Current Status and Future of Flavour Physics

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The Future of Particle Physics in the Post-Higgs Landscape

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What is Flavour 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.”

RMP 81 (2009) 1887
What is Flavour Physics?

Starting from the Standard Model parameters:

- 3 gauge couplings + QCD vacuum angle
- 2 Higgs parameters
- 6 quark masses
- 3 quark mixing angles + 1 phase
- 3 (+3) lepton masses
- (3 lepton mixing angles + 1 phase)

flavour parameters

( ) = with Dirac neutrino masses
What is Flavour Physics?

\[
\begin{align*}
\mu &\approx 3 \text{ MeV} \\
\mu_d &\approx 5 \text{ MeV} \\
\mu_s &\approx 100 \text{ MeV} \\
\mu_c &\approx 1300 \text{ MeV} \\
\mu_b &\approx 4200 \text{ MeV} \\
\mu_t &\approx 170000 \text{ MeV}
\end{align*}
\]

\[
\begin{align*}
\nu_1 &\leq 10^{-6} \text{ MeV} \\
\nu_2 &\leq 10^{-6} \text{ MeV} \\
\nu_3 &\leq 10^{-6} \text{ MeV} \\
\nu_e &\approx 0.5 \text{ MeV} \\
\nu_\mu &\approx 100 \text{ MeV} \\
\nu_\tau &\approx 1800 \text{ MeV}
\end{align*}
\]

The neutrinos have their own phenomenology

Studies of the u and d quarks are the realm of nuclear physics

Rare decays of kaons provide sensitive tests of the SM

Studies of electric and magnetic dipole moments of the leptons test the Standard Model

Searches for lepton flavour violation are another hot topic

The top quark has its own phenomenology (since it does not hadronise)
Heavy Flavour Physics

I will focus on:

◎ CKM matrix as source of CP violation in the Standard Model
◎ Rare decays as precision tests for the Standard Model

Hence specifically

◎ flavour-changing interactions of beauty quarks
  ○ charm is also very interesting and I will mention it

But quarks feel the strong interaction and hence hadronise:

◎ various different charmed and beauty hadrons
  ○ many, many possible decays to different final states
  ○ hadronisation greatly increases the observability of CP violation
  ○ leptonic decays can be calculated precisely to test the SM
Flavour for new physics discoveries

A lesson from history:

◎ New physics showed up at precision frontier before energy frontier
  ◯ GIM mechanism before discovery of charm
  ◯ CP violation / CKM before discovery of bottom & top
  ◯ Neutral currents before discovery of Z

◎ Particularly sensitive – loop processes
  ◯ Standard Model contributions suppressed / absent
  ◯ flavour changing neutral currents (rare decays)
  ◯ CP violation
  ◯ lepton flavour / number violation / lepton universality

FCNC suppressed ΔS=2 suppressed wrt ΔS=1

NP scale analysis from ΔS=2 processes
CP violation in the Standard Model: quark mixing

The charged current interaction gets a flavour structure encoded in the Cabibbo Kobayashi Maskawa (CKM) matrix $V$

$$\mathcal{L}_{CC} = -\frac{g}{\sqrt{2}} \left( \bar{U}_L \gamma^\mu W^+_{\mu} V \bar{D}_L + \bar{D}_L \gamma^\mu W^-_{\mu} V^\dagger \bar{U}_L \right).$$

$V_{ij}$ connects left-handed up-type quark of the $i$th generation to left-handed down-type quark of $j$th generation. Intuitive labelling by flavour:

$$V = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}, \quad V_{13} = V_{ub} \text{ etc}.$$

The only way to change flavour in the SM is via a W exchange.
CKM matrix: rotation decomposition

The CKM matrix can be seen as the product of three rotation matrices and each rotation involves two of the three families:

\[
V = \begin{pmatrix}
1 & 0 & 0 \\
0 & \cos \theta_{23} & \sin \theta_{23} \\
0 & -\sin \theta_{23} & \cos \theta_{23}
\end{pmatrix} \begin{pmatrix}
\cos \theta_{13} & 0 & \sin \theta_{13}e^{-i\delta} \\
0 & 1 & 0 \\
-\sin \theta_{13}e^{i\delta} & 0 & \cos \theta_{13}
\end{pmatrix} \begin{pmatrix}
\cos \theta_{12} & \sin \theta_{12} & 0 \\
-\sin \theta_{12} & \cos \theta_{12} & 0 \\
0 & 0 & 1
\end{pmatrix}
\]

which gives the classic exact parameterisation that can be found for example on the PDG:

\[
V = \begin{pmatrix}
c_{12}c_{13} \\
-s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} \\
s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta}
\end{pmatrix} \begin{pmatrix}
s_{12}c_{13} \\
c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} \\
-c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta}
\end{pmatrix} \begin{pmatrix}
s_{13}e^{-i\delta} \\
s_{23}c_{13} \\
c_{23}c_{13}
\end{pmatrix}
\]

with \(c_{ij}=\cos \theta_{ij}\) and \(s_{ij}=\sin \theta_{ij}\), and \(i,j=1,2,3\). \(\delta\) is the CP violating phase.
CKM matrix: Wolfenstein parameterisation

From the Wolfenstein parameter $\lambda = \sin\theta_{12} \sim 0.22$, we can get an idea on the sizes of the various CKM matrix elements:

$$V_{\text{CKM}} = \begin{pmatrix} 1 - \frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1 - \frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1 - \rho - i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4)$$

At $\lambda^2$ order, the third generation decouples

$\eta \neq 0$ signals CP violation

$\rightarrow$ imaginary part of the $V_{ub}$ and $V_{td}$ elements ($1^{\text{st}} \leftrightarrow 3^{\text{rd}}$ family)
CKM matrix: Wolfenstein parameterisation

From the Wolfenstein parameter $\lambda = \sin\theta_{12} \sim 0.22$, we can get an idea on the sizes of the various CKM matrix elements:

$$V_{\text{CKM}} = \begin{pmatrix}
\end{pmatrix} + \mathcal{O}(\lambda^4)$$

So the preferred decays are $t \rightarrow b \rightarrow c \rightarrow s \rightarrow u$
CKM matrix and the Wolfenstein parameterisation

\[
\begin{align*}
V_{ud} & \quad 1 - \lambda^2/2 \\
V_{us} & \quad \lambda \\
V_{ub} & \quad A\lambda^3(\rho - i\eta) \\
V_{cd} & \quad -\lambda \\
V_{cs} & \quad 1 - \lambda^2/2 \\
V_{cb} & \quad A\lambda^2 \\
V_{td} & \quad A\lambda^3(1 - \rho - i\eta) \\
V_{ts} & \quad -A\lambda^2 \\
V_{tb} & \quad 1
\end{align*}
\]
Neutral Meson Systems

