STCF 上超子半轻衰变过程$\Lambda \to pe^{-}\bar{\nu}_e$的预研究

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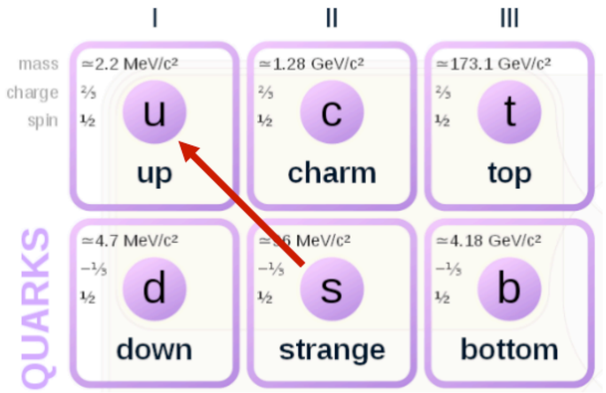
Outline

Motivation: Extract the solid CKM matrix element $|V_{us}|$

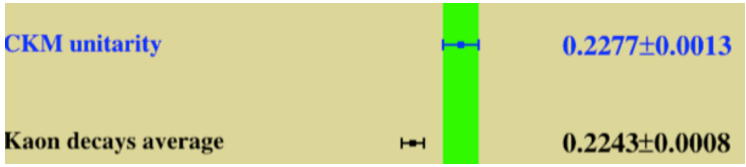
Phys. Rev. D 70, 114036



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

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

- $|V_{us}|$ describes the transition between s and a u quark
- Results from kaon decays indicate a 2.3σ deviation from CKM matrix unitary



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

- $\mathcal{B}_{\Lambda\to pe^-\bar{\nu}_e}$, $g_{av} \equiv \frac{g_1(0)}{f_1(0)}$, $g_w \equiv \frac{f_2(0)}{f_1(0)}$ from experimental measurement
- Assume $g_{av2} \equiv \frac{g_2(0)}{f_1(0)}=0$
- Get $f_1(0)$ through g_{av} measurement and LQCD input $g_1(0)$

Current research of the $|V_{us}|$ from different decays

PDG(2024): from independent measurements

$$|V_{ud}|^2+|V_{us}|^2+|V_{ub}|^2=0.9984\pm0.0007$$

2.3 σ tension ⟺

Through CKM unitarity

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

$|V_{ud}|$: Most precise; results from different decays are consistent at O(10^{-4})

$|V_{us}|$: there are different results from different decays as shown below.

$|V_{ub}|$: Small（$|V_{ub}|^2\cong1.7\times10^{-5}$） → The effect could be ignored in current precision.

Most precise	**Second most precise**	**Our target decay**
Kaon:2.3 σ tension from unitarity	Tau:3.7 σ tension from unitarity	Hyperon:consist with CKM unitarity
$|V_{us}|=0.22431\pm0.00085$	$|V_{us}|=0.2207\pm0.0014$	$|V_{us}|=0.2250\pm0.0027$
Cited in PDG 2024	**HFLAV 2022**	**PRL 92.251803(2004)**

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

but show large uncertainty.

Current research of the Form Factor from hyperon decays

	$\Lambda \to N$	$\Sigma \to N$
$f_1(0)/f_1^{SU(3)}$		
This work	0.963 ± 0.061	0.993 ± 0.059
Quark model [11]	0.987	0.987
Quark model [12]	0.976	0.975
χPT [20]	1.027	1.041
χPT [22]	$1.001^{+0.013}_{-0.010}$	$1.087^{+0.042}_{-0.031}$
$1/N_c$ expansion [23]	1.02 ± 0.02	1.04 ± 0.02
lattice QCD [31]		0.957 ± 0.01
$g_1(0)/f_1(0)$		
This work	0.708 ± 0.047	-0.327 ± 0.046
Cabibbo model [7]	0.731	-0.341
Quark model [13]	0.724	-0.260
Soliton model [17]	0.718 ± 0.003	-0.340 ± 0.003
Soliton model [18]	0.68	-0.27
$1/N_c$ expansion [23]	0.73	-0.34
lattice QCD [29, 30]		-0.287 ± 0.052
Exp [4]	0.718 ± 0.015	-0.340 ± 0.017
$f_2(0)/f_1(0)$		
This work	0.752 ± 0.074	-1.042 ± 0.090
Cabibbo model [7]	1.066	-1.292
Quark model [13]	1	-0.962
Soliton model [17]	0.637 ± 0.041	-0.709 ± 0.036
Soliton model [18]	0.71	-0.96
$1/N_c$ expansion [23]	0.90	-1.02
lattice QCD [29]		-1.52 ± 0.81
Exp [4]	1.32 ± 0.81 [65]	-0.97 ± 0.14

From PDG

The most precise Measurement

Cited from JHEP06(2024)122

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

INSPIRE s

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**				
$-0.719 \pm 0.016 \pm 0.012$	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

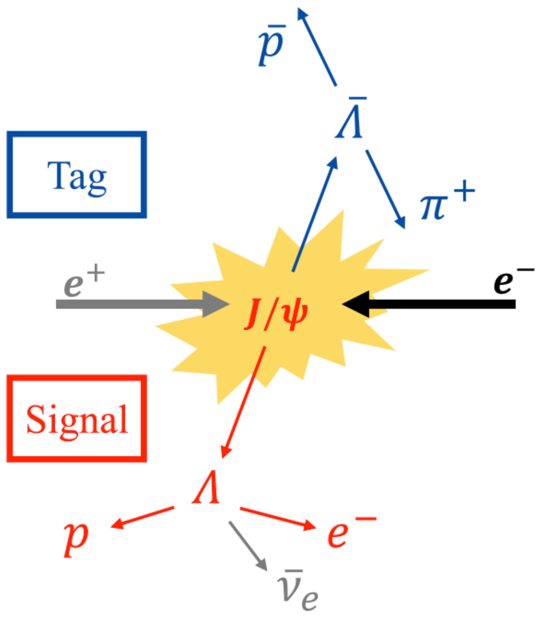
$g_{av} = g_1(0)/f_1(0)$ included in PDG are obtained 30 years ago

$g_w = f_2(0)/f_1(0)$ not cited by PDG for its high uncertainty

The more precise measurement of Form Factor at STCF is important.

