Trends in flavour physics

Fabrice Couderc *CEA/Irfu/DPhP*

October 12, 2017

This document gives an overview of current and future experiment dedicated to flavour physics. It will first focus on flavour in the quark sector and then briefly mention the prospects in the lepton sector.

Flavour changes are only possible via W boson interaction in the Standard Model (SM). These processes are therefore fully described by the CKM matrix in the quark sector and PMNS matrix in the lepton sector. Having three families of quarks and leptons yields CP violation in the SM which leads to number of interesting observables to constrain these matrices. This is the only source of CP violation in the SM and is known to be far too small to explain baryogenesis for example.

The general idea of flavour physics is first to measure the flavour-matrix elements with processes where the SM dominates (usually with a single tree level amplitude) and, using this precisely measured values, to predict loop-mediated processes where the contribution from new physics (NP) could potentially compete with the SM contribution.

This is what has been done in the quark sector in the last decades and we are now entering in the precision era where one tries to measure extremely rare processes to find sign of NP. And this will be described in the first section of this document.

In the lepton sector, the matrix is related to neutrino oscillations and therefore charged lepton flavour violation is nul in the SM (or extremely small given the size of the neutrino masses). Several NP models predict sizeable lepton flavour violation and dedicated experiments are trying to find these kinds of process. Lepton flavour dedicated measurements will be described in the second part of this document.

1 Flavour in the quark sector

Due to the long lifetime of K^+ and K_L, measurements in the kaon system needs dedicated experiments usually with a very long decay vessel. These experiments will be described first. In a second part we will give an overview of the so called heavy-flavour experiments, *i.e.* experiments which study the c and b quarks (and also usually have a large sample of τ leptons).

1.1 Experiments dedicated to kaon physics

CP violation was first discovered in the kaon system both in the mixing [1] (parameter $\epsilon_K \neq 0$ in 1964) and in the decay [2] (parameter $\epsilon^{'}_K \neq 0$ in 1999). Nevertheless these quantities are hard to predict from the theory point of view. Since recent years and the progress of lattice QCD, there is a revival of kaon physics interest and a vast program is being pursued with several experiments taking data and other foreseen in a near future.

The state of the art for this prediction is [1]:

$$\frac{\epsilon^{'}_K}{\epsilon_K}[\mathrm{SM}] = (1.1 \pm 4.7_{lattice} \pm 1.9_{NNLO} \pm 0.6_{iso.breaking} \pm 0.2 m_t) \times 10^{-4},$$

where the dominant uncertainty is due to lattice QCD. The current experimental value is much more precise (from NA62 and KTeV):

$$\frac{\epsilon^{'}_K}{\epsilon_K}[\mathrm{exp.}] = (16.6 \pm 2.3) \times 10^{-4}. \quad (1)$$

There is therefore a $2.8\ \sigma$ discrepancy between the SM prediction and the experimental value. NP models (especially within the MSSM) could accommodate for such a discrepancy though this require to keep ϵ_K close to its SM value while increasing $\epsilon^{'}_K$. These models are easily falsifiable using two trendy rare kaon decays:

$$\mathcal{B}\left(K^+ \to \pi^+ \nu\overline{\nu}\right)_{\mathrm{SM}} = (8.3 \pm 0.3) \times 10^{-11},$$
$$\mathcal{B}\left(K_L \to \pi^0 \nu\overline{\nu}\right)_{\mathrm{SM}} = (2.9 \pm 0.2) \times 10^{-11}.$$

[1] In neutral meson system $P^0 - \overline{P}^0$ oscillates with time because the flavour eigenstates are not the mass eigenstates. CP violation in the mixing means that $\Gamma(P^0 \to \overline{P}^0) \neq \Gamma(\overline{P}^0 \to P^0)$

[2] CP violation in the decay means that $\Gamma(P \to f) \neq \Gamma(\overline{P} \to \overline{f})$

These decay modes, though very rare, are theoretically very clean and any deviation in $\epsilon_K^{'}/\epsilon_K$ should show up in the measured rate of these two processes. In addition, they allow to constrain the B_d unitary triangle [3] from a different perspective than the usual approach in the B_d meson system, therefore probing the same CKM elements from a complete different perspective. Figure 1 shows the unitary constraints that can be obtained from the KOTO and NA62 experiments.