The amazing case of neutral non-flavourless meson systems → considering neutral mesons $u u'$ where $u$ has a different flavour with respect to $u' →$ so not applicable to $c c$ for example

These systems are:
→ $K^0 - \bar{K}^0$ ($d \bar{s}$), $D^0 - \bar{D}^0$ ($c \bar{u}$), $B^0 - \bar{B}^0$ ($d \bar{b}$), $B_s^0 - \bar{B}_s^0$ ($s \bar{b}$)

they are subject to the mixing phenomenon via box diagrams:

\[ \begin{array}{c}
\text{down-type} \\
\text{up-type}
\end{array} \]

\[ \begin{array}{c}
\text{down-type} \\
\text{up-type}
\end{array} \]
Neutral Meson Systems

These systems are:
→ $K^0$-$\bar{K}^0$ (ds), $D^0$-$\bar{D}^0$ (cu), $B^0$-$\bar{B}^0$ (db), $B_s^0$-$\bar{B}_s^0$ (sb)

The neutral meson mixing corresponds to another case of misalignment between two sets of eigenstates:

Flavour eigenstates → defined flavour content:

$M^0$ and $\bar{M}^0$

Mass eigenstates → defined masses $m_{1,2}$ and decay width $\Gamma_{1,2}$:

$pM^0 \pm q\bar{M}^0$

In the famous case of kaons: $K_{S,L} \sim (1+\varepsilon)K^0 \pm (1-\varepsilon)\bar{K}^0$

In the formalism for the B mesons: $B_{L,H} \sim pB^0 \pm q\bar{B}^0$

$p & q$ complex coefficients that satisfy $|p|^2 + |q|^2 = 1$
CKM matrix: unitarity relations

\[
\begin{pmatrix}
V_{ud} & V_{us} & V_{ub} \\
V_{cd} & V_{cs} & V_{cb} \\
V_{td} & V_{ts} & V_{tb}
\end{pmatrix}
\]

multiply with its hermitian conjugate
(complex conjugate + transpose)
\(VV^\dagger = V^\dagger V = 1\)

\[
\sum_i V_{ij} V_{ik}^* = \delta_{jk} \quad \text{column orthogonality}
\]

\[
\sum_j V_{ij} V_{kj}^* = \delta_{ik} \quad \text{row orthogonality}
\]

The six vanishing combinations can be represented as triangles in a complex plane.
CKM matrix: unitarity relations

The triangles obtained by taking scalar products of neighboring rows or columns are nearly degenerate. However, the areas of all triangles are the same, half of the Jarlskog invariant J.

\[ V_{ud} V_{us}^* + V_{cd} V_{cs}^* + V_{td} V_{ts}^* \simeq O(\lambda) + O(\lambda) + O(\lambda^5) = 0 \]

\[ V_{us} V_{ub}^* + V_{cs} V_{cb}^* + V_{ts} V_{tb}^* \simeq O(\lambda^4) + O(\lambda^2) + O(\lambda^2) = 0 \]

\[ V_{ud} V_{ub}^* + V_{cd} V_{cb}^* + V_{td} V_{tb}^* \simeq O(\lambda^3) + O(\lambda^3) + O(\lambda^3) = 0 \]
Third unitarity relation

\[ V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* \sim \mathcal{O}(\lambda^3) + \mathcal{O}(\lambda^3) + \mathcal{O}(\lambda^3) = 0 \]

\( V_{id}V_{ib}^* = 0 \) represents the orthogonality condition between the first and the third column of the CKM matrix (the orientation depends on the phase convention)

re-scaled version where sides have been divided by \( |V_{cd}V_{cb}^*| \)

In terms of the Wolfenstein parameterization, the coordinates of this triangle are \((0, 0), (1, 0)\) and \((\bar{\rho}, \bar{\eta})\): the two sides are \((\bar{\rho} + i\bar{\eta})\) and \((1 - \bar{\rho} - i\bar{\eta})\).
Prospects for Flavour Physics

CKM matrix and Unitarity Triangle

\[ V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0 \]

\[ \alpha = \pi - \beta - \gamma \]

\[ \rho + i \eta \]

\[ \gamma = \text{atan} \left( \frac{\eta}{\rho} \right) \]

\[ B^0 \rightarrow \pi \pi, \rho \pi \]

\[ 1 - \rho - i \eta \]

\[ \beta = \text{atan} \left( \frac{\eta}{(1 - \rho)} \right) \]

\[ \text{normalized: } \]

\[ \text{many observables functions of } \rho \text{ and } \eta: \]

overconstraining
Three Types of CP Violation

Need more than one amplitude to have a non-zero CP violation: \textit{interference}

1. Indirect CP violation, or CPV in mixing:
   \[ P( B^0 \rightarrow \bar{B}^0 ) \neq P( B^0 \rightarrow B^0 ) \]

2. Direct CP violation, or CPV in the decay:
   \[ P( B^0 \rightarrow f ) \neq P( \bar{B}^0 \rightarrow \bar{f} ) \]

3. CPV in the interference between mixing and decay.

Cartoon shows the decay of a $B^0$ or $\bar{B}^0$ into a common final state $f$. 
Three Types of CP Violation (B system)

Define the quantity $\lambda$:

$$\lambda_{f_{CP}} = \frac{q}{p} \cdot \frac{\bar{A}_{f_{CP}}}{A_{f_{CP}}}$$

1. Indirect CP violation, or CPV in the mixing:
   $$|q/p| \neq 1$$

2. Direct CP violation, or CPV in the decays:
   $$|\bar{A}/A| \neq 1$$

3. CP violation in interference between mixing and decay:
   $$\text{Im} \lambda \neq 0$$
Prospects for Flavour Physics

Time evolution and CP violation

◎ If we consider that both $B^0$ and $\bar{B}^0$ can decay to the same final state and considering here a final state that is a CP eigenstate, then the time evolution of the physical system becomes:

$$f(B_{phys}^0 \to f_{CP}, \Delta t) = \frac{T}{4} e^{-|\Delta t|} [1 - S_{f_{CP}} \sin(\Delta m_d \Delta t) + C_{f_{CP}} \cos(\Delta m_d \Delta t)]$$

$$f(\bar{B}_{phys}^0 \to f_{CP}, \Delta t) = \frac{T}{4} e^{-|\Delta t|} [1 + S_{f_{CP}} \sin(\Delta m_d \Delta t) - C_{f_{CP}} \cos(\Delta m_d \Delta t)]$$

