Fudan University

Experimental study of the hyperon semileptonic decays at BESIII

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(On behalf of BESIII Collaboration)

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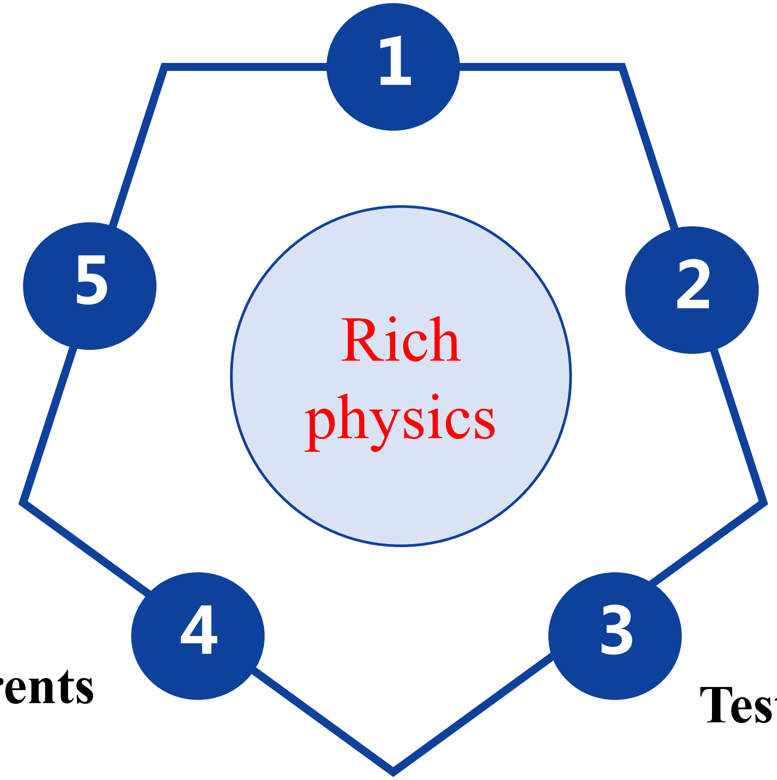
Why hyperon semileptonic decays?

1. Measure the CKM matrix element $|V_{us}|$
2. Measure the form factors
3. Test lepton flavor universality
4. Search for second-class currents
5. Search for rare/forbidden decays



Why hyperon semileptonic decays at BESIII?

Hyperon pair production

10 billion J/ψ, 3 billion $\psi(2S)$

Large datasets of hyperon pair

Double tag method

Large BFs in J/ψ, $\psi(2S)$ decays

Advantage of double tag method:

- ✓ Absolute BF
- ✓ Low background
- ✓ Cancel systematic uncertainties

Table 1: Hyperon pair production base on BESIII data

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
$\psi(2S) \to \Omega^-\bar{\Omega}^+$	0.06 ± 0.003	0.16 ± 0.01

Quantum correlated polarized-hyperon factories (BESIII&SCTF)

4-momentum conservation

Known initial 4-momentum

Information of the neutrino

Full and even extra information!
Higher single-event sensitivity!

Measure the CKM matrix element $|V_{us}|$

In the SM： First-row unitarity relation

$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1$$

2.2σ tension

⟺

A hint of new physics?

PDG 2022： Independent measurements

$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 0.99848 \pm 0.00070$$

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$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 0.99848 \pm 0.00070$$

- $|V_{ub}|$: Small（$|V_{ub}|^2 \cong 1.7\times10^{-5}$）➜ The effect could be ignored in current precision
- $|V_{ud}|$: Most precise; results from different decays are consistent at $\mathcal{O}(10^{-4})$ ➜ Precise and reliable
- $|V_{us}|$: $\sigma\,(|V_{us}|) = 2.6\times\sigma\,(|V_{ud}|)$

Measure the CKM matrix element $|V_{us}|$

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- $|V_{ud}|$: Most precise; results from different decays are consistent at $\mathcal{O}(10^{-4})$ ➜ Precise and reliable
- $|V_{us}|$: $\sigma(|V_{us}|) = 2.6\times\sigma(|V_{ud}|)$; inconsistence between results from different decays

PRL **92**, 251803 (2004)

Most precise	Second most precise	Largest uncertainty
Kaon: 2.2σ tension from CKM unitarity	**Tau**: 3.6σ deviation from CKM unitarity	**Hyperon**: consistent with CKM unitarity
$\lvert V_{us}\rvert = 0.2243 \pm 0.0008$	$\lvert V_{us}\rvert = 0.2207 \pm 0.0014$	$\lvert V_{us}\rvert = 0.2250 \pm 0.0027$
PDG 2022	HFLAV 2022	**Dominated by the $\Lambda \to p e^- \bar{\nu}_e$**

