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Flavor physics in and after the LHC era

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Summary. — We present a concise review of the status of flavor physics emphasizing that the current experimental resolutions are already testing territories of new physics models well beyond the LHC reach. The synergy and interplay among the LHC and high-precision low-energy experiments is our best chance to learn more about the origin of both electroweak and flavor symmetry breaking.

PACS `11.30.Hv` – Flavor symmetries.
PACS `11.30.Er` – Charge conjugation, parity, time reversal, and other discrete symmetries.

1. – Introduction

Flavor physics experiments probe mass scales well beyond those accessible by direct searches in collider experiments. Therefore, low-energy experiments will provide relevant constraints and complementary information on the structure of the new-physics (NP) models invoked to explain any discoveries at the LHC, and they have the potential to unveil NP that is inaccessible to the LHC.

In the past decade our understanding of flavor physics has improved significantly due to BaBar, Belle, the Tevatron experiments, and most recently LHCb. The outstanding consistency of all flavor measurements with the SM expectations is commonly referred to as the "new physics flavor puzzle", that is why the flavor structure of TeV-scale new physics is highly non-generic. Flavor physics, in particular measurements of meson mixing and CP violation, puts severe lower bounds on the scale of new physics, Λ. Conversely, for $\Lambda \sim 1\,\text{TeV}$, the NP flavor mixing angles must be extremely small. Therefore, there is a tension between the TeV scale required to stabilize the electroweak scale and the flavor data.

The motivation for a broad program of precision flavor physics measurements has been even reinforced after the first LHC run where only a new scalar, with properties similar to the SM Higgs boson, has been discovered. Indeed, the LHC has begun to test naturalness as a guiding principle. If the electroweak scale is unnatural, we have little information on the next energy scale to explore. If the electroweak symmetry breaking scale is stabilized by a natural mechanism, new particles should be found at the LHC. They would provide a novel probe of the flavor sector, and flavor physics and the LHC data would provide complementary information. Their combined study is our best chance to learn more about the origin of both electroweak and flavor symmetry breaking.

2. – Kaon physics

Kaon decays have played a crucial role to test the SM and they continue to have a high power to constrain the flavor sector of possible extensions of the SM. Among the most important FCNC channels are $K^+ \to \pi^+\nu\overline{\nu}$, $K_L \to \pi^0\nu\overline{\nu}$, $K_L \to \pi^0 e^+e^-$, and $K_L \to \pi^0\mu^+\mu^-$. Because of the peculiar suppression of the SM amplitude (where the top-quark loop is CKM-suppressed by $|V_{td}V_{ts}| \sim \lambda^5$, where λ is the Wolfenstein parameter $\lambda \sim 0.2$) which is not present in SM extensions, kaon FCNC modes offer a unique window into the flavor structure of new physics. Rare kaon decays can elucidate the flavor structure of SM extensions, information that is in general not accessible from high-energy colliders.

Discovery potential depends on the precision of the SM prediction for these kaon decays, the level of constraints from other observables, and how well we can measure their branching fractions. In the modes $K^+ \to \pi^+\nu\overline{\nu}$ and $K_L \to \pi^0\nu\overline{\nu}$, the intrinsic theoretical uncertainty is a small fraction of the total, which is currently dominated by the uncertainty in CKM parameters. It is expected that in the next decade progress in lattice QCD and in B meson measurements from LHCb and Belle II will reduce the theory uncertainty on both $K \to \pi\nu\overline{\nu}$ modes to the 5% level.

Besides the FCNC modes, kaon decays also provide exquisite probes of the charged-current sector of SM extensions, probing the TeV or higher scales. Theoretically, the cleanest probes are: 1) the ratio $R_K \equiv \Gamma(K \to e\nu)/\Gamma(K \to \mu\nu)$, which tests lepton universality, scalar, and tensor charged-current interactions; 2) the transverse muon polarization P_μ^T in the semi-leptonic decay $K^+ \to \pi^0\mu^+\nu_\mu$, which is sensitive to new sources of CP violation in scalar charged-current operators. In both cases there is a clean discovery window provided by the precise SM theoretical prediction of R_K and by the fact that P_μ^T is generated in the SM only by very small and known final state interactions. Table I provides a summary of SM predictions for these processes, along with current and projected experimental sensitivities at ongoing or planned experiments.

