arXiv:1201.0537 (Standard Model)
arXiv:1512.08749 (Higgs Physics)
arXiv:1805.08597 (Flavour Physics)

Flavour Physics

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1. **Elementary constituents & fundamental interactions**
2. **Flavour-changing phenomena**
3. **Meson mixing & CP violation**

2021 JENNIFER2 Summer School, 19-27 July 2021

Flavour Structure of the Standard Model

$$\begin{pmatrix} u & \nu_e \\ d & e^- \end{pmatrix} , \quad \begin{pmatrix} c & \nu_\mu \\ s & \mu^- \end{pmatrix} , \quad \begin{pmatrix} t & \nu_\tau \\ b & \tau^- \end{pmatrix}$$

Why 3 ?

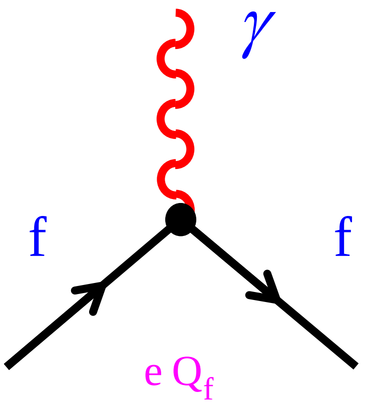
- **Pattern of masses**
- **Flavour Mixing**
- $\not{CP}$

Related to SSB

Scalar Sector (Higgs)

- **Kaon Factories :** u , d , s
- **τcF :** c , τ
- **BF:** b , c , τ
- **LHC :** t , b , c
- **LC, FCC :** t , b , c, τ
- **νF :** ν_e , ν_μ , ν_τ

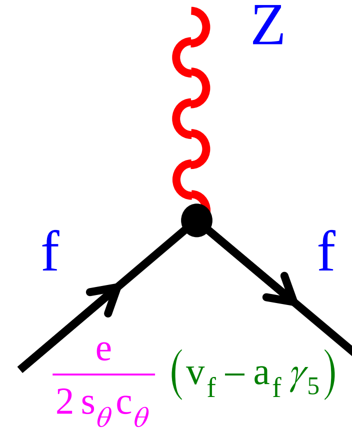
Universality: Family–Independent Couplings

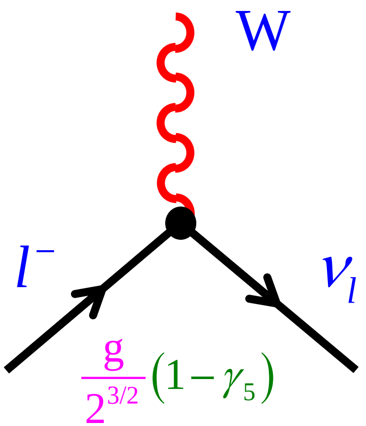


NEUTRAL

CURRENTS

Flavour Conserving



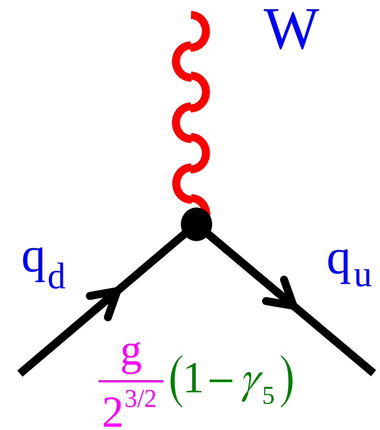


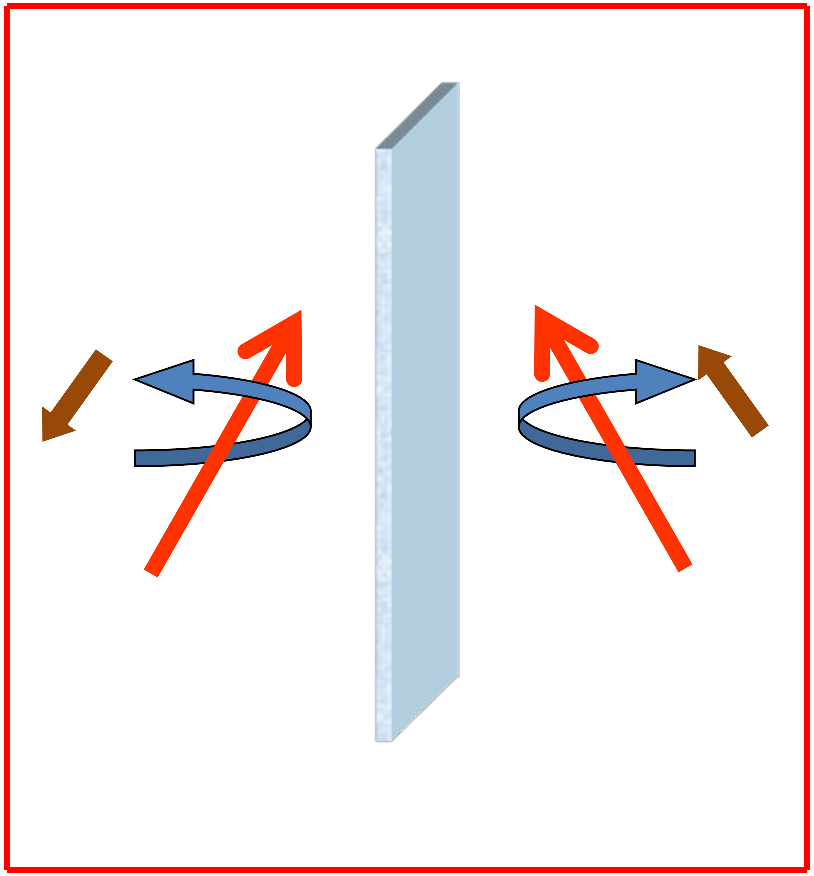
CHARGED

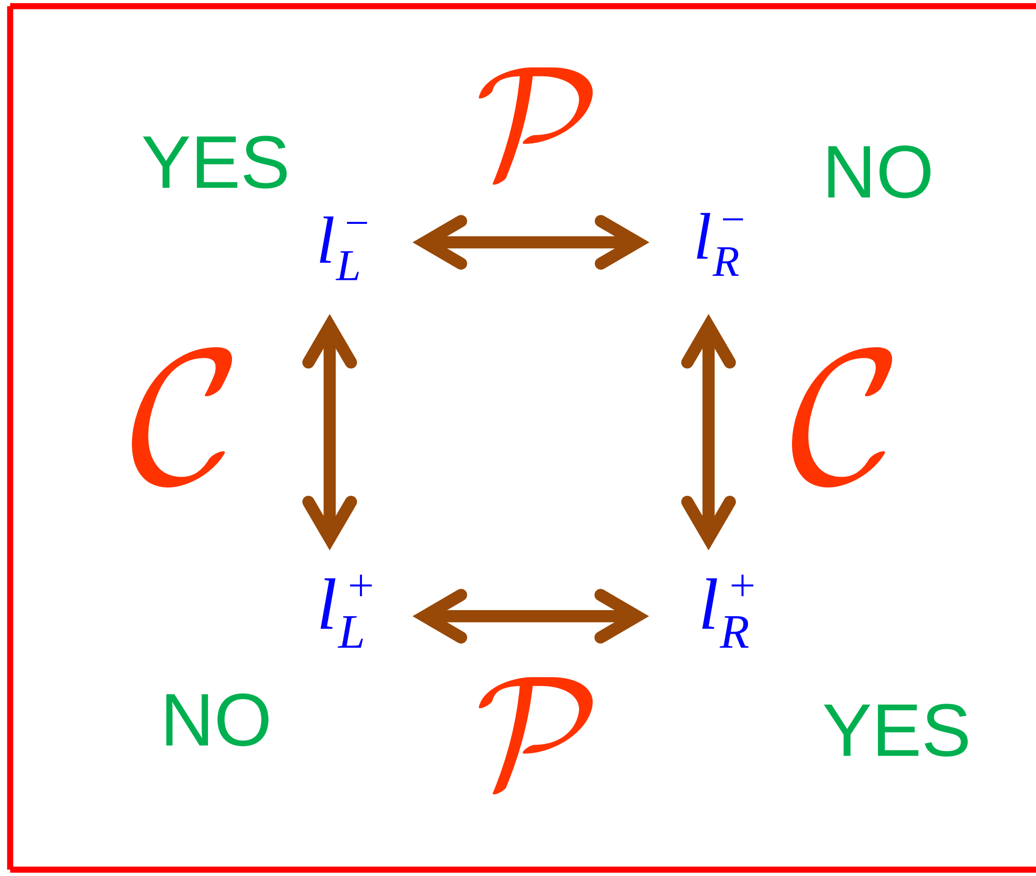
CURRENTS

Flavour Changing

Left Handed







$\not{\mathcal{P}}$ and $\not{\mathcal{C}}$ in Weak Interactions

$\mathcal{CP}$ still a good symmetry (1 family)

