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Flavor physics & beyond, a concluding overview

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Abstract. Flavor physics stands today at an exciting forefront. Unprecedentedly large flavorenriched data sets are allowing to reach high levels of precision and to explore new observables and rare sensitive processes. The large suite of precision measurements matching the expectation from the standard theory, the observation of its scalar, followed more recently by that of the Yukawa interaction, together with the negative outcome of the direct searches for new fundamental states, render the Standard Model an unexpectedly robust effective theory up to the TeV scale. At the same time, a coherent set of so-called flavor anomalies persistently emerge from the data, constituting a tantalising indication of the presence of New Physics. Explorations of the flavor sector in its many fronts are actively pursued and planned, which are bound to shed further light on the Standard Model and possibly reach beyond it in the near future.

BEACH'2018 Summary Talk

1. Introduction

The term *flavor* denotes the property that distinguishes fields that are assigned the same quantum charges. The fundamental fermions of the Standard Model (SM), quarks and leptons, are organised in four types, each coming in three flavors: up-type quarks (u, c, t), down-type quarks (d, s, b), charged leptons (e, μ, τ) , and neutrinos $(\nu_e, \nu_\mu, \nu_\tau)$. While the (unbroken) gauge interactions do not distinguish between flavors, the weak and Yukawa interactions do so. A flavor changing transition is one where the flavor number (i.e. the number of particles of a certain flavor minus the number of anti-particles of the same flavor) is not preserved. In the SM, flavor changing transitions involving both up-type and down-type fermions (charged currents) occur at tree-level, mediated by W bosons, while transitions involving either up-type or down-type fermions but not both (flavor changing neutral currents, FCNC) do not, and are thus often highly suppressed. A *flavor universal* interaction is one in which the fermions' couplings are blind to their flavor. In the charged-lepton sector, the observation of violation of flavor number (LFV) or universality (LFU) would require the presence of New Physics (NP) interactions beyond SM.

The motivation for studying flavor physics is manyfold. Foremost, it may allow to detect NP effects before the direct detection of NP particles is attained; the discovery of 'NP effects' through precision measurements in lower energy processes would certainly not be unprecedented historically speaking. Baryogenesis requires new sources of CP violation; increasing experimental precision is facilitated in the quark sector, and must be pursued also in the lepton sector. The majority of the SM parameters, pertaining to the flavor sector, display large hierarchies, for

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which the SM offers accommodation but no explanation. The so-called hierarchy problem, or the fine tuning of the Higgs mass, along with dark matter point to the need of NP at the TeV scale, which, under a generic flavor structure, would contribute to FCNCs above observed rates. Such flavor puzzles remain to be solved. A variety of anomalies, old and new, ought to be clarified. If or once NP is detected its flavor structure needs to be characterised. It is a timely occasion to take stock. This review presents a brief assessment of various fronts of the flavor exploration endeavor, reflecting the current status as reported at the BEACH'2018 Conference.

2. Heavy flavor production

Hadronic systems involving heavy quarks (b, c), commonly referred to as heavy flavor (HF), provide a suitable laboratory in which to study QCD. In the hadron collision environment, heavy quarkonia are particularly suitable for studying the underlying mechanisms of hadron production. These have historically displayed considerable deviations between expectation and data, and despite significant advancements models have fallen short of simultaneously describing production cross-sections and polarizations (the so-called *quarkonium puzzle*). These systems are also standard candles, explored for detector calibration and tuning of simulation tools, and an understanding of HF production and properties is further necessary for carrying out other measurements and searches, where they appear as part of the signal decay chain or as ubiquitous background.

The various LHC detectors have delivered extended measurements, of both hidden and open flavor hadrons, in exclusive or inclusive decays, from data sets taken at 2.76, 5.02, 7, 8, 13 TeV, complementarily covering wide kinematic regions, from central to forward rapidities, from low to high transverse momenta (p_T) . Such detailed measurements are contributing significantly to an improved understanding of QCD and characterisation of the collision environment.

Improved measurements of hadron properties are being achieved, in both hadron and electron collisions. A multitude of new decay channels of previously known sates is being detected, and various new states are being observed for the first time. The BEPC collider at IHEP is providing rich data sets in the energy range between 2.0 and 4.6 GeV, allowing the BESIII experiment to conduct a thorough exploration of the charm sector. When operating at energies near threshold for $D\bar{D}$, $D_s\bar{D}_s^*$, or $\Lambda_c\bar{\Lambda}_c$ production, a variety of new decay modes is detected and absolute branching fractions extracted. In the e^+e^- environment, even an undetected final-state particle may be reconstructed from the constrained decay; e.g. when a pair of particles is produced close to threshold in a quantum-entangled state, the decay properties of one may be inferred from the other (double tagging). This further allows for accurate measurements of decay form factors (e.g. with $D^0 \to K^- \mu^+ \nu_{\mu}$).

Heavier *b*-flavored states are accessed at the Tevatron and LHC. The first new state to have been observed at the LHC originated from a mass peak detected by ATLAS in the vicinity of 10.5 GeV, whose structure has now just been disentangled by CMS as the $\chi_{b1}(3P)$ and $\chi_{b2}(3P)$ Pwave bottomonium states. A variety of new *B* meson decay modes has been observed, especially by LHCb. Only the heaviest open-flavor (bottom charmed) meson family remains reduced to its lowest-lying state, the B_c , originally discovered by CDF, plus the excited $B_c(2S)$ state that has been reported by ATLAS and so far not independently confirmed, having been missed in a recent LHCb dedicated search. The first new baryon detected at the LHC was a Ξ_b excited state ($\Xi_b^*(5945)^0$) by CMS. Several other relatives ($\Xi_b^*/(5935)^-$, $\Xi_b'(5955)^-$) have been observed by LHCb since then, including a more recent addition ($\Xi_b/(6227)^-$) whose quantum numbers have yet to be determined. LHCb reports also the observation of a doubly charmed baryon, which is found to be incompatible (larger mass and lifetime) with being an isospin partner of the Ξ_{c+}^{++} state reported by SELEX earlier.

