Semileptonic hyperon decays at BESIII



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Outline

Why semileptonic hyperon decays?

Physics of semileptonic hyperon decay

1. **Test the SM prediction of the branching fraction**
2. **Test lepton flavor universality**
3. **Search for new CPV**
4. **Measure the form factors**
5. **Measure the CKM matrix element**
6. **Others**

1. Test the SM prediction of the branching fraction

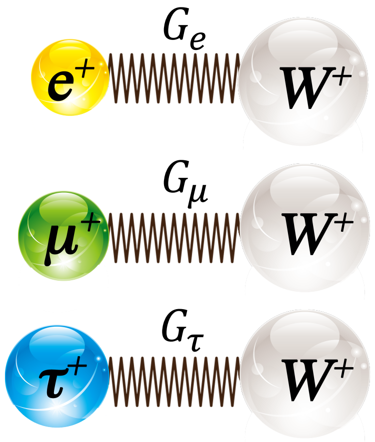
It has been about 60 years since Cabibbo proposed a model[1] for weak hadronic currents based on SU(3) symmetry. This model is now embedded in the standard model of quarks and leptons and their interactions and led to detailed predictions for the semileptonic decays of the baryon octet, in particular for the semileptonic decays of hyperons[2].

Observables	Experimental Data [1]	$\mathcal{B}r - S_1$	$\mathcal{B}r - S_2$	$\mathcal{B}r^L - S_2$
$\mathcal{B}(\Xi^- \to \Sigma^0 e^- \bar{\nu}_e)(\times 10^{-5})$	8.7 ± 1.7	8.12 ± 0.60	8.27 ± 0.58	5.23 ± 0.35
$\mathcal{B}(\Xi^- \to \Lambda^0 e^- \bar{\nu}_e)(\times 10^{-4})$	5.63 ± 0.31	1.21 ± 0.71	5.47 ± 0.15^{a}	4.94 ± 0.14
$\mathcal{B}(\Xi^0 \to \Sigma^+ e^- \bar{\nu}_e)(\times 10^{-4})$	2.52 ± 0.08	2.52 ± 0.08^{a}	2.52 ± 0.08^{a}	1.60 ± 0.06
$\mathcal{B}(\Lambda^0 \to p e^- \bar{\nu}_e)(\times 10^{-4})$	8.32 ± 0.14	8.32 ± 0.14^{a}	8.32 ± 0.14^{a}	6.05 ± 0.13
$\mathcal{B}(\Sigma^0 \to p e^- \bar{\nu}_e)(\times 10^{-13})$	$\cdots$	2.41 ± 0.32	2.46 ± 0.32	2.01 ± 0.26
$\mathcal{B}(\Sigma^- \to n e^- \bar{\nu}_e)(\times 10^{-3})$	1.017 ± 0.034	1.017 ± 0.034^{a}	1.013 ± 0.030^{a}	0.851 ± 0.034
$\mathcal{B}(\Xi^- \to \Sigma^0 \mu^- \bar{\nu}_\mu)(\times 10^{-6})$	≤ 800	1.08 ± 0.09	1.13 ± 0.08	0.57 ± 0.04
$\mathcal{B}(\Xi^- \to \Lambda^0 \mu^- \bar{\nu}_\mu)(\times 10^{-4})$	$3.5^{+3.5}_{-2.2}$	0.33 ± 0.19	1.58 ± 0.04	1.41 ± 0.04
$\mathcal{B}(\Xi^0 \to \Sigma^+ \mu^- \bar{\nu}_\mu)(\times 10^{-6})$	2.33 ± 0.35	2.14 ± 0.14	2.18 ± 0.1	1.09 ± 0.08
$\mathcal{B}(\Lambda^0 \to p \mu^- \bar{\nu}_\mu)(\times 10^{-4})$	1.57 ± 0.35	1.35 ± 0.02	1.40 ± 0.02	0.94 ± 0.02
$\mathcal{B}(\Sigma^0 \to p \mu^- \bar{\nu}_\mu)(\times 10^{-13})$	$\cdots$	1.05 ± 0.14	1.13 ± 0.15	0.92 ± 0.12
$\mathcal{B}(\Sigma^- \to n \mu^- \bar{\nu}_\mu)(\times 10^{-4})$	4.5 ± 0.4	4.53 ± 0.15	4.76 ± 0.14^{a}	3.99 ± 0.17
$\mathcal{B}(\Sigma^- \to \Sigma^0 e^- \bar{\nu}_e)(\times 10^{-10})$	$\cdots$	4.36 ± 4.01^{b}	1.35 ± 0.28^{b}	1.11 ± 0.23^{b}
$\mathcal{B}(\Sigma^- \to \Lambda^0 e^- \bar{\nu}_e)(\times 10^{-5})$	5.73 ± 0.27	5.73 ± 0.27^{a}	5.73 ± 0.27^{a}	3.18 ± 0.15
$\mathcal{B}(\Sigma^0 \to \Sigma^+ e^- \bar{\nu}_e)(\times 10^{-20})$	$\cdots$	3.41 ± 3.20^{b}	0.97 ± 0.35^{b}	0.80 ± 0.28^{b}
$\mathcal{B}(\Sigma^+ \to \Lambda^0 e^+ \nu_e)(\times 10^{-5})$	2.0 ± 0.5	1.88 ± 0.11	1.86 ± 0.11	1.04 ± 0.06
$\mathcal{B}(\Xi^- \to \Xi^0 e^- \bar{\nu}_e)(\times 10^{-9})$	$\leq 2.3 \times 10^6$	2.57 ± 2.53^{b}	0.42 ± 0.24^{b}	0.37 ± 0.21^{b}
$\mathcal{B}(n \to p e^- \bar{\nu}_e)$	100%	$100\%^{a}$	$100\%^{a}$	$(58.38 \pm 0.03)\%$

