Discovery potential in flavour physics

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Flavour Physics and the Standard Model

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

Cabibbo–Kobayashi–Maskawa
CKM matrix

Pontecorvo–Maki–Nakagawa–Sakata
PMNS matrix
Heavy Flavour Physics

I will focus on:

◎ CP violation in the Standard Model
◎ CKM matrix and possible space for NP
◎ Rare decays as precision tests for the Standard Model
◎ More tests for Lepton Flavour Universality

Hence specifically

◎ flavour-changing interactions of beauty quarks
  ◊ charm is also very interesting and I will include 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 $\Delta S=2$ suppressed wrt $\Delta S=1$

NP scale analysis from $\Delta S=2$ processes
CP violation
Neutral Meson Systems

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

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)

they are subject to the mixing phenomenon via box diagrams:
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 $\Gamma_{1,2}$:
  \[ pM^0 \pm qM^0 \]

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

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

Need more than one amplitude to have a non-zero CP violation: *interference*

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:**
   $$| \frac{q}{p} | \neq 1$$

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

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

Cartoon shows the decay of a $B^0$ or $\bar{B}^0$ into a common final state $f$. Both neutral and charged $M$.
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:

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

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

- direct CP violation $C \neq 0$
- CP violation in interference $S \neq 0$

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

\[
S_f = \frac{2 \text{Im} \lambda_{f_{CP}}}{1 + |\lambda_{f_{CP}}|^2}
\]
CP violation in the D system

• 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.
- \(D^0 \to K^+K^-\) and \(D^0 \to \pi^+\pi^-\) 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

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

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

The flavour of the initial state ($D^0$ or $D^*$) 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

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

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

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

- CP asymmetry
- Any charge-dependent asymmetry in muon reconstruction
- \( D^0 \) effective production asymmetry

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

\[ \Delta A_{CP} = A_{\text{raw}}(KK) - A_{\text{raw}}(\pi\pi) = A_{CP}(KK) - A_{CP}(\pi\pi) \]

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

LHCb: Phys. Rev. Lett. 122 (2019) 211803
First measurement of CP violation in the D system:

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

5.3σ

Interpretation:

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

\[ \langle t \rangle = \frac{\langle t \rangle_{KK} - \langle t \rangle_{\pi\pi}}{2} \]

\[ \Delta \langle t \rangle = \langle t \rangle_{KK} - \langle t \rangle_{\pi\pi} \]

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

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

HFLAV combination

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

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

Consistency with NO CPV hypothesis: $5 \times 10^{-8}$
CP violation parameters from time-dependent angular analysis on $B_s \to J/\psi\phi$

**LHCb:** with 1.9/fb of 13 TeV data (Run 2, 2015-2016),
LHCb, Eur. Phys. J. C79 (2019) 706, arXiv:1906.08356.

**ATLAS:** with 80.5/fb of 13 TeV data (Run 2, 2015-2017)
+ combination with 19.2/fb of 7-8 TeV data (Run 1)
ATLAS-CONF-2019-009

**CMS:** with 19.7/fb of 8 TeV data (Run 1),
Phys. Lett. B 757 (2016) 97, arXiv:1507.07527
**Time-dependent angular analysis of $B_s \rightarrow J/\psi\phi$**

- Parameters of the $B_s$ system:
  - Mixing → Decay width difference $\Delta \Gamma_s = \Gamma_L - \Gamma_S$
  - $\Delta \Gamma_s = 0.087 \pm 0.021 \text{ ps}^{-1}$ in the SM [arXiv:1102.4274]

\[
\Gamma_s \sim \left| \begin{array}{cc}
\Gamma_{\text{mixing}} & \Gamma_{\text{direct}} \\
\end{array} \right|^2
\]

- CPV phase $\varphi_s$ → weak phase between mixing and $b \rightarrow ccs$ decay
  - $\varphi_s = -2\beta_s$ with $\beta_s = \arg[-(V_{ts}V_{tb}^*)/(V_{cs}V_{cb}^*)]$
  - SM: $-2\beta_s = -0.0363 \pm 0.0016$ [arXiv:1106.4041], $0.0370 \pm 0.0010$ [UTfit18]

- Golden mode: penguin diagrams can contribute to the decay either with the same weak phase ($\lambda^2$) or they are CKM suppressed ($\lambda^4$)
Time-dependent angular analysis of $B_s \rightarrow J/\psi\phi$