Measure the branching faction

Double tag method



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

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

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

Get the absolute branching faction

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

$\mathcal{B}_{tag}$: Branching faction of $\bar{\Lambda} \to \bar{p}\pi^+$

$\mathcal{B}_{sig}$: Branching faction of $\Lambda \to pe^-\bar{\nu}_e$

N_{tag} : ST yield N_{sig} : DT yield

ϵ_{tag} : ST efficiency $\epsilon_{tag,sig}$: ST efficiency

Can be obtained in our analysis

Decay channel: $J/\psi \to \Lambda\bar{\Lambda}, \Lambda \to pe^-\bar{\nu}_e, \bar{\Lambda} \to \bar{p}\pi$

not include charge conjuration

Inclusive MC: 1 billion $J/\psi \to anything$ MC based on fast simulation

Measure the branching faction

Selection criteria at single tag

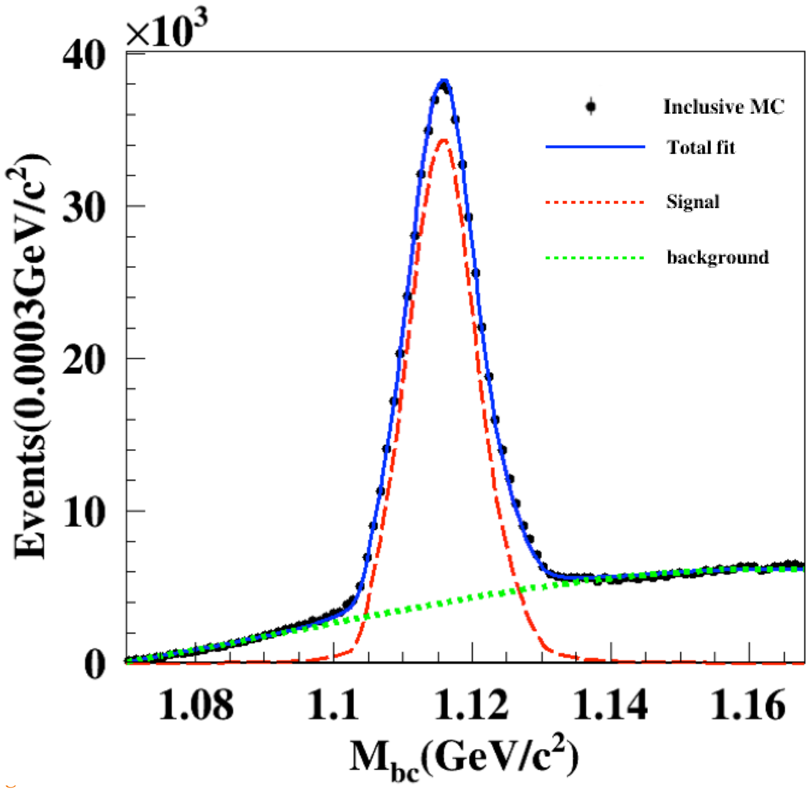
PhysRevLett.127.121802

$$M_{bc} = \sqrt{E_{beam}^2 - |\vec{P}_{ST}|^2}$$

- Good charged tracks
  - ✔ At least 2 oppositely-charged tracks
  - ✔ No vertex requirement due to existence of $\bar{\Lambda}$
  - ✔ $|cos\theta| < 0.93$

- Reconstruction of $\bar{\Lambda}$
  - ✔ Looping over all combinations with positive and negative charged tracks
  - ✔ Vertex and Second Vertex Fit for $\bar{\Lambda}$ based on $\bar{p}\pi^+$ hypothesis
  - ✔ The candidates are selected from combinations with the minimum $\Delta E = E_{beam} - E_{single}$
  - ✔ Vertex/second vertex fit: $\chi^2 < 100$, $L/\sigma > 2$

