Fudan University

Precision Hyperon (Semileptonic Decay) Physics at STCF

超级陶粲装置
Super Tau-Charm Facility

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Quantum correlated polarized-hyperon factory

Hyperon pair production

Huge J/ψ, $\psi(2S)$ datasets

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

Decay mode	Events at BESIII ($\times 10^6$)
$J/\psi \to \Lambda\bar{\Lambda}$	19.06 ± 0.91
$J/\psi \to \Sigma^0\bar{\Sigma}^0$	11.82 ± 0.32
$J/\psi \to \Sigma^+\bar{\Sigma}^-$	15.13 ± 2.42
$J/\psi \to \Sigma(1385)^-\bar{\Sigma}^+$ (or c.c.)	3.13 ± 0.50
$J/\psi \to \Sigma(1385)^-\bar{\Sigma}(1385)^+$ (or c.c.)	11.70 ± 0.50
$J/\psi \to \Xi^0\bar{\Xi}^0$	11.80 ± 0.40
$J/\psi \to \Xi^-\bar{\Xi}^+$	9.78 ± 0.81
$J/\psi \to \Xi(1530)^0\bar{\Xi}^0$	3.23 ± 1.41
$J/\psi \to \Xi(1530)^-\bar{\Xi}^+$	3.21 ± 0.08
$\psi(2S) \to \Omega^-\bar{\Omega}^+$	0.16 ± 0.01

STCF is expected to collect 1 trillion J/ψ and then provide $\sim 10^9$ hyperon pairs per year

(100× BESIII only 1 year)

Quantum correlated polarized-hyperon factory

4-momentum conservation

Known initial 4-momentum

Information of the neutrino

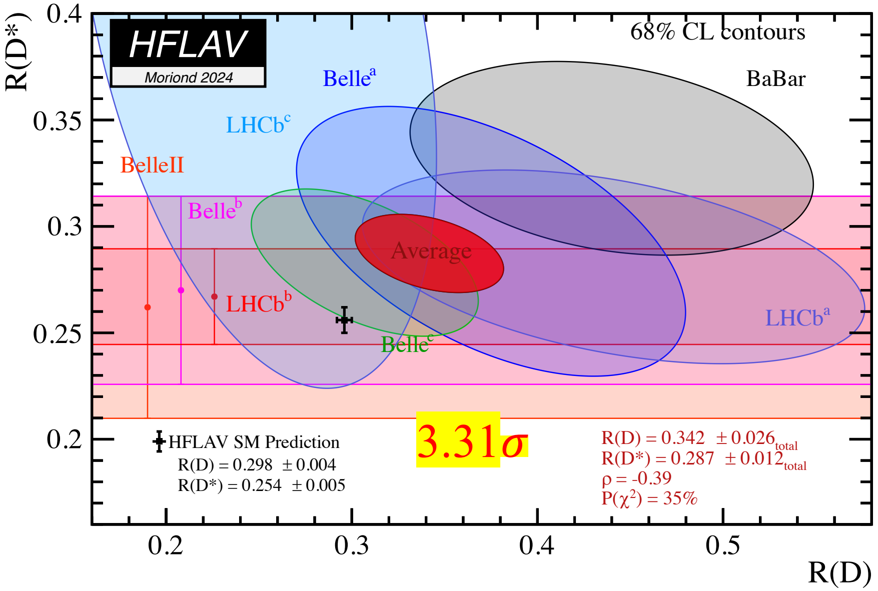
Full and even extra information!
Higher single-event sensitivity!

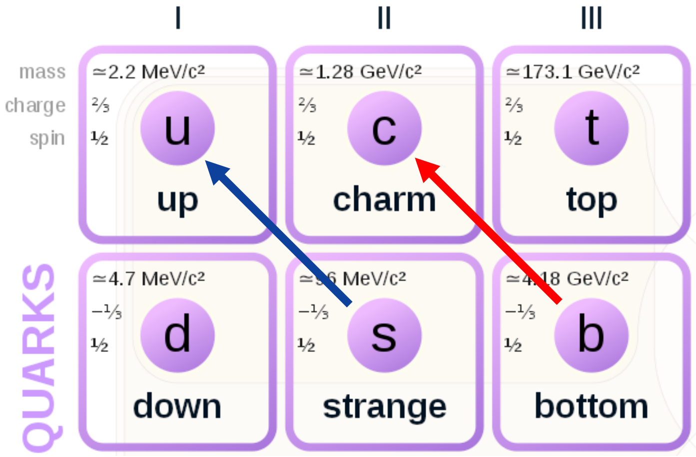
Background

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

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

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)

