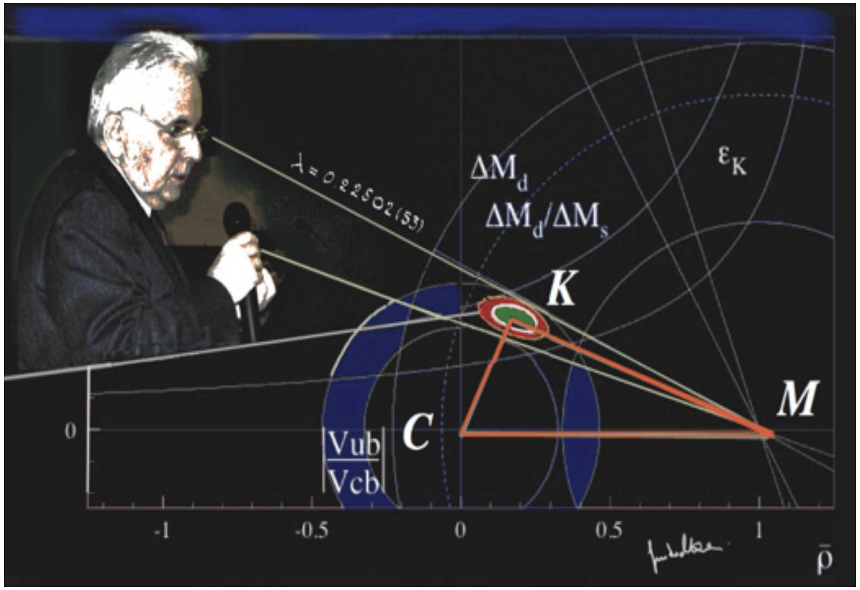

Flavour Physics

Gino Isidori
[*University of Zürich*]

- A bit of history
- The Flavour Problem(s)
- Recent developments
- Conclusions

University of Zurich UZH

European Research Council
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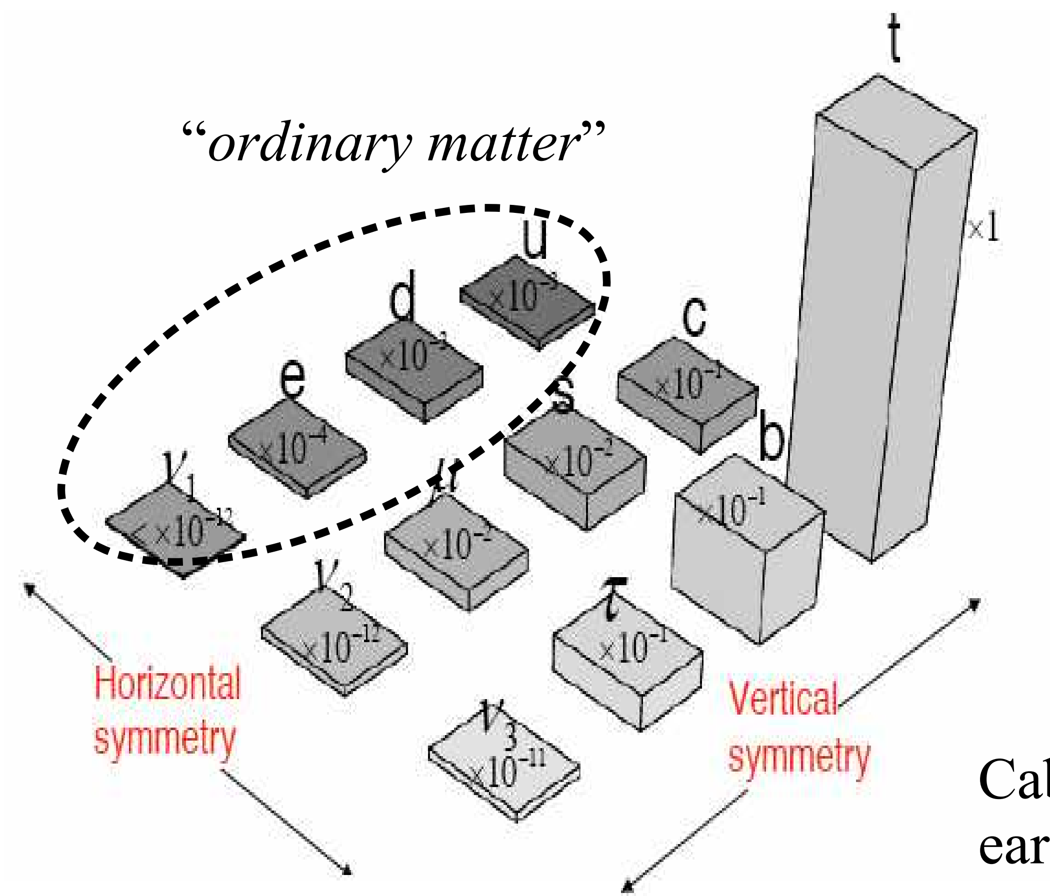
Introduction

The mystery of why we have three generations of quarks and leptons, and what distinguish them, is one of the most old, fascinating and, to a large extent, still open problems in particle physics



Cabibbo's contribution to this field in the early '60 has set the corner-stone of our present understanding of this problem.

As many others, I consider him the "father" of Flavour Physics

Introduction

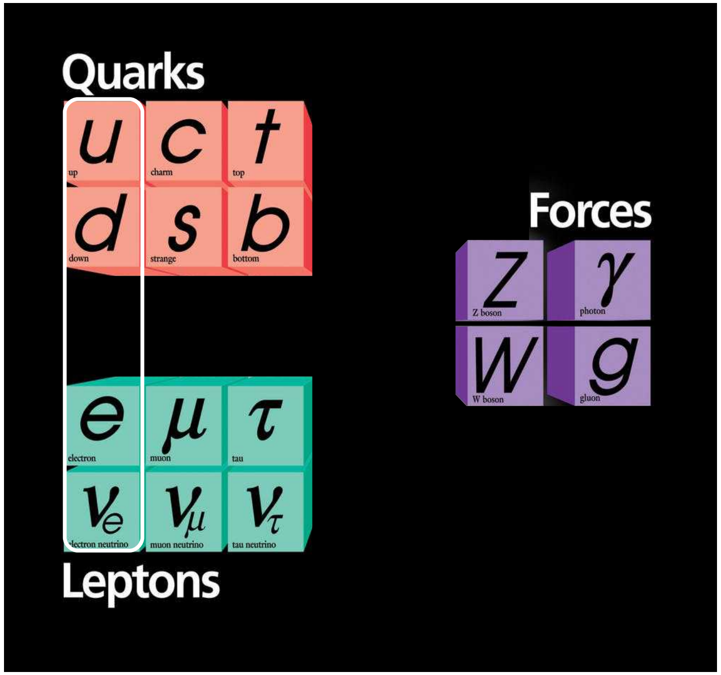
What we now know is that in the Standard Model there is a large flavor symmetry, given the three fundamental forces act in universal way on the three generations

$$\mathscr{L}_{\rm SM} = \mathscr{L}_{\rm gauge} + \mathscr{L}_{\rm Higgs}$$

Three identical replica of the basic fermion family
⇒ huge flavor-degeneracy [= flavor symmetry]

$$\mathscr{L}_{\rm gauge} = \Sigma_a -\frac{1}{4g_a^2}(F_{\mu\nu}^a)^2 + \Sigma_\psi \Sigma_i \bar{\psi}_i i\not{D}\psi_i$$

Sum of i=1…3



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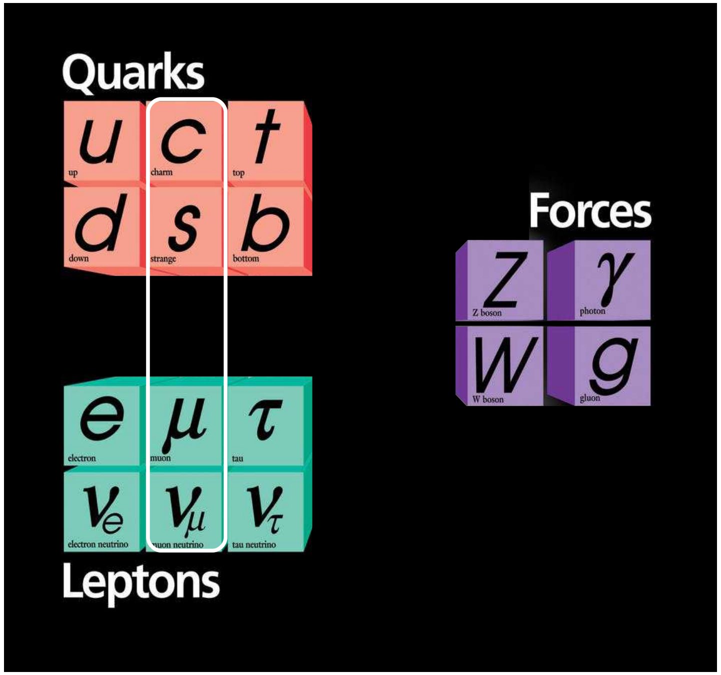

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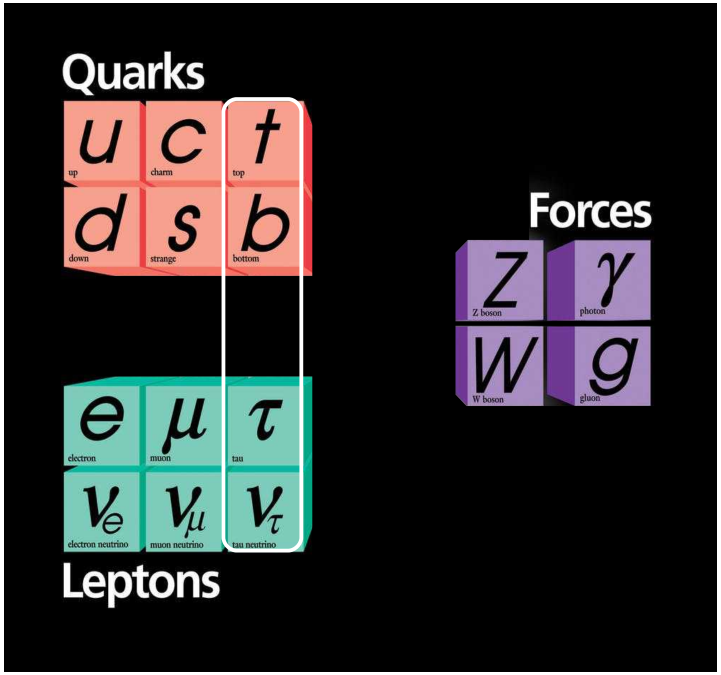