P_{ST}: The momentum of the $\bar{\Lambda}$



Can get N_{tag} and ϵ_{tag} from this fit to M_{bc}

Measure the branching faction

Selection criteria at double tag

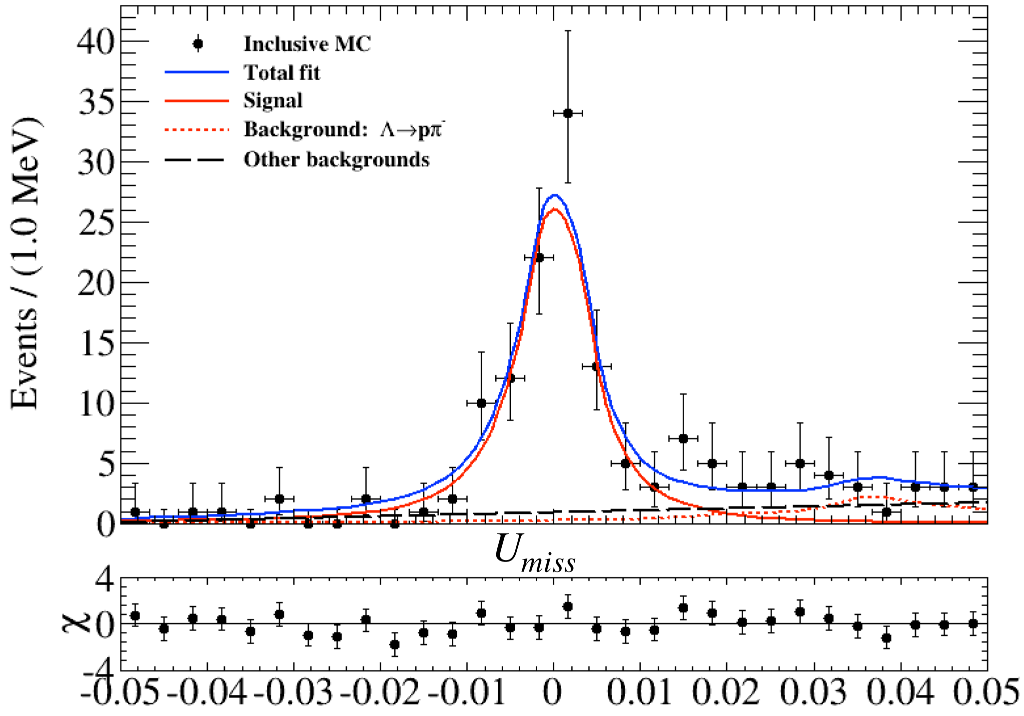
- Good charged tracks
  - ✔ 4 good tracks(another 2 tracks based on single tag)
  - ✔ No vertex requirement due to existence of Λ
  - ✔ $|cos\theta| < 0.93$
  - ✔ $\Sigma_i^4 Q_i = 0$
- Reconstruction of Λ
  - ✔ Vertex and second vertex Fit for Λ
  - ✔ Decay length >0
  - ✔ $\chi^2 < 100$
- Particle identification
  - ✔ Require one track to be electron strictly

    The other track is assumed to be a proton

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

E_{miss}: The energy of the missing neutrino

P_{miss}: The momentum of the missing neutrino



Can get N_{sig} and $\epsilon_{tag,sig}$ from this fit to U_{miss}

Measure the branching faction

Calculation of branching faction

$\epsilon_{tag} = 37.85\ \%$

$\epsilon_{tag,sig} = 14.13\ \%$

$N_{tag} = 455937 \pm 800$

$N_{sig} = 104.3 \pm 11.8$

$$\mathscr{B}_{sig} = \frac{N_{sig}/\epsilon_{tag,sig}}{N_{tag}/\epsilon_{tag}} = (6.12 \pm 0.61) * 10^{-4}$$

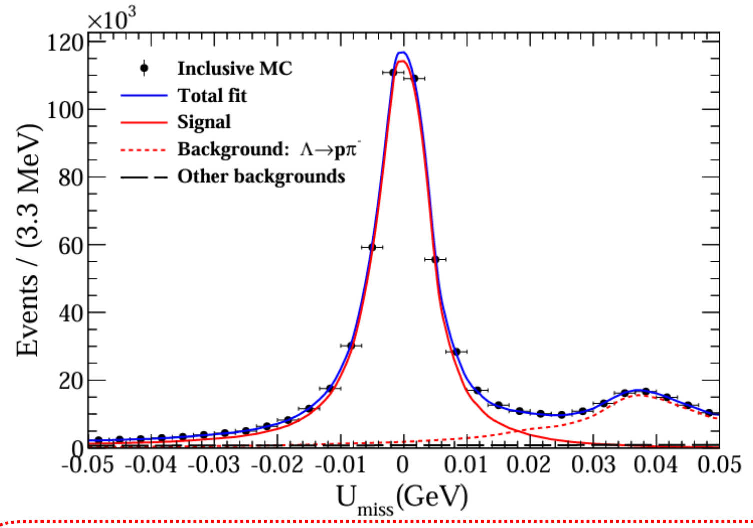
$$\mathscr{B}_{input} = 6.00 * 10^{-4}$$

The output branching faction is consistent with our input in 1 billion Inclusive MC, uncertainty is only statistical from N_{sig} to be 9.97%.

Further analysis and prospects

The STCF is prospected to collect 3.4 trillion J/ψ one year, then provide ~10^9 hyperon pairs per year.

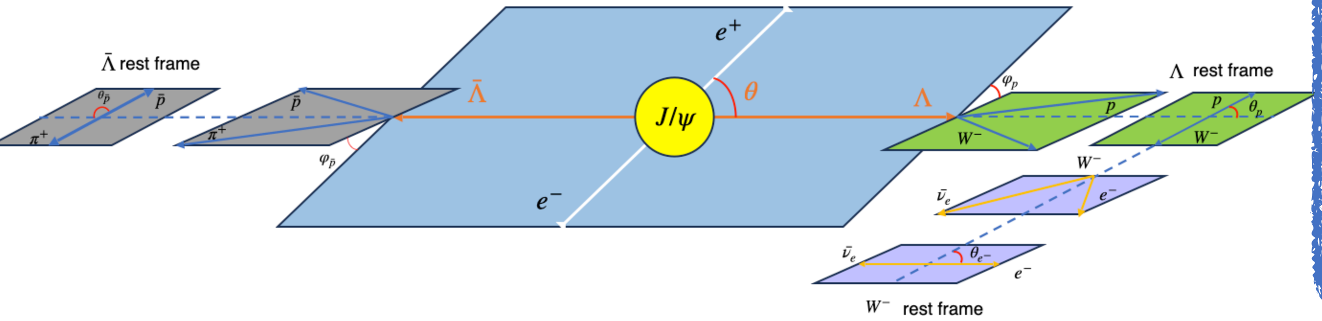
We can give a prospect of the statistical uncertainty through sampling method bootstrap.