Measurements of associated production, for example of multiple HF states or HF states and vector bosons, are performed which provide further insight into the underlying production mechanisms, and allow to determine the contribution from multi-parton scattering. Such studies also set the ground for searches of new processes and new resonant states.

3. Exotic spectroscopy

The discovery 15 years ago of the X(3872) state by Belle served as the herald of a new direction in hadron physics, that of exotic spectroscopy. To date, there have been in excess of 30 additional exotic states observed, collectively referred to as X, Y, Z and P_c states. These do not fit in the well-known picture from simplest quark and antiquark pairings, $q\bar{q}$ and qqq, and correspond best to tetraquark and pentaquark combinations. While competing pictures include hadron molecules, compact diquarks, quark-gluon hybrids, glueballs, and combinations thereof, the underlying dynamics of these states remain far from being understood.

New states may be suitably searched for via their prompt production or by studying resonant structures in the decay chain of other hadrons. The latter strategy was the one employed in the original detection of the X(3872), namely as a $J/\psi\pi\pi$ resonance structure tagged in the decay $B^+ \rightarrow J/\psi\pi\pi K$. It has in the meantime been seen and studied by many experiments, in prompt and indirect transitions. Its quantum numbers have been established ($J^{PC} = 1^{++}$) by LHCb, and it has been accordingly recently renamed (as $\chi_{c1}(3872)$). Still its nature remains to be clarified. Among the most recent explorations are studies of prompt and non-prompt contributions by ATLAS and of muoproduction by COMPASS.

The $J/\psi\phi$ spectrum, probed directly or tagged via $B^+ \to J/\psi\phi K^+$, is one in which resonances have been searched for, by several experiments, and with curious results. First, CDF detected in 2009 a structure near 4140 MeV. Then D0 also detected a similar structure plus another at a higher mass, and CMS in turn observed both structures. BaBar, LHCb and Belle did not (initially) see either one. LHCb has more recently carried out a full amplitude analysis of the final state, determining that the data is actually best described with four resonances. While some experimental agreement has been eventually reached, it remains partial: differing widths for the lightest state, the two heaviest reported by LHCb and another one reported by Belle yet to be confirmed. An agreed explanation of their nature remains also lacking.

The majority of these non-standard hadron states arises in the charmonium sector, with masses around 4 GeV. Belle has also observed two tetraquark states, $Z_b(10610)^+$ and $Z_b(10650)^+$, via their decays to $\Upsilon \pi$, thus involving *b* quarks $(b\bar{b}u\bar{d})$. The quark composition of all such states detected so far contains either a $c\bar{c}$ or a $b\bar{b}$ pair; no exotic hadron with a single *c* or a single *b* quark, or more than two heavy quarks, or doubly charged, has been found yet. Several searches for the bottomonium counterpart of the X(3872) have been conducted, yielding negative results. A tetraquark candidate reported by D0, via its $B_s\pi$ final state, has not been confirmed by other experiments. LHCb has detected two resonances, $P_c(4380)^+$, $P_c(4450)^+$, in the $J/\psi p$ channel in $\Lambda_b (\to J/\psi K^- p)$ decays, compatible with pentaquark states. First searches for *b*-flavoured pentaquarks, employing different final states, have been conducted with negative results. Recent searches for the beautiful tetraquark $(b\bar{b}b\bar{b})$ have yielded a similarly negative outcome for now.

The increasing suite of unconventional states challenges existing ideas about the underlying structure of hadrons. Considerable insight has been facilitated by the data which is being incorporated in ongoing model development. While both model predictions and mostly postdictions exist, the field remains primarily driven by experiment.

4. Heavy flavor probes of the QGP

Heavy ion collisions (HIC) recreate short-lived droplets of the matter that filled the universe about a microsecond or so after the Big Bang. By subjecting nuclear matter to extreme temperatures, through ultra-relativistic HIC, QCD predicts (and numerical calculations on the lattice show) that it undergoes a phase transition (through continuous crossover) to a state of deconfined quarks and gluons, referred to as quark-gluon plasma (QGP). This primordial matter

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Figure 1. [colors shown online] Left: Strong suppression of the excited Υ states in PbPb collisions [1]. Middle: Suppression of b, c and lighter hadrons in PbPb collisions [2]. Right: Strange hadrons to pion ratios as a function of number of charged particles in pp and pPb collisions [3].

may be thought of as a soup of quarks and gluons, where no hadrons are to be found, but where every parton is strongly coupled to its neighbours. The QGP may be considered the smallest and hottest droplet of liquid made on earth, displays a remarkably small specific viscosity (shear viscosity to entropy density ratio, η/s , smaller than that of any other fluid), being seen as the simplest form of complex quantum matter. HIC facilitate a unique laboratory in which to probe fundamental aspects of the strong interaction and of the primordial medium. HIC are nonetheless complex, consisting of several distinct stages, each probing different aspects of QCD. The physics area has seen tremendous developments in recent years. These result in good measure from considerable increases in collision energy and detector capability, attained with the LHC, which have facilitated higher medium temperatures and hard-probe cross sections, along with improved precision and many novel probes. With increased understanding also increasingly important puzzles have come to light.