Background

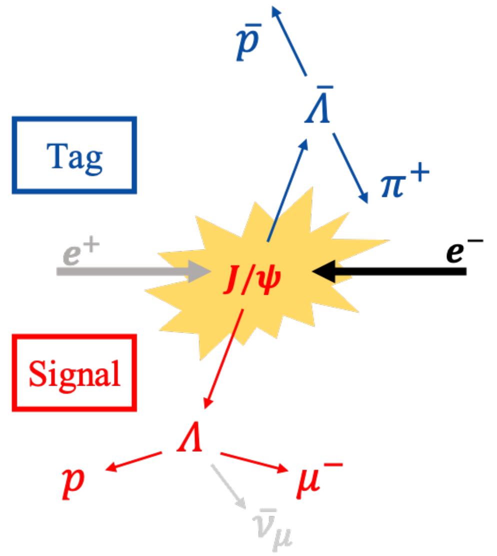
- Before our measurement, there are only **fixed-target experiments** performed about 50 years ago.
- All these previous branching fraction results are **relative with huge uncertainty**.
- The best previous result was obtained **based on only 14 events** selected from about 0.6M **bubble chamber pictures**.

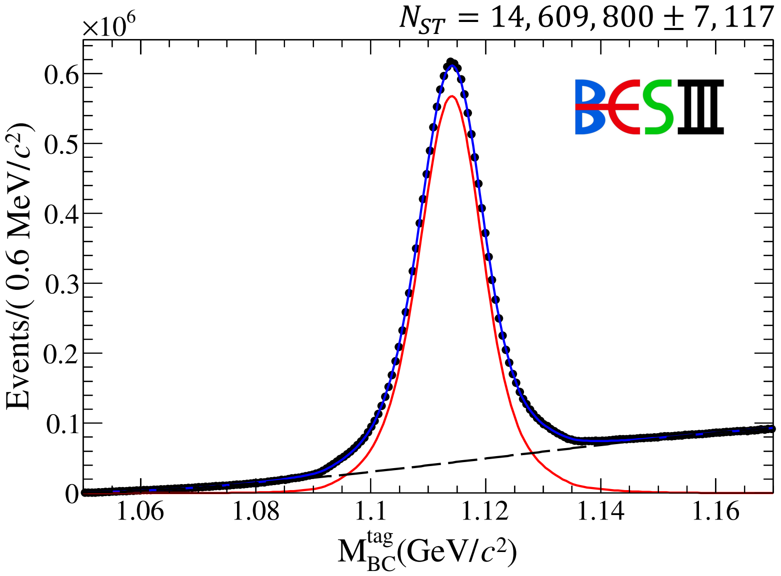
$\Lambda \to p\mu^-\bar{\nu}_\mu$ PDG 2020

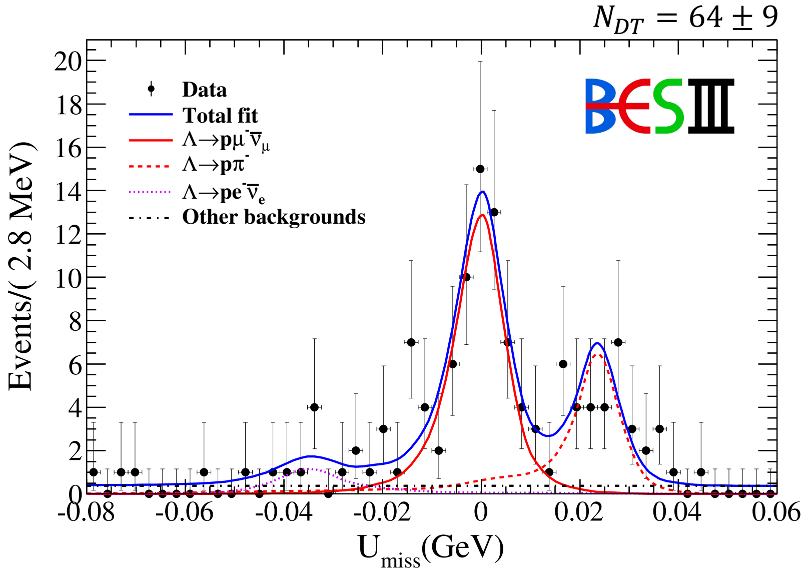
$\Gamma(\Lambda \to p\mu^-\bar{\nu}_\mu)/\Gamma(\Lambda \to N\pi)$