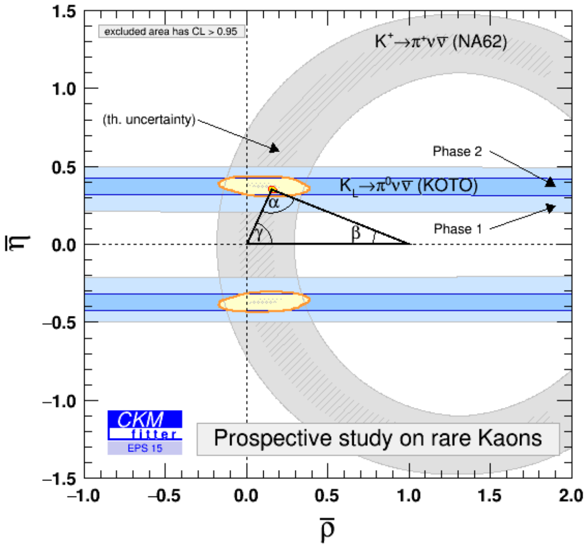

Figure 1: *Constrain from the K-meson system on the B_d unitary triangle.*

There are additional important physics subject that can be constrained with kaons decays:

- Leptonic and semi-leptonic decays: to measure $|V_{us}|$ and probe lepton universality
- Very rare flavour changing neutral currents (FCNC) decays probing $|Vtd|$ and NP

The KLOE-2 experiment located at the Daphne $e^+ - e^-$ collider at $\sqrt{s} = 1.02\text{GeV}$ (ϕ mass) is taking data since 2006. It has a very rich physics program but will stop in 2018 and therefore can not be considered as a future experiment.

Due to the very long lifetime of charged K and K_L, measuring their decay requires dedicated experiments about 100 m away from kaon production source. Three projects looks very promising on the short and longer term:

- **NA62** is located at CERN and has as primary focus the measurement of $\mathcal{B}(K^+ \to \pi^+\nu\overline{\nu})$ with a $10\ \%$ accuracy. It uses proton from the SPS colliding on a target, K^+ are detected in NA62, 100m away from the target. In order to achieve such a precision it should get 100 events with an S/B≈ 10 which requires 10^{13} kaons to be produced. The 2016 run was able to collect data at $40\ \%$ of the nominal intensity. Results are therefore expected in the coming years and should supersede the current best result, from E787/E949 experiments, $\mathcal{B}(K^+ \to \pi^+\nu\overline{\nu}) = 1.73^{+1.15}_{-1.05} \times 10^{-10}$.
- The **KOTO** experiment is located in Japan on the J-PARC 30GeV proton beam and should constrain $\mathcal{B}\left(K_L \to \pi^0\nu\overline{\nu}\right)$. Started in 2013, it has already published a result with its very first data [2] close to the best limit obtained by E391a $\mathcal{B}\left(K_L \to \pi^0\nu\overline{\nu}\right) < 2.8 \times 10^{-8}$, still quite far from the SM. The aim of KOTO is to reach the SM single-event-sensitivity by 2021. Nevertheless, one would need to measure this branching ratio at the $10\ \%$ accuracy, *i.e.* one needs about 100 events detected. This is the purpose of KOTO phase 2 described in the proposal [3] which requires to push the proton beam power intensity to 100kW, no final schedule is official yet (but not to be expected before 2025).
- The **KLEVER** proposal could be a competitor of KOTO phase 2 aiming to reach a $10\ \%$ accuracy on $\mathcal{B}\left(K_L \to \pi^0\nu\overline{\nu}\right)$. Preliminary design study indicates that such an experiment could be performed at the SPS during LHC run 4 (2026-2029). The goal would be to collect about 60 events. This is complementary technique to the KOTO phase 2 with different systematics (high energy K_L). The experiment would re-use the NA48 calorimeter as well as some of the NA62 infrastructure. Though there is no formal proposal yet, an Expression of Interest is currently being written and should be presented at the SPSC by spring 2018.

The DPhP has had a strong involvement in kaon physics, though this has stopped in the recent years. If there is some interest to revive this kind of physics at the DPhP, it seems that the KLEVER proposal could be an interesting project to investigate further.

1.2 Experiments dedicated to heavy-flavour physics

The experiments described in this section are related to heavy flavour physics, especially related to the b-quark sector but since they generally produced a copious dataset of τ leptons and c hadrons, they also cover τ and charm physics, as well as kaon physics sometimes. The physics program being extremely vast it can not be covered in such a document. In the next sections, we will first make a brief overview of the physics reach, focussing on the current disagreements between experimental data (mainly from LHCb, Belle and BaBar) and SM predictions. Then we will describe the (present) and future experiments LHCb, Belle-II, $e^+ - e^-$ machines and BESIII.

[3] the unitary triangle represents graphically, in the complex plane, the orthogonality of the first and last columns of the CKM matrix, *i.e.* the relation $V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$

Highlights of the physics program

Here we will focus on the physics done with b-hadrons. The b-quark being heavy, theoretical predictions are generally easier and some observables are quite clean from this perspective. Since the B-factories BaBar and Belle have discovered the CP violation in the b sector, constraints on the unitary triangle keep increasing.

The first objective is to constrain **CP violation and CKM constraints in the heavy quark sector**, especially to measure the phases α, β and γ of the unitary triable as well as the sides. The angle β is now very well known from the tree level decays. Entering the precision era, this angle is now measured in the so-called penguin (loop) modes where NP is likely to have a large impact. Differences between penguin and tree-level value might be the manifestation of NP. The angle γ is less well measured and LHCb have a strong impact in this matter. The B_s sector has not been probed by the B factory and is being investigated now by LHCb, the measurement of the related ϕ_s phase is crucial.