A number of rare kaon decay experiments are in progress in Japan and in Europe. These include: the NA62 experiment at CERN to measure the $K^+ \to \pi^+\nu\overline{\nu}$ branching fraction; KOTO at J-PARC, which expects to reach below the SM level for $K_L \to \pi^0\nu\overline{\nu}$; TREK at J-PARC, which will search for T-violation in $K^+ \to \pi^0\mu^+\overline{\nu}$ decays but also has a broader program of measurements; and KLOE-2 at the Frascati laboratory, which will improve measurements of neutral kaon interference, tests of CPT and quantum mechanics, and non-leptonic and radiative K decays.

No kaon experiments are currently underway in the U.S. The proposed ORKA experiment at Fermilab has the potential to utilize the Main Injector and other existing infrastructure, along with a well-tested experimental technique, to make a precise measurement of the $K^+ \to \pi^+\nu\overline{\nu}$ branching fraction based on 1000 or more events. ORKA will build on the proven background rejection of BNL E787/E949 (where seven $K^+ \to \pi^+\nu\overline{\nu}$ events were observed). The new detector will take advantage of technology improvements, but to achieve the goals of ORKA, the background rejection achieved at BNL is adequate. Since the Main Injector is already scheduled to run to support NOνA, ORKA provides the opportunity to mount a world-leading rare kaon decay experiment in this decade.

TABLE I. – *The reach of current and proposed experiments for some key rare kaon decay measurements, compared to SM theory and the current best experimental results. In the SM predictions for* $K \to \pi\nu\bar{\nu}$ *and* $K \to \pi\ell^+\ell^-$ *the first error is parametric, and the second is the intrinsic theoretical uncertainty* [1].

Observable	SM Theory	Current Expt.	Future Experiments
$\mathcal{B}(K^+ \to \pi^+\nu\bar{\nu})$	$7.81(75)(29) \times 10^{-11}$	$1.73^{+1.15}_{-1.05} \times 10^{-10}$ E787/E949	$\sim 10\%$ at NA62 $\sim 5\%$ at ORKA $\sim 2\%$ at ProjectX
$\mathcal{B}(K^0_L \to \pi^0\nu\bar{\nu})$	$2.43(39)(6) \times 10^{-11}$	$< 2.6 \times 10^{-8}$ E391a	1st observation at KOTO $\sim 5\%$ at ProjectX
$\mathcal{B}(K^0_L \to \pi^0 e^+e^-)$	$(3.23^{+0.91}_{-0.79}) \times 10^{-11}$	$< 2.8 \times 10^{-10}$ KTeV	$\sim 10\%$ at ProjectX
$\mathcal{B}(K^0_L \to \pi^0 \mu^+\mu^-)$	$(1.29^{+0.24}_{-0.23}) \times 10^{-11}$	$< 3.8 \times 10^{-10}$ KTeV	$\sim 10\%$ at ProjectX
$\lvert P_T \rvert$ in $K^+ \to \pi^0\mu^+\nu$	$\sim 10^{-7}$	< 0.0050	< 0.0003 at TREK < 0.0001 at ProjectX
$\Gamma(K_{e2})/\Gamma(K_{\mu 2})$	$2.477(1) \times 10^{-5}$	$2.488(10) \times 10^{-5}$ (NA62, KLOE)	$\pm 0.0054 \times 10^{-5}$ at TREK $\pm 0.0025 \times 10^{-5}$ at ProjectX
$\mathcal{B}(K^0_L \to \mu^\pm e^\mp)$	$< 10^{-25}$	$< 4.7 \times 10^{-12}$	$< 2 \times 10^{-13}$ at ProjectX

In the longer term, Project X has the potential to provide unprecedented beam power for producing kaons, leading to at least an order of magnitude higher kaon fluxes. Also, the CW-linac of Project X has the ability to provide a well-controlled bunch structure that can be exploited in rare K_L-decay experiments by use of time of flight to measure the decaying K_L momenta. This provides valuable kinematic information that will reduce background in a high-statistics $K_L \to \pi^0\nu\bar{\nu}$ measurement.

