Semileptonic decays of hyperons at the BESIII experiment

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Abstract. Semileptonic hyperon decays offer an independent and theoretically well-controlled access to the Cabibbo–Kobayashi–Maskawa matrix element $|V_{us}|$, complementary to the determinations from kaon and τ decays that presently show mutual tensions. Using the world's largest sample of 10^{10} J/ψ events collected by the BESIII detector, hyperon–antihyperon pairs are produced with transverse polarization and spin correlations, which can be exploited in a modular description of the complete production-and-decay chain. This approach recovers the kinematic information lost with the undetected neutrino and provides a strongly enhanced single-event sensitivity to the decay form factors. Recent results are reviewed: the first measurements of the absolute branching fractions of $\Lambda \to pe^-\bar{\nu}_e$ and $\Xi^- \to \Lambda e^-\bar{\nu}_e$, the determination of the axial-vector, weak-magnetism and – for the first time – weak-electricity couplings in Λ β decay, extraction of $|V_{us}|$, a lepton-flavour-universality test in $\Lambda \to p\mu^-\bar{\nu}_\mu$, and improved upper limits on decays violating SU(3) symmetry or the $\Delta S = \Delta Q$ rule.

1 Introduction

Semileptonic decays have been a central tool of weak-interaction physics for more than ninety years [1, 2]. The observation of semileptonic decays of strange mesons and baryons, together with the discovery of the SU(3) flavour symmetry of hadrons, led to the Cabibbo theory [3], which describes these transitions with a small number of parameters and predicts the elements of the Cabibbo–Kobayashi–Maskawa (CKM) matrix. Testing the unitarity of that matrix therefore probes the flavour structure of the Standard Model (SM).

The element $|V_{us}|$ is currently determined with subpercent precision from semileptonic and leptonic decays of K meson, $|V_{us}| = 0.22431 \pm 0.00085$ [4], and from inclusive τ decays, $|V_{us}| = 0.2207 \pm 0.0014$ [5]. These two results are mutually inconsistent and both lie below the value $|V_{us}| = 0.22799 \pm 0.00137$ [4] implied by first-row CKM matrix unitarity. An independent determination with a different set of theoretical inputs is therefore highly desirable.

Semileptonic hyperon decays (SLHDs), $Y_1 \to Y_2\ell^-\bar{\nu}_\ell$, provide an independent probe with a different theoretical input. Their branching fraction can be written as an expansion in the small parameter $\beta = (M_1 - M_2)/M_1$ with the initial and final baryon masses ($\beta \simeq 0.159$ for $\Lambda \to p\ell^-\bar{\nu}_\ell$) [3, 6],

$$\begin{aligned}\mathcal{B}_{\rm SLHD} = \frac{\tau_{Y_1}}{\hbar} G_F^2 (1+\delta_{\rm RC}) \frac{\beta^5 M_1^5}{60\pi^3} |V_{us}|^2 \\ \times \Big[(1-\tfrac{3}{2}\beta)(f_1^2+3g_1^2) - 4\beta g_1 g_2 \\ + \tfrac{2}{7}\beta^2 \mathcal{F}_2 + O(\beta^3)\Big],\end{aligned} \quad (1)$$

where $\mathcal{F}_2 = 3f_1^2 + 3f_1f_2 + 2f_2^2 + 6g_1^2 + 6g_2^2 + 21g_1g_2$, τ_{Y_1} is the initial hyperon lifetime, G_F is the weak decay constant, $\delta_{\rm RC}$ is the radiative correction, and $f_i \equiv f_i(q^2)$ and $g_i \equiv g_i(q^2)$ are the vector and axial-vector form factors (FFs), respectively[1]. Neglecting $O(\beta^3)$ terms, the q^2 dependence of the FFs and the second-class current g_2, Eq. (1) offers two routes to measure $|V_{us}|$: (i) from the measured $\mathcal{B}$, τ_{Y_1} and the ratio of FFs together with a theoretical value of f_1 vector FF as a normalization; or (ii) from the measured $\mathcal{B}$ and τ_{Y_1}, while all FFs taken from theory or calculated by lattice Quantum Chromodynamics (QCD). In contrast to the semileptonic K decays, the leading SU(3)-breaking corrections to f_1 are of second order, which makes the baryon channels theoretically attractive. Calculated more than three decades ago, the hyperon average, $|V_{us}| = 0.2250 \pm 0.0027$ [6], is statistically limited, where the single channel $\Lambda \to pe^-\bar{\nu}_e$ yields $|V_{us}| = 0.2224 \pm 0.0034$ [6].