◎ direct CP violation $\quad C \neq 0$

◎ CP violation in interference $\quad S \neq 0$

$$C_f(= -A_f) = \frac{1 - |\lambda_{f_{CP}}|^2}{1 + |\lambda_{f_{CP}}|^2}$$

$$S_f = \frac{2 \text{Im} \lambda_{f_{CP}}}{1 + |\lambda_{f_{CP}}|^2}$$
Time-dependent CP asymmetries

- Construct an asymmetry as a function of $\Delta t$:

$$A(\Delta t) = \frac{\Gamma(\Delta t) - \overline{\Gamma}(\Delta t)}{\Gamma(\Delta t) + \overline{\Gamma}(\Delta t)}$$

$$A(\Delta t) = S \sin(\Delta m_d \Delta t) - C \cos(\Delta m_d \Delta t)$$

Experimental effects we need to include:
- Detector resolution on $\Delta t$.
- Dilution from flavour tagging.
\[ \sin 2\beta \text{ in golden } b \rightarrow \bar{c}c\bar{s} \text{ modes} \]

Leading-order tree decays to \( \bar{c}c\bar{s} \) final states

\[ b \xrightarrow{V_{cb}} c \]
\[ \bar{c} \xrightarrow{V^*_{cs}} s \quad +d \quad K^0 \rightarrow K_{S,L} \]

Here the CKM elements contributing are \( V_{cb}V^*_{cs} \) that in our Wolfenstein CKM parameterisation have no phase.

The CP conjugated case is also leading to (about) the same final state:

\[ \bar{b} \xrightarrow{V^*_{cb}} \bar{c} \]
\[ c \xrightarrow{V_{cs}} s \quad +d \quad K^0 \rightarrow K_{S,L} \]
sin2β in golden b → ccs modes

leading-order tree decays to ccs final states

\[ \bar{b} \xrightarrow{V_{cb}^*} \bar{c} \]
\[ V_{cs} \]
\[ \bar{c} \xrightarrow{V_{td}^*} \bar{t} \]
\[ V_{tb} \]
\[ \bar{d} \]

because both B and \( \bar{B} \) can decay in this common final state, this can interfere with the oscillation diagram:

\[ \begin{align*}
\bar{b} & \xrightarrow{V_{tb}^*} \bar{t} \quad V_{td}^* \quad \bar{d} \\
B_d^0 & \xrightarrow{W} d \quad V_{td} \quad t \quad V_{tb} \quad b \\
\bar{B}_d^0 & \xrightarrow{W} \bar{B}_d^0
\end{align*} \]

\[ \lambda = \frac{q \frac{A(\bar{B} \rightarrow f)}{p A(B \rightarrow f)} = \frac{V_{tb}^* V_{td} \bar{A}}{V_{td} V_{tb} A} = e^{-i2\beta} \frac{\bar{A}}{A} }{ } \]
sin2\beta in golden b \to \bar{c}c\bar{s} modes

\[
B^0 \to J/\psi K_{S,L}
\]

no possibility to generate this way direct or indirect CPV

\[
|\lambda_{CP}| = 1
\]

\[C_{f_{CP}} = 0\]

\[S_{f_{CP}} = -\eta_{CP}\sin2\beta\]

CPV in interference between mixing and decay

\[
\lambda_{CP} = \eta_{CP} \frac{q}{p} \frac{\bar{A}}{A} = \eta_{CP} \frac{V_{td}V_{tb}^*}{V_{td}^*V_{tb}} \frac{V_{cb}V_{cd}^*}{V_{cb}^*V_{cd}}
\]

\[e^{-i2\beta}\]

\[
\begin{align*}
J/\psi (c\bar{c}) \to J^{PC} = 1^{-} \\
K_S \sim K_1 \to \eta_{CP} = +1 \\
L = 1 \to P = (-1)^L
\end{align*}
\]

\[
\eta_{CP}(J/\psi K_S) = -1
\]

\[
\eta_{CP}(J/\psi K_L) = +1
\]
CP violation in the B system

Time-dependent analysis
CP violation in interference
Less clean channel due to big penguin contributions

\[ S_{f_{CP}} \propto \sin2\alpha \]

Direct CP violation
Interference of two tree diagrams

\[ B^0 \rightarrow \pi \pi, \rho \pi \]

\[ V_{ud}V_{ub}^* \]

\[ \alpha(\phi_2) \]

\[ V_{td}V_{tb}^* \]

\[ \gamma(\phi_3) \]

\[ \beta(\phi_1) \]

\[ B^0 \rightarrow D K \]

\[ V_{cd}V_{cb}^* \]

\[ B^0 \rightarrow J/\psi K_s \]

\[ \eta_{CP} \sin2\beta \]

Time-dependent analysis
CP violation in interference

\[ S_{f_{CP}} = -\eta_{CP} \sin2\beta \]
α (φ₂) from ππ, ρρ, πρ decays with Isospin analysis

Interference between box mixing and tree diagrams results in an asymmetry that is sensitive to α in B → hh decays: h = π, ρ

Unlike for β, loop (penguin diagrams) corrections are not negligible for α

Need Isospin analysis including all modes (B of all charges and flavours) to obtain the α estimate
$\gamma$ ($\phi_3$) from B decays in DK

B to $D^{(*)}K^{(*)}$ decays: from BRs and BR ratios, no time-dependent analysis, just rates.

the phase $\gamma$ is measured exploiting interferences between $b \to c$ and $b \to u$ transitions: two amplitudes leading to the same final states some rates can be really small: $\sim 10^{-7}$

need to combine all the possible modes and analysis methods.
CP violation in the B system

- $B^0 \rightarrow \pi \pi, \rho \pi$
- $\alpha(\Phi_2)$
- $\gamma(\Phi_3)$
- $\beta(\Phi_1)$
- $B^0 \rightarrow D\bar{K}$
- $V_{cd}V_{cb}^*$
- $B^0 \rightarrow J/\psi K_S$
Angle fit from the global unitarity triangle fit

![Graph showing angle fit from global unitarity triangle fit.](image)