3. – Bottom and charm physics

B physics provides us with a plethora of interesting observables. The LHCb experiment has already delivered striking results, for example the first measurement of $B_s \to \mu^+\mu^-$. This experiment will continue running in its current configuration until 2018, when a major upgrade will be implemented during the LHC shutdown. Subsequently, LHCb will be able to collect $5\,\text{fb}^{-1}$ per year and should reach $50\,\text{fb}^{-1}$ around 2030. In Japan the KEK *B* factory is being upgraded to SuperKEKB, and the Belle II detector is being built to run there. SuperKEKB running is planned to begin in 2017, and an integrated luminosity of $50\,\text{ab}^{-1}$ is projected by 2023. In both cases these large data sets will make dramatic improvements in sensitivity to new physics across a broad program of measurements. Examples include precision measurements of phases and magnitudes of CKM angles (β_s, γ, $|V_{ub}|$, etc.), *CP* violation in decays dominated by loop diagrams, leptonic *B* decays, and properties of FCNC decays. The ATLAS and CMS experiments at LHC may be competitive on *B*-decay modes with dimuon final states, such as $B_{s,d} \to \mu^+\mu^-$. Belle II and LHCb will also have broad programs of charm studies, as well as bottomonium spectroscopy.

Tables II and III show the current and projected experimental precision for a number of important measurements for Belle II and LHCb, respectively, along with the SM theory uncertainties.

Table II. – *The expected reach of Belle II with* $50\,\mathrm{ab}^{-1}$ *of data for various topical* B *decay measurements. Also listed are the SM expectations and the current experimental results. For* $\mathcal{B}(B \to X_s \ell^+\ell^-)$*, the quoted measurement* [2] *covers the full* q^2 *range. For* $|V_{ub}|$ *and the* A_{FB} *zero crossing, we list the fractional errors* [1].

Observable	SM theory	Current measurement (early 2013)	Belle II ($50\,\mathrm{ab}^{-1}$)
$S(B \to \phi K^0)$	0.68	0.56 ± 0.17	± 0.03
$S(B \to \eta' K^0)$	0.68	0.59 ± 0.07	± 0.02
α from $B \to \pi\pi$, $\rho\rho$		$\pm 5.4^\circ$	$\pm 1.5^\circ$
γ from $B \to DK$		$\pm 11^\circ$	$\pm 1.5^\circ$
$S(B \to K_S \pi^0 \gamma)$	< 0.05	-0.15 ± 0.20	± 0.03
$S(B \to \rho\gamma)$	< 0.05	-0.83 ± 0.65	± 0.15
$A_{CP}(B \to X_{s+d}\,\gamma)$	< 0.005	0.06 ± 0.06	± 0.02
A^d_{SL}	-5×10^{-4}	-0.0049 ± 0.0038	± 0.001
$\mathcal{B}(B \to \tau\nu)$	1.1×10^{-4}	$(1.64 \pm 0.34) \times 10^{-4}$	$\pm 0.05 \times 10^{-4}$
$\mathcal{B}(B \to \mu\nu)$	4.7×10^{-7}	$< 1.0 \times 10^{-6}$	$\pm 0.2 \times 10^{-7}$
$\mathcal{B}(B \to X_s\gamma)$	3.15×10^{-4}	$(3.55 \pm 0.26) \times 10^{-4}$	$\pm 0.13 \times 10^{-4}$
$\mathcal{B}(B \to K\nu\overline{\nu})$	3.6×10^{-6}	$< 1.3 \times 10^{-5}$	$\pm 1.0 \times 10^{-6}$
$\mathcal{B}(B \to X_s \ell^+\ell^-)$ $(1 < q^2 < 6\,\mathrm{GeV}^2)$	1.6×10^{-6}	$(4.5 \pm 1.0) \times 10^{-6}$	$\pm 0.10 \times 10^{-6}$
$A_{\mathrm{FB}}(B^0 \to K^{*0}\ell^+\ell^-)$ zero crossing	7%	18%	5%
$\lvert V_{ub}\rvert$ from $B \to \pi\ell^+\nu$ $(q^2 > 16\,\mathrm{GeV}^2)$	9% → 2%	11%	2.1%