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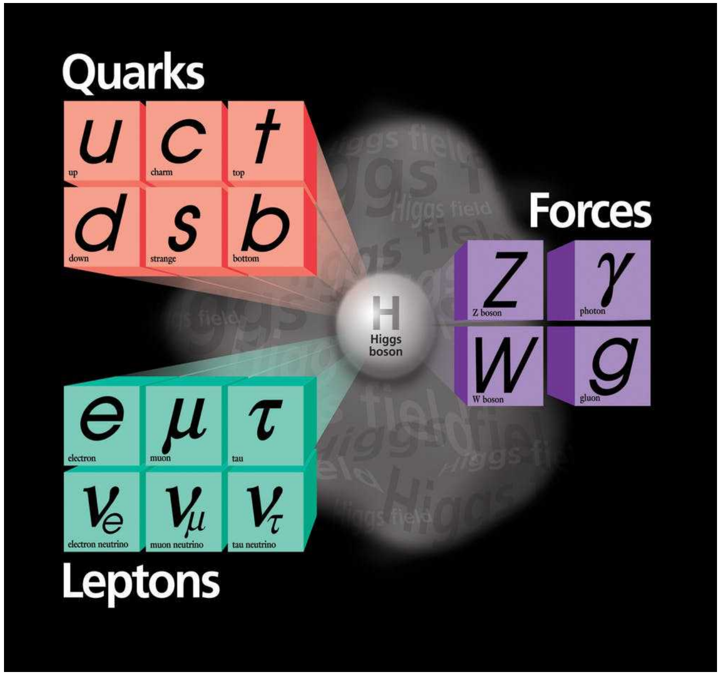

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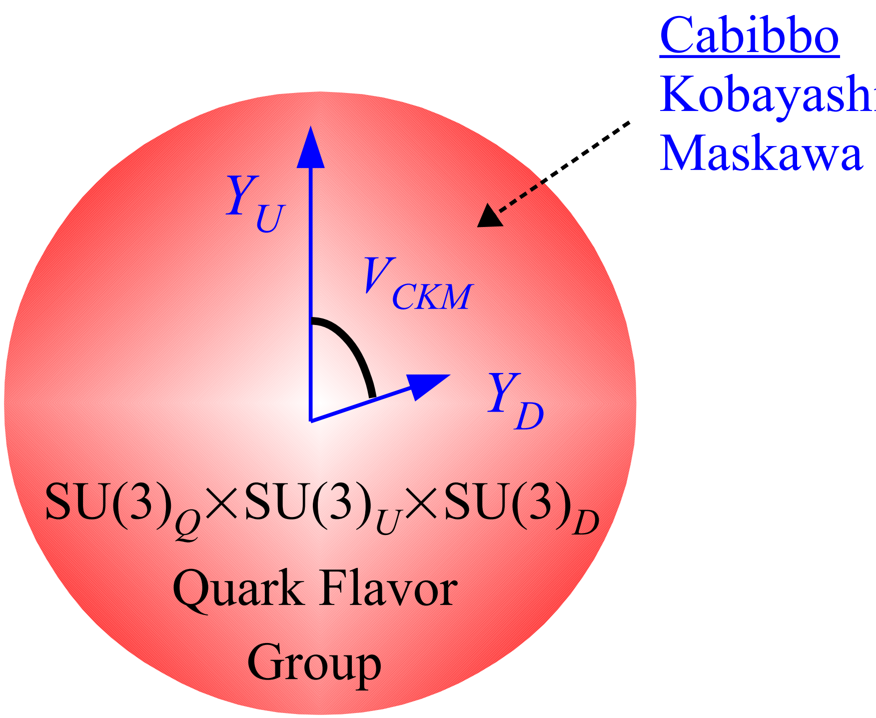

A bit of history

All this seems "quite obvious" these days, but it was highly non-trivial 60 years ago, when there was no electroweak theory, no quark model, no charm...

When the "particle physics zoo" was confined to a few light and strange hadrons.

I was not there at that time... but I think I got an idea of what happened hearing the story from Nicola and others, and I always find it *very inspiring* (*as my young collaborator know..*)

So, I cannot resit to recall here a few basic points, using the slides that Cabibbo presented at the CKM conference in 2008

[→ more in the talks by Luciano Maiani & Luca Silvestrini]

The First Problem

[Feynman & Gell-Mann – Phys. Rev. 109, 1958]

From the Feynman — Gell-Mann paper...

To account for all observed strange particle decays it is sufficient to add to the current a term like $(\bar{p}\Lambda^0)$, $(\bar{p}\Sigma^0)$, or $(\overline{\Sigma^-}n)$, in which strangeness is increased by one as charge is increased by one. For instance, $(\bar{p}\Lambda^0)$ gives us the couplings $(\bar{p}\Lambda^0)(\bar{e}\nu)$, $(\bar{p}\Lambda^0)(\bar{\mu}\nu)$, and $(\bar{p}\Lambda^0)(\bar{n}p)$. A direct consequence of the coupling $(\bar{p}\Lambda^0)(\bar{e}\nu)$ would be the reaction

$$\Lambda^0 \rightarrow p + e + \bar{\nu} \tag{14}$$

at a rate 5.3×10^7 sec^{-1}, assuming no renormalization of the constants.[18] ..... we should observe process (14) in about 1.6% of the disintegrations. This is not excluded by experiments. If a term like $(\Sigma^- n)$ appears, the decay $\Sigma^- \rightarrow n + e^- + \nu$ is possible at a predicted rate 3.5×10^8 sec^{-1} and should occur .....
... in about 5.6% of the disintegrations of the Σ^-.

Around 1962 it became clear than these rates were $\approx$ 20 times smaller!

The Second Problem

[Berman – Phys. Rev. 112, 1958]

The radiative corrections tended to worsen the disagreement between the Fermi constant as measured in beta decay and in muon decay, making it serious.

The result decreases the universal coupling constant obtained from O^{14} to $G=(1.37\pm0.02)\times10^{-49}$ erg cm^3 and increases the value of the predicted value of the muon lifetime from the value given above to $(2.33\pm0.05)\times10^{-6}$ sec, while the experimental value is $(2.22\pm0.02)\times10^{-6}$ sec. The disagreement between experiment and theory appears to be outside of the limit of experimental error and might be regarded as an indication of the lack of universality even by the strangeness-conserving part of the vector interaction. However, it is very difficult to understand the mechanism for such a slight deviation from universality; that is, if universality is to be broken at all why should it be by such a small amount?

Taking muon decay as the standard we have beta decay a few % weaker and hyperon semileptonic decays about 20 times weaker.

The Second Problem

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It is all about
universality
& non-universality

keep this in mind for the rest of the talk...!

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Those days Cabibbo was at CERN, and was very interested in weak decays, both from a theoretical perspective...

The Eightfold Way

In 1962 R. Gatto and I proposed that weak currents be classified in an SU(3) octet. This made the puzzle worse: the weakness of semileptonic $\Delta S = 1$ could not be a renormalization effect.

N.B.: before this work several people claimed that the weakness of ΔS=1 processes could be attributed to strong interactions

Those days Cabibbo was at CERN, and was very interested in weak decays, both from a theoretical perspective... as well as on more phenomenological aspects...

CERN – winter 1962-63

TEST OF THE CONSERVED VECTOR CURRENT HYPOTHESIS IN $\Sigma^{\pm} \to \Lambda^0$ LEPTONIC DECAYS

N. CABIBBO and P. FRANZINI *
CERN, Geneva

Received 13 December 1962

It has been proposed [1,2] that the decay processes

$$\Sigma^- \to \Lambda^0 + e^- + \bar{\nu} , \quad (1a)$$

$$\Sigma^+ \to \Lambda^0 + e^+ + \nu \quad (1b)$$

could provide a test of the conserved vector current hypothesis [3].

In the present work we show how such a test can be performed through the combined measurement of the branching ratio for the above decays, the average Λ^0 polarisation from unpolarised Σ's ** and the Λ^0 hyperon spectrum. The matrix element for process (1a) can be written as

form factors; for the case of even $\Sigma\Lambda$ parity we have

$$(2\pi)^3 \langle \Lambda^0 | J_\mu^V | \Sigma^- \rangle = \bar{u}^{\Lambda^0} [a(q^2)\gamma_\mu + b(q^2)\sigma_{\mu\nu}q_\nu + b'(q^2)q_\mu] u^{\Sigma^-} , \quad (3)$$

$$(2\pi)^3 \langle \Lambda^0 | J_\mu^A | \Sigma^- \rangle = \bar{u}^{\Lambda^0} [c(q^2)\gamma_\mu\gamma_5 + d(q^2)\sigma_{\mu\nu}q_\nu\gamma_5 + d'(q^2)q_\mu\gamma_5] u^{\Sigma^-} , \quad (4)$$

$$q_\mu = p_e^\mu + p_{\bar{\nu}}^\mu .$$

It is convenient to classify contributions according to forbiddenness: the terms with γ_μ and $\gamma_\mu\gamma_5$ give allowed contributions if $a(0)$ and respectively

Nicola, do something fundamental!

UNITARY SYMMETRY AND LEPTONIC DECAYS

Nicola Cabibbo
CERN, Geneva, Switzerland
(Received 29 April 1963)

We present here an analysis of leptonic decays based on the unitary symmetry for strong interactions, in the version known as "eightfold way,"[1] and the V-A theory for weak interactions.[2,3] Our basic assumptions on J_μ, the weak current of strong interacting particles, are as follows:

(1) J_μ transforms according to the eightfold representation of SU_3. This means that we neglect currents with $\Delta S = -\Delta Q$, or $\Delta I = 3/2$, which should belong to other representations. This limits the scope of the analysis, and we are not able to treat the complex of K^0 leptonic decays, or $\Sigma^+ \to n + e^+ + \nu$ in which $\Delta S = -\Delta Q$ currents play a role. For the other processes we make the hypothesis that the main contributions come from that part of J_μ which is in the eightfold representation.