Kaon ↔ Tau: **2.2σ tension**

Measure the CKM matrix element $|V_{us}|$

Decay width of $\Lambda \to pe^-\overline{\nu}_e$ in the SM

PRD **70**, 114036 (2004)

$$\Gamma_{SM} = \frac{\mathcal{B}_{\Lambda\to pe^-\overline{\nu}_e}}{\tau_\Lambda} = \frac{G_F^2|V_{us}|^2 f_1(0)^2\Delta^5}{60\pi^3}[(1-\frac{3}{2}\delta+\frac{6}{7}\delta^2)+\frac{4}{7}\delta^2 g_w^2 +\left(3-\frac{9}{2}\delta+\frac{12}{7}\delta^2\right)g_{av}^2+\frac{12}{7}\delta^2 g_{av2}^2+\frac{6}{7}\delta^2 g_w+(-4\delta+6\delta^2)g_{av}g_{av2}]$$

$$\Delta \equiv M_\Lambda - M_p$$

$$\delta \equiv \frac{M_\Lambda - M_p}{M_\Lambda}$$

- Extracting $|V_{us}|$, requires $\mathcal{B}_{\Lambda\to pe^-\overline{\nu}_e}$, $f_1(0)$, $g_{av} \equiv \frac{g_1(0)}{f_1(0)}$, $g_w \equiv \frac{f_2(0)}{f_1(0)}$, and $g_{av2} \equiv \frac{g_2(0)}{f_1(0)}$,
  - $f_1(0)$: From LQCD
  - $\mathcal{B}_{\Lambda\to pe^-\overline{\nu}_e}$, g_{av}, g_w, and g_{av2}: From experimental measurement

Research status of $\mathcal{B}_{\Lambda\to pe^-\bar{\nu}_e}$

- Only relative BF
- Old results (>40 years)
- Only fixed target experiment

$\Gamma(\Lambda\to pe^-\bar{\nu}_e)/\Gamma(\Lambda\to p\pi^-)$ — PDG 2023 updated — Γ_5/Γ_1

VALUE (10^{-3})	EVTS	DOCUMENT ID		TECN	COMMENT
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	
• • We do not use the following data for averages, fits, limits, etc. • •					
1.32 ±0.15	218	[1] LINDQUIST	1971	OSPK	See LINDQUIST 1977

Research status of g_{av}

- All assume $g_2 = 0$
- Old results (>30 years)
- Only fixed target experiment

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

PDGID:S018AV

INSPI

PDG 2023 updated

Measurements with fewer than 500 events have been omitted. Where necessary, signs have been changed to agree with our conventions, which are given in the "Note on Baryon Decay Parameters" in the neutron Listings. The measurements all assume that 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

