

Hyperon semileptonic weak decays at BESIII

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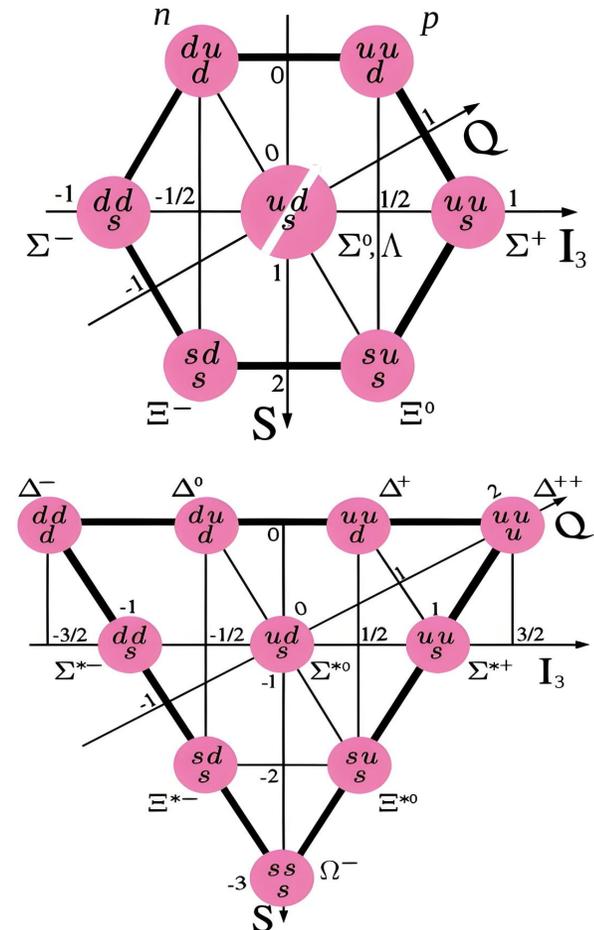
华北电力大学

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/// The hyperons

- Hyperons are the strange siblings of the proton and neutron

- **Half lives:** $\tau_Y \sim 10^{-10} \text{s}$;
 - ✓ 10^{-2} of τ for K^+, K_L
- **Rich phenomenology:**
 - ✓ Spin \rightarrow sensitivity to various NP structures
 - ✓ SU(3)-relations to nucleon-structure



/// Semileptonic decays: Extraction of V_{us}

Prelude: The Cabibbo-angle anomaly

In the SM: First-row unitarity relation

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

2.3 σ tension
 \longleftrightarrow
 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 ($|V_{ub}|^2 \cong 1.5 \times 10^{-5}$) → 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

☹️ $|V_{us}|$: $\sigma(|V_{us}|) = 2.6 \times \sigma(|V_{ud}|)$; inconsistency between results from different decays

[PRL 92, 251803 \(2004\)](#)

Most precise

Kaon: 2.2 σ tension from CKM unitarity

$$|V_{us}| = 0.2243 \pm 0.0008$$

PDG 2024

Second most precise

Tau: 3.6 σ deviation from CKM unitarity

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

HFLAV 2022

Largest uncertainty

Hyperon: consistent with CKM unitarity

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

Dominated by the $\Lambda \rightarrow pe^- \bar{\nu}_e$

2.2 σ tension

Semileptonic hyperon decays gives additional inputs for $|V_{us}|$!

/// Semileptonic decays: Extraction of V_{us}

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

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

[PRD 70, 114036 \(2004\)](#)

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

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

➤ Extracting $|V_{us}|$, requires $\mathcal{B}_{\Lambda \rightarrow pe^{-}\bar{\nu}_e}$, $f_1(0)$, $g_{av} \equiv \frac{g_1(0)}{f_1(0)}$, $g_w \equiv \frac{f_2(0)}{f_1(0)}$, and $g_{av2} \equiv \frac{g_2(0)}{f_1(0)}$,

□ $f_1(0)$: From LQCD

[PRL 114, 161802 \(2015\)](#)

□ $\mathcal{B}_{\Lambda \rightarrow pe^{-}\bar{\nu}_e}$, g_{av} , g_w , and g_{av2} : From experimental measurement

f_1 : the vector form factor

g_1 : the axial-vector form factor

f_2 : the weak-magnetism form factor

g_2 : the weak electric form factor

/// Semileptonic decays: Current status of $\mathcal{B}_{\Lambda \rightarrow pe^- \bar{\nu}_e}$

 Only relative BF

 Old results (>40 years)

 Only fixed target experiment

$\Gamma(\Lambda \rightarrow pe^- \bar{\nu}_e) / \Gamma(\Lambda \rightarrow p\pi^-)$		PDG 2024		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	$\pi^- p \rightarrow K^0 \Lambda$	
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	

/// Semileptonic decays: Current status of g_{AV}

 All assume $g_2 = 0$

 Old results (>30 years)

 Only fixed target experiment

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

PDGID:S018AV INSP

PDG 2024

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			
$-0.719 \pm 0.016 \pm 0.012$	37k	¹ DWORKIN	1990 SPEC	$e\nu$ angular corr.
-0.70 ± 0.03	7111	BOURQUIN	1983 SPEC	$\Xi \rightarrow \Lambda \pi^-$
-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

/// Semileptonic decays: Current status of g_w , and g_{av2}

g_w :



Results are old and scarce



3.05σ deviation

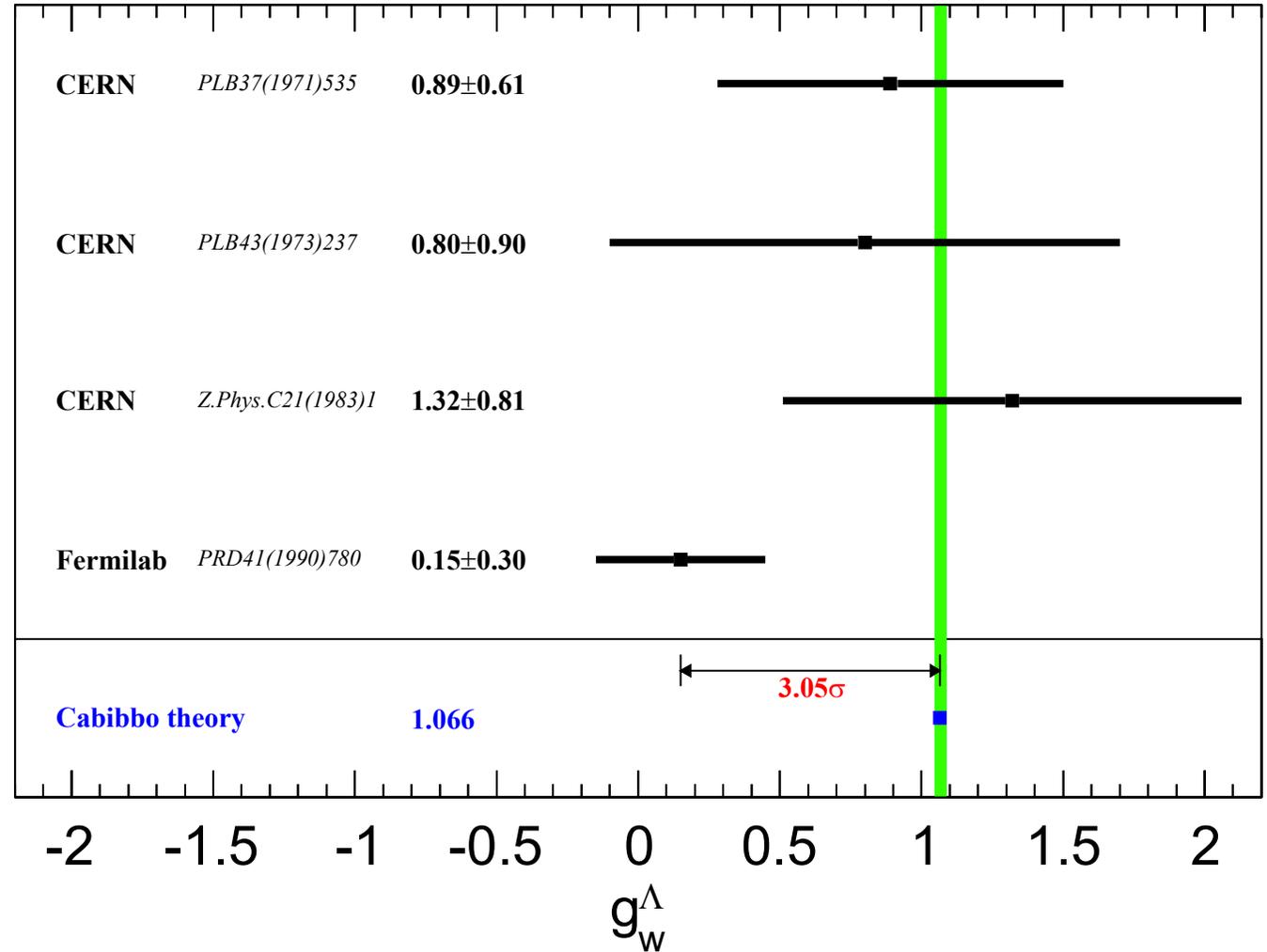


Only fixed target experiment

g_{av2} :



No experimental measurement



/// Semileptonic decays: The lepton-universality Test

$$R_{B_1 B_2} = \frac{\Gamma(B_1 \rightarrow B_2 \mu^- \bar{\nu}_\mu)}{\Gamma(B_1 \rightarrow B_2 e^- \bar{\nu}_e)}$$

SM: Only phase-space up to $\mathcal{O}(\delta^2)$! [Chang, Gonzalez-Alonso and JMC PRL114\(2015\)16,161802](#)

$$R_{B_1 B_2}^{\text{SM}} = \sqrt{1 - \frac{m_\mu^2}{\Delta^2}} \left(1 - \frac{9}{2} \frac{m_\mu^2}{\Delta^2} - 4 \frac{m_\mu^4}{\Delta^4} \right) + \frac{15}{2} \frac{m_\mu^4}{\Delta^4} \operatorname{arctanh} \left(\sqrt{1 - \frac{m_\mu^2}{\Delta^2}} \right)$$

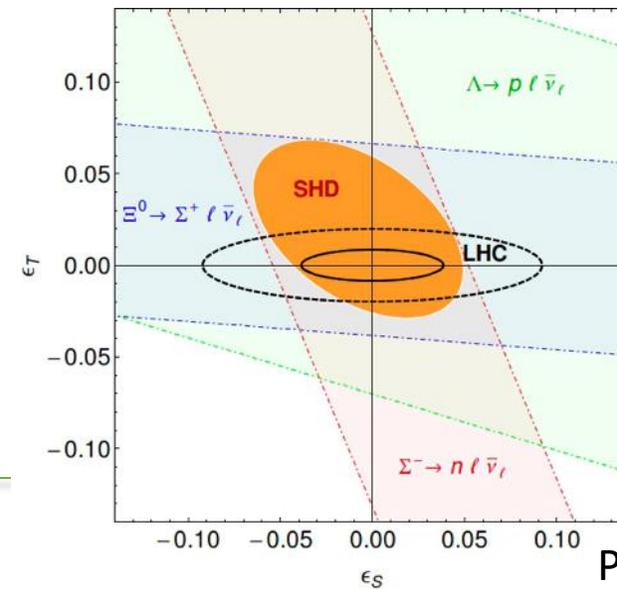
$R^{\mu e}$	$\Lambda \rightarrow p l^- \bar{\nu}_l$	$\Sigma^- \rightarrow n l^- \bar{\nu}_l$	$\Xi^0 \rightarrow \Sigma^+ l^- \bar{\nu}_l$	$\Xi^- \rightarrow \Lambda l^- \bar{\nu}_l$
Experiment	0.189 ± 0.041	0.442 ± 0.039	0.0092 ± 0.0014	0.6 ± 0.5
SM NLO	0.153 ± 0.008	0.444 ± 0.022	0.0084 ± 0.0004	0.275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

LUV does not depend on FFs up to $\mathcal{O}(\delta^2)$

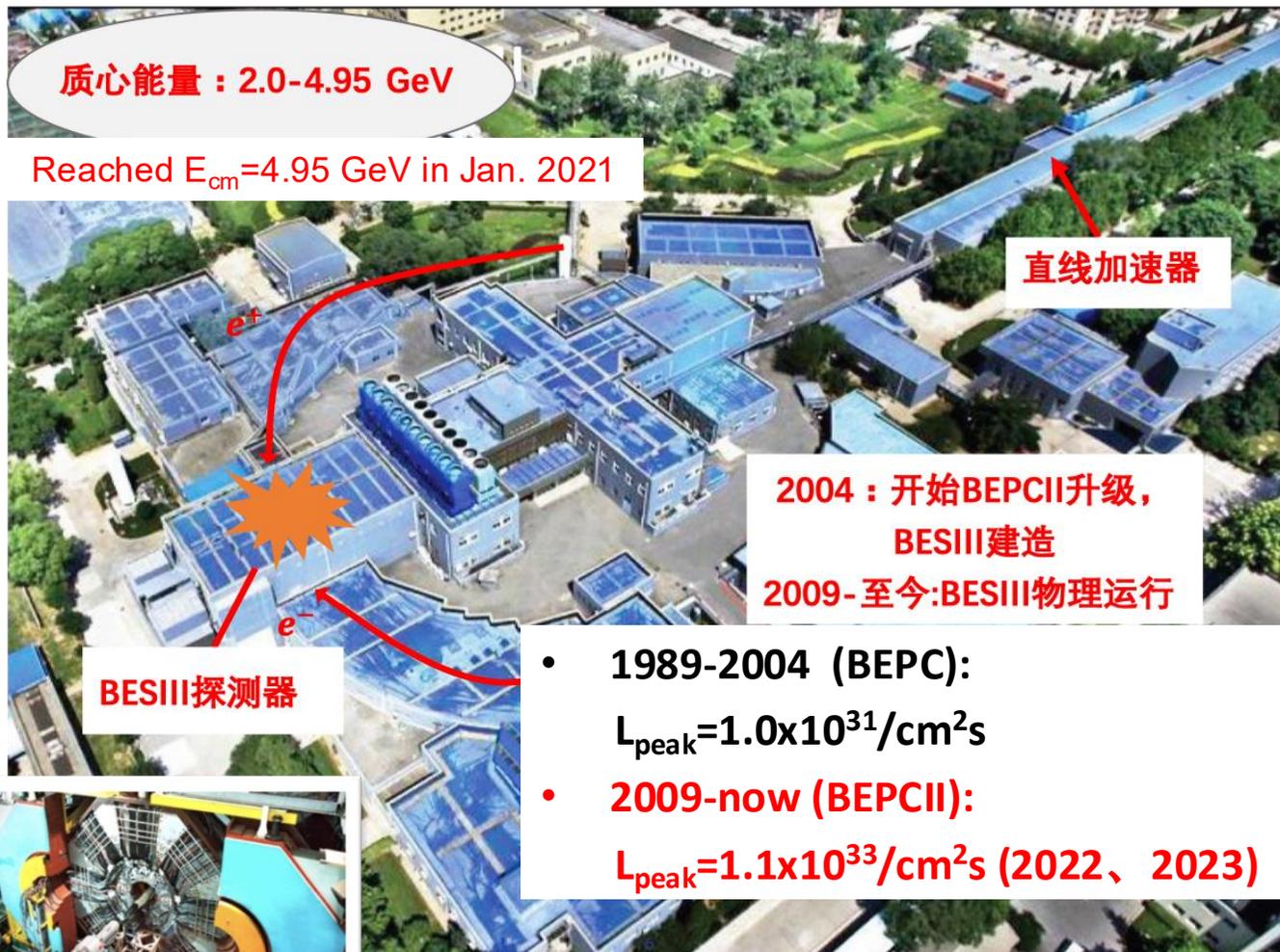
New-Physics:

Scalar and tensor operators

$$\mathcal{L}_{\text{NP}} \supset \frac{G_F V_{us}}{\sqrt{2}} \left(\epsilon_T (\bar{u} \sigma^{\mu\nu} (1 - \gamma_5) s) (\bar{\ell} \sigma_{\mu\nu} (1 - \gamma_5) \nu) + (\bar{u} (\epsilon_S - \epsilon_P \gamma_5) s) (\bar{\ell} (1 - \gamma_5) \nu) \right)$$