Heavy-flavor hadrons constitute key probes of the QGP: owing to their large mass, they are produced in the initial stages of the collision, experiencing thus the full evolution of the system. Novel hidden- and open-flavor probes that have become accessible with the LHC allow to test different aspects of the medium. The suppression of heavy quarkonia is a longpredicted smoking-gun signature of the QGP. While the charmonium states had been previously extensively explored, the heavier bottomonium family had not. It has been used by CMS to establish the sequential pattern of quarkonium suppression: the larger and less strongly bound states $(\Upsilon(2S), \Upsilon(3S))$ are melt to a greater extent than the $\Upsilon(1S)$ ground state, when the quarkonium $(b\bar{b} \text{ pair})$ finds itself immersed in the QGP, as the medium weakens the attractive force between the pair via Debye screening (Fig. 1 left). The original observation of this beautiful text book result, obtained during Run 1 at 2.76 TeV, has been recently refined with 5 TeV PbPb data. The relative melting of quarkonium states serves as an effective thermometer of the QGP. Extended studies of charmonia and bottomonia have been performed, including measurements of nuclear modification factors (R_{AA}) and elliptic flow (v_2) , in various systems, and as functions of the mesons' kinematics and particle multiplicity.

Open heavy flavor probes the energy loss mechanisms in the QGP. HF have in the past been studied in an inclusive fashion (by reconstructing the electron or muon from their semileptonic decays). The sophisticated tracking systems of the LHC experiments allow for semi-inclusive detection (b hadrons detected through non-prompt charm, ψ or D mesons) and also fully exclusive measurement (the full decay chain of the meson is reconstructed). While inclusive measurements are more efficient (higher yields), exclusive measurements offer higher purity and, importantly, allow to determine the meson's flavor. The latter capability is used to test the flavor/mass dependence of energy loss, where the expected hierarchy (*dead cone* effect) is $R_{AA}(g) < R_{AA}(u, d, s) < R_{AA}(c) < R_{AA}(b)$. The data (Fig. 1 middle) are consistent with expectation.

The enhancement of strangeness production is another predicted QGP signature that is explored. Strange HF states (D_s, B_s) are measured relative to corresponding non-strange (B, D) mesons, where the former appear to be less suppressed in the data; uncertainties are still exceedingly large however. Studies of the relative production of various particle species $(p, \pi, K, D, D_s, \Lambda, \Xi, \Omega, B, B_s$ and heavier states being also pursued) are carried out as function of kinematic and environment variables.

The complexity of HIC requires the study of multiple collision systems, processes, and observables in order to attempt to disentangle and identify the underlying physics phenomena that are at play. Various mechanisms can mimic some effects of the deconfined phase; these are referred to as cold nuclear matter effects, and some arise simply from the nuclear environment (e.g. nuclear shadowing, modifications to parton density functions). Experimentally these are targeted by studying smaller colliding systems (i.e. proton-proton, proton-nucleus). Produced electroweak bosons (W, Z, γ) are left unperturbed by the plasma, and are used to help to characterise the initial state, e.g. through their associated production with jets. top quarks have been also recently reconstructed in pPb collisions. Not only particle yields (compared across collision systems and species), but also azimuthal distributions of particle momenta and multiparticle correlations are extensively explored.

The wealth of HIC data available has provided tremendous advancements, along with some puzzles. A variety of measurements point, unexpectedly, to the presence of some degree of collectivity in smaller systems. These appear for example in long-range angular correlations ('ridge effect', elliptic flow in HF and lighter systems), quarkonium suppression, strangeness enhancement (Fig. 1 right). Such observables appear as surprisingly similar across a variety of colliding systems, when mapped in terms of particle multiplicity.

The largest energies, attained progressively from SPS, to RHIC, on to the LHC, are allowing to probe QCD matter at increasingly high temperatures, and to characterise one edge (that of small net baryon number density, μ_B) of the phase diagram. Lower collision energies are underway at SPS and RHIC, with even lower energies planned at FAIR and NICA, which should allow to complementarily map the QCD phase diagram.

5. CKM paradigm & CP violation

The CKM (Cabibbo-Kobayashi-Maskawa) paradigm provides the basis for flavor physics and CP violation (CPV). Since its formulation half a century ago, it has triumphantly passed intense experimental scrutiny. Following the observation of large B^0 mixing (Argus, 1987), which foretold the heaviness of the top quark, the B factories (BaBar, Belle) were constructed and most successfully explored, also measuring the CPV phase of B^0 mixing. This together with the observation of B_s mixing (CDF, 2006) yielded the confirmation of the CKM paradigm (Nobel prize award in 2008). This success is well illustrated (Fig. 2 left) by systematic improvements in precision reflected in global fits performed to the CKM parameters, involving hundreds of experimental measurements, with SM constraints and calculations, which display an impressive level of consistency. The resulting evolution of the constraints on the unitarity triangle, whose area reflects the amount of CPV, has been thrilling.

The extraction of the CKM angle γ (Fig. 2 left) is challenging, and it has remained the least precisely measured. Significant improvements have been made, exploring a variety of channels of B^+ but also B^0 , B_s (Fig. 2 middle) to open charm. The measurements involved tree-level processes only and is thus theoretically clean ($\Delta\gamma/\gamma \approx 10^{-7}$). A 7% precision level has been already achieved by LHCb, $\gamma = (76.8^{+5.1}_{-5.7})^{\circ}$, and the uncertainty is expected to be reduced to sub-degree level by LHCb and Belle2.



Figure 2. [colors shown online] Left: Constraining the CKM unitarity triangle [4]. Middle: Combination of CKM γ angle results (from left to right: B^+ , combined, B^0, B_s modes) [5]. Right: Combined measurements of the B_s CPV mixing phase and decay width difference [4].

The observation of B_s mixing by CDF became the precursor of related measurements in the hadron collision environment, where baseline analysis methodologies (e.g. tagging of production flavor, treatment of trigger induced bias in proper decay time reconstruction) were also established. While Tevatron's original measurement of the B_s system's mass difference (oscillation frequency) Δm_s was made with high precision, for the width difference $\Delta\Gamma_s$ and CPV phase ϕ_s dramatic improvements in precision have been attained at the LHC (Fig. 2 right). The experimental precision of $\Delta\Gamma_s$ has now surpassed that of the theory determination. The CPV phase is detected from the interference of decays with and without mixing to a flavor unspecific final state. The golden channel $B_s \rightarrow J/\psi\phi$ has been explored by CDF, D0, ATLAS, CMS, and LHCb, while the latter used several additional decay modes. The world average of $\phi_s = -0.021 \pm 0.031$ has been obtained, compatible with the SM prediction of $\phi_s^{SM} = -0.0376 \pm 0.0008$. While the data uncertainty remains still far from reaching the theory precision, thus still leaving ample space for NP in B_s mixing, improvements in the experimental precision will require good control of penguin pollution from hadronic effects.