NP could also show up in **rare decays** which are also loop mediated. There is a plethora of new results from LHCb, CMS and Atlas experiments, one can cite benchmark desintegrations like $B_s/B_d \to \mu^+\mu^-$ which have been awaited for since a long time and are found to be in agreement with the SM. Nevertheless some tensions exists between the SM predictions and the experimental data. In the $b \to s\mu^+\mu^-$ transition, the CP asymmetries in the $B \to K^*\mu^+\mu^-$ is found to be significantly different from its SM prediction by the LHCb experiment, while the CMS measurement is somewhat more in agreement with the SM, though less precise. Fig. 2 shows the current state of the art for the P_5' observable. The data disagree with the SM at low $q^2 = m^2_{\mu\mu}$. It turns out that LHCb also observe several discrepancies in other $b \to s\mu^+\mu^-$ channels. Nevertheless some debates are still raging on the accuracy of the SM prediction.

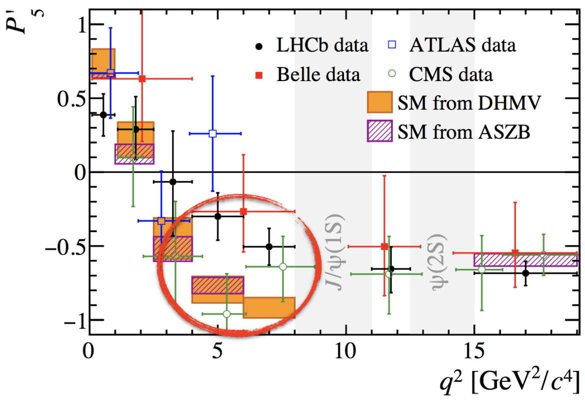

Figure 2: *Status of the P_5' CP observable in the $B \to K^*\mu^+\mu^-$ decay. P_5' is a complex combination of several simpler observable, its main purpose is to be theoretically clean from form factors uncertainties.*

Semi-leptonic b-decays are used to constrained $|V_{ub}|$ and $|V_{cb}|$. But it also provides other tests of the SM. Tensions exist between the measured and expected branching fractions of semi-leptonic tauonic decays. This is parametrised as the ratio to electron and muon semi-leptonic decays $R(X) = \frac{\mathcal{B}(B\to X\tau\nu)}{\mathcal{B}(B\to X\ell\nu)}$. Both $R(D)$ and $R(D^*)$ differ from their respective SM expectations, reaching an overall disagreement of 4 σ as shown in Fig. 3. The theoretical predictions are very reliable since they rely on lepton universality. Therefore, only a larger dataset can fix the issue.

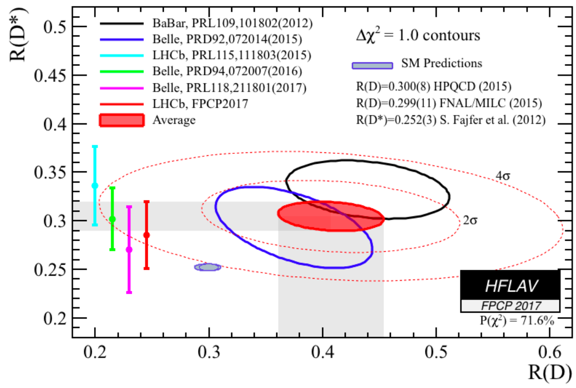

Figure 3: *Measured $R(D)$ and $R(D^*)$ vs their SM predictions. The current discrepancy is at the 4 σ level.*

Several tests of lepton number violation and lepton universality violation can also be performed in this type of experiments. Besides $R(D)$ and $R(D^*)$ which differs from the SM, LHCb also find that $R(K)$ and $R(K^*)$ are low compared to the SM prediction, with $R(X) \equiv \frac{\mathcal{B}(B\to X\mu^+\mu^-)}{\mathcal{B}(B\to Xe^+e^-)}$. This is shown on Fig. 4, in both channels one gets roughly a 2 σ deviation. Nevertheless, it has to be noted that electron identification in jets in the complex LHCb is difficult and the statistics for the electron process is fairly low. A confirmation from a B-factory type machine would be very welcome.

Charm physics is also intensively studied with these datasets. In the neutral D meson system the mixing is very small and the mixing parameters measurement can be further improved. The CP violation in the D system is yet to be established, at the moment only upper limit exist. CP asymmetries are expected to be very small in the SM but are also very difficult to predict.

Eventually these experiments are a rich source of b/c-hadrons **spectroscopy**. In the last decade, several new states (X,Y, Z ...) have been observed in Belle, Babar, LHCb, or BESIII. The interpretations of these new states is still under investigation and larger datasets will help greatly.

