Questions of flavour

50 years of charm

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A short History of Flavour

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A short History of Flavour

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- The complete Table of Elementary Particles the year 1932.

Matter particles : $\begin{pmatrix} p \\ n \end{pmatrix}$ $\begin{pmatrix} \nu \\ e \end{pmatrix}$

Radiation : γ

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- Three simple rules

• All matter particles have spin one-half. Radiation quanta have spin one.

• Lepton – Hadron Symmetry

• The role of each one of the elementary particles in the structure of matter is clear and well understood.

A short History of Flavour

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- *Who ordered that ?* (I. Rabi, 1947)

  The first Question of flavour

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Muon : The devine laughter

- *Who ordered that ?* (I. Rabi, 1947)

  The first Question of flavour

- More than seventy years later, we still do not know the answer !

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Chaotic Inflation

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- What is "an elementary particle" ?

- All three simple rules were violated :

  • "Particles" of any spin. No clear distinction between matter constituents and mediators of forces.

  • No signs of a Lepton – Hadron Symmetry.

  • As for the role of all these particles in the structure of matter, physicists did not even dare to ask the question.

A short History of Flavour

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- 1964 : The Cabibbo angle

A short History of Flavour

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- The complete Table of Elementary Particles the year 1964.

Matter particles : $\begin{pmatrix} u \\ d \end{pmatrix}$ $\quad s \quad$ $\begin{pmatrix} \nu_e \\ e \end{pmatrix}$ $\begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix}$

Radiation : γ IVB "gluons"

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• Lepton – Hadron Symmetry NO

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- 1972 : Anomalies *Bouchiat, Jl, Meyer ; Gross, Jackiw*
  $\Rightarrow$ Lepton-hadron symmetry is a fundamental law of Nature.
- 1975 - : Discovery of the third family : b, t, τ, ν_τ
  The quarks predicted by Kobayashi-Maskawa, the associated leptons by lepton-hadron symmetry
  $\Rightarrow$ The family is complete

A short History of Flavour

THE WORLD IS NOT SO SIMPLE !

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THE WORLD IS NOT SO SIMPLE !

- The complete Table of Elementary Particles today.

Matter particles : $\begin{pmatrix} u \\ d \end{pmatrix} \begin{pmatrix} c \\ s \end{pmatrix} \begin{pmatrix} t \\ b \end{pmatrix} \quad \begin{pmatrix} \nu_e \\ e \end{pmatrix} \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix} \begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}$

Radiation : γ $W^\pm$, Z^0 8 QCD gluons

The BEH scalar : H

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- This last failure brings us back to Rabi's question :
  Who ordered flavour ?

Flavour : Organised but not understood

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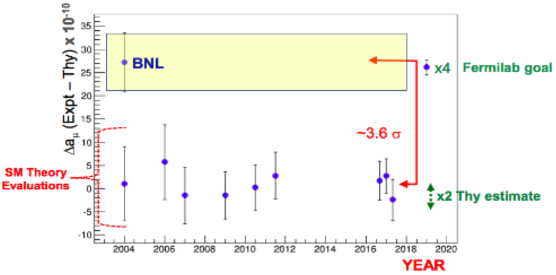
- Study of the CKM matrix and CP violation
- Neutrino oscillations
- Heavy quark spectroscopy
- Precision measurements and/or study of rare events as signs for new physics

High precision measurements

Anomalous magnetic moment of the muon

Long-standing discrepancy with the SM

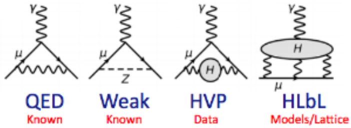


a_μ is now measured to 540 ppb; Goal is 140 ppb

FNAL exp't in commissioning phase

High precision measurements

Arduous computation of ever more precise SM prediction



New lattice computation for HLBL term

- physical pion mass and large lattice
- Statistical precision x2 improvement
- Systematics in progress

