Flavour

Flavour (and associated topics) as a tool towards new physics

Flavor physics is a cornerstone for probing the Standard Model (SM) and search for the physics that lies beyond (BSM). Longstanding experimental observations not accounted for by the SM include the observed matter-antimatter imbalance in the Universe, neutrino masses, and dark matter. These appear along with fine tunings within the SM such as electroweak hierarchy problem, strong CP problem, and flavor puzzle (number of fermion generations, mass and coupling hierarchies, insufficient CP violation).

The search for BSM physics ought to be pursued in complementary ways. Direct searches at the LHC, while resulting in extended exclusions, did not yet reveal BSM. This may be because BSM particles are too heavy or couple too feebly. While direct sensitivity to TeV-scale particles will increase only slowly, limited by $\sqrt{s}$, the high-luminosity phase of the LHC (HL-LHC) will provide much increased sensitivity for direct searches at intermediate (GeV) scales and for indirect searches through virtual contributions of new heavier particles.

Heavy flavour provides a main avenue for revealing the presence of BSM, indirectly through precision measurements and rare decays, and directly as a source of feebly interacting particles (FIPs). Flavour processes further serve as tools for probing new and exotic states, the mechanisms of hadron formation and properties of deconfined media, quark Yukawa couplings and unique neutrino measurements. These may be explored with general-purpose (CMS, ATLAS) and dedicated detectors at the LHC (LHCb, SND@LHC, FASER) and elsewhere (SHiP, Mu2e, BelleII) over the next two decades, and beyond at an e^+e^- factory (such as the FCC).

The flavour anomalies

Decades of testing electroweak interactions have demonstrated the robustness of the SM under rigorous scrutiny. However, recent experimental observations in the flavour sector have revealed discrepancies with SM predictions, leading to the identification of what are now termed 'flavour anomalies.' These anomalies are associated with processes that are particularly sensitive to virtual contributions from heavy or weakly interacting particles, suggesting the possible involvement of BSM physics, such as new gauge bosons or leptoquarks.

Notable flavour anomalies include discrepancies observed in the rates and angular distributions of flavour-changing neutral-current (FCNC) decays involving the $b \to s\mu^+\mu^-$ quark-level transition, where measurements indicate a deviation from the SM predictions in certain kinematic regions. Similarly, the anomalous magnetic moment of the muon ($g-2$) has raised questions about the potential influence of new particles or interactions that could affect its behavior beyond the SM. These tensions between experimental results and SM expectations, while still under investigation, provide valuable insights into potential directions for extending the SM. If confirmed, these anomalies could represent first evidences of BSM physics.

Flavour as probes of matter under extreme conditions

Heavy flavor provides invaluable novel probes of the quark-gluon plasma (QGP), a state of matter formed at extremely high temperatures and energy densities where hadrons melt into their constituent particles. This exotic state provides a unique environment to study the fundamental properties of quantum chromodynamics (QCD), the theory governing the strong force, when droplets form in ultra-relativistic heavy-ion collisions. Being massive, heavy flavour quarks are predominantly produced in the early stages of such a collision and so they traverse the droplet, interacting with the QGP through both elastic and radiative processes. Recent analyses employ charm and beauty mesons as probes to explore QGP effects in the hadronization of traversing quarks and learn about the transport properties of the medium.

A future hadron collider operating at a center-of-mass energy an order of magnitude higher than the current one opens new avenues for advancing our understanding of the QGP. Current studies at the LHC have provided many valuable insights into the properties of the QGP, such as its near-perfect fluidity, transport coefficients, and energy loss mechanisms for heavy quarks and jets. However, higher collision energies would enable the production of a hotter and denser QGP, expanding the range of phenomena that can be studied. For instance, abundant production of heavy quarks would be facilitated in such a scenario, including top quarks, allowing for unprecedented precision in probing the QGP transport properties. Furthermore, it would enable access to harder scattering processes and multi-parton interactions, offering much greater sensitivity to study jet quenching, parton energy loss, and medium-induced modification. These advancements would complement and extend ongoing QGP research, providing a more comprehensive picture of QCD matter under extreme conditions and potentially uncovering new emergent phenomena in the strongly coupled regime of the QGP.

CMS@HL-LHC

As a general-purpose detector, CMS contributes to the exploration of the TeV scale and of the electroweak and Higgs sectors, having established itself in addition as a leading apparatus in the exploration of the low-mass region. The high-precision Silicon-based vertex and tracking inner detector and robust muon system, the flexibility of the trigger system along with the deployment of innovative data-taking approaches, allow for fully benefitting from the high luminosities delivered by the LHC and result in the collection of unique, large, flavor-enriched data samples. These have allowed for recent observations of rare decays (e.g. η, ψ, B) and new states (conventional and exotic), along with a rich suite of precision measurements, tests of fundamental symmetries, and searches, including processes related to the flavour anomalies.

The upcoming comprehensive upgrade of the CMS detector will allow the experiment to maintain an equally high performance in the high-luminosity environment, with broad physics sensitivity and increased acceptance. The embedded track-trigger capability (allowing to select at hardware trigger level tracks down to a few GeV) and precision timing layer (facilitating hadron identification capability) are two major relevant additions.

Portugal has a leading experimental involvement in heavy flavor physics through CMS. Expertise developed at the Tevatron helped to efficiently advance the foundations of b-quark physics at the LHC. Group members steered first quarkonium and B meson measurements in proton and ion collisions, and made leading contributions to flagship observations such as of quarkonium melting and ultra-rare B meson decays. Group members serve(d) as coordinators of multiple working groups (production, quarkonia, exclusive decays, CP violation, rare decays, analysis tools), as convener of the overall CMS B heavy flavor analysis group, and of the LHC-wide heavy flavor working group.

Interests of the group that will be facilitated by the HL-LHC phase involve exploration of rare heavy flavor processes along with precision measurements. This builds up on the group's involvement in the observation of the Bs to dimuon ultra-rare decay and the measurement of the rare B0 decay to dimuon plus kaon. Both of these involve the same quark-level transition (b to s ll), that displays high sensitivity to BSM effects. The larger datasets that will be accumulated, with enhanced detector capability, will allow to probe rarer processes, and perform extensive tests of lepton flavor violation (LFV) and lepton flavor universality (LFU). Precision measurements of flavor mixing and CP violation will be further enabled. The combined exploration of (rarer) heavy flavor probes in pp and heavy ion collisions shall shed light on underlying QCD mechanisms, the nature of exotic hadrons and of the QGP medium, and provide novel avenues for BSM searches.

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