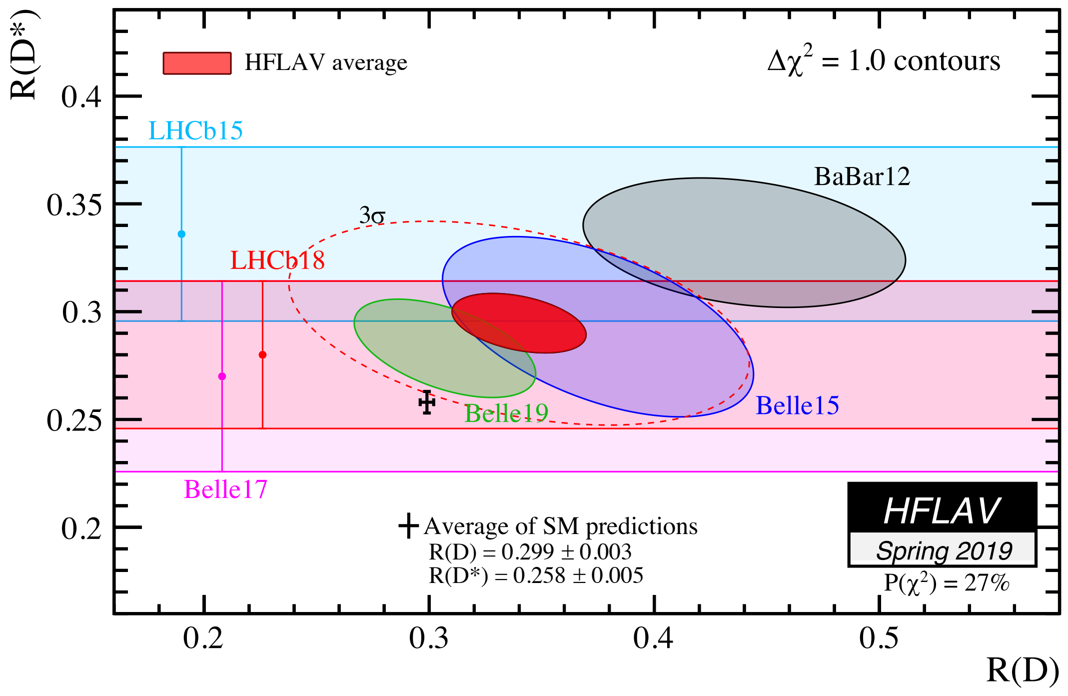
[1] Phys. Rev. Lett. **10**, 531 (1963)   [2] Phys. Rev. D **100**, 076008 (2019)

2. Test lepton flavor universality

$$R(D^{(*)}) = \frac{\mathcal{B}(\bar{B} \to D^{(*)}\tau^-\bar{\nu}_\tau)}{\mathcal{B}(\bar{B} \to D^{(*)}l^-\bar{\nu}_l)}$$



$$G_F = G_e = G_\mu = G_\tau$$



Average of R(D) and R(D*) for spring 2019 from HFLAV[3].

2. Test lepton flavor universality

The semileptonic hyperon decay can be denoted as: $B \to b l^- \bar{\nu}_l$

Then, $R^{\mu e} = \dfrac{\mathcal{B}(B \to b\mu^- \bar{\nu}_\mu)}{\mathcal{B}(B \to b e^- \bar{\nu}_e)}$

$R^{\mu e}$	$\Lambda \to p l^- \bar{\nu}_l$	$\Sigma^- \to n l^- \bar{\nu}_l$	$\Xi^0 \to \Sigma^+ l^- \bar{\nu}_l$	$\Xi^- \to \Lambda l^- \bar{\nu}_l$
Experiment	0.189±0.041	0.442±0.039	0.0092±0.0014	0.6±0.5
SM NLO	0.153±0.008	0.444±0.022	0.0084±0.0004	0.275±0.014

Comparisons between the predictions of $R^{\mu e}$ in the SM at next-to-leading order and experimental measurements for different semileptonic hyperon decay[4].

[4] Phys. Rev. Lett. **114**, 161802 (2015)

3. Search for new CPV

- ✓ In 1964, CPV was observed in K meson decay[5] → Nobel prize in Physics 1980
- ✓ In 2001, CPV was observed in B meson decay[6,7] → Nobel prize in Physics 2008
- ✓ In 2019, CPV was observed in D meson decay[8]

- ☐ More CPV is needed to explain the observed matter-antimatter asymmetry in the Universe.
- ☐ CPV has not yet been observed in the decays of any baryon.
- ☐ Recently, the BESIII collaboration reported the most precise direct test of CPV in hyperon nonleptonic decays[9-11]. In comparison, no search for CPV in semileptonic hyperon decays has yet been reported.

