Snowmass 2021 Letter of Interest:
QCD and Hadronization Studies at Belle II

on behalf of the U.S. Belle II Collaboration

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Abstract:

Due to the precise knowledge of the initial state and clean experimental environment, electron-positron annihilation data have historically been of utmost importance to study the hadronization of light and charm quarks. The record setting luminosities of the B-factories Belle and BaBar made groundbreaking measurements in this field possible. This trend will be continued by Belle II. Housed at the SuperKEKB facility at KEK in Tsukuba, Japan, Belle II is a significant upgrade of Belle and aims to record $50\times$ the integrated luminosity of Belle over the next 10 years. This contribution will focus on two topics where Belle II will have a high impact. Studying the fragmentation of polarized and unpolarized light and charm quarks into hadrons as well as jets, and the measurement of hadronic cross-sections and transition form factors which are important inputs to constrain the theoretical uncertainty on the anomalous magnetic moment of the muon. As part of the Snowmass process, we invite anyone interested in these topics to join us in leveraging the massive data samples that will be available at Belle II.

1 Hadron and Jet Fragmentation Studies at Belle II as input for the EIC

Electron-positron annihilation data are crucial to study the fragmentation of light quarks into hadrons. This process is described by fragmentation functions [1] (FFs). Since FFs are non-perturbative objects, they have to be measured in experiments. They can be seen as the time-like counterparts to parton distribution functions (PDFs). But unlike PDFs, they are currently inaccessible on the lattice. Similar to PDFs, the study of FFs can reveal aspects of QCD that are not directly evident from the Lagrangian.

However, FFs receive arguably most attention as necessary ingredients to extract aspects of the proton wave functions, e.g., encoded in PDFs, from semi-inclusive deep-inelastic scattering data. For example, the first extraction of the distribution of transversely polarized quarks in a transversely polarized nucleon, the so called transversity PDF, which is one of the three collinear PDFs which are needed to describe the nucleon structure at leading twist, could only be extracted in a global fit including the first measurement of the transverse polarization dependent Collins FF at Belle [2;3]. The B-factories were the first e^+e^- machines to record enough data to be sensitive to polarization and transverse momentum dependent FFs. These extractions had and still have a profound impact on the field of nuclear physics. However, to interpret results from the current and next generation SIDIS experiments, such as JLab12 and the future Electron Ion Collider (EIC), which will collect orders of magnitude more statistics and have physics programs focusing on more sophisticated final states, such as polarized hyperons, the statistics collected at the first generation B-factories may not be enough for some final states. For light hadron spin and transverse momentum dependent fragmentation functions higher statistics would allow a more sophisticated multi-dimensional analysis which may be even of interest as input for transverse momentum dependent distributions functions relevant at the LHC. For heavier final states, such as hyperons or charmed bayrons, the fragmentation measurements have just begun at Belle [4] but statistics are in some cases still limited. There is a clear need for Belle II to collect a data-set orders of magnitude larger to extract FFs for more luminosity hungry final states and to map them out in multiple dimensions. This need is even more urgent as the nuclear physics community just committed to build the EIC at Brookhaven National Laboratory over the next decade at a cost which is currently projected to be between $\$1.6 - \$2.6$ billion. It is also envisioned to operate Belle II with a polarized e^- beam from 2026 onwards, collecting between $20 - 40\text{fb}^{-1}$ in that configuration. This would enable the measurement of a new class of observables sensitive to the hadronic mass generation [5;6].

In addition to semi-inclusive hadron production, jet physics will play an important role in accessing the three-dimensional nucleon structure at the EIC [7;8]. The corresponding theory is very much an active field of development and data from Belle II would provide ideal precision tests for the framework [9;10]. In particular the addition of jet substructure measurements may help to increase the flavor sensitivity [11] at an EIC.

2 Impact of Belle II data in reducing theoretical uncertainty on muon $g-2$

The experimental value for the muon anomalous magnetic moment $(g-2)$ [12]is currently 3.7σ higher than the expected theoretical value [13].

The experimental uncertainty will soon be reduced by a factor of four by the new experiment currently running at Fermilab [14]. Another factor-of-four improvement is expected from the future J-PARC experiment [15]. This necessitates a similar reduction in the theoretical uncertainties dominated by contributions from the hadronic vacuum polarization (HVP), and, to a lesser extent, by the hadronic light-by-light contribution (HLbL). The most precise evaluation of HVP is based on the measurements of $e^+e^- \to$ hadrons cross-sections at low center-of-mass energies ($\sqrt{s} < 2$ GeV. New high-statistics measurements related to the HVP contribution are necessary to reduce experimental systematic uncertainties and remove the existing discrepancies between two most precise measurements of the $e^+e^- \to \pi^+\pi^-$ of BaBar [16] and KLOE [17]. The integrated luminosity of 50 ab^{-1} expected at Belle II, two orders of magnitude higher than that of BaBar, and new Belle II trigger will allow precision measurements of various low energy hadronic cross-sections using initial-state radiation and aiming at a total error needed to be sensitive to new physics with the novel $g-2$ measurements. For a more detailed discussion see Ref. [18].

In addition to the important role the Belle II data will play in reducing the uncertainties on the HVP contribution, experimental results on $\gamma\gamma \to$ hadrons processes at Belle II will help constrain uncertainties on the HLbL contribution. Experimental input from Belle II will also play a role as a cross-check for first-principle theoretical calculations of both the HVP and HLbL contributions on the lattice, see the discussion in Refs. [13;18] and references therein.

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