Kinked tracks from Σ^+ baryons as a probe of light quark polarizations

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ABSTRACT: Jets initiated by energetic quarks carry in an obvious way approximate information about the original quark energy and momentum. In a less obvious way, they also carry information about the quark polarization. Previous works have shown how the polarization information can be extracted by ATLAS and CMS using events in which the quark hadronizes to an energetic baryon — Λ_b for b quarks, Λ_c for c quarks and Λ for s quarks. In this paper we extend these proposals to Σ^+ baryons, which can provide sensitivity to polarizations of s and u quarks. We analyze the various aspects of how the kinked track signature of the $\Sigma^+ \to p\pi^0$ decay can be used for this purpose. We evaluate the feasibility of such measurements in $t\bar{t}$ samples.

Contents

1 Introduction and motivation

When a baryon is one of the leading hadrons in a jet, it partly preserves the polarization of the quark that produced the jet. From the theory side, this can be argued rigorously for heavy quarks, $m_q \gg \Lambda_{\mathrm{QCD}}$ [1–4], and it is expected to hold also for light quarks, as we will review. From the experiment side, the LEP experiments have already observed the polarizations transferred to the Λ_b [5–7] and Λ [8–10] baryons from the longitudinally polarized quarks produced in Z decays. In the case of Λ baryons produced from strange quarks, the polarization transfer was found to be significant when the baryon carried a sizable fraction ($\gtrsim 30\%$) of the quark momentum.

There exist at least two motivations for measuring baryon polarizations in samples of polarized quarks. First, these measurements contribute to the theoretical understanding, or at least the phenomenological description, of the spin structure of baryons and the fragmentation process. This is important both from the purely theoretical perspective and for tuning Monte Carlo generators. Second, once techniques for measuring the baryon polarizations, and relations between the quark and baryon polarizations, are established, it becomes possible to measure polarizations of quarks in new processes.

Measurements of the transverse Λ_b polarization from QCD production were performed by CMS [11] and LHCb [12], and similarly for the Λ by ATLAS [13]. However, extracting information from such measurements is difficult because the transverse polarization of quarks in QCD samples is an NLO effect, which is sizable only for soft quarks and depends strongly on the kinematics of the event. Additionally, different from the case of longitudinal polarization, parity invariance allows transverse polarization to be generated in the hadronization process even for initially unpolarized quarks [14, 15], further complicating the interpretation.

Longitudinally polarized quarks produced in electroweak processes can therefore be a more convenient target. In this regard, it has been argued [4, 16] that meaningful measurements of the longitudinal Λ_b, Λ_c and Λ polarizations due to the b, c and s quarks from top or W decays in $t\bar{t}$ samples are possible in the Run 2 datasets of ATLAS and CMS. The statistics of such polarized quark samples is already comparable to that of the hadronic Z decays at LEP. The initial quark polarization in the $t\bar{t}$ samples (before the small one-loop QCD effects [17]) is close to -1, while at LEP it was about -0.94 for the down-type quarks and -0.67 for the up-type ones. For the Λ_b it will be the first time to obtain precision of order 10%, and for the Λ_c the first time to measure longitudinal polarization of energetic charm quarks [4]. For the Λ, it will be the first time to experimentally disentangle the contributions of the different quark flavors [16]. Another promising sample is Λ_c baryons from $W+c$ production [18]. In the current work we extend these studies to the interesting case of the Σ^+ baryon.

There are several reasons to consider the Σ^+ (whose valence quark content is uus) despite its similarity to the Λ (uds). First, the probability for a strange quark to hadronize to a Σ^+ is lower than to a Λ by only a factor of about 2 (in the relevant range of momentum fractions, which we will take to be $z > 0.3$) [19]. Thus, if a spin-sensitive decay of the Σ^+ can be reconstructed with a sufficiently high efficiency and low background, it will be possible to reduce the statistical uncertainty of the strange-quark polarization measurement relative to what can be obtained [16] by using the Λ alone. The reconstruction efficiency of the Λ decays in ATLAS and CMS in the relevant range of p_T is somewhat low, $\mathcal{O}(10\%)$ [13], due to their very large displacement. The Σ^+ decays, which are less displaced by a factor of 3.3, might therefore be competitive. We consider the decay

$$\Sigma^+ \to p\pi^0 \,, \tag{1.1}$$

whose branching fraction is about 52% (cf. 64% for $\Lambda \to p\pi^-$) and spin analyzing power[1] $\alpha \approx -0.98$ (cf. 0.73 for $\Lambda \to p\pi^-$) [20]. The π^0 has the disadvantage of not creating tracks (but only calorimeter deposits). On the other hand, the possibility to measure the Σ^+ track directly presents an opportunity, as we will discuss. The other important decay mode, $\Sigma^+ \to n\pi^+$, is not useful since it has a much lower spin analyzing power, of about 0.07 [20], and at the same time is not obviously much easier to reconstruct. For the same reason we do not consider the Σ^-, which decays almost 100% as $\Sigma^- \to n\pi^-$, with a spin analyzing power of about -0.07 [20]. The Σ^0 baryon decays almost entirely as $\Sigma^0 \to \Lambda\gamma$. Since the resulting prompt photon is very soft, it is difficult to isolate Σ^0 events from the inclusive Λ events, therefore we do not consider the Σ^0 either.

Even in the case that the statistics of the Σ^+ samples from strange quarks ends up somewhat lower than for the analogous Λ samples, an even more interesting reason for measuring the Σ^+ is that it can provide qualitatively different information, especially in the context of the u quark polarization. In the naïve quark model, the spin of the Λ is carried entirely by the s quark, while the u and d form a spin-0 diquark. This suggests

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[1]The spin analyzing power, which is also called the decay asymmetry parameter, describes the sensitivity of the angular distribution of the decay to the hadron polarization; see eq. (3.1) below.

that Λ baryons produced in the hadronization of polarized u or d quarks do not retain much of the polarization. Differently, in the Σ^+, still in the naïve quark model, the two u quarks form a spin-1 diquark, so one can expect Σ^+ baryons produced from polarized u quarks to be polarized. As we will review, more sophisticated approaches also predict the Σ baryons to be much more sensitive to the polarizations of the u and/or d quarks than the Λ baryons.

It is also important to note that the experimental question of Σ^+ reconstruction at the LHC that we address in this work will be relevant to studies of fragmentation functions involving the Σ^+ at the high-luminosity phase of the LHC (continuing and complementing the LEP program [21–23]), even outside the context of the polarization. In fact, certain measurements of b-quark fragmentation in $t\bar{t}$ events have already begun in ATLAS [24] and CMS [25].

Finally, the Σ^+ decay that we will study here has an interesting signature, a kinked track, which will require a dedicated reconstruction procedure that is not currently being employed in any ATLAS or CMS analyses. Kinked tracks may appear also due to particles beyond the Standard Model (e.g., in various supersymmetric scenarios [26–28]), and the Σ^+ analyses we propose here could lay the ground for future searches for such new physics scenarios.

2   Theoretical status

The probabilities for a given quark to produce a given hadron with a specific momentum fraction z are described by fragmentation functions. Polarized fragmentation functions take the spins of the quark and hadron into account as well (see, e.g., [29]). Analogous to the parton distribution functions (PDFs), the fragmentation functions are not computable analytically because they depend on non-perturbative QCD physics. However, they can be measured in some process and then, again like the PDFs, used for describing another process after they are evolved to the appropriate scale. The evolution equations are known from perturbative QCD at the next-to-leading order (see, e.g, [30]). The LEP experiments measured the fragmentation of quarks from Z decays into Σ^+ [21–23], as well as Σ^- [21, 22, 31] and Σ^0 [22, 23, 32, 33], without measuring the polarization. Unfortunately, even the unpolarized fragmentation functions for specific quark flavors into the Σ^+ cannot be extracted from these results directly due to the flavor-inclusive nature of the measurements. Flavor-specific fragmentation functions were extracted [19] from part of these data [22] by assuming that they behave according to the so-called statistical model. In view of the reliance on this assumption, one should not necessarily be too discouraged by the result of [22] that the probability for a u quark to produce a Σ^+ is lower than its probability to produce a Λ (in the relevant range of momentum fractions) by a factor of ~ 10. (For the s quark, the reduction is by a factor of ~ 2.) In any case, as will become clear in the next section, $t\bar{t}$ samples at the LHC provide an opportunity to measure these numbers more directly.

