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The strange charm of hyperons

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Abstract. In these proceedings, the merits of hyperons as a diagnostic tool will be outlined. Hyperons shed light on some of the most challenging problems of contemporary physics: the strong interaction in the confinement domain and the matter-antimatter asymmetry of the Universe. Recent progress will be reviewed and future prospects at world-wide facilities will be summarised.

1. Introduction
The Standard Model (SM) of particle physics describes the elementary quarks and gluons and their interactions, mediated by gauge bosons. The theory of Quantum ChromoDynamics (QCD), an inherent part of the SM, has been successful in describing the strong interaction between colour charged quarks and gluons at short distances. At this scale, the coupling strength \( \alpha_s \) between the quarks and gluons is sufficiently so small that they act as free particles. This phenomenon emerges as a consequence of QCD and is referred to as asymptotic freedom [1]. As the distance increases, the coupling \( \alpha_s \) grows and hence also the potential energy. For instance, if one tries to separate a quark and an anti-quark, the potential energy will at some point be large enough to create a new quark-antiquark pair. As a consequence, quarks cannot be observed as free particles but only confined into colour neutral hadrons, e.g. mesons (\( q\bar{q} \)) or baryons (\( qqq \)). This empirically well-established phenomenon is referred to as confinement and has, in contrast to asymptotic freedom, not yet been rigorously shown to be a consequence of QCD. To understand QCD in the confinement domain is one of the most challenging problems in contemporary physics.

The second problem addressed here is the matter-antimatter asymmetry: According to today’s paradigm, equal amounts of matter and antimatter were created in the Big Bang. However, according to all observations, our visible Universe consists almost purely of matter. Where did the antimatter go? The dynamical enrichment of matter with respect to antimatter is called Baryogenesis [2]. It is only possible if the following criteria are fulfilled: i) processes exist which violate baryon number conservation ii) there are reactions in which charge conjugation (C) and charge conjugation and parity (CP) symmetry are violated and iii) the processes in i) and ii) occurred outside thermal equilibrium. The CP violation allowed by the SM is very small, and any observation beyond this amount indicates physics beyond the Standard Model.

These two problems both address the foundations of physics and provide two independent angles to the SM and physics beyond it. QCD in the confinement domain represents the Low Energy Frontier whereas the search for CP symmetry belongs to the High Precision Frontier. These two frontiers of the SM are complementary to the High Energy Frontier that is extensively studied at the LHC at CERN.
2. Hyperons
Confinement and the matter-antimatter asymmetry may seem relatively different from a theoretical point of view. However, from an experimentalist’s perspective, they are connected by a common diagnostic tool: hyperons. Hyperons are similar to protons, but whereas protons only consist of light up- and down-quarks, hyperons contain one or several heavier quarks, e.g. strange or charm.

The scale of processes involving hyperons is governed by the mass of the quarks in the system. The mass of the strange quark, \( m_s \approx 95 \text{ MeV} \), is close to the hadronization scale \( \Lambda_{QCD} \approx 200 \text{ MeV} \) which defines the confinement domain. By studying processes involving strange quarks we probe this challenging regime of QCD. The over ten times heavier charm quark, \( m_c \approx 1275 \text{ MeV} \), probes the energy domain just below the scale where perturbative QCD breaks down. Hyperons of different flavours can therefore provide a bridge between the well understood perturbative regime to the puzzling confinement domain.

The weak decays provide information that is not straightforward to access for nucleons. These decays are self-analysing, meaning the daughter particles from a hyperon decay are emitted according to the direction of the spin of the mother hyperon. This is illustrated for the two-body decay \( Y \to BM \) in Figure 1, where a spin 1/2 hyperon \( Y \) decays into a spin 1/2 baryon \( B \) and a pseudo-scalar meson \( M \). The angular distribution of \( B \) in the rest system of \( Y \) is given by

\[
W(\cos \theta_B) = \frac{1}{4\pi} (1 + \alpha P_y(\cos \theta_Y) \cos \theta_B).
\]

(1)

Here, \( P_y(\cos \theta_Y) \) is the polarisation with respect to some reference axis \( \hat{y} \) as a function of the \( Y \) scattering angle. \( P_y \) carries information about the production process and depends on the energy. The decay asymmetry \( \alpha \) is related to the interference between the parity violating and the parity conserving decay amplitudes, \( T_s \) and \( T_p \) [6]. Equation 1 demonstrates how the experimentally measurable decay angular distribution is related to quantities with physical meaning, i.e. \( P_y \) and \( \alpha \). This feature makes hyperons a powerful diagnostic tool.