(2) The vector part of J_μ is in the same octet as the electromagnetic current. The vector contribution can then be deduced from the electromagnetic properties of strong interacting particles. For $\Delta S = 0$, this assumption is equivalent to vector-

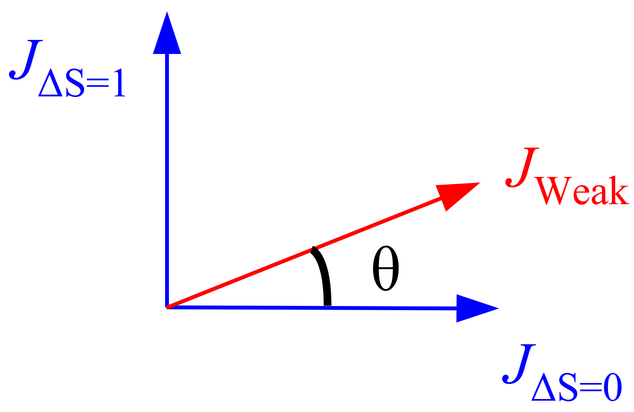
Thanks, Paolo…

A bit of history

Some key dates in flavour physics:

1963 Cabibbo's paper

$$J_\mu^{Weak} = (\cos\theta J_\mu^{\Delta S=0} + \sin\theta J_\mu^{\Delta S=1})$$



A bit of history

Some key dates in flavour physics:

1963 Cabibbo's paper

1964 Discovery of CP violation

1970 GIM (Glashow, Iliopoulos, Maiani)

Weak Interactions with Lepton-Hadron Symmetry*

S. L. Glashow, J. Iliopoulos, and L. Maiani†
Lyman Laboratory of Physics, Harvard University, Cambridge, Massachusetts 02139
(Received 5 March 1970)

We propose a model of weak interactions in which the currents are constructed out of four basic quark fields and interact with a charged massive vector boson. We show, to all orders in perturbation theory, that the leading divergences do not violate any strong-interaction symmetry and the next to the leading divergences respect all observed weak-interaction selection rules. The model features a remarkable symmetry between leptons and quarks. The extension of our model to a complete Yang-Milis theory is discussed.

from

$$J_\mu^{Weak} = (\cos\theta J_\mu^{\Delta S=0} + \sin\theta J_\mu^{\Delta S=1})$$

to

$$\longrightarrow \quad (u,c)_L\, \gamma^\mu \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} d \\ s \end{pmatrix}$$

A bit of history

Some key dates in flavour physics:

1963	Cabibbo's paper
1964	Discovery of CP violation
1970	GIM (Glashow, Iliopoulos, Maiani)
1971	Weinberg paper on SU(2)xU(1)
1973	Kobayashi, Maskawa
1974	Discovery of charm... and later tau ('75) & bottom ('77)
….	
2000's	*Triumph of the CKM picture*

$$\bar{Q}_L{}^i\, Y_D{}^{ik}\, d_R{}^k\, \mathrm{H} \;\to\; \bar{d}_L{}^i\, M_D{}^{ik}\, d_R{}^k + \ldots$$

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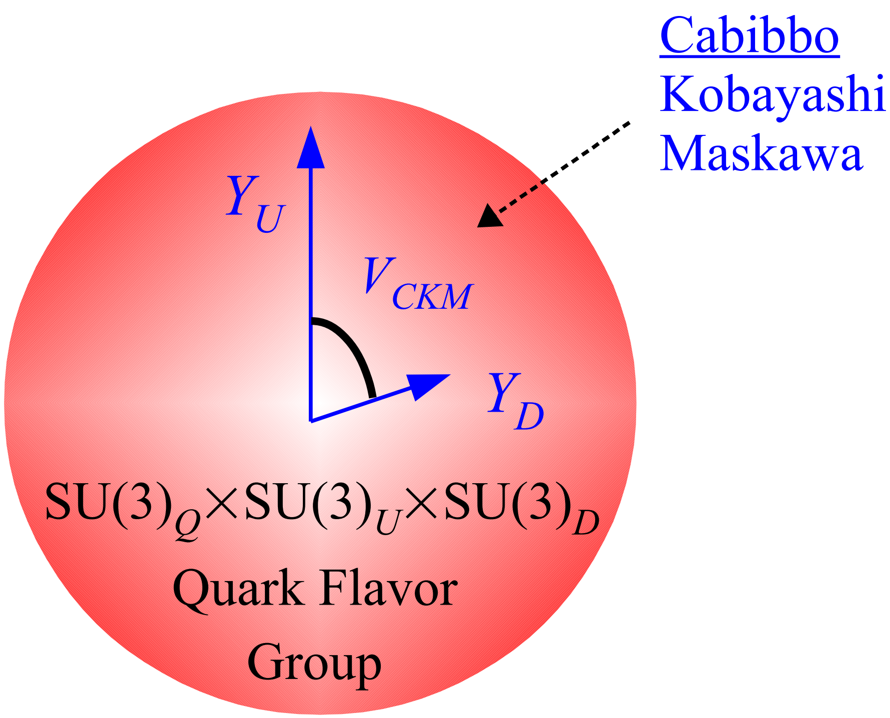
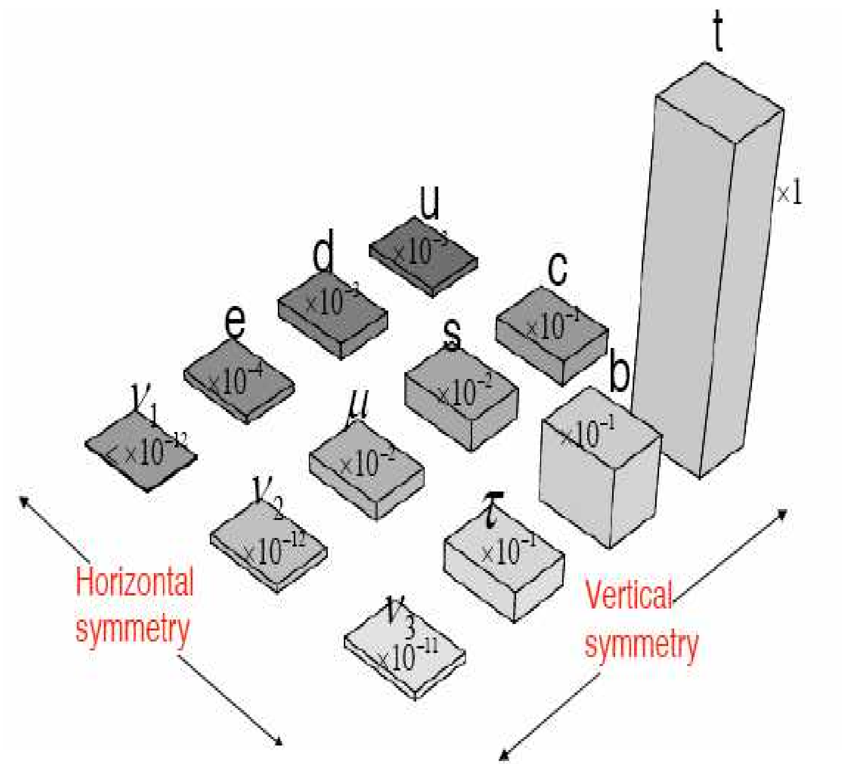


The Flavour Problem(s)



One summer I sat down and said: "*This is the summer when I'm not going to do anything but solve* [the flavour] *problem.*" This was 40 years ago and I haven't solved it. No one has. I thought it would be a simple matter of extending the kind of symmetry principles I used in the electroweak theory to have some kind of symmetry that involved electrons turning into muons and I could never make it work. That's been a frustration now for 40 years...

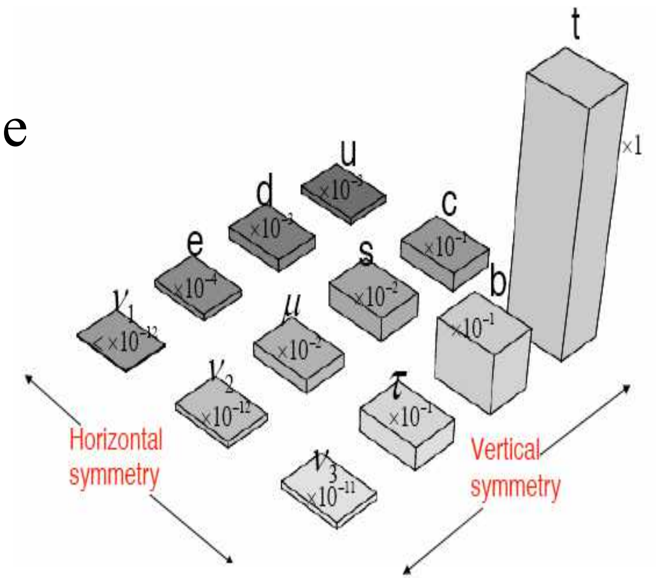
[S.Weinberg, 2013]

The Flavor Problem(s)

$$\mathscr{L}_{\rm SM} = \mathscr{L}_{\rm gauge} + \mathscr{L}_{\rm Higgs}$$

Within the SM the Yukawa interactions perfectly describe quark & lepton masses, as well as the CKM angles.

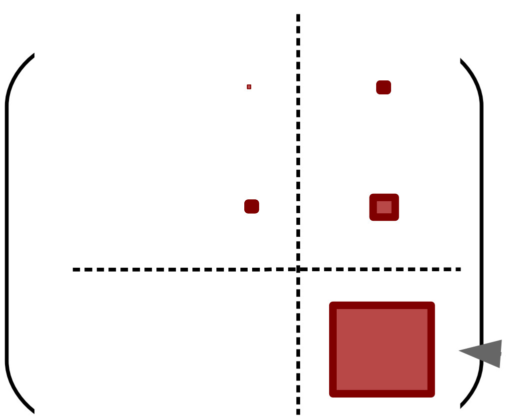
$$y_{ij}\, \psi_i \psi_j\, H \rightarrow m_{ij}\, \psi_i \psi_j$$



What is rather puzzling are the peculiar values of the Yukawa entries, which span 5 orders of magnitude & do not appear at all accidental:

The SM Flavor problem

E.g.:

$Y_U \sim$ 

$$y_t = \frac{\sqrt{2}\, m_t}{\langle H \rangle} \approx 1$$

The Flavor Problem(s)

$$\mathscr{L}_{\text{SM-EFT}} = \mathscr{L}_{\text{gauge}} + \mathscr{L}_{\text{Higgs}} + \Sigma_i \frac{1}{\Lambda_i^{d-4}} O_i^{d\geq 5}$$

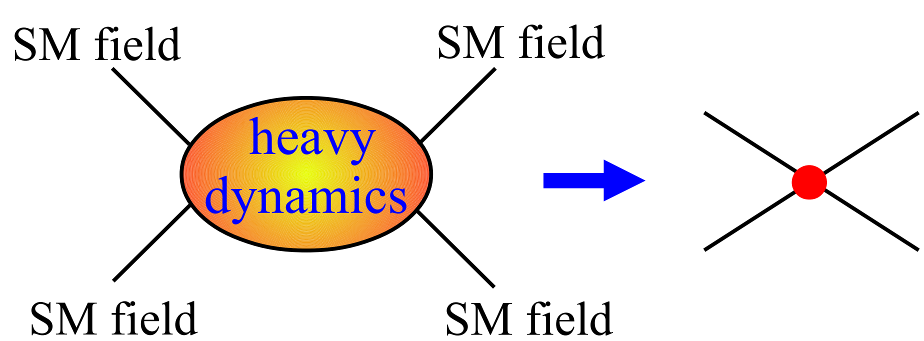
An additional problem arises when we consider the SM as the low-energy limit of a "more complete theory" (*modern point of view: SM → SM-EFT*)

General description of the heavy dynamics, as long as we do not have enough energy to directly excite it

UV Theory

↓

SM (EFT)



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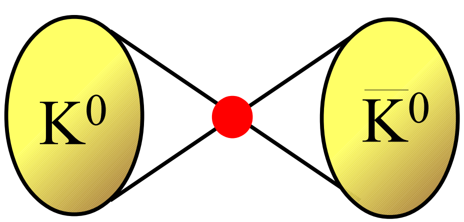
In this case we would expect many other sources of flavor non-degeneracy from the heavy dynamics that completes the SM spectrum.

