Aspects of Flavour with Vector-Like Quarks

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Plan of the talk

- Recalling the Dogma of massless neutrinos and the analogy between ν_R and vector-like quarks (VLQs)
- How VLQs violate some of the dogmas of the SM in a reasonable way.
- What VLQs can do for you
- Conclusions

The SM is 50 years old!

One may consider that the SM was finally born in 1971, with the discovery of renormalizability of gauge theories by 't Hooft and Veltman.

The "birth" took 10 years (1961-1971)

Glashow paper

why 1971??

What were particle physicists doing in 1968? 3

↓

Consult ICHEP 1968

One of the most exceptional Conferences of all times. Number of Nobel Laureates (either already Nobel or Nobel later) : 19 !!

Nobody was doing "gauge theories"

In spite of the recent flavour anomalies, the development that ruled out the SM, as suggested by Glashow, Salam and Weinberg was the Discovery of neutrino oscillations indicating that at least two neutrinos have non-zero masses.

What is the key message that Nature is telling us so far:

Choose Simplicity!!

Indeed the SM is almost the simplest possibility to put together "charged current interactions and electromagnetism.

Why "Almost"? Recall Lepton-Quark symmetry

The νSM is simpler. By νSM

we mean

$$SM + \nu_R$$

Then "following the rules" one has to include

$$M \, \nu_R^T C \nu_R \rightarrow \text{SSaw mechanism}$$

Marshak's question: Why they put ν_R in their pocket?

Historically there were other motivations

SO(10)

Left-right symmetry...

But Peter Minkowsky was the first one to write the seesaw-formula and forgot about it !!!

Of course, at the moment one does not know whether neutrinos are Dirac or Majorana particles. But if we follow the "Simplicity Principle", neutrino should be Majorana particles

For a long time there was a profound prejudice in favour of massless neutrinos...

This prejudice was "extended" to GUTS ...

The only "reasonable" GUT was SU(5) where one has again massless neutrinos (B-L is an accidental symmetry in SU(5))

- It was "almost forbidden" to talk about SO(10). Recall Gell-Mann's remark at Columbia University...
- Apparently Georgi discovered SO(10) before SU(5), but...

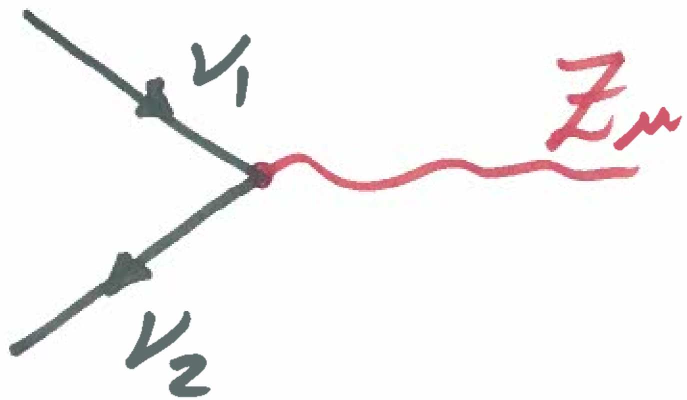
Another related dogma:
There should be no Flavour-Changing Neutral Currents (FCNC) at tree-level, either in the lepton or the quark sectors.
This dogma was extended to the scalar sector: "No scalar mediated FCNC"

↓

This dogma can be "reasonably violated" in the BGL framework –
Scalar FCNC are naturally suppressed by small V_{CKM} elements.
See talks by F. Botella and João Alves.

In the seesaw framework the PMNS matrix is not 3x3 unitary. This leads to violation of the dogma.

Lepton FCNC appear at tree-level but are naturally suppressed.



Vector-like Quarks (VLQs)

VLQs are very similar to ν_R.

Consider an extension of the SM where new quarks of charges $Q = -1/3$ and $Q = 2/3$ are introduced such that the terms

$$\bar{D}_L D_R \text{ and/or } \bar{u}_L u_R \text{ are } SU(2) \times U(1)$$

invariant. The simplest possibility is to assume that the VLQs are isosinglets.

VLQs have in common with ν_R, the fact that a new scale is introduced. This scale can be above the scale of electroweak symmetry breaking!

Like ν_R, VLQs lead to violations of 3x3 unitarity in $V_{CKM}^{3\times 3}$ which in turn lead to Z-mediated FCNC.

Both violations are naturally suppressed.

A crucial Question :

what can VLQs do for you?

Partial list :

(i) They provide a simple alternative solution to the Strong CP problem, without axions.

(ii) They provide the simplest extension of the SM with Spontaneous CP violation in a model consistent with experiment

Multi-Higgs extension are also viable

See talks by F. Botella and J. Alves

By this we mean:

a) Lagrangian should be CP invariant but CP invariance should be broken by the vacuum

b) The ~~vacuum~~ phase should be able to generate a complex CKM phase.

Recall that $\gamma \neq 0, \pi$!!!

(iii) Provide a simple framework where there are New Physics (NP) contributions to $B_d - \bar{B}_d$ mixing, $B_s - \bar{B}_s$ mixing and/or to $D^0 - \bar{D}_0$ mixing as well new contributions to

$$t \to c Z_\mu$$

(iv) May (?) provide a solution to the "Flavour Alignment Problem"

Contrary to the "usual belief" in the SM, there is no reason to have:

$$|V_{us}|^2 + |V_{ub}|^2 \approx \lambda^4 \approx 10^{-3}$$

In the SM (as well as in the νSM) one expects:

$$|V_{us}|^2 + |V_{ub}|^2 \approx O(1)$$

Crucial point: It is easy to prove that in the deep chiral limit ($m_u = m_c = 0$, $m_d = m_s = 0$) V_{tb} is in general $\neq 1$!!