FERMION MASSES

Scalar – Fermion Couplings allowed by Gauge Symmetry

$$\mathcal{L}_Y = -\,(\bar{q}_u\,,\bar{q}_d)_L \left[c^{(d)} \begin{pmatrix} \phi^{(+)} \\ \phi^{(0)} \end{pmatrix} (q_d)_R + c^{(u)} \begin{pmatrix} \phi^{(0)\dagger} \\ -\phi^{(+)\dagger} \end{pmatrix} (q_u)_R \right] - (\bar{\nu}_l,\bar{l}\,)_L\; c^{(l)} \begin{pmatrix} \phi^{(+)} \\ \phi^{(0)} \end{pmatrix} l_R + \text{h.c.}$$

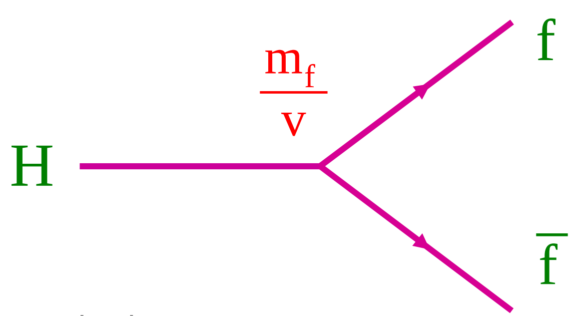
$\phi^{(0)} \to \frac{1}{\sqrt{2}}\,(\mathrm{v}+\mathrm{H})$, $\phi^{(+)} \to 0$

SSB

$$\mathcal{L}_Y = -\left(1+\frac{H}{\mathrm{v}}\right) \left\{ m_{q_d}\; \bar{q}_d\, q_d + m_{q_u}\; \bar{q}_u\, q_u + m_l\; \bar{l}\, l \right\}$$

Fermion Masses are
New Free Parameters

$$\left[m_{q_d}\,,\; m_{q_u}\,,\; m_l \right] = \left[c^{(d)}\,,\; c^{(u)}\,,\; c^{(l)} \right] \frac{\mathrm{v}}{\sqrt{2}}$$



Couplings Fixed: $g_{Hf\bar{f}} = \frac{m_f}{v}$

FERMION GENERATIONS

$\mathrm{N_G} = 3$ **Identical Copies** — **Masses are the only difference**

$$\begin{matrix} Q=0 \\ Q=-1 \end{matrix} \quad \begin{pmatrix} \nu'_j & u'_j \\ l'_j & d'_j \end{pmatrix} \quad \begin{matrix} Q=+2/3 \\ Q=-1/3 \end{matrix} \qquad (j=1,\cdots,\mathrm{N_G})$$

WHY ?

$$\mathcal{L}_Y = -\sum_{jk} \left\{ \left(\bar{u}'_j, \bar{d}'_j\right)_L \left[c_{jk}^{(d)} \begin{pmatrix} \phi^{(+)} \\ \phi^{(0)} \end{pmatrix} d'_{kR} + c_{jk}^{(u)} \begin{pmatrix} \phi^{(0)\dagger} \\ -\phi^{(+)\dagger} \end{pmatrix} u'_{kR} \right] - \left(\bar{\nu}'_j, \bar{l}'_j\right)_L c_{jk}^{(l)} \begin{pmatrix} \phi^{(+)} \\ \phi^{(0)} \end{pmatrix} l'_{kR} \right\} + \text{h.c.}$$

SSB

$$\mathcal{L}_Y = -\left(1 + \frac{H}{\mathrm{v}}\right) \left\{ \bar{d}'_L \cdot \mathbf{M}'_d \cdot d'_R + \bar{u}'_L \cdot \mathbf{M}'_u \cdot u'_R + \bar{l}'_L \cdot \mathbf{M}'_l \cdot l'_R + \text{h.c.} \right\}$$

Arbitrary Non-Diagonal Complex Mass Matrices

$$\left[\mathbf{M}'_d \,,\, \mathbf{M}'_u \,,\, \mathbf{M}'_l \right]_{jk} = \left[c_{jk}^{(d)} \,,\, c_{jk}^{(u)} \,,\, c_{jk}^{(l)} \right] \frac{\mathrm{v}}{\sqrt{2}}$$

DIAGONALIZATION OF MASS MATRICES

$$\mathbf{M}'_d = \mathbf{H}_d \cdot \mathbf{U}_d = \mathbf{S}_d^\dagger \cdot \boldsymbol{\mathcal{M}}_d \cdot \mathbf{S}_d \cdot \mathbf{U}_d$$

$$\mathbf{M}'_u = \mathbf{H}_u \cdot \mathbf{U}_u = \mathbf{S}_u^\dagger \cdot \boldsymbol{\mathcal{M}}_u \cdot \mathrm{S}_u \cdot \mathbf{U}_u$$

$$\mathbf{M}'_l = \mathbf{H}_l \cdot \mathbf{U}_l = \mathbf{S}_l^\dagger \cdot \boldsymbol{\mathcal{M}}_l \cdot \mathbf{S}_l \cdot \mathbf{U}_l$$

$$\mathbf{H}_\mathrm{f} = \mathbf{H}_\mathrm{f}^\dagger$$

$$\mathbf{U}_\mathrm{f} \cdot \mathbf{U}_\mathrm{f}^\dagger = \mathbf{U}_\mathrm{f}^\dagger \cdot \mathbf{U}_\mathrm{f} = 1$$

$$\mathbf{S}_\mathrm{f} \cdot \mathbf{S}_\mathrm{f}^\dagger = \mathbf{S}_\mathrm{f}^\dagger \cdot \mathbf{S}_\mathrm{f} = 1$$

$$\mathcal{L}_Y = -\left(1 + \frac{H}{v}\right) \left\{ \bar{\mathrm{d}} \cdot \boldsymbol{\mathcal{M}}_d \cdot \mathrm{d} + \bar{\mathrm{u}} \cdot \boldsymbol{\mathcal{M}}_u \cdot \mathrm{u} + \bar{l} \cdot \boldsymbol{\mathcal{M}}_l \cdot l \right\}$$

$$\boldsymbol{\mathcal{M}}_u = \mathrm{diag}\,(m_u, m_c, m_t) \quad ; \quad \boldsymbol{\mathcal{M}}_d = \mathrm{diag}\,(m_d, m_s, m_b) \quad ; \quad \boldsymbol{\mathcal{M}}_l = \mathrm{diag}\,(m_e, m_\mu, m_\tau)$$

$$\mathrm{d}_L \equiv \mathbf{S}_d \cdot \mathrm{d}'_L \quad ; \quad \mathrm{u}_L \equiv \mathbf{S}_u \cdot \mathrm{u}'_L \quad ; \quad l_L \equiv \mathbf{S}_l \cdot l'_L$$

$$\mathrm{d}_R \equiv \mathbf{S}_d \cdot \mathbf{U}_d \cdot \mathrm{d}'_R \quad ; \quad \mathrm{u}_R \equiv \mathbf{S}_u \cdot \mathbf{U}_u \cdot \mathrm{u}'_R \quad ; \quad l_R \equiv \mathbf{S}_l \cdot \mathbf{U}_l \cdot l'_R$$

Mass Eigenstates $\neq$ Weak Eigenstates

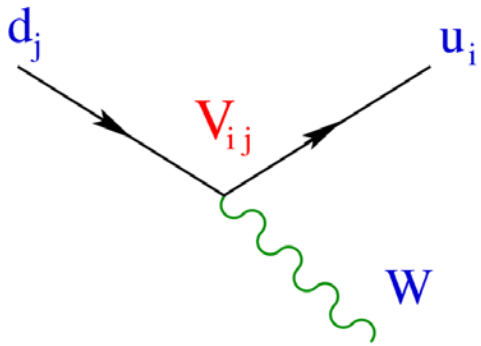
$$\bar{\mathrm{f}}'_L \, \mathrm{f}'_L = \bar{\mathrm{f}}_L \, \mathrm{f}_L \quad ; \quad \bar{\mathrm{f}}'_R \, \mathrm{f}'_R = \bar{\mathrm{f}}_R \, \mathrm{f}_R \quad \Longrightarrow \quad \mathcal{L}'_{\mathrm{NC}} = \mathcal{L}_{\mathrm{NC}}$$