- $\alpha$: 6%
- $\beta$: 2.6%
- $\gamma$: 6%
Global fit: the observables

Tree-level diagrams: $|V_{ub}|$, $|V_{cb}|$, $\gamma$

Loop diagrams: $\Delta m_d$, $\Delta m_s$, $\epsilon_K$

CP-conserving: $|V_{xb}|$, $\Delta m_d$, $\Delta m_s$

CP-violating: $\sin(2\beta)$, $\alpha$, $\gamma$, $\epsilon_K$
### CKM parameter extraction

<table>
<thead>
<tr>
<th>Example of observables</th>
<th>Standard Model + OPE/HQET/ Lattice QCD to go from quarks to hadrons</th>
</tr>
</thead>
<tbody>
<tr>
<td>$(b \to u)/(b \to c)$</td>
<td>$(\bar{\rho}^2 + \bar{\eta}^2)$</td>
</tr>
<tr>
<td>$\epsilon_K$</td>
<td>$\bar{\eta}[(1 - \bar{\rho}) + P]$</td>
</tr>
<tr>
<td>$\Delta m_d$</td>
<td>$(1 - \bar{\rho})^2 + \bar{\eta}^2$</td>
</tr>
<tr>
<td>$\Delta m_d/\Delta m_s$</td>
<td>$(1 - \bar{\rho})^2 + \bar{\eta}^2$</td>
</tr>
<tr>
<td>$A_{CP}(J/\psi K_S)$</td>
<td>$\sin 2\beta$</td>
</tr>
<tr>
<td>$\Lambda, \lambda_1, F(1), \ldots$</td>
<td>$B_K$ [ \frac{f_B^2 B_B}{\xi} ] [ m_t ]</td>
</tr>
</tbody>
</table>

M. Bona et al. (UTfit Collaboration)  

M. Bona et al. (UTfit Collaboration)  
Unitarity Triangle analysis in the SM:

\[ r = 0.148 \pm 0.013 \]
\[ h = 0.348 \pm 0.010 \]

\( \rho = 0.148 \pm 0.013 \)
\( \eta = 0.348 \pm 0.010 \)
Prospects for Flavour Physics

UT analysis including new physics

fit simultaneously for the CKM and the NP parameters (generalized UT fit)

- add most general loop NP to all sectors
- use all available experimental info
- find out NP contributions to $\Delta F=2$ transitions

$B_d$ and $B_s$ mixing amplitudes

(2+2 real parameters):

$$A_q = C_{B_q} e^{2i \phi_{B_q}} A_{q}^{SM} e^{2i \phi_{q}^{SM}} = \left(1 + \frac{A_{q}^{NP}}{A_{q}^{SM}} e^{2i(\phi_{q}^{NP} - \phi_{q}^{SM})}\right) A_{q}^{SM} e^{2i \phi_{q}^{SM}}$$

$$\Delta m_{q/K} = C_{B_q/\Delta m_K} (\Delta m_{q/K})^{SM}$$
$$A_{CP}^{B_d \rightarrow J/\psi K_s} = \sin 2(\beta + \phi_{B_d})$$
$$A_{SL}^{q} = \text{Im}\left(\Gamma_{12}^{q} / A_{q}\right)$$

$$\varepsilon_K = C_{\varepsilon} \varepsilon^{SM}_K$$
$$A_{CP}^{B_s \rightarrow J/\psi \phi} \sim \sin 2(-\beta_s + \phi_{B_s})$$
$$\Delta \Gamma^{q} / \Delta m_{q} = \text{Re}\left(\Gamma_{12}^{q} / A_{q}\right)$$
NP analysis results

\[ r = 0.144 \pm 0.028 \]
\[ h = 0.378 \pm 0.027 \]

SM is
\[ \bar{\rho} = 0.148 \pm 0.013 \]
\[ \bar{\eta} = 0.348 \pm 0.010 \]

only shown the constraints unaffected by NP
NP parameter results

$$A_q = \left( 1 + \frac{A_{q}^{NP}}{A_{q}^{SM}} e^{2i(\phi_{q}^{NP} - \phi_{q}^{SM})} \right) A_{q}^{SM} e^{2i\phi_{q}^{SM}}$$

The ratio of NP/SM amplitudes is:

- < 18% @68% prob. (30% @95%) in $B_d$ mixing
- < 20% @68% prob. (30% @95%) in $B_s$ mixing
Testing the new-physics scale

At the high scale
new physics enters according to its specific features

At the low scale
use OPE to write the most
general effective Hamiltonian.
the operators have different
chiralities than the SM
NP effects are in the Wilson
Coefficients $C$

$$
\mathcal{H}_{\text{eff}}^{\Delta B=2} = \sum_{i=1}^{5} C_i Q_i^{bq} + \sum_{i=1}^{3} \tilde{C}_i \tilde{Q}_i^{bq}
$$

$$
Q_1^{iq_j} = \bar{q}_j^\alpha \gamma_\mu q_i^\alpha \bar{q}_j^\beta \gamma_\mu q_i^\beta,
Q_2^{iq_j} = \bar{q}_j^\alpha q_i^\alpha \bar{q}_j^\beta q_i^\beta,
Q_3^{iq_j} = \bar{q}_j^\alpha q_i^\alpha \bar{q}_j^\beta q_i^\beta,
Q_4^{iq_j} = \bar{q}_j^\alpha q_i^\alpha \bar{q}_j^\beta q_i^\beta,
Q_5^{iq_j} = \bar{q}_j^\alpha q_i^\alpha \bar{q}_j^\beta q_i^\beta.
$$

function of the NP flavour couplings
loop factor (in NP models with no tree-level FCNC)
NP scale (typical mass of new particles mediating $\Delta F=2$ processes)
Testing the TeV scale

The dependence of $C$ on $\Lambda$ changes depending on the flavour structure.

