Quark polarization measurements: from the Standard Model to characterizing New Physics

Letter of Interest for Snowmass 2021

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Abstract: Polarization of quarks produced in hard collisions is largely retained when these quarks hadronize into baryons. We outline a number of measurements that can be performed at the LHC which would characterize the polarization retention fractions for b, c, s and even u and d quarks. These inputs would allow the quark polarization measurements to be performed in new interactions, expanding the present situation in which only polarization measurements of top quarks are part of the standard toolkit.

Introduction. In this Letter of Interest we point out that there is experimental sensitivity to the polarization of energetic quarks created in particle collisions. Such a handle on quark polarizations is indispensable to fully characterize the interactions of new particles that may be discovered at the HL-LHC or FCC. At the LHC, ATLAS and CMS already measure the polarization of top quarks. In single top production, the top quarks are found to be highly polarized [1, 2], as expected from the parity-violating electroweak nature of the process. In contrast, the tops from pair production are found to be unpolarized [3, 4], in agreement with expectations for QCD production.

Analogous polarization measurements could be performed for quarks other than the top [5–7]. The fact that this is possible is not immediately obvious, because these quarks are observed only as jets of hadrons. However, if the initial quark hadronizes in a baryon that carries a large fraction of the jet momentum, the polarizations of the baryon and of the initial quark are related.

Heavy quarks. For heavy quarks, i.e., the b and c quarks, the polarization retention is the consequence of the fact that the b and c quark masses are well above the QCD scale, $m_{b,c} \gg \Lambda_{\rm QCD}$. Typically, the hard-emission quark ends up in a very energetic heavy-flavored hadron [8, 9] that is easy to tell apart from the other hadrons in the jet. When this hadron is a baryon, an $\mathcal{O}(1)$ fraction of the quark polarization is expected to be retained in the hadron [10–12]. In the $m_b \to \infty$ limit, the polarization of the b quark is preserved by the QCD interactions. The dominant chirality flipping interactions are due to the b-quark chromomagnetic moment, $\mu_b \propto 1/m_b$, which are suppressed for $m_b \gg \Lambda_{\rm QCD}$. The b quark polarization should thus be approximately preserved during hadronization. If the light degrees of freedom in the baryon form a spin-0 state, as in the Λ_b baryon, the b polarization is preserved also by the hadronic dynamics during the hadron's lifetime, τ, even though $\tau \gg 1/\Lambda_{\rm QCD}$. The light degrees of freedom may also be in a spin-1 state, as in Σ_b and Σ_b^* baryons, with spins 1/2 and 3/2, respectively. In this case the b spin direction oscillates during the baryon's lifetime, and thus the original b quark polarization gets modified. The total fragmentation fraction $f(b \to \text{baryons}) \approx 8\%$, and the baryons are almost entirely Λ_b, produced either directly or via decays of $\Sigma_b^{(*)}$.

For the c quark, one also has $m_c \gg \Lambda_{\rm QCD}$, although only as a rough approximation. The analogs of the Σ_b and Σ_b^* baryons are $\Sigma_c(2455)$ and $\Sigma_c(2520)$. The fragmentation fraction to baryons in this case is $f(c \to \text{baryons}) \approx 6\%$.

Notably, the ALEPH, DELPHI, and OPAL experiments at LEP have attempted to measure the polarization transfer from quarks to baryons by analyzing the Λ_b baryons in $Z \to b\bar{b}$ events, and have indeed found $\mathcal{O}(1)$ retention of the longitudinal polarization, although the statistical uncertainties were too large to extract a precise value of the longitudinal polarization retention fraction r_L [13–15].

Light quarks. Moving to the strange quark, one cannot argue for polarization retention based on the heavy-quark picture. At the same time, one cannot argue for complete polarization loss either. The Λ polarization studies done in Z decays at LEP have found $\mathcal{O}(1)$ polarization retention for Λ baryons that carry a significant fraction of the original quark's momentum [16–18]. The dependence of the polarization transfer on the momentum fraction is described by the polarized (or spin-dependent) fragmentation functions [19]. These are universal functions, up to renormalization-group evolution, similar to the parton distribution functions.

Similarly to the strange quark, up and down quarks are also expected to retain a fraction of their polarization when hadronizing to baryons. However, this will be difficult to measure, because the baryons most frequently produced in the u and d hadronization, namely the protons and neutrons, do not decay within the detector. One may still try to use the Λ, for example, although that will require significantly more statistics.