Phenomenological expectations regarding the salient features of polarized fragmentation functions are usually based on the spin distributions in the hadrons (polarized PDFs).

For the nucleons, the spin distributions are known experimentally [34, 35]. For the Λ and Σ^+ baryons that we discuss here, they can be estimated either by applying the SU(3) flavor symmetry (which is only approximate because $m_s/\Lambda_{\rm QCD}$ is non-negligible) to the nucleon data [36, 37], or from a phenomenological model of QCD, or by a lattice simulation [38, 39]. While one does not expect a simple general relation between PDFs and fragmentation functions since even their renormalization group evolution is different, an approximate relation at a low scale can be argued to exist [40].

The spin distributions of quarks in a fully-polarized spin-1/2 hadron h are described at the simplest level in terms of the quantities

$$\Delta q_h = \int dx \left[q_h^\uparrow(x) - q_h^\downarrow(x) \right], \tag{2.1}$$

where $q_h^s(x)$ describes the probability to find a quark of flavor q and momentum fraction x in the hadron h, with polarization projection s on the direction of the hadron spin. If the hadron spin were determined by the valence quark spins alone, one would have $\sum_q \Delta q_h = 1$. This is the case in the naïve quark model, where

$$\Delta u_p = \frac{4}{3}, \quad \Delta d_p = -\frac{1}{3}, \tag{2.2}$$

$$\Delta u_\Lambda = \Delta d_\Lambda = 0, \quad \Delta s_\Lambda = 1, \tag{2.3}$$

$$\Delta u_{\Sigma^+} = \frac{4}{3}, \qquad \Delta s_{\Sigma^+} = -\frac{1}{3}. \tag{2.4}$$

In reality, $\sum_q \Delta q_h \neq 1$ because orbital angular momentum, gluons, and sea quarks and antiquarks also contribute to the hadron spin. For the proton, the spin distributions are measured to be [35]

$$\Delta U_p = 0.835 \pm 0.015, \qquad \Delta D_p = -0.435 \pm 0.015, \qquad \Delta S_p = -0.095 \pm 0.015, \tag{2.5}$$

where the usage of capital U, D, S symbols indicates that antiquark contributions are included. The SU(3) flavor symmetry relations [36, 37, 41, 42]

$$\Delta U_\Lambda = \Delta D_\Lambda = \frac{1}{6}\Delta U_p + \frac{2}{3}\Delta D_p + \frac{1}{6}\Delta S_p, \tag{2.6}$$

$$\Delta S_\Lambda = \frac{2}{3}\Delta U_p - \frac{1}{3}\Delta D_p + \frac{2}{3}\Delta S_p \tag{2.7}$$

and

$$\Delta U_{\Sigma^+} = \Delta U_p, \qquad \Delta D_{\Sigma^+} = \Delta S_p, \qquad \Delta S_{\Sigma^+} = \Delta D_p \tag{2.8}$$

then predict

$$\Delta U_\Lambda = \Delta D_\Lambda \approx -0.17, \qquad \Delta S_\Lambda \approx 0.64, \tag{2.9}$$

$$\Delta U_{\Sigma^+} \approx 0.835, \qquad \Delta D_{\Sigma^+} \approx -0.095, \qquad \Delta S_{\Sigma^+} \approx -0.435. \tag{2.10}$$

Lattice QCD simulations of the proton [43] give

$$\Delta U_p = 0.864 \pm 0.016, \qquad \Delta D_p = -0.426 \pm 0.016, \qquad \Delta S_p = -0.046 \pm 0.008, \tag{2.11}$$

in a reasonable agreement with the measured values in eq. (2.5). For the Λ and Σ^+, available lattice results [38, 39] include only connected contributions (i.e. valence quarks) and they are

$$\Delta u_\Lambda = \Delta d_\Lambda \approx -0.02\,, \qquad \Delta s_\Lambda \approx 0.68\,, \tag{2.12}$$

$$\Delta u_{\Sigma^+} \approx 0.81\,, \qquad \Delta s_{\Sigma^+} \approx -0.25\,. \tag{2.13}$$

We see that regardless of the approach taken, the spin distributions differ significantly between the Λ and the Σ^+. The spin of the Λ is predominantly on the s quark, while the spin of the Σ^+ is predominantly on the u quarks. It is reasonable to expect analogous differences in the polarization transfer in fragmentation. In particular, polarization transfer from the u quark to the Σ^+ is expected to be more significant than to the Λ. Note that to estimate the polarization transfer factor for $u \to \Sigma^+$, one should divide Δu_{Σ^+} by 2 because there are two valence u quarks in the Σ^+. However, even after accounting for that, the u-quark polarization transfer to the Σ^+ is expected to be better than in the Λ case by more than a factor of 2, or perhaps even a bigger factor if a significant fraction of ΔU_Λ is due to antiquarks, which is a plausible scenario [37].[2] The s-quark polarization transfer to the Σ^+ is somewhat worse than in the Λ case, but still sizable and includes a sign flip.

More generally, both the quark spin distributions in hadrons and the quark-to-hadron polarization transfer in fragmentation depend on the momentum fraction of the quark in the hadron (x) or the quark momentum fraction taken by the hadron (z), respectively.[3] The polarization transfer from the u and d quarks to the Λ might have a particularly strong z dependence since the inclusive numbers, as quoted above, are small.[4] For the polarization transfer from the u to the Σ^+, it is likely much less of an issue.

Let us now compile all the theoretical factors to compare the prospects of the Σ^+-based and Λ-based measurements for identical samples of s and u jets. The statistical significance of the results will behave as

$$n_\sigma(q, h) \propto |\alpha_h\, \Delta\hat{q}_h|\sqrt{N(q, h)}\,,$$

where $q = s$ or u, $h = \Lambda$ or Σ^+, α_h is the spin analyzing power of the decay, $\Delta\hat{q}_h$ is the polarization transfer factor that we estimate from the spin distributions Δq_h discussed above, and $N(q, h)$ is the number of decays available for the analysis, which is proportional to the $q \to h$ fragmentation fraction and the h decay branching fraction. Collecting the numbers quoted above, we obtain

$$\frac{n_\sigma(s, \Sigma^+)}{n_\sigma(s, \Lambda)} \sim 0.4\,, \qquad \frac{n_\sigma(u, \Sigma^+)}{n_\sigma(u, \Lambda)} \sim 1\,.$$

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[2]For various approaches to estimating the antiquark contributions, see e.g. [44–47].

[3]For attempts to predict the z dependence of the various fragmentation functions based on phenomenological models, see [48–55].

[4]Since the contributions are bounded between -1 and 1, an $\mathcal{O}(1)$ inclusive number would suggest that the relative variation of the contributions with x is not very large. On the other hand, a small inclusive number does not preclude significant x dependence. In fact, significant x dependence of the u-quark polarization in the Λ, including even a change of sign, is predicted by several phenomenological models (see, e.g., figure 2 in ref. [54]).

We see that the prospects of Σ^+-based analyses (at the theoretical level, before accounting for backgrounds and experimental factors) are comparable to those of Λ-based analyses, particularly for u quarks. It is therefore worth exploring the experimental feasibility of both approaches, especially in view of the fact that they will provide complementary information.

3 Experimental opportunities

So far, neither ATLAS nor CMS have reported any analyses involving a reconstruction of the $\Sigma^+ \to p\pi^0$ decays. We hope this work will provide a motivation for such analyses.

