The flavor of the fundamental interactions

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Physics Colloquium at the UNAM

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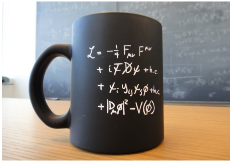
Outline

1. Where we are in particle physics?
2. What is flavor physics?
    - Flavor in the Standard Model of Particle Physics
    - Flavor beyond the Standard Model
3. The flavor anomalies

Where do we stand in Particle Physics?

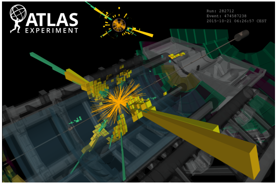
1. We have a **fundamental theory** that explains *almost all* experimental data!

Standard Model (SM) of Particle Physics



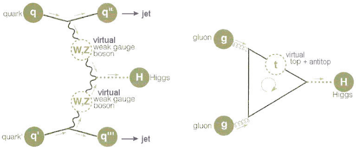
2. . . . and the **Large Hadron Collider (LHC)** to ***directly*** explore the shortest scales ever probed ($\lambda \sim 10^{-3}$ fm) ...

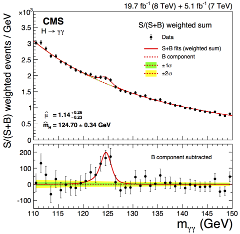
- $E \simeq h/\lambda$: **High-energy physics**
- $E = m\,c^2$: **New & heavy (TeV)** particles!

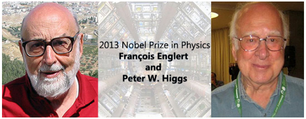


Discovery of the Higgs! (2012)

- **Produced at the LHC!**
- **Mass of the Higgs** $\simeq 125 \times$ **proton mass**



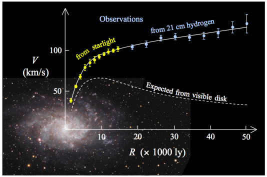




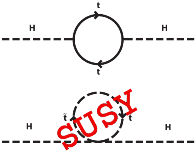
Major milestone of the LHC and completion of the SM!

Physics Beyond the Standard Model?

- Compelling empirical facts that the SM *do not explain*. For example:
  - **What is the astrophysical & cosmological dark matter?**



- Theoretical problems about the values and quantum stability of the parameters...
  - **Why is the Higgs mass so much smaller than $M_{\rm Planck} \simeq 10^{18}$ GeV?**



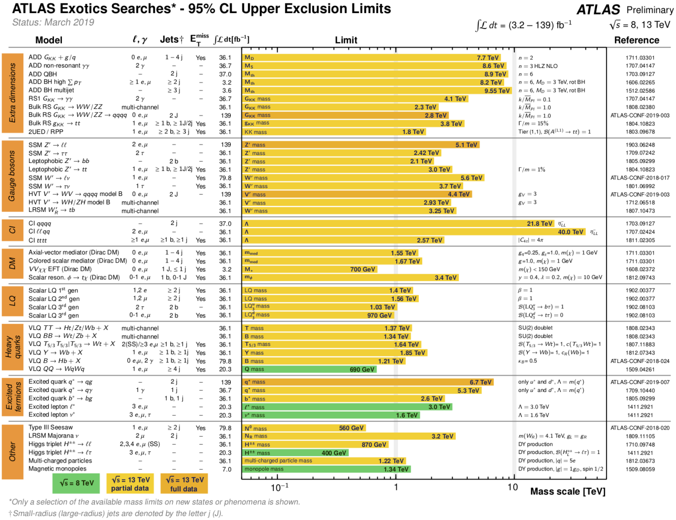
- Quantum corrections *quadratically* sensitive to mass of new physics

$$(m_H^{\rm phys})^2 = (m_H^0)^2 + \frac{y_{\rm top}^2 N_c}{8\pi^2}\left(\Lambda^2_{\rm NewPhysics} + \ldots\right)$$