Measure the CKM matrix element $|V_{us}|$

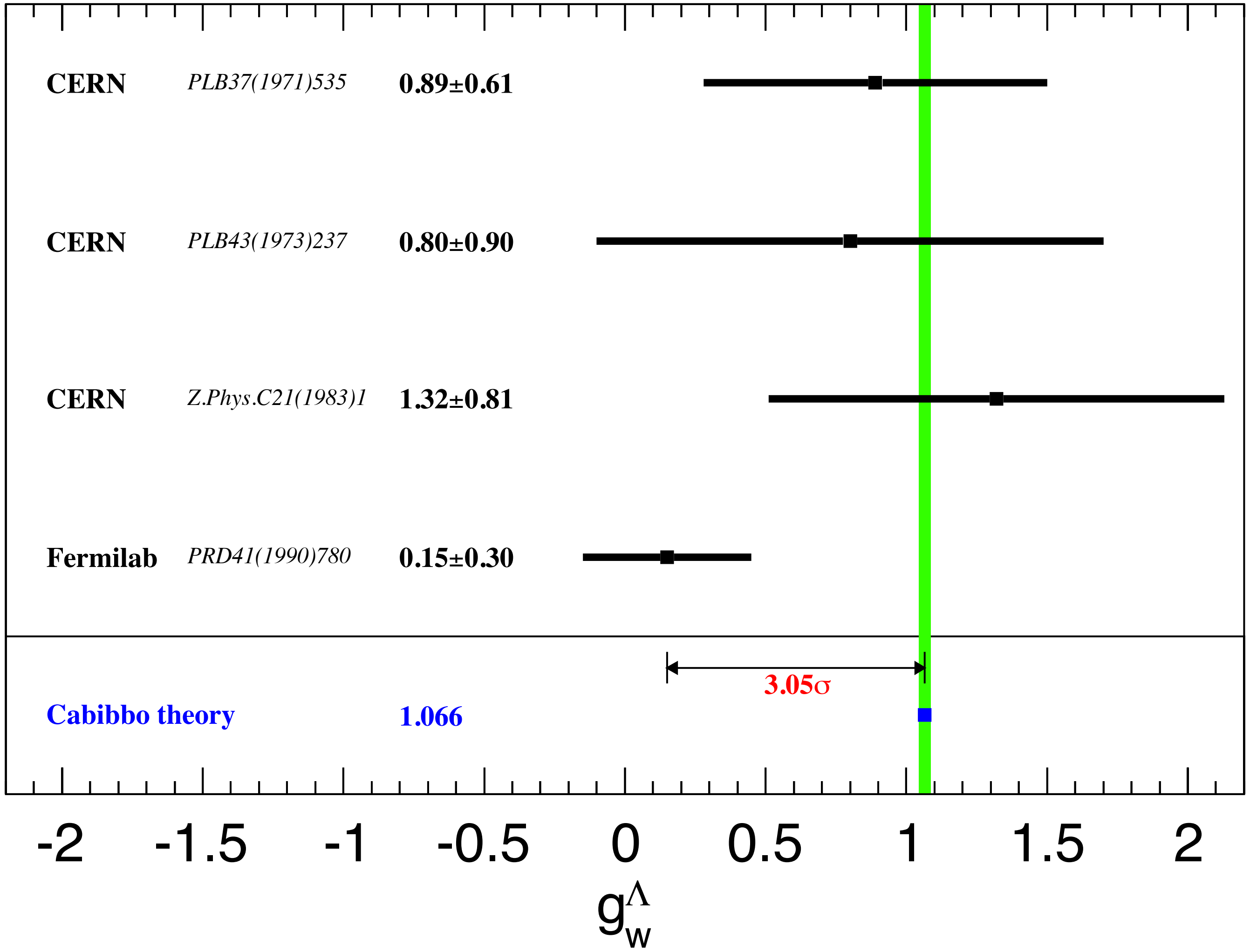
Research status of g_w, and g_{av2}

g_w:

- Results are old and scarce
- 3.05σ deviation
- Only fixed target experiment

g_{av2}:

- No experimental measurement



Measure the CKM matrix element $|V_{us}|$

Inputs from BESIII

- Updated study after > 30 years break
- First measurement of the absolute $\mathcal{B}_{\Lambda\to pe^-\bar{\nu}_e}$ (Double tag method)
- First simultaneous measurement of the g_{av}, g_w, and g_{av2} (Complete information of the whole decay chain)

