

First measurement of the absolute branching fractions of Σ^+ nonleptonic decays and test of the $\Delta I = 1/2$ rule

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Based on $(10087 \pm 44) \times 10^6$ J/ψ events collected by the BESIII detector at the center-of-mass energy $\sqrt{s} = 3.097$ GeV, the first absolute measurement of the branching fractions for the decays $\Sigma^+ \rightarrow p\pi^0$ and $\Sigma^+ \rightarrow n\pi^+$ is performed. The branching fractions are determined to be $B_{\Sigma^+ \rightarrow p\pi^0} = (49.79 \pm 0.06 \pm 0.22)\%$ and $B_{\Sigma^+ \rightarrow n\pi^+} = (49.87 \pm 0.05 \pm 0.29)\%$, where the first uncertainties are statistical and the second systematic. Our results show significant deviations from the Particle Data Group values for both decays, with differences of 4.4σ for $\Sigma^+ \rightarrow p\pi^0$ and 3.4σ for $\Sigma^+ \rightarrow n\pi^+$. These measurements will play important roles in precise studies of the decay properties of strange, charmed, and beauty baryons with Σ^+ in the final states. Furthermore, the $\Delta I = 1/2$ rule is tested in nonleptonic $\Sigma^\pm$ decays. The observed results deviate from zero by more than 5σ , indicating the presence of the $\Delta I = 3/2$ transition amplitude in the Σ hyperon decays.

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The study of hyperons has long provided a unique window into the nonperturbative regime of the standard model (SM), where the weak decays of strange baryons serve as sensitive probes of hadronic structure and fundamental symmetries [1–9]. In recent years, both collider and fixed-target experiments have driven a renewed surge of interest in hyperon physics. In particular, the BESIII experiment has performed numerous studies of hyperon production and decay, exploiting quantum-entangled hyperon-antihyperon pairs produced in J/ψ and $\psi(3686)$ decays [10–24]. These developments demonstrate that precise experimental measurements of hyperon decays provide powerful probes of the interplay between weak and strong interactions in the nonperturbative regime of the SM.

Recently, the absolute branching fraction (BF) of $\Sigma^+ \rightarrow p\gamma$ ($B_{\Sigma^+ \rightarrow p\gamma}$) was measured for the first time using the double-tag method by BESIII [18], revealing a discrepancy of 4.2 standard deviations from the Particle Data Group (PDG) value [25]. Notably, this PDG value was not derived from a direct measurement of the absolute BF, but inferred by multiplying the BF of $\Sigma^+ \rightarrow p\pi^0$ ($B_{\Sigma^+ \rightarrow p\pi^0}$) with the ratio $B_{\Sigma^+ \rightarrow p\gamma}/B_{\Sigma^+ \rightarrow p\pi^0}$, which was averaged from several measurements conducted before 1995 [26–28]. Moreover, the PDG value of $B_{\Sigma^+ \rightarrow p\pi^0}$ itself was determined from

various relative measurements with missing systematic uncertainties. The significant discrepancy observed by BESIII then raises questions about the reliability of the current PDG value of $B_{\Sigma^+ \rightarrow p\pi^0}$, and a recent theoretical paper predicts a value for $B_{\Sigma^+ \rightarrow p\pi^0}$ that is 1.5σ below the PDG average [29], thereby highlighting the need for an independent and direct absolute measurement. Besides, the PDG value for the BF of $\Sigma^+ \rightarrow n\pi^+$ ($B_{\Sigma^+ \rightarrow n\pi^+}$) also relies solely on relative measurements, further calling for the absolute BF measurement of these decays. Precise measurements of these decay modes are essential for detailed studies of the decay properties of many other baryons—such as the $\Lambda(1405)$, $\Sigma(1385)^+$, and Λ_c , Ξ_c —that decay into final states involving Σ^+ .