However we observe none (beside a few *anomalies* → *more later...*)

→ Stringent bounds on the possible scale of new physics

E.g.:



$$\frac{1}{\Lambda^2}(\bar{\psi}_i \psi_j)^2$$

▶ The Flavor Problem(s)

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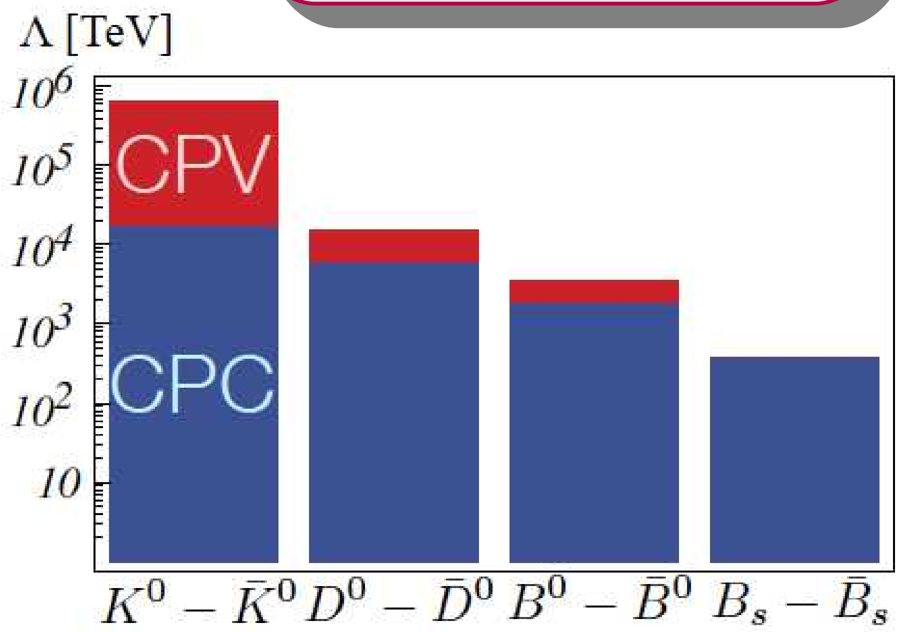
The NP Flavor problem



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These problems have been with us since a long time... and we tried to solve them in different ways.

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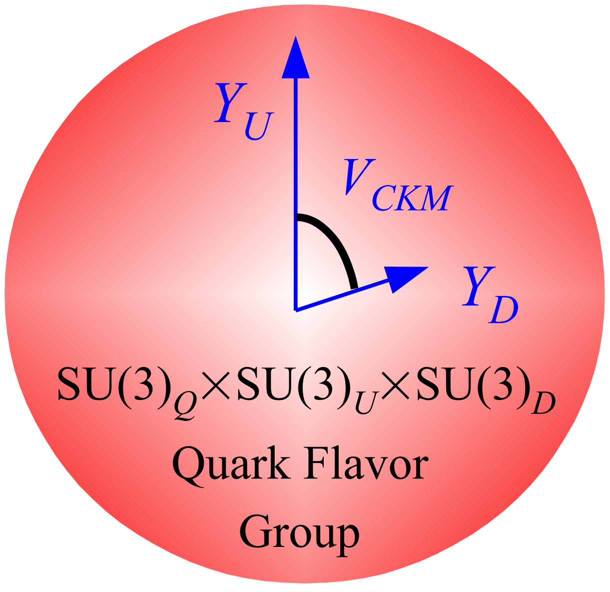
A popular option in the pre-LHC era was the Minimal Flavour Violation hypothesis:

- MFV= postpone the solution of the SM flavour problem to very high scales, and assume no other sources of flavor-breaking at low-energies
  $\longrightarrow$ expect flavour blind TeV-scale new-physics



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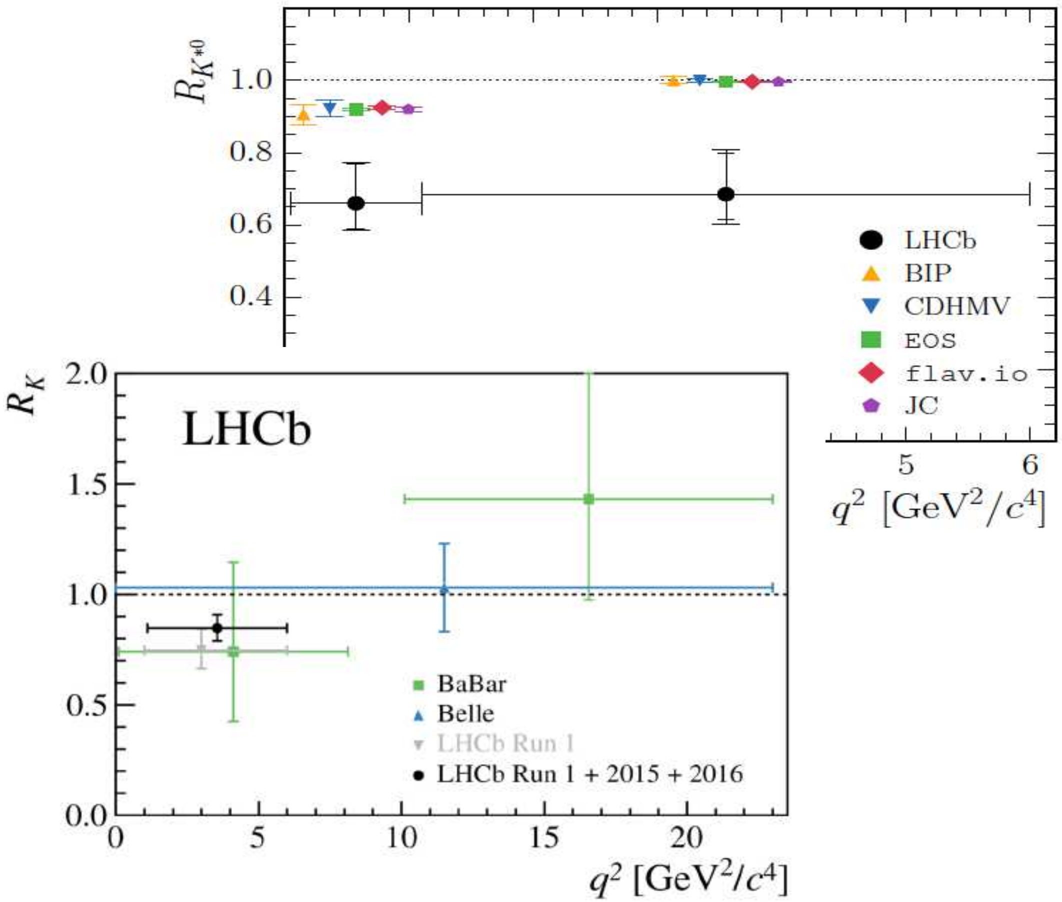
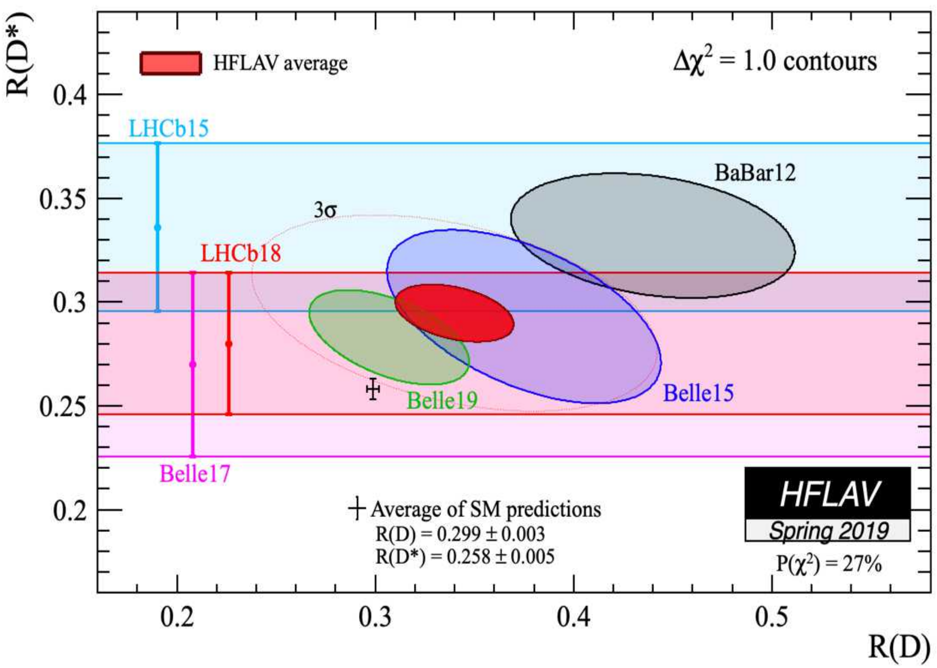
→ expect ~~flavour blind TeV-scale new-physics~~
- The absence of TeV-scale new physics has reinforced other hypotheses, such as those based on *anthropic arguments* – *I don't find these very compelling...*
- Very recently a more interesting direction emerged, triggered by some recent anomalous results in B-physics: the idea of flavour non-universal (gauge) interactions at the TeV scale

Recent developments

[On the recent hints of LFU violations in B decays]





Recent developments

Recent data show some convincing evidences of Lepton Flavour Universality violations in semi-leptonic decays of the b quark.