→ Fresh $|V_{us}|$ result from hyperon

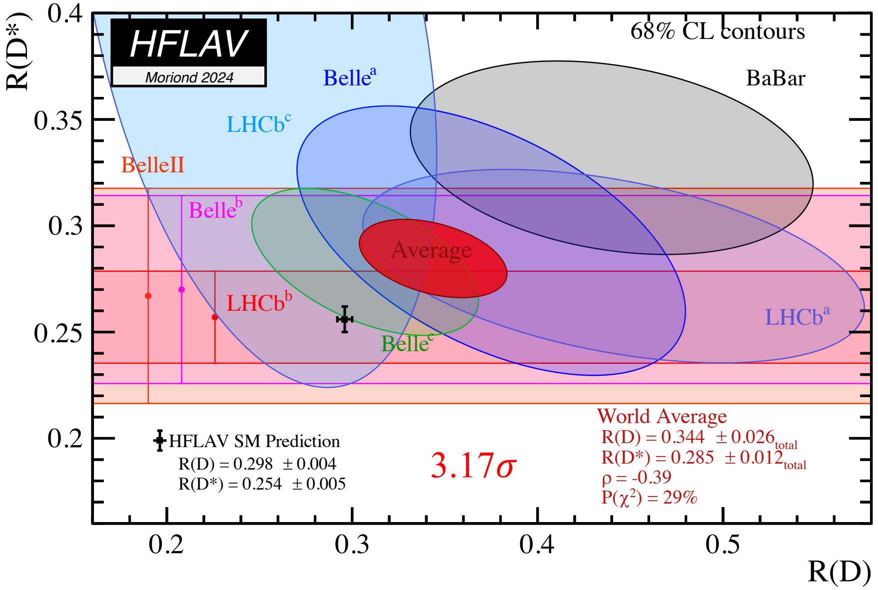
All these results are coming

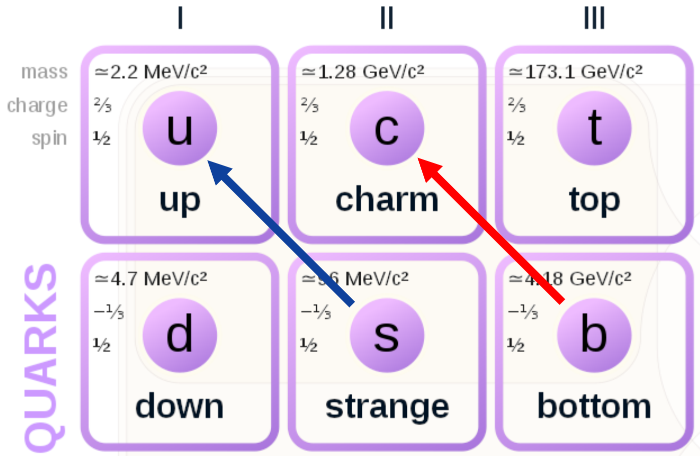
Test lepton flavor universality

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

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

Average of R(D) and R(D*) from HFLAV (2024)





Experiment vs. SM NLO for $R^{\mu e}$ from hyperon semileptonic decays[1].

$R^{\mu e}$	$\Lambda \to p l^- \bar{\nu}_l$	$\Sigma^- \to n l^- \bar{\nu}_l$	$\Xi^0 \to \Sigma^+ l^- \bar{\nu}_l$	$\Xi^- \to \Lambda l^- \bar{\nu}_l$
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

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

Motivation

- Before our measurement, there are only **fixed-target experiments** 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** selected from about 0.6M **bubble chamber pictures**.

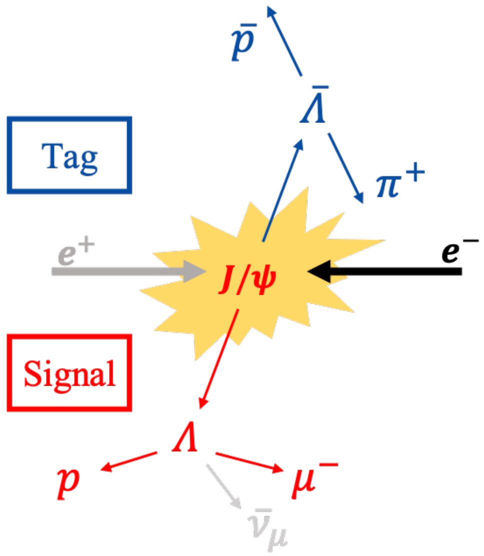
$\Lambda \to p\mu^-\bar{\nu}_\mu$ PDG 2020

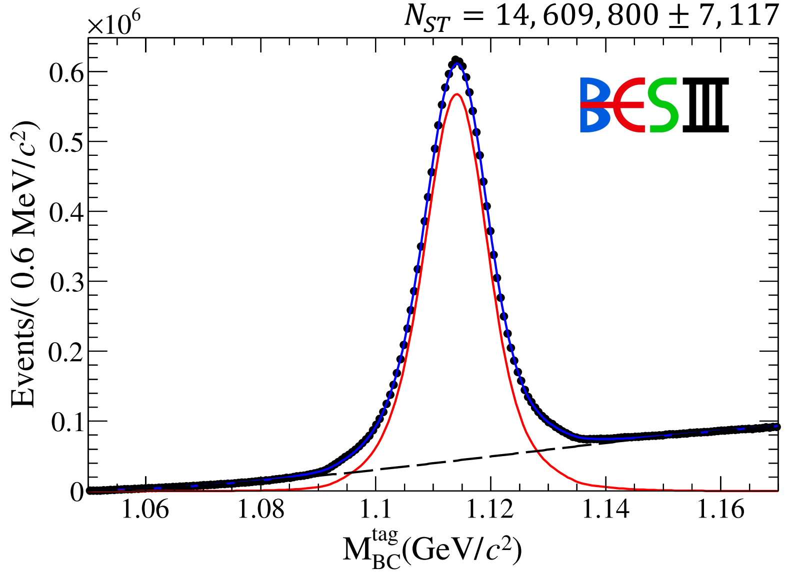
$\Gamma(\Lambda \to p\mu^-\bar{\nu}_\mu)/\Gamma(\Lambda \to N\pi)$