Although isospin symmetry is explicitly broken in weak interactions, experiments have established a striking empirical pattern known as the $\Delta I = 1/2$ rule, which describes the predominance of transition amplitudes with a total isospin change of $1/2$ in nonleptonic strange-hadron decays [30,31]. This rule has been well verified in both kaon and hyperon systems. Lattice QCD calculations have provided a first-principles derivation of this enhancement in $K \rightarrow \pi\pi$ decays, demonstrating that the observed hierarchy between the $I = 1/2$ and $I = 3/2$ amplitudes originates from nonperturbative QCD dynamics [32]. However, recent observations of deviations from this rule in Ω^- and Λ hyperon decays [17,33] raise important questions about its universality. These developments motivate further experimental tests of the $\Delta I = 1/2$ rule in hyperon decays. In Σ hyperon decays, the $\Delta I = 1/2$ rule imposes specific constraints on the decay amplitudes [34]

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$$\mathcal{M}_{\Sigma^- \rightarrow n\pi^-} - \mathcal{M}_{\Sigma^+ \rightarrow n\pi^+} + \sqrt{2}\mathcal{M}_{\Sigma^+ \rightarrow p\pi^0} = 0, \quad (1)$$

where $\mathcal{M}$ represents the A or B amplitudes [34], corresponding to the parity-violating S -wave and parity-conserving P -wave components of these decays [25], respectively. The A and B (also the S -wave and P -wave) amplitudes can be extracted from the precisely measured BFs and the corresponding decay parameters (see Refs. [35–41] for details). With the updated A and B amplitudes of the Σ^+ nonleptonic decays, a new and stringent test of the $\Delta I = 1/2$ rule can be performed. Moreover, the extracted S -wave and P -wave amplitudes provide critical insights into the longstanding S -wave/ P -wave puzzle [42], and are indispensable for theoretical predictions of both CP violation in these decay modes [9] and the rare decays $\Sigma^+ \rightarrow p l^+ l^-$ ($l = e$ or μ) [43].

The large yield of quantum-entangled $\Sigma^+ \bar{\Sigma}^-$ pairs at BESIII [44] enables the first precise measurement of the absolute BFs of the dominant Σ^+ nonleptonic decays, $\Sigma^+ \rightarrow p\pi^0$ and $\Sigma^+ \rightarrow n\pi^+$, by employing a double-tag (DT) method [45]. The single-tag (ST) events of $\bar{\Sigma}^-$ hyperons are reconstructed via the decay $\bar{\Sigma}^- \rightarrow \bar{p}\pi^0$. The events where a signal candidate can be reconstructed from the particles recoiling against the ST $\bar{\Sigma}^-$ hyperons are called DT events. To improve the detection efficiencies, only the p and π^+ from Σ^+ decays are reconstructed on the signal side for the decay modes $\Sigma^+ \rightarrow p\pi^0$ and $\Sigma^+ \rightarrow n\pi^+$, respectively, whereas the π^0 and the neutron are not reconstructed (unless otherwise noted, the charge-conjugated decays are always implied). The BF of a signal decay is determined by

$$\mathcal{B}_{\text{sig}} = \frac{N_{\text{DT}} \epsilon_{\text{ST}}}{N_{\text{ST}} \epsilon_{\text{DT}}} = \frac{N_{\text{DT}}}{N_{\text{ST}} \epsilon_{\text{sig}}}, \quad (2)$$

where N_{ST} and N_{DT} are the ST and DT yields, respectively. The $\epsilon_{\text{sig}} = \epsilon_{\text{DT}}/\epsilon_{\text{ST}}$ is the signal efficiency in the presence of an ST $\bar{\Sigma}^-$ hyperon, with ϵ_{ST} and ϵ_{DT} denoting the ST and DT efficiencies.