Blum etal, 1705.01067, 1610.04603

Contribution	Value $\times 10^{10}$	Uncertainty $\times 10^{10}$
QED	11 658 471.895	0.008
Electroweak Corrections	15.4	0.1
HVP (LO) [7]	692.3	4.2
HVP (LO) [8]	694.9	4.3
HVP (NLO)	-9.84	0.06
HVP (NNLO)	1.24	0.01
HLbL	10.5	2.6
Total SM prediction [7]	11 659 181.5	4.9
Total SM prediction [8]	11 659 184.1	5.0
BNL E821 result	11 659 209.1	6.3
Fermilab E989 target		≈ 1.6

$$a_\mu^{\text{HLbL}} = 5.35(1.35) \times 10^{-10}$$

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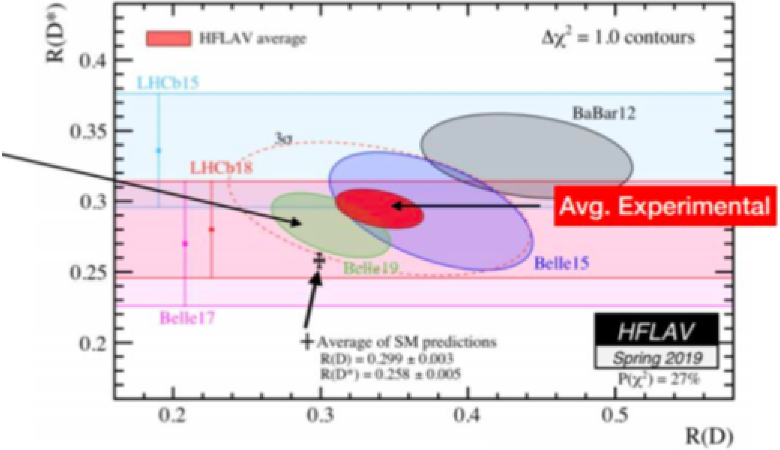
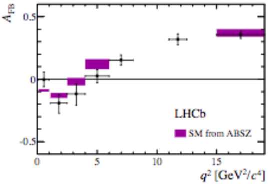
Heavy flavour decays

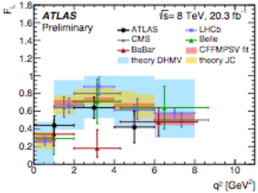


Heavy flavour decays

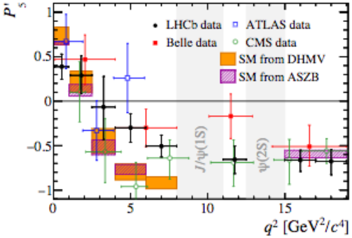
Flavour changing neutral currents

$B_d^0 \to K^* \mu^+ \mu^-$ results





- Several observables appear different than SM
- In particular P_5' has significant discrepancy
- Global fits show large disagreement



Heavy flavour decays

Summary of B anomalies

Are we there yet?

1. Low $b \to s\mu\mu$ branching fractions
2. Discrepancies in angular observables of $B_d^0 \to K^*\mu^+\mu^-$
3. Signs of lepton non-universality in: $B^+ \to K^+\mu^+\mu^-$ and $B_d^0 \to K^*\mu^+\mu^-$

- All seems to be related to a change in the C_9 coefficient (or maybe C_9 and C_{10}, but V-A)
- Global fits start to exhibit several standard deviations of discrepancy
- $c\bar{c}$ interference explanation seems not justified
- Additional discrepancies in tree-level $B \to D^{(*)}\ell\nu$ decays
- Many NP explanations: Z', leptoquarks, low mass resonances etc

Neutrino masses and oscillations

Neutrino Physics

Fundamental Questions addressed by Diverse Neutrino Program

- What is the origin of neutrino mass?
- How are the neutrino masses ordered?
  - *Oscillation experiments*
- What is the absolute neutrino mass scale?
  - *Beta-decay spectrum*
  - *Cosmic surveys*
- Do neutrinos and anti-neutrinos oscillate differently?
  - *Oscillation experiments*
- Are there additional neutrino types and interactions?
  - *Oscillation experiments*
  - *Cosmic surveys*
- Are neutrinos their own anti-particles?
  - *Neutrinoless double-beta decay*

Neutrino masses and oscillations

My conclusion :

• A data-driven subject in which theorists have not played the major role.

• Substantial improvement in precision could be expected during the coming years.

• The significance of such improvements is not easy to judge.

• So far no real illumination came from leptons to be combined with the quark sector for a more complete theory of flavour

The trouble is that I do not see how this could change !

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- Our generation built a very successful Standard Theory and it is normal that we leave the problem of its extension to the younger ones.
- Nevertheless, I am confident that the GIM trio, together with all our friends, will have again great pleasure in it.
- I am looking forward to the celebration of the 75 years of GIM and I expect to give a talk on

THE THEORY OF FLAVOUR