The relative statistical uncertainty from N_{sig} can be deduced to be 0.16%， consist with our input too.

Measure the Form Factor

The Formalism for this decay



Definition of the helicity angles

[Phys. Rev. D 108, 016011]

$$d\Gamma \propto \mathscr{W}(\boldsymbol{\xi}; \alpha_\psi, \Delta\Phi, g_{av}^{\Lambda}, g_w^{\Lambda}, \alpha_\Lambda) \quad \Omega = (\alpha_\psi, \Delta\Phi, g_{av}, g_w, \alpha_\Lambda)$$

$$\sigma_\Lambda^{sl}(\boldsymbol{\xi}'')\Big[\mathscr{F}_0(\boldsymbol{\xi}') + \alpha_\psi \mathscr{F}_1(\boldsymbol{\xi}')$$
$$+a_\Lambda^{sl}(\xi'')\alpha_{\bar{\Lambda}}\left(\mathscr{F}_2(\xi') + \alpha_\psi \mathscr{F}_3(\xi') + \sqrt{1-\alpha_\psi^2}\cos(\Delta\Phi)\mathscr{F}_4(\xi')\right)$$
$$+I_\Lambda^{sl}(\boldsymbol{\xi}'')\alpha_{\bar{\Lambda}}\left(\mathscr{F}_2'(\boldsymbol{\xi}') + \alpha_\psi \mathscr{F}_3'(\boldsymbol{\xi}') + \sqrt{1-\alpha_\psi^2}\cos(\Delta\Phi)\mathscr{F}_4'(\boldsymbol{\xi}')\right)$$
$$+\sqrt{1-\alpha_\psi^2}\sin(\Delta\Phi)\left(a_\Lambda^{sl}(\xi'')\mathscr{F}_5(\xi') + I_\Lambda^{sl}(\xi'')\mathscr{F}_5'(\xi') + \alpha_{\bar{\Lambda}}\mathscr{F}_6(\xi')\right)\Big]$$

$\xi' = (\theta_\Lambda, \theta_p, \phi_p, \theta_{\bar{p}}, \phi_{\bar{p}}), \xi = (\theta_\Lambda, \theta_p, \phi_p, \theta_e, q^2, \theta_{\bar{p}}, \phi_{\bar{p}}), \xi'' = (\theta_e, q^2)$.

We assume the $\alpha_\Lambda = \alpha_{\bar{\Lambda}}$,$g_2(0)$=0

Parameters input

Mode	$\boldsymbol{\alpha_\psi}$	$\Delta\Phi$	$\boldsymbol{\alpha_\Lambda/\alpha_{\bar{\Lambda}}}$	$g_w^{\Lambda}/g_w^{\bar{\Lambda}}$	$g_{av}^{\Lambda}/g_{av}^{\bar{\Lambda}}$
$\Lambda \to pe^-\bar{\nu}_e$	0.4748	0.7521	0.4748	1.066	0.719

The $g_{av}^{\Lambda}/g_{av}^{\bar{\Lambda}}$ value input is the most precise measurement from experiments.

The $g_w^{\Lambda}/g_w^{\bar{\Lambda}}$ value input is from Cabibbo theory.

Maximum likelihood fit

$$-\ln \mathscr{L} = -\sum_{i=1}^{N} \ln \frac{\mathscr{W}(\xi_i;\Omega)}{\mathscr{N}(\Omega)}$$

$$-\ln \mathcal{L}_{sig} = -\ln \mathcal{L}_{data} + \ln \mathcal{L}_{bkg-p\pi}$$

$$\Omega = (\alpha_\psi, \Delta\Phi, g_{av}, g_w, \alpha_\Lambda)$$

$g_{av}^{\Lambda}/g_{av}^{\bar{\Lambda}}$, $g_w^{\Lambda}/g_w^{\Lambda}$ are floating.

The other 3 parameters are fixed.

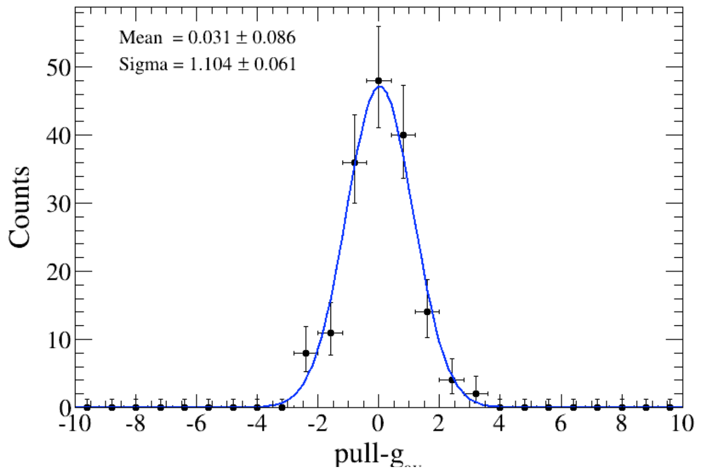
Normalization factor is got using mDIY MC