Clearly, kaon physics has been pivotal in last century's developments leading to the construction of the SM and its flavor sector; in addition, it also provided the first observation of CPV (1964) and, more recently, also of direct CPV. . Interestingly, some excitement persists in that the world average ratio ϵ'/ϵ (that parameterises the size of direct relative to indirect CPV) measured by NA48 and KTeV, lies considerably (3σ) above SM calculations. A considerable tension with the B sector oscillation frequencies $\Delta m_{s,d}$ is also implied within the SM by current lattice QCD results.

The charm sector, where SM CP asymmetries are small, is also a suitable place in which to look for NP. The D^0 system is where mixing and CPV can be detected in the up-type quark system. Like for the kaon and beauty sectors, flavor oscillations have now been well established also for charm (observation by LHCb 2013, following first evidence by *B* factories six years prior), in the time-dependent ratio of $D^0 \to K^+\pi^-$ decays to its charge conjugate, tagged via $D^{*+} \to D^0\pi^+$. The $K^+\pi^-$ final state can be reached via the Cabbibo-favoured tree diagram, or through mixing together with the double Cabbibo-suppressed process. Such processes are at play also in the above mentioned measurements of the γ angle. CPV is probed via Cabbibosuppressed decay modes or through mixing. Measurements of CP asymmetries are reaching permill level precision approaching and surpassing SM bounds. While sizable CPV asymmetries in the charm sector would point to NP, none has been hinted so far.

The CKM is one of the pillars of the SM structure, in which despite extensive inspection no cracks have been spotted. This solidifies the Higgs mechanism, Yukawa interaction, and quark mixing at the core of the fundamental theory. Still, the lack of a more organizing flavor family IOP Conf. Series: Journal of Physics: Conf. Series 1137 (2019) 012060 doi:10.1088/1742-6596/1137/1/012060



Figure 3. [colors shown online] Left: NA62 search for $K^+ \to \pi^+ \nu \bar{\nu}$; signal region marked as red boxes [6]. Middle: Observation of $B_s \to \mu \mu$ [7]. Right: The P'_5 angular observable measured in the $B^0 \to K^{*0} \mu \mu$ decay [8].

symmetry and of enhanced CPV needed for Baryogenesis stand out. And there is certainly still space for NP to be hiding, which motivates the considerable advancements that are to be further expected, namely with increasing LHCb data sets and the arrival of Belle2. But the success that the standard CKM sector has enjoyed also augurs NP contributions may well be small. Which in turn motivates the search for NP in processes where the SM contribution is absent or highly suppressed.

6. Rare decays

The exploration of rare processes constitutes a most promising means for detecting NP. Rareness in the SM may arise in processes that involve FCNC, unfavored CKM transitions, helicity constraints, or other suppression mechanisms. In NP scenarios any of these may be lifted thus leading to potentially large rate enhancements. For example, while FCNC can occur in the SM only at loop level, NP scenarios may introduce additional couplings to new heavy mediators also at tree level, which could result in measurable deviations in decay branching fractions and angular observables.

Some of the most promising FCNC processes arise in the kaon sector, namely $K \to \pi \nu \bar{\nu}$. These $s \to dll$ golden modes occur at leading order in the SM through Z-penguin and W-box diagrams, being strongly suppressed by both the GIM (Glashow-Iliopoulos-Maiani) mechanism (smallness of mass-squared difference of virtual light quarks exchanged and W) and CKM $(V_{ts}^*V_{td})$ hierarchies. The decay dynamics are thus dominated by short-distance contributions offering sensitivities to energy scales as high as O(100 TeV). The golden decays $K^+ \to \pi^+ \nu \bar{\nu}$ and $K_L \to \pi^0 \nu \bar{\nu}$ are theoretically clean, with hadronic form factors K_{l3} extracted from data $(K^{\pm} \rightarrow l^{\pm} \pi \bar{\nu}_l)$ by NA48, and precision dominated by uncertainties in CKM parameters V_{cb} and γ . The SM branching fractions for the charged and neutral channels are $(8.4 \pm 1) \times 10^{-11}$ and $(3.4\pm0.6)\times10^{-11}$, respectively. The most precise (70% level) measurement of the charged mode is $(17.3^{+11.5}_{-10.5}) \times 10^{-11}$ (BNL's E787/E949) based on 7 observed events. The NA62 experiment had its physics run from 2016 to 2018, expecting to collect 20 SM events, and clarify the mild experimental excess; validation of the decay-in-flight technique was achieved with 1% of the data set collected during 2016 where 1 signal candidate was observed (Fig. 3 left); 10% is the targeted precision with full data set. The neutral mode is no less challenging: it is rarer, and instead of one track (as in the charged mode) here two photons $(\pi^0 \to \gamma \gamma)$ need to be detected. An experimental limit at 90% C.L. of 2.6×10^{-8} has been set by JPARC's E391a, while KOTO at the same facility has started its datataking, targeting a 10% precision. The KLEVER project is also under evaluation at CERN's SPS, with first data envisioned by mid 2020's.