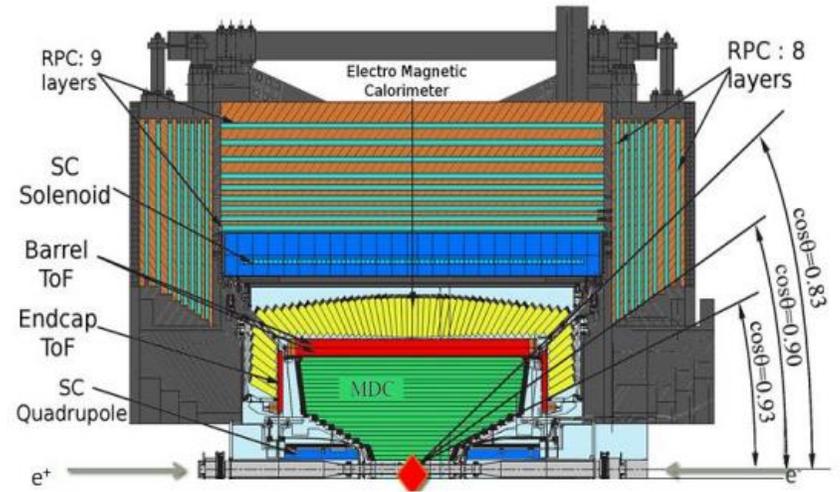


/// BEPCII and BESIII



Electromagnetic Calorimeter
 CsI(Tl): $L=28$ cm
 Barrel $\sigma_E=2.5\%$
 Endcap $\sigma_E=5.0\%$

Muon Counter RPC
 Barrel: 9 layers
 Endcap: 8 layers
 $\sigma_{\text{spatial}}=1.48$ cm



Main Drift Chamber
 Small cell, 43 layer
 $\sigma_{xy}=130$ μm
 $dE/dx \sim 6\%$
 $\sigma_p/p = 0.5\%$ at 1 GeV

Time Of Flight
 Plastic scintillator
 $\sigma_T(\text{barrel})=80$ ps
 $\sigma_T(\text{endcap})=110$ ps
 (update to 65 ps with MRPC)

Hyperon Study at BESIII

10 billion J/ψ and 3 billion $\psi(2S)$ events collected

Large BF's in J/ψ decays

Large datasets of hyperon pair

Hyperon pair production

Double tag method

Polarized-hyperon Quantum correlated factories (BESIII&SCTF)

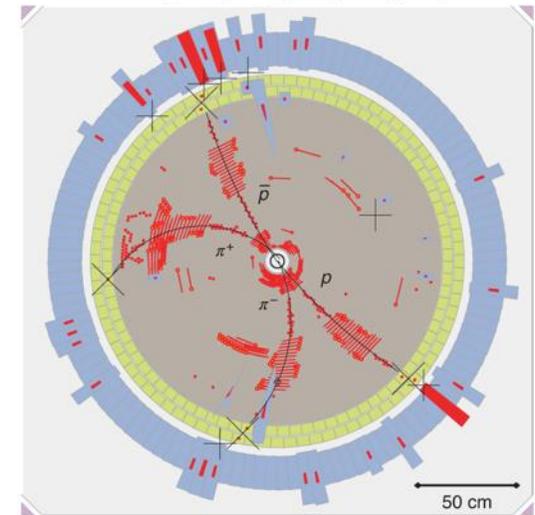
Decay mode	$\mathcal{B}(\times 10^{-3})$	$N_{B\bar{B}}(\times 10^6)$
$J/\psi \rightarrow \Lambda\bar{\Lambda}$	1.89 ± 0.09	19.06 ± 0.91
$J/\psi \rightarrow \Sigma^0\bar{\Sigma}^0$	1.17 ± 0.03	11.82 ± 0.32
$J/\psi \rightarrow \Sigma^+\bar{\Sigma}^-$	1.50 ± 0.24	15.13 ± 2.42
$J/\psi \rightarrow \Sigma(1385)^-\bar{\Sigma}^+$ (or c.c.)	0.31 ± 0.05	3.13 ± 0.50
$J/\psi \rightarrow \Sigma(1385)^-\bar{\Sigma}(1385)^+$ (or c.c.)	1.16 ± 0.05	11.70 ± 0.50
$J/\psi \rightarrow \Xi^0\bar{\Xi}^0$	1.17 ± 0.04	11.80 ± 0.40
$J/\psi \rightarrow \Xi^-\bar{\Xi}^+$	0.97 ± 0.08	9.78 ± 0.81
$J/\psi \rightarrow \Xi(1530)^0\bar{\Xi}^0$	0.32 ± 0.14	3.23 ± 1.41
$J/\psi \rightarrow \Xi(1530)^-\bar{\Xi}^+$	0.32 ± 0.01	3.21 ± 0.08
$\psi(2S) \rightarrow \Omega^-\bar{\Omega}^+$	0.05 ± 0.004	0.16 ± 0.01

4-momentum conservation

Known initial 4-momentum

Information on the neutrino

$J/\psi \rightarrow (\Lambda \rightarrow p\pi^-)(\bar{\Lambda} \rightarrow \bar{p}\pi^+)$



Nature Physics 15, 631-634(2019)

Advantage of double tag method:

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

/// Determination of CKM matrix element and axial vector form factors from weak decays of quantum-entangled strange baryons

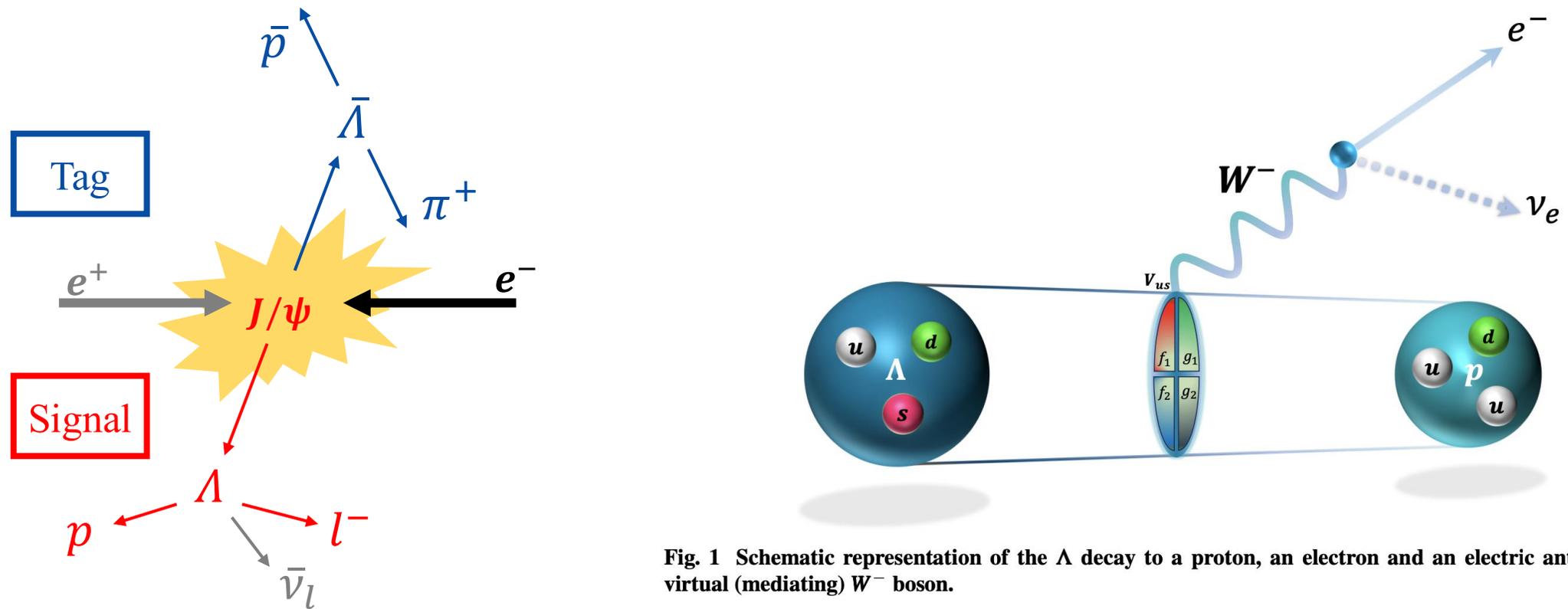
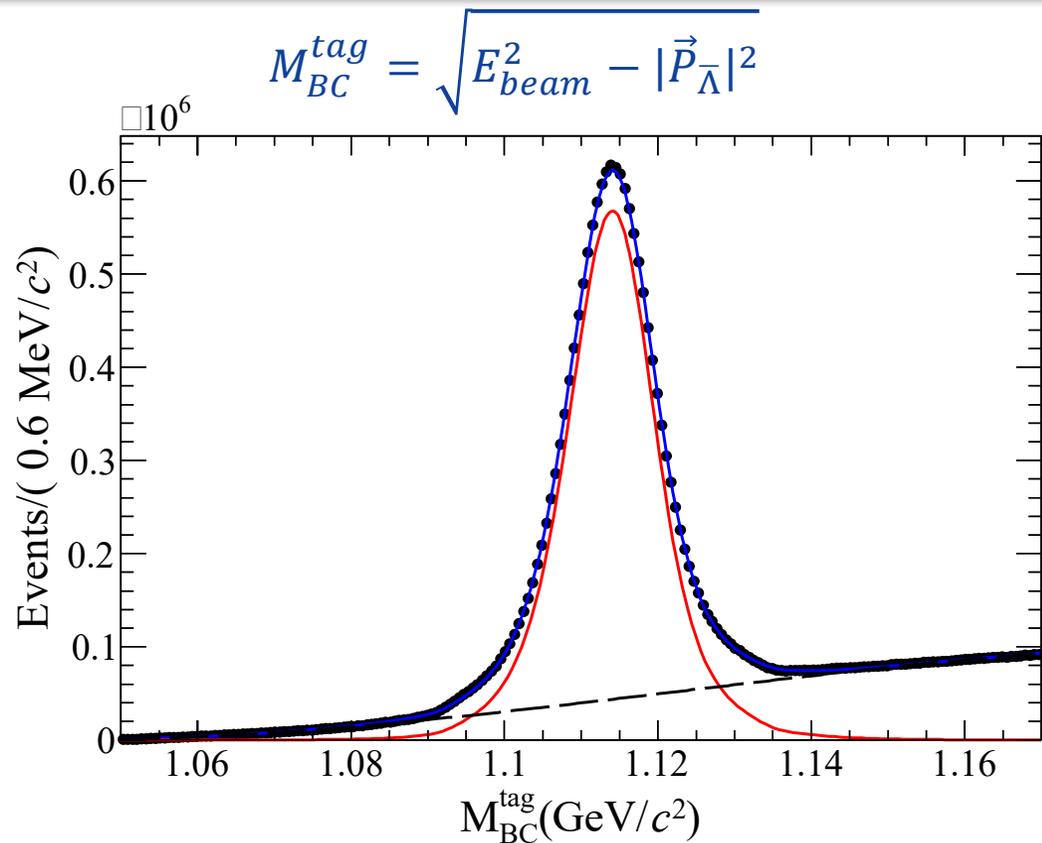


Fig. 1 Schematic representation of the Λ decay to a proton, an electron and an electric anti-neutrino via virtual (mediating) W^- boson.

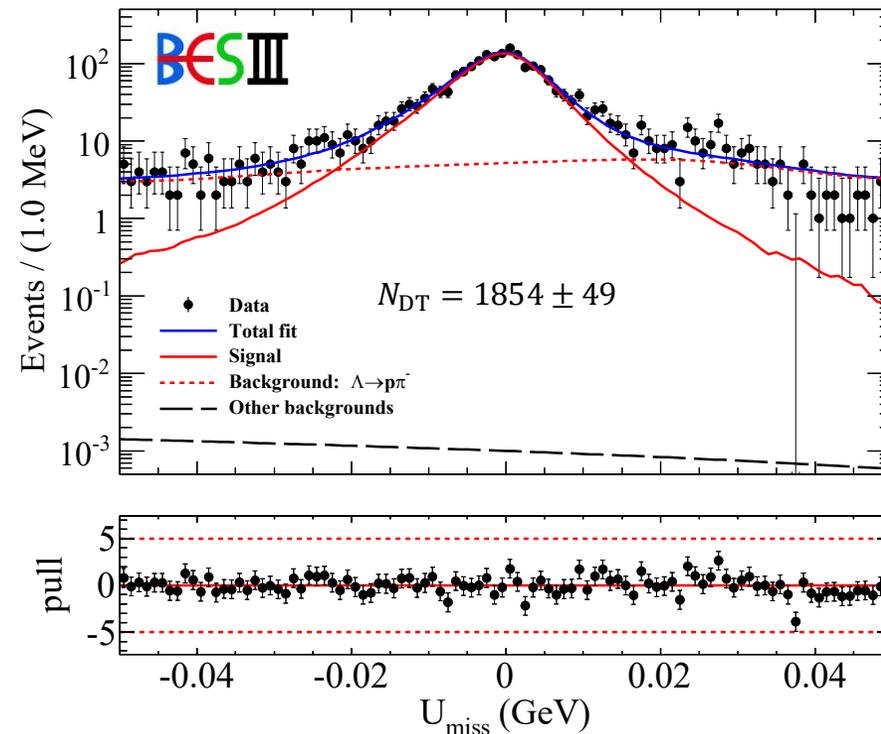
/// First absolute BF measurement of $\Lambda \rightarrow pe^- \bar{\nu}_e$



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

First absolute BF measurement

$$\mathcal{B}(\Lambda \rightarrow pe^- \bar{\nu}_e) = (8.16 \pm 0.22 \pm 0.15) \times 10^{-4}$$



BESIII: arXiv:2509.09266

/// Determination of form factors of $\Lambda \rightarrow p e^- \bar{\nu}_e$

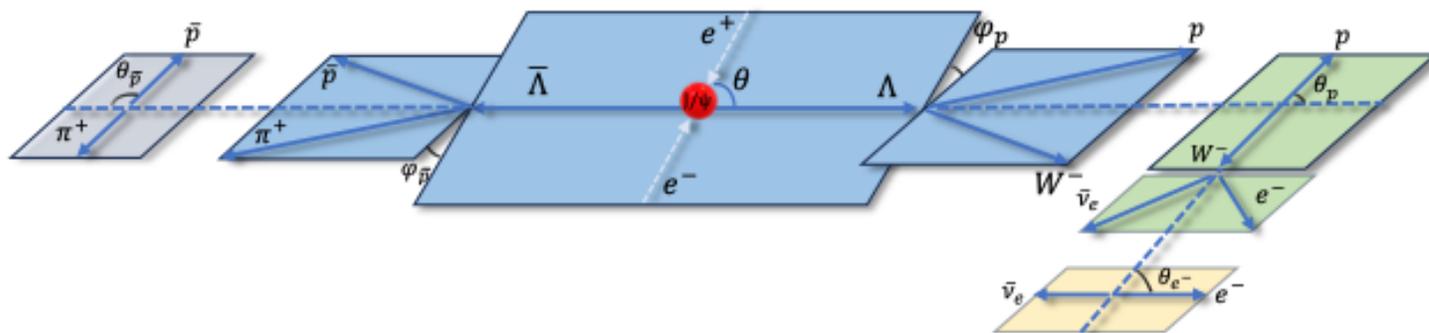
Observable	This work	Previous result
g_{av}^-	$0.742_{-0.057}^{+0.075} \pm 0.009$	0.718 ± 0.015 [PDG2024]
g_{av}^+	$-0.706_{-0.073}^{+0.069} \pm 0.014$	-
$\langle g_{av} \rangle$	$0.729_{-0.047}^{+0.048} \pm 0.007$	-
g_w^-	$0.93 \pm 0.51 \pm 0.17$	0.15 ± 0.30 [PRD41(1990)780]
g_w^+	$0.89 \pm 0.49 \pm 0.20$	-
$\langle g_w \rangle$	$0.89 \pm 0.35 \pm 0.14$	-
$\langle g_{av} \rangle$	$0.706_{-0.086}^{+0.089}$	-
$\langle g_w \rangle$	$0.77_{-0.49}^{+0.53}$	-
$\langle g_{av2} \rangle$	$-0.19_{-0.63}^{+0.65}$	-

BESIII: arXiv:2509.09266

Used approach allows FF extraction with reasonable uncertainties using limited data

Assuming $g_{av2} = 0$

- This work:
 $1.8 \cdot 10^3$ events $\rightarrow \sigma_{\langle g_{av} \rangle} = 0.049$
- Fermilab [PRD41(1990)780]:
 $37 \cdot 10^3$ events $\rightarrow \sigma_{g_{av}} = 0.020$



- The first exploitation of polarization and quantum entanglement in baryon semi-leptonic decays.
- The first usage of joint angular-distribution fit method in hyperon semi-leptonic decays.