The analysis presented in this Letter is based on a sample of $(10087 \pm 44) \times 10^6$ J/ψ events [46] collected with the BESIII detector at the BEPCII collider. Details about BEPCII and BESIII can be found in Refs. [47–52]. Simulated data samples produced with Geant4-based [53] Monte Carlo (MC) software, which includes the geometric description of the BESIII detector and the detector response, are used to determine detection efficiencies and estimate background contribution. The simulations model the beam energy spread and initial state radiation in the e^+e^- annihilations with the generator KKMC [54]. An inclusive MC sample of J/ψ resonance is produced, in which the known decay modes are modeled with EvtGen [55], and the remaining unknown decays are modeled with Lundcharm [56]. To determine the detection efficiencies, the signal MC samples, $J/\psi \rightarrow \Sigma^+(\rightarrow p\pi^0)\bar{\Sigma}^-(\rightarrow \bar{p}\pi^0)$ and

$J/\psi \rightarrow \Sigma^+(\rightarrow p\pi^0)\bar{\Sigma}^-(\rightarrow \bar{n}\pi^-) + \text{c.c.}$, are generated according to the angular distributions measured in Refs. [15,24]. In addition, a phase space MC sample of $J/\psi \rightarrow \Delta^+\bar{\Delta}^-$, $\Delta^+ \rightarrow \text{anything}$ is generated to study potential backgrounds, where the Δ^+ mass and width are fixed at the PDG value.

Charged tracks detected in the multilayer drift chamber (MDC) are required to be within a polar angle (θ) range of $|\cos\theta| < 0.93$, where θ is defined with respect to the z -axis, which is the symmetry axis of the MDC. For each track, the point of closest approach to the interaction point must be within 2 cm in the plane perpendicular to the beam direction and within 10 cm along the beam direction. Particle identification (PID) for charged tracks combines measurements of the specific ionization energy loss in the MDC (dE/dx) and the flight time in the time-of-flight system to form likelihoods $\mathcal{L}(h)$ ($h = p, K, \pi$) for various hadron h hypotheses. Charged tracks with $\mathcal{L}(p) > \mathcal{L}(K)$, $\mathcal{L}(p) > \mathcal{L}(\pi)$, and $\mathcal{L}(p) > 0.001$ are identified as protons, and those with $\mathcal{L}(\pi) > \mathcal{L}(K)$ are identified as pions.

The photons used to reconstruct the π^0 candidates are identified using showers in the electromagnetic calorimeter (EMC). The deposited energy of each shower must be more than 25 MeV in the barrel region ($|\cos\theta| < 0.80$) and more than 50 MeV in the end-cap region ($0.86 < |\cos\theta| < 0.92$). To exclude showers that originate from charged tracks, the angle subtended by the EMC shower and the position of the closest charged track at the EMC must be greater than 10 degrees (20 degrees if the track is antiproton), as measured from the interaction point. To suppress electronic noise and showers unrelated to the event, the difference between the EMC time of the photon candidate and the event start time is required to be within $[0, 700]$ ns. The π^0 candidates are formed by the $\gamma\gamma$ pairs, with the requirements that at least one photon comes from the barrel region and the invariant mass is within the range $[0.115, 0.150]$ GeV/ c^2 . A kinematic fit constraining the $\gamma\gamma$ invariant mass to the known π^0 mass [25] is performed, and the updated four-momentum is used in further analysis.

The ST $\bar{\Sigma}^-$ candidates are required to have at least one $\bar{p}$ and one π^0 . If there is more than one $\bar{p}\pi^0$ candidate, the one with the minimum $|M_{\bar{p}\pi^0} - m_{\bar{\Sigma}^-}|$ is retained for further analysis, where $m_{\bar{\Sigma}^-}$ is the known $\bar{\Sigma}^-$ mass [25]. The invariant mass of the retained $\bar{p}\pi^0$ pair is required to be within $[1.169, 1.205]$ GeV/ c^2 .