The charm sector also offers sensitive (FCNC, GIM, CKM) suppressed modes. The $D^0 \rightarrow \mu\mu$ mode has a further helicity suppression, and the upper bound on the SM prediction is at 6×10^{-11} . The current experimental bound (LHCb 2013), at 7.6×10^{-9} at 90% C.L., leaves about 3 orders

of magnitude to be explored to reach sensitivity to the theory prediction. The four-body decays $D^0 \rightarrow hh\mu\mu$, with $hh = KK, K\pi, \pi\pi$, have been observed (LHCb 2016, 2017). With a measured branching fraction of $(7.8 \pm 2.1) \times 10^{-8}$, the $D^0 \rightarrow \pi^+\pi^-\mu^+\mu^-$ charm decay is the rarest yet to have been observed. Improved limits on di-photon and radiative decays, of charmed neutral and charged mesons and baryons, are being pursued by LHCb and Belle.

A wealth of data on rare b-hadron decays has recently been gathered by the LHC experiments. Exciting results have emerged from those data, namely in processes mediated by the $b \rightarrow sll$ FCNC transition. Certainly, a major highlight from LHC Run 1 is the observation of the $B_s \rightarrow \mu \mu$ (joint analysis of CMS and LHCb, 2015; Fig. 3 middle). This golden channel has been searched for over 3 decades, by many experiments in several facilities prior to the LHC, with a strong pursuit at the Tevatron. The motivation was not that the SM sensitivity had been reached (it had not), but that potentially sizable enhancements by up to three orders of magnitude were predicted in the context of favored theory scenarios. In short, it offered a hopeful shortcut pathway for discovering supersymmetry. The $B \to ll$ leptonic decays are among the most important indirect searches for NP at the LHC, which are not only loop and CKM suppressed but also helicity suppressed (pseudo-scalar B to two spin 1/2 leptons) strongly suppressed in the SM and theoretically clean. The SM predicted (time-integrated) branching fractions are $(8.24 \pm 0.36) \times 10^{-14}$, $(3.52 \pm 0.15) \times 10^{-9}$, $(7.46 \pm 0.30) \times 10^{-7}$, respectively, for the B_s electron, muon, and tau channels, with a further order of magnitude reduction for the corresponding B^0 di-leptonic modes. Following the $B_s \to \mu \mu$ observation by CMS and LHCb, ATLAS has also released (2016) its Run 1 result and LHCb has released (2017) an observation by combined Run1 and partial Run2 data. While the analyses were optimized primarily for the B_s channel, an earlier 3σ level hint of the B^0 channel had been reported, which was not confirmed with more data. The current branching fraction results (LHCb) are $\mathcal{B}(B_s \to \mu\mu) = (3.0 \pm 0.6^{+0.3}_{-0.2}) \times 10^{-9}$ and $\mathcal{B}(B^0 \to \mu\mu) < 4.2 \times 10^{-9}$ (95% C.L.). While these are found in agreement with the SM prediction, they impose a strong rejection of classes of NP models, including of minimal supersymmetry and other extended scalar sectors. Precision measurements of the B_s mode and observation of the B^0 mode are targets for the upcoming Run and the high-luminosity phase (HL-LHC). The di-muon final state is the most accessible experimentally; the di-electron is further (helicity-) suppressed, and both the electron and tau, but specially the latter, given their relatively low momenta, are particularly challenging to efficiently reconstruct in the hadronic environment. The tauonic modes are nevertheless of particular interest, in view of recent hints of LFU violation (as discussed in the next section). The current limits, by LHCb, are $\mathcal{B}(B^0 \to \tau \tau) < 1.6 \times 10^{-3}$ and $\mathcal{B}(B_s \to \tau \tau) < 5.2 \times 10^{-3}$ (90%) C.L.), which lie more than 4 orders of magnitude away from the SM sensitivity.

The B_s is a remarkable system of extremes – it spontaneously undergoes oscillations between particle and antiparticle at 3 billion times a second during its long lifetime and when the time finally comes for it to decay it does so to di-leptons 3 times in a thousand million – which also renders it extremely sensitive to the underlying physics. These aspects may be explored together for the already detected $B_s \rightarrow \mu\mu$ channel. Indeed, only the heavy mass eigenstate decays to a muon pair in the SM, a condition that is however not necessarily held in NP scenarios. The different eigenstate widths can be used to disentangle their contributions, what is more readily done through an analysis of the decay effective lifetime $\tau_{\text{eff}}^{\mu\mu}$ which thus offers complementary sensitivity to NP. A first $\tau_{\text{eff}}^{\mu\mu}$ result was obtained by LHCb, which despite the insufficient precision allowed by the current data set serves as proof of principle. A precision of 3% is forecasted with the full HL-LHC data set.

The same $b \to s\mu\mu$ transition can also be explored in semileptonic B decays, namely in exclusive processes $B \to S\mu\mu$, where S is a strange hadron (e.g. K, K^*, ϕ, Λ). Compared to the purely leptonic processes just discussed, these decays while rare have larger branching fractions of order $O(10^{-6})$, allowing more detailed measurements with the data set sizes available. The



Figure 4. [colors shown online] Flavor anomalies. Left: LFU ratio $R_{K^{*0}}$ in neutral current transitions $b \to sll$ with $l = e, \mu$ [9]. Middle: Global fit to FCNC $b \to sll$ transitions [10]. Right: Fit to LFU ratios R_{D^*} and R_{D^*} in charged current transitions $b \to cl\nu$ with $l = \tau, \mu$ [4].