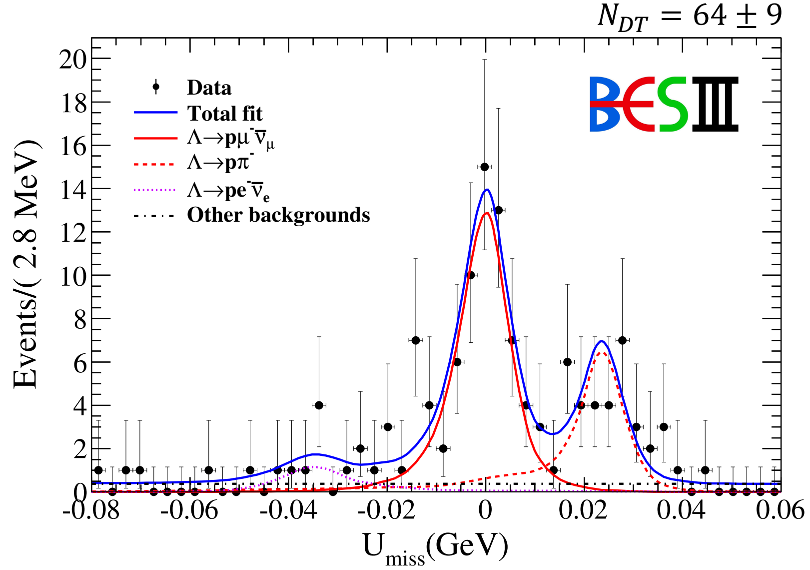
VALUE (10^{-4})	EVTS	DOCUMENT ID		TECN	COMMENT
1.57 ± 0.35	**OUR FIT**				
1.57 ± 0.35	**OUR AVERAGE**				
1.4 ±0.5	14	BAGGETT	1972B	HBC	K^-p at rest
2.4 ±0.8	9	CANTER	1971B	HBC	K^-p at rest
1.3 ±0.7	3	LIND	1964	RVUE	
1.5 ±1.2	2	RONNE	1964	FBC	

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

BESIII, PRL 127, 121802 (2021)







First absolute BF measurement

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

- ✓ Update measurement after about 50 years break
- ✓ The first study at a collider experiment
- ✓ The most precise result to date

Test lepton flavor universality

$$R^{\mu e} = \frac{\mathcal{B}(\Lambda \to p\mu^-\bar{\nu}_\mu)}{\mathcal{B}(\Lambda \to pe^-\bar{\nu}_e)_{PDG}} = 0.178 \pm 0.028$$

Consistent with LFU

$R^{\mu e}_{SM} = 0.153 \pm 0.008$

PRL **114**, 161802 (2015)

Search for CP violation

$$\mathcal{A}_{CP} = \frac{\mathcal{B}_{\Lambda\to p\mu^-\bar{\nu}_\mu} - \mathcal{B}_{\bar{\Lambda}\to\bar{p}\mu^+\nu_\mu}}{\mathcal{B}_{\Lambda\to p\mu^-\bar{\nu}_\mu} + \mathcal{B}_{\bar{\Lambda}\to\bar{p}\mu^+\nu_\mu}} = 0.02 \pm 0.14 \pm 0.02$$

Consistent with CP symmetry

Motivation

- About second-class currents, previous nuclear β decay experiments gave contradictory conclusions.
  - ✓ Refs. [1-4] are in favor of the existence of the second-class currents
  - ✓ Refs. [5-8] reported the absence of second-class currents.

- In hyperon β decay, flavor-SU(3)-symmetry-breaking effects [9-10] or second-class currents [11] can cause a nonzero axial-vector form factor g_2, and some of the experiments suggest a large g_2 [12].

[1] Phys. Rev. Lett. **35**, 1566 (1975).
[2] Phys. Rev. Lett. **34**, 1533 (1975).
[3] Phys. Rev. C **59**, 1113 (1999).
[4] Phys. Rev. C **95**, 035501 (2017).
[5] Phys. Rev. Lett. **26**, 1127 (1971).
[6] Phys. Rev. Lett. **32**, 314 (1974).
[7] Eur. Phys. J. A **7**, 307 (2000).
[8] Phys. Rev. C **84**, 055501 (2011).
[9] Phys. Rev. D **8**, 2963 (1973).
[10] Phys. Rev. D **79**, 074508 (2009).
[11] Annu. Rev. Nucl. Part. Sci. **53**, 39 (2003).
[12] Phys. Rev. D **3**, 2638 (1971).

Motivation

- In order to confirm the existence of second-class currents, a unique observable (R) was first proposed by S. Weinberg [1] in 1958.

$$R \equiv \frac{\Gamma(\Sigma^- \to \Lambda e^- \bar{\nu}_e)}{\Gamma(\Sigma^+ \to \Lambda e^+ \nu_e)}$$

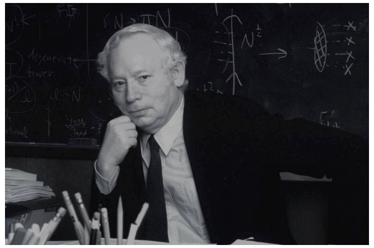
- If there is no second-class currents, R value should be just the phase-space ratio for these two decays , no matter flavor-SU(3)-symmetry-breaking effects exist or not, so any experimental deviation from this deduction would be decisive evidence for the existence of second-class currents.