More precisely, we seem to observe a different behaviour (*beside pure kinematical effects*) of different lepton species in the following processes:

- $b \to c\, l\nu$ (charged currents): τ vs. light leptons (μ, e)
- $b \to s\, l^+l^-$ (neutral currents): μ vs. e

IF taken together... this is probably the largest "coherent" set of deviations from the SM we have ever seen...

I cannot resist to compare this to what happened 60 years ago:

- *two sets of deviations from universality, one large & one small...*
- *many physicists still skeptical thinking theory is not precise...*

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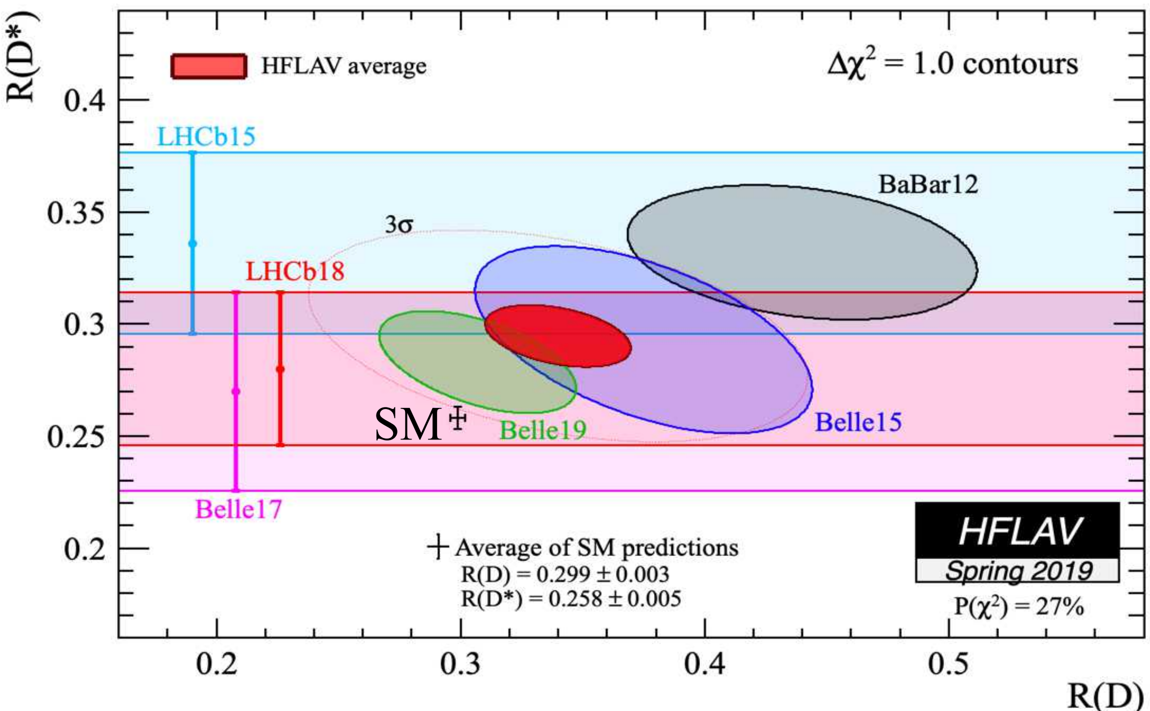
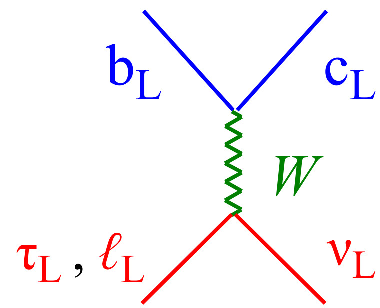
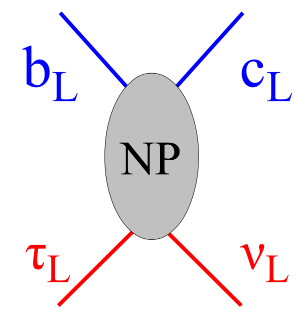


Several results by different exps.
all central values above the SM
[*combined significance:* 3.1σ]





- Data well described by New Physics contributing only to $b_L \to c_L\, \tau_L\, \nu_L$

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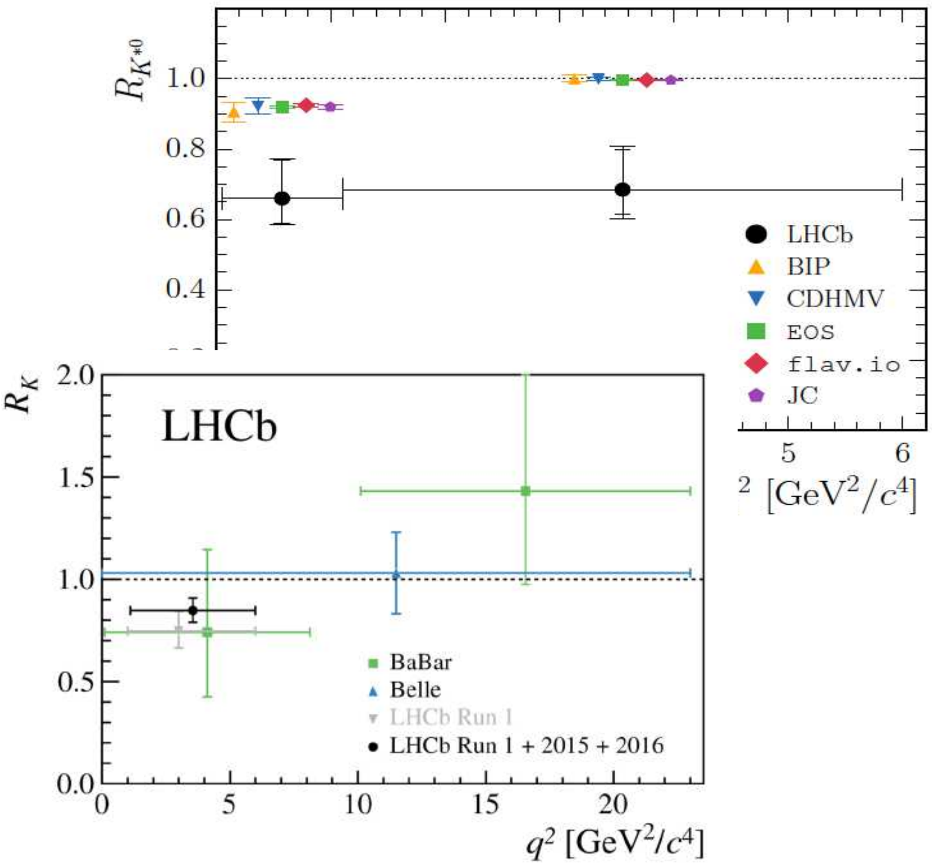
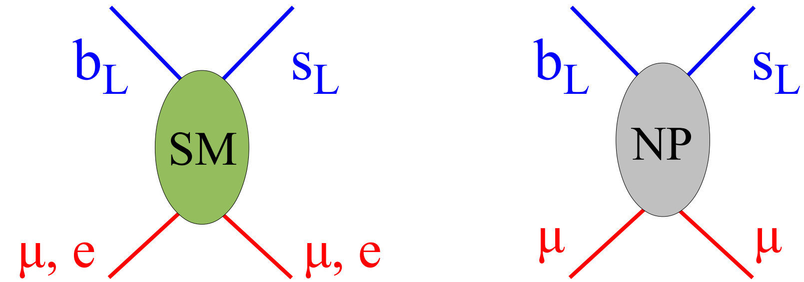




Coherent indications from several observ.
→ New Physics of short-distance origin
[4.2σ significance from "theoretically clean" observables only]

- Data can be explained by NP contributing only to $b_L \to s_L\, \mu_L\mu_L$ (*but other amplitudes possible.... & in this case definitely welcome*)

Recent developments

Recent data show some convincing evidences of Lepton Flavour Universality violations:

- $b \to c\, l\nu$ (charged currents): τ vs. light leptons (μ, e)
- $b \to s\, l^+l^-$ (neutral currents): μ vs. e

IF taken together... this is probably the largest "coherent" set of deviations from the SM we have ever seen...

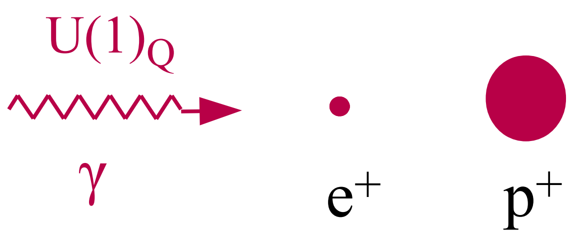
What is particularly interesting, is that these anomalies are challenging an assumption (Lepton Flavour Universality), that we gave for granted for many years (*without many good theoretical reasons...*)

⬇

Personally, I think this is a clear hint that we should
not postpone the solution of the Flavour Problem

Some general considerations on LFU

Suppose we could test matter only with long wave-length photons...



We would conclude that these two particles are "identical copies" but for their mass ...

Some general considerations on LFU

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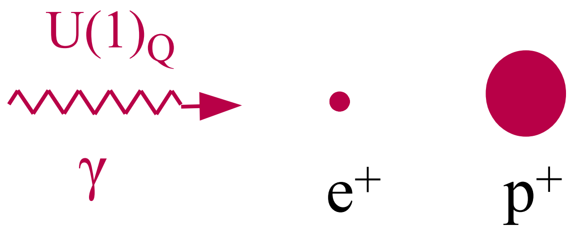
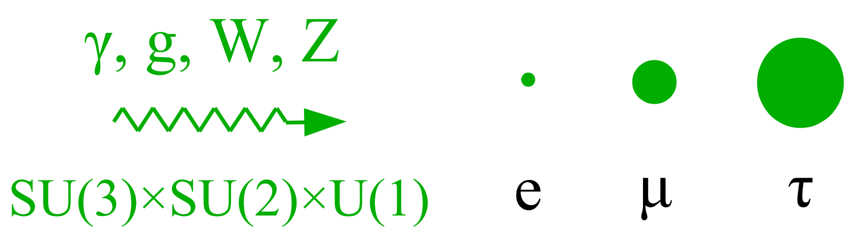


We would conclude that these two particles are "identical copies" but for their mass ...