Since the Σ^+ is long-lived ($c\tau \approx 2.4\,\text{cm}$), its signature would often include a kink in the tracker (formed by the Σ^+ and p tracks) as well as a π^0 candidate in the electromagnetic calorimeter. Once the decay kinematics is reconstructed, the Σ^+ polarization, $\mathcal{P}(\Sigma^+)$, can be obtained using the fact that the angular distribution of the proton momentum in the Σ^+ rest frame behaves as

$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\vartheta} = \frac{1}{2}\left(1 + \alpha\,\mathcal{P}(\Sigma^+)\cos\vartheta\right), \tag{3.1}$$

where ϑ is the proton momentum angle relative to the polarization axis and $\alpha = -0.982 \pm 0.014$ [20]. For longitudinal polarization, this axis is the Σ^+ direction of motion in the lab frame.

3.1 Kinked track

We are mostly interested in Σ^+ baryons carrying about 30–50% of the jet's momentum. Much softer Σ^+ baryons are common in secondary fragmentation processes, where they will usually be unrelated to the original quark, while harder Σ^+ baryons are very rare. This means that a typical p_T of the Σ^+, for example in jets from W decays in $t\bar{t}$ samples (which we will consider in the following), will be $p_T \sim 15$ GeV. Then the kink will occur at a typical distance of

$$r = c\tau\,\frac{p_T}{m} \sim 30 \text{ cm} \tag{3.2}$$

from the beam axis. This falls near the beginning of the SCT (Semiconductor Tracker) in ATLAS or the TIB (Tracker Inner Barrel) in CMS. A typical Σ^+ track will therefore pass through all the layers of the Pixel Detector in either ATLAS or CMS, and often also the first layer(s) of the SCT or TIB.[5] The proton track will pass through the rest of the tracker.

While there have been no analyses targeting kinks so far (even though various motivations exist [26–28] in addition to ours), searches for *disappearing tracks* are being conducted by ATLAS [60, 61] and CMS [62–64]. The Run 2 ATLAS searches [60, 61] reconstruct disappearing tracks with Pixel Detector hits alone, similar to what would be required for

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[5]The Pixel Detector layers in ATLAS are positioned at $r = 3.3$, 5.05, 8.85, 12.25 cm [56], and in CMS at $r = 3.0$, 6.8, 10.2, 16.0 cm [57]. The rest of the barrel tracker in ATLAS consists of the Semiconductor Tracker (SCT) between $r = 30$ and 52 cm and the Transition Radiation Tracker (TRT) between $r = 56$ and 107 cm [58]. The rest of the barrel tracker in CMS consists of the strip tracker inner barrel (TIB) between $r = 20$ and 55 cm and the strip tracker outer barrel (TOB) between $r = 55$ and 116 cm [59].

reconstructing the Σ^+ track. The track p_T threshold in [60, 61] is 20 GeV, comparable to the p_T of the Σ^+ in the samples of interest. In the Run 2 CMS searches [63, 64], multiple options for the disappearing track length were addressed, including tracks that extend beyond the pixel detector, with p_T values down to 15 GeV [63]. For muon tracks from Z decays, with typical $p_T \sim 45$ GeV, the pixel-only tracks in ATLAS have p_T resolution of about 60% [60], so for a $p_T \sim 15$ GeV pixel-only track we should expect $\sim 20\%$ resolution in p_T. Similar resolution is expected in CMS, where the pixel layers have similar geometry, and the bigger pixel size than in ATLAS is compensated by a larger magnetic field.[6] Significantly better resolution, of $\sim 5\%$, will be obtained for tracks reaching the first layers of the SCT or TIB, which will be common in our case. Further improvement will be attained in the high-luminosity phase of the LHC, once the upgrades to $25 \times 100 \, \mu m^2$ pixels in ATLAS [65] and $50 \times 50 \, \mu m^2$ or $25 \times 100 \, \mu m^2$ pixels in CMS [66] are implemented.

The Σ^+ kink angle φ is given by

$$\sin\varphi = \frac{1}{\sqrt{1 + \dfrac{\gamma^2 \left(\cos\vartheta + \beta E_p/p_p\right)^2}{\sin^2\vartheta}}} \simeq \frac{\sin\vartheta}{\gamma\left(\cos\vartheta + E_p/p_p\right)} \,, \tag{3.3}$$

where ϑ is the rest-frame decay angle from eq. (3.1), β is the Σ^+ velocity, $\gamma = 1/\sqrt{1-\beta^2}$ is the corresponding boost factor, and E_p and p_p are the energy and momentum of the proton in the Σ^+ rest frame, where one has $E_p/p_p \approx 5.1$ (see appendix A for these and other details of the kinematics). In the last step in eq. (3.3), we took the ultra-relativistic limit $\gamma \gg 1$. We see that the typical kink angle in our case ($\gamma \sim 15$) will be $\varphi \sim 10$ mrad (see also table 1). It is measurable.[7] However, since $E_p/p_p \approx 5.1 \gg 1$, eq. (3.3) implies that the kink angle φ is not very sensitive to the forward/backwardness of the proton (i.e., the sign of $\cos\vartheta$). In fact, most values of φ can be obtained from two very different values of $\cos\vartheta$ with opposite signs. This happens because the proton is nonrelativistic in the Σ^+ rest frame. As a result, the longitudinal component (with respect to the Σ^+ direction of motion) of its momentum in the lab frame is dominated by the boost of its mass (rather than its 3-momentum) from the Σ^+ rest frame. Instead of using φ itself, it may be convenient to extract $\cos\vartheta$ via

$$\cos\vartheta = \frac{\beta}{p_p}\left(\frac{p'_p}{p'_{\Sigma^+}}m_{\Sigma^+}\cos\varphi - E_p\right) \approx \beta\left(6.3\,\frac{p'_p}{p'_{\Sigma^+}}\cos\varphi - 5.1\right) \simeq 6.3\,\frac{p'_p}{p'_{\Sigma^+}} - 5.1\,, \tag{3.4}$$

where the primed ($'$) quantities denote lab-frame momenta, and in the last step we assumed the Σ^+ to be relativistic. Since the range of $\cos\vartheta$ is $[-1, 1]$, the momenta of the proton and Σ^+ need to be measured with precision of $\sim 10\%$ in order for them to provide useful

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[6]The pixel size in the ATLAS Pixel Detector is $50 \times 250 \, \mu m^2$ for the innermost layer and $50 \times 400 \, \mu m^2$ for the other layers [56], and in CMS it is $100 \times 150 \, \mu m^2$ [57], where the first dimension is the transverse one, which is the one relevant for the p_T measurement. In ATLAS's SCT and in the first layers of CMS's TIB the pitch is $80 \, \mu m$ [58, 59]. The magnetic field is 2 T in ATLAS and 3.8 T in CMS.

[7]For example, even the Run-1 CMS three-layer Pixel Detector alone was capable of measuring the track momentum parameters ϕ and θ with resolutions of roughly 3 mrad and 1 mrad, respectively, for tracks with $p_T \sim 10$ GeV [59].

Decay	$\left(\dfrac{P}{15\,\text{GeV}}\right) \times \varphi$ [mrad]		
$\vartheta =$	$\pi/4$	$\pi/2$	$3\pi/4$
$\Sigma^+ \to p\pi^0$	10	16	13
$\Sigma^+ \to n\pi^+$	29	63	103
$\pi^+ \to \mu^+\nu_\mu$	1	3	2
$K^+ \to \mu^+\nu_\mu$	13	30	60
$K^+ \to \pi^+\pi^0$	12	27	46
$\overline{\Sigma}^+ \to \overline{n}\pi^+$	29	65	107
$\overline{\Xi}^+ \to \pi^+\overline{\Lambda}$	29	62	88

Table 1. The kink angle φ for three values of the rest-frame decay angle $\vartheta = \pi/4$, $\pi/2$, $3\pi/4$, where P is the lab-frame momentum of the mother hadron, which is assumed to be relativistic, $\gamma \gg 1$.

information about $\cos\vartheta$. Based on the discussion in the previous paragraph, it seems realistic despite the shortness of the Σ^+ track.