We can consider different flavour scenarios:

- **Generic:**
  $$C(\Lambda) = \frac{\alpha}{\Lambda^2} \quad \text{F}_i \sim 1, \text{arbitrary phase}$$

- **NMFV:**
  $$C(\Lambda) = \alpha \times \frac{|F_{\text{SM}}|}{\Lambda^2} \quad \text{F}_i \sim |F_{\text{SM}}|, \text{arbitrary phase}$$

- **MFV:**
  $$C(\Lambda) = \alpha \times \frac{|F_{\text{SM}}|}{\Lambda^2} \quad \text{F}_1 \sim |F_{\text{SM}}|, \text{F}_{i \neq 1} \sim 0, \text{SM phase}$$

$\alpha (L_i)$ is the coupling among NP and SM

- $\alpha \sim 1$ for strongly coupled NP
- $\alpha \sim \alpha_W (\alpha_S)$ in case of loop coupling through weak (strong) interactions

If no NP effect is seen lower bound on NP scale $\Lambda$

$F$ is the flavour coupling and so $F_{\text{SM}}$ is the combination of CKM factors for the considered process.
Results from the Wilson coefficients

**Generic:** \( C(\Lambda) = \alpha / \Lambda^2 \),

\( F_i \sim 1 \), arbitrary phase

\( \Lambda > 4.1 \times 10^5 \) TeV

\( \alpha \sim \alpha_w \) in case of loop coupling through weak interactions

\( \Lambda > 1.2 \times 10^4 \) TeV

**NMFV:** \( C(\Lambda) = \alpha \times |F_{SM}| / \Lambda^2 \),

\( F_i \sim |F_{SM}| \), arbitrary phase

\( \Lambda > 90 \) TeV

\( \alpha \sim \alpha_w \) in case of loop coupling through weak interactions

\( \Lambda > 2.7 \) TeV

Lower bounds on NP scale (at 95% prob.)

\( \Lambda > 4.1 \times 10^5 \) TeV

\( \Lambda > 90 \) TeV

for lower bound for loop-mediated contributions, simply multiply by \( \alpha_s (\sim 0.1) \) or by \( \alpha_w (\sim 0.03) \).
Neutral meson systems: $B_S$

The time evolution of the meson $B_S$ and $\bar{B}_S$ is described by the superposition of $B_H$ and $B_L$ states, with masses $m_S \pm \Delta m_S/2$ and lifetimes $\Gamma_S \pm \Delta \Gamma_S /2$.

These states deviate from defined values $\text{CP} = \pm 1$, as described in the SM by the mixing phase $\phi_S$ ($\phi_S = -2\beta_S$),

$$\text{SM prediction (fit): } \phi_S = -0.0368 \pm 0.0018 \text{ rad}$$

$$\Delta \Gamma_S = 0.082 \pm 0.021 \text{ ps}^{-1}$$

New Physics can contribute to $\phi_S$, and change the ratio $\Delta \Gamma_S /\Delta m_S$.

In general, the decay to a final state that is coupled to $B_S$ and/or $\bar{B}_S$, exhibits fast oscillations driven by $\Delta m_S$. Interference between amplitudes for both states generates CP violation, and conveys information on $\phi_S$.

If $B/\bar{B}$ flavour at production is not determined (not tagged), the fast oscillations cannot be observed, but interference terms remain if the final state is described by a superposition of amplitudes of different CP values.
Neutral meson systems: $B_s$

- In the decay $B_s(\bar{B}_s) \to J/\psi \phi \to l^+l^- K^+K^-$
  - different components in the angular-distributions amplitudes correspond to $CP = +1$ or $-1$
- The “transversity angles” are used to describe the angular distributions

Very preliminary HFLAV combination

$$\phi_s = -0.054 \pm 0.021 \text{ rad}$$
$$\Delta \Gamma_s = 0.0762 \pm 0.0034 \text{ ps}^{-1}$$
Neutral meson system: CP violation in the D system

• The time-integrated CP asymmetry have contributions from both direct CP violation (in the decays) and indirect CP violation (in the mixing or in interference)
• In the SM, indirect CP violation in charm is expected to be very small and universal between CP eigenstates: ⇒ predictions of about $O(10^{-3})$ for CPV parameters
• Direct CP violation can be larger in SM: it depends on final state (on the specific amplitudes contributing)
  ⇒ negligible in Cabibbo-favoured modes
  (SM tree dominates everything)
  ⇒ in singly-Cabibbo-suppressed modes:
    up to $O(10^{-4} - 10^{-3})$ plausible
• Both can be enhanced by NP, in principle up to $O(\%)$
Direct CP violation in the D system

• Remember: need (at least) two contributing amplitudes with different strong and weak phases to get CPV.
• $D^0 \rightarrow K^+K^-$ and $D^0 \rightarrow \pi^+\pi^-$ decays:
  • Singly-Cabibbo-suppressed modes with gluonic penguin diagrams
  • Several classes of NP can contribute ...
    ... but also non-negligible SM contribution
Direct CP violation in the D system

CP asymmetry is defined as

$$A_{CP}(f) = \frac{\Gamma(D^0 \rightarrow f) - \Gamma(D^0 \rightarrow f)}{\Gamma(D^0 \rightarrow f) + \Gamma(D^0 \rightarrow f)}$$

with $f = K^-K^+$ and $f = \pi^-\pi^+$

The flavour of the initial state ($D^0$ or $\bar{D}^0$) is tagged by the charge of the slow pion from $D^{*\pm} \rightarrow D^0\pi^+$ or muon from $B \rightarrow D^0(\rightarrow f)\mu^-X$

The raw asymmetry for tagged $D^0$ decays to a final state $f$ is given by

$$A_{raw}(f) = \frac{N(D^0 \rightarrow f) - N(\bar{D}^0 \rightarrow f)}{N(D^0 \rightarrow f) + N(\bar{D}^0 \rightarrow f)}$$

where $N$ refers to the number of reconstructed events of decay after background subtraction
Direct CP violation in the D system

What we measure is the physical asymmetry plus asymmetries due both to production and detector effects

$$A_{\text{raw}}(f) = A_{CP}(f) + A_D^\times(f) + A_D(\mu^-) + A_{P,\text{eff}}(D^0)$$

- No detection asymmetry for $D^0$ decays to $K^-K^+$ or $\pi^-\pi^+$
- ... if we take the raw asymmetry difference

$$\Delta A_{CP} \equiv A_{\text{raw}}(KK) - A_{\text{raw}}(\pi\pi) = A_{CP}(KK) - A_{CP}(\pi\pi)$$

- the $D^0$ effective production and the muon detection asymmetries will cancel
Direct CP violation in the D system