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	

Test lepton flavor universality







BESIII, PRL **127**, 121802 (2021)

First absolute BF measurement

$$\mathcal{B}(\Lambda \to p\mu^-\bar{\nu}_\mu) = (1.48 \pm 0.21 \pm 0.08)\times 10^{-4}$$

Test lepton flavor universality

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

Consistent with LFU

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

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

PRL **114**, 161802 (2015)

Discussion and perspective

BESIII

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

BESIII, PRL **127**, 121802 (2021)

consistent

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

PRL **114**, 161802 (2015)

100× statistics at STCF

Assuming the central values are same and the systematical uncertainty is comparable to the statistical one.

Half uncertainty

Inputs from theorists are needed !!!

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$$R^{\mu e} = \frac{\mathcal{B}(\Lambda \to p\mu^- \bar{\nu}_\mu)_{STCF}}{\mathcal{B}(\Lambda \to p e^- \bar{\nu}_e)_{STCF}} = \mathbf{0.178 \pm 0.0036}$$

4.6σ deviation

$$R^{\mu e}_{SM} = \mathbf{0.153 \pm 0.004}$$

Background

- 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).

Search for second-class currents

Background

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

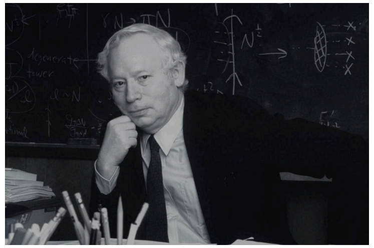
$$R \equiv \frac{\Gamma(\Sigma^- \to \Lambda e^- \bar{\nu}_e)}{\Gamma(\Sigma^+ \to \Lambda e^+ \nu_e)}$$

- 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)



Phys. Rev. **112**, 1375 (1958)

Background

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

$$R_{\text{theory}} \cong 1.57$$

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)

Phys. Rev. **119**, 1410 (1960)

Background

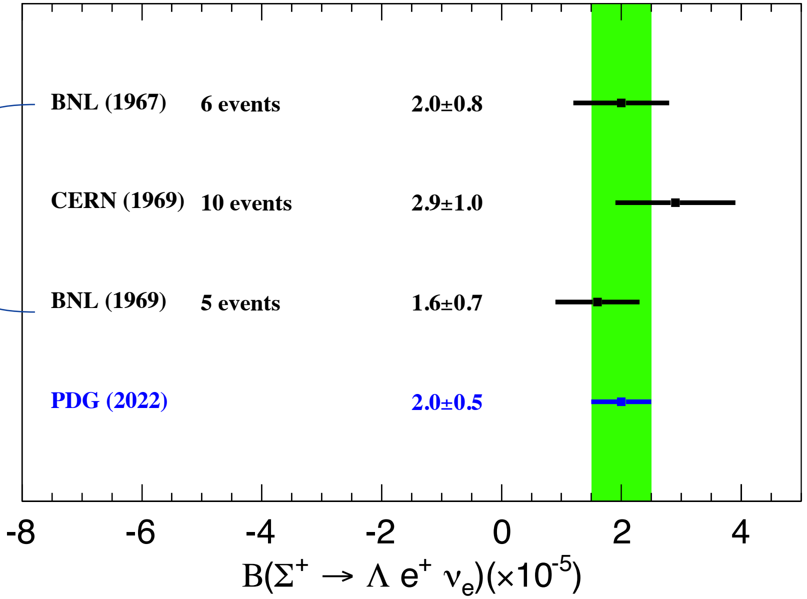
$$R \equiv \frac{\Gamma(\Sigma^- \to \Lambda e^- \bar{\nu}_e)}{\Gamma(\Sigma^+ \to \Lambda e^+ \nu_e)} = \frac{\mathcal{B}(\Sigma^- \to \Lambda e^- \bar{\nu}_e) \cdot \tau_{\Sigma^+}}{\mathcal{B}(\Sigma^+ \to \Lambda e^+ \nu_e) \cdot \tau_{\Sigma^-}}$$