There will be background due to kinks produced by other decays of charged hadrons: $\Sigma^+ \to n\pi^+$, $\pi^+ \to \mu^+\nu_\mu$, $K^+ \to \mu^+\nu_\mu$, $K^+ \to \pi^+\pi^0$, $\overline{\Sigma}^+ \to \overline{n}\pi^+$ and $\overline{\Xi}^+ \to \pi^+\overline{\Lambda}$. We note that among these, only $\Sigma^+ \to n\pi^+$ can arise from a primary strange quark. Nonprimary hadrons (namely ones not carrying the original quark) will typically be soft relative to the jet, thus not of interest to us in any case. Therefore, for a high-purity sample of strange quarks, like the one obtained for instance in the $t\bar{t}$ selection described below, $\Sigma^+ \to n\pi^+$ will make the dominant contribution to this background. Luckily, this contribution can be largely eliminated using the fact that the kink angle in this case is usually much larger than in the decay of interest, as shown in table 1. For a sample of up quarks, the typical size of the kink angle can also be used to reduce some of the contributions.

Kinks can also be created by interactions of charged hadrons with the detector material— either an elastic scattering with a large momentum transfer or an inelastic scattering such as $\pi^+ + n \to \pi^0 + p$. However, in the elastic scattering case the scattering angle is typically much smaller than the Σ^+ kink angle. The width of the scattering angle distribution is given by (section 34.3 of [20])

$$\varphi_{\text{rms}} \simeq \frac{13.6\ \text{MeV}}{P}\sqrt{2\frac{x}{X_0}}\,, \tag{3.5}$$

where P is the hadron momentum and x/X_0 is the medium thickness in radiation lengths. For ATLAS,[8] in the range $15\,\text{cm} < r < 35\,\text{cm}$, we have $x/X_0 \sim 0.05$ [68], thus

$$\varphi_{\text{rms}} \sim \left(\frac{15\,\text{GeV}}{P}\right) \times 0.3\,\text{mrad}\,, \tag{3.6}$$

which is more than an order of magnitude smaller than the kink angle in the $\Sigma^+ \to p\pi^0$ decay (see table 1).

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[8]We could not find an analogous number for CMS, but it seems [57, 59, 67] that there is no reason to expect a significantly bigger number.

Part of the inelastic scattering background can be avoided by requiring the momentum of the second part of the track to be consistent with the proton produced in the decay, which is expected to carry between 65%–96% of the Σ^+ momentum. Both of the material-induced backgrounds can be reduced significantly, without too much efficiency loss to the signal, by vetoing kinks occurring near detector layers. A detailed simulation of the ATLAS and/or CMS detector, which is not available to the author, would be needed to define the details of this procedure and estimate the background that will remain.

3.2 π^0

It is not straightforward to associate a π^0 with a candidate Σ^+ decay because the trackless π^0 cannot be assigned to a specific vertex, and there are various ways in which unrelated π^0s can be produced inside a jet or from pile-up, especially considering that our π^0 is very soft ($E_{\pi^0} \sim 3$ GeV for $p_T^{\Sigma^+} \sim 15$ GeV). Note though that if the Σ^+ and p momenta are well-measured, measuring the π^0 is not essential for reconstructing the decay. Still, it may be useful to include a loose requirement that a π^0 candidate with the expected energy[9] and position in the calorimeter be present in the jet, to suppress backgrounds. For $p_T^{\Sigma^+} \sim 15$ GeV, a typical deviation of the π^0 from the Σ^+ direction will be 80 mrad.

It is also worth checking whether one can identify the non-pointing and/or delayed nature of the π^0 photons related to the large displacement of the Σ^+ decay vertex, along the lines of [73–76], which would eliminate much of the background π^0s. These analyses determine the flight direction of the photon based on its shower shape in the electromagnetic calorimeter [73–75] (or e^+e^- tracks in the case of converted photons [76]) and/or measure the delay in the arrival time relative to a photon that would arrive directly from the primary vertex [73–75].

In principle, it might also be possible to reconstruct the Σ^+ decay using just the proton and the π^0, without relying on a direct measurement of the Σ^+ momentum. This was done (although with relatively low efficiencies) by OPAL [22] and L3 [23] in samples of hadronic Z decays at LEP and by LHCb (as a control channel for another measurement) in inclusive QCD samples [77]. However, given the potential difficulty in identifying the relevant soft π^0, we leave the exploration of this interesting alternative beyond the scope of this paper.

3.3 Proposed analyses in $t\bar{t}$ events

We propose to measure the polarization transfer from the s and u quarks to the Σ^+ baryon using $t\bar{t}$ samples in ATLAS and CMS.

We envision starting with a standard $t\bar{t}$ event selection in the lepton+jets channel. Such a selection usually requires the event to contain one isolated electron or muon, at least four jets, one or two of which are required to be b tagged, and satisfy a mild cut

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[9]The electromagnetic calorimeter resolution is given by

$$\frac{\sigma_E}{E} = \frac{a}{\sqrt{E/\text{GeV}}} \oplus \frac{b}{E/\text{GeV}} \oplus c \,,$$

where $a = 10.1 \pm 0.1\%$, $b \approx 8\%$, $c = 0.17 \pm 0.04\%$ in ATLAS [69–71], and $a \approx 2.8\%$, $b \approx 12\%$, $c \approx 0.3\%$ in CMS [72], so the energy of the π^0 can be measured with a precision of around 5%.

on the missing energy and/or the transverse mass of the leptonically decaying W. After a kinematic reconstruction of the event, information about the flavor of the jets from the hadronic W decay can be obtained using charm tagging. Demanding a charm tag will produce high-purity and high-efficiency samples of c and s jets from the

$$W^+ \to c\bar{s} \tag{3.7}$$

decays. For example, charm tagging working points with 40% (or 30%) efficiency for c jets and $\sim 3\%$ (or 1%) efficiency for light jets are possible in both ATLAS [78] and CMS [79]. Events with Σ^+ baryons in the s-jet candidates will then allow measuring the

$$s \to \Sigma^+ \tag{3.8}$$

polarization transfer.

Alternatively, vetoing on a loose charm tag will provide high-efficiency samples of

$$W^+ \to u\bar{d} \tag{3.9}$$

decays, which can be used for measuring the

$$u \to \Sigma^+ \tag{3.10}$$

polarization transfer. The sample will, however, contain a significant contamination from $W^+ \to c\bar{s}$. For example, with the charm tagging algorithm of ref. [79], only 80% of the $c\bar{s}$ decays will be successfully vetoed while keeping 50% of the $u\bar{d}$ decays. The impact of the contamination from $c\bar{s}$ will be further enhanced by Σ^+ baryons being more readily produced from c quarks than from u quarks, on which we will elaborate below. Production from the $\bar{d}$ or $\bar{s}$ antiquarks is not an issue: their jets will not contribute many energetic Σ^+ baryons because the Σ^+ does not contain valence antiquarks. Here we assume that the W charge, and correspondingly the charge expected for the Σ^+, is determined by the lepton on the other side of the event.