PHYSICAL REVIEW VOLUME 112, NUMBER 4 NOVEMBER 15, 1958

Charge Symmetry of Weak Interactions*

STEVEN WEINBERG
Columbia University, New York, New York

(Received June 25, 1958)



Motivation

- T. D. Lee and C. N. Yang [1] calculate R on the basis of no second-class currents.

$$R = 1.57$$

PHYSICAL REVIEW VOLUME 119, NUMBER 4 AUGUST 15, 1960

Implications of the Intermediate Boson Basis of the Weak Interactions: Existence of a Quartet of Intermediate Bosons and Their Dual Isotopic Spin Transformation Properties

T. D. LEE
Columbia University, New York, New York

AND

C. N. YANG
Institute for Advanced Study, Princeton, New Jersey

(Received April 11, 1960)


Chen Ning Yang


Tsung-Dao Lee

Motivation

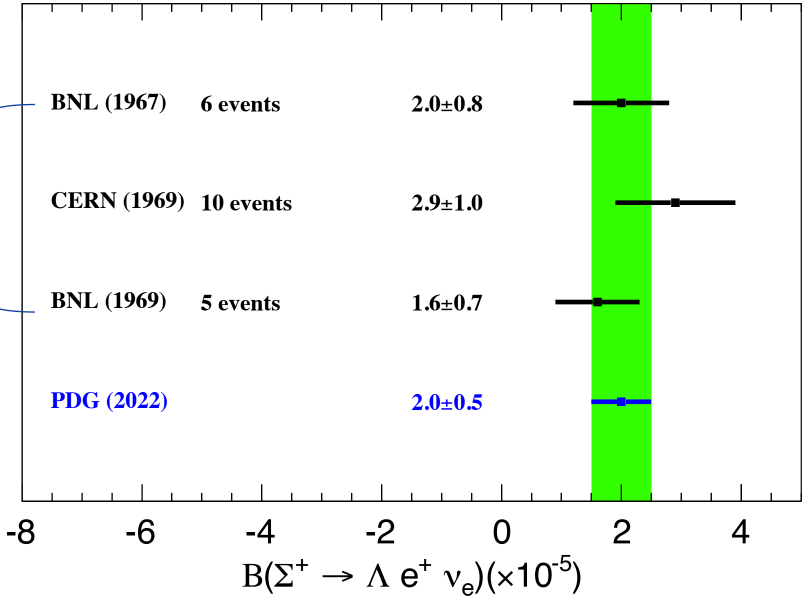
$$R \equiv \frac{\Gamma(\Sigma^- \to \Lambda e^- \bar{\nu}_e)}{\Gamma(\Sigma^+ \to \Lambda e^+ \nu_e)} = \frac{\mathcal{B}(\Sigma^- \to \Lambda e^- \bar{\nu}_e)\cdot\tau_{\Sigma^+}}{\mathcal{B}(\Sigma^+ \to \Lambda e^+ \nu_e)\cdot\tau_{\Sigma^-}}$$

From PDG2022 [1]:

$\sigma(\tau_{\Sigma^+}) \sim 0.3\%$ $\quad$ $\sigma[\mathcal{B}(\Sigma^- \to \Lambda e^- \bar{\nu}_e)] \sim 4.7\%$

$\sigma(\tau_{\Sigma^-}) \sim 0.7\%$ $\quad$ $\sigma[\mathcal{B}(\Sigma^+ \to \Lambda e^+ \nu_e)] \sim 25\%$