[5] Phys. Rev. Lett. **13**, 138 (1964)
[6] Phys. Rev. Lett. **87**, 091802 (2001)
[7] Phys. Rev. Lett. **87**, 091801 (2001)
[8] Phys. Rev. Lett. **122**, 211803 (2019)
[9] Nat. Phys. **15**, 631(2019)
[10] Phys. Rev. Lett. **125**, 052004 (2020)
[11] arXiv:2105.11155

4. Measure the form factors

The transition matrix element for the generic hyperon semileptonic decay process $B \to b l^- \bar{\nu}_l$, where B and b are the initial- and final-state baryons, can be written in the form[12]

$$\mathcal{M} = \frac{G_S}{\sqrt{2}} \bar{u}_b \left(O_\alpha^V + O_\alpha^A \right) u_B \bar{u}_e \gamma^\alpha (1 + \gamma_5) v_\nu,$$

where

$$O_\alpha^V = f_1(q^2)\gamma^\alpha + \frac{f_2(q^2)}{M_B} \sigma_{\alpha\beta} q^\beta + \frac{f_3(q^2)}{M_B} q_\alpha$$

and $$O_\alpha^A = \left(g_1(q^2)\gamma^\alpha + \frac{g_2(q^2)}{M_B} \sigma_{\alpha\beta} q^\beta + \frac{g_3(q^2)}{M_B} q_\alpha \right) \gamma_5.$$

The momentum transfer is $q^\alpha = (p_e + p_\nu)^\alpha = (p_B - p_b)^\alpha$, and the coupling strength is $G_S = G_F V_{us}$ for $|\Delta S| = 1$ and $G_S = G_F V_{ud}$ for $\Delta S = 0$, where G_F is the Fermi coupling constant and V_{us}, V_{ud} are the appropriate CKM matrix elements.

5. Measure the CKM matrix element

Kobayashi & Maskawa[13] generalized Cabibbo universality to three generations of quarks through a 3×3 matrix V is known as the Cabibbo-Kobayashi-Maskawa (CKM) matrix. They observed that three generations could accommodate CP violation.

$$V_{\mathrm{CKM}} \equiv V_L^u V_L^{d\dagger} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

From PDG2021, using the independently measured CKM elements, we obtain $|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 0.9985 \pm 0.0005$ which indicates 3σ tension with unitarity in the 1st row.

Besides, the value of V_{us} dominantly derived from K semileptonic decays.

[13] Prog. Theor. Phys. **49**, 652 (1973)

Why semileptonic hyperon decays at BESIII?

Introduction

Hyperon pair production

10 billion J/ψ events collected

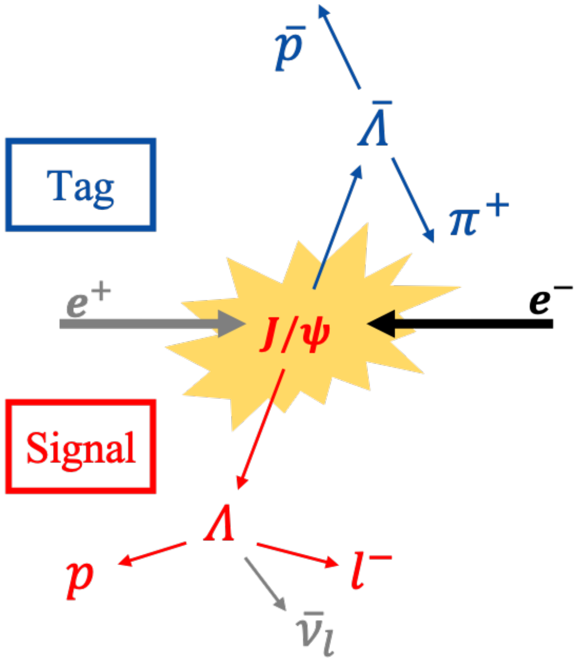
Large datasets of hyperon pair

Double tag method

Large BFs in J/ψ decays

Table 1: Hyperon pair production via J/ψ resonance at BESIII

Decay mode	$\mathcal{B}(\times 10^{-3})$	$N_{B\bar{B}}(\times 10^{6})$
$J/\psi \to \Lambda\bar{\Lambda}$	1.89 ± 0.09	19.06 ± 0.91
$J/\psi \to \Sigma^0\bar{\Sigma}^0$	1.17 ± 0.03	11.82 ± 0.32
$J/\psi \to \Sigma^+\bar{\Sigma}^-$	1.50 ± 0.24	15.13 ± 2.42
$J/\psi \to \Sigma(1385)^-\bar{\Sigma}^+$ (or c.c.)	0.31 ± 0.05	3.13 ± 0.50
$J/\psi \to \Sigma(1385)^-\bar{\Sigma}(1385)^+$ (or c.c.)	1.16 ± 0.05	11.70 ± 0.50
$J/\psi \to \Xi^0\bar{\Xi}^0$	1.17 ± 0.04	11.80 ± 0.40
$J/\psi \to \Xi^-\bar{\Xi}^+$	0.97 ± 0.08	9.78 ± 0.81
$J/\psi \to \Xi(1530)^0\bar{\Xi}^0$	0.32 ± 0.14	3.23 ± 1.41
$J/\psi \to \Xi(1530)^-\bar{\Xi}^+$	0.32 ± 0.01	3.21 ± 0.08



4-momentum conservation

Known initial 4-momentum

Information on the neutrino

Advantage of double tag method:

- ✓ Absolute BF
- ✓ Low background
- ✓ Cancel the systematic uncertainties in tag side

$$\Lambda \to p\mu^- \bar{\nu}_\mu$$

Phys. Rev. Lett. **127**. 121802 (2021)

Background

- Before our measurement, the experimental information comes only from **fixed-target experiments**[14-17] which were performed about 50 years ago.
- All these previous branching fraction results are **relative with huge uncertainty**.
- The best previous result was obtained **based on only 14 events** that are selected from about 0.6M **bubble chamber pictures**.