From PDG2022 [1]:

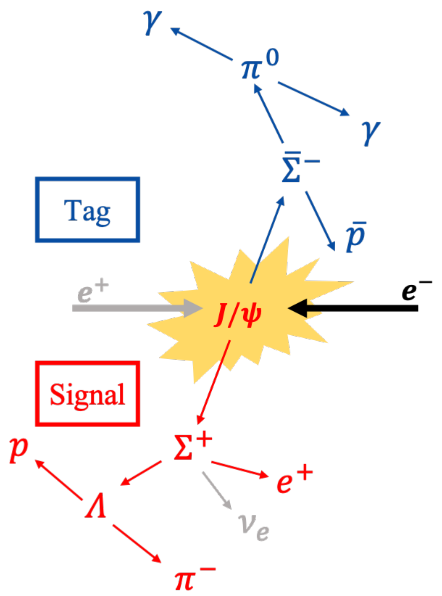
$\sigma(\tau_{\Sigma^+}) \sim 0.3\%$ $\sigma[\mathcal{B}(\Sigma^- \to \Lambda e^- \bar{\nu}_e)] \sim 4.7\%$

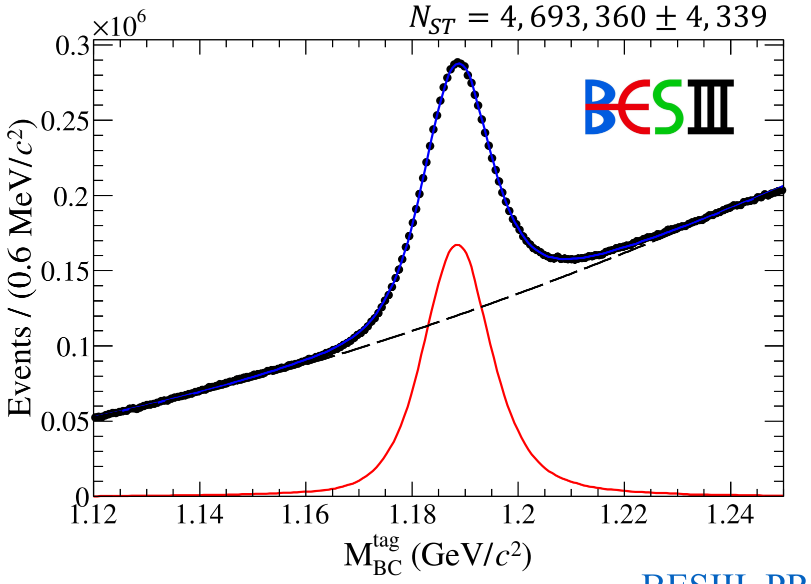
$\sigma(\tau_{\Sigma^-}) \sim 0.7\%$ $\sigma[\mathcal{B}(\Sigma^+ \to \Lambda e^+ \nu_e)] \sim 25\%$

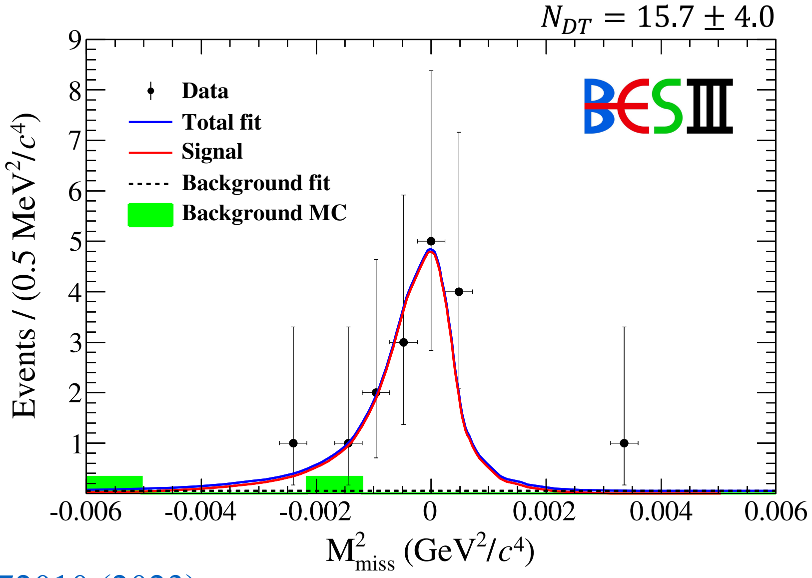
1. Fixed-target experiments
2. Bubble chamber pictures
3. Indirect measurement