1. Fixed-target experiments
2. Bubble chamber pictures
3. Indirect measurement



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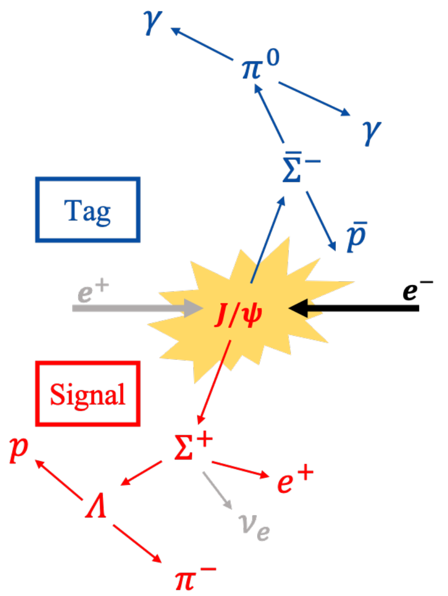
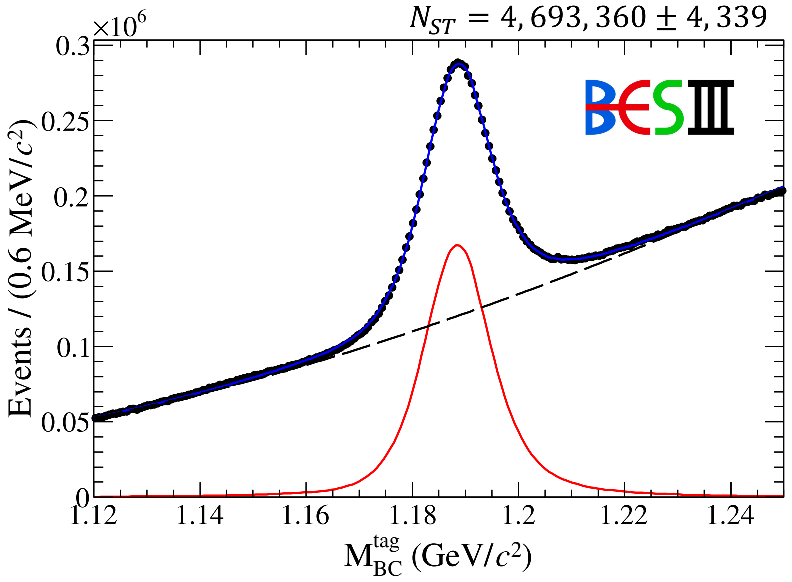
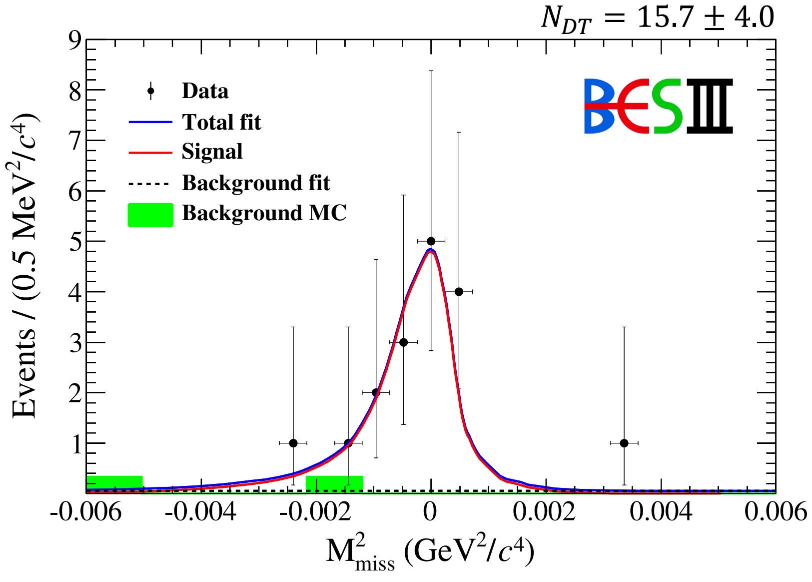
$\Sigma^+ \to \Lambda e^+ \nu_e$

BESIII, PRD 107, 072010 (2023)







First derect measurement of absolute BF

$$\mathcal{B}(\Sigma^+ \to \Lambda e^+ \nu_e) = (2.93 \pm 0.74 \pm 0.13) \times 10^{-5}$$

Search for second-class currents

$$R \equiv \frac{\Gamma(\Sigma^- \to \Lambda e^- \bar{\nu}_e)}{\Gamma(\Sigma^+ \to \Lambda e^+ \nu_e)} = \frac{\mathcal{B}(\Sigma^- \to \Lambda e^- \bar{\nu}_e)_{PDG} \cdot \tau_{\Sigma^+ PDG}}{\mathcal{B}(\Sigma^+ \to \Lambda e^+ \nu_e) \cdot \tau_{\Sigma^- PDG}} = 1.06 \pm 0.28$$