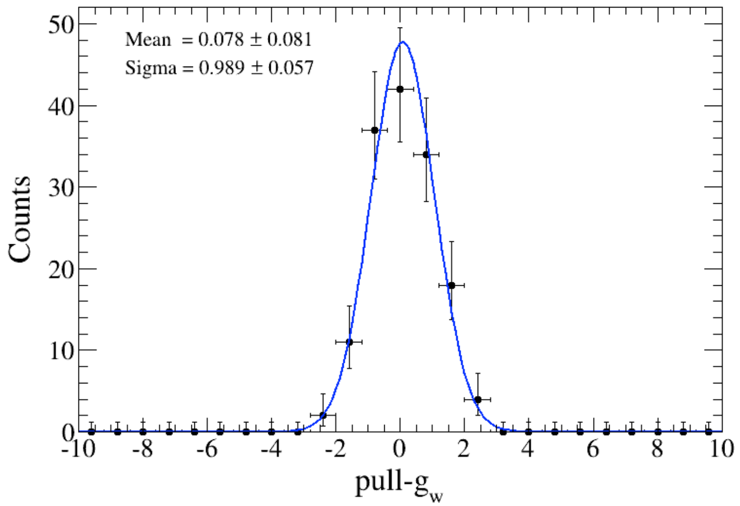
Contributions from backgrounds can be subtracted

The dominated contributions from $p\pi$ is considered

Selection criteria is similar to measuring $\mathscr{B}$ besides U_{miss} cut.

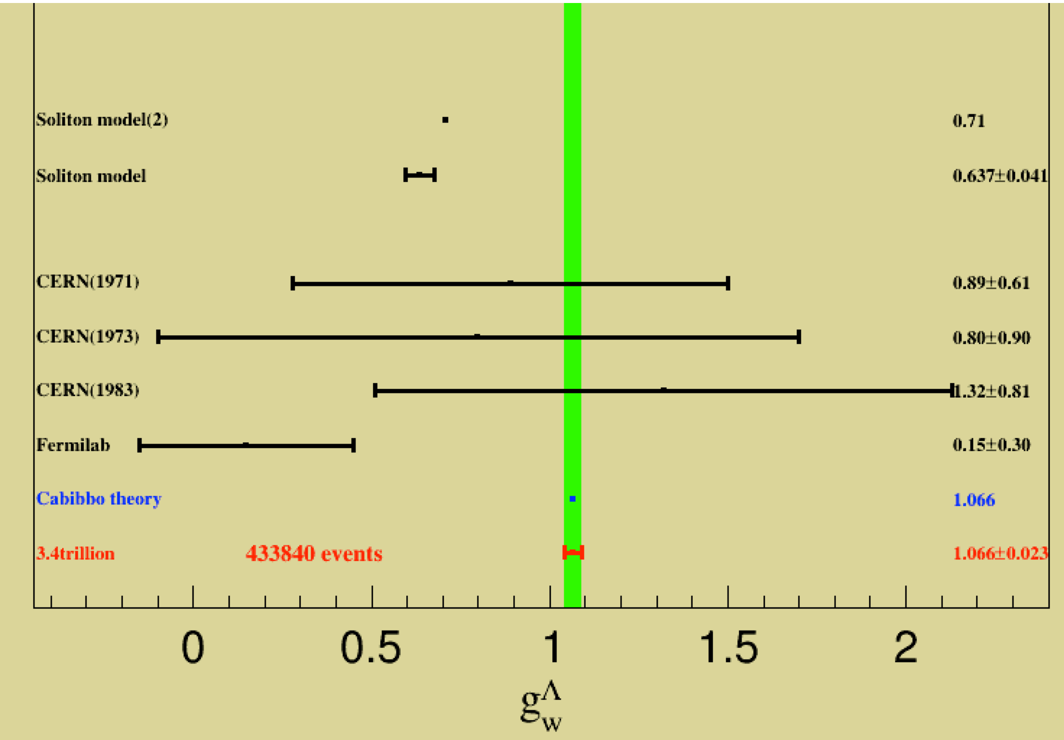
I/O check for our method

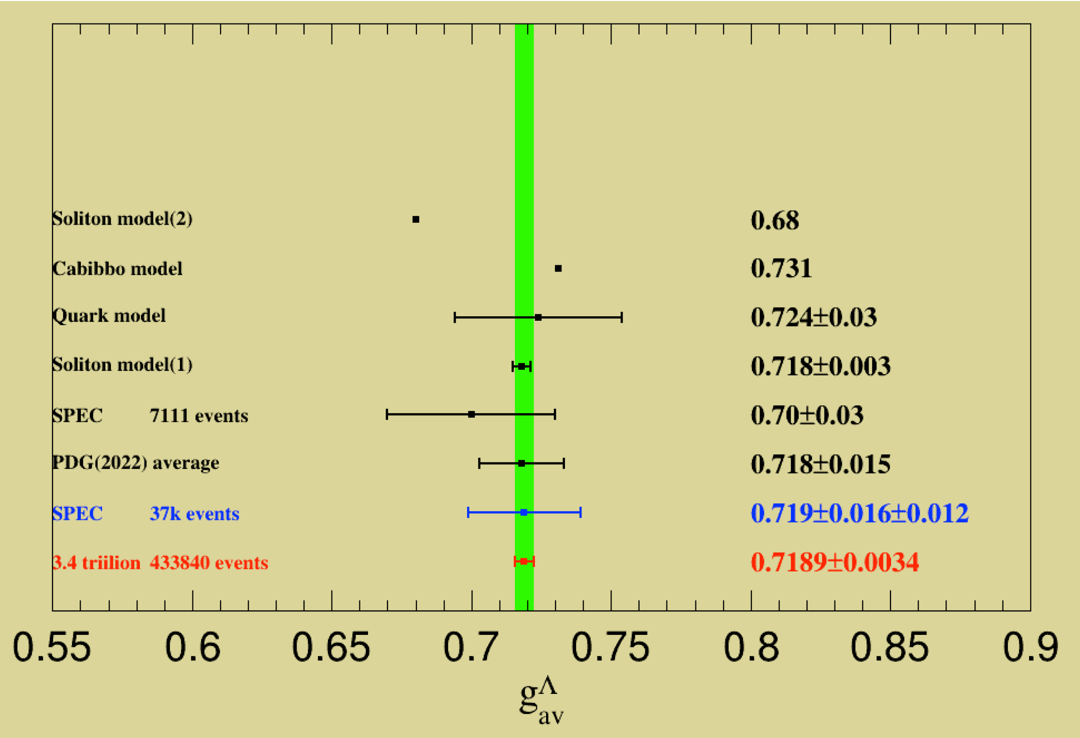




It should be a standard normal distribution.