Strong motivations to search for TeV-scale New Physics

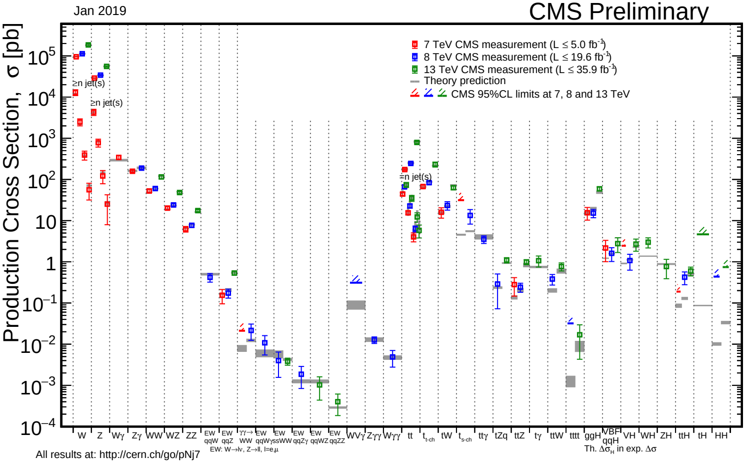
- **Super-Symmetry** (SUSY)

Physics Beyond the Standard Model?



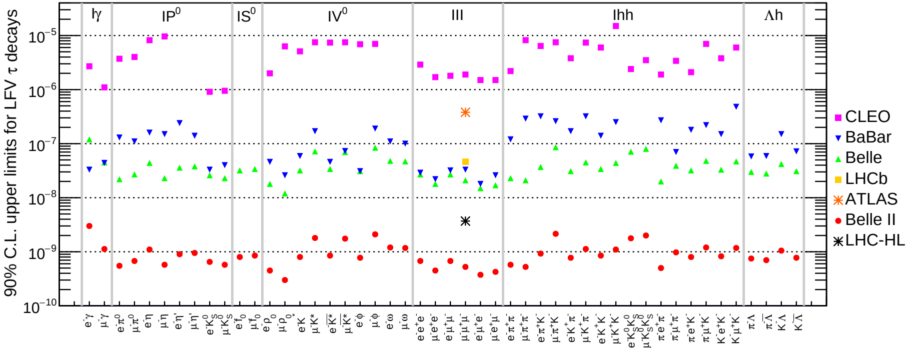
No new particles found at the LHC

Physics Beyond the Standard Model?



Precision SM calculations agree with high-energy data. . .

Physics Beyond the Standard Model?



Precision SM calculations agree with low-energy data. . .

Summary

Overwhelming majority of particle-physics experiments agree with the SM predictions

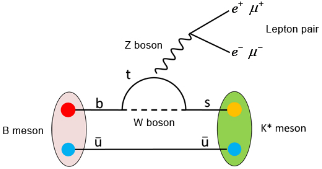
Physics Beyond the Standard Model?

- **Except for a few remarkable exceptions . . .**

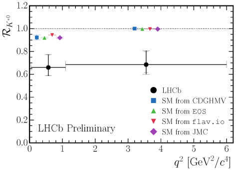
Flavor Anomalies

- "Coherent set of tensions" with SM in decays of "B mesons" in "charged leptons"
- Violation of symmetry of interactions for different leptons ("lepton universality")

- **Example:** $B \to K^* \mu^+ \mu^-$ *vs.* $B \to K^* e^+ e^-$



- The "R_{K^*} anomaly"



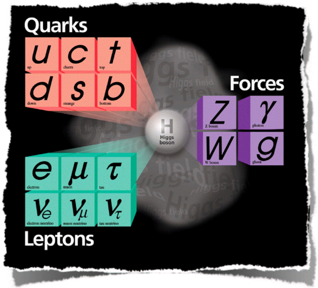
- **Other persisting "anomalies":** like muon's $(g-2)$ or proton charge radius

What is Flavor?

Gell-Mann and Fritzsch (1971)

- "Just as ice-cream has both *colour* and *flavour* so do quarks."
- Only three quarks known at the time *up*, *down* and *strange*.
- Extended to leptons.

- **Modern SM**

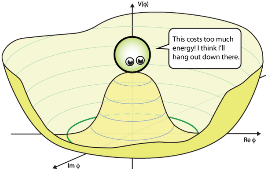


- **3 *almost* identical families of "Matter" (fermions)**
  - ★ "Neutral leptons": Neutrinos
  - ★ "Charged leptons": e, μ and τ
  - ★ "Up quarks": "*up*", "*charm*", "*top*"
  - ★ "Down quarks": "*down*", "*strange*", "*bottom*"
- **"Identical":** Same "charges" of the gauge forces (e.g. electric charge)
- **"*Almost*":** Different masses!