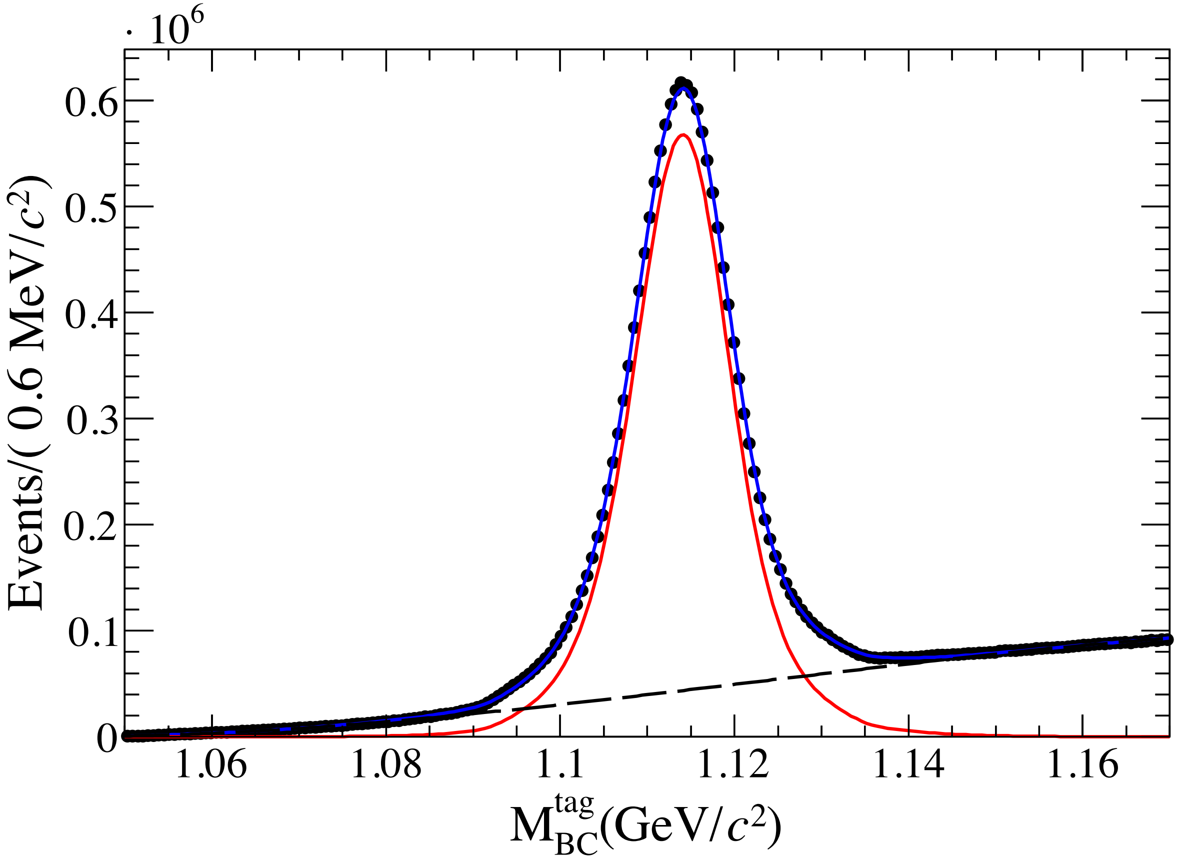
$\Lambda \to p\mu^-\bar{\nu}_\mu$

$\Gamma(\Lambda \to p\mu^-\bar{\nu}_\mu)/\Gamma(\Lambda \to N\pi)$

VALUE (10^{-4})	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
1.57 ± 0.35	**OUR FIT**				
1.57 ± 0.35	**OUR AVERAGE**				
1.4 ±0.5	14	BAGGETT	1972B	HBC	K^-p at rest
2.4 ±0.8	9	CANTER	1971B	HBC	K^-p at rest
1.3 ±0.7	3	LIND	1964	RVUE	
1.5 ±1.2	2	RONNE	1964	FBC	

[14] Phys. Lett. **11**, 357 (1964)
[15] Stern, Phys. Rev. **135**, B1483 (1964)
[16] Phys. Rev. Lett. **27**, 59 (1971)
[17] Zeitschrift fu¨r Physik A Hadrons and nuclei **252**,362 (1972)

