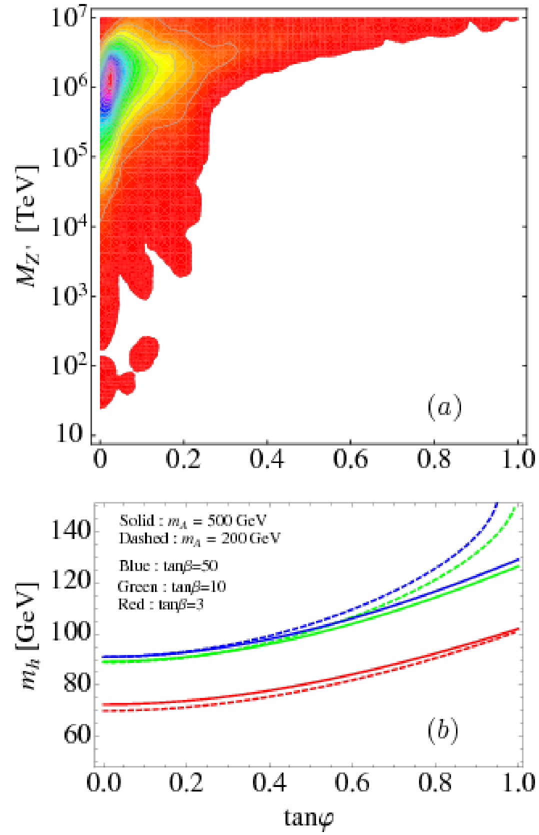



FIG. 1. Masses of $(a)$ $Z'$ and $(b)$ the lightest CP even Higgs $m_h$ as functions of $\tan\varphi$. The total number of data points is 14, 235, and the region with no data points is white. From the red color, the colors are separated by the density of points, increment of ten for each step.

# Conclusion

I enjoyed working with Peter for a long time.  It started with the mu problem. Here, I talked topics around mu paying attention to my recent papers.

1. One pair of Higgs doublets.

2. A final form of CKM matrix.

3. There is no Z' below 10 TeV, otherwise our wisdom to the standard model is in trouble.

Happy 60$^{th}$ birthday again, Peter.