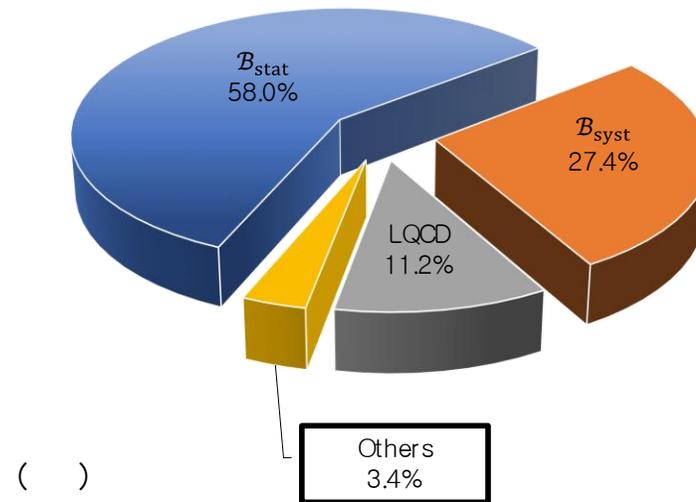
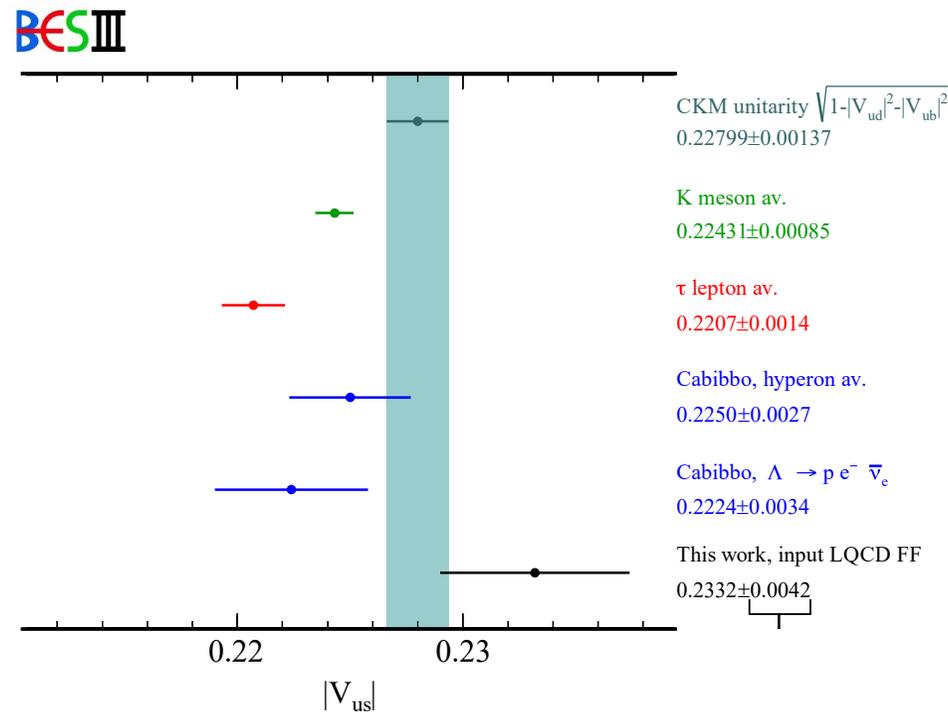
$$\omega = \{ \alpha_\psi, \Delta\Phi, g_{av}, g_w, g_{av2}, \alpha_+ (\alpha_-) \}$$

Extraction of $|V_{us}|$ from $\Lambda \rightarrow p e^- \bar{\nu}_e$

- Assume SU(3) is conserved, $f_1 = \sqrt{3/2}$ [PRL92(2004)251803]
 $|V_{us}|_{\text{SU}(3)} = 0.2190 \pm 0.0036_{\text{BESIII BF}} \pm 0.0087_{\text{BESIII FF}} \pm 0.0004_{\tau_\Lambda} \pm 0.0005_{\text{RC}}$

BESIII: arXiv:2509.09266

- Using LQCD FF prediction [arXiv:2507.09970]
 $|V_{us}|_{\text{LQCD}} = 0.2339 \pm 0.0038_{\text{BESIII BF}} \pm 0.0011_{\text{LQCD}} \pm 0.0004_{\tau_\Lambda} \pm 0.0006_{\text{RC}}$



STCF!!!

/// Impact of LQCD Calculations on $|V_{us}|$ Measurement Precision

Impact of LQCD Calculations on $|V_{us}|$ Measurement Precision

LQCD calculation: PRL **135**, 231901 (2025)

BESIII measurement, arXiv:2509.09266

Before LQCD Publication

$$|V_{us}|_{\text{SU}(3)} = 0.2190 \pm 0.0094$$

Dominant Uncertainty :

BESIII form factor: ± 0.0087

Total uncertainty $\downarrow \sim 56\%$



Form factor uncertainty $\downarrow \sim 87\%$

After LQCD Publication

$$|V_{us}|_{\text{LQCD}} = 0.2339 \pm 0.0041$$

Reduced Uncertainty:

LQCD form factor: ± 0.0011

LQCD improves the precision of $|V_{us}|$ by more than twofold, **reducing the total uncertainty from 0.0094 to 0.0041**
Theoretical inputs are so important!

/// First absolute BF measurement of $\Xi^- \rightarrow \Lambda e^- \bar{\nu}_e$

- Before our measurement, the experimental information comes only from **fixed-target experiments** which were performed about 40 years ago.
- All these previous branching fraction results are **relative**.

$\Gamma_3 \quad \Xi^- \rightarrow \Lambda e^- \bar{\nu}_e$
 $(5.63 \pm 0.31) \times 10^{-4}$
190

[▶ expand all datablocks](#)

$[\Gamma(\Xi^- \rightarrow \Lambda e^- \bar{\nu}_e) + \Gamma(\Xi^- \rightarrow \Sigma^0 e^- \bar{\nu}_e)] / \Gamma(\Xi^- \rightarrow \Lambda \pi^-)$ $(\Gamma_3 + \Gamma_5) / \Gamma_1$

VALUE (10 ⁻³)	EVTS	DOCUMENT ID	TECN	COMMENT
• • We do not use the following data for averages, fits, limits, etc. • •				
0.651 ± 0.031	3011	¹ BOURQUIN	1983	SPEC SPS hyperon beam
0.68 ± 0.22	17	² DUCLOS	1971	OSPK

¹ See the separate BOURQUIN 1983 values for $\Gamma(\Xi^- \rightarrow \Lambda e^- \bar{\nu}_e) / \Gamma(\Xi^- \rightarrow \Lambda \pi^-)$ and $[\Gamma(\Xi^- \rightarrow \Sigma^0 e^- \bar{\nu}_e) \Gamma(\Xi^- \rightarrow \Lambda \pi^-)]$ above.

² DUCLOS 1971 cannot distinguish Σ^0 's from Λ 's. The Cabibbo theory predicts the Σ^0 rate is about a factor 6 smaller than the Λ rate.

References ^

BOURQUIN 1983 ZPHY C21 1 Measurements of Hyperon Semileptonic Decays at the CERN Super Proton Synchrotron. 2. The $\Lambda \rightarrow p e^- \bar{\nu}_e$, $\Xi^- \rightarrow \Lambda e^- \bar{\nu}_e$, and $\Xi^- \rightarrow \Sigma^0 e^- \bar{\nu}_e$ Decay Modes

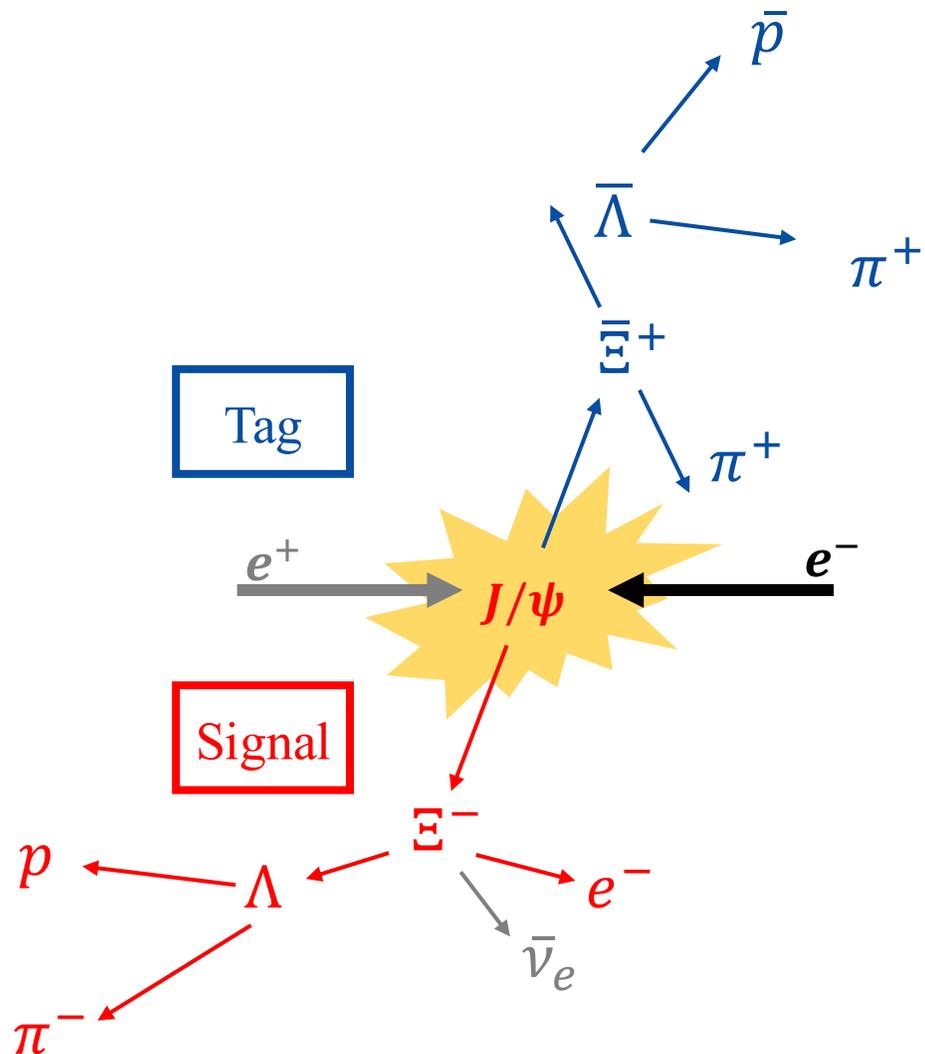
DUCLOS 1971 NP B32 493 A Spark Chamber Experiment of the β Decay of Ξ^- Hyperons

$\Gamma(\Xi^- \rightarrow \Lambda e^- \bar{\nu}_e) / \Gamma(\Xi^- \rightarrow \Lambda \pi^-)$ Γ_3 / Γ_1

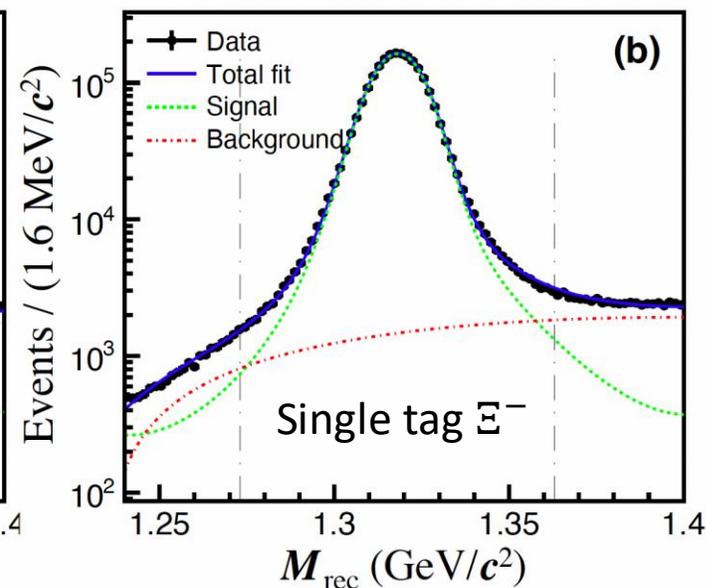
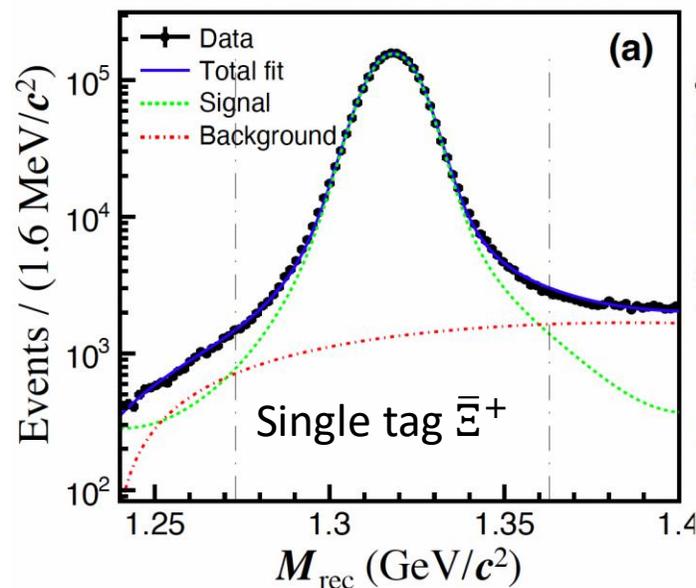
VALUE (10 ⁻³)	EVTS	DOCUMENT ID	TECN	COMMENT
0.564 ± 0.031	OUR FIT			
0.564 ± 0.031	2857	BOURQUIN	1983	SPEC SPS hyperon beam
• • We do not use the following data for averages, fits, limits, etc. • •				
0.30 ± 0.13	11	THOMPSON	1980	ASPK Hyperon beam

Study of the Semileptonic Decay $\Xi^- \rightarrow \Lambda e^- \bar{\nu}_e$

BESIII: arXiv:2512.15273

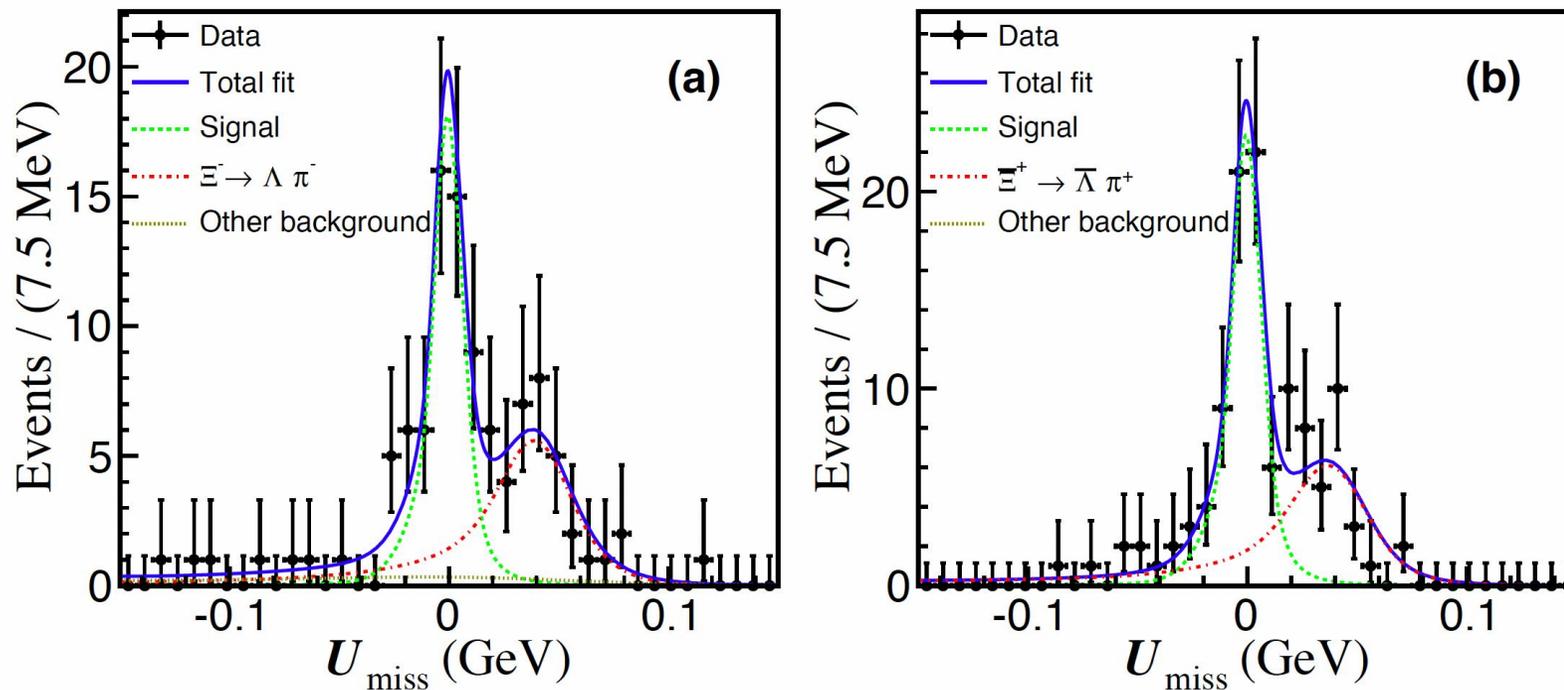


$$M_{rec} \equiv \sqrt{(E_{CM} - E_{\bar{\Lambda}\pi^+})^2 - |\vec{P}_{\bar{\Lambda}\pi^+}|^2}$$