Single tag analysis



$$M_{BC}^{tag} = \sqrt{E_{beam}^2 - |\vec{P}_{\bar{\Lambda}}|^2}$$

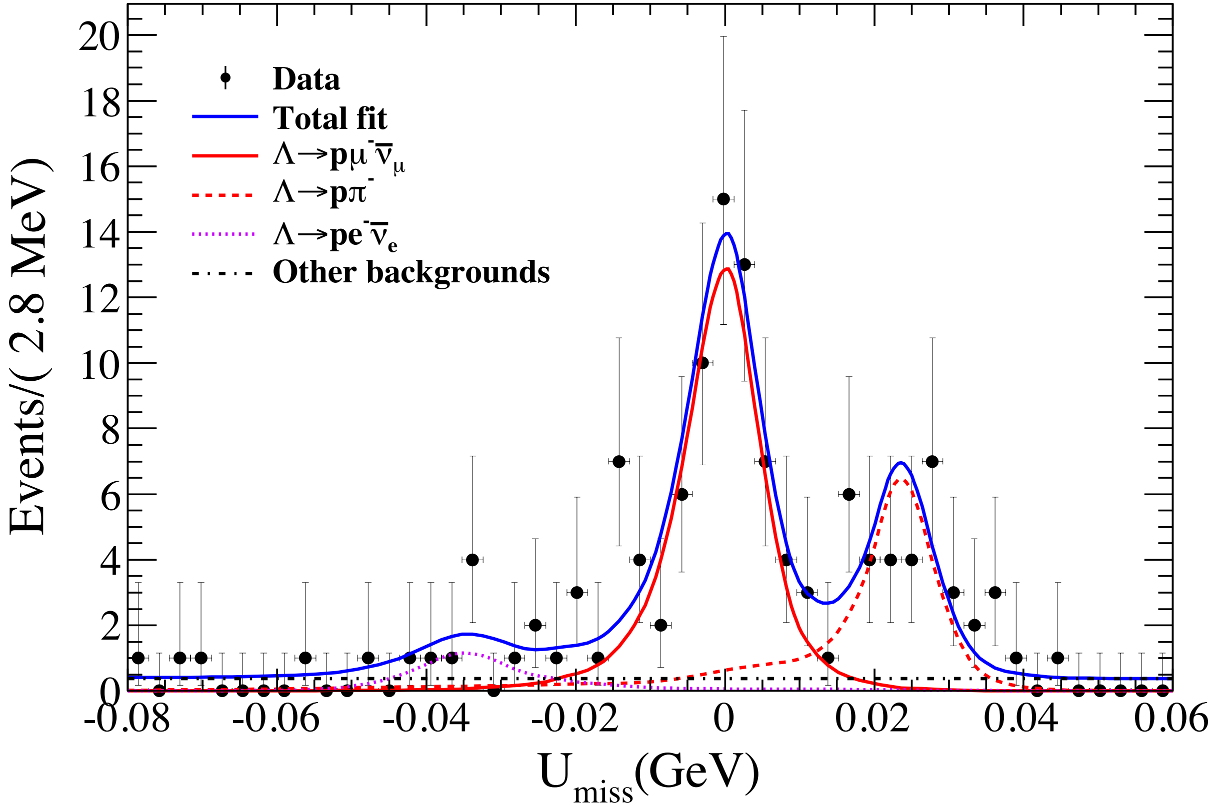
- Use the minimun $|\Delta E|$ to select the best ST $\bar{\Lambda}$ candidates, where

$$\Delta E \equiv E_{\bar{\Lambda}} - E_{beam}$$

- The total ST $\bar{\Lambda}$ yield:

$$N_{ST} = 14,609,800 \pm 7,117(stat)$$

Double tag analysis



$$U_{miss} \equiv E_{miss} - c|\vec{P}_{miss}|$$

$$E_{miss} = E_{beam} - E_p - E_{\mu^-}$$

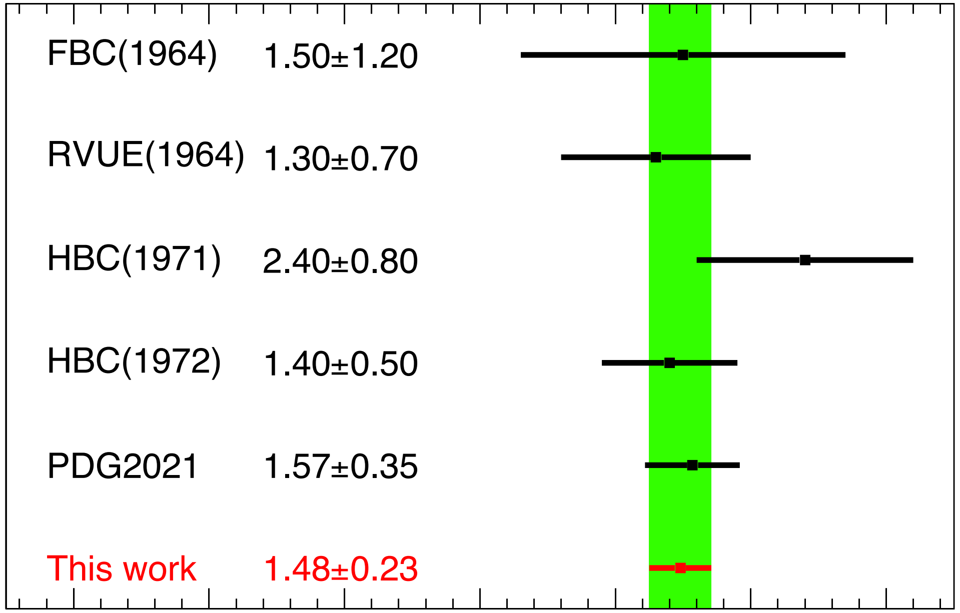
$$\vec{P}_{miss} = |\vec{P}_\Lambda - \vec{P}_p - \vec{P}_{\mu^-}|$$

$$\vec{P}_\Lambda = -\frac{\vec{P}_{\bar{\Lambda}}}{|\vec{P}_{\bar{\Lambda}}|}\sqrt{E_{beam}^2 - m_\Lambda^2}$$

- The total DT yield:

$$N_{DT} = 64.12 \pm 9.13(stat)$$

Results



Theory	Prediction of $\mathcal{B}(\Lambda \to p\mu^-\bar{\nu}_\mu)\times10^{-4}$
SU(3) symmetry without symmetry breaking	1.40 ± 0.02[2]
The factorization of the contribution of valence quarks and chiral effects	1.50[18]

$$\mathcal{B}(\Lambda \to p\mu^-\bar{\nu}_\mu) = [1.48 \pm 0.21(stat) \pm 0.08(syst)]\times10^{-4}$$

✓ The first absolute BF measurement.