measured observables are made in different ranges of the di-lepton invariant mass q^2 ; these regions are sensitive to contributions from different physics operators; the regions in the vicinity of the two charmonium resonances ψ $(J/\psi, \psi(2S))$ are excluded (in the analyses these states are actually employed for calibration). The differential branching fractions $d\mathcal{B}/dq^2$ measured for the abovementioned decays are in general found to lie below the SM expectation. This constitutes an intriguing pattern of deviations. It is remarked that the SM predictions for these decays are however affected by hadronic uncertainties, including the $B \to S$ form factors, and so-called charm loops (wherein the di-lepton pair may originate from a photon with highly enhanced rates in q^2 regions near the charmonium resonances) that are challenging (non-factorizable QCD) to calculate precisely. These processes offer, in addition to the branching fractions, a rich set of sensitive angular observables. These include forward-backward asymmetries of the leptons and longitudinal polarization fractions, which also offer more robust theoretical calculations. For the $B^0 \to K^{*0} \mu \mu$ decay, a set of observables P'_n has been defined with further reduced form-factor uncertainties (claimed to be mostly free from such uncertainties in the low q^2 region). While a resonable agreement between data and theory expectation was found for the various observables measured in different decays, LHCb originally reported a deviation in the P'_5 variable in the $4 < q^2 < 8 \,\mathrm{GeV}^2$ region (Fig. 3 right). Such a discrepancy has been corroborated with additional data sets collected by LHCb; also Belle and ATLAS obtained results that support the deviation, while a CMS result displays a better agreement with theory, although the measurements are affected by limited signal yields. Taken together, a global fit to the above $b \rightarrow s\mu\mu$ observables yields a deviation from the SM prediction exceeding 4σ (Fig. 4 middle).

7. Flavor universality & anomalies

The universality of lepton flavor is accidental in the SM gauge sector. LFU is broken only by the Yukawa interactions, which are flavor specific. These however have a negligible effect on the detected decay branching fractions. LFU is well tested in tree-level decays of tau leptons, light mesons, and gauge bosons. Nevertheless, over the last several years, several hints of LFU breaking in semileptonic *B* decays, governed by both $b \rightarrow sll$ and $b \rightarrow cl\nu$ transitions, have been accumulating. These currently amount to a significant deviation from the LFU principle.

Tests of LFU have been investigated in rare semileptonic $b \to sll$ decays, as those described in the previous section. In particular, the ratio of branching fractions R_S between $B \to S\mu\mu$ and $B \to See$ decays is formed. Form factor and other hadronic uncertainties involved in the $B \to Sll$ decays mostly cancel in the R_S ratios. These observables are predicted to be unity within O(1%)precision. These LFU ratios are defined in q^2 ranges, excluding the resonant charmonium regions. The muon and electron channel yields are measured relative to the more abundant resonant $B \to S\psi$ decays, with ψ reconstructed in the $\mu^+\mu^-$ and e^+e^- final states; such a double ratio provides a robust control of systematic uncertainties associated to lepton reconstruction. The R_S ratios are therefore quite robust observables, both theoretically and experimentally. Measurements of the LFU R_K observable, in $B^+ \to K^+ l^+ l^-$ decays, performed at B factories have yielded results compatible with unity with a 20-50% precision. A measurement performed at LHCb (2014), in the $1.1 < q^2 < 6.0 \text{ GeV}^2/c^4$ range, yields $R_K = 0.745 \substack{+0.090 \\ -0.074} \pm 0.036$, consistent with the SM but 2.6σ below its unity prediction. As for the decays $B^0 \to K^{*0}l^+l^-$, the ratio R_{K^*} has been later measured by LHCb (2017) to be $0.66 \substack{+0.11 \\ -0.07} \pm 0.03$ and $0.69 \substack{+0.11 \\ -0.07} \pm 0.05$, respectively for the $0.045 < q^2 < 1.1 \text{ GeV}^2/c^4$ and $1.1 < q^2 < 6.0 \text{ GeV}^2/c^4$ regions (Fig. 4 left). For the lower q^2 region, the 2.2σ deviation is perhaps less expected in view of dominant contributions from (QED, LFU conserving) $B^0 \to K^{*0} \gamma^{(*)}$. The results yield a compatibility with (but are below) the SM expectation at the $2.1 - 2.6\sigma$ level. The $R_{K^{(*)}}$ results are currently dominated by statistical uncertainties, and their precision will improve with LHC Run2 data. The main systematic uncertainties are associated to electron misidentification and bremsstrahlung losses affecting the B mass shape. The increasing data set should further allow for additional R_S measurements, including R_{Λ_b} and R_{ϕ} , to be performed.

A global fit to the combined $b \to sll$ anomalies, including the branching fractions and angular observables described in the previous section along with the LFU $R_{K^{(*)}}$ ratios just mentioned yield a deviation from the SM in excess of 5σ . In a model-independent effective-theory operator expansion, global fits favor NP contributions in the vector coupling (the C_9 Wilson coefficient, associated to the $(\bar{q}\gamma_{\mu}b \ l \ \gamma^{\mu}l)$ operator) (Fig. 4 middle). Measurements of the $B \to K^{*0}ll$ decays with additional statistical precision and observables, such as $P_5^{\prime\mu} - P_5^{\prime e}$, are being pursued. Simultaneous amplitude analyses of the decays are proposed which enable the determination of the relevant Wilson coefficients (or differences thereof, $\Delta C_i = C_i^{\mu} - C_i^e$), with further reduced or absent theoretical uncertainties. Improved measurements utilizing the full LHCb Run 2 data set along with improved model-independent global analyses are shown to have the potential of establishing NP discovery.