$$N_{ST} = 2,069,000 \pm 2,000(stat) \quad N_{ST} = 2,157,000 \pm 2,000(stat)$$

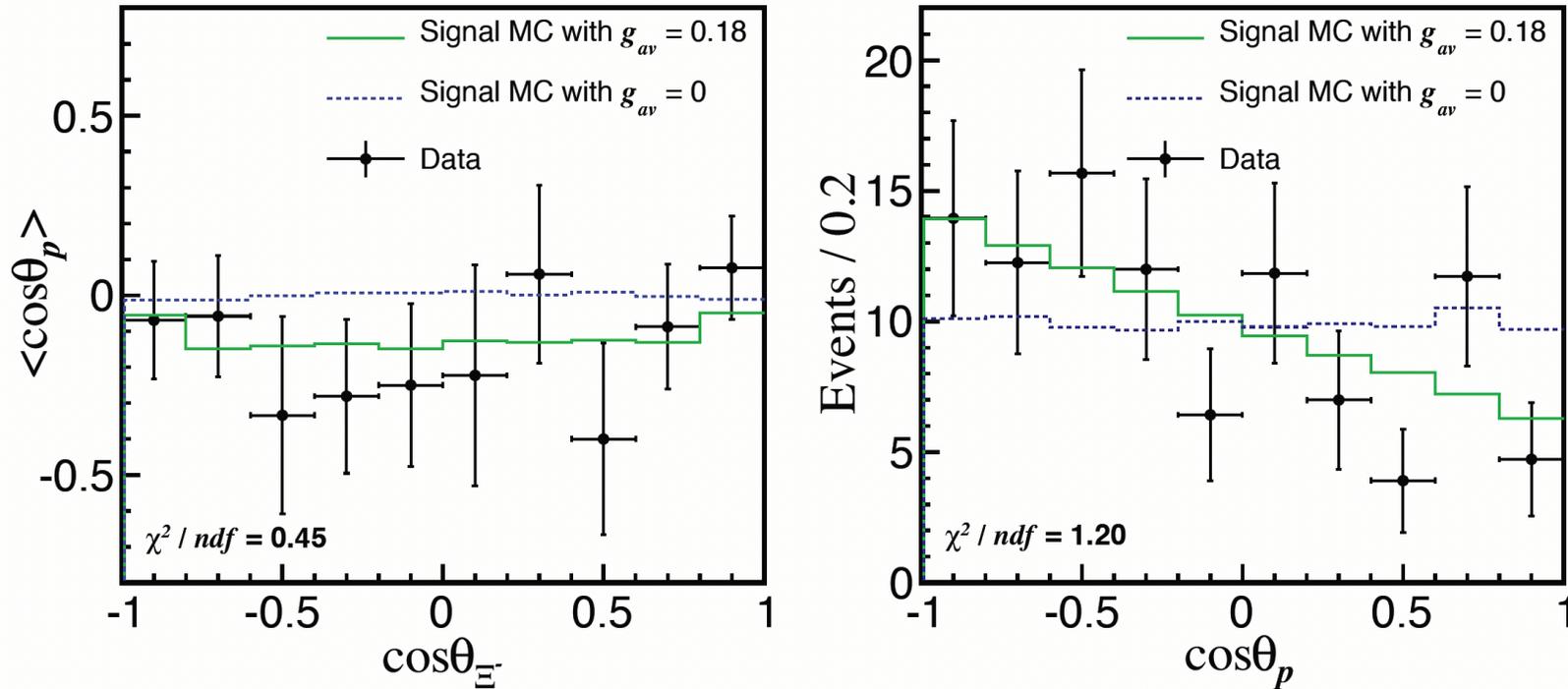
/// First absolute BF measurement of $\Xi^- \rightarrow \Lambda e^- \bar{\nu}_e$



Mode	$\Xi^- \rightarrow \Lambda e^- \bar{\nu}_e$	$\Xi^+ \rightarrow \bar{\Lambda} e^+ \nu_e$
$N_{\text{ST}}(10^3)$	2069 ± 2	2157 ± 2
$\epsilon_{\text{ST}}(\%)$	28.71 ± 0.02	30.53 ± 0.02
N_{DT}	49.4 ± 8.5	61.5 ± 9.4
$\epsilon_{\text{DT}}(\%)$	3.39 ± 0.02	3.18 ± 0.02
Indiv. BF(10^{-4})	3.13 ± 0.54	4.04 ± 0.62
Simul. BF(10^{-4})	$3.60 \pm 0.40 \pm 0.10$	

BESIII: arXiv:2512.15273

/// Determination of form factors of $\Xi^- \rightarrow \Lambda e^- \bar{\nu}_e$



$$\xi = (\theta_{\Xi^-}, \theta_{\Lambda}, \phi_{\Lambda}, \theta_{e^-}, \phi_{e^-}, \theta_p, \phi_p, \theta_{\bar{\Lambda}}, \phi_{\bar{\Lambda}}, \theta_{\bar{p}}, \phi_{\bar{p}})$$

$$\omega = (\alpha_{\Psi}, \Delta\Phi, \alpha_{\Xi^-}, \phi_{\Xi^-}, \alpha_{\bar{\Lambda}}, g_{av}, g_w, g_{av2}, \alpha_{\Lambda})$$

$$\mathcal{W}(\xi; \omega) = \sum_{\mu, \bar{\nu}=0}^3 \sum_{\mu'=0}^3 \sum_{\bar{\nu}'=0}^3 C_{\mu\bar{\nu}} B_{\mu\mu'}^{\Xi^-} A_{\mu'0}^{\Lambda} A_{\bar{\nu}\bar{\nu}'}^{\Xi^+} A_{\bar{\nu}'0}^{\bar{\Lambda}}$$

/// Summary of the Results for $\Xi^- \rightarrow \Lambda e^- \bar{\nu}_e$

- The axial-vector to vector coupling:

$$g_{av} = 0.18 \pm 0.07_{stat.} \pm 0.02_{syst.}$$

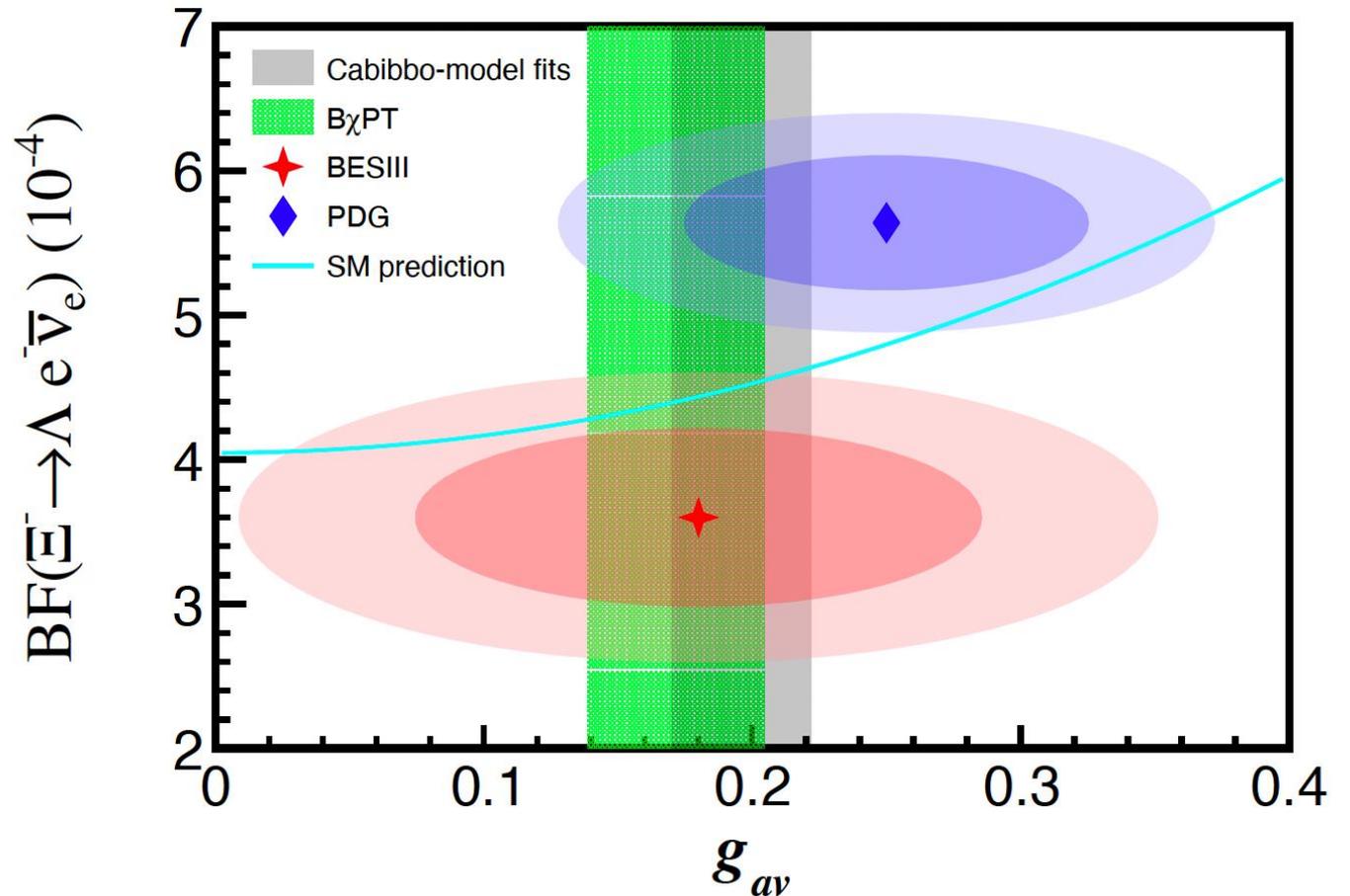
A comparable precision achieved with 1/20 data size

- Taking $f_1 = \sqrt{3/2}$, the axial charge of the Ξ^- :

$$\begin{aligned} g_A^H &= g_{av} \times f_1 \\ &= 0.22 \pm 0.08_{stat.} \pm 0.02_{syst.} \end{aligned}$$

Updated for the first time in over 40 years

- The absolute BF is lower than the PDG value by 3.9σ
- g_{av} is consistent with the previous result and in good agreement with prediction of chiral perturbation theory



BESIII: arXiv:2512.15273

/// First absolute BF measurement of $\Lambda \rightarrow p\mu^-\bar{\nu}_\mu$

- Before our measurement, the experimental information comes only from **fixed-target experiments**^[1-4] 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**.

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

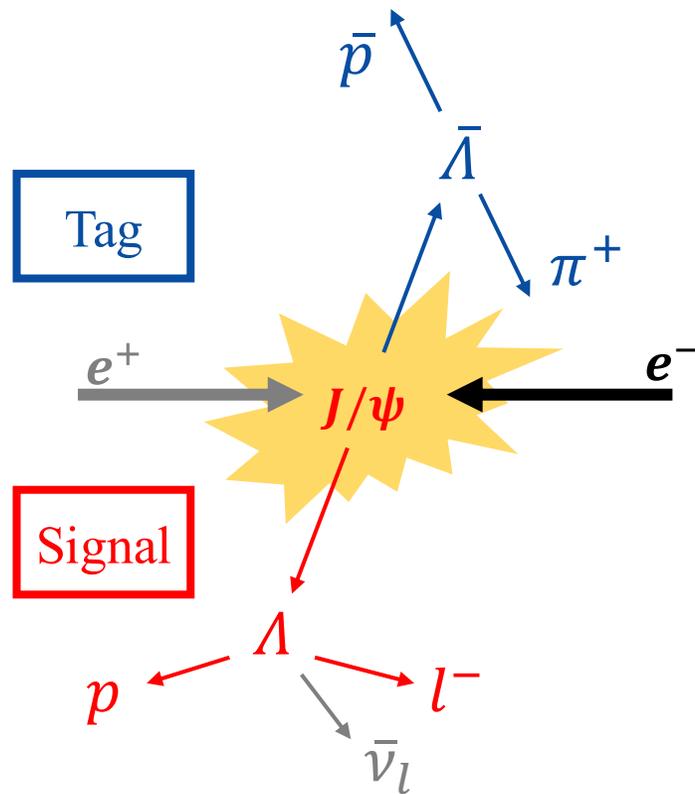
[1] Phys. Lett. **11**, 357 (1964)

[2] Stern, Phys. Rev. **135**, B1483 (1964)

[3] Phys. Rev. Lett. **27**, 59 (1971)

[4] Zeitschrift für Physik A Hadrons and nuclei **252**,362 (1972)

/// Double Tag method



The charge-conjugated channel is also implied.

$$N_{tag} = 2N_{\Lambda\bar{\Lambda}}\mathcal{B}_{tag}\epsilon_{tag}$$

$$N_{sig} = 2N_{\Lambda\bar{\Lambda}}\mathcal{B}_{tag}\mathcal{B}_{sig}\epsilon_{tag,sig}$$

$$\mathcal{B}_{sig} = \frac{N_{sig}/\epsilon_{tag,sig}}{N_{tag}/\epsilon_{tag}}$$

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

$N_{\Lambda\bar{\Lambda}}$: the number of $\Lambda\bar{\Lambda}$ pairs

\mathcal{B}_{tag} : branching fraction of $\bar{\Lambda} \rightarrow \bar{p}\pi^+$

\mathcal{B}_{sig} : **branching fraction of $\Lambda \rightarrow pl^-\bar{\nu}_l$**

N_{tag} : ST yield

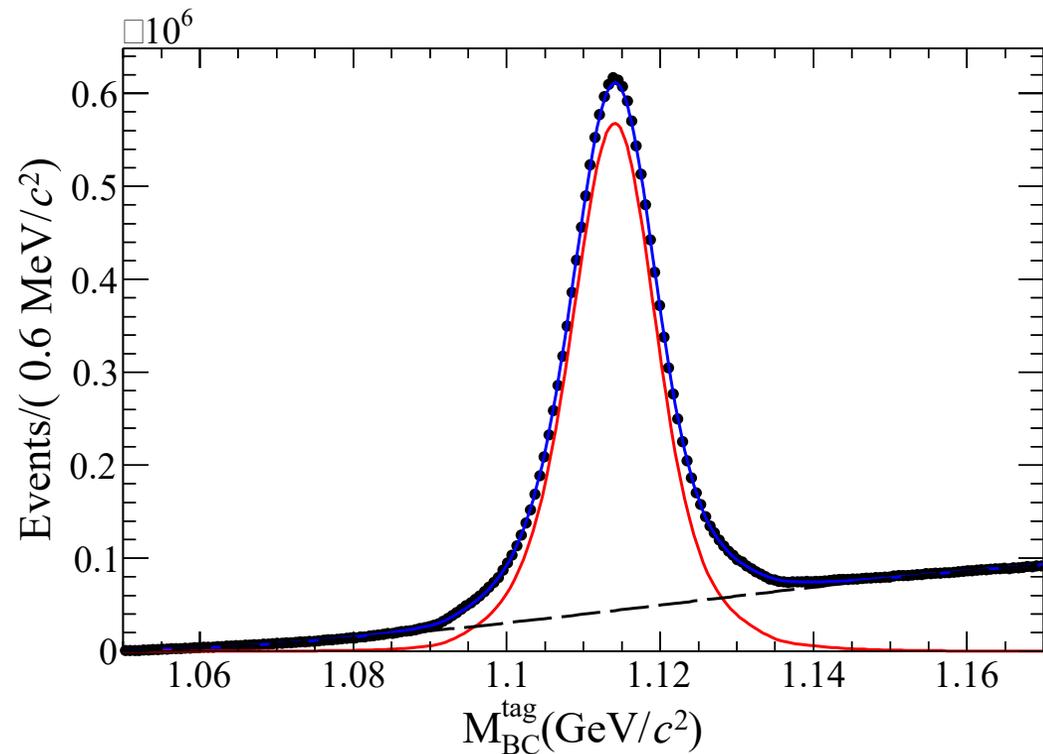
N_{sig} : DT yield

ϵ_{tag} : ST efficiency

$\epsilon_{tag,sig}$: DT efficiency

Obtained in the analysis

Number of observed $\bar{\Lambda}$ in single tag analysis



- ✓ **Signal:**
MC-simulated shape \otimes a double-Gaussian
- ✓ **Background:**
3rd order Chebyshev function