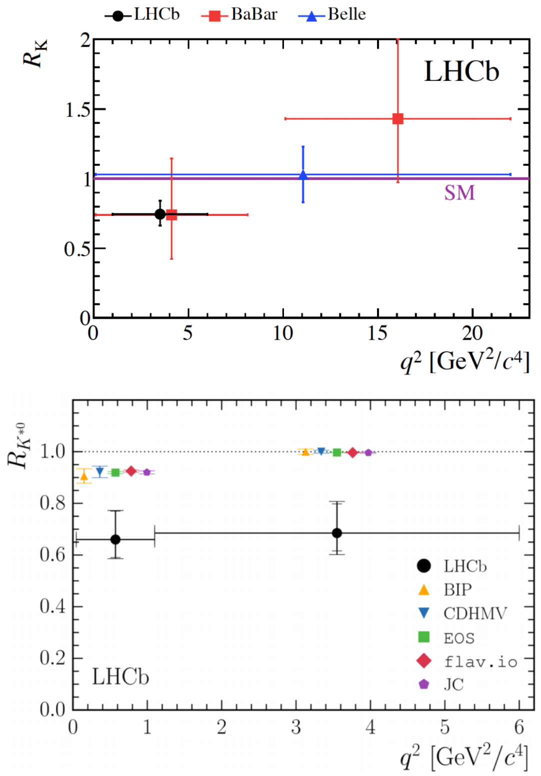

Figure 4: *Measured $R(K)$ (top) and $R(K^*)$. Both channels show roughly a 2 σ deviations.*

LHCb experiment

LHCb has collected about 3 fb^{-1} at 7+8 TeV during the run1 of the LHC. By the beginning of the so-called LHC long stop 2 (LS2), end of 2018, it should have collected about 6 fb^{-1} at 13 TeV, which represents 4-5 times the statistics collected during run1. During LS2, the LHCb experiment will go under a major upgrade of its trigger system, all the detectors will be read at 40MHz allowing for a full software trigger, this will allow an operational luminosity of $\mathcal{L} = 2 \times 10^{-33}\text{cm}^{-2}\text{s}^{-1}$, *e.g.* 5 times higher than the current LHCb instantaneous luminosity. The tracking system will also be fully upgraded as well as the RICH detectors (particle identification devices). On top of the luminosity gain, this will allow a significant improvement in the hadronic mode reconstruction efficiency. Fig. 5 shows the physic reach increase from the upgrade compared to the theory uncertainties in different topics, these results are taken from [5]. The bottom line is that after the first LHC run, most of the observables will still be statistically limited with theory uncertainties much below the experimental ones.

Beyond 2029, LHCb foresees an other upgrade [6] named phase 2 upgrade. The aim is to sustain a luminosity of $\mathcal{L} = 2 \times 10^{-34}\text{cm}^{-2}\text{s}^{-1}$ and to collect up to 500 fb^{-1}. Besides the luminosity upgrade, the detector would get a new high granularity tungsten calorimeter to improve the π^0 and electron detection and an extended tracker coverage for low pT tracks, the vertex detector and the RICH would also be revisited.

Type	Observable	Current precision	LHCb 2018	**Upgrade** ($50\,\text{fb}^{-1}$)	Theory uncertainty
B^0_s mixing	$2\beta_s$ ($B^0_s \to J/\psi\ \phi$)	0.10 [138]	0.025	0.008	~ 0.003
	$2\beta_s$ ($B^0_s \to J/\psi\ f_0(980)$)	0.17 [214]	0.045	0.014	~ 0.01
	a^s_{sl}	6.4×10^{-3} [43]	0.6×10^{-3}	0.2×10^{-3}	0.03×10^{-3}
Gluonic penguins	$2\beta^{\text{eff}}_s(B^0_s \to \phi\phi)$	–	0.17	0.03	0.02
	$2\beta^{\text{eff}}_s(B^0_s \to K^{*0}\bar{K}^{*0})$	–	0.13	0.02	< 0.02
	$2\beta^{\text{eff}}(B^0 \to \phi K^0_S)$	0.17 [43]	0.30	0.05	0.02
Right-handed currents	$2\beta^{\text{eff}}_s(B^0_s \to \phi\gamma)$	–	0.09	0.02	< 0.01
	$\tau^{\text{eff}}(B^0_s \to \phi\gamma)/\tau_{B^0_s}$	–	5 %	1 %	0.2 %
Electroweak penguins	$S_3(B^0 \to K^{*0}\mu^+\mu^-; 1 < q^2 < 6\,\text{GeV}^2/c^4)$	0.08 [67]	0.025	0.008	0.02
	$s_0\ A_{\text{FB}}(B^0 \to K^{*0}\mu^+\mu^-)$	25 % [67]	6 %	2 %	7 %
	$A_{\text{I}}(K\mu^+\mu^-; 1 < q^2 < 6\,\text{GeV}^2/c^4)$	0.25 [76]	0.08	0.025	~ 0.02
	$\mathcal{B}(B^+ \to \pi^+\mu^+\mu^-)/\mathcal{B}(B^+ \to K^+\mu^+\mu^-)$	25 % [85]	8 %	2.5 %	~ 10 %
Higgs penguins	$\mathcal{B}(B^0_s \to \mu^+\mu^-)$	1.5×10^{-9} [13]	0.5×10^{-9}	0.15×10^{-9}	0.3×10^{-9}
	$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B^0_s \to \mu^+\mu^-)$	–	~ 100 %	~ 35 %	~ 5 %
Unitarity triangle angles	γ ($B \to D^{(*)}K^{(*)}$)	~ 10–12° [244, 258]	4°	0.9°	negligible
	γ ($B^0_s \to D_sK$)	–	11°	2.0°	negligible
	β ($B^0 \to J/\psi\ K^0_S$)	0.8° [43]	0.6°	0.2°	negligible
Charm CP violation	A_Γ	2.3×10^{-3} [43]	0.40×10^{-3}	0.07×10^{-3}	–
	$\Delta\mathcal{A}_{CP}$	2.1×10^{-3} [18]	0.65×10^{-3}	0.12×10^{-3}	–