Results of our fit





a prospect of the statistical uncertainty through sampling method bootstrap same as measuring BF.

Calculation of $|V_{us}|$

Phys. Rev. D 70, 114036

$$\int_{q^2_{\min}}^{q^2_{\max}} \frac{\Gamma_{e,\,\mathrm{SM}}}{dq^2} dq^2 = \frac{\mathcal{B}_{B_1\to B_2+\ell+\bar{\nu}_l}}{\tau_{B_1}},$$

$$\frac{\Gamma_{e,\,\mathrm{SM}}}{dq^2} = \frac{G_F^2\,|V_{us}|^2\,\Delta^5}{60\pi^3}[(1-\frac{3}{2}\delta+\frac{6}{7}\delta^2)f_1(q^2)^2+\frac{4}{7}\delta^2 f_2(q^2)^2 + (3-\frac{9}{2}\delta+\frac{12}{7}\delta^2)g_1(q^2)^2+\frac{6}{7}\delta^2 f_1(q^2)f_2(q^2)],$$

$$f_1(q^2) = f_1(0)\times[1+q^2(\frac{1}{m_V^2}+\frac{1}{m_V^2+\alpha_R^{-1}})],$$

$$f_2(q^2) = f_2(0)\times[1+q^2(\frac{1}{m_V^2}+\frac{1}{m_V^2+\alpha_R^{-1}}+\frac{1}{m_V^2+2\alpha_R^{-1}})],$$

$$g_1(q^2) = g_1(0)\times[1+q^2(\frac{1}{m_A^2}+\frac{1}{m_A^2+\alpha_R^{-1}})],$$

Through $g_{av} \equiv \frac{g_1(0)}{f_1(0)}$, $g_{av} \equiv \frac{f_2(0)}{f_1(0)}$, $g_1(0) = -0.9263 \pm 0.0023$(From LQCD)

Physics Letters B 686 (2010) 36–40

We can get the result of $|V_{us}|$

Uncertainties from our prospects and PDG

From BF(prospect):0.0002;

From LQCD:0.0005;

From PDG:0.0009;

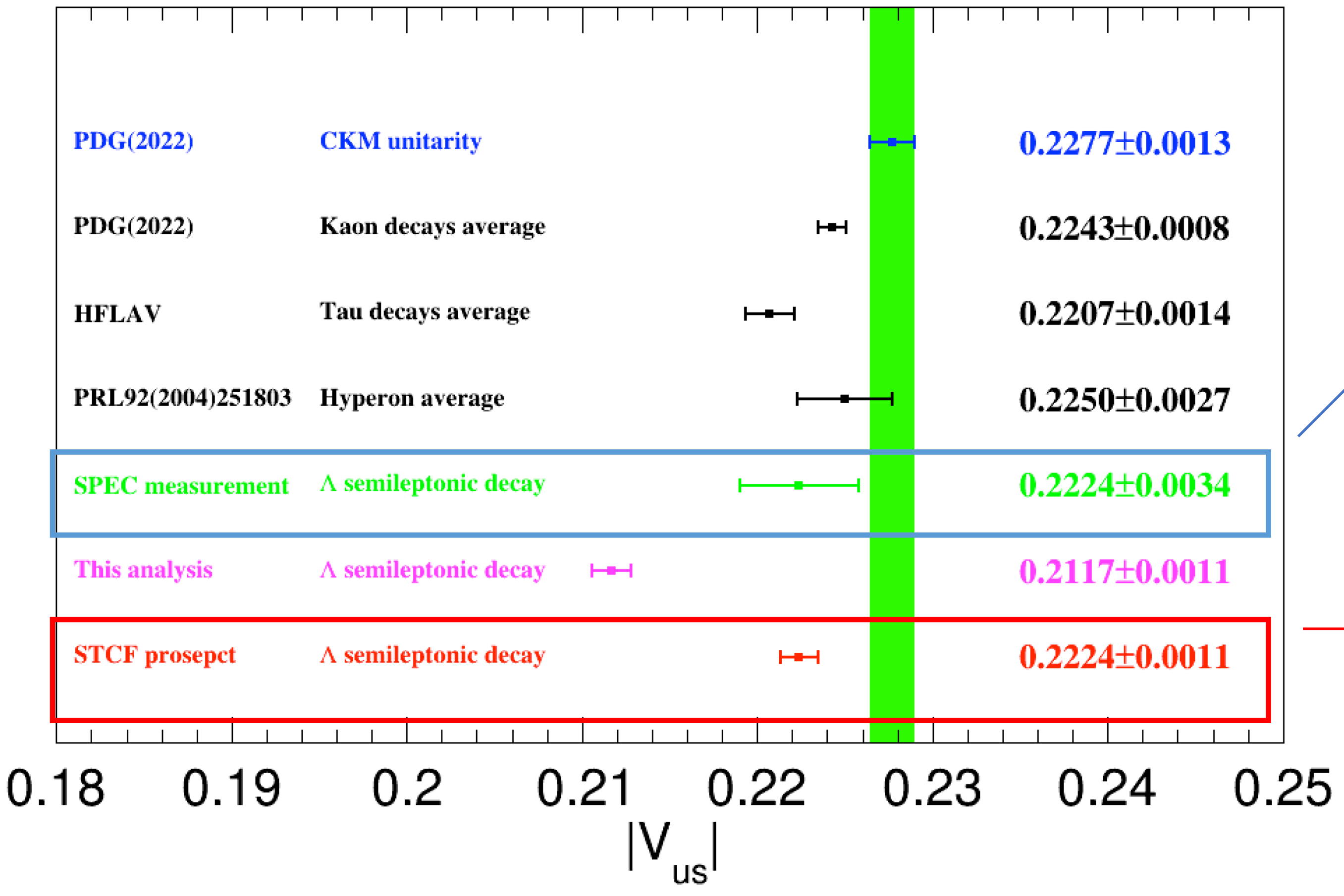
From FF(prospect):0.0004;