![Figure 1](image.png)

**Figure 1.** The \( Y \to BM \) decay, with the spin direction of \( Y \) along the \( y \)-axis.

3. Hyperon Structure
The ElectroMagnetic Form Factors (EMFFs) are fundamental observables of the strong interaction. They describe the inner, dynamical structure of hadrons and quantify the deviation from point-like objects. Theoretical predictions of EMFFs can be made using e.g. Chiral Perturbation Theory [7, 8] or Lattice QCD [9].

EMFF’s can be space-like, studied in elastic electron-hadron scattering, or time-like. The space-like region provides an intuitive interpretation of the intrinsic structure of composite objects since it relates the electric form factor \( G_E \) and the magnetic form factor \( G_M \) to the charge and magnetisation densities, respectively [10, 3]. Unfortunately, the space-like region is hard to access experimentally for hyperons since they are unstable and hence unfeasible as beams or targets in electron-hyperon scattering experiments. Instead, time-like form factors constitute the most viable structure observables for hyperons [11]. The experimentally accessible time-like form factors are related to the more intuitive space-like form factors by dispersion relations. In the time-like region, the EMFFs can be complex with a relative phase. This phase reflects the existence of intermediate states whose amplitudes interfere. A non-zero phase
implies a polarising effect on the final state hyperons, even if the initial state is unpolarised [12]. Analyticity requires that at \(|q^2| \rightarrow \infty\), the space-like form factors should equal the corresponding time-like form factors. Since the space-like form factors are real, the phase must go to zero for large \(q^2\). By measuring the phase at different \(q^2\), the scale at which the hyperon time-like EMFFs approach the space-like can be established. The corresponding scale for nucleons, where the phase is less straightforward to measure, can be obtained by comparing the measured values of the time-like and space-like form factors, since both regions are experimentally accessible for nucleons. Hence, phase measurements provide a unique tool to directly compare nucleon and hyperon EMFFs beyond simple cross section measurements.

The time-like region can be further divided into two distinct parts with respect to the momentum transfer squared, \(q^2\):

- The high-\(q^2\) part, explored when an \(e^+e^-\) pair annihilates to form a hyperon-antihyperon pair \((e^+e^- \rightarrow Y_1Y_2, \text{see the right-most part of Figure 2})\). This region covers momentum transfers larger than the sum of the masses of the produced hyperons \((q^2 > (m_{Y1} + m_{Y2})^2)\).
- The low-\(q^2\) part, probed in hyperon Dalitz decays \((Y_1 \rightarrow Y_2 e^+e^-, \text{shown to the right of the y-axis in Figure 2})\) and covering momentum transfers below the difference in mass between the hyperons \((q^2 < (m_{Y1} - m_{Y2})^2)\).

\[ \begin{align*}
    \text{Space-like} & \quad e^-B \rightarrow e^-B \\
    \text{Low-}q^2 & \quad B_1 \rightarrow B_2 e^+e^- \\
    \text{unphysical region} & \quad pp \rightarrow e^+e^-\pi^0 \\
    \text{High-}q^2 & \quad B^+B^- \rightarrow e^+e^- \\
\end{align*} \]

\(q^2 = 0\) \quad \(q^2 = (m_{B1} - m_{B2})^2\) \quad \(q^2 = (m_{B1} + m_{B2})^2\)

\(B \leftrightarrow \bar{B}\)

**Figure 2.** Processes for extracting EMFF in the space-like (left) and time-like (right) region. The low-\(q^2\) \((4m_e^2 < q^2 < (M_{B1} - M_{B2})^2)\) part of the time-like region is studied by Dalitz decays, the unphysical region \((4m_e^2 < q^2 < (M_{B1} + M_{B2})^2))\) by \(pp \rightarrow \ell^+\ell^-\pi^0\) and the high-\(q^2\) region \((q^2 > (M_{B1} + M_{B2})^2))\) by \(B\bar{B} \leftrightarrow e^+e^-\). Note that the unphysical region is only accessible for protons.

The different \(q^2\) regions with their corresponding form factors and the processes where they are accessed, are shown in Fig. 2.