Figure 5: *Statistical sensitivities of the LHCb upgrade phase1 to key observables.*

Belle-II and super KEK B

After the success of the Belle and BaBar experiments, the upgrade of the KEK collider (SuperKEK) will allow a 40 times higher luminosity than its ancestor, reaching a peak luminosity $\mathcal{L} = 8 \times 10^{-35}\text{cm}^{-2}\text{s}^{-1}$. This has been achieved by reducing considerably the β^* and the emittance (nano beam structure) as well as increasing the beam current. The asymmetric beam energies have also been changed to $\text{HER} = 7$ GeV and $\text{LER} = 4$ GeV, slightly less asymmetric than the KEK beam energies. The integrated luminosity increase is shown on Fig. 6 and Belle-II should collect 50 ab^{-1} by 2025. In 2016, first beams were circulated in the machine, allowing to tune the accelerator parameters as well as doing beam background studies.

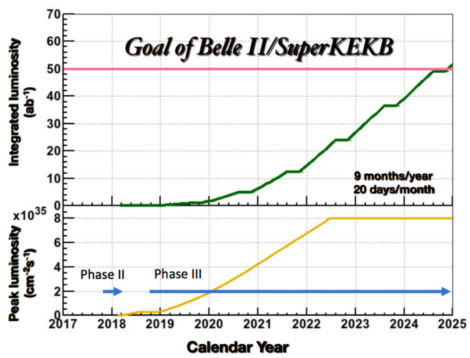

Figure 6: *Super KEK luminosity scenario.*

With such a luminosity the background from the beam is an issue, it will represent 50 % of the electromagnetic calorimeter energy and dominate the vertex detector occupancy. To overcome the high luminosity challenges, the Belle detector has been significantly upgraded. The silicon vertex detector and the tracker have smaller granularity and larger volume (more layers for the vertex detector). The particle ID detectors have also been changed as well as the endcap electromagnetic calorimeter electronics. The trigger system has been fully re-designed to cope with these very high rates.

The Belle-II experiment should collect 55 billions of $B\overline{B}$ pairs, 65 billions of $c\overline{c}$ pairs and 65 billions of $\tau^+\tau^-$ pairs, hence it will cover a vast physics program not only in the b-meson system but also in charm and tau lepton physics.

The french community is already involved in the Belle-II collaboration via the LAL Orsay and the IPHC Strasbourg. While the DPhP had a very strong involvement in BaBar, it did not pursue its interest in heavy flavour physics, being absent from the LHCb collaboration. If some DPhP physicists want to revive the engagement in this kind of physics, participating to the Belle-II program seems likely to be the very best way.

Belle-II vs LHCb

The two experiments are complementary in several aspects. LHCb has a tremendous statistics and is the only one which has access to b-baryons. On the other hand Belle-II has several advantages over LHCb to cope with a lower statistics:

- a cleaner environment,
- a much easier access to decay channels with γ (thus π^0!), electrons which are hard to reconstruct in jets,
- B-beams! Since Bs are pair produced, by fully reconstructing one B, one gets access to the kinematic of its companion without reconstructing it, alloring to either do inclusive measurements or a clean access to decay involving neutrinos ($B \to \tau\nu$, $B \to D^{(*)}\tau\nu$ etc).

Table 7 extracted from the Belle-II Theory Interface Platform shows the complementary between the two experiments. Belle-II dominates the measurement involving photons, electrons, and also semi-leptonic decays with neutrinos, while LHCb will be crucial for the B_s system, and generally all decays channels involving muons.

$e^+ - e^-$ colliders at the Z pole

Machines like the ILC and the FCC-ee are mainly discussed in the prospective "physique aux futurs collisionneurs", but they will also produce a very large sample of $Z \to b\bar{b}$ which can be used to study flavour physics. The FCC-ee is certainly a better machine in this particular case since the luminosity at the Z pole is much higher than the ILC one.