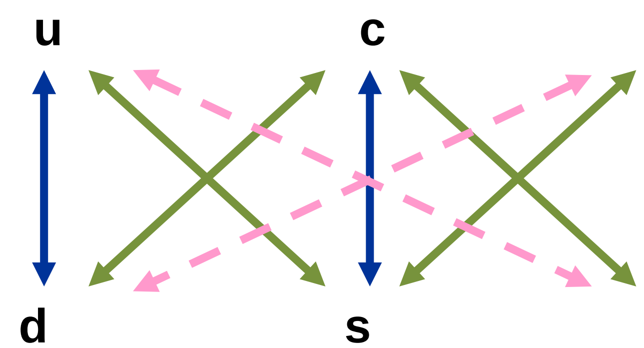
$$\bar{\mathrm{u}}'_L \, \mathrm{d}'_L = \bar{\mathrm{u}}_L \cdot \mathbf{V} \cdot \mathrm{d}_L \quad ; \quad \mathbf{V} \equiv \mathbf{S}_u \cdot \mathbf{S}_d^\dagger \quad \Longrightarrow \quad \mathcal{L}'_{\mathrm{CC}} \neq \mathcal{L}_{\mathrm{CC}}$$

QUARK MIXING

Flavour Changing Charged Currents

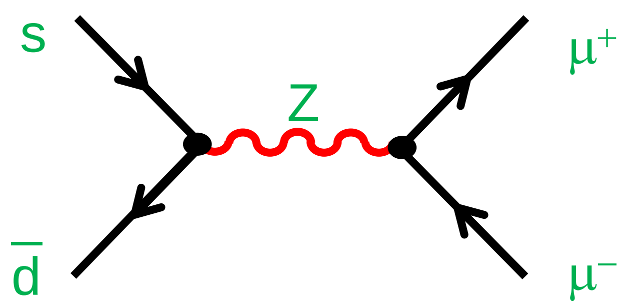
$$\mathcal{L}_{CC} = -\frac{g}{2\sqrt{2}}\, W_\mu^\dagger \left[\sum_{ij} \bar{u}_i \gamma^\mu (1-\gamma_5)\, \mathbf{V}_{ij}\, d_j + \sum_l \bar{\nu}_l \gamma^\mu (1-\gamma_5)\, l \right] + \text{h.c.}$$





Flavour Conserving Neutral Currents (GIM)

NO

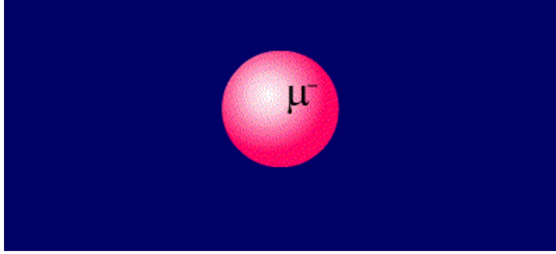


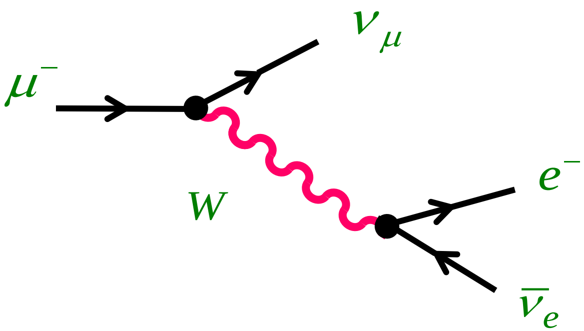
LHCb, 2001.10354

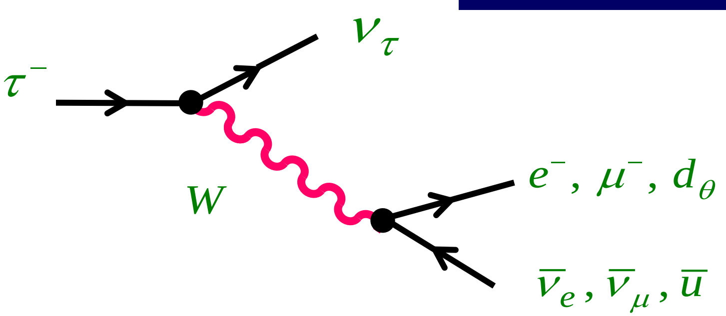
$$\mathrm{Br}(K_S \to \mu^+\mu^-) < 2.1\times 10^{-10}$$

(90% CL)

Weak Decays







$$T(l \to \nu_l \, l' \bar{\nu}_{l'}) \sim \frac{g^2}{M_W^2 - q^2} \xrightarrow{q^2 \ll M_W^2} \frac{g^2}{M_W^2} = 4\sqrt{2}\, G_F$$

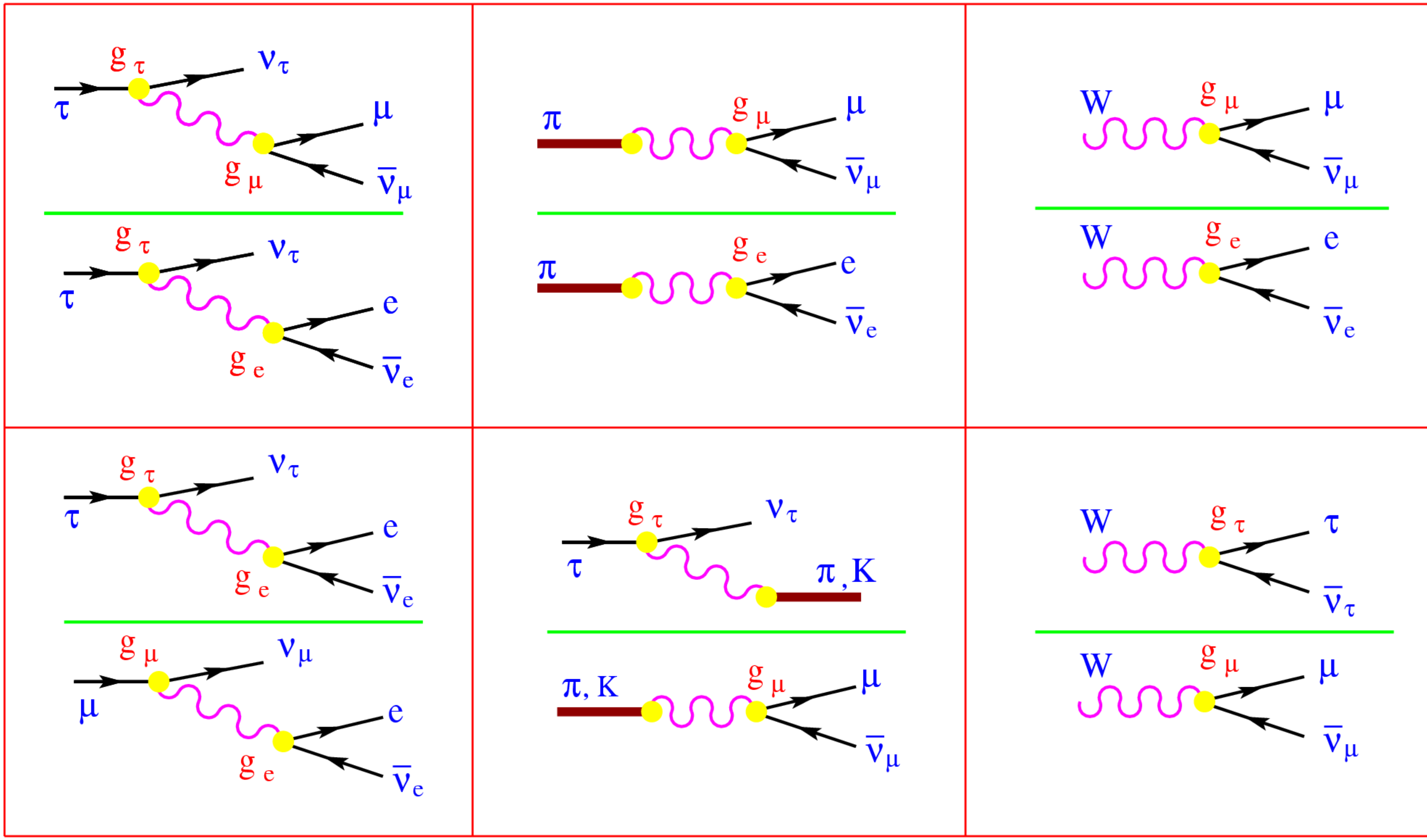
$$\frac{1}{\tau_\mu} = \frac{G_F^2 m_\mu^5}{192\pi^3} f(m_e^2/m_\mu^2)\, r_{EW} \quad \Longrightarrow \quad G_F = (1.166\,378\,7 \pm 0.000\,000\,6) \times 10^{-5}\ \text{GeV}^{-2}$$

$$r_{EW} = \left[1 + \frac{\alpha(m_\mu)}{2\pi}\left(\frac{25}{4} - \pi^2\right) + C_2 \frac{\alpha(m_\mu)^2}{\pi^2}\right] = 0.9958 \quad ; \quad f(x) = 1 - 8x + 8x^3 - x^4 - 12x^2 \log x$$

