Flavorful ways to New Physics

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What is flavor (in particle physics)?
The term flavor was first used in particle physics in the context of the quark model of hadrons. It was coined in 1971 by Murray Gell-Mann and his student at the time, Harald Fritzsch, at a Baskin-Robbins ice-cream store in Pasadena. Just as ice cream has both color and flavor so do quarks.

Review of Modern Physics 81 (2009) 1887
The birth of flavor physics

• 1932: discovery of the neutron

• (Almost) Same mass as the proton

• Same coupling to the strong interaction (i.e., the force that bounds atomic nuclei)

• Is there a real difference between the proton and the neutron?
Isospin

- Same year, Heisenberg proposed neutron and proton are an ‘isospin doublet’
  - Two quantum states of the same particle (like spin-\(\uparrow\) and spin-\(\downarrow\) electron)
    
    \[
    \begin{align*}
    p: (l, l_3) &= (1/2, +1/2) \\
    n: (l, l_3) &= (1/2, -1/2)
    \end{align*}
    \]

- Later extended to other particles: e.g., pions form an isospin triplet
  
  \[
  \begin{align*}
  \pi^+: (l, l_3) &= (1, +1) \\
  \pi^0: (l, l_3) &= (1, 0) \\
  \pi^-: (l, l_3) &= (1, -1)
  \end{align*}
  \]
The eightfold way (1953)

\[
\begin{align*}
    I_3 &= -1, & I_3 &= 0, & I_3 &= +1 \\
    I_3 &= -1/2, & I_3 &= +1/2 \\

    S &= 0, & S &= +1, & S &= -1 \\
    Q &= -1, & Q &= 0, & Q &= +1
\end{align*}
\]
The quark model

Quarks are confined into bound states called hadrons

• $q_1 \bar{q}_2 = \text{meson}$

• $q_1 q_2 q_3 = \text{baryon}$

+ more complex states (e.g., pentaquarks)

• Exception is top, which is too heavy and decays before forming hadrons

+ antimatter counterparts ($\bar{u}$, $\bar{d}$, ...)

with opposite quantum numbers
The eightfold way with quark flavors

Mesons

$Q = -1$ $Q = 0$ $Q = +1$

$S = -1$ $S = 0$ $S = +1$

$I_3 = -1$ $I_3 = 0$ $I_3 = +1$

$I_3 = -1/2$ $I_3 = +1/2$
The eightfold way with quark flavors

\[ I_3 = -1 \quad I_3 = 0 \quad I_3 = +1 \]

\[ I_3 = -1/2 \quad I_3 = +1/2 \]

\[ S = 0 \quad S = -1 \quad S = +1 \]

\[ Q = 0 \quad Q = -1 \quad Q = +1 \]

\[ \frac{u \bar{u} - d \bar{d}}{\sqrt{2}} \]

Mesons
Flash question

• What is the quark content of the nucleons?

\[ p: (Q, l_3, S) = (+1, +1/2, 0) \quad n: (Q, l_3, S) = (0, -1/2, 0) \]
Flash question

• What is the quark content of the nucleons?

\[
p: (Q, l_3, S) = (+1, +1/2, 0) \quad \text{and} \quad n: (Q, l_3, S) = (0, -1/2, 0)
\]

\[
p = (uud) \quad \text{and} \quad n = (udd)
\]
Homework assignment: determine quark content of the baryon octet
# Standard Model of Elementary Particles

<table>
<thead>
<tr>
<th>Quarks</th>
<th>Leptons</th>
<th>Gauge Bosons</th>
<th>Scalar Bosons</th>
</tr>
</thead>
<tbody>
<tr>
<td>up (u)</td>
<td>electron (e)</td>
<td>Z boson (Z)</td>
<td>Higgs (H)</td>
</tr>
<tr>
<td>charm (c)</td>
<td>muon (μ)</td>
<td>W boson (W)</td>
<td></td>
</tr>
<tr>
<td>top (t)</td>
<td>tau (τ)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>down (d)</td>
<td>electron neutrino (ν_e)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>strange (s)</td>
<td>muon neutrino (ν_μ)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>bottom (b)</td>
<td>tau neutrino (ν_τ)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Masses
- up (u): 2.2 MeV/c²
- charm (c): 1.28 GeV/c²
- top (t): 173.1 GeV/c²
- down (d): 4.7 MeV/c²
- strange (s): 96 MeV/c²
- bottom (b): 4.18 GeV/c²
- electron (e): 0.511 MeV/c²
- muon (μ): 105.66 MeV/c²
- tau (τ): 1.7768 GeV/c²
- electron neutrino (ν_e): <1.0 eV/c²
- muon neutrino (ν_μ): <0.17 MeV/c²
- tau neutrino (ν_τ): <18.2 MeV/c²
- Z boson: 91.19 GeV/c²
- W boson: 80.39 GeV/c²