This is exactly the same (*potentially misleading*) argument we use to infer LFU in the SM...



These three (families) of particles seems to be "identical copies" but for their mass ...

The SM quantum numbers of the three families could be an "accidental" low-energy property: the different families may well have a very different behavior at high energies, as signaled by their different mass

Some general considerations on LFU

So far, the vast majority of model-building attempts to extend the SM was based on the following two (*implicit*) hypotheses:

- Concentrate on the Higgs hierarchy problem
- Postpone (*ignore*) the flavour problem ➡ The 3 gen. as "identical" copies (*but for Yukawa-type interactions*)

▶ *Some general considerations on LFU*

So far, the vast majority of model-building attempts to extend the SM was based on the following two (*implicit*) hypotheses:

- Concentrate on the Higgs hierarchy problem
- Postpone (*ignore*) the flavour problem ➡ ~~The 3 gen. as "identical" copies (*but for Yukawa-type interactions*)~~

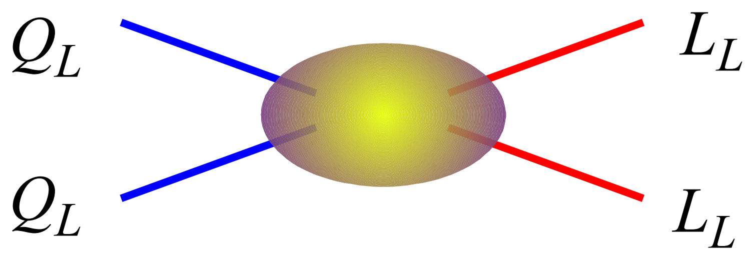
The recent flavor anomalies seem to suggest a new avenue in BSM approaches:

- We should not ignore the flavor problem
  → *new (non-Yukawa) interactions at the TeV scale distinguishing the different families*

- A (very) different behavior of the 3 families (with special role for 3rd gen.), reflecting the indications we have from the SM Yukawa couplings, may be the key to solve/understand also the gauge hierarchy problem
  → *Higgs mostly coupled to 3rd gen.*
  → *TeV-scale NP mainly coupled to 3rd gen. could have escaped direct searches*

Addressing the anomalies: EFT considerations

- Anomalies are seen only in semi-leptonic (quark×lepton) operators
- Data largely favor non-vanishing left-handed current-current operators [*Fermi-like effective theory*], although other contributions are also possible



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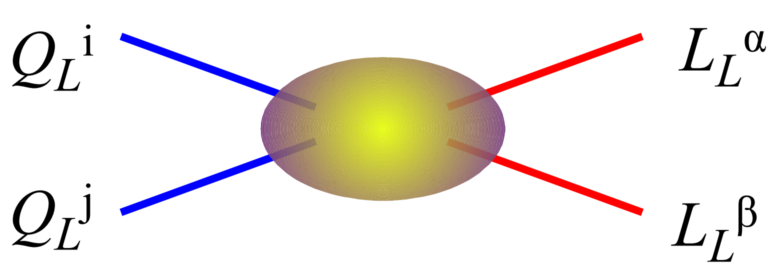

- Large coupling [*competing with SM tree-level*] in $bc \to l_3\,\nu_3$ [R_D, R_{D*}]
- Small coupling [*competing with SM loop-level*] in $bs \to l_2\;l_2$ [R_K, R_{K*}, ...]

↓

$C_{ij\alpha\beta} \propto$ large for 3$^{\text{rd}}$ generation + small terms for 2$^{\text{nd}}$ (& 1$^{\text{st}}$) generations → *Link to pattern of the Yukawa couplings !*

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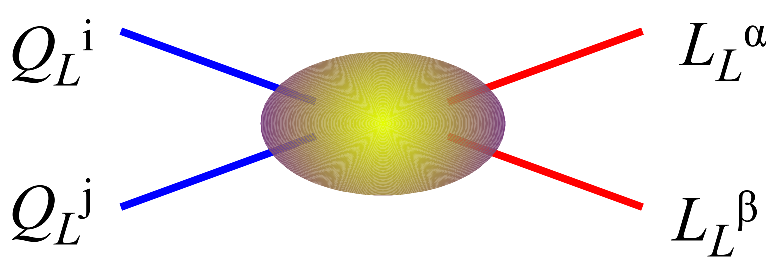


Highly non-trivial to build a consistent EFT, given the *long list of constraints* from other rare processes, where we do not see large deviations from the SM

⬇

Essential role of *flavor symmetries*, to explain the observed pattern of the anomalies and, at the same time, "protect" against too large effects in other low-energy observables

Addressing the anomalies: EFT considerations

A very good candidate to address both these issues (link with the origin of the Yukawa couplings + compatibility with other low-energy data) is a chiral flavour symmetry of the type $U(2)^n$

$$\psi = \left[\begin{array}{c} \begin{pmatrix} \psi_1 \\ \psi_2 \end{pmatrix} \\ \hdashline \psi_3 \end{array} \right]$$

← light generations (*flavor doublet*)

← 3^{rd} generation (*flavor singlet*)

↑ SM fermion (e.g. q_L)

….with suitable (small) symmetry-breaking terms, related to the structures observed in the SM Yukawa couplings (*i.e. what we started to learned with the work of Cabibbo...*)

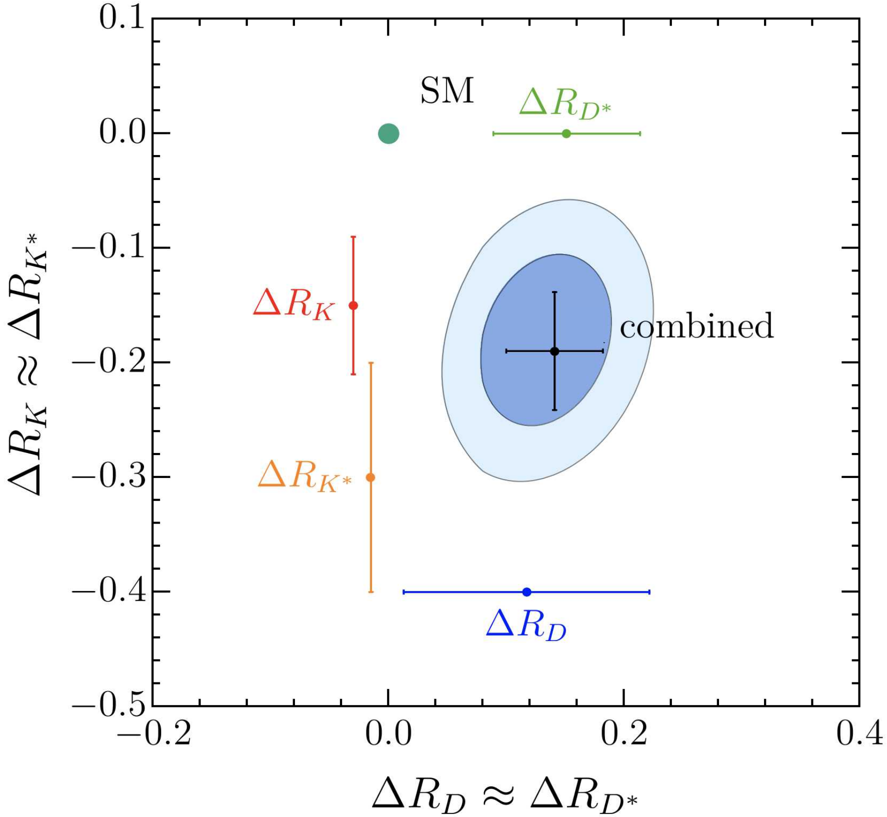
Barbieri, G.I., Jones-Perez, Lodone, Straub, '11

NB: This flavor symmetry does not need to be a "fundamental" symmetry, it could well be an "accidental" symmetry, resulting from non-universal interactions that distinguish the 3^{rd} family

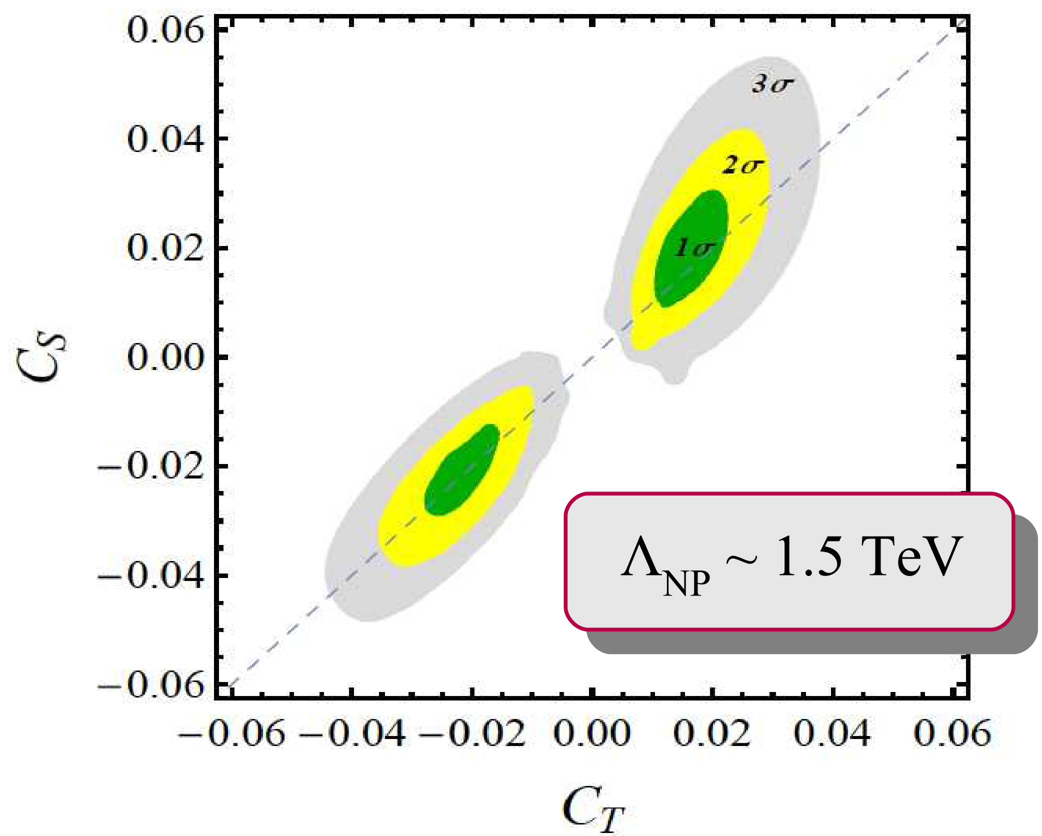
▸ *Addressing the anomalies: EFT considerations*

Employing this symmetry in the EFT, it is possible to pass all bounds without fine-tuning and have an excellent description of present data:

four main free parameters: $C_{S,T} = O\left(\frac{\langle H \rangle}{\Lambda_{NP}^{2}}\right)$, $\theta_{bs} = O(|V_{cb}|)$, $\theta_{\tau\mu} = O(|V_{cb}|)$



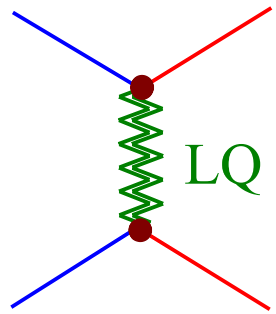
Buttazzo, Greljo, GI, Marzocca, '17

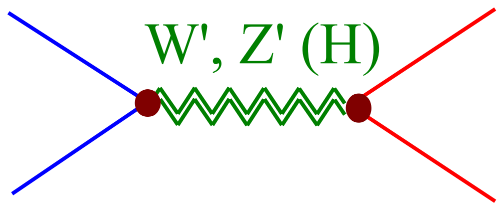


$\Lambda_{NP} \sim 1.5$ TeV

Addressing the anomalies: model-building considerations

If we ask which tree-level mediators can generate the effective operators required by the EFT fit, we have not many possibilities...