Hot out of the press [LHCb-PAPER-2019-006]
First measurement of CP violation in the D system:

$$\Delta A_{CP} = (-15.4 \pm 2.9) \times 10^{-4}$$

Interpretation:

$$\Delta A_{CP} \approx \Delta a_{CP}^{\text{dir}} \left( 1 + \frac{\langle t \rangle}{\tau(D^0)} y_{CP} \right) + \frac{\Delta \langle t \rangle}{\tau(D^0)} a_{CP}^{\text{ind}}$$

$$\langle t \rangle = \frac{\langle t \rangle_{KK} - \langle t \rangle_{\pi\pi}}{2} \quad \Delta \langle t \rangle = \langle t \rangle_{KK} - \langle t \rangle_{\pi\pi}$$

$\langle t \rangle_f$ is the reconstructed decay time of a given decay
Direct CP violation in the D system

\[ \Delta A_{CP} \simeq \Delta a_{CP}^{dir} \left( 1 + \frac{\langle t \rangle}{\tau(D^0)} y_{CP} \right) + \frac{\Delta \langle t \rangle}{\tau(D^0)} a_{CP}^{ind} \]

HFLAV combination

\[ a_{CP}^{ind} = (0.028 \pm 0.026)\% \]

\[ \Delta a_{CP}^{dir} = (-0.164 \pm 0.028)\% \]

Consistency with NO CPV hypothesis: $5 \times 10^{-8}$
More tests of the Standard Model

With measurements that can be precisely predicted/calcualted within the Standard Model, we can perform indirect searches for new physics.

Notable examples and hot topics in the last year(s):

- Flavour changing neutral currents (FCNC):
  - forbidden in the Standard Model
  - have to proceed via loop diagrams
  - rare (and semirare) decays
- Lepton universality violation in both:
  - neutral (b to s) currents
  - charged (b to c) currents
- Lepton flavour violation
Rare decays: $B_{(s)}$ to two muons

- Decays of $B^0$ and $B^0_s$ into two leptons have to proceed through Flavour Changing Neutral Currents (FCNC) → forbidden at tree level in the SM
- In addition, they are CKM and helicity suppressed.
- Within the SM, they can be calculated with small theoretical uncertainties of order 6-8%

<table>
<thead>
<tr>
<th>meson type</th>
<th>Lepton type</th>
<th>$e$</th>
<th>$\mu$</th>
<th>$\tau$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B^0$</td>
<td>$e$</td>
<td>$(2.48 \pm 0.21) \times 10^{-15}$</td>
<td>$(1.06 \pm 0.09) \times 10^{-10}$</td>
<td>$(2.22 \pm 0.19) \times 10^{-8}$</td>
</tr>
<tr>
<td>$B^0_s$</td>
<td>$\mu$</td>
<td>$(8.54 \pm 0.55) \times 10^{-14}$</td>
<td>$(3.65 \pm 0.23) \times 10^{-9}$</td>
<td>$(7.73 \pm 0.49) \times 10^{-7}$</td>
</tr>
</tbody>
</table>

- Perfect ground for indirect new physics searches:
  - virtual new particles can contribute to the loop
  - both enhancement and suppression effects are possible

Bobeth et al., PRL 112 (2014) 101801
[includes NLO EM and NNLO QCD corrections]
Rare decays: $B_{(s)}$ to two muons

Latest experimental results: compatible with the SM

arXiv:1812.03017

ATLAS

$B(B^0 \to \mu^+ \mu^-) [10^{-9}]$

Run 1 + 2015-2016 data

LHCb Run 1 + partial Run 2 data

Likelihood contours for

$-2 \Delta \ln(L) = 2.3, 6.2, 11.8$

ATLAS: 2.4σ with the SM

$B(B_s^0 \to \mu^+ \mu^-) [10^{-9}]$
Rare decays: $B_{(s)}$ to two muons

Prospects:
- Additional information from measurements of the effective lifetime and time-dependent CP asymmetry
  - Sensitive to NP from scalar and pseudo-scalar sectors
  - Complementary to the branching ratio
- Inclusion of $B_s \rightarrow \mu\mu\gamma$ studies
  - Sensitive to extra effective operators ($O_7$, $O_9$, $O_{10}$)
  - No helicity suppressed (one order of magnitude gained)
- $B_d$ decay still to be observed
- Electrons and taus final states also still to be observed

- Other $b$ to $s$ FCNC are very interesting:
  part of the current “B anomalies”
  - $B$ to $K^*\mu\mu$ angular analysis
  - Ratio measurement $R(K^{(*)}) = \text{BR}(B \rightarrow K^{(*)}\mu\mu) / \text{BR}(B \rightarrow K^{(*)}ee)$
Semi-rare decays: angular analysis on $B \rightarrow K^*\mu\mu$

- another way to look at FCNC: $b \rightarrow s$ transition with a BR $\sim 1.1 \times 10^{-6}$
- angular distribution of the 4 particles in the final state sensitive to new physics for the interference of NP and SM diagrams
- allows measuring a large set of angular parameters sensitive to Wilson coefficients $C^{(i)}_7$, $C^{(i)}_9$, $C^{(i)}_{10}$, $C^{(i)}_{S,P}$

- decay described by three angles ($\theta_L$, $\theta_K$, $\phi$) and the di-muon mass squared $q^2$ → the angular distribution is analysed in finite bins of $q^2$ as a function of $\theta_L$, $\theta_K$ and $\phi$. 
Semi-rare decays: angular analysis on $B \rightarrow K^* \mu\mu$

- Some tension between the experimental results and the theoretical expectations (2.7 to 3.6$\sigma$ w.r.t. DHMV)
- Theory here is less clean as hadronic effects are not thought as completely under control
- Need more data
Lepton Universality tests in $b$ to $s$

Ratio measurement \( R(K^*) = \frac{\text{BR}(B \to K^*(\mu\mu))}{\text{BR}(B \to K^*(ee))} \)

- Neutral current $\to$ photon and Z boson couple with the same strength to the three lepton families $\to$ lepton universality
- Ratio expected to be 1 in the SM
- Clean observable as all the hadronic uncertainties cancel
- If confirmed, new physics implications!

\[ R(K) \to 2.5\sigma \text{ effect} \]
\[ R(K^*) \to 2.1-2.5\sigma \text{ effect} \]
Lepton Universality tests in b to c

Ratio measurement \( R(D^{(*)}) = \frac{\text{BR}(B \to D^{(*)}\tau\nu)}{\text{BR}(B \to D^{(*)}\ell\nu)} \)

- Tree level processes
- Charge current → lepton flavour universality (LFU) is an accidental symmetry broken only by the Yukawa interactions → differences between the expected branching fraction of semileptonic decays into the three lepton families originate from the different masses of the charged leptons
- Ratio expected to be 0.25-0.30 in the SM
Lepton Universality tests in $b$ to $c$

Ratio measurement $R(D^{(*)}) = \frac{\text{BR}(B \to D^{(*)}\tau\nu)}{\text{BR}(B \to D^{(*)}\ell\nu)}$

If confirmed, new physics implications!