Flavor Physics in the Standard Model

Yukawa sector of the Standard Model

$$-\mathcal{L}_Y = \bar{q}_L Y_D d_R H + \bar{q}_L Y_U u_R \tilde{H} + \bar{\ell}_L Y_e e_R H + \text{h.c.}$$



- **Fermion mass generation:** $H \to \text{vev} + h^0$
- Yukawa matrices diagonalizable

$$M_U \equiv \begin{pmatrix} m_u & 0 & 0 \\ 0 & m_c & 0 \\ 0 & 0 & m_t \end{pmatrix} = \text{vev} \times L_u^\dagger Y_U R_u$$

$$M_D \equiv \begin{pmatrix} m_d & 0 & 0 \\ 0 & m_s & 0 \\ 0 & 0 & m_b \end{pmatrix} = \text{vev} \times L_d^\dagger Y_D R_d$$

- **Cabibbo-Kobayashi-Maskawa:** Flavor violation in $W^\pm$ (charged-current) coup's

$$V_{\text{CKM}} = L_u^\dagger L_d$$

Flavor Physics in the Standard Model

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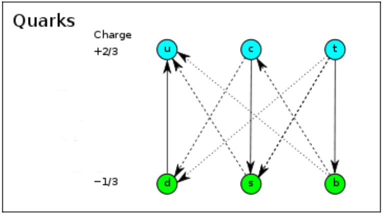
$$-\mathcal{L}_Y = \bar{q}_L Y_D d_R H + \bar{q}_L Y_U u_R \tilde{H} + \bar{\ell}_L Y_e e_R H + \text{h.c.}$$

The CKM Matrix:

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix}_J = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}_M$$

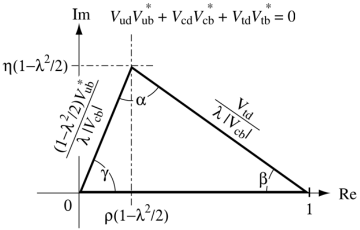
- The CKM are very hierarchical (almost diagonal matrix)

$$V_{\text{CKM}} = \begin{pmatrix} 0.97446 \pm 0.00010 & 0.22452 \pm 0.00044 & 0.00365 \pm 0.00012 \\ 0.22438 \pm 0.00044 & 0.97359^{+0.00010}_{-0.00011} & 0.04214 \pm 0.00076 \\ 0.00896^{+0.00024}_{-0.00023} & 0.04133 \pm 0.00074 & 0.999105 \pm 0.000032 \end{pmatrix}$$



The CKM unitary triangle

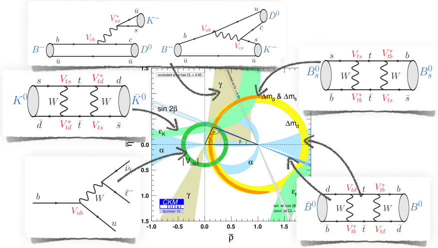
- Complex and Unitary matrix $\Longrightarrow$ Parametrized by **3 angles** and **1** ***CP*** **phase**



Unitary Triangle

- **Unitary relations:** Triangles in complex plane
- **Few parameters** compared to **thousands** of processes they describe – **PDG**

- Experimental sources of the "UT"



Jure Zupan, arXiv: 1903.05062

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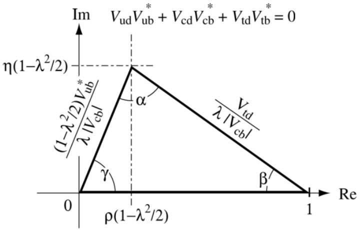

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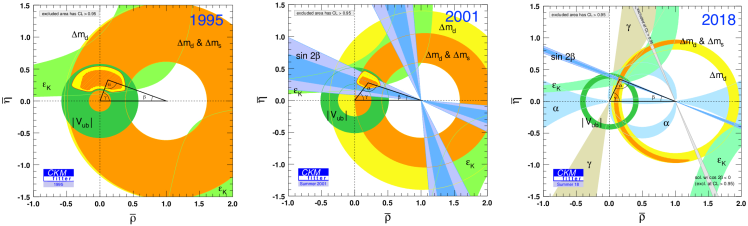
- **Flavor Physics** has become a very mature field