LEPTON UNIVERSALITY

$\frac{g_\mu}{g_e}$

$\frac{g_\tau}{g_\mu}$



CHARGED CURRENT UNIVERSALITY

A. Pich, arXiv:2012.07099

$|g_\mu / g_e|$

$B_{\tau\to\mu}/B_{\tau\to e}$	1.0017 ± 0.0016
$B_{\pi\to\mu}/B_{\pi\to e}$	1.0010 ± 0.0009
$B_{K\to\mu}/B_{K\to e}$	0.9978 ± 0.0018
$B_{K\to\pi\mu}/B_{K\to\pi e}$	1.0010 ± 0.0025
$B_{W\to\mu}/B_{W\to e}$	0.998 ± 0.004

$|g_\tau / g_\mu|$

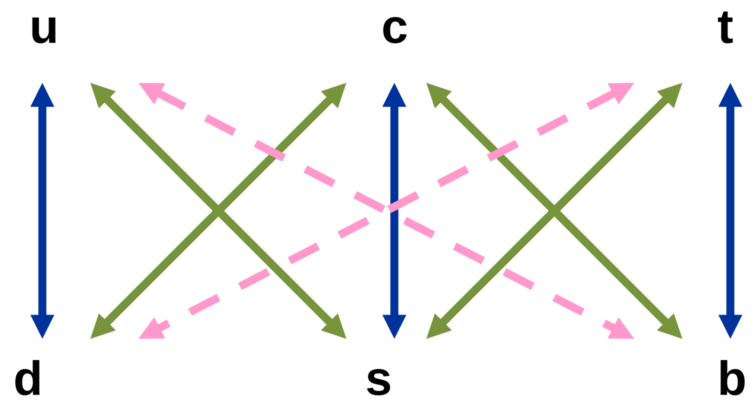
$B_{\tau\to e}\;\tau_\mu/\tau_\tau$	1.0011 ± 0.0014
$\Gamma_{\tau\to\pi}/\Gamma_{\pi\to\mu}$	0.9965 ± 0.0026
$\Gamma_{\tau\to K}/\Gamma_{K\to\mu}$	0.986 ± 0.007
$B_{W\to\tau}/B_{W\to\mu}$	1.004 ± 0.016

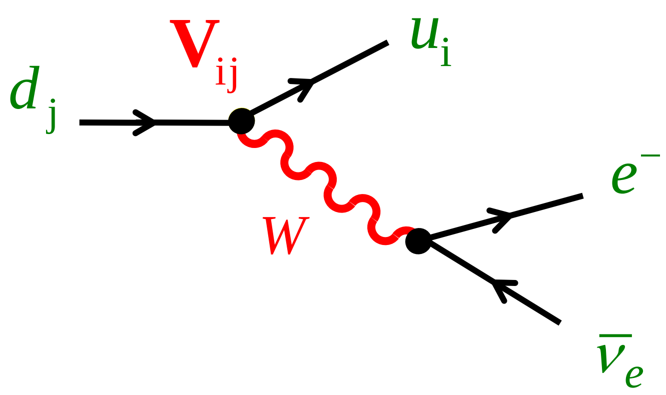
$|g_\tau / g_e|$

$B_{\tau\to\mu}\;\tau_\mu/\tau_\tau$	1.0028 ± 0.0015
$B_{W\to\tau}/B_{W\to e}$	1.022 ± 0.012

0.997 ± 0.011 (CMS preliminary)

Flavour Changing Charged Currents





$$\Gamma(d_j \to u_i \, e^- \, \overline{\nu}_e) \propto \left|\mathbf{V}_{ij}\right|^2$$

We measure decays of hadrons (no free quarks)

Important QCD Uncertainties

V_{ij} Determinations

PDG 2020

CKM entry	Value	Source
$\|V_{ud}\|$	0.97370 ± 0.00014	Nuclear β decay
$\|V_{us}\|$	0.2245 ± 0.0008	$K \to (\pi)\ell\nu$
$\|V_{cd}\|$	0.221 ± 0.004	$D \to (\pi)\ell\nu\,,\ \nu d \to c\,X$
$\|V_{cs}\|$	0.987 ± 0.011	$D \to K\,\ell\nu\,,\ D_s \to \ell\nu$
$\|V_{cb}\|$	0.0410 ± 0.0014	$b \to c\,\ell\,\nu\,,\ B \to D^{(*)}\ell\,\nu$
$\|V_{ub}\|$	0.00382 ± 0.00024	$b \to u\,\ell\,\nu\,,\ B \to \pi\,\ell\,\nu$
$\|V_{tb}\|$	1.013 ± 0.030	$p\bar{p},\, p\,p \to tb + X$
$\|V_{tb}\| \Big/ \sqrt{\sum_q \|V_{tq}\|^2}$	> 0.975 (95% CL)	$t \to bW \,/\, t \to qW$
$\|V_{td}\|$	0.0080 ± 0.0003	$B_d^0 - \bar{B}_d^0$ mixing
$\|V_{ts}\|$	0.0388 ± 0.0011	$B_s^0 - \bar{B}_s^0$ mixing

PDG 2018

0.97420 (21)

0.2243 (5)

0.9994 ± 0.0005 (PDG 2018)

$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 0.9985 \pm 0.0005$$

$$|V_{cd}|^2 + |V_{cs}|^2 + |V_{cb}|^2 = 1.025 \pm 0.022$$

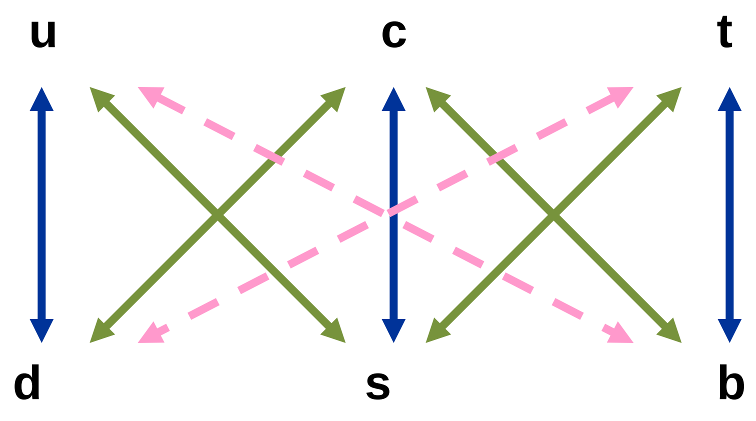
$$|V_{ub}|^2 + |V_{cb}|^2 + |V_{tb}|^2 = 1.028 \pm 0.061$$

$$\sum_j \left(|V_{uj}|^2 + |V_{cj}|^2 \right) = 2.002 \pm 0.027 \quad \text{(LEP)}$$

Hierarchical Structure

$$\mathbf{V} \approx \begin{bmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{bmatrix} + \mathcal{O}\left(\lambda^4\right)$$

$$\lambda \approx \sin\theta_C \approx 0.225 \quad ; \quad A \approx 0.81 \quad ; \quad \sqrt{\rho^2+\eta^2} \approx 0.4$$



QUARK MIXING MATRIX

- **Unitary** $N_G \times N_G$ **Matrix:** N_G^2 **parameters**

$$\mathbf{V} \cdot \mathbf{V}^\dagger = \mathbf{V}^\dagger \cdot \mathbf{V} = \mathbf{1}$$