Search for second-class currents







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

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

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

NO evindence for second-class currents

Discussion and perspective

BESIII

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

BESIII, PRD **107**, 072010 (2023)

1.8σ

$$R_{\text{theory}} \cong \mathbf{1.57}$$

Phys. Rev. **119**, 1410 (1960)

100× statistics at STCF

Assuming the central values are same and the systematical uncertainty is comparable to the statistical one.

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$$R = \frac{\mathcal{B}(\Sigma^- \to \Lambda e^- \bar{\nu}_e)_{STCF} \cdot \tau_{\Sigma^+ PDG}}{\mathcal{B}(\Sigma^+ \to \Lambda e^+ \nu_e)_{STCF} \cdot \tau_{\Sigma^- PDG}} = \mathbf{1.06 \pm 0.05}$$

10σ deviation

Inputs from theorists are needed !!!

Without the certain mean value and the corresponding uncertaity, we cannot claim the observation of second-class currents.

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

In the SM：First-row unitarity relation

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

2.3σ tension

A hint of new physics?

PDG 2024：Independent measurements

$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 0.9984 \pm 0.0007$$

- $|V_{ub}|$: 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
- $|V_{us}|$: $\sigma(|V_{us}|) = 2.7\times\sigma(|V_{ud}|)$； inconsistence between results from different decays

PRL **92**, 251803 (2004)

Most precise

Kaon：2.3σ tension from CKM unitarity

$$|V_{us}| = 0.22431 \pm 0.00085$$

PDG 2024

Second most precise

Tau：3.7σ deviation from CKM unitarity

$$|V_{us}| = 0.2207 \pm 0.0014$$

HFLAV 2022

2.2σ tension

Largest uncertainty

Hyperon：consistent with CKM unitarity

$$|V_{us}| = 0.2250 \pm 0.0027$$

Dominated by the $\Lambda \to pe^-\overline{\nu}_e$

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

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

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

PRD **70**, 114036 (2004)

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

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

- 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

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

	Current status
$\mathcal{B}_{\Lambda\to pe^-\bar{\nu}_e}$	No absolute measurement [1]
g_{av2}	No measurement [1]
g_{av}	Measured based on two assumptions of $g_{av2}=0$ and $g_w=0.97$ [1]
g_w	The latest and most precise measurement is $g_w=0.15\pm0.30$ [2]

The assumption of $g_{av2}=0$ has not been verified

The assumption of $g_w=0.97$ deviates from the measurement 2.7σ

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- 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)

More solid $|V_{us}|$ from hyperon

[1] PDG 2024 [2] Phys. Rev. D **41**, 780 (1990).

Discussion and perspective

BESIII

$\sim$2k events of $\Lambda \to pe^-\bar{\nu}_e$

$|V_{us}| = xxx \pm (\sim 0.010_{\text{exp}})$, using Cabibbo $f_1(0)$

100× statistics at STCF

Assuming the systematical uncertainty is comparable to the statistical one.

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$\sim$0.2M events of $\Lambda \to pe^-\bar{\nu}_e$

$|V_{us}| = xxx \pm (\sim 0.0013_{\text{exp}})$, using Cabibbo $f_1(0)$

Comparable to the averaged $\sigma_{|V_{us}|}$ from Kaon ($\sim$0.0009) are Tau ($\sim$0.0014)

Inputs from theorists are needed !!!

$f_1(0)$ from LQCD

Precision calculation for the radiative correction

Summary

- The proposed STCF is expected to collect 1 trillion J/ψ and then provide $\sim 10^9$ hyperon pairs per year, which enables us to pursue precision hyperon selmileptonic decay physics including:
  - ① Test the lepton flavor universality
  - ② Search for second-class currents
  - ③ Test the CKM matrix unitarity

- To achieve these goals, inputs from theorists are needed !!!

Thank you~!