2 Modular method

The hadronic matrix element of the weak charged current for a $1/2^+ \to 1/2^+$ transition is parametrised by six FFs [7],

$$\begin{aligned}\langle Y_2(p_2)|J_\mu^{V+A}|Y_1(p_1)\rangle = \bar{u}(p_2)\Big[\gamma_\mu(f_1+g_1\gamma_5) \\ + \frac{i\sigma_{\mu\nu}q^\nu}{M_1}(f_2+g_2\gamma_5) \\ + \frac{q^\mu}{M_1}(f_3+g_3\gamma_5)\Big]u(p_1),\end{aligned} \quad (2)$$

with transfer momentum $q_\mu = (p_1 - p_2)_\mu$. For electron modes the induced scalar f_3 and pseudoscalar g_3 FFs

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[1]Throughout this paper, $f_i \equiv f_i(q^2 = 0)$ and $g_i \equiv g_i(q^2 = 0)$ are implied, unless explicitly noted.

are suppressed by $O(m_e^2/2q^2)$ and can be neglected, so that the decay is characterised by the axial-vector, weak-magnetism and weak-electricity couplings

$$g_{av}(0) = \frac{g_1(0)}{f_1(0)}, \quad g_w(0) = \frac{f_2(0)}{f_1(0)}, \quad g_{av2}(0) = \frac{g_2(0)}{f_1(0)}. \quad (3)$$

The six FFs are equivalently expressed through three vector and three axial-vector helicity amplitudes $H^{V,A}_{\lambda_2,\lambda_W}$, which enter the hadronic tensor bilinearly. Their q^2 dependence is conventionally parametrised by a dipole expansion, $F_i(q^2) = F_i(0)[1 + r_i q^2 + \dots]$ with radii $r^{V,A} = 2/m^2_{V,A}$ and the vector mass $m_V = m_{K^*(892)}$, the axial-vector mass $m_A = m_{K^*(1270)}$ for $|\Delta S| = 1$ transitions. Over the small q^2 range accessible in hyperon β decays this dependence is a percent-level effect.

At an e^+e^- collider operating at the J/ψ resonance the reaction $e^+e^- \to J/\psi \to Y_1\bar{Y}_1$ produces a spin-entangled baryon–antibaryon pair whose spin-density matrix, $\rho_{1/2,\overline{1/2}} = \frac{1}{4}\sum_{\mu\bar{\nu}} C_{\mu\bar{\nu}} \sigma^{Y_1}_{\mu} \otimes \sigma^{\bar{Y}_1}_{\bar{\nu}}$, is fully determined by the angular-distribution parameter α_ψ and the relative phase $\Delta\Phi$ between the two helicity amplitudes [8]. The matrix $C_{\mu\bar{\nu}}$ contains both the transverse polarization of the (anti)hyperon, $\propto \beta_\psi = \sqrt{1-\alpha_\psi^2}\sin\Delta\Phi$, and the spin-correlation terms.

In the modular approach of Ref. [9] the transition of the initial hyperon to the final baryon is described by $\sigma^{Y_1}_{\mu} \to \frac{3(q^2-m_\ell^2)}{4\pi^3}\sum_\nu \mathcal{B}_{\mu\nu}\sigma^{Y_2}_{\nu}$, with $\mathcal{B}_{\mu\nu} = \sum_\kappa \mathcal{R}_{\mu\kappa}(\Omega_2)\, b_{\kappa\nu}(q^2, \Omega_\ell)$. Here $\mathcal{R}_{\mu\kappa}$ is a 4×4 rotation matrix, describing the angular distribution of final baryon in the initial hyperon rest frame, and the coefficients $b_{\kappa\nu}$, determining the transition from initial to final baryon and the angular distribution of the lepton pair. The decay matrix $b_{\kappa\nu}$ can be reduce to the constant matrix $a_{\kappa\nu}$ which is built from the asymmetry parameters $(\alpha_D, \beta_D, \gamma_D)$ in the case of a two-body non-leptonic decay $Y_1 \to Y_2\pi$ [8, 10]. Chaining the production and the decay modules gives the joint angular distribution of the full decay chain,