FCC-ee could collect about 10^{12} Z decays. More specific to these machines which provide a clean environment compared to hadron machines are the modes involving B_s as well as the lepton flavour violation at the Z pole. The FCC-ee team is for example focussing on the benchmarks: $B_s/B_d \to \tau^+\tau^-$, $B_s \to \gamma\gamma$,

Observables	Expected th. accuracy	Expected exp. uncertainty	Facility (2025)
UT angles & sides			
ϕ_1 [°]	***	0.4	Belle II
ϕ_2 [°]	**	1.0	Belle II
ϕ_3 [°]	***	1.0	Belle II/LHCb
$S(B_s \to J/\psi\phi)$	***	0.01	LHCb
$\lvert V_{cb}\rvert$ incl.	***	1%	Belle II
$\lvert V_{cb}\rvert$ excl.	***	1.5%	Belle II
$\lvert V_{ub}\rvert$ incl.	**	3%	Belle II
$\lvert V_{ub}\rvert$ excl.	**	2%	Belle II/LHCb
CPV			
$S(B \to \phi K^0)$	***	0.02	Belle II
$S(B \to \eta' K^0)$	***	0.01	Belle II
$\beta_s^{\text{eff}}(B_s \to \phi\phi)$ [rad]	**	0.1	LHCb
$\beta_s^{\text{eff}}(B_s \to K^{*0}\bar{K}^{*0})$ [rad]	**	0.1	LHCb
$\mathcal{A}(B \to K^0\pi^0)[10^{-2}]$	***	4	Belle II
$\mathcal{A}(B \to K^+\pi^-)$ $[10^{-2}]$	***	0.20	LHCb/Belle II
(Semi-)leptonic			
$\mathcal{B}(B \to \tau\nu)$ $[10^{-6}]$	**	3%	Belle II
$\mathcal{B}(B \to \mu\nu)$ $[10^{-6}]$	**	7%	Belle II
$R(B \to D\tau\nu)$	***	3%	Belle II
$R(B \to D^*\tau\nu)$	***	2%	Belle II/LHCb
Radiative & EW Penguins			
$\mathcal{B}(B \to X_s\gamma)$	**	4%	Belle II
$A_{CP}(B \to X_{s,d}\gamma)$ $[10^{-2}]$	***	0.005	Belle II
$S(B \to K_S^0\pi^0\gamma)$	***	0.03	Belle II
$2\beta_s^{\text{eff}}(B_s \to \phi\gamma)$	***	0.05	LHCb
$S(B \to \rho\gamma)$	**	0.07	Belle II
$\mathcal{B}(B_s \to \gamma\gamma)$ $[10^{-6}]$	**	0.3	Belle II
$\mathcal{B}(B \to K^*\nu\bar{\nu})$ $[10^{-6}]$	***	15%	Belle II
$\mathcal{B}(B \to K\nu\bar{\nu})$ $[10^{-6}]$	***	20%	Belle II
$q_0^2 A_{\text{FB}}(B \to K^*\mu\mu)$	**	0.05	LHCb/Belle II
$\mathcal{B}(B_s \to \tau\tau)$ $[10^{-3}]$	***	< 2	Belle II
$\mathcal{B}(B_s \to \mu\mu)$	***	10%	LHCb/Belle II
Charm			
$\mathcal{B}(D_s \to \mu\nu)$	***	0.9%	Belle II
$\mathcal{B}(D_s \to \tau\nu)$	***	2%	Belle II
$\Delta A_{CP}(D^0 \to K^+K^-)$ $[10^{-4}]$	**	0.1	LHCb
$A_{CP}(D^0 \to K_S^0\pi^0)$ $[10^{-2}]$	**	0.03	Belle II
$\lvert q/p\rvert(D^0 \to K_S^0\pi^+\pi^-)$	***	0.03	Belle Ii
$\phi(D^0 \to K_S^0\pi^+\pi^-)$ [°]	***	4	Belle II
Tau			
$\tau \to \mu\gamma$ $[10^{-9}]$	***	< 5	Belle II
$\tau \to e\gamma$ $[10^{-9}]$	***	< 10	Belle II
$\tau \to \mu\mu\mu$ $[10^{-9}]$	***	< 0.3	Belle II/LHCb

Figure 7: *Belle-II and LHCb experiment complementarity. These numbers need to be taken with care but give the overall picture.*

$B_s \to D_s^{\pm}K^{\mp}$ (measuring the angle γ and ϕ_s) and the particularly interesting lepton flavour violating decay $Z \to \tau\ell$ where ℓ is either an electron or a muon. In this latter example it could reach branching ratio down to 10^{-10}.

These machines are yet to be accepted and the timeline will not be discussed here (see "physique aux futurs collisionneurs" for more information).

BESIII and a potential follow-up HIEPA

BESIII is operating on BEPCII which is an $e^+ - e^-$ collider with a tunable center of mass energy $\sqrt{s}$ from 2 to 4.6 GeV located in Beijing. It started collecting data in 2009 and the luminosity is currently $\mathcal{L} = 10^{33}$ cm^{-2}s^{-1}, peak luminosity reached in 2016. Similarly to the B factory, it can produce entangled $D - \overline{D}$ pairs, using the ψ resonances. It can therefore produced measurements of exclusive and inclusive D meson decay branching ratio, form factors, decay constants, CP violation parameters, and also perform charm spectroscopy.