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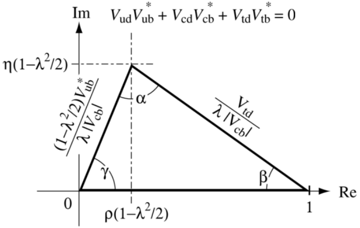

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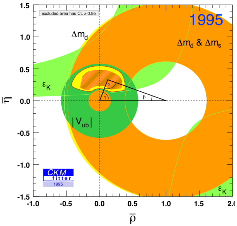
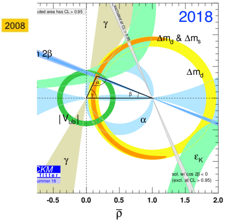


Kobayashi - Maskawa

$\bar\rho$

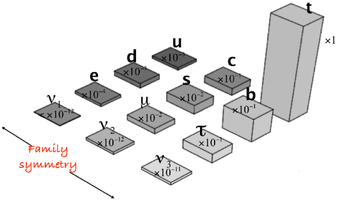


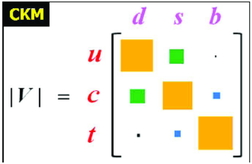
The SM Flavor Puzzle

- CKM and mass matrices: **Parametrizations** of flavor phenomena in the SM

Strong hierarchies in masses and mixings (PDG)

$m_{\rm up} = 0.0022(5)$ GeV $\qquad m_{\rm top} = 173.0(4)$ GeV



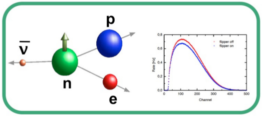


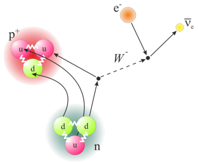
- Specific values of **light quarks** seem "tuned" (**Anthropic arguments!**)
- Origin of *CP*-violation
- **Why does Nature need three generations at all?**

Where is "flavor" coming from?

Testing the Standard Model with Flavor Physics

- **Effective field theories**
  - Add all operators consistent with **symmetries** and **matter content**
  - **Infinite terms? NO** if there is a **mass gap** $\Lambda_{\rm NewPhysics} \gg$ vev
- The classic example: Fermi theory for β decay!





$$\mathcal{L}_{\rm Fermi} = \frac{G_F}{\sqrt{2}}(\bar{p}n)_{V-A}(\bar{e}\nu)_{V-A}$$

- **Size of coupling contain info about Λ**

$$G_F = 1.1663787(6) \times 10^{-5}\text{GeV}^{-2} \simeq \frac{1}{m_W^2}$$

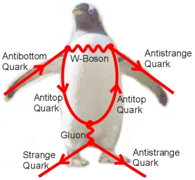
Standard Model EFT ($\Lambda \gg v_{\rm EW}$) Buchmuller & Wyler '88

$$\mathcal{L}_{\rm SMEFT} = \mathcal{L}_{\rm SM} + \frac{1}{\Lambda}\mathcal{O}_W^{(5)} + \overbrace{\frac{1}{\Lambda^2}\sum_i \mathcal{O}_i^{(6)}}^{\text{Generic New Physics}}$$

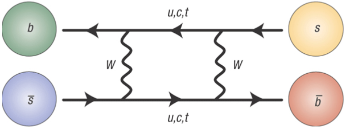
The Flavor Changing Neutral Currents (FCNC)

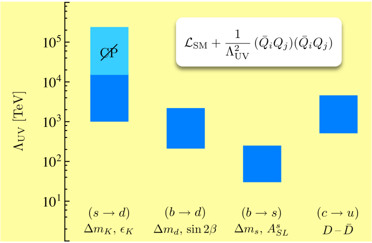
- **Theorem:** FCNC are **“Loop-Suppressed”** in the SM!