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

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

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

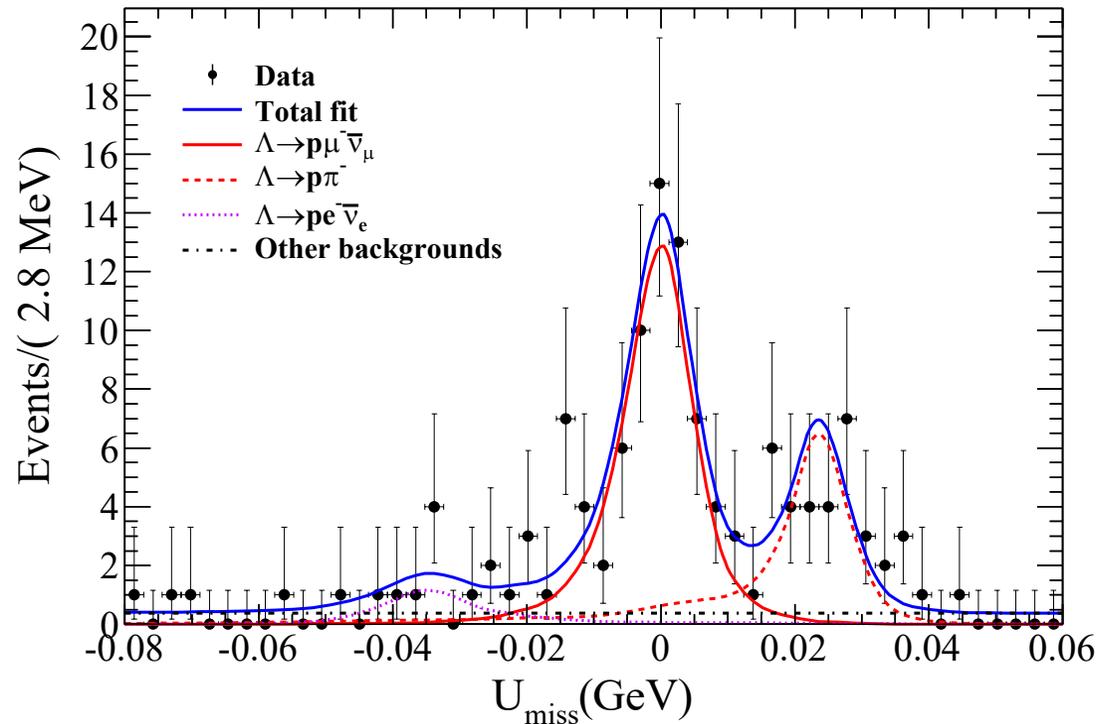
- The total ST $\bar{\Lambda}$ yield:

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

Reconstructed via $\bar{\Lambda} \rightarrow \bar{p}\pi^+$

Number of observed $\Lambda \rightarrow p\mu^-\bar{\nu}_\mu$ signals in double tag analysis from 10 billion J/ψ

BESIII: Phys. Rev. Lett. 127. 121802 (2021)



- The total DT yield:

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

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

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

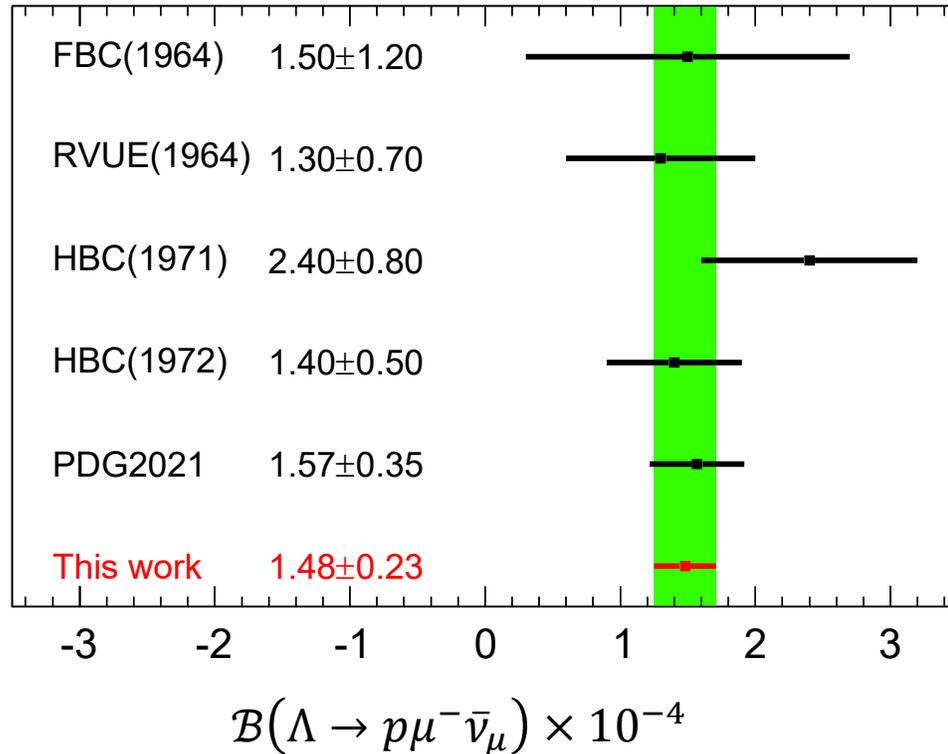
$$\vec{P}_{miss} = |\vec{P}_\Lambda - \vec{P}_p - \vec{P}_{\mu^-}|$$

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

- ✓ **Signal:** MC-simulated shape \otimes a Gaussian
- ✓ **Background 1:** MC-simulated shape from $J/\psi \rightarrow \Lambda\bar{\Lambda}$, $\Lambda \rightarrow p\pi^-$, $\bar{\Lambda} \rightarrow \bar{p}\pi^+$
- ✓ **Background 2 (dashed):** MC-simulated shape from $J/\psi \rightarrow \Lambda\bar{\Lambda}$, $\Lambda \rightarrow pe^-\bar{\nu}_e$, $\bar{\Lambda} \rightarrow \bar{p}\pi^+ + c.c.$
- ✓ **Other background (dashed):** 1st order polynomial

/// First absolute BF measurement of $\Lambda \rightarrow p\mu^-\bar{\nu}_\mu$

BESIII: Phys. Rev. Lett. 127, 121802 (2021)



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

Open a new area of studying hyperon semi-leptonic decays in electron-positron collisions!

Theory	Prediction of $\mathcal{B}(\Lambda \rightarrow p\mu^-\bar{\nu}_\mu) \times 10^{-4}$
SU(3) symmetry without symmetry breaking	1.40 ± 0.02
The factorization of the contribution of valence quarks and chiral effects	$1.50^{[1]}$

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

- ✓ The first absolute BF measurement.
- ✓ The most precise result to date.

/// The lepton-universality Test in $\Lambda \rightarrow p l^- \bar{\nu}_l$

Prediction from SM

PRL 114, 161802(2015)

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

Consistent
with LFU

Experimental measurement

From this work

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

From PDG 2021

BESIII: Phys. Rev. Lett. 127, 121802 (2021)

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

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

Consistent
with CP symmetry

- ✓ The $R^{\mu e}$ result agrees with the SM supporting NO LFUV.
- ✓ No evidence of CP violation.

Discussion and Prospect

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

[BESIII, PRL 127, 121802 \(2021\)](#)

BESIII



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

[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 !!!



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

STCF
超级陶粲装置
Super Tau-Charm Facility



$$R_{SM}^{\mu e} = 0.153 \pm 0.004$$

/// First direct absolute BF measurement of $\Sigma^+ \rightarrow \Lambda e^+ \nu_e$

- 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 form factor g_2 , and some of the polarized Λ experiments suggest a large g_2 [12].

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

where

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

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

[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).

/// First direct absolute BF measurement of $\Sigma^+ \rightarrow \Lambda e^+ \nu_e$

- In order to confirm the existence of **second-class currents**, a unique observable (R) was first proposed by S. Weinberg [13] in 1958.

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

- 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)

[13] Phys. Rev. **112**, 1375 (1958).

/// First direct absolute BF measurement of $\Sigma^+ \rightarrow \Lambda e^+ \nu_e$

➤ T. D. Lee and C. N. Yang [14] 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)

[14] Phys. Rev. **119**, 1410 (1960).

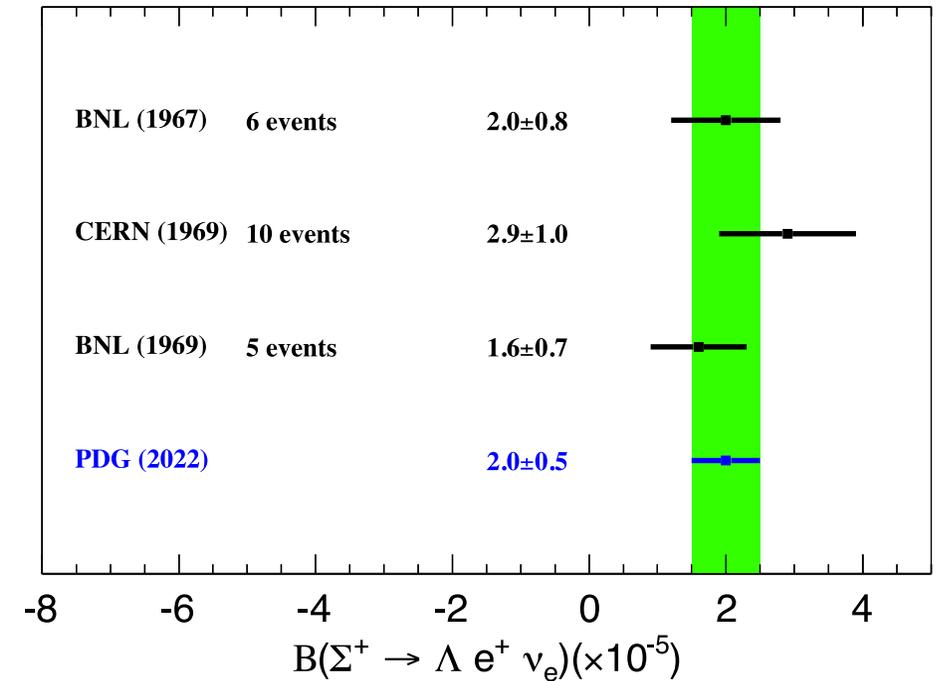
/// First direct absolute BF measurement of $\Sigma^+ \rightarrow \Lambda e^+ \nu_e$

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

PDG2022:

$$\sigma(\tau_{\Sigma^+}) \sim 0.003 \quad \sigma(\mathcal{B}(\Sigma^- \rightarrow \Lambda e^- \bar{\nu}_e)) \sim 0.047$$

$$\sigma(\tau_{\Sigma^-}) \sim 0.007 \quad \sigma(\mathcal{B}(\Sigma^+ \rightarrow \Lambda e^+ \nu_e)) \sim \mathbf{0.250}$$



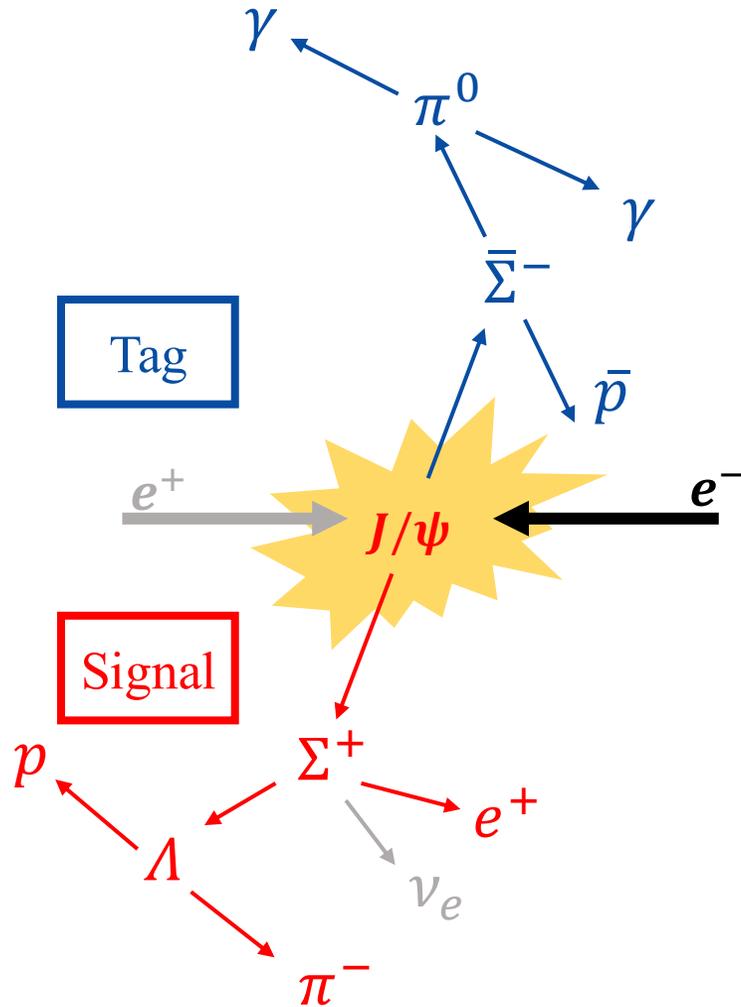
- The $\Sigma^+ \rightarrow \Lambda e^+ \nu_e$ was studied at the fixed-target experiments with the bubble chamber pictures, $\text{Br}(\Sigma^+ \rightarrow \Lambda e^+ \nu_e)$ was measured with indirect method
- All the experimentally determined R values are consistent with theoretical calculation, i.e. 1.57, within uncertainty.

/// First direct absolute BF measurement of $\Sigma^+ \rightarrow \Lambda e^+ \nu_e$

Previous experiment	BESIII
Fixed-target	e^+e^- collider
bubble chamber pictures	spectrometer system
Indirect measurement	Direct measurement

- ❑ A direct measurement of the absolute $\mathcal{B}(\Sigma^+ \rightarrow \Lambda e^+ \nu_e)$ is crucial to provide a more credible input.
- ❑ An independent measurement at a modern collider experiment is essential for higher precision and cross checking.

/// Double Tag method



$$N_{\text{tag}} = 2N_{\Sigma^+\bar{\Sigma}^-} \mathcal{B}_{\text{tag}} \epsilon_{\text{tag}}$$

$$N_{\text{sig}} = 2N_{\Sigma^+\bar{\Sigma}^-} \mathcal{B}_{\text{tag}} \mathcal{B}_{\text{sig}} \mathcal{B}_{\text{sig}}^{\text{sub}} \epsilon_{\text{tag,sig}}$$

$$\mathcal{B}_{\text{sig}} = \frac{N_{\text{sig}}/\epsilon_{\text{tag,sig}}}{N_{\text{tag}}/\epsilon_{\text{tag}}} \times \frac{1}{\mathcal{B}_{\text{sig}}^{\text{sub}}}$$

$N_{\Sigma^+\bar{\Sigma}^-}$: the number of $\Sigma^+\bar{\Sigma}^-$ pairs

\mathcal{B}_{tag} : branching fraction of tag channel

\mathcal{B}_{sig} : **branching fraction of signal channel**

$\mathcal{B}_{\text{sig}}^{\text{sub}}$: branching fraction of sub-decay

N_{tag} : ST yield

N_{sig} : DT yield

ϵ_{tag} : ST efficiency

$\epsilon_{\text{tag,sig}}$: DT efficiency

Obtained in the analysis

/// Number of observed $\bar{\Sigma}^-$ in single tag analysis

- Use the minimum $|\Delta E|$ to select the best ST candidates, where

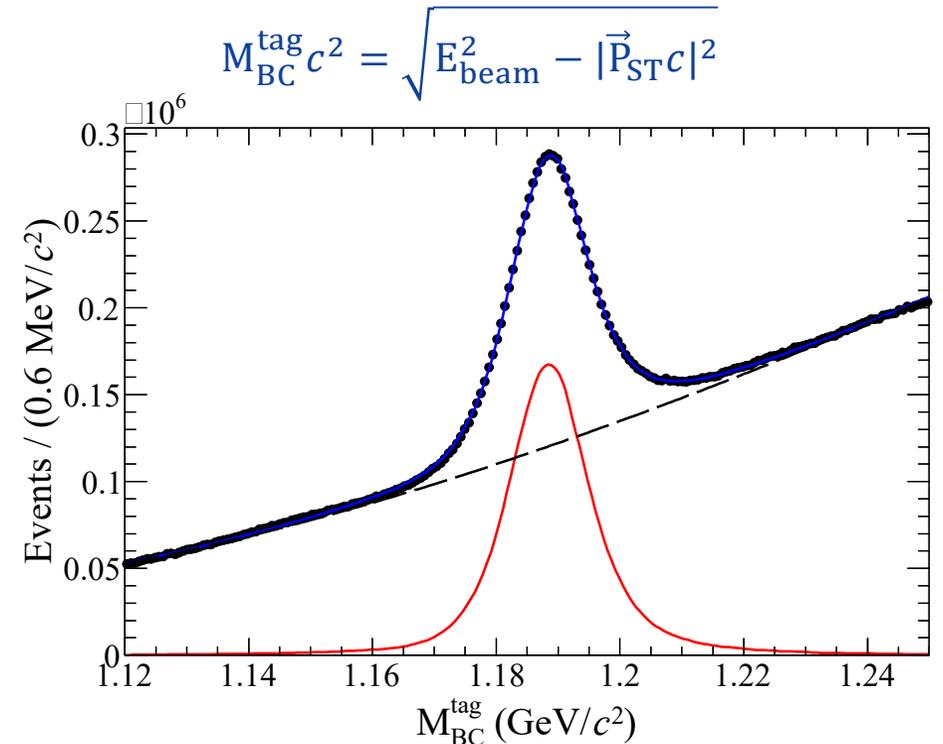
$$\Delta E \equiv E_{\text{beam}} - E_{\text{ST}}$$

- The ST signal yield is estimated in the mass region $|M_{\text{BC}}^{\text{tag}} - m_{\bar{\Sigma}^-}| < 0.049 \text{ GeV}/c^2$ which is corresponding to approximate $\pm 3\sigma$ of the $M_{\text{BC}}^{\text{tag}}$ distribution.