$\frac{1}{2} N_G (N_G - 1)$ moduli, $\frac{1}{2} N_G (N_G + 1)$ phases

- $2 N_G - 1$ **arbitrary phases:** $\overline{u}_i \, \mathbf{V}_{ij} \, d_j$

$$u_i \to e^{i\phi_i} u_i \quad ; \quad d_j \to e^{i\theta_j} d_j \quad \Rightarrow \quad \mathbf{V}_{ij} \to e^{i(\theta_j - \phi_i)} \mathbf{V}_{ij}$$

$\Downarrow$

$\mathbf{V}_{ij}$ Physical Parameters:

$\frac{1}{2} N_G (N_G - 1)$ **moduli** ; $\frac{1}{2} (N_G - 1)(N_G - 2)$ **phases**

- **$N_f = 2$: 1 angle, 0 phases (Cabibbo)**

$$\mathbf{V} = \begin{bmatrix} \cos\theta_C & \sin\theta_C \\ -\sin\theta_C & \cos\theta_C \end{bmatrix} \Rightarrow \text{No } \not{\mathcal{CP}}$$

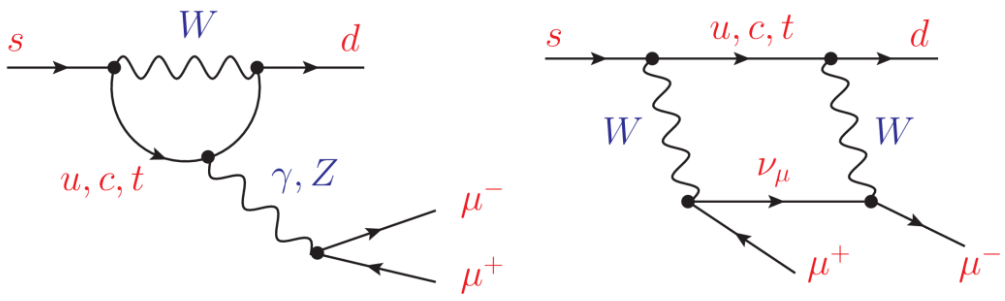
- **$N_f = 3$:** 3 angles, 1 phase **(CKM)** $\quad c_{ij} \equiv \cos\theta_{ij} \;;\; s_{ij} \equiv \sin\theta_{ij}$

$$\mathbf{V} = \begin{bmatrix} c_{12}\,c_{13} & s_{12}\,c_{13} & s_{13}\,e^{-i\delta_{13}} \\ -s_{12}\,c_{23} - c_{12}\,s_{23}\,s_{13}\,e^{i\delta_{13}} & c_{12}\,c_{23} - s_{12}\,s_{23}\,s_{13}\,e^{i\delta_{13}} & s_{23}\,c_{13} \\ s_{12}\,s_{23} - c_{12}\,c_{23}\,s_{13}\,e^{i\delta_{13}} & -c_{12}\,s_{23} - s_{12}\,c_{23}\,s_{13}\,e^{i\delta_{13}} & c_{23}\,c_{13} \end{bmatrix}$$

$$\approx \begin{bmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{bmatrix} + \mathcal{O}\left(\lambda^4\right)$$

$\lambda \approx \sin\theta_C \approx 0.225 \;;\; A \approx 0.81 \;;\; \sqrt{\rho^2+\eta^2} \approx 0.4$ $\qquad \delta_{13} \neq 0 \;\; (\eta \neq 0) \Rightarrow \not{\mathcal{CP}}$

GIM Mechanism



$$\mathcal{M} \propto \sum_{i=u,c,t} V_{is} V_{id}^* F(m_i^2/M_W^2)$$

$$\sum_{i=u,c,t} V_{is} V_{id}^* = 0 \quad \Rightarrow \quad \mathcal{M} = 0 \quad \text{if} \quad m_u = m_c = m_t$$

$$\tilde{F}(x) \equiv F(x) - F(0) \quad \Rightarrow$$

$$\mathcal{M} \propto V_{cs} V_{cd}^* \tilde{F}(m_c^2/M_W^2) + V_{ts} V_{td}^* \tilde{F}(m_t^2/M_W^2)$$

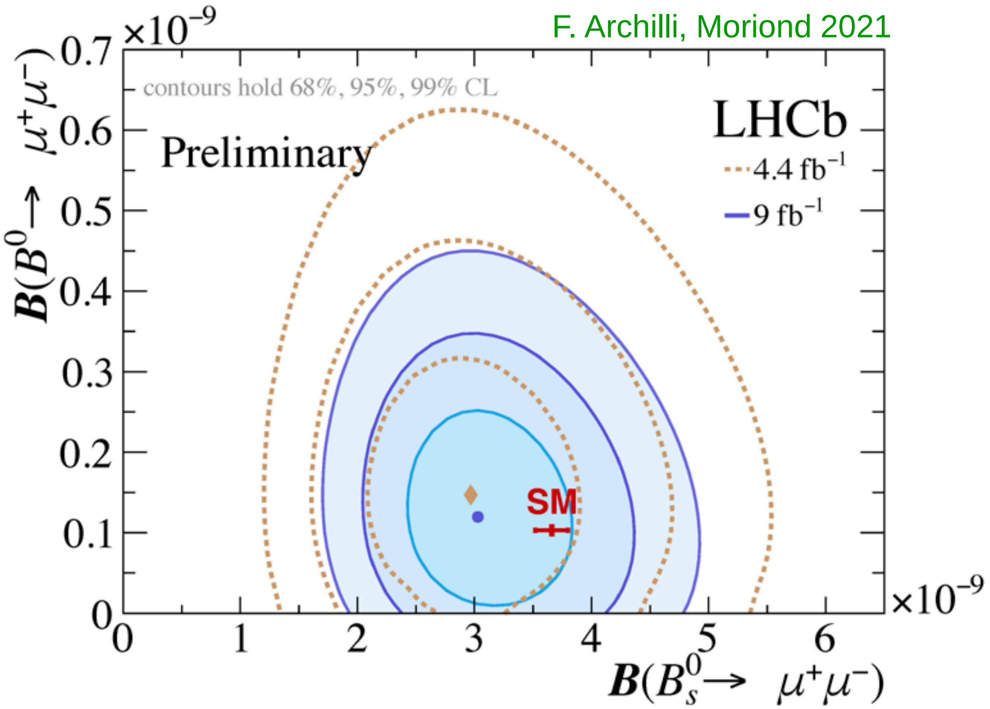
$$\approx -\lambda \tilde{F}(m_c^2/M_W^2) - \lambda^5 A^2 (1-\rho+i\eta) \tilde{F}(m_t^2/M_W^2)$$

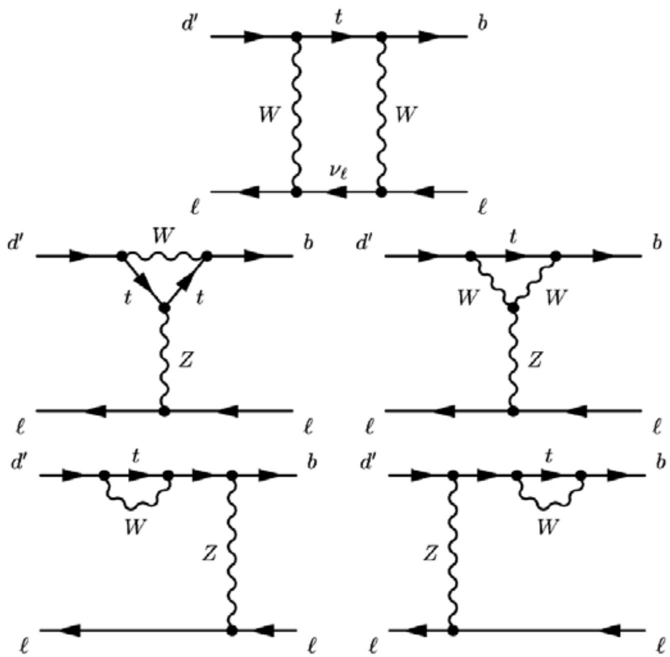
- **Top contribution dominates. Strong suppression:** $\mathcal{M} \propto \frac{g^4}{16\pi^2} \left[\lambda^5 A^2 \frac{m_t^2}{M_W^2}, \lambda \frac{m_c^2}{M_W^2} \right]$
- **C̸P effects fully governed by top contribution** $\left[\text{Im}(V_{cs} V_{cd}^*) = -\text{Im}(V_{ts} V_{td}^*) \right]$