$\ell$ is a muon for LHCb and an average of electrons and muons in BaBar and Belle

$\Delta \chi^2 = 1.0$ contours

Average of SM predictions

R(D) = 0.299 ± 0.003
R(D*) = 0.258 ± 0.005

~4σ effect

HFLAV
Summer 2018
P($\chi^2$) = 74%
Prospects for Flavour Physics

Lepton Universality tests in $b$ to $s/c$

- $R(K) \rightarrow 2.5\sigma$ effect

- $R(D^{(*)}) = \frac{BR(B \rightarrow D^{(*)}\tau\nu)}{BR(B \rightarrow D^{(*)}\ell\nu)} \sim 4\sigma$ effect

- $R(K^{(*)}) = \frac{BR(B \rightarrow K^{(*)}\mu\mu)}{BR(B \rightarrow K^{(*)}ee)}$

- $b$ to $s$ anomalies
- 1-loop processes in the SM
- The scale of NP can be “high”
  $\Lambda \sim 30-50$ TeV

- $b$ to $c$ anomalies
- Tree processes in the SM
- The scale of NP must be “low”
  $\Lambda \sim$ TeV

Marcella Bona (QMUL)
Conclusions

- Flavour physics represents one of the precision frontiers for testing the Standard Model.

- The Unitarity Triangle analysis (UTA) via global fits can provide the best determination of CKM parameters, and test the consistency of the SM and can also determine the available space for new physics contributions to DF=2 amplitudes. It currently leaves space for new physics at the level of 25-30%.

- The scale analysis points to high scales for the generic scenario and at the limit of LHC reach for weak coupling
  - Indirect searches are complementary to direct searches.

- Indirect searches are effective for those observables that can be precisely estimated within the Standard Model.

  - Rare leptonic decays: no significant deviation from SM
  - Semi-rare FCNC decays: some anomalies are seen → could be a SM effect from hadronic contributions
  - Lepton flavour universality: some anomalies are seen both in b to s and in b to c transitions → clean observables → excitement in the community → stay tuned for the updates on these measurements
Prospects

- LHCb is the LHC experiment focused on beauty and charm physics
  - Enormous amount of results dominating current flavour results
  - Not ideal for neutral final states
  - Excellent K/p separation / particle identification / mass resolution

- ATLAS and CMS can be competitive in some cases:
  - Potentially higher statistic samples
  - Trigger cutting into the efficiencies → topological solutions or delayed streams
  - Good timing and competitive mass resolution

- Belle II is a B-factory style experiment at a electron-positron collider
  - Complementary to LHC
  - Can measure all neutral final states and absolute branching ratios
  - Limited statistics in Bs system
  - Starting data taking now

- Exciting times ahead
Back up slides
Unitary matrix independent parameters

In general, an $n \times n$ unitary matrix has $n^2$ real and independent parameters:

- A $n \times n$ matrix would have $2n^2$ parameters.
- The unitary condition imposes $n$ normalization constraints.
- $n(n - 1)$ conditions from the orthogonality between each pair of columns:

$$2n^2 - n - n(n - 1) = n^2.$$ 

In the CKM matrix, not all of these parameters have a physical meaning:

- Given $n$ quark generations, $2n - 1$ phases can be absorbed by the freedom to select the phases of the quark fields.

Each $u, c$ or $t$ phase allows for multiplying a row of the CKM matrix by a phase, while each $d, s$ or $b$ phase allows for multiplying a column by a phase.

Thus:

$$n^2 - (2n - 1) = (n - 1)^2.$$ 

Among the $n^2$ real independent parameters of a generic unitary matrix:

- $\frac{1}{2} n(n - 1)$ of these parameters can be associated to real rotation angles, so the number of independent phases in the CKM matrix case is:

$$n^2 - \frac{1}{2} n(n - 1) - (2n - 1) = \frac{1}{2} (n - 1)(n - 2).$$ 

<table>
<thead>
<tr>
<th>$n$(families)</th>
<th>Total indep. params.</th>
<th>Real rot. angles</th>
<th>Complex phase factors</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$(n - 1)^2$</td>
<td>$\frac{1}{2}n(n - 1)$</td>
<td>$\frac{1}{2}(n - 1)(n - 2)$</td>
</tr>
<tr>
<td>2</td>
<td>1</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>3</td>
<td>4</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>4</td>
<td>9</td>
<td>6</td>
<td>3</td>
</tr>
</tbody>
</table>
CKM matrix: Wolfenstein parameterisation

From measurements, $V$ results hierarchical $\Rightarrow \theta_{13} \ll \theta_{23} \ll \theta_{12}$

We can see this hierarchy via the Wolfenstein parameterisation:

$\Rightarrow$ the CKM matrix elements are expanded in order of $\sin \theta_{12}$

historically called Cabibbo angle $\theta_c$:

$\Rightarrow$ Wolfenstein parameter $\lambda = \sin \theta_{12} \sim 0.22$

\[
V_{\text{CKM}} = \begin{pmatrix}
1 - \frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho - i\eta) \\
-\lambda & 1 - \frac{\lambda^2}{2} & A\lambda^2 \\
A\lambda^3(1 - \rho - i\eta) & -A\lambda^2 & 1
\end{pmatrix} + \mathcal{O}(\lambda^4)
\]

$\Rightarrow$ Wolfenstein parameters: $\lambda \sim 0.22$, $A \sim 0.83$, $\rho \sim 0.15$, $\eta \sim 0.35$
CKM matrix: values of the elements

\[
\begin{pmatrix}
0.974 & 0.226 & 0.004 \\
-0.226 & 0.973 & 0.041 \\
0.009 & -0.041 & 0.999 \\
\end{pmatrix}
\]