### Charges
- up (u): 2/3
- charm (c): 2/3
- top (t): 2/3
- down (d): -1/3
- strange (s): -1/3
- bottom (b): -1/3
- electron (e): -1
- muon (μ): -1
- tau (τ): -1
- electron neutrino (ν_e): 0
- muon neutrino (ν_μ): 0
- tau neutrino (ν_τ): 0
- Z boson: 0
- W boson: ±1
- Higgs (H): 0
What is flavor physics?

- Studies the flavor structure of the Standard Model
  - Why are there so many fermions? Why are they arranged into generations? Why exactly 3 generations? …
  - It includes kaon physics (strange quark), charm & beauty physics (heavy quarks), some aspects of top physics, charged leptons and neutrinos
- No time to cover everything — it's a huge and diverse field
- Focus will be on flavor-changing interactions of heavy quarks
Heavy-flavor physics

- Quarks change flavor through the charged weak interaction

\[
\begin{align*}
V_{cb} & \\
b & \rightarrow & c \\
W^- & \rightarrow & \mu^- \\
\bar{\nu}_\mu & \rightarrow & \\
V_{cb} & 
\end{align*}
\]
Heavy-flavor physics

• Quarks change flavor through the charged weak interaction

• But... they are bound by the strong interaction into hadrons

• Cannot observe weak interaction in isolation ➞ makes theoretical predictions tougher
Heavy-flavor physics

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- But... they are bound by the strong interaction into hadrons
- Cannot observe weak interaction in isolation → makes theoretical predictions tougher
- Many possible quark combinations → many possible decays and wide program of measurements to over-constrain the SM parameter-space
Heavy-flavor physics

- Quarks change flavor through the charged weak interaction
- But... they are bound by the strong interaction into hadrons
- Cannot observe weak interaction in isolation → makes theoretical predictions tougher
- Many possible quark combinations → many possible decays and wide program of measurements to over-constrain the SM parameter-space
- The hardest part of quark flavor physics is learning the names and properties of all the damned hadrons!
Why is heavy-flavor physics interesting?

• Sensitive to effects of new particles and forces beyond the Standard Model — even particles too massive to be produced at the energy frontier (\textit{i.e.}, at the LHC)

• May explain the ‘matter dominance’ of the Universe — one of the big mysteries linking particle physics and cosmological observations $\Rightarrow CP$ violation
Flavor as a probe of New Physics

- Look for the effects of exchange of virtual new particles in suppressed (loop) processes

Standard Model

- Quantum-probe of higher energies than directly accessible
Flavor as a probe of New Physics

- Look for the effects of exchange of virtual new particles in suppressed (loop) processes

**Standard Model**

**New Physics?**

- Quantum-probe of higher energies than directly accessible
Flavor as a probe of New Physics

- High-energy production of new particles
- Low-energy precision measurements
Flavor as a probe of New Physics

(Often) New Physics shows up at precision frontier before energy frontier
A lesson from history: the GIM mechanism

- Some apparently allowed decays are never observed: e.g.,

\[ K^+ \rightarrow \mu^+\nu_\mu \text{ is observed } \]
\[ K^0 \rightarrow \mu^+\mu^- \text{ is not, why?} \]
A lesson from history: the GIM mechanism

- Some apparently allowed decays are never observed: e.g.,

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\[ K^0 \rightarrow \mu^+\mu^- \text{ is not, why?} \]

- Glashow, Iliopoulos, Maiani postulated in 1970 a fourth quark (charm) to introduce a new amplitude with equal magnitude but opposite sign \( \rightarrow \) total amplitude highly suppressed!

\[(cancellation \text{ not perfect because } m_u \neq m_c) \]

\[ V_{us}V_{ud}^* f(m_u/m_W) + V_{cs}V_{cd}^* f(m_c/m_W) \approx 0 \]
Discovery of charm

\[ J \ (Ting; \ BNL)/\psi \ (Richter, \ SLAC) \] discovery, 1974

Bound state of two charm quarks (c\bar{c})
Meson-antimeseson mixing

- The ultimate loop experiment

- Results in ‘oscillations’ between particles and antiparticles as a function of time
Meson-antimeson mixing