Rare Decays

Loop & CKM suppression
Sensitivity to New Physics

$B_{s,d} \to \mu^+\mu^-$





$W^{\pm} \leftrightarrow H^{\pm}$, $Z \leftrightarrow H^0, A^0$

$$\bar{B}(B_s^0 \to \mu^+\mu^-)_{\rm exp} = (2.9 \pm 0.4) \cdot 10^{-9}$$

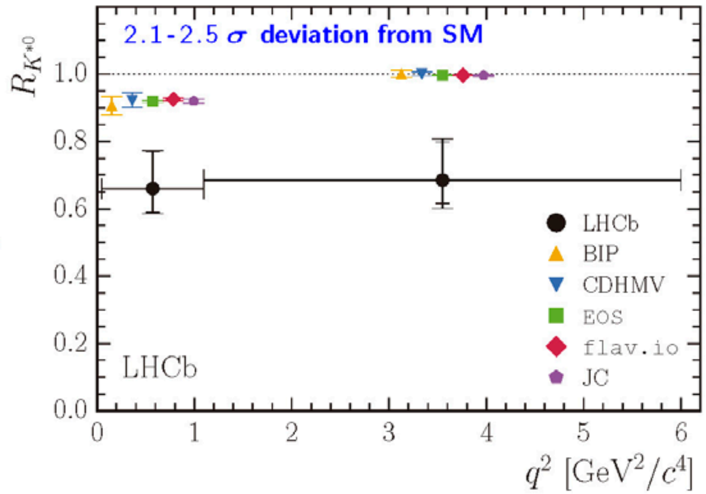
$$\bar{B}(B_d^0 \to \mu^+\mu^-)_{\rm exp} = \left(0.5 {}^{+1.7}_{-1.5}\right) \cdot 10^{-10}$$

Sensitive to (pseudo) scalar contributions

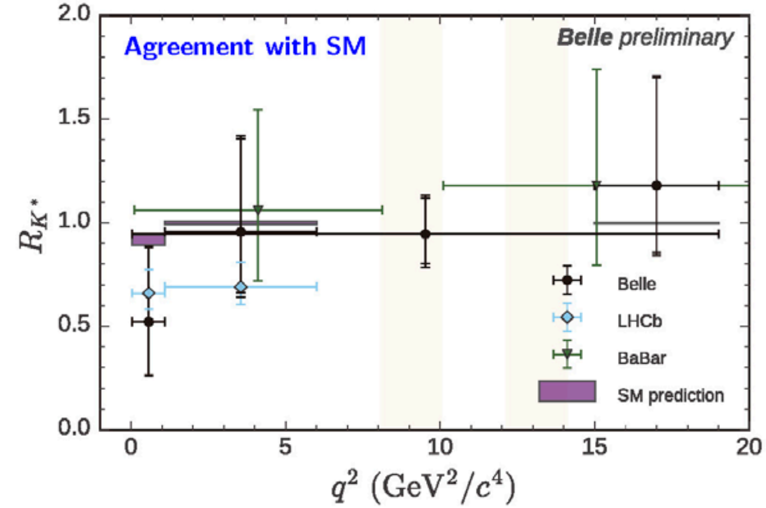
Violations of Lepton Flavour Universality

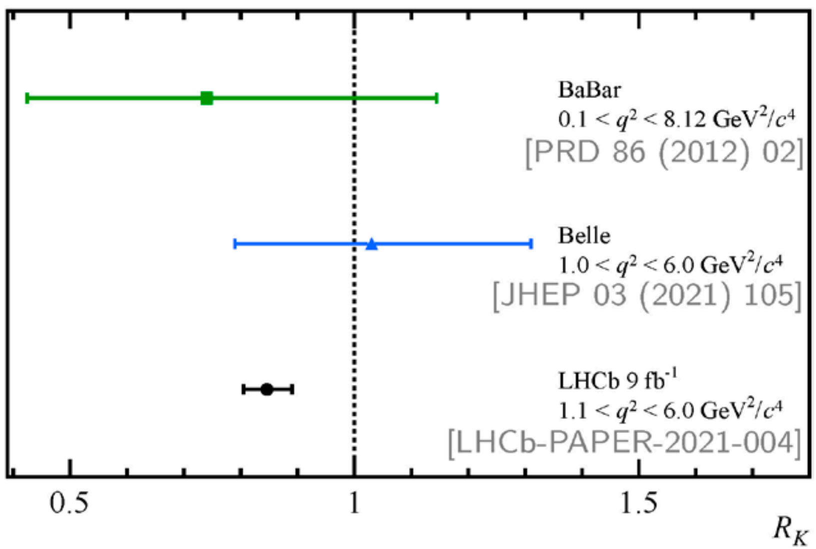
$$\frac{\Gamma(B \to K^* \mu^+ \mu^-)}{\Gamma(B \to K^* e^+ e^-)}$$

LHCb 1705.05802



Belle 1904.02440





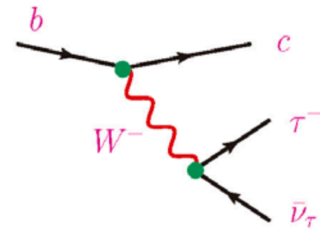
$$R_K \equiv \frac{\Gamma(B^+ \to K^+ \mu^+ \mu^-)}{\Gamma(B^+ \to K^+ e^+ e^-)} = 0.846 \, {}^{+0.042}_{-0.039} \, {}^{+0.013}_{-0.012}$$

3.1 σ below the SM

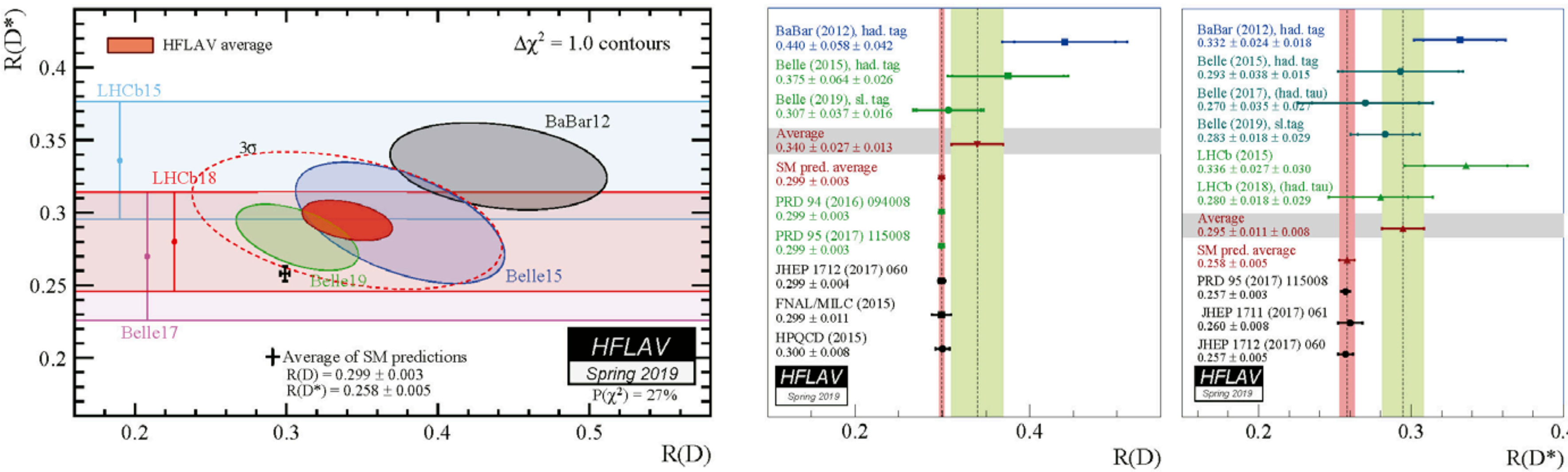
Flavour Anomaly (charged currents)

$$\mathcal{R}_{D^{(*)}} \equiv \frac{\mathcal{B}(\bar{B} \to D^{(*)} \tau^- \bar{\nu}_\tau)}{\mathcal{B}(\bar{B} \to D^{(*)} \ell^- \bar{\nu}_\ell)}$$