$$\mathcal{W}(\boldsymbol{\xi}, \boldsymbol{\omega}) = \sum_{\mu,\bar{\nu}=0}^{3} C_{\mu\bar{\nu}} \sum_{\kappa,\bar{\kappa}=0}^{3} \mathcal{R}_{\mu\kappa} b^{Y_1}_{\kappa 0} \mathcal{R}_{\bar{\nu}\bar{\kappa}} a^{\bar{Y}_1}_{\bar{\kappa}0}, \quad (4)$$

where $\boldsymbol{\xi} = (\alpha_\psi, \Delta\Phi, g_{av}, g_w, g_{av2}, \alpha_{\bar{Y}_1})$ is the set of parameters to be determined and $\boldsymbol{\omega}$ collects the helicity angles and q^2. Because Eq. (4) retains the polarization and the entanglement of the $Y_1\bar{Y}_1$ pair, the information carried by the undetected neutrino is partly recovered through the spin of the tagged antihyperon, which dramatically improves the sensitivity per event.

3 The BESIII experiment

BESIII [11] is a general-purpose magnetic spectrometer at the BEPCII double-ring e^+e^- collider [12], operating in the centre-of-mass energy range $2.0 < E_{\rm CMS} < 4.95$ GeV with a peak luminosity of 10^{33} cm^{-2}s^{-1}. It covers 93% of the 4π solid angle inside a 1.0 T superconducting solenoid. The momentum resolution is 0.5% at 1 GeV/c, the dE/dx resolution is 6% for electrons and the time-of-flight resolution is 68 (65) ps in the barrel (end cap) region. Since 2009 BESIII has accumulated $N_{J/\psi} \sim 10^{10}$ and $N_{\psi(2S)} \sim 3\cdot10^9$ events, the largest such samples in the world. About one in a thousand J/ψ decays yields a $\Lambda\bar{\Lambda}$ pair, making BESIII a uniquely clean hyperon factory.

4 Experimental results

4.1 $\Lambda \to pe^-\bar{\nu}_e$ decay

The decay chain $e^+e^- \to J/\psi \to \Lambda\bar{\Lambda} \to (pe^-\bar{\nu}_e)(\bar{p}\pi^+) +$ c.c. [13] is reconstructed with a double-tag technique: the non-leptonic decay of one (anti)hyperon tags the event, while the signal side is identified through the missing-mass-like variable $U_{\rm miss} = E_{\rm miss} - c\cdot|\vec{p}_{\rm miss}|$, in which $E_{\rm miss}$ and $\vec{p}_{\rm miss}$ denote the missing energy and momentum of the semileptonic decay, respectively. Within $U_{\rm miss} \in (-0.02, 0.02)$ GeV, a total number of signal candidates is 1791 ± 47 obtained with a selection efficiency of $\varepsilon_{\rm sig} = (8.58 \pm 0.01)\%$, where the corresponding fit is shown in Fig. 1.

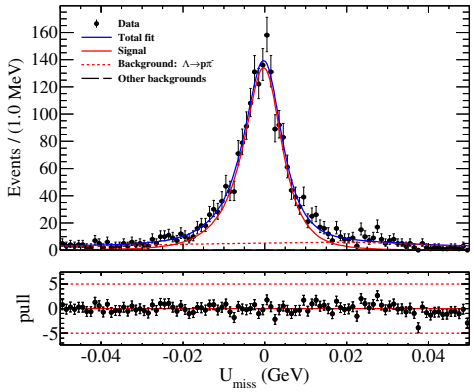


Figure 1. The $U_{\rm miss}$ distribution for the combined $\Lambda \to pe^-\bar{\nu}_e$ and $\bar{\Lambda} \to \bar{p}e^+\nu_e$ samples. The points with error bars represent the observed number of events in each bin, with statistical uncertainties. The solid blue line shows the total fit, which includes the signal candidates (solid red line), the dominant background (dashed red line) and the other background contributions (long-dashed black line).