✓ The most precise result to date.

[18] Phys. Rev. D **78**, 094005 (2008)

$\Lambda \to p\mu^- \bar{\nu}_\mu$

Phys. Rev. Lett. **127**. 121802 (2021)

Prediction from SM[4]

$$R_{SM}^{\mu e} = \frac{\mathcal{B}(\Lambda \to p\mu^- \bar{\nu}_\mu)}{\mathcal{B}(\Lambda \to pe^- \bar{\nu}_e)} = 0.153 \pm 0.008$$

$$\mathcal{A}_{CP} \equiv \frac{\mathcal{B}_{\Lambda \to p\mu^- \bar{\nu}_\mu} - \mathcal{B}_{\bar{\Lambda} \to \bar{p}\mu^+ \nu_\mu}}{\mathcal{B}_{\Lambda \to p\mu^- \bar{\nu}_\mu} + \mathcal{B}_{\bar{\Lambda} \to \bar{p}\mu^+ \nu_\mu}}$$

$$\mathcal{A}_{CP} = 0.02 \pm 0.14(stat) \pm 0.02(syst)$$

Experimental measurement

From this work

$$R^{\mu e} = \frac{\mathcal{B}(\Lambda \to p\mu^- \bar{\nu}_\mu)}{\mathcal{B}(\Lambda \to pe^- \bar{\nu}_e)} = \frac{(1.48 \pm 0.23)\times 10^{-4}}{(8.32 \pm 0.14)\times 10^{-4}} = 0.178 \pm 0.028$$

From PDG 2021

- ✓ The $R^{\mu e}$ result agrees with the SM prediction assuming LFU.
- ✓ No evidence for *CP* violation is found.

$$\Xi^- \to \Xi^0 e^- \bar{\nu}_e$$

Phys. Rev. D **104**. 072007 (2021)

Background

- Theoretical calculation shows that the effect of flavor SU(3) symmetry breaking is particularly evident in the process of $\Xi^- \to \Xi^0 e^- \bar{\nu}_e$.[19]
- The decay mode of $\Xi^- \to \Xi^0 e^- \bar{\nu}_e$ has not been observed experimentally, but only the upper limit 2.3×10^{-3} at 90% C. L. was set in 1974.[20]

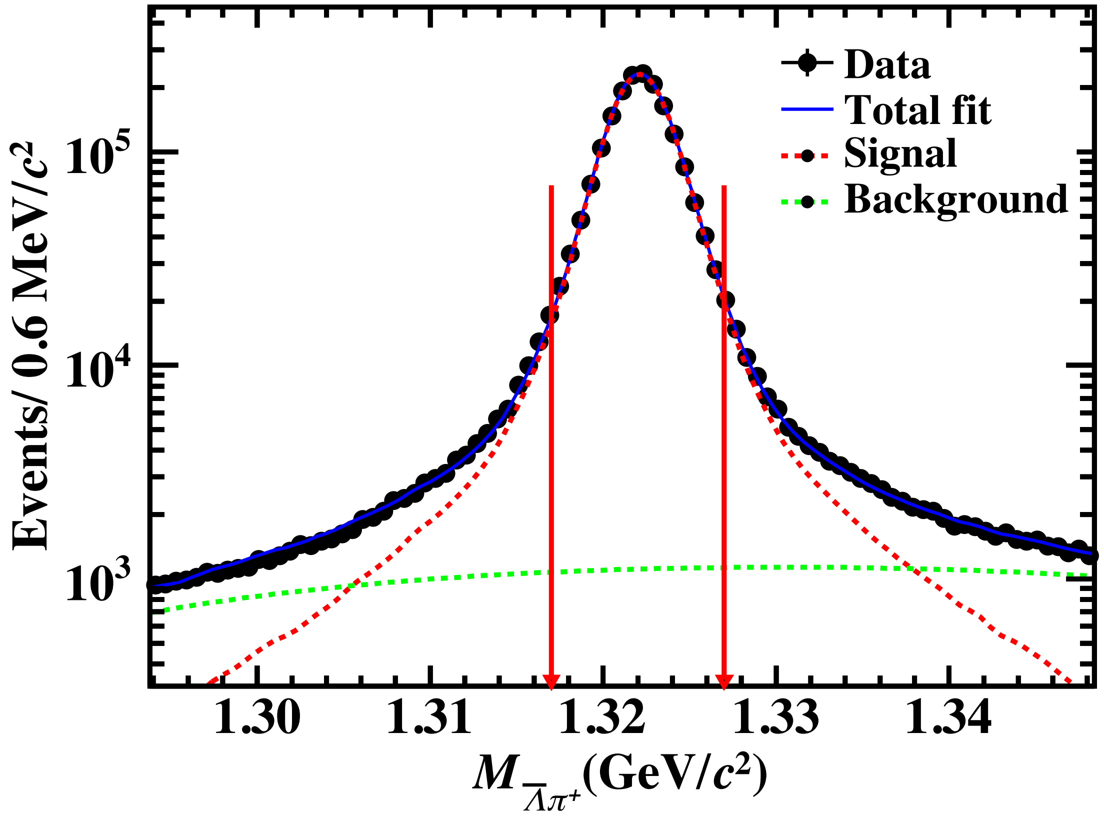
$\Gamma(\Xi^- \to \Xi^0 e^- \bar{\nu}_e)/\Gamma(\Xi^- \to \Lambda\pi^-)$ Γ_7/Γ_1