Blue line:
given a $P^0$ at $t=0$, the probability of finding a $P^0$ at $t$

Red Line:
given a $\bar{P}^0$ at $t=0$, the probability of finding a $\bar{P}^0$ at $t$

Neutral kaons
$K^0=(d\bar{s}), \bar{K}^0=(\bar{d}s)$

Neutral charm mesons
$D^0=(c\bar{u}), \bar{D}^0=(\bar{c}u)$

Neutral beauty mesons
$B^0=(b\bar{d}), \bar{B}^0=(b\bar{d})$

Neutral beauty-strange mesons
$B_s^0=(b\bar{s}), \bar{B}_s^0=(b\bar{s})$

[arXiv:1209.5806]
Meson-antimeson mixing

\[ B^0_s \rightarrow D_s^- \pi^+ \quad \text{and} \quad \overline{B}^0_s \rightarrow D_s^- \pi^+ \quad \text{Untagged} \]
Meson-antimeson mixing

\( D^0 \rightarrow K^+\pi^- \)

- Data
- Mixing fit
- No-mixing fit

LHCb
Reach

\[ \mathcal{L} = \mathcal{L}_{SM} + \frac{1}{\Lambda^2} \mathcal{O}_{\Delta F=2} \]

Energy scale of New Physics [TeV]

- $K^0$ mixing
- $D^0$ mixing
- $B^0$ mixing
- $B_s^0$ mixing

Reach of direct searches

[arXiv:1302.0661]
C, P and CP symmetries

• Quantum-mechanical operators

\(C\): transforms particles in antiparticles

\(P\): flips spatial coordinates (mirror symmetry)

\(CP\): combination of both, distinguishes matter from antimatter

• \(P\) and \(C\) are both maximally violated by weak interactions (no right-handed neutrinos, no left-handed antineutrinos), \(CP\) assumed to be conserved until 1964
Discovery of $CP$ violation

- Produce pure beam of $CP$-odd neutral kaons ($K_L$)
- Look for decays to $CP$-even $\pi^+\pi^-$ state $\rightarrow$ produced back-to-back, so $\cos(\theta) = 1$
The Cabibbo-Kobayashi-Maskawa matrix

- The matrix that describes the couplings of quark-flavor-changing interactions

\[
V \approx \begin{pmatrix}
1 & \lambda & \lambda^3 e^{i\varphi} \\
-\lambda & 1 & \lambda^2 \\
-\lambda^3 e^{-i\varphi} & -\lambda^2 & 1
\end{pmatrix}
\]

\[\lambda \approx 0.22\]
The Cabibbo-Kobayashi-Maskawa matrix

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The Cabibbo-Kobayashi-Maskawa matrix

- The matrix that describes the couplings of quark-flavor-changing interactions
- With 3 generations of quarks the matrix has one imaginary number (phase)
- Such phase is responsible for CP violation: weak-interaction couplings differ for quarks and antiquarks because CP flips the sign of imaginary numbers
Unitarity triangle

- CKM matrix is unitary $\rightarrow$ 9 equations relates its elements: e.g.,

$$1 + \frac{V_{td}V_{tb}^*}{V_{cd}V_{cb}^*} + \frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*} = 0$$
Unitarity triangle

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Experiments test the theory by constraining the position of the apex
Unitarity triangle

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Experiments test the theory by constraining the position of the apex

Area of the triangle quantifies amount of $CP$ violation
CKM angle $\gamma$

- The only $CP$ violation parameter that can be measured from tree diagrams $\implies$ negligible theory uncertainties

The two diagrams interfere when $D^0$ and $\bar{D}^0$ decay to the same final state (needed to observe $CP$ violation)
CKM angle $\gamma$

$B^+ \rightarrow DK^+$

$B^- \rightarrow DK^-$

$D \rightarrow K_S^0 \pi^+ \pi^-$
CKM angle $\gamma$

$B^+ \rightarrow DK^+$

$B^- \rightarrow DK^-$

$D \rightarrow K_{S0}^0 \pi^+ \pi^-$

$CP$ violation

LHCb
CKM angle $\gamma$
All consistent...