- Golden channel for measuring the $B_s$ parameters
- Pseudoscalar $B_0$s to the vector–vector $J/\psi(\mu^+\mu^-)\phi(K^+ K^-)$ final state
  $\rightarrow$ admixture of CP-odd and CP-even states ($L = 0, 1$ or $2$).
- $L = 0$ or $2 \rightarrow$ CP-even states, while $L = 1 \rightarrow$ CP-odd state.
- Same final state can also be $K^+ K^-$ pairs in S-wave $\rightarrow$ CP-odd.
- CP states are separated statistically using an angular analysis
- Differential decay rate:
  \[
  \frac{d^4\Gamma}{dt \, d\Omega} = \sum_{k=1}^{10} O^{(k)}(t) g^{(k)}(\theta_T, \psi_T, \phi_T),
  \]
  with $O^{(k)}(t)$ time-dependent functions corresponding to the contributions of amplitudes ($A_0, A_{||}, A_\perp,$ and $A_S$) (and interferences) and $g^{(k)}(\theta_T, \psi_T, \phi_T)$ are angular functions.
- Flavour tagging is used to distinguish between the initial $B_0^s$ and $\bar{B}_0^s$ states.
Flavour tagging

CP measurement from time-dependent analysis of B0 decays needs the determination of the B flavour (b or \(\bar{b}\)) at production.

Tagging power

1.65 ± 0.01% <= \(\epsilon D^2\) => 4.73 ± 0.34%
Time-dependent angular analysis of $B_s \to J/\psi\phi$

Analysis strategy and experimental inputs:
- Measurement of the proper decay time $t = L_{xy} m_B/p_T^B$
- Flavour tagging to identify the flavour of the $b$ quark
- Unbinned maximum-likelihood fit:
  - $B_s$ properties: reconstructed mass $m_B$, proper decay time $t$, proper decay time uncertainty $\sigma_t$, tagging probability $P(B|Q_x)$
  - Transversity angles: $\Omega(\theta_T, \psi_T, \phi_T)$ of each $B_s^0 \to J/\psi\phi$ decay candidate
  - Physical parameters: $\Delta\Gamma_s$, $\varphi_s$, $\Gamma_s$, $(\Delta m_s)$, $(|\lambda|)$, $|A_0(0)|^2$, $|A_{\parallel}(0)|^2$, $\delta_{\parallel}$, $\delta_{\perp}$, $|A_s(0)|^2$ and $\delta_s$
Prospects for Flavour Physics

Run 2, 2015-2016

LHCb

ATLAS

\[
\begin{array}{l}
N(B_s^0) & 477\,240 \pm 760 \\
\sigma(\tau) & 69\,\text{fs} \\
\epsilon D^2 & 1.65 \pm 0.01\% \\
\end{array}
\]

\begin{array}{l}
117\,000 \\
45.54 \pm 0.04 \pm 0.05\,\text{fs} \\
4.73 \pm 0.34\% \\
\end{array}

\begin{array}{lll}
\text{Parameter} & \text{Value} & \text{Statistical uncertainty} & \text{Systematic uncertainty} \\
\hline
\phi_s [\text{rad}] & -0.068 & 0.038 & 0.018 \\
\Delta \Gamma_s [\text{ps}^{-1}] & 0.067 & 0.005 & 0.002 \\
\Gamma_s [\text{ps}^{-1}] & 0.669 & 0.001 & 0.001 \\
|A_\parallel(0)|^2 & 0.219 & 0.002 & 0.002 \\
|A_0(0)|^2 & 0.517 & 0.001 & 0.004 \\
|A_S(0)|^2 & 0.046 & 0.003 & 0.004 \\
\delta_\perp [\text{rad}] & 2.946 & 0.101 & 0.097 \\
\delta_\parallel [\text{rad}] & 3.267 & 0.082 & 0.201 \\
\delta_\perp - \delta_S [\text{rad}] & -0.220 & 0.037 & 0.010 \\
\end{array}