VALUE (10^{-3})	*CL%*	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
$<$ **2.3**	90	0	YEH	1974	HBC	Effective denom.=1000

References:

YEH	1974	PR D10 3545	Observation of Rare Decay Modes of the Ξ Hyperons

Single tag analysis

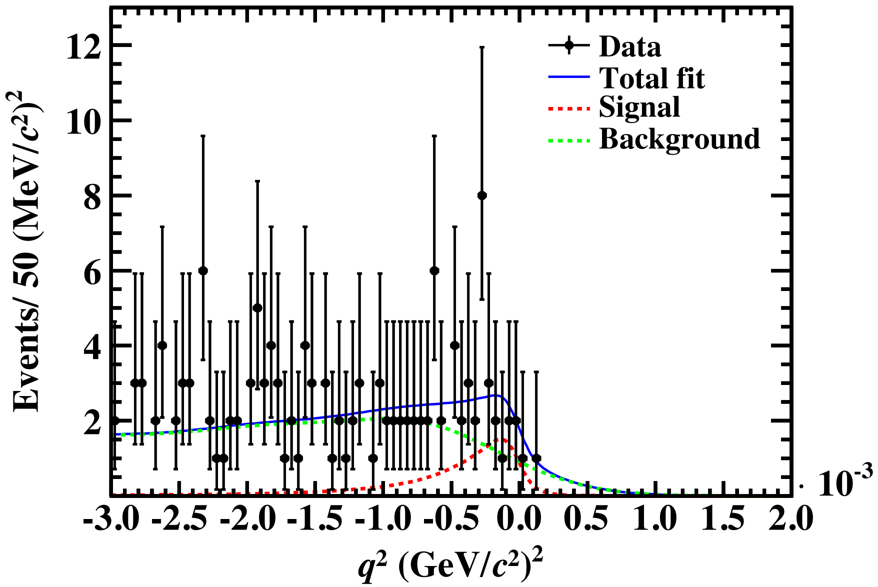


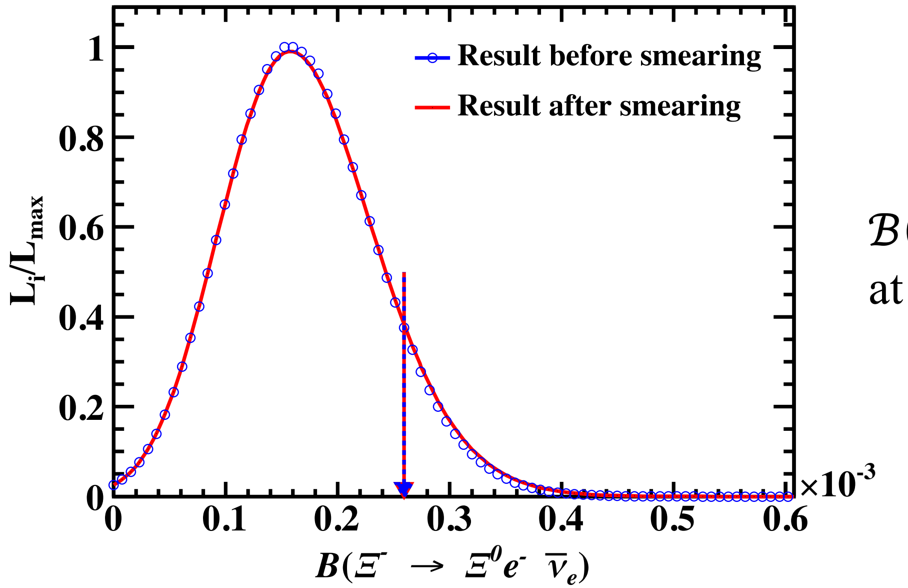
- Use the minimun $\left|M_{\bar{p}\pi^+} - M_{\bar{\Lambda}}^{PDG}\right| + \left|M_{\bar{\Lambda}\pi^+} - M_{\bar{\Xi}^+}^{PDG}\right|$ to select the best ST $\bar{\Xi}^+$ candidates.

- The total ST $\bar{\Xi}^+$ yield:

$$N_{ST} = 1,780,070 \pm 1,366(stat)$$

Double tag analysis and result





$\mathcal{B}(\Xi^- \to \Xi^0 e^- \bar{\nu}_e) < 2.59\times10^{-4}$ at 90% C. L.

$q^2 \equiv (E_{CM} - E_{\bar{\Xi}^+} - E_{\Xi^0})^2 - (\vec{p}_{CM} - \vec{p}_{\bar{\Xi}^+} - \vec{p}_{\Xi^0})^2$

No obvious signal is observed.

- ✓ One order of magnitude more strict than that of previous measurement.
- ✓ Provides an important experimental constraint for the theoretical study of the SU(3) symmetry-breaking mechanism.

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

Under study

Background

- The experimental information comes only from fixed-target experiments.
- All the measurements were obtained over 30 years ago.