- A global campaign of thousands of measurements conducted in the past 25+ years to experimentally explore the quark-flavor sector.

- The Standard Model seems sufficient to accommodate all quark-flavor phenomena observed so far.
...or maybe not?

- Consistent pattern of deviations in $b \rightarrow s \mu^+ \mu^-$ transitions, but predictions have large hadronic uncertainties
A much cleaner probe

• Contrarily to quarks, the couplings of the electroweak force to charged leptons are universal

• Branching fractions of $b$ hadrons into $e$, $\mu$ and $\tau$ differ only because of the different lepton masses
Violation of lepton-flavor universality?

- Couplings of New Physics particles to leptons may instead depend on flavor.
- Violation of lepton flavor universality would be an unambiguous sign of physics beyond the Standard Model.
Violation of lepton-flavor universality?

$$R_{K^{(*)}} = \frac{\mathcal{B}(B \to K^{(*)} \mu^+ \mu^-)}{\mathcal{B}(B \to K^{(*)} e^+ e^-)}$$

<table>
<thead>
<tr>
<th>$q^2$ [GeV$^2$/c$^4$]</th>
<th>LHCb</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0</td>
<td>1.0</td>
</tr>
<tr>
<td>5.0</td>
<td>1.5</td>
</tr>
<tr>
<td>10.0</td>
<td>2.0</td>
</tr>
<tr>
<td>15.0</td>
<td>2.5</td>
</tr>
<tr>
<td>20.0</td>
<td>3.0</td>
</tr>
</tbody>
</table>

2.3-2.5σ per bin}

LHCb

BaBar

Belle

LHCb 9 fb$^{-1}$
Could it be new physics?

Fit from W. Altmannshofer and P. Stangl arXiv:2103.13370

Consistent with new physics in channels with muons

Couplings to new particles

Similar fits from other groups:
Algueró et al., arXiv:1903.09578
Kowalska et al., arXiv:1903.10932
Ciuchini et al., arXiv:2011.01212
Datta et al., arXiv:1903.10086
Arbey et al., arXiv:1904.08399
Geng et al., arXiv:2103.12738
And there’s even more…

\[ R_{D^{(*)}} = \frac{\mathcal{B}(B \rightarrow D^{(*)} \tau^+ \nu_\tau)}{\mathcal{B}(B \rightarrow D^{(*)} \mu^+ \nu_\mu)} \]

\[ \Delta \chi^2 = 1.0 \text{ contours} \]
Heavy-flavor experiments

LHCb @ LHC (pp collider)
CERN, Switzerland

Belle II @ SuperKEKB (e+e− collider)
KEK, Japan

ATLAS and CMS @ LHC
(do a bit of heavy-flavor physics)

BESIII @ BEPCII (e+e− collider)
IHEP, China
Summary

• Quark-flavor physics allows to explore some of the deepest questions that are not answered by the Standard Model

• A diverse and rich field: many hadrons, many final states, many observables sensitive to New Physics

• And to energy scales much higher than directly accessible at colliders

• After 20+ years of confirming the Standard Model, some intriguing hints of unexpected phenomena are popping up

• Exciting times: New Physics may be just around the corner
Any Questions
Interference and CP violation

Direct CPV: $|A| \neq |\bar{A}|$; $A_{CP} \equiv \frac{\Gamma(B \rightarrow f) - \Gamma(\bar{B} \rightarrow \bar{f})}{\Gamma(B \rightarrow f) + \Gamma(\bar{B} \rightarrow \bar{f})} \neq 0$

- Easiest way to get CPV is with 2 interfering amplitudes (e.g. tree and penguin) with different weak (CP-odd) and strong (CP-even) phases

\[ A(B \rightarrow f) = A = A_1 + A_2 \]
\[ A(\bar{B} \rightarrow \bar{f}) = \bar{A} = \bar{A}_1 + \bar{A}_2 \]

CP transformation:
strong phase: $\delta \rightarrow \delta$
weak phase: $\phi \rightarrow -\phi$

\[ A_1 = |A_1| \]
\[ A_2 = |A_2|e^{i\delta}e^{i\phi} \]

\[ \bar{A}_1 = |A_1| \]
\[ \bar{A}_2 = |A_2|e^{i\delta}e^{-i\phi} \]

$|A| \neq |\bar{A}|$

$A_{CP} = \frac{2r \sin \delta \sin \phi}{1 + r^2 + 2r \cos \delta \cos \phi}$