The first measurement of the *absolute* branching fraction is performed:

$$\mathcal{B}(\Lambda \to pe^-\bar{\nu}_e) = (8.16 \pm 0.22 \pm 0.15)\cdot10^{-4}, \quad (5)$$

where the first uncertainty is statistical and the second systematic, in agreement with the world average value, $(8.34 \pm 0.14)\cdot10^{-4}$ [4].

A simultaneous fit of the joint angular distribution of Eq. (4), with α_ψ, $\Delta\Phi$ and $\alpha_{\Lambda,\bar{\Lambda}}$ fixed to the values of Ref. [14], yields the couplings listed in Table 1, both under the assumption $g_2 = 0$ and float it. The axial-vector coupling is in good agreement with the world average, the weak-magnetism coupling is measured with a precision similar to the best previous determination, and the weak-electricity coupling g_{av2} – which vanishes in the exact SU(3) limit and would signal a second-class current

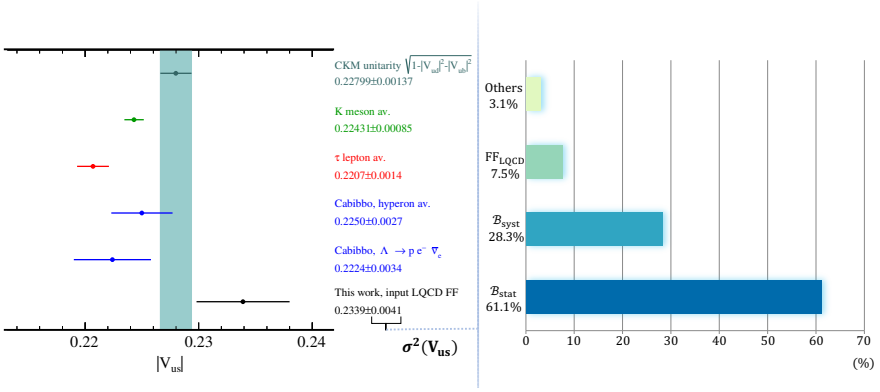


Figure 2. (left) The first-row CKM unitarity constraint and K average are from [4]. The τ average is from Ref. [5]. The two hyperon results were evaluated by Cabibbo [3, 6]. (right) The contributing sources to the $|V_{us}|$ uncertainty, in terms of the variance [13].

if found to be non-zero – is determined for the first time. The power of the method is best illustrated by a comparison with the Fermilab measurement [15]: $1.8 \cdot 10^3$ $\Lambda\beta$ decays at BESIII give $\sigma(\langle g_{av}\rangle) = 0.049$, whereas $37 \cdot 10^3$ events were needed there to reach $\sigma(g_{av}) = 0.020$. Although Fermilab dataset is approximately 20 times larger than BESIII, a comparable precision for g_w is achieved, whereas the uncertainty on g_{av} is only about a factor of 2.5 larger and, most notably, the g_{av2} is determined for the first time, a parameter previously inaccessible.

Table 1. Form-factor couplings extracted from the joint angular distribution [13], compared with previous results. The superscripts − and + refer to Λ and $\bar{\Lambda}$ decays; the averages assume $g^-_{av_i} = -g^+_{av_i}$ and $g^-_w = g^+_w$.