Table III. – *Sensitivity of LHCb to key observables. The current sensitivity (based on* 1–3 fb^{-1}*, depending on the measurement) is compared to that achievable with* $50\,\mathrm{fb}^{-1}$ *by the upgraded experiment* [1].

Observable	Current SM theory uncertainty	Precision as of 2013	LHCb Upgrade ($50\,\mathrm{fb}^{-1}$)
$2\beta_s(B_s \to J/\psi\phi)$	~ 0.003	0.09	0.008
$\gamma(B \to D^{(*)}K^{(*)})$	$< 1^\circ$	8°	0.9°
$\gamma(B_s \to D_s K)$	$< 1^\circ$	–	2°
$\beta(B^0 \to J/\psi K^0_S)$	small	0.8°	0.2°
$2\beta^{\mathrm{eff}}_s(B_s \to \phi\phi)$	0.02	1.6	0.03
$2\beta^{\mathrm{eff}}_s(B_s \to K^{*0}\bar{K}^{*0})$	< 0.02	–	0.02
$2\beta^{\mathrm{eff}}_s(B_s \to \phi\gamma)$	0.2%	–	0.02
$2\beta^{\mathrm{eff}}(B^0 \to \phi K^0_S)$	0.02	0.17	0.05
A^s_{SL}	0.03×10^{-3}	6×10^{-3}	0.25×10^{-3}
$\mathcal{B}(B_s \to \mu^+\mu^-)$	8%	36%	5%
$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s \to \mu^+\mu^-)$	5%	–	$\sim 35\%$
$A_{\mathrm{FB}}(B^0 \to K^{*0}\mu^+\mu^-)$ zero crossing	7%	18%	2%

TABLE IV. – *Sensitivities of Belle II and LHCb to CP violation in D^0 mixing* [1].

Observable	Current status	Belle II ($50\,\mathrm{ab}^{-1}$)	LHCb upgrade ($50\,\mathrm{fb}^{-1}$)
$\lvert q/p\rvert$	0.91 ± 0.17	± 0.03	± 0.03
$\arg(q/p)$	$(-10.2 \pm 9.2)^\circ$	$\pm 1.4^\circ$	$\pm 2.0^\circ$

Searches for new physics in charm decays are complementary to K and B physics, since they are a unique window into up-quark–type dynamics. CP violation in D^0-$\bar{D}^0$ mixing is especially interesting, and table IV summarizes the future prospects, using the usual convention for D^0-$\bar{D}^0$ mixing, where the mixing parameters satisfy $|q/p| = 1$ and $\arg(q/p) = 0$ in the absence of CP violation. The study of many D decay rates and strong phases between amplitudes is also crucial for the B physics program, for example, the extraction of the CKM phase γ.

A convincing new physics effect has to be several times larger than the experimental uncertainty of the measurement and the theoretical uncertainty of the SM prediction. Theoretical uncertainties can be classified as perturbative and nonperturbative. Perturbative uncertainties stem from the truncation of expansions in small coupling constants. The major limiting uncertainties arise from nonperturbative effects because QCD becomes strongly interacting at low energies. However, there are several cases where we can get rid of most of the above uncertainties.

- For some observables the hadronic parameters (mostly) cancel, or can be extracted from data.