\phi_s = -0.083 \pm 0.041 \pm 0.006\,\text{rad}

|\lambda| = 1.012 \pm 0.016 \pm 0.006

\Gamma_s - \Gamma_d = -0.0041 \pm 0.0024 \pm 0.0015\,\text{ps}^{-1}

\Delta \Gamma_s = 0.077 \pm 0.008 \pm 0.003\,\text{ps}^{-1}

\Delta m_s = 17.703 \pm 0.059 \pm 0.018\,\text{ps}^{-1}

|A_\perp|^2 = 0.2456 \pm 0.0040 \pm 0.0019

|A_0|^2 = 0.5186 \pm 0.0029 \pm 0.0024

\delta_\perp - \delta_0 = 2.64 \pm 0.13 \pm 0.10\,\text{rad}

\delta_\parallel - \delta_0 = 3.06^{+0.08}_{-0.07} \pm 0.04\,\text{rad}.
\[ \phi_s = -0.080 \pm 0.032 \text{ rad}, \]
\[ |\lambda| = 0.993 \pm 0.013, \]
\[ \Gamma_s = 0.6570 \pm 0.0023 \text{ ps}^{-1}, \]
\[ \Delta \Gamma_s = 0.0784 \pm 0.0062 \text{ ps}^{-1}, \]
\[ \Delta m_s = 17.691 \pm 0.042 \text{ ps}^{-1}, \]
\[ |A_\perp|^2 = 0.2486 \pm 0.0035, \]
\[ |A_0|^2 = 0.5197 \pm 0.0035, \]
\[ \delta_\perp - \delta_0 = 2.88 \pm 0.11 \text{ rad}, \]
\[ \delta_\parallel - \delta_0 = 3.155 \pm 0.079 \text{ rad}. \]
Time-dependent angular analysis of $B_s \rightarrow J/\psi\phi$

Preliminary HFLAV average:

$\phi_s = -0.055 \pm 0.021 \text{ rad}$

$\Delta \Gamma_s = 0.0764 \pm 0.0034 \text{ ps}^{-1}$
CP violation in the B system:
state of the art from the global fit
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:

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

Matrix $V$ is unitary by construction.

The only way to change flavour in the SM is via a $W$ exchange.
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)
CP violation in the B system

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

\[ S_{f_{\text{CP}}} \propto \sin 2\alpha \]

Direct CP violation
Interference of two tree diagrams

\[ S_{f_{\text{CP}}} = -\eta_{\text{CP}} \sin 2\beta \]
CP violation in the B system

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

\[ V_{ud} V_{ub}^* \alpha(\phi_2) V_{td} V_{tb}^* \gamma(\phi_3) \beta(\phi_1) \]

\[ B^0 \rightarrow D K \]

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

\[ B^0 \rightarrow J/\psi K_S \]
Angle fit from the global unitarity triangle fit
Global fit: the observables

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

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

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

CP-violating: $\sin(2\beta), \alpha, \gamma, \varepsilon_K$
Prospects for Flavour Physics

Unitarity Triangle analysis in the SM:

\[ \bar{\rho} = 0.148 \pm 0.013 \]
\[ \bar{\eta} = 0.348 \pm 0.010 \]
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):

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

$$\Delta m_{q/K} = C_{B_q/\Delta m_K} (\Delta m_{q/K})^{SM}$$

$$A_{CP}^{B_d \rightarrow J/\psi K_s} = \sin 2(\beta + \phi_{B_d})$$

$$A_{SL}^q = \text{Im} \left( \frac{\Gamma_{12}^q}{A_q} \right)$$

$$\varepsilon_K = C_{\varepsilon} \varepsilon^{SM}_K$$

$$A_{CP}^{B_s \rightarrow J/\psi \phi} \sim \sin 2(-\beta_s + \phi_{B_s})$$

$$\Delta \Gamma^q/\Delta m_q = \text{Re} \left( \frac{\Gamma_{12}^q}{A_q} \right)$$
NP analysis results

\[ \rho = 0.144 \pm 0.028 \]
\[ \eta = 0.378 \pm 0.027 \]

SM is
\[ \bar{\rho} = 0.148 \pm 0.013 \]
\[ \bar{\eta} = 0.348 \pm 0.010 \]
The ratio of NP/SM amplitudes is:

\[ A_q = \left( 1 + \frac{A_q^{NP}}{A_q^{SM}} e^{2i(\phi_q^{NP} - \phi_q^{SM})} \right) A_q^{SM} e^{2i\phi_q^{SM}} \]

\[ A_{B_d}^{NP} / A_{B_d}^{SM} \]

\[ A_{B_s}^{NP} / A_{B_s}^{SM} \]

The ratio of NP/SM amplitudes is:

\(< 18\% @68\% \text{ prob. (30\% @95\%) in } B_d \text{ mixing}\)

\(< 20\% @68\% \text{ prob. (30\% @95\%) in } B_s \text{ mixing}\)
rare $B$ decays $B_{(s)} \rightarrow \mu^+ \mu^-$

LHCb:
Phys. Rev. Lett. 118 (2017), 191801, arXiv:1703.05747

ATLAS:
JHEP 04 (2019) 098, arXiv:1812.03017

CMS
Submitted to J. High Energy Phys., arXiv:1910.12127
Motivations and Predictions

- 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%

| meson   | $e$          | $\mu$        | $\tau$       |
|---------|--------------|--------------|--------------|
| $B^0$   | $(2.48 \pm 0.21) \times 10^{-15}$ | $(1.06 \pm 0.09) \times 10^{-10}$ | $(2.22 \pm 0.19) \times 10^{-8}$ |
| $B^0_s$ | $(8.54 \pm 0.55) \times 10^{-14}$ | $(3.65 \pm 0.23) \times 10^{-9}$  | $(7.73 \pm 0.49) \times 10^{-7}$ |