After applying the above selection, the ST yield is determined by performing an unbinned maximum likelihood fit to the recoil-mass spectrum of the reconstructed $\bar{\Sigma}^-$ candidate, shown in Fig. 1, and defined as

$$RM_{\bar{\Sigma}^-} = \sqrt{\frac{(E_{\text{cms}} - E_{\bar{p}\pi^0})^2}{c^4} - \frac{\vec{P}_{\bar{p}\pi^0}^2}{c^2}} + M_{\bar{p}\pi^0} - m_{\bar{\Sigma}^-}. \quad (3)$$

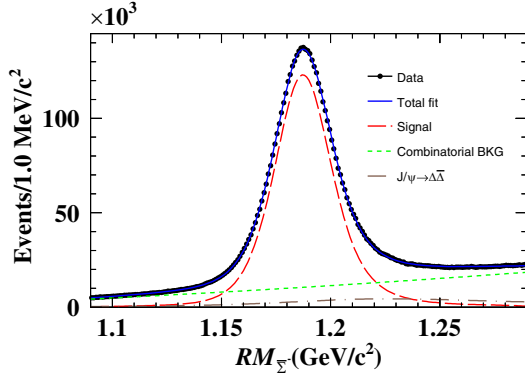


FIG. 1. Fit to the RM_{Σ^-} distribution for the ST sample. The dots with error bars are data, the blue solid line is the total fit, the red long-dashed line denotes the fitted signal shape, and the green short-dashed and brown dot-dashed lines represent the combinatorial background and $J/\psi \rightarrow \Delta^+ \bar{\Delta}^-$ shapes, respectively.

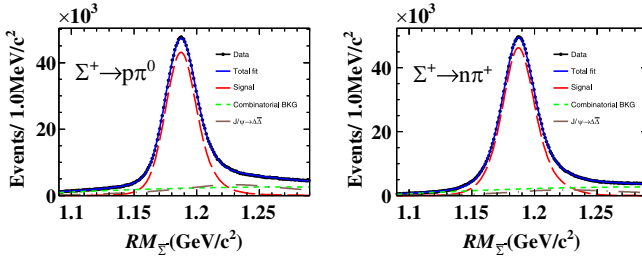


FIG. 2. Fit to the RM_{Σ^-} distributions for the DT $\bar{\Sigma}^- p$ (left) and $\bar{\Sigma}^- \pi^+$ (right) samples. The dots with error bars are data, the blue solid line is the total fit, the red long-dashed line denotes the fitted signal shape, and the green short-dashed and brown dot-dashed lines represent the combinatorial background and $J/\psi \rightarrow \Delta^+ \bar{\Delta}^-$ shapes, respectively.

Here, E_{cms} is the center-of-mass energy, while $E_{\bar{p}\pi^0}$ and $\vec{P}_{\bar{p}\pi^0}$ are the energy and momentum of the tagged $\bar{p}\pi^0$ in the J/ψ rest frame, respectively. The term $M_{\bar{p}\pi^0} - m_{\Sigma^-}$ is introduced to improve the recoil-mass resolution of $\bar{\Sigma}^-$. In the fit, the signal shape is described by the MC-simulated shape convolved with a Gaussian function, where the Gaussian function is used to compensate for the difference in the mass resolution between data and MC simulation. The background shape, which is dominated by combinatorial backgrounds and a broad peak from $J/\psi \rightarrow \Delta^+ \bar{\Delta}^-$, is described by the MC-simulated shape from $J/\psi \rightarrow \Delta^+ \bar{\Delta}^-$ plus a second-order Chebyshev polynomial. The ST yield is

determined to be 4504566 ± 3320 , with a corresponding efficiency of 41.66%, as listed in Table I.

The signal processes $\Sigma^+ \rightarrow p\pi^0$ and $\Sigma^+ \rightarrow n\pi^+$ are searched for in the remaining charged tracks on the recoil side of the ST $\bar{\Sigma}^-$ candidates. As aforementioned, only the charged tracks p and π^+ are reconstructed for the decays $\Sigma^+ \rightarrow p\pi^0$ and $\Sigma^+ \rightarrow n\pi^+$, respectively. To suppress background contributions, the number of additional charged tracks in the event is required to be zero. In the BF measurement of $\Sigma^+ \rightarrow p\pi^0$, if both Σ^+ and $\bar{\Sigma}^-$ can be reconstructed in one event, this event would be counted twice in the DT sample ($\Sigma^+ \bar{p}$ and $\bar{\Sigma}^- p$). To avoid double counting, only the combination with the tagged Σ that has the closest invariant mass to the Σ^+ known mass [25] is kept as a DT event for further study.