- The total ST yield:

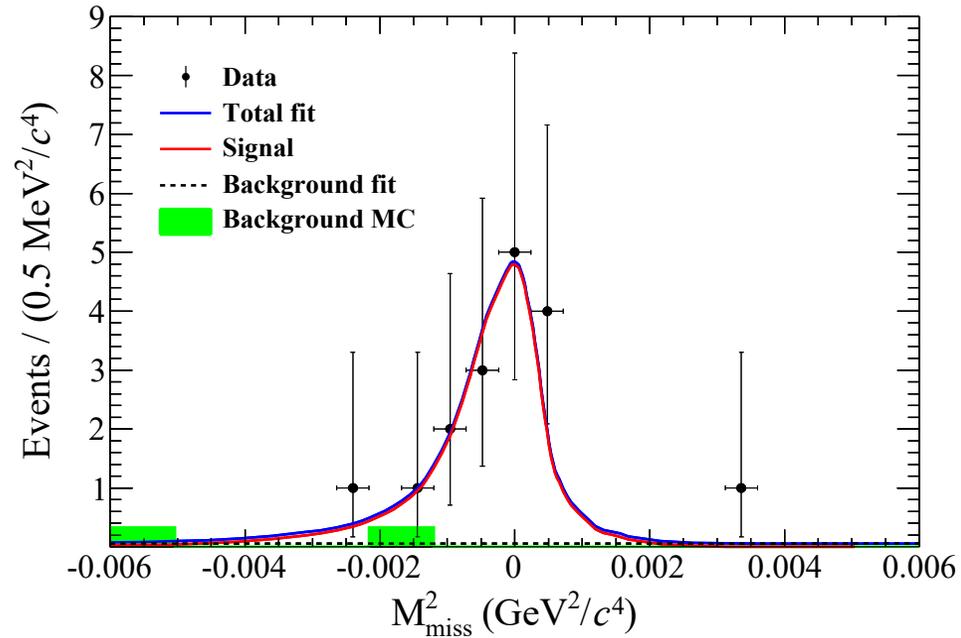
$$N_{\text{ST}} = 4,693,360 \pm 4,339(\text{stat})$$

BESIII: Phys. Rev. D 107. 072010 (2023)



- ✓ **Signal:**
MC-simulated shape \otimes a Gaussian resolution function
- ✓ **Background:**
3rd order Chebyshev function

/// Number of observed $\Sigma^+ \rightarrow \Lambda e^+ \nu_e$ signals in double tag analysis from 10 billion J/ψ



- ✓ **Signal:** MC shape \otimes a Gaussian resolution function
- ✓ **Background:** A flat shape

BESIII: Phys. Rev. D 107. 072010 (2023)

$$M_{\text{miss}}^2 c^4 = E_{\text{miss}}^2 - p_{\text{miss}}^2 c^2$$

$$E_{\text{miss}} = E_{\text{beam}} - E_{\Lambda} - E_{e^+}$$

$$p_{\text{miss}} = |\vec{p}_{\Sigma^+} - \vec{p}_{\Lambda} - \vec{p}_{e^+}|$$

$$\vec{p}_{\Sigma^+} = -\frac{\vec{p}_{\Sigma^-}}{c|\vec{p}_{\Sigma^-}|} \sqrt{E_{\text{beam}}^2 - m_{\Sigma^+}^2 c^4}$$

- The total DT yield:

$$N_{\text{DT}} = 15.7 \pm 4.0(\text{stat})$$

/// First Direct Measurement of the Absolute Branching

Fraction of $\Sigma^+ \rightarrow \Lambda e^+ \nu_e$

- ✓ The absolute branching fraction of $\Sigma^+ \rightarrow \Lambda e^+ \nu_e$ is measured at a collider experiment for the first time:

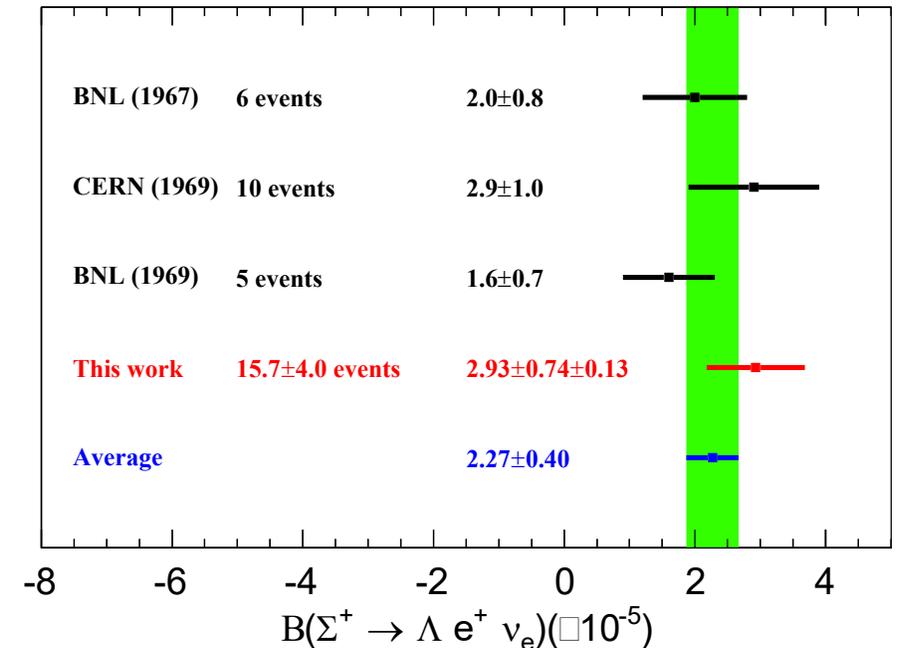
$$\mathcal{B}(\Sigma^+ \rightarrow \Lambda e^+ \nu_e) = [2.93 \pm 0.74(\text{stat}) \pm 0.13(\text{syst})] \times 10^{-5}$$

which is the **first direct measurement** of the

Σ^+ semileptonic decay rate and also the **most precise result**

obtained **in a single experiment**.

This results is consistent with all the previous measurements within uncertainty.



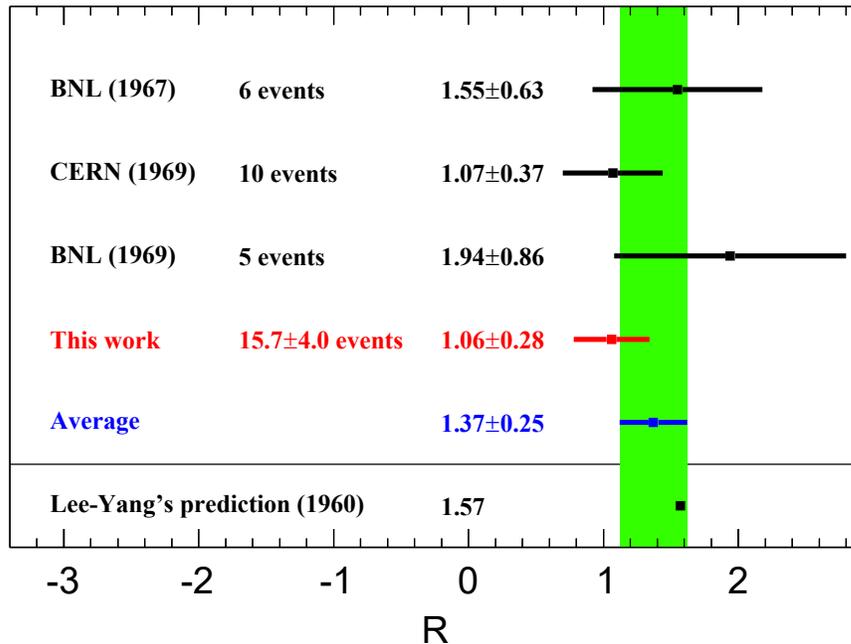
The “Average” denotes the updated weighted average value including our measurement.

BESIII: Phys. Rev. D 107. 072010 (2023)

SM test with R value

- ✓ Combining our result with the τ_{Σ^\pm} and $\mathcal{B}(\Sigma^- \rightarrow \Lambda e^- \bar{\nu}_e)$ from PDG, the R is determined to be:

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



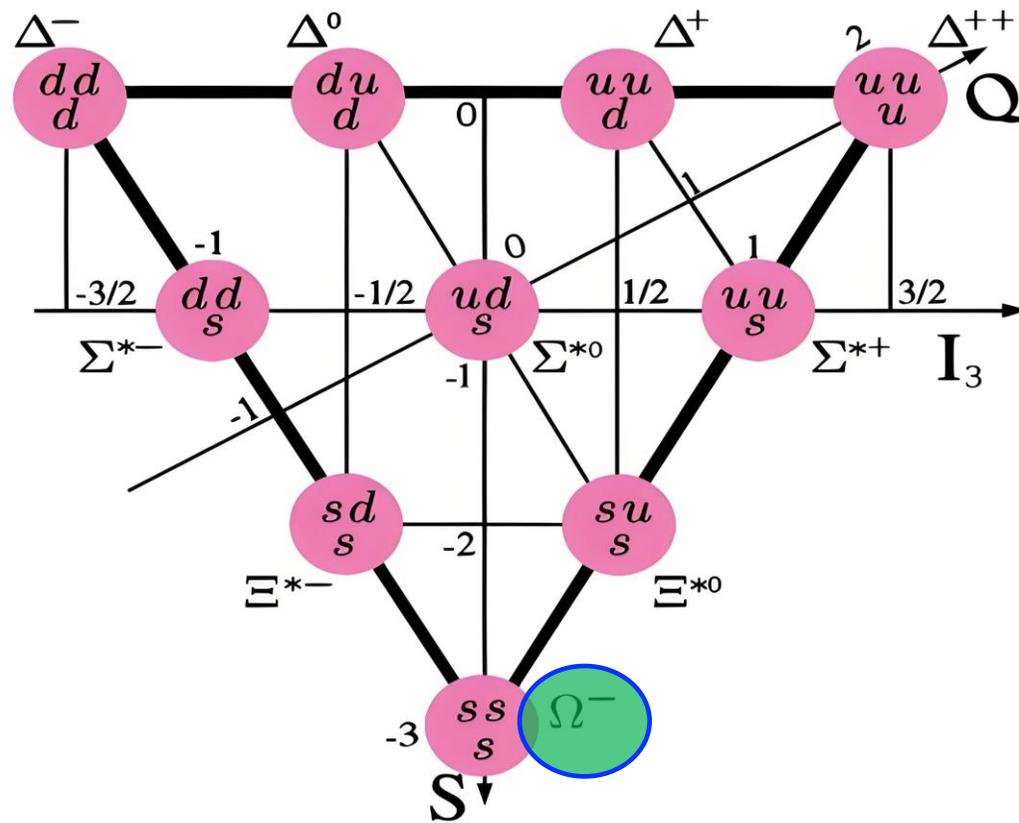
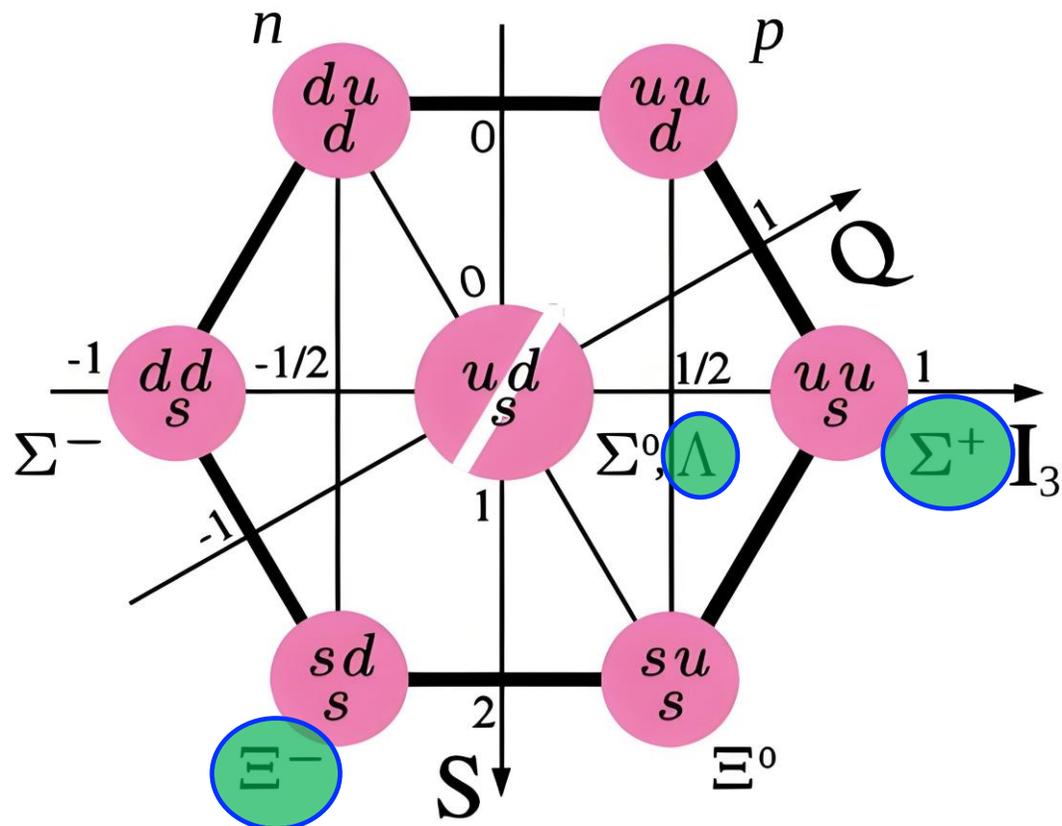
The **most precise measurement of R** in a single experiment, which **is still hard to judge the existence of second-class currents** that are excluded from the SM.