Let us now estimate the statistics available for these analyses. A standard $t\bar{t}$ selection in the lepton+jets channel in the ATLAS Run 2 dataset [80] results in 5.6×10^6 $t\bar{t}$ events and a background of 1.1×10^6 events from other processes. The CMS analysis in the same final state [81] also describes how the event kinematics can be reconstructed to determine, in particular, which of the observed jets come from the W decay. We envision a similar procedure for our proposed analysis. Charm tagging, which we would use anyway to select the sample of strange jets that accompany the charm jets in the $W^+ \to c\bar{s}$ decays, will aid the reconstruction. Since approximately half of the hadronic W decays produce $c\bar{s}$, and assuming 40% charm tagging efficiency, we obtain a sample of about 1.1×10^6 strange jets. Based on the fragmentation functions from ref. [19], the probability for a strange quark to produce an energetic Σ^+, which we define as carrying at least 30% of the jet momentum (i.e., $z > 0.3$), is about 1.6%. Taking into account also the branching fraction for $\Sigma^+ \to p\pi^0$, we are left with about 9000 such decays in the Run 2 samples. Even if only a fraction of the kinks are reconstructed and certain additional mild cuts are applied to

reduce backgrounds, there will likely still remain a sizable $s \to \Sigma^+$ sample to study even in the data that has already been collected.

For $u \to \Sigma^+$, the statistics is more challenging because the corresponding fragmentation fraction for $z > 0.3$ is only about 2.2×10^{-4} [19]. Estimating as in the previous case and assuming 50% efficiency for passing the loose charm tag veto, we are left with about 160 decays in the Run 2 dataset before accounting for the kink reconstruction efficiency and the need to deal with significant backgrounds in this case. As mentioned above, there is a sizable contamination due to c jets that evade the charm tag veto. They contribute primarily via $\Lambda_c^+ \to \Sigma^+ + X$. The fragmentation fraction for $c \to \Lambda_c^+$ is about 6% (at high p_T) [82–84] and the branching fraction of $\Lambda_c^+ \to \Sigma^+$ (+ anything) is about 11% [20].[10] About half of these decays (such as the most common one, $\Lambda_c^+ \to \Sigma^+ \pi^+ \pi^-$) produce only charged particles in addition to the Σ^+ and can therefore be vetoed via Λ_c^+ mass reconstruction. This leaves us with a probability of 3×10^{-3} for a c jet to contribute a Σ^+ while evading the charm tag veto and the Λ_c^+ reconstruction veto. A significant fraction of these Σ^+ baryons are likely sufficiently energetic to compete with the $u \to \Sigma^+$ signal which has a fragmentation fraction of 2.2×10^{-4} for $z > 0.3$. Since the number of c jets entering the sample after the charm tag veto is smaller than the number of u jets by only a factor of about 2.5, the c-jet background is nonnegligible, but at the same time it is not prohibitively large. One may consider using the deviation of the Σ^+ trajectory from the jet axis as a handle to further reduce such contributions. While the statistics of 160 signal events (before accounting for the reconstruction efficiency and addressing backgrounds) is problematic, it will increase by a factor of at least 20 at the high-luminosity LHC, along with detector upgrades, and then a meaningful measurement may become possible for this process as well.

4 Summary

Top-quark pair production ($pp \to t\bar{t}$) samples at the LHC are a high-statistics and relatively clean source of polarized quarks of various flavors — b, c, s, d, u — that can be studied by ATLAS and CMS. Decay angular distributions of energetic baryons inside the jets are sensitive to the original quark polarization. Previous proposals focused on the Λ_b and Λ_c baryons from the b and c quarks, respectively [4], and the Λ baryons from the s quarks [16]. In the current paper we considered the production of Σ^+ baryons from the s or u quarks, which can provide complementary information.

We proposed to use the kinked track signature of the $\Sigma^+ \to p\pi^0$ decay (possibly along with the electromagnetic signature of the displaced π^0) to identify the Σ^+ baryons in s and u jet candidates and measure their polarization. Measuring the $s \to \Sigma^+$ polarization transfer seems feasible with existing data, while the $u \to \Sigma^+$ measurement, where statistics is lower

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[10]Known contributions to BR($\Lambda_c^+ \to \Sigma^+$anything) are BR($\Lambda_c^+ \to \Sigma^+\pi^+\pi^-$) = (4.50 ± 0.25)%, BR($\Lambda_c^+ \to \Sigma^+\omega$) = (1.70 ± 0.21)%, BR($\Lambda_c^+ \to \Sigma^+\pi^0\pi^0$) = (1.55 ± 0.15)%, BR($\Lambda_c^+ \to \Sigma^+\eta'$) = (1.5 ± 0.6)%, BR($\Lambda_c^+ \to \Sigma^+\pi^0$) = (1.25 ± 0.10)%, BR($\Lambda_c^+ \to \Sigma^+\eta$) = (0.44 ± 0.20)%, BR($\Lambda_c^+ \to \Sigma^+K^+K^-$) = (0.35 ± 0.04)%, BR($\Lambda_c^+ \to \Sigma^+K^+\pi^-$) = (0.21 ± 0.06)% [20]. They add up to (11.5 ± 0.7)%. It is also known that BR($\Lambda_c^+ \to \Sigma^\pm$ anything) = (10 ± 5)% [85].

and backgrounds are larger, will probably become possible only at the high-luminosity LHC.

Apart from measuring polarization transfer, analyses with kink reconstruction could be useful for measuring fragmentation functions involving the Σ^+ and other hadrons with kinked track signatures, as well as searching for certain scenarios in which particles beyond the Standard Model produce kinked tracks [26–28]. We hope this paper will further motivate such analyses.

Acknowledgments

A   Kinematics

This appendix collects formulas and numbers relevant to the kinematics of the $\Sigma^+ \to p\pi^0$ decay. The symbols Σ and π below refer to the Σ^+ and π^0, respectively. Energies and momenta in the lab frame will be denoted with a prime ($'$), so transformations from the Σ rest frame are written as

$$E' = \gamma \left(E + \beta p_\parallel \right) , \qquad p'_\parallel = \gamma \left(p_\parallel + \beta E \right) , \qquad \vec{p}'_\perp = \vec{p}_\perp , \tag{A.1}$$

where β is the Σ velocity in the lab frame, $\gamma = 1/\sqrt{1 - \beta^2}$ is the corresponding Lorentz factor, $\parallel$ and $\perp$ denote the momentum components with respect to the boost direction.

Quantities in the Σ rest frame

The energies and momenta are given by

$$E_\pi = \frac{m_\Sigma^2 + m_\pi^2 - m_p^2}{2m_\Sigma} \approx 0.232 \, \text{GeV} , \qquad E_p = \frac{m_\Sigma^2 + m_p^2 - m_\pi^2}{2m_\Sigma} \approx 0.957 \, \text{GeV} , \tag{A.2}$$

$$p_p = p_\pi = \sqrt{E_\pi^2 - m_\pi^2} \approx 0.189 \, \text{GeV} , \tag{A.3}$$

where we used the masses [20]

$$m_\Sigma \approx 1.1894 \text{ GeV} , \qquad m_\pi \approx 0.1350 \text{ GeV} , \qquad m_p \approx 0.9383 \text{ GeV} . \tag{A.4}$$

Proton momentum and pion energy in the lab frame

For a relativistic Σ (i.e. $\beta \simeq 1$), the proton, which is produced non-relativistic in the Σ rest frame ($v_p = p_p/E_p \approx 0.20$), acquires momentum of roughly

$$p'_p \simeq \gamma\beta E_p = \frac{p'_\Sigma}{m_\Sigma} E_p \approx 0.80 \, p'_\Sigma \approx 12 \, \text{GeV} \times \left(\frac{p'_\Sigma}{15 \, \text{GeV}} \right) \tag{A.5}$$

in the lab frame.