Branching Fraction

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

$\Gamma(\Lambda \to pe^-\bar{\nu}_e)/\Gamma(\Lambda \to p\pi^-)$

VALUE (10^{-3})	EVTS	DOCUMENT ID		TECN	COMMENT
1.301 ± 0.019	**OUR FIT**				
1.301 ± 0.019	**OUR AVERAGE**				
1.335 ±0.056	7111	BOURQUIN	1983	SPEC	SPS hyperon beam
1.313 ±0.024	10k	WISE	1980	SPEC	
1.23 ±0.11	544	LINDQUIST	1977	SPEC	$\pi^- p \to K^0 \Lambda$
1.27 ±0.07	1089	KATZ	1973	HBC	
1.31 ±0.06	1078	ALTHOFF	1971	OSPK	
1.17 ±0.13	86	1 CANTER	1971	HBC	$K^- p$ at rest
1.20 ±0.12	143	2 MALONEY	1969	HBC	
1.17 ±0.18	120	2 BAGLIN	1964	FBC	K^- freon 1.45 GeV/c
1.23 ±0.20	150	2 ELY	1963	FBC	

- There are only relative branching fraction results.

Form Factor

g_A / g_V FOR $\Lambda \to pe^-\bar{\nu}_e$

Measurements with fewer than 500 events have been omitted. Where necessary, signs have been changed to agree with ou conventions, which are given in the ``Note on Baryon Decay Parameters" in the neutron Listings. The measurements all assu the form factor $g_2 = 0$. See also the footnote on DWORKIN 1990 .

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
−0.718 ± 0.015	**OUR AVERAGE**				
−0.719 ±0.016 ±0.012	37k	1 DWORKIN	1990	SPEC	$e\nu$ angular corr.
−0.70 ±0.03	7111	BOURQUIN	1983	SPEC	$\Xi \to \Lambda\pi^-$
−0.734 ±0.031	10k	2 WISE	1981	SPEC	$e\nu$ angular correl.
• • • We do not use the following data for averages, fits, limits, etc. • • •					
−0.63 ±0.06	817	ALTHOFF	1973	OSPK	Polarized Λ

- In PDG2021, all the form factor results were obtained from SPEC experiments.
- At BESIII, we have precise knowledge of polarized Λ produced via J/ψ resonance[9].

Expected results

- ✓ Same single tag analysis as $\Lambda \to p\mu^-\bar{\nu}_\mu$ → $N_{ST} = 14,609,800 \pm 7,117(stat)$
- ✓ ~12K $\Lambda \to p e^- \bar{\nu}_e$ will be produced after single tag

- ☐ First study with new technology and method at a collider experiment;
- ☐ First update after over 30 years break;
- ☐ First measurement of the absolute branching fraction;
- ☐ First measurement of form factors in $\bar{\Lambda} \to \bar{p} e^+ \nu_e$.

$$\Sigma^+ \to \Lambda e^+ \nu_e$$

Under study

Background

- In 1958, Steven Weinberg predicted that in the absence of second-class currents, the ratio of the rates $\frac{\Gamma(\Sigma^{+} \to \Lambda e^{+} \nu_e)}{\Gamma(\Sigma^{-} \to \Lambda e^{-} \bar{\nu}_e)}$ should be just the phase-space ratio for these two decays. "Any inequality in the rates for the Σ^{+} and Σ^{-} modes would be evidence for the existence of second-class interactions." [21]

- In 1960, T. D. Lee and C. N. Yang also predicted the same rate except for the phase space factor due to the difference between $\Sigma^{\pm}$ masses as a consequence of the assumption that the strangeness-conserving weak current transforms as an isotopic vector [22].

Background

- In Ref. [23-25], the aforementioned predictions were proved to be correct while use the related value of BFs, lifes and masses obtained in that years. Currently, all the measurements of the lifes and masses have been updated, also for the $\mathcal{B}(\Sigma^- \to \Lambda e^- \bar{\nu}_e)$.

- In comparison, there is little existing data on the decay $\Sigma^+ \to \Lambda e^+ \nu_e$.
- All the experimental information for the decay $\Sigma^+ \to \Lambda e^+ \nu_e$ has only come from the indirect measurements at the fixed-target experiments, which were performed fifty years ago [23-25].
- The most precise branching fraction of the decay $\Sigma^+ \to \Lambda e^+ \nu_e$ was determined based on 10 signal events which were selected from the bubble chamber pictures.

[23] Phys. Rev. Lett. **22**, 615 (1969) [24] Z.Phys. **221**, 1 (1969) [25] Phys.Rev.Lett. **19**, 181 (1967)

Expected results

- First direct measurement of the absolute branching fraction;
- New measurement of the $\mathcal{B}(\Sigma^+ \to \Lambda e^+ \nu_e)$ with higher precision;
- Perform the measurement with new technology and method at a collider experiment.

- Test the prediction from Steven Weinberg, T. D. Lee and C. N. Yang.

Summary

- ✓ With 10 billion J/ψ events collected and it's special advantage, BESIII can touch the rich physics of semileptonic hyperon decays.
- ✓ To date, for the study of semileptonic hyperon decays, BESIII has reported the first absolute branching fraction measurement of $\Lambda \to p\mu^{-}\bar{\nu}_{\mu}$ and its related LFU test and CPV search, and a search for the $\Xi^{-} \to \Xi^{0}e^{-}\bar{\nu}_{e}$.

□ More interesting results are coming.

Thank you~!