Through MC method

$|V_{us}|$ = 0.2117 ± 0.0011

The uncertainties of BF and FF contribution mainly come from statistical uncertainty

Comparison of $|V_{us}|$



The most precise measurement from $\Lambda \to p e^- \bar{\nu}_e$ show 1.5σ deviation from the CKM unitarity.

If our central value measurement is comparable to the most accurate one previously.

The prospect results show 4.8σ deviation from the CKM unitarity .

Summary & discussion

1.Give a prospect of the $|V_{us}|$ measurement with its uncertainty at STCF.

2.As prospect, the results will test the CKM matrix unitarity with higher precision in **Hyperon decay**.

3.The result can be combined with other SL decay to prospect **lepton flavor universality**.

1.A full **systematic uncertainty** study is not included until the design is completed finally.

2.More precise kinematic fit and uncertainty can be considered in further software framework **OSCAR**.

3.Currently, the rough prospect of statistical uncertainty depends on sampling method not real data. With the help of **OSCAR and new fast simulation**, more precise results can be given in the future.

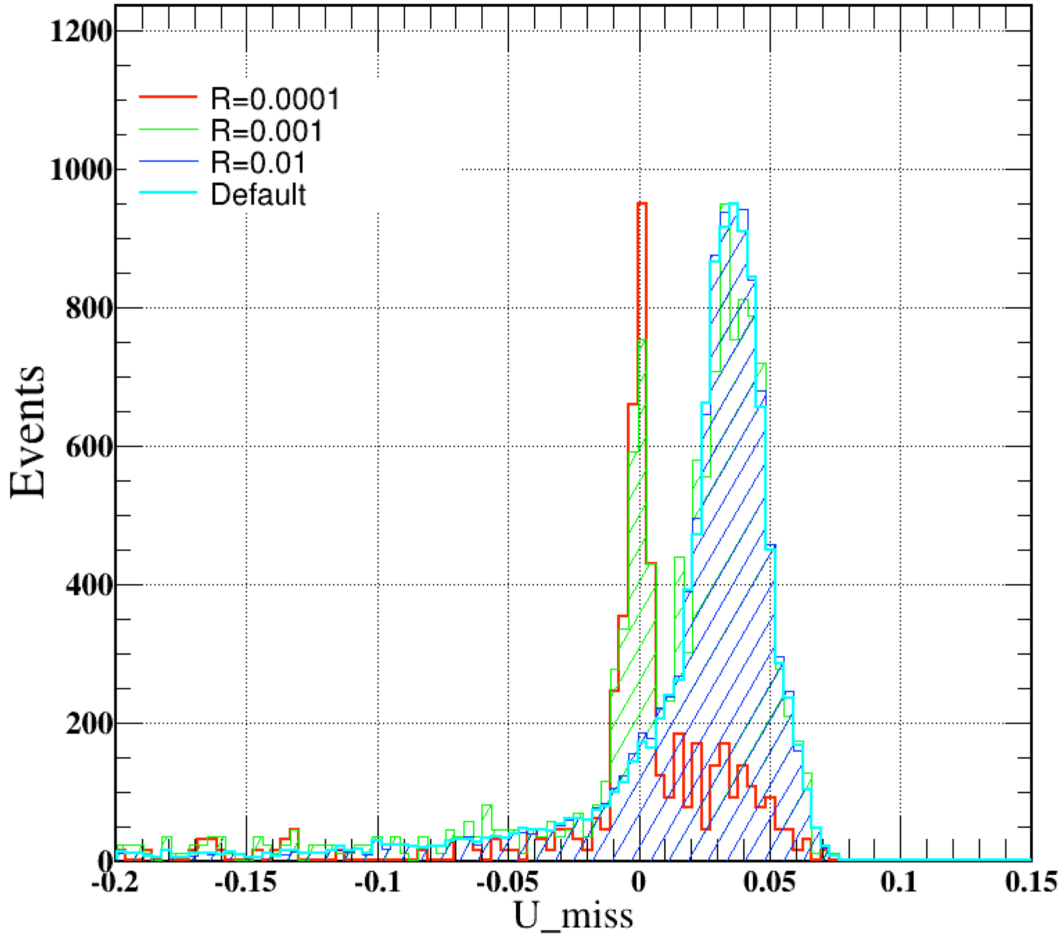
Thank you!