The recoil masses against the reconstructed $\bar{\Sigma}^- p$ ($\bar{\Sigma}^- \pi^+$), defined as

$$RM_{\bar{\Sigma}^- p(\pi)} = \sqrt{\frac{(E_{\text{cms}} - E_{\bar{p}\pi^0} - E_{p(\pi)})^2}{c^4} - \frac{(\vec{P}_{\bar{p}\pi^0} + \vec{P}_{p(\pi)})^2}{c^2}} + M_{\bar{p}\pi^0} - m_{\Sigma^-}, \quad (4)$$

accumulate around the invariant mass of the unreconstructed particle π^0 (n). Here, $E_{p(\pi)}$ and $\vec{P}_{p(\pi)}$ are the energy and momentum of the $p(\pi^+)$ in the J/ψ rest frame, respectively. The $RM_{\bar{\Sigma}^- p(\pi)}$ is used to suppress the background events by requiring it to lie within $[0.034, 0.231]$ ($[0.881, 0.997]$) GeV/c^2 , corresponding to $\pm 3\sigma$ around the known $\pi^0(n)$ mass, where σ denotes the resolution of the corresponding recoil mass, and the distribution of $RM_{\bar{\Sigma}^- p(\pi)}$ can be found in Ref. [35]. Then, the DT yield is extracted by performing an unbinned maximum likelihood fit using the same fitting strategy as described for the ST sample, shown in Fig. 2. The signal and background shapes are taken from the MC samples corresponding to the DT selection. The number of DT events of the $\bar{\Sigma}^- p(\bar{\Sigma}^- \pi^+)$ sample is determined to be 1437863 ± 1672 (1638422 ± 1780), with a corresponding DT efficiency of 26.71(30.38)%, as summarized in Table I.

Based on Eq. (2), the absolute BFs of $\Sigma^+ \rightarrow p\pi^0$ and $\Sigma^+ \rightarrow n\pi^+$ are determined to be $\mathcal{B}_{\Sigma^+ \rightarrow p\pi^0} = (49.79 \pm 0.06)\%$ and $\mathcal{B}_{\Sigma^+ \rightarrow n\pi^+} = (49.87 \pm 0.05)\%$, as listed in Table I. The uncertainties here are only statistical.

With the DT method, most systematic uncertainties associated with the ST selection cancel out. The sources

TABLE I. The ST yields (N_{ST}), ST efficiency (ϵ_{ST}), DT yields (N_{DT}), DT efficiency (ϵ_{DT}), and the absolute BFs of the two dominant Σ^+ decays, $\Sigma^+ \rightarrow p\pi^0$ and $\Sigma^+ \rightarrow n\pi^+$. The uncertainties are statistical only.

Decay mode	N_{ST}	ϵ_{ST} (%)	N_{DT}	ϵ_{DT} (%)	BF (%)
$\Sigma^+ \rightarrow p\pi^0$	4504566 ± 3320	41.66	1437863 ± 1672	26.71	49.79 ± 0.06
$\Sigma^+ \rightarrow n\pi^+$			1638422 ± 1780	30.38	49.87 ± 0.05

TABLE II. Relative systematic uncertainties of BF measurement in %.

Source	$\mathcal{B}_{\Sigma^+ \rightarrow p\pi^0}$	$\mathcal{B}_{\Sigma^+ \rightarrow n\pi^+}$
Proton/pion tracking	0.14	0.27
Proton/pion PID	0.09	0.33
Signal shape	0.18	0.26
Background shape	0.30	0.26
Background fluctuation of ST yields	0.06	0.06
DT peaking background	0.12	...
Misidentification of p/π	0.01	0.05
Requirement on $RM_{\bar{\Sigma}^- p}/M_{\bar{\Sigma}^- \pi^+}$	0.14	0.16
MC generator	0.05	0.04
MC statistics	0.04	0.03
Total	0.44	0.59

of the systematic uncertainties are summarized in Table II, and each contribution is discussed below.