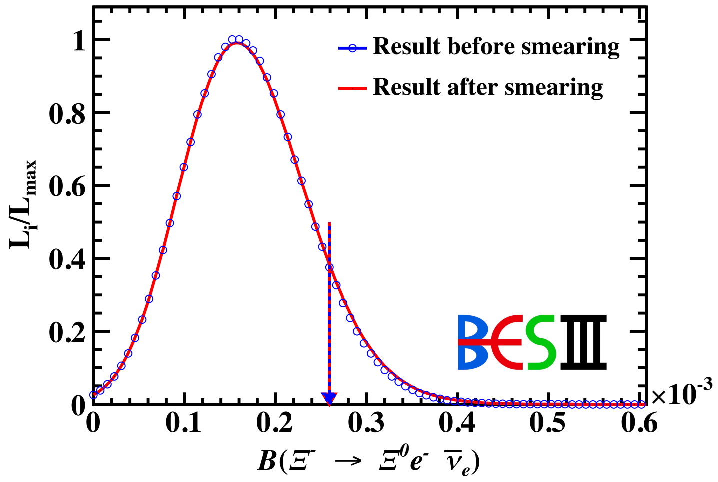
- ✓ Update measurement after about 50 years break
- ✓ The first study at a collider experiment
- ✓ The most precise result in a single experiment

Supports NO second-class currents

Search for rare/forbidden decays

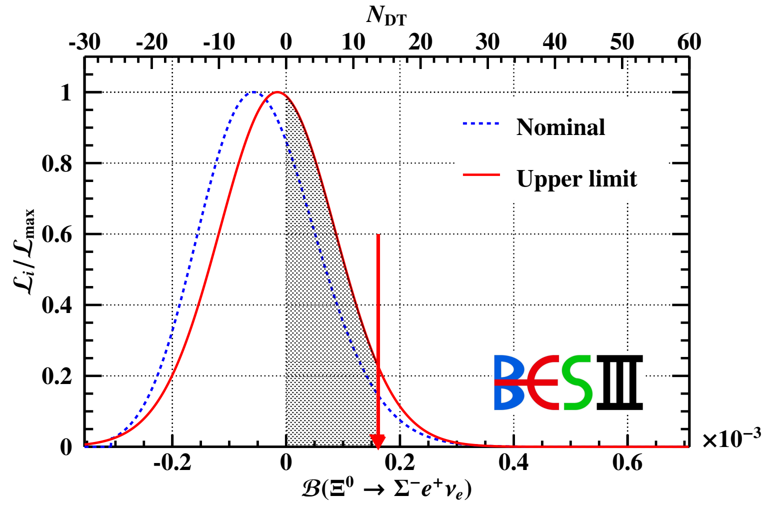
Search for the hyperon semileptonic decay $\Xi^- \to \Xi^0 e^- \bar{\nu}_e$

BESIII, PRD **104**, 072007 (2021)



Search for hyperon $\Delta S = \Delta Q$ violating decay $\Xi^0 \to \Sigma^- e^+ \nu_e$

BESIII, PRD **107**, 012002 (2023)



$$\mathcal{B}(\Xi^- \to \Xi^0 e^- \bar{\nu}_e) < 2.59\times10^{-4} \text{ @90\%CL}$$

$$\mathcal{B}(\Xi^0 \to \Sigma^- e^+ \nu_e) < 1.6\times10^{-4} \text{ @90\%CL}$$

Front. Phys. **12(5)**, 121301 (2017)

	Decay mode	$\mathcal{B}$ ($\times10^{-6}$) @90% C.L.	ΔS
$\Delta S = -\Delta Q$	$\Sigma^+ \to n e^+ \nu_e$ *	< 5	1
	$\Xi^0 \to \Sigma^- e^+ \nu_e$ *	< 900	1
$\Delta S = 2$	$\Xi^0 \to p e^- \bar{\nu}_e$	< 1300	2
	$\Xi^- \to n e^- \bar{\nu}_e$	< 3200	2
	$\Omega^- \to \Lambda e^- \bar{\nu}_e$	–	2
	$\Omega^- \to \Sigma^0 e^- \bar{\nu}_e$	–	2

Further study could be done

Summary

With 10 billion J/ψ and 3 billion $\psi(2S)$ events collected and the special advantages of BESIII, we can investigate the rich physics of hyperon semileptonic decays.

✓ What have been published:

- ✓ Test lepton flavor universality ($\Lambda \to p\mu^-\bar{\nu}_\mu$);
- ✓ Search for second-class currents ($\Sigma^+ \to \Lambda e^+\nu_e$);
- ✓ Search for rare/forbidden decays ($\Xi^- \to \Xi^0 e^-\bar{\nu}_e$ and $\Xi^0 \to \Sigma^- e^+\nu_e$)

☐ More interesting results are coming:

- ☐ $\Lambda \to pe^-\bar{\nu}_e$ (Measure the form factors and CKM matrix element)
- ☐ $\Omega^- \to \Xi^0 l^-\bar{\nu}_l$ (The only decuplet hyperon semileptonic decay that can be experimental studied right now)

Thank you~!