

Vector-Like Quarks

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Plan of the talk

- **Analogy** between χ_R and vector-like quarks (VLQ)
- How **VLQ** violate some of the **Flavour-dogmas** of the SM in a reasonable way
- What VLQs can do for you
- Conclusions

The SM is 52 years old!! $\lfloor 2$

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 Proceedings

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

But:

Nobody was working on gauge theories!

This illustrates the importance of the work of 't Hooft and Veltman in proving renormalizability of spontaneously broken gauge theories.

This completed the construction of the SM, in 1971.

The SM, as suggested by Glashow, Salam and Weinberg has been ruled out by 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 5
simplest possibility to put together
charged current interactions and electro-
magnetism. Why "Almost"?

The VSM is simpler. By VSM

we mean

$$SM + \nu_R$$

Then "following the rules" one has to
include

$$M \nu_R^T C \nu_R$$

→ Seesaw
mechanism

"Recalling the rules":

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• Write the most general Lagrangians consistent with gauge invariance and renormalizability

Historically, there were other "motivations" to introduce **LR**. $SO(10)$, 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" [7] neutrinos 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 $SU(5)$
($B-L$ is an accidental symmetry in $SU(5)$)

- It was "almost forbidden" to talk about $SO(10)$
Recall Gell-Mann's remark at a talk given at Columbia University.

Another related dogma in Flavour Physics

D_1 : There should be no Flavour-Changing Z mediated Neutral Currents (FCNC) at tree level

either in the quark or lepton sectors.

The dogma was extended to the scalar sector

D_2 : No scalar mediated FCNC at tree level

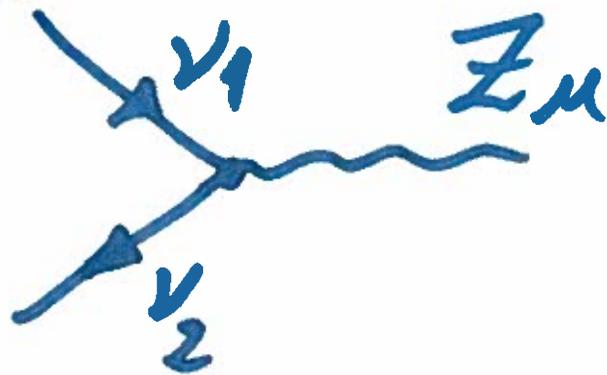
D_1 → violated in the lepton sector by Majorana neutrinos

D_2 → This dogma can be safely violated in BGL models. Botella, Rebelo, GCB

$D_1 \rightarrow$ Can be safely violated in the presence ⁹
of vector-like quarks

In the seesaw framework, the PMNS matrix is not 3×3 unitary. This leads to violation of the dogma D_1 .

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



Vector-Like Quarks (VLQ) ¹⁰

VLQ are analogous to ν_R .

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

$$D_L D_R \text{ and/or } \bar{U}_L U_R \text{ are}$$

The simplest possibility is to assume that VLQ are isosinglets

VLQs have in common with ν_R the fact that a new scale (call it V) is introduced. This scale can be above the scale of electroweak symmetry breaking.

Like ν_R in the leptonic sector, VLQs leads to violations of 3×3 unitarity in $V_{CKM}^{3 \times 3}$ matrix which in turn lead to Z mediated FCNC. Both effects are related and naturally suppressed by $\frac{\nu}{V}$.

A crucial question:

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What can VLQs do for you?

- (i) They provide a simple alternative solution to the Strong CP problem without axions. Barr and Nelson
- (ii) They provide the simplest extension of the SM with ~~Spontaneous~~ CP Violation in a model consistent with experiment.

Requirements to have a viable model of Spontaneous CP Violation:

- Lagrangian should be CP invariant but CP invariance should be broken by the vacuum.

One has to be careful. Often a "geometrical" vacuum phase does not violate CP

- The vacuum phase should be able to generate a complex CKM matrix

Experimentally $\delta \neq 0, \pi$

(iii) Provide a simple framework (14)
where there are New Physics (NP)
contributions to $B_d - \bar{B}_d$ mixing, $B_s - \bar{B}_s$ mixing
and/or $\bar{D}^0 - D^0$ mixing; Also new contri-
butions to

$$t \rightarrow c Z_\mu$$


may receive tree-level contributions
in models with up-type VLQs

IV VLQs may populate the desert 15
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 Spins

V VLQs may play an *important rôle* 16
in providing an explanation for the
VCKM 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,
published in JHEP GCB

See also nice work by Belfatto and
Borzghiani

Question : Should we take this

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"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 !!

VI VLQs provide a simple framework¹¹⁸
where one can have a common origin
of all CP violations: M.N.Rebelo, P.Parada,
GCB

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

A simple example

L. Bento, P. Paradá,
GCB

Consider the SM (or the ν SM) with the 19
addition of a $Q = -1/3$ VLQ, denoted D
and a $SU(2) \times U(1)$ singlet complex scalar
 S . Introduce a \mathbb{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.

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

$$i = 1, 2, 3$$

$$\alpha = 1 \dots 4$$

The $SU(2) \times U(1) \times \mathbb{Z}_2$ invariant Yukawa L20
couplings can be written:

$$\mathcal{L}_Y = -\sqrt{2} (\bar{u} \bar{d})_L^i \left(\gamma_{d_{ij}} d_R^j \phi + \gamma_u u^j \tilde{\phi} \right) - \\ - M \bar{D}_L D_R - \sqrt{2} [f_i S + f_i' S^*] \bar{D}_L d_R^i + \text{h.c.}$$

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_{up} is diagonal.

The down quark mass matrix is:

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$$M_d = \begin{pmatrix} m_d & 0 \\ M_0 & M \end{pmatrix}$$

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

$$M_d = f_i V e^{i\alpha} + f'_i V e^{-i\alpha} \rightarrow \text{complex}$$

The model provides the minimal implementation of the Barr-Nelson mechanism to obtain

$$\bar{\Theta} = \Theta_{\text{QCD}} + \Theta_{\text{QFD}} = 0 \quad \text{at tree level}$$

M_d is diagonalised by:

$$U_L M_d U_R = \begin{bmatrix} \bar{m} & 0 \\ 0 & \bar{M} \end{bmatrix}$$

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

$$U_L = \begin{bmatrix} K R \\ S T \end{bmatrix}$$

$$K K^\dagger = 1 - R R^\dagger$$

$$K^\dagger K = 1 - S^\dagger S$$

Using unitarity one can show that:

$$S \cong - \frac{M_D m_d^\dagger K}{M^2} \left(1 + \frac{\bar{m}^2}{M^2} \right); \quad R \cong \frac{m_d M_D^\dagger}{M^2}$$

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

Using the fact that 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, 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.

Conclusions

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

- VLQs may have a profound effect 25
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.

Drawback: as it is the case of (26)
all suggested models of Beyond SM
physics, one does not know the
mass scale of VLG

- Recall the case of SUSY

No clear-cut mass scale is predicted!!!