The pion energy in the lab frame is

$$E'_\pi = \gamma \left(E_\pi + \beta p_{\pi,\parallel} \right) \simeq \frac{p'_\Sigma}{m_\Sigma} \left(E_\pi + p_{\pi,\parallel} \right). \tag{A.6}$$

Since $p_{\pi,\parallel}$ can be both positive and negative and its maximal magnitude is somewhat smaller than E_π, the typical value of the pion energy can be estimated to be

$$E'_\pi \sim \frac{p'_\Sigma}{m_\Sigma} E_\pi \approx 2.9 \, \text{GeV} \times \left(\frac{p'_\Sigma}{15 \, \text{GeV}} \right). \tag{A.7}$$

Kink angle as a function of the rest-frame decay angle

Denoting the rest-frame decay angle (direction of proton momentum relative to the boost direction) by ϑ, we have

$$p'_{p,\parallel} = \gamma \left(p_p \cos\vartheta + \beta E_p \right), \qquad p'_{p,\perp} = p_p \sin\vartheta, \tag{A.8}$$

which gives the kink angle φ as

$$\sin\varphi = \frac{p'_{p,\perp}}{p'_p} = \frac{1}{\sqrt{1 + p'^2_{p,\parallel}/p'^2_{p,\perp}}} = \frac{1}{\sqrt{1 + \dfrac{\gamma^2 \left(\cos\vartheta + \beta E_p/p_p \right)^2}{\sin^2\vartheta}}}, \tag{A.9}$$

where $E_p/p_p \approx 5.1$, as we computed above. For $\gamma \gg 1$,

$$\sin\varphi \simeq \frac{\sin\vartheta}{\gamma \left(\cos\vartheta + E_p/p_p \right)} \sim \frac{\sin\vartheta}{5\gamma}, \tag{A.10}$$

where the last expression is a rough approximation.

A similar calculation applies to the pion. Since $E_\pi/p_\pi \approx 1.2$, a typical angle of the pion momentum relative to the Σ^+ momentum will be

$$\sin\varphi_\pi \sim \frac{1}{\gamma} \simeq \frac{m_\Sigma}{p'_\Sigma} \approx 0.08 \times \left(\frac{15 \, \text{GeV}}{p'_\Sigma} \right). \tag{A.11}$$

Extraction of the decay angle from the measured momenta

From the Lorentz transformation for $p'_{p,\parallel} = p'_p \cos\varphi$ we obtain

$$\cos\vartheta = \frac{1}{p_p} \left(\frac{p'_p \cos\varphi}{\gamma} - \beta E_p \right) = \frac{\beta}{p_p} \left(\frac{p'_p}{p'_\Sigma} m_\Sigma \cos\varphi - E_p \right). \tag{A.12}$$

Substituting the numerical values for the fixed quantities, we get

$$\cos\vartheta \approx \beta \left(6.3 \frac{p'_p}{p'_\Sigma} \cos\varphi - 5.1 \right) \simeq 6.3 \frac{p'_p}{p'_\Sigma} - 5.1, \tag{A.13}$$

where in the last step we assumed the Σ to be relativistic (so that $\beta \simeq 1$ and $\cos\varphi \simeq 1$).

References

[1] T. Mannel and G. A. Schuler, "Semileptonic decays of bottom baryons at LEP," *Phys. Lett.* **B279** (1992) 194.

[2] F. E. Close, J. G. Körner, R. J. N. Phillips, and D. J. Summers, "Report of the b-fragmentation working group. Section 5: b polarization at LEP," *J. Phys.* **G18** (1992) 1703.

[3] A. F. Falk and M. E. Peskin, "Production, decay, and polarization of excited heavy hadrons," *Phys. Rev.* **D49** (1994) 3320, `arXiv:hep-ph/9308241`.

[4] M. Galanti, A. Giammanco, Y. Grossman, Y. Kats, E. Stamou, and J. Zupan, "Heavy baryons as polarimeters at colliders," *JHEP* **11** (2015) 067, `arXiv:1505.02771 [hep-ph]`.

[5] ALEPH Collaboration, D. Buskulic *et al.*, "Measurement of Λ_b polarization in Z decays," *Phys. Lett.* **B365** (1996) 437.

[6] OPAL Collaboration, G. Abbiendi *et al.*, "Measurement of the average polarization of b baryons in hadronic Z^0 decays," *Phys. Lett.* **B444** (1998) 539, `arXiv:hep-ex/9808006`.

[7] DELPHI Collaboration, P. Abreu *et al.*, "Λ_b polarization in Z^0 decays at LEP," *Phys. Lett.* **B474** (2000) 205.

[8] ALEPH Collaboration, D. Buskulic *et al.*, "Measurement of Λ polarization from Z decays," *Phys. Lett.* **B374** (1996) 319.

[9] ALEPH Collaboration, "Update of Λ polarization from Z decays," Tech. Rep. CERN-OPEN-99-328, 1997. `http://cds.cern.ch/record/407920`.

[10] OPAL Collaboration, K. Ackerstaff *et al.*, "Polarization and forward-backward asymmetry of Λ baryons in hadronic Z^0 decays," *Eur. Phys. J.* **C2** (1998) 49, `arXiv:hep-ex/9708027`.

[11] CMS Collaboration, A. M. Sirunyan *et al.*, "Measurement of the Λ_b polarization and angular parameters in $\Lambda_b \to J/\psi\,\Lambda$ decays from pp collisions at $\sqrt{s} = 7$ and 8 TeV," *Phys. Rev.* **D97** (2018) 072010, `arXiv:1802.04867 [hep-ex]`.

[12] LHCb Collaboration, R. Aaij *et al.*, "Measurement of the $\Lambda_b^0 \to J/\psi\Lambda$ angular distribution and the Λ_b^0 polarisation in pp collisions," *JHEP* **06** (2020) 110, `arXiv:2004.10563 [hep-ex]`.

[13] ATLAS Collaboration, G. Aad *et al.*, "Measurement of the transverse polarization of Λ and $\bar{\Lambda}$ hyperons produced in proton-proton collisions at $\sqrt{s} = 7$ TeV using the ATLAS detector," *Phys. Rev.* **D91** (2015) 032004, `arXiv:1412.1692 [hep-ex]`.

[14] P. J. Mulders and R. D. Tangerman, "The complete tree-level result up to order $1/Q$ for polarized deep-inelastic leptoproduction," *Nucl. Phys.* **B461** (1996) 197, `arXiv:hep-ph/9510301`. [Erratum: *Nucl. Phys.* **B484** (1997) 538].

[15] M. Anselmino, D. Boer, U. D'Alesio, and F. Murgia, "Λ polarization from unpolarized quark fragmentation," *Phys. Rev.* **D63** (2001) 054029, `arXiv:hep-ph/0008186`.

[16] Y. Kats, "Measuring polarization of light quarks at ATLAS and CMS," *Phys. Rev.* **D92** (2015) 071503, `arXiv:1505.06731 [hep-ph]`.

[17] J. G. Körner, A. Pilaftsis, and M. M. Tung, "One-loop QCD mass effects in the production of polarized bottom and top quarks," *Z. Phys.* **C63** (1994) 575, `arXiv:hep-ph/9311332`.

[18] Y. Kats, "Measuring c-quark polarization in $W+c$ samples at ATLAS and CMS,"

JHEP **11** (2016) 011, `arXiv:1512.00438 [hep-ph]`.

[19] C. Bourrely and J. Soffer, "Statistical approach for unpolarized fragmentation functions for the octet baryons," *Phys. Rev.* **D68** (2003) 014003, `arXiv:hep-ph/0305070`.

[20] Particle Data Group, R. L. Workman *et al.*, "Review of Particle Physics," *PTEP* **2022** (2022) 083C01.

[21] DELPHI Collaboration, P. Abreu *et al.*, "Strange baryon production in Z hadronic decays," *Z. Phys.* **C67** (1995) 543.

[22] OPAL Collaboration, G. Alexander *et al.*, "Σ^+, Σ^0 and Σ^- hyperon production in hadronic Z^0 decays," *Z. Phys.* **C73** (1997) 587.

[23] L3 Collaboration, M. Acciarri *et al.*, "Inclusive Σ^+ and Σ^0 production in hadronic Z decays," *Phys. Lett.* **B479** (2000) 79, `arXiv:hep-ex/0002066`.

[24] ATLAS Collaboration, G. Aad *et al.*, "Measurements of jet observables sensitive to b-quark fragmentation in $t\bar{t}$ events at the LHC with the ATLAS detector," *Phys. Rev. D* **106** no. 3, (2022) 032008, `arXiv:2202.13901 [hep-ex]`.