- 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 (2104)
101801
[includes NLO EM and NNLO QCD corrections]
Experimental Strategy

- Trigger with very low-threshold muons: few GeV
- Branching ratio extracted via a known reference channel (JψK or Kπ)

$$\mathcal{B}(B^0_s \rightarrow \mu^+ \mu^-) = \frac{N_{d(s)}}{\varepsilon_{\mu^+ \mu^-}} \times \frac{\varepsilon_{J/\psi K^+}}{N_{J/\psi K^+}} \times \frac{f_u}{f_d(s)}$$

$$\times [\mathcal{B}(B^+ \rightarrow J/\psi K^+) \times \mathcal{B}(J/\psi \rightarrow \mu^+ \mu^-)]$$

- Correction for the different hadronisation probabilities for $B^0_s$ and $B^0$ vs $B^{\pm}$
- Include the $B^{\pm}$ and J/ψ branching fractions
- Data-driven correction for the efficiencies of the two channels
- Main backgrounds:
  - Charmless two-body B decays (indistinguishable, need particle identification or low muon misidentification)
  - Partially reconstructed B decays (accumulating on the low mass sideband)
  - Combinatorial background (linear/exponential distribution, boosted decision tree trained on the mass sidebands and signal simulation)
- Maximum likelihood fit on the dimuon mass to extract the signal and separate the background above
Prospects for Flavour Physics

Experimental results

With 2011–2016 LHCb data (4.4 fb$^{-1}$):

\[
\mathcal{B}(B_s^0 \to \mu^+ \mu^-) = (3.0 \pm 0.6^{+0.3}_{-0.2}) \times 10^{-9}
\]

\[
\mathcal{B}(B^0 \to \mu^+ \mu^-) = (1.5^{+1.2}_{-1.0}^{+0.2}_{-0.1}) \times 10^{-10}
\]

B$_d$ decay at 1.6$\sigma$

Effective lifetime:

\[
\tau_{B_s^0 \to \mu^+ \mu^-} = 2.04 \pm 0.44 \pm 0.05 \text{ ps}
\]
**Experimental results**

With 2011–2016 CMS data (61 fb\(^{-1}\)):

\[
B(B_s^0 \rightarrow \mu^+\mu^-) = \left(2.9 \pm 0.7 \pm 0.2\right) \times 10^{-9}
\]

\[
B(B^0 \rightarrow \mu^+\mu^-) < 3.6 \times 10^{-10} \text{ at 95%}
\]

Effective lifetime:

\[
\tau_{\mu^+\mu^-} = 1.70^{+0.61}_{-0.44} \text{ ps}
\]
Experimental results

Run 1 + Run 2 (2015+2016) combination: compatible with SM at 2.4σ

\[ \mathcal{B}(B_s^0 \to \mu^+ \mu^-) = (2.8^{+0.8}_{-0.7}) \times 10^{-9} \]
\[ \mathcal{B}(B^0 \to \mu^+ \mu^-) < 2.1 \times 10^{-10} \]

Ongoing work towards the LHC combination: stay tuned!
Experimental results

Run 1 + Run 2 (2015+2016) combination: compatible with SM at $2.4\sigma$

\[
\mathcal{B}(B_s^0 \to \mu^+\mu^-) = \left(2.8^{+0.8}_{-0.7}\right) \times 10^{-9}
\]

\[
\mathcal{B}(B^0 \to \mu^+\mu^-) < 2.1 \times 10^{-10}
\]

Ongoing work towards the LHC combination: stay tuned!
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 $R(K^{(*)}) = BR(B \rightarrow K^{(*)}\mu\mu)/BR(B \rightarrow K^{(*)}ee)$
Lepton Flavour Universality

More from $b$ to $s \ell^- \ell^+$
FCNC transitions
**R_k and R_{k*} measurements**

\[ R_X \equiv \left( \frac{\int_{q_{min}^2}^{q_{max}^2} dq^2 \frac{d\Gamma(B \rightarrow X \mu^+\mu^-)}{dq^2}}{\int_{q_{min}^2}^{q_{max}^2} dq^2 \frac{d\Gamma(B \rightarrow X e^+e^-)}{dq^2}} \right) \]