Experimental opportunities. There are a number of different experimental strategies that can be pursued to measure quantities describing the polarization retention in hadronization of polarized quarks. For instance, samples of highly-polarized quarks are available in $pp \to t\bar{t}$ events [5, 6]: the decays $t \to W^+ b$ produce polarized b quarks, and the subsequent decays $W^+ \to c\bar{s}, u\bar{d}$ produce polarized c, s, u, and d quarks. It is relatively straightforward to select a clean $t\bar{t}$ sample, e.g., in the lepton+jets channel. The kinematic reconstruction of the event, along with charm tagging, enables to obtain separate samples of jets dominated by b, c, or s jets. Furthermore, already by the end of LHC Run 2, the statistics of polarized quarks from $t\bar{t}$ events is as high as of those produced in the Z decays at LEP. Thus, using the $t\bar{t}$ samples in ATLAS and CMS one can perform: *i)* the longitudinal Λ_b (Λ_c) polarization measurement in b jets from top decays (and c jets from W decays), which will determine r_L for the b (c) quark; *ii)* the longitudinal Λ polarization measurement in s jets from W decays, which will provide information about the longitudinally-polarized $s \to \Lambda$ fragmentation function. In the far future, a longitudinal Λ polarization measurement could be performed also for u and d jets from W decays. This will provide information about the longitudinally-polarized $u \to \Lambda$ and $d \to \Lambda$ fragmentation functions.

Another potentially useful source of polarized charm quarks is available in $pp \to Wc$ events (with $W \to \ell\nu$) [7]. The statistics here are even higher than for $pp \to t\bar{t}$ (by an order of magnitude), but the backgrounds are higher too. Using $W(\to \ell\nu) + c$ samples in ATLAS, CMS, and perhaps LHCb one could perform: *i)* a longitudinal Λ_c polarization measurement in the c jets, which will determine r_L for the charm; *ii)* LHCb in particular may attempt separating out the $\Sigma_c^{(*)} \to \Lambda_c \pi$ contributions.

It is also interesting to consider the dominant production mechanism of b quarks at the LHC, namely the inclusive QCD production, $pp \to b\bar{b} + X$. Despite the enormous cross section of this process, it is not the most promising avenue for polarization measurements because these quarks are produced unpolarized at the leading order. However, a small transverse polarization is predicted at the next-to-leading order [20, 21]. In QCD production of hard quarks in ATLAS, CMS, and LHCb, a measurement of transverse Λ_b (maybe also Λ_c) polarization, properly binned in the event kinematics, may give access to the transverse polarization retention fraction, r_T, for the bottom (charm) quarks.

In any (even unpolarized) samples of hard quarks in LHCb, ATLAS, and CMS one could measure the $\Sigma_b^{(*)}$ production yields (relative to direct Λ_b production), and the pion angular distribution in the Σ_b^* decays. This will determine the parameters A and w_1, parametrizing the polarization loss for the bottom quark due to the $\Sigma_b^{(*)}$ decays [5, 12]. Similarly, a measurement of the $\Sigma_c^{(*)}$ production yields (relative to direct Λ_c production), and the pion angular distribution in the Σ_c^* decays will determine the parameters A and w_1, respectively, for the charm quark.

In case new particles are discovered and they decay hadronically, their characterization could greatly advance by performing measurements of the final-state quark polarizations using the above methods. The results will provide important information about the structure of the new-physics interactions. Given that no new physics has been discovered so far, and considering the price one needs to pay in fragmentation and branching fractions to measure quark polarizations, statistics will likely be a serious limitation for such measurements at the LHC, but they can become feasible at a future collider.

In $t\bar{t}$ and Wc production, ATLAS, CMS, and LHCb can, in the long term, perform the measurements of the full polarized fragmentation functions for the various quark flavors. It will be then possible to confront the results with models based on the heavy-quark effective theory for the b and c quarks, and more phenomenological models of QCD for the light quarks. Additionally, knowing the full fragmentation functions will allow computing the scale dependence (due to the renormalization group evolution) [22] of the polarization retention fractions.

Conclusions. We outlined a number of measurements in SM processes to be performed at the LHC and future colliders that target the polarization of quarks. Those SM measurements would also provide the necessary inputs to enable polarization measurements of quarks in non-standard hard processes at the LHC and beyond.

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