The Penguin Diagram



- Powerful probes of new physics!
- **Prototypical example:** Neutral-meson mixing





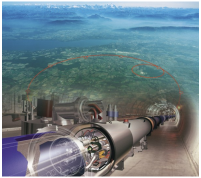
Generic bounds without a flavor symmetry

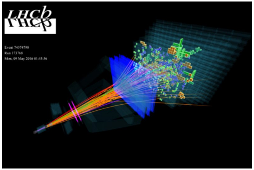
M. Neubert at EPS 2011

The experimental landscape in flavor physics

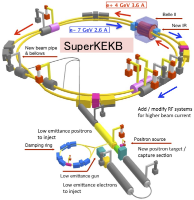
- Very exciting times in Flavor physics!

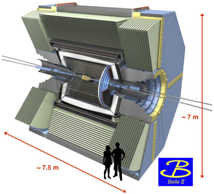
1. **Hadronic Machines:** Huge Statistics **vs.** Large backgrounds
   LHCb and **ATLAS** and **CMS** (CERN)





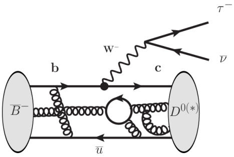
2. **Electron-Positron colliders:** Small statistics **vs** Clean environment
   SuperKEK-B and Belle 2 (Japan)



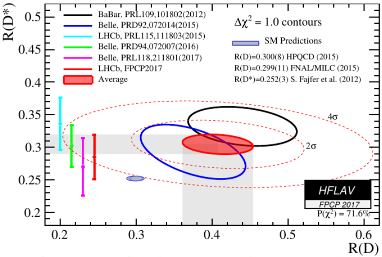


The Flavor Anomalies

LFUV in charged currents: $b \to c\tau\nu$



$$R_{D^{(*)}} = \frac{\mathcal{B}(\bar{B} \to D^{(*)}\tau^- \bar{\nu})}{\mathcal{B}(\bar{B} \to D^{(*)}\ell^- \bar{\nu})} \quad \text{where} \quad \ell = e, \mu$$



Belle: Hadronic tag, leptonic τ Semileptonic tag, leptonic τ Hadronic tag, hadronic τ

BaBar: Hadronic tag, leptonic τ LHCb: leptonic τ hadronic τ

- Several tensions in **two decay channels** by **three experiments**

$$\Lambda_{\mathrm{New-Physics}} \sim 3 \text{ TeV}$$

EFT of new-physics in $b \to c\tau\nu$

- **Form factors:** Decays difficult to predict because of **strong interactions**

Leptons do not feel the strong force

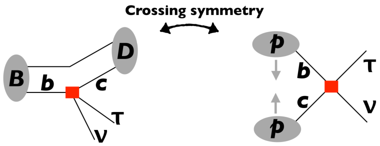
Form factors should cancel in ratios!

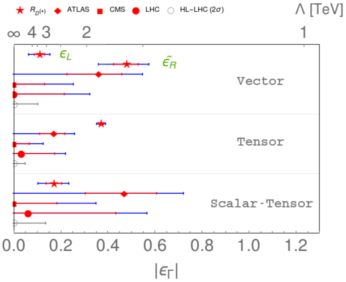
  - The SM + 5 New-Physics operators

    "V — A was the key", S. Weinberg

- **New-Physics Scale is 3 TeV $\Longrightarrow$ New-Physics is accesible at the LHC!**

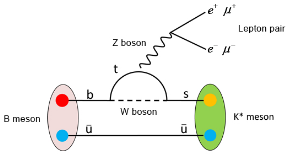
  - Collision of heavy "sea quarks"



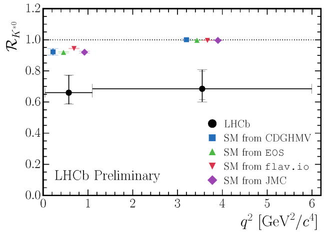


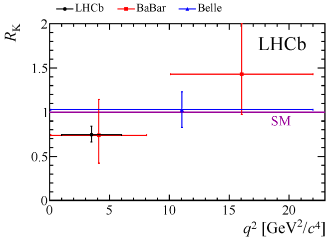
Phys. Rev. Lett., Greljo, Martin Camalich & Alvarez-Ruiz

Lepton-universality in Flavor-Changing-Neutral-Currents: $b \to s\ell^+\ell^-$



$$R_{K^{(*)}} = \frac{\mathcal{B}(\bar{B}\to K^{(*)}\mu^+\mu^-)}{\mathcal{B}(\bar{B}\to K^{(*)}e^+e^-)} \overset{\text{SM}}{\simeq} 1$$



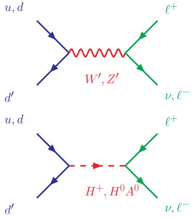


- Other "anomalies" in $\sim$ **100 observables** of the $b \to s\mu^+\mu^-$ mode
  - **Consistent tension** with the SM at close to discovery (5σ)!