First hints of LFU violation in B decays has actually been uncovered by BaBar (2012), by studying $B \to D^{(*)} l \nu$ decays, where the semitauonic decay rate relative to the total e, μ rate appeared to deviate from the SM expectation. The ratio $R_{D^{(*)}}$ of branching fractions of these semileptonic decays involving τ versus the lighter leptons $l = \mu, e$ are accurately determined in the SM to be $R_D^{\text{SM}} = 0.299 \pm 0.003$ and $R_{D^*}^{\text{SM}} = 0.258 \pm 0.005$, for the decays involving the D^0 and D^{*0} mesons, respectively. The ratios differ from unity in view of the large $\tau - \mu/e$ mass difference. The experimental world averages, using measurements by BaBar, Belle, and LHCb, yield $R_D = 0.407 \pm 0.039 \pm 0.024$ and $R_{D^*} = 0.306 \pm 0.013 \pm 0.007$, which exceed the SM expectations respectively by 2.3σ and 3.0σ . Together these result in a combined tension with the SM of 3.8σ (Fig. 4 right). These measurements are challenging in the hadronic collision environment, particularly regarding the reconstruction of τ leptons at low p_T . LHCb has nevertheless succeeded is employing both leptonic $\tau^- \to \mu^- \bar{\nu}_\mu \nu_\tau$ and hadronic $\tau^- \to \pi^+ \pi^- \pi^- (\pi^0) \nu_\tau$ decays. These decays correspond to tree-level $b \to c l \nu$ transitions. These can be alternatively probed using additional observables, including R_{D^+} and $R_{\Lambda_c^{(*)}}$, as well as B_c decays. For the latter, LHCb already reported a measurement of the ratio $R_{J/\psi}$ of tauonic to muonic $B_c \to J/\psi l\nu$ decays, yielding $0.71 \pm 0.17 \pm 0.18$, a value compatible (but also exceeding) the SM prediction within 2σ . Here the theory prediction is however affected by $B_c \to J/\psi$ form factors, with a central value in the [0.15 - 0.28] range.

The above anomalies result in a considerable tension between data and SM. With the goal of identifying a possible common NP contribution that would relax this tension, correlated analyses of the ensemble of measured observables have been pursued. A coherent picture does seem to emerge from the tensions observed in $b \rightarrow sll$ and $b \rightarrow cl\nu$ transitions. Complementary measurements of correlated observables and more precise q^2 dependency determinations will result from the inclusion of LHCb's Run 2 data. Added reliability will

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Figure 5. [colors shown online] Examples of high- p_T direct searches. Left: Di-tau spectrum [11]. Middle: Z' phase space [12]. Right: Leptoquark phase space [13]. The region favored by the flavor anomalies (dashed or dark color cones in the mass-coupling plane) being probed by direct searches.

be facilitated by measurements performed by independent experimental setups. In this regard, further contributions from ATLAS and CMS based on their Run 2 data sets will be equally welcome, as will undoubtedly be the future measurements by the newly started Belle2.

8. High mass frontier

Direct searches for NP particles are conducted across the energy spectrum, from sub-GeV to multi-TeV scales, through the intensity and energy frontiers, and exploring a large variety of final states. This being a paramount goal for the LHC physics program, a multitude of final states has been investigated in the data, involving a variety of combinations of physics objects - which include leptons, photons, jets, vector bosons, but also the heavier top and Higgs, and varied combinations thereof, as allowed by the data set sizes. Missing momentum signatures have been explored thoroughly since the turn-on of the LHC. When probing for massive states, even the heavier of those probed physics objects will then tend to have large p_T , displaying highly boosted topologies, for which dedicated reconstruction techniques have been deployed by the experiments (ATLAS, CMS). Both model-inspired and signature-based searches have been actively pursued. In addition to more standard strategies and analysis configurations, also more exotic avenues have been followed. As an example, a compelling class of the exotic flavor consists of long-lived signatures – which would leave striking signals in the detectors (e.g. highly displaced vertices, appearing/disappearing tracks, highly ionizing particles), which in turn also require less standard (and challenging) reconstruction and trigger strategies. The goal being, beyond the motivation of pursuing specific physics scenarios, that of *leaving no stone unturned*. Some *bumps* and others *excesses* that have been hinted in the data did not persist when larger LHC data sets were scrutinized. (The 750 GeV $\gamma\gamma$ hiccup, hinted in 2015 and gone by summer 2016, did offer understandably a large level of excitement, which in that case however well surpassed that of the statistical significance offered by the data themselves).

At the end of Run 2 the LHC has delivered almost $200 fb^{-1}$ worth of pp collision data, of which much has yet to be analyzed. This corresponds to less than 7% of the total LHC target integrated luminosity $(3ab^{-1})$. While large improvements in sensitivity have been quickly attained with past jumps in \sqrt{s} , the sensitivy will continue to grow, steadily if with a lower slope, accompanying the pace of luminosity integration, and allowing NP to appear in the tails of probed distributions. Upgraded accelerator and detectors, novel analysis techniques and strategies and vet unexplored signatures are guaranteed to lead to ground breaking outcomes. Clearly, the large data sets already at hand and the much larger and refined ones that will be accumulated will facilitate unprecedented levels of precision. Allowing to explore and correlate IOP Conf. Series: Journal of Physics: Conf. Series 1137 (2018) 012060

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Figure 6. [colors online] The scalar sector. Left: Higgs differential cross section as function of p_T [14]. Middle: Higgs couplings versus particle mass [15]. Right: $H \to \gamma \gamma$ mass distribution in the $t\bar{t}H$ observation [16].

sensitive observables in the Higgs, electroweak, top and flavor sectors.

The *flavor anomalies* reported in the previous sections are also motivating a renewed and dedicated look into high mass spectra. Indeed, these point to NP mass scales that may be directly probed at the LHC. On general grounds, the charged-current anomalies $(b \rightarrow c l \nu)$ may hint at an effective scale of order O(3TeV), while the neutral-current ones $(b \rightarrow sll)$ point to scales around O(30 TeV). Potential tree-level NP models have been investigated in global fits to those observables. Such model building and corresponding UV completions are challenging in view of existing constraints in the flavor sector (e.g. B_s mixing) and high- p_T searches (e.g. di-lepton spectra; Fig. 5 left). Candidate simplified models include color-neutral vector bosons (Z', W') or color-triplet scalar or vector leptoquarks (LQ). The former class of Z' models is disfavoured by existing constraints (Fig. 5 middle), when their flavor structure follows minimal flavor violation (MFV). Related models with MFV lifted remain interestingly viable. Scalar LQ models, however, are favourably singled out by the anomalies. Having both quark and lepton quantum numbers, LQ are good candidates to accommodate LFU breaking observables. While contributing at tree-level to $b \rightarrow sll$, LQ would contribute only at loop level to B_s mixing thus more easily satisfying such constraints. Dedicated LQ direct searches are starting to probe the parameter space favored by the anomalies (Fig. 5 right). Important constraints are also imposed by the analysis of $\tau\tau$ spectra (Fig. 5 left), which disfavor models for $b \to c l \nu$ with exclusive couplings to the third family, but with relaxed constraints otherwise.