[25] CMS Collaboration, "Measurement of the shape of the b quark fragmentation function using charmed mesons produced inside b jets from $t\bar{t}$ pair decays," Tech. Rep. CMS-PAS-TOP-18-012, CERN, Geneva, 2021. `https://cds.cern.ch/record/2771694`.

[26] A. J. Barr, C. G. Lester, M. A. Parker, B. C. Allanach, and P. Richardson, "Discovering anomaly mediated supersymmetry at the LHC," *JHEP* **03** (2003) 045, `arXiv:hep-ph/0208214`.

[27] S. Asai, Y. Azuma, M. Endo, K. Hamaguchi, and S. Iwamoto, "Stau Kinks at the LHC," *JHEP* **1112** (2011) 041, `arXiv:1103.1881 [hep-ph]`.

[28] S. Jung and H.-S. Lee, "Constraining Higgsino Kink Tracks from Existing LHC Searches," *Int. J. Mod. Phys.* **A32** (2017) 1750070, `arXiv:1503.00414 [hep-ph]`.

[29] D. de Florian, M. Stratmann, and W. Vogelsang, "QCD analysis of unpolarized and polarized Λ-baryon production in leading and next-to-leading order," *Phys. Rev.* **D57** (1998) 5811, `arXiv:hep-ph/9711387`.

[30] M. Stratmann and W. Vogelsang, "Next-to-leading order evolution of polarized and unpolarized fragmentation functions," *Nucl. Phys.* **B496** (1997) 41, `arXiv:hep-ph/9612250`.

[31] DELPHI Collaboration, P. Abreu *et al.*, "Inclusive Σ^- and $\Lambda(1520)$ production in hadronic Z decays," *Phys. Lett.* **B475** (2000) 429, `arXiv:hep-ex/0103020`.

[32] DELPHI Collaboration, W. Adam *et al.*, "Production of Σ^0 and Ω^- in Z decays," *Z. Phys.* **C70** (1996) 371.

[33] ALEPH Collaboration, R. Barate *et al.*, "Studies of quantum chromodynamics with the ALEPH detector," *Phys. Rept.* **294** (1998) 1.

[34] C. A. Aidala, S. D. Bass, D. Hasch, and G. K. Mallot, "The Spin Structure of the Nucleon," *Rev. Mod. Phys.* **85** (2013) 655, `arXiv:1209.2803 [hep-ph]`.

[35] COMPASS Collaboration, C. Adolph *et al.*, "The spin structure function $g_1^{\rm p}$ of the proton and a test of the Bjorken sum rule," *Phys. Lett.* **B753** (2016) 18, `arXiv:1503.08935 [hep-ex]`.

[36] M. Burkardt and R. L. Jaffe, "Polarized $q \to \Lambda$ fragmentation functions from

$e^+e^- \to \Lambda + X$," *Phys. Rev. Lett.* **70** (1993) 2537, `arXiv:hep-ph/9302232`.

[37] R. L. Jaffe, "Polarized Λ's in the current fragmentation region," *Phys. Rev.* **D54** (1996) 6581, `arXiv:hep-ph/9605456`.

[38] QCDSF Collaboration, M. Göckeler *et al.*, "A lattice study of the spin structure of the Λ hyperon," *Phys. Lett.* **B545** (2002) 112, `arXiv:hep-lat/0208017`.

[39] CSSM, QCDSF/UKQCD Collaboration, A. J. Chambers *et al.*, "Feynman-Hellmann approach to the spin structure of hadrons," *Phys. Rev.* **D90** (2014) 014510, `arXiv:1405.3019 [hep-lat]`.

[40] V. Barone, A. Drago, and B.-Q. Ma, "Connection between distribution and fragmentation functions," *Phys. Rev.* **C62** (2000) 062201, `arXiv:hep-ph/0011334`.

[41] C. Boros and Z. Liang, "Spin content of Λ and its longitudinal polarization in e^+e^- annihilation at high energies," *Phys. Rev.* **D57** (1998) 4491, `arXiv:hep-ph/9803225`.

[42] D. Ashery and H. J. Lipkin, "Expected polarization of Λ particles produced in deep inelastic polarized lepton scattering," *Phys. Lett.* **B469** (1999) 263, `arXiv:hep-ph/9908355`.

[43] C. Alexandrou, S. Bacchio, M. Constantinou, J. Finkenrath, K. Hadjiyiannakou, K. Jansen, G. Koutsou, H. Panagopoulos, and G. Spanoudes, "Complete flavor decomposition of the spin and momentum fraction of the proton using lattice QCD simulations at physical pion mass," *Phys. Rev. D* **101** no. 9, (2020) 094513, `arXiv:2003.08486 [hep-lat]`.

[44] M. Gluck, E. Reya, M. Stratmann, and W. Vogelsang, "Models for the polarized parton distributions of the nucleon," *Phys. Rev.* **D63** (2001) 094005, `arXiv:hep-ph/0011215`.

[45] D. de Florian, R. Sassot, M. Stratmann, and W. Vogelsang, "Extraction of Spin-Dependent Parton Densities and Their Uncertainties," *Phys. Rev.* **D80** (2009) 034030, `arXiv:0904.3821 [hep-ph]`.

[46] NNPDF Collaboration, E. R. Nocera, R. D. Ball, S. Forte, G. Ridolfi, and J. Rojo, "A first unbiased global determination of polarized PDFs and their uncertainties," *Nucl. Phys.* **B887** (2014) 276, `arXiv:1406.5539 [hep-ph]`.

[47] J.-W. Chen, S. D. Cohen, X. Ji, H.-W. Lin, and J.-H. Zhang, "Nucleon Helicity and Transversity Parton Distributions from Lattice QCD," *Nucl. Phys.* **B911** (2016) 246, `arXiv:1603.06664 [hep-ph]`.

[48] B.-Q. Ma, I. Schmidt, and J.-J. Yang, "Quark structure of Λ from Λ polarization in Z decays," *Phys. Rev.* **D61** (2000) 034017, `arXiv:hep-ph/9907224`.

[49] B.-Q. Ma, I. Schmidt, J. Soffer, and J.-J. Yang, "Λ, $\overline{\Lambda}$ polarization and spin transfer in lepton deep inelastic scattering," *Eur. Phys. J.* **C16** (2000) 657, `arXiv:hep-ph/0001259`.

[50] B.-Q. Ma, I. Schmidt, J. Soffer, and J.-J. Yang, "The flavor and spin structure of hyperons from quark fragmentation," *Phys. Rev.* **D62** (2000) 114009, `arXiv:hep-ph/0008295`.

[51] B.-Q. Ma, I. Schmidt, J. Soffer, and J.-J. Yang, "Quark distributions of octet baryons from SU(3) symmetry," *Phys. Rev.* **D65** (2002) 034004, `arXiv:hep-ph/0110029`.

[52] J.-J. Yang, "Quark fragmentation functions in a diquark model for Λ production," *Phys. Rev.* **D64** (2001) 074010, `arXiv:hep-ph/0111188`.

[53] J.-J. Yang, "$q \to \Lambda$ fragmentation function and nucleon transversity distribution in a diquark model," *Nucl. Phys.* **A699** (2002) 562, `arXiv:hep-ph/0111382`.

[54] H. Liu, Y. Chi, L. Shao, and B.-Q. Ma, "Octet Quark Contents from SU(3) Flavor Symmetry," *Europhys. Lett.* **94** (2011) 31001, `arXiv:1104.3737 [hep-ph]`.

[55] Y. Chi and B.-Q. Ma, "Quark to Λ-hyperon spin transfers in the current-fragmentation region," *Phys. Lett.* **B726** (2013) 737, `arXiv:1310.2005 [hep-ph]`.