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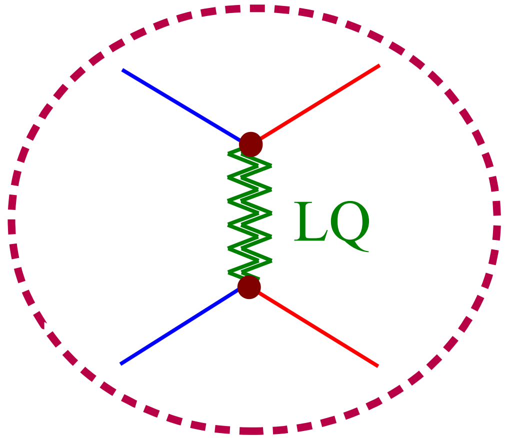
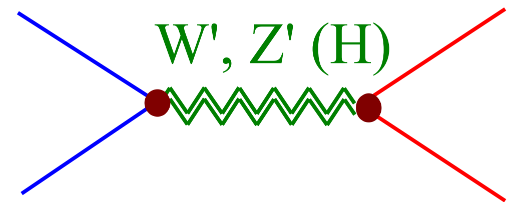
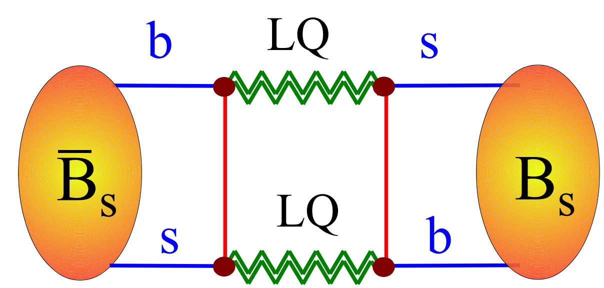




Lepto-quark meditators have strong advantage with respect to the other mediators:

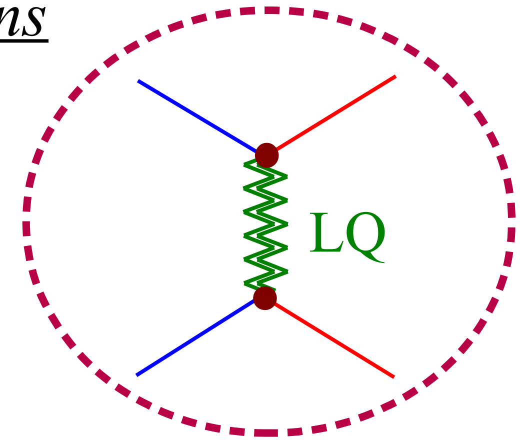
Tree-level contribution to semi-leptonic decays [→ anomalies]

One-loop contribution to $\Delta F=2$ amplitudes [→ no large deviations]



Also as far as direct searches are concerned, massive LQ coupled mainly to the 3rd generation are in good shape (*contrary to the Z'...*).

Addressing the anomalies: model-building considerations

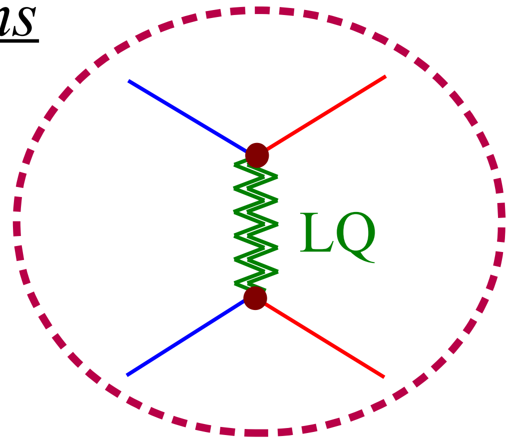


Leptoquarks suffered of an (*undeserved*) "bad reputation" for two main reasons:

- Could mediate proton decay → not a general feature of the LQ: it depends on the model...! [*e.g. not the case in the Pati-Salam model*]

- Severe bounds from flavour-changing processes → avoided with non-trivial flavour structure [*e.g. non-univ. interactions*]

Addressing the anomalies: model-building considerations



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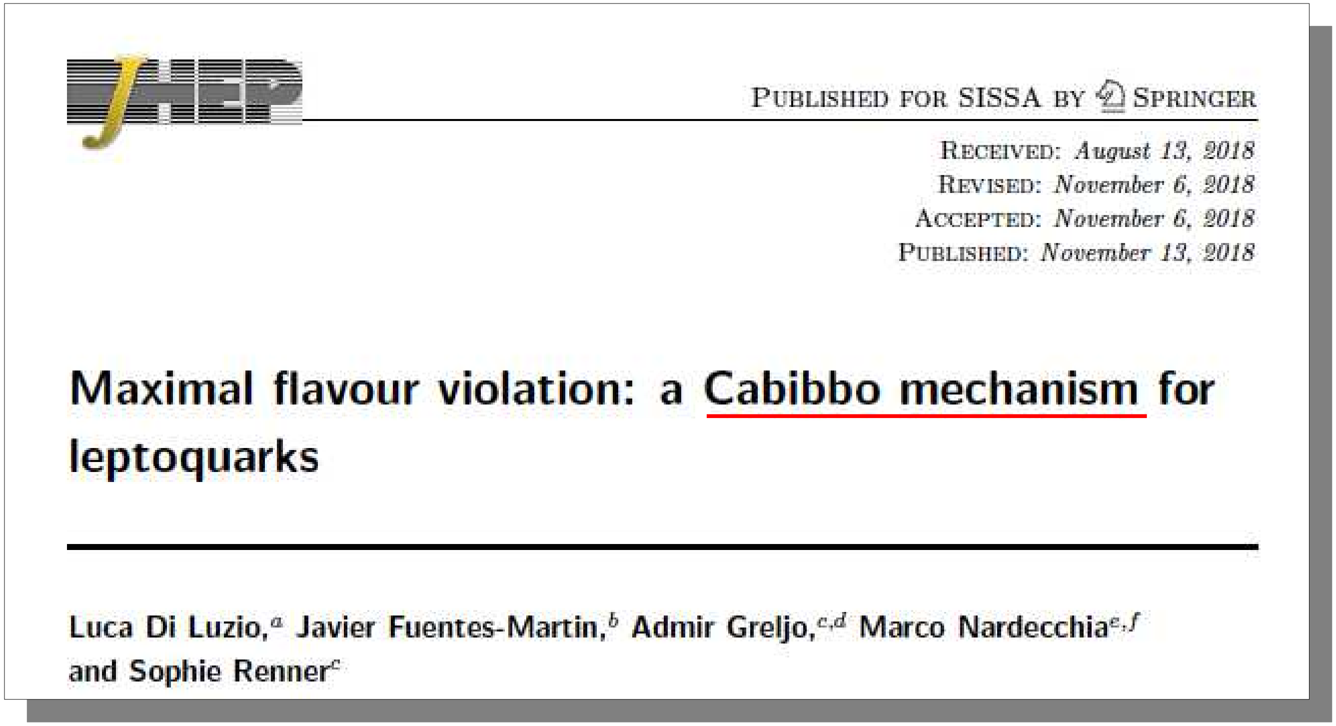

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Maximal flavour violation: a Cabibbo mechanism for leptoquarks

Luca Di Luzio,[a] Javier Fuentes-Martin,[b] Admir Greljo,[c,d] Marco Nardecchia[e,f] and Sophie Renner[c]

Addressing the anomalies: my favourite model

Starting observation: a gauge theory proposed in the 70's to unify quarks and leptons by Pati & Salam predicts a massive vector LQ with the correct quantum numbers to fit the anomalies (*best single mediator*):

Pati-Salam group: $SU(4)\times SU(2)_L\times SU(2)_R$

Fermions in SU(4): $\begin{bmatrix} Q_L^{\alpha} \\ Q_L^{\beta} \\ Q_L^{\gamma} \\ L_L \end{bmatrix}$ $\begin{bmatrix} Q_R^{\alpha} \\ Q_R^{\beta} \\ Q_R^{\gamma} \\ L_R \end{bmatrix}$

Main Pati-Salam idea:
Lepton number as "the 4th color"

The massive LQ [U_1] arise from the breaking $SU(4) \to SU(3)_c$

$$SU(4) \sim \begin{bmatrix} SU(3)_C & 0 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} 0 & LQ \\ LQ & \end{bmatrix} \begin{bmatrix} \frac{1}{3} & 0 \\ 0 & -1 \end{bmatrix}$$

▸ *Addressing the anomalies: my favourite model*

New ingredient (*related to flavour*): at high energies the 3 families are charged under 3 independent gauge groups (*gauge bosons carry a flavour index !*)

$$[\ \mathrm{PS}\ ]^3 = [\ SU(4)\times SU(2)_L\times SU(2)_R\ ]^3$$

Bordone, Cornella, Fuentes-Martin, GI, '17

UV

PS_1 $\psi_1^{L,R}$ PS_2 $\psi_2^{L,R}$ PS_3 $\psi_3^{L,R}$

Unification of quarks and leptons [natural explanation for $U(1)_Y$ charges]