The systematic uncertainties arising from the p, π^+ tracking, and PID efficiencies are estimated by a control sample of $J/\psi \rightarrow p\bar{p}\pi^+\pi^-$. The efficiency differences between data and MC simulation from the control samples are used to reweight the signal MC samples. The differences between the detection efficiencies with and without corrections are taken as the systematic uncertainties, which are 0.14% (0.09%) for $\mathcal{B}_{\Sigma^+ \rightarrow p\pi^0}$ measurement and 0.27% (0.33%) for $\mathcal{B}_{\Sigma^+ \rightarrow n\pi^+}$, corresponding to the tracking (PID) contributions.

The systematic uncertainties related to the ST and DT signal shapes of the $RM_{\bar{\Sigma}^-}$ distribution are estimated by varying the signal MC shape convolved with a Gaussian function in the fit model to the signal MC shape. The resulting changes in the BF's are taken as the systematic uncertainties, which are 0.18% and 0.26% for $\mathcal{B}_{\Sigma^+ \rightarrow p\pi^0}$ and $\mathcal{B}_{\Sigma^+ \rightarrow n\pi^+}$, respectively.

The uncertainties associated with the ST and DT background shapes are estimated by refitting the distributions with alternative fourth-order Chebyshev polynomials to describe all background components due to the relative broad distribution of the $J/\psi \rightarrow \Delta^+\bar{\Delta}^-$ process in the fit range. The resulting uncertainties are 0.30% and 0.26% for $\mathcal{B}_{\Sigma^+ \rightarrow p\pi^0}$ and $\mathcal{B}_{\Sigma^+ \rightarrow n\pi^+}$, respectively. In addition, the uncertainty due to the background statistical fluctuation of the ST yield, 0.06%, is also considered as a systematic uncertainty.

In the analysis, the $RM_{\bar{\Sigma}^-}$ distributions are used to determine the DT yields. All the Σ^+ decay channels with a proton in the final state that can pass the event selection are referred to as the signal in the fit for the DT sample of $\bar{\Sigma}^- p$, and the channels with a π^+ are regarded as the signal for $\bar{\Sigma}^- \pi^+$. Therefore, MC simulations of all the known Σ^+ decay modes other than the signal processes with a proton or π^+ , namely, $\Sigma^+ \rightarrow p\gamma$, $\Sigma^+ \rightarrow \Lambda e^+\nu_e$, and $\Sigma^+ \rightarrow n\pi^+\gamma$, are generated to estimate the potential impact on the BF's from these channels. These uncertainties (denoted as DT

peaking background in Table II) are evaluated to be 0.12% for $\mathcal{B}_{\Sigma^+ \rightarrow p\pi^0}$ and negligible for $\mathcal{B}_{\Sigma^+ \rightarrow n\pi^+}$. The misidentifications of proton and pion could also contribute to the systematic uncertainties, and they are determined to be 0.01% and 0.05% for $\mathcal{B}_{\Sigma^+ \rightarrow p\pi^0}$ and $\mathcal{B}_{\Sigma^+ \rightarrow n\pi^+}$, respectively, from the MC simulation.

The mass windows of $RM_{\bar{\Sigma}^- p}$ and $RM_{\bar{\Sigma}^- \pi^+}$ distributions are about $\pm 3\sigma$ around the known π^0 and neutron masses [25], respectively. We change the mass window to $\pm 2.5\sigma$, $\pm 3.5\sigma$, or $\pm 4\sigma$ to study the systematic uncertainties from the requirements on $RM_{\bar{\Sigma}^- p}$ and $RM_{\bar{\Sigma}^- \pi^+}$. The largest deviations from the nominal values, 0.14% and 0.16%, are taken as the systematic uncertainties for $\mathcal{B}_{\Sigma^+ \rightarrow p\pi^0}$ and $\mathcal{B}_{\Sigma^+ \rightarrow n\pi^+}$, respectively.