Tree-level process



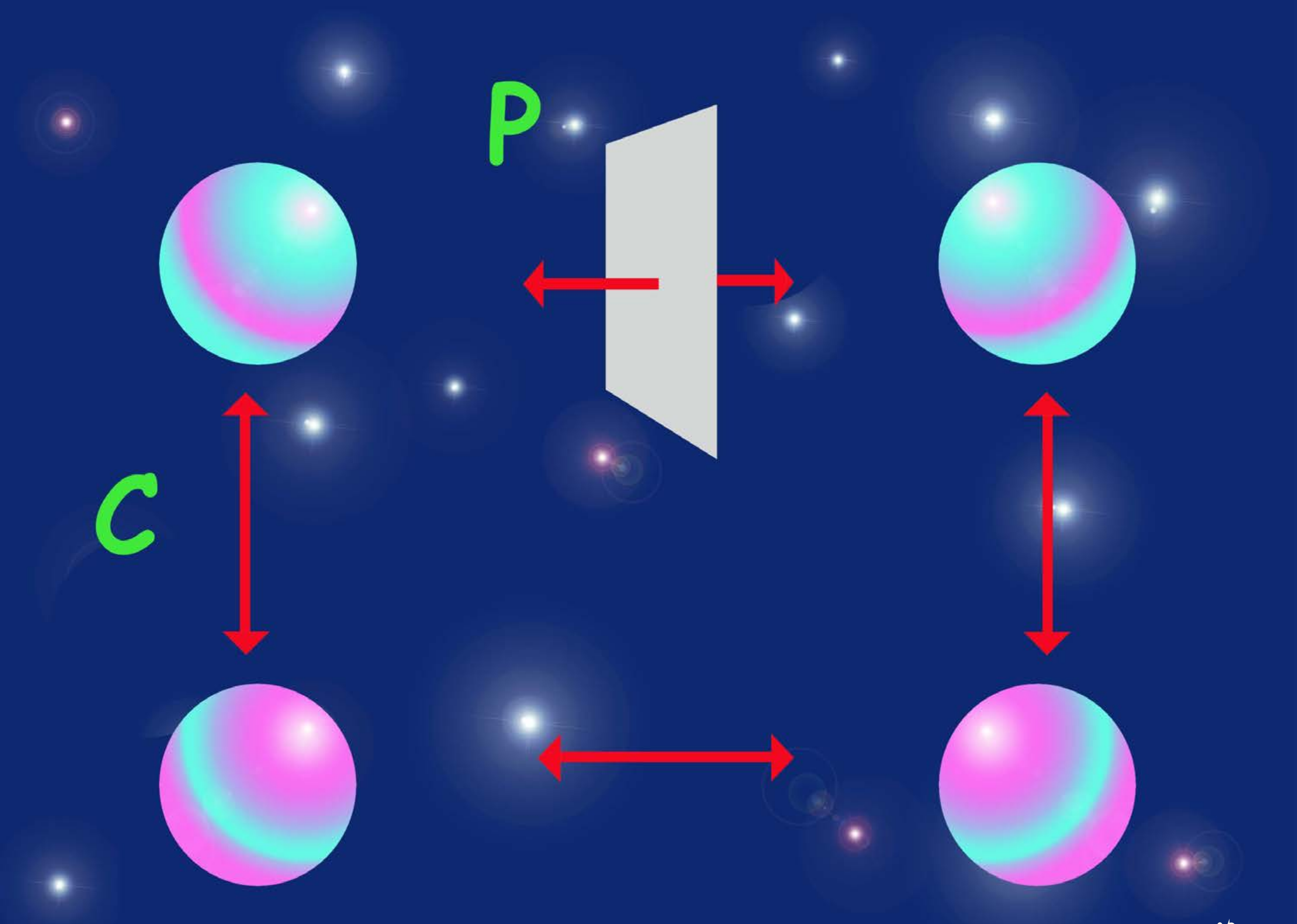
3.08 σ discrepancy (3.2 σ with more recent predictions)



LHCb, 1711.05623: $\mathcal{R}_{J/\psi} \equiv \frac{\mathcal{B}(B_c \to J/\psi \tau \bar{\nu}_\tau)}{\mathcal{B}(B_c \to J/\psi \mu \bar{\nu}_\mu)} = 0.71 \pm 0.17 \pm 0.18$ $(1.7\,\sigma)$ $\mathcal{R}^{\rm SM}_{J/\psi} \approx 0.26 - 0.28$

Belle, 1903.03102: $F_L^{D^*} = 0.60 \pm 0.08 \pm 0.04$ $(1.6\,\sigma)$ $F^{D^*}_{L,\rm SM} = 0.455 \pm 0.003$

Belle, 1612.00529: $\mathcal{P}_\tau^{D^*} = -0.38 \pm 0.51^{+0.21}_{-0.16}$ $\mathcal{P}^{D^*}_{\tau,\rm SM} = -0.499 \pm 0.003$


P
C

- $\mathcal{C}$, $\mathcal{P}$: Violated maximally in weak interactions
- $\mathcal{CP}$: Symmetry of nearly all observed phenomena
- Slight (~ 0.2 %) $\not{\mathcal{CP}}$ in K^0 decays (1964)
- Sizeable $\not{\mathcal{CP}}$ in B^0 decays (2001)
- Huge Matter — Antimatter Asymmetry in our Universe

  → Baryogenesis

- Small $\not{\mathcal{CP}}$ in D^0 decays (LHCb, 2019)

$\mathcal{CPT}$ Theorem: $\not{\mathcal{CP}}$ ⟷ $\not{\mathcal{T}}$

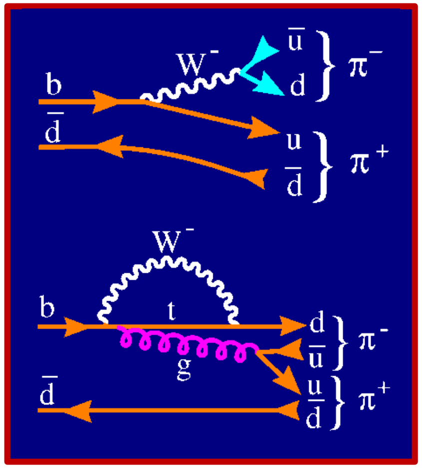
Thus, $\not{\mathcal{CP}}$ requires:

- Complex Phases
- Interferences

DIRECT $\not{\mathcal{CP}}$

$$\left|\mathbf{T}(P \to f)\right| \neq \left|\mathbf{T}(\overline{P} \to \overline{f})\right|$$

$\overline{B}_d^0$



$$\mathbf{T}(P \to f) = T_1\, e^{i\phi_1}\, e^{i\delta_1} + T_2\, e^{i\phi_2}\, e^{i\delta_2}$$

$\mathcal{CP}$

$$\mathbf{T}(\overline{P} \to \overline{f}) = T_1\, e^{-i\phi_1}\, e^{i\delta_1} + T_2\, e^{-i\phi_2}\, e^{i\delta_2}$$

$$A^{CP}_{P\to f} \equiv \frac{\Gamma(P\to f) - \Gamma(\overline{P}\to\overline{f})}{\Gamma(P\to f) + \Gamma(\overline{P}\to\overline{f})} = \frac{-2\, T_1 T_2\, \sin(\phi_2-\phi_1)\, \sin(\delta_2-\delta_1)}{T_1^{\,2} + T_2^{\,2} + 2\, T_1 T_2\, \cos(\phi_2-\phi_1)\, \cos(\delta_2-\delta_1)}$$

One needs:

- **2 Interfering Amplitudes**
- **2 Different Weak Phases** $\left[\sin(\phi_2-\phi_1)\neq 0\right]$
- **2 Different FSI Phases** $\left[\sin(\delta_2-\delta_1)\neq 0\right]$