- The electroweak couplings of all three charged leptons are identical in the SM and the decay properties (and the hadronic effects) are expected to be the same up to corrections related to the lepton mass, regardless of the lepton flavour \( \rightarrow \) this is lepton universality.
- The ratio can be calculated and predicted in defined ranges of the dilepton mass squared \( q^2 \) \( \rightarrow \) ratio expected to be 1 in the SM
- Clean observable as all the hadronic uncertainties cancel
- Experimentally measured via double ratios to more abundant resonant channels, e.g.:

\[ R_K = \frac{\mathcal{B}(B^+ \rightarrow K^+\mu^+\mu^-)}{\mathcal{B}(B^+ \rightarrow J/\psi(\rightarrow \mu^+\mu^-)K^+)} \bigg/ \frac{\mathcal{B}(B^+ \rightarrow K^+e^+e^-)}{\mathcal{B}(B^+ \rightarrow J/\psi(\rightarrow e^+e^-)K^+)} \]
Rₖ measurements

LHCb:
Phys. Rev. Lett. 122 (2019) 191801, arXiv:1903.09252

In the range:
1.1 < q² < 6 GeV²/c⁴

From the fits:
1943 ± 49 B⁺ → K⁺μ⁺μ⁻
766 ± 48 B⁺ → K⁺e⁺e⁻

\[ R_K = 0.846 ± 0.060 ± 0.016 - 0.054 - 0.014 \]

(2.5σ from the SM)
**R_K measurements**

**Belle:**

arXiv:1908.01848

Using $772 \times 10^6$ BB pairs reconstructing:

- $\mathbf{B}^+ \to K^+\ell^+\ell^-$ and
- $\mathbf{B}^0 \to K_S^0\ell^+\ell^-$

$137 \pm 14 \mathbf{B}^+ \to K^+\mu^+\mu^-$

$138 \pm 15 \mathbf{B}^+ \to K^+e^+e^-$

$27 \pm 6 \mathbf{B}^0 \to K_S^0\mu^+\mu^-$

$22 \pm 7 \mathbf{B}^0 \to K_S^0e^+e^-$

$$R_K = \begin{cases} 
0.95 \pm 0.27 & q^2 \in (0.1, 4.0) \text{ GeV}^2/c^4, \\
0.81 \pm 0.28 & q^2 \in (4.0, 8.12) \text{ GeV}^2/c^4, \\
0.98 \pm 0.27 & q^2 \in (1.0, 6.0) \text{ GeV}^2/c^4, \\
1.11 \pm 0.29 & q^2 > 14.18 \text{ GeV}^2/c^4.
\end{cases}$$
**R_{K^*} measurements**

**Belle:**
ArXiv: 1904.02440

Using 711 fb$^{-1}$ data

\[140 \pm 16 \text{ B} \rightarrow K^* \mu^+\mu^-\]
\[103 \pm 13 \text{ B} \rightarrow K^* e^+e^-\]

Adding $B^0$ and $B^+$

Cross-check:

\[r_{J/\psi} = 1.015 \pm 0.025 \pm 0.038\]
Prospects for Flavour Physics

**R_K and R_{K*} measurements**

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

LHCb: 2.5σ at central $q^2$
LHCb: 2.4-2.5σ at central $q^2$
Branching ratios in $b$ to $s\ell^-\ell^+$

LHCb measurements tend to lie below the SM predictions for low $q^2$

$LHCb$ $B^0 \to K^{*0}\mu^+\mu^-$

$LHCb$ $B^0 \to \phi \mu^+\mu^-$

$LHCb$ $B^+ \to K^+\mu^+\mu^-$

$LHCb$ $\Lambda_b^0 \to \Lambda\mu^+\mu^-$

$LHCb$ $B^0 \to K^0\mu^+\mu^-$

$LHCb$ $B^+ \to K^{*+}\mu^+\mu^-$

JHEP 11 (2016) 047

JHEP 09 (2015) 179

JHEP 06 (2014) 133
Angular analysis on $B \rightarrow K^* \mu^+ \mu^-$

**LHCb:**
Run 1 data: HEP 02 (2016) 104, arXiv:1512.04442

**ATLAS:**
Run 1 data: JHEP 10 (2018) 047, arXiv:1805.04000

**CMS:**
2011 data: Phys. Lett. B 727 (2013) 77
2012 data: Phys. Lett. B 753 (2016) 424
PLB 781 (2018) 517, arXiv:1710.02846
Angular analysis on $B \rightarrow K^*\mu^+\mu^-$

- another way to look at $b$ to $s$ FCNC
- 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 $C_{7}^{(i)}, C_{9}^{(i)}, C_{10}^{(i)}, C_{S,P}^{(i)}$

- 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 $\phi$. 
Angular analysis on $B \to K^* \mu^+ \mu^-$