A continuation to the BEPCII program could be the HIEPA for High Intensity Electron Proton Accelerator (HIEPA) which would reach in the same energy range instantaneous luminosities 100 times larger than BEPCII. HIEPA is one of the option for the future of

HEP in China though certainly less supported than CEPC (see the prospectives physique aux futurs collisionneurs).

One word on the top sector

In the top sector, numerous flavour tests can be done and are usually part of the the so-called top physics group in high energy experiments such as CMS or Atlas. They are not treated here since there is no dedicated experiment.

2 Flavour in the charged lepton sector

In this section we will look at flavour physics in the lepton sector. First the different tests available of lepton flavour violation (LFV) and lepton flavour universality (LFU). Then a brief mention of the update on the muon anomalous magnetic moment measurement is made. The last section is devoted to "other" experiments.

2.1 Test of charged lepton flavour violation and lepton flavour universality

In the SM, lepton flavour is strictly conserved while the lepton universality is only violated by the Yukawa couplings, while NP could lead to sizeable violations of these numbers referred respectively as LFV and LFU. This can be tested in $e^+ - e^-$ and hadron colliders in several manners which be briefly mentioned. Several experiments are dedicated to these measurements and are described hereafter.

LFV and LFU in colliders

As already alluded to in section 1.2, several tests of LFV and LFU can be performed in $e^+ - e^-$ and hadron colliders. First at high energy in the decay of hypothetic particles directly violating these numbers like this is the case for some $Z^{'}$ models or charged Higgs decay, but also in the b and c-hadron decays as already mentioned.

τ lepton decay can also be directly studied in these machines. The third lepton family could be of special importance as some NP models predict that LFV could be non universal, the heavier leptons being more affected. A large number of LFV τ decays has been searched for in the past experiments. An overview of all the available limits is summarised in Fig. 8, the take-home message being that one reaches exclusions of $\mathcal{B}(\tau \to X_{LVF}) < 10^{-8} - 10^{-7}$.

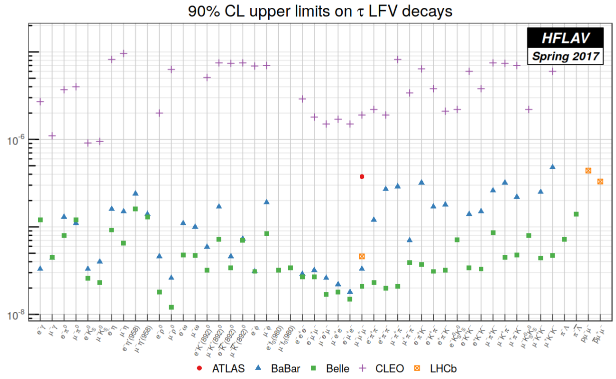

Figure 8: *Overview of the different LFV searched for in τ decays from recent collider machines.*

MEG-II and Mu3e experiments

MEG-II and Mu3e experiments are both studying muon decays violating the lepton flavour using the muon beam from PSI (Paul Scherrer Institute in Zurich). MEG and Mu3e are respectively devoted to the $\mu \to e\gamma$ and $\mu \to eee$ decays which are barely allowed within the SM (only because of neutrino oscillations), indeed one expects un-measurable SM branching ratios $\mathcal{B} \approx 10^{-54}$. The PSI muon beam will deliver about 10^8 muon/s with a momentum $p = 29$ MeV. Muons are then in a thin target placed at the center of the detectors.

MEG-II is an upgrade of MEG which already set the strongest limit to date $\mathcal{B}(\mu \to e\gamma) < 4.2 \times 10^{-13}$, the energy resolution will be increased by a factor 2. MEG-II is expected to start next year an engineering run followed by a physics run. The target sensitivity is to reach $BR(\mu \to e\gamma) < 4 \times 10^{-14}$, improving the current best limit by a factor 10 by 2021.

Mu3e is a brand new detector which aims to set limit on $BR(\mu \to eee)$ down to 10^{-15} in a first phase pushing it to a few 10^{-16} in a second phase, the current best limit being $BR(\mu \to eee) < 4 \times 10^{-12}$ (from SINDRUM @ PSI). The R&D phase has been completed and the construction phase is on-going. An engineering run should start in 2019.

Mu2e and COMET experiments

These two experiments are studying $\mu \to e$ conversions using a muon beam stopped in a target. Muonic atoms are formed and the decay in orbit of muons give a mono-energetic electron. Both experiments are using Al targets. As a comparison to MEG and Mu3e experiments an even larger number of muons is needed about $10^{11} muons/s$. The current best limit for $\mu \to e$ conversion is $R_{e\mu}e = \frac{\Gamma(\mu N \to eN)}{\Gamma(\mu N \to \mathrm{allcaptures})} < 7 \times 10^{-13}$ (from SINDRUM @ PSI).