Even if the NP mass scale lies well beyond the LHC kinematical reach for on-shell production, effects on the high- p_T tails of the spectra might still be observed. The endeavor of establishing a NP signal will be thus continued to be complementarily pursued with high-precision measurements at high and low energies.

9. Higgs & electroweak precision

With the discovery of the fundamental scalar by ATLAS and CMS in Run 1 (2012), a new portal for NP searches and precision measurements opened up. The data accumulated since then has allowed the investigation of production and decay processes and of the scalar properties. Such verifications come with the goal, first of all, of verifying whether the detected new state is the SM scalar (or perhaps the first member of an enlarged NP scalar family). The answer obtained here is that it is (the SM particle), within the precision allowed by the existing data. A precision of the H mass at a permill level (0.2%) and of the cross section within 10% of the SM have been reached. It is most remarkable that the Higgs has now joined the flavor and electroweak gauge sectors in the era of the *differential measurement* (Fig. 6 left).

At the moment, all main production and decay modes of the Higgs have been established.

In addition to the couplings to the gauge bosons, that are more readily accessed $(H \rightarrow \gamma\gamma, ZZ, W^+W^-)$, the Higgs couplings to fermions have been also pursued (Fig. 6 middle). Importantly, the couplings to all third generation fermions have been now observed, through the processes $H \rightarrow \tau^+\tau^-$, $t\bar{t}H$ associated production (Fig. 6 right), and finally $H \rightarrow b\bar{b}$, all detected with a statistical significance in excess of 5σ independently by CMS and ATLAS.

The exploration of the lighter generations would be the next logical step, but it will however come with even greater challenges. Indeed, the direct detection of couplings to second generation quarks will be daunting, in view of the ubiquitous QCD background. Current experimental limits lie two orders of magnitude above theory expectation. Improvements in charm tagging techniques will be pursued, as will alternative paths such as the investigation of H decays to quarkonia (which would provide clean signals but being rather rare will also require considerably larger data sets). One fermion of the second generation (the muon) is however well in reach, namely through the decay $H \rightarrow \mu^+\mu^-$. This provides a clean signal, for which current limits lie at about twice the SM expectation, and for which a first detection may be achieved already with Run 2(3) data.

The all-important Higgs self-coupling may be directly probed by observing di-Higgs production. With a current limit at about 13 times the SM expectation, this is a major item that is being prepared and will be further probed in the HL-LHC phase.

10. Concluding remarks

A wealth of experimental data along with theoretical computations have resulted in stringent tests of the standard theory. The precision of these tests is expected to be further improved considerably over the next few years. With the discovery of the scalar with a mass of 125 GeV and the verification of its main couplings, the very large number of processes tested to high precision, and the absence of unambiguous direct signals beyond it, the SM is left reinforced as an effective theory up to the electroweak symmetry breaking scale and arguably beyond into the TeV scale. That NP has escaped our detection so far may be due perhaps to its scale lying above that directly accessible at present colliders, or it featuring relevant signatures beyond those already probed, or it coupling very weakly to the SM sector. These possibilities are all targeted by novel strategies and dedicated instruments.

Various anomalous signals have nonetheless been hinted in the data. The majority came and went, as it more usually than not tends to happen, having failed to pass the test of independent confirmation facilitated by separate data sets and instruments. Some however remained or got preliminarily reinforced. This is the case in particular in the flavor realm, where a recent coherent set of deviations have emerged from the data from semileptonic *B* decays (e.g. LFU ratios, P'_5 and other angular and rate observables), joining other longstanding ones (e.g. ϵ'/ϵ , $(g-2)_{\mu}$). This gives tantalizing evidence that NP is within reach, and hope that it may soon be established, with data already collected or soon to be gathered. While much needs to be researched yet, should the flavor anomalies be eventually confirmed, truly groundbreaking progress would have been achieved.

The recent detection of Higgs decays to (third generation) fermions marks the direct observation of the Yukawa interaction – which lies at the heart the SM, and at the origin of the flavor sector. It constitutes thus a symbolic milestone in this regard. In much the same way that the observation of the Higgs boson establishes the SM mechanism of electroweak symmetry breaking while emphasizing the underlying fine tuning associated to its mass calculation and the corresponding desire for a stabilization mechanism; similarly, the observation of the Yukawa interaction corroborates the source of the CKM (and PMNS) ansatz while emphasizing the desire for an underlying flavor symmetry. Both of these issues have been around for a long while, well predating any of the recent developments that indeed corroborate their pertinence. The first of these, the *hierarchy problem*, has been the main driver for NP model building over

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the last several decades and into the LHC era. The *flavor problem* has remained seemingly more intractable and effectively placed on hold. In case the emergent flavor anomalies would persist and be established, and on-shell NP signals would remain missing, a potential change of paradigm may be considered where the latter of the two long-standing issues would also be more directly tackled. Perhaps a lesson to take from the anomalies, whatever their fate will turn out to be, is that time may be ripe for renewed and revised focus in our approaches.

The overarching endeavor of detecting NP beyond the standard theory ought to continue to be pursued through various complementary avenues. Exploring the energy, intensity, and cosmic frontiers. The large data sets already at hand and the ones that are expected to be accumulated with upgraded and new instruments will be bound to further illuminate the NP window. New phenomena may be revealed directly, possibly via unexpected signatures, or through precision and rare signals. Chances are also that NP may start showing up in extended correlated analyses of ensembles of sensitive observables across the board, in a *multi-messenger* fashion. Data is bound to tell – and plenty of them are already or will be there for us to exploit and learn from.

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