The uncertainties from the MC generators are investigated by varying the decay parameters by $\pm 1\sigma$ of the measured values [15,24]. The corresponding efficiency changes are taken as the systematic uncertainties, which are 0.05% and 0.04% for $\mathcal{B}_{\Sigma^+ \rightarrow p\pi^0}$ and $\mathcal{B}_{\Sigma^+ \rightarrow n\pi^+}$, respectively. The uncertainties due to the MC statistics are estimated to be 0.05% and 0.04% for $\mathcal{B}_{\Sigma^+ \rightarrow p\pi^0}$ and $\mathcal{B}_{\Sigma^+ \rightarrow n\pi^+}$, respectively.

Adding all systematic uncertainties in quadrature, we obtain the total systematic uncertainties for the measurement of $\mathcal{B}_{\Sigma^+ \rightarrow p\pi^0}$ and $\mathcal{B}_{\Sigma^+ \rightarrow n\pi^+}$ to be 0.44% and 0.59%, respectively.

In summary, using $(10087 \pm 44) \times 10^6$ J/ψ events collected with the BESIII detector, the absolute BF's of $\Sigma^+ \rightarrow p\pi^0$ and $\Sigma^+ \rightarrow n\pi^+$ are measured for the first time. The comparison of our results with all the previous measurements is shown in Fig. 3, where the obtained results are the most precise in the world. The ratio between $\mathcal{B}_{\Sigma^+ \rightarrow p\pi^0}$ and

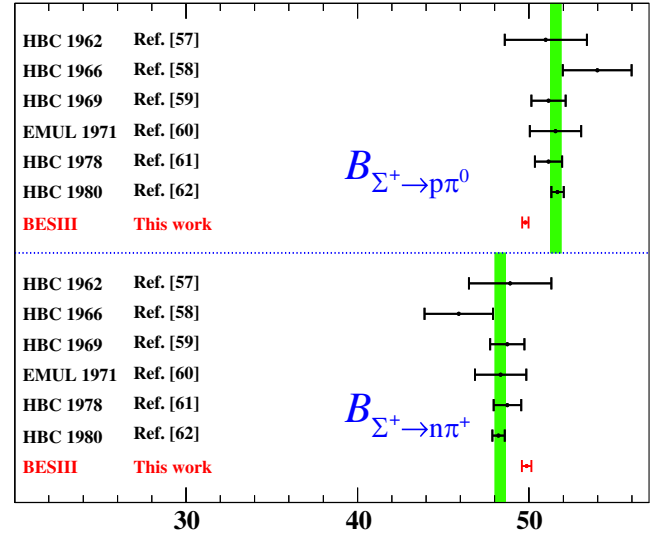


FIG. 3. Comparisons of the BF's (%) of $\Sigma^+ \rightarrow p\pi^0$ and $\Sigma^+ \rightarrow n\pi^+$ with previous experimental measurements [57–62]. The green bands correspond to the 1σ limit of the PDG values.

TABLE III. The measured BF's $\mathcal{B}_{\Sigma^+ \rightarrow p\pi^0}$ and $\mathcal{B}_{\Sigma^+ \rightarrow n\pi^+}$, and their ratio, along with the PDG values. The “Difference” marks the differences between the results and the PDG values. The first and second uncertainties presented in this work are statistical and systematic, respectively.

	$\mathcal{B}_{\Sigma^+ \rightarrow p\pi^0} (\%)$	$\mathcal{B}_{\Sigma^+ \rightarrow n\pi^+} (\%)$	$\mathcal{B}_{\Sigma^+ \rightarrow p\pi^0} / \mathcal{B}_{\Sigma^+ \rightarrow n\pi^+}$
This work	$49.79 \pm 0.06 \pm 0.22$	$49.87 \pm 0.05 \pm 0.29$	$0.9984 \pm 0.0016 \pm 0.0073$
PDG	51.47 ± 0.30	48.43 ± 0.30	1.0628 ± 0.0090
Difference	4.4σ	3.4σ	5.5σ