- $B^0$ flavour eigenstate can be identified through the $K^* \to K^- \pi^+$ decay
- Angular distribution given by:

$$
\frac{1}{d\Gamma/dq^2} \frac{d^4\Gamma}{d\cos\theta_\ell d\cos\theta_K d\phi dq^2} = \frac{9}{32\pi} \left[ \frac{3(1 - F_L)}{4} \sin^2\theta_K + F_L \cos^2\theta_K + \frac{1 - F_L}{4} \sin^2\theta_K \cos 2\theta_\ell 
- F_L \cos^2\theta_K \cos 2\theta_\ell + S_3 \sin^2\theta_K \sin^2\theta_\ell \cos 2\phi + S_4 \sin 2\theta_K \sin 2\theta_\ell \cos \phi 
+ S_5 \sin 2\theta_K \sin \theta_\ell \cos \phi + S_6 \sin^2\theta_K \cos \theta_\ell 
+ S_7 \sin 2\theta_K \sin \theta_\ell \sin \phi + S_8 \sin 2\theta_K \sin 2\theta_\ell \sin \phi 
+ S_9 \sin^2\theta_K \sin^2\theta_\ell \sin 2\phi \right].
$$

- The $S$ parameters are translated into the $P^{(i)}$ parameters via

$$
P_1 = \frac{2S_3}{1 - F_L} \quad P'_{i=4,5,6,8} = \frac{S_{j=4,5,7,8}}{\sqrt{F_L(1 - F_L)}}
$$

- The $P^{(i)}$ parameters are expected to have a reduced dependence on the hadronic form factors.
- ATLAS and CMS need to fold the angular distribution via trigonometric relations to reduce the number of free parameters.
Angular analysis results on $B \rightarrow K^*\mu^+\mu^-$

- LHCb gets a deviation of about $2.8/3.0\sigma$ in $P$ ($q^2$ dependent)
- ATLAS gets deviations of about $2.5\sigma$ ($2.7\sigma$) from DHMV in $P'_4(P'_5)$ in $[4,6]$ GeV$^2$

CFFMPSV: Ciuchini et al.; JHEP 06 (2016) 116.
DHMV: Decotes-Genon et al.; JHEP 12 (2014) 125.
JC: Jäger-Camalich; Phys. Rev. D93 (2016) 014028.
Lepton Flavour Universality

From b to c\ell^-\ell^+
Lepton Universality tests in b to c

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

- 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 $c$

$$R(D^{(*)}) = BR(B \to D^{(*)} \tau \nu)/BR(B \to D^{(*)} \ell \nu)$$

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

The scale of NP must be “low” \(\Lambda \sim \text{TeV}\)

BABAR [PRL 109 101802 (2012)] [PRD 88 072012 (2013)] Belle [PRD 92 072014 (2015)] [PRL 118 211801 (2017)] [PRD 97 012004 (2018)] [arXiv:1904.08794] LHCb [PRL 115 (2015) 111803] [PRL 120 (2018) 171802]. Theory [FLAG EPJC77 (2017) 112], [Faijfer et al., PRD 85 094025 (2012)]
Prospects for flavour physics at LHC

HL-LHC: arXiv:1812.07638
Future Prospects for ATLAS and CMS

- ATLAS&CMS can be competitive on favourable final states
- Di-muon is the quintessence of low-$p_T$ clean signature @LHC
- More statistics will allow to improve these results
- New triggers (e.g., tracking @L1) will allow to deal with 200 PU
- Detector limitation: experiments designed to do something else, namely cover 10-1000 GeV range
  - going below 10 GeV (e.g., with electrons and muons) requires effort
- Limited trigger bandwidth (general purpose vs. dedicated experiments)
- Needed customisation (reconstruction, trigger, etc.) vs working force (<50 people)
- Muons are the essential handle for flavour physics in ATLAS & CMS
- Electron reconstruction at ATLAS & CMS is about matching a track to $\geq 1$ calorimeter deposit
  - At low $p_T$, the track might not even make it to the calorimeter and, in any case, deposits are very low energetic: difficult to disentangle them from noise, pileup, etc
- Taus are getting interesting and should be investigated/studied
Prospects on $B_{(s)} \rightarrow \mu^+\mu^-$ at HL-LHC

- Theory prediction limited by $|V_{cb}|$
- Experimental uncertainty on $B_s$ dominated by $f_s/f_d$
- Mass resolution improvements will help reduce the $B_s$-$B_d$ mass correlation
- Additional information from measurements of the effective lifetime and time-dependent CP asymmetry
  - Sensitive to NP from scalar and pseudo-scalar sectors
  - Complementary to BR
- 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)

arXiv:1812.07638
Prospects on $B \rightarrow K^* \mu^+\mu^-$ at HL-LHC

- Large data set allows for precise determination of the angular observables in narrow bins of $q^2$ or using a $q^2$-unbinned approach
- ~440k signal events in LHCb / ~700k events in CMS
- Most systematic uncertainties expected to reduce significantly with luminosity due to larger control samples $\rightarrow$ not systematically limited