[56] ATLAS Pixel Collaboration, H. Pernegger, "The Pixel Detector of the ATLAS experiment for LHC Run-2," *JINST* **10** no. 06, (2015) C06012.

[57] CMS Collaboration, A. Dominguez *et al.*, "CMS Technical Design Report for the Pixel Detector Upgrade," Tech. Rep. CERN-LHCC-2012-016, CMS-TDR-011, FERMILAB-DESIGN-2012-02, 2012. `http://cds.cern.ch/record/1481838`.

[58] ATLAS Collaboration, "ATLAS Inner Detector: Technical Design Report. Vol. 1," Tech. Rep. ATLAS-TDR-4, CERN-LHCC-97-16, CERN, Geneva, 1997. `http://cds.cern.ch/record/331063`.

[59] CMS Collaboration, S. Chatrchyan *et al.*, "Description and performance of track and primary-vertex reconstruction with the CMS tracker," *JINST* **9** (2014) P10009, `arXiv:1405.6569 [physics.ins-det]`.

[60] ATLAS Collaboration, M. Aaboud *et al.*, "Search for long-lived charginos based on a disappearing-track signature in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector," *JHEP* **06** (2018) 022, `arXiv:1712.02118 [hep-ex]`.

[61] ATLAS Collaboration, G. Aad *et al.*, "Search for long-lived charginos based on a disappearing-track signature using 136 fb^{-1} of pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector," *Eur. Phys. J. C* **82** no. 7, (2022) 606, `arXiv:2201.02472 [hep-ex]`.

[62] CMS Collaboration, A. M. Sirunyan *et al.*, "Search for disappearing tracks as a signature of new long-lived particles in proton-proton collisions at $\sqrt{s} = 13$ TeV," *JHEP* **08** (2018) 016, `arXiv:1804.07321 [hep-ex]`.

[63] CMS Collaboration, A. M. Sirunyan *et al.*, "Searches for physics beyond the standard model with the M_{T2} variable in hadronic final states with and without disappearing tracks in proton-proton collisions at $\sqrt{s} = 13$ TeV," *Eur. Phys. J. C* **80** no. 1, (2020) 3, `arXiv:1909.03460 [hep-ex]`.

[64] CMS Collaboration, A. M. Sirunyan *et al.*, "Search for disappearing tracks in proton-proton collisions at $\sqrt{s} = 13$ TeV," *Phys. Lett. B* **806** (2020) 135502, `arXiv:2004.05153 [hep-ex]`.

[65] ATLAS Collaboration, "Technical Design Report for the ATLAS Inner Tracker Pixel Detector," Tech. Rep. CERN-LHCC-2017-021. ATLAS-TDR-030, CERN, Geneva, Sep, 2017. `https://cds.cern.ch/record/2285585`.

[66] CMS Collaboration, "Technical Proposal for the Phase-II Upgrade of the CMS Detector," Tech. Rep. CERN-LHCC-2015-010. LHCC-P-008. CMS-TDR-15-02, Geneva, Jun, 2015. `https://cds.cern.ch/record/2020886`.

[67] CMS Collaboration, A. M. Sirunyan *et al.*, "Precision measurement of the structure of the CMS inner tracking system using nuclear interactions," *JINST* **13** no. 10, (2018) P10034, `arXiv:1807.03289 [physics.ins-det]`.

[68] ATLAS Collaboration, M. Aaboud *et al.*, "Study of the material of the ATLAS inner detector for Run 2 of the LHC," *JINST* **12** (2017) P12009, `arXiv:1707.02826 [hep-ex]`.

[69] ATLAS Electromagnetic Barrel Calorimeter Collaboration, M. Aharrouche *et al.*, "Energy linearity and resolution of the ATLAS electromagnetic barrel calorimeter in an electron

test-beam," *Nucl. Instrum. Meth.* **A568** (2006) 601, `arXiv:physics/0608012`.

[70] ATLAS Collaboration, G. Aad *et al.*, "The ATLAS Experiment at the CERN Large Hadron Collider," *JINST* **3** (2008) S08003.

[71] ATLAS Collaboration, G. Aad *et al.*, "Electron and photon energy calibration with the ATLAS detector using LHC Run 1 data," *Eur. Phys. J.* **C74** (2014) 3071, `arXiv:1407.5063 [hep-ex]`.

[72] CMS Collaboration, S. Chatrchyan *et al.*, "Energy Calibration and Resolution of the CMS Electromagnetic Calorimeter in pp Collisions at $\sqrt{s} = 7$ TeV," *JINST* **8** (2013) P09009, `arXiv:1306.2016 [hep-ex]`.

[73] ATLAS Collaboration, G. Aad *et al.*, "Search for nonpointing and delayed photons in the diphoton and missing transverse momentum final state in 8 TeV pp collisions at the LHC using the ATLAS detector," *Phys. Rev.* **D90** (2014) 112005, `arXiv:1409.5542 [hep-ex]`.

[74] CMS Collaboration, A. M. Sirunyan *et al.*, "Search for long-lived particles using delayed photons in proton-proton collisions at $\sqrt{s} = 13$ TeV," *Phys. Rev. D* **100** no. 11, (2019) 112003, `arXiv:1909.06166 [hep-ex]`.

[75] ATLAS Collaboration, "Search for displaced photons produced in exotic decays of the Higgs boson using 13 TeV pp collisions with the ATLAS detector," `arXiv:2209.01029 [hep-ex]`.

[76] CMS Collaboration, "Search for displaced photons using conversions at 8 TeV," Tech. Rep. CMS-PAS-EXO-14-017, CERN, Geneva, 2015. `http://cds.cern.ch/record/2019862`.

[77] LHCb Collaboration, R. Aaij *et al.*, "Evidence for the rare decay $\Sigma^+ \to p\mu^+\mu^-$," *Phys. Rev. Lett.* **120** (2018) 221803, `arXiv:1712.08606 [hep-ex]`.

[78] ATLAS Collaboration, "ATLAS flavour-tagging algorithms for the LHC Run 2 pp collision dataset," `arXiv:2211.16345 [physics.data-an]`.

[79] CMS Collaboration, A. Tumasyan *et al.*, "A new calibration method for charm jet identification validated with proton-proton collision events at $\sqrt{s} = 13$ TeV," *JINST* **17** no. 03, (2022) P03014, `arXiv:2111.03027 [hep-ex]`.

[80] ATLAS Collaboration, G. Aad *et al.*, "Measurement of the $t\bar{t}$ production cross-section in the lepton+jets channel at $\sqrt{s} = 13$ TeV with the ATLAS experiment," *Phys. Lett. B* **810** (2020) 135797, `arXiv:2006.13076 [hep-ex]`.

[81] CMS Collaboration, A. Tumasyan *et al.*, "Measurement of differential $t\bar{t}$ production cross sections in the full kinematic range using lepton+jets events from proton-proton collisions at $\sqrt{s} = 13$ TeV," *Phys. Rev. D* **104** no. 9, (2021) 092013, `arXiv:2108.02803 [hep-ex]`.

[82] L. Gladilin, "Fragmentation fractions of c and b quarks into charmed hadrons at LEP," *Eur. Phys. J.* **C75** (2015) 19, `arXiv:1404.3888 [hep-ex]`.

[83] M. Lisovyi, A. Verbytskyi, and O. Zenaiev, "Combined analysis of charm-quark fragmentation-fraction measurements," *Eur. Phys. J.* **C76** (2016) 397, `arXiv:1509.01061 [hep-ex]`.

[84] B. A. Kniehl, G. Kramer, I. Schienbein, and H. Spiesberger, "$\Lambda_c^\pm$ production in pp collisions with a new fragmentation function," *Phys. Rev. D* **101** no. 11, (2020) 114021, `arXiv:2004.04213 [hep-ph]`.

[85] Particle Data Group, M. Tanabashi *et al.*, "Review of Particle Physics," *Phys. Rev. D* **98** no. 3, (2018) 030001.