	Observable	This work	Previous
$g_2 = 0$	g^-_{av}	$0.742^{+0.075}_{-0.057} \pm 0.009$	0.718 ± 0.015 [4]
	g^+_{av}	$-0.706^{+0.073}_{-0.069} \pm 0.014$	–
	$\langle g_{av}\rangle$	$0.729^{+0.048}_{-0.047} \pm 0.007$	–
	g^-_w	$0.93 \pm 0.51 \pm 0.17$	0.15 ± 0.30 [15]
	g^+_w	$0.89 \pm 0.49 \pm 0.20$	–
	$\langle g_w\rangle$	$0.89 \pm 0.35 \pm 0.14$	–
$g_2 \neq 0$	$\langle g_{av}\rangle$	$0.706^{+0.089}_{-0.086} \pm 0.026$	–
	$\langle g_w\rangle$	$0.77^{+0.53}_{-0.49} \pm 0.14$	–
	$\langle g_{av2}\rangle$	$-0.19^{+0.65}_{-0.63} \pm 0.18$	–

Two determinations of $|V_{us}|$ value are performed. Assuming the exact SU(3) symmetry, $f_1 = -\sqrt{3/2}$ [6], and using the measured branching fraction and g_{av},

$$|V_{us}|_{\mathrm{SU(3)}} = 0.2194 \pm 0.0036_{\mathcal{B}} \pm 0.0087_{\mathrm{FF}} \pm 0.0004_{\tau_\Lambda} \pm 0.0005_{\mathrm{RC}}, \quad (6)$$

where the uncertainty comes from the measured branching fraction, FFs and Λ lifetime, and the theoretical calculation of the radiative corrections [16], respectively. The result is 0.9σ below the unitarity expectation. Alternatively, taking the FF values from the recent lattice-QCD calculation [17],

$$|V_{us}|_{\mathrm{LQCD}} = 0.2339 \pm 0.0038_{\mathcal{B}} \pm 0.0004_{\tau_\Lambda} \pm 0.0006_{\mathrm{RC}} \pm 0.0011_{\mathrm{LQCD}}, \quad (7)$$

i.e. 1.4σ above unitarity. This model-independent result, shown together with the other determinations in Fig. 2, is dominated by the experimental uncertainty on the branching fraction (61.1% statistical and 28.3% systematic of the total variance), while the lattice input contributes only about 7.5%. A larger size of data sample will therefore directly translate into an improved $|V_{us}|$.

The two numbers straddle the unitarity band and differ from each other by about 1.4σ, which quantifies the size of the SU(3)-breaking correction to f_1 implicitly assumed in the first approach. Since the second determination no longer relies on the measured form factors, its precision is limited almost entirely by the size of the data sample: with the statistics expected after the BEPCII crab waist (CW) upgrade, and with lattice input at the present level of accuracy, a sub-percent determination of $|V_{us}|$ from $\Lambda\,\beta$ decay alone comes within reach.

4.2 $\Xi^- \to \Lambda e^- \bar{\nu}_e$

The same strategy applied to $e^+e^- \to \Xi^-\bar{\Xi}^+ \to (\Lambda e^-\bar{\nu}_e)(\bar{\Lambda}\pi^+)$ + c.c. gives the selected number of signal candidates $\simeq 111 \pm 13$ with the signal efficiency $(3.29 \pm 0.03)\%$ in $U_{\mathrm{miss}} \in (-0.03, 0.02)$ GeV [18]. This is allowed to measure the *absolute* branching fraction for the first time,

$$\mathcal{B}(\Xi^- \to \Lambda e^-\bar{\nu}_e) = (3.60 \pm 0.40 \pm 0.10) \cdot 10^{-4}. \quad (8)$$

The obtained value deviates by 3.9σ from the world average value [4, 19], as illustrated in Fig. 3. An eleven-dimensional angular analysis, built on the same modular description, yields the axial-vector coupling $g_{av} = 0.18 \pm 0.07 \pm 0.02$ to be compared with $\sigma(g_{av}) = 0.05$ obtained at the CERN SPS experiment from $\sim 2 \cdot 10^3$ $\Xi\beta$ decays [19]. A comparable precision with roughly 5% of the statistics is observed. In the SU(3)-symmetry limit this translates into the axial charge $g^H_A = 0.22 \pm 0.08 \pm 0.02$, which together with the branching fraction can be confronted with Cabibbo-model fits and with baryon chiral perturbation theory, as shown in Fig. 3.

