May 3, 2020

Letter of Interest from the US LHCb Group

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Abstract

The US LHCb group will submit a document describing our future physics goals and intention to further upgrade the detector. These goals include many precision measurements using b and c quark decays to find physics beyond the Standard Model, studies of exotic hadron spectroscopy, searches for dark-sector particles, Majorana neutrinos, study of nuclear collisions, *etc.* These topics are part of the "Rare Processes and Precision," "Energy," "Instrumentation," and "Computing" frontiers.

The LHCb experiment has diverse physics objectives. The primary goal is to find physics beyond the Standard Model (SM), often referred to as "New Physics" (NP). There are many ways to do this, reflected in the diverse studies being performed of various decay channels of hadrons containing heavy b or c quarks. The basic idea is that any as yet undiscovered particles participate in these decays, via virtual quantum contributions, and thus can modify either decay rates, angular distributions, and CP violations from SM expectations. Sensitivity to the masses of these new particles can range up to $\sim 10^5$ TeV, depending on the process and its couplings to SM particles [1] (also see Fig. 5.1 in [2]).

Increasing the amount of data can vastly increase the discovery potential and allow for new studies. For example, the data collected by LHCb in its first two runs has been used to study CP violation in a variety of b-hadron decays leading to accurate measurements of the angles β and γ, cornerstones of the Unitarity Triangle, and to place limits on the related angle ϕ_s in B_s^0 decays [3]. LHCb also made the first significant measurement of direct CP violation in D^0 decays [4]. In another example, studies have revealed the possibility of the violation of lepton flavor universality (LFU), a central assumption in the SM, comparing electrons and muons in $B \to K^{(*)}\mu^+\mu^-$ decays [5,6], reinforced somewhat by studies of angular distributions in $B^0 \to K^{*0}\mu^+\mu^-$ decays [7]. There is also some evidence for unexpected differences between τ^- and μ^- leptons in $B \to D^{(*)}(\tau \text{ or } \mu)\nu$ decays [8]. Numerous additional measurements testing LFU are expected to come in the next few years, including those using decays of B_c^-, Λ_b^0 and B_s^0 hadrons.

Another way to search for NP is to look for particles that are components of the dark sector of matter. Here again there are several avenues that LHCb can exploit. LHCb has done searches for dark photons using decays to $\mu^+\mu^-$ pairs [9], which are the world's best in several mass regions and are expected to greatly improve using upcoming data [10]. A new technique to be employed in the next LHC run with the Upgrade I detector uses the process $D^{*0} \to e^+e^-D^0$, where the dark photon materializes to an e^+e^- pair, to extend this search to regions of lower masses and moderate mixing with photons, where there are no current limits [11]. LHCb also has world-leading results on Higgs-portal models at low masses [12]. Furthermore, Ann Nelson developed several models of dark matter that can be investigated using b-hadron decays [13,14].

LHCb has also searched for Majorana neutrinos using $B^- \to \pi^+\mu^-\mu^-$ decays where the neutrino would be observed to decay into $\pi^+\mu^-$ [15]. This search has been done as a function of neutrino mass and lifetime. The observed exclusion upper limit on the coupling $|V_{\mu 4}|$ is, roughly speaking, a few times 10^{-3} over the Majorana mass range from 1 to 5 GeV. LHCb has also examined the decays $B^- \to D^{(*)+}\mu^-\mu^-$ which could result from virtual Majorana neutrinos [16].

Exotic hadrons have become an important method of understanding Quantum Chromo-Dynamics. LHCb has contributed several key results including the discovery of pentaquark candidates decaying into $J/\psi p$ [17], studies of the $Z(4430)$ meson [18], the $X(3872)$ meson [19], and $J/\psi\phi$ resonances [20]. All of these mesons are tetraquark candidates.

Other areas of investigation include studies of electroweak interactions, *e.g.* measurements of the Z^0 boson cross-section at high rapidities both in pp [21] and pPb [22] interactions; other measurements in $PbPb$ collisions, and in proton gas collisions, e.g. $pHe \to \overline{p}X$ [23], which is very useful for astrophysical studies.

We now discuss the timeline for data taking and upgrades for the LHCb experiment. The dates given here are ones projected before the COVID-19 pandemic. A delay of approximately one year could possibly be anticipated. LHCb will have completed installing the Upgrade I detector at the end of 2020. Most detector elements have been rebuilt and the hardware based trigger has been eliminated, replaced by a purely software trigger [24], containing GPU processors [25]. Besides the trigger and online systems, the silicon-strip vertex detector has been changed to a pixel detector. The straw-tube tracking system after the magnet has been replaced with a scintillating fiber system. The tracking system in front of the magnet, based on silicon-strips, called the "UT" for Upstream Tracking, has been rebuilt with a much larger bandwidth to support the trigger, has better segmentation, and larger spatial coverage; this latter effort has been led by the US group. Other improvements have been made to the RICH systems, including replacement of the photodetectors. The experiment will take data at an instantaneous luminosity of $2 \times 10^{33}\mathrm{cm}^{-2}\mathrm{s}^{-1}$, five times the previous rate. In 2021 the detector will be commissioned and we expect a few months of early running at lower luminosities. The years 2022-2024 are scheduled for running at full luminosity totaling $\sim 30\,\mathrm{fb}^{-1}$.

LHCb, however, has plans for further improvements. During long shutdown 3 of the LHC, scheduled for 2025 to mid 2027, consolidation of Upgrade I is proposed consisting of two tracking detector upgrades. The first would reduce the lengths of the scintillating tracker fibers near the beam pipe and to instrument this area with a pixels having increased granularity. These pixels will be placed closer to the beam pipe than the fibers, so the acceptance will be increased. The second advancement is to include scintillating fiber tracking along the inner faces of the bending dipole magnet in order to increase the acceptance for slow tracks in many processes, *e.g.* the pion in $D^{*+} \to \pi^+ D^0$ decays.

A further set of improvements, called Upgrade II, is proposed to occur during long shutdown 4, currently scheduled for 2031. The instantaneous luminosity would be increased by a factor of 7.5 in order to accumulate 300 fb^{-1}. Upgrade II requires the replacement or modification of most of LHCb's detection elements, especially the Electromagnetic Calorimeter which was not improved in Upgrade I. Installation would occur in long shutdown 4 scheduled for 2031. Many exciting physics results can be expected from these improvements [26], as recognized in the European Strategy Briefing Book [2]. We note that the CERN Research Board at its September 2019 meeting stated "The LHCC encourages LHCb to proceed with the preparation of a framework TDR for its Upgrade II, to be submitted in 2021" (https://cds.cern.ch/record/2689832/files/M-230.pdf). In conclusion, LHCb has great potential for discovering NP, especially with upgraded detectors and orders of magnitude more integrated luminosity.

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