- Combining many observables help discriminate NP scenarios.
- Potential sensitivity to the SM and to NP scenarios motivated by LHCb anomalies,
- Scenarios are $C_9 = -1.4$ (vector current) and $C_9 = -C_{10} = -0.7$ (pure left-handed current).
- Included are the branching fraction of $B_s \rightarrow \mu^+\mu^-$ and the angular observables of $B^0 \rightarrow K^0\mu^+\mu^-$ in the low-$q^2$ region (e.g., $P_5^0$).
- ATLAS and CMS combined after the HL-LHC phase. Expectations for ATLAS and CMS in Phase I from the CMS projection scaled by $1/\sqrt{2}$
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 $\Delta F=2$ 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 → cleaner observables → need more 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/π 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
  - Competitive time measurements and mass resolution (CMS)

- 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/no statistics in Bs system

- Exciting times ahead
Back up slides
$B \to \mu^+ \mu^-$ AFTER Summer 2019

Thanks to David Straub for the updated plot
**sin2\(\beta\) in golden \(b \rightarrow c\bar{c}s\) modes**

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

\[ b \xrightarrow{V_{cb}} c \]
\[ \bar{c} \xleftarrow{V^{*}_{cs}} c \]

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:

\[ \bar{b} \xrightarrow{V^{*}_{cb}} \bar{c} \]
\[ c \xleftarrow{V_{cs}} \bar{s} \]
\[ +d \quad K^{0} \rightarrow K_{S,L} \]
\[ \bar{B}^{0} \rightarrow J/\psi K_{S,L} \]
\[ B^{0} \rightarrow J/\psi K_{S,L} \]
sin2\(\beta\) in golden \(b \rightarrow c\bar{c}c\bar{s}\) modes

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

\[
\begin{align*}
\bar{b} & \rightarrow V^*_{cb} c \\
 & \rightarrow V_{cs} s + d \\
\bar{B}^0 & \rightarrow J/\psi K_{S,L}
\end{align*}
\]

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

\[
\begin{align*}
\bar{B}^0 & \rightarrow J/\psi K_{S,L} \\
B^0 & \rightarrow J/\psi K_{S,L}
\end{align*}
\]

K mixing

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

\[
\begin{align*}
B^0 \rightarrow J/\psi K_{S,L}
\end{align*}
\]

No possibility to generate this way direct or indirect CPV

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

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

\[
\text{Im} \lambda_{CP} = -\eta_{CP} \sin2\beta
\]

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

CPV in interference between mixing and decay

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

\[
\begin{align*}
\eta_{CP} (J/\psi K_S) = -1 \\
\eta_{CP} (J/\psi K_L) = +1
\end{align*}
\]
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 $b \rightarrow c$ and $b \rightarrow u$ 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.
$V_{cb}$ and $V_{ub}$ from semileptonic B decays

From tree level processes: semileptonic B decays
$B \rightarrow X_{u,c} l\nu$
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

| Observables     | Measurements | Prediction | Pull (#σ) |
|-----------------|--------------|------------|-----------|
| sin2β           | 0.689 ± 0.018 | 0.738 ± 0.033 | ~ 1.2     |
| γ               | 70.0 ± 4.2   | 65.8 ± 2.2 | ~ 1       |
| α               | 93.3 ± 5.6   | 90.1 ± 2.2 | < 1       |
| |V_{ub}| · 10^3     | 3.72 ± 0.23 | 3.66 ± 0.11 | < 1     |
| |V_{ub}| · 10^3 (incl) | 4.50 ± 0.20 | - | ~ 3.8 |
| |V_{ub}| · 10^3 (excl) | 3.65 ± 0.14 | - | < 1     |
| |V_{cb}| · 10^3     | 40.5 ± 1.1  | 42.4 ± 0.7 | ~ 1.4    |
| BR(B → τν) [10^{-4}] | 1.09 ± 0.24 | 0.81 ± 0.05 | ~ 1.2    |
| A_{SL}^d · 10^3  | -2.1 ± 1.7   | -0.292 ± 0.026 | ~ 1       |
| A_{SL}^s · 10^3  | -0.6 ± 2.8   | 0.013 ± 0.001 | < 1       |
exclusives vs inclusives

only exclusive values

only inclusive values
new-physics-specific constraints

\begin{equation}
A_{SL}^s = \frac{\Gamma(B_s \rightarrow \ell^+ X) - \Gamma(B_s \rightarrow \ell^- X)}{\Gamma(B_s \rightarrow \ell^+ X) + \Gamma(B_s \rightarrow \ell^- X)} = \text{Im} \left( \frac{\Gamma_{12}^s}{A_{SL}^{full}} \right)
\end{equation}

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.