$\mathcal{B}_{\Sigma^+ \rightarrow n\pi^+}$ is determined to be $0.9984 \pm 0.0017 \pm 0.0069$, where the systematic uncertainties associated with the ST yields are canceled out in the calculation. These results are summarized in Table III, alongside the PDG values for comparison. Notably, our measurement deviates from the PDG values [25] by 4.4σ for $\mathcal{B}_{\Sigma^+ \rightarrow p\pi^0}$ and 3.4σ for $\mathcal{B}_{\Sigma^+ \rightarrow n\pi^+}$. The measured value is somewhat lower than the prediction reported in Ref. [29]. Given the model-dependent nature of the calculation, further theoretical improvements will be necessary for a more precise comparison. As one of the ground state hyperons, these precisely measured BF's $\mathcal{B}_{\Sigma^+ \rightarrow p\pi^0}$ and $\mathcal{B}_{\Sigma^+ \rightarrow n\pi^+}$ will serve as fundamental inputs for studies of numerous heavier baryon decays. In addition, the ratio between these two BF's obtained in this Letter exhibits a deviation of 5.5σ from the PDG value. Moreover, $\mathcal{B}_{\Sigma^+ \rightarrow p\gamma} = (1.19 \pm 0.06) \times 10^{-3}$ has been recalculated by multiplying our new result of $\mathcal{B}_{\Sigma^+ \rightarrow p\pi^0}$ with the PDG average of $\mathcal{B}_{\Sigma^+ \rightarrow p\gamma} / \mathcal{B}_{\Sigma^+ \rightarrow p\pi^0}$. This result differs from the direct measurement by BESIII by 2.9σ , which is significantly smaller than the previous reported discrepancy of 4.2σ [18].

Furthermore, the A and B amplitudes of the nonleptonic decays of Σ^+ have been updated based on the BF's obtained in this work, combined with the latest BESIII result of the decay parameter [24]. The detailed numerical values can be found in Ref. [35]. These more precise measurements will provide a crucial foundation for future studies of CP violation and rare decays in the Σ^+ sector. Together with the A and B amplitudes for Σ^- decay (extracted with the PDG values), the $\Delta I = 1/2$ rule could be quantitatively tested (in units of $G_F m_{\pi^+}^2$),

$$\begin{aligned}
 A_{n\pi^-}^{\Sigma^-} - A_{n\pi^+}^{\Sigma^+} + \sqrt{2}A_{p\pi^0}^{\Sigma^+} &= -0.127 \pm 0.014 \text{ (this work)} \\
 &= -0.180 \pm 0.063 \text{ (PDG)}, \\
 B_{n\pi^-}^{\Sigma^-} - B_{n\pi^+}^{\Sigma^+} + \sqrt{2}B_{p\pi^0}^{\Sigma^+} &= -2.78 \pm 0.16 \text{ (this work)} \\
 &= -2.50 \pm 0.76 \text{ (PDG)}. \quad (5)
 \end{aligned}$$

Notably, both quantities deviate from zero by more than 5σ , providing the first compelling evidence for a non-negligible $\Delta I = 3/2$ transition amplitude in Σ hyperon decays. The observed violation of the $\Delta I = 1/2$ rule in hyperon decays could help to elucidate the underlying dynamics of isospin

symmetry breaking in weak decays. In Ref. [35], we present the measured amplitudes of the S -wave and P -wave, together with the corresponding theoretical predictions from various models. Although some models can approximately reproduce parts of the data, none of the existing theoretical frameworks provide a complete description of the observed pattern of amplitudes. The improved experimental precision reported in this work, therefore, provides important new input for understanding the nonperturbative dynamics of nonleptonic weak decays in baryon systems.

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Data availability. The data that support the findings of this article are not publicly available upon publication because it is not technically feasible and/or the cost of preparing, depositing, and hosting the data would be prohibitive within the terms of this research project. The data are available from the authors upon reasonable request.

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