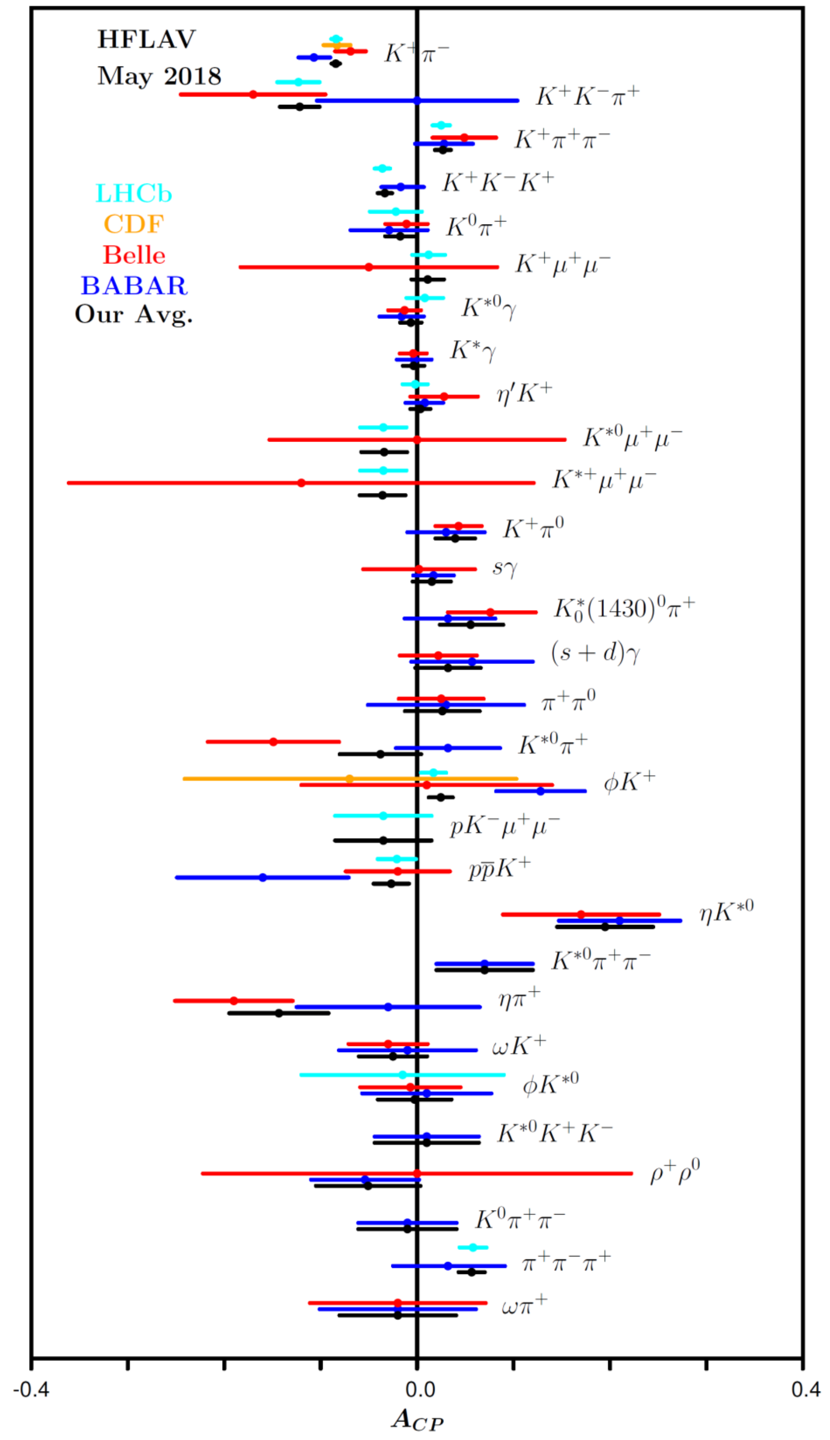
DIRECT $C\!\!\!/P$

$$A_{CP}(B \to f) \equiv \frac{\mathrm{Br}(\bar{B} \to \bar{f}) - \mathrm{Br}(B \to f)}{\mathrm{Br}(\bar{B} \to \bar{f}) + \mathrm{Br}(B \to f)}$$

$$A_{CP}(B_d^0 \to \pi^- K^+) = -0.084 \pm 0.004$$ **(21 σ)**

$$A(B_s^0 \to \pi^- K^+) = -0.213 \pm 0.017$$ **(12.5 σ)**

$$A_{CP}(B^+ \to K^+ K^- \pi^+) = -0.122 \pm 0.021$$ **(5.8 σ)**



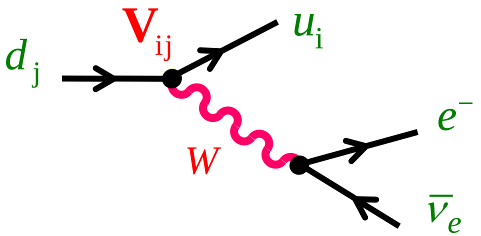
Large & Interesting Signals

Big challenge: Get reliable SM predictions

Severe hadronic uncertainties

Backup

$\mathbf{V_{ij}}$ Determination $(0^- \to 0^-)$



$K \to \pi \ell \nu$, $D \to K \ell \nu \ldots$

$$\langle P'(k')|\bar{u}_i\gamma^\mu d_j|P(k)\rangle = C_{PP'}\left\{(k+k')^\mu \; f_+(q^2) + (k-k')^\mu \; f_-(q^2)\right\}$$

$$\Gamma(P \to P' l \nu) = \frac{G_F^2 M_P^5}{192\pi^3} \, |\mathbf{V_{ij}}|^2 \, C_{PP'}^2 \, |f_+(0)|^2 \, \mathbf{I} \, (1+\delta_{\mathrm{RC}})$$

$$\mathbf{I} \approx \int_0^{(M_P-M_{P'})^2} \frac{dq^2}{M_P^8} \, \lambda^{3/2}(q^2, M_P^2, M_{P'}^2) \left|\frac{f_+(q^2)}{f_+(0)}\right|^2$$

$f_-(q^2)$ suppressed

$(k-k')^\mu \; \bar{l}\gamma_\mu(1-\gamma_5)\nu_l \sim m_l$

- Measure the q^2 distribution ➡ $\mathbf{I}$
- Measure Γ ➡ $f_+(0)\,|\mathbf{V_{ij}}|$
- Get a theoretical prediction for $f_+(0)$ ➡ $|\mathbf{V_{ij}}|$

Theory is always needed: Symmetries

PDG parametrization of the CKM matrix

$$\mathbf{V} = \begin{bmatrix} c_{12}\, c_{13} & s_{12}\, c_{13} & s_{13}\, e^{-i\delta_{13}} \\ -s_{12}\, c_{23} - c_{12}\, s_{23}\, s_{13}\, e^{i\delta_{13}} & c_{12}\, c_{23} - s_{12}\, s_{23}\, s_{13}\, e^{i\delta_{13}} & s_{23}\, c_{13} \\ s_{12}\, s_{23} - c_{12}\, c_{23}\, s_{13}\, e^{i\delta_{13}} & -c_{12}\, s_{23} - s_{12}\, c_{23}\, s_{13}\, e^{i\delta_{13}} & c_{23}\, c_{13} \end{bmatrix}$$

$$= \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}\, e^{-i\delta_{13}} \\ 0 & 1 & 0 \\ -s_{13}\, e^{i\delta_{13}} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

Wolfenstein: $s_{12} \equiv \lambda \quad , \quad s_{23} \equiv A\lambda^2 \quad , \quad s_{13}\, e^{-i\delta_{13}} \equiv A\lambda^3(\rho - i\eta)$

$$\Rightarrow \quad \mathbf{V} \approx \begin{bmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3\,(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\,\lambda^2 \\ A\lambda^3\,(1-\rho-i\eta) & -A\,\lambda^2 & 1 \end{bmatrix} + \mathcal{O}\left(\lambda^4\right)$$

Standard Model $\not{\mathcal{CP}}$: 3 fermion families needed

$$\not{\mathcal{CP}} \quad \Longleftrightarrow \quad \mathbf{H}(M_u^2) \cdot \mathbf{H}(M_d^2) \cdot \mathbf{J} \neq 0$$

$$\mathbf{H}(M_u^2) \equiv (m_t^2 - m_c^2)\,(m_c^2 - m_u^2)\,(m_t^2 - m_u^2)$$

$$\mathbf{H}(M_d^2) \equiv (m_b^2 - m_s^2)\,(m_s^2 - m_d^2)\,(m_b^2 - m_d^2)$$

$$\mathbf{J} = c_{12}\, c_{13}^2\, c_{23}\, s_{12}\, s_{13}\, s_{23} \sin\delta_{13} = \left| A^2 \lambda^6 \eta \right| < 10^{-4}$$

- **Low-Energy Phenomena**

$\Rightarrow$

- **Small Effects ~ J**
- **Big Asymmetries $\Longleftrightarrow$ Suppressed Decays**
- **B Decays are an optimal place for $\not{\mathcal{CP}}$ signals**