Mu2e is located at Fermilab and will use the 8 GeV protons from the booster (8 kW). The beam line are under construction while the detector building should start next year (2018). Physics data taking is scheduled in 2022 for 3 years which should allow to reach the nominal sensitivity of $R_{e\mu} < 8 \times 10^{-17}$. There is a possibility of an upgrade to Mu2e-II using the planned upgrade of the proton beam (PIP-II) with a much higher power. The goal being to get the limit down by another factor 10.

COMET uses the $8\ \mathrm{GeV}$ proton beam of the J-PARC facility. COMET has a staged approach with a first beam intensity of 3.2kW upgrading in a second step to 52kW. The beam line and detectors are currently under construction and physics run should start in the course of 2019 to reach a sensitivity of $R_{e\mu} < 3 \times 10^{-15}$ after half a year. The COMET phase-II schedule is not yet known, it requires in addition a new curved solenoid after the target. The final goal being to reach limit down to 10^{-17}.

2.2 Neutral lepton number violation

In the SM, this is due to neutrino masses implying neutrino oscillations. One should refer to the Neutrino oscillation perspectives.

2.3 Muon anomalous g-2

The discrepancy between the measured and expected value of the anomalous magnetic moment of the muon $a_\mu \equiv (g-2)/2$ is a long standing saga. Since 15 years there is between 3.3 and 3.8 σ difference between the SM prediction and the experimental value:

$$a_\mu^{E821} = (116592089 \pm 63) \times 10^{-11}$$
$$a_\mu^{SM} = (116591802 \pm 49) \times 10^{-11},$$

the SM value being slightly dependent on the authors. In the difference $a_\mu^{E821} - a_\mu^{SM}$, the error budget is shared between the experimental errors and the theory ones, the experimental one being slightly dominant. From the theory side, the overly dominant uncertainty is due a_μ^{had}, the hadronic vacuum polarisation, which can be constrained from e^+e^- low energy collisions.

To improve the experimental uncertainty, the experiment E989 at Fermilab will collect 20 times more statistics than its predecessor E821 which should improve the experimental uncertainty by a factor 4. The discrepancy could therefore reach the $8\ \sigma$ level if the central value stays the same. Hence, E989 will constitute a major milestone in this field. A first result with the equivalent of E821 statistics should be available by 2019 and the final result around 2020 (reaching an error of 0.14 ppm).

This is also worth noting the alternate approach to this measurement which is pursued at J-PARC, the idea being to use ultra-cold muons instead of the $3.094\ \mathrm{GeV}$ muons used at BNL or Fermilab. This allows to reduce considerably the size of the storage ring (33.3 cm in this case), which, in turns, allows to increase and to better control the magnetic field. The aim is to start stage-1 in 2019 targeting an error of 0.40 ppm and reach a sensitivity similar to Fermilab later. This is a very complementary approach with different sources of systematics.

2.4 Other experiments

Electric dipole moments (EDMs)

The choice has been made to not report here on these experiments since the DPhP has no really expertise in this domain yet. Nevertheless there is a variety of upcoming proposals. The current leader for the neutron EDM is PSI with a potential reach of $10^{-27}\ e$cm. Concerning proton EDM, the target is to get down to sensitivities of $10^{-29}\ e$cm. There is also a proposal to probe charm baryon EDMs at the LHC.

Search for Hidden Particles: SHiP experiment

SHiP is an experiment proposal at CERN which could start taking data as soon as 2026. The point is to study neutral long lived particles produced by a proton beam from the SPS on a target. It can be either SM neutrinos or new particles, the original idea being to probe heavy neutral leptons from the νMSM [7] model which predicts 3 new heavy neutrinos (one being a dark matter candidate). The conceptual design report should be available in 2018.

Summary

There is a large number of future projects that will greatly improved our knowledge of flavour physics. In this context and given the expertise at the DPhP, an involvement in Belle-II would be a natural continuation with a guaranteed large physics output. Kaon experiments have also been central in the physics program of the DPhP though this field of research has disappeared in the recent years. Upcoming kaon experiments at CERN (KLEVER) might be an opportunity to revive this field.

References

[1] U. Nierste, *Past, present and future CP violation*, Flavour Physics conference, XIII rencontres du Vietnam , 2017, and references therein.

[2] arXiv:1609.03637

[3] KOTO proposal, http://koto.kek.jp/pub/p14.pdf

[4] KLEVER proposal, https://indico.cern.ch/event/525259/attachments/1264623/1871266/NA62-16-03.pdf

[5] LHCb collaboration, *Implications of LHCb measurements and future prospects*, arXiv:1208.3355, 2012.

[6] LHCb collaboration, *Expression of Interest for a Phase-II LHCb Upgrade*, CERN-LHCC-2017-003.

[7] T.Asaka, M.Shaposhnikov **PLB** 620 (2005) 17