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

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

Cleo, BaBar, Belle, D0 and LHCb

D0 arXiv:1106.6308

HFLAV

Marcella Bona (QMUL)
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 $C$

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

- $Q_1^{q_i q_j} = \bar{q}_{jL} \gamma_\mu q_{iL} \bar{q}_{jL} \gamma^\mu q_{iL}$
- $Q_2^{q_i q_j} = \bar{q}_{jR} q_{iL} \bar{q}_{jR} q_{iL}$
- $Q_3^{q_i q_j} = \bar{q}_{jR} \gamma_\mu q_{iL} \bar{q}_{jR} q_{iL}^\mu$
- $Q_4^{q_i q_j} = \bar{q}_{jR} q_{iL} \bar{q}_{jL} q_{iR}^\beta$
- $Q_5^{q_i q_j} = \bar{q}_{jR} q_{iL} \bar{q}_{jL} q_{iR}^\alpha$

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)
Prospects for Flavour Physics

Testing the TeV scale

The dependence of $C$ on $\Lambda$ changes depending on the flavour structure. We can consider different flavour scenarios:

- **Generic**: $C(\Lambda) = \frac{\alpha}{\Lambda^2}$, $F_i \sim 1$, arbitrary phase
- **NMFV**: $C(\Lambda) = \alpha \times \frac{|F_{SM}|}{\Lambda^2}$, $F_i \sim |F_{SM}|$, arbitrary phase
- **MFV**: $C(\Lambda) = \alpha \times \frac{|F_{SM}|}{\Lambda^2}$, $F_1 \sim |F_{SM}|$, $F_i \neq 1 \sim 0$, 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 $F_{SM}$ is the combination of CKM factors for the considered process
Prospects for Flavour Physics

\[ \Lambda > 90 \text{ TeV} \]

\[ \Lambda > 4.1 \times 10^5 \text{ TeV} \]

\[ \Lambda > 1.2 \times 10^4 \text{ TeV} \]

\[ \Lambda > 2.7 \text{ TeV} \]

\[ \alpha \sim \alpha_W \text{ in case of loop coupling through weak interactions} \]

\[ \alpha \sim \alpha_W \text{ in case of loop coupling through weak interactions} \]

\[ \alpha \sim \alpha_s (\sim 0.1) \text{ or by } \alpha_W (\sim 0.03). \]

\[ C(\Lambda) = \alpha / \Lambda^2, \]

\[ C(\Lambda) = \alpha \times |F_{SM}| / \Lambda^2, \]

\[ F_i \sim 1, \text{ arbitrary phase} \]

\[ F_i \sim |F_{SM}|, \text{ arbitrary phase} \]

Results from the Wilson coefficients

Generic:

\[ C(\Lambda) = \alpha / \Lambda^2, \]

\[ F_i \sim 1, \text{ arbitrary phase} \]

NMFV:

\[ C(\Lambda) = \alpha \times |F_{SM}| / \Lambda^2, \]

\[ F_i \sim |F_{SM}|, \text{ arbitrary phase} \]

\[ \Lambda > 4.1 \times 10^5 \text{ TeV} \]

\[ \Lambda > 90 \text{ TeV} \]

\[ \alpha \sim 1 \text{ for strongly coupled NP} \]
NP parameter results

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

$$A_q = C_{B_q} \ e^{2i\phi_{B_q}} \ A_{q}^{SM} \ e^{2i\phi_{q}^{SM}}$$

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

$C_{B_s} = 1.11 \pm 0.09$
$\phi_{B_s} = (0.4 \pm 0.9)^\circ$

$C_{eK} = 1.11 \pm 0.12$

K system
CP violation in the SM and NP:

- $B_{(s)}$ systems are giving us a rather precise picture
- However there is some space for NP
- Could appear as new contributions in $\Delta F=2$ loop processes

The ratio of NP/SM amplitudes need to be:

- $< 18\% @68\%$ prob.
  - (30\% @95\%)
  - in $B_d$ mixing
- $< 20\% @68\%$ prob.
  - (30\% @95\%)
  - in $B_s$ mixing

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

[0707.0636 hep-ph]
some old plots coming back to fashion:

As NA62 and KOTO are analysing data:

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

2007 global fit area

E949 central value

projection

100 events

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

\[
\begin{align*}
\bar{\rho} &= 0.154 \pm 0.015 \\
\bar{\eta} &= 0.344 \pm 0.013 \\
\rho &= \pm 0.015 \\
\eta &= \pm 0.015 \\
\bar{\rho} &= 0.150 \pm 0.027 \\
\bar{\eta} &= 0.363 \pm 0.025 \\
\rho &= \pm 0.016 \\
\eta &= \pm 0.019
\end{align*}
\]

*current sensitivity*