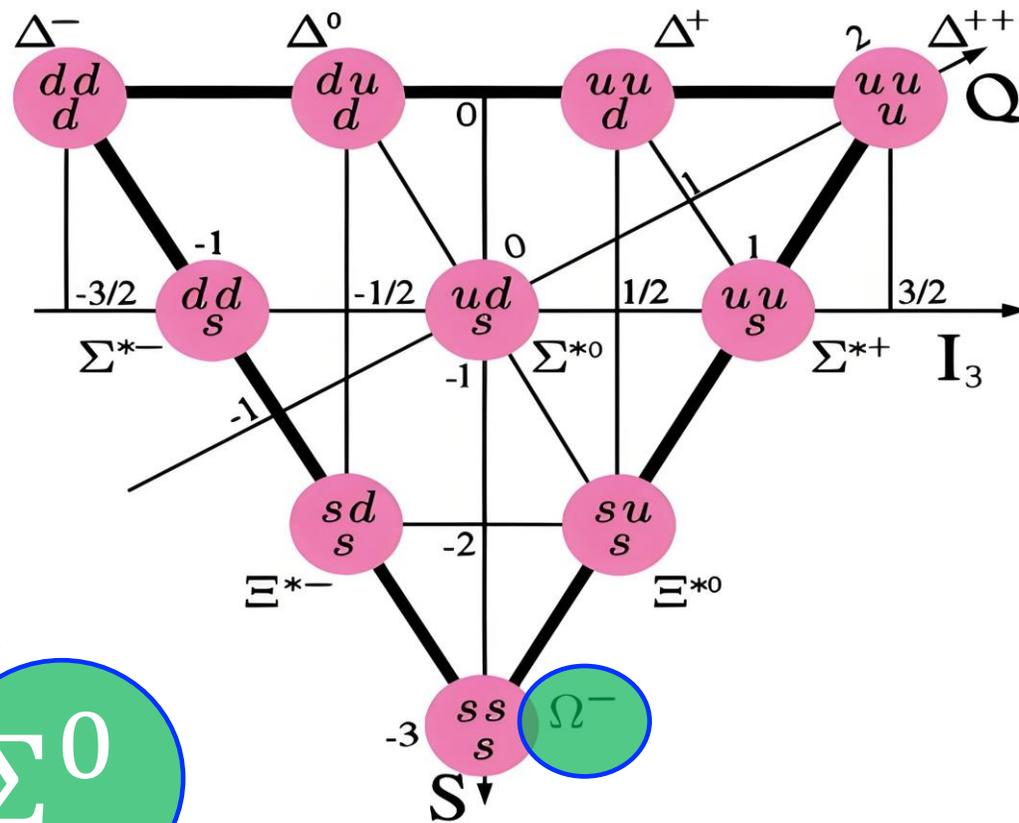
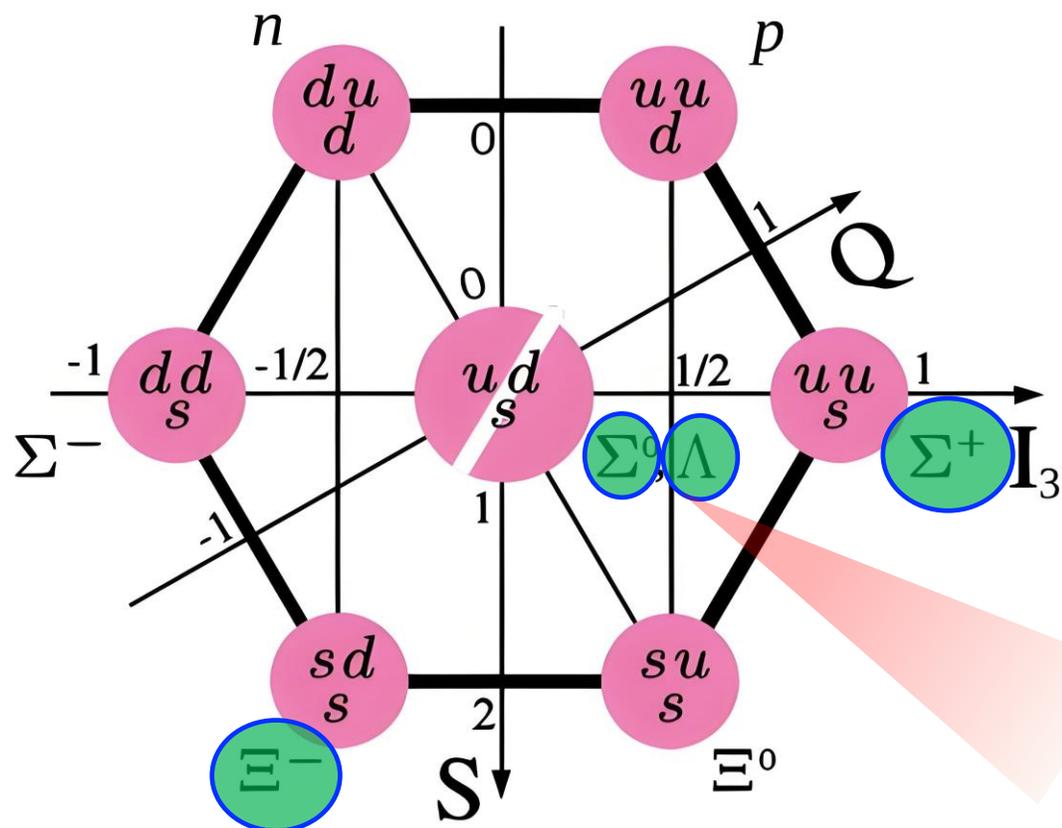
BESIII: Phys. Rev. D 107. 072010 (2023)

The “Average” denotes the updated weighted average value including our measurement.

/// More BESIII results are coming.....

- Study of $\Omega^- \rightarrow \Xi^0 l^- \bar{\nu}_l$
- $\Delta S = 2$ forbidden modes
-

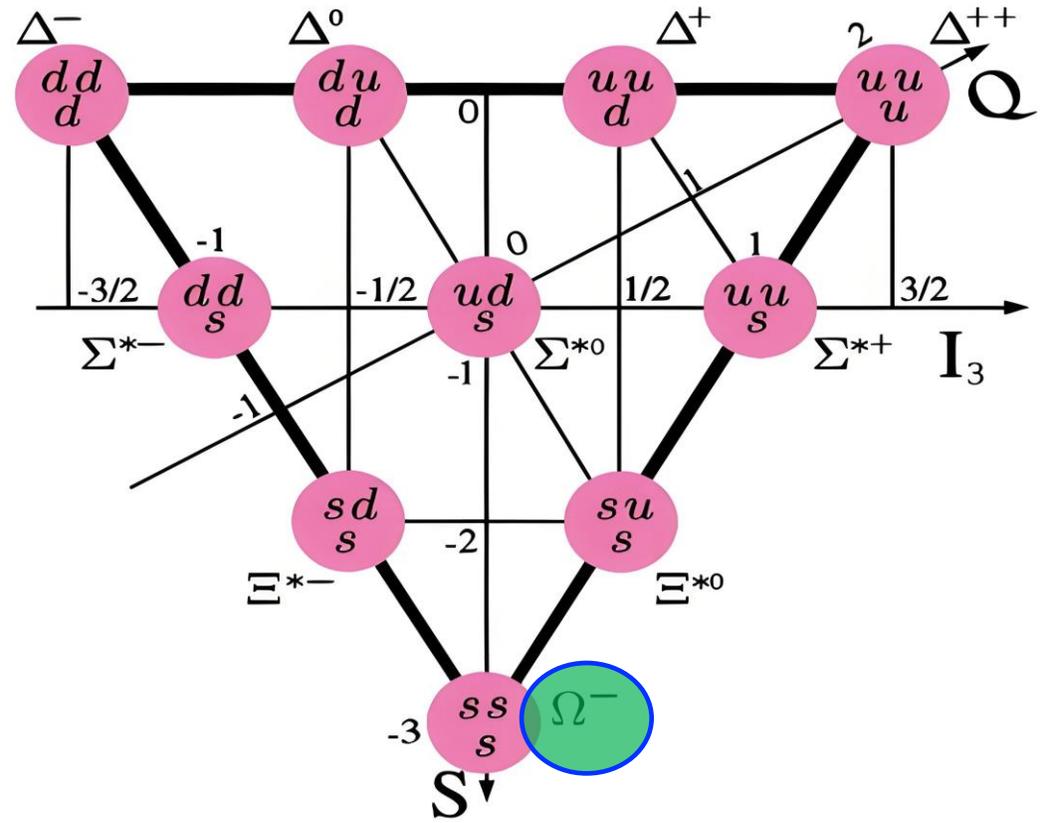
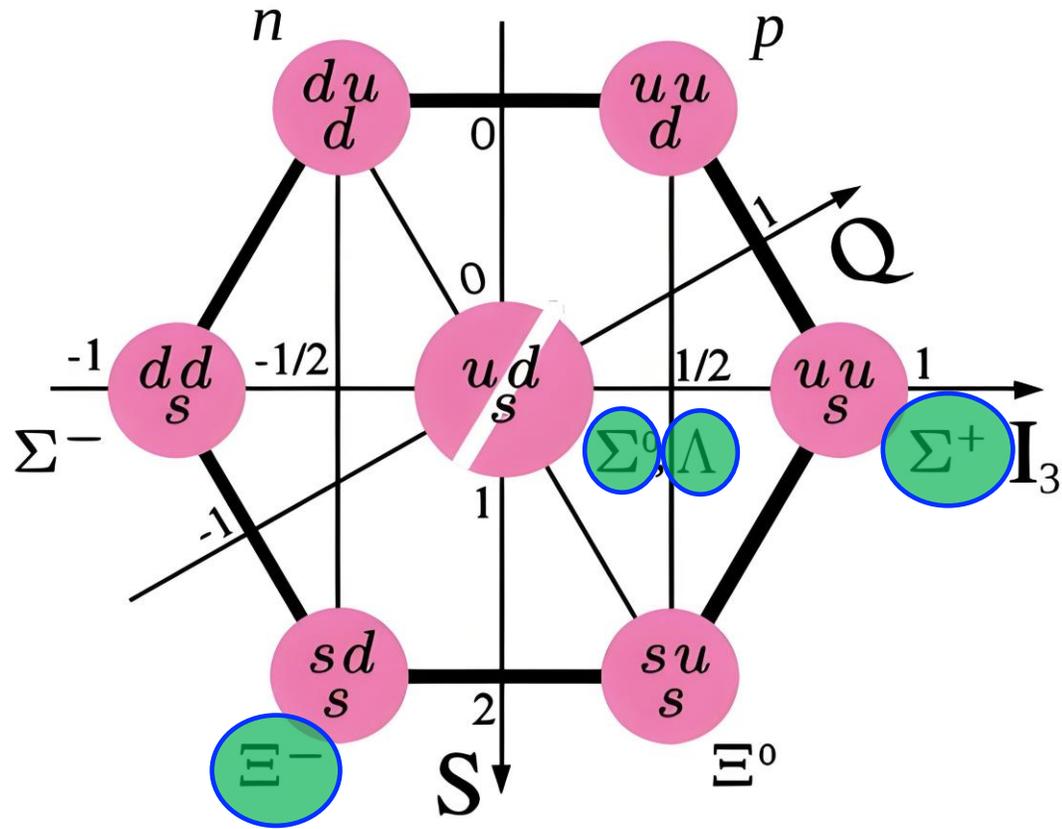


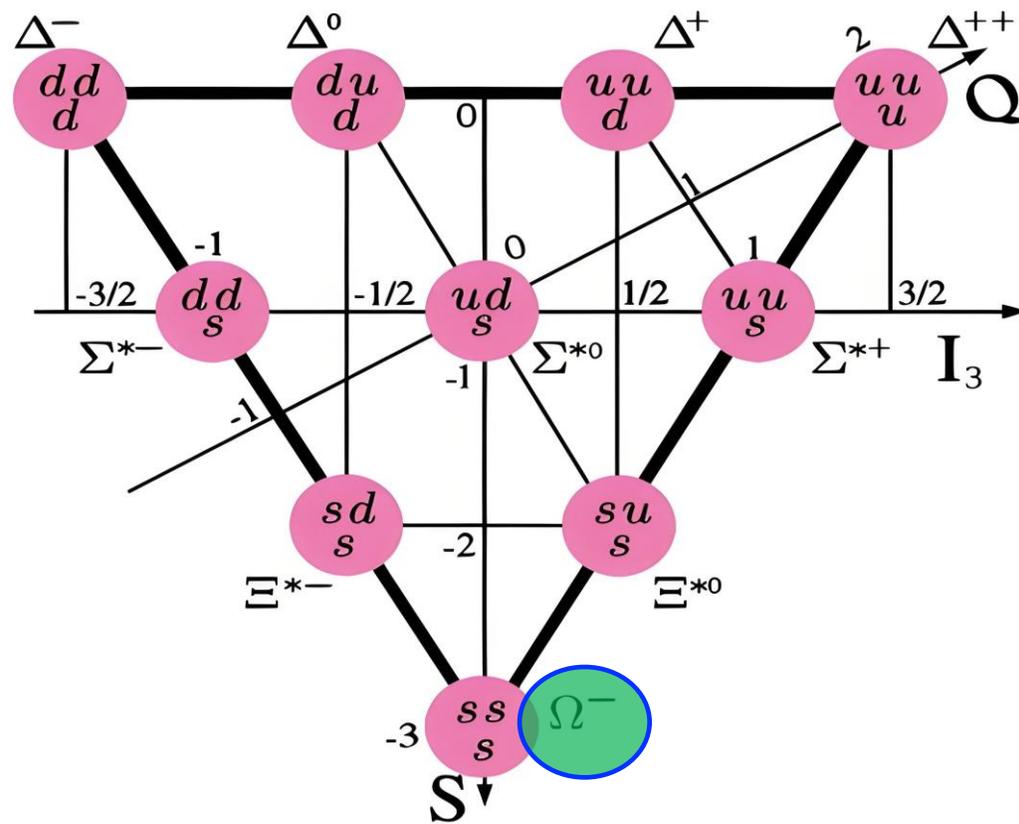
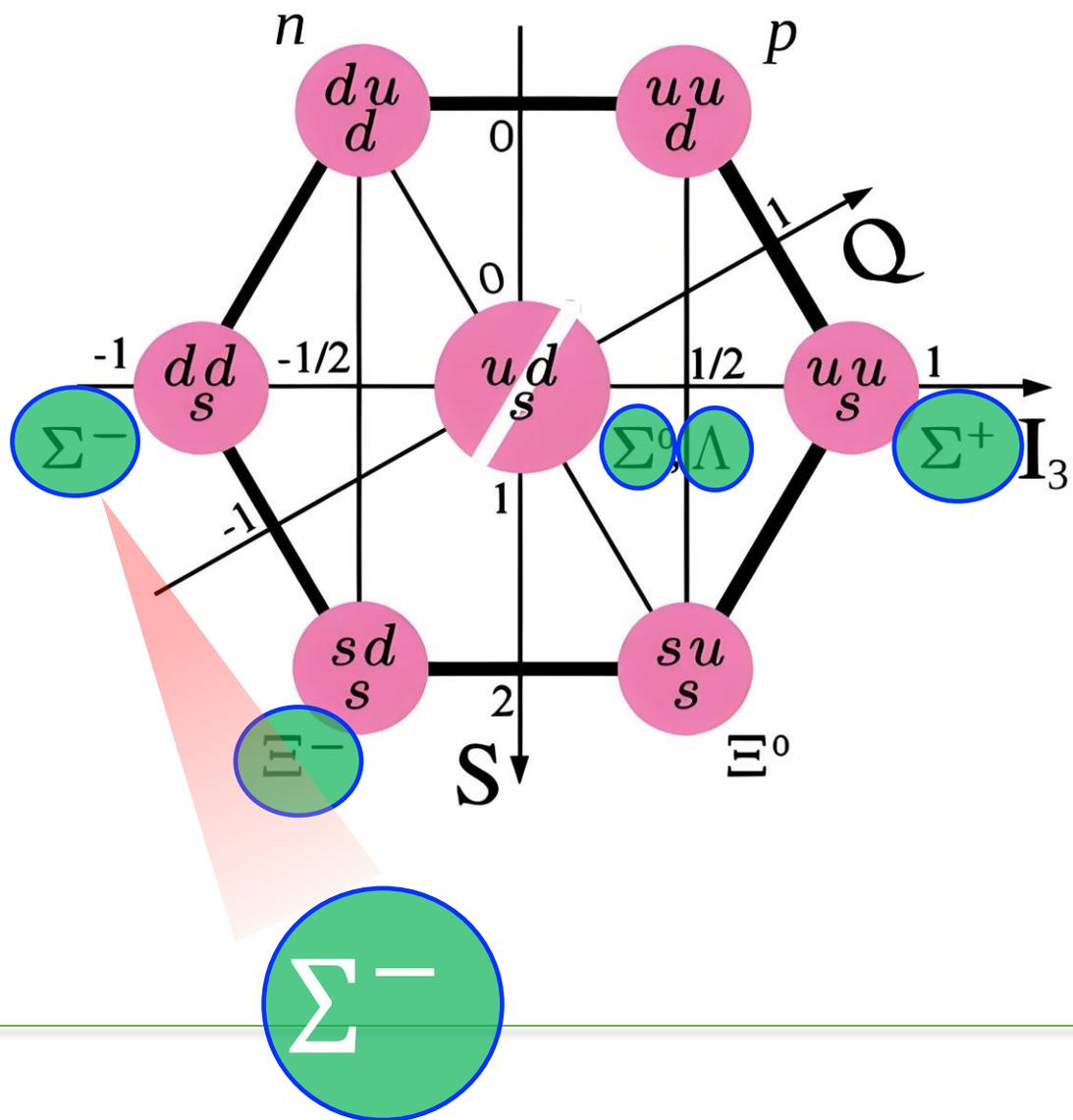


Σ^0 DECAY MODES

<i>Mode</i>		<i>Fraction (Γ_i / Γ)</i>	<i>Scale Factor/ Conf. Level</i>	<i>P(MeV/c)</i>	
Γ_1	$\Lambda\gamma$	$\sim 100\%$		74	▼
Γ_2	$\Lambda\gamma\gamma$	$<3\%$	CL=90%	74	▼
Γ_3	Λe^+e^-	[1] $(5) \times 10^{-3}$		74	▼