So far, only a few measurements of hyperon form factors exist and they are all in the high-\(q^2\) region. Cross section measurements of the \(e^+e^- \rightarrow YY\) process were studied for different hyperons by BaBar [14], CLEO-c [15] and BESIII [16] but the data samples were too small to separate the electric and the magnetic form factors \(|G_E|\) and \(|G_M|\) with any conclusive precision. In a recent measurement from BESIII, \(|G_E|\) and \(|G_M|\) of the \(\Lambda\) hyperon were successfully separated for the first time. Furthermore, a first measurement of the relative phase was measured it was found to be significantly different from zero [17]. Some information about the structure of \(\Lambda_c^+\) has been obtained by measurement by Belle [18] and BESIII [19].

The high-\(q^2\) region can be further explored by BESIII (strange and single charm hyperons) and Belle II (primarily charmed hyperons). In particular, if sufficiently large data samples are
collected at strategic off-resonance energies, the $q^2$ dependence of the phase could be obtained. Furthermore, the FAIR Phase 0 experiment PANDA@HADES enable pioneering measurements in the low-$q^2$ region through hyperon Dalitz decays [20].

4. Hyperon Decays

In the past, it was believed that CP symmetry is exact, i.e. the laws of Nature are the same for matter and antimatter. Indeed, this seems to be true for strong and electromagnetic interactions. However, in weak interaction, CP violation is possible by the Cabibbo-Kobayashi-Maskawa mechanism [21, 22], now an inherent part of the SM. Numerous CP violating effects in $K_0$ and $B$ meson decays have been found by BaBar, Belle and at Fermilab and CERN [23]. However, the only indication of CP violation in a baryon decay has been observed very recently by the LHCb collaboration [24]. So far, all observed violations of CP symmetry are within the predictions from the SM, and are too small to explain the observed matter-antimatter asymmetry of the Universe. As a consequence, baryogenesis requires physics beyond the Standard Model [25].

Hyperon-antihyperon ($Y\bar{Y}$) production from, e.g. $p\bar{p}$ or $e^+e^-$ annihilations provide a clean environment for CP tests since there can be no mixing of the $Y\bar{Y}$ final state. Two-body hyperon decays are particularly convenient since it provides well-defined CP-odd observables related to the decay pattern of the hyperon and the antihyperon. CP conservation means that particles and antiparticles decay in the same way. This means that for a hyperon, the $\alpha$ in Eq. 1 should be the same as the $-\bar{\alpha}$ of the corresponding antihyperon. Defining the asymmetry

$$A_{CP} = \frac{\alpha + \bar{\alpha}}{\alpha - \bar{\alpha}},$$

a non-zero value indicates CP violation. In such decays, Super Symmetry (SuSy) [26] predicts CP violating effects that are one to two orders of magnitudes larger than in the SM [27]. On the experimental side, the most precise CP test in the strange sector so far is provided by the HyperCP collaboration in the study of $\Xi^-$ and $\Xi^+$ decay chains. The result was found to be consistent with CP conservation with a precision of $10^{-4}$ [28].

The BESIII collaboration has recently measured the corresponding quantity for the $\Lambda$ hyperon. An exclusive event selection of the full final state enabled a multi-dimensional, model-independent fit method. This resulted in the most precise test of CP symmetry in $\Lambda$ decays so far [29].

Further tests of CP violation in baryon decays can be undertaken at LHCb at CERN, Belle II at SuperKEKB, BESIII at BEPC-II and the future PANDA experiment at FAIR. The optimal CP experiment should fulfill the following criteria:

(i) Very large data rates (high statistical precision).
(ii) Low background.
(iii) Exclusive event reconstruction.
(iv) Symmetric particle- and antiparticle detection conditions.
(v) Known or parameterizable production mechanism.

In principle, LHCb fulfills i)-iv) whereas Belle II and BESIII fulfills ii)-v). PANDA is expected to fulfill all criteria once it reaches full luminosity [30].

5. Summary

Hyperons provide a powerful diagnostic tool to study the strong interaction in the confinement domain as well as the matter-antimatter asymmetry of the Universe. This is largely due to their self-analysing decays which gives straight-forward access to spin observables. In particular, spin observables reveal the electromagnetic structure in the time-like region. Furthermore, they are
sensitive to CP violation. Existing and future facilities world wide can provide important pieces to some of the most challenging puzzles in modern physics. With this, I would like to encourage the young participants of this conference to stay tuned or even join the efforts in hyperon physics.

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