These numbers are obtained with their uncertainties from the processes mentioned before or global fits

\[
V_{CKM} = \begin{pmatrix}
(0.97431 \pm 0.00012) e^{i(0.0351 \pm 0.0010)^\circ} & (0.22514 \pm 0.00055) e^{i(-0.001880 \pm 0.000052)^\circ} & (0.00365 \pm 0.00010) e^{i(-66.8 \pm 2.0)^\circ} \\
(-0.22500 \pm 0.00054) e^{i(-22.23 \pm 0.63)^\circ} & (0.97344 \pm 0.00012) e^{i(0.001880 \pm 0.000052)^\circ} & (0.04241 \pm 0.00065) \\
(0.00869 \pm 0.00014) e^{i(1.056 \pm 0.032)^\circ} & (-0.04124 \pm 0.00056) e^{i(1.056 \pm 0.032)^\circ} & (0.999112 \pm 0.000024) \\
\end{pmatrix}
\]

summer 2018 analysis from UTfit: www.utfit.org
CKM matrix: Wolfenstein parameterisation

Usually the Buras correction to the Wolfenstein parameterisation is used:

\[ \begin{align*}
\bar{\rho} &= \rho \ (1 - \lambda^2/2) \\
\bar{\eta} &= \eta \ (1 - \lambda^2/2)
\end{align*} \]

\[ V = \begin{pmatrix}
1 - \frac{\lambda^2}{2} & \lambda & A\lambda^3(\bar{\rho} - i\bar{\eta}) \\
-\lambda & 1 - \frac{\lambda^2}{2} & A\lambda^2 \\
A\lambda^3(1 - \bar{\rho} - i\bar{\eta}) & -A\lambda^2 & 1
\end{pmatrix} + \mathcal{O}(\lambda^4) \]

Looks identical to the Wolfenstein one but now the matrix is unitary also in this "approximation" at all \( \lambda \) orders.

Also \( \bar{\rho} + i\bar{\eta} \) is phase-convention independent:

\[ \bar{\rho} + i\bar{\eta} \equiv -\frac{V_{ud} V_{ub}^*}{V_{cd} V_{cb}^*} \]
**$V_{cb}$ and $V_{ub}$ from semileptonic B decays**

From tree level processes:

semileptonic B decays

$B \rightarrow X_{u,c} \ell \nu$

Use theory to relate partial branching fractions to $V_{xb}$

for a given region of phase space.

Can study modes exclusively or inclusively:

different experimental and theoretical issues.
## Compatibility of the constraints

obtained excluding the given constraint from the fit

<table>
<thead>
<tr>
<th>Observables</th>
<th>Measurements</th>
<th>Prediction</th>
<th>Pull (/#σ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>sin2β</td>
<td>0.689 ± 0.018</td>
<td>0.738 ± 0.033</td>
<td>~ 1.2</td>
</tr>
<tr>
<td>γ</td>
<td>70.0 ± 4.2</td>
<td>65.8 ± 2.2</td>
<td>~ 1</td>
</tr>
<tr>
<td>α</td>
<td>93.3 ± 5.6</td>
<td>90.1 ± 2.2</td>
<td>&lt; 1</td>
</tr>
<tr>
<td></td>
<td>Vub</td>
<td>· 10^3</td>
<td>3.72 ± 0.23</td>
</tr>
<tr>
<td></td>
<td>Vub</td>
<td>· 10^3 (incl)</td>
<td>4.50 ± 0.20</td>
</tr>
<tr>
<td></td>
<td>Vub</td>
<td>· 10^3 (excl)</td>
<td>3.65 ± 0.14</td>
</tr>
<tr>
<td></td>
<td>Vcb</td>
<td>· 10^3</td>
<td>40.5 ± 1.1</td>
</tr>
<tr>
<td>BR(B → τν) [10^{-4}]</td>
<td>1.09 ± 0.24</td>
<td>0.81 ± 0.05</td>
<td>~ 1.2</td>
</tr>
<tr>
<td>A_{SL}^d · 10^3</td>
<td>-2.1 ± 1.7</td>
<td>-0.292 ± 0.026</td>
<td>~ 1</td>
</tr>
<tr>
<td>A_{SL}^s · 10^3</td>
<td>-0.6 ± 2.8</td>
<td>0.013 ± 0.001</td>
<td>&lt; 1</td>
</tr>
</tbody>
</table>
semileptonic asymmetries in $B^0$ and $B_s$: sensitive to NP effects in both size and phase. Taken from the latest HFLAV.

same-side dilepton charge asymmetry: admixture of $B_s$ and $B_d$ so sensitive to NP effects in both.

\[ A^\mu\mu_{SL} \times 10^3 = -7.9 \pm 2.0 \]

lifetime $\tau^{FS}$ in flavour-specific final states: average lifetime is a function to the width and the width difference

\[ \tau^{FS}(B_s) = 1.527 \pm 0.011 \text{ ps} \]

$\phi_s=2\beta_s$ vs $\Delta \Gamma_s$ from $B_s \rightarrow J/\psi \phi$

angular analysis as a function of proper time and b-tagging
NP parameter results

dark: 68%
light: 95%
SM: red cross

\[ A_q = C_{B_q} e^{2i\phi_{B_q}} A_q^{SM} e^{2i\phi_{q}^{SM}} \]

- \( C_{Bd} = 1.05 \pm 0.11 \)
- \( \phi_{Bd} = (-2.0 \pm 1.8)^\circ \)

- \( C_{Bs} = 1.11 \pm 0.09 \)
- \( \phi_{Bs} = (0.4 \pm 0.9)^\circ \)

K system

\( C_{eK} = 1.11 \pm 0.12 \)
some old plots coming back to fashion:

As NA62 and KOTO are analysing data:

\[ \text{BR}(K^+ \rightarrow \pi^+\nu\bar{\nu}) \]

E949 central value

projection
100 events

2007 global fit area

SM central value

projection
100 events

including
\[ \text{BR}(K^0 \rightarrow \pi^0\nu\bar{\nu}) \]

SM central value

7 events
Look at the near future

**Future I scenario:** errors from Belle II at 5/ab + LHCb at 10/fb

**Current sensitivity:**
\[
\tilde{\rho} = 0.154 \pm 0.015 \\
\tilde{\eta} = 0.344 \pm 0.013
\]

\[
\rho = \pm 0.015 \\
\eta = \pm 0.015
\]

\[
\rho = \pm 0.016 \\
\eta = \pm 0.019
\]
exclusives vs inclusives

only exclusive values

only inclusive values

\[ \bar{\rho} \]
exclusives vs inclusives

- only exclusive values
- only inclusive values

\[ \Delta m_s \]
\[ \rho \]
exclusives vs inclusives

only exclusive values

only inclusive values

preliminary for CKM 2018
only exclusive values

only inclusive values

exclusives vs inclusives

preliminary for CKM 2018