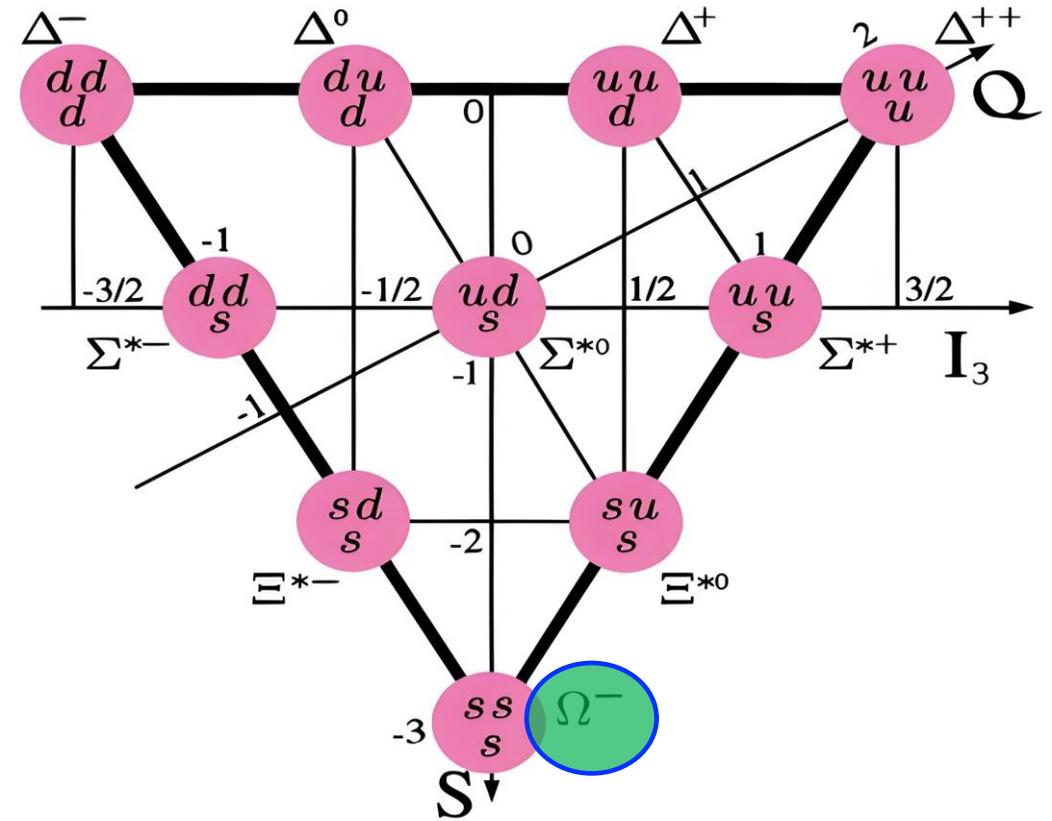
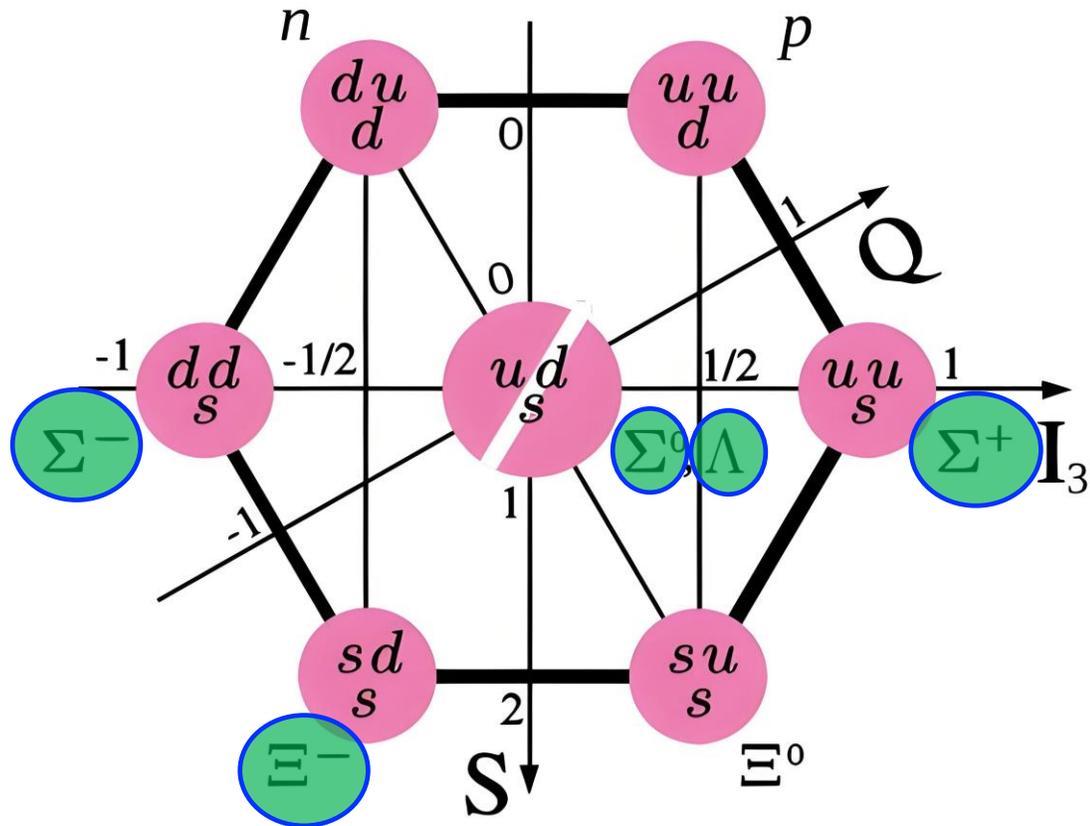
[1] A theoretical value using QED.

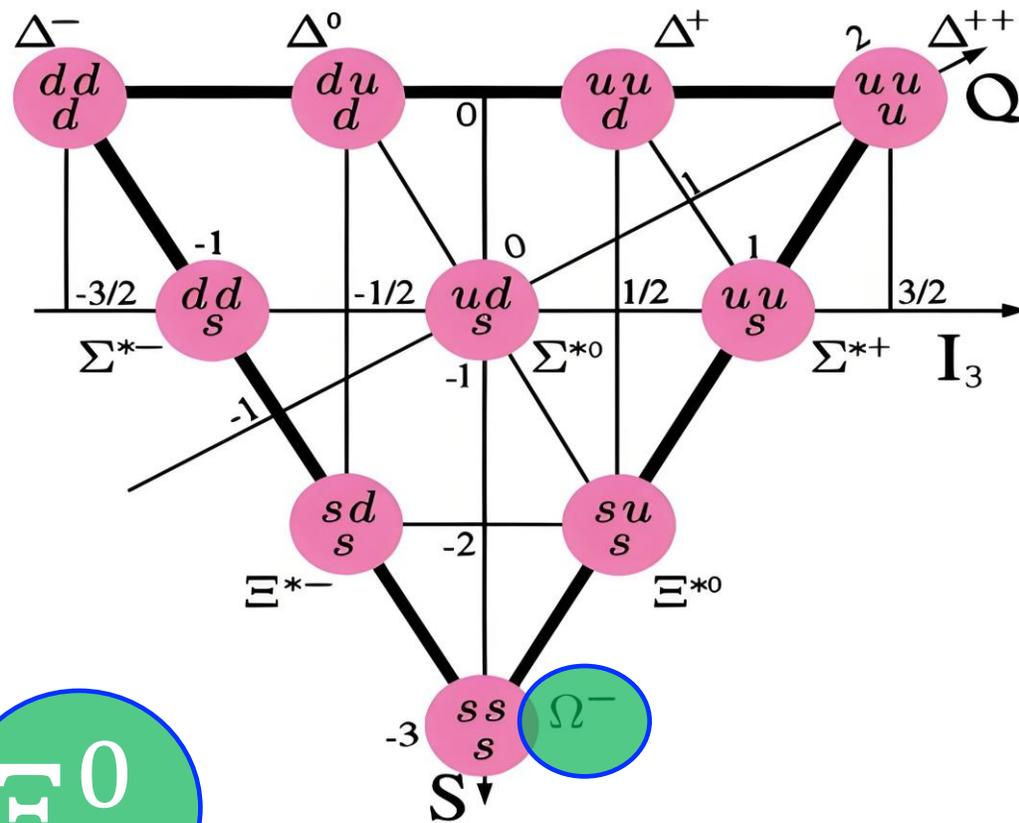
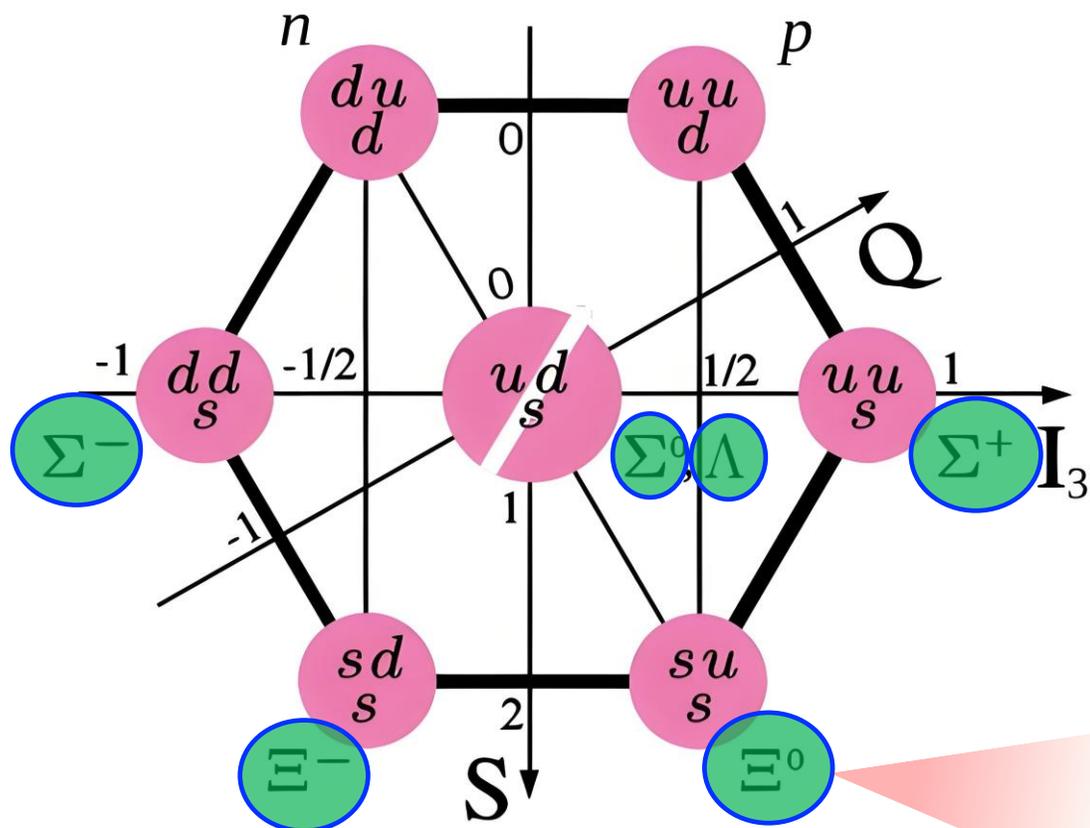




Σ^- DECAY MODES

<i>Mode</i>		<i>Fraction (Γ_i / Γ)</i>	<i>Scale Factor/ Conf. Level</i>	<i>P(MeV/c)</i>	
Γ_1	$n\pi^-$	$(99.848 \pm 0.005) \%$		193	▼
Γ_2	$n\pi^-\gamma$	[2] $(4.6 \pm 0.6) \times 10^{-4}$		193	▼
Γ_3	$ne^-\bar{\nu}_e$	$(1.017 \pm 0.034) \times 10^{-3}$		230	▼
Γ_4	$n\mu^-\bar{\nu}_\mu$	$(4.5 \pm 0.4) \times 10^{-4}$		210	▼
Γ_5	$\Lambda e^-\bar{\nu}_e$	$(5.73 \pm 0.27) \times 10^{-5}$		79	▼
Γ_6	$\Sigma^+ X$	$< 1.2 \times 10^{-4}$	CL=90%		▼





Ξ^0 DECAY MODES

Mode		Fraction (Γ_i / Γ)	Scale Factor/ Conf. Level	P(MeV/c)	
Γ_1	$\Lambda\pi^0$	$(99.524 \pm 0.012) \%$		135	▼
Γ_2	$\Lambda\gamma$	$(1.17 \pm 0.07) \times 10^{-3}$		184	▼
Γ_3	$\Lambda e^+ e^-$	$(7.6 \pm 0.6) \times 10^{-6}$		184	▼
Γ_4	$\Sigma^0\gamma$	$(3.33 \pm 0.10) \times 10^{-3}$		117	▼
Γ_5	$\Sigma^+ e^- \bar{\nu}_e$	$(2.52 \pm 0.08) \times 10^{-4}$		120	▼
Γ_6	$\Sigma^+ \mu^- \bar{\nu}_\mu$	$(2.33 \pm 0.35) \times 10^{-6}$		64	▼



Confirm the efficiency (0.4M signal MC)

	Xi0 -> Sigma+ e nu	effi	relative effi	anti-Xi0 -> anti-Sigma- e nu	effi	relative effi	total
ST	26225	13.11%	-	27481	13.74%	-	13.43%
only rec p	24983	12.49%	95.26%	23069	11.53%	83.95%	12.01%
only rec pi0	19398	9.70%	73.97%	20849	10.42%	75.87%	10.06%
only rec Sigma+	18494	9.25%	70.52%	17558	8.78%	63.89%	9.01%
only rec e	11769	5.88%	44.88%	11885	5.94%	43.25%	5.91%
rec all tracks	6441	3.22%		5877	2.94%		3.08%

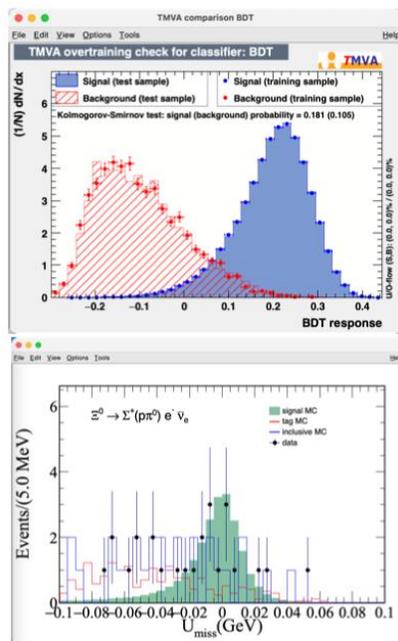
Expect Signal Num 172

Expect Signal Num 61

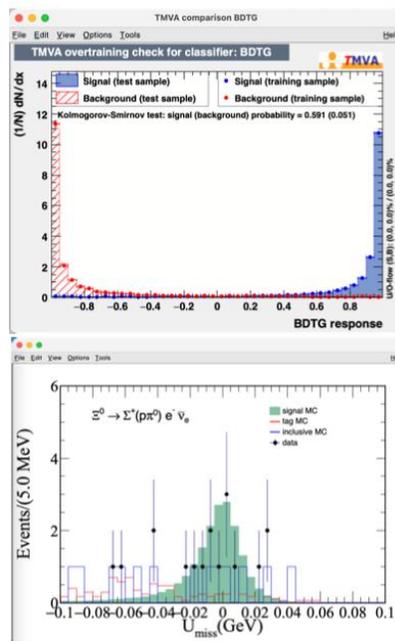


Try different models

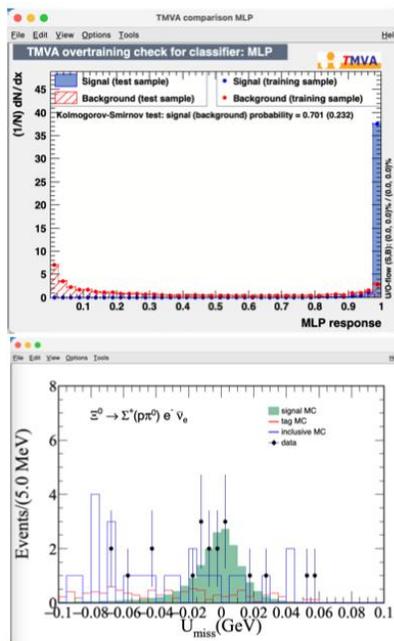
BDT method



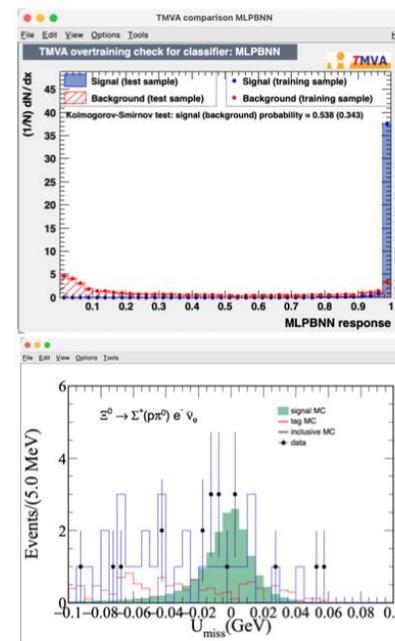
BDTG method



MLP method



MLPBNN method



Background can be well suppressed.

But the signal efficiency still smaller than 3%.

Expected number of signal < 30

Before TMVA training, the expected number of signal ~ 60

/// Summary

- **Hyperons are a laboratory for strong interaction, weak interaction, baryon structure and symmetry studies. BESIII provides huge amount quantum-correlated hyperon pairs!**
- Time for a precise and robust $|V_{us}|$ determination from hyperons!
- Update form factor measurement from hyperon semi-leptonic decays!
- Renew the branching fractions with absolute Br at a modern collider experiment!
- Test LFUV ratios for scalar-tensor NP!
- Search for rare decays to probe NP!
- More data are definitely required for Hyperon semileptonic weak decay study, STCF.

Thank you!

Backup