V VLQ's may "populate the Desert" between v and some higher scale (M_{GUT}?) without worsening the hierarchy problem.

To my knowledge, this was first emphasized in a paper by Pierre Ramond "Fermions in the Desert" talk given at Erice

Appears in Spires!!

(vi) VLQs may play an important rôle in providing an explanation for the V^{CKM} unitarity problem:

$$|V_{us}|^2 + |V_{ud}|^2 + |V_{ub}|^2 < 1$$ at the level of 2, 3 standard deviations.

See J. T. Penedo, Pedro Pereira, M. N. Rebelo, J. Silva Marcos, GCB

Details will be explained in this meeting by Pedro Pereira.

See also nice work by Belfatto and Berezhiani

Question: Should we take this "deviation of unitarity" seriously?

My approach was: "When you are not sure, ask a friend who is a specialist."

In this case, we asked "Bill Marciano"

His answer: Yes, it should be taken seriously!


VINHO VERDE

(vii) VLQs provide a simple framework where one can have a common origin of all CP violations:
MN Rebelo, P. Parada, GCB

- CP violation in the quark sector
- CP violation which can be observed in neutrino oscillations
- CP violation needed to generate the observed Baryon Assym. of the Universe through Leptogenesis

L. Bento, P. Parada,
GCB

A simple example

- Consider the SM (or the νSM) with the addition of one $Q = -1/3$ VLQ, denoted D, and a $SU(2) \times U(1)$ singlet scalar S
- Introduce a Z_2 symmetry where all fields of the SM transform trivially, while the new fields D_L, $D_R \equiv d_R^4$ and S are odd

$$\begin{pmatrix} u \\ d \end{pmatrix}_L^i, \quad u_R^i \quad d_R^\alpha, \ D_L, \ \phi, \ S$$

$$i = 1, 2, 3 \ ; \quad \alpha = 1 \ldots 4$$

The $SU(2)\times U(1)\times Z_2$ invariant Yukawa couplings can be written: L. Bento, P. Parada, GCB

$$\mathcal{L}_Y = -\sqrt{2}\,(\bar{u}\ \bar{d})^i_L \left[Y_{d_{ij}}\, d^j_R\, \phi + Y_{u_{ij}}\, \tilde{\phi}\, u^j \right] - M\, \bar{D}_L D_R - \sqrt{2}\left[f_i S + f'_i S^* \right] \bar{D}_L\, d^i_R + \text{h.c.}$$

All couplings are real, so CP is a good symmetry of the Lagrangian.

Without loss of generality one may choose to work in a WB where m_{u} is diagonal

The down quark mass matrix is:

$$\mathcal{M}_d = \begin{bmatrix} m_d & 0 \\ M_D & M \end{bmatrix}$$

$m_d = (Y_d)_{ij} \langle v \rangle \rightarrow$ real

$M_d = \left(f_i V e^{i\alpha} + f_i' V e^{-i\alpha} \right) \rightarrow$ complex

The model provides the minimal implementation of the Barr-Nelson mechanism to obtain $\bar{\theta} = \theta_{QCD} + \theta_{QFD} = 0$ at tree level

M_d is diagonalised by:

$$\mathcal{U}_L \mathcal{M}_d \mathcal{U}_R = \begin{bmatrix} \bar{m} & 0 \\ 0 & \bar{M} \end{bmatrix}$$

$\bar{m} = \text{diag.}(m_d, m_s, m_b)$; $\bar{M}$ – heavy quark mass

$$\mathcal{U}_L = \begin{bmatrix} K & R \\ S & T \end{bmatrix} \quad ; \quad \begin{aligned} KK^\dagger &= 1 - RR^\dagger \\ K^\dagger K &= 1 - S^\dagger S \end{aligned}$$

Using unitarity one can show that:

$$S \simeq - \frac{M_D m_d^\dagger K}{\tilde{M}^2} \left(1 + \frac{\bar{m}^2}{\tilde{M}^2}\right) \qquad R \simeq \frac{m_d M_D^\dagger}{\tilde{M}^2}$$

$$\tilde{M}^2 = (M_D M_D^\dagger + M^2)$$

Using the fact that $\mathcal{U}$ is unitary one can show that K is obtained from:

$$K \, \bar{m}^2 K^{-1} = m_d m_d^\dagger - \frac{m_d M_D^\dagger M_D m_d^\dagger}{M_D M_D^\dagger + M^2}$$

SM contribution

N.P. contribution

Crucial point: If M_D, M are of the same order of magnitude, even if both very large, the N.P. contribution is of the same order as the SM contribution.

- Vector like quarks may have a profound impact in the search for the flavour structure of Yukawa couplings, in a bottom-up approach to flavour.

Conclusions

- We need a "Guiding Principle" in the search for New Physics. A possible principle is "Simplicity". We have argued that the νSM is simpler than the SM and is in agreement with experiment.
- Neutrinos should be Majorana Particles
- VLQs are "cousins" of ν_R and may also violate some of the dogmas of the SM in "a reasonable way"

- VLQs may have a profound effect in the search for the Flavour Structure of Yukawa Couplings in a bottom-up approach to the flavour problem.

- VLQs may be at the reach of the next round of experiments