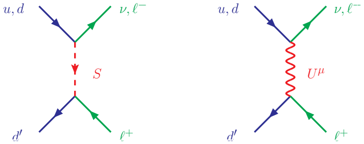
$$\Lambda_{\text{New}-\text{Physics}} \sim 30 \text{ TeV}$$

Are we really on the verge of discovering new physics?

- New stron-neutral particles: Vector triplet W', Z'

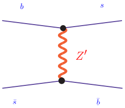


- New strong-interacting particles: Leptoquarks S, U^μ

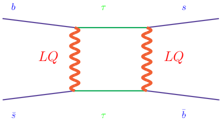


- **Extra bounds from low energy**

- Z' exchange at tree level



- LQ exchanges at loop level



The fate of the Flavor Anomalies

- **If confirmed Flavor anomalies would lead to a new revolution in Fundamental Physics**

> The new analysis of R_K is expected to be announced **tomorrow**

- LHCb and Belle II, but may more experiments doing specific studies
- ...and heavy involvement of ATLAS and CMS looking for the new particles!
  - **Also important in shaping the future experimental program in Particle Physics**

CERN Council Open Symposium on the Update of

European Strategy for Particle Physics

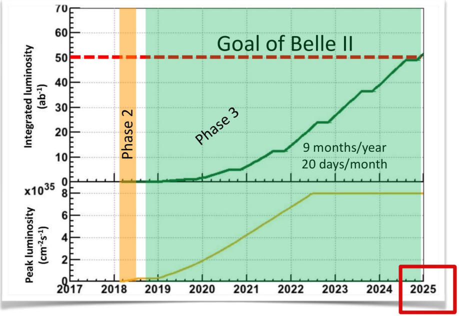
13-16 May 2019 - Granada, Spain

- **LHCb** and **ATLAS** and **CMS**

2019 2020	2021 2022 2023	2024 2025 2026	2027 2028 2029	2030 2031	2032 203+
	Run III		Run IV		Run V
LS2		LS3		LS4	
LHCb 40 MHz UPGRADE	$L = 2 \times 10^{33}$	LHCb Consolidation	$L = 2 \times 10^{33}$ 50 fb^{-1}	LHCb Ph II UPGRADE *	$L = 2 \times 10^{34}$ 300 fb^{-1}
ATLAS Phase I Upgr	$L = 2 \times 10^{34}$ 300 fb^{-1}	ATLAS Phase II UPGRADE	HL-LHC $L = 5 \times 10^{34}$	ATLAS	HL-LHC $L = 5 \times 10^{34}$ 3000 fb^{-1}
CMS Phase I Upgr		CMS Phase II UPGRADE		CMS	
Belle II	5 ab^{-1} $L = 8 \times 10^{35}$	50 ab^{-1}			

  - **LHCb now:** $\sim$ 10 fb^{-1} with many analysis only with $\sim$ 3 fb^{-1}!

- **Belle2**



Concluding Remarks

Flavor physics was instrumental in **discovering** and **shaping** the SM

- **Nuclear β-decays:** Discovery **weak interactions** and **neutrino**
- **Rare Kaon-decays:** Discovery of the **charm quark**
- **Kaon decays:** Discovery of *CP* **violation** $\Longrightarrow$ Discovery of **3 generations**

Flavor physics in the 21st century: A powerful field for discoveries!

- Addresses very fundamental theoretical questions
- Strong experimental program extending for the next **two decades**
- Strong interplay with other areas: Cosmology, Neutrinos, Collider Physics,...

★ **Discovery of *CP* violation in charmed system announced TODAY by LHCb!**