- In many cases, CP invariance of the strong interaction implies that the dominant hadronic physics cancels, or is CKM suppressed.

- In some cases symmetries of the strong interaction that arise in certain limits, such as the chiral or the heavy quark limit, can establish that nonperturbative effects are suppressed by small parameters.

- Lattice QCD is a model-independent method to address nonperturbative phenomena. The most precise results to date are for matrix elements involving at most one hadron in the initial and the final state (allowing, *e.g.*, extractions of magnitudes of CKM elements).

In the last five years lattice QCD has matured into a precision tool. A sample of present errors is collected in table V. The lattice community is embarking on a three-pronged program of future calculations: 1) make significant improvements in “standard” matrix elements of the type just described in the last bullett above, leading to better precision for CKM parameters; 2) calculate results for many additional matrix elements relevant for searches for new physics; 3) extend lattice methods to more challenging matrix elements, which can both make use of old results and provide important information for upcoming experiments. These plans rely crucially on access to high-performance computing, as well as support for algorithm and software development.

TABLE V. – *History, status and future of selected lattice-QCD calculations needed for the determination of CKM matrix elements* [1].

Quantity	CKM element	Present exp. error	2007 forecast lattice error	Present lattice error	2018 lattice error
f_K/f_π	$\lvert V_{us}\rvert$	0.2%	0.5%	0.4%	0.15%
$f_+^{K\pi}(0)$	$\lvert V_{us}\rvert$	0.2%	–	0.4%	0.2%
f_D	$\lvert V_{cd}\rvert$	4.3%	5%	2%	$< 1\%$
f_{D_s}	$\lvert V_{cs}\rvert$	2.1%	5%	2%	$< 1\%$
$D \to \pi\ell\nu$	$\lvert V_{cd}\rvert$	2.6%	–	4.4%	2%
$D \to K\ell\nu$	$\lvert V_{cs}\rvert$	1.1%	–	2.5%	1%
$B \to D^*\ell\nu$	$\lvert V_{cb}\rvert$	1.3%	–	1.8%	$< 1\%$
$B \to \pi\ell\nu$	$\lvert V_{ub}\rvert$	4.1%	–	8.7%	2%
f_B	$\lvert V_{ub}\rvert$	9%	–	2.5%	$< 1\%$
$(f_{B_s}/f_B)\sqrt{B_{B_s}/B_B}$	$\lvert V_{ts}/V_{td}\rvert$	0.4%	2–4%	4%	$< 1\%$
Δm_s	$\lvert V_{ts}V_{tb}\rvert^2$	0.24%	7–12%	11%	5%
B_K	$\mathrm{Im}(V_{td}^2)$	0.5%	3.5–6%	1.3%	$< 1\%$

4. – Lepton physics

In the last two decades, dedicated experiments have firmly established the existence of neutrino oscillations and most of the neutrino parameters have been measured (see [3]). Despite of the tremendous experimental progress, it is fair to say that the same is not true in the theoretical side. Indeed, the current data might be reproduced in a number of different ways, spanning from anarchy to discrete flavor symmetries (see [3]). As a result, the flavor structure of the three fermion generations remains a mystery.

The search for LFV in charged leptons is probably the most interesting goal of flavor physics in the next years. The observation of neutrino oscillations has clearly demonstrated that lepton flavor is not conserved. The question is whether LFV effects can be visible also in the charged lepton sector. Indeed, in the SM with massive neutrinos, LFV effects are loop suppressed and proportional to the GIM factor $(m_\nu/M_W)^4$, therefore, completely negligible. As a result, the observation of LFV processes such as $\mu \to e\gamma$, $\mu \to eee$, $\mu \to e$ conversion in Nuclei as well as τ LFV processes would clearly point towards a NP signal. The future sensitivities of next-generation experiments are collected in table VI. The question of which are the best probes of LFV among the various processes $\mu \to \gamma$, $\mu \to eee$ and $\mu \to e$ conversion in Nuclei is a model-dependent question.