"De-unification" (= *flavour deconstruction*) of the gauge symmetry

SM

IR

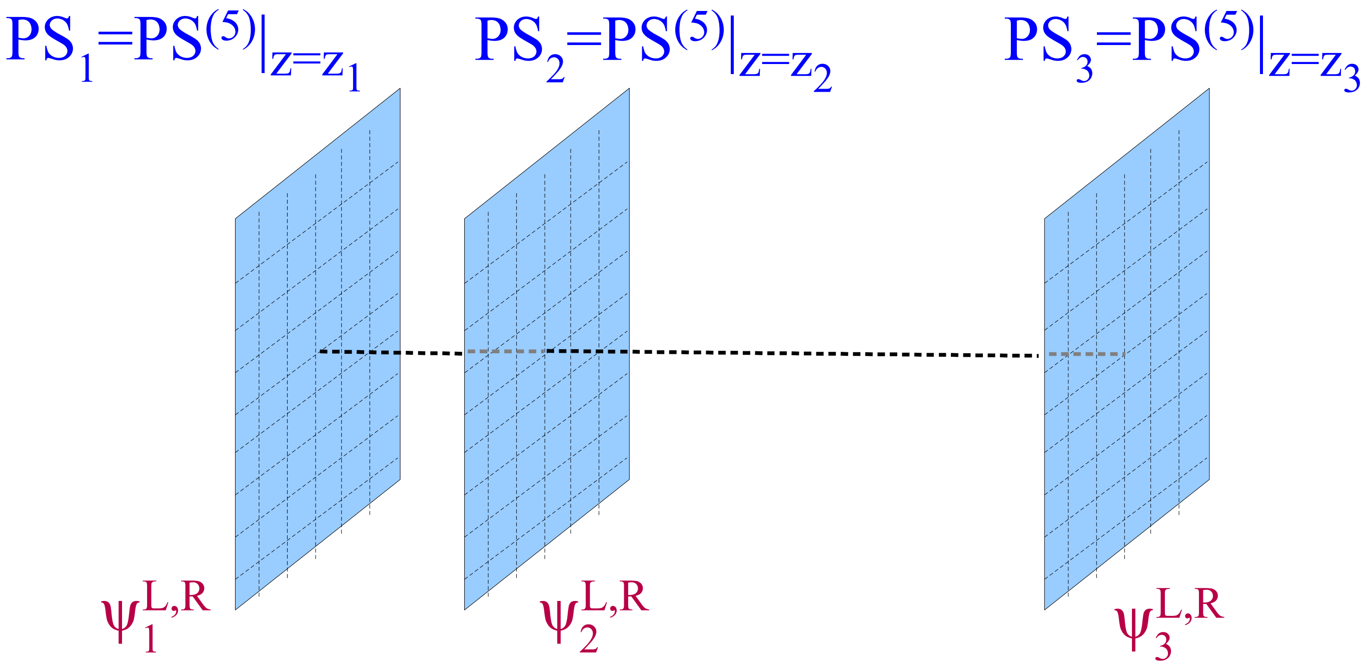
Q_i, u_i, d_i, L_i, e_i

Key advantages:

- Light LQ coupled mainly to 3rd gen.
- Accidental flavour symmetry "protecting" light-fermions
- Natural structure of SM Yukawa couplings

▸ *Addressing the anomalies: my favourite model*

$$[\ \mathrm{PS}\ ]^3 = [\ SU(4)\times SU(2)_L\times SU(2)_R\ ]^3$$



Unification
of quarks and leptons

"De-unification"
(= *flavor deconstruction*)
of the gauge symmetry

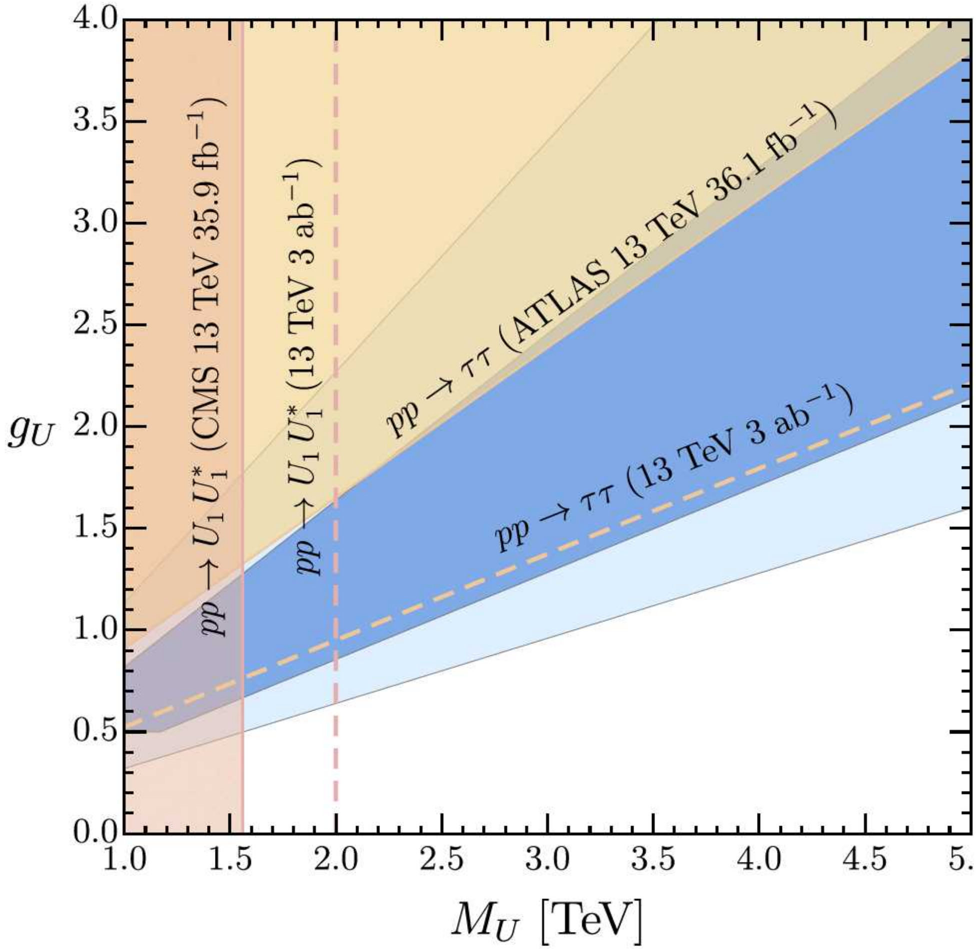
This construction can find a "natural" justification in the context of models with extra space-time dimensions

What we denote as "flavour" corresponds to a special position (*topological defect*) in an extra (compact) space-like dimension

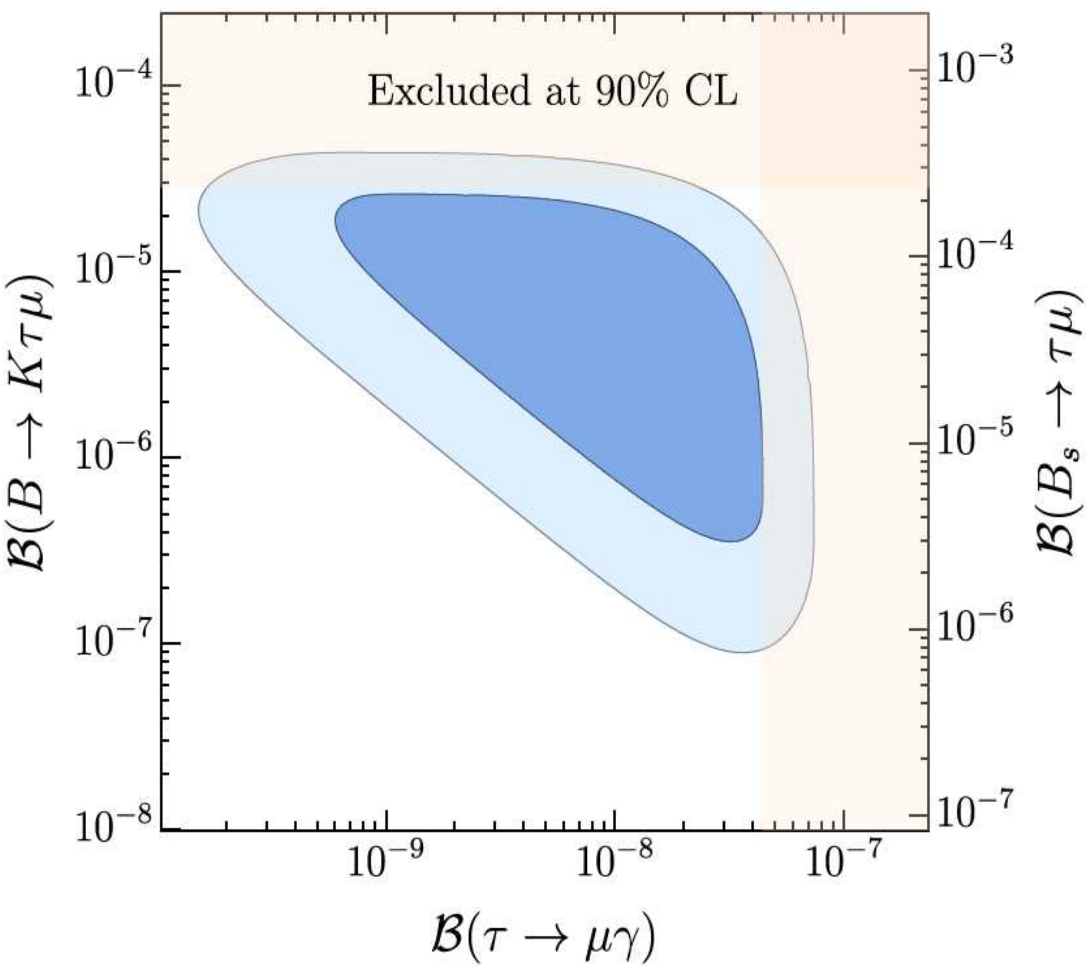
Dvali & Shifman, '00

Addressing the anomalies: model-building considerations

Independently of the details of the model, if these anomalies are true we should expect to see soon clear signatures at high-p_T & at low energies:



Baker et al. '19



Cornella et al. '19

Conclusions

Nicola Cabibbo laid down the cornerstone of Flavor Physics.

His works has had –and continues to have– an enormous influence on generations of physicists (*including myself...*).

Having had the privilege to work with him, I will never forget his "*passion for experimental data*" and his "*research toward simplicity*" in the description of physical phenomena.