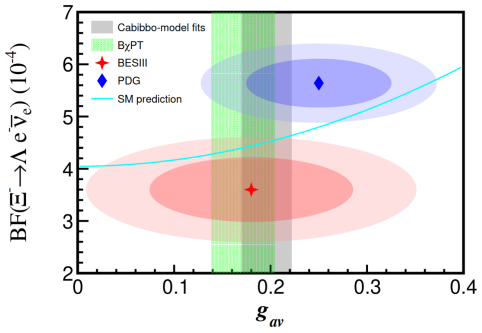


Figure 3. Branching fraction versus g_{av} of the $\Xi^- \to \Lambda e^- \bar{\nu}_e$ decay. The red star denotes the results measured by BESIII and the red contours correspond to the 68%/95% confidence level of the results. The blue diamond represents the PDG values and the blue contours correspond to the 68%/95% confidence level of the PDG values [4]. The cyan line shows the predicted $\mathcal{B}$ as a function of g_{av} [20]. The grey box shows g_{av} from the Cabibbo model global fit [6]. The green box shows the g_{av} pre- diction from baryon chiral perturbation theory (BχPT) [21].

4.3 Other absolute branching fractions and searches

Using the same J/ψ sample, the first absolute measurement of $\mathcal{B}(\Lambda \to p\mu^-\bar{\nu}_\mu) = (1.48 \pm 0.21 \pm 0.08) \cdot 10^{-4}$ is obtained from 64 ± 9 signal candidates, improving the precision by 30% [22]. The resulting lepton-flavour-universality ratio $R^{\mu e} \equiv \Gamma(\Lambda \to p\mu^-\bar{\nu}_\mu)/\Gamma(\Lambda \to pe^-\bar{\nu}_e) = 0.178 \pm 0.028$ agrees with the lattice-QCD prediction $R^{\mu e}_{\rm SM} = 0.16638 \pm 0.00020$ [17].

For $\Sigma^+ \to \Lambda e^+ \nu_e$ decay, selected 15 ± 7 signal events give $\mathcal{B} = (2.93 \pm 0.74 \pm 0.13) \cdot 10^{-5}$. The obtained result is improved the precision by 25% [23]. Combined with $\mathcal{B}(\Sigma^- \to \Lambda e^- \bar{\nu}_e)$ and the $\Sigma^\pm$ lifetimes [4], the ratio $R = \Gamma(\Sigma^- \to \Lambda e^- \bar{\nu}_e)/\Gamma(\Sigma^+ \to \Lambda e^+ \nu_e) = 1.06 \pm 0.28$ differs by 1.8σ from the expectation in the absence of second-class currents.

Two decays forbidden at leading order have been searched for. The SU(3)-violating mode $\Xi^- \to \Xi^0 e^- \bar{\nu}_e$ is constrained to $\mathcal{B} < 2.59 \cdot 10^{-4}$ at 90% confidence level [24], and the $\Delta S = \Delta Q$ violating decay $\Xi^0 \to \Sigma^- e^+ \nu_e$ to $\mathcal{B} < 1.6 \cdot 10^{-4}$ [25]. Both limits are an order of magnitude more stringent than the previous ones.

5 Summary and outlook

With 10^{10} J/ψ events, BESIII has measured for the first time the absolute branching fractions of the Λ and Ξ^- semileptonic decays, determined the axial-vector couplings $g_{av}^{\Lambda,\Xi}$ and the weak-magnetism coupling g_w^Λ, and performed the first measurement of the weak-electricity coupling g_{av2} in Λ β decay. The combination of experimental input with lattice-QCD form factors would allow to reach the $|V_{us}|$ sensitivity comparable to that of kaon decays.

The modular method [9] applies directly to other semileptonic decays, including those of heavier baryons. The BEPCII-CW upgrade will raise the peak luminosity from 10^{33} to 10^{34} cm^{-2}s^{-1}, and the physics programme outlined here can be extended at a future Super J/ψ Factory [26] and at Compressed Baryon Matter experiment at GSI/FAIR [27].

Acknowledgements. V.Batozskaya acknowledge a support from the Polish National Science Center through Grant No. 2025/58/E/ST2/00051.

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