Back up

Table 2: The input value and their contribution to final result

Source	input value	relative uncertainty(%)	contribution to $\delta_{V_{us}}$
$\mathcal{B}(\Lambda \to pe^- \bar{\nu}_e)$	$8.32*10^{-4}$	0.17	0.0002_{stat}
g_{av}	0.7189	0.47	0.0004_{stat}
g_w	1.066	2.12	
G_F	$1.1664*10^{-5}\text{GeV}/c^2$	$5.14*10^{-5}$	0.0009
m_Λ	$1.1157\text{GeV}/c^2$	$5.38*10^{-4}$	
m_p	$0.9382\text{GeV}/c^2$	$3.09*10^{-8}$	
τ_Λ	$2.6170*10^{-10}\text{s}$	0.38	
$g_{A,NN}$	1.2574	0.10	
$g^R_{A,\Lambda N}$	1.779	0.22	0.0005

Back up



R is the factor of the misidentification pi/e

Back up

System uncertainty at BESIII

BAM-00767: Study of Lambda -> p e- anti-nu, Shun Wang et al.

Table 12: Relative systematic uncertainties (in %) in the measurement of the BF for $\Lambda \to p e^- \bar{\nu}_e$.

Sources	Uncertainties
Fitting $M_{\rm bc}$	0.37
Fitting $U_{\rm miss}$	0.80
$N_{Trk} = 4$	0.03
Λ reconstruction through vertex fit	0.20
Tracking of p	0.26
Electron detection	1.55
Kinematic fit	0.22
Total	1.83

After taking the efficiency correction and systematic uncertainty into account, the BF for $\Lambda \to p e^- \bar{\nu}_e$

.s updated to be:

$$\mathcal{B}(\Lambda \to p e^- \bar{\nu}_e) = [8.16 \pm 0.22(\text{stat}) \pm 0.15(\text{syst})] \times 10^{-4},$$

Table 15: Absolute systematic uncertainties in the measurement of the form factor.

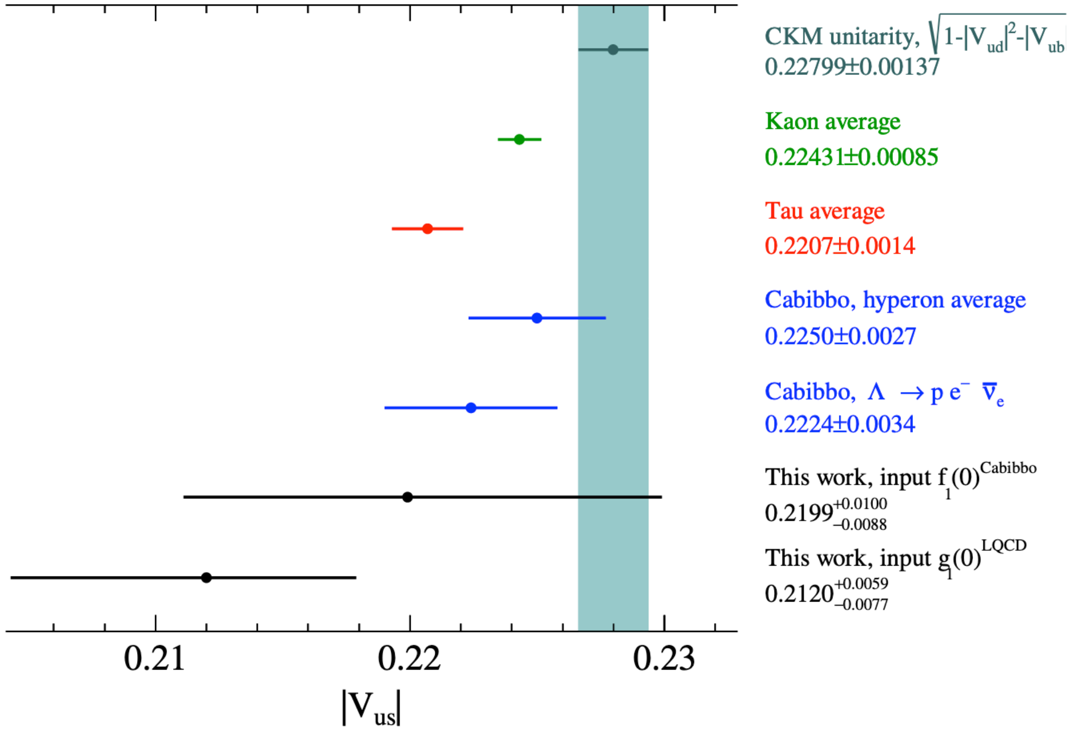
Decay mode	$\Lambda \to p e^- \bar{\nu}_e$		$\bar{\Lambda} \to \bar{p} e^+ \nu_e$		$\Lambda \to p e^- \bar{\nu}_e + c.c.$	
Form factor / Uncertainty	$f_\perp^{\Lambda}$	g_+^{Λ}	$f_\perp^{\bar{\Lambda}}$	$g_+^{\bar{\Lambda}}$	$f_\perp^{\Lambda}/f_\perp^{\bar{\Lambda}}$	$g_+^{\Lambda}/g_+^{\bar{\Lambda}}$
Fitting method – I/O check	0.013	0.001	0.006	0.004	0.032	0.001
Fitting method – Formalism	0.001	0.001	0.001	0.002	0.007	0.001
Fixed parameters The number of $\Lambda \to p\pi^-$ background events The number of other background events MC correction factors	0.272	0.004	0.337	0.012	0.217	0.006
Cut on p_e	0.132	0.008	0.160	0.006	0.123	0.004
Cut on decay length of Λ Cut on χ^2 of kinematic fit	Negligible					
Sum	0.303	0.009	0.373	0.014	0.252	0.007

This work is also carried out at BESIII now, So we can cite uncertainties just for rough estimation.

Back up

Recent results at BESIII

BAM-00767: Study of Lambda -> p e- anti-nu, Shun Wang et al.



Uncertainties from different items

① From BF: 0.0035;
② From FF: 0.0058;
③ From Lattice: 0.0005;
④ From PDG: 0.0009.

From our measurements (① + ②): 0.0068