Questions of flavour

50 years of charm

T.D. Lee Institute

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ENS, Paris
A short History of Flavour

1932  THE WORLD IS SIMPLE!

The complete Table of Elementary Particles the year 1932.

<table>
<thead>
<tr>
<th>Matter particles</th>
<th>Radiation</th>
</tr>
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<tbody>
<tr>
<td>(p) (n) (ν_e)</td>
<td>γ</td>
</tr>
</tbody>
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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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Matter particles: \((p)\) \((n)\) \((\nu)\) \((e)\)

Radiation: \(\gamma\)
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Muon : The devine laughter

Who ordered that? (I. Rabi, 1947)

More than seventy years later, we still do not know the answer!
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The first *Question of flavour*
A short History of Flavour

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Chaotic Inflation

In the 1940s and 1950s, the extensive use of accelerators resulted into a huge proliferation of new hadronic states.

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.
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▶ 1953 : Strangeness *Gell-Mann, Nishijima*

▶ 1960 : The problem of strangeness changing neutral currents

▶ 1962 : Existence of a $\nu_{\mu}$ experimentally established

⇒ A second leptonic flavour.

▶ 1964 : The quarks or, the missing triplet

▶ 1964 : The Cabibbo angle
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1964 THE WORLD IS NOT SIMPLE!
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The complete Table of Elementary Particles the year 1964.

Matter particles: \( (u,d) \quad s \quad (\nu_e) \quad (\nu_\mu) \)

Radiation: \( \gamma \quad \text{IVB} \quad \text{“gluons”} \)
A short History of Flavour

1964 THE WORLD IS NOT SIMPLE!

The complete Table of Elementary Particles the year 1964.

Matter particles: \[
\begin{pmatrix}
u \\
d
\end{pmatrix}
\begin{pmatrix}
\nu_e \\
e
\end{pmatrix}
\begin{pmatrix}
\nu_\mu \\
\mu
\end{pmatrix}
\]

Radiation: \(\gamma\) IVB “gluons”

Out of the three simple rules

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

• Lepton – Hadron Symmetry NO

• The role of each one of the elementary particles in the structure of matter is clear and well understood. NO
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1969 : GIM ⇒ Restore lepton-hadron symmetry. No FCNC

1972 : Anomalies Bouchiat, JI, Meyer ; Gross, Jackiw ⇒ Lepton-hadron symmetry is a fundamental law of Nature.

1975 - : Discovery of the third family : $b, t, \tau, \nu_\tau$ ⇒ The quarks predicted by Kobayashi-Maskawa, the associated leptons by lepton-hadron symmetry ⇒ The family is complete
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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: 
\[
\begin{pmatrix}
u_e \\ 
u_\mu \\ 
u_\tau \\
\end{pmatrix}
\begin{pmatrix}
u_e \\ 
u_\mu \\ 
u_\tau \\
\end{pmatrix}
\begin{pmatrix}
u_e \\ 
u_\mu \\ 
u_\tau \\
\end{pmatrix}
\begin{pmatrix}
u_e \\ 
u_\mu \\ 
u_\tau \\
\end{pmatrix}
\begin{pmatrix}
u_e \\ 
u_\mu \\ 
u_\tau \\
\end{pmatrix}
\begin{pmatrix}
u_e \\ 
u_\mu \\ 
u_\tau \\
\end{pmatrix}
\]

Radiation: 
\[
\begin{pmatrix}
\gamma \\ W^\pm, Z^0 \\
\end{pmatrix}
\begin{pmatrix}
\gamma \\ W^\pm, Z^0 \\
\end{pmatrix}
\begin{pmatrix}
\gamma \\ W^\pm, Z^0 \\
\end{pmatrix}
\begin{pmatrix}
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\end{pmatrix}
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\gamma \\ W^\pm, Z^0 \\
\end{pmatrix}
\begin{pmatrix}
\gamma \\ W^\pm, Z^0 \\
\end{pmatrix}
\]

The BEH scalar: 
\[
H
\]
THE WORLD IS NOT SO SIMPLE!
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- Out of the three simple rules
  - All matter particles have spin one-half. Radiation quanta have spin one. YES
    *But the BEH scalar has spin zero!*
  - Lepton – Hadron Symmetry YES
  - The role of each one of the elementary particles in the structure of matter is clear and well understood. NO
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  - All matter particles have spin one-half. Radiation quanta have spin one. YES
  - *But the BEH scalar has spin zero!*
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- This last failure brings us back to Rabi’s question: Who ordered flavour?
Flavour : Organised but not understood

Even if we do not know why they are there, heavy flavours have opened vast fields of research:

▶ 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
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High precision measurements

Anomalous magnetic moment of the muon

Long-standing discrepancy with the SM

$\Delta a_\mu$ is now measured to 540 ppb; Goal is 140 ppb
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

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

$\alpha_{\mu}^{\text{HLBL}} = 5.35(1.35) \times 10^{-10}$
Heavy flavour decays

\[
\Delta \chi^2 = 1.0 \text{ contours}
\]

- **LHCb15**
- **BaBar12**
- **LHCb18**
- **Belle19**
- **Belle15**
- **Belle17**
- **HFLAV average**
- **Avg. Experimental**

**Average of SM predictions**

- \( R(D) = 0.299 \pm 0.003 \)
- \( R(D^*) = 0.258 \pm 0.005 \)

\( \text{HFLAV Spring 2019} \)

\( \text{P}(\chi^2) = 27\% \)
Heavy flavour decays

Flavour changing neutral currents

- Several observables appear different than SM
- In particular $P_0'$ 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 $B^0_d \to K^* \mu^+ \mu^-$
3. Signs of lepton non-universality in: $B^+ \to K^+ \mu^+ \mu^-$ and $B^0_d \to K^* \mu^+ \mu^-$
   - 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*
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!
My Conclusions

Today we celebrate 50 years of GIM

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
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