It should be stressed that 1) ratios for branching ratios of processes such as $\mu \to e\gamma$ and $\tau \to \mu\gamma$ would provide a direct access to the flavor structure of the NP model while 2) a comparative analysis of processes with the same underlying flavor transition (such as $\mu \to e\gamma$ and $\mu \to eee$) would provide information about the operators which are generating potential LFV signals.

The flavor-conserving component of the same diagrams generating $\mu \to e\gamma$ induces non-vanishing contributions to the anomalous magnetic moment of leptons as well as to

TABLE VI. – *Future sensitivities of next-generation experiments.*

LFV process	Experiment	Future limits	Year (expected)
BR($\mu \to e\gamma$)	MEG [5]	$\mathcal{O}(10^{-13})$	~ 2013
	Project X [6]	$\mathcal{O}(10^{-15})$	> 2021
BR($\mu \to eee$)	Mu3e [7]	$\mathcal{O}(10^{-15})$	~ 2017
	"	$\mathcal{O}(10^{-16})$	> 2017
	MUSIC [8]	$\mathcal{O}(10^{-16})$	~ 2017
	Project X [6]	$\mathcal{O}(10^{-17})$	> 2021
CR($\mu \to e$)	COMET [8]	$\mathcal{O}(10^{-17})$	~ 2017
	Mu2e [9]	$\mathcal{O}(10^{-17})$	~ 2020
	PRISM/PRIME [10, 8]	$\mathcal{O}(10^{-18})$	~ 2020
	Project X [6]	$\mathcal{O}(10^{-19})$	> 2021
BR($\tau \to \mu\gamma$)	Belle II [11]	$\mathcal{O}(10^{-8})$	> 2020
BR($\tau \to \mu\mu\mu$)	Belle II [11]	$\mathcal{O}(10^{-10})$	> 2020
BR($\tau \to e\gamma$)	Belle II [11]	$\mathcal{O}(10^{-9})$	> 2020
BR($\tau \to \mu\gamma$)	Belle II [11]	$\mathcal{O}(10^{-9})$	> 2020
BR($\tau \to \mu\mu\mu$)	Belle II [11]	$\mathcal{O}(10^{-10})$	> 2020

the leptonic EDMs. In this context, the current anomaly for the muon $(g-2)$, reinforces the expectation of detecting $\mu \to e\gamma$ within the reach of the MEG experiment.

As discussed in [4], the anomalous magnetic moment of the electron a_e can be viewed today as a new player among the low-energy processes that are able to probe new-physics effects. This novel status of a_e stems from recent improvements on both the experimental and theoretical fronts. One important ingredient is the measurement of α from atomic-physics experiments, which are becoming competitive with a_e in the determination of the fine-structure constant. The second ingredient is the ongoing effort to measure a_e with better experimental accuracy. The third element is a more precise theoretical determination of a_e in the SM. From the theoretical point of view, the great interest in testing new-physics effects in a_e comes from the well-known discrepancy between the experimental measurement and the SM prediction of a_μ. Observing or excluding an anomaly in a_e could become the most convincing way to establish the origin of the a_μ discrepancy.

5. – Conclusions

Despite of the fact that the origin of flavor remains a major open problem, significant progress has been achieved in the phenomenological investigation of the sources of flavor symmetry breaking which are accessible at low energies, ruling out models with significant misalignments from the SM Yukawa couplings at the TeV scale.

The Intensity Frontier physics program is diverse and very rich. Experiments that study the properties of highly suppressed decays of leptons, strange, charm, and bottom quarks have the potential to unveil new physics effects arising from mass scales well beyond those directly accessible by current or foreseeable accelerators.

If the electroweak scale is unnatural, we have little information on the next energy scale to explore. If the electroweak symmetry breaking scale is stabilized by a natural mechanism, new particles should be found at the LHC. They would provide a novel probe of the flavor sector, and flavor physics and the LHC data would provide complementary information. Their combined study is our best chance to learn more about the origin of both electroweak and flavor symmetry breaking.

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